Physics 214 UCSD
Physics 225a UCSB
Experimental Particle Physics

Lecture 2

Fast forward through HEP

Detectors

Range of force for massive mediator

- We have two ways of handwaving our way to see finite range:
  - Uncertainty principle of Energy and time
  - Yukawa potential as solution to Klein-Gordon equation

Range of “force” as quantum fluctuation

$$\Delta E \Delta t \approx h$$

$$\Delta E = mc^2$$

$$\Rightarrow \Delta t \approx \frac{h}{mc^2}$$

$$R \approx c\Delta t = \frac{h}{mc}$$

R ∝ 1/m

Range of force is inverse proportional to mass of mediator.

A bit more rigorous: Yukawa

Static source of "charge"
=> Spherical potential.

$$U(r) = \frac{Q}{r} e^{-r/R}$$

As solution to: $$E^2 = P^2 + m^2 \Leftrightarrow -\nabla^2 \Phi + m^2 \Phi = 0$$

Given that QM tells us: $$\vec{P} = -i\vec{\nabla}$$

$$E = i\partial / \partial t \Rightarrow 0$$ due to static potential

We then get: $$\nabla^2 \Phi = m^2 \Phi = \frac{\Phi}{R^2}$$

Yukawa Potential

$$\nabla^2\Phi = m^2\Phi = \frac{\Phi}{R^2}$$

- For m $\neq$ 0 this equation is solved by:

$$\Phi(r) = \frac{Q}{r}e^{-r/R}$$

A potential with a characteristic range R, and a “charge” or “coupling strength” Q.

Add to this Fermi's Golden Rule:

- Incoming plane wave => outgoing whatever
- Rate of transition = $2\pi\, |M_{if}|^2\, \rho(E_f)$
- With: $M_{if} = \int \psi_f^* \, U(r)\, \psi_i \, dVol$
- As the wave functions are plane waves, this is nothing more than the fourier transform of the potential, with k being the momentum transfer in the collision.

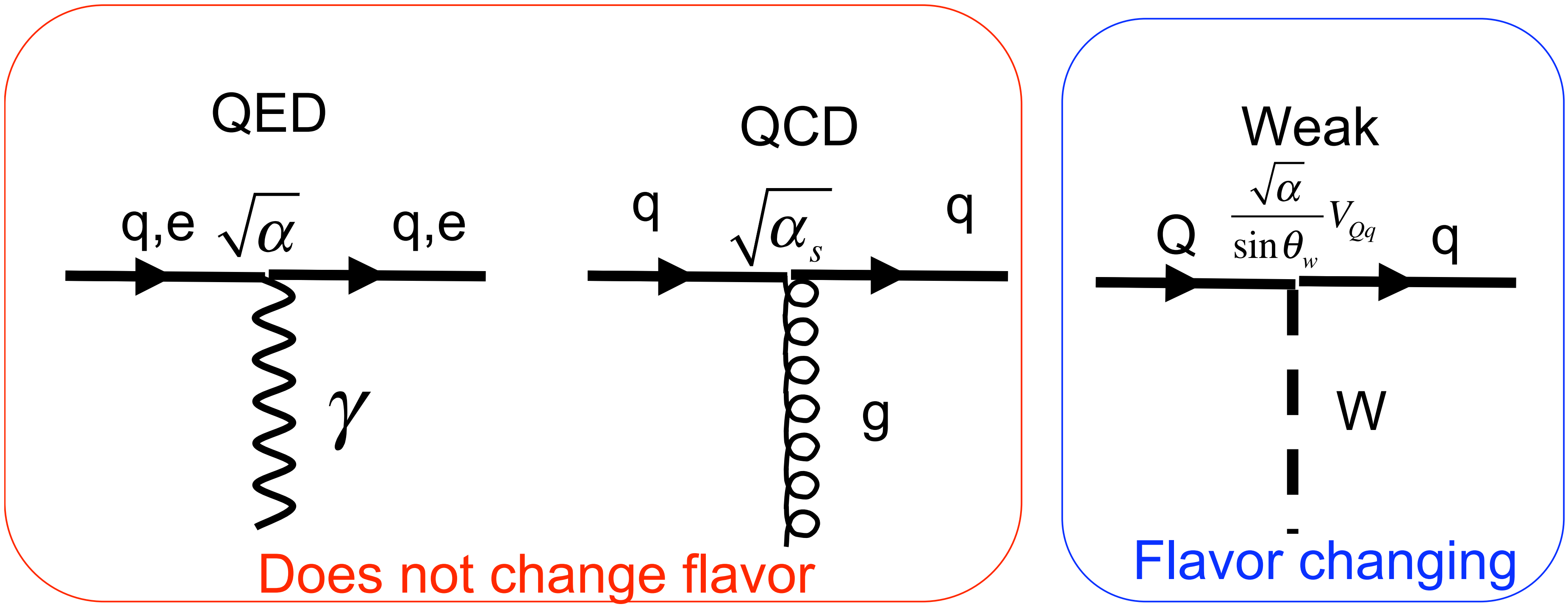
For Yukawa: $$M_{if}(k^2) \propto qQ \bullet \frac{1}{k^2 + m^2}$$

Things to remember:

- Rate of transition $\propto$ $|\text{Amplitude}|^2$
- Amplitude = vertex factors * propagator

All of this is for single boson exchange,
i.e. leading order process only!

Rules for Standard Model Interactions



Amplitude = vertex factors times propagators

Note: The formalism is the same with new physics. All you do is add new particles and rules for the interactions.

Orders of magnitude of interactions:

Interaction	Typical τ	Typical σ	coupling
strong	$\sim 10^{-23}$ sec $\Delta \rightarrow p\pi$	~ 10mb $p\pi \rightarrow p\pi$	$\alpha_s \sim 1$
EM	$\sim 10^{-18}$ sec $\pi^0 \rightarrow \gamma\gamma$	$\sim 10^{-3}$mb $\gamma p \rightarrow p\pi^0$	$\alpha_{EM} \sim 10^{-2}$
weak	$> \sim 10^{-12}$ sec $\pi^- \rightarrow \mu^- \nu$	$\sim 10^{-11}$mb $\nu p \rightarrow e^- p\pi^+$	α_{EM} with massive propagator

Can we understand these numbers?

Note: 1 barn = 10^{-28} m^2

1st order = coupling^2 x propagator^2

EM & Strong mediated by massless particles …
… but with different couplings.

$$\frac{\alpha_s}{\alpha_{EM}} \sim 10^4$$

EM & weak have ~ same coupling …
… but with different mass for propagator.

Processes we listed have roughly k~1GeV

$$\frac{EM}{Weak} \sim \left(\frac{\frac{1}{k^2}}{\frac{1}{k^2 + m_W{}^2}} \right)^2 = \frac{m_W{}^4}{k^4} \sim 10^8$$

Impressive how well these simple relative estimates work!

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10^4

10^8

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What about estimating the absolute scale?

Assume pion-proton scattering is nothing more than
Solid sphere's hitting each other:

$$\sigma \sim A \sim \pi R^2 \sim 3\ (1\text{fm})^2 \sim 30\text{mb}$$

Lifetime of strong decaying particle is defined by range based on exchange of lightest colorless hadron:

$$\tau \sim 1/m_\pi \sim 1/100\text{MeV} \sim 10^{-23}\ \text{sec}$$

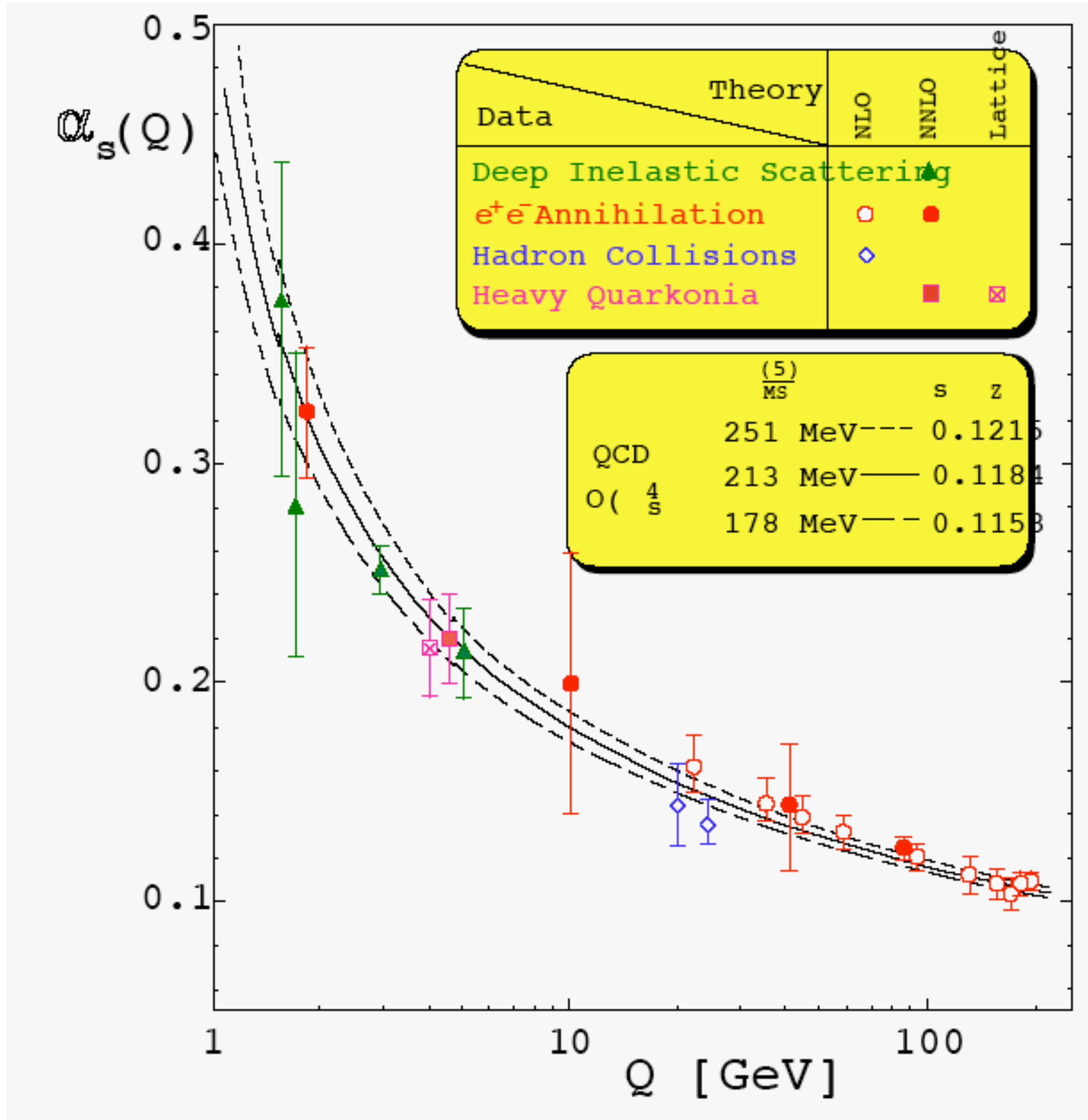
Sort of works in both cases.

Aside on running couplings

Couplings depend on momentum transfer, Q

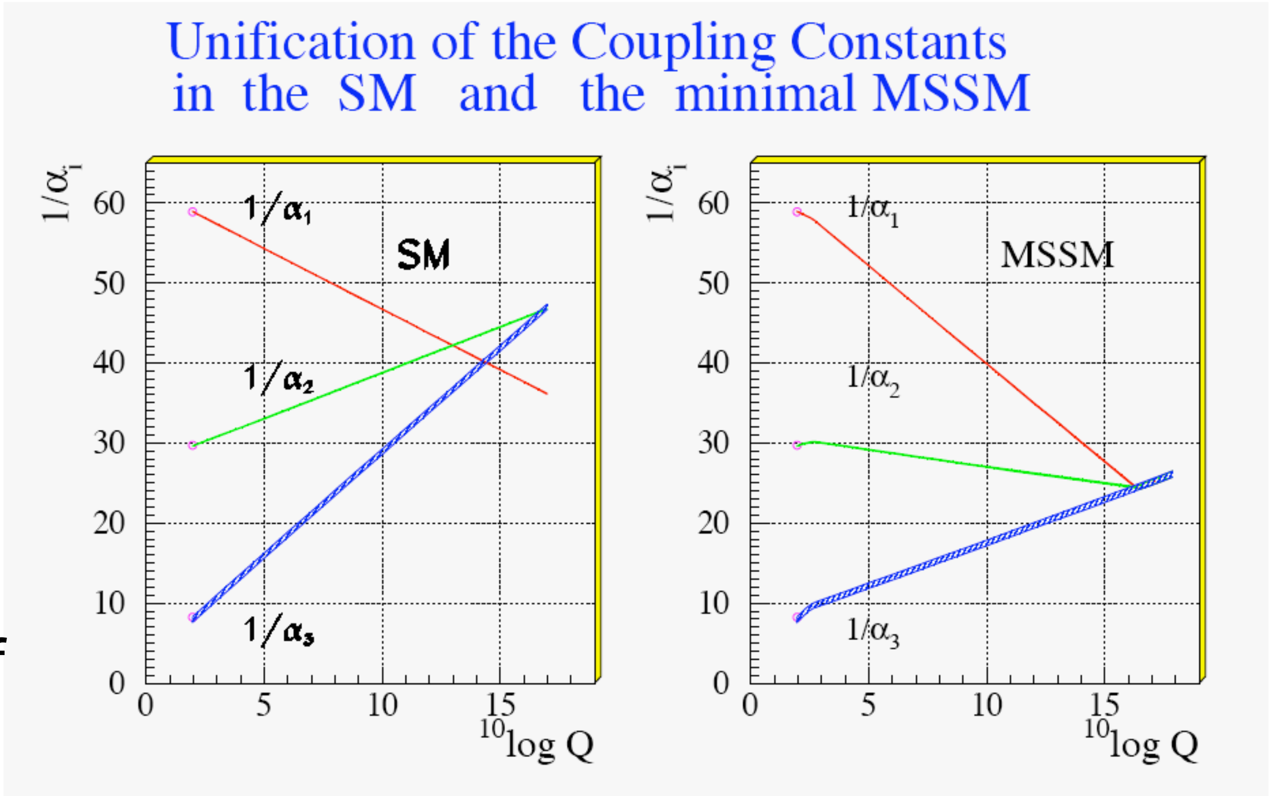
Strong coupling is O(1) at the scale of hadron masses, thus ***confinement***, but becomes O(0.1), and thus perturbative, at O(100GeV), i.e. ***asymptotic freedom.***

hep-ph/0012288v2



The “Q” here is actually k^2/μ^2, with μ being a reference scale, e.g. M_Z , at which the couplings are measured.

Coupling Unification ???



Details of the running depends on gauge boson self-couplings, # of families, and # of Higgs doublets, and Particle content and Masses in the theory.

$$\alpha_1 = (5/3)g'^2/(4\pi) = 5\alpha/(3\cos^2\theta_W),$$
$$\alpha_2 = g^2/(4\pi) = \alpha/\sin^2\theta_W,$$
$$\alpha_3 = g_s^2/(4\pi)$$

hep-ph/0012288v2

Aside on lifetime of unstable particles

Issues around unstable particles (1)

- Assume we have a large number N of particles of a certain type, at $t=t_0$. How many are left at $t=t_0+dt$?

p(t)dt = prob. for decay during dt := k dt

P(t) = prob. for survival at t

Exponential decay law follows directly from assumption of constant rate of decay, i.e. transition rate that is independent of N(t=0).

$$P(t+dt) = P(t)(1-kdt)$$

$$-kP(t) = \frac{dP}{dt}$$

$$P(t) = N(t=0)\bullet e^{-kt}$$

$$\tau \equiv 1/k \Rightarrow P(t) = N(t=0)\bullet e^{-t/\tau}$$

Issues around unstable particles (2)

- We refer to τ as the "lifetime" of the particle because $\langle t \rangle_{decay} = \tau$
- We refer to $\Gamma = 1/\tau$ as the Total Width, or total decay rate.
- In general, a particle may decay via more than one path, or into more than one distinct final state. E.g. $Z \to e^+e^-$, $\mu^+\mu^-$, etc. We refer to the decay rate into a given final state as the partial with, Γ_i .
  - The total width is given by the sum of all partial widths.
- We refer to the ratio of Γ_i / Γ as the "branching ratio" into the final state i.
  - The sum of all branching ratios adds up to 1.

Issues around unstable particles (3)

- *What's the mass of an unstable particle?*

  $\Delta E\ \Delta t \sim 1$

  In rest frame E=M,

  In general $\Delta t \sim \tau$, => $\mathbf{\Delta M \sim \Gamma}$

- *If mass isn't well defined, then what's the probability distribution for finding a particle with a given mass?*
  - We call this the "lineshape" of the particle.

$$|\psi(t)\rangle = |\psi(0)\rangle e^{-iE_0 t}$$

$$\langle\psi(t)|\psi(t)\rangle = 1$$ ← Normalization for stable particle.

$$\langle\psi(t)|\psi(t)\rangle = e^{-t/\tau}$$ ← Normalization for unstable particle.

We can get to this normalization if we replace:
E_0 by E_0 - i $\Gamma/2$.

We then get the lineshape from fourier transformation:

$$\left|\psi(E)\right\rangle = \frac{1}{\sqrt{2\pi}} \int_0^\infty dt e^{iEt} \left|\psi(t)\right\rangle = \frac{1}{\sqrt{2\pi}} \int_0^\infty dt e^{i(E-E_0-\Gamma/2)t} \left|\psi(0)\right\rangle$$

$$\left\langle\psi(E)\middle|\psi(E)\right\rangle = \frac{1/2\pi}{(E-E_0)^2 + (\Gamma/2)^2}$$

Identify E with M and you get the non-relativistic Breit-Wigner lineshape.

In real live, hadronic resonances are not this simple because …

- Interference with higher resonances.
- Total width depends on M.
- Phase space affects lineshape
- Finite size effects (Blatt-Weisskopf barrier penetration factor)

I'll show you examples for the first 3, and refer you to references for further reading:

http://mit.fnal.gov/~fkw/teaching/references/1018.html

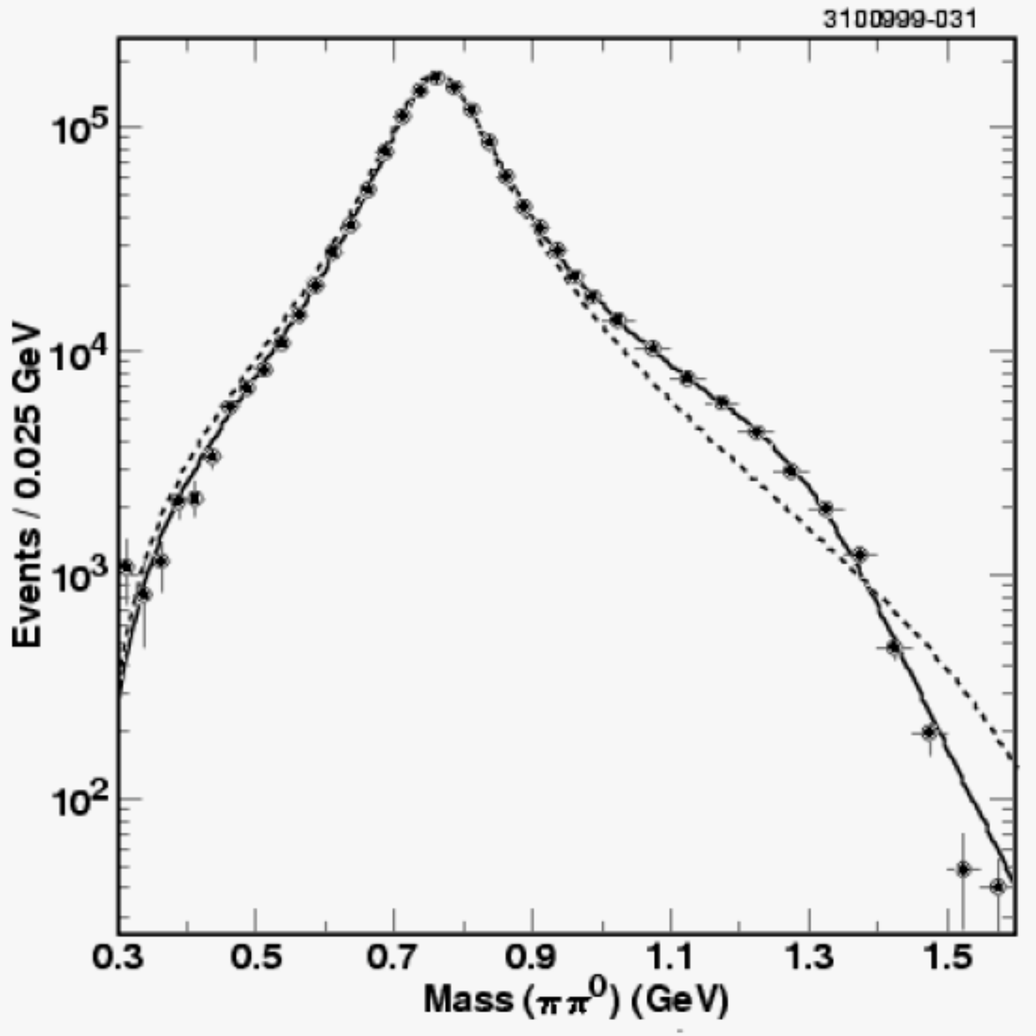
This page has links to the original papers for the plots I am showing, as well as a memo on BW's et al. by Alan Weinstein, Caltech.

Interference with higher resonances

Data from tau decays to two pions at CLEO.

Dotted line is without a rho’. Solid line with. The data clearly demands the rho’.

(Feel free to look up rho and rho’ in the PDG)



$$BW(\pi^+\pi^0) = BW_\rho + \beta BW_{\rho'}$$

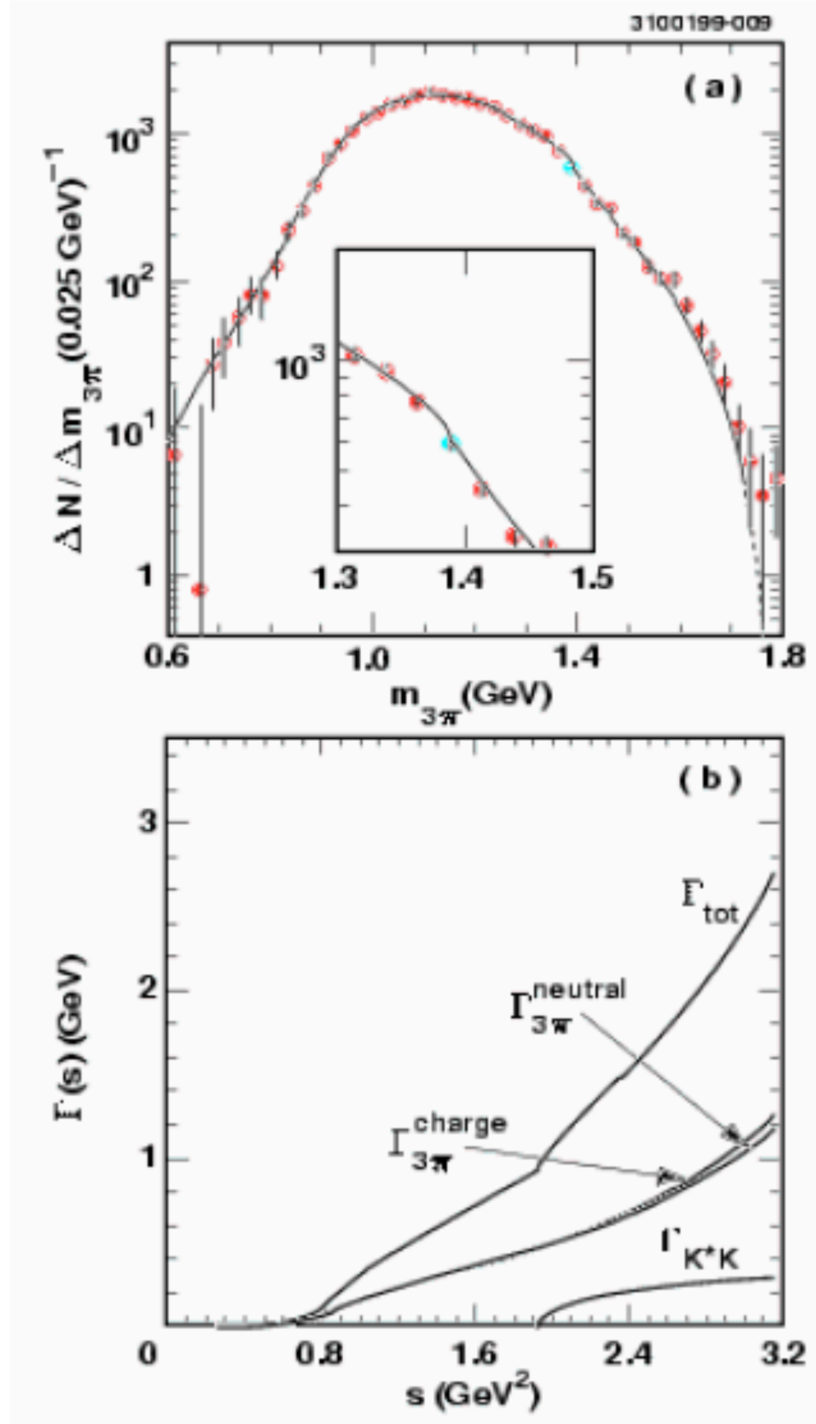
Mass dependent width

Data from tau decays to three pions at CLEO.

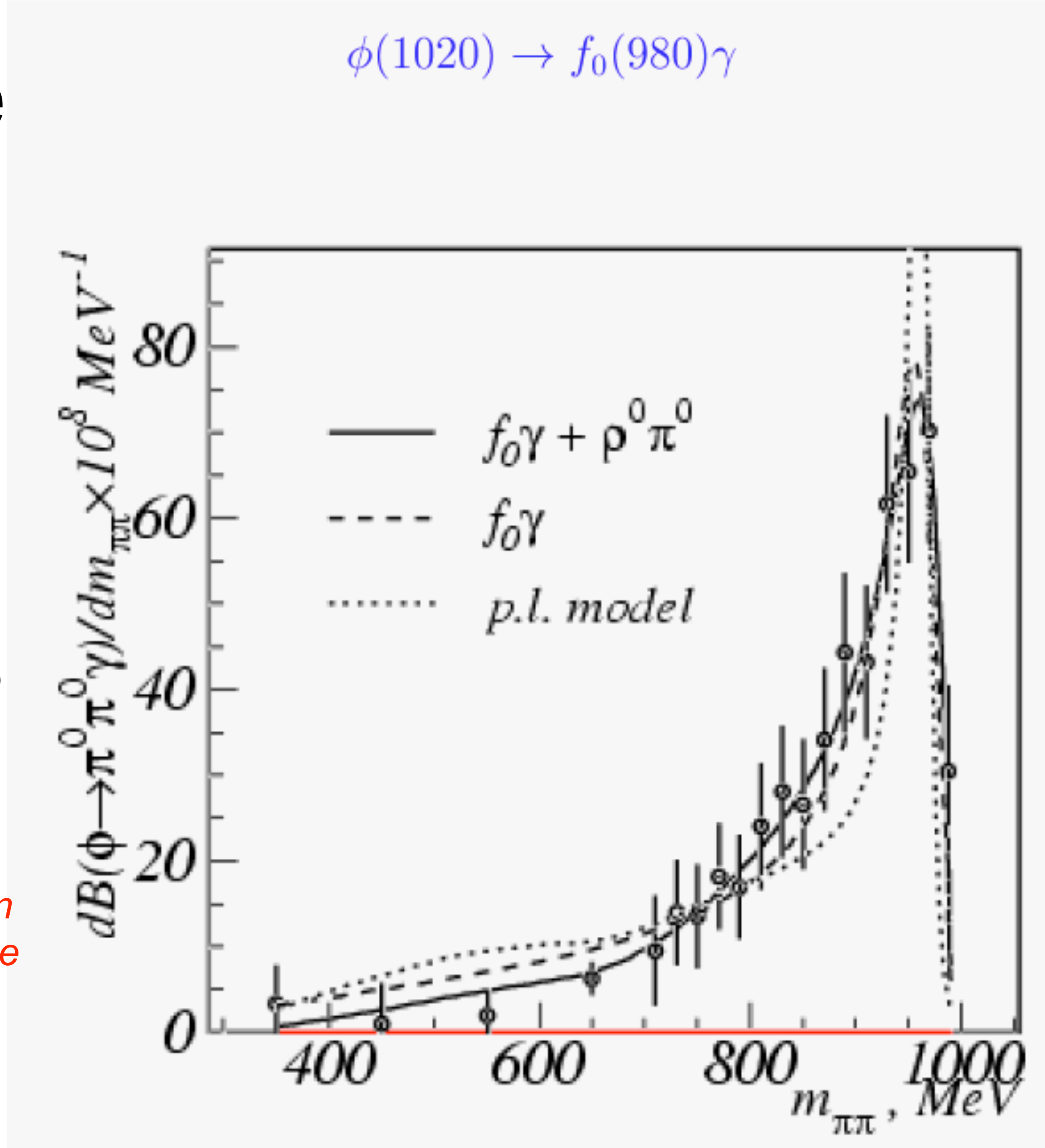
The data requires that one allows for a K^*K partial width once allowed kinematically.

However, even without it, the total width increases significantly as a function of 3-pion invariant mass.

(Feel free to look up the a1 in PDG)



Lineshape sculpting due to phase space constraints



Note: The f0 is actually wider on the high side than the low side because of the KK kinematic threshold!

Switch gear now!

Let’s talk about detectors for a bit.

Let’s do this with Atlas and CMS in mind.

Suggested References:
PDG Chapter 27 & 28
http://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf
http://pdg.lbl.gov/2009/reviews/rpp2009-rev-particle-detectors.pdf
Kleinknecht (see website for citation)
CMS physics TDR vol. 1 (on the web at:
http://cmsdoc.cern.ch/cms/cpt/tdr/)

Overview

- We will go through this in 3 rounds:
  - Round 1: basic concept overview of a collider detector.
  - Round 2: the detection principles, i.e. particle interactions with matter.
  - Round 3: performance characteristics of the detector.

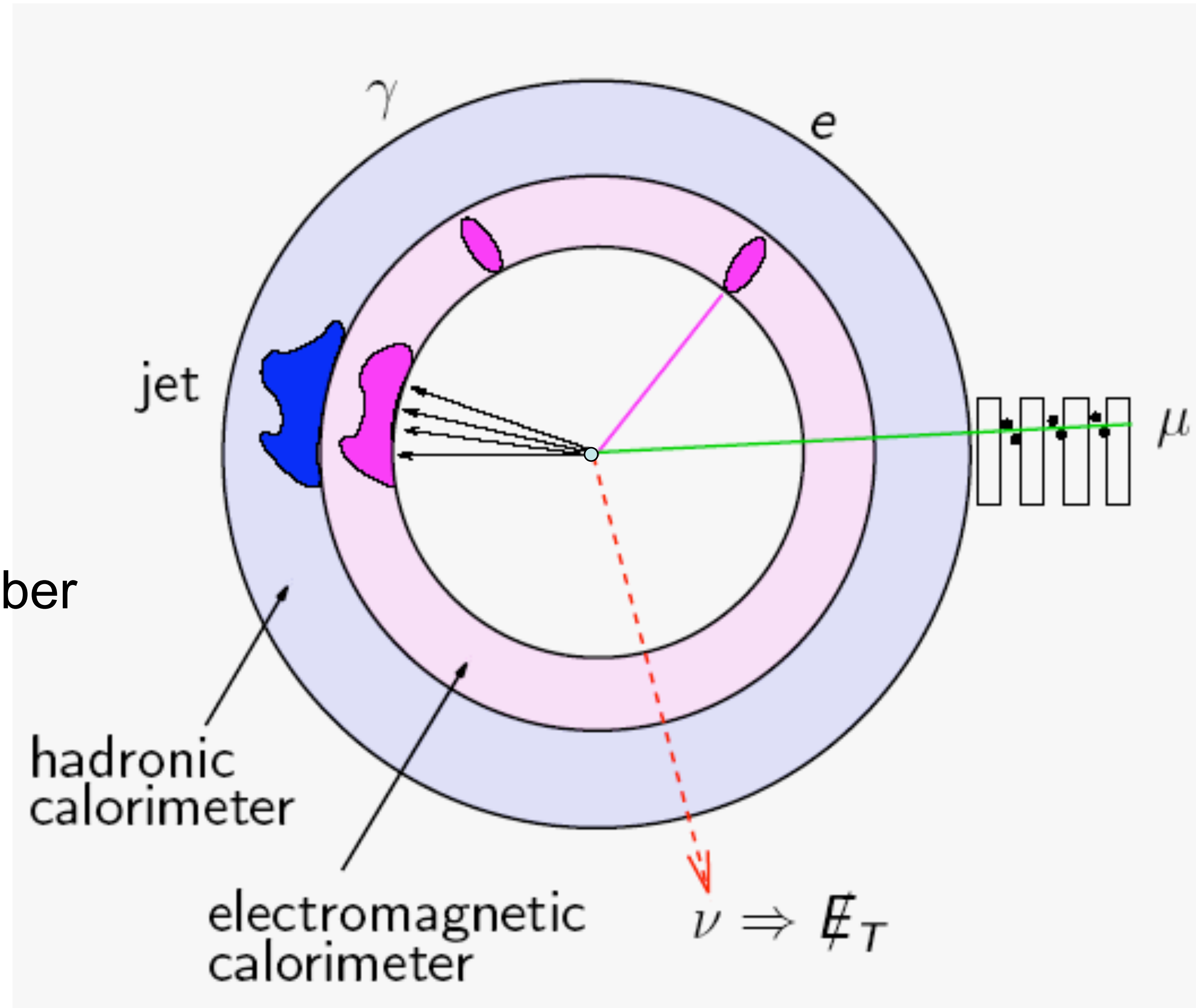
What do we need to detect?

- Momenta of all stable particles:
  - Charged: Pion, kaon, proton, electron, muon
  - Neutral: photon, K^0_s , neutron, K^0_L , neutrino, dark matter (if it is produced)
- Particle identification for all of the above.
- "Unstable" particles:
  - Pizero
  - b-quark, c-quark, tau, top-quark
  - Gluon and light quarks
  - W,Z,Higgs
  - … anything new we might discover …

All modern collider detectors look alike

Increasing radius

beampipe
tracker
ECAL
solenoid
HCAL
Muon chamber



Tracking

- Zylindrical geometry of central tracking detector.
  - Charged particles leave energy in segmented detectors.
    - ⇒ Determines position at N radial layers
- Solenoidal field forces charged particles onto helical trajectory
  - Curvature measurement determines charged particle momentum.
- Limits to precision are given by:
  - Precision of each position measurement
  - Number of measurements
  - B field and lever arm
  - Multiple scattering

Momentum Resolution

Two contributions with different dependence on p_T

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_{r\phi} p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

Device resolution

$$\frac{\sigma(p_T)}{p_T} = \frac{0.05}{BL}\sqrt{\frac{1.43L}{X_0}}$$

Multiple cattering

Will go through multiple scattering in more detail next lecture

ECAL

- Detects electrons and photons via energy deposited by electromagnetic showers.
  - Electrons and photons are completely contained in the ECAL.
  - ECAL needs to have sufficient radiation length X_0 to contain particles of the relevant energy scale.
- Energy resolution $\propto 1/\sqrt{E}$

We will talk more about this next lecture.

HCAL

- Only stable hadrons and muons reach the HCAL.
- Hadrons create hadronic showers via strong interactions
- Similar to EM showers, except that the length scale is determined by the nuclear absorption length λ, instead of the electromagnetic radiation length X_0 for obvious reason.
- Energy resolution $\propto 1/\sqrt{E}$

Difference in objective between HCAL and ECAL

- ECAL's objective is
  - measure single isolated particles: photons and electrons.
  - measure the primary photon content of jets.
- HCAL's objective is to measure "jets".
  - Quarks and gluons turn into "sprays of hadrons" because of confinement over fm distance scales.
  - The detector thus sees "jets" of hadrons in the direction of the original quark or gluon.
- Both Calorimeters combined measure "missing transverse energy" (MET).

Primary vs "secondary" photons

- When a quark or gluon "hadronizes", it turns into a jet of hadrons, mostly pions.
  - Charged pions are long lived
  - Neutral pions decay to two photons immediately => primary photons detected in ECAL.
- Charged pions hit HCAL, and cause hadronic showers.
  - Again mostly pions
  - Charged pions "feed" the showering
  - Neutral pions decay to two photons immediately => "secondary" photons detected in HCAL

“Compensating” Calorimeter

- Due to isospin, roughly half as many neutral pions are produced in hadronic shower than charged pions.
- However, only charged pions “feed” the hadronic shower as pi0 immediately decay to di-photons, thus creating an electromagnetic component of the shower.
- Resolution is best if the HCAL has similar energy response to the EM part of the shower as the hadronic part.

One of the big differences between ATLAS and CMS is that ATLAS HCAL is compensating, while CMS has a much better ECAL but a much worse HCAL response to photons.

Muon Detectors

- Muons are minimum ionizing particles, i.e. small energy release, in all detectors.
- Thus the only particles that range through the HCAL.
- Muon detectors generally are another set of tracking chambers, interspersed with steal or iron absorbers to stop any hadrons that might have “punched through” the HCAL.

More Details on all of this next lecture.