# Nucleon-pair Production Near Threshold at BESIII

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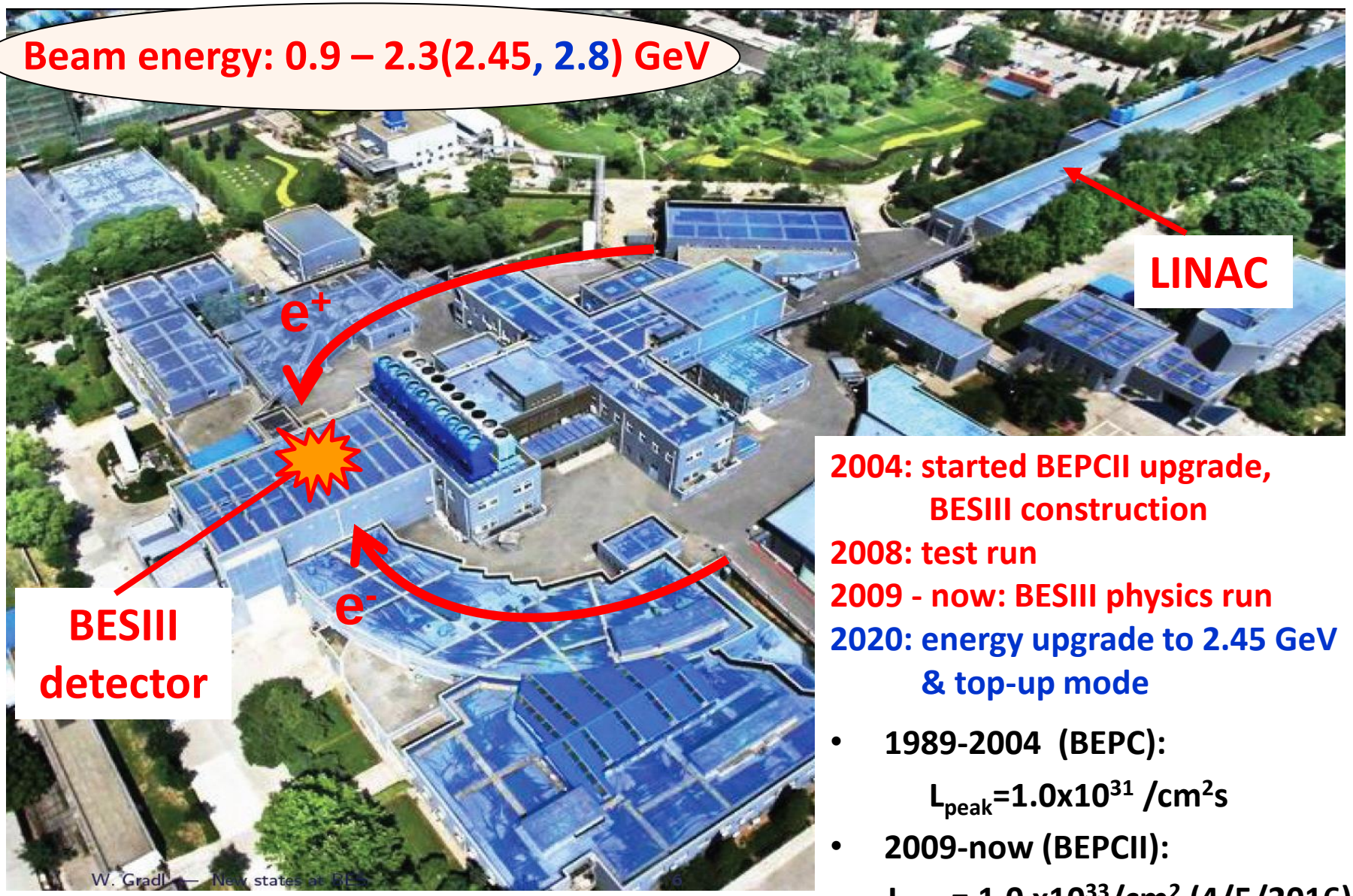
# Outline

- BEPCII/BESIII
- Nucleon-pair production thresholds
- Threshold effects of baryon-pair productions
- Production of nucleon-pair across thresholds

- A new window: 1.8-2.0 GeV at BESIII

# Beijing Electron Positron Collider (BEPCII)




2004: started BEPCII upgrade, BESIII construction

2008: test run

2009 - now: BESIII physics run

2020: energy upgrade to 2.45 GeV & top-up mode

- 1989-2004 (BEPC):

  $L_{peak}$=1.0x$10^{31}$ /cm$^2$s

- 2009-now (BEPCII):

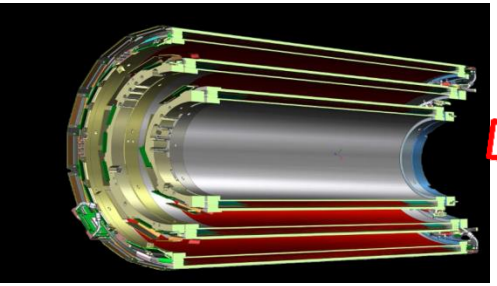
  $L_{peak}$= 1.0 x$10^{33}$/cm$^2$ (4/5/2016)

# The BESIII Detector

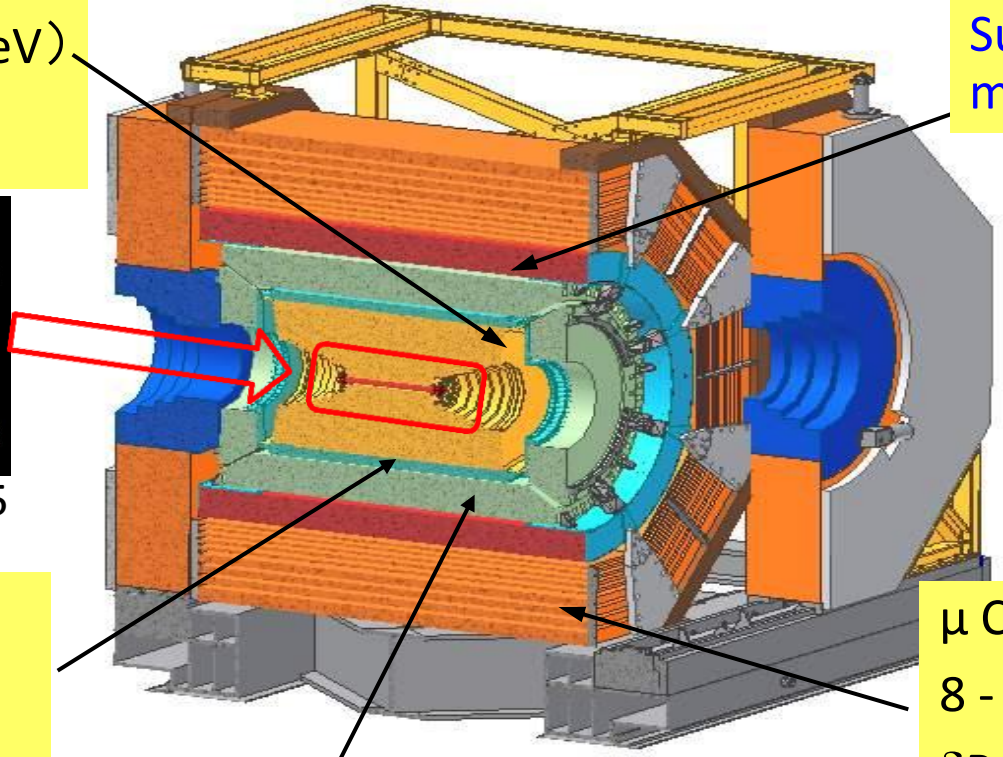
Drift Chamber (MDC)

$\sigma p/p\ (^0/_0) = 0.5\%(1GeV)$

$\sigma_{dE/dx}\ (^0/_0) = 6\%$



On 2024.10.5



Super-conducting magnet (1.0 Tesla)

Time of Flight (TOF)

$\sigma_T$: 90 ps for Barrel;

110 ps $\rightarrow$ 65 ps for Endcaps

μ Counter

8 - 9 layers RPC

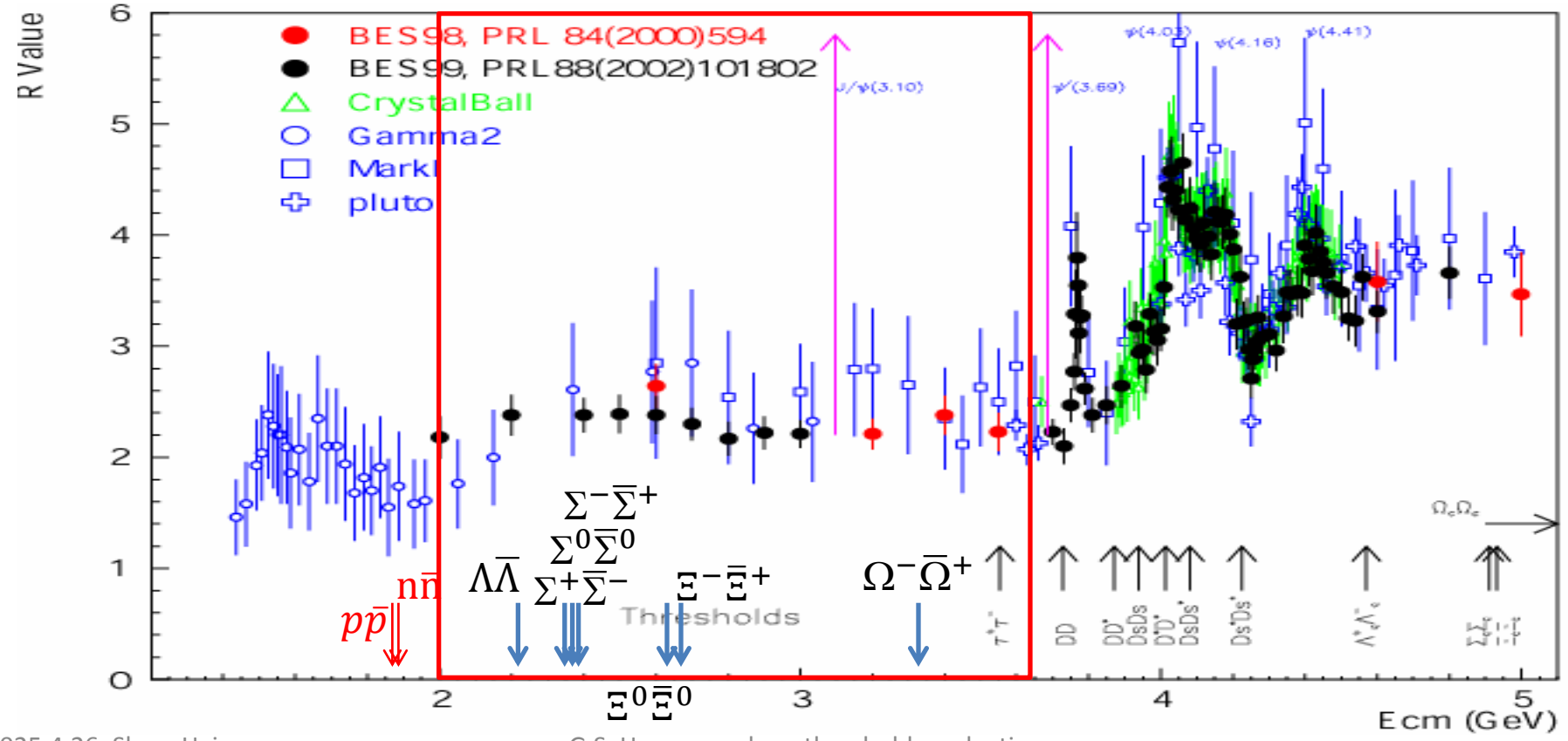
$\delta R$=1.4 cm~1.7 cm

EMC: $\sigma E/\sqrt{E}(^0/_0) = 2.5\ \%$ (1 GeV)

(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

# Features in zone of BEPCII/BESIII

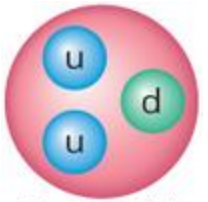
- Transition region for (non-)perturbative QCD;
- Rich charmonium, charmonium-like states;
- Excited and exotic light hadron states;
- **Baryon-pair production thresholds**.



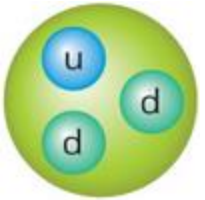
# Nucleon production at BESIII

- As cornerstone of our matter world, the properties of nucleon (proton and neutron), such as size, mass, spin and magnetic moment, 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)

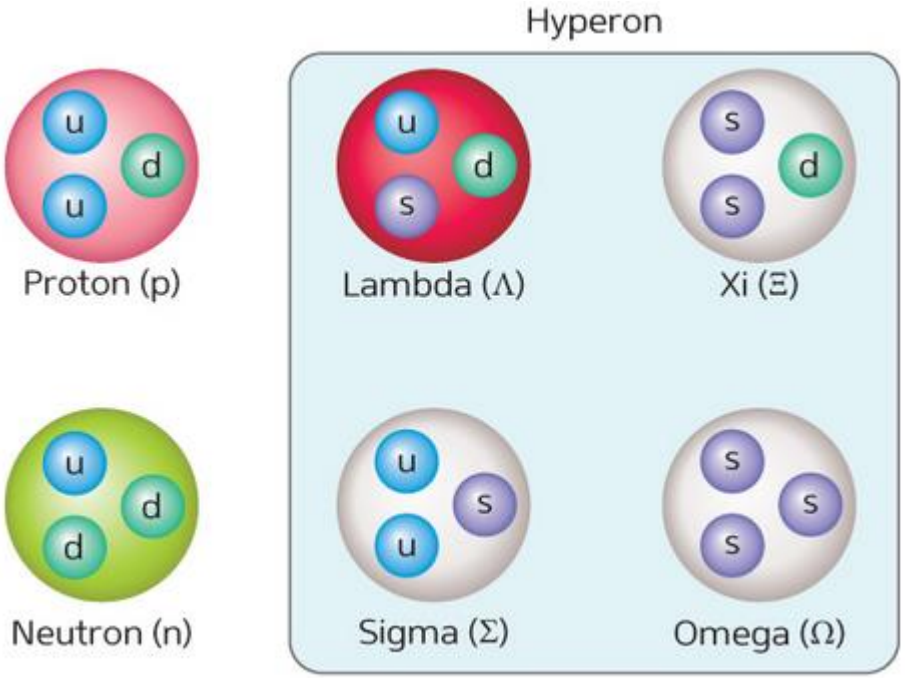


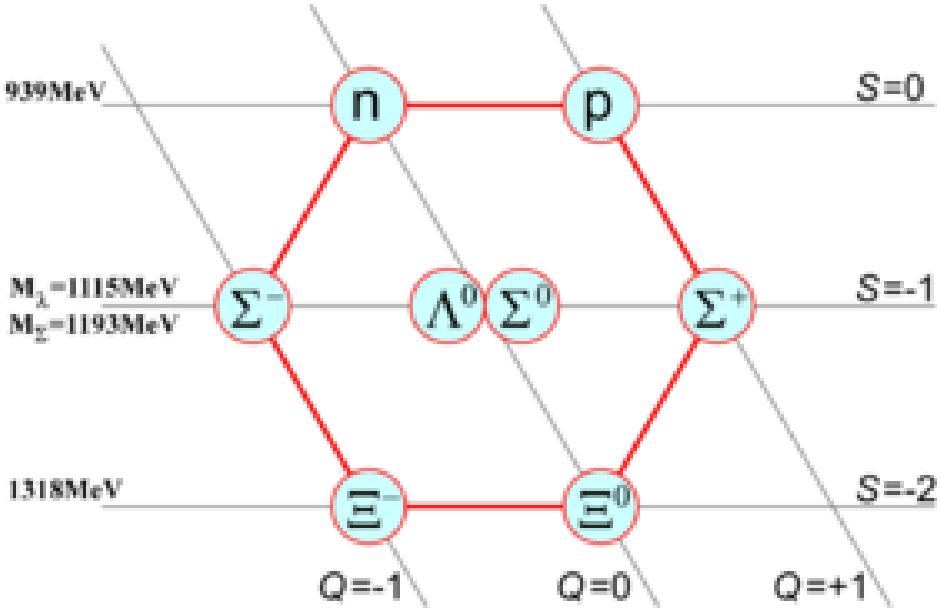
Neutron (n)

# 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

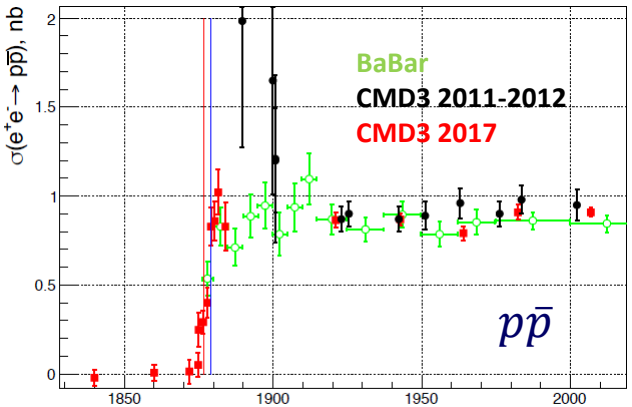
# Baryon-pair production near threshold

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

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

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

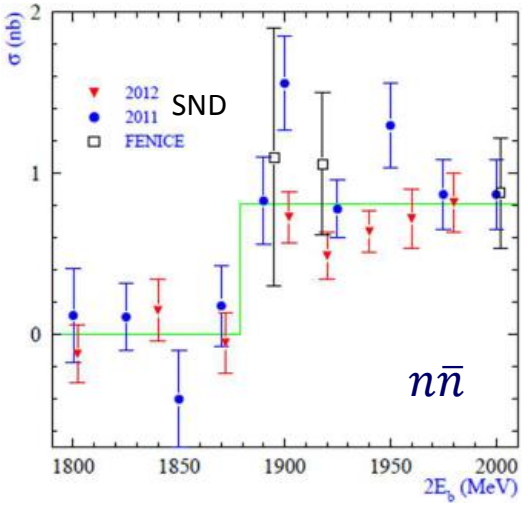
Coulomb factor $C = \begin{cases} \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}, & \text{for charged } B\bar{B} \\ 1, & \text{for neutral } B\bar{B} \end{cases}$




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

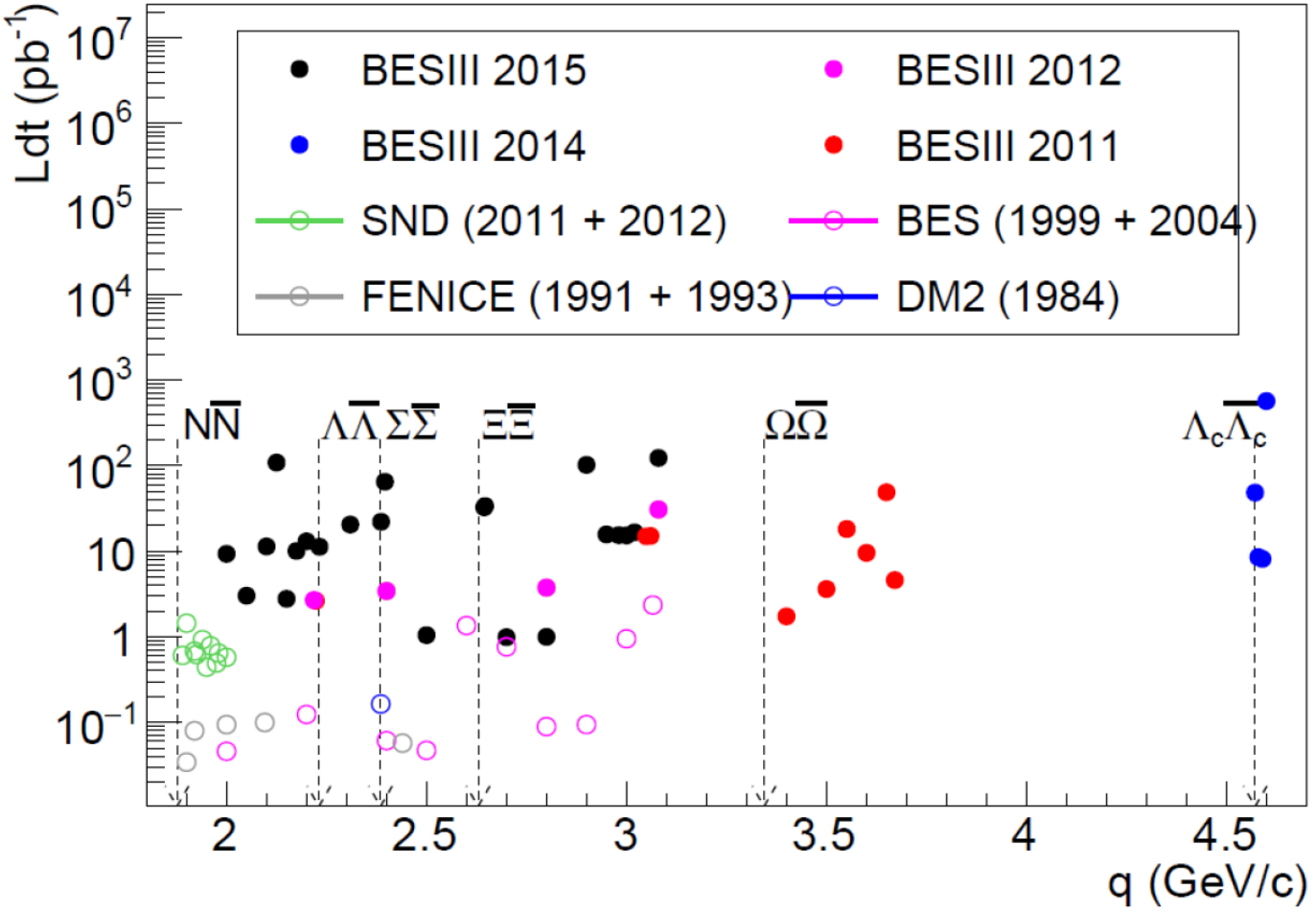
How about other baryon-pairs?

0 expected at threshold!



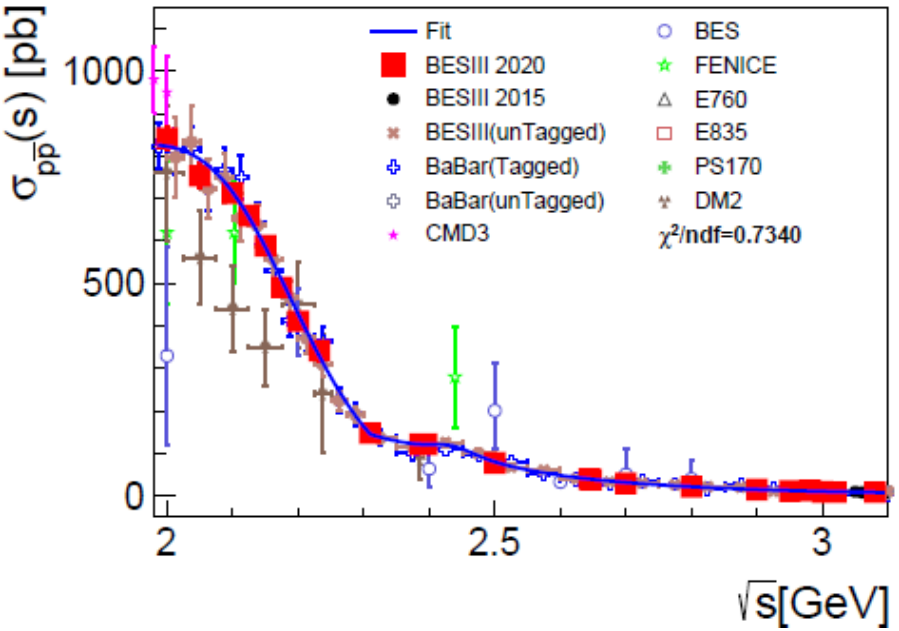
# Previous BESIII data at continuum

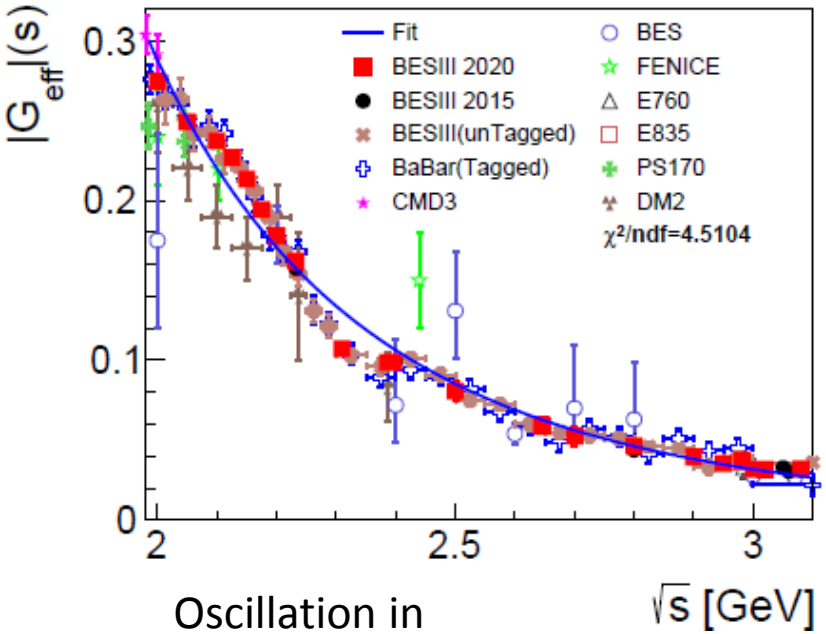
- Lowest energy is 2.0 GeV;
- ~800 $pb^{-1}$ in 2.0 – 3.671 GeV.

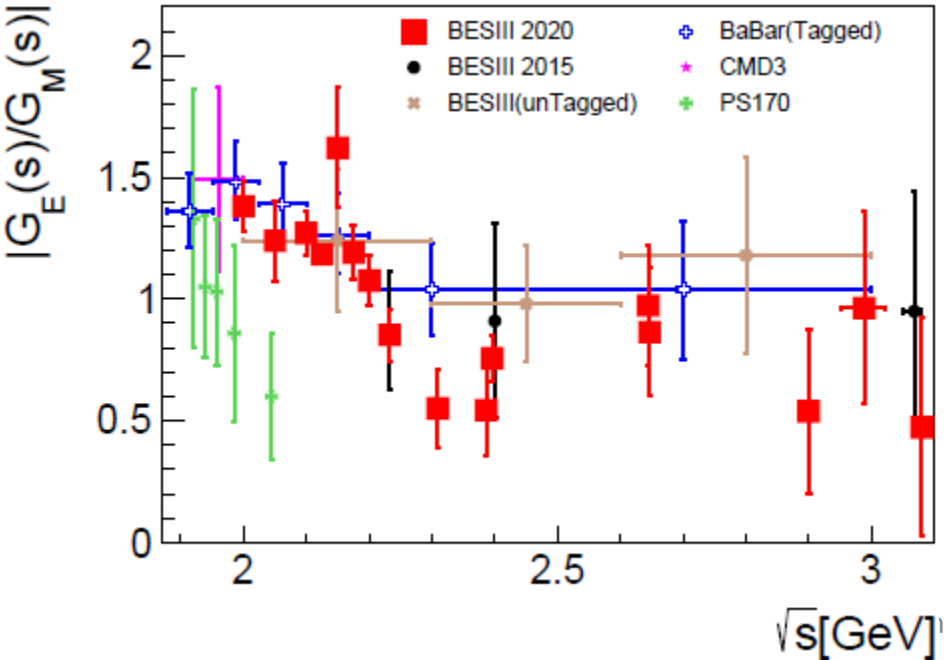


# $e^+e^- \to p\bar{p}$

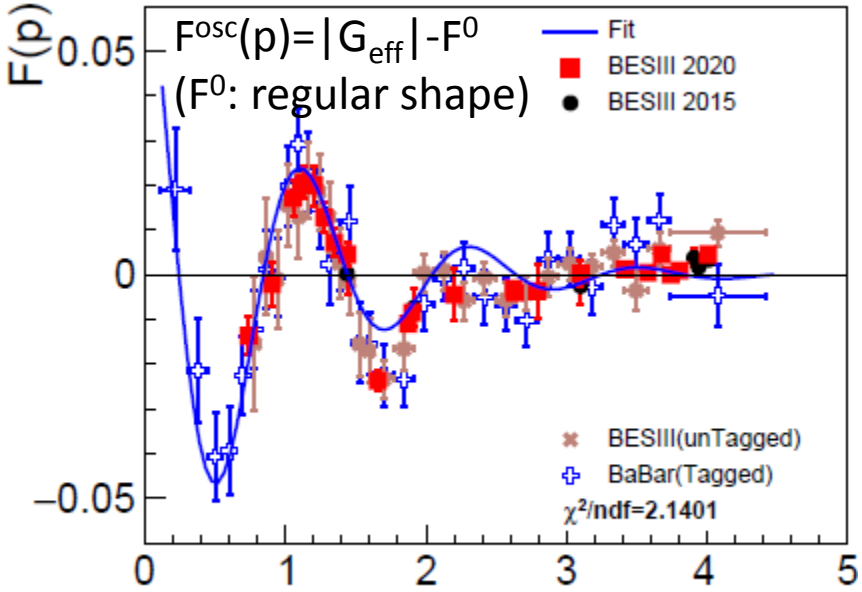
PRL 124, 042001 (2020)



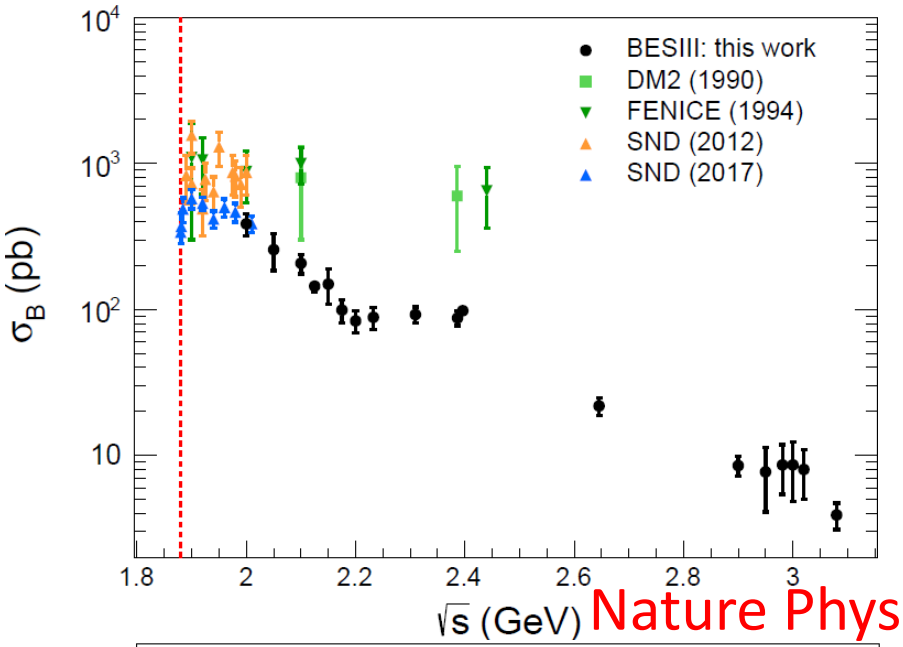



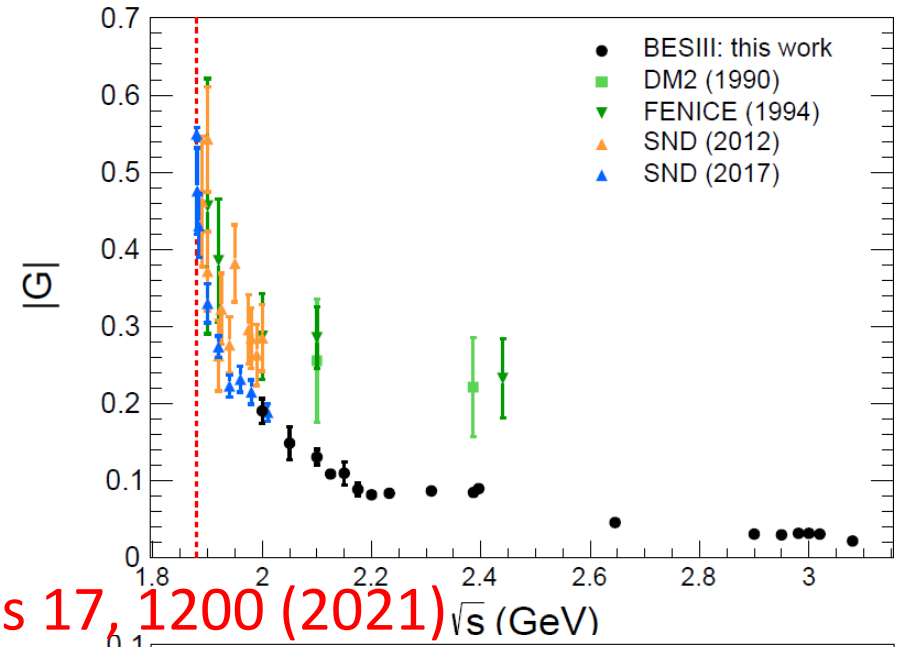




Oscillation in
$F^{osc}(p)=|G_{eff}|-F^0$
($F^0$: regular shape)

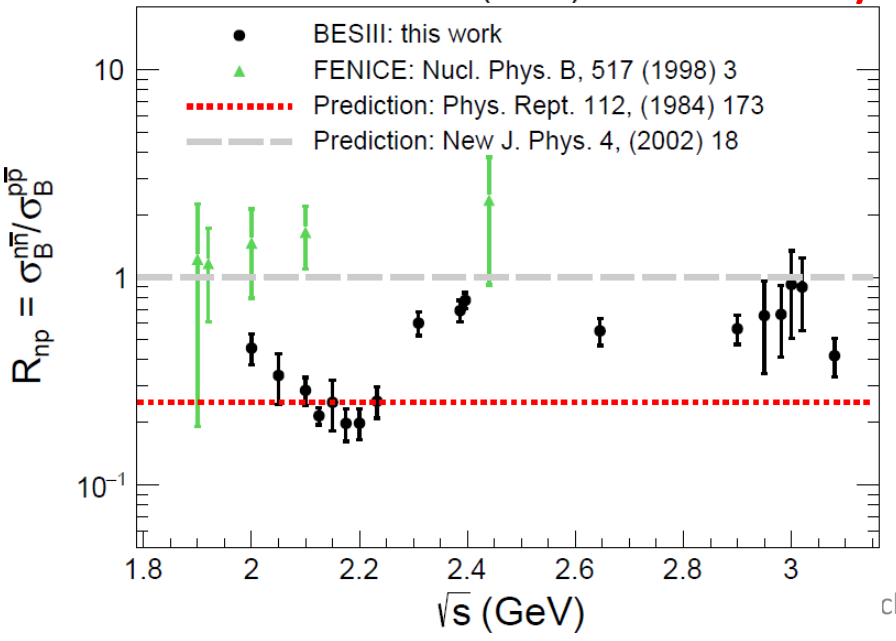


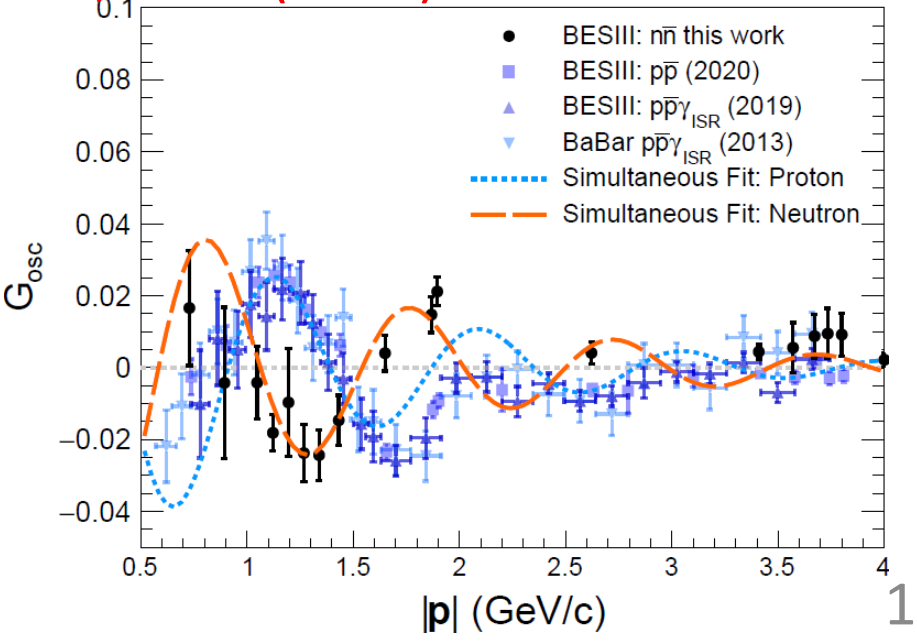
# Neutron cross section and effective FF



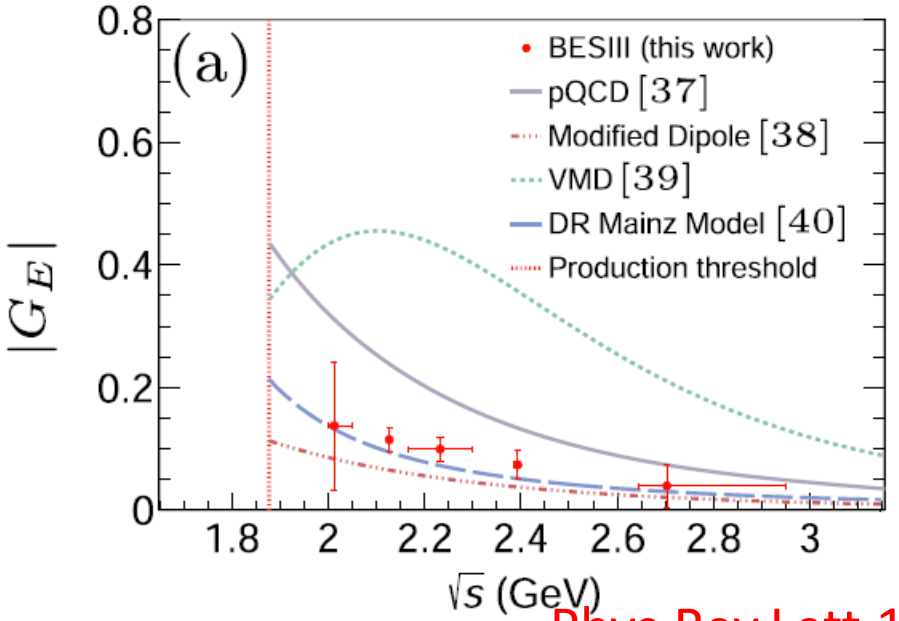



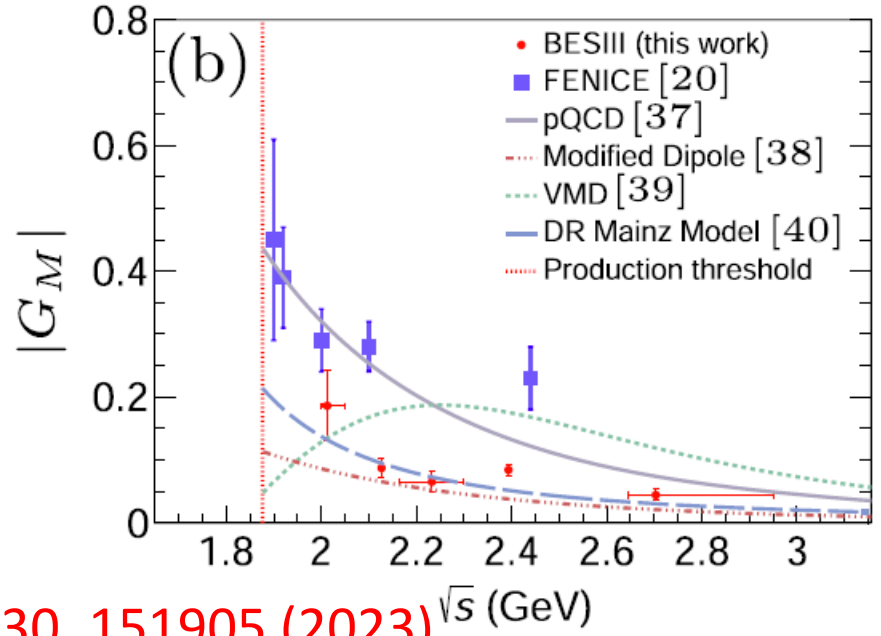

Nature Physics 17, 1200 (2021)



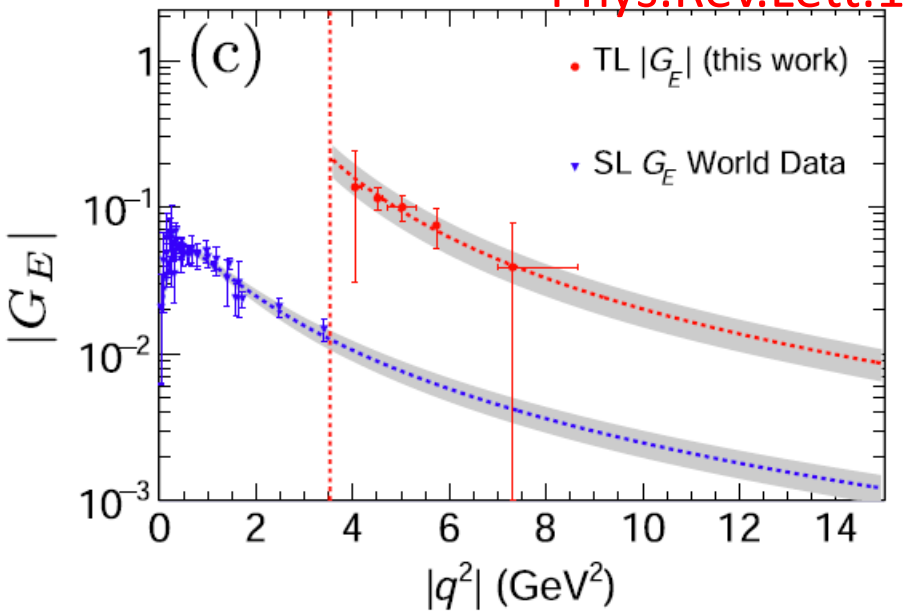



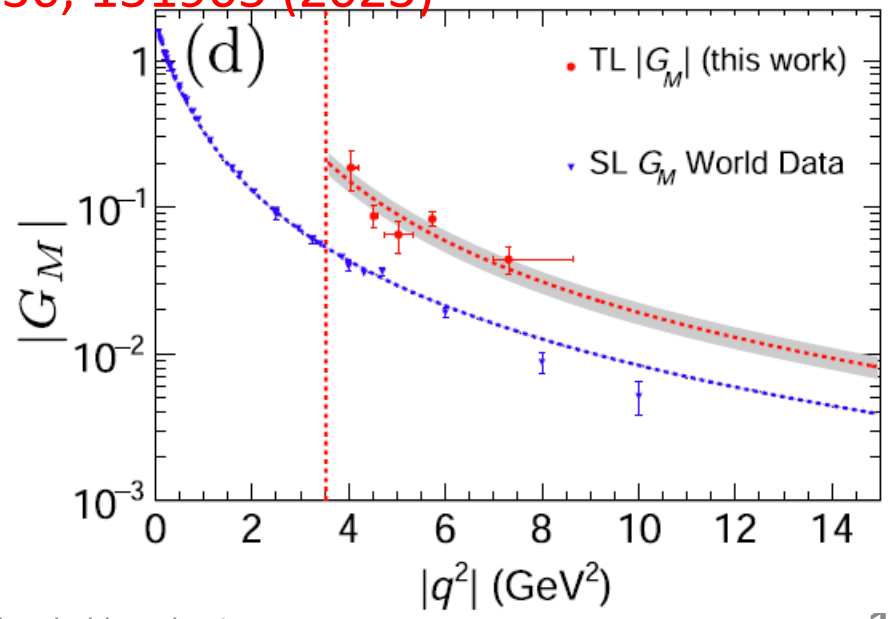
# Neutron E&M form factors




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



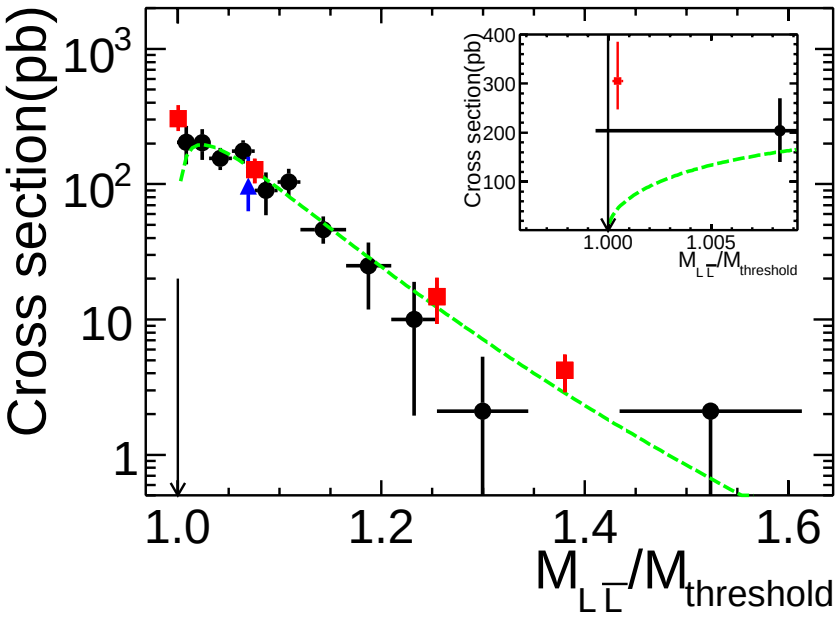



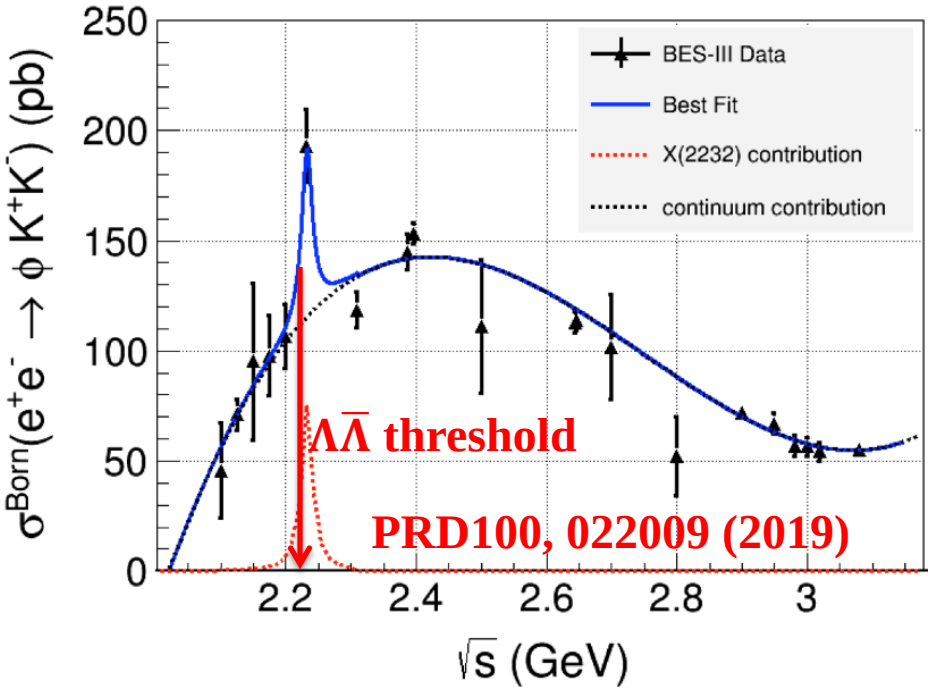
# $e^+e^- \to \Lambda\bar{\Lambda}$

| $\sqrt{s}$ (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 | $43 \pm 7$ | 12.9 | $312 \pm 51^{+72}_{-45}$ | |
| $2.2324_2$ | 2.63 | $22 \pm 6$ | 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 | $45 \pm 7$ | 25.3 | $128 \pm 19 \pm 18$ | $12.7 \pm 0.9 \pm 0.9$ |
| 2.800 | 3.75 | $8 \pm 3$ | 36.1 | $14.8 \pm 5.2 \pm 1.9$ | $4.10 \pm 0.72 \pm 0.26$ |
| 3.080 | 30.73 | $13 \pm 4$ | 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!
Related? $\phi K^+K^-$ &$2(K^+K^-)$:

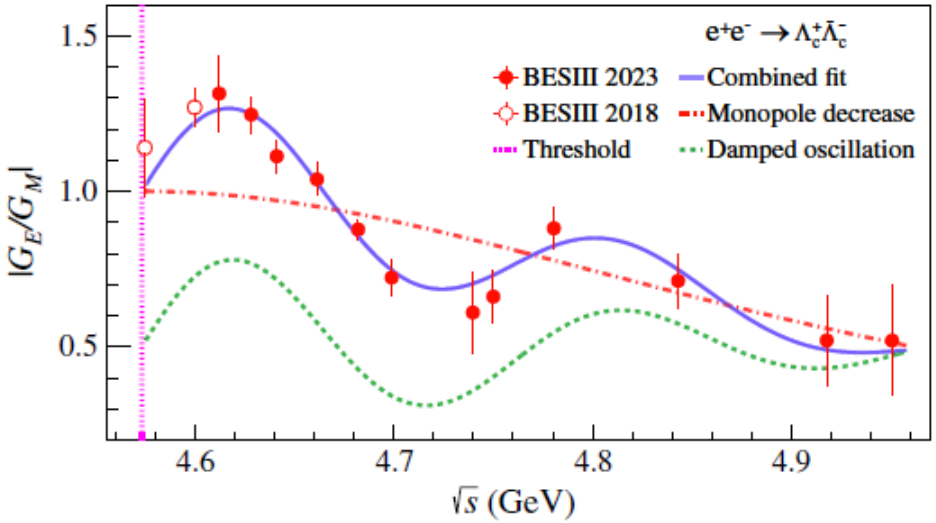
**PRD 97, 032013 (2018)**

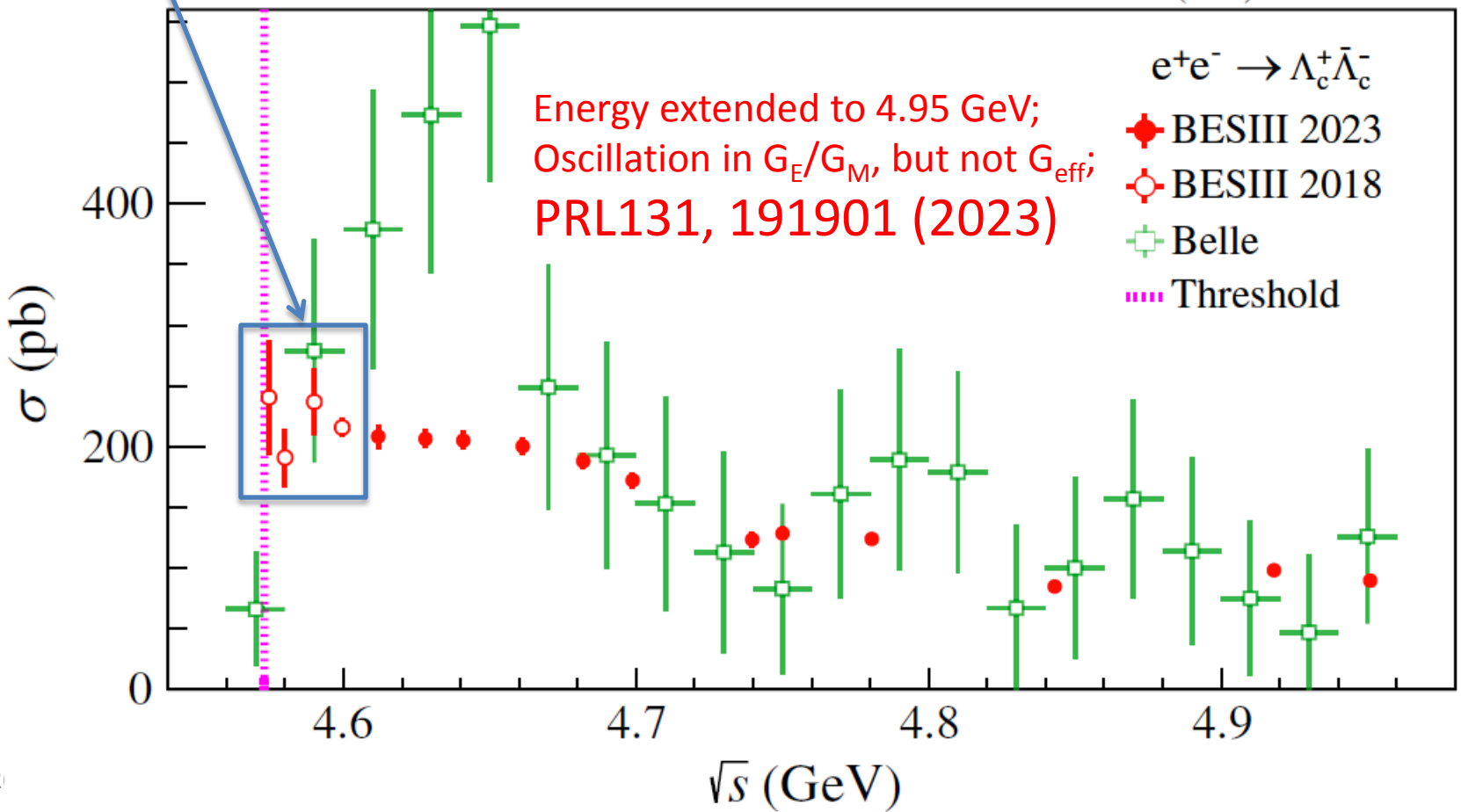


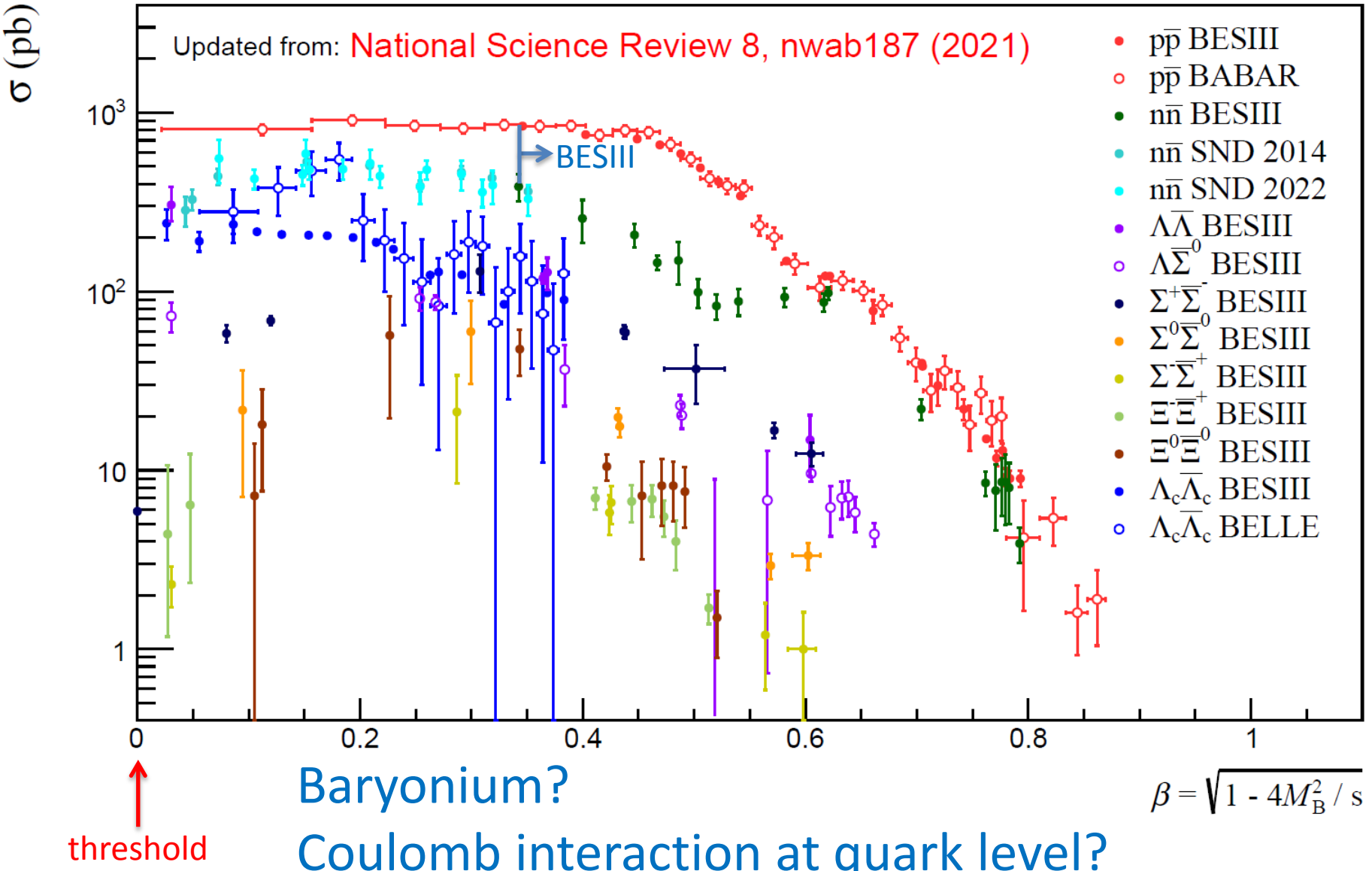
# $e^+e^- \to \Lambda_c\bar{\Lambda}_c$

First observation of non-zero cross section near threshold;
first $\Lambda_c$ 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)

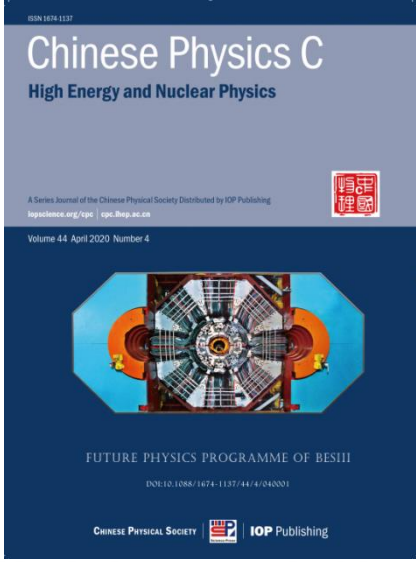



Table 7.1. List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The rightmost column shows the number of required data taking days with the current ($T_C$) and upgraded ($T_U$) machine. The machine upgrades include top-up implementation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

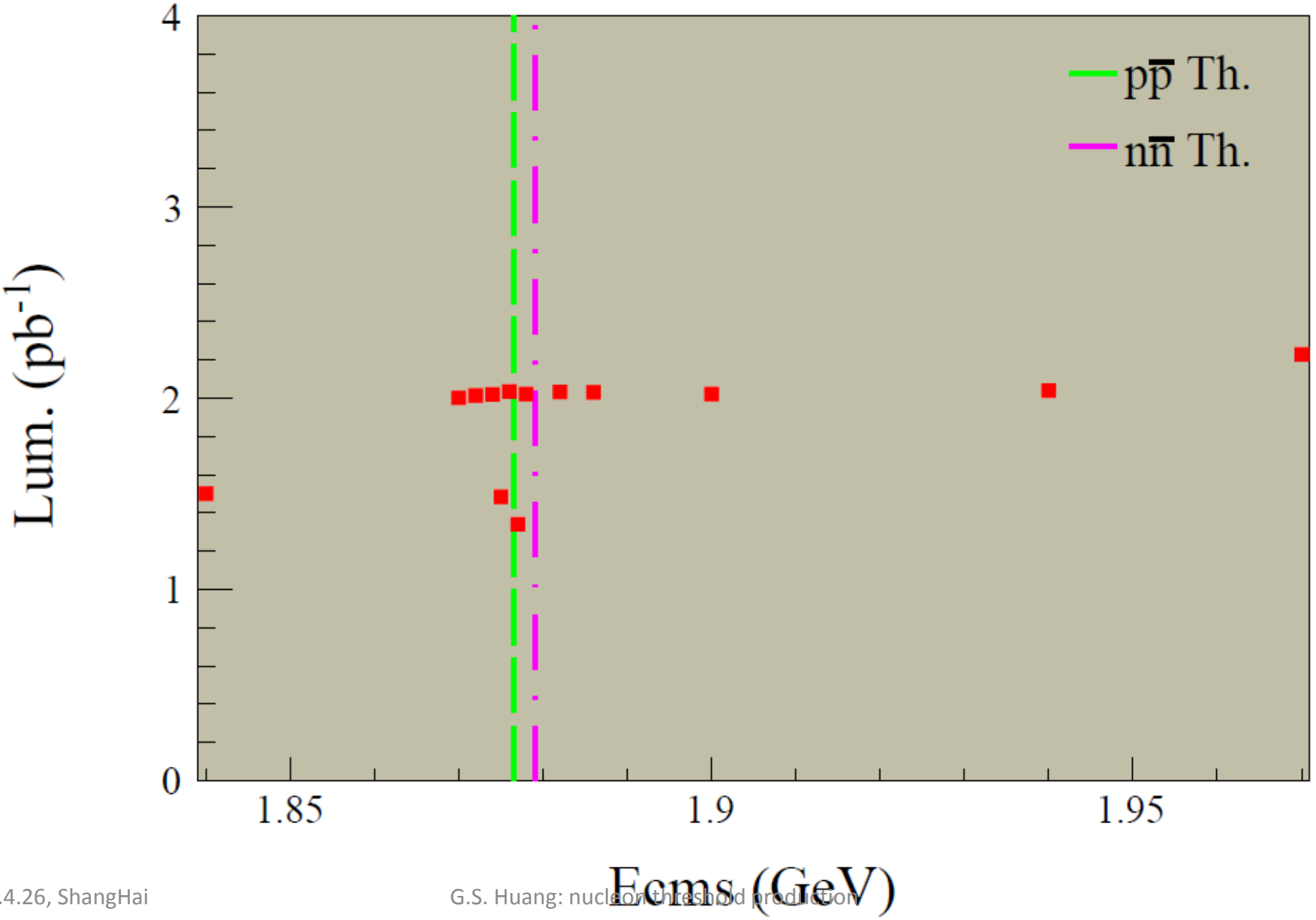
| Energy | Physics motivations | Current data | Expected final data | $T_C$ / $T_U$ |
|---|---|---|---|---|
| 1.8 - 2.0 GeV | $R$ values Nucleon cross-sections | N/A | 0.1 fb$^{-1}$ (fine scan) | 60/50 days |
| 2.0 - 3.1 GeV | $R$ values Cross-sections | Fine scan (20 energy points) | Complete scan (additional points) | 250/180 days |
| $J/\psi$ peak | Light hadron & Glueball $J/\psi$ 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 | $\Xi_c$ decays | N/A | 1.0 fb$^{-1}$ | 130/50 days |

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

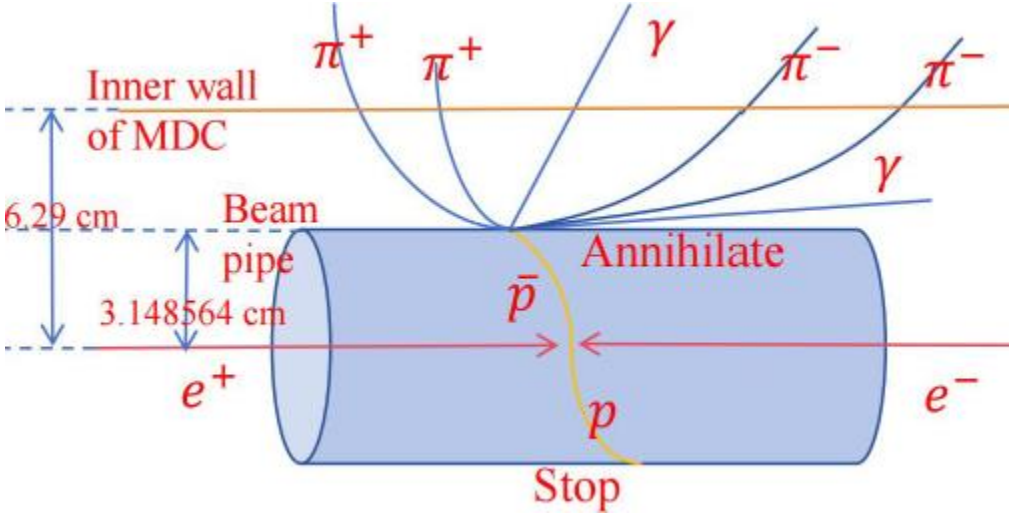
Actual/plan: 13/23 points, 24.8/95.5 pb$^{-1}$ (26%) ☹

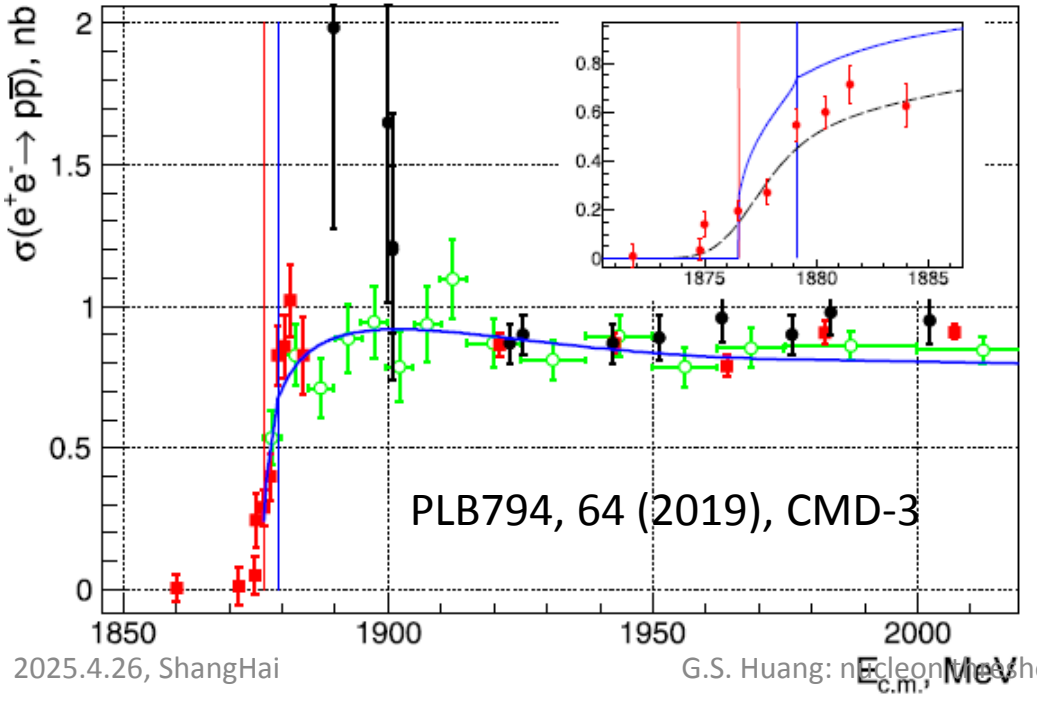
| Ecm (MeV) | Run range | #runs | $\mathcal{L}_{\rm online}$ (nb$^{-1}$) | Dates / time span (day) |
|---|---|---|---|---|
| 1840 | 81849-81970 | 113 | 1501.22 | 20240404-20240412 / 8.2 |
| 1870 | 81971-82104 | 131 | 2002.61 | 20240412-20240421 / 9.3 |
| 1872 | 82543-82656 | 112 | 2014.24 | 20240517-20240523 / 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



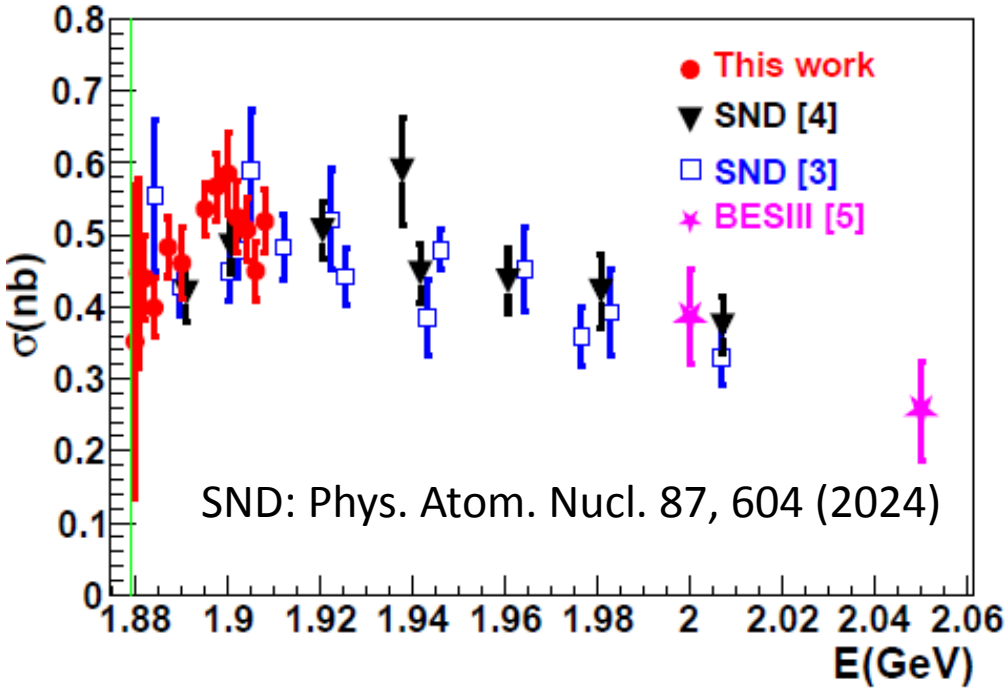
# $p\bar{p}$ : across the threshold



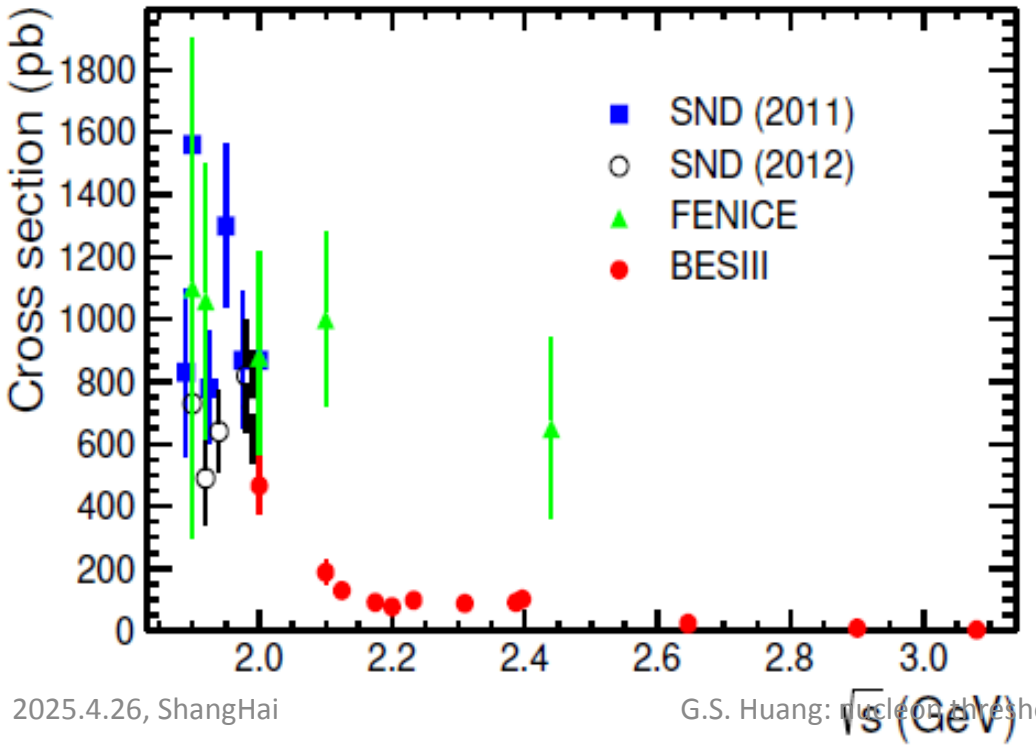



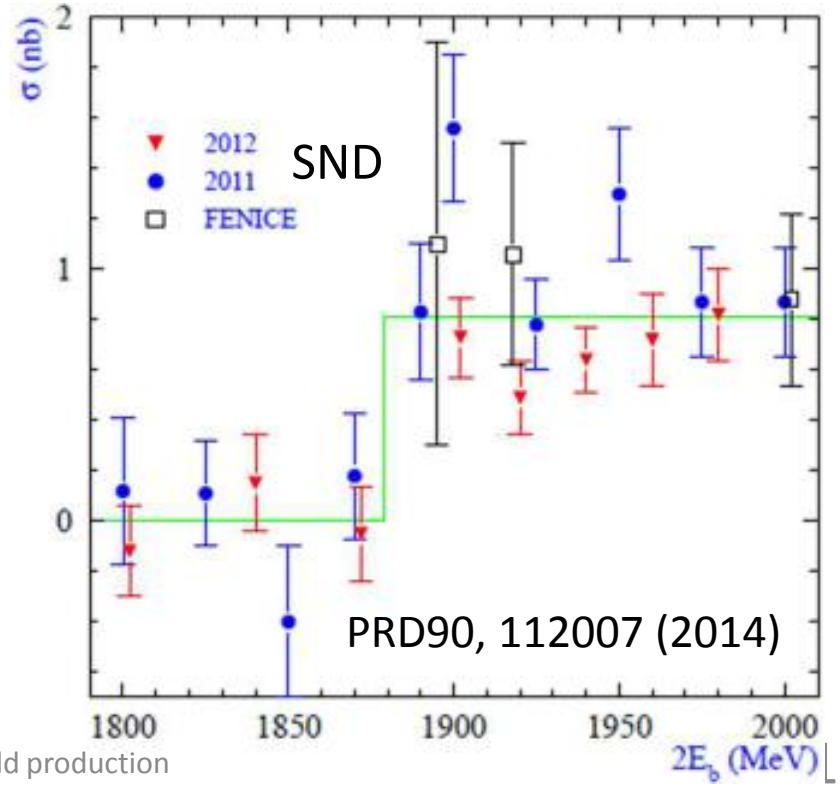

- Very close to threshold (≤1.94 GeV): vertex of secondary particles from annihilation;
- For higher energies (≥1.94 GeV): normal reconstruction;
- @1.94 GeV, try both methods.
- Looks promising!

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




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

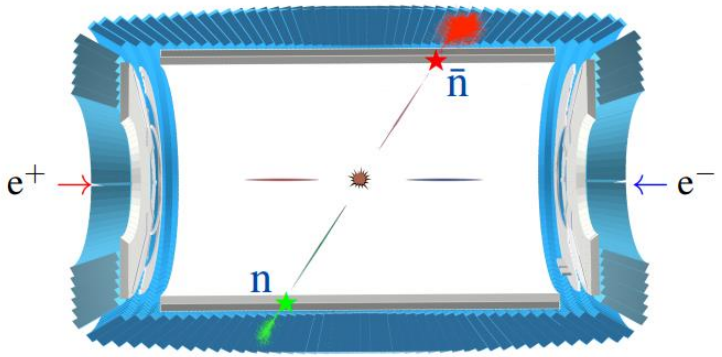


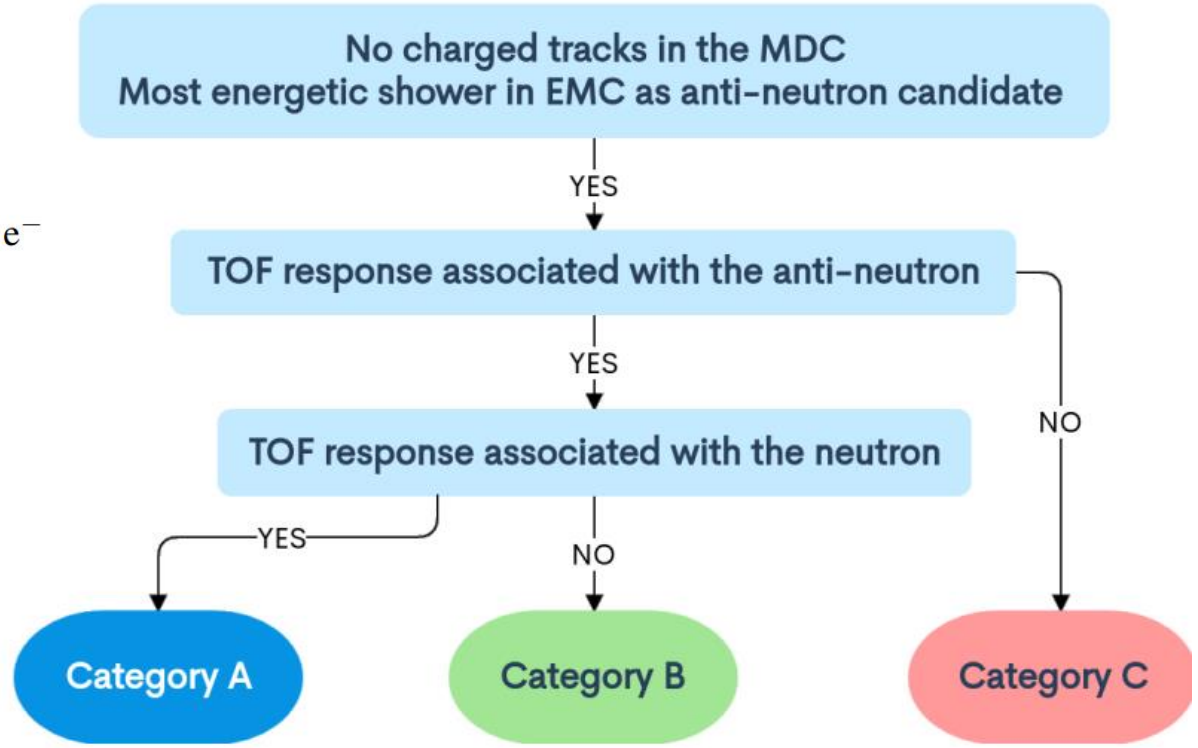

PRD90, 112007 (2014)

# $n\bar{n}$ : previous experience

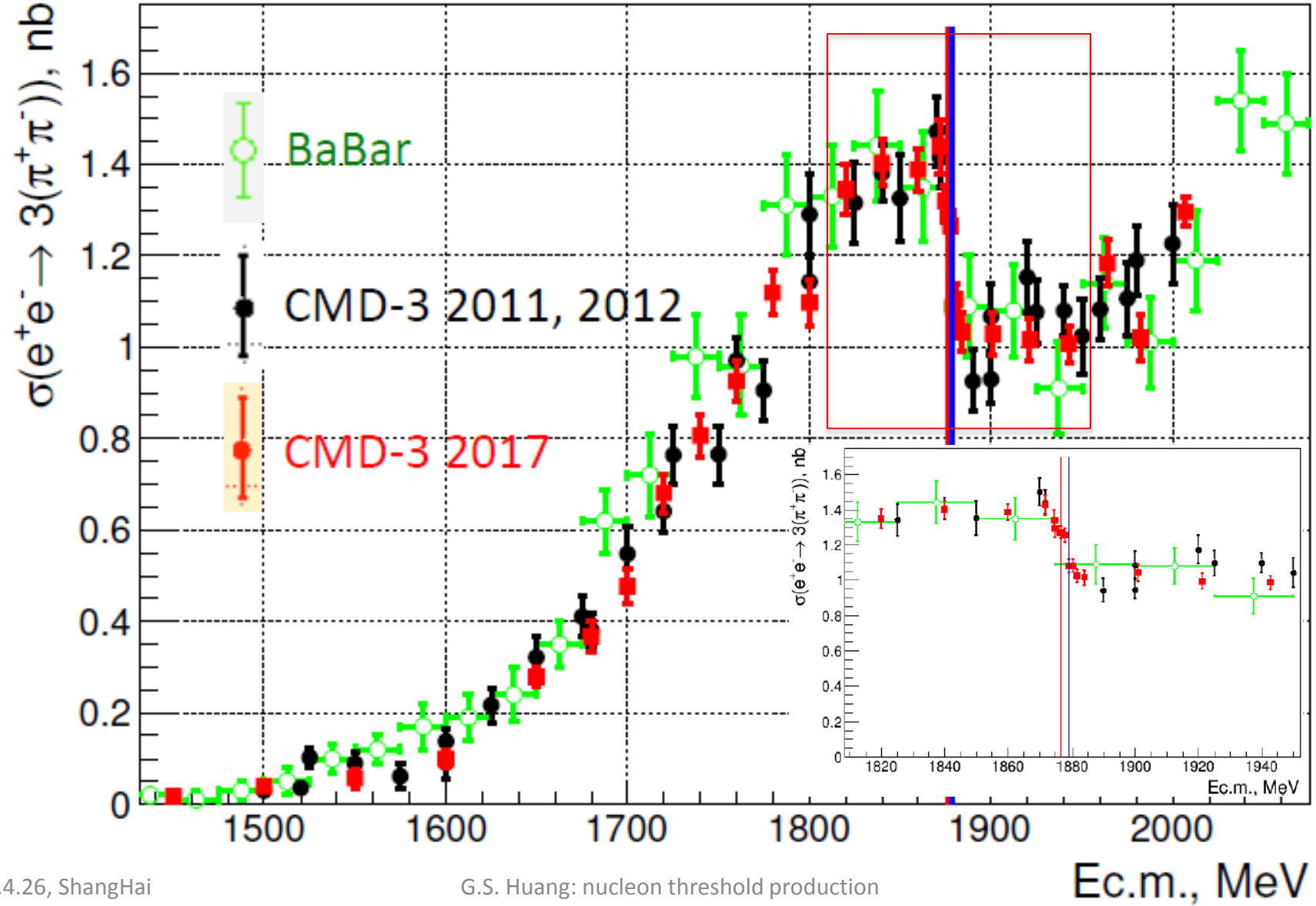
- Event selection very challenging;
- Successful in [2.0, 3.08] GeV, low efficiency;
- Expect to improve at energies  < 2.0 GeV.



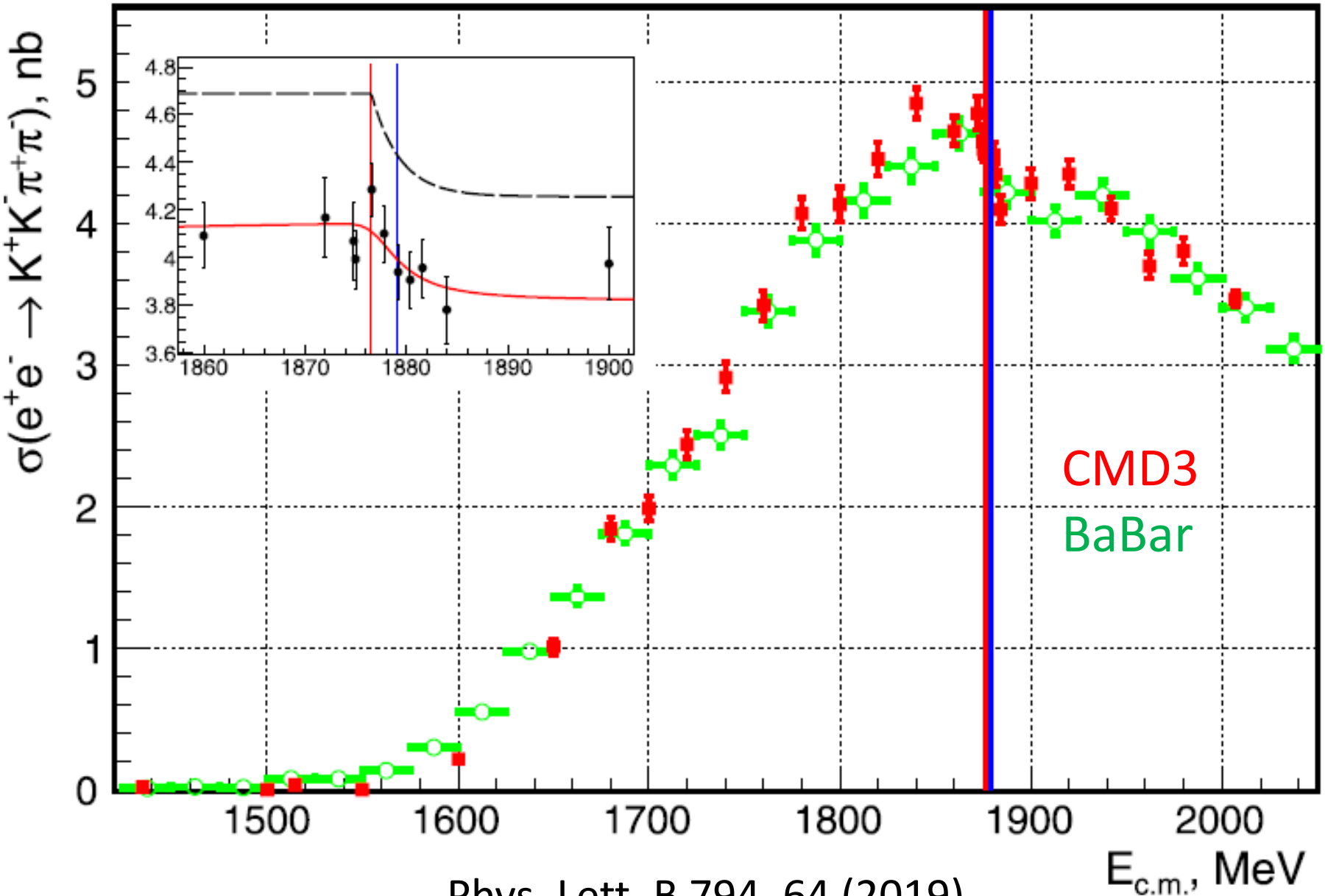

A typical event



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



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

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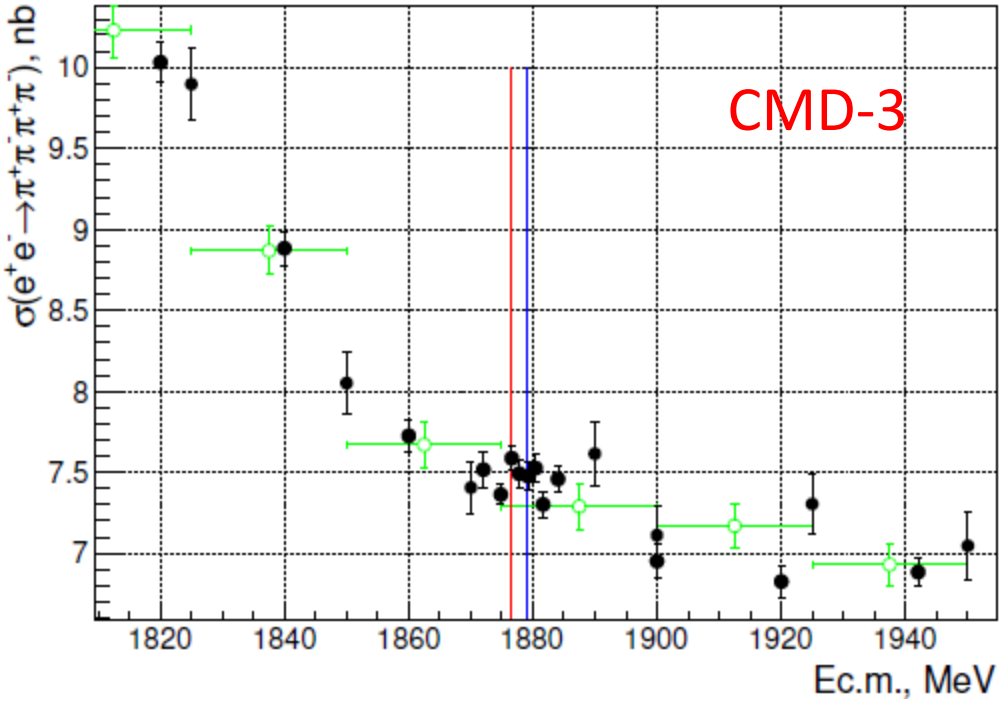
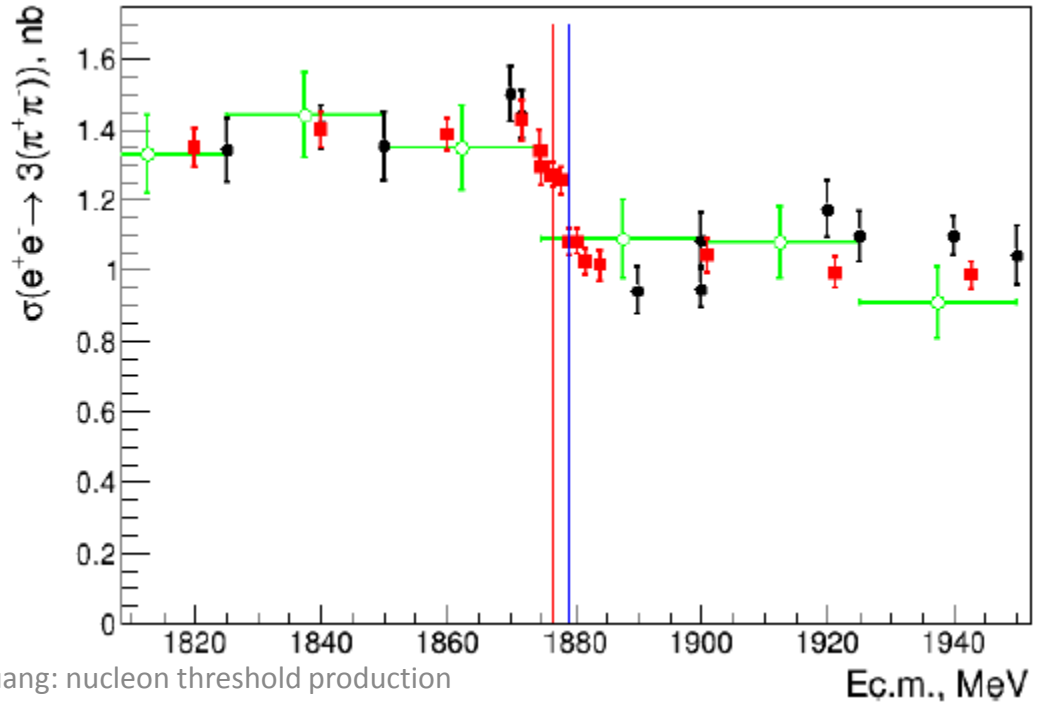
# But no structure in $2(\pi^+\pi^-)$!

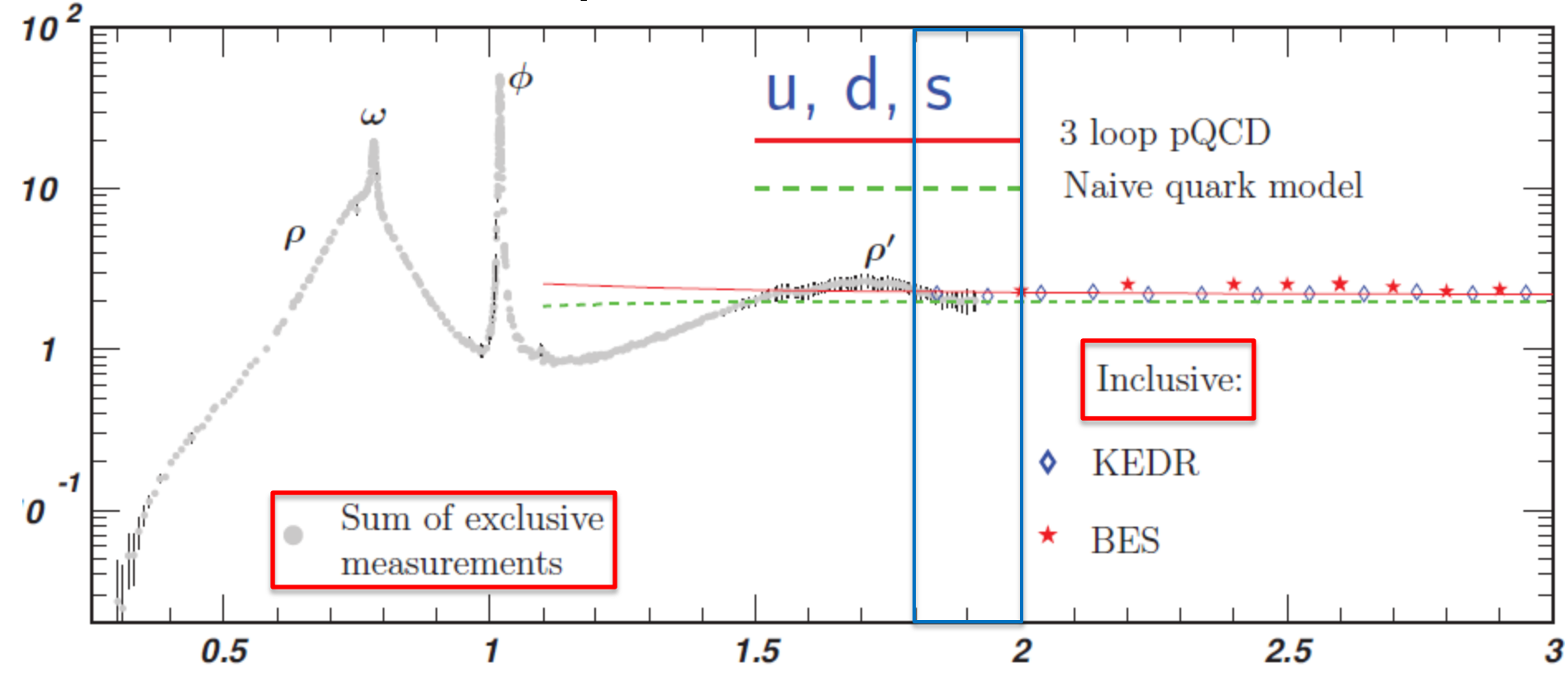



Contrary to $3(\pi^+\pi^-)$

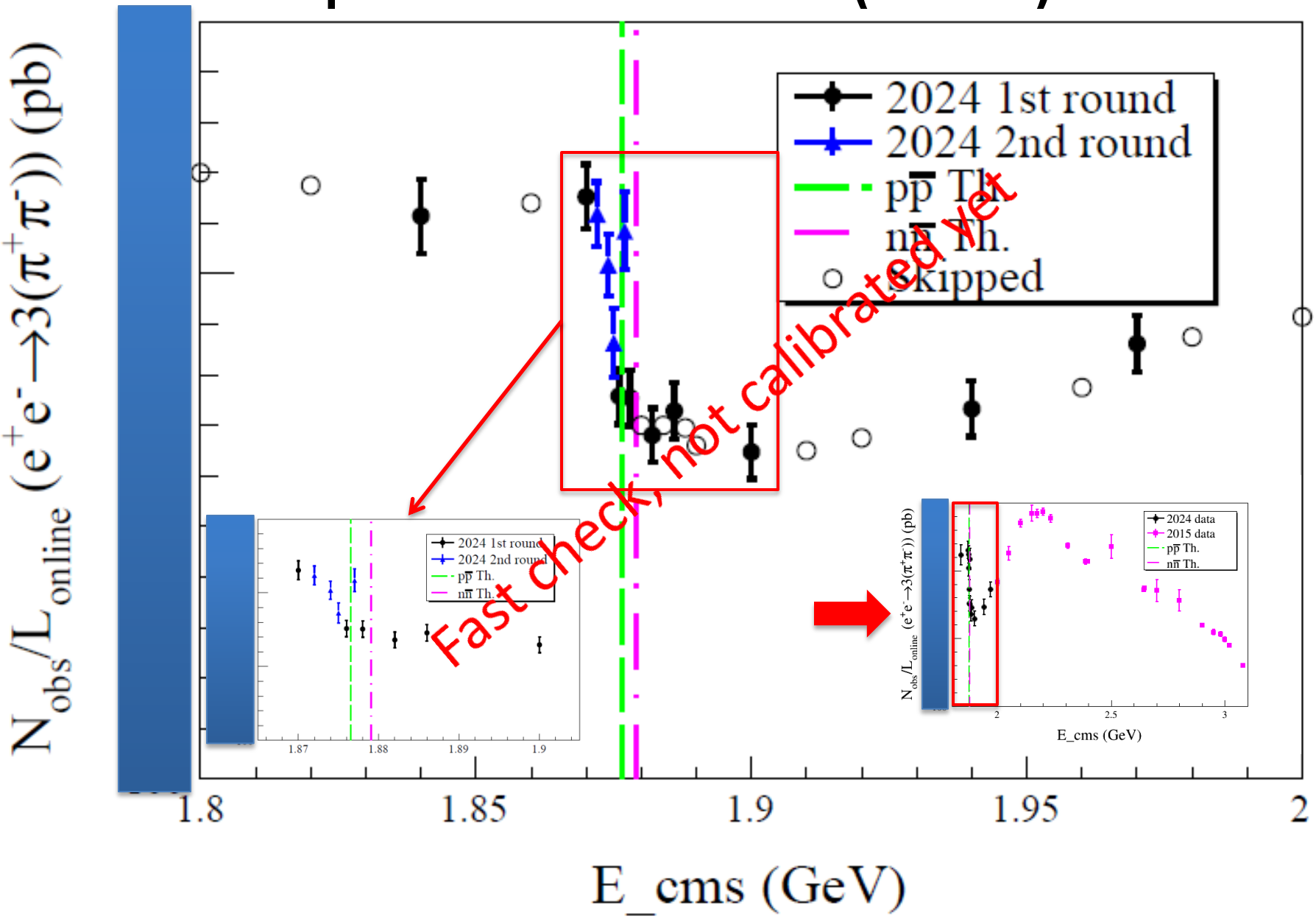


# R: inclusive vs exclusive

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



# 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!