Partículas Elementales
una vista desde San Luis Potosí

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Outline

- Introduction
- Conservation Laws and Violation
- Charm – SELEX
- CP Violation in Kaons – CKM
- Summary

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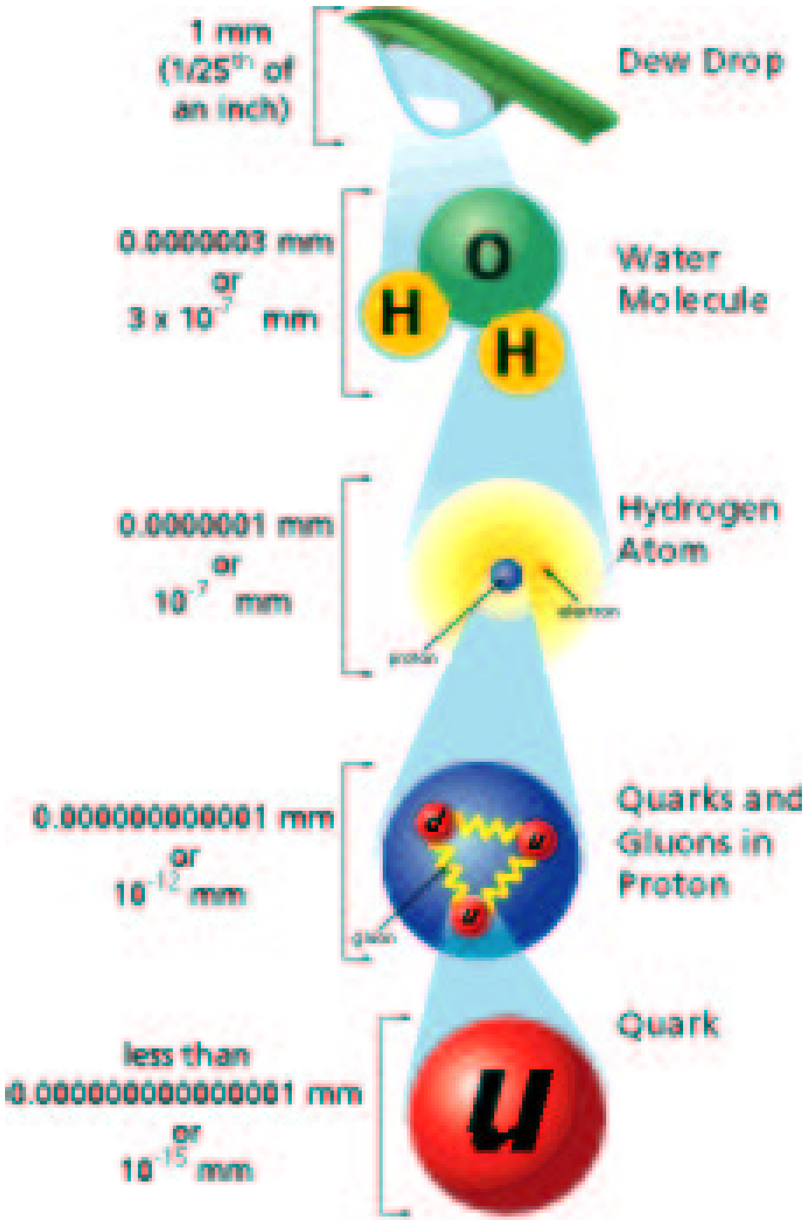
Some centuries ago...

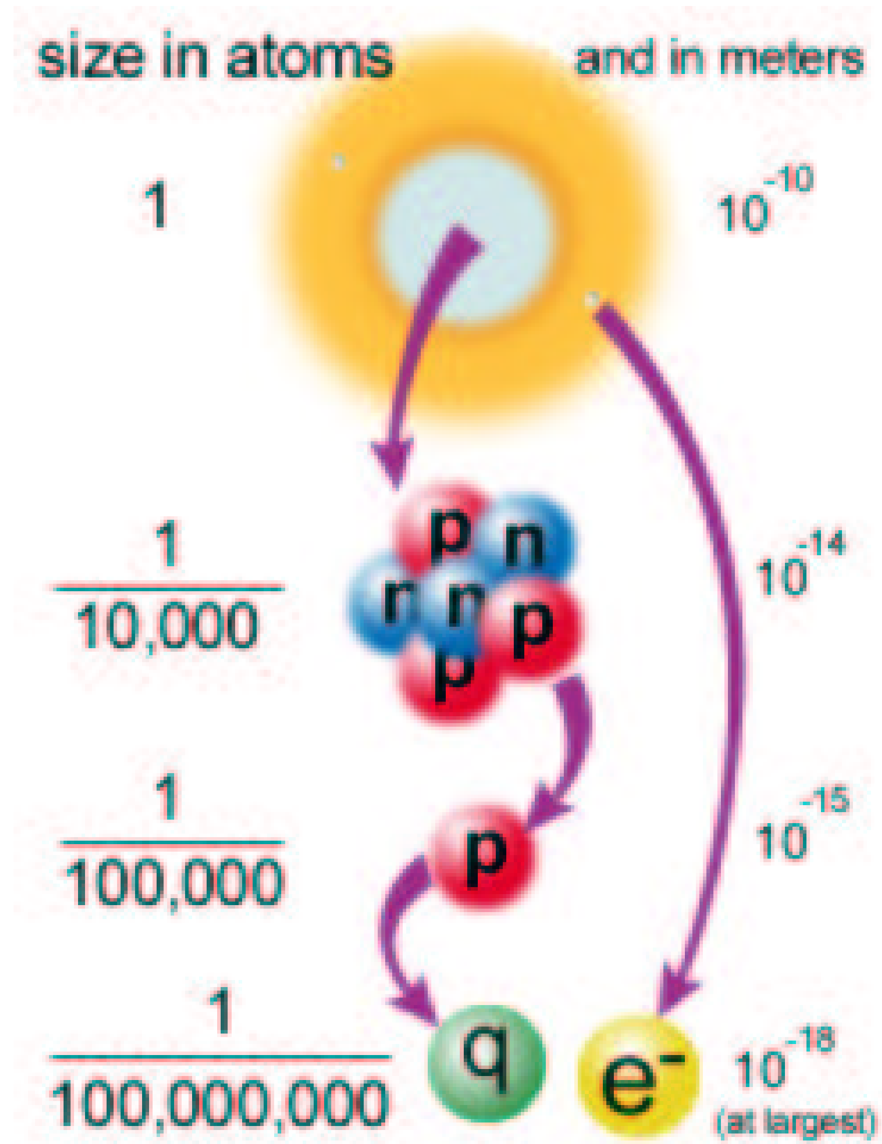
Mendeleev (19. Century)

PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907215)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57–71 Lantha- nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (208.982415)	85 At Astatine (209.987131)	86 Rn Radon (222.017570)
87 Fr Francium (223.019731)	88 Ra Radium (226.025402)	89–103 Actinides	104 Rf Rutherford. (261.1089)	105 Db Dubnium (262.1144)	106 Sg Seaborg. (263.1186)	107 Bh Bohrium (262.1231)	108 Hs Hassium (265.1306)	109 Mt Meitner. (266.1378)	110 (269, 273)	111 (272)	112 (277)						

Lanthanide series	57 La Lanthan. 138.9055	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912745)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide series	89 Ac Actinium (227.027747)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.048166)	94 Pu Plutonium (244.064197)	95 Am Americ. (243.061372)	96 Cm Curium (247.070346)	97 Bk Berkelium (247.070298)	98 Cf Californ. (251.079579)	99 Es Einstein. (252.08297)	100 Fm Fermium (257.095096)	101 Md Mendelev. (258.098427)	102 No Nobelium (259.1011)	103 Lr Lawrenc. (262.1098)


1 mm
(1/25th of an inch)
Dew Drop
0.0000003 mm
or
3 x 10-7 mm
O
H
H
Water Molecule
0.0000001 mm
or
10-7 mm
Hydrogen Atom
0.000000000001 mm
or
10-12 mm
Quarks and Gluons in Proton
less than
0.000000000000001 mm
or
10-15 mm
Quark
u


size in atoms
and in meters
1
10-10
1/10,000
10-14
1/100,000
10-15
p
1/100,000,000
q
e-
10-18
(at largest)

Elementary Particles

≈ 1950 : Known elementary particles:

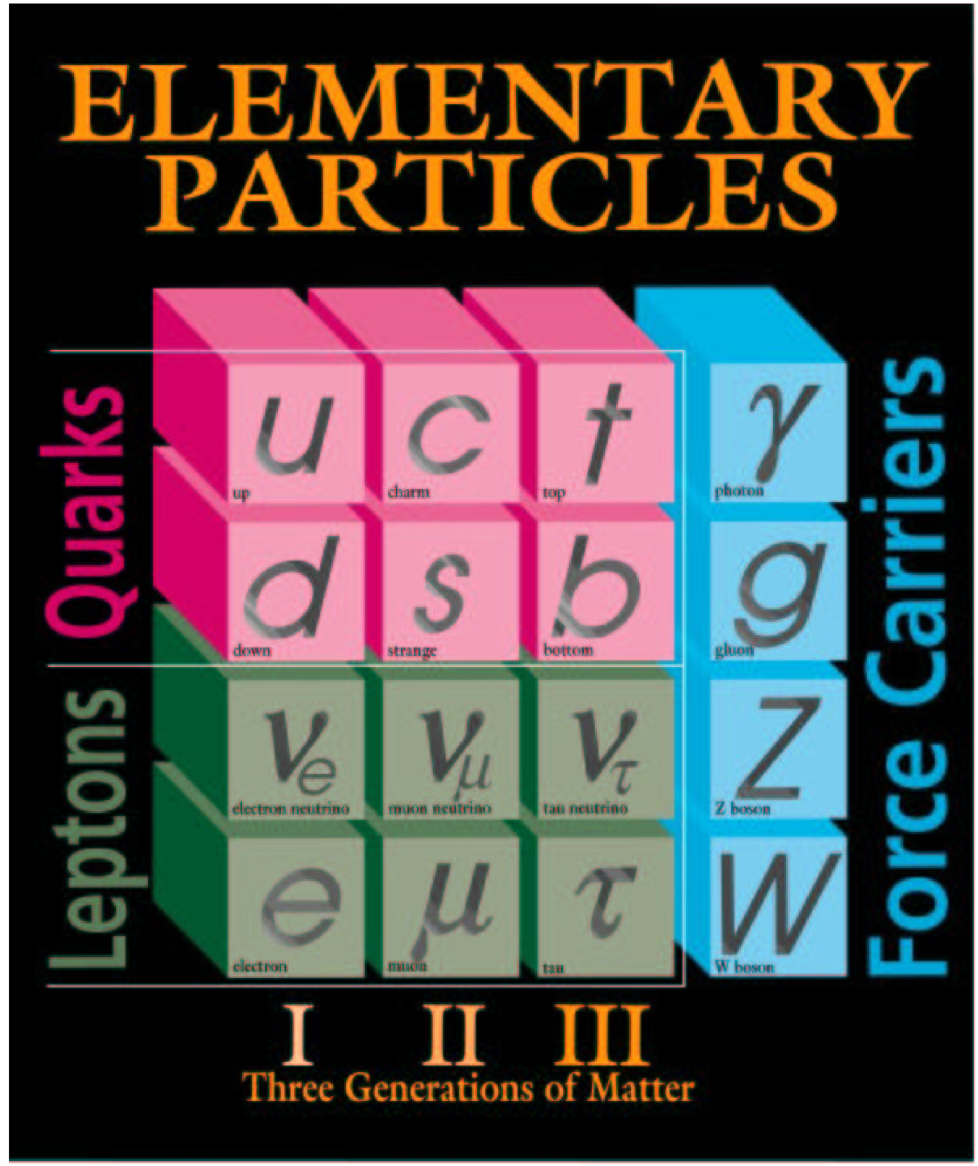
- Electron (1897)
- Proton (1905)
- Neutron (1932)
- Positron (1932)
- Myon (1937)
- Pion (1947)

Last discovered:

- top quark (1995)
- tau neutrino (ν_τ) (2000)

Still missing today:

- Higgs
- Graviton



Fermilab 95-759

Composition of Hadron

Exhibit Strong Interaction, composed of Quark

- Baryon: 3 quarks. Example: proton, neutron
- Meson: 1 quark, 1 antiquark. Example: pion, kaon

Do we understand this? Somehow....

- quarks carry additional quantum number color (*strong charge*)
- 3 colors, 3 anti-colors (compare to EM: 1 charge)
- Described by Group Theory SU(3) (compare: EM charge U(1), spin SU(2))
- "Gluons" mediate interaction (compare EM: photon)
- Only color singlets (white) objects observable as free particles

Experimental Observations:

- All possible Mesons from 5 quarks observed
- Baryons: all combinations up to one c-quark, and $\Lambda_b\,(bud)$

Open Questions

- More "white" objects are possible:
  - 2 quarks, 2 antiquarks
  - 4 quarks, 1 antiquark (Pentaquarks)
  - 3 quarks, 3 antiquarks (H)
- Most extreme case: A lot of Quarks and Gluons form one soup:
  Quark-Gluon Plasma

Conservation Laws

Classical

Hamiltonian invariant under space translation

$\Longrightarrow$ Conservation of momentum

Hamiltonian invariant under time translation

$\Longrightarrow$ Conservation of energy

Hamiltonian invariant under rotation

$\Longrightarrow$ Conservation of angular momentum

gauge invariant

$\Longrightarrow$ Conservation of electric charge

Quantum Mechanics

equivalent description:

(a) Momentum is conserved

(b) Hamiltonian is invariant under space translations

(c) Momentum operator commutes with Hamiltonian

Important in Particle Physics: Discrete Symmetries

- Parity $\mathcal{P}$

$$\mathcal{P}\Psi(\vec{r}) \rightarrow \Psi(-\vec{r})$$

  - Strong and Electromagnetic Interaction conserve Parity
  - Weak Interaction violates Parity (1957)

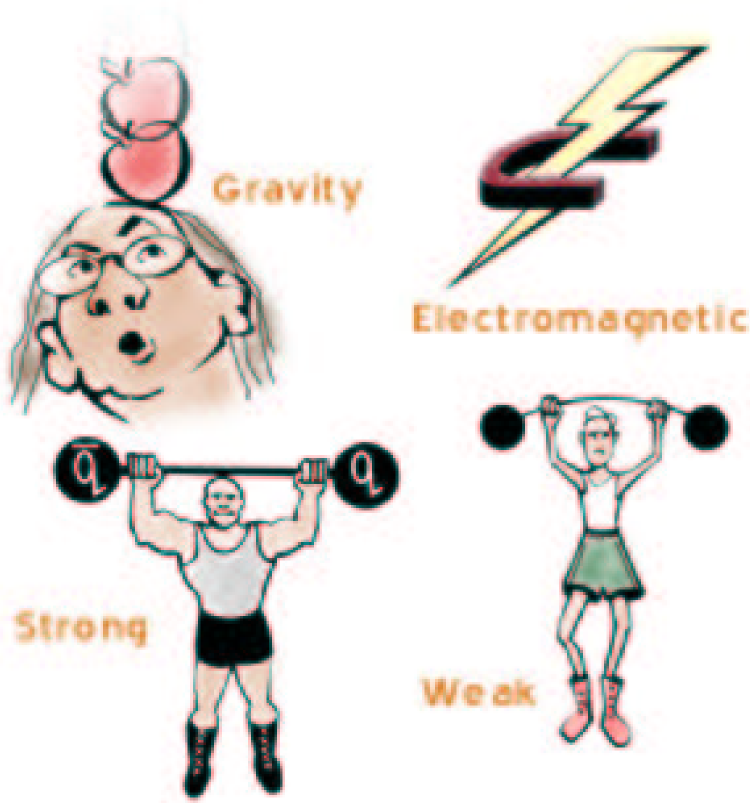
- Charge Conjugate $\mathcal{C}$
  - exchange sign of electric charge and magn. moment
  - exchange particle with antiparticle

- Time Reversal $\mathcal{T}$

Until 1964: All Interaction are invariant under $\mathcal{CP}$

$$\begin{array}{llll} K_L^0 & \rightarrow \pi^0\pi^0\pi^0 & (21\%) & \mathcal{CP} = +1 \\ & \rightarrow \pi^+\pi^-\pi^0 & (13\%) & \mathcal{CP} = +1 \\ & \rightarrow \pi^+\pi^- & (0.2\%) & \mathcal{CP} = -1 \quad \text{CP Violation!!!} \end{array}$$

Basic Interactions



Weak Interaction

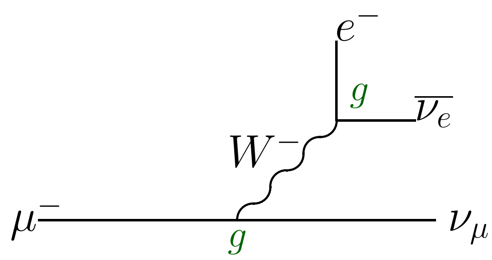
$\approx$ 1960 weak decay of strange particles

- Why "strange"?
  - produced abondandly
  - long living
- Explanation:
  - produced in pairs by Strong Interaction
  - decay by Weak Interaction supressed
    eigenstates to Strong Interaction and mass are **NOT** eigenstates to Weak Interaction
- $\longrightarrow$ Cabbibo theory (1963)
  - 2×2 rotation matrix for quarks (not! for leptons)

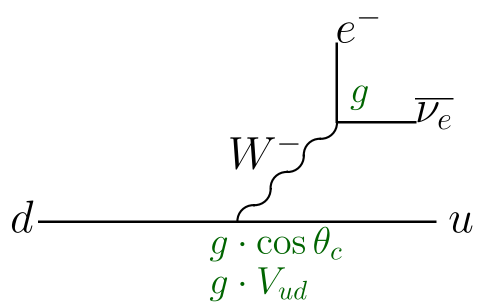
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Examples for Weak Decays

- $\mu^- \longrightarrow e^- + \overline{\nu_e} + \nu_\mu$



- beta decay: $n \longrightarrow p + e^- + \overline{\nu_e}$.
  On quark level: $d \longrightarrow u + e^- + \overline{\nu_e}$



Some more History

- 1970: Are there more quarks? (most people: NO!)
  If yes, how to change Cabbibo theory?
- 1972: Kobayashi and Maskawa: If there are 6 quark, we can describe $\mathcal{CP}$ Violation (3×3 matrix)
- 1974: "November Revolution" charm quark discovered (Brookhaven, SLAC)
- 1976: b quark (Fermilab)
- 1994: t quark (Fermilab)

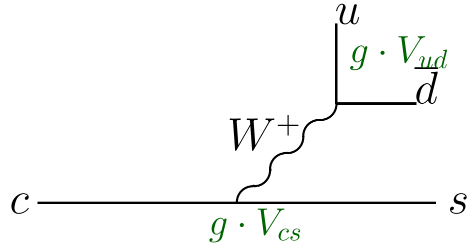
Cabibbo-Kobayashi-Maskawa (CKM) Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.9745 - 0.9760 & 0.217 - 0.224 & 0.0018 - 0.0045 \\ 0.217 - 0.224 & 0.9737 - 0.9753 & 0.036 - 0.042 \\ 0.004 - 0.013 & 0.035 - 0.042 & 0.9991 - 0.9994 \end{pmatrix}$$

Decay of charm

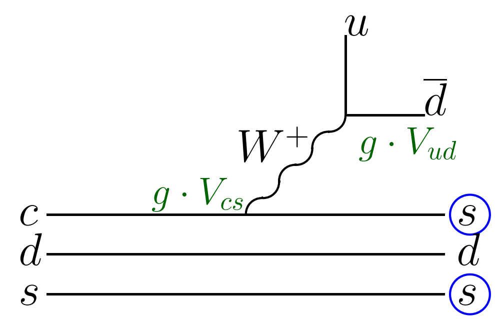
Just like strange:



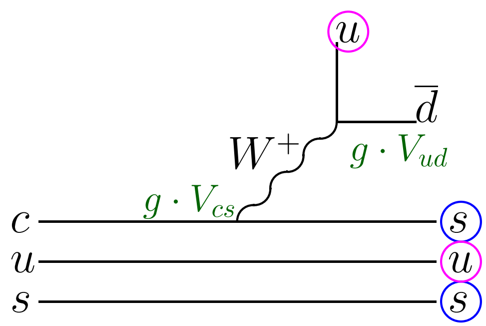
Measure V_{cs}? Yes, but... quarks are never alone!
Need a lot of measurements $\longrightarrow$ SELEX

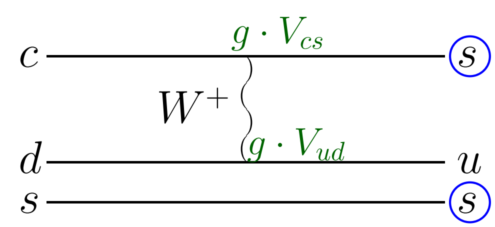
Lifetime Difference of Charm Particles – The Ξ_c as Example

Ξ_c^0 (csd) decay: $\tau = 98 \cdot 10^{-15}\,\mathrm{sec}$



Ξ_c^+ (csu) decay: $\tau = 442 \cdot 10^{-15}\,\mathrm{sec}$





Experimental Setup

To do a good job on charm, you need:

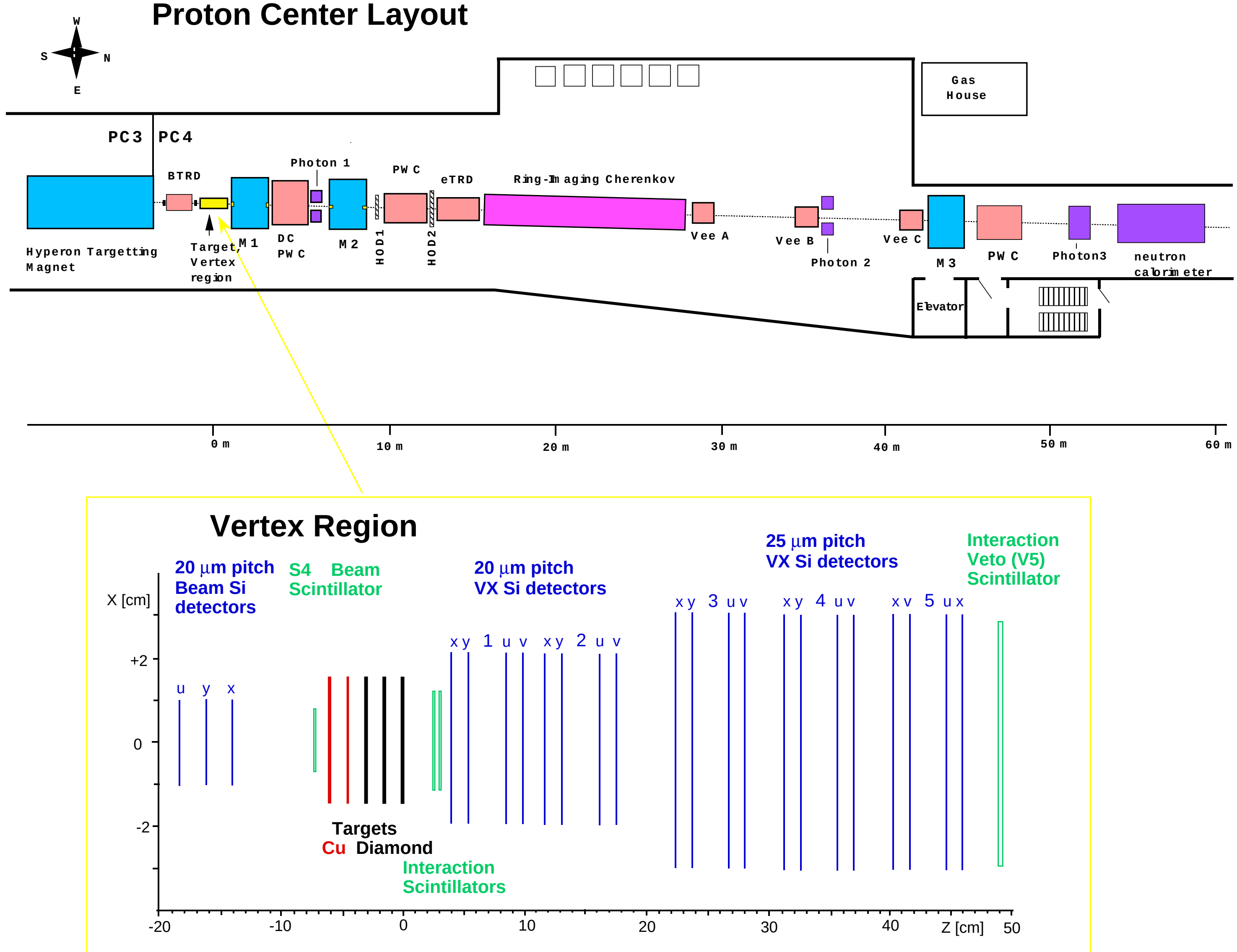
- High Statistic (charm cross section small)
- Good Trigger or Software Filter ($\sigma_c \approx 10^{-3}\sigma_{tot}$)
- Extremely good Silicon Detectors (secondary vertex, lifetime)
- Extremely good Particle Identification (proton, kaon)

Or even better: All of the above!

Fermilab Tevatron

Fermilab – High Rise and Fixed Target Area

Selex (E781)
Proton Center Layout



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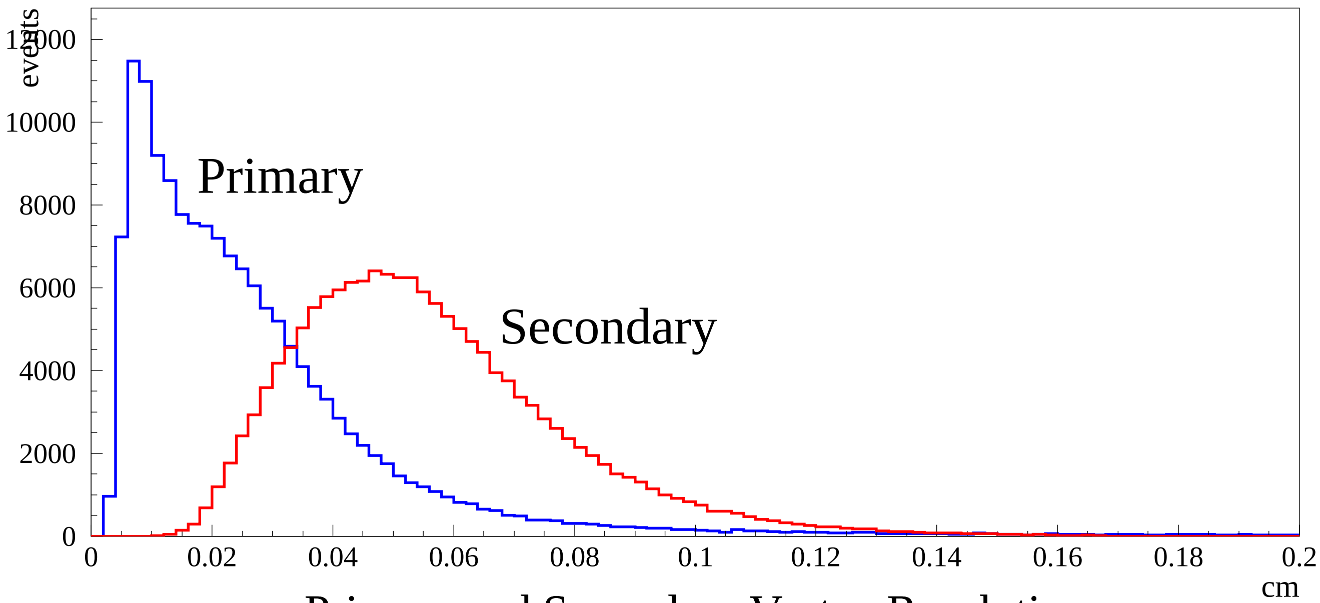
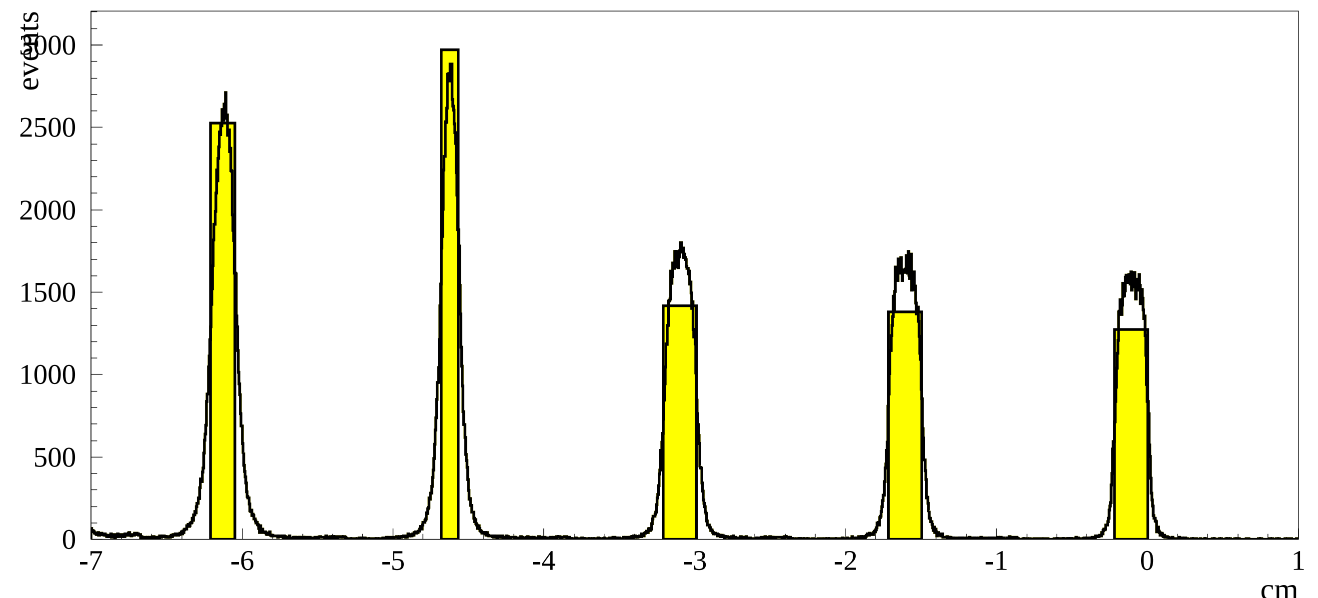
SELEX Appartus

3 segment forward spectrometer ($x_F > .1$)

- 74000 strip silicon system, 4 μm transverse position resolution at 600 GeV
- Beam tagging (Σ^-/π^-, p/π^+) with Beam TRD
- 3000 phototube RICH – K/π separation up to 165 GeV
- Secondary e^- identification with Electron TRD for semileptonic decays
- Precise downstream tracking
  - 18 large silicon planes ($\sigma \sim 8\,\mu$m)
  - 26 PWC planes ($\sigma \sim 0.6 - 1$ mm)
  - 3×24 Vector Drift Chambers ($\sigma \sim 100\,\mu$m)
- 3 lead glass photon detectors

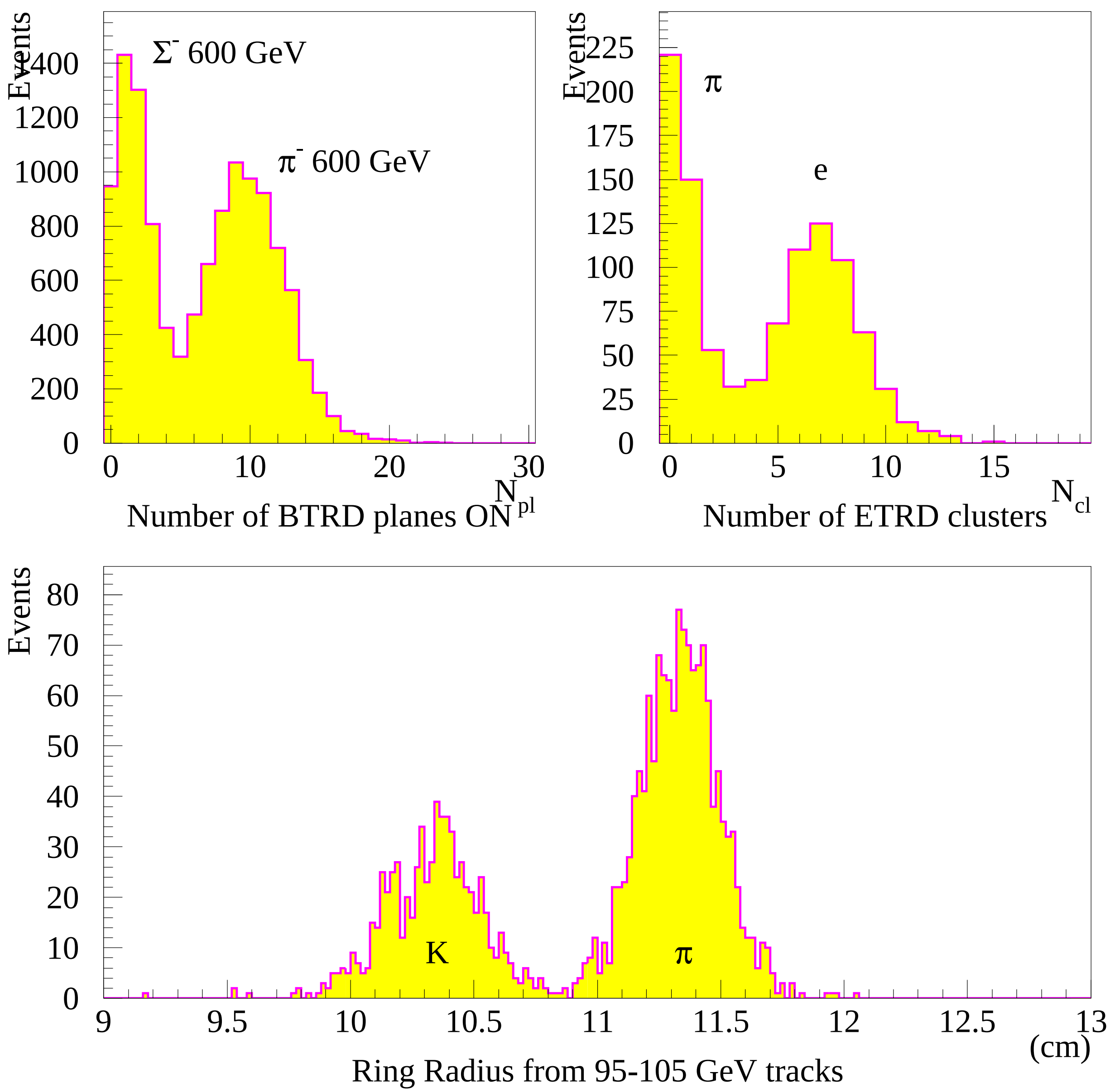


Primary and Secondary Vertex Resolution



Primary vertex positions

SELEX Particle ID detectors



Online Filter

Filter is Online Program which select events that have evidence for a secondary vertex.

- Algorithm:
  - Start from downstream tracking to find high-momentum ($p > 20\,\mathrm{GeV}/c$) tracks in PWCs
  - extrapolate tracks back to vertex silicon within the roads predicted by downstream tracking
  - Rejext events if tracks form just a primary vertex
- Charm efficiency about 50 %, Rejection 8
- 4 times more charm per tape, 8 times faster to process.

Reconstruction of Λ_c^+

- Λ_c^+ consists of (udc) quarks
- Mass $m_0 = 2.285\,\mathrm{GeV}/c^2$ (remember: proton $0.938\,\mathrm{GeV}/c^2$)
- Lifetime: $\tau = (2.0 \pm 0.06) \cdot 10^{-13}\,\mathrm{sec}$ (SELEX Collaboration, PRL **86** 5243)
- Decays to $\Lambda_c \rightarrow pK^-\pi^+$ in 5.0 % of the time.
- Only in 1 out of 1000 collisions a charm quark gets produced.

Special Theory of Relativity:

$$E = m \cdot c^2$$

$$m = m_0 \cdot \gamma$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{E \cdot c^2}{m_0}$$

$$p = m \cdot v \approx m_0 \cdot \gamma \cdot c$$

$$\text{Time dilation:} \quad t = t_0 \cdot \gamma$$

$$\text{Mean flight path:} \quad L = c \cdot \tau \cdot \gamma$$

$\Longrightarrow$ A Λ_c^+ with momentum $200\,\mathrm{GeV}/c$ flies on avarage 5.4 mm

$\Longrightarrow$ Do a Fixed Target Experiment – But even there we cannot observe a Λ_c directly

What do we do?

- Measure type, direction, momentum, and charge of all decay products
- Apply momentum and energy conservation to "interesting" decay vertex and calculate energy and momentum of hypothetical mother particle
- Transform into rest system of mother particle to obtain rest mass ("Invariant Mass")
- Do this for a lot of events, fill histogram with results

Measuring direction and decay vertex

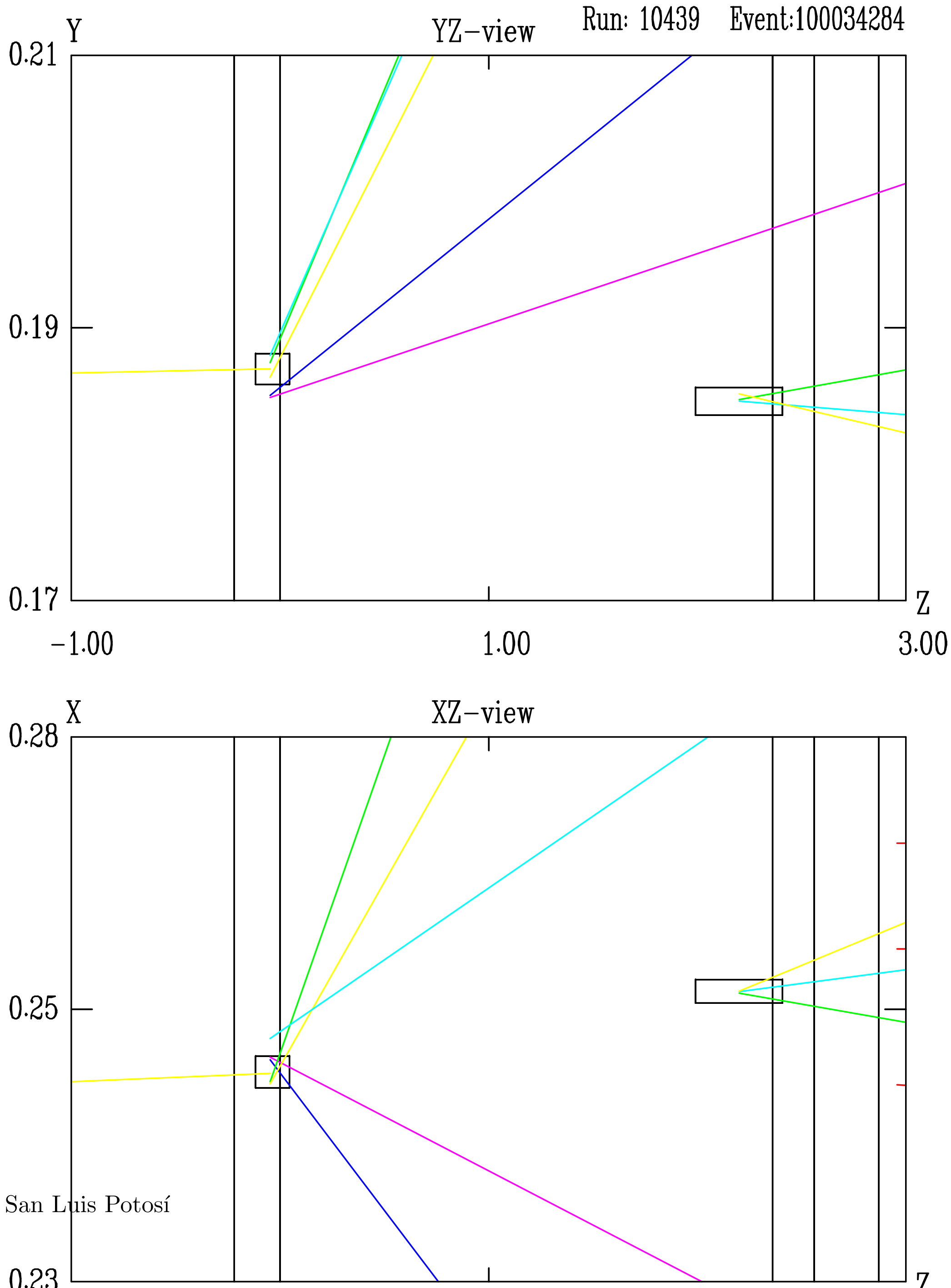
- Use silicon microstip detectors

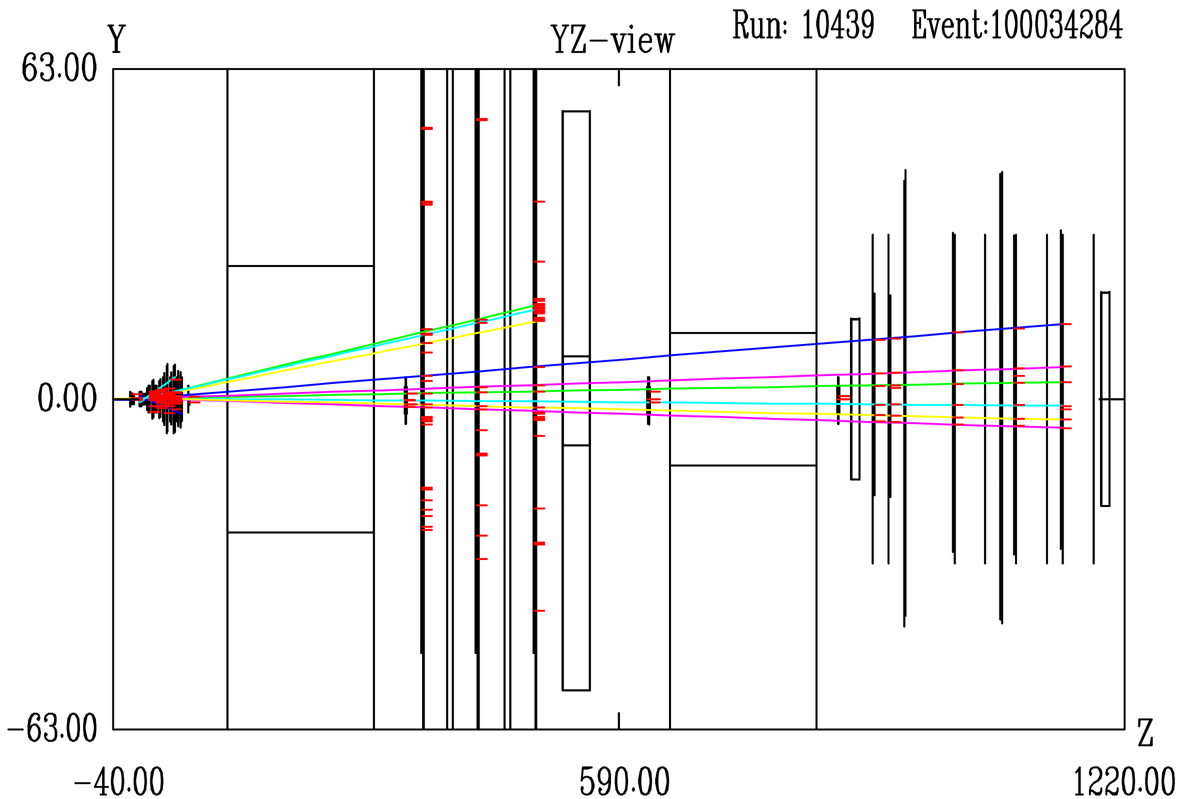
Measuring momentum and charge

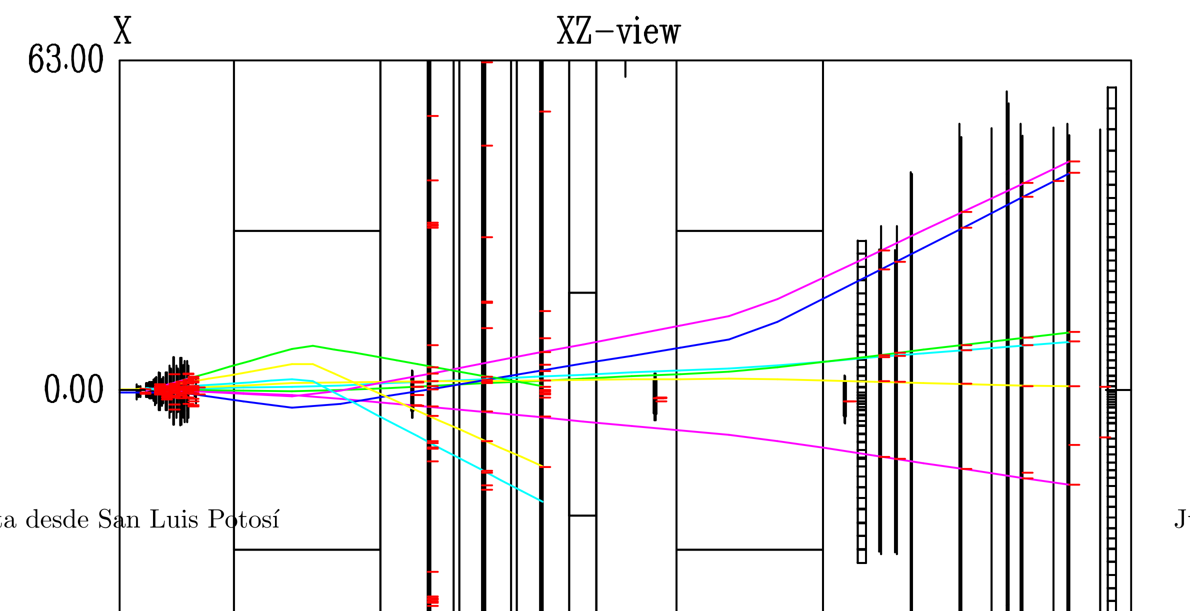
- Deflection in magnetic field, measure track angles before and after with wire chambers

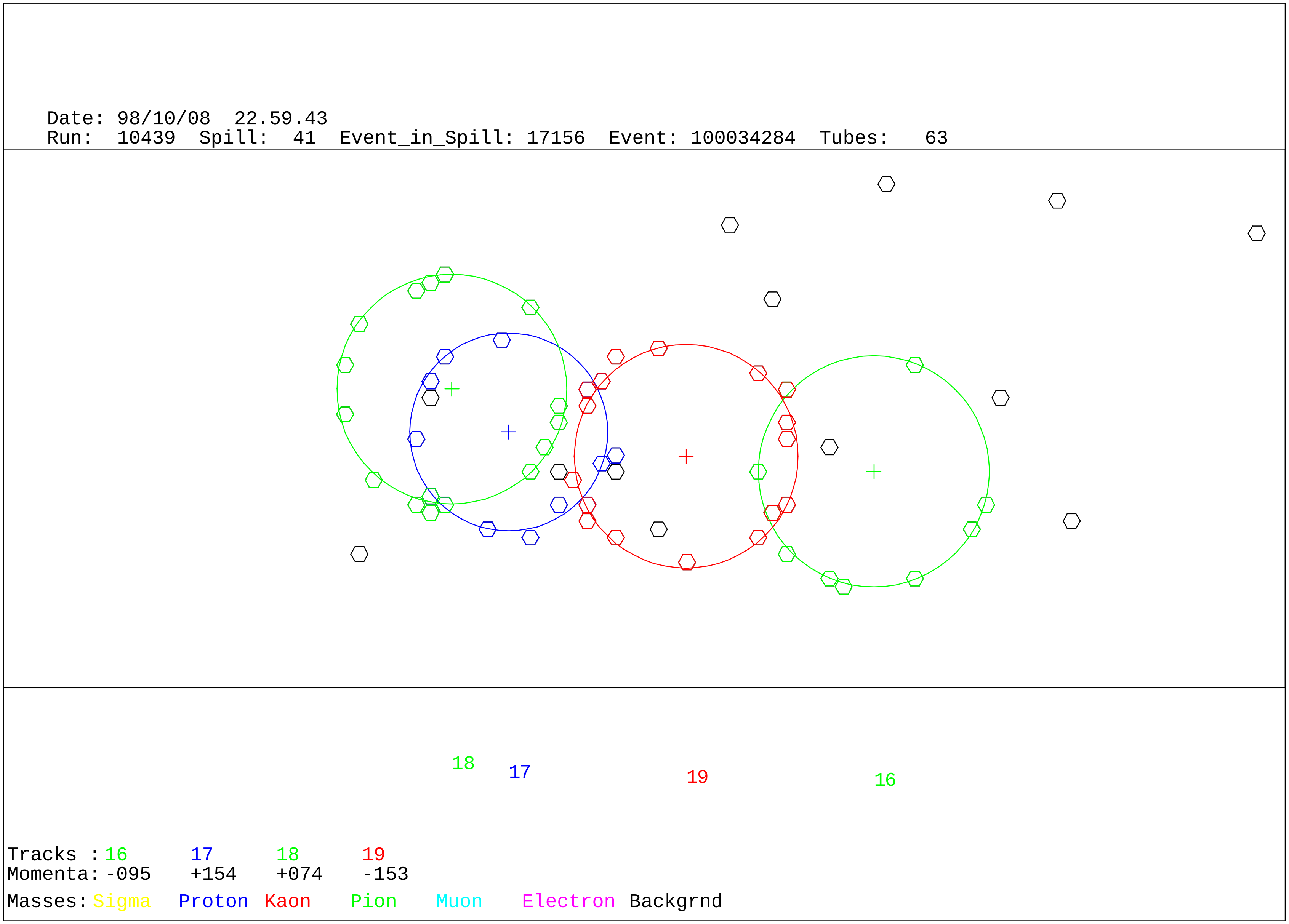
Measuring type (is it a proton?)

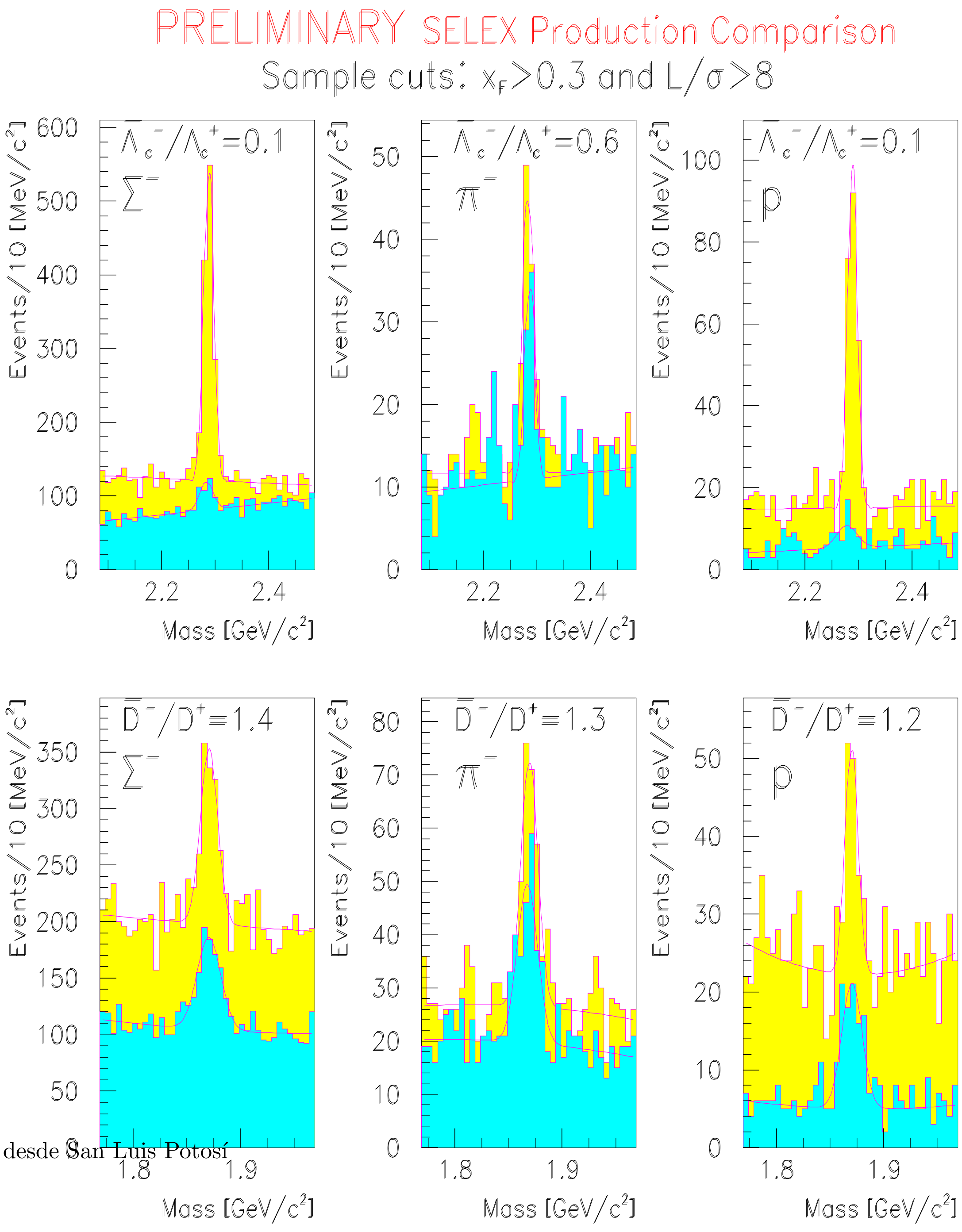
- Measure total energy in calorimeter, calculate mass
- Measure velocity with Cherenkov effect


Run: 10439 Event:100034284
Y
YZ−view
0.21
0.19
0.17
Z
−1.00
1.00
3.00
X
XZ−view
0.28
0.25
0.23
Z


Run: 10439 Event:100034284
YZ−view
Y
63.00
0.00
−63.00
Z
−40.00
590.00
1220.00


XZ−view
X
63.00
0.00


Date: 98/10/08 22.59.43
Run: 10439 Spill: 41 Event_in_Spill: 17156 Event: 100034284 Tubes: 63
18
17
19
16
Tracks : 16 17 18 19
Momenta: -095 +154 +074 -153
Masses: Sigma Proton Kaon Pion Muon Electron Backgrnd


PRELIMINARY SELEX Production Comparison
Sample cuts: $x_F>0.3$ and $L/\sigma>8$
$\bar{\Lambda}_c^-/\Lambda_c^+=0.1$
Σ^-
$\bar{\Lambda}_c^-/\Lambda_c^+=0.6$
π^-
$\bar{\Lambda}_c^-/\Lambda_c^+=0.1$
p
$\bar{D}^-/D^+=1.4$
Σ^-
$\bar{D}^-/D^+=1.3$
π^-
$\bar{D}^-/D^+=1.2$
p
Events/10 [MeV/c^2]
Mass [GeV/c^2]

Cherenkov Radiation

A charged particle with a velocity v larger than the velocity of light in a medium emits light
(Pavel A. Cherenkov, Ilja M. Frank, Igor Y. Tamm, Nobel Price 1958)

Threshold: $$\beta_{\text{thres}} = \frac{v_{\text{thres}}}{c} \geq \frac{1}{n} \qquad \gamma_{\text{thres}} = \frac{n}{\sqrt{n^2 - 1}}$$

Angle of emission: $$\cos\theta_c = \frac{1}{\beta\, n} = \frac{1}{\frac{v}{c}\, n}$$

$$\theta_c^{\max} = \arccos\frac{1}{n} \quad \text{Water: } \theta_c^{\max} = 42^\circ \quad \text{Neon (1atm): } \theta_c^{\max} = 11\,\text{mrad}$$

Number of photons: $$\frac{d^2N}{dEdl} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{(\beta n)^2}\right) = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c$$

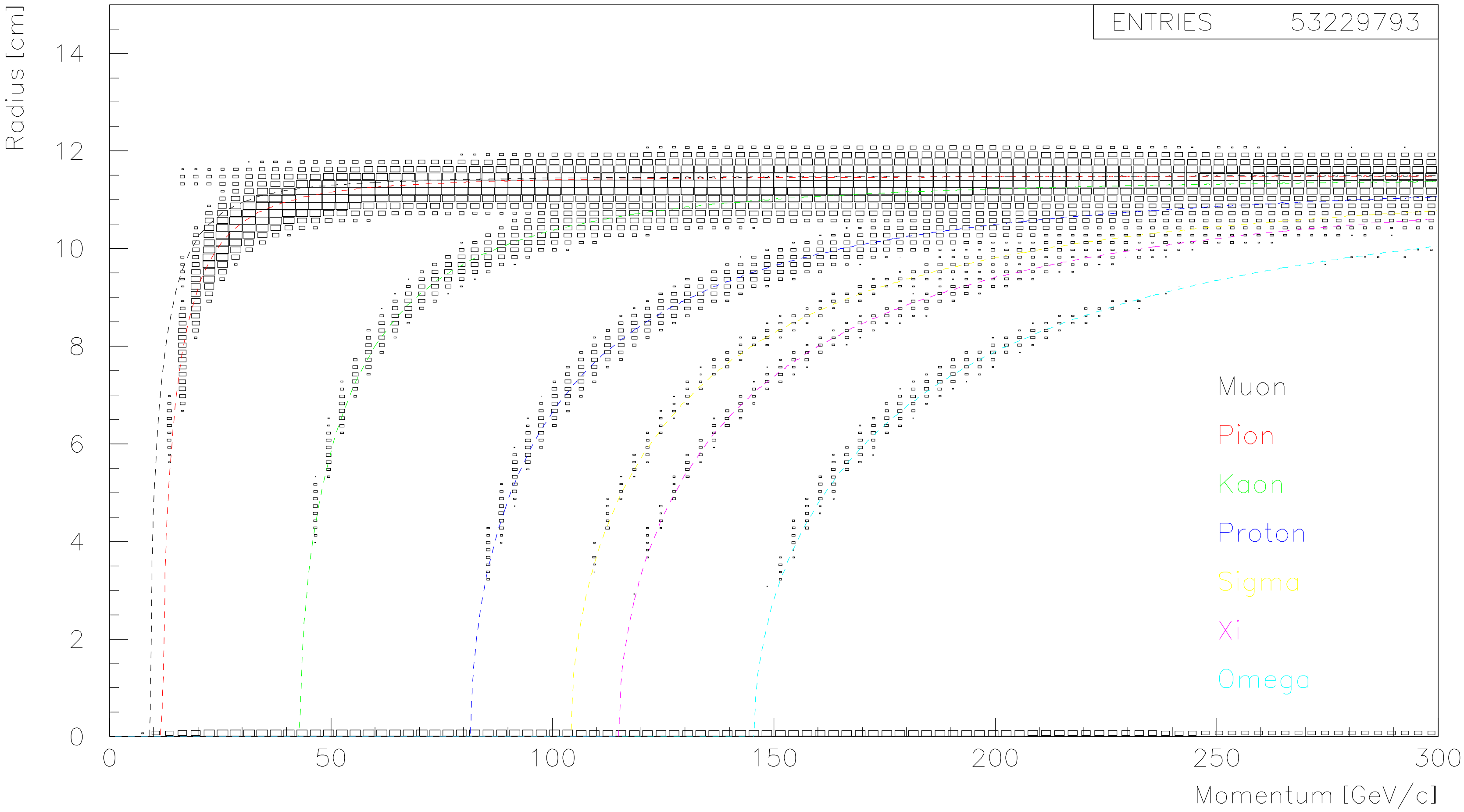
$$\frac{d^2N}{d\lambda dl} = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_c$$

Usage in Detectors

- Water Cherenkov Detectors (SuperKamiokande, Auger Tanks)
- Threshold Cherenkov Detectors (Beamlines, Experiments)
- Ring Imaging Cherenkov Counters – RICH

Ring Imaging Cherenkov Detectors

Measure Cherenkov angle, not only threshold



SELEX RICH, 53 Million single negative track events

J. Engelfried et al., Nucl. and Instr. and Methods A 50 2 (2003) 62-65

SELEX Publications

Non-Charm Topics

1. *Measurement of the Σ^- Charge Radius by Σ^-–Electron Elastic Scattering*. Physics Letters **B522** (2001) 233-239.

2. *Radiative decay width of the $a_2(1320)^-$ meson*. Physics Letters **B521** (2001) 171-180.

3. *First Measurement of $\pi^- e \to \pi^- e \gamma$ Pion Virtual Compton Scattering*. Phys. Rev. C **66**, 034613 (2002).

4. *Total Cross Section Measurements wit π^-, Σ^- and Protons on Nuclei and Nucleons around* 600 GeV/c. Nucl. Phys. B 579 (2000) 277-312.

Charm Topics

5. *Observation of the Cabibbo-suppressed decay $\Xi_c^+ \to pK^-\pi^+$*. Phys. Rev. Letter **84** (2000) 1857-1861.

6. *Precision measurements of the Λ_c^+ and D^0 lifetimes*. Phys. Rev. Letter **86** (2001) 5243-5246.

7. *Hadronic Production of Λ_c from 600 GeV/c π^-, Σ^- and p beams*. Physics Letters **B528** (2002), 49-57.

8. *Measurement of the D_s lifetime*. Physics Letters **B523** (2001) 22-28.

9. *First Observation of the Doubly Charmed Baryon Ξ_{cc}^+*. Phys. Rev. Letters **89** 112001 (2002).

10. *Production Asymmetry for D_s for 600 GeV/c Σ^- and π^- beam*. Physics Letters **B558** (2003) 34-40.

10 publications (2 more submitted), 3 of them PRL. Plus several detector publications.

The Double-Charm

VOLUME 89, NUMBER 11 PHYSICAL REVIEW LETTERS 9 SEPTEMBER 2002

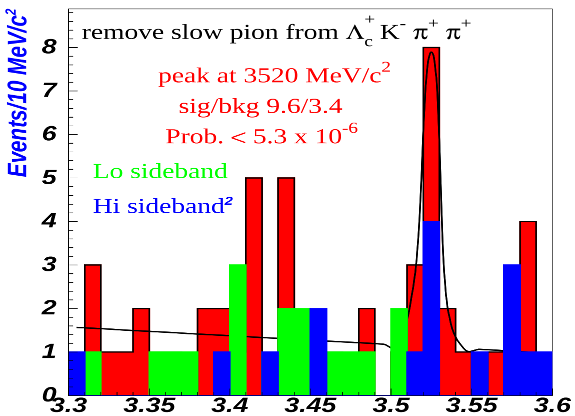
First Observation of the Doubly Charmed Baryon Ξ^+_{cc}

M. Mattson,[3] G. Alkhazov,[11] A. G. Atamantchouk,[11,a] M. Y. Balatz,[8,a] N. F. Bondar,[11] P. S. Cooper,[5] L. J. Dauwe,[17] G. V. Davidenko,[8] U. Dersch,[9,b] A. G. Dolgolenko,[8] G. B. Dzyubenko,[8] R. Edelstein,[3] L. Emediato,[19] A. M. F. Endler,[4] J. Engelfried,[5,13] I. Eschrich,[9,c] C. O. Escobar,[19,d] A. V. Evdokimov,[8] I. S. Filimonov,[10,a] F. G. Garcia,[5,19] M. Gaspero,[18] I. Giller,[12] V. L. Golovtsov,[11] P. Gouffon,[19] E. Gülmez,[2] He Kangling,[7] M. Iori,[18] S. Y. Jun,[3] M. Kaya,[16] J. Kilmer,[5] V. T. Kim,[11] L. M. Kochenda,[11] I. Konorov,[9,e] A. P. Kozhevnikov,[6] A. G. Krivshich,[11] H. Krüger,[9,f] M. A. Kubantsev,[8] V. P. Kubarovsky,[6] A. I. Kulyavtsev,[3,5] N. P. Kuropatkin,[5,11] V. F. Kurshetsov,[6] A. Kushnirenko,[3] S. Kwan,[5] J. Lach,[5] A. Lamberto,[20] L. G. Landsberg,[6] I. Larin,[8] E. M. Leikin,[10] Li Yunshan,[7] M. Luksys,[14] T. Lungov,[19,g] V. P. Maleev,[11] D. Mao,[3,h] Mao Chensheng,[7] Mao Zhenlin,[7] P. Mathew,[3,i] V. Matveev,[8] E. McCliment,[16] M. A. Moinester,[12] V. V. Molchanov,[6] A. Morelos,[13] K. D. Nelson,[16,j] A. V. Nemitkin,[10] P. V. Neoustroev,[11] C. Newsom,[16] A. P. Nilov,[8] S. B. Nurushev,[6] A. Ocherashvili,[12,k] E. Oliveira,[4] Y. Onel,[16] E. Ozel,[16] S. Ozkorucuklu,[16] A. Penzo,[20] S. V. Petrenko,[6] P. Pogodin,[16] M. Procario,[3,l] V. A. Prutskoi,[8] E. Ramberg,[5] G. F. Rappazzo,[20] B. V. Razmyslovich,[11,m] V. I. Rud,[10] J. Russ,[3] P. Schiavon,[20] J. Simon,[9,n] A. I. Sitnikov,[8] D. Skow,[5] V. J. Smith,[15] M. Srivastava,[19] V. Steiner,[12] V. Stepanov,[11,m] L. Stutte,[5] M. Svoiski,[11,m] N. K. Terentyev,[3,11] G. P. Thomas,[1] L. N. Uvarov,[11] A. N. Vasiliev,[6] D. V. Vavilov,[6] V. S. Verebryusov,[8] V. A. Victorov,[6] V. E. Vishnyakov,[8] A. A. Vorobyov,[11] K. Vorwalter,[9,o] J. You,[3,5] Zhao Wenheng,[7] Zheng Shuchen,[7] and R. Zukanovich-Funchal[19]

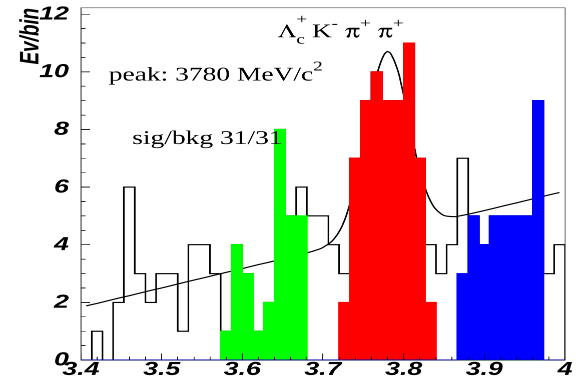
(SELEX Collaboration)

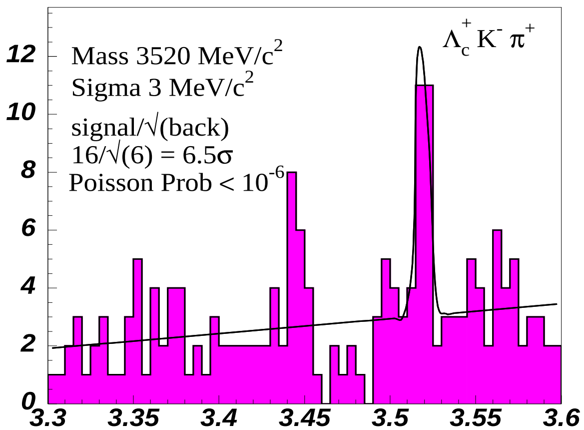
Also mentioned in “Physics News Update”
Article in “La Jornada”
Frontpage (with photo) “El Sol de San Luis”

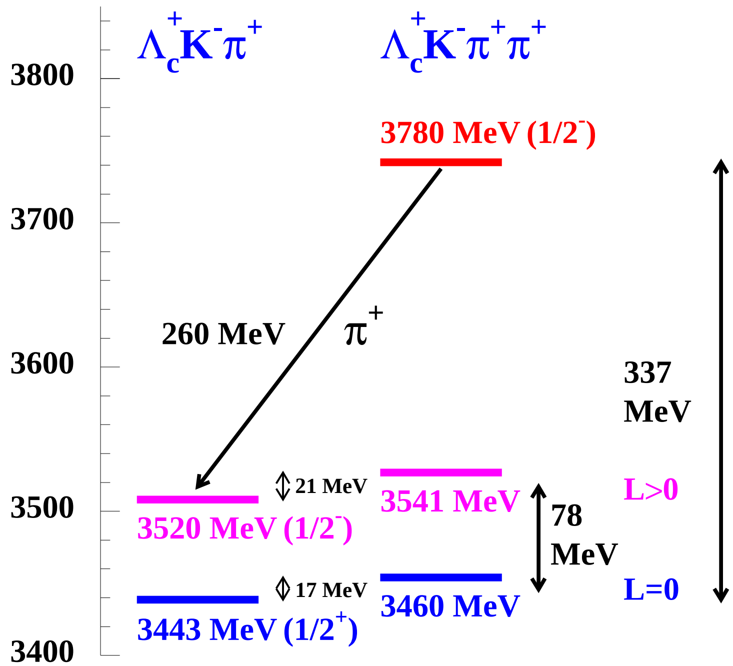
SELEX Double Charmed Baryon States

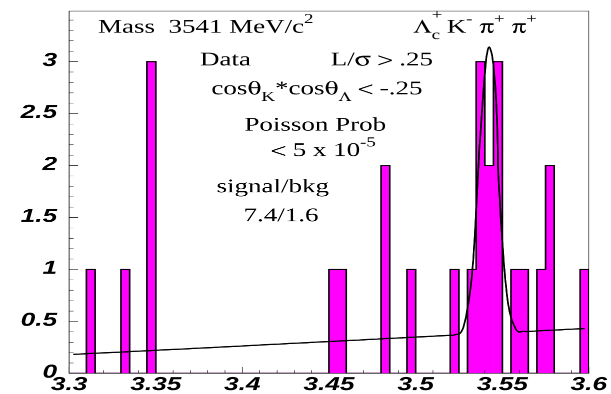


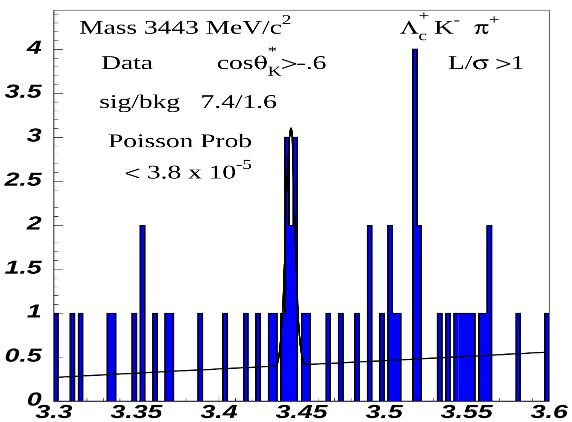
An exited state and a pair of isodoublets?

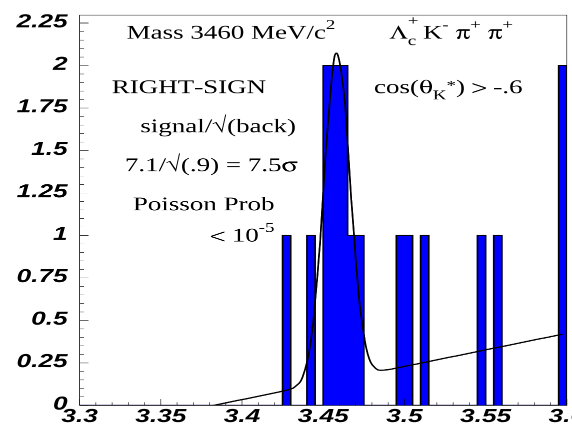












Work in San Luis Potosí on SELEX

Mostly analysis work:

- Search for exotic state decaying into $\Lambda\bar{p}\pi^+\pi^+$ (Master)
- Semileptonic decay of $\Lambda_c^+ \rightarrow pK^-e^+\nu_e$ (Ph.D., finish in $\sim$ 6 months)
- Double Charm Baryons – search and properties (Ph.D., one more year)
- Charmed Strange Baryons – properties (Ph.D., two more years)
- Hyperon Properties, production cross section and multiplicities (Licenciatura, Master)
- Search for Pentaquarks ($\Theta(1540)$ and charmed partner)

The CKM Experiment

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Theory (Standard Model): Matrix is unitary (rotation).

$$|V| = \begin{pmatrix} 0.9741 - 0.9756 & 0.219 - 0.226 & 0.0025 - 0.0048 \\ 0.219 - 0.226 & 0.9732 - 0.9748 & 0.038 - 0.044 \\ 0.004 - 0.014 & 0.037 - 0.044 & 0.9990 - 0.9993 \end{pmatrix}$$

Wolfenstein parameterization:

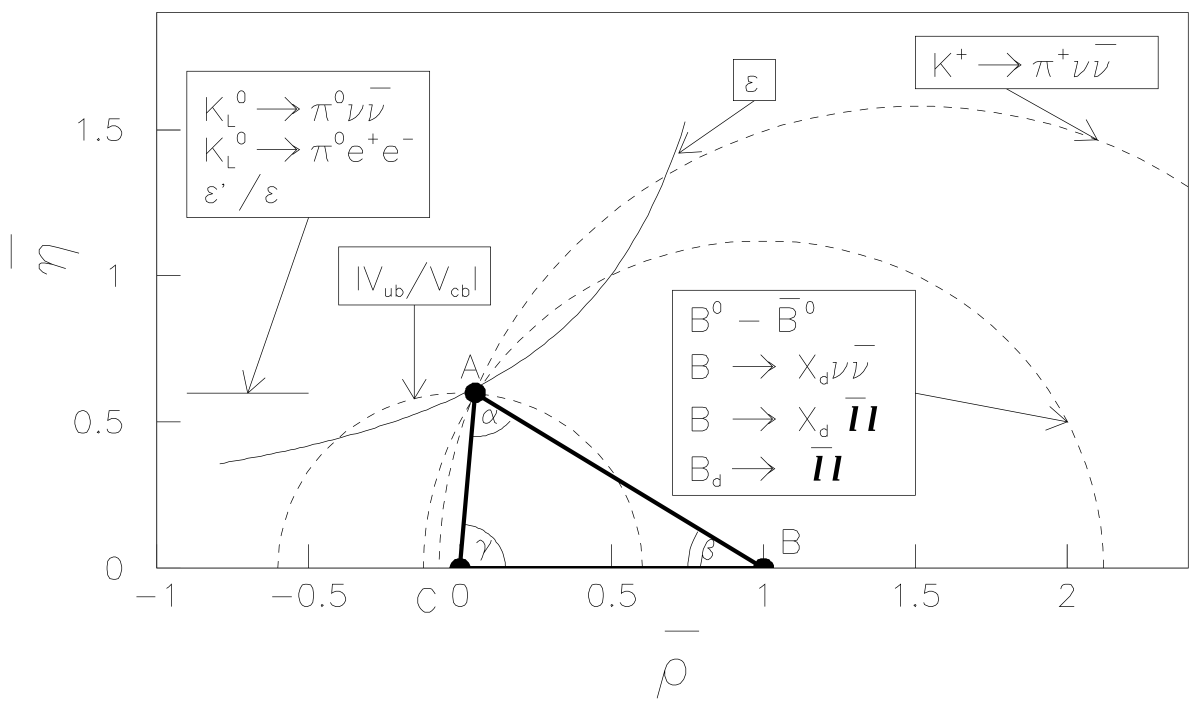
$$V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parameterization:

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\bar\rho = \rho(1-\frac{\lambda^2}{2})$$

$$\bar\eta = \eta(1-\frac{\lambda^2}{2})$$



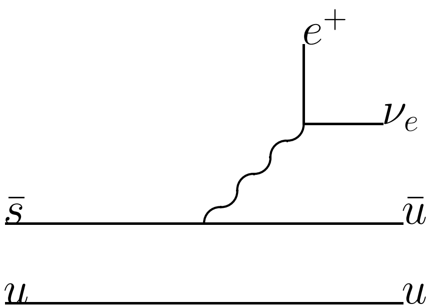
Quantitative Access to CKM parameters

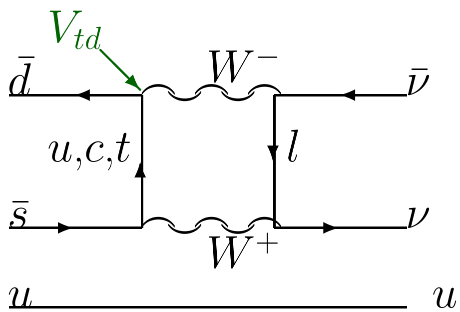
- Goal is to test the Standard Model hypothesis that a single phase in the CKM matrix is the sole source of CP violation.
- This means *over-constraining* the prediction, and testing for consistency. Paraphrasing Wolfenstein: "…I invented the parameters ρ and η, and I don't care what the values are so why should you?? The substance here is to *over-constrain* the model and test for consistency…"[2]
- To falsify the Standard Model hypothesis the only foreseeable results with controlled errors are:
  - B physics: $B_d^0 \to \Psi K_s$, x_s/x_d mixing.
  - K physics: $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0 \to \pi^0\nu\bar{\nu}$.

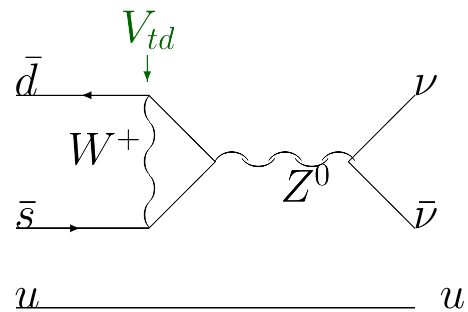
[2] Wolfenstein at Kaon'99

$K^+ \to \pi^+ \nu\bar{\nu}$ Theory

Calculated[3] by weak isospin rotation from $K^+ \to \pi^0 e^+ \nu$







$$\frac{B(K^+ \to \pi^+ \nu\bar{\nu})}{B(K^+ \to \pi^0 e^+ \nu)} = \frac{3\alpha^2}{8\pi^2 \sin^4 \theta_W} |V_{cs}^* V_{cd} D(X_c) + V_{ts}^* V_{td} D(X_t)|^2 \frac{1}{|V_{us}|^2}$$

$$D(X) = \frac{1}{8}\{1 + \frac{3}{(1-X)^2} - \frac{(4-X)^2}{(1-X)^2}\} X ln(X) + \frac{X}{4} - \frac{3X}{4(1-X)}$$

$$X_j = \{\frac{m_j}{m_W}\}^2; \quad j = c, t.$$

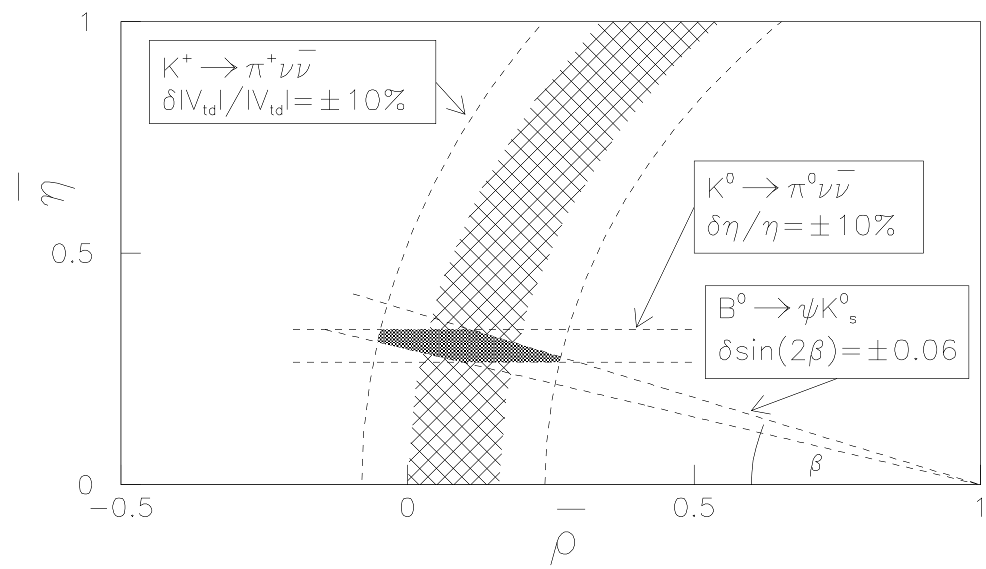
$$\begin{aligned} Br[K^+ \to \pi^+ \nu\bar{\nu}] &= 0.55 \times 10^{-10}[(1.35 - \bar{\rho})^2 + (1.05\bar{\eta})^2] \\ &= (0.72 \pm 0.21) \times 10^{-10} \end{aligned}$$

[3] T. Inami and C.S. Lim, Progress of Theoretical Physics **65** (1981) 297-314

$K^+ \to \pi^+\nu\bar{\nu}$ Theory (cont.)

- Total theoretical uncertainty of 8 % estimated by Buras, et al.[4]
- Dominated by uncertainty in charmed quark mass.
- Structure of K^+ is put in with measured $K^+ \to \pi^0 e^+ \nu$ branching ratio.
- All other corrections are small and calculated (NLO QCD, isopsin, long distance contributions).

$\Longrightarrow$ We can measure V_{td} to 10 % if we can measure $Br[K^+ \to \pi^+\nu\bar{\nu}]$ to 10 % (100 Events).



[4] A.J. Buras, hep-ph/971217

A short estimate for an inflight decay experiment

- $BR = 10^{-10}$
- 100 Events
- Acceptance $\sim 1\,\%$

$\Longrightarrow 10^{14}$ live K^+

- Duty cycle of machine $30\,\%$ (Fermilab Main Injector)
- Uptime of machine and experiment $50\,\%$
- 2 years of running time (lifetime of a graduate student)

$\Longrightarrow 30\,$MHz of K^+

In addition: Only a few background events
$\Longrightarrow$ Suppress background to 10^{-12}

Charged Kaons at the Main Injector

A Proposal for a Precision Measurement of the Decay $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ and Other Rare K^+ Processes at Fermilab Using the Main Injector

J. Frank, S. Kettell, R. Strand
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G. Britvich, V. Burtovoy, A.V. Inyakin, V. Kurshetsov, A. Kushnirenko, L.G. Landsberg,V. Molchanov, V. Obraztsov, S.I. Petrenko, V.I. Rykalin, A. Soldatov, M.M. Shapkin, O.G. Tchikilev, D. Vavilov, O. Yushchenko
Institute of High Energy Physics, Serpukhov, Russia

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Experimental Method

BIGGEST PROBLEM IS BACKGROUND

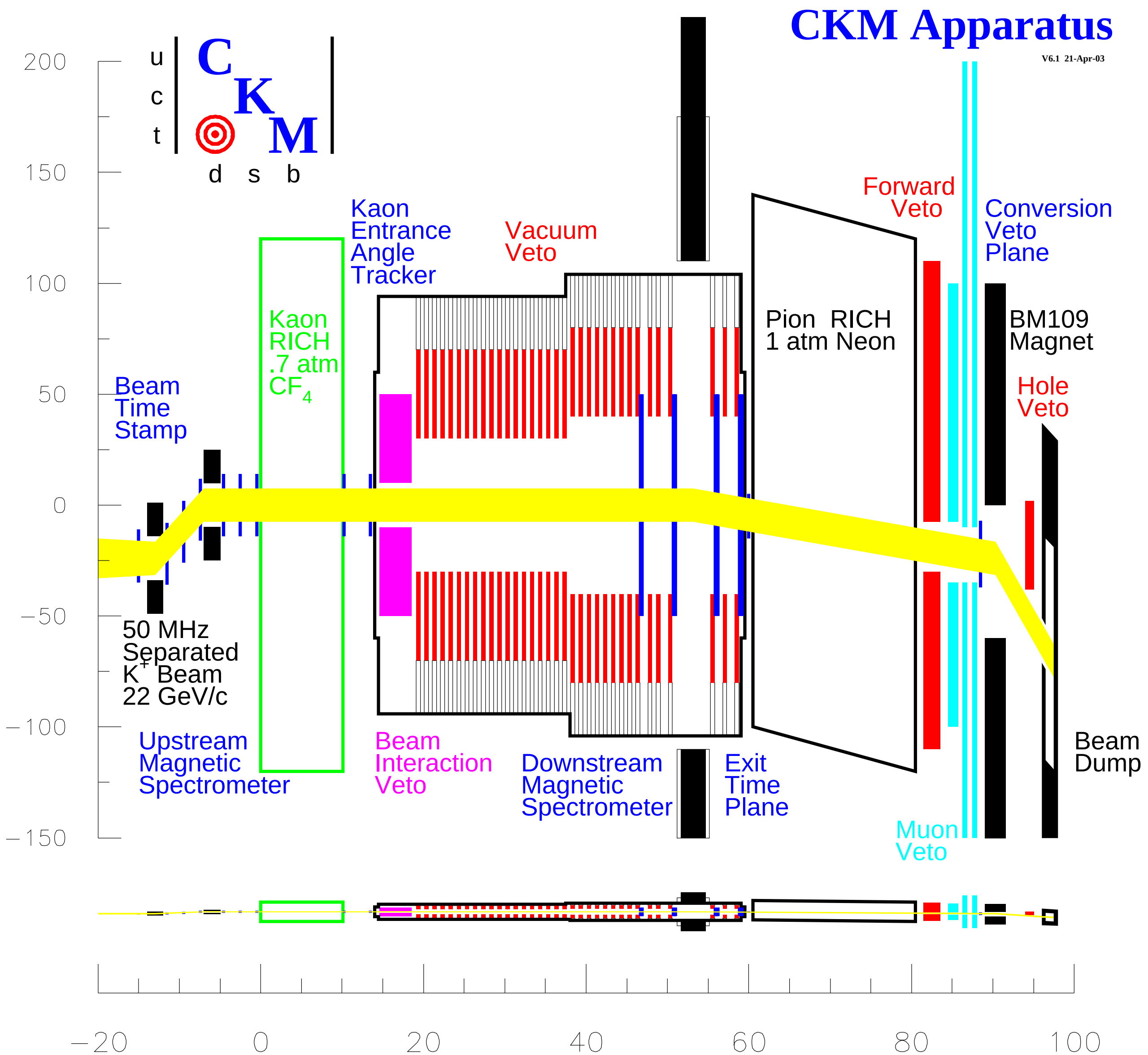
- Signal: $K^+ \to \pi^+ \nu \bar{\nu}$. Only measurable: K^+, π^+
- Biggest backgrounds: $K^+ \to \mu^+ \nu$ (64 %) and $K^+ \to \pi^+ \pi^0$ (21 %)

Calculate "Missing Mass"

$$M_{miss}^2 = M_K^2 (1 - p_\pi / p_K) + m_\pi^2 (1 - p_K / p_\pi) - p_\pi p_K \theta^2$$

For 2-body decays, M_{miss} is fixed value. For signal, M_{miss} has distribution.

- Reduce all material to minimum
- Make redundant measurements
- Use only proven detector technology


CKM Apparatus
V6.1 21-Apr-03
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Angle
Tracker
Vacuum
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Veto
Plane
Pion RICH
1 atm Neon
BM109
Magnet
Hole
Veto
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Separated
K^+ Beam
22 GeV/c
Upstream
Magnetic
Spectrometer
Beam
Interaction
Veto
Downstream
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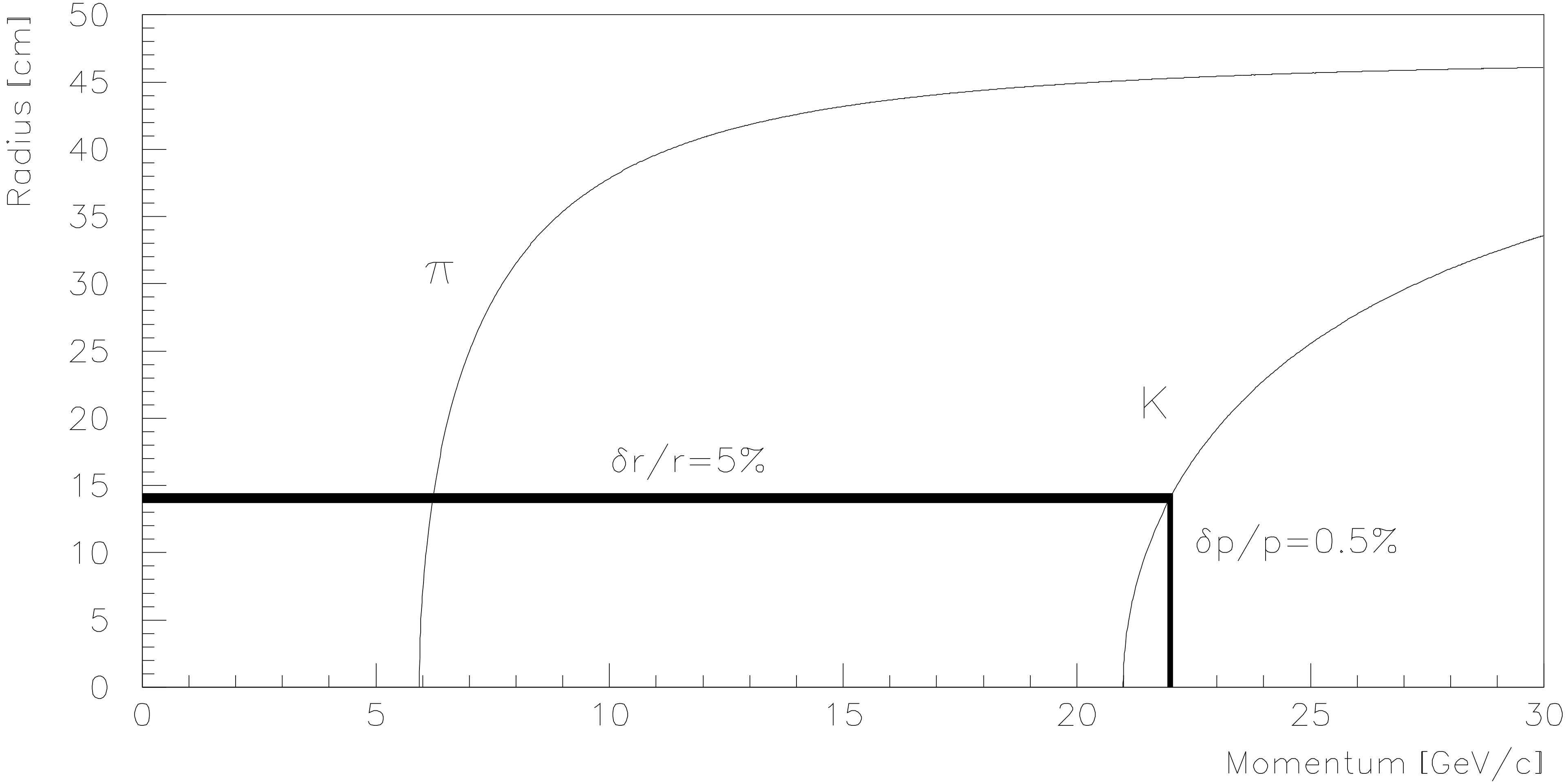
Velocity Spectrometers: 2 RICH Detectors

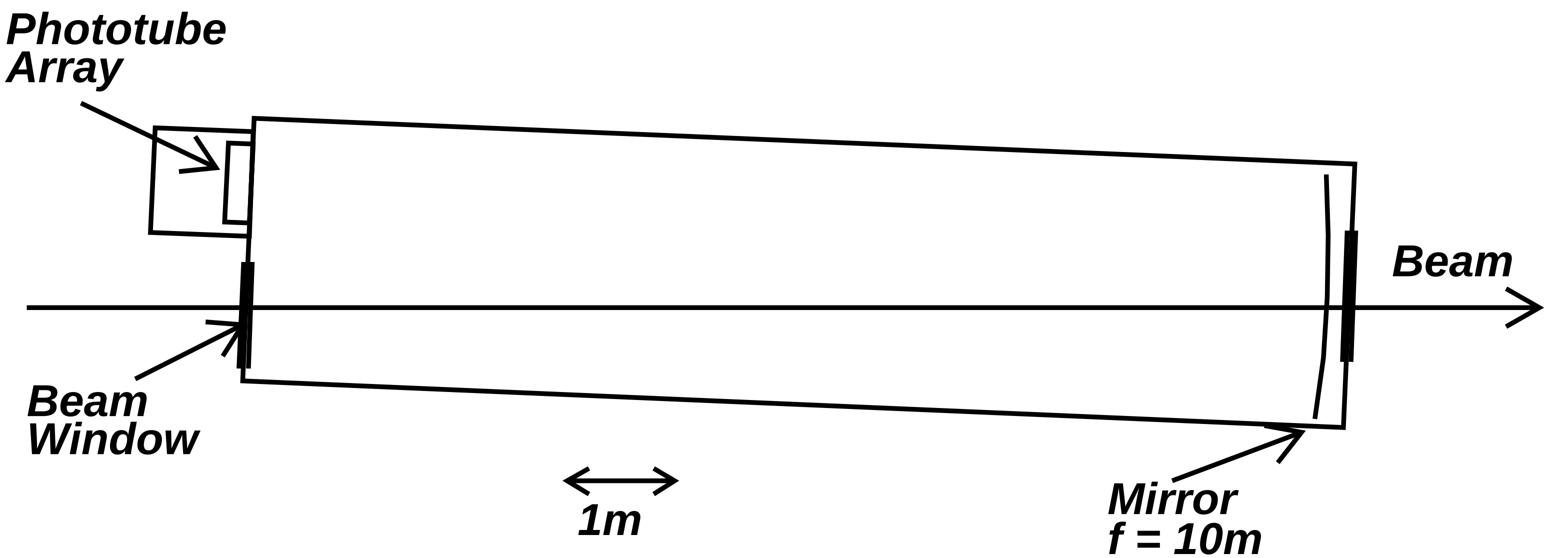


- Ring Radius depends on velocity
- Ring Center depends on track angles

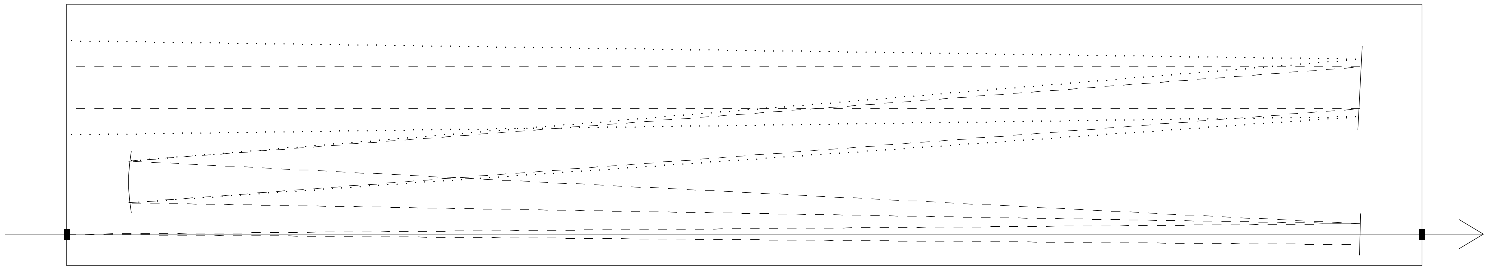
} ⟹ RICH measures vector velocity

Design of RICH Detectors

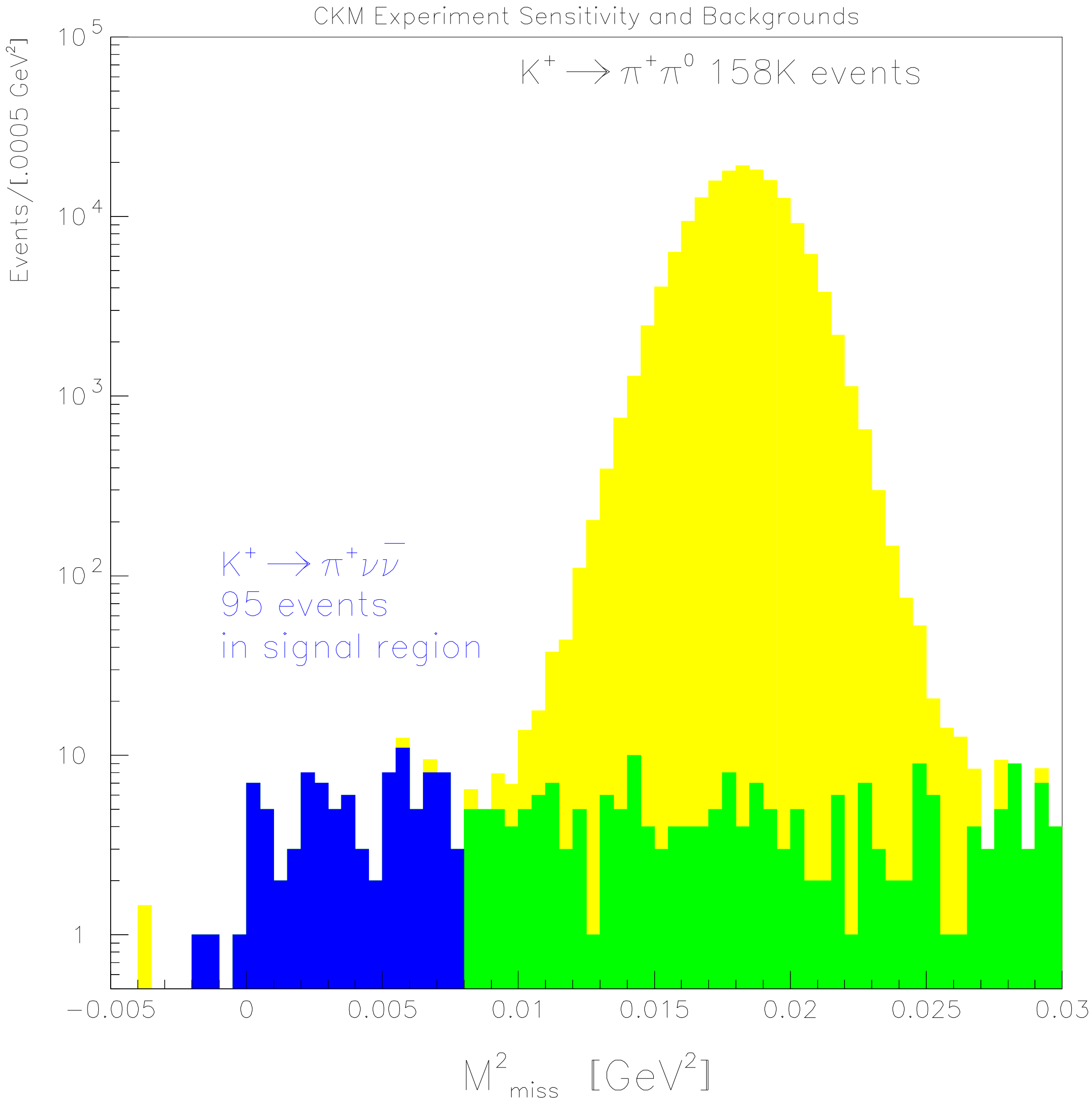
Pion RICH: Like SELEX RICH, but with 20 m Vessel



Kaon RICH: 10 m Vessel, folded light path



The Final Signal Plot



Other possible measurements

10^{-12} in single event sensitivity is a long way.
There are a lot of interesting modes to be picked up.
This list is NOT finished, and is open to more suggestions.

These are just a few examples we where thinking of:

- $K^+ \to \mu^+ \nu_\mu \gamma$ Form Factor: Test of Chiral Perturbation Theory
- $K^+ \to \pi^+ e^+ e^-$, $K^+ \to \pi^+ \mu^+ \mu^-$, Form Factor and Branching Ratio: Test of Chiral Perturbation Theory
- $K^\pm \to \pi^\pm \pi^+ \pi^-$, $K^\pm \to \pi^\pm \pi^0 \pi^0$, $K^\pm \to \pi^\pm \pi^0 \gamma$, $K^\pm \to \pi^\pm \gamma\gamma$: Test of Chiral Perturbation Theory, Search for Direct CP Violation in $K^\pm$ decays.
- $K^+ \to \pi^0 e^+ \nu$, $K^+ \to \pi^0 \mu^+ \nu$ Branching Ratio: Measurement of V_{us}

Work in San Luis Potosí

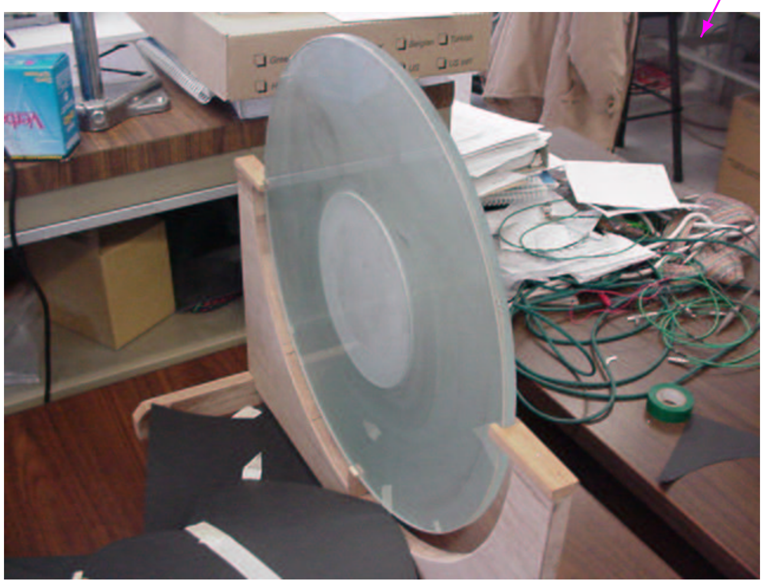
- Design work on Kaon and Pion RICH
- Monte Carlo studies
- Construction of flat, thin mirror for Kaon RICH
- Tests and Classifications of Photomultipliers
- (Maybe:) Supervision of spherical mirror production (in Mexico?)

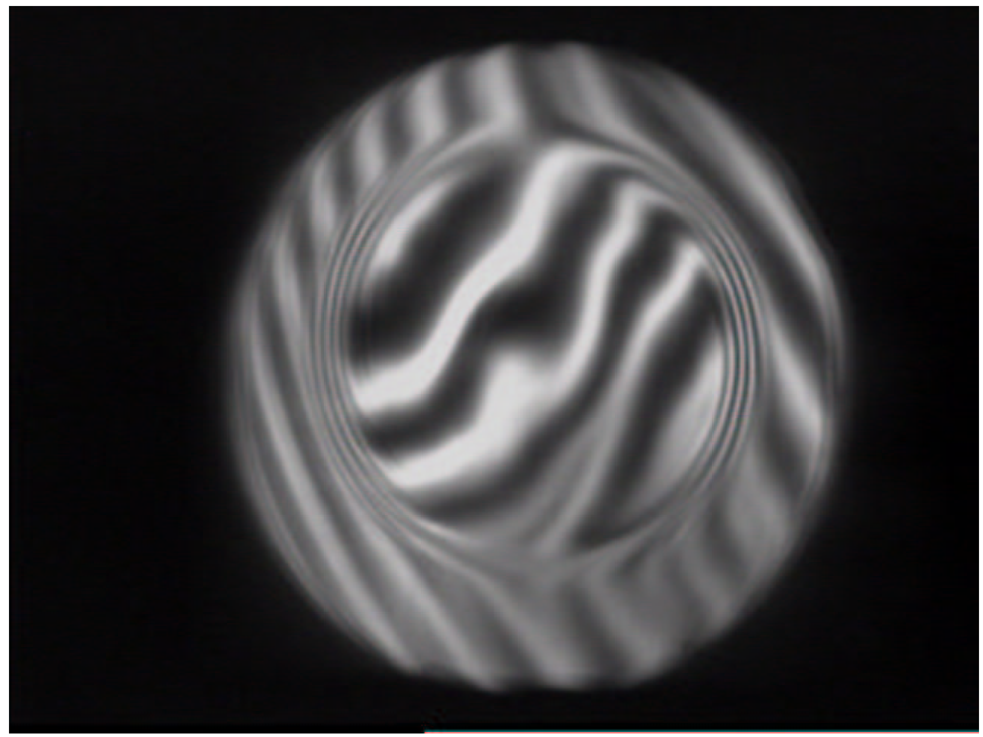
Flat Mirror Prototypes

"Good" spherical mirror to test flat mirrors

First Prototype (glass, CIO Leon)

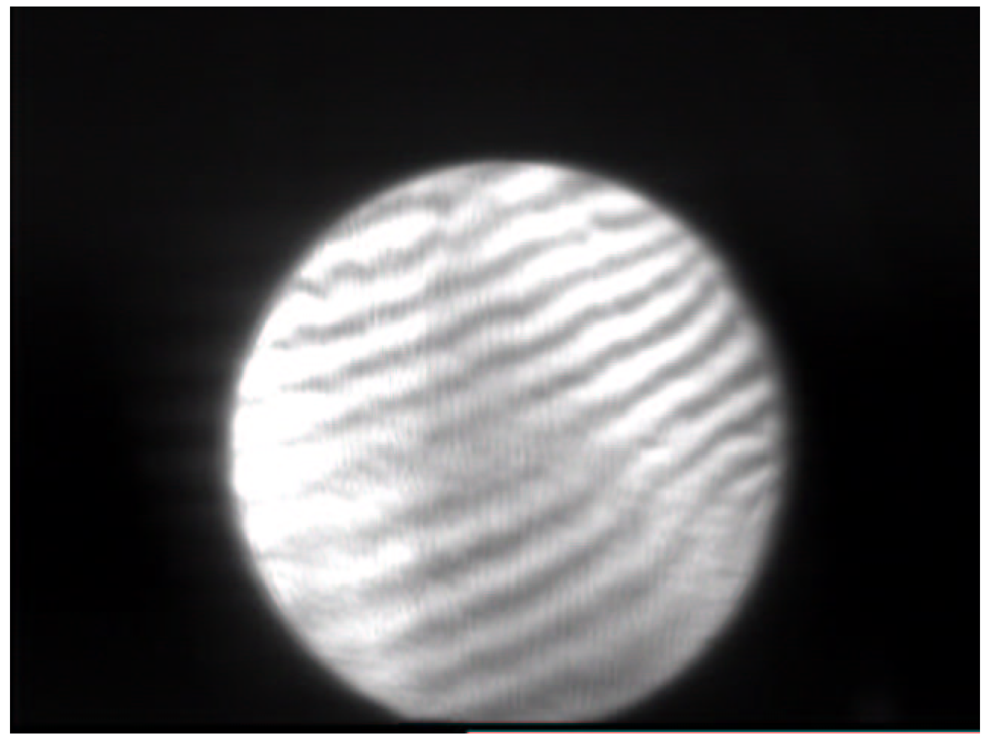
Ronchigram of first prototype





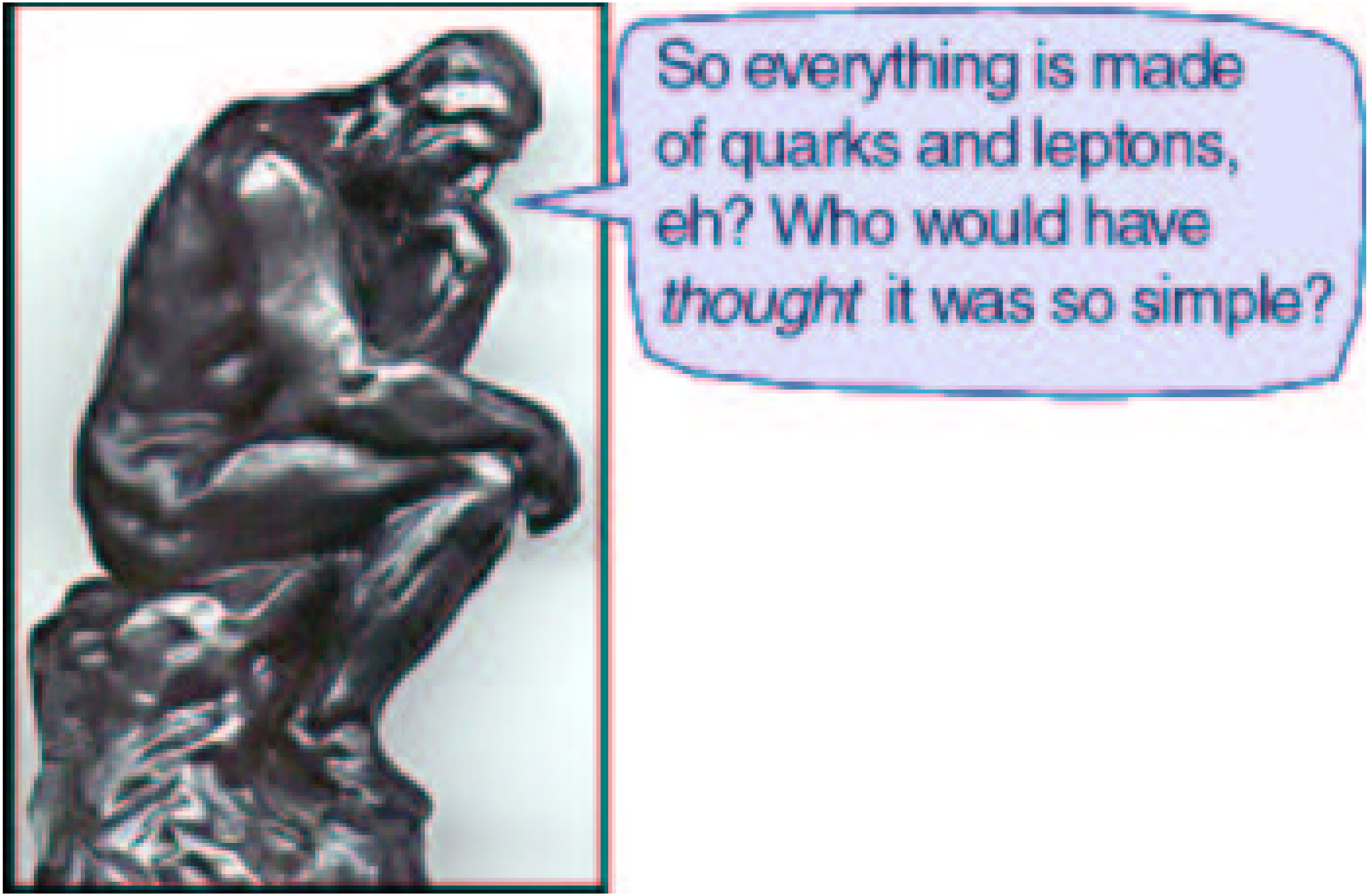
Flat Mirror Prototypes (cont.)

Second Prototype: Aluminized Mylar, Plastic Ring



Schedule CKM Experiment

- April 1996: Expression of Interest (EOI)
- April 1998: Proposal (version 1) submitted
- October 1998: Approved as an Fermilab R&D project
- October 1999: R&D project financed
- April 2001: Proposal (version 2) submitted
- June 2001: EXPERIMENT RECEIVED STAGE1 (Physics) APPROVAL from Fermilab
- September 2003: EXPERIMENT was killed by P5 committee
- Beginning 2004: Redesigning to for unseparated beam, at Fermilab or CERN
- 2004-????: Testbeams, construction
- ????-   : Data taking


So everything is made of quarks and leptons, eh? Who would have *thought* it was so simple?

My Personal List of Unanswered Questions

- Why do particles have mass? (Higgs)
- Are there other states of matter, in addition to Baryons and Mesons?
  - Quark-Gluon Plasma
  - 4-quark states, Pentaquarks
- Why is there more matter than anti-matter in the Universe? ($\mathcal{CP}$ Violation)
- What is the mass of the neutrinos?
- Why do we have exactly 3 generations?
- What is the orign of the Cosmic Rays?
- **Of what is the Universe made?**

Conclusions

- High Energy Physics is a very active field – Experimentally and Theoretically
- There are still a lot of unanswered questions
- IF-UASLP is collaborating in SELEX – mostly with data analysis
- IF-UASLP is collaborating in CKM – preparing the experiment, including hardware!
- IF-UASLP has 2 (nearly 3) theoreticians

Fermilab:	`http://www.fnal.gov`
IF-UASLP:	`http://www.ifisica.uaslp.mx`
Jurgen:	`http://www.ifisica.uaslp.mx/~jurgen`
SELEX:	`http://www-selex.fnal.gov`
CKM:	`http://www.fnal.gov/projects/ckm/Welcome.html`
RICH2004:	`http://www.ifisica.uaslp.mx/rich2004`