Baryons at BES

30 years at BES

-- 35 yrs at IHEP --

Yang Heng 1984

at Zheng Zhi Peng's home in 1984

Stephen Lars Olsen UCAS

University of Chinese Academy of Sciences

BES 30th Anniversary Symposium, September 5-6, 2019

September 5, 2019

My Boss

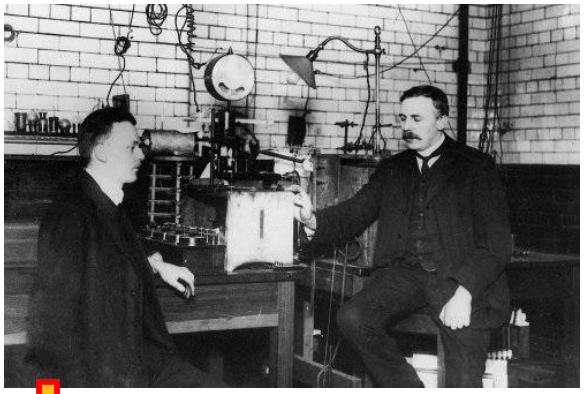
Beiwei & Zhipeng in Hawaii

2019: 100th year of the proton

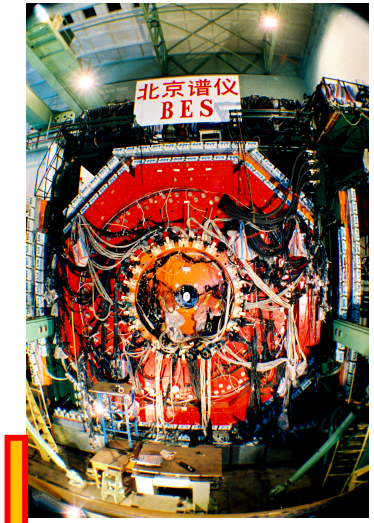
The proton was already 70 yrs old when BES started

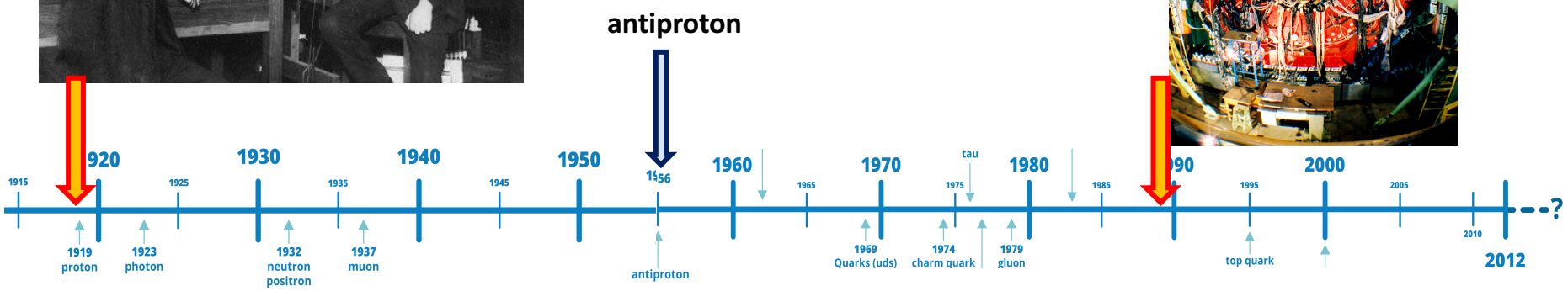
How can BES have *anything new* to say about protons (& baryons)?

proton's 100th Anniversary



BES's 30th anniversary



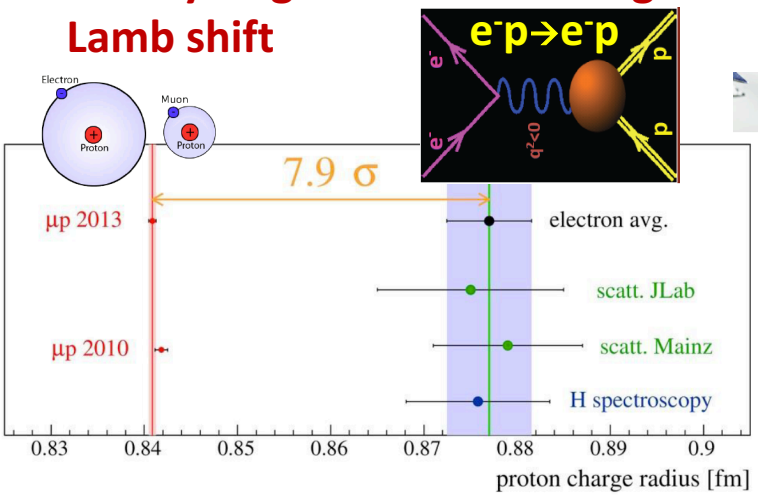


After 100 years, proton remains mysterious

proton's radius = ???

muonic hydrogen Lamb shift

ep elastic scattering



different ways to measure it give different results

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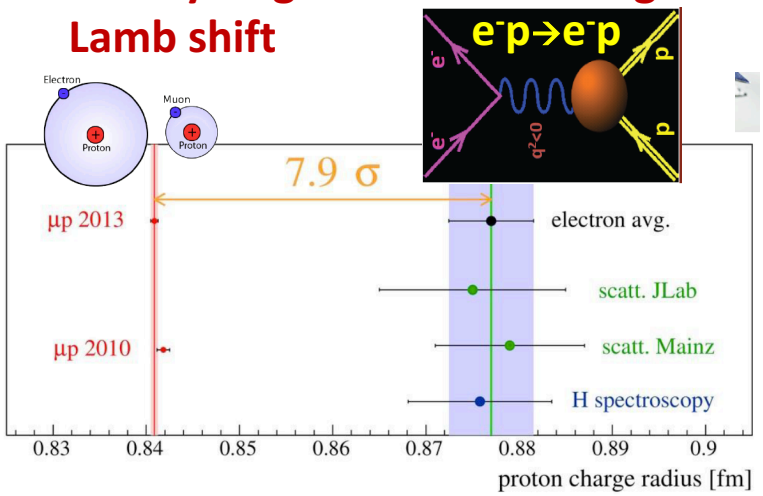
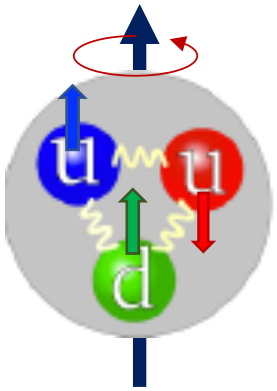


different ways to measure it give different results

what accounts for the proton's spin?

$$J_{\text{proton}} = \frac{1}{2}\hbar$$

Quarks?



$$J_{\text{quarks}} \sim 0.15\hbar$$

quarks account for only a fraction of J_{proton}

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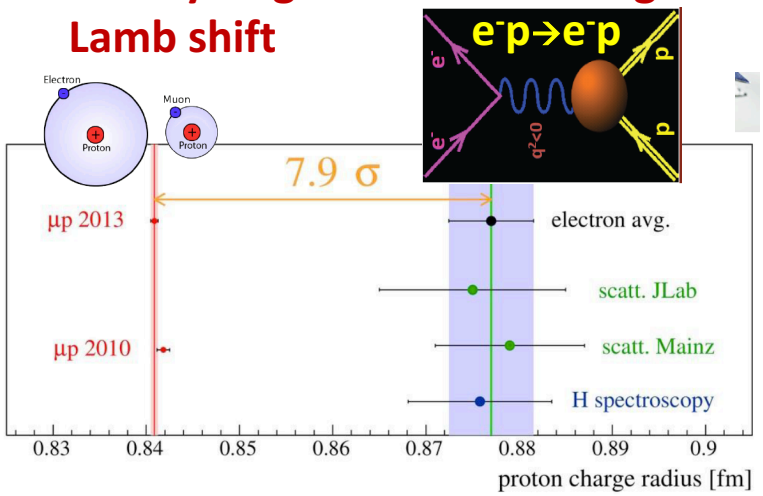

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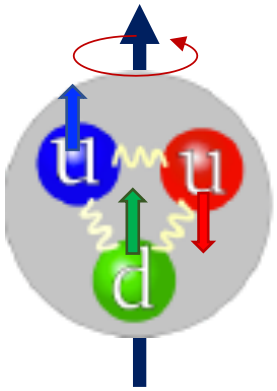

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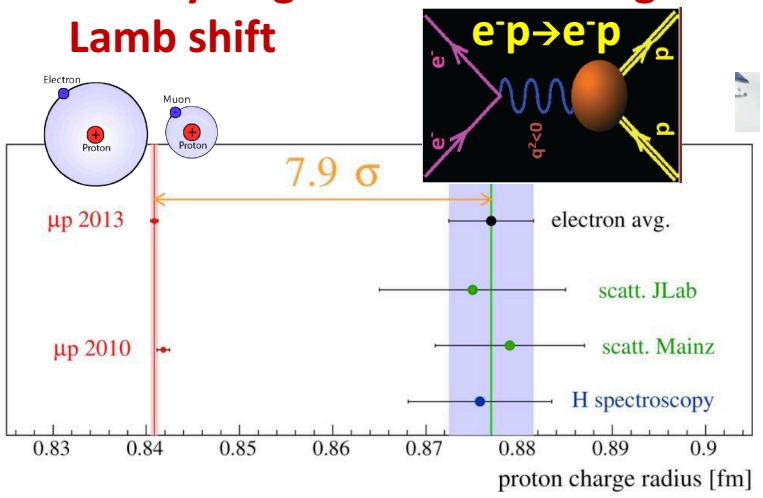
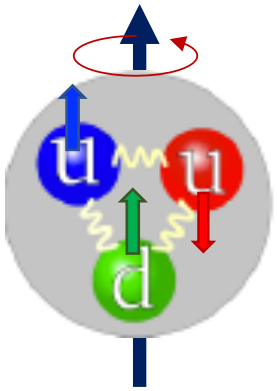


different ways to measure it give different results

what accounts for the proton's spin?

$$J_{\text{proton}} = \Delta Q + \Delta G + \Delta L = \tfrac{1}{2}\hbar$$

Quarks?



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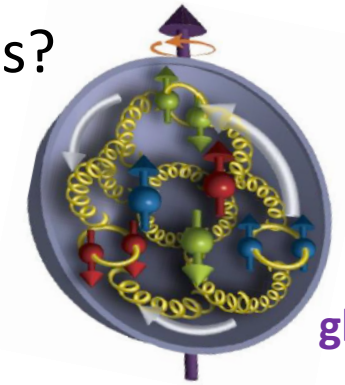
Gluons?



$\Delta G \sim 0.2\,\hbar$

gluons account for most, but not all, of the rest

After 100 years, proton remains mysterious

proton's radius = ???

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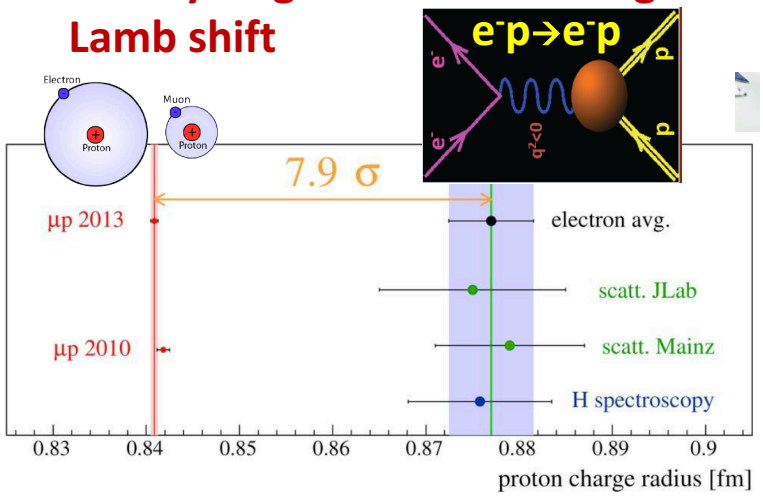

different ways to measure it give different results

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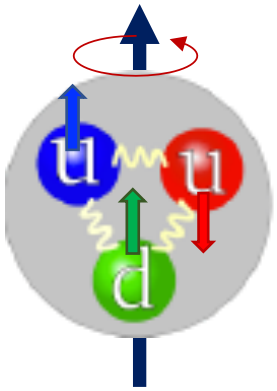
Quarks?



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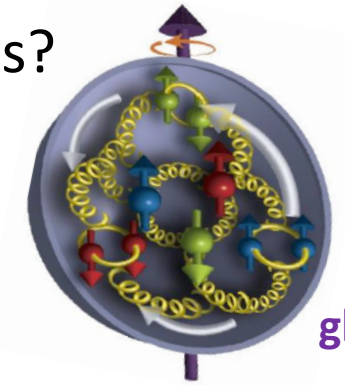


$\Delta G \sim 0.2\,\hbar$

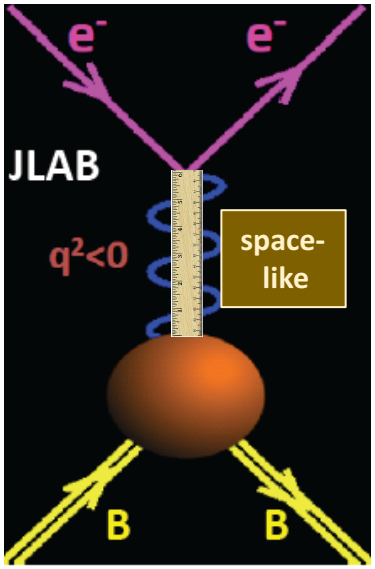
gluons account for most, but not all, of the rest

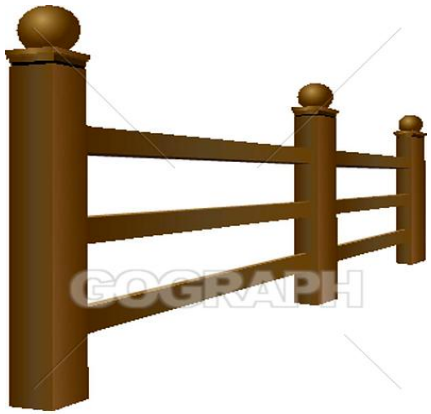
20th century techniques have failed

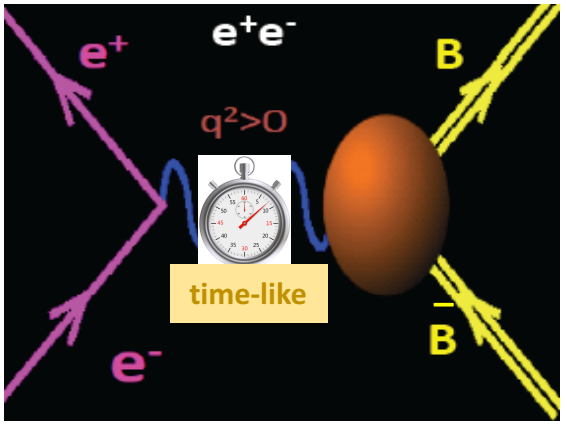
we need new, 21st century, techniques

time-like baryon form-factors

-- the view from the side of the fence --

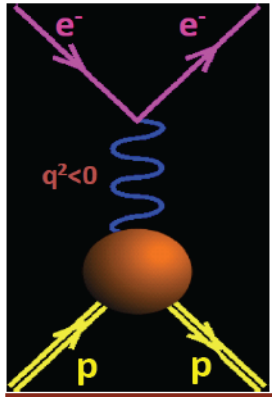






proton form-factors

Space-like ($q^2<0$)



Huge amount of data

100's of experiments starting in 1954

Separate determinations of G_E, G_M & G_{pol}

1961 Nobel Prize

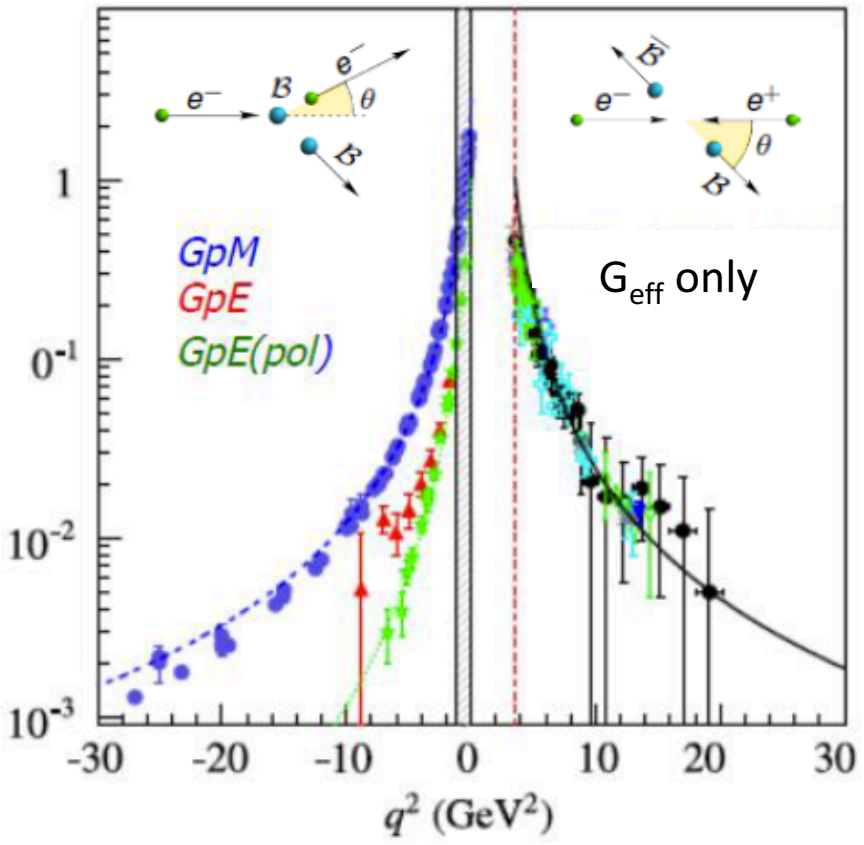
Robert Hofstadter

related by crossing symmetry

$$\langle N(p')|j^\mu|N(p)\rangle \rightarrow \langle \bar{N}(p')N(p)|j^\mu|0\rangle$$

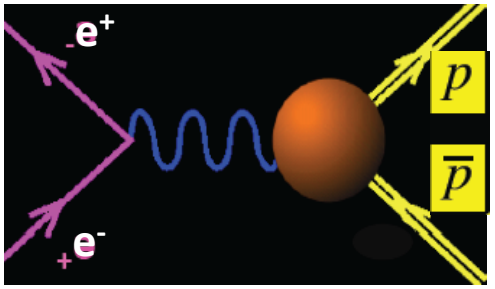
$$J^\mu = \langle N(p')|j^\mu|N(p)\rangle = e\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_2(q^2)\right]u(p)$$

Fermi & Dirac form factors



S. Pacetti et al., Phys Rep 550-551 (2015) 1

Time-like ($q^2>4m_p^2$)



Very little data

only combined

$$|G_{eff}|^2 = \frac{|G_M|^2 + \frac{1}{2\tau}|G_E|^2}{1+\frac{1}{2\tau}}$$

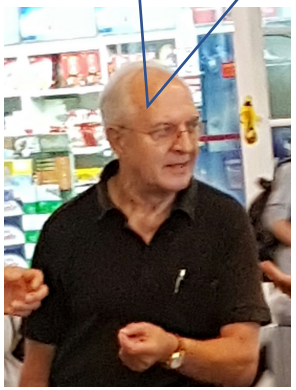
is measured

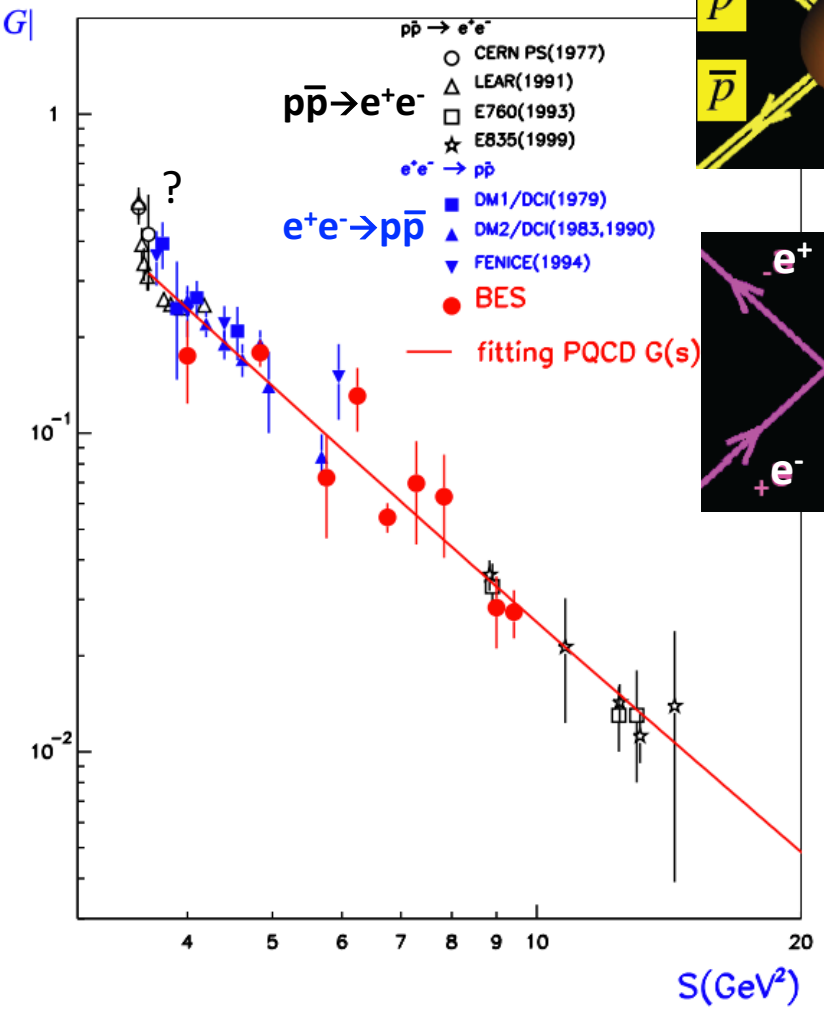
form-factors are complex

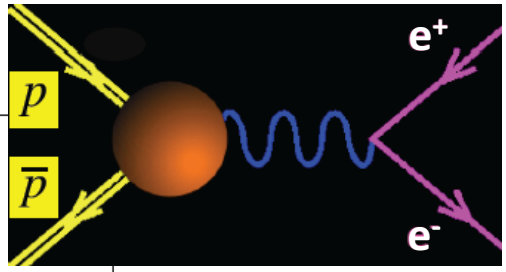
hyperon form-factors are accessible

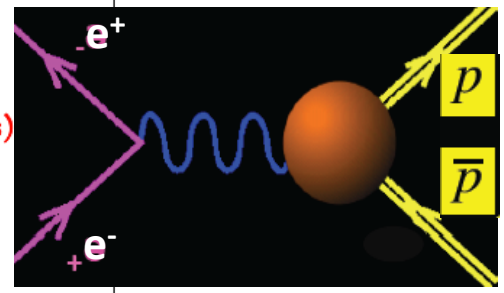
time-like proton form-factor in 2005

We must investigate the anomaly seen in $p\bar{p} \rightarrow e^+e^-$







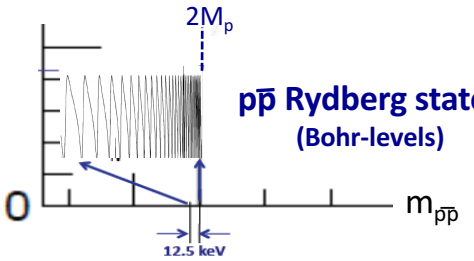


$e^+e^- \to p\bar{p}$ at threshold

Integrated cross section: $$\sigma_{p\bar{p}}(m_{p\bar{p}}) = \frac{4\pi\alpha^2 \beta C}{3m_p^2}\left|G_{eff}\left(m_{p\bar{p}}\right)\right|^2\left(1+1/2\tau\right)$$

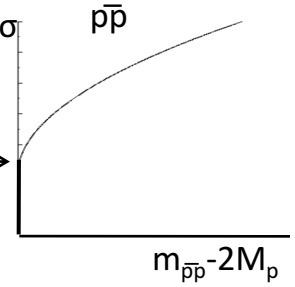
for point-like charged particles: $$C = \frac{\pi\alpha/\beta}{1-\exp\left(-\pi\alpha/\beta\right)} \to \frac{\pi\alpha}{\beta} \quad \leftarrow \text{when } \beta \to 0$$

Sommerfeld resummation factor



$$\sigma_0 = \frac{\pi^2\alpha^3}{2M_p^2}\left|G_{eff}(2M_p)\right|^2$$

$$\approx 0.85\text{nb}\left|G_{eff}(2M_p)\right|^2$$

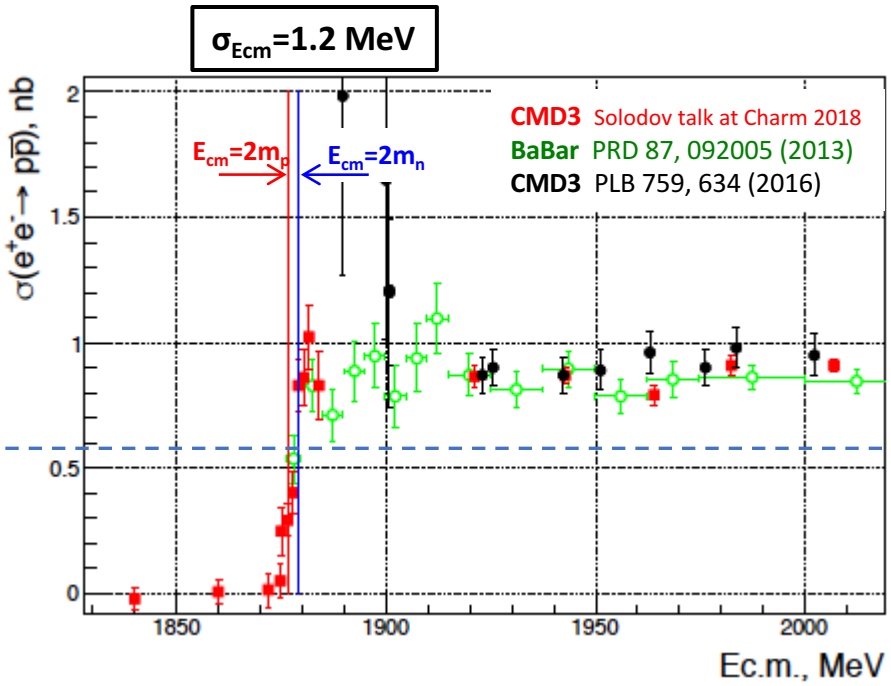


in point-like approx:
a non-zero cross-section right at the threshold!

This is what is seen

-- fast cross section jump at threshold: σ_{th}<1 MeV --

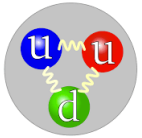
not by BESIII 😟 but by BaBar and CMD



850pb

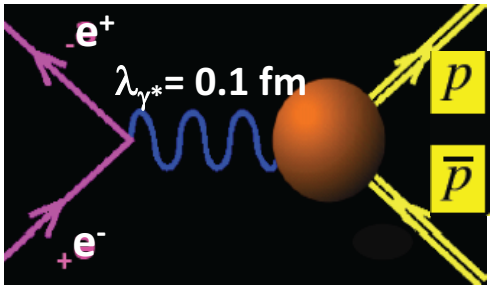
Just as expected for a charge=1 point-like fermion

but the proton is *not* point-like



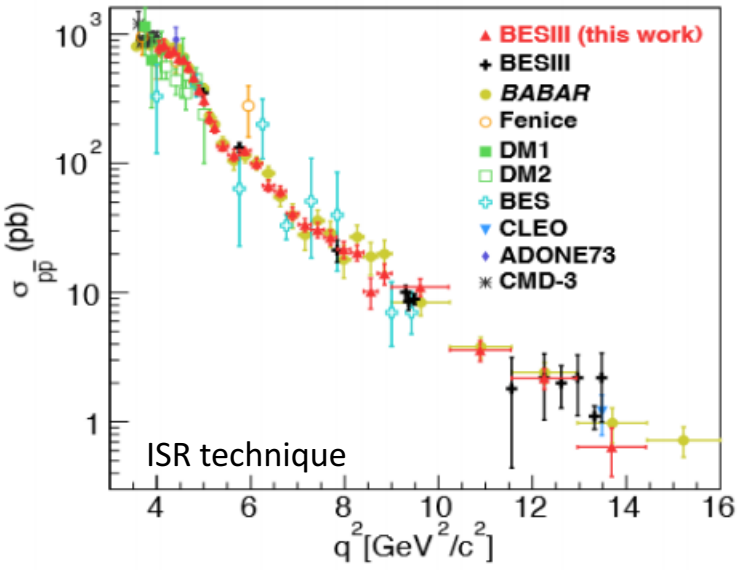
r_{proton}= 0.85 fm

& produced by a $q^2 \approx 3.5$ GeV γ^*

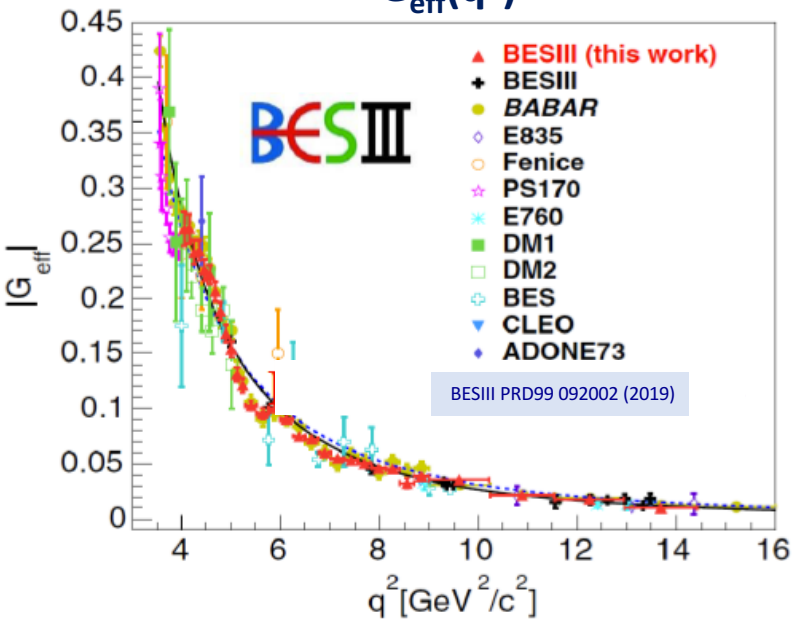


2019 results from BESIII

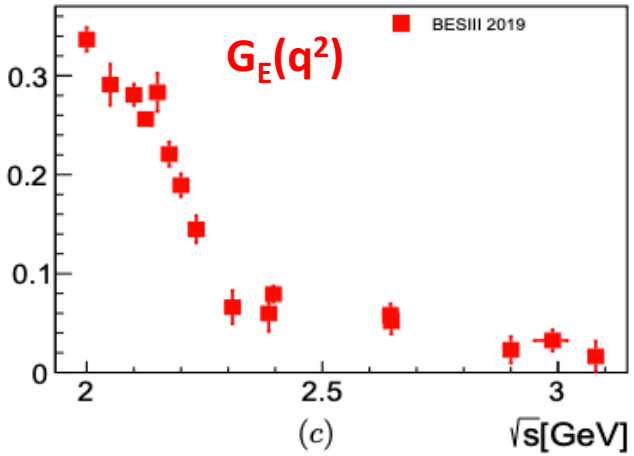
$\sigma(e^+e^- \rightarrow p\bar{p})$

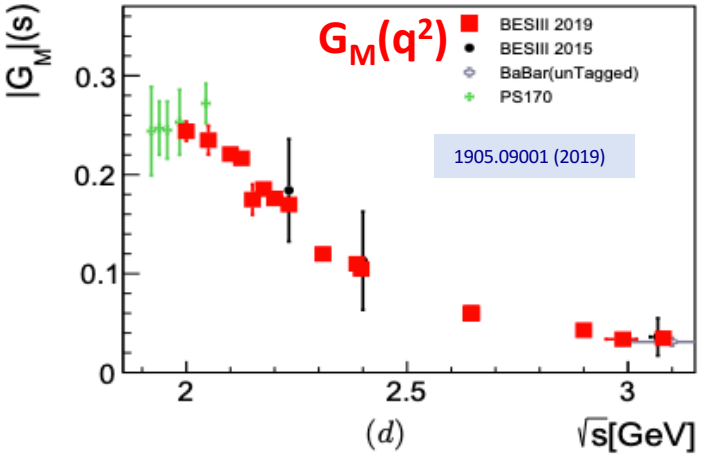


$G_{eff}(q^2)$



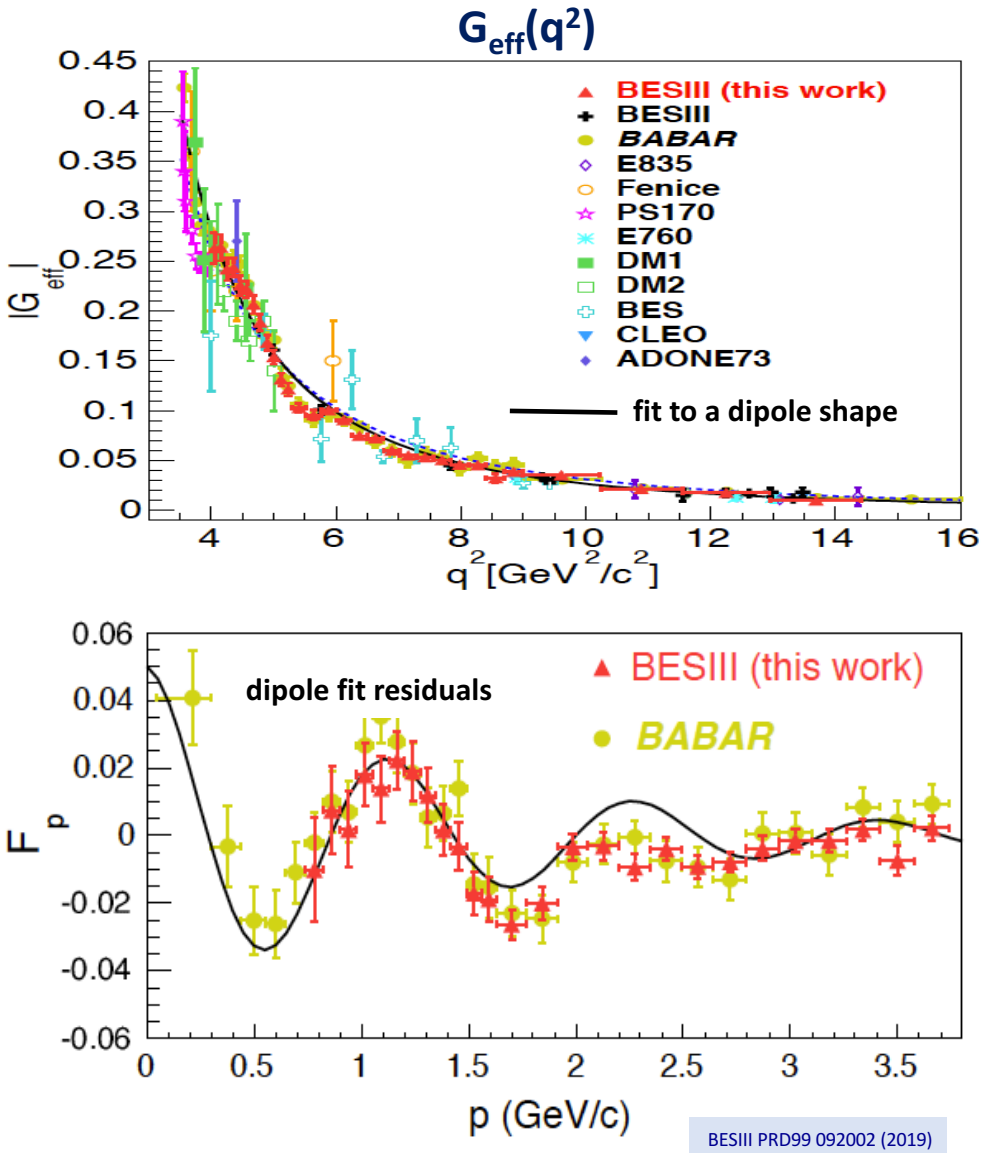
1st precise separate determinations of G_E and G_M





time-like proton form-factor oscillations?

confirm BaBar discovery



BESIII PRD99 092002 (2019)

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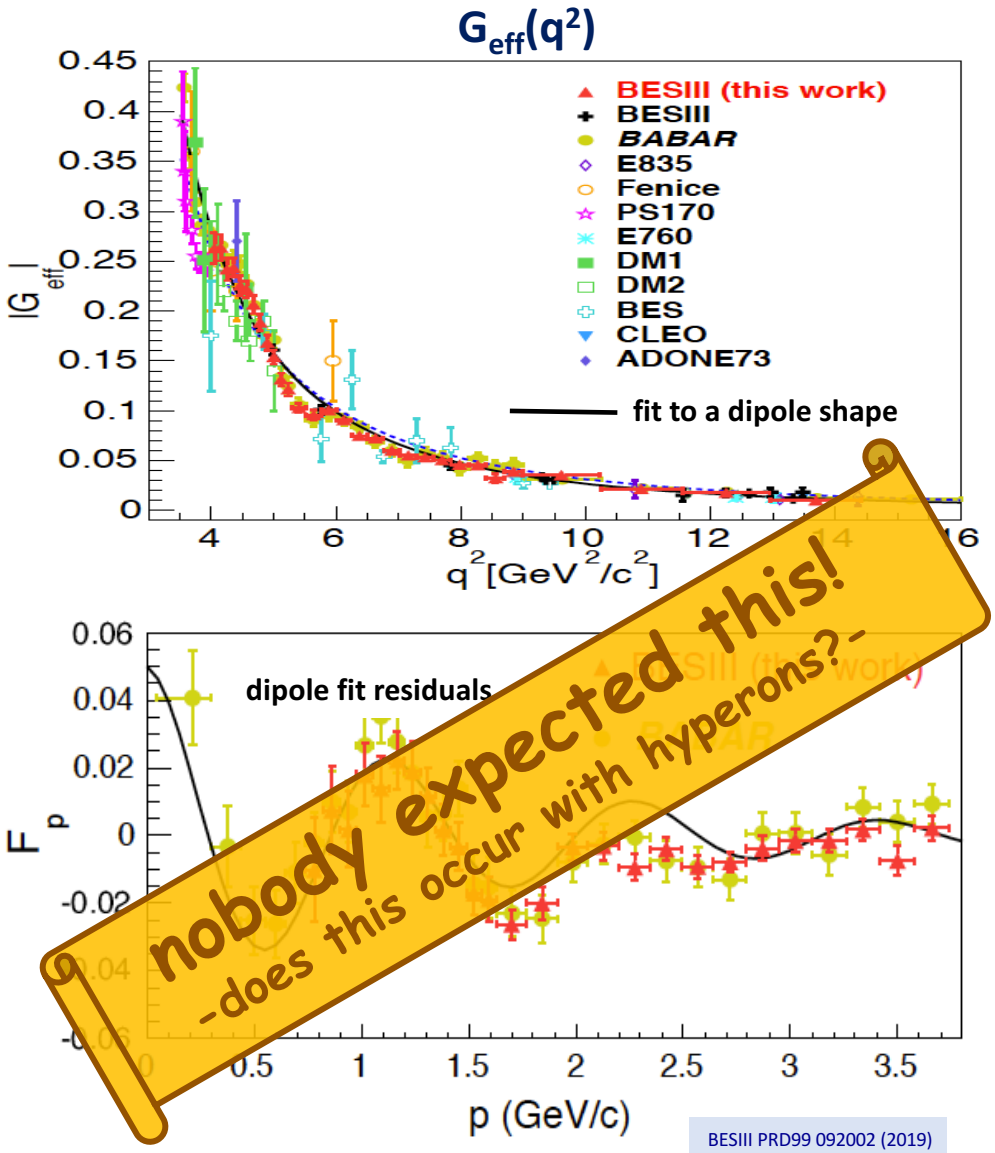


BESIII PRD99 092002 (2019)

What about neutral baryons?

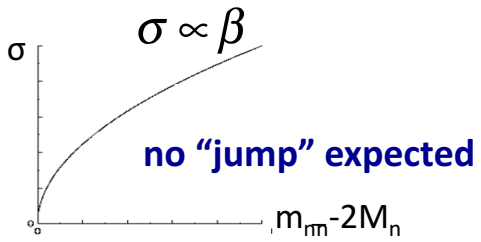
$e^+e^- \rightarrow n\bar{n}$ (or $\Lambda\bar{\Lambda}$) at threshold

Integrated cross section: $$\sigma_{n\bar{n}}(m_{n\bar{n}}) = \frac{4\pi\alpha^2\beta C}{3m_n^2}\left|G_{eff}\left(m_{n\bar{n}}\right)\right|^2\left(1+1/2\tau\right)$$

for point-like neutal particles ($n\bar{n}$ or $\Lambda\bar{\Lambda}$): $C = 1$

in point-like approx:

no Rydberg states
(Bohr-levels)



a $\sigma(e^+e^- \to n\bar{n})$ threshold jump

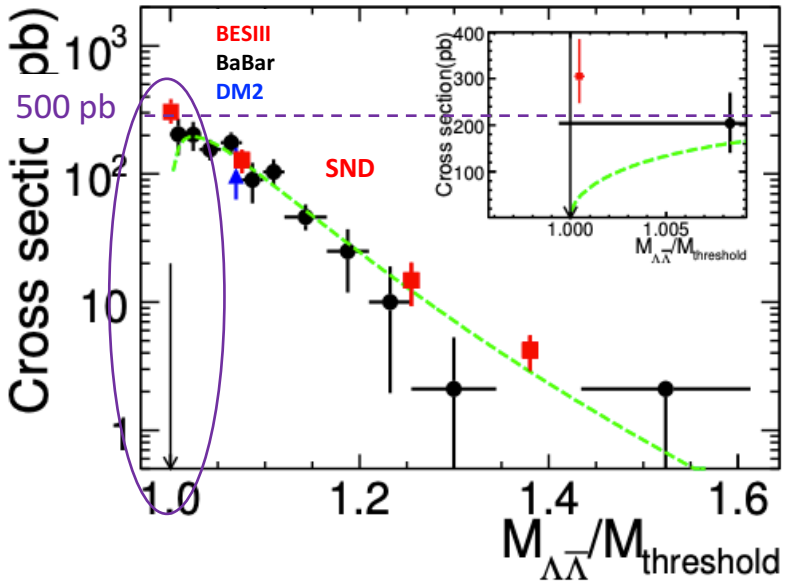
similar to the $p\bar{p}$ with large errors

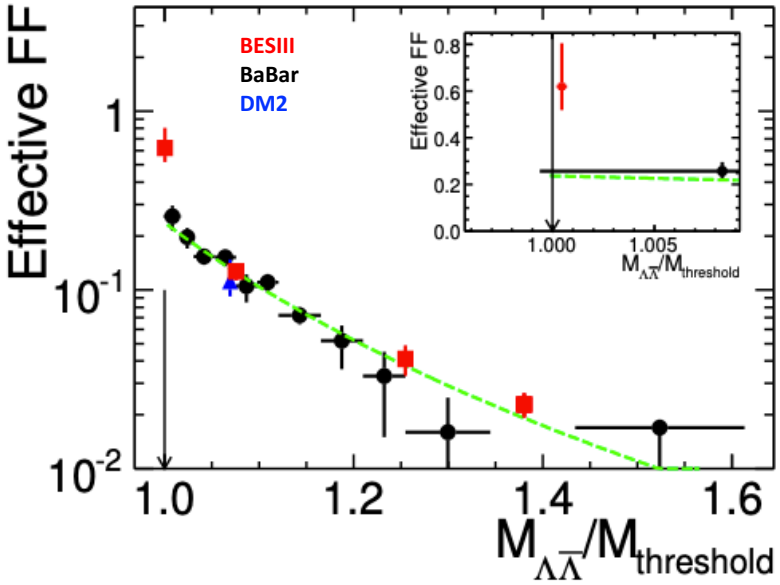
BESIII results will be reported soon

$\sigma(e^+e^- \to \Lambda\bar{\Lambda})$ & G_{eff} at threshold

$$\sigma_{\Lambda\bar{\Lambda}}\left(m_{\Lambda\bar{\Lambda}}\right) = \frac{4\pi\alpha^2\beta}{3m_{\Lambda}^2}\left|G_{eff}\left(m_{\Lambda\bar{\Lambda}}\right)\right|^2\left(1+1/2\tau\right)$$

no sign of $\sigma \propto \beta$ threshold behaviour

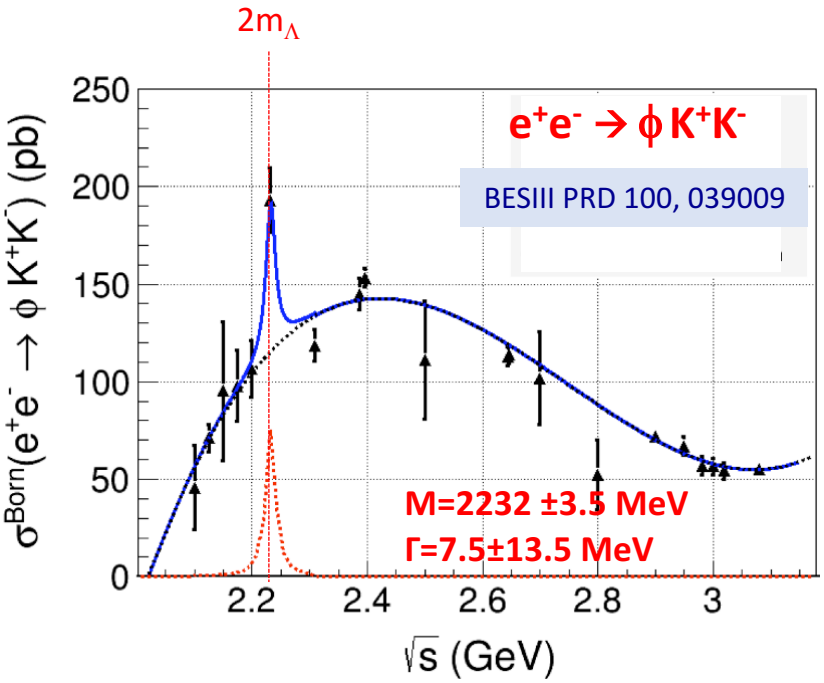


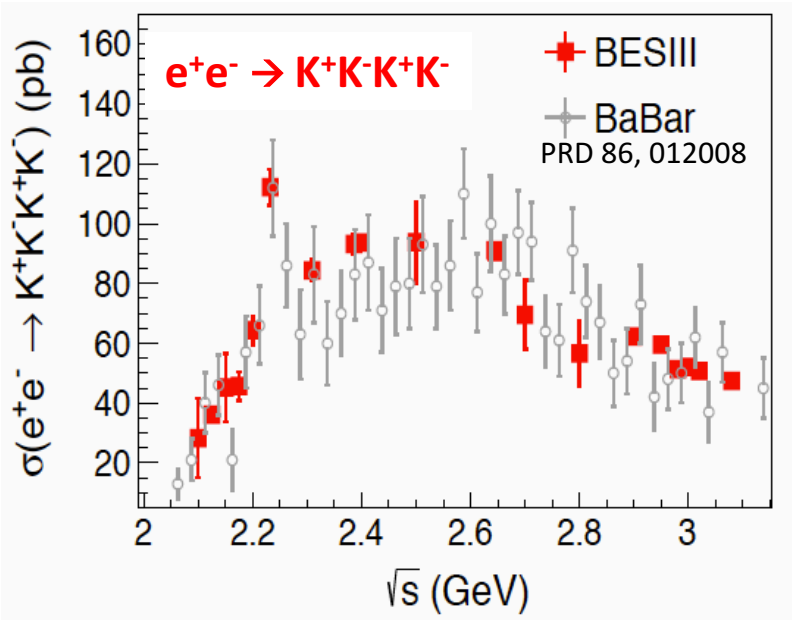


BESIII PRD 97, 032013 (2018)

Hint of $\sigma(e^+e^- \to K^+K^- K^+K^-)$ peak @ $2m_\Lambda$

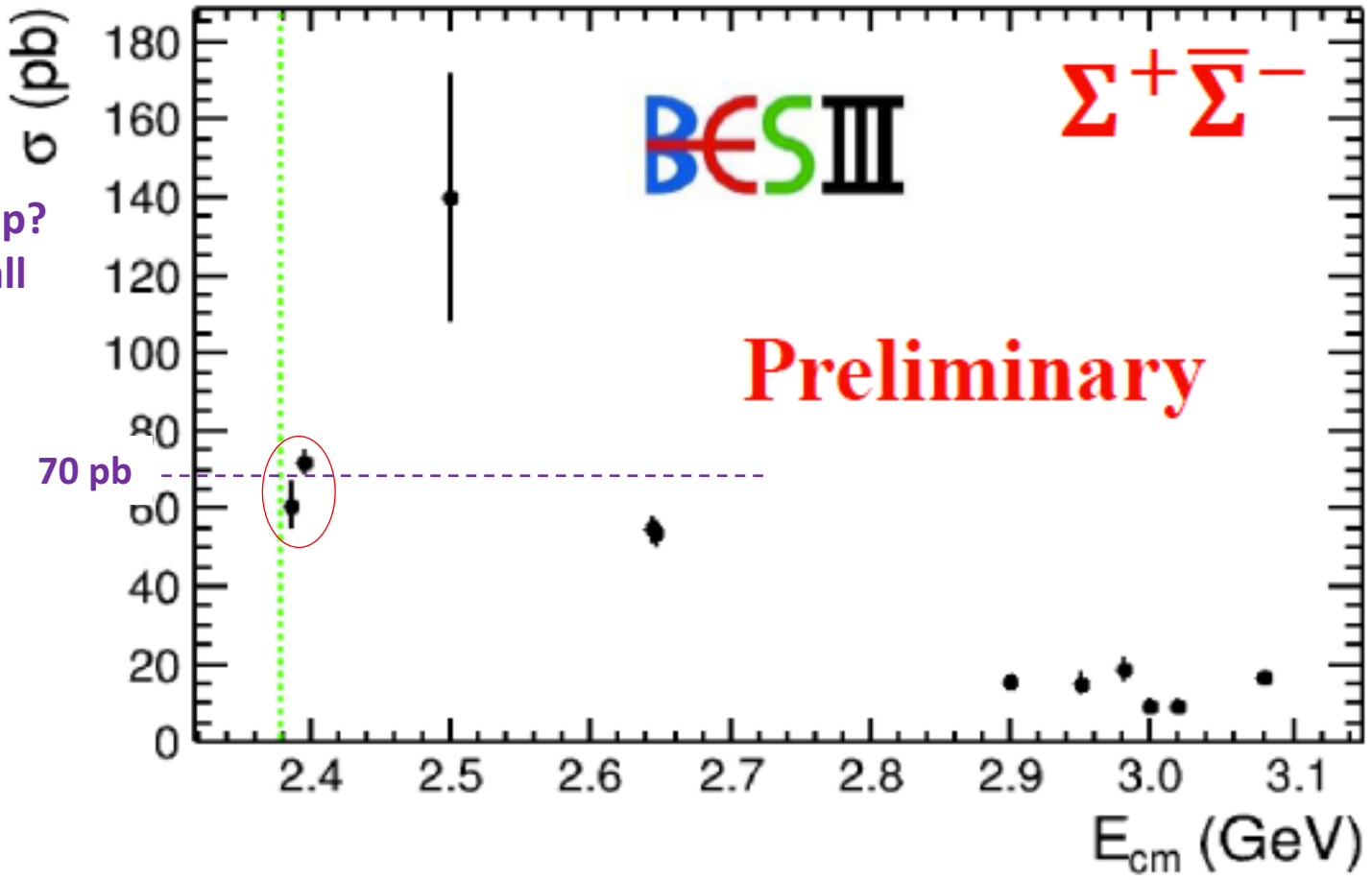
-- "seen" by both BaBar and BESIII --



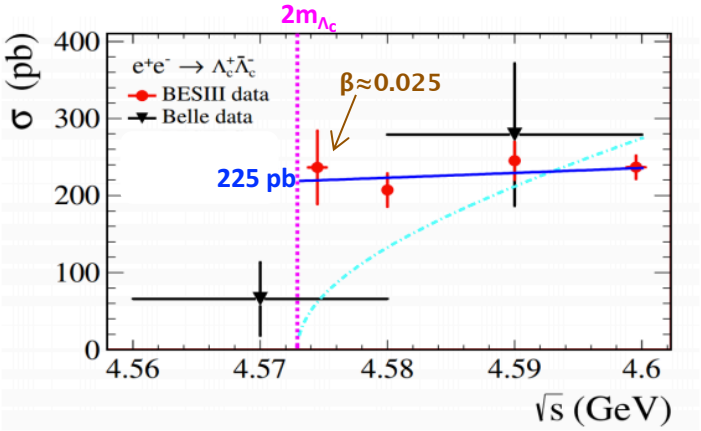


$e^+e^- \to \Sigma^+\bar{\Sigma}^-$ at threshold

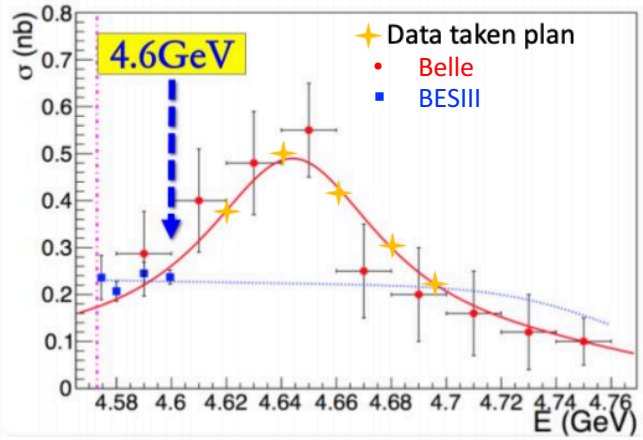
threshold jump?
is so, it's small
$\Delta\sigma \lesssim 70$ pb

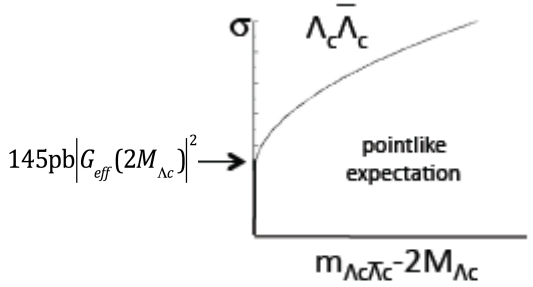


$e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$



Belle PRL 101 172001
BESIII PRL 120 132001





≈225 pb "jump" at threshold

consistent with $\Delta\sigma \approx 145$ pb jump
expected for $|G_{eff}|=1$ & a pointlike Λ_c

compare $e^+e^- \to B\bar{B}$ threshold "jumps"

baryons are not point-like charged & neutral particles
-- but their constituents are --

$$\sigma_0 = \frac{\pi^2 \alpha^3}{2 M_B^2}$$

"jump" for a point-like q=1 charged particle

		$\Sigma(e_q)^2$	$\Delta\sigma/\sigma_0$	
p	uud	1	0.89±0.33	Solodov CMD3
n	udd	2/3	0.60±0.20	Serednyakov SND
Λ	uds	2/3	0.51±0.10	BESIII PRD 97 032013
Σ^+	uus	1	≲0.13	BESIII preliminary
Σ^0	uds	2/3	???	
Σ^-	dds	1/3	???	need data at these thresholds
Ξ^0	uss	2/3	???	
Ξ^-	dss	1/3	???	
Ω^-	sss	1/3	???	
Λ_c	ucd	1	1.7±0.3	BESIII PRL 120 132001

compare $e^+e^- \to B\bar{B}$ threshold "jumps"

new way to look at baryons

$$\sigma_0 = \frac{\pi^2\alpha^3}{2M_B^2}$$

"jump" for a point-like q=1 charged particle

		$\Sigma(e_q)^2$	$\Delta\sigma/\sigma_0$	
p	uud	1	0.89±0.33	Golodov CMD3
n	udd	2/3	0.60±0.10	Serednyakov SND
Λ	uds	2/3	0.51±0.10	BESIII PRD 97 032013
Σ^+	uus	1	≈0.13	BESIII preliminary
Σ^0	uds	2/3	???	
Σ^-	dds	1/3	???	
Ξ^0	dss	2/3	???	
Ξ^-	dss	1/3	???	
Ω^-	sss	1/3	???	
Λ_c	ucd	1	1.7±0.3	BESIII PRL 120 132001

what does this tell us about baryon structure?

need data at these thresholds

only possible at an e^+e^- facility with $E_{CM} = 2m_p \sim 2m_{\Omega^-}$

CP violation searches with hyperons

- 1964: CPV discovered neutral Kaon system
- 2001: CPV in B-meson decays established
- 2019: CPV discovered in D-mesons decays
- all CPV effects seen to date are consisent with CKM
- still no evidence for CPV with strange hyperons

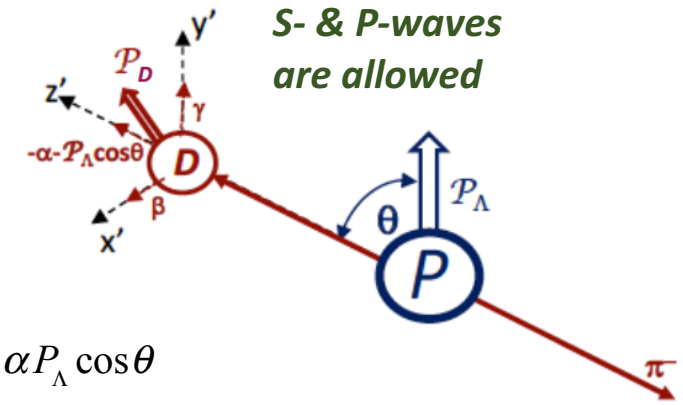
Lee & Yang: α, β & γ parameters for for *P*→π *D* hyperon decays

Parent *Daughter*

Phys. Rev. 108 1645 (1957)

General Partial Wave Analysis of the Decay of a Hyperon of Spin ½

T. D. Lee* and C. N. Yang
Institute for Advanced Study, Princeton, New Jersey
(Received October 22, 1957)



S- & P-waves are allowed

$$\alpha = \frac{2\,\mathrm{Re}(S^* P)}{|S|^2 + |P|^2}$$

$$\beta = \frac{2\,\mathrm{Im}(S^* P)}{|S|^2 + |P|^2}$$

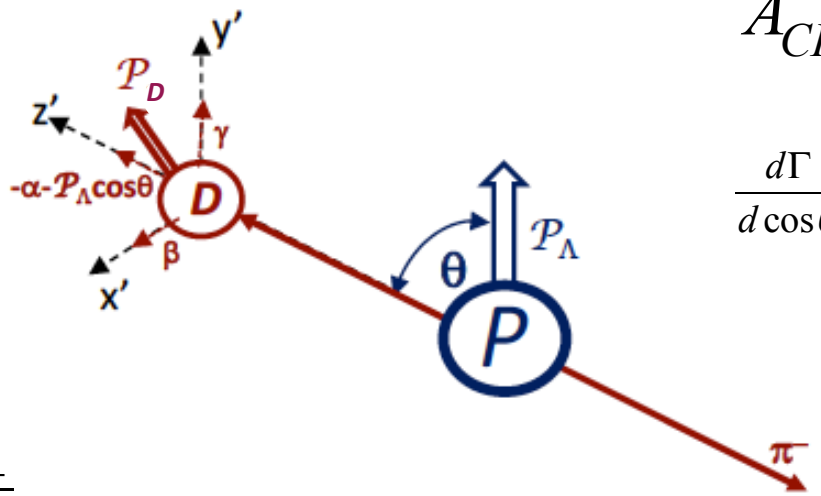
$$\gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$$

$$P_p = \frac{(\alpha + P_\Lambda \cos\theta)\hat{z}' + \beta P_\Lambda \hat{x}' + \gamma P_\Lambda \hat{y}'}{1 + \alpha P_\Lambda \cos\theta}$$

CPV observables



$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$$

$$\alpha_- : \; P \to \pi^- D$$

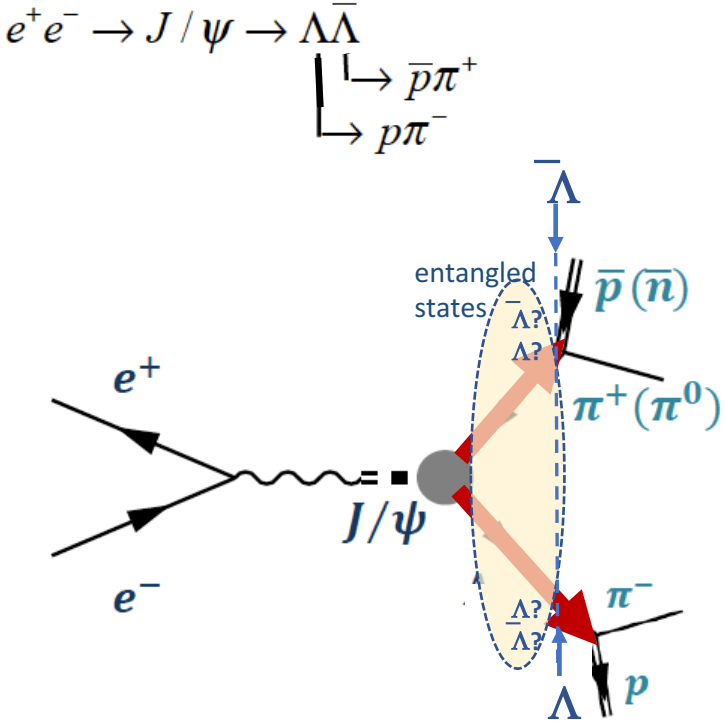
$$\alpha_+ : \; \overline{P} \to \pi^+ \overline{D}$$

$$\Delta\beta = \frac{\beta_- + \beta_+}{\beta_- - \beta_+}$$

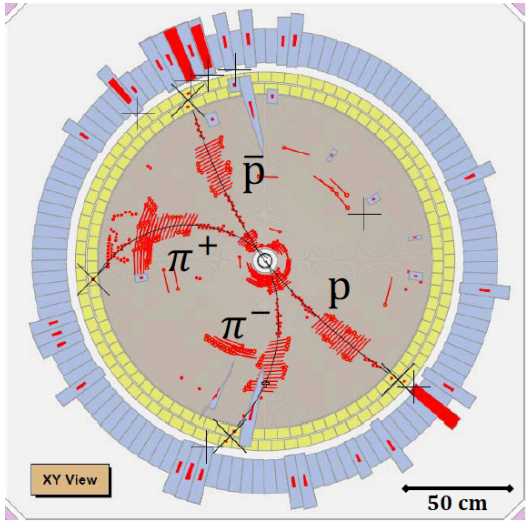
$$\beta_- : \; P \to \pi^- D$$

$$\beta_+ : \; \overline{P} \to \pi^+ \overline{D}$$

Measuring these at BESIII



high reconstruction efficiency: ~40%
negligible backgrounds: S/B~10^3



Angular distibution

$$d\Gamma \propto 1 + \alpha_\psi \cos^2\theta_\Lambda$$

$$+ \alpha_-\alpha_+ \left[\sin^2\theta_\Lambda \left(n_{1,x}n_{2,x} - \alpha_\psi n_{1,y}n_{2,y}\right) + \left(\cos^2\theta_\Lambda + \alpha_\psi\right) n_{1,z}n_{2,z}\right]$$

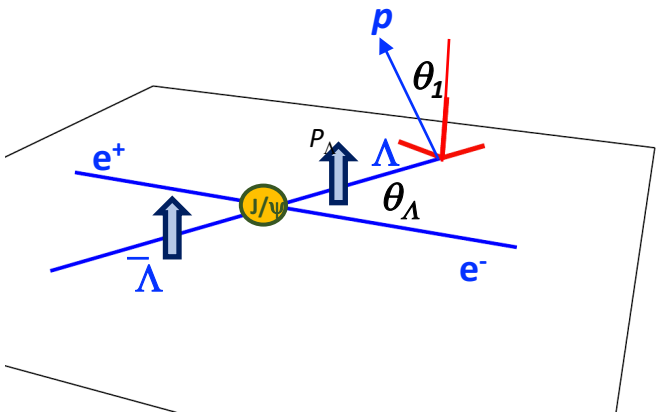
$$+ \alpha_-\alpha_+ \sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda \left(n_{1,x}n_{2,z} + n_{1,z}n_{2,x}\right)$$

$$+ \sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\,\sin\theta_\Lambda\cos\theta_\Lambda \left(\alpha_- n_{1,y} + \alpha_+ n_{2,y}\right),$$

$$+ (1+\alpha_\psi\cos^2\theta_\Lambda) P_\Lambda(\theta)\left(\alpha_-\cos\theta_1 + \alpha_+\cos\theta_2\right)$$

$$P_\Lambda(\theta) = \frac{\sqrt{1-\alpha_\psi^2}\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}\sin\Delta\Phi$$

if the Λs are unpolarized, only only $\alpha_-\alpha_+$ can be measured



complex phase between A_{++} &A_{+-} heliciity amplitudes

polarization-term allows for independent α_- and α_+ dependence and search for CPV

Angular distibution

$$d\Gamma \propto 1 + \alpha_\psi \cos^2\theta_\Lambda$$

$$+ \alpha_-\alpha_+ \left[\sin^2\theta_\Lambda \left(n_{1,x}n_{2,x} - \alpha_\psi n_{1,y}n_{2,y}\right) + \left(\cos^2\theta_\Lambda + \alpha_\psi\right) n_{1,z}n_{2,z}\right]$$

$$+ \alpha_-\alpha_+ \sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda \left(n_{1,x}n_{2,z} + n_{1,z}n_{2,x}\right)$$

$$+ \sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\,\sin\theta_\Lambda\cos\theta_\Lambda \left(\alpha_- n_{1,y} + \alpha_+ n_{2,y}\right),$$

$$+ (1+\alpha_\psi\cos^2\theta_\Lambda) P_\Lambda(\theta)\left(\alpha_-\cos\theta_1 + \alpha_+\cos\theta_2\right)$$

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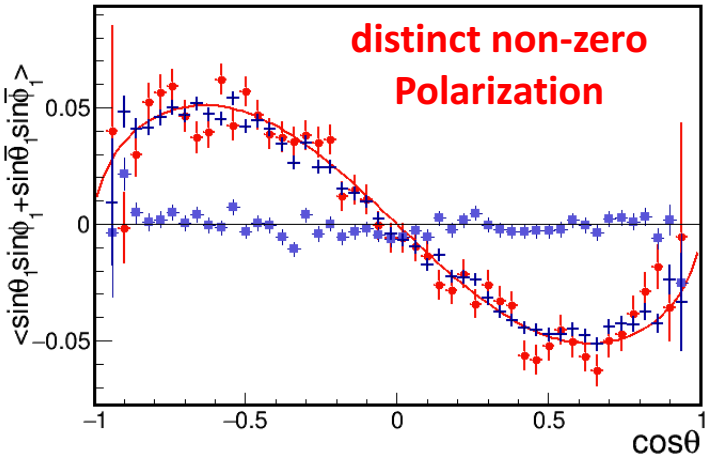
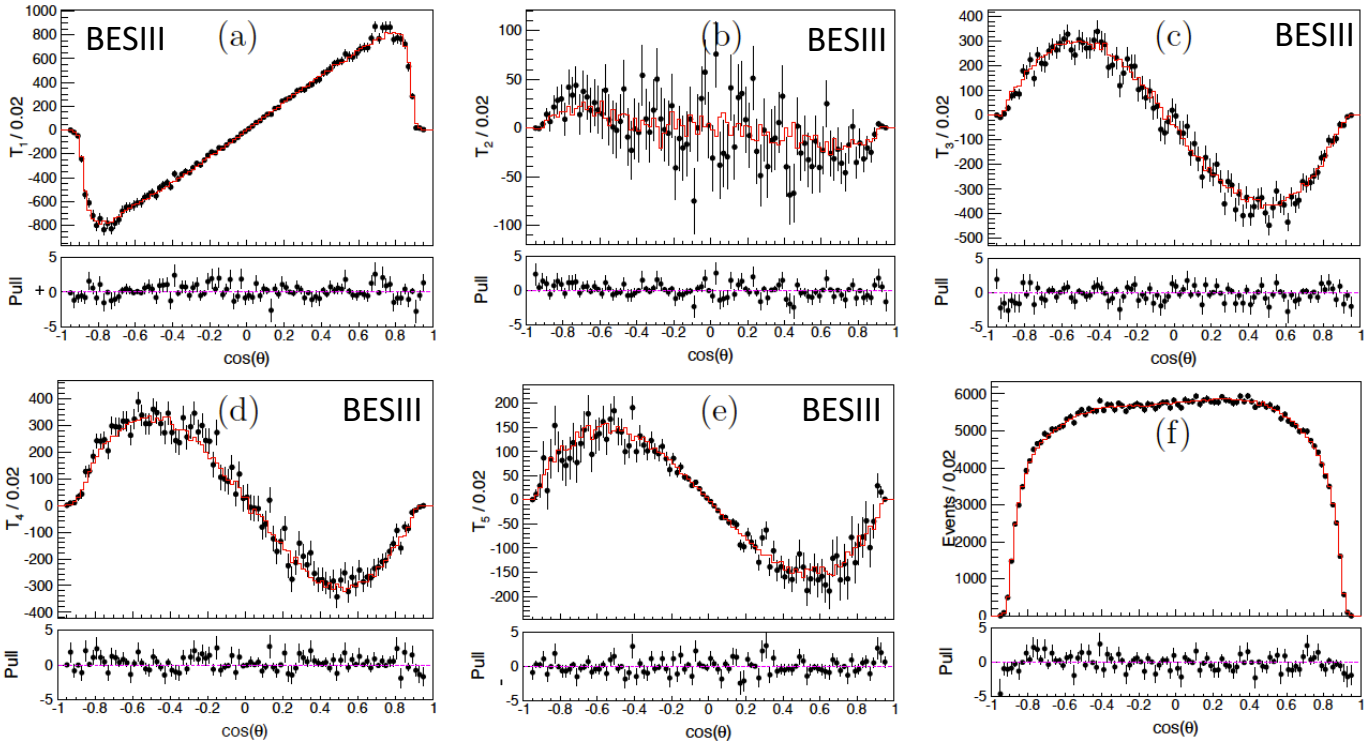


complex phase between A_{++} &A_{+-} heliciity amplitudes

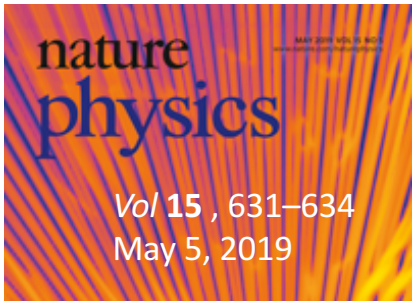
polarization-term allows for independent α_- and α_+ dependence and search for CPV

5-dimensional likelihood fit

$\mathcal{L}_{max}$: 3781 $\Rightarrow$ 12020 $\Leftarrow \sqrt{\Delta L_{max}} \approx 90!$



BESIII, *Nature Physics* 15 , 631 (2019)



results

Parameters	BESIII (2019)	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [14]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [16]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [16]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [16]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

← ~7σ upward shift from all previous measurements

← best measurement to date (with ~1/8th of available data)

arXiv:1808.08917

CPV observables in $\Xi^- \to \pi^- \Lambda$ decay

up-down asymmetry difference

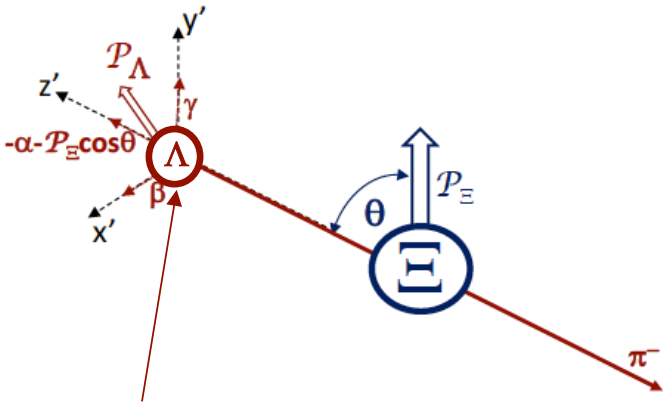
$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

final-state polarization difference

$$\Delta\beta = \frac{\beta_- + \beta_+}{\beta_- - \beta_+}$$

The polarization of the final-state Λ is determined from the $\Lambda \to \pi^- p$ up-down decay asymmetry

Huge bonus from Ξ CPV studies



these Λs are 100% polarized and, event-by-event, the $\mathcal{P}_\Lambda$ direction is well known.

experimental sensitivity for $A_{CP}(\Lambda)$:

$$\delta(A_{CP}^{\Lambda}) \propto \sqrt{N_{evts}}$$

$$\delta(A_{CP}^{\Lambda}) \propto \left|P_{\Lambda}\right|$$

for J/ψ→Λ $\bar{\Lambda}$: $\langle\mathcal{P}_\Lambda\rangle \approx 0.13$

for J/ψ→ Ξ(→πΛ) $\bar{\Xi}$(→π$\bar{\Lambda}$) : $\langle\mathcal{P}_\Lambda\rangle = 1$

although $N_{evt}(J/\psi\to\Xi^-\bar{\Xi}^+) \simeq 0.25\ N_{evt}(J/\psi\to\Lambda\bar{\Lambda})$,

A_{CP}^{Λ} sensitivities for Λs from Ξ decays are ~3x better than those from J/ψ→Λ$\bar{\Lambda}$

BESIII sensitivities with 10B J/ψ events

-- compare $\Xi^-\bar{\Xi}^+$ with $\Lambda\bar{\Lambda}$ --

Numbers of reconstructed events

decay mode	$\mathcal{B}$(units 10^{-4})	eff	reconstructed events	
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	40%	3200×10^3	←3.2 M events
$\psi(2S) \to \Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	40%	650×10^3	
$J/\psi \to \Xi^0\bar{\Xi}^0$	11.65 ± 0.04	14%	670×10^3	
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	2.73 ± 0.03	14%	160×10^3	
$J/\psi \to \Xi^-\bar{\Xi}^+$	10.40 ± 0.06	19%	810×10^3	←0.8 M events
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	2.78 ± 0.05	19%	210×10^3	

$\Xi^-\bar{\Xi}^+$ has ~3x $\Lambda\bar{\Lambda}$ sensitivity

meaurement sensitivities ($\sigma \times \sqrt{N_{evts}}$)

	$\langle\alpha_\Xi\rangle$	A_Ξ	$\langle\alpha_\Lambda\rangle$	A_Λ	$\langle\alpha_\Xi\alpha_\Lambda\rangle$	$A_{\Xi\Lambda}$	$\langle\phi_\Xi\rangle$	$B_{\bar{\Lambda}}^{\Xi}$	
$J/\psi \to \Lambda\bar{\Lambda}$	–	–	1.8	8.8	–	–	–	–	→A_{CP}=?? ±0.005
$J/\psi \to \Xi^-\bar{\Xi}^+$ $\Delta\Phi = 0$	1.4	3.7	1.7	3.5	0.78	4.0	4.1	110	±0.0025
$J/\psi \to \Xi^-\bar{\Xi}^+$ $\Delta\Phi = \pi/2$	1.4	3.5	1.6	3.1	0.76	3.9	3.8	100	→A_{CP}=?? ±0.003
$e^+e^- \to \Xi^-\bar{\Xi}^+$ $\alpha_\psi = 1$	1.3	3.4	1.4	3.1	0.76	4.0	3.5	96	
$\eta_c, \chi_{c0} \to \Xi^-\bar{\Xi}^+$	1.1	2.9	1.0	2.6	0.72	3.9	2.6	71	

Adlarson and Kupsc, arXiv:1908.03102

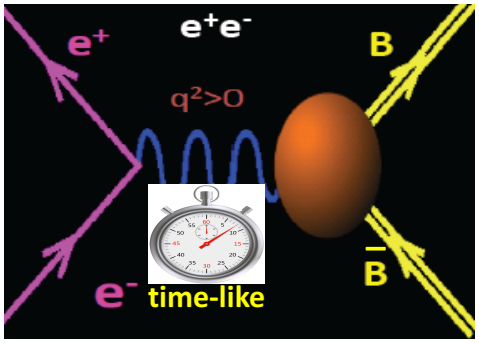
will go down to 10^{-3} when *all* existing data are fully analyzed

BESIII and baryons

-- unique capabilities not even dreamed of in our original plans --

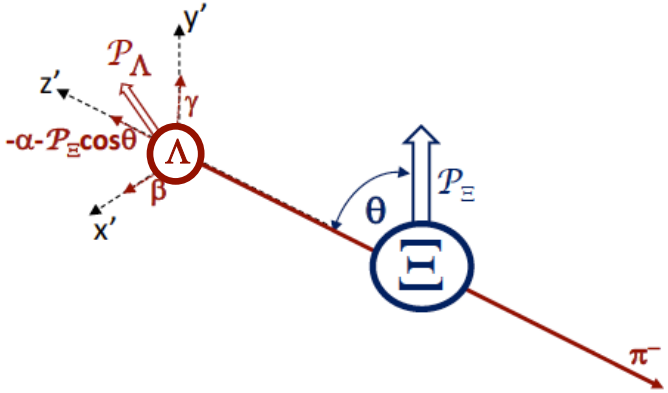
Time-like form-factors of nucleons and hyperons

-- 21st century probes of the structure of baryons



World's most sensitive searches for CPV in hyperon decays

-- a new frontier for CPV studies

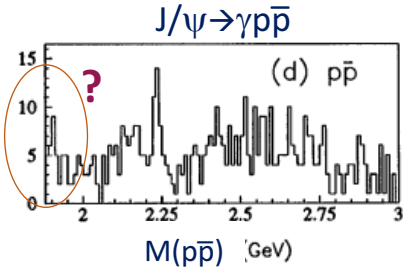


Afterword

What did I learn during 30 yrs at BES?

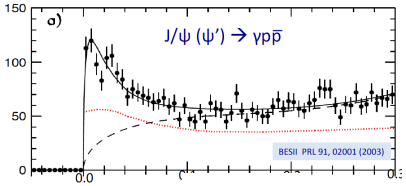
you never have enough J/ψ events

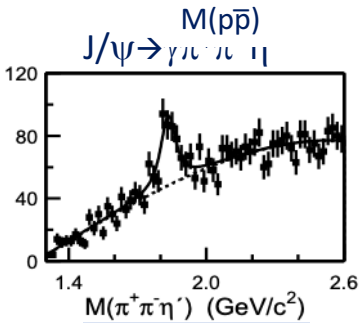
1996: 8 M J/ψ's



PRL 76, 3502

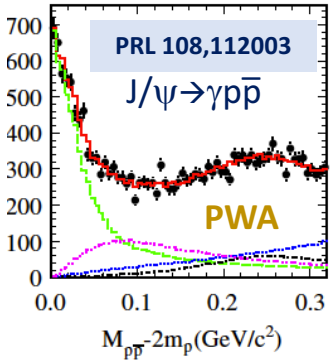
2002: 58 M J/ψ's

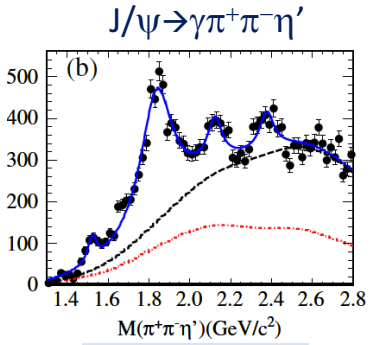




PRL 95,262001

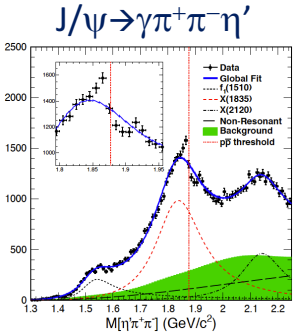
2011: 225 M J/ψ's





PRL 106,072002

2016: 1.3 B J/ψ's



PRL 117,042002

2019: 10 B J/ψ's

???

Thank you