The Physics at BESIII

Weimin Song (宋维民)

weiminsong@jlu.edu.cn

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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

I got all the following information form the references which will be listed later, but I am brave enough to be in charge of all of the mistakes!

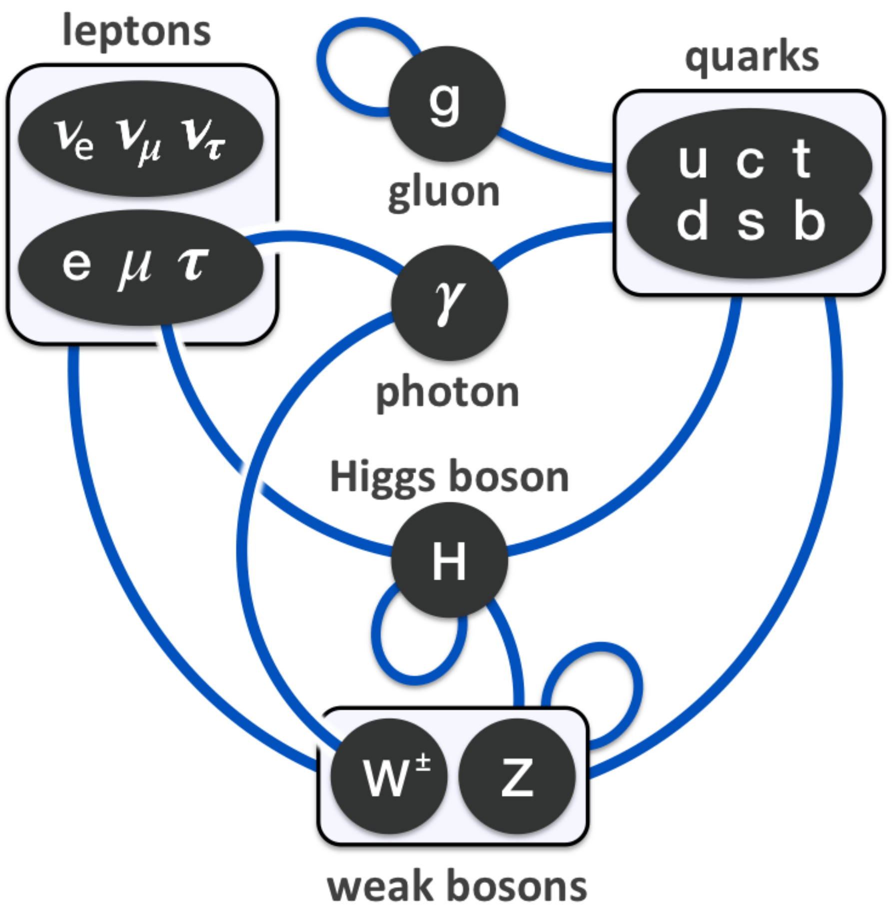
The Standard Model of Particle Physics and its problems

The Lagrangian of SM

$$
\begin{aligned}
\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_s^2 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_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac12 \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)) - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
&Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(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) - \tfrac12\partial_\mu H\partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 - \\
&\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
&g\alpha_h M\,(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \\
&\tfrac18 g^2\alpha_h\,(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2) - \\
&gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
&\tfrac12 ig\,(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)) + \\
&\tfrac12 g\,(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)) + \tfrac12 g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
&M\,(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac14 g^2 W^+_\mu W^-_\mu\,(H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \tfrac18 g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\,(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-) - \\
&\tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac12 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_wA_\mu\,(-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)) + \\
&\tfrac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\tfrac43 s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
&(\bar u^\lambda_j\gamma^\mu(1 - \tfrac83 s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt2}W^+_\mu\,((\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)) + \\
&\tfrac{ig}{2\sqrt2}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\sqrt2}\phi^+\,(-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) + \\
&\tfrac{ig}{2M\sqrt2}\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 g2\tfrac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
&\tfrac g2\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) - \tfrac14\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa - \\
&\tfrac14\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa + \tfrac{ig}{2M\sqrt2}\phi^+\,(-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) + \\
&\tfrac{ig}{2M\sqrt2}\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 g2\tfrac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \\
&\tfrac g2\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_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \\
&\partial_\mu\bar X^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 - \\
&\partial_\mu\bar X^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+ X^+ - \\
&\partial_\mu\bar X^- X^-) + igs_wA_\mu(\partial_\mu\bar X^+ X^+ - \\
&\partial_\mu\bar X^- X^-) - \tfrac12 gM\left(\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) + \\
&\tfrac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + \\
&\tfrac12 igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right)
\end{aligned}
$$

Everything is on one piece of A4 Paper!

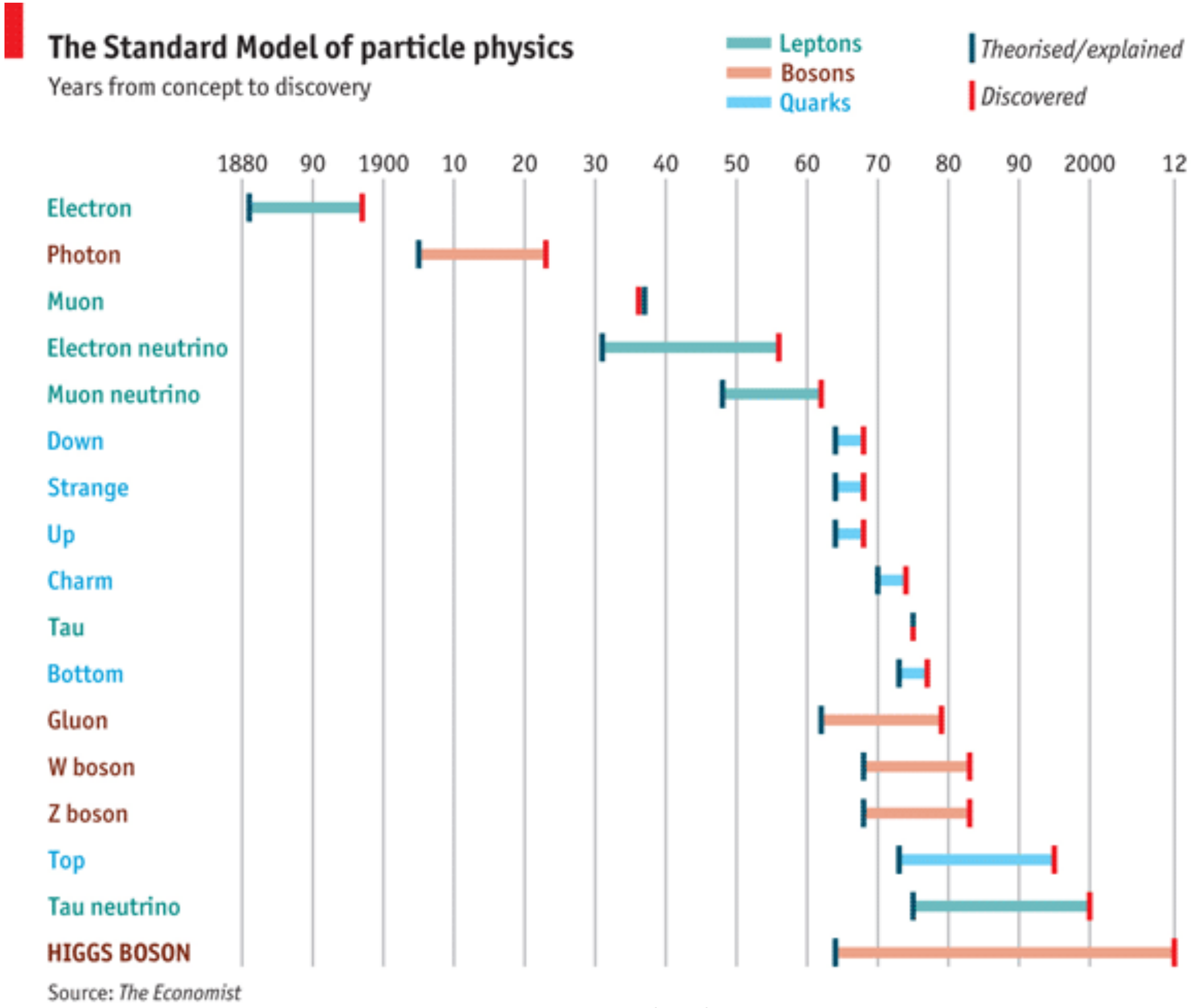
The particles and interactions



Fundamental Force Particles

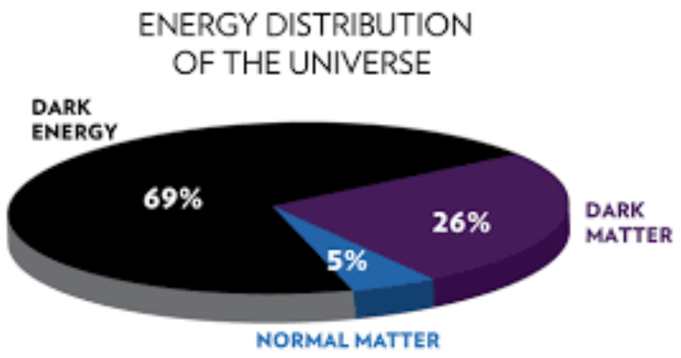
Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts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

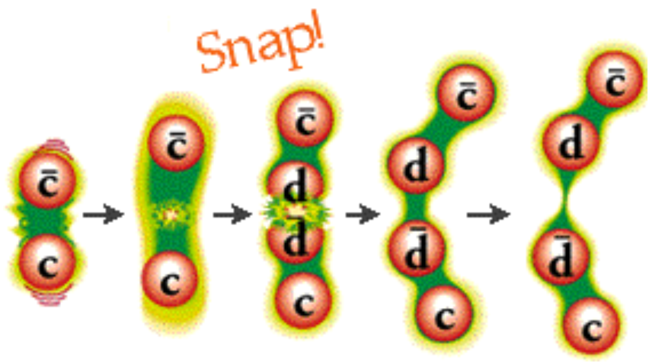
A brief history of SM

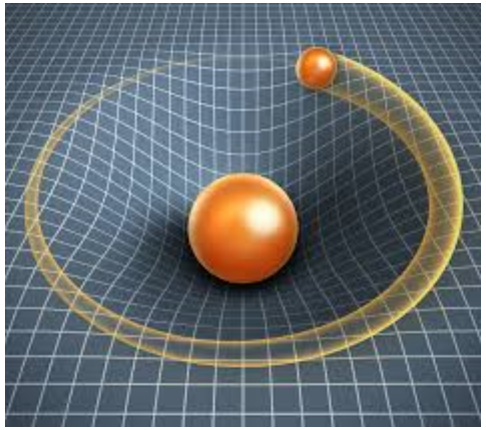


100 years with a lot of heroes!

The known unknown of SM







There are of course of unknown-unknown!

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

The Physics processes at $\sqrt{s}$=2-5 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)
- Air shower

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

Physics processes at Ecm=2-5 GeV

QED

- Bhabha
- Di-mu
- Di-tau
- Di-gamma

→ Luminosity measurement, detector calibration and so on

Hadrons at continuum

- Continuum production of hadrons
- Two-photon processes

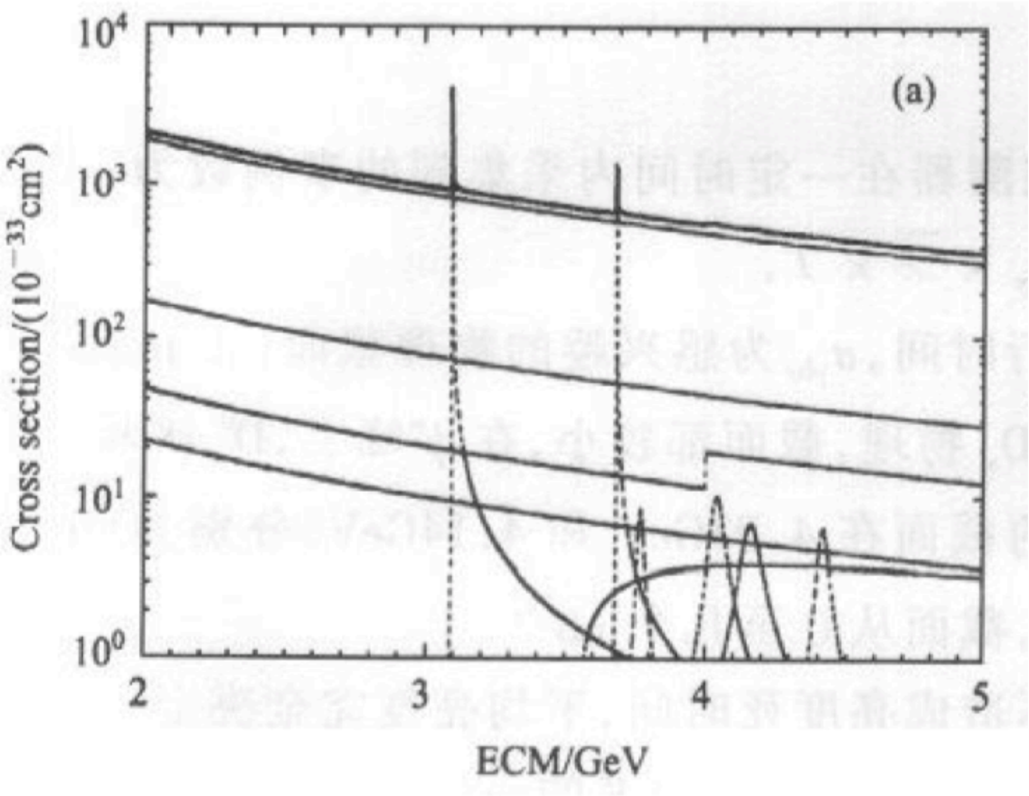
→ R-value measurement, form factor measurement ……

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/ψand ψ(3686) peaks, the Bhabha is the dominant process in this energy region!

QED processes kinematics (1)

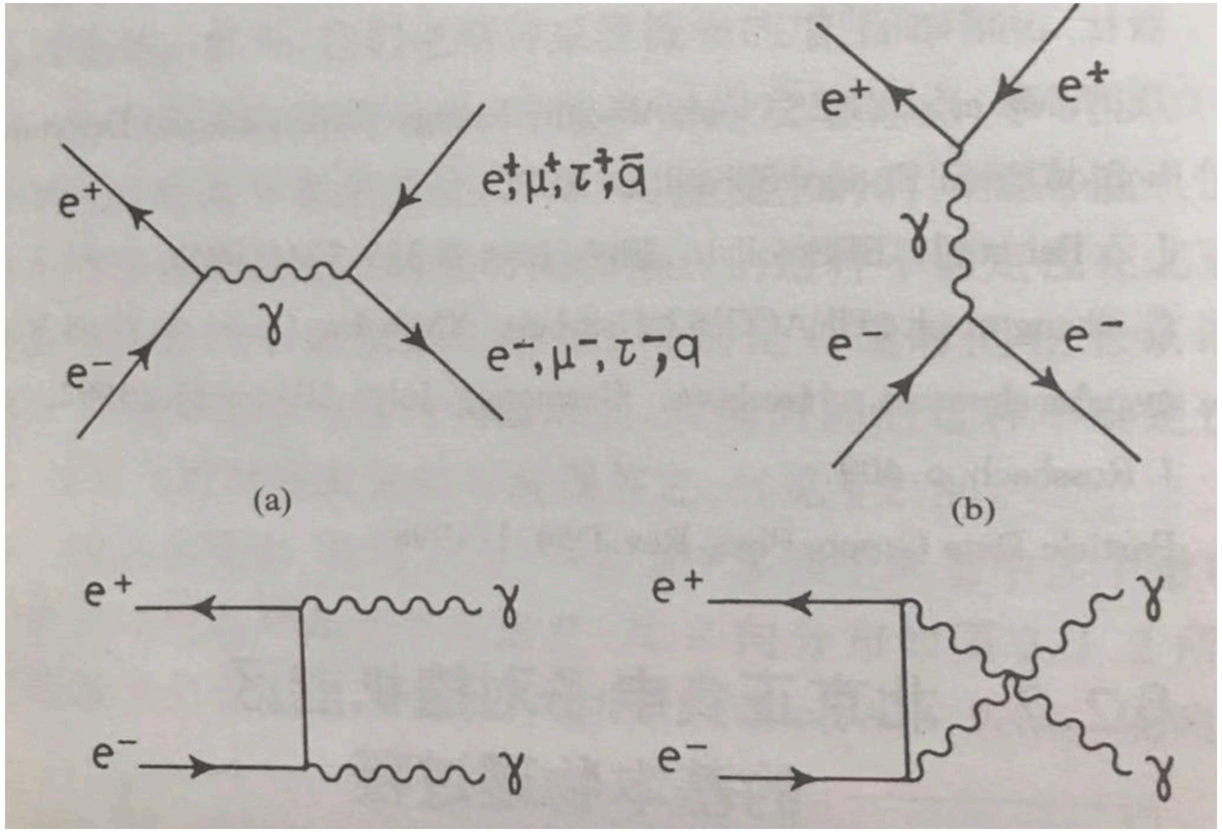
Leading order differential cross section for Bhabha:

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

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:

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

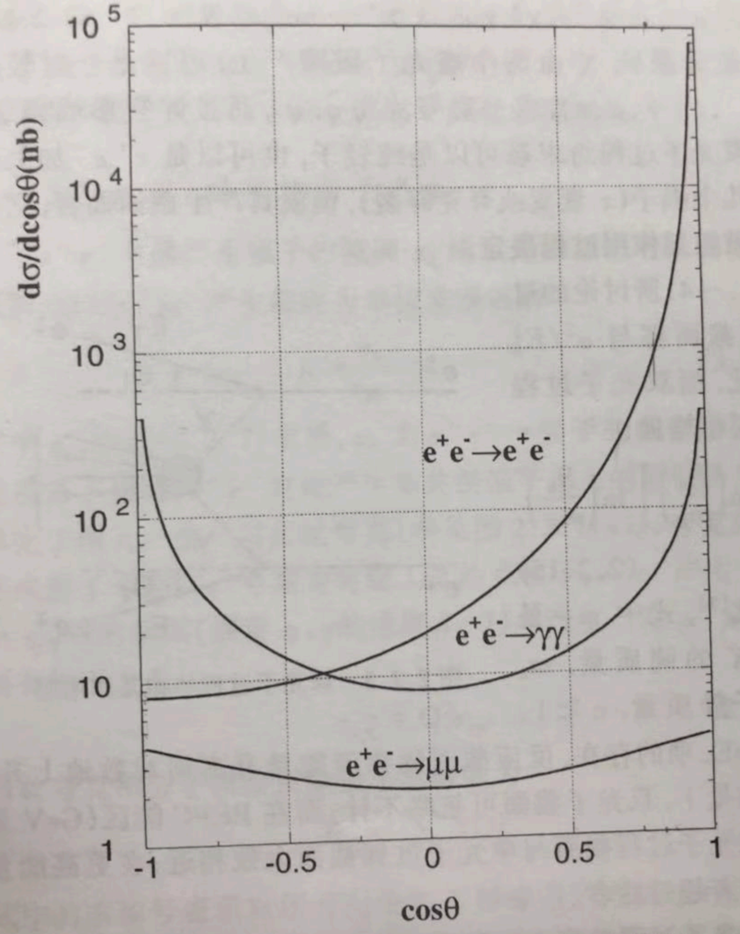
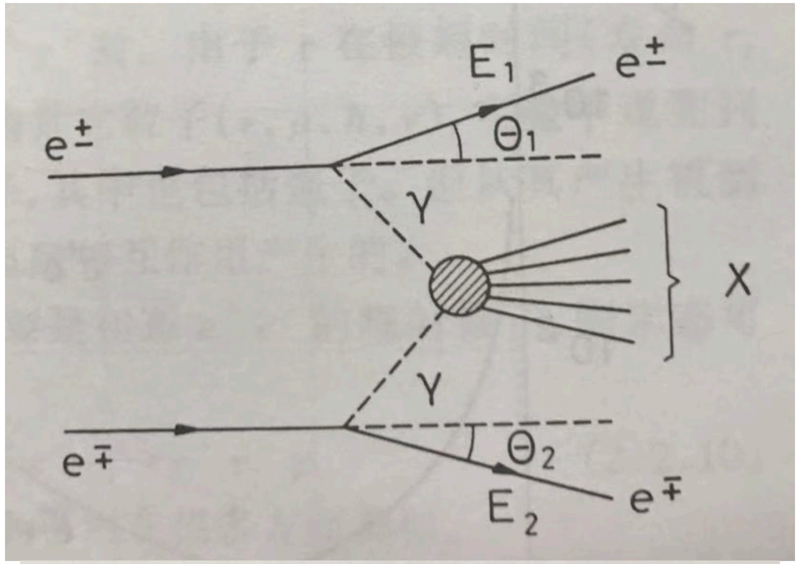


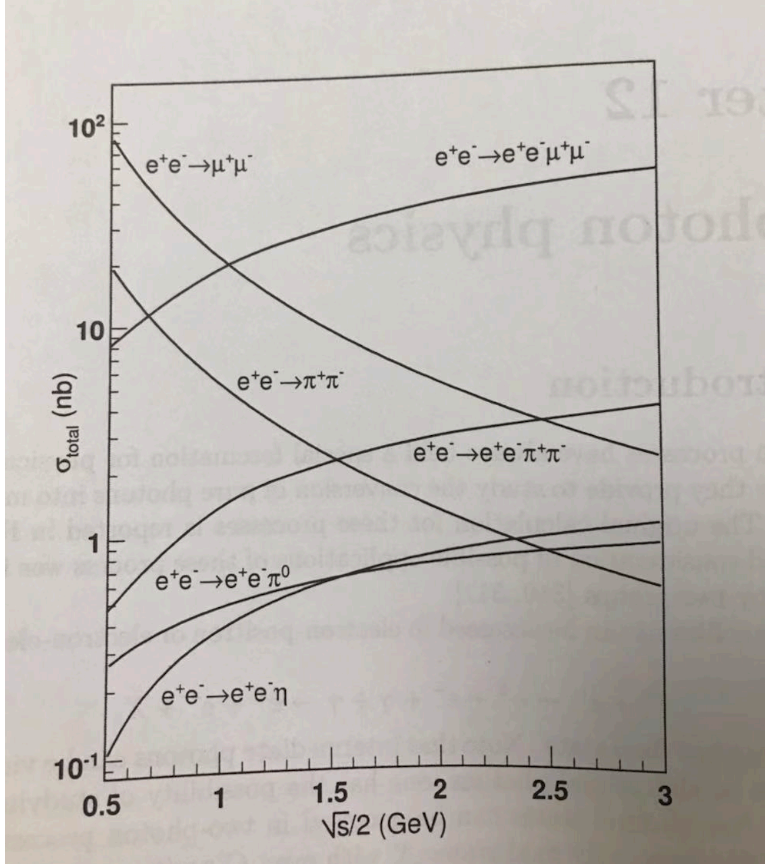
图 2.2.2　$e^+e^-\longrightarrow e^+e^-$、$\mu^+\mu^-$、$\gamma\gamma$ 在束流能量 $E_b=2$GeV 处的微分截面

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:

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

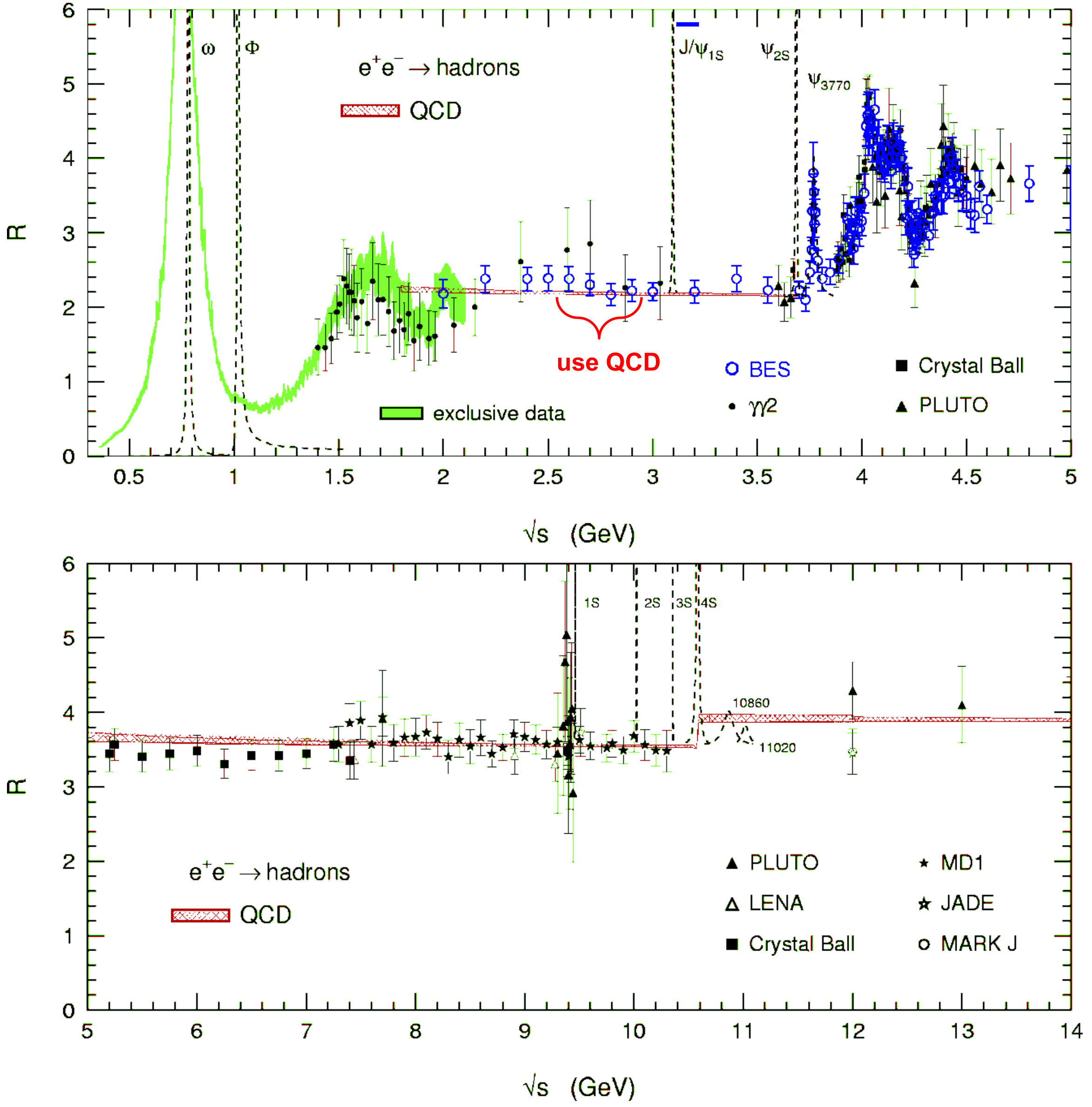
3 is from the color of quark!

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 values



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

Resonance production

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

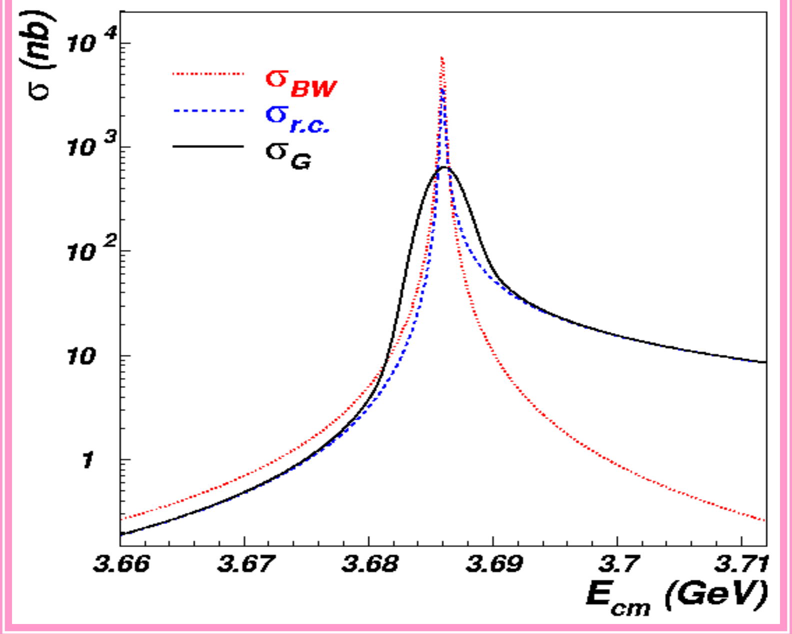
J=1

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



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

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

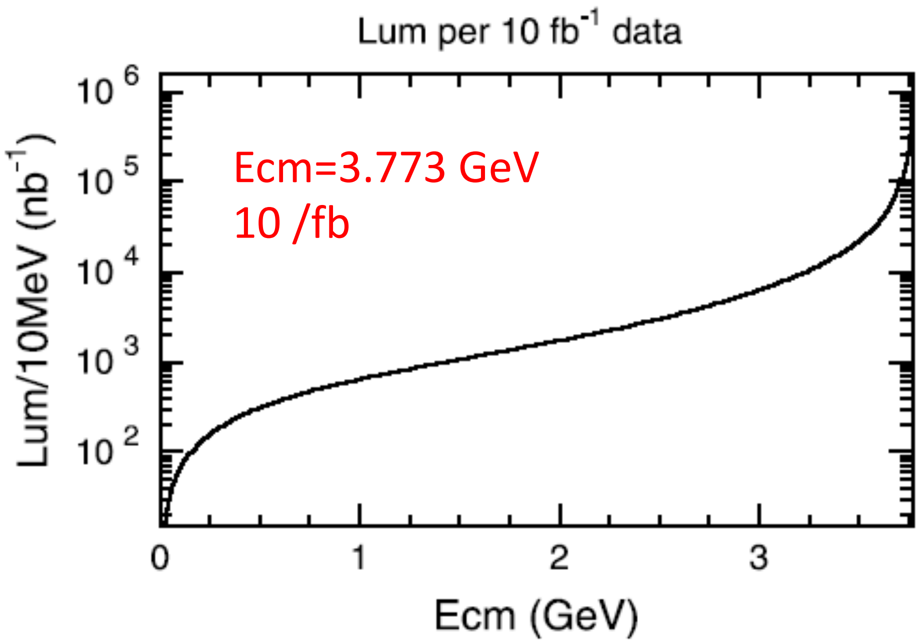
$$\sigma_{exp}(W) = \int_0^{\infty} dW' \sigma_{r.c.}(W') G(W', W)$$

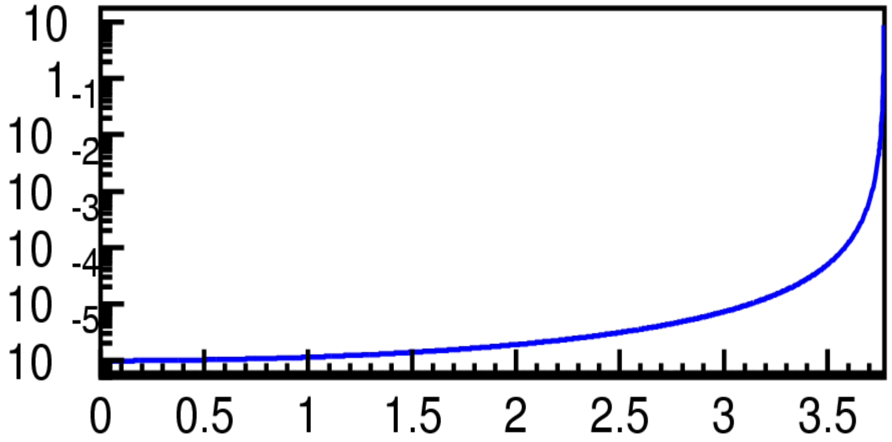
$$G(W, W') = \frac{1}{\sqrt{2\pi}\Delta} e^{-\frac{(W-W')^2}{2\Delta^2}}$$

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!

Measurement at Ecm





$$\sigma^B = \frac{N^{obs}}{\mathcal{L}_{int}(1+\delta)\epsilon\mathcal{B}}$$

Vacuum polarization

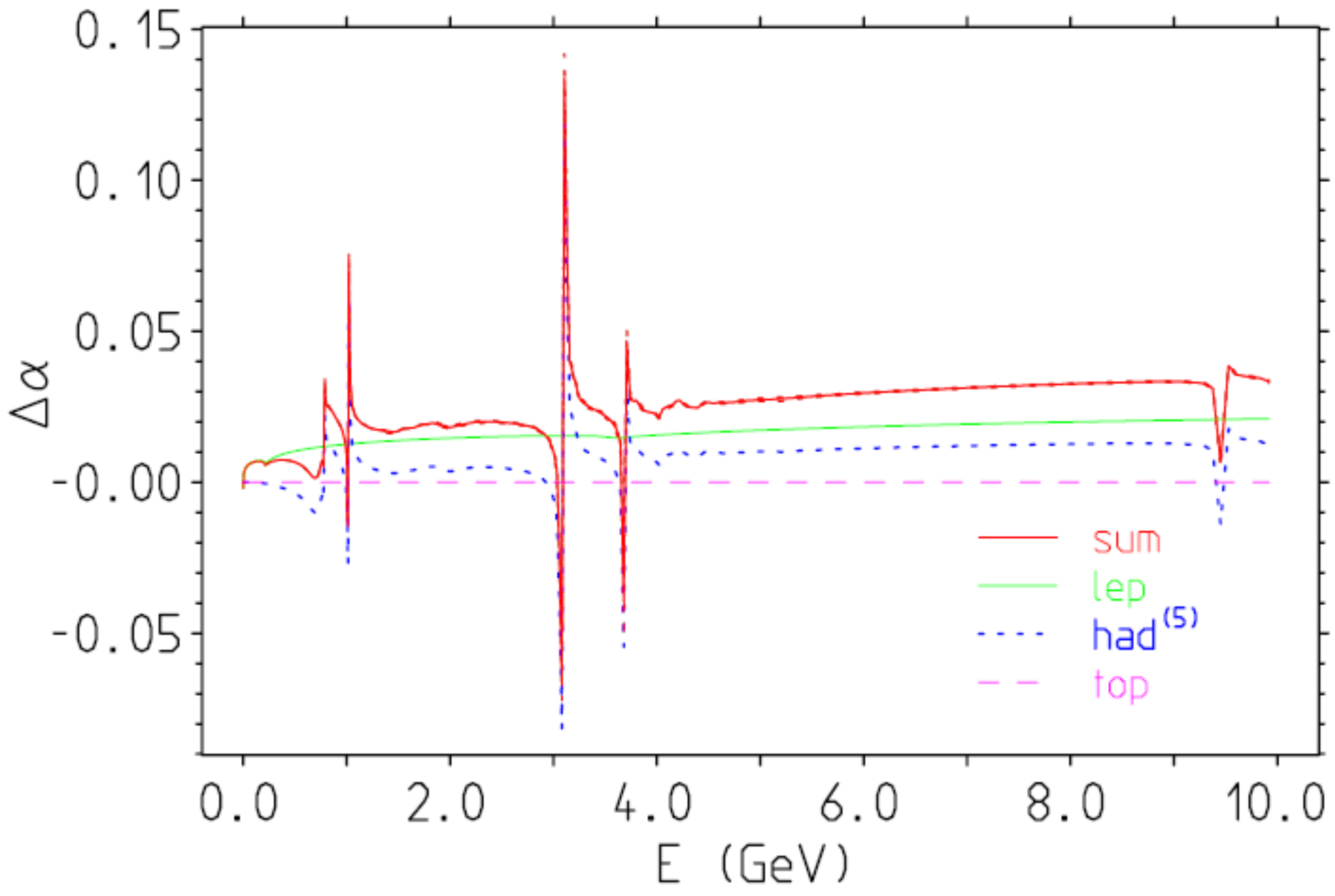
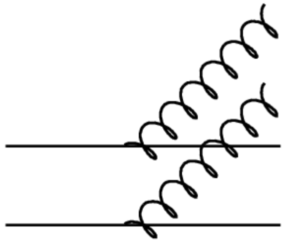
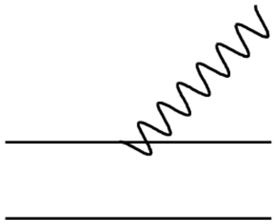


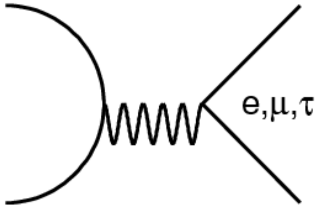
Fig. 81 Different contributions to $\Delta\alpha(s)$ in the time-like region as given by the routine from Fred Jegerlehner (version February 2010)

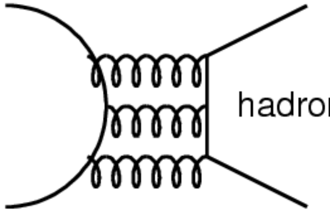
ψ’ decays

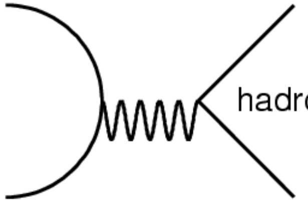


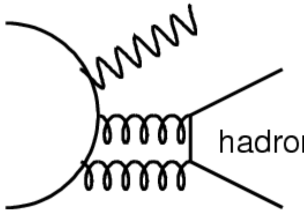


- Transitions (~82%)
  - Hadronic transitions (~54%)
  - Radiative transitions (~28%)
- Leptonic decays (~ 2%)
- Hadronic decays (~15%)
  - Strong decays (~13%)
  - EM decays (~ 2%)
- Radiative decays (~ 1%)
- Rare decays and beyond SM (<<1%)









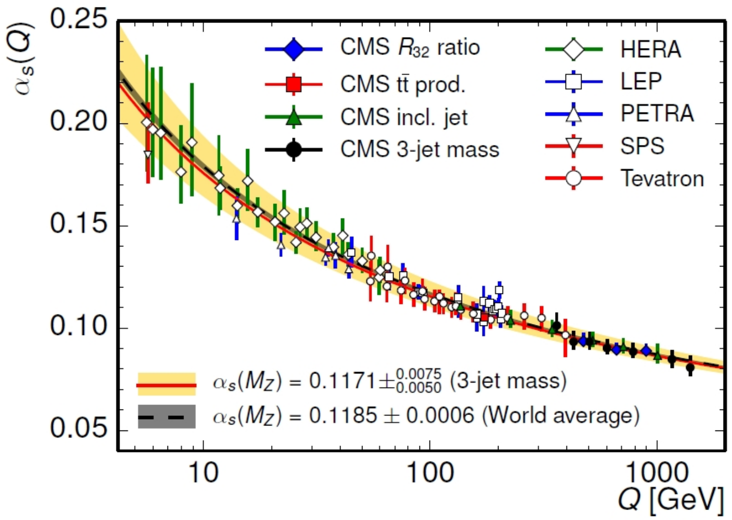
Similar for J/ψ decays, but BR different.

How often we will get a physics event on BESIII?

- Assume on $\Psi(3686)$ 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 $\Psi(3686)$ 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; well 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

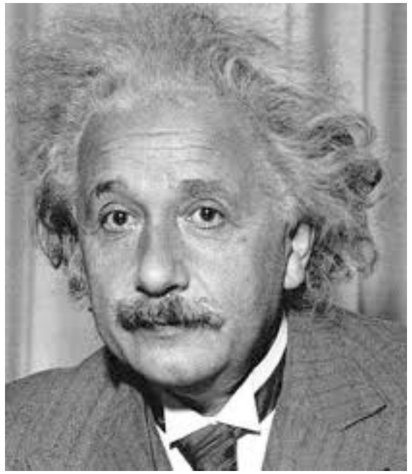


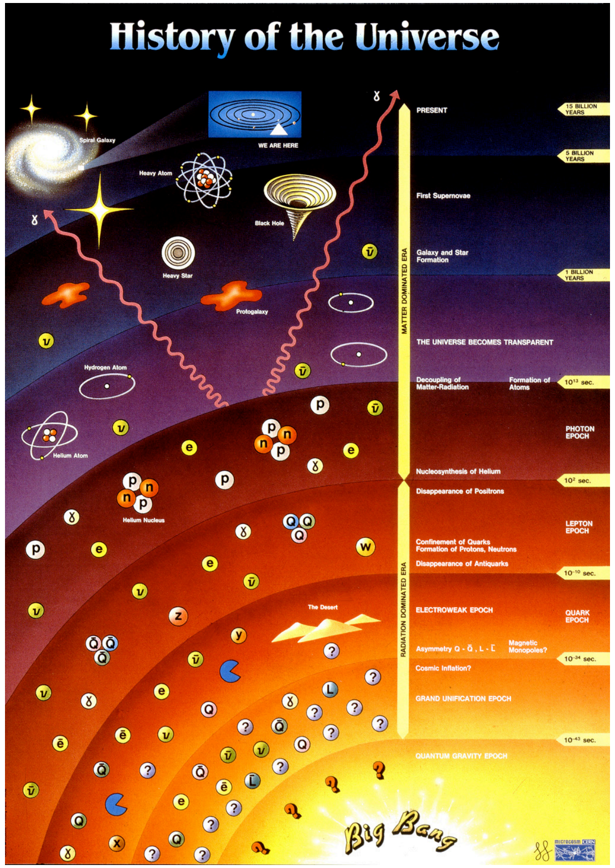
Introduction to accelerator

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

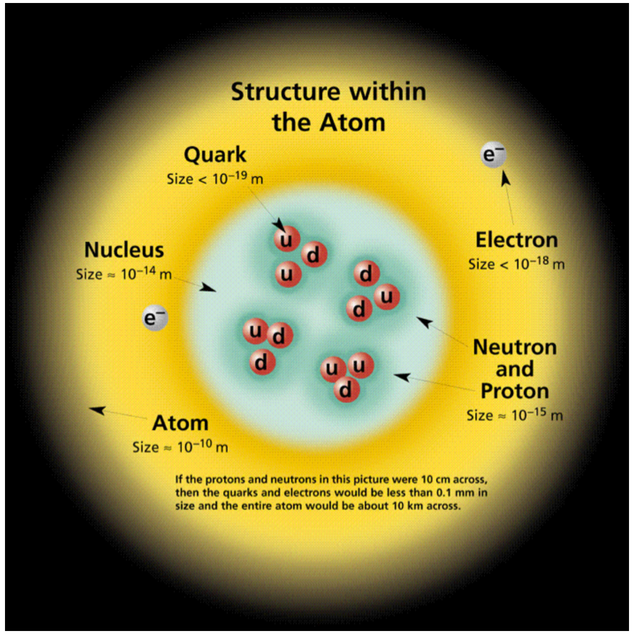
λ = 400 ➔ 700 nm

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

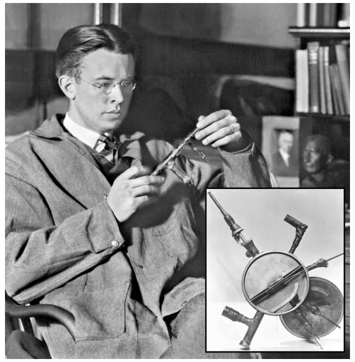
- Cyclotrons
- FFAG
- Synchrotrons
- Synchrotron light sources (e^-)
- Lin. & Circ. accelerators/Colliders

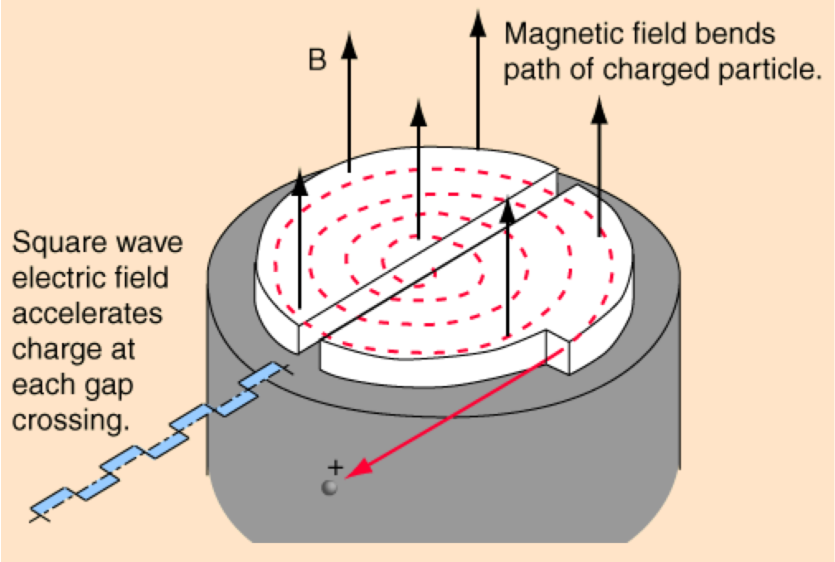
**Source: World Scientific Reviews of Accelerator Science and Technology A.W. Chao*

Cyclotron

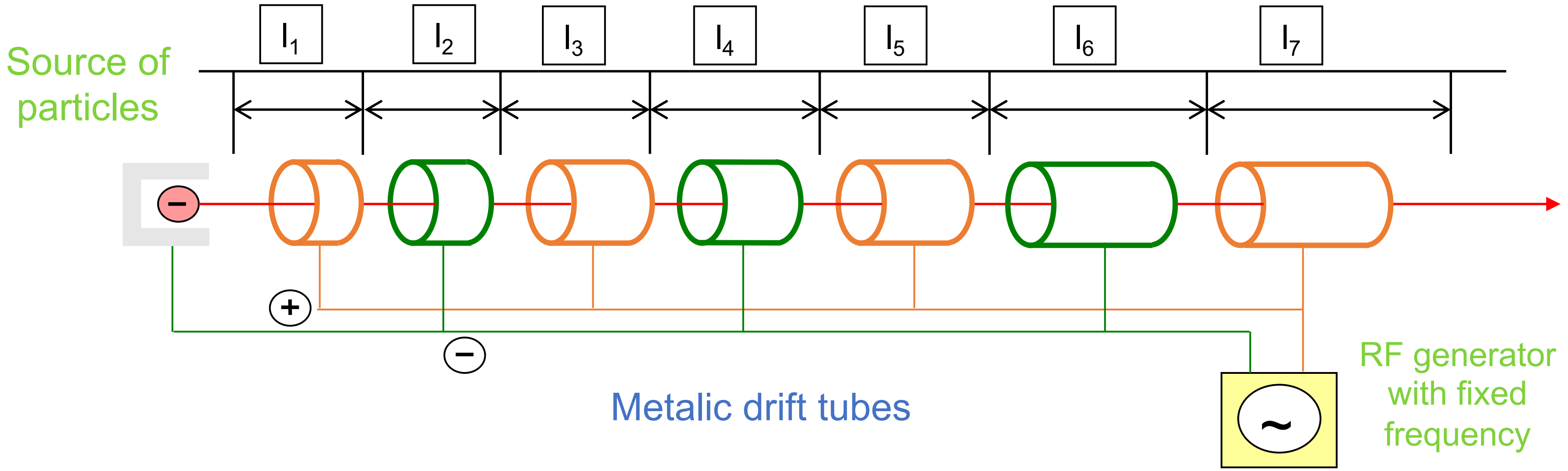
- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- Constant magnetic field
- Alternating voltage between the two D's
- Increasing particle orbit radius
- Development lead to the synchro-cyclotron to cope with the relativistic effects.

In 1939 Lawrence received the Noble prize for his work.





Linear Accelerator

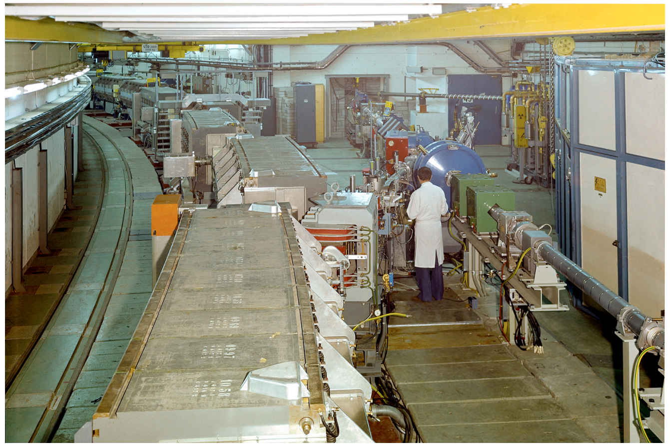


- Many people involved: Wideroe, Sloan, Lawrence, Alvarez,….
- Main development took place between 1931 and 1946.
- Development was also helped by the progress made on high power high frequency power supplies for radar technology.
- Today still the first stage in many accelerator complexes.
- Limited by energy due to length and single pass.

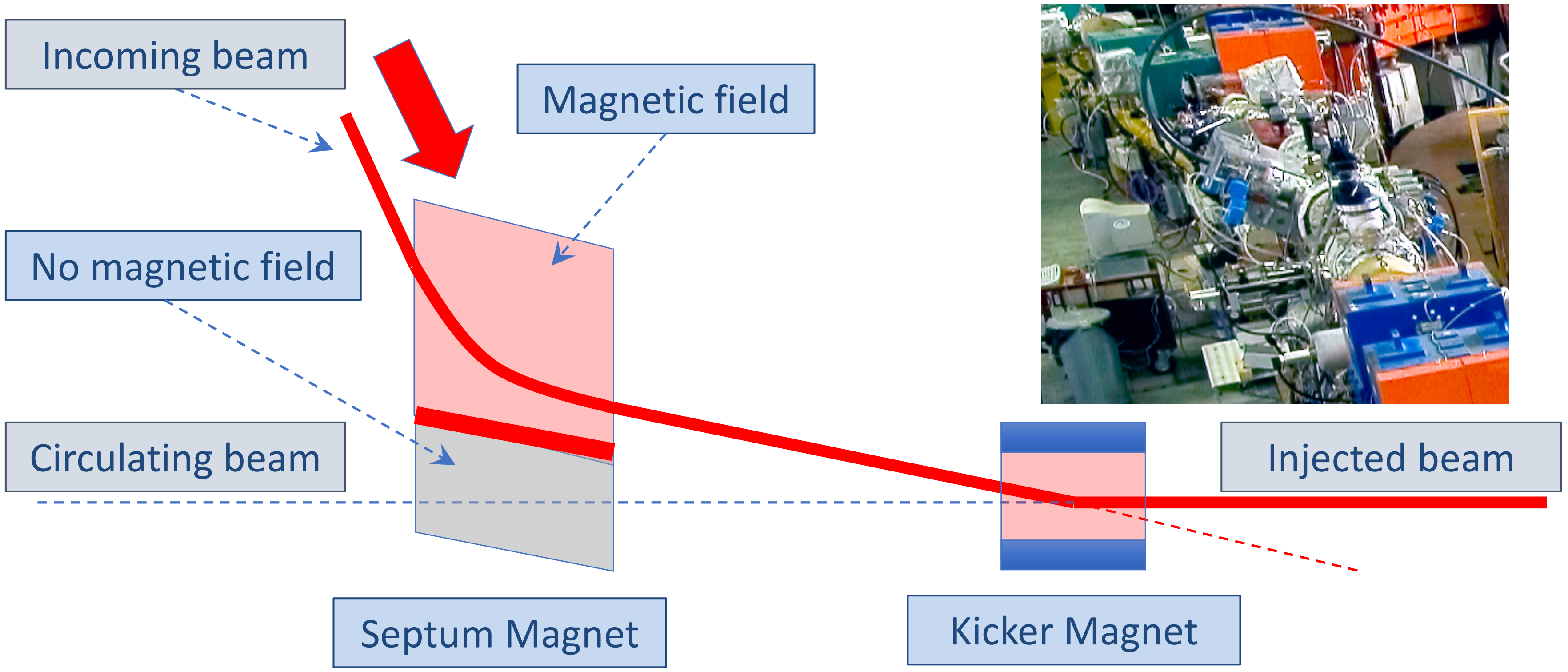
Synchrotrons

- 1943: M. Oliphant described his synchrotron invention in a memo to the UK Atomic Energy directorate

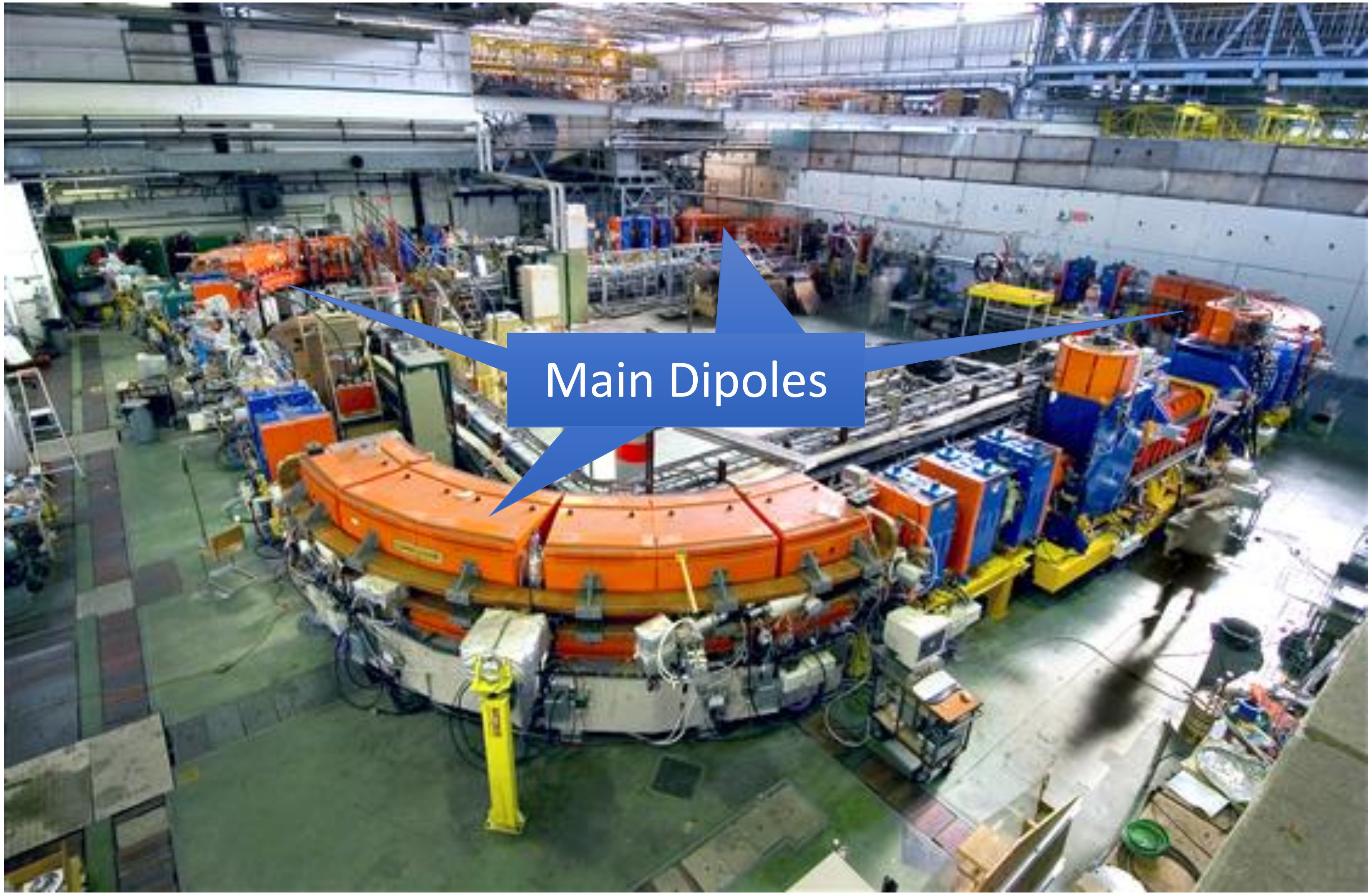
- 1959: CERN-PS and BNL-AGS
- Fixed radius for particle orbit
- Varying magnetic field and radio frequency
- Phase stability
- Important focusing of particle beams (Courant – Snyder)
- Providing beam for fixed target physics
- Paved the way to colliders



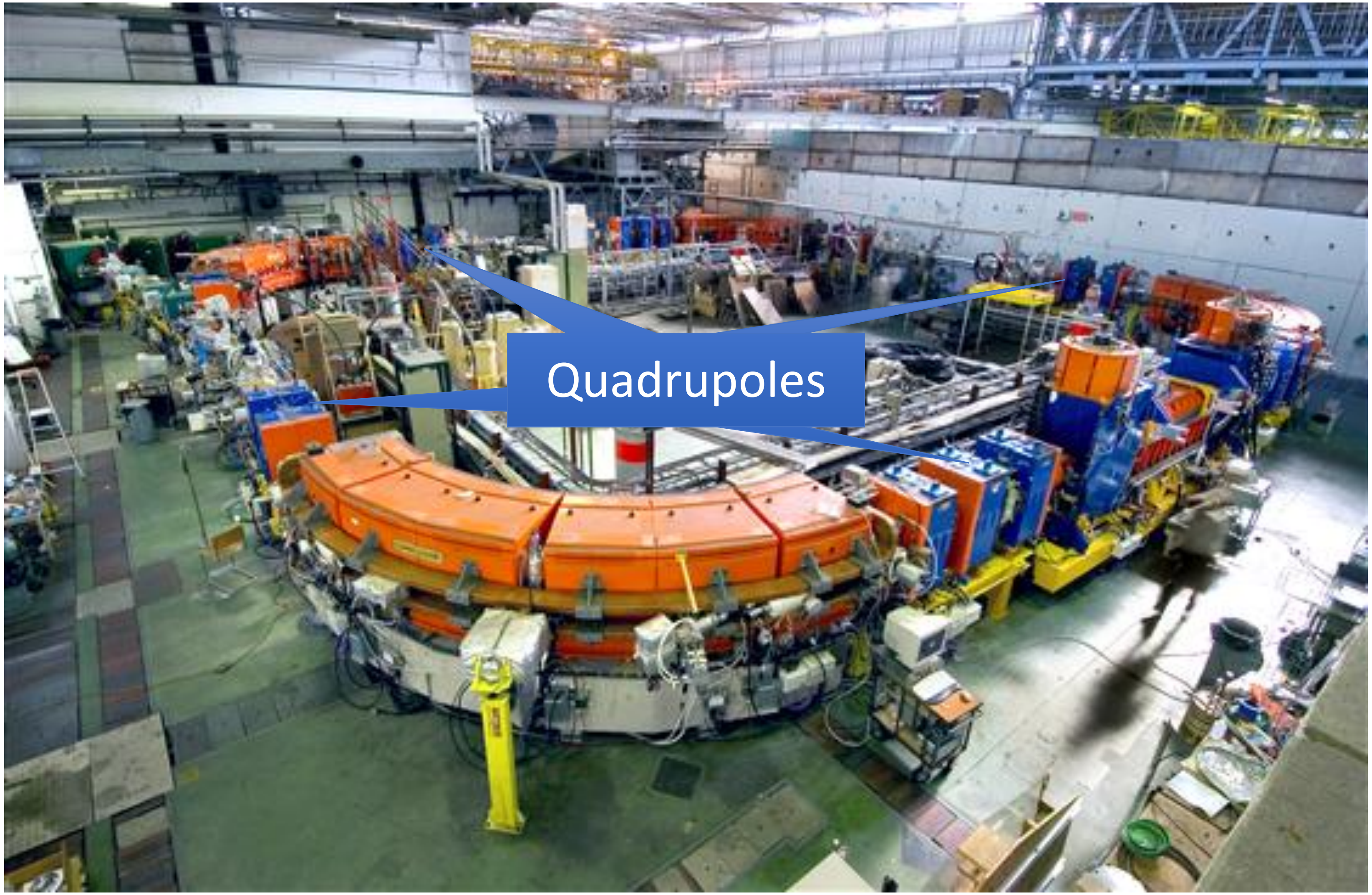
Injecting & Extracting Particles



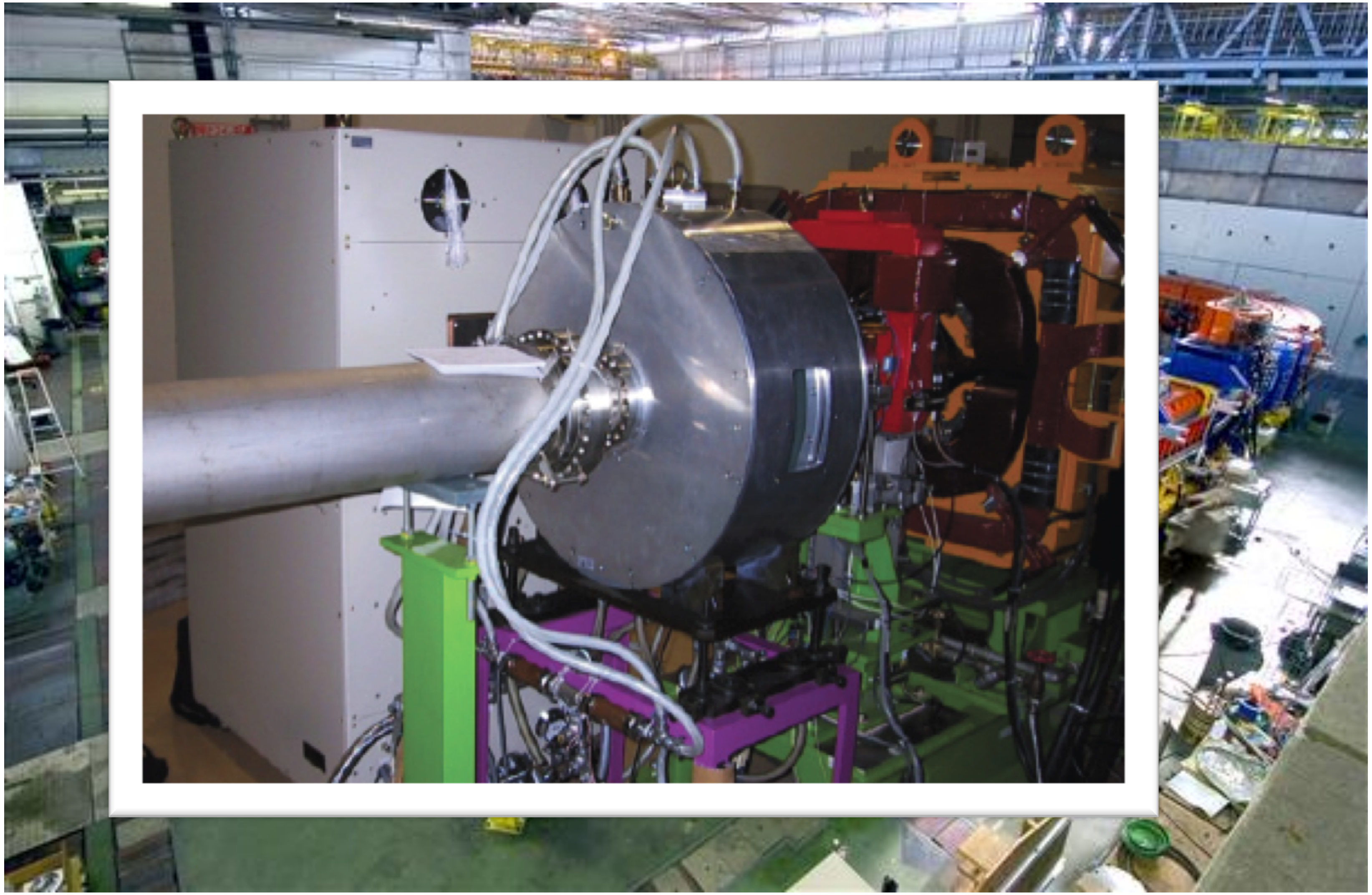
Make Particles Circulate



Focusing the Particles



Accelerating Particles

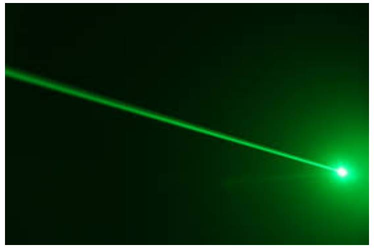


Figures of Merit in accelerators

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

Fixed Target Physics:

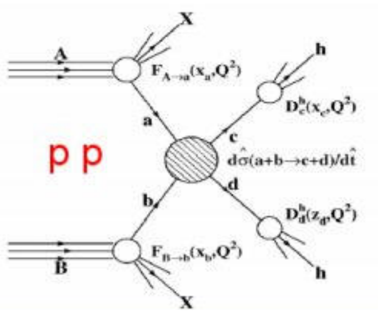
Light Sources:

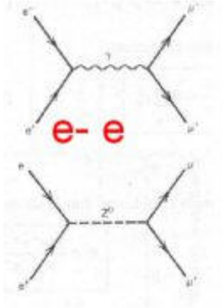


Collider Physics:

Main parameters: particle type

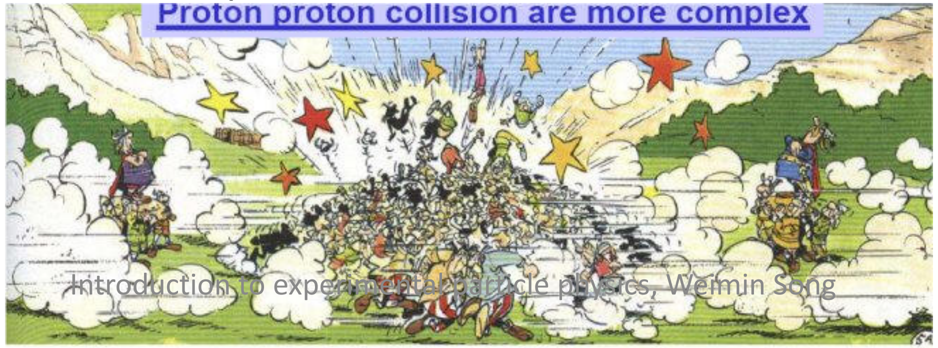
- Hadron collisions: compound particles
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - ***Hadron collisions*** $\Rightarrow$ ***large discovery range***





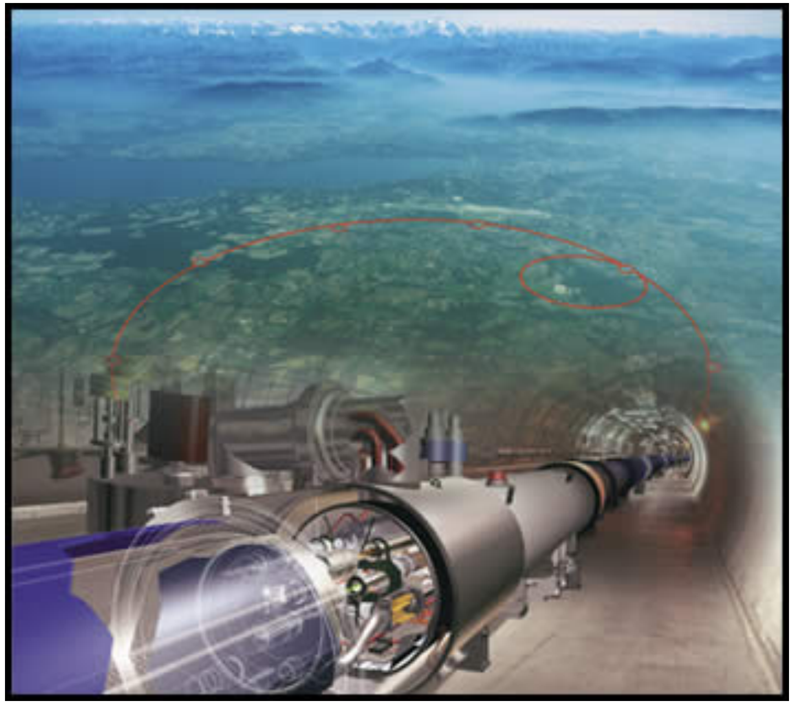
- Lepton collisions: elementary particles
  - Collision process known
  - Well defined energy
  - ***Lepton collisions*** $\Rightarrow$ ***precision measurement***

"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: particle energy

- New physics can be found at larger unprobed energies
- Energy for particle creation: centre-of-mass energy, E_{CM}
- Assume particles in beams with parameters m, E, E >> mc^2
  - Particle beam on fixed target: $\mathrm{E_{CM}} = \sqrt{mE}$
  - Colliding particle beams: $\mathrm{E_{CM}} = 2E$
- $\Rightarrow$ Colliding beams much more efficient

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 $\mathcal{L} >> 10^{30}\ \text{cm}^{-2}\text{s}^{-1}$ 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

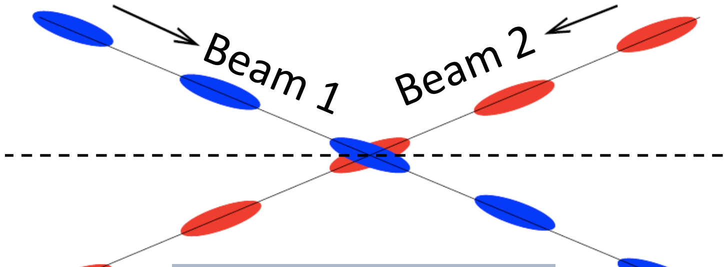
$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$

Reduce the β* (σ)

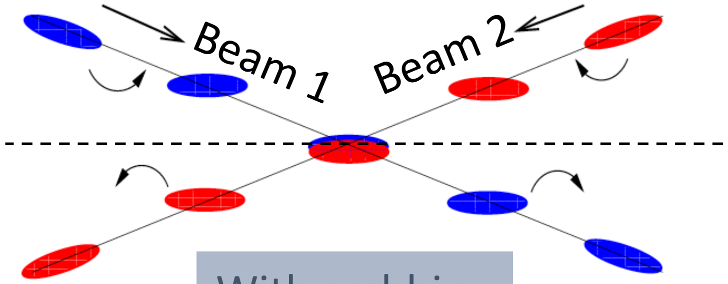
- Stronger focusing around the interaction points

Use crab cavities to reduce the crossing angle effect (s)

- Tilt the bunches to have more head-on collision effect

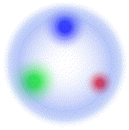


Without crabbing



With crabbing

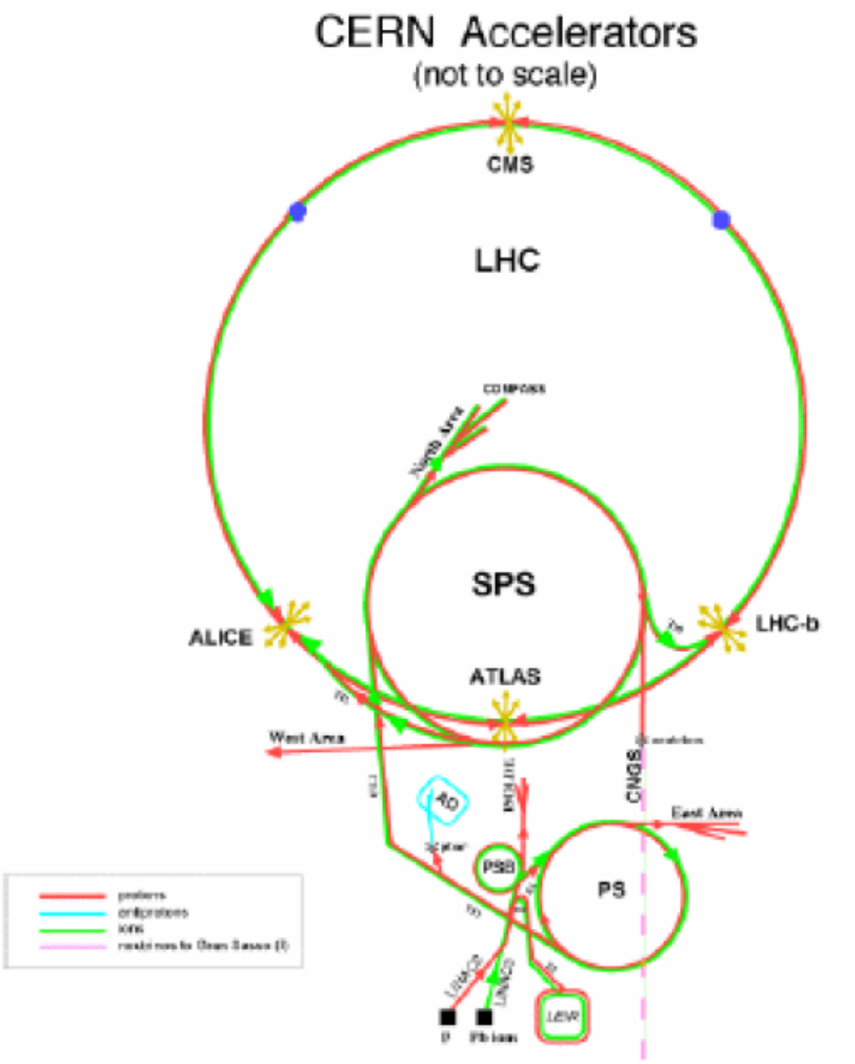
Main parameters: LEP and LHC

	LEP	LHC
Particle type(s)	**e^+** and **e^-** 	**p,** ions (**Pb, Au**) 
Collision energy (E_{cm})	**209 GeV** (max)	p: **14 TeV** at p (~ 2-3 TeV mass reach, depending on physics) Pb: 1150 TeV
Luminosity ($\mathcal{L}$)	Peak: **10^{32} cm^{-2}s^{-1}** Daily avg last years: 10^{31} cm^{-2}s^{-1} Integrated: ~ 1000 pb^{-1} (per experiment)	Peak: **10^{34} cm^{-2}s^{-1}** (IP1 / IP5)

LHC

LHC injector system

- LHC is responsible for accelerating protons from 450 GeV up to 7000 GeV
- 450 GeV protons injected into LHC from the SPS
- PS injects into the SPS
- LINACS injects into the PS
- The protons are generated by a Duoplasmatron Proton Source



Introduction to detector

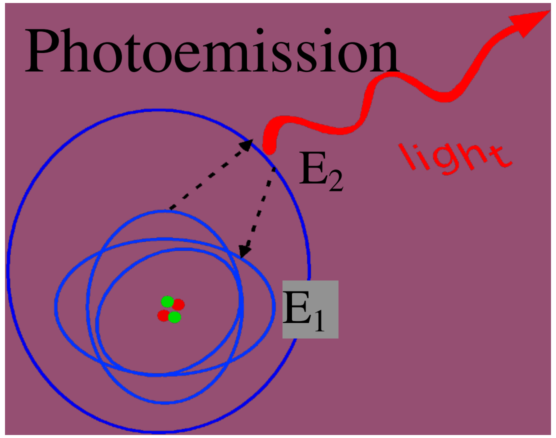
Just to get started…

- **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



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

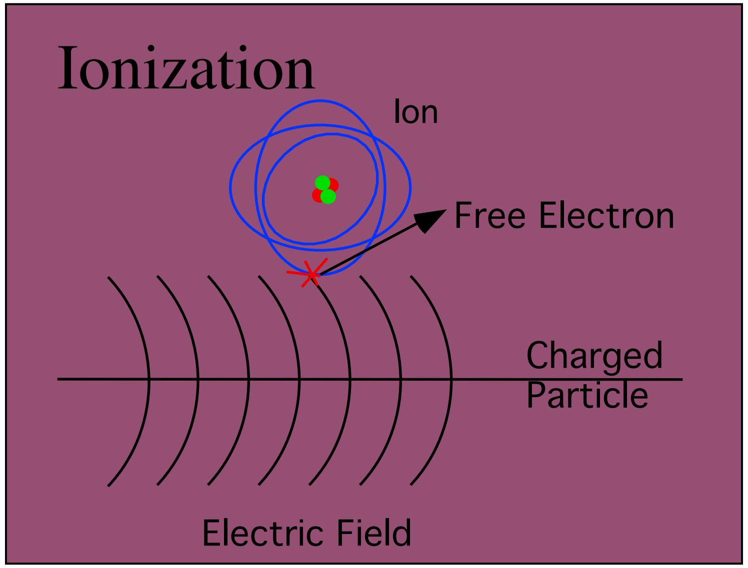
Before:
- **Fast-moving charged particle or photon.**
- **Detector Atom/Molecule, at rest.**

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".



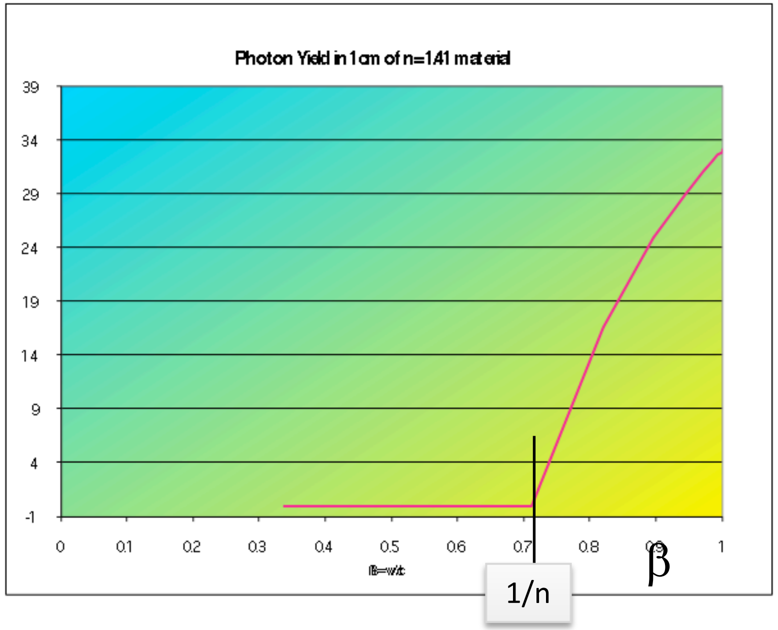
Before:
- **Fast-moving charged particle or photon.**
- **Detector Atom/Molecule, at rest.**

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

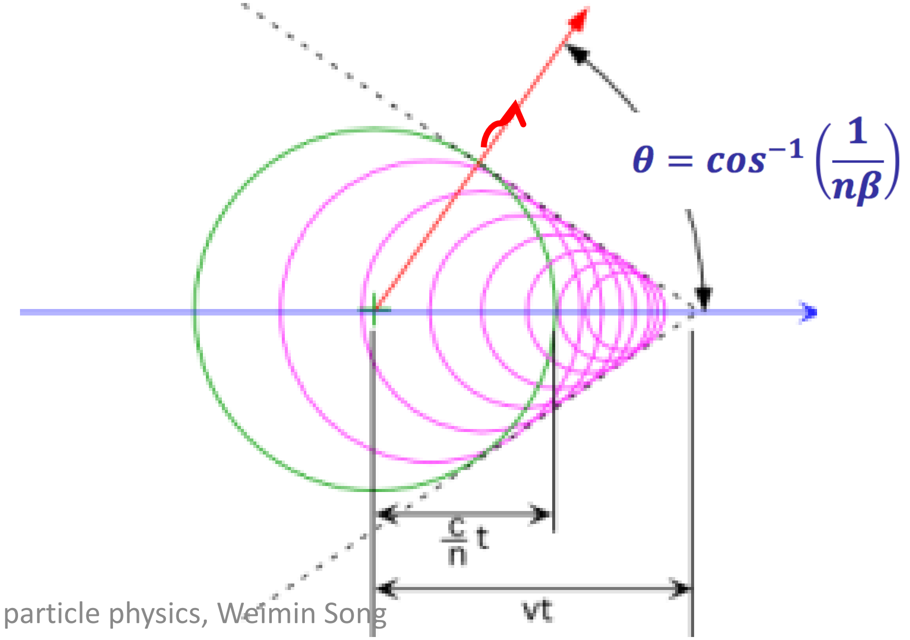
The electric field of a particle may have a long-range interaction with material as it passes through a continuous medium.



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: γ >~ 1000

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

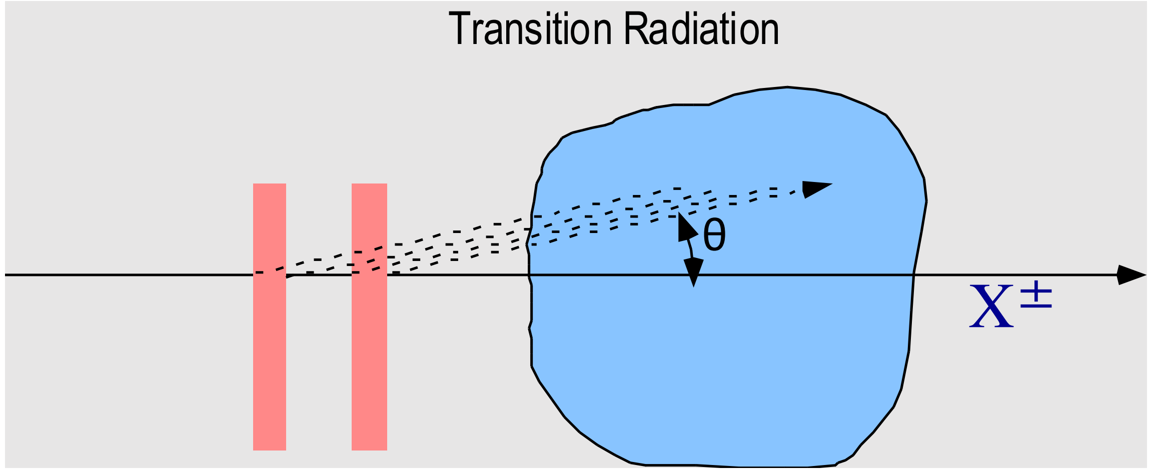
Light is emitted at the angle

$\theta \sim 1/\gamma$

(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 - Effect on the Particle

- For a particle to be detected it must interact with our apparatus.

ACTION = REACTION

- The properties of the particle may be different after we have detected it:
  - Different Momentum (direction)
  - Lower Energy
  - Completely Stopped

In fact, one method of determining a particle's energy is simply to measure how far it goes through a material before coming to rest.

Interactions of Particles with Matter - Effect on the Particle

- Detector: Pavement.
- Signal: skid marks.
- Effect on car: reduced energy; altered momentum.

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.

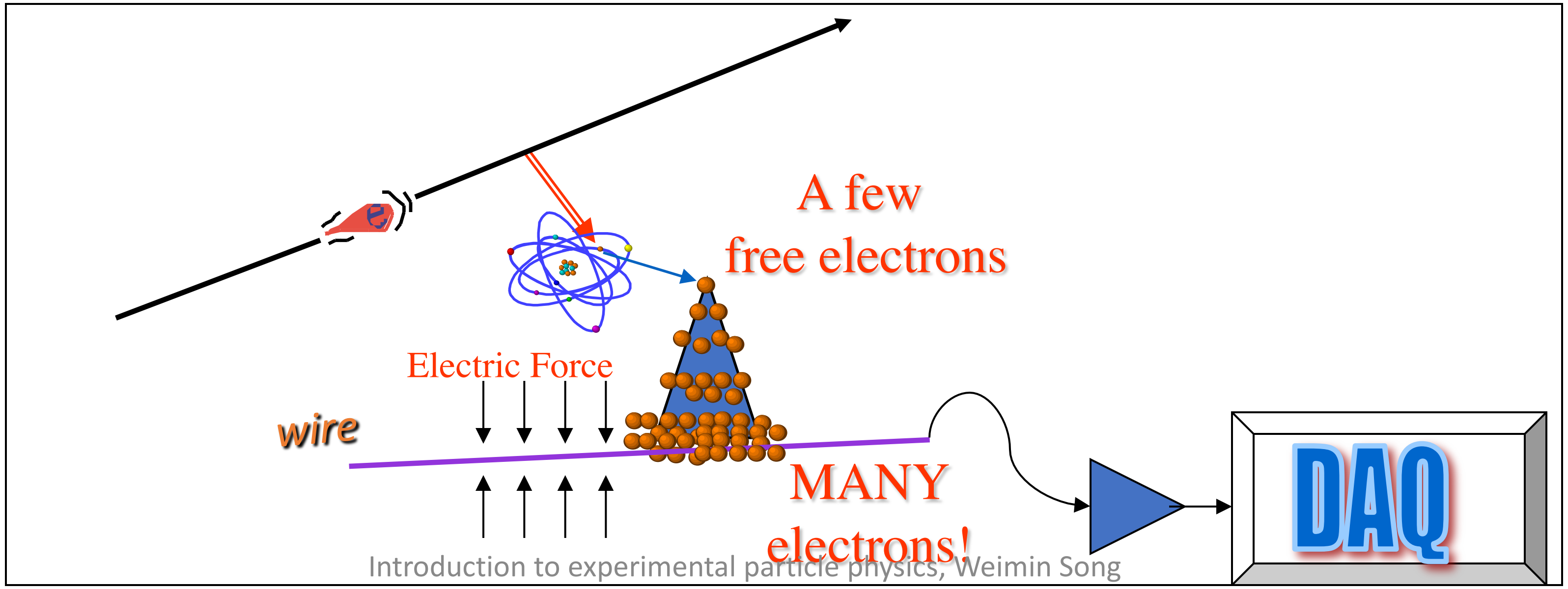
But, typical electronic circuits are sensitive to $\sim 1\mu A = 6.2 \times 10^{12}\ e^{-}/s$ which is >> "a few"

We need to *amplify* the ionization electrons.

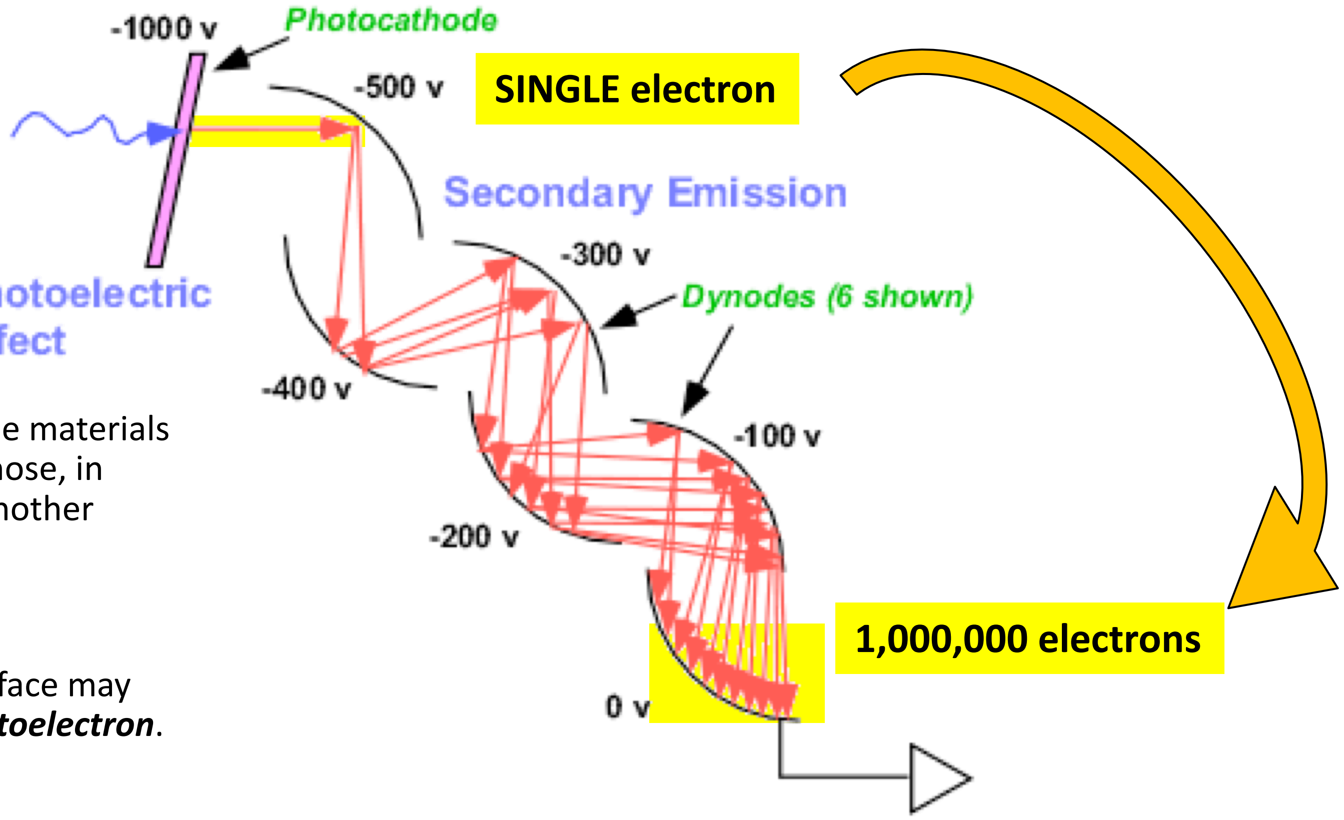
By giving them a *push*, we can make them move fast enough so that they *ionize* other atoms when they collide. *Push* those *new* electrons and each one ionizes *more* atoms, releasing *more* electrons. After this has happened several times we have a sizeable free charge that can be sensed by an electronic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

Particle Detectors: Avalanche Multiplication in a Gas

- **Avalanche Gain**
  - **Electric Field accelerates electrons, giving them enough energy to cause another ionization. Then those electrons do it again...**
  - **In the end we have enough electrons to provide a large electric current... detectable by sensitive electronics.**



Particle Detectors: Avalanche Multiplication on Metal Surface



Secondary Emission

- Energetic electrons striking some materials can liberate MORE electrons. Those, in turn, can be accelerated onto another surface … and so on.

Photoelectric Effect

- A photon striking a material surface may liberate a single electron: a ***photoelectron***.

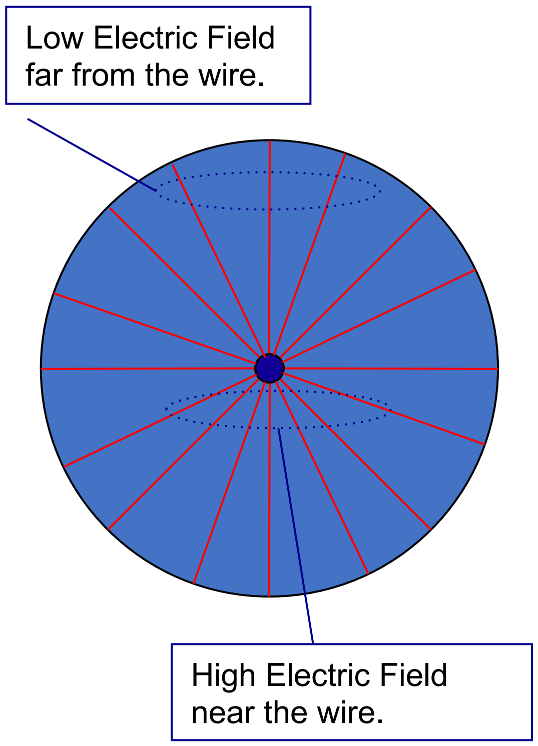
Photomultiplier Tube (PMT)

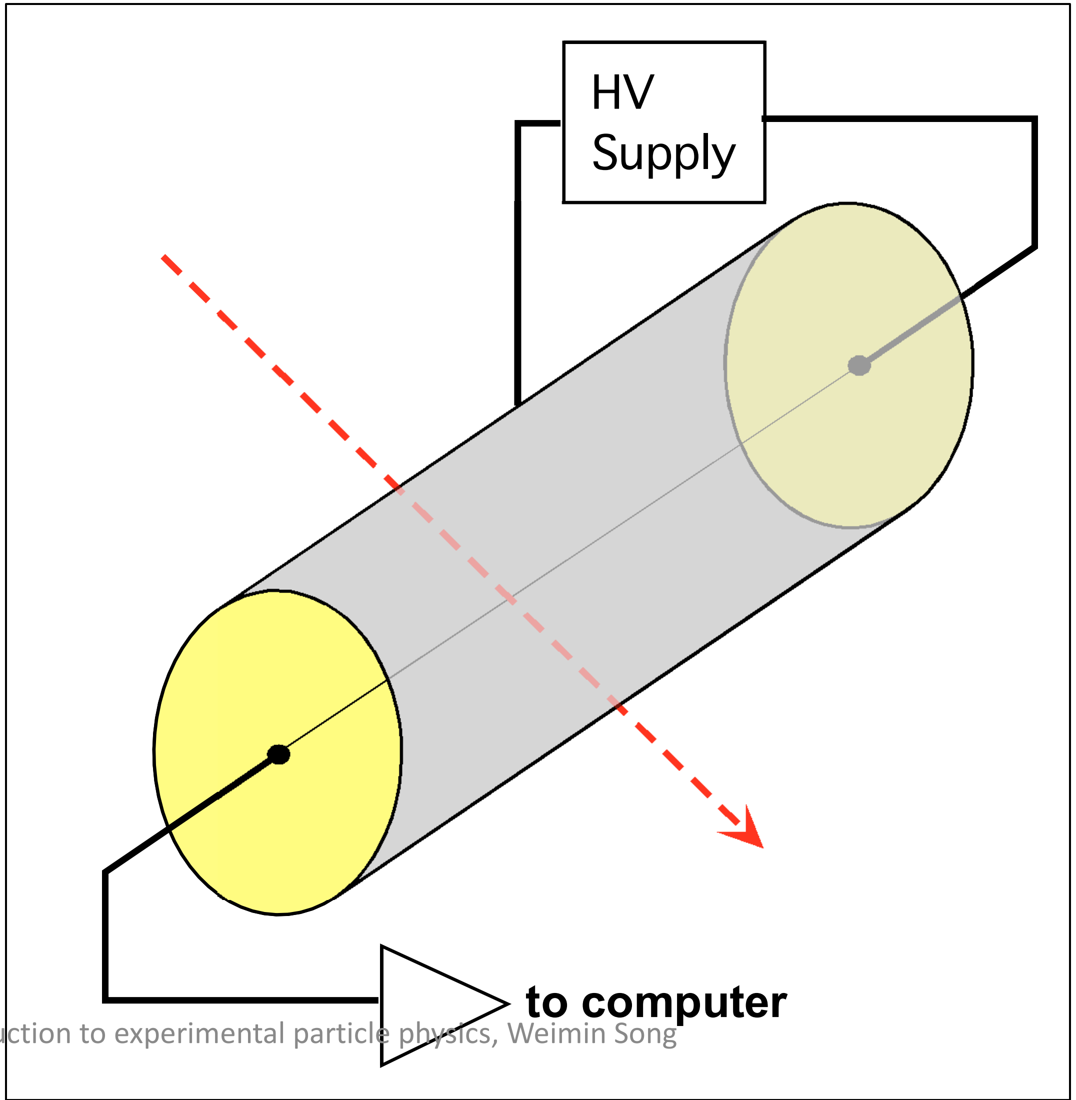
Particle Detectors: Gas Filled Wire Chamber

Let's use *Ionization* and *Avalanche Multiplication in Gas* to build a detector…

- Make a Box.
- Fill it with some gas: noble gases are more likely to ionize than others. Use Argon.
- Insert conducting surfaces to make an intense electric field: The field at the surface of a small wire gets extremely high, so use tiny wires.
- Attach electronics and apply high voltage.
- We' re done!!

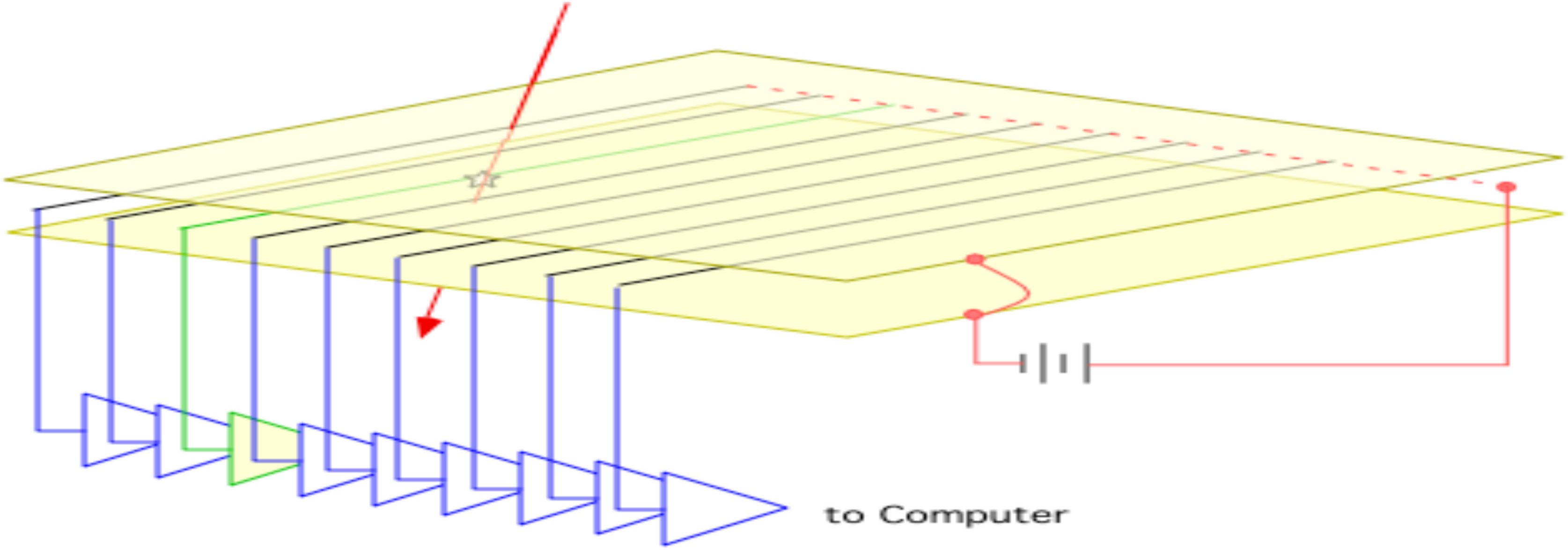
Particle Detectors: A Single-wire Gas Chamber





Particle Detectors: Multi-Wire Gas Chamber

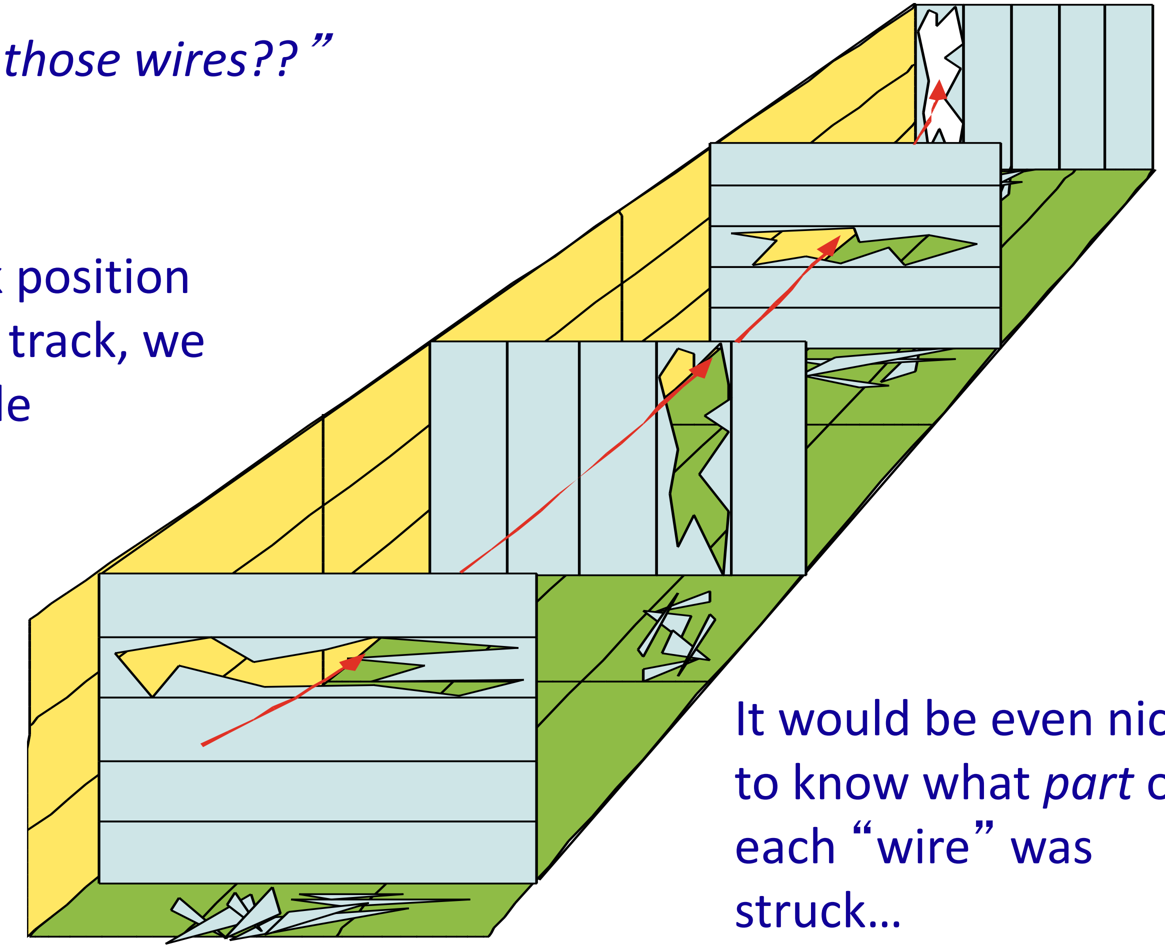
- Multiwire Chamber:
  - WHICH WIRE WAS NEAREST TO THE TRACK?



Particle Detectors: tracking

"Why does he want all those wires??"

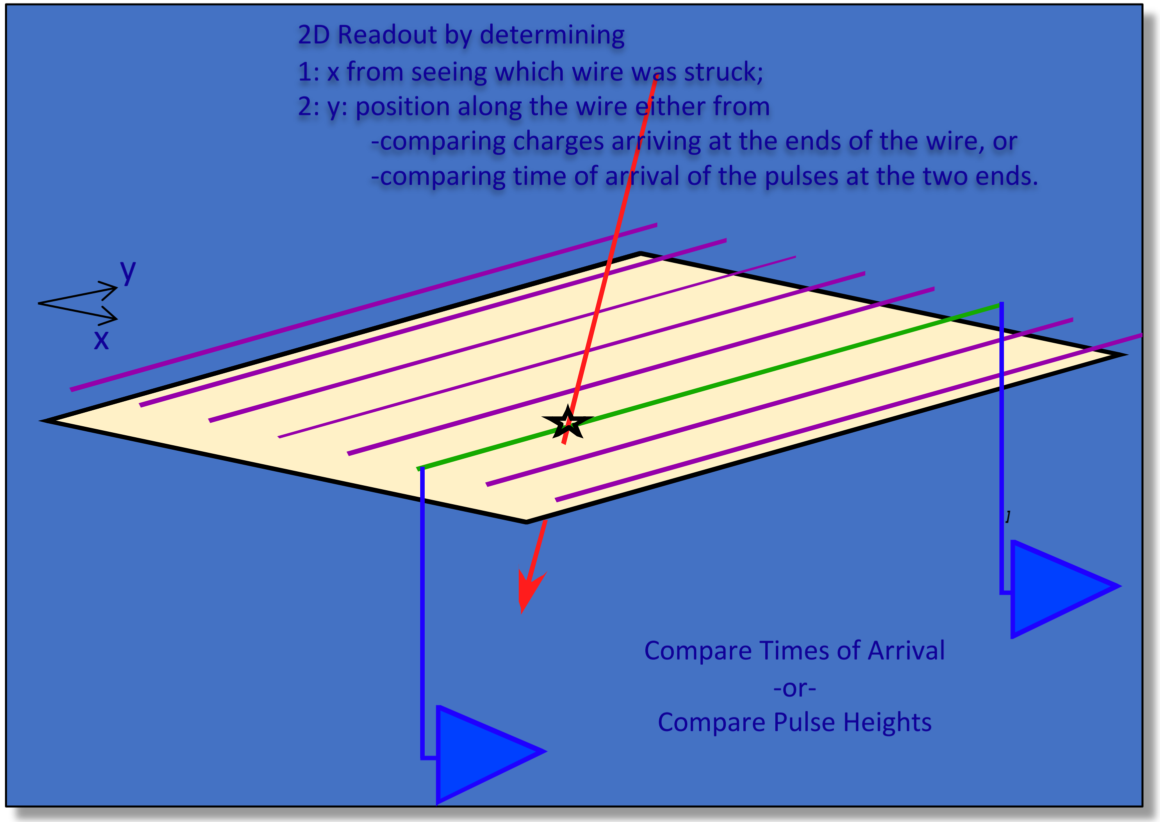
If we make several measurements of track position along the length of the track, we can figure out the whole trajectory.



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…

Particle Detectors: higher resolution tracking

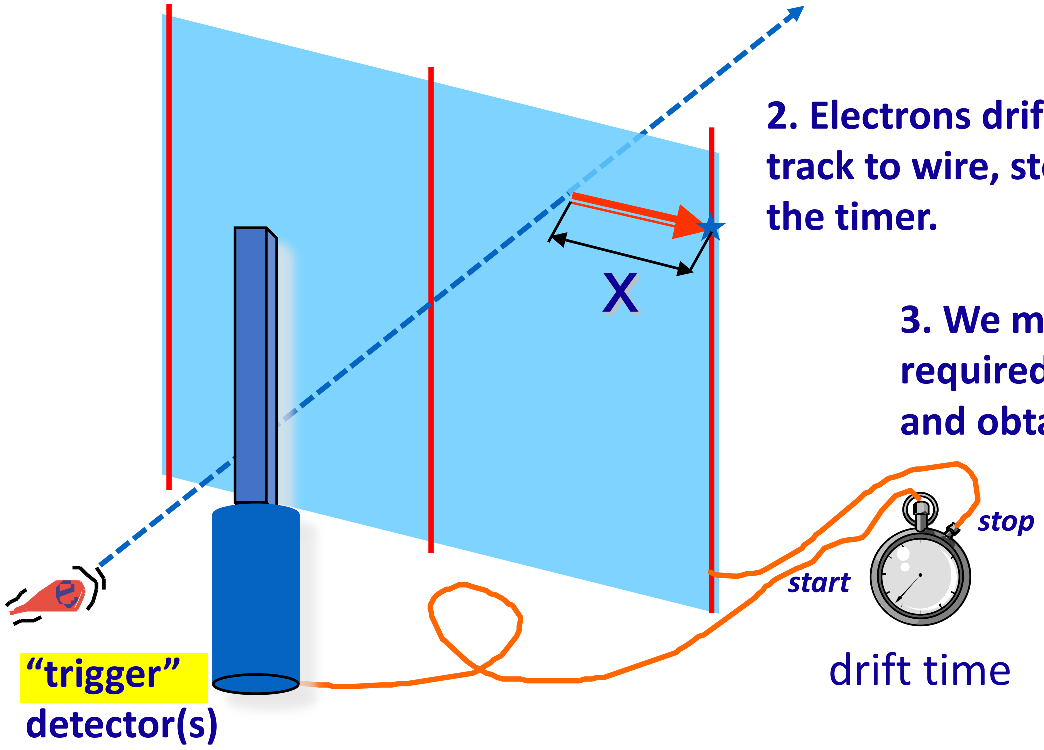
Drift Chambers…

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.

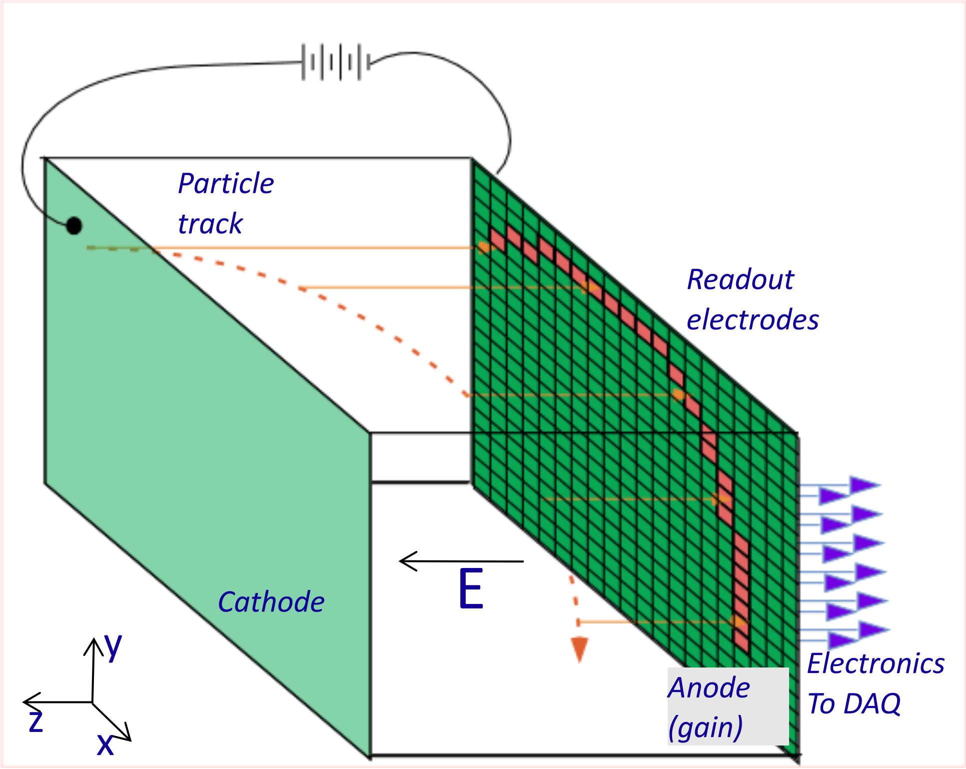
3. We measure the time required to drift to the wire and obtain the distance X.



Particle Detectors: TPC, 3D position information

Time Projection Chamber (TPC): Drift through a <u>Volume</u>

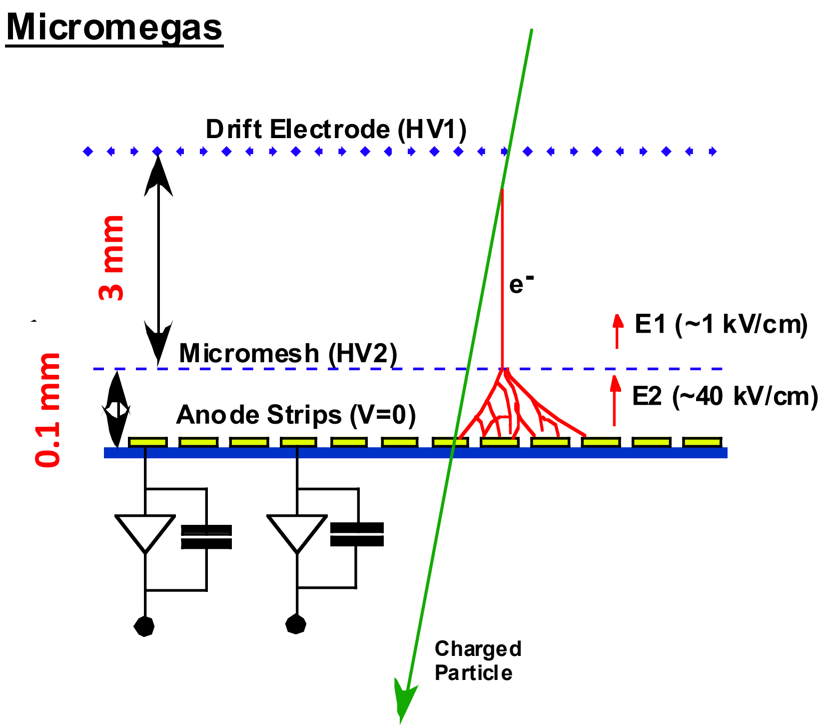
- Just a box of gas with
  - Electric Field and
  - Readout Electrodes
- Readout elements only on one surface.
- Ionization Electrons drift to Surface for
  - Amplification
  - Charge Collection
- Readout Electrode Position gives (x,y)
- Time of Arrival gives (z).



Other ways to get avalanche gain: Micromegas

- **Gas *Ionization* and *Avalanche Multiplication* again, but…**
  - **… a different way to get an intense electric field,**
  - **… no tiny wires,**
  - **… a monolithic structure.**

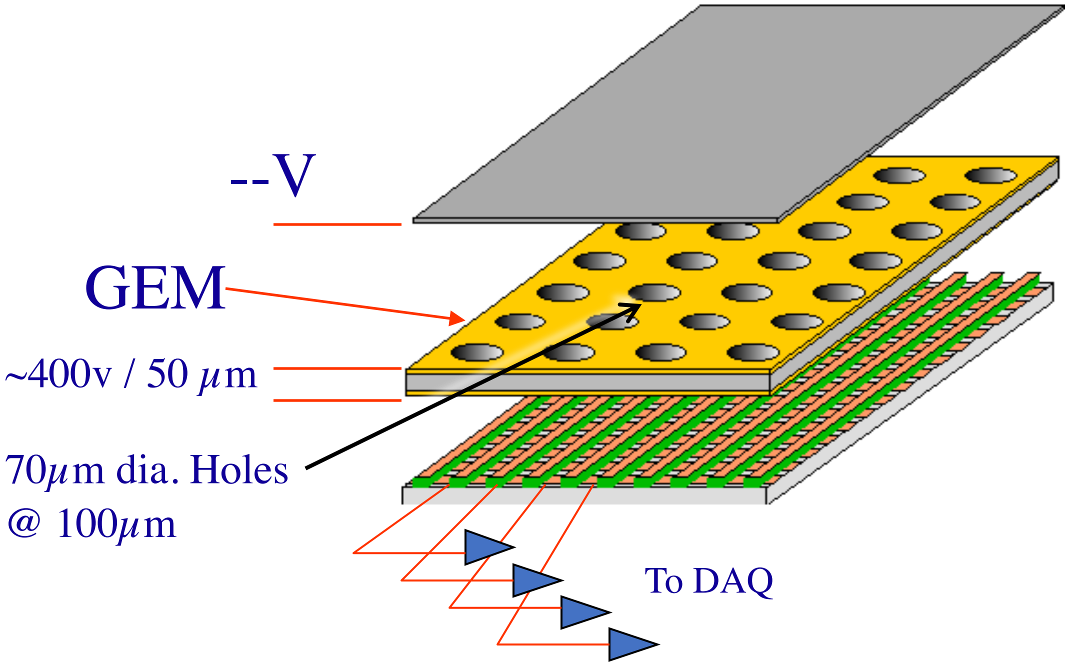
<u>Micro</u> (small)
<u>Mesh</u>
<u>Gas</u> (sensitive medium)

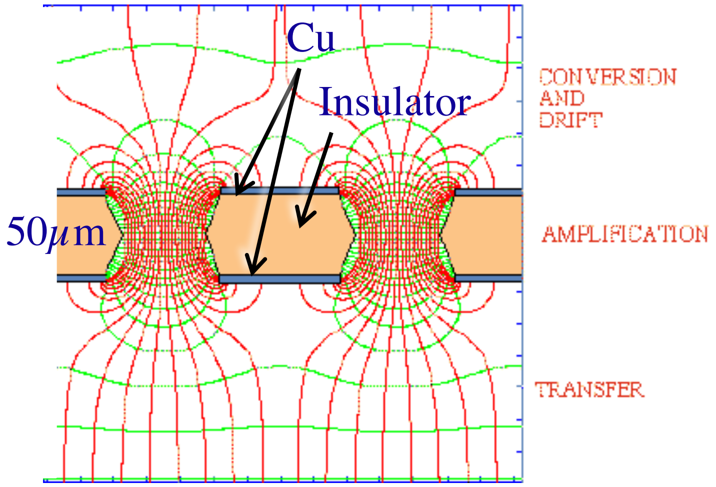


Y. Giomataris, Ph. Rebourgeard, J.P. Robert, and G. Charpak, NIM A376 (1996) 29

Other ways to get avalanche gain: GEM

- **Gas Electron Multipliers**
  - … yet another way to get an intense electric field,
  - … isolates electronics from high-field region.





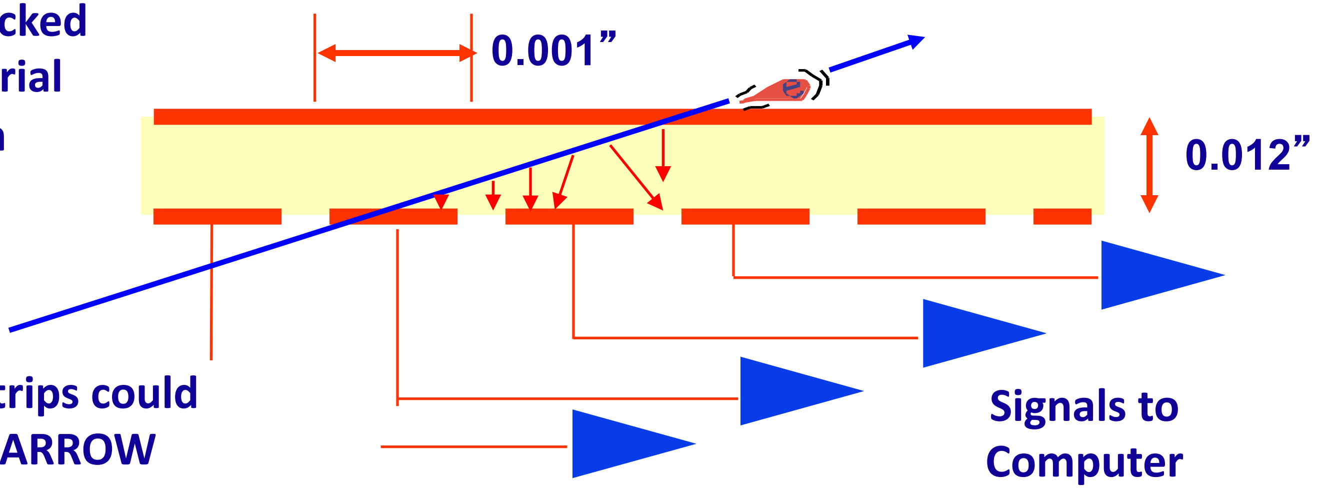
http://gdd.web.cern.ch/GDD/

Particle Detectors: Ionization Detectors

- **Ionization Chambers:** **<u>Dense Material => Lots of Charge. Typically no Amplification</u>**
  - **Solid Semiconductor**
    - **Silicon**
    - **Diamond**

    Strips
    Pixels
    Drift
  - **Noble Liquid**
    - **Liquid Argon Calorimeter**

Electrons are knocked loose in the material and drift through it to electronics.



Readout strips could be VERY NARROW

Particle Detectors: Using the Light

Enough of Ionization!

What about Detectors that use the produced light?

- Scintillators
- Cerenkov Counters

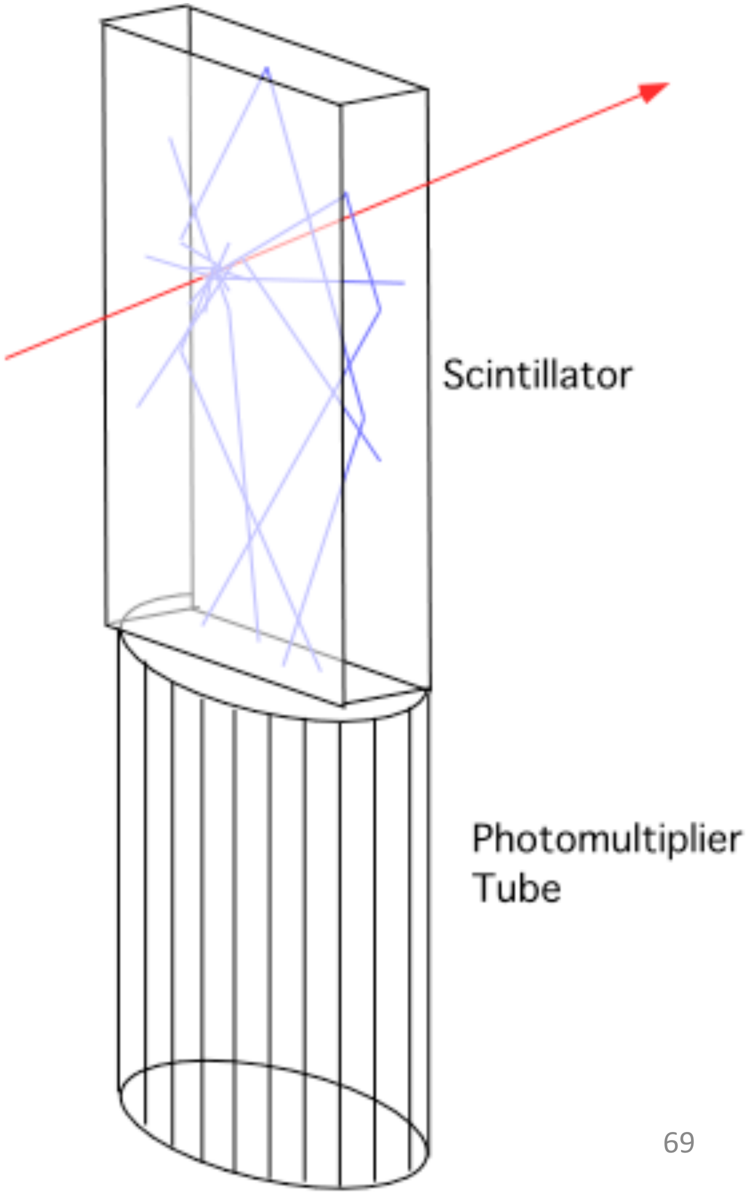
Photo-sensors

Particle Detectors using the Light: Scintillators

Materials that are good at emitting light when traversed by energetic particles are called **SCINTILLATORS**.

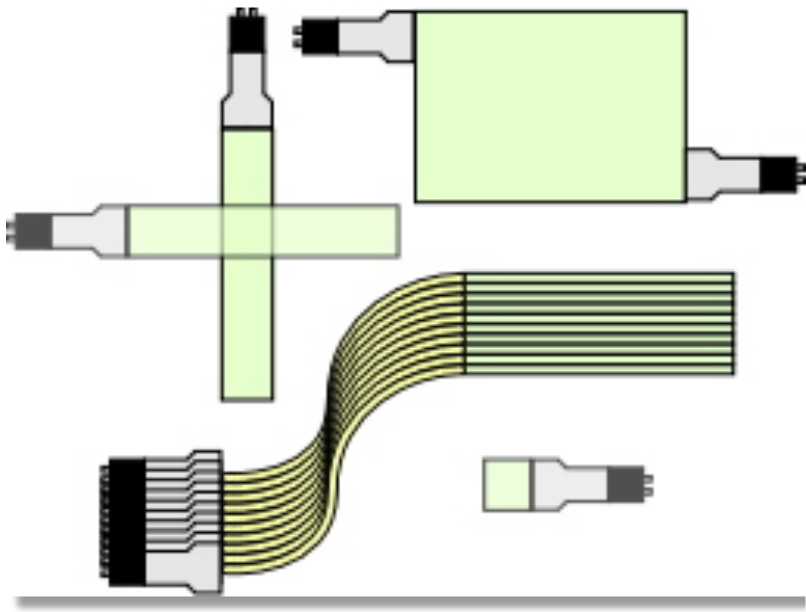
Many materials radiate light, but most also absorb that light so that it never gets out.

Scintillation Counters are probably the most widely used detectors in Nuclear and High Energy Physics.



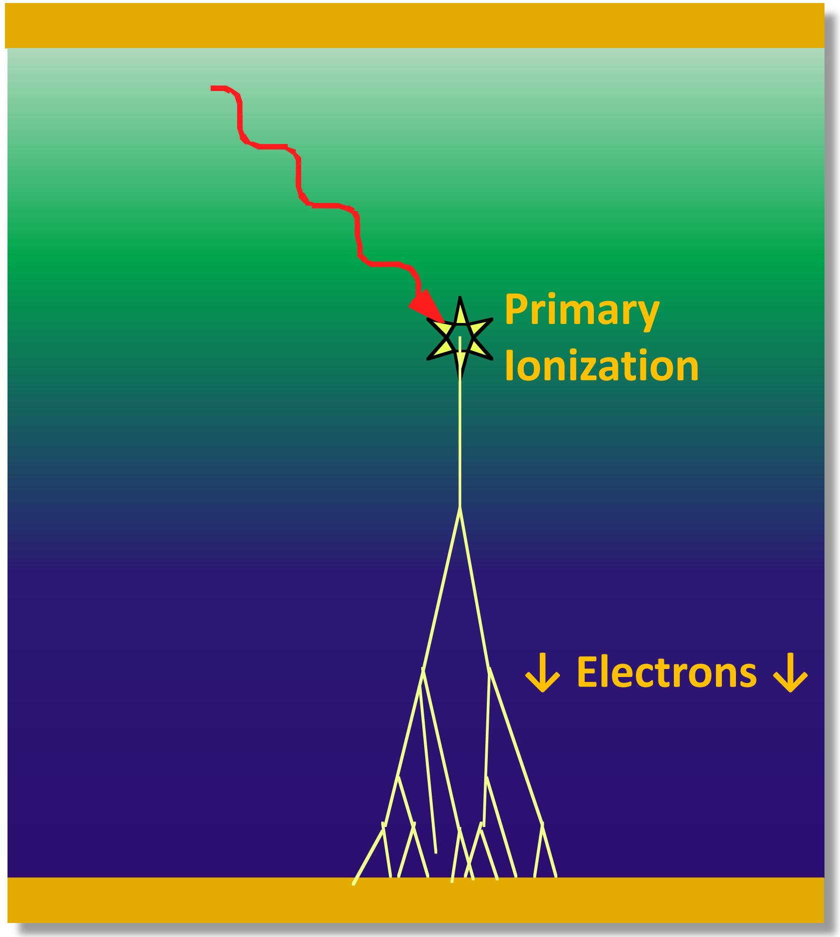
Particle Detectors using the Light: Scintillator Uses

- **Scintillation Counter Uses**
  - Timing and Triggering
    - Paddles or Sheets
  - Tracking
    - Paddles or Strips
    - Fibers
  - Calorimetry & Particle ID
- Each one consists of a piece of scintillating material optically coupled to a light-sensitive transducer.



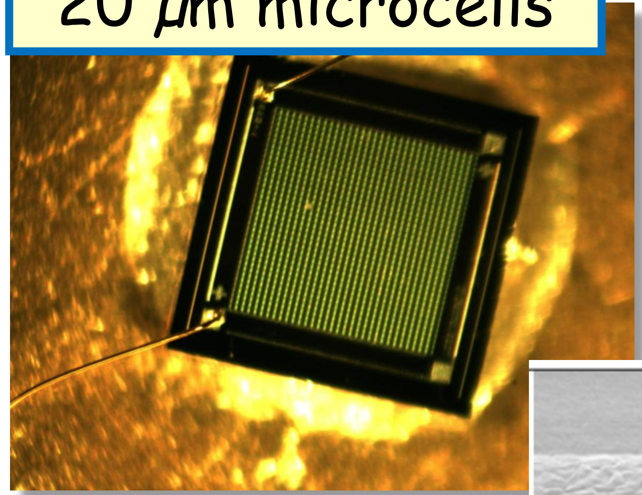
Types of Photon Sensors: Avalanche Photo-Diode (APD)

- **Ionization in a silicon lattice produces electron/hole pairs.**
- **If they are accelerated in an E-field, they avalanche.**
- **At modest field strength APD's provide stable gain ~100. This is the "linear mode".**
- **At higher fields, above the "breakdown voltage", both the <u>electrons</u> and the <u>holes</u> become important.**
  - The gain can be very large, but the device deadtime may be too long.



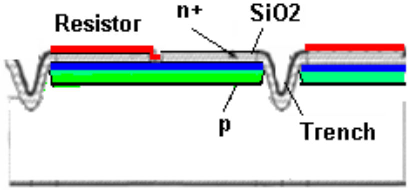
Types of Photon Sensors: Silicon Photomultiplier (SiPM)

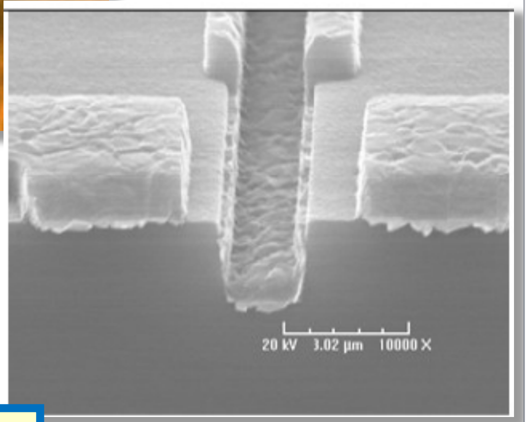
20 μm microcells



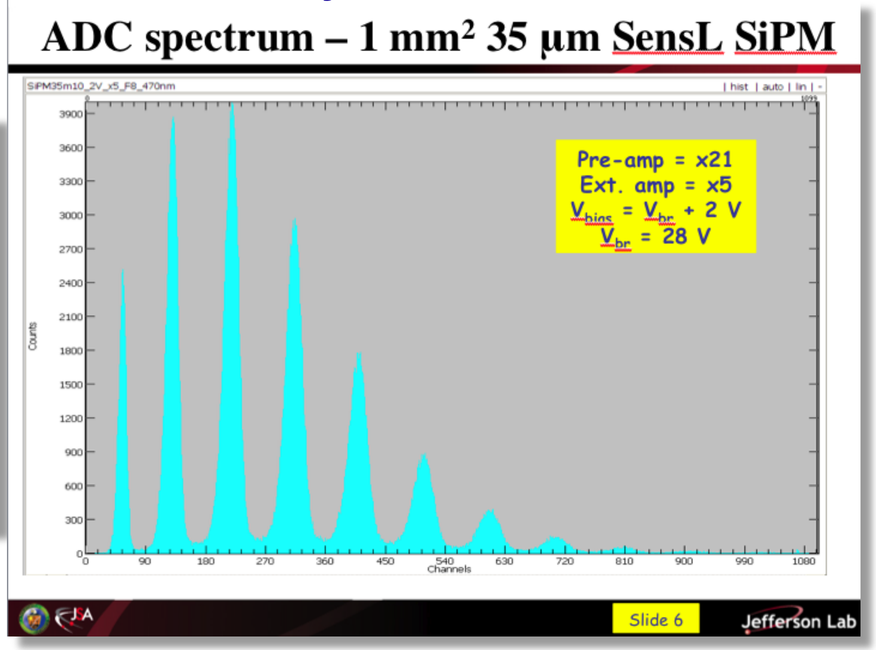
Array of many tiny APD's. Each one operates ~independently of the rest.

Even though some of the APD pixels may be busy recharging, the others are ready to detect new photons.





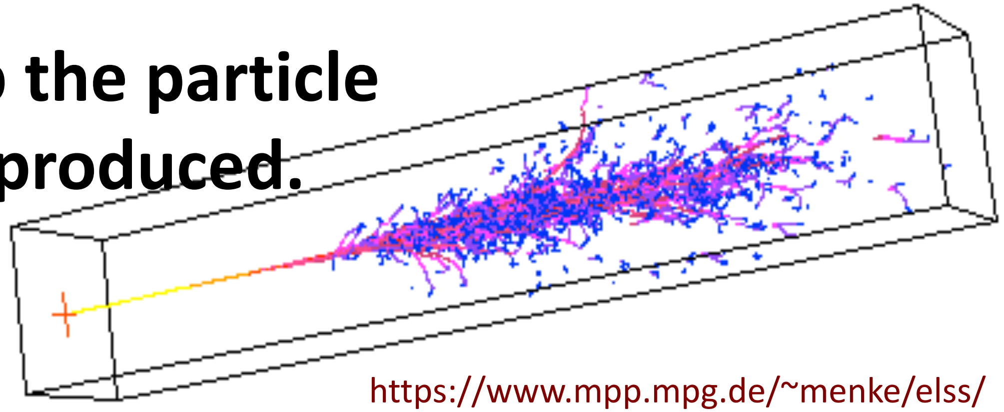
Trench to block photon crosstalk



Calorimetry – Measuring Energy: Light-Collecting Calorimeter

Energy Measurement - stop the particle and collect the light that is produced.

- **Large Blocks or**
- **Large Volumes of Liquid**



https://www.mpp.mpg.de/~menke/elss/

If we **STOP** the particle in a **SCINTILLATOR** or in a block of **LEAD_GLASS**, then the **AMOUNT** of light detected provides a measure of the total **ENERGY** that the particle had. This detector is a **CALORIMETER**.

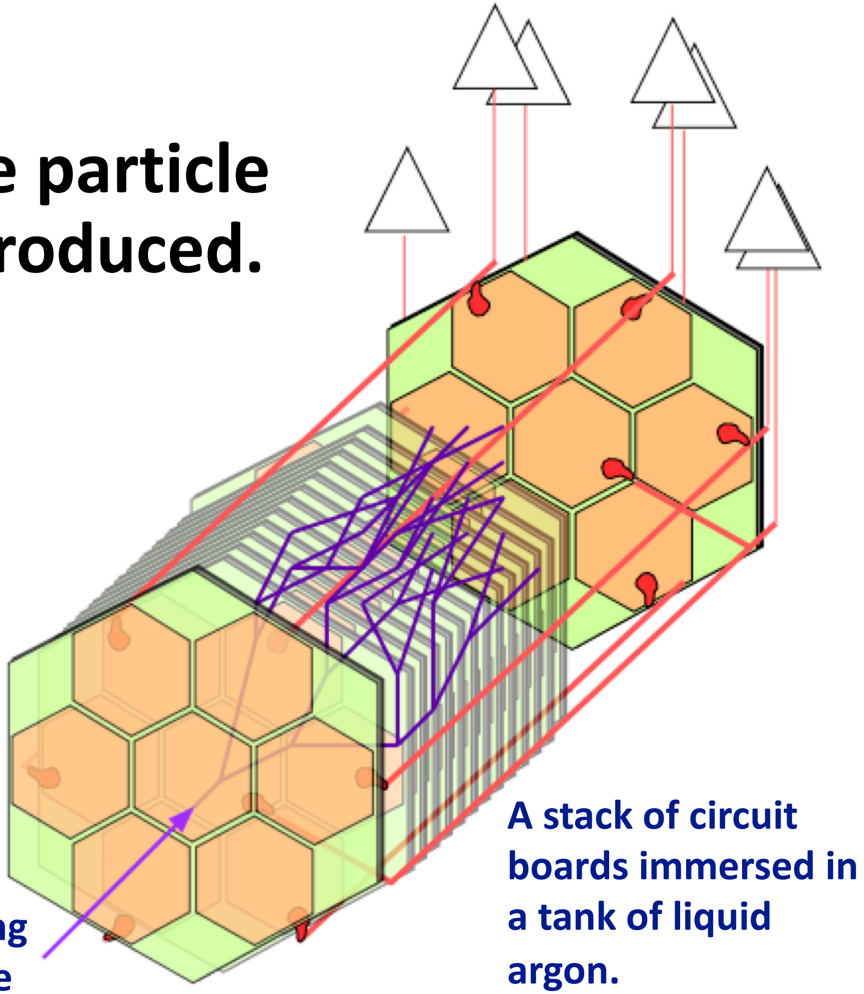
NOTE: light is produced in **LEAD_GLASS** *by the Cerenkov Effect, not by scintillation.*

Calorimetry – Measuring Energy: Ionization Calorimeter

Energy Measurement - stop the particle and collect the charge that is produced.

- **Liquid Argon or similar**

Charged particle shower ionizes the liquid. Electrons/ions are collected on the nearby electrodes.



Particle Detectors…

- That's it! Those are (most of) the Detector Tools!
  - Gas Ionization Chambers
    - Single Wire
    - Multi-Wire
    - Drift, TPC, etc.
  - Solid State Detectors
  - Scintillators
  - Cerenkov Counters
  - Calorimeters

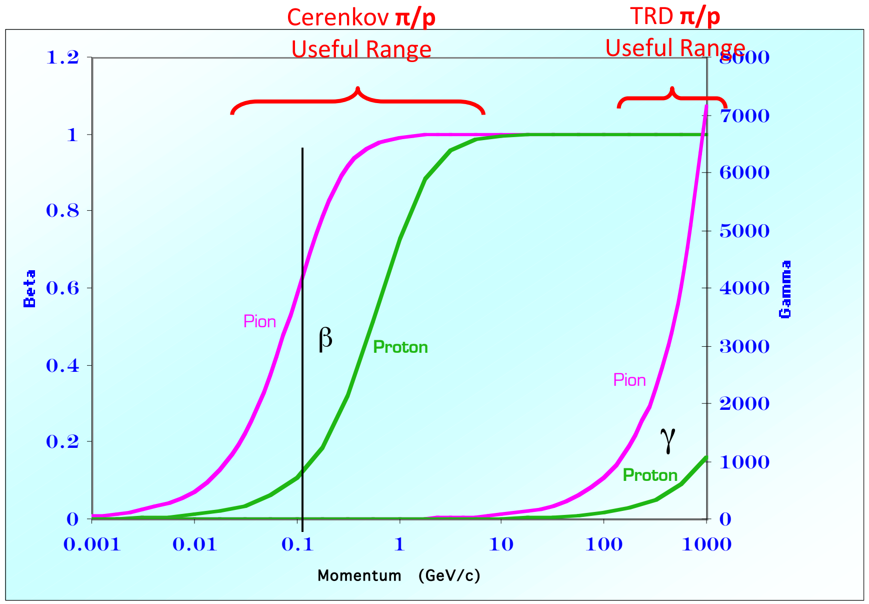
Particle Identification

Cerenkov and **Transition Radiation Detectors** are used primarily for **Particle Identification.**

- At fixed momentum, Heavy particles radiate less than Low-mass particles.
- The angular distribution of radiation varies with particle speed.

Cerenkov Counters – sensitive to β

$$\beta = \frac{v}{c} = \frac{p}{E} = \frac{p}{\sqrt{m^2 + p^2}}$$



Momentum (GeV/c)

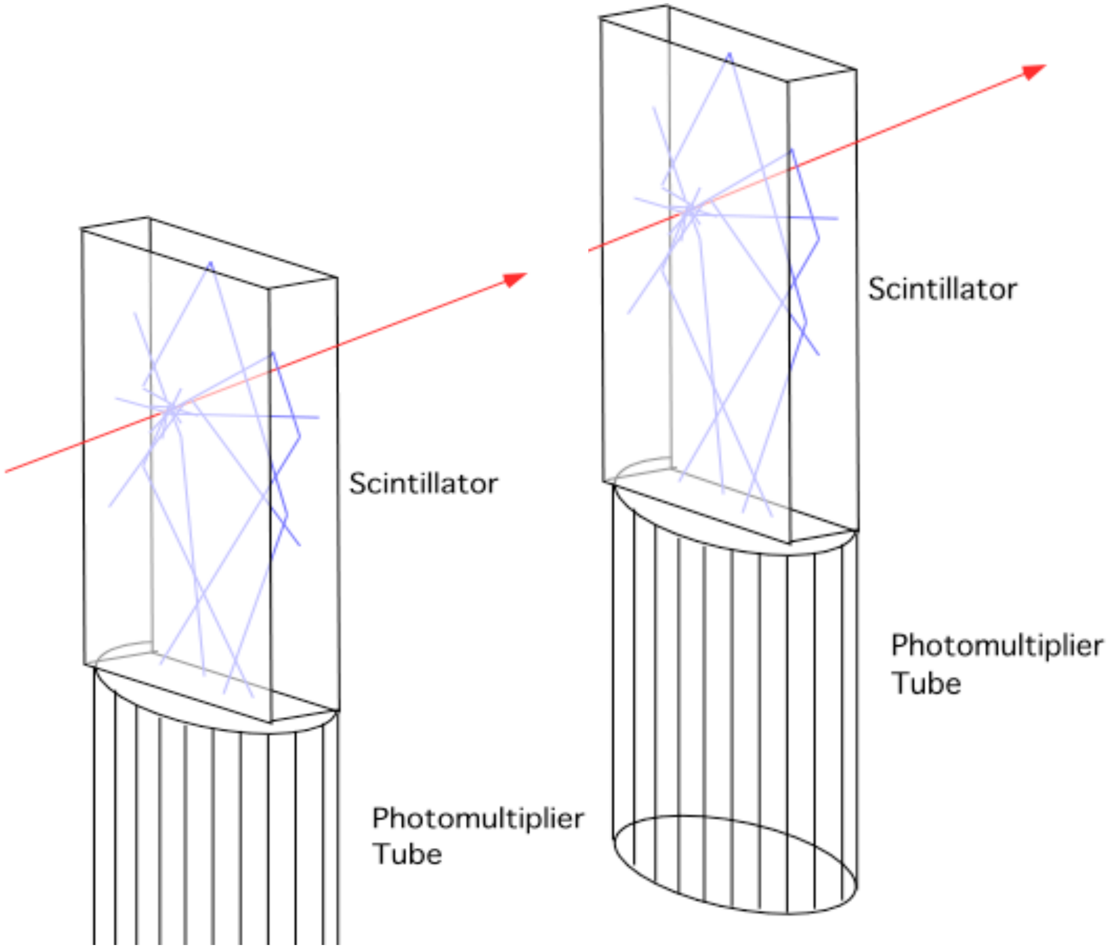
TRD Counters – sensitive to γ

$$\gamma = (1 - \beta^2)^{-1/2} = E/m = \frac{\sqrt{m^2 + p^2}}{m}$$

Particle Identification: Time of Flight

77The most straightforward way to measure particle speed is to *time* it:

A Time-of-Flight (TOF) Counter



Knowing the separation of the scintillators and measuring the difference in arrival time of the signals gives us the particle speed.

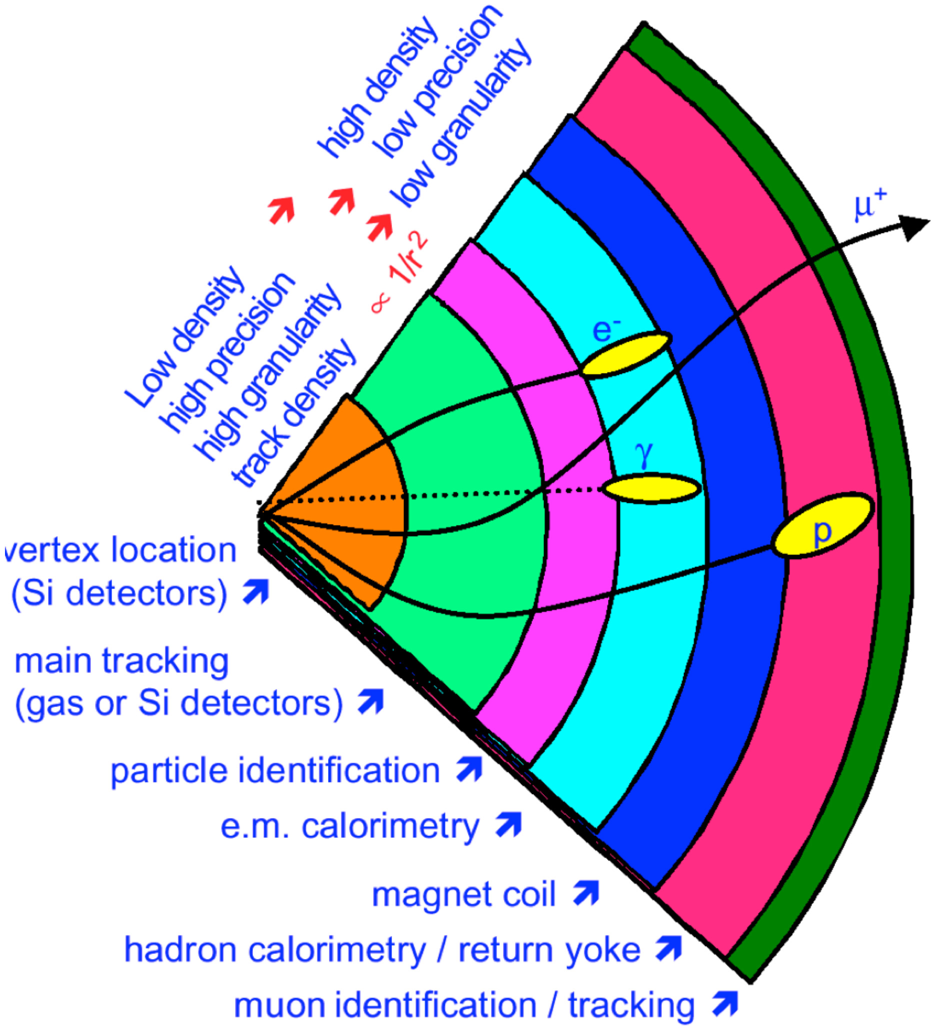
Detector configuration

Various detectors and combination of information can provide particle identification:

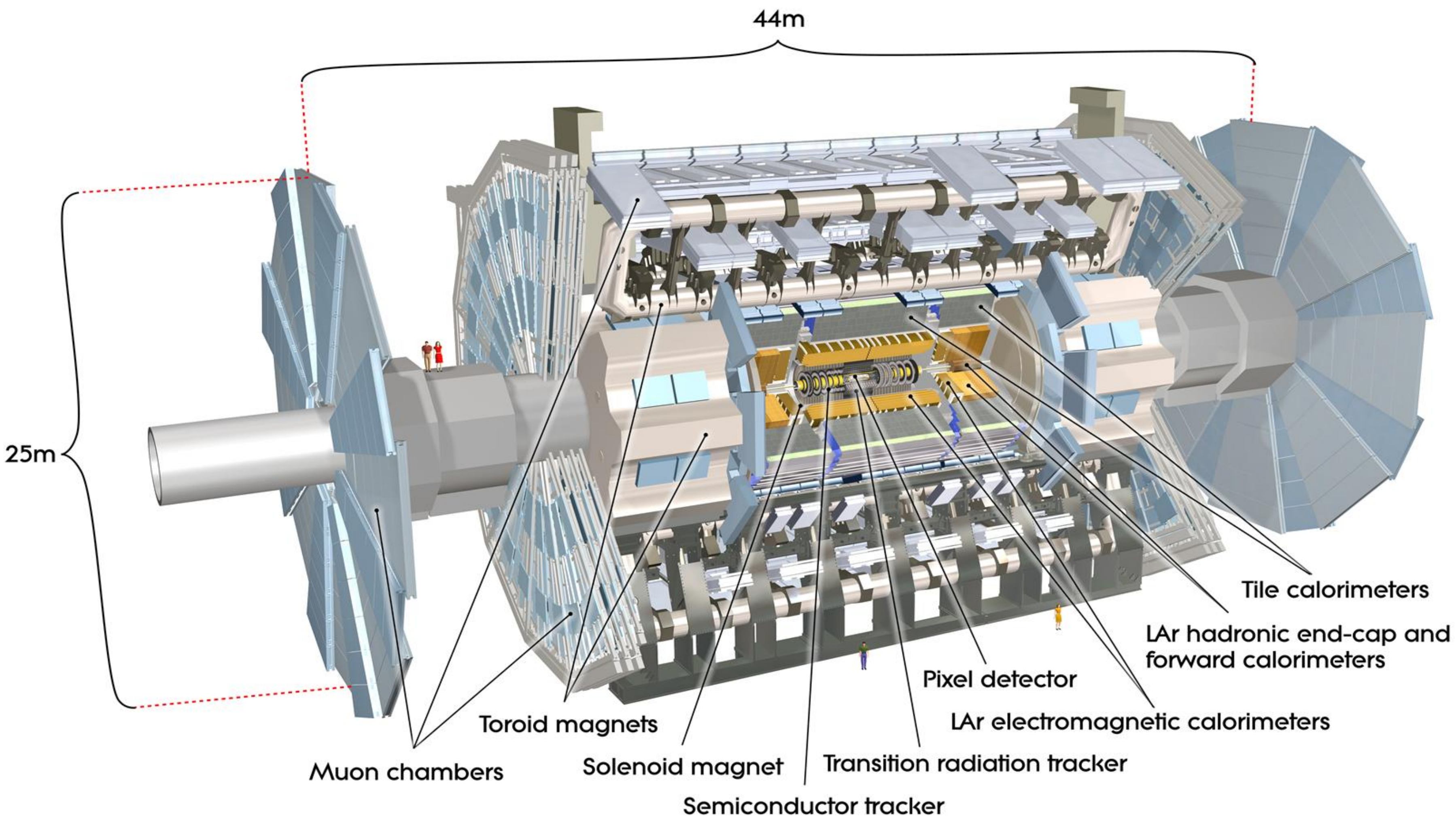
Momentum versus EM energy for electrons, EM/HAD provide additional information. Only muons reach the outer detectors.

EM response without tracks indicate a photon.

Secondary vertices identify b,c, τ's. Isolation cuts help to identify leptons



Detector system example: ATLAS

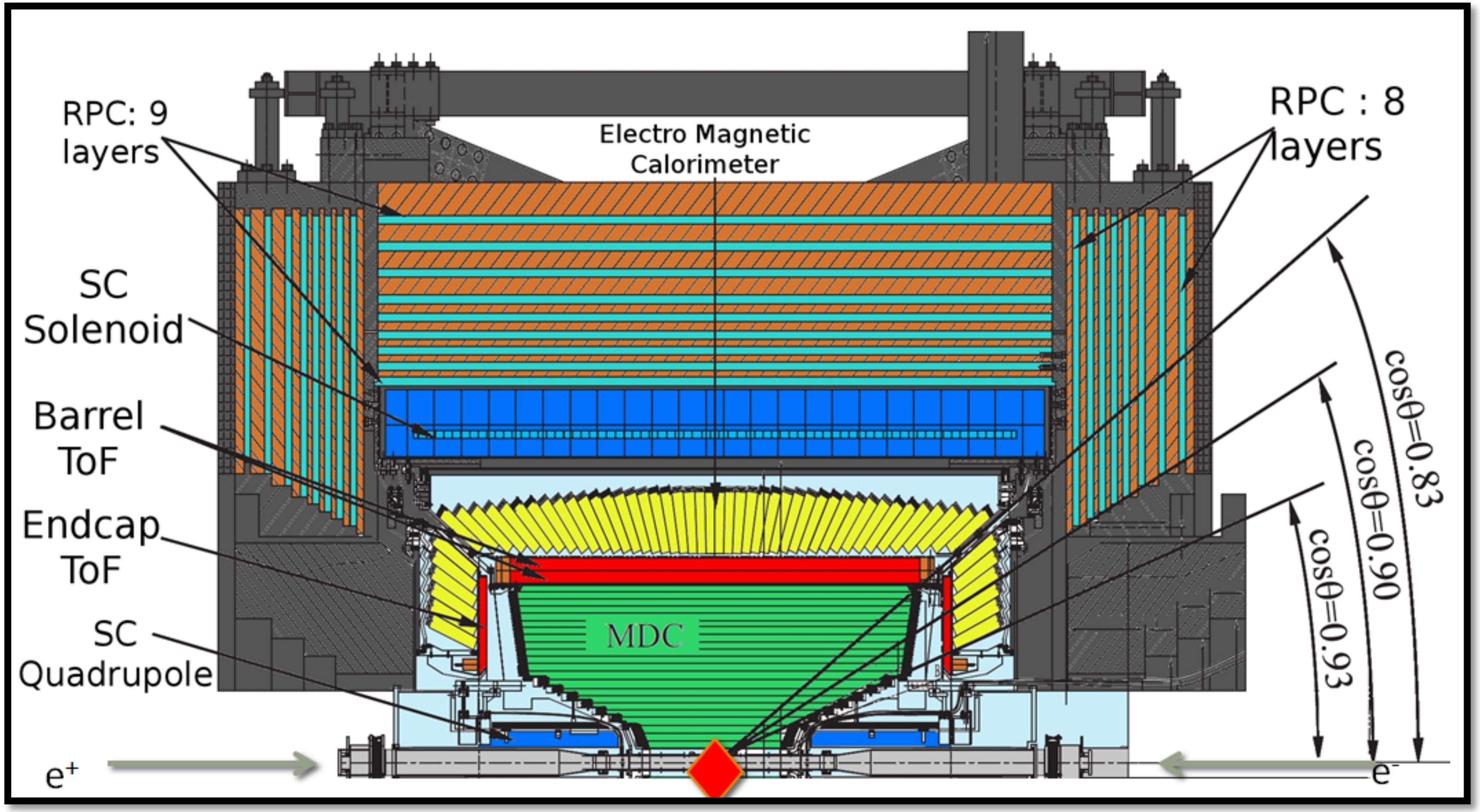


The results from BESIII and how they help to solve the problems

Upgraded Beijing Electron Positron Collider (BEPCII)

Beam energy:
1-2.3 GeV
(This year will try to reach 2.35 GeV)
Design luminosity:
$1\times10^{33}\ cm^{-2}s^{-1}$
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



>500 Members from 72 institutions in 15 countries!

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:

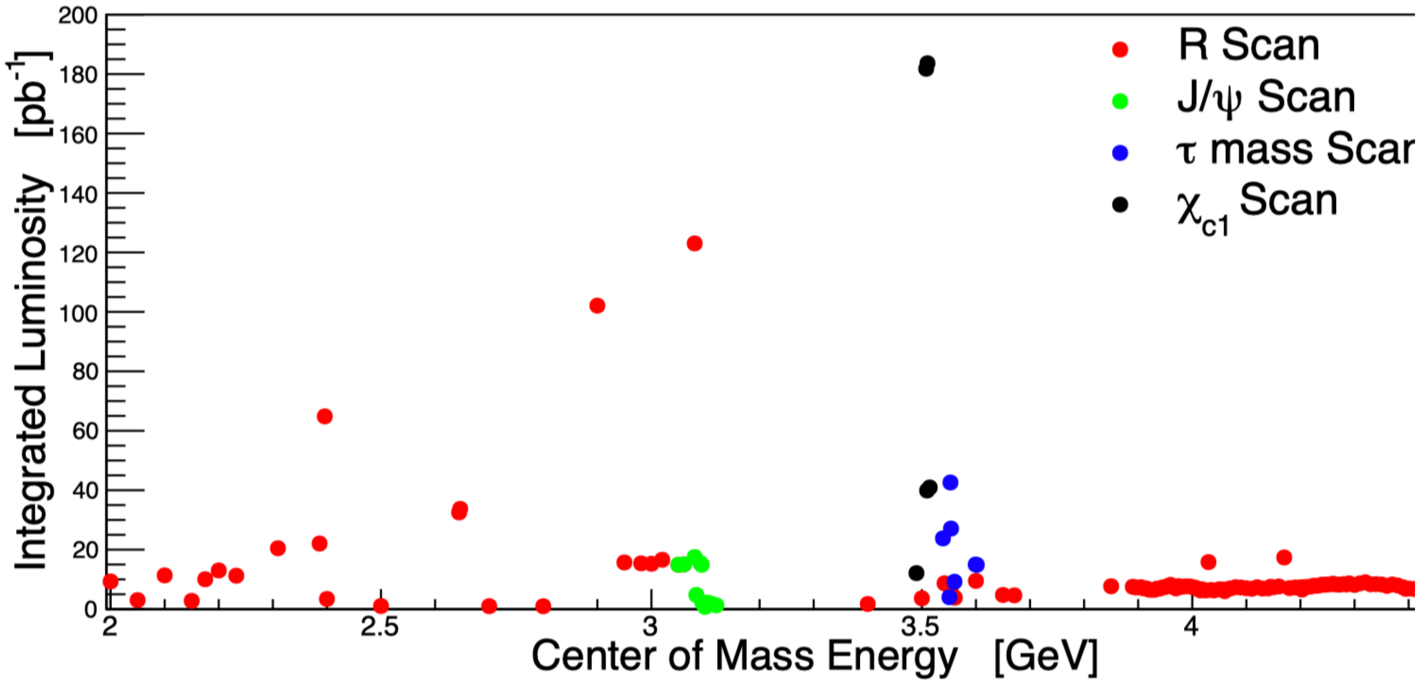
- precision spectroscopy
- transitions and decays
- charmoniumlike states

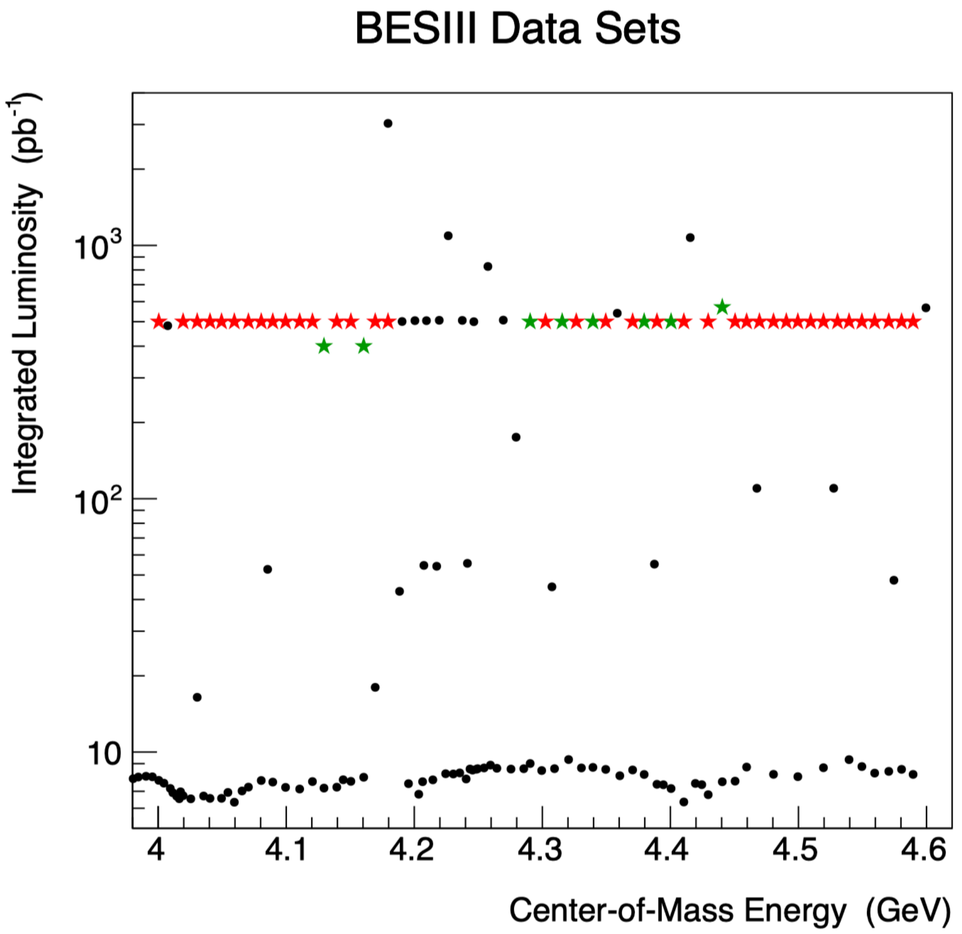
QCD & τ-physics:

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

QCD
New Physics

BESIII data samples





10 B J/ψ
0.45 B $\psi(3686)$
2.9 fb^{-1} $\psi(3770)$

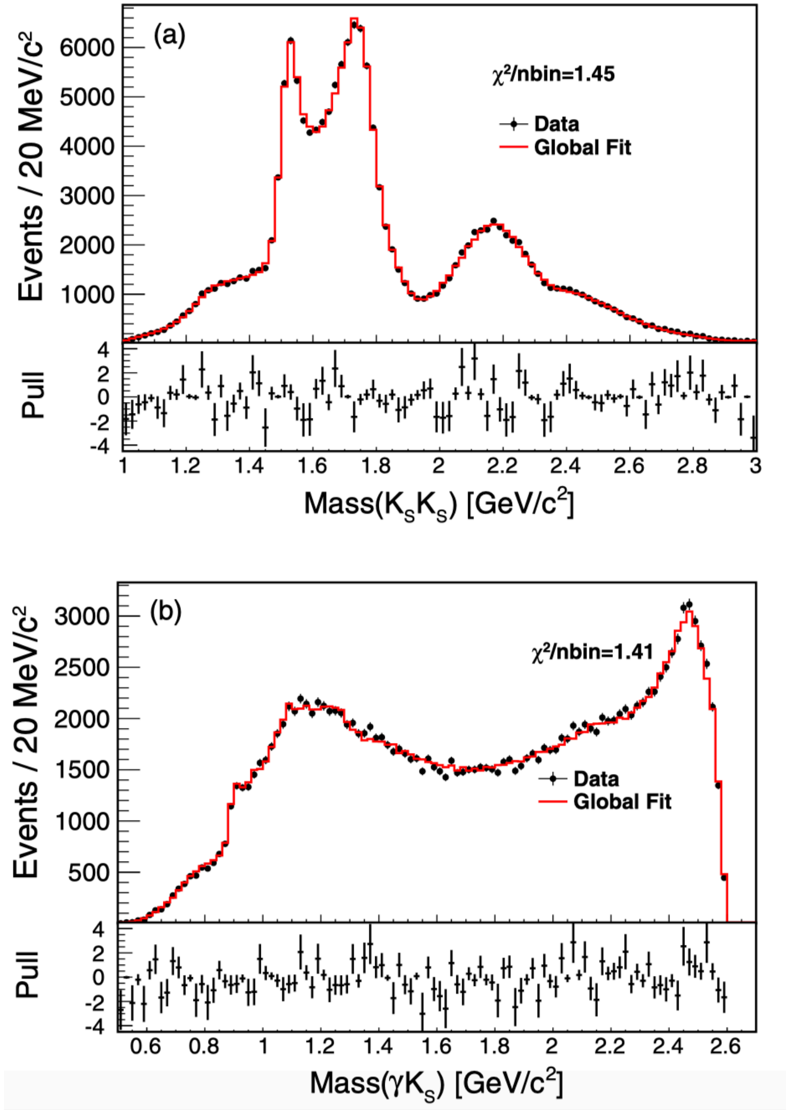
BESIII publications

There are more than 60 publications in 2019!

Light hadron physics

PRD 98, 072003

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



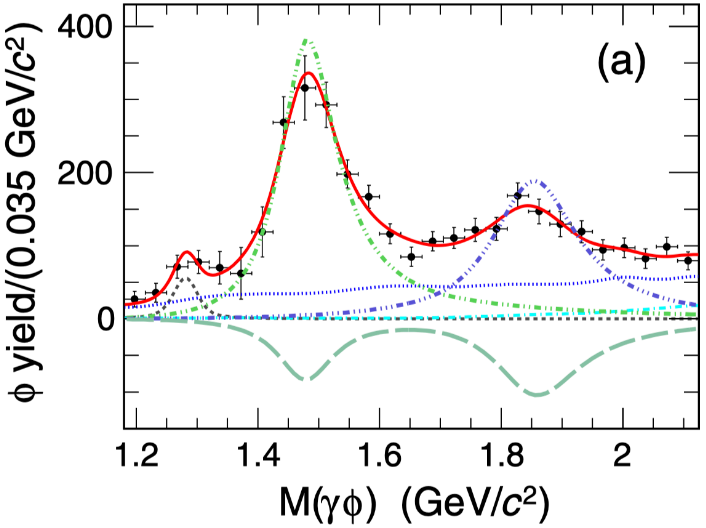
Production rate for $f_0(1710)$ is 10 times larger $f_0(1500)$⇒the former has larger overlap with glueball;

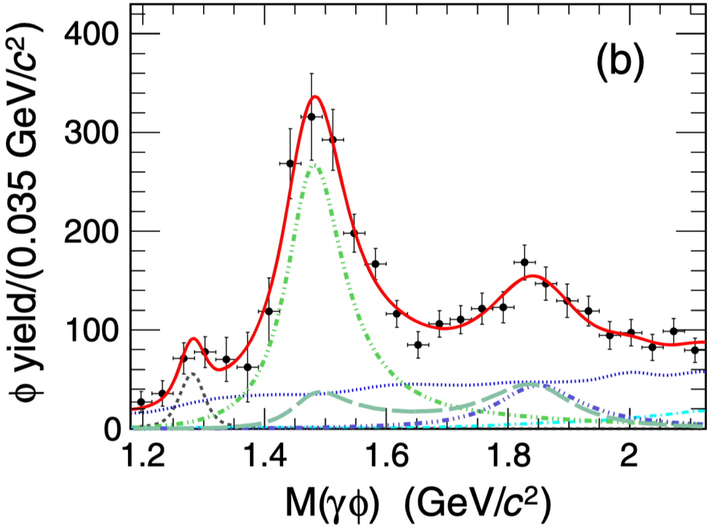
Production of $f_2(2340)$ is consistent with the pure gauge tensor glueball prediction made by LQCD.

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	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	...	$146 \pm 14^{+7}_{-15}$	...	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	...	$349 \pm 18^{+23}_{-1}$	...	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	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	...	...	...	...	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	...	...	...	...	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

PRD 97, 051101(R)

Study of $J/\Psi \to \gamma(\gamma\phi)$



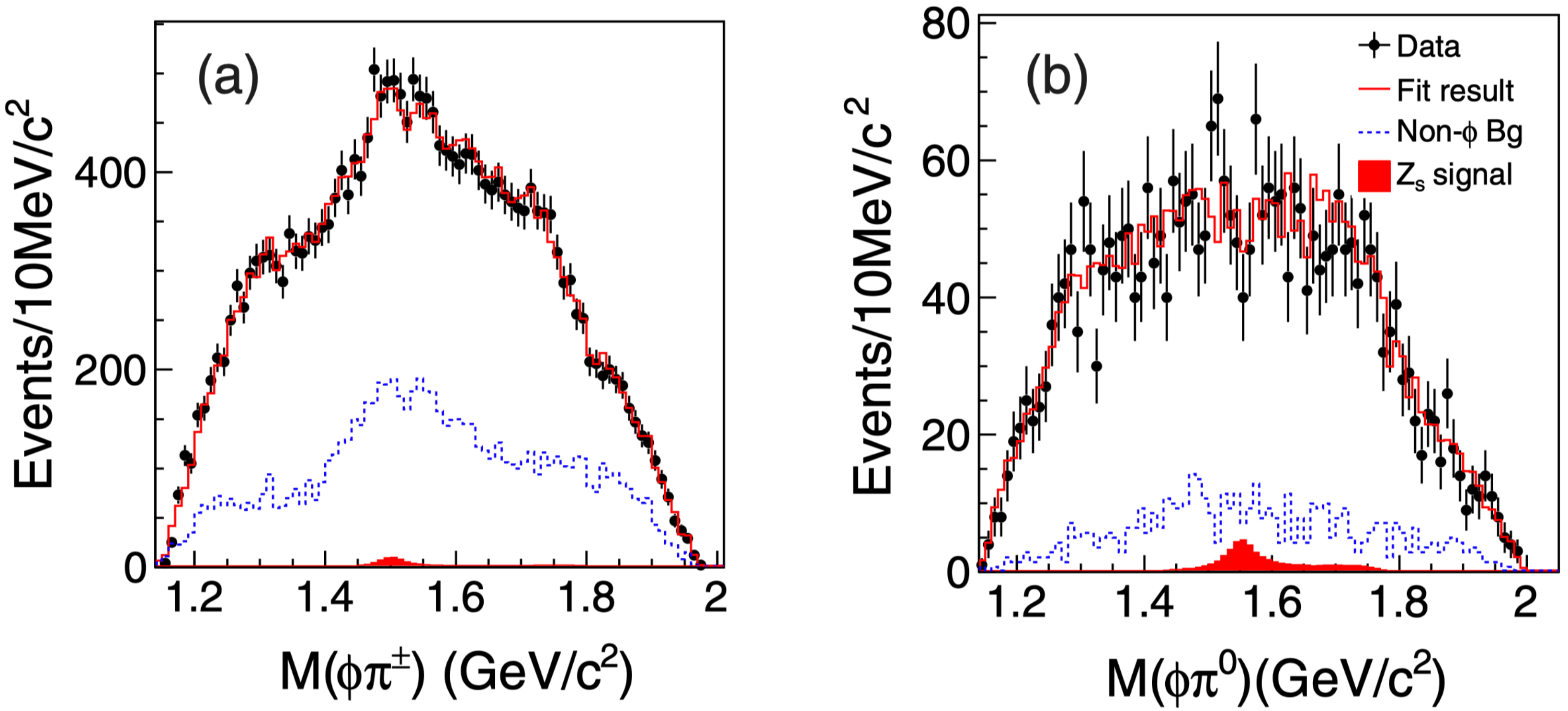


For the first time, we discovered the η(1475) and X(1835) in the $\gamma\phi$ final state!

Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)	B (10^{-6})
I	$\eta(1475)$	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$	$7.03 \pm 0.92 \pm 0.91$
	$X(1835)$	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$	$1.77 \pm 0.35 \pm 0.25$
II	$\eta(1475)$	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$	$10.36 \pm 1.51 \pm 1.54$
	$X(1835)$	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$	$8.09 \pm 1.99 \pm 1.36$

PRD 99, 011101

Study of $\phi\pi\pi$ and search for Zs



No clear Zs is found!
Strange sector is different from the charm/beauty sector!

$\phi\sigma$, $\phi f_0(980)$, $\phi f_0(1370)$, $\phi f_2(1270)$, and Zs ($J^P=1^+$ with mass and width 1.5 GeV and 50 MeV) are taken into in the amplitude analysis together with the non-ϕ background.

Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ threshold

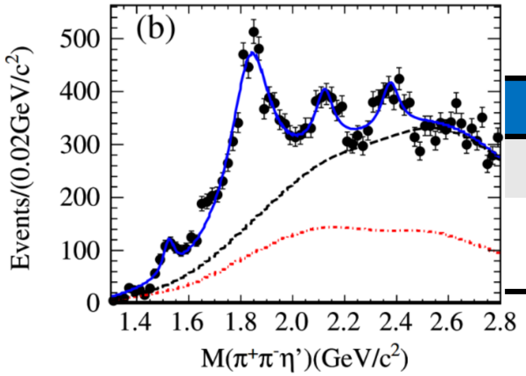
X(1835) observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$

Phys. Rev. Lett. 106, 072002 (2011)

0.2B J/ψ evts

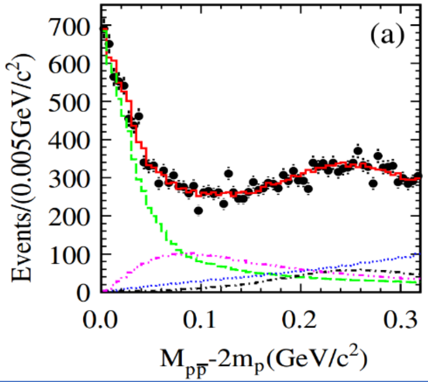
$X(p\bar{p})$ observed in $J/\psi\to\gamma p\bar{p}$

PRL 108, 112003 (2012); PRL 115, 091803 (2015)



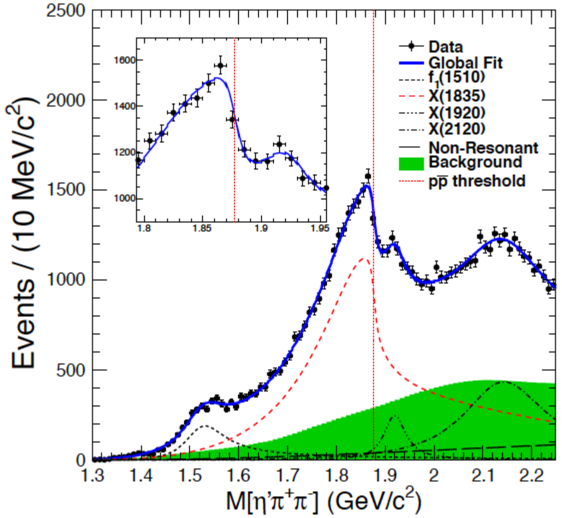
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

$X(p\bar{p})$ $J^{PC}=0^{-+}$
$M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 MeV/c^2 @ 90% C.L.)



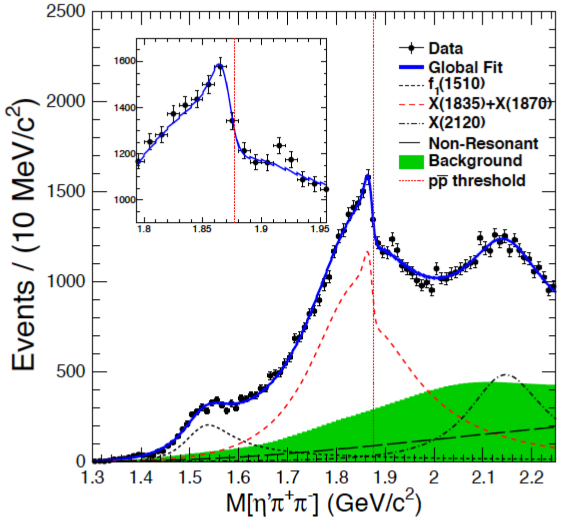
1.3B J/ψ evts

PRL 117, 042002 (2016)



Model I:
Flatte line shape with strong coupling to $p\bar{p}$ and one additional narrow BW at ~ 1920 MeV

Model II:
Two coherent BW, X(1835) and one additional, narrow BW at ~ 1870 MeV significance > 7σ



- Existence of a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold
- Existence of a $p\bar{p}$ molecule-like state or bound state?

Search for X(1835)'s other decay modes

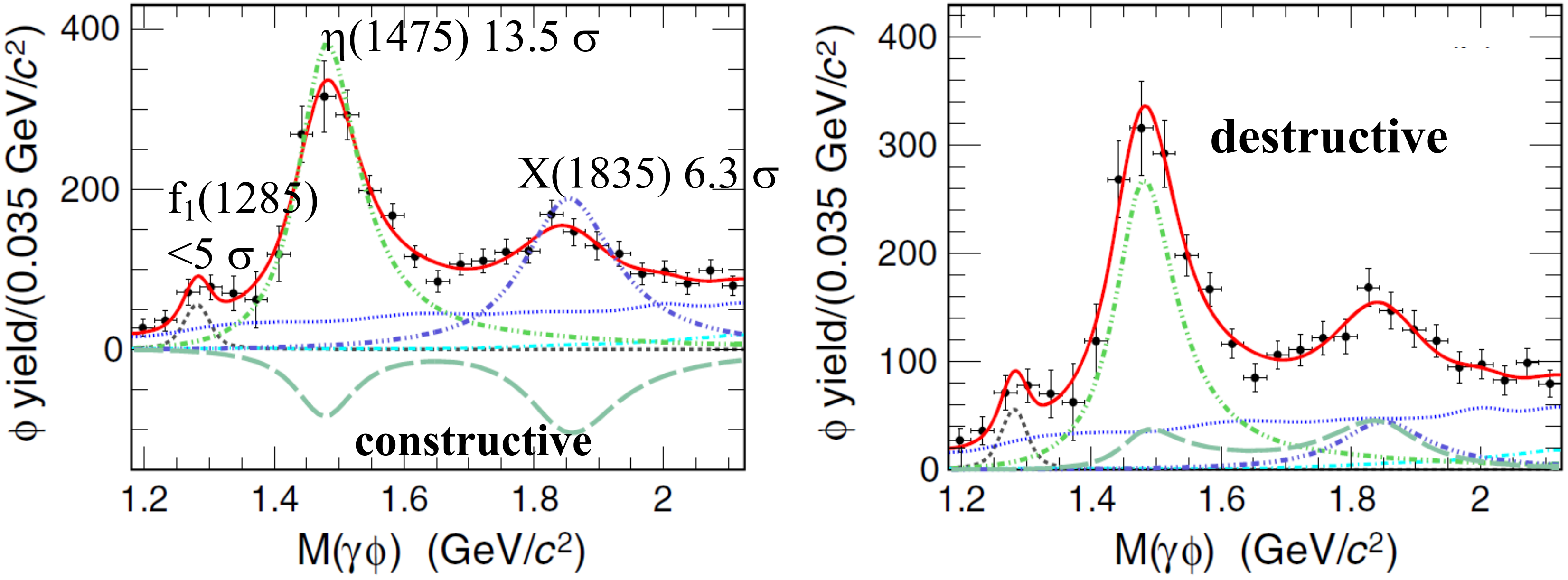
$J/\psi \rightarrow \gamma\gamma\phi$:

- ✓ First observation of $\eta(1475)/X(1835) \rightarrow \gamma\phi$.
- ✓ Angular distribution favor $J^{PC} = 0^{-+}$.

$J/\psi \rightarrow \omega\pi^+\pi^-\eta'$:

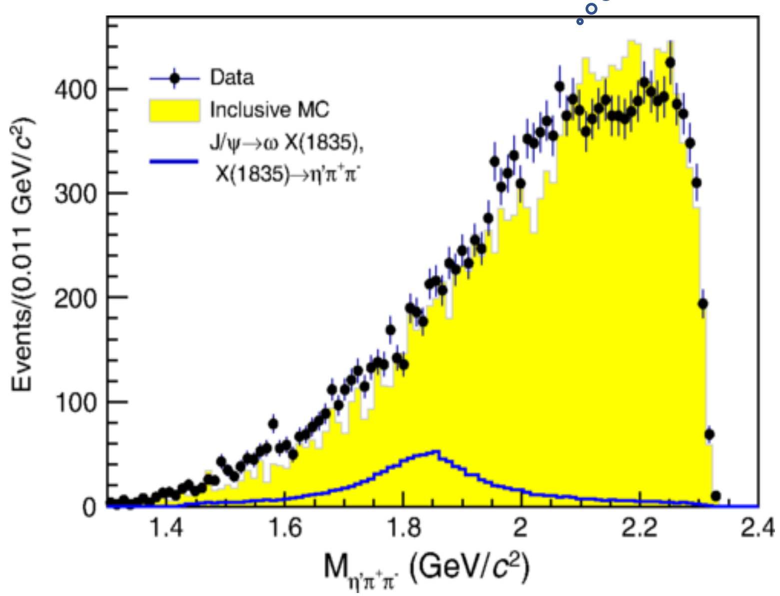
- ✓ No obvious signal of X(1835) is found.
- ✓ B.R.< 6.2×10^{-5} @ 90% C. L.

Sizeable $s\bar{s}$ component in X(1835)



Phys. Rev. D 97, 051101(R) (2018)

New!

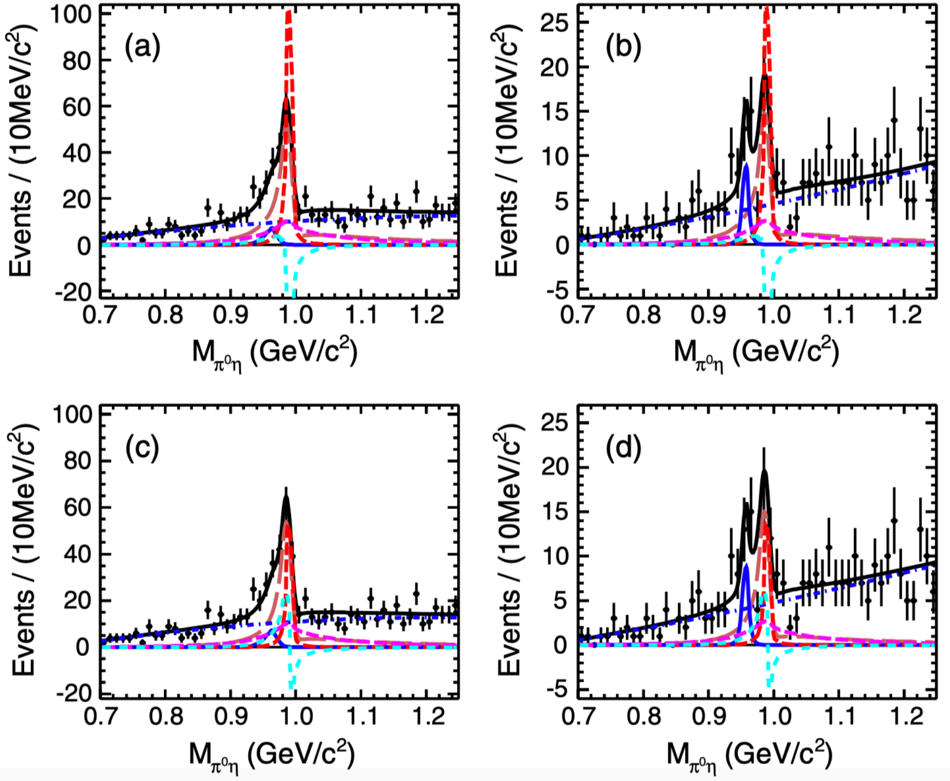


Phys. Rev. D 99, 071101(R) (2019)

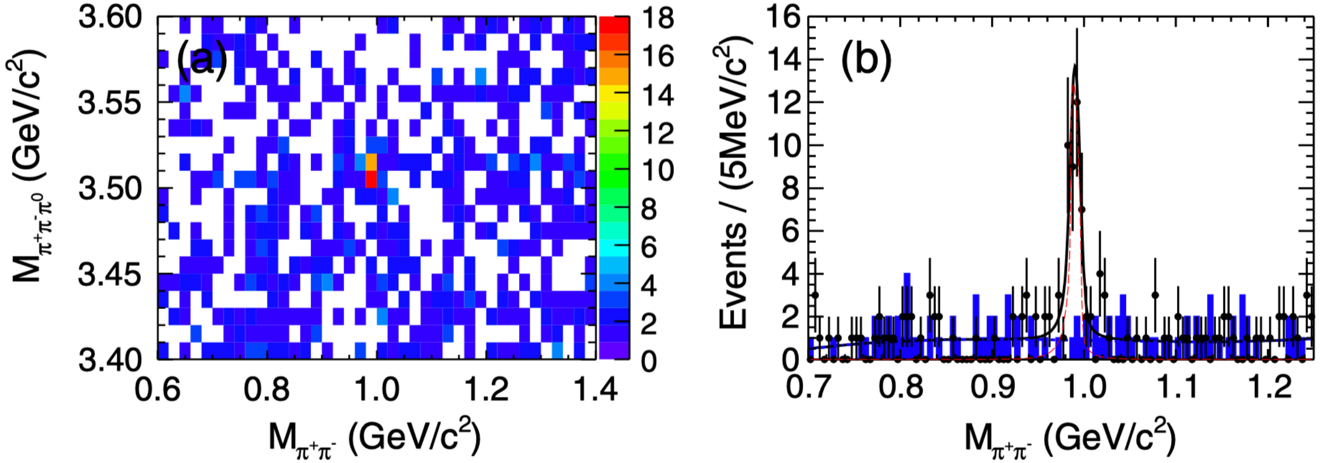
PRL 121, 022001

Observation of $a_0^0(980)$-$f_0(980)$ Mixing

With $J/\Psi \to \phi$ a/f



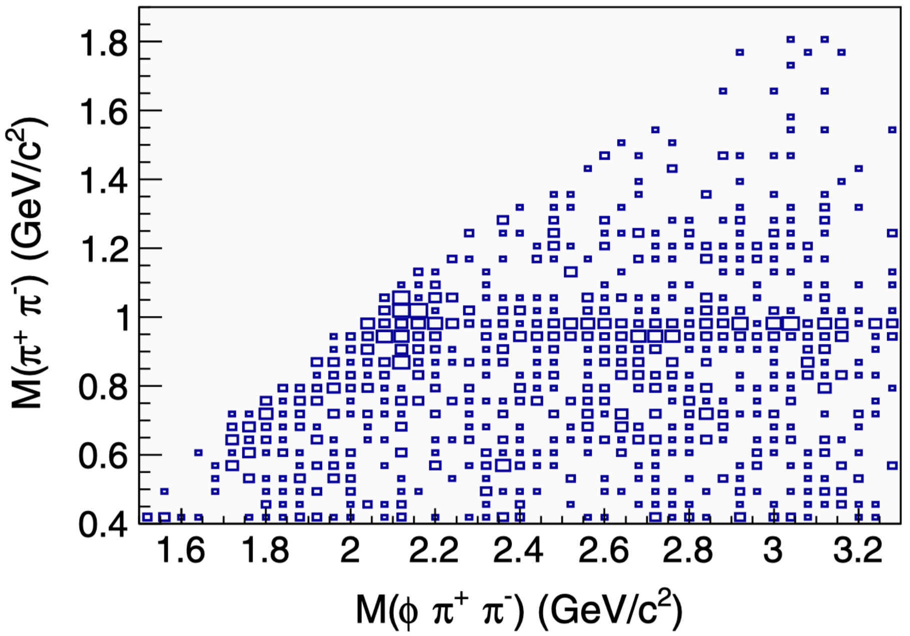
With $\chi_{c0} \to \pi^0$ a/f



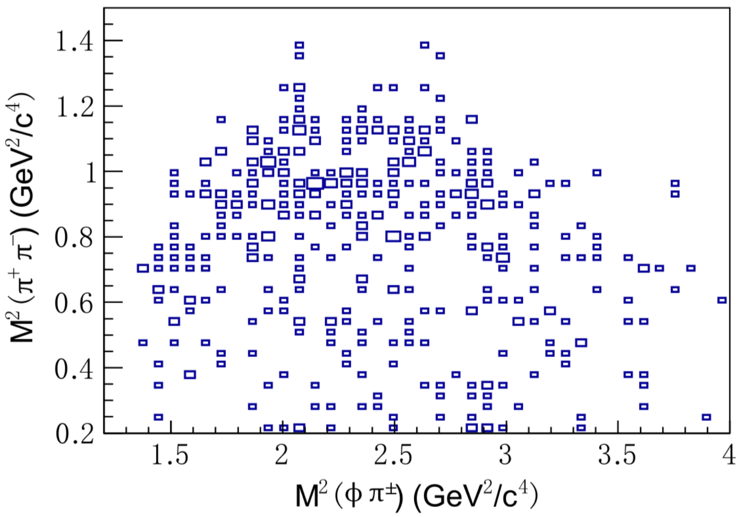
	$J/\psi \to \phi\eta\pi^0$		
Channel	Solution I	Solution II	$\chi_{c1} \to 3\pi$
N (mixing)	$161 \pm 26 \vert 45 \pm 7$	$67 \pm 21 \vert 19 \pm 6$	42 ± 7
N (EM)	$162 \pm 54 \vert 46 \pm 16$	$130 \pm 51 \vert 37 \pm 14$	...
φ (degree)	23.6 ± 11.3	-51.5 ± 21.3	...
S (mixing)	7.4σ		5.5σ
S (EM)	4.6σ		...

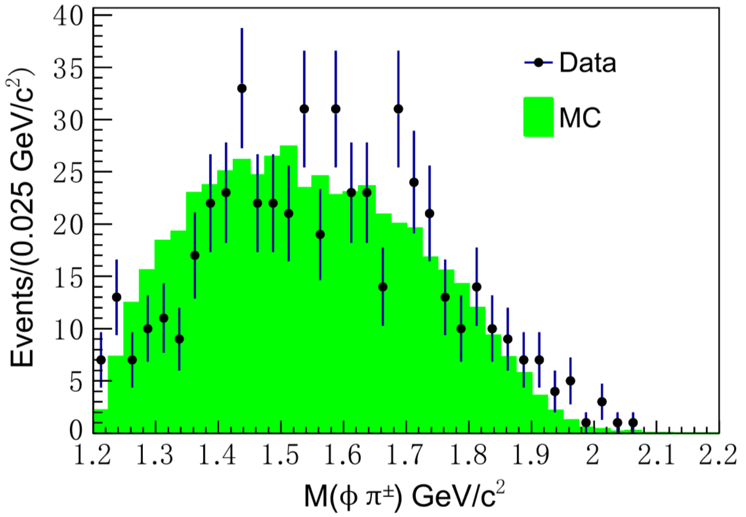
The mixing is observed for the first time!

Observation of $e^+e^- \to \eta Y(2175)$



No Zs is observed!

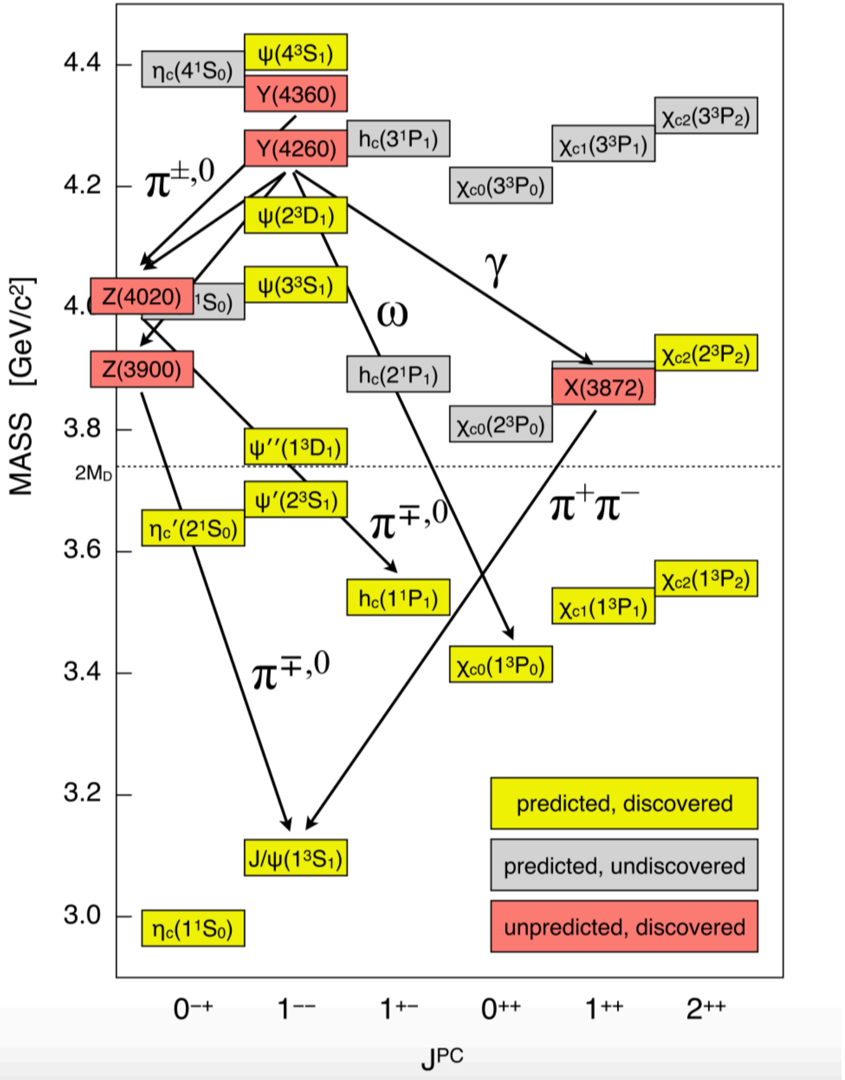




Clear Y(2175) is observed, and the from the ηY(2175) cross section as the function of center-of-mass energy, it seems that it is not from any vector charmonium decays!

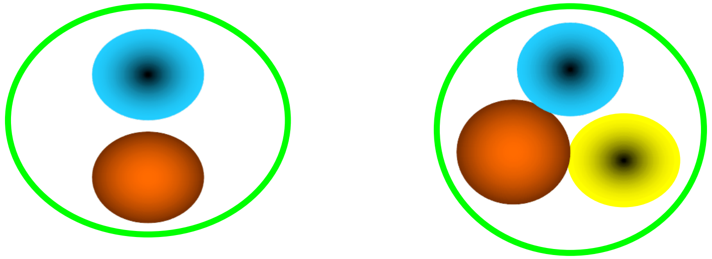
Charmoniumlike states

Charmonium spectroscopy



Hadrons：traditional & exotic

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



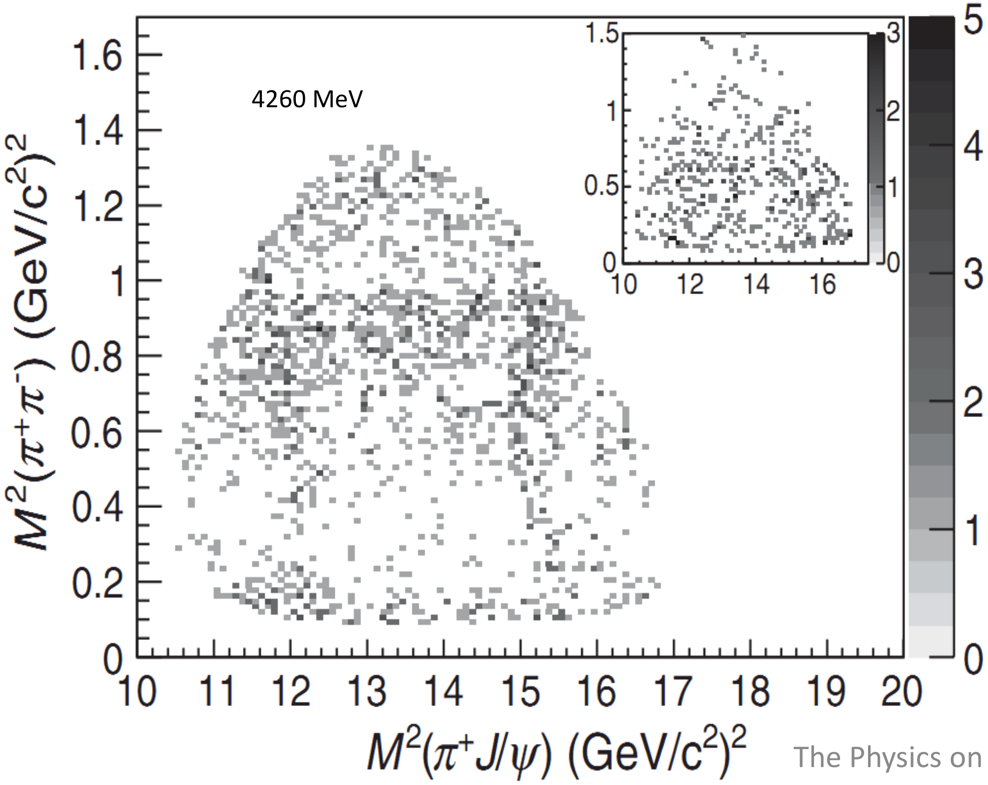
- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - multiquark state : $N_{quarks} > 3$
  - molecule : bound state of more than 2 hadrons
  - …

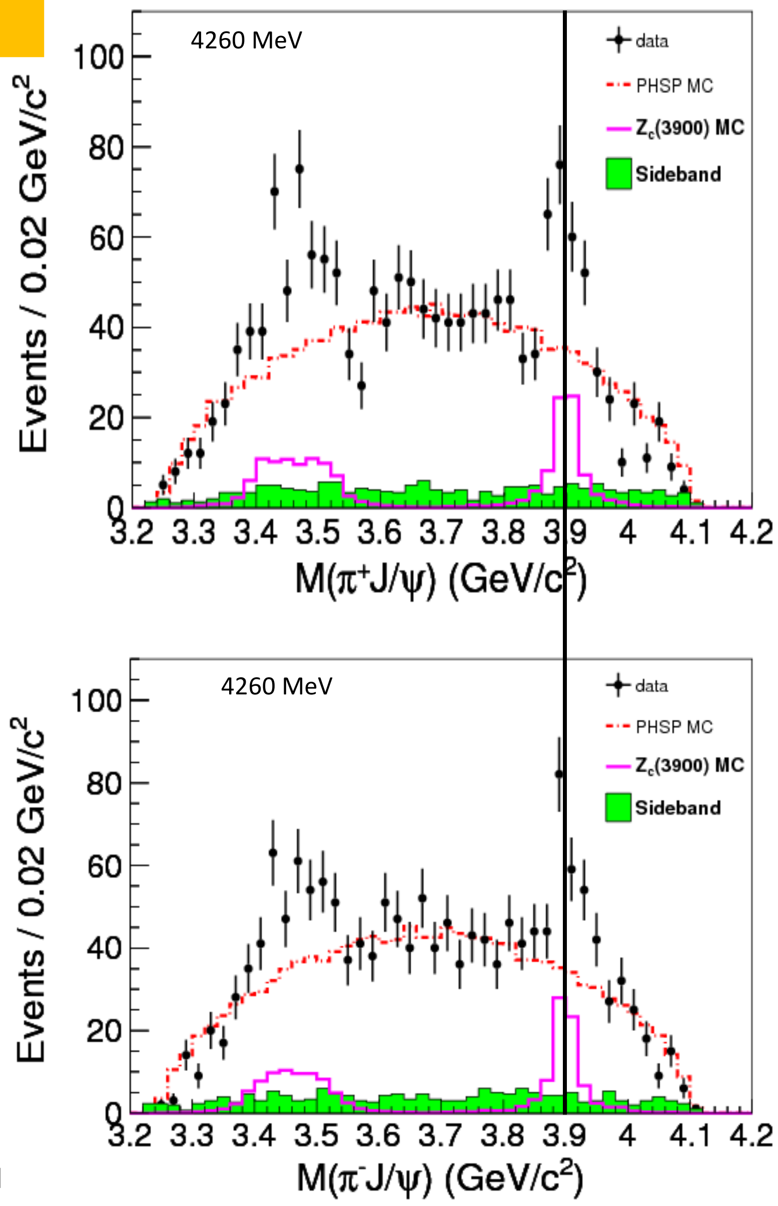
BESIII@BEPCII is collecting data to study this.

PRL 110, 252001

The discovery of $Z_c(3900)^{\pm}$

Study the $e^+e^- \to \pi^+\pi^- J/\psi$ process at 4.26 GeV, structures are there!





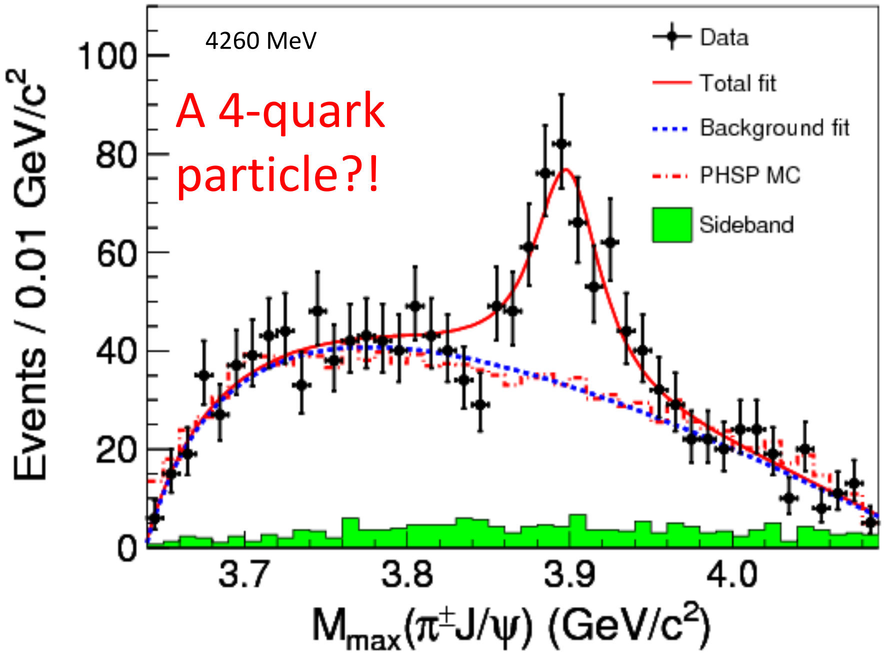
$Z_c(3900)^+$:

$$m = (3899.0 \pm 3.6 \pm 4.9)\ \mathrm{MeV}/c^2$$

$$\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}$$

Mass close to $D\bar{D}^*$ threshold

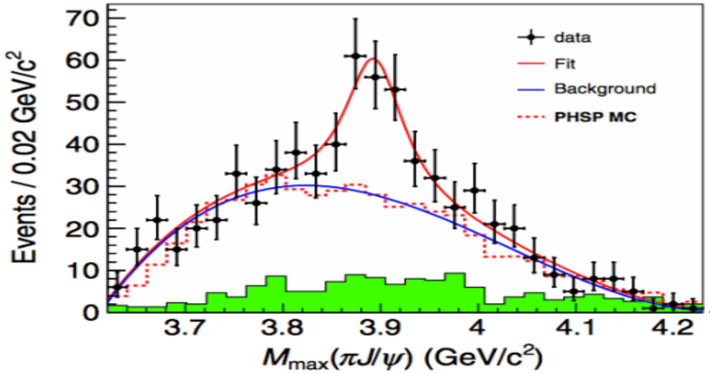
Decays to J/ψ → contains $c\bar{c}$
Electric charge → contains $u\bar{d}$



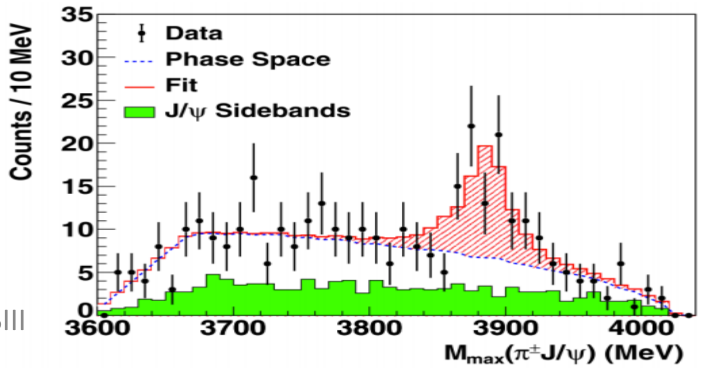
$$\sigma[e^+e^- \to \pi^+\pi^- J/\psi] = 62.9 \pm 1.9 \pm 3.7 \text{ pb at } 4.26 \text{ GeV}$$

$$\frac{\sigma[e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi]}{\sigma[e^+e^- \to \pi^+\pi^- J/\psi]} = (21.5 \pm 3.3 \pm 7.5)\% \text{ at } 4.26 \text{ GeV}$$

Belle with ISR data (PRL 110, 252002)

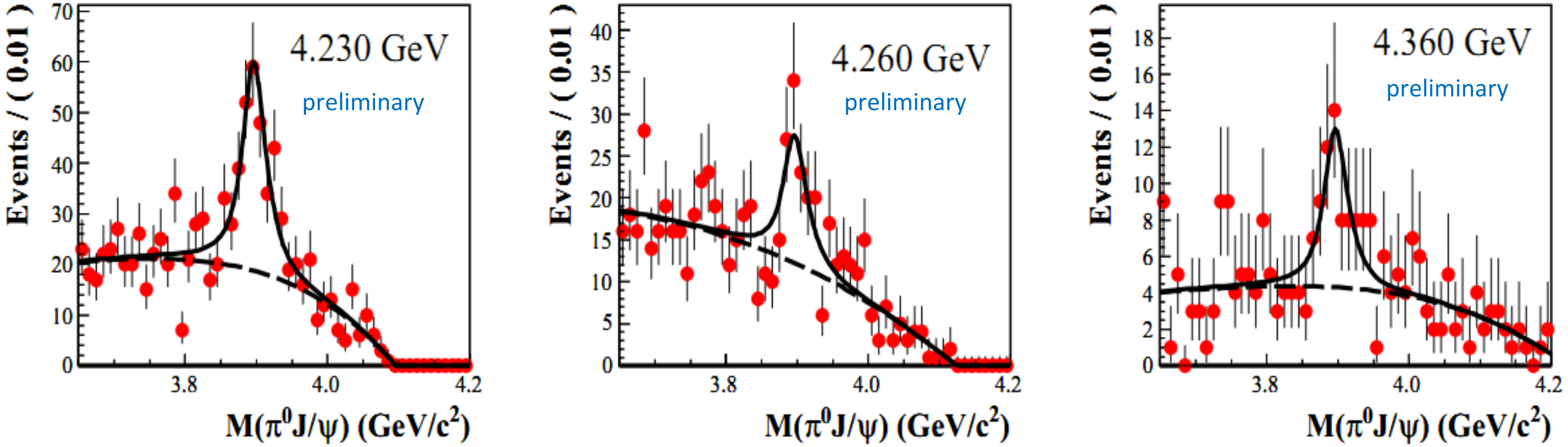


CLE0c data at 4.17 GeV (PLB 727, 366)



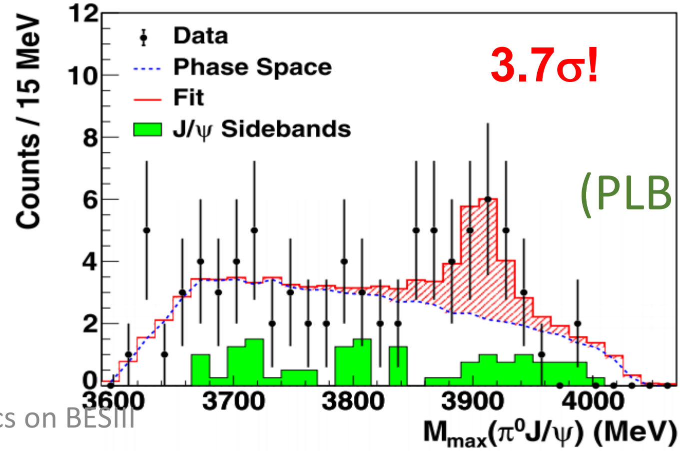
The neutral isospin partner: $Z_c(3900)^0$

Studying the $e^+e^- \to \pi^0\pi^0 J/\psi$ process



A structure on $\pi^0 J/\psi$ invariant mass spectrum can be observed:

Mass = 3894.8±2.3 MeV
Width = 29.6±8.2 MeV
Significance = 10.4 σ



(PLB 727, 366)

Isospin triplet is established!

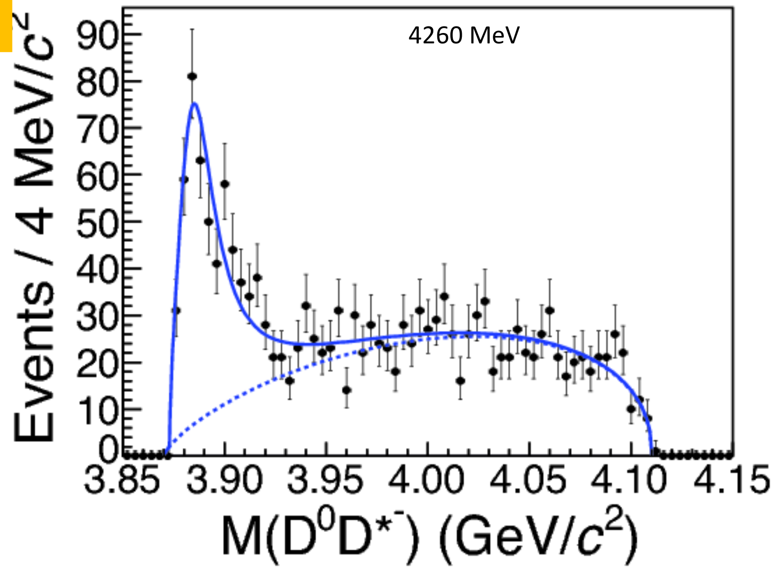
PRL 112, 022001

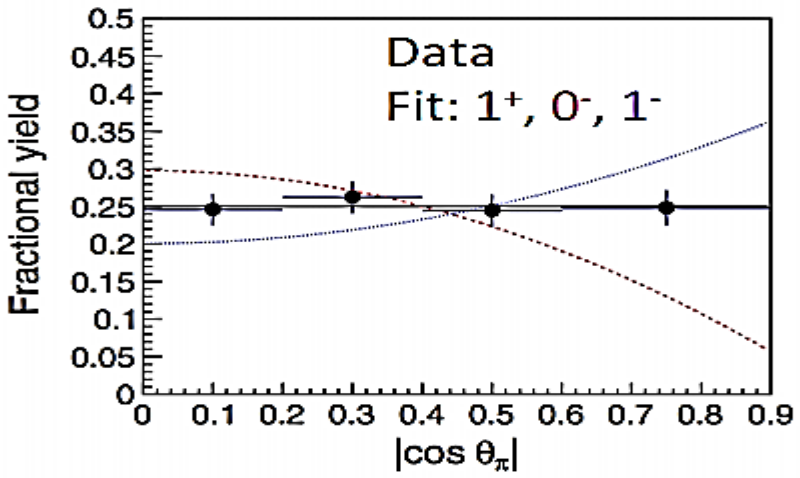
The study of $e^+e^- \to \pi^\pm(D\overline{D^*})^\mp$ process

Reconstruct the π^+ and $D^0 \to K^-\pi^+$ and infer the D^{*-}.
(Also analyze $\pi^+D^-D^{*0}$ with the same method.)

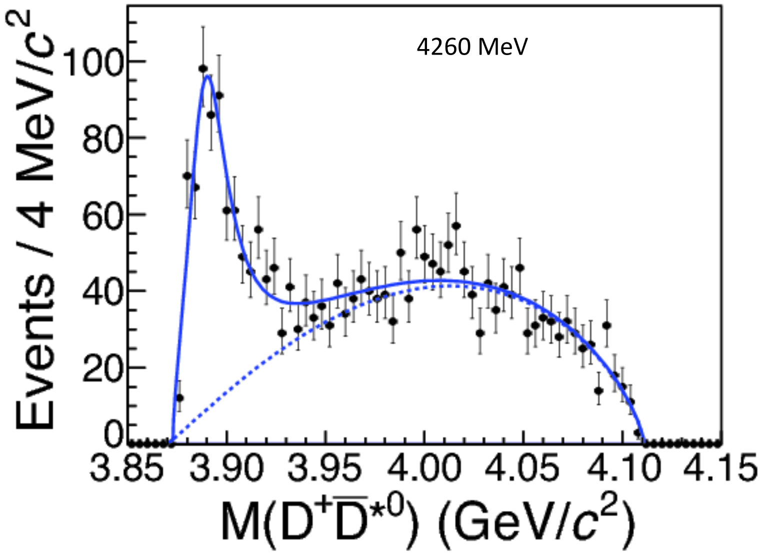
Enhancement at $D\bar{D}^*$ threshold in both channels ($Z_c(3885)^+$):

Mass = 3883.9±1.5±4.2 MeV, **(fit with BW function)**
Width = 24.8±3.3 ±11.0 MeV





Fit to angular distribution favors $J^P = 1^+$ over 0^- and 1^-



A comparison between Zc(3885) and Zc(3900)

	$Z_c(3885) \to D\bar{D}^*$	$Z_c(3900) \to \pi J/\psi$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$	$3899.0 \pm 3.6 \pm 4.9$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$	$46 \pm 10 \pm 20$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$	$13.5 \pm 2.1 \pm 4.8$

- The mass and width are consistent within **2σ!**
- If this is $Z_c(3900)^+$, open charm decays are suppressed, since

$$\frac{\mathcal{B}(Z_c \to D^* \bar{D})}{\mathcal{B}(Z_c \to J/\psi\, \pi)} = 6.2 \pm 1.1 \pm 2.7$$

Compared to e.g.

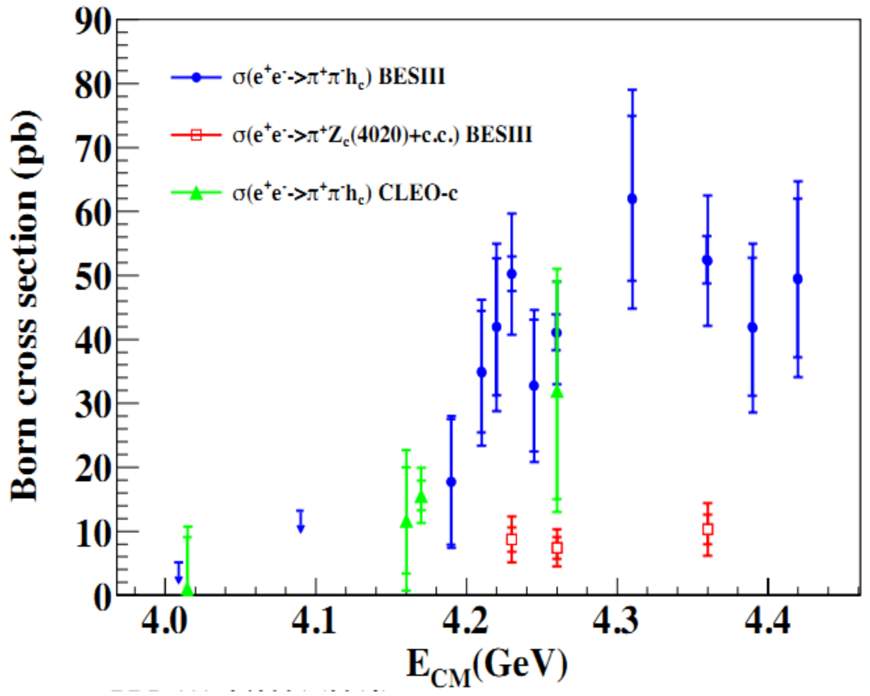
$$\frac{\mathcal{B}(\psi(4040) \to D^{(*)} \bar{D}^{(*)})}{\mathcal{B}(\psi(4040) \to J/\psi\, \eta)} = 192 \pm 27$$

⇒ Different dynamics in Y(4260)-Zc(3900) system!

The study of $e^+e^- \to \pi^+\pi^- h_c$ process

$h_c \to \gamma\eta_c$,
$\eta_c \to$ 16 hadronic decay modes

PRL 111, 242001

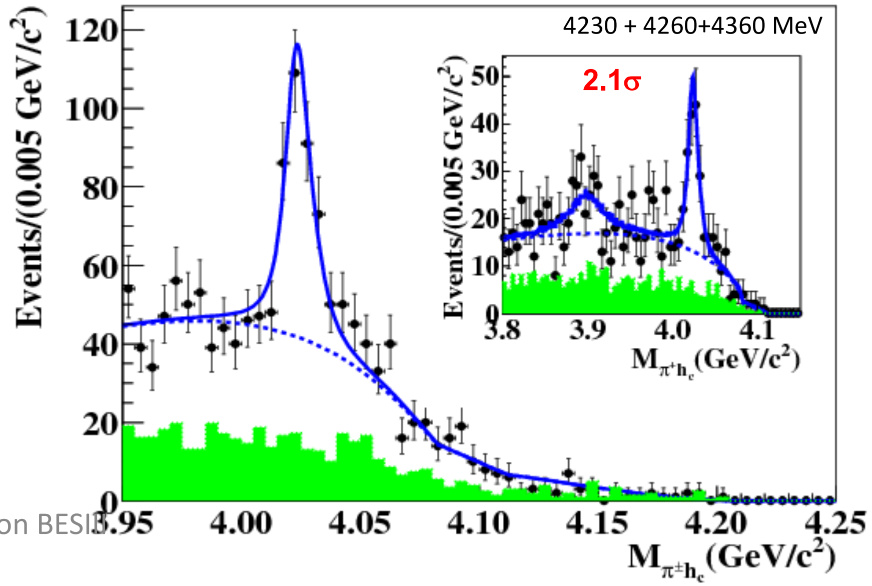


The cross section of $e^+e^- \to \pi^+\pi^- h_c$ is measured, and the shape is not trivial.

A structure, $Z_c(4020)^\pm$, is observed.

Mass = 4022.9±0.8 ±2.7 MeV,
Width = 7.9±2.7 ±2.6 MeV

A weak evidence for $Z_c(3900)^\pm \to \pi^\pm h_c$



The neutral isospin partner: $Z_c(4020)^0$

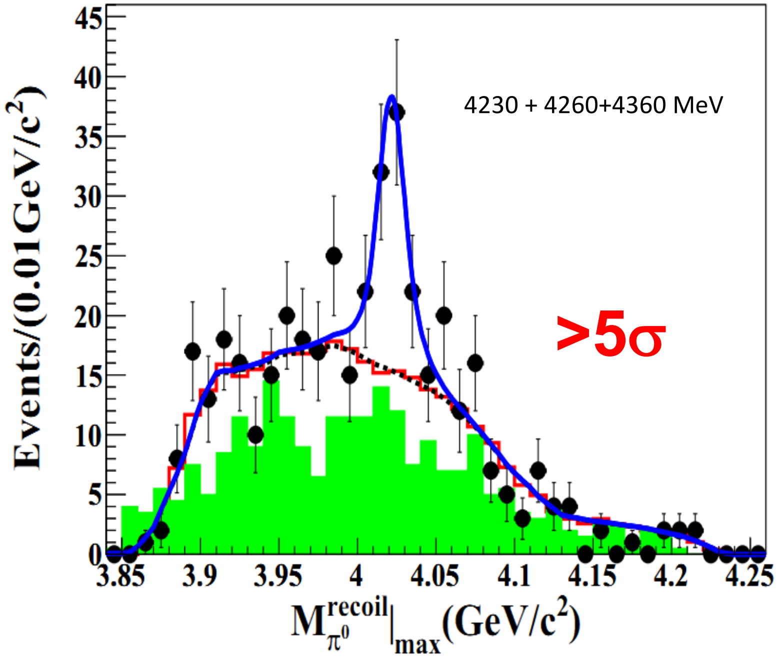
arXiv:1409.6577

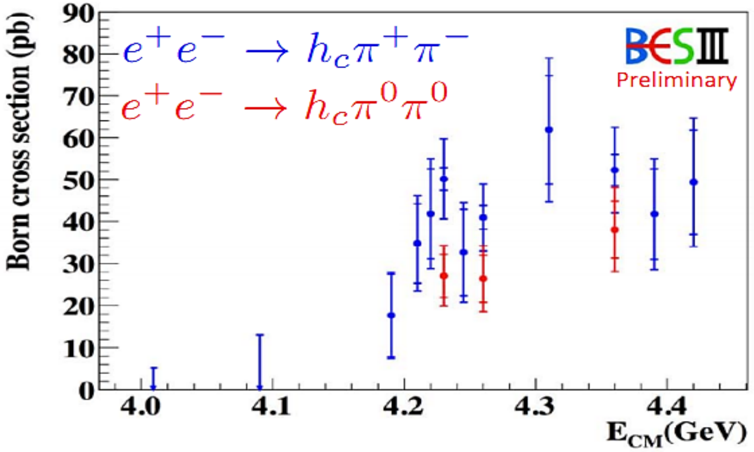
Studying the $e^+e^- \to \pi^0\pi^0 h_c$ process

A structure on π^0hc invariant mass spectrum can be observed:

Mass = 4023.9±2.2 ±3.8 MeV, Width is fixed to be same as its charged partner.

Another isospin triplet is established!





Cross sections for $e^+e^- \to h_c\pi^+\pi^-$ and $e^+e^- \to h_c\pi^0\pi^0$ are in agreement with isospin conservation

The study of $e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp$ process

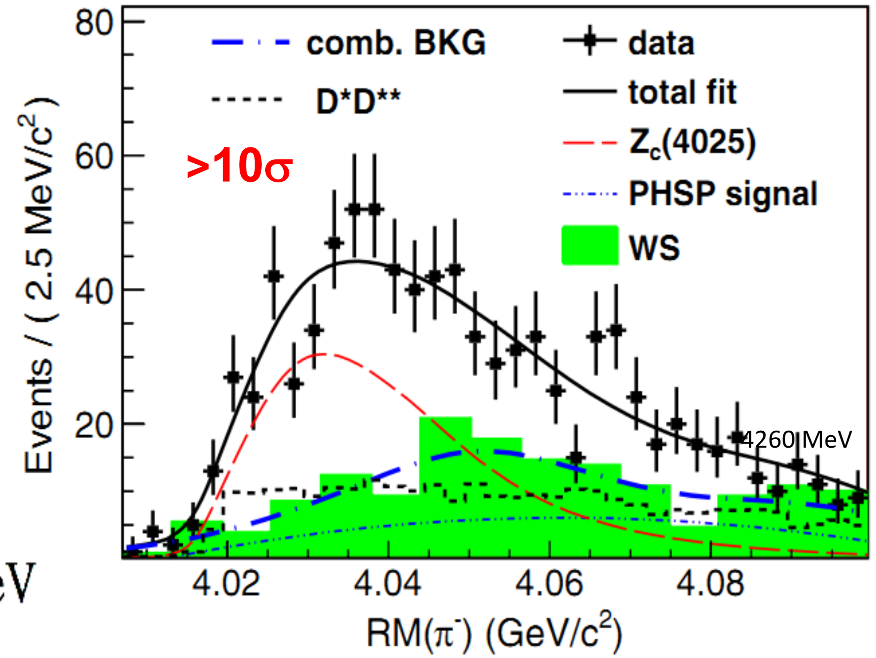
PRL 112, 132001

Tag a D^+ and a bachelor π^-, reconstruct one π^0 to suppress the background.

A structure, named as Zc(4025), can be observed in the recoil mass of the bachelor π^- .

$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV;

$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV



$$\sigma[e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp] = 137 \pm 9 \pm 15 \text{ pb at } 4.26 \text{ GeV}$$

$$\frac{\sigma[e^+e^- \to \pi^\pm Z_c(4025)^\mp \to (D^*\bar{D}^*)^\pm\pi^\mp]}{\sigma[e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp]} = 0.65 \pm 0.09 \pm 0.06 \text{ at } 4.26 \text{ GeV}$$

Coupling to $\bar{D}^*D^*$ is much larger than to πh_c if $Z_c(4025)$ and $Z_c(4020)$ are the same state.

PRL 112, 132001

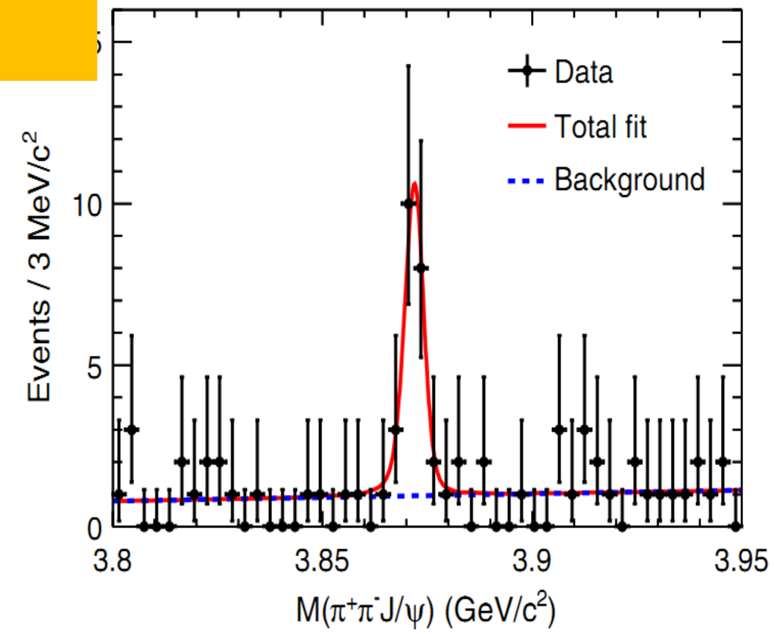
Observation of e+e-$\rightarrow \gamma X(3872) \rightarrow \gamma\pi^+\pi^- J/\psi$

significance = 6.3σ

N = 20.1 ± 4.5 events

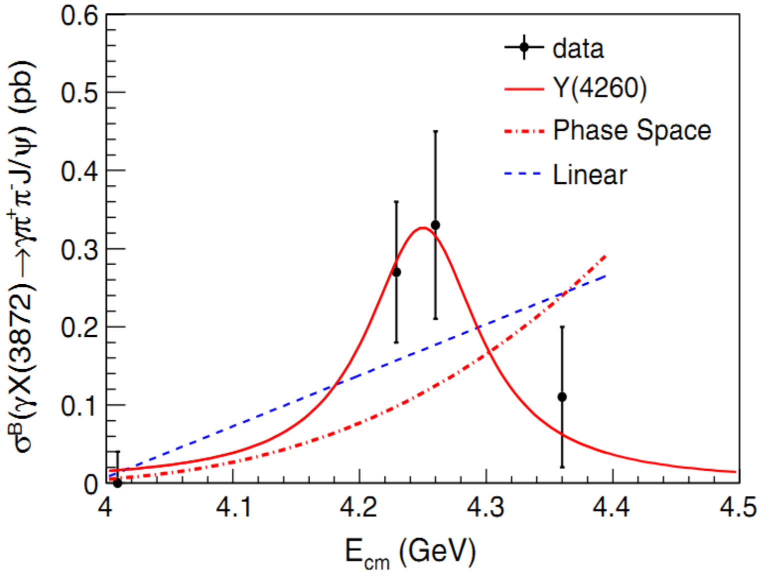
M = 3871.9 ± 0.7 ± 0.2 MeV

Γ consistent with resolution



The resonant contribution with Y(4260) line shape provides a better description of the data than either a linear continuum or a E1- transition phase space distribution.

The Y(4260)->γ X(3872) could be another previously unseen decay mode of the Y(4260) resonance.



First observation of $e^+e^- \to \omega\chi_{c0}$ preliminary

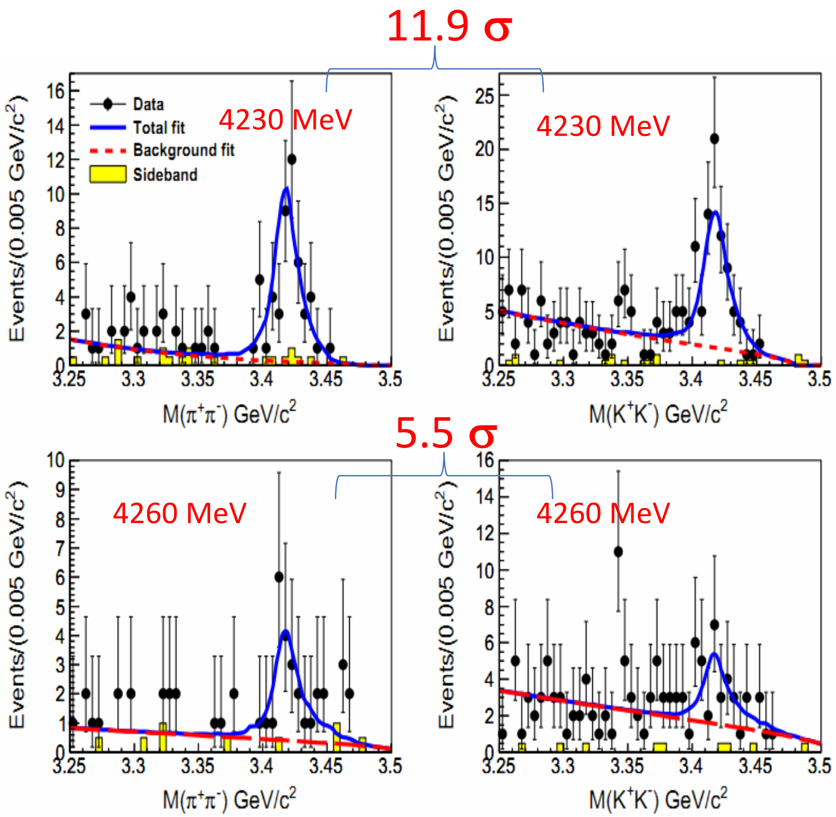
The events are reconstructed exclusively:

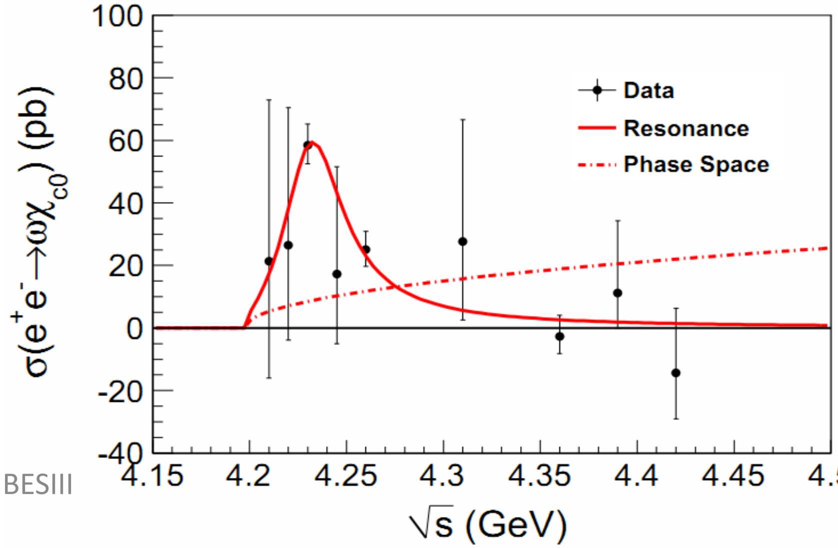
$$\omega \to \pi^+\pi^-\pi^0$$

$$\chi_{c0} \to \pi^+\pi^-, K^+K^-$$

The first observation of this process.

Fit with single Breit-Wigner yields mass lower than *Y*(4260)

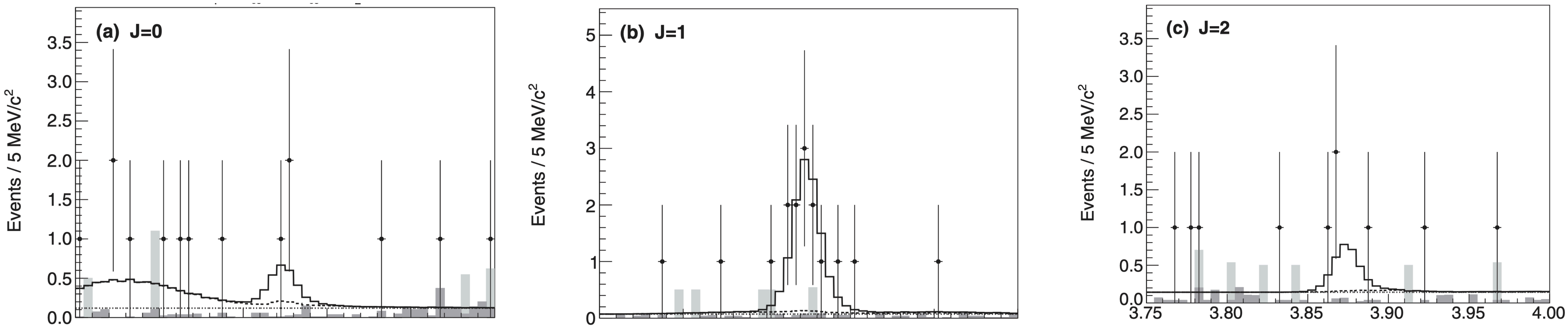




PRL 122, 202001

Observation of X(3872) → $\pi^0\chi_{c1}(1P)$

$M(\pi^0\chi_{c0}(1P))$ **$M(\pi^0\chi_{c1}(1P))$** **$M(\pi^0\chi_{c2}(1P))$**

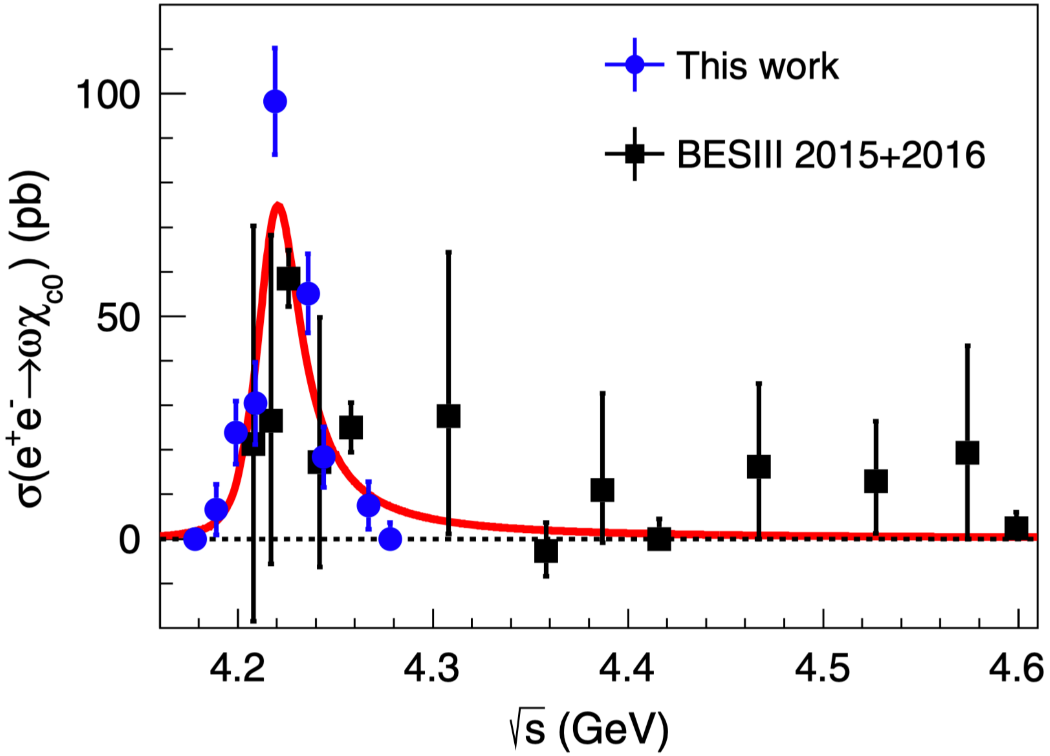


The result will imply the $\Gamma(\pi^0\chi_{c1}(1P))$~1.0-2.0 keV, which disfavors the $\chi_{c1}(2P)$ interpretation of X(3872)!

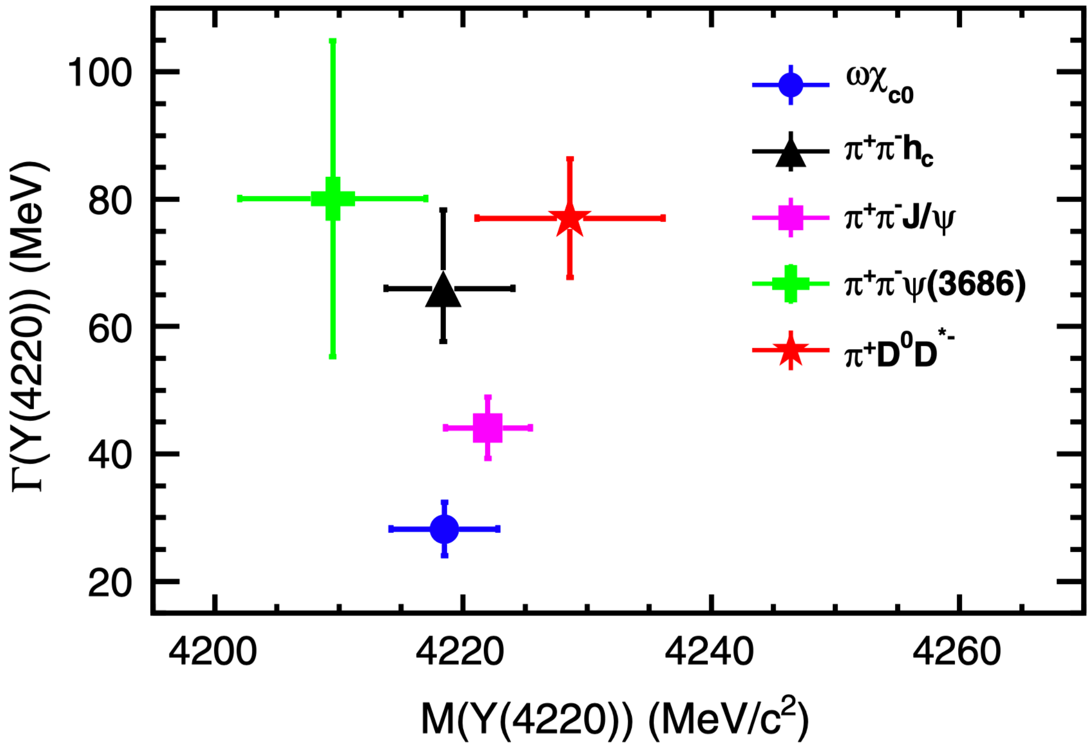
PRD 99, 091103(R)

Study of $e^+e^- \to \omega\chi_{c0}$

A vector state is observed!

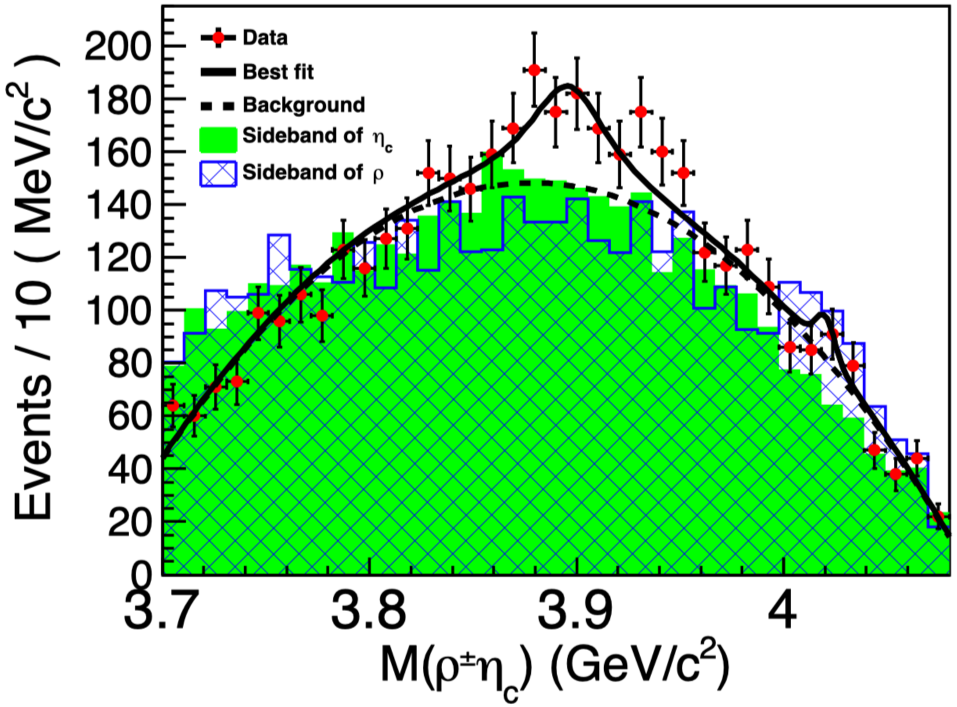


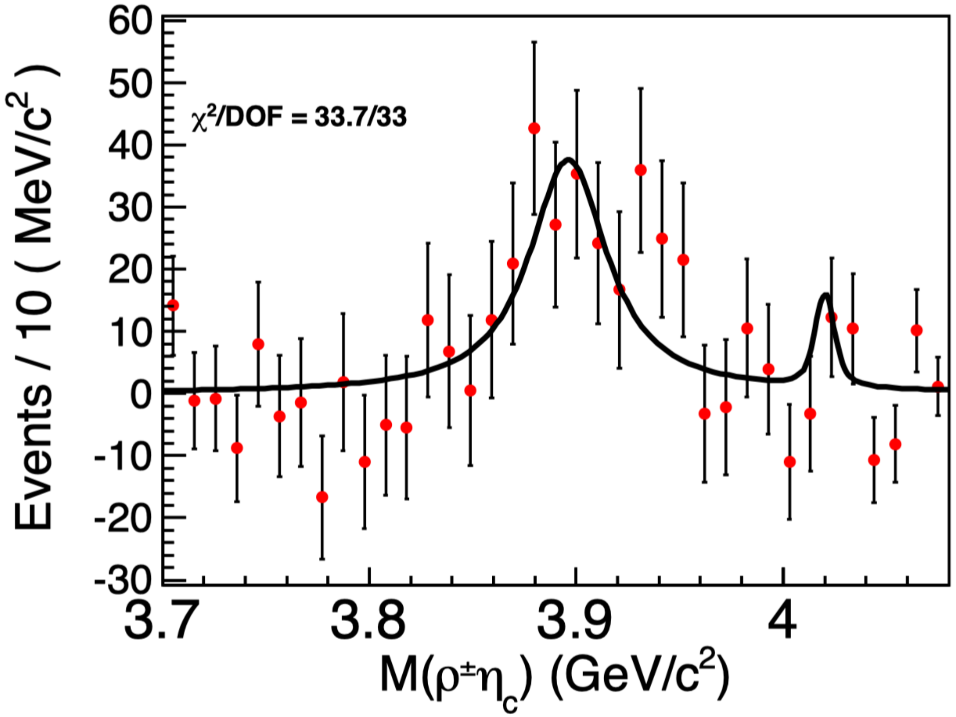
Are they the same state?



PRD 99, 091103(R)

Evidence for Zc(3900) in $\rho\eta_c$

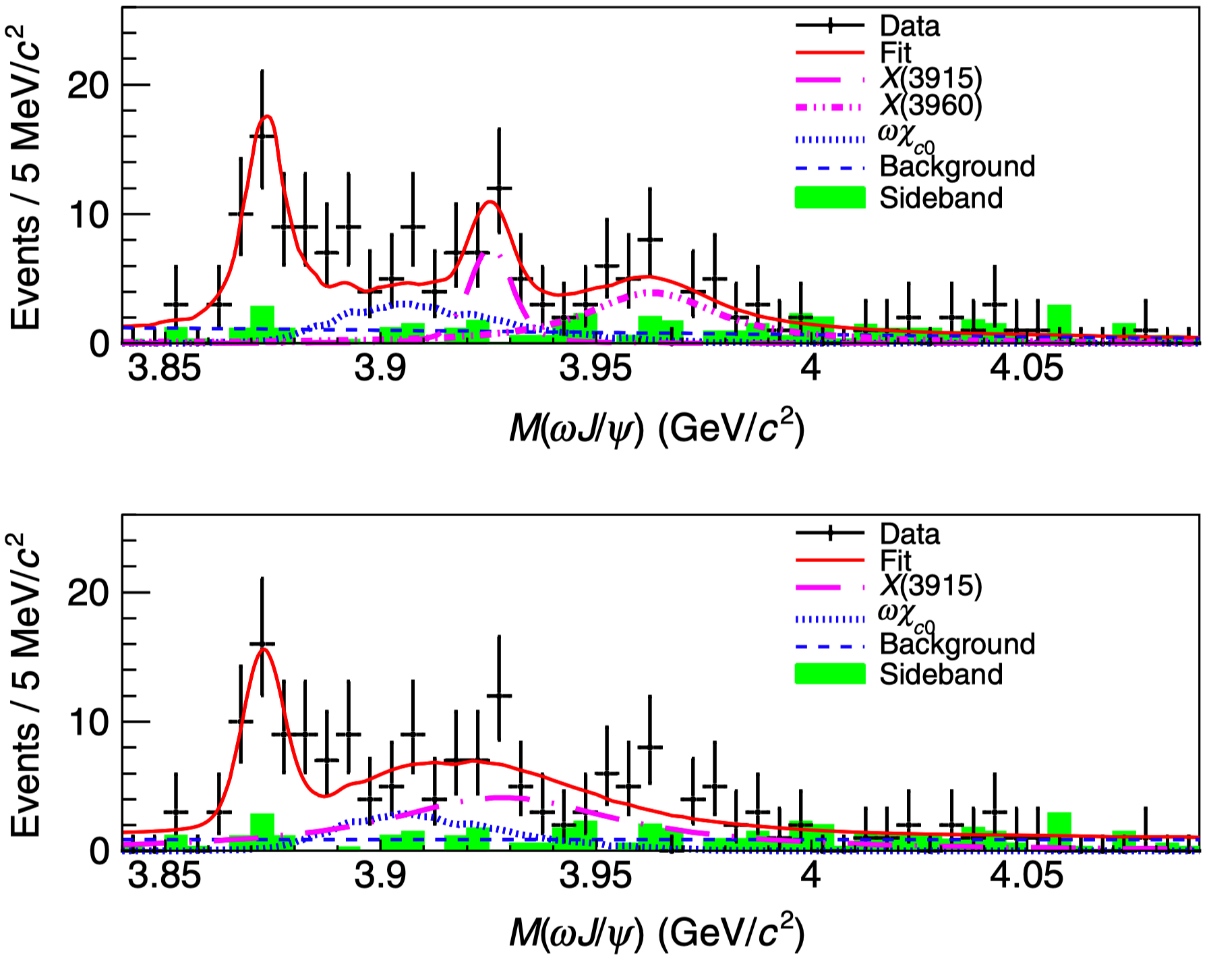




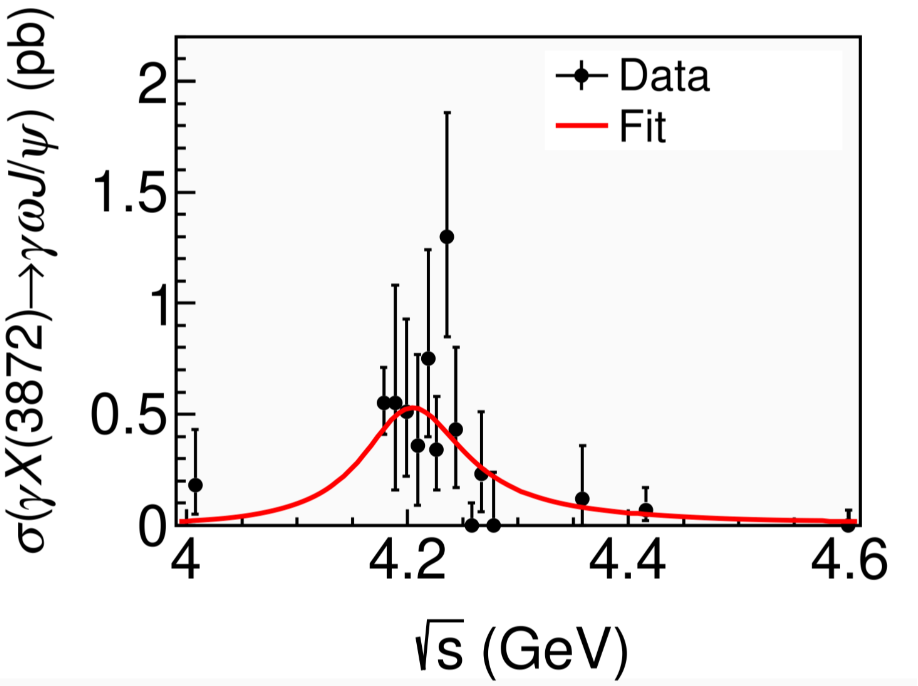
Disfavor the molecule explanation of Zc(3900)!

	$\sqrt{s} = 4.226$ GeV	$\sqrt{s} = 4.258$ GeV	$\sqrt{s} = 4.358$ GeV	Type-I	Type-II	Molecule
$R_{Z_c(3900)}$	2.2 ± 0.9	< 5.6	...	230^{+330}_{-140}	$0.27^{+0.40}_{-0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_c(4020)}$	< 1.6	< 0.9	< 1.4	$6.6^{+56.8}_{-5.8}$		$0.010^{+0.006}_{-0.004}$

Observation of X(3872) → ωJ/Ψ



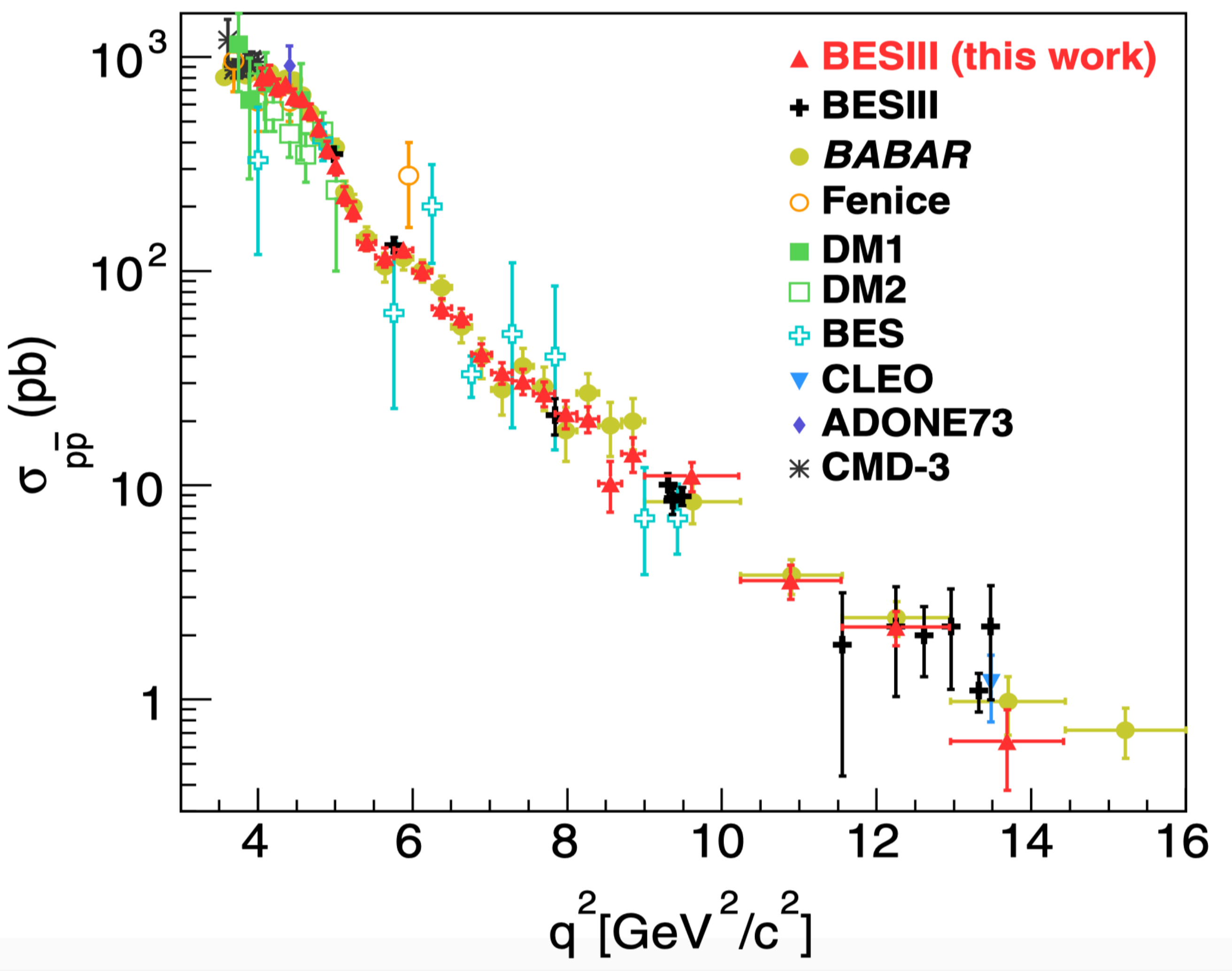
X(3872) is observed in ωJ/Ψ; we need at least an other structure of describe the ωJ/Ψ line-shape;
The production rate of ωJ/Ψ provides input for the molecule interpretation of X(3872);
The line-shape of γX(3872) is similar to the one in $\pi\pi$J/Ψ!



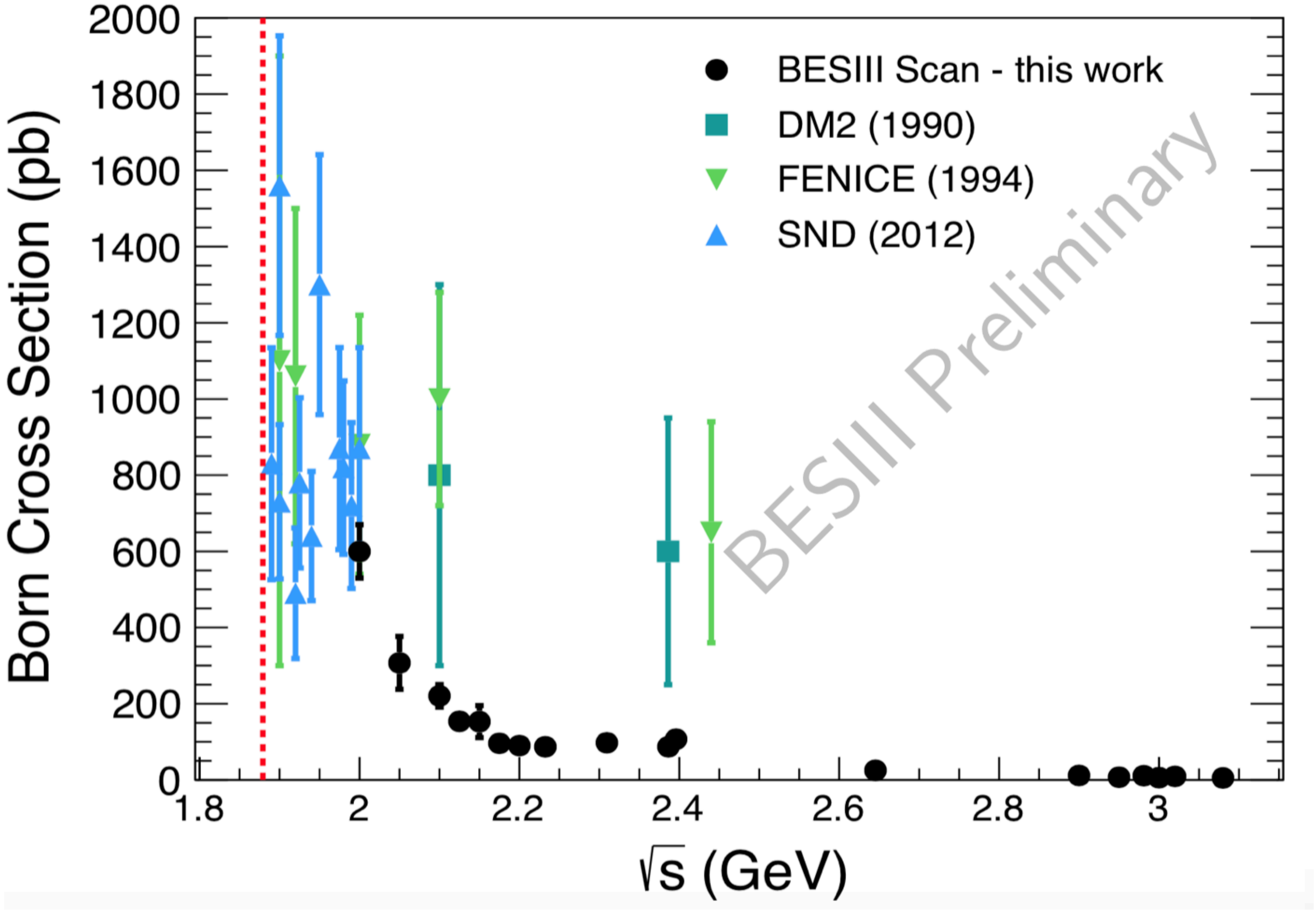
Enhancement near the threshold

PRD 99, 092002

$e^+e^- \to p\bar{p}$

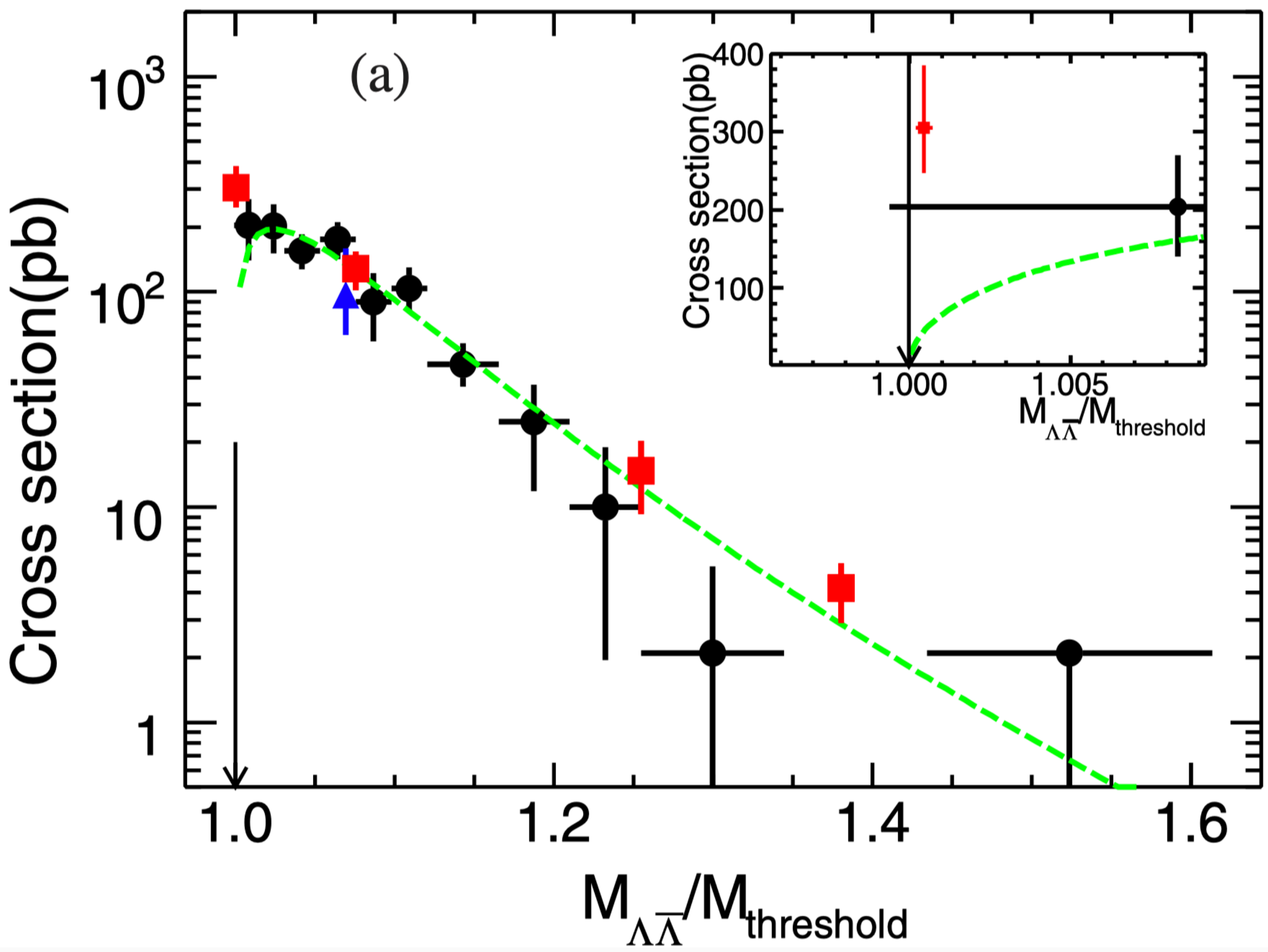


$e^+e^- \to n\bar{n}$


Born Cross Section (pb)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1.8
2
2.2
2.4
2.6
2.8
3
√s (GeV)
BESIII Scan - this work
DM2 (1990)
FENICE (1994)
SND (2012)
BESIII Preliminary

$e^+e^- \to \Lambda\bar{\Lambda}$

PRD 97, 032013



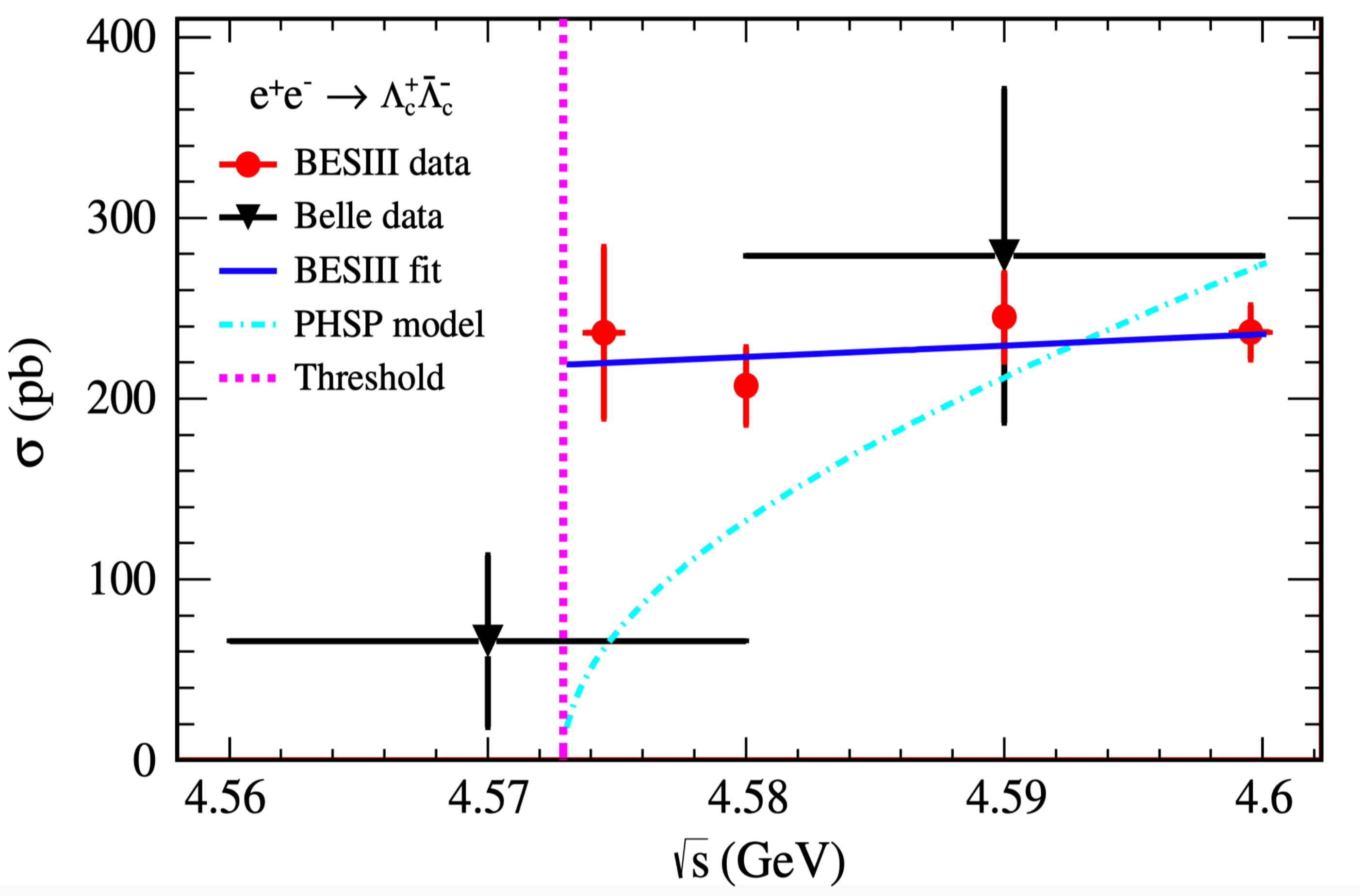
Red: BESIII

Black: BABAR

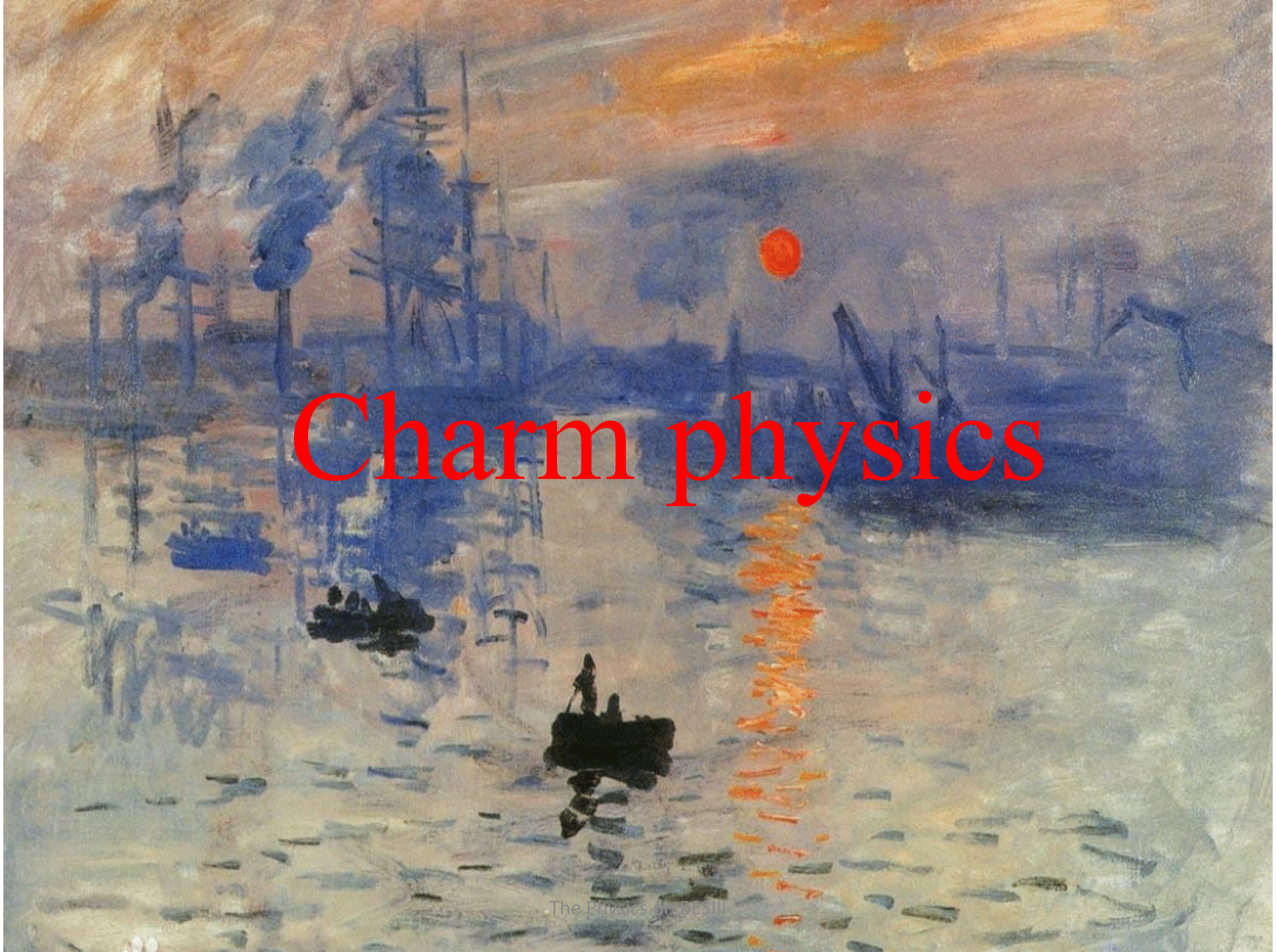
Blue: DM2

$e^+e^- \to \Lambda_c\bar{\Lambda}_c$

PRL 120, 132001

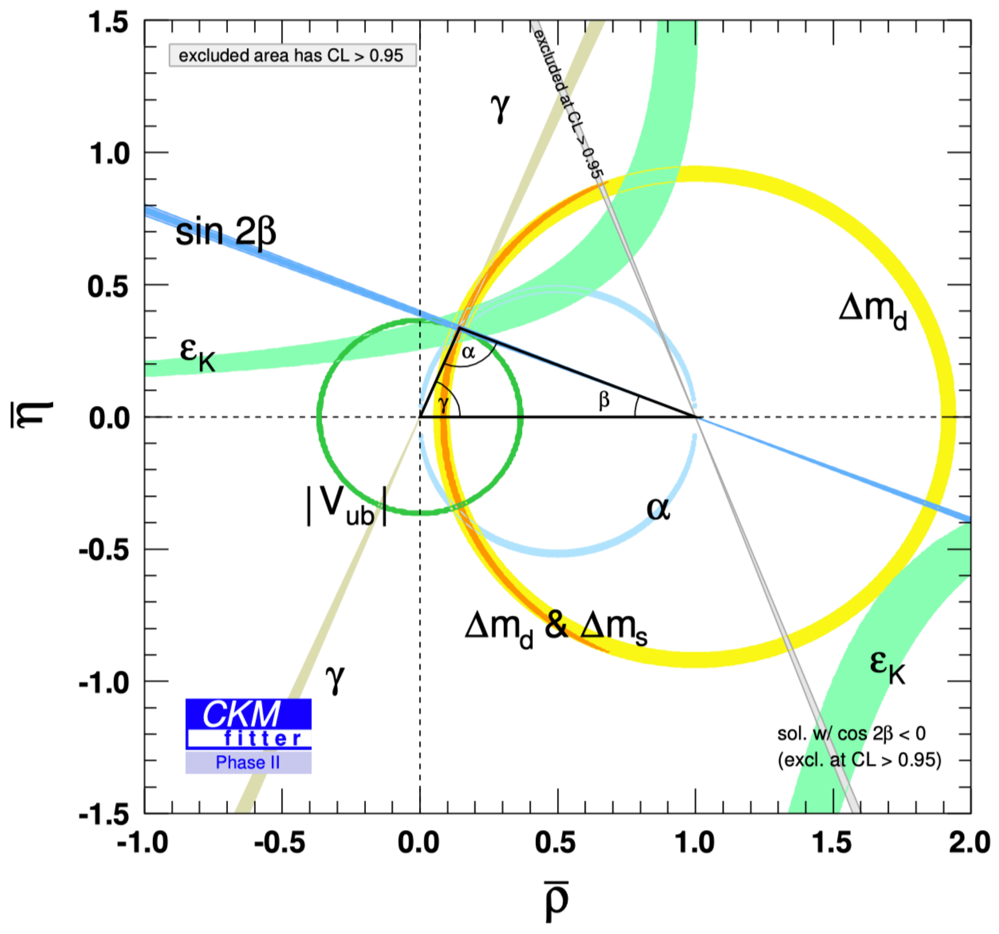


Charm physics



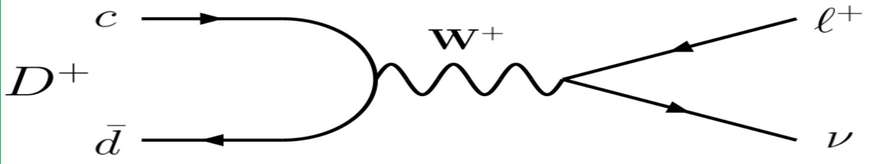
Introduction to CKM matrix

It is a close triangle in SM, and any derivation is a hint for new physics!



The study of the leptonic decay of $D^+ \to \mu^+\nu$

PRD, 89, 051104



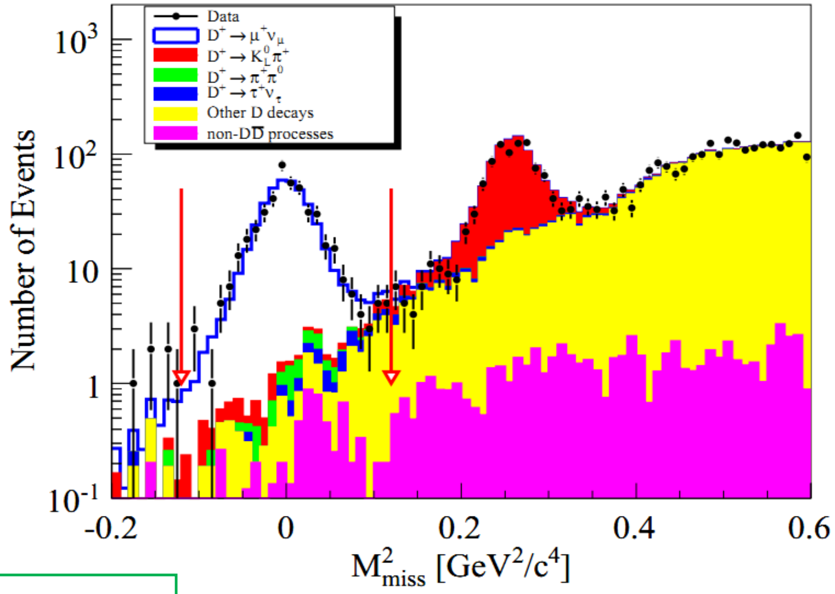
$$\Gamma(D^+ \to \ell^+\nu_\ell) = f_D^2 |V_{cd}|^2 \frac{G_F^2}{8\pi} m_D m_\ell^2 \left(1 - \frac{m_\ell^2}{m_D^2}\right)^2$$

The |Vcb| and f_{D+} are the critical parameters of the heavy-flavor physics!

Double tag method:

$N_{tag} = 1703054 \pm 3405$ from 9 tag modes;

$N_{sig} = 409.0 \pm 21.2 \pm 2.3$ from $Mmiss^2$



$B(D^+ \to \mu^+\nu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$

$f_{D+} = (203.2 \pm 5.3 \pm 1.8)$ |Vcd| from CKM-Fitter as input

$|Vcd| = 0.221 \pm 0.006 \pm 0.005$ LQCD calculated fD+ as input.

The most precise single measurement!

Measurement of the $D \to K^{+}$p^{-}strong phase difference

PLB 734, 227-233

Mixing parameters:

$$x = 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2} \qquad y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

Experimental measurement:

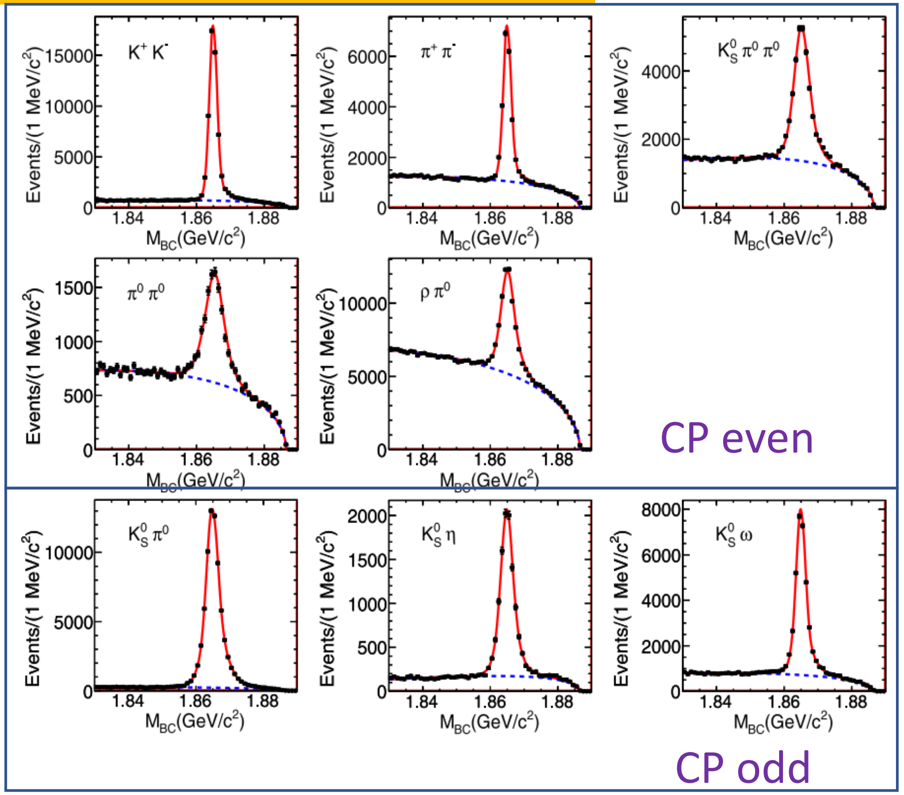
$$y' \equiv y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$
$$x' \equiv x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$

The strong phase:

$$2r\cos\delta_{K\pi} + y = (1 + R_{WS}) \cdot \mathcal{A}^{CP}_{K\pi}$$

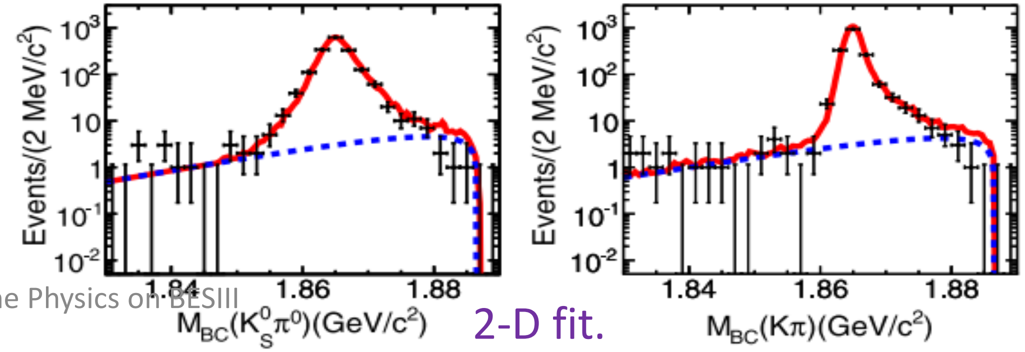
This measurement:

$$\mathcal{A}^{CP}_{K\pi} \equiv \frac{\mathcal{B}_{D^{S-}\to K^-\pi^+} - \mathcal{B}_{D^{S+}\to K^-\pi^+}}{\mathcal{B}_{D^{S-}\to K^-\pi^+} + \mathcal{B}_{D^{S+}\to K^-\pi^+}}$$



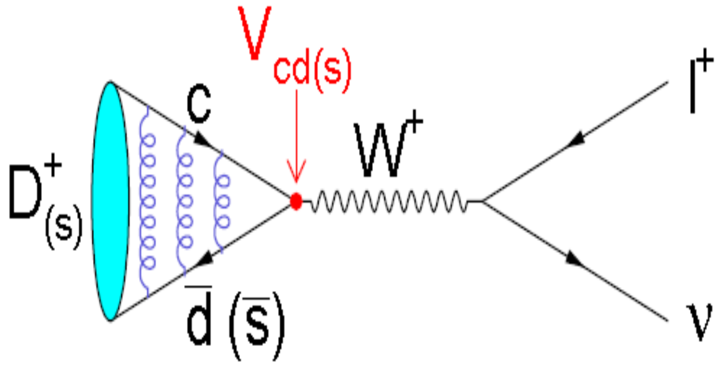
$$\mathcal{A}^{CP}_{K\pi} = (12.7 \pm 1.3 \pm 0.7) \times 10^{-2}$$
$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

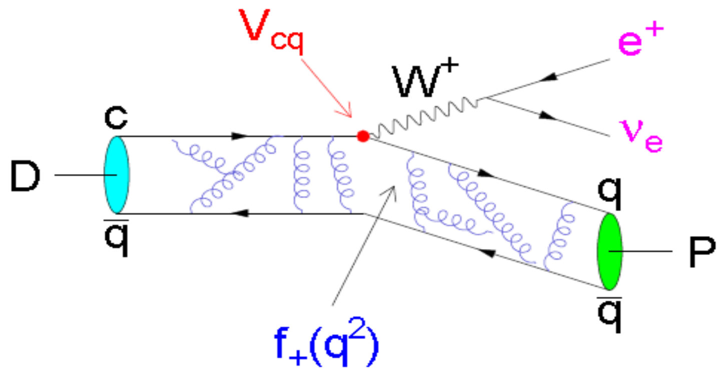
The most precise results to date!



2-D fit.

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

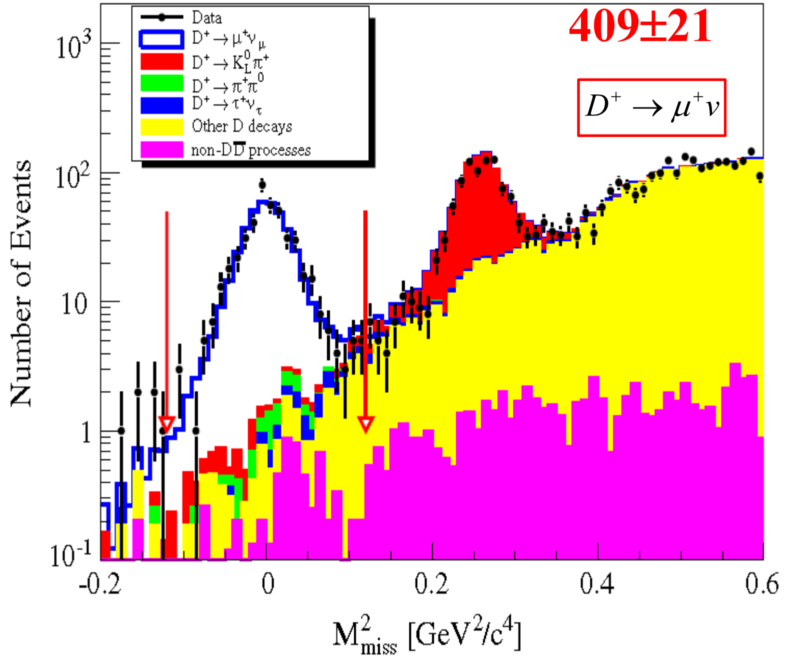
1. **$|V_{cs(d)}|$: better test on CKM matrix unitarity**
2. **(Semi-)leptonic $D_{(s)}$ decays allow for LFU tests**
3. **$f_{D(s)+}$, $f_+^{K(\pi)}(0)$: test of LQCD**

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

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

2.93 fb^{-1} data@ 3.773 GeV

PRD89, 051104 (2014)

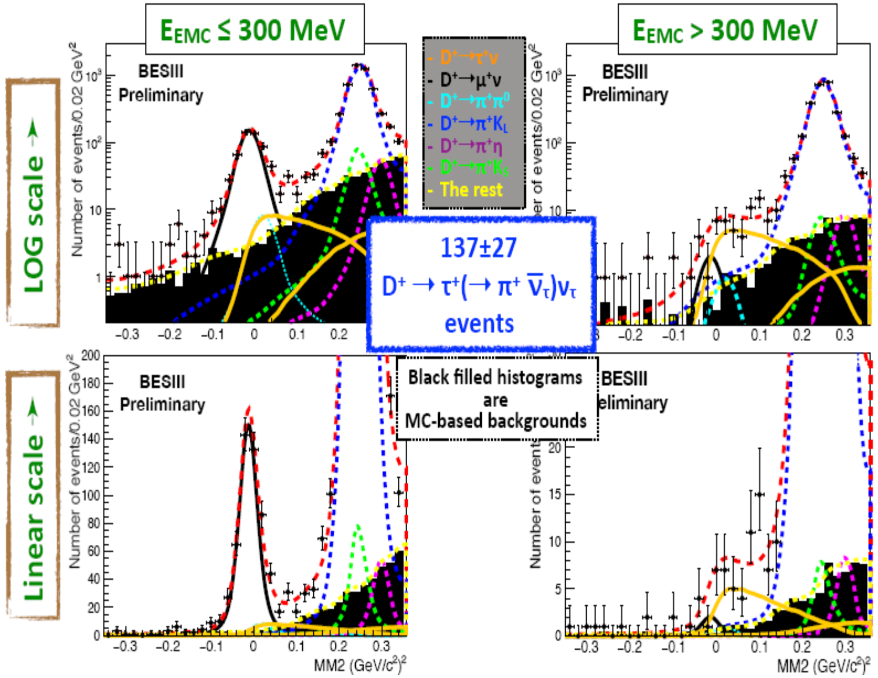


$$B[D^+ \to \mu^+ \nu] = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

$$f_{D^+}|V_{cd}| = 45.75 \pm 1.20 \pm 0.39 \text{ MeV}$$

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

BESIII preliminary



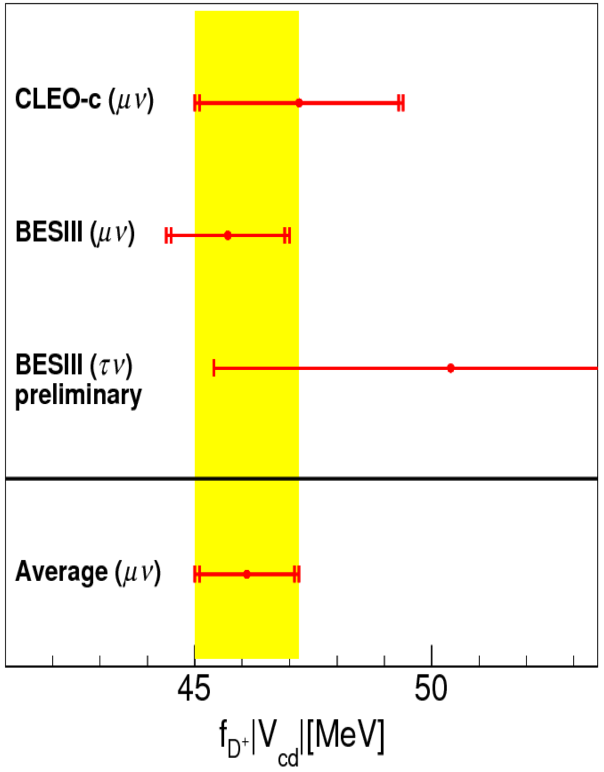
$$B[D^+ \to \tau^+ \nu] = (1.20 \pm 0.24_{stat}) \times 10^{-3}$$

$$f_{D^+}|V_{cd}| = 50.4 \pm 5.0_{stat} \text{ MeV}$$

statistical error dominant

New inputs from PDG2018:

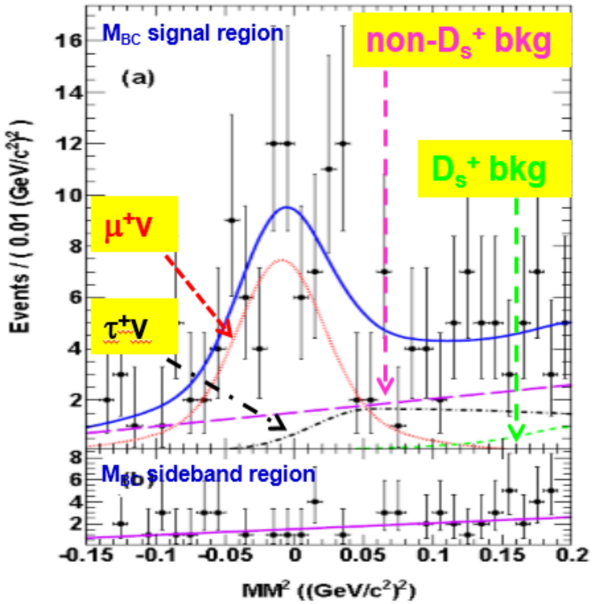
	value
m_μ	0.1056583745(24) GeV
m_τ	1.77686(12) GeV
m_{D^+}	1.86965(5) GeV
τ_{D^+}	1.040(7) ps
G_F	$1.1663787(6)\times10^{-5}$ GeV^{-2}



$f_{D_s^+}|V_{cs}|$ from $D_s^+ \rightarrow l^+ \nu$

0.48 fb^{-1} data@4.01 GeV

PRD94, 072004 (2016)



$$B[D_s^+ \rightarrow \mu^+ \nu] = (5.17 \pm 0.75 \pm 0.21) \times 10^{-3}$$

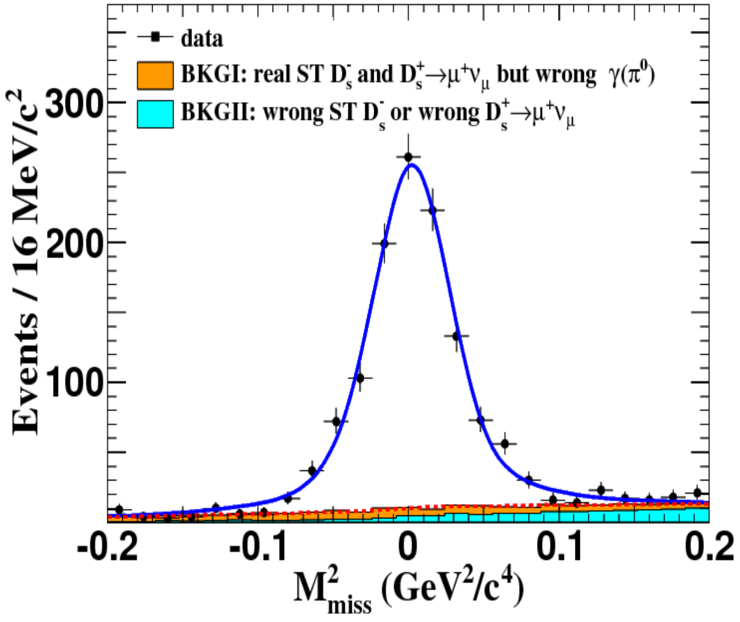
$$B[D_s^+ \rightarrow \tau^+ \nu] = (3.28 \pm 1.83 \pm 0.37)\%$$

$$f_{D_s^+}|V_{cs}| = 239 \pm 17 \pm 5 \text{ MeV } [\mu]$$

$$f_{D_s^+}|V_{cs}| = 193 \pm 54 \pm 11 \text{ MeV } [\tau]$$

3.19 fb^{-1} data@4.178 GeV

PRL122, 071802 (2019)

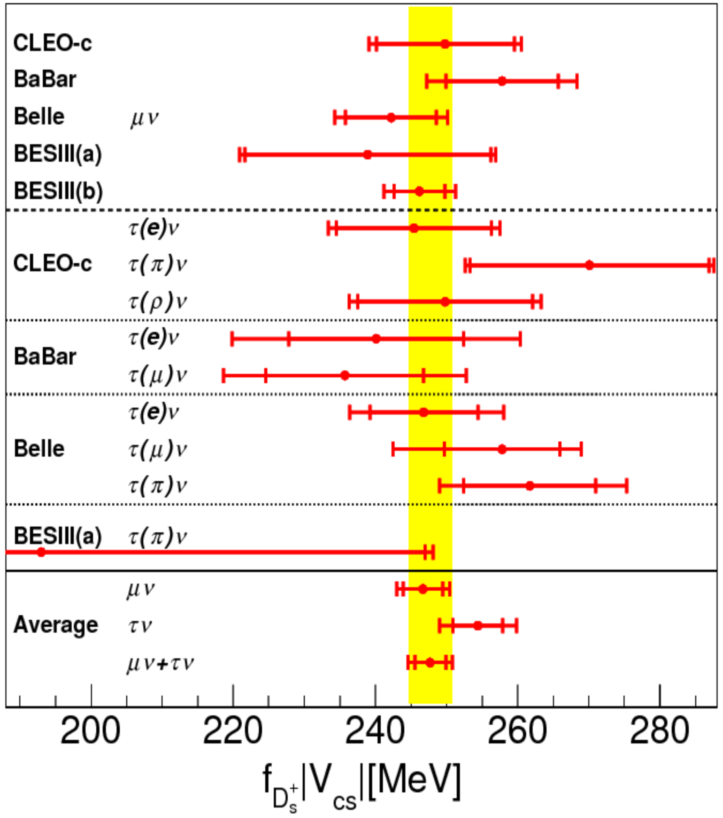


$$B[D_s^+ \rightarrow \mu^+ \nu] = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

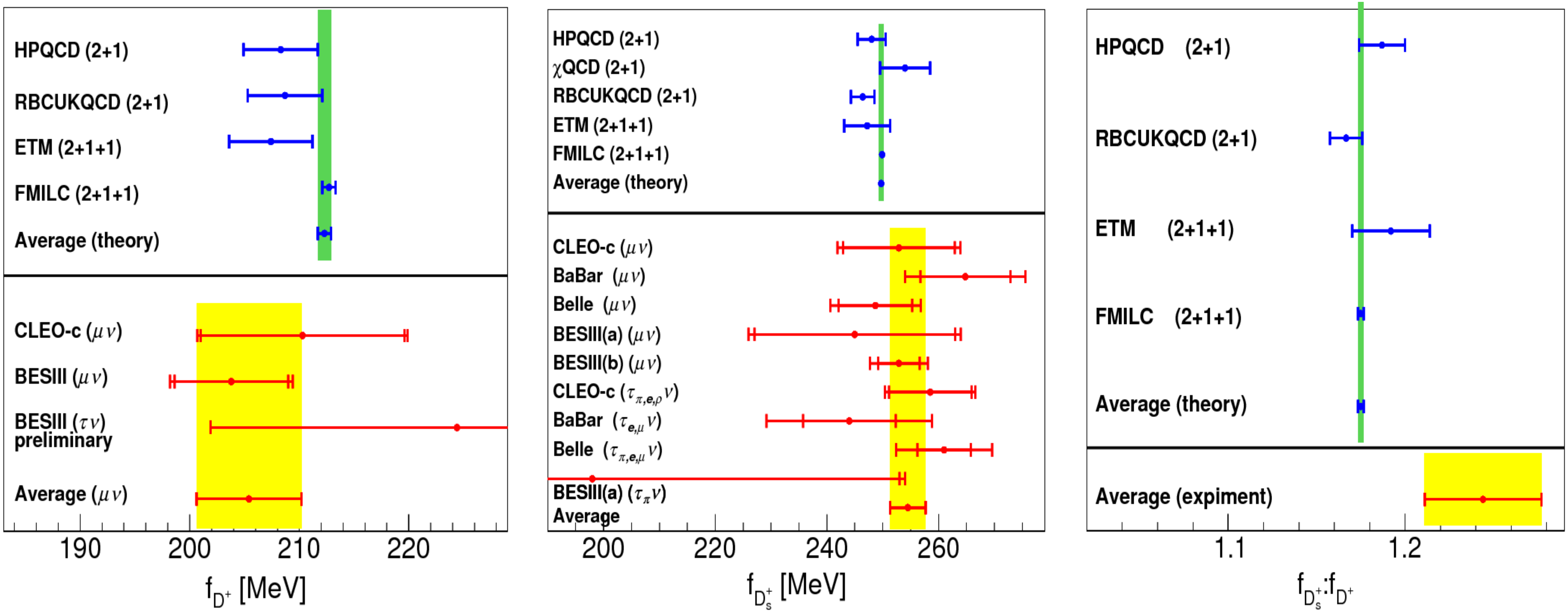
$$f_{D_s^+}|V_{cs}| = 246.2 \pm 3.6 \pm 3.5 \text{ MeV}$$

New inputs from PDG2018:

	value
m_μ	0.1056583745(24) GeV
m_τ	1.77686(12) GeV
$m_{D_s^+}$	1.96834(7) GeV
$\tau_{D_s^+}$	504(4) ps
G_F	$1.1663787(6)\times10^{-5}$ GeV^{-2}



Comparisons of f_{D+}, f_{Ds+} and $f_{D+}:f_{Ds+}$



-1.4σ difference **+1.5σ difference** **2σ difference**

➔ More discussion in Prof. Gottlieb's talk next session.

$f^K_+(0)|V_{cs}|$ from $D^0 \to K^-\mu^+\nu$

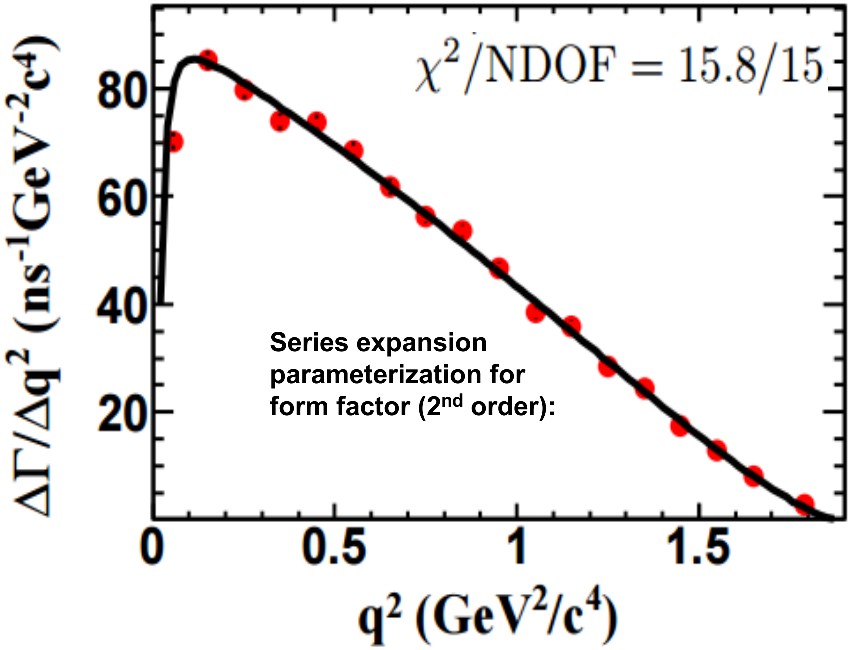
PRL122, 011804 (2019)

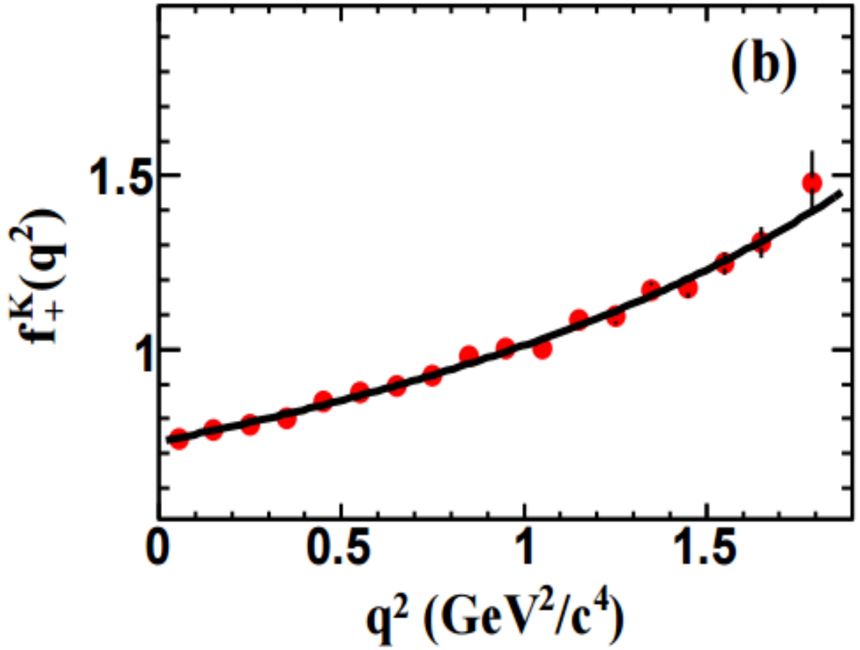
Differential partial widths

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cs}|^2}{8\pi^3 m_D}|\vec{p}_K||f_+^K(q^2)|^2\left(\frac{W_0-E_K}{F_0}\right)^2$$
$$\times\left[\frac{1}{3}m_D|\vec{p}_K|^2 + \frac{m_\ell^2}{8m_D}(m_D^2+m_K^2+2m_DE_K)\right.$$
$$+\frac{1}{3}m_\ell^2\frac{|\vec{p}_K|^2}{F_0}+\frac{1}{4}m_\ell^2\frac{m_D^2-m_K^2}{m_D}\mathrm{Re}\left(\frac{f_-^K(q^2)}{f_+^K(q^2)}\right)$$
$$\left.+\frac{1}{4}m_\ell^2F_0\left|\frac{f_-^K(q^2)}{f_+^K(q^2)}\right|^2\right]$$

Assumed to be independent of q^2 following FOCUS's treatment (PLB607, 233 (2005))

$$q = p_\mu + p_\nu$$
$$W_0 = (m_D^2 + m_K^2 - m_\ell^2)/2m_D$$
$$F_0 = W_0 - E_K + m_\ell^2/2m_D$$





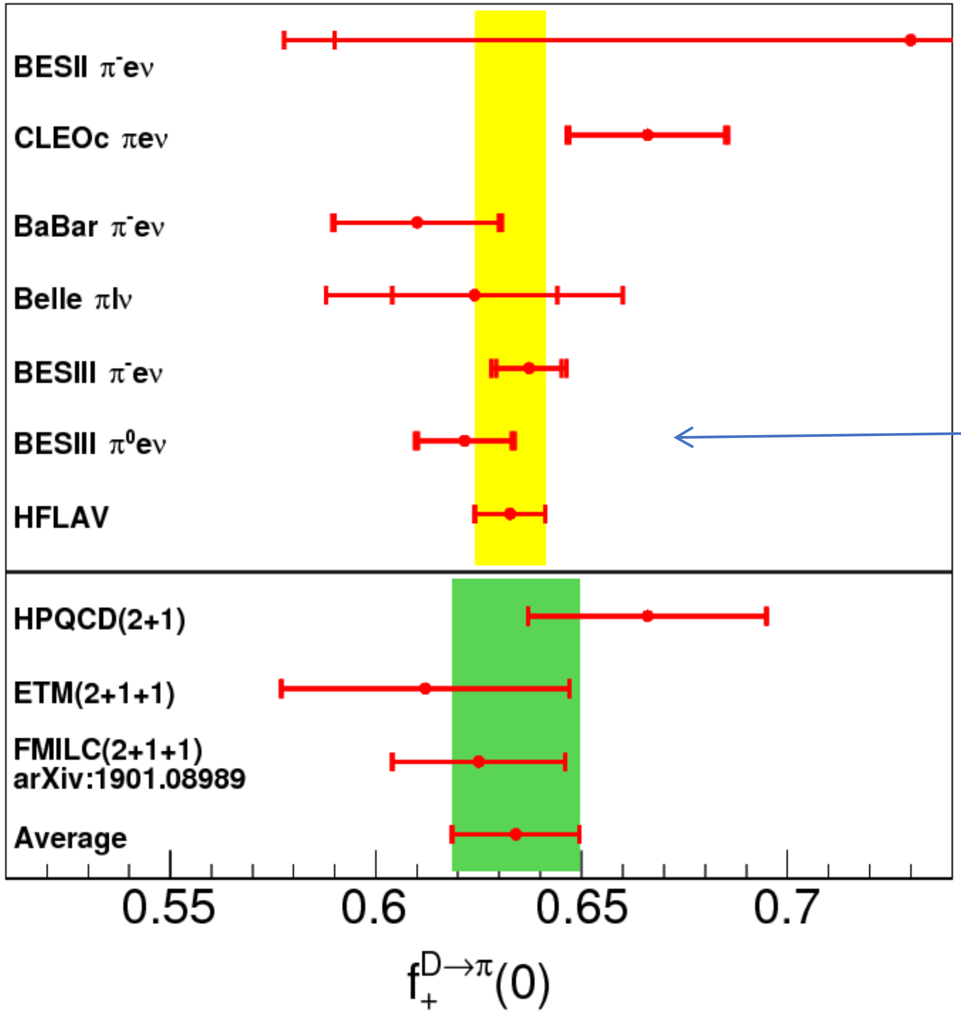
$$\boxed{f_+^K(0)\,|V_{cs}| = 0.7148(38)(29)}$$

Comparisons of form factors $f_+^{K(\pi)}(0)$

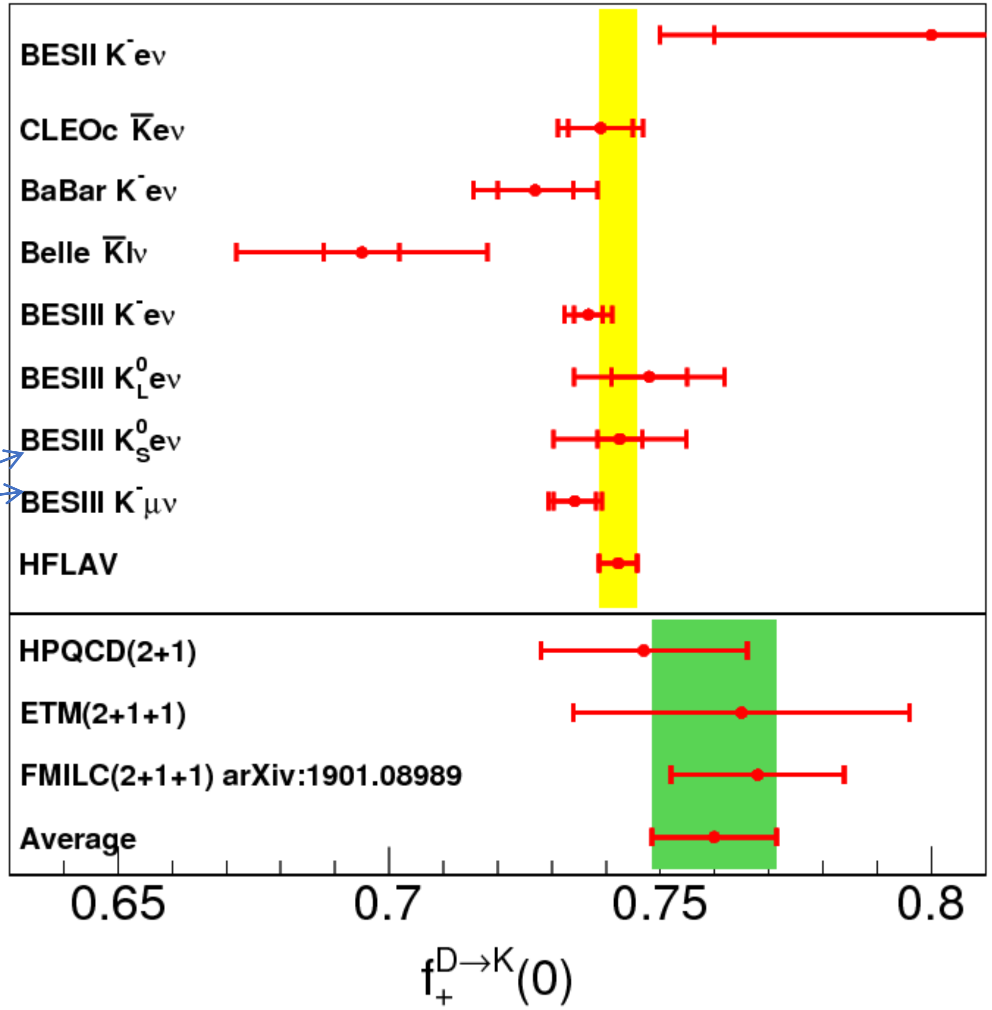
HFLAV16 averages based on a combined analysis of all D→K(π)lν measurements before 2016 using series expansion

$$f_+^K(0)|V_{cs}| = 0.7226(22)(26)$$

$$f_+^\pi(0)|V_{cd}| = 0.1426(17)(08)$$



Not included for averages



LFU test with semileptonic decays

Mode	D^0 decay BR (%)	D^+ decay BR (%)
$K e \nu$	3.505 ± 0.035	8.60 ± 0.16
$K \mu \nu$	3.413 ± 0.040	8.72 ± 0.19
$\pi e \nu$	0.295 ± 0.005	0.363 ± 0.009
$\pi \mu \nu$	0.272 ± 0.010	0.350 ± 0.015

$$R_0^\pi = \frac{\Gamma(D^0 \to \pi^- \mu^+ \nu)}{\Gamma(D^0 \to \pi^- e^+ \nu)} = 0.922 \pm 0.037$$

$$R_+^\pi = \frac{\Gamma(D^+ \to \pi^0 \mu^+ \nu)}{\Gamma(D^+ \to \pi^0 e^+ \nu)} = 0.964 \pm 0.045$$

$$R_0^K = \frac{\Gamma(D^0 \to K^- \mu^+ \nu)}{\Gamma(D^0 \to K^- e^+ \nu)} = 0.974 \pm 0.014$$

$$R_+^K = \frac{\Gamma(D^+ \to \bar{K}^0 \mu^+ \nu)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu)} = 1.014 \pm 0.017$$

Theoretical expectation:

$$R^\pi = 0.985 \pm 0.002$$

$$R^K = 0.975 \pm 0.001$$

Lepton universality tested at % level!

τ and R-QCD

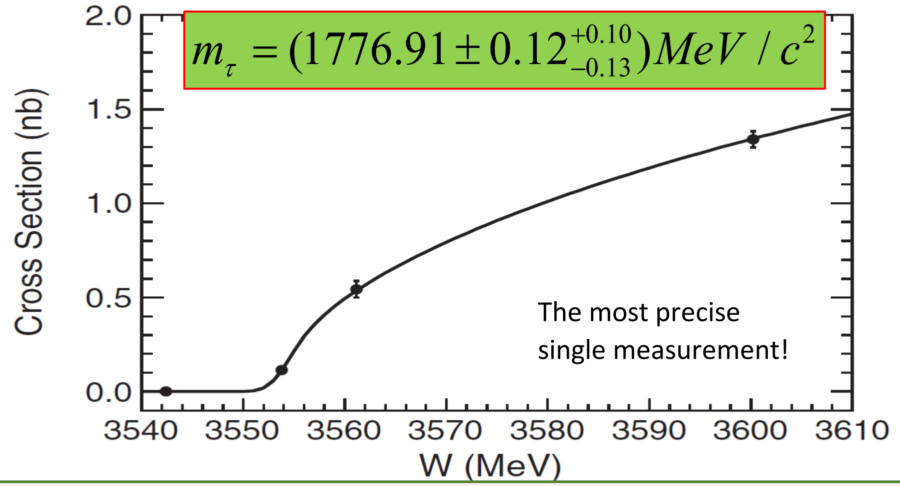
Precision measurement of the τ mass

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



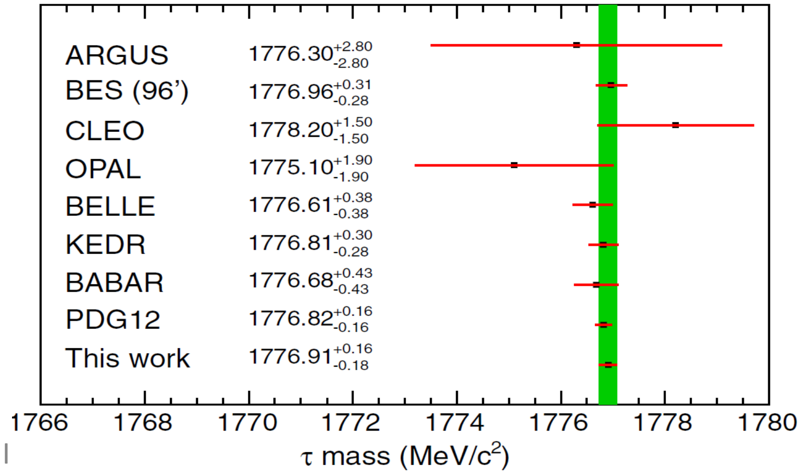
$$\sigma(E_{\rm c.m.}, m_\tau, \delta_w^{\rm BEMS}) = \frac{1}{\sqrt{2\pi}\delta_w^{\rm BEMS}} \int_{2m_\tau}^{\infty} dE'_{\rm c.m.}\, e^{\frac{-(E_{\rm c.m.}-E'_{\rm c.m.})^2}{2(\delta_w^{\rm BEMS})^2}} \int_0^{1-\frac{4m^2}{E'^2_{\rm c.m.}}} dx F(x, E'_{\rm c.m.}) \frac{\sigma_1(E'_{\rm c.m.}\sqrt{1-x},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

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

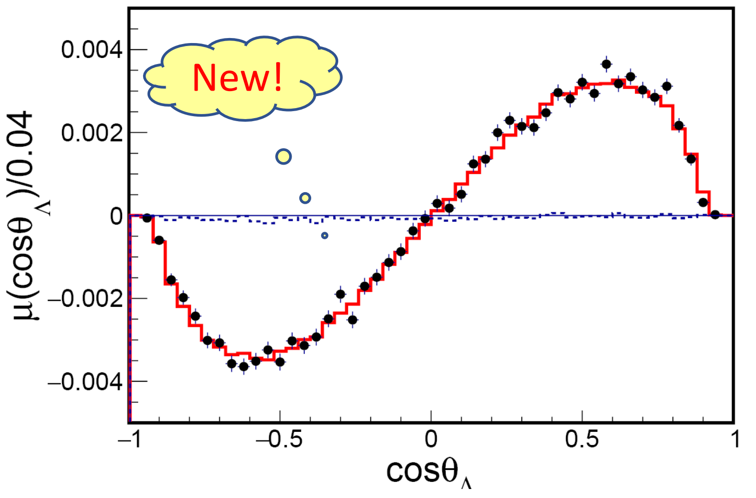
$$g_\tau = (1.1650 \pm 0.0034) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

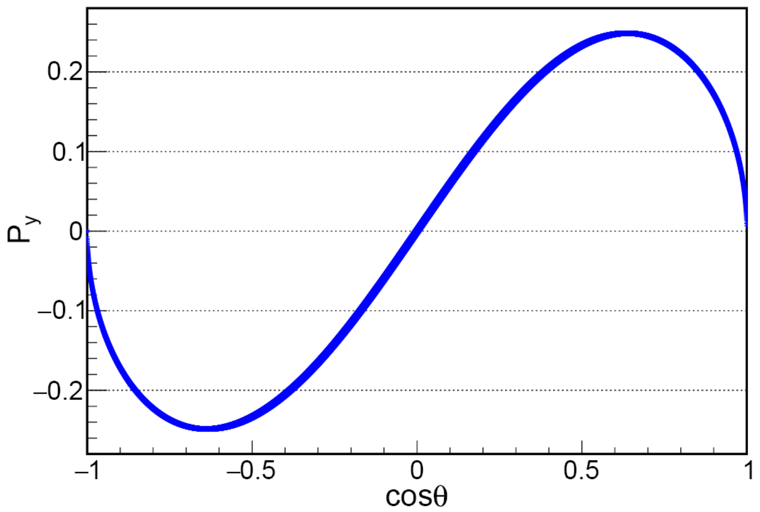
$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B(\tau \to e\nu\bar{\nu})}{B(\mu \to e\nu\bar{\nu})}(1+F_W)(1+F_\gamma)$$

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



Polarization of Λ hyperon and CPV





420K selected $J/\psi \to \Lambda\bar{\Lambda}$ in 1.3B J/ψ events.

First observation of Λ polarization!

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

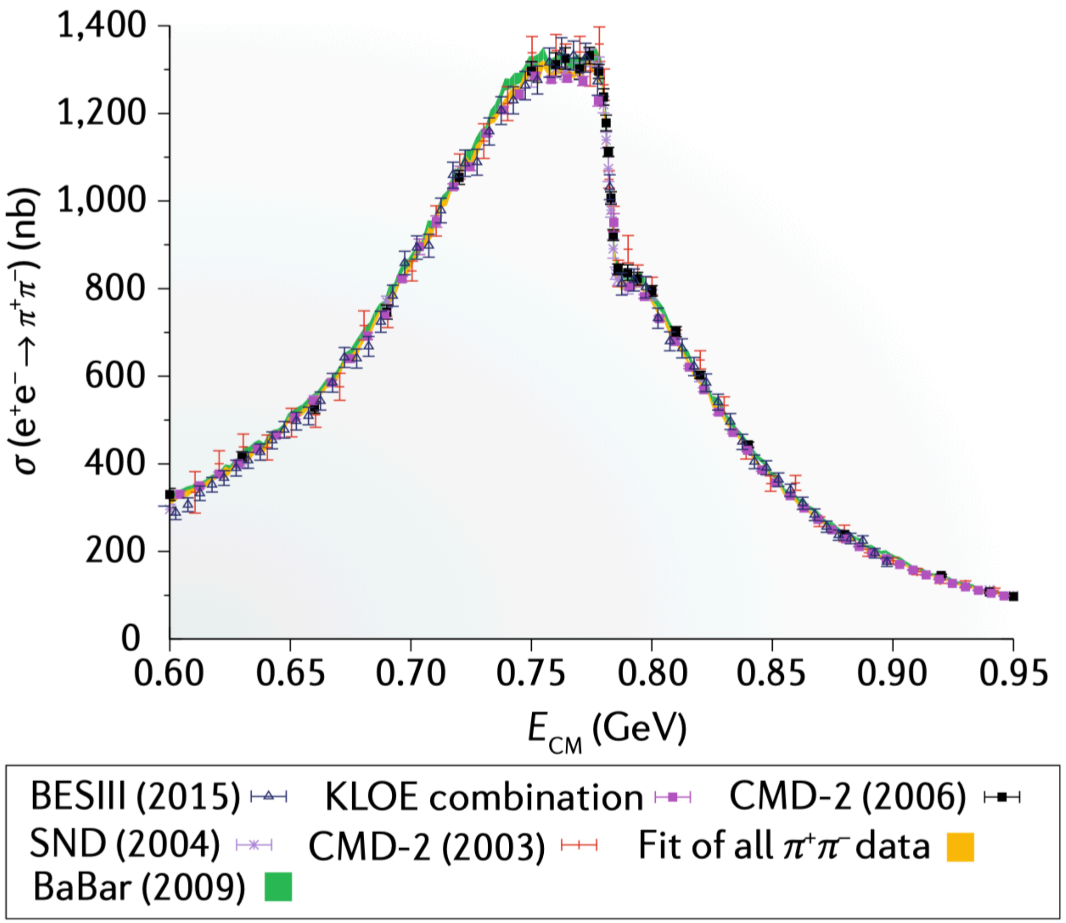
Only measurement used in PDG 2019

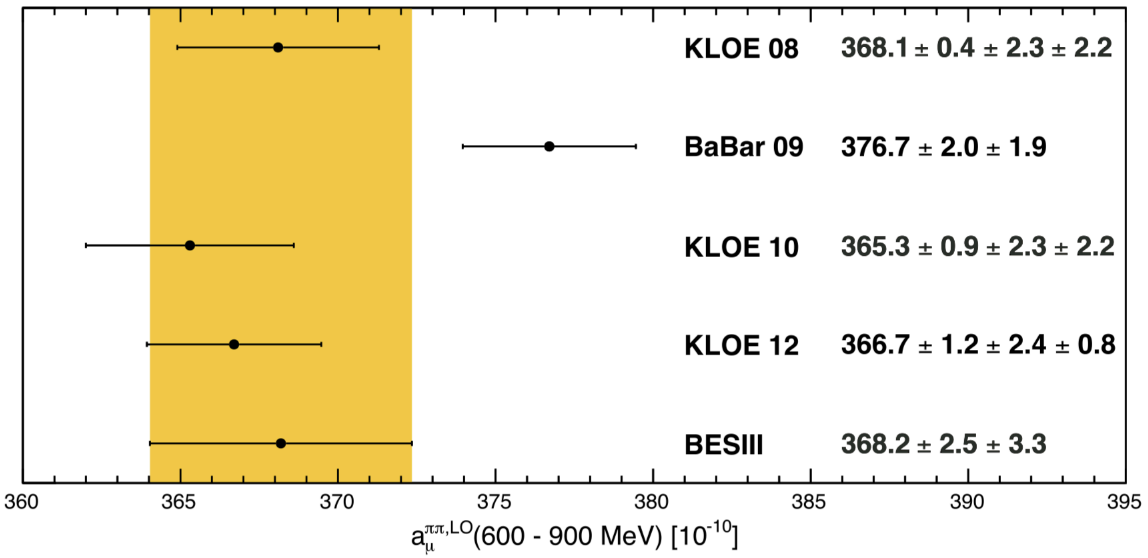
2% level sensitivity for CPV test

Highest sensitivity test of CPV in baryon decays!

arXiv: 1808.08917, Nature Physics (2019) https://www.nature.com/articles/s41567-019-0494-8

Precision measurement of $e^+e^- \to \pi^+\pi^-$





Physics Letters B 753 (2016) 629–638

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;

Still a rich program ahead

arXiv:1912.05983

Table 7.1: List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The most right column shows the number of required data taking days in current (T_C) or upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

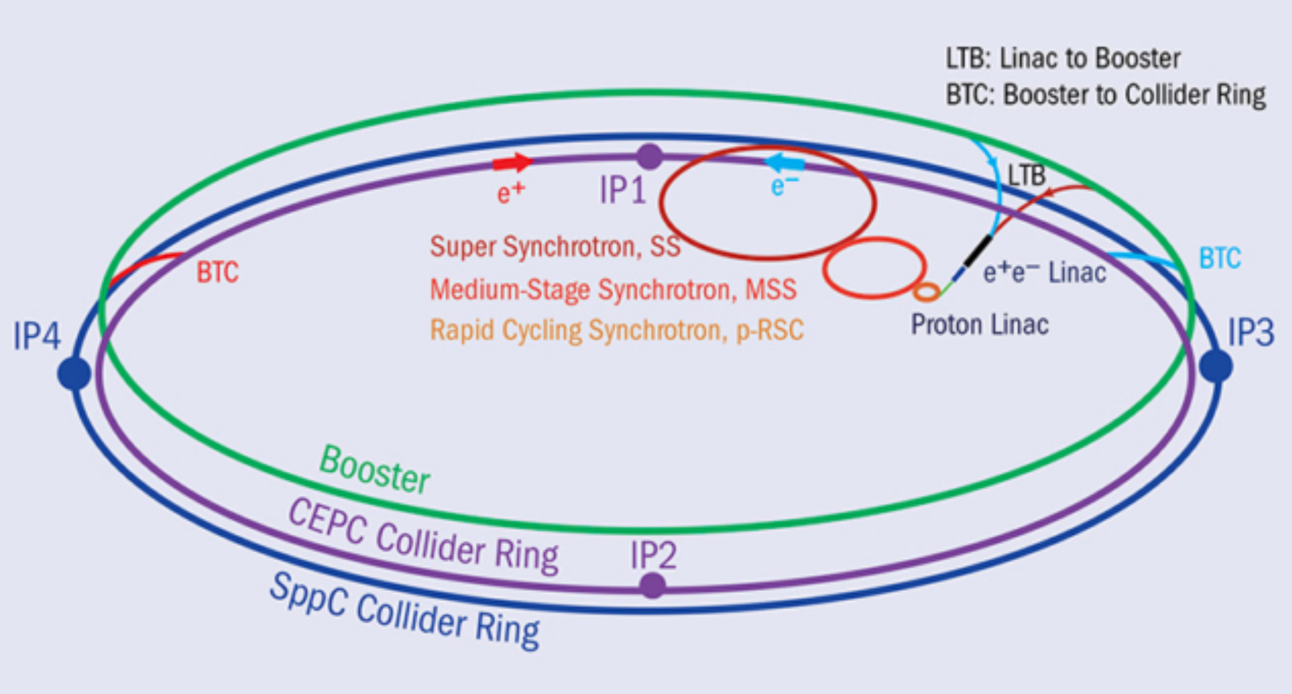
Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

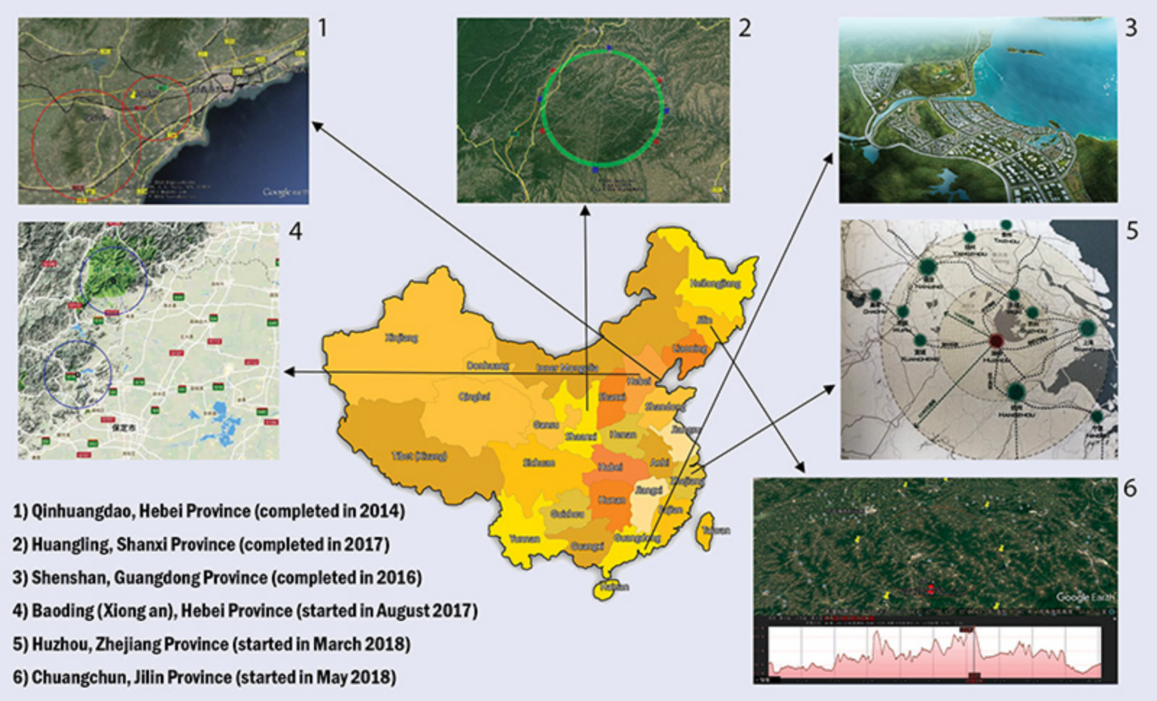
Luminosity upgrade plan in the near future

	Present BEPCII	L*2.0	L*2.5	L*3.0
β_y^*	1.5 cm	1.5cm	1.2cm	1.05cm
Bunch currnt	7mA	9mA	9mA	9mA
Bunch number	80	120	120	120
SR power	125kW	250kW	250kW	250kW
Beam-beam	0.036	0.04	0.04	0.04
RF voltage	1.6 MV	2.2 MV	> 3.4 MV	> 4.0 MV
ν_s	0.028	0.033	0.041	0.044
HOM power	7.7 kW	19.1 kW	29.7 kW	38.8 kW
RF cavity		1 new RFC/ring	2 RFC/ring	2 new RFC/ring
Coupling	1	1	*0.8	*0.7
Dynamic aperture	1	1	*0.8	*0.7
Beam lifetime	2 hr	1 hr	0.64 hr	0.5 hr

Dedicated for the beam energy above 2.1 GeV. 3~4 years after the project is approved.

From BEPC to CEPC





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