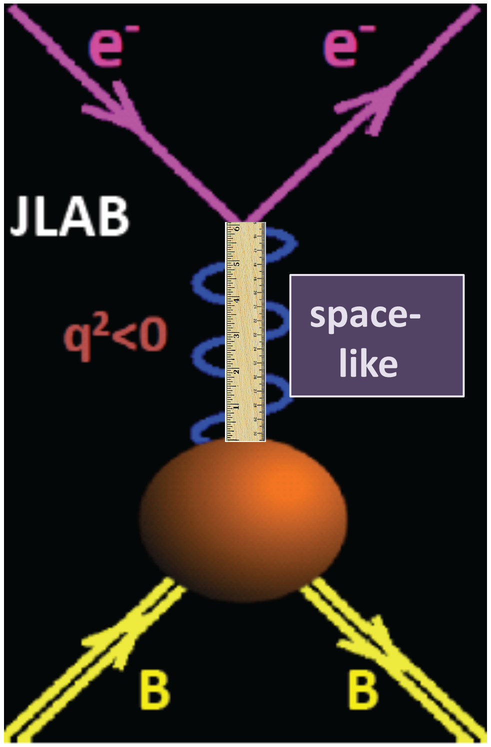
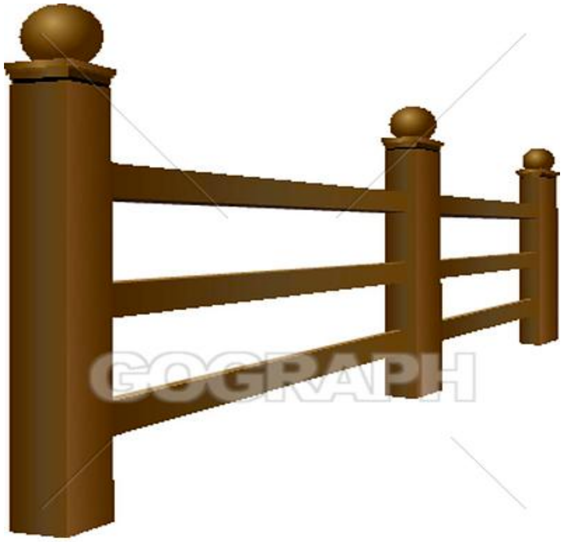
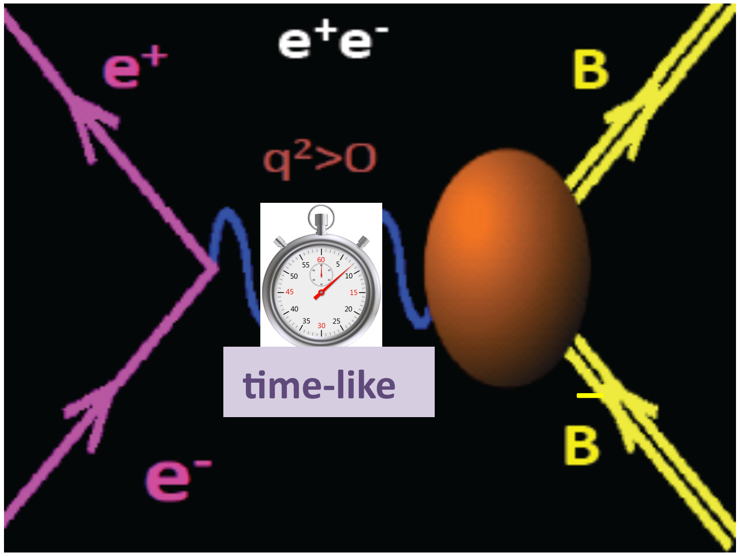
Baryon form-factors

-- the view from the time-like side --







Stephen Lars Olsen UCAS

中国科学院大学

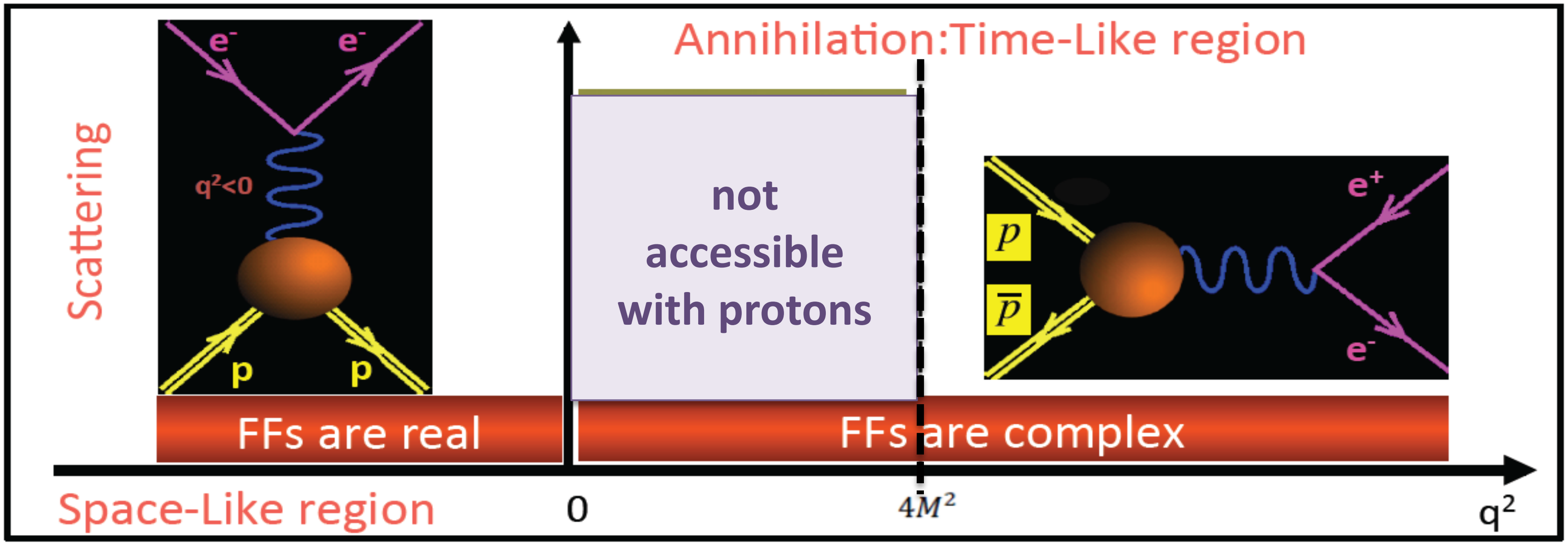
University of Chinese Academy of Sciences

Hadron Mass and Quark-Gluon Confinement, APCTP, Pohang, KOREA, May 21-25,2018

for B=p: JLAB & e^+e^- are complementary

Crossing symmetry:

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



Annihilation:Time-Like region

Scattering

not accessible with protons

FFs are real

FFs are complex

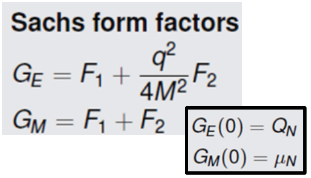
Space-Like region

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

Fermi & Dirac form factors

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

-- formulae & definitions --

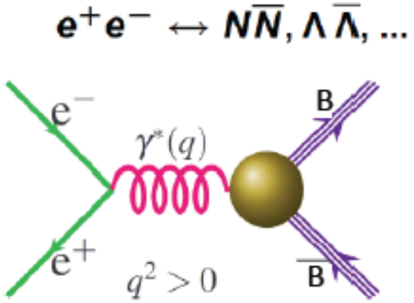

Sachs form factors

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

$$G_M = F_1 + F_2$$

$$\boxed{\begin{array}{l} G_E(0) = Q_N \\ G_M(0) = \mu_N \end{array}}$$

Born cross section:



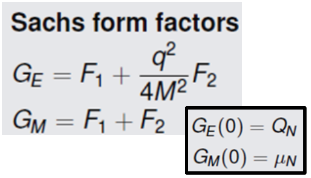
time-like "Sachs" form-factors

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta\, C}{4m_{B\bar{B}}^2}\left[\left(1+\cos^2\theta\right)\left|G_M(m_{B\bar{B}})\right|^2 + \frac{1}{\tau}\sin^2\theta\left|G_E(m_{B\bar{B}})\right|^2\right]$$

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

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

-- formulae & definitions --



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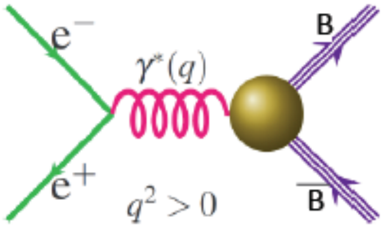
$$\boxed{\begin{matrix} G_E(0) = Q_N \\ G_M(0) = \mu_N \end{matrix}}$$

Born cross section:

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



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

Coulomb enhancement factor

$$C_{\text{charged}} = \frac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)} \xrightarrow{(\beta\to 0)} \pi\alpha/\beta$$

$$C_{\text{neutral}} = 1$$

in point-like approx

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

-- formulae & definitions --

Sachs form factors

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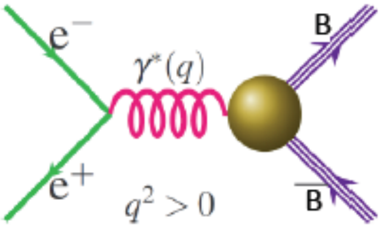

time-like "Sachs" form-factors

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta\, C}{4m_{B\bar{B}}^2}\left[\left(1+\cos^2\theta\right)\left|G_M(m_{B\bar{B}})\right|^2 + \frac{1}{\tau}\sin^2\theta\left|G_E(m_{B\bar{B}})\right|^2\right]$$

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in point-like approx

integrated cross section:

$$\sigma_{B\bar{B}}\left(m_{B\bar{B}}\right) = \frac{4\pi\alpha^2\beta C}{3m^2}\left[\left|G_M(m_{B\bar{B}})\right|^2 + \frac{1}{2\tau}\left|G_E(m_{B\bar{B}})\right|^2\right] = \frac{4\pi\alpha^2\beta C}{3m^2}\left|G_{eff}(m_{B\bar{B}})\right|^2\left(1+1/2\tau\right)$$

"effective" form factor

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

-- formulae & definitions --

Sachs form factors

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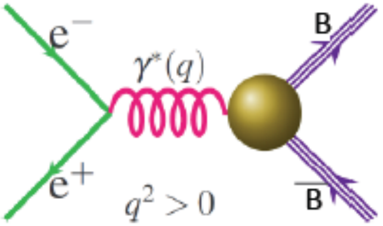

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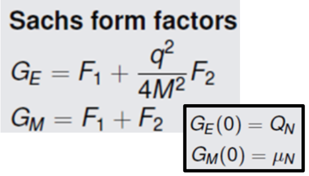
"effective" form factor

effective form factor:

$$\left|G_{eff}\right|^2 = \frac{\left|G_M\right|^2 + \frac{1}{2\tau}\left|G_E\right|^2}{1+\frac{1}{2\tau}}\sigma_{B\bar{B}}\left(m_{B\bar{B}}\right) \quad \Rightarrow \left|G_{eff}\right| = \left(\frac{3m^2_{B\bar{B}}}{\pi\alpha^2\beta C\left(1+\frac{1}{2\tau}\right)}\right)^{\frac{1}{2}}\sqrt{\sigma_{B\bar{B}}}$$

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

-- formulae & definitions --



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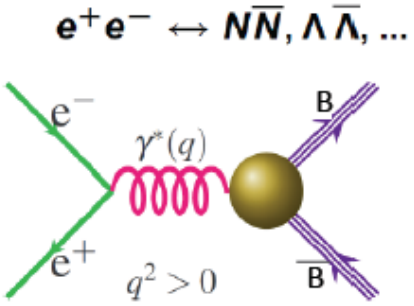

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integrated cross section:

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effective form factor:

$$\left|G_{eff}\right|^2 = \frac{\left|G_M\right|^2 + \frac{1}{2\tau}\left|G_E\right|^2}{1+\frac{1}{2\tau}}\sigma_{B\bar{B}}\left(m_{B\bar{B}}\right) \quad \Rightarrow \left|G_{eff}\right| = \left(\frac{3m_{B\bar{B}}^2}{\pi\alpha^2\beta C\left(1+\frac{1}{2\tau}\right)}\right)^{\frac{1}{2}}\sqrt{\sigma_{B\bar{B}}}$$

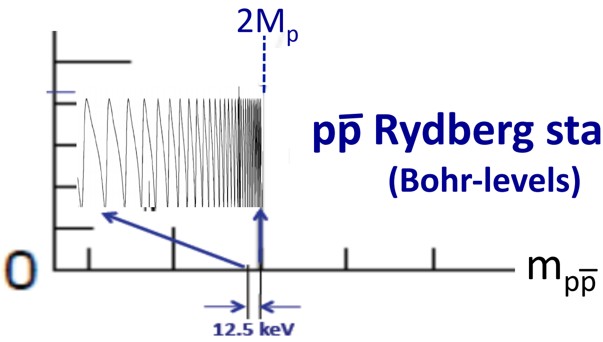
analyticity:

$$G_M(4M_B^2) = G_E(4M_B^2) \quad \Rightarrow \; G_{eff}(4M_B^2) = G_M(4M_B^2)$$

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

Integrated cross section:

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



pp̄ Rydberg states

(Bohr-levels)

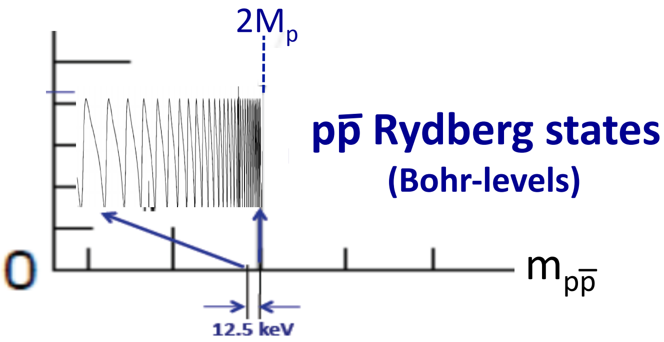
$$\text{for } p\bar{p}\text{: } C = \frac{\pi\alpha/\beta}{1 - \exp(-\pi\alpha/\beta)} \to \frac{\pi\alpha}{\beta}$$

Sommerfeld resummation factor

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

Integrated cross section:

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



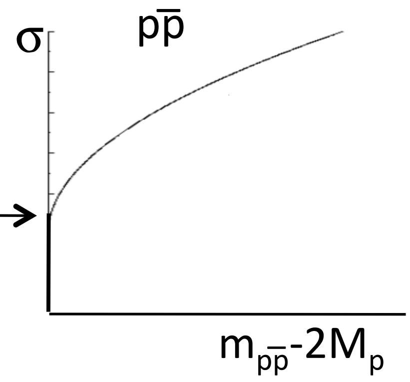
$$\text{for } p\bar{p}\text{: } C = \frac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)} \rightarrow \frac{\pi\alpha}{\beta}$$

Sommerfeld resummation factor

in point-like approx:

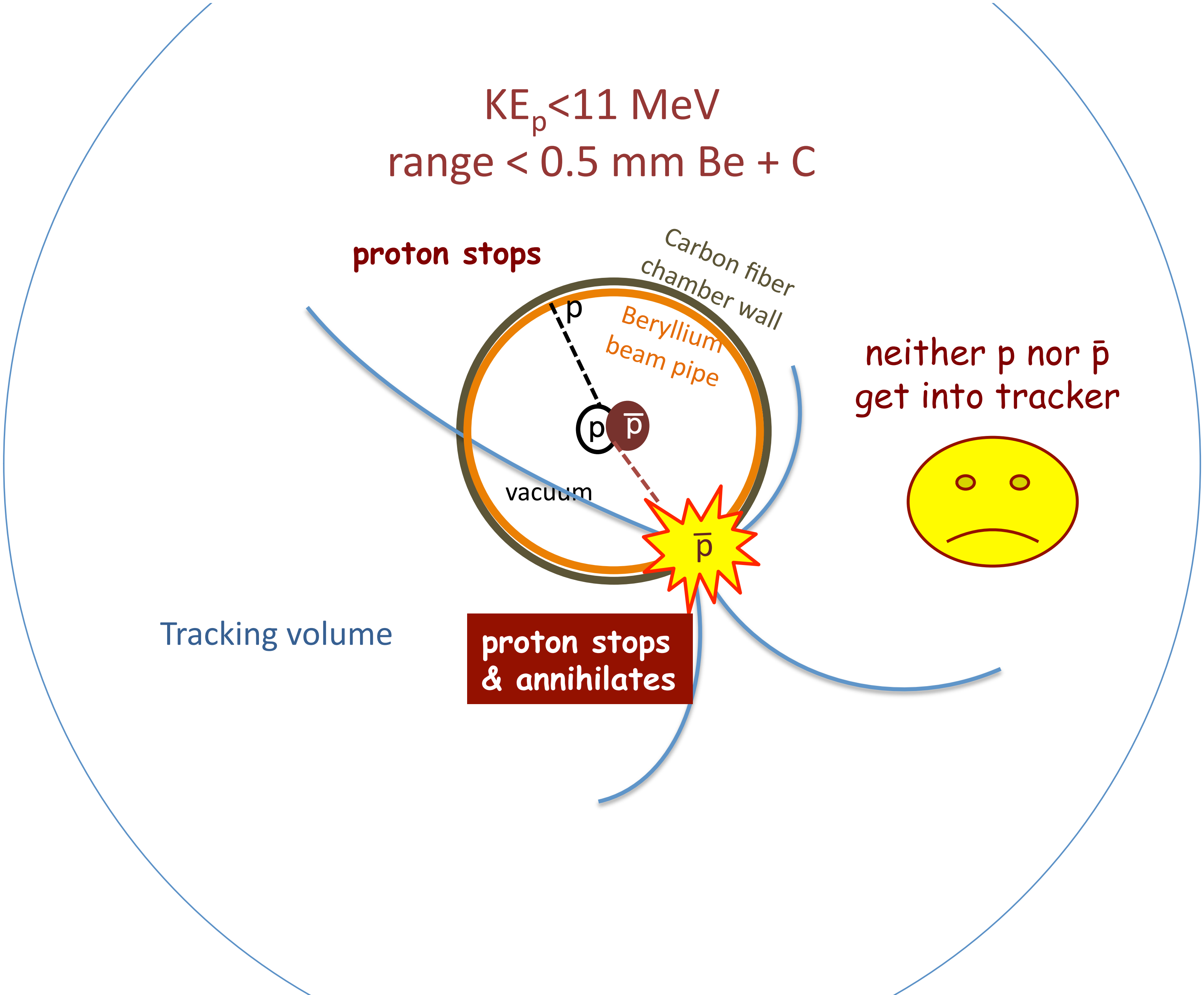
$$\sigma_0 = \frac{\pi^2\alpha^3}{2M_p^2} \left| G_{eff}(2M_p) \right|^2$$

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



e^+e- → $p\bar{p}$ near threshold for E_{cm}<1.9 GeV

-- experimental issues --



KE_p<11 MeV

range < 0.5 mm Be + C

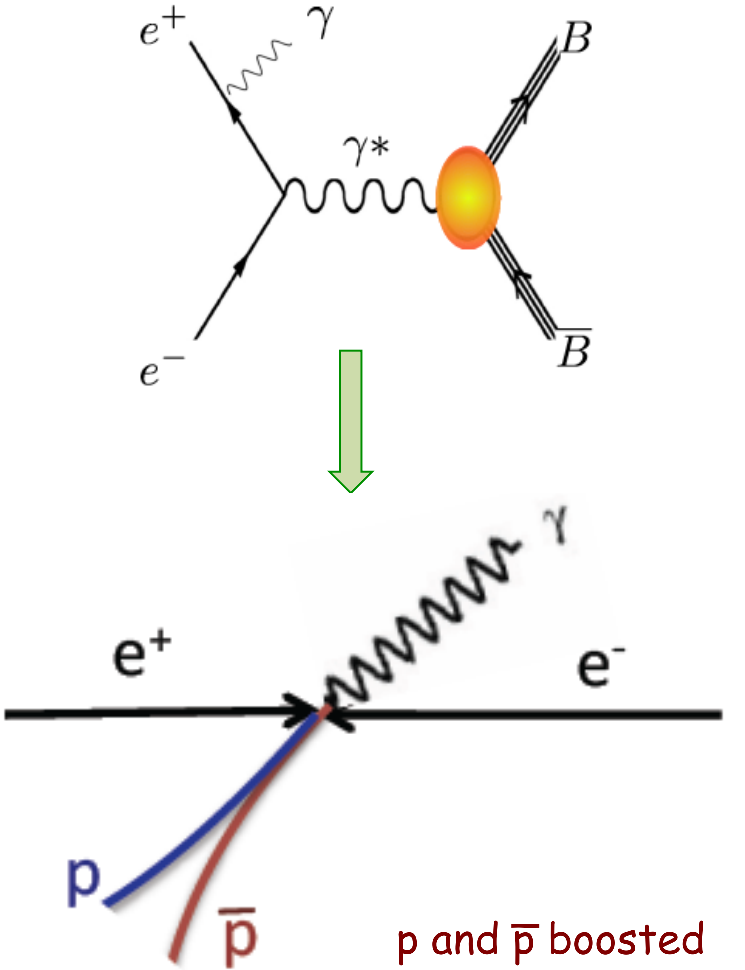
proton stops

proton stops & annihilates

neither p nor $\bar{p}$ get into tracker

BaBar: produce boosted pp pairs via isr

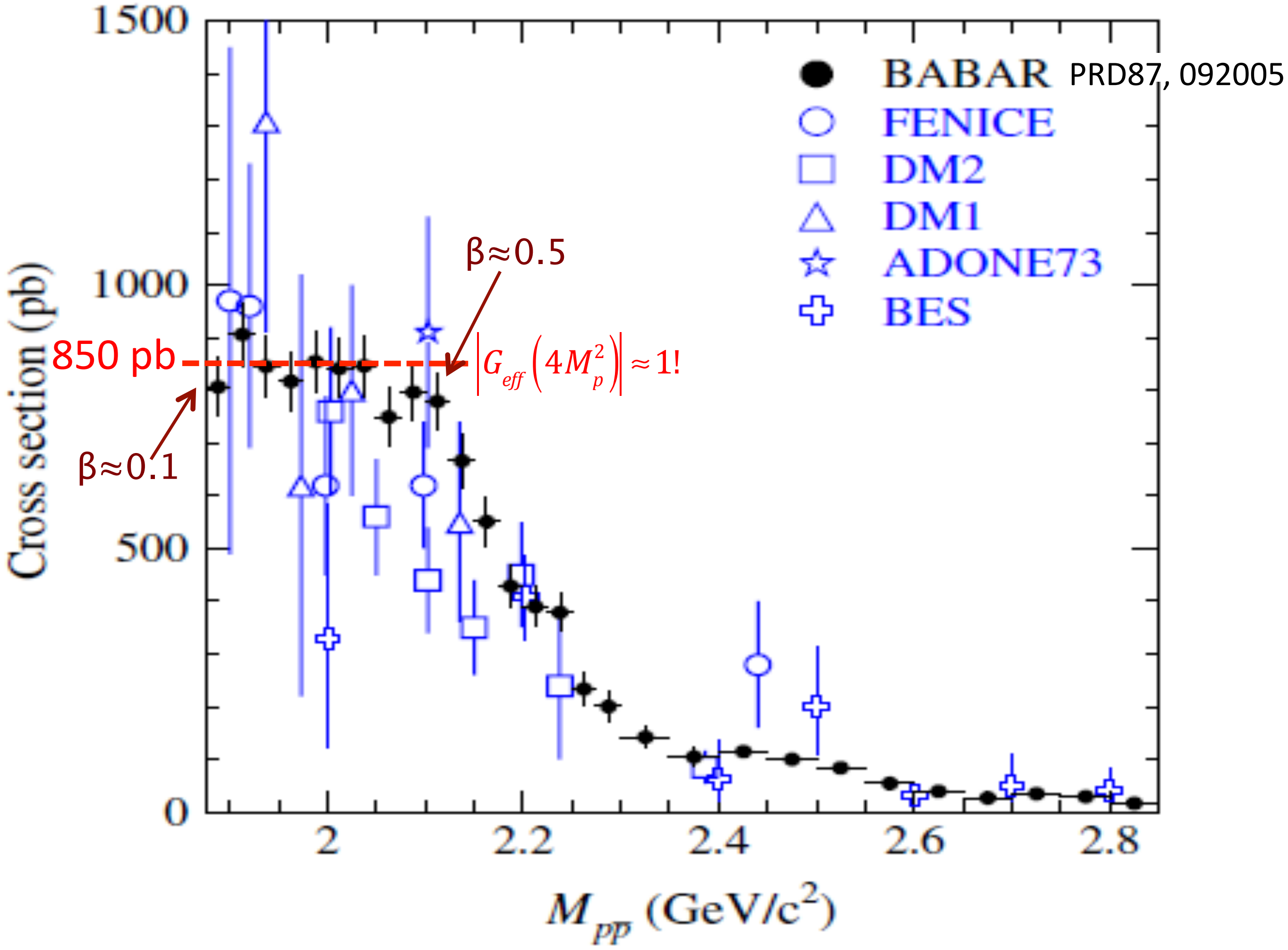
large angle initial state radiation (isr):



p and p̄ boosted
into the detector

$e^+e^- \rightarrow p\bar{p}$ data near threshold via isr

large-angle initial state radiation



PRD87, 092005

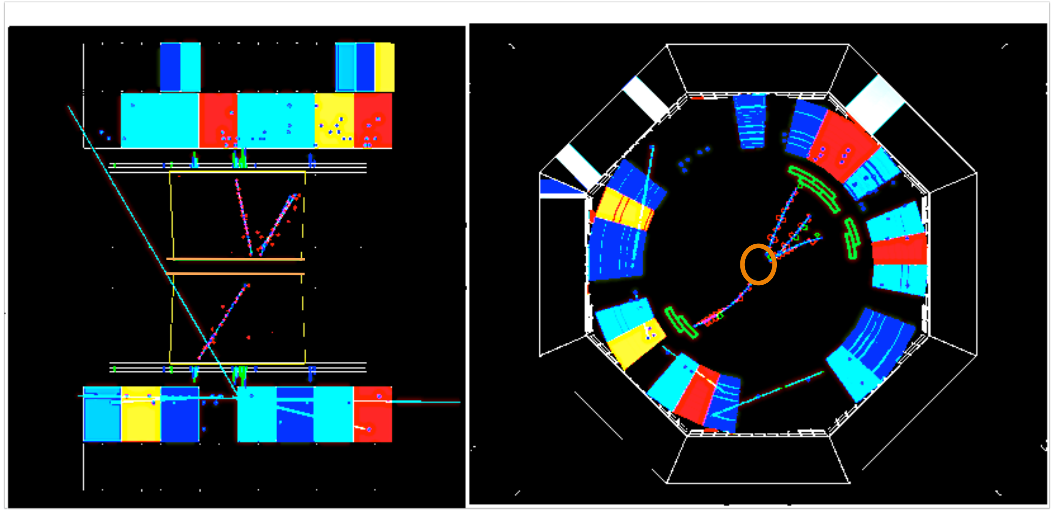
850 pb

β≈0.5

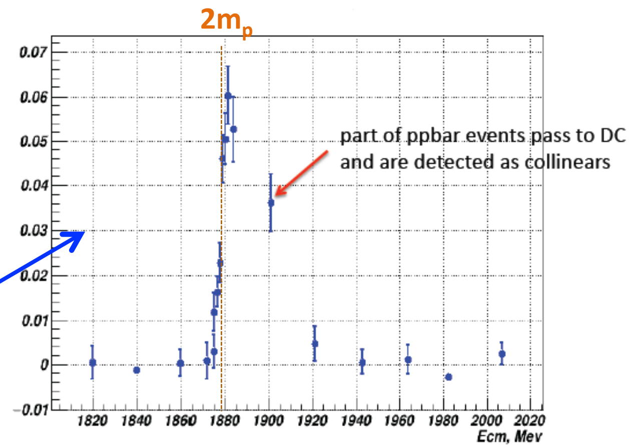
β≈0.1

$\left|G_{eff}\left(4M_p^2\right)\right| \approx 1!$

CMD3: Detect p̄ annihilations in beam pipe

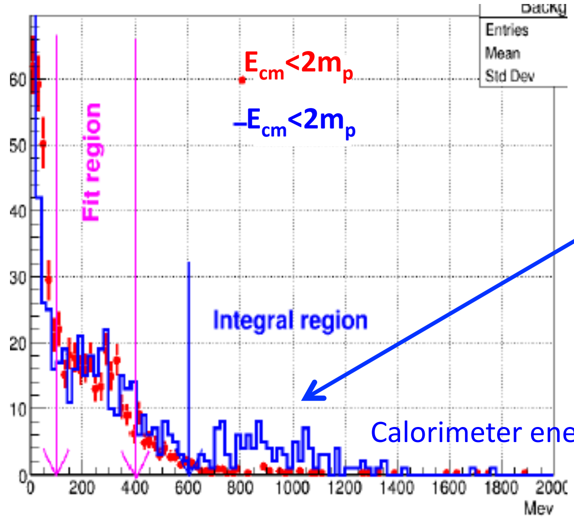


Solodov talk at Bad Honnef 2018



part of ppbar events pass to DC and are detected as collinears

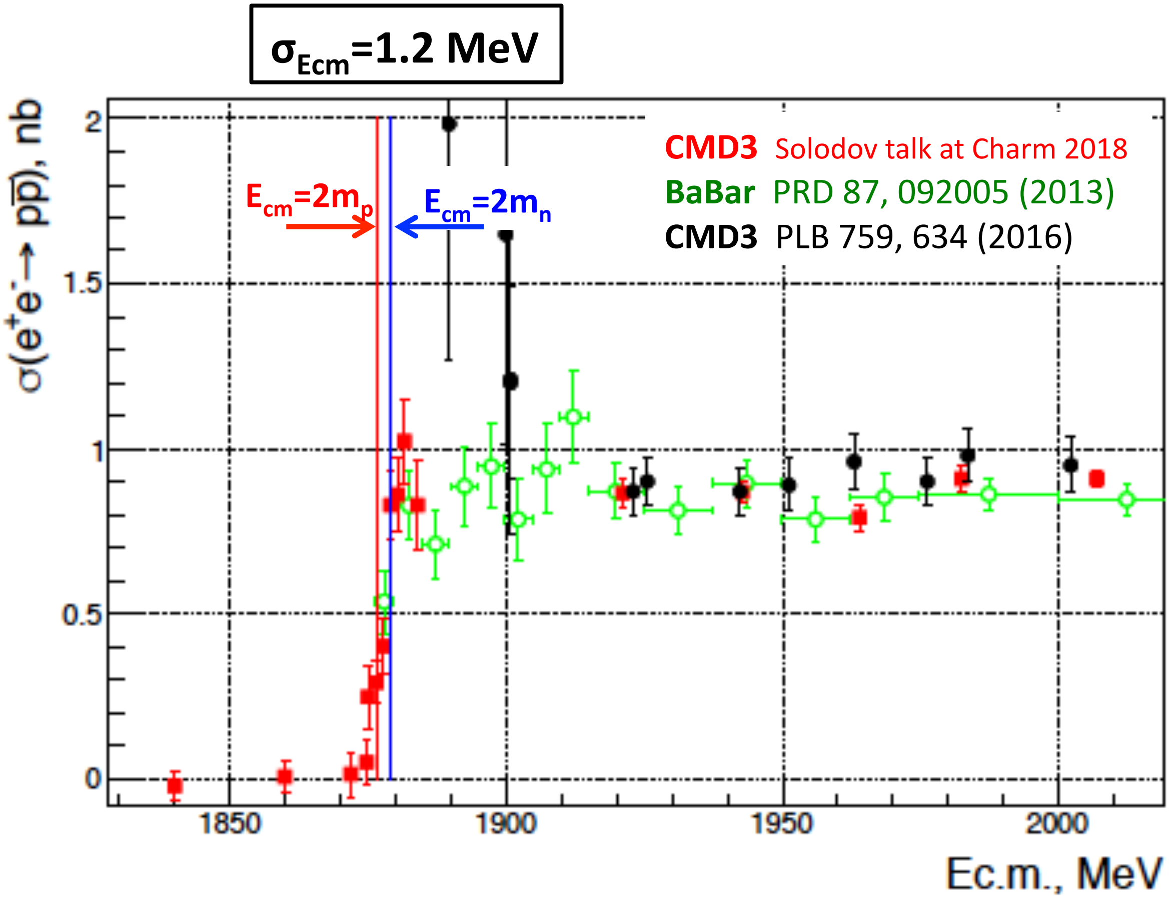
490 events have been found



Calorimeter energy

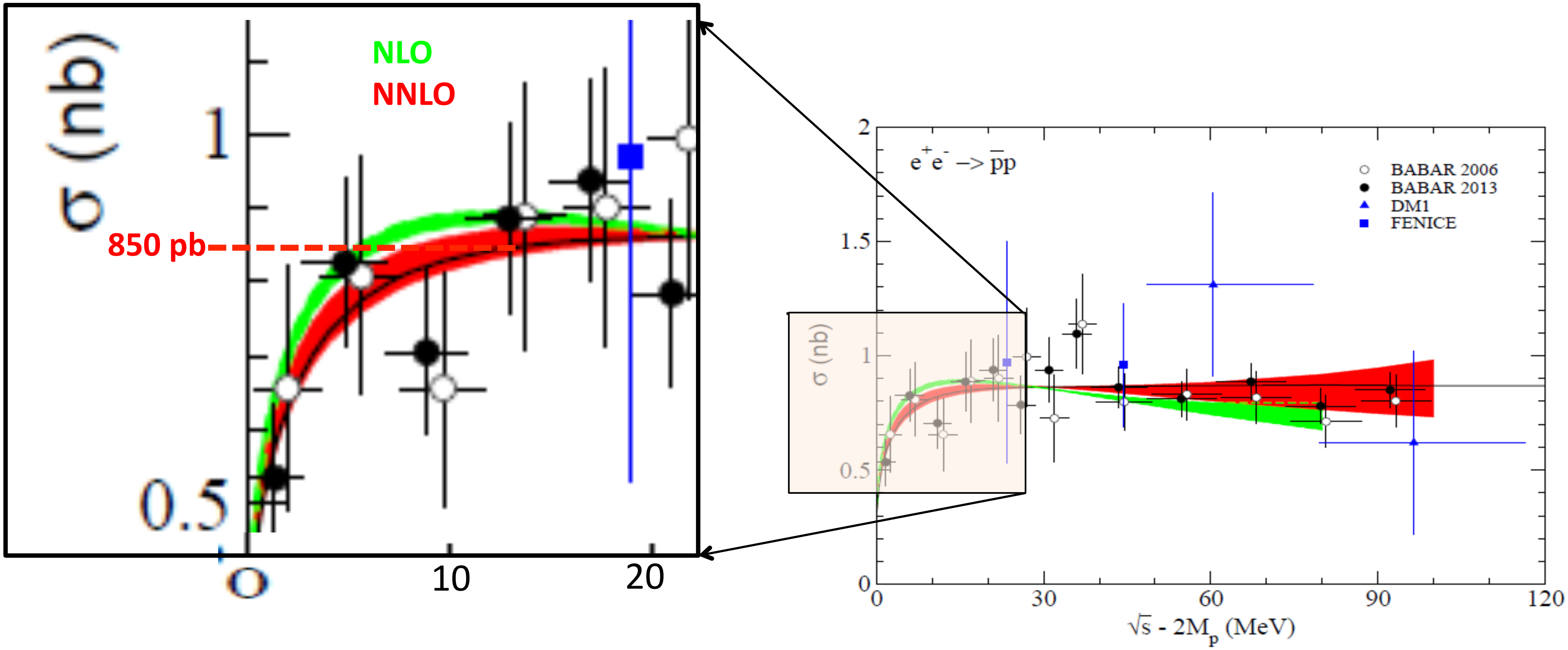
CMD3: $e^+e^- \rightarrow p\bar{p}$ at $E_{cm}=2m_p$ threshold

-- fast cross section jump at threshold: $\sigma_{th}<1$ MeV --



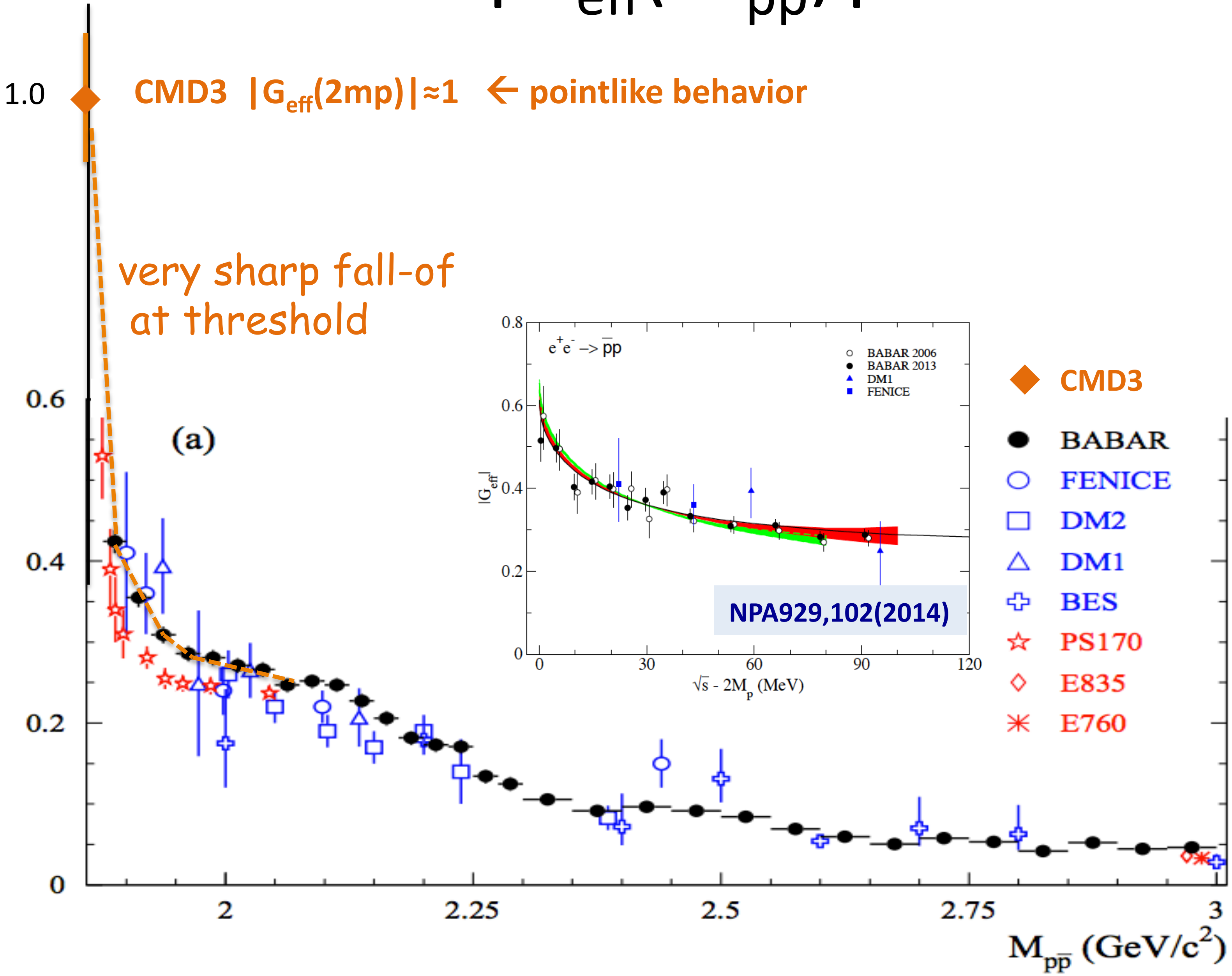
“excellent” FSI fit, pre-CMD3 data

fails to get the rapid jump in cross section seen by CMD3



J. Haidenbauer, X.-W. Kang and U.-G. Meißner, Nucl. Phys. A **929**, 102 (2014).

$|G_{eff}(M_{pp})|$



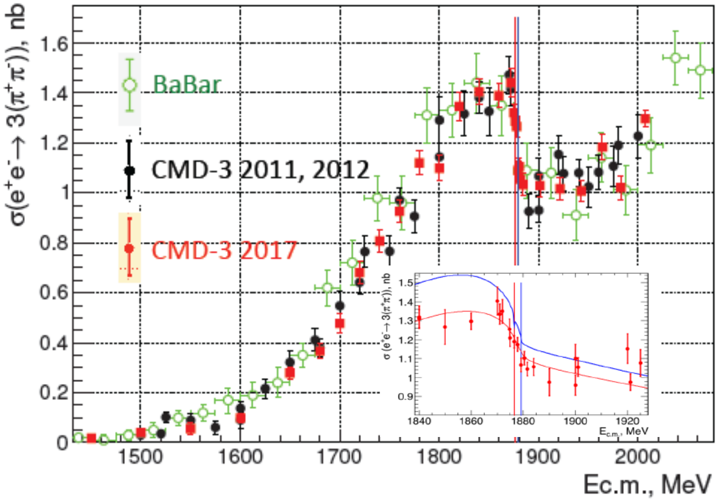
CMD3 $|G_{eff}(2mp)|\approx1$ ← pointlike behavior

very sharp fall-of
at threshold

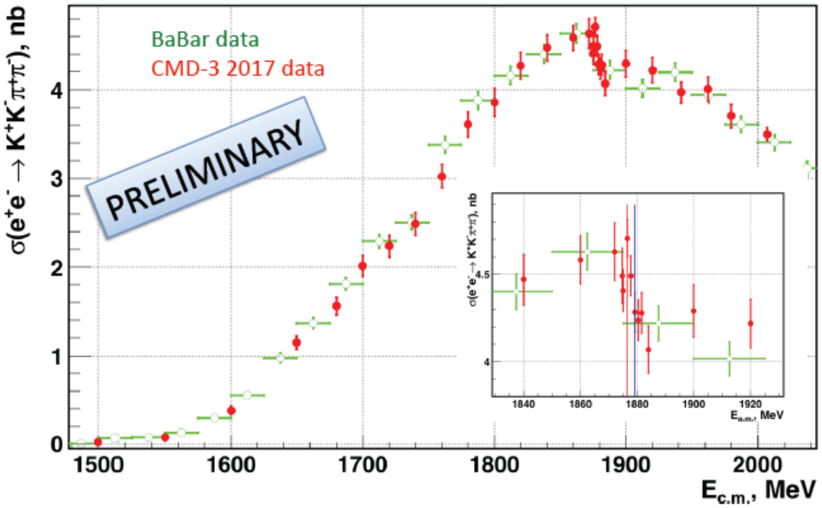
NPA929,102(2014)

look at other channels

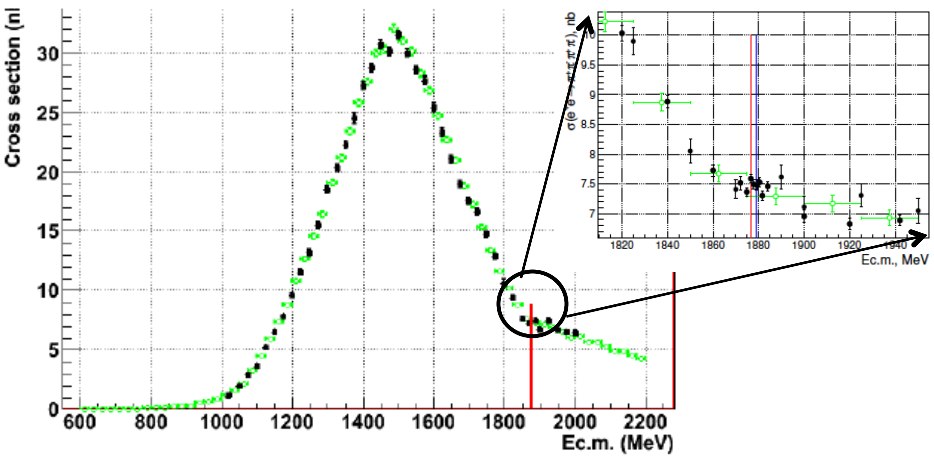
rapid dips in $\sigma(e^+e^- \to 3(\pi^+\pi^-))$



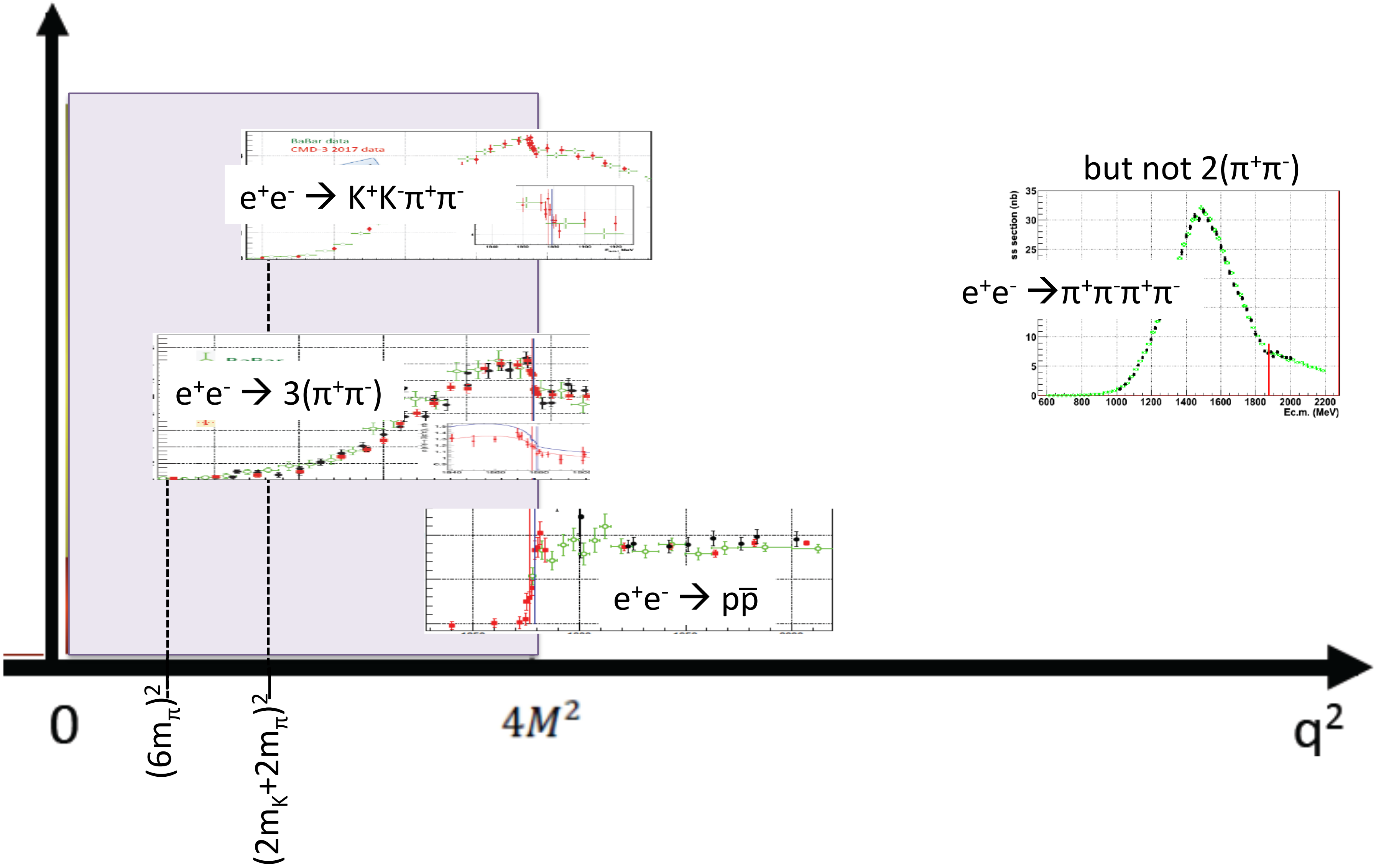
and $\sigma(e^+e^- \to K^+K^-\pi^+\pi^-))$



but not in $\sigma(e^+e^- \to 2(\pi^+\pi^-))$



$3(\pi^+\pi^-)$ & $K^+K^-\pi^+\pi^-$ important for $q^2<4m_p^2$



$e^+e^- \rightarrow K^+K^-\pi^+\pi^-$

$e^+e^- \rightarrow 3(\pi^+\pi^-)$

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

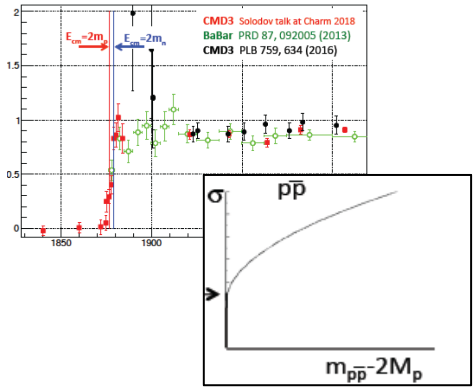
but not $2(\pi^+\pi^-)$

$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$

remarks

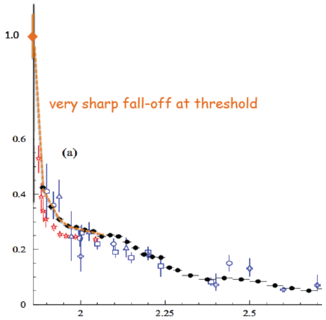
rapid threshold jump in $\sigma(e^+e^- \to p\bar{p})$

- much faster than growth of phase space
- consistent with expectations for point-like charged particles



≈ constant above threshold cross section

- rapid fall-off of effective form-factor
- very different from point-like expectations

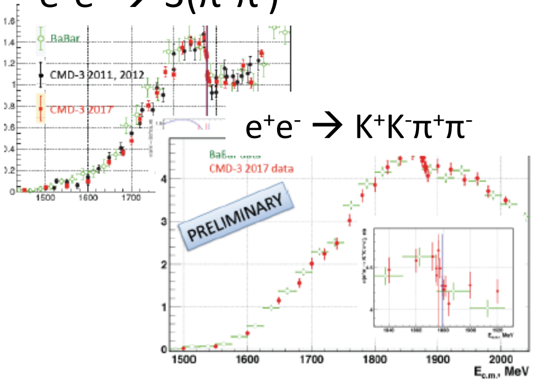


drops in $\sigma(e^+e^- \to 3(\pi^+\pi^-))$ & $\sigma(e^+e^- \to K^+K^-\pi^+\pi^-)$

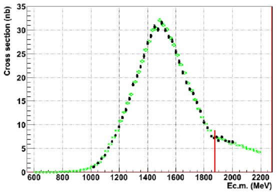
- but not in $\sigma(e^+e^- \to 2(\pi^+\pi^-))$

$e^+e^- \to 3(\pi^+\pi^-)$

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



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



What about other baryons?

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

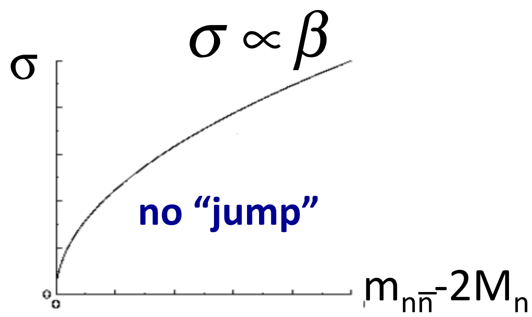
Integrated cross section:

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

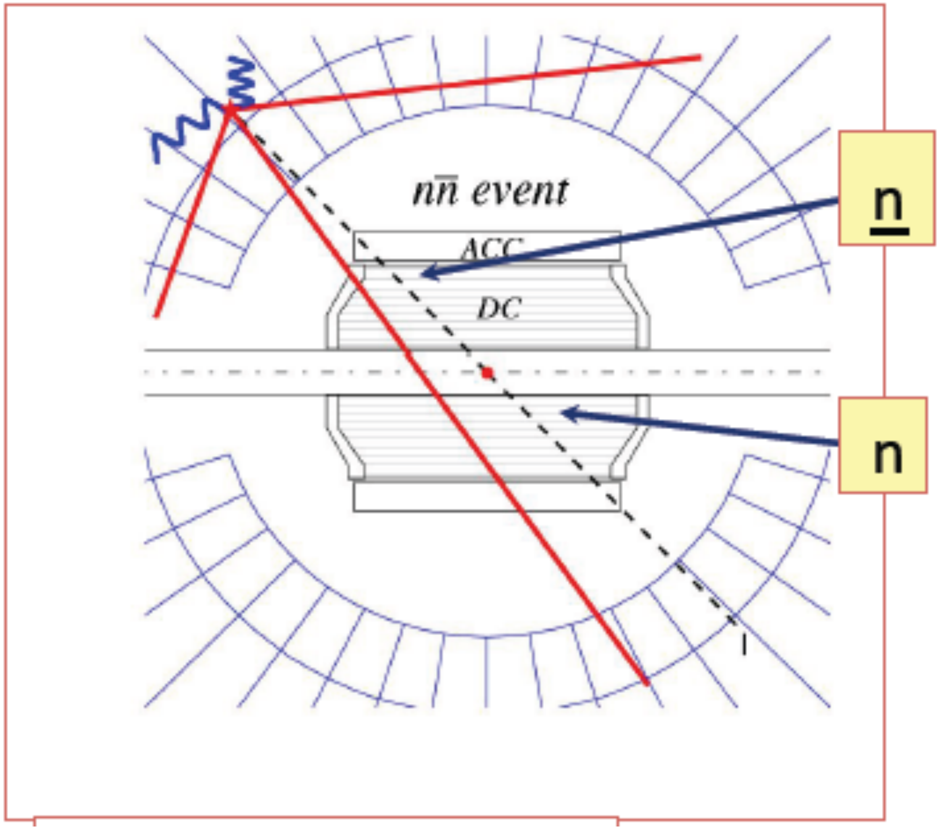
no Rydberg states
(Bohr-levels)

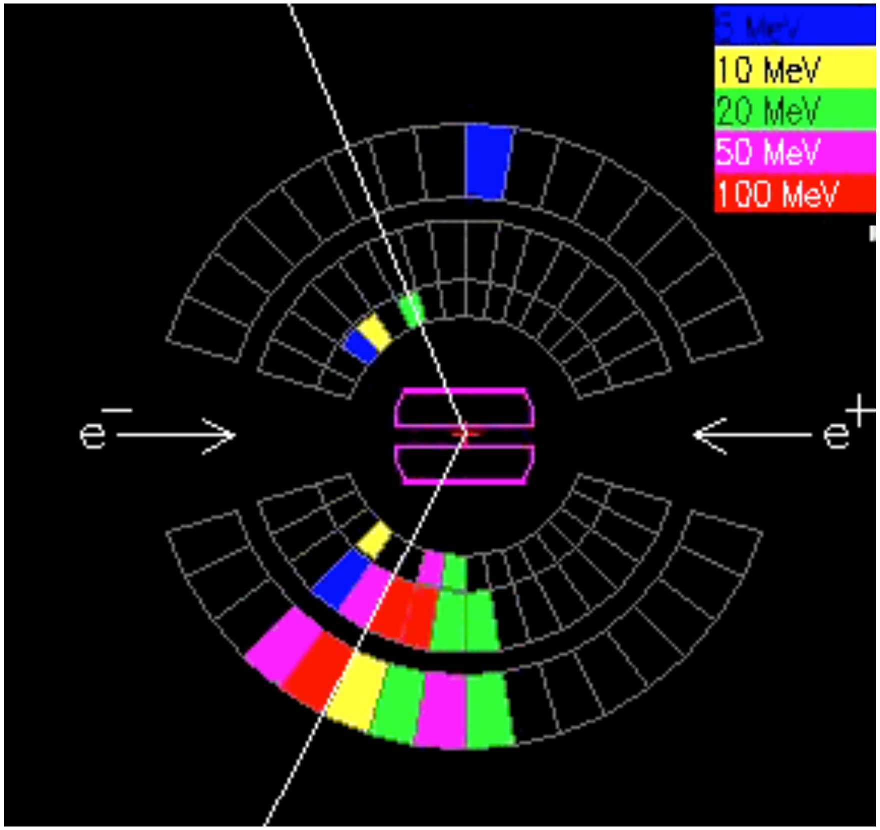
for $n\bar{n}$ ($\Lambda\bar{\Lambda}$): C=1

in point-like approx:

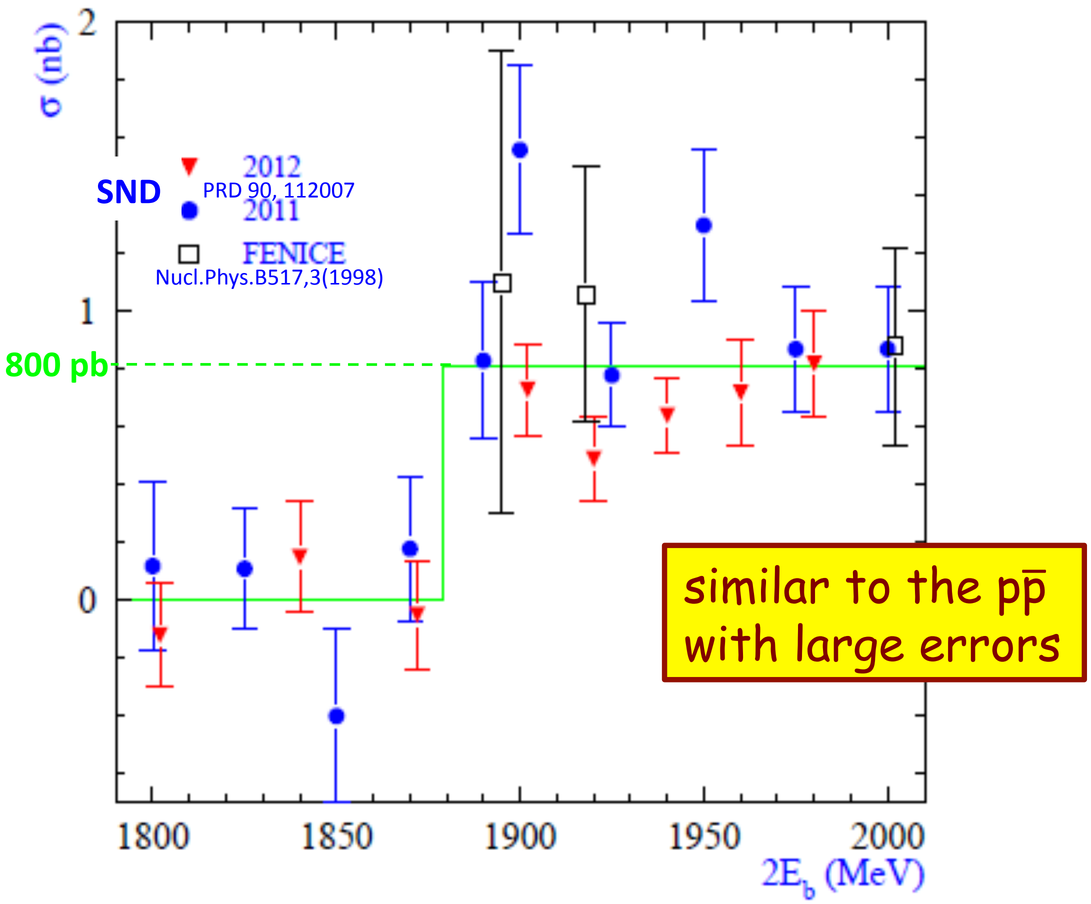


SND: $e^+e^- \to n\bar{n}$ at threshold





indications of $\sigma(e^+e^- \rightarrow n\bar{n})$ jump at $E_{cm}=2m_n$

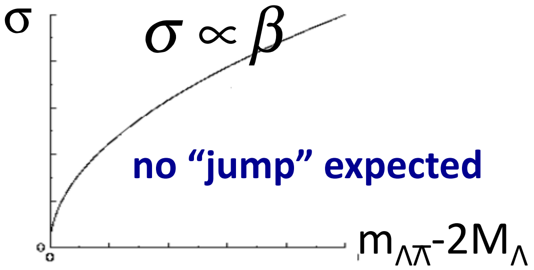


expecting new SND, CMD3, & BESIII data soon

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

Electrically neutral → no Ryberg states

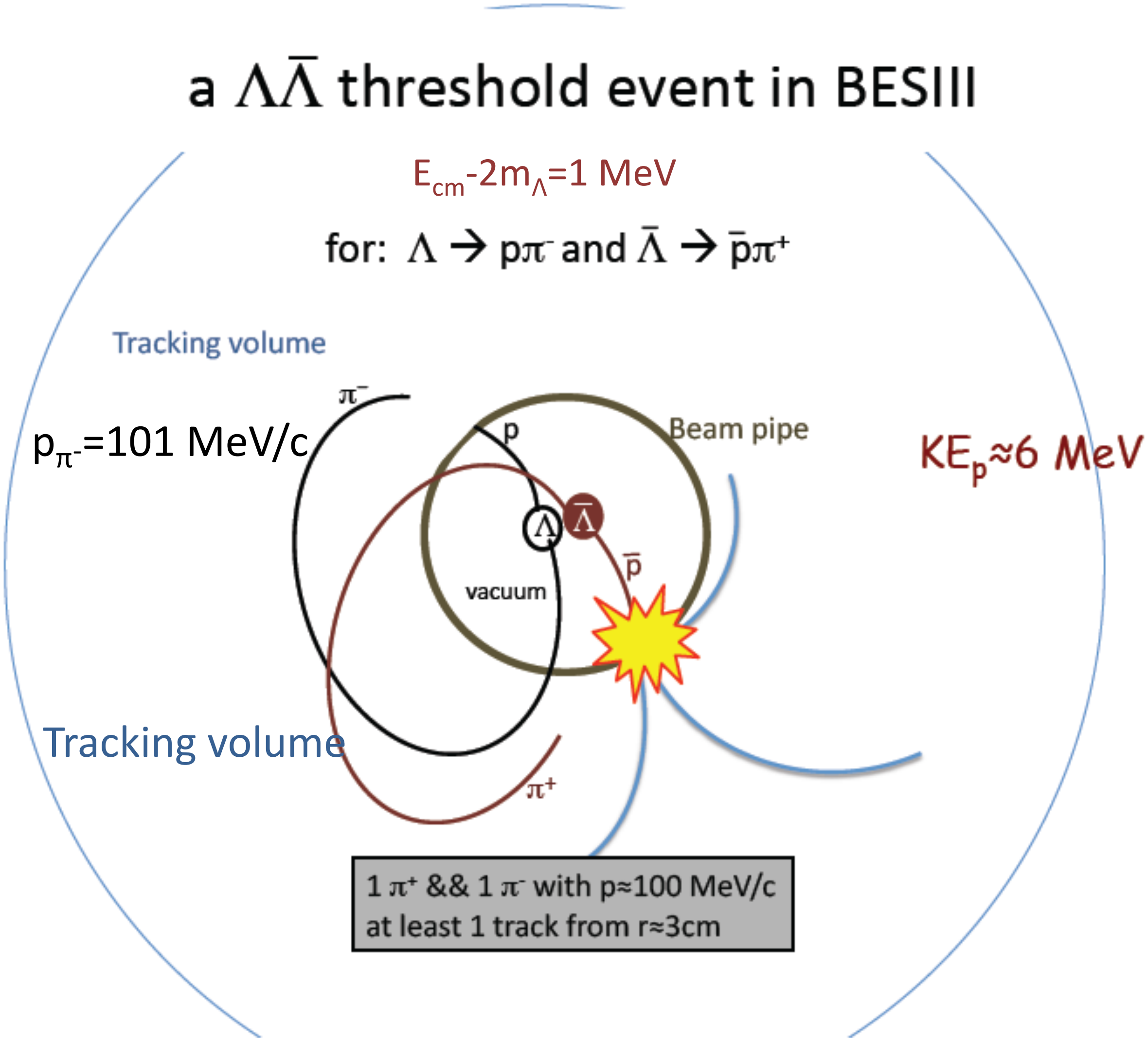
- no Coulomb enhancement



Isospin singlet, π-exchange not allowed

- Λ-$\bar{\Lambda}$ molecule is unlikely

BESIII: $\sigma(e^+e^- \rightarrow \Lambda\bar{\Lambda})$ @ $E_{cm}=2m_\Lambda$



a $\Lambda\bar{\Lambda}$ threshold event in BESIII

$E_{cm}-2m_\Lambda=1$ MeV

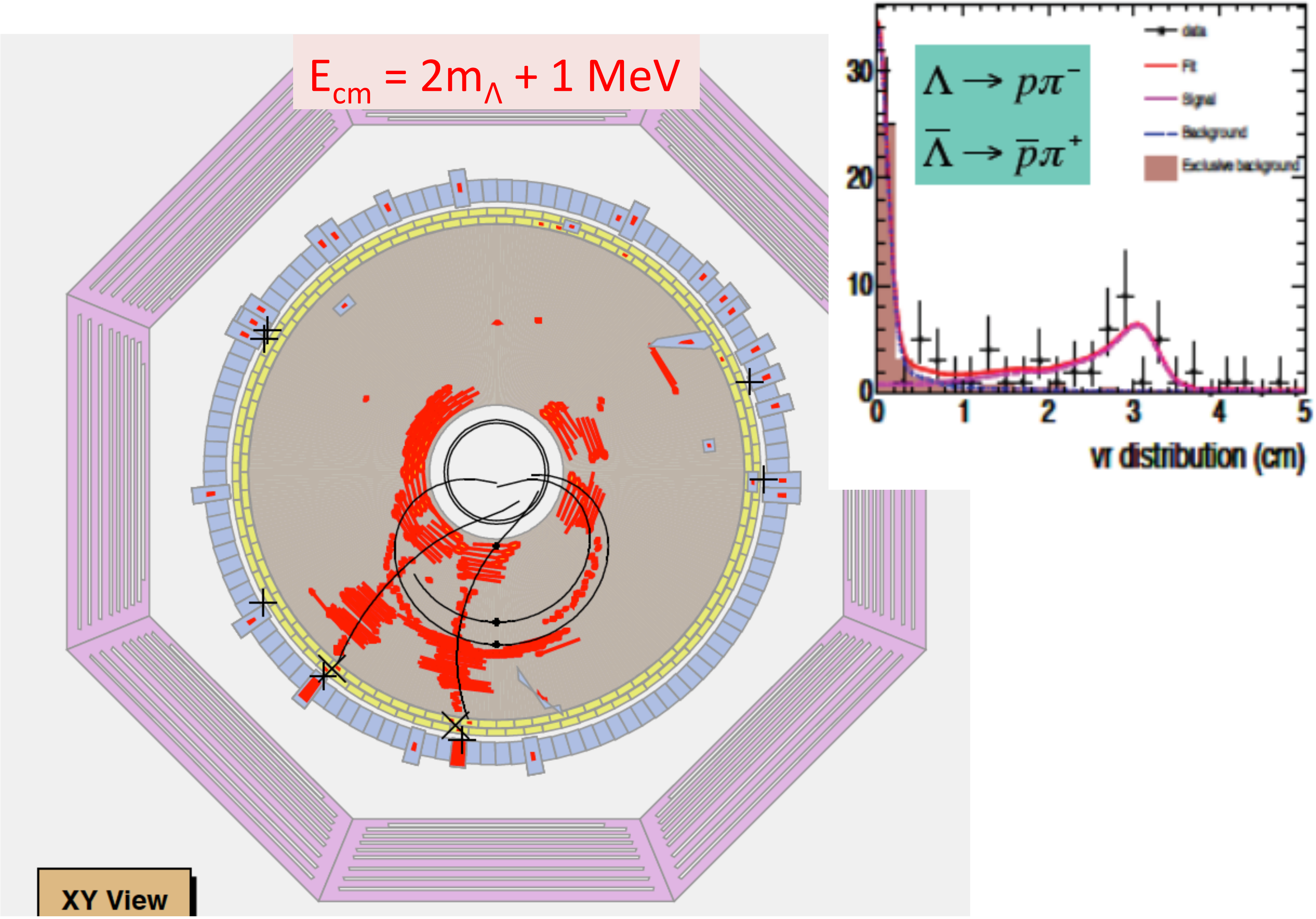
for: $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

$p_{\pi^-}=101$ MeV/c

$KE_p \approx 6$ MeV

1 π^+ && 1 π^- with p≈100 MeV/c
at least 1 track from r≈3cm

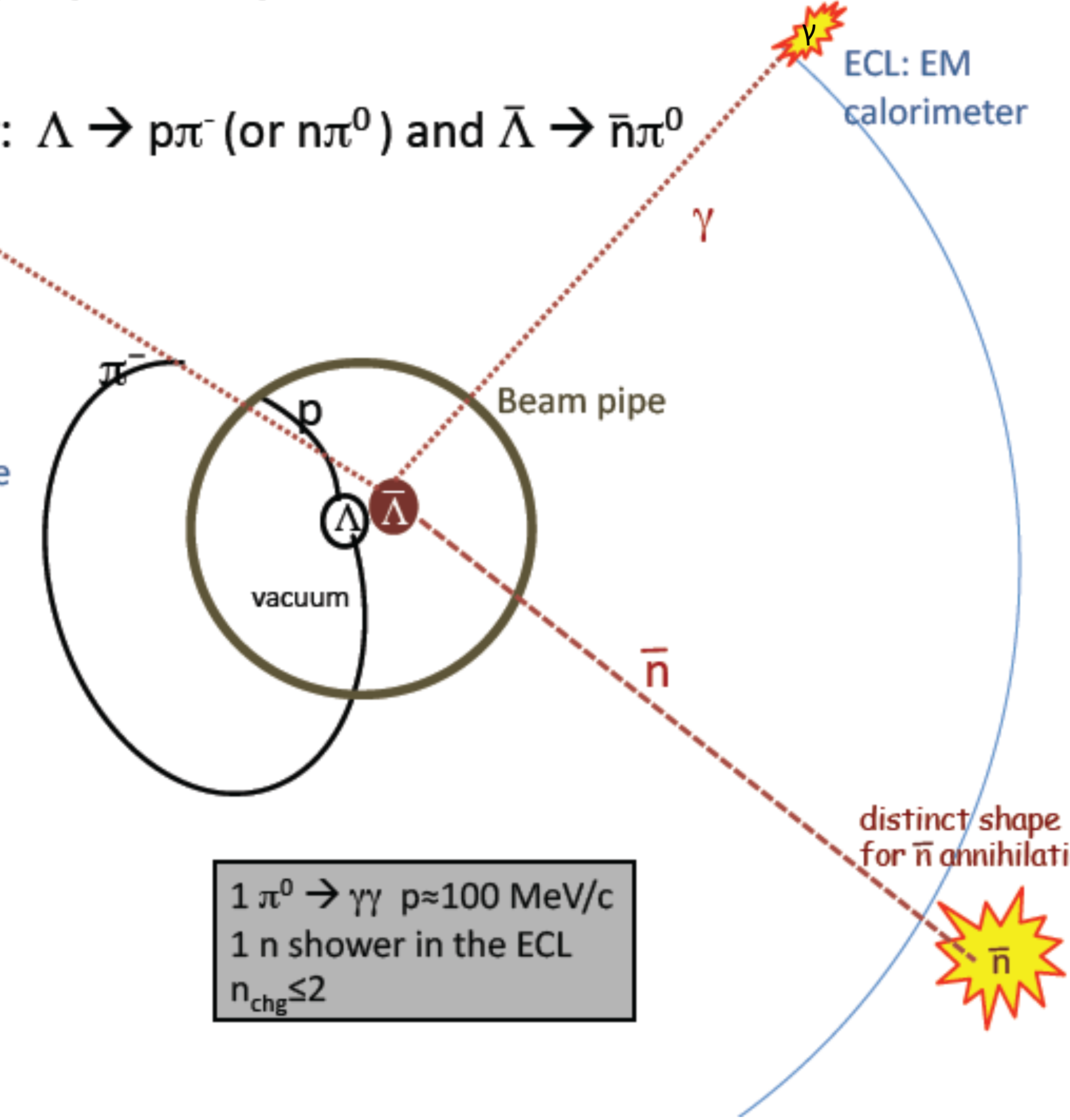
BESIII sees events like this



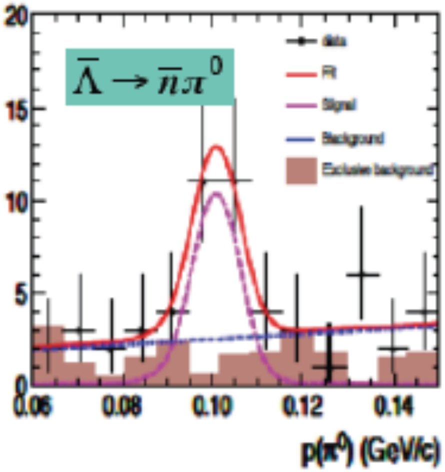
$E_{cm} = 2m_\Lambda + 1$ MeV

a $(\Lambda\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow\bar{n}\pi^0)$ threshold event in BESIII

for: $\Lambda \rightarrow p\pi^-$ (or $n\pi^0$) and $\bar{\Lambda} \rightarrow \bar{n}\pi^0$



$E_{cm} = 2m_\Lambda + 1$ MeV



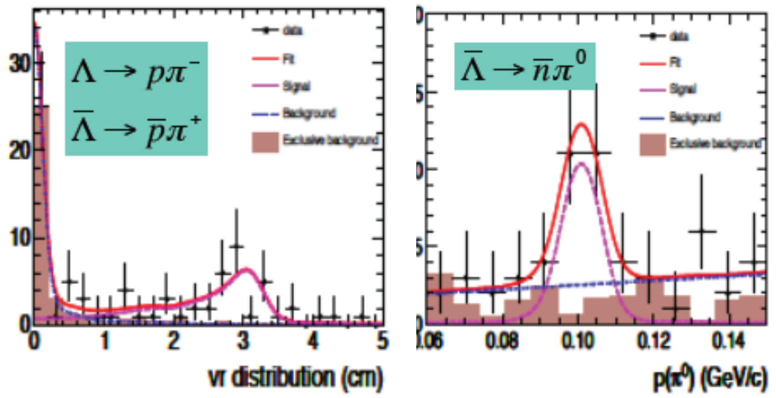
$1\ \pi^0 \rightarrow \gamma\gamma$ p≈100 MeV/c

1 n shower in the ECL

$n_{chg} \leq 2$

BESIII $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ measurements

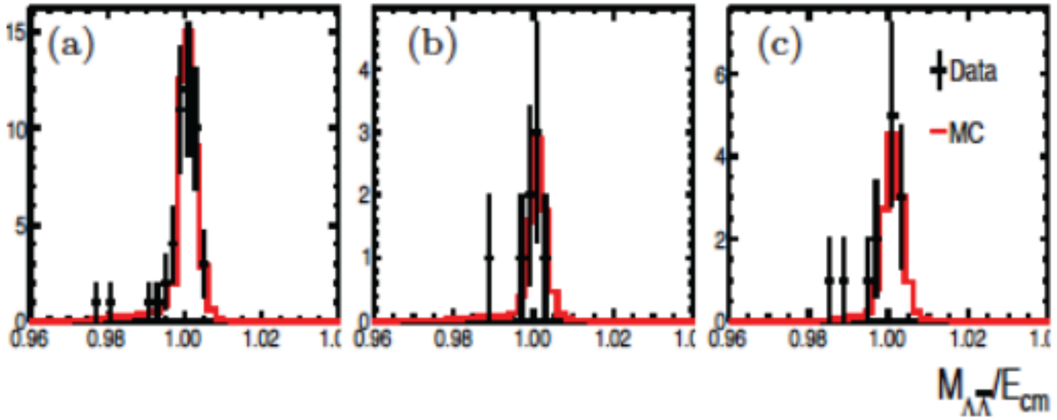
$E_{cm} = 2m_\Lambda + 1$ MeV



$2m_\Lambda$+9 MeV

$2m_\Lambda$+409 MeV

$2m_\Lambda$+689 MeV



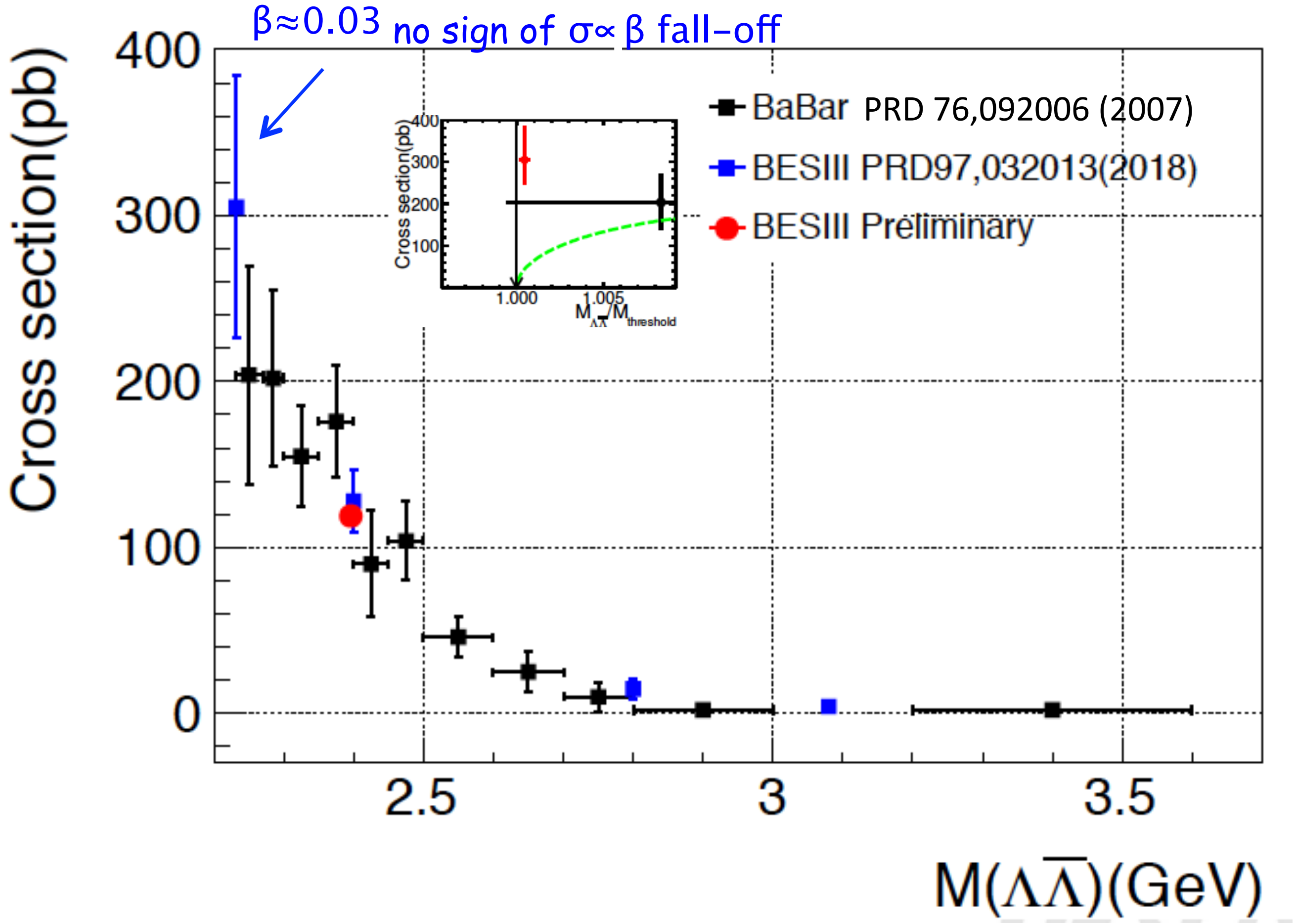
$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$N_{\rm obs}$	$\epsilon(1+\delta)$ (%)	$\sigma^{\rm B}$ (pb)	$\lvert G\rvert$ ($\times10^{-2}$)
2.2324_1	2.63	43 ± 7	12.9	$312\pm51^{+72}_{-45}$	
2.2324_2	2.63	22 ± 6	8.25	$288\pm96^{+64}_{-36}$	
2.2324_c				$305\pm45^{+66}_{-36}$	$61.9\pm4.6^{+18.1}_{-9.0}$
2.400	3.42	45 ± 7	25.3	$128\pm19\pm18$	$12.7\pm0.9\pm0.9$
2.800	3.75	8 ± 3	36.1	$14.8\pm5.2\pm1.9$	$4.10\pm0.72\pm0.26$
3.080	30.73	13 ± 4	24.5	$4.2\pm1.2\pm0.5$	$2.29\pm0.33\pm0.14$

$\Lambda \rightarrow \pi^- p$ & $\pi^0 n$ modes are consistent

conventional analyses at higher energies

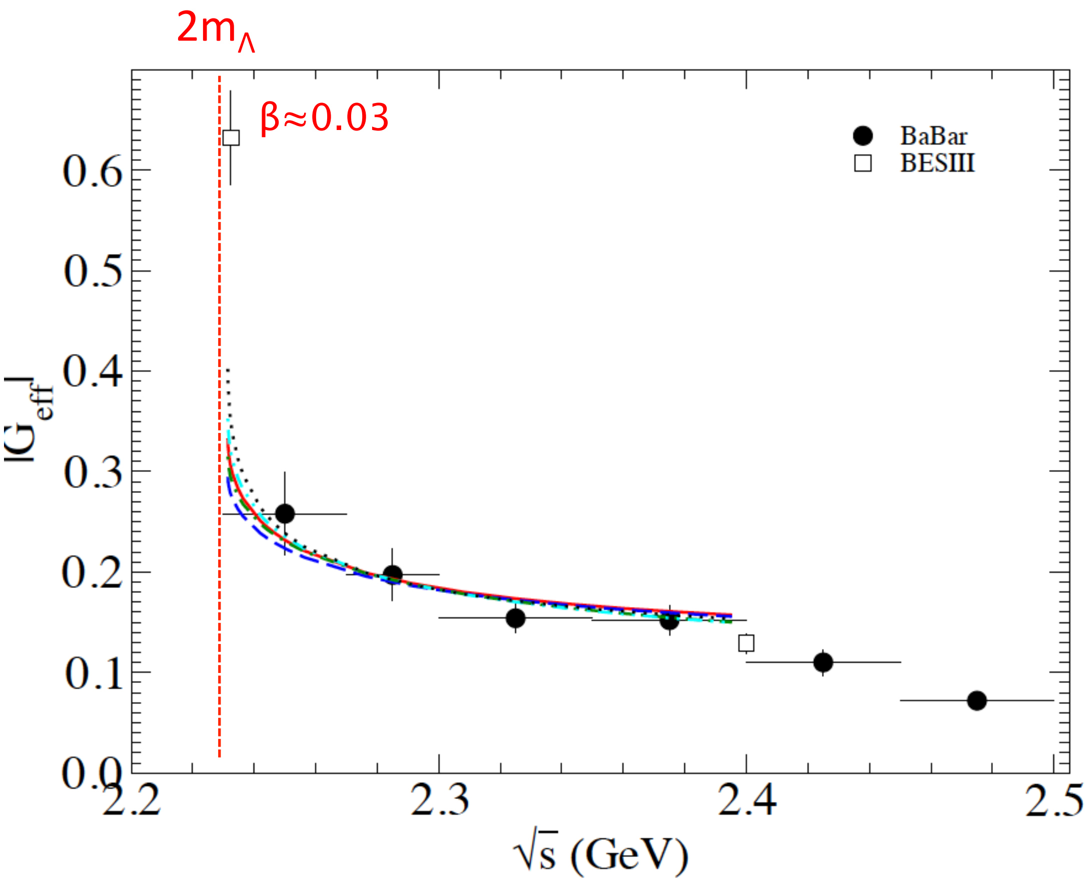
$\sigma(e^+e^- \rightarrow \Lambda\bar{\Lambda})$ at $E_{cm}\approx 2m_\Lambda$ threshold

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

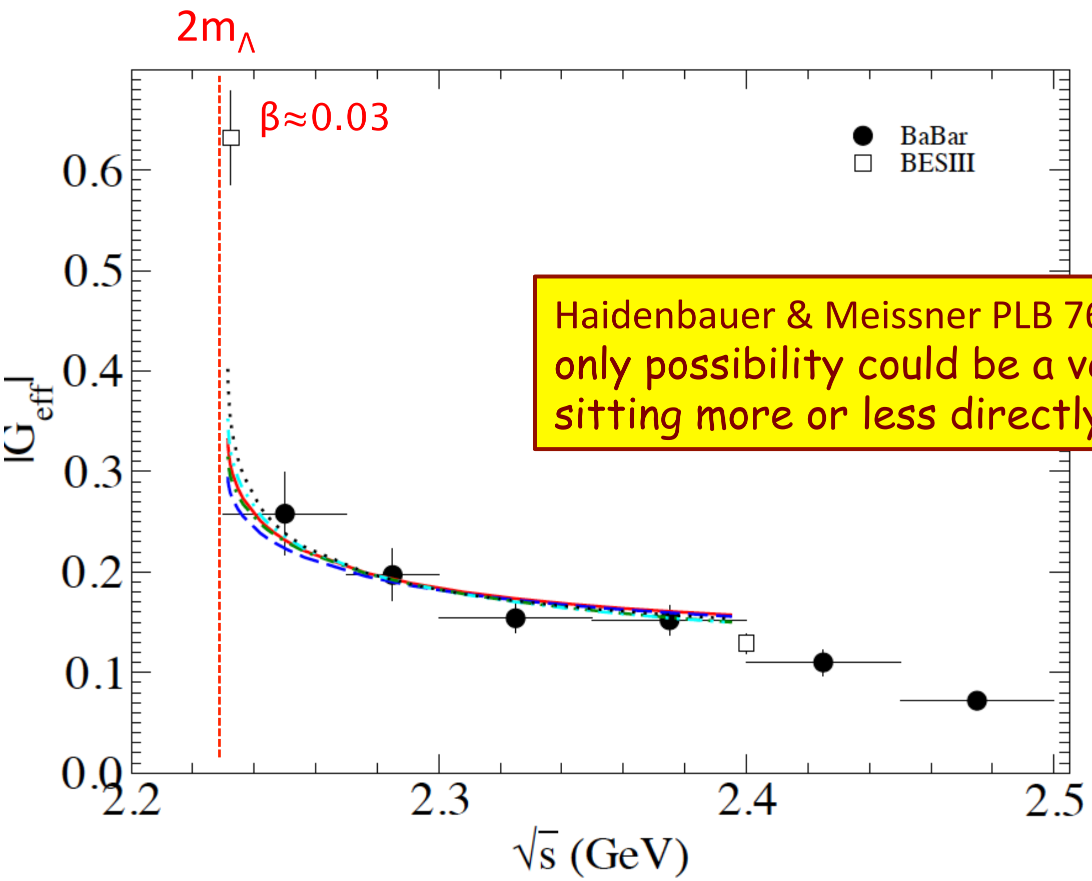


$\beta\approx0.03$ no sign of $\sigma\propto\beta$ fall-off

$|G_{eff}(2m_\Lambda)| \rightarrow 1$??

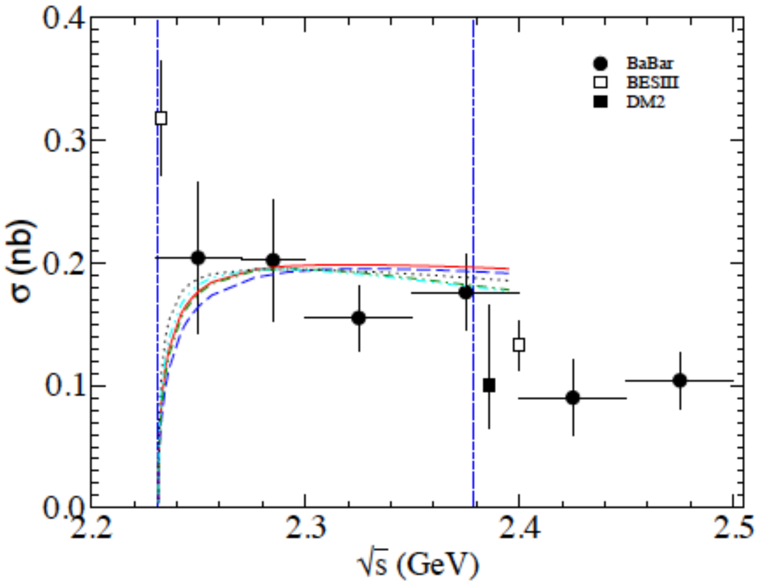


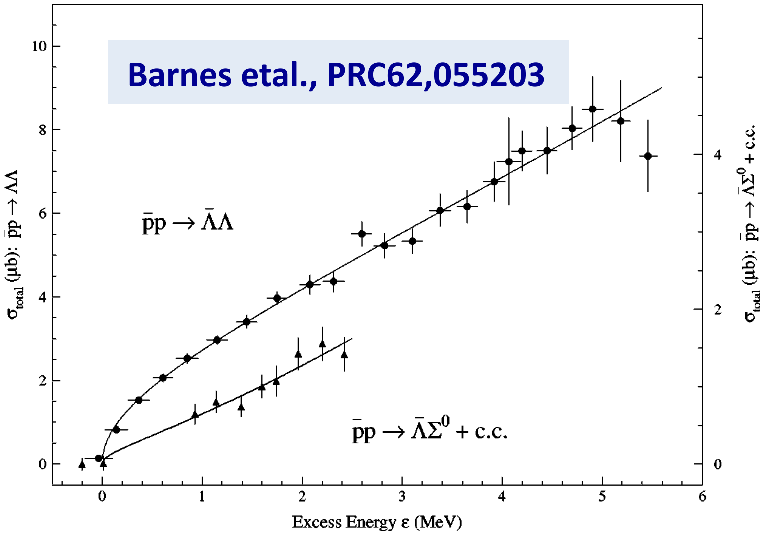
$|G_{eff}(2m_{\Lambda})| \rightarrow 1$??



Haidenbauer & Meissner PLB 761,456 (2017): "The only possibility could be a very narrow resonance sitting more or less directly at the threshold … "

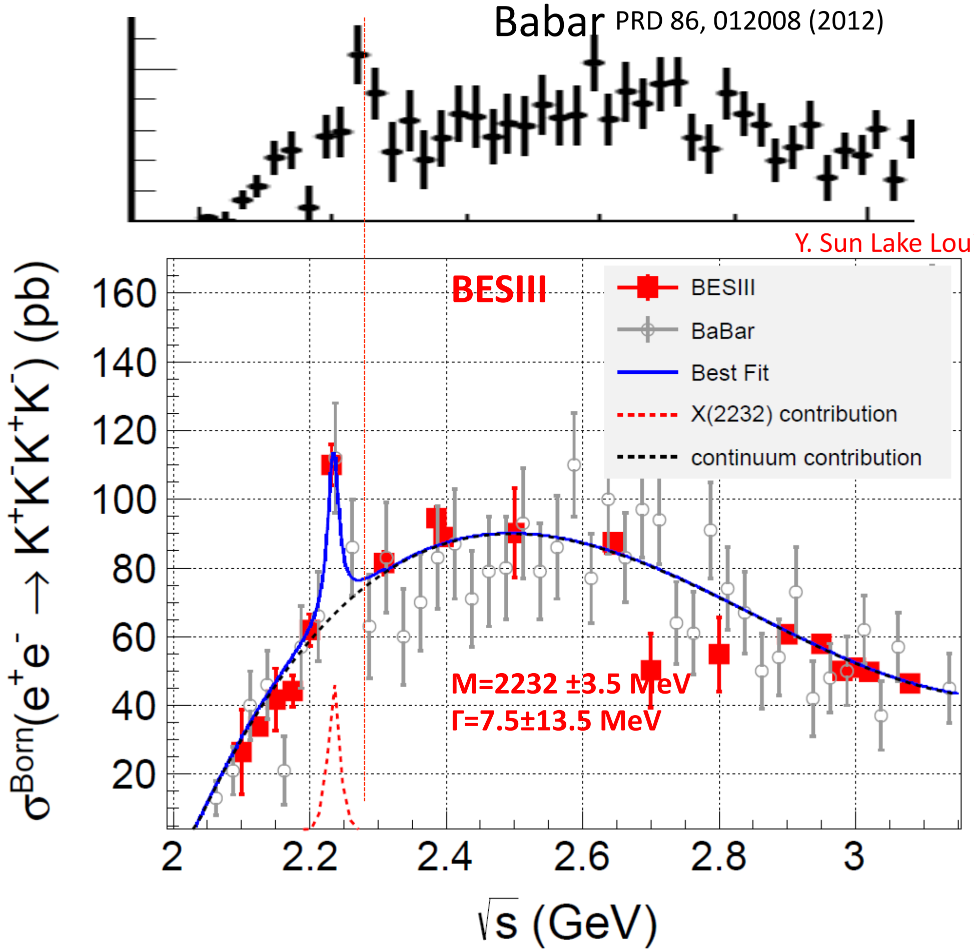
$e^+e^- \rightarrow \Lambda\bar{\Lambda}$ very different from $p\bar{p} \rightarrow \Lambda\bar{\Lambda}$




Barnes etal., PRC62,055203

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

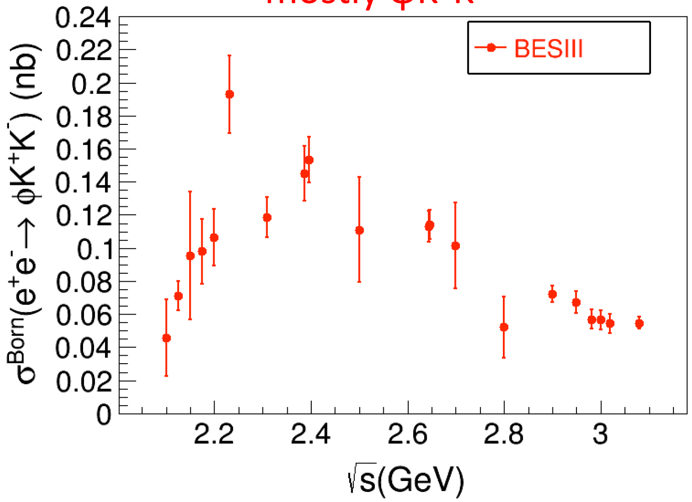
-- seen by both BaBar and BESIII --



Babar PRD 86, 012008 (2012)

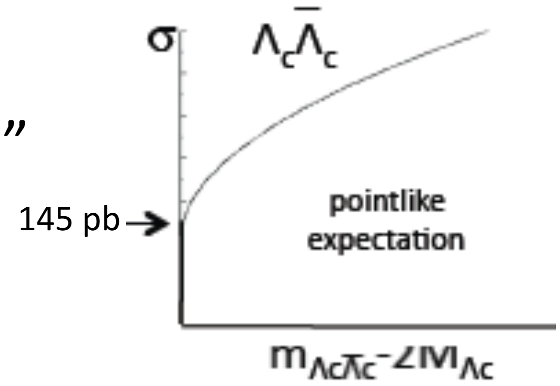
Y. Sun Lake Louise 2018

mostly ϕK^+K^-



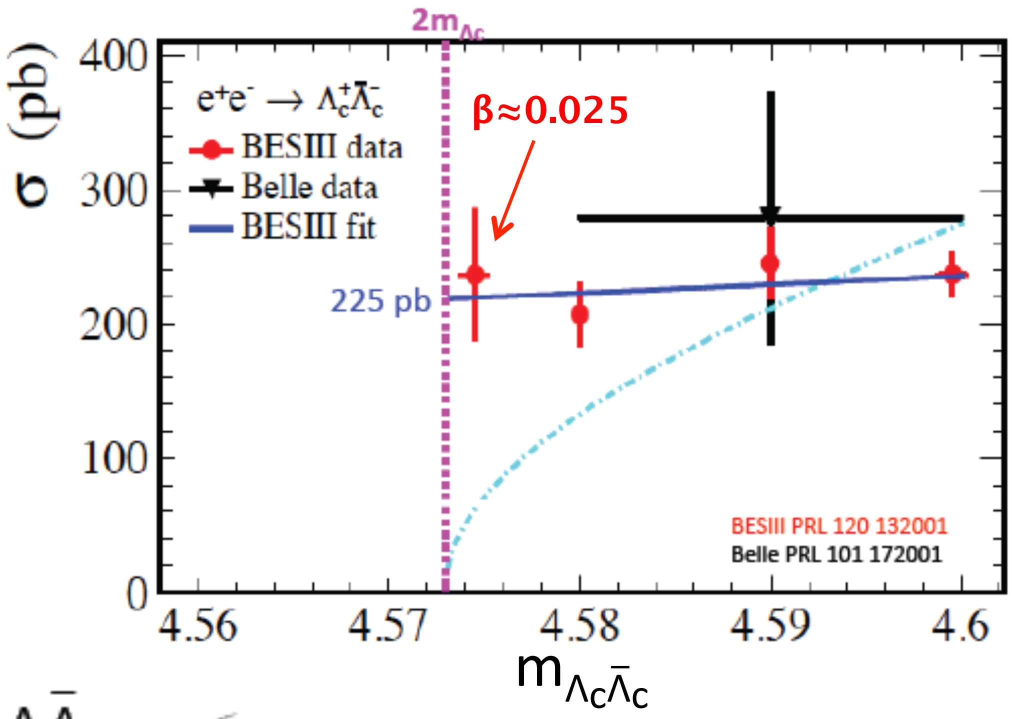
$e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$

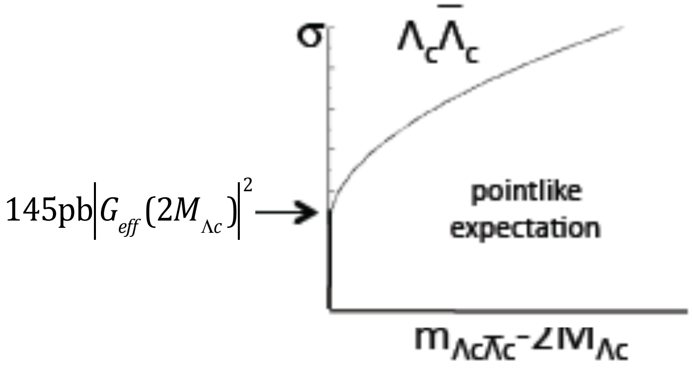
Λ_c is charged, expect ≈145pb "jump"
in point-like approximation



Λ_c is an Isospin singlet, no π-exchange
Λ_c-Λ_c moleculelike states expected

$\sigma(e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-)$ @threshold



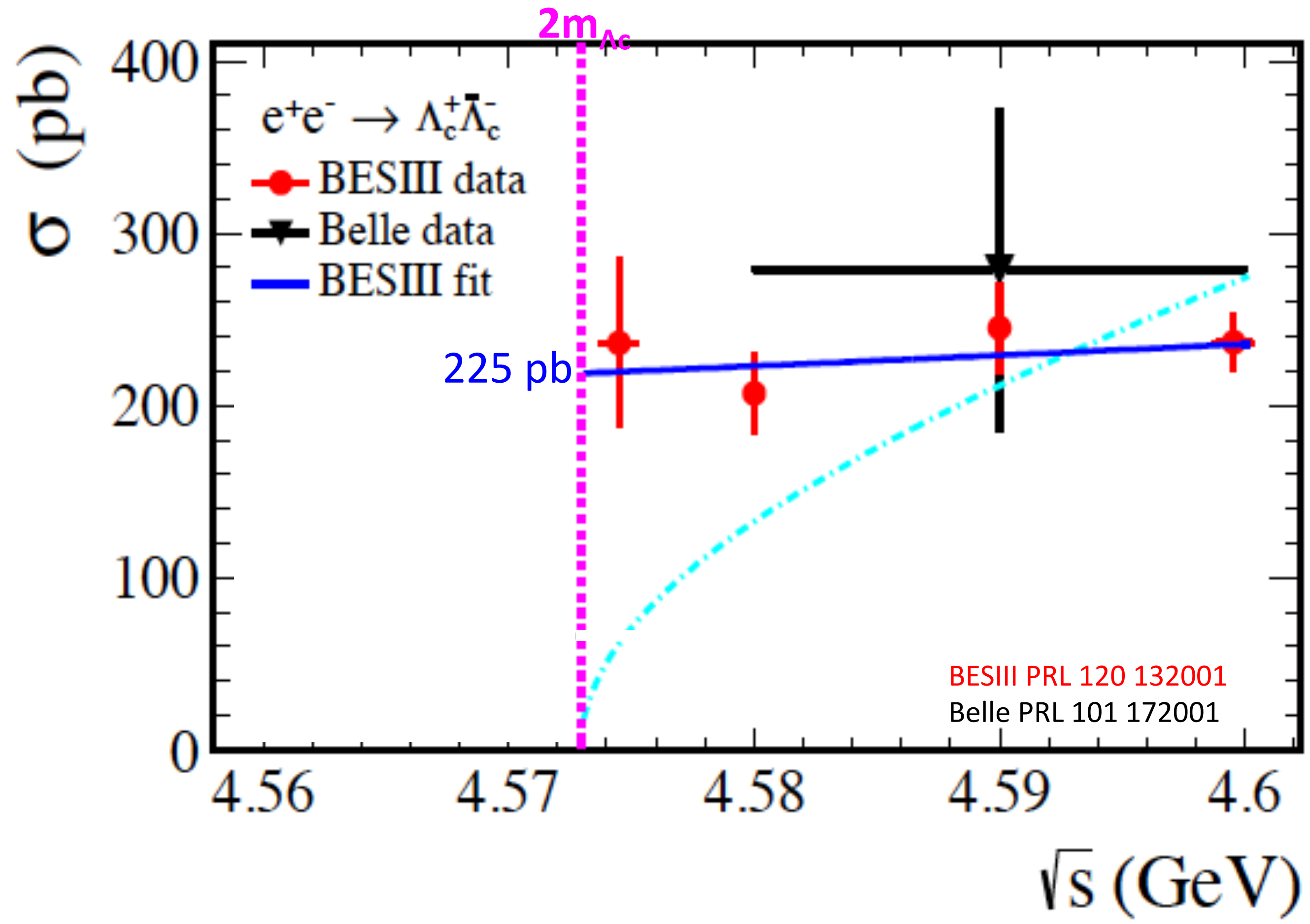


≈225 pb “jump” at threshold

≈consistent with $\delta\sigma \approx 145$ pb
$|G_{eff}|=1$ pointlike jump

but ≈flat after that (like pp)

$\sigma(e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-)$ @ threshold

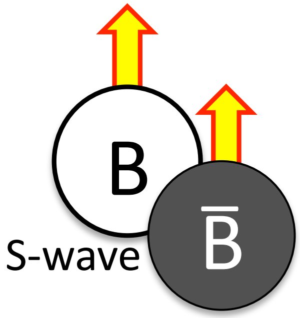


BESIII PRL 120 132001

Belle PRL 101 172001

baryonium?

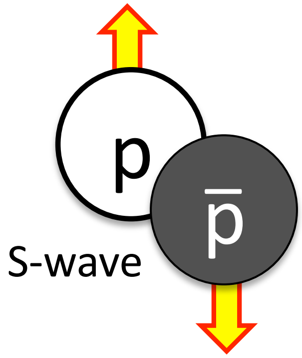
-- sub-threshold $B\bar{B}$ QCD S-wave bound states --



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

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

a 0^{-+} $p\bar{p}$ bound state is well established

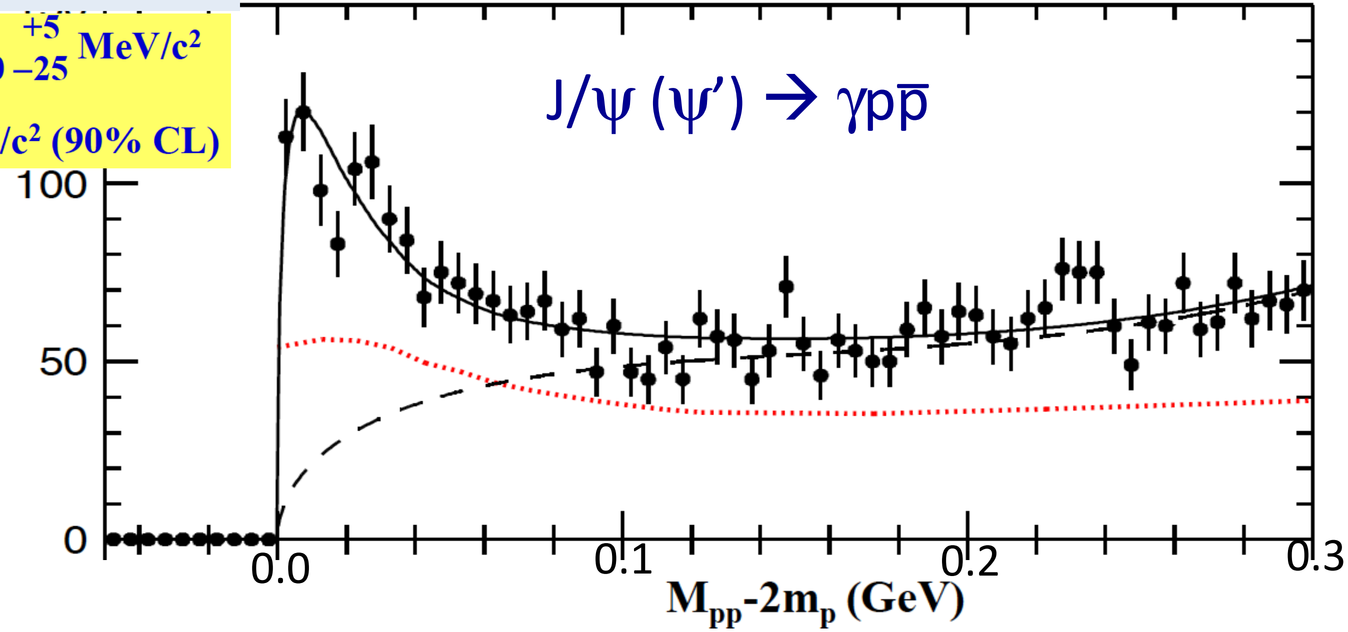


$J^{PC}=0^{-+}$

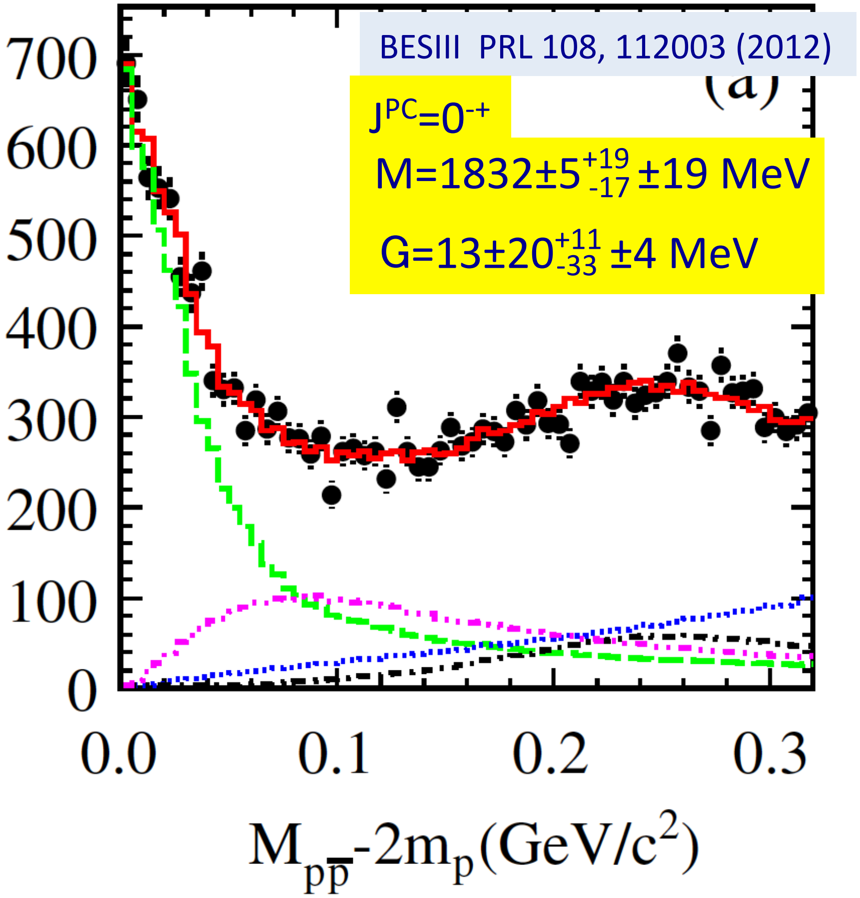
BESII PRL 91, 02001 (2003)

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

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



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



BESIII PRL 108, 112003 (2012)

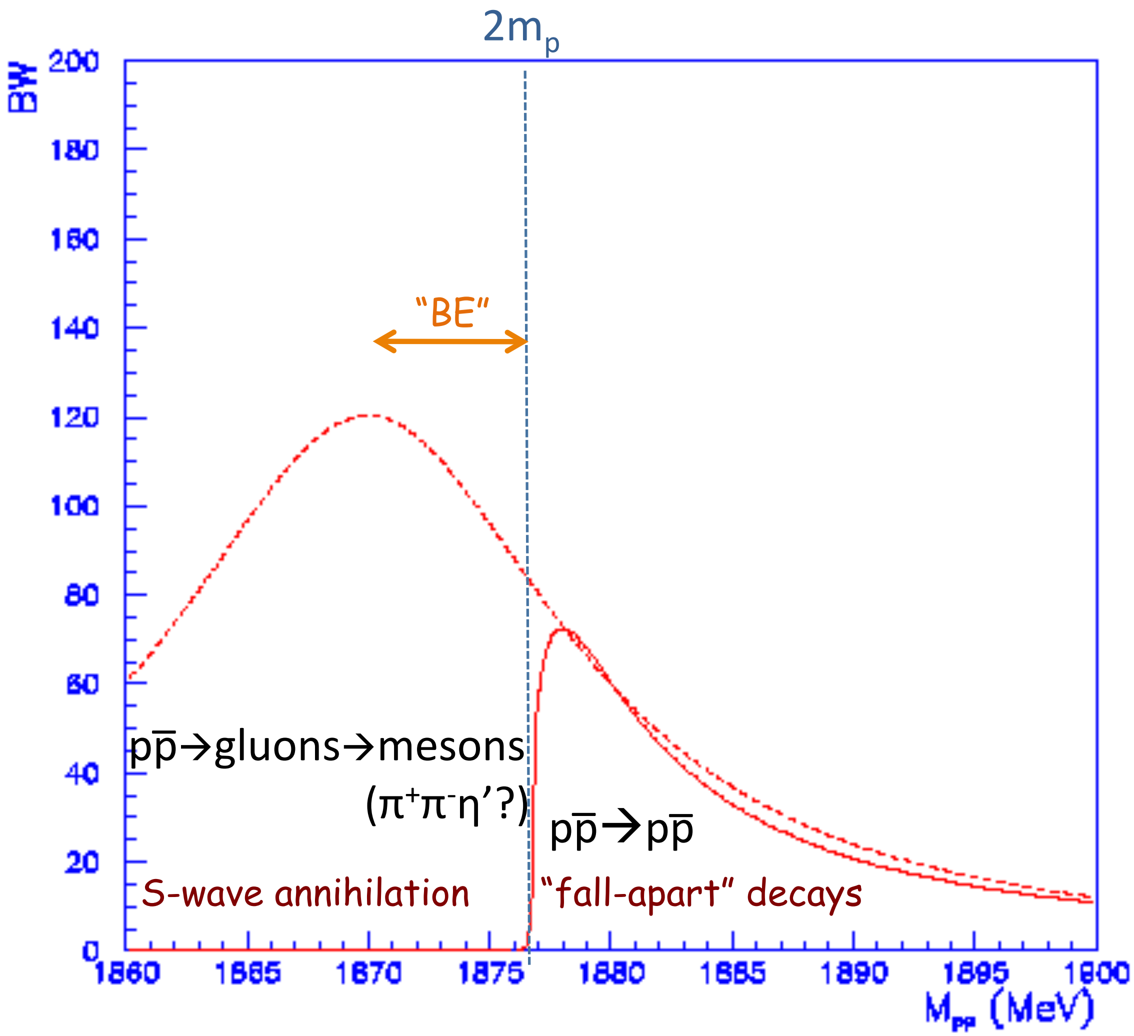
$J^{PC}=0^{-+}$

$M=1832\pm5^{+19}_{-17}\pm19$ MeV

$G=13\pm20^{+11}_{-33}\pm4$ MeV

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

“protononium:” a $p\bar{p}$ bound state?

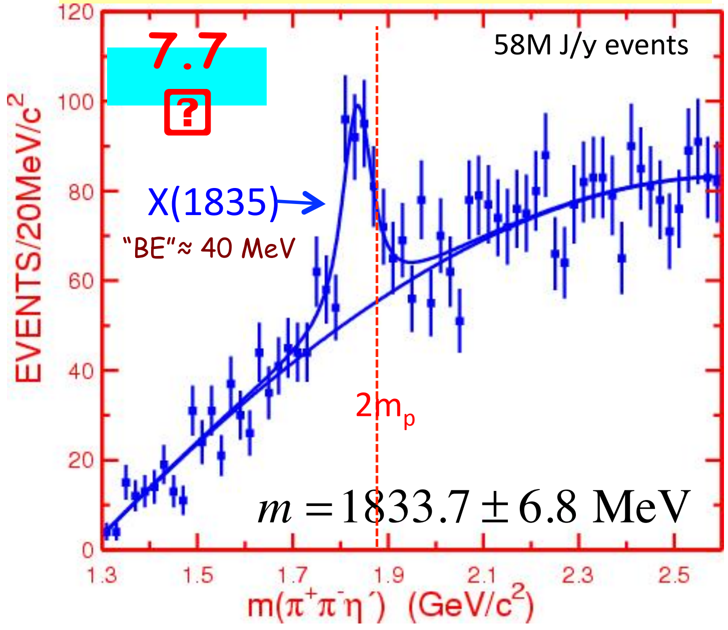


G.J. Ding & M.L. Yan Phys. Rev. C 72, 015208

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

BESII observation of X(1835) in

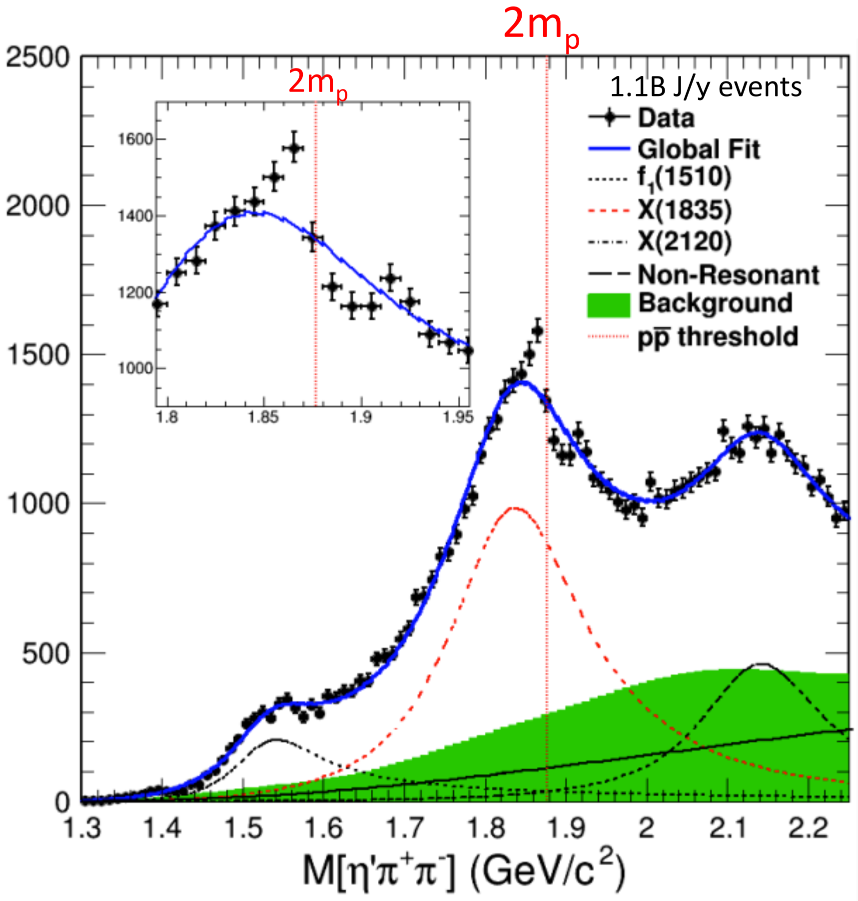
$$J/\psi \to \gamma\pi^+\pi^-\eta'$$



BESII PRL 95, 262001 (2005)

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

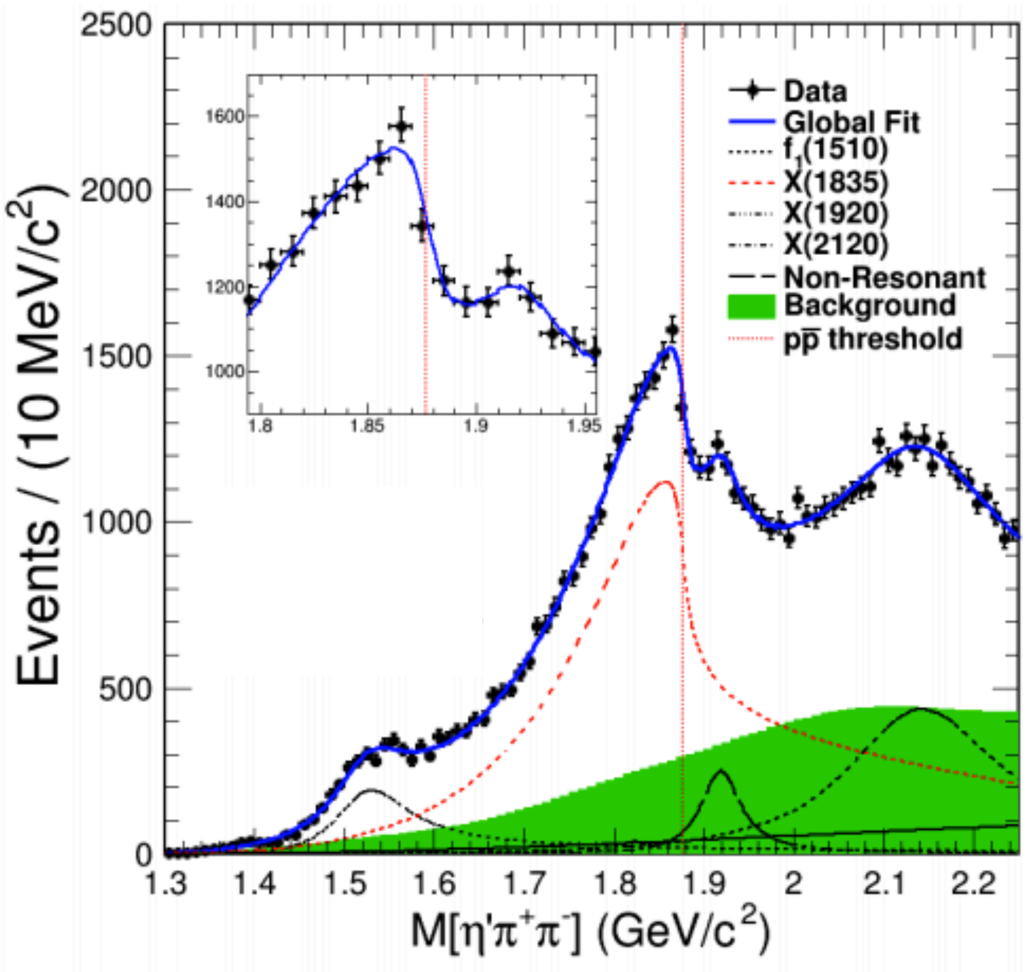
$$J/\psi \to \gamma\pi^+\pi^-\eta'$$



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. Flatté 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

summary

Cross section threshold jumps see for $e^+e^- \rightarrow B\bar{B}$

- -- both for charged ($p\bar{p}$ & $\Lambda_c\bar{\Lambda}_c$) and neutral ($n\bar{n}$ & $\Lambda\bar{\Lambda}$) pairs
- -- jump times < 1 ns (faster than phase space)
- -- consistent with expectations for pointlike, charged particles
- -- above threshold behavior is decidedly non-pointlike

Accompanying structures seen in other channels

- -- dips in $\sigma(e^+e^- \rightarrow 3(\pi^+\pi^-)$ & $K^+K^- \pi^+\pi^-)$ at $E_{cm}=2m_p$ (but not $2(\pi^+\pi^-)$)
- -- peak in $e^+e^- \rightarrow \phi K^+K^-$ at $E_{cm}=2m_\Lambda$

A subthreshold 0^{-+} $p\bar{p}$ state seen in $J/\psi \rightarrow \gamma p\bar{p}$

- -- associated structure seen in $e^+e^- \rightarrow \pi^+\pi^- \eta'$

More results expected soon

- -- $e^+e^- \rightarrow \Sigma\bar{\Sigma}$ and $\Xi\bar{\Xi}$ at threshold from BESIII
- --more $e^+e^- \rightarrow p\bar{p}$ and $n\bar{n}$ from CMDS, SND & BESIII

There is lots still to be learned about the ”well known’’ stable baryons