第五届北京谱仪十一科学研讨会

The Physics at BESIII

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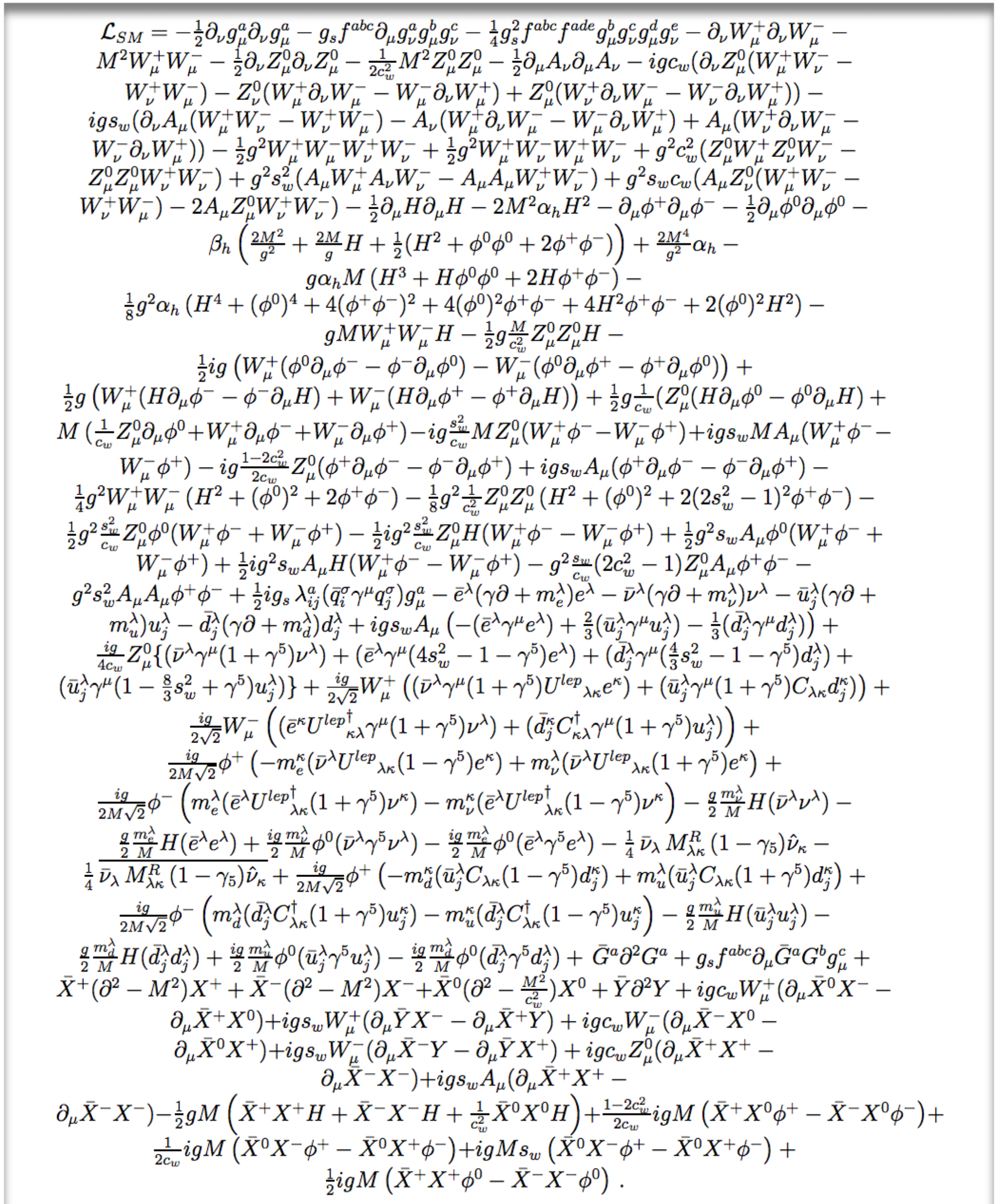
2023年9月23日-10月6日，内蒙古大学

Outline

- The Standard Model of Particle Physics and its problems
- Physics processes at $\sqrt{s}$=2-5 GeV and the kinematics
- General introduction to accelerator and detector
- The results from BESIII and how they help to solve the problems
- Prospect for next 10 years of BESIII
- Some suggestions for new comers

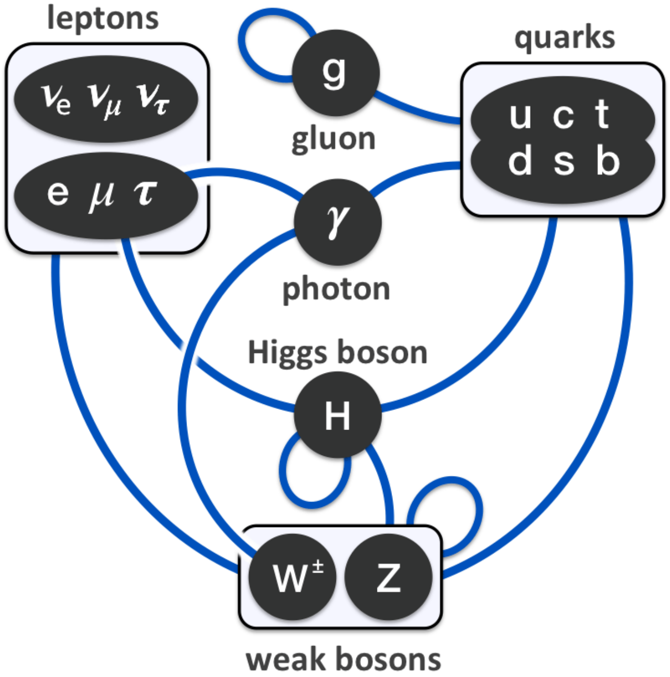
The Standard Model of Particle Physics and its Problems

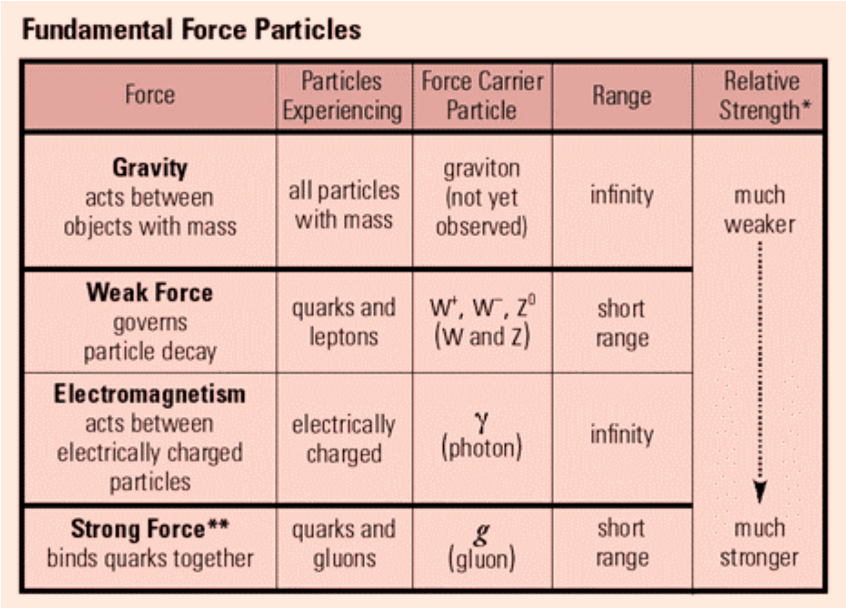


$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c^2_w}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s^2_w A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s^2_w + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5){U^{lep}}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa {U^{lep}}^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda {U^{lep}}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda {U^{lep}}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda {U^{lep}}^\dagger_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda {U^{lep}}^\dagger_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\underline{\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) +} \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w}\bar{X}^0 X^0 H\right) + \tfrac{1-2c^2_w}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}
$$

Everything is on one piece of A4 Paper!

The particles and interactions

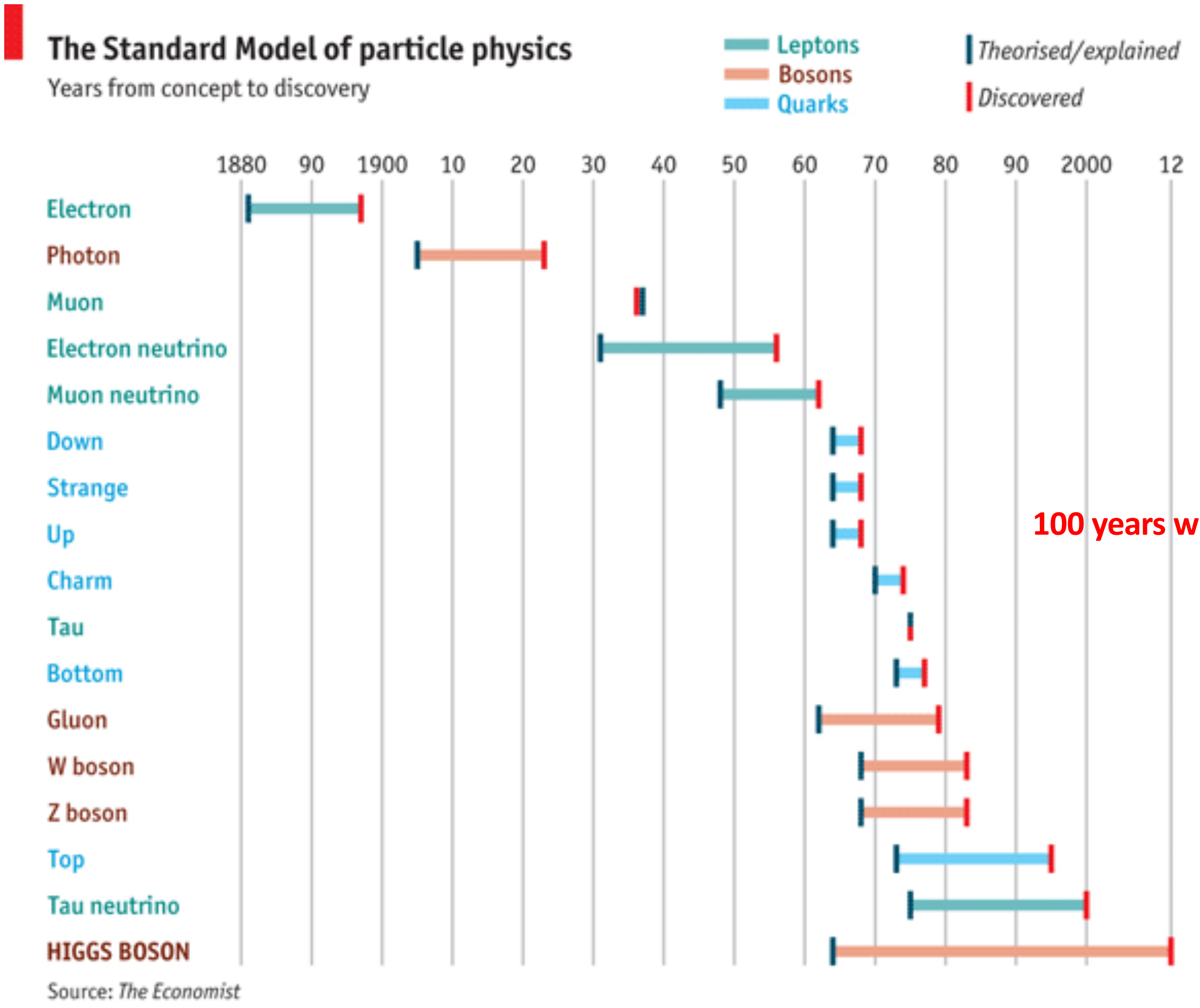




Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

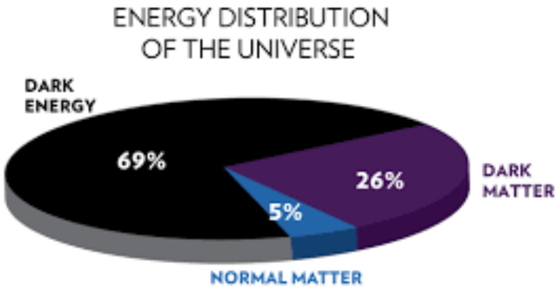
A brief history of SM

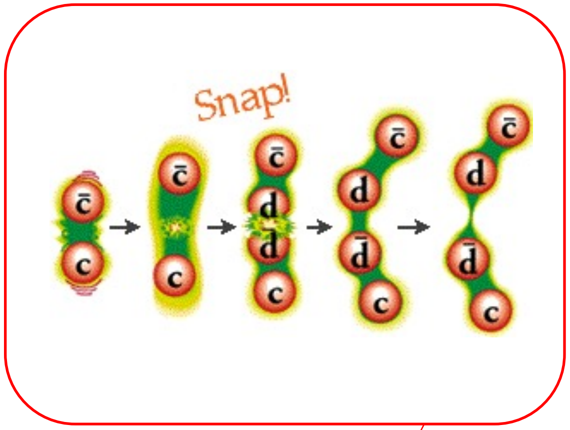


Source: *The Economist*

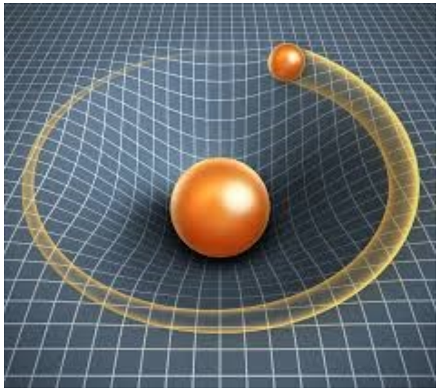
100 years with a lot of heroes!

The known unknown of SM





BESIII not only focus on QCD, also on electroweak, for example, charmed hadron decays!



There are of course of unknown-unknown!

The physics processes at $\sqrt{s}=2\text{-}5$ GeV and the kinematics

Events in detector: trigger fired and data saved

- e+e- annihilation
- Synchrotron radiation
- Beam-gas
- Beam wall (e-p, e-n, ...)
- Beam-beam interaction
- Lost beam particles
- Electronic noise (junk event)
- Nuclear interaction (final state particle + detector)
- Cosmic rays (angular distribution, rate)
- ……

Non-Physics processes should be considered in the experiment design also!

Physics processes at Ecm=2-5 GeV

QED

- Bhabha
- Di-mu
- Di-tau (above threshold)
- Di-gamma

Luminosity measurement, detector calibration and so on

Hadrons at continuum

- Continuum production of hadrons
- Two-photon processes

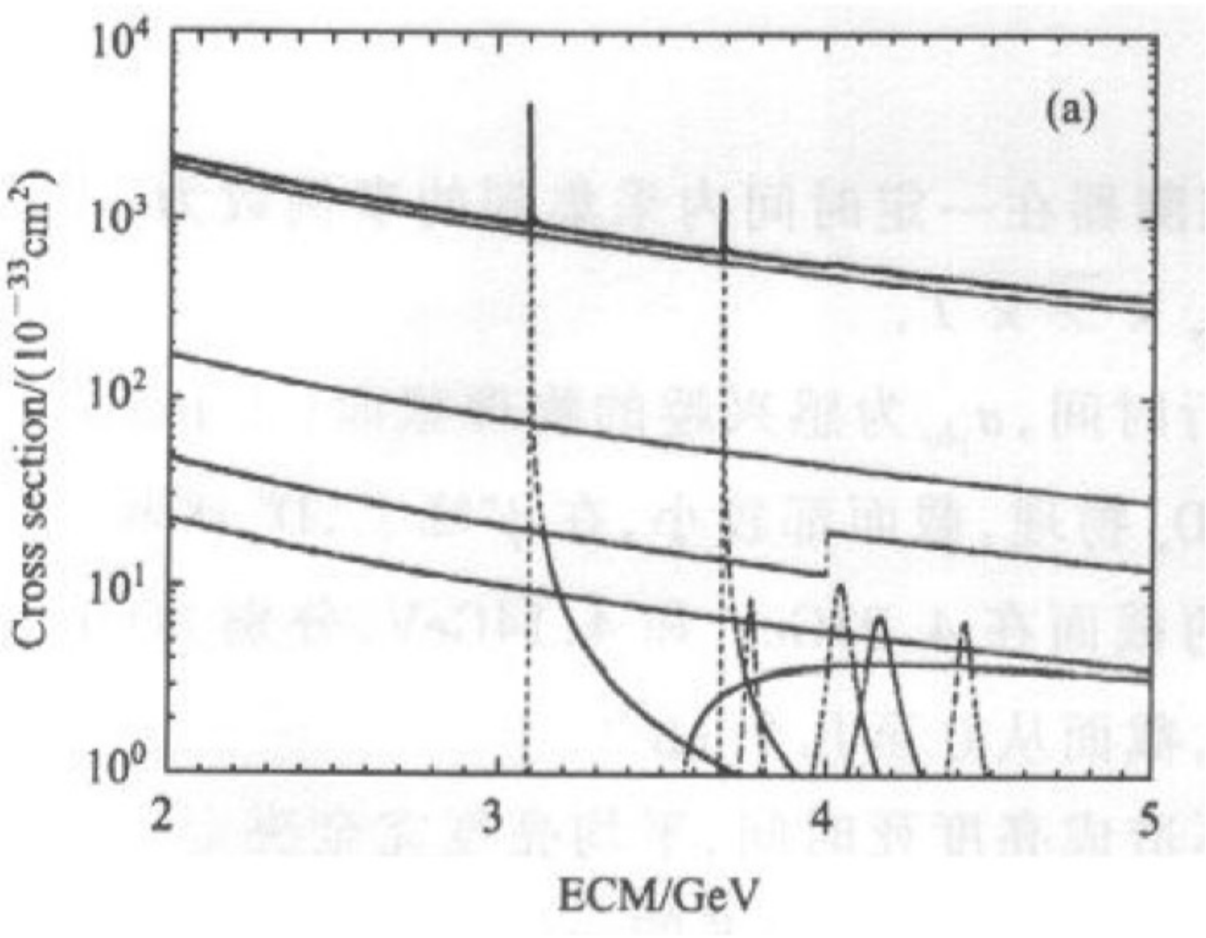
R-value measurement, form factor measurement ……

Resonances and their decays

- ISR
- Beam energy spread

The working horse of BESIII!

Cross sections



The lines from top to bottom:

1. Total cross section
2. Bhabha process
3. Di-gamma
4. Continuum
5. Di-muon
6. Di-tau

Resonances from left to right:

1. J/ψ
2. ψ(3686)
3. ψ(3770)
4. ψ(4040)
5. ψ(4160)
6. ψ(4415)

Except for J/ψ and ψ(3686) peaks, the Bhabha is the dominant process in this energy region!

QED processes kinematics (1)

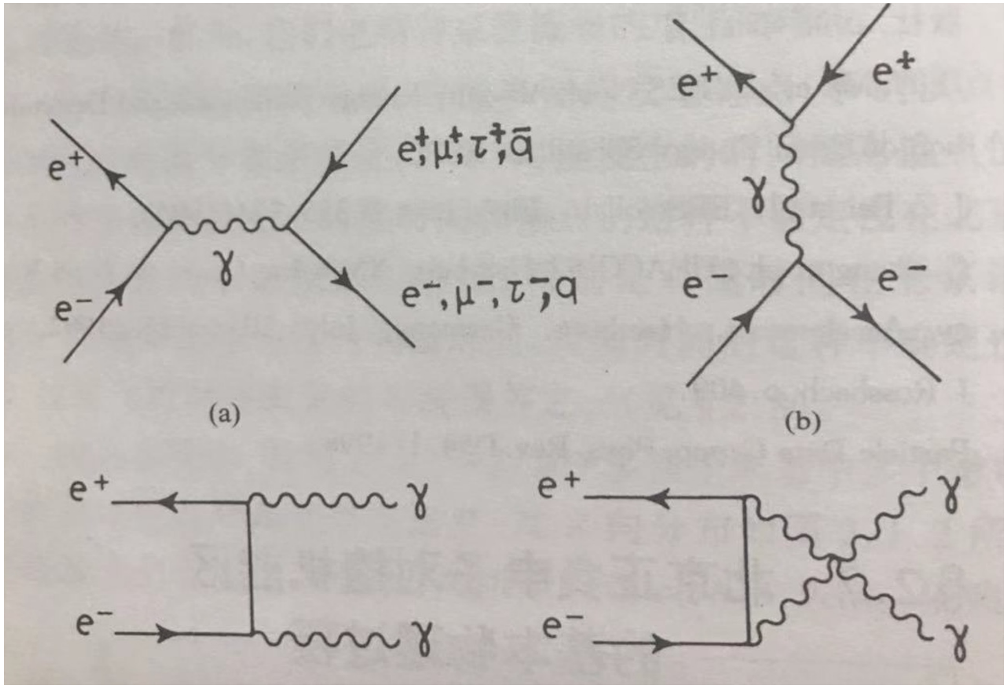
Leading order differential cross section for Bhabha:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4S}\left(\frac{3 + cos^2\theta}{1 - cos\theta}\right)^2$$

Leading order differential cross section for Di-muon and Di-tau:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4S}\beta\big((1 + cos^2\,\theta) + (1 - \beta^2)sin^2\theta\big)$$

$$\beta = \frac{P}{E}$$



QED processes kinematics (2)

For muon, whose mass is small, P=E, then

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4S}(1 + cos^2\theta)$$

$$\sigma = \frac{4\pi\alpha^2}{3S} = \frac{86.8\,nb}{S}$$

Leading order differential cross section for Di-gamma:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{S}\left(\frac{1 + cos^2\theta}{1 - cos^2\theta}\right)$$

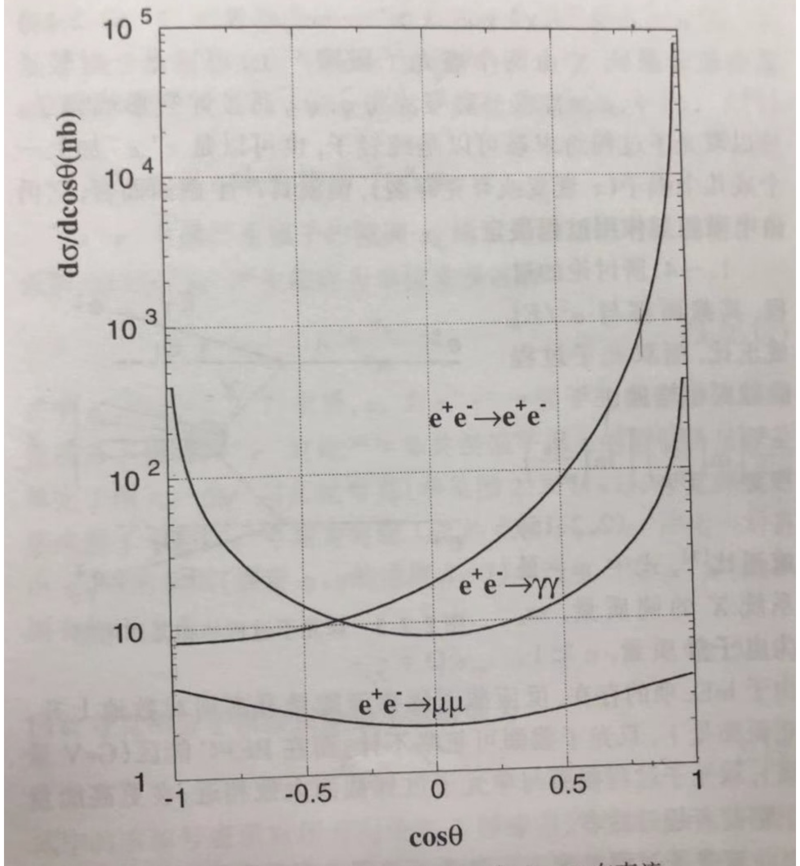
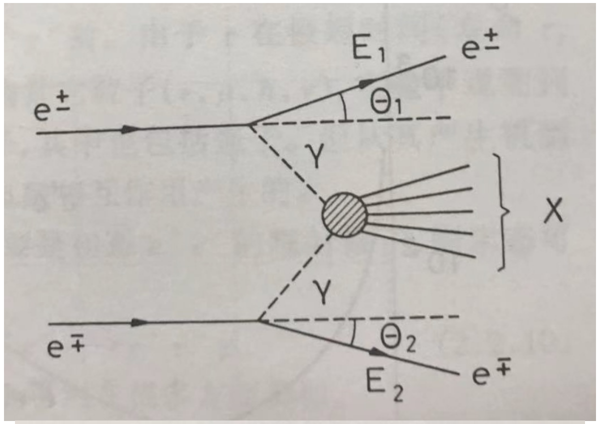


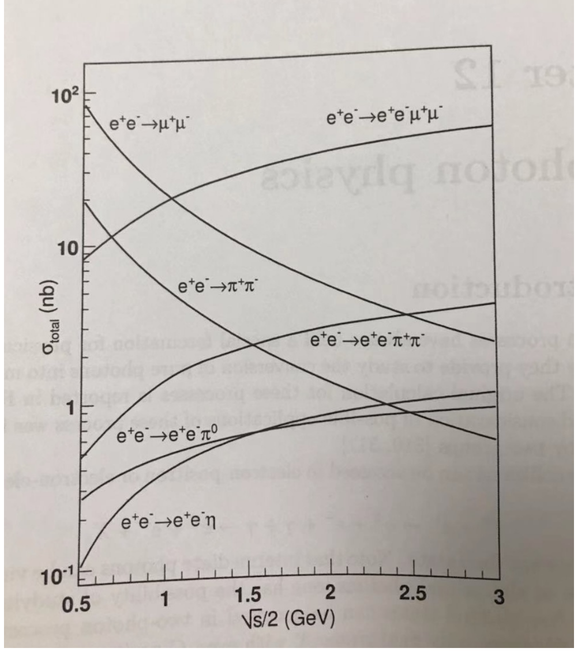
图 2.2.2 $e^+e^- \longrightarrow e^+e^-$、$\mu^+\mu^-$、$\gamma\gamma$ 在束流能量 $E_b = 2\text{GeV}$ 处的微分截面

Two-photon process

The cross section roughly proportional to:

$$\frac{\alpha^4}{m_X^2}(\ln(\frac{E_b}{m_e}))^2 ln(\frac{E_b}{m_X})^n$$





The cross section at BESIII energy region is not small!

But the X and its decay products are close to the beam line!

Continuum hadron production

The process is similar to Di-muon, but change the muon to quark, and the quark will form the hadron based on the fragmentation function, thus we define the R value:

$$R = \frac{\sigma_h}{\sigma_{uu}} = \sum_i 3{Q_i}^2$$

3 is from the color of quark!

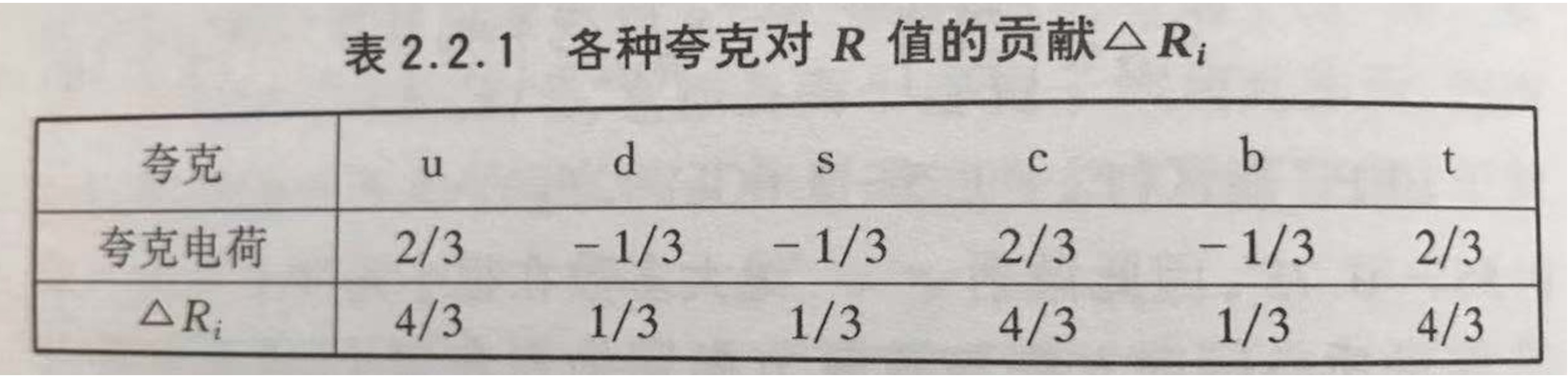


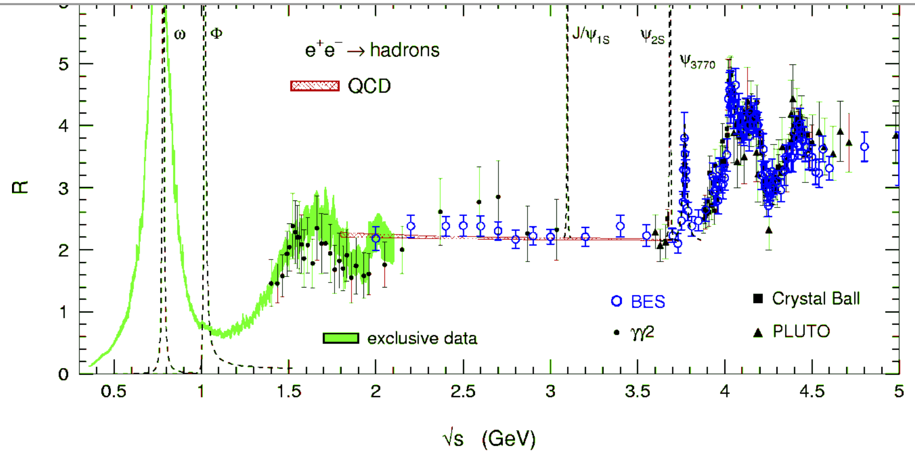
表 2.2.1　各种夸克对 R 值的贡献 $\triangle R_i$

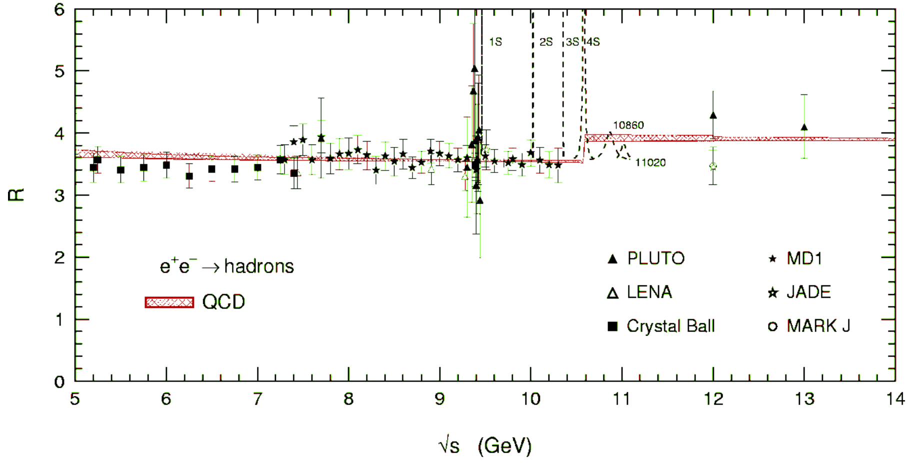
夸克	u	d	s	c	b	t
夸克电荷	2/3	−1/3	−1/3	2/3	−1/3	2/3
$\triangle R_i$	4/3	1/3	1/3	4/3	1/3	4/3

With the correction from gluon: $R = Rq(1 + \frac{\alpha_s}{\pi} + C2(\frac{\alpha_s}{\pi})^2 + \ldots\ldots$

R value

Agreement between Data (BES) and pQCD (within correlated systematic errors)





Resonance production

$$\sigma = \frac{4\pi(2J+1)\Gamma\Gamma_e}{(s-M^2)^2+M^2\Gamma^2}$$

$J=1$

Resonance	Mass	Width	Partial width to ee
J/ψ	3096.9 MeV	92.9 keV	5.53 keV
Ψ(3686)	3686.1 MeV	294 keV	2.33 keV
Ψ(3770)	3773.1 MeV	27.2 MeV	0.262 keV
Ψ(4040)	4039 MeV	80 MeV	0.86 keV
Ψ(4160)	4191 MeV	70 MeV	0.48 keV
Ψ(4415)	4421 MeV	62 MeV	0.58 keV

For narrow peak, the production cross section is heavily affected by beam energy spread;

Initial state radiation and vacuum polarization correction are important also!

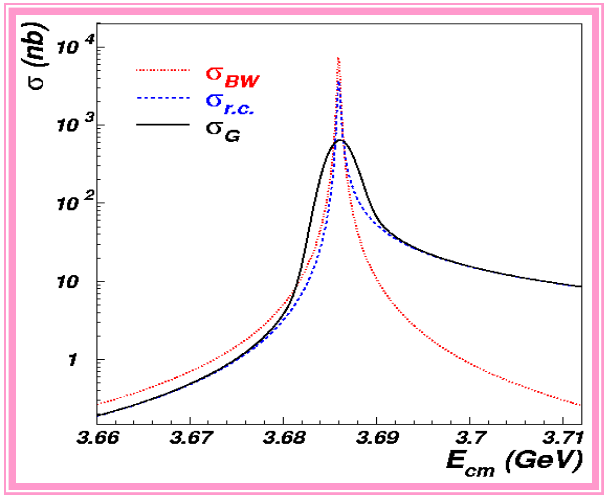
At resonance peak

$$\sigma_{BW}(W) = \frac{12\pi \cdot \Gamma_e \Gamma_f}{(W^2 - M^2)^2 + \Gamma_t^2 M^2}$$

$$\sigma_{r.c.}(W) = \int_0^{x_m} dx F(x,s) \frac{1}{|1 - \Pi(s(1-x))|^2} \sigma_{BW}(s(1-x))$$

$$\sigma_{exp}(W) = \int_0^{\infty} dW' \sigma_{r.c.}(W') G(W', W)$$

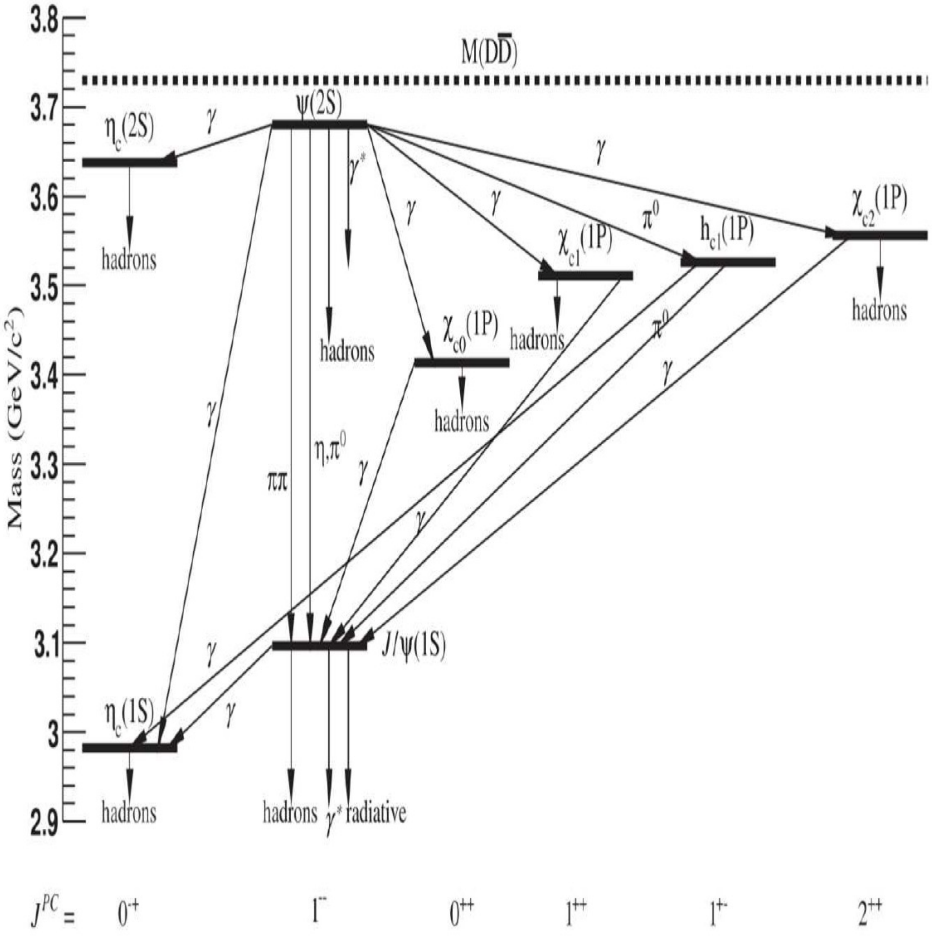
$$G(W, W') = \frac{1}{\sqrt{2\pi}\Delta} e^{-\frac{(W-W')^2}{2\Delta^2}}$$



At ψ(2S)	Born	ISR	Δ=1.3MeV
σ_{RES} (nb)	**7887**	**4046**	**640**
σ_{CON} (nb)	**~14**	**~14**	**~14**

Continuum contribution becomes larger after considering ISR and beam spread!

Charmonium states



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

J^PC	L	S	J
0-+	0	0	0
1--	0	1	1
0++	1	1	0
1++	1	1	1
1+-	1	0	1
2++	1	1	2

Charmonium states

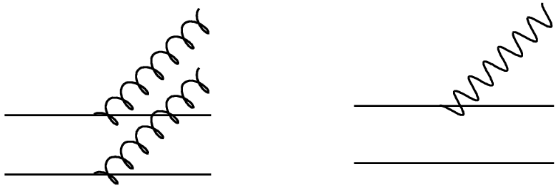
J^PC	L	S	J
0-+	0	0	0
1--	0	1	1
0++	1	1	0
1++	1	1	1
1+-	1	0	1
2++	1	1	2
2-+	2	0	2
3--	2	1	3
2--	2	1	2
1--	2	1	1
3+-	3	0	3
4++	3	1	4
3++	3	1	3
2++	3	1	2

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

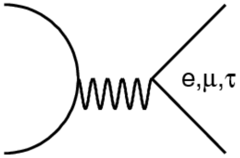
So 0+1, 0--, 1-+, 2+-…… are missing!

ψ′ decays

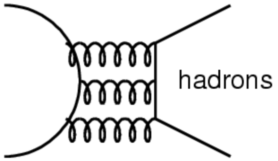
- Transitions (~82%)
  - Hadronic transitions (~54%)
  - Radiative transitions (~28%)

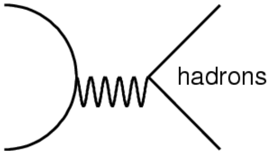


- Leptonic decays (~ 2%)

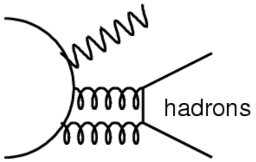


- Hadronic decays (~15%)
  - Strong decays (~13%)
  - EM decays (~ 2%)



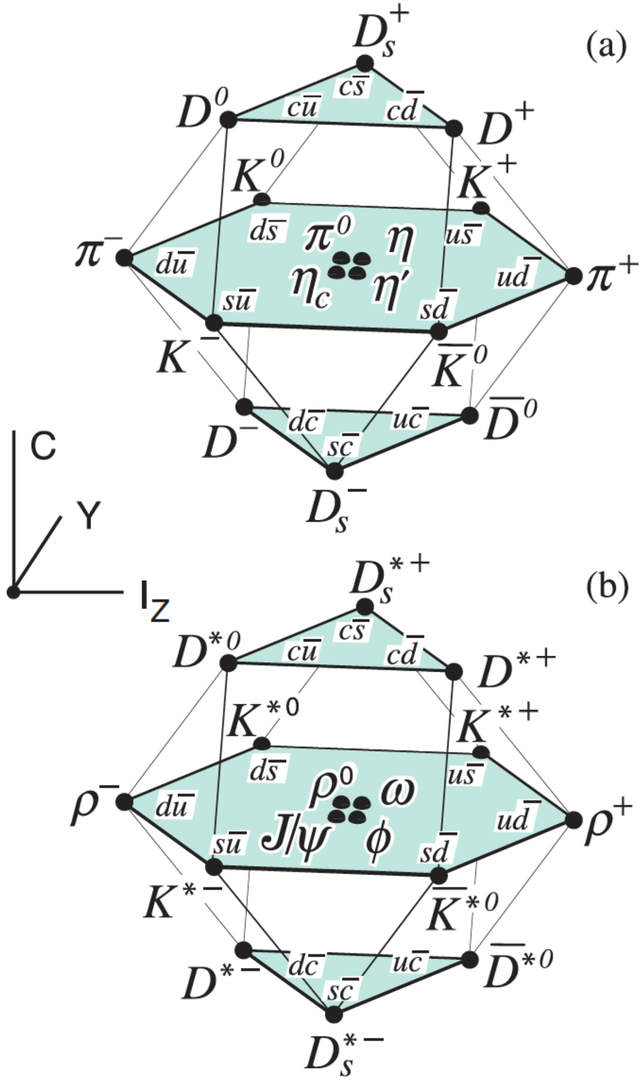


- Radiative decays (~ 1%)
- Rare decays and beyond SM (<<1%)



Similar for J/ψ decays, but BR different.

Charm mesons



0-+

1--

Vacuum polarization

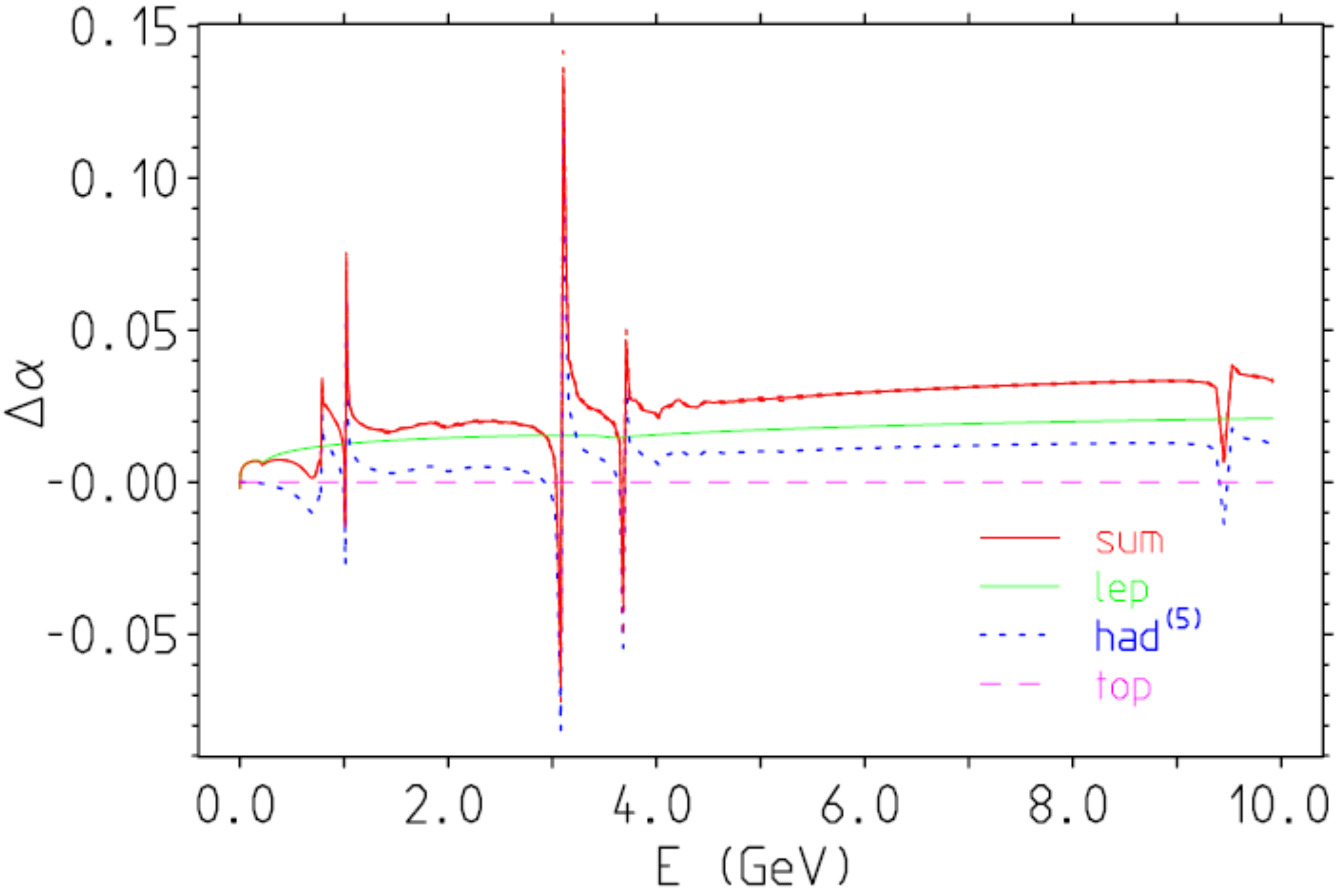


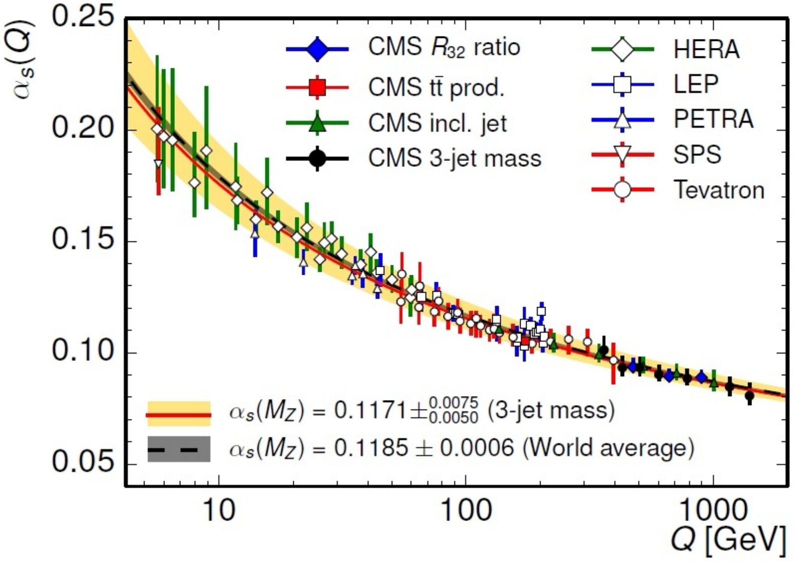
Fig. 81 Different contributions to $\Delta\alpha(s)$ in the time-like region as given by the routine from Fred Jegerlehner (version February 2010)

How often we will get a physics event on BESIII?

- Assume on Ψ(3686) peak, the cross section is 640 nb
- The instantaneous luminosity of BESIII is assumed to be $1*10^{33}cm^{-1}s^{-1}$
- Then the event rata R=640 Hz
- The bunch crossing time of BEPCII is 8 ns, which means the collision rate is 1/8ns=125 000 000 Hz
- We could conclude that even running at Ψ(3686) peak, only in 640/125 000 000 collision, we will get the event we care about.
- That is the main reason why 4k Hz trigger rate is large enough for BESIII

Introduction to QCD

- QCD is short for quantum chromodynamics, is the accepted theory for strong interaction
- In the high energy regime, perturbation theory works well; in very low energy regime, chiral perturbation theory works well; we in the energy region between, we need Lattice QCD or QCD-inspired models, such as NRQCD
- BESIII or charm quark is in this special region

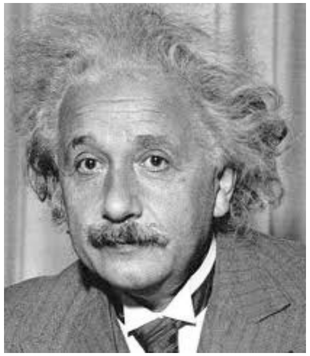


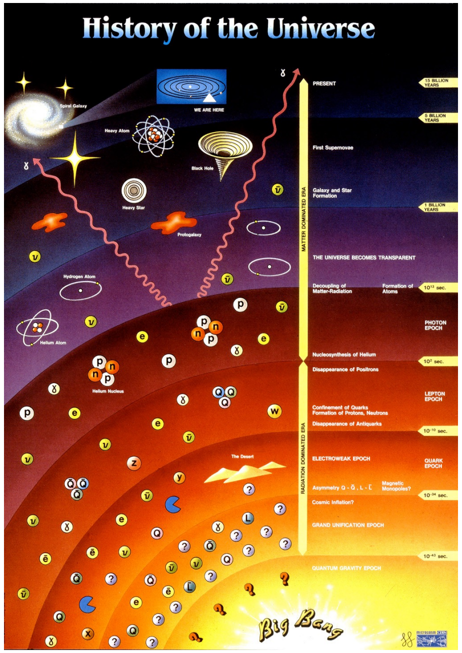
Introduction to accelerator

Matter versus Energy

$E = m c^2$

During the Big Bang Energy was transformed in matter





In our accelerators we provide energy to the particle we accelerate.

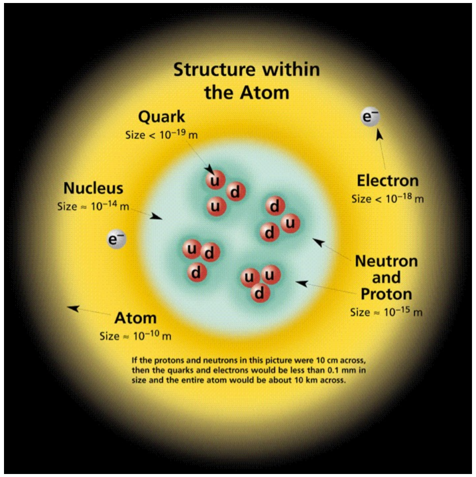
In the detectors we observe the matter

Looking to smaller dimensions

Visible light
λ = 400 ➔ 700 nm

X-ray
λ = 0.01 ➔ 10 nm

Particle accelerators
λ < 0.01 nm



$$\lambda = \frac{h\,c}{E}$$

Increasing the energy will reduce the wavelength

Fixed Target vs. Colliders

Fixed Target

$$E \propto \sqrt{E_{beam}}$$

Much of the energy is lost in the target and only part results in usable secondary particles

Collider

$$E = E_{beam1} + E_{beam2}$$

All energy will be available for particle production

Accelerators and Their Use

Today: ~ **30’000 accelerators** operational world-wide*

The **large majority** is used in **industry** and **medicine**

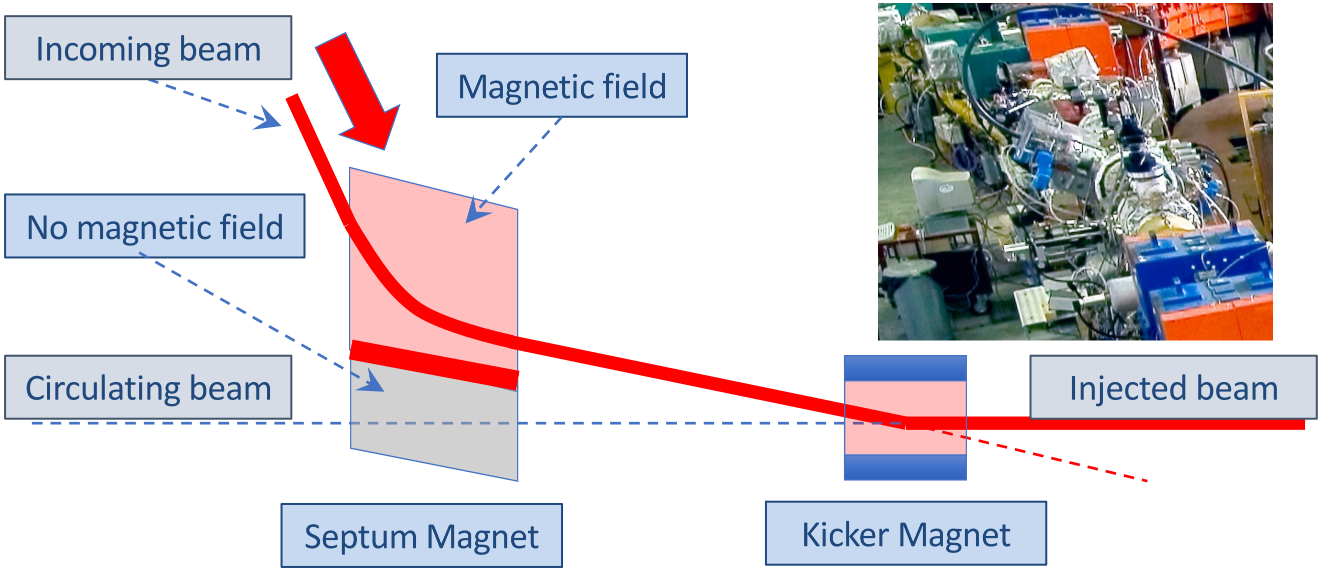
- Industrial applications: ~ 20’000*
- Medical applications: ~ 10’000*

Les than a fraction of a percent is used for **research** and discovery science

- Cyclotrons
- FFAG
- Synchrotrons
- Synchrotron light sources (e^-)
- Lin. & Circ. accelerators/Colliders

**Source: World Scientific Reviews of Accelerator Science and Technology A.W. Chao*

Injecting & Extracting Particles



Incoming beam

Magnetic field

No magnetic field

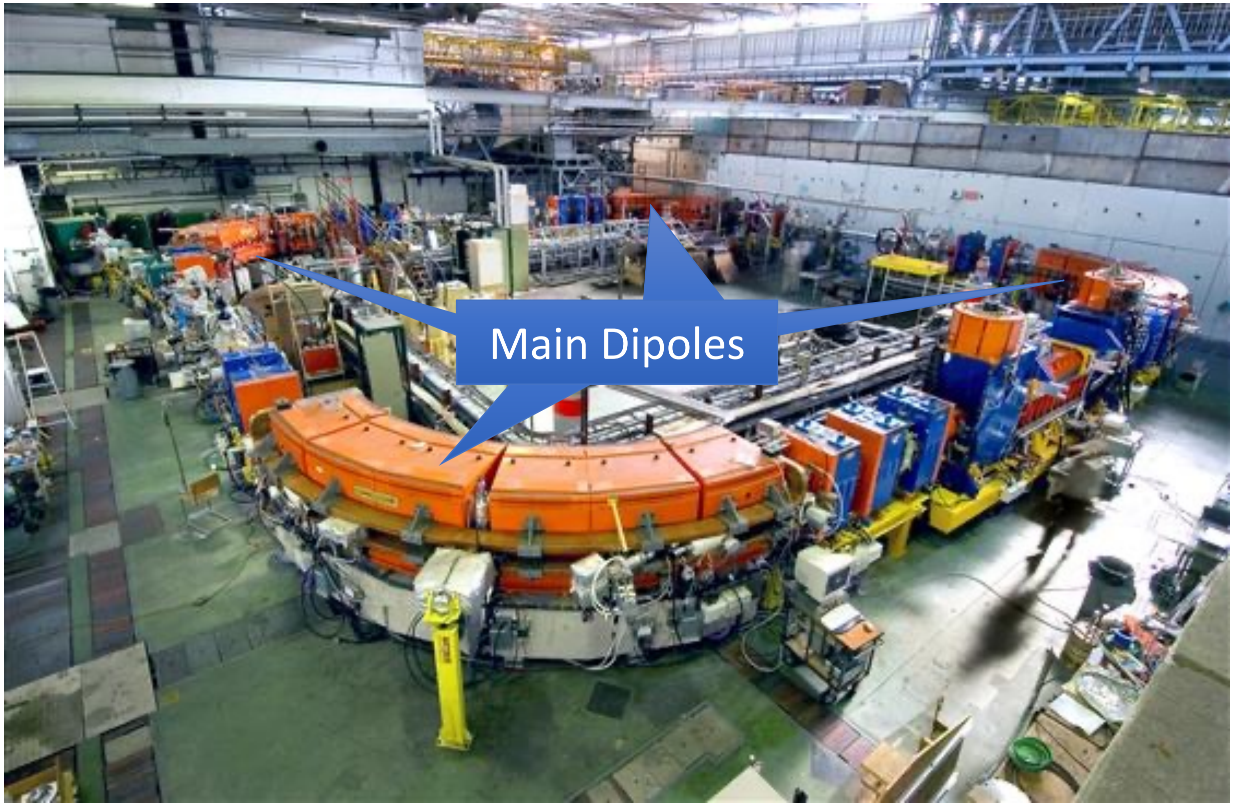
Circulating beam

Injected beam

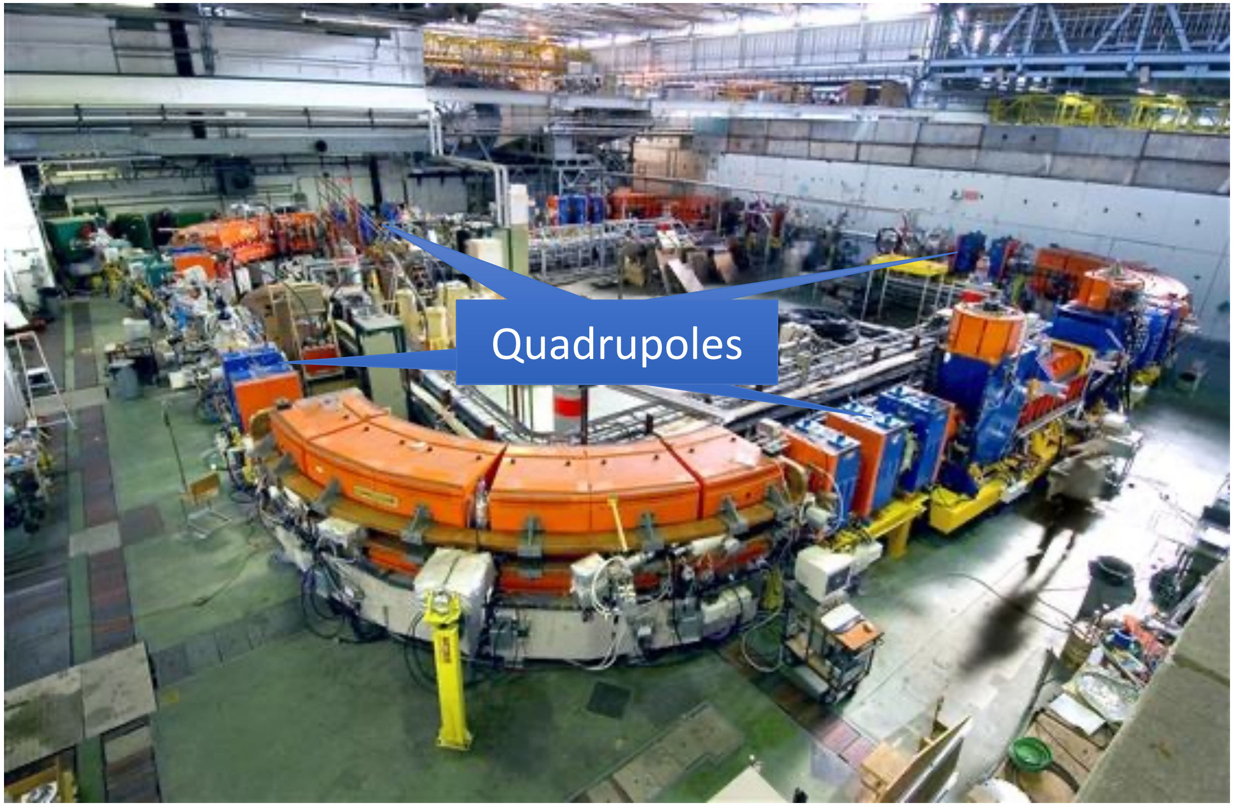
Septum Magnet

Kicker Magnet

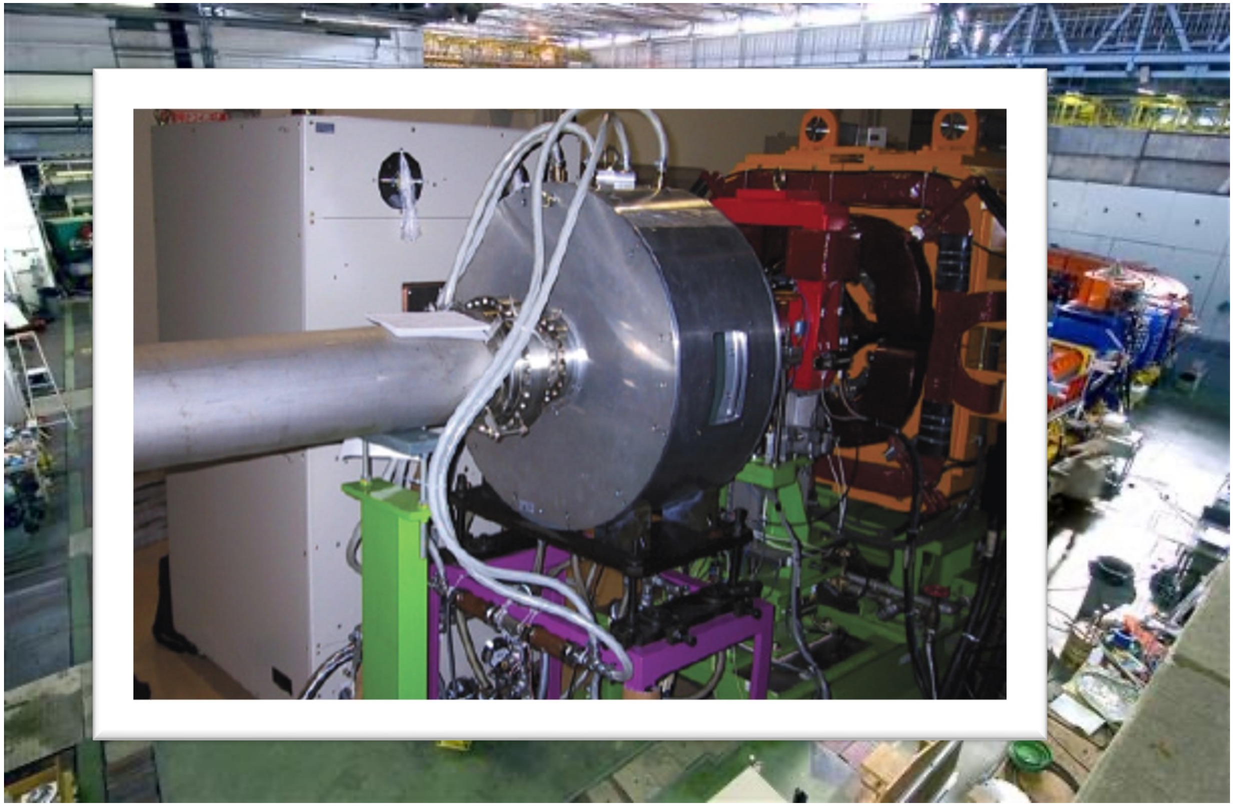
Make Particles Circulate



Focusing the Particles



Accelerating Particles

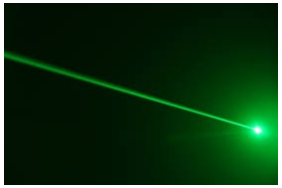


Figures of Merit in accelerators

For different accelerators and experiments different beam characteristics are important. However, a major division can be made between:

Fixed Target Physics:

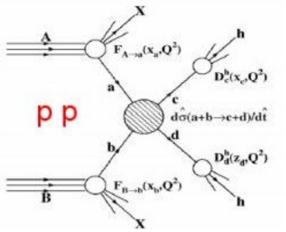
Light Sources:



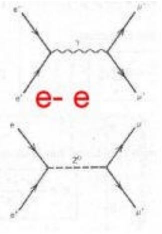
Collider Physics:

Main parameters: particle type

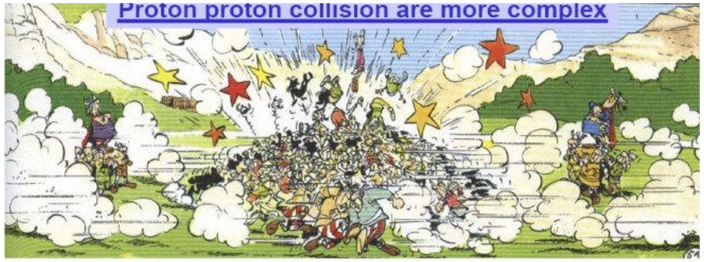
- Hadron collisions: compound particles
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - ***Hadron collisions*** $\Rightarrow$ ***large discovery range***



- Lepton collisions: elementary particles
  - Collision process known
  - Well defined energy
  - ***Lepton collisions*** $\Rightarrow$ ***precision measurement***

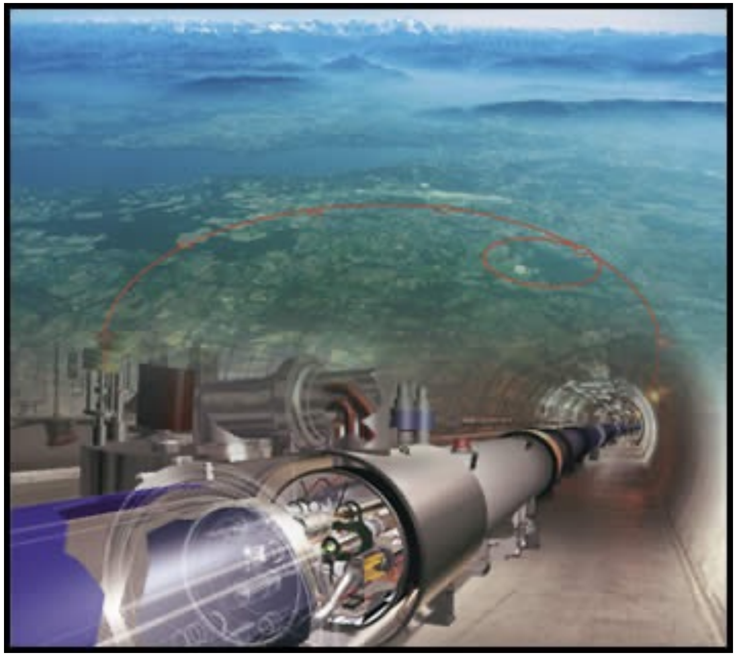


"If you know what to look for, collide leptons, if not collide hadrons"



Main parameters: particle type

Discovery



LHC/SPPC

Precision

LEP / ILC/CEPC

Main parameters: luminosity

- High energy is not enough !
- Cross-sections for interesting processes are very small (~ pb = 10^{-36} cm²) !
  - $\sigma(gg \rightarrow H)$ = 23 pb [at $s^2_{pp} = (14\ \text{TeV})^2$, $m_H = 150\ \text{GeV}/c^2$]

$$R = \mathcal{L}\sigma$$

  - We need $\mathcal{L} \gg 10^{30}\ \text{cm}^{-2}\text{s}^{-1}$ in order to observe a significant amount of interesting processes!
- $\mathcal{L}$ [$\text{cm}^{-2}\text{s}^{-1}$] for "bunched colliding beams" depends on
  - number of particles per bunch (n_1, n_2)
  - bunch transverse size at the interaction point (σ_x, σ_y)
  - bunch collision rate (f)

$$\mathcal{L} = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

Ways to Increase Luminosity

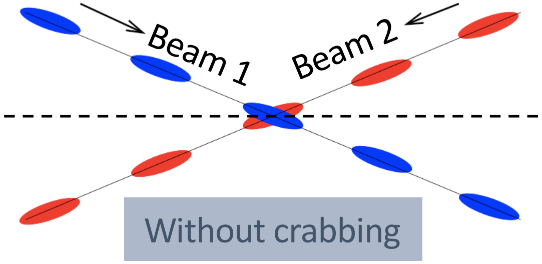
Increase the beam brightness from the injectors (N and σ)
- More particle in smaller beams (increase brightness)

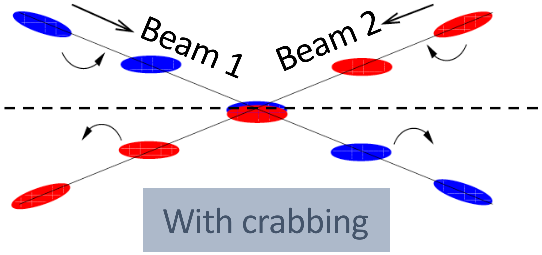
Increase number of bunches
- Higher harmonic RF systems

Reduce the β* (σ)
- Stronger focusing around the interaction points

Use crab cavities to reduce the crossing angle effect (s)
- Tilt the bunches to have more head-on collision effect

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$





Introduction to detector

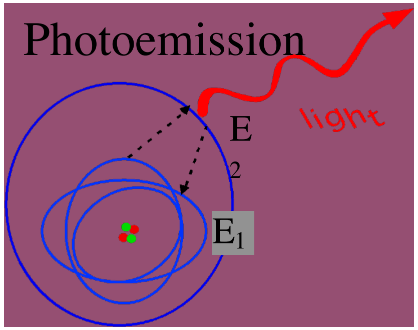
Just to get started…

- **p = momentum**
- **m = mass**
- **E = energy**
- **c = speed of light in vacuum**
- **v = speed of the particle we are observing**
- **β = v/c = p/E**
- **$\gamma = (1-\beta^2)^{-1/2}$ = E/m**
- **n = index of refraction**
  - **Light speed in the medium is c/n**

Interactions of Particles with Matter - Photoemission

- **Excitation** (followed by de-excitation)
  1. Atomic Electron (energy E_1)
  2. Promoted to higher energy state (E_2)
     - Energy comes from Charged Particle passing nearby
  3. a. Electron falls back to ground state (E_1)

     b. Released energy is carried by a Photon



$$E_{photon} = E_2 - E_1$$

Before:
- **Fast-moving charged particle or photon.**
- **Detector Atom/Molecule, at rest.**

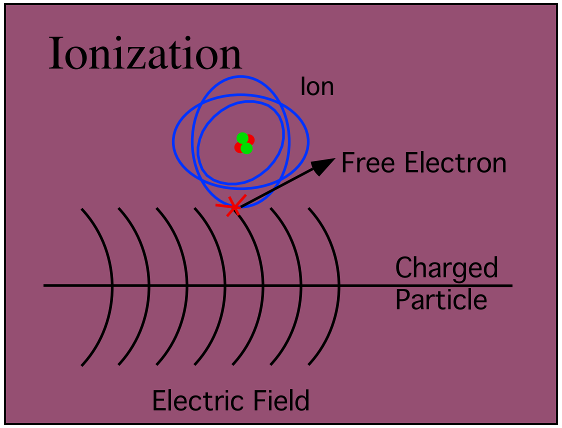
→

After:
- **The initial Charged Particle**
- **An Emitted Photon**
- **Atom/Molecule (possibly in excited state)**

Energy: conserved

Interactions of Particles with Matter - Ionization

- **Ionization**
  - Atomic electron is knocked free from the atom.
  - The remaining atom now has a net charge (it is an **ion**).
  - The atom may also be left in an excited state and emit a photon as it returns to its ground state.
  - In a crystal lattice such as Silicon, the ionized atom is called a “hole”.



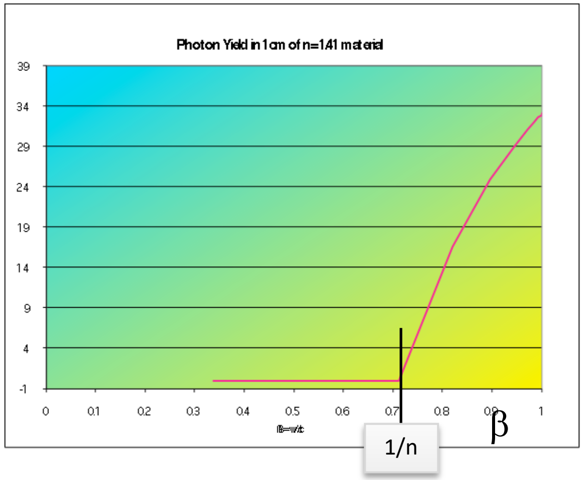
Before:
- **Fast-moving charged particle or photon.**
- **Detector Atom/Molecule, at rest.**

After:
- **The initial particle or photon.**
- **A Free Electron**
- **Ionized atom (possibly in excited state)**
- **Photon (sometimes)**

Energy: conserved

Interactions of Particles with Matter - Collective Effects

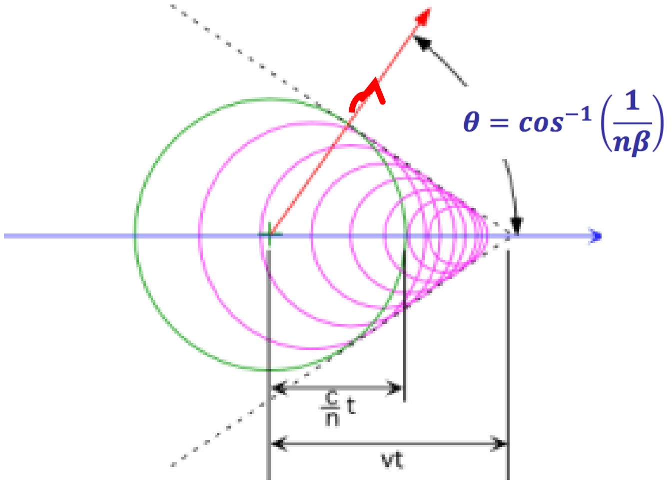
The electric field of a particle may have a long-range interaction with material as it passes through a continuous medium.



Cerenkov Effect:

Critical Parameter is β

Turns ON when particle speed is greater than light speed in the medium: v = βc > c/n



Interactions of Particles with Matter - Collective Effects

Transition Radiation:

Critical Parameter is γ

The sudden change in electric field as an *ultrarelativistic* charged particle passes from one medium to another results in ~keV photons (x-rays).

Ultrarelativistic: $\gamma \gtrsim 1000$

$\gamma \equiv (1-\beta^2)^{-1/2} = E/m$

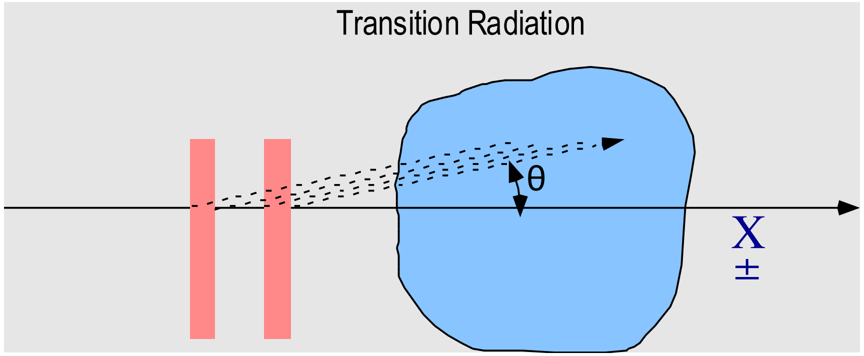
Light is emitted at the angle

$\theta \sim 1/\gamma$

(1 milliradian or less)

6 GeV/c

	electron	pion	proton
mass	0.000511	0.139	0.939
beta	0.999999996	0.999731761	0.987974331
gamma	11741.7	43.2	6.5



Interactions of Particles with Matter - Radiation Damage

- Particles can have lasting effects on the detector materials.
  - Nuclear Collision
    - Particle undergoes interaction directly with atomic nucleus.
    - May transmute the element (radiation damage).
    - May generate secondary particles which themselves are detectable (neutron detector).
  - Lattice Dislocation
    - Crystalline structure of a material may be disrupted (diode leakage current increases).
  - Chemical Change
    - Photographic Film (photos fogged at airports) or Emulsion (visible particle tracks).
    - Changed molecular bond in a clear material may create color centers

While these effects can be exploited for particle detection,
they may also cause permanent damage to detector components resulting in a detector which stops working.

This is sometimes referred to as “aging”.

Interactions of Particles with Matter

- **Summary:** When charged particles pass through matter they usually produce either free electric charges (ionization) or light (photoemission).

- **Ahead:** Most "particle" detectors actually detect the light or the charge that a particle leaves behind.

- **Next:** In all cases we finally need an electronic signal which is big enough to use in a Data Acquisition System.

Particle Detectors: Avalanche Multiplication

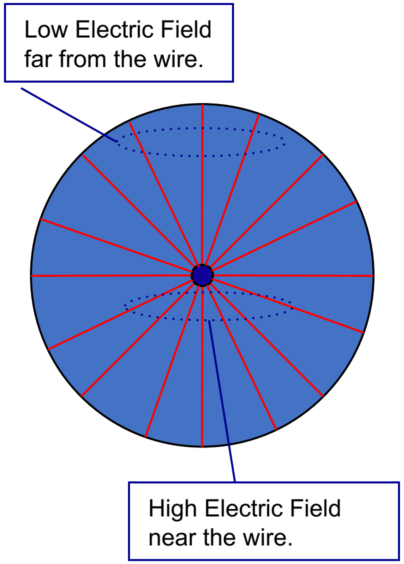
We need devices that are sensitive to the few electron charges coming from a ionization.

But, typical electronic circuits are sensitive to ~1μA = 6.2×10^{12} e^-/s which is >> "a few"

We need to *amplify* the ionization electrons.

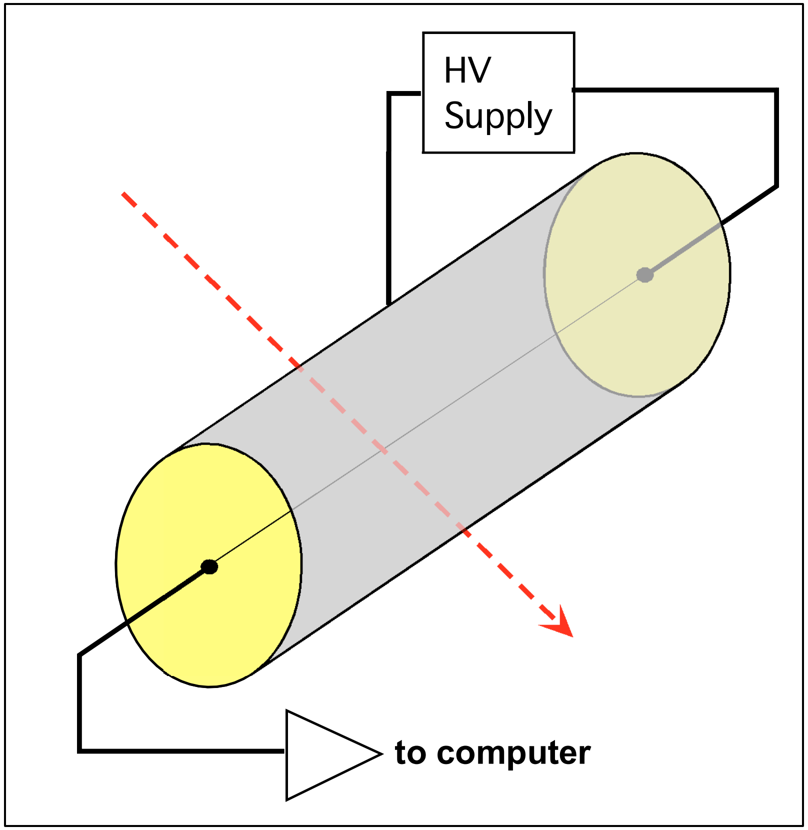
By giving them a *push*, we can make them move fast enough so that they *ionize* other atoms when they collide. *Push* those *new* electrons and each one ionizes *more* atoms, releasing *more* electrons. After this has happened several times we have a sizeable free charge that can be sensed by an electronic circuit.

Particle Detectors: A Single-wire Gas Chamber



Low Electric Field far from the wire.

High Electric Field near the wire.

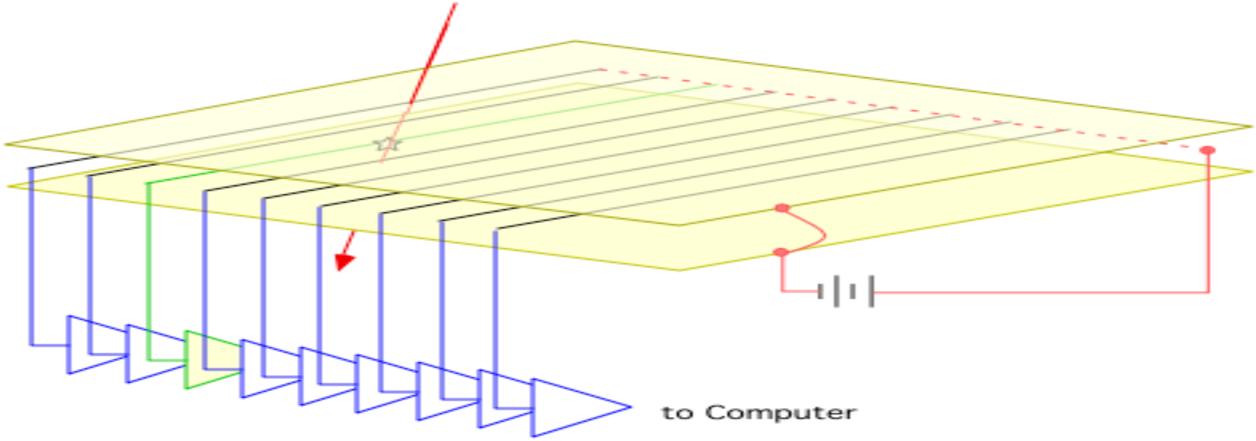


HV Supply

to computer

Particle Detectors: Multi-Wire Gas Chamber

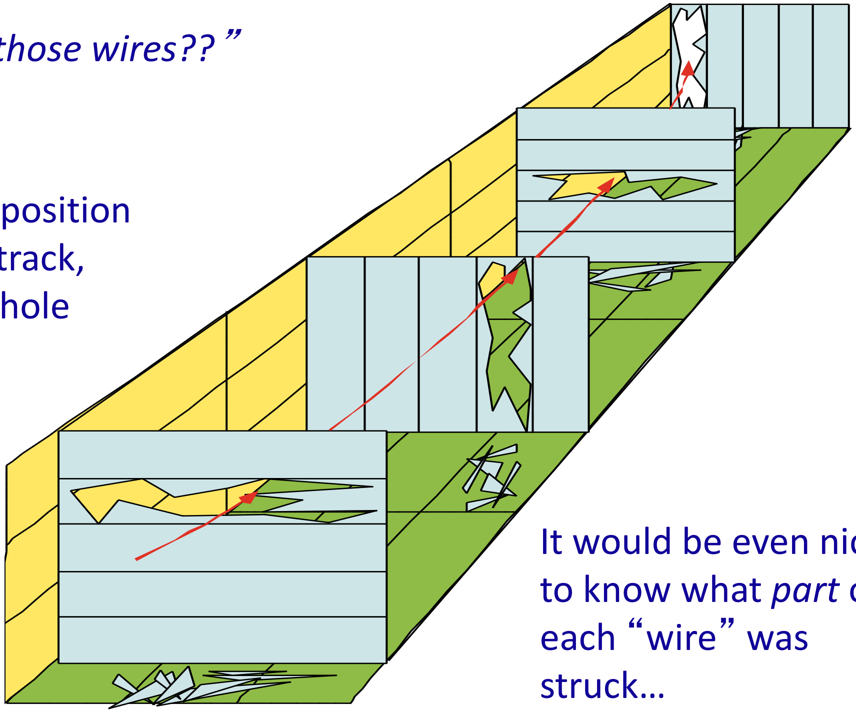
- Multiwire Chamber:
  - WHICH WIRE WAS NEAREST TO THE TRACK?



Particle Detectors: tracking

"Why does he want all those wires??"

If we make several measurements of track position along the length of the track, we can figure out the whole trajectory.

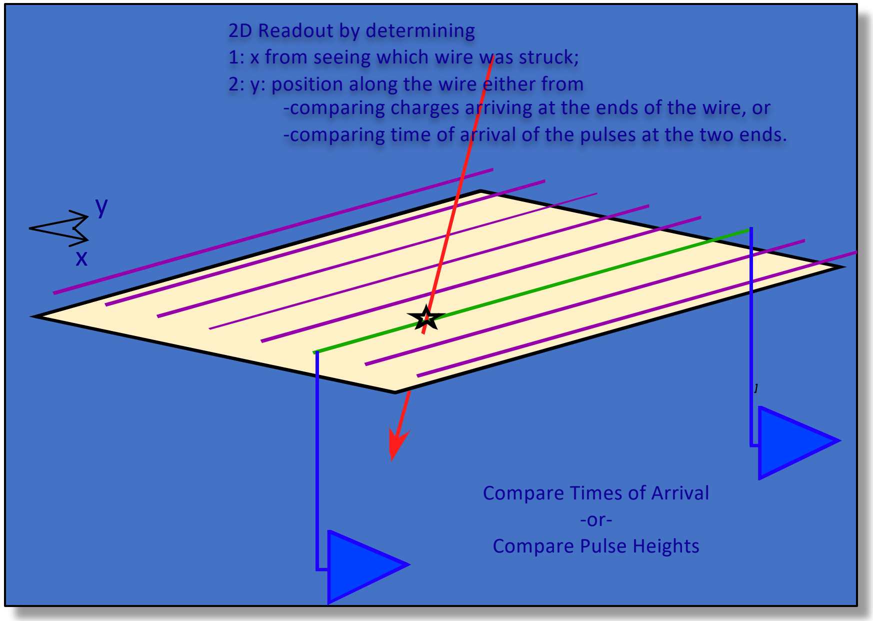


It would be even nicer to know what *part* of each "wire" was struck…

Particle Detectors: better position information

- Readout Options for Improved Resolution
  - And for flexible design
    - Charge Division
    - Time Division
    - Charge Interpolation
  - Wire Position gives “x”
  - Measurement along wire length gives “y”.

It would be nicer still if we knew the distance between the particle and the struck wire…



2D Readout by determining
1: x from seeing which wire was struck;
2: y: position along the wire either from
-comparing charges arriving at the ends of the wire, or
-comparing time of arrival of the pulses at the two ends.

Compare Times of Arrival
-or-
Compare Pulse Heights

Particle Detectors: higher resolution tracking

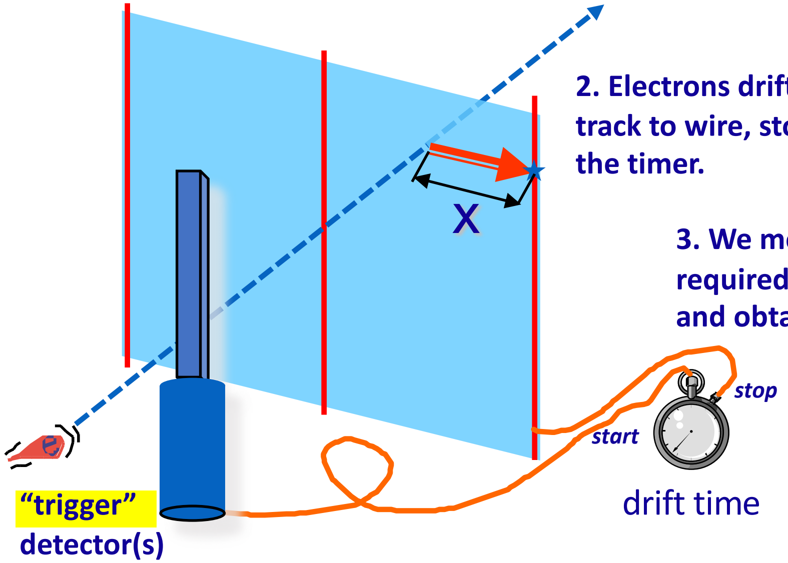
Drift Chambers…

HOW FAR TO THE NEAREST WIRE?

1. Particle ionizes gas; the "trigger" starts the timer.

2. Electrons drift from track to wire, stopping the timer.

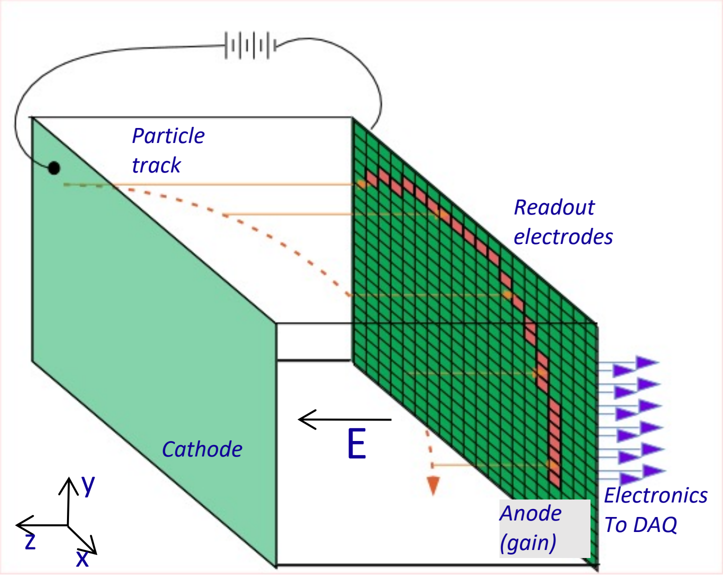
3. We measure the time required to drift to the wire and obtain the distance X.



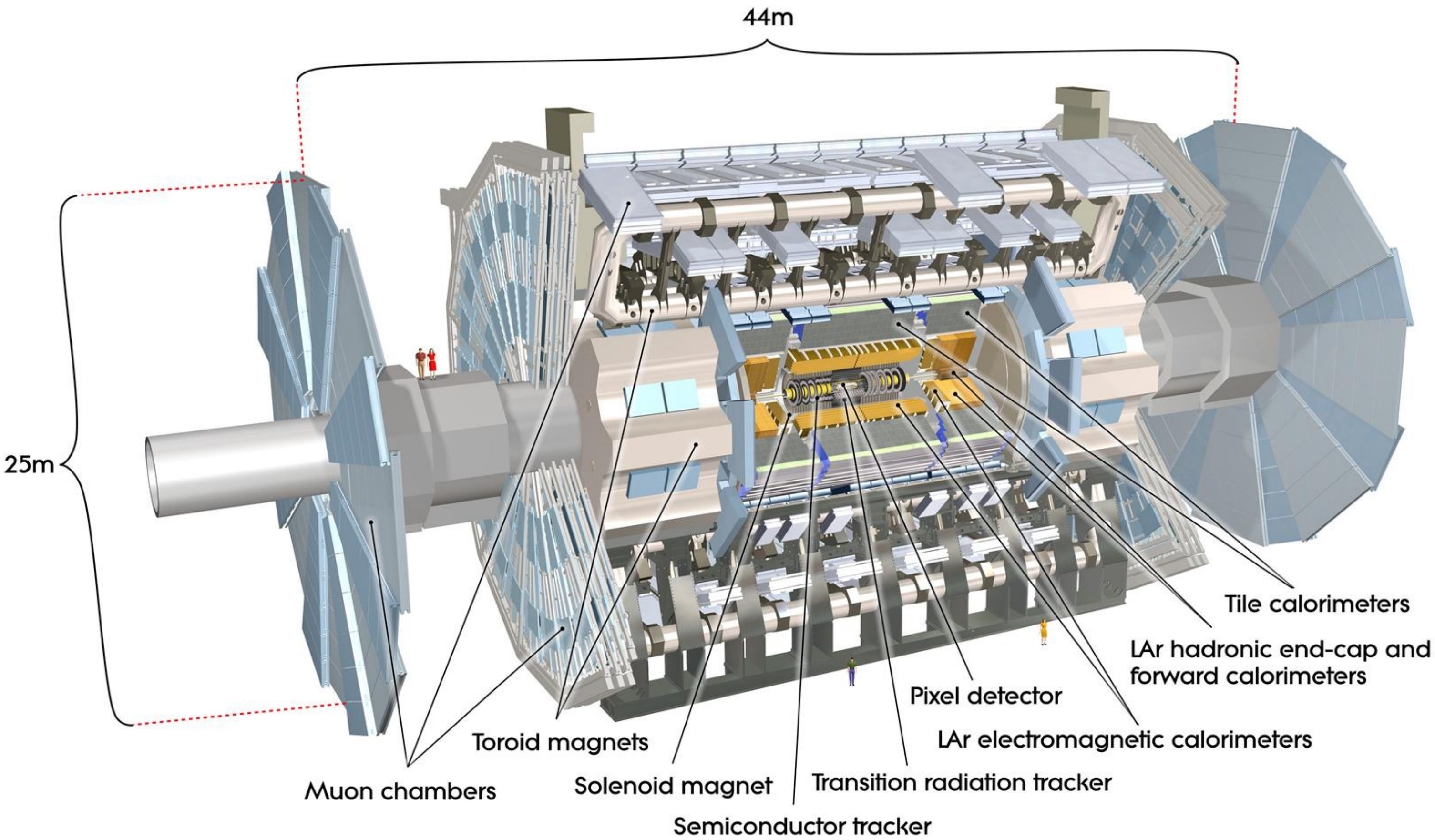
Particle Detectors: TPC, 3D position information

Time Projection Chamber (TPC): Drift through a Volume

- Just a box of gas with
  - Electric Field and
  - Readout Electrodes
- Readout elements only on one surface.
- Ionization Electrons drift to Surface for
  - Amplification
  - Charge Collection
- Readout Electrode Position gives (x,y)
- Time of Arrival gives (z).



Detector system example: ATLAS



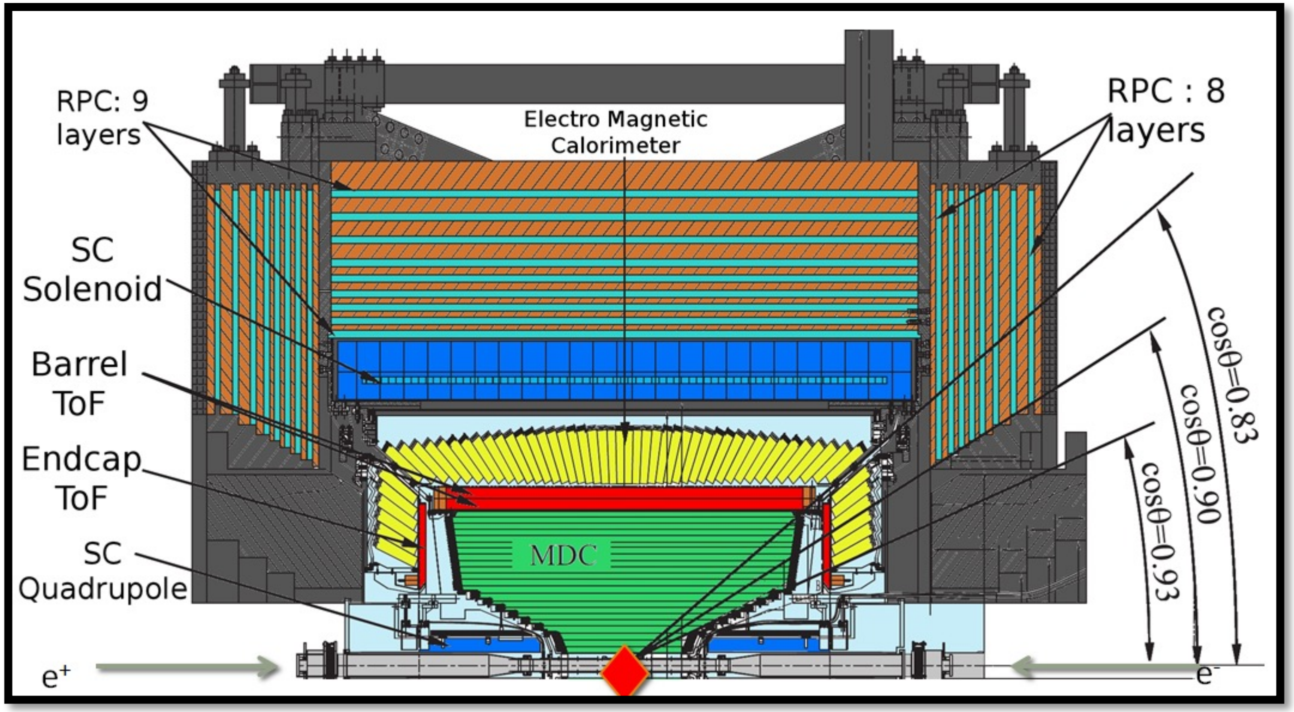
The results from BESIII and how they help to solve the problems

Beijing Electron Positron Collider (BEPCII)

2004: started BEPCII/BESIII construction
2008: test run
2009 - now: BESIII physics run

Beam energy:
1-2.3 GeV
(This year will try to reach 2.35 GeV)
Design luminosity:
$1\times10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
Bunch length:1.5 cm
Total current: 0.91 A
Linac: ~200 m
Circular:~240 m
Double rings with tiny crossing angle

BESIII detector



Charged-particle momentum resolution@1GeV: 0.5%

Photon energy resolution@1 GeV: 2.5% (5%) for barrel (endcap); position resolution 6mm

dE/dx resolution: 6% for electrons from Bhabha process

Time resolution of TOF: 68 ps (60 ps) for barrel (endcap)

SC magnetic: 1 T

Trigger and DAQ: 4 kHz, with event size 12 Kbytes

Physics program @ BESIII

Light hadron physics

-meson & baryon spectroscopy
-glueballs & hybrids

Charm physics:

- f_D & f_{D_s} decay consts.
- CKM matrix: V_{cd}, V_{cs}
- strong phase

New physics:

- *rare decays*
- dark sector

Charmonium physics:

- precision spectroscopy
- transitions and decays
- charmoniumlike states

QCD & τ-physics:

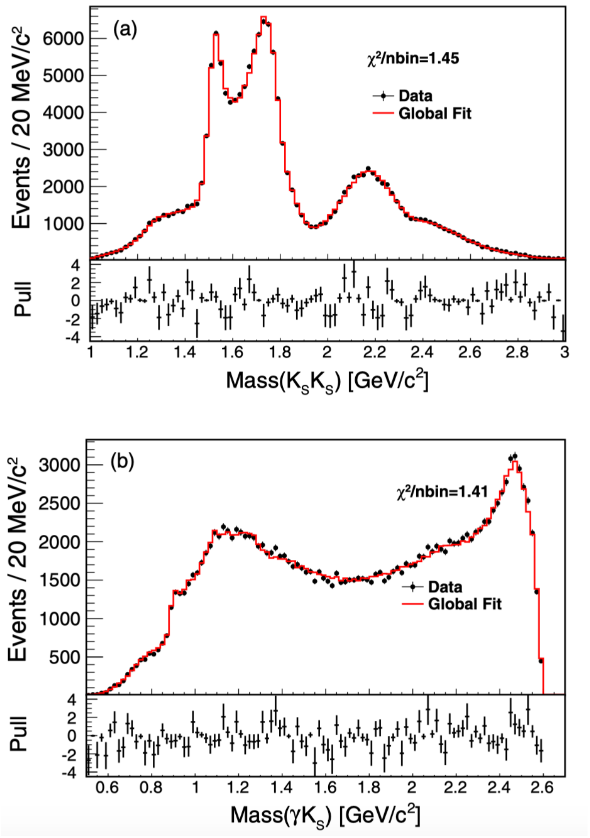
- precision R-measurement
- τ lepton mass
- two-photon physics

QCD
New Physics

Light hadron physics

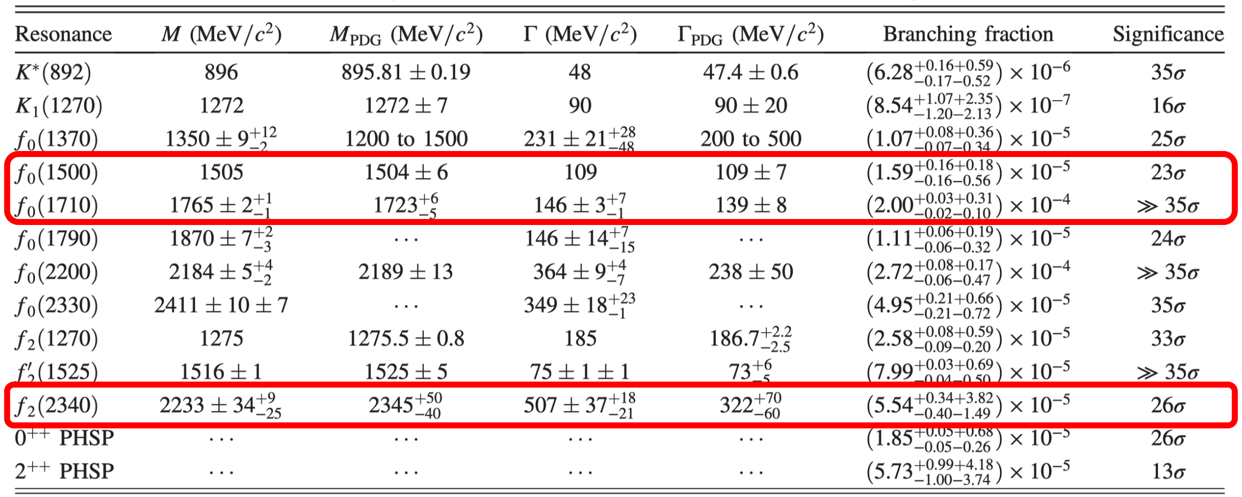
Amplitude analysis of $J/\Psi \rightarrow \gamma K_S K_S$

PRD 98, 072003



Production rate for $f_0(1710)$ is 10 times larger $f_0(1500)$⇒the former has larger overlap with glueball;

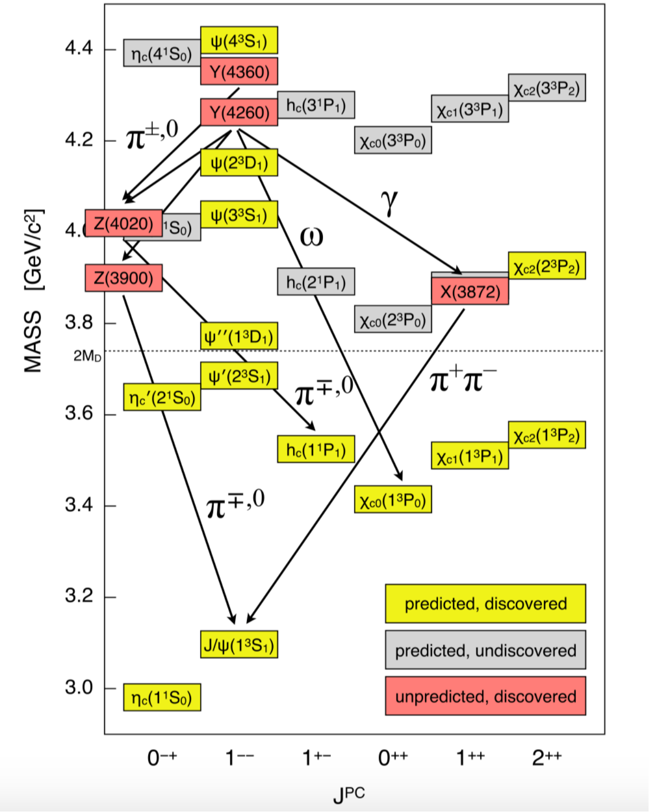
Production of $f_2(2340)$ is consistent with the pure gauge tensor glueball prediction made by LQCD.



Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	1200 to 1500	$231 \pm 21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$	25σ
$f_0(1500)$	1505	1504 ± 6	109	109 ± 7	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$	23σ
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	1723^{+6}_{-5}	$146 \pm 3^{+7}_{-1}$	139 ± 8	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$\cdots$	$146 \pm 14^{+7}_{-15}$	$\cdots$	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	$\cdots$	$349 \pm 18^{+23}_{-1}$	$\cdots$	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	35σ
$f_2(1270)$	1275	1275.5 ± 0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$	33σ
$f_2'(1525)$	1516 ± 1	1525 ± 5	$75 \pm 1 \pm 1$	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$	$\gg 35\sigma$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	2345^{+50}_{-40}	$507 \pm 37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$	26σ
0^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

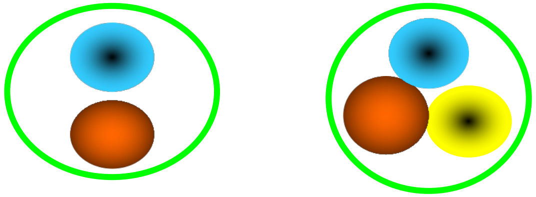
Charmoniumlike states

Charmonium spectroscopy



Hadrons : traditional & exotic

- Hadrons are composed of 2 quarks (meson) or 3 quarks (baryon) in Quark Model

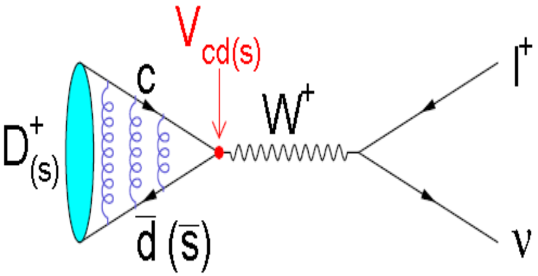


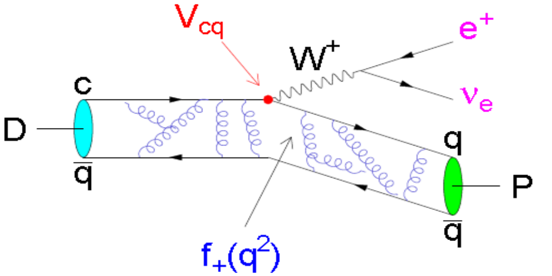
- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - multiquark state : $N_{quarks} > 3$
  - molecule : bound state of more than 2 hadrons
  - …

BESIII@BEPCII is collecting data to study this.

Charm physics

Leptonic & semileptonic decays





$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2 |V_{cd(s)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2$$

Leptonic and semileptonic decays of charmed hadrons (D^0, D^+, D_s^+, Λ_c^+) provide ideal testbeds to explore weak and strong interactions

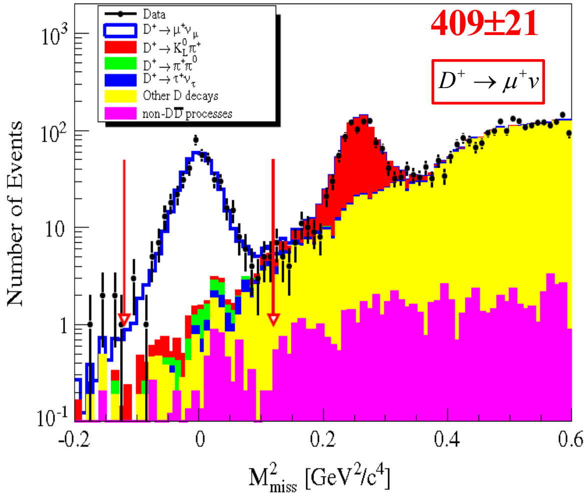
1. **$|V_{cs(d)}|$: better test on CKM matrix unitarity**
2. **(Semi-)leptonic $D_{(s)}$ decays allow for LFU tests**
3. **$f_{D(s)+}$, $f_+^{K(\pi)}(0)$: test of LQCD**

$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \boxed{V_{cd} \quad V_{cs}} & & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$f_{D^+}|V_{cd}|$ from $D^+\to l^+\nu$

2.93 fb^{-1} data@ 3.773 GeV

PRD89, 051104 (2014)



409±21

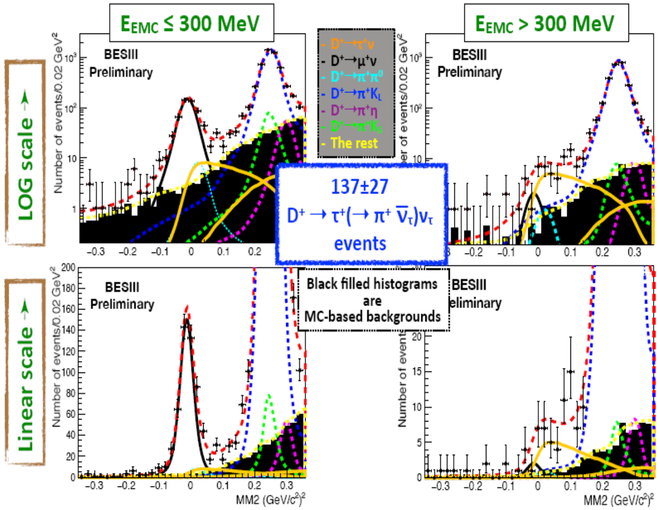
$D^+\to\mu^+\nu$

$$B[D^+\to\mu^+\nu]=(3.71\pm0.19\pm0.06)\times10^{-4}$$

$$f_{D^+}|V_{cd}|=45.75\pm1.20\pm0.39\ \text{MeV}$$

$D^+\to\tau^+\nu$

BESIII preliminary



137±27

$D^+\to\tau^+(\to\pi^+\bar{\nu}_\tau)\nu_\tau$

events

Black filled histograms are MC-based backgrounds

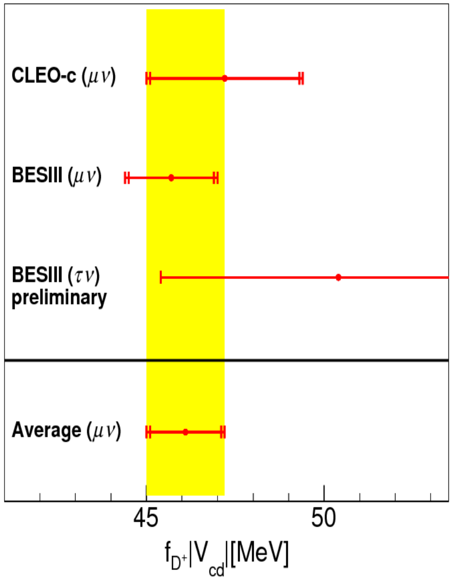
$$B[D^+\to\tau^+\nu]=(1.20\pm0.24_{\text{stat}})\times10^{-3}$$

$$f_{D^+}|V_{cd}|=50.4\pm5.0_{\text{stat}}\ \text{MeV}$$

statistical error dominant

New inputs from PDG2018:

	value
m_μ	0.1056583745(24) GeV
m_τ	1.77686(12) GeV
m_{D^+}	1.86965(5) GeV
τ_{D^+}	1.040(7) ps
G_F	$1.1663787(6)\times10^{-5}$ GeV^{-2}



τ and R -QCD

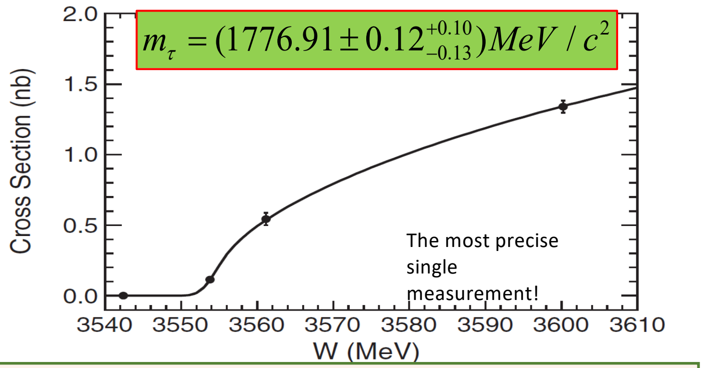
Precision measurement of the τ mass

PRD 90, 012001

A fundamental parameter of the SM!
Check the universality of the leptons!

Near threshold scan method:

- * 4 scan points with well optimization
- * 13 decay modes of the t pair
- * With beam energy measurement system



$$m_\tau = (1776.91 \pm 0.12^{+0.10}_{-0.13})MeV / c^2$$

The most precise single measurement!

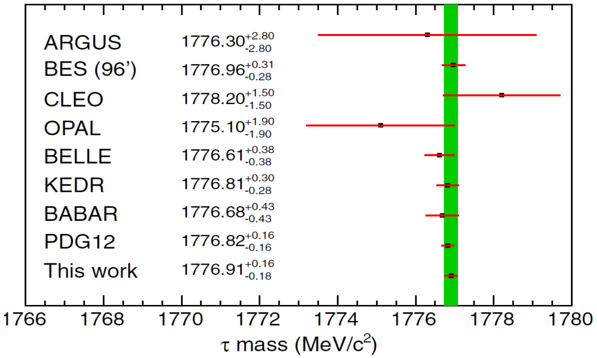
$$\sigma(E_{c.m.}, m_\tau, \delta_w^{BEMS}) = \frac{1}{\sqrt{2\pi}\delta_w^{BEMS}} \int_{2m_\tau}^{\infty} dE'_{c.m.} e^{\frac{-(E_{c.m.}-E'_{c.m.})^2}{2(\delta_w^{BEMS})^2}} \int_0^{1-\frac{4m^2}{E'^2_{c.m.}}} dx F(x, E'_{c.m.}) \frac{\sigma_1(E'_{c.m.}\sqrt{1-x}, m_\tau)}{|1-\prod(E_{c.m.})|^2}$$

$$\frac{B(\tau \to e\nu\bar{\nu})}{\tau_\tau} = \frac{g_\tau^2 m_\tau^5}{192\pi^3}$$

$$g_\tau = (1.1650 \pm 0.0034) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B(\tau \to e\nu\bar{\nu})}{B(\mu \to e\nu\bar{\nu})}(1+F_W)(1+F_\gamma)$$

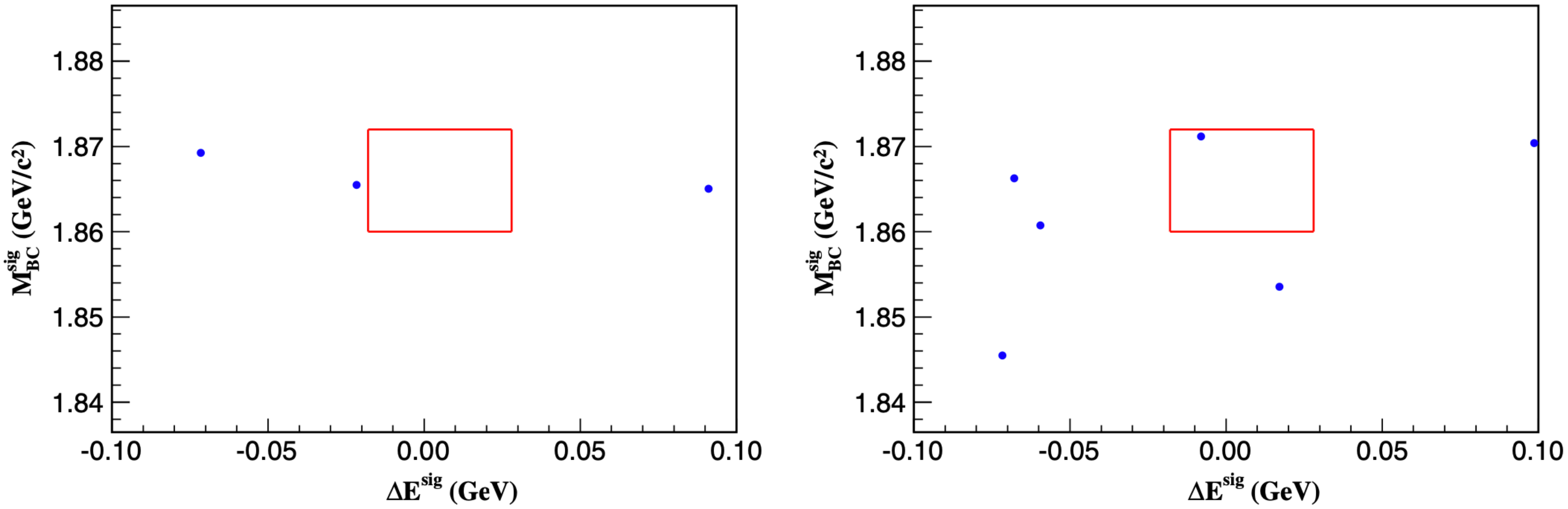
$$\left(\frac{g_\tau}{g_\mu}\right)^2 = 1.0016 \pm 0.0042$$



New Physics

PHYSICAL REVIEW D **105**, 032006 (2022)

Search for baryon- and lepton-number violating decays $D^0 \to \bar{p}e^+$ and $D^0 \to pe^-$



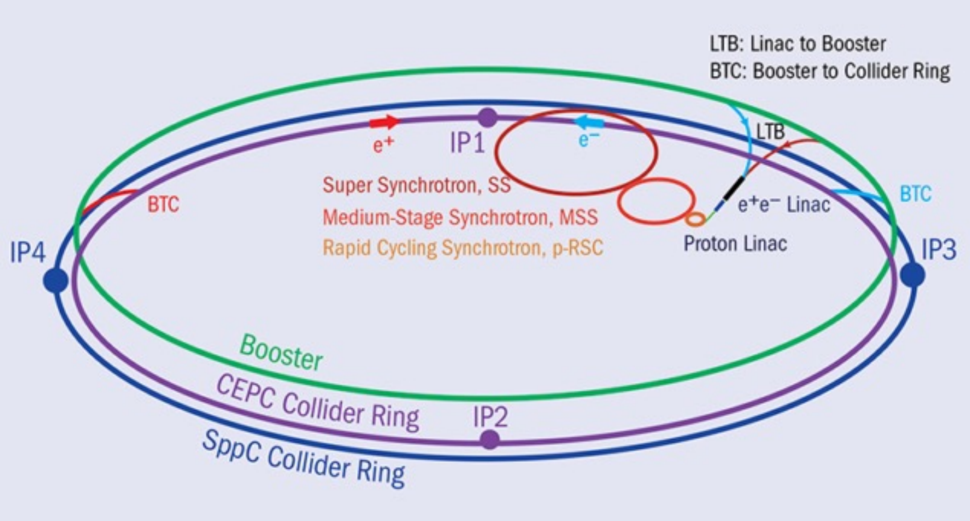
(a) (b)

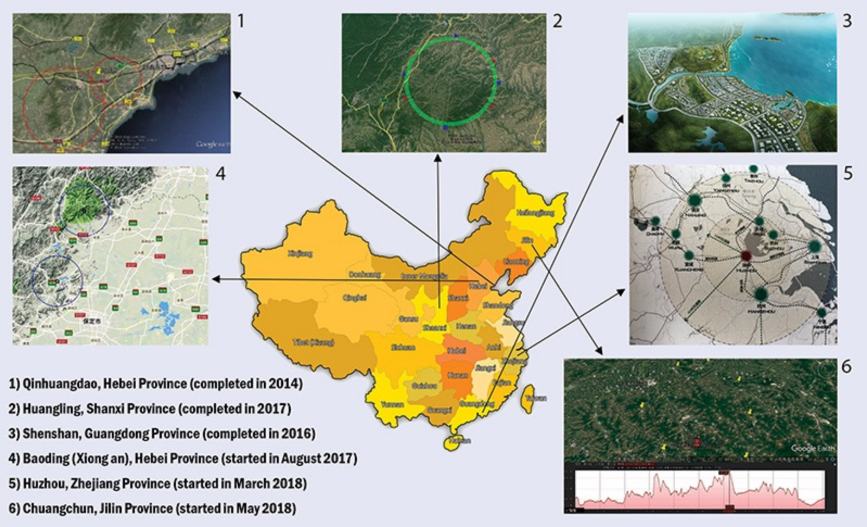
We have 10 years of running for BESIII

☐ Even though we have so many publications, we do not solve the problems we mentioned in the beginning totally, but we either find some hints to the solutions or find more problems. That is the reason we want to continuum the running of BESIII detector for an other 10 years;

☐ With the next 10 years, we will upgrade the detector, and the luminosity/energy of BEPC will be expanded also; we will get more data sample, which means that we could perform more precision measurement; at the same time better understanding of the detector will be reached, which means smaller systematic uncertainty;

From BEPC to CEPC





1) Qinhuangdao, Hebei Province (completed in 2014)
2) Huangling, Shanxi Province (completed in 2017)
3) Shenshan, Guangdong Province (completed in 2016)
4) Baoding (Xiong an), Hebei Province (started in August 2017)
5) Huzhou, Zhejiang Province (started in March 2018)
6) Chuangchun, Jilin Province (started in May 2018)

Tips for First-Time Learners

Love lxslc: stay with it as long as you can; Familiarize yourself with the BESIII software platform and contribute improvements if you have innovative ideas. Develop your own operational scripts, whether by adapting existing ones or creating new ones from scratch. Maintain an organized and efficient personal folder

Tips for First-Time Learners

Participate in meetings: train your ears and mouth to become familiar with English and the jargon used in BESIII. Familiarize yourself with the BESIII publication procedure. Gain a comprehensive understanding of the physics and techniques discussed in the presentations. Make an effort to ask questions and offer suggestions.

Tips for First-Time Learners

Regularly report your results and take care in preparing your slides. Clearly explain how you obtained your results, allowing others to assess their accuracy. It's your responsibility to ensure others understand your findings, rather than simply attributing any misunderstandings to their intelligence.

Tips for First-Time Learners

Begin writing the analysis note as soon as possible. In the introduction section, ensure you thoroughly read and comprehend the references you've cited. Seek input from your supervisor for refining the analysis note, but put in your best effort before seeking their assistance.

Tips for First-Time Learners

Continue to cherish life even if you encounter challenges you can't immediately resolve.

GOOD LUCK!

GOOD BYE!