Reactions with $^1S_0$ diproton production: history and possible studies at SPD

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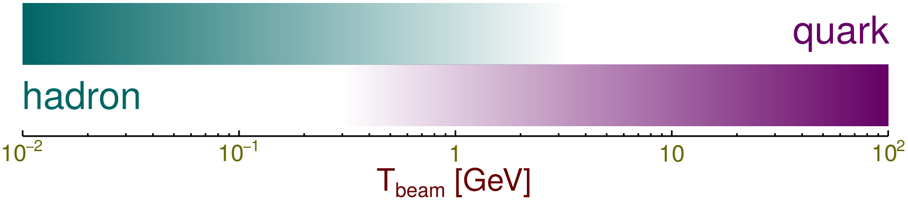
Motivation

Intermediate energies



- Low energies — hadronic degrees of freedom, pion exchange models;
- High energies — quark degrees of freedom, perturbative QCD;
- Intermediate energies — transition from hadronic to quark degrees of freedom, phenomenological models;
  - beam energies $T_{\text{beam}} \sim 1$ GeV;
  - momentum transfers $q \sim 200$—400 MeV$/c$;
  - radius of interaction $r \sim 0.5$—1.0 fm;
  - Additional experimental data desired.

Diprotons

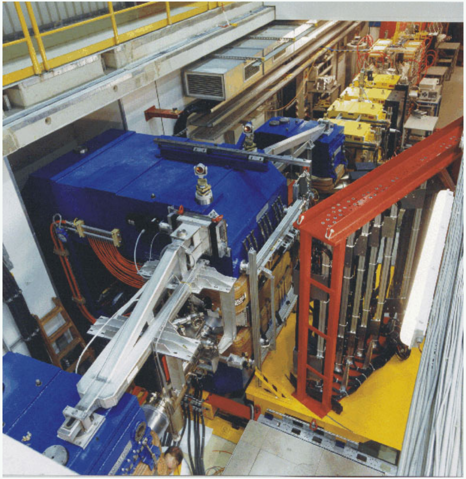
- **The main method of studying strong interactions at intermediate energies:**
  $NN \to NN\pi$;
- **A classic example of this channel:**
  $pp \to d\pi^+$ $(I = 0, S = 1, L = 0, 2)$;
- **Spin isospin partner:**
  $pp \to \{pp\}_s\pi^0$ $(I = 1, S = 0, L = 0)$,
  where $\{pp\}_s$ — diproton in final $^1S_0$ state ($E_{pp} < 3$ MeV);
- **Quasibinary reaction:**
  simplified kinematics, PWA possible;
- **Spin structure simplifies theoretical analysis:**
  half of the angular momenta forbidden in intermediate state;
- **Maximum possible momentum transfers:**
  short-range interaction (at the baryon-size distances).

Diproton studies at ANKE

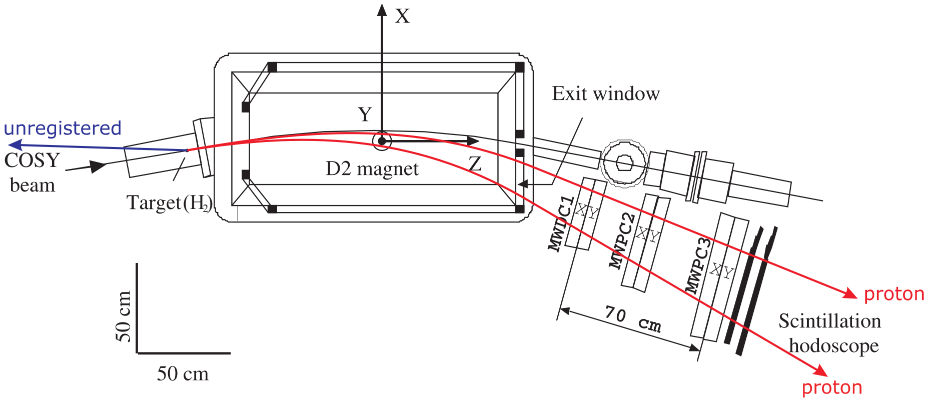
Experimental setup

COSY synchrotron

ANKE spectrometer

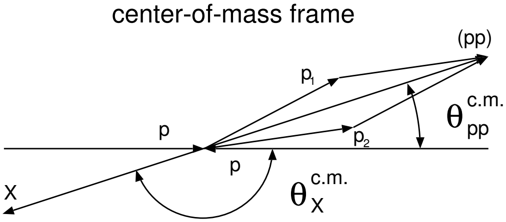


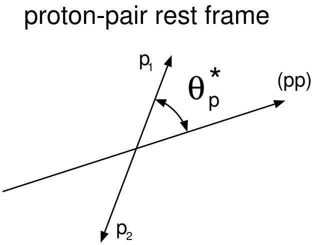
Forward detector

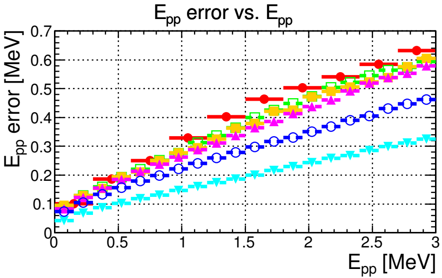


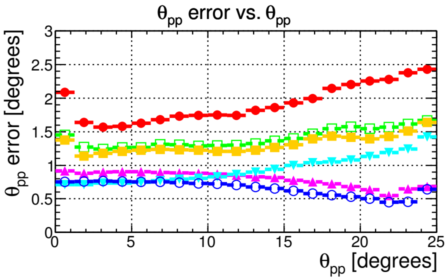
- Unpolarized or transversely polarized proton beam
- Internal unpolarized hydrogen cluster-jet target
- Track-reconstruction precision: $\sigma(p)/p \approx 1\%, \quad \sigma(\theta) \approx 0.2^\circ$

Diproton quasibinary kinematics

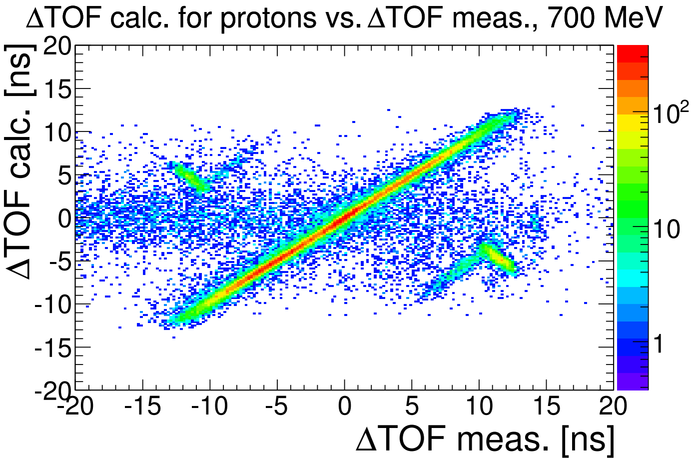






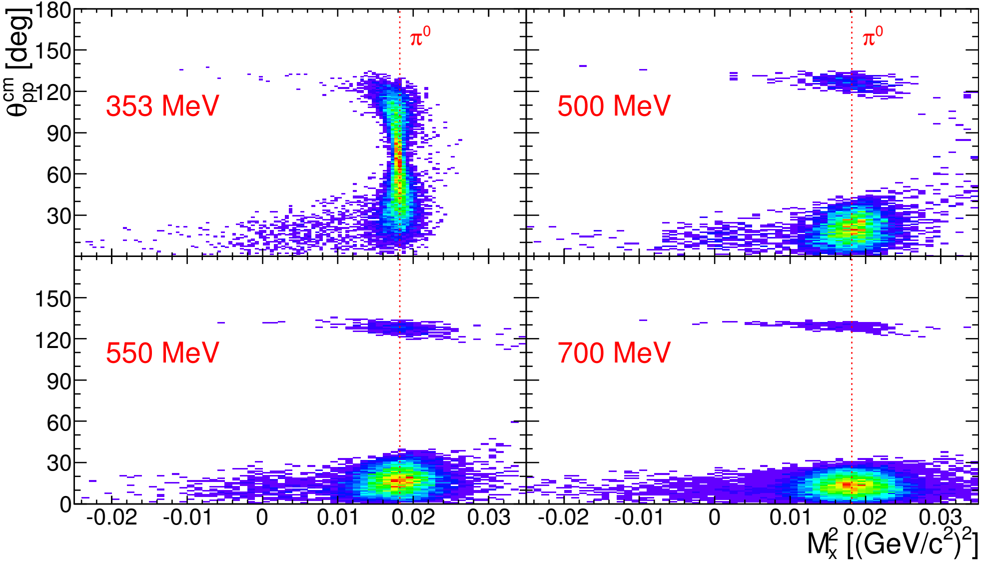


Identification of double-track events

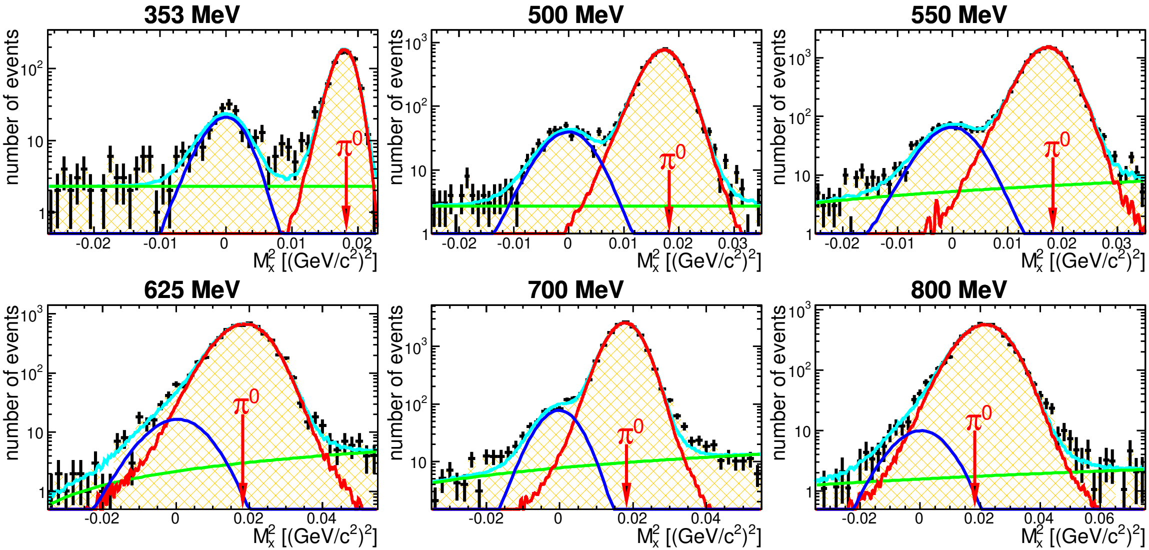


Time of flight difference: measured and calculated from momenta and trajectories assuming proton pairs

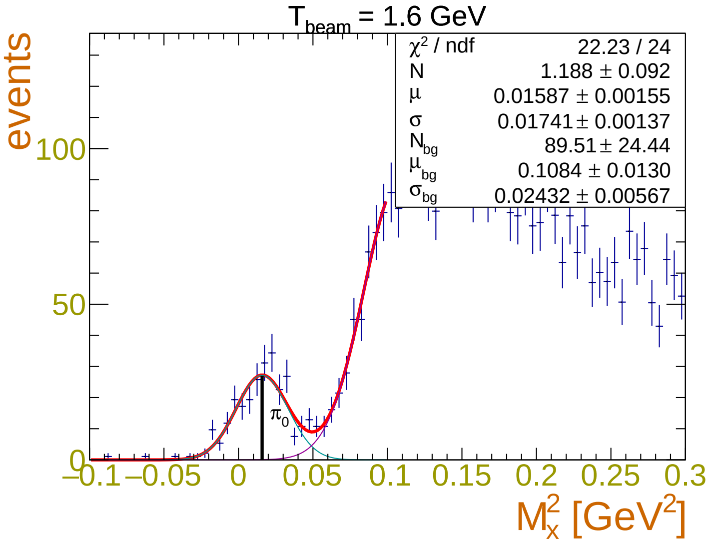
Forward detector double-track acceptance



Separation of $pp \to \{pp\}_s\pi^0$ and $pp \to \{pp\}_s\gamma$



Separation of $pp \to \{pp\}_s\pi^0$ and $pp \to \{pp\}_s\pi\pi$



Fitting function

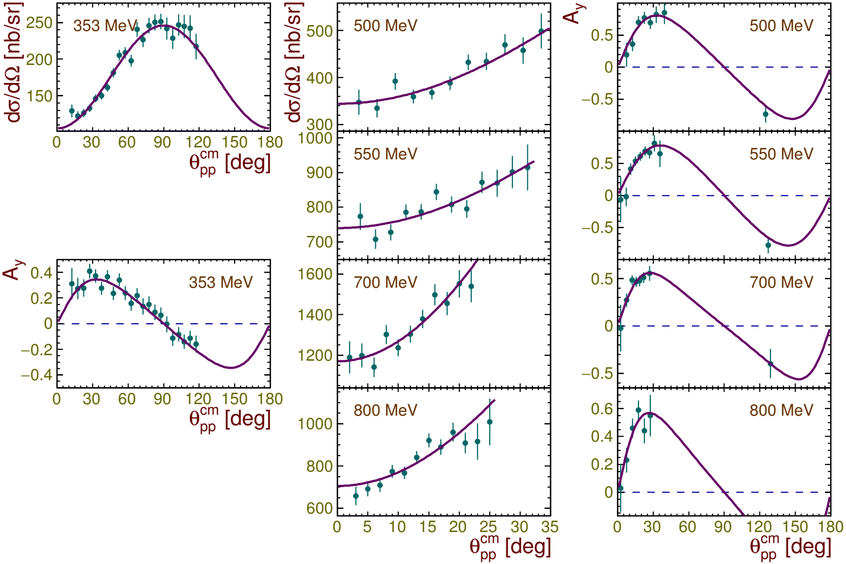
$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{k}{4p}\left(a_0 + a_2\cos^2\theta_{pp} + a_4\cos^4\theta_{pp} + \ldots\right) \\ A_y\frac{d\sigma}{d\Omega} &= \frac{k}{4p}\sin\theta_{pp}\cos\theta_{pp}\left(b_2 + b_4\cos^2\theta_{pp} + \ldots\right) \end{aligned}$$

For pion angular momenta $\ell \leqslant 2$ one can choose the following parametrization:

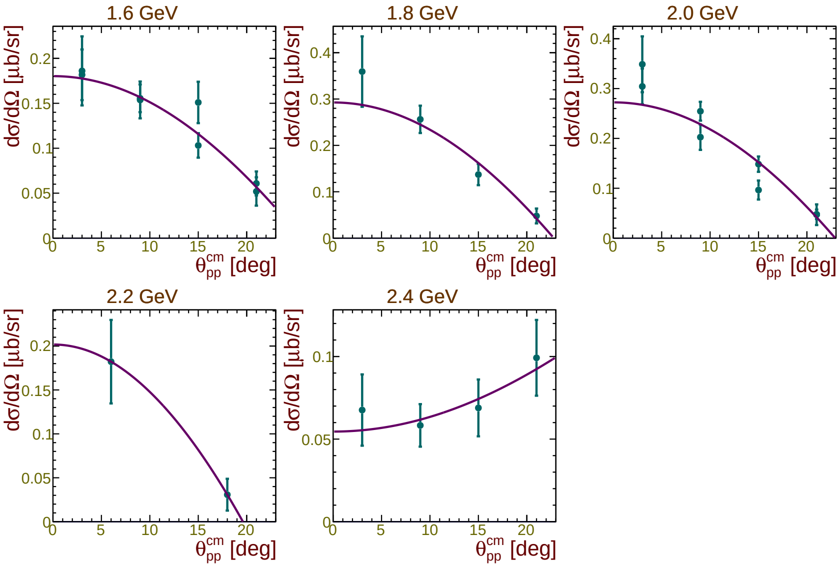
$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{d\sigma_0}{d\Omega}\left(1 + \kappa\sin^2\theta_{pp}\right) \\ A_y &= \frac{A_y^{\max}\sqrt{1+\kappa}\sin 2\theta_{pp}}{1 + \kappa\sin^2\theta_{pp}} \end{aligned}$$

- $d\sigma_0/d\Omega$ — differential cross section at zero angle;
- κ — angular slope of the differential cross section;
- $A_y^{\max}$ — maximum vector analyzing power.

Angular dependences for $d\sigma/d\Omega$ and A_y in the first peak region

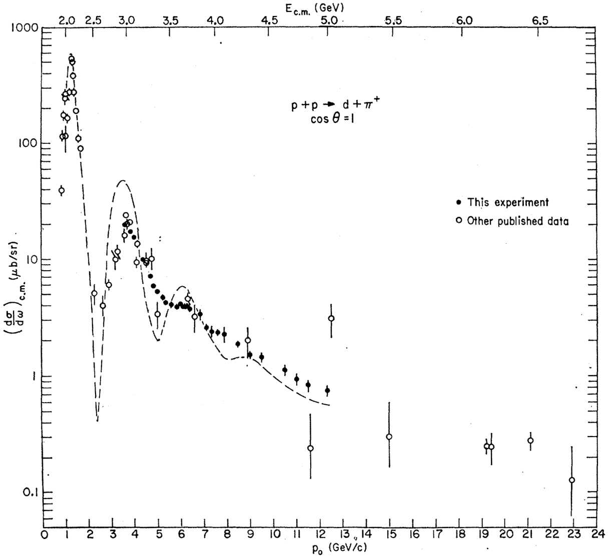


Angular dependences for $d\sigma/d\Omega$ and A_y in the second peak region



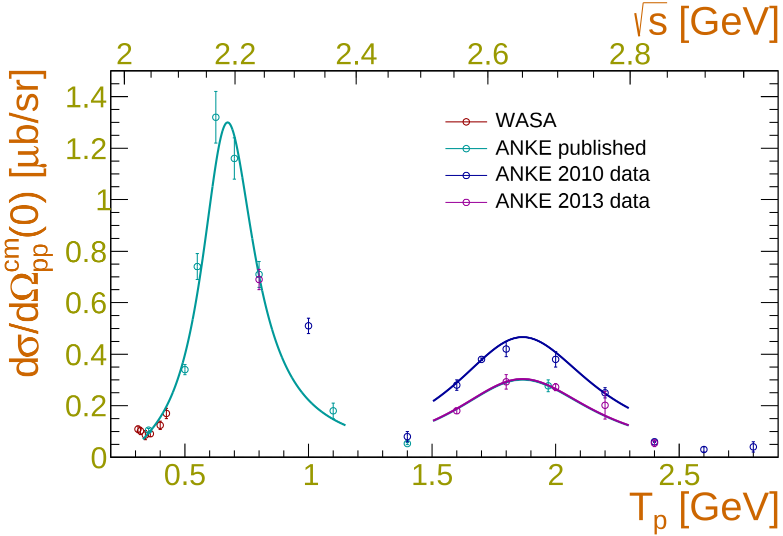
Diprotons and dibaryon resonances

Energy dependence of forward differential cross section for $pp \to d\pi^+$



H.L. Anderson *et al.*,
Phys. Rev. D **3** (1971) 1536.

Energy dependence of forward differential cross section for $pp \to \{pp\}_s\pi^0$



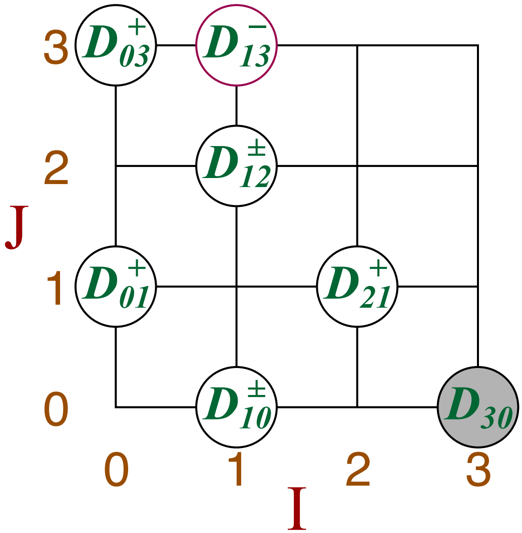
R. Bilger *et al.*, Nucl. Phys. A **693** (2001) 633.

V. Komarov *et al.*, Phys. Rev. C **93** (2016) 065206.

V. Kurbatov *et al.*, EPJ Web of Conf. **204** (2019) 08008.

B. Baimurzinova *et al.*, AYSS-2021.

Known dibaryons



D_{01}^{+} deuteron

D_{10}^{+} $^1S_0$ diproton, $^1S_0$ $\{pp\}_s$-pair

D_{10}^{-} $^3P_0$ $(pp \to \{pp\}_s\pi^0)$

D_{03}^{+} $^3D_3$ $(pd \to pd\pi\pi)$

D_{12}^{+} $^1D_2$ $(pp \to d\pi^+)$

D_{12}^{-} $^3P_2$ $(pp \to d\pi^+/\{pp\}_s\pi^0)$

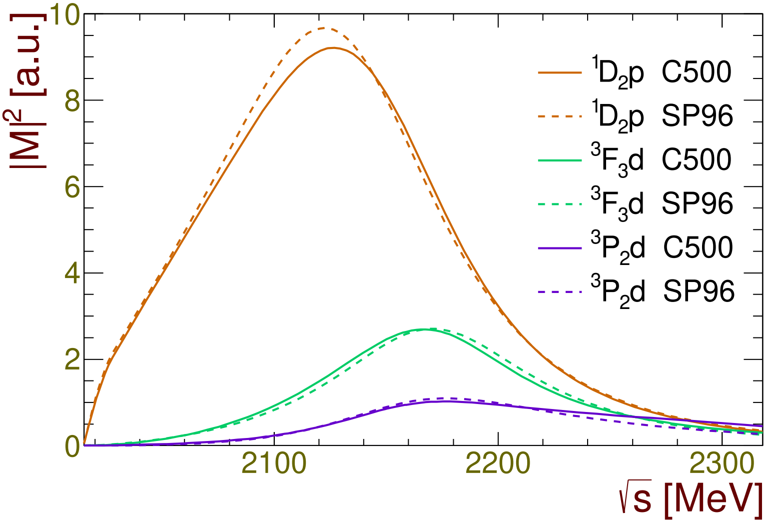
D_{21}^{+} with charge 3 $(pp \to pp\pi^+\pi^-)$

D_{13}^{-} $^3F_3$ $(pp \to d\pi^+)$

D_{30} with charge 4 (???)

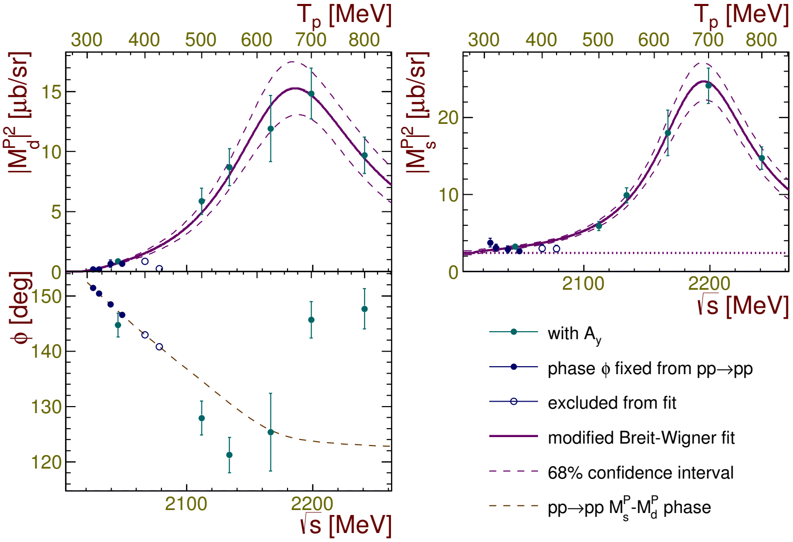
We are at the birth of dibaryon spectroscopy.

Dibaryon resonances in $pp \to d\pi^+$



- Three main dibaryon resonance transitions are known: $^1D_2$, $^3F_3$, $^3P_2$ ($^{2S+1}L_J$ for pp-pair);
- $^1D_2$, $^3F_3$ — well known from PWA of $pp \to pp$ and $pp \to d\pi^+$ reactions;
- $^3P_2$ — significant inaccuracies.

Dibaryon resonances in $pp \to \{pp\}_s \pi^0$



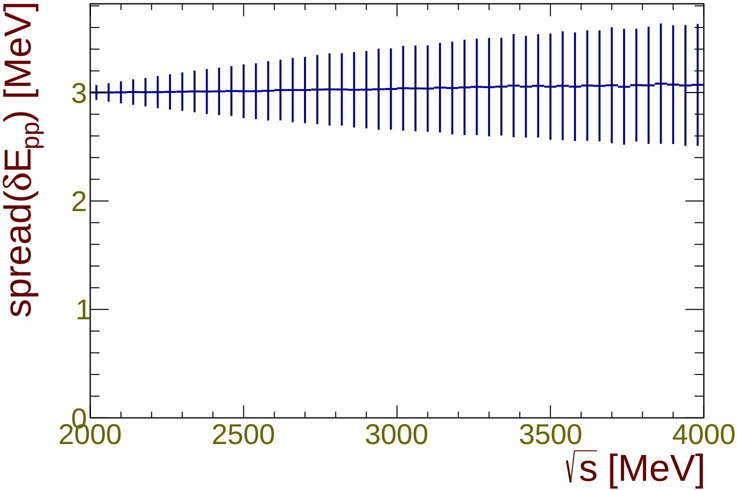
- $\ell \leqslant 2$ — three possible transitions: $^3P_0 \to {^1S_0}s$, $^3P_2 \to {^1S_0}d$, $^3F_2 \to {^1S_0}d$;
- $^3F_2 \to {^1S_0}d$ is considered negligible;
- Two basic transitions $^3P_0 \to {^1S_0}s$, $^3P_2 \to {^1S_0}d$.

Scientific novelty and practical significance

- The energy and angular dependences $d\sigma/d\Omega$ and A_y for the $\vec{p}p \to \{pp\}_s\pi^0$ process at small polar angles in the $\Delta(1232)$ resonance excitation region are measured for the first time;
- The partial-wave analysis of the reaction has been carried out, revealing ${}^3P_0s$ and ${}^3P_2$ dibaryon resonance transitions, the resonance behavior of ${}^3P_0s$ observed for the first time;
- The peculiarities observed are explained by the interference of ${}^3P_0 \to {}^1S_0s$ and ${}^3P_2 \to {}^1S_0d$ transitions;
- P-wave dibaryons are important for developing the theory of dibaryon resonances and their role in hadronic interactions at small distances, see:
  - M. N. Platonova & V.I. Kukulin, Phys. Rev. D **94** 054039 (2016);
  - V.I. Kukulin *et al.*, Phys. Atom. Nucl. **82** 934 (2019);
  - O.A. Rubtsova & V.I. Kukulin & M.N. Platonova, Phys. Rev. D **102** 114040 (2020).

Prospects for diproton studies at SPD

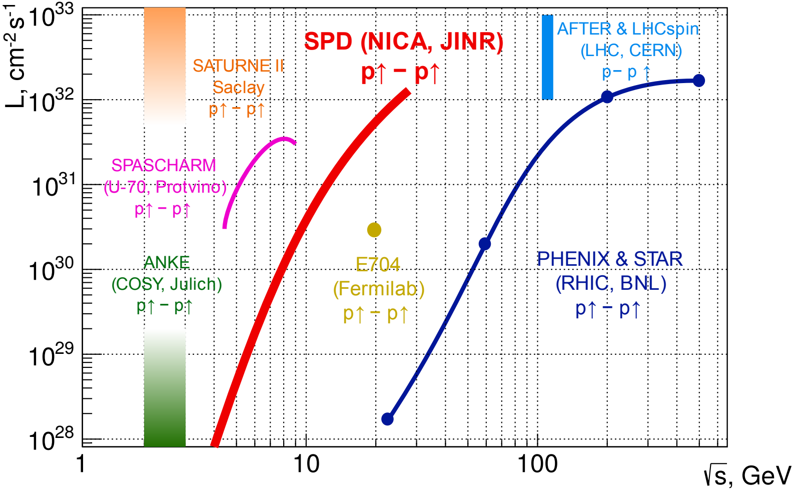
Precision for E_{pp} measurement



$\sigma_{p_T}/p_T \approx 2\%$

[Conceptual design of the Spin Physics Detector]

Luminosity and statistics



$$t = \frac{N_{\text{bin}}}{d\sigma/d\Omega \cdot \Delta\Omega \cdot \mathcal{L}}$$

- $N_{\text{bin}} \gtrsim 100$;
- $\Delta\Omega \sim 0.1 \cdot 4\pi \sim 1$ sr;
- $\mathcal{L} \lesssim 10^{28}\ \text{cm}^{-2}\text{s}^{-2}$;
- $\dfrac{d\sigma}{d\Omega} \sim 0.1\text{–}1\ \dfrac{\mu\text{b}}{\text{sr}} \sim$
  $\sim 10^{-31}\text{–}10^{-30}\ \dfrac{\text{cm}^2}{\text{sr}}$.

$$t \gtrsim \frac{100}{10^{-31} \cdot 1 \cdot 10^{28}}\ \text{s} =$$
$$= 10^5\ \text{s} \sim 24\ \text{h}$$

Main prospects I

Energy region of the first peak

Aim: Full PWA with three allowed $\ell \leq 2$ transitions

Pros:
- Full angular range available
- Double polarization observables
- Theory developed, transparent analysis

Cons:
- Low luminosity, several days to collect enough statistics for each energy

Main prospects II

Energy region of the second peak

Aim: PWA to search for heavy dibaryons

Pros:
- Full angular range available
- Single and double polarization observables

Cons:
- Low luminosity, several days to collect enough statistics for each energy
- Partial waves $\ell > 2$, complicates PWA
- Theory not developed

Main prospects III

Energies $\sqrt{s} > 3$ GeV

Aim: Search for resonance peaks in the cross section

Pros:
- Full angular range available
- Single and double polarization observables
- Luminosity increases

Cons:
- Low cross section
- Partial waves $\ell > 2$, complicates analysis
- Theory not developed

Thank you for your attention!