# Recent developments in NN and NY Interactions or New results in an old field

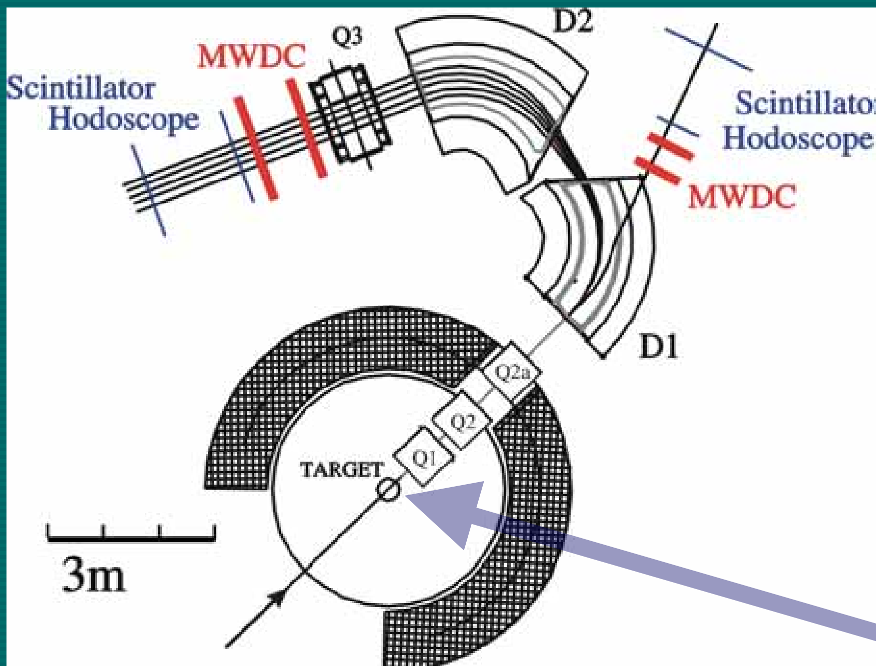
HM

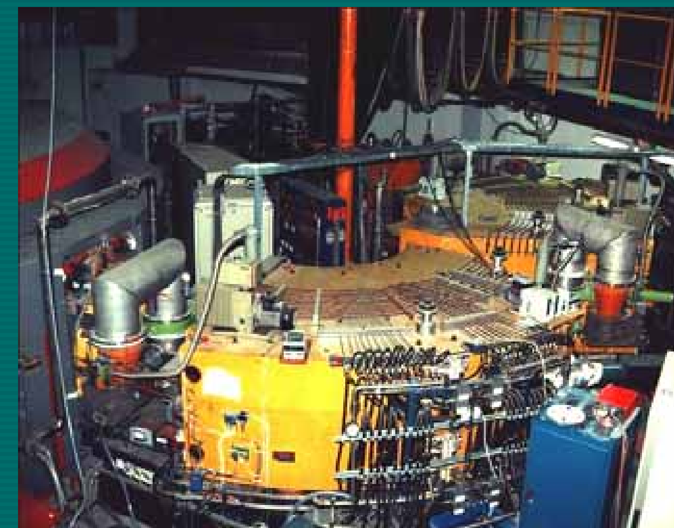
FZ Jülich and Univ. Duisburg-Essen

Why is this important?

- NN interactions ←→ Nuclear potential, nuclear structure
- NY interactions ←→ Hypernuclear potential, hypernuclear structure

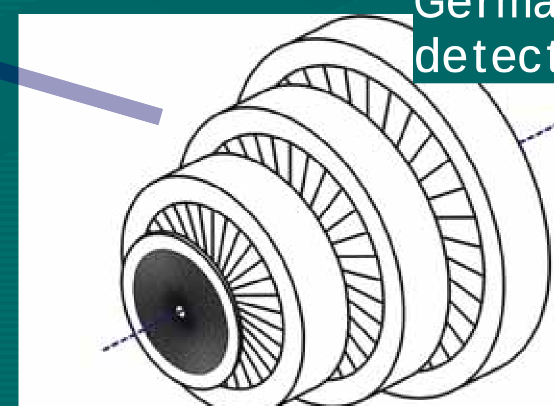
# Detectors: Big Karl+Ge-Wall



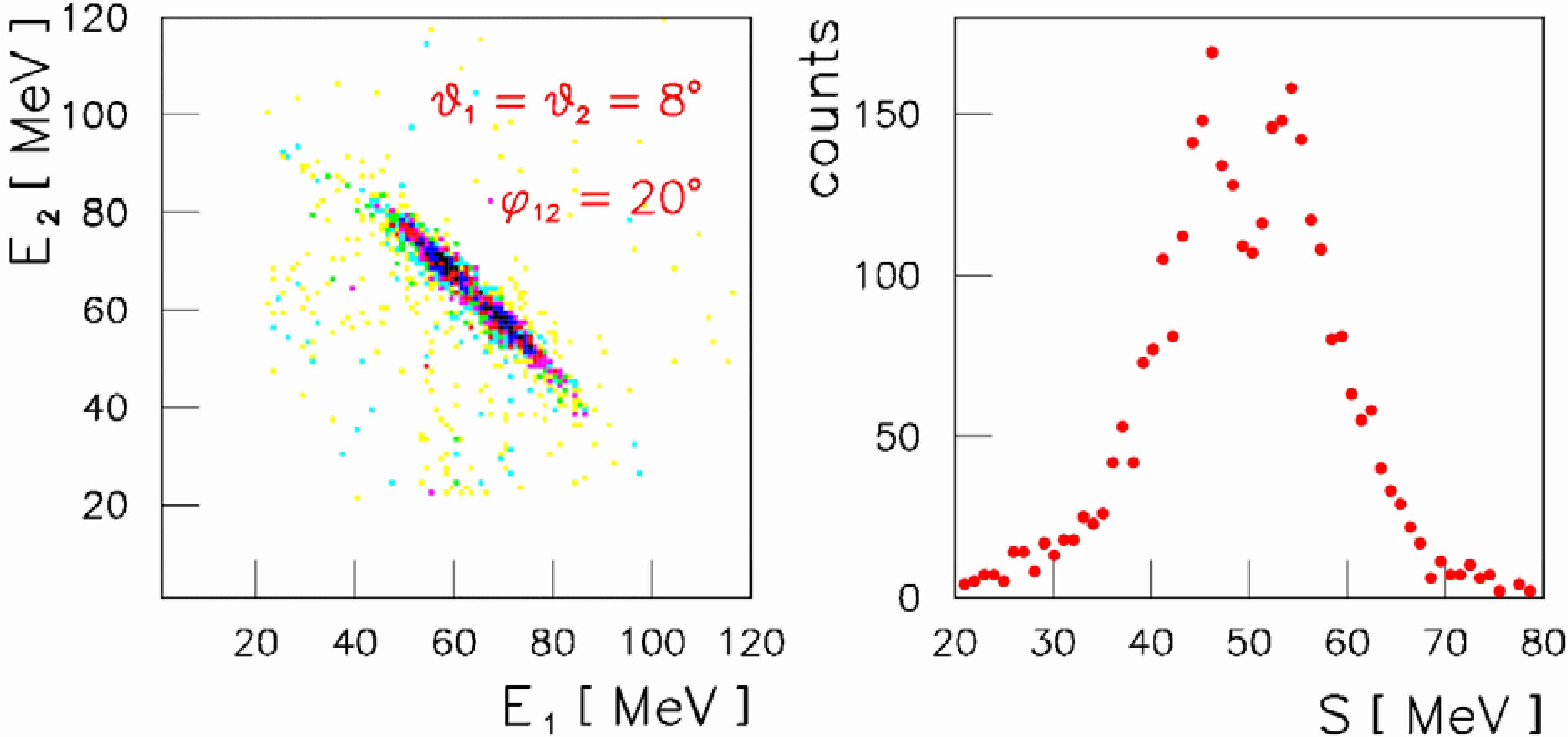
- focussing spectrometer ($\Omega = 10$ msr)
- high resolution $\Delta p/p < 5\times10^{-5}$
- combined with detectors close to target:
- multi-layer Germanium detector GEM

Germanium detector



# Response of the GE Wall

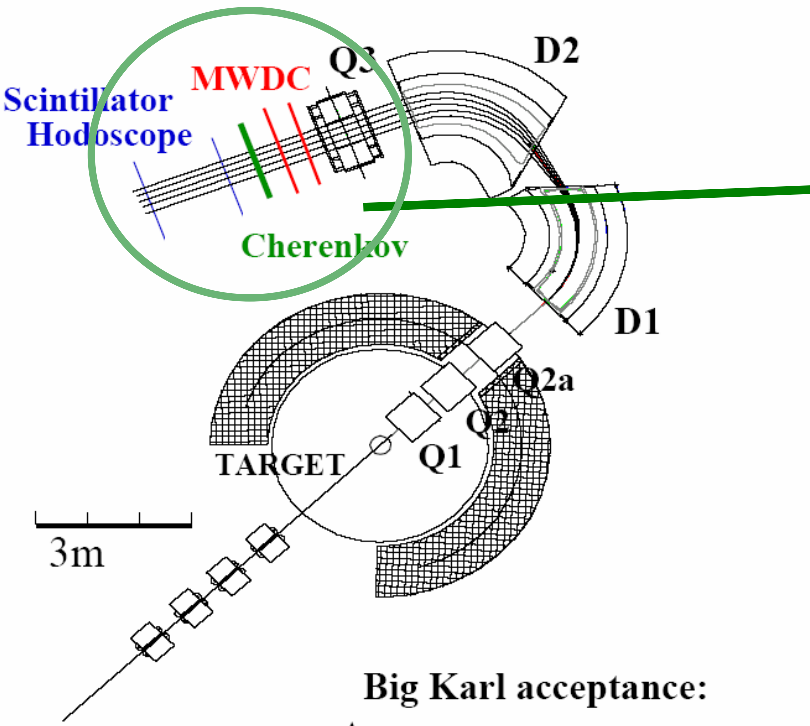
$$\vec{d} + p \rightarrow p_1 + p_2 + n$$



# Particle identification

## BIG KARL – Magnetic Spectrometer

resolution $\frac{\Delta p}{p} \sim 10^{-4}$



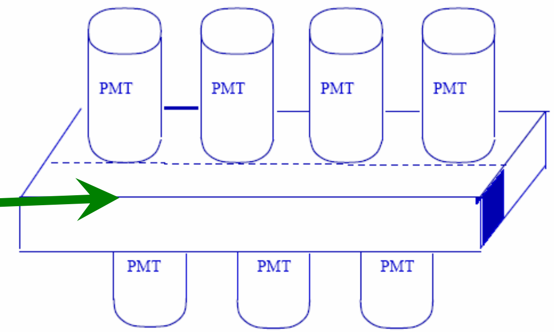

Big Karl acceptance:

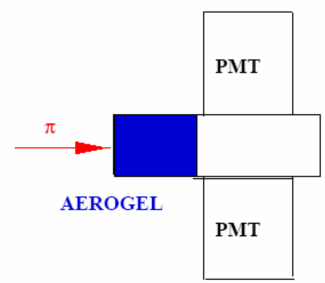
$\frac{\Delta p}{p} = \pm \ 4.5\ \%$

$\Delta\ X = \pm \ 28\ \text{mrad}$

$\Delta\ Y = \pm \ 100\ \text{mrad}$

## Silica aerogel threshold Čerenkov detector




- aerogel of n=1.05 from Matsushita Electric Work, Japan
- Goretex reflector
- Burle 8854 photomultiplier

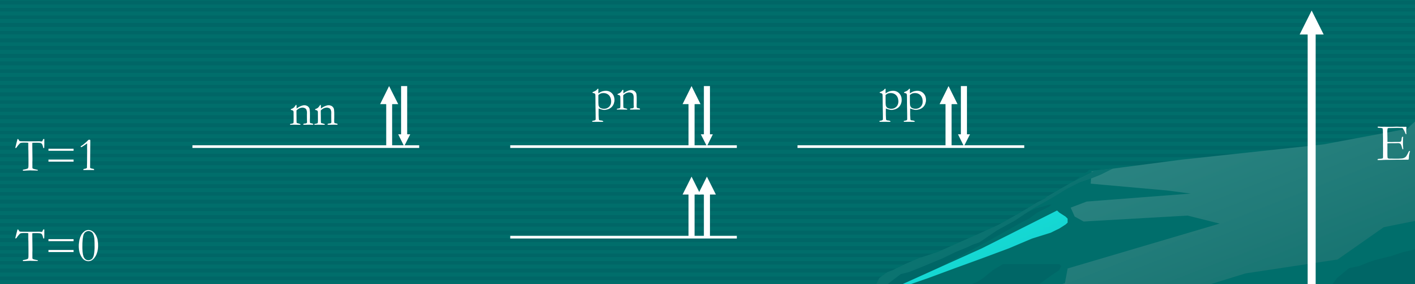
# All possible interactions

| | $T=0$ | $T=\frac{1}{2}$ | $T=1$ | $T=\frac{3}{2}$ | $T=2$ |
|---|---|---|---|---|---|
| $S=0$ | $NN$ | | $NN$ | | |
| $S=-1$ | | $(\Lambda N, \Sigma N)$ | | $\Sigma N$ | |
| $S=-2$ | $(\Lambda\Lambda, \Xi N, \Sigma\Sigma)$ | | $(\Xi N, \Sigma\Lambda, \Sigma\Sigma)$ | | $\Sigma\Sigma$ |
| $S=-3$ | | $(\Xi\Lambda, \Xi\Sigma)$ | | $\Xi\Sigma$ | |
| $S=-4$ | $\Xi\Xi$ | | $\Xi\Xi$ | | |

| | $Q=-2$ | $Q=-1$ | $Q=0$ | $Q=+1$ | $Q=+2$ |
|---|---|---|---|---|---|
| $S=0$ | | | $nn$ | $np$ | $pp$ |
| $S=-1$ | | $\Sigma^- n$ | $(\Lambda n, \Sigma^0 n, \Sigma^- p)$ | $(\Lambda p, \Sigma^+ n, \Sigma^0 p)$ | $\Sigma^+ p$ |
| $S=-2$ | $\Sigma^-\Sigma^-$ | $(\Xi^- n, \Sigma^-\Lambda, \Sigma^-\Sigma^0)$ | $(\Lambda\Lambda, \Xi^0 n, \Xi^- p, \Sigma^0\Lambda, \Sigma^0\Sigma^0, \Sigma^-\Sigma^+)$ | $(\Xi^0 p, \Sigma^+\Lambda, \Sigma^0\Sigma^+)$ | $\Sigma^+\Sigma^+$ |
| $S=-3$ | $\Xi^-\Sigma^-$ | $(\Xi^-\Lambda, \Xi^0\Sigma^-, \Xi^-\Sigma^0)$ | $(\Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^+)$ | $\Xi^0\Sigma^+$ | |
| $S=-4$ | $\Xi^-\Xi^-$ | $\Xi^-\Xi^0$ | $\Xi^0\Xi^0$ | | |

# Isospin decomposition

nucleon-nucleon case

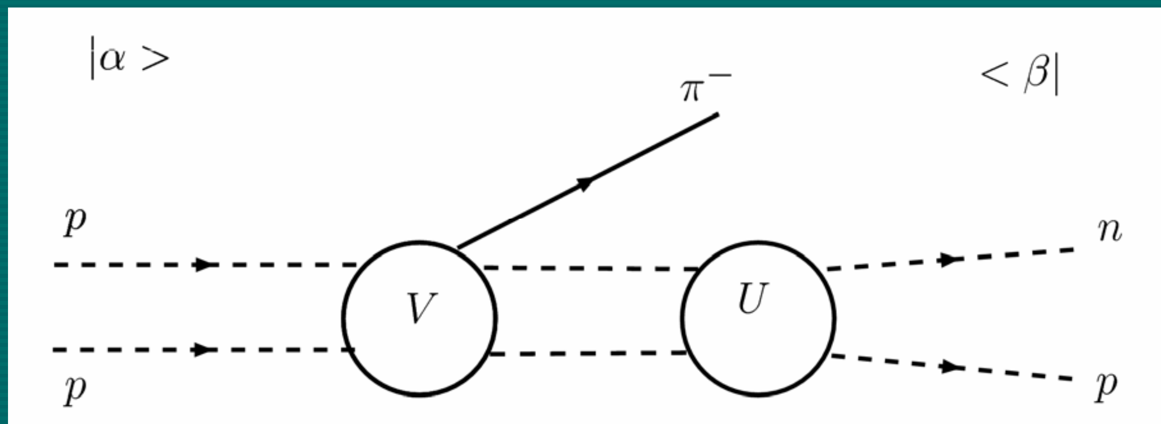



Two possibilities J=L+S: 0+1 or -1+2

hyperon-nucleon case

# Problem

Often the target or the beam is not available or even impossible. Way out: three body final states with fsi (Watson+Migdal theory):




factorisation: $$\Psi_{\beta} = \chi(\pi)\chi(p)\chi(n) = \chi(\pi)\chi(r_p + r_n)\Psi(q, \mathbf{r_p} - \mathbf{r_n}).$$

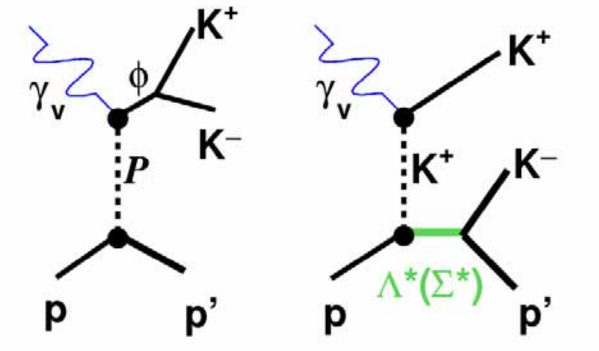
with $$\left(\frac{d^2}{dr^2} + U\right)\Psi = q^2\Psi.$$

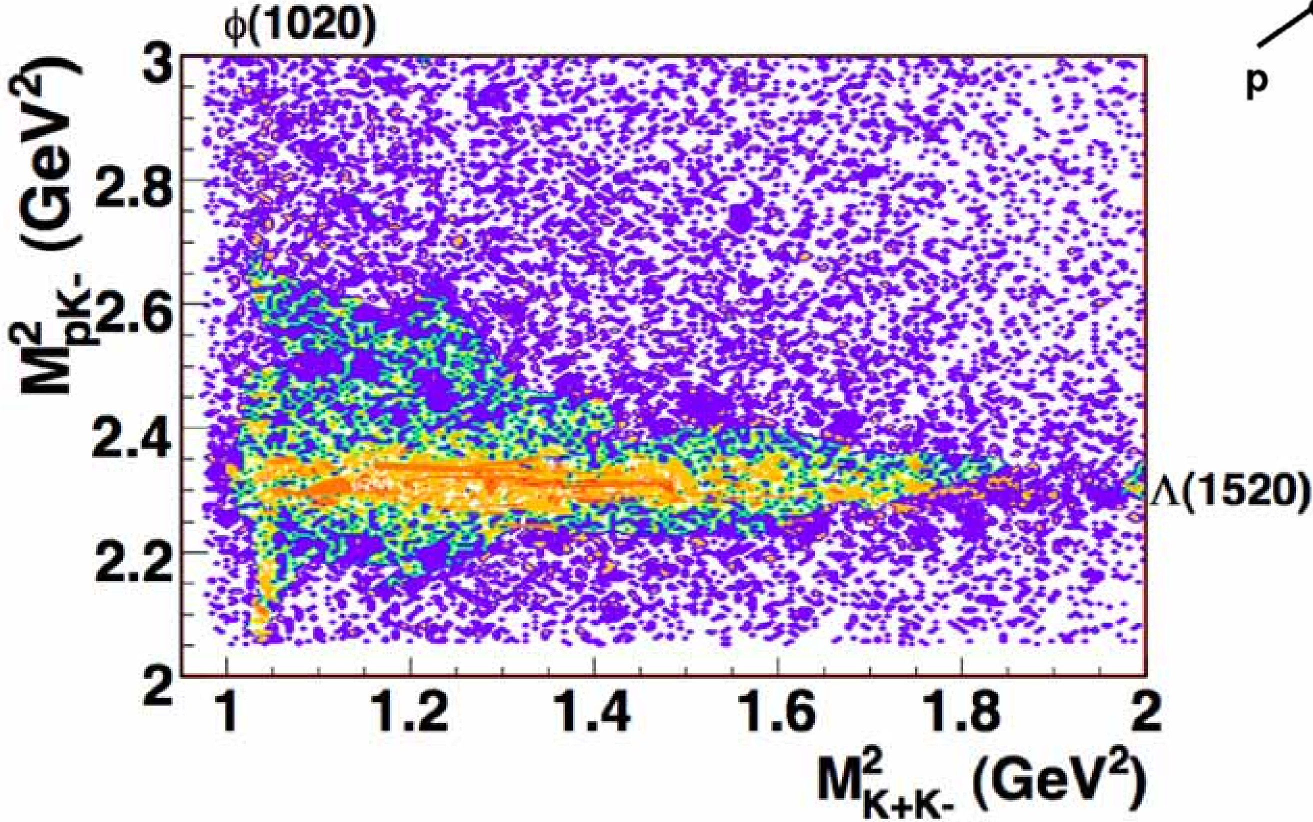
leads to $$<\beta \,|\, T \,|\, \alpha > \Psi(q,0) < \beta \,|\, T_B \,|\, \alpha > .$$

$\Psi(q,0)$ enhancement factor

# Works the factorisation always?

$$e + p \rightarrow e' + p + K^- + K^+$$



# Approximations

Scattering length $-a_0 \approx \lim_{k\to 0} \frac{\delta_0}{k}$ expansion $\frac{1}{a(k)} = \frac{1}{a} - k^2 \frac{r_{eff}}{2} + \ldots$

$$|T(a+b\to 1+2+3)|^2 = |J_{ab}|^2 |T_0|^2 |J_{12}|^2 |J_{23}|^2 |J_{31}|^2$$

$$|T(p+p\to p+n+\pi^+)|^2 = |J_{pp}|^2 |T_0|^2 |J_{pn}|^2 |J_{p\pi}|^2 |J_{\pi n}|^2$$

$$\approx |T_0|^2 |J_{pn}|^2 = \frac{1}{4}|T_{0,s}|^2 |J_{pn,s}|^2 + \frac{3}{4}|T_{0,t}|^2 |J_{pn,t}|^2$$

$T_{ij}$ can have a Breit-Wigner form

$|J_{pn}|^2$ calculated by a nd $r_{eff}$

# The $^1S_0$ data

| | nn | $nn^N$ | np | pp | $pp^N$ |
|---|---|---|---|---|---|
| -a (fm) | 18.5 ±0.3 | 18.8 ±0.3 | 23.748 ±0.009 | 7.8063 ±0.0026 | 17.3 ±0.4 |
| $r_{eff}$ (fm) | 2.75 ±0.11 | 2.75 ±0.11 | 2.75 ±0.05 | 2.794 ±0.0014 | 2.85 ±0.04 |

All scattering lengths are negative → no bound state!

# np $^3S_1$ data

$^3S$ Effective Range Parameters

| Potential | $a(F)$ | $r_e(F)$ | $P$ |
|---|---|---|---|
| HC | 5.397 | 1.724 | −.011 |
| SC | 5.390 | 1.720 | −.027 |
| SCA | 5.390 | 1.720 | −.027 |

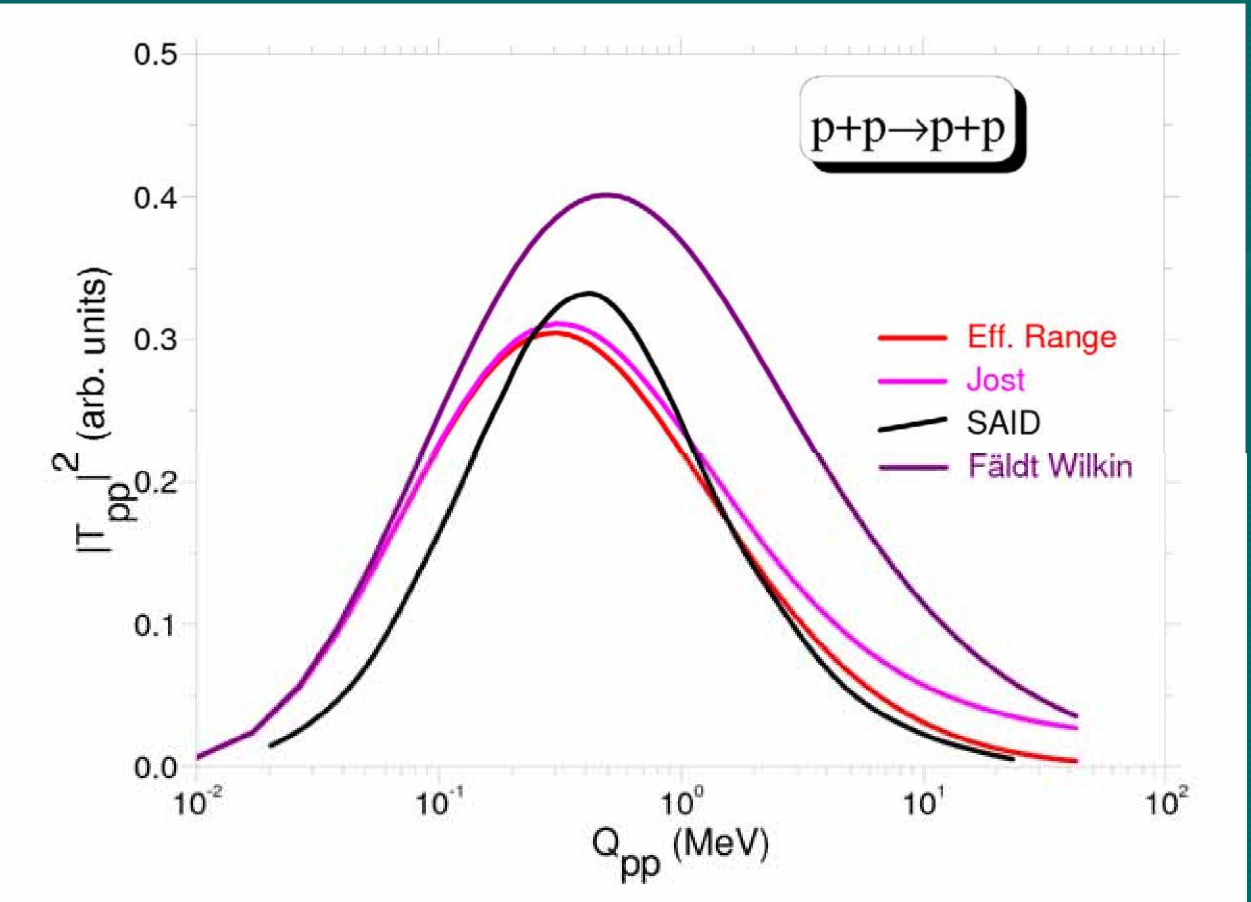
The scattering length os positive → bound state!

Properties of the Deuteron

| Potential | $E$ (MeV) | $Q$ ($F^2$) | $P_D$ (%) | $A_D/A_S$ |
|---|---|---|---|---|
| HC | 2.22464 | .2770 | 6.497 | .02590 |
| SC | 2.22460 | .2796 | 6.470 | .02622 |
| SCA | 2.22464 | .2762 | 6.217 | .02596 |

# FSI approaches

A lot of studies made use of a Gauss potential. However the Bargman potential is the potential which has the effective range expansion as exact solution: a, r → α, β. α defines the pole position (positive ↔ bound, negative ↔ unbound).




$$|J_{Jost}|^2 = \left(\frac{k - i\beta}{k + i\alpha}\right)^2$$

$$|J_{ER}|^2 \propto \left(k^2 + \frac{1}{a(k)^2}\right)^{-1}$$

$$|J_{FW}|^2 = \frac{2\beta}{\alpha + \sqrt{\alpha^2 + Q_{pp} m_p}}$$

All with Gamow factor

# The nn-case

$$n + n \rightarrow n + n$$

Planned (pulsed reactor, spallation neutron sources)

$$n + d \rightarrow n + n + p$$

fsi nn and np, Fadeev equations

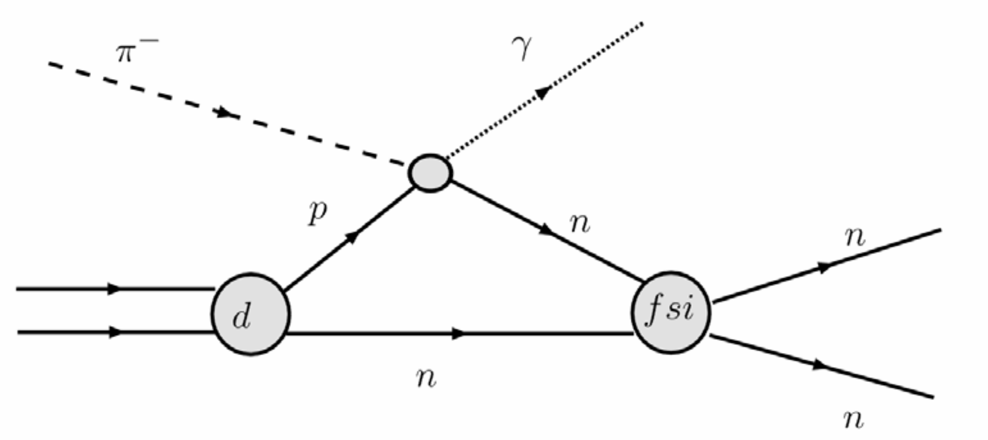
Bonn: $a_{nn}$=-16.1±0.4 fm

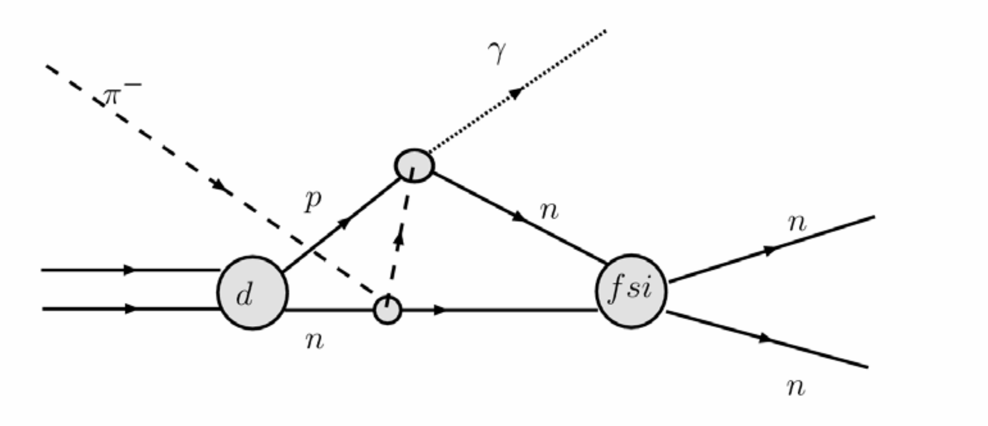
Duke: $a_{nn}$=-18.7±0.7 fm

However: both groups agree on $a_{pn}$

# The nn-case (II)

$$\pi^- + d \rightarrow n + n + \gamma$$




$a_{nn}$=-18.5±0.4 fm

However: theory required, yielding ±0.3 fm uncertainty.

Recently, Garstedig (N3Lo): ±0.05 fm

Planned:

$$\mu^- + d \rightarrow n + n + \nu_\mu$$

# The pp-case

Elastic pp scattering, Coulomb force seems to be well under controle: $a_{pp}$=-7.83 fm

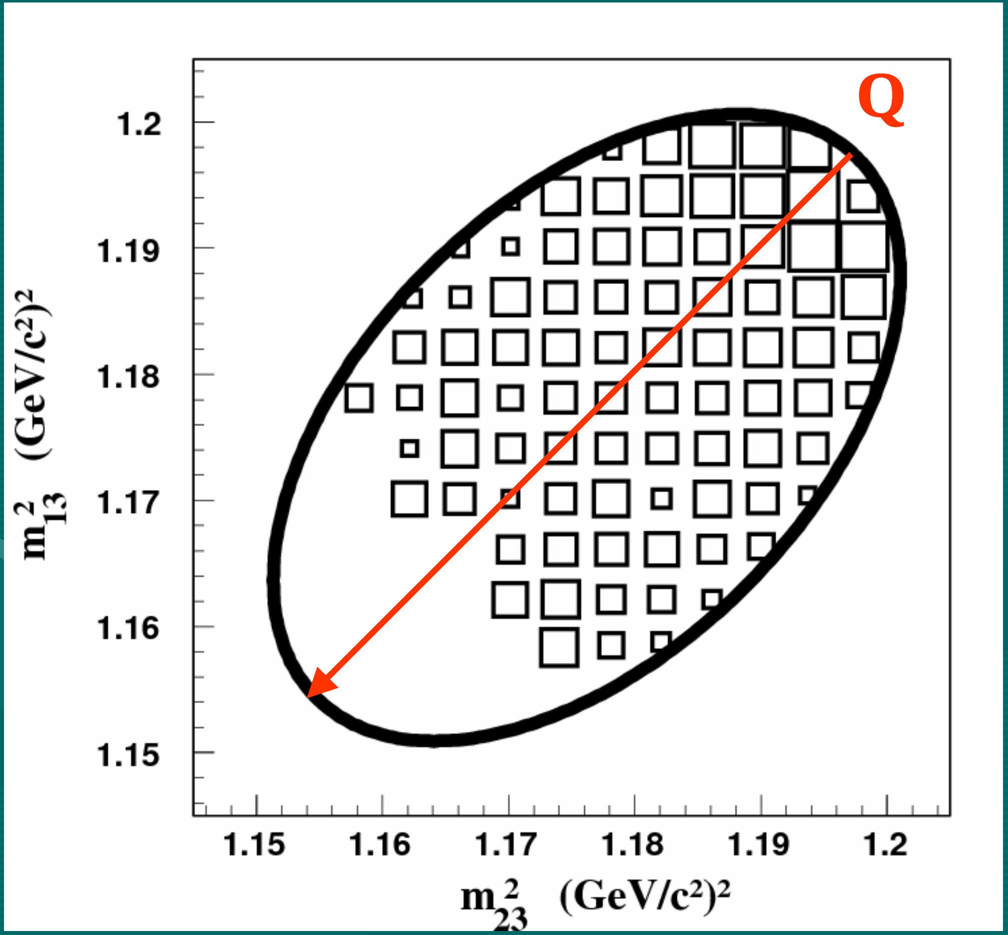
However: an IUCF group

$$p + p \rightarrow p + p + \pi^0$$

Claimed „…the data require $a_{pp}$=-1.5 fm.“ They questioned the validity of the factorization.

Experiment at GEM, differential and total cross sections.

# Dalitz plot




$$p + p \to p + p + \pi^0$$

# Modell

$$\frac{d\sigma}{dQ} = \frac{1}{4sp_i^*} |T(Q)|^2 \rho_3(Q)$$

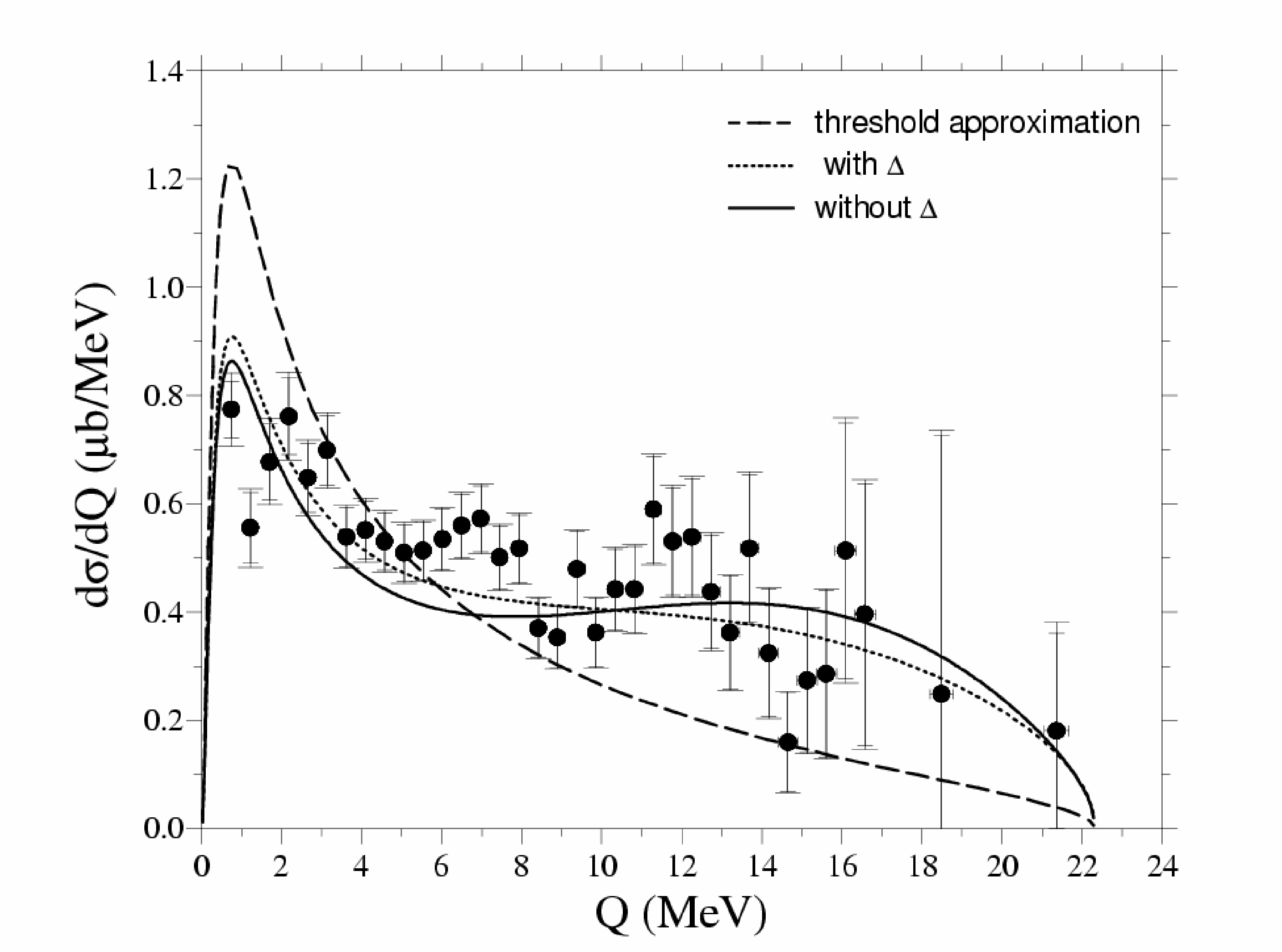
$$|T_{Ss}|^2 = |T_{00}|^2 |T_{FSI}|^2$$

$$T_{L_i,Ll} = \sqrt{a_{L,l}} < j_L(pr) j_l(qr/2) | V(r) | j_{L_i}(p_p^* r) >$$

$$V(r) = e^{-\mu r}/r$$

All with Gamow factor

# Differential x-sections



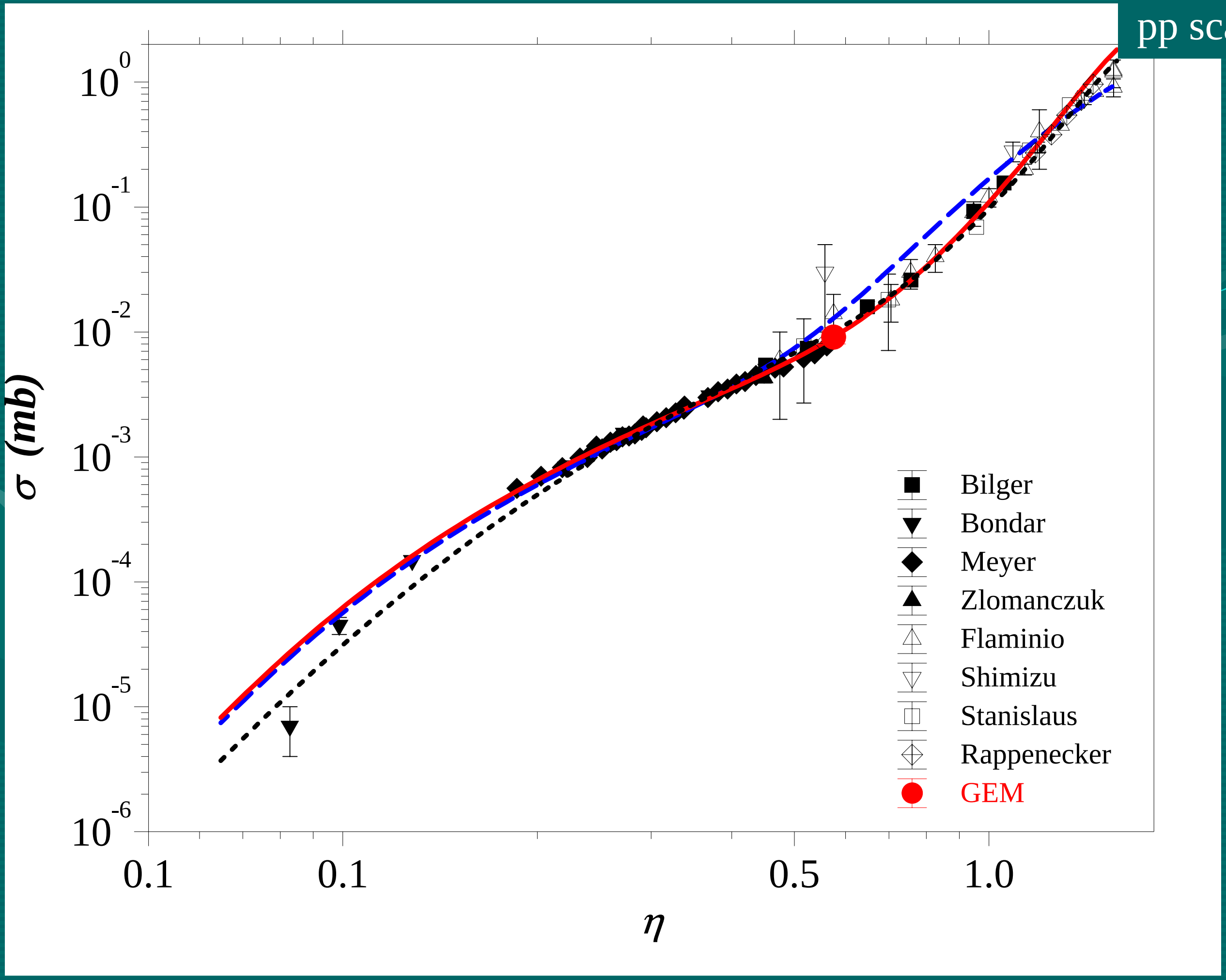
# $pp \rightarrow pp\pi^0$

FIT Ss, Pp (Ps from polarisation experiments)

blue: no Δ resonance

red: with Δ resonance, usual fsi

black: with Δ but fsi with half the usual pp scattering length

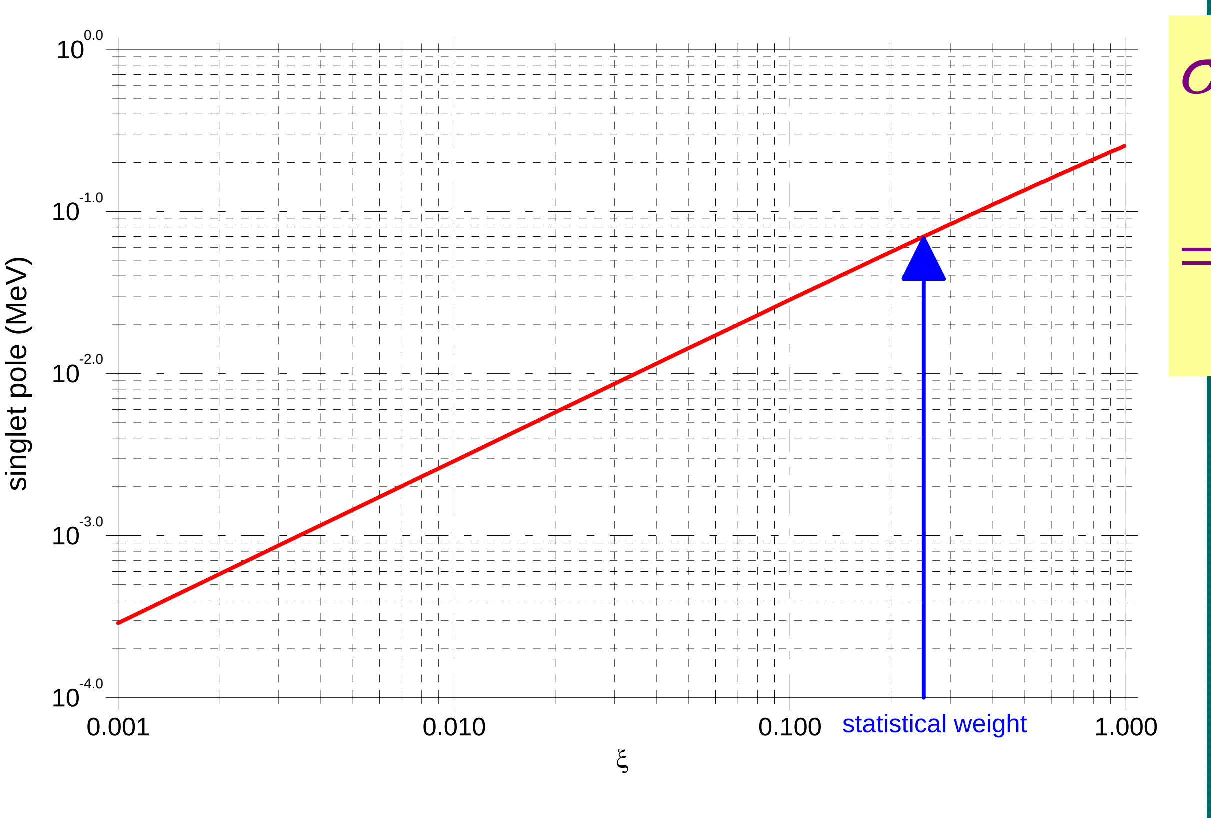



No need for a change of the scattering length!

# The np case

The only case with two possible isospin states.

The only case with a bound state: the deuteron. The spin singlet state was never observed in the deuteron. Where should be the spin singlet state (= isospin triplet state)?




$$\sigma_0 = \xi\sigma_s + (1-\xi)\sigma_t = \frac{4\pi\hbar^2}{m_p}\left(\frac{\xi}{|\varepsilon_s|} + \frac{1-\xi}{\varepsilon_t}\right)$$

A pole at +68 keV!

# Connection bound-continuum

Fäldt & Wilkin derived a formula ( for small k) $|\Psi_k(r)|^2 \approx \frac{2\pi}{\alpha\left(k^2+\alpha^2\right)} |\Psi_\alpha(r)|^2$

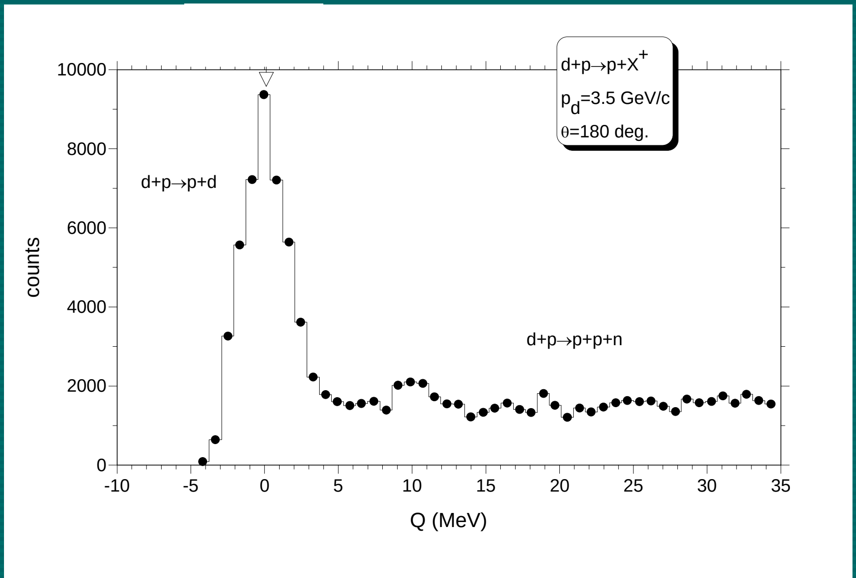
From this follows, that from a the cross section of a known pole (bound or quasi bound) the continuum cross section is given [$N(d) \rightarrow N(pn)_t \rightarrow \xi N(pn)_s$].

The fsi is large for excitation energies Q of only a few MeV.

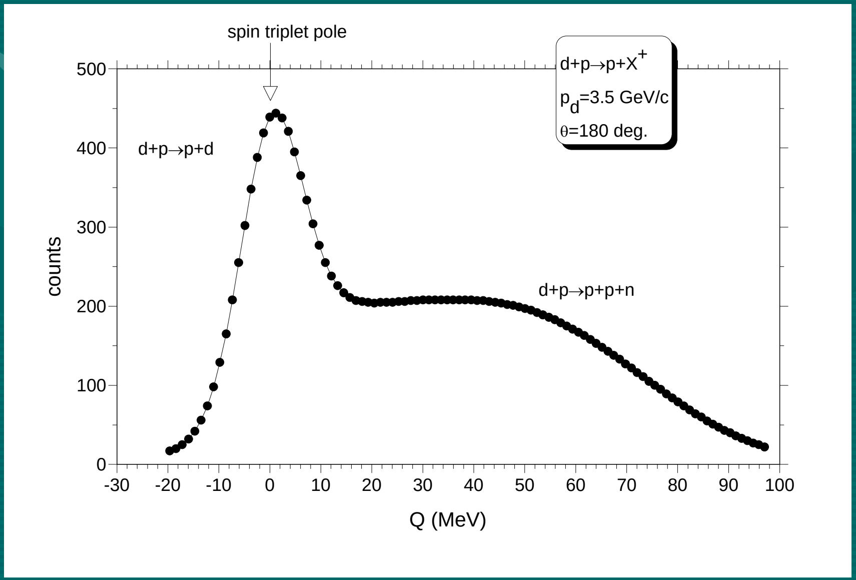
| type | pro | contra |
|---|---|---|
| single arm | absolute normalization of the triplet fraction | contamination from deuteron |
| double arm | no contamination from deuteron | no absolute normalization |

best: an experiment avoiding the con's. → high resolution single arm

# d+p→p+(pn)

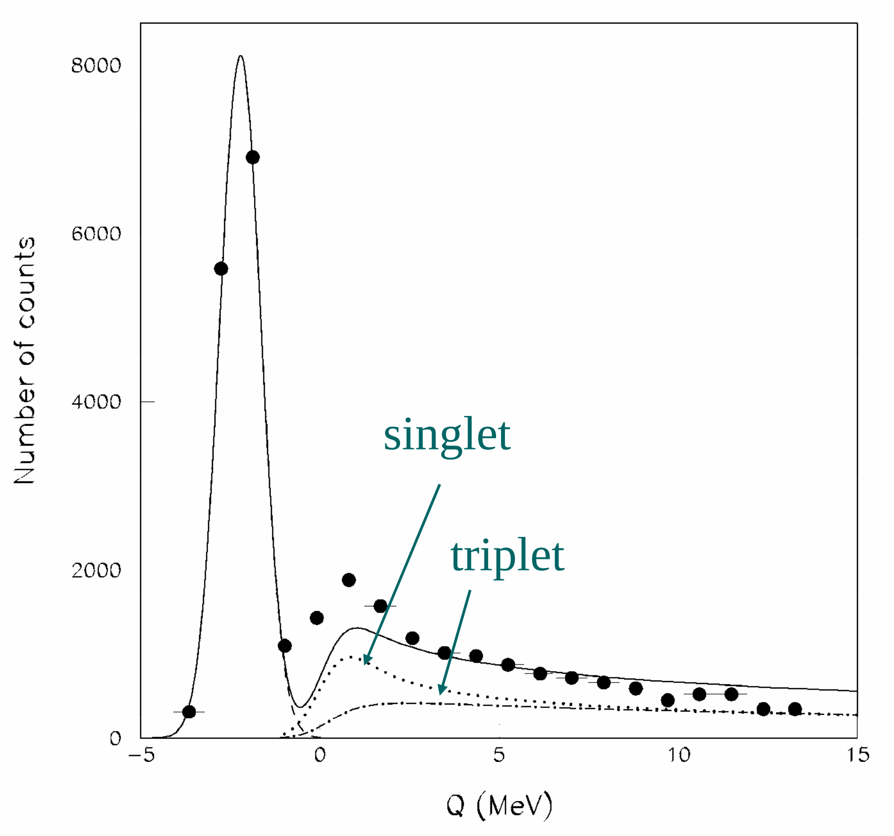



Saclay (unpublished)

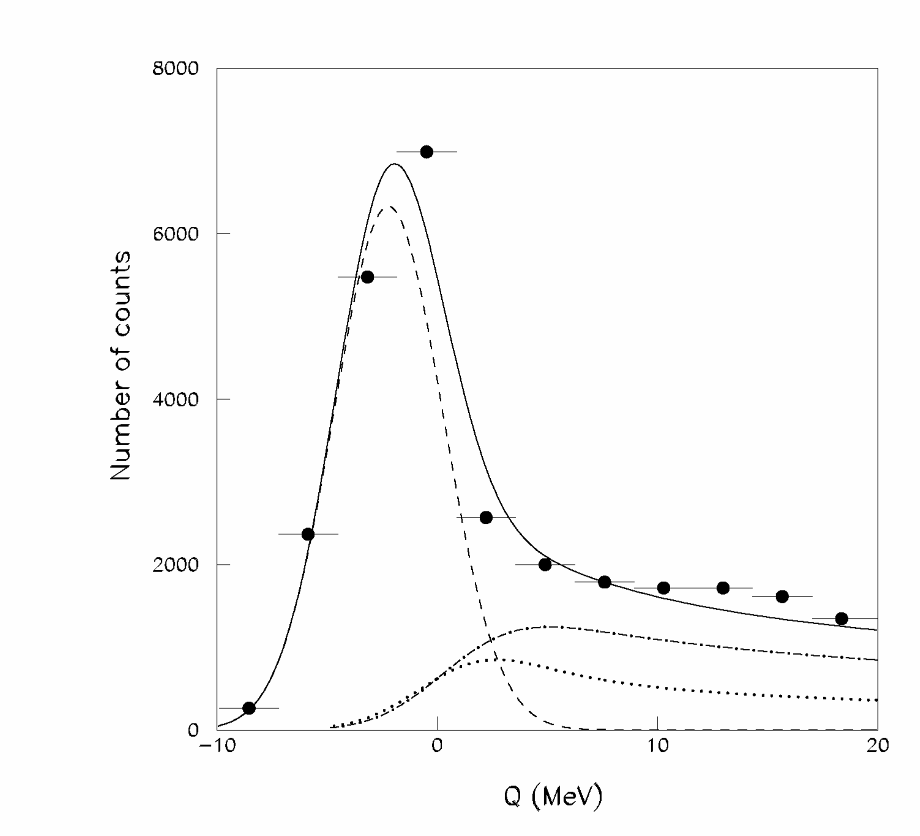



Dubna

# Saclay d+p→p+(pn)

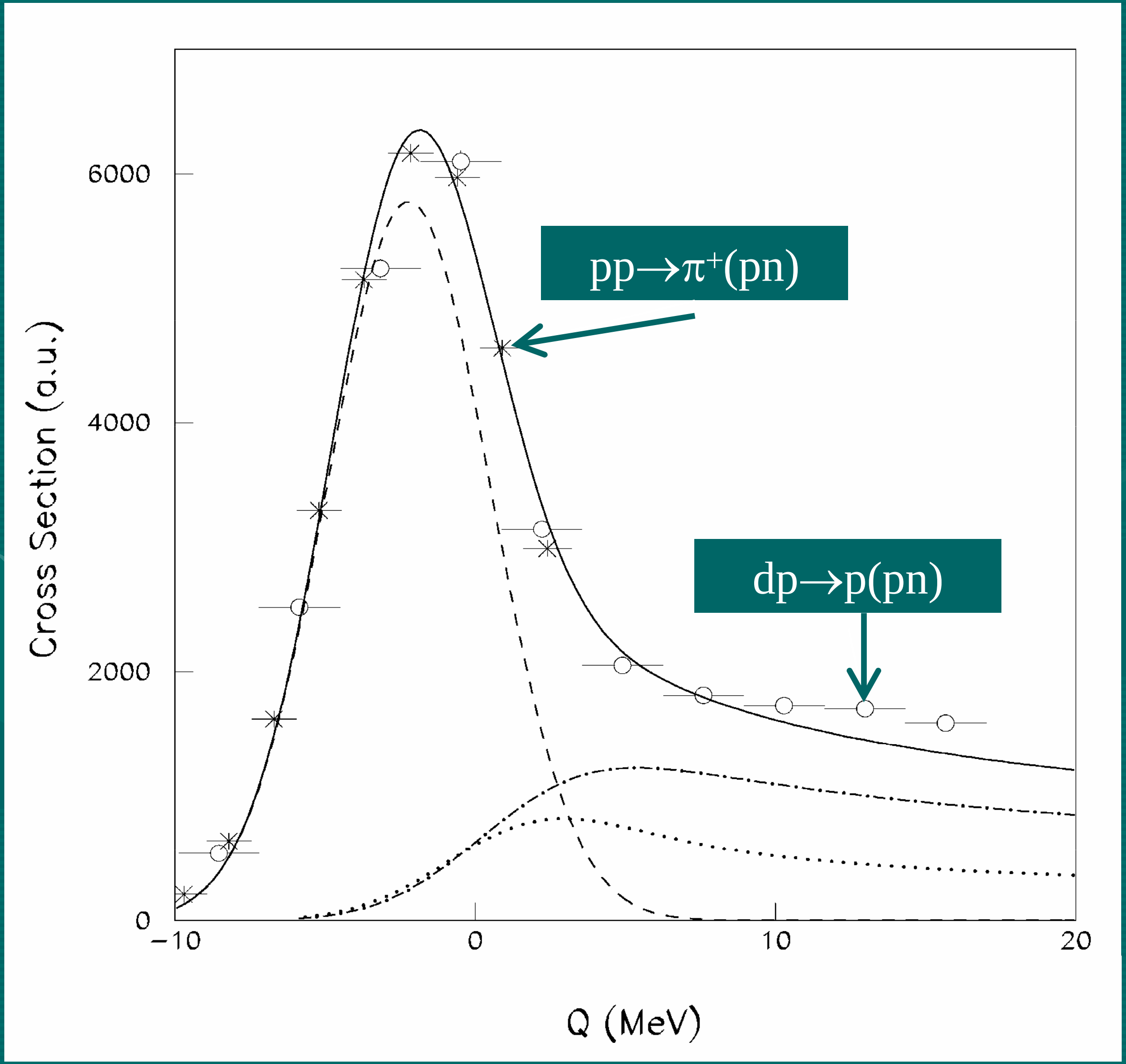



$T_d$=1600 MeV

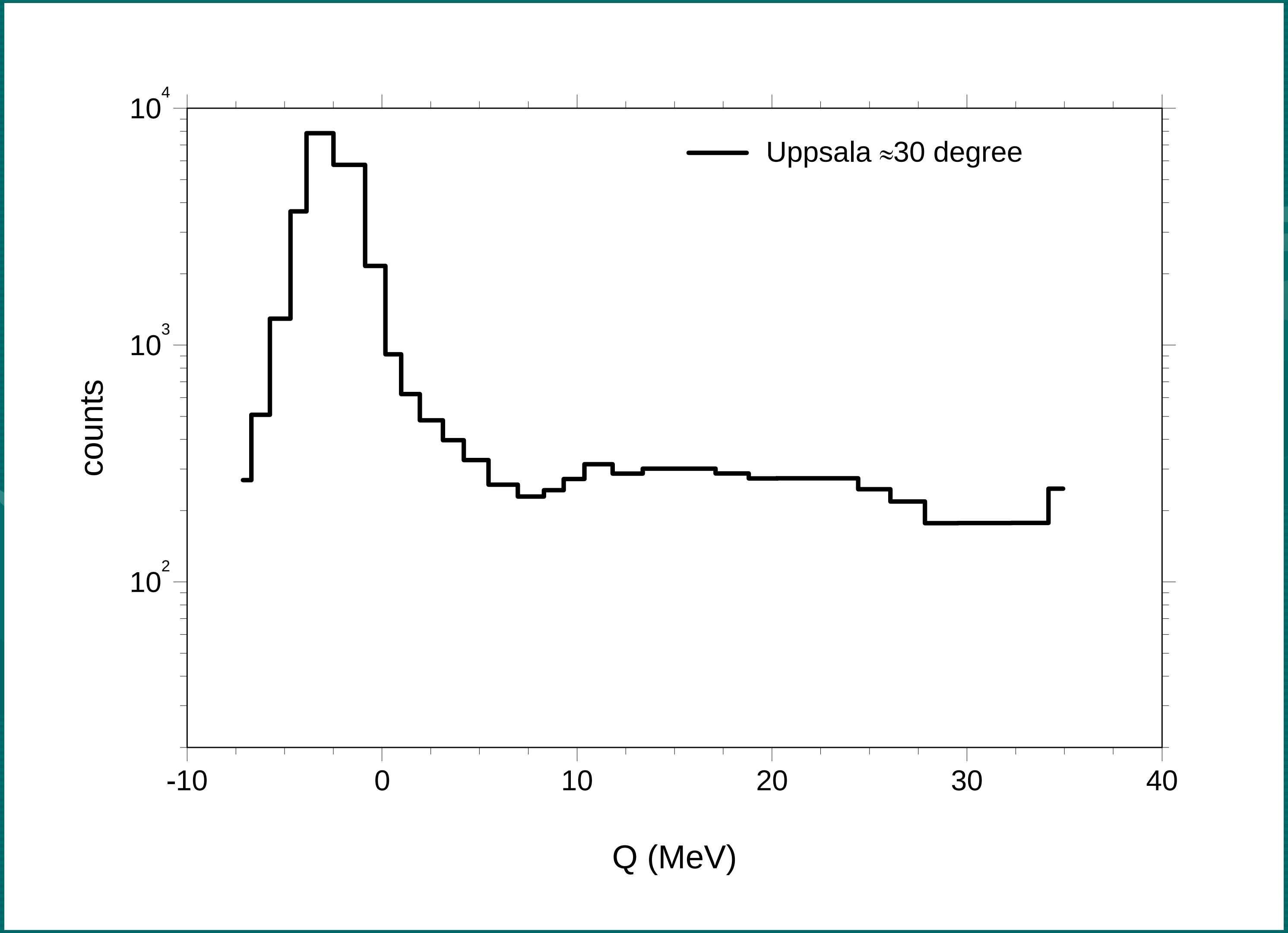



$T_d$=400 MeV

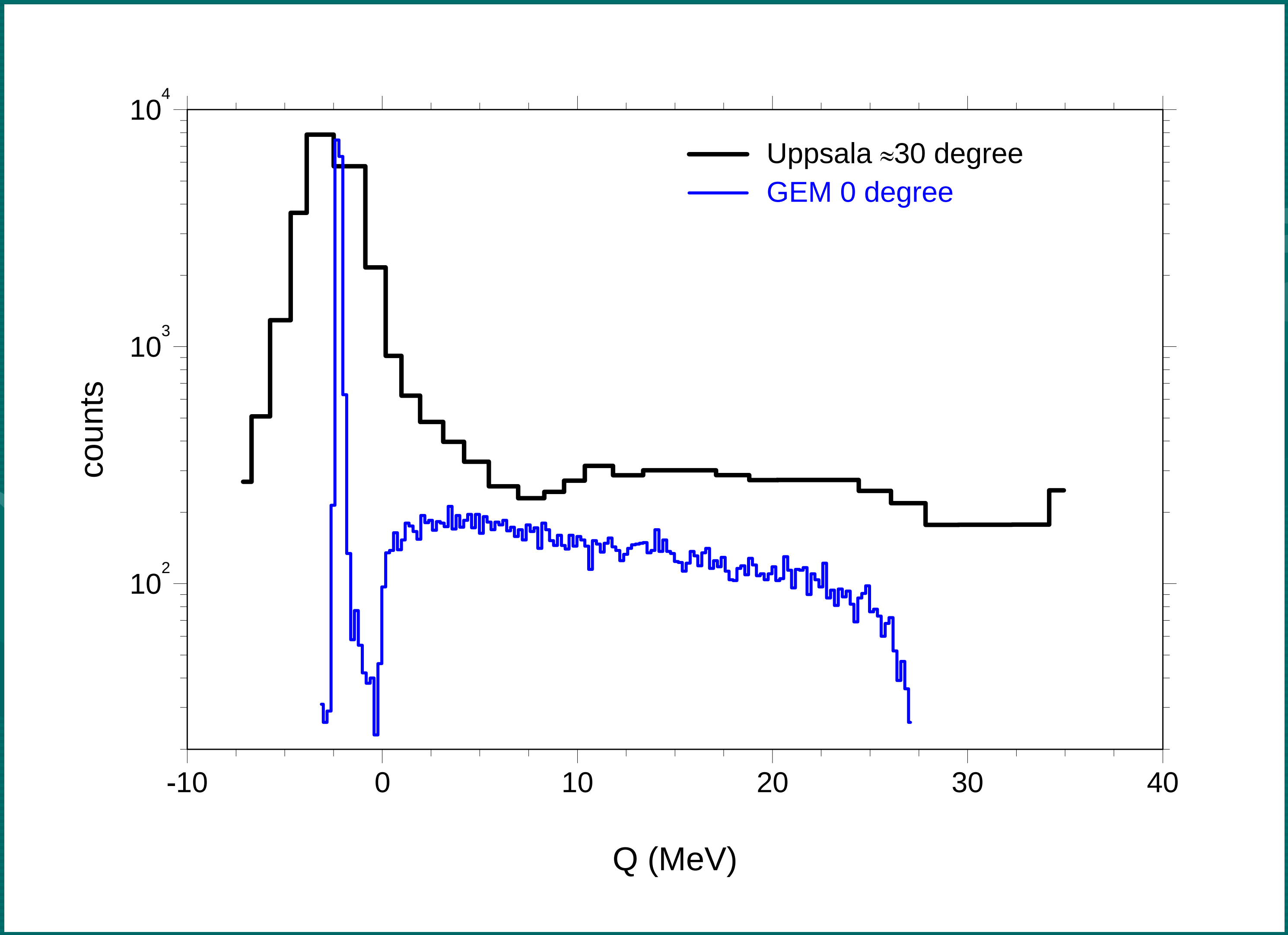
# Saclay pp→$\pi^+$(pn) 1000 MeV



# New data Uppsala

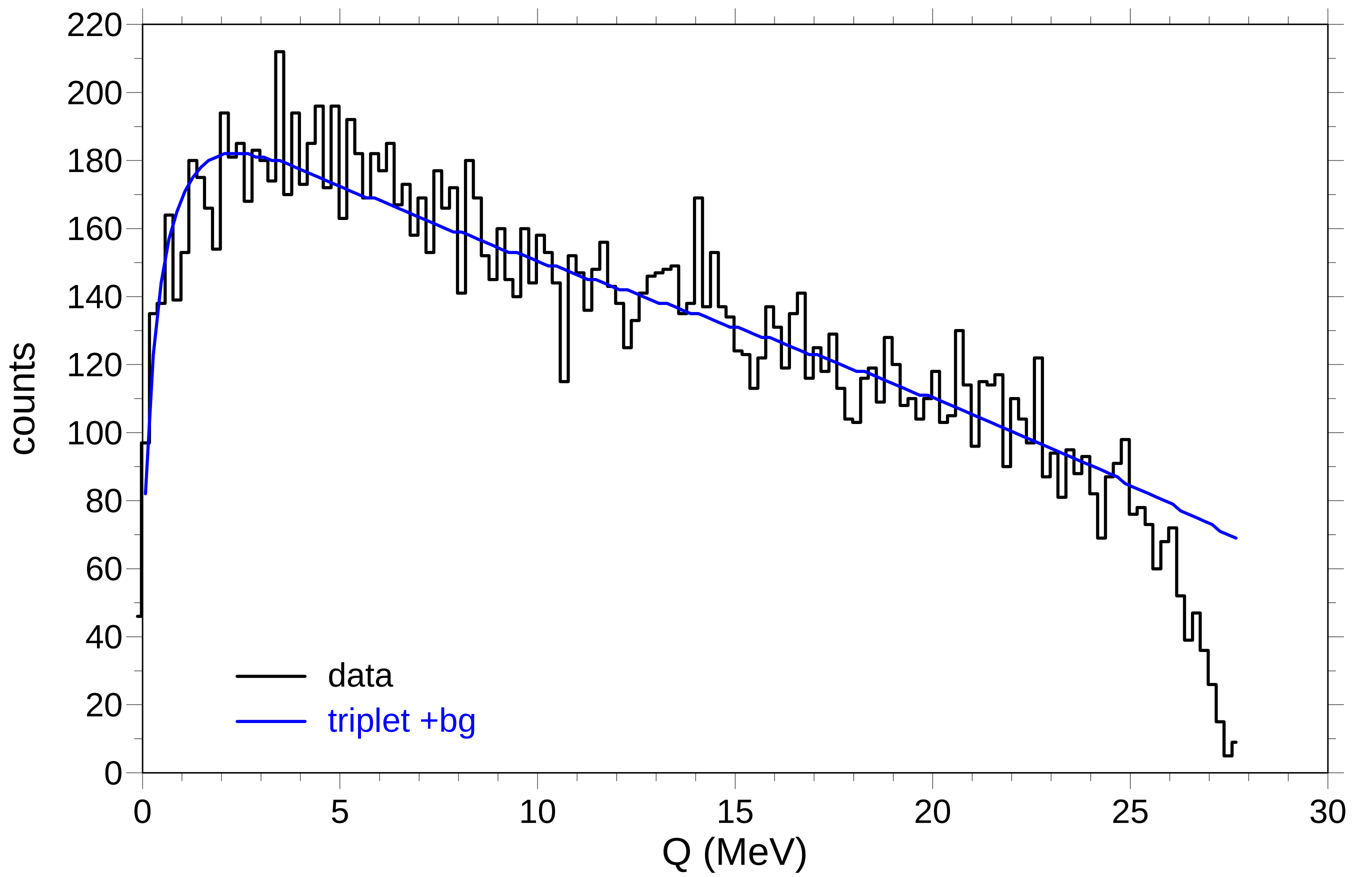


# New data Uppsala and GEM

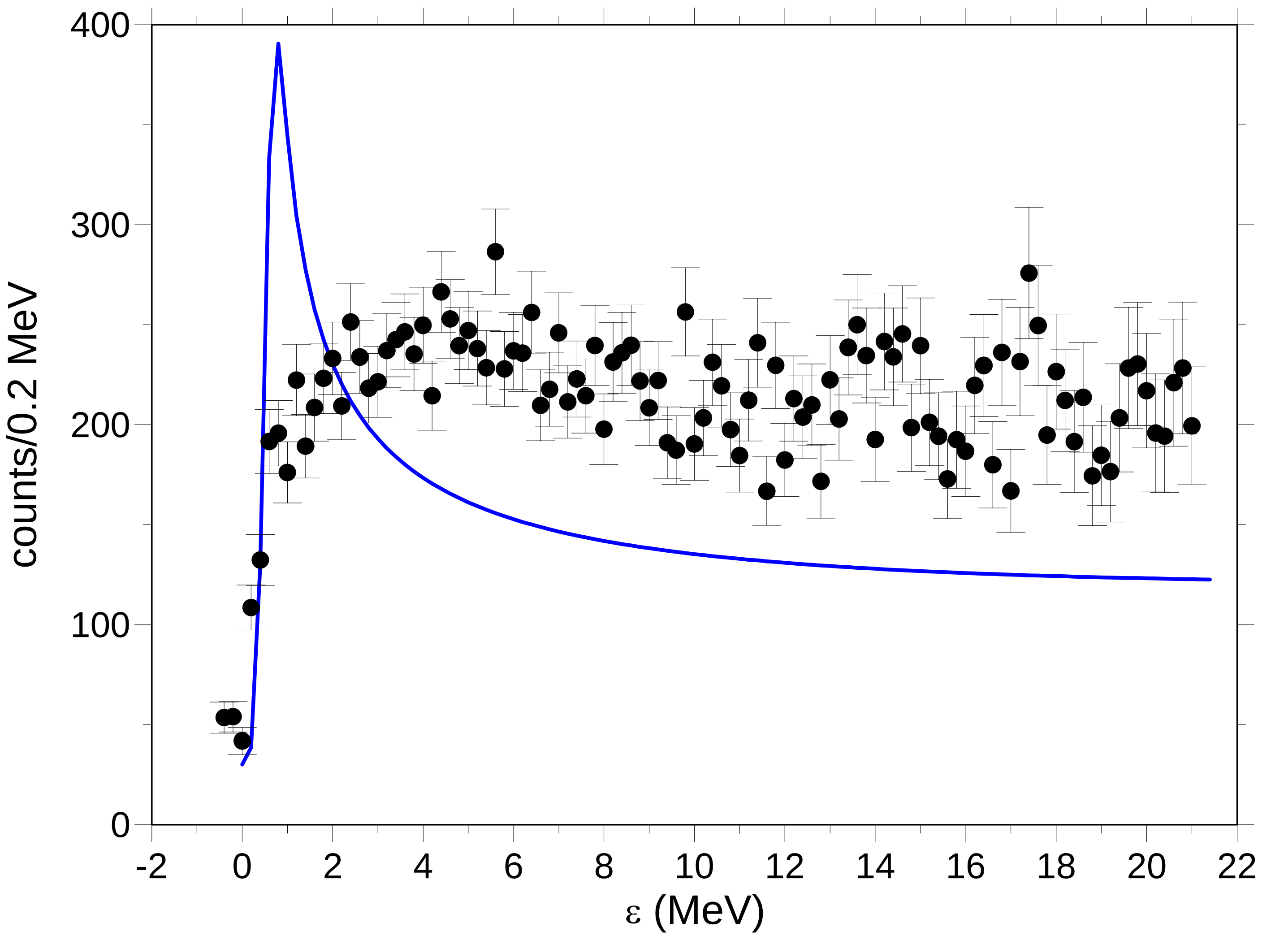



p=1642.5 MeV/c

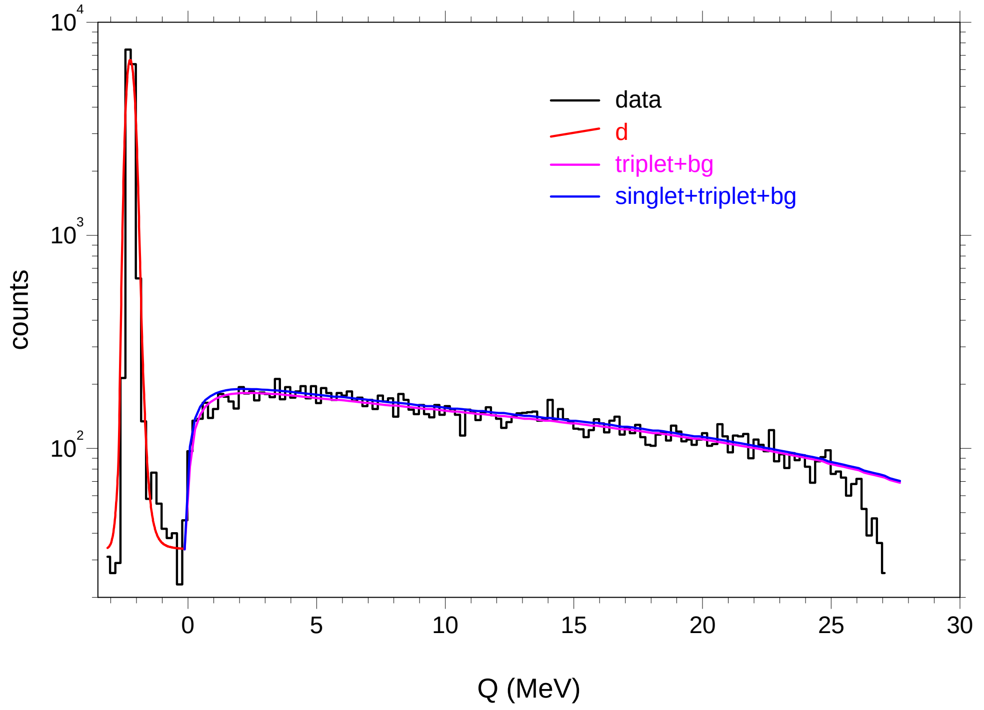
# Triplet FSI absolute



# Singlet FSI absolute



# Full spectrum




| singlet fraction | Ref. |
|---|---|
| 0.40±0.05 | Boudard et al. |
| < 0.10 | Betsch et al. |
| <0.10 | Uzikov & Wilkin |
| < 0.10 | Abaev et al. |
| < 0.003 | this work |

Why is there no singlet state?

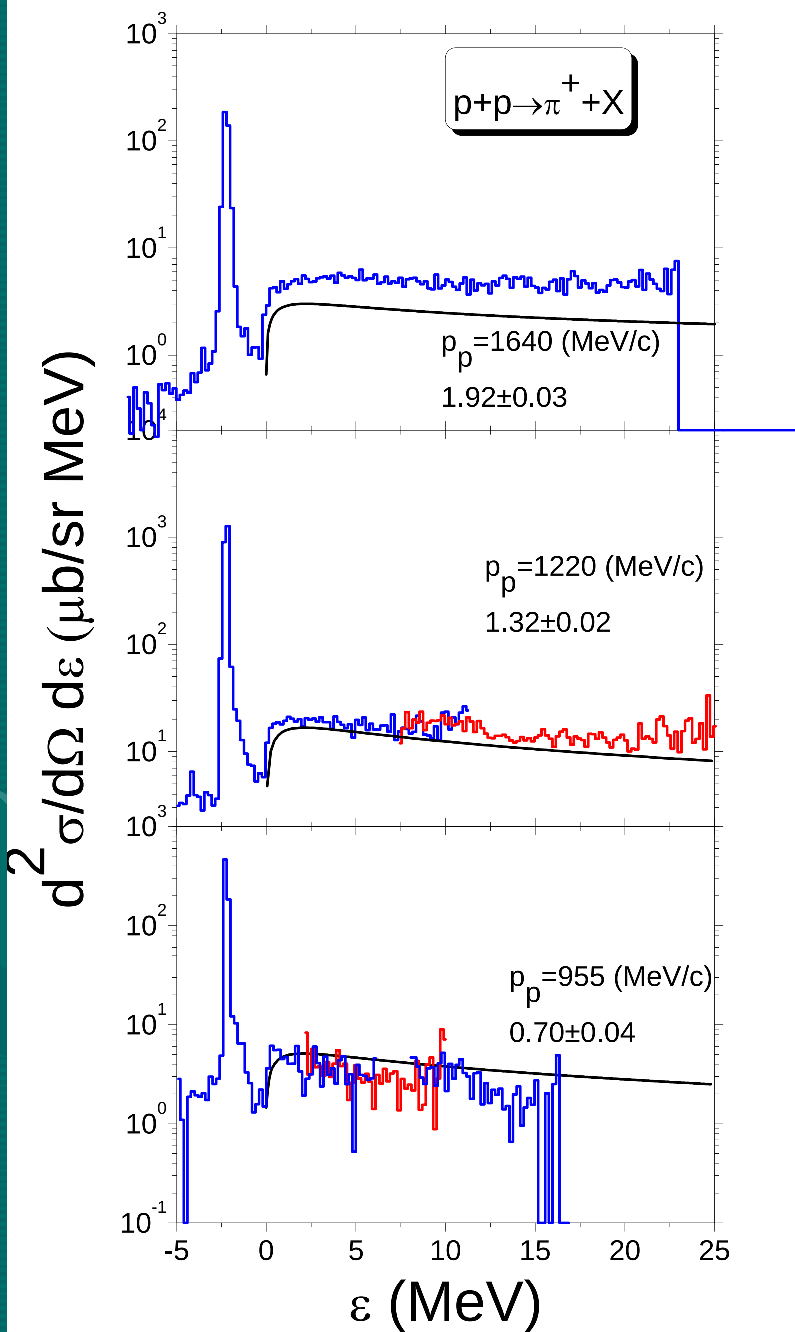
•first high resolution measurement allowing to study the threshold region of the d break up

•fixed cross section for the unbound triplet state

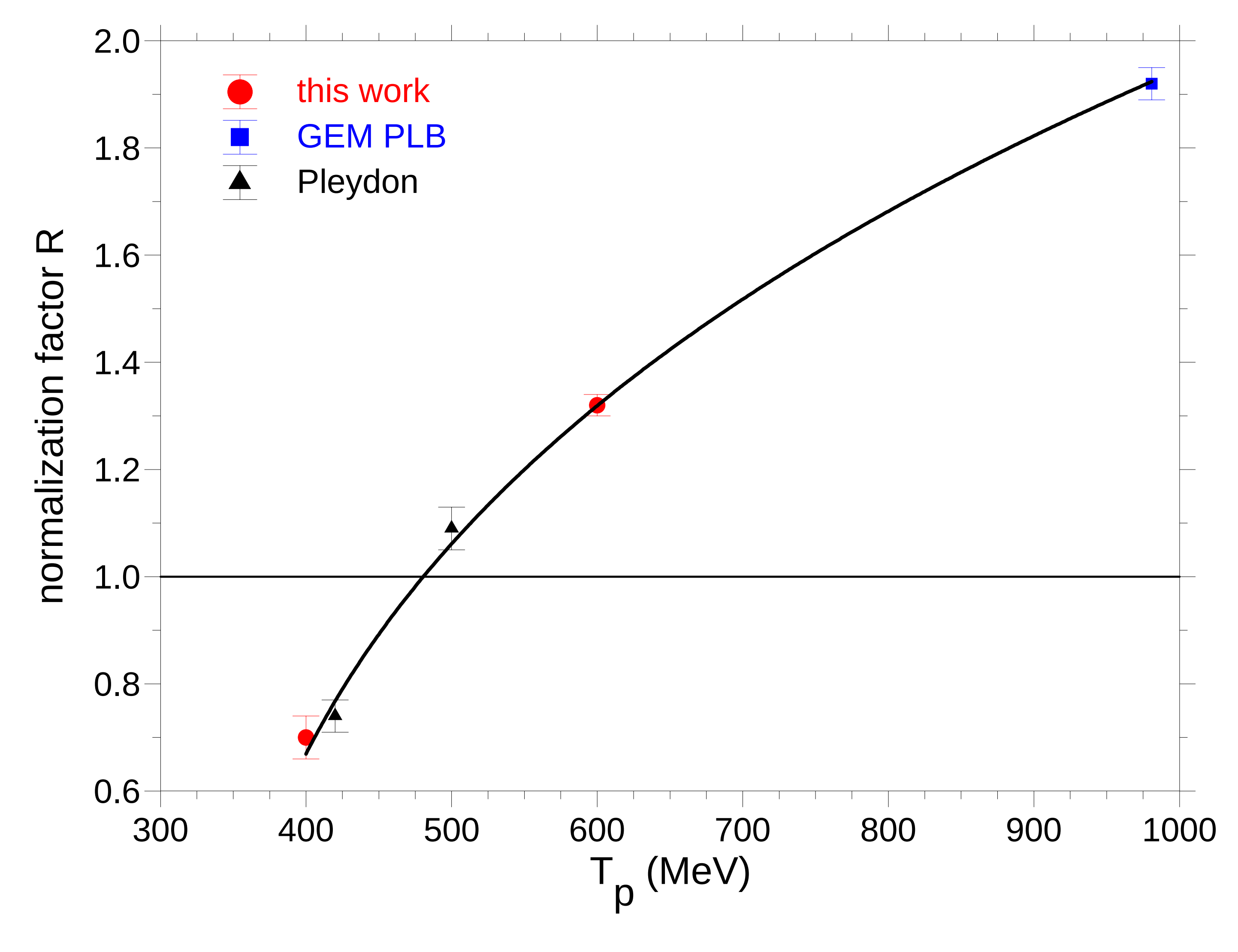
• the upper limit for the singlet break up contribution was reduced by a factor of 3

•the ratio for unbound to bound state is < (1.9±0.5) $\times 10^{-3}$

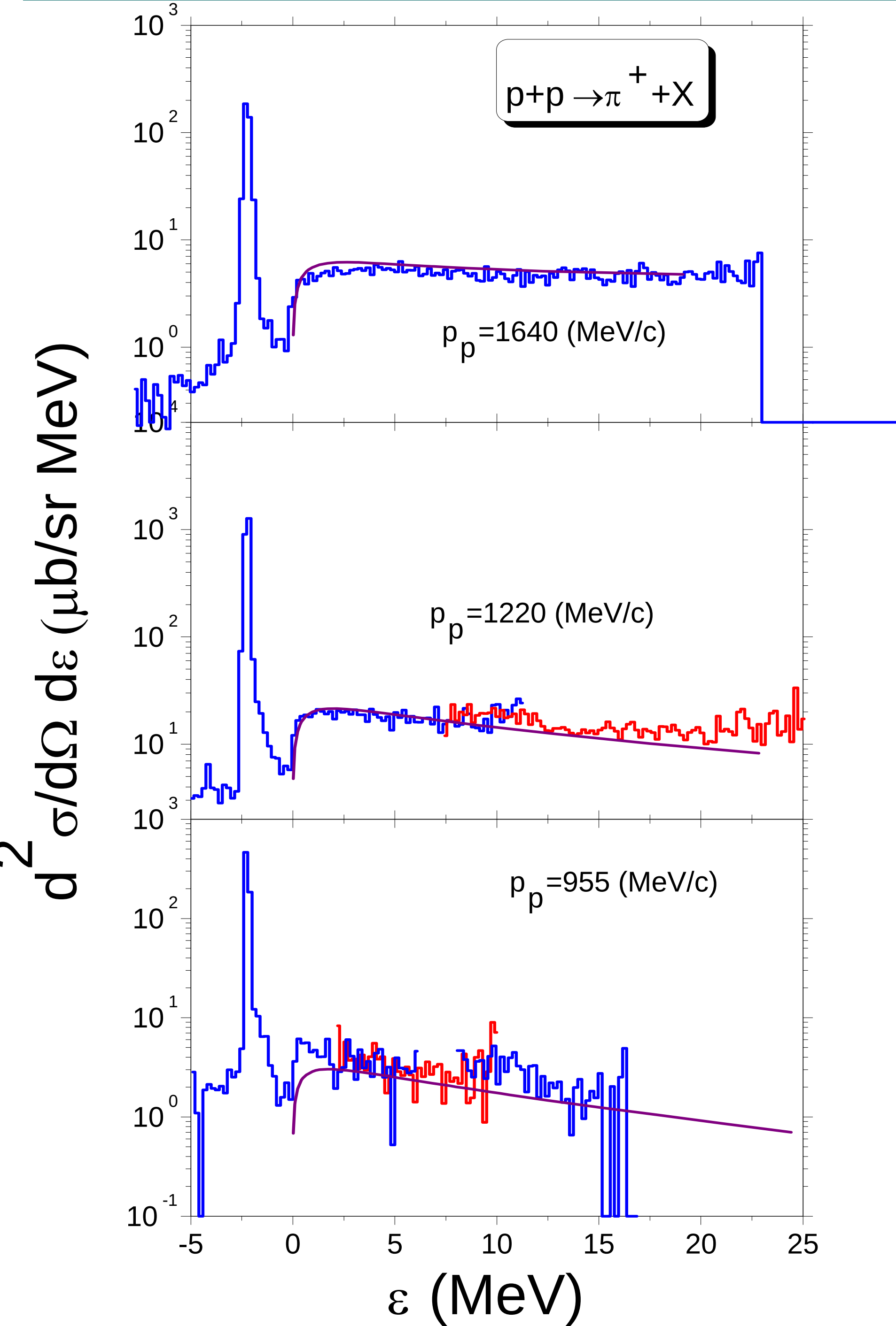
# More experiments



# Scaling factor



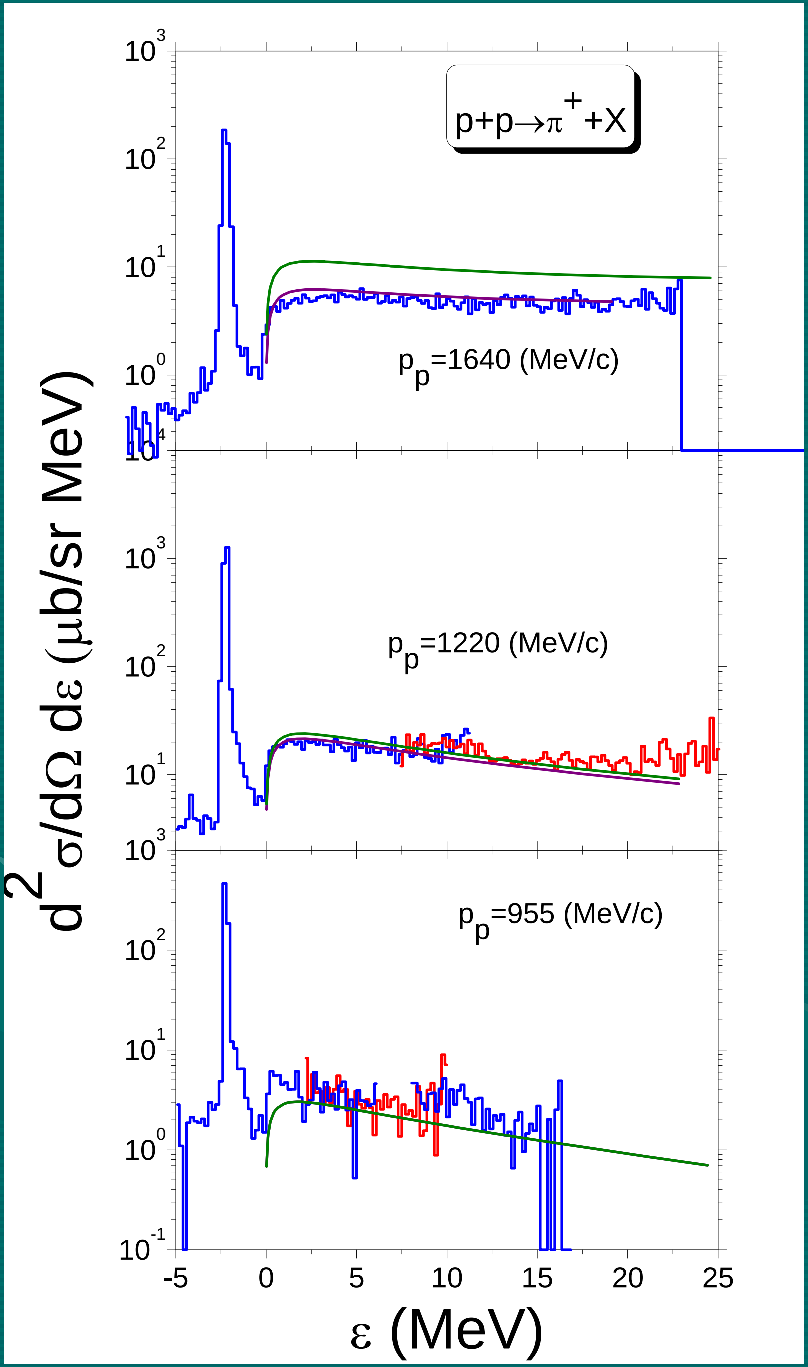
# Full 3 body calculation




Relativistic phase space

Reid soft core

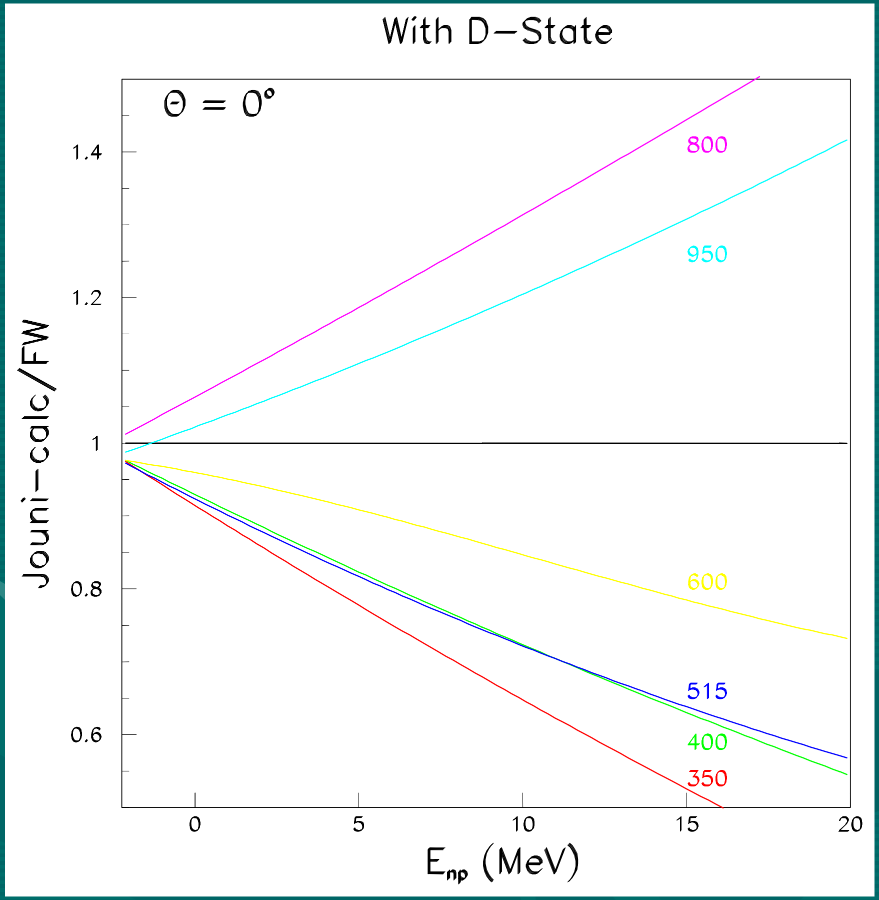
# Full 3 body calculation

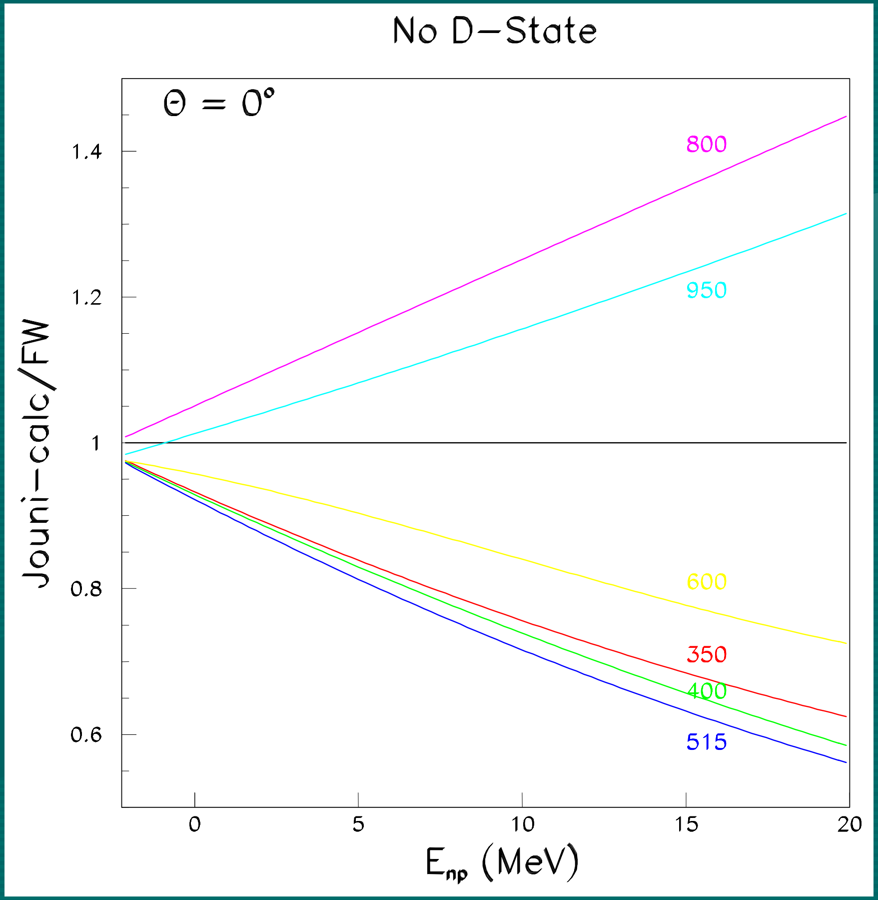



Relativistic phase space

Reid soft core, no tensor force, no d-state in the deuteron.

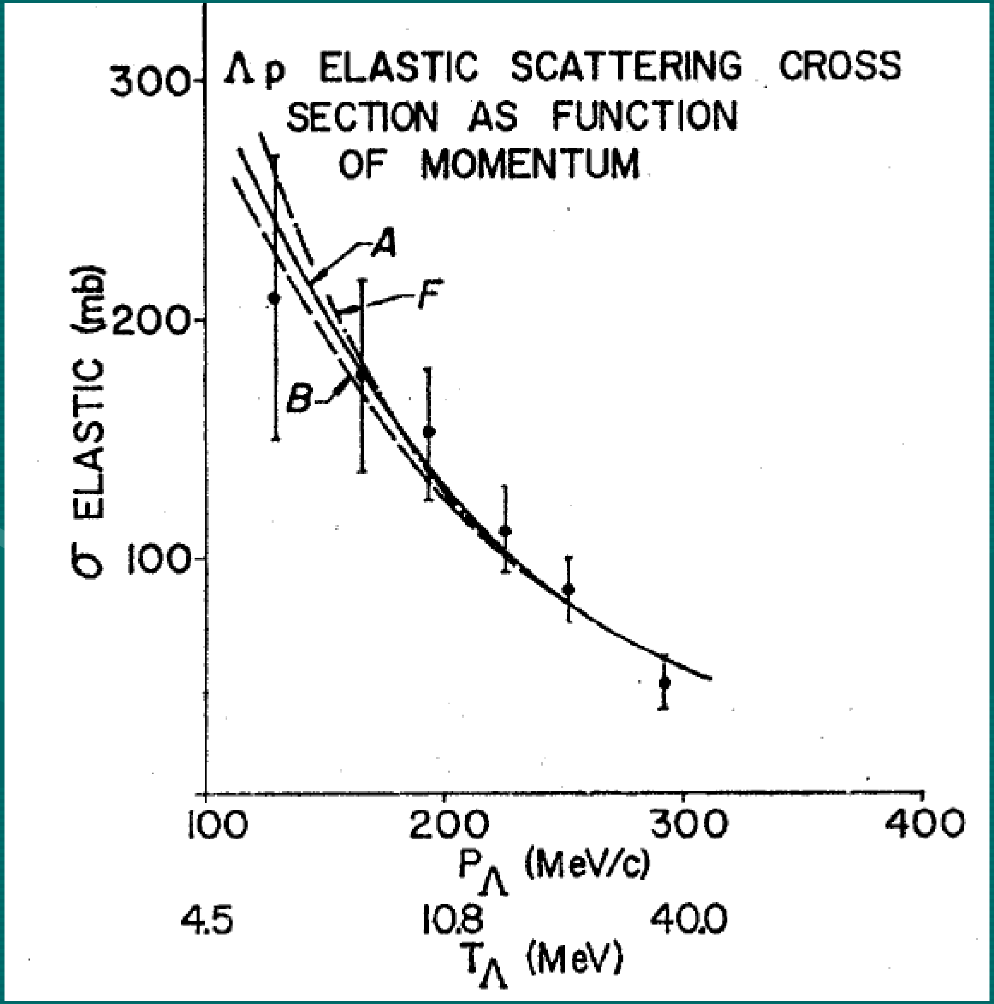
# It's not the tensor force!




## What is it then?

# Λp elastic scattering




378+224 events in a 82 cm bubble chamber

| | $a_s$ | $r_s$ | $a_t$ | $r_t$ |
|---|---|---|---|---|
| A | -2.0 | 5.0 | -2.2 | 3.5 |
| B | 0 | 0 | -2.3 | 3.0 |
| F | -8.0 | 1.5 | -0.6 | 5.0 |

# ΛN interaction

| | $a_s$ (fm) | $r_s$ (fm) | $a_t$ (fm) | $r_t$ (fm) |
|---|---|---|---|---|
| A | −1.56 | 1.43 | −1.59 | 3.16 |
| $\tilde{A}$ | −2.04 | 0.64 | −1.33 | 3.91 |
| B | −0.56 | 7.77 | −1.91 | 2.43 |
| $\tilde{B}$ | −0.40 | 12.28 | −2.12 | 2.57 |
| D | −1.90 | 3.72 | −1.96 | 3.24 |
| F | −2.29 | 3.17 | −1.88 | 3.36 |
| NSC | −2.78 | 2.88 | −1.41 | 3.11 |

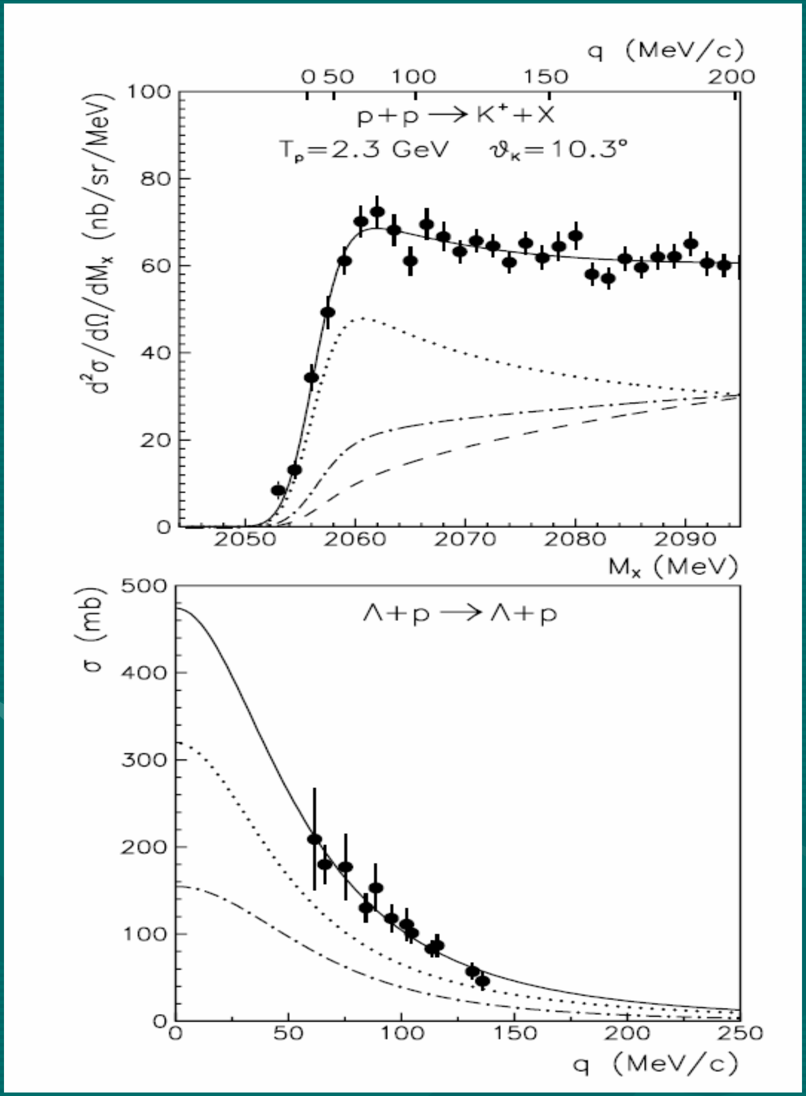
Jülich models

Nijmwegen model

No bound state!

pp→$K^+\Lambda p$

# FSI parameters of the Λp system

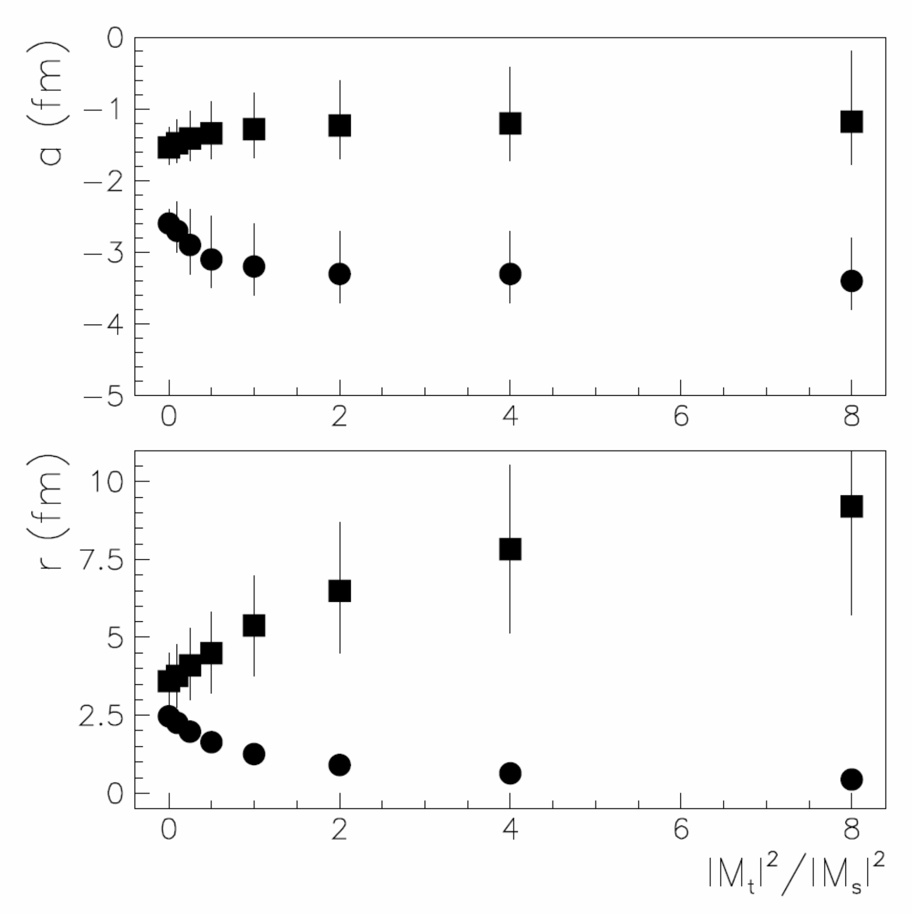


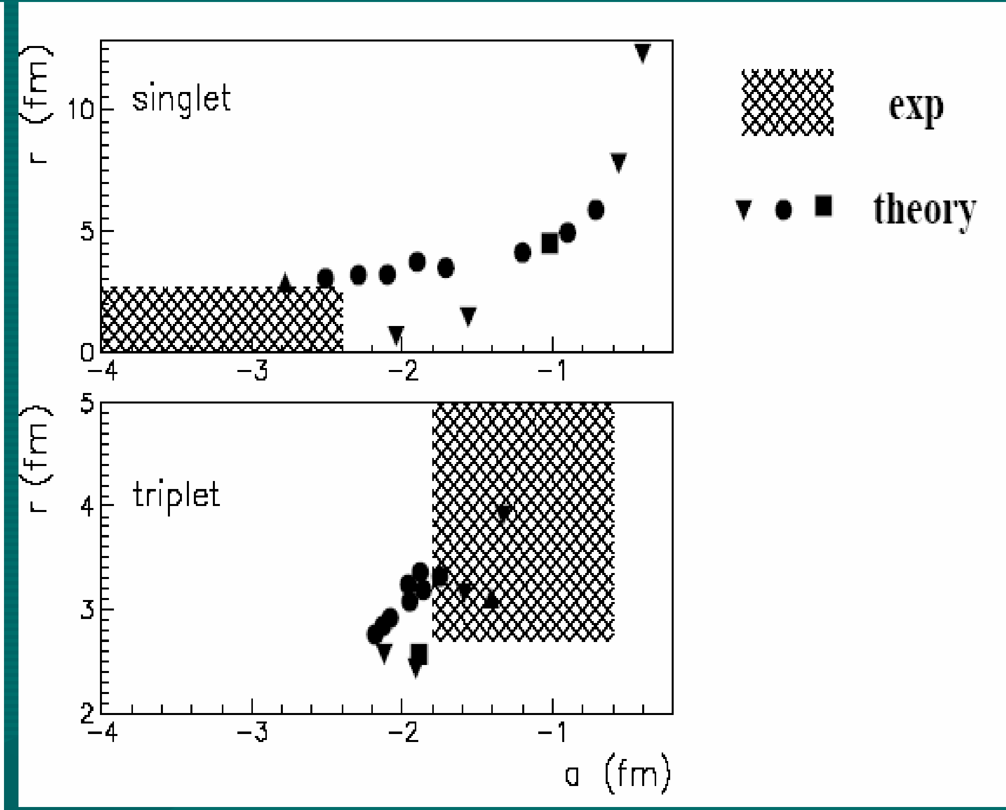

$|J_s| = |J_t|$

| $a_s$ | $r_s$ | $a_t$ | $r_t$ |
|---|---|---|---|
| -3.2 | 1.25 | -1.3 | 5.4 |

**F. Hinterberger and A. Sibirtsev,**
**Eur. J. Phys. A 21 (2004) 313**
**Data from Nucl. Phys. A 567(1994) 819**

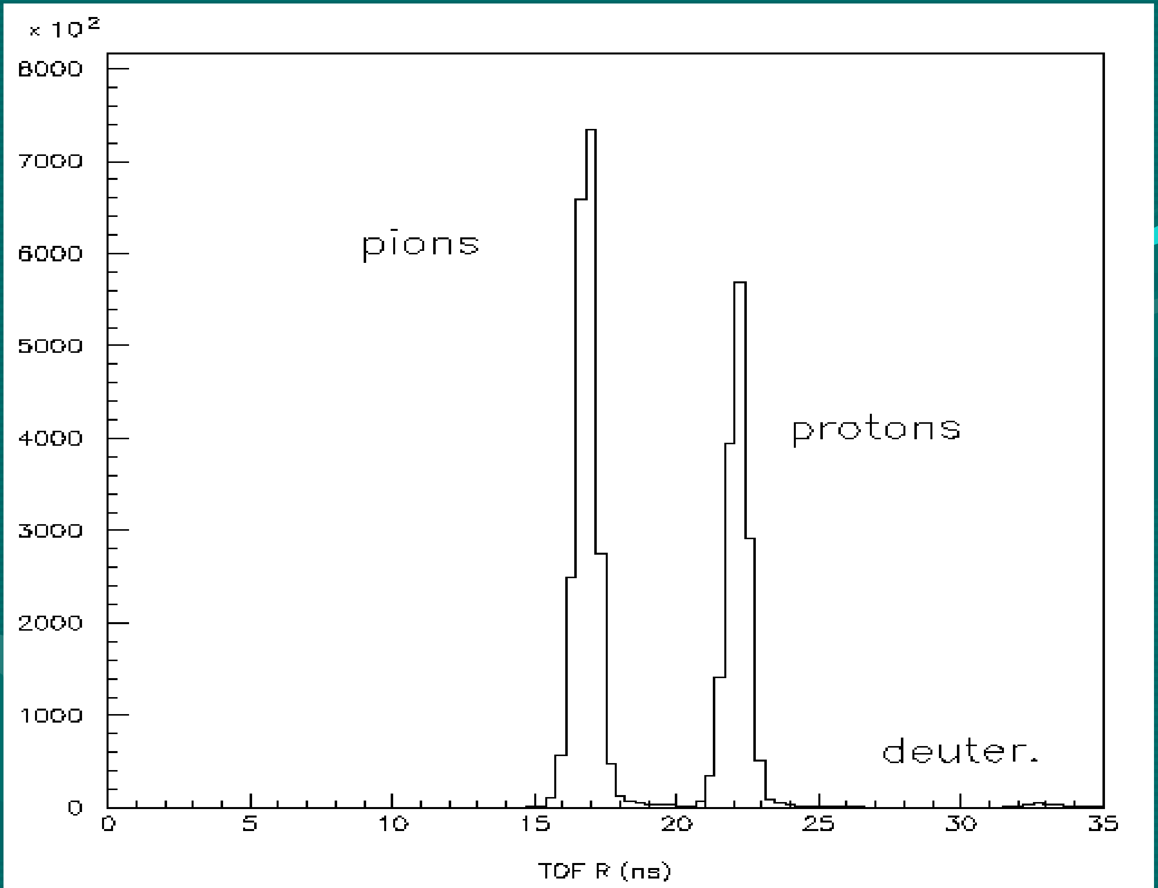
# FSI parameters of the Λp system



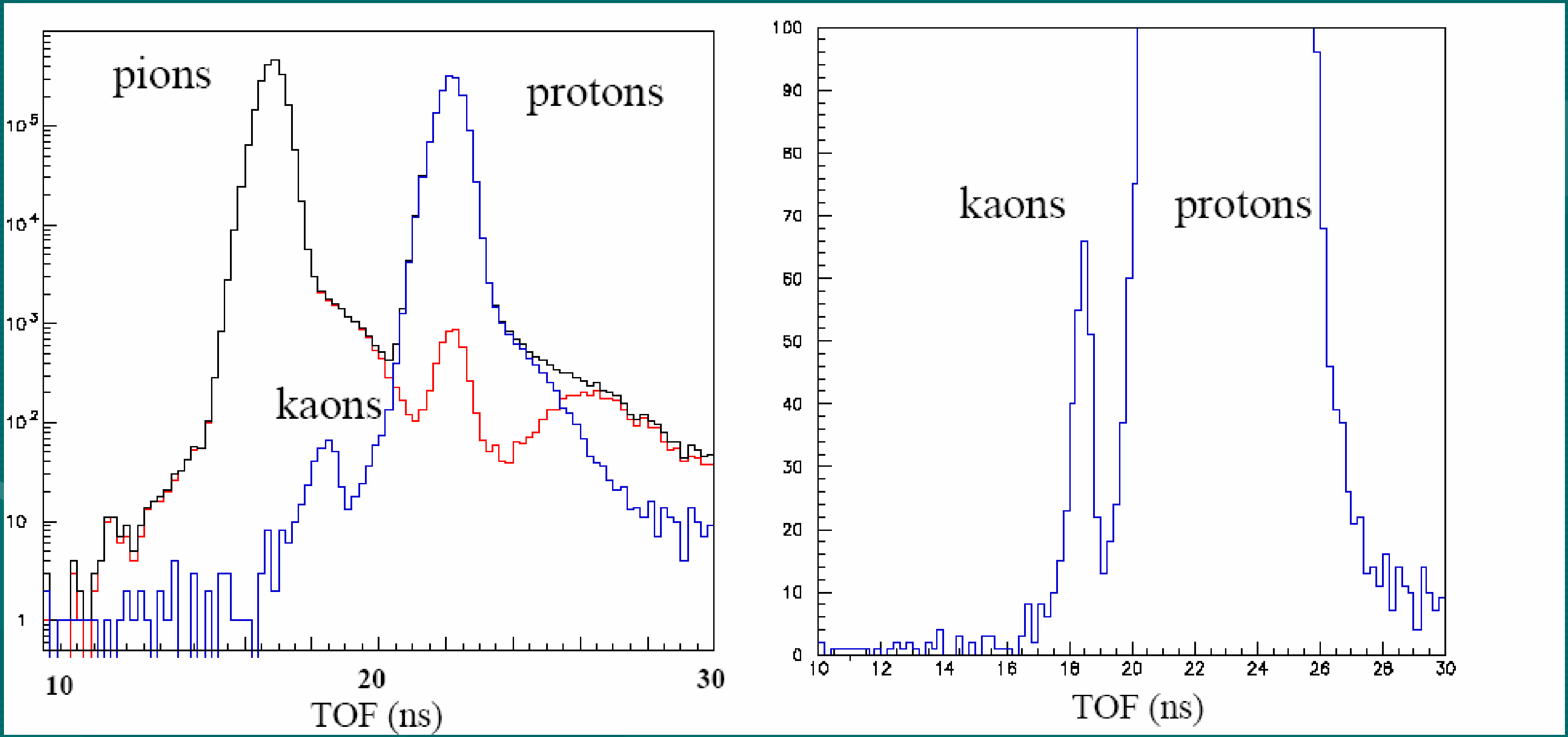
# p+p → X

$P_{beam}$ =2735 MeV/c $p_{BK}$ = 1070 MeV/c



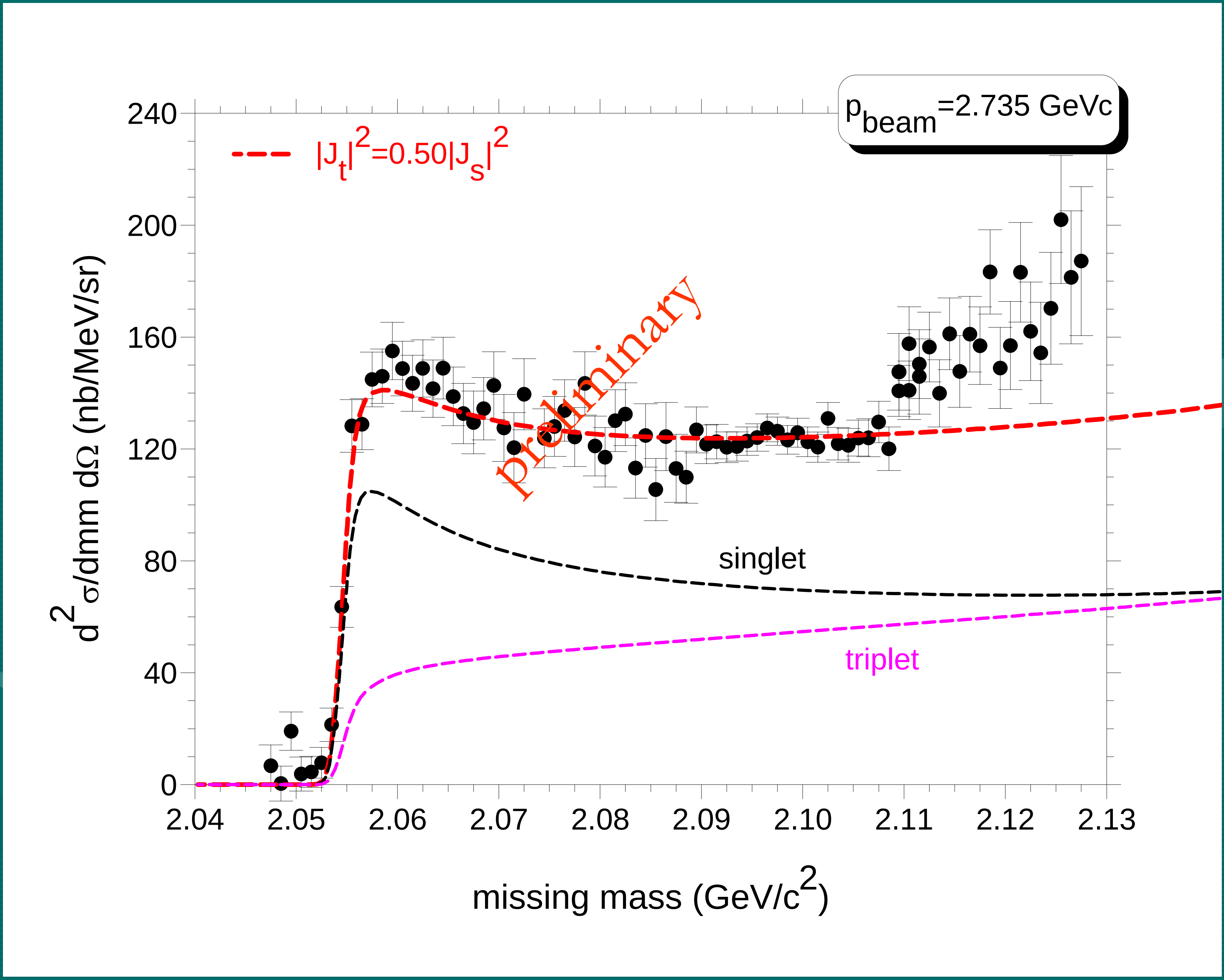
# p(p,X)

$P_{beam}$ =2735 MeV/c $p_{BK}$ = 1070 MeV/c

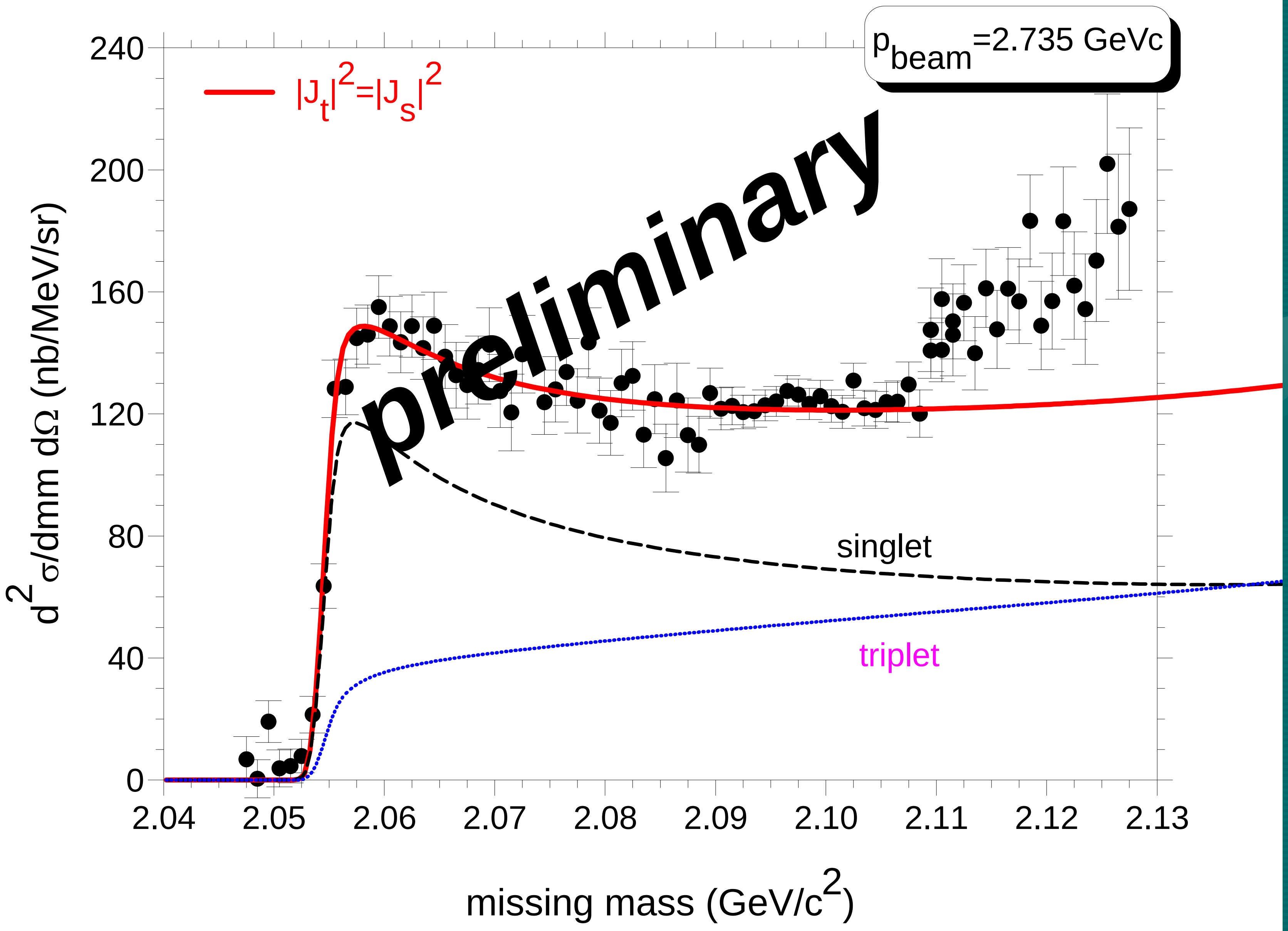



cherenkov signal

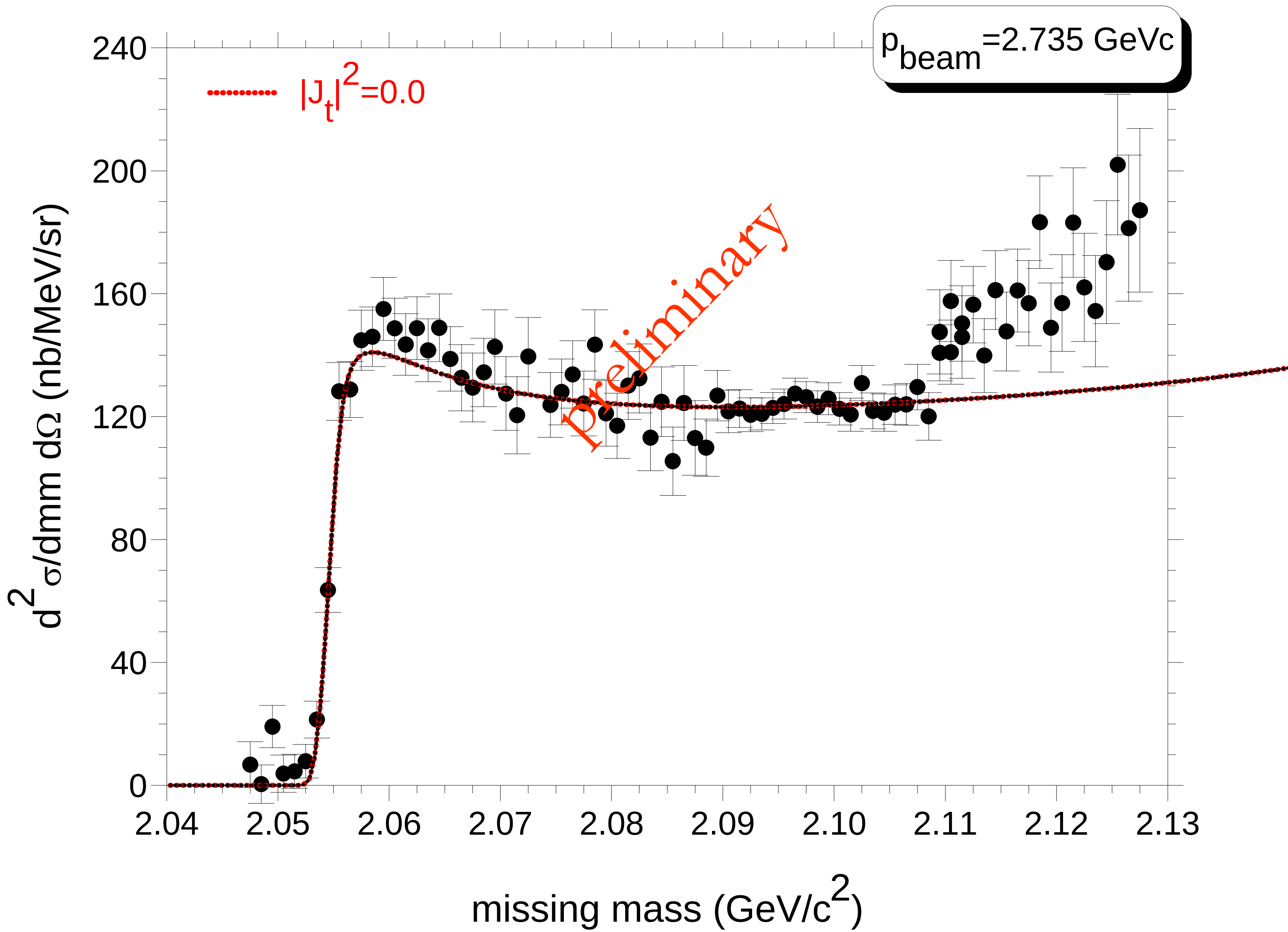
vetoed with cherenkov signal



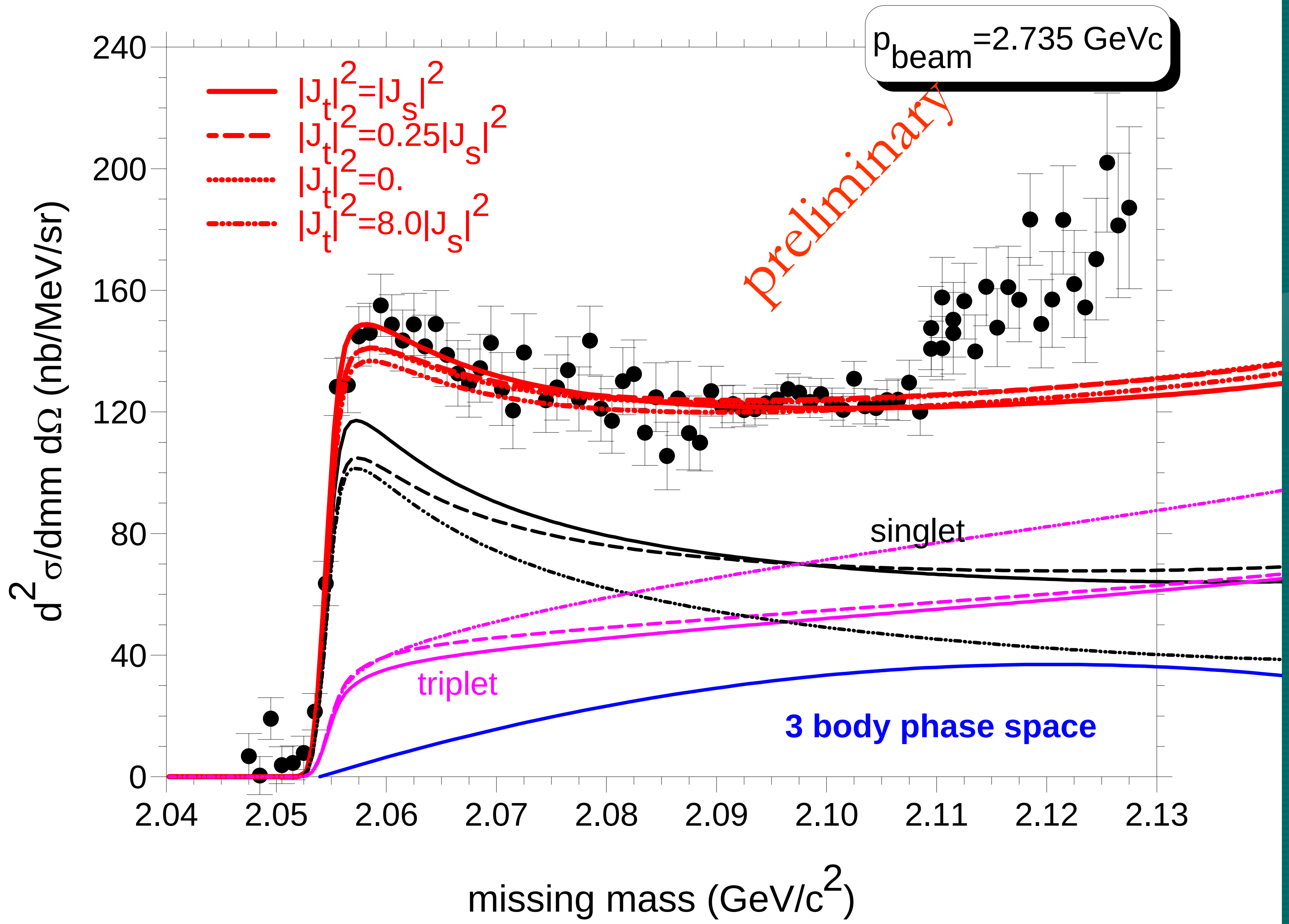
$p_{beam}$=2.735 GeVc
$|J_t|^2=0.50|J_s|^2$
preliminary
singlet
triplet
$d^2\sigma/dmm\ d\Omega$ (nb/MeV/sr)
missing mass (GeV/$c^2$)
0
40
80
120
160
200
240
2.04
2.05
2.06
2.07
2.08
2.09
2.10
2.11
2.12
2.13



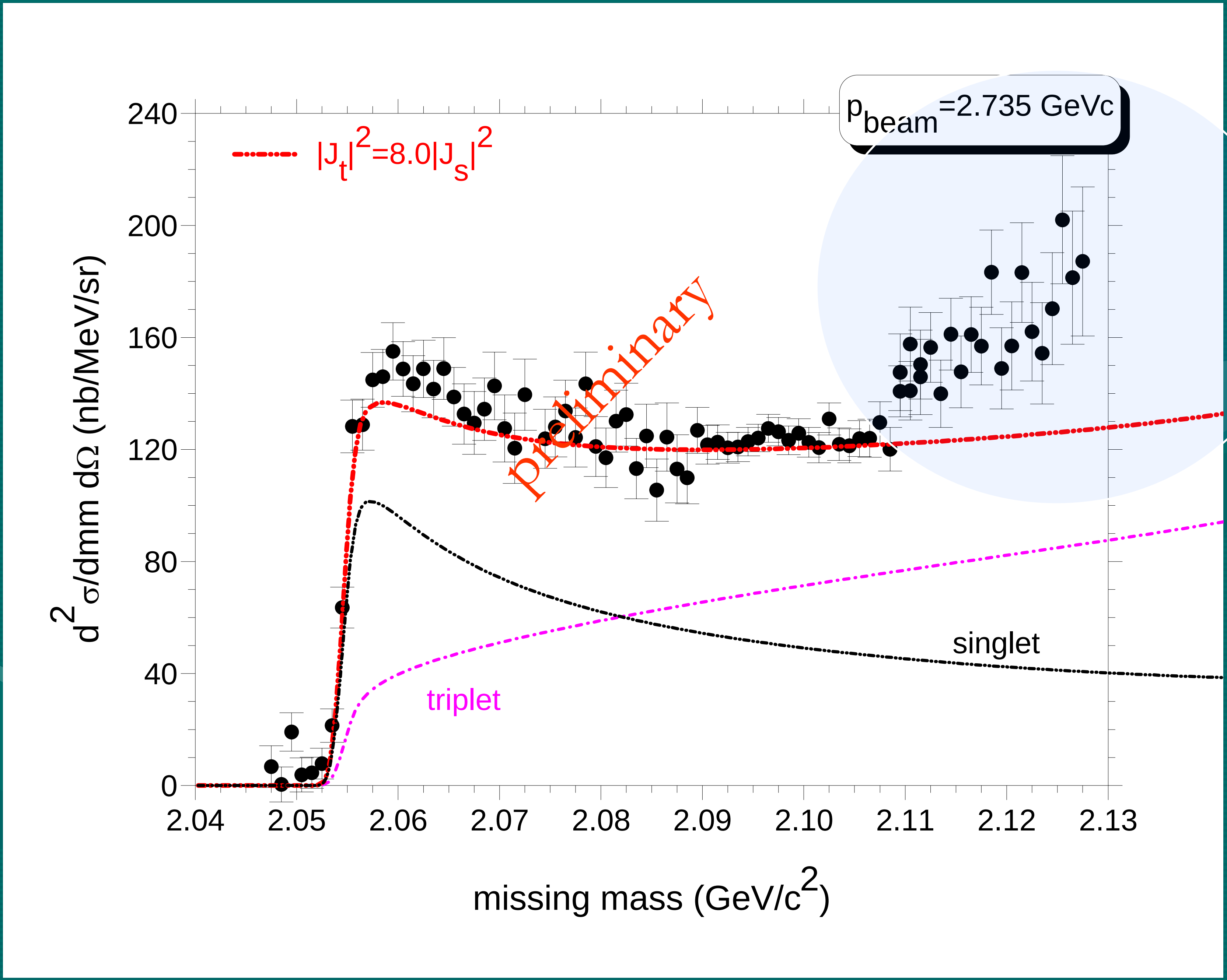
p_beam=2.735 GeVc
|J_t|^2=|J_s|^2
preliminary
singlet
triplet
240
200
160
120
80
40
0
2.04
2.05
2.06
2.07
2.08
2.09
2.10
2.11
2.12
2.13
d^2σ/dmm dΩ (nb/MeV/sr)
missing mass (GeV/c^2)



p_beam=2.735 GeVc
|J_t|^2=0.0
preliminary
240
200
160
120
80
40
0
d^2σ/dmm dΩ (nb/MeV/sr)
2.04
2.05
2.06
2.07
2.08
2.09
2.10
2.11
2.12
2.13
missing mass (GeV/c^2)

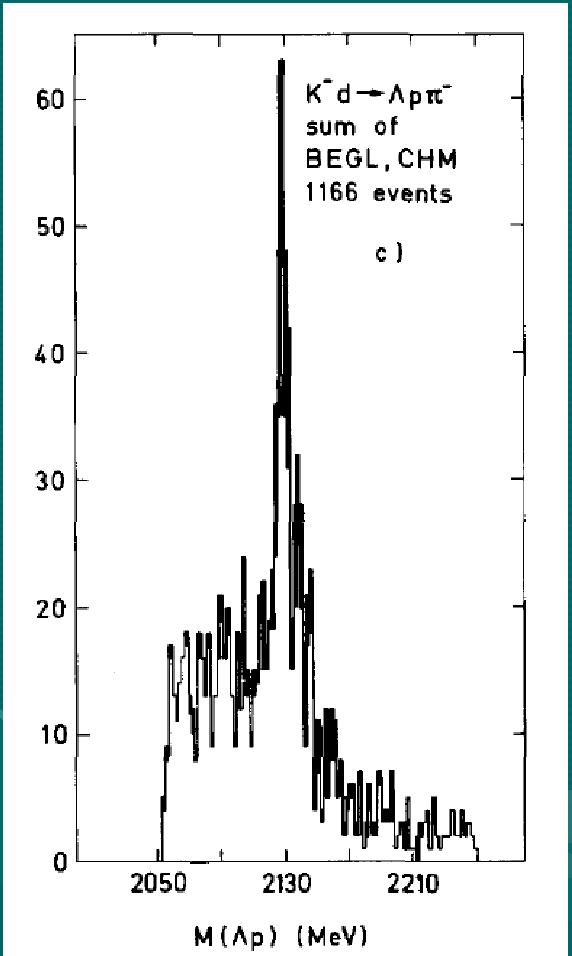


$p_{beam}$=2.735 GeVc
$|J_t|^2=|J_s|^2$
$|J_t|^2=0.25|J_s|^2$
$|J_t|^2=0.$
$|J_t|^2=8.0|J_s|^2$
preliminary
singlet
triplet
3 body phase space
$d^2\sigma/dmm\ d\Omega$ (nb/MeV/sr)
missing mass (GeV/$c^2$)
0
40
80
120
160
200
240
2.04
2.05
2.06
2.07
2.08
2.09
2.10
2.11
2.12
2.13

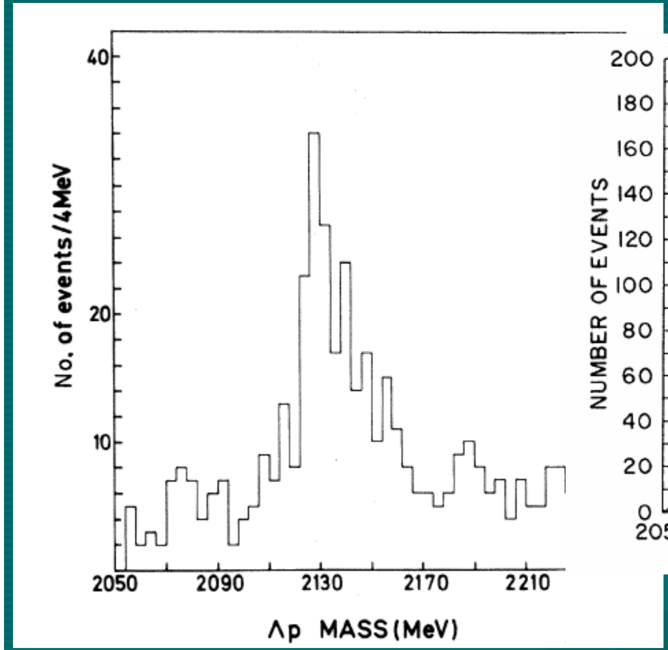


$|J_t|^2=8.0|J_s|^2$
$p_{beam}$=2.735 GeVc
preliminary
singlet
triplet
$d^2\sigma/dmm\ d\Omega$ (nb/MeV/sr)
missing mass (GeV/$c^2$)
0
40
80
120
160
200
240
2.04
2.05
2.06
2.07
2.08
2.09
2.10
2.11
2.12
2.13

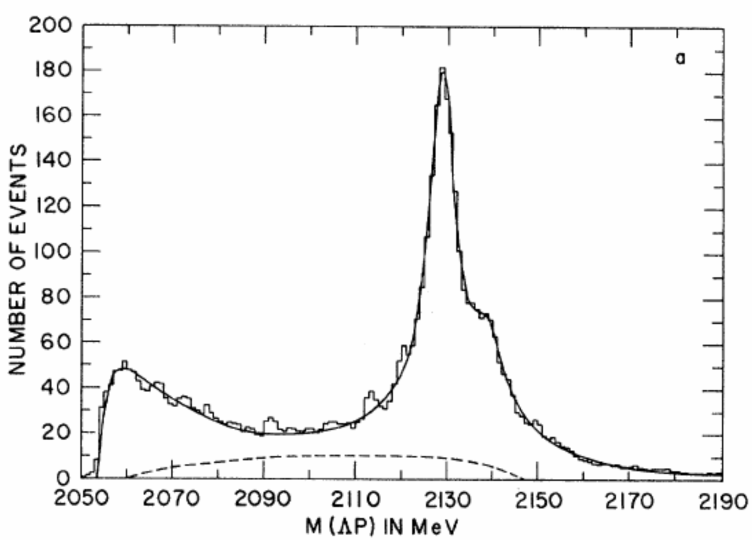
# Peak below p$\Sigma^0$ threshold




Brown et al., NP B 124(1977)45




Eastwood et al., PR D 3(1971)2603 124(1977)45




Tai Ho Tan, PRL 23(1969)395

$K^-d \to \Lambda p \pi^-$ 5 Exp. (4 in flight, 1 stop)

$n^{12}C \to \Lambda p X$

$pp \to \Lambda p K^+$

-New resonance?

- bound state? Excluded

–$\Sigma N \to \Lambda p$ FSI, mixing?

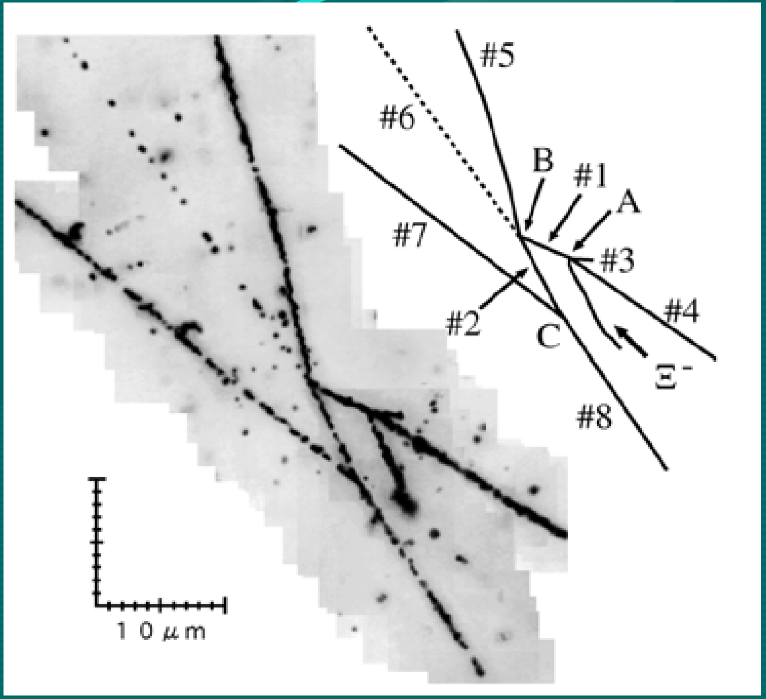
# All ΛΛ experiments

| year | Ref. | $K^-$ | stops | $B_{\lambda\Lambda}$ (MeV) | $\Delta B_{\lambda\Lambda}$ (MeV) |
|---|---|---|---|---|---|
| 1963 | Danycz et al. | | | | |
| | ${}^{10}_{\Lambda\Lambda}Be \rightarrow {}^{9}_{\Lambda}Be + p + \pi^-$ | $10^5$ | $\approx 2$ | 17.7±0.4 | 4.3±0.4 |
| | \| | | | | |
| | $\rightarrow \alpha + \alpha + p + \pi^-$ | | | | |
| 1965 | Prowse et al. | | | | |
| | ${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$ | $10^6$ | $\approx 30$ | 10.9±0.8 | 4.7±1.0 |
| | \| | | | | |
| | $\rightarrow \alpha + p + \pi^-$ | | | | |
| 1991 | Aoki et al. | $10^9$ | 80 | | |
| | ${}^{10}_{\Lambda\Lambda}Be \rightarrow {}^{9}_{\Lambda}B + \pi^-$ | | | 8.5±0.7 | -4.9±0.7 |
| | \| | | | | |
| | $\rightarrow {}^{3}He + \alpha + p + n + n$ | | | | |
| | OR | | | | |
| | ${}^{14}_{\Lambda\Lambda}C^* + n \rightarrow {}^{13}_{\Lambda\Lambda}B + p + n$ | | | 27.5±0.7 | 4.8±0.7 |
| | \| | | | | |
| | $\rightarrow {}^{13}_{\Lambda}C + \pi^-$ | | | | |
| | \| | | | | |
| | $\rightarrow {}^{3}He + \alpha + \alpha + n + n$ | | | | |
| 2001 | Takahashi et al. | | | | |
| | ${}^{12}C + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}He + \alpha + t$ | | | $7.25\pm0.19^{+0.18}_{-0.11}$ | $1.01\pm0.20^{+0.18}_{-0.11}$ |
| | \| | | | | |
| | ${}^{5}_{\Lambda}He + p + \pi^-$ | | | | |

$$K^- + p \rightarrow K^+ + \Xi^-$$

$$\Xi^- + p \rightarrow \Lambda + \Lambda$$

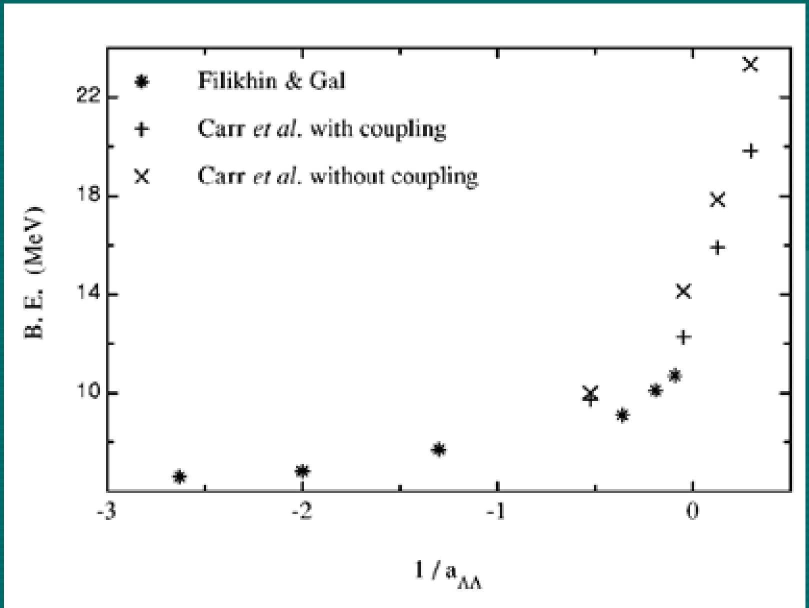
Event Nagara



# Theory: ΛΛ interaction

All information from 3 ΛΛ hypernuclei

( ${}^{4}_{\Lambda\Lambda}H$ observed):




Is there a bound Di Lambda or even a H_dibaryon?

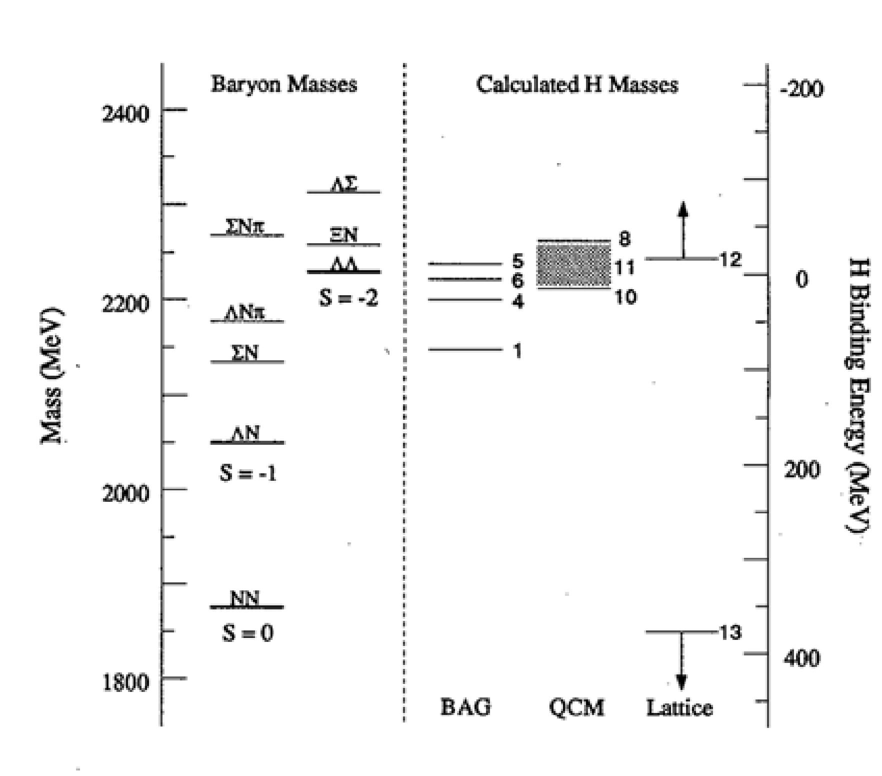
Latter excluded with 2.136 < *M (H)* < 2.231 GeV

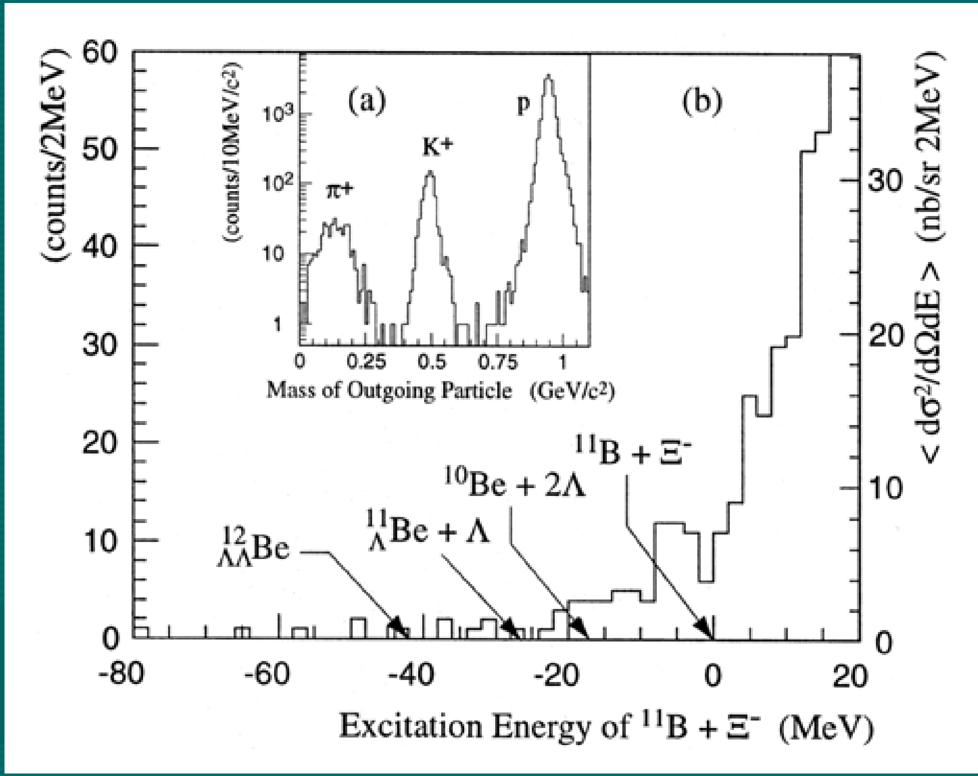
| | $B^{exp}_{\Lambda\Lambda}$ |
|---|---|
| ${}^{6}_{\Lambda\Lambda}He$ | $7.25^{+0.38}_{-0.31}$ |
| ${}^{10}_{\Lambda\Lambda}Be$ | $17.7 \pm 0.4$ |
| ${}^{13}_{\Lambda\Lambda}B$ | $27.5 \pm 0.7$ |

→ a=-0.5 fm

→ $a=5.6_{-2.0}^{6.0}$ fm

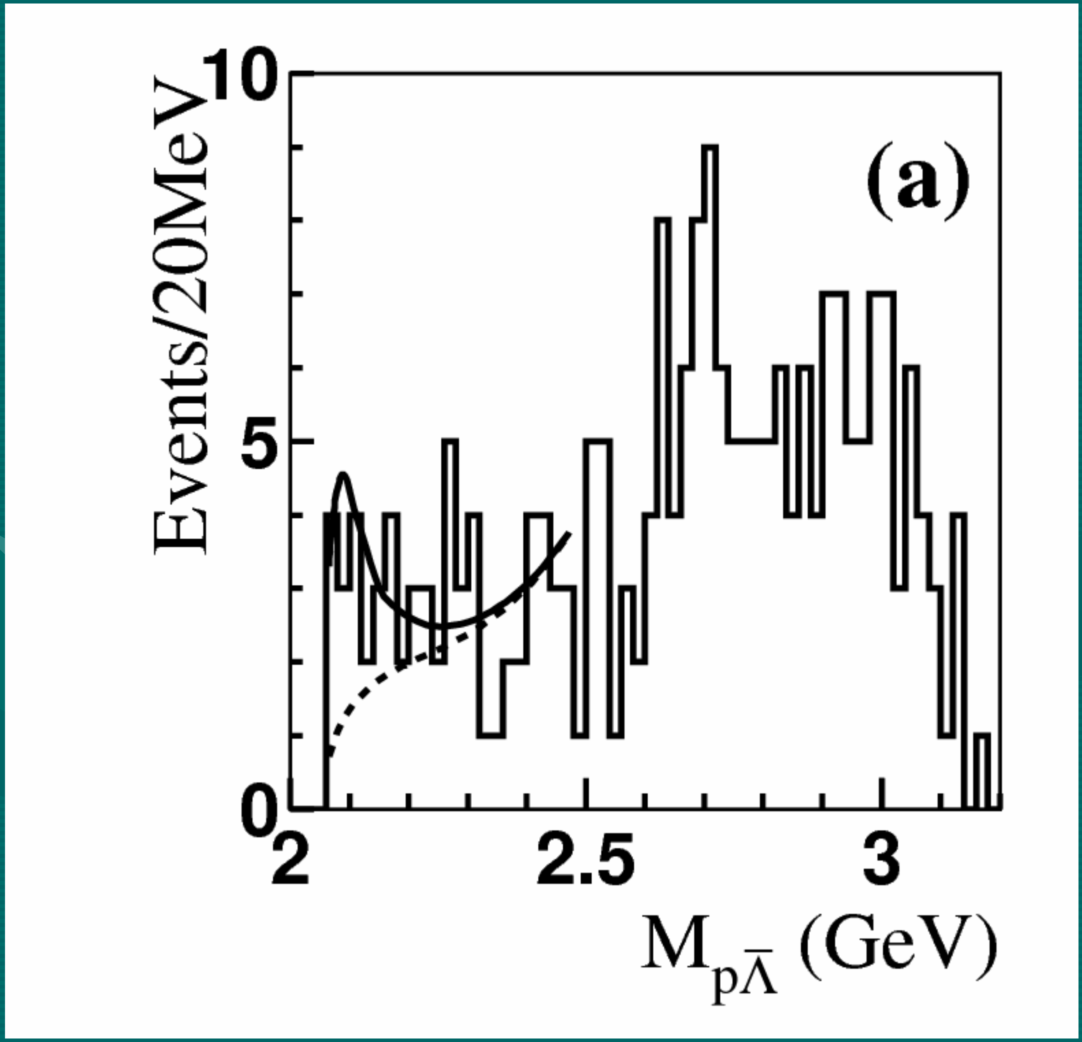
# Search for H-dibaryon




Yamamoto et al., PLB 478(2000) 401

# To be confirmed at PANDA




$e^+e^- \to J/\Psi(\Psi') \to p\bar{\Lambda}(\bar{p}\Lambda)$ $+c.c.$

Ablikim et al. (BES) PRL

$M_{res}$=2075±12 MeV

Γ=90±35 MeV

7 σ effect

# Future experiments

- J-PARC more intense K⁻ beam
- FAIR stopped anti-protons (Kilian, FLAR)

$\bar{p} + p \rightarrow K^{*-} + K^{*+}$ with very small momenta

$K^{*-} + p \rightarrow K^{+} + \Xi^{-}$ again small momenta, large probability for

$\Xi^{-} + p \rightarrow \Lambda + \Lambda$

# GEM Collaboration

A. Budzanowski, A. Chatterjee, R. Gebel, P. Hawranek, R. Jahn, V. Jha,

K. Kilian, S. Kliczewski, Da. Kirillov, Di. Kirillov, D. Kolev, M. Kravcikova,

M. Lesiak, J. Lieb, H. Machner, A. Magiera, R. Maier, G. Martinska,

S. Nedev, J. Niskanen, N. Piskunov, D. Prasuhn, D. Protic, J. Ritman,

P. von Rossen, B. J. Roy, I. Sitnik, R. Siudak, R. Tsenov, J. Urban,

G. Vankova, C. Wilkin

Thank you …

# pp effective range

$$C^2 k \cot \delta + 2k\eta h(\eta) = -1/a + \tfrac{1}{2} r_e k^2 - P r_e{}^3 k^4$$

where

$$C^2 = 2\pi\eta/(e^{2\pi\eta} - 1)$$

$$\eta = Me^2/(2\hbar^2 k)$$

$$h(\eta) = -\gamma - \log \eta + \eta^2 \sum_{m=1}^{\infty} [m(m^2 + \eta^2)]^{-1} \quad \text{and} \quad \gamma = .5772 \cdots$$

$^1S$ EFFECTIVE RANGE PARAMETERS INCLUDING COULOMB EFFECTS

| Potential | $a(F)$ | $r_e(F)$ | $P$ |
|---|---|---|---|
| HC | −7.75 | 2.78 | .024 |
| SC | −7.78 | 2.72 | .028 |
| SCA | −7.77 | 2.72 | .027 |