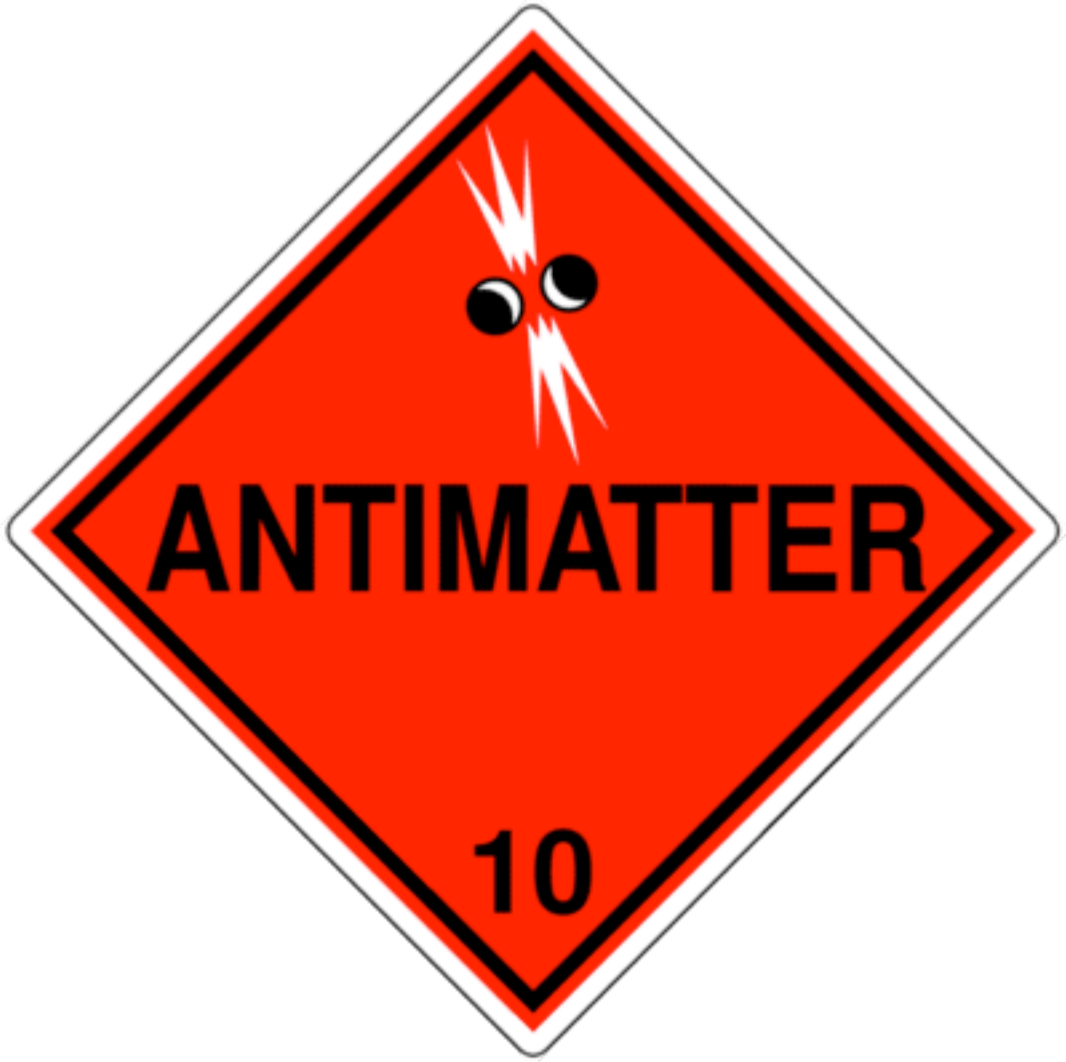
Lectures on Antimatter



Michael Doser / CERN

This is what it's all about:

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This is what it’s all about:

“abbiamo l’antimateria!”

(in the film Angels and Demons)

Overview:

1. Introduction and overview
2. Antimatter at high energies (SppS, LEP, Fermilab)
3. Meson spectroscopy (antimatter as QCD probe)

4. Astroparticle physics and cosmology
5. CP and CPT violation tests
6. Precision tests with Antimatter

7. Precision tests with Antihydrogen
8. Applications of antimatter

Acknowledgement:

These lectures contain a wide range of material, from many sources. I have endeavored to provide links to publications in many places. Some of the sources, from which slides, graphs, drawings or thoughts were liberally appropriated are in addition presentations, lectures or publications by:

Gerald Gabrielse, Eberhard Widmann, Rolf Landua, Michael Holzscheiter, and many resources from the internet, specifically those dealing with the astroparticle-physics and cosmological aspects of antimatter.

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7. Precision tests with Antihydrogen
8. Applications of antimatter

Introduction and overview

1. A bit of theory

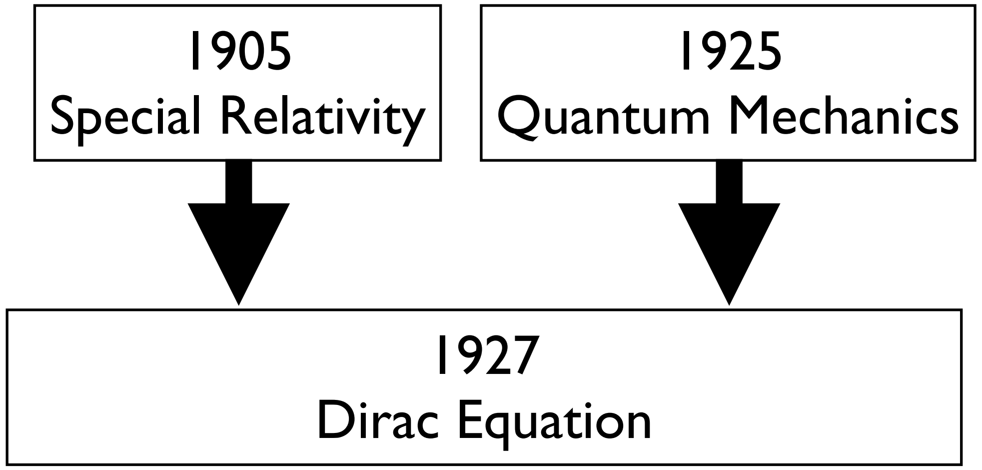
2. A bit of history

3. The making of...

1905
Special Relativity

1905
Special Relativity

1925
Quantum Mechanics


1905
Special Relativity
1925
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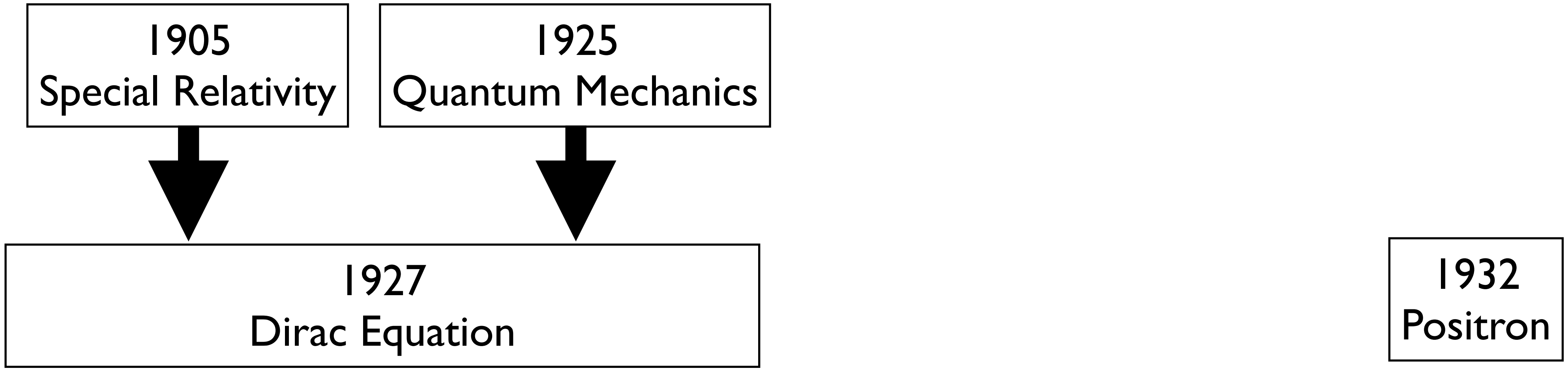
1927
Dirac Equation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1932
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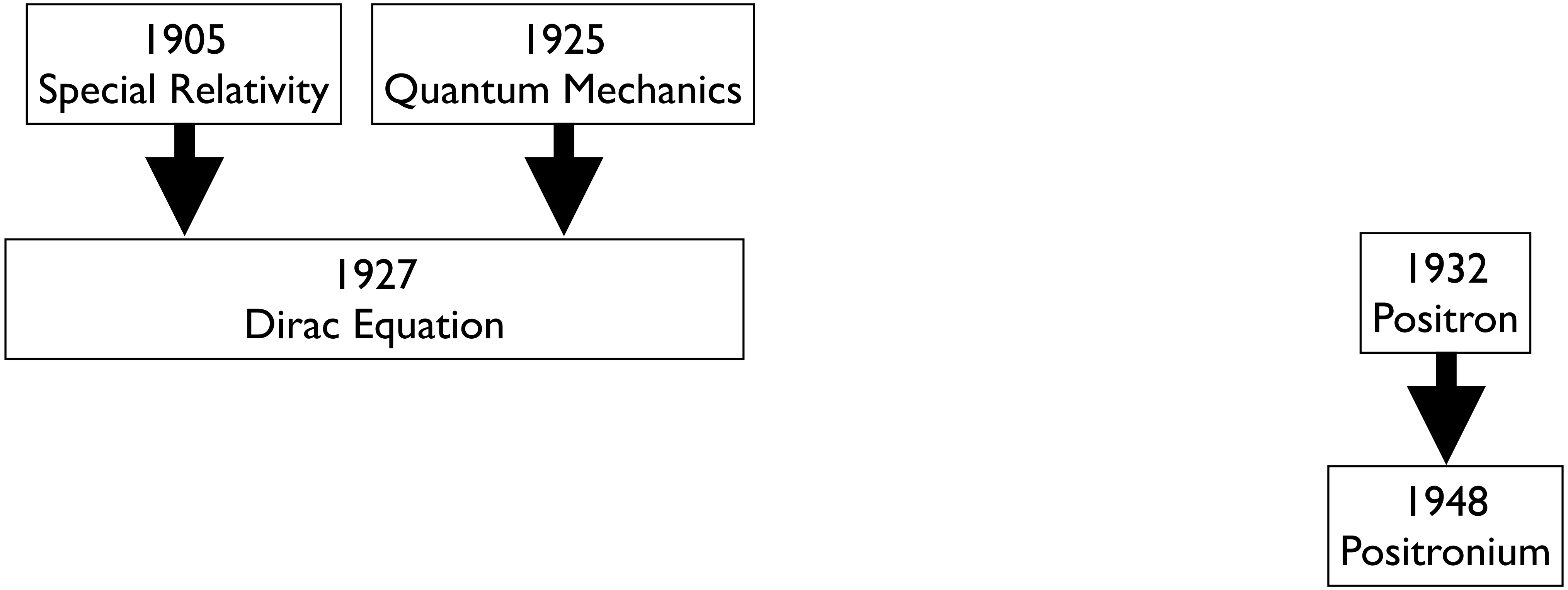
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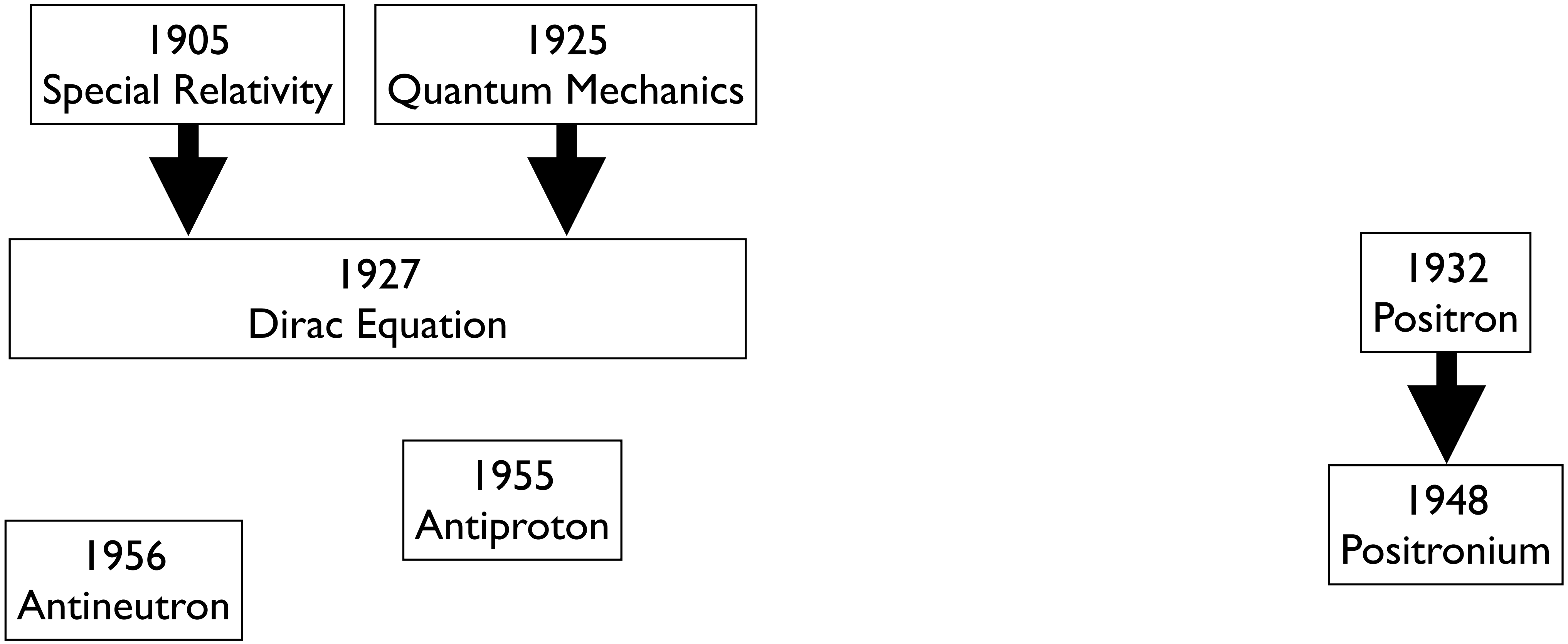
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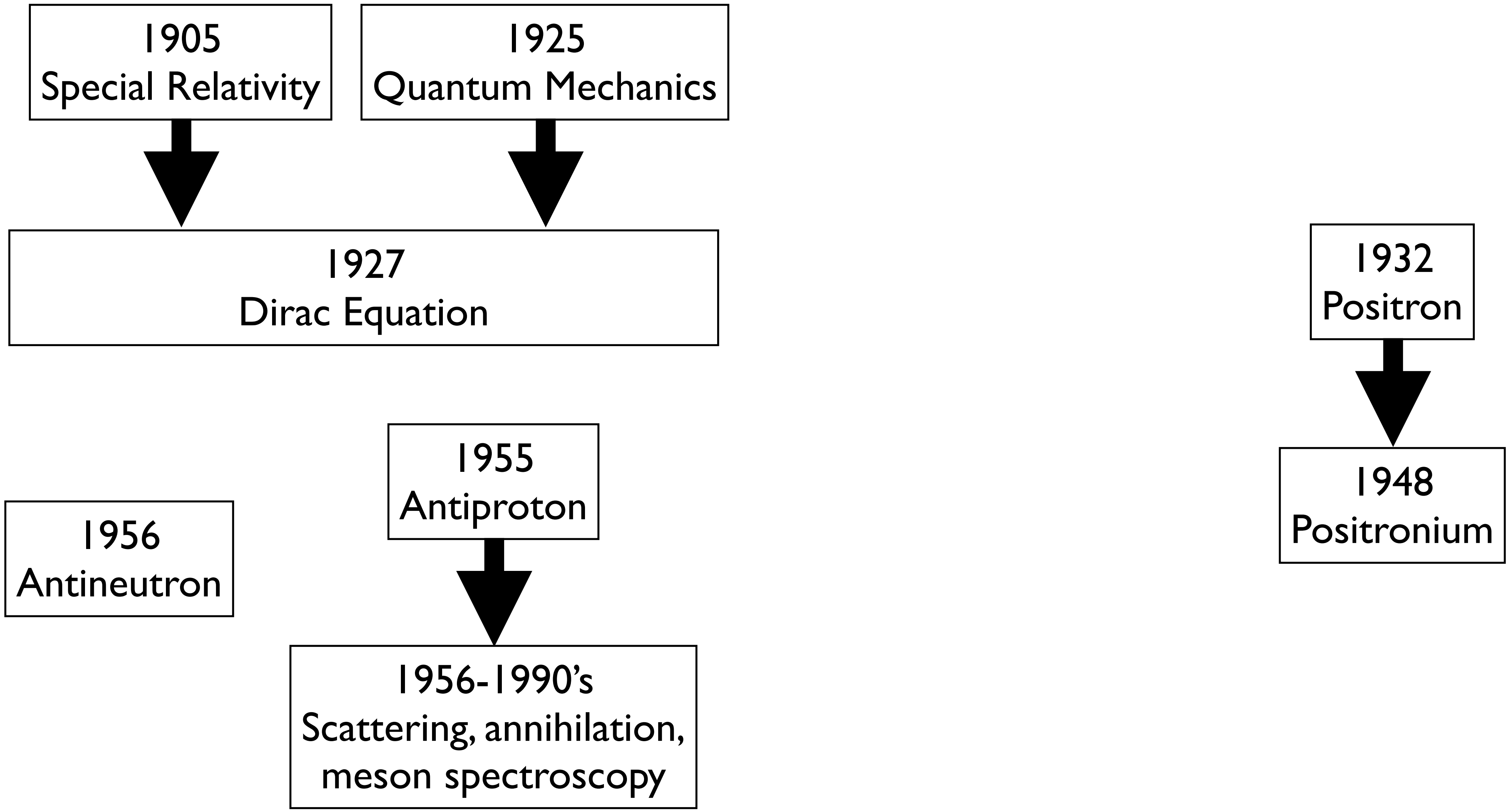
Antiproton
1956
Antineutron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1956-1990's
Scattering, annihilation, meson spectroscopy

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Scattering, annihilation, meson spectroscopy

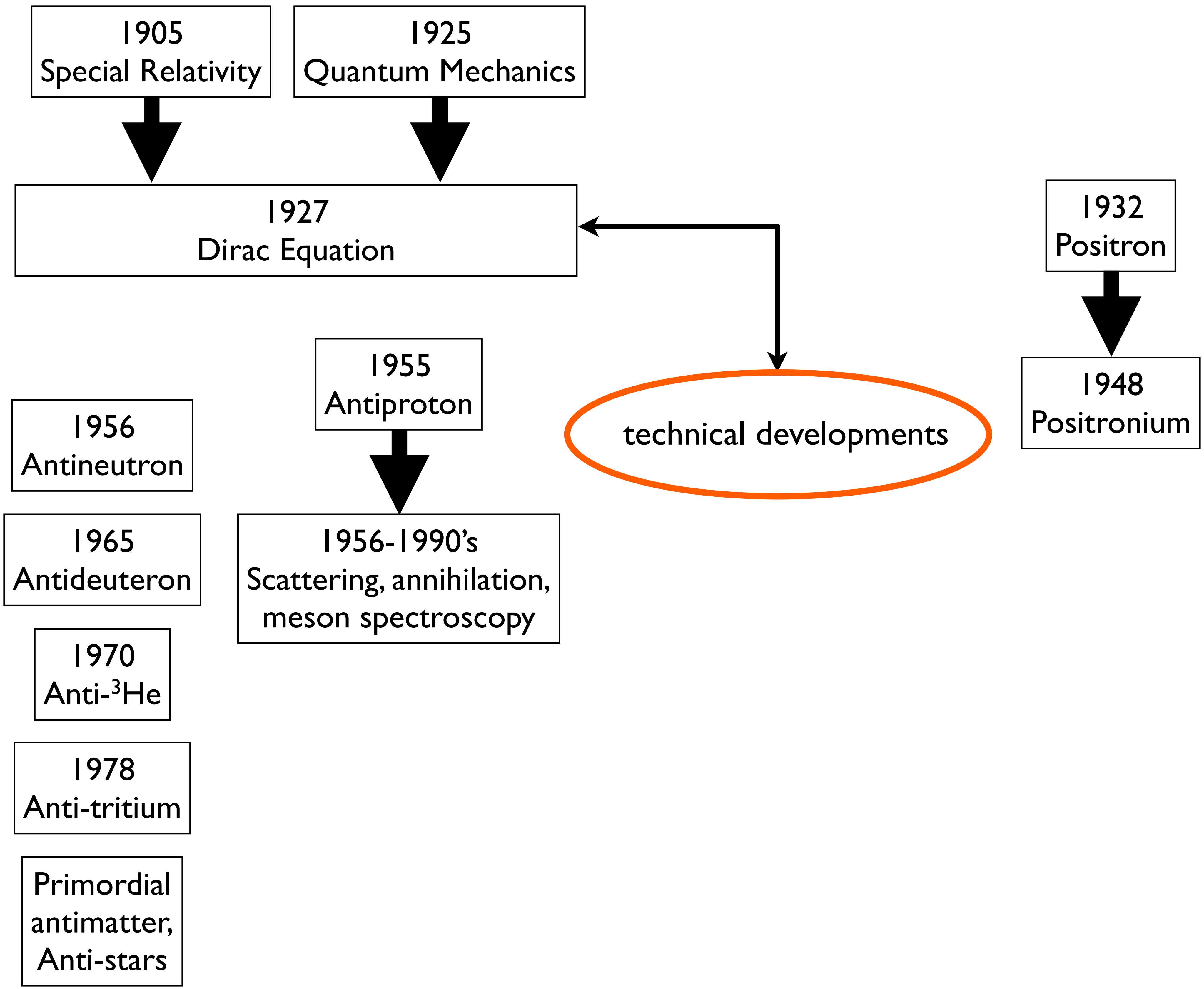
1956
Antineutron

1965
Antideuteron

1970
Anti-^{3}He

1978
Anti-tritium

Primordial antimatter, Anti-stars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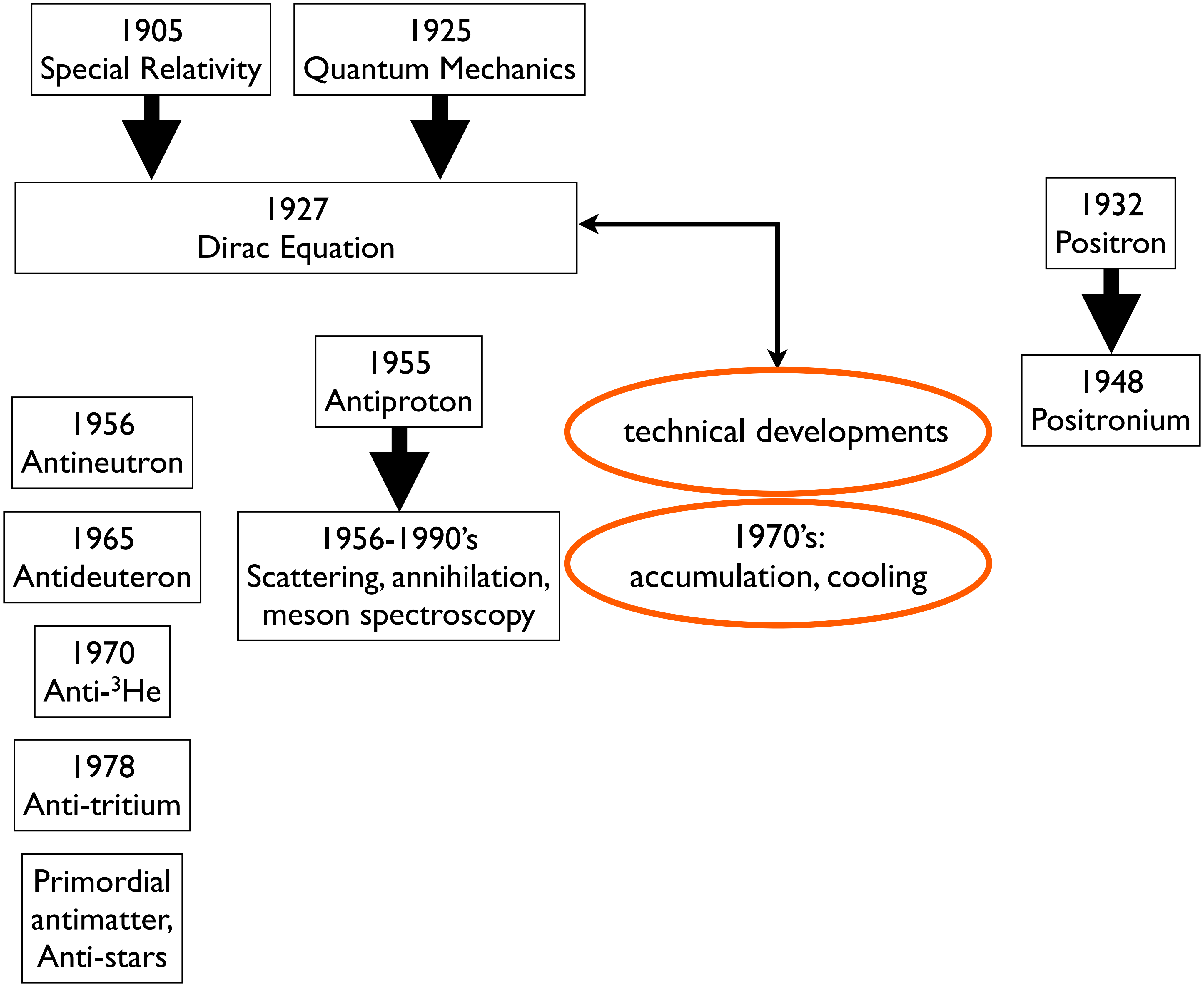
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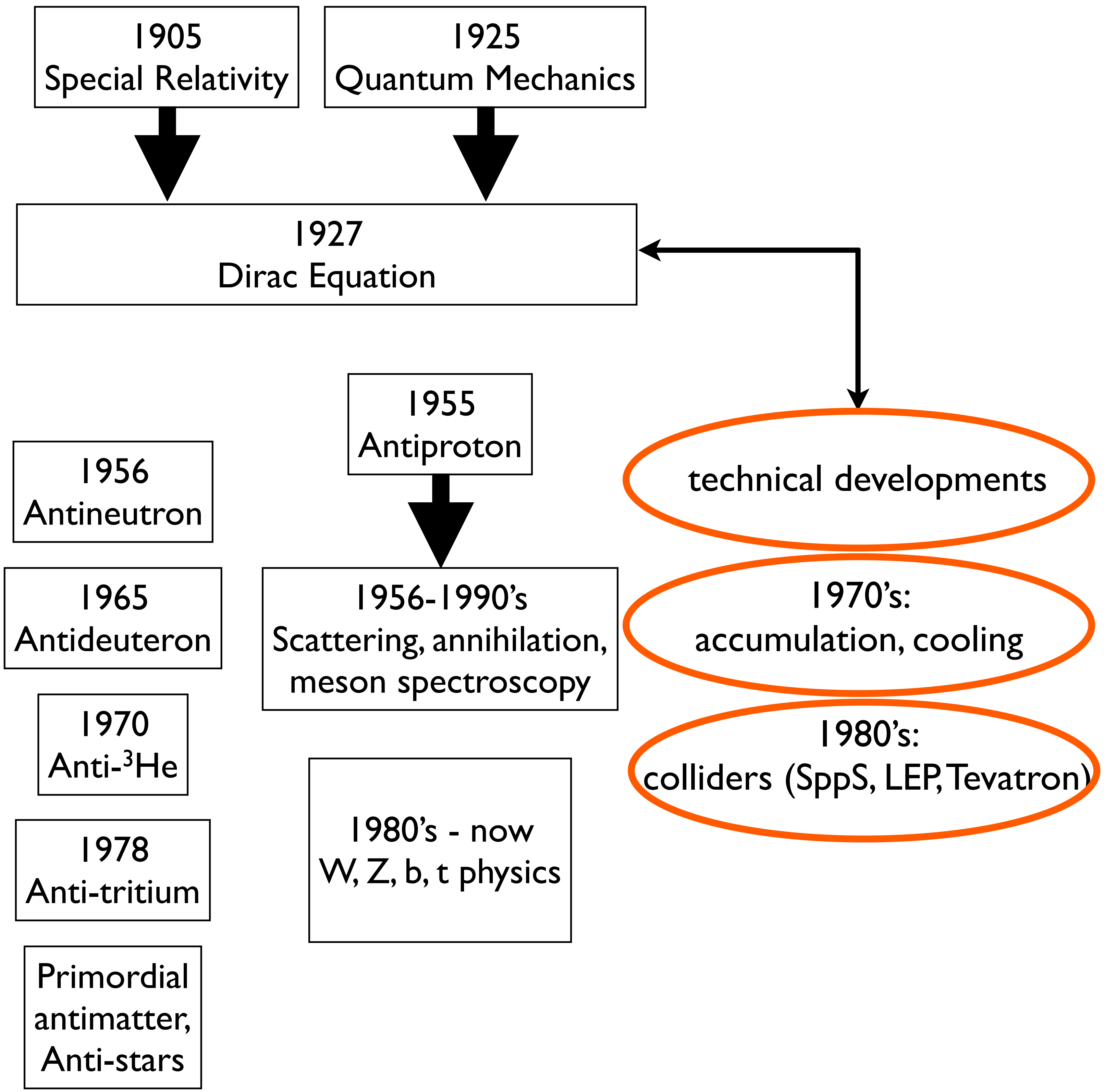
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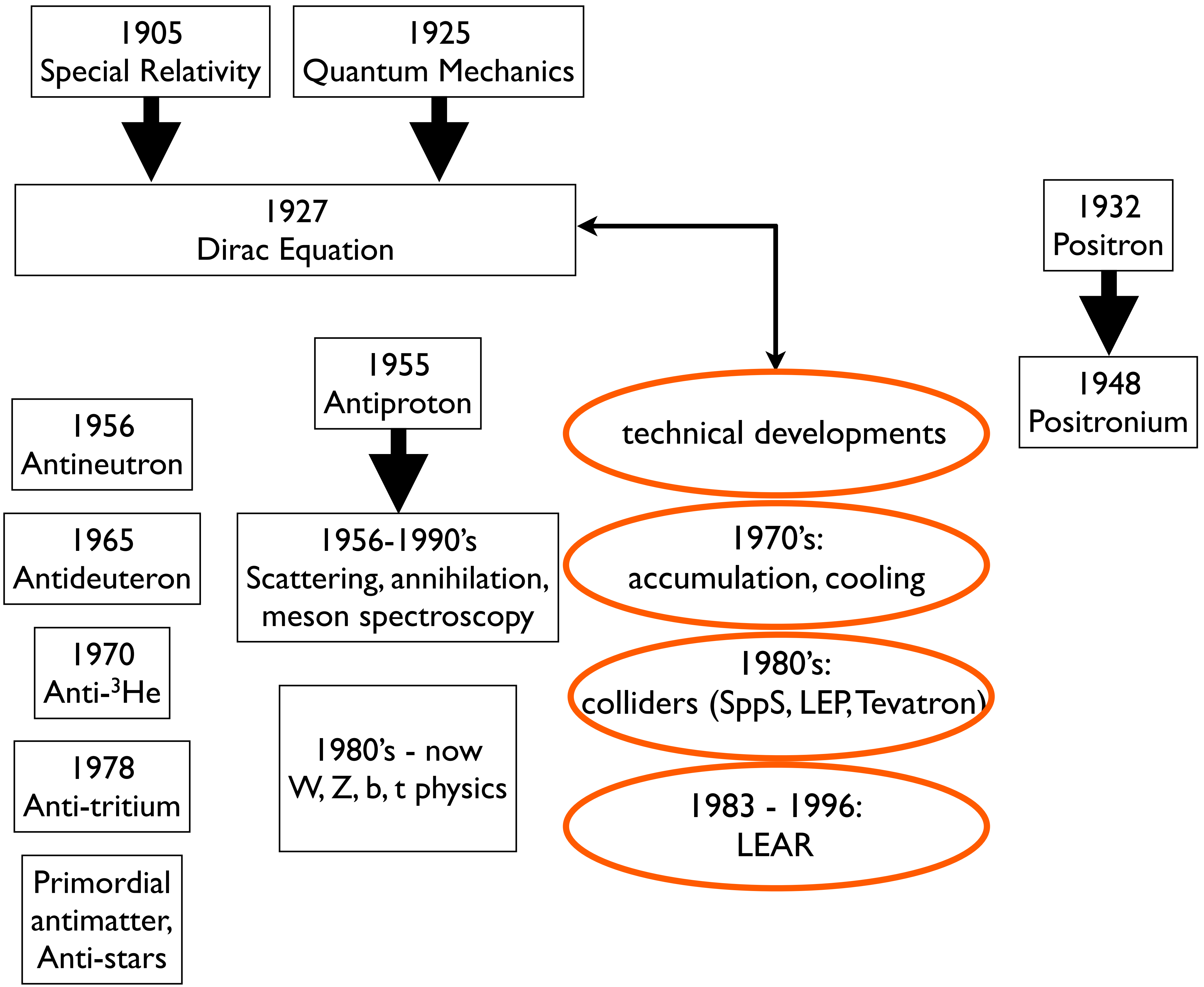
1980's - now
W, Z, b, t physics
Primordial antimatter, Anti-stars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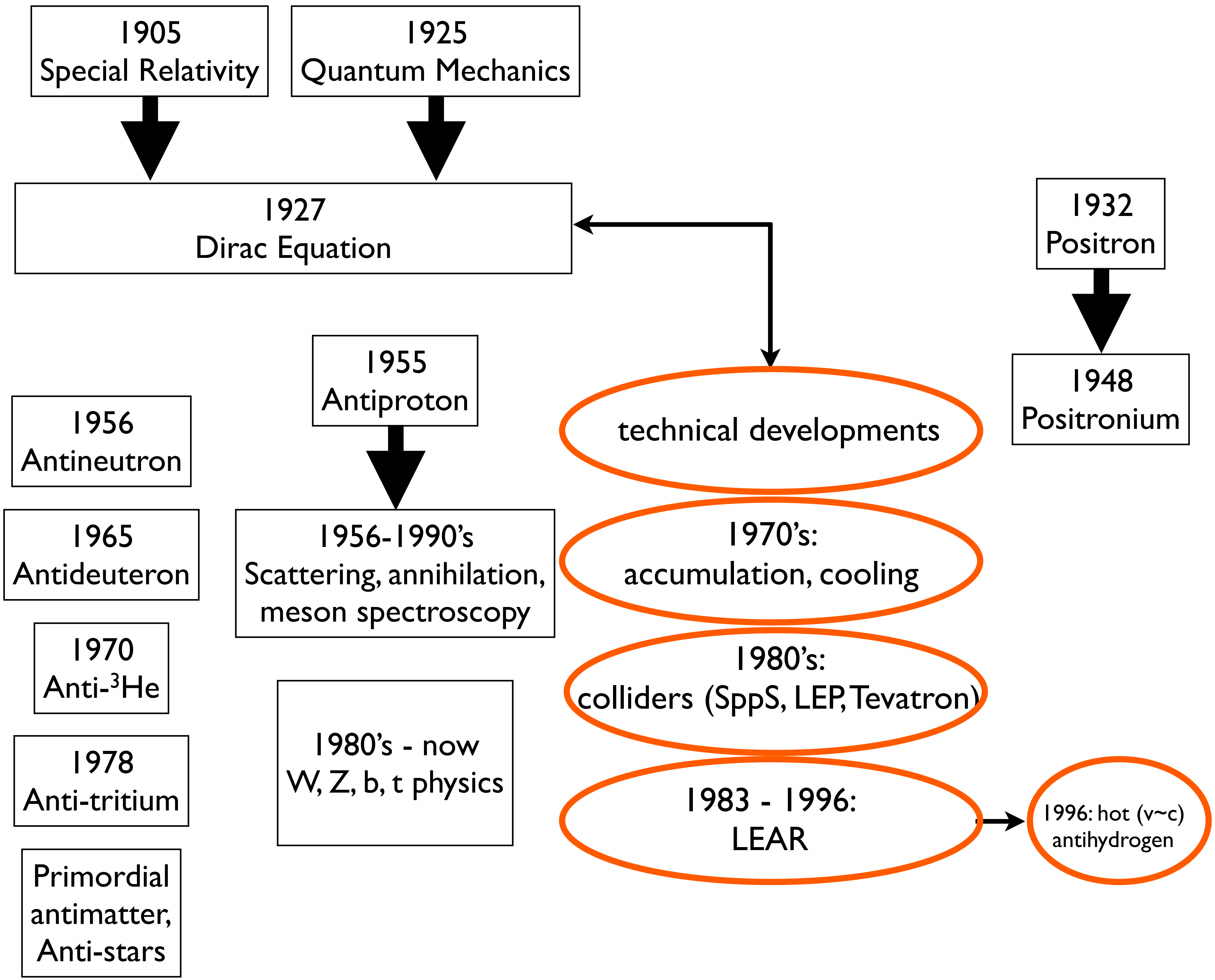
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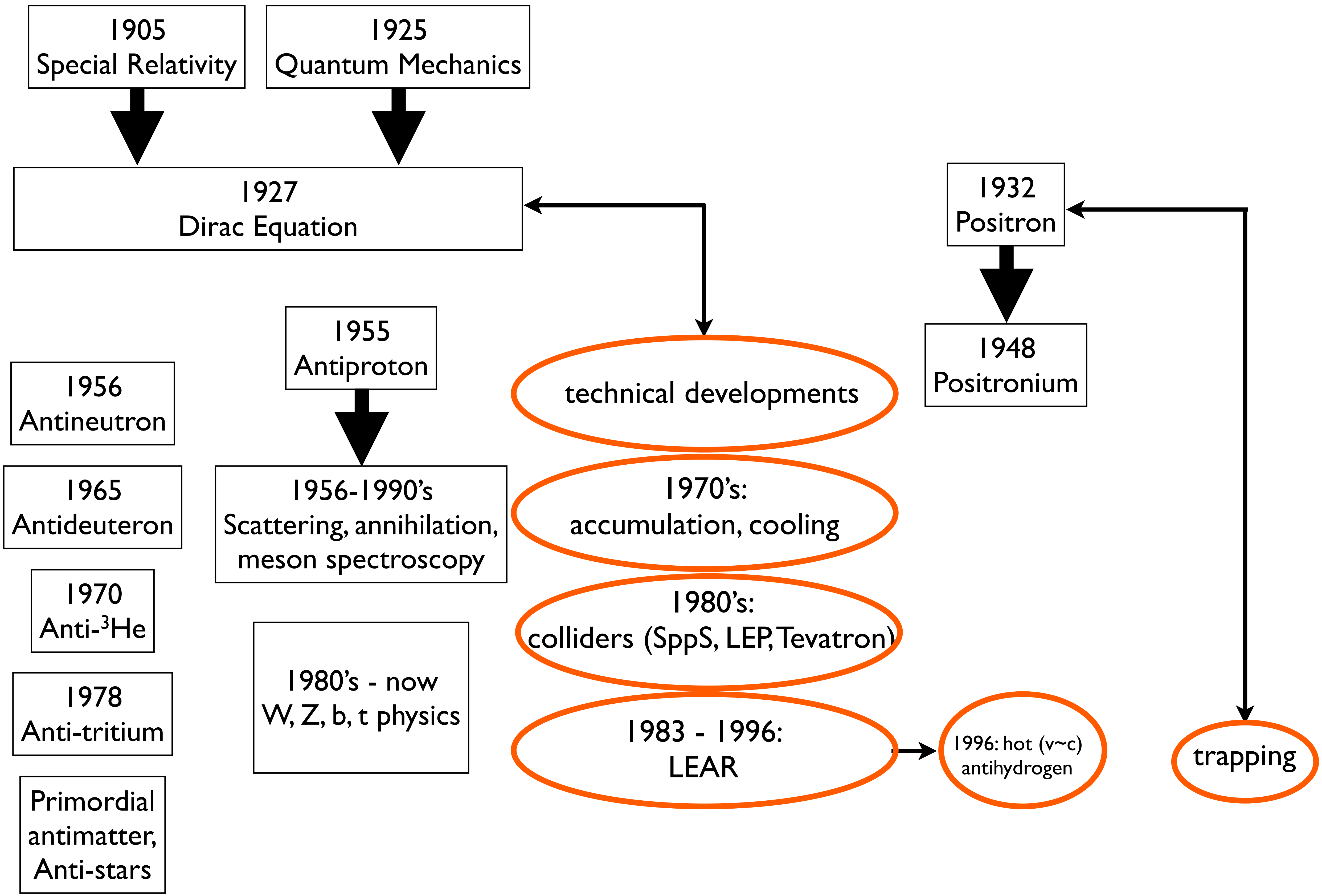
1996: hot (v~c) antihydrogen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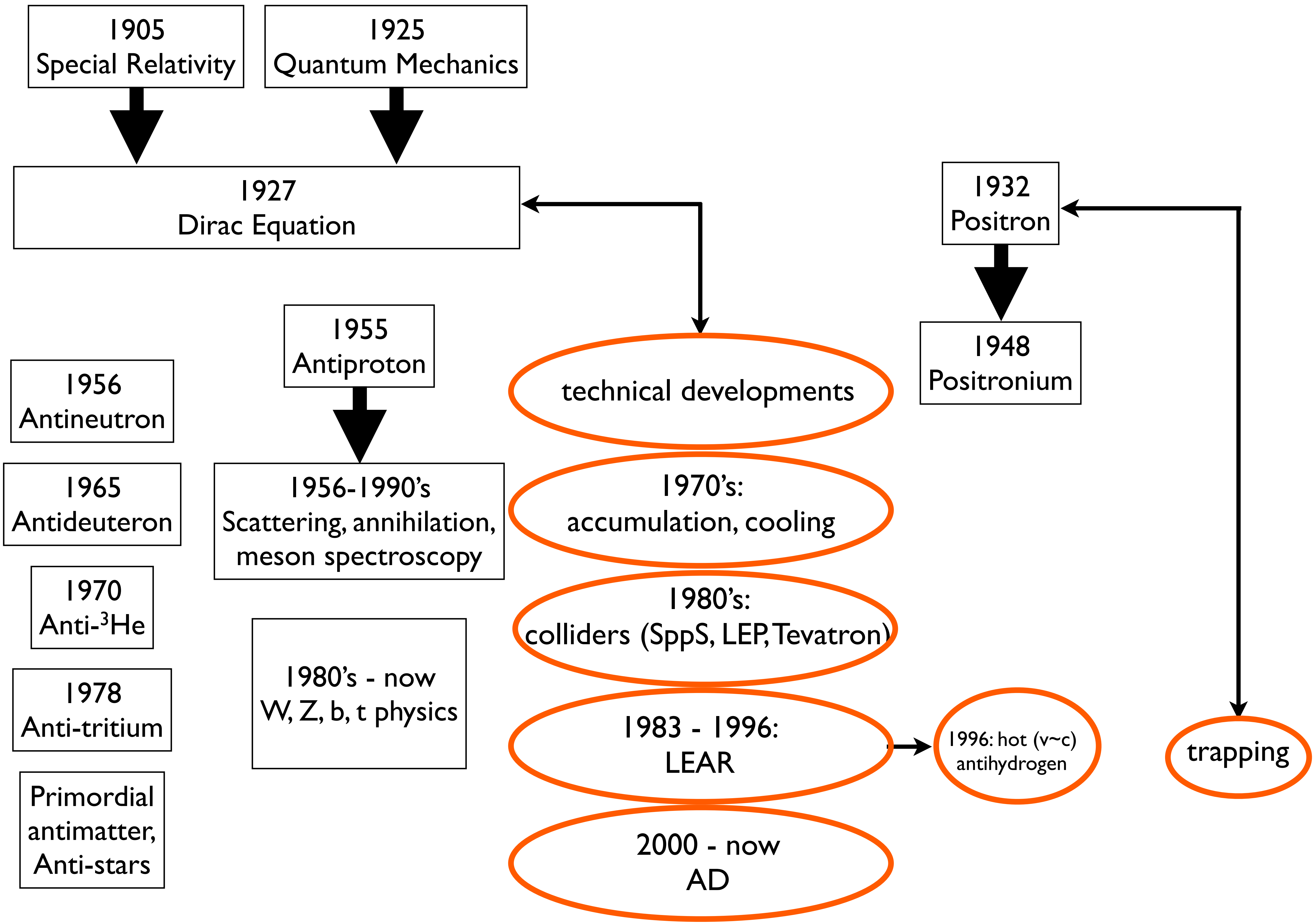
trapping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2000 - now
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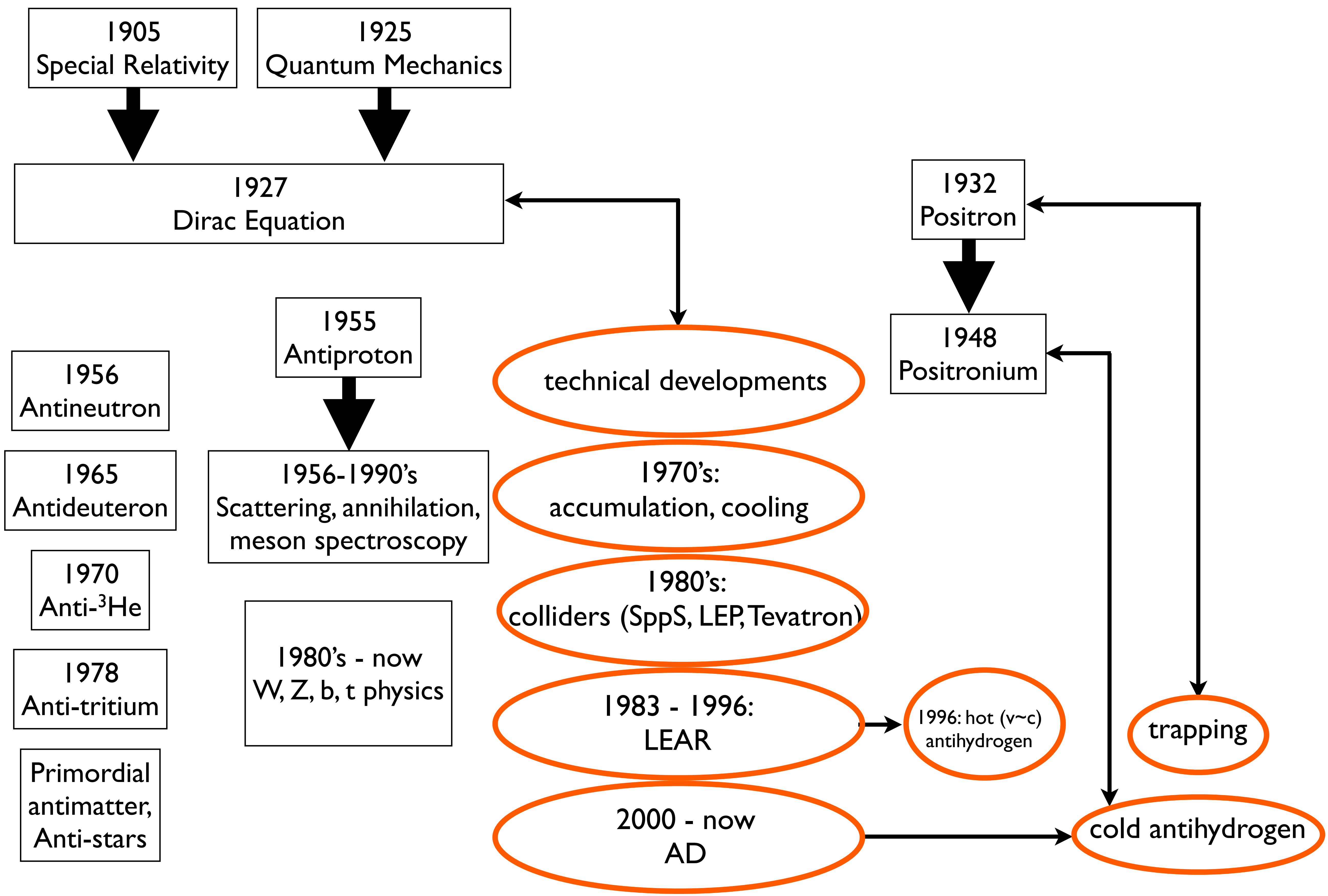
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2000 - now
AD
trapping
cold antihydrogen

Schrödinger:

classical energy-momentum relation

acts on wavefuntion $\psi(\mathbf{x}, t)$

$$E = \frac{p^2}{2m} \rightarrow \quad i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi$$

non-relativistic

$E \rightarrow i\hbar\frac{\partial}{\partial t}$

$p \rightarrow -i\hbar\nabla$

differential operators

classical energy-momentum relation

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differential operators

relativistic energy-momentum relation

Klein-Gordon:

$$E^2 = p^2 + m^2 \rightarrow -\hbar^2\frac{\partial^2}{\partial t^2}\psi = -\hbar^2\nabla^2\psi + m^2\psi$$

relativistic, spin 0
(number of particles not conserved)

classical energy-momentum relation

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energy Eigenvalues (free particle)
$E = +/- (\mathbf{p}^2+m^2)^{1/2}$

negative energy solutions with
negative probability density

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linear in $\frac{\partial}{\partial t}$ and ∇

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linear in $\frac{\partial}{\partial t}$ and ∇

general form: $$H\psi = (\boldsymbol{\alpha}\cdot\mathbf{P} + \beta m)\psi$$

classical energy-momentum relation

acts on wavefuntion $\psi(\mathbf{x}, t)$

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linear in $\frac{\partial}{\partial t}$ and ∇

general form: $$H\psi = (\boldsymbol{\alpha}\cdot\mathbf{P} + \beta m)\psi$$

energy-momentum relationship: $H^2\psi = (\mathbf{P^2} + m^2)\psi$

$$H\psi = (\boldsymbol{\alpha} \cdot \mathbf{P} + \beta m)\psi$$

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1

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1 0

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1 0 0 1

$\alpha_1, \alpha_2, \alpha_3, \beta$ anticommute with each other

$\alpha_1^2 = \alpha_2^2 = \alpha_3^2 = \beta^2 = 1$

$$H\psi = (\boldsymbol{\alpha} \cdot \mathbf{P} + \beta m)\psi$$

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lowest dim. matrices: 4x4 ; Pauli-Dirac representation

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ψ : 4-component column vector (Dirac spinor)
(E>0,+1/2);(E>0,-1/2);(E<0,+1/2);(E<0,-1/2)

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$\times\beta$

$$i\beta\frac{\partial\psi}{\partial t} = -i\beta\alpha\nabla\psi + m\psi$$

$$H\psi = (\boldsymbol{\alpha}\cdot\mathbf{P} + \beta m)\psi$$

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$\times\beta$

$$i\beta\frac{\partial\psi}{\partial t} = -i\beta\alpha\nabla\psi + m\psi$$

$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

$$H\psi = (\boldsymbol{\alpha} \cdot \mathbf{P} + \beta m)\psi$$

$$H^2\psi = (\mathbf{P^2} + m^2)\psi$$

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relativistic, spin 1/2
(number of particles conserved)

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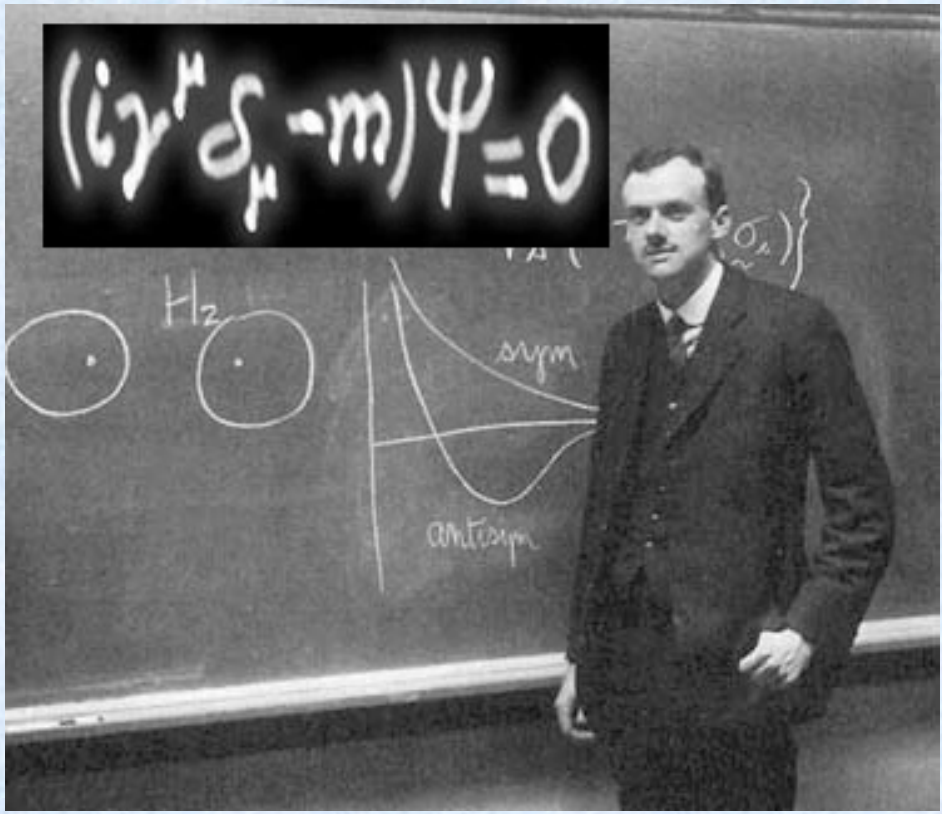

$\times\beta$

$$i\beta\frac{\partial\psi}{\partial t} = -i\beta\alpha\nabla\psi + m\psi$$

$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

Benefit of hindsight: Quantum Field Theory

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The electron (field) is no longer described by a wave function but an operator that creates and destroys particles. All energies are positive.

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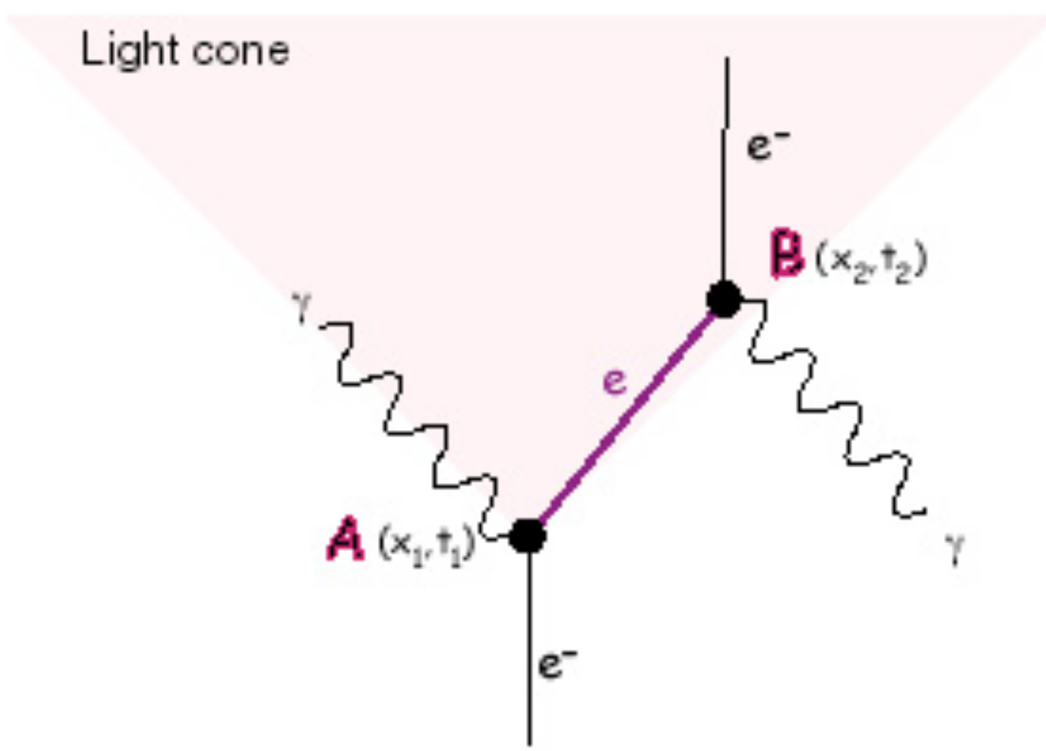

Observer #1 : A happens before B

Benefit of hindsight: Quantum Field Theory

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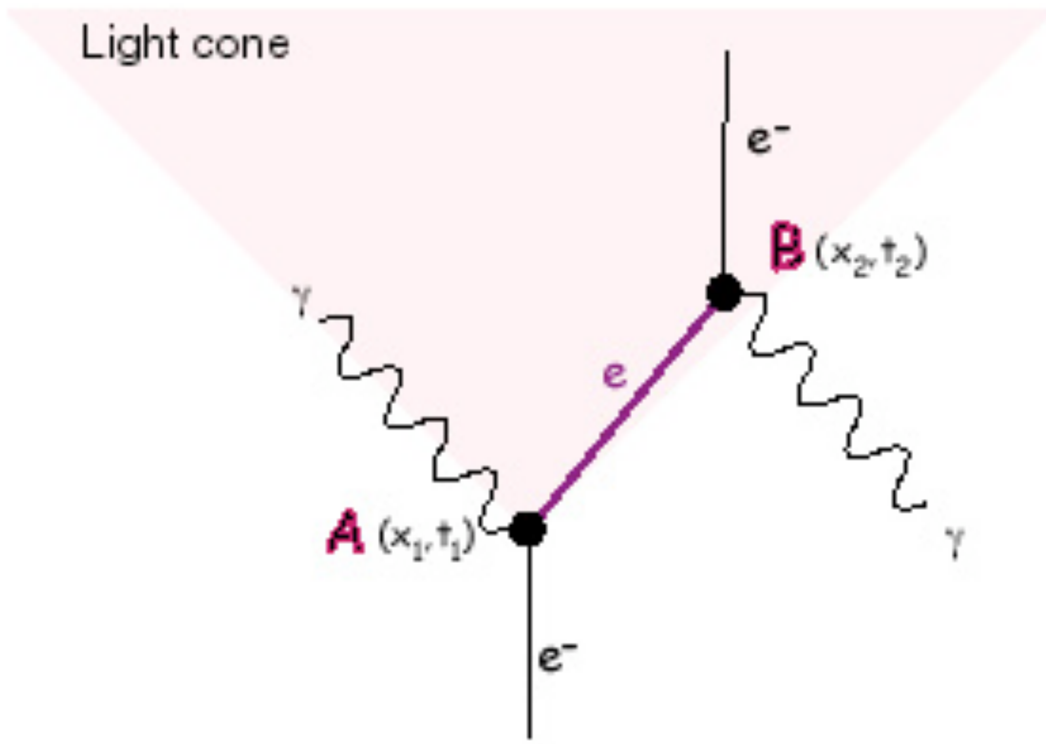

Observer #1 : A happens before B

An electron can emit a photon at A, propagate a certain distance, and then absorb another photon at B.

Wave function only localized within Compton wave length ($\lambda \sim 1/m$).

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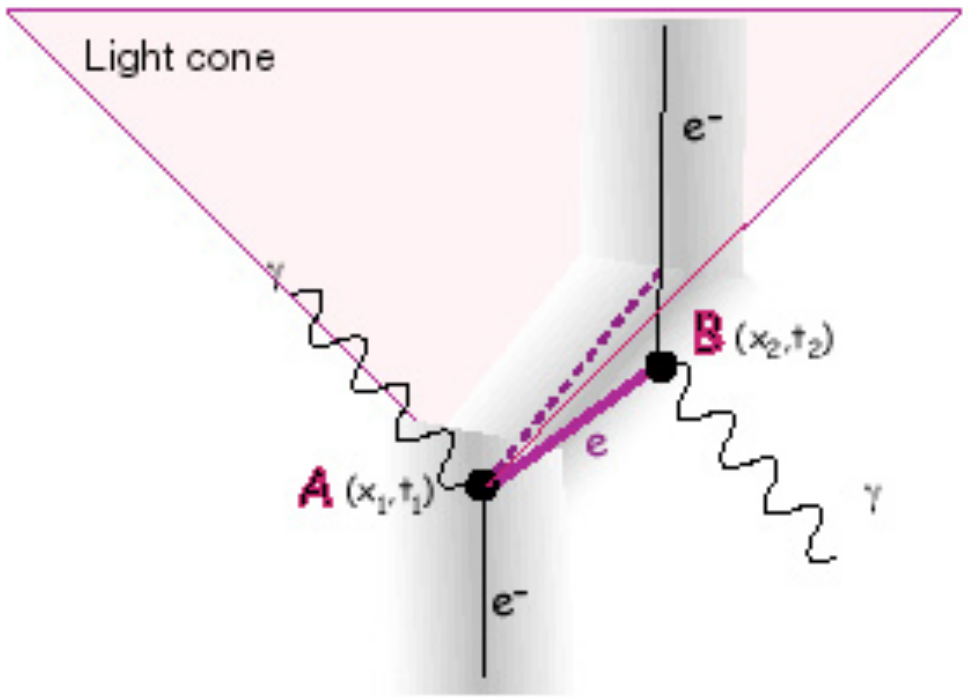
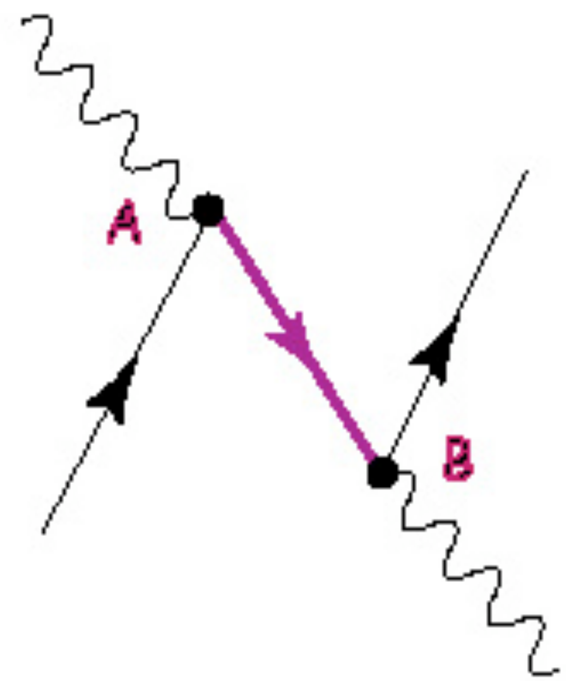


Quantum relativity: electron wave function can be **outside the light cone** (Compton wave length $l = h/m_e c$)



For a moving observer, event B can therefore happen before event A. The process at B is then interpreted as 'pair creation'.

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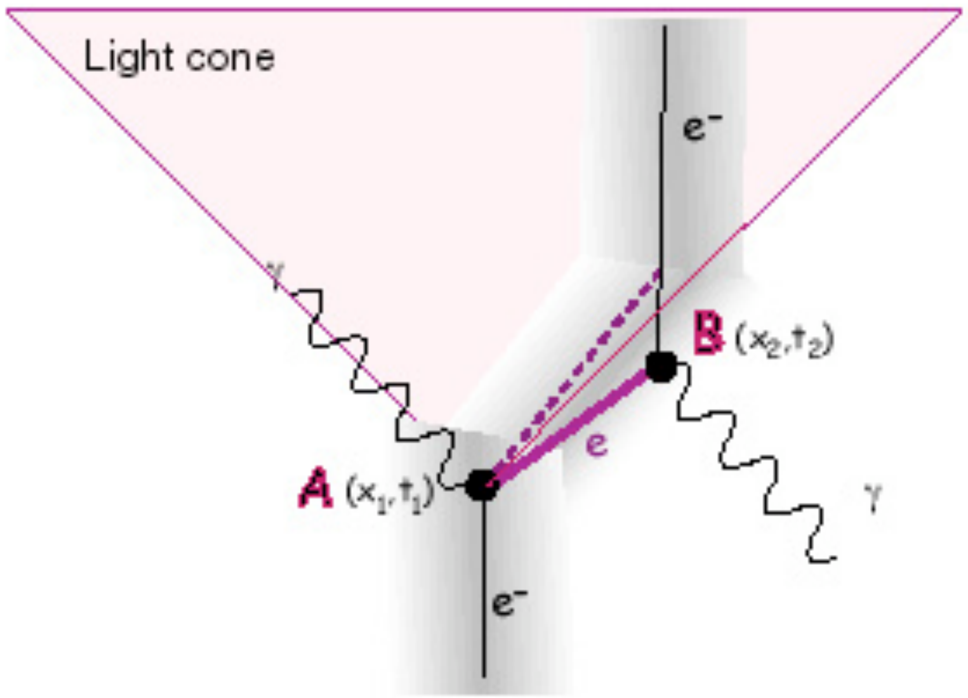

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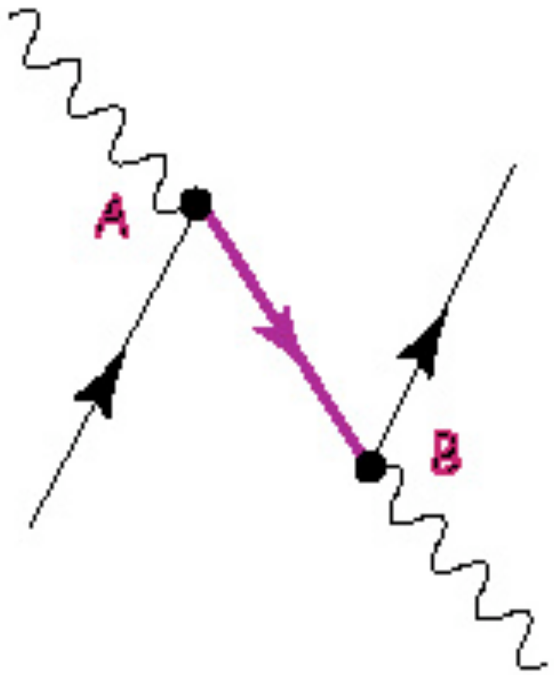

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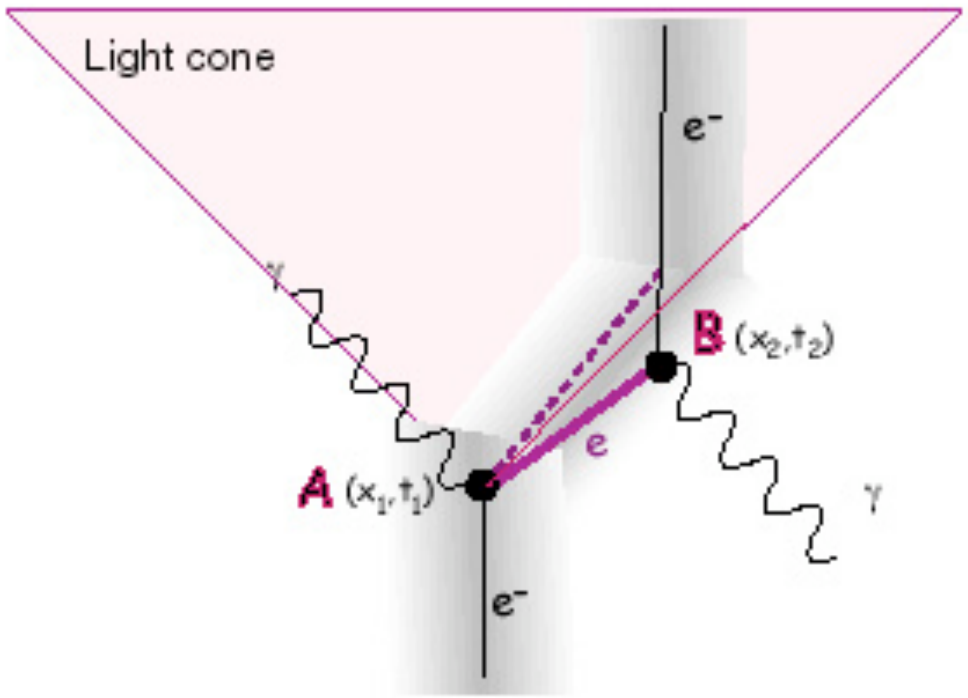

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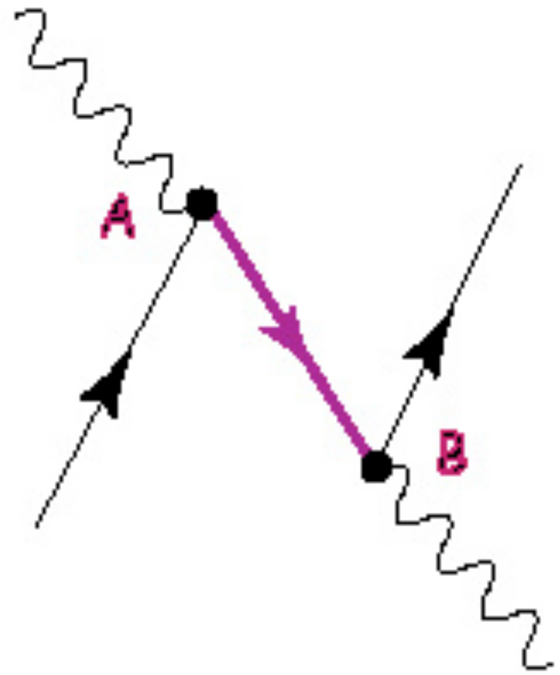

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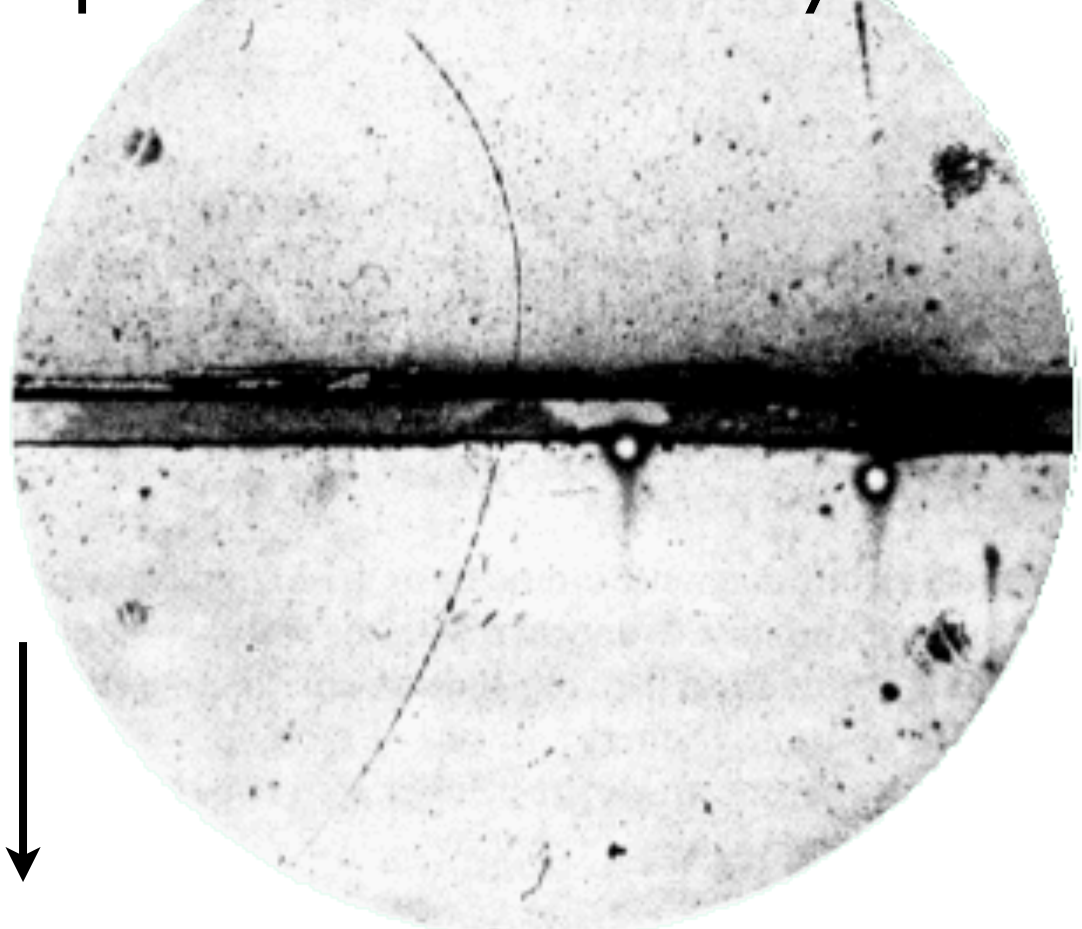
"One observer's electron is the other observer's positron"

Causality requires antiparticles to exist

Antimatter:

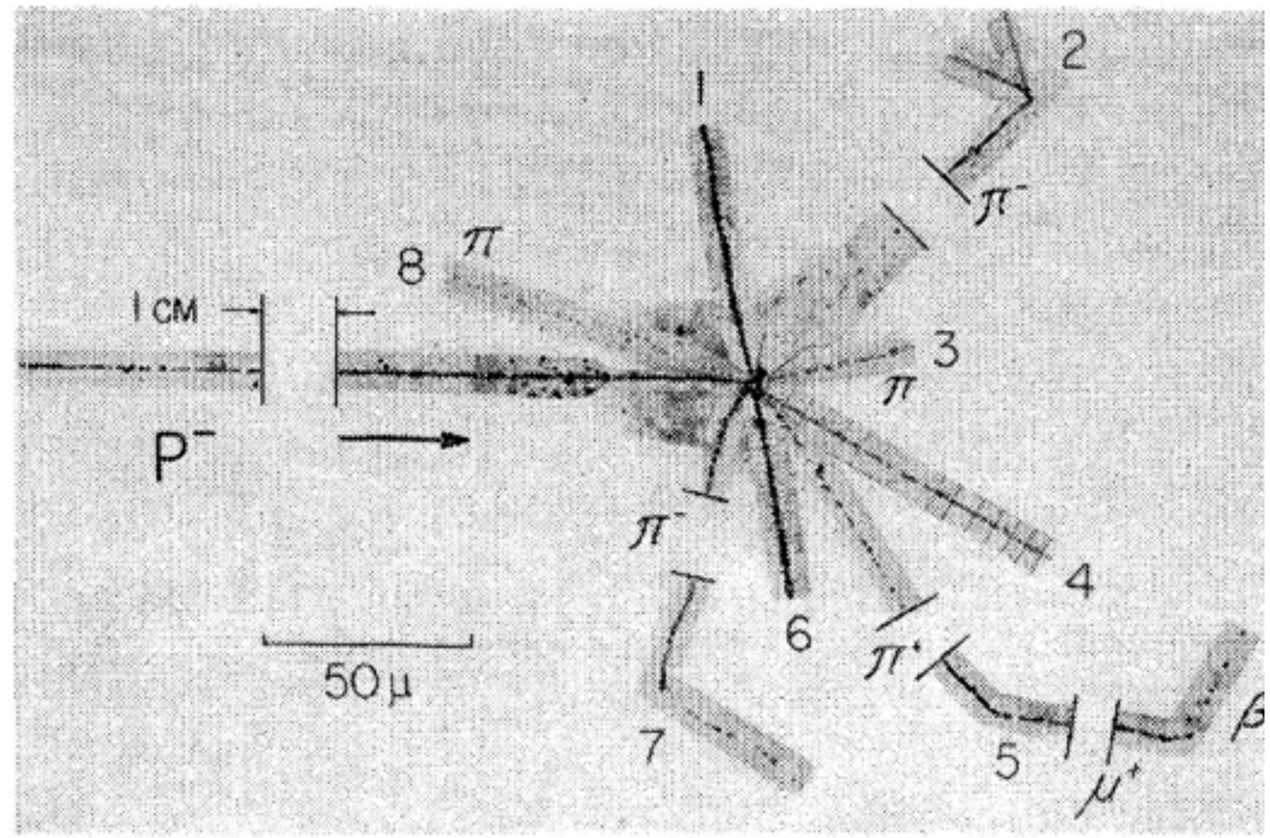
1932 - Anderson discovers the positron in cosmic rays



this way up ↓

Cloud chamber photograph by Andersen
Phys. Rev. 43, 491 (1933)
Nobel prize 1936

1955 - intentional production of antiprotons in an accelerator



- Energy release 1350 ± 50 MeV > m_p
- Total 35 annihilations!
  - Chamberlain et al., Phys. Rev. 102, 902 (1956)
- final proof of antimatter character

Discovery of the Antiproton

- Bevatron 5.6 GeV
  - Just at threshold!
- Discrimination against π^-: measure
  - Momentum
    - Magnets: 1.19 GeV
  - Velocity
    - TOF 51 vs. 40 ns
  - Cherenkov counter veto
- 60 events in 1955
- $\Delta m/m_p \sim 5\%$
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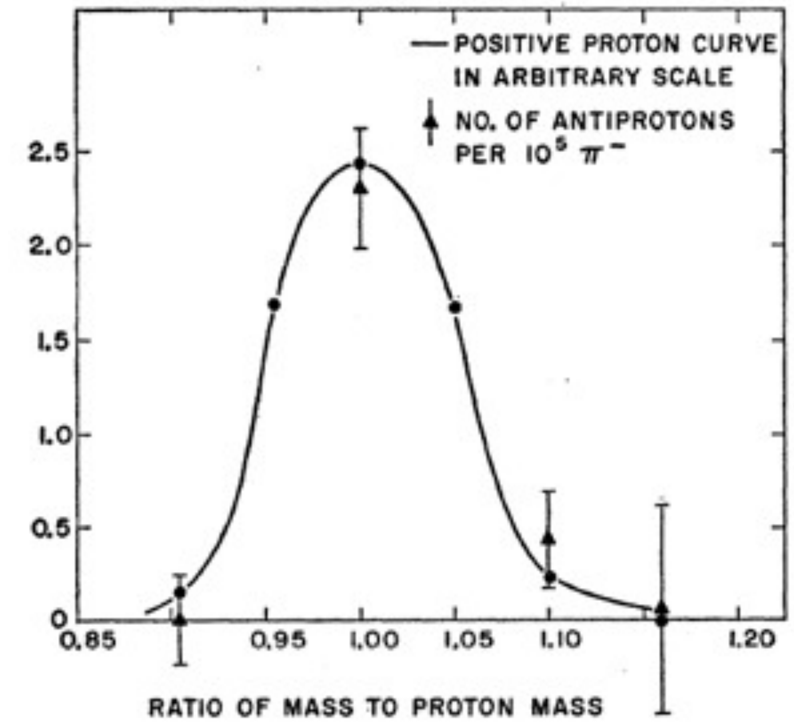
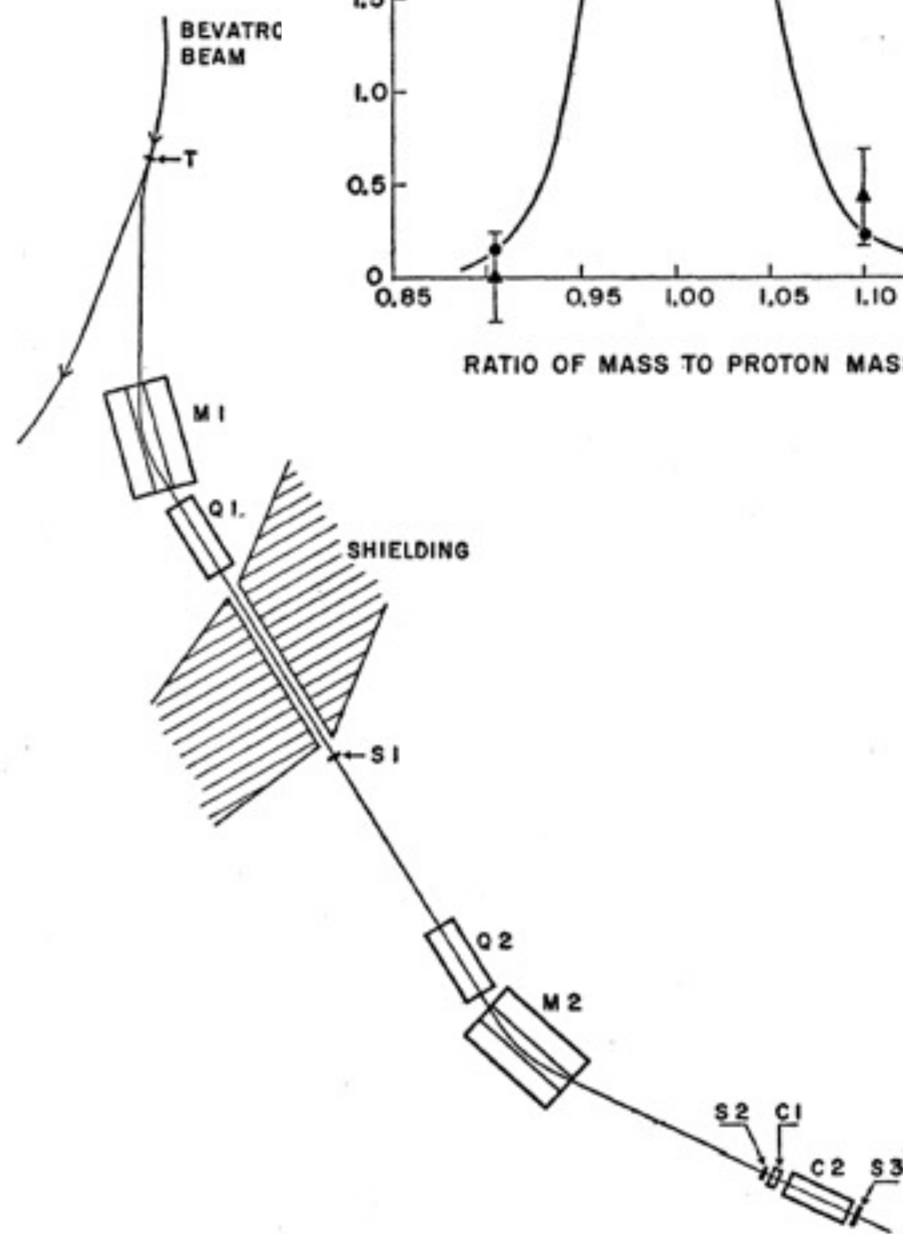
- Nobelprize Chamberlain & Segre 1959





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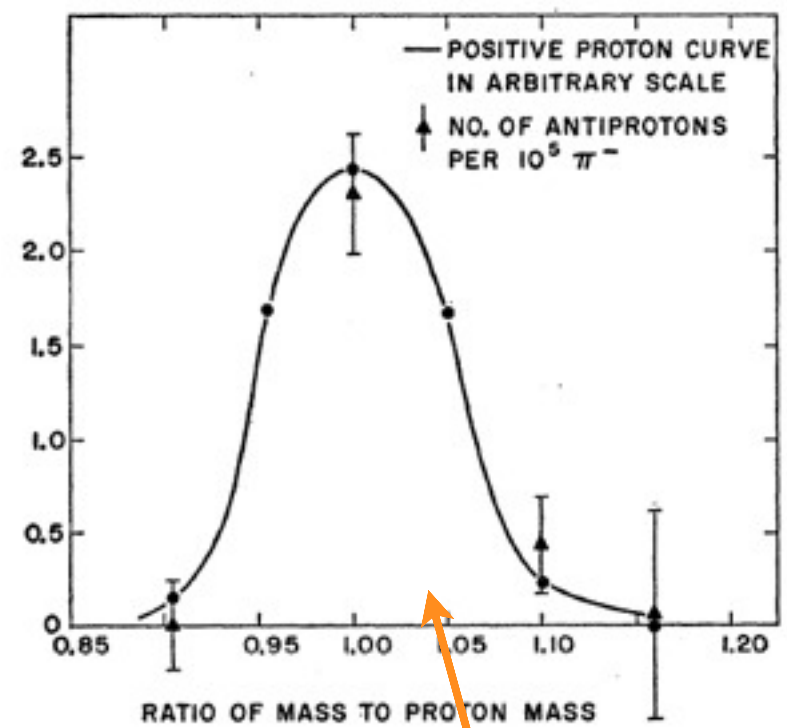
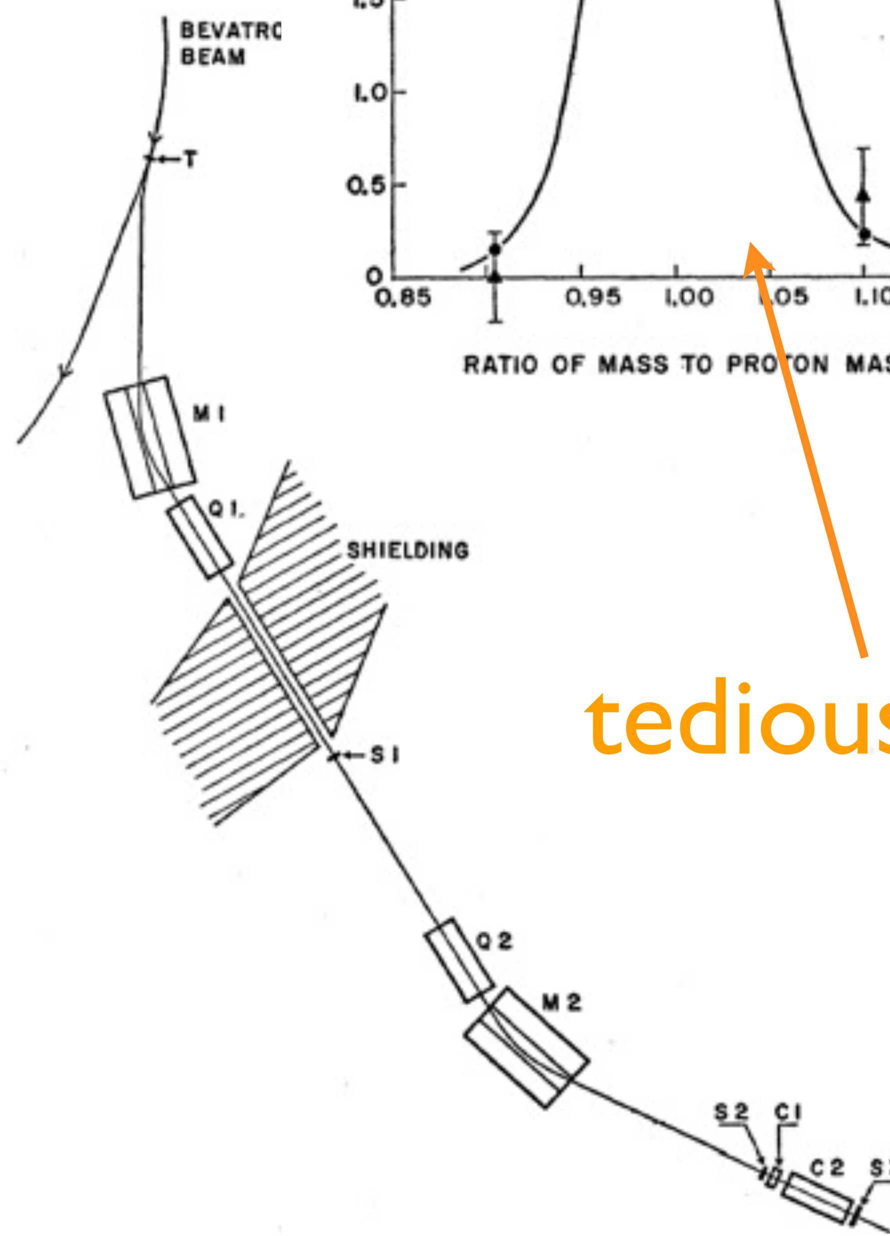


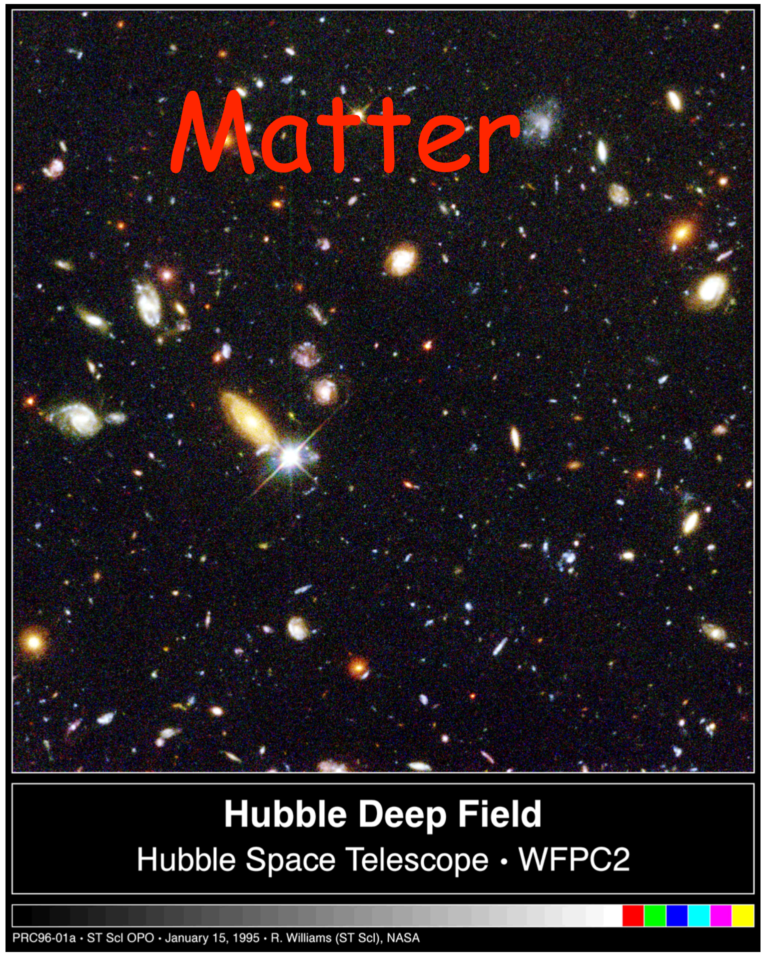


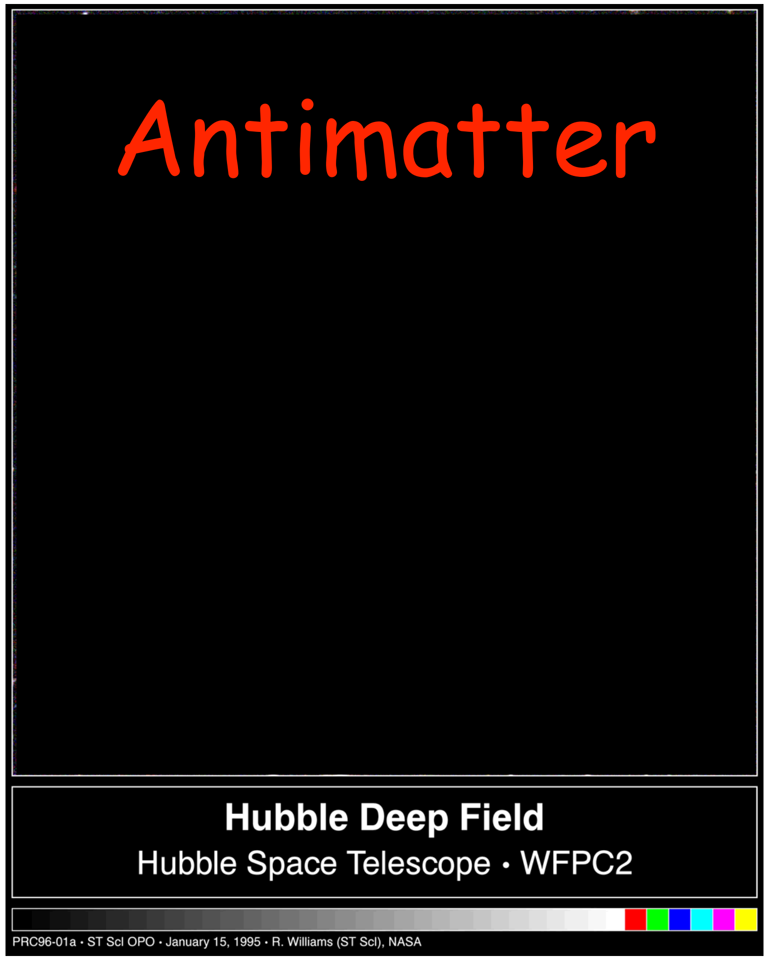
tedious analysis!

Study antimatter

Baryon asymmetry

Investigate symmetries





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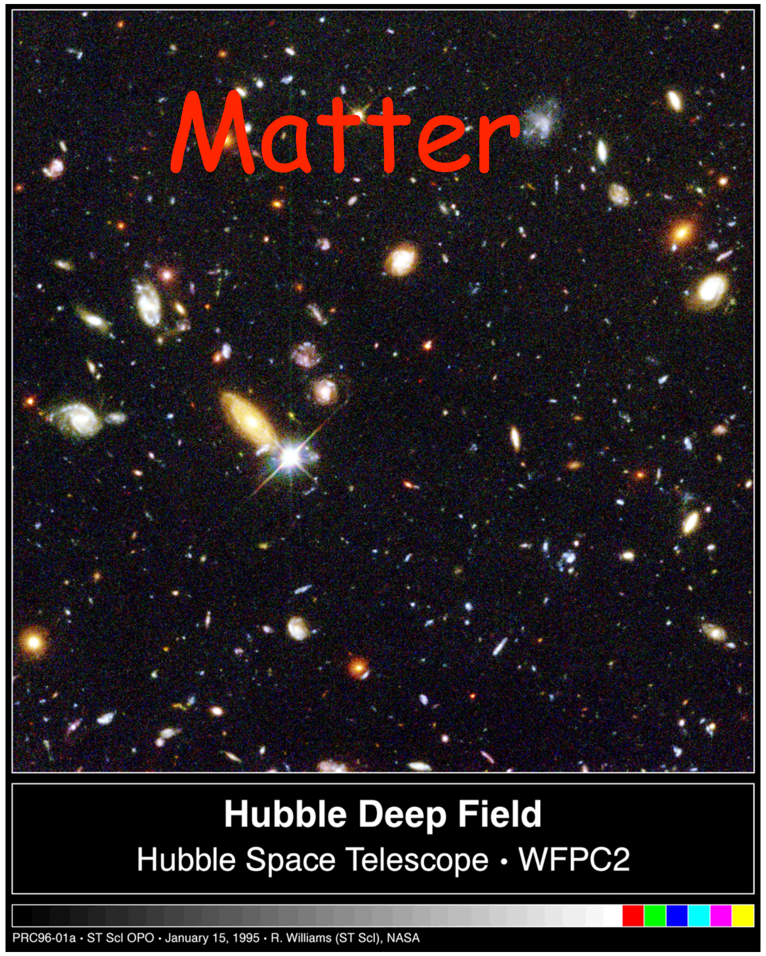

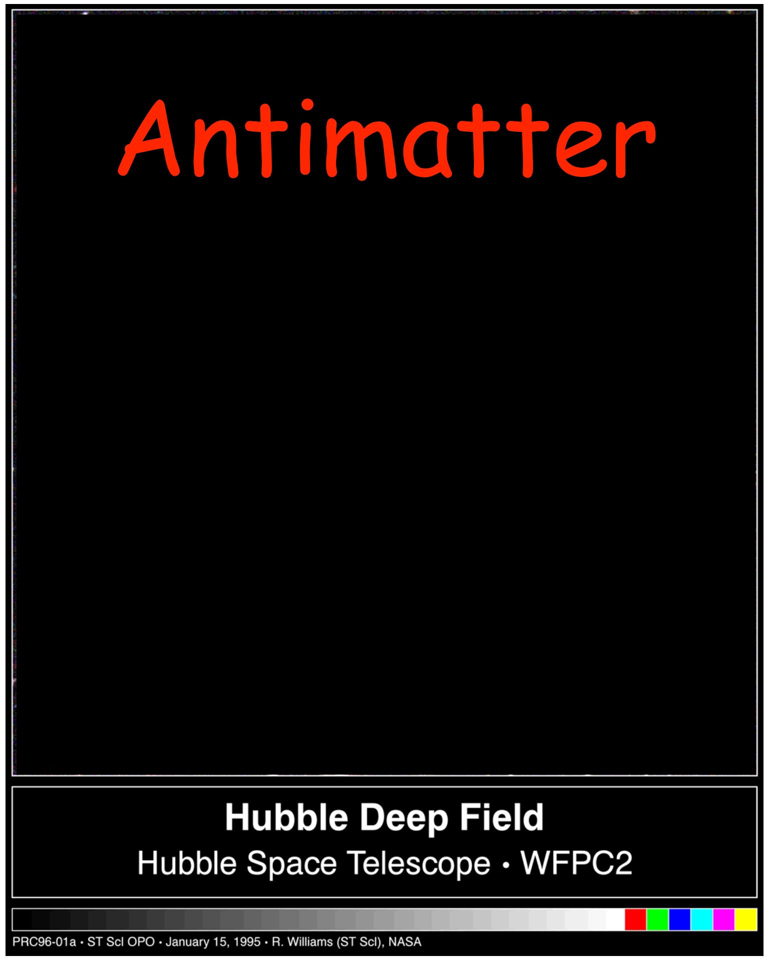

Use antimatter as tool

Matter-antimatter annihilation: source of new particles

Investigate symmetries

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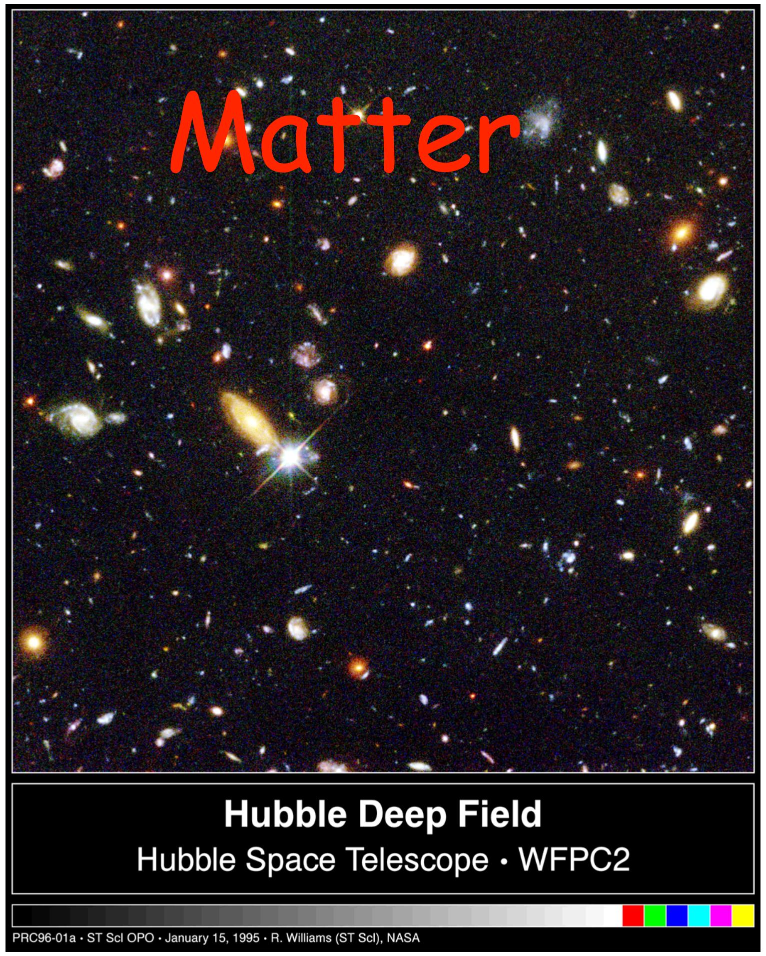
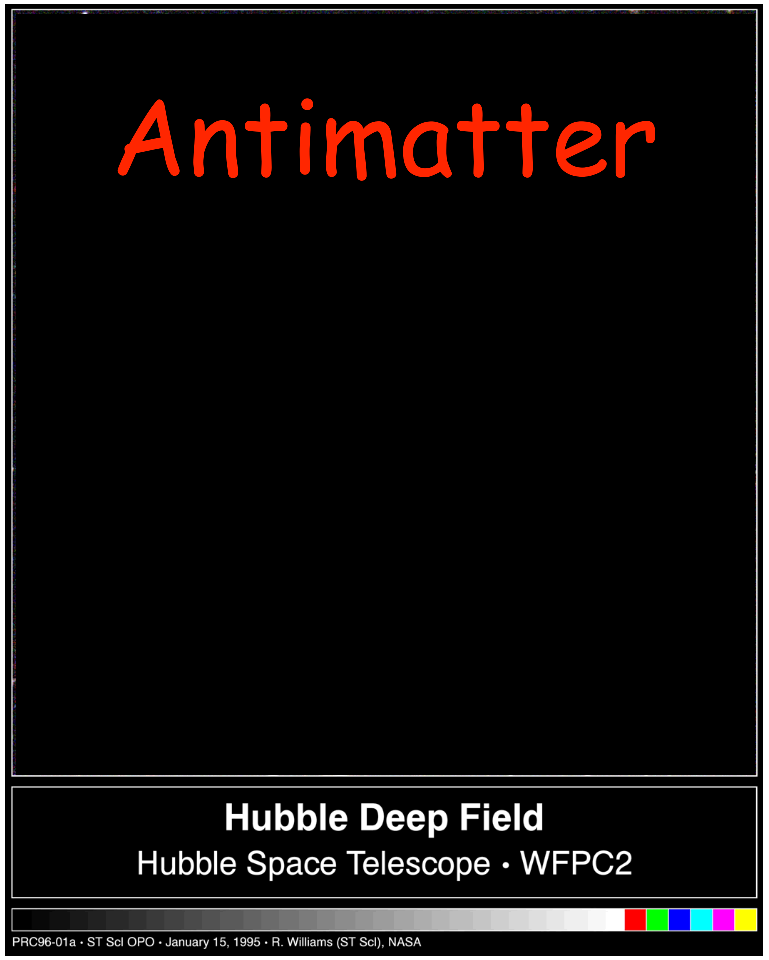




Use antimatter as tool

Matter-antimatter annihilation: source of new particles

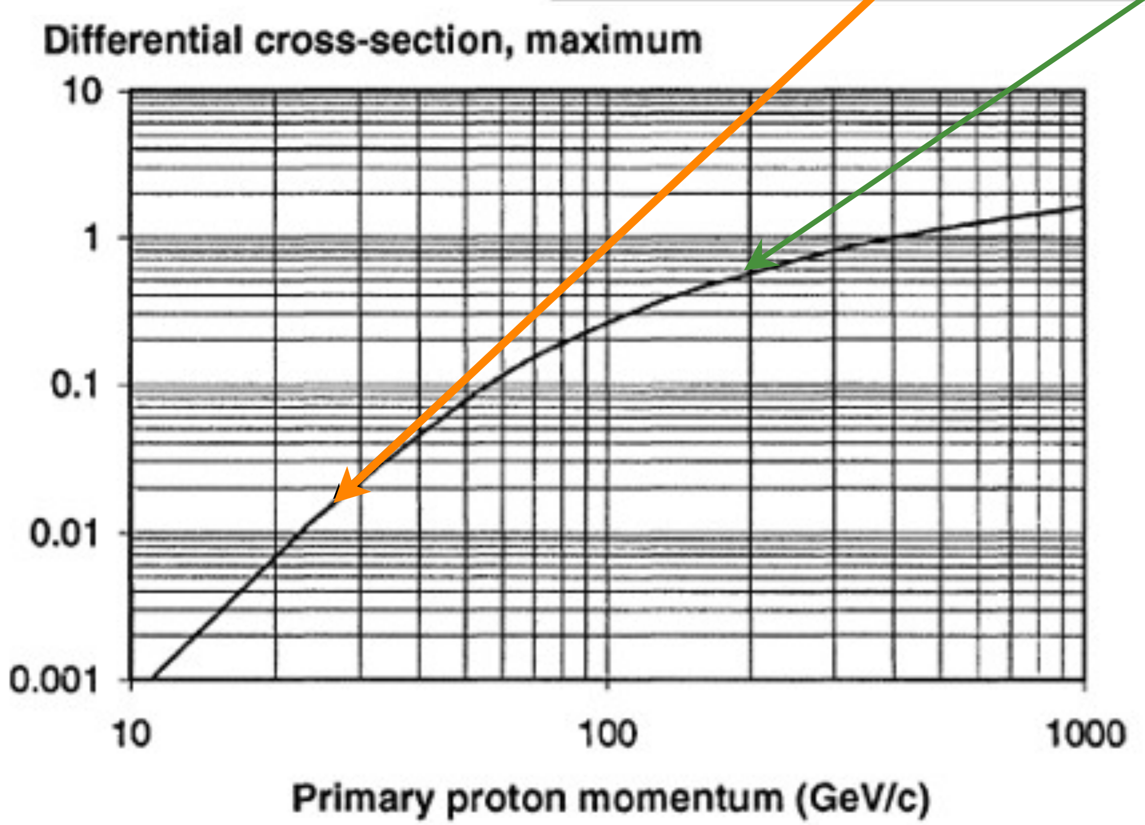
Investigate symmetries

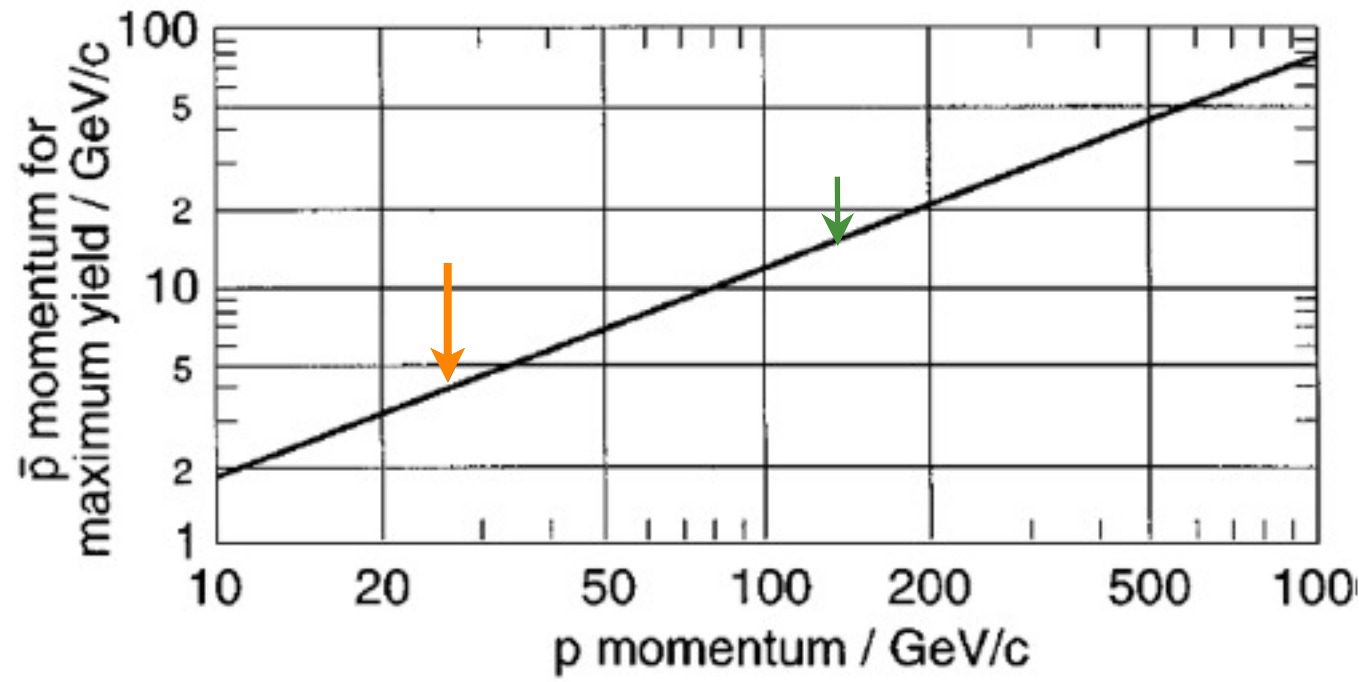
need to make it, though...

Production Energy $pN \rightarrow pXp\bar{p}$

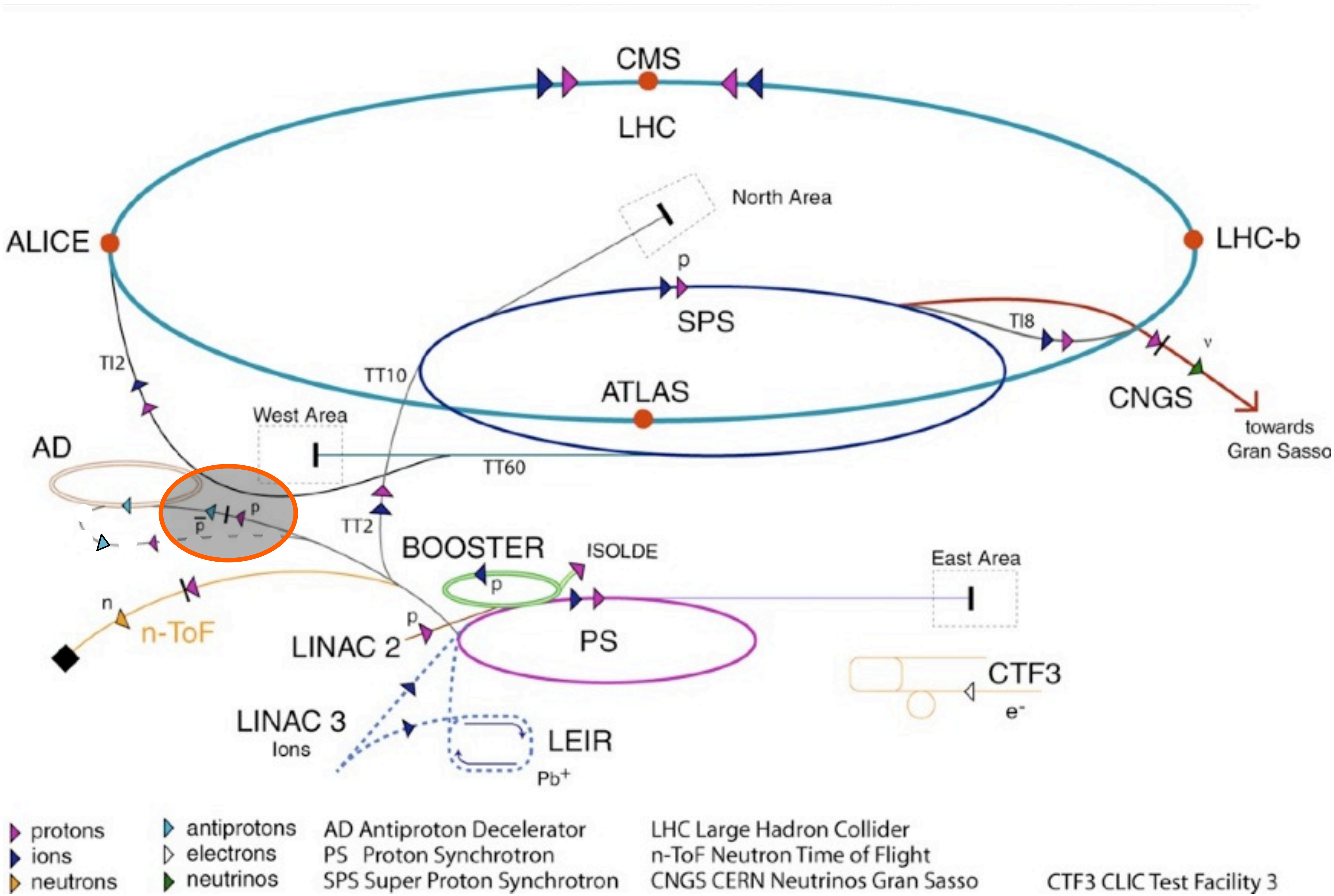
TABLE II. Comparison of CERN and Fermilab antiproton sources: for Fermilab the upgrading program quoted in Church and Marriner (1993) has been anticipated; for CERN the measured yield with magnetic horn has been used.

Machine		CERN Antiproton Collector	Fermilab debuncher
Production momentum (GeV/c)		26	120
Collection momentum (GeV/c)		3.5	9
$\bar{p}$/sr/GeV/c/Interacting p		0.013	0.25
Acceptances	A_h (π mm mrad)	200	25
	A_v (π mm mrad)	200	25
	$\Delta p/p \times 10^{-3}$	60	40
$\sqrt{A_h A_v} \times \Delta p/p$($\pi$ mm mrad$\times 10^{-3}$)		12×10^3	10^3
Yield ($\bar{p}/p$)		3.5×10^{-6}	14×10^{-6}
Protons per pulse		1.5×10^{13}	0.5×10^{13}
Antiprotons per pulse		5×10^7	7×10^7





CERN Accelerator Complex



Overview:

1. Introduction and overview
2. Antimatter at high energies ($Sp\bar{p}S$, LEP, Fermilab)
3. Meson spectroscopy (antimatter as QCD probe)

4. Astroparticle physics and cosmology
5. CP and CPT violation tests
6. Precision tests with Antimatter

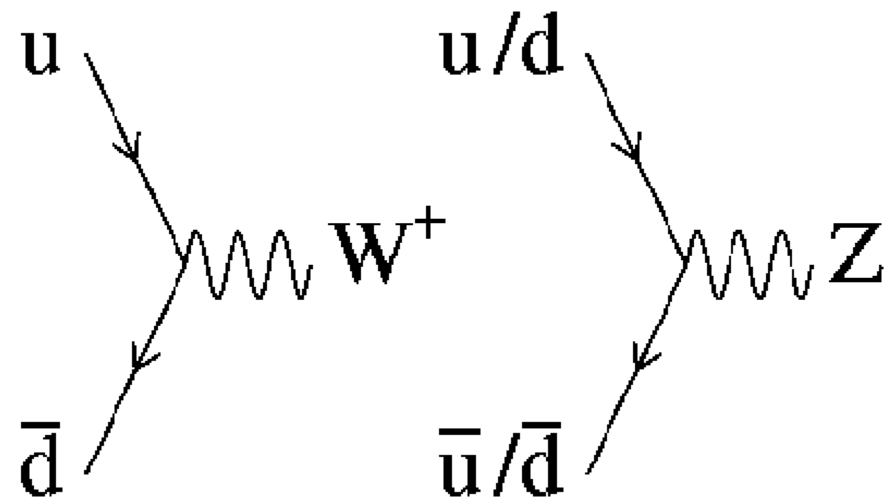
7. Precision tests with Antihydrogen
8. Applications of antimatter

Use matter and antimatter to study high energy interactions, and establish the standard model

1. Proton-antiproton collisions at $Sp\bar{p}S$
2. Positron-electron interactions (at KEK, SLC, LEP)
3. Proton-antiproton interactions at Fermilab
4. Proton-antiproton for meson spectroscopy

Antimatter (+matter) is a tool to produce new particles, but it also allows to study the couplings between different particle types.

Electroweak interactions (1970's)



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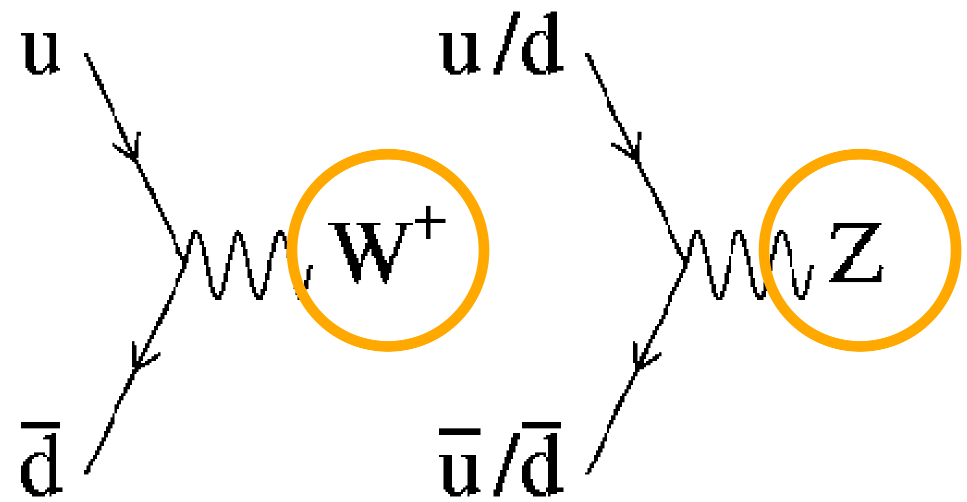
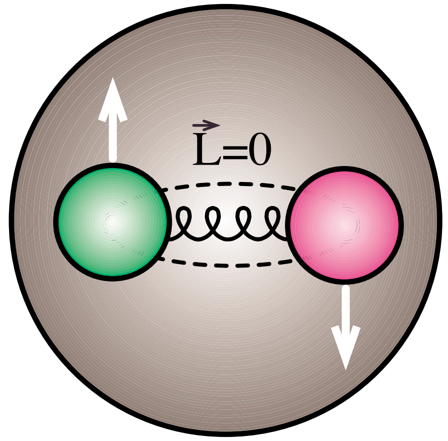
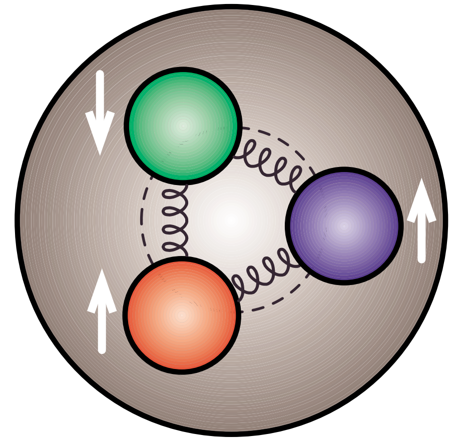


Where do we get the antiquarks from?

QCD

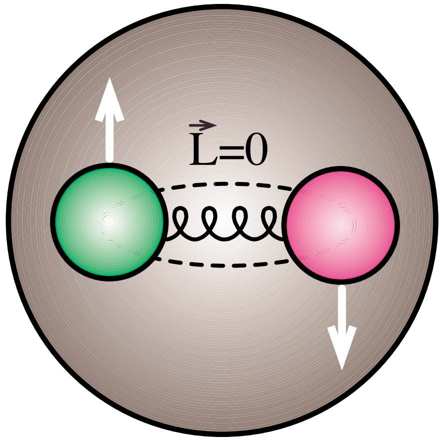


Meson ($q\bar{q}$)



Baryon (qqq)

QCD



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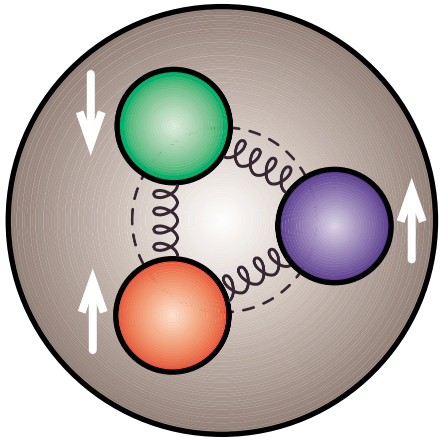

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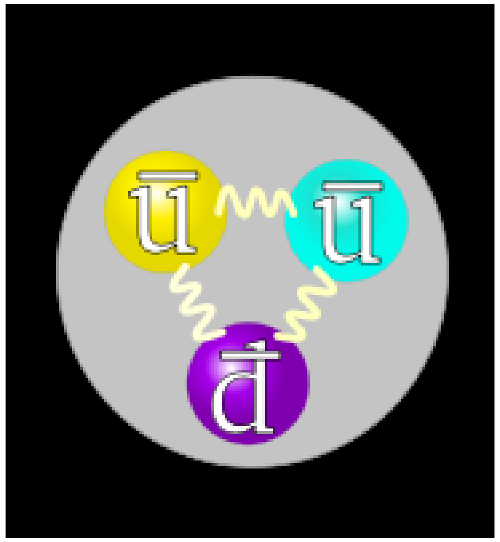


Antibaryon ($\bar{q}\bar{q}\bar{q}$)

Collisional energy Q in parton-parton center-of-mass frame:

$$Q^2 = x_1 x_2 E^2_{cm}$$

The probability of a proton containing a parton of type i at the appropriate values of x_1 and Q^2 is given by a 'parton distribution function' (PDF), $f_i(x_1, Q^2)$

(must be measured, i.e. at H1/Zeus @ HERA)

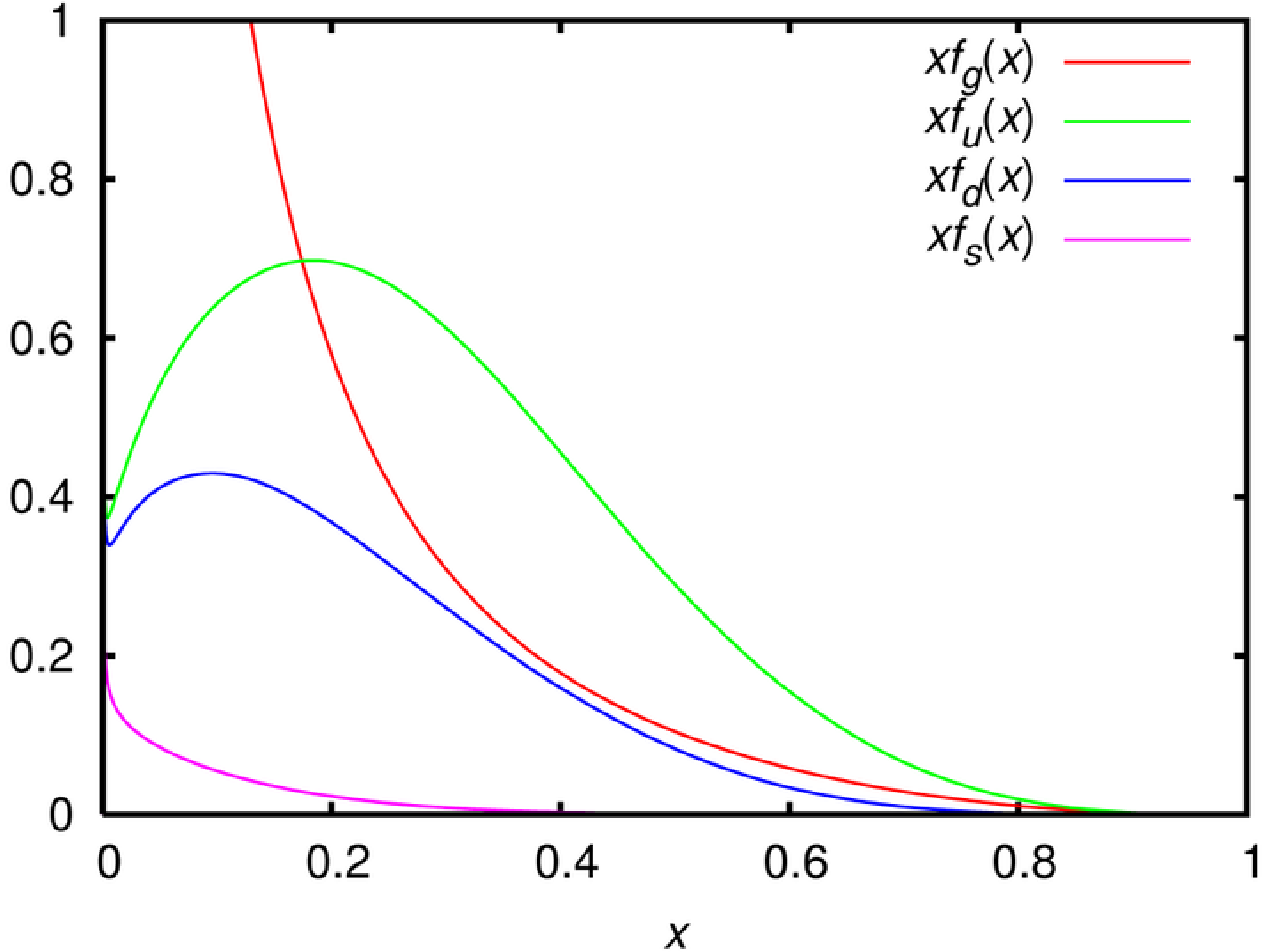
Sum over all possible combinations of incoming partons and integrate over the momentum fractions x_1 and x_2

$$\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 \, f_i(x_1, Q^2) \cdot \bar{f}_j(x_2, Q^2) \cdot \hat{\sigma}(Q^2)$$

(anti)proton beam = broadband beam of (anti)partons

(initial-state partons have a high probability of radiating gluons before they collide, so not even the nominal energy is available)

Fraction of momentum carried by ...



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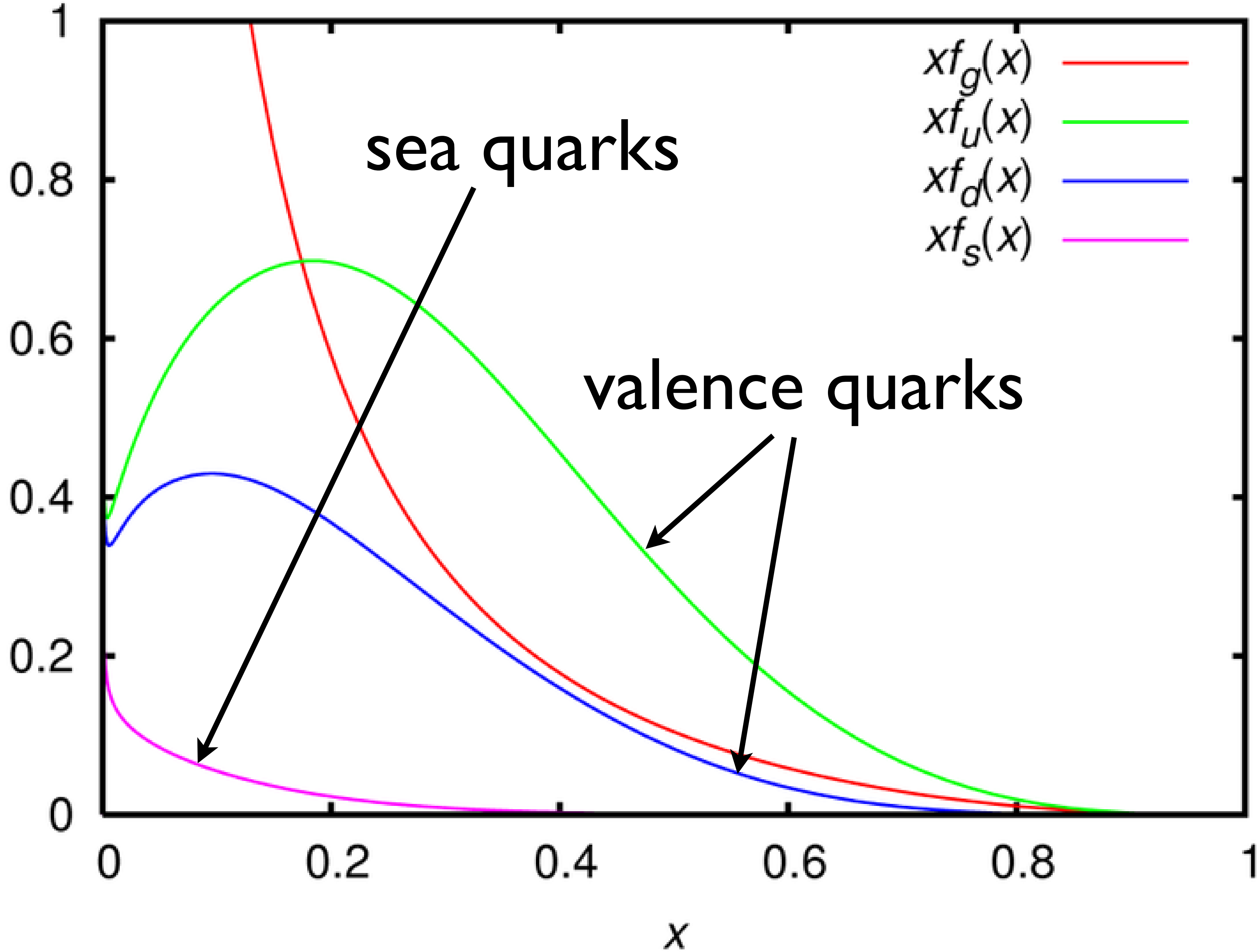

The use of antiproton-proton collisions allows for
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This is because the valence quarks in the proton,
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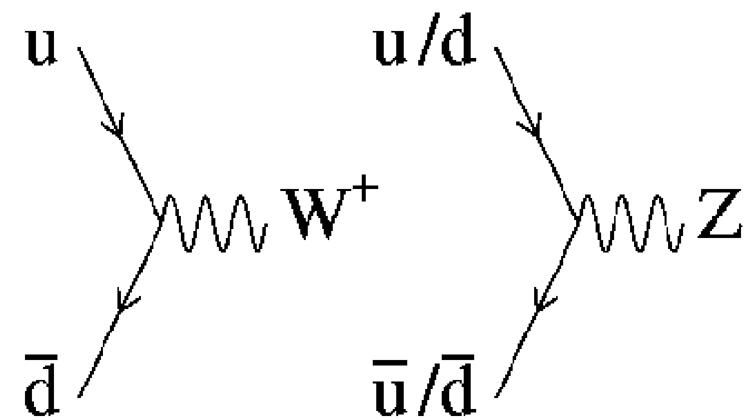
= poor man’s high-energy collider

$Sp\bar{p}S$ (1980's)



valence quarks

sea quarks

requires antiprotons

requires significantly higher energy

$$\sigma(p\bar{p} \to W^{\pm} \to e^{\pm} + \nu) \simeq 0.4 \times 10^{-33}\ k\ \mathrm{cm}^2$$

$$\sqrt{s} = 540\ \mathrm{GeV}$$

Design luminosity: 10^{30} $\mathrm{cm^{-2}s^{-1}}$

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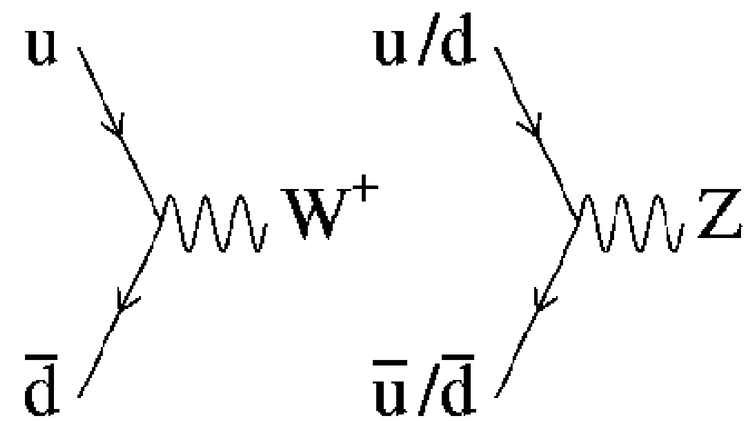

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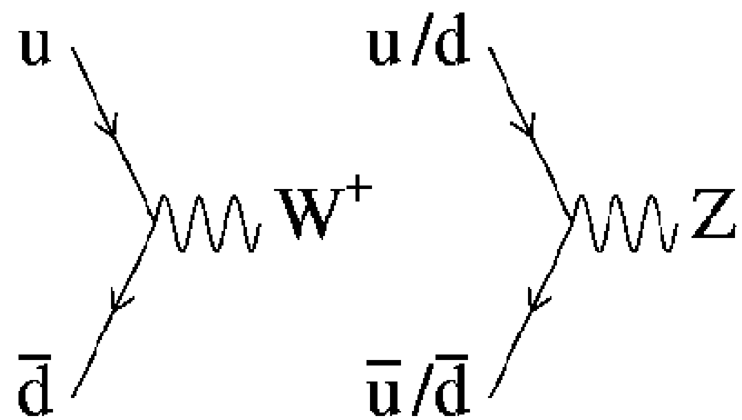

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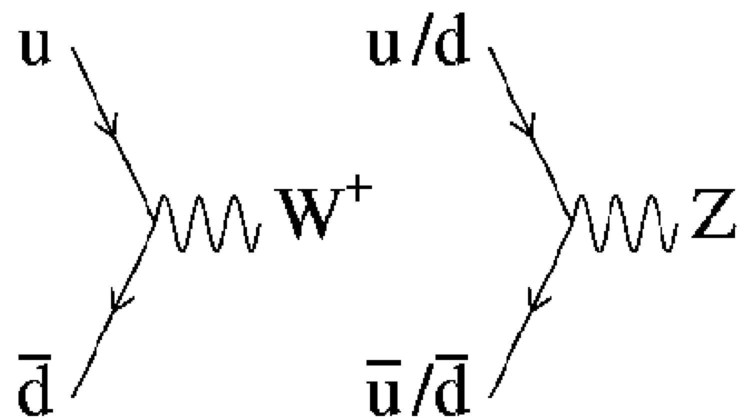

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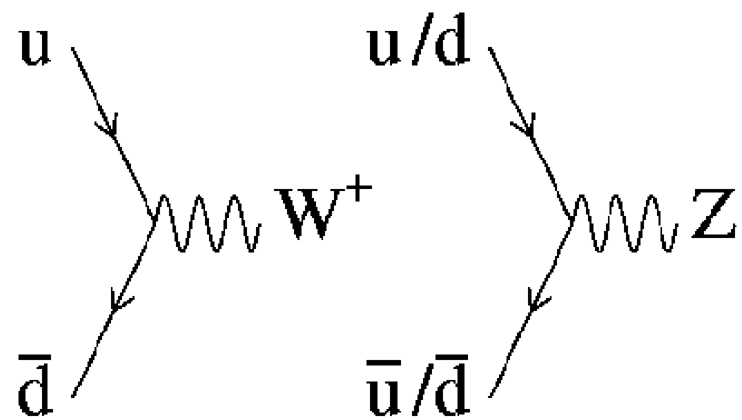

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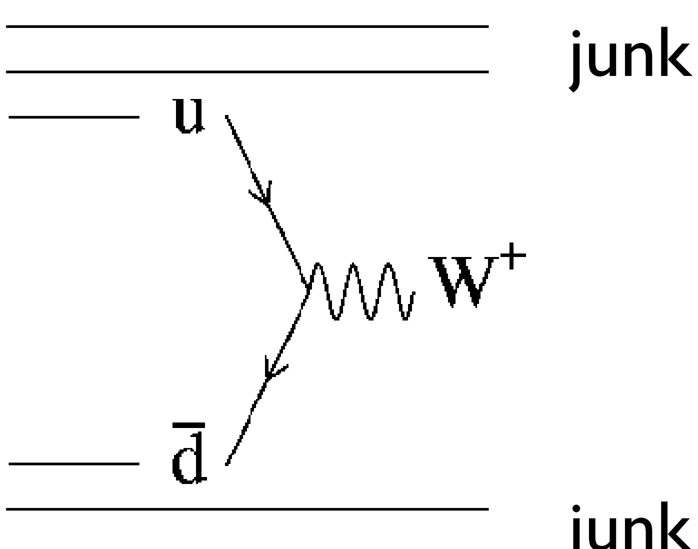
$$\bar{p} + p \rightarrow W^{\pm} + X,\ W \rightarrow e^{\pm} + \nu;$$

- isolated large E_T electrons
- isolated large E_T neutrinos



Arnison, G. *et al*. (UA1 Collaboration). Experimental observation of isolated large transverse energy electrons with associated missing energy at s = 540 GeV. *Phys. Lett. B* **122**, 103–116 (1983)

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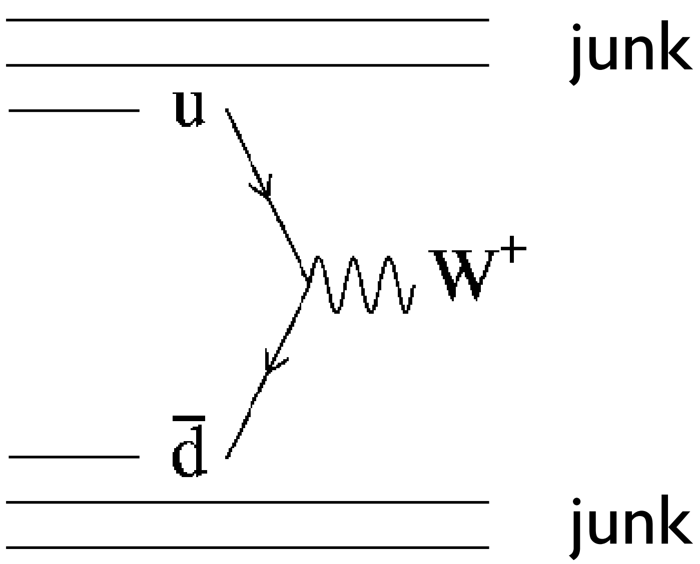

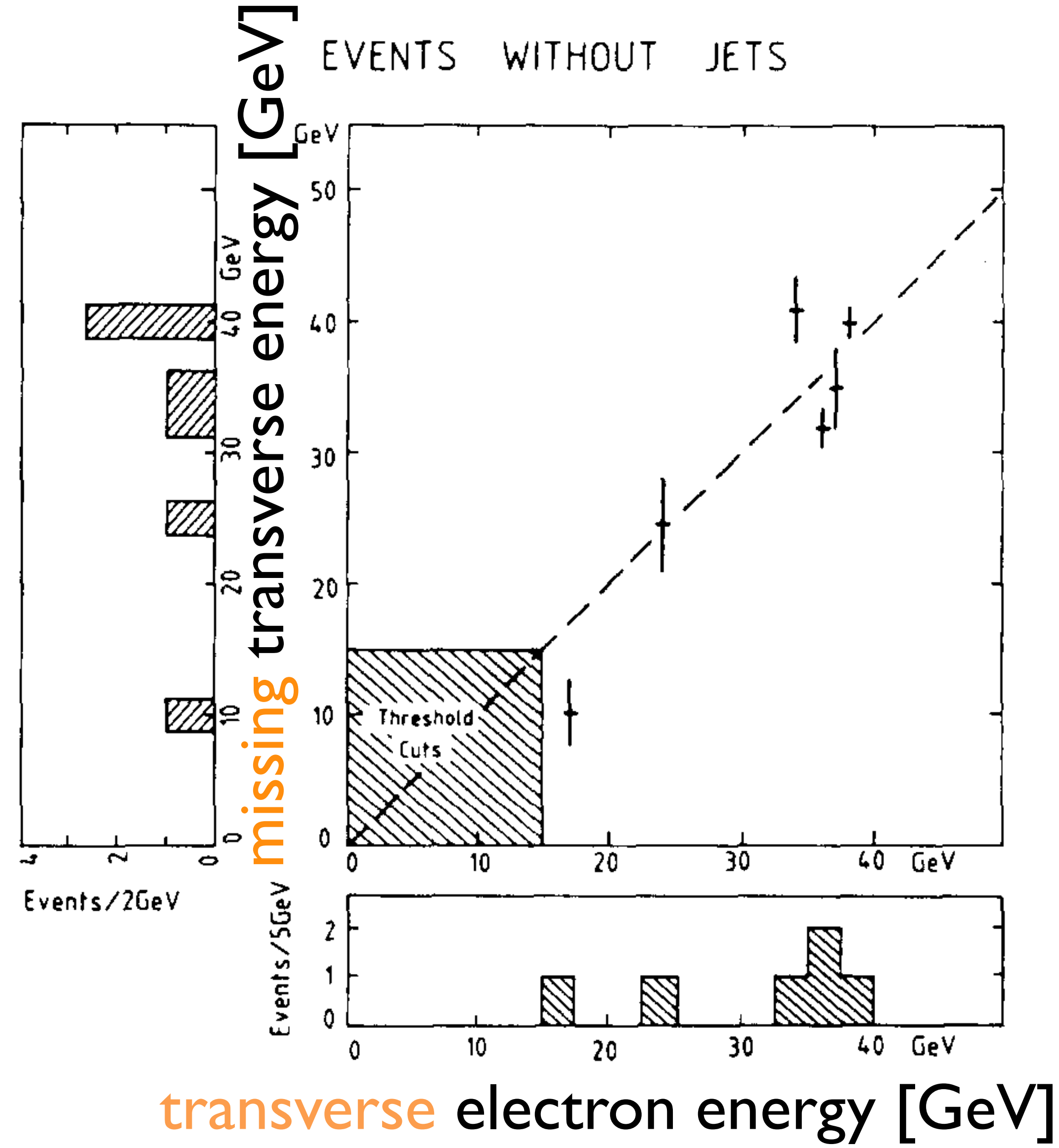

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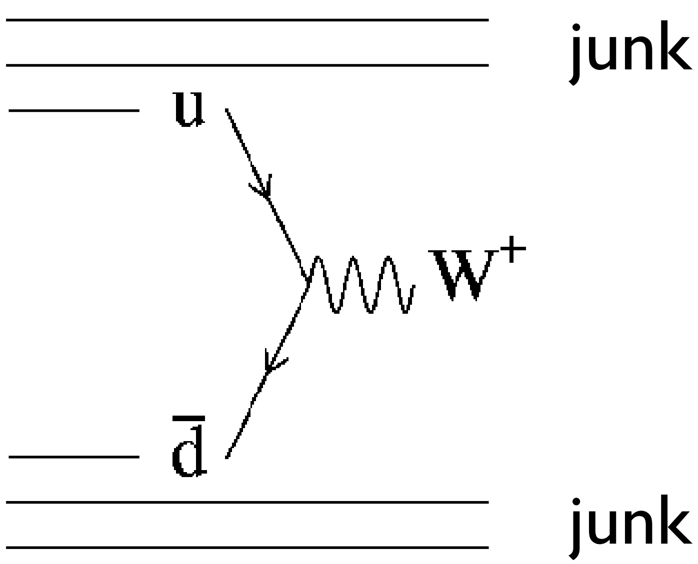

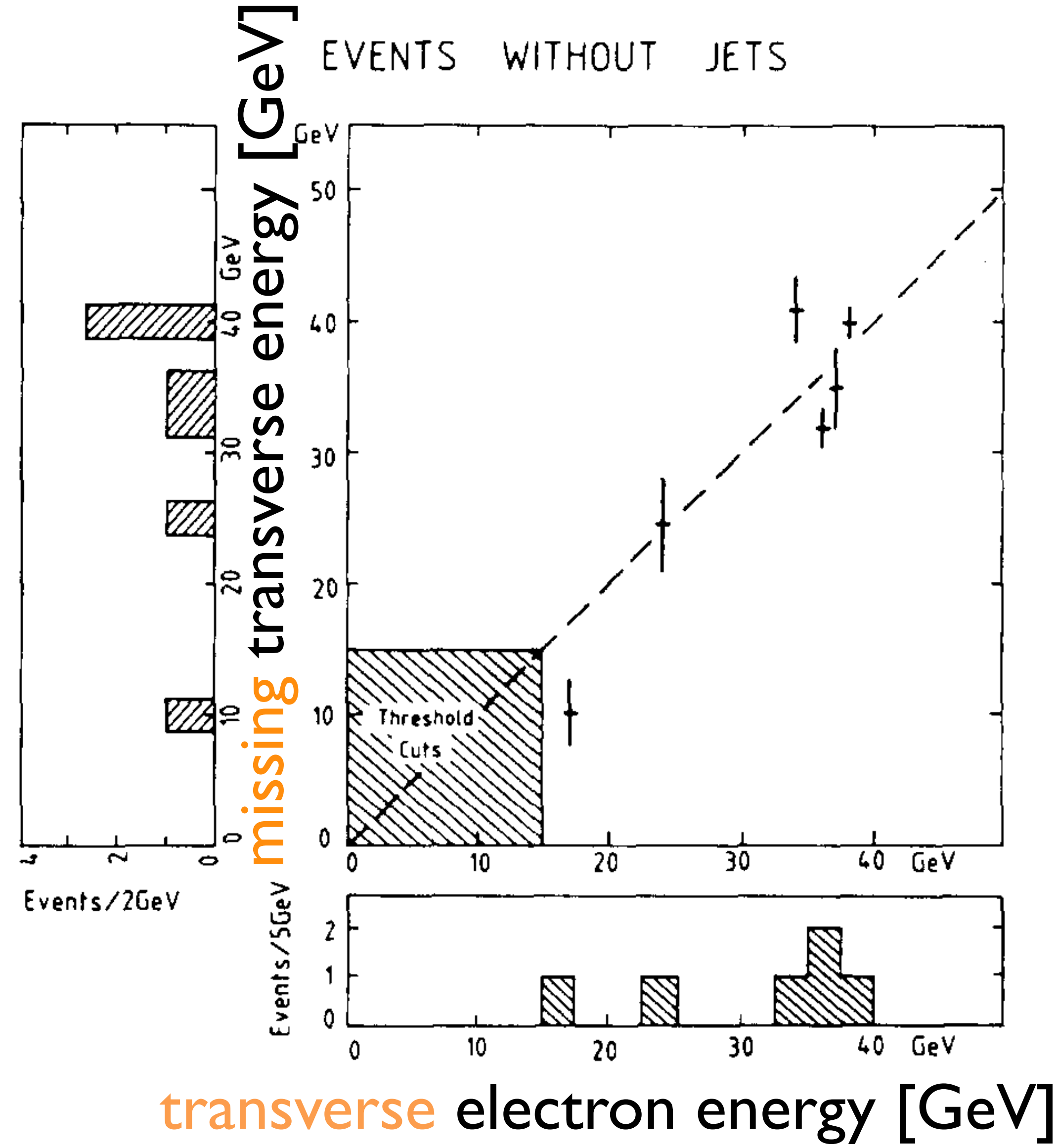

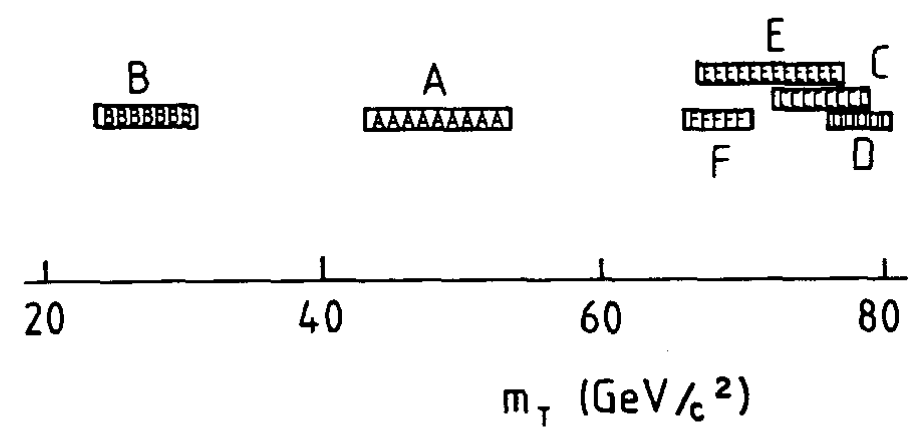

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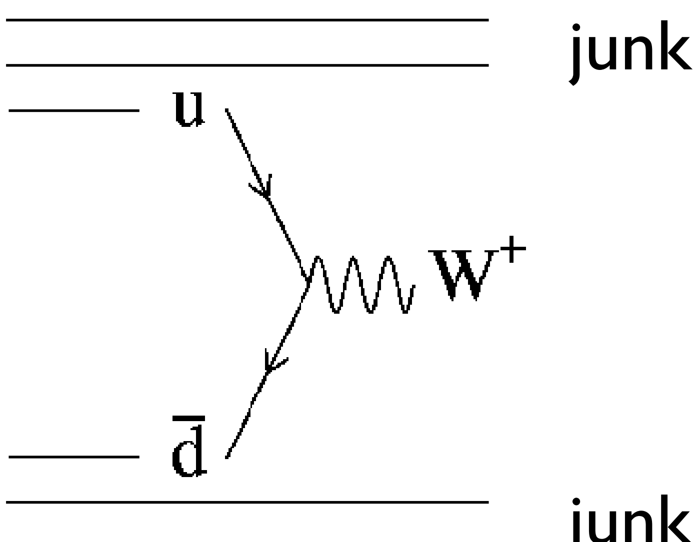

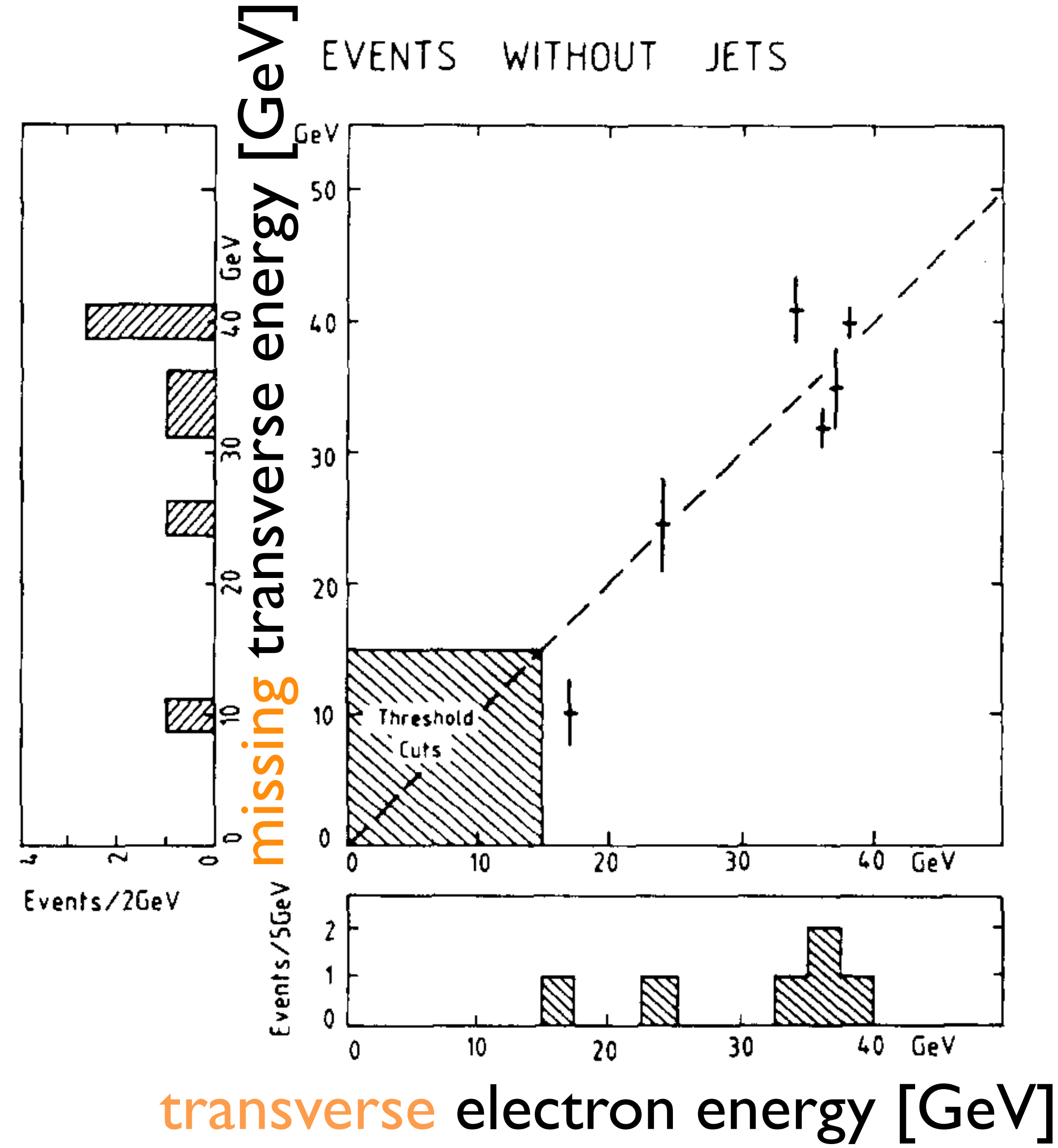

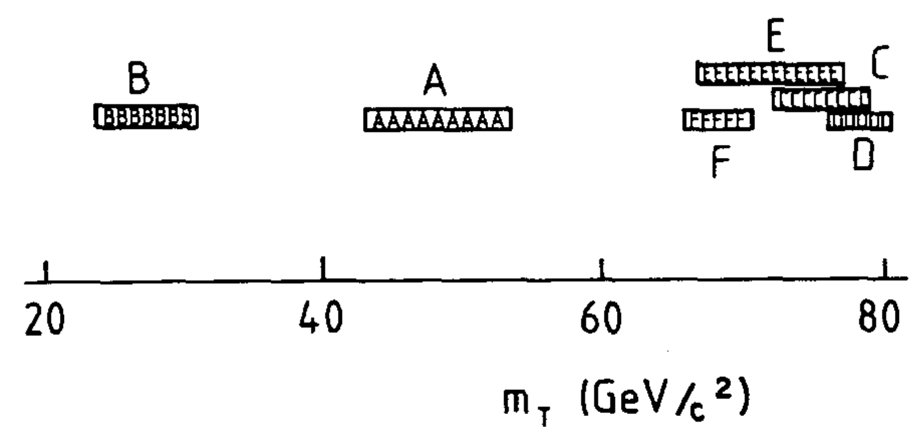

$$m_W = (81 {}^{+5}_{-5})\ \mathrm{GeV}/c^2$$

Arnison, G. *et al*. (UA1 Collaboration). Experimental observation of isolated large transverse energy electrons with associated missing energy at s = 540 GeV. *Phys. Lett. B* **122**, 103–116 (1983)

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2) how to detect Z

$$\bar{p} + p \rightarrow Z^0 + X$$
$$\quad\quad \hookrightarrow e^+ + e^- \quad \text{or} \quad \mu^+ + \mu^-$$

The paper is based on an early analysis of a sample of collisions with an integrated luminosity of 55 nb^{-1}. In this event sample, 27 $W^{\pm} \rightarrow e^{\pm}\nu$ events have been recorded [5] ‡2. According to minimal SU(2) × U(1), the Z^0 mass is predicted to be [6] ‡3 $m_{Z^0} = 94 \pm 2.5$ GeV/c^2. The reaction (1) is then approximately a factor of 10 less frequent than the corresponding $W^{\pm}$ leptonic decay channels [9] ‡4.

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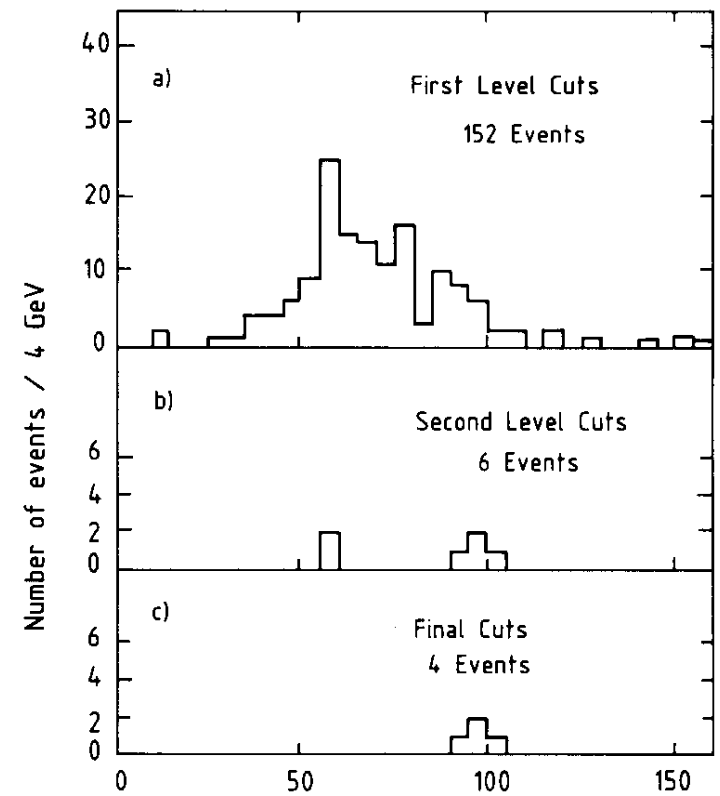

all

at the end of a track

"isolation"

invariant mass of two EM clusters [GeV]

Arnison, G. *et al*. (UA1 Collaboration). Experimental observation of lepton pairs of invariant mass around 95 GeV/c^2 at the CERN SPS collider. *Phys. Lett. B* **126**, 398–410 (1983).

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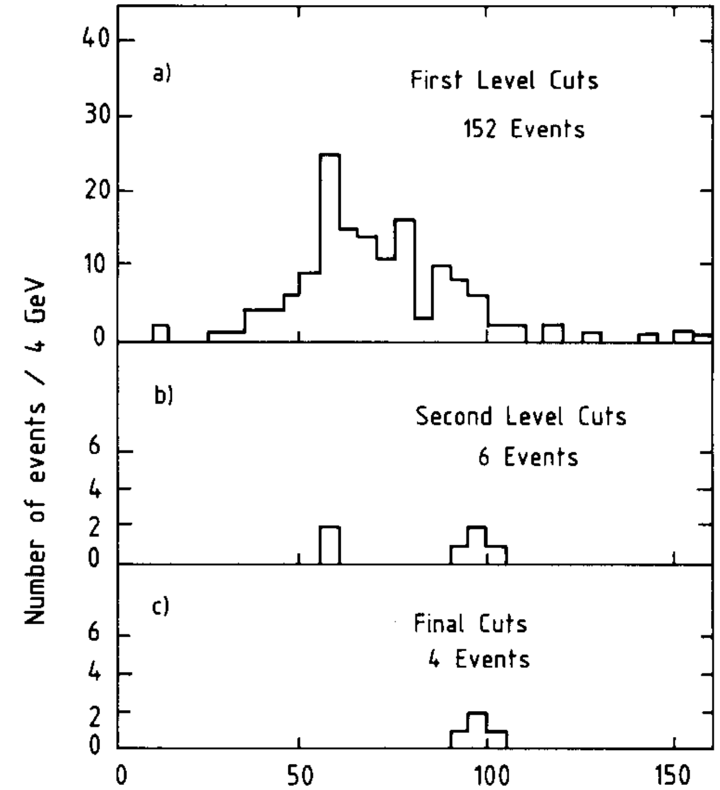
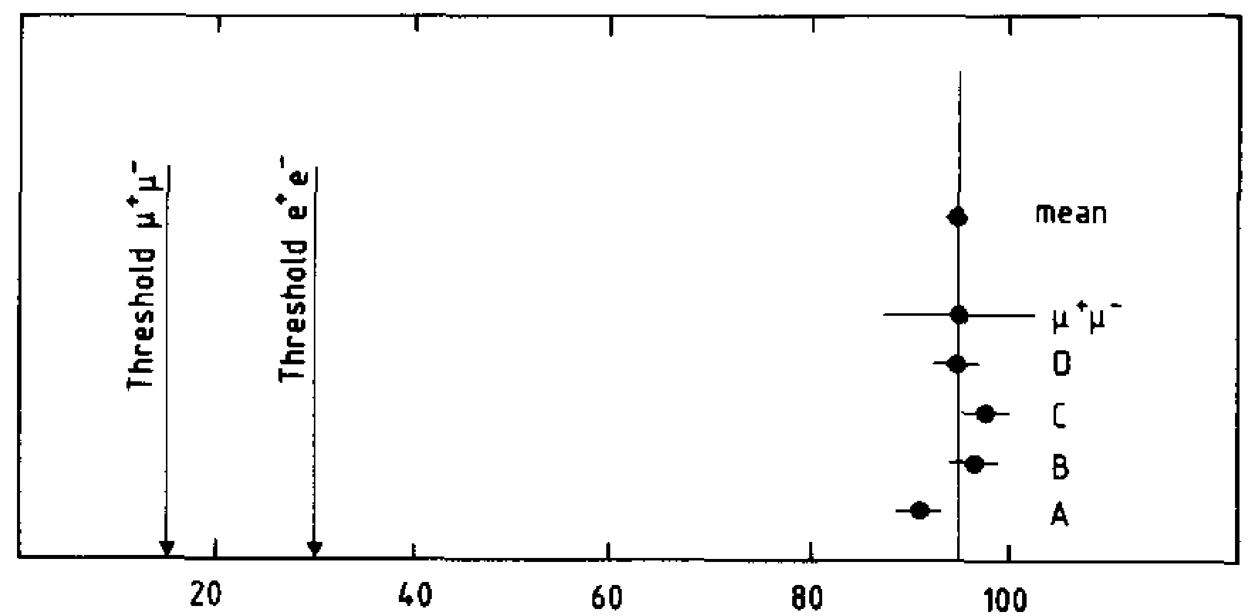


invariant mass of two EM clusters [GeV]

all

at the end of a track

"isolation"



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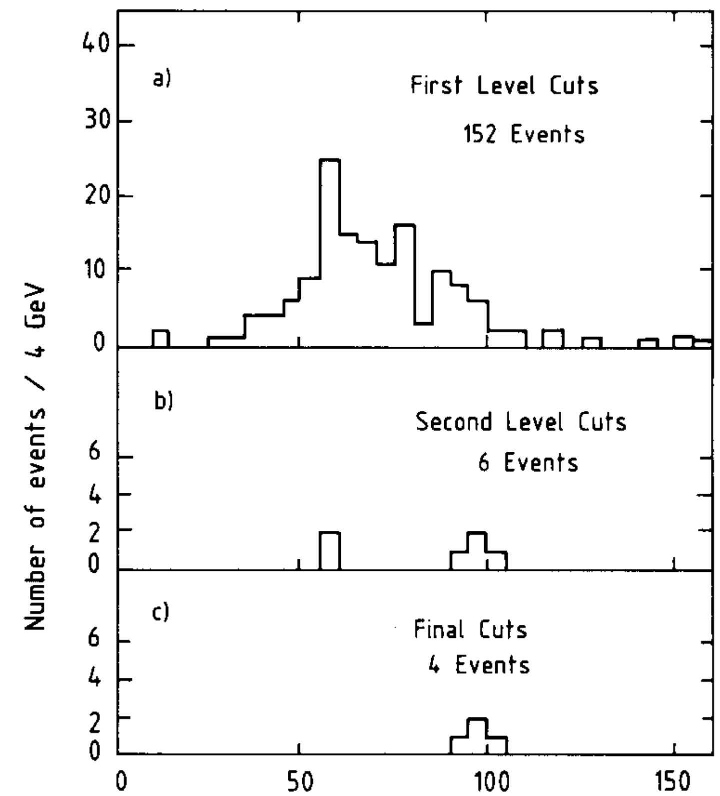
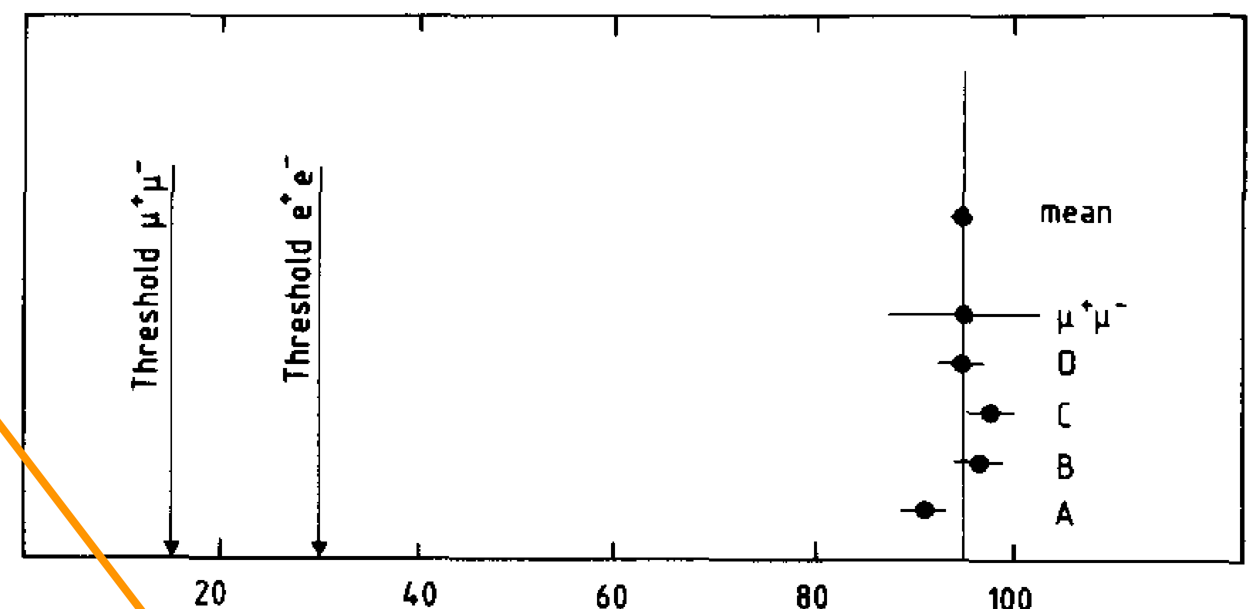


invariant mass of two EM clusters [GeV]

all

at the end of a track

"isolation"



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$$m_{Z^0} = (95.2 \pm 2.5) \text{ GeV}/c^2$$

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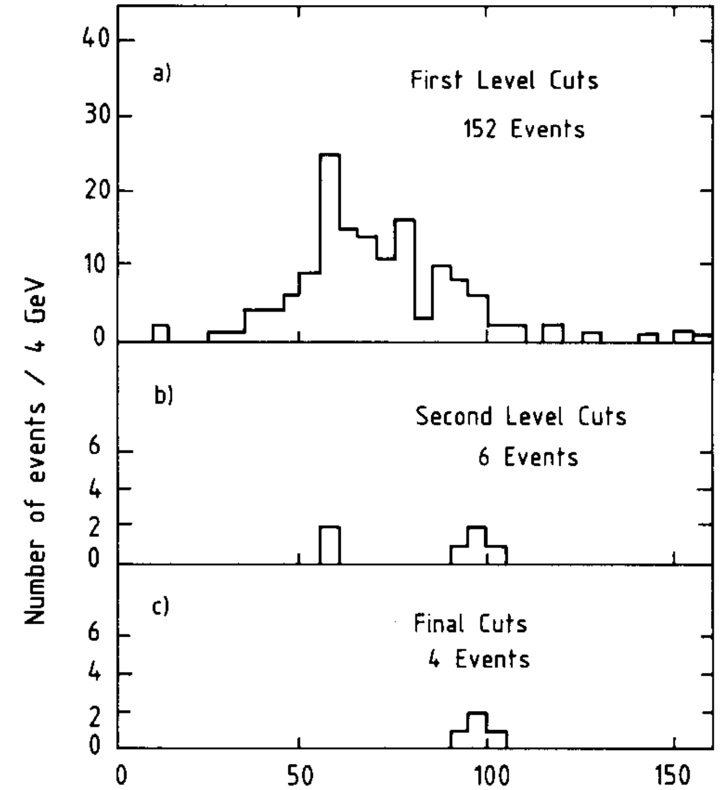

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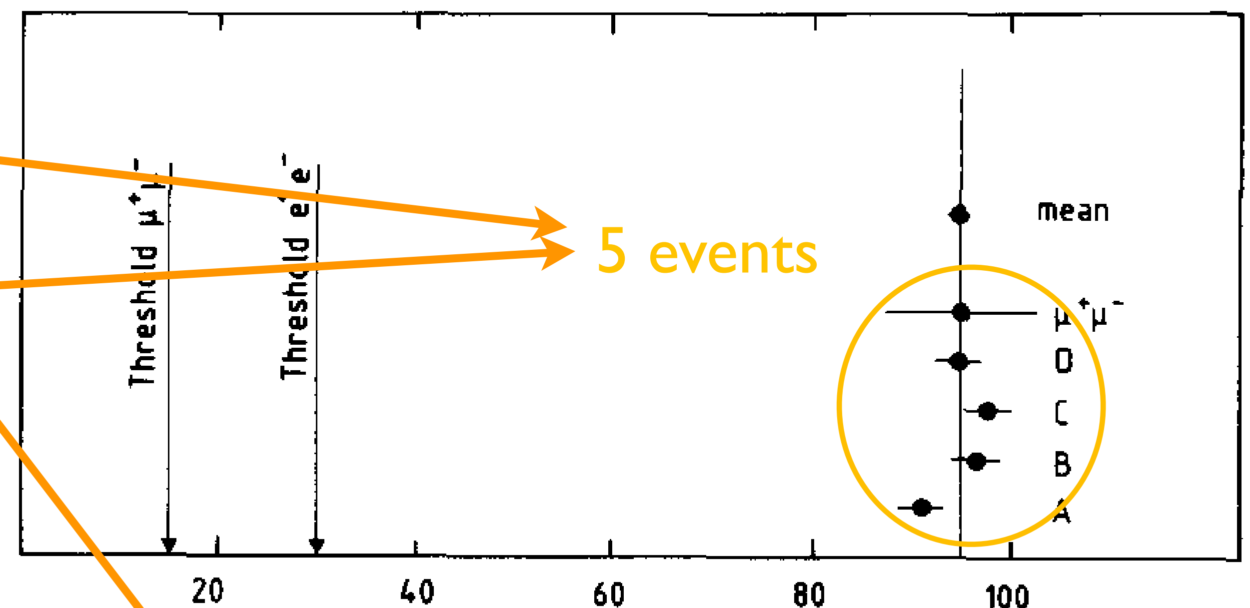
5 events



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4 events — 1 event

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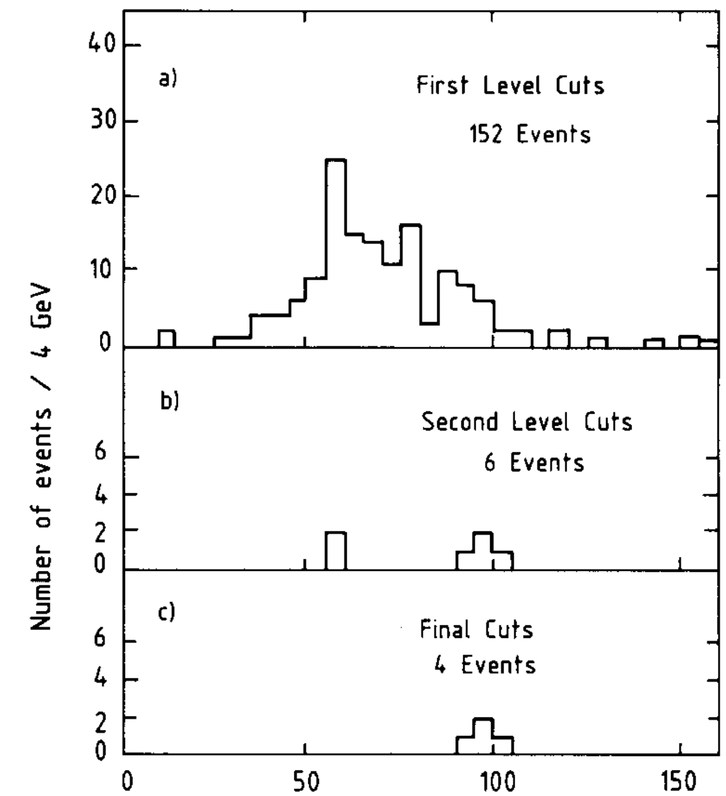
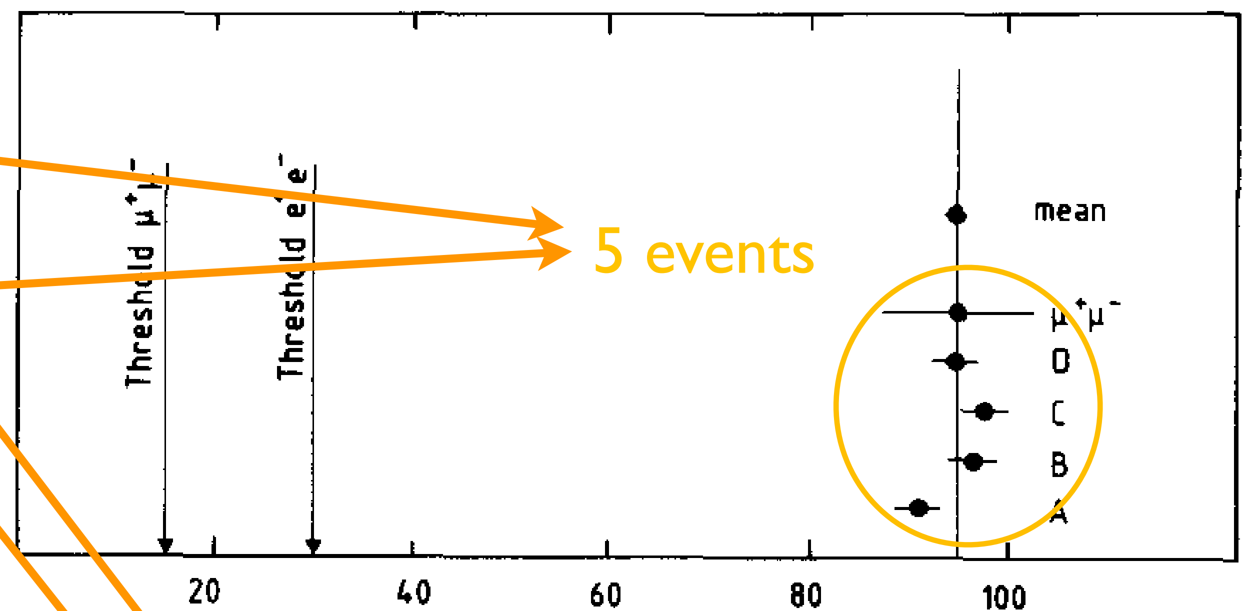


invariant mass of two EM clusters [GeV]

all

at the end of a track

"isolation"



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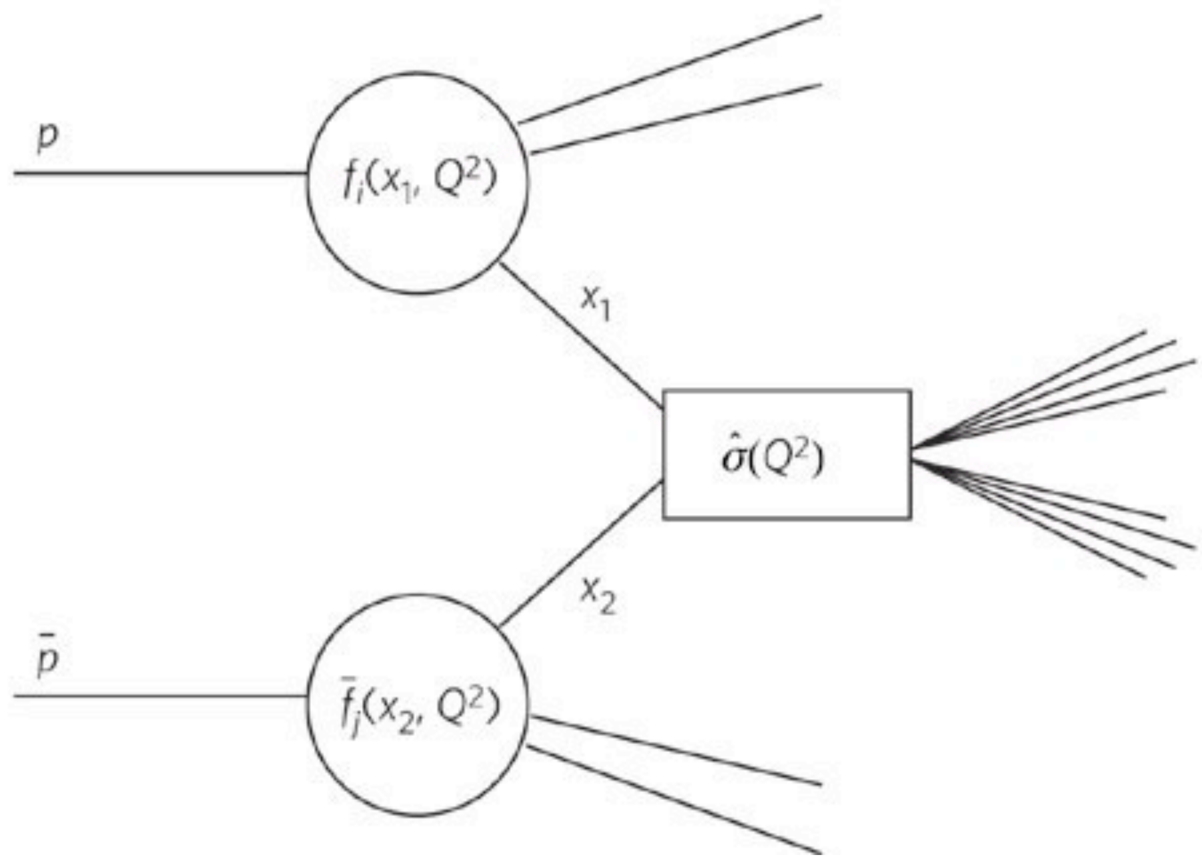
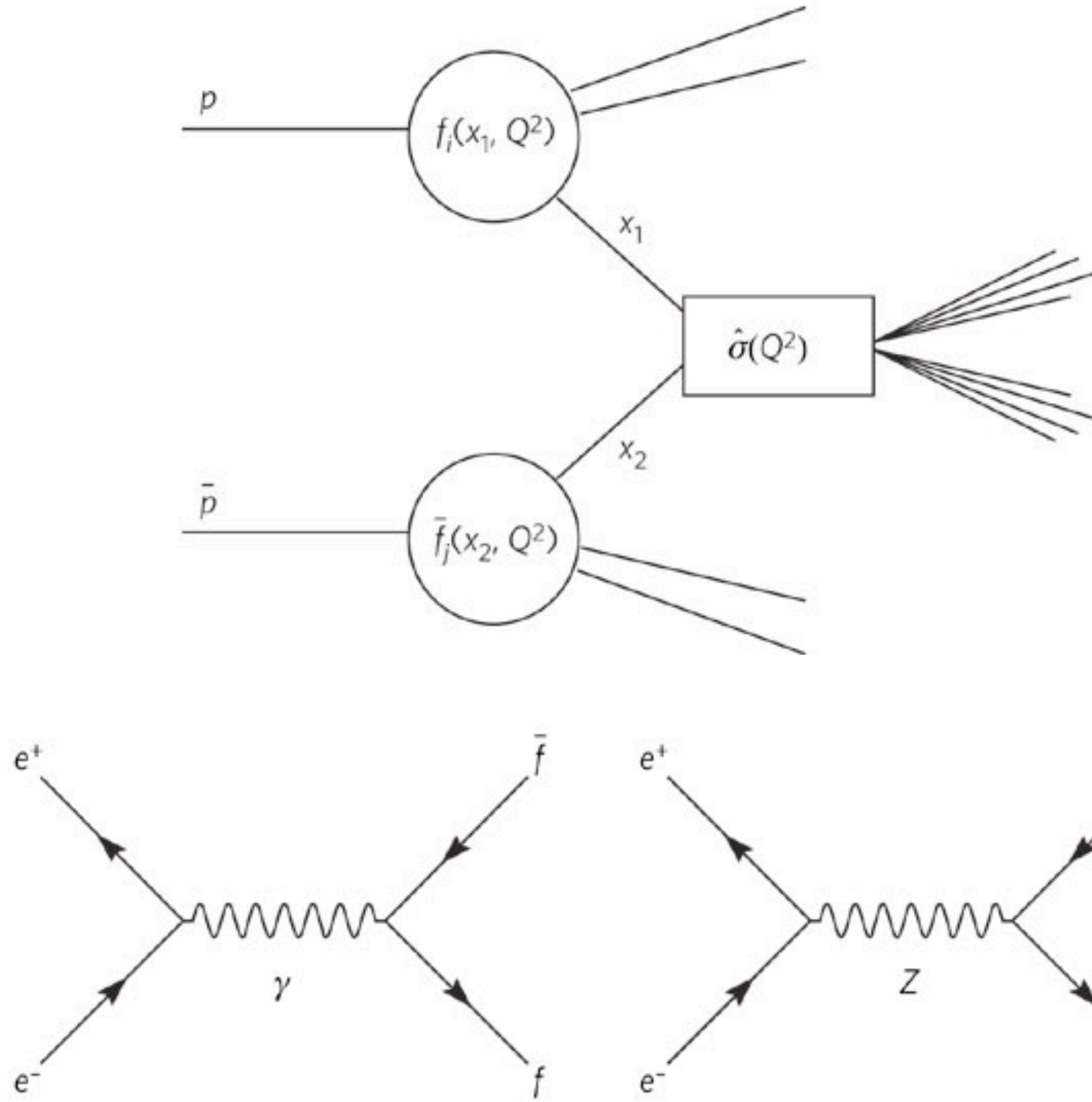
lepton universality

Arnison, G. *et al*. (UA1 Collaboration). Experimental observation of lepton pairs of invariant mass around 95 GeV/c^2 at the CERN SPS collider. *Phys. Lett. B* **126**, 398–410 (1983).

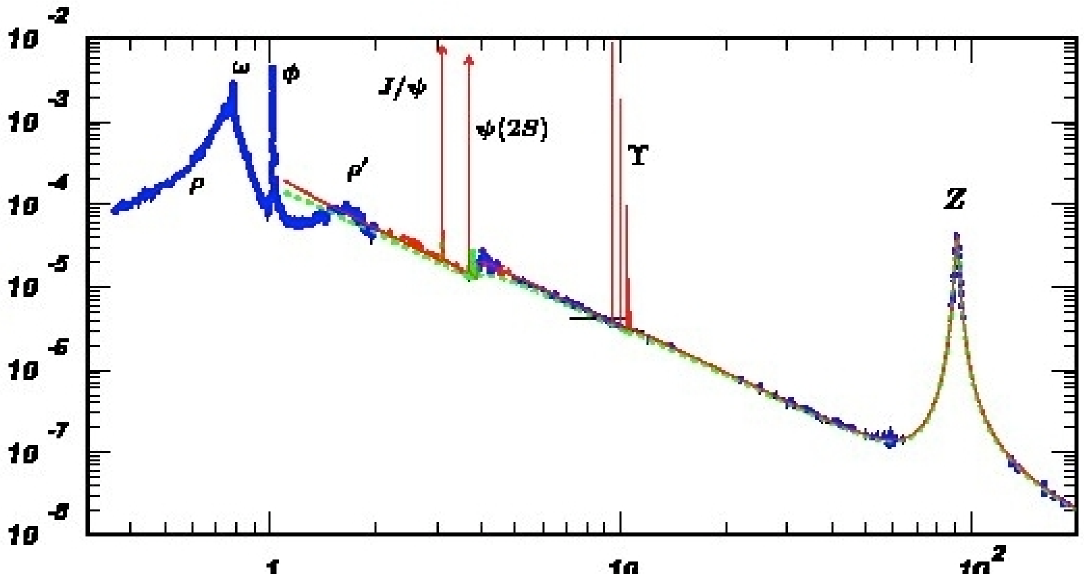
Comparing $\bar{p}p$ with e^+e^-



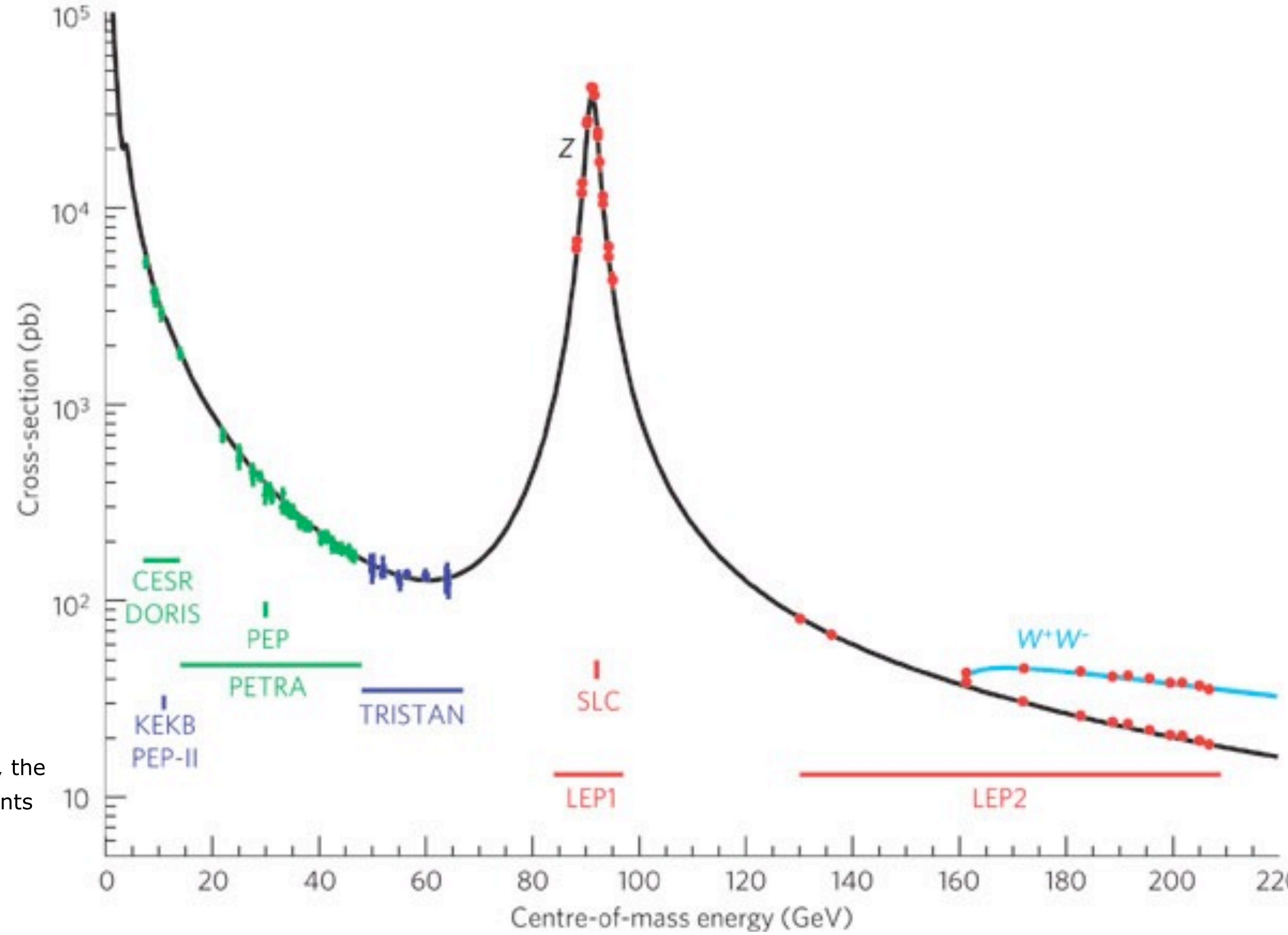
Comparing $\bar{p}p$ with e^+e^-



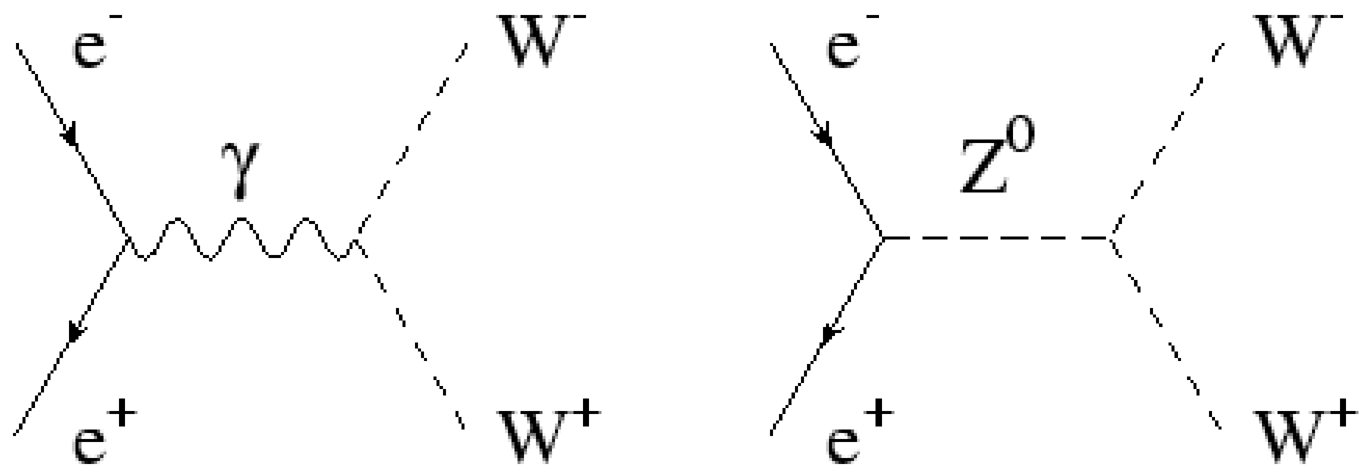
e^+e^- colliders up to LEP

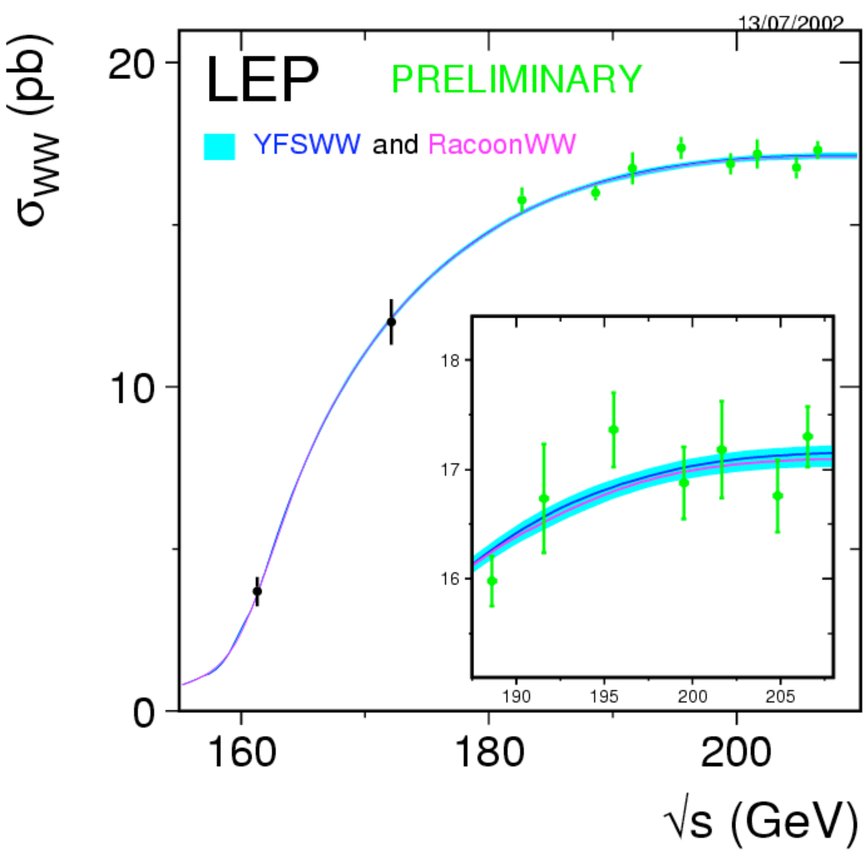


ALEPH, DELPHI, L3, OPAL, SLD collaborations, LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavour Groups. Precision electroweak measurements on the *Z* resonance. *Phys. Rep.* **427**, 257–454 (2006)



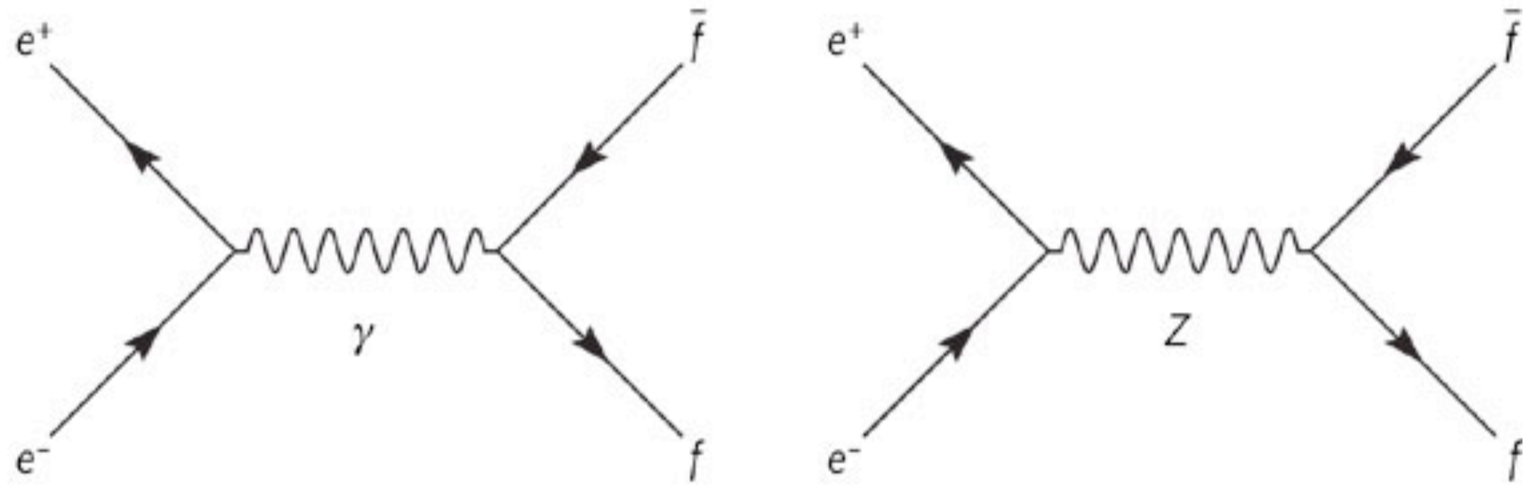
W pair production (LEP2)





many (confirming) results.....
but the t was still missing....

Interference effects in $e^+e^- \rightarrow f\bar{f}$



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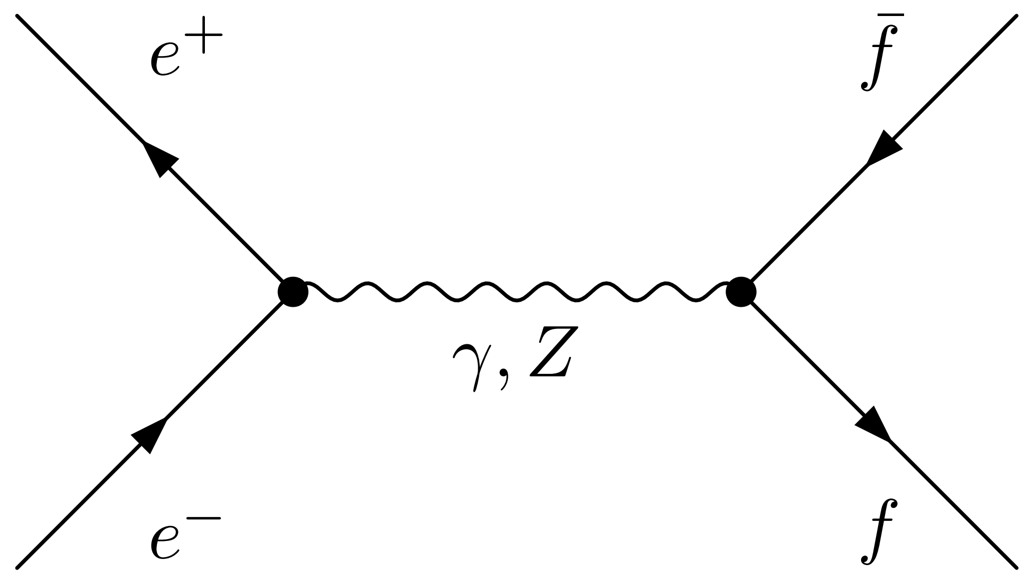

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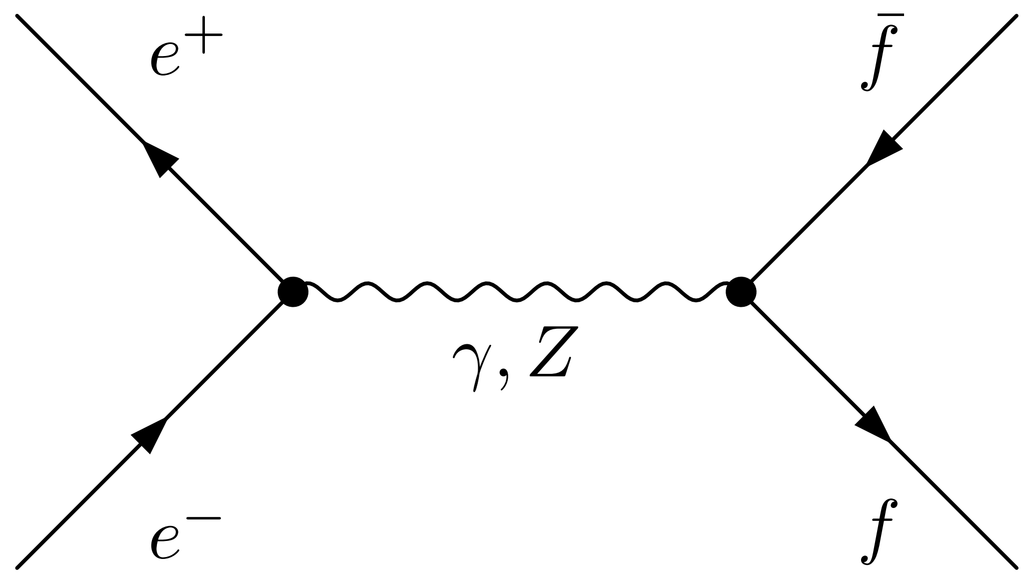

interference from presence of axial+vector couplings of leptons, quarks to Z

$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma_{f\bar{f}}(1 + \cos^2\theta + \frac{8}{3}A^f_{FB}\cos\theta),$$

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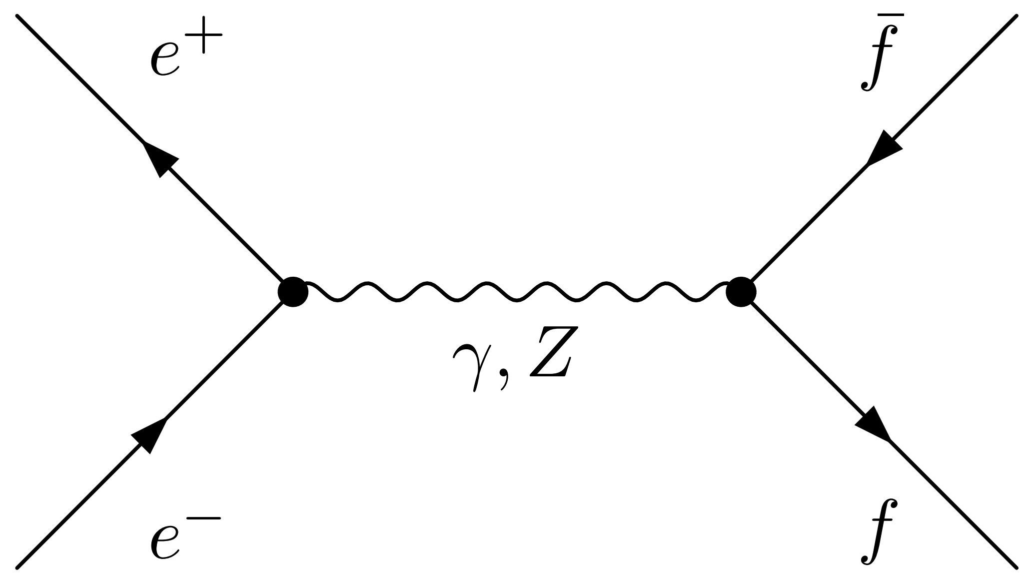

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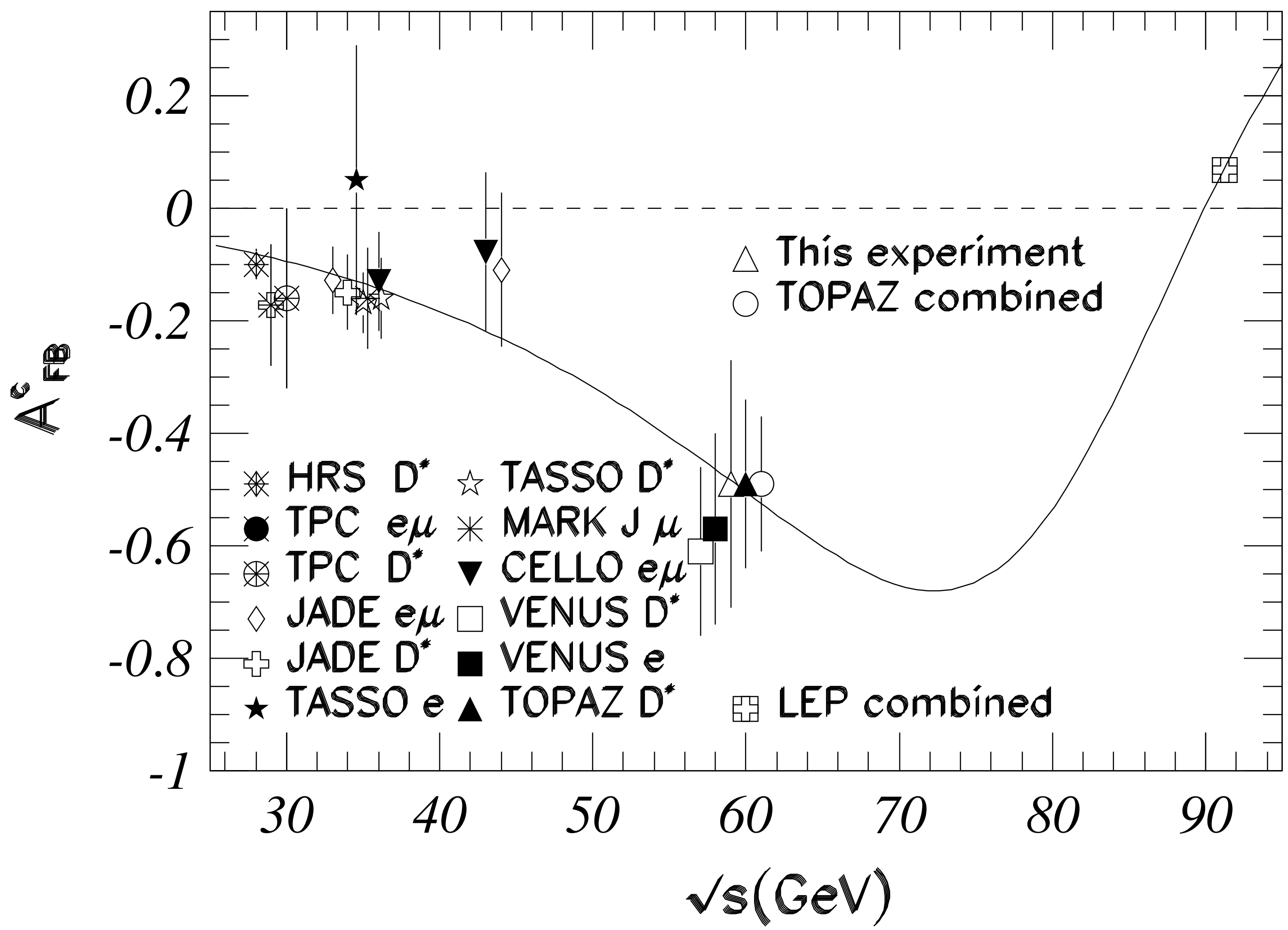
Effects small and swamped by huge Z exchange cross section on Z pole

A_{FB} depends on weak isospin, charge of quarks. At TRISTAN (60 GeV):

$$A^c_{FB} = -0.47,$$
$$A^b_{FB} = -0.59$$

TRISTAN at KEK (60 GeV)



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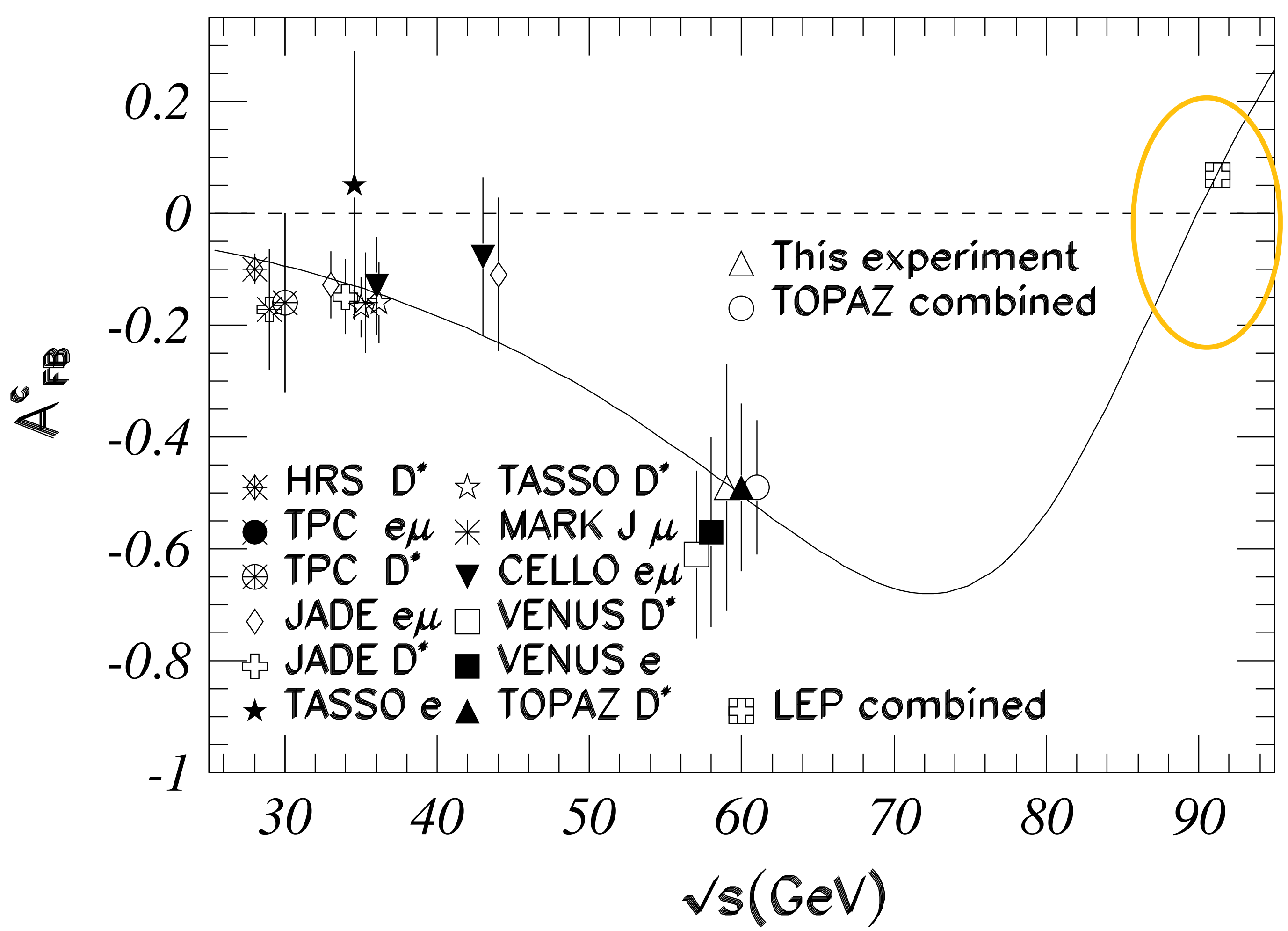
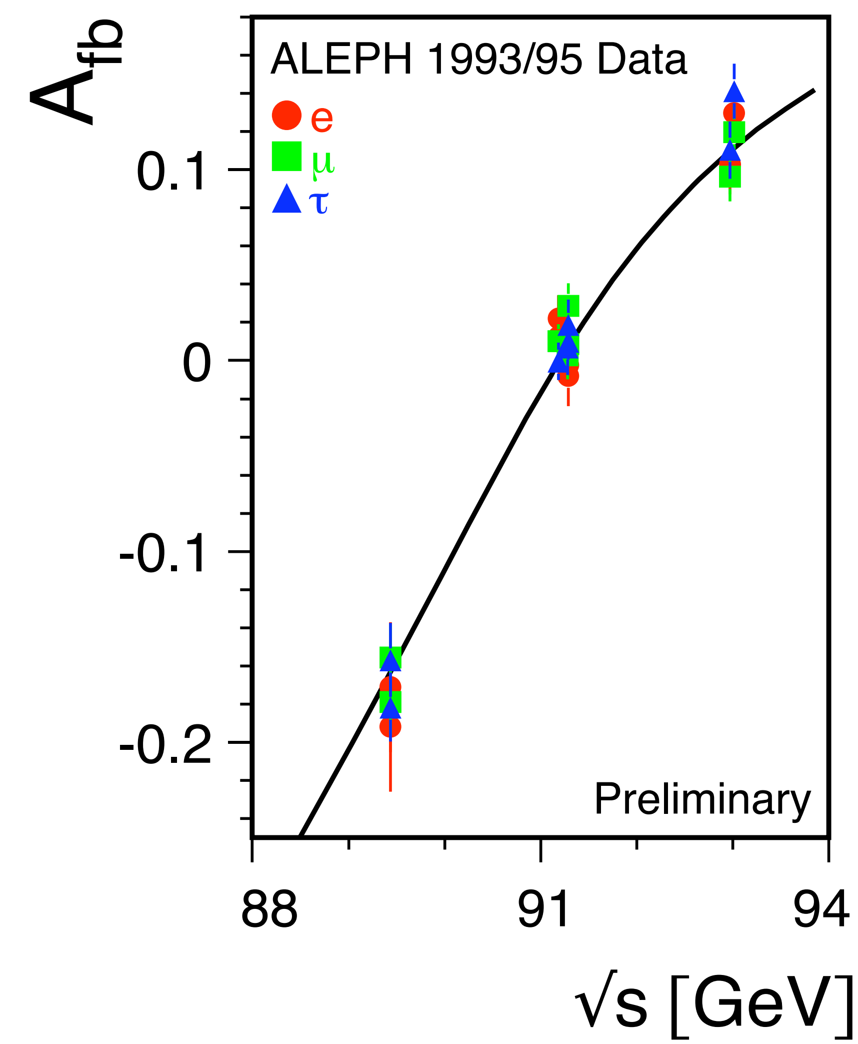


ALEPH at LEP (90 GeV)



LEP and SLD

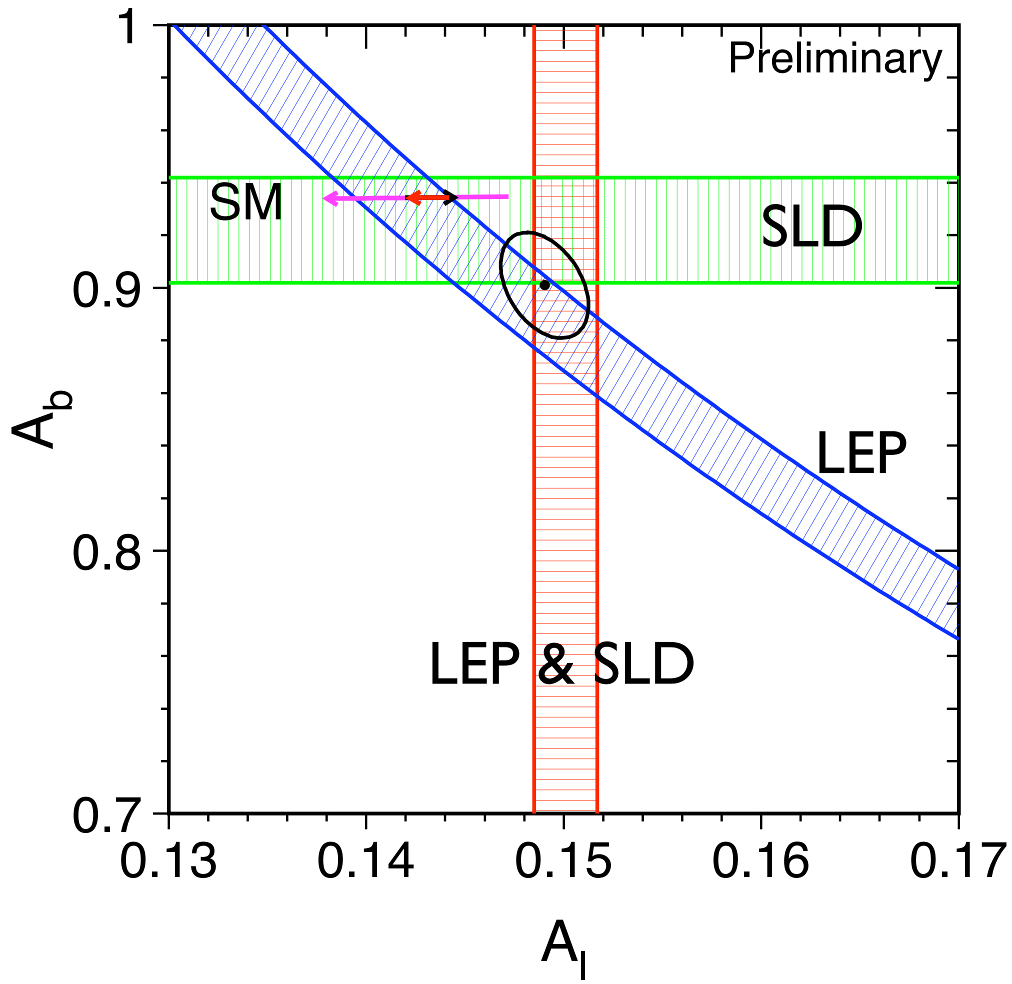
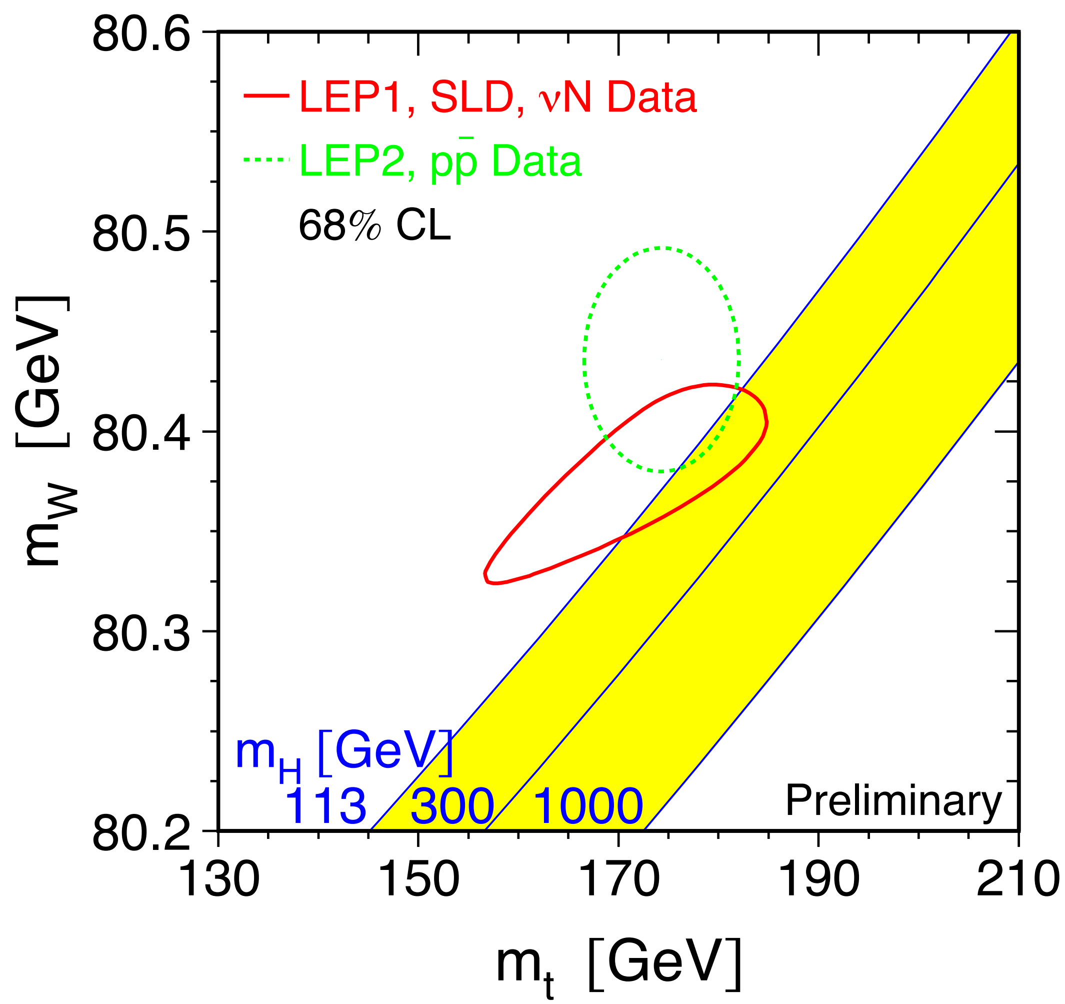


Figure 5. The measurements of the combined LEP+SLD $\mathcal{A}_l$ (vertical band), SLD $\mathcal{A}_b$ (horizontal band) and LEP $A_{FB}^{b,0}$ (diagonal band), compared to the Standard Model expectation (arrow).



precision measurements were sensitive to m_t before top was discovered (and also sensitive to m_H)

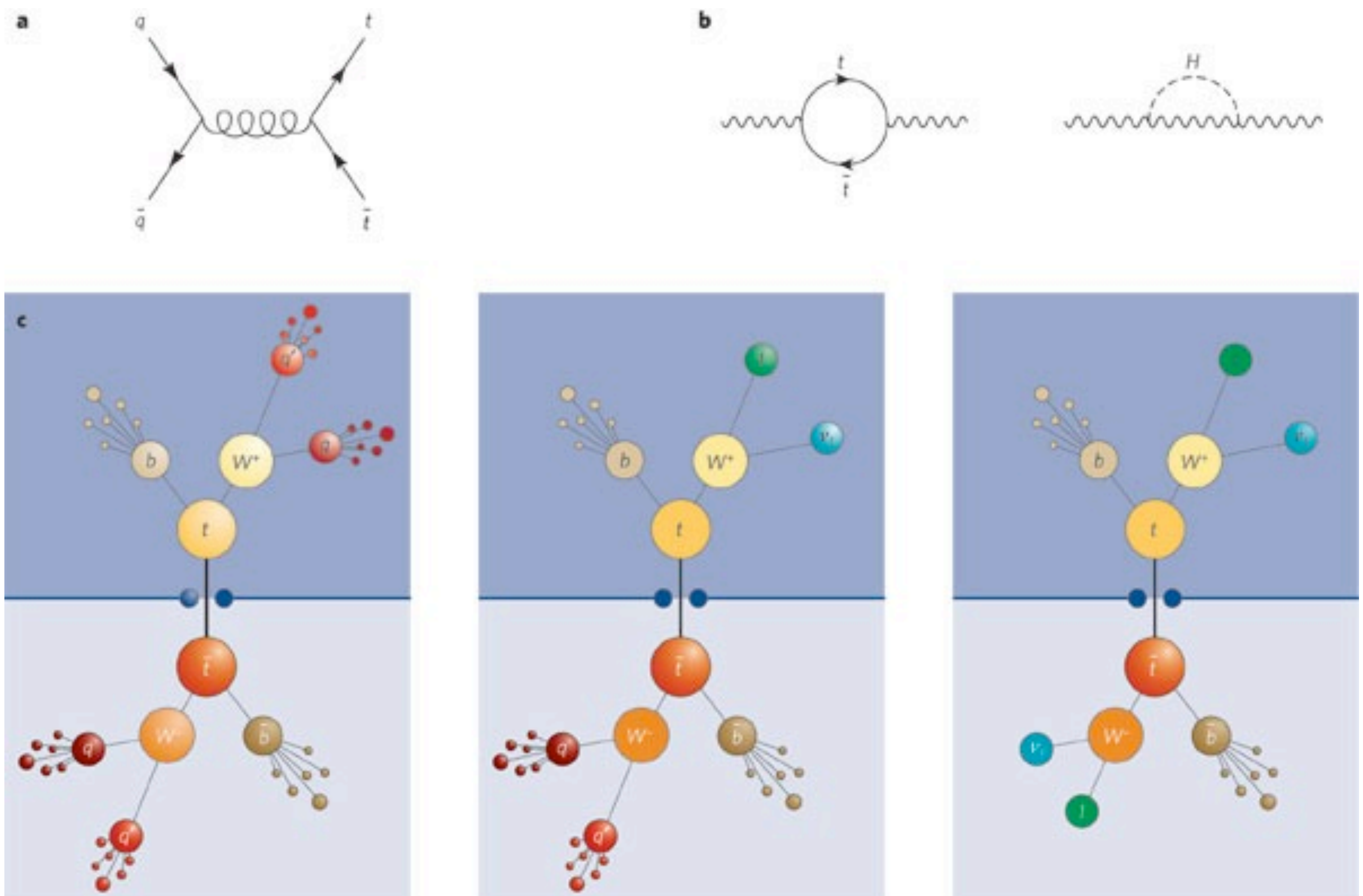
Tevatron:

top physics
W physics
search for Higgs

Tevatron: top physics

W physics

search for Higgs



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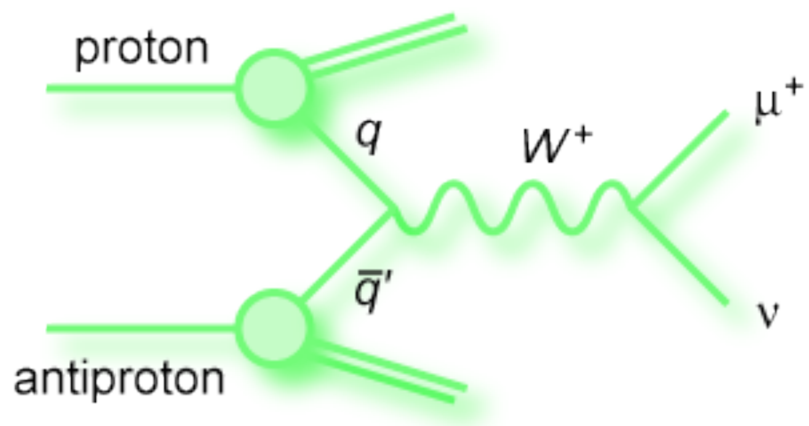

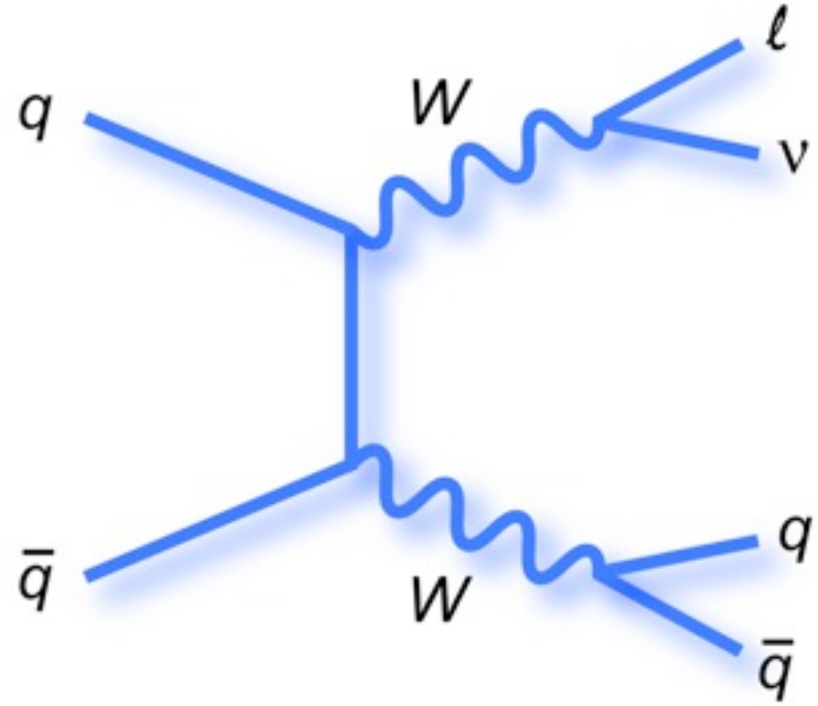

Tevatron:

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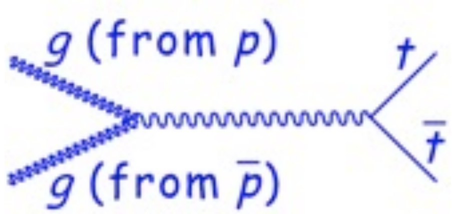
Tevatron: Discovery of the Top-Quark

FNAL: 1995

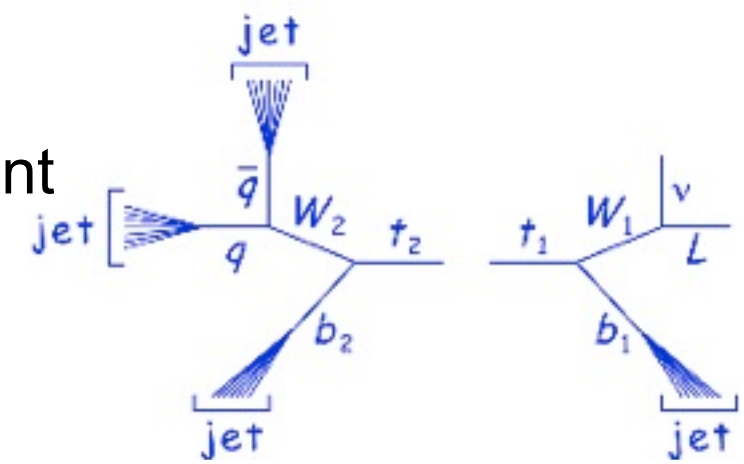
Tevatron : $\sqrt{s}$ = 1.8 TeV
Detectors : CDF, D∅

Dominant Production

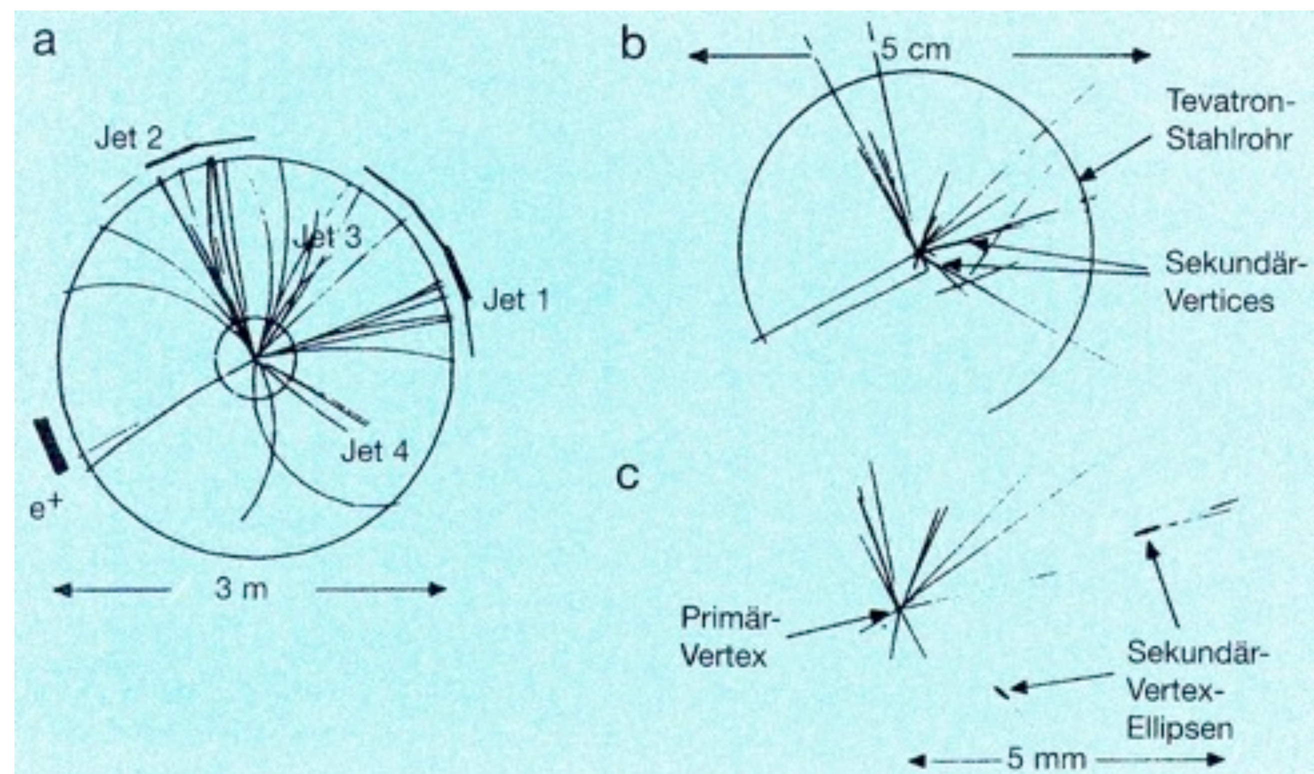


σ ≈ 4 pb (High p⊥)
(σTot ≈ 60 mb (10 o.m. bigger) (< p⊥ > ≈ 0.5 GeV))

Dominant Decay



Trigger on high p⊥ and secondary (b) vertex



⇒ m_t = (174.3 ± 5.1) GeV/c2

σ($p\bar{p}$) → $t\bar{t}$ in agreement with SM-predictions

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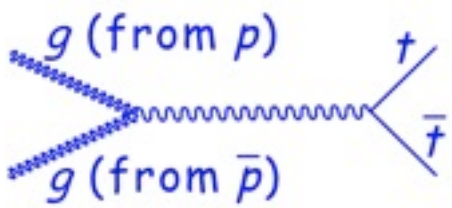

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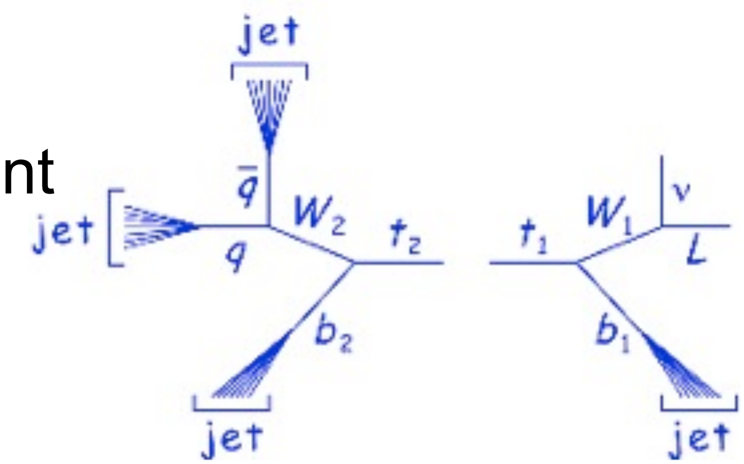
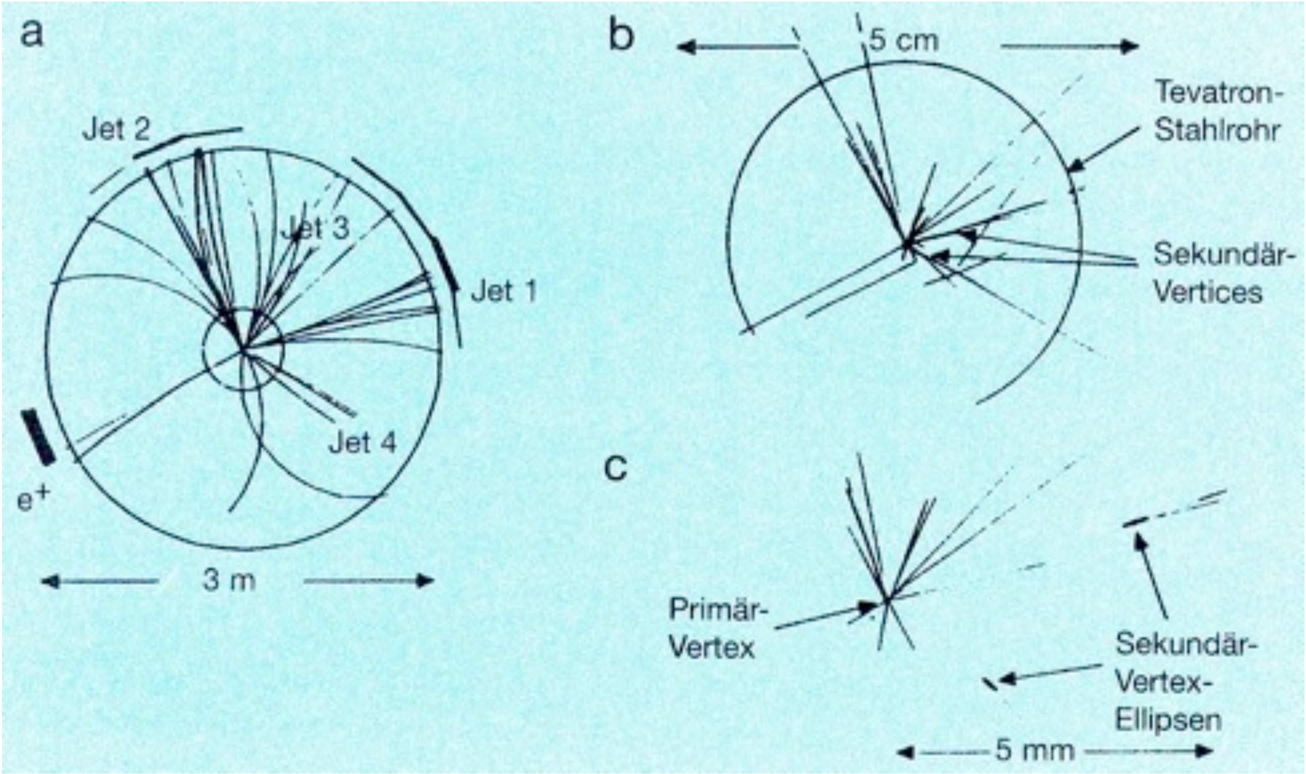
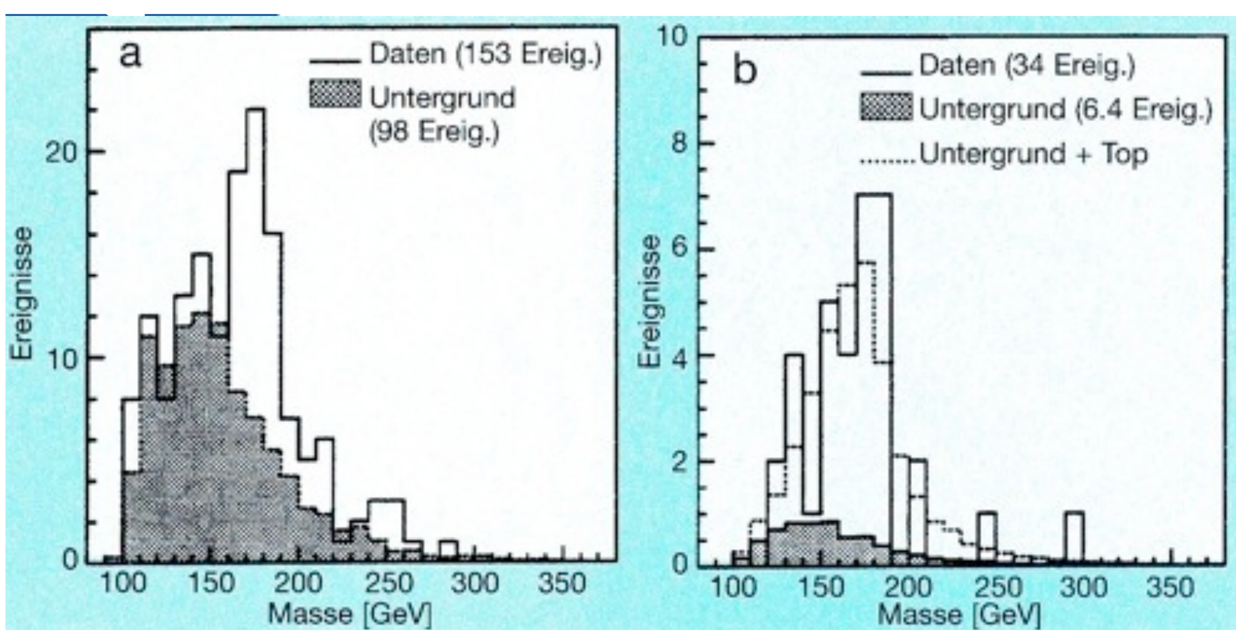
Dominant Decay



Trigger on high p⊥ and secondary (b) vertex



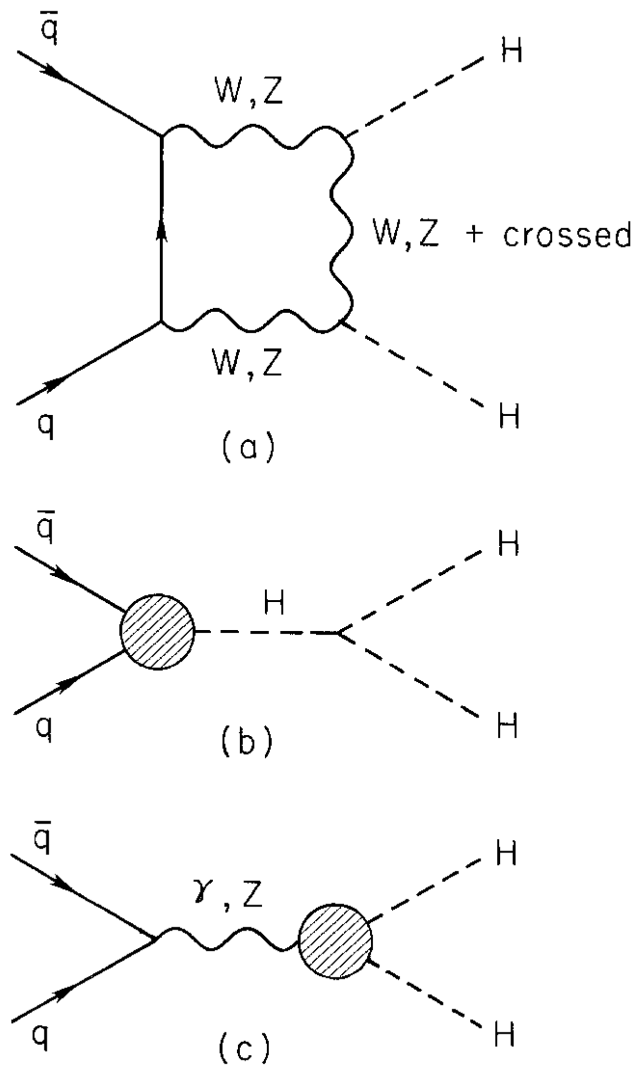


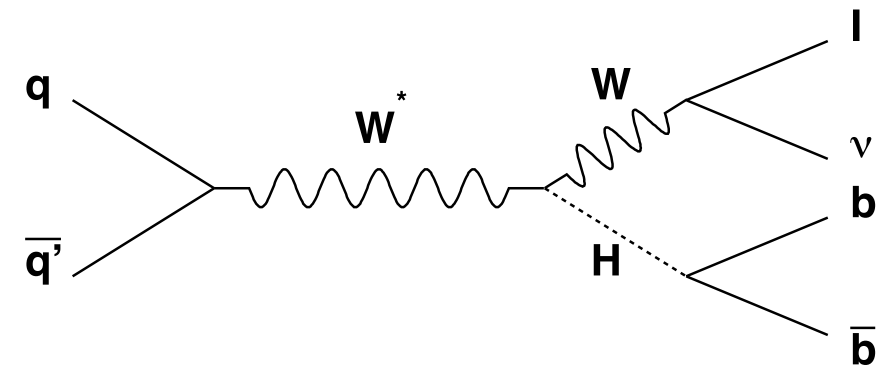
⇒ m_t = (174.3 ± 5.1) GeV/c2

σ(pp̄) → tt̄ in agreement with SM-predictions

Thursday, August 8, 2013

on to the Higgs; why not $\bar{p}p$?

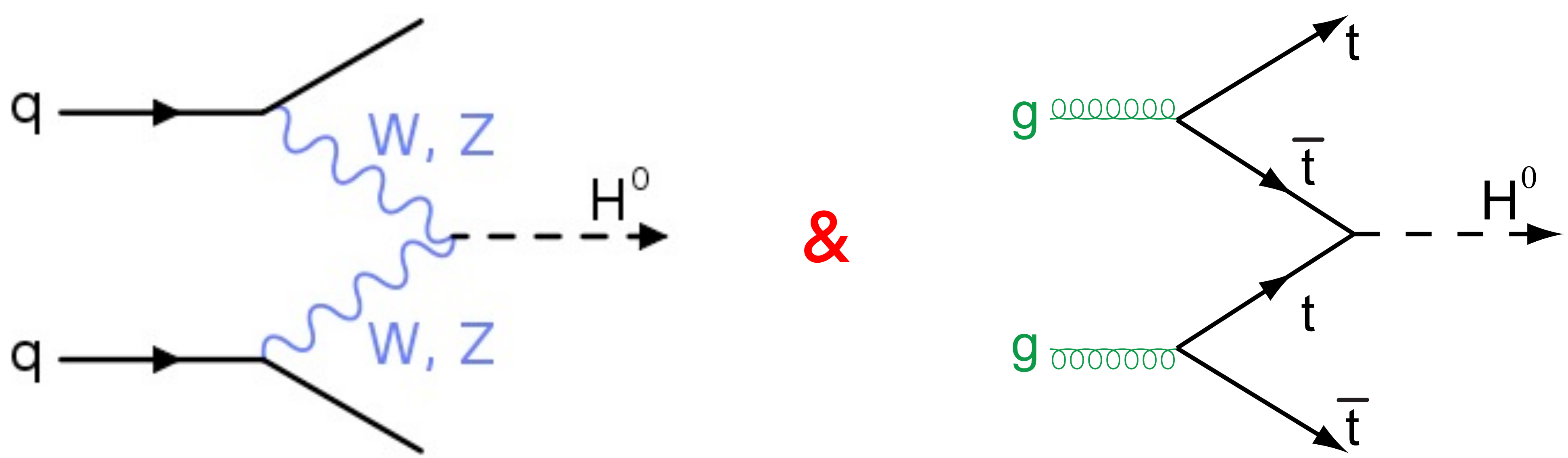


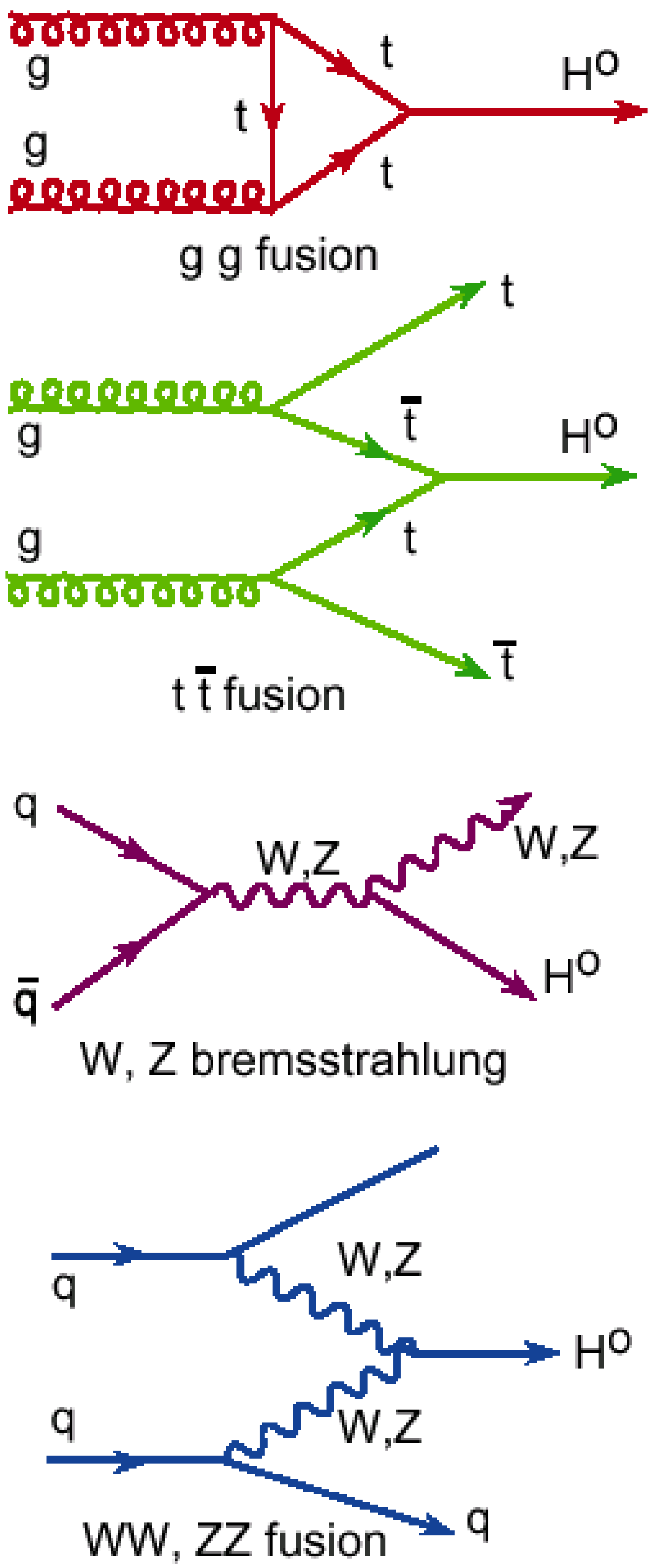


all perfectly respectable production mechanisms, but ...

on to the Higgs; why not $\bar{p}p$?

all perfectly respectable
production mechanisms, but ...

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W, Z bremsstrahlung
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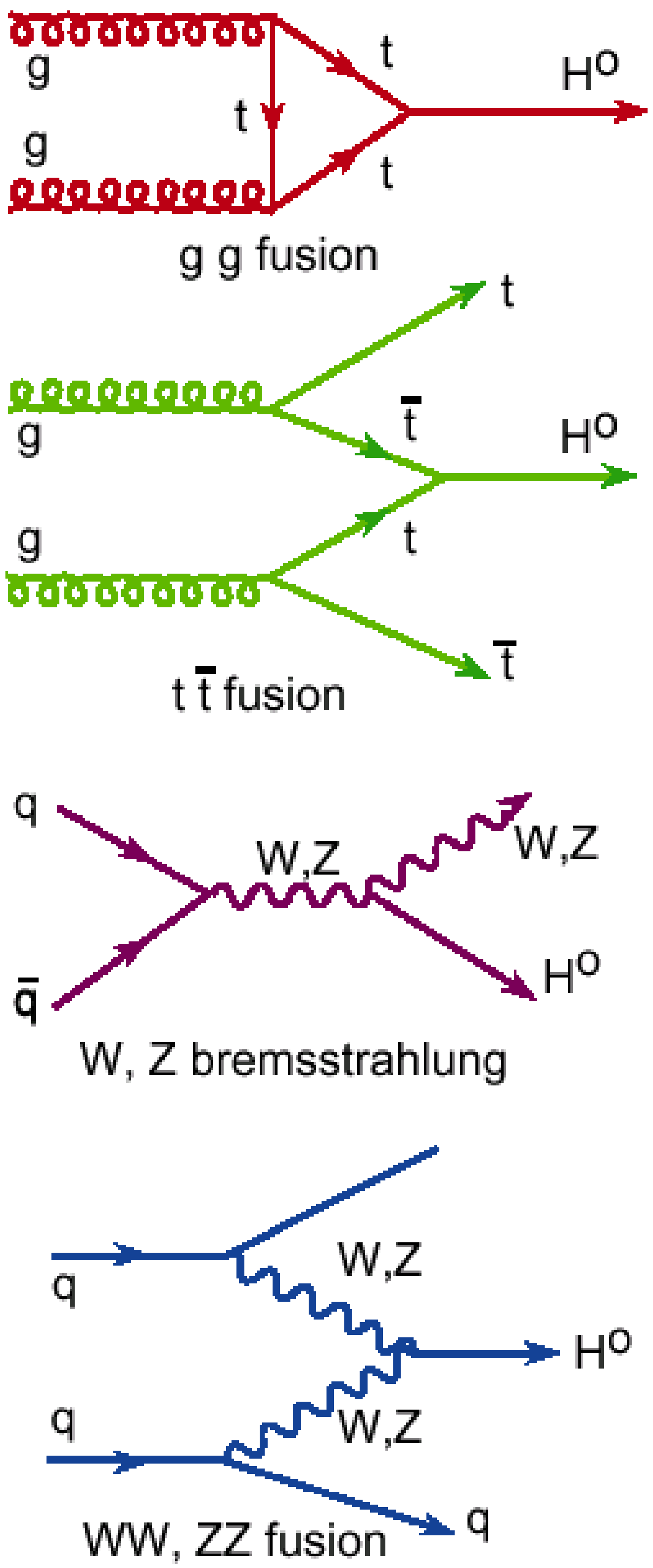
W,Z
q
WW, ZZ fusion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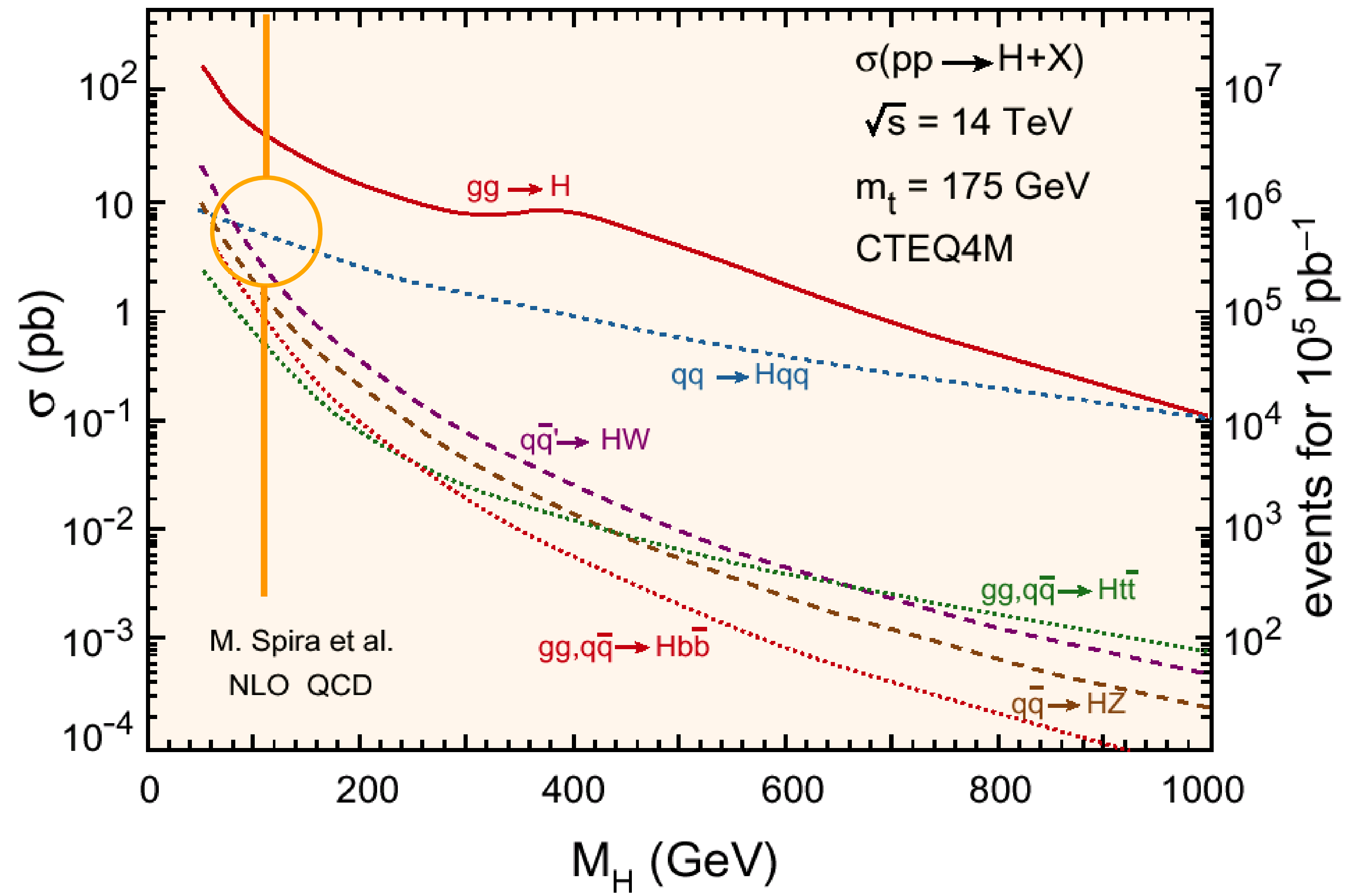
Hº
q
WW, ZZ fusion


σ(pp → H+X)
√s = 14 TeV
m_t = 175 GeV
CTEQ4M
gg → H
qq → Hqq
qq̄ → HW
gg,qq̄ → Htt̄
gg,qq̄ → Hbb̄
qq̄ → HZ
M. Spira et al.
NLO QCD
σ (pb)
events for 10^5 pb^-1
M_H (GeV)

Advantages of $\bar{p}$-p vs. p-p

Advantages of p-p vs. p-$\bar{p}$

Advantages of $\bar{p}$-p vs. p-p

higher reaction rates at low (~ 1TeV) energies for specific processes

Advantages of p-p vs. p-$\bar{p}$

higher reaction rates at high (~ 10 TeV) energies

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quark-antiquark fusion dominant at low energies

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gluon fusion is dominant process in any hadronic machine at high energies

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gluon fusion is dominant process in any hadronic machine at high energies

at high energies, gluon fusion is the dominant process, and the gluon pdf's are the same for p as for $\bar{p}$

Advantages of $\bar{p}$-p vs. p-p

higher reaction rates at low (~ 1TeV) energies for specific processes

quark-antiquark fusion dominant at low energies

one single set of magnet rings (counter-propagating beams, same charges)

Advantages of p-p vs. p-$\bar{p}$

higher reaction rates at high (~ 10 TeV) energies

gluon fusion is dominant process in any hadronic machine at high energies

two magnet rings required (counter-propagating beams, opposite charges)

at high energies, gluon fusion is the dominant process, and the gluon pdf's are the same for p as for $\bar{p}$

Advantages of $\bar{p}$-p vs. p-p

higher reaction rates at low (~ 1 TeV) energies for specific processes

quark-antiquark fusion dominant at low energies

Advantages of p-p vs. p-$\bar{p}$

higher reaction rates at high (~ 10 TeV) energies

gluon fusion is dominant process in any hadronic machine at high energies

at high energies, gluon fusion is the dominant process, and the gluon pdf's are the same for p as for $\bar{p}$

one single set of magnet rings (counter-propagating beams, same charges)

two magnet rings required (counter-propagating beams, opposite charges)

far easier production of projectiles (antiproton production and cooling is still very difficult and inefficient)

Overview:

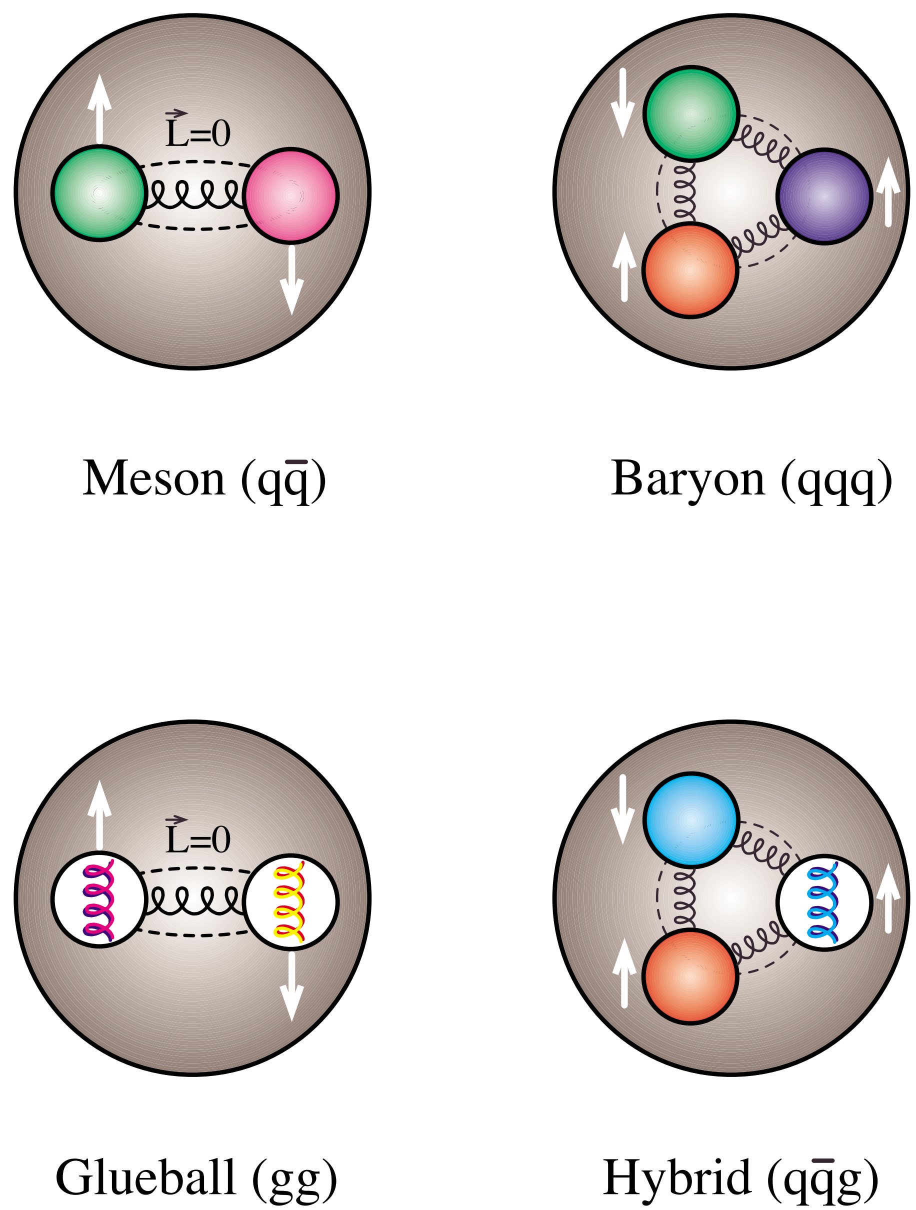
1. Introduction and overview
2. Antimatter at high energies (SppS, LEP, Fermilab)
3. Meson spectroscopy (antimatter as QCD probe)

4. Astroparticle physics and cosmology
5. CP and CPT violation tests
6. Precision tests with Antimatter

7. Precision tests with Antihydrogen
8. Applications of antimatter

Testing QCD with antimatter

QCD



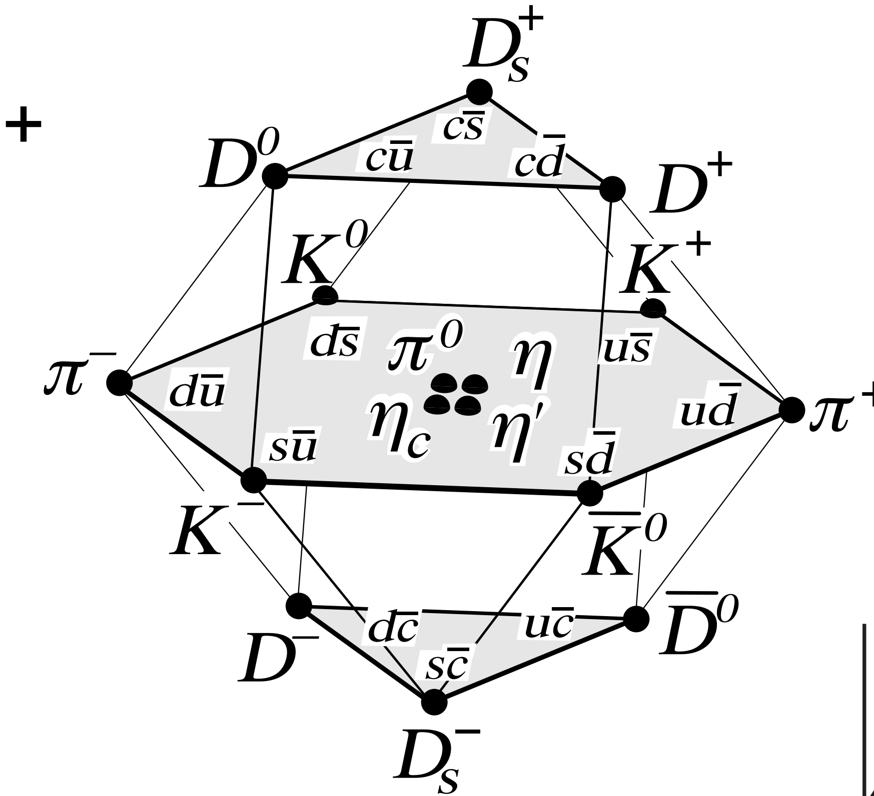
$q\bar{q}$ states

Classification scheme: multiplets

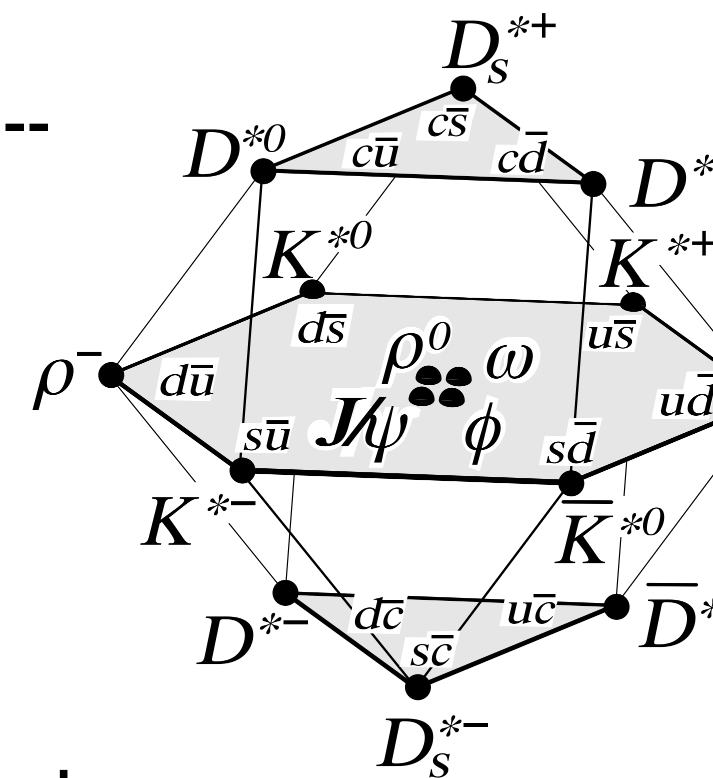
$P(\bar{q}q) = (-1)^L$

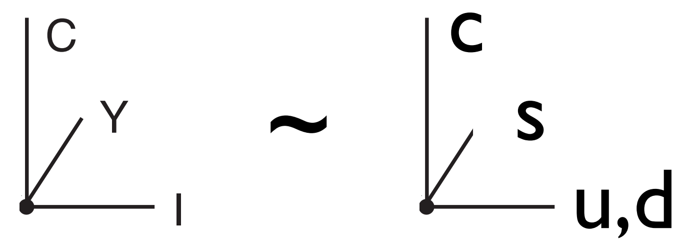
$C(\bar{q}q) = (-1)^{L+S}$

0^{-+}



1^{--}





3 quarks: SU(3) $3 \otimes 3 = 8 \oplus 1$ symmetry breaking through quark mass difference

But of course, there are gluons, virtual quark-antiquark pairs, leading to a whole cryptozoology of exotics (glueballs, hybdrids, pentaquarks, ...)

Testing the quark model = search for non-$\bar{q}q$ states

fermionic system

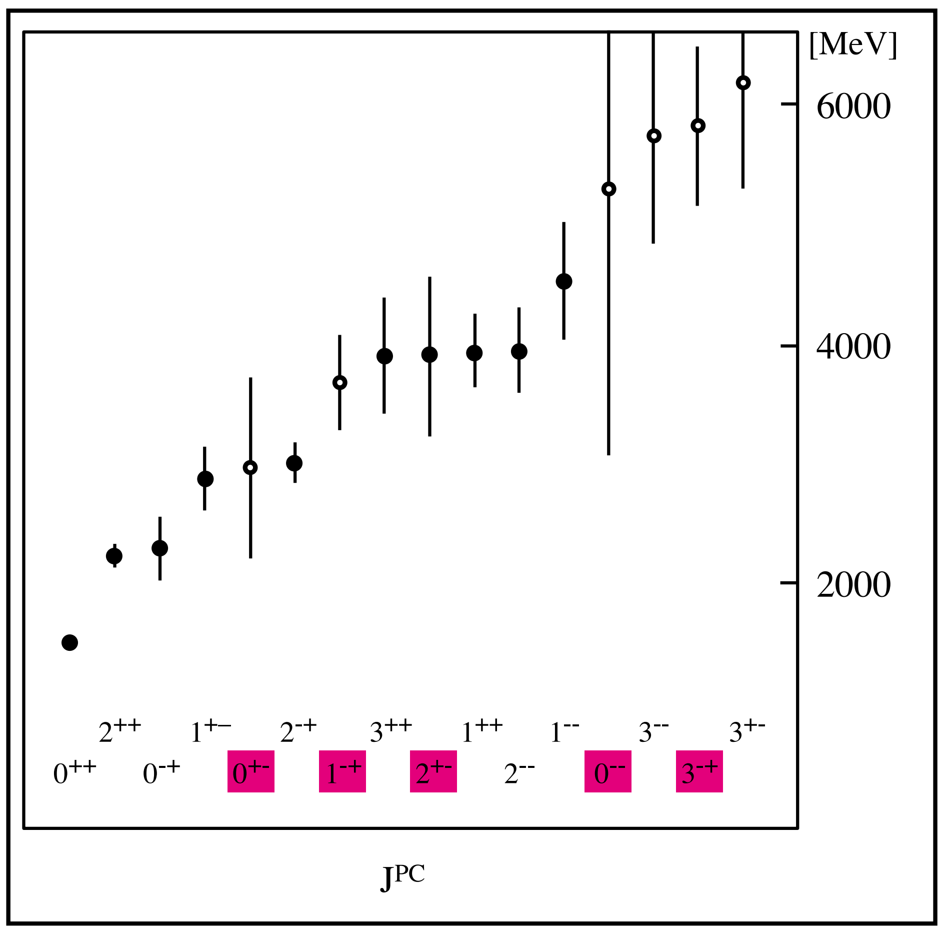
$$P(\bar{q}q) = (-1)^{L}$$
$$C(\bar{q}q) = (-1)^{L+S}$$

mesons

bosonic system

$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

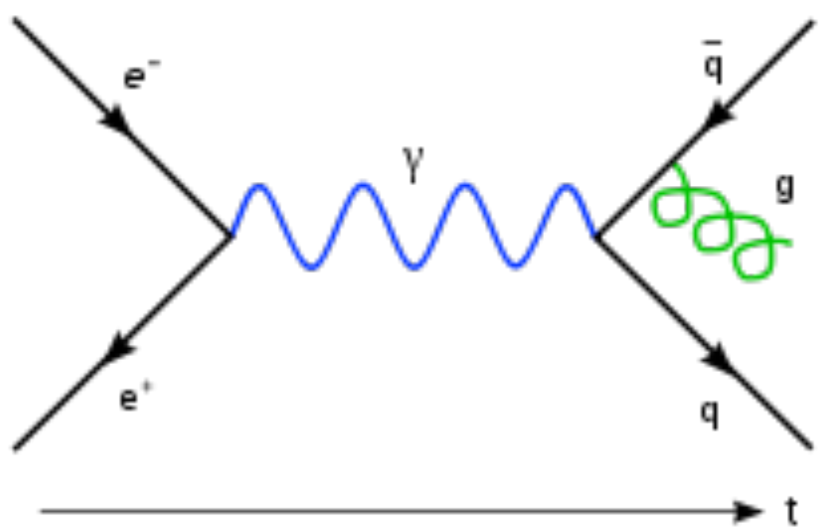
glueballs



The glueball spectrum predicted by lattice calculations [10]. Exotic quantum numbers are marked as boxes.

color charge: gluons couple to other gluons and can form bound states

Evidence for gluons: e^+e^- annihilation



The idea of searching for gluon jets had actually been proposed by John Ellis, Mary Gaillard and Graham Ross in a seminal paper that appeared in 1976. Under the apparently imperative title "Search for Gluons in e^+-e^- Annihilation", the authors suggested the existence of "hard-gluon bremsstrahlung", which should give rise to events with three jets in the final state. According to the laws of field theory, the outgoing quarks can radiate field quanta of the strong interaction, i.e. gluons, which should in turn fragment into hadrons and thus create a third hadron jet forming a plane with the other two (see figure 1). At the particle energies of up to 15GeV per beam delivered by DESY's newly built PETRA electron-positron storage ring, the probability for such hard-gluon bremsstrahlung processes to occur might amount to a few percent.

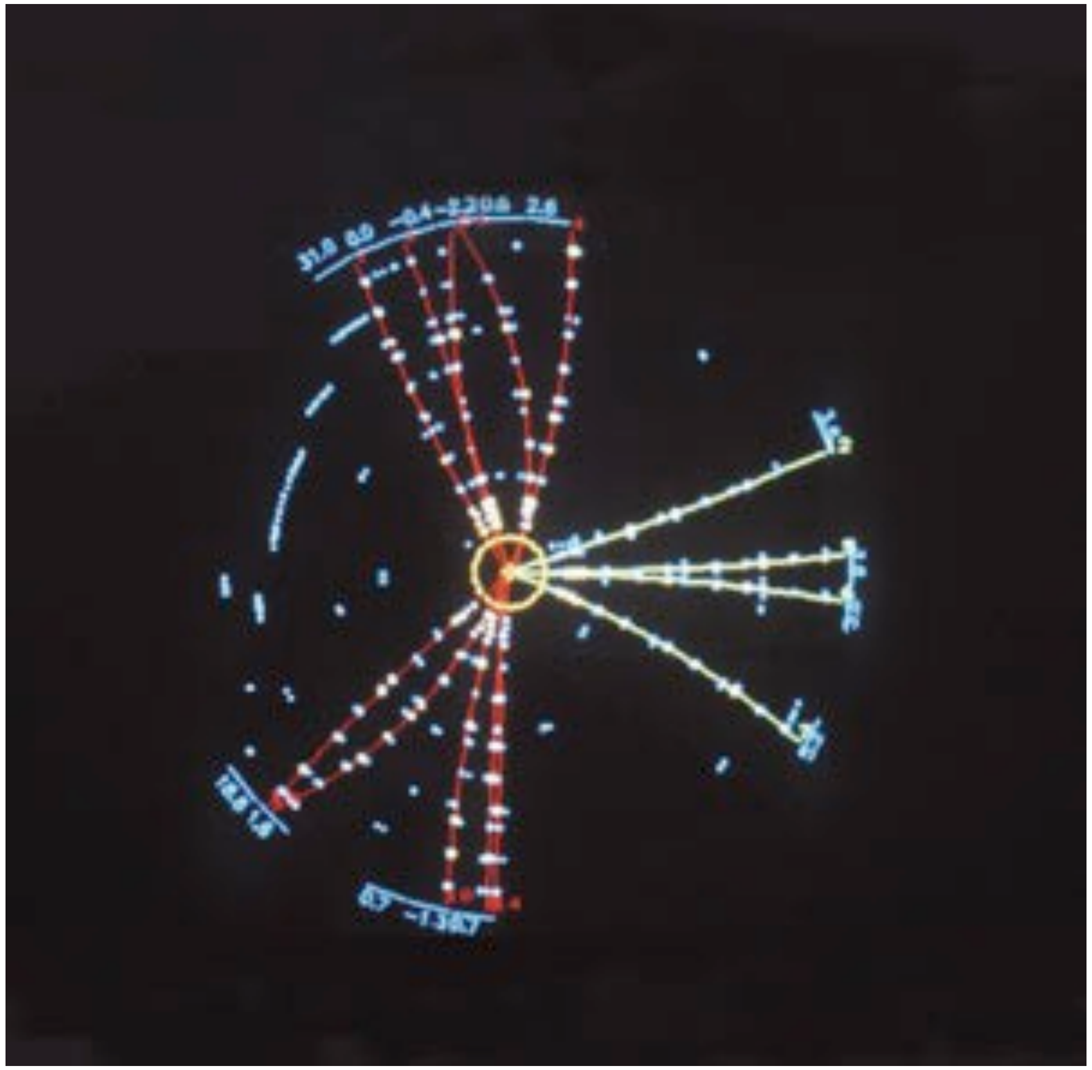


Fig. 10.19 The same as Fig. 10.17 except that this event is one of the rare, separated, three jet events. The total energy is 35.16 GeV.

TASSO experiment at DESY (PETRA, 1978)

Antiproton-proton annihilation (at rest)

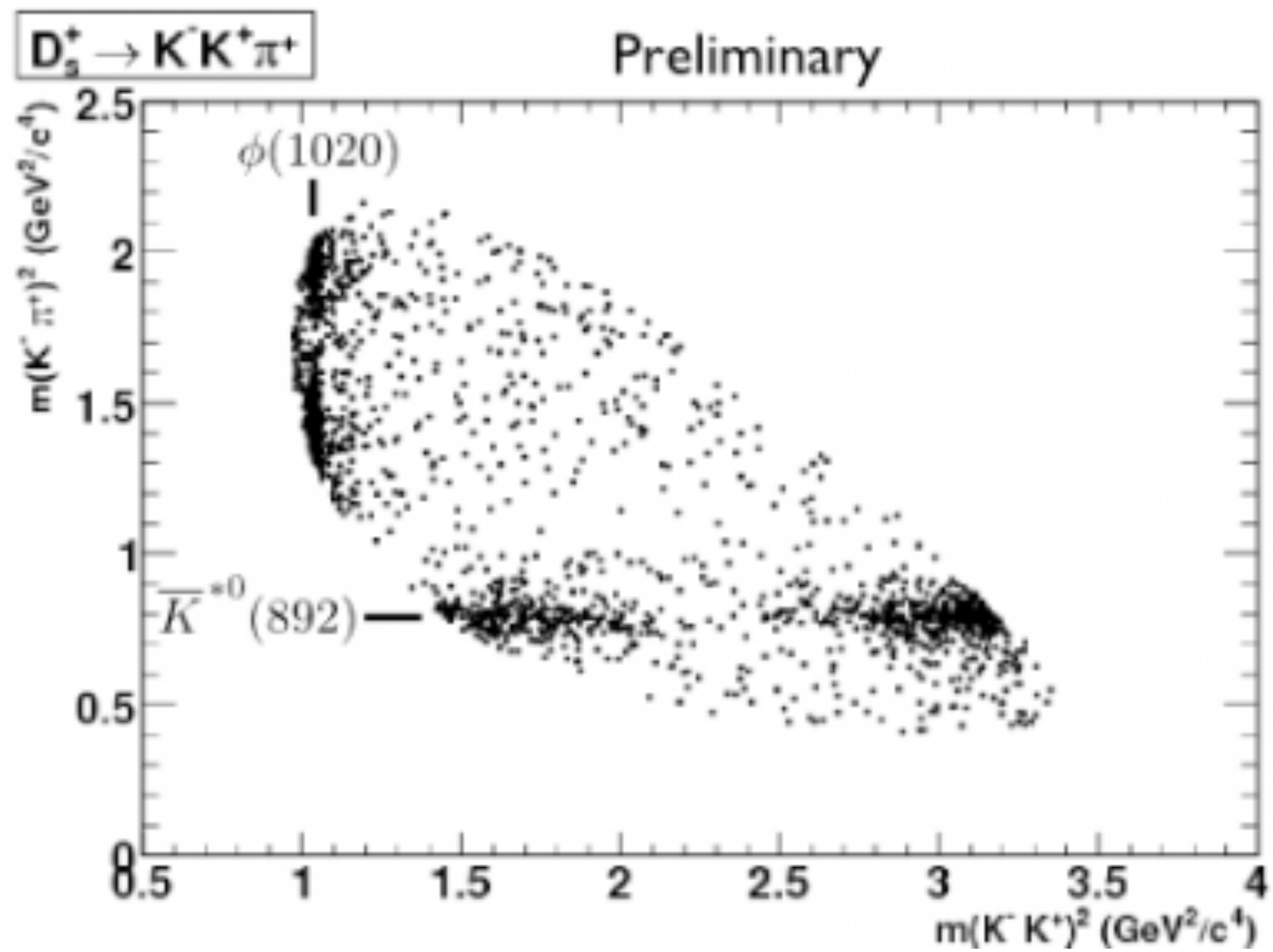
Available energy = 2 m_p <annihilation> ~ 3π

Dalitz plot (any 3-body final state)

m^2 is relativistically invariant;
plot m^2_{12} vs. m^2_{23}

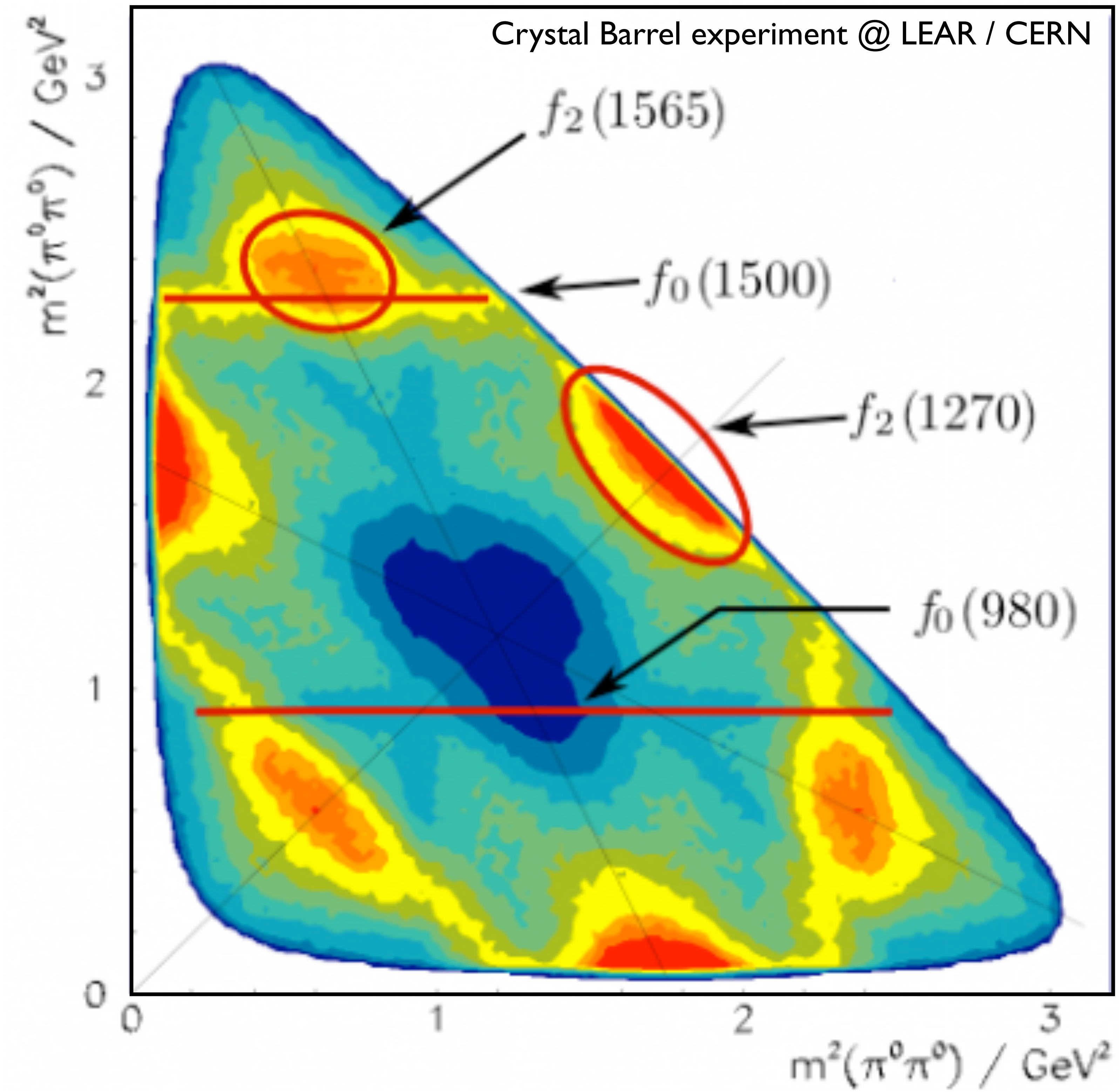
energy-momentum conservation
= limits of contour

no resonances = uniform population
intermediate states = structures

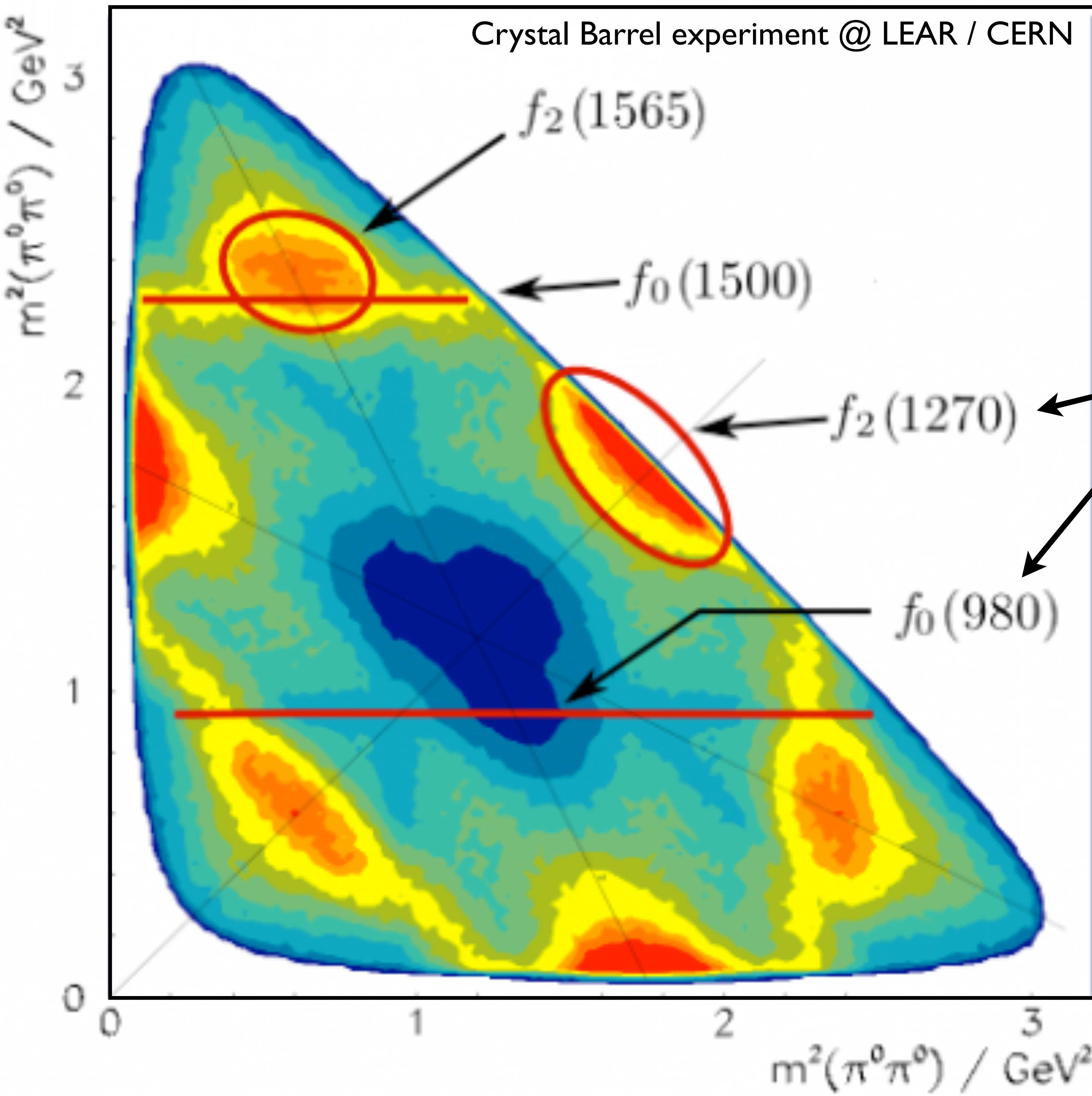


http://superweak.wordpress.com/2006/07/31/dalitz-plots/

$p\bar{p} \rightarrow 3\pi^0$

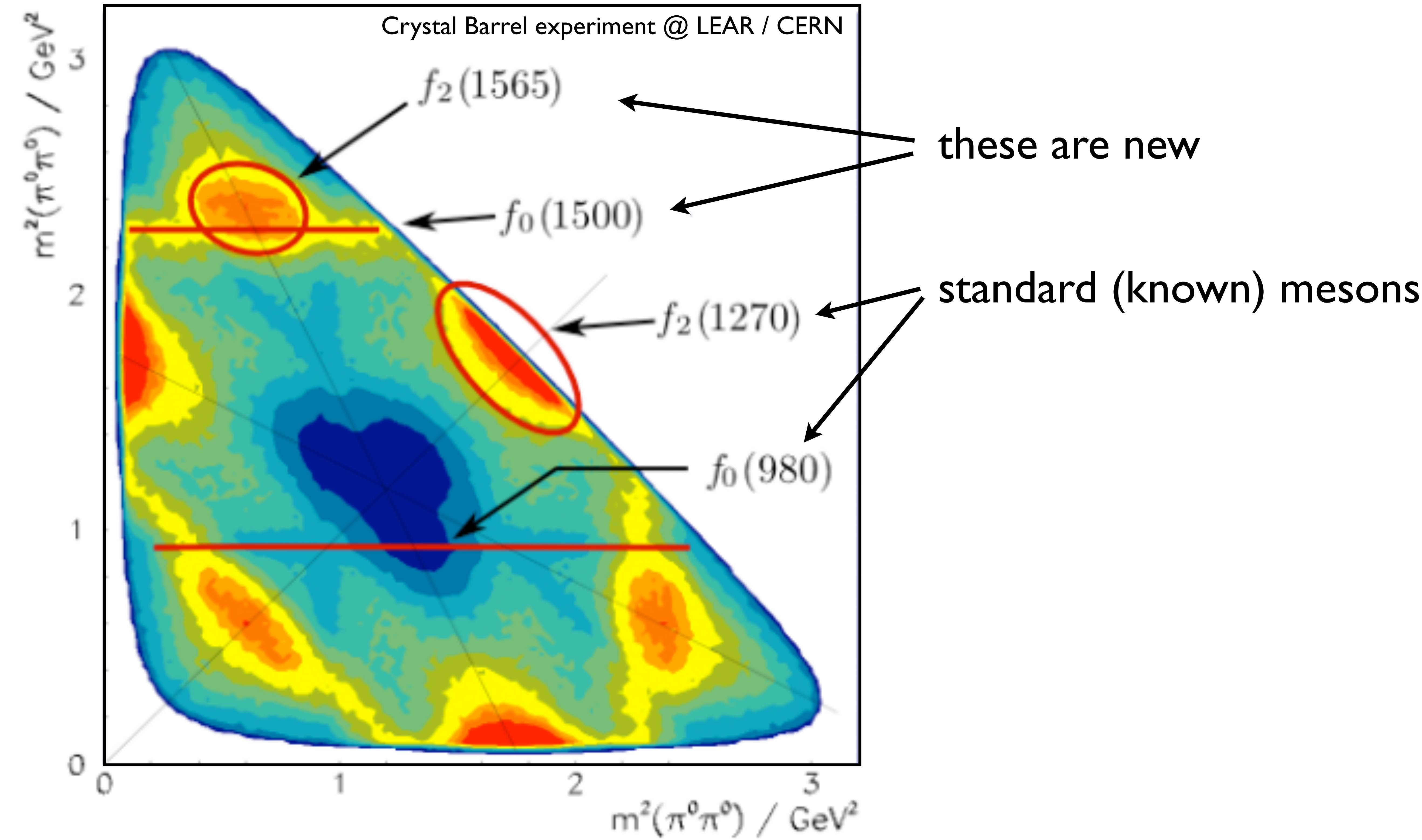


$p\bar{p} \rightarrow 3\pi^0$

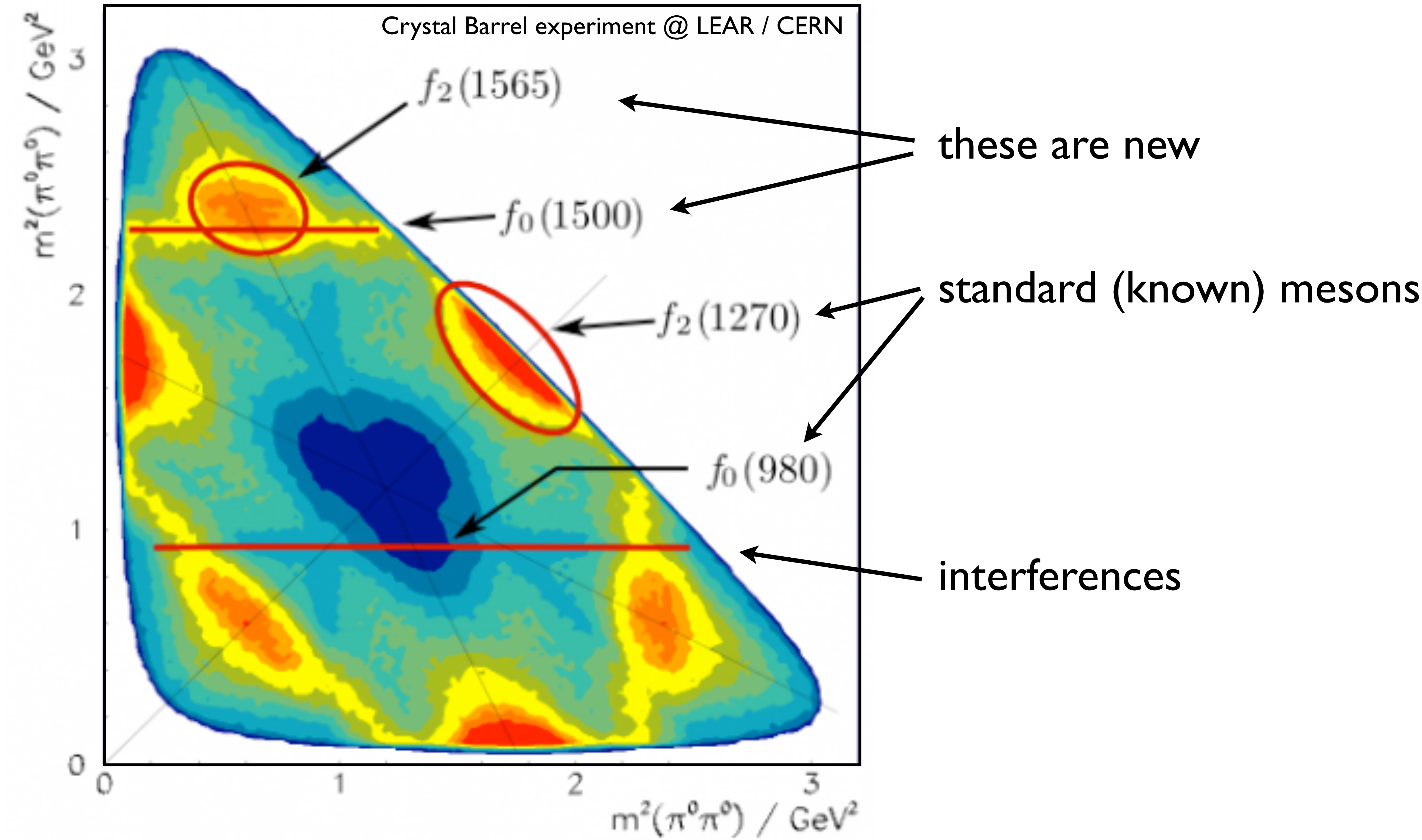


standard (known) mesons

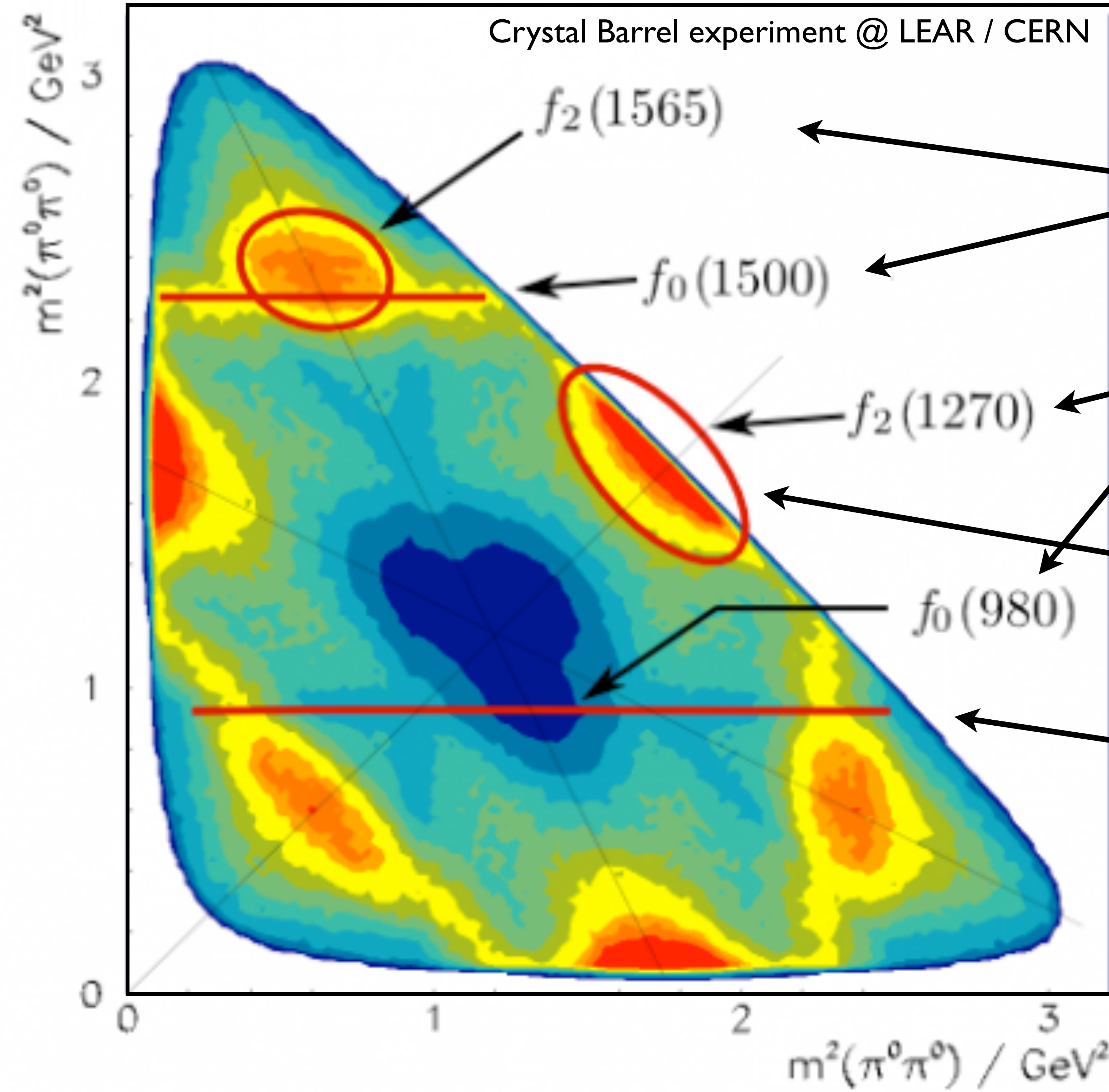
$p\bar{p} \rightarrow 3\pi^0$



$p\bar{p} \rightarrow 3\pi^0$



$p\bar{p} \rightarrow 3\pi^0$



these are new

standard (known) mesons

angular distribution ~ J^{PC}

interferences

Dalitz plot formalism

3-body decay of a spin 0 particle into pseudoscalars

$$\Gamma = \frac{1}{(2\pi)^3 32\sqrt{s^3}} \left|\mathcal{M}\right|^2 dm_{ab}^2\, dm_{bc}^2\,,$$

kinematic factors dynamics

$\left|\mathcal{M}\right|^2$ constant = uniform population

non-uniform population = dynamics

helicity states

$R \to rc, r \to ab$

$$\mathcal{M}_r(J,L,l,m_{ab},m_{bc}) = \sum_{\lambda} \langle ab|r_\lambda\rangle\, T_r(m_{ab})\, \langle cr_\lambda|R_J\rangle$$

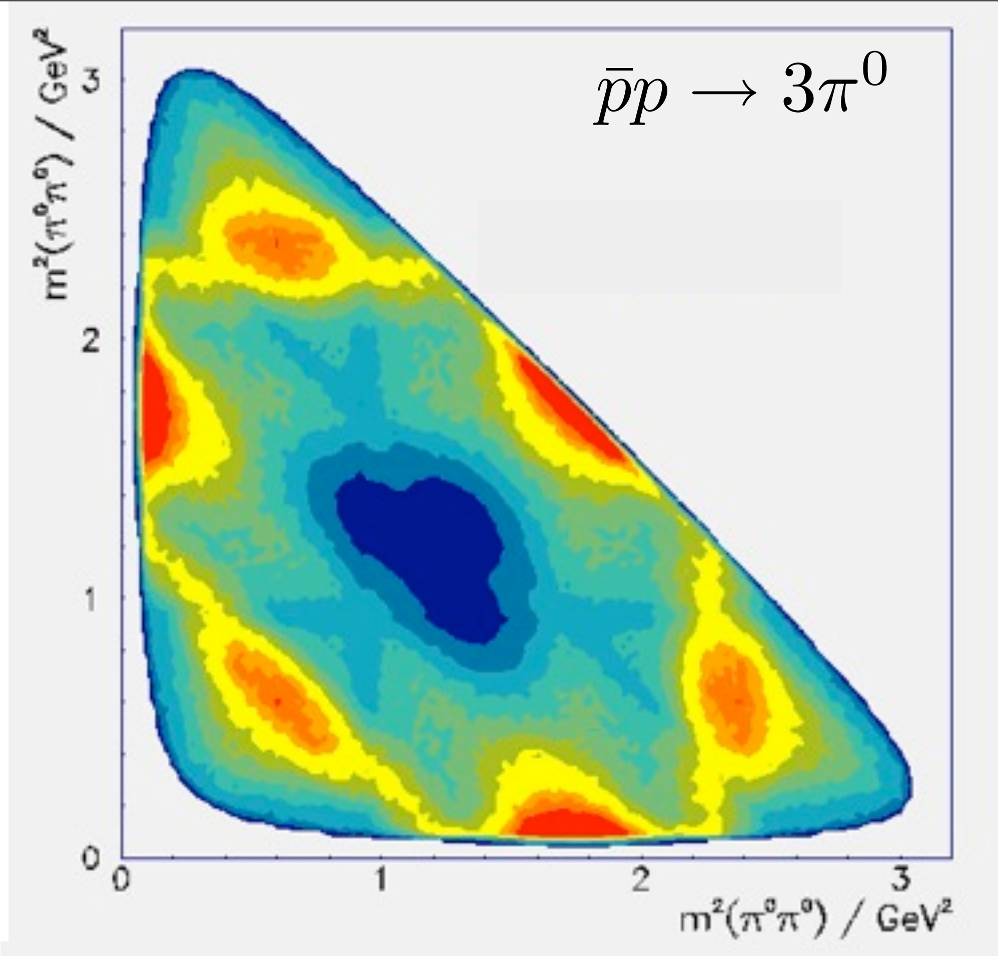
$$= Z(J,L,l,\vec{p},\vec{q}) B_L^R(|\vec{p}|) B_L^r(|\vec{q}|) T_r(m_{ab})\,.$$

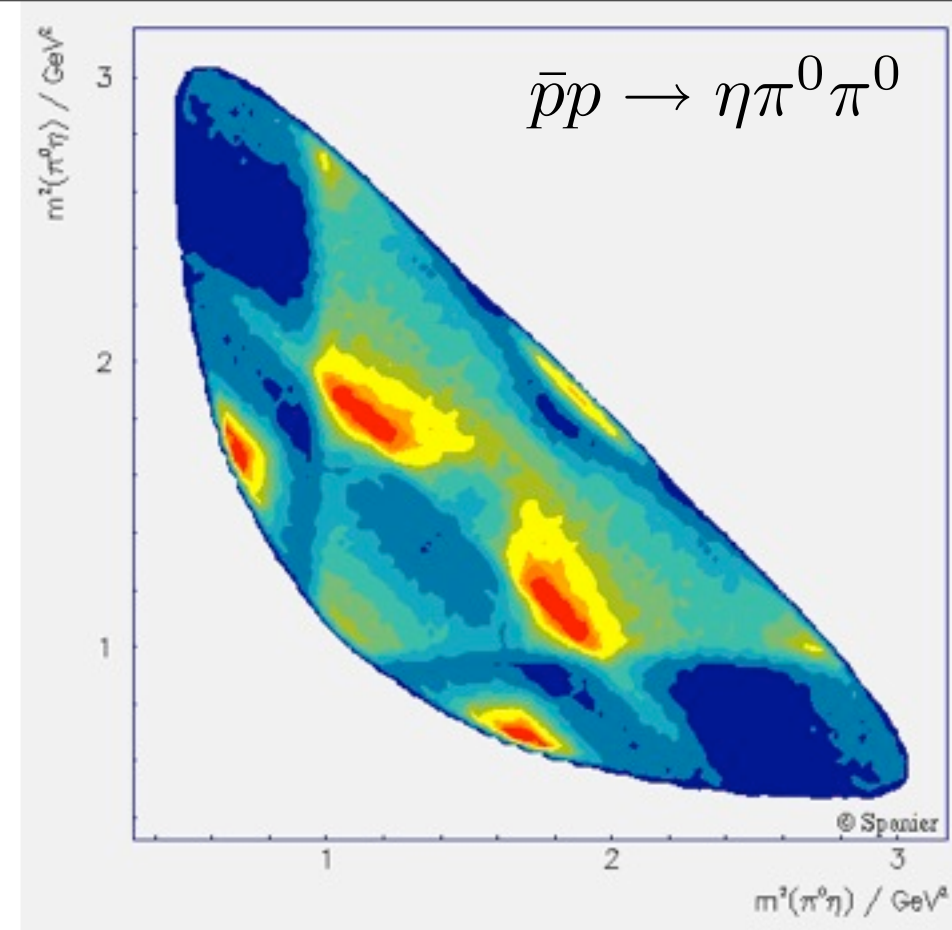
angular distribution

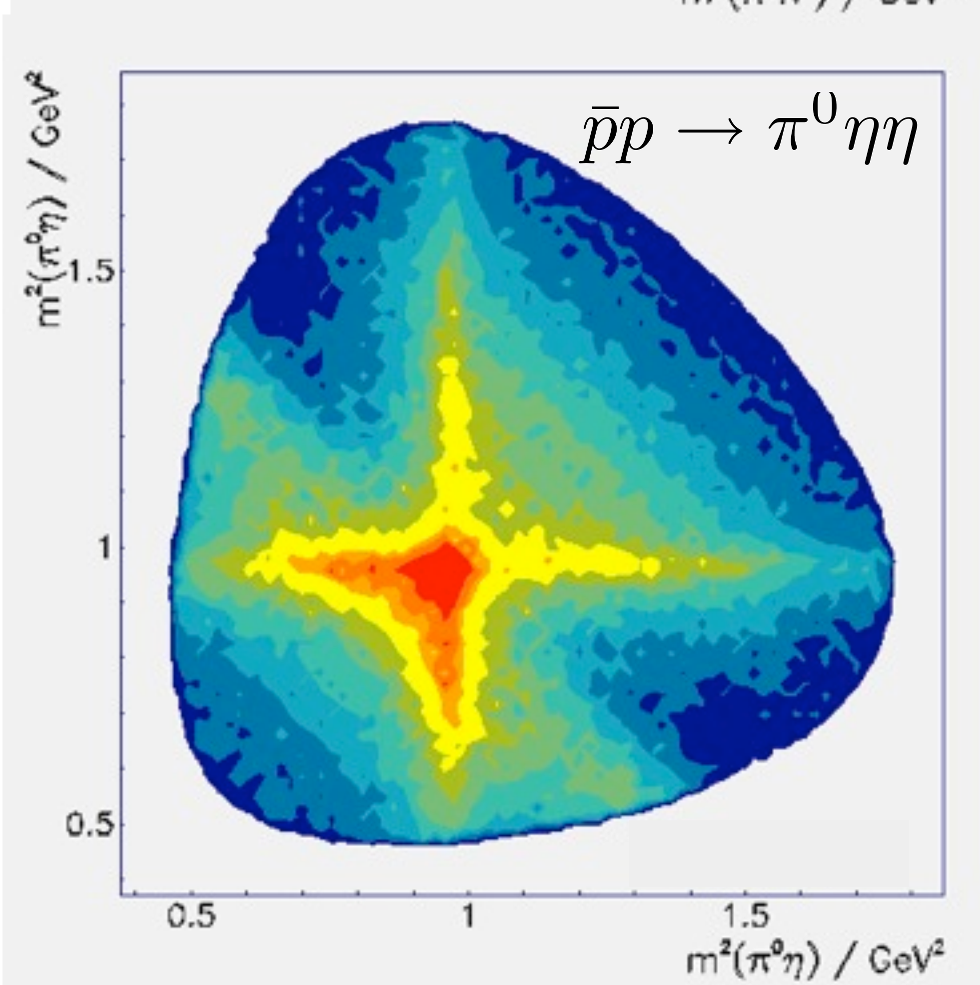
momenta in r rest frame

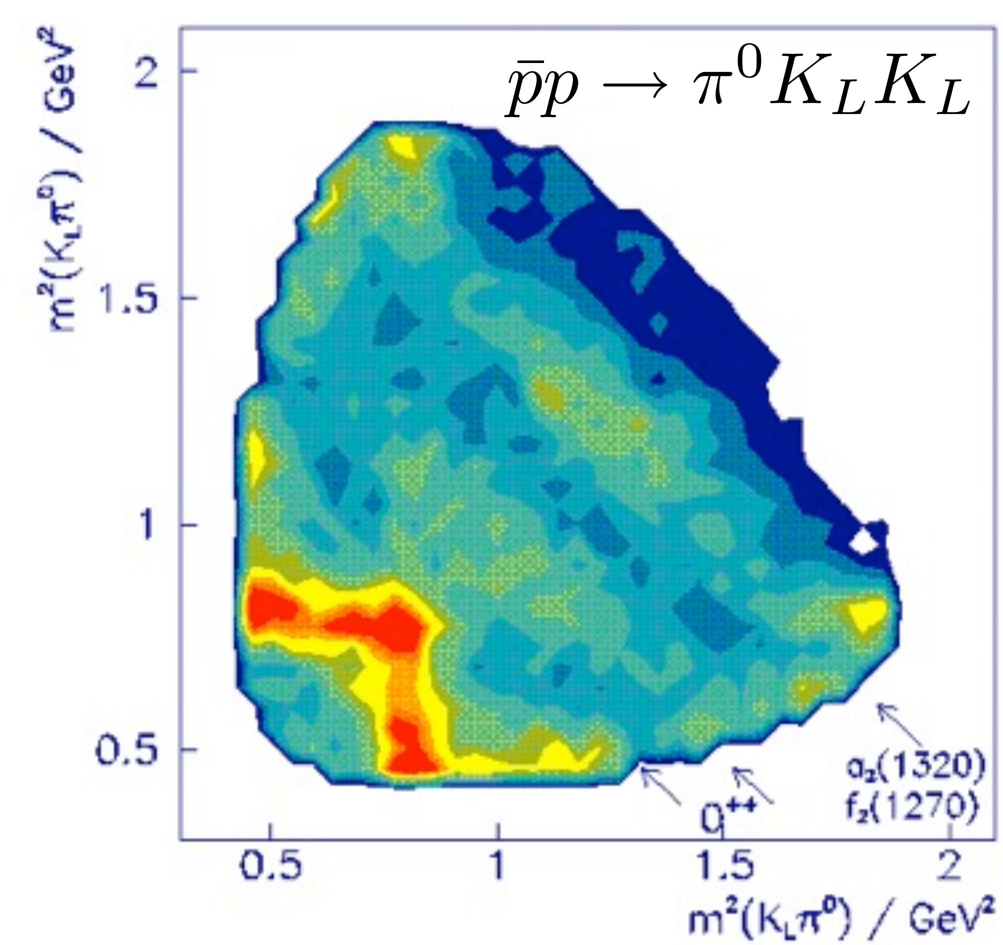
barrier factors

dynamical function descr. resonance = Breit-Wigner or K-matrix or ...


$\bar{p}p \rightarrow 3\pi^0$
$m^2(\pi^0\pi^0)$ / GeV^2
0
1
2
3
$m^2(\pi^0\pi^0)$ / GeV^2


$\bar{p}p \rightarrow \eta\pi^0\pi^0$
$m^2(\pi^0\eta)$ / GeV^2
1
2
3
© Spanier
$m^2(\pi^0\eta)$ / GeV^2


$\bar{p}p \rightarrow \pi^0\eta\eta$
$m^2(\pi^0\eta)$ / GeV^2
0.5
1
1.5
$m^2(\pi^0\eta)$ / GeV^2


$\bar{p}p \rightarrow \pi^0 K_L K_L$
$m^2(K_L\pi^0)$ / GeV^2
0.5
1
1.5
2
0^{++}
$a_2(1320)$
$f_2(1270)$
$m^2(K_L\pi^0)$ / GeV^2

Review of Particle Physics 2000

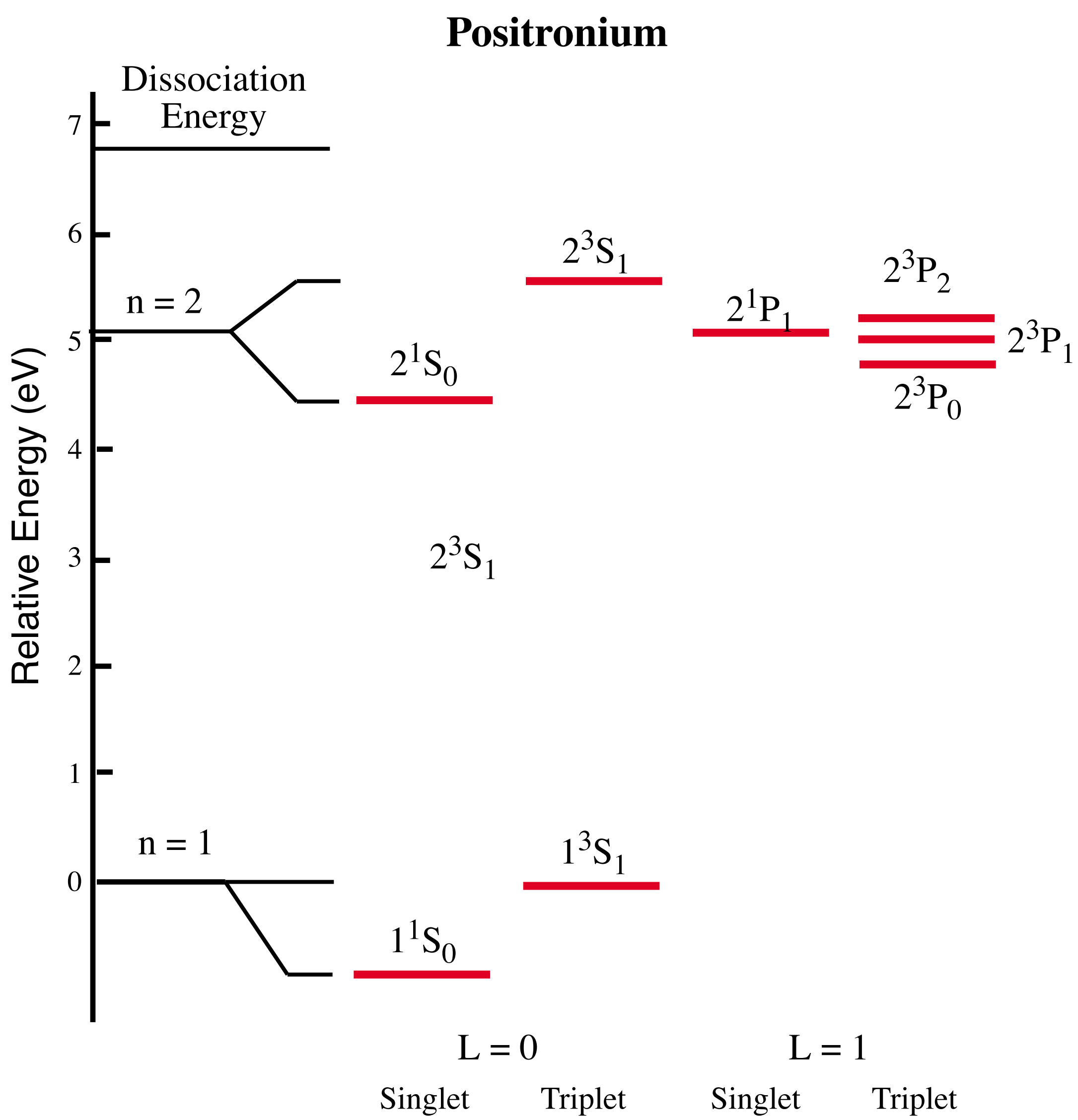
$N\ ^{2S+1}L_J$	J^{PC}	$u\bar{d}, u\bar{u}, d\bar{d}$ $I = 1$	$u\bar{u}, d\bar{d}, s\bar{s}$ $I = 0$	$\bar{s}u, \bar{s}d$ $I = 1/2$
$1\ ^1S_0$	0^{-+}	**π**	**η, η'**	**K**
$1\ ^3S_1$	1^{--}	**ρ**	**ω, φ**	**K*(892)**
$1\ ^1P_1$	1^{+-}	**b_1(1235)**	**h_1(1170)**, h_1(1380)	**K_{1B}**†
$1\ ^3P_0$	0^{++}	**a_0(1450)***	**f_0(1370)***, **f_0(1710)***	**K_0*(1430)**
$1\ ^3P_1$	1^{++}	**a_1(1260)**	**f_1(1285), f_1(1420)**	**K_{1A}**†
$1\ ^3P_2$	2^{++}	**a_2(1320)**	**f_2(1270), f_2'(1525)**	**K_2*(1430)**
$1\ ^1D_2$	2^{-+}	**π_2(1670)**	η_2(1645), η_2(1870)	**K_2(1770)**
$1\ ^3D_1$	1^{--}	**ρ(1700)**	**ω(1650)**	**K*(1680)**‡
$1\ ^3D_2$	2^{--}			**K_2(1820)**
$1\ ^3D_3$	3^{--}	**ρ_3(1690)**	**ω_3(1670), ϕ_3(1850)**	K_3*(1780)
$1\ ^3F_4$	4^{++}	**a_4(2040)**	**f_4(2050)**, f_4(2220)	**K_4*(2045)**
$2\ ^1S_0$	0^{-+}	**π(1300)**	**η(1295), η(1440)**	K(1460)
$2\ ^3S_1$	1^{--}	**ρ(1450)**	**ω(1420), φ(1680)**	**K*(1410)**‡
$2\ ^3P_2$	2^{++}		f_2(1810), **f_2(2010)**	K_2*(1980)
$3\ ^1S_0$	0^{-+}	**π(1800)**	η(1760)	K(1830)

[shaded box] contributions from LEAR experiments

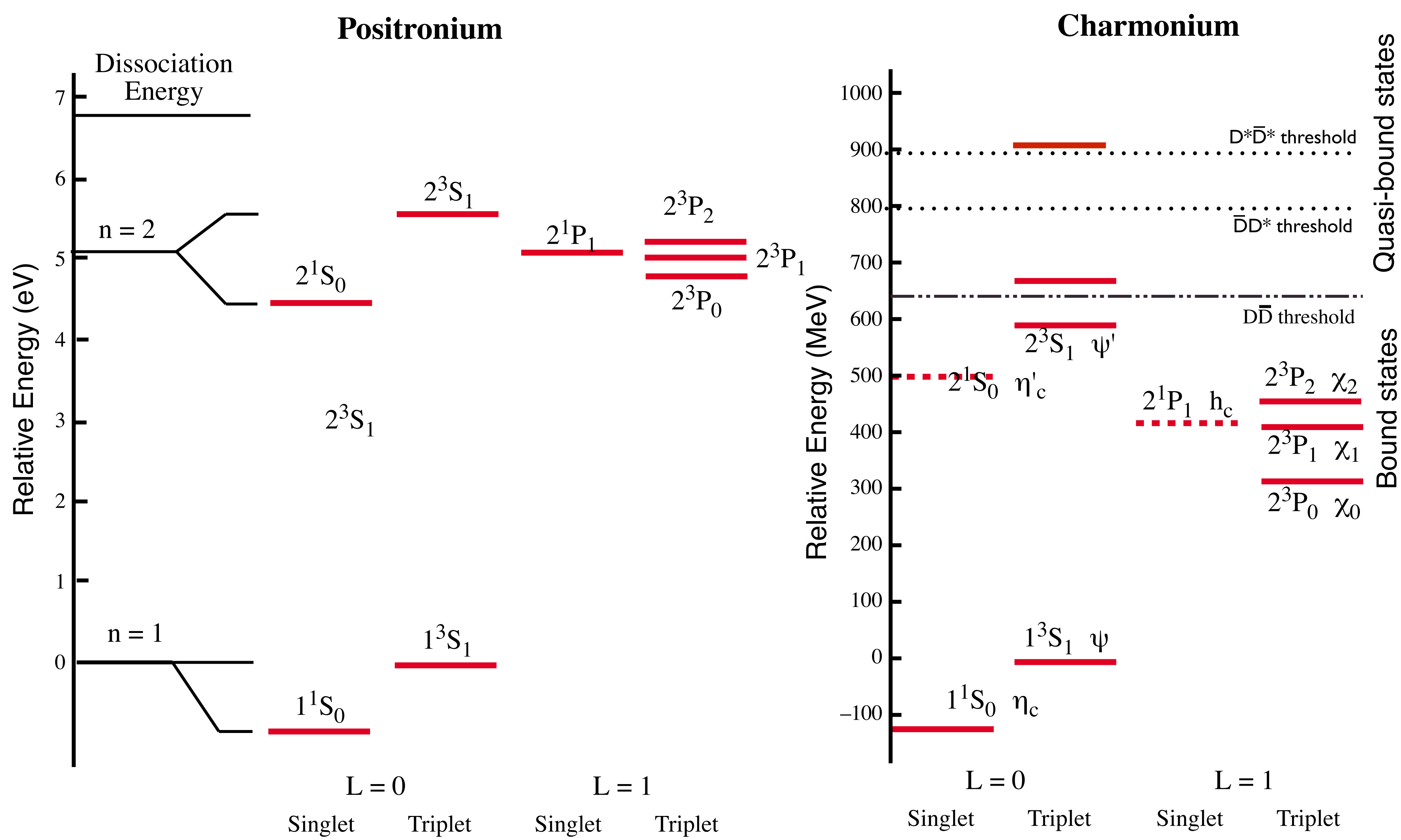
significant contributions, but:

- mass range limited
- states are broad
- no good theory predictions
- need input from other production mechanisms

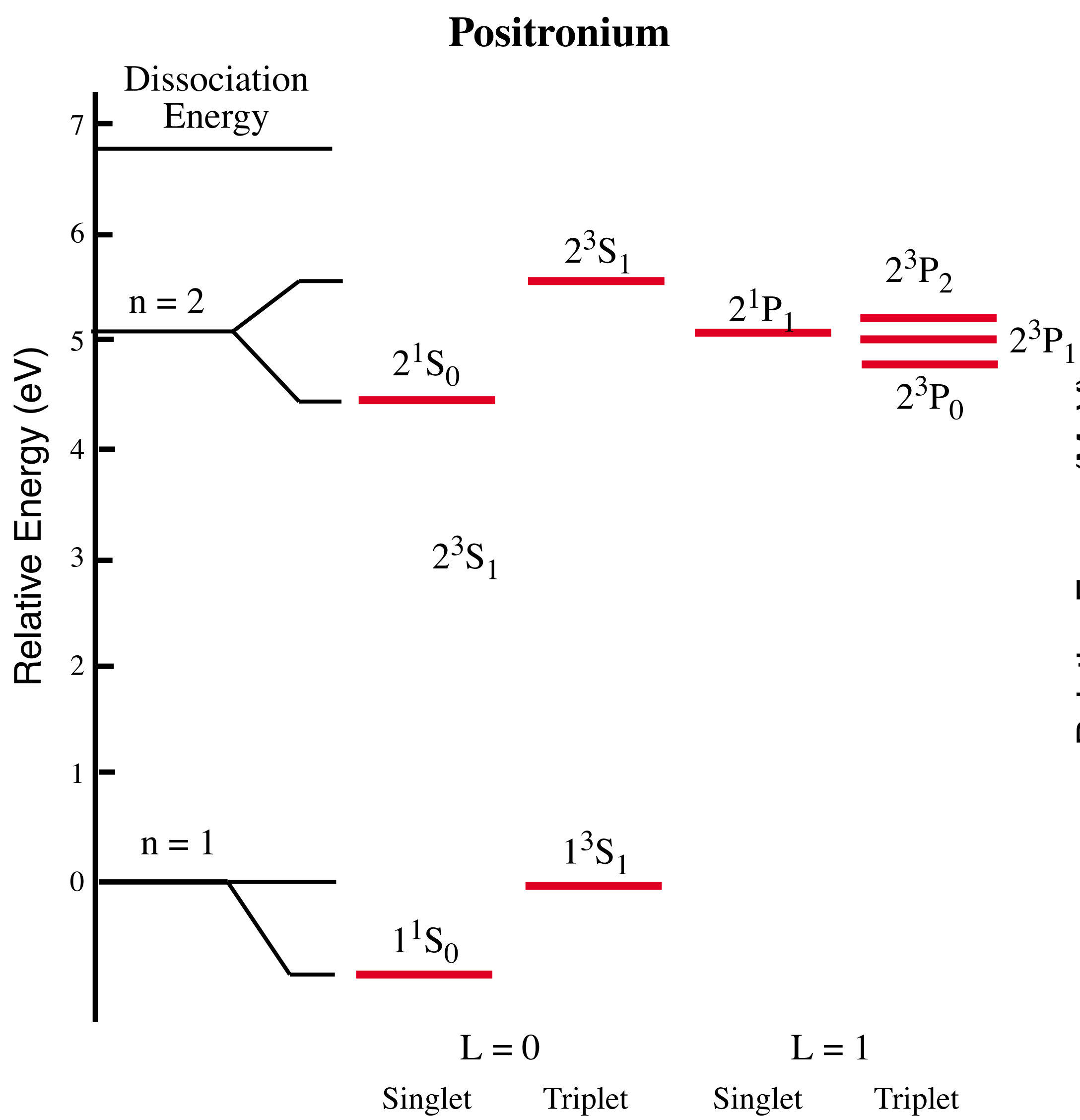
“cleaner” systems

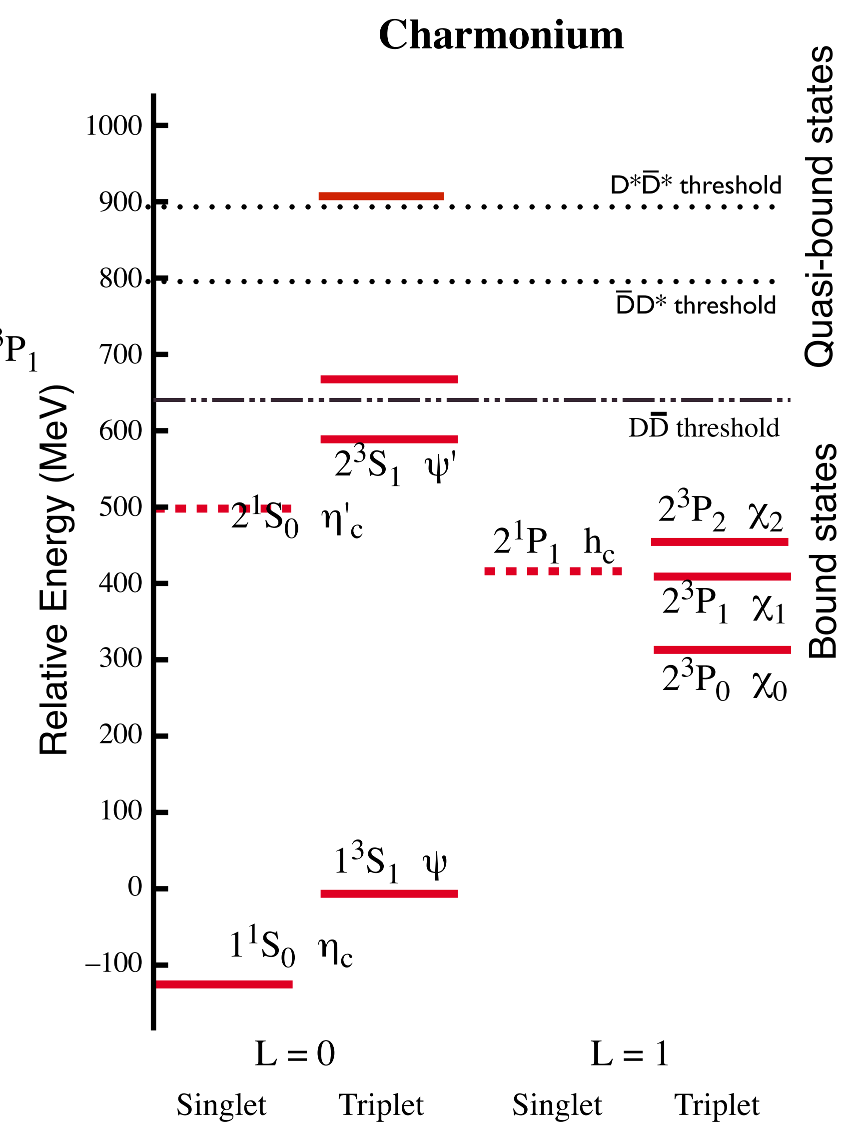


“cleaner” systems



“cleaner” systems

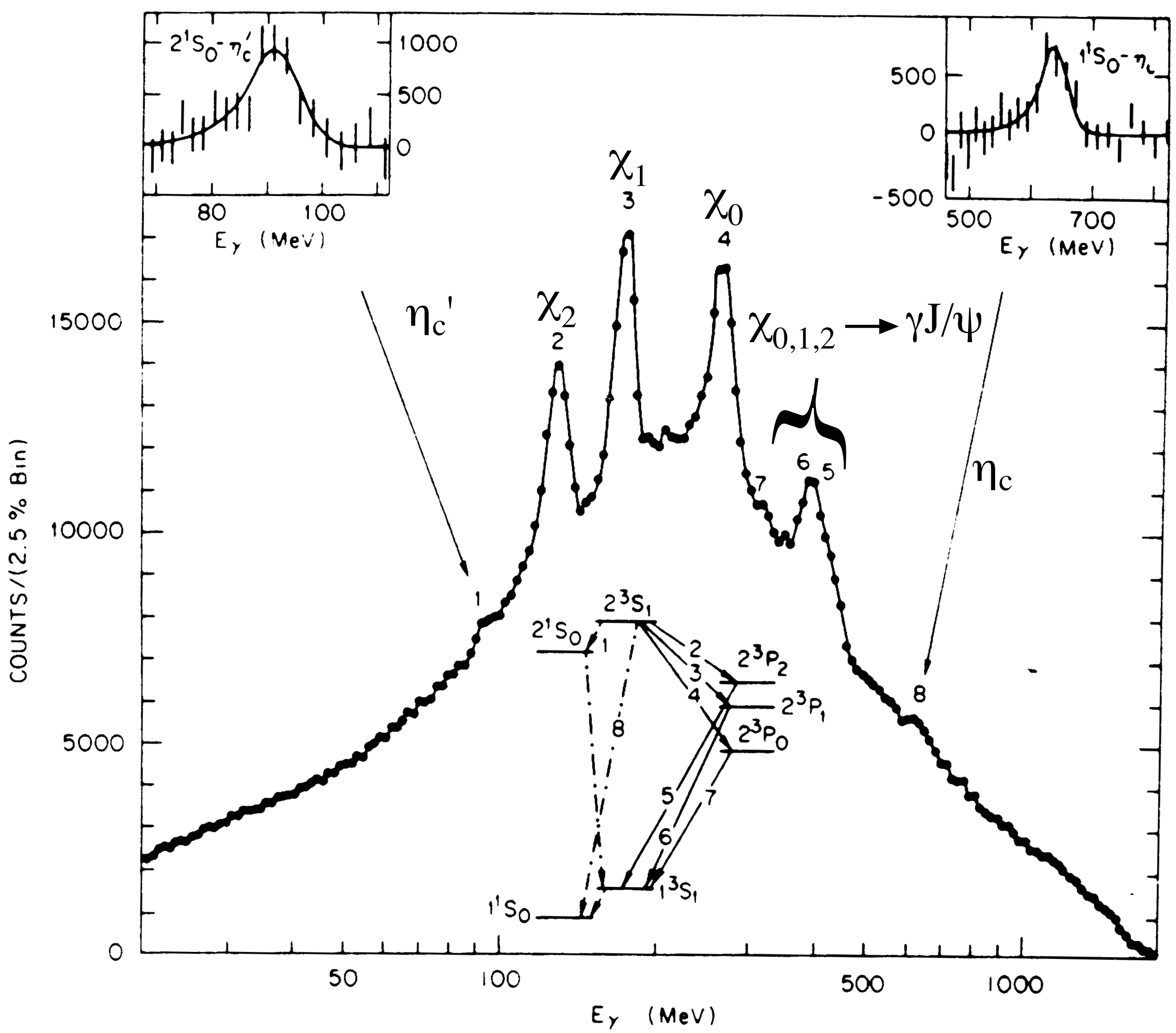




charmonium is the positronium of QCD

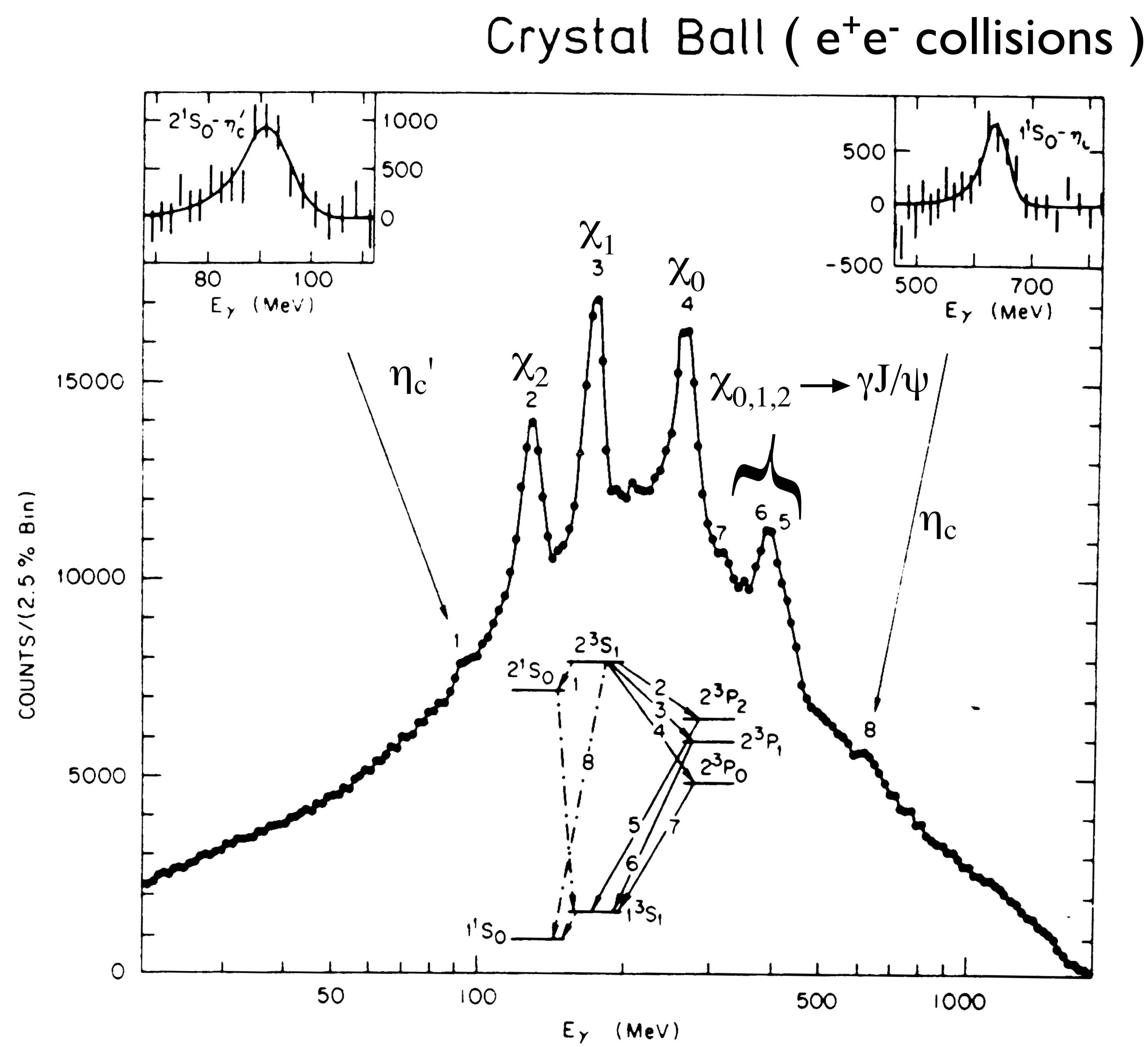
Charmonium Spectrum

Crystal Ball (e^+e^- collisions)



Charmonium Spectrum

"atomic" spectroscopy of $c\bar{c}$ system

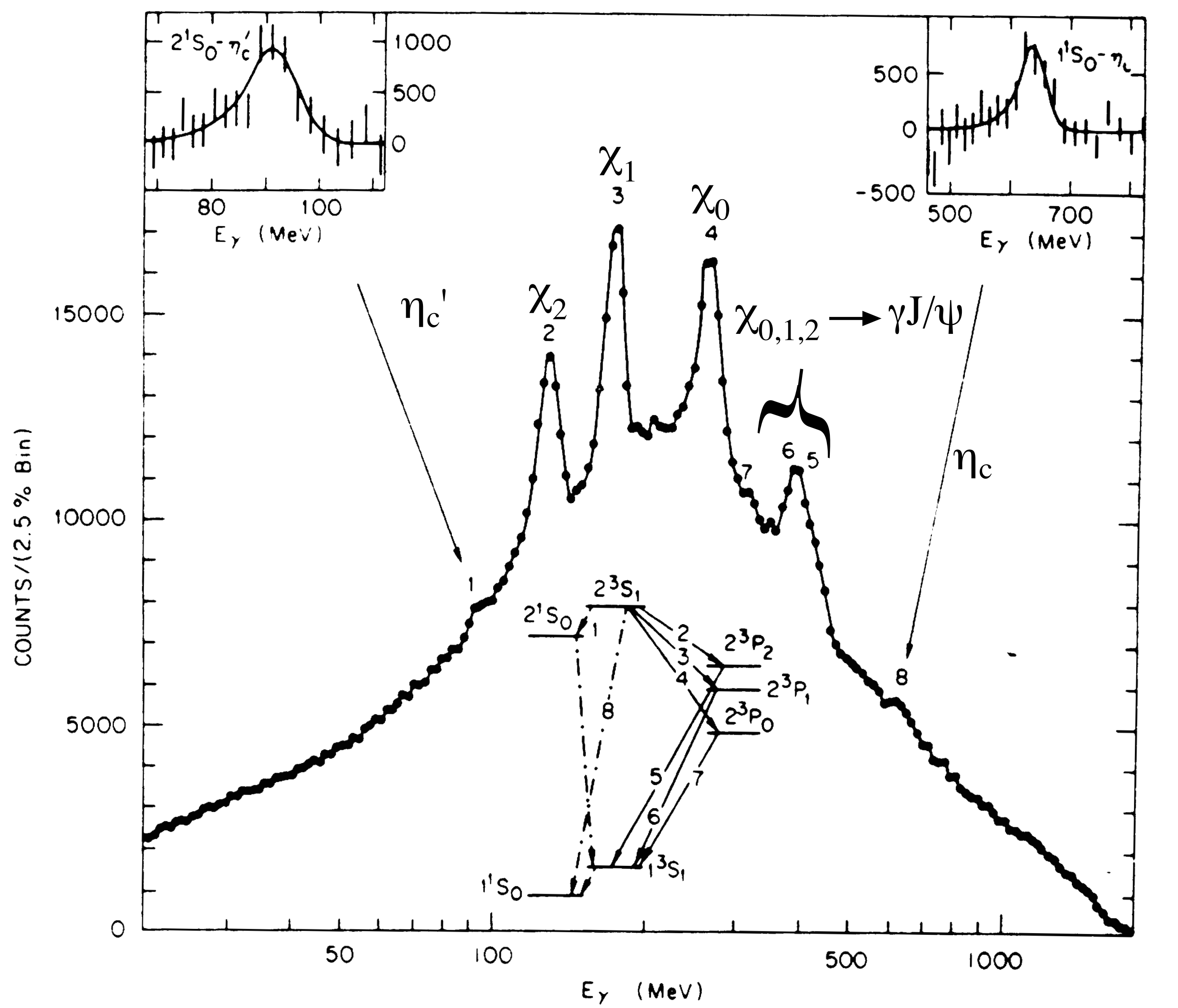


Charmonium Spectrum

"atomic" spectroscopy of $c\bar{c}$ system

clean data but... picture is incomplete

Crystal Ball (e^+e^- collisions)



Production:

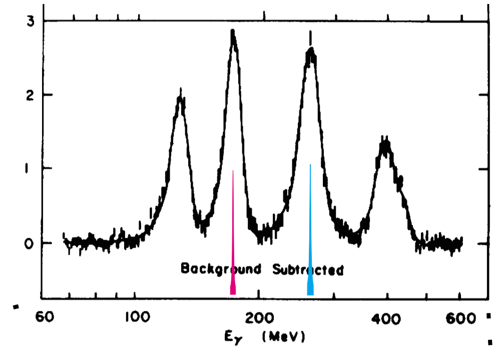
$e^+e^- \rightarrow \psi'$

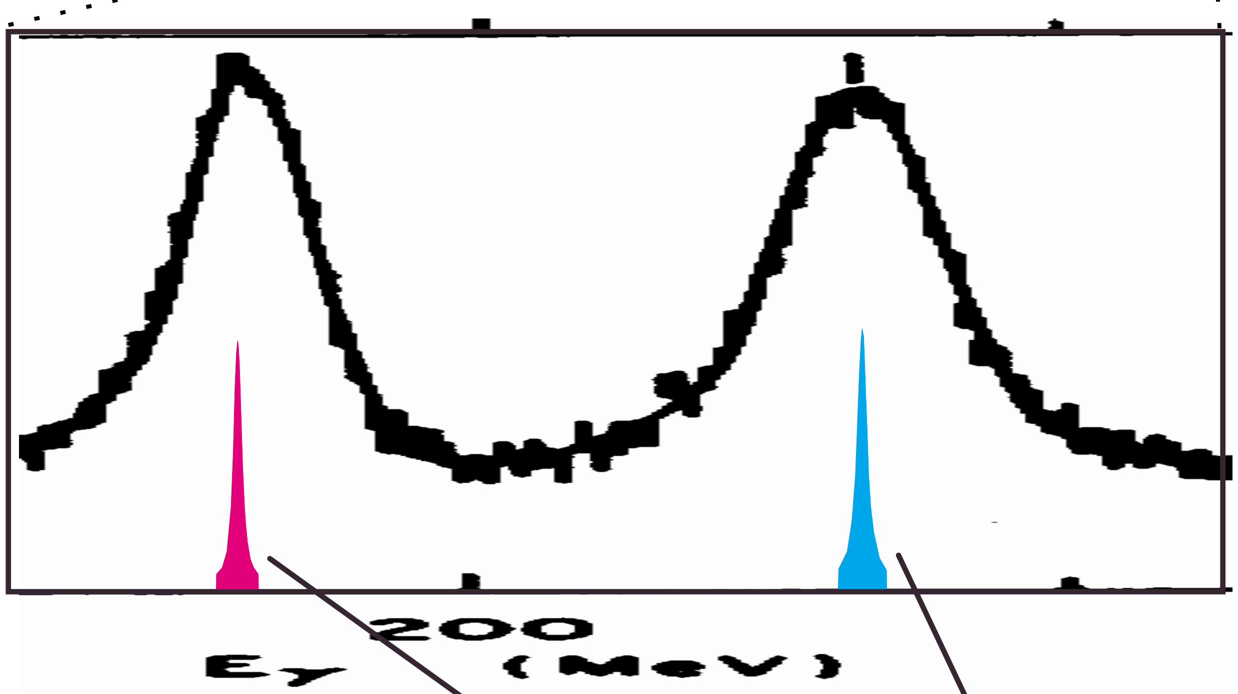
$\hookrightarrow \gamma\, \chi_{1,2}$

$\hookrightarrow \gamma\, \gamma\, J/\psi$

$\hookrightarrow \gamma\, \gamma\, e^+e^-$

Crystal Ball





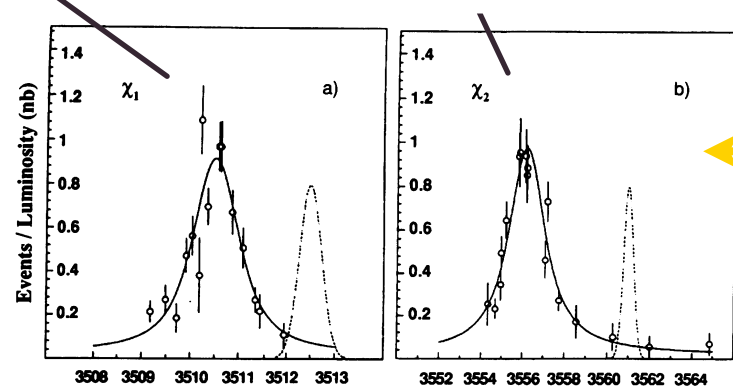
E 760 (Fermilab)

Formation:

$\bar{p}p \rightarrow \chi_{1,2}$

$\hookrightarrow \gamma\, J/\psi$

$\hookrightarrow \gamma\, e^+e^-$



σ_m (beam) = 0.5 MeV

Production:

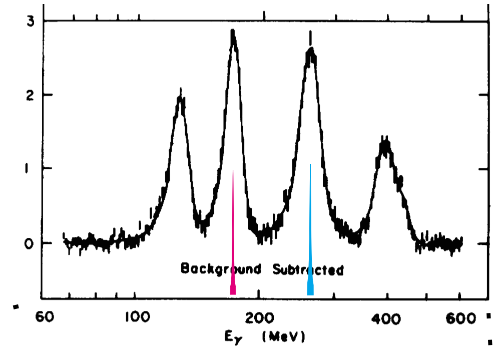
$e^+e^- \to \psi'$

$\hookrightarrow \gamma\, \chi_{1,2}$

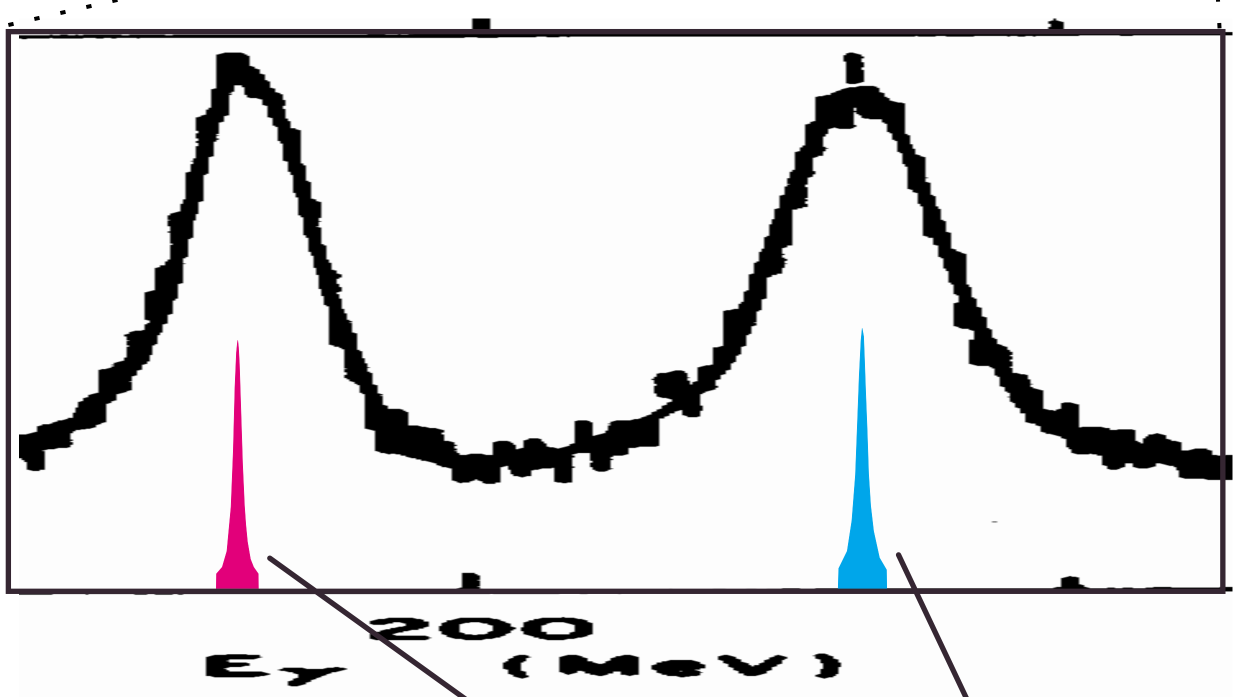
$\hookrightarrow \gamma\, \gamma\, J/\psi$

$\hookrightarrow \gamma\, \gamma\, e^+e^-$

Crystal Ball



← resolution limited by detector



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Formation:

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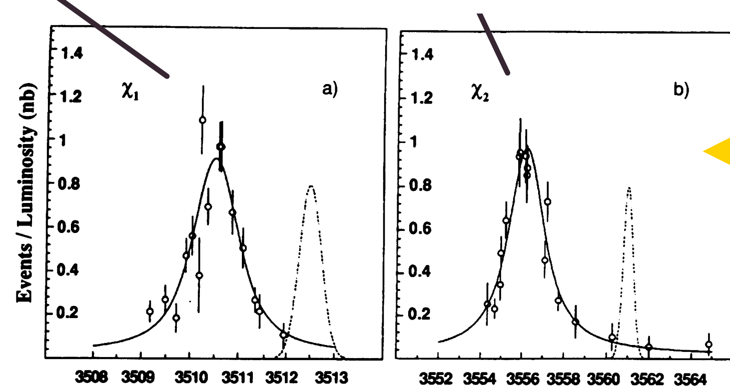

σ_m (beam) = 0.5 MeV

← resolution limited by knowledge of accelerator frequency

... in spite of many years of efforts, no clean understanding of low energy QCD. It is still a field with many open questions...

HEP however has mostly moved on ...

... in spite of many years of efforts, no clean understanding of low energy QCD. It is still a field with many open questions...

HEP however has mostly moved on ...

The end

(Actually, not really. Rather, the beginning: tomorrow, we go back to the Big Bang)