第七届全国重味物理与量子色动力学研讨会

Hadron Production Near Nucleon-Pair Threshold

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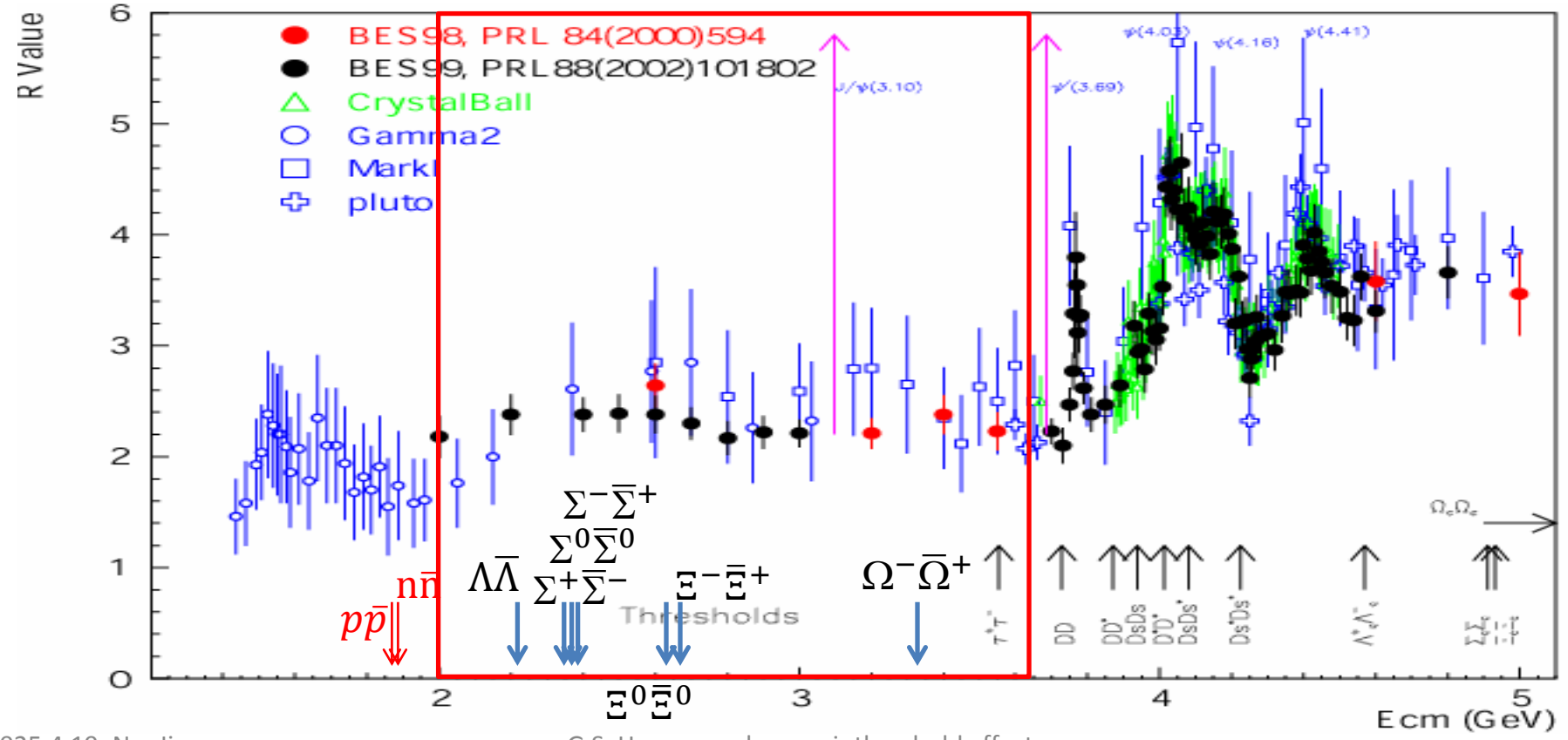
Outline

- Nucleon-pair production thresholds
- Threshold effects of baryon-pair productions
- Production of nucleon-pair across thresholds
- Cross sections of multi-meson channels

- A new window: 1.8-2.0 GeV at BESIII

Features in zone of BEPCII/BESIII

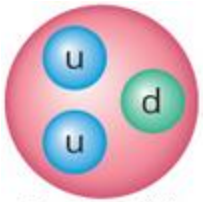
- Transition region for (non-)perturbative QCD;
- Rich charmonium, charmonium-like states;
- Excited and exotic light hadron states;
- **Baryon-pair production thresholds**.



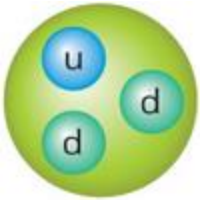
Nucleon production at BESIII

- As cornerstone of our matter world, the properties of nucleon (proton and neutron) are not fully understood yet;
- Can be produced via $e^+e^- \to N\bar{N}$;
- Threshold for $p\bar{p}$ is 1876.54 MeV,

  and for $n\bar{n}$ is 1879.13 MeV;
- Accessible at BEPCII/BESIII?



Proton (p)

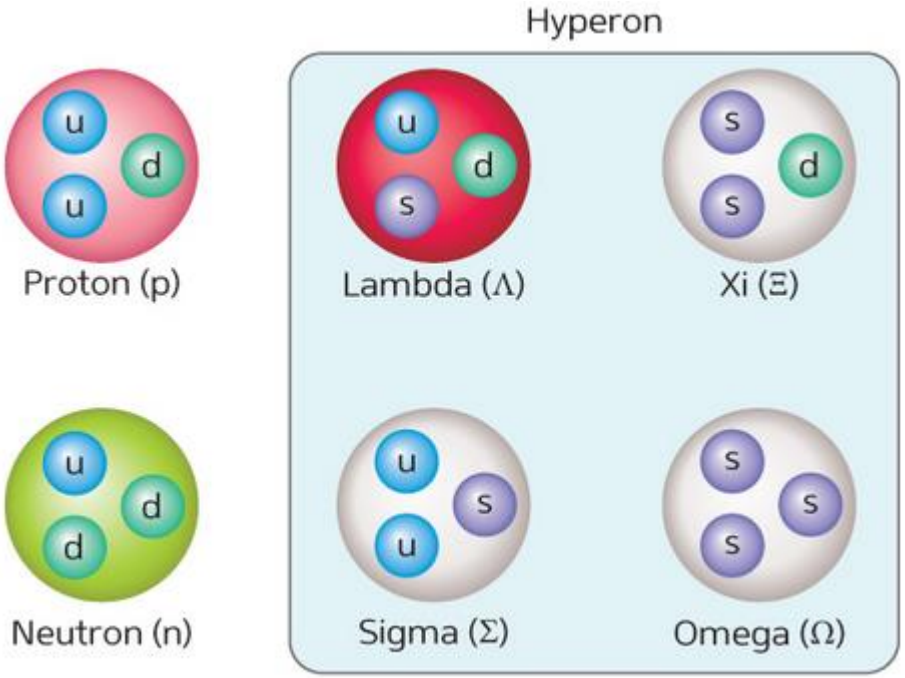


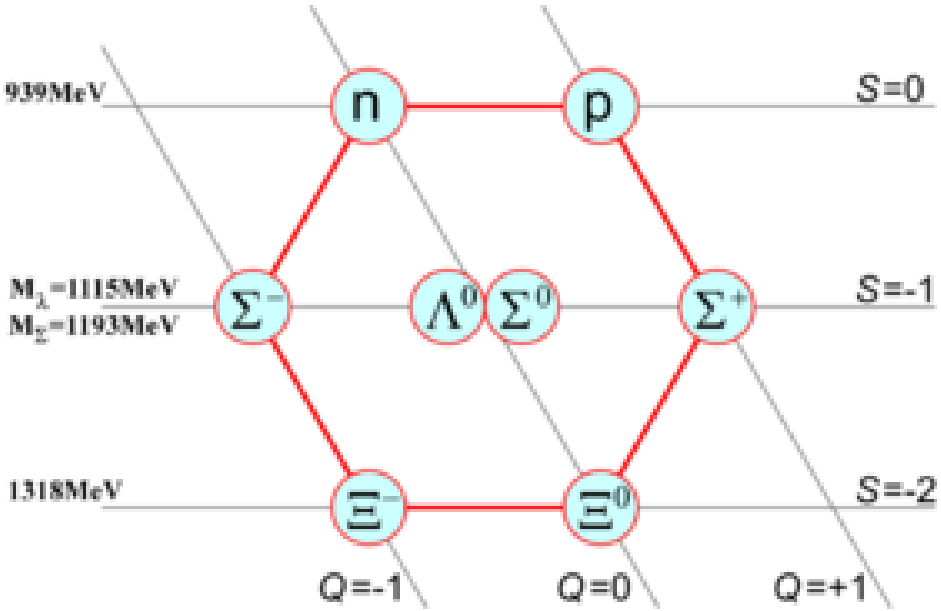
Neutron (n)

Baryon: production and structure

Key question:

"What happens with the baryon structure when a light quark is replaced by a heavier one?"





Spin $\frac{1}{2}^{+}$ SU(3) octet

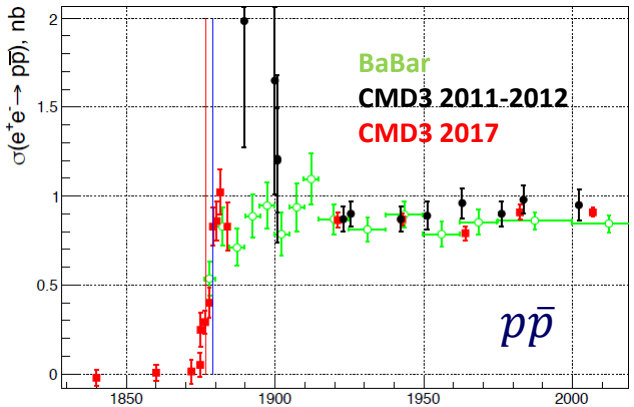
Baryon-pair production near threshold

$\bar{p}p$	$\bar{\Lambda}\Lambda$	$\bar{\Sigma}^-\Sigma^+$	$\bar{\Sigma}^0\Sigma^0$	$\bar{\Sigma}^-\Sigma^+$	$\bar{\Xi}^0\Xi^0$	$\bar{\Xi}^+\Xi^-$	$\bar{\Omega}^+\Omega^-$	$\bar{\Lambda}_c^-\Lambda_c^+$
↓	↓	↓	↓	↓	↓	↓	↓	↓
$p\pi^-$	$p\pi^0$	$\Lambda\gamma$	$n\pi$	$\Lambda\pi^0$	$\Lambda\pi$	ΛK	$\Lambda\pi$
64%	52%	≈ 100%	≈ 100%	≈ 100%	≈ 100%	68%	≈ 1%

$e^+e^- \to \gamma^* \to B\bar{B}$ production cross section:

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

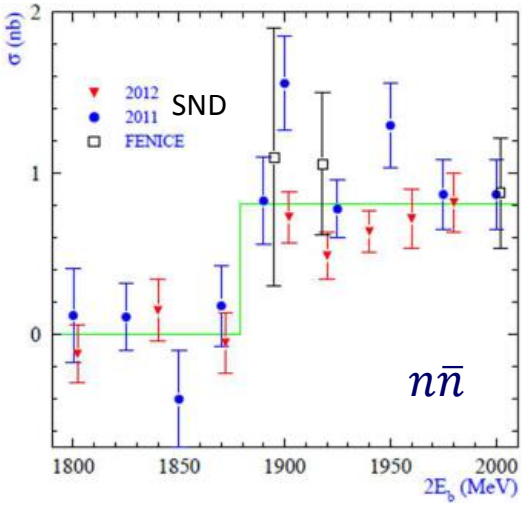
Coulomb factor $C = \begin{cases} \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}, & \text{for charged } B\bar{B} \\ 1, & \text{for neutral } B\bar{B} \end{cases}$



$p\bar{p}$、$n\bar{n}$ should be different, but poor precision for latter.

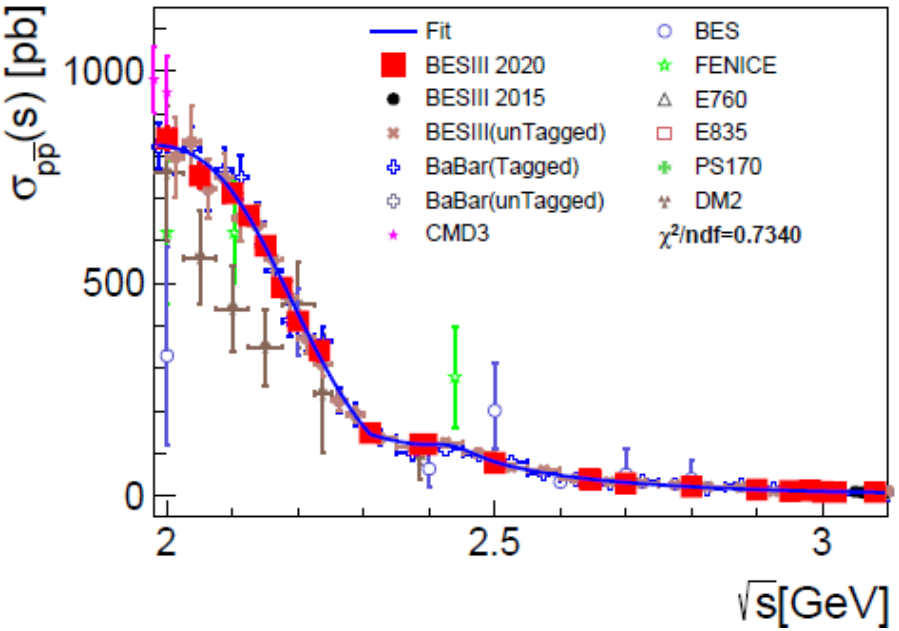
How about other baryon-pairs?

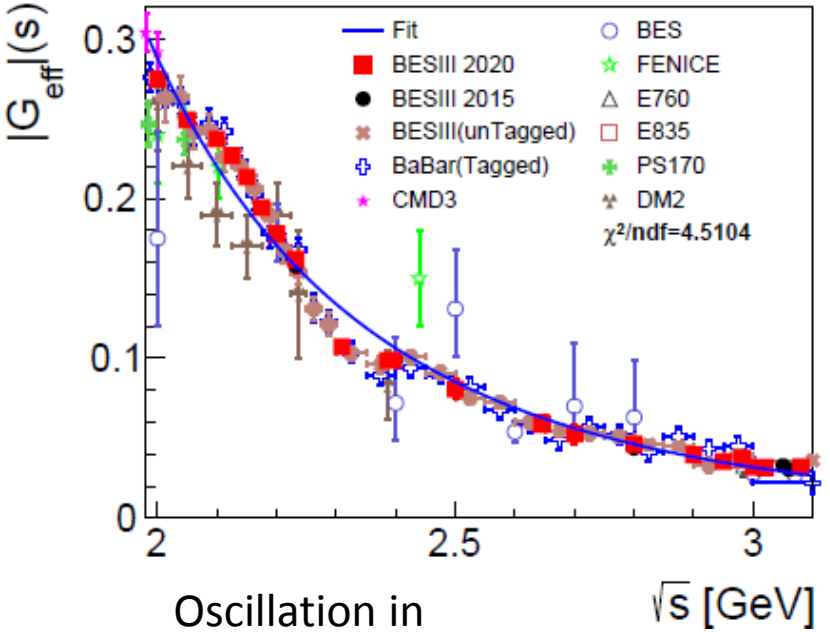
0 expected at threshold!

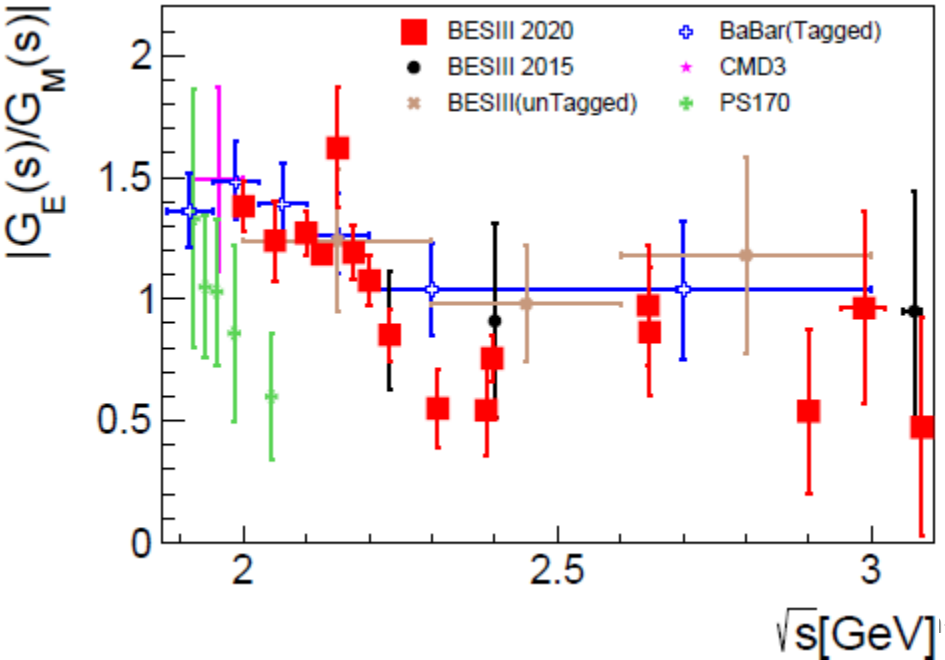


$e^+e^- \to p\bar{p}$

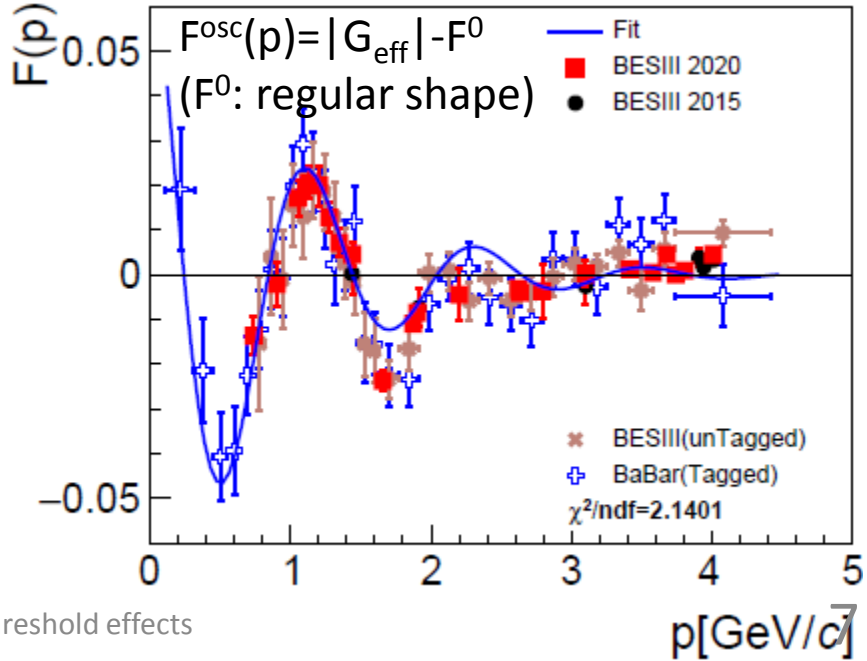
PRL 124, 042001 (2020)



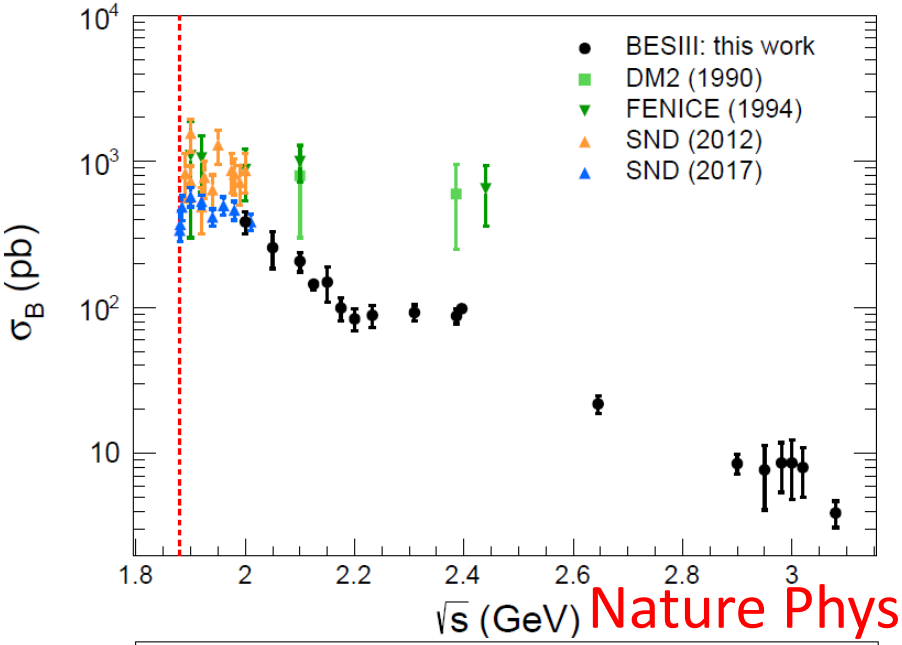


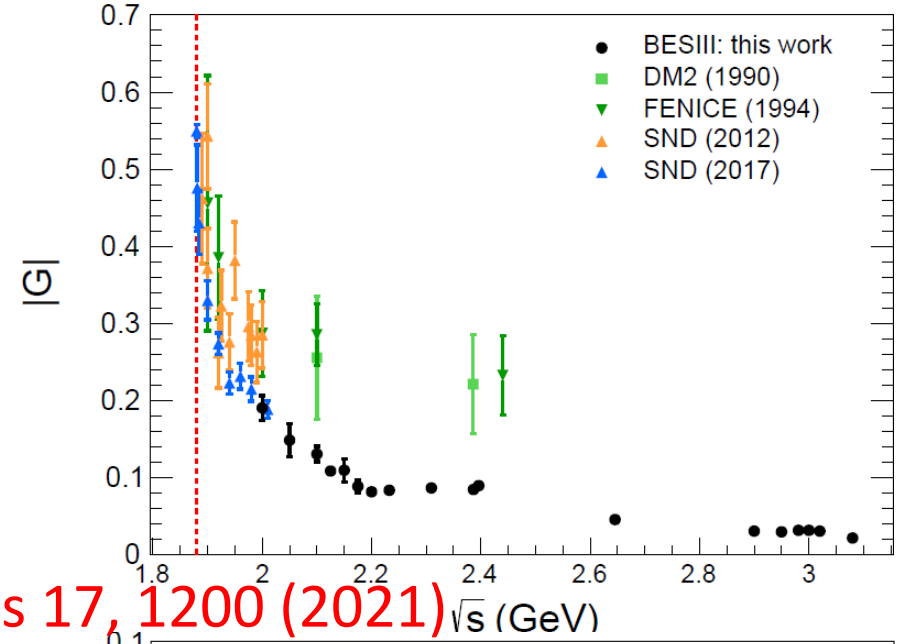


Oscillation in
$F^{osc}(p)=|G_{eff}|-F^0$
(F^0: regular shape)

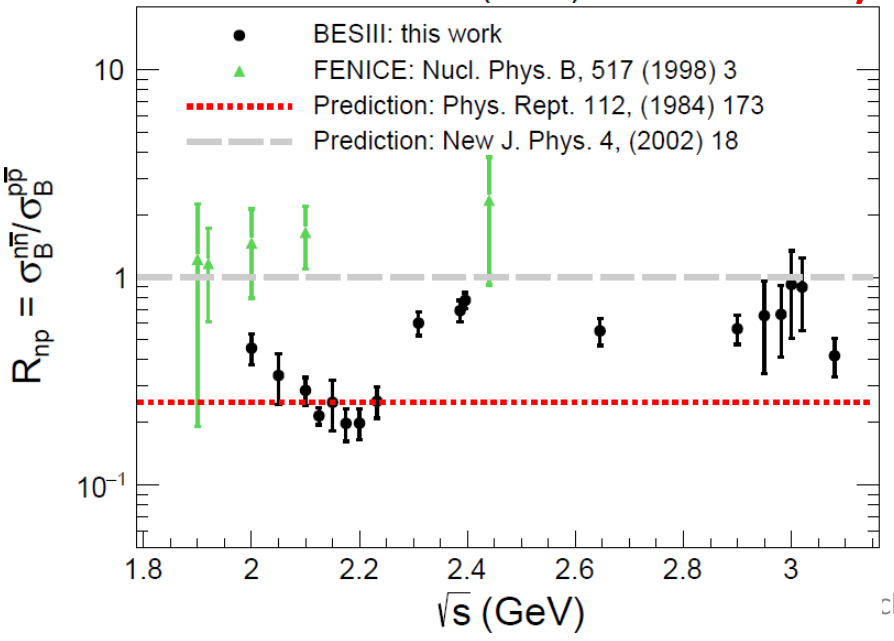


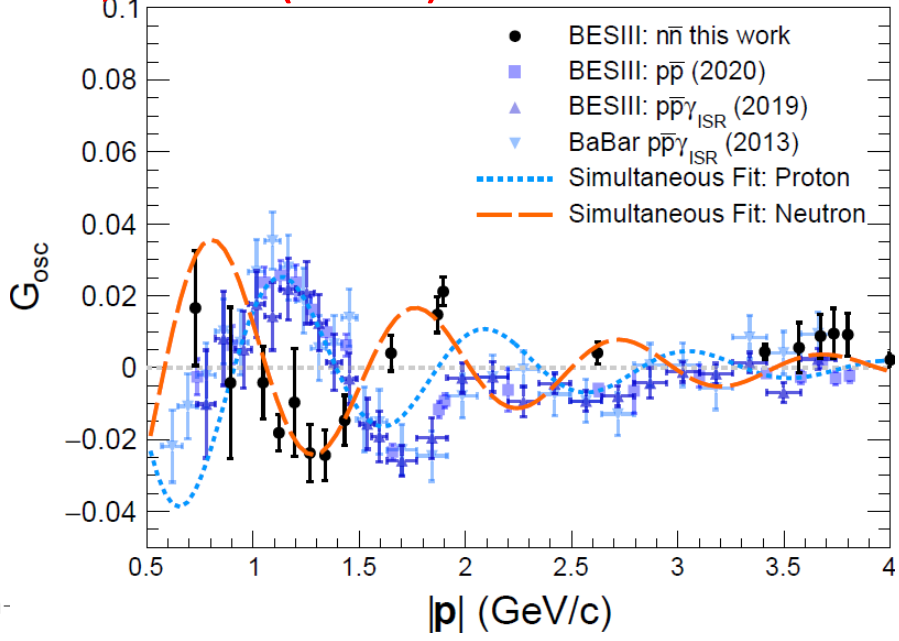
Neutron cross section and effective FF



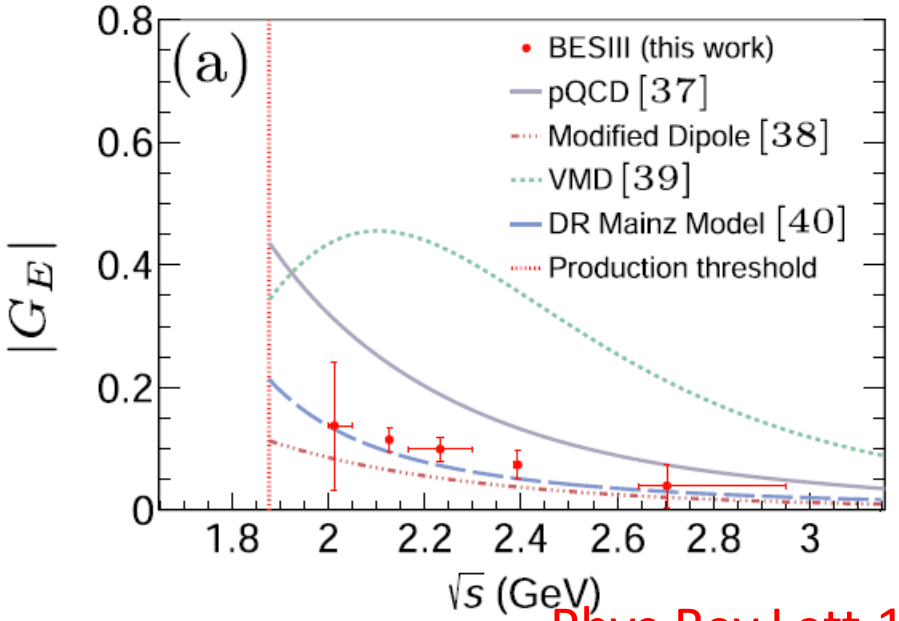


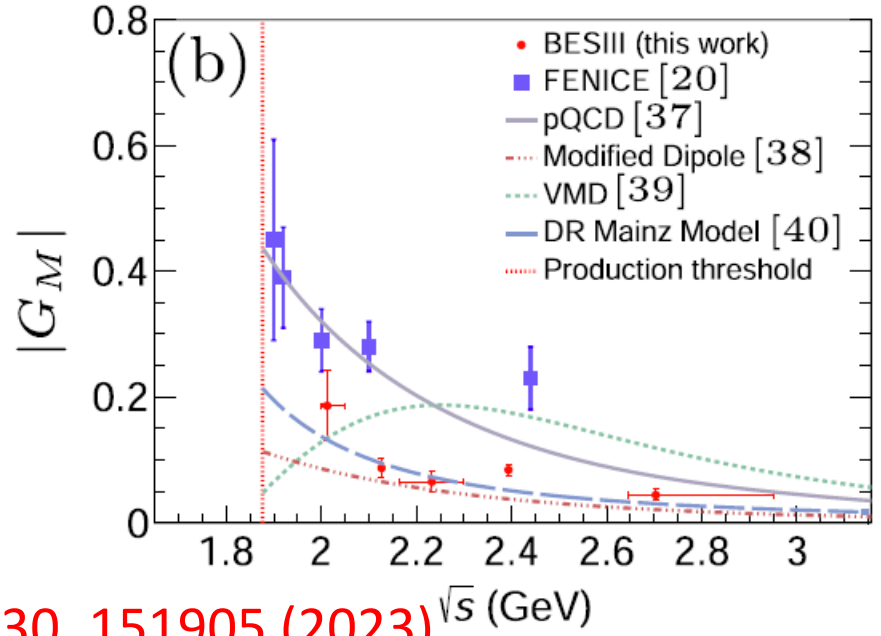
Nature Physics 17, 1200 (2021)



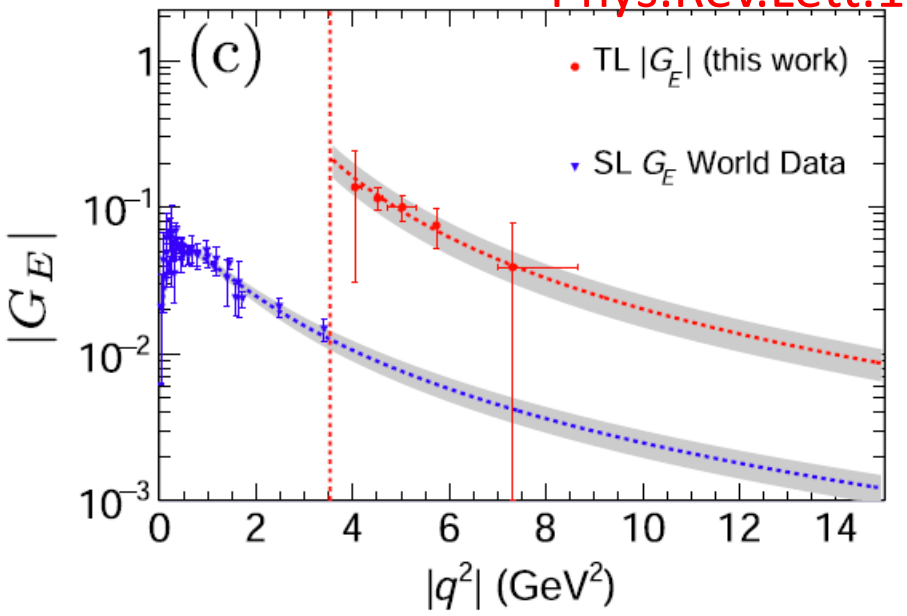


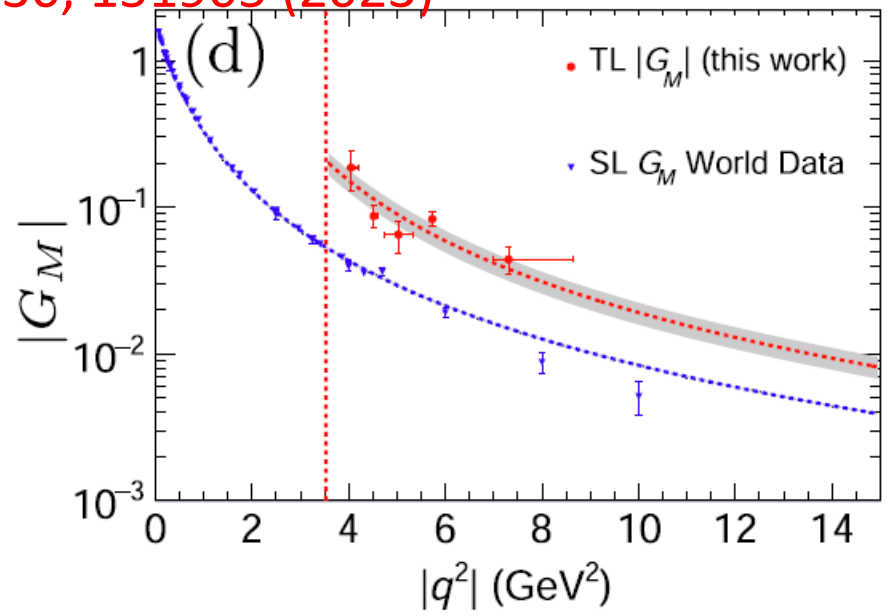
Neutron E&M form factors





Phys.Rev.Lett.130, 151905 (2023)



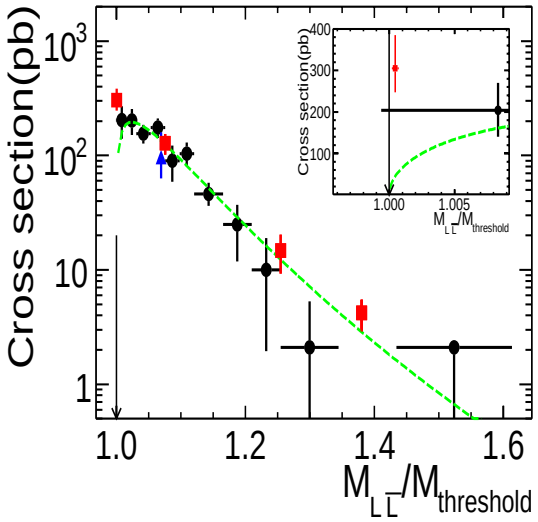


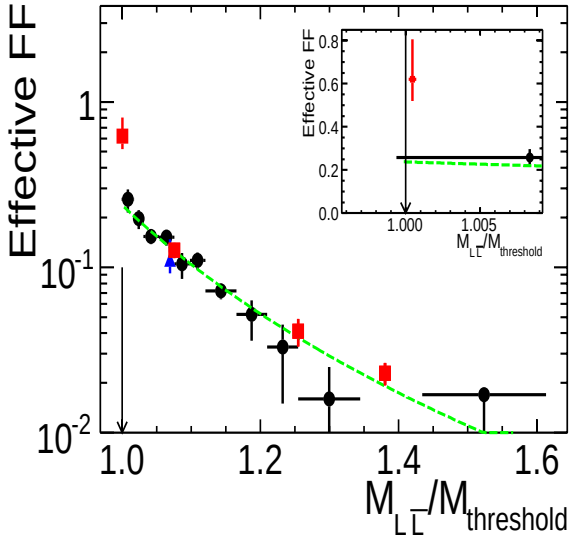
$e^+e^- \to \Lambda\bar{\Lambda}$

Phys. Rev. D 97, 032013 (2018)

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ ($\rm pb^{-1}$)	$N_{\rm obs}$	$\epsilon(1+\delta)$ (%)	$\sigma^{\rm B}$ (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)
2.2324_1	2.63	43 ± 7	12.9	$312 \pm 51^{+72}_{-45}$	
2.2324_2	2.63	22 ± 6	8.25	$288 \pm 96^{+64}_{-36}$	
2.2324_c				$305 \pm 45^{+66}_{-36}$	$61.9 \pm 4.6^{+18.1}_{-9.0}$
2.400	3.42	45 ± 7	25.3	$128 \pm 19 \pm 18$	$12.7 \pm 0.9 \pm 0.9$
2.800	3.75	8 ± 3	36.1	$14.8 \pm 5.2 \pm 1.9$	$4.10 \pm 0.72 \pm 0.26$
3.080	30.73	13 ± 4	24.5	$4.2 \pm 1.2 \pm 0.5$	$2.29 \pm 0.33 \pm 0.14$

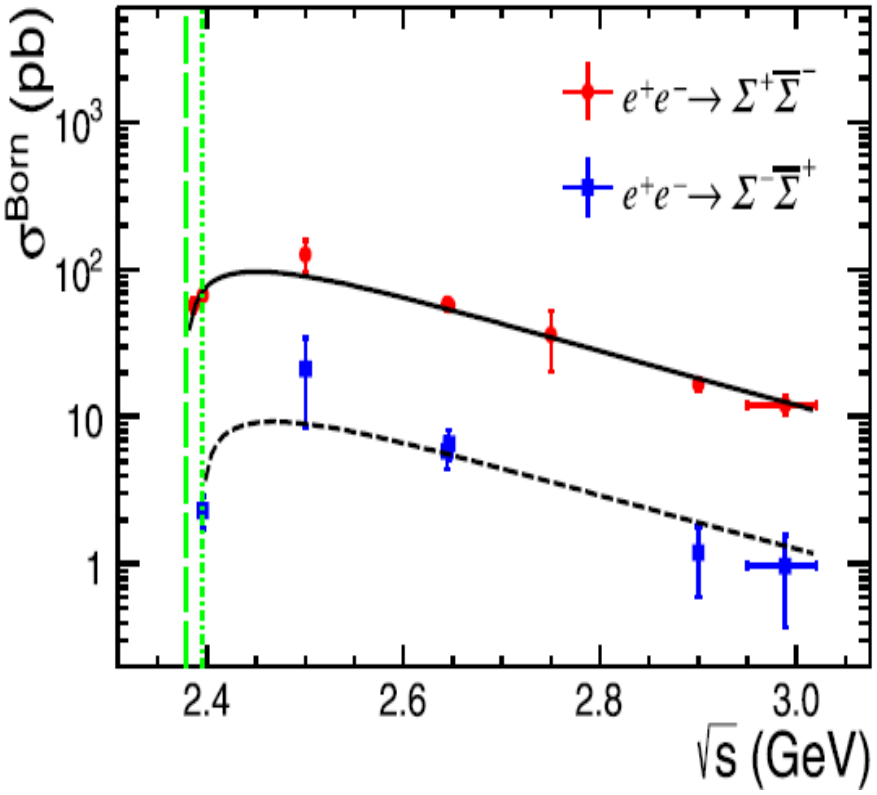
The anomalous behavior differing from the pQCD prediction at threshold is observed: non-vanishing cross section!

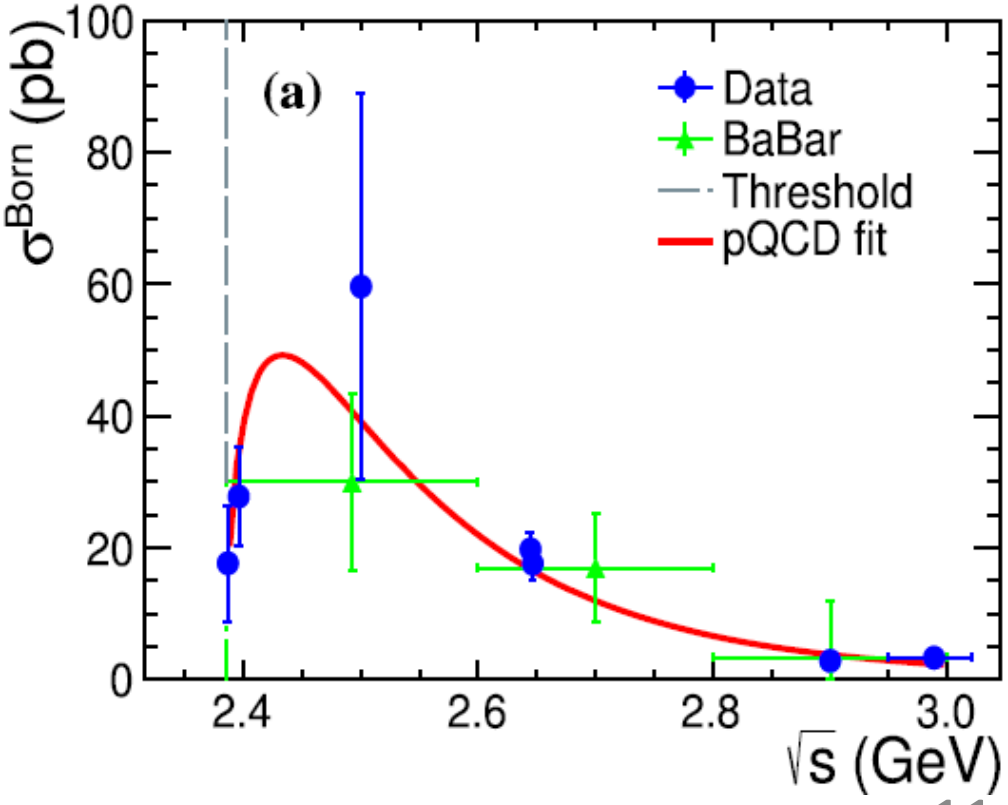




$e^+e^- \to \Sigma^+\bar{\Sigma}^-/\Sigma^-\bar{\Sigma}^+$、$\Sigma^0\bar{\Sigma}^0$

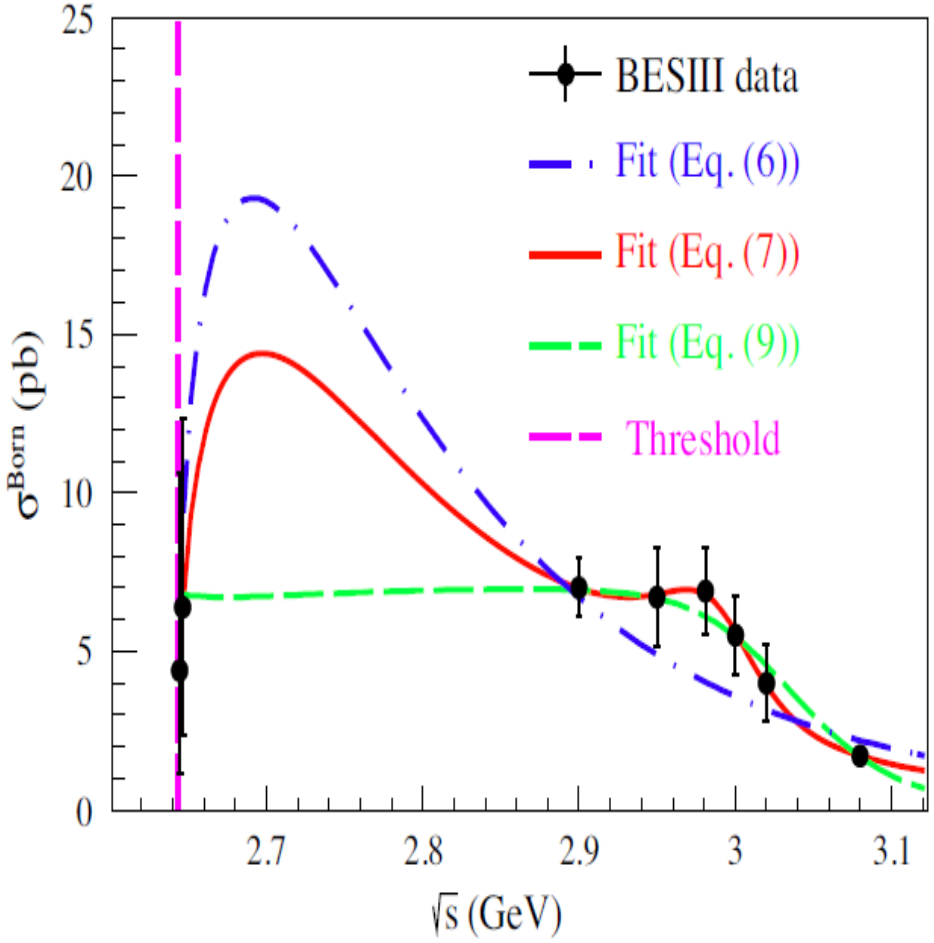
PLB814, 136110 (2021) PLB831, 137187 (2022)

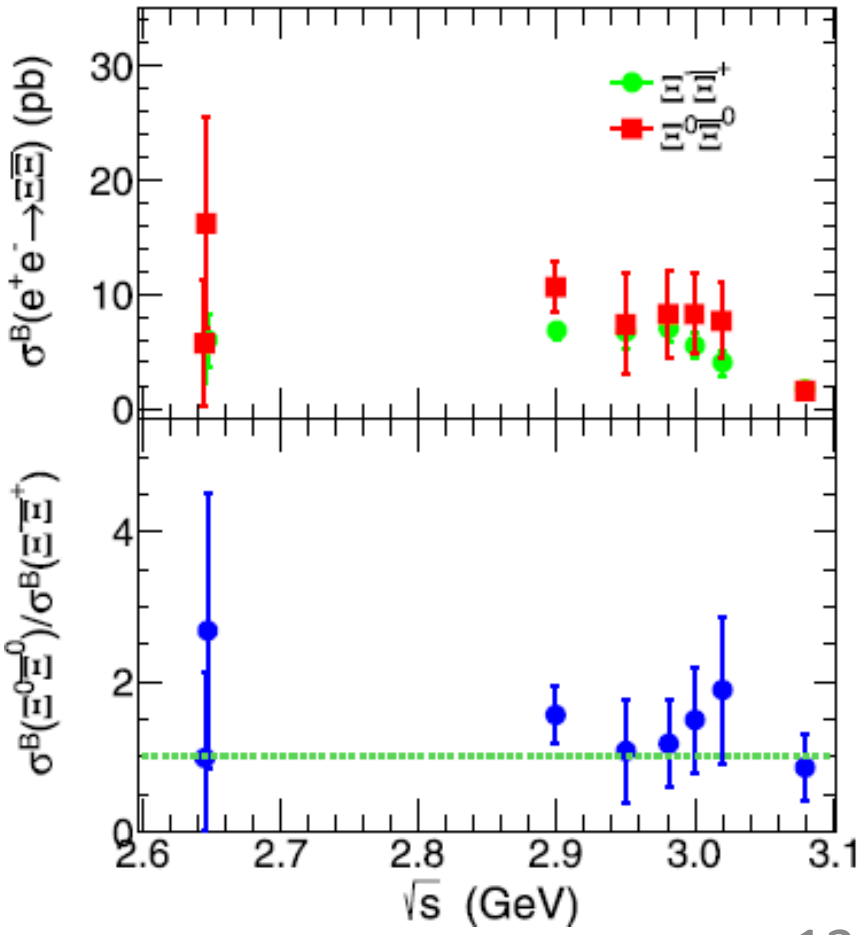




$e^+e^- \to \Xi^-\bar{\Xi}^+$、$\Xi^0\bar{\Xi}^0$

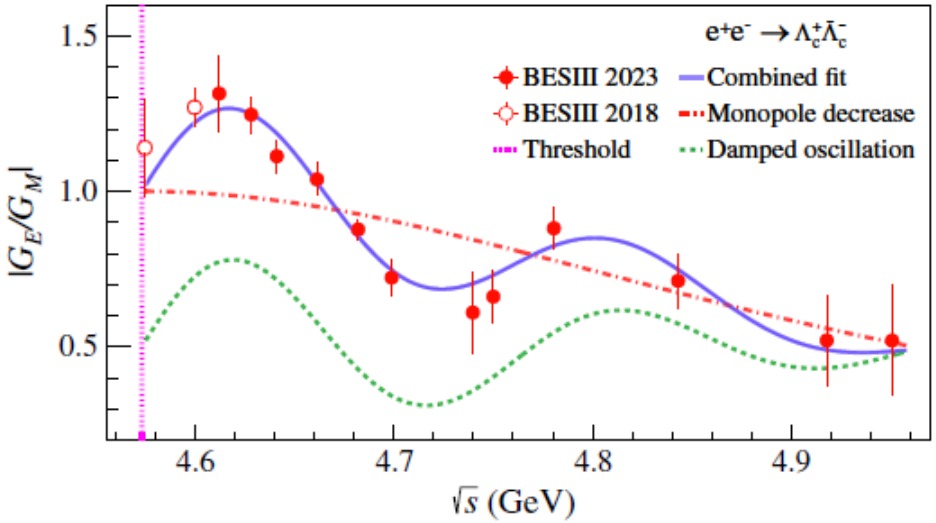
PRD103, 012005 (2021), PLB820, 136557 (2021)

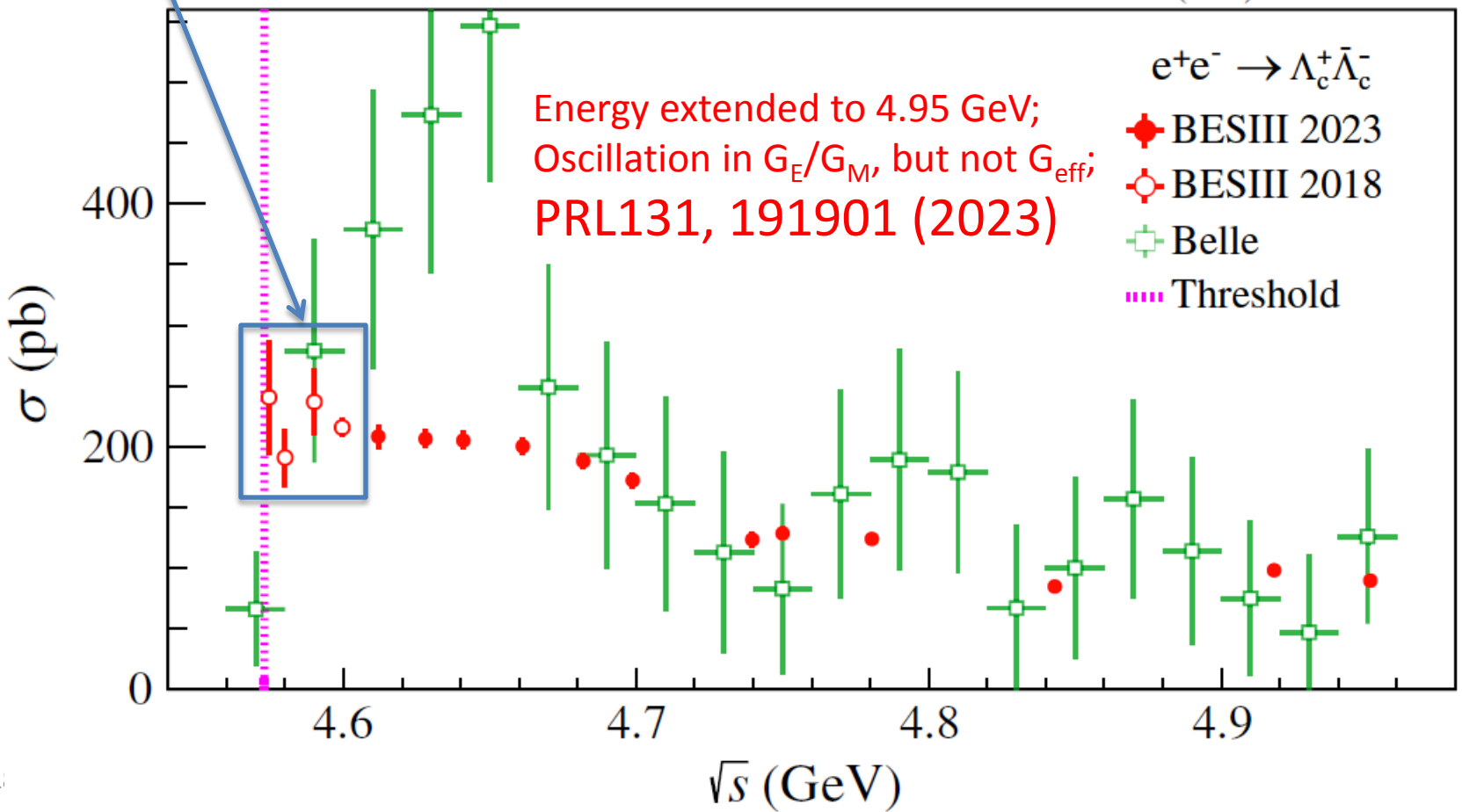




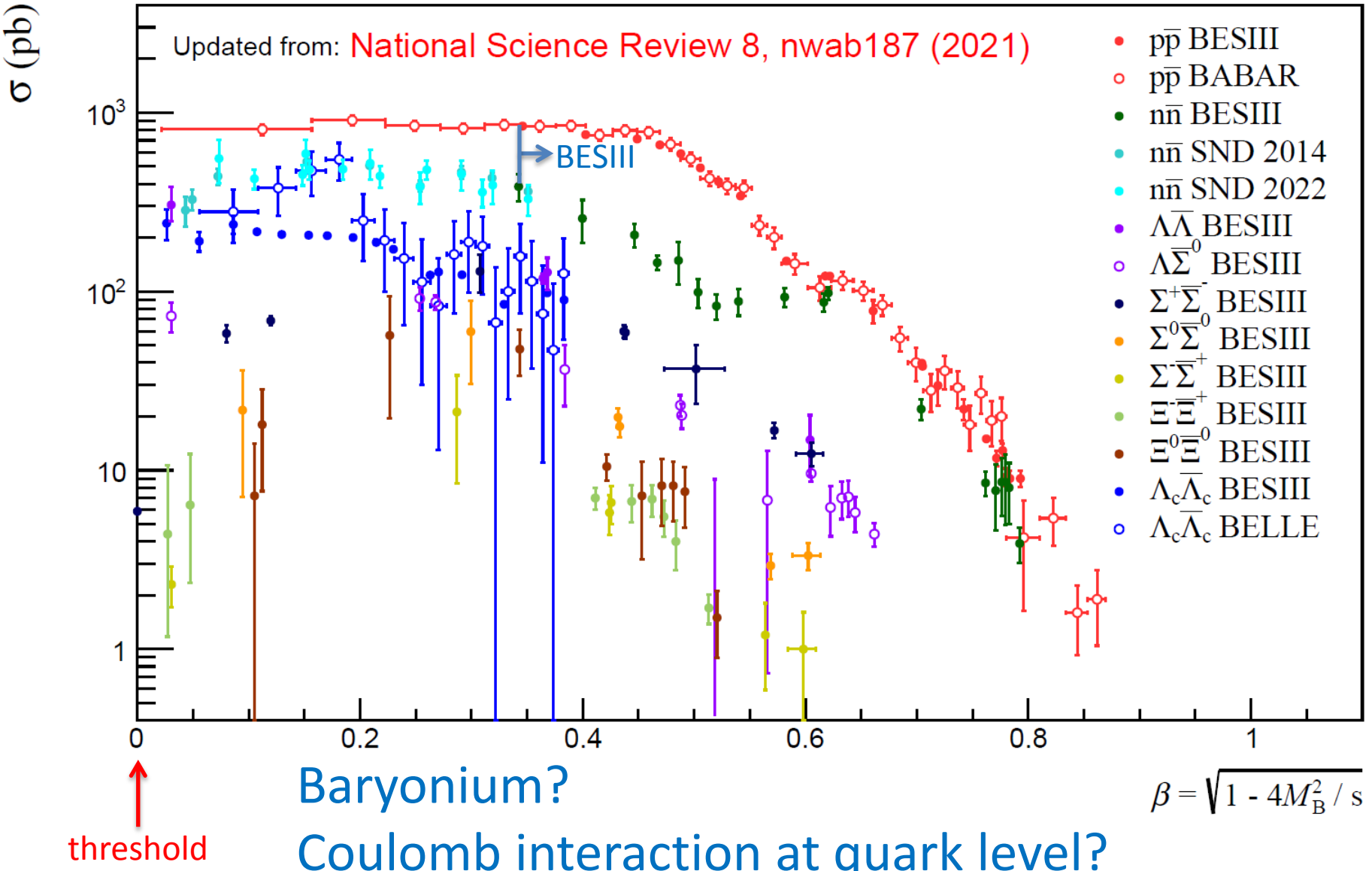
$e^+e^- \to \Lambda_c\bar{\Lambda}_c$

First observation of non-zero cross section near threshold;
first Λ_c form factor measurement.
PRL 120,132001 (2018)





Baryon-pair productions in a glance



Baryonium?

Coulomb interaction at quark level?

To access nucleon-pair threshold!

- Low down to ~1.8GeV? Original design 2-4.6GeV;
- First proposed in 2018.11;
- Discussed & refined within τ-QCD group;
- 2020.4 recognized in BESIII White Paper;
- On schedule 2024.3;
- 2024.4-6 data taken!

BESIII white paper →

- Future Physics Programme of BESIII Chin.Phys.C44, 040001 (2020)

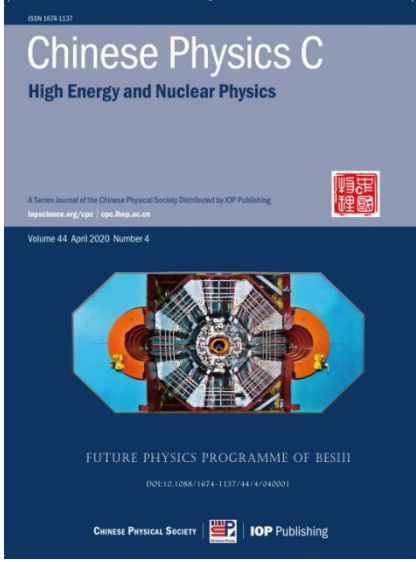


Table 7.1. List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The rightmost column shows the number of required data taking days with the current (T_C) and upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

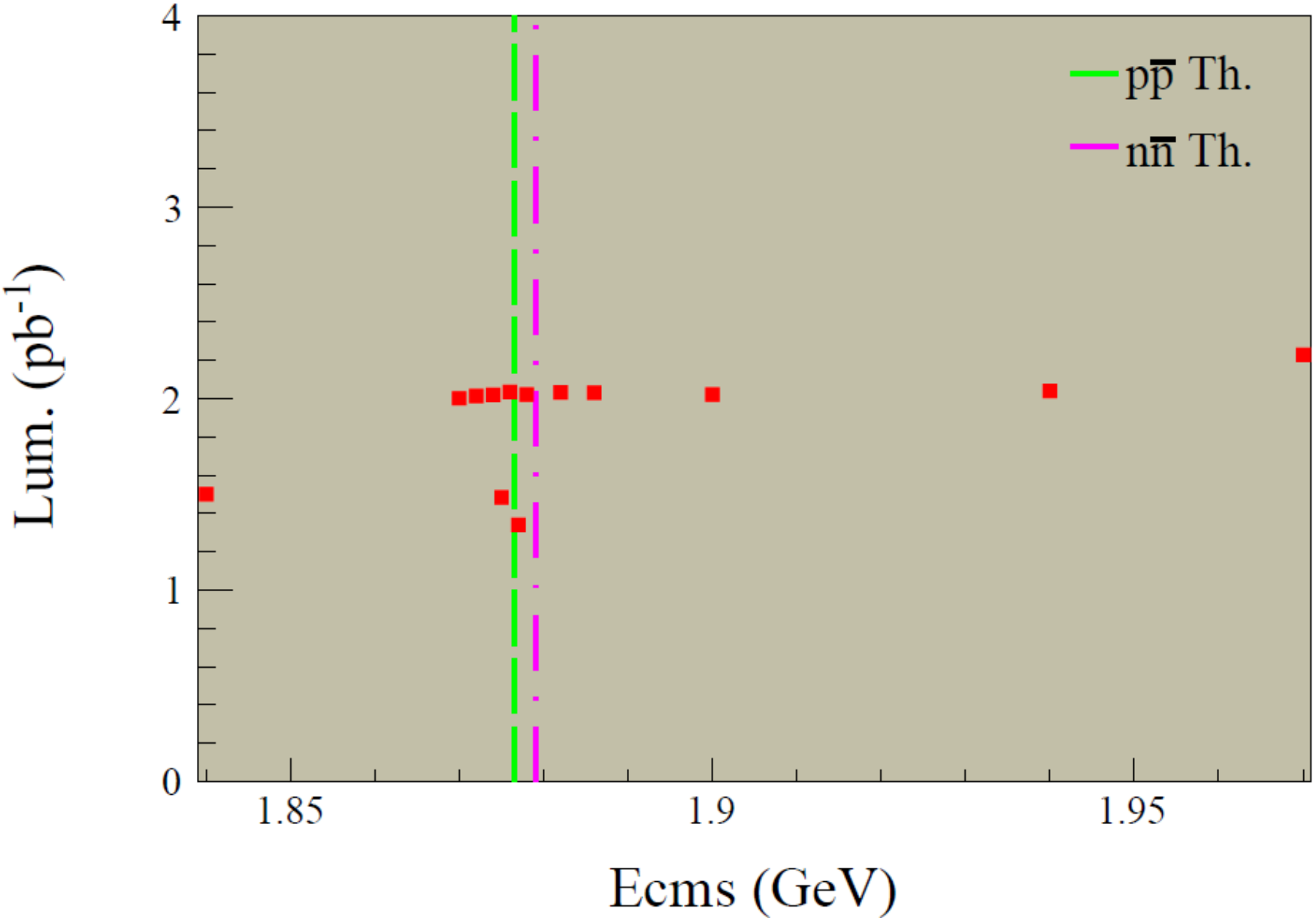
Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

Data @ 13 points in [1.84, 1.97] GeV ☺

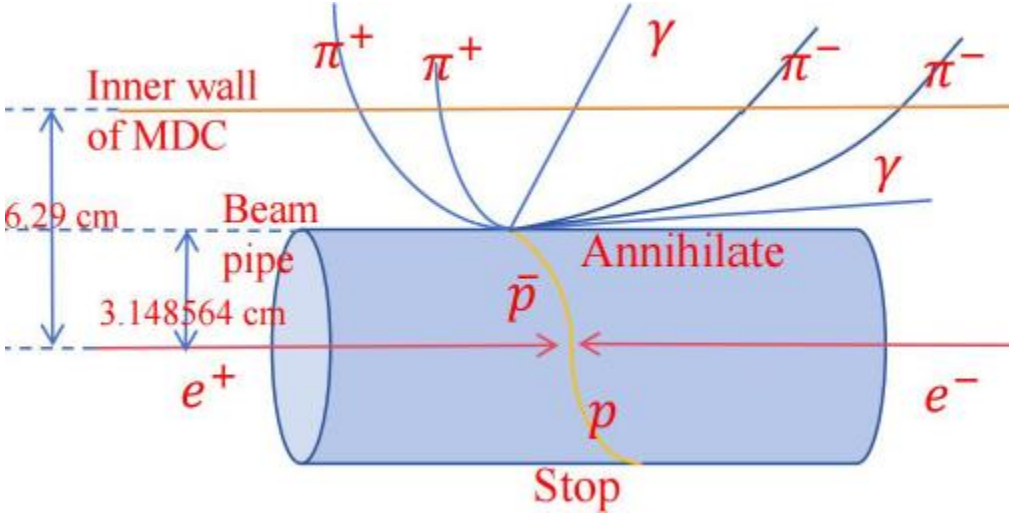
Actual/plan: 13/23 points, 24.8/95.5 pb^{-1} (26%) ☹

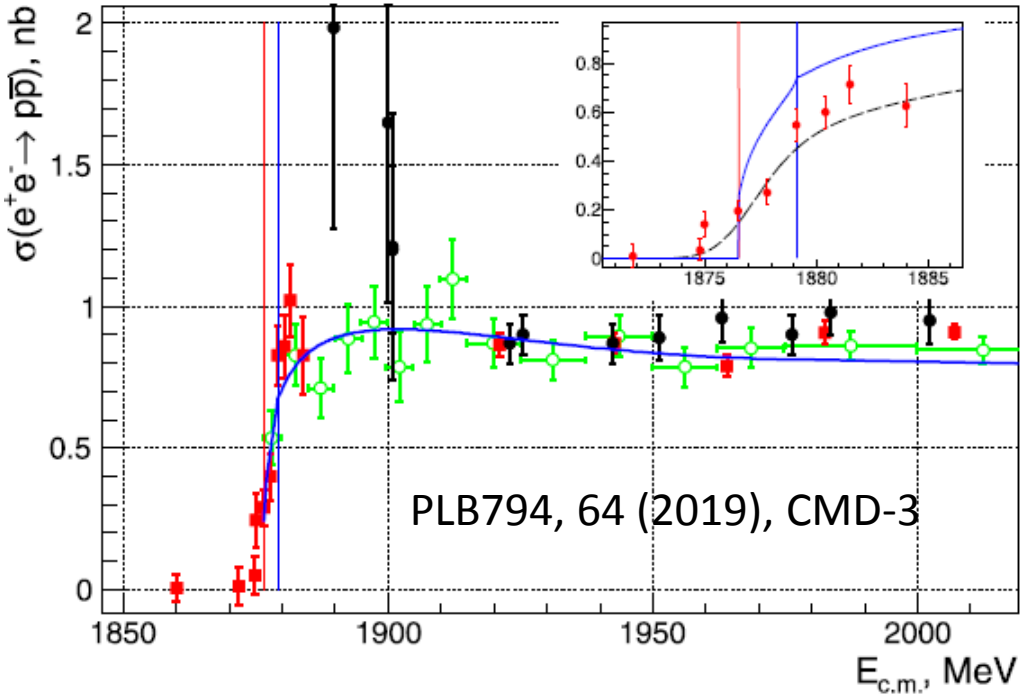
Ecm (MeV)	Run range	#runs	$\mathcal{L}_{\text{online}}$ (nb^{-1})	Dates / time span (day)
1840	81849-81970	113	1501.22	20240404-20240412 / 8.2
1870	81971-82104	131	2002.61	20240412-20240421 / 9.3
1872	82543-82656	112	2014.24	20240517-20240523 / 7.0
1874	82657-82783	107	2018.93	20240523-20240529 / 6.3
1875	82835-82909	71	1485.36	20240602-20240607 / 4.9
1876	82105-82203	88	2032.83	20240421-20240427 / 6.0
1877	82784-82834	50	1340.88	20240530-20240602 / 3.3
1878	82204-82261	57	2020.96	20240427-20240501 / 3.4
1882	82262-82310	49	2032.73	20240501-20240503 / 2.9
1886	82311-82358	47	2031.15	20240504-20240506 / 2.8
1900	82359-82404	46	2022.17	20240507-20240509 / 3.0
1940	82405-82462	57	2036.92	20240510-20240512 / 2.8
1970	82463-82530	66	2229.10	20240513-20240516 / 3.3
Total	81849-82909	994	24769.10	20240329-20240607 / 70

Online luminosity at each point



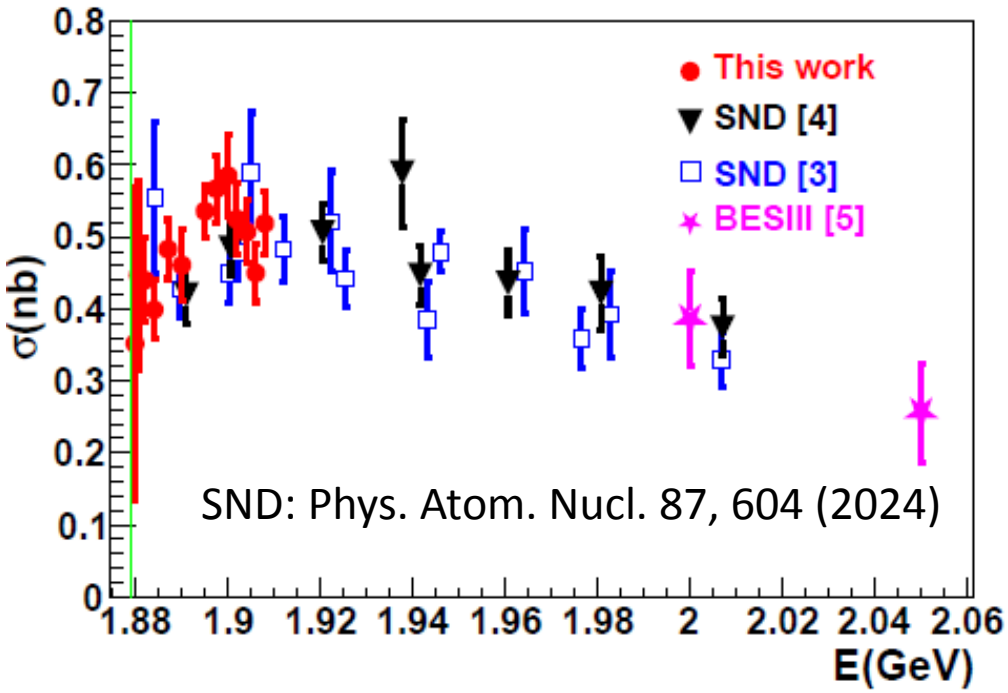
$p\bar{p}$: across the threshold



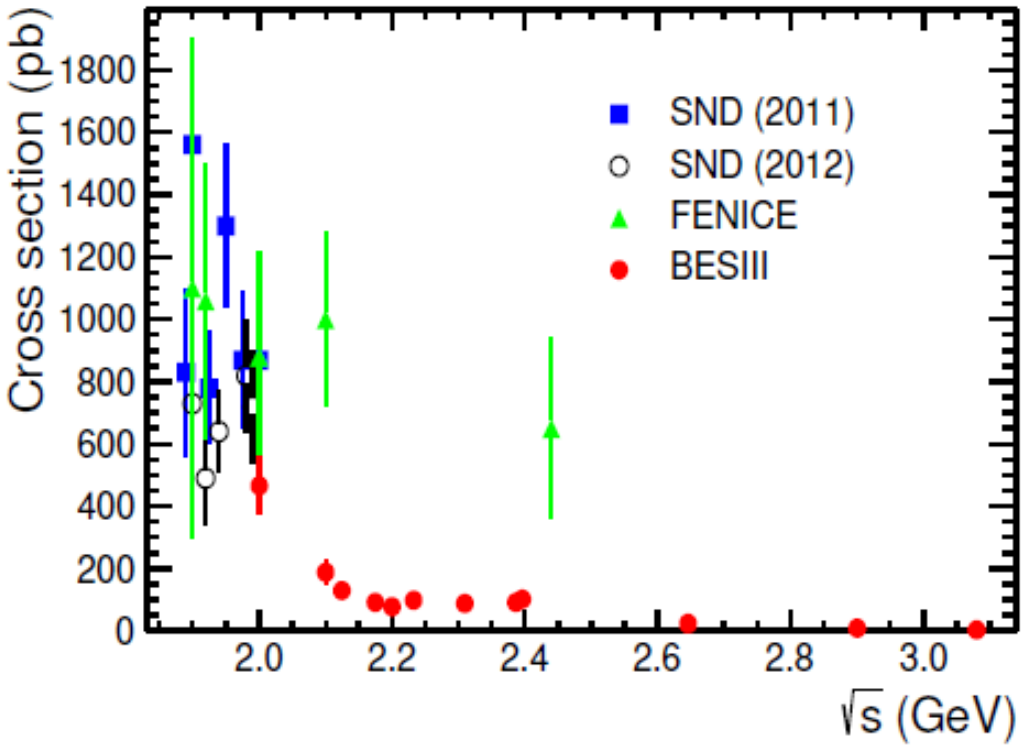


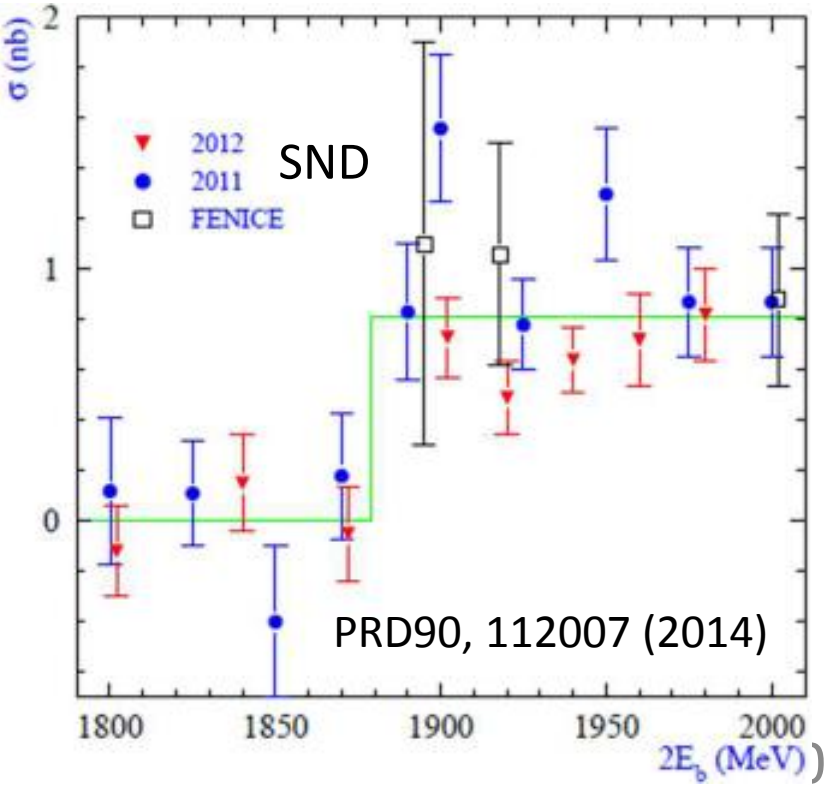
- Very close to threshold (≤1.94 GeV): vertex of secondary particles from annihilation;
- For higher energies (≥1.94 GeV): normal reconstruction;
- @1.94 GeV, try both methods.
- Looks promising!

$n\bar{n}$ production: across threshold



SND: Phys. Atom. Nucl. 87, 604 (2024)

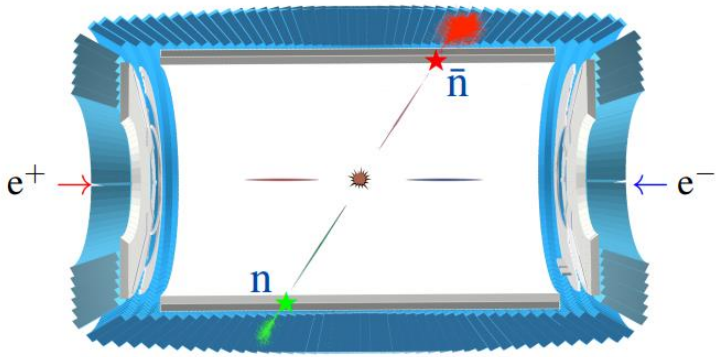




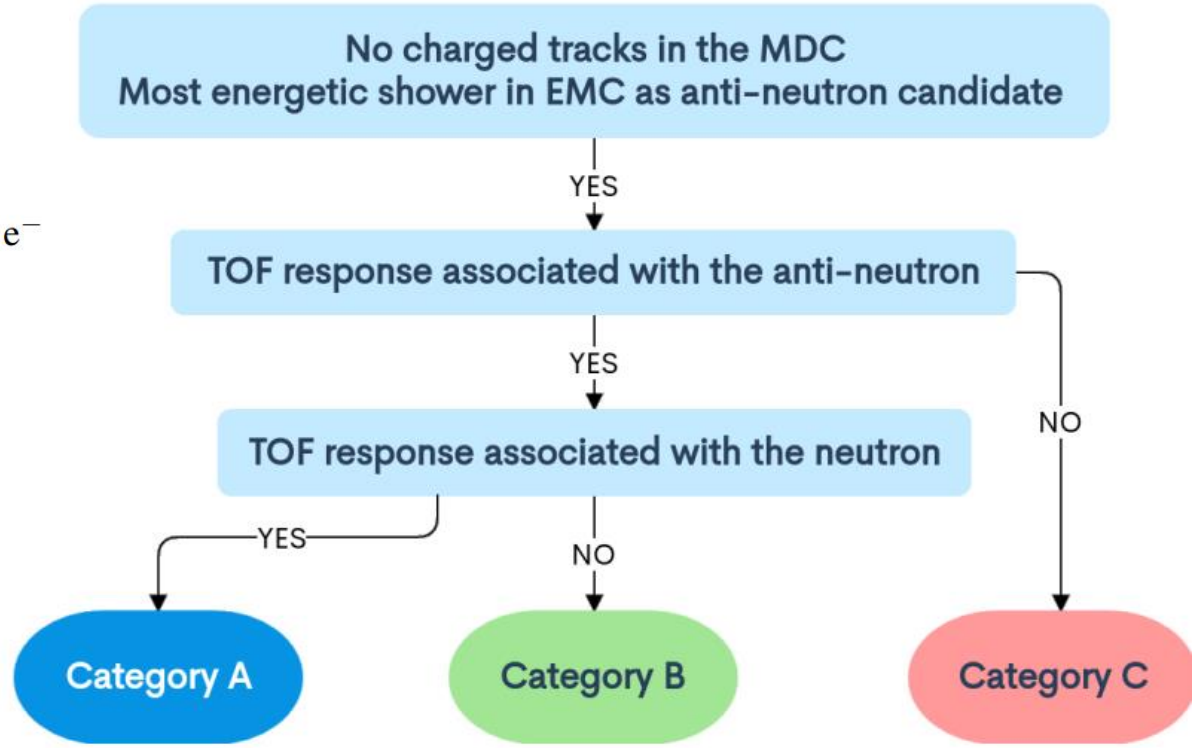
PRD90, 112007 (2014)

$n\bar{n}$: previous experience

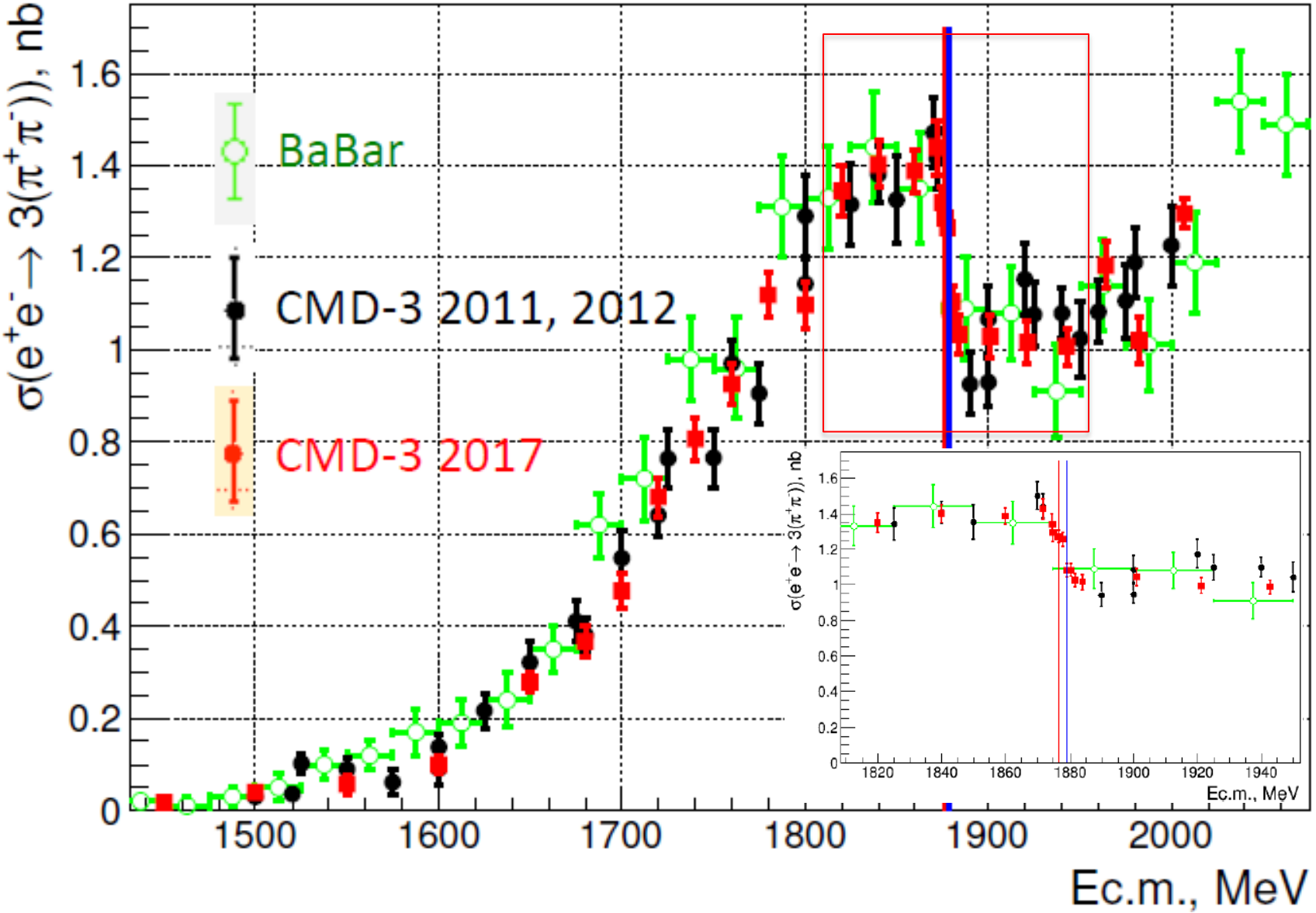
- Event selection very challenging;
- Successful in [2.0, 3.08] GeV, low efficiency;
- Expect to improve at energies < 2.0 GeV.



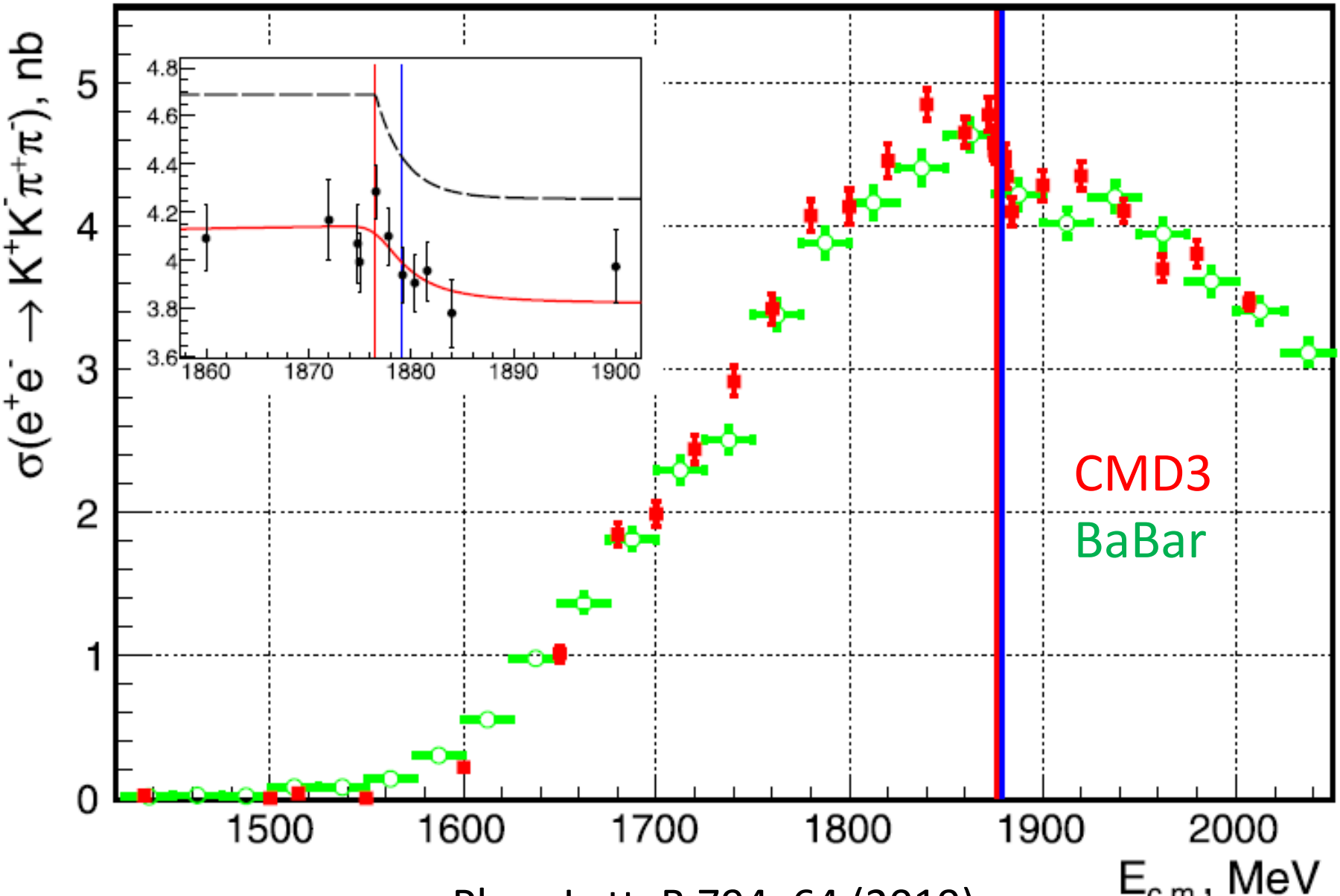
A typical event



$3(\pi^+\pi^-)$: sharp drop, at NN threshold?



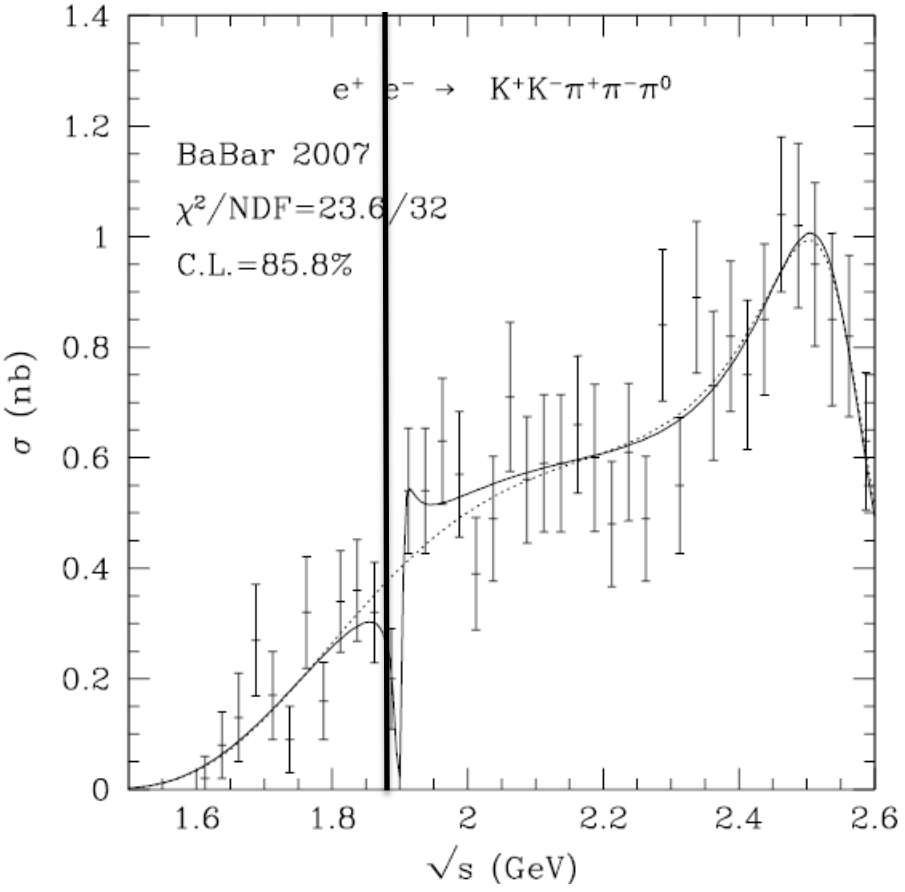
Structure also in $K^+K^-\pi^+\pi^-$

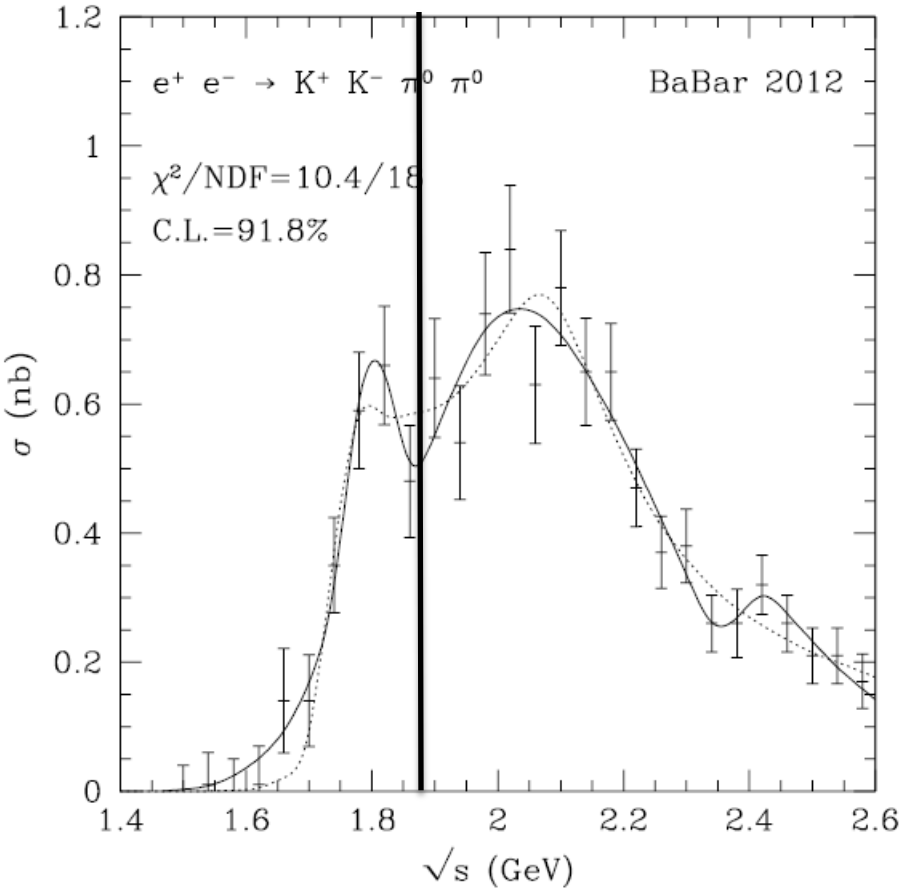


Phys. Lett. B 794, 64 (2019)

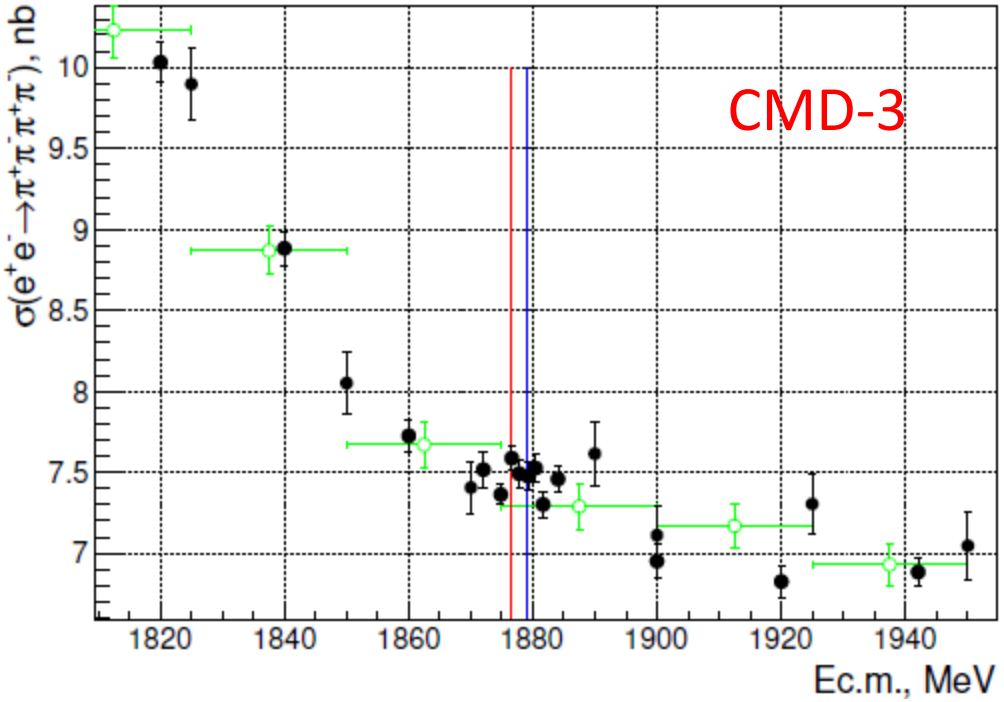
The $K^+K^-\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0\pi^0$ cases?

- Seems, but statistics not enough.

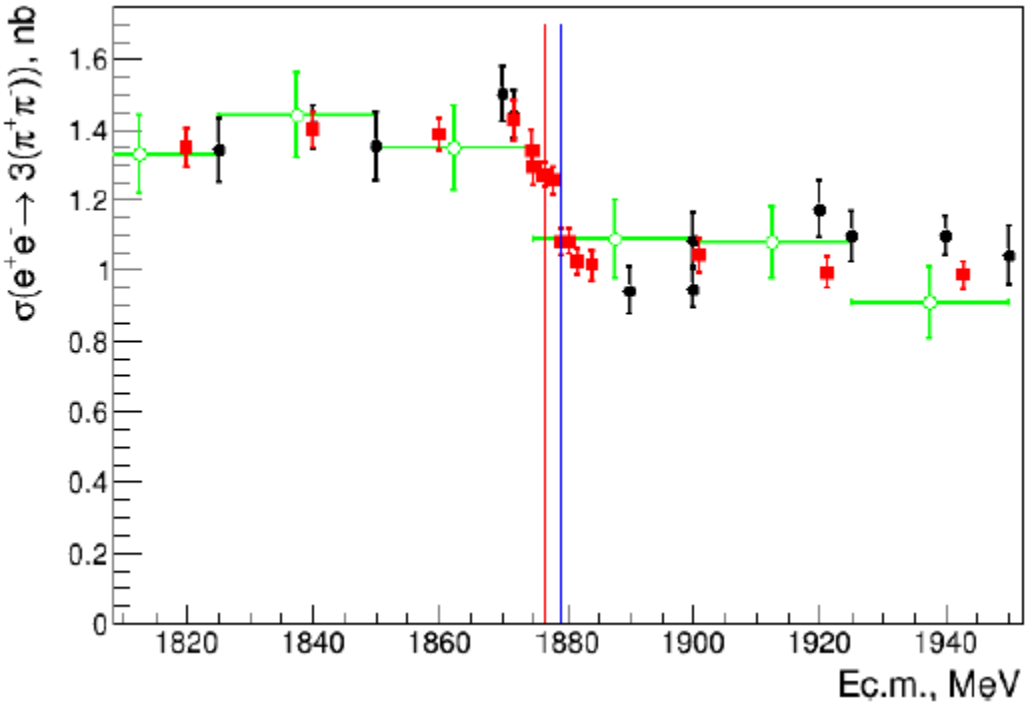




But no structure in $2(\pi^+\pi^-)$!

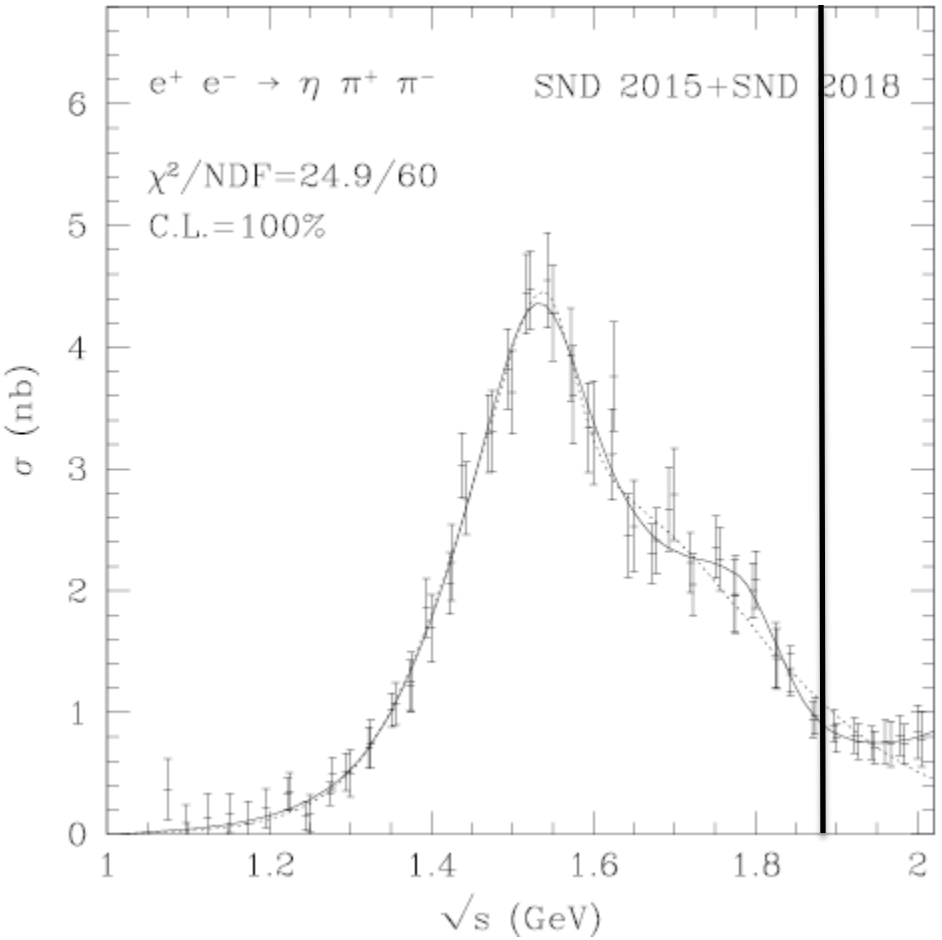


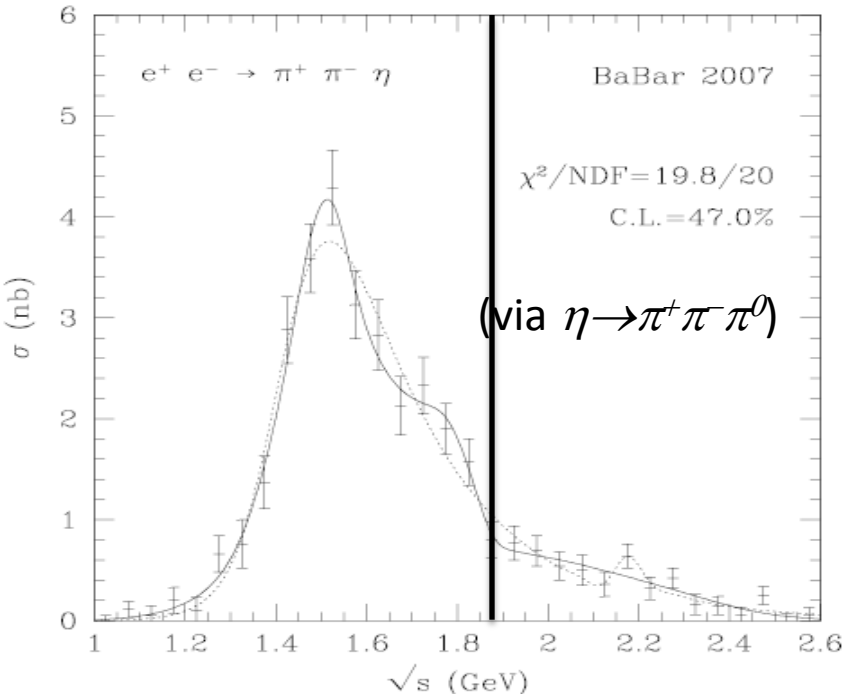
Contrary to $3(\pi^+\pi^-)$

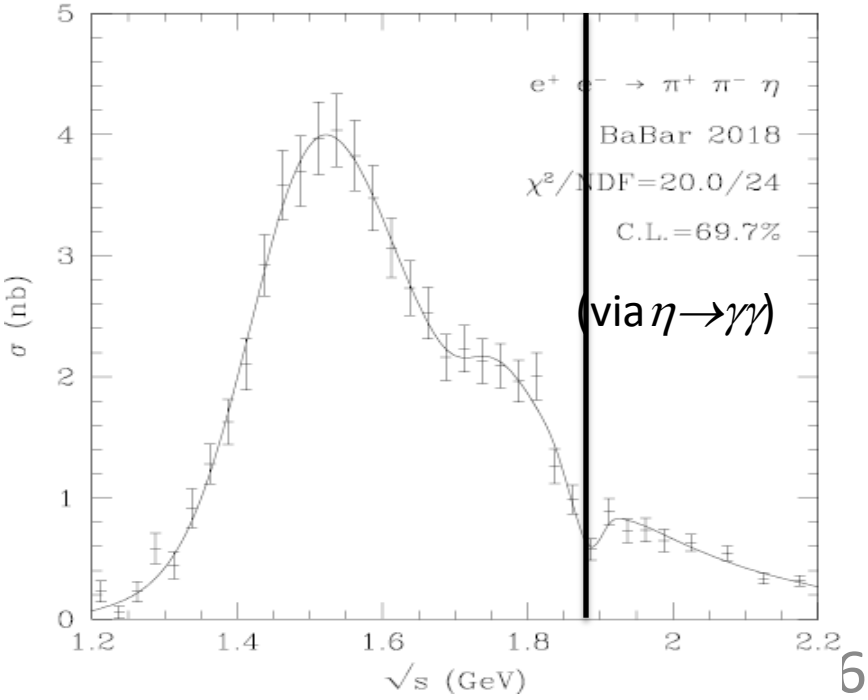


$\eta\pi^+\pi^-$

- Cross section drop

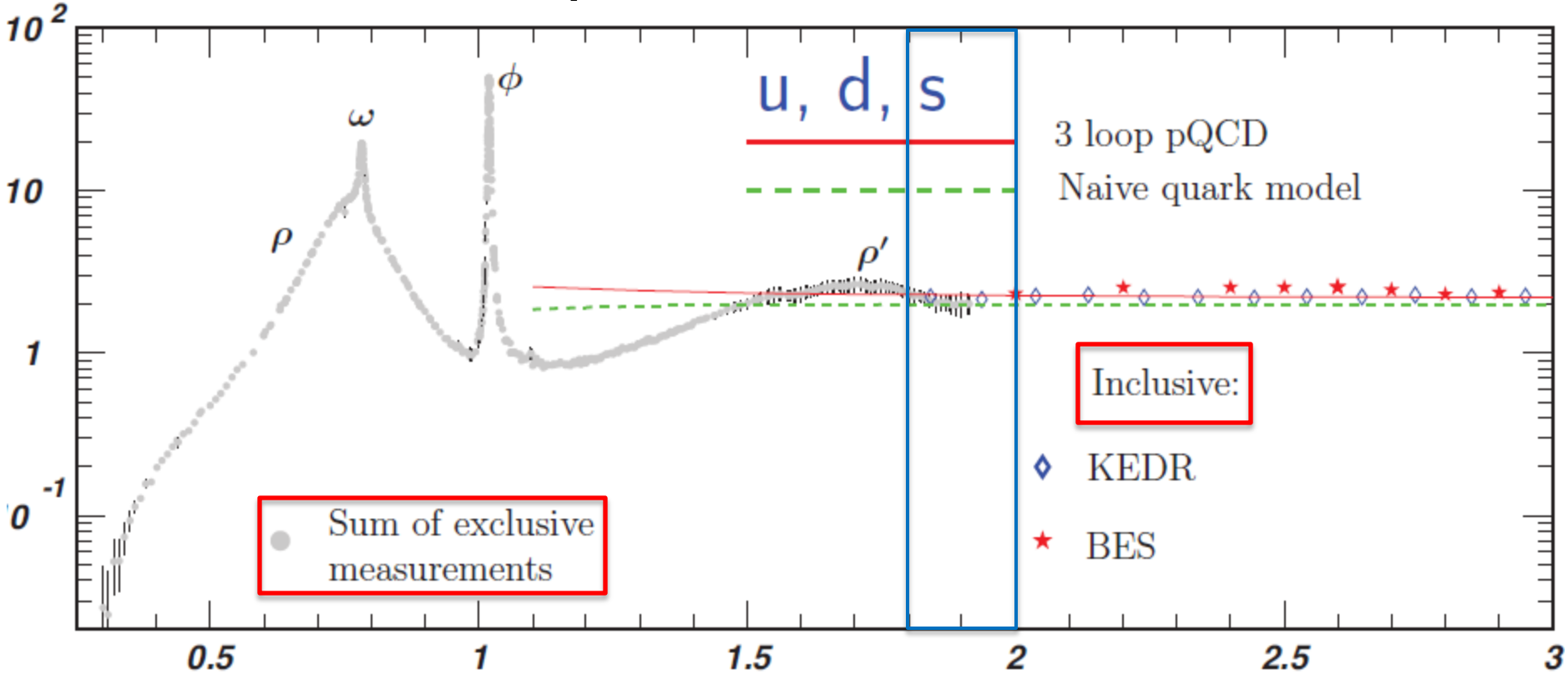






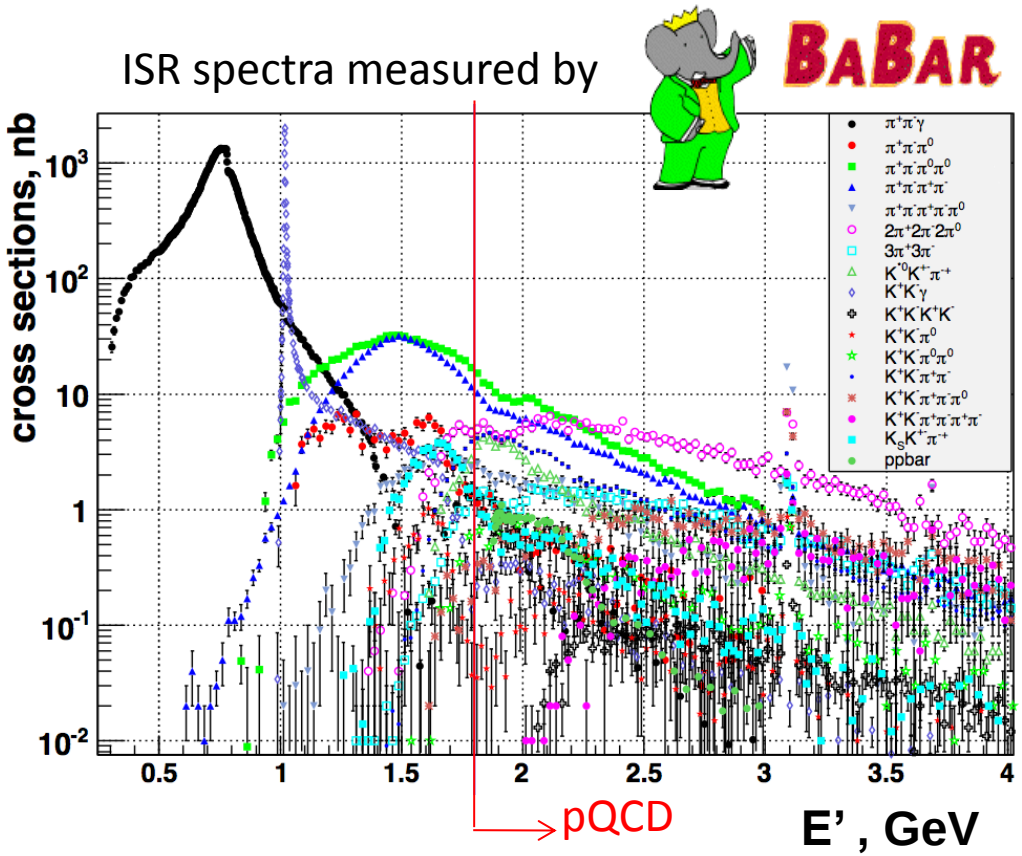
R: inclusive vs exclusive

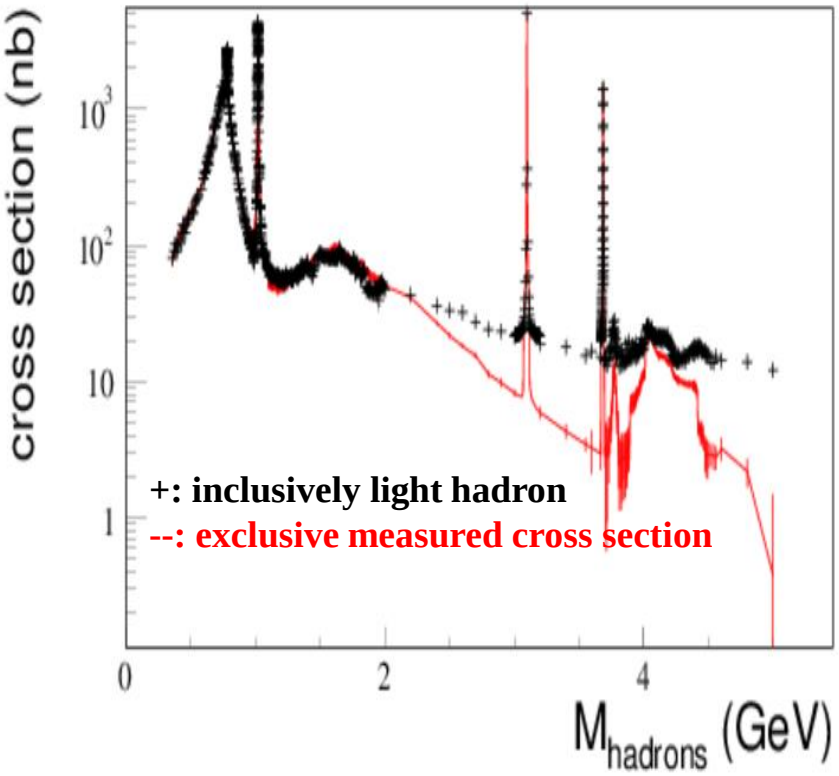
- <2 GeV: exclusive; >2 GeV: inclusive
- 1.8-2.0 GeV: try both exclusive and inclusive.



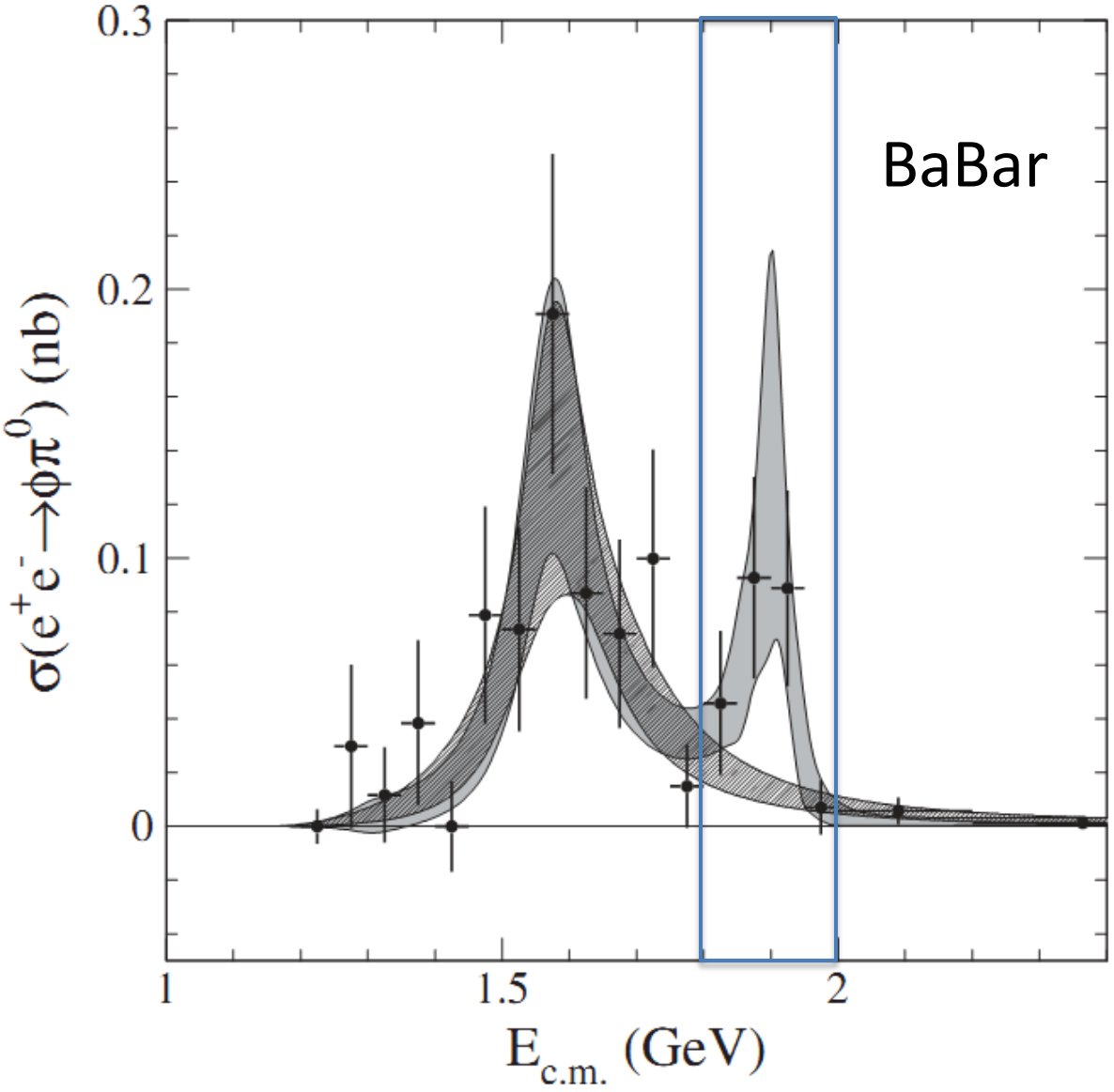
R: inclusive vs exclusive

- Most exclusive channels measured with ISR

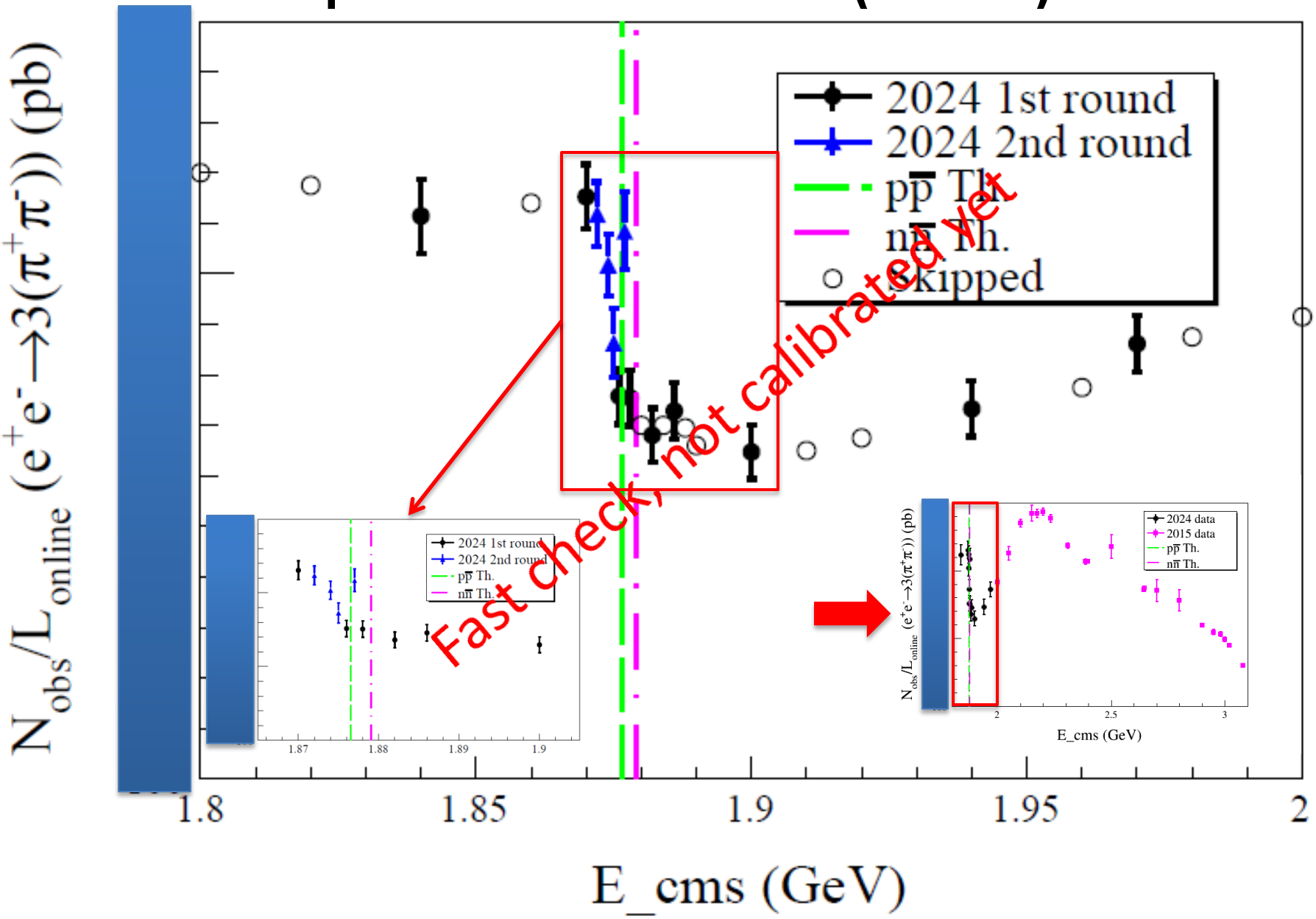




Search for ρ(1910)?



A peek: $e^+e^- \to 3(\pi^+\pi^-)$



Summary

- Mysterious $N\bar{N}$ threshold;
- 1.84–1.97 GeV: new record for BEPC/BES;
- Data @ 13 energies, 24.8 pb^{-1} (online);
- Data ready for physics analysis;
- Opportunity to explore interesting behaviors.

- Inputs from theorists are extremely welcome!