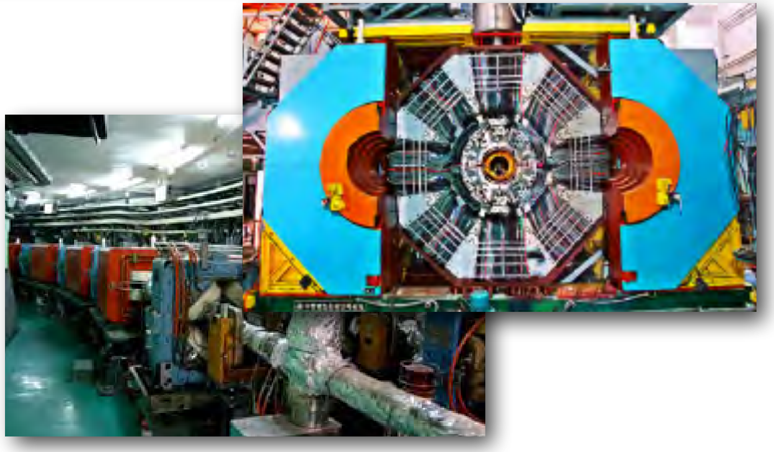
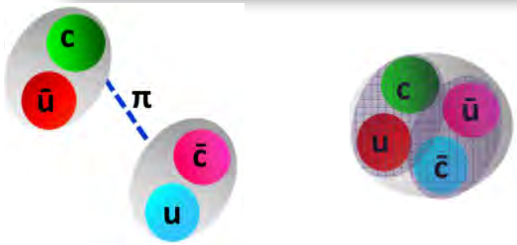
Recent Highlights from BESIII

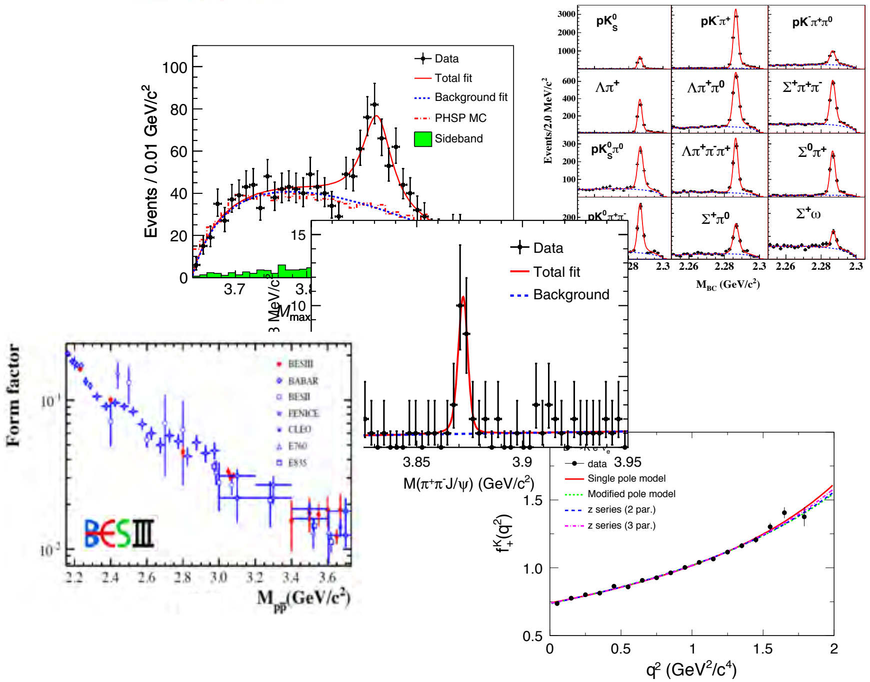
Wolfgang Kühn, JLU Giessen (BESIII Collaboration)

Outline

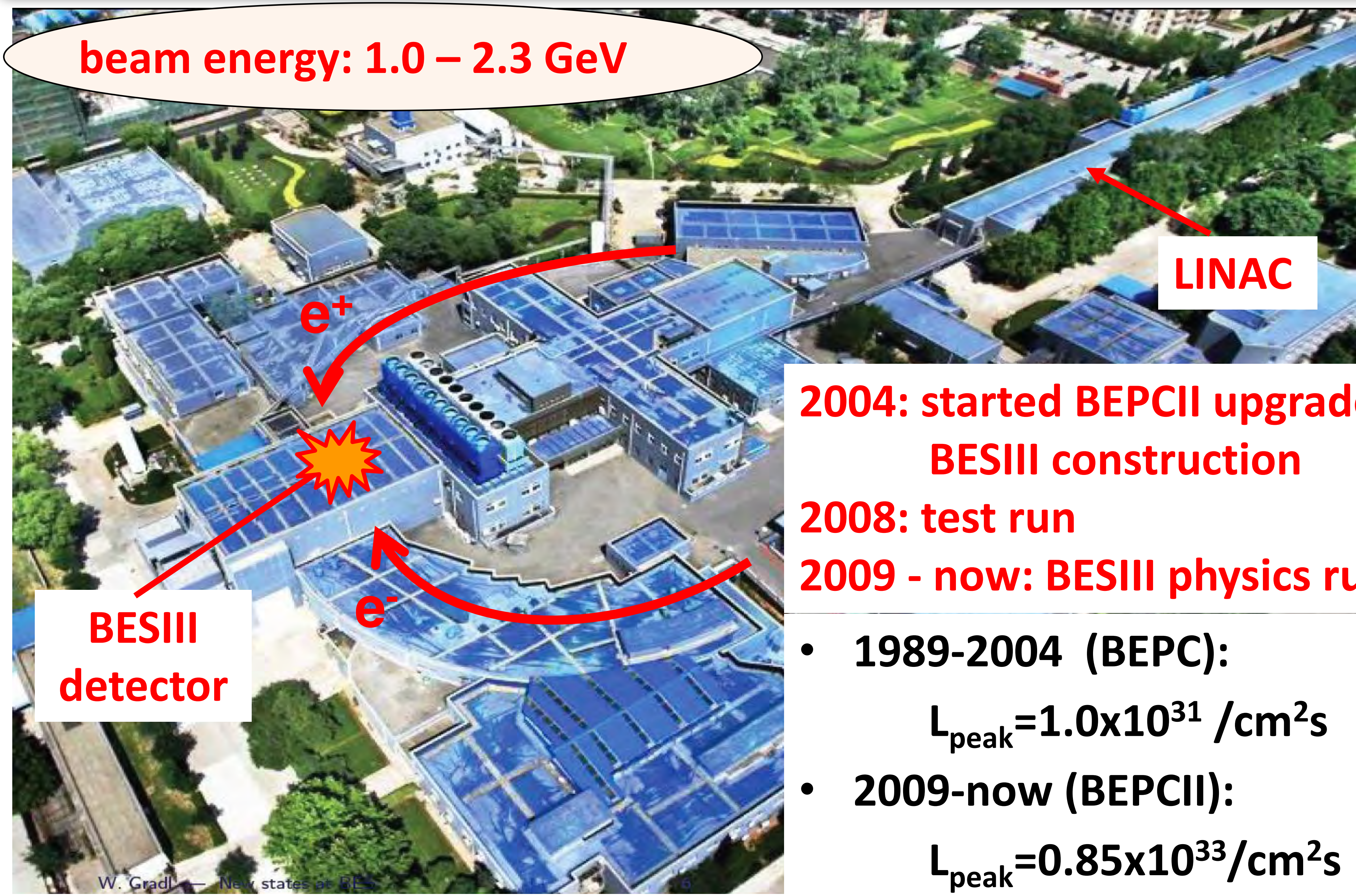
- BEPCII collider and BESIII detector
- Data sets and BES III Physics Program
- Focus for today:
  - **Light hadron spectroscopy**
  - **Time-like form factors**
  - **Exotic charmonium-like states**
  - **Charmed hadrons**
- Conclusions and outlook







The BEPCII Collider at IHEP Beijing



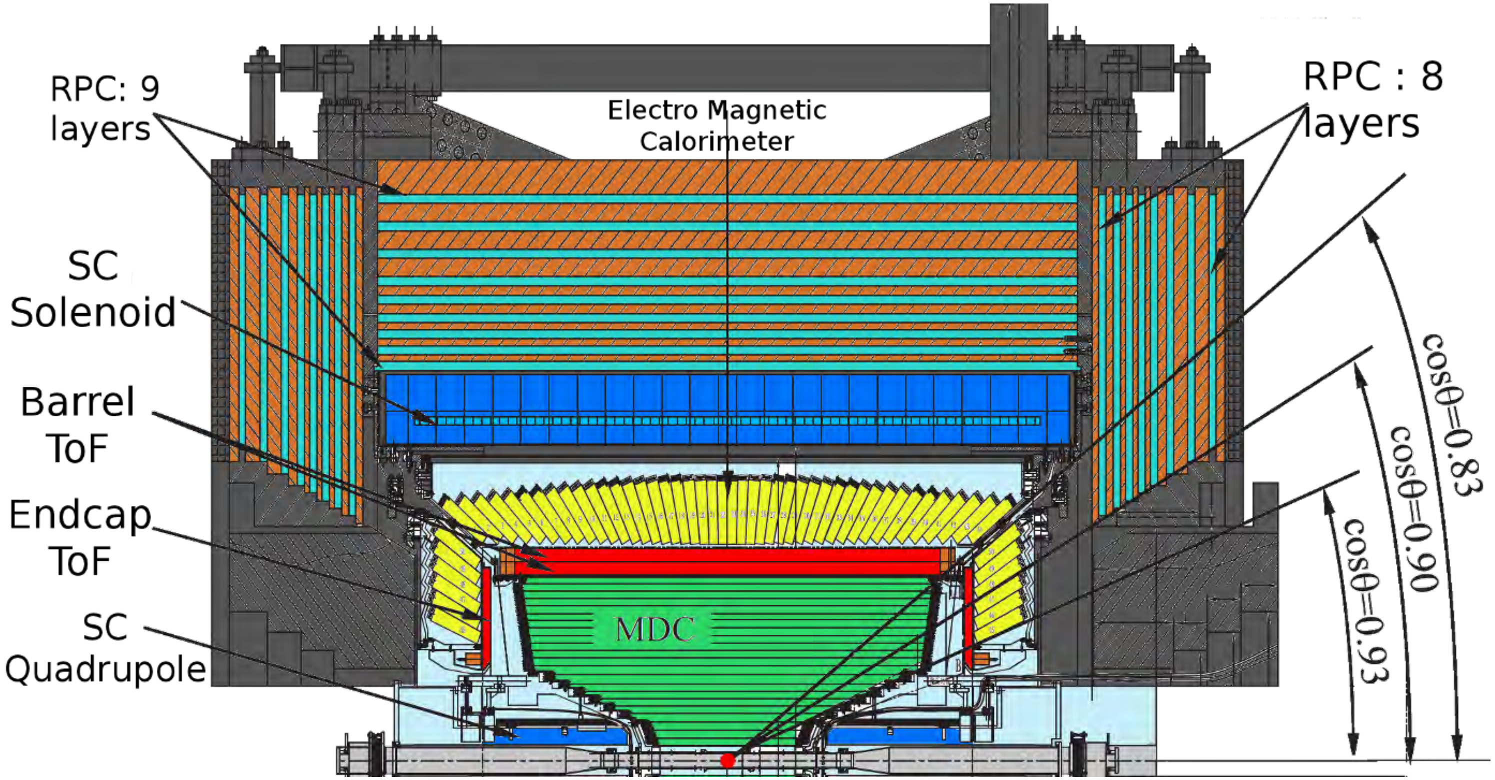
2004: started BEPCII upgrade, BESIII construction

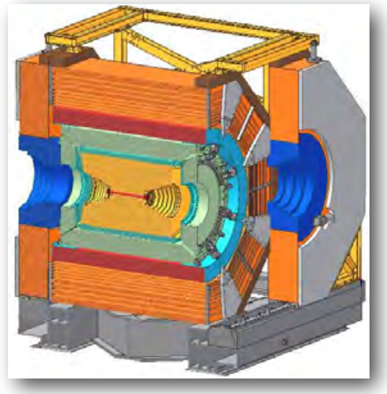
2008: test run

2009 - now: BESIII physics run

- **1989-2004 (BEPC):**
  L_{peak}=1.0x10^{31} /cm^{2}s
- **2009-now (BEPCII):**
  L_{peak}=0.85x10^{33}/cm^{2}s

BESIII - Detector





Muon Chambers

- 8 – 9 layers of RPC
- p>400 MeV/c
- δRΦ = 1.4 ~ 1.7 cm

Superconducting Magnet

- 1 T magnetic field

EMC

- 6240 CsI(Tl) crystals
- $\sigma(E)/E = 2.5\%$
- $\sigma_{Z.\Phi}(E) = 0.5 – 0.7$ cm

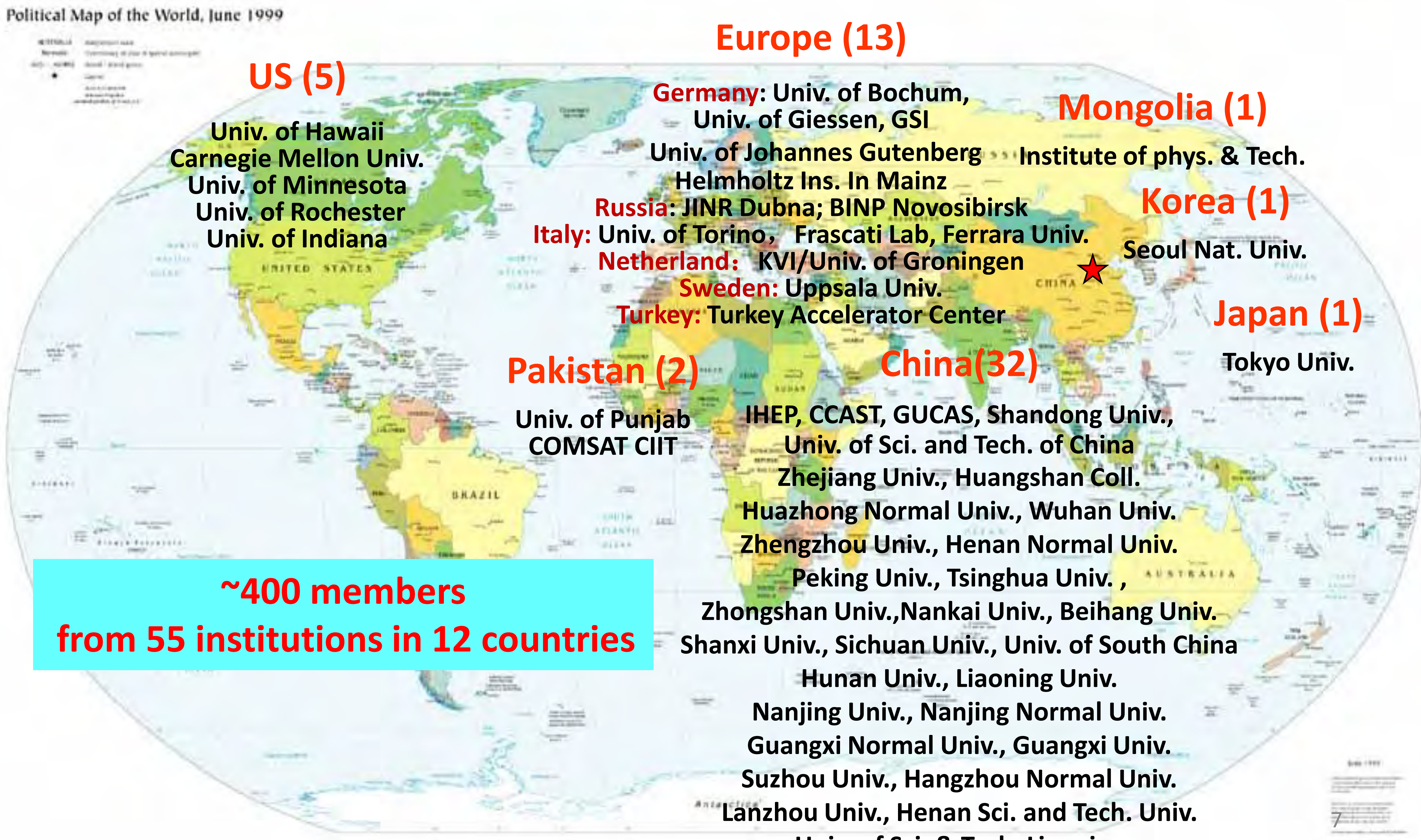
Mini Drift Chamber (MDC)

- $\sigma(p)/p = 0.5\%$
- $\sigma_{dE/dx} = 6.0\%$

Time-of-flight system (TOF)

- $\sigma(t)$ = 80ps (barrel)
- $\sigma(t)$ = 110ps (endcap)

BESIII - Collaboration



Europe (13)

Germany: Univ. of Bochum, Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino， Frascati Lab, Ferrara Univ.
Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

US (5)

Univ. of Hawaii
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Mongolia (1)

Institute of phys. & Tech.

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

Pakistan (2)

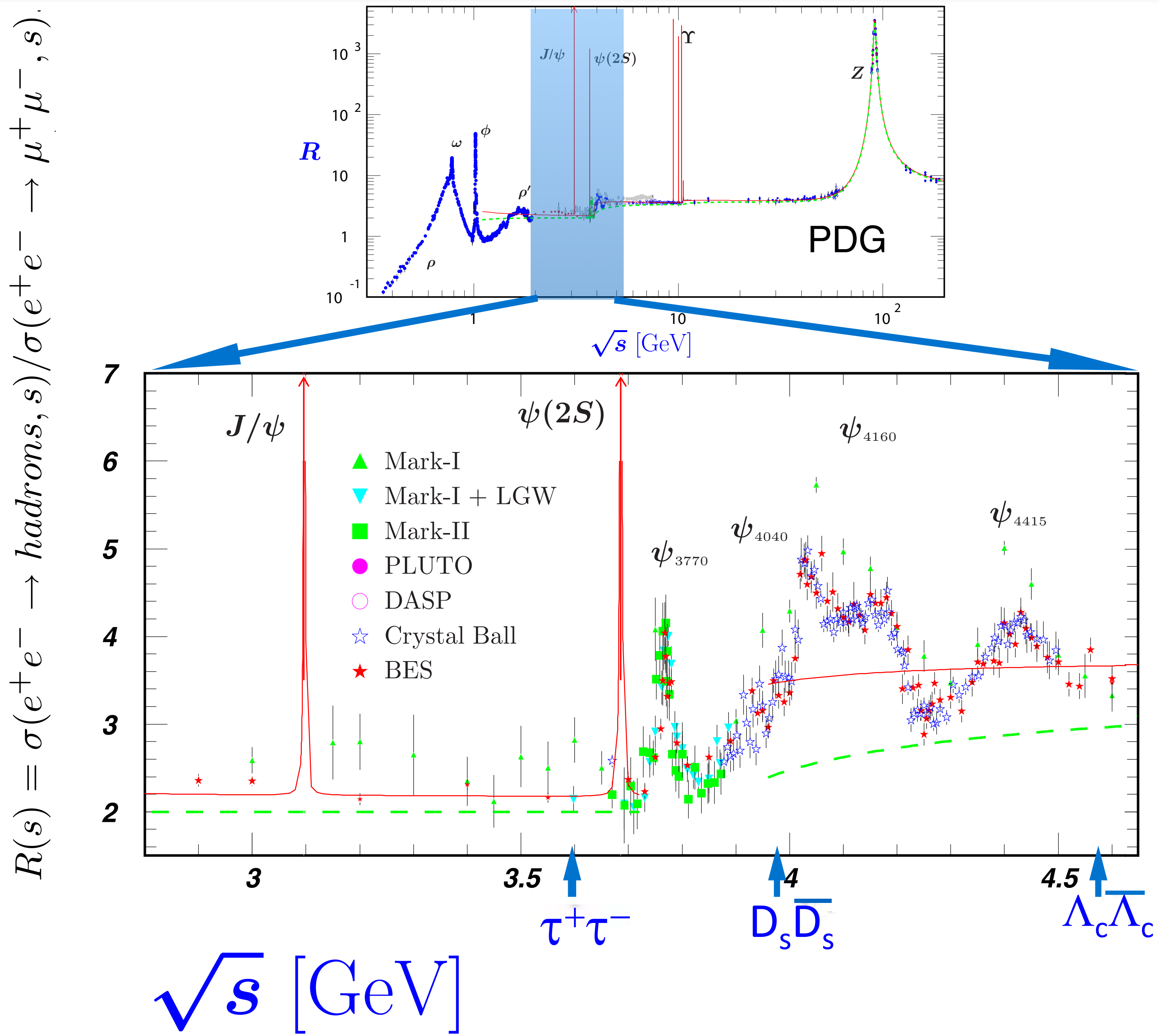
Univ. of Punjab
COMSAT CIIT

China(32)

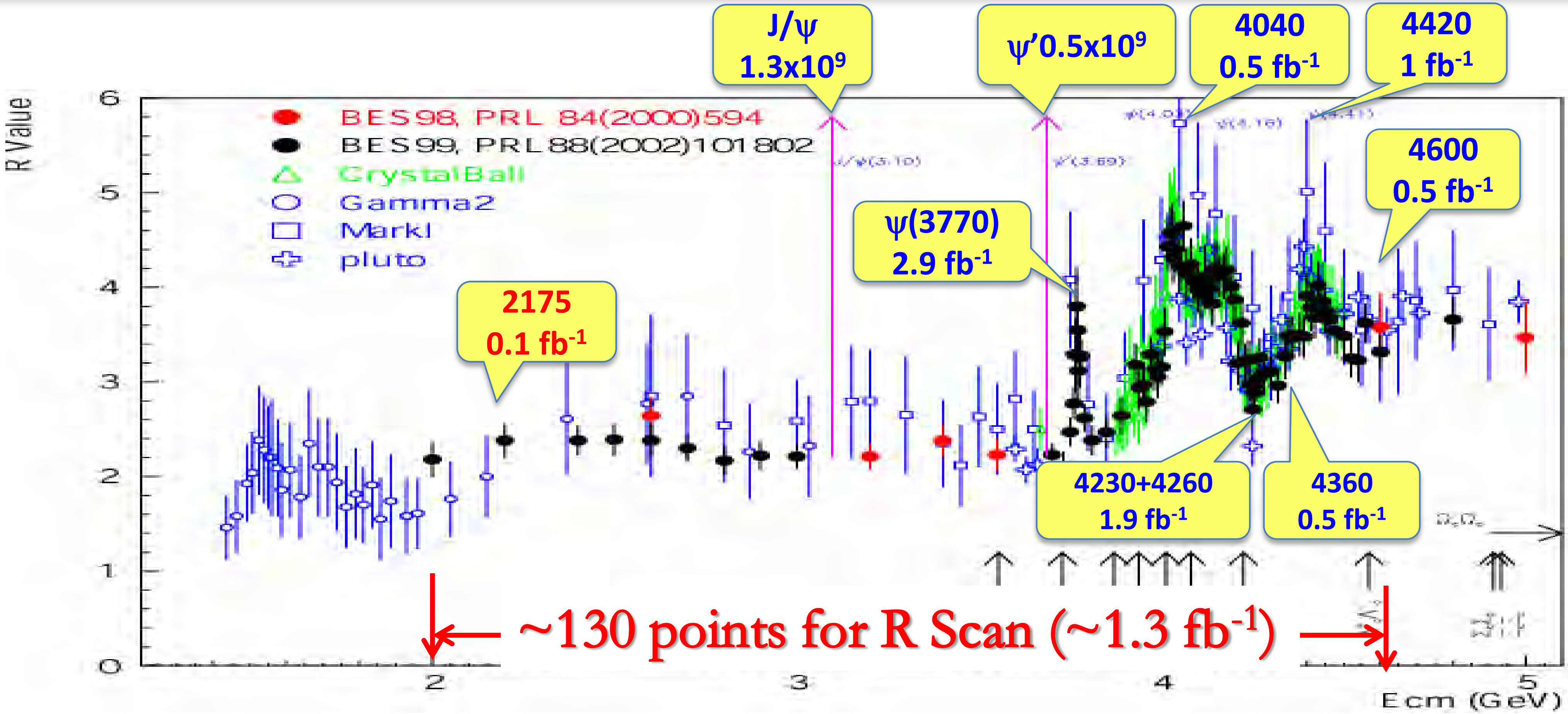
IHEP, CCAST, GUCAS, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ., Beihang Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Univ. of Sci. & Tech. Liaoning

~400 members
from 55 institutions in 12 countries

Energy Regime of BESIII



BESIII Data Samples



- The world's larges samples of $J^{PC}=1^{--}$ states produced in e^+e^- annihilation

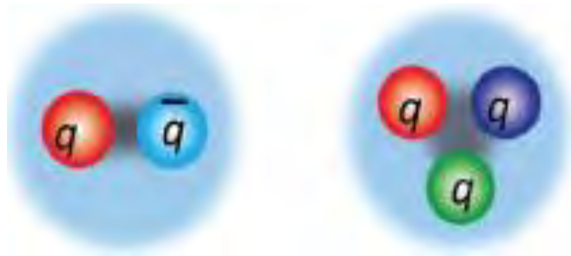
- In addition: ISR physics, photon-photon physics

BESIII Physics Program

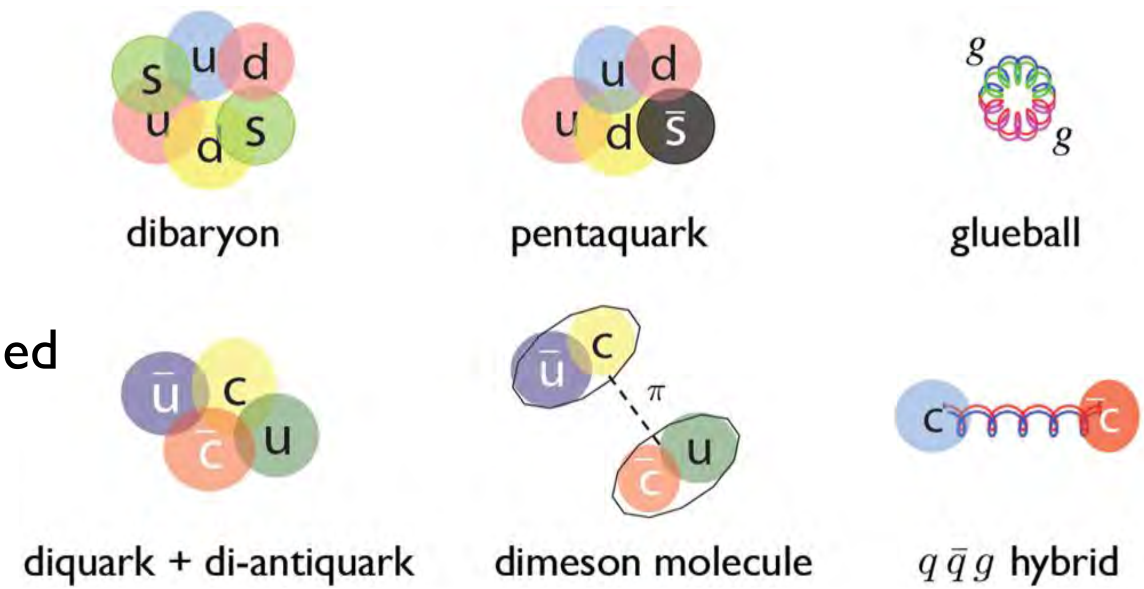
- Light hadron physics
  - Spectroscopy, search for exotic hadrons
  - Time-like form factors
- Charmonium and Charmonium-like exotic (XYZ) states
- Charmed mesons and baryons
- Precision measurement of the tau lepton mass and the R value
- Rare and forbidden decays, search for BSM physics
- **Rich physics program**
  - **Started data taking in 2009, first publication in 2010**
  - **Now: more than 100 publications including 19 Physical Review Letters**

Reminder: Hadrons

- Hadrons are the **bound states of QCD**
- All hadrons are **color singlets**
- Well established hadrons
  - **Mesons** (quark/antiquark states)
  - **Baryons** (3-quark states)



- However: **QCD allows more configurations:**
  - Experimentally not well established

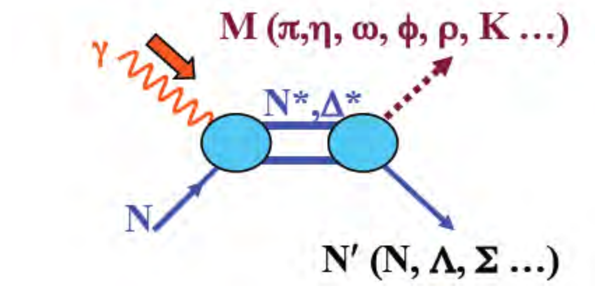


Light Hadrons: Baryon Spectroscopy

- Long-standing problem: missing baryon resonances

- Conventional approach: scattering of photons, pions, kaons etc off nucleons

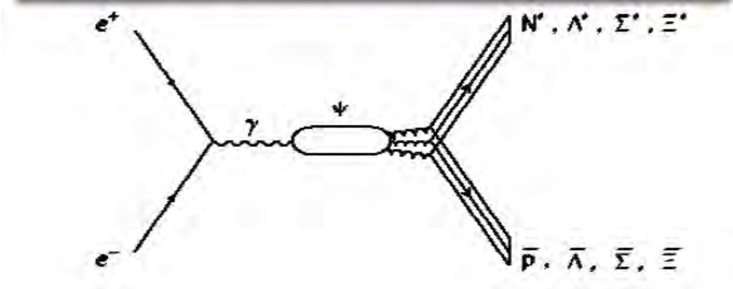
JLAB, MAMI, ELSA, …..



Caveat: only resonances coupling to the entrance channel can be populated

- BESIII: Charmonium decay into Baryon-Resonance+Anti-Baryon

$$J/\psi(\psi') \rightarrow \overline{B}BM \;\Rightarrow\; N^*, \Lambda^*, \Sigma^*, \Xi^*$$

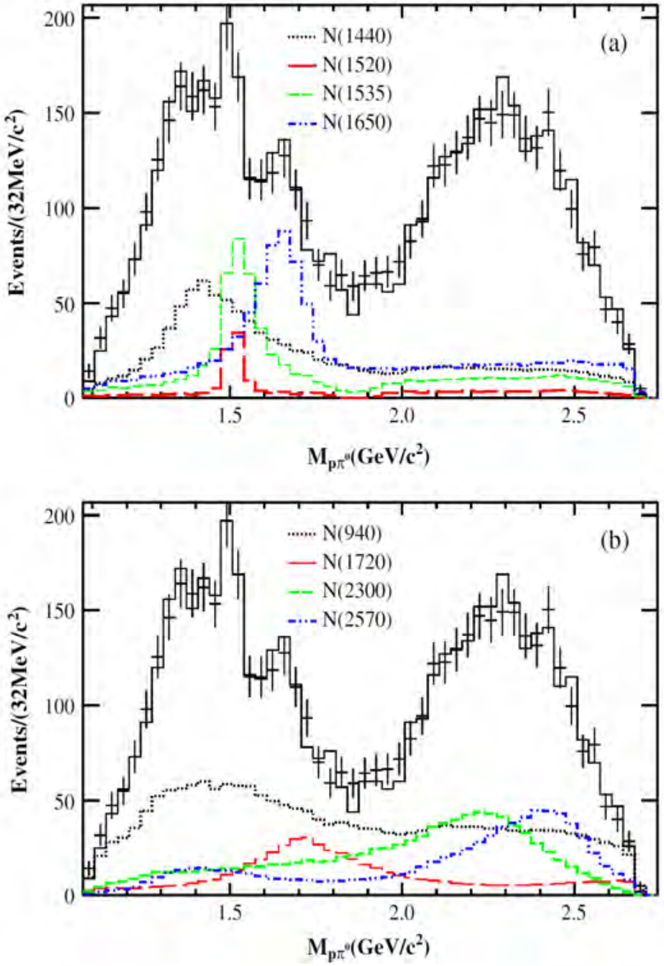


Final state: Baryon, Anti-Baryon and Meson
Works also for strange baryons

Baryon Resonances from Charmonium Decays

PWA of $\psi(2S) \to \pi^0 p\bar{p}$

Phys. Rev. Lett. **110**, 022001 (2013)

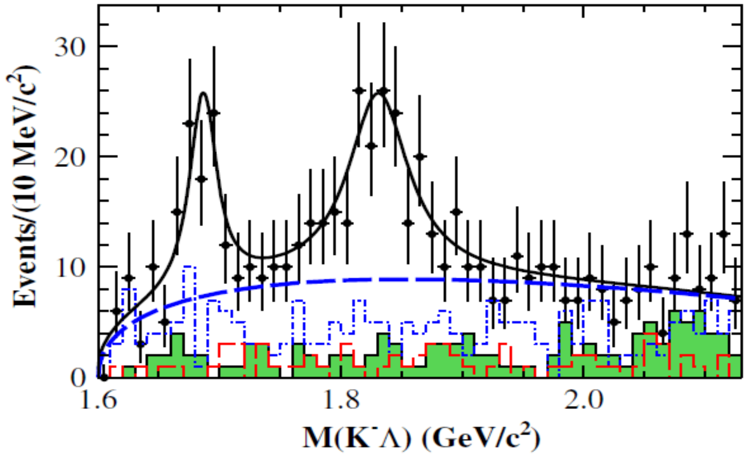


N(2300)	$2300^{+40+109}_{-30-0}$	$340^{+30+110}_{-30-58}$	120.7	4	15.0σ
N(2570)	2570^{+19+34}_{-10-10}	250^{+14+69}_{-24-21}	78.9	6	11.7σ

$\psi(2S) \to K^-\Lambda\bar{\Xi}^+$

Observation of $\Xi(1690)^-/\Xi(1820)^-$

Phys. Rev. D **91**, 092006 (2015)

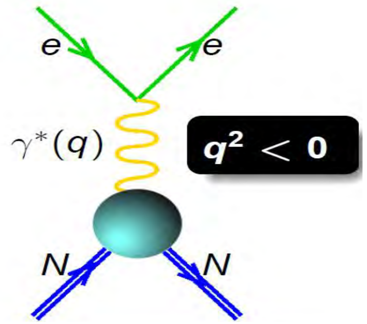


	$\Xi(1690)^-$	$\Xi(1820)^-$
$M(\mathrm{MeV}/c^2)$	$1687.7 \pm 3.8 \pm 1.0$	$1826.7 \pm 5.5 \pm 1.6$
$\Gamma(\mathrm{MeV})$	$27.1 \pm 10.0 \pm 2.7$	$54.4 \pm 15.7 \pm 4.2$
Event yields	74.4 ± 21.2	136.2 ± 33.4
Significance(σ)	4.9	6.2
Efficiency(%)	32.8	26.1
$\mathcal{B}(10^{-6})$	$5.21 \pm 1.48 \pm 0.57$	$12.03 \pm 2.94 \pm 1.22$
$M_{\mathrm{PDG}}(\mathrm{MeV}/c^2)$	1690 ± 10	1823 ± 5
$\Gamma_{\mathrm{PDG}}(\mathrm{MeV})$	< 30	24^{+15}_{-10}

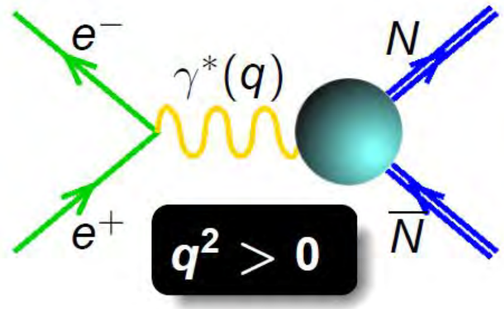
Time-Like Baryon Form Factors

Space-like:
FF real

$eN \rightarrow eN$



$e^+e^- \leftrightarrow N\bar{N}\ ,\Lambda\bar{\Lambda}$



Time-like:
FF complex

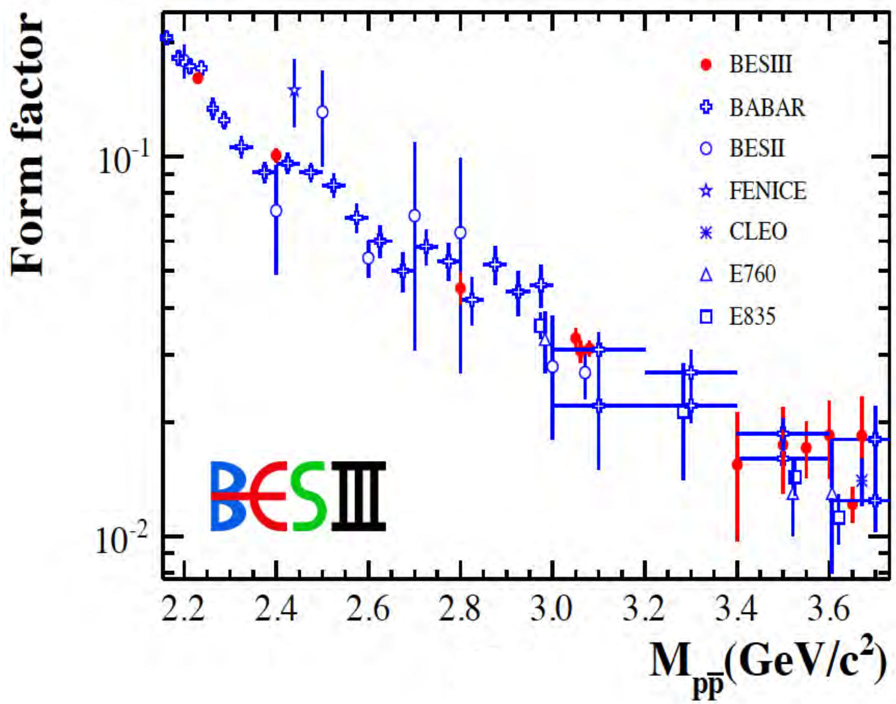
- QCD predictions:
  - at large q^2, absolute value of $FF(q^2)=FF(-q^2)$
    - Experiment: time-like FF much larger than space-like FF
  - Squared ratio of neutron/proton form factors ≈ 0.25
    - Problem: only very poor data for neutron form factor

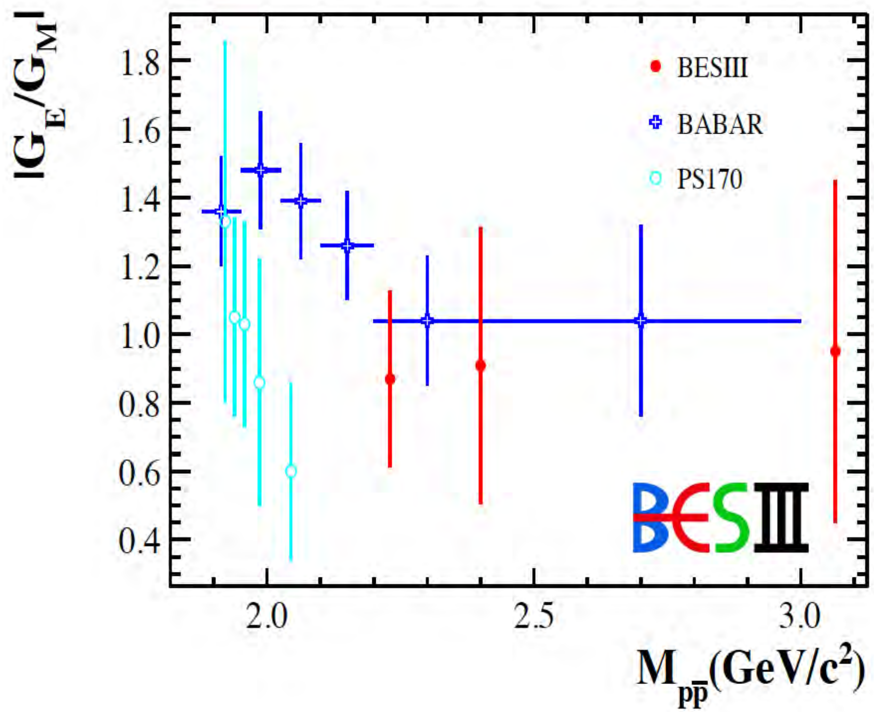
Measurement of the Time-like Proton Form Factor

- Angular analysis allows extraction of $|G_E/G_M|$

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

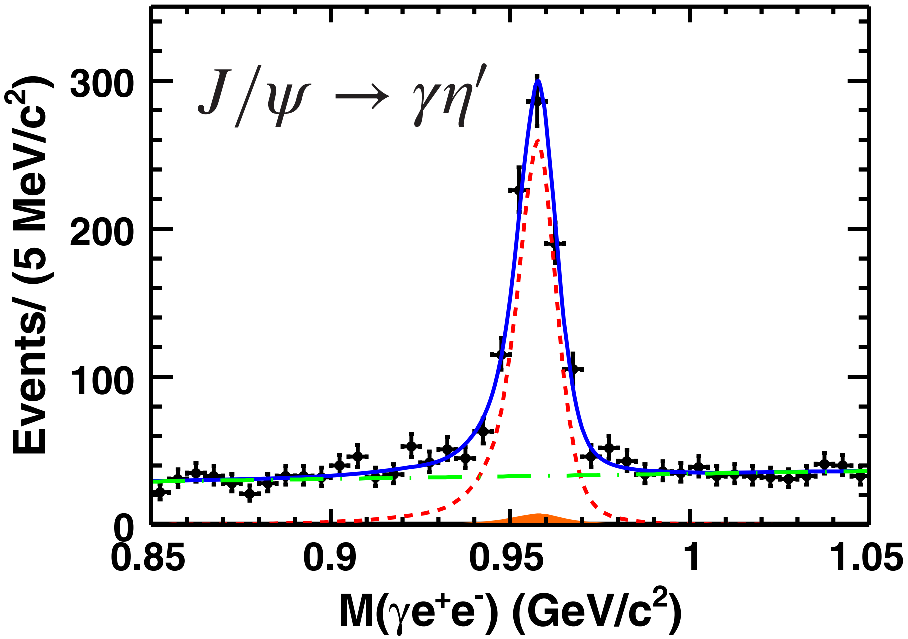
PHYSICAL REVIEW D **91,** 112004 (2015)

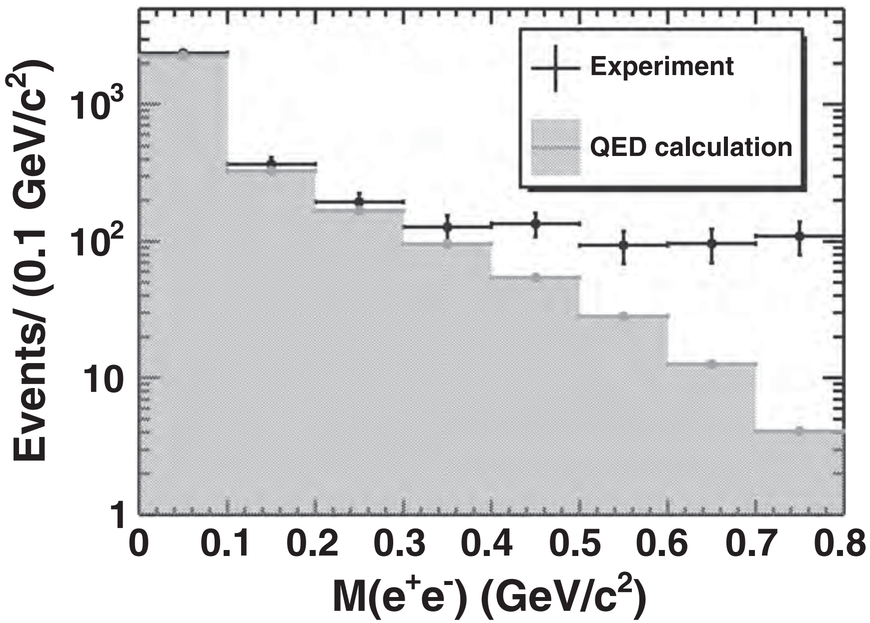




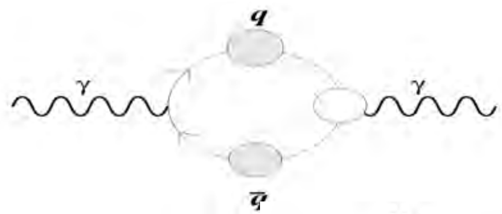
Observation of the Dalitz Decay $\eta' \to \gamma e^+ e^-$

- Contains information about time-like FF at small q^2

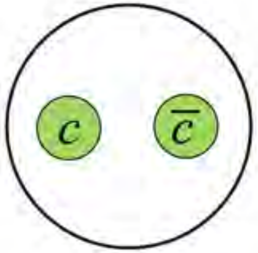




- At large q^2, strong enhancement compared to QED calculation for point-like hadron
  - Possible explanation: vector meson dominance:

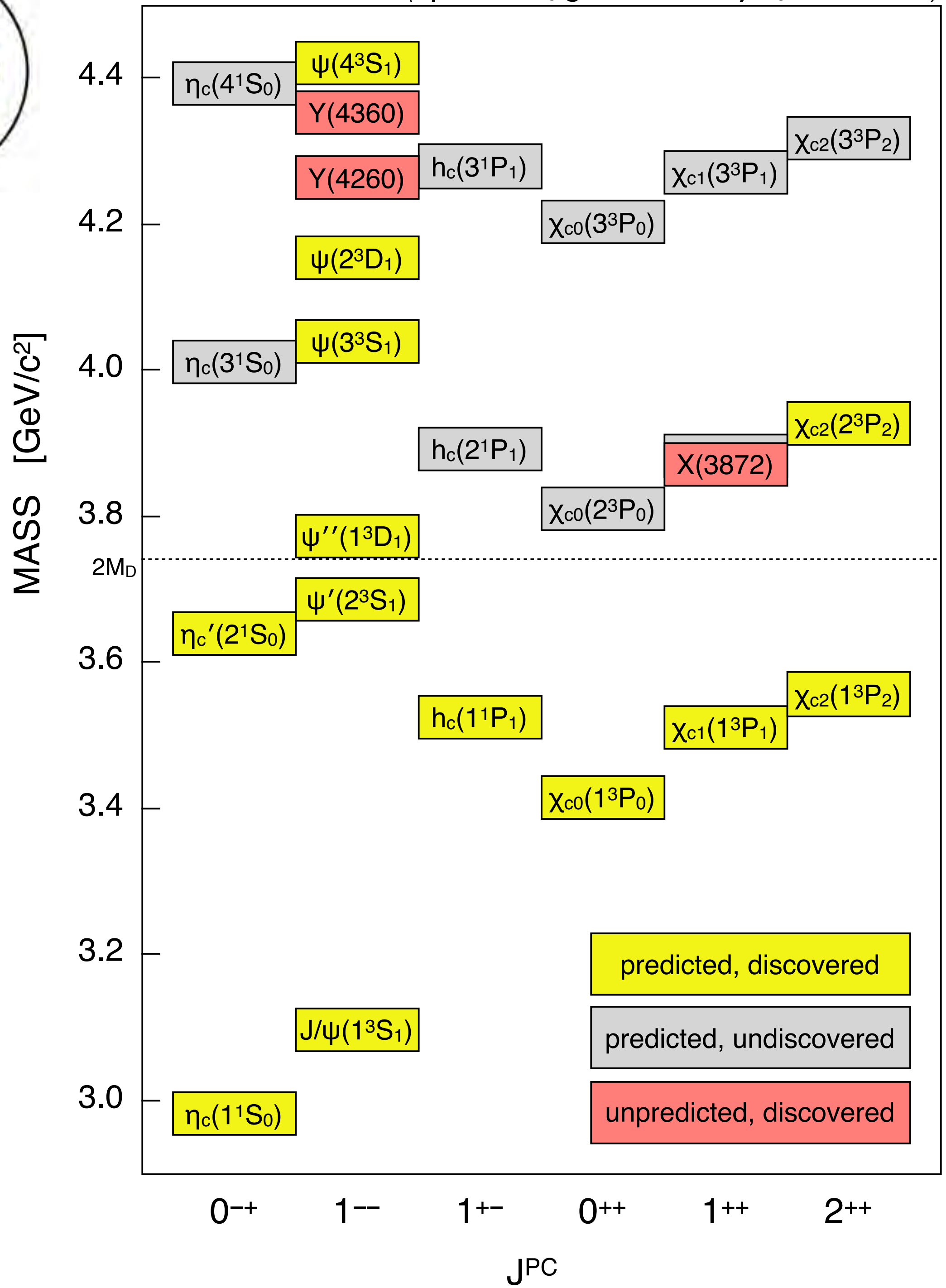


Charmonium and Charmonium-like States



- **Charmonium in QCD is like positronium in QED**
  - Bound states of charm/anti-charm quarks
- **Levels below the open charm threshold** (“ionization”) well understood
  - Experiment and theory agree well
- **Above the open charm threshold,** situation more complex
  - Some of the predicted states have been found, many have not yet been observed
  - **New unpredicted states have been found** with properties that are not consistent with conventional charmonium states => “**XYZ states**”

(Spectrum figures courtesy of R. Mitchell)



Prediction: Barnes, Swanson, and Godfrey, PRD 72, 054026 (2005)

XYZ - Physics

- **X** : neutral charmonium - like states with quantum numbers other than 1^{--} (vector)

- **Y** : neutral charmonium - like states with 1^{--} (vector) quantum number

  - Can be directly formed in an e^+e^- collision

- **Z** : charged charmonium-like states

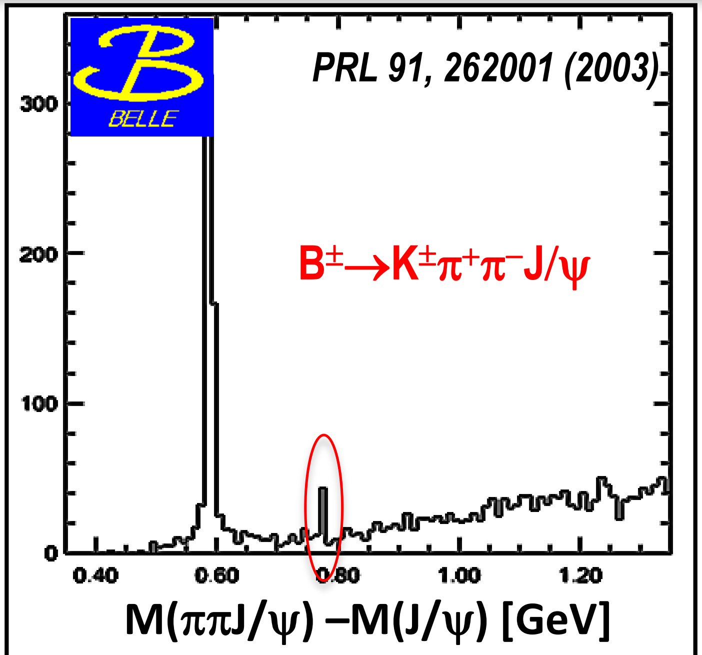
  - Such a state must consist of at least 2 quarks and 2 antiquarks

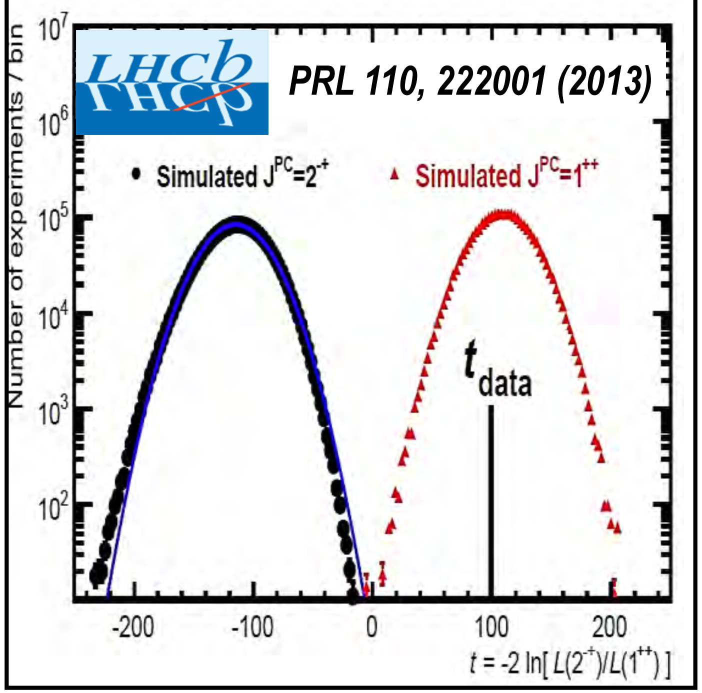
X(3872) - the first XYZ state discovered in 2003

- First X - state discovered in B decays at Belle
- Extremely narrow resonance at 3872 MeV
  - Mass(D^0)+mass(D^{*0})=3871.84±0.28 MeV ? ?
  - Width < 1.2 MeV
    - compare ψ(3770) : Γ = 27.2 MeV
- Seen in many other experiments
- Peculiar decay modes:

Γ_i	Mode	Fraction (Γ_i / Γ)
Γ_1	$X(3872) \to e^+e^-$	
Γ_2	$X(3872) \to \pi^+\pi^- J/\psi(1S)$	>2.6 %
Γ_3	$X(3872) \to \rho^0 J/\psi(1S)$	
Γ_4	$X(3872) \to \omega J/\psi(1S)$	>1.9 %
Γ_5	$X(3872) \to D^0\overline{D}^0\pi^0$	>3.2 ×10^{-1}
Γ_6	$X(3872) \to \overline{D}^{*0} D^0$	>2.4 ×10^{-1}

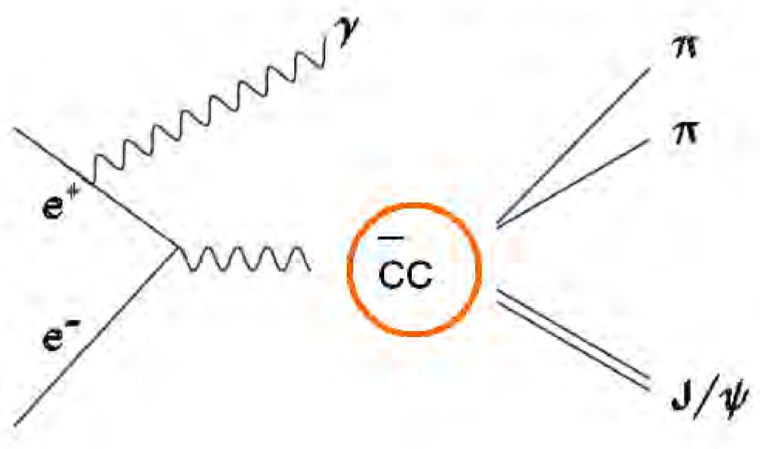
- Recently, LHCb has determined the quantum numbers to be J^{PC} = 1^{++}





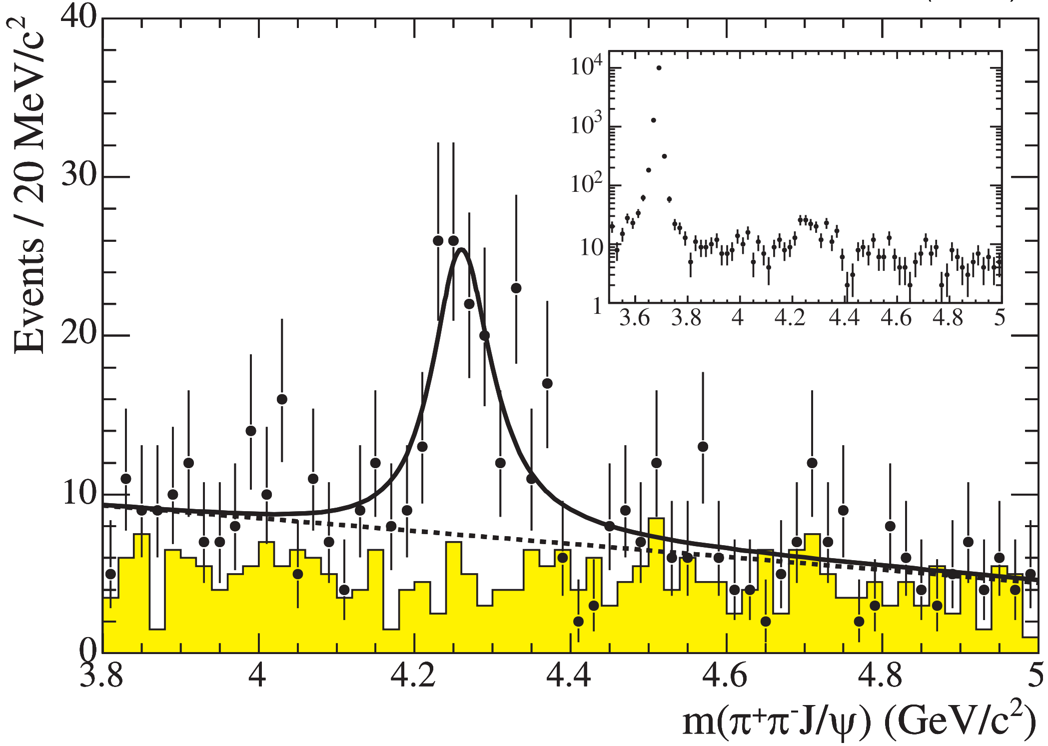
The first exotic 1^{--} state: Y(4260), discovered by BaBar

- Discovered in **initial state radiation:**



$$e^+e^- \rightarrow \gamma_{ISR} \underbrace{J/\psi\pi^+\pi^-}_{\text{resonant state?}}$$

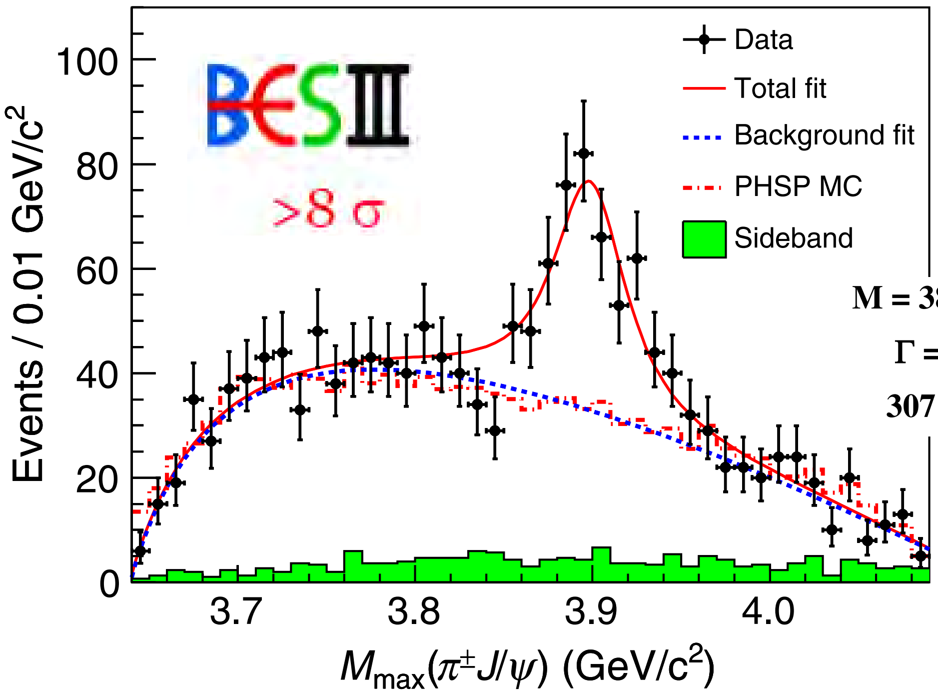
The BaBar Collaboration, PRL 95, 142001 (2005)



- Why is this no conventional charmonium state ?
  - Does not fit predicted spectrum of vector states, overpopulation of 1^{--} states
  - Peculiar decay pattern: $$\frac{\mathcal{B}(Y(4260) \rightarrow D\bar{D})}{\mathcal{B}(Y(4260) \rightarrow \pi\pi J/\psi)} < 4$$
    - Compare to ψ(3770) : ratio is ≈ 500 ! (open charm decays dominant)

Z(3900): Discovery of a charged Charmonium-Like State by BESIII, confirmed by Belle and CLEOc Data

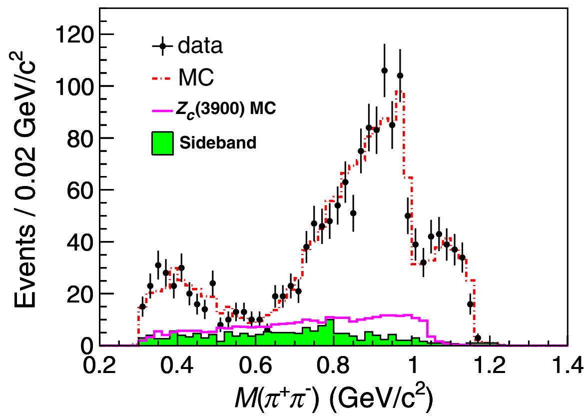
- Idea: Y(4260) seems exotic - let's look at its decay products
- Strong decay to $J/\psi\ \pi^+\pi^-$
- Analyze Dalitz plot, understand structures in $\pi^+\pi^-$ mass spectrum (scalar mesons)



M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

307 ± 48 events, >8σ



- **Clear evidence for a charged charmonium-like state !**

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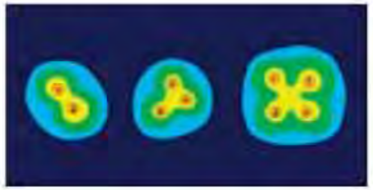
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

PHYSICS VIEWPOINT



New Particle Hints at Four-Quark Matter

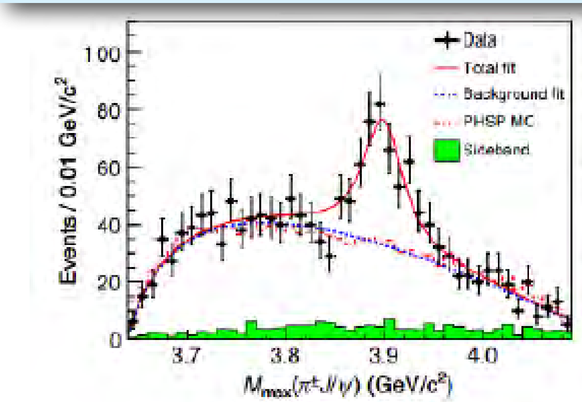
Published 17 June 2013

Two experiments have detected the signature of a new particle, which may combine quarks in a way not seen before.

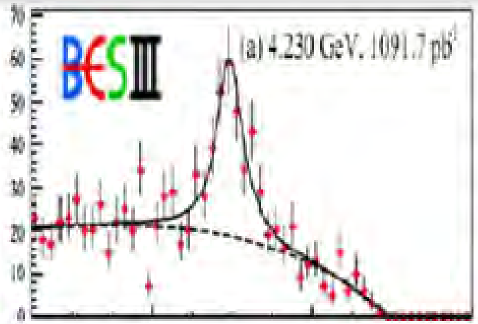
This is the first charged Z state observed by 2 experiments!

named „APS Highlight of the year 2013“
among others, e.g. extra-solar neutrinos by IceCube

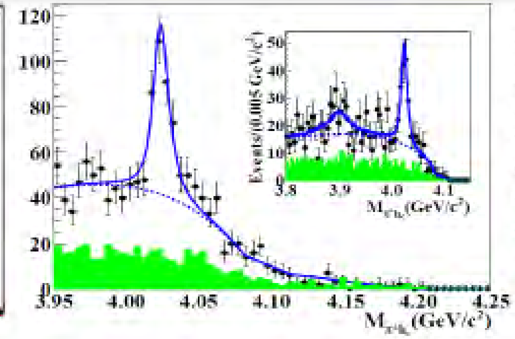
Discovery of 2 Charmonium-like Isospin Triplets



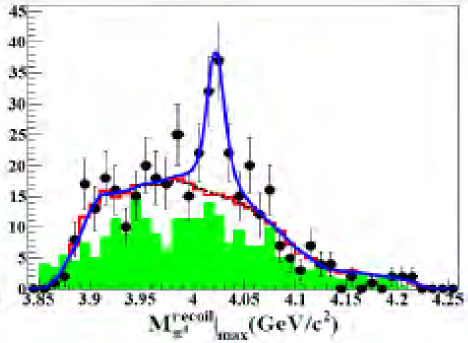
$e^+e^- \to \pi^-\pi^+ J/\psi$



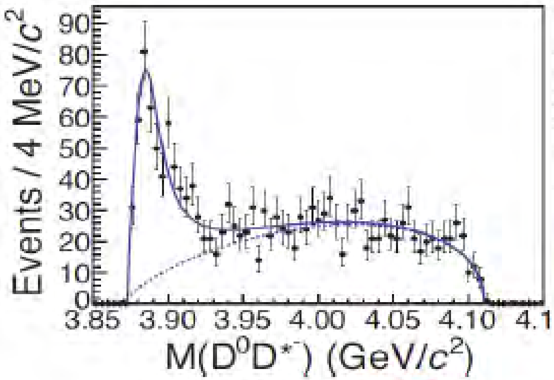
$e^+e^- \to \pi^0\pi^0 J/\psi$



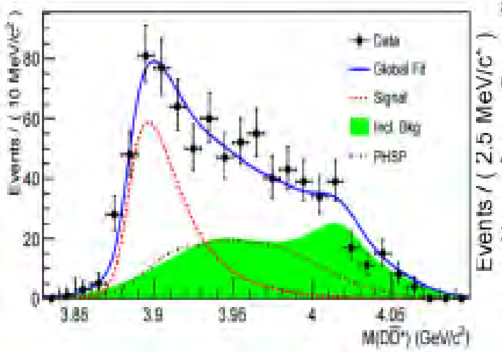
$e^+e^- \to \pi^-\pi^+ h_c$



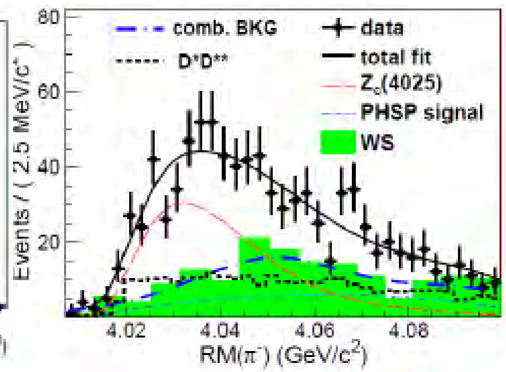
$e^+e^- \to \pi^0\pi^0 h_c$



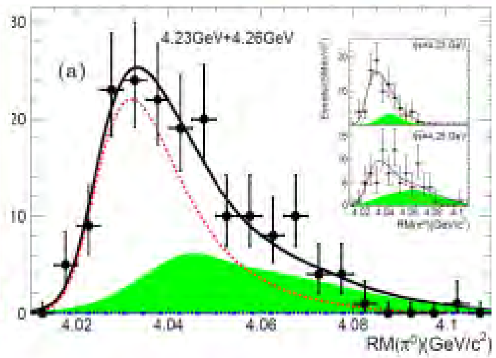
$e^+e^- \to \pi^\pm (D\bar{D}^*)^{-/+}$



$e^+e^- \to \pi^0 (D\bar{D}^*)^0$



$e^+e^- \to \pi^\pm (D^*\bar{D}^*)^{-/+}$

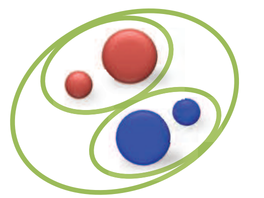


$e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$

$Z_c(3900)^+$? **$Z_c(3900)^0$?** **$Z_c(4020)^+$?** **$Z_c(4020)^0$?**

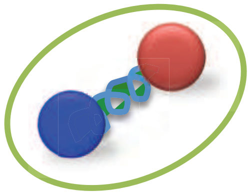
- States observed via open charm decays and via pion decay have compatible mass and width
- Suggestion: we are seeing **two isospin triplets in two different decay modes**

What are these states ?



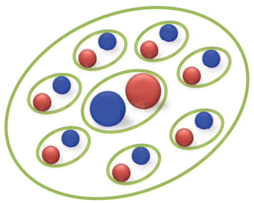
Tetraquark

$\rightarrow$ Compact object formed from (Qq) and $(\bar{Q}\bar{q})$



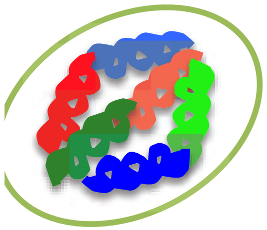
Hybrid

$\rightarrow$ Compact with active gluons and $\bar{Q}Q$



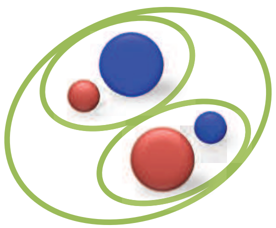
Hadro-Quarkonium

$\rightarrow$ Compact $(\bar{Q}Q)$ surrounded by light quarks



Glueball

$\rightarrow$ Compact object just made off gluons



Hadronic-Molecule

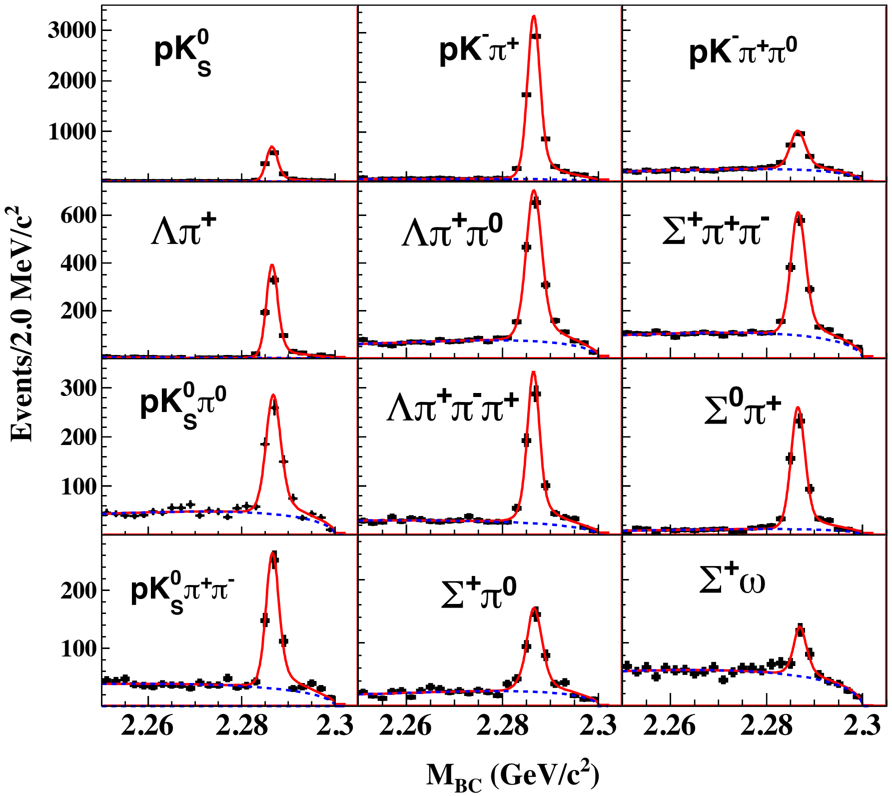
$\rightarrow$ Extended object made of $(\bar{Q}q)$ and $(Q\bar{q})$

....or...mixtures of such configurations with/without conventional charmonium states

(Slide stolen from Christoph Hanhart)

Charmed Baryons: Λ_c decays

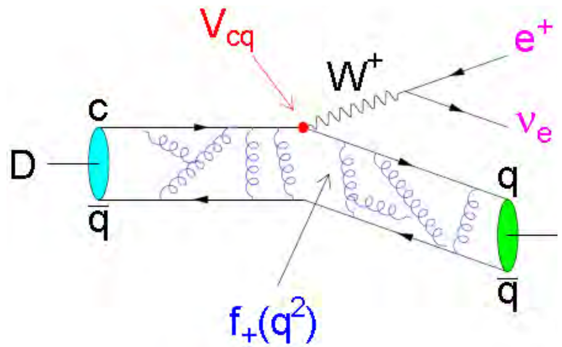
- Measurement of absolute breaching fractions for Cabibbo-favored hadronic decays using double-tagged data



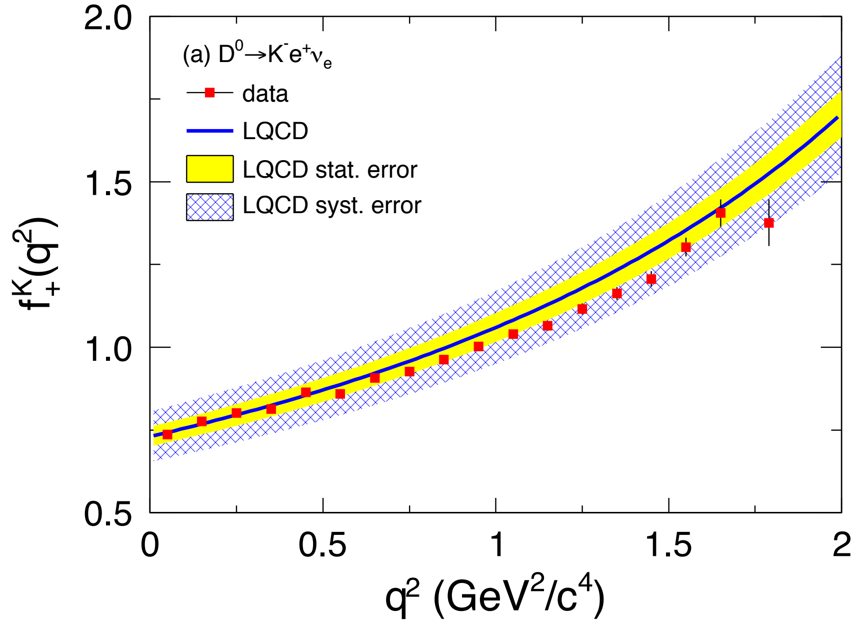
Mode	This work(%)	PDG(%)	Belle(%)
pK^0_S	$1.47 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	$5.64 \pm 0.27 \pm 0.22$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK^0_S\pi^0$	$1.75 \pm 0.12 \pm 0.05$	1.65 ± 0.50	
$pK^0_S\pi^+\pi^-$	$1.46 \pm 0.10 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	$4.22 \pm 0.23 \pm 0.28$	3.4 ± 1.0	
$\Lambda\pi^+$	$1.19 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	$6.67 \pm 0.35 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	$3.66 \pm 0.23 \pm 0.17$	2.6 ± 0.7	
$\Sigma^0\pi^+$	$1.21 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	$1.13 \pm 0.09 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	$4.05 \pm 0.23 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	$1.50 \pm 0.20 \pm 0.09$	2.7 ± 1.0	

Charmed Mesons:
Form Factors for Semi-leptonic Decays

Measure semi-leptonic decay rate

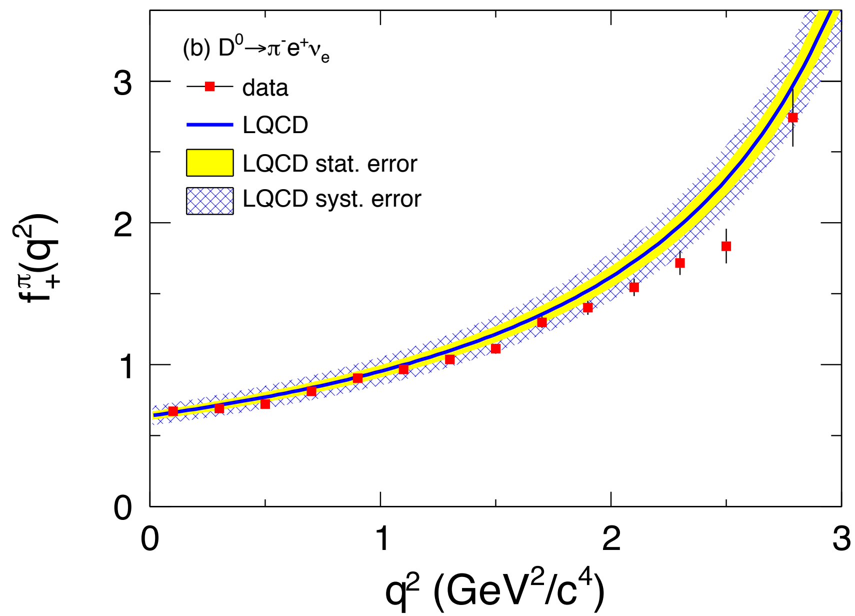


$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{cs(d)}|^2|\vec{p}_{K^-(\pi^-)}|^3|f_+^{K(\pi)}(q^2)|^2$$



Two options:

1. Take CKM matrix element (unitarity!) and determine FF
    1. Important benchmark for LQCD
2. Take FF from LQCD and determine CKM ma element



Summary and Outlook

- Rich Physics Program at BESIII !
- Charmonium decays as a source of light hadrons for spectroscopy and form factor measurements
- Charmonium spectroscopy is an excellent probe to study QCD in the transition between the perturbative and non-perturbative regime
- Within the last 10 years, a whole new class of charmonium -like states has been discovered that have properties which cannot be understood in terms of conventional charmonium states
  - **The structure of these states is not well understood, we know hat the charged structures must contain at least two quark/antiquark pairs**
- BESIII has discovered two isospin triplets of such charmonium-like structures
  - This looks like that QCD has to offer more types of bound states than just mesons and baryons - see also: Charmonium-like pentaquark at LHCb !!!
    - Tetraquarks, meson molecules, pentaquarks….. ???
- BESIII has excellent opportunities in open charm physics: precision measurement of form factors and decay constants, charmed baryon decay, …
- Not covered today: precision measurement of the tau lepton mass, R-Value scan, search for BSM physics
- The BESIII experiment will be running for many more years, with an upgraded detector configuration: expect to see a lot of exciting results in the future!