Monte Carlo Simulations for $\bar{\text{P}}$ANDA

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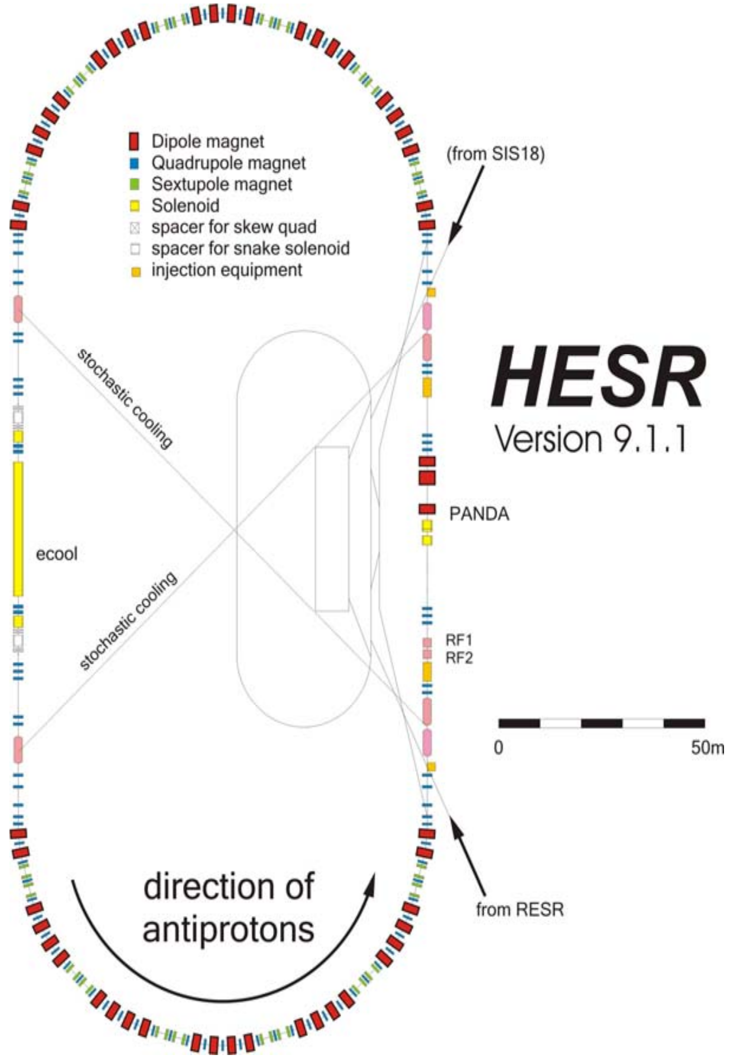
Outline

- Introduction
  - The $\bar{\text{P}}$ANDA Physics Program
  - The $\bar{\text{P}}$ANDA Physics Book
- Monte Carlo Simulations
  - General Features
  - Charmonium decays to J/ψ
  - $h_c \rightarrow \eta_c + \gamma$
  - $\bar{D}D$ channels
- Conclusions

High-Energy Storage Ring

- Production rate 2×10^7/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = 5×10^{10} $\bar{p}$
- Internal Target



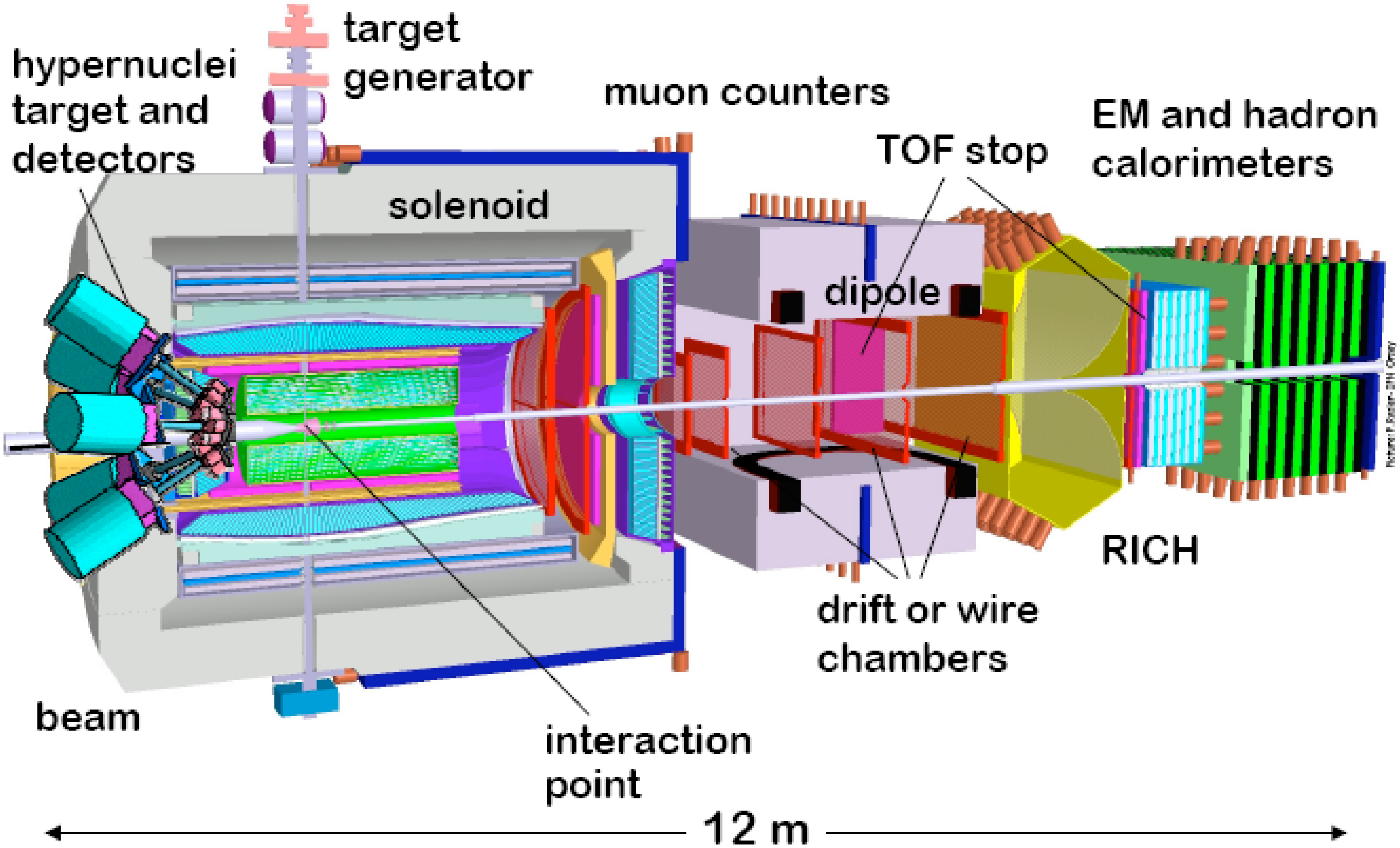
High resolution mode

- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = 10^{31} cm^{-2} s^{-1}

High luminosity mode

- Lumin. = 2×10^{32} cm^{-2} s^{-1}
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)

$\bar{\mathrm{P}}$ANDA Detector



$\bar{\text{P}}$ANDA Physics Program

The HESR at the GSI FAIR facility will deliver $\bar{p}$ beams of unprecedented quality with momenta up to 15 GeV/c ($\sqrt{s} \approx 5.5$ GeV).

This will allow $\bar{\text{P}}$ANDA to carry out the following measurements:

SPECTROSCOPY

- High-resolution charmonium spectroscopy in formation experiments
- Study of gluonic excitations (hybrids and glueballs) and other exotica (e.g. multiquark states)
- Study of hadrons in nuclear matter
- Open charm physics
- Hypernuclear physics

NUCLEON STRUCTURE

- Proton Timelike Form Factors
- Crossed-Channel Compton Scattering
- Drell-Yan

The $\overline{\text{P}}$ANDA Physics Book

First version of Physics Book with the following goals:

- Demonstrate that we can study the physics cases with the $\overline{\text{P}}$ANDA detector.
- Demonstrate the physics performance of the $\overline{\text{P}}$ANDA detector
- Demonstrate that we can simulate, reconstruct and analyze a very large amount of data (deliverable of DIRAC EU-project in FP6)
- Studies should be as detalied as possible
- Only one specific detector setup to be studied

The Physics Book will be delivered at the end of the year.

Physics Performance Report for:

$\overline{\text{P}}$ANDA

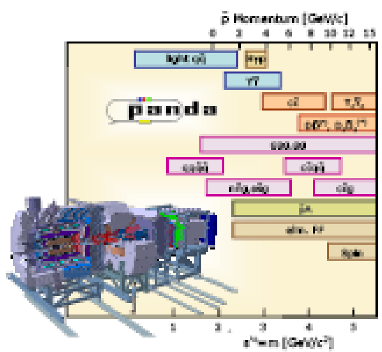
(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

$\overline{\text{P}}$ANDA Collaboration

November 28, 2008 - Revision: 683

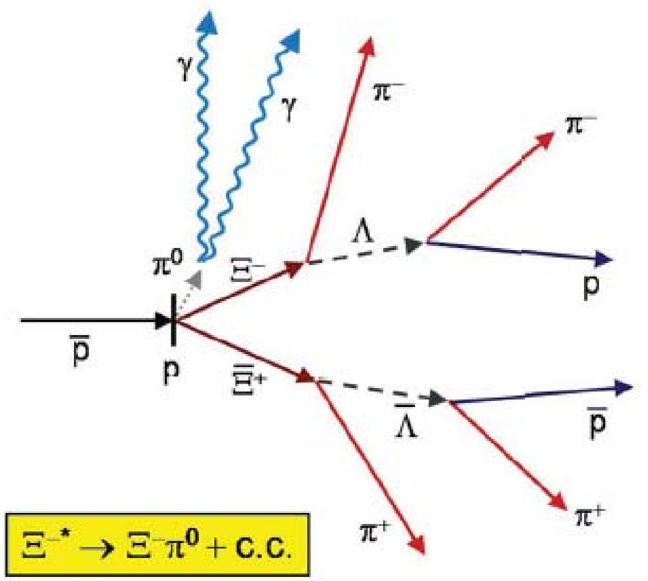
To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\text{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\text{P}}$ANDA and what performance can be expected.



Physics Performance

QCD BOUND STATES

- CHARMONIUM (D. Bettoni/M. Negrini)
  - $J/\psi\pi^+\pi^+$, $J/\psi\pi^0\pi^0$, $J/\psi\gamma$, $J/\psi\eta$, $\chi\gamma$ at various CM energies
  - $h_c \rightarrow \eta_c\gamma$, $\eta_c \rightarrow \phi\phi$
  - $D\ \bar{D}$
- GLUONIC EXCITATIONS (K. Peters)
  - $\bar{p}p \rightarrow \eta_{c1}\eta$, $\eta_{c1} \rightarrow \chi_{c1}\pi^0\pi^0$, $\eta_{c1} \rightarrow DD^*$
  - $\bar{p}p \rightarrow f_2(2000\text{-}2500) \rightarrow \phi\phi$
  - $J/\psi\omega$
  - $\psi(2S)\pi^+\pi^+$
- HEAVY-LIGHT SYSTEMS (A. Gillitzer)
  - $\bar{p}p \rightarrow D^{\pm}D_{s0}^{*}(2317)$
- STRANGE AND CHARMED BARYONS (A. Gillitzer)



Physics Performance

NON PERTURBATIVE QCD DYNAMICS (T. Johansson)

- $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$
- $\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{-}$

HADRONS IN THE NUCLEAR MEDIUM (A. Gillitzer)

- $\bar{p}\,^{40}Ca \rightarrow J/\psi + X$, $J/\psi \rightarrow e^{+}e^{-}, \mu^{+}\mu^{-}$

HYPERNUCLEAR PHYSICS (J. Pochodzalla / A. Feliciello / F. Iazzi)

NUCLEON STRUCTURE

- GENERALIZED DISTRIBUTION AMPLITUDES (GDA) (M. Düren)
  - $\bar{p}p \rightarrow \gamma\gamma$, $\bar{p}p \rightarrow \pi^{0}\gamma$
- DRELL-YAN (M.Bussa / M. Maggiora)
  - $\bar{p}p \rightarrow \mu^{+}\mu^{-} X$
- ELECTROMAGNETIC FORM FACTORS (F. Maas)
  - $\bar{p}p \rightarrow e^{+}e^{-}$

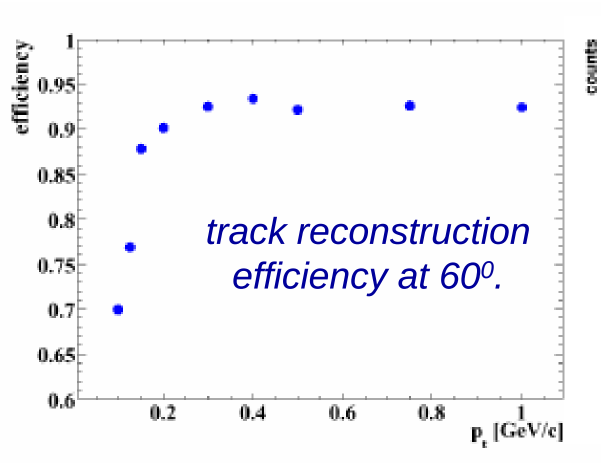
ELECTROWEAK PHYSICS (L. Schmitt)

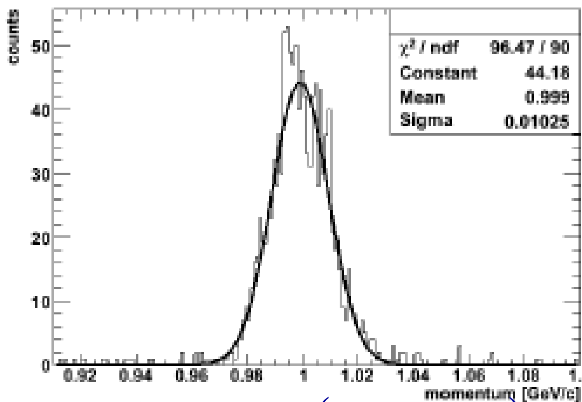
Monte Carlo Simulations

- Event generators with accurate decay models for the individual physics channels as well as for the relevant background channels (e.g. Dual Parton Model, UrQMD, ...).
- Particle tracking through the complete $\bar{\text{P}}$ANDA detector by using the GEANT4 transport code.
- Digitization which models the signals of the individual detectors and their processing in the frontend electronics.
- Reconstruction and identification of charged and neutral particles, providing lists of particle candidates for the physics analysis.

  Kalman Filter for charged particle tracking.
- High-level analysis tools which allow to make use of vertex and kinematical fits and to reconstruct decay trees.

MC Performance

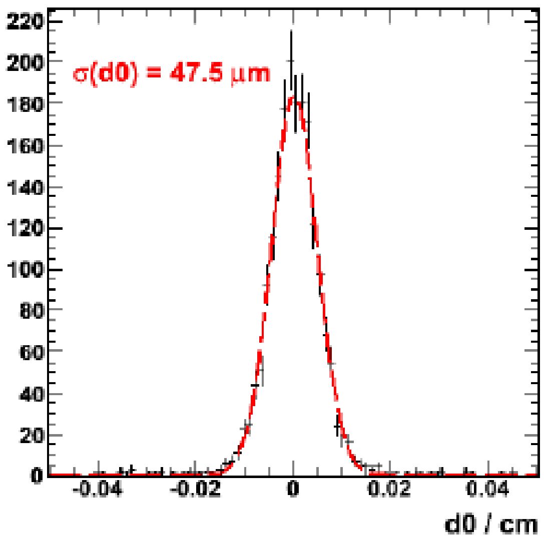


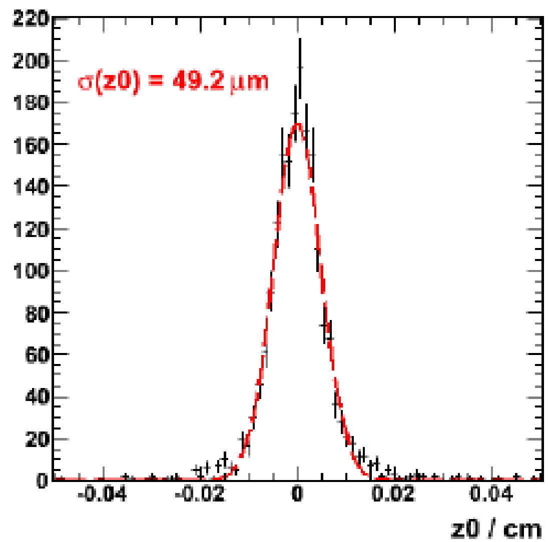


$$\sigma_p / p = 1\% \left(1\, GeV\ \pi\right)$$

Energy thresholds in the Calorimeters

	Central ($PbWO_4$)	Forward (Shashlik)
single crystal	3 MeV	8 MeV
Cluster	10 MeV	15 MeV
Max	20 MeV	10 MeV

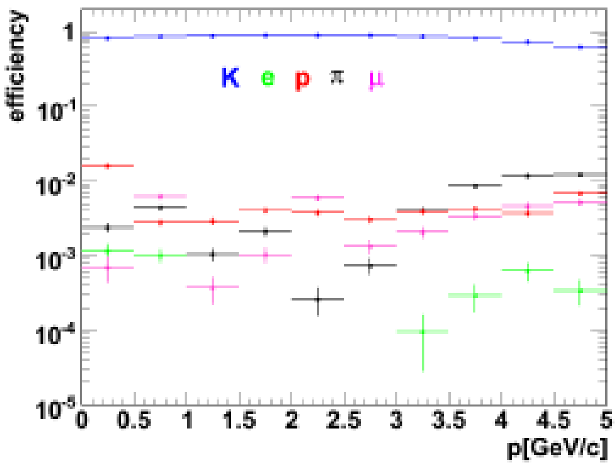




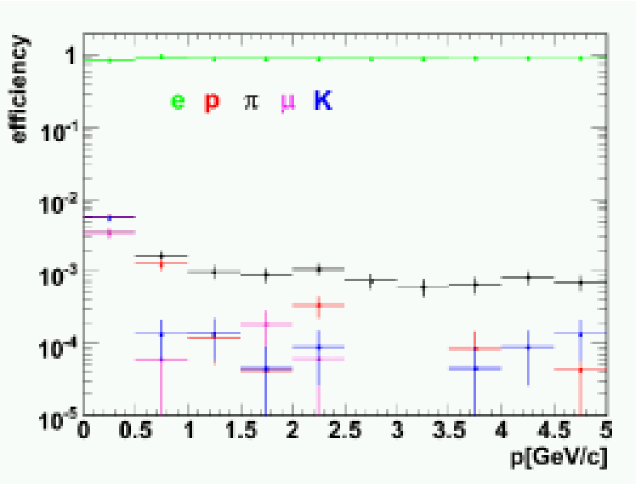
Particle ID

Particle ID:
- dE/dx
  - MVD,STT
- Calorimeter information
- DIRC counter
- Muon detector

	VeryLoose	Loose	Tight	VeryTight
e	20 %	85 %	99 %	99.8 %
μ	20 %	45 %	70 %	85 %
π	20 %	30 %	55 %	70 %
K	20 %	30 %	55 %	70 %
p	20 %	30 %	55 %	70 %



K VeryTight Efficiency and contamination



e VeryTight Efficiency and contamination

Event Mass Production

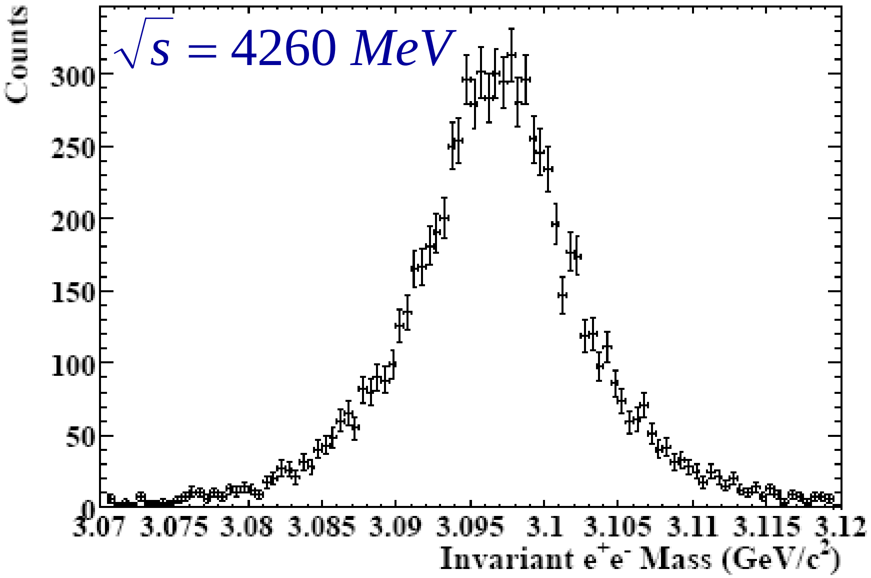
- Event mass production at GSI, Lyon, Orsay, Bochum.
- $\sim 1.3 \times 10^9$ events available.
  - signal events for all benchmark channels
  - background events for all channels
- Filter at the generator level to speed up the generation procedure: require charged tracks to lie within J/ψ mass window.

Site	*GSI*	*Lyon*	*Orsay*	*Bochum*
#events/10^8	*3.1*	*5.5*	*1.5*	*3.0*

Charmonium Decays to J/ψ

$$\bar{p}p \rightarrow \bar{c}c \rightarrow J/\psi + X,\ J/\psi \rightarrow e^+e^-, (\mu^+\mu^-)$$

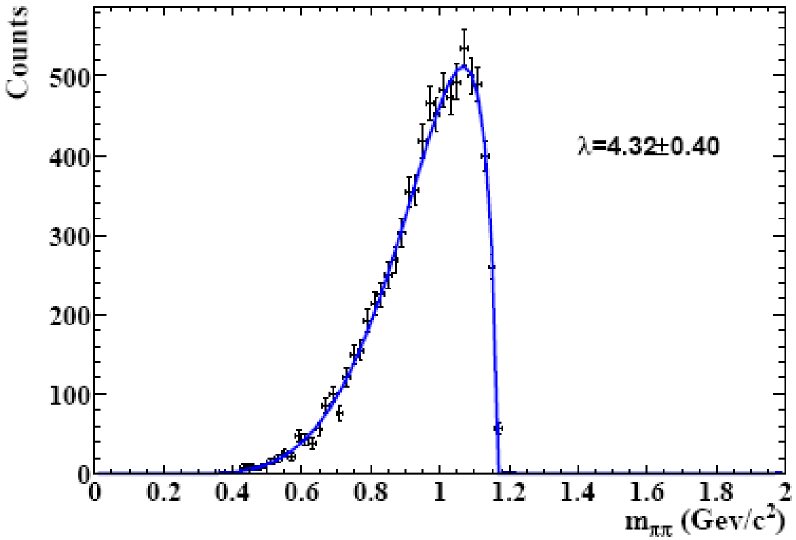
- Tagged by lepton pair with invariant mass equal to $M(J/\psi)$.
- Main background source: misidentified $\pi^+\pi^-$ pairs.
- Electron analysis:
  - two electron candidates: one Loose one Tight.
  - kinematic fit to J/ψ hypothesis with vertex constraint.
  - $P(fit) > 0.001$.
- Additional cuts for exclusive final states:
  - $\bar{p}p \rightarrow J/\psi\pi^+\pi^-$
  - $\bar{p}p \rightarrow J/\psi\pi^0\pi^0$
  - $\bar{p}p \rightarrow \chi_{c1,c2}\gamma \rightarrow J/\psi\gamma\gamma$
  - $\bar{p}p \rightarrow J/\psi\gamma$
  - $\bar{p}p \rightarrow J/\psi\eta$



$\bar{p}p \rightarrow J/\psi\, \pi^+ \pi^- \rightarrow e^+ e^- \pi^+ \pi^-$

- J/ψ selection
- two pion candidates (VeryLoose)
- vertex fit to $J/\psi \pi^+ \pi^-$

$$\frac{dN}{dm_{\pi\pi}} \propto PHSP \cdot \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2$$



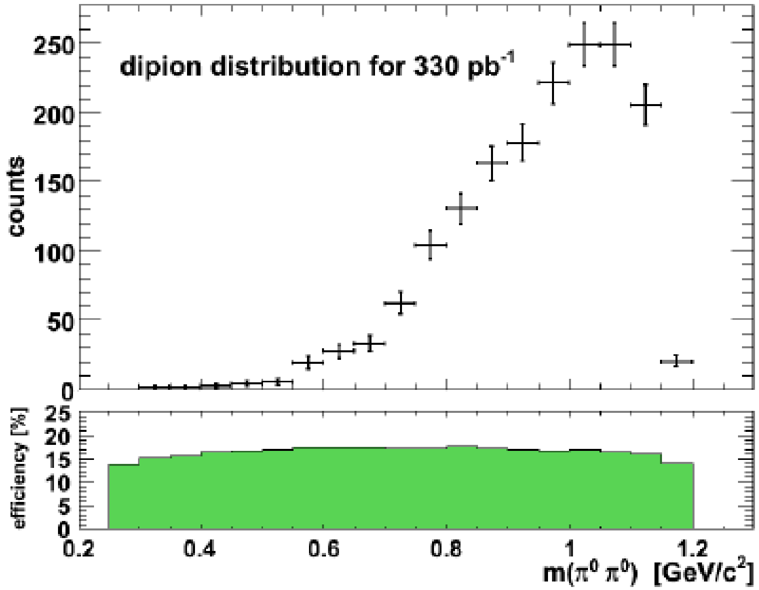
$\sqrt{s}$ [GeV]	Eff [%]	RMS [MeV]
3.526	27.52	3.7
3.686	30.90	5.7
3.872	32.07	8.3
4.260	32.58	13.4
4.600	30.60	18.5
5.000	29.70	24.3

Main background process:

$\bar{p}p \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

Estimated background cross section < 10 pb

$\bar{p}p \to J/\psi\, \pi^0 \pi^0 \to e^+ e^- \pi^0 \pi^0$



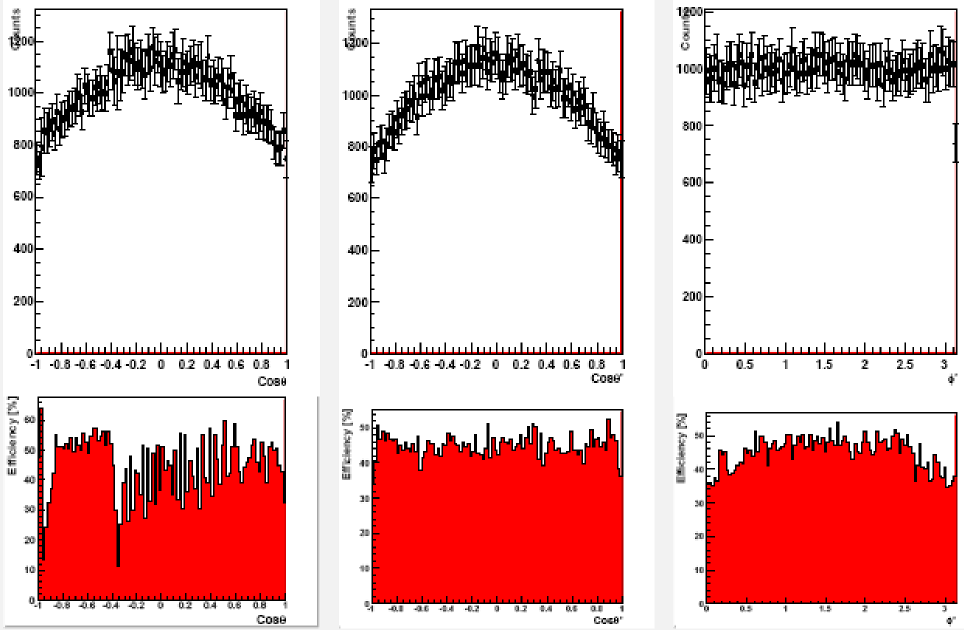
Main background process:

$\bar{p}p \to \pi^+ \pi^- \pi^0 \pi^0$

Estimated S/B 25

channel	assumed σ	efficiency	
$\bar{p}p \to J/\psi\pi^0\pi^0 \to e^+e^-4\gamma$	30 pb	16.9 %	n_{rec}= 40 events / day
background reactions:			
$\bar{p}p \to \pi^+\pi^-\pi^0\pi^0 \to \pi^+\pi^-4\gamma$	50 μb	1 / 250M	S/B= 25
$\bar{p}p \to J/\psi\eta\pi^0 \to e^+e^-4\gamma$	<30 pb	0 / 20K	S/B> 10^3
$\bar{p}p \to J/\psi\omega\pi^0 \to e^+e^-5\gamma$	<10 pb	4 / 20K	S/B> 10^3

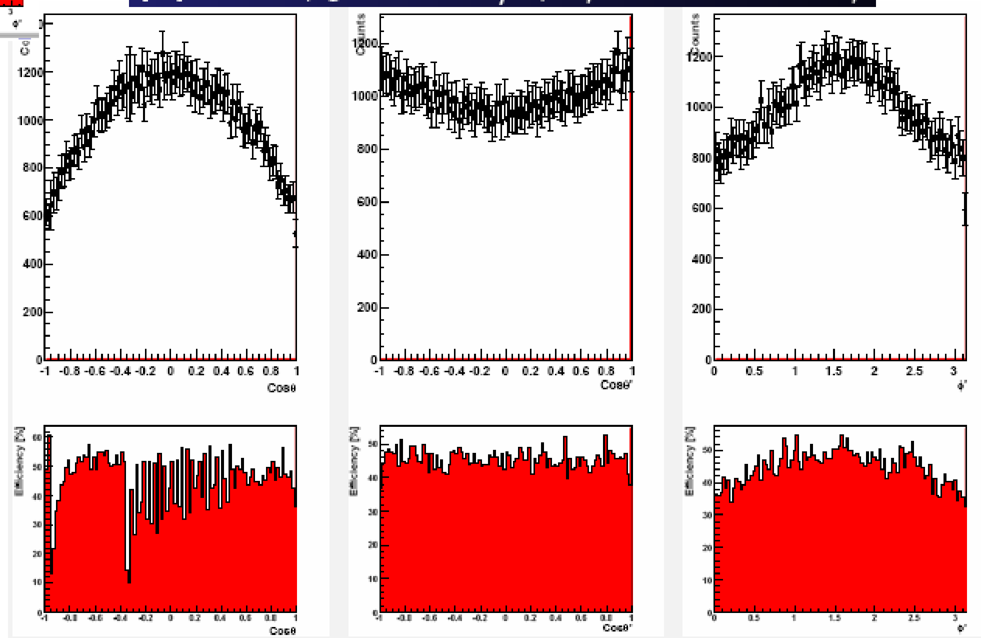
$\bar{p}p \rightarrow \chi_1 \rightarrow J/\psi\gamma \rightarrow e^+e^-\gamma$



$\chi_1 \rightarrow J/\psi\gamma$

- Mean = 3.512 GeV
- RMS = 11.4 MeV
- Eff = 45.27%

$\bar{p}p \rightarrow \chi_2 \rightarrow J/\psi\gamma \rightarrow e^+e^-\gamma$



$\chi_2 \rightarrow J/\psi\gamma$

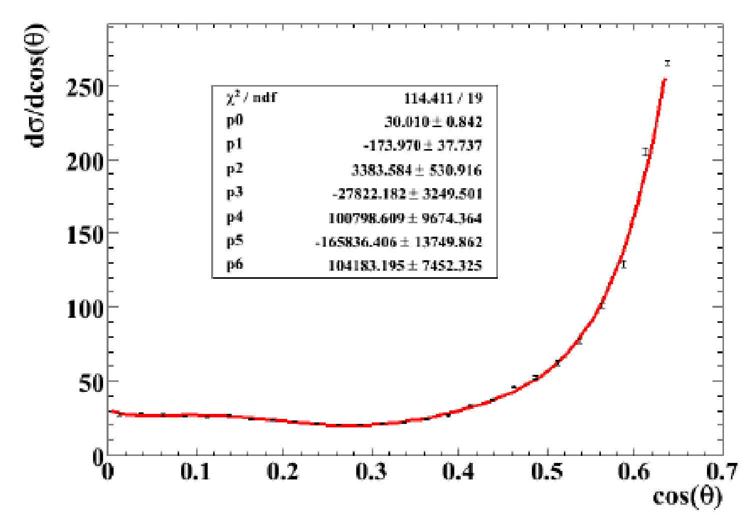
- Mean = 3.557 GeV
- RMS = 12.0 MeV
- Eff = 45.84%

$h_c \to \eta_c\gamma \to 3\gamma$

$E_\gamma = 503\ MeV$

$\Gamma_{p\bar{p}}\mathcal{B}_{\eta_c\gamma} = 10\ eV \quad \Rightarrow \quad \sigma_p = 33\ nb$

- Pair 2 γs to form η_c mass ($\gamma_1\gamma_2$).
- 4C fit to h_c candidate.
- $N_\gamma=3$.
- CL (4C fit) > 10^{-4}.
- $0.4\ GeV < E_\gamma < 0.6\ GeV$.
- $|cos\theta| < 0.6$.
- $M(\gamma_1\gamma_3), M(\gamma_2\gamma_3) > 1\ GeV$.



Channel	σ (nb)	number of events
$\bar{p}p \to h_c \to 3\gamma$		20 k
$\bar{p}p \to \pi^0\pi^0$	31.4	1.3 M
$\bar{p}p \to \pi^0\gamma$	1.4	100 k
$\bar{p}p \to \pi^0\eta$	33.6	1.3 M
$\bar{p}p \to \eta\eta$	34.0	1.3 M
$\bar{p}p \to \pi^0\eta'$	50.0	100 k

$h_c \rightarrow \eta_c\gamma \rightarrow 3\gamma$

Cut	h_c	$\pi^0\gamma$	$\pi^0\pi^0$	$\pi^0\eta$	$\eta\eta$	$\pi^0\eta'$
preselection	0.70	0.43	0.14	$8.2 \cdot 10^{-2}$	$4.0 \cdot 10^{-2}$	$8.5 \cdot 10^{-2}$
$3\ \gamma$	0.47	0.31	$1.3 \cdot 10^{-2}$	$7.5 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$	$8.7 \cdot 10^{-3}$
$CL > 10^{-4}$	0.44	0.30	$9.9 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$7.2 \cdot 10^{-4}$	$5.7 \cdot 10^{-3}$
E_γ [0.4;0.6] GeV	0.43	0.12	$3.9 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$2.8 \cdot 10^{-4}$	$2.3 \cdot 10^{-3}$
$\lvert\cos(\theta)\rvert < 0.6$	0.22	$9.2 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$	$7.0 \cdot 10^{-5}$	$7.5 \cdot 10^{-4}$
$m_{12}^2, m_{23}^2 > 1.0\,\mathrm{GeV}$	$8.1 \cdot 10^{-2}$	0	0	0	0	0

In high-luminosity mode ($L = 2\times10^{32}cm^{-2}s^{-1}$) expect 20 signal events/day.

Channel	S/B ratio
$\bar{p}p \rightarrow \pi^0\pi^0$	> 94
$\bar{p}p \rightarrow \pi^0\gamma$	> 164
$\bar{p}p \rightarrow \pi^0\eta$	> 88
$\bar{p}p \rightarrow \eta\eta$	> 87
$\bar{p}p \rightarrow \pi^0\eta'$	> 250

$h_c \to \eta_c\gamma \to \phi\phi\gamma \to 4K\gamma$

Channel	N of events	
$\bar{p}p \to h_c \to \phi\phi\gamma$	20 k	
$\bar{p}p \to K^+K^-K^+K^-\pi^0$	6.2 M	σ~345 nb
$\bar{p}p \to \phi K^+K^-\pi^0$	200 k	σ~60 nb
$\bar{p}p \to \phi\phi\pi^0$	4.2 M	σ< 3 nb
$\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0$	5 M + 15 M	σ~30 μb
	100 k	

} DPM estimate

- ϕ candidates: K pairs in appropriate mass window.
- 4C fit to beam-momentum
- CL (4C) > 0.05
- η_c invariant mass [2.9, 3.06] GeV .
- E_γ [0.4, 0.6] GeV
- ϕ mass [0.99, 1.05] GeV
- no π^0 in event

Selection criteria	signal	$4K\pi^0$	$\phi K^+K^-\pi^0$	$\phi\phi\pi^0$	$K^+K^-\pi^+\pi^-\pi^0$
pre-selection	0.51	$9.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$	$4.9 \cdot 10^{-2}$	$9.0 \cdot 10^{-6}$
$CL > 0.05$	0.36	$1.5 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$7.0 \cdot 10^{-3}$	$4.0 \cdot 10^{-8}$
$m(\eta_c), E_\gamma$	0.34	$4.1 \cdot 10^{-4}$	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$	0
$m(\phi)$	0.31	$4.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-4}$	$1.7 \cdot 10^{-3}$	0
$no\ \pi^0(30\,MeV)$	0.26	$2.7 \cdot 10^{-6}$	$4.5 \cdot 10^{-5}$	$9.2 \cdot 10^{-4}$	0
$no\ \pi^0(10\,MeV)$	0.24	$1.8 \cdot 10^{-6}$	$3.0 \cdot 10^{-5}$	$7.1 \cdot 10^{-4}$	0

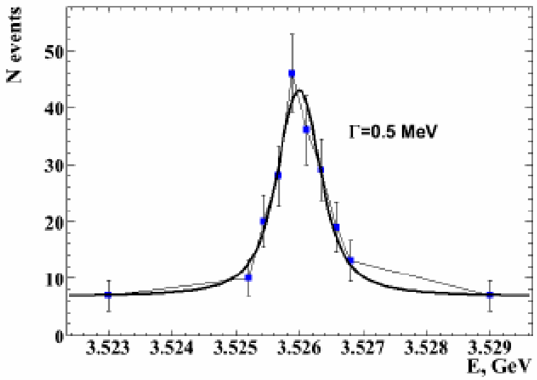
In high-luminosity mode ($L = 2\times10^{32}cm^{-2}s^{-1}$) expect 92 signal events/day.

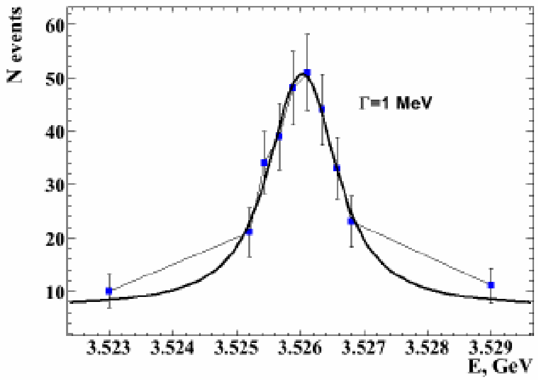
channel	Signal/Background
$\bar{p}p \to K^+K^-K^+K^-\pi^0$	8
$\bar{p}p \to \phi K^+K^-\pi^0$	8
$\bar{p}p \to \phi\phi\pi^0$	> 10
$\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0$	> 12

Sensitivity to h_c Width Measurement

$$p\bar{p} \rightarrow h_c \rightarrow \eta_c + \gamma \rightarrow K^+K^-K^+K^-\gamma$$

$$\nu_i = [\varepsilon \times \int Ldt]_i \times [\sigma_{bkgd}(E) + \frac{\sigma_p \Gamma_R^2/4}{(2\pi)^{1/2}\sigma_i} \times \int \frac{e^{-(E-E')^2/2\sigma_i^2}}{(E'-M_R)^2 + \Gamma_R^2/4} dE'],$$





signal efficiency ε=0.24

each point corresponds to 5 days of data taking

Likelihood function:

$$\mathcal{L} = \prod_{j=1}^{N} \frac{\nu_j^{n_j} e^{-\nu_j}}{n_j!}.$$

$\Gamma_{R,MC}$, MeV	$\Gamma_{R,reco}$, MeV	$\Delta\Gamma_R$, MeV
1	0.92	0.24
0.75	0.72	0.18
0.5	0.52	0.14

$\bar{p}p \rightarrow \bar{D}D$

- Charmonium states above open charm threshold
- Charm spectroscopy
- Search for hybrids decaying to $\bar{D}D$
- Rare D decays (and CP violation)

Main issue: separation of charm signal from large hadronic background

$$\bar{p}p \rightarrow D^{+}D^{-} \quad D^{+} \rightarrow K^{-}\pi^{+}\pi^{+} \qquad \sqrt{s} \rightarrow \psi(3770)$$

$$\bar{p}p \rightarrow D^{*+}D^{*-} \quad D^{*+} \rightarrow D^{0}\pi^{+} \quad D^{0} \rightarrow K^{-}\pi^{+} \qquad \sqrt{s} \rightarrow \psi(4040)$$

Cross section estimates: Breit-Wigner, with $\bar{p}p$ BR scaled from ψ

$$\sigma\left(\bar{p}p \rightarrow \psi(3770) \rightarrow D^{+}D^{-}\right) = 3.9\ nb$$

$$\sigma\left(\bar{p}p \rightarrow \psi(4040) \rightarrow D^{*+}D^{*-}\right) = 0.9\ nb$$

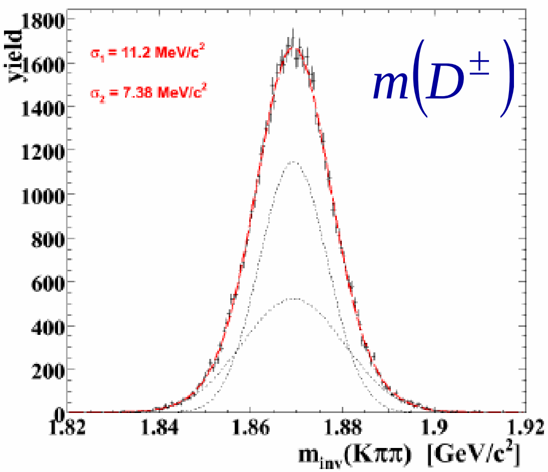
channel	D^+D^-	$D^{*+}D^{*-}$
decay	$D^\pm \rightarrow K^\mp\pi^\pm\pi^\pm$ (9.2 %)	$D^{*+} \rightarrow D^0\pi^+$ (67.7 %) $D^0 \rightarrow K^-\pi^+$ (3.8 %)
R	4×10^{-10}	1×10^{-11}

Event Selection

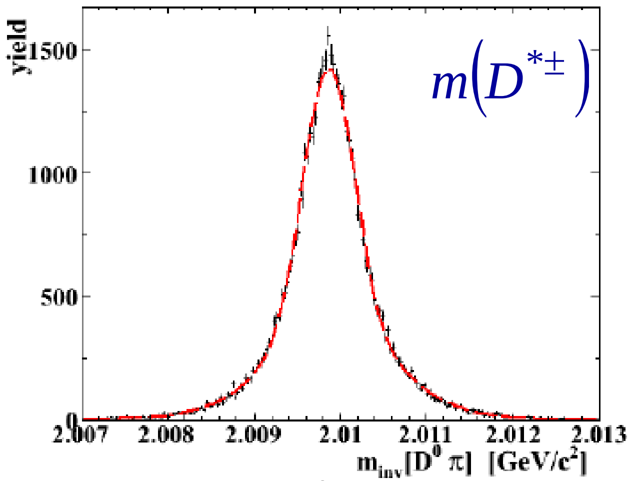
- Loose mass window cut before vertex fitting $\Delta m = \pm 0.3\ GeV/c^2$.
- Minimum 6 charged tracks.
- All decay particles must form a common vertex.
- 4C kinematic fit to constrain beam energy and momentum: $CL > 5\times 10^{-2}$.
- K/π selection Loose ($LH > 0.3$).
- Only one combination per event.

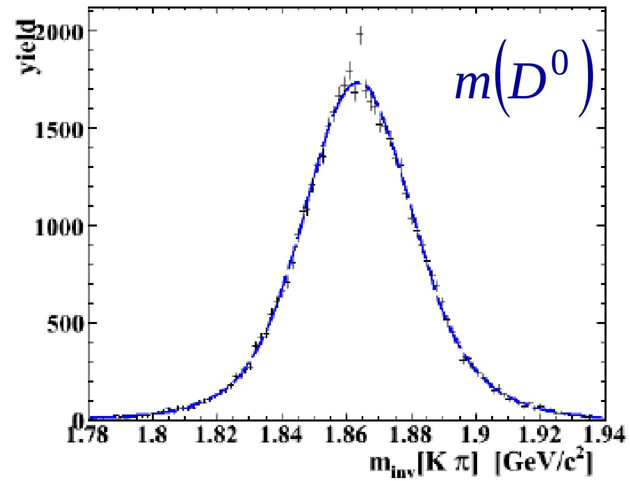
Signal Efficiency

$\bar{p}p \to D^+ D^-$



$\bar{p}p \to D^{*+} D^{*-}$





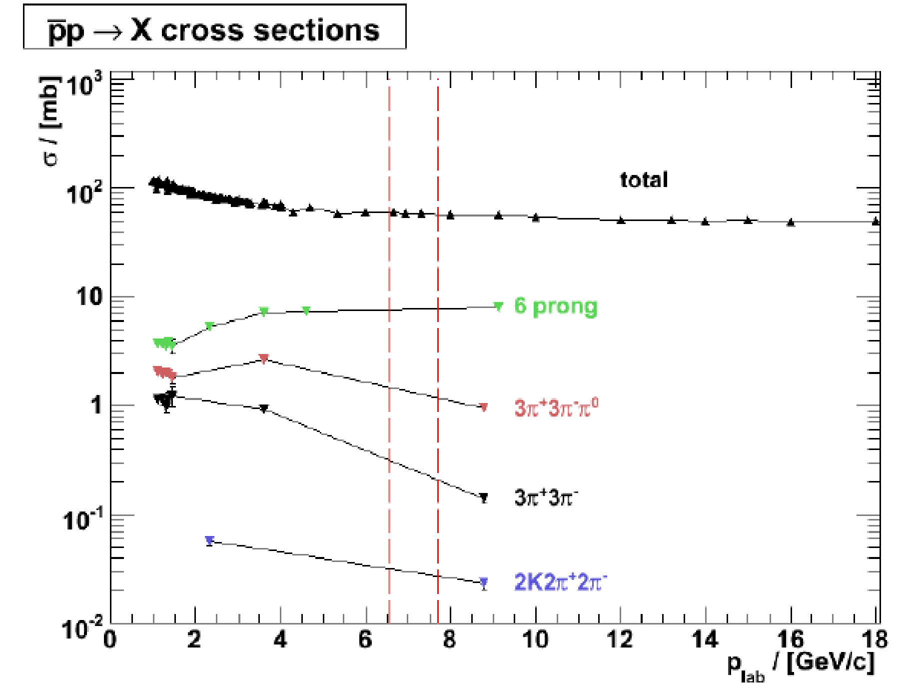
after 5C fit (D^0 mass constraint)

overall efficiency
ε(signal) = 40 %

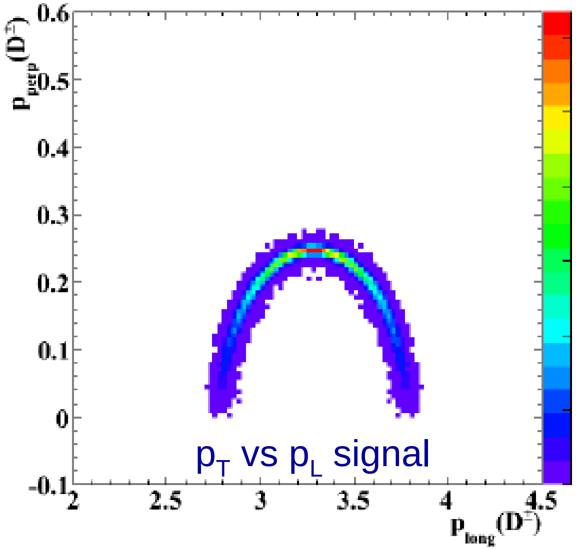
overall efficiency *ε(signal) = 27.4 % (4C* fit)
overall efficiency *ε(signal) = 24.0 % (5C* fit)

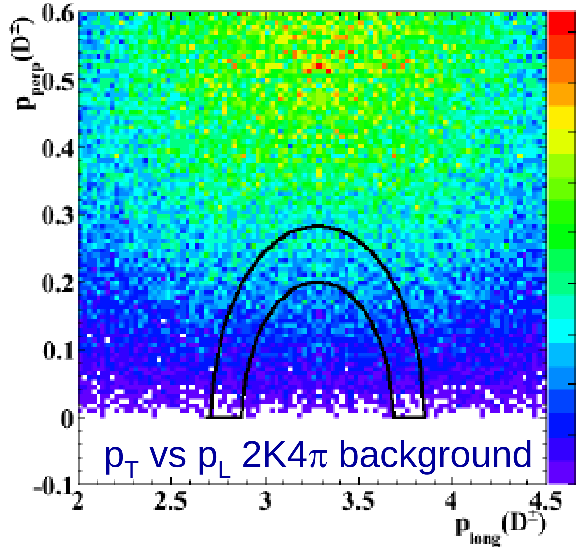
Background studies

channel	D^+D^-	$D^{*+}D^{*-}$	Ratio to $\bar{p}p$
DPM	100 M	-	-
$3\pi^+3\pi^-\pi^0$	50 M	43 M	2.5×10^{-2}
$3\pi^+3\pi^-$	10 M	14 M	5×10^{-3}
$K^+K^-2\pi^+2\pi^-$	1 M	10 M	5×10^{-4}

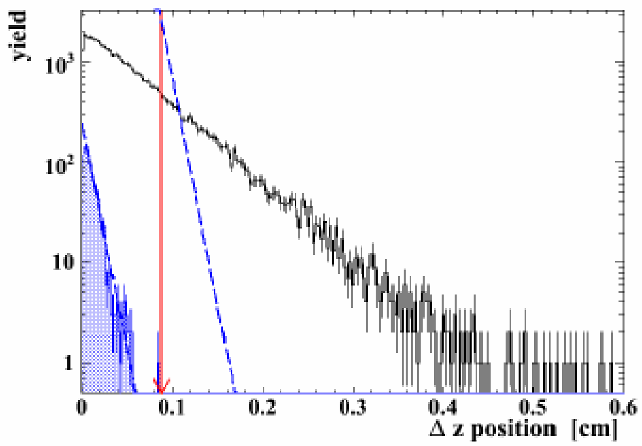


$2K4\pi$ Background





Two-dimensional cut on $D^{\pm}$ momentum reduces $2K4\pi$ background by factor 26.



Cut on Δz of $D^{\pm}$ decay vertex:
$\Delta z > 0.088$ cm $S/B = 1$ $\varepsilon(signal) = 7.8$ %

For the $D^{*+}D^{*-}$ channel the analysis gives $S/B = 1/3$. An additional cut on the Δz of the D^0 decay vertex gives $S/B=3/2$, bringing the signal efficiency from 24 % to 12.7 %.

Non strange background

selection	efficiency			signal/background	
selection	D^+D^-	$3\pi^+3\pi^-$	$3\pi^+3\pi^-\pi^0$	$\frac{D^+D^-}{3\pi^+3\pi^-}$	$\frac{D^+D^-}{3\pi^+3\pi^-\pi^0}$
preselection	0.43	$5.4 \cdot 10^{-3}$	$9.6 \cdot 10^{-4}$	-	-
4C-fit	0.40	$1.4 \cdot 10^{-6}$	$4.2 \cdot 10^{-7}$	0.02	0.015
$D^\pm$ momentum	0.40	$< 1.1 \cdot 10^{-8}$	$< 3.6 \cdot 10^{-9}$	> 2.7	> 1.8
K LH > 0.3	0.23	$< 1.8 \cdot 10^{-9}$	$< 1.7 \cdot 10^{-9}$	> 6.4	> 2.9

selection	efficiency			signal/background	
selection	$D^{*+}D^{*-}$	$3\pi^+3\pi^-$	$3\pi^+3\pi^-\pi^0$	$\frac{D^{*+}D^{*-}}{3\pi^+3\pi^-}$	$\frac{D^{*+}D^{*-}}{3\pi^+3\pi^-\pi^0}$
preselection	0.27	$5.0 \cdot 10^{-7}$	$7.5 \cdot 10^{-8}$	-	-
5C-fit	0.24	$5.0 \cdot 10^{-11}$	$7.5 \cdot 10^{-12}$	≥ 10	≥ 14

Measurement of the $D^*_{s0}(2317)$ Width

inclusive $D_s(2317)$ reconstruction:

$\bar{p}p \to D_s^{\pm} D_{s0}^{\mp *}(2317)$

$D_s^{\pm} \to \phi\pi^{\pm}$, $\phi \to K^+K^-$

$D_{s0}^{\mp *}(2317) \to$ anything: ⇒ ε_{signal}, $\varepsilon_{background}$, S/B

The production cross section around threshold depends on the total width.

input

$$\int \mathcal{L}dt = 126\ pb^{-1} (14\ \text{days})$$

$$S/B = 1/3$$

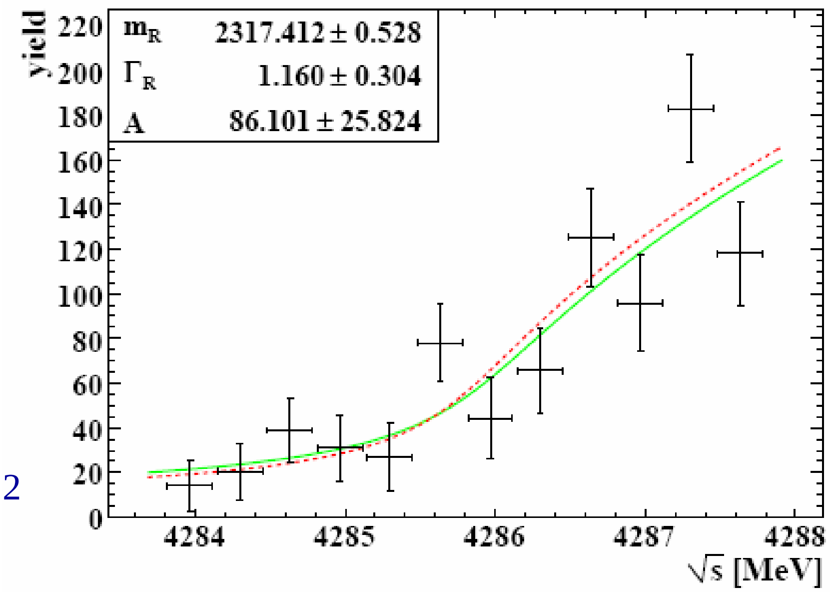
$$\Gamma = 1\ MeV$$

$$m = 2317.30\ MeV/c^2$$

output

$$\Gamma = (1.16 \pm 0.30)\ MeV$$

$$m = (2317.41 \pm 0.53)\ MeV/c^2$$



Conclusions

- In order to perform the PB studies a number of tools have been developed which include:
  - Generation of signal and background events
  - Full simulation of detector response
  - Reconstruction and analysis tools (e.g. Kalman Filter, Kinematic fitting)
- The performance of the detector and the sensitivity to the various physics channels have been estimated reliably:
  - Acceptance
  - Resolution
  - Signal/Background
- For charmonium the simulations show that the final states of interest can be detected with good efficiency and that the background situation is under control.