Hyperon (& Other) Physics with Antiprotons

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Antiproton Physics at the Intensity Frontier

Fermilab

18 Nov. 2011

Outline

- Hyperon CP violation
- Charmonium & *XYZ*s
- $\bar{p}$ Drell-Yan
- Summary

Hyperon CP Violation

- An old topic:

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Final-State Interactions in Nonleptonic Hyperon Decay

O. E. Overseth*
The University of Michigan, Ann Arbor, Michigan 48104

AND

S. Pakvasa†
University of Hawaii, Honolulu, Hawaii 96822
(Received 1 April 1969)

⋮

E. Tests for *CP* and *CPT* Invariance

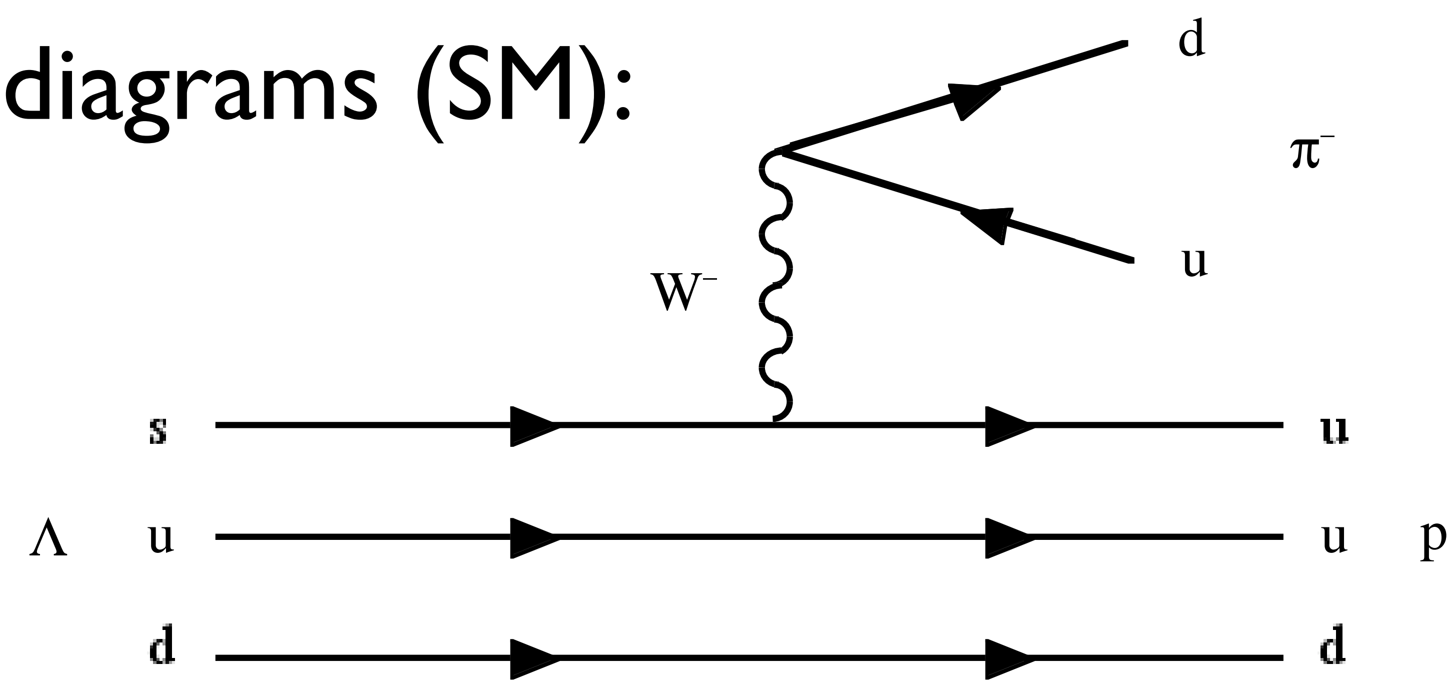
Thus in hyperon decay, $\bar{\alpha} \neq -\alpha$ implies *CP* violation in this process independent of the validity of the *CPT* theorem. This is also true if $\bar{\beta} \neq -\beta$.

Also, as usual, *CPT* invariance implies equality of Λ^0 and $\bar{\Lambda}^0$ lifetimes, whereas *CP* invariance implies equality of partial rates $\Gamma^0 = \bar{\Gamma}^0$, and $\Gamma^- = \bar{\Gamma}^+$. This is also true when final-state interactions are included in the analysis.

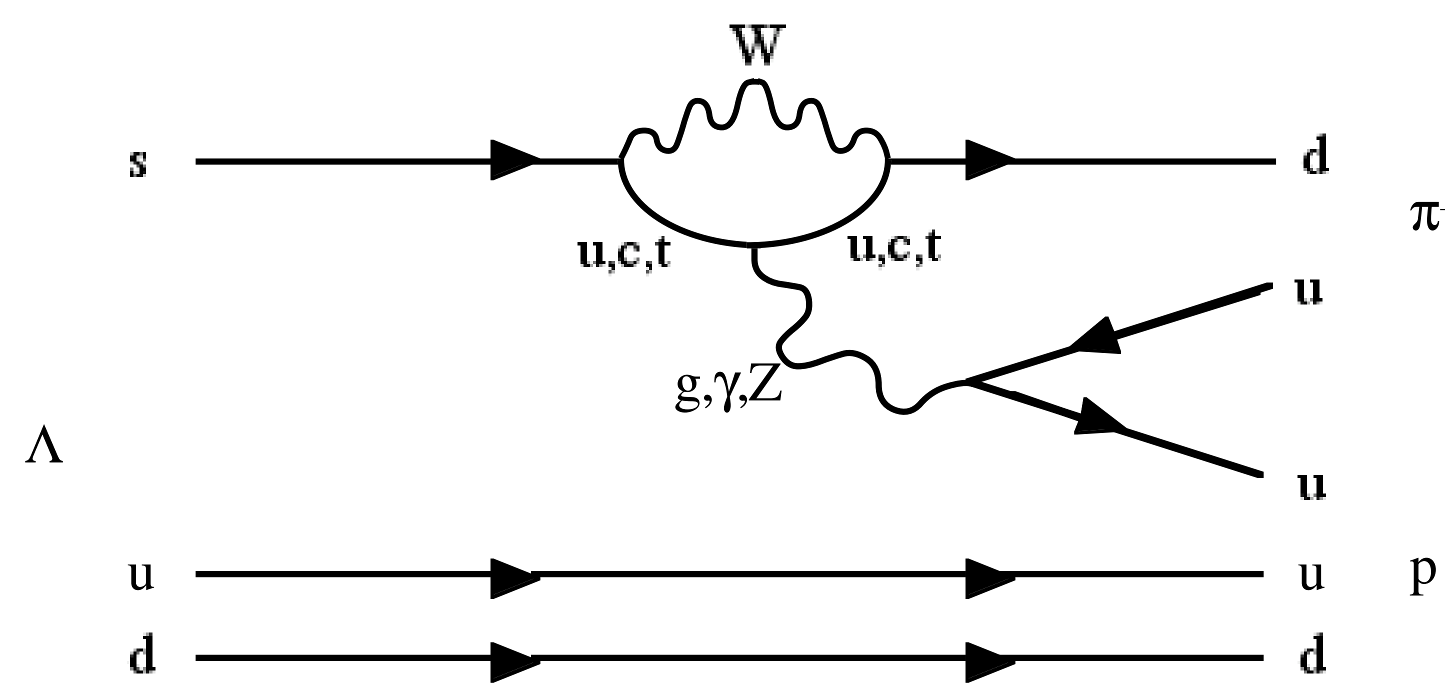
Hyperon CP Violation

- Example Feynman diagrams (SM):

Λ decay:



Λ penguin decay:



- "New physics" (SUSY, etc.) could also contribute!

Hyperon CP Violation

- Hyperon decay violates parity, as described by Lee & Yang (1957) via "α" and "β" parameters
  - e.g., decay of polarized Lambda hyperons:

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{q}_p)$$

⟶ nonuniform proton angular distribution in Λ rest frame w.r.t. average spin direction $\vec{P}_\Lambda$

  - size of α indicates degree of nonuniformity:

$\alpha_\Lambda = 0.642\ (\pm 0.013) \Rightarrow p$ emitted preferentially along polarization (Λ spin) direction

☞ Large size of α looks favorable for CPV search!

Hyperon CP Violation

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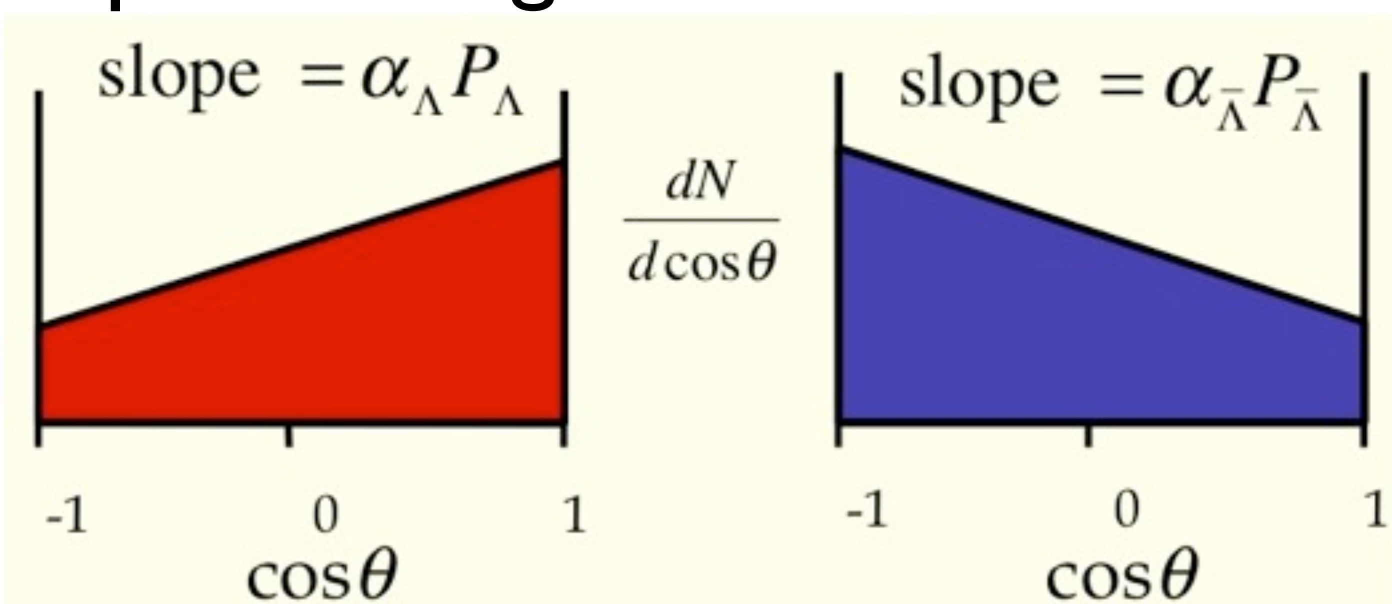
  - e.g., decay of polarized Lambda hyperons:

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{q}_p)$$

⟶ nonuniform proton angular distribution in Λ rest frame:

$\Lambda \to p\pi^-$



$\bar\Lambda \to \bar{p}\pi^+$

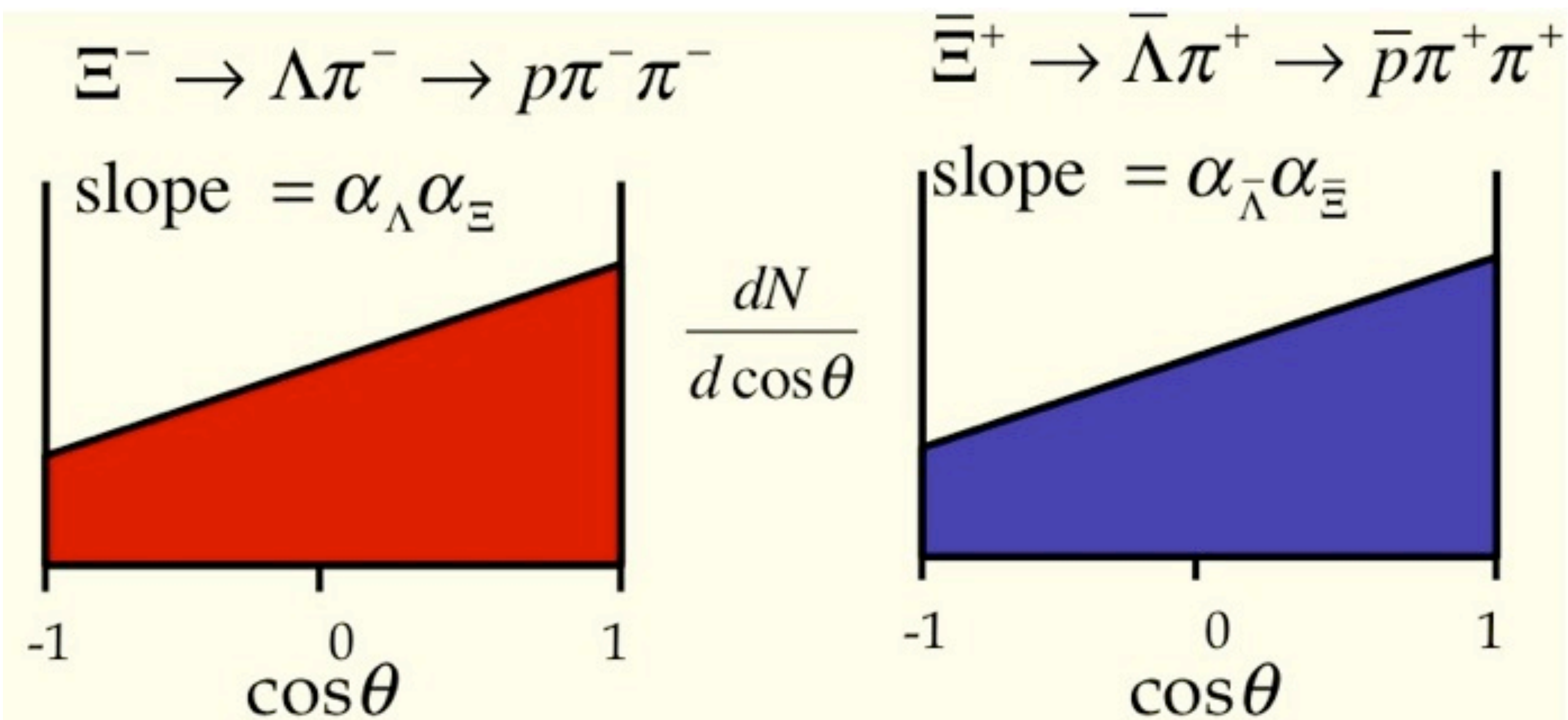
$$\Rightarrow A_\Lambda \equiv \frac{\alpha_\Lambda + \bar\alpha_\Lambda}{\alpha_\Lambda - \bar\alpha_\Lambda},\ B_\Lambda \equiv \frac{\beta_\Lambda + \bar\beta_\Lambda}{\beta_\Lambda - \bar\beta_\Lambda},\ \Delta_\Lambda \equiv \frac{\Gamma_{\Lambda\to P\pi} - \bar\Gamma_{\Lambda\to P\pi}}{\Gamma_{\Lambda\to P\pi} + \bar\Gamma_{\Lambda\to P\pi}}$$

CP-odd

Hyperon CP Violation

- But, for precise measurement of A_Λ, need excellent knowledge of relative Λ and $\bar{\Lambda}$ polarizations!

➡ HyperCP "trick": $\Xi^- \to \Lambda\pi^-$ decay gives $\vec{P}_\Lambda = -\vec{P}_{\bar{\Lambda}}$



- Unequal slopes ⇒ CP violated!

Hyperon CP Violation

- Differently sensitive to New Physics than *B*, *K* CPV
- Standard Model 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]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 5 \times 10^{-5}$	$\leq 1.9 \times 10^{-3}$	[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].

☞ Small sizes of $(A,\Delta)_{SM}$ favorable for NP CPV search!

Hyperon CP Violation

- Measurement history:

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]

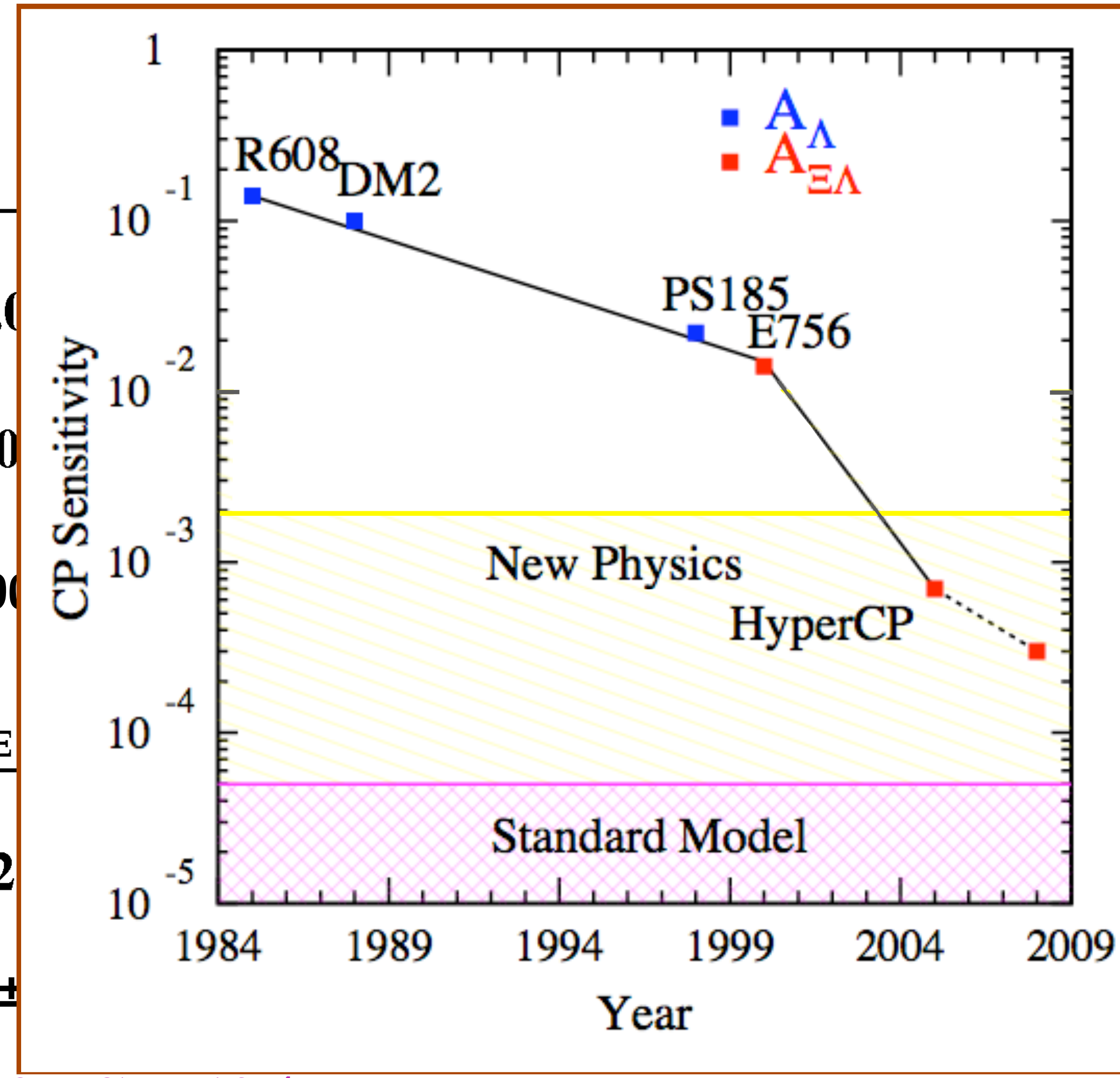
Experiment	Decay Mode	$A_\Xi + A_\Lambda$	
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**0.012 ± 0.014**	[K.B. Luk et al., PRL 85, 4860 (2000)]
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**$(0.0 \pm 6.7) \times 10^{-4}$**	[T. Holmstrom et al., PRL 93. 262001 (2004)]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

Hyperon CP Violation

- Measurement history:

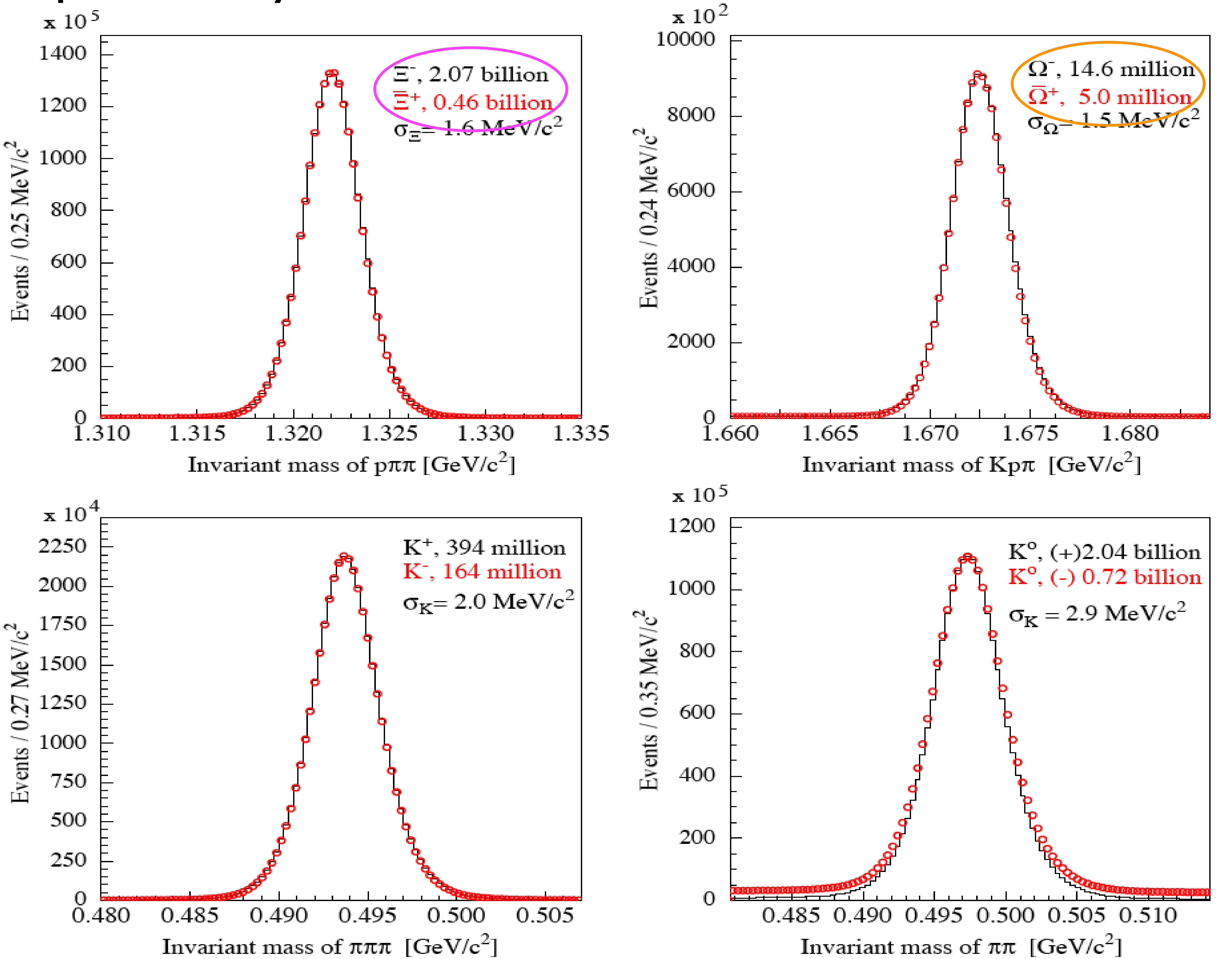
Experiment	Decay Mode	
R608 at ISR	$pp \rightarrow \Lambda X, \bar{p}p \rightarrow \bar{\Lambda} X$	-0.0
DM2 at Orsay	$e^+e^- \rightarrow J/\Psi \rightarrow \Lambda\bar{\Lambda}$	0.0
PS185 at LEAR	$p\bar{p} \rightarrow \Lambda\bar{\Lambda}$	0.0

Experiment	Decay Mode	A_Ξ
E756 at Fermilab	$\Xi \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$	0.012
E871 at Fermilab (HyperCP)	$\Xi \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$	(0.0 ±

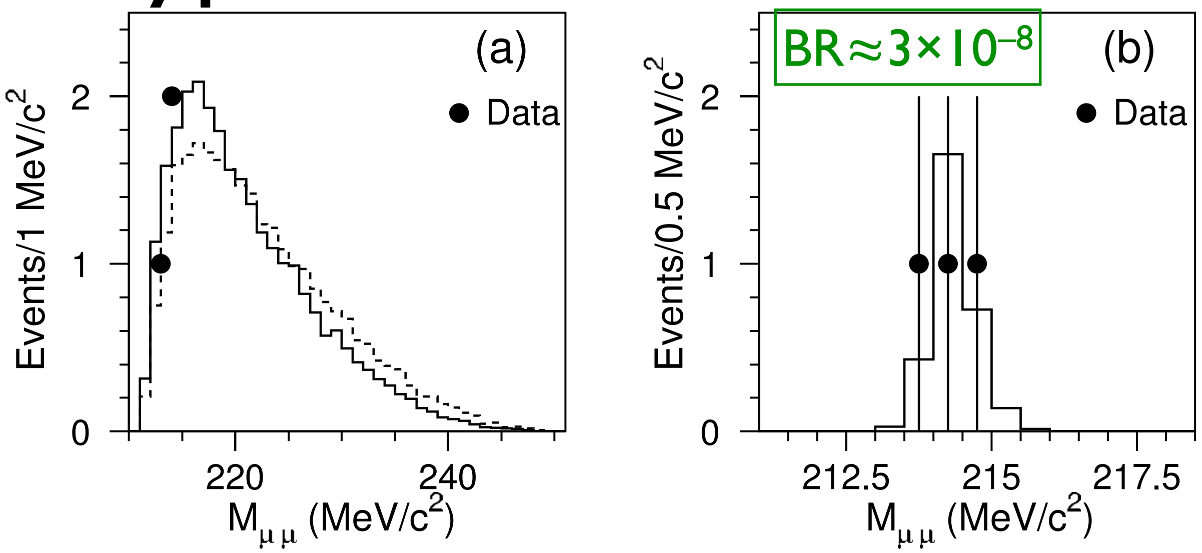


$(-6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary; PRL in prep]

Made possible by... Enormous HyperCP Dataset



HyperCP also → 10^{10} Σ^+



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

≈2.4σ fluctuation of SM? or

- SUSY Sgoldstino?
- SUSY light Higgs?
- other pseudo-scalar or axial-vector state?

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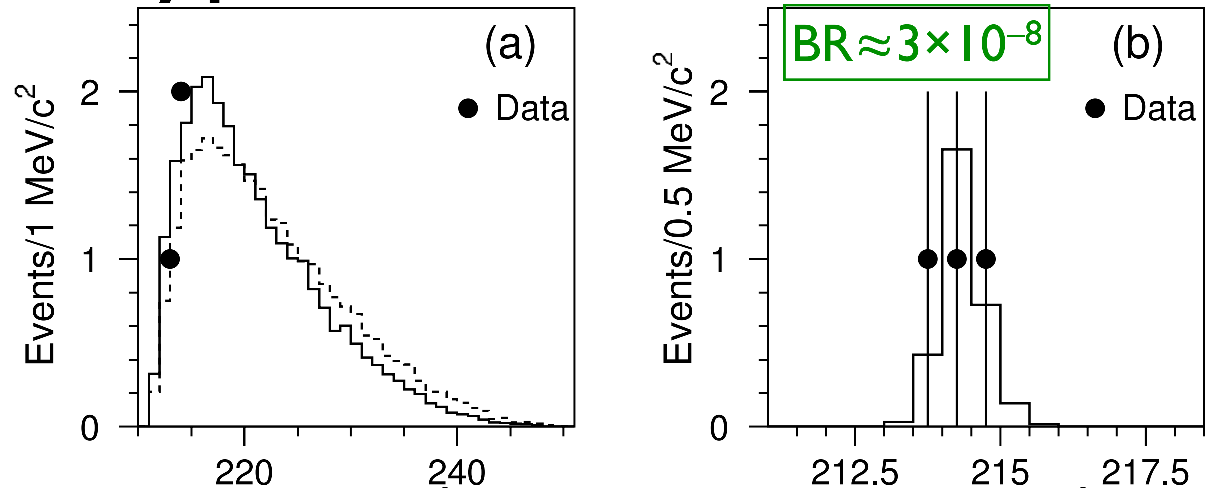

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Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?

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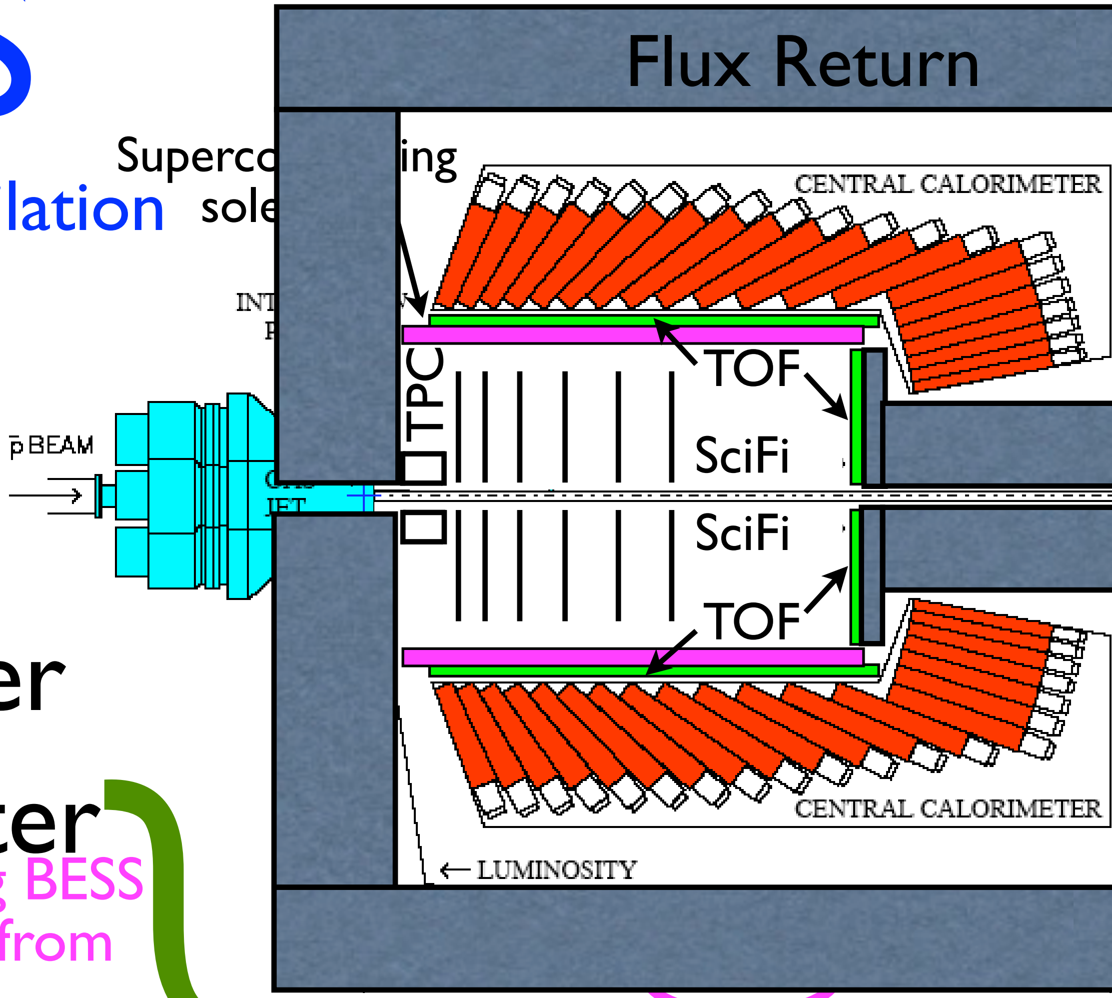
(Received 2 November 2006; published 22 February 2007)

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.

TAPAS

(The AntiProton Annihilation Specrometer)



Our proposal:

- Now that Tevatron finished,
  - Reinstall E760 barrel calorimeter
  - Add small magnetic spectrometer
  - Add precision TOF system
  - Add thin targets
  - Add fast trigger & DAQ systems
  - 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)

[existing BESS magnet from KEK & SciFi DAQ from DØ & FNAL iron]

} ≲$10M

➡ ~10^8 $\Omega^- \bar{\Omega}^+$/yr + ~10^{12} inclusive hyperon events!
+ possibly ~10^{10} $\Xi^- \bar{\Xi}^+$

What Can This Do?

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

- Discover or limit $\Omega^- \to \Xi^-\mu^+\mu^-$ and confirm or refute new-physics 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

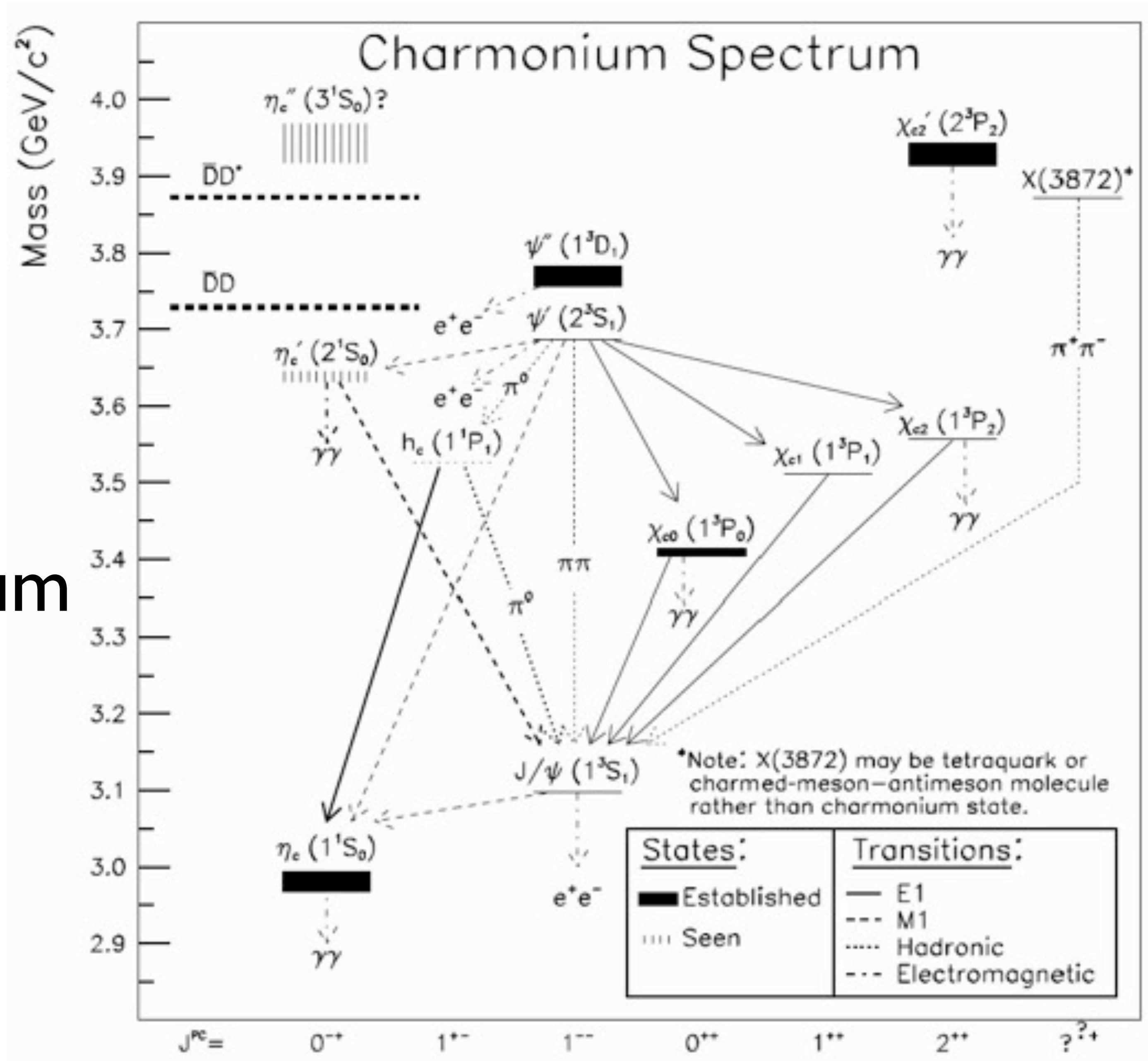
Predicted $\Delta\mathcal{B}/\mathcal{B} \sim 10^{-5}$ in SM, $\lesssim 10^{-3}$ if NP

- Observe ~ 10^{10} $\overline{\Xi}^+\Xi^-$ pairs, measure both $A_{\Xi\Lambda}$ and B_{Ξ}, and extract A_{Ξ} and A_{Λ}, with 10^{-4} precision*

*if deceleration through transition solved

What Else Can This Do?

- Also good for "charmonium" ($c\bar{c}$ QCD "hydrogen atom"):
  - Fermilab E760/835 used Antiproton Accumulator for precise (≲100 keV) measurements of charmonium parameters, e.g.:
    - best measurements of η_c, χ_c, h_c masses, widths, branching ratios,...



- $\bar{p}p$ produces *all* $c\bar{c}$ quantum states (not just 1^{--}), unlike e^+e^-

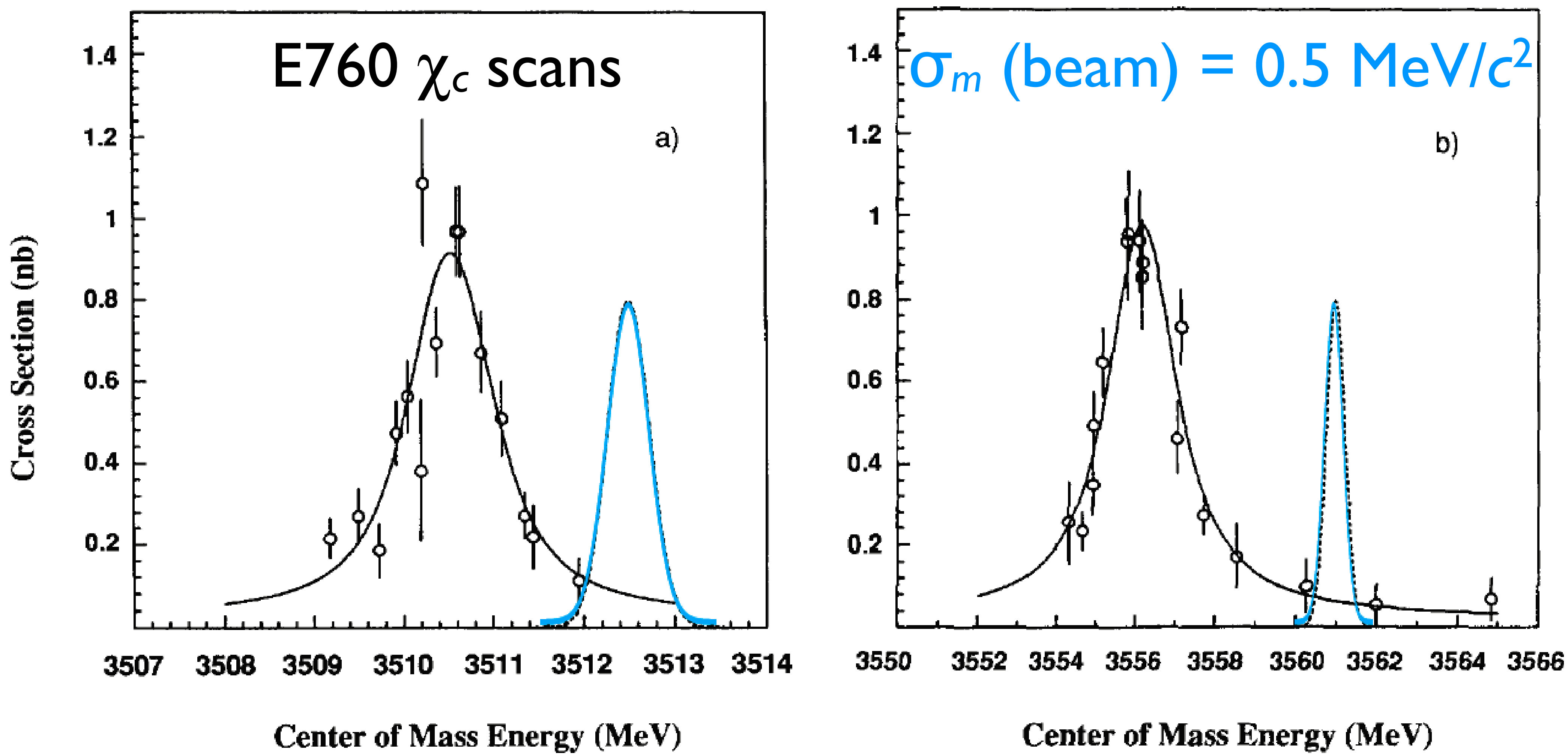
What ^Else^ Can This Do?

- 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 because it may be the first meson-antimeson ($D^0 \overline{D}^{*0}$ + c.c.) molecule

➡ need *very* precise mass measurement to confirm or refute

➡ $\bar{p}p \to X(3872)$ formation *ideal* for this...

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.

What ^Else Can This Do?

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➡ need *very* precise mass measurement to confirm or refute

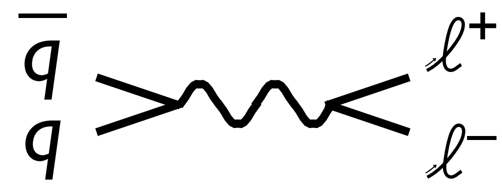
➡ $\bar{p}p \to X(3872)$ formation *ideal* for this...

- Plus other *XYZ*, charmonium measurements, etc...

What Else?

- QCD tests:
  - event shapes and distributions
  - intrinsic charm $q\overline{q}$ component in the nucleon?
- Search for new, exotic states of matter:
  - pentaquarks, gluonic hybrids, etc.
- Target-*A* dependence:
  - possible calibration for heavy-ion effects
- Drell-Yan electron-positron pair production:
  - can signal be distinguished from background?

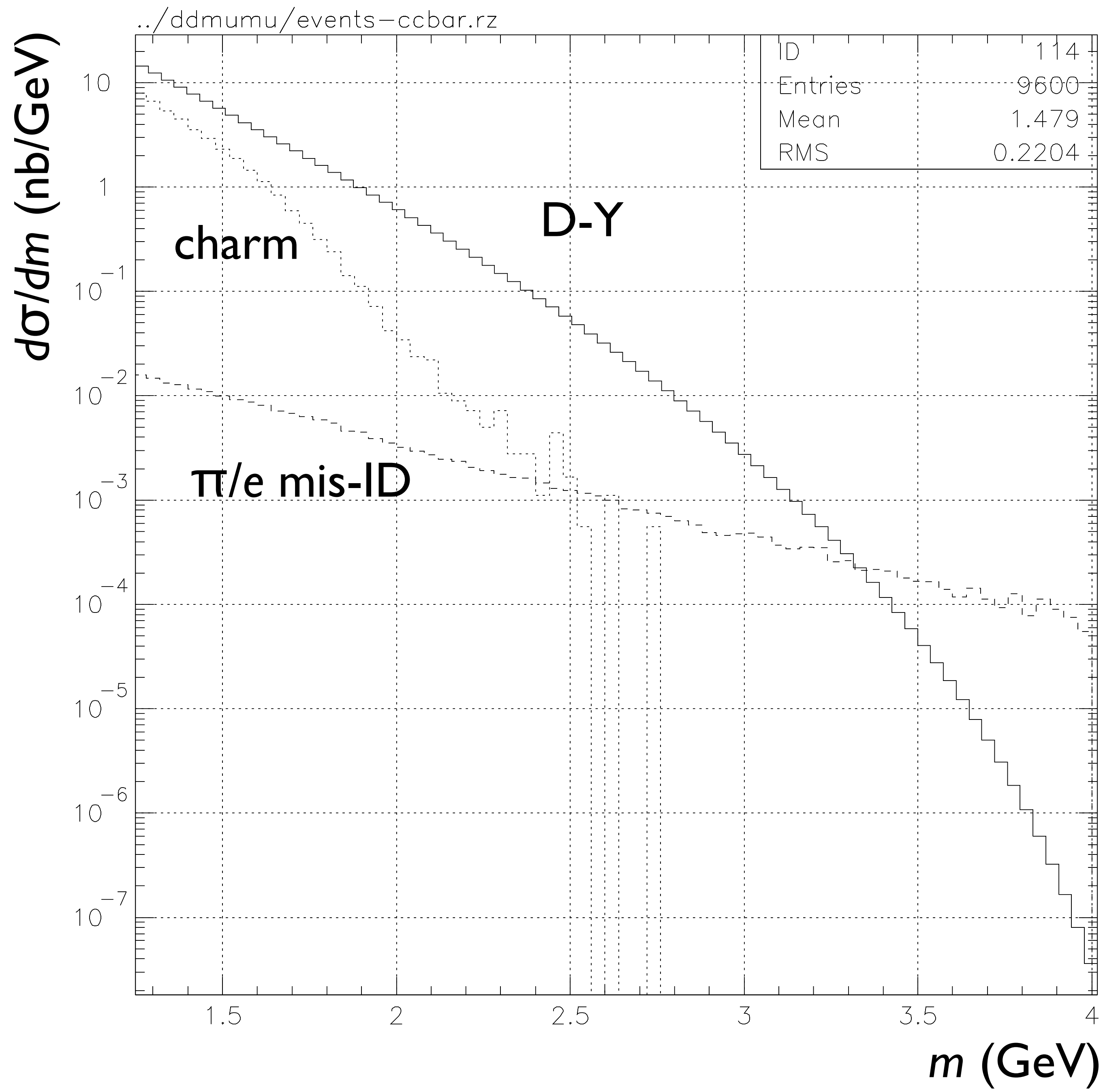
$\bar{p}p$ Drell-Yan



- $\ell^+\ell^-$ invariant-mass and momentum distributions sensitive to quark and antiquark distributions inside colliding protons and neutrons
- Global fits of nucleon structure suffer from significant tension among datasets
- $\bar{p}p$ or $\bar{p}A$ Drell-Yan can potentially add new constraints with very different systematics
  - "valence-valence" quark-antiquark annihilation

⟹ Can signal be dug out of the background???

$\bar{p}p$ Drell-Yan



Compare signal with main backgrounds

- Low energy is advantageous:
  - ➡ less charm background
  - ➡ fewer pions to confuse
  - ➡ allows measurement in new kinematic region

$\bar{p}p$ Drell-Yan

- Medium Energy $\bar{p}$ Drell-Yan also studies
  1. Lam-Tung-relation violation in πN DY
  2. Boer-Mulders (quark spin–p_t correlation) function
  3. Weinberg angle (NuTeV anomaly) via FB asymmetry
  4. Threshold resummation (important for JLab as well as intrinsically interesting)

Breadth of Program

- *Partial* list of physics papers/thesis topics:

General	
1	Particle multiplicities in medium-energy pbar-p collisions
2	Particle multiplicities in medium-energy pbar-N collisions
3	Total cross section for medium-energy pbar-p collisions
4	Total cross section for medium-energy pbar-N collisions
Charm	
5	Production of charm in medium-energy pbar-p collisions
6	Production of charm in medium-energy pbar-N collisions
7	A-dependence of charm production in medium-energy pbar-N collisions
8	Associated production of charm baryons in medium-energy pbar-N collisions
9	Production of charm baryon-antibaryon pairs in medium-energy pbar-N collisions
10	Measurement of D0 mixing in medium-energy pbar-N collisions
11	Search for/Observation of CP violation in D0 mixing
12	Search for/Observation of CP violation in D0 decays
13	Search for/Observation of CP violation in charged-D decays
Hyperons	
14	Production of Lambda hyperons in medium-energy pbar-p collisions
15	Production of Sigma0 in medium-energy pbar-p collisions
16	Production of Sigma- in medium-energy pbar-p collisions
17	Production of Xi- in medium-energy pbar-p collisions
18	Production of Xi0 in medium-energy pbar-p collisions
19	Production of Omega- in medium-energy pbar-p collisions
20	Production of Lambda Lambdabar pairs in medium-energy pbar-p collisions
21	Production of Sigma+ Sigmabar- pairs in medium-energy pbar-p collisions
22	Production of Xi- Xibar+ pairs in medium-energy pbar-p collisions
23	Production of Omega- Omegabar+ pairs in medium-energy pbar-p collisions
24	Rare decays of Sigma+
25	Rare decays of Xi-
26	Rare decays of Xi0
27	Rare decays of Omega-
28	Search for/Observation of CP violation in Omega- decay
Charmonium	
29	Production of X(3872) in medium-energy pbar-p collisions
30	Precision measurement of X(3872) mass, lineshape, and width
31	Decay modes of X(3872)
32	Limits on rare decays of X(3872)
33	Production of other XYZ states in medium-energy pbar-p collisions
34	Precision measurement of the eta_c mass, line shape and width
35	Precision measurement of the h_c mass, line shape and width
36	Precision measurement of the eta_c' mass, line shape and width
37	Complementary scans of J/psi and psi'
38	Precise determination of the chi_c COG
39	Production of J/psi and Chi_cJ in association with pseudoscalar meson(s)

- TAPAS could maintain hadron physics at post-Tevatron Fermilab, multiplying physics output several-fold

Summary

- Best experiment ever on hyperons, charmonia, and charm may soon be feasible at Fermilab
  - possibly world's most sensitive study of charm mixing, charm & hyperon CPV & rare decays, + unique $\bar{p}$ DY
- Existing equip't enables quick, cost-effective effort
  - could start data-taking by 2014
- Preserves options for antihydrogen experiments
  - CPT, gravity tests
- World's best $\bar{p}$ source offers simple way to broad physics program in pre-Project X era

➡ Can Oddone's mind be changed?

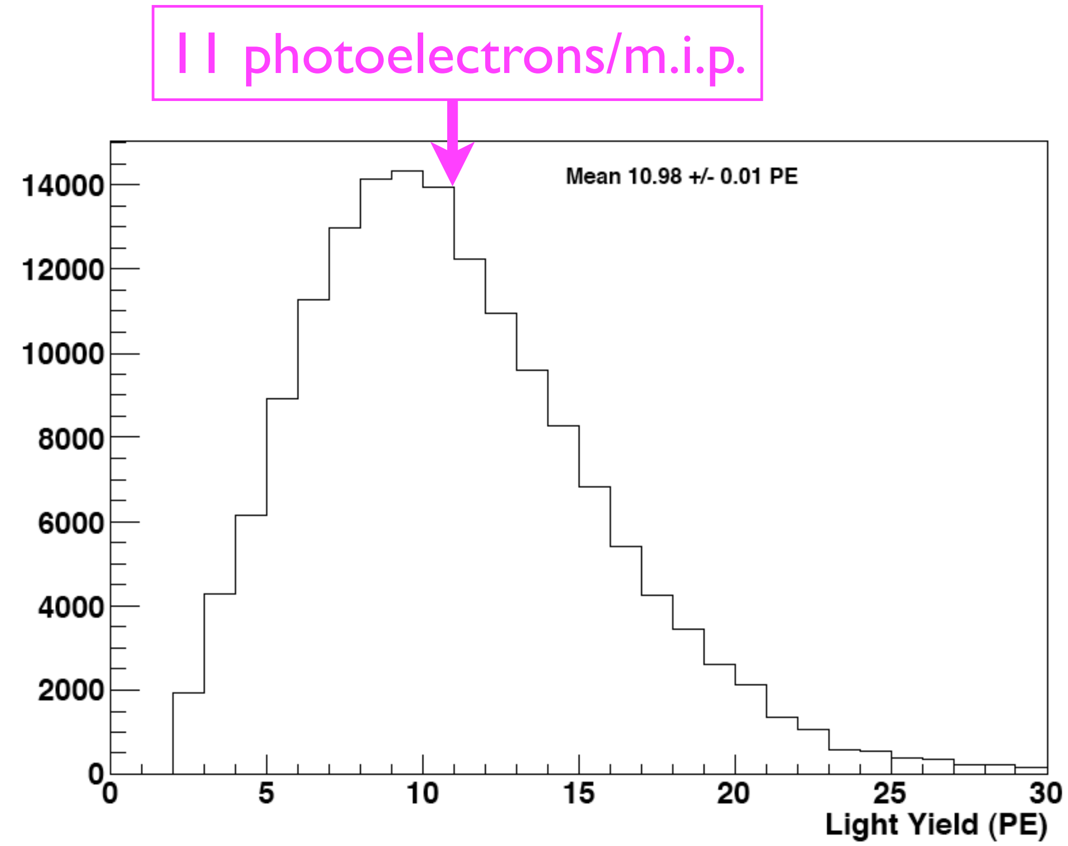
Can you help???

Backup

Fine-Pitch Scintillating Fibers

- MICE SciFi Trackers with VLPC readout

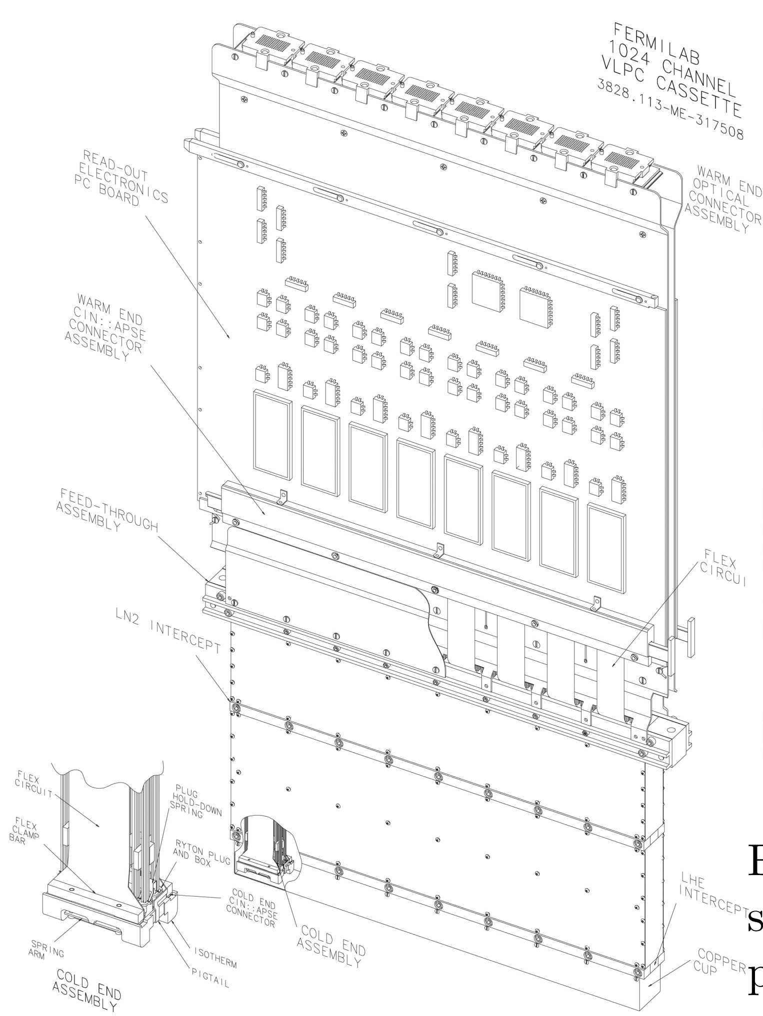
→ ≈ 85% Q.E.

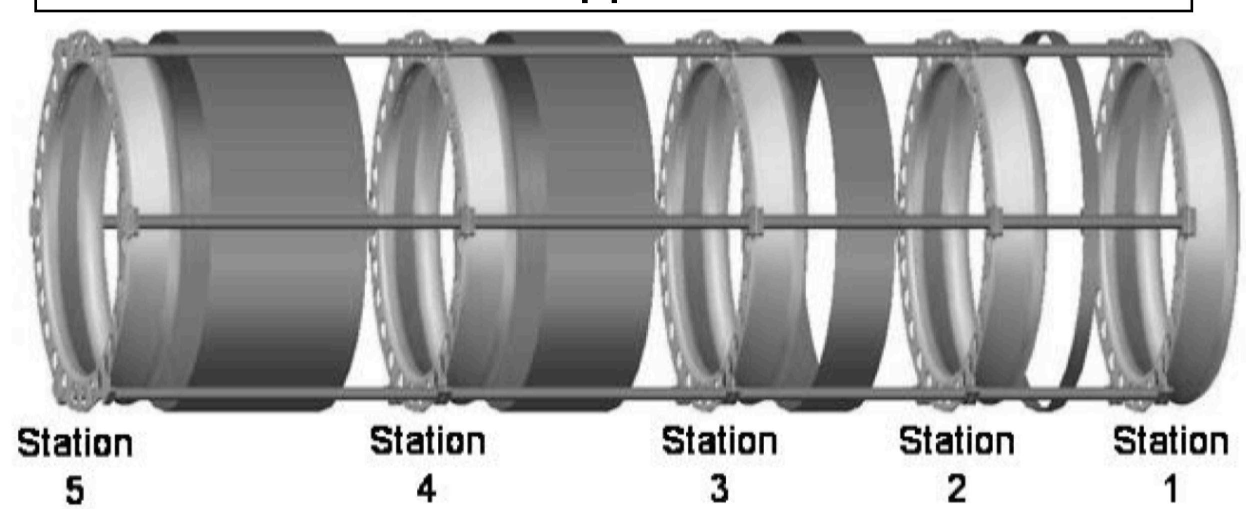


- 11 p.e. from 350 μm scintillating fiber

⇒ 240 μm feasible

Muon Ionization Cooling Experiment
Rutherford Appleton Lab, UK





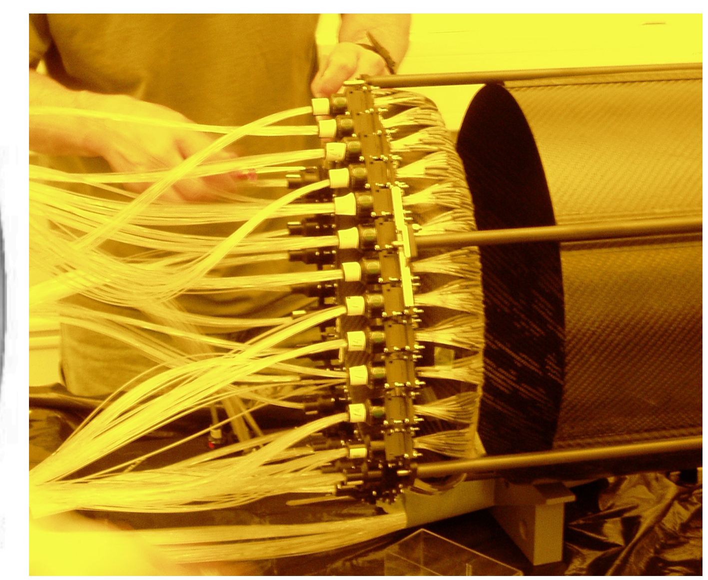


Figure 23: (left) CAD drawing of MICE tracker support frame, showing five carbon-fiber station support bodies mounted on space frame; (right) photo of carbon-fiber station support body.

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
hyperon CP run	~12 mo
install/debug hadron-ID upgrade	~3 mo
charm CP run	~12 mo

} if σ's favorable (applies to the last four rows: *X*(3872) run, hyperon CP run, install/debug hadron-ID upgrade, charm CP run)

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

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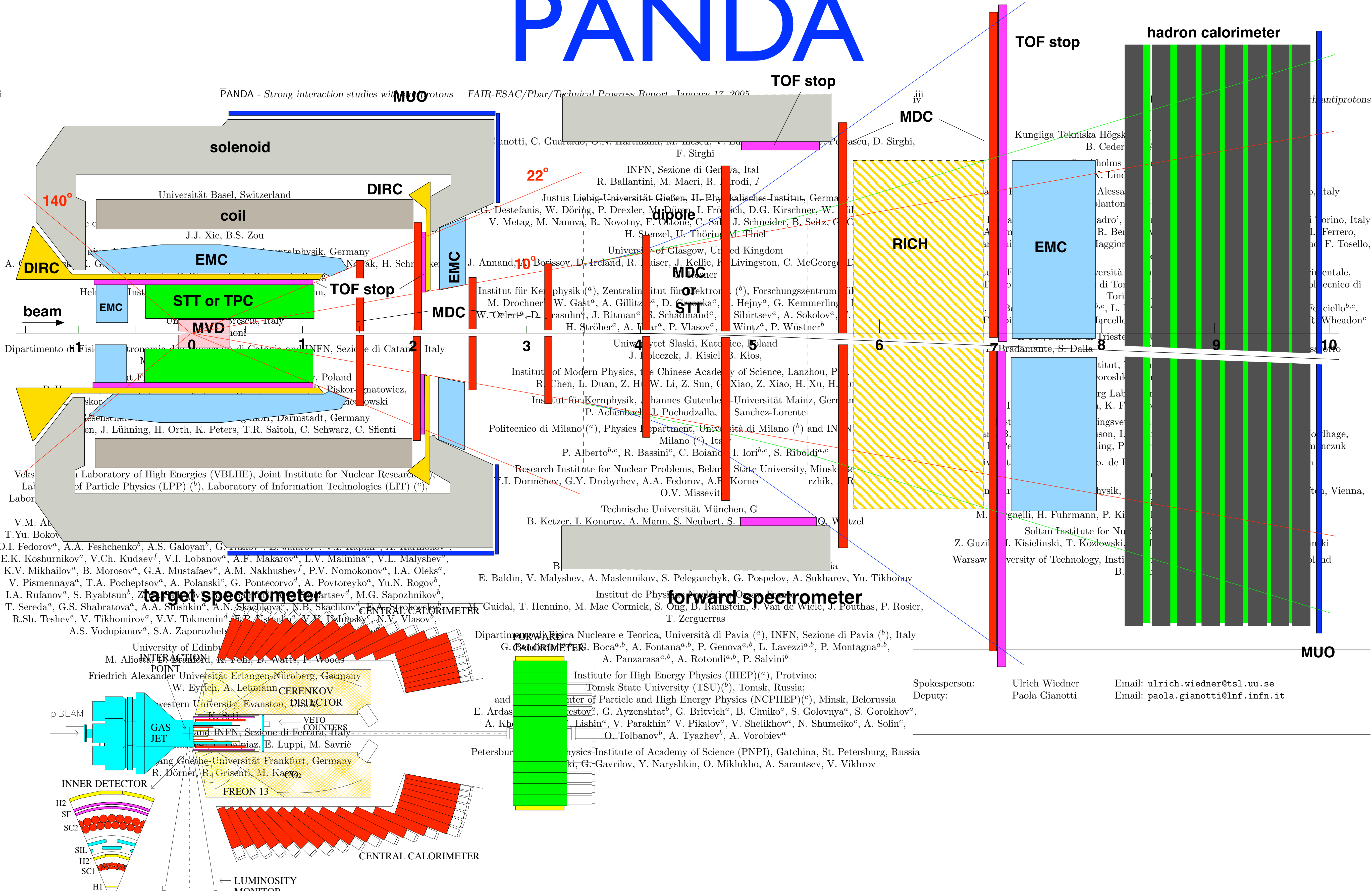
P̄ANDA

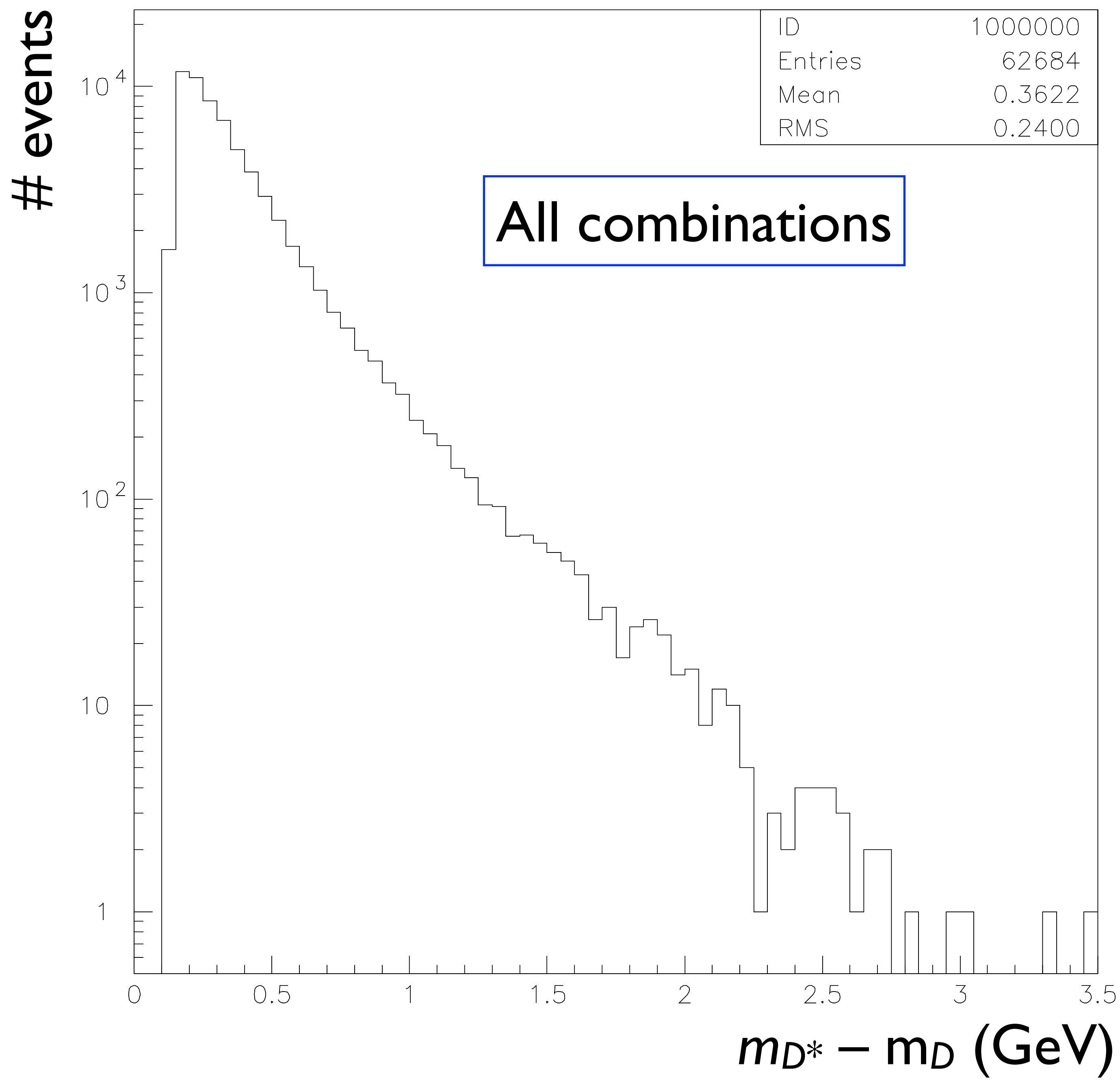

solenoid
coil
DIRC
EMC
STT or TPC
MVD
TOF stop
MDC
MUO
dipole
MDC or STT
RICH
hadron calorimeter
140°
22°
10°
beam
target spectrometer
forward spectrometer
CENTRAL CALORIMETER
FORWARD CALORIMETER
INTERACTION POINT
CERENKOV DETECTOR
VETO COUNTERS
GAS JET
p̄ BEAM
FREON 13
CO2
INNER DETECTOR
LUMINOSITY MONITOR
2.63m

$\bar{\text{P}}$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

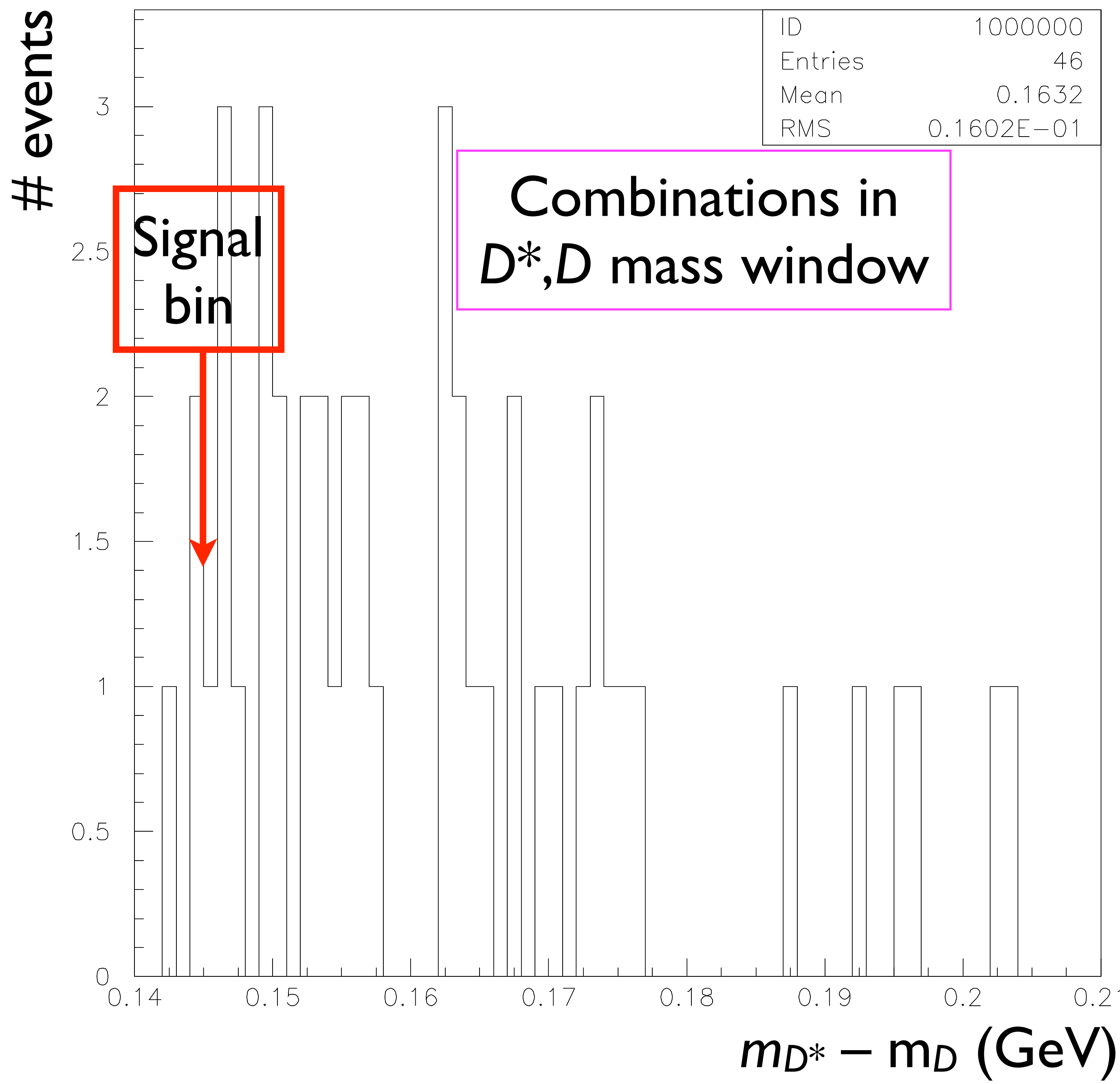
Background Study

- MIPP D^* – D mass:



Background Study

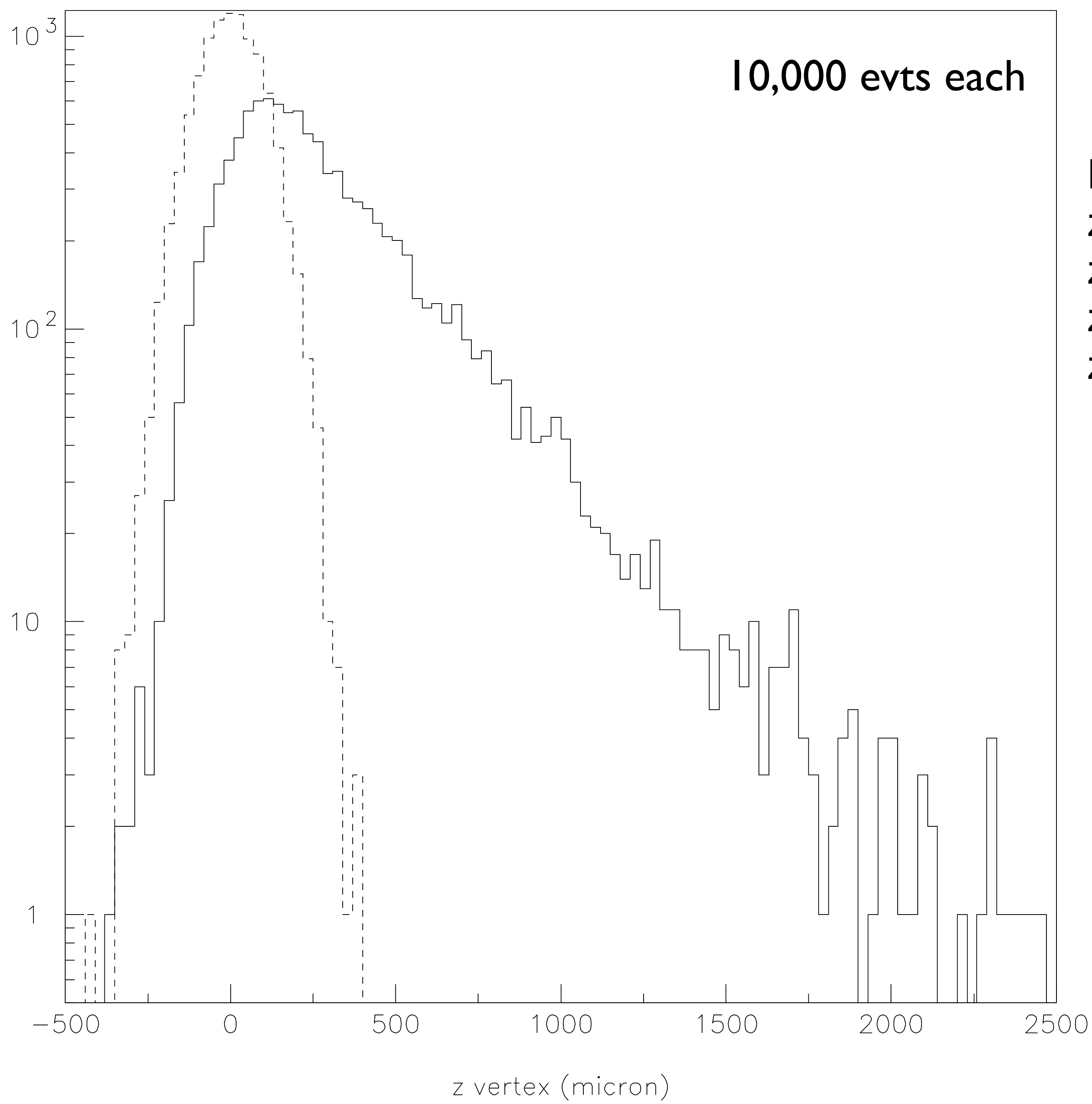
- MIPP *D** – *D* mass:



- Only a few background events – with *no* kaon ID!

Background Study

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

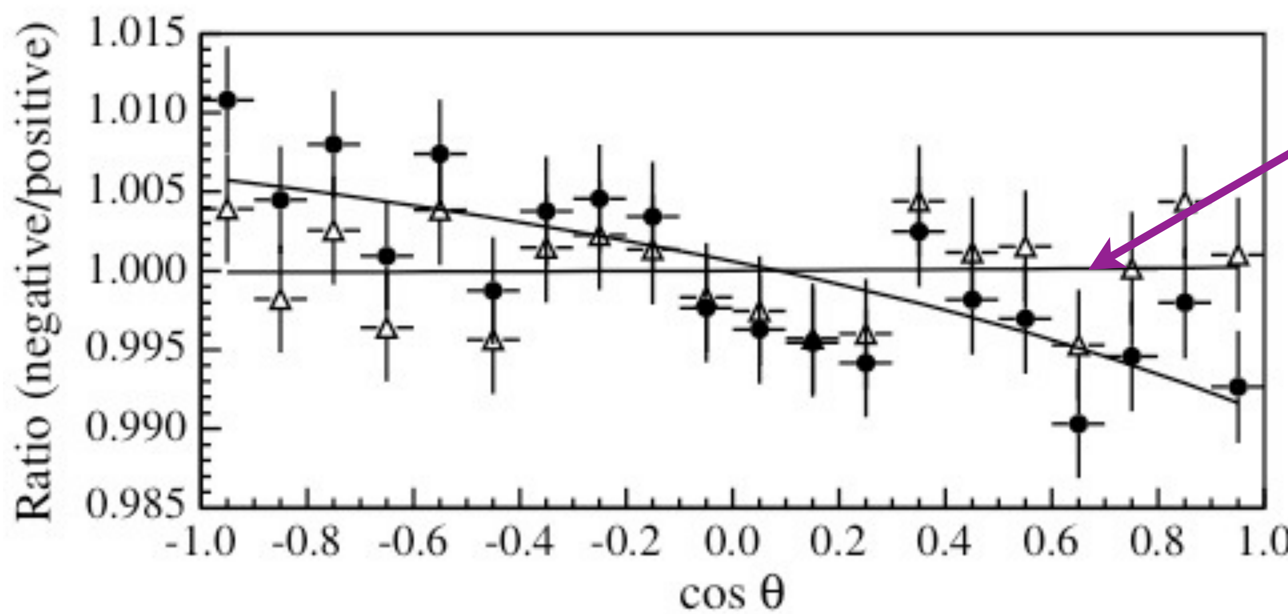


vtx cut	#bkg	#sig	sig/bkg	D accept.
No cut on z	10,000	10,000	1	50%
z>100 microns	1,589	7,106	4.5	35%
z>200 microns	238	5,168	22	25%
z>300 microns	14	3,679	250	18%
z>400 microns	0	2,669	>1000	13%

(Based on 240 μm SciFi)

$\Xi^{\pm}$ CP Violation

- Holmstrom et al., PRL **93**, 26201 (2004):
  - analysis of ≈5% of Ξ^{-} sample, 10% of Ξ^{+}

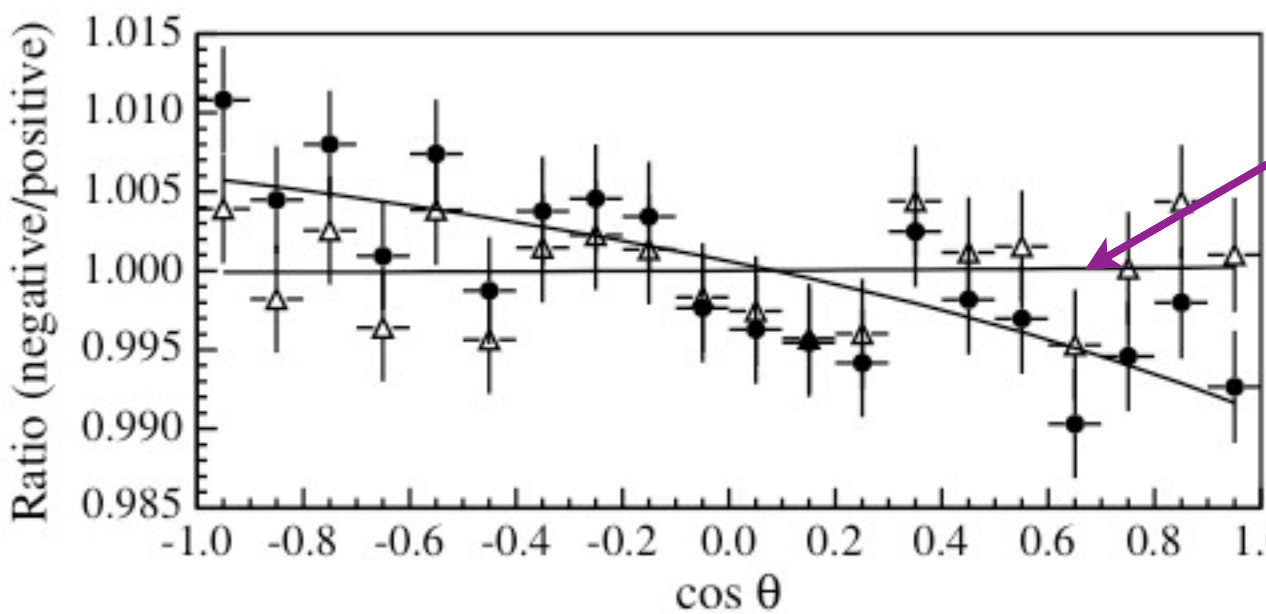


After weighting events to correct for unequal production spectra, etc.: $\delta(\cos\theta \text{ slope}) = 0$

- C. Materniak, BEACH08:

$\Xi^{\pm}$ CP Violation

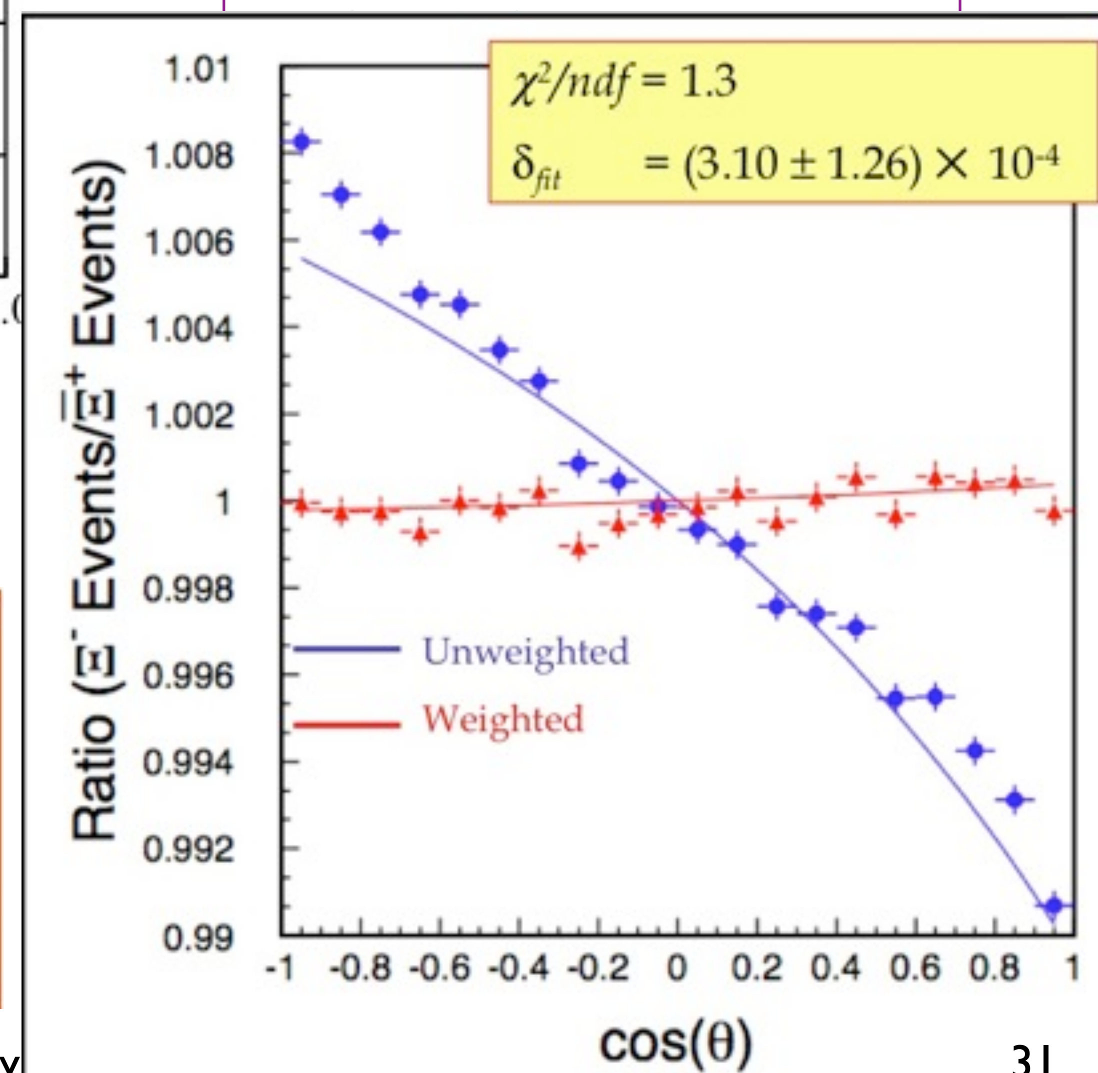
- Holmstrom et al., PRL **93**, 26201 (2004):
  - analysis of ≈5% of Ξ^- sample, 10% of Ξ+



After weighting events to correct for unequal production spectra, etc.:

- C. Materniak, BEACH08:

$$A_{\Xi\Lambda} = \frac{\alpha_{\Xi}\alpha_{\Lambda} - \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}}{\alpha_{\Xi}\alpha_{\Lambda} + \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}}$$
$$= [-6.0 \pm 2.1(stat) \pm 2.1(syst)] \times 10^{-4}$$



Some HyperCP Publications:

- L. C. Lu *et al.*, "Measurement of the asymmetry in the decay $\overline{\Omega}^{+} \rightarrow \overline{\Lambda} K^{+} \rightarrow \overline{p} \pi^{+} K^{+}$," Phys. Rev. Lett. **96**, 242001 (2006).
- D. Rajaram *et al.*, "Search for the Lepton-Number-Violating Decay $\Xi^{-} \rightarrow p \mu^{-} \mu^{-}$," Phys. Rev. Lett. **94**, 181801 (2005).
- C. G. White *et al.*, "Search for Delta $\Delta S = 2$ Nonleptonic Hyperon Decays," Phys. Rev. Lett. **94**, 101804 (2005).
- H. K. Park *et al.*, "Evidence for the Decay $\Sigma^{+} \rightarrow p \mu^{+} \mu^{-}$," Phys. Rev. Lett. **94**, 021801 (2005).
- M. Huang *et al.*, "New Measurement of $\Xi^{-} \rightarrow \Lambda \pi^{-}$ Decay Parameters," Phys. Rev. Lett. **93**, 011802 (2004);
- M. J. Longo *et al.*, "High-Statistics Search for the $\Theta^{+}(1.54)$ Pentaquark," Phys. Rev. D **70**, 111101(R) (2004);
- T. Holmstrom *et al.*, "Search for CP Violation in Charged-Ξ and Λ Hyperon Decays," Phys. Rev. Lett. **93**, 262001 (2005);
- Y. C. Chen *et al.*, "Measurement of the Alpha Asymmetry Parameter for the $\Omega^{-} \rightarrow \Lambda K^{-}$ Decay," Phys. Rev. D **71**, 051102(R) (2005);
- L. C. Lu *et al.*, "Observation of Parity Violation in the $\Omega^{-} \rightarrow \Lambda K^{-}$ Decay," Phys. Lett. B **617**, 11 (2005).
- R. A. Burnstein *et al.*, "HyperCP: A High-Rate Spectrometer for the Study of Charged Hyperon and Kaon Decays," Nucl. Instrum. Methods A **541**, 516 (2005).

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