# Hadron Spectroscopy: State of the Art and Future Challenges

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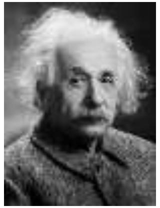
Feb. 21th, 2020

# Agenda

- The discovery of antimatter
- Cosmic Rays
- Neutrinos
- Hadrons: Baryons & Mesons
- Electromagnetic vs Strong Interaction
- Light Scalar Mesons, Nonets
- The $J/\psi$ discovery
- D-Mesons & Charmonium States
- Quantum Chromodynamics Predictions
- Glueballs, Tetraquarks and Hybrids
- BESIII Experiment
- Isobar Model: Analysis of $J/\psi \rightarrow \phi\pi\pi$
- The $Z_c(3900)^{\pm}$ discovery
- Future experiments SuperCharm-tau & CEPC



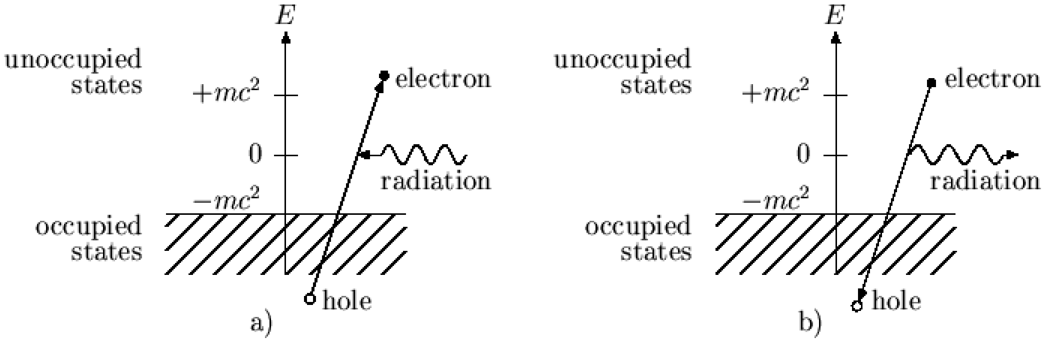
# Particles & Anti-particles (Albert Einstein and Paul Dirac) and the positron discovery

four-vectors or four-momenta: $p \equiv (p_x, p_y, p_z, E)$

Dirac relatovistic energy-momentum equation: $E^2 = \vec{p}^2 c^2 + m_0^2 c^4$

if a particle is at rest: $v = 0, p = 0 \Rightarrow E = \sqrt{m_0^2 c^4}, E = \pm m_0 c^2$

Two solutions of Dirac's equation: one with positive and one with negative energy!



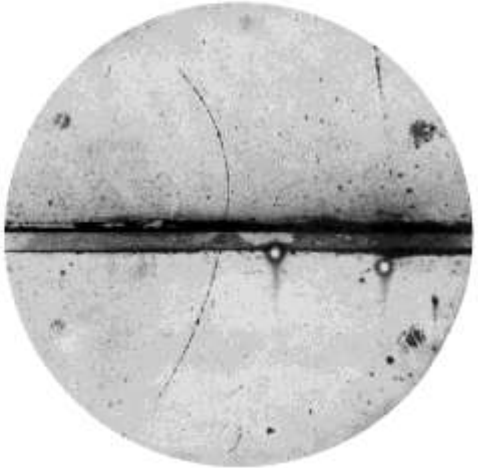

Units: $E = m_0 c^2 \Rightarrow m_0 = E/c^2$ $\quad E = pc \Rightarrow p = E/c$

mass: eV/c$^2$ , momemtum: eV/c$^2$

1 MeV= $10^6$ eV, 1 GeV=$10^9$ eV, 1 TeV= $10^{12}$ eV, 1PeV=$10^{15}$eV, 1 EeV=$10^{18}$ eV

electron's and proton's rest mass: $m_{e^-} \sim 0.5\,\mathrm{MeV/c^2}, m_p = 938\,\mathrm{MeV/c^2}$

# Positron Discovery
# (Carl David Anderson)



*Cloud chamber and lead plate immersed in a magnetic field: the curvature on the charged track depends on the velocity of the particle:*

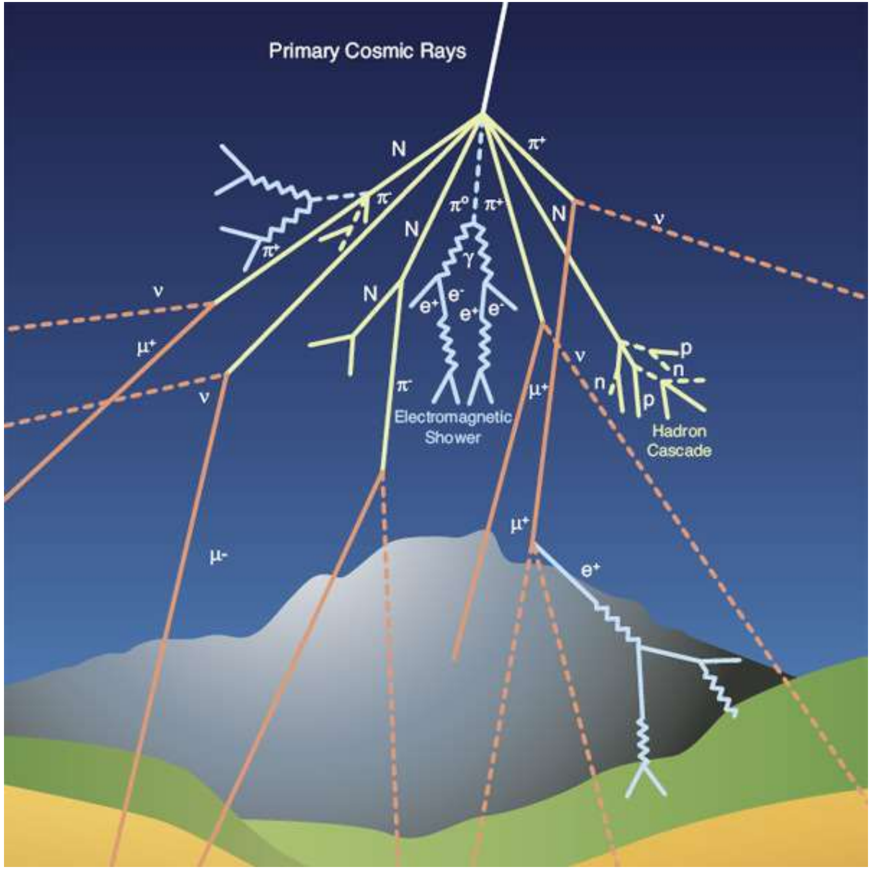
$$Bqv = ma = m\frac{v^2}{r} \Rightarrow \frac{q}{m} = \frac{v}{Br} = \frac{e}{m}$$

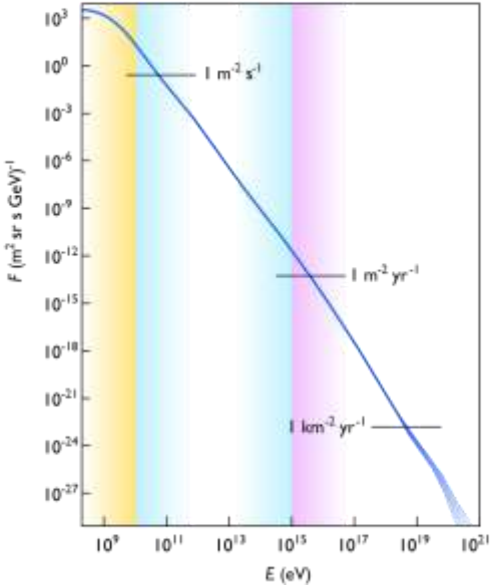
*Charge/mass ratio same as the one of the electron, direction of motion of a positive charge*

*Positron originated from cosmic rays: Nobel price in Physics in 1936 (for the discovery of the positron and the muon).*

$$m_{e^-} = m_{e^+} \sim 0.5\,\mathrm{MeV/c^2} \qquad q_{e^+} = -q_{e^-} = +e \qquad s_{e^-} = s_{e^+} = \frac{1}{2}$$

# What are the cosmic rays?



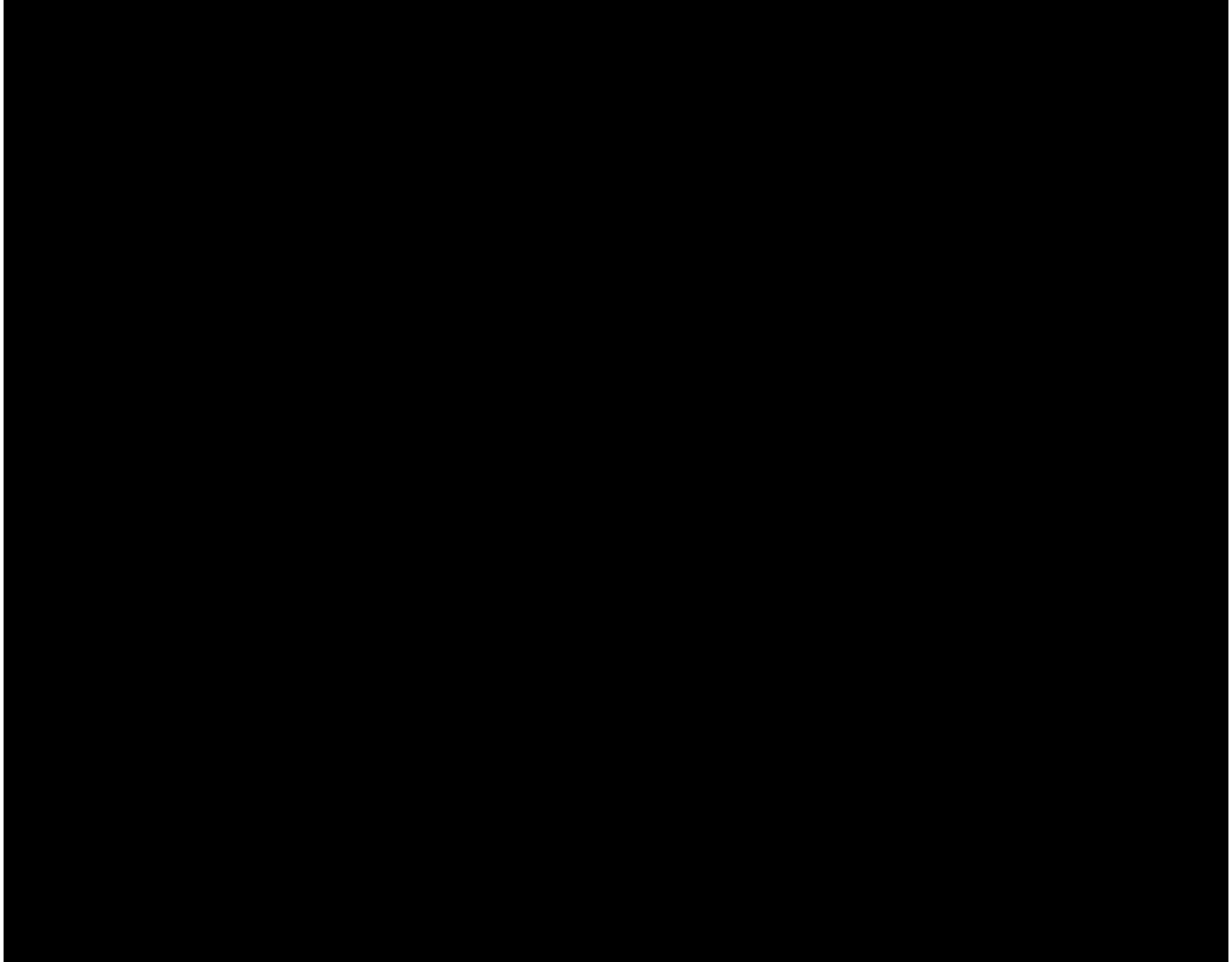



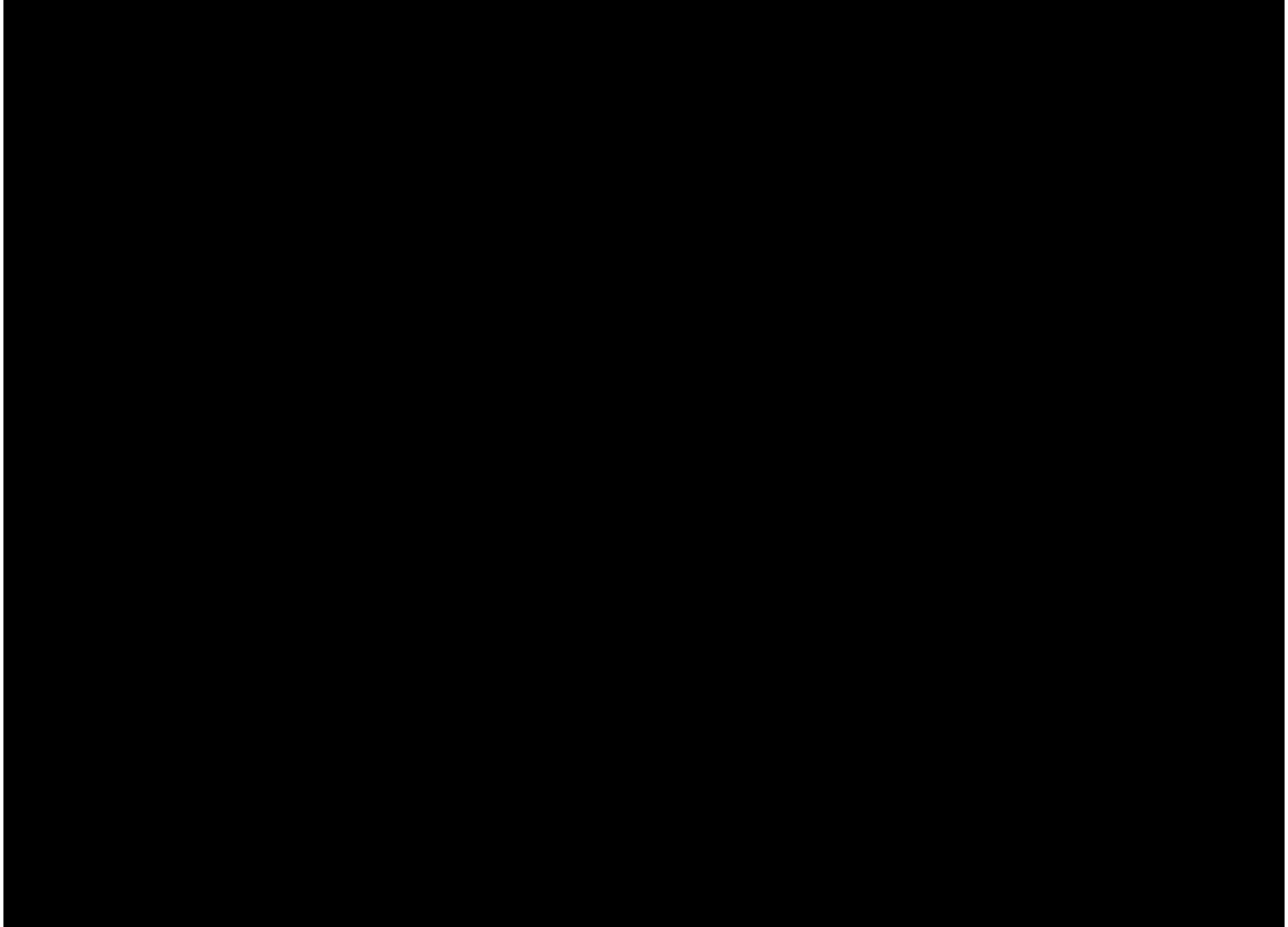

*Particles from outer space: mainly protons and heavier nucleons: their origin is still unknown.*

*Energies of a primaru cosmic ray particle can reach* $10^{20}$ eV, *a factor* $10^7$ *of the maximum energies obtained at CERN!*

*Every minute about 600 muons cross our body with an energy between* 3 *to* 4 GeV!

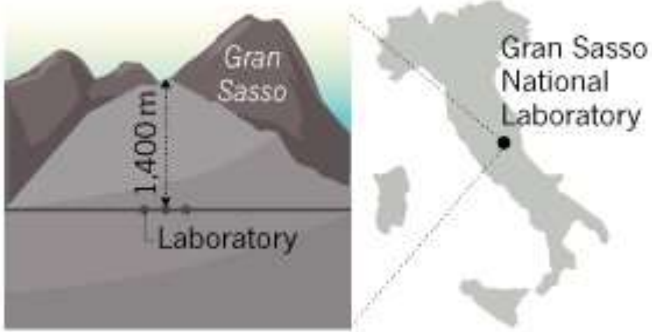
$$m_{\mu^-} = m_{\mu^+} \sim 106\,\mathrm{MeV/c^2}$$

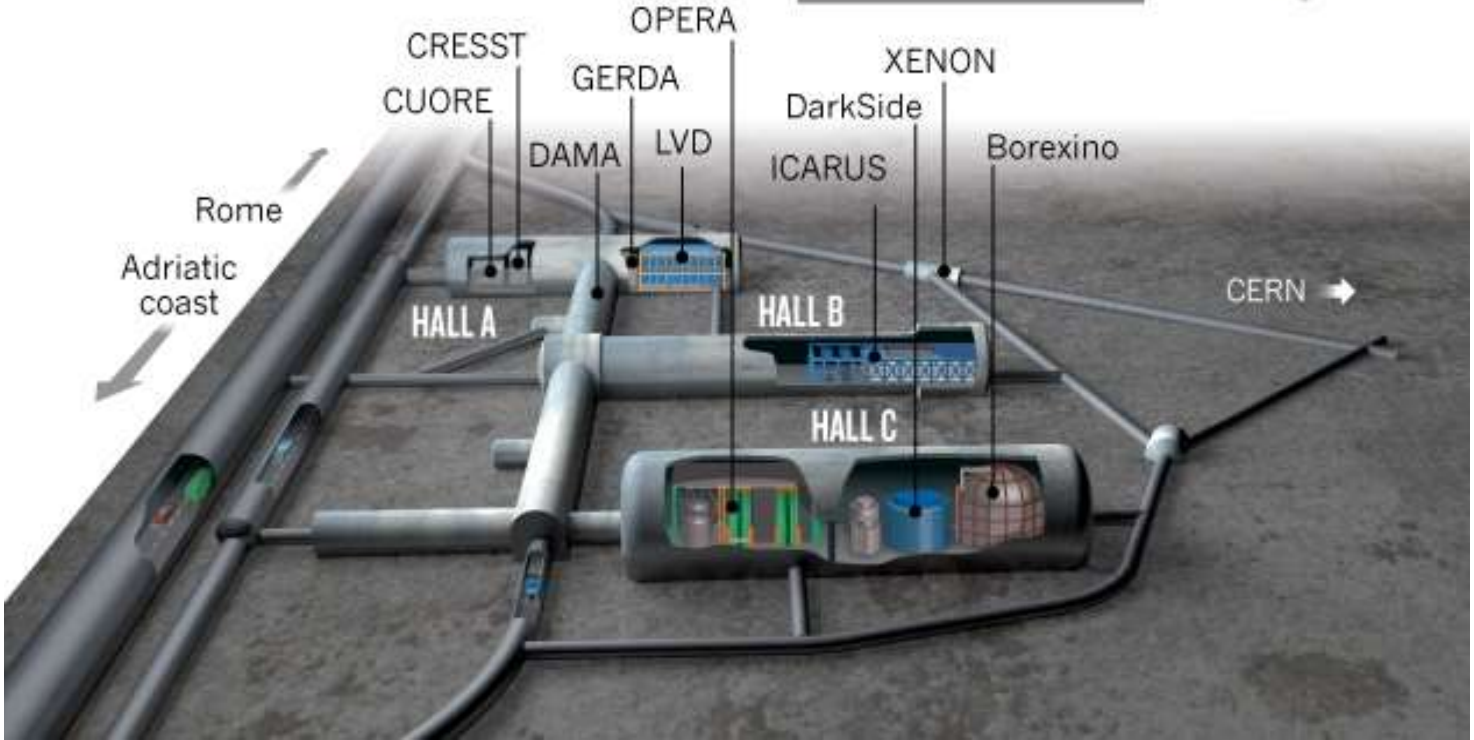




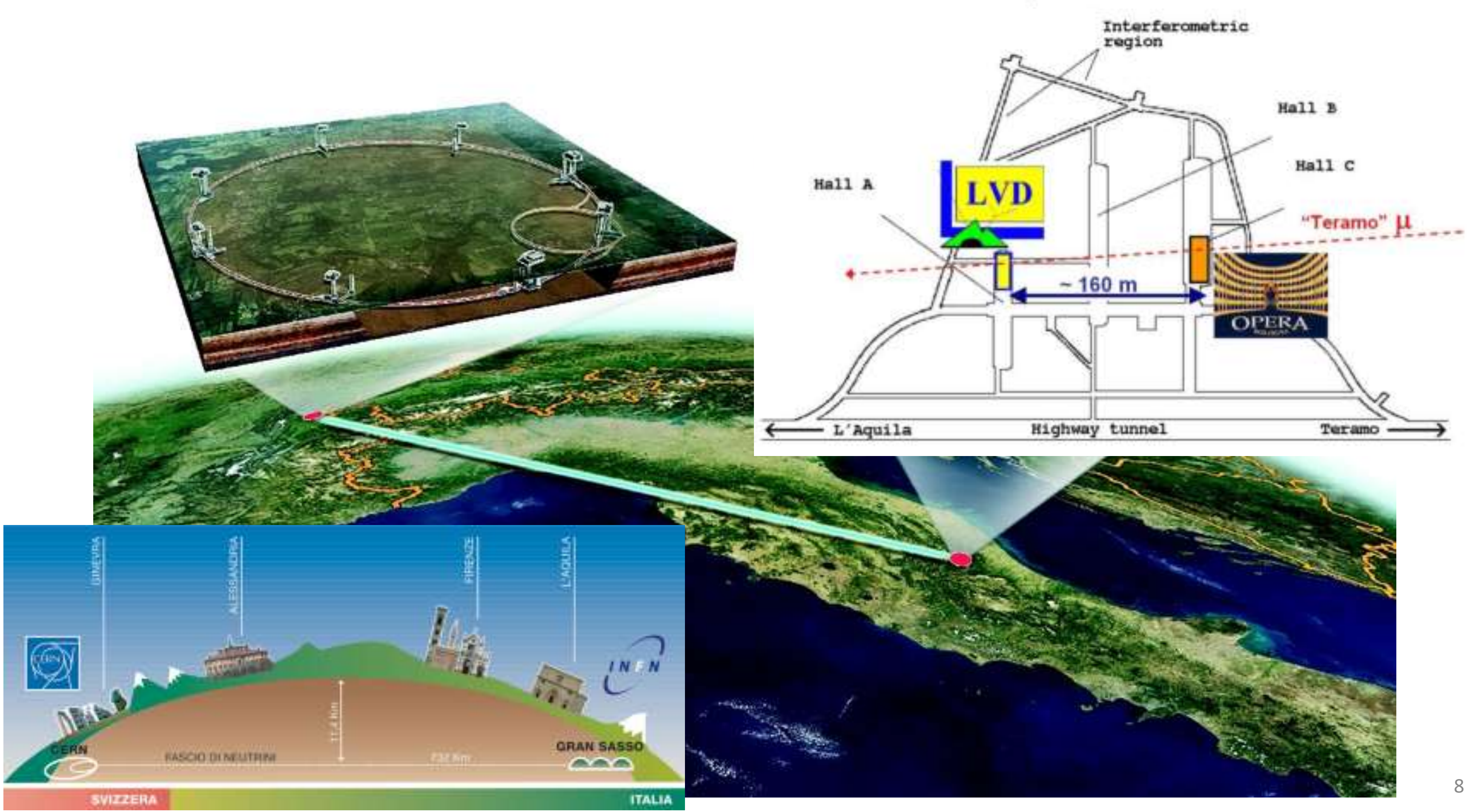
# THE A, B AND C OF GRAN SASSO

Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.

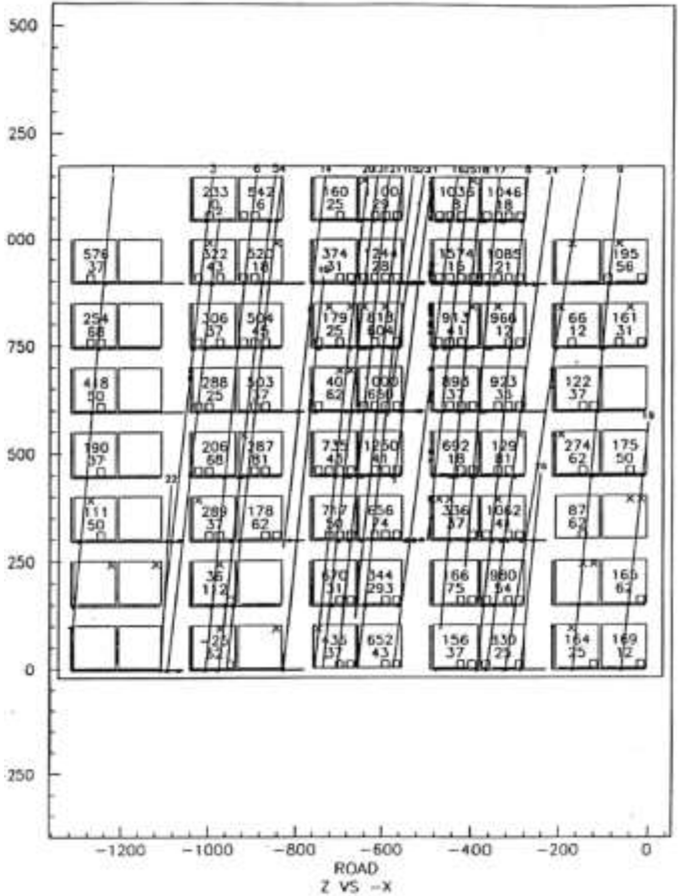


# CERN- LNGS Distance



# Multiple Muon Event recorded by LVD experiments at LNGS



# The 'ghostly' neutrino particle

- Second most abundant particle in the Universe, after photons of light

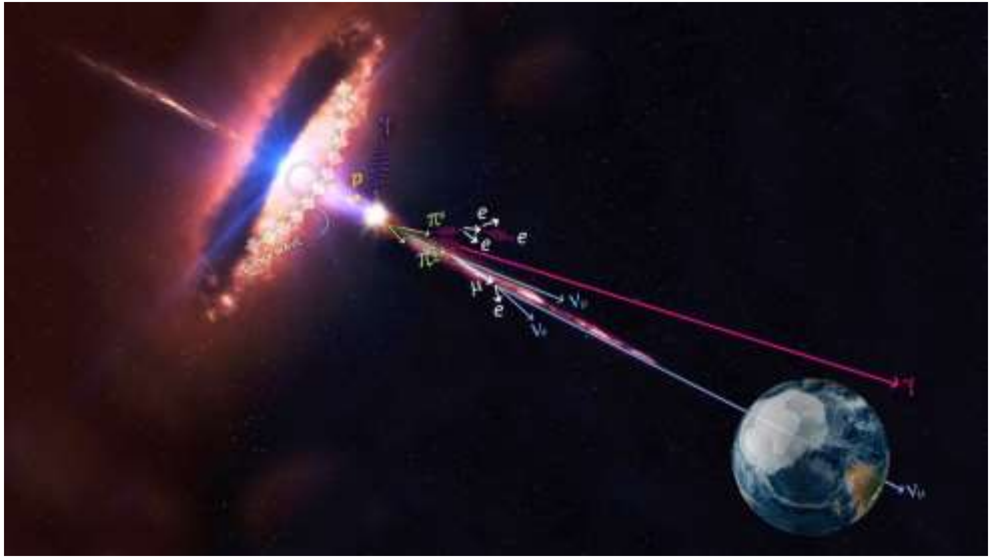
- Neutrino means 'small neutral one' in Italian; was first proposed by Wolfgang Pauli in 1930

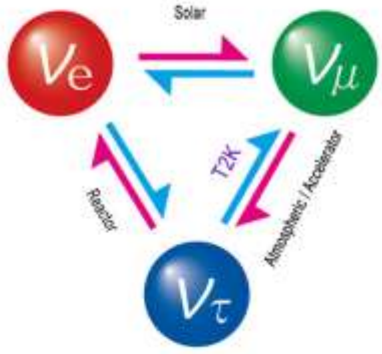
- Uncharged, and created in nuclear reactions and some radioactive decay chains

- Shown to have a tiny mass, but hardly interacts with other particles of matter

- Comes in three flavours, or types, referred to as muon, tau and electron

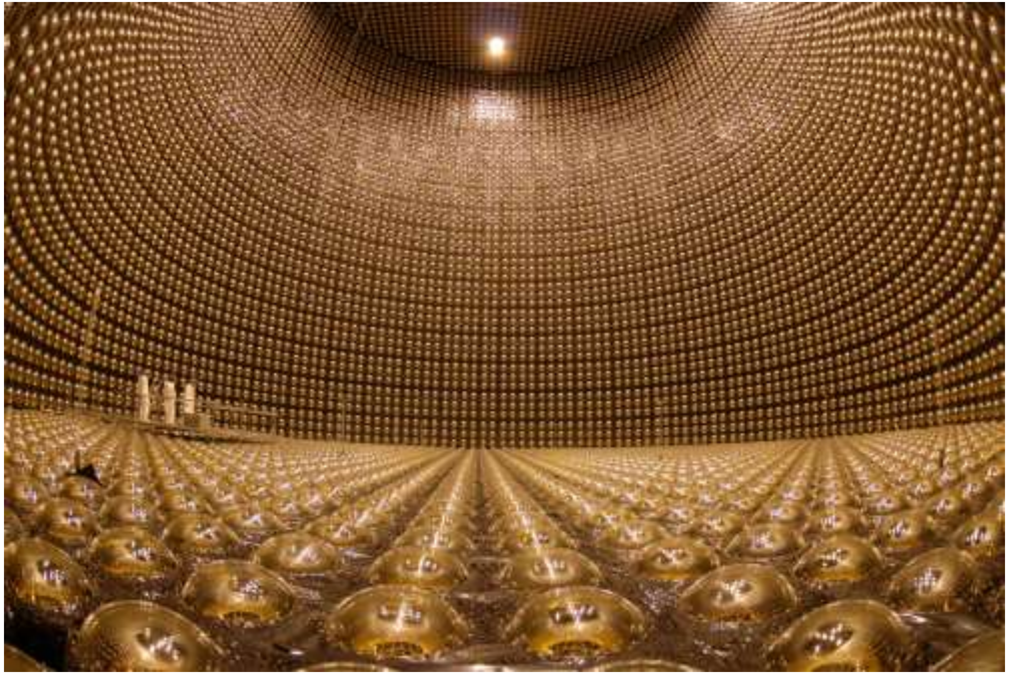
- These flavours are able to oscillate - flip from one type to another - during flight

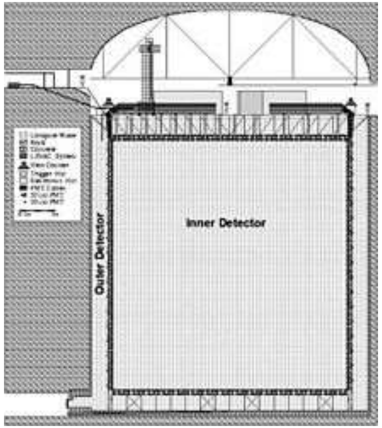





Neutrino oscillation between three generations

# SuperKamiokande Experiment in Japan



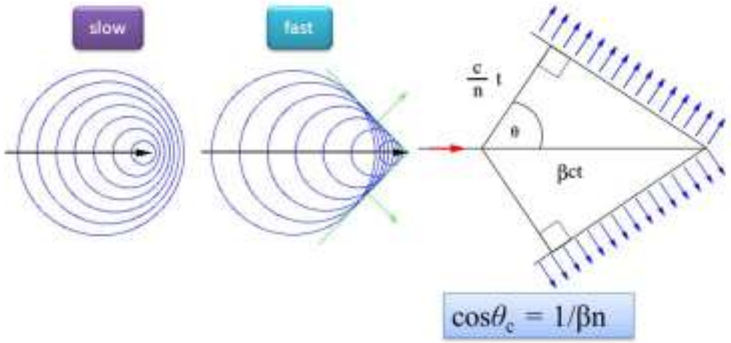


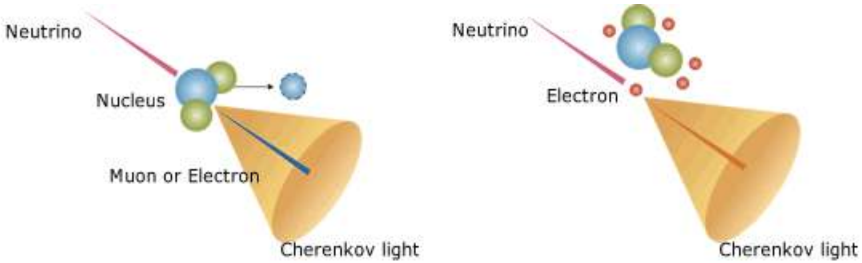

- as high as 15 store building
- 1000 m underground
- 50,000 tonnes of water
- 13000 Photo Multiplier Tubes
- Cherenkov Radiation:
charged particles like muons when travel faster than light speed in water emit blue radiation

# Neutrino Observation by Cherenkov Radiation

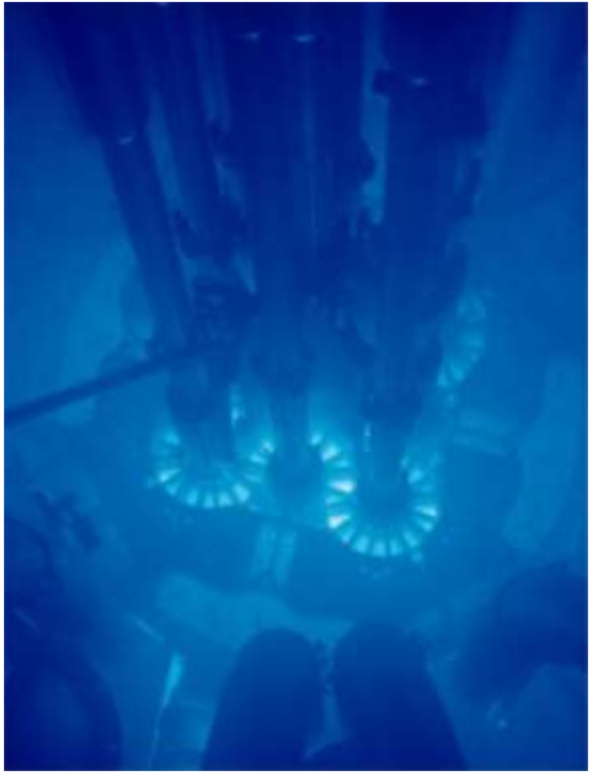
## Cherenkov Radiation

In the figure, v is the velocity of the particle (red arrow), β; is v/c, n is the refractive index of the medium. The blue arrows are photons.




The generated charged particle emits the Cherenkov light.

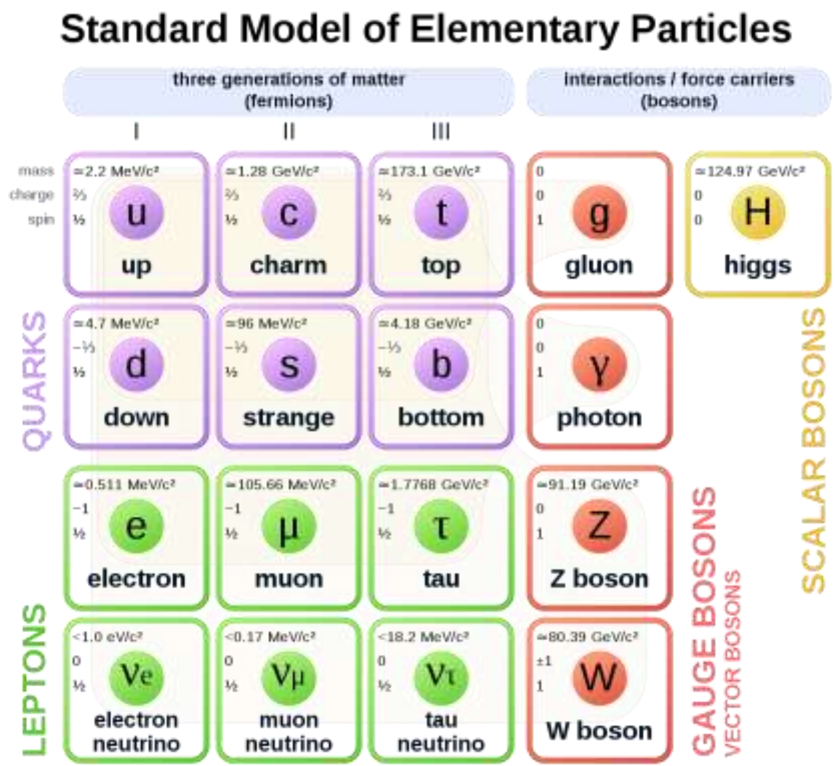


# The Neutrino Catchers:
# Takaaki Kajita and Arthur B.McDonald
# 2015 Nobel Price in Physics

"Neutrinos are unusual, ghost-like particles. Every second, more than 60 billion of them pass through every square centimetre of our body (and through everything else); most of them originate from the Sun." Quote by Takaaki Kajita

"(…) you have the ability to observe particles that come directly from the core of the Sun. They're telling you what's happing there right now in terms of the nuclear reactions that are powering it, you are able to make measurements of the fundamental properties of the neutrinos themselves (…)." Quote from Arthur B. McDonald

# Baryons and their Quark Structure




proton (anti-proton): $p(\bar{p})$

$m_p = m_{\bar{p}} \sim 938\,\mathrm{MeV/c^2}$

$q_p = +e, q_{\bar{p}} = -e$

$s_p = s_{\bar{p}} = \frac{1}{2}$

mean lifetime: $\tau > 10^{29}$ years

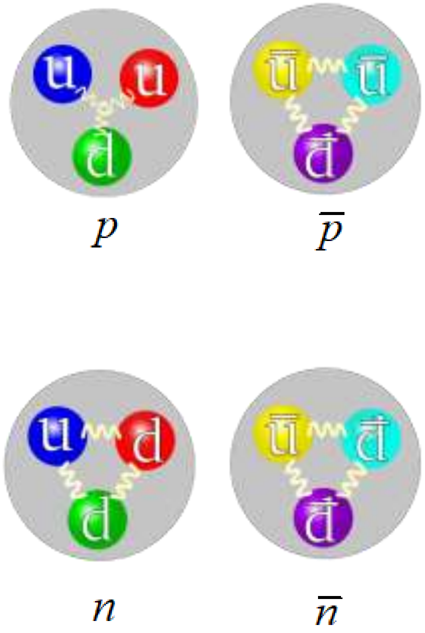
neutron (anti-neutron): $n(\bar{n})$

$m_n = m_{\bar{n}} \sim 940\,\mathrm{MeV/c^2}$

$q_n = q_{\bar{n}} = 0$

$s_n = s_{\bar{n}} = \frac{1}{2}$

mean lifetime: $\tau = 881\mathrm{s}$



# Light Scalar Mesons and their Quark Structure

pions: $\pi^+, \pi^-, \pi^0$

$$m_{\pi^+} = m_{\pi^-} \sim 140\,\mathrm{MeV/c^2}$$

$$m_{\pi^0} \sim 135\,\mathrm{MeV/c^2}$$

$$q_{\pi^+} = +e, q_{\pi^-} = -e, q_{\pi^0} = 0$$

$$s_{\pi^+} = s_{\pi^-} = s_{\pi^0} = 0$$

kaons:

$$m_{K^+} = m_{K^-} \sim 494\,\mathrm{MeV/c^2}$$

$$m_{K^0} \sim 498\,\mathrm{MeV/c^2}$$

$$q_{K^+} = +e, q_{K^-} = -e, q_{K^0} = 0$$

$$s_{K^+} = s_{K^-} = s_{K^0} = 0$$


$\pi^+$


$K^+$

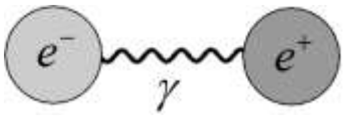

$K^-$


$K^0$

# Electromagnetic vs. Strong Force

## Electromagnetic Interaction

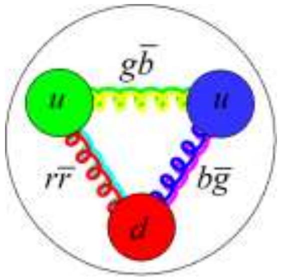
Example:
positronium



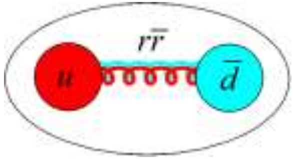

- particles can have positive, negative or zero electric e.m. charge
- photons are the carriers of the e.m. force
- photons do not have e.m. charge
- the e.m. force acts on a long distance
- photons do not interact with other photons

## Strong Interaction

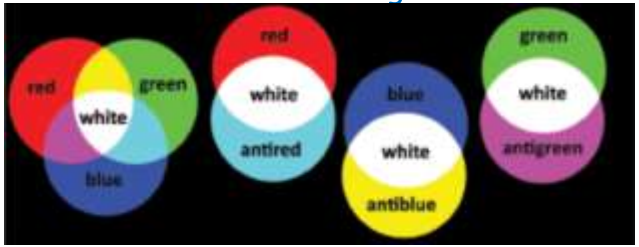
baryons




meson
s

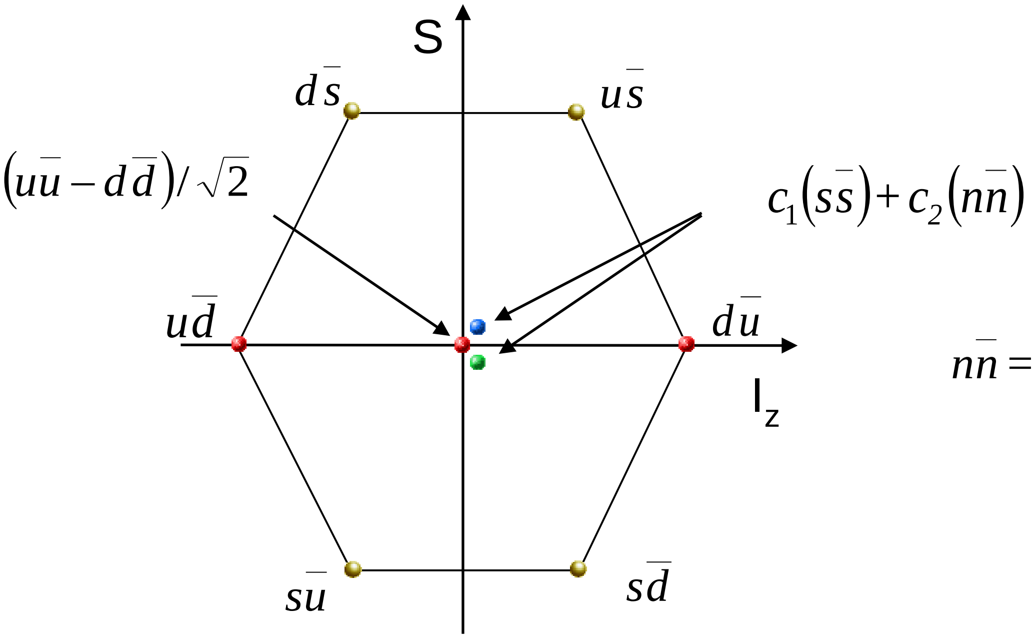



- quarks have only one "colour" charge out of three
- baryons and mesons are "colourless"
- gluons are the carriers of the force
- gluons have two "colour" charges: a colour and an anti-colour (9-1=8 carriers)
- the strong force acts on a short distance
- quarks are "confined"
- gluon can interact with other gluons



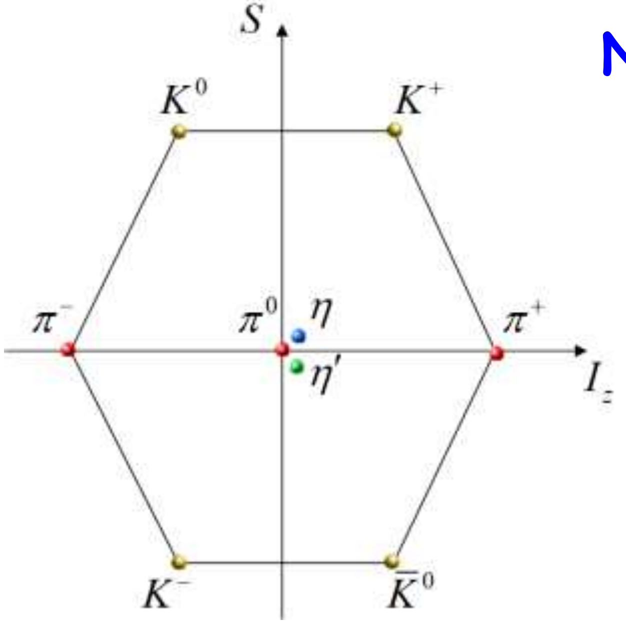
# The Eightfold Way, Nonets, Mixing

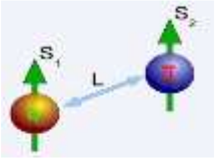
$q\bar{q}$ -states: from SU(3) with u,d,s $\Rightarrow 3 \otimes \bar{3} = 1 \oplus 8$

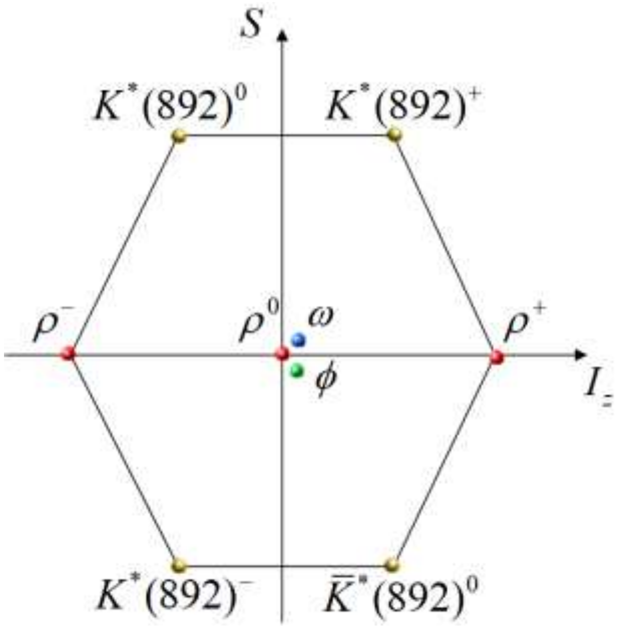



$n\bar{n} = (u\bar{u} \pm d\bar{d})/\sqrt{2}$

# Nonet Configurations




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

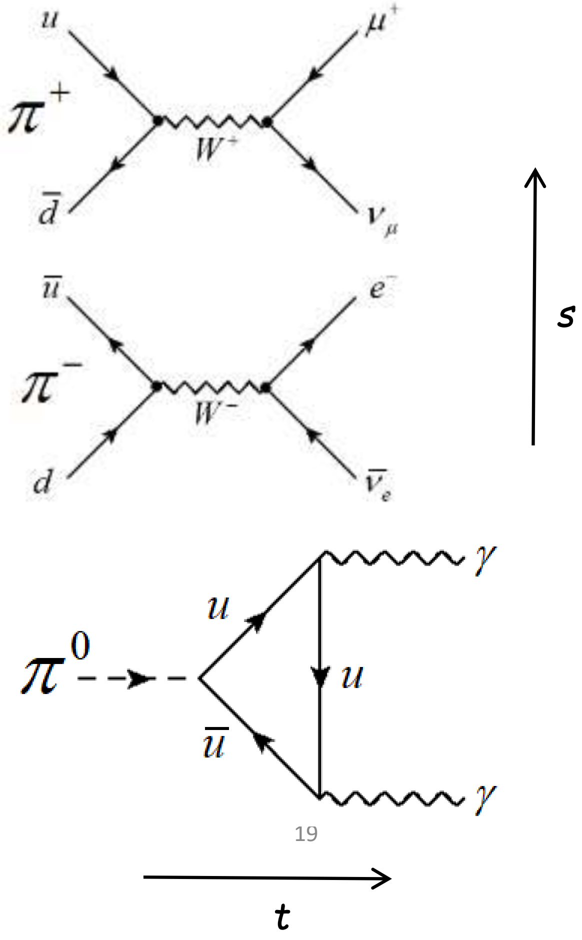
$1^1S_0\ (0^{-+})$
Pseudoscalar meson nonet

$1^3S_1\ (1^{--})$
Vector nonet

| $n^{2S+1}L_J(J^{PC})$ | I=1 | I=0 | I=0 $(n\bar{n})$ | I=1/2 $(s\bar{s})$ |
|---|---|---|---|---|
| $1^1S_0\ (0^{-+})$: | $\pi(135)$, | $\eta(547)$, | $\eta'(958)$, | $(0^-)$: K(495) |
| … | | | | |
| $1^3S_1\ (1^{--})$: | $\rho(770)$, | $\omega(780)$, | $\phi(1020)$, | $(1^-)$: $K^*(892)$ |
| $2^3S_1\ (1^{--})$: | $\rho(1450)$, | $\omega(1450)$, | $\phi(1680)$, | $(1^-)$: $K_1^*(1410)$ |
| … | | | | |
| $1^3P_2\ (2^{++})$: | $a_2(1320)$, | $f_2(1275)$, | $f_2'(1525)$, | $(2^+)$: $K_2^*(1430)$ |
| … | | | | |

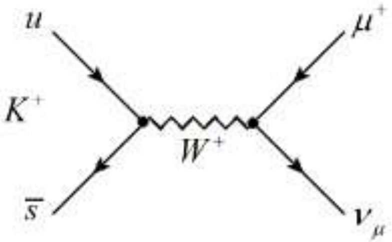
# Light Mesons Decays, Branching Ratios and Forces

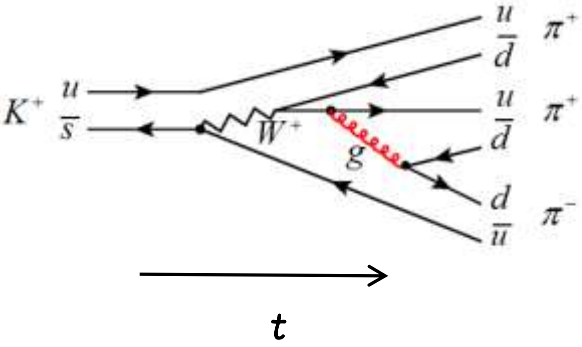
| decay | branching ratio | force |
|---|---|---|
| $\pi^+ \to \mu^+ + \nu_\mu$ | 0.999877 | weak |
| $\pi^- \to \mu^- + \overline{\nu}_\mu$ | 0.999877 | weak |
| $\pi^+ \to e^+ + \nu_e$ | 0.000123 | weak |
| $\pi^- \to e^- + \overline{\nu}_e$ | 0.000123 | weak |
| $\pi^0 \to 2\gamma$ | 0.98823 | electromagnetic |
| $\pi^0 \to \gamma + e^+ + e^-$ | 0.01174 | electromagnetic |



# Strange Mesons Decays, Branching Ratios and Forces

| decay | branching ratio | force |
|---|---|---|
| $K^+ \rightarrow \mu^+ + \nu_\mu$ | 0.6355 | weak |
| $K^+ \rightarrow \pi^+ + \pi^0$ | 0.2066 | weak |
| $K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$ | 0.0559 | weak+strong |
| $K^+ \rightarrow \pi^+ + \pi^0 + \pi^0$ | 0.0176 | weak+strong |
| $K^+ \rightarrow \pi^0 + e^+ + \nu_e$ | 0.0507 | weak |
| $K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$ | 0.0335 | weak |



# SPEAR Experiment at SLAC (California, USA)

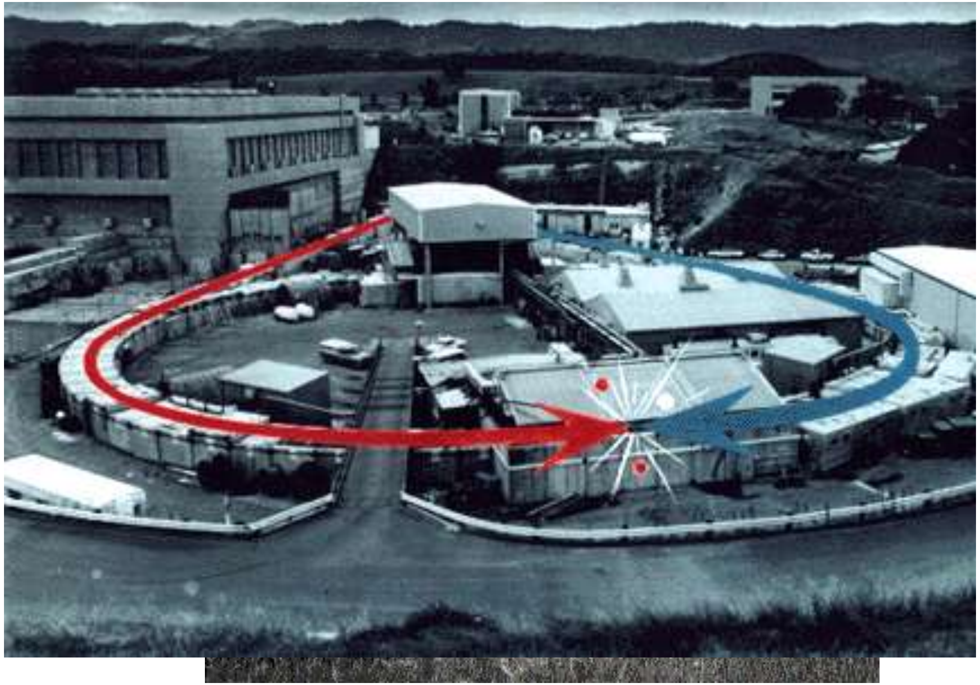
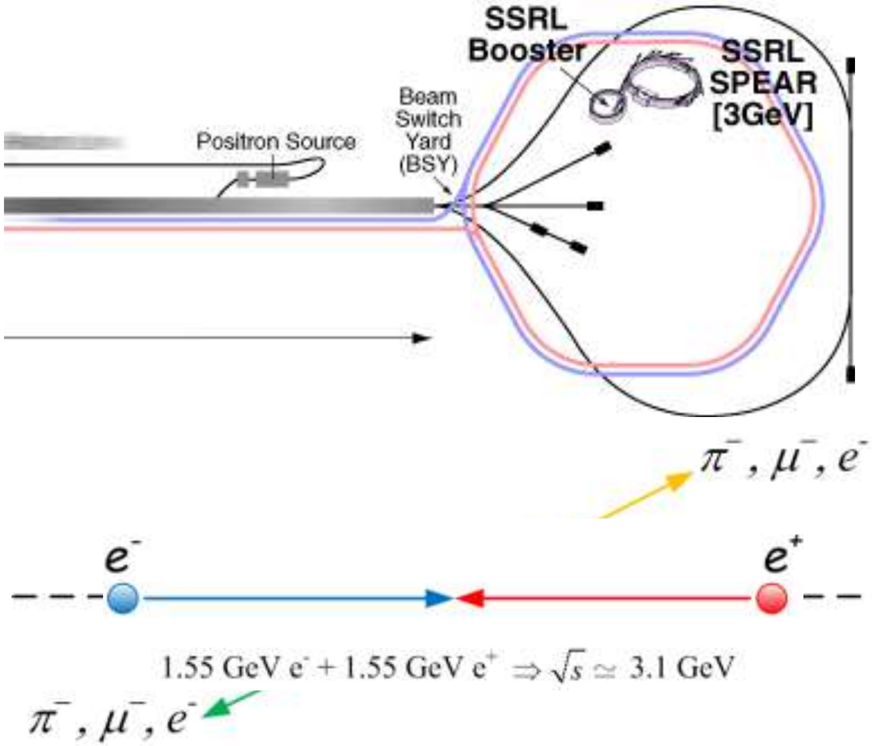


Photo of the newly completed SPEAR taken on April 26, 1972. (SLAC), California



# J/psi Discovery (1974): the November Revolution

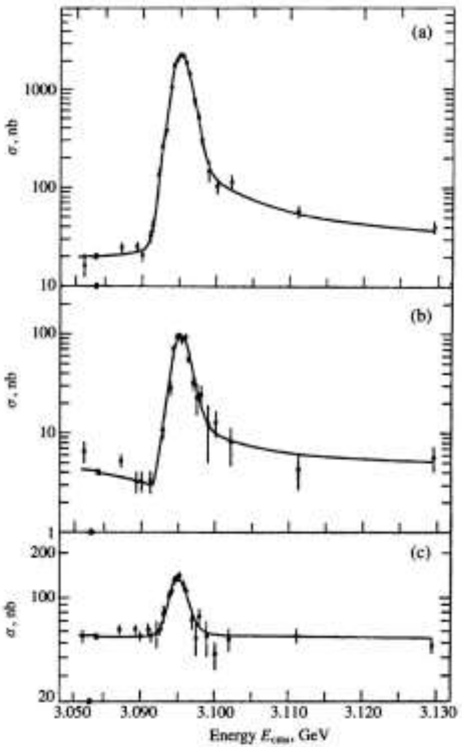
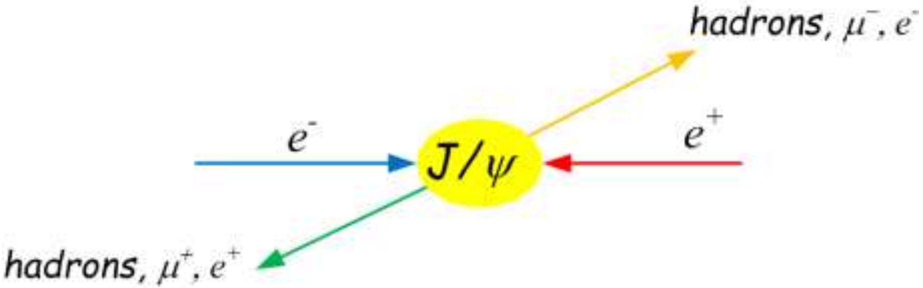



Fig. 4.1. Results of Augustin *et al.* (1974) showing the observation of the $J/\psi$ resonance of mass 3.1 GeV, produced in $e^+e^-$ annihilation at the SPEAR storage ring, SLAC. (a) $e^+e^- \to$ hadrons; (b) $e^+e^- \to \mu^+\mu^-$, $|\cos\theta| \le 0.6$; (c) $e^+e^- \to e^+e^-$, $|\cos\theta| \le 0.6$.

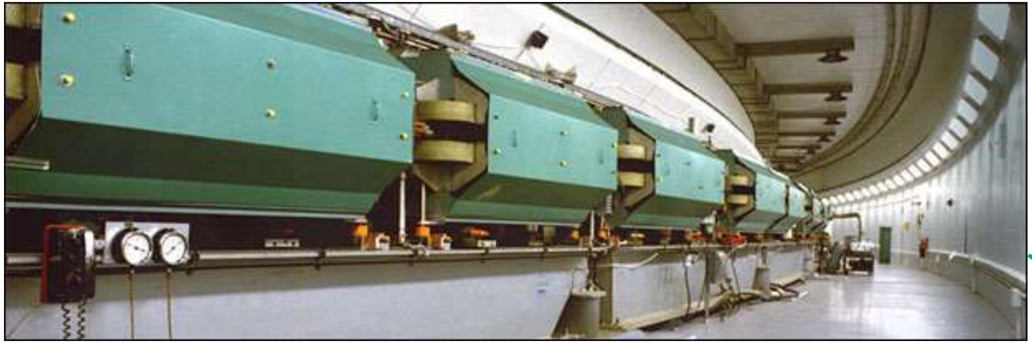
Experiment was carried in 1974 at SLAC (Stanford) using the e+ e- SPEAR collider at different center-of-mass energies from ~3.050 GeV to ~3.130 GeV

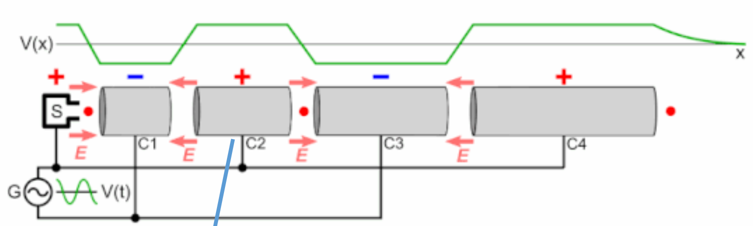
An increase of the cross section around an energy of 3.096 GeV was observed.



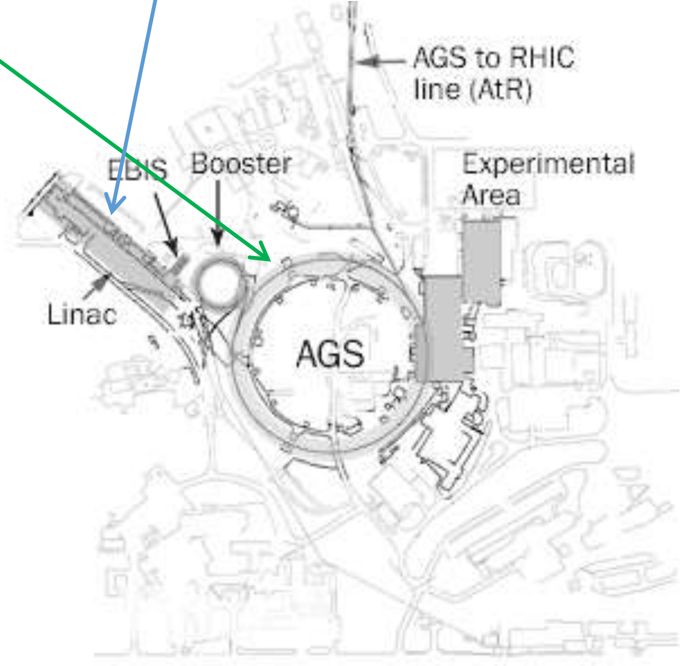

A new state called J/ψ was just discovered!

# AGS Experiment at Brookhaven National Laboratory,



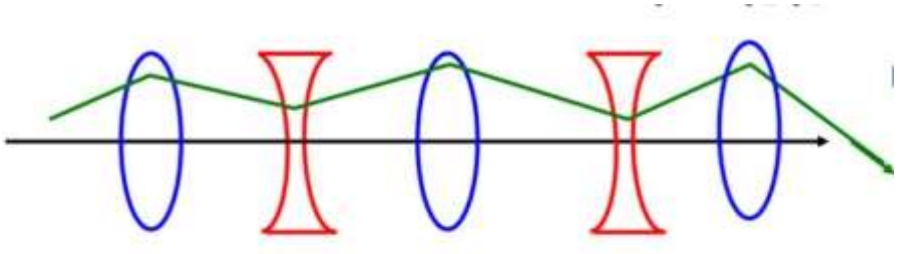



Since 1960, the Alternating Gradient Synchrotron (AGS) has been one of the world's premier particle accelerators, well known for the three Nobel Prizes won as a result of research performed there.
LINAC: Linear Accelerator
EBIS: Electron Beam Ion Sourve
AGS: Alternating Gradient Focusing with 240 magnets.

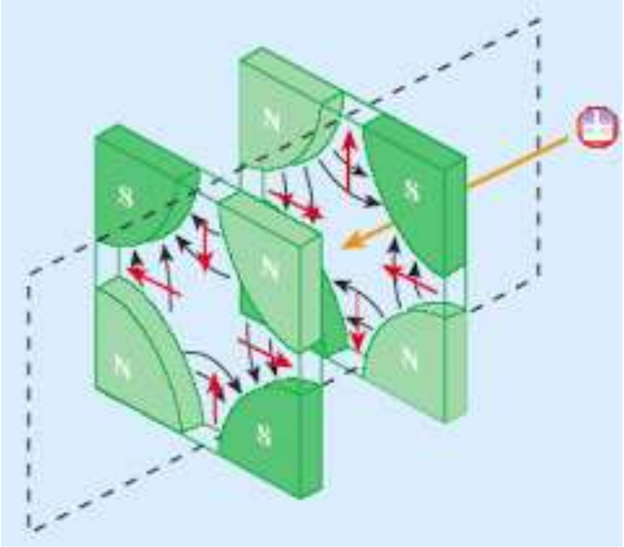



Experiment was capable of accelerating 70 trillion protons with every pulse, and heavy ions such as gold and iron, the AGS receives protons and other ions from the AGS Booster and delivers them to the Relativistic Heavy Ion Collider after acceleration.

# Beam Focusing (analogy with optics)



The AGS name s derived from the concept of alternating gradient focusing, in which the field gradients of the accelerator's 240 magnets are successively alternated inward and outward, permitting particles to be focused in both the horizontal and vertical plane at the same time.



# J/psi Discovery (1974): confirmation of AGS

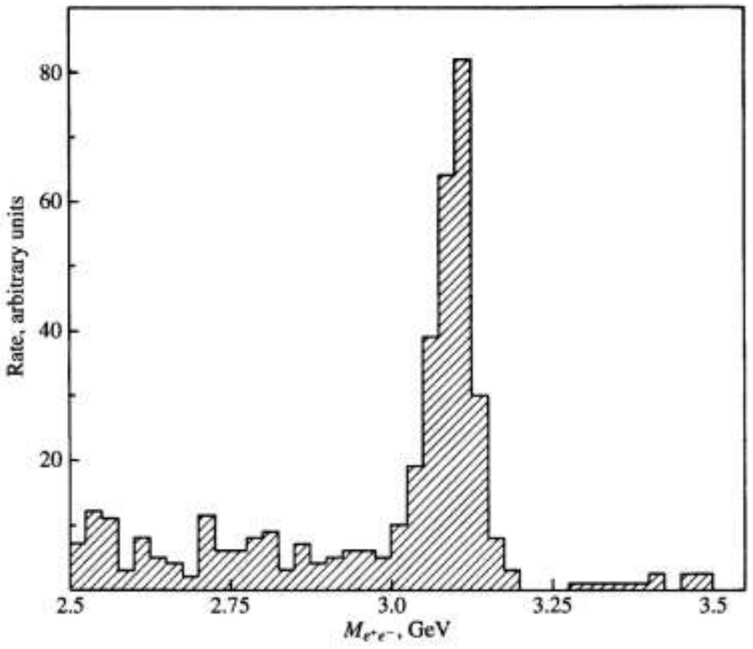
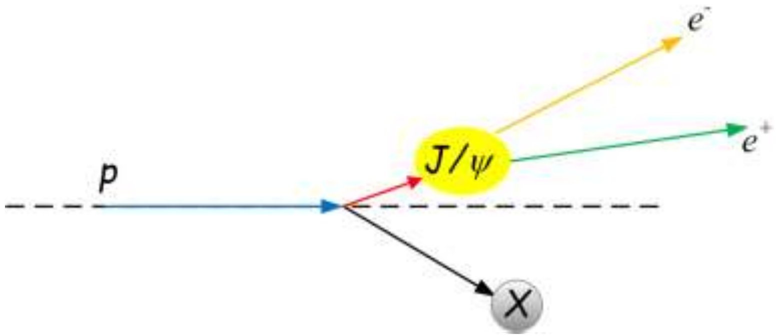
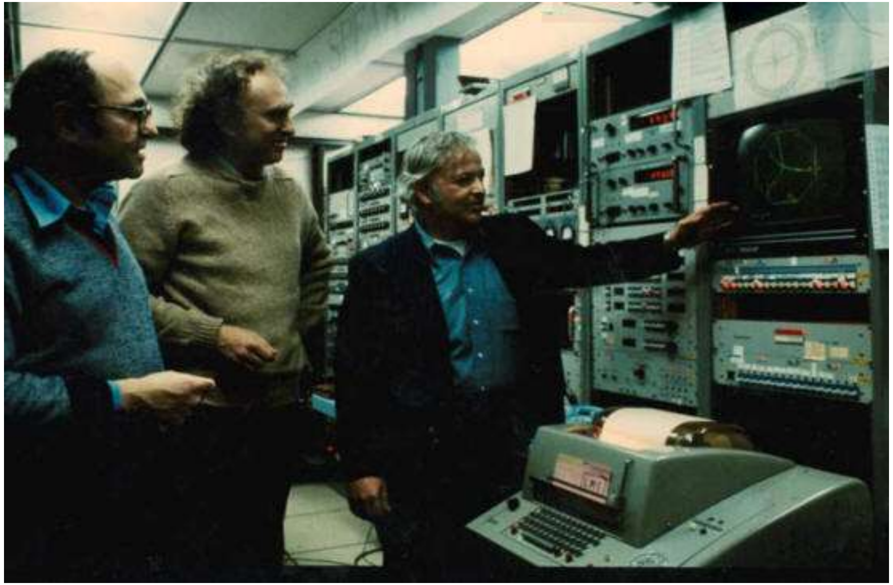



Fig. 4.2. Results of Aubert *et al.* (1974) indicating the narrow resonance $J/\psi$ in the invariant-mass distribution of $e^+e^-$ pairs produced in inclusive reactions of protons with a beryllium target, $p + \mathrm{Be} \rightarrow e^+ + e^- + X$. The experiment was carried out with the 28 GeV AGS at Brookhaven National Laboratory.




*Both experiments (SPEAR and AGS) observe an object in different reactions which had* ***the same invariant mass****: one can conclude that it is the same resonance decaying to an electron and a positron.*

# SPEAR (MARK I) Collaborators at SLAC and AGS Coll. at BNL



Gerson Goldhaber, Martin Perl, and Burton Richter view an event display in the SPEAR (Mark I) counting room.

Prof. Samuel Ting and coll. at the Brookhaven's Alternating Gradient Synchrotron

# Nobel Price in Physics (1976)

## Burton Richter

The Nobel Prize in Physics 1976

Prize motivation: "for their pioneering work in the discovery of a heavy elementary particle of a new kind"
Born: 22 March 1931, Brooklyn, NY, USA

Died: 18 July 2018, Stanford, CA, USA

more

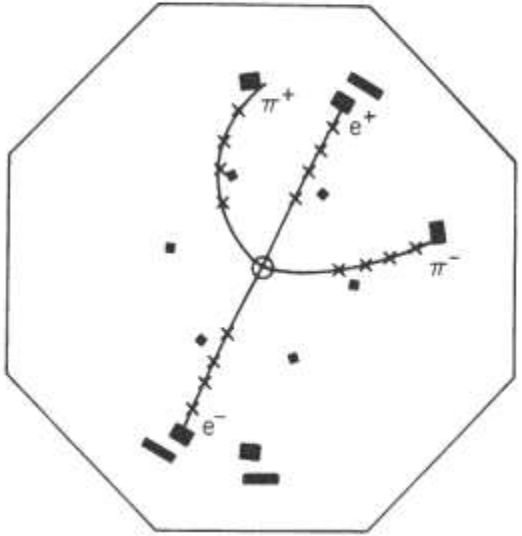
## Samuel C.C. Ting

The Nobel Prize in Physics 1976

Prize motivation: "for their pioneering work in the discovery of a heavy elementary particle of a new kind"
Born: 27 January 1936, Ann Arbor, MI, USA

more

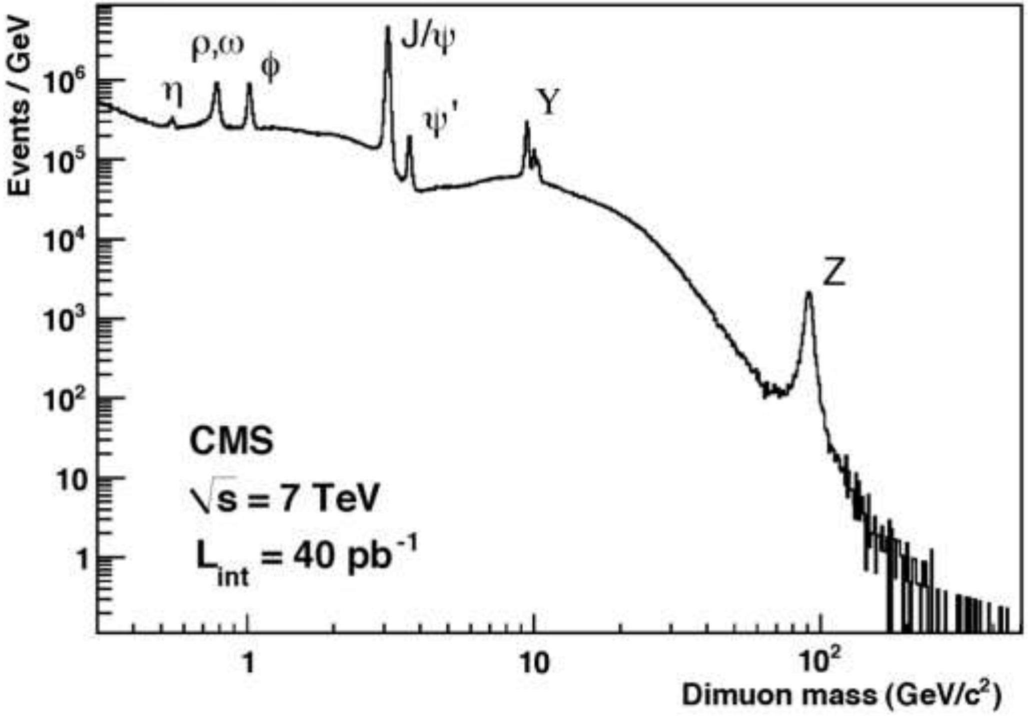
# J/Ψ ,Ψ' and the particle zoo



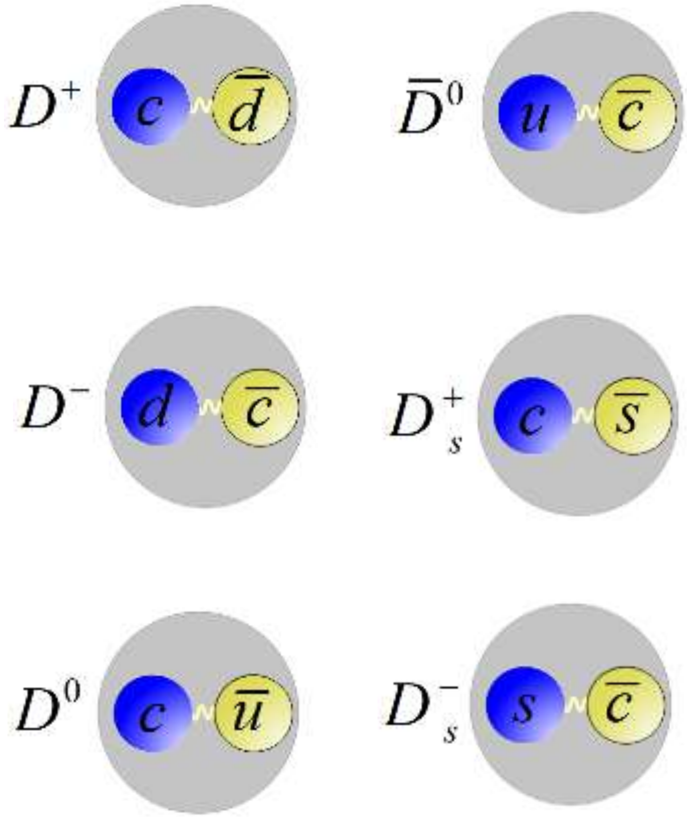

$$\psi'(3.686\,\mathrm{GeV}) \rightarrow J/\psi(3.1\,\mathrm{GeV}) + \pi^+ + \pi^-$$

$$J/\psi(3.1\,\mathrm{GeV}) \rightarrow e^+ + e^-$$

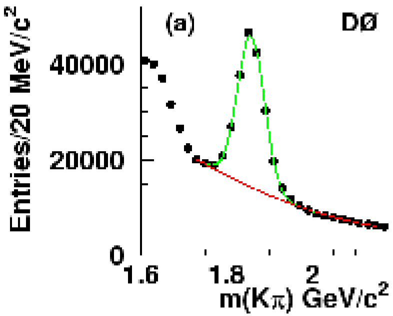
Computer reconstruction of a psi-prime decay in the Mark I detector at SPEAR, making a near-perfect image of the Greek letter psi.



# D Mesons




Discovered in 1976 by the Mark I detector at the Stanford Linear Accelerator Center (California) (2 mi = 3.2km)



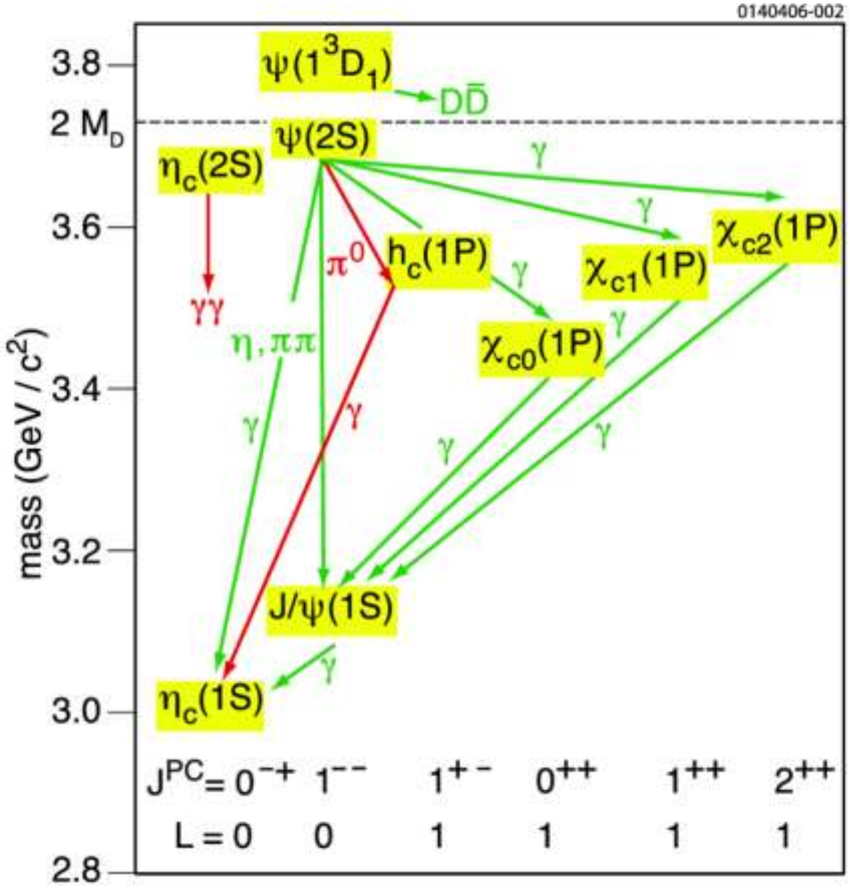

$$m_{D^+} = m_{D^-} \sim 1870\,\mathrm{MeV/\,c^2}$$

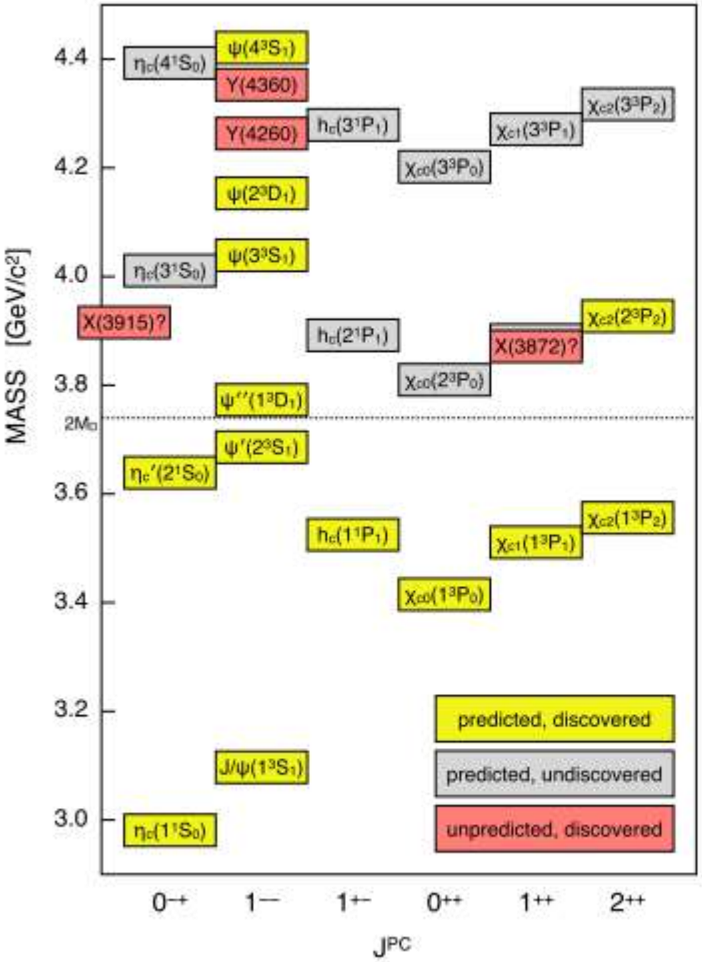
$$m_{D^o} = m_{\bar{D}^0} \sim 1865\,\mathrm{MeV/\,c^2}$$

$$m_{D_s^+} = m_{D_s^-} \sim 1868\,\mathrm{MeV/\,c^2}$$

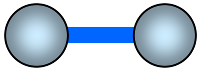
$$s_{D^\pm} = s_{D^0} = s_{\bar{D}^0} = s_{D_s^\pm} = 0$$

# Charmonium states



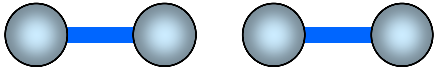
# Quantum Chromodynamics Predictions



**mesons:** bound state of $q\bar{q}$ with quantum numbers

$I^G\ (J^{PC})$ $P=(-1)^{L+1}$, $C=(-1)^{L+S}$, $G=(-1)^{I+L+S}$

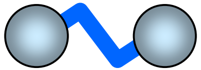
other color-neutral configurations



**tetra-quarks**

$q\bar{q}q\bar{q}$

Case 1: same quantum numbers of conventional mesons



**hybrids**

$q\bar{q}g$

Case 2: exotic quantum numbers

eg.: $J^{PC}= 0^{--}\ 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

**glueballs**

$gg \quad ggg$

# Lattice QCD

Lattice QCD predicts that lowest mass glueballs have conventional quantum numbers

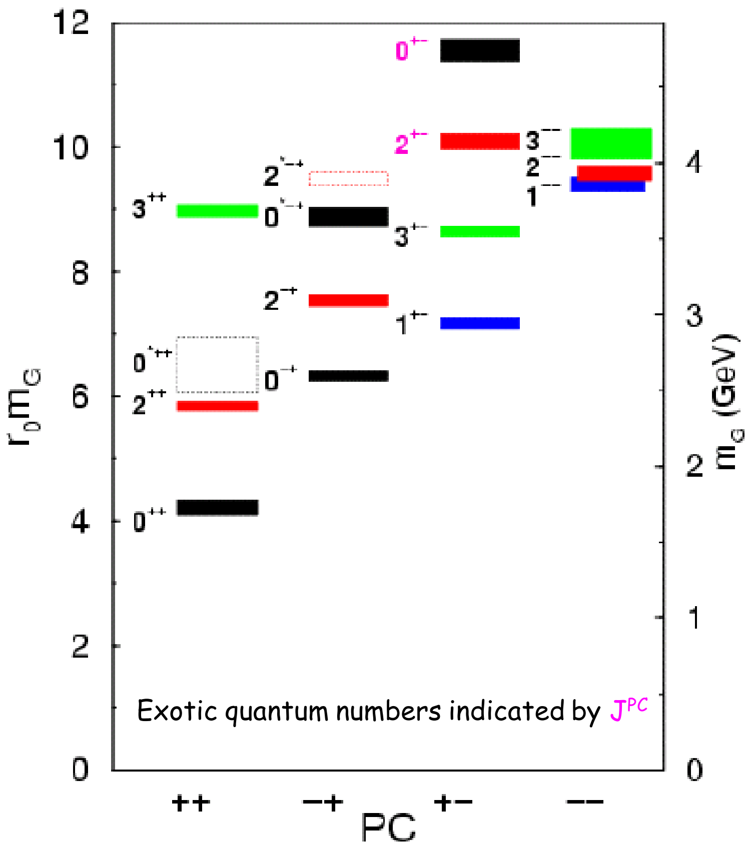
$M_{0^{++}}$~1.6 GeV

$M_{2^{++}}$~2.3 GeV

$M_{0^{-+}}$~3.5 GeV

Glueballs with exotic quantum numbers are much higher in mass

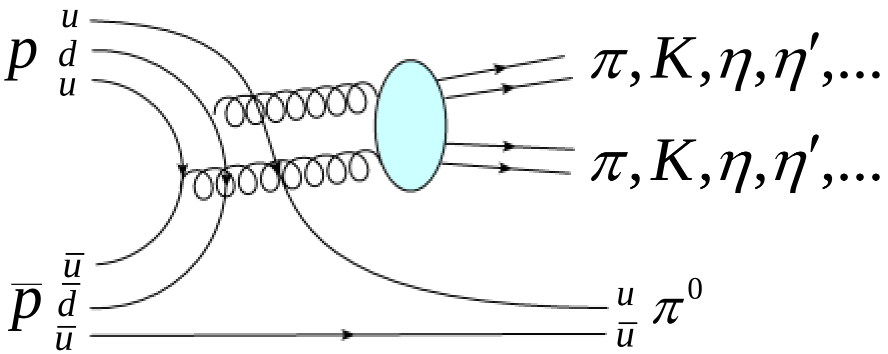
Difficult to disantangle high mass glueballs without exotic quantum numbers because of dense background of conventional states




Morningstar et al.

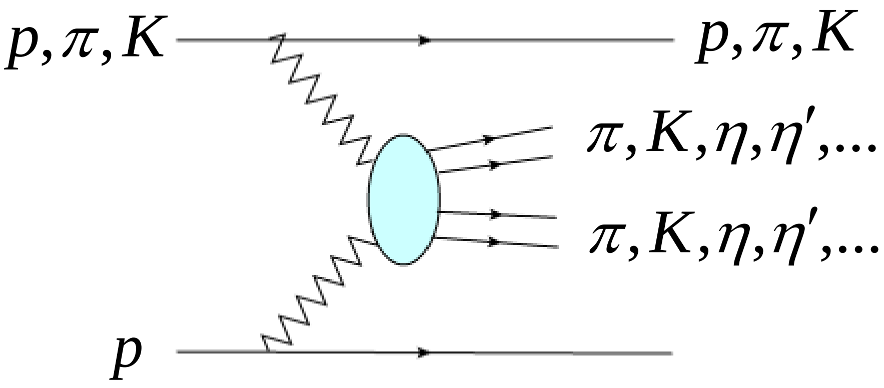
# Glueball Production Mechanisms

**antiproton-proton annihilation**




**CBAR, OBELIX, Fermilab E835**

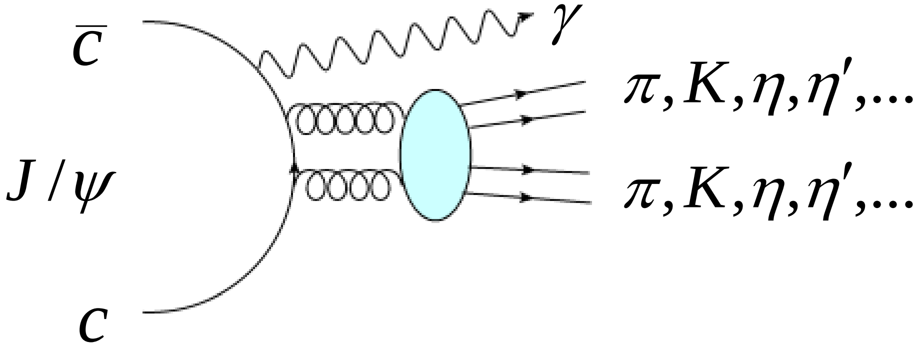
**central production**




**WA102, COMPASS**

# Glueball Production in J/ψ decays

## J/y radiative decay




BESIII, BELLE, MARK

# $1^3P_0$ ($0^{++}$): Lightest Scalar Resonances Puzzle

$a_0(980)$, $f_0(980)$, $f_0(500)$ or $\sigma$ , $K_0^*(800)$ or $\kappa$,

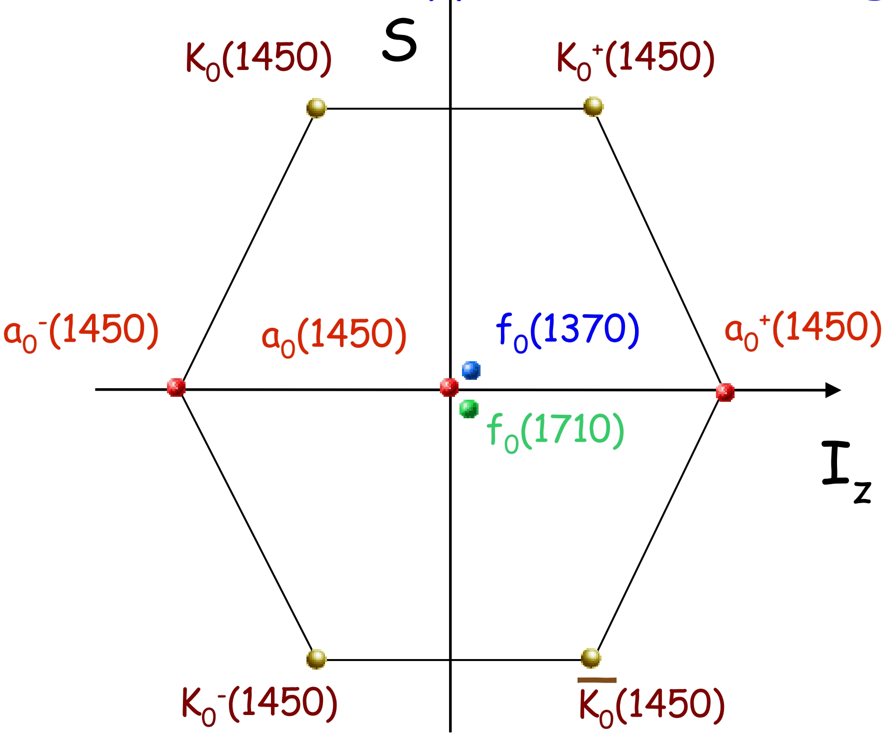
$a_0(1450)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, $K_0(1450)$

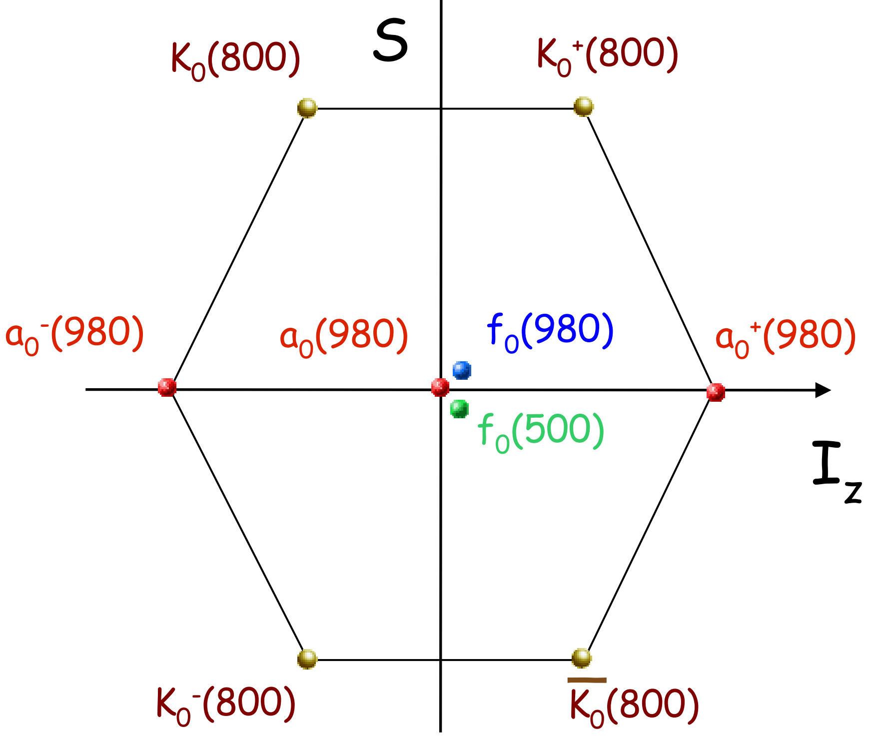
too many supernumerary candidates!

⬇

two nonets + glueball

# Hypothetical configuration of scalar nonets




$1^3P_0\ (0^{++})$
Conventional
meson nonet

$f_0(1500)$
supernumerary
⬇
best glueball candidate

$1^3P_0\ (0^{++})$
Tetra-quark nonet

# Branching Fractions

From theory if we assume "flavor blind " decay:

$$\frac{\Gamma(G \to \pi\pi, K\bar{K}, \eta\eta, \eta\eta', \eta'\eta')}{PhaseSpace} = 3:4:1:0:1$$

From experiments:

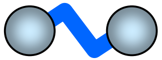
$$\frac{\Gamma(G \to \pi\pi, K\bar{K}, \eta\eta, \eta\eta', \eta'\eta')}{PhaseSpace} = 5.1(\pm 2.0):0.71(\pm 0.21):1:1.3(\pm 0.5):?$$

Mixing may occur (Close and Kirk, 2000) :

$$f = \alpha|n\bar{n}| + \beta|s\bar{s}| + |G| + \delta|q\bar{q}q\bar{q}|$$

# Mixing?

## Case 1: different quantum numbers



hybrids

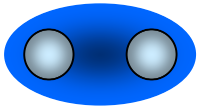
eg.: $J^{PC} = 0^{--}\ 0^{+-}, 1^{-+}, 2^{+-},...$

Do not mix with conventional mesons: easy to identify them. However so far only one or two candidate has been observed

by B525(BNL), CBAR(CERN), OBELIX (CERN), COMPASS(CERN)

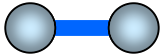
$1^{-+}$: $\pi_1(1400)$, $\pi_1(1600)$

## Case 2: same quantum numbers



observed states

=

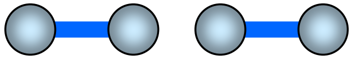


mesons

+

glueballs

+



tetra-quarks

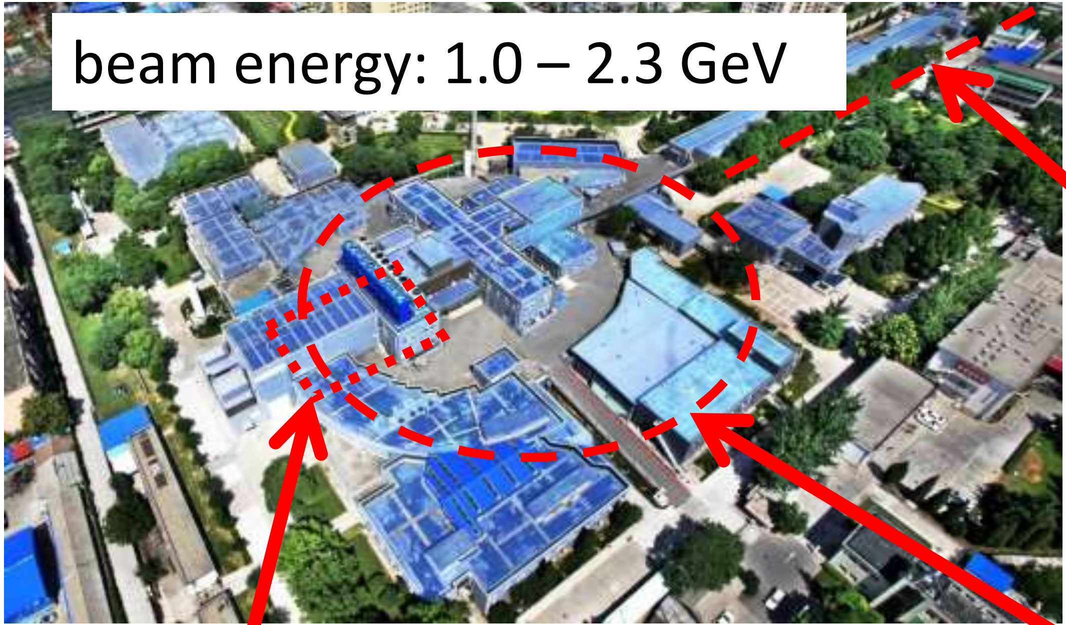
eg.: $J^{PC} = 0^{++}, 2^{++},...$

$0^{++}$: $f_0(1500)$, $f_0(1710)$,

$2^{++}$: ..., f2(2340), ...

# BESIII Experiment at the BEPCII Accelerator

beam energy: 1.0 – 2.3 GeV



Injector (~200 m)

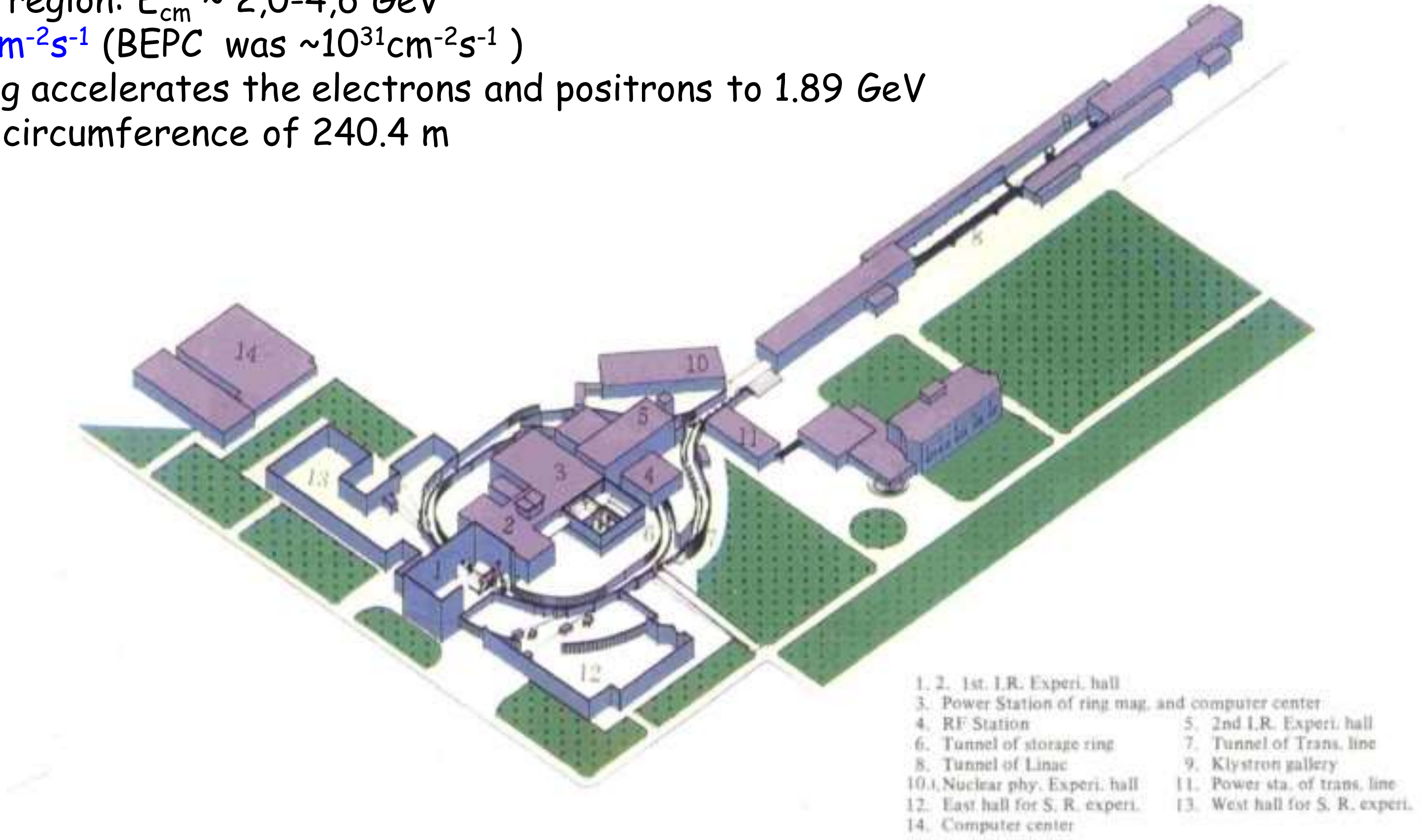


Storage Ring
(~240 m)

BEPCII/BESIII – unique facility at τ-charm energy region in the word now.

# BEPCII Accelerator

- BEPCII: electron-positron collider
- tau-charm energy region: $E_{cm}$ ~ 2,0-4,6 GeV
- Luminosity $\sim 10^{33} cm^{-2} s^{-1}$ (BEPC was $\sim 10^{31} cm^{-2} s^{-1}$ )
- LINAC: 202 m long accelerates the electrons and positrons to 1.89 GeV
- STORAGE RING: circumference of 240.4 m




## USA(5)

Carnegie Mellon University, Pittsburgh, PA
Indiana University, Bloomington, IN
University of Hawaii, Honolulu, Hawaii
University of Minnesota, MN
University of Rochester, NY

## EUROPE (16)

Bochum University, Germany
Budker Instituteof Nuclear Physics, Novosibirsk, Russia
Ferrara University, Italy
GSI Darmstadt, Germany
Helmholtz Institute Mainz, Germany
INFN, Laboratori Nazionali di Frascati
Johannes Gutenberg University of Mainz, Germany
Joint Institute for Nuclear Research (JINR) Dubna, Russia
KVI/University of Groningen, The Netherlands
Universitaet Giessen, Germany
University of Manchester, United Kingdom
University of Münster, Germany
University of Oxford, United Kingdom
University of Turin, Italy
Uppsala University, Sweden

## OTHERS IN ASIA(8)

COMSATS Institute of Information Technology(CIIT)
Indian Institute of Technology, Madras, India
Institute of Physics and Technology, Mongolia
Tokyo University, Japan
Seoul National University
Suranaree University of Technology, Thailand
University of the Punjab, Lahore Pakistan
University of Lahore, Pakistan

## CHINA (43)

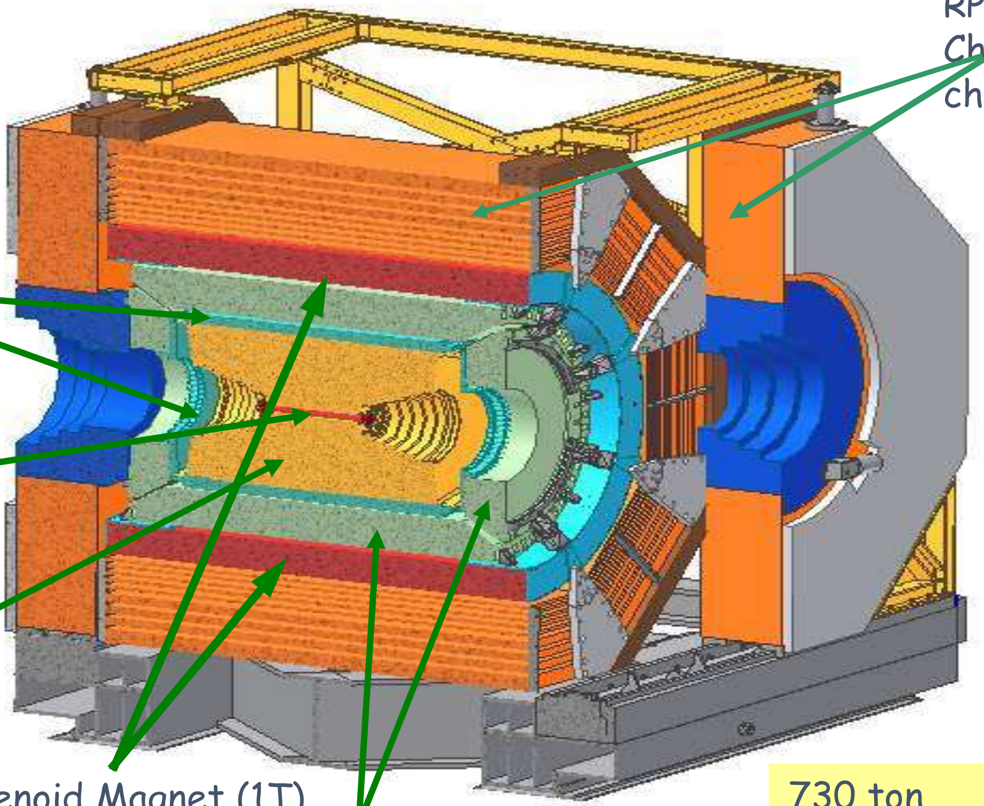
Beijing Institute of Petro-chemical Technology, Beihang University
China Center of Advanced Science and Technology, Fudan University
Guangxi Normal University, Guangxi University
Hangzhou Normal University, Henan Normal University
Henan University of Science and Technology, Huazhong Normal University
Huangshan College, Hunan University, Hunan Normal University
Institute of High Energy Physics, Institute of modern physics
Jilin University, Lanzhou University, Liaoning Normal University
Liaoning University, Nanjing Normal University, Nanjing University
Nankai University, Peking University, Qufu normal university
Shanxi University, Shanxi Normal University, Sichuan University
Shandong Normal University, Shandong University
Shanghai Jiaotong Univeristy, Soochow University, Southeast University
Sun Yat-sen University, Tsinghua University
University of Chinese Academy of Sciences, University of Jinan
University of Science and Technology of China
University of Science and Technology Liaoning
University of South China, Wuhan University, Xinyang Normal University
Zhejiang University, Zhengzhou University

**~480 members**
**72 institutions from 14 countries**

**TAC-PF group members (since 2011):**

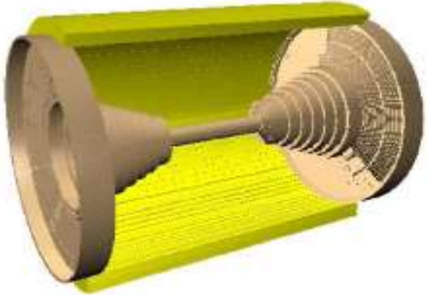
Orhan Çakır* (Ankara Ü.), Serkant Çetin (Doğuş Ü.),
İsmail Uman (**Yakin Doğu Ü.**), İlhan Tapan* (Uludağ Ü.),
Engin Eren* (Boğaziçi Ü.), Nurdan Güler* (Uludağ Ü.),
Onur Kolcu (Arel Ü., İst. Ü.), Alperen Yüncü (Boğaziçi Ü.)
*: *left collaboration*


BESIII Collaboration Meeting in Winter of 2019
November 18-22, 2019 IHEP BEIJING

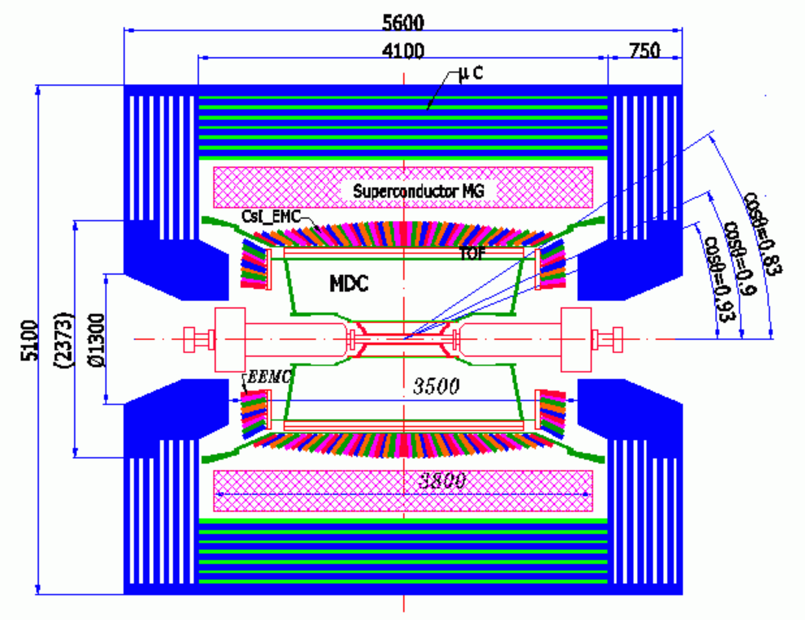



730 ton,
~40,000 channels,
data speed: 5kHz, 50Mb/s

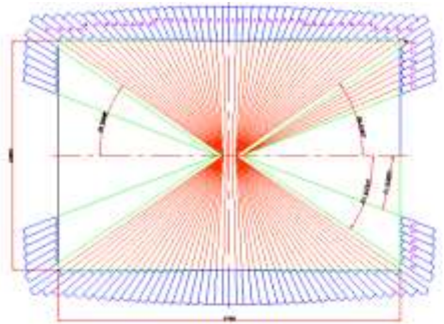
## MDC



R inner: 63mm ;
R outer: 810mm
Length: 2582 mm
Layers: 43

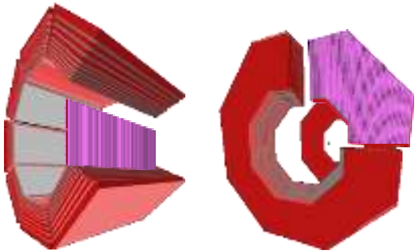



## CsI(Tl) EMC



Crystals: 28 cm(15 $X_0$)
Barrel: $|\cos\theta|<0.83$
Endcap: $0.85 < |\cos\theta| < 0.93$

## RPC MUC



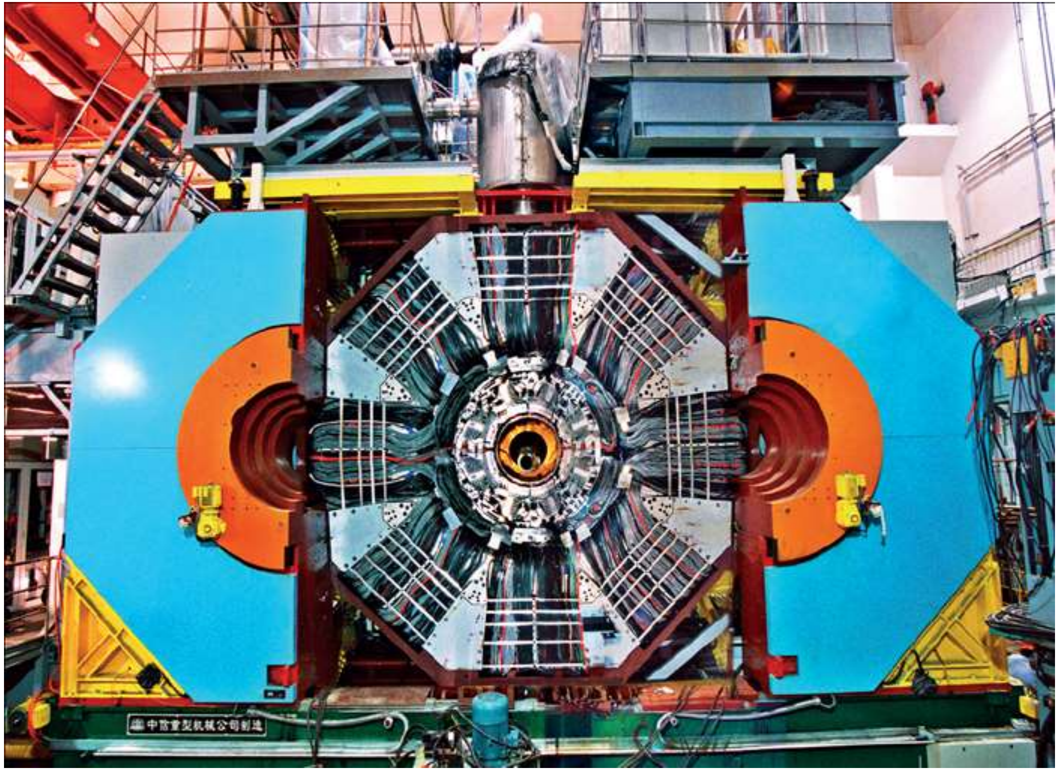
BMUC: 9 layers – 72 modules
EMUC: 8 layers – 64 modules

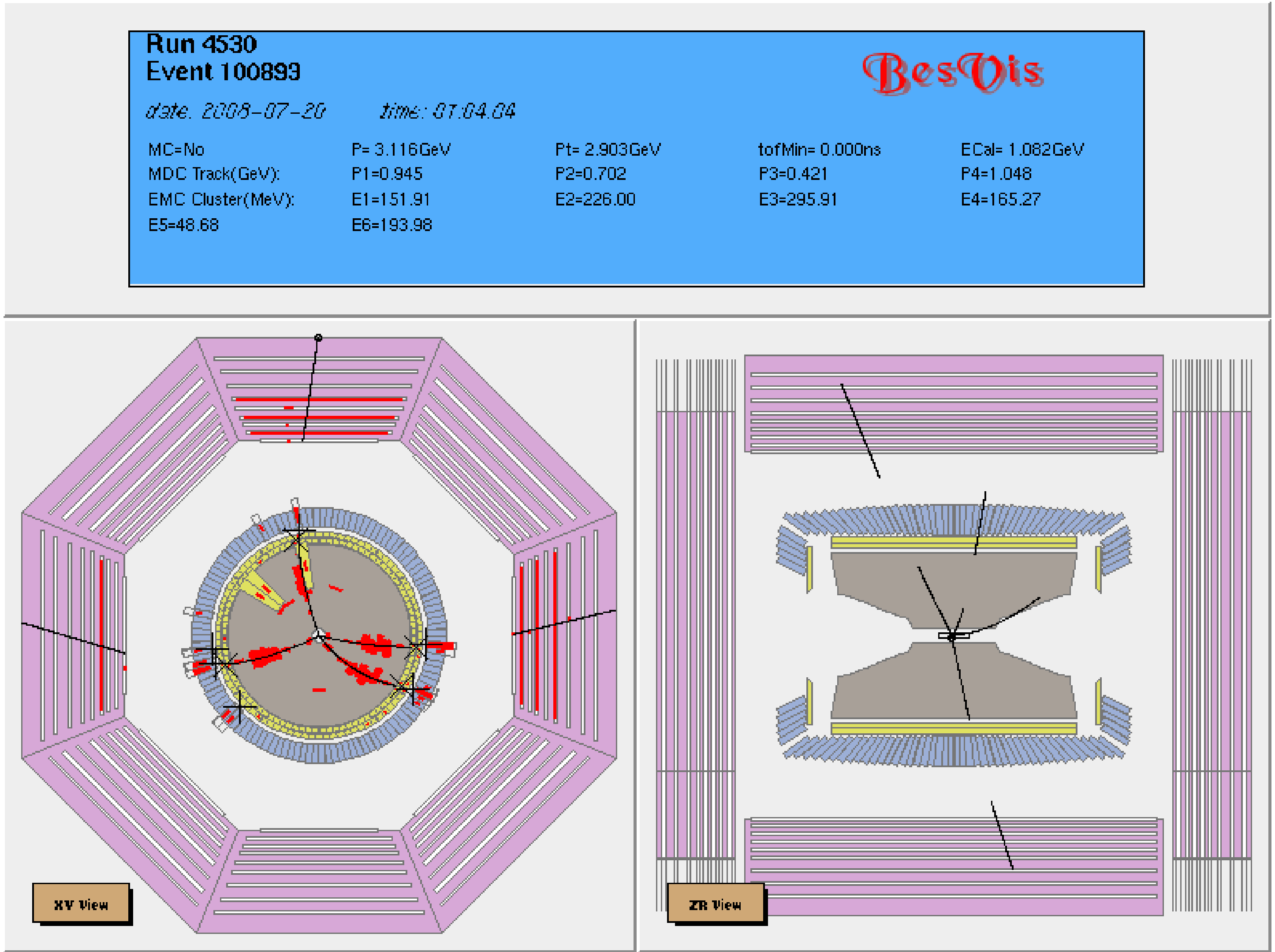
## TOF

BTOF: two layers
ETOF: 48 crys. for each

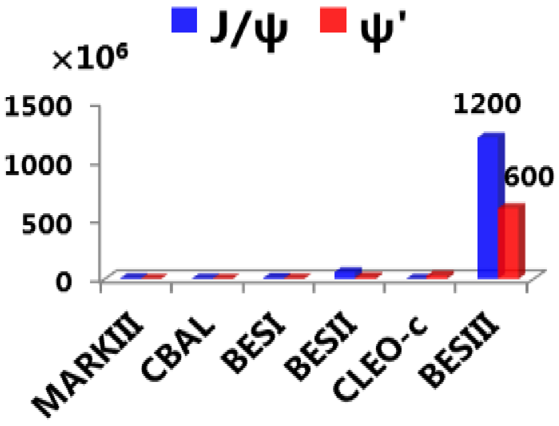
MDC

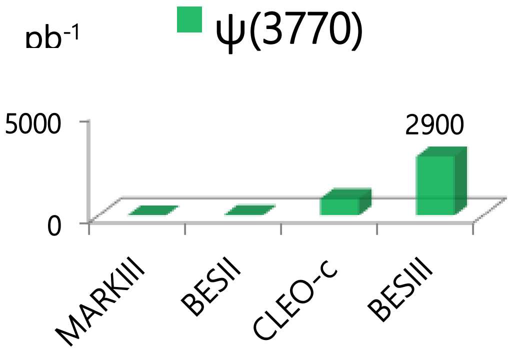
BESIII Detector




Run 4530
Event 100899
date. 2008-07-20
time: 07:04.04
MC=No
P= 3.116GeV
Pt= 2.903GeV
tofMin= 0.000ns
ECal= 1.082GeV
MDC Track(GeV):
P1=0.945
P2=0.702
P3=0.421
P4=1.048
EMC Cluster(MeV):
E1=151.91
E2=226.00
E3=295.91
E4=165.27
E5=48.68
E6=193.98
BesVis
XY View
ZR View

# BESIII Data Statistics

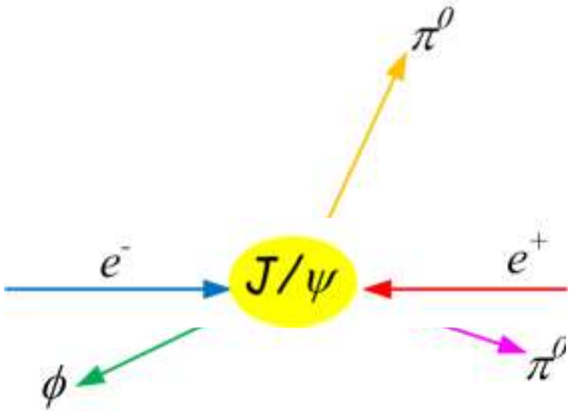


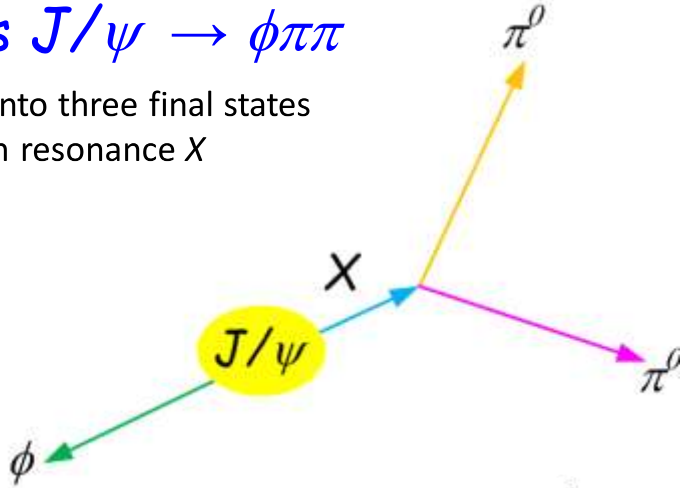

| |
|---|
| $10 \times 10^9$ J/ψ at Ecm=3.097 GeV, 2009 ($0.225 \times 10^9$) + 2012 ($1.0 \times 10^9$) + + 2018 ($4.6 \times 10^9$) +2019 ($4.1 \times 10^9$) |
| $0.4 \times 10^9$ ψ(3686) at Ecm=3.686 GeV, 2009 ($0.106 \times 10^9$) + 2012 |
| 2.9 $fb^{-1}$ ψ(3770) at 3.773 GeV, 2010 + 2011 |
| 0.5 $fb^{-1}$ ψ(4040) at 4.009 GeV, 2011 |
| 0.024 $fb^{-1}$ τ mass scan at around 3.554 GeV, 2011 |
| 1.9 $fb^{-1}$ Y(4260) at 4.23 and 4.26 GeV, 2013 |
| 0.5 $fb^{-1}$ Y(4360) at 4.36 GeV, 2013 |
| 0.5 $fb^{-1}$ Y(4260) and Y(4360) scan, 2013 |
| 0.8 $fb^{-1}$ R scan, 104 energy points between 3.85 and 4.59 GeV, 2014 |
| 0.5 $fb^{-1}$ at 4.60 GeV, 2014 |

# Isobar Model in the process $J/\psi \to \phi\pi\pi$

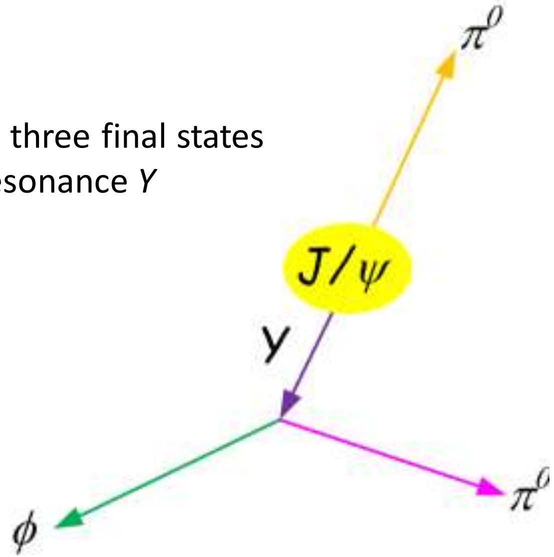
Direct decay into three final states




Decay into three final states through resonance *X*




Decay into three final states through resonance *Y*




- All the three reactions are possible.
- Resonances like X or Y are called isobars
- Isobars can be conventional mesons or exotic states depending their properties, like mass, spin, and the other quantum numbers

# PWA Analysis

- Covariant tensor formalism of $\psi$ decays to mesons by B.S. Zou and D.V. Bugg.
- Coupled channel analysis of $J/\psi \to \phi\pi^0\pi^0$ and $\phi KsKs$
- Isobar Model: eg.: $J/\psi \to \phi X$, $X \to \pi^0\pi^0$ and $J/\psi \to Y\pi^0$, $Y \to \phi\pi^0$
- Dynamical parts of the amplitude:

  Relativistic Breit Wigner formula with mass dependent width:

$$BW = \frac{1}{M^2 - s - iM\Gamma(M)}$$

  Flattè formula for $f_0(980)$

$$BW_{f_0(980)} = \frac{1}{M^2 - s - i(g_1\rho_{\pi\pi} + g_2\rho_{KK})}$$

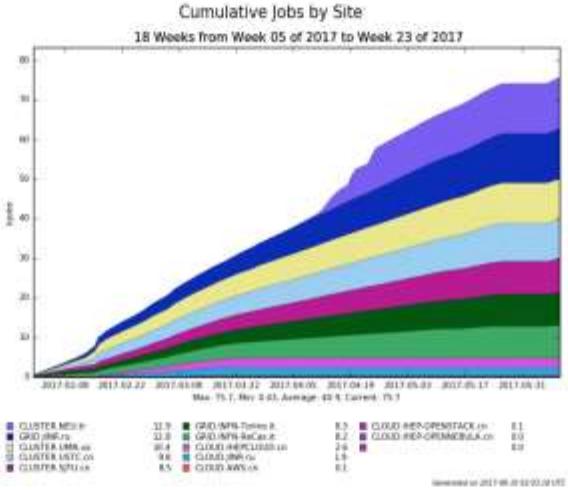
  $M, \Gamma, g_1, g_2$ are the fitted parameters

- Angular part of the amplitude depends on the resonance spin J.
- Other quantum numbers are determined using selection rules
- Log-likelihood minimization method (FUMILI).

# BESIII distributed computing

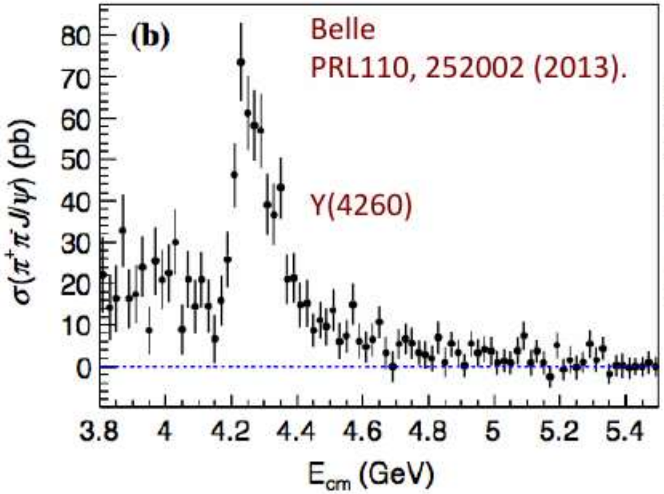
- In the last three months, about 76K BESIII jobs have been run in the platform
  - 10 sites join the production
- CLUSTER.NEU.tr is newly added from Turkey site
  - From IITC, Near East University in Turkey
  - 448 CPU cores HTCondor farm
  - 5TB StoRM SE
  - Both CE and SE are working fine
  - Thank Mustafa Arici and İSMAİL RUHİ UMAN for good cooperation

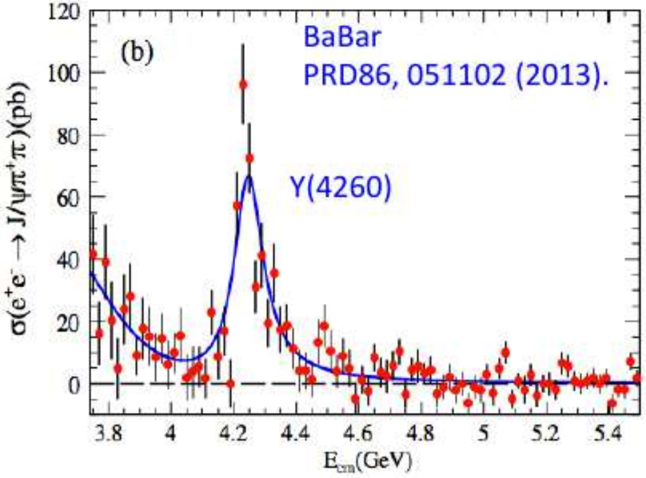
Thanks also to Ahmet Çağman, Özlem Tanrıkulu and İlker Dağlı




| Site | SiteType | | MaskStatus | CE-Test | SE-Test | Efficiency(%) | WN Status |
|---|---|---|---|---|---|---|---|
| CLUSTER.NEU.tr | CLUSTER | | Active | OK | OK | 100 | OK |

# Study of Y(4260)



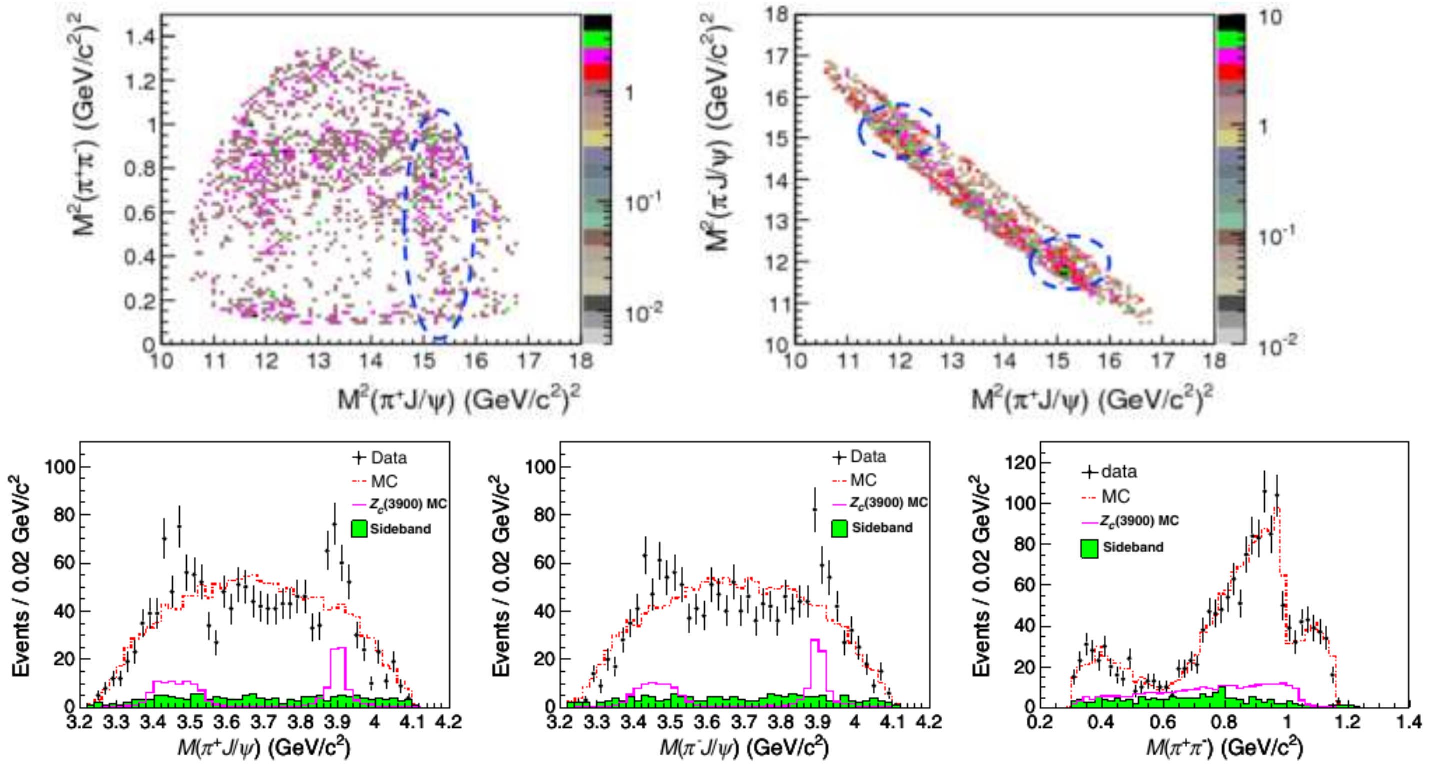

| $\sqrt{s}$ (GeV) | $\mathcal{L}$ ($pb^{-1}$) |
|---|---|
| 3.900 | 52.8 |
| 4.009 | 482.0 |
| 4.090 | 51.0 |
| 4.190 | 43.0 |
| 4.210 | 54.7 |
| 4.220 | 54.6 |
| 4.230 | 1090.0 |
| 4.245 | 56.0 |
| 4.260 | 826.8 |
| 4.310 | 44.9 |
| 4.360 | 544.5 |
| 4.390 | 55.1 |
| 4.420 | 44.7 |

BESIII: 525$pb^{-1}$ @ 4.26 GeV world's largest data set

Y(4260)→ $\pi^+\pi^-$ J/ψ , J/ψ → $e^+e^-$,$\mu^+\mu^-$ four charged tracks detection.

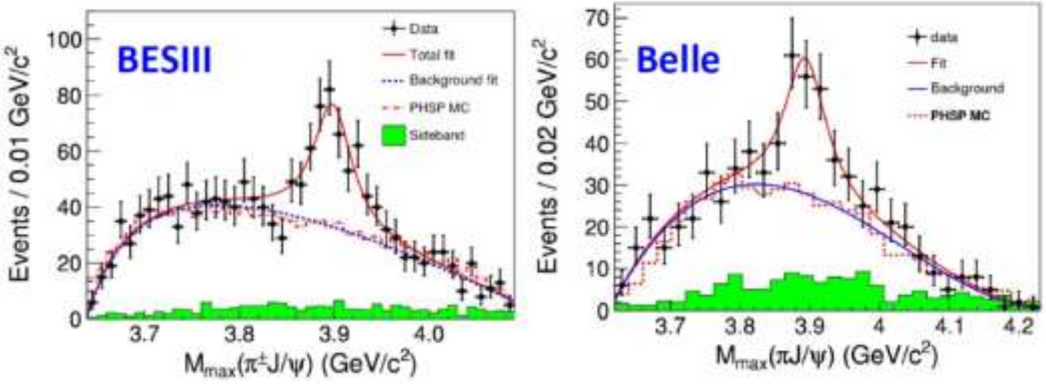
Exclusive and simple analysis in the rest frame

# Study of Y(4260): the $Z_c(3900)^{\pm}$ discovery




$\pi^+\pi^-$ invariant masses show contributions of $\sigma(500)$ and f0(980): are included in the MC simulation together with $\pi^+\pi^-$nonresonant amplitude.

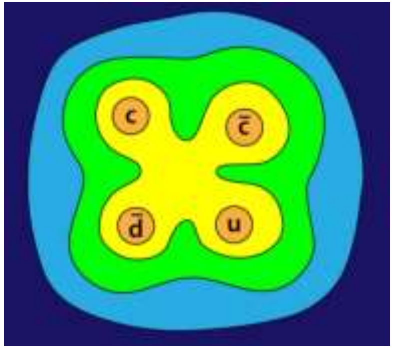
# The $Z_c(3900)^{\pm}$ discovery




- *Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s}$=4.26 GeV*, BESIII Collaboration, Mar 24, 2013. **Phys.Rev.Lett. 110 (2013) 25, 252001**
<u>already cited by 161 record!</u>
- *Study of $e+e- \to \pi+\pi- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle*, **BELLE Collaboration 17 June 2013 Phys. Rev. Lett. 110, 252002**

**M=(3899.0±3.6±4.9)MeV/c2;**
**Γ=(46±10±20)MeV.**

- Couples to $c\bar{c}$
- Has electric charge
- At least 4-quarks



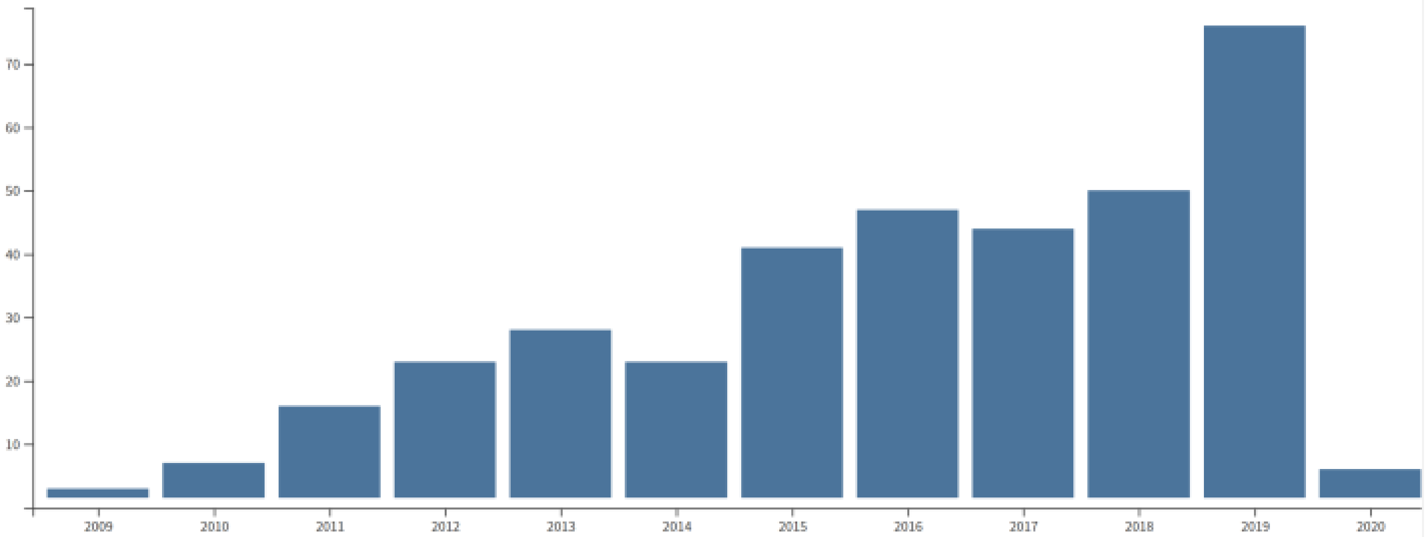
# BESIII Publications (since 2009)

-- 245 papers published in high impact factor journals

(NATURE 1, PRL 52, PRD 162, PLB 16, CPC 13, EPJCA 1)

Total Publications

364

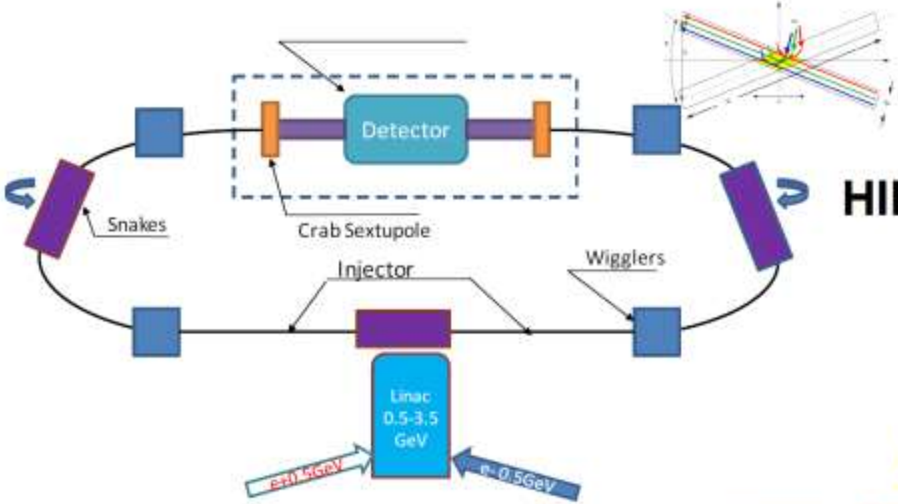


# Luminosity upgrade plan in the near future

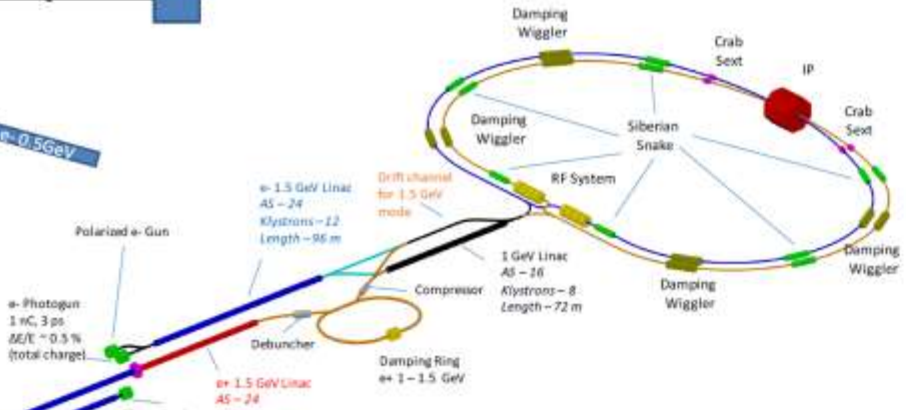
| Luminosity gain | Present BEPCII | *2.0 | *2.5 |
|---|---|---|---|
| $\beta_y^*$ | 1.5 cm | 1.5cm | 1.2cm |
| Bunch currnt | 7mA | 9mA | 9mA |
| Bunch number | 80 | 120 | 120 |
| SR power | 125kW | 250kW | 250kW |
| Beam-beam | 0.036 | 0.04 | 0.04 |
| RF voltage | 1.6 MV | 2.2 MV | > 3.4 MV |
| $\nu_s$ | 0.028 | 0.033 | 0.041 |
| HOM power | 7.7 kW | 19.1 kW | 29.7 kW |
| RF cavity | | 1 new RFC/ring | 2 RFC/ring |
| Coupling | 1 | 1 | *0.8 |

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

# Proposals of the Super Tau-Charm Factory (STCF)




**HIEPA in China**




**Super-CT Project in Russia**

**Total number of accelerating structures: 104**
**Klystron number: 52**
**Total length of the linacs: ~440 m**

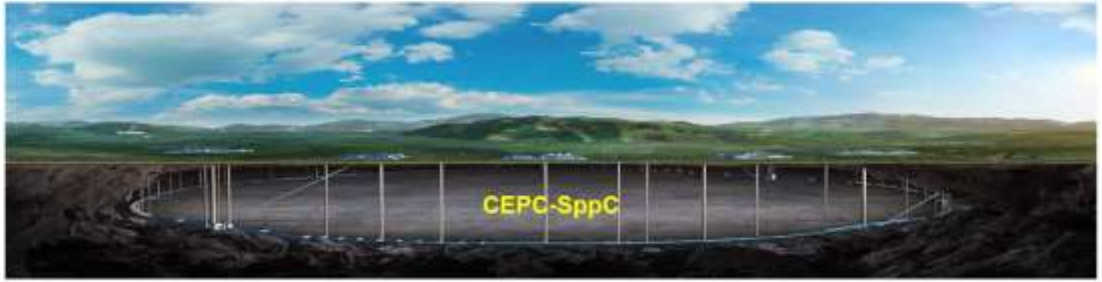
energy of 1.5 – 2.5 (3) GeV

# CEPC Accelerator


J. Gao

IHEP

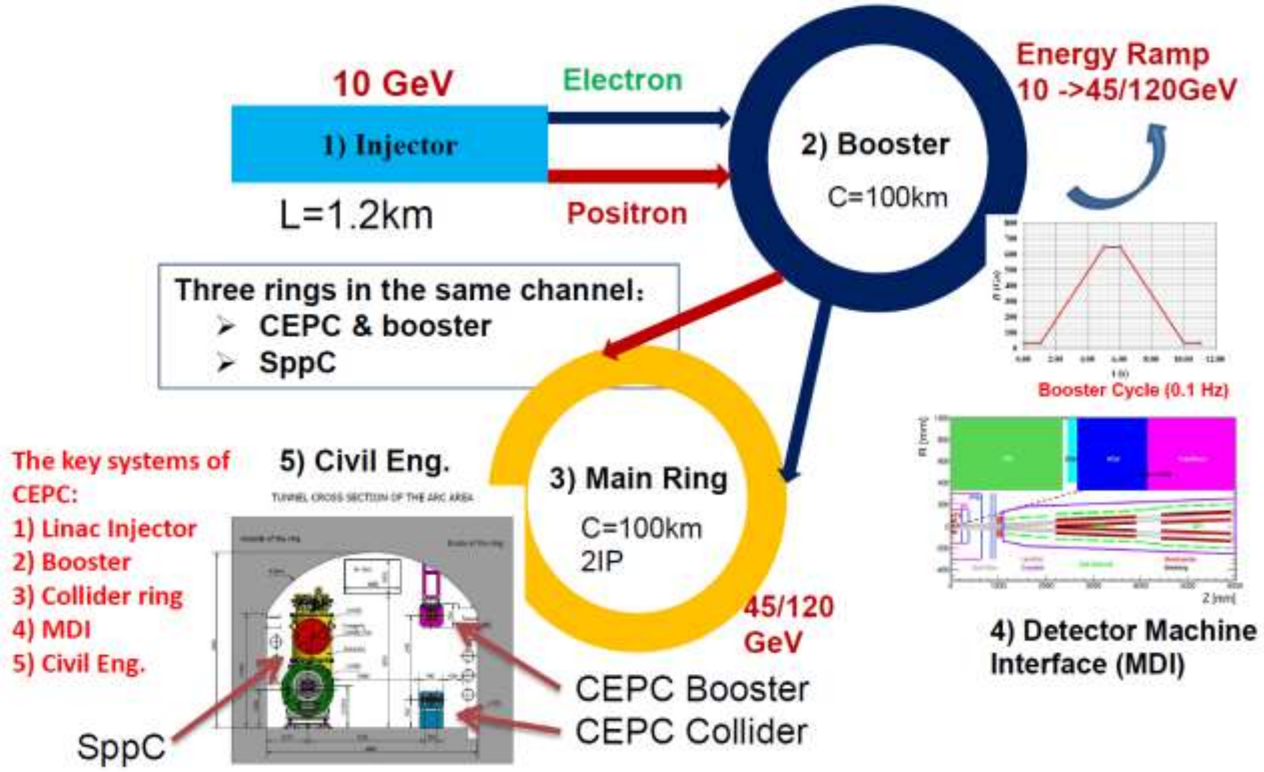
On behalf of CEPC Group

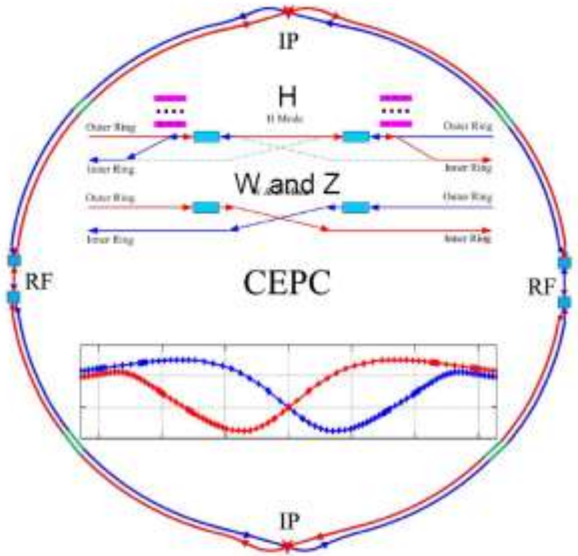

The 2019 International Workshop on the High Energy Circular Electron-Positron Collider (CEPC)

Nov. 18-20, 2019, IHEP, Beijing

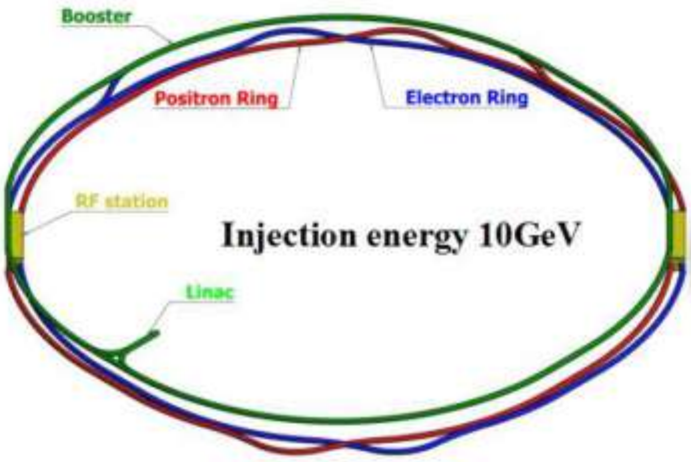
# CEPC Accelerator Chain and Systems



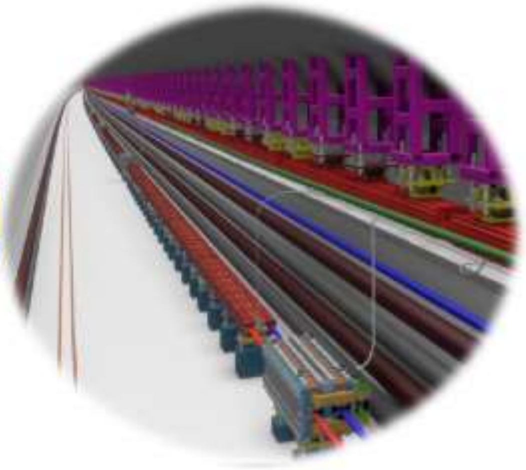
# CEPC CDR Baseline Layout

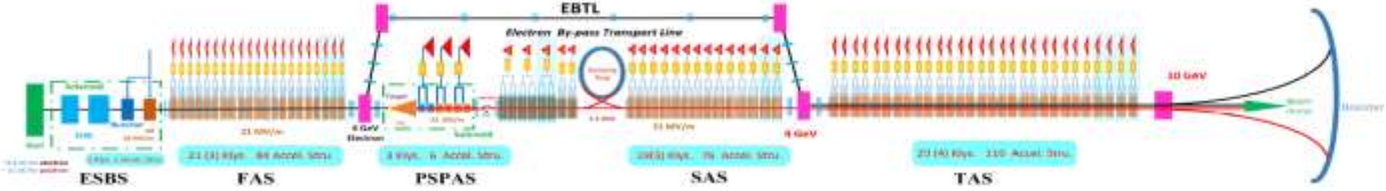



CEPC collider ring (100km)




CEPC booster ring (100km)






CEPC Linac injector (1.2km, 10GeV)

# CEPC CDR Parameters

| | *Higgs* | *W* | *Z* (3T) | *Z* (2T) |
|---|---|---|---|---|
| Number of IPs | 2 | | | |
| Beam energy (GeV) | **120** | **80** | **45.5** | |
| Circumference (km) | 100 | | | |
| Synchrotron radiation loss/turn (GeV) | 1.73 | 0.34 | 0.036 | |
| Crossing angle at IP (mrad) | 16.5×2 | | | |
| Piwinski angle | 2.58 | 7.0 | 23.8 | |
| Number of particles/bunch $N_e$ ($10^{10}$) | 15.0 | 12.0 | 8.0 | |
| **Bunch number (bunch spacing)** | **242 (0.68μs)** | **1524 (0.21μs)** | **12000 (25ns+10%gap)** | |
| Beam current (mA) | 17.4 | 87.9 | 461.0 | |
| **Synchrotron radiation power /beam (MW)** | **30** | **30** | **16.5** | |
| Bending radius (km) | 10.7 | | | |
| Momentum compact ($10^{-5}$) | 1.11 | | | |
| **β function at IP $\beta_x^*$ / $\beta_y^*$ (m)** | **0.36/0.0015** | **0.36/0.0015** | **0.2/0.0015** | **0.2/0.001** |
| Emittance $\varepsilon_x/\varepsilon_y$ (nm) | 1.21/0.0031 | 0.54/0.0016 | 0.18/0.004 | 0.18/0.0016 |
| Beam size at IP $\sigma_x/\sigma_y$ (μm) | 20.9/0.068 | 13.9/0.049 | 6.0/0.078 | 6.0/0.04 |
| Beam-beam parameters $\xi_x/\xi_y$ | 0.031/0.109 | 0.013/0.106 | 0.0041/0.056 | 0.0041/0.072 |
| RF voltage $V_{RF}$ (GV) | 2.17 | 0.47 | 0.10 | |
| RF frequency $f_{RF}$ (MHz) (harmonic) | 650 (216816) | | | |
| Natural bunch length $\sigma_z$ (mm) | 2.72 | 2.98 | 2.42 | |
| Bunch length $\sigma_z$ (mm) | 3.26 | 5.9 | 8.5 | |
| HOM power/cavity (2 cell) (kw) | 0.54 | 0.75 | **1.94** | |
| Natural energy spread (%) | 0.1 | 0.066 | 0.038 | |
| Energy acceptance requirement (%) | **1.35** | **0.4** | **0.23** | |
| Energy acceptance by RF (%) | 2.06 | 1.47 | 1.7 | |
| Photon number due to beamstrahlung | 0.1 | 0.05 | 0.023 | |
| Lifetime _simulation (min) | 100 | | | |
| Lifetime (hour) | **0.67** | **1.4** | **4.0** | **2.1** |
| $F$ (hour glass) | 0.89 | 0.94 | 0.99 | |
| **Luminosity/IP $L$ ($10^{34}$cm$^{-2}$s$^{-1}$)** | **2.93** | **10.1** | **16.6** | **32.1** |

# Summary
# of Hadron Spectroscopy

- Tetraquark candidates are making the news in Hadron Spectroscopy
- Unprecedented high statistics BESIII data will allow to

  - establish the lightest scalar nonet puzzle,

  - verify the mixing mechanism and

  - establish the glueball content of observed states.

  - BESIII experiment will run presumably until end of 2020.

- New facilities are plan to be built in this promising energy sector and beyond CERN


谢谢