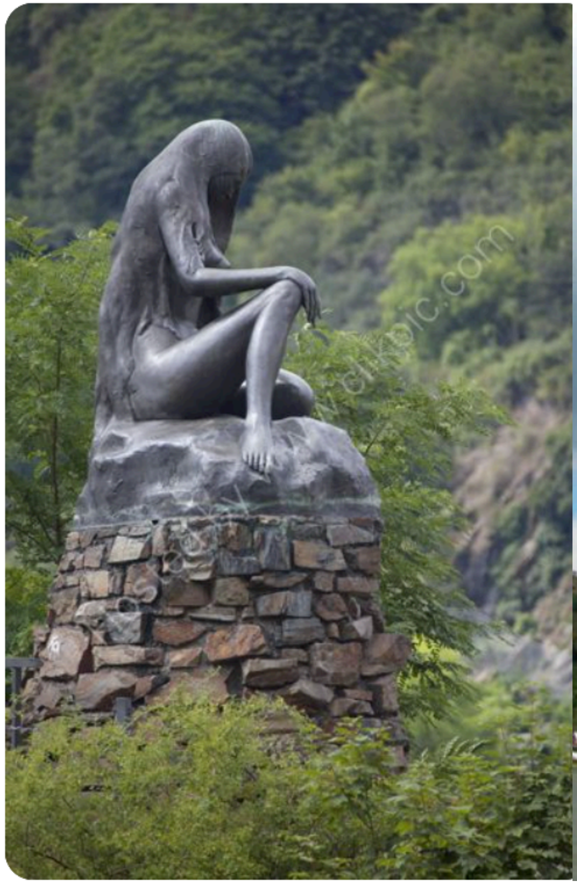
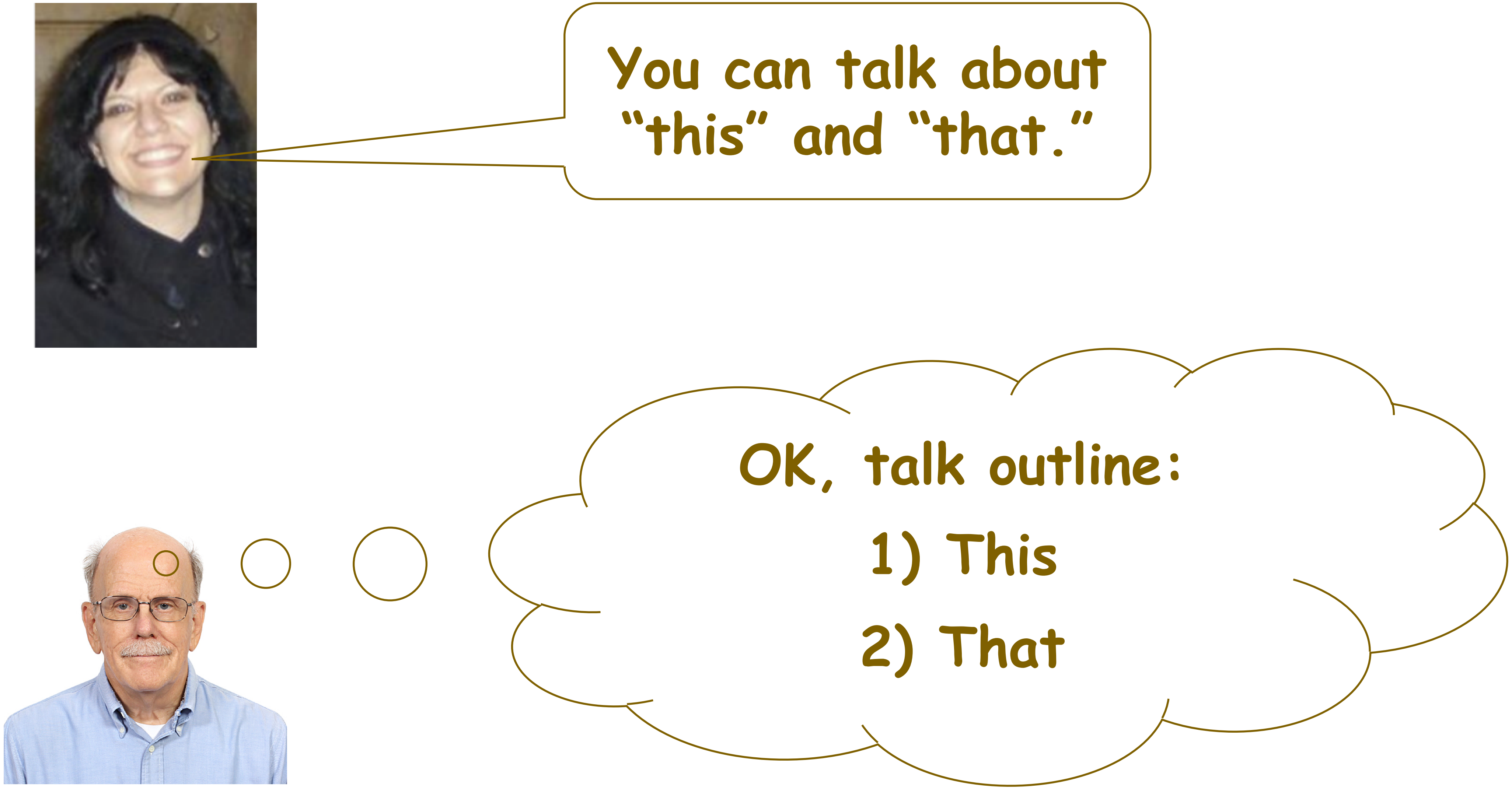
The persistent allure of hadron physics




allure (n): the quality of being powerfully and ***mysteriously attractive*** or ***fascinating.***

Stephen Lars Olsen
Institute for Basic Science (Korea)

MITP Workshop March


You can talk about "this" and "that."
OK, talk outline:
1) This
2) That

Part-I: “This”

some history

the proton, the oldest and most common hadron

Discovered by Rutherford 105 years ago

The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science ›

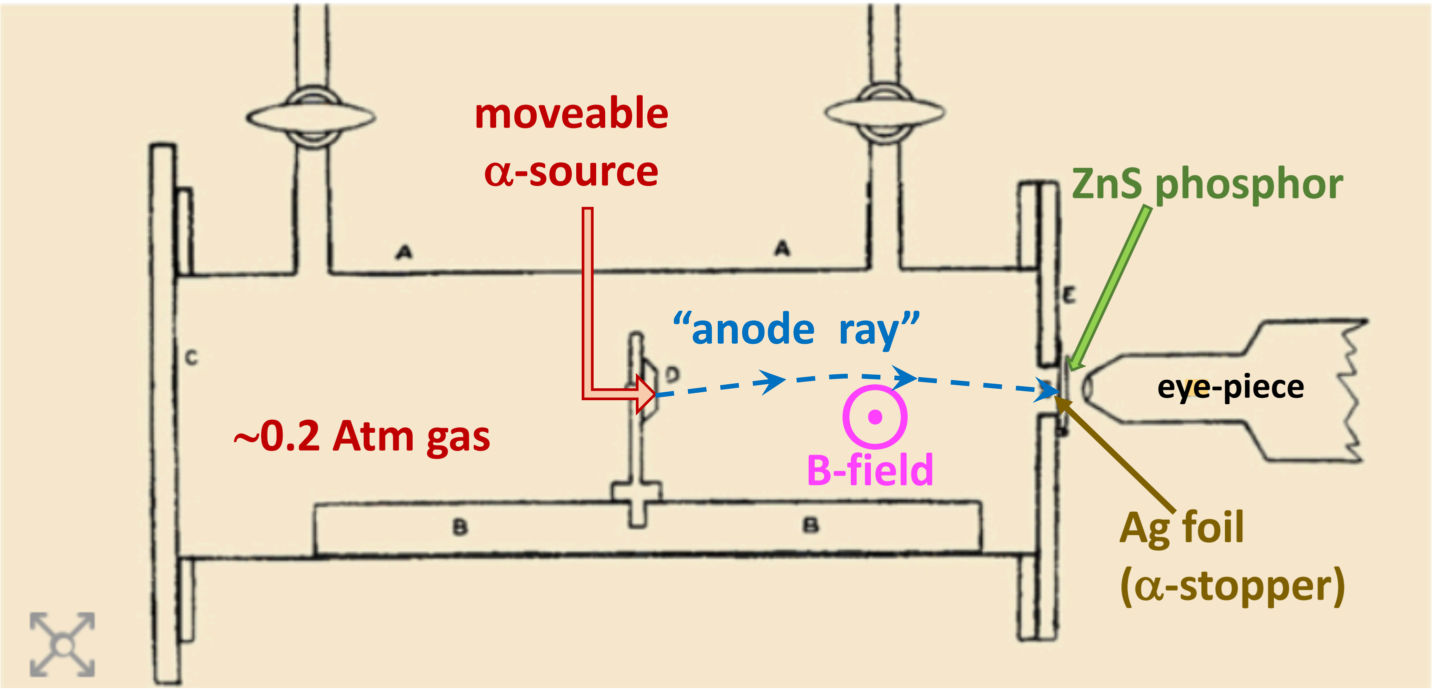
Series 6

Volume 37, 1919 - Issue 222

[581]

LIV. *Collision of α Particles with Light Atoms. IV. An Anomalous Effect in Nitrogen. By* Professor Sir E. Rutherford, *F.R.S.**

"…we must conclude … that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus."



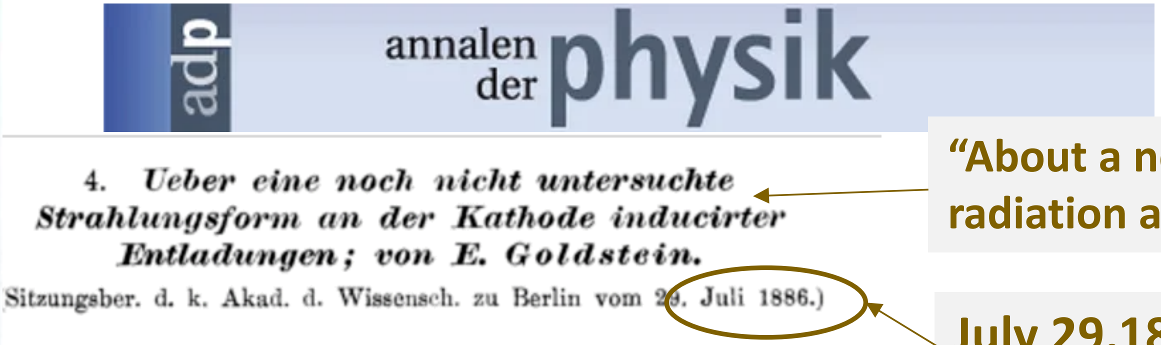
strongest signal for N_2:

$$\alpha + {}^{14}N \rightarrow {}^{17}O + p$$

$$KE_p = KE_\alpha - 1.21\ \text{MeV}$$

1st identified nuclear Transmutation reaction

Eugen Goldstein 1850– 1930

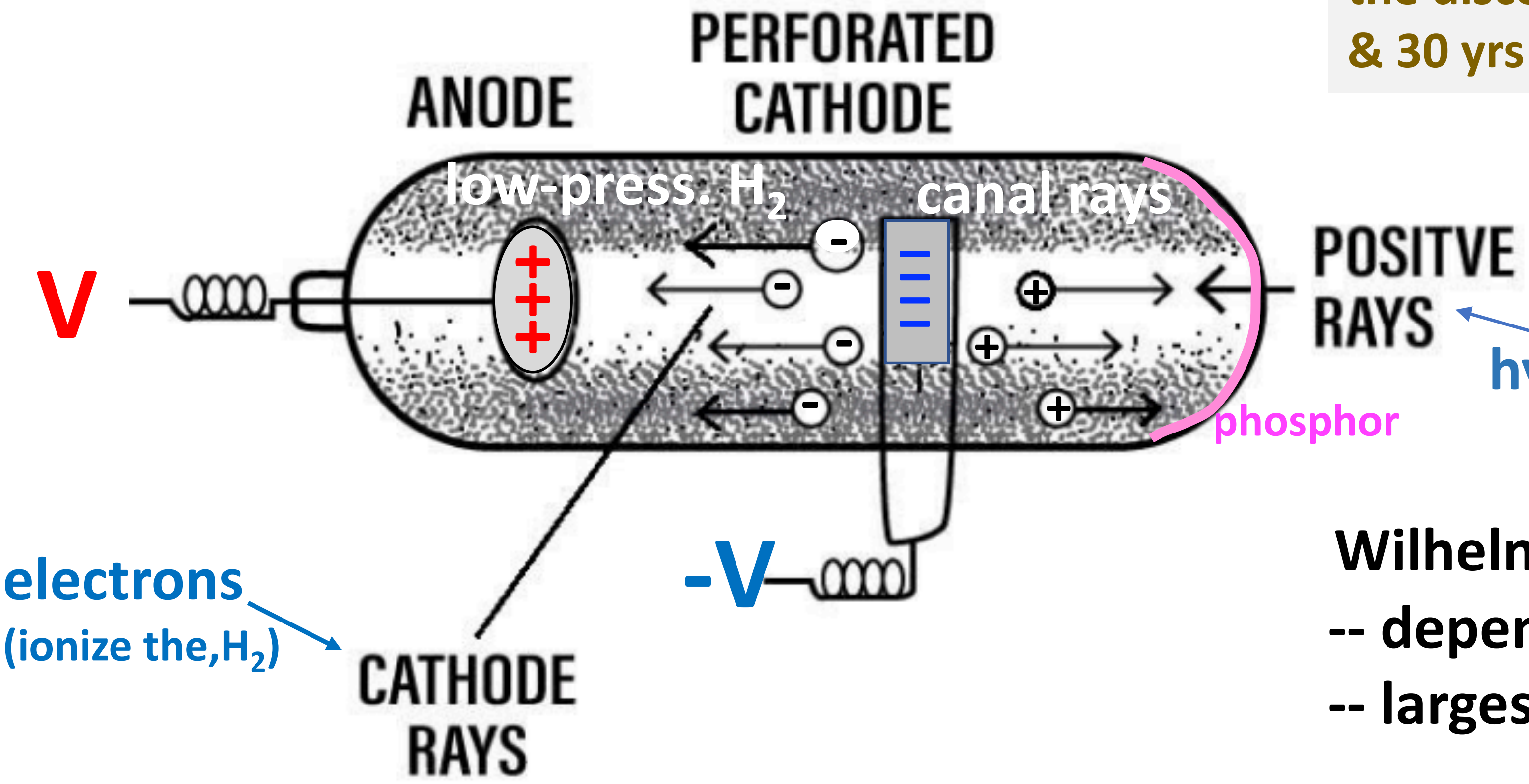

annalen der physik

4. Ueber eine noch nicht untersuchte Strahlungsform an der Kathode inducirter Entladungen; von E. Goldstein.

Sitzungsber. d. k. Akad. d. Wissensch. zu Berlin vom 29. Juli 1886.)

"About a not yet examined form of radiation at Cathode-Induced Discharges"

July 29,1886, 10 years before the discovery of the electron & 30 yrs before Rutherford



Wilhelm Wien measured *q*/m

-- depended on the type of gas

-- largest for hydrogen

1956, Hofstadter: the proton isn't a point particle

$e^- p \rightarrow e^- p$ elastic scattering

Robert Hofstadter
1915-1990

PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Structure of the Proton*

E. E. CHAMBERS† AND R. HOFSTADTER
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California
(Received April 2, 1956)

Fermi & Dirac form factors

What's F_1 and F_2?

assume exponential shapes:

$F_1 = F_2$: $\rho(r) = \rho_0 \exp(-r/r_0)$

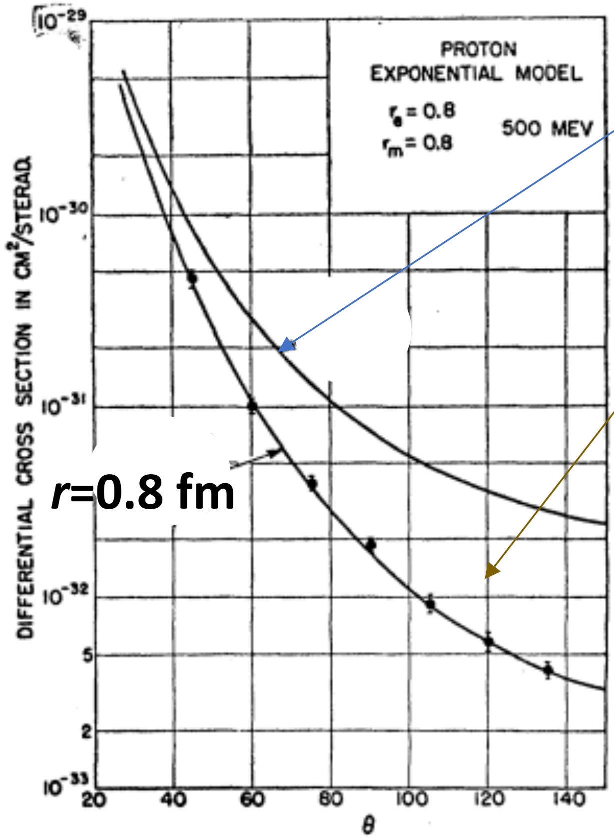
pointlike

$$\sigma = \frac{e^4}{4E^2}\left(\frac{\cos^2(\theta/2)}{\sin^4(\theta/2)}\right)\frac{1}{1+(2E/M)\sin^2(\theta/2)}$$

$$\times\left\{F_1^2 + \frac{q^2}{4M^2}\left[2(F_1+\mu F_2)^2 \tan^2(\theta/2) + \mu^2 F_2^2\right]\right\},$$

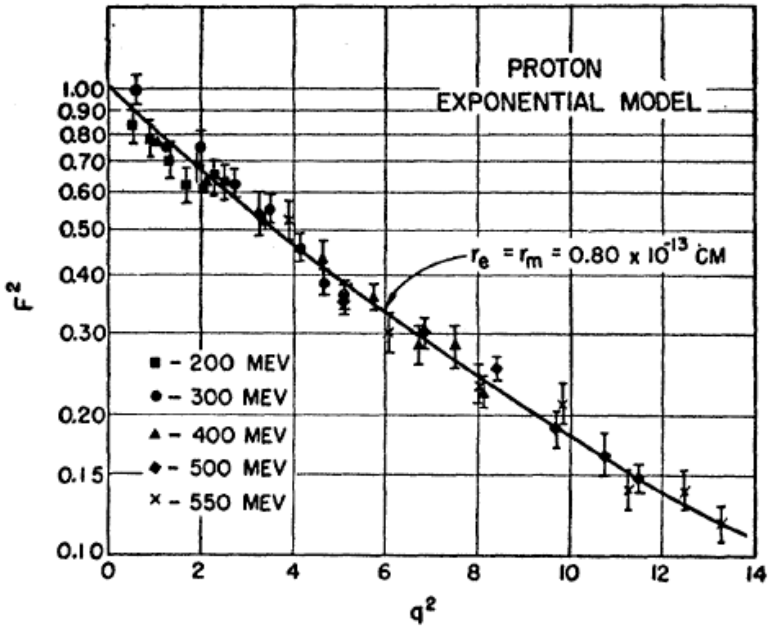
form factors

16 M. N. Rosenbluth, Phys. Rev. 79, 615 (1950).



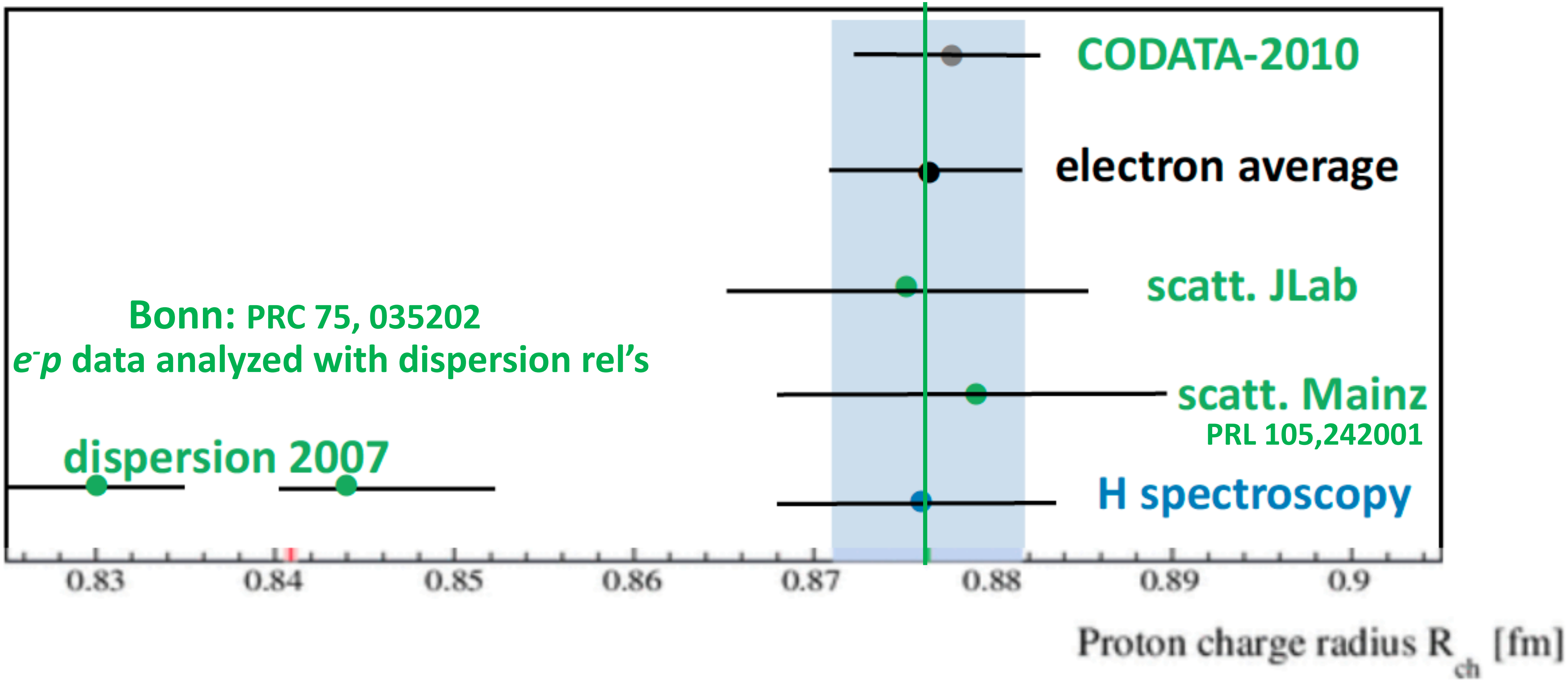
1956 result

r =0.77±0.10 fm



Status of r_E circa 2009 (5 decades later)

$$r_E = \left(\frac{6}{G_E(0)} \frac{dG_E(Q^2)}{dt} \bigg|_{Q^2=0} \right)^{1/2} = 0.8772 \pm 0.0046 \text{ fm}$$



Issues

$G_E(Q^2)$ is not a a simple dipole

$$G_E(Q^2) \neq G_{\rm dipole} = \left(1 + \frac{Q^2}{0.71({\rm GeV}^2)}\right)^{-2}$$

nucleons' pion clouds produce
"bumps" near Q^2=0.15 GeV^2

two approaches:

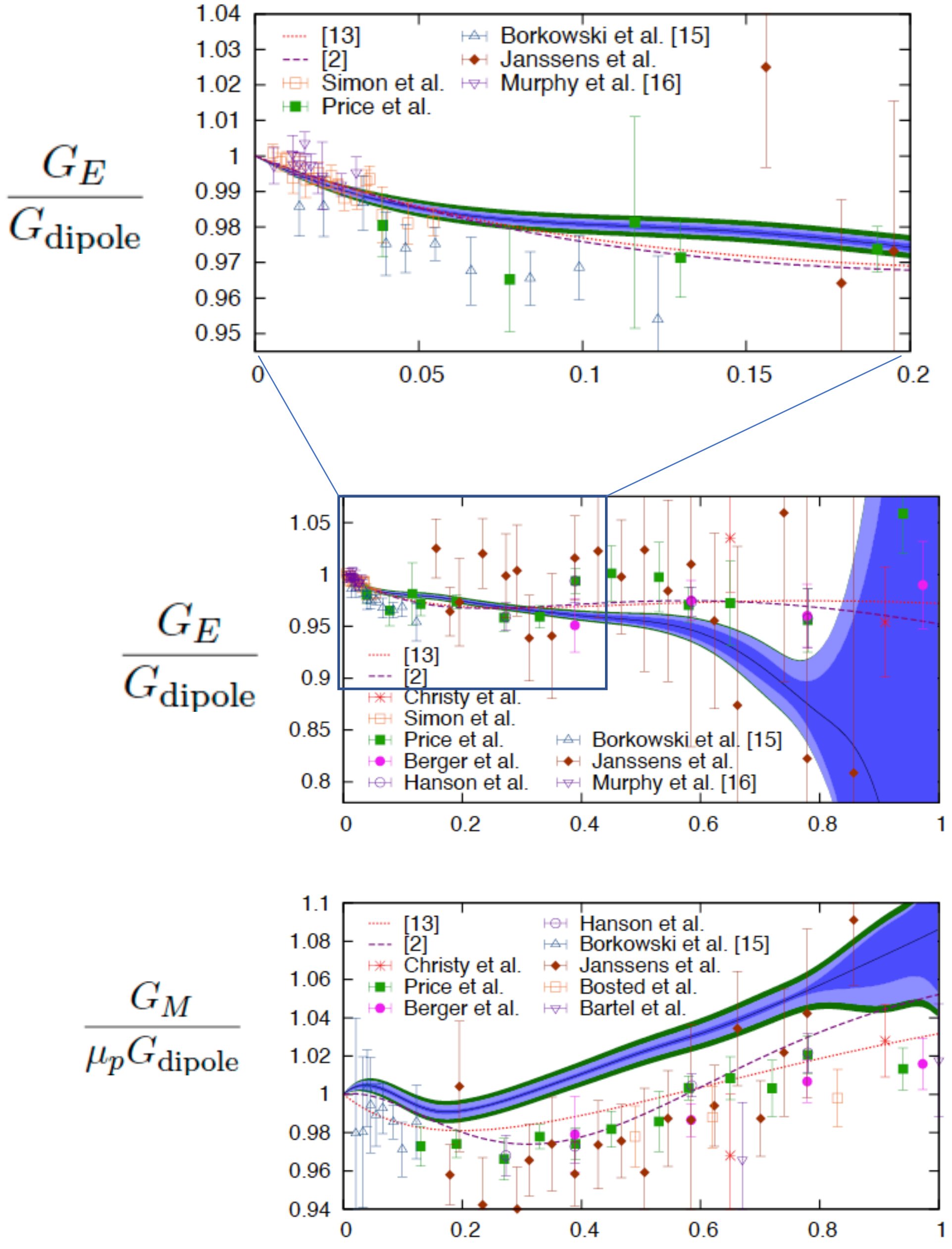
1) extrapolate to zero using model-motivated polynomial or spline fits to the data

(see Bernauer & Distler arXiv:1606.02159)

2) extract pion cloud effects from $e^+e^- \to \pi^+\pi^-$ and $\pi N \to \pi N$ data and include this in a dispersion relation

(see Lin, Hammer, Meissner PLB816,136254)

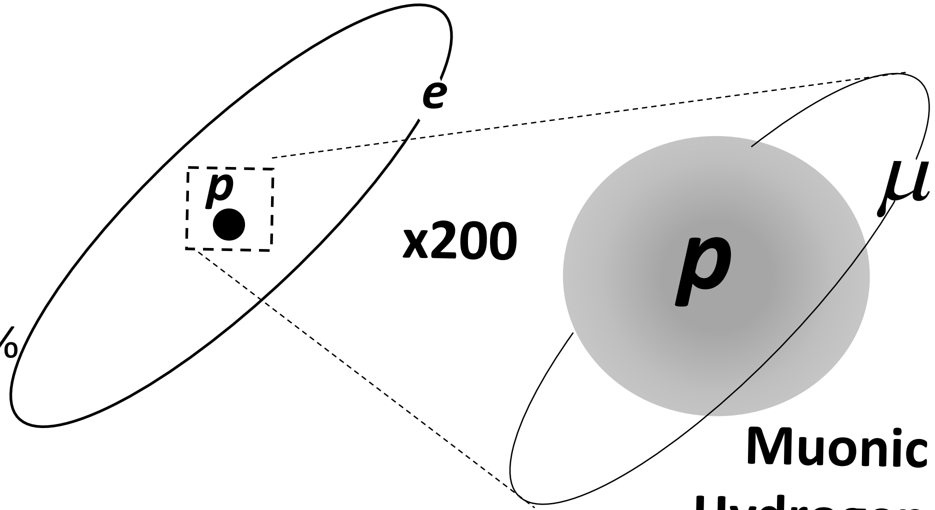
(MAMI) PRL 105,242001



2010: r_E from muonic-Hydrogen Lamb-shift

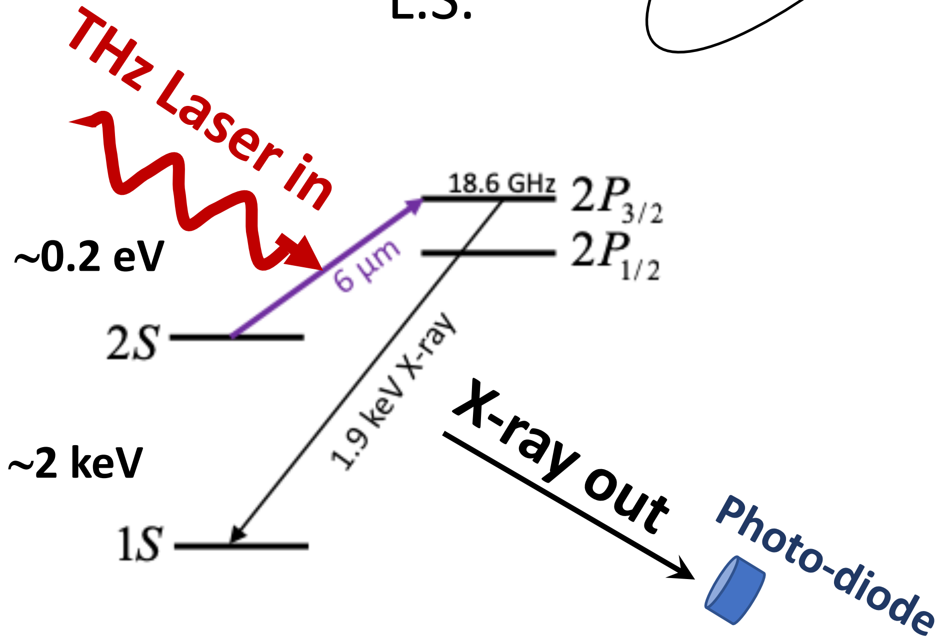
Ordinary Hydrogen

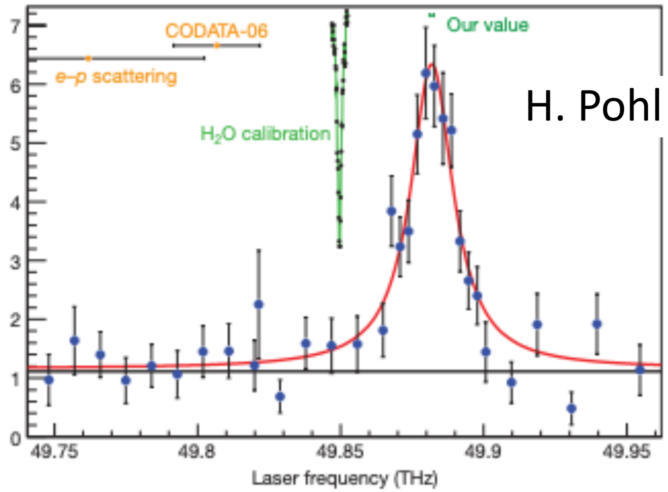
$\frac{\delta_{L.S.}}{L.S.} = 0.014\%$



Muonic Hydrogen

$\frac{\delta_{L.S.}}{L.S.} = 2\%$

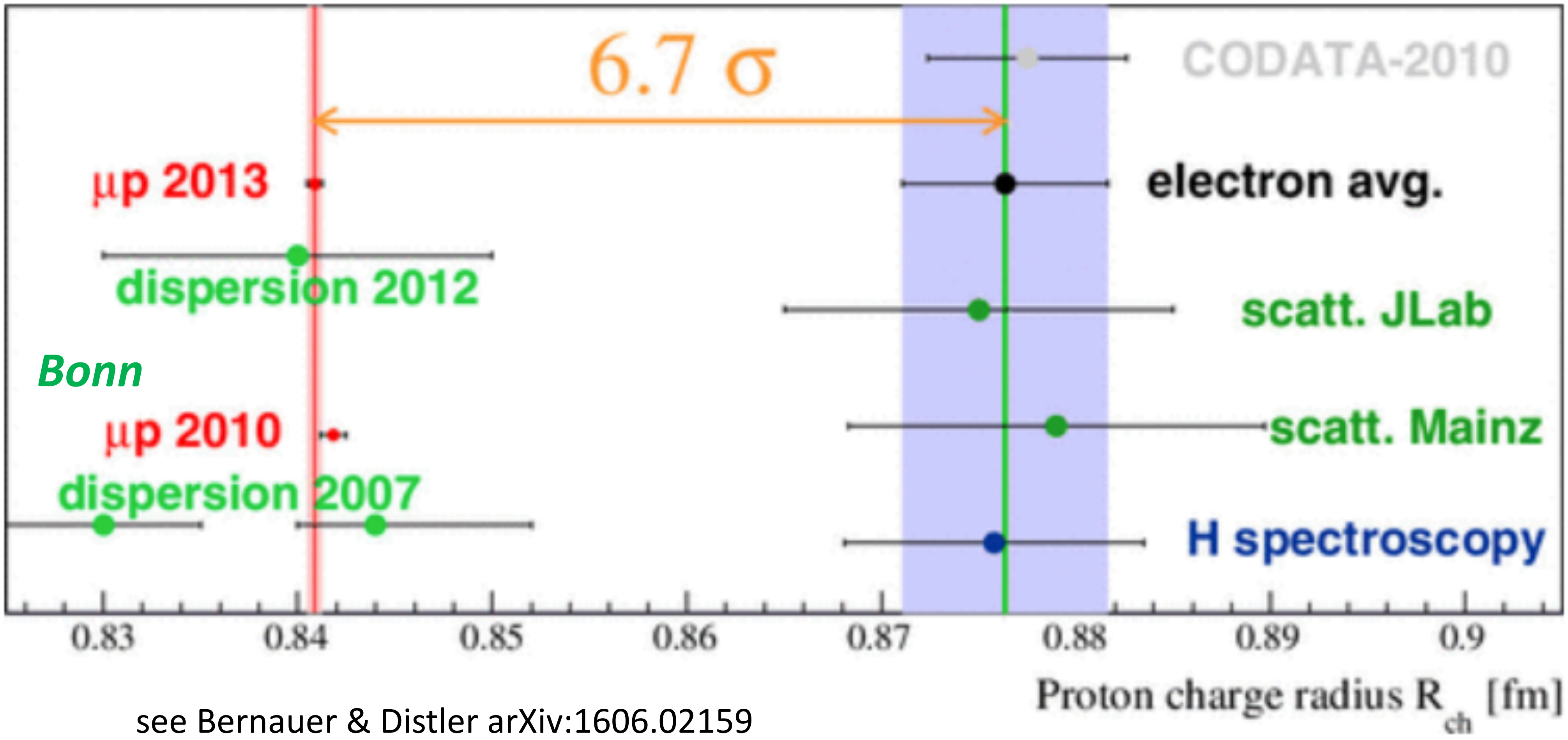




H. Pohl et al.,Nature 466, 213

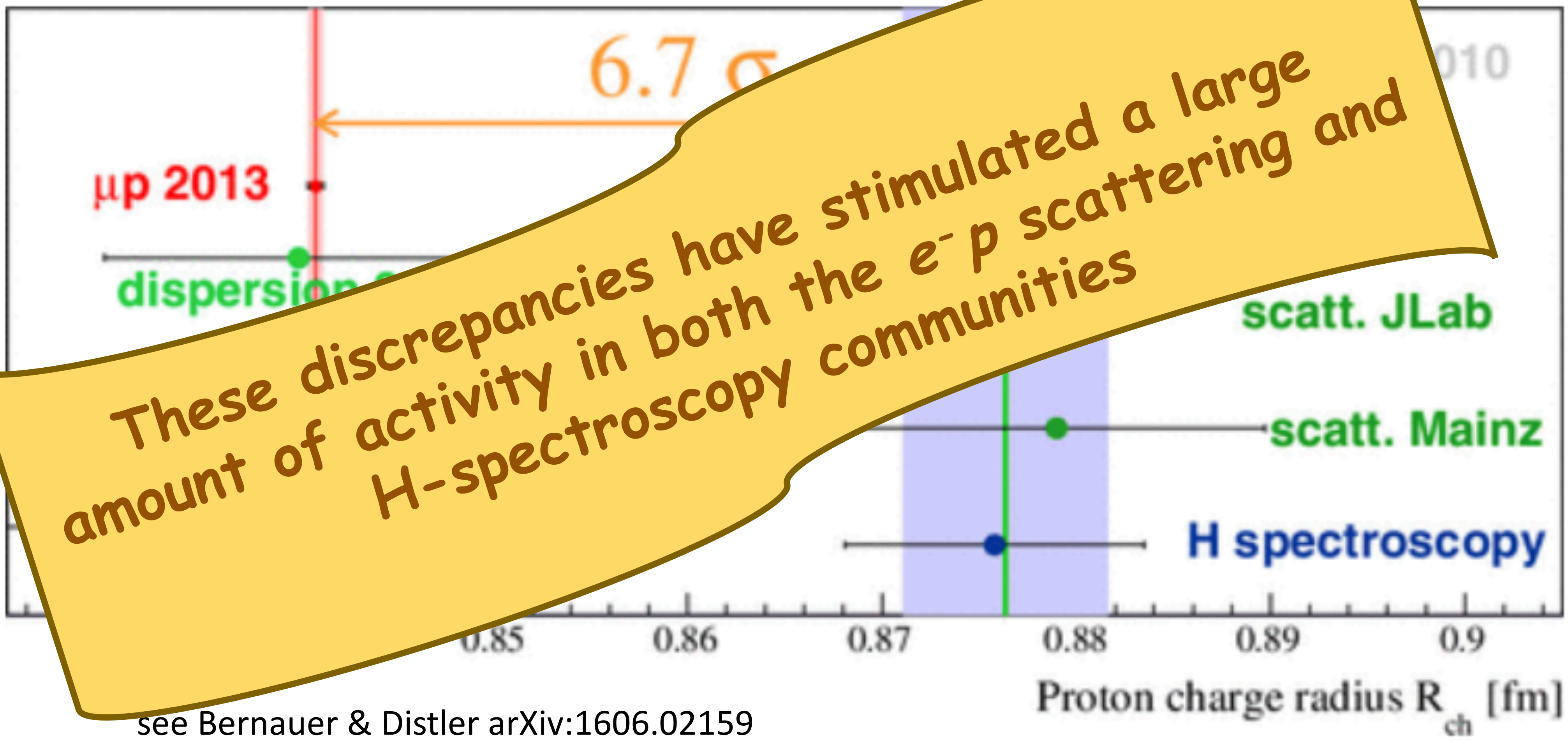
$$\Delta E_{2S-2P} = 206.0808(61)\ \text{meV} - 5.2272\, r_p^2\ \text{meV fm}^{-2}.$$

66 yrs after Hofstader, r_E still uncertain to ~ ±5%



see Bernauer & Distler arXiv:1606.02159

66 yrs after Hofstader, r_E still uncertain to ~ ±5%



These discrepancies have stimulated a large amount of activity in both the $e^- p$ scattering and H-spectroscopy communities

see Bernauer & Distler arXiv:1606.02159

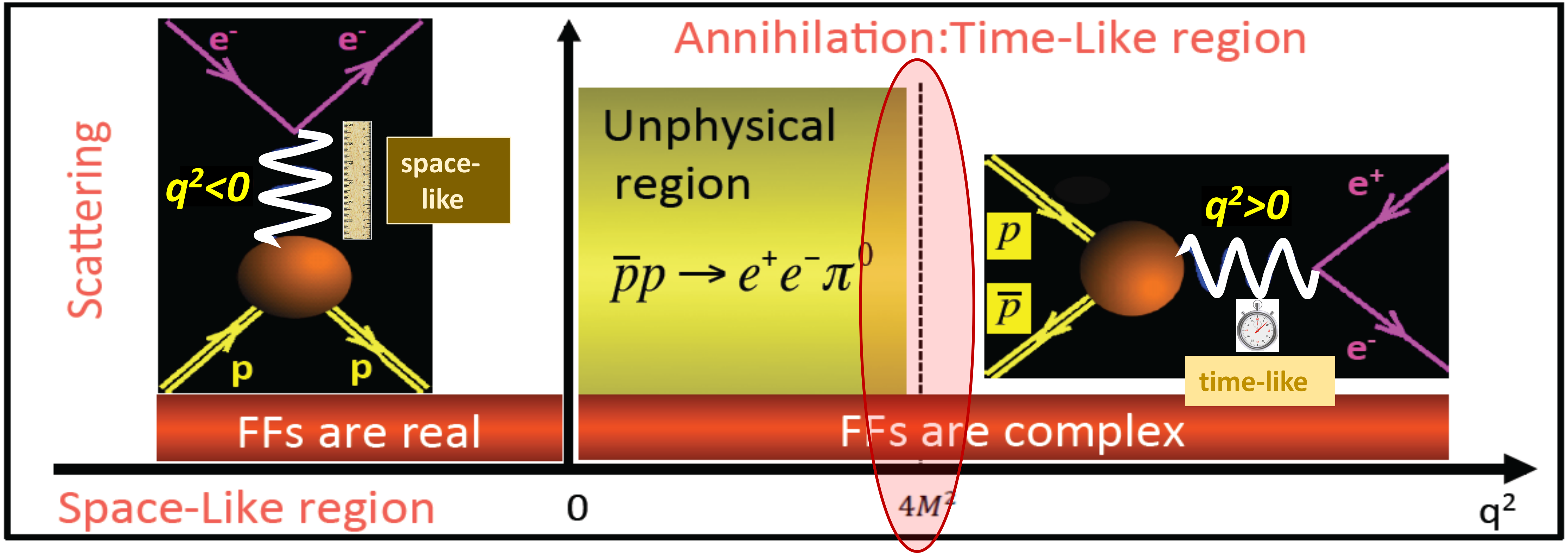
100 yrs later, the is proton still the source of interesting puzzles

Part-II: “That”

hadron thresholds

Time-like & space-like proton form-factors

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

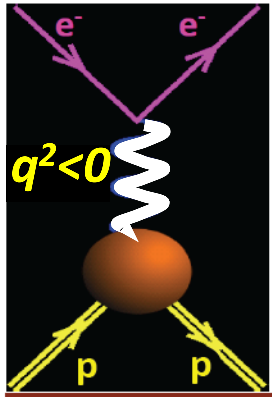


Crossing symmetry:

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

the neglected time-like region

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



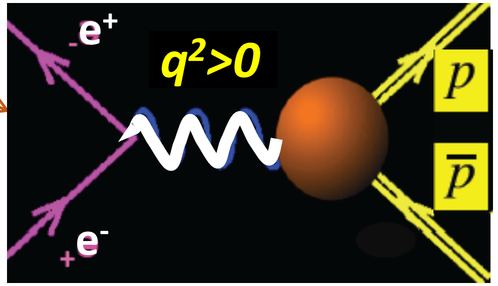
related by crossing symmetry

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

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

Fermi & Dirac form factors

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



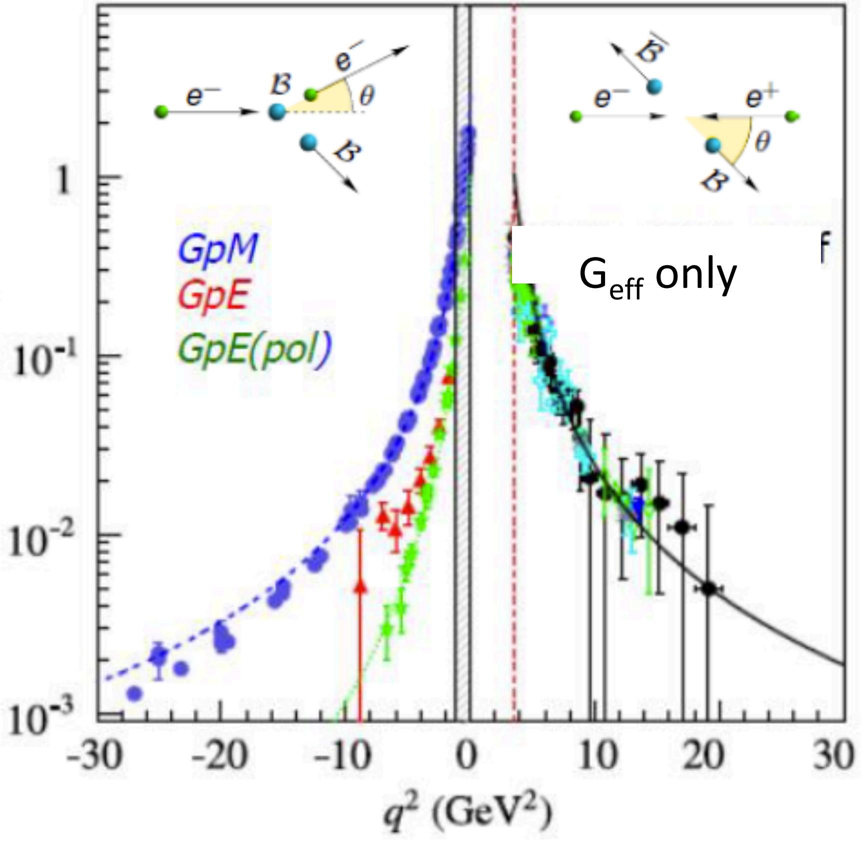
Huge amount of data

100's of experiments starting in 1954

Separate determinations of G_E, G_M & G_{pol}

1961 Nobel Prize

Robert Hofstadter



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

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

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

Sachs form factors

$$G_E = F_1 + \frac{q^2}{4M^2}F_2$$
$$G_M = F_1 + F_2$$

$$G_E(0) = Q_N$$
$$G_M(0) = \mu_N$$

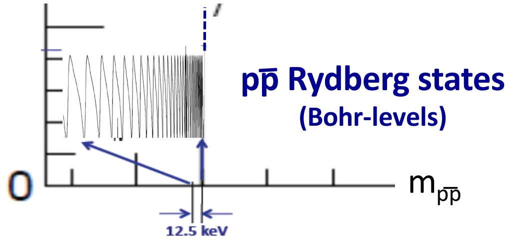
$$|G_{eff}|^2 = \frac{|G_M|^2 + \frac{1}{2\tau}|G_E|^2}{1+\frac{1}{2\tau}}$$

$$\tau = \frac{m_{B\bar{B}}^2}{4M_B^2} \quad \beta = \sqrt{1-\frac{1}{\tau}}$$

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

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

Sommerfeld resummation factor



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

Sachs form factors

$$G_E = F_1 + \frac{q^2}{4M^2}F_2$$

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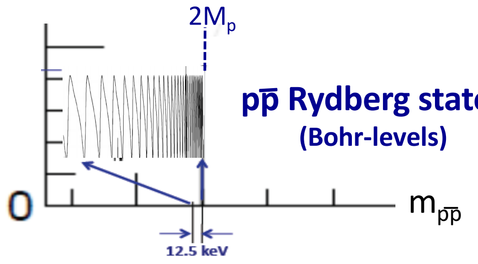
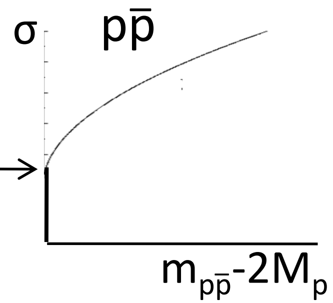
for point-like charged particles: $$C = \frac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)} \rightarrow \frac{\pi\alpha}{\beta} \quad \leftarrow \text{when } \beta \rightarrow 0$$

Sommerfeld resummation factor



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

$$\sigma_{jump} \approx 0.85\text{nb}|G_{eff}(2M_p)|^2 \rightarrow$$



in point-like approx, there is a *non-zero* cross-section right at the threshold!

This is what is seen

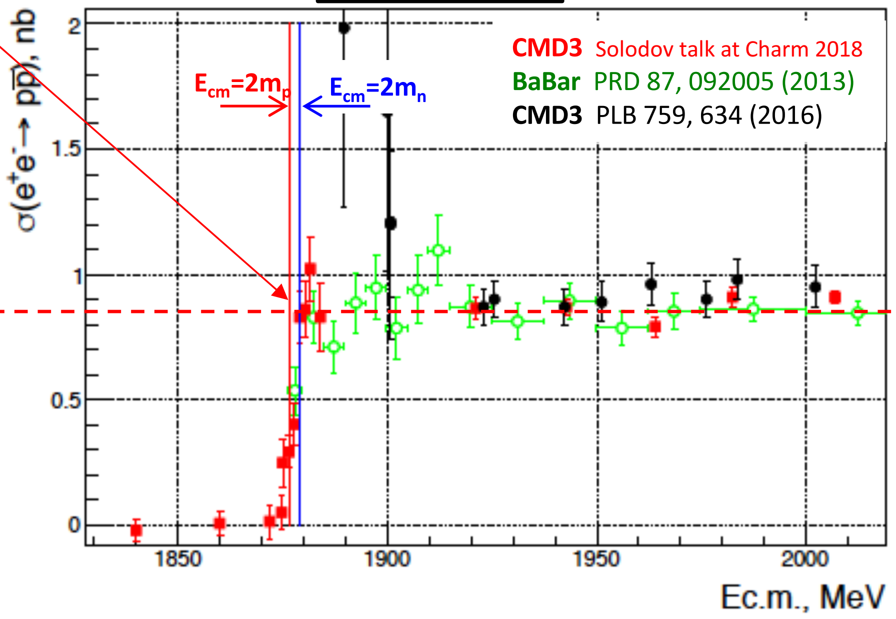
by BaBar and CMD

cross section jumps to 850 pb
within 1 MeV from threshold!

$\beta \approx 0.03$; no sign of a phase-space factor

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

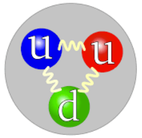
σ_{Ecm}=1.2 MeV



$\sigma_{jump} \approx 850$pb

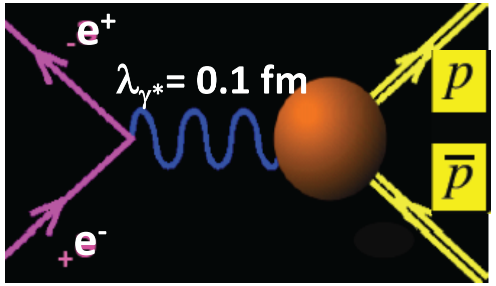
Just as expected for a charge=1 point-like fermion

but the proton is *not* point-like



$R_{proton} \approx 0.85$ fm

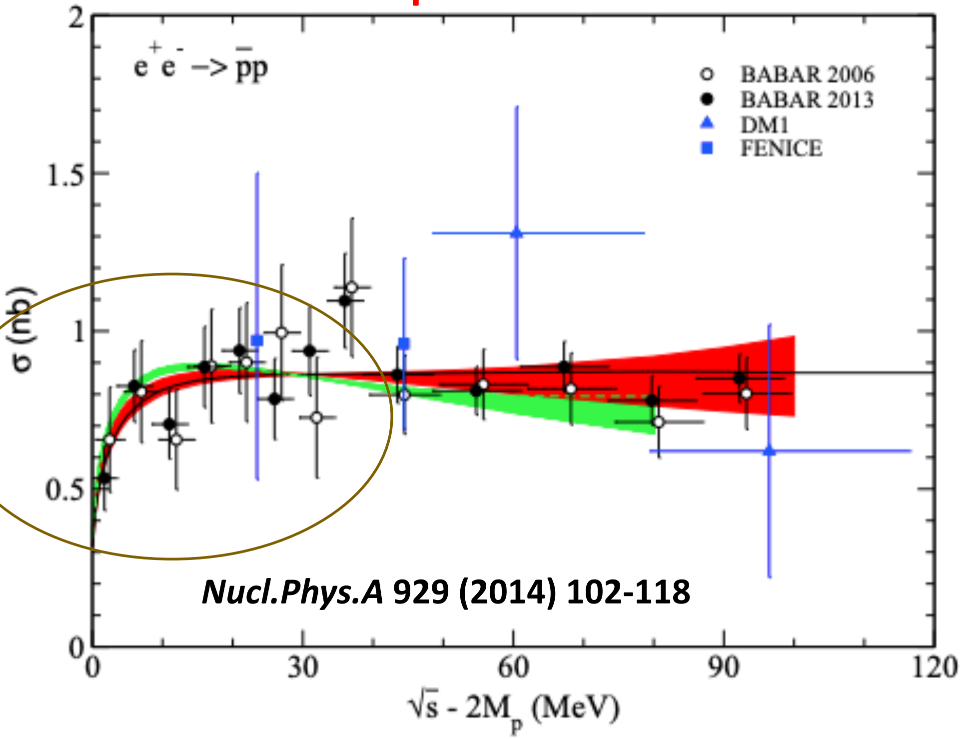
& is produced by a $Q^2 \approx 3.5$ GeV γ^*



inconsistent with theory

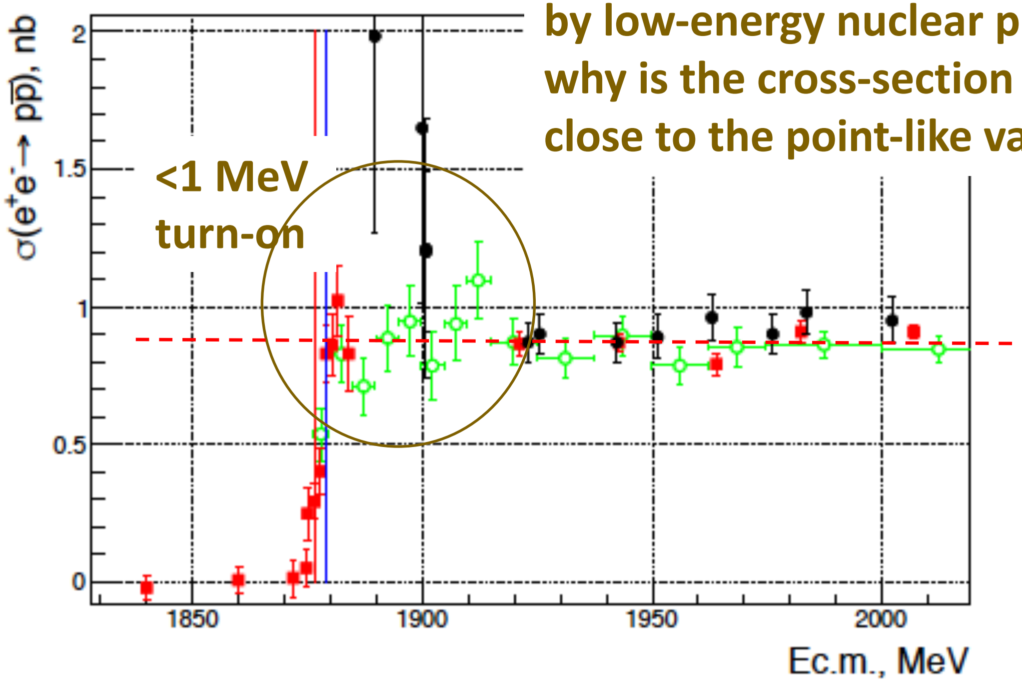
fit to pre SND data

~15 MeV turn-on



Nucl.Phys.A 929 (2014) 102-118

<1 MeV turn-on



The final state is dominated by low-energy nuclear physics, why is the cross-section so close to the point-like value?

What about neutral baryons?

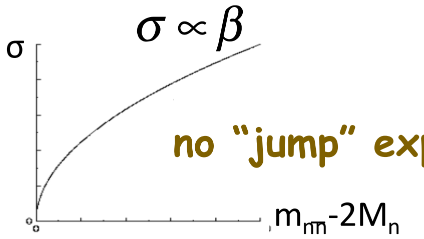
$e^+e^- \rightarrow n\bar{n}$ or $\Lambda\bar{\Lambda}$ (or $\Sigma^0\bar{\Sigma}^0$ or $\Xi^0\bar{\Xi}^0$) at threshold

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 $\Lambda\bar{\Lambda}$): $C = 1$

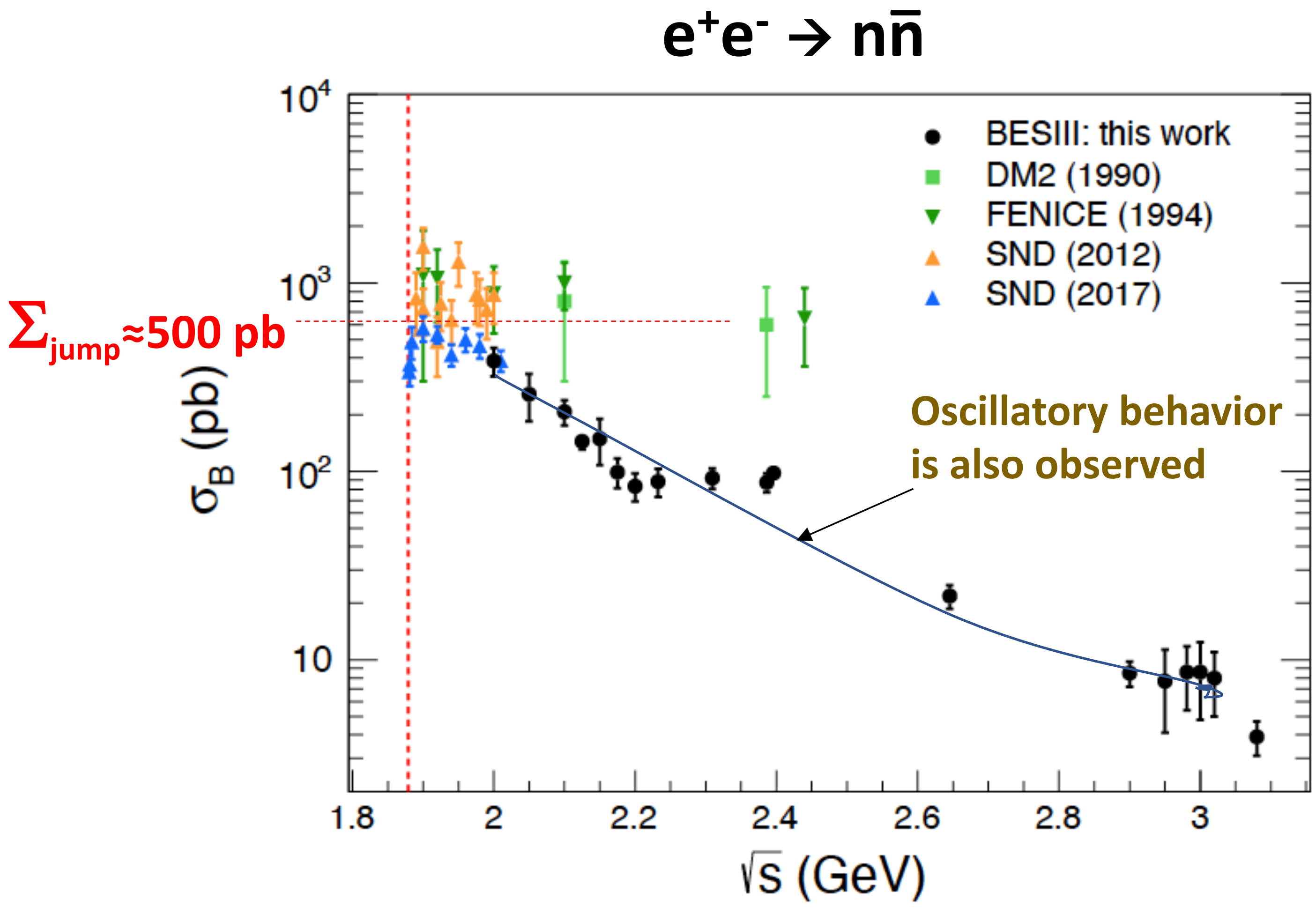
in point-like approx:

no Rydberg states (Bohr-levels)



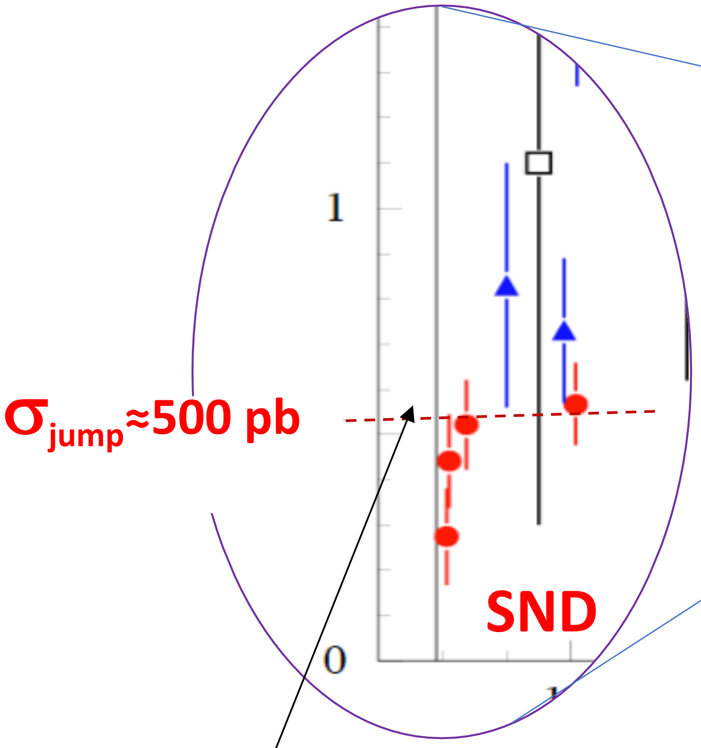
no "jump" expected

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

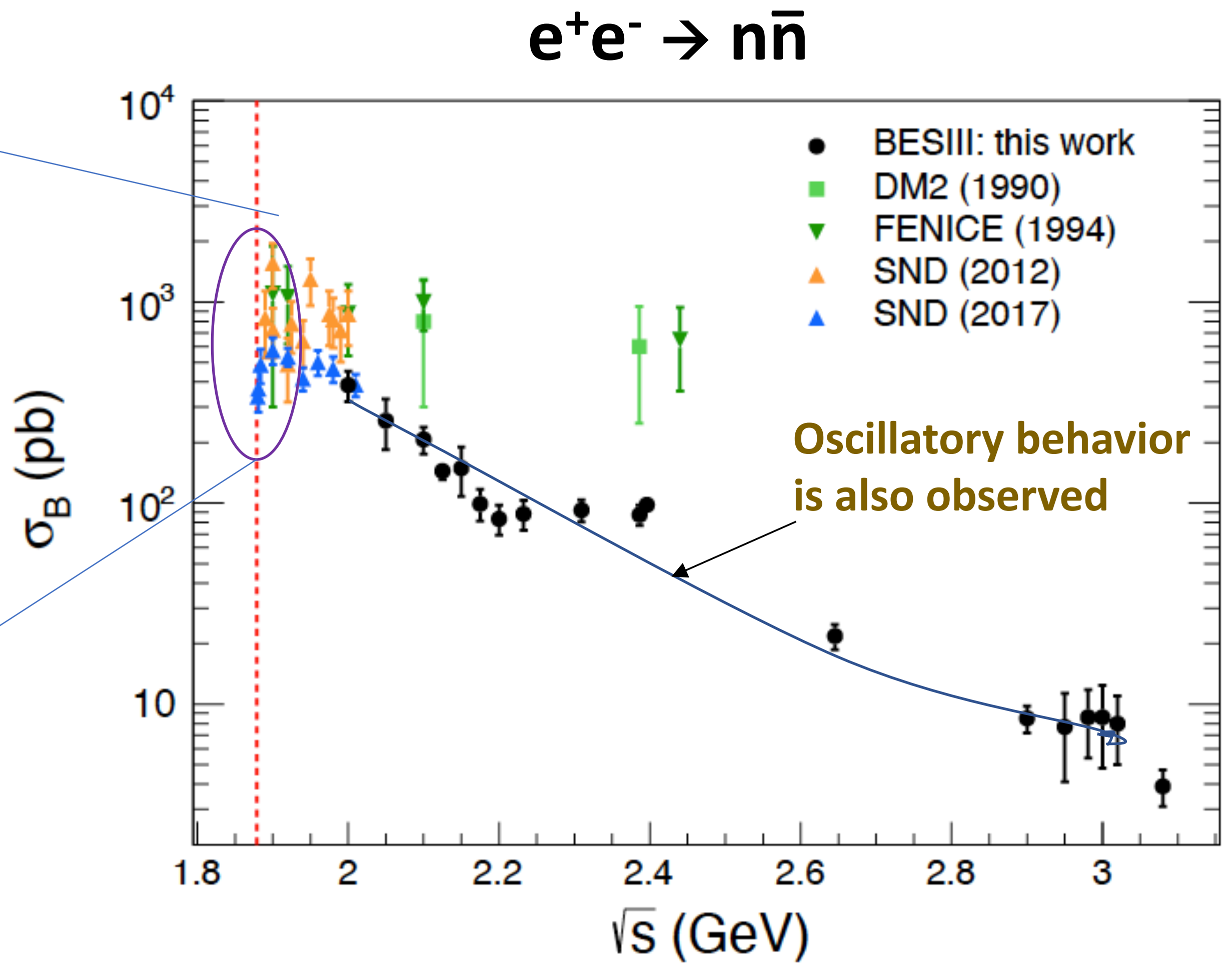


BESIII Nature Phys17, 1200

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



Threshold "jump"
this one is ~500pb &
2/3rds the $p\bar{p}$ one



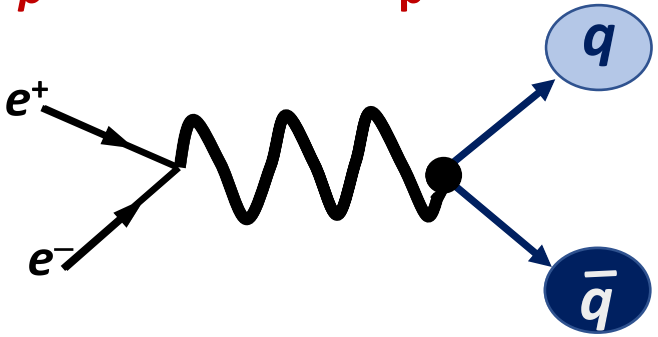
BESIII Nature Phys17, 1200

SND: *EPJ Web Conf.* 212 (2019) 07007

initial state → final state: very different scales

quarks are point particles

$\lambda_{Compton} \approx 1/2m_p \approx 0.1$ fm $<< r_p$



QED:

$e^+e^- \rightarrow u\bar{u} \rightarrow p\bar{p}$ $\quad \sigma_u = q_u^2 \sigma_{point}$

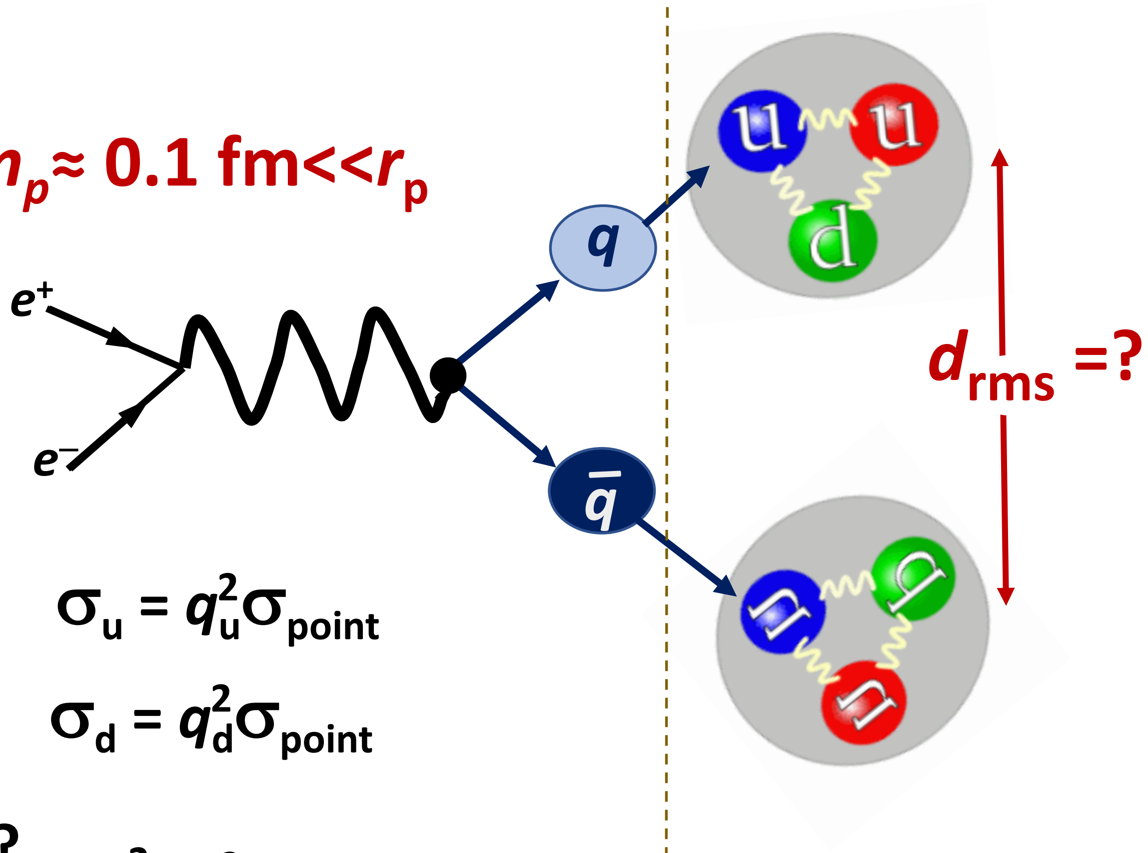
$e^+e^- \rightarrow d\bar{d} \rightarrow p\bar{p}$ $\quad \sigma_d = q_d^2 \sigma_{point}$

$$\sigma_{p\bar{p}} \stackrel{?}{=} (2q_u^2 + q_d^2)\,\sigma_{point}$$

initial state → final state: very different scales

quarks are point particles | nucleons are point particles

$\lambda_{Compton} \approx 1/2m_p \approx 0.1\ \text{fm} << r_p$



QED:

$e^+e^- \rightarrow u\bar{u} \rightarrow p\bar{p}$ $\quad \sigma_u = q_u^2 \sigma_{point}$

$e^+e^- \rightarrow d\bar{d} \rightarrow p\bar{p}$ $\quad \sigma_d = q_d^2 \sigma_{point}$

$$\sigma_{p\bar{p}} \stackrel{?}{=} (2q_u^2 + q_d^2)\, \sigma_{point}$$

Nuclear Physics:

low energy $p\bar{p}$
scattering length

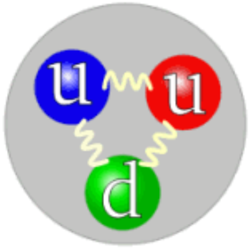
$$d_{rms} = \frac{1}{\sqrt{2\mu_{p\bar{p}}|\Delta E|}}$$

for $p\bar{p}$ within 1 MeV
of the $2m_p$ threshld:
$d_{rms} \approx 7\ \text{fm} >> r_p$

add (quark charges)^2

incoherent sums!

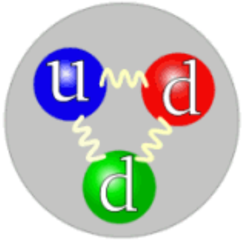
proton



$$\sum q_i^2 = \left(\frac{2}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 = 1$$

$\Delta\sigma_{jump}$=1×850 pb

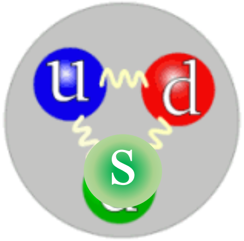
neutron



$$\sum q_i^2 = \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 = \frac{2}{3}$$

$\Delta\sigma_{jump}$=(2/3)×850 pb = 570 pb

$\Lambda^0/\Sigma^0/\Xi^0$



$$\sum q_i^2 = \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 = \frac{2}{3}$$

predictions?

$\Delta\sigma^{\Lambda}_{jump}=(2/3)\times\left(\frac{m_p}{m_\Lambda}\right)^2 850\text{ pb} \stackrel{?}{=} 400\text{ pb}$

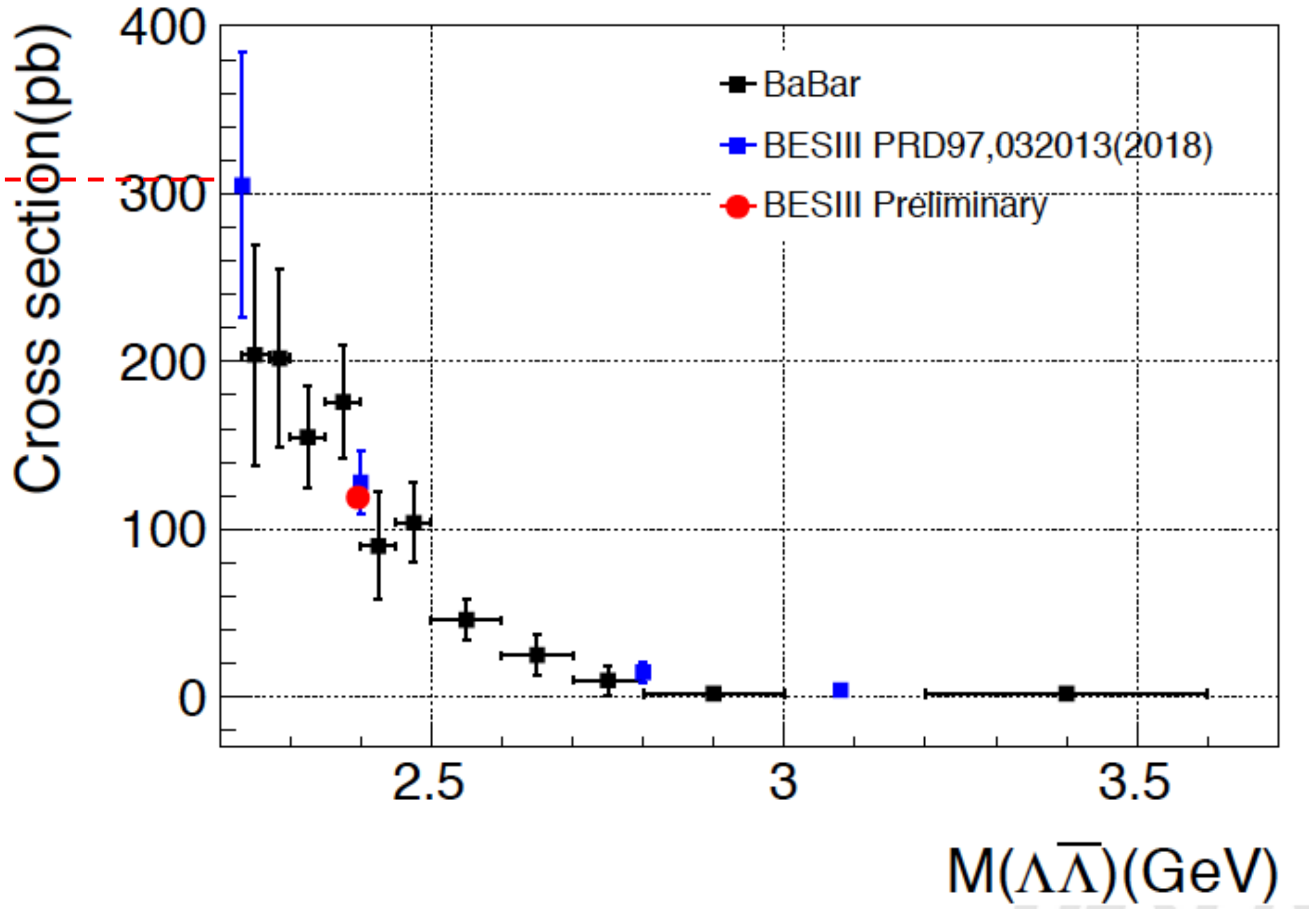
$\Delta\sigma^{\Sigma^0}_{jump}=(2/3)\times\left(\frac{m_p}{m_\Sigma}\right)^2 850\text{ pb} \stackrel{?}{=} 350\text{ pb}$

$\Delta\sigma^{\Xi^0}_{jump}=(2/3)\times\left(\frac{m_p}{m_\Xi}\right)^2 850\text{ pb} \stackrel{?}{=} 290\text{ pb}$

$e^+e^- \to \Lambda^0 \bar{\Lambda}^0$ at Threshold

$\Delta\sigma_{jump} \approx 300 \pm 50$ pb

Predicted 400 pb



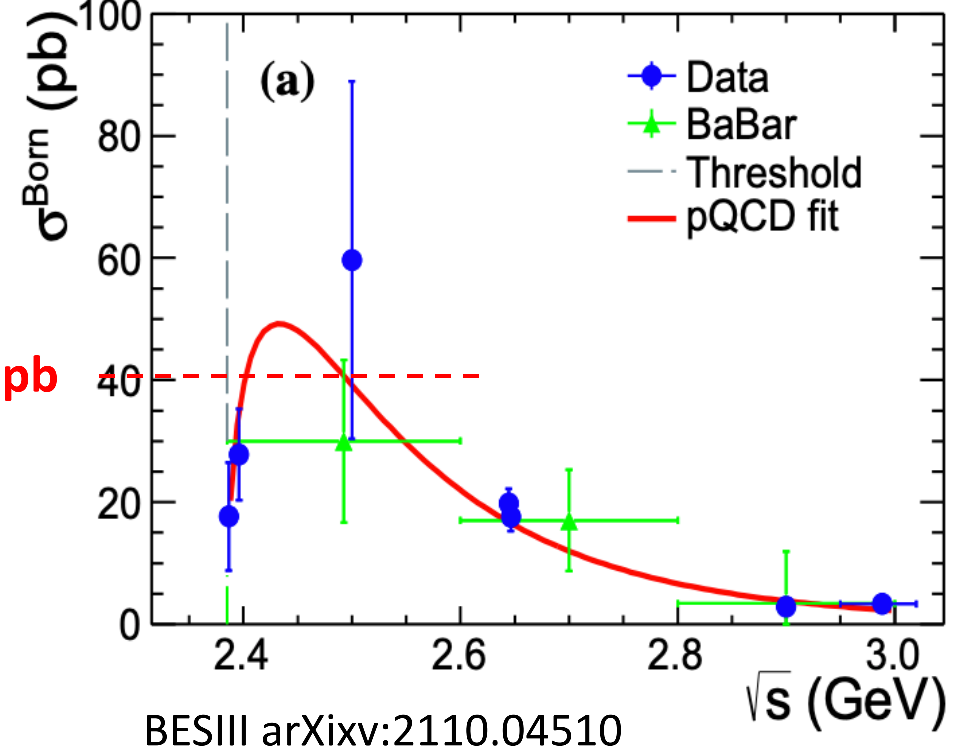
$e^+e^- \to \Sigma^0\bar{\Sigma}^0$ and $\Xi^0\bar{\Xi}^0$ at Threshold

no jumps!

$e^+e^- \to \Sigma^0\bar{\Sigma}^0$

$\Sigma_{jump} \lesssim 40$ pb

Predicted: 350 pb

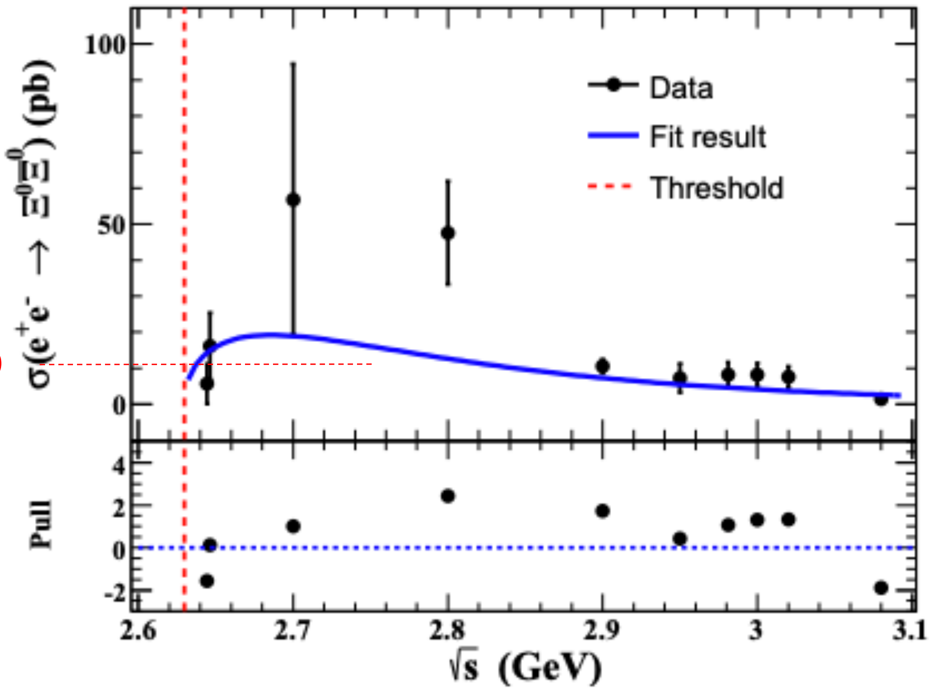


BESIII arXixv:2110.04510

$e^+e^- \to \Xi^0\bar{\Xi}^0$

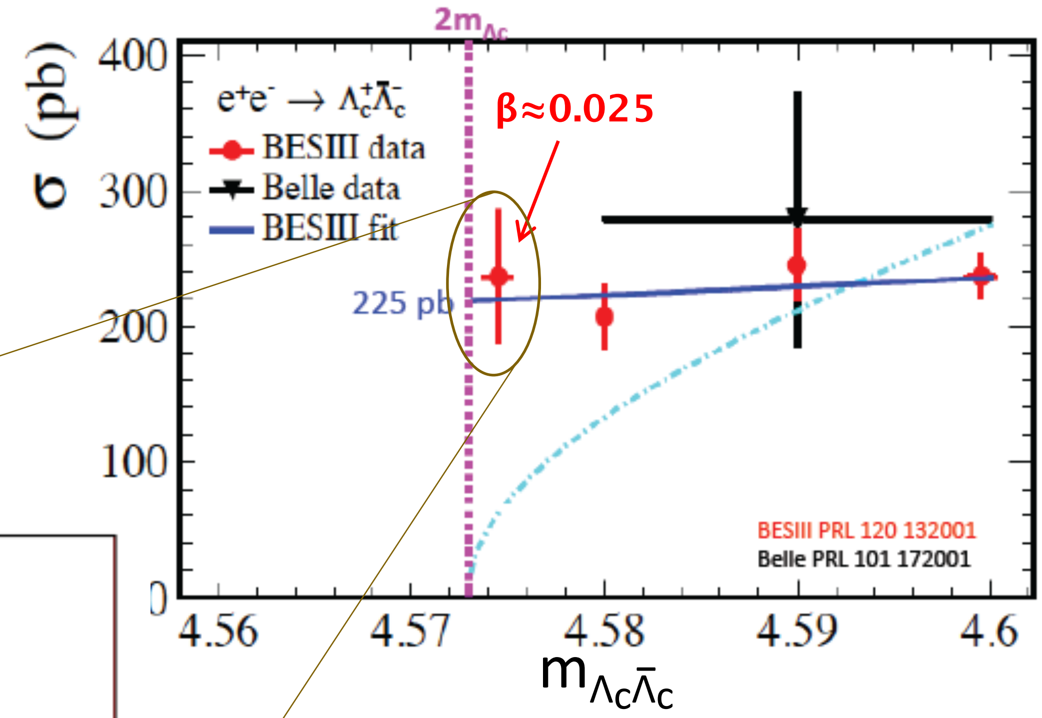
$\Sigma_{jump} \lesssim 10$ pb

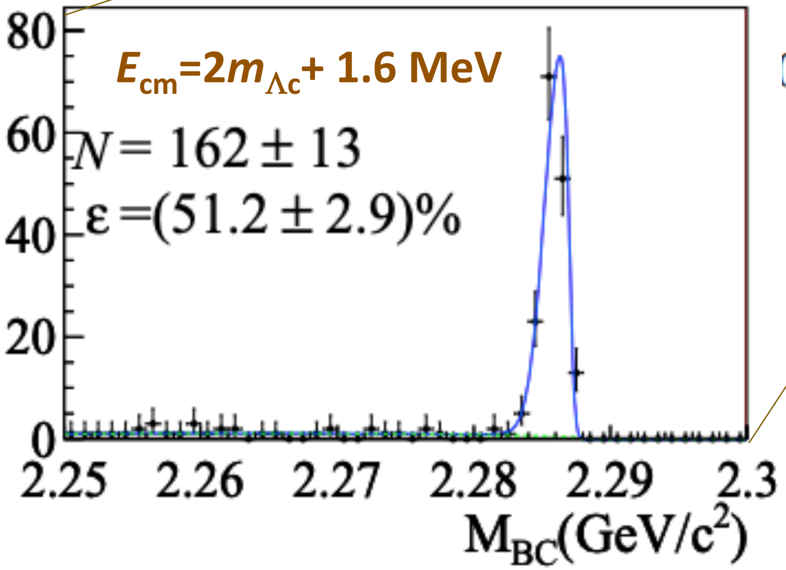
Predicted: 290 pb

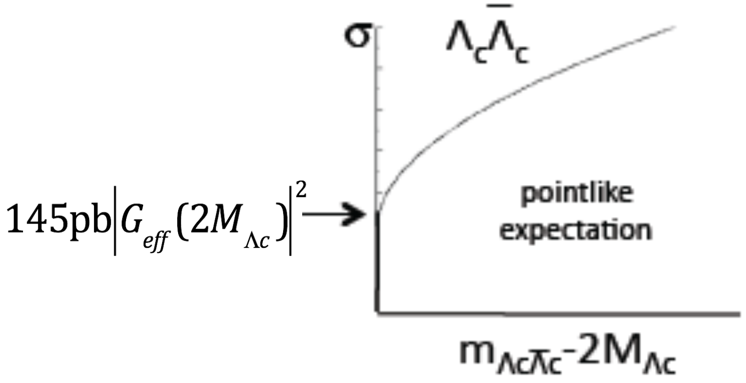


BESIII PLB820,137557

$\sigma(e^+e^- \to \Lambda_c^+\Lambda_c^-)$ has a threshold jump



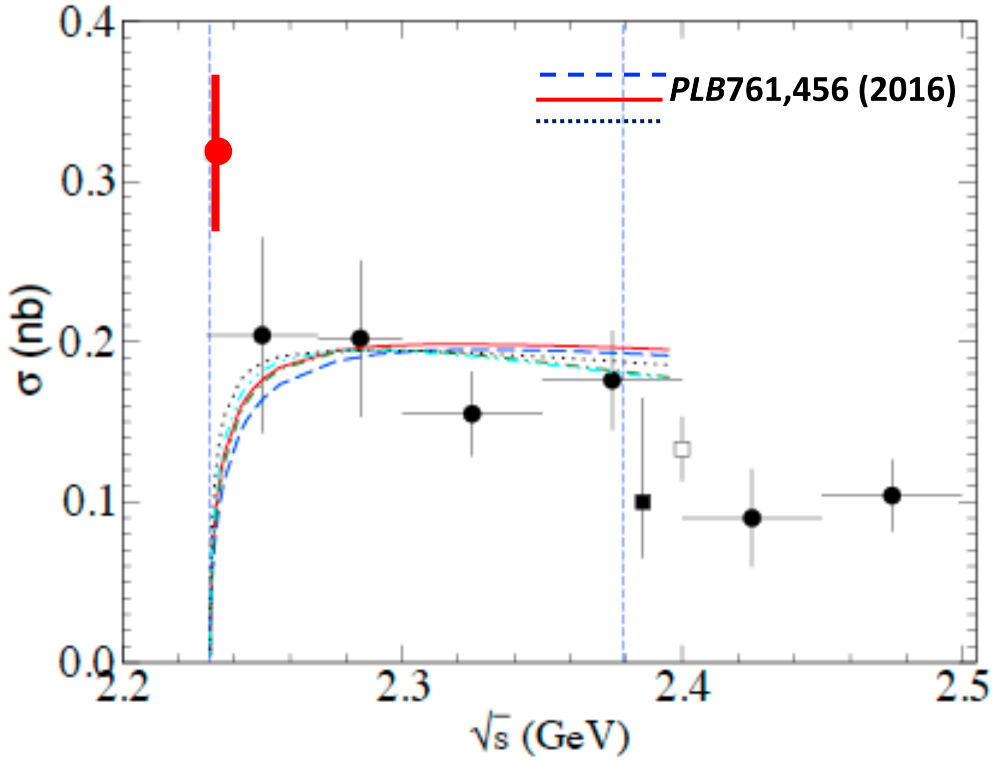




σ_{jump}≈225 pb ⟹ consistent with σ_{jump}≈ 145 pb expected for a point-like particle

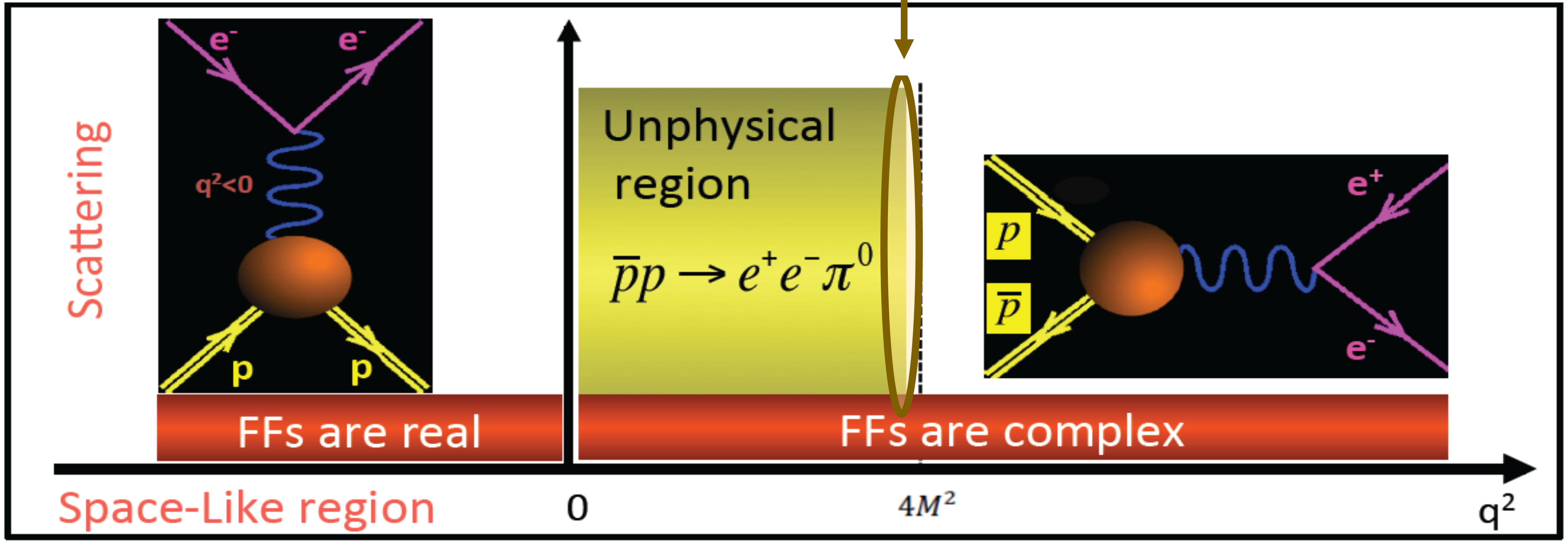
flat after that (like $p\bar{p}$)

$e^+e^- \to \Lambda\bar{\Lambda}$ not explained by final state interactions



adding (quark charges)^2 only works sometimes what else?

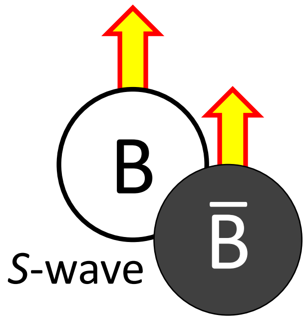
what's happening here (below threshold)



are there bound states in some channels, but not others?

$J^{PC}=1^{--}$ baryonium?

-- spin=1 sub-threshold $B\bar{B}$ *S*-wave bound states --

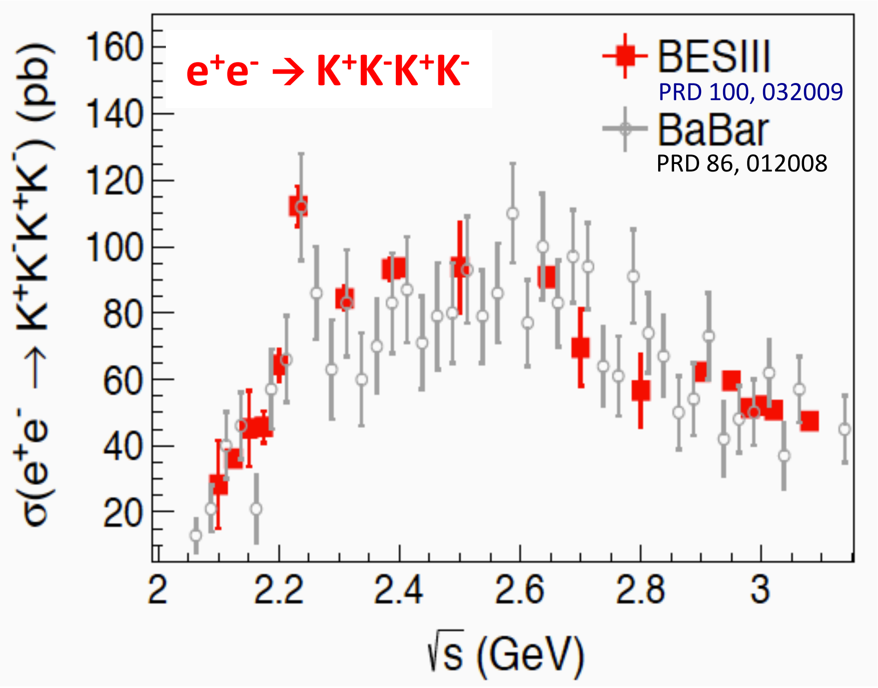


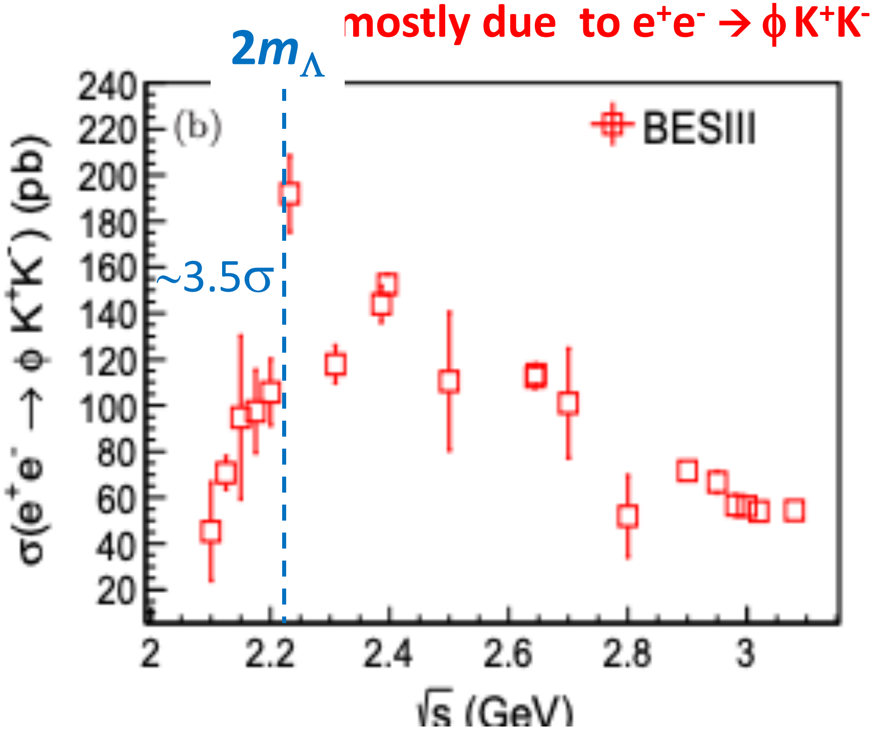
$J^{PC}=1^{--}$

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

Is there a sub-threshold $\Lambda\bar{\Lambda}$ state?

Hints of a $\sigma(e^+e^- \rightarrow K^+K^- K^+K^-)$ peak @ $2m_\Lambda$ seen in BaBar & BESIII



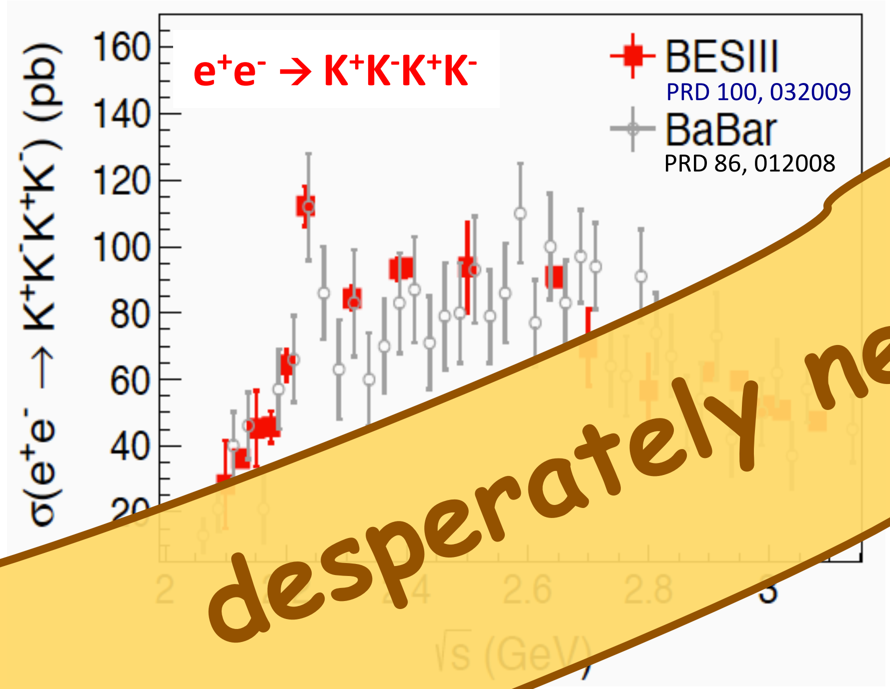


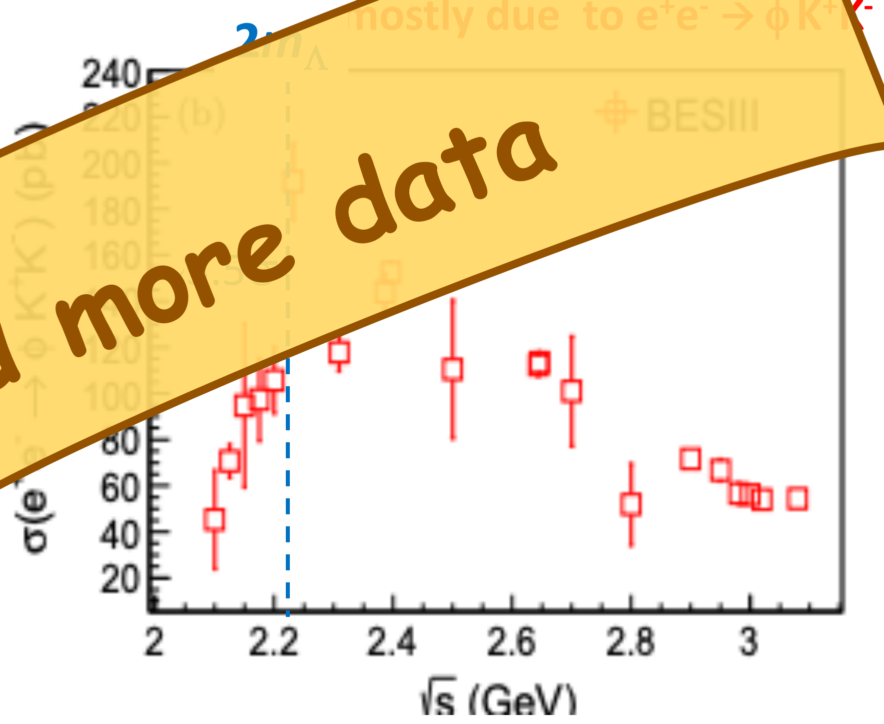
M=2232 ±3.5 MeV $\Longrightarrow$ M-$2m_\Lambda$= 0.8 ± 3.5 MeV

Γ<14 MeV

Is there a sub-threshold $\Lambda\bar{\Lambda}$ state?

Hints of a $\sigma(e^+e^- \to K^+K^- K^+K^-)$ peak @ $2m_\Lambda$ seen in BaBar & BESIII



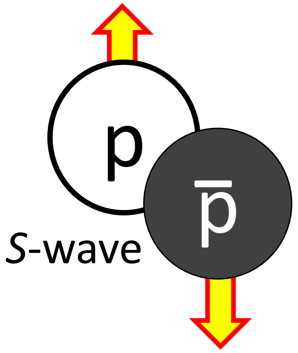


M=2232 ±3.5 MeV $\Longrightarrow$ M-$2m_\Lambda$= 0.8 ± 3.5 MeV

Γ<14 MeV

$J^{PC}=0^{-+}$ baryonium?

-- spin=0 sub-threshold $B\bar{B}$ *S*-wave bound states? --



$J^{PC}=0^{-+}$

$J/\psi \rightarrow \gamma\, B\bar{B}$

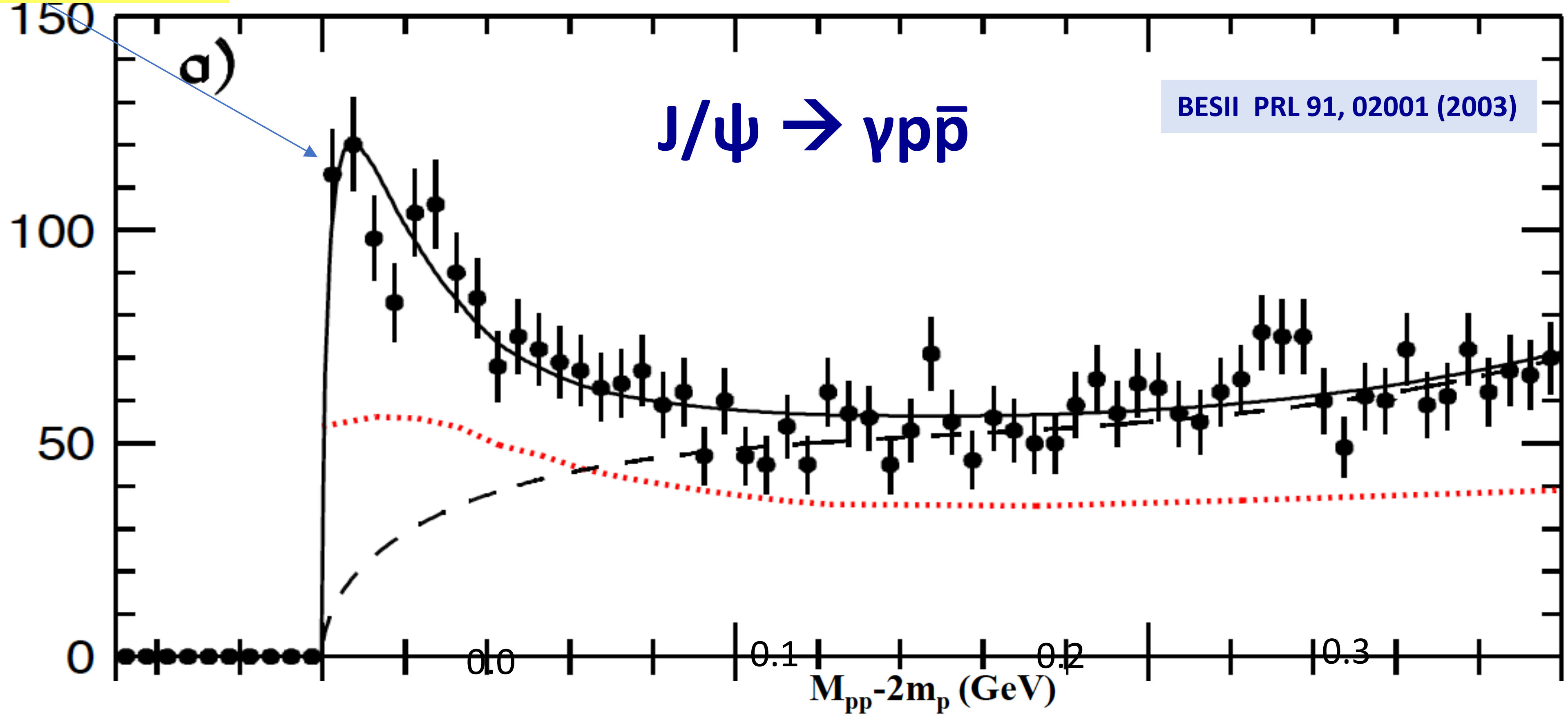
1st proposed by Fermi & Yang in 1949 (6 yrs prior to the $\bar{p}$ discovery) *Phys.Rev.* 76 (1949) 1739-1743

Candidate 0^{-+} $p\bar{p}$ bound state 1st seen in 2003

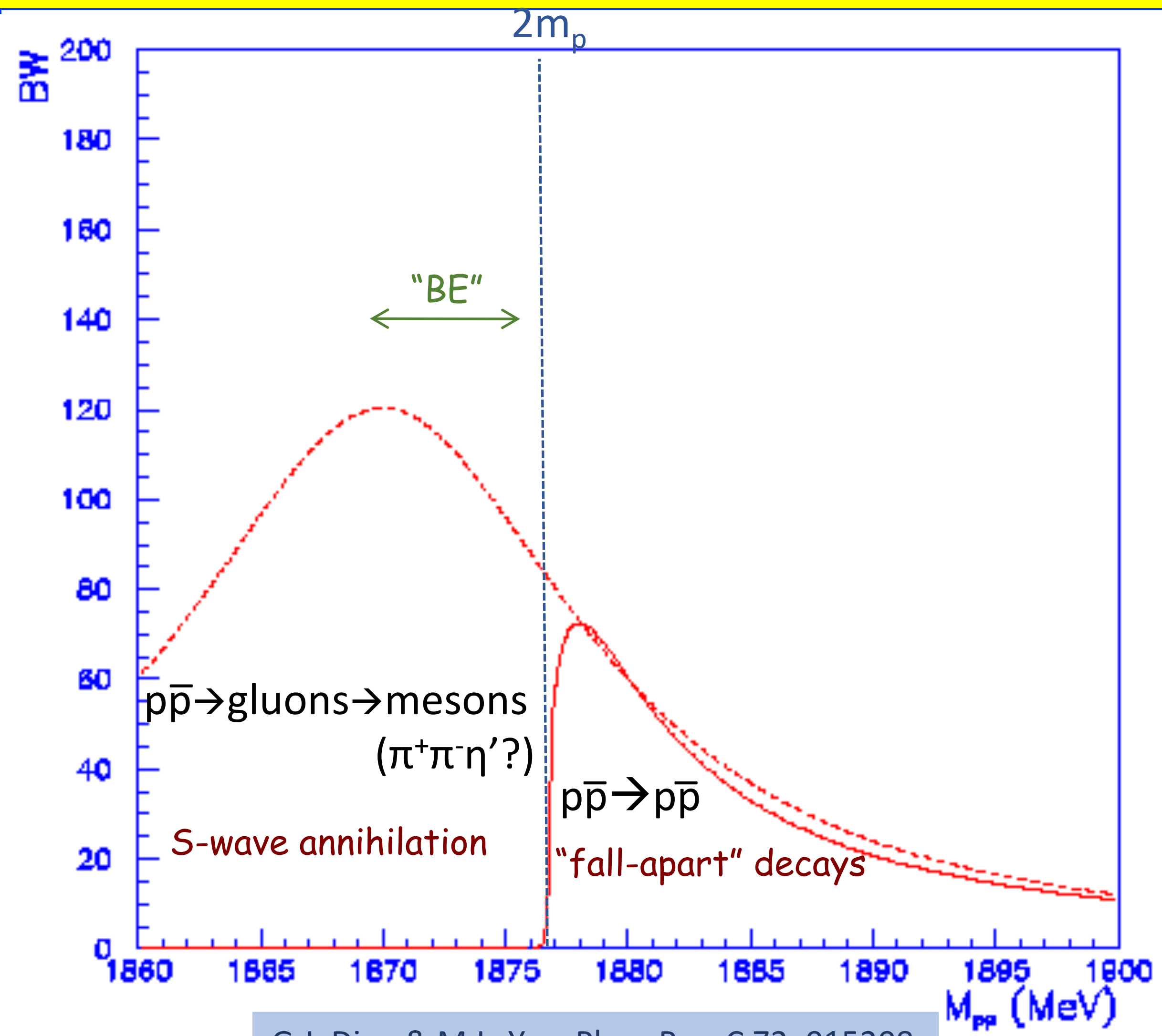
$M=1859^{+3}_{-10}{}^{+5}_{-25}$ MeV/c^2

$\Gamma < 30$ MeV/c^2 (90% CL)

$J^{PC}=0^{-+}$



"protonium:" a p$\bar{p}$ bound state?



G.J. Ding & M.L. Yan Phys. Rev. C 72, 015208

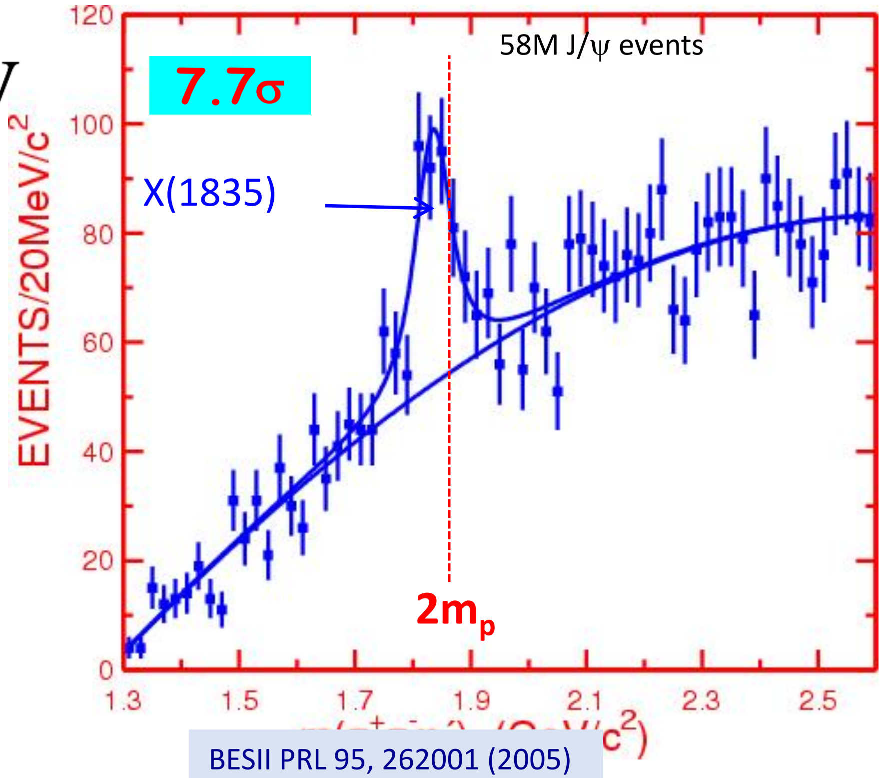
$X(1835) \rightarrow \pi^+\pi^-\eta'$ with 58M J/ψ decays (BESII)

BESII observation of X(1835) in

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

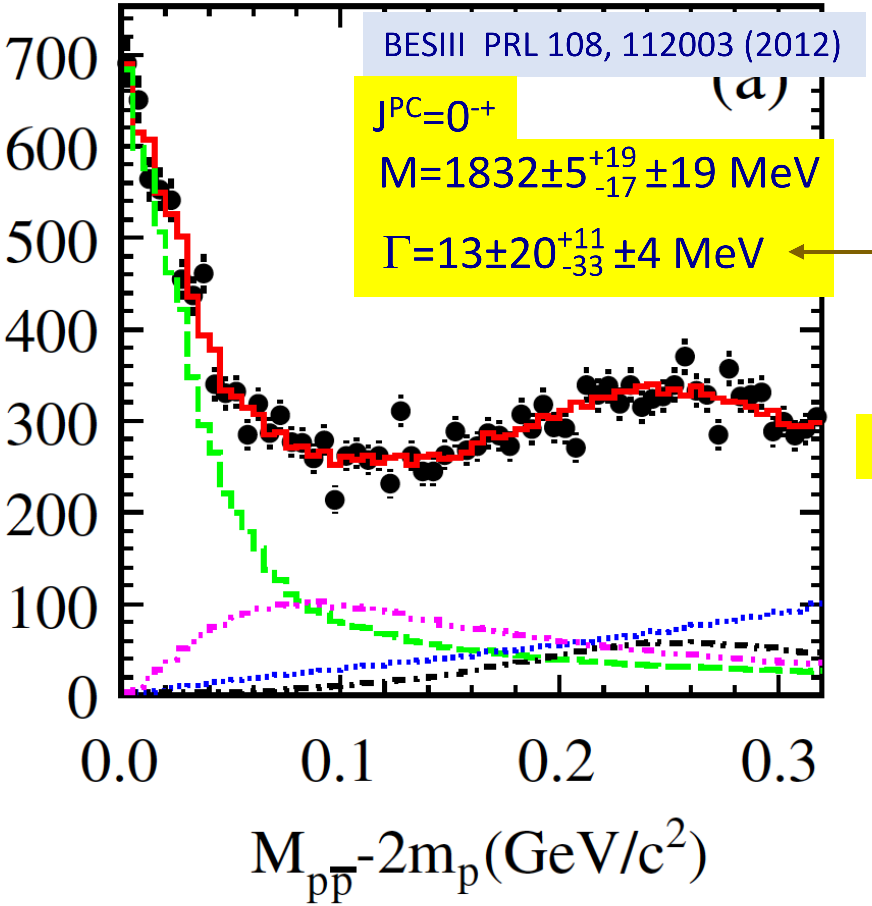
$$m = 1833.7 \pm 6.8 \text{ MeV}$$

"BE"≈ 40 MeV



BESII PRL 95, 262001 (2005)

$J/\psi \rightarrow \gamma\, p\bar{p}$ at BESIII (PWA)



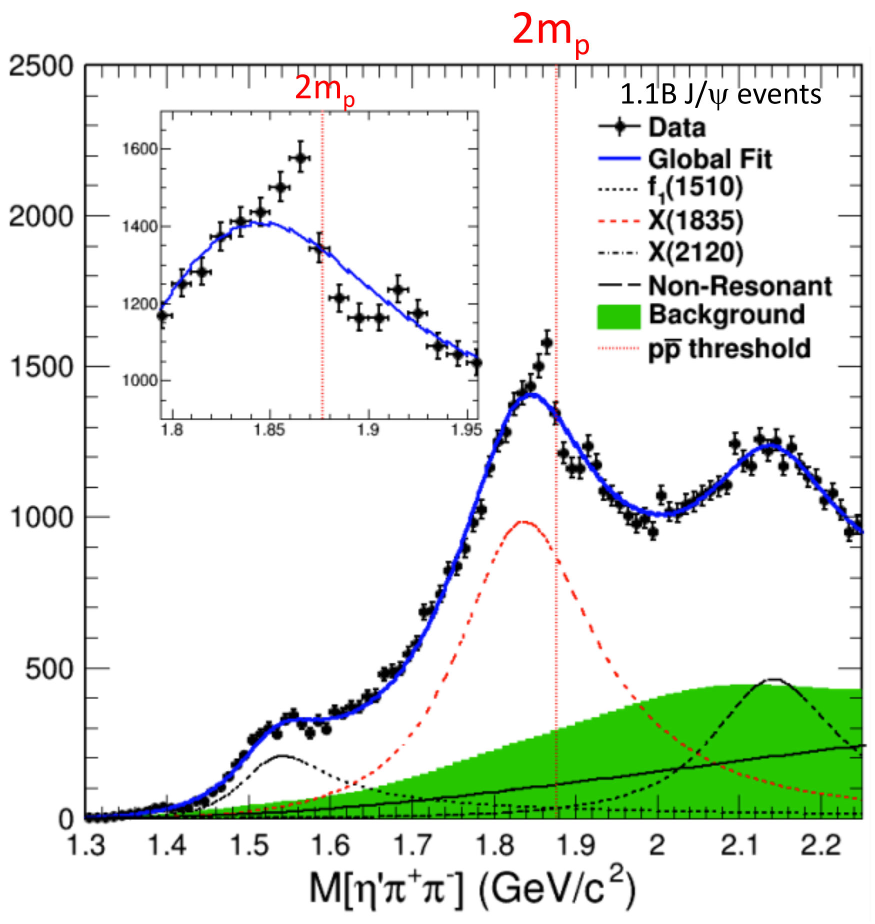
very narrow

FSI included: A. Sibirtsev et al, PRD71, 054010 (2005)

***$p\bar{p}$* bound state is required:** Kang, Haidenbauer, Meissner: *Phys.Rev.D* 91 (2015) 7, 074003

$X(1835) \rightarrow \pi^+\pi^-\eta'$ with 1.1B J/ψ events (BESIII)

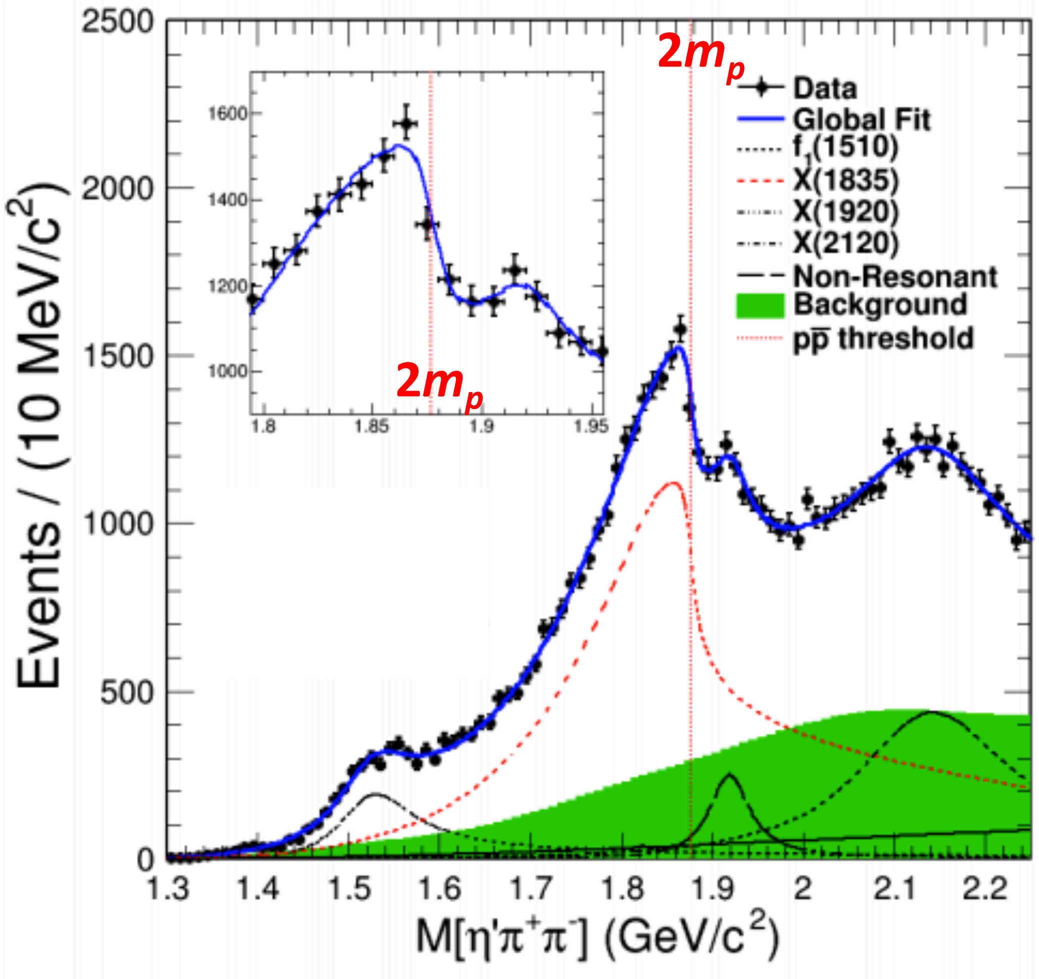
$$J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$$



Flatté formula fit:

$$T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i\sum_k g_k^2 \rho_k}, \sum_k g_k^2 \rho_k \simeq g_0^2 \left(\rho_0 + \frac{g_{p\bar{p}}^2}{g_0^2} \rho_{p\bar{p}}\right)$$

S.M. Flatte
PLB 63, 224 (1976)



Fit results:

$$\frac{g_{p\bar{p}}^2}{g_0^2} = 2.31 \pm 0.37$$

X coupling to $p\bar{p}$

X coupling to everything else

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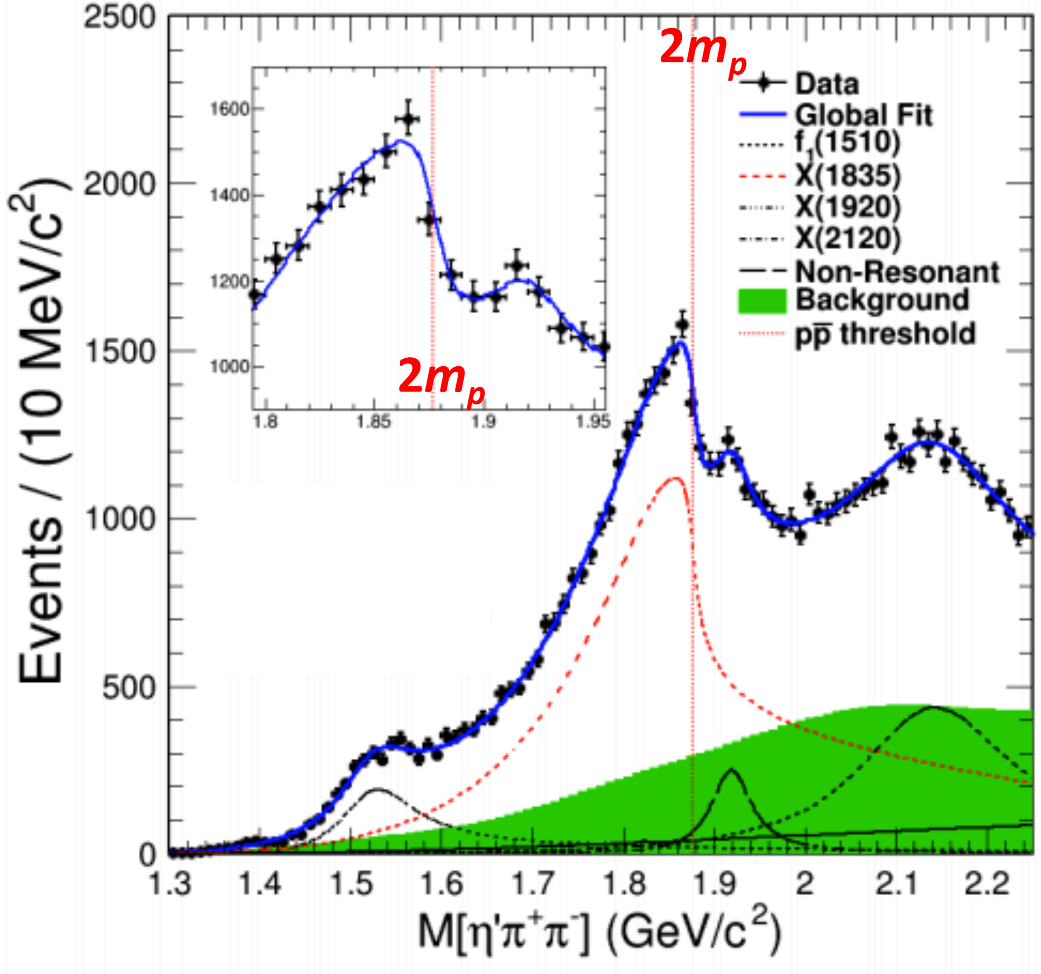
S.M. Flatte PLB 63, 224 (1976)



Fit results:

X coupling to $p\bar{p}$

$$\frac{g_{p\bar{p}}^2}{g_0^2} = 2.31 \pm 0.37$$

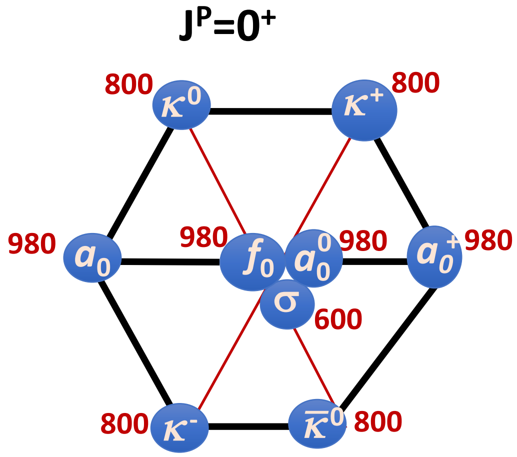
X coupling to everything else

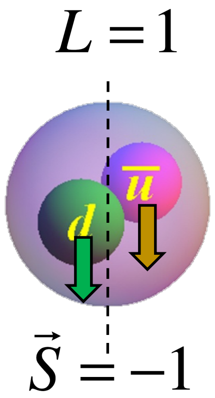
unlike any other meson

After ~130 years, still lots to learn about the proton

the scalar mesons near the $K\bar{K}$ threshold

the "light" scalar-meson nonet

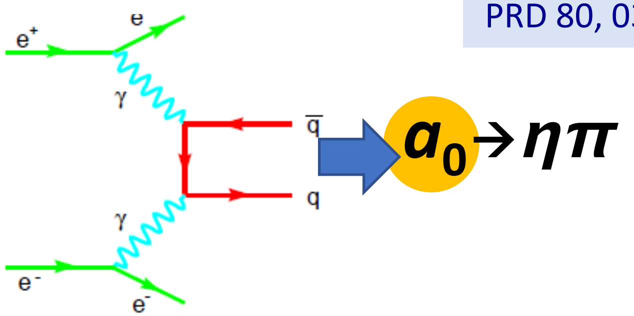


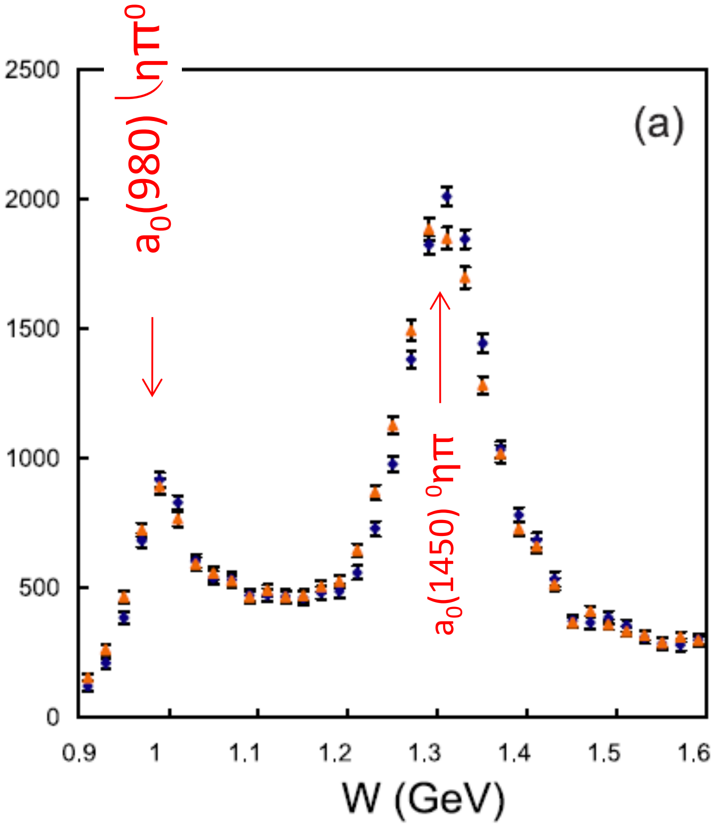


Signal for $a_0(980) \to \eta\pi$

$\gamma\gamma \to \eta\pi^0$ Belle

Belle Collab:
PRD 80, 032001 (2009)



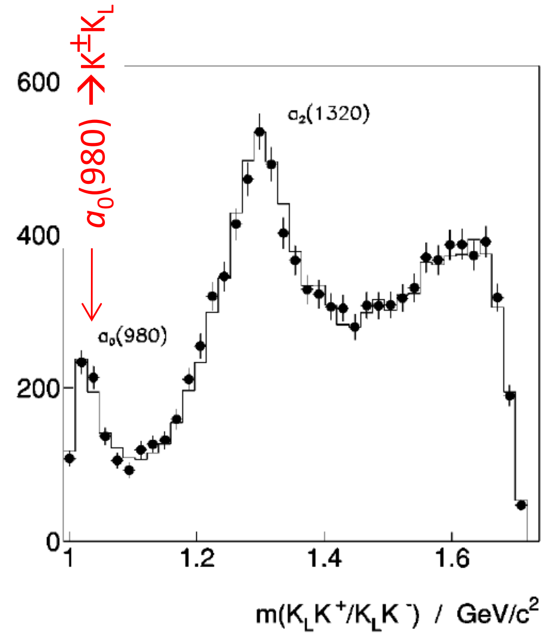


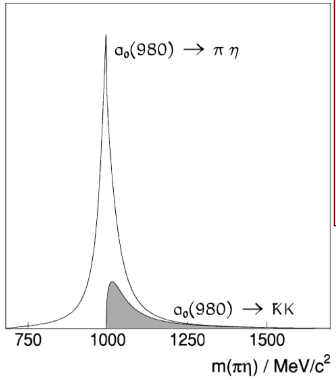
PHYSICAL REVIEW D **80**, 032001 (2009)

Signal for $a_0(980) \to K^+K^-$

$\bar{p}p$ ANNIHILATION AT REST INTO $K_L K^{\pm} \pi^{\mp}$

Crystal Barrel Collab: PRD 57, 3860 (1998)





strong $a_0(980)$ coupling to KK

$$\frac{g_{KK}}{g_{\eta\pi}} = 1.03 \pm 0.14$$

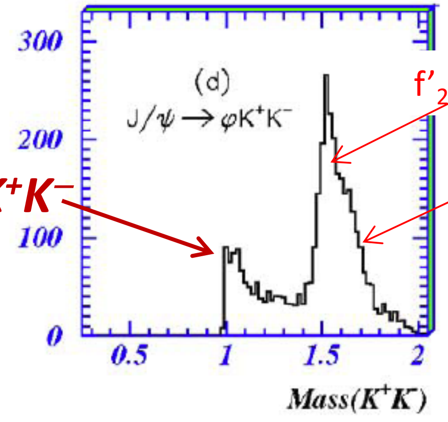
Signals for $f_0(980) \to \pi^+\pi^-$ & K^+K^-

Resonances in $J/\psi \to \phi\pi^+\pi^-$ and ϕK^+K^-

BES Collaboration

BESII PLB 607, 243 (2005)

$f_0(980) \to K^+K^-$

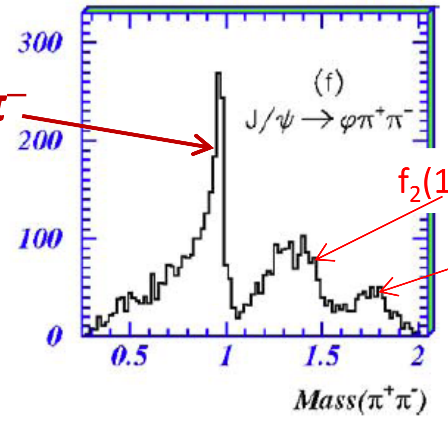


$f'_2(1525)+f_0(1710) \to K^+K^-$

strong $f_0(980)$ coupling to $K\bar{K}$

$$\frac{g_{KK}}{g_{\pi\pi}} = 4.2 \pm 0.3$$

$f_0(980) \to \pi^+\pi^-$

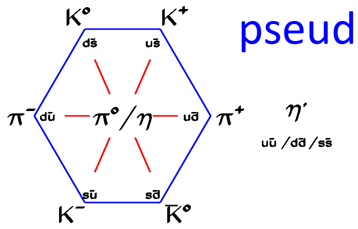


$f_2(1270)+f_0(1370) \to \pi^+\pi^-$

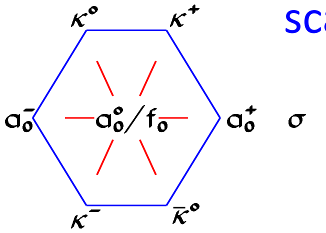
$f_0(1790) \to \pi^+\pi^-$

$Bf(J/\psi \to \phi f_0(980)) = 0.32 \pm 0.09 \times 10^{-3}$

lots of puzzles:

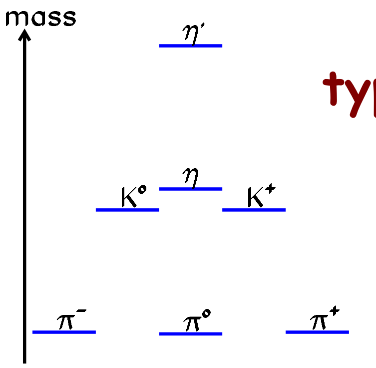


pseudoscalars

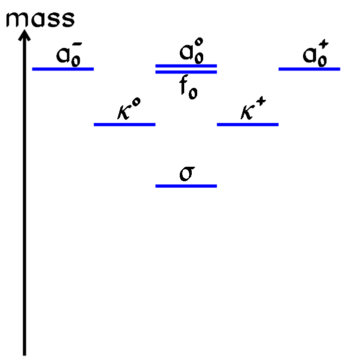


scalars

masses are inverted



typical

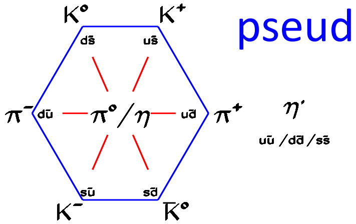


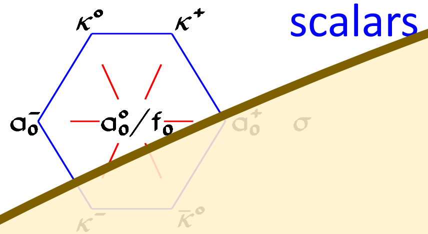
unique

also:

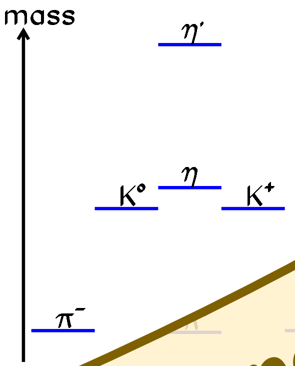
- **No "light" $J^P=1^+$ and 2^{++} partner nonets in the same mass range.**
- **In $q\bar{q}$ meson nonets, the I=1 mesons have no s-quarks and are the lightest. However, the I=1 a_0(980) mesons are the nonet's heaviest.**
- **The a_0(980) triplet has strong couplings to $K\bar{K}$.**
- **m(f_0(980))~m(a_0(980)) implies "ideal" mixing & *small* s-quark content in f_0(980)**
- **Strong couplings to $K\bar{K}$ violate the OZI rule**

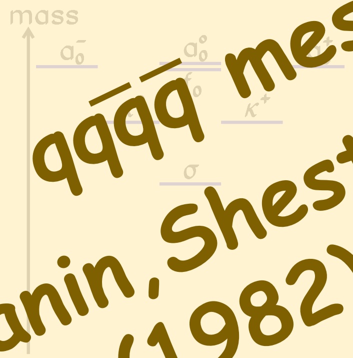
lots of puzzles:





masses are inverted





Oldest candidates for $qq\bar{q}\bar{q}$ mesons:
Jaffe (1976); Achasov, Devanin, Shestakov (1979);
Isgur, Weinstein (1982)

also:

- No light $J^P=1^+$ and 2^+ partner nonets in the same mass range.
- In $q\bar{q}$ meson nonets, the I=1 mesons have no *s*-quarks and are the lightest. However, the *I*=1 $a_0(980)$ mesons are the nonet's heaviest.
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- m(f_0(980))~m(a_0(980)) implies "ideal" mixing & *small s*-quark content in f_0(980)
- Strong couplings to $K\bar{K}$ violate the OZI rule

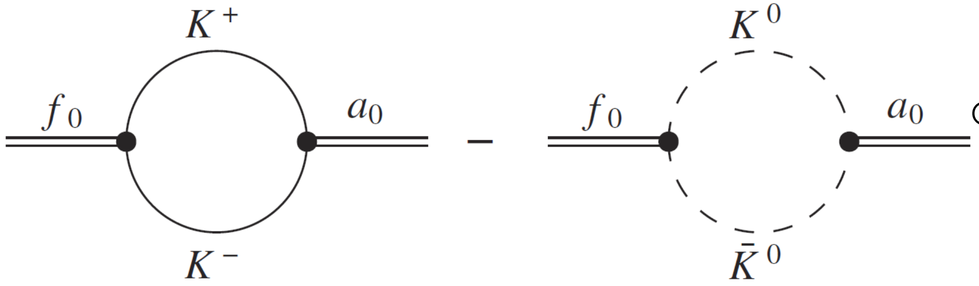
$a_0(980)^0 \longleftrightarrow f_0(980)$ mixing

a_0—f_0 substructure probe
1^{st} proposed in 1979

Achasov, Devanin & Shestakov, Phys. Lett. B88, 367 (1979)

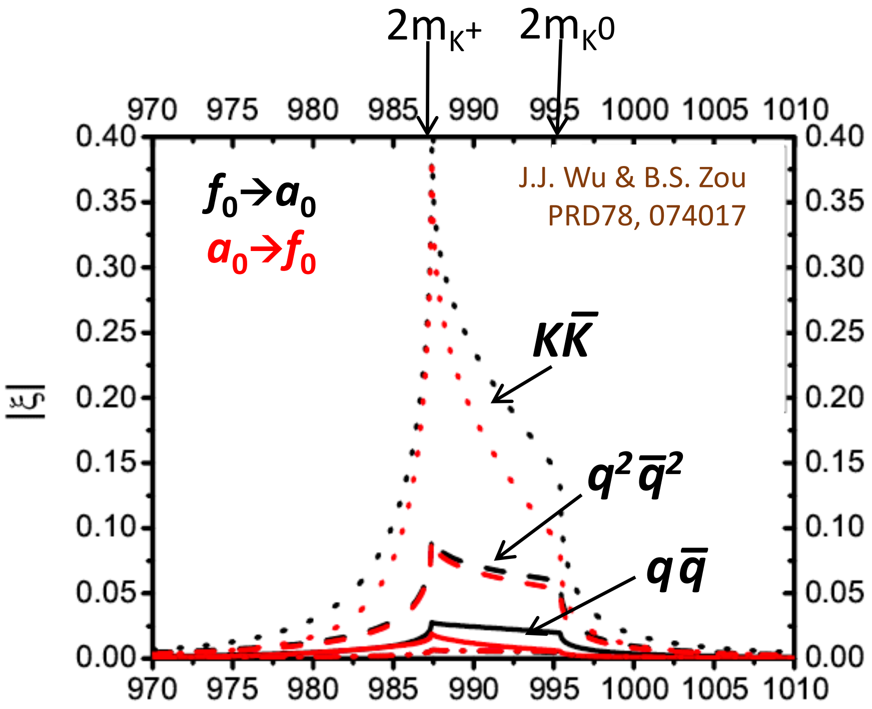
$2m_{K^+} = 987.4$ MeV $2m_{K^0} = 995.2$ MeV

isospin violation enhanced by $K^0 - K^+$ mass difference



phase space factors

$$\propto \left| \frac{g_{a_0^0 K^+K^-} g_{f_0 K^+K^-}}{g_{a_0^0 \pi^0\eta} g_{f_0 \pi^0\pi^0}} \right|^2 \frac{|\rho_{K^+K^-}(s) - \rho_{K^0\bar{K}^0}(s)|^2}{3\rho_{\pi\pi}(s)\rho_{\pi\eta}(s)}$$



Hanhart, Kubis, & Pelaez Phys. Rev. D76, 074028

signal is a narrow line shape:
$\Gamma \approx 2(m_{K^0} - m_{K^+}) = 7.8$ MeV
much narrower than Γ_{a0} or Γ_{f0}

PDG2020:

$M_{f0} = 990 \pm 20$ MeV
Γ_{f0} = ~50 MeV

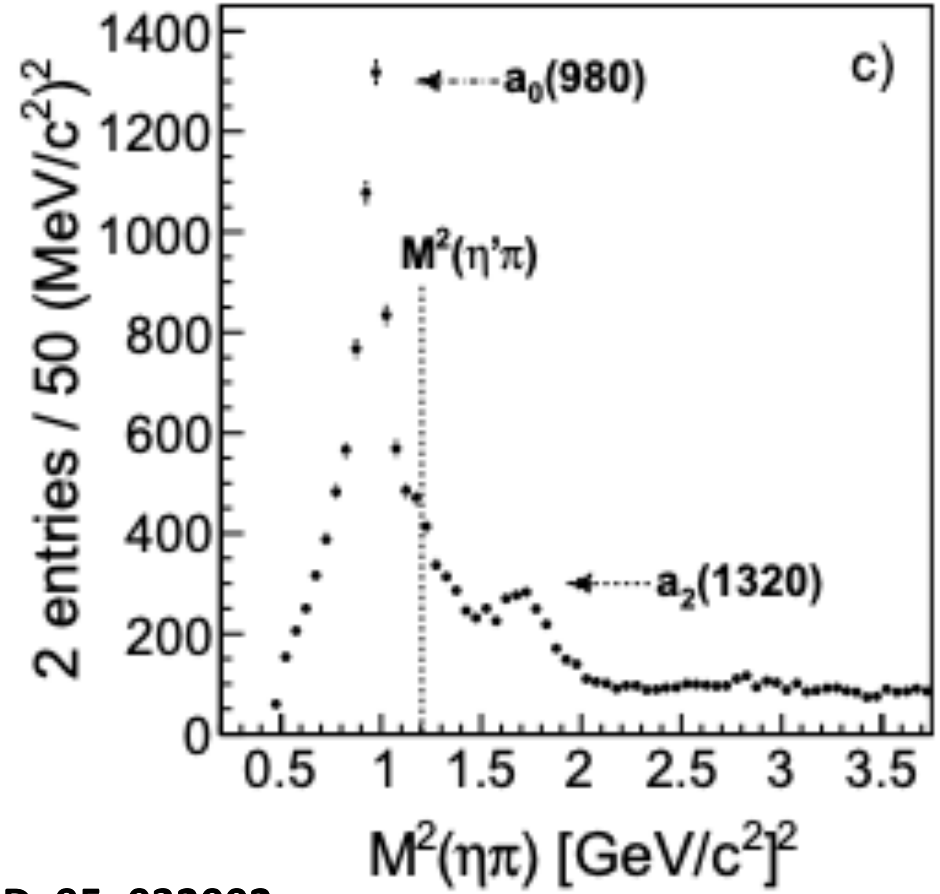
$M_{a0} = 980 \pm 20$ MeV
Γ_{a0} = 50 ~ 100 MeV

$a_0(980) \rightarrow f_0(980)$ mixing

39 yrs after it was 1st proposed

$\chi_{c1} \rightarrow a_0(980)\pi$

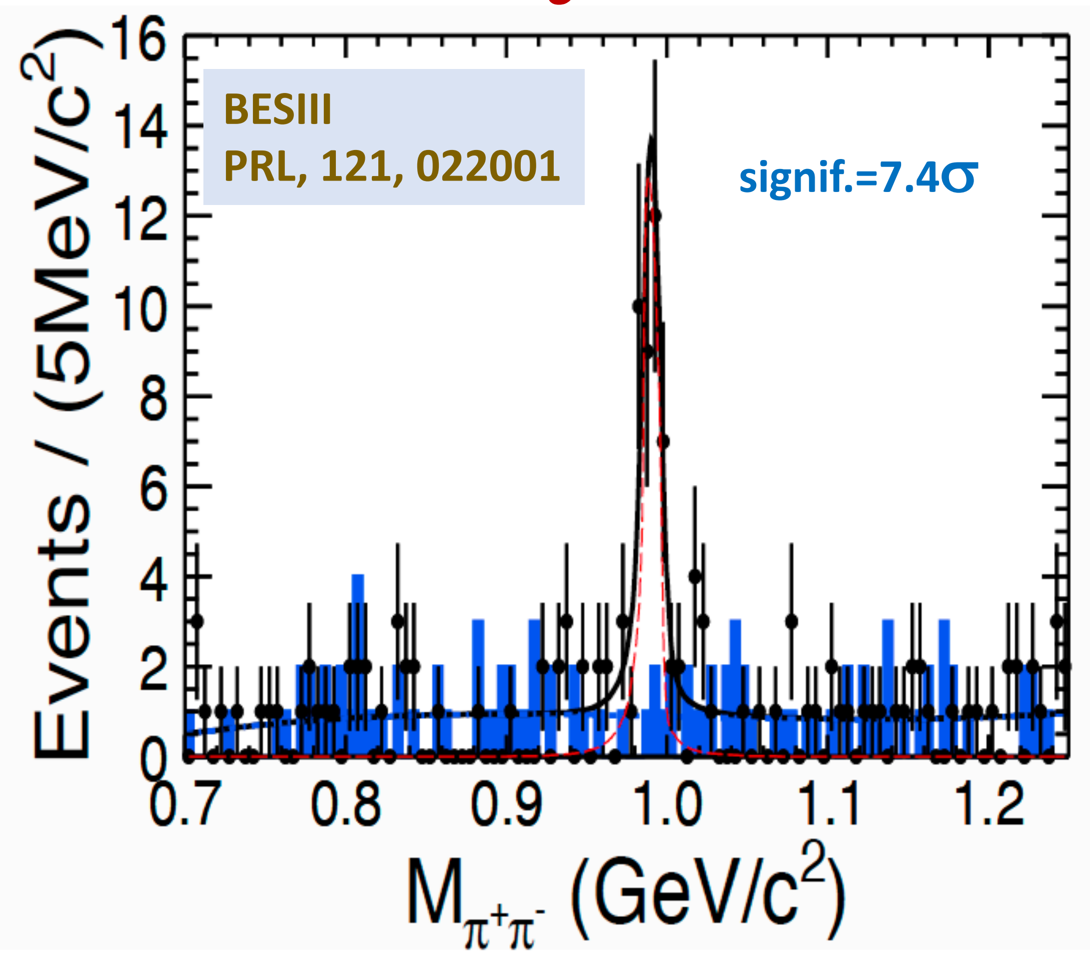
$\hookrightarrow \eta\pi^0$



BESIII PRD, 95, 032002

$\chi_{c1} \rightarrow a_0(980)\pi$

$\hookrightarrow f_0(980) \rightarrow \pi^+\pi^-$

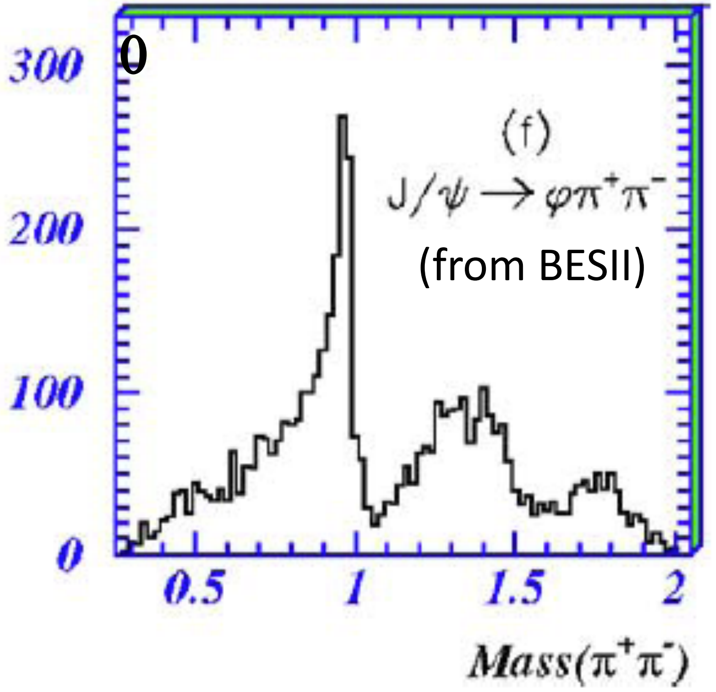


$f_0(980) \to a_0(980)$ mixing

39 yrs after it was 1st proposed

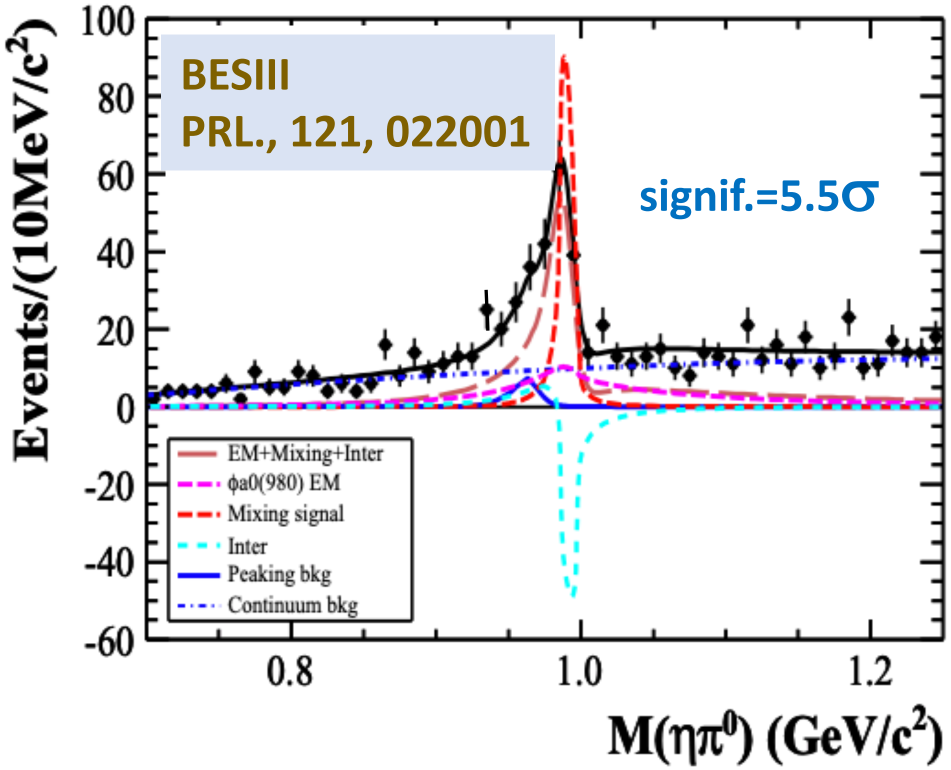
$J/\psi \to f_0(980)\phi$

$\hookrightarrow \pi^+\pi^-$



$J/\psi \to f_0(980)\phi$

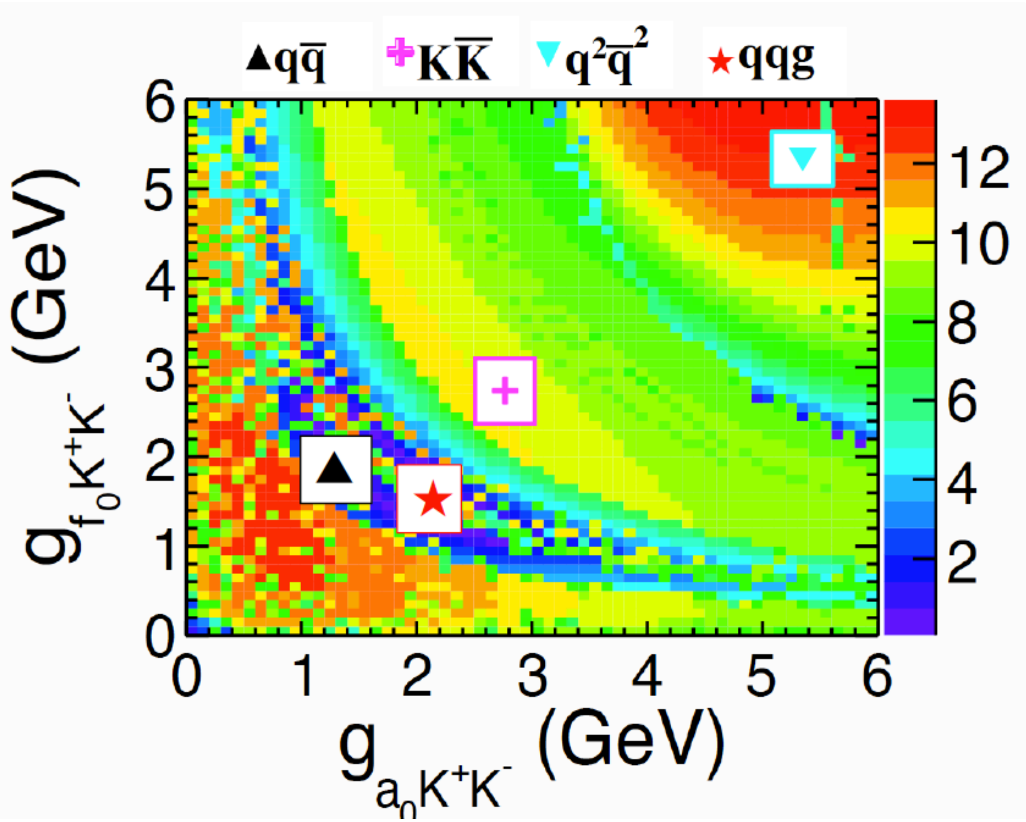
$\hookrightarrow a_0(980) \to \eta\pi^0$



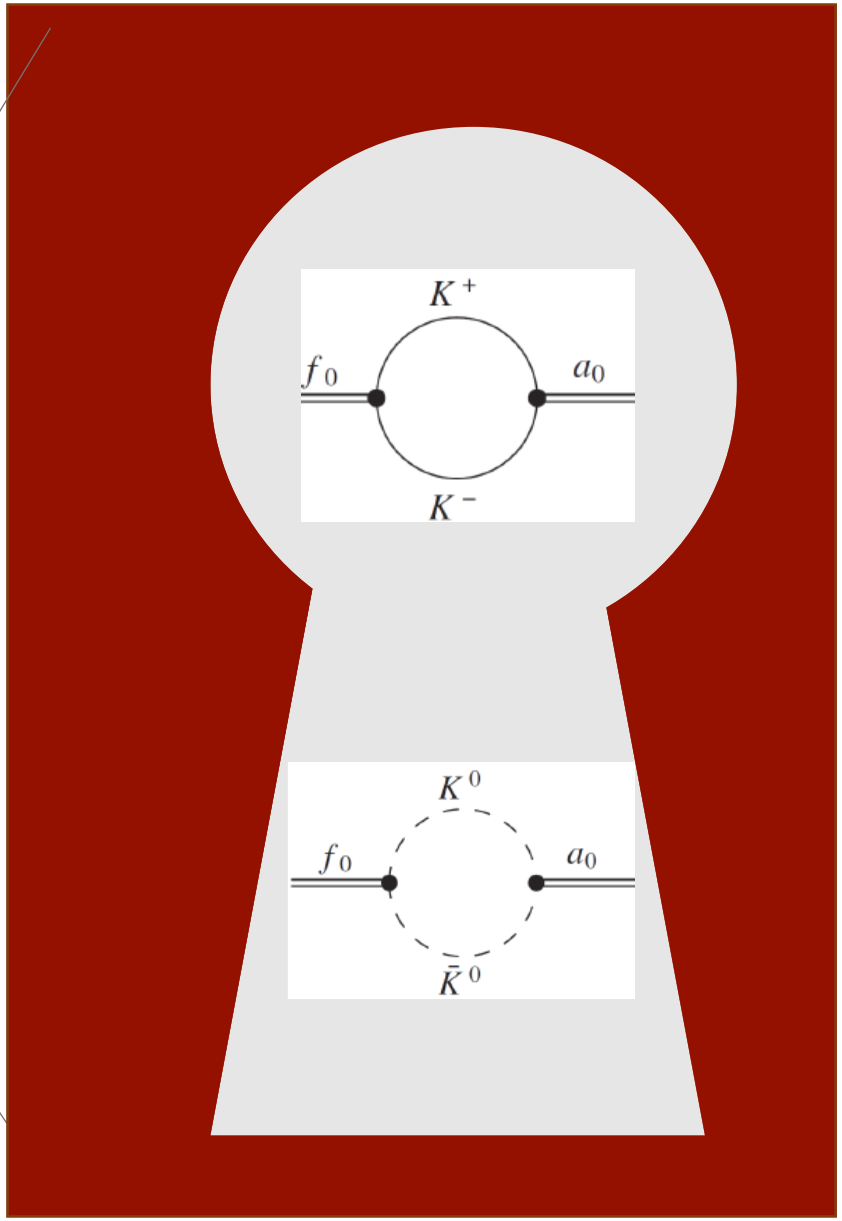
BESIII PRL., 121, 022001

BESII PLB 607, 243 (2005)

compare with models



peeking at the insides of the a_0-f_0 mesons



Summary

J.D. Bjorken

It is important to pay attention to the difficulties in a subject, rather than the successes. It is in thinking about the difficulties, more than in celebrating the progress, that advances are made.

Summary

J.D. Bjorken

It is important to pay attention to the difficulties in a subject, rather than the successes. It is in thinking about the difficulties more than celebrating the progress, that advances are made.

This is why hadron physics is so interesting -- lots of puzzles, lots to learn – (even with "old" hadrons}