P986:
Medium-Energy Antiproton Experiments at Fermilab

Daniel M. Kaplan

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Physics Advisory Committee
Fermilab
Batavia, IL
Mar. 5, 2009

Outline

(Varied menu!)

- Antiproton sources
- Hyperon CP violation
- A new experiment
- Issues in charmonium
- Charm mixing
- Summary

Antiproton Sources

- Fermilab Antiproton Source is world's most intense (and highest-energy)

Facility	$\overline{p}$ K.E. (GeV)	Stacking: Rate (10^{10}/hr)	Stacking: Duty Factor	Hours /Yr	$\overline{p}$/Yr (10^{13})
CERN AD	0.005, 0.047	–	–	3800	0.4
FNAL (Accumulator)	≈3.5–8	20	15%	5550	17
~~FNAL (New Ring)~~	~~2–20?~~	~~20~~	~~90%~~	~~5550~~	~~100~~
FAIR (≥2016)	2–15	3.5	90%	2780*	9

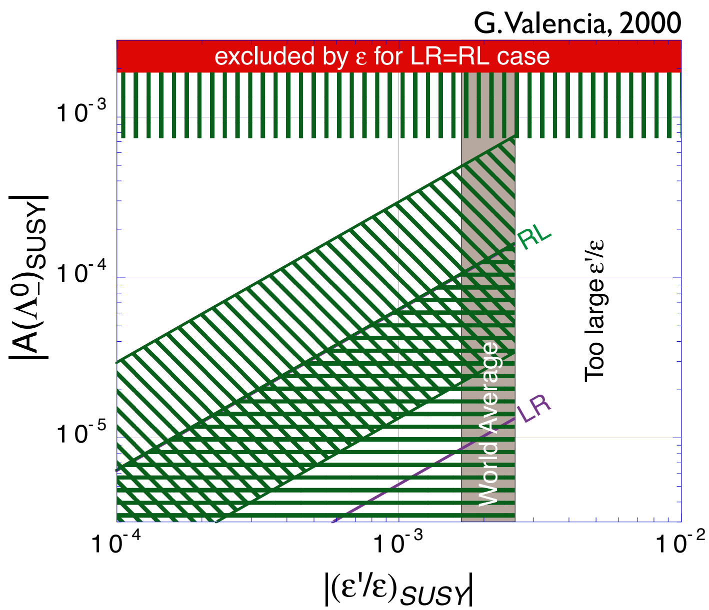
* The lower number of operating hours at FAIR compared with that at other facilities arises from medium-energy antiproton operation having to share time with other programs.

...even after GSI FAIR turns on (has yet to break ground; will likely take some time to reach this goal)

Hyperon CP Violation

- Differently sensitive to new physics than *B*, ε′/ε (parity-*conserving* interactions)
  - complementary to mu2e
- B Factories have shown *B* mixing & CPV dominantly SM

$\Longrightarrow$ worth looking elsewhere!



- Leading potential signals are A_Λ, $A_{\Xi\Lambda}$, B_Ξ, Δ_Ω:

$$A_\Lambda \equiv \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda},\quad B_\Lambda \equiv \frac{\beta_\Lambda + \bar{\beta}_\Lambda}{\beta_\Lambda - \bar{\beta}_\Lambda},\quad \Delta_\Lambda \equiv \frac{\Gamma_{\Lambda\to P\pi} - \bar{\Gamma}_{\Lambda\to P\pi}}{\Gamma_{\Lambda\to P\pi} + \bar{\Gamma}_{\Lambda\to P\pi}}$$

CP-odd

- $\bar{p}$ source can produce ~10^8 $\Omega^-\,\overline{\Omega}^+$, & maybe ~$10^{10}$ $\Xi^-\,\overline{\Xi}^+$ (transition crossing)

Hyperon CP Violation

- SM predicts small CP asymmetries in hyperon decay
- NP can amplify them by orders of magnitude:

Table 5: Summary of predicted hyperon CP asymmetries.

Asymm.	Mode	SM	NP	Ref.
A_Λ	$\Lambda \to p\pi$	$\lesssim 10^{-5}$	$\lesssim 6 \times 10^{-4}$	[68]
$A_{\Xi\Lambda}$	$\Xi^{\mp} \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 0.5 \times 10^{-4}$	$\leq 1.9 \times 10^{-3}$	[69]
$A_{\Omega\Lambda}$	$\Omega \to \Lambda K,\ \Lambda \to p\pi$	$\leq 4 \times 10^{-5}$	$\leq 8 \times 10^{-3}$	[36]
$\Delta_{\Xi\pi}$	$\Omega \to \Xi^0\pi$	2×10^{-5}	$\leq 2 \times 10^{-4}$ *	[35]
$\Delta_{\Lambda K}$	$\Omega \to \Lambda K$	$\leq 1 \times 10^{-5}$	$\leq 1 \times 10^{-3}$	[36]

*Once they are taken into account, large final-state interactions may increase this prediction [56].

Hyperon CP Violation

- Theory & experiment:

Theory [Donoghue, He, Pakvasa, Valencia, et al., e.g., PRL 55, 162 (1985); PRD 34, 833 (1986); PLB 272, 411 (1991)]

- SM: $A_\Lambda \sim 10^{-5}$, $|A_{\Xi\Lambda}| < 5 \times 10^{-5}$ [J. Tandean, G. Valencia, Phys. Rev. D 67, 056001 (2003)]
- Other models: $\mathcal{O}(10^{-3})$
  [e.g. SUSY gluonic dipole: X.-G.He et al., PRD 61, 071701 (2000)]

Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	**-0.02 ± 0.14**	[P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	**0.01 ± 0.10**	[M.H. Tixier et al., PL B212 (1988) 523]
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	**0.006 ± 0.015**	[P.D. Barnes et al., NP B 56A (1997) 46]

Experiment	Decay Mode	$A_\Xi + A_\Lambda$	
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**0.012 ± 0.014**	[K.B. Luk et al., PRL 85, 4860 (2000)]
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**$(0.0 \pm 6.7) \times 10^{-4}$**	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		$(6 \pm 2 \pm 2) \times 10^{-4}$	[BEACH08 preliminary]

Hyperon CP Violation

- Theory & experiment:

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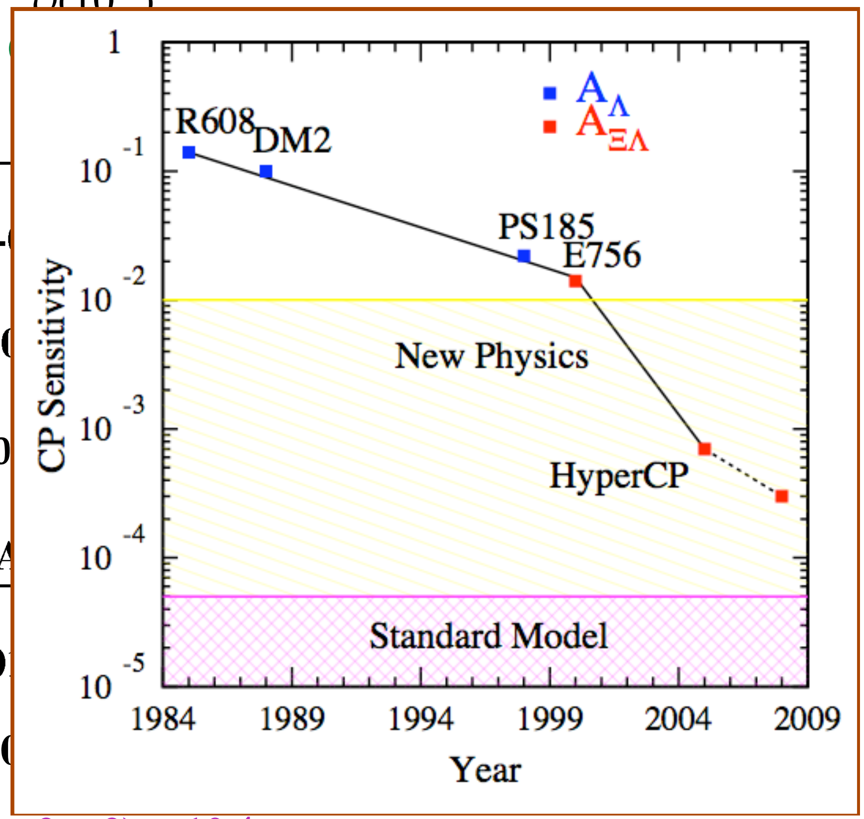
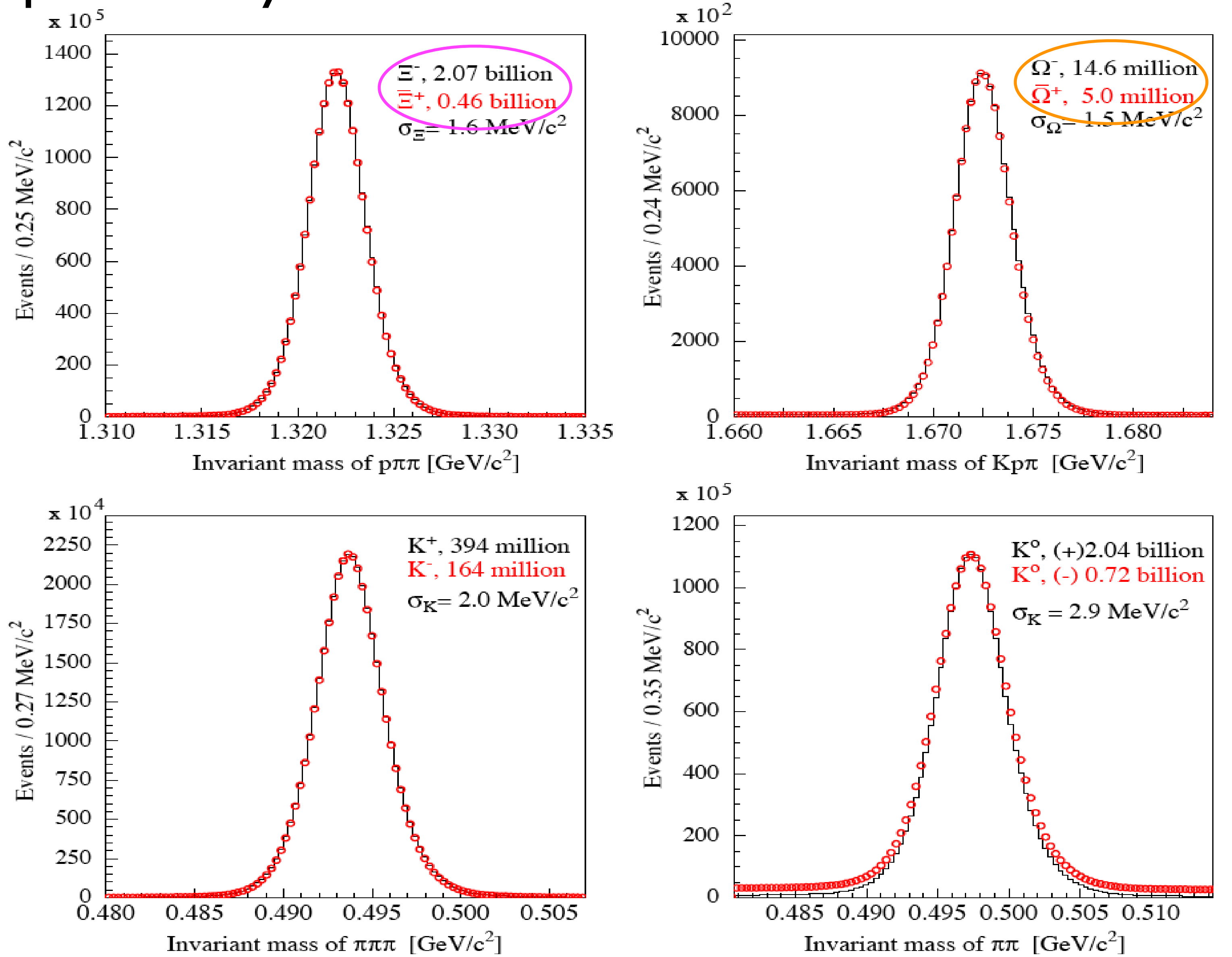
Experiment	Decay Mode	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	-(
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	(
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0

Experiment	Decay Mode	A
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	0.0
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	(0.(



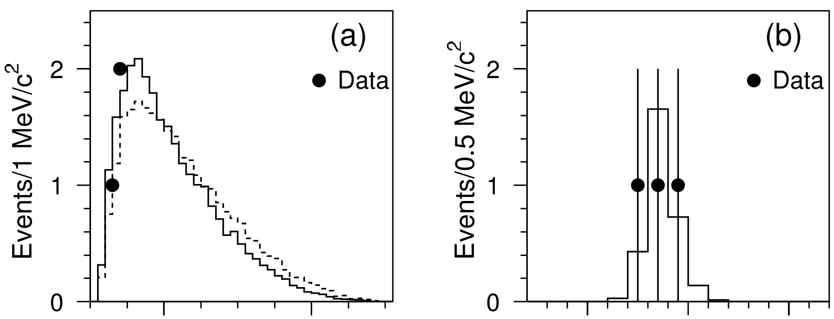
$(6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary]

Made possible by... Enormous HyperCP Dataset



- $\bar{p}$ source can produce ~10^8 $\Omega^- \bar{\Omega}^+$/y & maybe ~10^{10} $\Xi^- \bar{\Xi}^+$

HyperCP also → 10^{10} Σ^+



$\Sigma^+ \to p\mu^+\mu^-$ Decay

≈2.4σ fluctuation of SM? or

- SUSY Sgoldstino?
- SUSY light Higgs?

PRL **98,** 081802 (2007) PHYSICAL REVIEW LETTERS week ending 23 FEBRUARY 2007

Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?

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(Received 2 November 2006; published 22 February 2007)

The HyperCP Collaboration has observed three events for the decay $\Sigma^+ \to p\mu^+\mu^-$ which may be interpreted as a new particle of mass 214.3 MeV. However, existing data from kaon and B-meson decays provide stringent constraints on the construction of models that support this interpretation. In this Letter we show that the "HyperCP particle" can be identified with the light pseudoscalar Higgs boson in the next-to-minimal supersymmetric standard model, the A_1^0. In this model there are regions of parameter space where the A_1^0 can satisfy all the existing constraints from kaon and B-meson decays and mediate $\Sigma^+ \to p\mu^+\mu^-$ at a level consistent with the HyperCP observation.

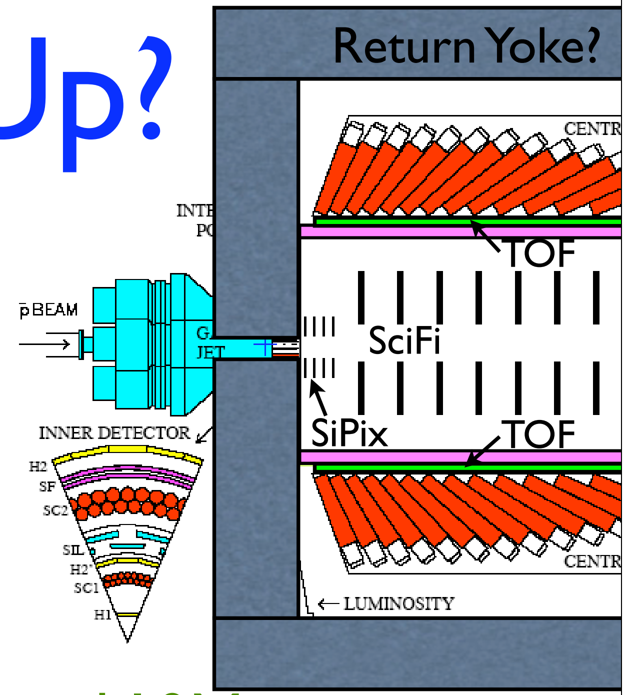
How Follow Up?

One possibility:

- Once Tevatron shuts down (≈2010),
  - Reinstall E835 EM spectrometer
  - Add small magnetic spectrometer
  - Add precision TOF system
  - Add wire or pellet target
  - Add 2^{ndary}-vertex trigger
  - Run $p_{\bar{p}}$ = 5.4 GeV/c ($2m_{\Omega} < \sqrt{s} < 2m_{\Omega} + m_{\pi^0}$) @ $\mathcal{L} \sim 10^{32}$ cm^{-2} s^{-1} (10 × E835)

}<$10M

➡ $\sim 10^8\ \Omega^- \overline{\Omega}^+$/yr + $\sim 10^{12}$ inclusive hyperon events!



What Can This Do?

- Observe many more $\Sigma^+ \to p\mu^+\mu^-$ events and confirm or refute SUSY interpretation

- Discover or limit $\Omega^- \to \Xi^-\mu^+\mu^-$ and confirm or refute SUSY interpretation

Predicted $\mathcal{B} \sim 10^{-6}$ if P^0 real

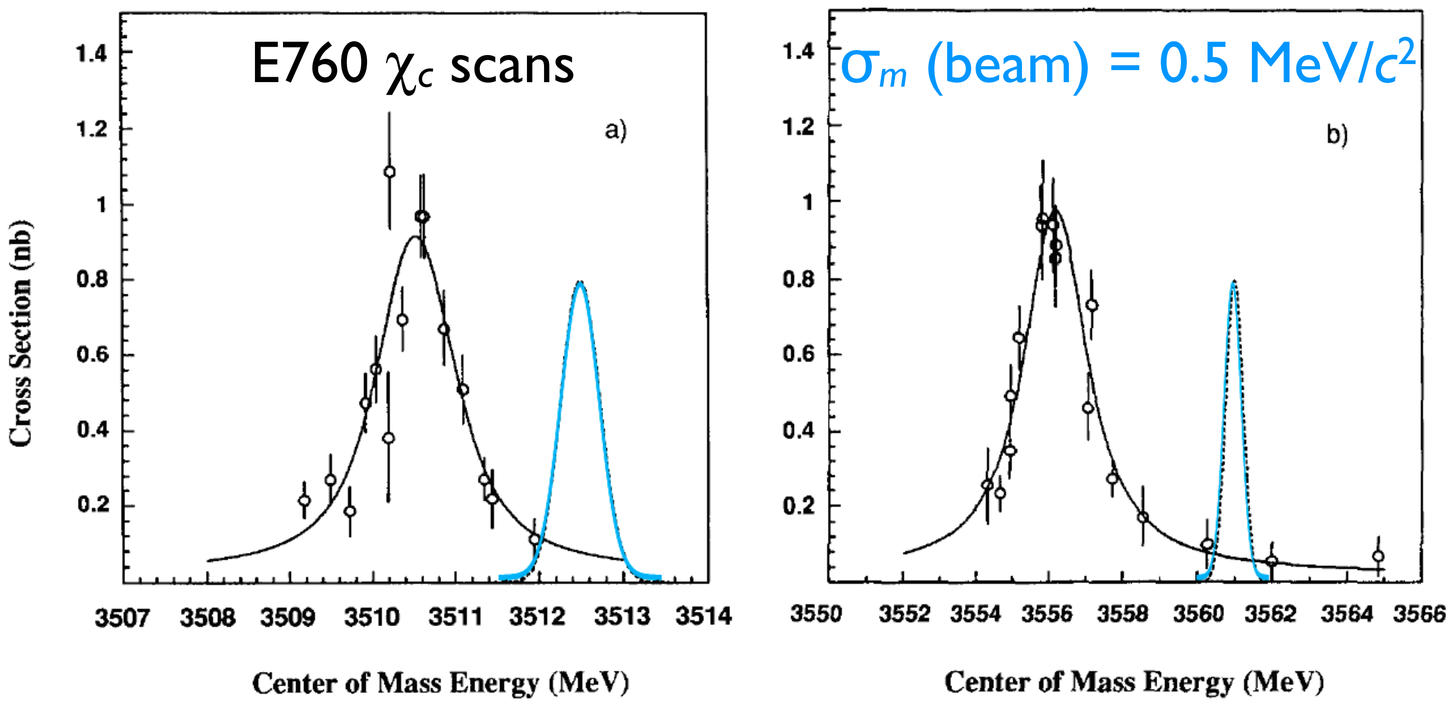
- Discover or limit *CP* violation in $\Omega^- \to \Lambda K^-$ and $\Omega^- \to \Xi^0\pi^-$ via partial-rate asymmetries

Predicted $\Delta\mathcal{B} \sim 10^{-5}$ in SM, $\lesssim 10^{-3}$ if NP

What Else Can This Do?

- Much interest lately in new states observed in charmonium region: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$
- $X(3872)$ of particular interest: may be the first meson-antimeson ($D^0\,\overline{D}^{*0}$ + c.c.) molecule (or tetraquark or what?)
  - ➡ need *very* precise mass & width measurement to confirm or refute
  - ➡ $\bar{p}p \to X(3872)$ formation *ideal* for this
- Also h_c mass & width, χ_c radiative-decay angular distributions, η_c' full and radiative widths,...

Example: precision $\bar{p}p$ mass & width measurements



- The beam is the spectrometer! → $\begin{cases} \delta m(\chi_c) \approx 0.1 \pm 0.02 \text{ MeV}/c^2 \\ \delta\Gamma(\chi_c) \approx 0.1 \pm 0.01 \text{ MeV}/c^2 \end{cases}$
- The experiment is just the detector.

Example: precision $\bar{p}p$ mass & width measurements

- Works even for ψ′:
  - E835 measured
    Γ = (290 ± 25 ± 4) keV
    with 2,700 events
  - used "complementary scans" to reduce systematics

⇒ Best technique for *X*(3872) mass & (sub-MeV?) width measurement

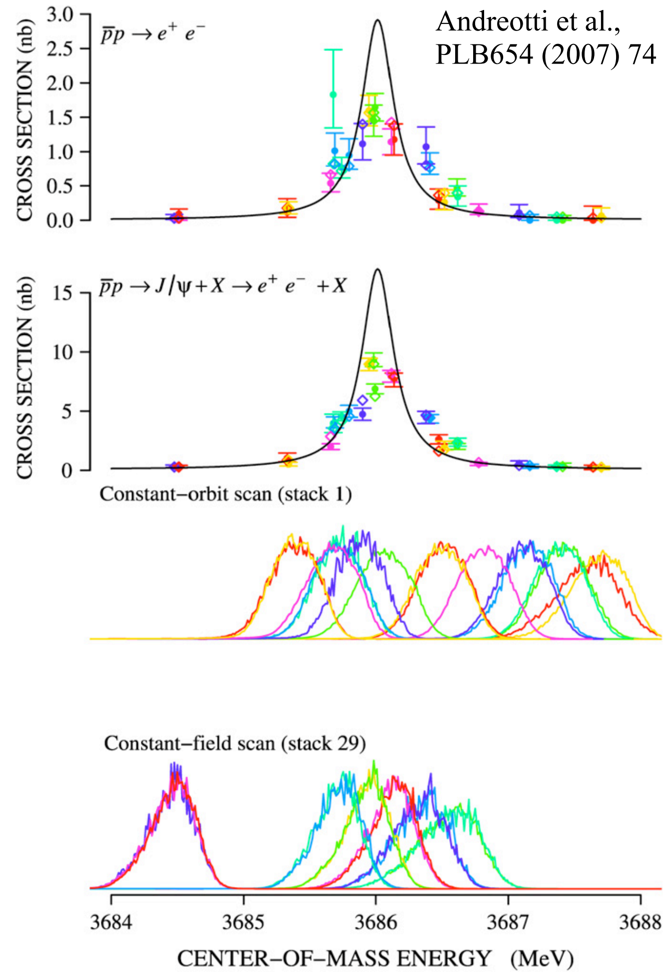


Fig. 2. $\psi(2S)$ resonance scans: the observed cross section for each channel (filled dots); the expected cross section from the fit (open diamonds); the 'bare' resonance curves σ_{BW} from the fit (solid lines). The two bottom plots show the normalized energy distributions B_i.

What Else Can This Do?

Charm?

PHYSICAL REVIEW D **77**, 034019 (2008)

Estimate of the partial width for $X(3872)$ into $p\bar{p}$

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(Received 13 November 2007; published 25 February 2008)

We present an estimate of the partial width of $X(3872)$ into $p\bar{p}$ under the assumption that it is a weakly bound hadronic molecule whose constituents are a superposition of the charm mesons $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$. The $p\bar{p}$ partial width of X is therefore related to the cross section for $p\bar{p} \to D^{*0}\bar{D}^0$ near the threshold. That cross section at an energy well above the threshold is estimated by scaling the measured cross section for $p\bar{p} \to K^{*-}K^+$. It is extrapolated to the $D^{*0}\bar{D}^0$ threshold by taking into account the threshold resonance in the 1^{++} channel. The resulting prediction for the $p\bar{p}$ partial width of $X(3872)$ is proportional to the square root of its binding energy. For the current central value of the binding energy, the estimated partial width into $p\bar{p}$ is comparable to that of the P-wave charmonium state χ_{c1}.

- Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming D^*D molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\bar{D}^0$ cross section

Charm?

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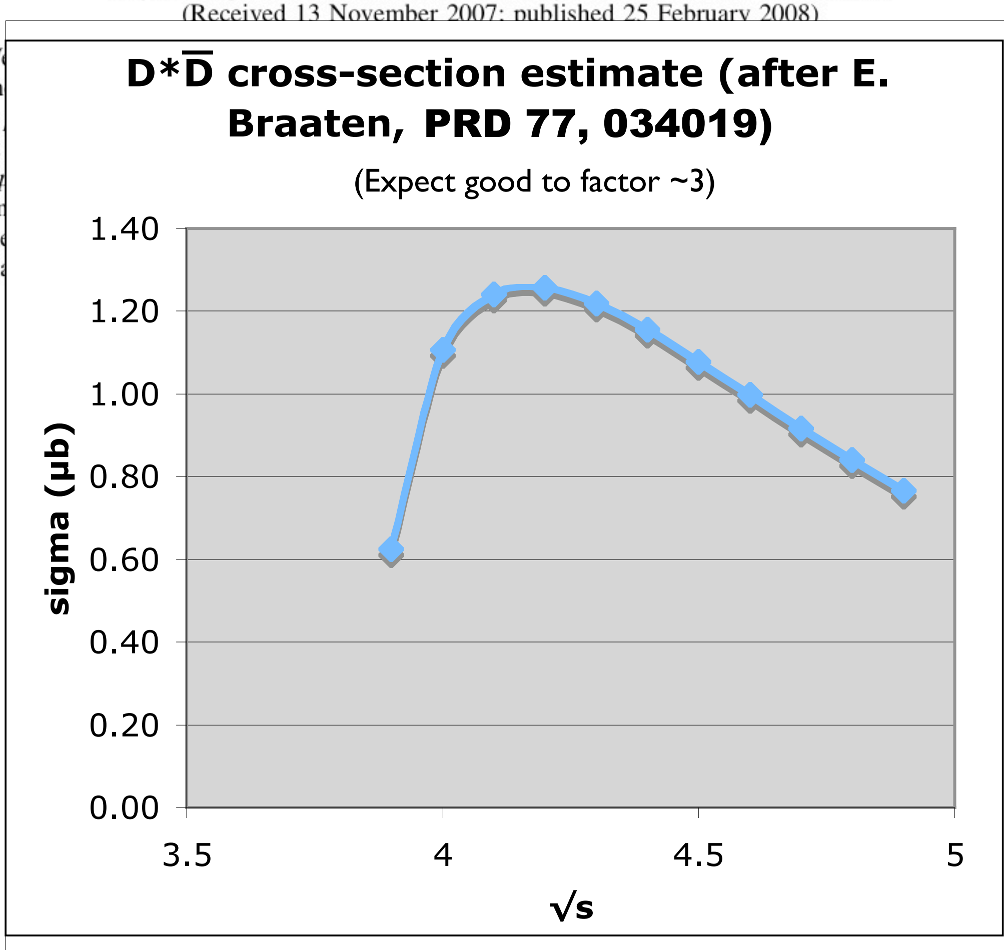
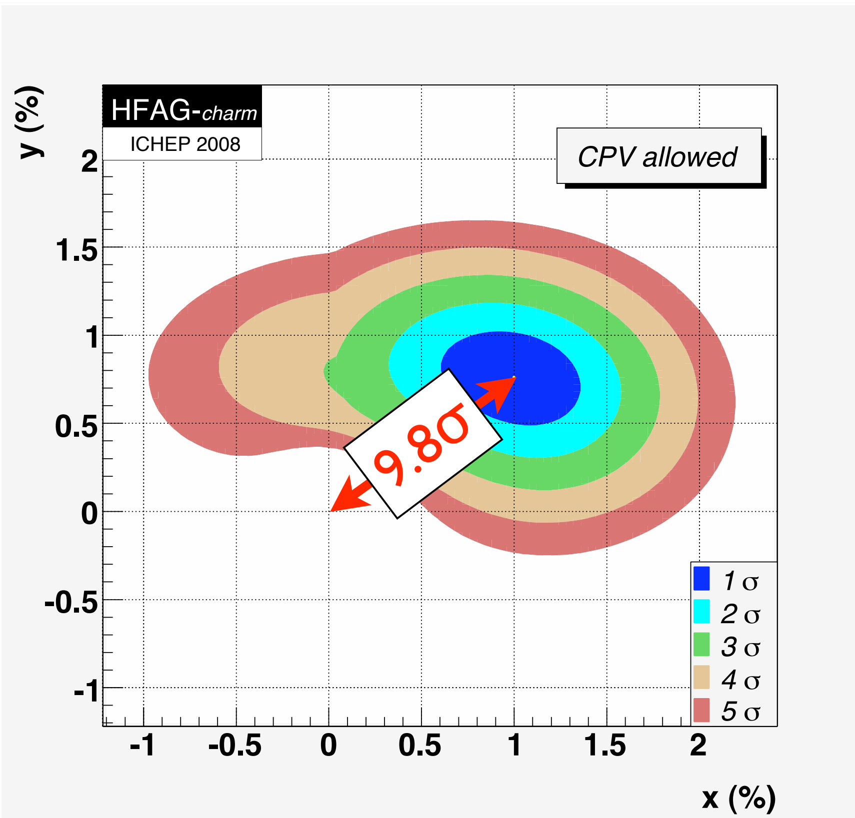


- Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming D^*D molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\bar{D}^0$ cross section
- 1.3 μb → 5 ×10⁹/year
- Expect efficiency as at *B* factories

Charm?

- D^0's mix! (*c* is only up-type quark that can)

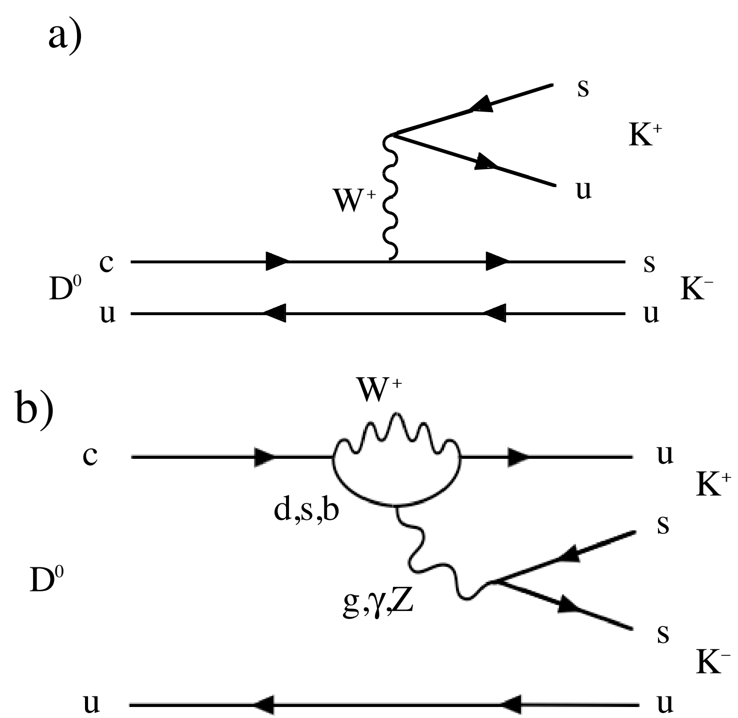


- *Big question:*
  New Physics or old?

Charm?

- D^0's mix! (*c* is only up-type quark that can)

Singly Cabibbo-supressed (CS) *D* decays have 2 competing diagrams:



- *Big question:* New Physics or old?

➡ key is *CP* Violation! Possible in CF, DCS only if New Physics

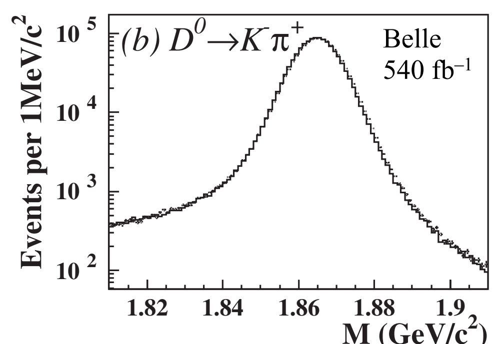
- *B* factories have ~10^9 open-charm events
- $\bar{p}p$ can produce ~10^{10}/y

➡ world's best sensitivity to charm CPV

Charm?

- Ballpark sensitivity estimate using cross section based on Braaten $\bar{p}p \to D^{*0}\bar{D}^0$ formula and assuming $\sigma \propto A^{1.0}$:

Quantity	Value	Unit
Running time	2×10^7	s/y
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Target A	27	
$A^{0.29}$	2.6	(known from H.E. fixed-target)
$\sigma(\bar{p}p \to D^{*+}X)$	1.25	μb
# $D^{*\pm}$ produced	2.1×10^{10}	events/y
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.677	
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.0389	
Acceptance	0.5	(signal MC)
Efficiency	0.1	(see below)
Total	2.7×10^7	events/y



- Compare with 1.22×10^6 tagged events at Belle [M. Staric et al., PRL **98**, 211803 (2007)]

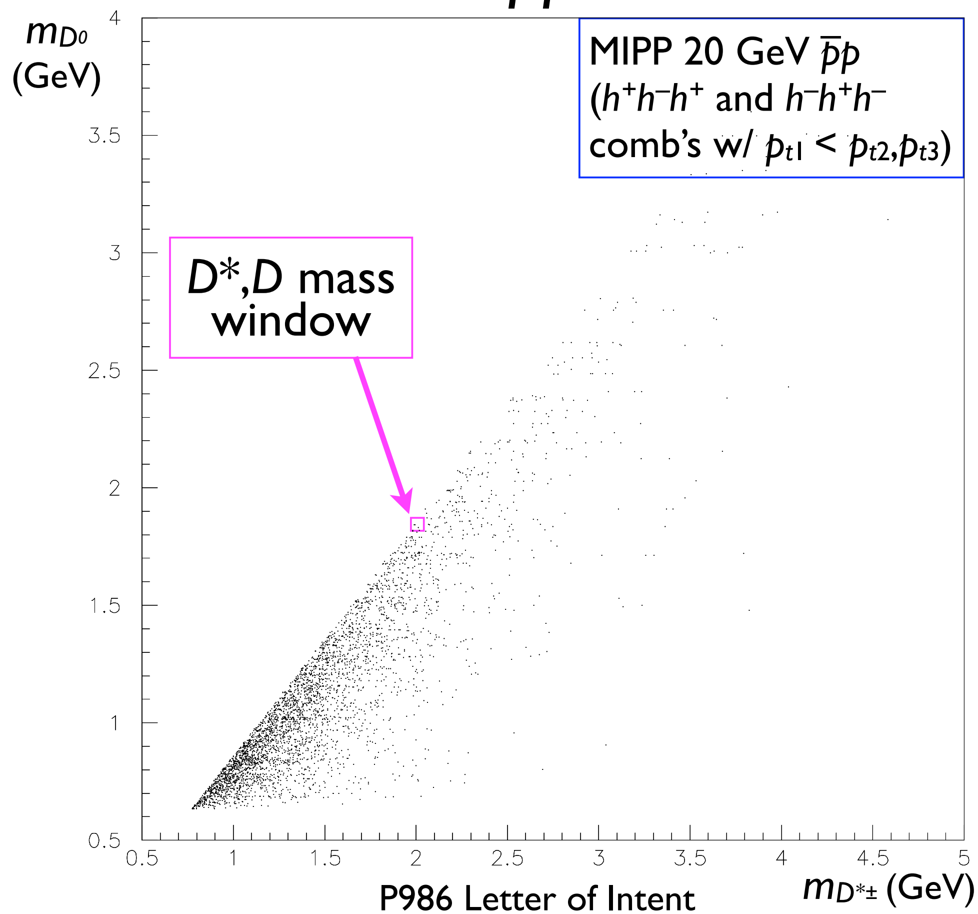
- LHC*b* will have comparable statistics but diff't systematics

Charm?

- Another possibility (E. Braaten): use the X(3872) as a pure source of $D^{*0}\overline{D}^0$ events
  - the $\bar{p}p$ equivalent of the ψ(3770)!?
  - assuming current Antiproton Accumulator parameters ($\Delta p/p$) & Braaten estimate, produce ~10^8 events/year
  - comparable to BES-III statistics
  - could gain factor ~5 via AA e^- cooling?
- Proposed expt will establish feasibility & reach

Background Study

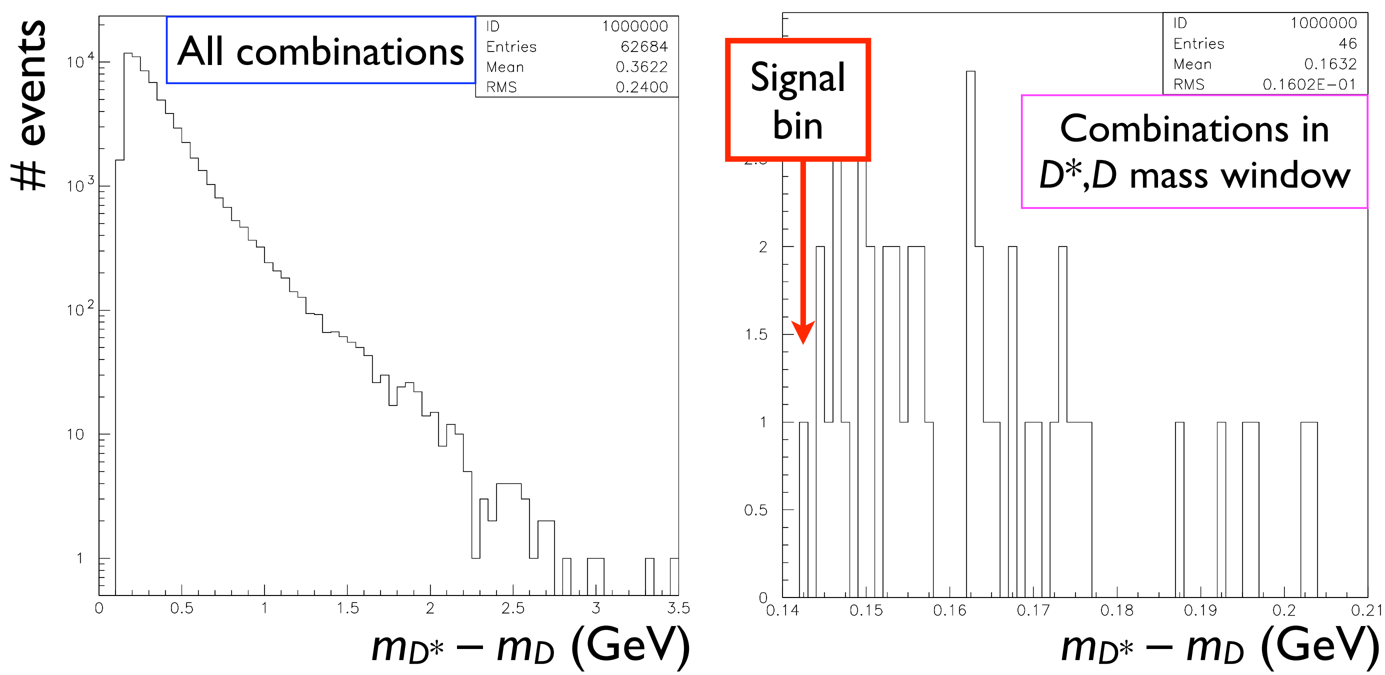
- How efficiently can we identify $D^* \rightarrow D^0$ decays while adequately suppressing background?
- Study via MIPP 20 GeV $\bar{p}p$ data:



1st-order correction for higher beam energy:
$p_z \rightarrow 0.65 p_z$
(conservative)

Background Study

- Cut on *D** and *D* masses and *D**–*D* mass difference:



- Leaves only ~1 background event – with *no* kaon ID!

Background Study

- MIPP normalization @ 20 GeV not yet worked through in detail, but sample sensitivity ~ 1 evt/μb
- Suppose total inclusive σ(*D**) ~ 10 μb (incl. *A*-dep.)

  x $\mathcal{B}$: 0.67 x 0.039 → ~ 1/4 evt signal

  ➡ sig/bkg ~ 0.1 (with above *D**–*D* cuts)
- Kaon ID → ~ x 10
- Lifetime cuts → ~ x 10 –100

⇒ Clean sample can likely be obtained with reasonable (~0.1) efficiency

Summary

- Best experiment ever on hyperons, charm, and charmonia may soon be feasible at Fermilab
  - including world's most sensitive charm CPV study?
- Mix of speculative and established physics goals
  - for some, feasibility depends on poorly known cross sections
  - we can measure them quickly and cost-effectively
  - no modification of accelerator complex required
- World's best $\bar{p}$ source → simple way to broad physics program in (pre-)Project X era

0^{th}-order run-plan example:

install/debug	~3 mo	
find $X(3872)$	~1 mo	
measure $\sigma(D^*)$	~1 mo	
measure $\sigma(\Omega\bar{\Omega})$	~1 mo	
charmonium	~3 mo	
$X(3872)$ run	~12 mo	if σ's favorable
hyperon CP run	~12 mo	if σ's favorable
install/debug hadron-ID upgrade	~3 mo	if σ's favorable
charm CP run	~12 mo	if σ's favorable

- Our request:
  - encouragement from Directorate to continue simulation, design, & planning studies & develop proposal

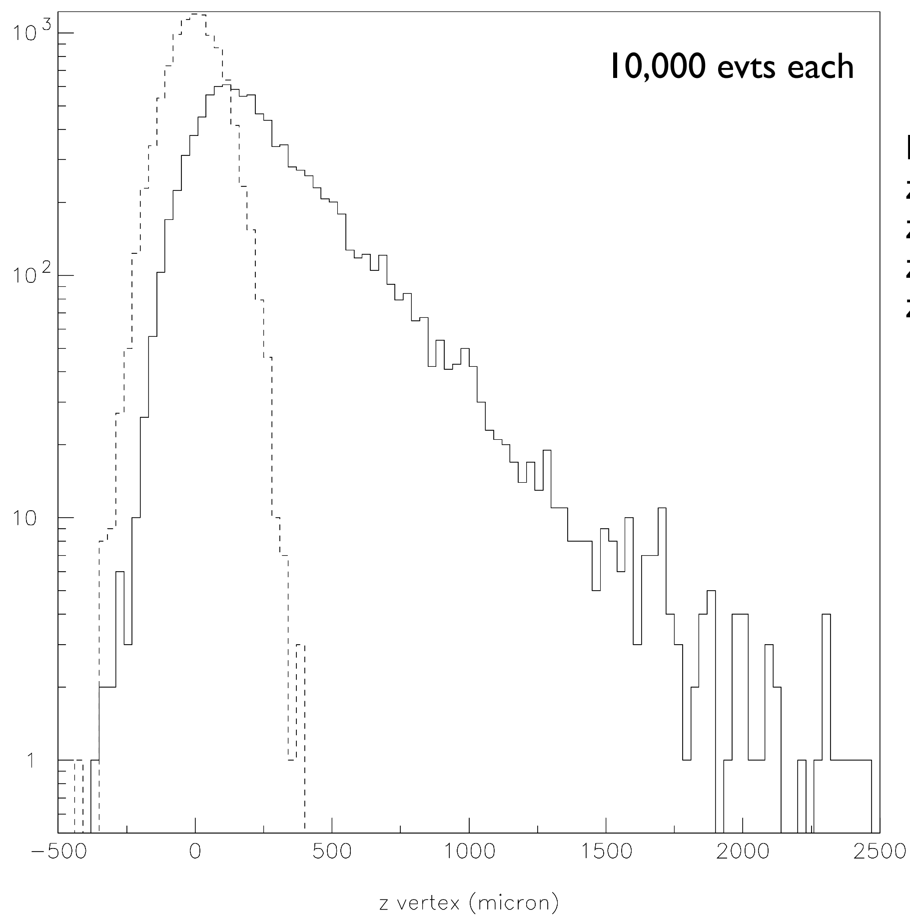
International Aspect

- Potential European interest (e.g. PANDA)
  - opportunity for early data & experience
- Could significantly reduce needed US resources
- But recent US HEP events cautionary

➡ need indication of US interest to begin negotiation

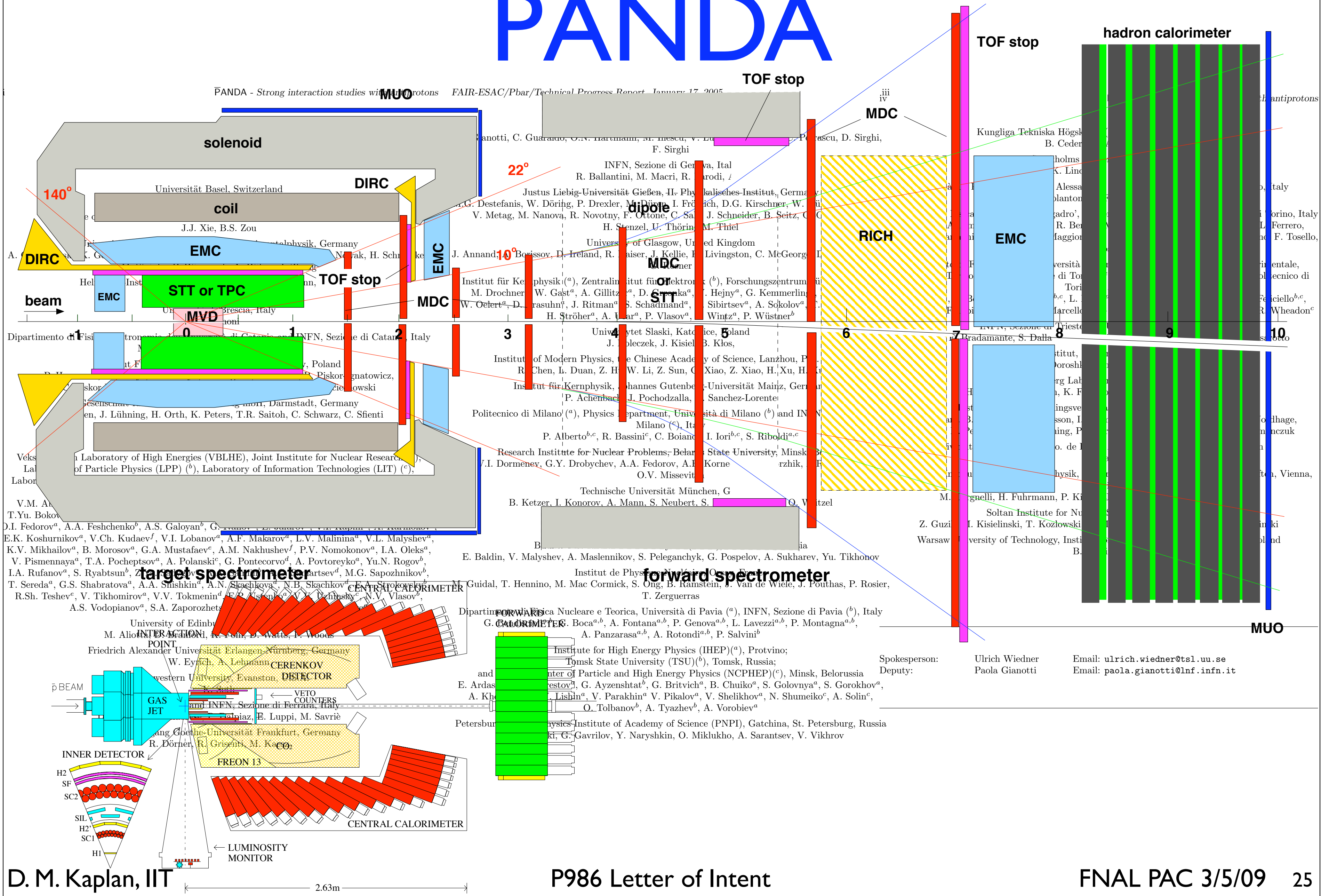
Background Study

- MC comparison of $D^0 \rightarrow K\pi$ signal & prompt background



vtx cut	#bkg	#sig	sig/bkg	D accept.
No cut on z	10,000	10,000	1	50%
z>100 microns	1,589	7,106	4.5	35%
z>200 microns	238	5,168	22	25%
z>300 microns	14	3,679	250	18%
z>400 microns	0	2,669	>1000	13%

P̄ANDA



TOF stop
hadron calorimeter
TOF stop
MDC
MUO
solenoid
DIRC
coil
22°
140°
dipole
RICH
EMC
DIRC
EMC
10°
MDC
or
STT
STT or TPC
TOF stop
MDC
EMC
beam
MVD
-1
0
1
2
3
4
5
6
7
8
9
10
target spectrometer
forward spectrometer
MUO
CENTRAL CALORIMETER
FORWARD CALORIMETER
INTERACTION POINT
CERENKOV DETECTOR
p̄ BEAM
GAS JET
VETO COUNTERS
FREON 13
INNER DETECTOR
H2
SF
SC2
SIL
H2'
SC1
H1
CENTRAL CALORIMETER
LUMINOSITY MONITOR
2.63m

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

- Charmonium ($c\bar{c}$) spectroscopy (mass, widths, branching ratios)
- Establishment of the QCD-predicted gluonic excitations (charmed hybrids, glueballs) in the 3–5 GeV/c^2 mass range
- Search for modifications of meson properties in the nuclear medium
- Precision γ-ray spectroscopy of single and double hypernuclei
- Extraction of generalized parton distributions from $\bar{p}p$ annihilation
- *D* meson decay spectroscopy (rare decays)
- Search for CP violation in the charm and strangeness sector

Backup

- Some Hyperon CP references:

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Some HyperCP Publications:

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