Energy Dependence of Prompt Fission Neutron Multiplicity in the ^{239}Pu(n,f) Reaction

P. Marini, J. Taieb, D. Neudecker,

G. Bélier, A. Chatillon, D. Etasse, B. Laurent,P. Morfouace, B. Morillon, M. Devlin,

J. A. Gomez, R. C. Haight, K. J. Kelly, J. M. O'Donnell

CEA, DAM, DIF, F-91297 Arpajon, France

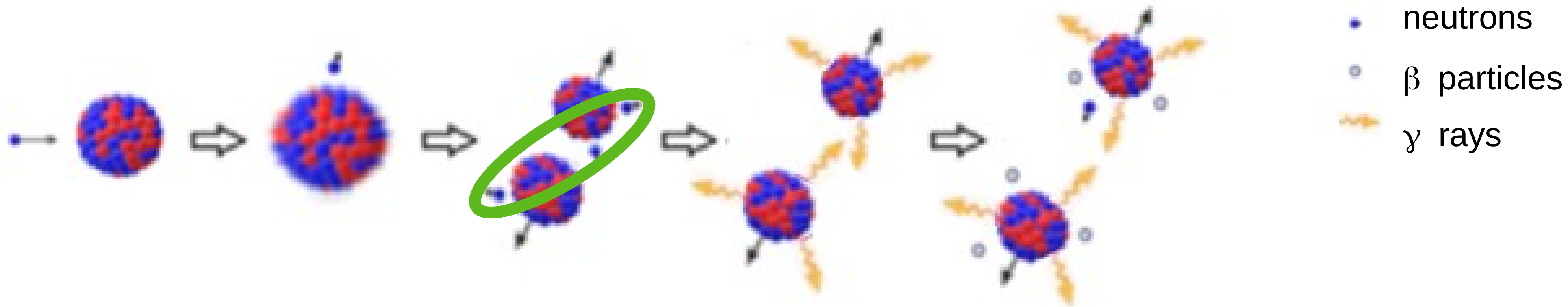
LP2I Bordeaux, UMR5797, Université de Bordeaux, CNRS, F-33170, Gradignan, France

Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France

Los Alamos National Laboratory, Los Alamos, NM-87545, USA

Normandie Univ., ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, 14000 Caen, France

Prompt Fission Neutron Multiplicity ($\overline{\nu}_p$) : why?



Accurate $\overline{\nu}_p$ in n-induced fission:

WHY

Fundamental physics: sharing between kinetic and E* of fission fragments

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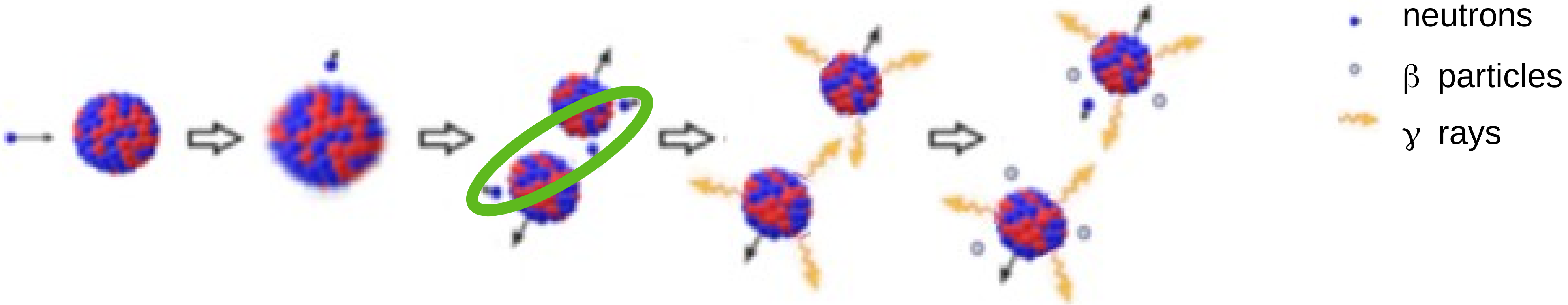

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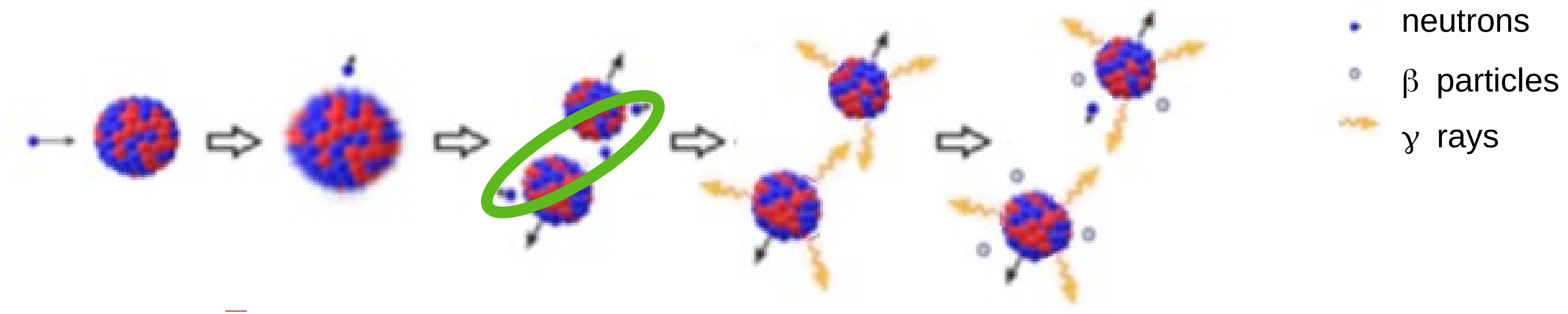
Fundamental physics: sharing between kinetic and E* of fission fragments

Applied nuclear physics: ^{235}U, ^{238}U, **^{239}Pu** →

Criticality
Efficiency
Safety
Lifetime

Generation
IV systems

Prompt Fission Neutron Multiplicity ($\overline{\nu}_p$) : why?



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Applied nuclear physics: $\xrightarrow{^{235}U,\ ^{238}U,\ ^{239}Pu}$

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EXAMPLE

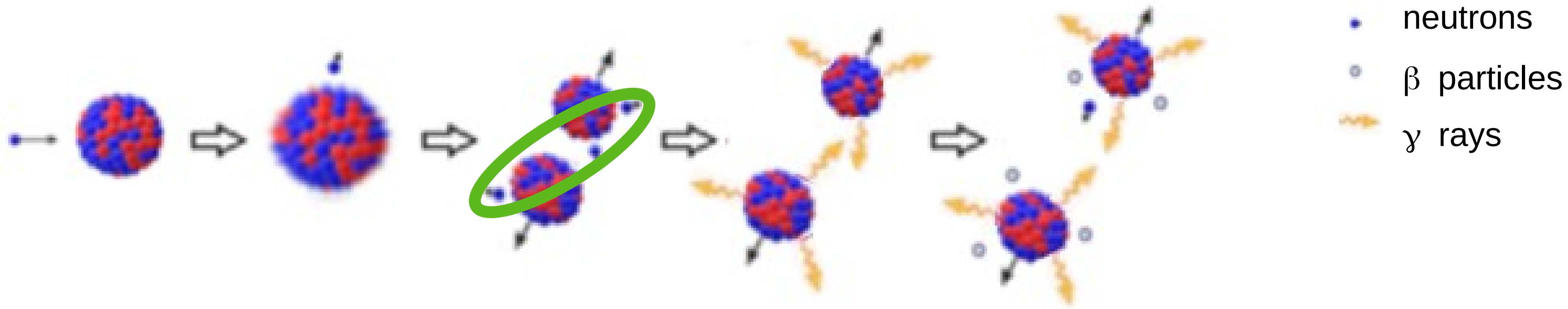
Sustainability of fission reaction chain k_{eff}

$$k_{eff} \propto \overline{\nu_p}$$

$\Delta\overline{\nu}_p$ = 1% => Δk_{eff} ~1000pcm = 3 times the range between a **controlled** and **uncontrolled** Pu critical assembly

D. Neudecker et al.,
Nucl. Data Sheets 167 (2020),
Ann. Nucl. Energy 159 (2021)

Prompt Fission Neutron Multiplicity ($\overline{\nu}_p$) : why?



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HOW

Theory lacks of accuracy => applications rely on evaluated data

INPUTS : measured $\overline{\nu}_p$ data
BENCHMARK : measured k_{eff} data

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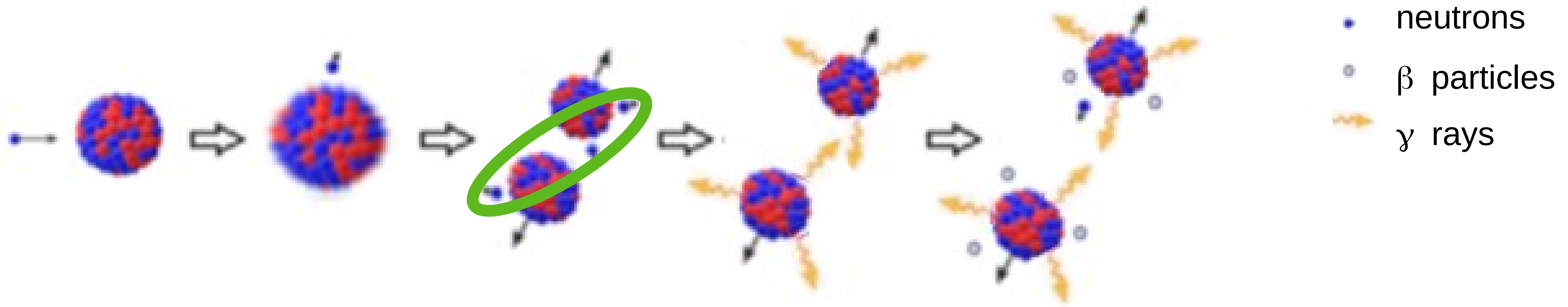

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Theory lacks of accuracy => applications rely on evaluated data

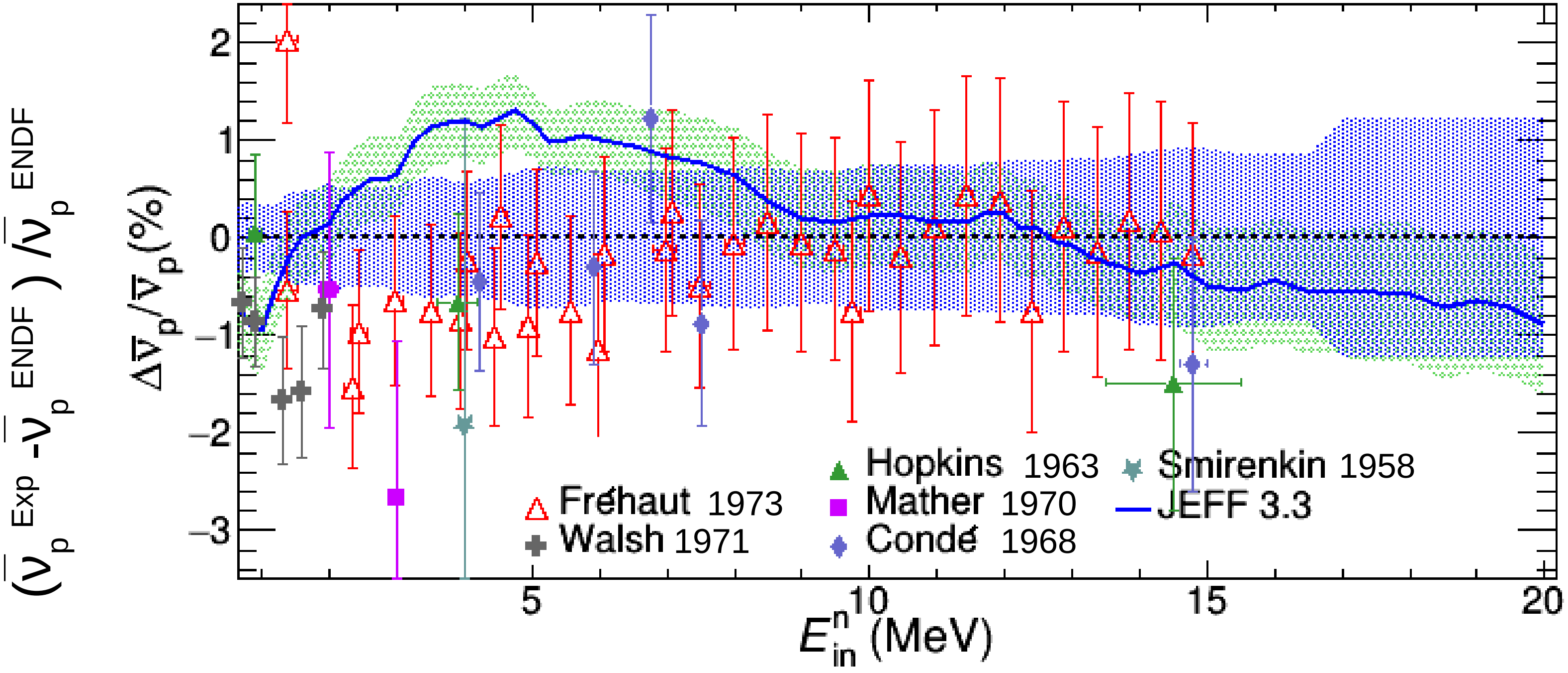
INPUTS : measured $\bar{\nu}_p$ data
BENCHMARK : measured k_{eff} data

^{239}Pu(n,f)

ENDF/B-VIII.0 $\bar{\nu}_p$ are **obtained from exp.** $\bar{\nu}_p$ data
BUT
adjusted to obtain the measured k_{eff}

D. A. Brown et al. Nucl. Data Sheets 148 (2018)

^{239}Pu(n,f) $\overline{\nu}_p$: status of the art



→ Data are **systematically lower** than ENDF/B-VIII.0 in [0-8] MeV

→ All data but Hopkins : **same experimental technique** (4π scintillator tank)

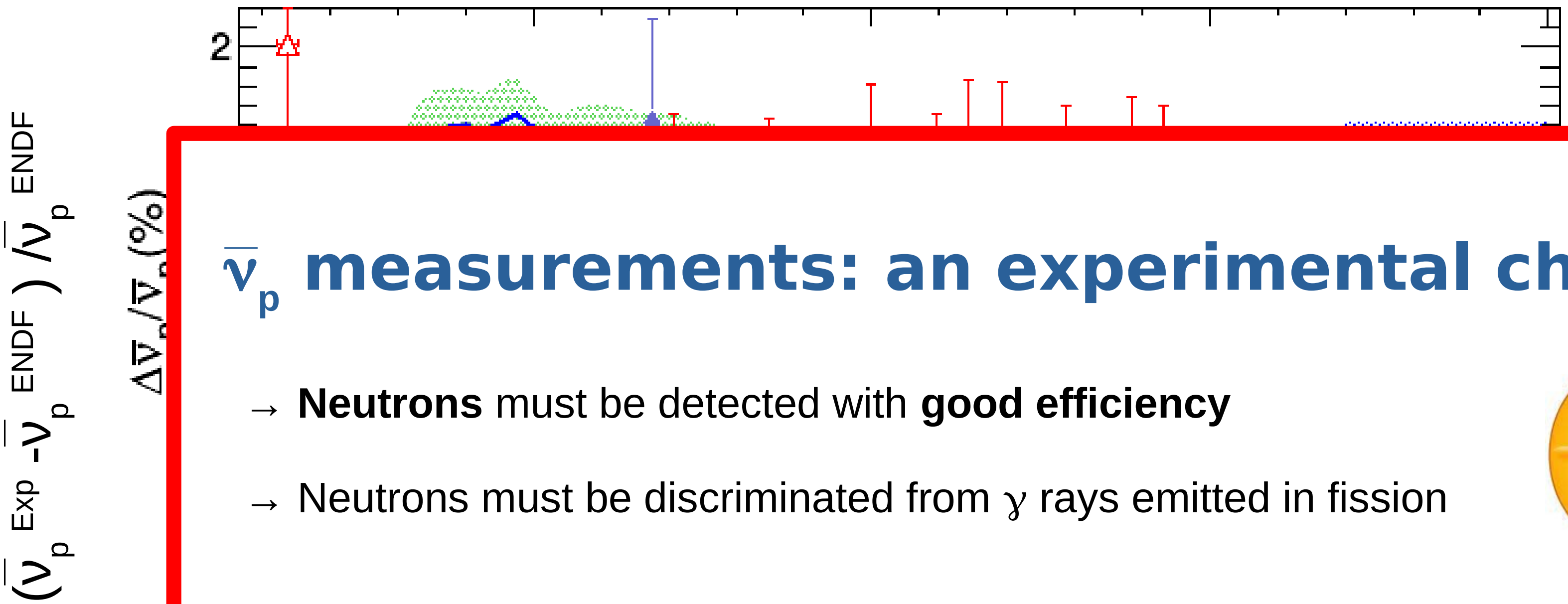
→ All data measured in ‘70s

✔ high statistics

✗ no angular distribution information

✗ no E_n-dependent efficiency

^{239}Pu(n,f) $\bar{\nu}_p$: status of the art



$\bar{\nu}_p$ measurements: an experimental challenge…

→ **Neutrons** must be detected with **good efficiency**

→ Neutrons must be discriminated from γ rays emitted in fission

→

→

→

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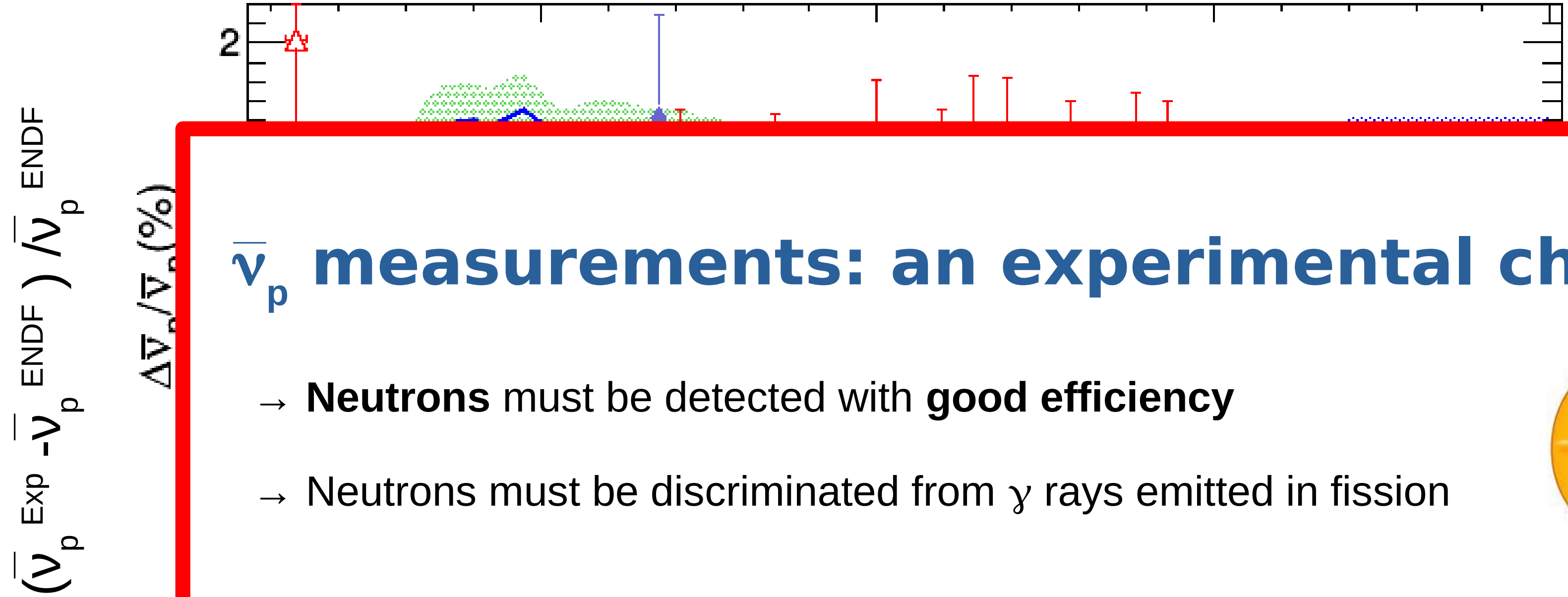


$\bar{\nu}_p$ measurements: an experimental challenge…

→ **Neutrons** must be detected with **good efficiency**

→ Neutrons must be discriminated from γ rays emitted in fission

…even harder for the ^{239}Pu(n,f)$\bar{\nu}_p$

→ unambiguous identification of **fission events** from a **very intense α-decay background**

→

→

→

- ✔ high statistics
- ✗ no angular distribution information
- ✗ no E_n-dependent efficiency

Our wish list

→ **independent** measurement → no 4π scintillator tank

→ **reduce uncertainties** → high statistics and
high precision

→ **correct for systematic biases**

* measure the **whole TKE-θ FF distributions** → unambiguous **discrimination** of fission and α-decay

* neutrons **angular distribution** → **segmented** high efficiency neutron detector

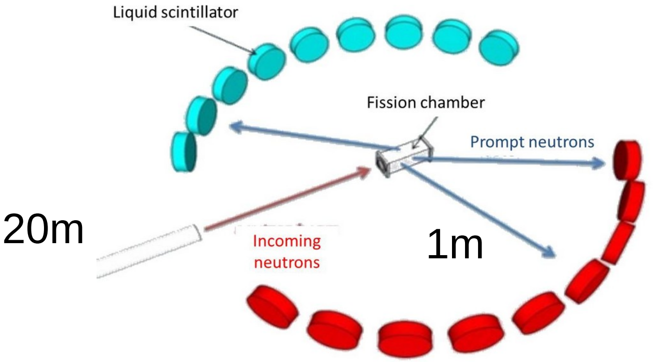
* **E_n-dependent efficiency** → measure the “**whole**” prompt-fission neutron spectra

* other effects

- detector energy thresholds → n-γ discrimination + large dynamical range
- dead-time → fast detectors and DAQ
- wrap-around

The experiment: goals and challenges

→ **independent** measurement ➡ **Double time-of-flight** technique



Tof resolution (FWHM)

Incoming n <0.8ns → E_{in} 0.08%

Outgoing n 1.5ns → E_n 0.4%-6%

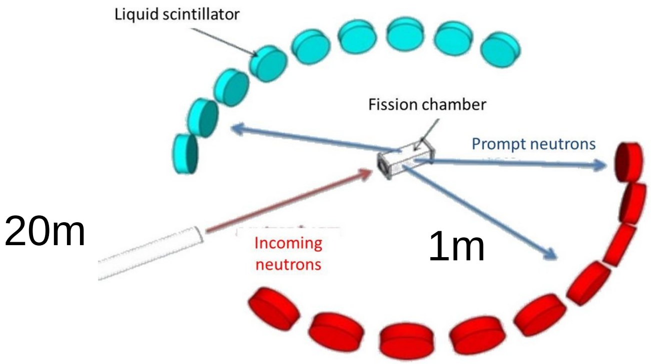
The experiment: goals and challenges

→ <u>independent</u> measurement

→ **reduce uncertainties** → high stats

high-intensity, pulsed, white neutron source at **WNR@LANL**

Double time-of-flight technique



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↓

high-intensity, pulsed, white
neutron source at WNR@LANL

→ **correct for systematic biases**

* measure the **whole TKE-θ FF distributions**

↓

newly-developed fission chamber →

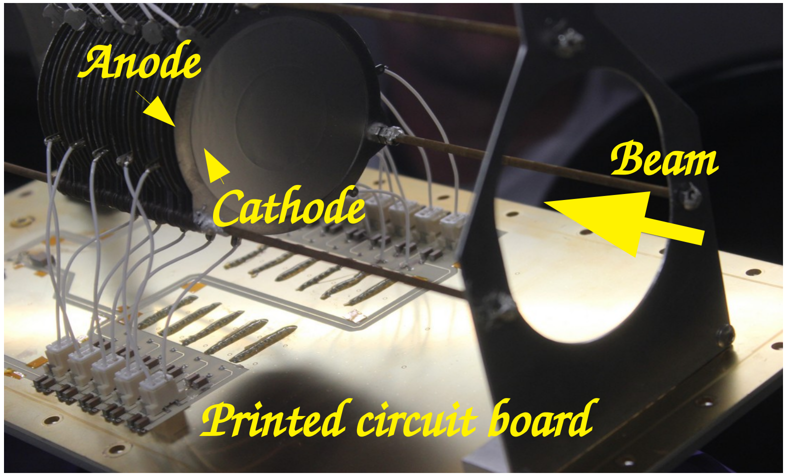
J. Taieb et al. NIM A 833 (2016)

47mg ^{239}Pu target, ~3cm Ø, 22 channels

→ light-weighted: **reduced n scattering**

→ **fast** (CF$_4$@100mbar): tof(FWHM) <0.8ns

→ Dedicated PA and shapers



J. Taieb et al. NIM A 833 (2016)

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→ **independent** measurement → **Double time-of-flight** technique

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high-intensity, pulsed, white
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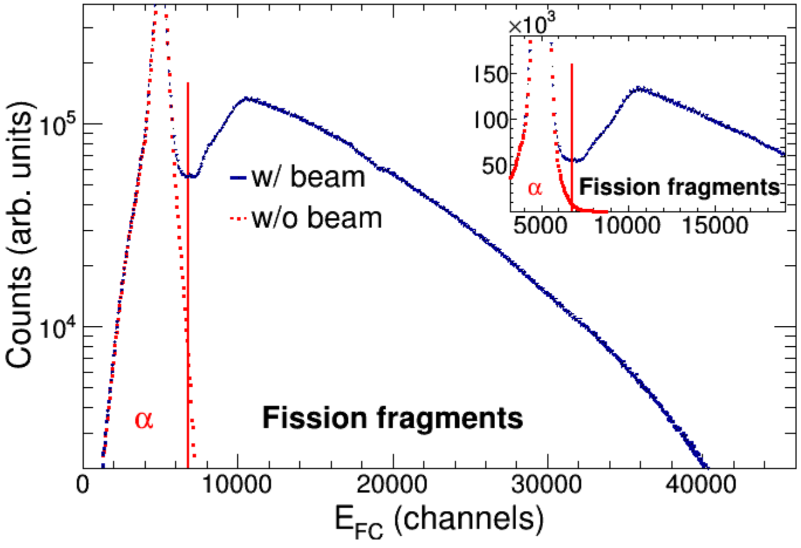
* measure the **whole TKE-θ FF distributions**

newly-developed fission chamber

J. Taieb et al. NIM A 833 (2016)

Unambiguous α-FF discrimination



$\varepsilon_{\text{fission}} \geq 95\%$

~10MBq α/deposit
10 fissions/s/deposit

P. Marini et al., PRC 101 (2020)

The experiment: goals and challenges

→ <u>**independent**</u> measurement → **Double time-of-flight** technique

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high-intensity, pulsed, white
neutron source at WNR@LANL

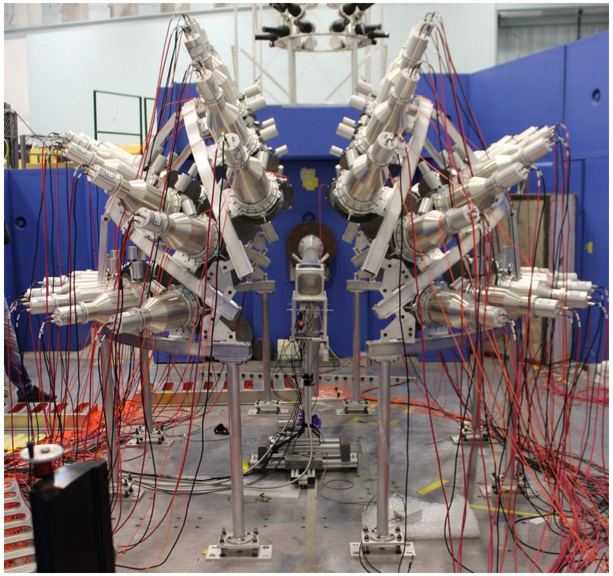
→ **correct for systematic biases**

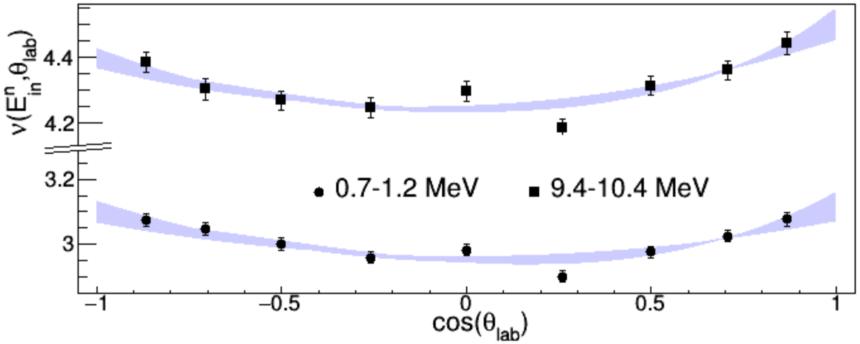
* measure the **whole TKE-θ FF distributions**

newly-developed fission chamber
J. Taieb et al. NIM A 833 (2016)

* neutrons **angular distribution** →

54 scintillators from the ChiNu array
R. C. Haight et al. J. Inst. 7 (2012)





P. Marini et al., PRC 101 (2020), PLB 835 (2022)

The experiment: goals and challenges

→ **independent** measurement → **Double time-of-flight** technique

→ **reduce uncertainties** → high stats

→ **correct for systematic biases**

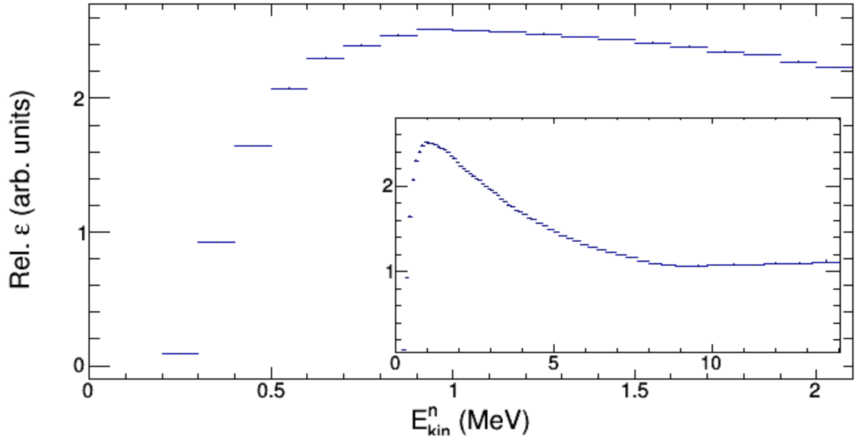
* measure the **whole TKE-θ FF distributions**

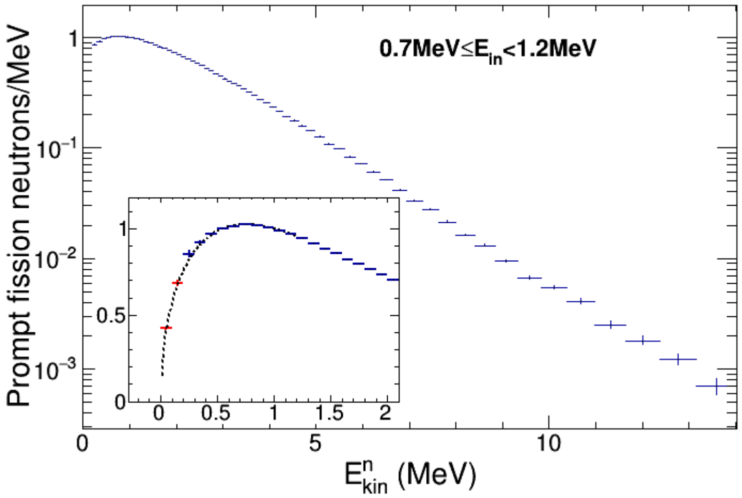
* neutrons **angular distribution**

→ measure prompt-fission neutron spectra [0.2-14] MeV

* **E_n-dependent efficiency**

^{252}Cf determined n detector efficiency





P. Marini et al., PRC 101 (2020)

The experiment: goals and challenges

→ **independent** measurement ➡ **Double time-of-flight** technique

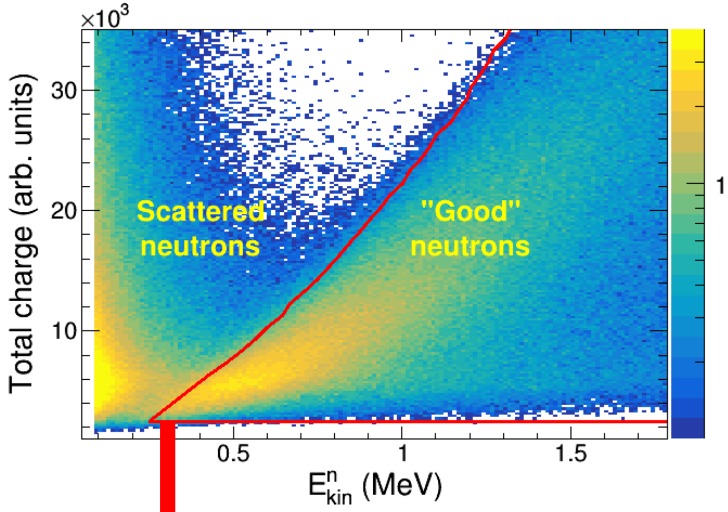
→ **reduce uncertainties** → high stats

→ **correct for systematic biases** ➡ measure **PFNS**

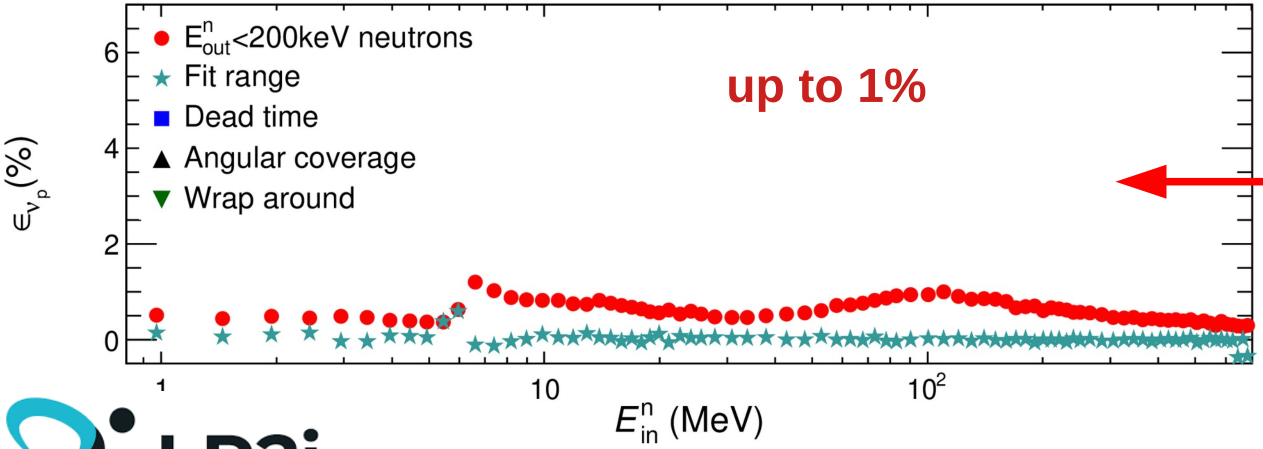
* other effects → **must be estimated**

- detector energy thresholds

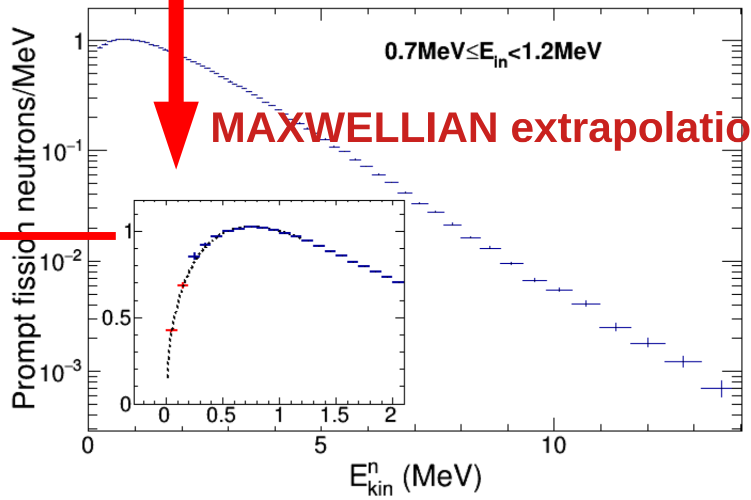
at **low** energy (**<200keV**): n-γ discrimination



Relative correction contribution to $\overline{\nu}_p$



up to 1%



MAXWELLIAN extrapolation

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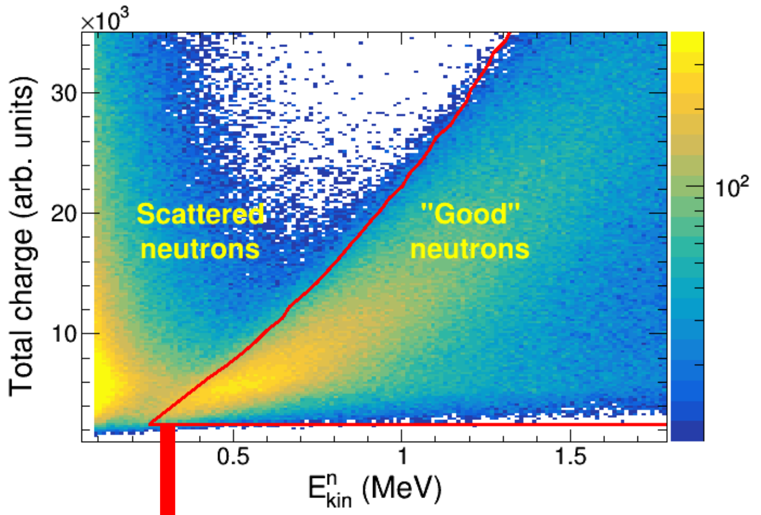
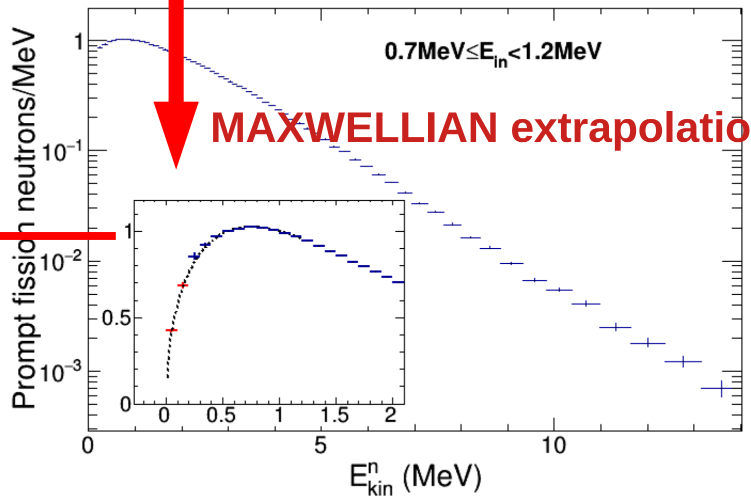
at **low** energy (**<200keV**): n-γ discrimination

VENDETA
76 EJ309 w/ double gain electronics
n-γ discrimination down to **80keV**





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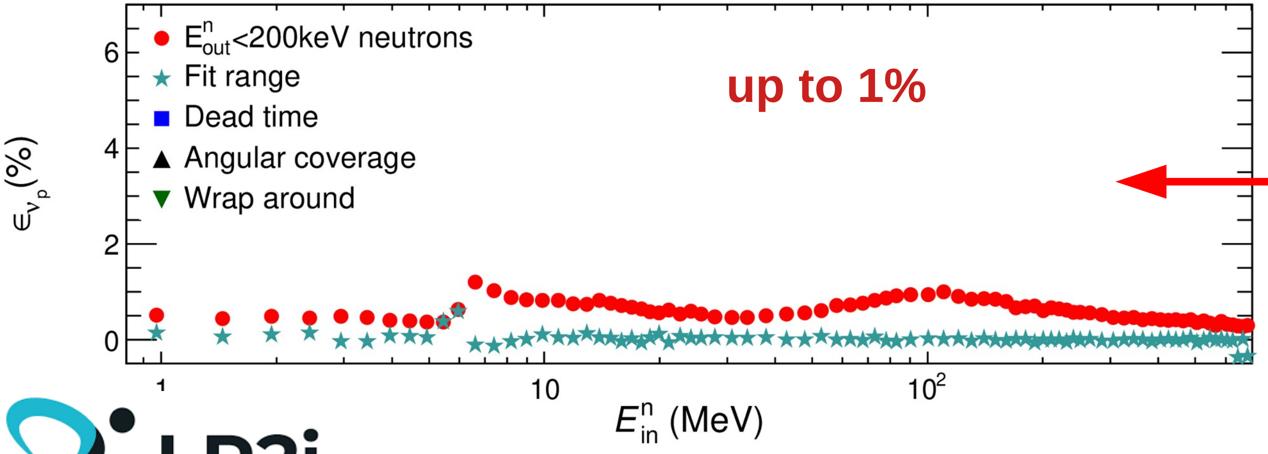


up to 1%

The experiment: goals and challenges

→ **<u>independent</u>** measurement ➡ **Double time-of-flight** technique

→ **reduce uncertainties** → high stats

→ **correct for systematic biases** ➡ measure **PFNS**

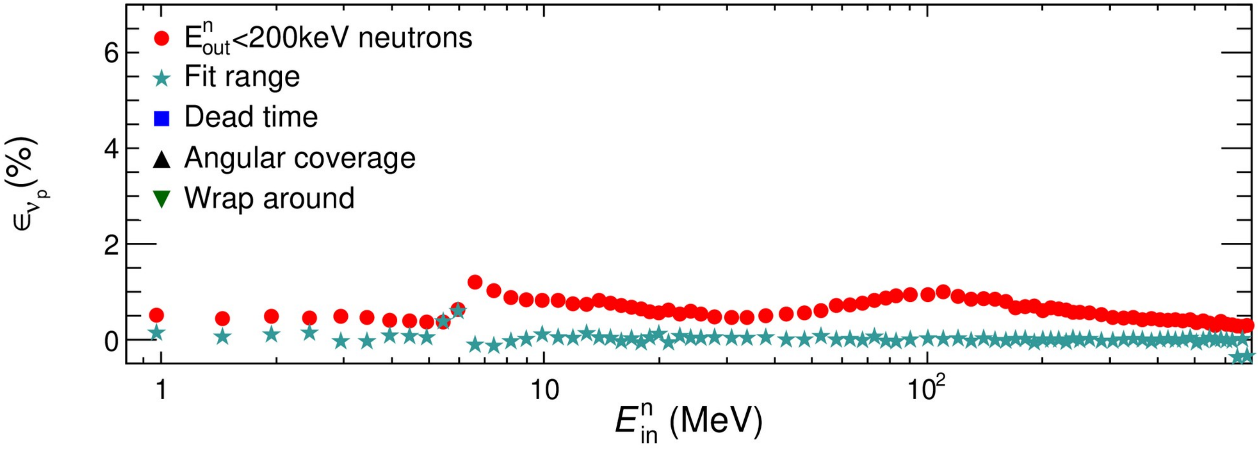
* other effects → **must be estimated**

- detector energy thresholds

at **low** energy (<200keV): n-γ discrimination

at **high** energy (>14MeV): dynamical range → $\Delta\bar{\nu}_p$ ~0.9% at E_{in}=24MeV (TALYS)

Relative correction contribution to $\bar{\nu}_p$



The experiment: goals and challenges

→ **independent** measurement → **Double time-of-flight** technique

→ **reduce uncertainties** → high stats

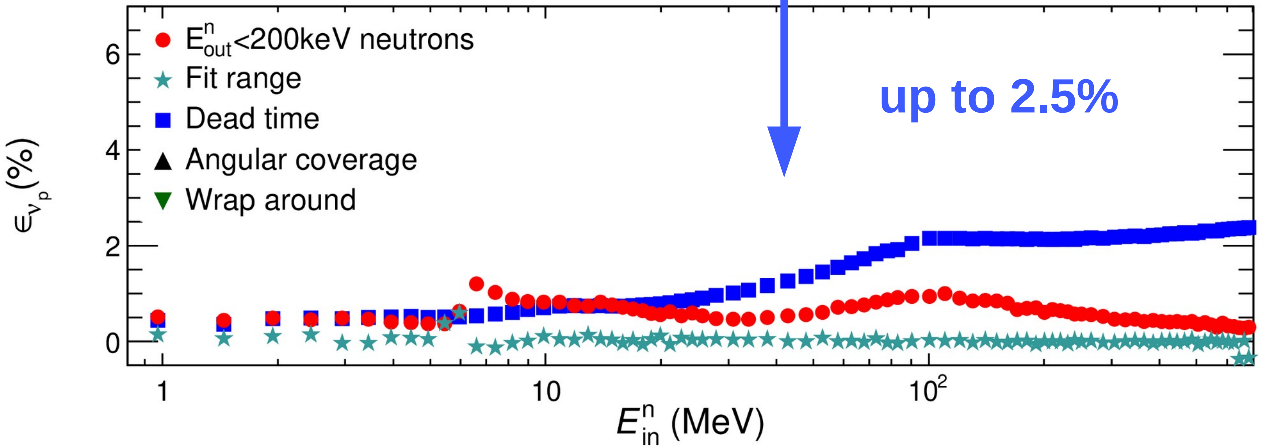
→ **correct for systematic biases** → measure **PFNS**

* other effects → **must be estimated**

- detector energy thresholds
- detector **dead-time** → fast detectors and numerical DAQ FASTER LPC-Caen http://faster.in2p3.fr, (2013)

Full Monte Carlo simulation

Relative correction contribution to $\overline{\nu}_p$



up to 2.5%

The experiment: goals and challenges

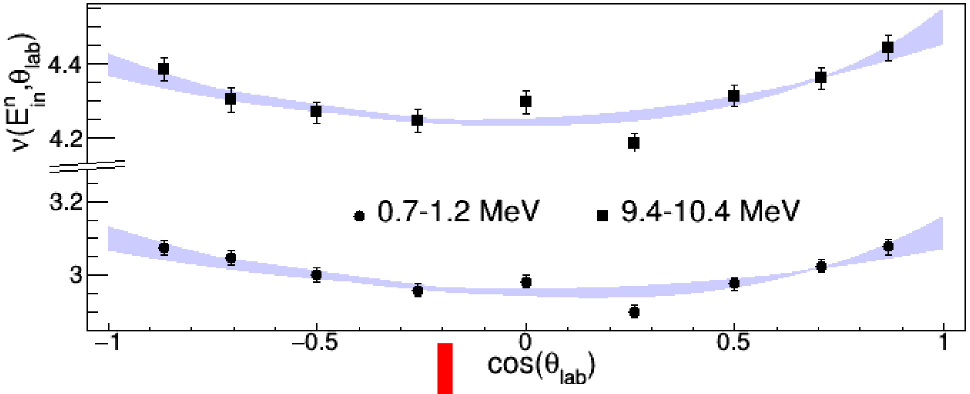
→ <u>**independent**</u> measurement ➡ **Double time-of-flight** technique

→ **reduce uncertainties** → high stats

→ **correct for systematic biases** ➡ measure **PFNS**

* other effects → **must be estimated**

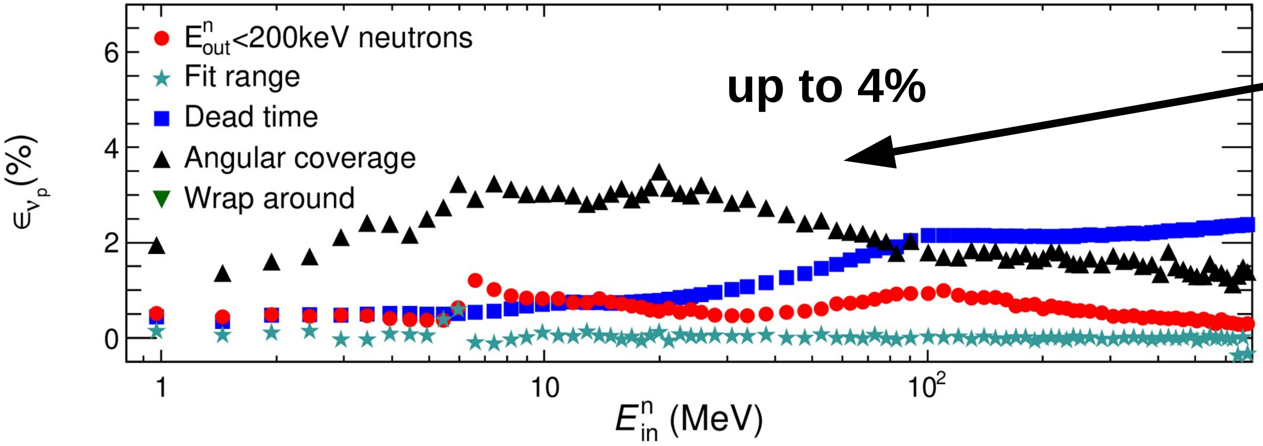
- detector energy thresholds
- detector dead-time
- limited **angular coverage**



Extrapolation from measured neutron angular distribution

mainly from forward and backward angles

Relative correction contribution to $\bar{\nu}_p$



up to 4%

The experiment: goals and challenges

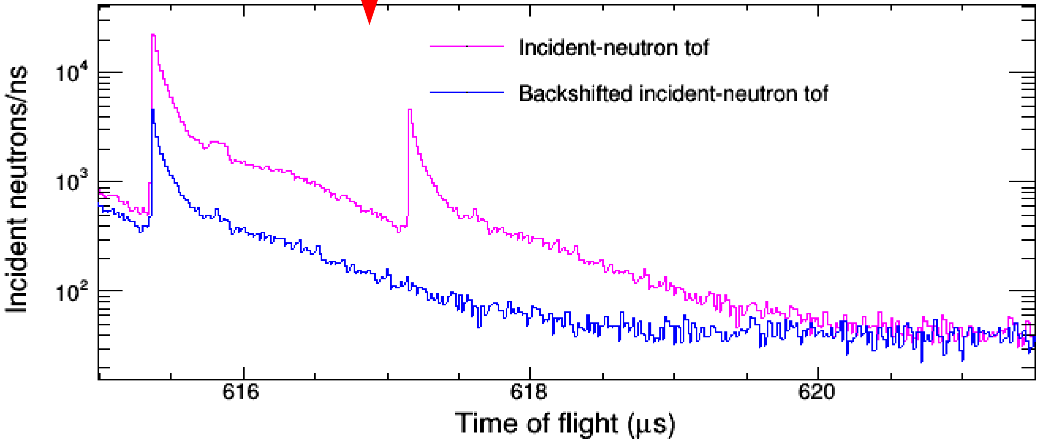
→ **independent** measurement → **Double time-of-flight** technique

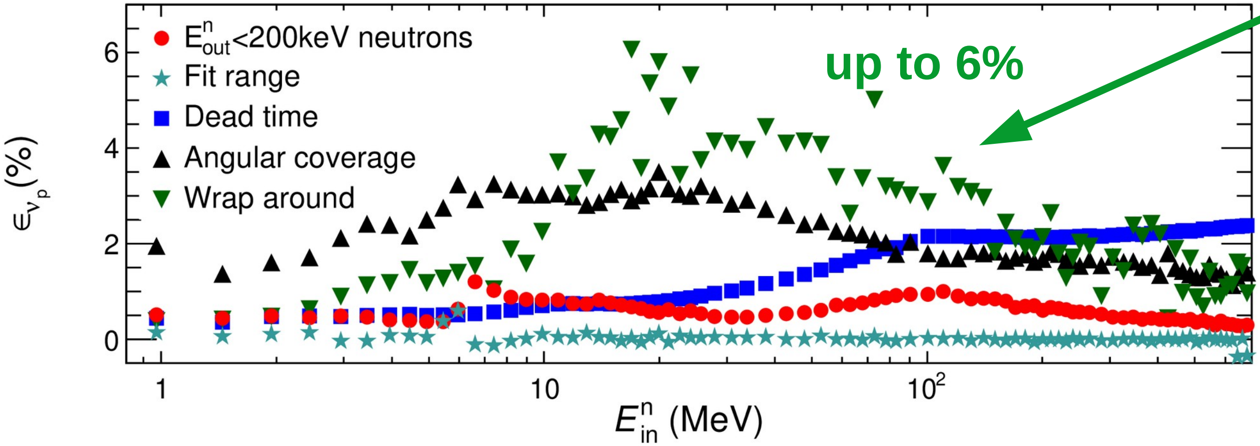
→ **reduce uncertainties** → high stats

→ **correct for systematic biases** → measure **PFNS**

* other effects → **must be estimated**

- detector energy thresholds
- detector dead-time
- limited angular coverage
- wrap-around background





up to 6%

The experiment: goals and challenges

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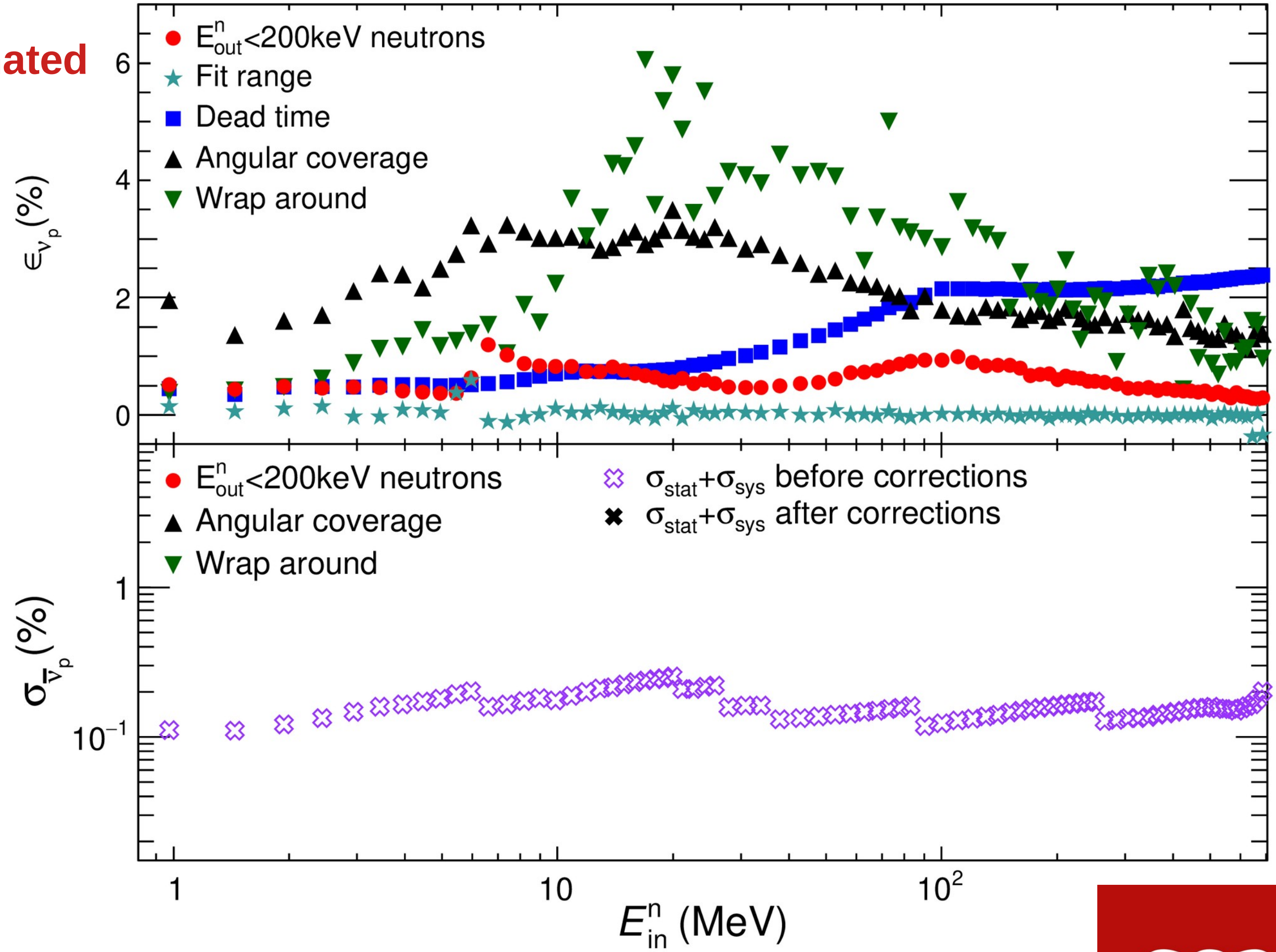
- detector energy thresholds
- detector dead-time
- limited angular coverage
- wrap-around background



The experiment: goals and challenges

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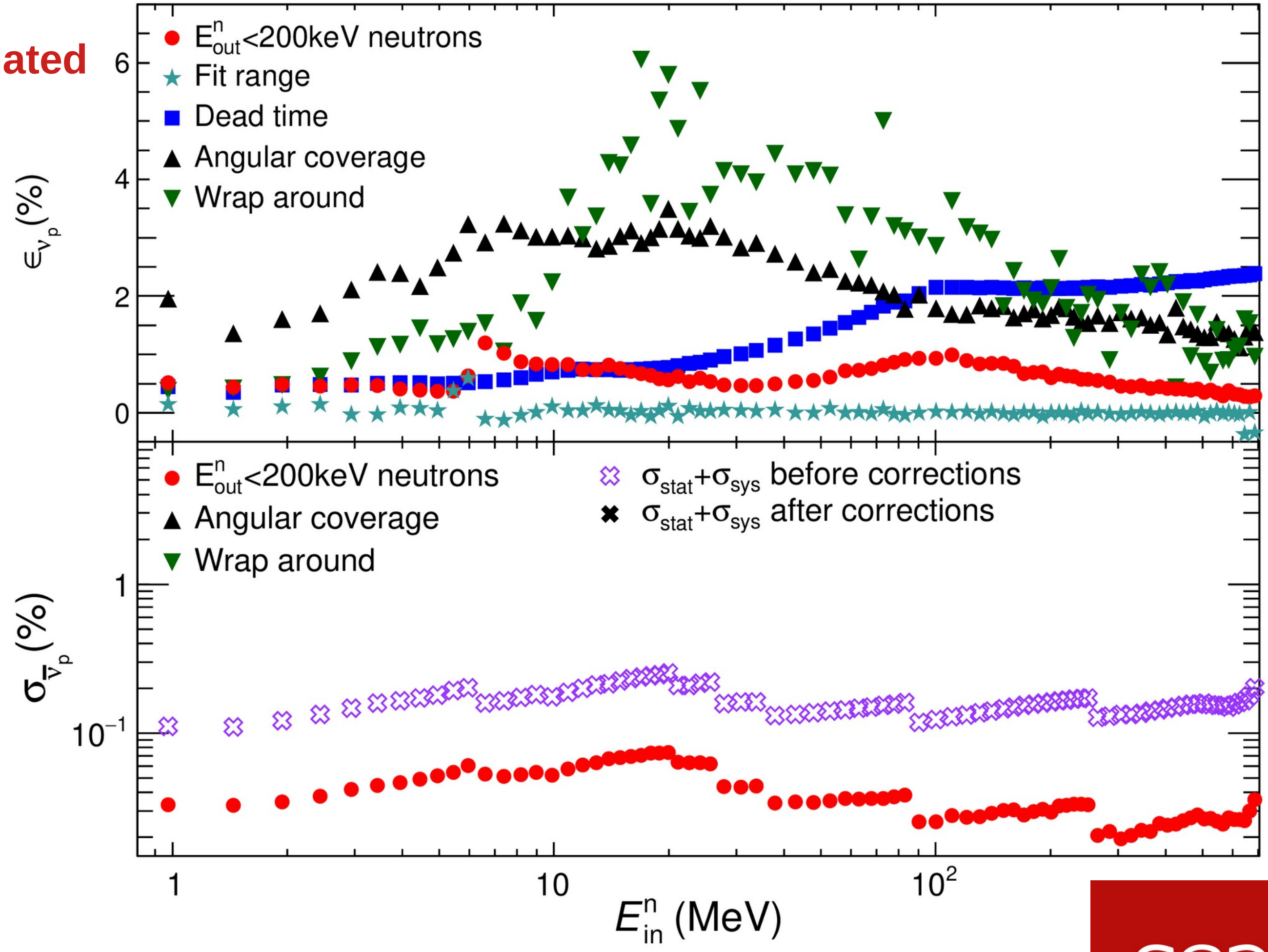

The experiment: goals and challenges

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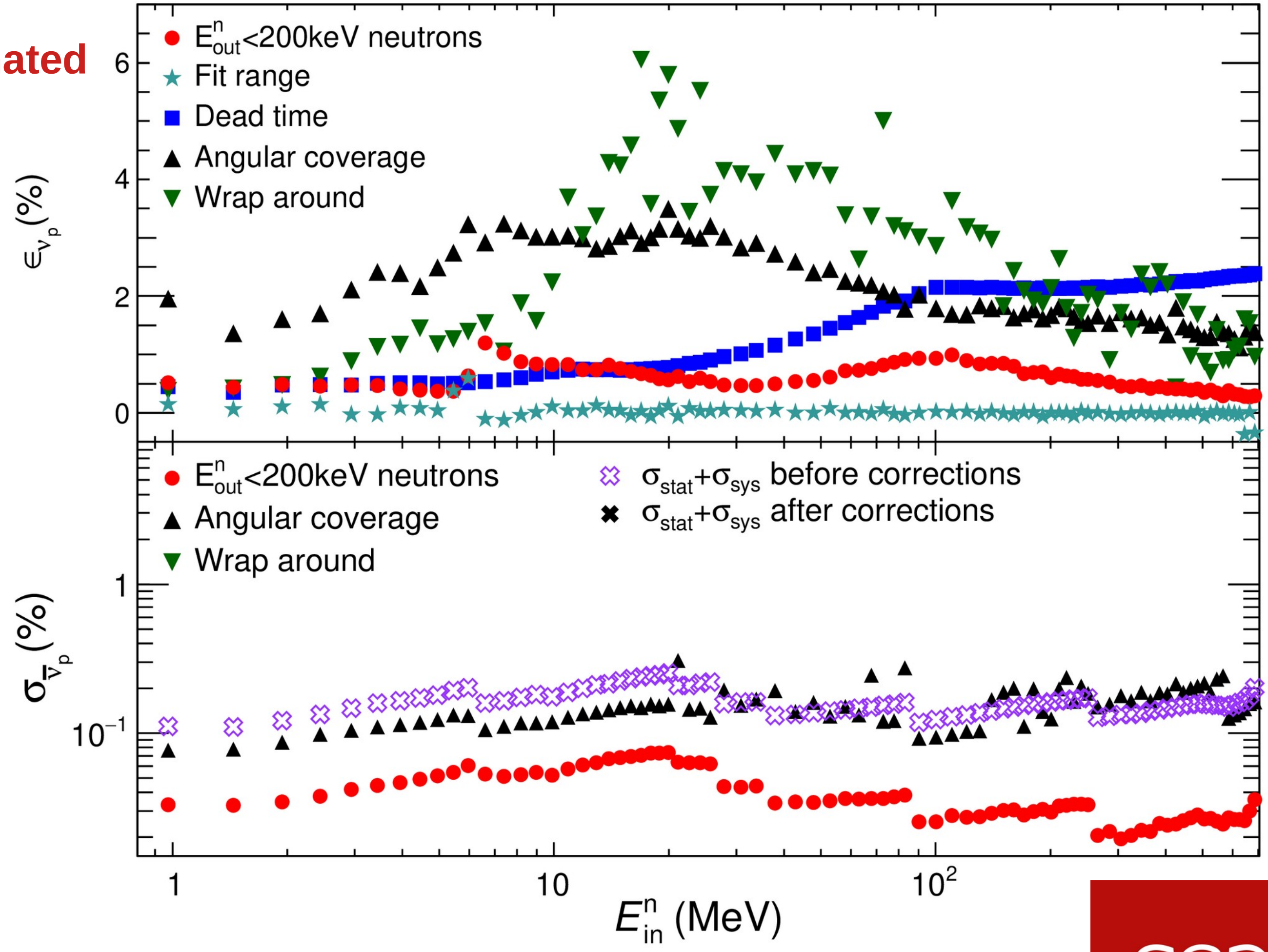

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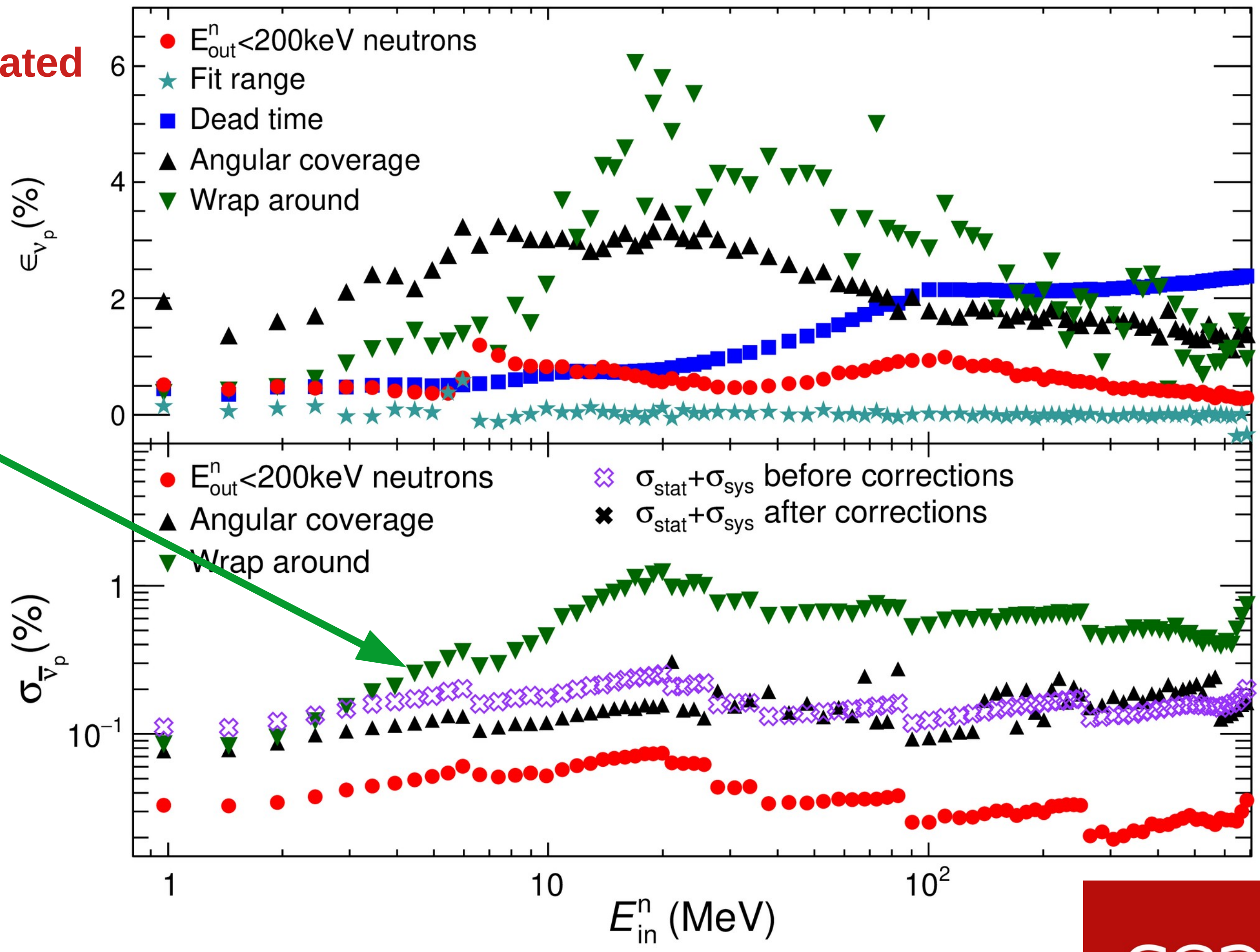

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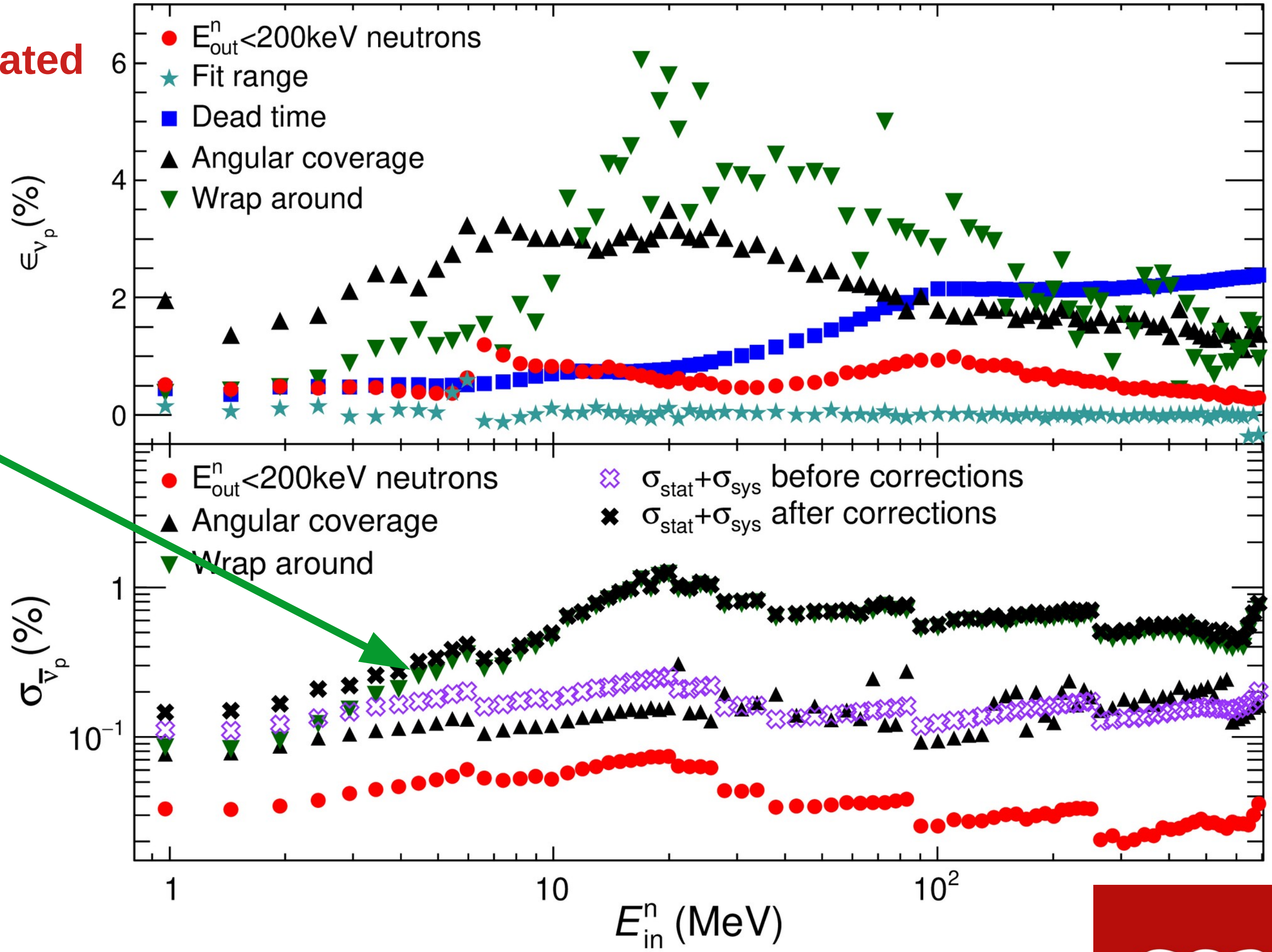
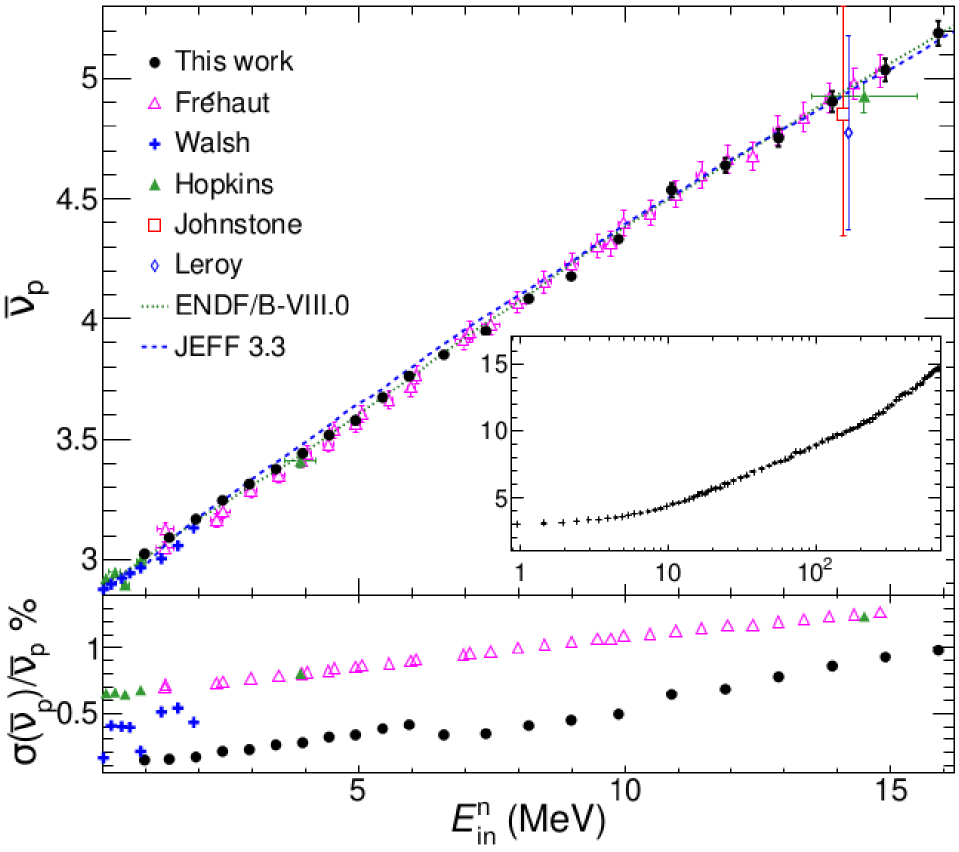


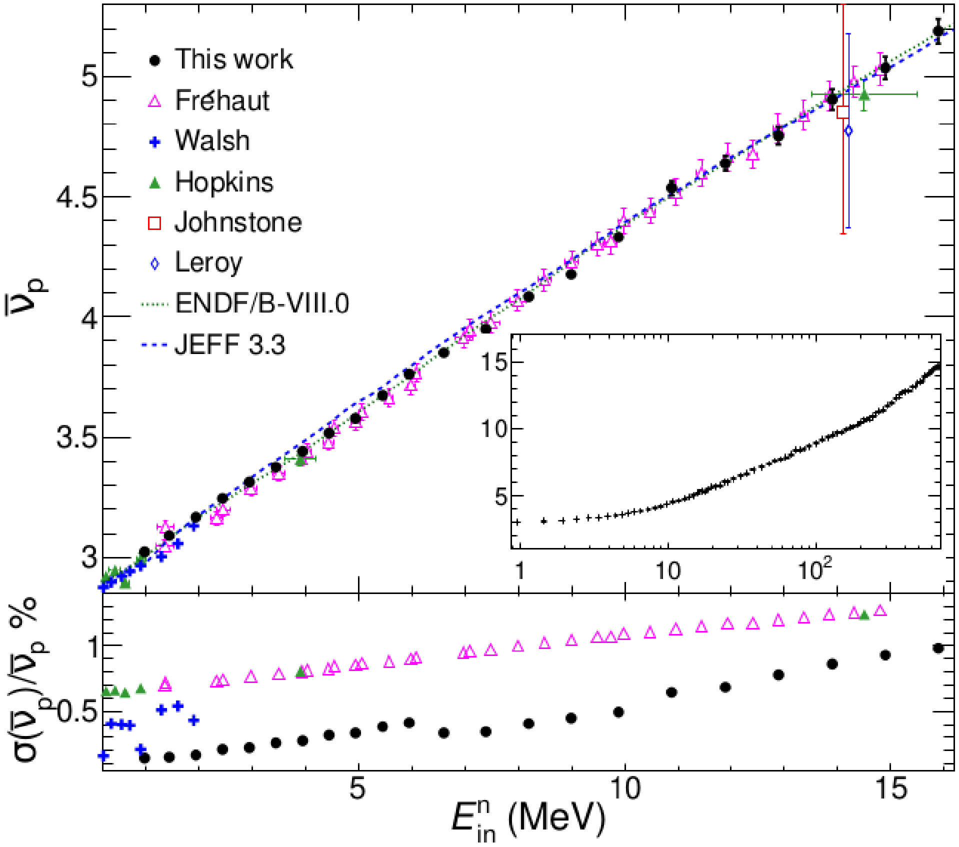
Results: achieved precision



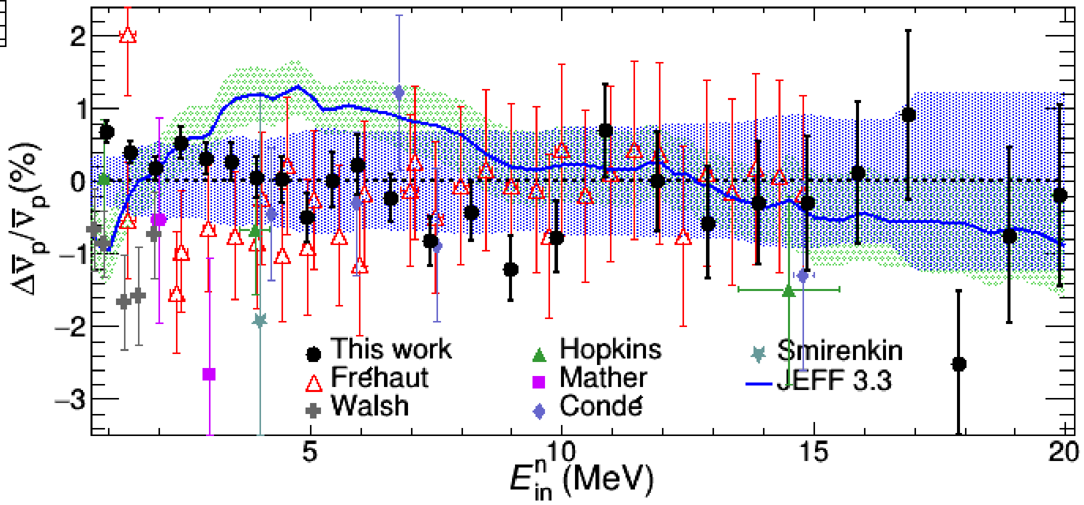
- ✔ **$\sigma(\overline{\nu}_p) < 1\%$** below 14MeV E_{in}

P. Marini et al., PLB 835 (2022)

Results: achieved precision

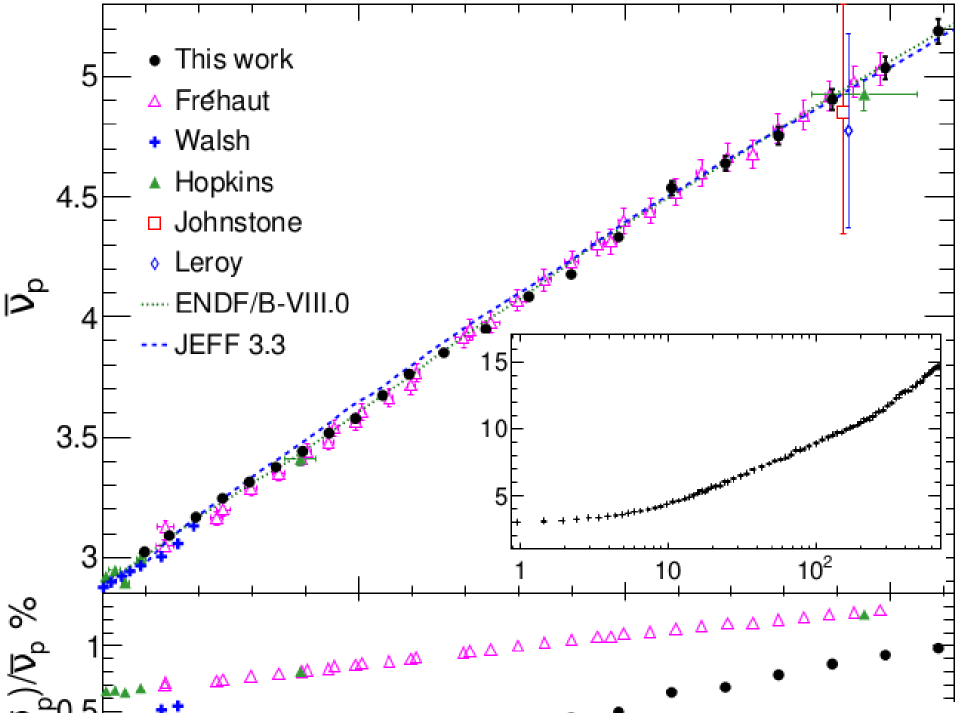


- ✔ **$\sigma(\bar{\nu}_p) < 1\%$** below 14MeV E_{in}
- ✔ Agreement with ENDF/B-VIII.0 below 8MeV E_{in}



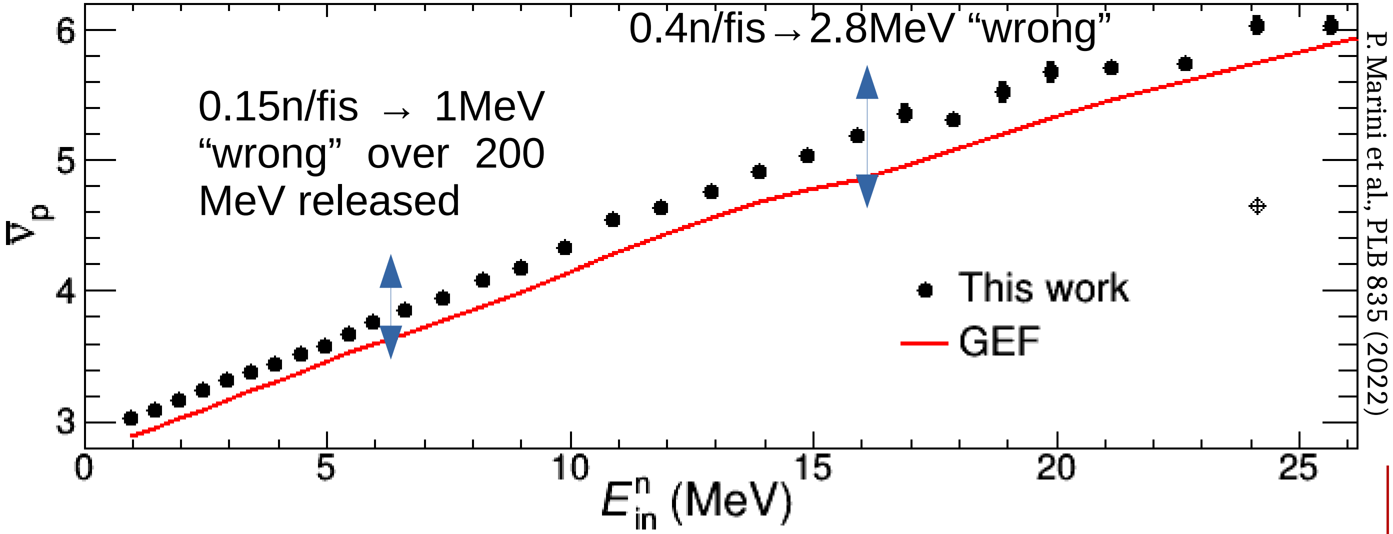
P. Marini et al., PLB 835 (2022)

Results: what do we learn?



- ✔ **$\sigma(\bar{\nu}_p) < 1\%$** below 14MeV E_{in}
- ✔ Agreement w/ ENDF/B-VIII.0 below 8MeV Ein

Fundamental physics: sharing between kinetic and E* of fission fragments

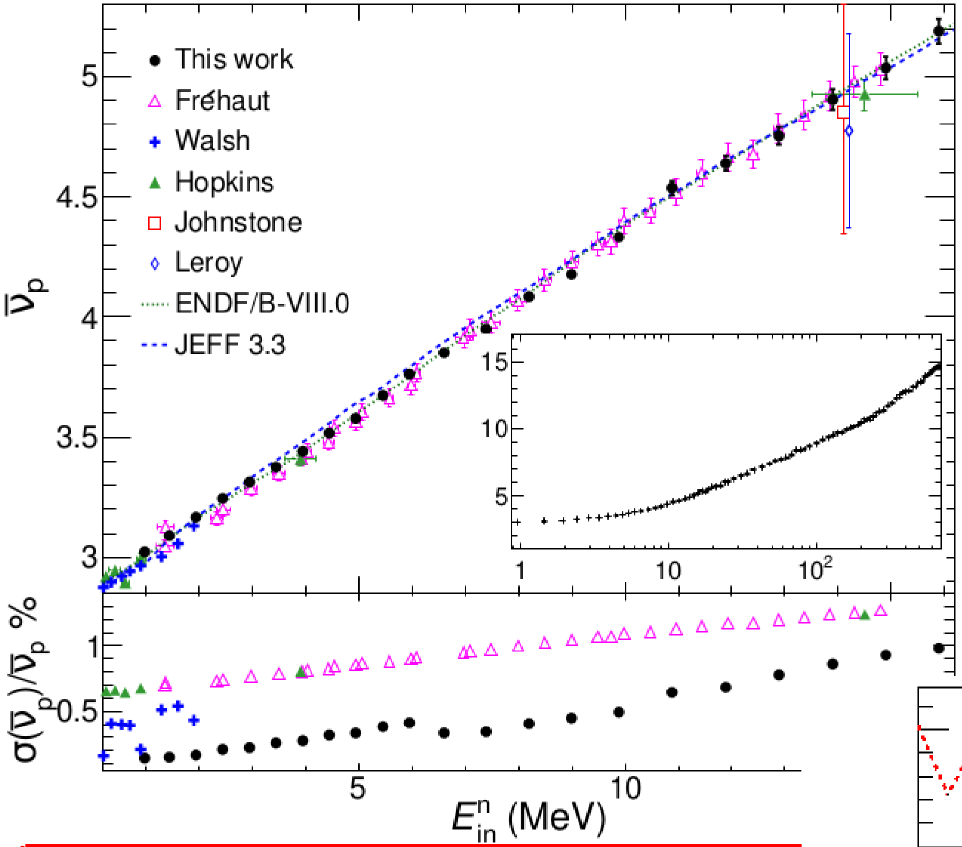


0.4n/fis → 2.8MeV “wrong”

0.15n/fis → 1MeV “wrong” over 200 MeV released

P. Marini et al., PLB 835 (2022)

Results: what do we learn?



✔ $\sigma(\bar{\nu}_p) < 1\%$ below 14MeV E_{in}

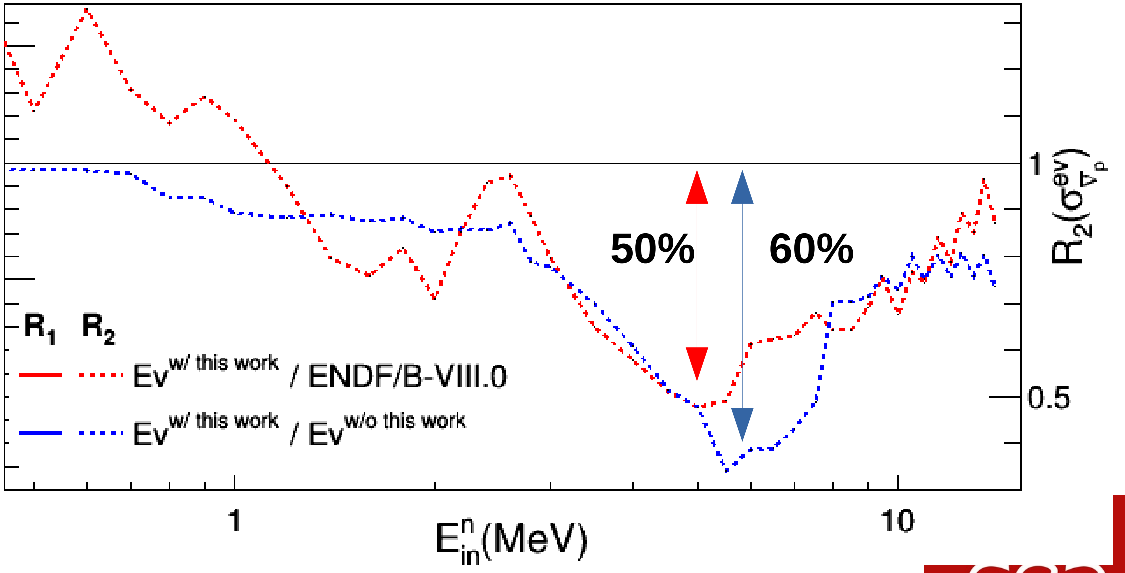
✔ Agreement w/ ENDF/B-VIII.0 below 8MeV Ein

Fundamental physics: sharing between kinetic and E* of fission fragments

Applied nuclear physics:

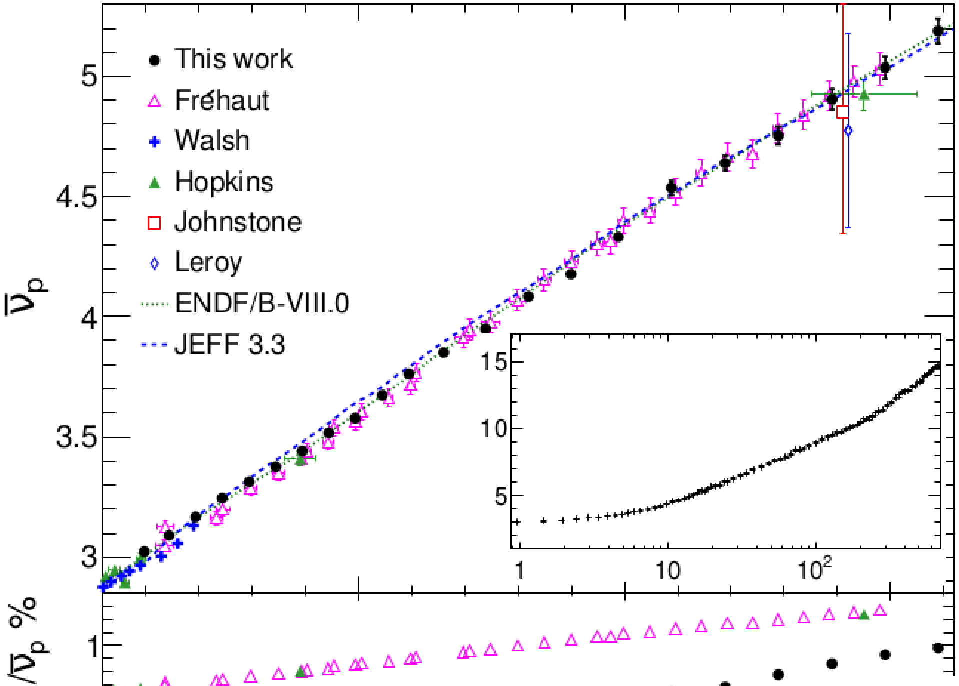
new evaluations

Reduction of evaluated $\bar{\nu}_p$ **uncertainty** up to 50-60%



P. Marini et al., PLB 835 (2022)

Results: what do we learn?



- ✔ $\sigma(\overline{\nu}_p)$ **< 1%** below 14MeV E_{in}
- ✔ Agreement w/ ENDF/B-VIII.0 below 8MeV Ein

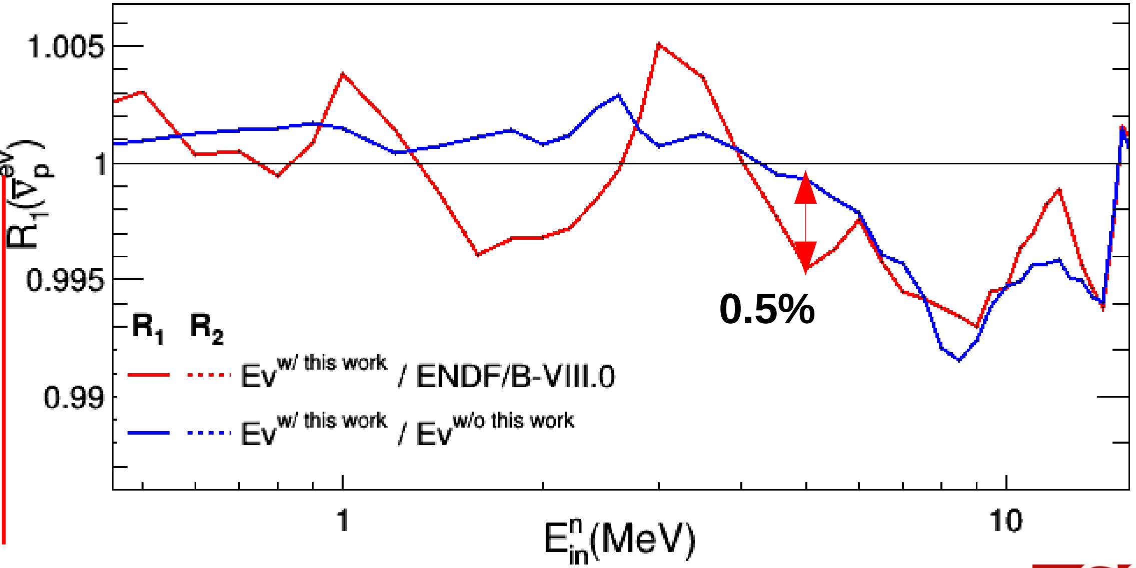
Fundamental physics: sharing between kinetic and E* of fission fragments

Applied nuclear physics:

new evaluations

Reduction of evaluated $\overline{\nu}_p$ **uncertainty** up to 50-60%

$\overline{\nu}_p$ modified by max 0.005% for E_{in}<5MeV → **independent validation** of ENDF/B-VIII.0



P. Marini et al., PLB 835 (2022)

Conclusions and perspectives

- ✔ double **time-of-flight** technique and an **innovative setup** ► account for experimental systematic bias

- ✔ previously unattained **precise and accurate** new data on **^{239}Pu ν_p** from 1 to 700 MeV

  → below 5 MeV : very **first independent validation** of ENDF/B-VIII.0 evaluation

  → significant **reduction of the uncertainty** on evaluated nuclear-data libraries for the ^{239}Pu, crucial for nuclear energy applications

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FUTURE

Possibility of precisely investigating **other high-activity actinide** nuclei

New high-precision **^{239}Pu ν_p measurements from 200keV to 2 MeV**, where existing data are highly spread, **and down to 1keV** where no data exist

VENDETA detector : PFNS from 80keV to 14MeV

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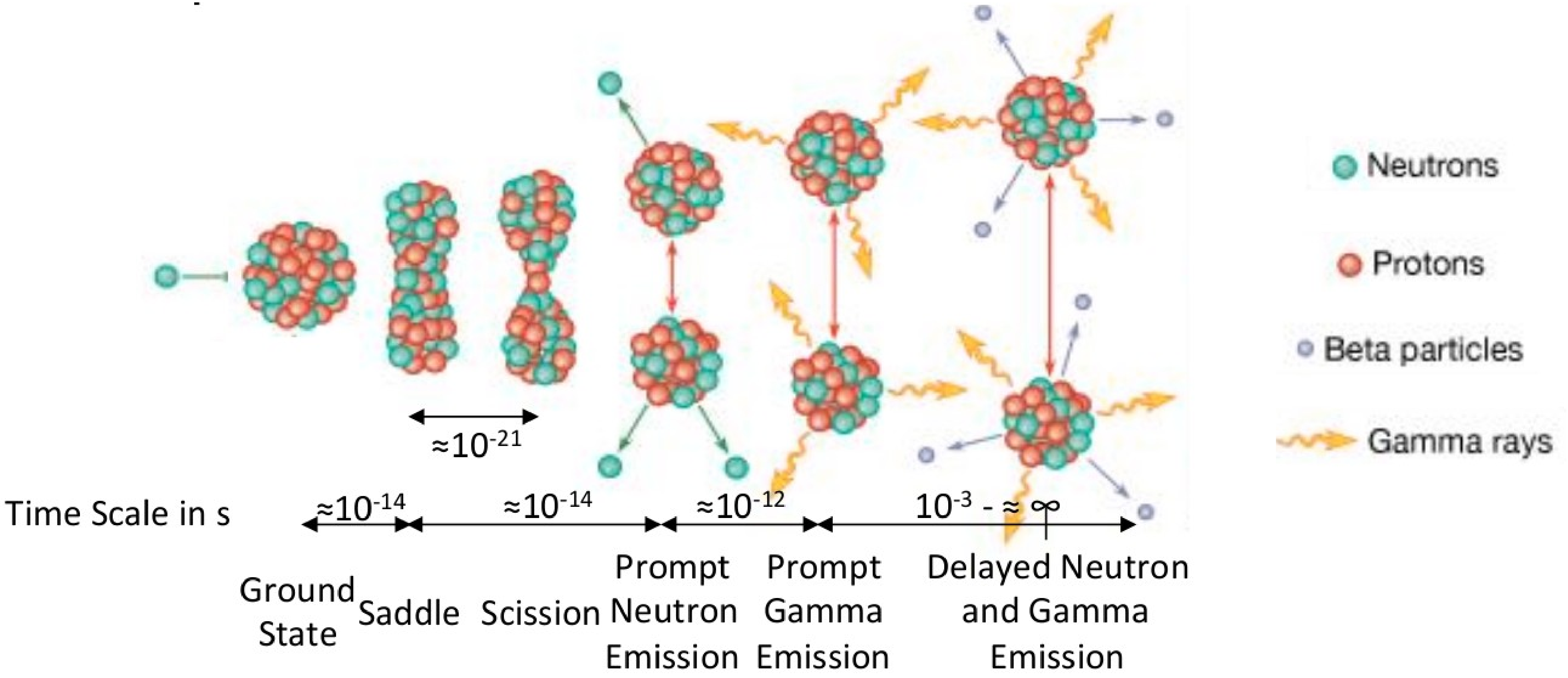
Thank you for your attention

Fission time scale



≈10^{-21}

Time Scale in s ≈10^{-14} ≈10^{-14} ≈10^{-12} 10^{-3} - ≈ ∞

Ground State

Saddle

Scission

Prompt Neutron Emission

Prompt Gamma Emission

Delayed Neutron and Gamma Emission

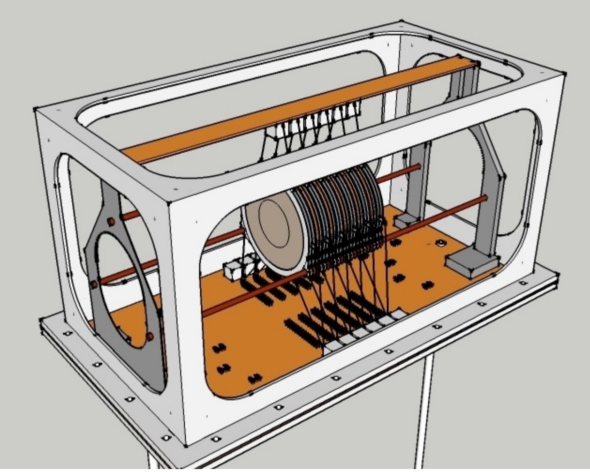
The experiment

→ White pulsed well-collimated neutron beam (800MeV p on W target)

20 effective days data taken w/ 150fission/s

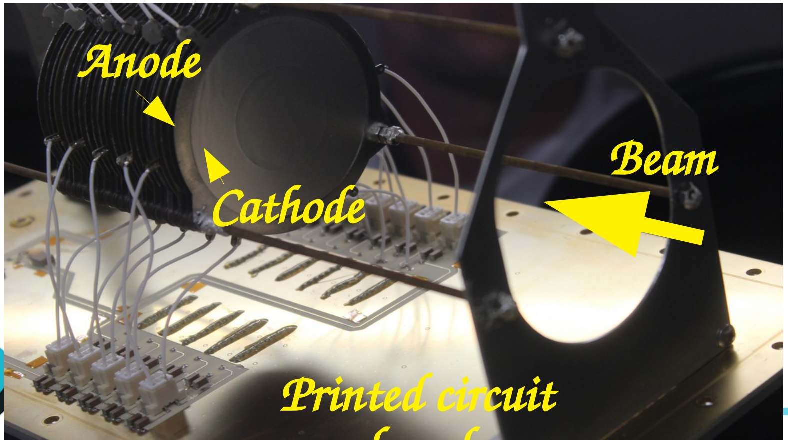
→ 47mg ^{239}Pu target (purity > 99.90%), ~3cm diameter, 22 channels

→ **Fission chamber** J. Taieb et al. NIM A 833 (2016)



CF4 @100mbar => light-weighted chamber to **reduce n scattering**

Dedicated PA and shapers



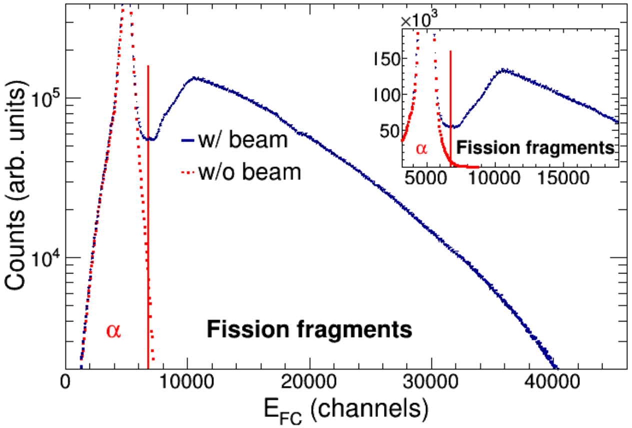
~10MBq α/ch
10 fissions/ch

➡ $\varepsilon_{\text{fission}} \geq$ **95%**

C. Budtz-Jørgensen et al.
Nucl. Sc. En. 86 (1984)

➡ FWHM$_{\text{tof}}$<0.8ns

➡ Unambiguous α-FF discrimination



P. Marini et al., PRC 101 (2020)

The experiment

→ White pulsed well-collimated neutron beam (800MeV p on W target)

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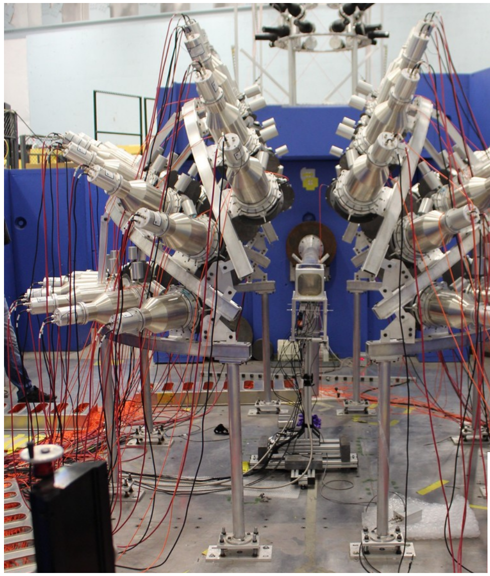
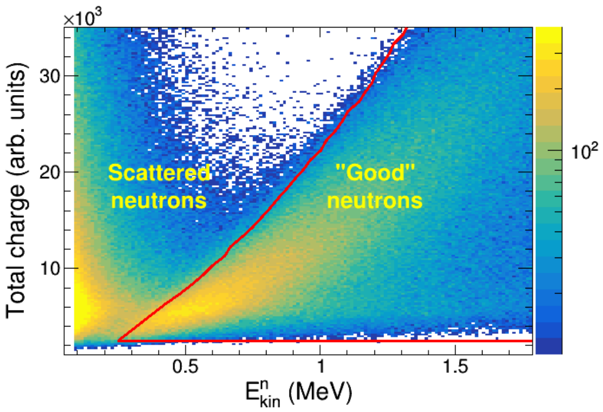
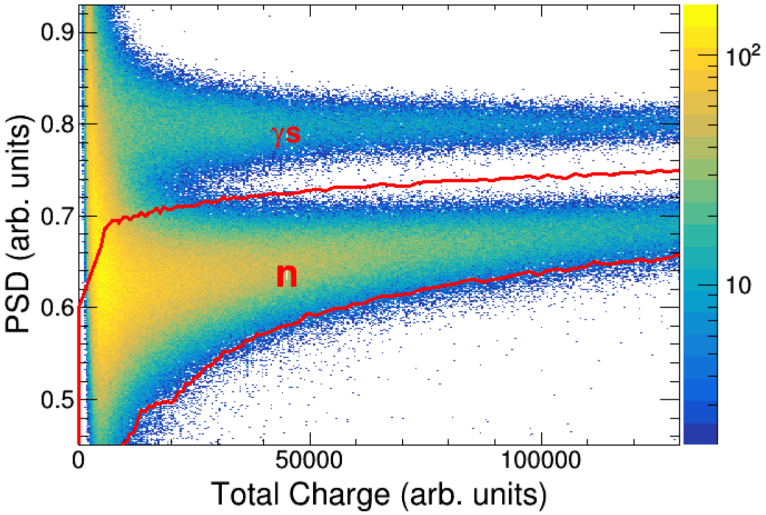
→ Chi-Nu liquid **scintillator array** R. C. Haight et al. J. Inst. 7 (2012).



54 EJ309



- ➡ **n-γ discrimination** via PSA down to 200keV
- ➡ n **angular distribution**



P. Marini et al., PRC 101 (2020)

The experiment

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→ digital Fast Acquisition System for nuclEar Research (**FASTER**)

FASTER. LPC-Caen http://faster.in2p3.fr, (2013)

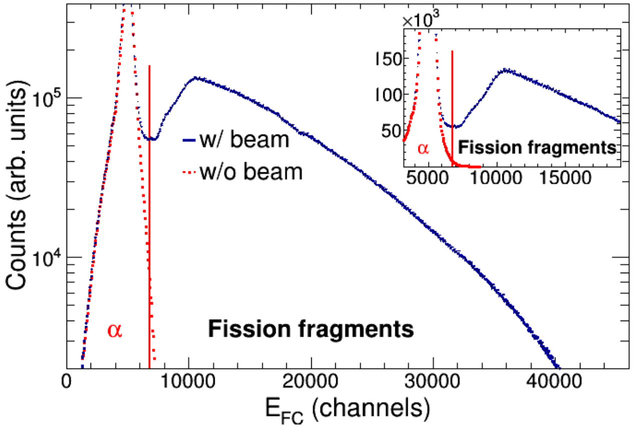
➡ DAQ time resolution : 7.8ps

➡ near complete avoidance of numerical dead time

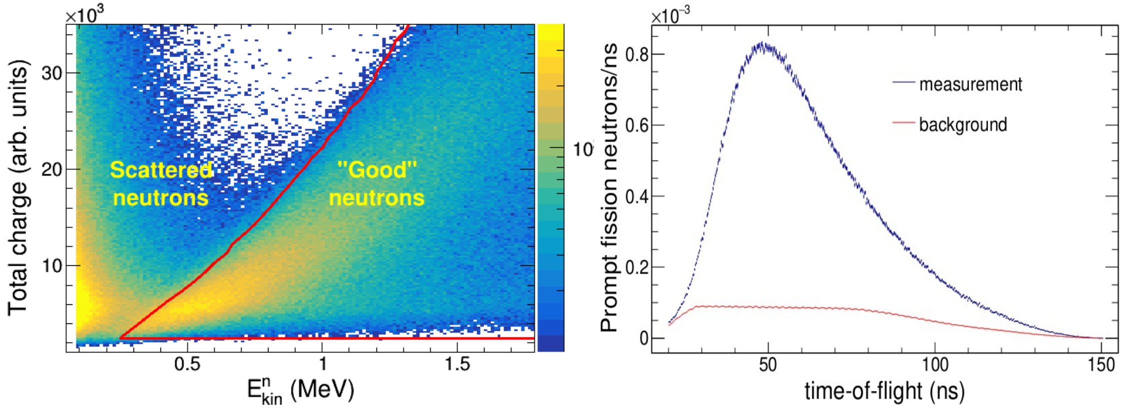
Data analysis

P. Marini et al., PRC 101 (2020)

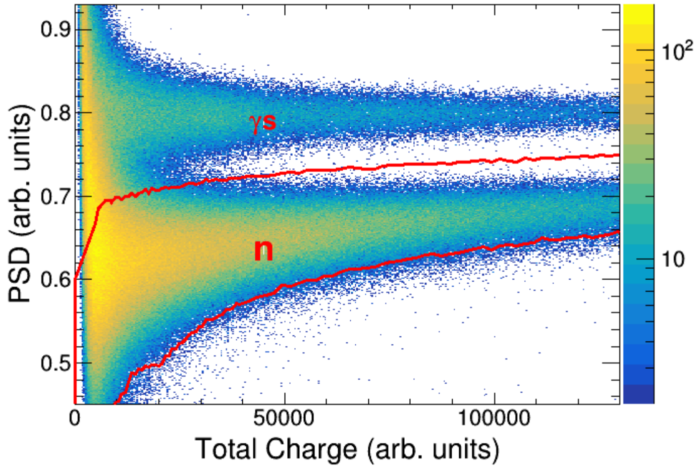
→ Event selection : α-FF discrimination



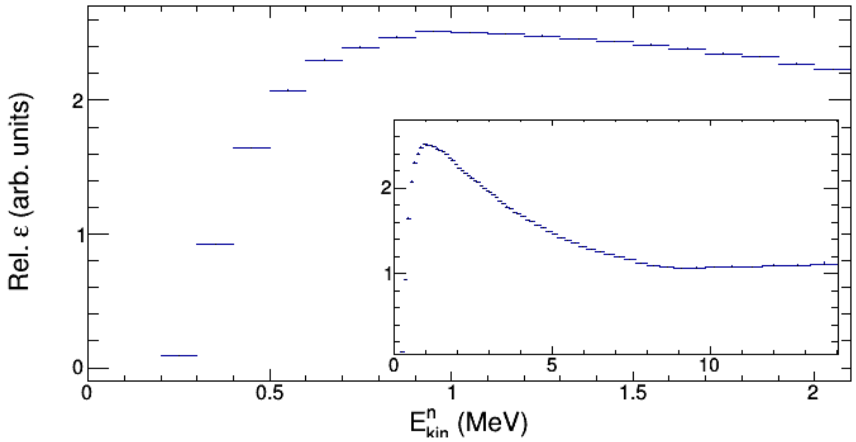
→ Scattering corrections



→ n selection : n-γ discrimination



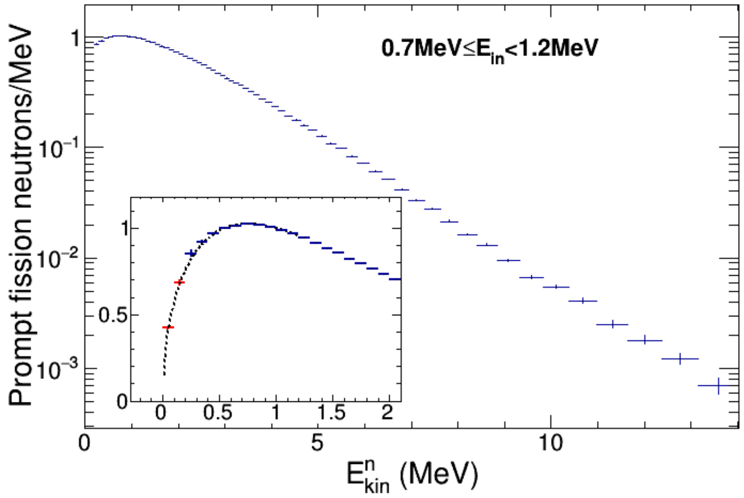
→ neutron detector efficiency



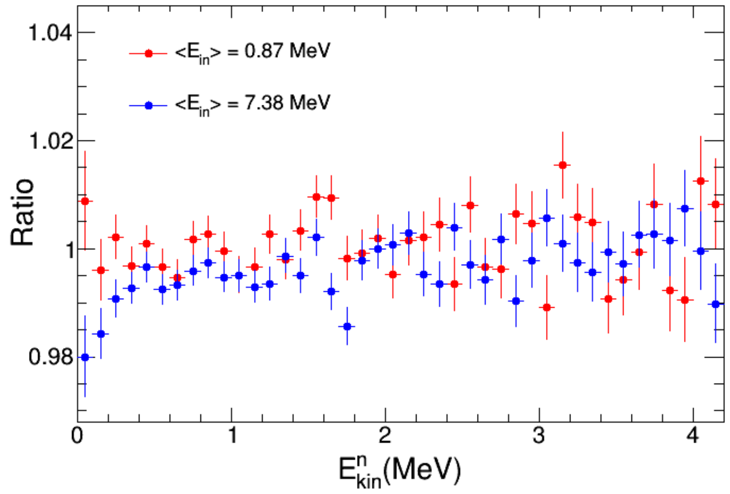
Data analysis

P. Marini et al., PRC 101 (2020)

→ Extrapolation to low E_n



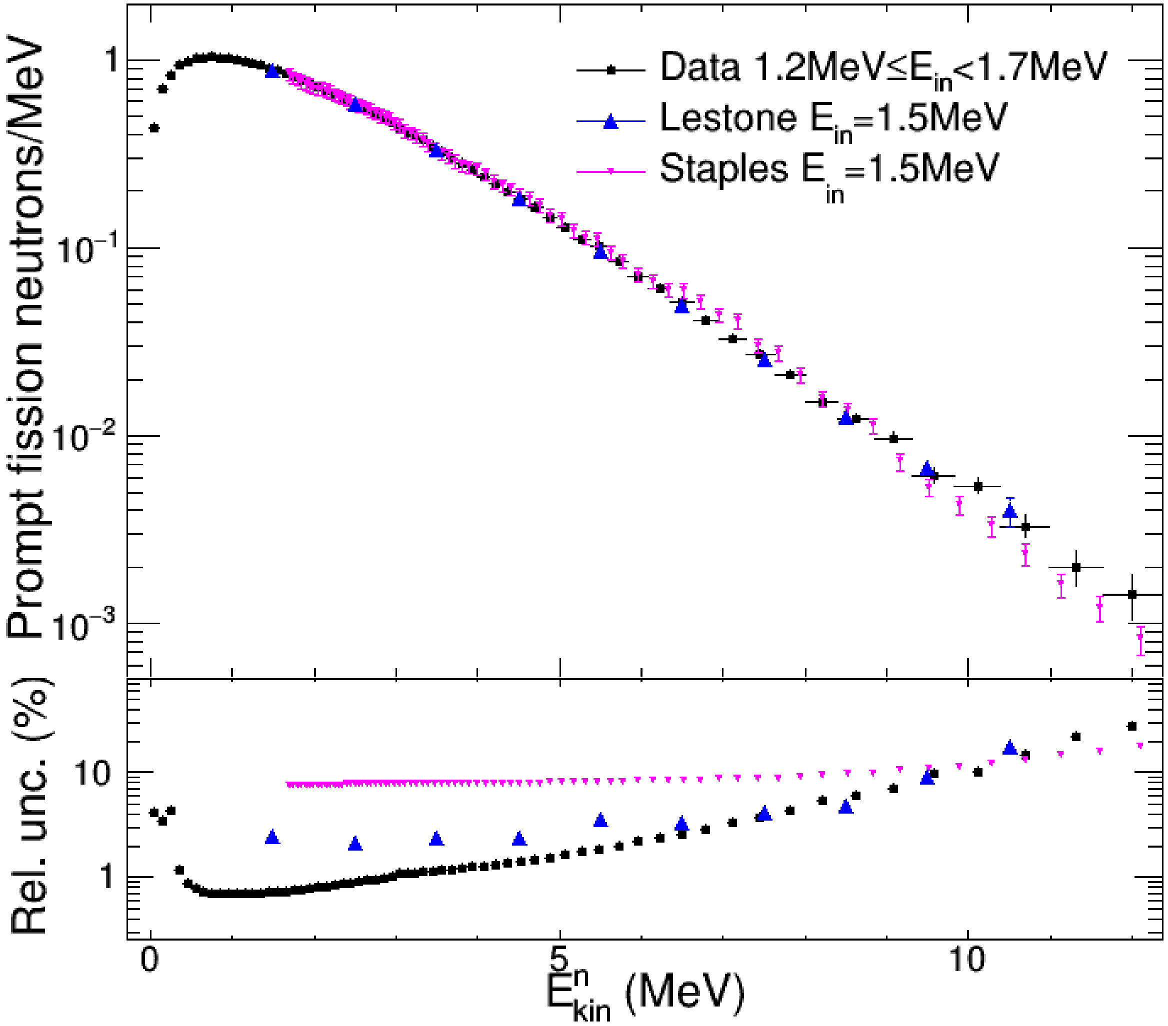
→ Study of distortion introduced by ^{252}Cf and ^{239}Pu PFNS differences



PFNS results

P. Marini et al., PRC 101 (2020)

→ Prompt Fission Neutron Spectra



But also :

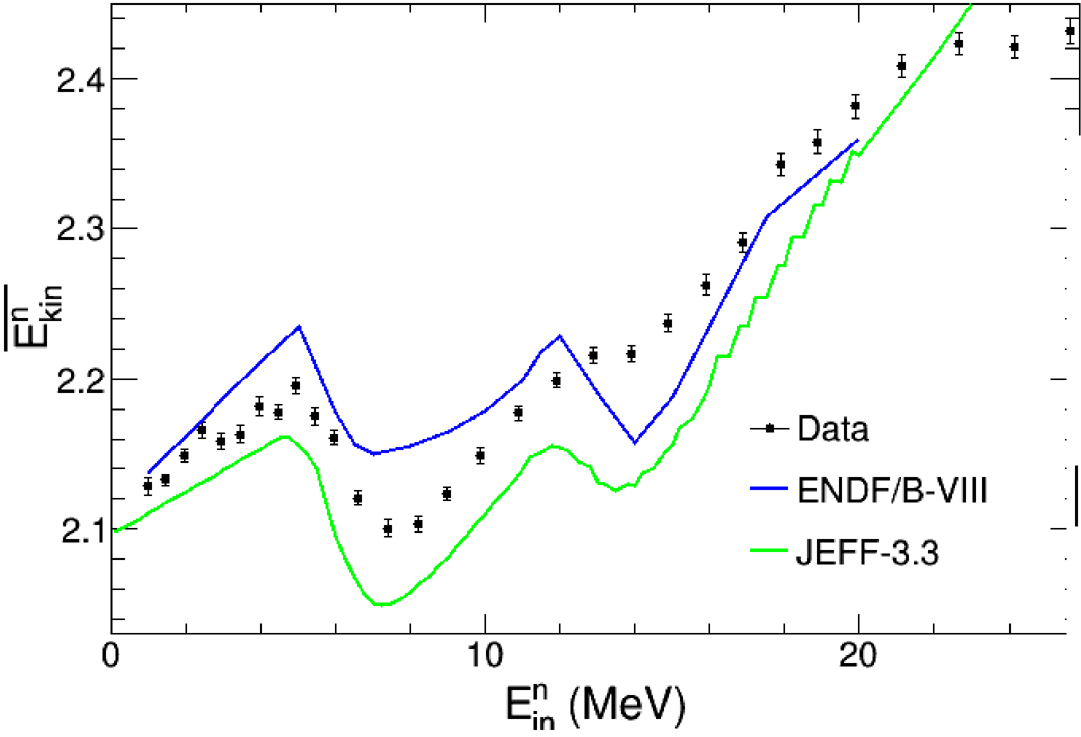
→ mean energy of prompt fission neutrons

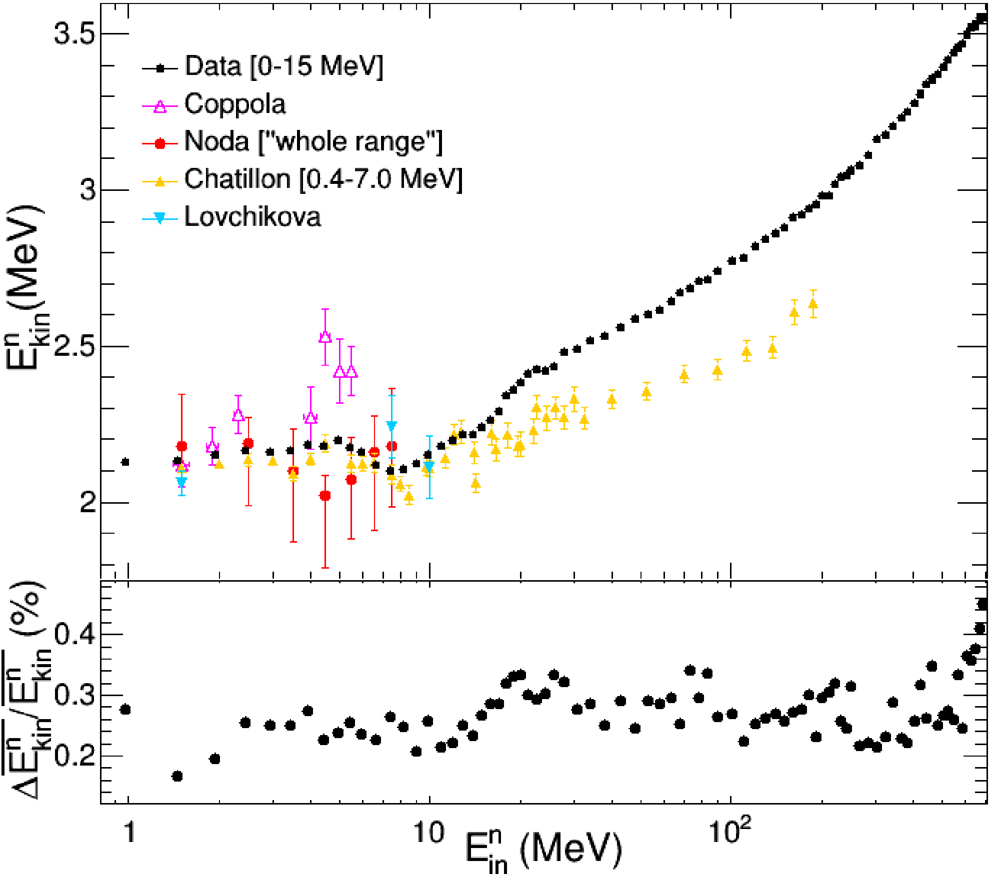
→ multiplicity of prompt fission neutrons

PFNS results

P. Marini et al., PRC 101 (2020)

→ Mean Energy of Prompt Fission Neutrons





Correction of systematic biases

P. Marini et al., PLB 835 (2022)

→ **correct for systematic biases**

* measure the whole TKE-θ FF distributions

* neutrons angular distribution

* E_n-dependent efficiency

* **detector energy thresholds**

- lower limit [200keV]

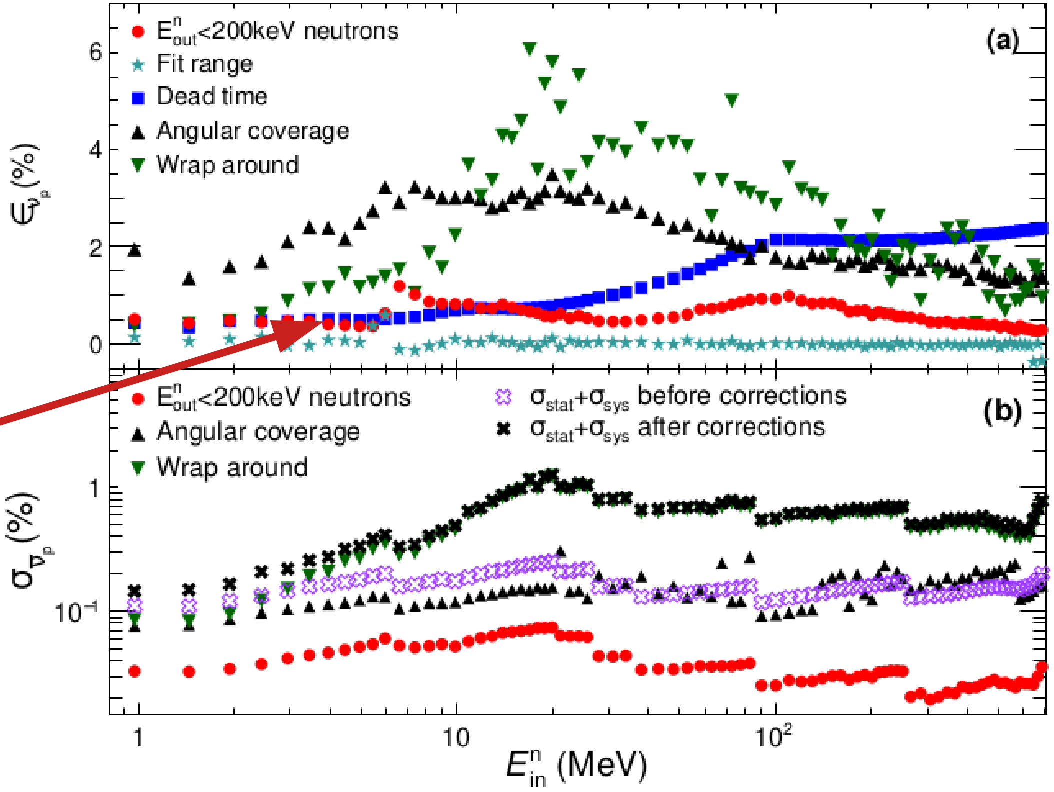
  ° due to threshold for n-γ discrimination

  ° extrapolation w/ a Maxwellian spectrum

- higher limit [14MeV]

  ° due to dynamic range of electronics

  ° TALYS : 0.9% contribution to ν_p of n of E_n>14MeV at 25MeV E_{in}

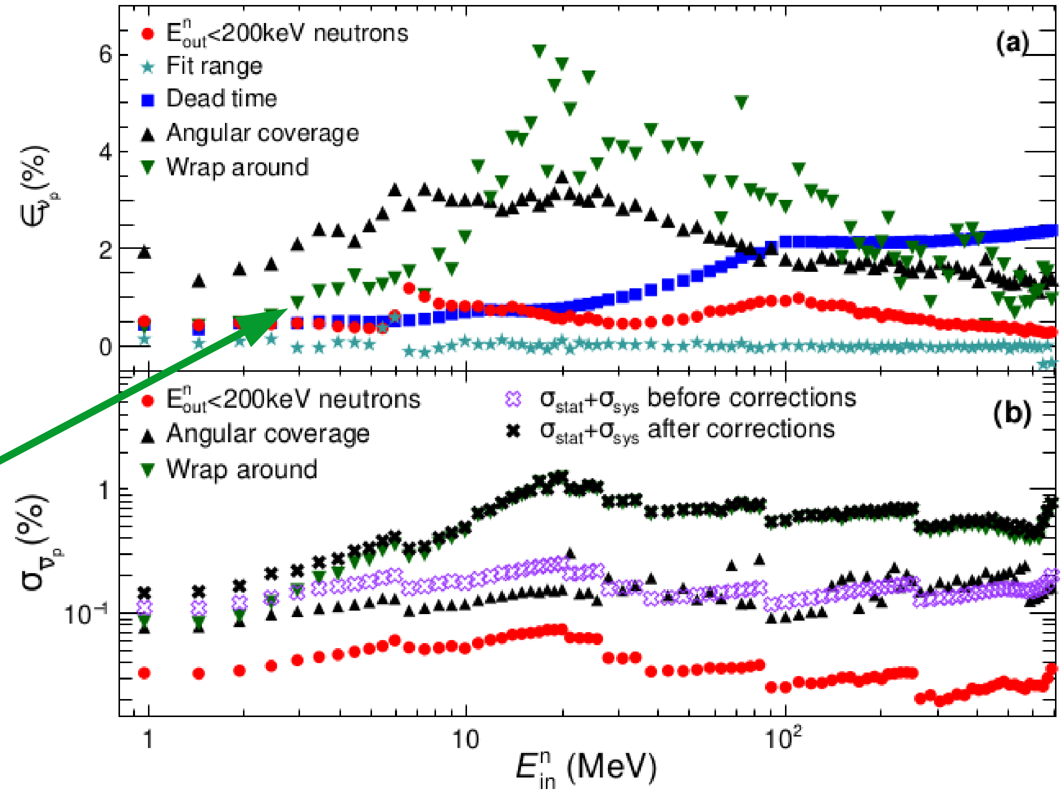


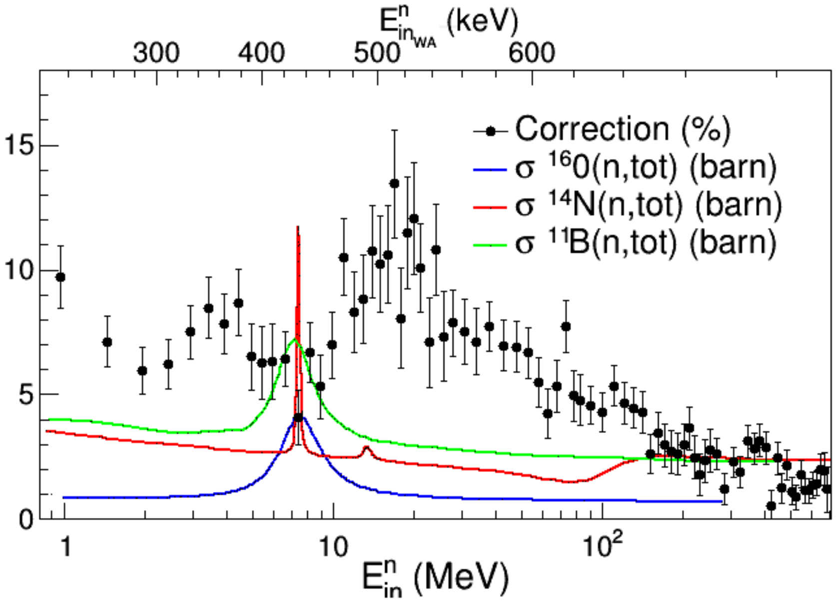
Correction of systematic biases

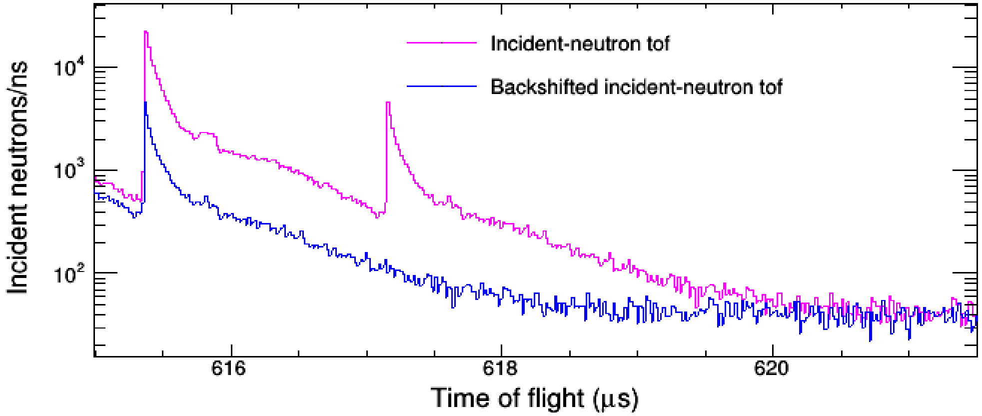
P. Marini et al., PLB 835 (2022)

→ **correct for systematic biases**

- * measure the whole TKE-θ FF distributions
- * neutrons angular distribution
- * E_n-dependent efficiency
  - * detector energy thresholds
  - * **wrap-around**: neutrons emitted in fissions induced by slower-than-measured neutrons







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P. Marini et al., PLB 835 (2022)

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- * measure the whole TKE-θ FF distributions
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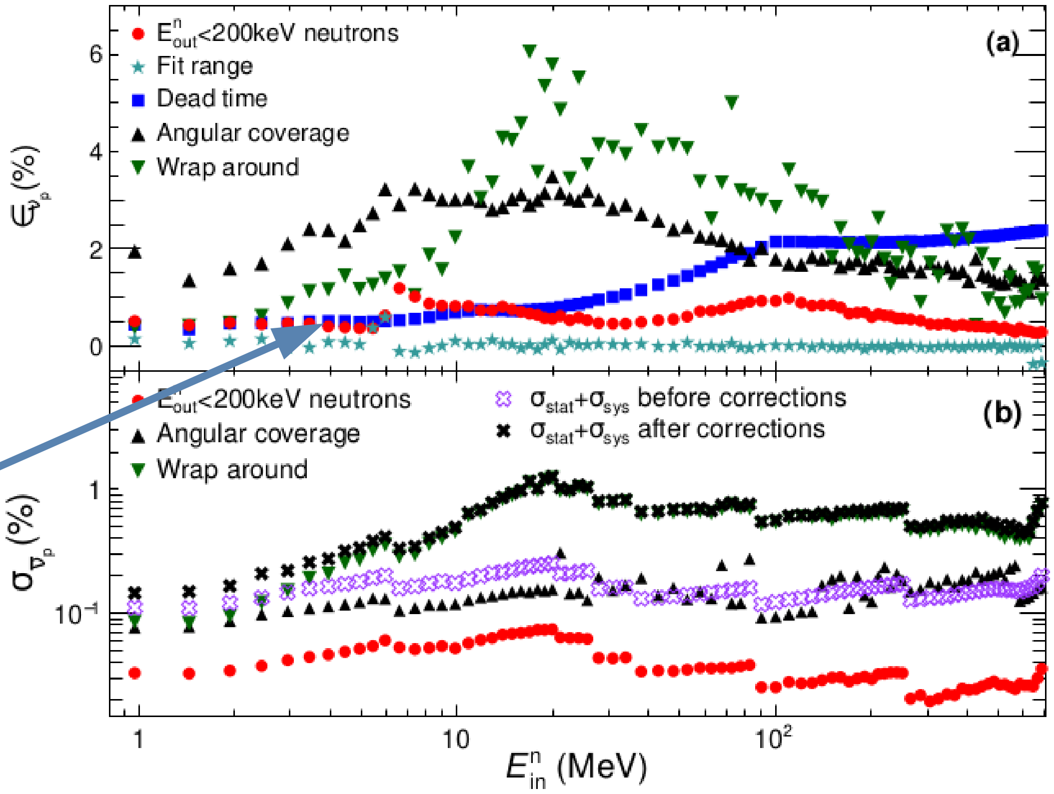
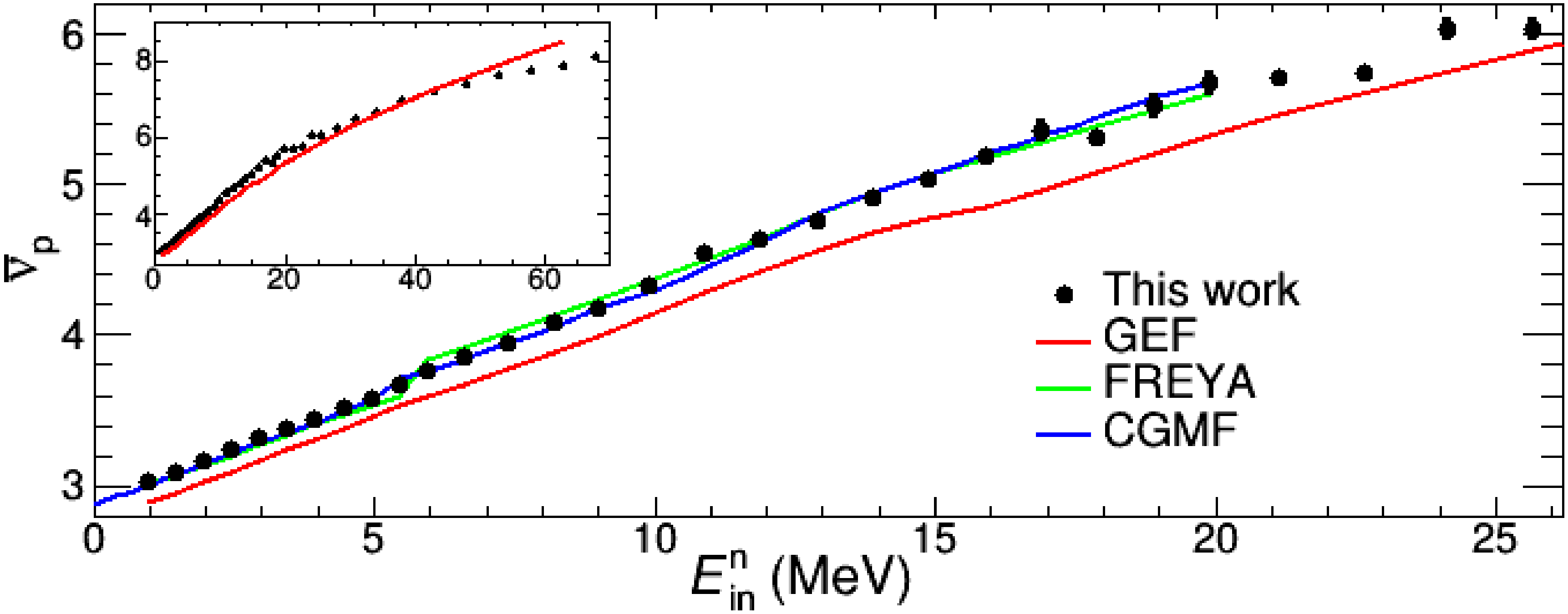
- * E_n-dependent efficiency
  - * detector energy thresholds
  - * wrap-around
  - * **detector dead-time**



full Monte Carlo simulation based
on experimental distributions

Results

P. Marini et al., PLB 835 (2022)



FREYA and CGMF adjust the FF kinetic energy to obtain the experimental ν_p

➡ Not predictions