Carsten Hast
DESY
HERA-B Collaboration
SLAC
7-May-1997

HERA-B:

An Experiment to Study CP-Violation in the B-System Using an Internal Target at the HERA Proton Ring

- HERA-B History and Collaboration
- Physics Goals of HERA-B
- HERA-B Target
- HERA-B Detector
  - ▷ Vertex ▷ Tracker ▷ Rich
- 1996 Test Run
- Trigger and DAQ
- Status and Timeschedules

A Brief History of HERA – B

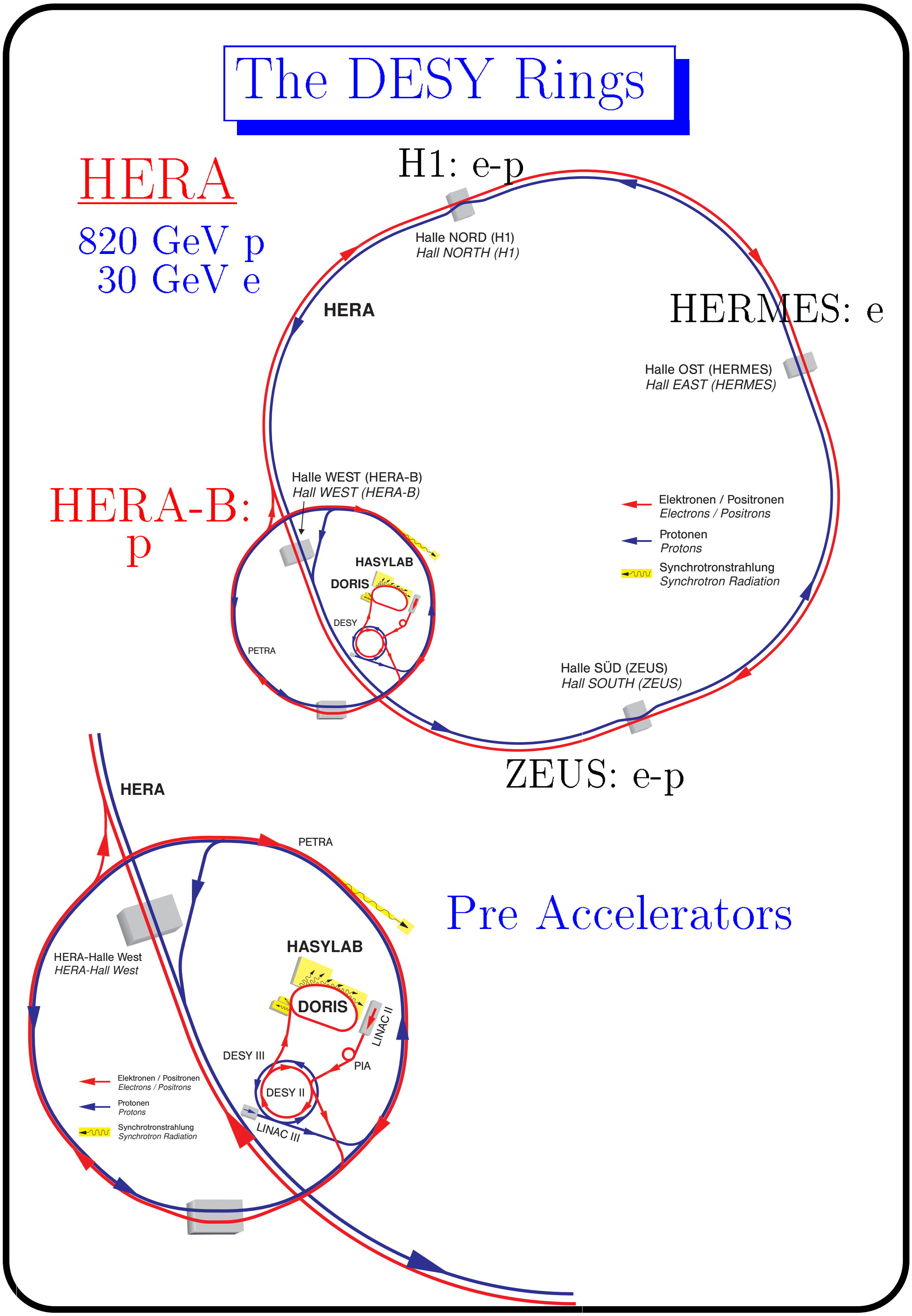
October 92	Letter of Intent
March 93	Progress Report
May 94	Proposal
June 94	Conditional Approval
October 94	Open Collaboration meeting
January 95	Technical Design Report
February 95	Final Approval of HERA – B
November 95	Vertex vessel delivered
December 95	Spectrometer magnet operational
April 96	HERA lattice modifications finished
July 96	1996 Engineering Run Started
August 96	Decision on PM's for RICH
December 96	Decision to use Sharc-DSP's as Switch and LINUX-PC's as SLT/TLT
February 97	1997 Run Started
February 97	Installation of Central Plattform Electronics Hut and Gas House
March 97	Outer Tracker Mass Production Started

The HERA – B Collaboration

250 physicists from 33 institutes

Humboldt-Universität Berlin Universität Dortmund DESY, Hamburg Universität Hamburg MPI Heidelberg Universität Heidelberg Universität Mannheim MPI München Universität Siegen DESY – IfH, Zeuthen	Germany
IHEP Beijing	P.R. China
Niels Bohr Institutet, København	Denmark
Università di Bologna and INFN	Italy
NIKHEF, Amsterdam Universiteit Utrecht	Netherlands
University of Oslo	Norway

ITEP, Moscow JINR Dubna, Moscow MEPHI, Moscow PNPI, St. Peterburg	Russia
Univerza v Ljubljani	Slovenia
University of Barcelona	Spain
Lund University	Sweden
University of Zürich	Switzerland
Ukrainian Aca. of Science, Kiev	Ukraine
University of Texas, Austin Wayne State University, Detroit Northwestern Uni., Evanston University of Houston Uni. of California, Los Angeles Yale University, New Haven Princeton University Brookhaven Nat. Lab., Upton	USA


The DESY Rings
HERA
820 GeV p
30 GeV e
H1: e-p
Halle NORD (H1)
Hall NORTH (H1)
HERA
HERMES: e
Halle OST (HERMES)
Hall EAST (HERMES)
HERA-B:
p
Halle WEST (HERA-B)
Hall WEST (HERA-B)
HASYLAB
DORIS
DESY
PETRA
Elektronen / Positronen
Electrons / Positrons
Protonen
Protons
Synchrotronstrahlung
Synchrotron Radiation
Halle SÜD (ZEUS)
Hall SOUTH (ZEUS)
ZEUS: e-p
HERA
PETRA
Pre Accelerators
HERA-Halle West
HERA-Hall West
HASYLAB
DORIS
LINAC II
DESY III
PIA
DESY II
LINAC III
Elektronen / Positronen
Electrons / Positrons
Protonen
Protons
Synchrotronstrahlung
Synchrotron Radiation

Our Goal:

Measure CP Violation in B System

Quark Transitions in Standard Modell:

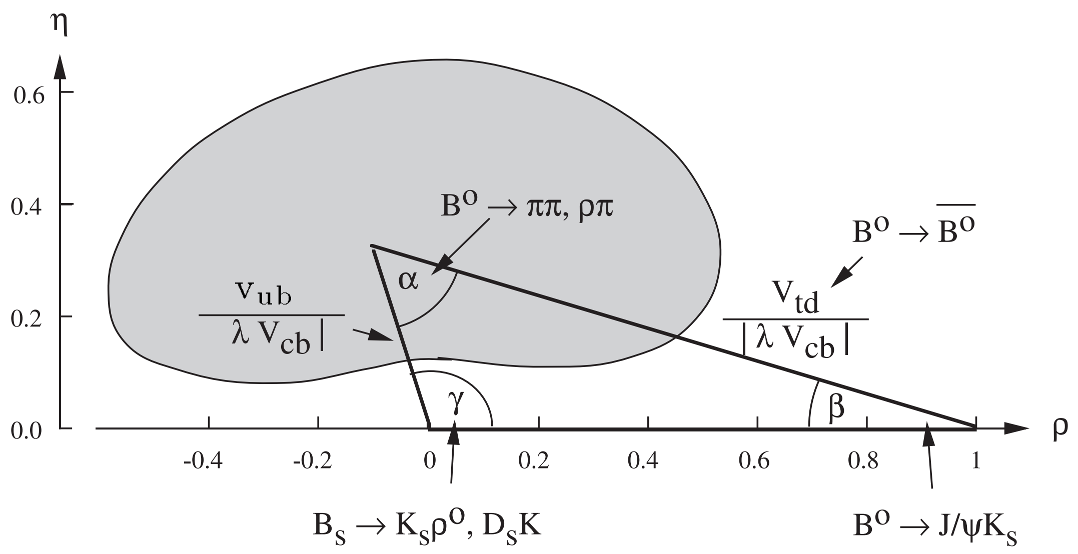
$$\mathrm{CKM-Matrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

3 Mix. $\angle$
1 Phase

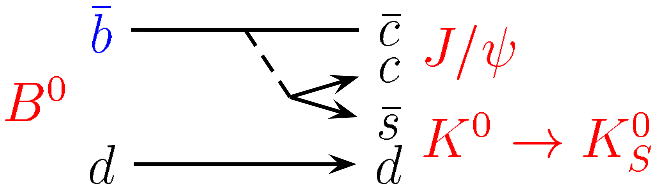
▷ unitarity: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

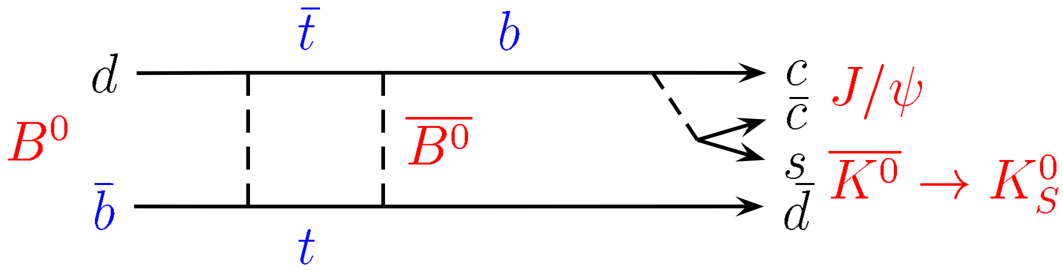
▷ $C\!\!\not{P}$: $\quad I(\mathrm{CKM}) \neq 0 \equiv \mathrm{Phase} \neq 0$

Wolfenstein Parameterization:



CP Violation in $\mathrm{B}^0 \to \mathrm{J}/\psi\,\mathrm{K}^0_\mathrm{S}$





CP violation in the interference of

$\mathrm{B}^0 \to \mathrm{J}/\psi\,\mathrm{K}^0_\mathrm{S}$ and $\mathrm{B}^0 \to \overline{\mathrm{B}^0} \to \mathrm{J}/\psi\,\mathrm{K}^0_\mathrm{S}$

Why looking at this system?

- only one dominating decay diagram
  $\Longrightarrow$ small hadronic amplitudes.
- small theoretical uncertainties.
- large CP asymmetry for $\mathrm{B}^0 \to \mathrm{J}/\psi\,\mathrm{K}^0_\mathrm{S}$
- good trigger conditions.

Principle of Measurement

Pure B^0 beam: $n(t) \propto e^{-t}\,(1 + \sin 2\beta\ \sin xt)$

Pure $\overline{B^0}$ beam: $\bar{n}(t) \propto e^{-t}\,(1 - \sin 2\beta\ \sin xt)$

(mixing parameter $x = \Delta M/\Gamma \approx 0.67$)

$$a(t) = \frac{n(t) - \bar{n}(t)}{n(t) + \bar{n}(t)} = \sin 2\beta\ sinxt$$

Time integrated asymmetry:

$$A_{int} = \frac{\int n(t)\,\mathrm{d}t - \int \bar{n}(t)\,\mathrm{d}t}{\int n(t)\,\mathrm{d}t + \int \bar{n}(t)\,\mathrm{d}t} = \sin 2\beta\ \frac{x}{1+x^2}$$

≈ 0.46

asymmetry proportional to $\sin 2\beta$

1. Count number of decays $B^0 \to J/\psi\, K^0_S$
2. Count number of decays $\overline{B^0} \to J/\psi\, K^0_S$

necessary:

tag of the initial flavour (b or $\overline{\mathrm{b}}$)

with the second B meson

Precision in $\sin 2\beta$

Statistical error:

suppress background $\rightarrow$ require B vertex

($\equiv$ cut in proper decay time, $t > t_{cut}$)

$$A_{int}(t_{cut}) = \sin 2\beta \; M_{int}(t_{cut})$$

$$\text{with} \quad M_{int}(t_{cut}) = \frac{\sin x t_{cut} + x \; \cos x t_{cut}}{1 + x^2}$$

$$\boxed{\Delta \; \sin 2\beta = \frac{1}{M_{int}(t_{cut})} \cdot \frac{1}{\sqrt{N(t_{cut}) + \bar{N}(t_{cut})}}}$$

Mixing of the tagging B:

Probability of flavour change before tagging:

$$f_M = \frac{x^2}{2(1 + x^2)}$$

$$n_{obs}(t) = n(t)(1 - f_M) + \bar{n}(t) f_M$$

$$\bar{n}_{obs}(t) = \bar{n}(t)(1 - f_M) + n(t) f_M$$

$$\boxed{A_{obs}(t_{cut}) = D_M \; M(t_{cut}) \; \sin 2\beta}$$

$$\text{with} \quad \mathrm{D_M} = (1 - 2\mathrm{f_M}) = \frac{1}{1 + \mathrm{x}^2} \approx 0.67$$

Precision in $\sin 2\beta$ contd.

Mistagging with a probability f_T:

Dilution factor $D_T = (1 - 2f_T)$

$$\boxed{A_{obs}(t_{cut}) = D_T\, D_M\, M(t_{cut})\, \sin 2\beta}$$

$$\sin 2\beta \sim 0.5 \rightarrow A_{obs} \sim 0.15 - 0.2$$

Total Error on $\sin 2\beta$:

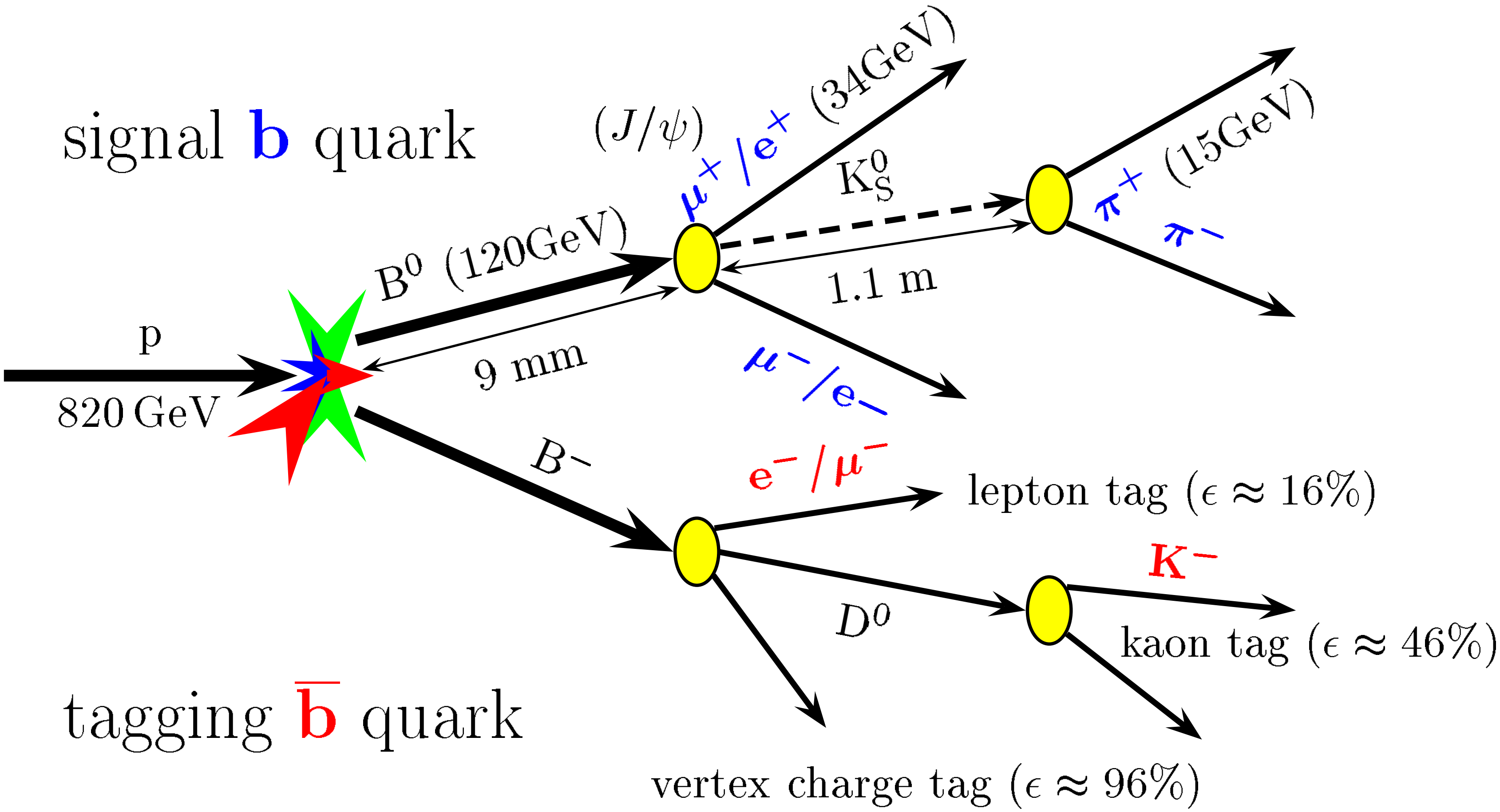
$$\boxed{\Delta \sin 2\beta = \frac{1}{M_{int}(t_{cut})} \cdot \frac{1}{P} \cdot \frac{1}{\sqrt{N_{\mathrm{B}^0}}}}$$

with tagging power $P = D_M D_T \sqrt{\epsilon_{tag}}$

N_{B^0} = Number of reconstructed B^0 mesons

$$\boxed{\Delta \sin 2\beta \approx 0.10 \Rightarrow N_{\mathrm{B}^0}\ \mathcal{O}(1500)}$$

The Golden Decay: $B^0 \to J/\psi\, K^0_S$



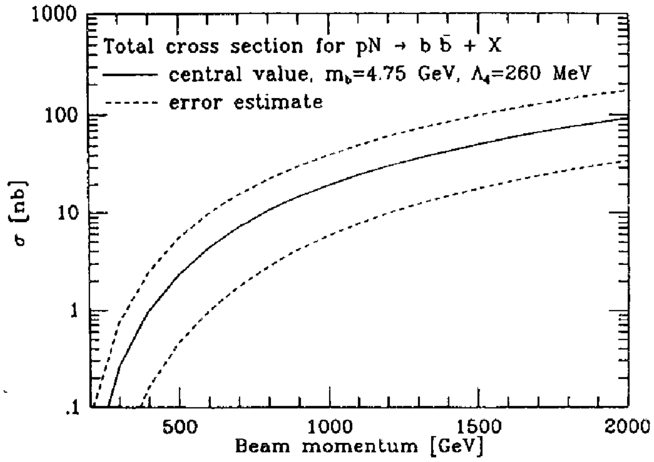
$b\bar{b}$ Cross Section

- QCD–Calculation to α_s^3

$\sigma_{b\bar{b}}^{tot} =$

12 nb @ 820 GeV

20 nb @ 1000 GeV

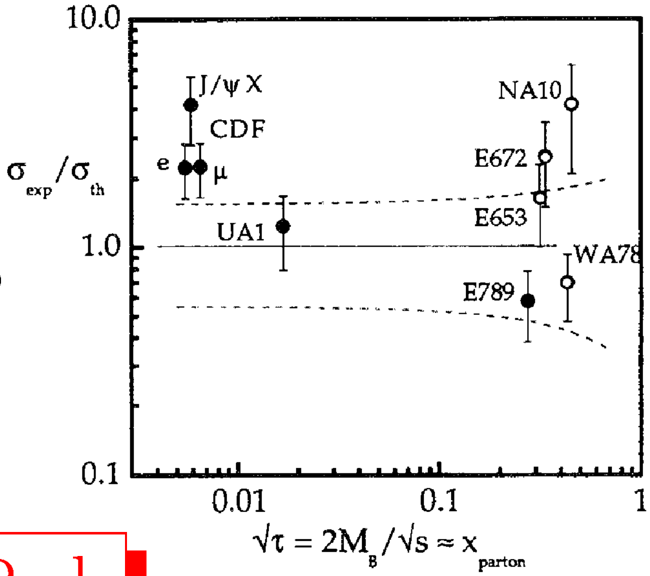


  - ▷ depends on m_b (4.5–5 GeV)
  - ▷ depends on scale for α_s calculation

- Measurements of $\sigma_{b\bar{b}}$

E789:

$\sigma_{b\bar{b}}^{tot} \approx (7 \pm 2.5)$ nb



$$\boxed{\sigma_{b\bar{b}}^{tot} \approx 6 - 12\,\text{nb}}$$

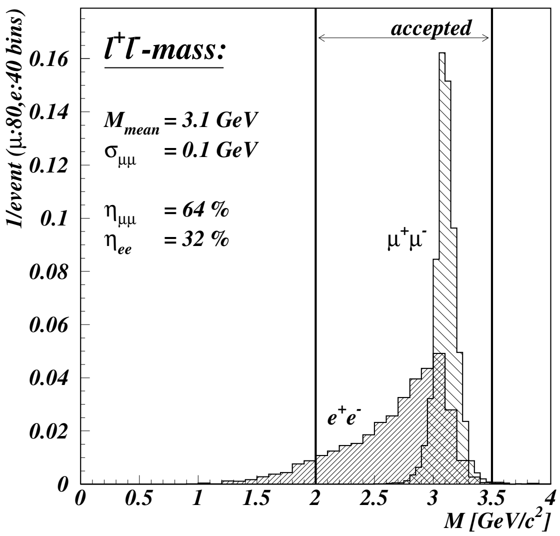
Efficiency

- Trigger Efficiency of $B^0 \rightarrow J/\psi\, K^0_S$

Reco. Masses of

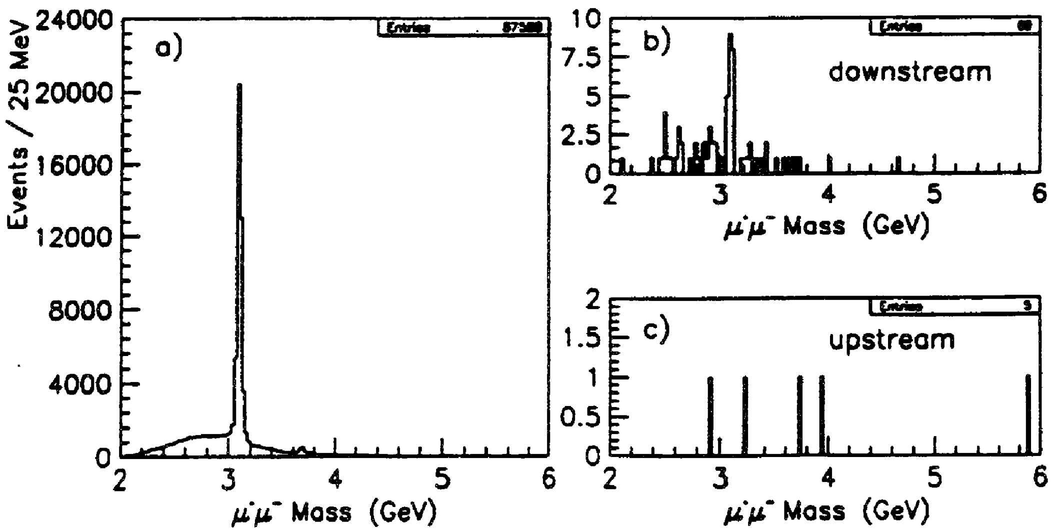
$J/\psi \rightarrow \mu^+\mu^-$

$J/\psi \rightarrow e^+e^-$



	$J/\psi \rightarrow \mu^+\mu^-$	$J/\psi \rightarrow e^+e^-$
Trigger	0.62	0.45
Tracking Leptons	0.89	0.89
Tracking K^0_S	0.61	0.61
Lepton–Identification	0.94	0.85
J/ψ / B^0 Reconstruction	0.95	0.73
Kinematical cuts	0.80	0.80
Vertex cut	0.69	0.69
Reco. Probability	≈ 0.17	≈ 0.09

J/ψ–Trigger: E789



$B^0 \to J/\psi\, X$ very clean

$B^0 \to J/\psi\, K^0_S$ even cleaner

Tag Probability

	Lepton Tag	Kaon Tag	Charge Tag
eff.(tag found)	0.16	0.46	0.96
eff.(tag correct)	0.12	0.31	0.56
eff.(tag wrong)	0.04	0.15	0.40
Dilution $D = \frac{k-f}{k+f}$	0.43	0.36	0.16
Tagging Power	0.17	0.24	0.16
$P = D \cdot \sqrt{\mathrm{eff}}$		0.31	

Background (MC Studies)

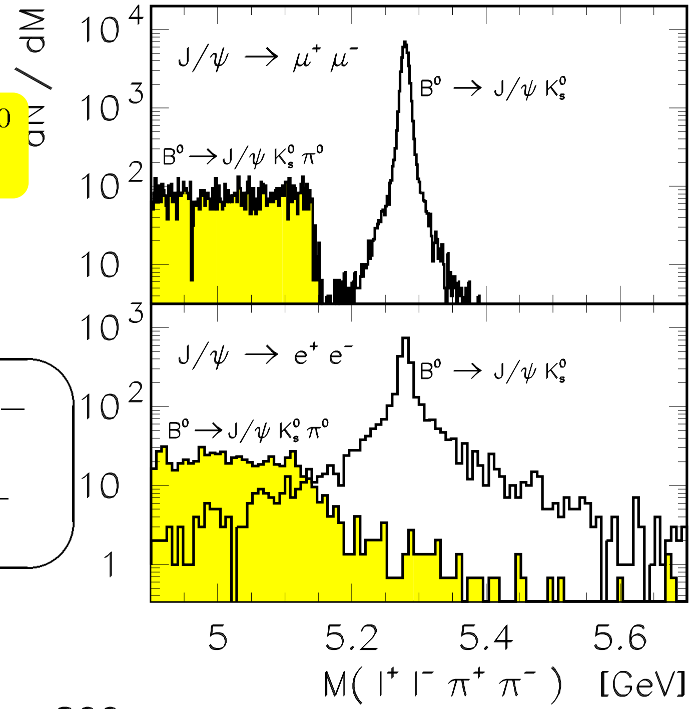
Reco. Masses of:

$B^0 \to J/\psi\, K^{*0} \to \underbrace{J/\psi\, K^0_S}_{\text{Fake } B^0 \text{ decay}}\, \pi^0$

(oposite CP Asymmetrie)

$S/B > 1600 \quad , \mu^+\mu^-$

$S/B = 170 \quad , e^+e^-$



$c\bar{c} \to l^+ l^- X$

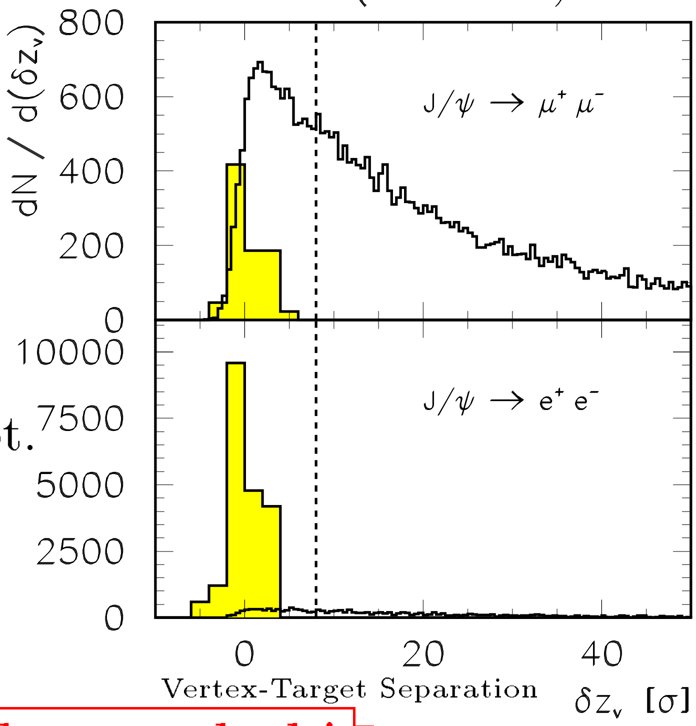
$S/B > 120 \quad , \mu^+\mu^-$

$S/B > 2 \quad , e^+e^-$

Min.Bias $\to$ Fake Lept.

$S/B > 3 \quad , \mu^+\mu^-$

$S/B > 0.6 \quad , e^+e^-$



Background ok!

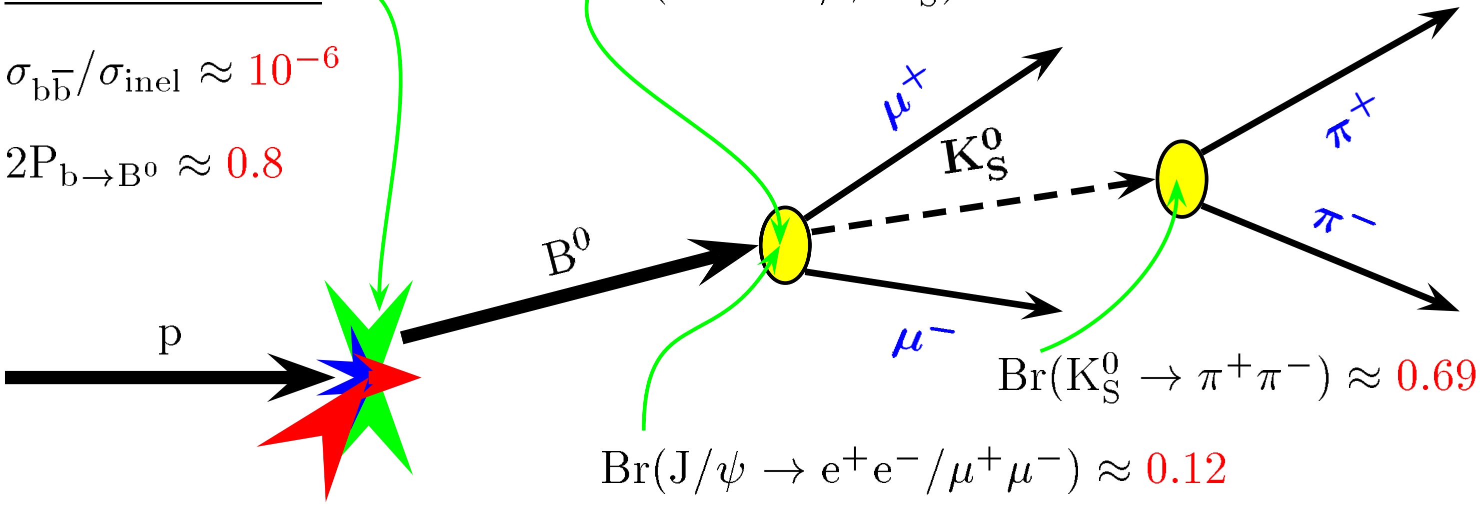
Production Rates and Reconstruction Efficiencies

production rate

$\sigma_{b\bar{b}}/\sigma_{\text{inel}} \approx 10^{-6}$

$2P_{b\to B^0} \approx 0.8$

$\text{Br}(B^0 \to J/\psi\, K^0_S) \approx 5 \cdot 10^{-4}$



$\text{Br}(K^0_S \to \pi^+\pi^-) \approx 0.69$

$\text{Br}(J/\psi \to e^+e^-/\mu^+\mu^-) \approx 0.12$

$\text{eff(trig, rec, vertex)} \approx 0.17;\quad \text{total Efficiency} \approx 4 \cdot 10^{-12}$

$\Delta \sin 2\beta = 0.13 \Longrightarrow 1500$ Events

Required interactions $\boldsymbol{\approx 4 \cdot 10^{14}}$ $(\sigma^{\text{tot}}_{b\bar{b}} = 12\,\text{nb}, 1\,\text{y} \;@\; 40\text{MHz})$

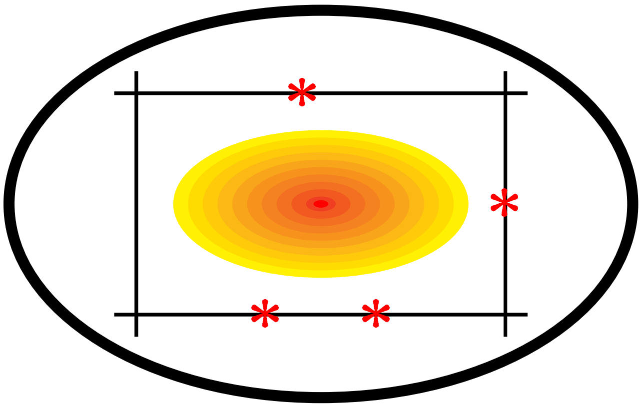
HERA-p as a B-Factory

Introduce thin wires (50 μm) inside the beam halo
$\Rightarrow$ absorb protons leaving the beam core

Requirements:

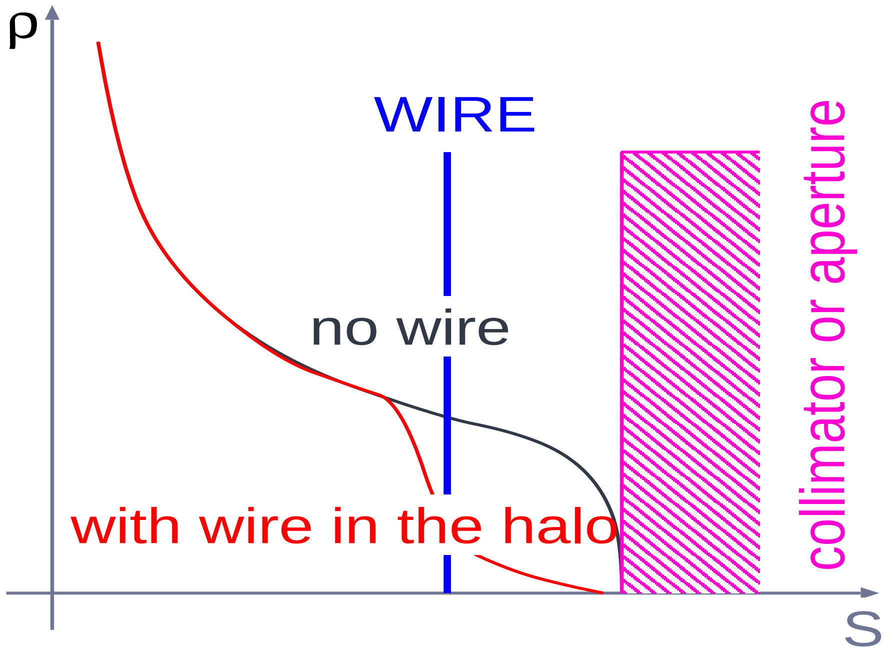
- 40 MHz rate $\Longrightarrow$ 5 IA/BX
- well localized vertices $\Longrightarrow$ 8 Targets
- no interference with ep-operation

Wire target in HERA-p:



- 8 Targets: $500 \times 50 \mu\mathrm{m}^2$ (Al, Cu, C)
- p(820 GeV) + N(target) $\Rightarrow$ X + $b\,\bar{b}$

Principle of a Halo Wire Target



Efficient competition with collimators needed !

<u>What is limiting the efficiency ?</u>

Diffusion of Halo Protons

requires: small v_D and large Z

(fast absorption)

Multiple Scattering in Target

$\Delta\epsilon = \Theta^2\beta, \quad \Theta = 14\ \mathrm{MeV/p}\sqrt{X_{int}/X_{rad}}$

requires: small β-function, low Z

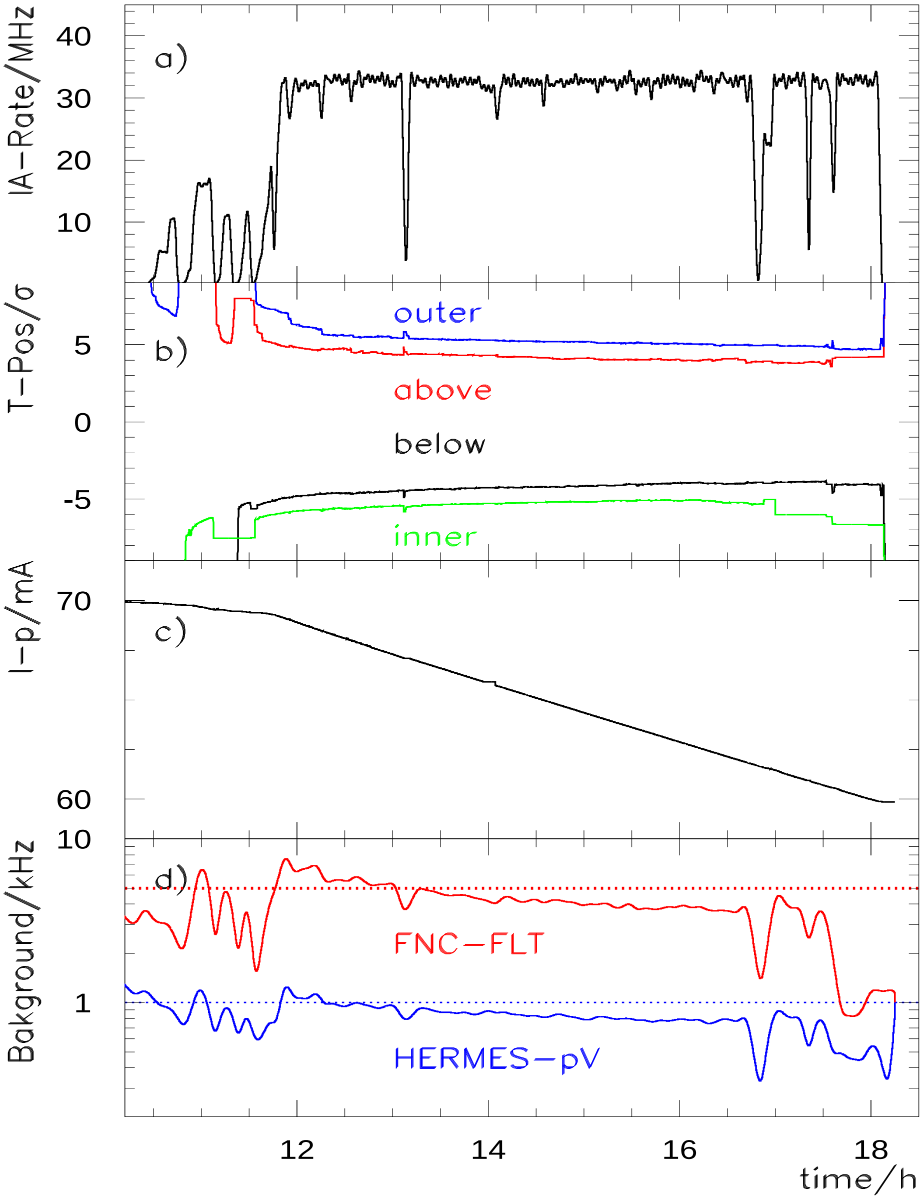
Rate Requirements

- physics goal: $\delta[\sin 2\beta] \approx 0.1...0.15$ (1 year)
  $\Rightarrow$ requires: $\approx$ 1500 events/year
- $\sigma_{b\bar{b}}$, BR's and efficiencies:
  $\Rightarrow \quad \approx 3...4 \cdot 10^{14}$ i.a./year (10^7 sec)
  $= 30...40$ MHz
- HERA - p:
  bunch frequency: $\approx$ 8.2 MHz
  $I = 80$ mA: $N_p = 10^{13}$ p, $\tau \approx 100$ h
  $\Rightarrow$ natural loss rate: $\approx$ 30 MHz
- Target Efficiency ϵ_T:
  ϵ_T = Interaction Rate / HERA-p Loss Rate

required target performance:
$< 5 >$ interactions per bx
$\mathrm{eff}_{\mathrm{Target}} > 50\%$

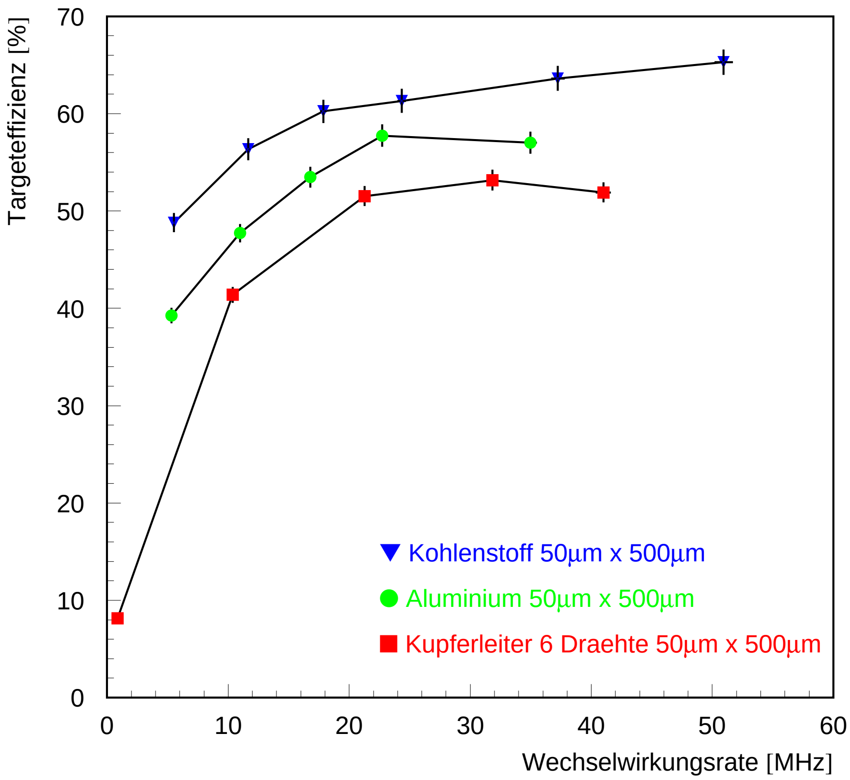
Target Run in '96

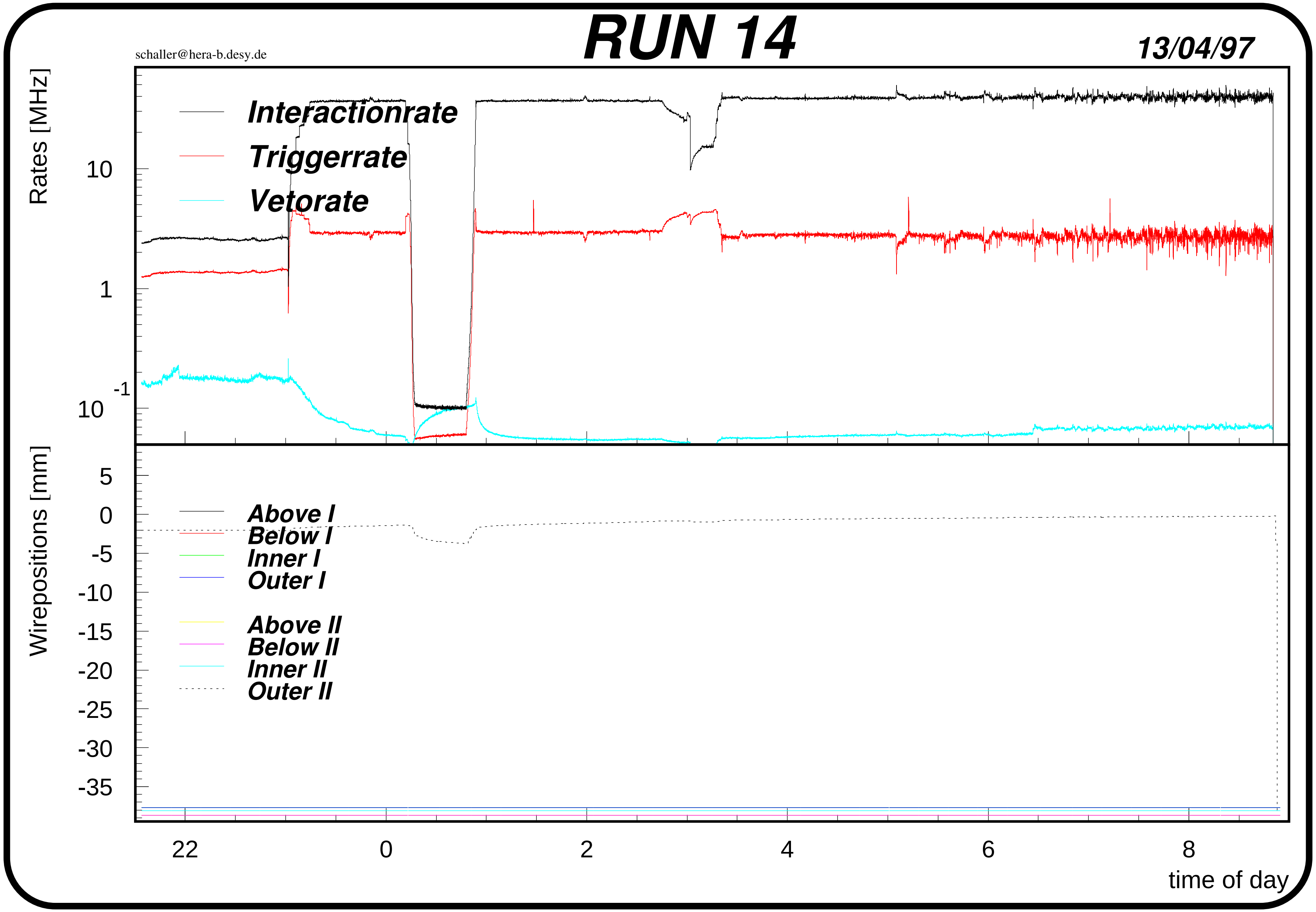
- high rates (40 MHz) achieved, $\epsilon_T \geq 60\%$
- reliable, secure multiwire automatic
- small background at other experiments

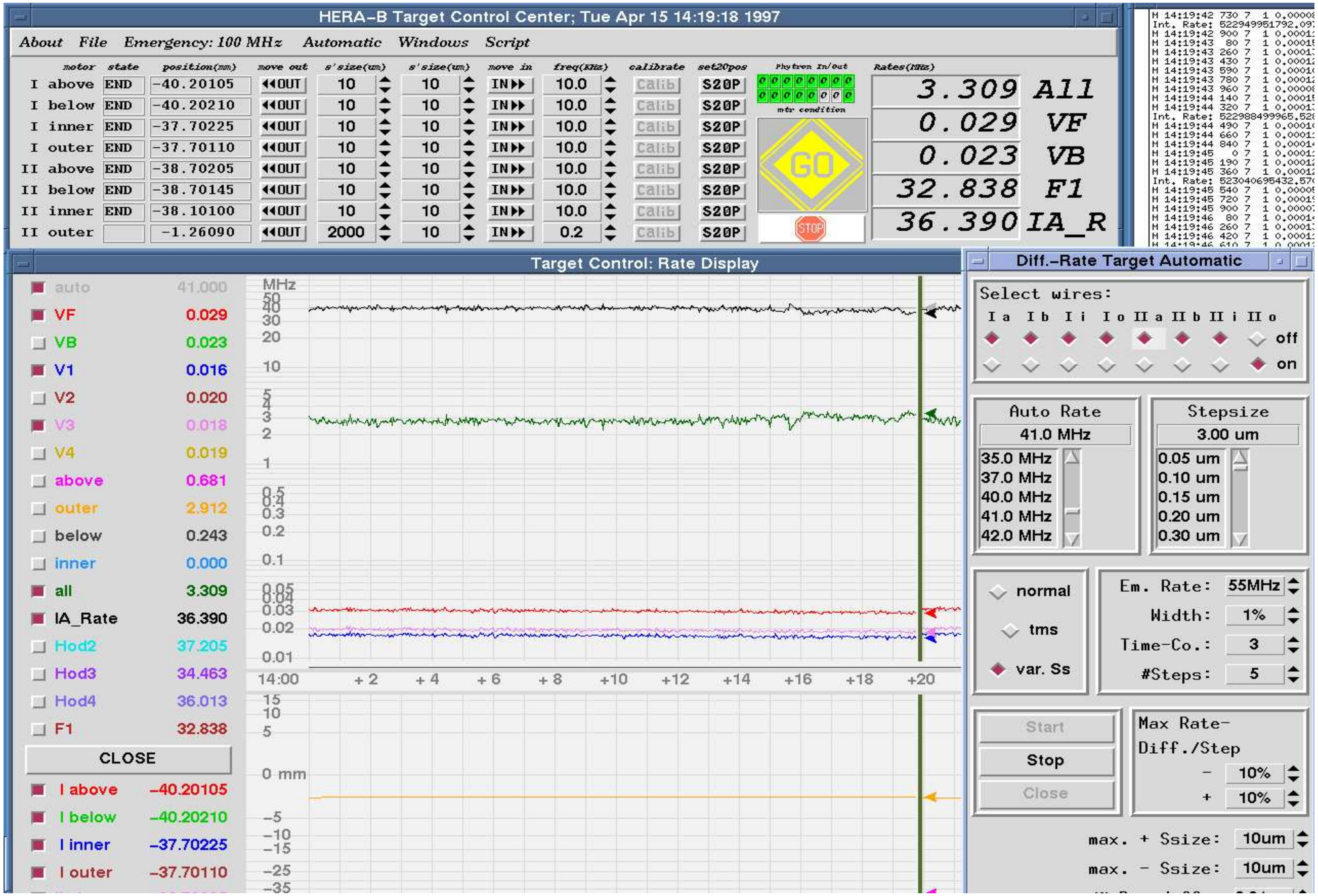


Target Efficiency in '96

- ▷ Typical Values: C (65 %), Al (55 %), Cu (50 %)
- ▷ Carbon Fibre is higher than Aluminum than Copper
- ▷ As expected for a machine with very high lifetimes, dominated by multiple scattering and appertures
- ▷ But: No. of produced B-Mesons is too small for C




RUN 14
schaller@hera-b.desy.de
13/04/97
Rates [MHz]
Interactionrate
Triggerrate
Vetorate
10
1
10
-1
Wirepositions [mm]
5
0
-5
-10
-15
-20
-25
-30
-35
Above I
Below I
Inner I
Outer I
Above II
Below II
Inner II
Outer II
22
0
2
4
6
8
time of day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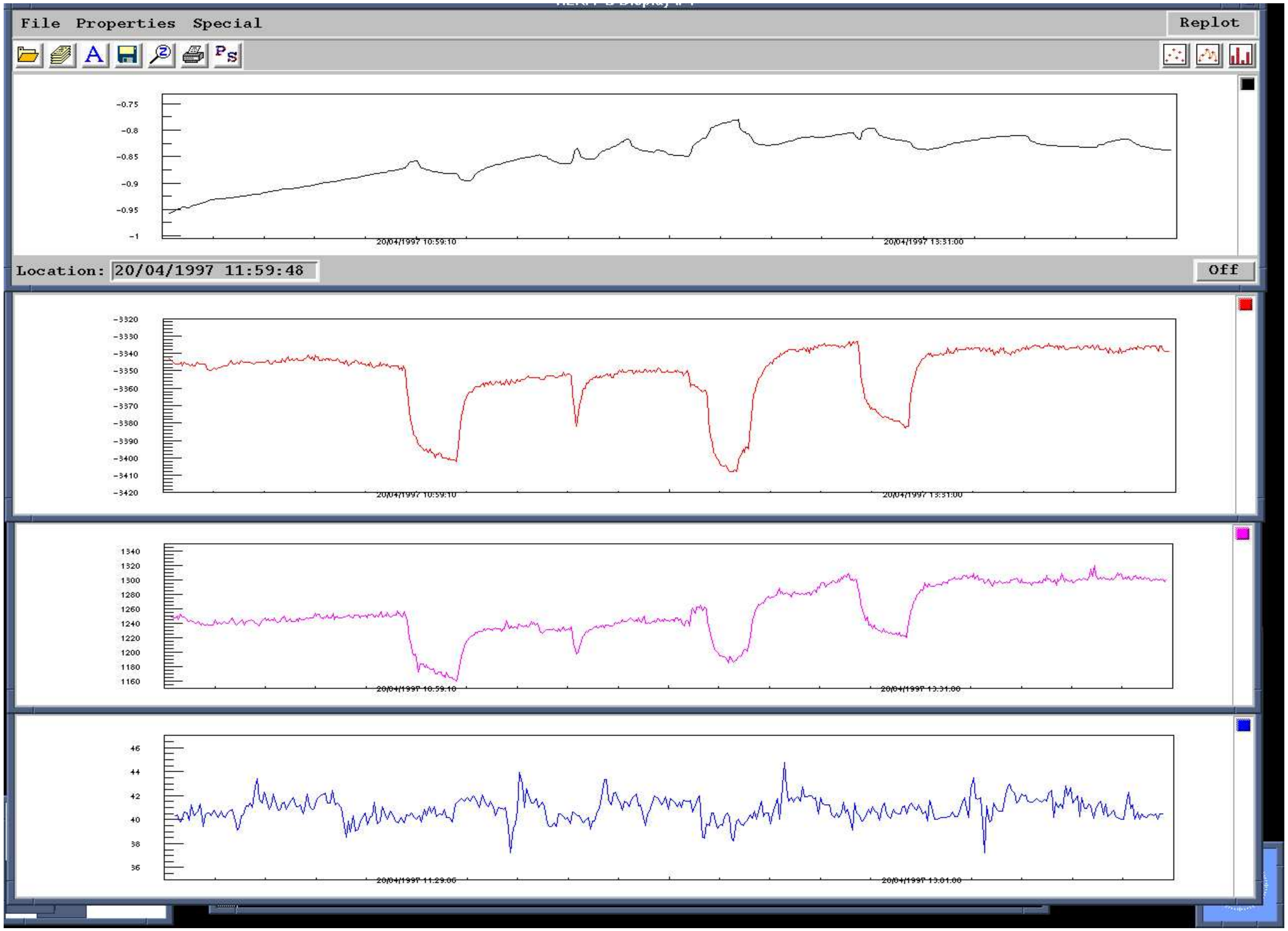
About File Emergency: 100 MHz Automatic Windows Script
Target Control: Rate Display
Diff.–Rate Target Automatic


File Properties Special
Replot
-0.75
-0.8
-0.85
-0.9
-0.95
-1
20/04/1997 10:59:10
20/04/1997 13:31:00
Location: 20/04/1997 11:59:48
Off
-3320
-3330
-3340
-3350
-3360
-3370
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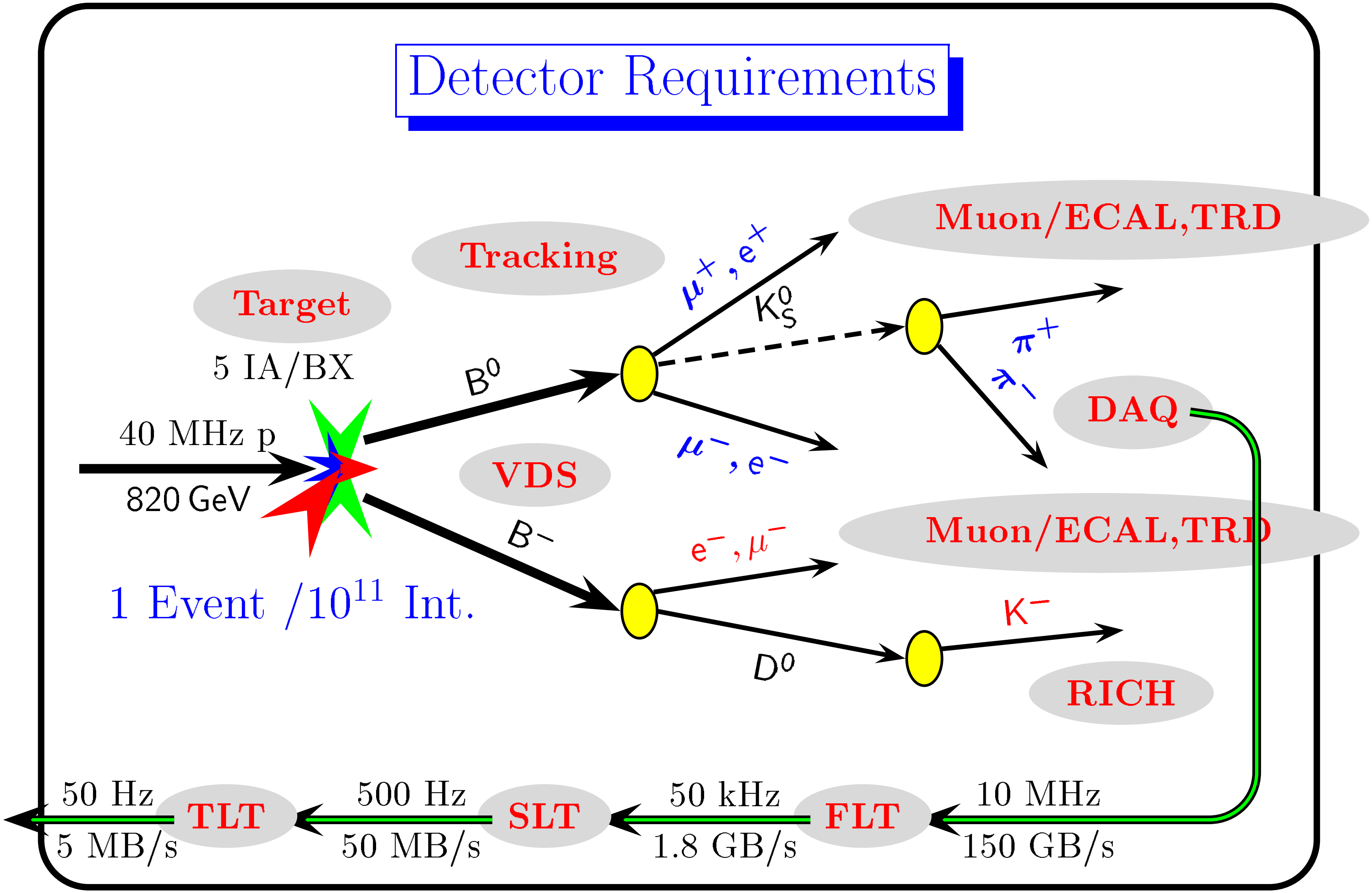
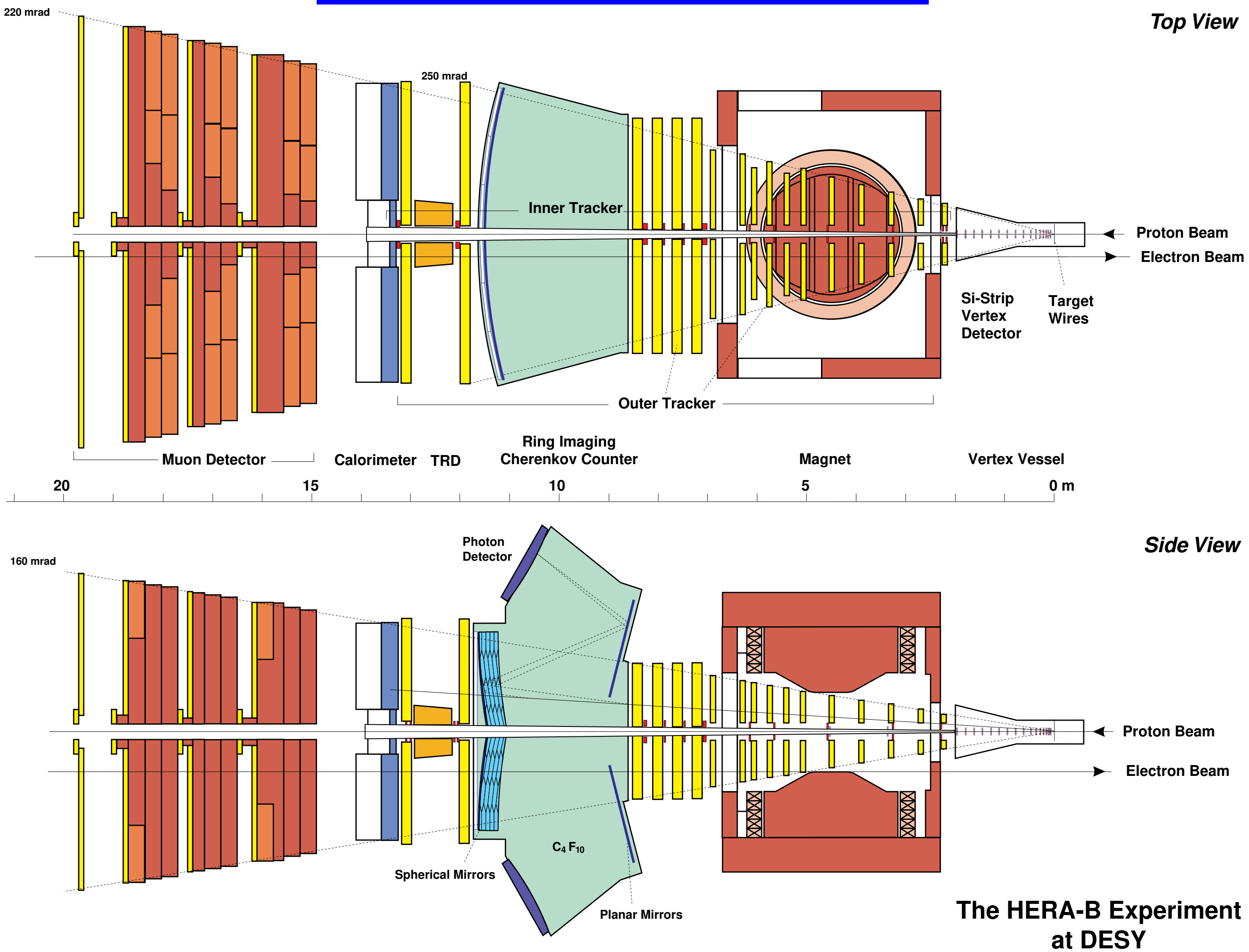
20/04/1997 13:01:00



Detector Requirements
Muon/ECAL,TRD
Tracking
Target
5 IA/BX
μ^+, e^+
K^0_S
B^0
π^+
π^-
DAQ
40 MHz p
820 GeV
μ^-, e^-
VDS
Muon/ECAL,TRD
B^-
e^-, μ^-
K^-
1 Event /10^{11} Int.
D^0
RICH
50 Hz
5 MB/s
TLT
500 Hz
50 MB/s
SLT
50 kHz
1.8 GB/s
FLT
10 MHz
150 GB/s

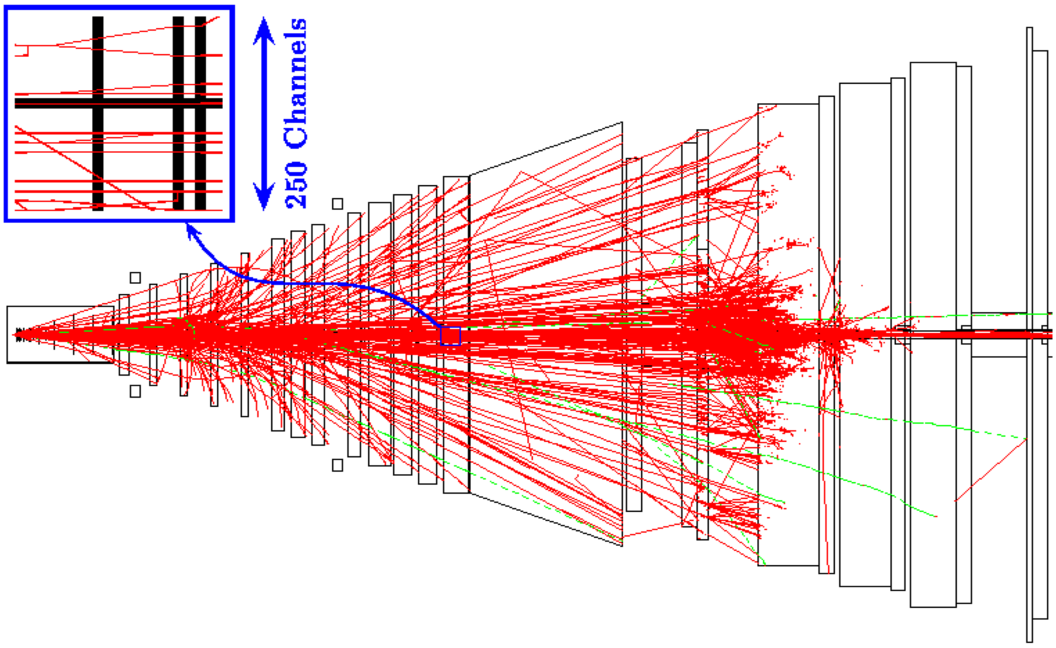
The HERA-B detector



The HERA-B Experiment at DESY

Typical Event with 5 I.A. (GEANT)

(Charged tracks only)

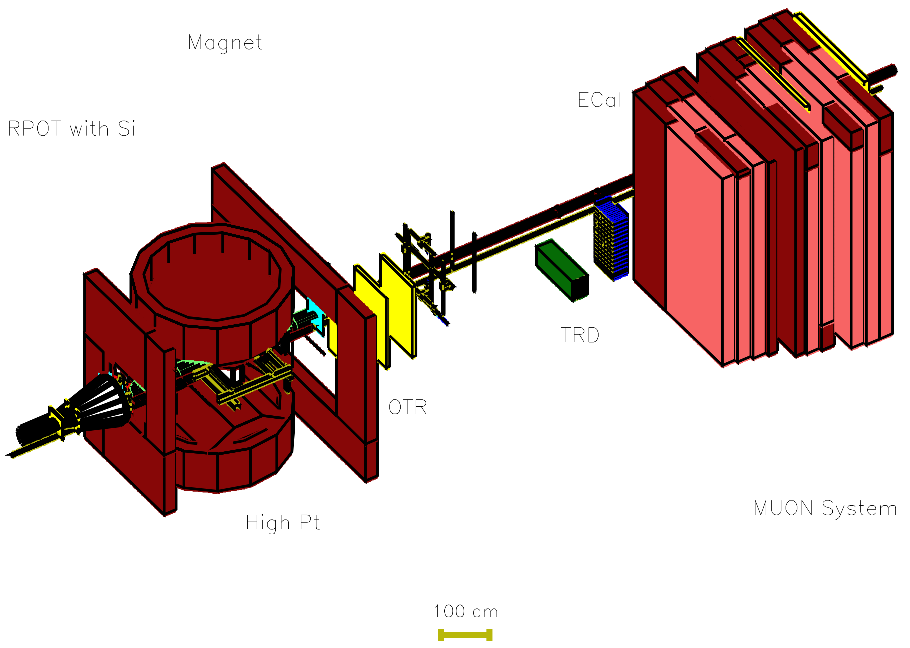


- bunch crossing (BX) every 96 nsec
- $\approx$ 5 Proton-Nucleon-interactions per BX
- $\mathcal{O}(60-200)$ charged tracks per BX
- Very high track densities:
  - high occupancies (Reconstruction)
  - high radiation (Si: 10 Mrad/y)

Main Detector Components

detector	*technology*	*number of channels*	*hits per BX*
Vertex detector	Si-strip	136 k	≈ 0.05
Tracker			
inner (2-6 cm)	Si-strip	40 k	≈ 0.02
inner (6-19 cm)	microstrip gas-chamber (GEM) or fibers	135 k	≈ 0.04
outer (>19 cm)	honeycomb-DC	120 k	≈ 0.15
High-p_T trigger $B^0 \to \pi^+\pi^-$	gas pixel/straw	26 k	≈ 0.05
RICH Kaon iden.	C_4F_{10} radiator PMT photon detector	32 k	≈ 0.1
Small-Angle TRD Electron iden.	fibre radiator straw chambers	15.7 k	≈ 0.1
EM calorimeter Electron iden.	W/Pb scint. shashlik	5.8 k	≈ 0.2
Muon system Muon iden.	gas pad + pixel prop. tubes	31.3 k	< 0.01
Total		≈ 550 k	

Detector setup in 1996 (97)



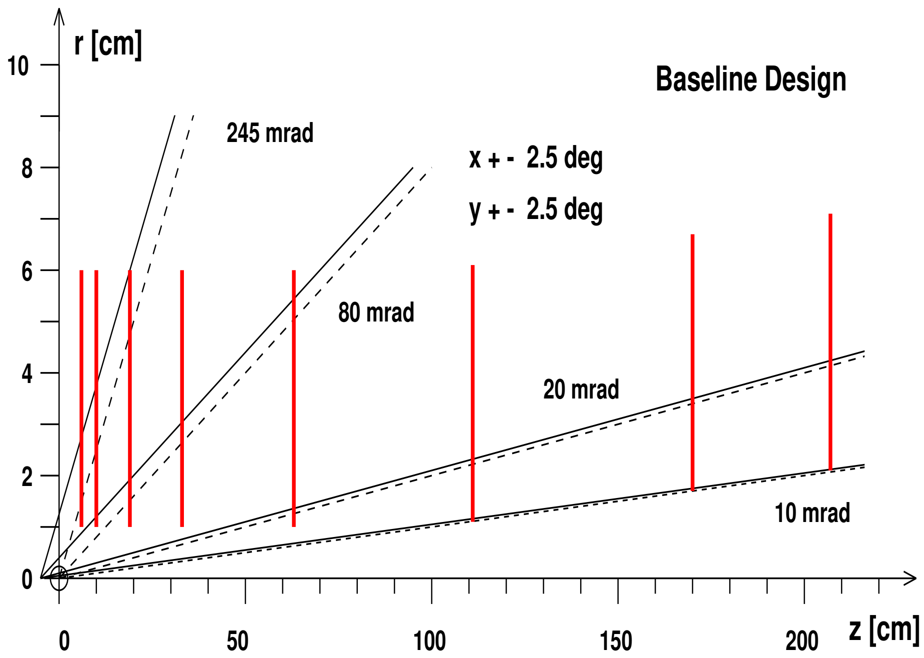
- VDS-vessel with 3 double sided Si-strip detectors with 6000 channels and 8 targets
- Al beam pipe 0.5 mm
- Magnet and e-compensation coil
- High-Pt gas pixel chambers
- 3 superlayers of the OTR
- MSGC (GEM) and Fiber test modules
- ECAL with 320 channels
- 1/12 TRD
- MUON absorber with 24 tube and 7 pad chambers

Silicon Vertex Detector System

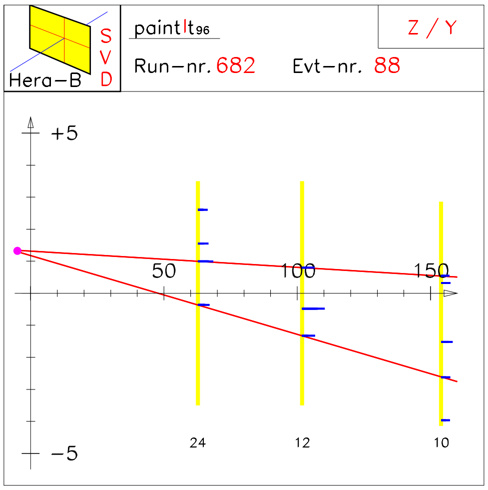
reconstruction of $(J/\psi \rightarrow l^+l^-)$ vertex (SLT)
resolution: $\sigma_{x,y} \approx 20\ \mu$m and $\sigma_z \approx 500\ \mu$m
angular coverage 90%

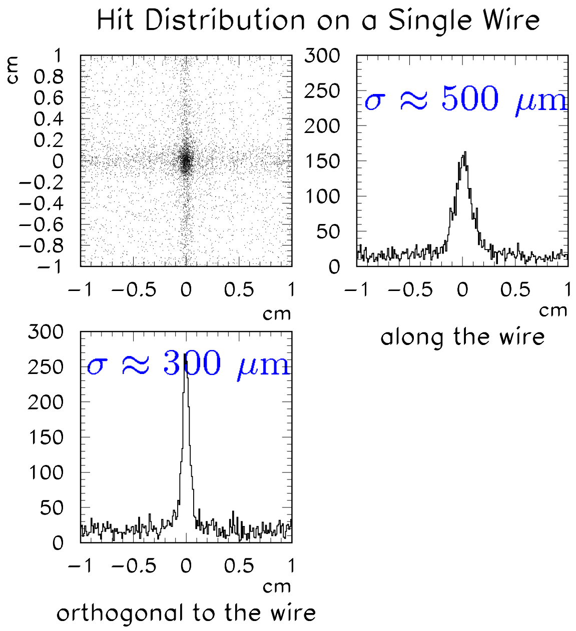
lot of challenging tasks:

- ▷ operation in close vicinity to the beam (< 10 mm)
- ▷ large radiation dose requires radiation hard detectors and cooling
- ▷ operation in sec. vacuum (less material to keep multiple scattering low) $\rightarrow$ thin Al-caps (150 μm)
- ▷ moveable Roman-Pot system and RF-shielding



Vertex Detector 1996



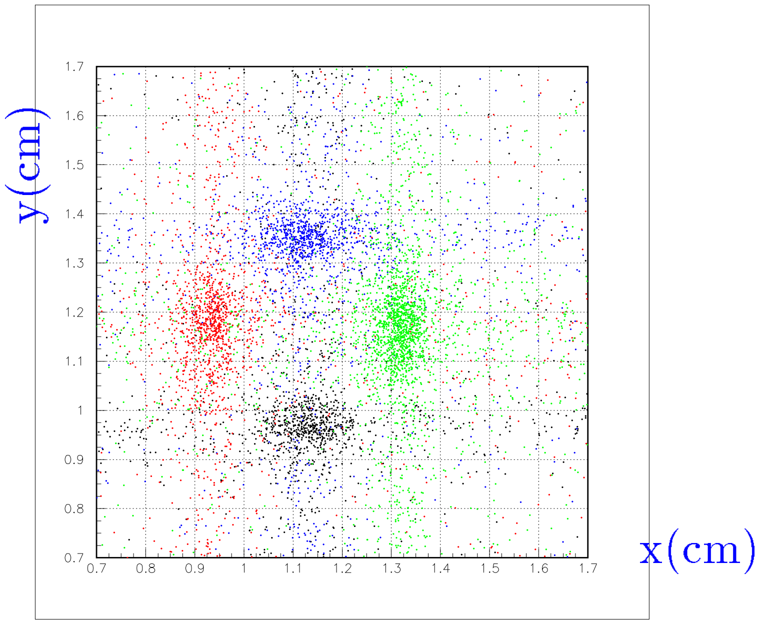


Tracks seen by the VDS

Resolution

The four target wires seen by the vertex detector.

(x,y) coordinates of track candidates at $z_{\rm target}$.



Inner Tracker

- covers "hot" area from 10 to 20 mrad
- provides fast readout for first level trigger

Micro Strip Gaseous Chamber

- now with Gas Electron Multiplier (GEM)
- Tested during last 3 weeks @ HERA

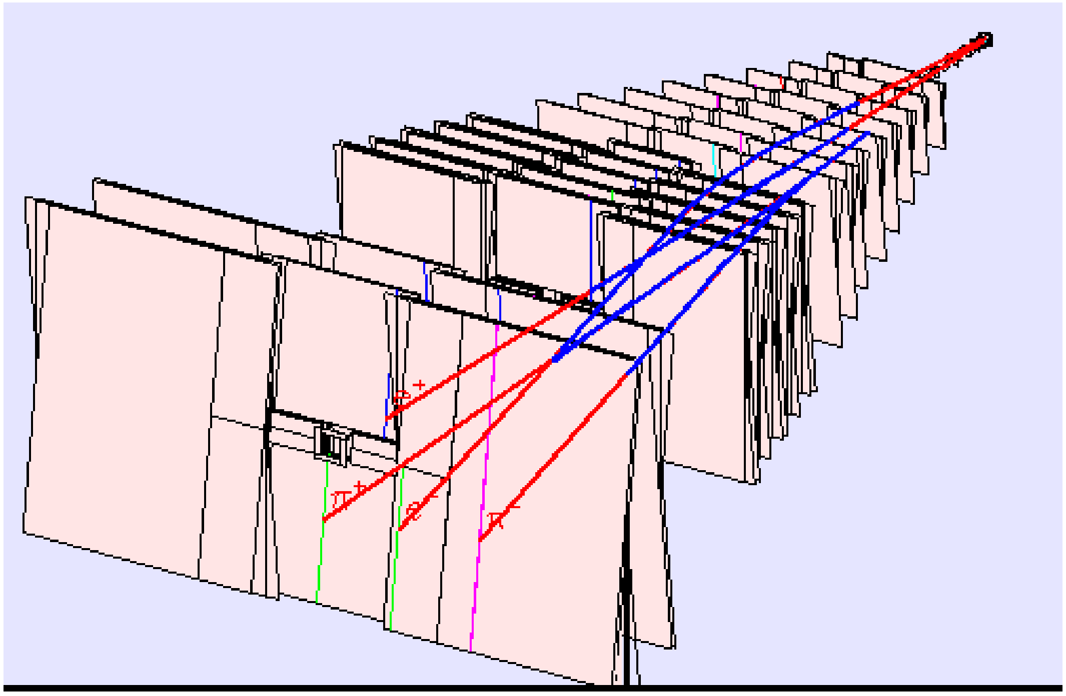
Radiation Hard and Spark Resistent

Fiber Tracker

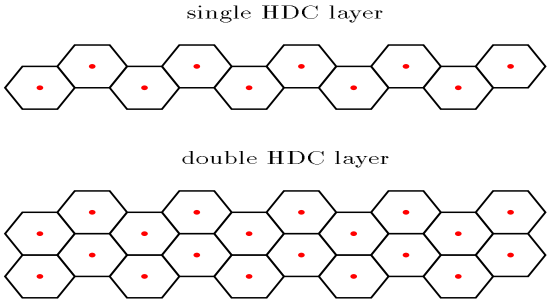
- radiation hard
- light output seems to be ok
- use of PMTs in magnet unclear

Can Be Used as ITR for HERA-B

Outer Tracker

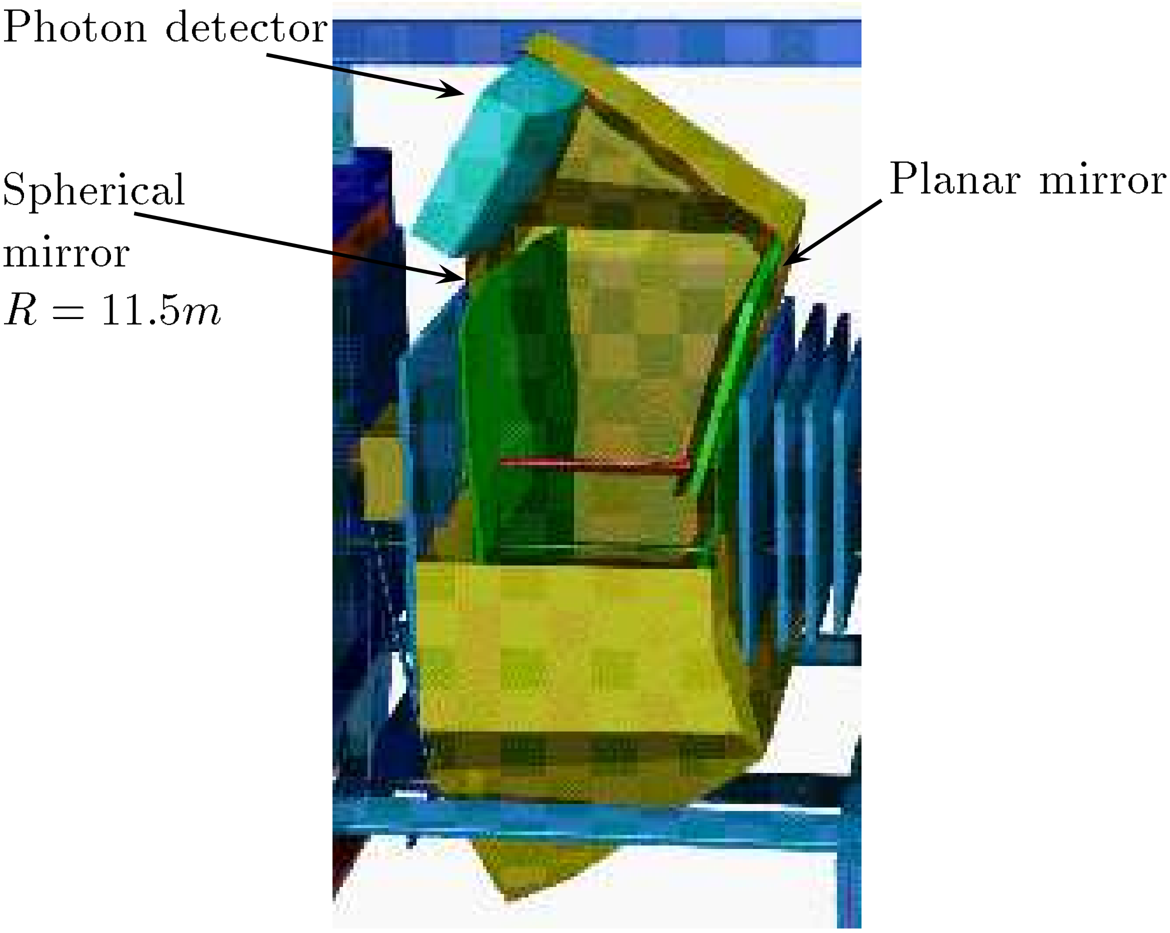


- # of superlayers: 15
- gas : 80% $CF_4 + 20\%\ CH_4$
- drift velocity : 100 μm/ns
- spatial resolution : 150 μm
- tubes : 10 mm und 5 mm

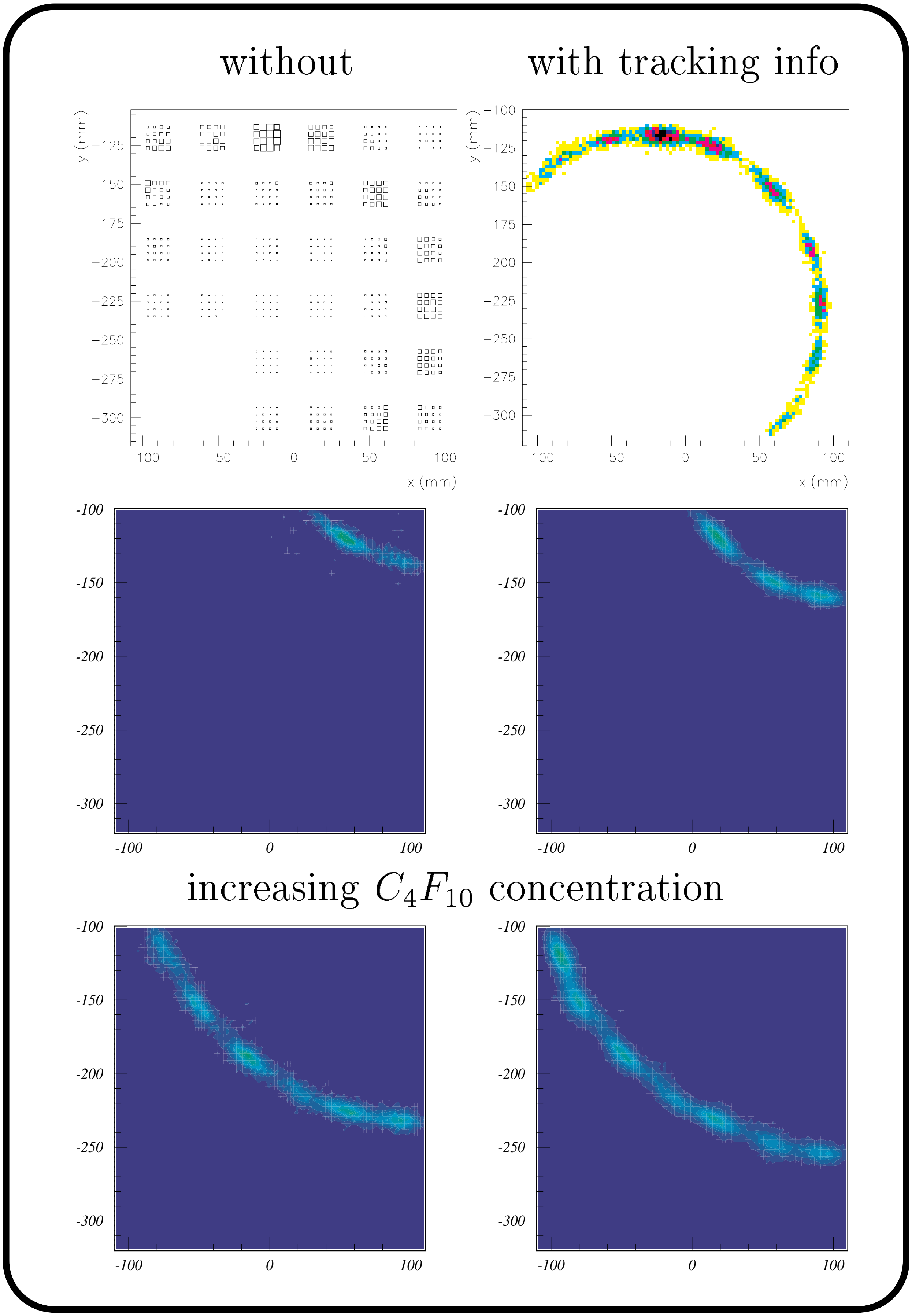


Structure : Honeycomb

Ring Image CHerenkov



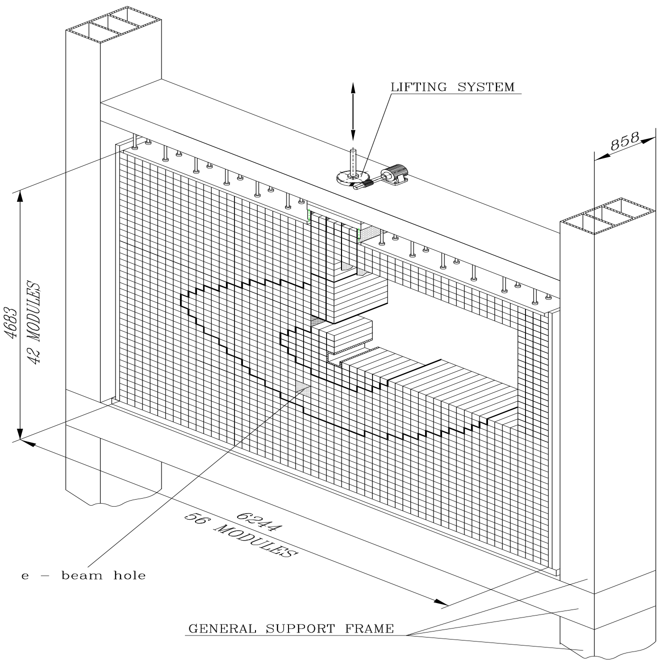
- K/π separation : 3 σ (10 – 75 GeV)
- Radiator: C_4F_{10},   Lenght: 2.7 m
- Cherencov angle for $\beta = 1$ is 55.6 mrad
- Photon detectors: 16(4) multianode PMT (out of detector acceptance)
- # γ/particle detected > 34



without
with tracking info
y (mm)
x (mm)
increasing C_4F_{10} concentration

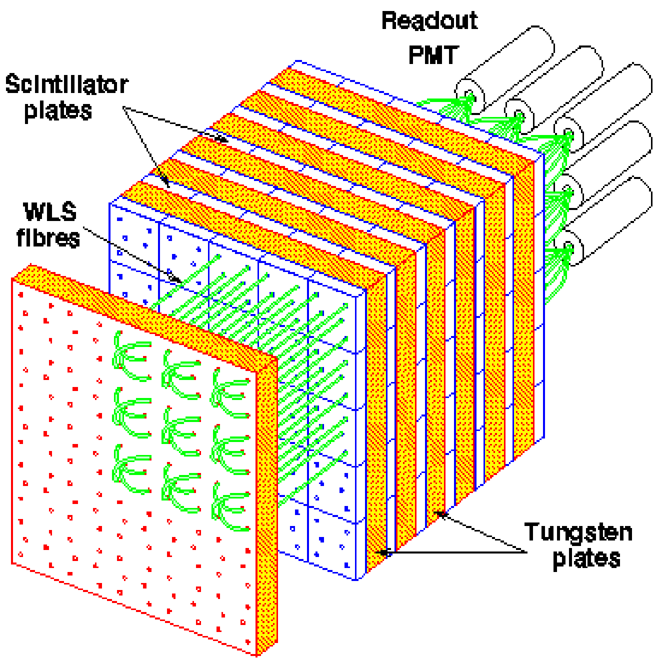
Electromagnetic CALorimeter

Shashlik
with 3 sections :
inner:
$2.2 \cdot 2.2$ cm^2, 22 X_0
mid.:
$5.58 \cdot 5.58$ cm^2, 20 X_0
Outer:
$11.2 \cdot 11.2$ cm^2, 20 X_0



Inner module

absorber: W-Ni-Fe
WLS: Kuraray Y-7
PM : FEU-68



$$\boxed{\sigma(E)/E = 15\%/\sqrt{E} + 1.3\%}$$

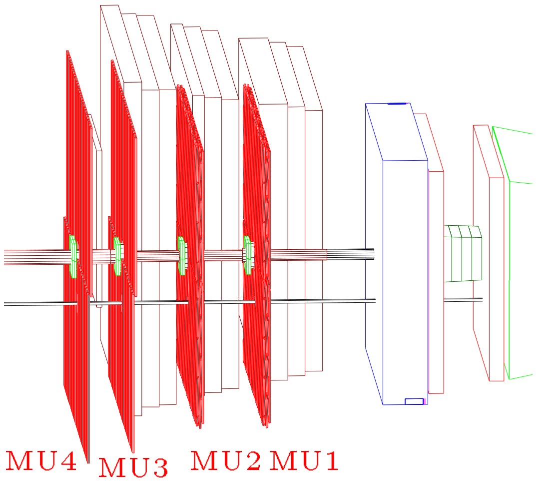
MUON system

Tubes, Pads & Pixels

$\approx$ 32000 channels

Surface.: 340 m^2

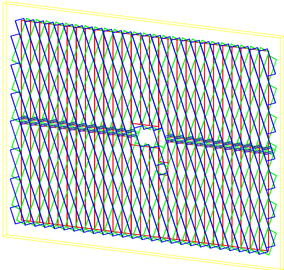
Gas : 80% $Ar + 20\%\ CF_4$



MU1-2: Tube chambers

Double layers : 0^o, $\pm 20^o$

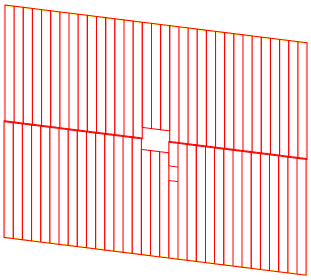
signal : 40 μm Au-W wires



MU3-4: Pads

projective arrangement

signal : pads and wires



Inner chambers: Gas pixel

cell size (x,y,z)MU1-3: 9 x 9 x 30 mm^3

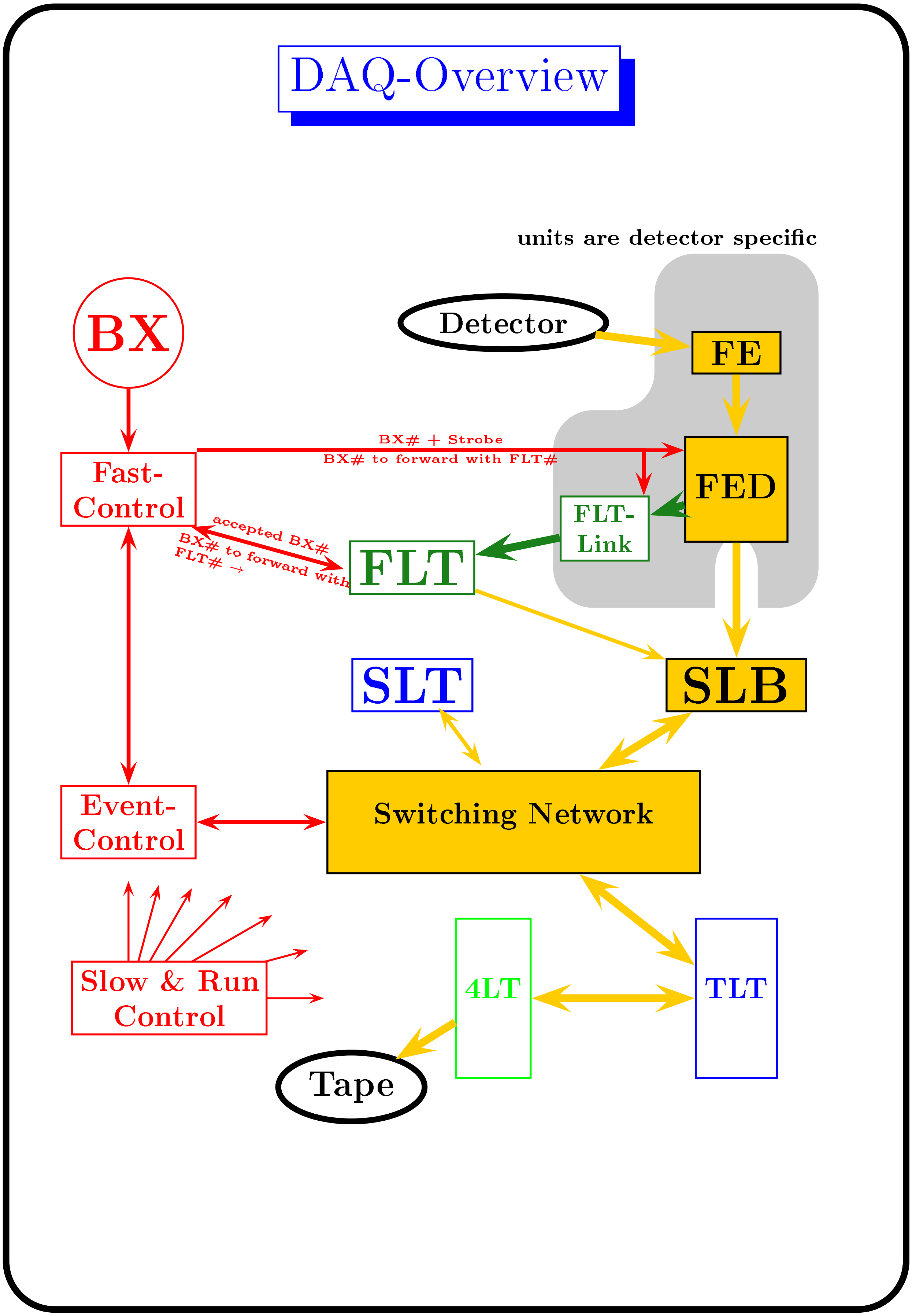
cell size (x,y,z)MU4 : 9.4 x 9.4 x 30 mm^3

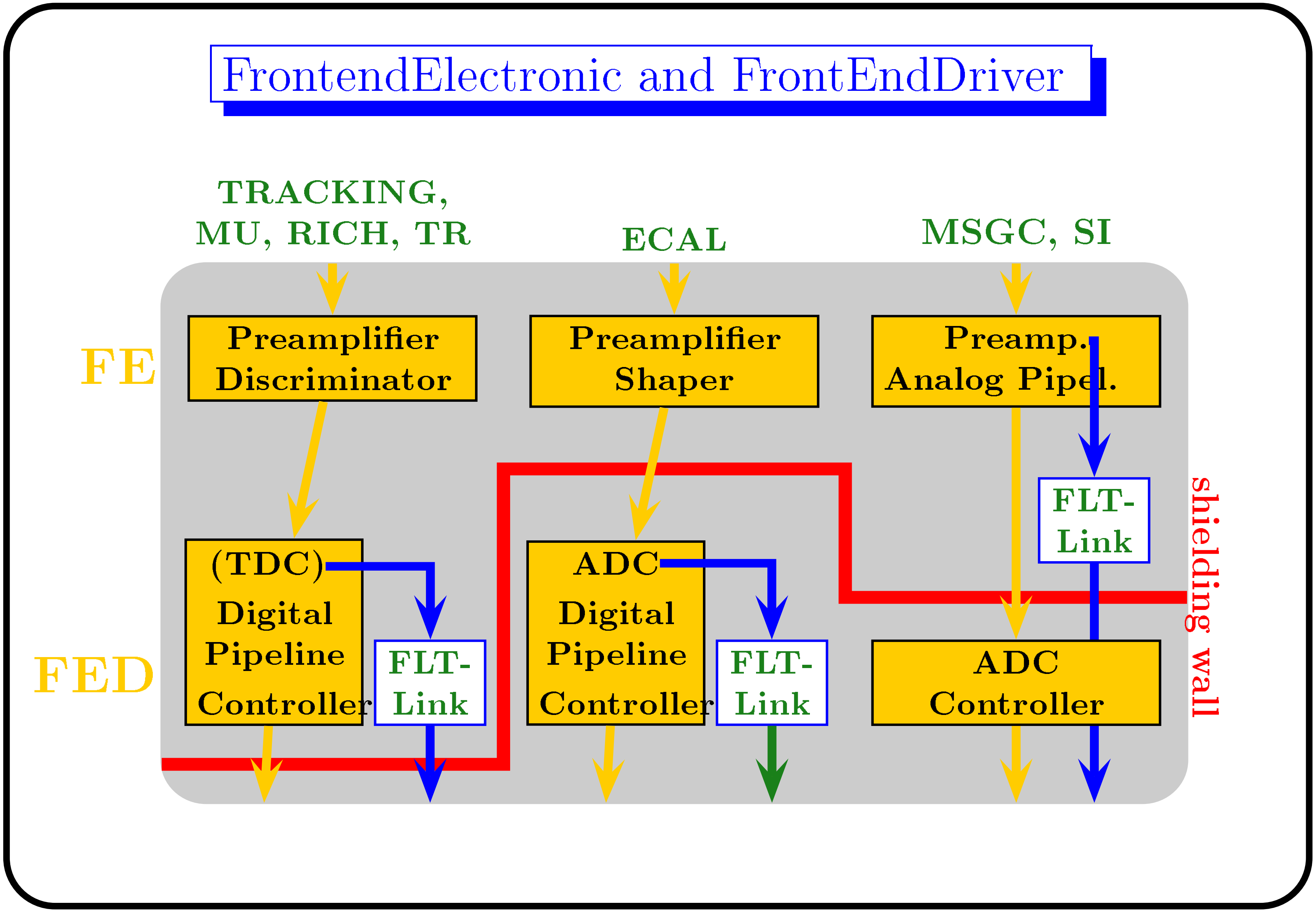
Some Results of the 1996 Run

- Successful Target operation: reliable, secure, long term, multiwire, high rates, efficient
  no disturbance of other HERA experiments
- Tracks reconstructed by the VDS and OTR
- Occupancies in all detectors in good agreement with GEANT MC calculations

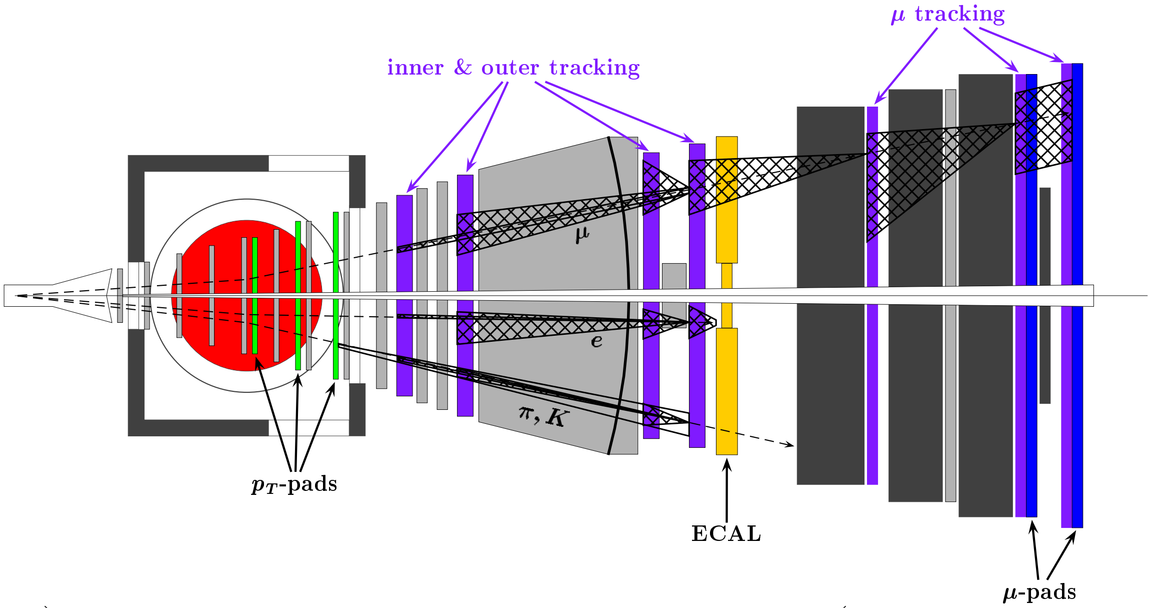
  - High-Pt tracks observed
  - Transition Radiation signals observed
  - ECAL calibrated (MIP-signals)
  - Readout of several detectors synchronized
  - essential parts of DAQ system operational: FED, FCS, Sharcs ...
  - Track and vertex reconstruction software ready
- '97 run: Inner Tracker prove to work

successful operation of prototypes


DAQ-Overview
units are detector specific
BX
Detector
FE
Fast-Control
BX# + Strobe
BX# to forward with FLT#
FED
FLT-Link
accepted BX#
BX# to forward with FLT# →
FLT
SLT
SLB
Switching Network
Event-Control
Slow & Run Control
4LT
TLT
Tape


FrontendElectronic and FrontEndDriver
TRACKING, MU, RICH, TR
ECAL
MSGC, SI
FE
Preamplifier Discriminator
Preamplifier Shaper
Preamp. Analog Pipel.
FLT-Link
shielding wall
(TDC) Digital Pipeline Controller
FLT-Link
ADC Digital Pipeline Controller
FLT-Link
ADC Controller
FED

First Level Trigger



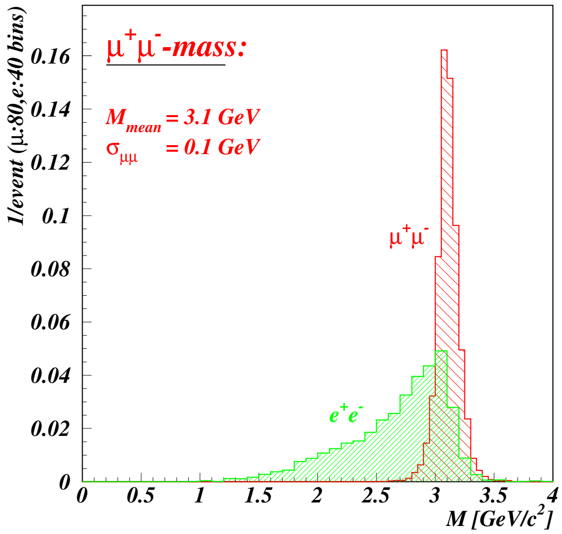
1) e, μ, h identification $\Rightarrow$ Track seeding: RoI (Region of Interest)

2) Tracking towards the target. $\Rightarrow$ compute track parameters

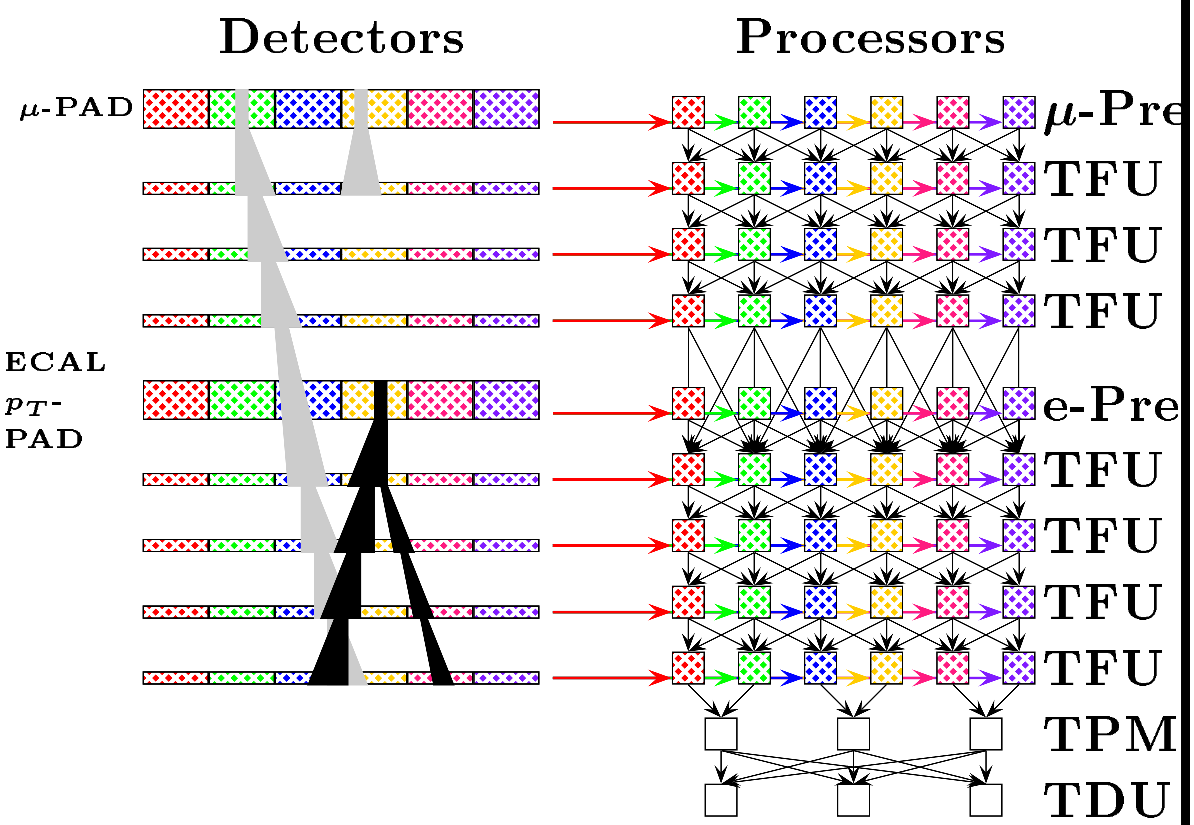
3) Trigger decision $\Rightarrow$ based on track parameters and pair masses

FLT reconstructed J/ψ masses

- $\mathrm{Eff}(J/\psi \to e^+e^-) \sim 40\%$
- $\mathrm{Eff}(J/\psi \to \mu^+\mu^-) \sim 60\%$
- $\mathrm{Eff}(B^0 \to \pi^+\pi^-) \sim 30\%$
- $\mathrm{Eff}(B \to X\gamma) \sim 10\%$



FLT: hardware realization



- Execution time: 12 μs/BX
- # used channels : 150000
- Technique: asynchronous parallel pipelines $\Rightarrow$ processor operates on local data
- Input rate : 10 MHz $< \ 5 \ IA/BX >$
- Output rate : 50 kHz

Trigger efficiencies

Mode	Physics topics	Trigger efficiency				
		J/ψ trigger	Dilepton trigger	High p_t lepton	Di-hadron	All
$B \to J/\psi X \to \ell\ell X$	CP violation,...	56%	25%	9%	-	58%
$B_1 B_2 \to \ell_1 \ell_2 X$	B mixing, CKM	10%	18%	7%	-	29%
$B \to \ell_1 D X \to \ell_1 \ell_2 X$	D^0 mixing, CKM	5%	2%	5%	-	10%
$B \to \ell_1 X$	Inclusive 2nd B	-	-	4%	-	4%
$C_1 C_2 \to \ell_1 \ell_2 X$	Semilept. charm	0.05%	0.01%	-	-	0.06%
$B \to h^+ h^-$	CP in $B \to \pi^+ \pi^-$	-	-	-	35%	35 %

Triggers and Data Rates

Trigger Level	Event Rate	Data Rate	Mean Time	Red. Factor	Method
Pre-Trigger	10 MHz		1μs	1	ECAL & MUON Track Seeds
L1	10 MHz	150 GB/s	10μs	200	Tracking-RoI J/ψ mass
L2	50 - 100 kHz	50 MB/s per node	10 - 50 msec	100	L1-Refit Tracking & Vertex
L3	0.5 - 1 kHz	50 MB/s	100 msec	10	Event Building Tracking and Part.-ID
L4	50 Hz	5 MB/s	4 s	2.5	Full Reconstruction Monitoring

Time Schedule

1997 mass production: Outer Tracker, Silicon Vertex Detector, Muon, Inner Tracker, ...

1997 running period: Technical Test Run

Optimize beam and target operations.
Final prototype tests.
Setup complete DAQ chain: FCS, pretrigger, FLT, Switch, SLT, ... for common data taking

1997 installation: OTR, RICH and ECAL on main platform; assembly of electronics hut, Farm

10/1997–5/1998 shutdown: Detector Installation

Main platform and 2/2 μ-absorber into beam position, tracking system in magnet, final vertex detector ...

1998 running period: Detector Setup

Complete readout electronics, tune detectors, triggers and DAQ system. Physics Run.

Jan 1999 shutdown: Final Installation.

ITR, Complete OTR and do some repairs

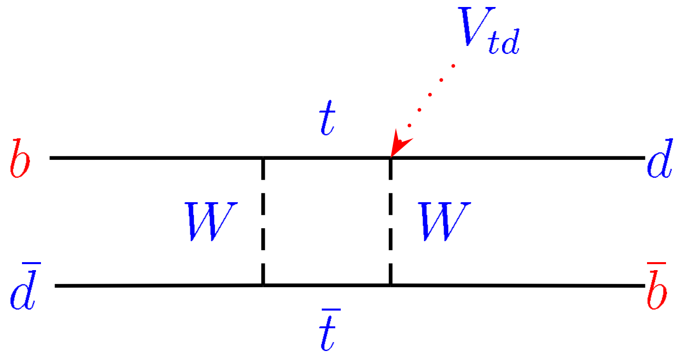
1999 running period: Physics Run

Measurement of CP – Violation

Additional Physics

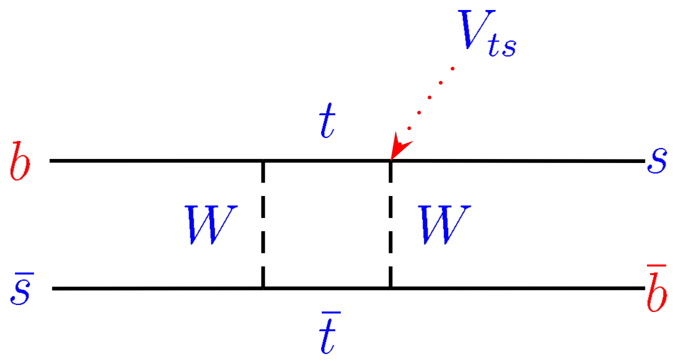
- B^0 mixing

  measurement of V_{td}



- B^0_s mixing

  measurement of V_{ts}



$$\frac{x_s}{x_d} = \frac{m_{B_s}\tau_{B_s}\eta_{B_s}f^2_{B_s}B_s}{m_{B_d}\tau_{B_d}\eta_{B_d}f^2_{B_d}B_d}\left|\frac{v_{ts}}{v_{td}}\right|^2$$

- tag $\mathrm{B_s^0} \to \mathrm{l^+} \nu \, \mathrm{X}$
- reco $\overline{\mathrm{B_s^0}} \to \mathrm{B_s^0} \to \mathrm{l^+} \nu \, \mathrm{D_s^{(*)-}}$, 900 events

  (BR $\approx 8\,\%$)

  $\to \phi\pi^-,\ \phi\pi^+\pi^-\pi^-,\ \mathrm{K^{*0}K^-}$ (BR $\approx 8.8\,\%$)

▷ dilepton trigger

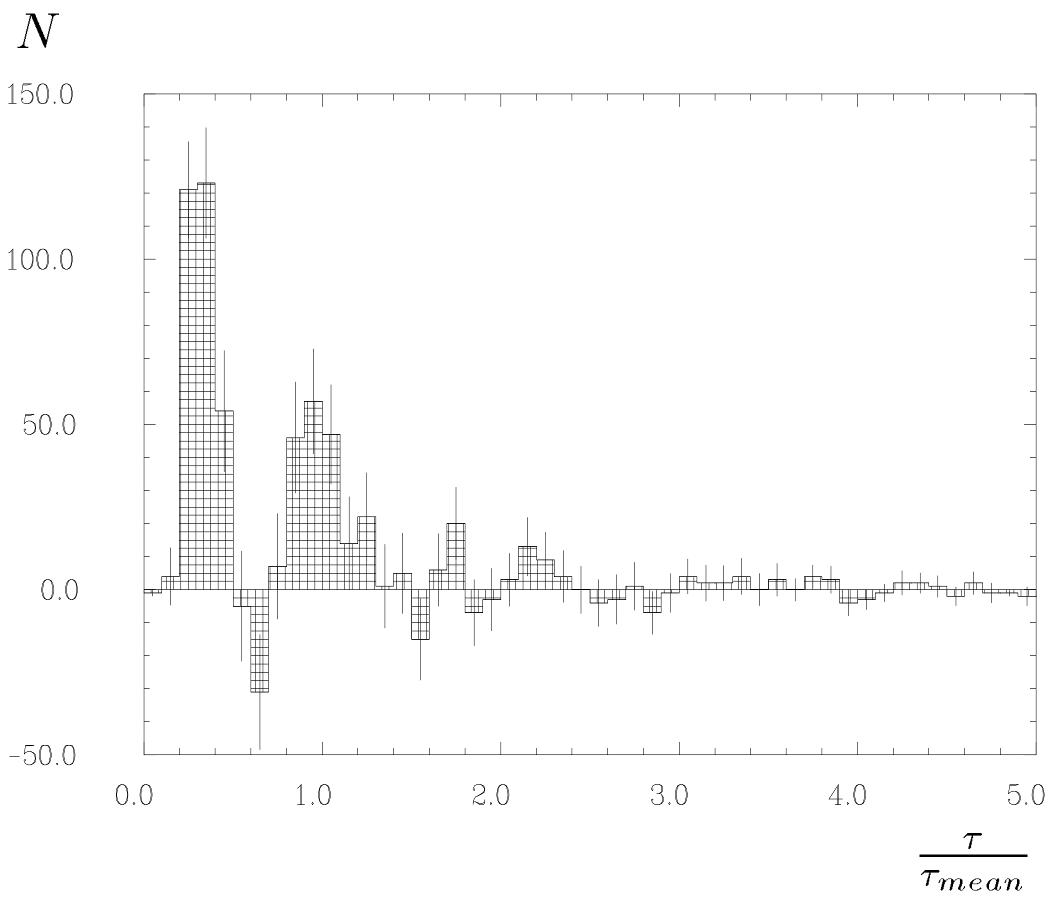
▷ vertex χ^2

▷ B decays length $> 4\,\sigma$

▷ $\mathrm{m(D_s - lepton)} > 4\,\mathrm{GeV/c^2}$

- kinematics of $\mathrm{B_s^0} \to \mathrm{l}\,\nu\,\mathrm{D_s^{(*)}}$ can be reconstructed up to a two-fold ambiguity with
  - ▷ direction of $\mathrm{B_s^0}$ known
  - ▷ measure $\mathrm{(D_s - lepton)}$ 4-momentum
  - ▷ B mass constraint

B_s oscillation for $x_s = 10$

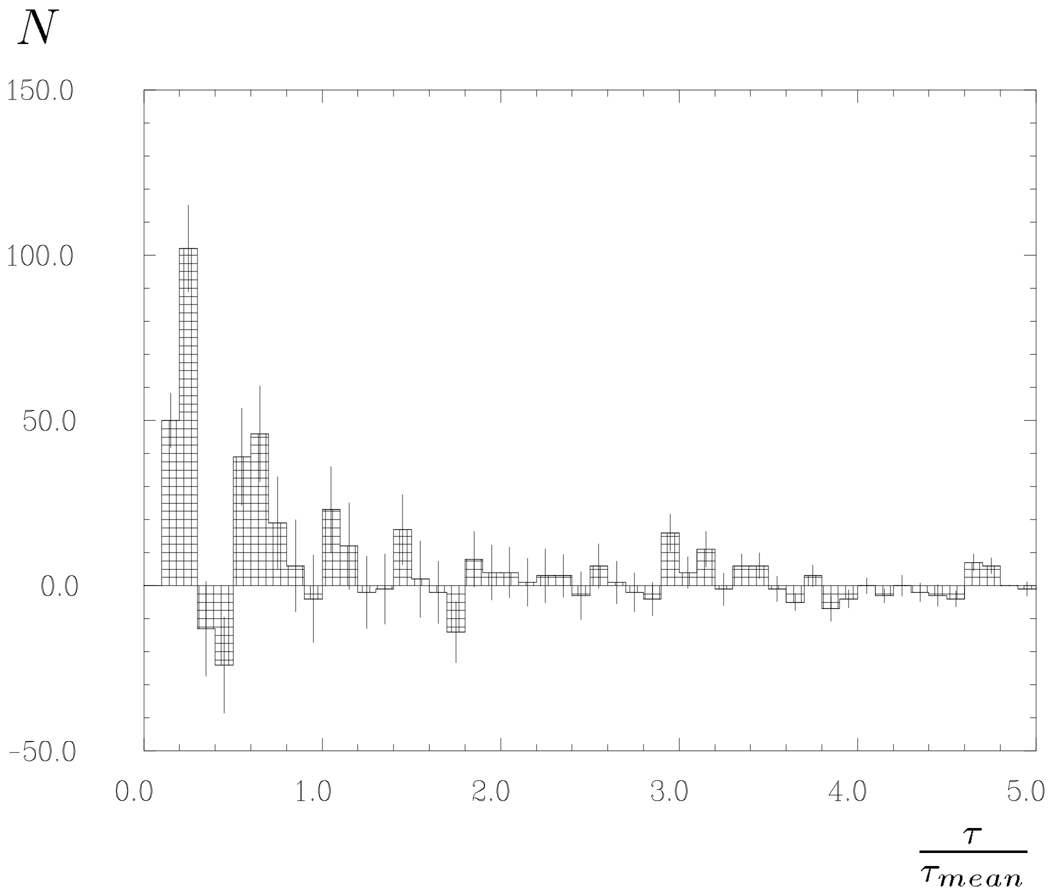


theory: $7 < x_s < 52$

central value: $x_s \approx 12$

experiment: $x_s > 13$ (@ 90% CL)

B_s oscillation for $x_s = 15$



oscillations clearly recognizable up to about $x_s = 15$

at $x_s = 17$ sensitivity is lost

1 year running:	background:
900 events	$b\bar{b}$(fake) ≈ 180
$\Delta x_s \approx 0.1$	$b\bar{b}$(cascade) ≈ 20

$\boxed{\mathbf{B_s^0} \text{ mixing up to } \mathbf{x_s < 17}}$

- # Hadronic B decays

  – investigate hadronic B decays with J/ψ in final state

  – hadronic transition form factors, model tests

  – error for lifetime measurement in the order a few %

  – dynamics of hadronic final states in B decays is poorly understood (discrepancies between theoretical predictions and experimental results for semileptonic BR's)

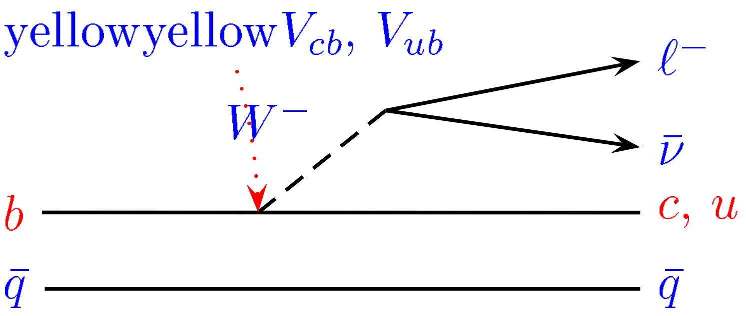
  – corrections to spectator model $\Rightarrow$ lifetime differences between different species of B hadrons

  – number of expected events per year:

quark state	produced events	decay	BR	reconstr. events
$\bar{b}d, b\bar{d}$	$3.2 \cdot 10^8$	$B^0 \to J/\psi K_s^0$	$5 \cdot 10^{-4}$	1500
		$B^0 \to J/\psi K^{*0}$	$1.6 \cdot 10^{-3}$	5500
$\bar{b}u, b\bar{u}$	$3.4 \cdot 10^8$	$B^+ \to J/\psi K^+$	$1 \cdot 10^{-3}$	7000
		$B^+ \to J/\psi K^{*+}$	$1.7 \cdot 10^{-3}$	1500
$\bar{b}s, b\bar{s}$	$6 \cdot 10^7$	$B_s^0 \to J/\psi \phi$	$2 \cdot 10^{-3}$	1500
$bud, \bar{b}\bar{u}\bar{d}, \ldots$	$2.7 \cdot 10^7$	$\Lambda_b \to J/\psi \Lambda$	$1.4 \cdot 10^{-2}$	500

• Semileptonic B decays

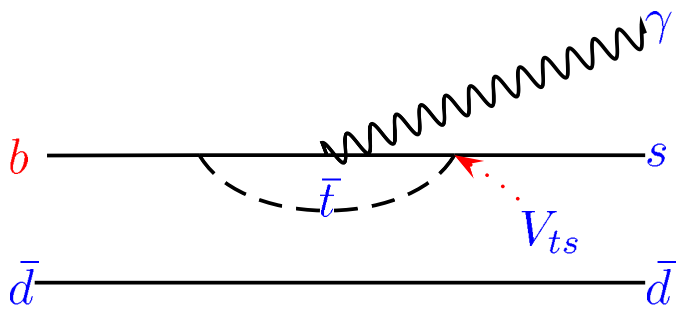
measurement of V_{cb} and V_{ub}



- V_{cb}
  - look at $B^0 \to D^{*-} l^+ \nu$, $D^{*-} \to D^0 \pi^-$, $D^0 \to K^+ \pi^-$
  - gain in model independent determination of V_{cb}
- V_{ub}
  - look at $B^0 \to \pi^+ \pi^- l \nu$
  - $b \to u$ transition
  - strong boost of decaying B mesons $\Rightarrow$ large separation of prim. and sec. vertices
  - error of V_{ub} about 10%

• Rare B decays

penguin decays



– for example $\mathrm{B} \to \mathrm{K}\mathrm{l}^+\mathrm{l}^-$

$$
\begin{aligned}
\mathrm{BR}(\mathrm{B} \to \mathrm{K}\mu^+\mu^-) &\approx 5 \cdot 10^{-7} \\
\mathrm{BR}(\mathrm{B} \to \mathrm{K}\mathrm{e}^+\mathrm{e}^-) &\approx 5 \cdot 10^{-7} \\
\mathrm{BR}(\mathrm{B} \to \mathrm{K}^*\mu^+\mu^-) &\approx 2 \cdot 10^{-6} \\
\mathrm{BR}(\mathrm{B} \to \mathrm{K}^*\mathrm{e}^+\mathrm{e}^-) &\approx 4 \cdot 10^{-6} \\
\mathrm{BR}(\mathrm{B} \to \mu^+\mu^-) &\approx 2 \cdot 10^{-9}
\end{aligned}
$$

– test of SM, search for new physics

- ## Exotic states

  for example B_c decays (mass, lifetime)

  - bound states of b and $\bar{c}$ never observed
  - test quark potential models and QCD sum rules
  - three classes of decays:
    - decays of b quark with final states like $J/\psi\, e^+\nu$ or $J/\psi\, \pi^+$
    - decays of c quark with final state $B_s\, e^+\nu$
    - annihilation of heavy quarks resulting in $\tau^+\nu$
  - predicted BR's:
    $BR(B_c \to J/\psi\, e^+\nu) \approx 2 - 4\%$
    $BR(B_c \to J/\psi\, \pi^+) \approx 0.2 - 0.4\%$
  - both have clean signature, high detection efficiencies

    and are covered by standard trigger
  - 10 - 100 B_c mesons reconstructible per year
  - sufficient for mass and lifetime measurement

- B baryon decays
  - estimated branching ratios for B baryon decays:

B *Baryon*	Mode	BR
Λ_b^0	$\Lambda J/\psi$	$\approx 2\cdot 10^{-2}$
Λ_b^0	$\ell^-\nu p$	$\approx 2\cdot 10^{-3}$
Λ_b^0	$\ell^-\nu\Lambda_c^+$	$\approx 2\cdot 10^{-1}$
Σ_b^0	$\Lambda J/\psi$	$\approx 2\cdot 10^{-2}$
Ξ_b^0	$\Lambda J/\psi$	$\approx 10^{-3}$
Ξ_b^0	$\Xi^0 J/\psi$	$\approx 2\cdot 10^{-2}$
Ξ_b^-	$\Xi^- J/\psi$	$\approx 2\cdot 10^{-2}$
Ω_b^-	$\Omega^- J/\psi$	$\approx 2\cdot 10^{-2}$
Ω_b^-	$\Xi^- J/\psi$	$\approx 10^{-3}$

  - measure angular distribution and decay parameters
  - measurement of Λ_b^0 and Ξ_b^- lifetimes
  - measurement of $|\mathrm{V_{ub}}/\mathrm{V_{cb}}|$ based on semileptonic decays
  - study of beauty baryon polarization
  - search for CP violation

- Direct production

  production of J/ψ, Υ and Drell Yan lepton pairs

  - enormous yield of directly produced J/ψ, Υ mesons and large mass Drell Yan lepton pairs
  - detailed tests of QCD
    (resummation of higher orders and description of
    higher twist effect near the limits of phase space)
  - found disagreement with QCD predictions in angular distribution in Drell Yan lepton pair production by NA10
  - HERA-B has more events and uniform acceptance
    over phase space
  - expected samples of directly produced J/ψ, Υ and Drell-Yan lepton pairs:

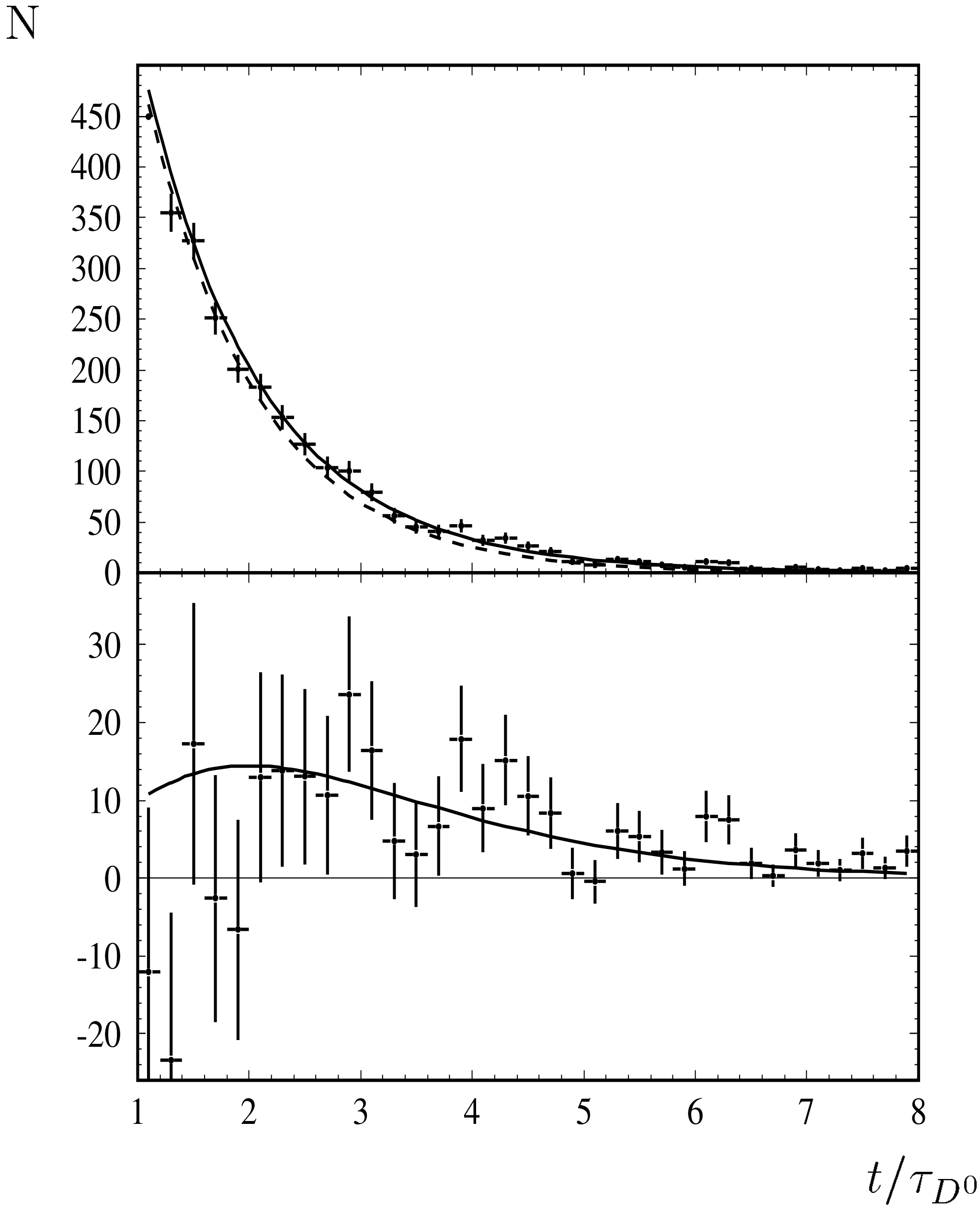
object	existing samples	exp. events per year
Direct J/ψ	$3 \cdot 10^5$	few 10^7 to 10^8
Direct Υ	$2 \cdot 10^4$	$4 \cdot 10^4$
Drell-Yan $\mu^+\mu^-$ (M $>$ 4 GeV)	$5 \cdot 10^5$	$1 - 2 \cdot 10^6$

- ## Charm physics

measure D^0 mixing

  - more than 10^{11} charmed hadrons produced per year
  - main limitation: bandwidth and trigger rate of DAQ system (maximum: 100 Hz)
  - in SM D^0 mixing predicted at 10^{-4} level
  - use $B \to D\,l\,\nu \to l\,l\,\nu\,X$ cascade given by J/ψ and dilepton trigger
  - tagging of initial flavour of charmed meson by charge of lepton from B
  - error in D^0 mixing determination about $2 \cdot 10^{-5}$

– decay time distribution for D^0 mixing candidates:



- Deviations from the SM / new physics

  for example $B_s^0 \to J/\psi\,\phi$

  - same rate and detection efficiency of $B_s^0 \to J/\psi\,\phi$ like $B_s^0 \to J/\psi\,K_s^0$
  - predicted BR between 0.14 and 0.3%
  - SM prediction for CP asymmetry is a 'clean zero'
  - candidates for new physics:
    * significant new contributions to FCNC
    * new sources for CP violation
  - possible extensions of the SM:
    * non-minimal SUSY models, where squark-gluino box diagrams may contribute to B_s^0 mixing and add new phases in mixing matrix
    * multi-scalar models, where scalar-mediated tree diagrams contribute to B_s^0 mixing
    * models with $SU(2)$-singlet down-like quarks

  * fourth-generation quarks, where box diagrams with a top contribute with new phases to B_s^0 mixing

– asymmetries are large enough to become visible at HERA-B

	# events per year	**HERA – B physics**
$B \to J/\psi\, X$	$\approx 2.6 \cdot 10^5$	$\approx 17\,000$ reconstructed B decays $1500 \quad J/\psi\, K^0_S$ $5500 \quad J/\psi\, K^{*0}$ } B^0 $7000 \quad J/\psi\, K^+$ $1500 \quad J/\psi\, K^{*+}$ } B^+ $1500 \quad J/\psi\, \phi$ } B_s $500 \quad J\psi\, \Lambda$ } Λ_B – lifetimes $\Rightarrow |v_{cb}|$ – unbiased B sample – CP violation – B_c, Λ_b – rare decays – QCD ($gg \to b\bar{b}$) – other CP decays – $B \to ll$
$B_1 B_2 \to l_1 l_2\, X$	$\approx 1.4 \cdot 10^6$	– $B^0\overline{B^0}$ mixing – $B^0_s\overline{B^0_s}$ mixing ($l_1\, l_2\, D_s^{(*)} \nu\nu$)
$B \to l_1\, C\, X$	$\approx 3.8 \cdot 10^5$	– $D^0\overline{D^0}$ mixing ($B \to [D^0 \leftrightarrow \overline{D^0}]\, l\, \nu \to l^\pm\, l^\pm\, X$) – v_{cb} – v_{ub}, B_c, $B \to ll$, rare decays – source for unbiased B mesons
$B \to l\, X$	$\approx 3.2 \cdot 10^6$	– unbiased tag of the second B meson

Other CP Channels

Trigger

▷ corresponding triggers needed

▷ only stringent triggers usefull

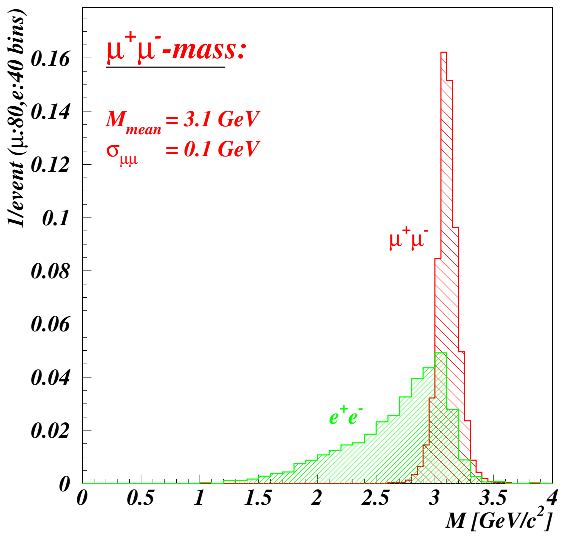
- J/ψ trigger

  lepton pairs of any charge and flavour with

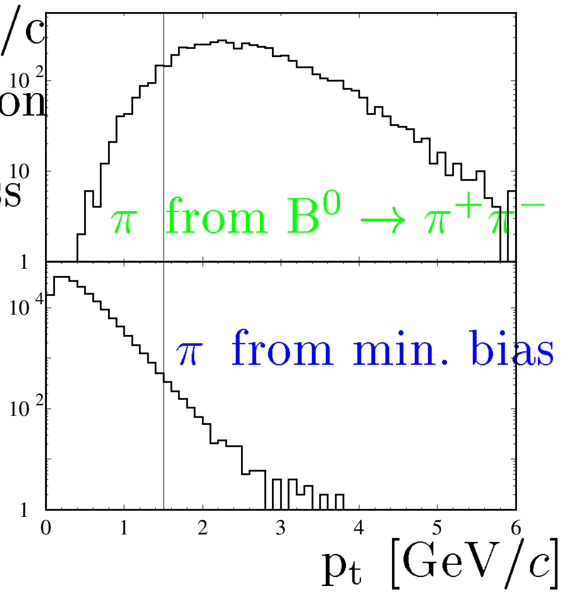
  - $2.5 < m_{\mu^+\mu^-}$ and $p > 5\,GeV/c$
  - $2.0 < m_{e^+e^-} < 3.5$ and $p > 5\,GeV/c$ and $p_t > 0.5\,GeV/c$

$J/\psi \rightarrow \mu^+\mu^-$
$(\epsilon \approx 62\%)$

$J/\psi \rightarrow e^+e^-$
$(\epsilon \approx 45\%)$

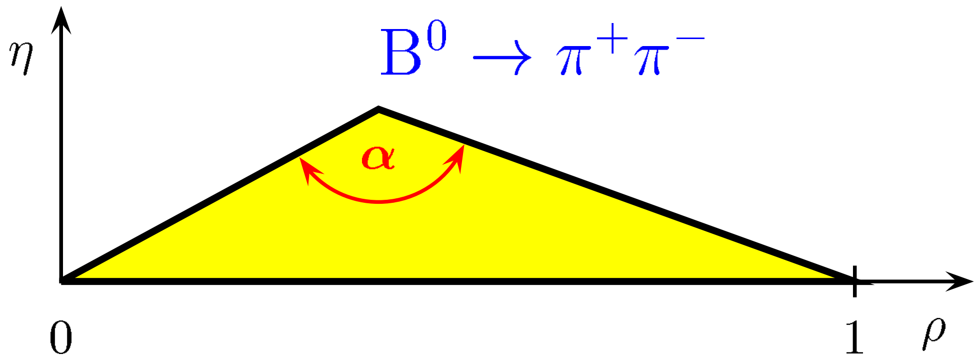


- high p_t dilepton trigger
  lepton pairs of any charges and flavours with
  - $p_t > 1.0$ GeV/c for μ
  - $p_t > 1.2$ GeV/c for e
- high p_t single lepton trigger
  leptons with
  - $p_t > 2.5$ GeV/c for μ
  - $p_t > 3.0$ GeV/c for e
- high p_t dihadron trigger
  hadron pairs with
  - $p_t > 1.5$ GeV/c
    for each hadron
  - invariant mass
    near B mass



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

- measurement of angle α



- high p_t dihadron trigger needed
- mass resolution about 20 MeV/c^2
- large minimum bias BG:
  - without cuts: $B/S \approx 10^5$
  - vertex cut: $B/S \approx 10^3$
  - lepton tag: $B/S \approx 10 - 100$
  - event topology: $B/S \approx 10$

$B^0 \to x$	$\pi^+\pi^-$	$J/\psi\, K^0_S \to l^+l^-\pi^+\pi^-$
BR	$\approx 1.5 \cdot 10^{-5}$	$\approx 3 \cdot 10^{-5}$
trigger,reco	$\approx 20\,\%$	$\approx 17\,\%$
events / year	≈ 800	≈ 1500
total error	$\Delta \sin 2\alpha \approx 0.14\sqrt{1 + B/S}$	$\Delta \sin 2\beta \approx 0.13$

$B^0 \to \pi^\pm a_1^\mp$

- final state not CP eigenstate, but asymmetry related to α expected, 300 events/year
- four π's from one common secondary vertex $\Rightarrow$ low BG
- lepton-tagged $B^0 \to \pi^\pm a_1^\mp$ decays per $b\bar{b}$ event:

		$B^0 \to \pi^\pm a_1^\mp$
Physics	$b\bar{b} \to B^0(\bar{B}^0)$	0.8
	$B^0 \to \pi^\pm a_1^\mp$	$2 \cdot 4.5 \cdot 10^{-5}$
	$a_1^+ \to 3\pi^\pm$	0.5
Trigger	$p_T(\mu) > 1.0$ GeV/c	
	$p_T(e) > 1.4$ GeV/c	0.077
	$p_T(had) > 1.8$ GeV/c	0.84
Tracking of a_1^+	geometry	0.79
	pattern	0.85
Tracking of π^+	geometry	0.86
	pattern	0.95
Vertex B^0	decay length cut	0.69
Summary		$8.8 \cdot 10^{-7}$

$B_s^0 \to D_s^\pm K^\mp$

- measurement of γ
- study time dependent asymmetry
- $BR(B_s^0 \to D_s^- K^+) \approx 2.0 \cdot 10^{-3}$
  $BR(B_s^0 \to D_s^+ K^-) \approx 1.0 \cdot 10^{-3}$
- 20 reconstructed events/year
  tagged by high p_t lepton trigger
- background from $B_s^0 \to D_s^\pm \pi^\mp$ $\Rightarrow$ RICH needed

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

- measurement of β
- $BR \approx 0.005\%$
- take final state with only charged particles
- if longitudinally polarized final states dominate
  $\Rightarrow$ CP asymmetry can be determined
- amount about 20% of $J/\psi\, K_s^0$ events
  $\Rightarrow$ 20 % increase of CP statistics

$B^0 \to D^{*+} D^{*-}$

- measurement of β
- BR about 0.1%
- more 'penguin pollution' than in $J/\psi\, K_s^0$
- again assumption that one polarization of final state dominates
- dilepton trigger needed
- number of $B^0 \to D^{*+} D^{*-}$ with $D^{*\pm} \to \pi^{\pm} + X$ similar to number of $J/\psi\, K_s^0$ events

CP reach

$\sigma_{b\bar{b}}$	6 nb	12 nb	17 nb
σ_{inel}	13 mb	13 mb	13 mb
$\sigma_{b\bar{b}}/\sigma_{inel}$	$4.6{\cdot}10^{-7}$	$9.2{\cdot}10^{-7}$	$1.3{\cdot}10^{-6}$
trigger rate	40 MHz	40 MHz	40 MHz
b$\bar{\text{b}}$ rate	18 Hz	37 Hz	52 Hz
fraction of det. $B^0 \to J/\psi K^0_S$	$4.2 \cdot 10^{-6}$	$4.2 \cdot 10^{-6}$	$4.2 \cdot 10^{-6}$
# $J/\psi K^0_S$ per 10^7 s	$\approx$ 800	$\approx$ 1500	$\approx$ 2200
statistical factor	2.3	2.3	2.3
tagging power P_{tag}	0.31	0.31	0.31
Δ sin 2β after 10^7 s	**0.18**	**0.13**	**0.11**

Tagging efficiencies and dilution

	Lepton tag	Kaon tag	Charge tag
Cuts:			
p	$> 5\,\mathrm{GeV/c}$	$\epsilon\,[5, 50]\,\mathrm{GeV/c}$	–
p_t	$> 0.8\,\mathrm{GeV/c}$	–	–
$\chi^2(v_B, t)$	–	> 2	> 2
$\delta(v_B, t)$	$< 1\,\mathrm{mm}$	$< 1\,\mathrm{mm}$	$< 1\,\mathrm{mm}$
$\chi^2(v_X, t)$	> 4	> 4	> 5
Tag: sign(x)	q_l	q_K	$\sum_i q_i \cdot p_i$
Efficiencies:			
ϵ (tag found)	16.1%	46.0%	96.4%
ϵ_c (correct)	11.5%	31.3%	56.0%
ϵ_w (wrong)	4.6%	14.7%	40.4%
Significance:			
Dilution $D = \frac{\epsilon_c - \epsilon_w}{\epsilon}$	0.43	0.36	0.16
Power $P = D \cdot \sqrt{\epsilon}$	0.17	0.24	0.16
Combined Power:	$P = 0.31 \pm 0.03$		

Expected number of events

Mode	Trigger	Events/year
$B^0 \to J/\psi K^0_S$	J/ψ	$\approx$ 1500
$B^0 \to J/\psi K^{*0}$	J/ψ	$\approx$ 5500
$B^+ \to J/\psi K^+$	J/ψ	$\approx$ 7000
$B^+ \to J/\psi K^{*+}$	J/ψ	$\approx$ 1500
$B^0_s \to J/\psi \phi$	J/ψ	$\approx$ 1500
$\Lambda_b \to J/\psi \Lambda$	J/ψ	$\approx$ 500
$B^0_s \to D_s^{(*)} \ell^+ \nu$	$\ell\ell$	$\approx$ 900
$B^0_s \to D_s^{(*)} \pi^+$	ℓh	$\approx$ 200
$B^0_s \to D_s^{(*)} \pi^+\pi^+\pi^-$	ℓh	$\approx$ 200
$B^0 \to \pi^+\pi^-$	hh	$\approx$ 800
$B^0 \to \pi^\pm a_1^\mp$	hh	$\approx$ 300
$B^+ \to \rho^0 K^+$	hh	$\approx$ 500

$$\sigma_{\mathrm{bb}}^{\mathrm{tot}} = 12\,\mathrm{nb} \ @\ 40\,\mathrm{MHz}$$