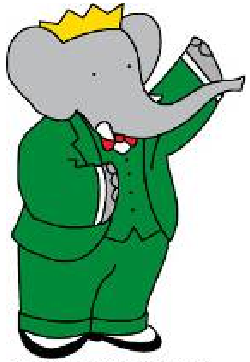

Exploring the Richness of Flavor Physics

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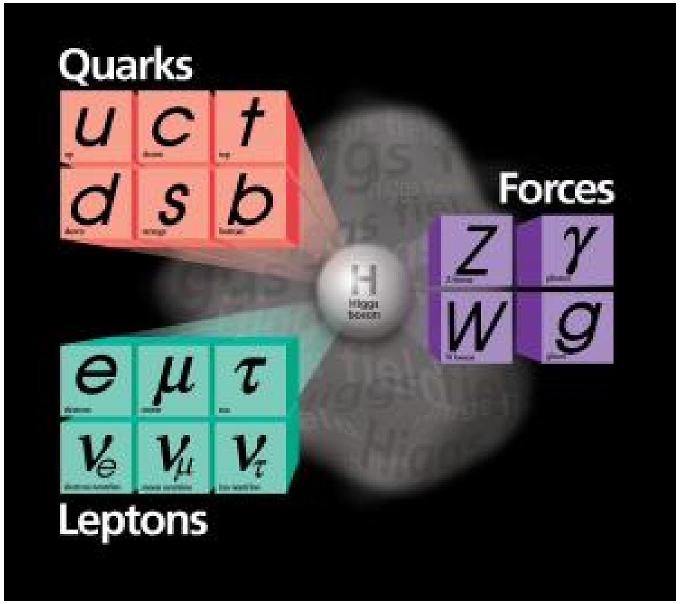
Physics Colloquium at University of Hawaii
October 15, 2009

Outline

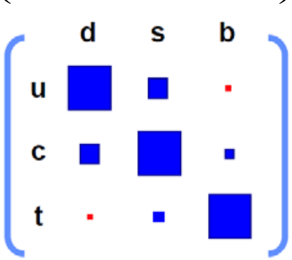
- Motivation: Flavor Physics
- Introduction to PEP-II and BaBar
- Why and How to Trigger for Physics
- Selected Physics Topics
  - Leptonic decays of D_s and hints of new physics
  - Two-photon physics
- Conclusions and Prospects

Some Big Questions in Particle Physics



Cabibbo-Kobayashi-Maskawa (CKM) matrix

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



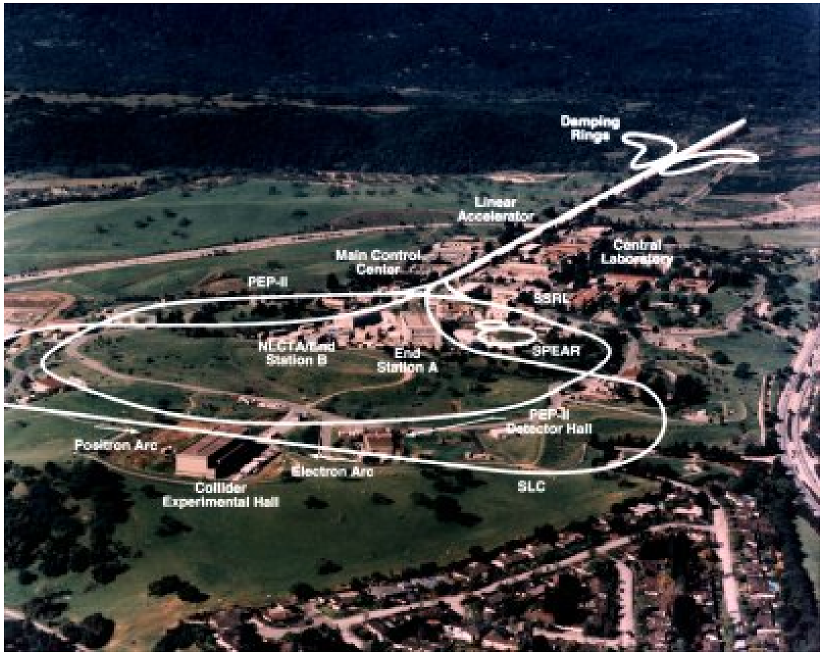
- Why do we have exactly three generations of quarks and leptons in the Standard Model (SM)?
- Why is the flavor structure in the weak interaction so complicated?
- What is the source of CP violation that produced the Baryon asymmetry?
- Where is the theorized Higgs boson that responsible for the generation of mass?
- Is there physics beyond the SM?

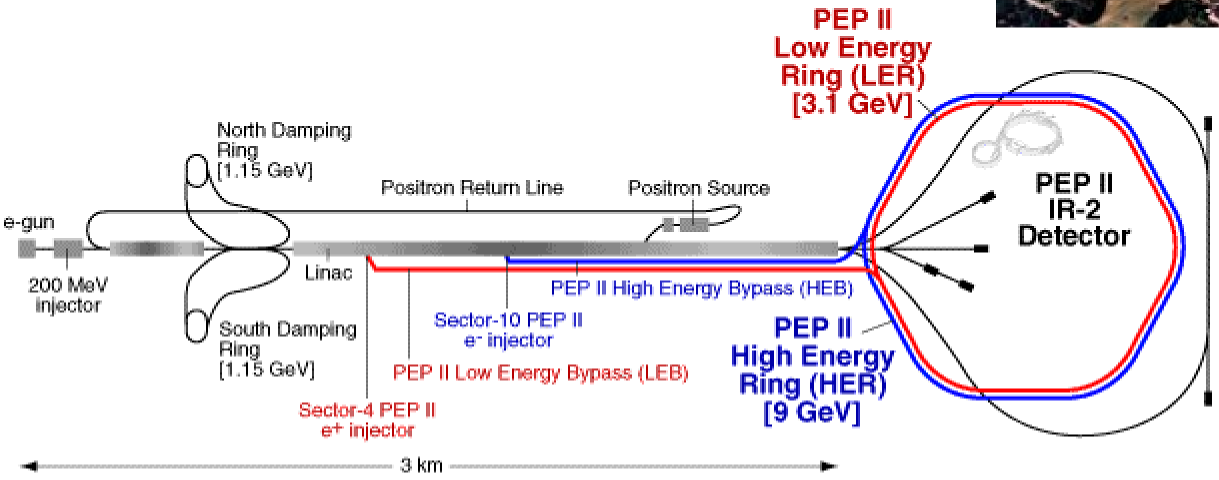
Colliders Comparison

	Accelerator (Detector)	Time between collisions (ns)	Peak luminosity (10^{34} $cm^{-1}s^{-1}$)	Energy (GeV)
e^+e^-	BEPCII (BES-III)	8	0.03	1(2.3) x 1(2.3)
	CESR (CLEO)	4.2	0.2	5.29 x 5.29
	KEKB (Belle)	2.1	2.1	8 × 3.5
	PEP-II (BaBar)	4.2	1.2	9 × 3.1
	LEP (Aleph, Delphi, Opal, L3)	2200	0.005	105 ×105
	SLC (SLD)	8000000	0.0003	46 ×46
e p	HERA (H1, Zeus)	96	0.0014	920 × 30
p $\bar{p}$	Tevatron (D0, CDF)	396 (132)	0.02	1000 × 1000
p p	LHC (Atlas, CMS)	25	1.0	7000 × 7000

PEP-II at SLAC

- PEP-II collides e^+ and e^- inside the BaBar detector with a center of mass energy of ~10.58 GeV.
- Operation: 1999-2008

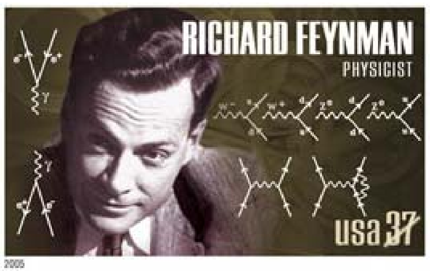


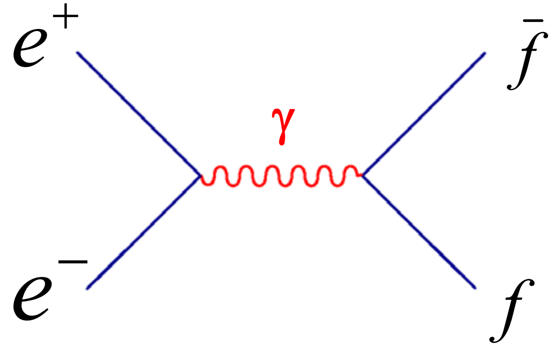


PEP-II ring: C=2.2 km

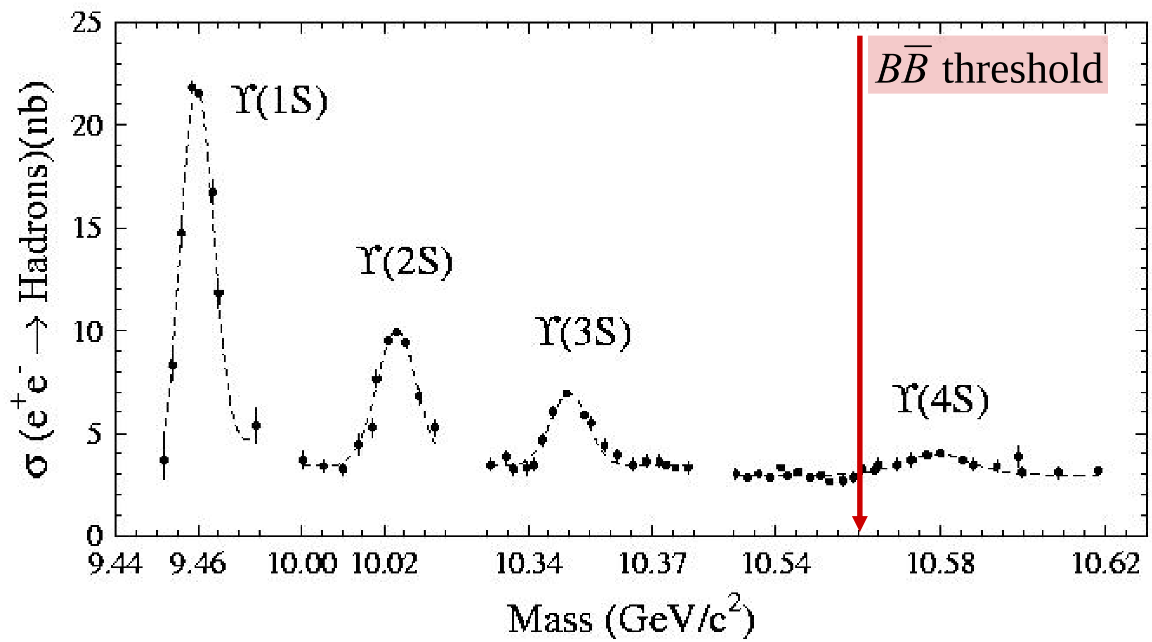
The Physics Programs

$$e^+e^- \to \gamma \to u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b},\ e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-$$

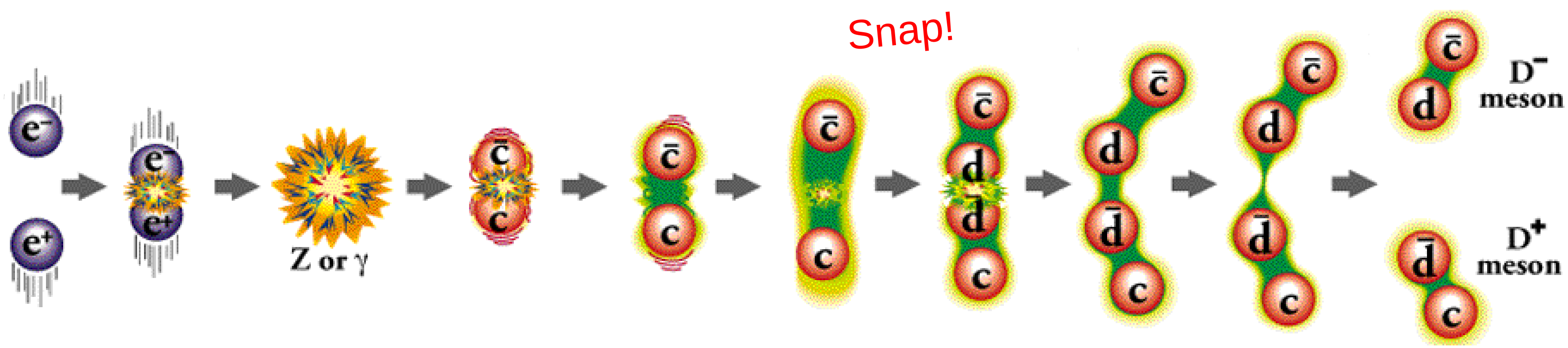




Where f is a fermion (a quark or lepton)



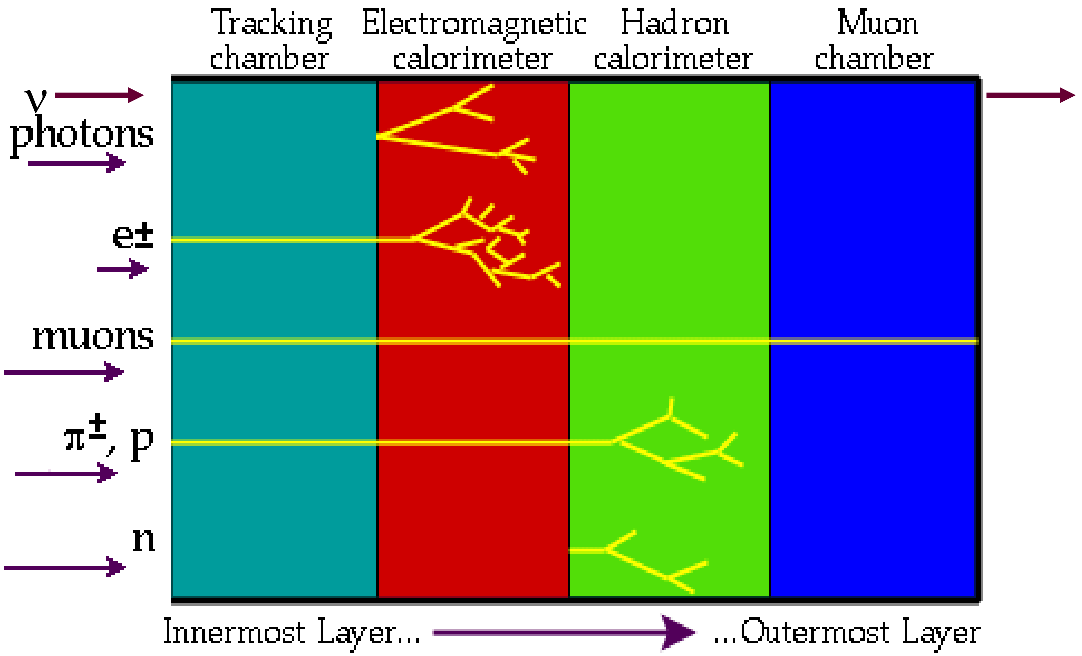
The e^+e^- collisions

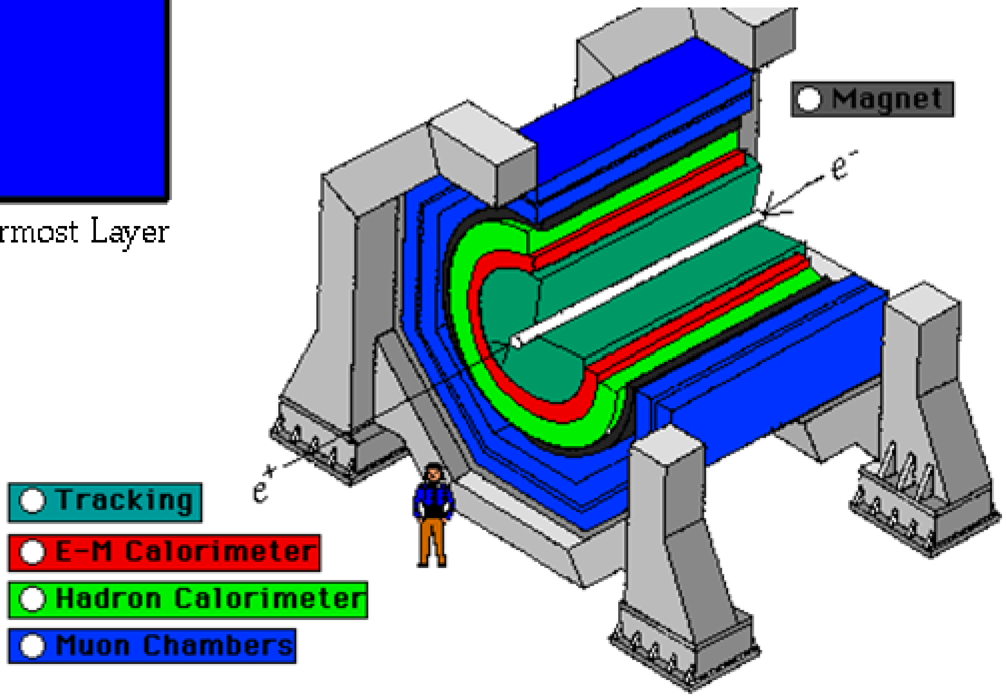


The intermediate stages of this process occur in about a billionth of a billionth of a billionth of a second, and are not observable.

www.particleadventure.org

How to Detect Particles?





The BaBar Detector

Detector of Internally Reflected Cherenkov light

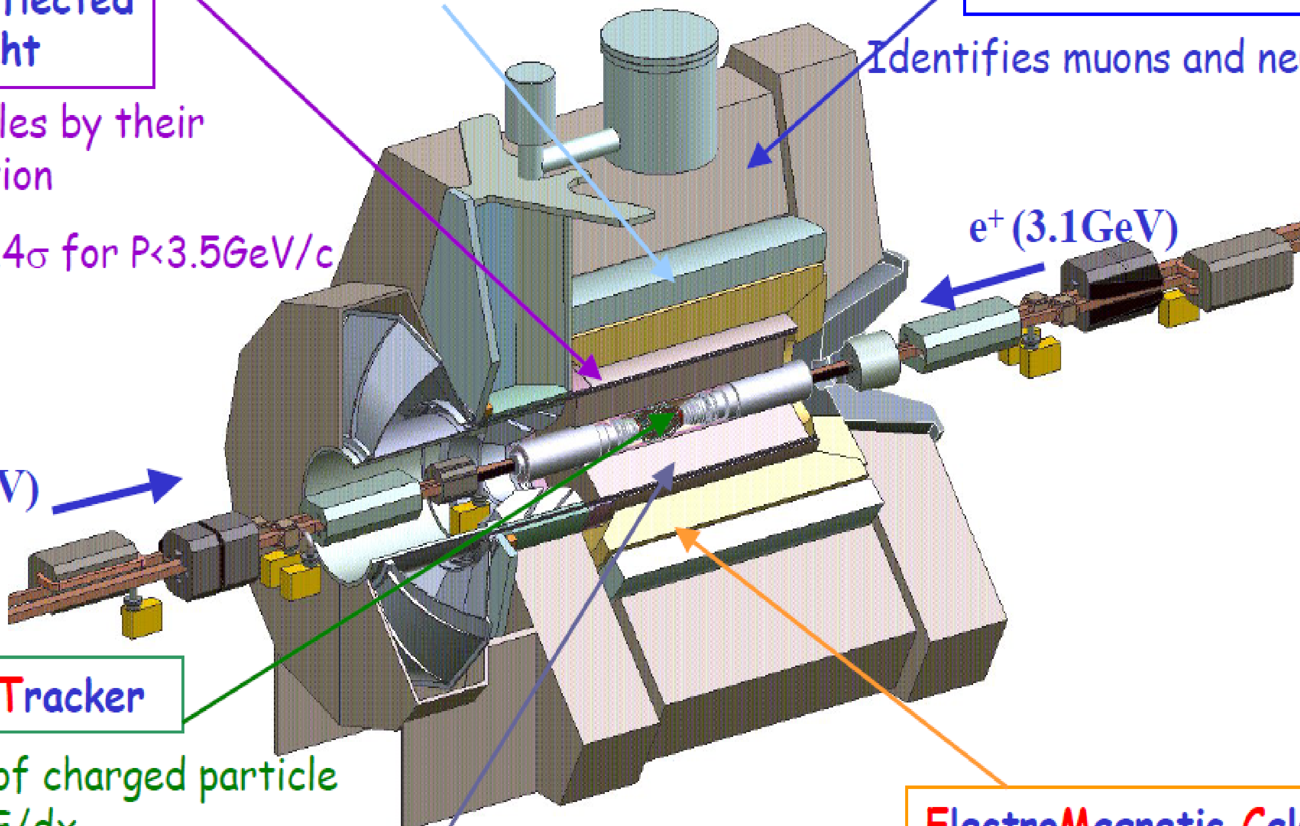
Identifies particles by their Cherenkov radiation

K-π separation>3.4σ for P<3.5GeV/c

1.5T solenoid

Instrumented Flux Return

Identifies muons and neutral hadrons



e^+ (3.1GeV)

e^- (9GeV)

Silicon Vertex Tracker

Measures origin of charged particle Trajectories + dE/dx

97% efficiency

Drift CHamber

Measures momentum of charged particles + dE/dx

$\sigma(p_T)/P_T=0.13\%P_T\oplus0.45\%$

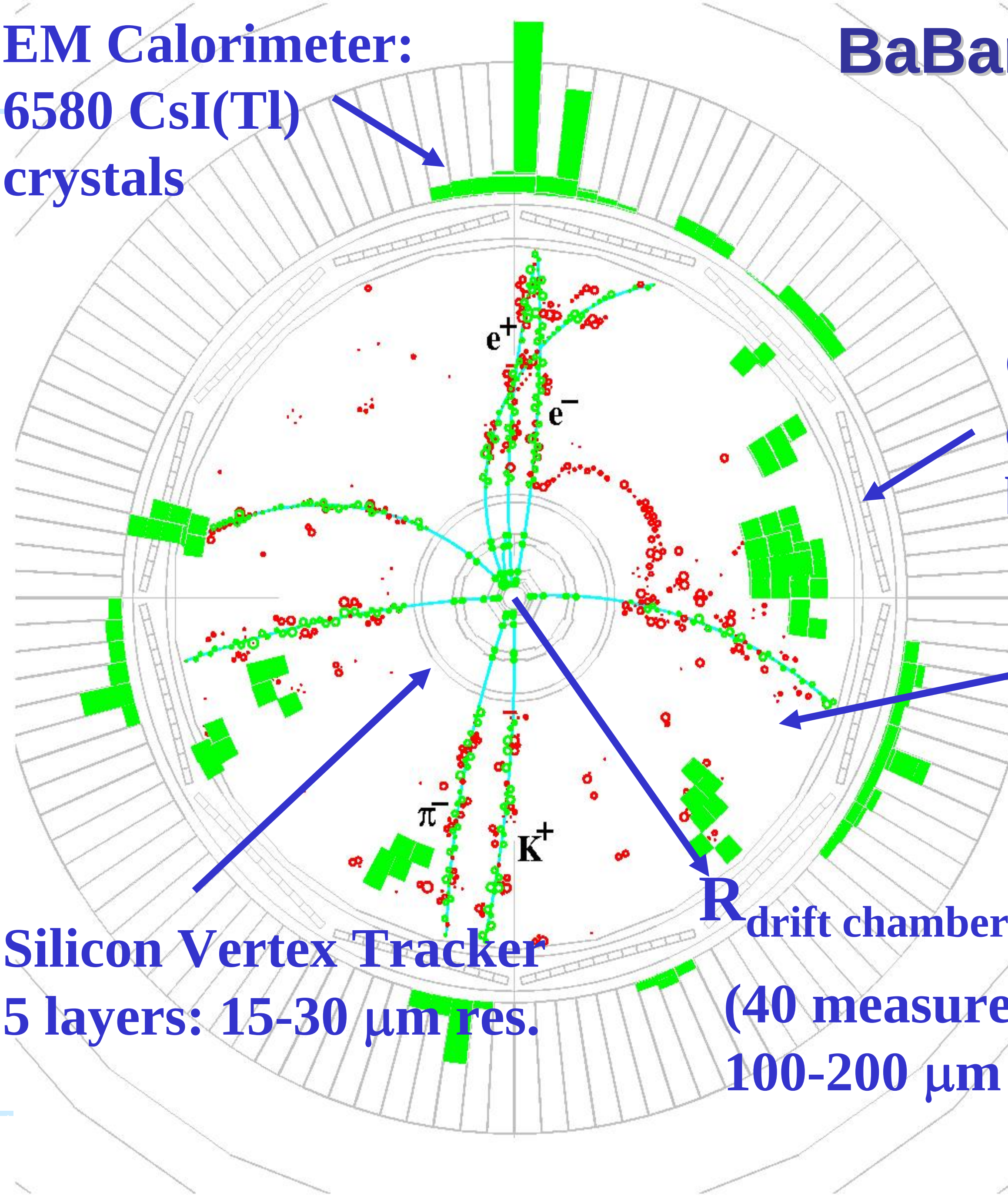
ElectroMagnetic Calorimeter

Measures energy of electrons and photons

$\sigma(E)/E=1.33\%E^{-1/4}\oplus2.1\%$

BaBar Event Display

EM Calorimeter:
6580 CsI(Tl) crystals



Cerenkov ring imaging detectors: 144 quartz bars (measure *velocity*)

Tracking volume:
B=1.5 T

$R_{drift\ chamber}$ = 80.9 cm

(40 measurement points, each with 100-200 μm res. on charged tracks)

Silicon Vertex Tracker
5 layers: 15-30 μm res.

Event Rates on the Υ(4S) Energy

Event Type	Cross Section	Event Rate *
Interesting physics!: $b\bar{b}$	1.05 nb	~65 Hz
$c\bar{c}$	1.30 nb	
$s\bar{s}$	0.35 nb	
$u\bar{u}$	1.39 nb	
$d\bar{d}$	0.35 nb	
$\tau^+\tau^-$	0.94 nb	
$\mu^+\mu^-$	1.16 nb	
e^+e^-	~50 nb	~ 500 Hz
Beam background		> 20 kHz

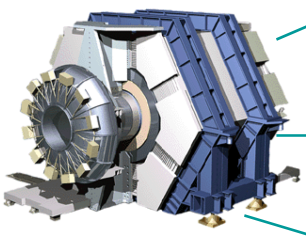
* at PEP-II luminosity of about $10^{34} cm^{-2} s^{-1}$

Why and How to Trigger?

- Data processing is limited to a few hundred Hz $\Rightarrow$ trigger to select interesting events
- BaBar trigger characteristics:
  - ❖ Continuous readout & pipelined
  - ❖ Trigger lines defined by generic topology
- Goals:
  - ❖ Eliminate background as early as possible
  - ❖ Keep interesting physics events
- Challenge:
  - ❖ Maintaining high efficiency for physics while reducing trigger rate with limited time to make decisions

A Snapshot at What a Trigger Does

- Level 1 (L1) is a hardware based Trigger



Calorimeter Trigger (Neutrals)

Drift Chamber Trigger (Tracks)

Muon Trigger (Tracks)

Global Trigger → L1 accepts

~12 μs latency

~ 238 MHz → **L1** → ~2500 Hz → **L3** → ~350 Hz

- Level 3 (L3) is a software based Trigger
  - Slightly more sophisticated algorithms used to separate background physics processes from the interesting processes.
  - A farm (composed of 50 Linux dual-core CPU's)

Execute algorithms: ~10 ms per event

Explore the Flavor Physics of Quarks

CP-violation

- Phases of CKM elements from CP violating observables: α, β, γ (ϕ_3, ϕ_1, ϕ_2)

Flavor mixing

- Magnitudes of CKM elements: V_{cb}, V_{ub}, V_{td}, V_{ts}.

Studies of decay dynamics

- Test predictions of heavy-quark expansions
- Test QCD predictions
- Semileptonic, leptonic, hadronic, and rare decays

Searches for new particles

- Charm spectroscopy
- Charmonium spectroscopy
- Exotic hadrons?

Effects of new physics

Look for unexpected

- Decay rates
- Patterns of CP asymmetries
- Kinematic distributions

Selected Physics Topics

$$1)\ e^+e^- \to c\bar{c}$$

$$2)\ e^+e^- \to e^+e^-\gamma\gamma$$

Discrete Symmetry Operators: C, P, T

Charge conjugation

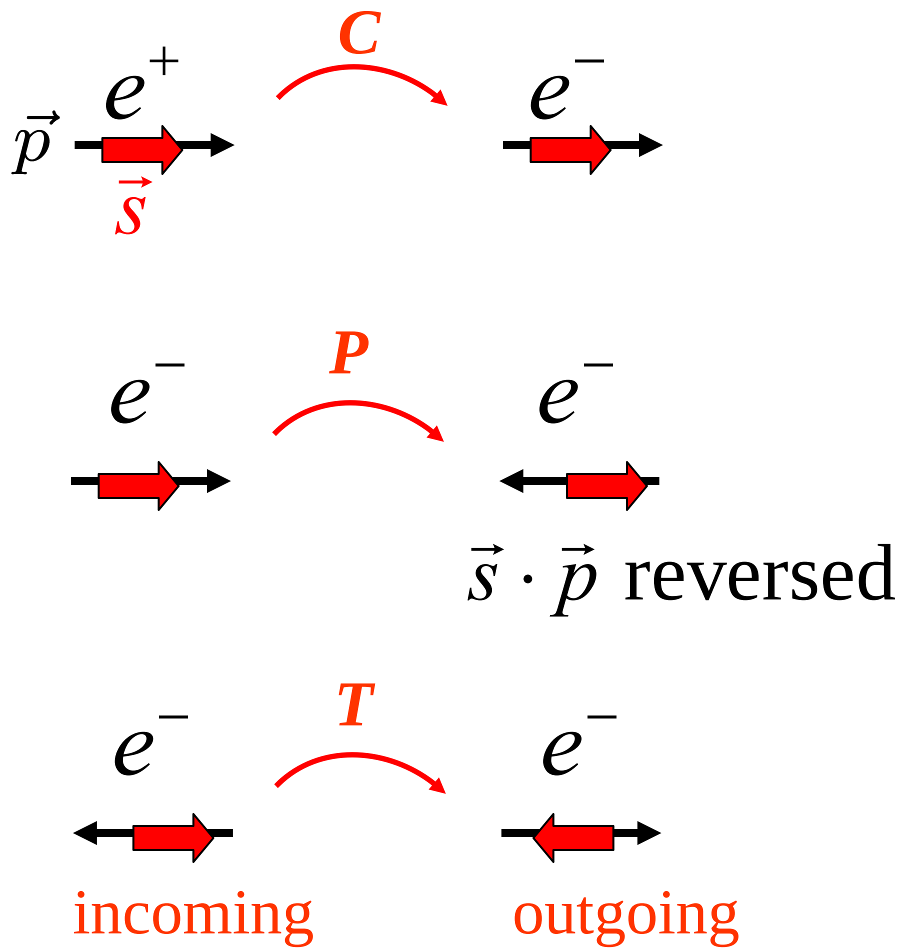
$$C:\ a \rightarrow \overline{a}$$

Parity

$$P:\ \vec{r} \rightarrow -\vec{r}$$

Time/motion reversal

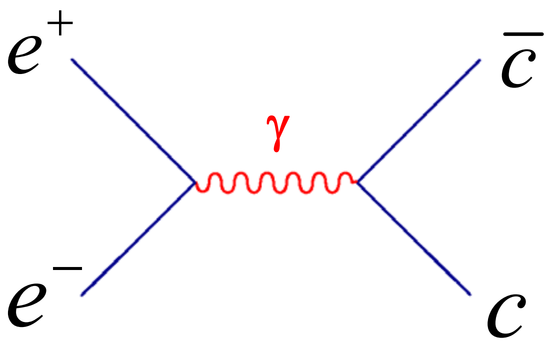
$$T\ :t \rightarrow -t$$



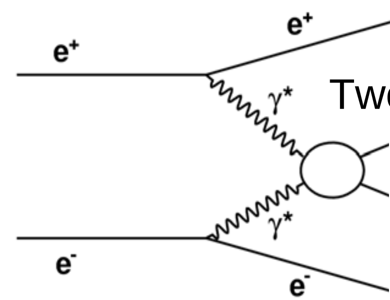
Discrete symmetry transformations: multiplicative (not additive) quantum numbers. The weak interactions violate C, P, CP, T.

Physics Processes

One-photon processes C=−

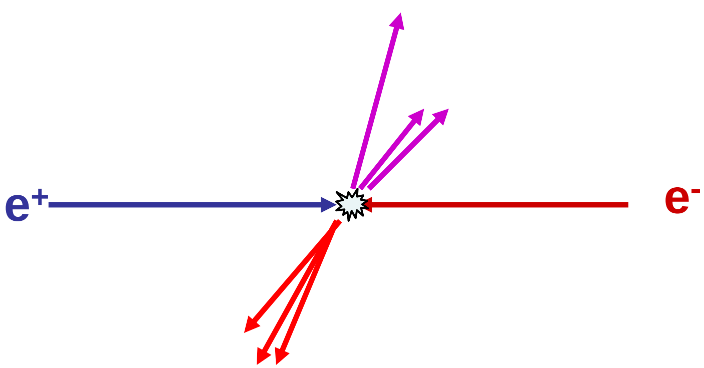


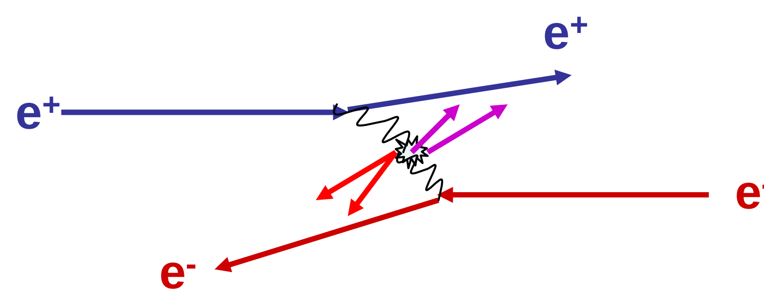
Two-photon processes C=+



Two-Photon Physics

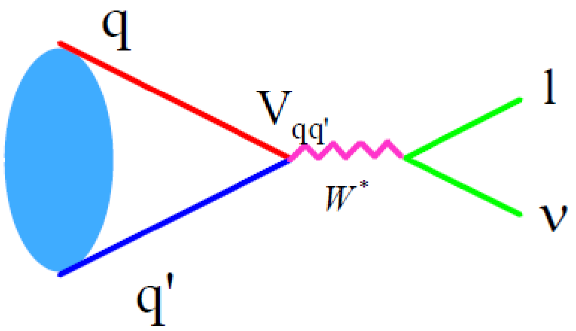
Event topology:





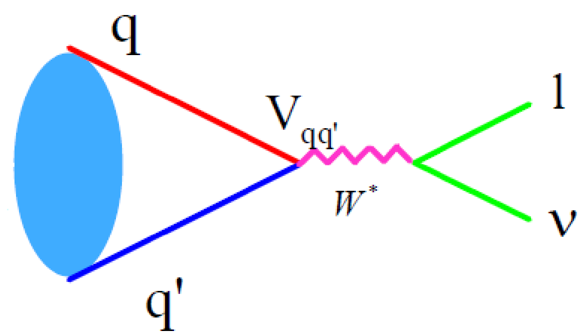
$$e^{+}e^{-} \rightarrow c\bar{c} \text{ Example:}$$

Leptonic Decays of Charged Heavy Mesons



Why Is Leptonic Decay Important?

$$D^+ = c\bar{d}$$
$$D_s^+ = c\bar{s}$$
$$B^+ = u\bar{b}$$

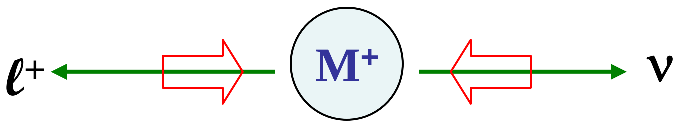


- It gives access to the decay constant and the CKM matrix element.
- Only one hadronic current is involved ⇒ theoretically easier to calculate in QCD.
- It provides calibration for decay processes involving mesons containing b quarks.
- Lattice predictions for f_B/f_{Bs} are a key part in translating B and B_s mixing rates into CKM constraints.
- Leptonic *B* decays provide interesting sensitivity to new physics (tree-level sensitivity to charged Higgs).

Leptonic Decay of Mesons

- Measure the decay constants f_D, f_{D_s} to compare with Lattice QCD
- Experimentally hard to measure because of CKM suppression, helicity suppression, and neutrino reconstruction.

Helicity suppressed



J=0

Decay Mode	Decay Constant	CKM Element
$D^+ \to \ell^+\nu$	f_D	$\lvert V_{cd}\rvert \approx 0.23$
$D_s^+ \to \ell^+\nu$	f_{D_s}	$\lvert V_{cs}\rvert \approx 0.97$
$B^+ \to \ell^+\nu$	f_B	$\lvert V_{ub}\rvert \approx 0.004$

lepton mass effects

$$\Gamma(M \to l\nu) = \frac{1}{8\pi} G_F^2 f_M^2 m_l^2 M_M \left(1 - \frac{m_l^2}{M_M^2}\right)^2 \left|V_{qq'}\right|^2$$

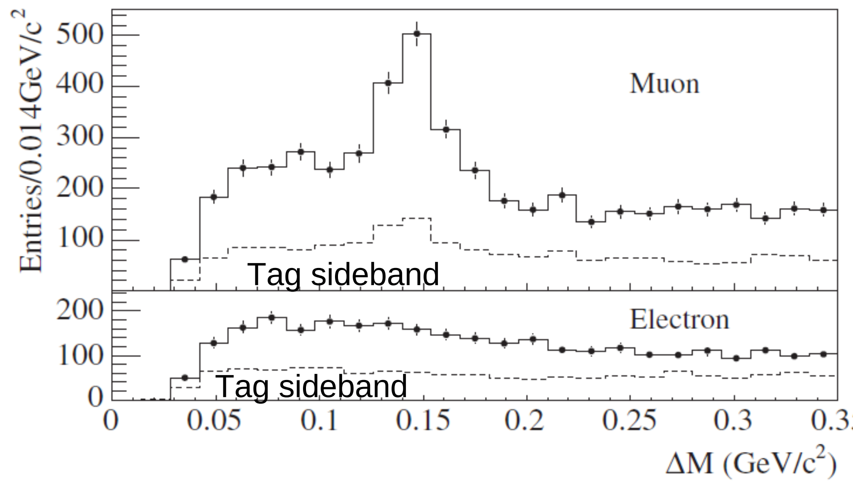
$$\Gamma(D_s^+ \to e^+\nu_e) : \Gamma(D_s^+ \to \mu^+\nu_\mu) : \Gamma(D_s^+ \to \tau^+\nu_\tau) \approx 10^{-5} : 1 : 10$$

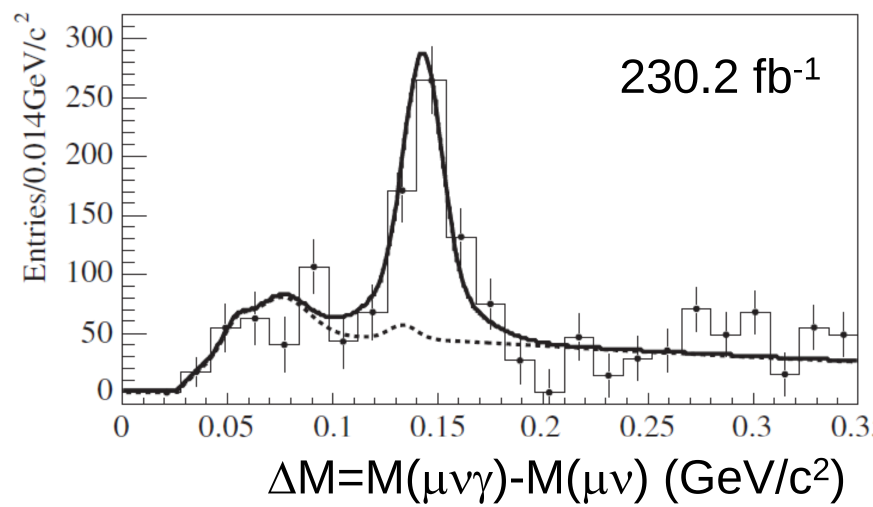
Analysis of $D_s \to \mu\nu$ from BaBar

Signal: $e^+e^- \to xD_{(s)}D_s^*$, $D_s^* \to D_s\gamma$, $D_s \to \mu\nu$

Partial reconstruction method

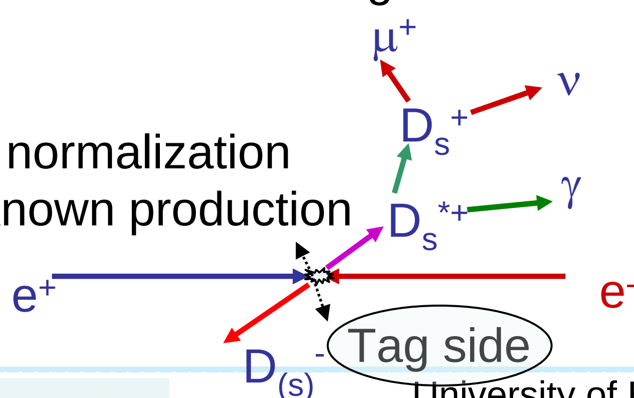
- Reconstruct a charm decay as tagging D, D^*, D_s
- Look for a μ^+ and "reconstruct" a ν from (E_{miss},p_{miss})
- Combine μ and ν to make a D_s
- Combine D_s with a γ to make a D_s^*
- Compute $\Delta M = M(\mu\nu\gamma) - M(\mu\nu)$
- Subtract background
  - sidebands of the tag sample
  - electron sample
- Fit ΔM distribution to extract signal events





$f_{D_s} = (283 \pm 17 \pm 7 \pm 14)$ MeV

Use $D_s \to \phi\pi$ for normalization because of unknown production rate of $D_s^{(*)}$



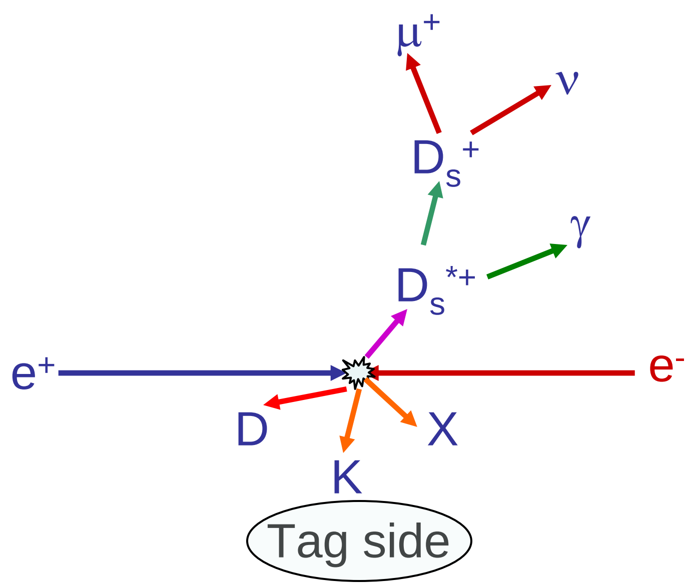
PRL 98, 141801 (2007)

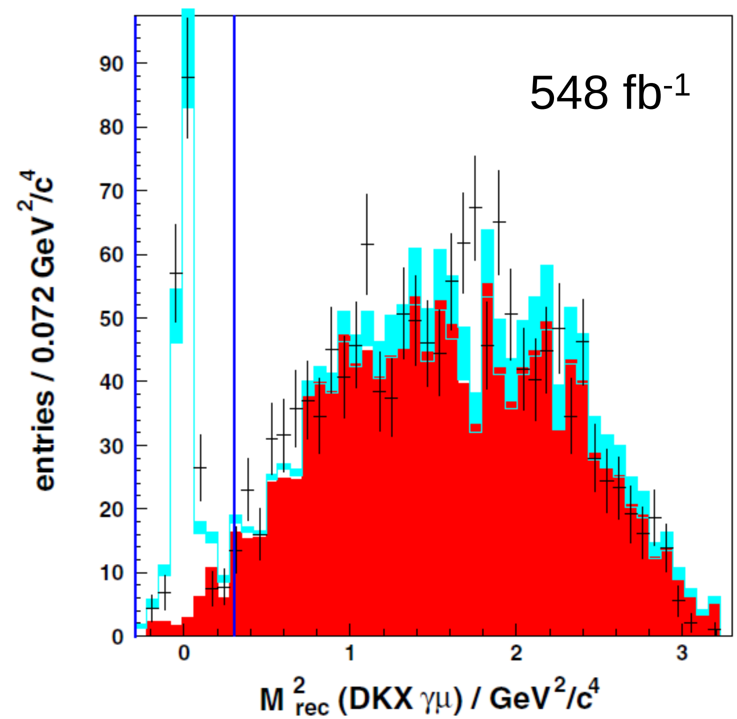
Analysis of $D_s \to \mu\nu$ from Belle

$e^+e^- \to DKXD_s^*$, $D_s^* \to D_s\gamma$, $D_s \to \mu\nu$
where X: n(π) and up to one γ

Full reconstruction method

- D_S is not observed but inferred from calculating the neutrino candidate mass: $M_{rec}^2(DKX\gamma\mu)$
- No normalization mode needed
- High signal-to-backgroud ratio



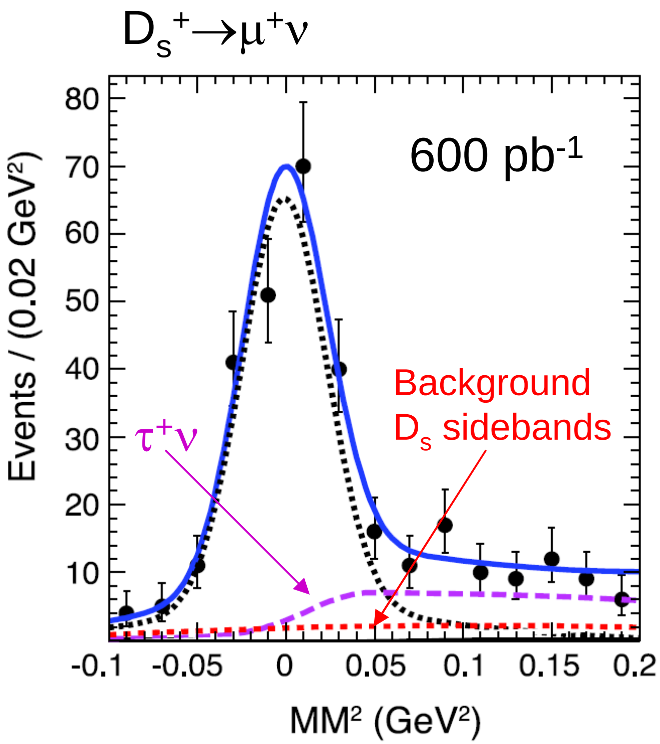


f_{D_S}=(275±16±12) MeV

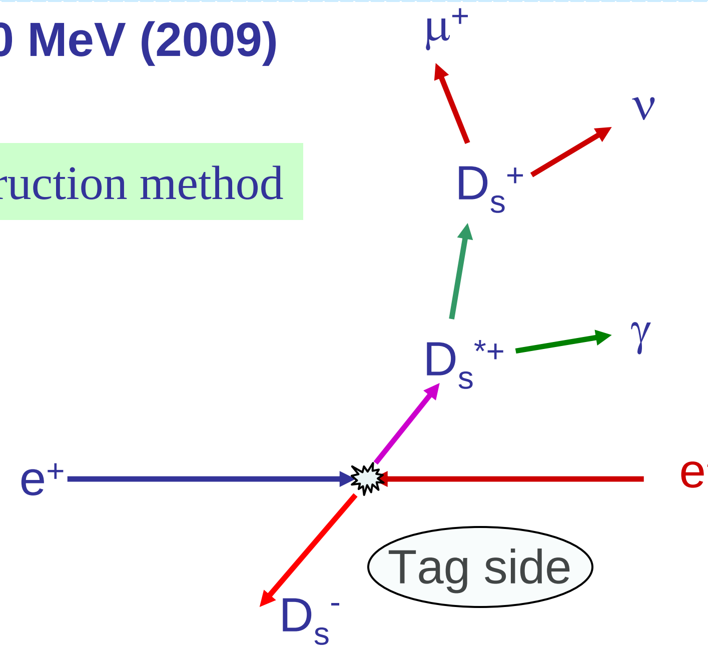
PRL 100, 241801 (2008)

Analysis of $D_s \to \mu\nu$ from CLEO-c

CLEO-c: $e^+e^- \to D_s D_s^*$ at 4170 MeV (2009)



Full reconstruction method



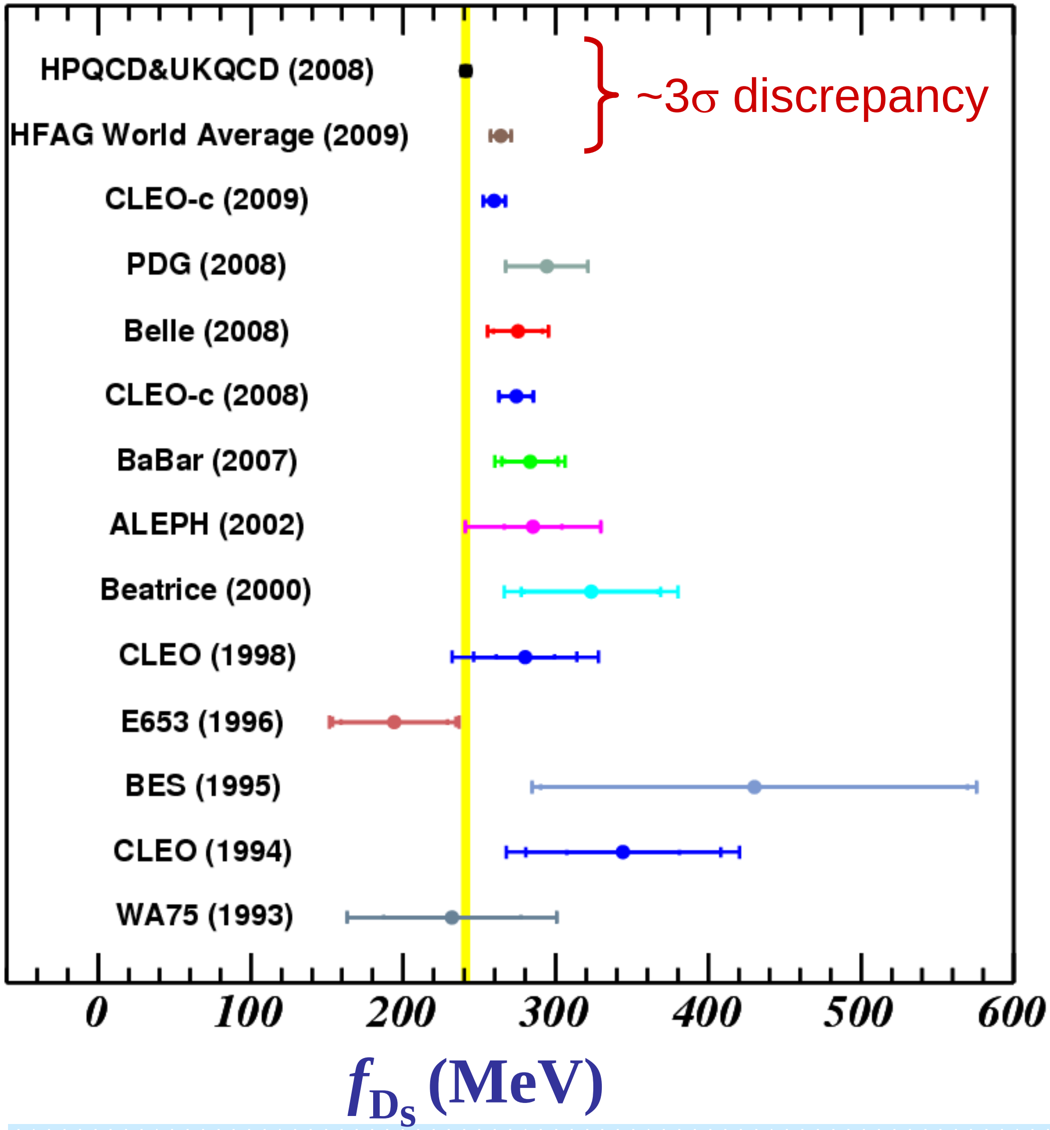
$$\mathrm{MM}^2 = \left(E_{CM} - E_{D_s} - E_\gamma - E_\mu\right)^2 - \left(p_{CM} - p_{D_s} - p_\gamma - p_\mu\right)^2$$

f_{D_s}=(263.3±8.2±3.9) MeV

PRD 79, 052001 (2009)

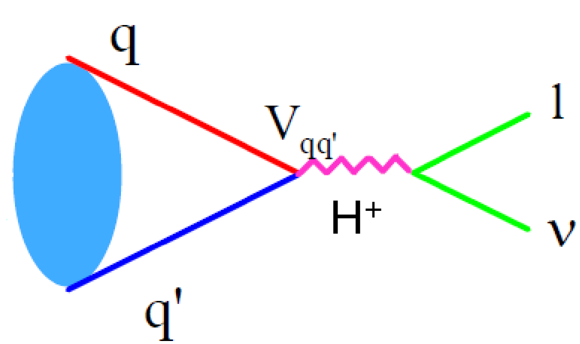
Similar method can be applied to BES-III data!

Experimental Results and Predictions

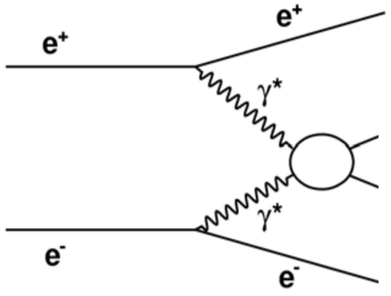


- More progress can be made from BaBar, Belle, and BES-III.
- Possibility to probe new physics
  - Charged Higgs boson or leptoquark

PRL 100, 241802 (2008)



Two-Photon Physics



hadrons

What Is Two-Photon Physics?

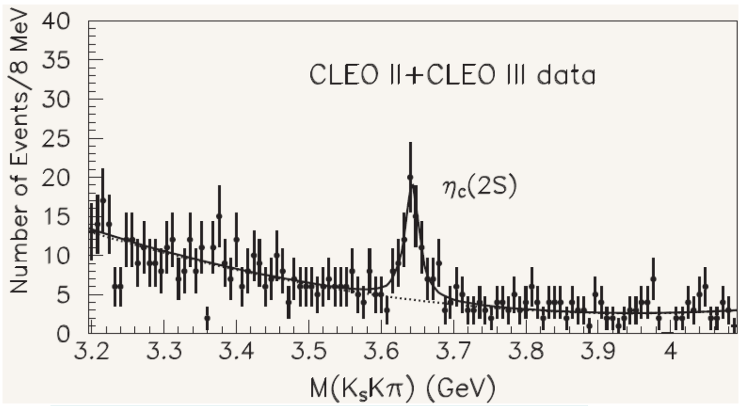
- It is the study of interactions between two photons.
- Electron-positron machines allowed first observation of $\gamma\gamma$ processes.
- Unique feature: produce hadronic states with C=+ $\Rightarrow$ have access to some states that might not be produced or detected otherwise
  - ➢ Examples: η_c, non-strongly interacting supersymmetric particles, Higgs bosons, etc.
    - Good calibration channels: $\gamma\gamma \rightarrow e^+e^-$, $\mu^+\mu^-$

Early History of Two-Photon Physics

- 1932: Early interest after the discovery of positron
- 1960: Theoretical papers relevant to two-photon physics at e^+e^- storage rings
  - resonance production (by F. Low)
  - meson pair production (by F. Calogero and C. Zemach)
- 1969: First experimental results on two-photon QED reactions from Novosibirsk and Frascati.
- 1969-1970: Theory papers on $\gamma\gamma \rightarrow$hadrons
  - ➢ Brodsky, Kinoshita, and Terazawa: $\gamma\gamma$ collisions will become dominant as the energy increases.
- 1979: Experimental activities resumed by Mark II at SPEAR (SLAC)

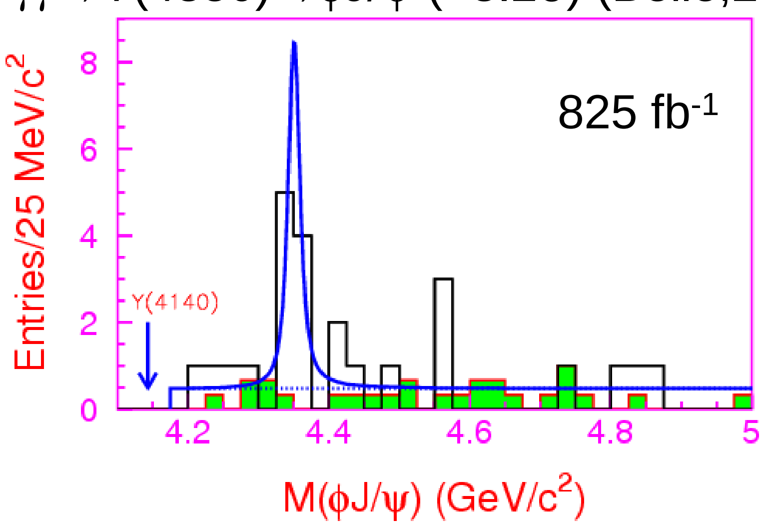
"Recent" Discoveries from γγ Fusions

$\gamma\gamma \to \eta_c' \to K_S^0 K^{\pm}\pi^{\mp}$ (6.5σ) (CLEO,2004)



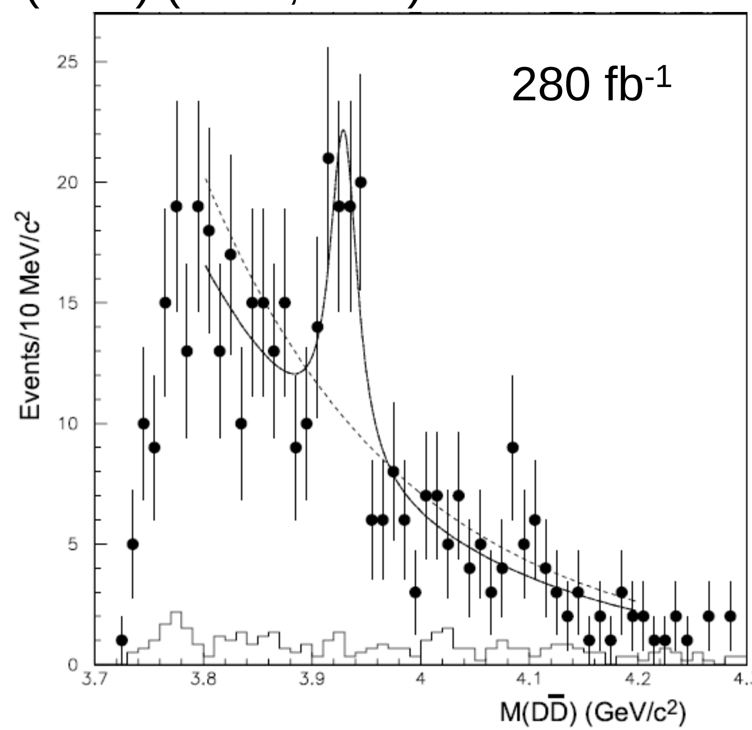
PRL 92, 142001 (2004)

γγ→Y(4350)→φJ/ψ (>3.2σ) (Belle,2009)



$\gamma\gamma \to Z(3930) \to D\overline{D}$

Candidate for a charmonium state χ'_{c2} (5.5σ) (Belle,2005)



PRL 96, 082003 (2006)

Why Is Two-Photon Physics Interesting?

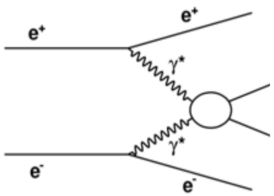
- Study or look for C=+ resonances
- Photon-to-meson transition form factors
  - Window to hadron distribution amplitudes
  - $\gamma^*\gamma^*\rightarrow\pi^0$, f_0,η, σ, η_c, η_b, etc.
- Exclusive hadron pair production in two-photon reactions
- Photon structure function

Three Different Kinematic Conditions

Larger data statistics

More kinematic info

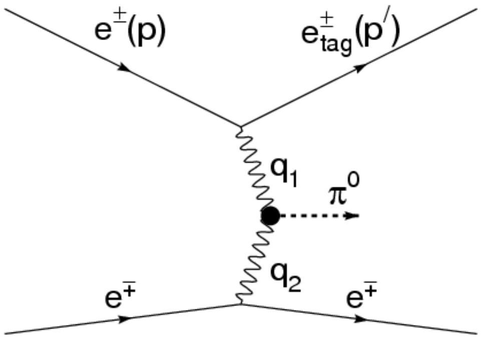
- Double-tag: the scattered e^+ and e^- are both detected
  - Ideal for two-photon physics



- Single-tag: only one scattered e^+ or e^- is detected
  - Determination of the Q^2 dependence of resonance couplings or of the total cross section
- No-tag: neither the e^+ nor the e^- is detected
  - Preferentially small total transverse momentum Σp_T of the detected particles $\Rightarrow$ restrict both Q^2 values to be small

An Analysis of $\gamma\gamma^* \to \pi^0$

- $e^+e^- \to e^+e^-\gamma\gamma^*$, where $\gamma\gamma^* \to \pi^0$ in the single-tag mode:



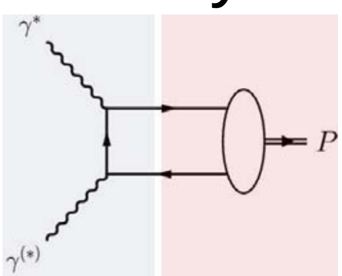
Tagged: momentum transfer $Q^2 = -q_1^2 = -(p - p')^2 > 3\ GeV^2$
$\Rightarrow$ Highly virtual photon

Untagged: momentum transfer $q^2 = -q_2^2 \sim 0\ GeV^2$
$\Rightarrow$ Quasi-real photon

- The differential cross section for this process depends on only one form factor $F(Q^2) = \int T(x,Q^2)\ \phi_\pi(x, Q^2)\ dx$.

Calculable hard-scattering amplitude for $\gamma\gamma \to q\ \bar{q}$

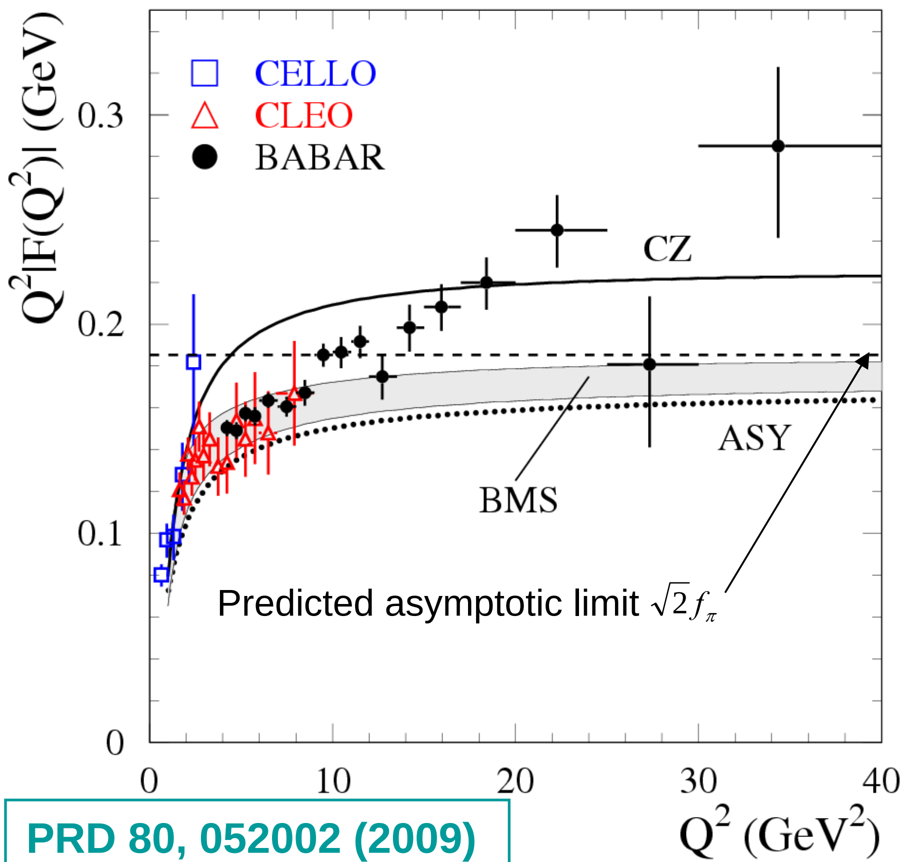
Nonperturbative pion distribution amplitude (DA) for $q\ \bar{q} \to \pi$



(x = fraction of the π^0 momentum carried by one of the quarks)

- Experimental data on $F(Q^2)$ help determine the unknown dependence on x for $\phi_\pi(x, Q^2)$.

The π^0 Transition Form Factor

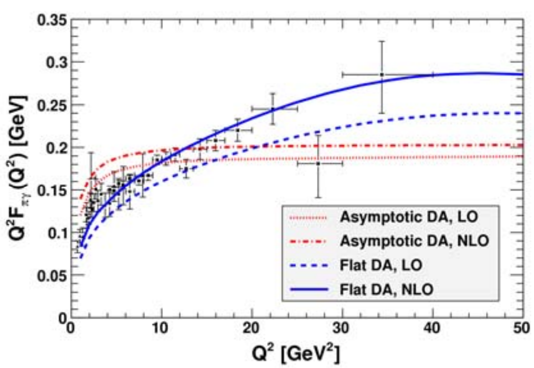


PRD 80, 052002 (2009)

Data: $Q^2|F(Q^2)| \sim Q^{1/2}$
Leading order pQCD: $Q^2|F(Q^2)| \sim$ const.
(in the asymptotic limit)

After public release of this result, a flat pion distribution amplitude is used to reproduce the Q^2 dependence of BABAR data.

A.V. Radyuskin, arXiv:0906.0323
M.V. Polyakov, arXive:0906.0538
H.N. Li and S. Mishima, arXiv:0907.0166

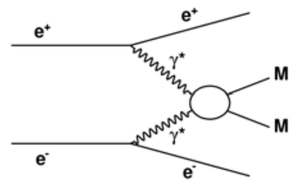


- The Chernyak-Zhitnitsky DA (CZ) — Nucl. Phys. B201, 492 (1982)
- The asymptotic DA (ASY) — Phys. Lett. B87, 359 (1979)
- The DA derived from QCD sum rules with non-local condensates (BMS) — Phys. Lett. B508, 279 (2001)

Analysis of Neutral Pair Production

- At the B factories, two-photon physics can be studied from the process: **$e^+ e^- \to e^+ e^- \gamma \gamma$** .
  - **no-tag** analysis: $e^+ e^-$ scatter at very small angles and escape undetected

quasi-real photons

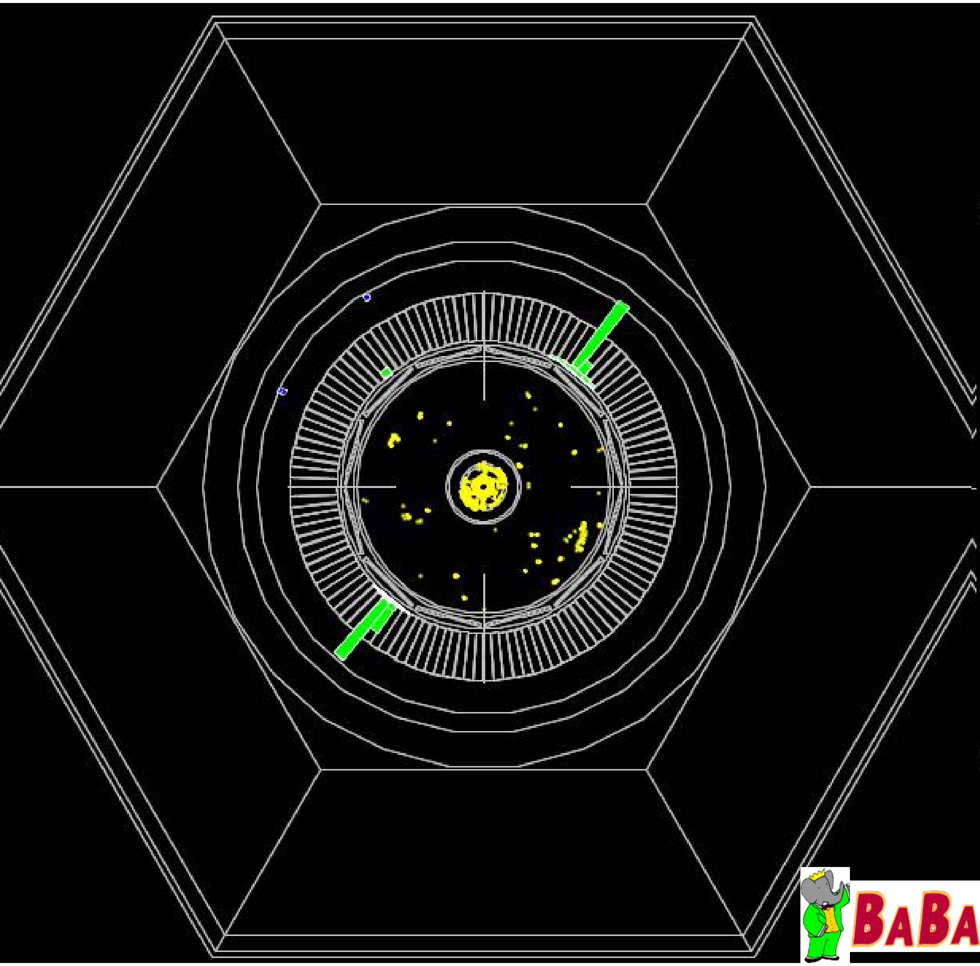


$$\pi^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right)$$

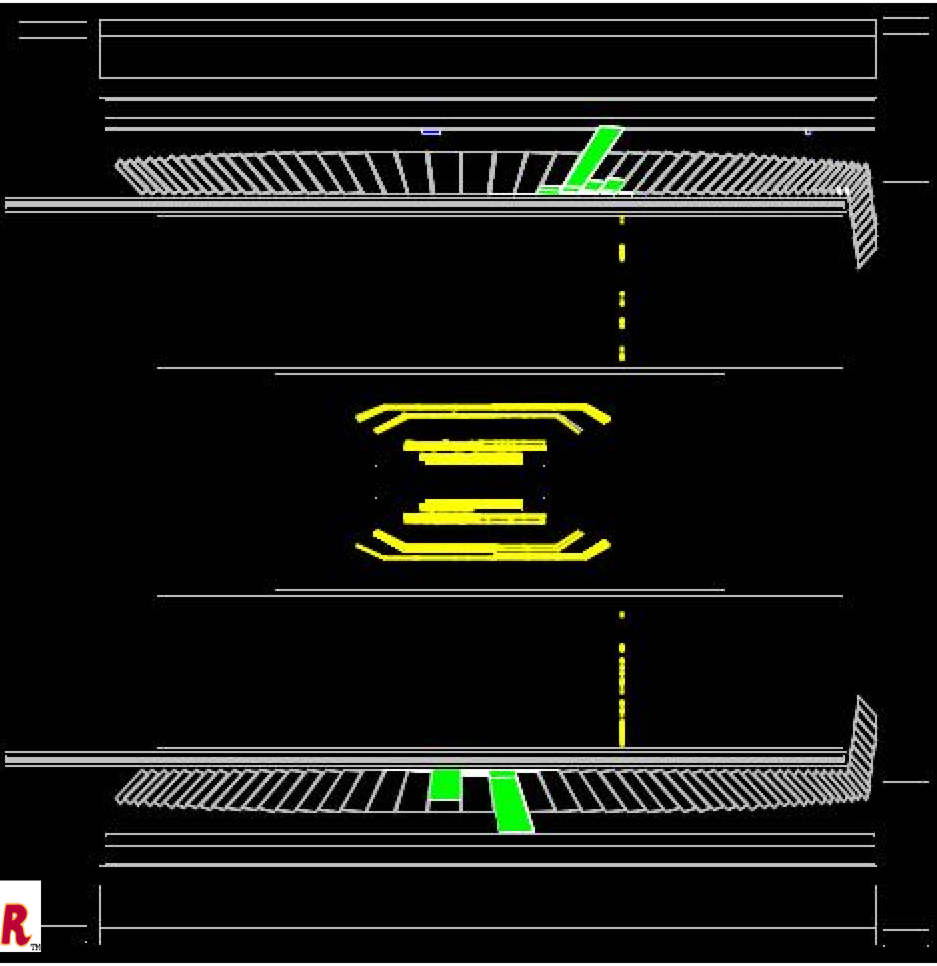
- **What:** study meson pair production $\gamma\gamma \to MM$, where M can be π^0 or η
- **Why:**
  - Neutral pair production allows a determination of the meson wave function
  - Test QCD models: pQCD vs "handbag model" for hadron pair production
- **Why now:**
  - The virtual photon flux falls off rapidly at increasing center of mass energy W, so it had been difficult to use the two-photon reaction to study high-mass final states.
  - But, the high luminosity at the B factories makes this possible.
- **Goal:** measure the neutral pair production cross sections and angular distributions from BaBar data taken at $\sqrt{s} = M(\Upsilon(4S)) = 10.58$ GeV

An Event Display of $\gamma\gamma \to \pi^0\pi^0$

- A x-y view

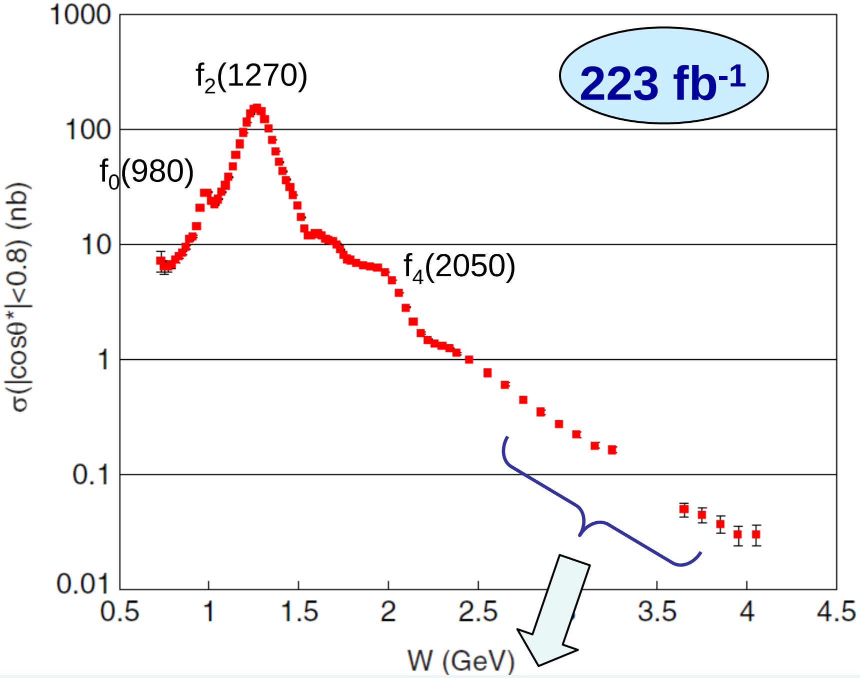


- A ρ-z view:

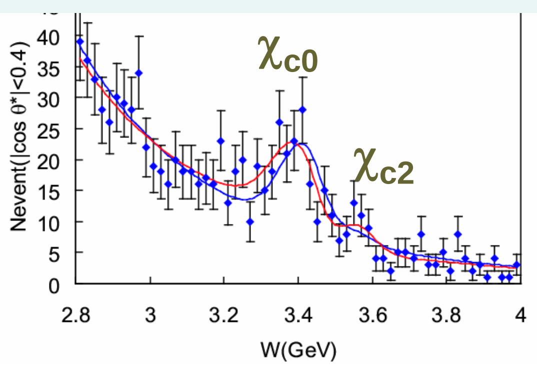


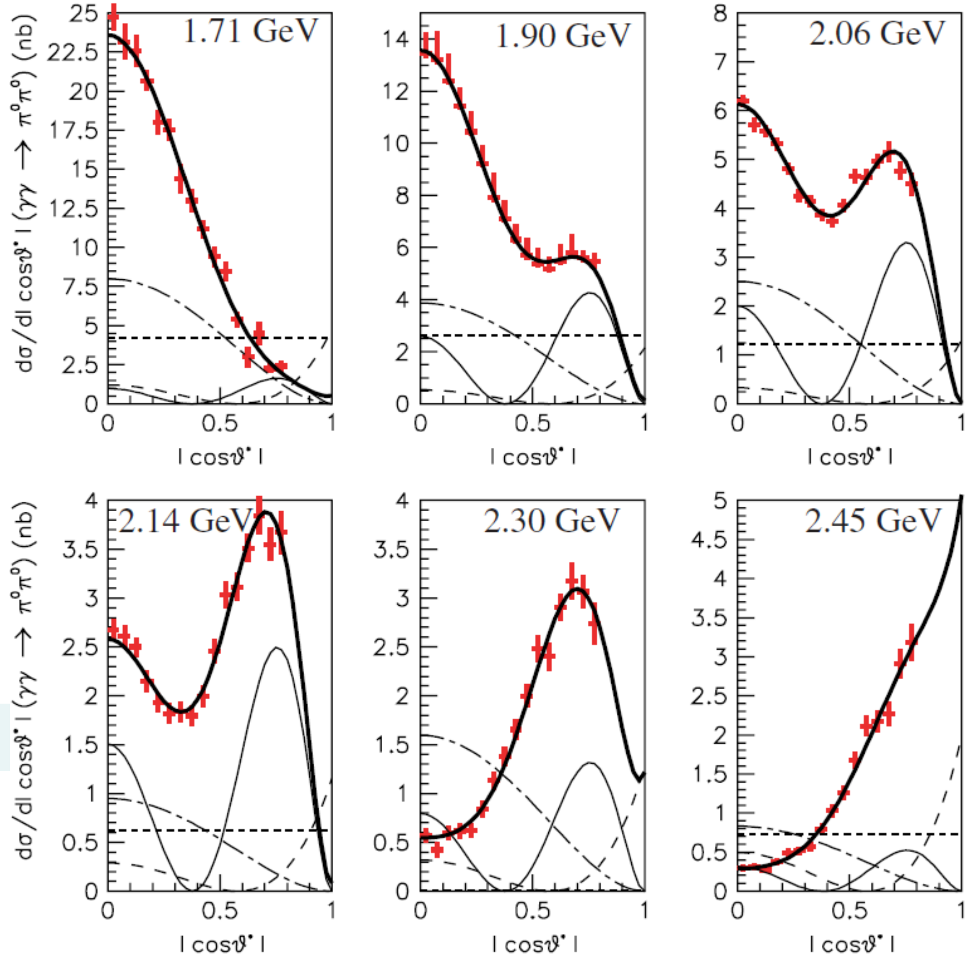
Results of $\gamma\gamma \to \pi^0\pi^0$ from Belle

$\sigma(\gamma\gamma \to \pi^0\pi^0)$ for $|\cos\theta^*|<0.8$:



The $c\bar{c}$ charmonium states are observed





θ^*: the π^0 scattering angle in the $\gamma\gamma$ CM frame

PRD79, 052009 (2009)

What Have We Learned from $\gamma\gamma$ Physics?

- Resonance production
  - The charmonium χ_{c0} and χ_{c2} states are observed in $\gamma\gamma \rightarrow \pi^0\pi^0$.
  - Search for new/exotic resonance on going

- Angular analyses:
  - Non-perturbative QCD $\rightarrow$ perturbative QCD
  - At high energy, differential cross section ~ $\sin^{-4}\theta^*$ as predicted by pQCD

Prospects for e^+e^- Colliders

- The B-factory and flavor physics experiments (i.e. BaBar, Belle, BES-III) are complementary to the Large Hadron Collider program.
  - High statistics data samples give sensitivity to rare decays $\Rightarrow$ good place to search for new physics
  - Explore the deviations from SM in flavor physics
- Next phase in flavor physics studies:
  - Belle-II/SuperB are great facilities for precision tests
- Potentials in two-photon physics:
  - Search for new resonances with C=+
  - (Light) Higgs production
  - (Light) supersymmetric particle production
  - More single- and double-tag analyses possible

Conclusions

- The B factories continue to explore the richness of flavor physics and produce significant physics results.
- Improved precision measurements of D_s decay are expected:
  - Large datasets from BaBar and Belle (and even more from Belle-II)
  - Unique datasets to study D_s meson from BES-III
  - New physics effects or not?
- Two-photon physics should be explored further
  - To gain full potential for discovery
  - To help understand the fundamental hadron wave function and the photon structure
- A lot of interesting physics is still waiting to be explored.
- Some of the big questions in particle physics can be answered with our current and future experiments.