

SOFIA UNIVERSITY  
MARKING MOMENTUM  
FOR INNOVATION AND  
TECHNOLOGICAL TRANSFER



LHC  
Scattering and Neutrino Detector  
at the LHC



# Статут и перспективи пред експеримента SND@LHC

Катедра “Атомна физика” на 80 години

16 – 18 Април

Ивайло Дионисов



Финансирано от  
Европейския съюз  
NextGenerationEU

Национален план за  
възстановяване и устойчивост



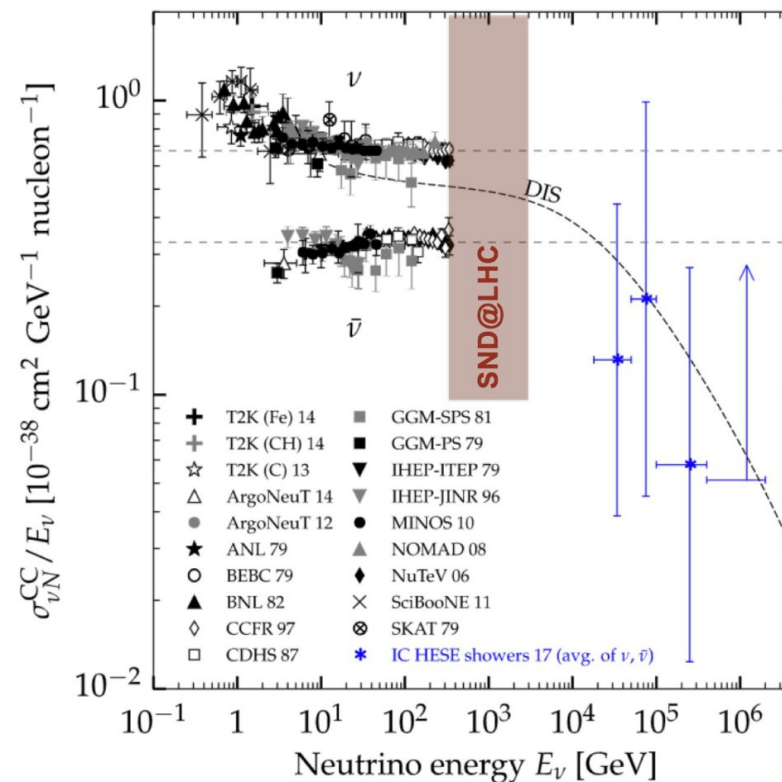
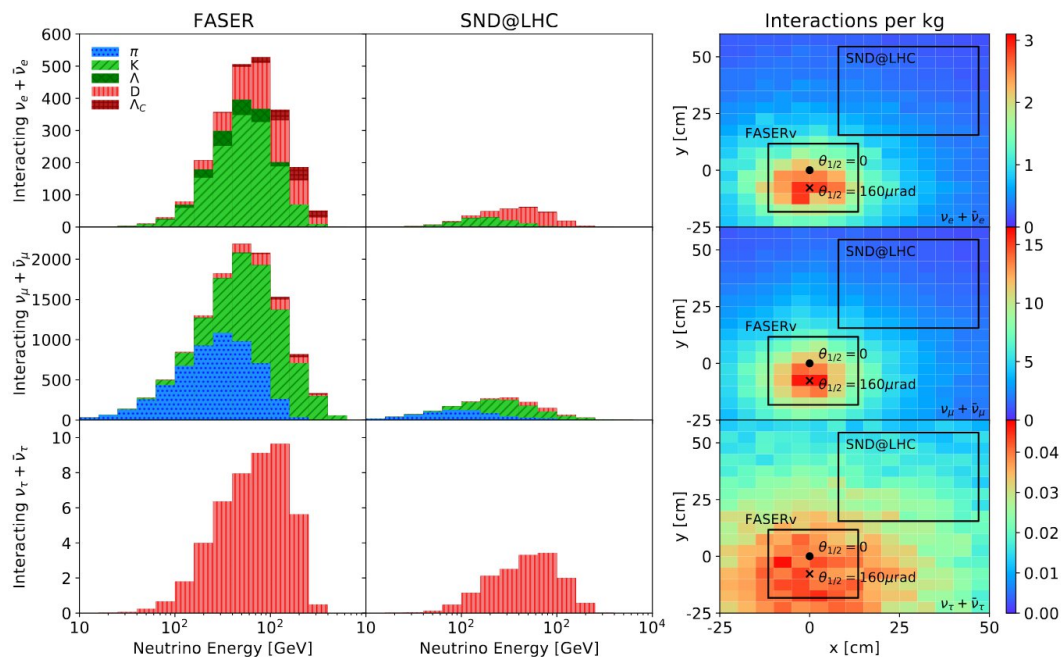
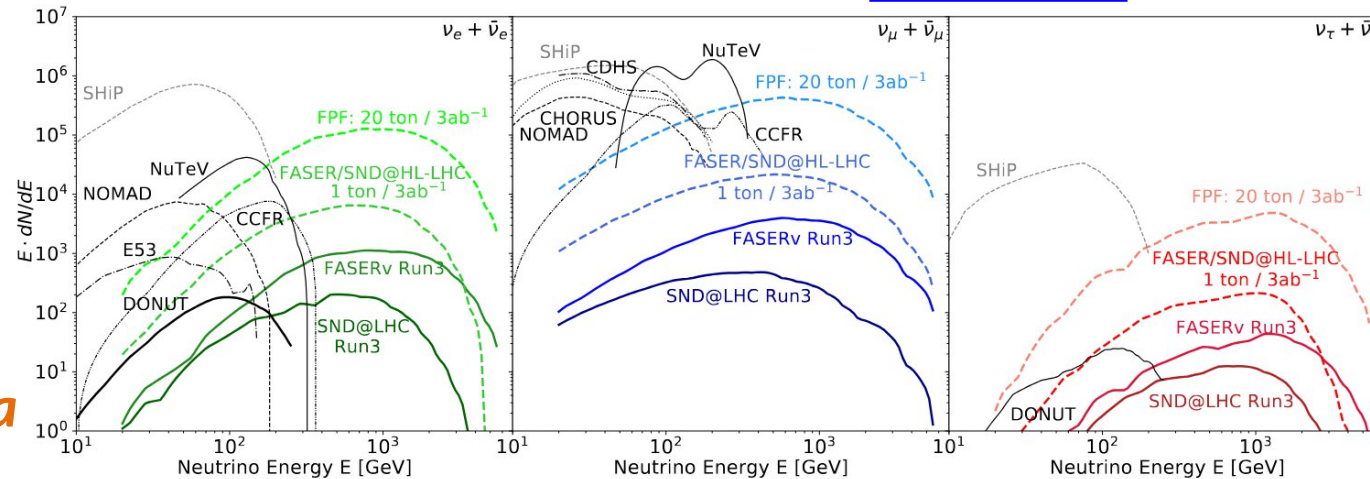
НА РЕПУБЛИКА БЪЛГАРИЯ

# Неутрина при LHC

LHC произвежда най-високоенергийните неутрина създавани от ускорител

➤ Мост между ускорителната физика и високоенергийната неутринна астрономия.

arXiv:2501.10078v1



PRI\_122(2019)041101

arXiv:2501.10078v1

# SND@LHC (*Scattering Neutrino Detector at the LHC*)

На 480 м от ATLAS – защитен от 100 м скала и магнитната система на LHC.

## Научна програма

### Неутринни взаимодействия

- Измерване  $\nu$  взаимодействия в неизследван  $\sim$ TeV енергиен диапазон
- Наблюдения на  $\nu_\tau$

### Лептони в слабите взаимодействия

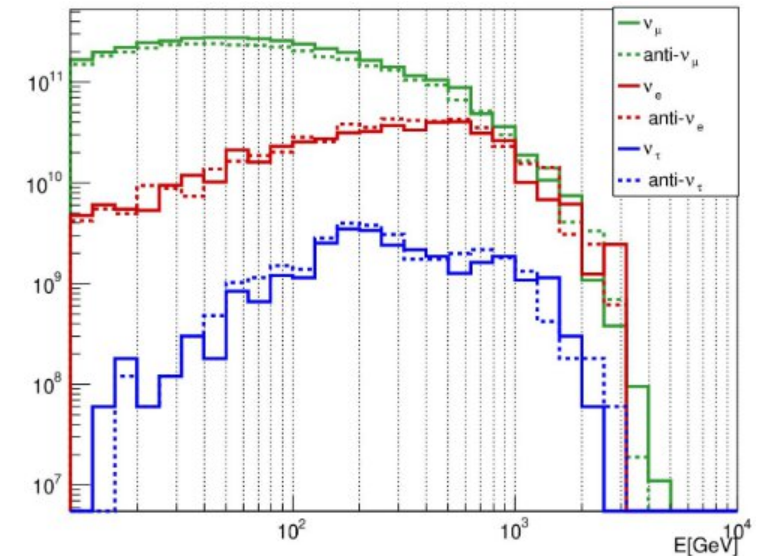
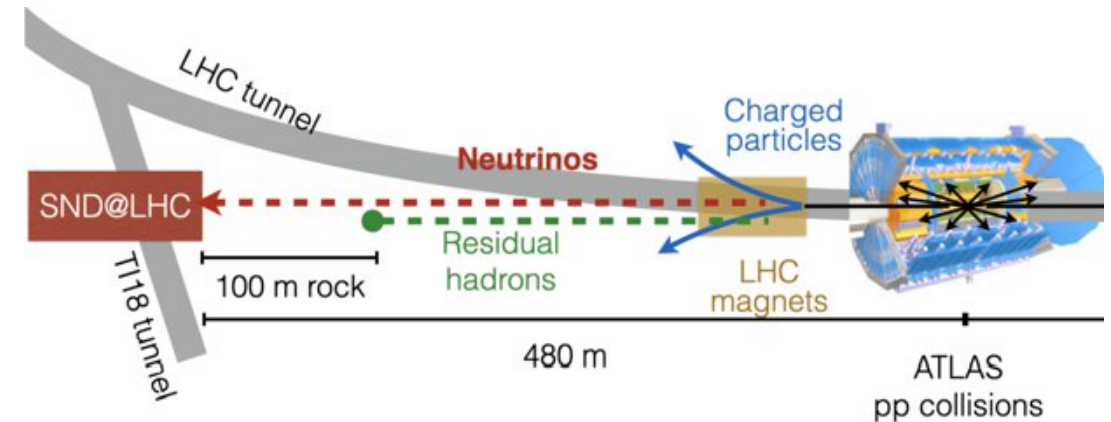
- Различаване на трите аромата  $\rightarrow$  тест на универсалността на ароматите (LFU)

### Силни взаимодействия (QCD)

- Подбор на неутрина от разпади на  $c$ -кварки  $\rightarrow$  Измерване на продукцията на чаровни кварки в предно направление  $\nu_e$

### Отвъд стандартен модел (BSM)

- Търсене на нови леки частици, които се разпадат или разсейват в обема на детектора



# Детектор

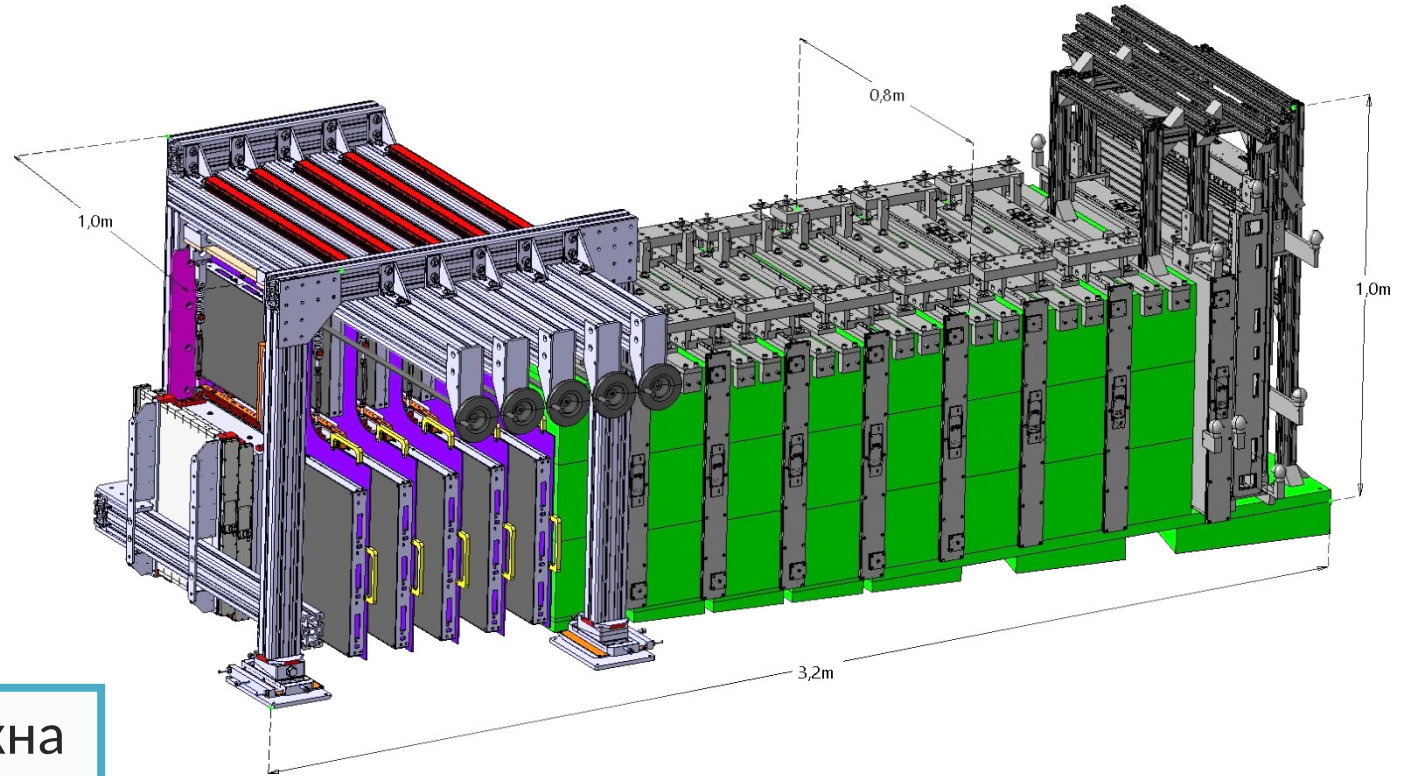
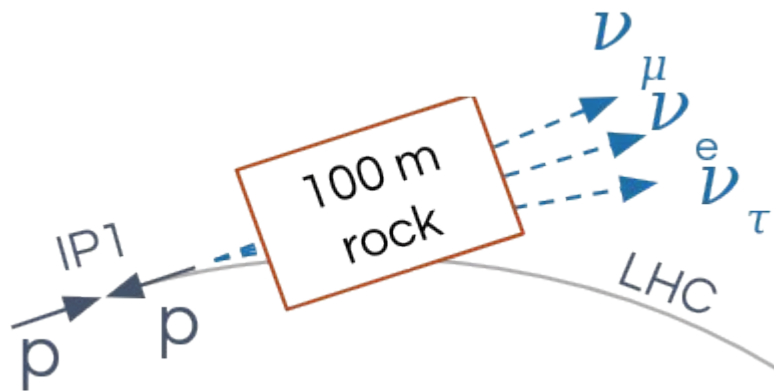
## Вето система

[JINST 20 P07011](#)

— 2 (2022 – 2023) / 3 (2024 - )  
сцинтилационни равнини.

## Мишена, vertex детектор и ECAL

- 830 кг волфрамова мишена
- Пет стени x 59 слоя емулсии
- + пет станции от сцинтилационни влакна
- $84 X_0$ ,  $3 \lambda_{int}$



Off-axis:  $7.2 < \eta < 8.4$

Подбор на неутринен поток с чаровен призход.

## HCAL и мюонна система

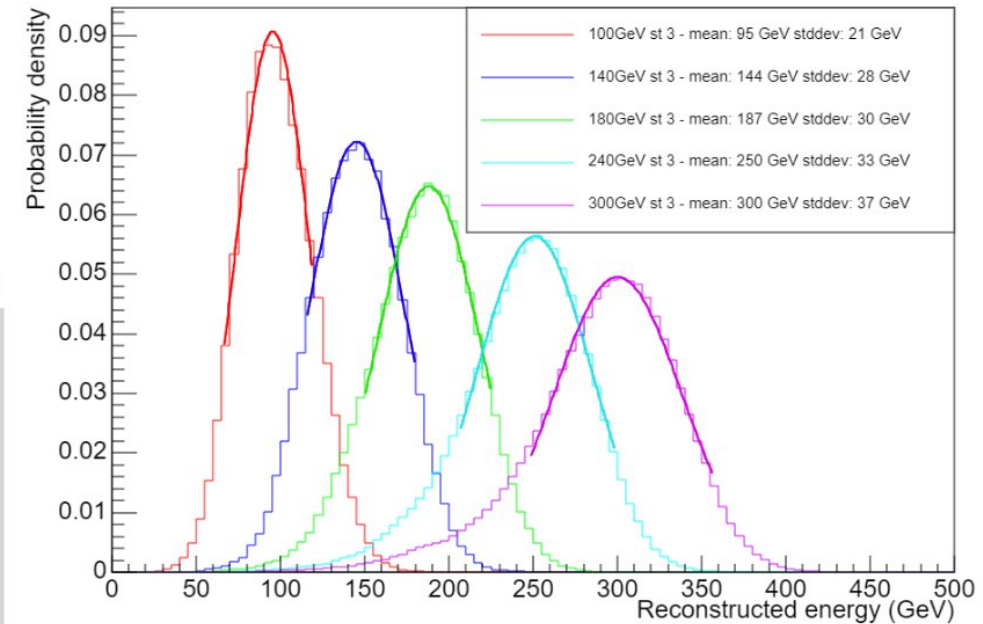
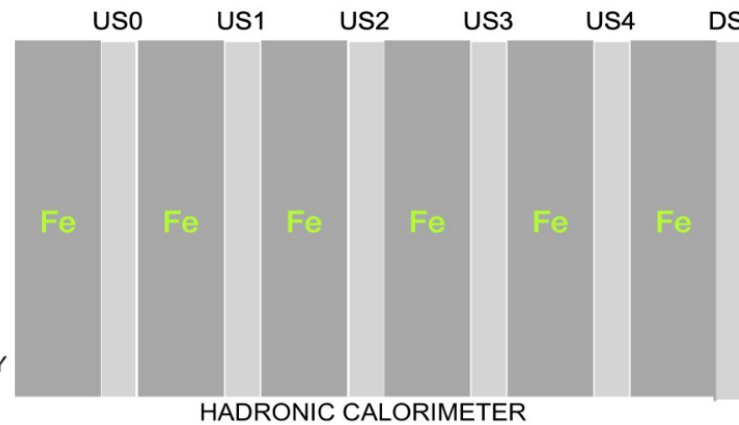
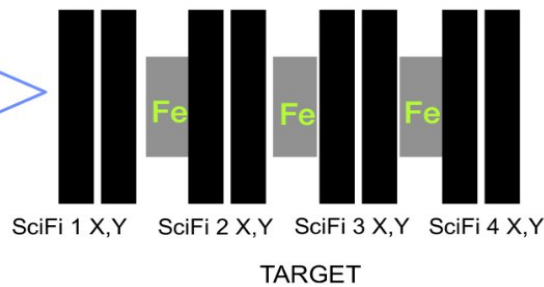
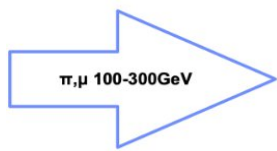
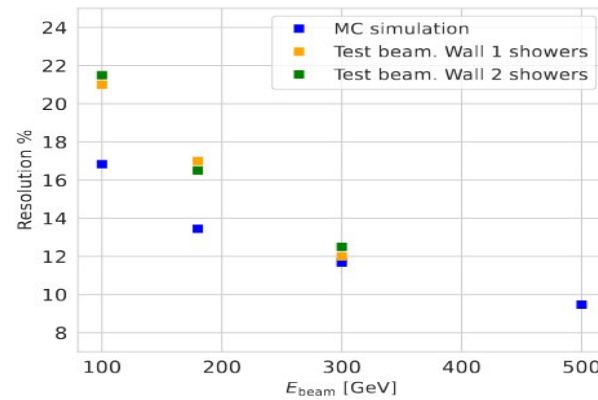
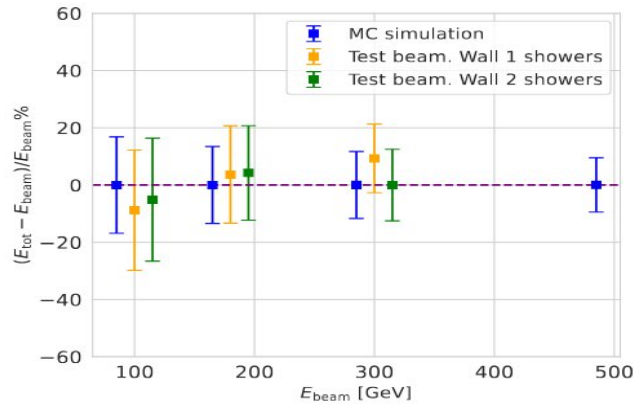
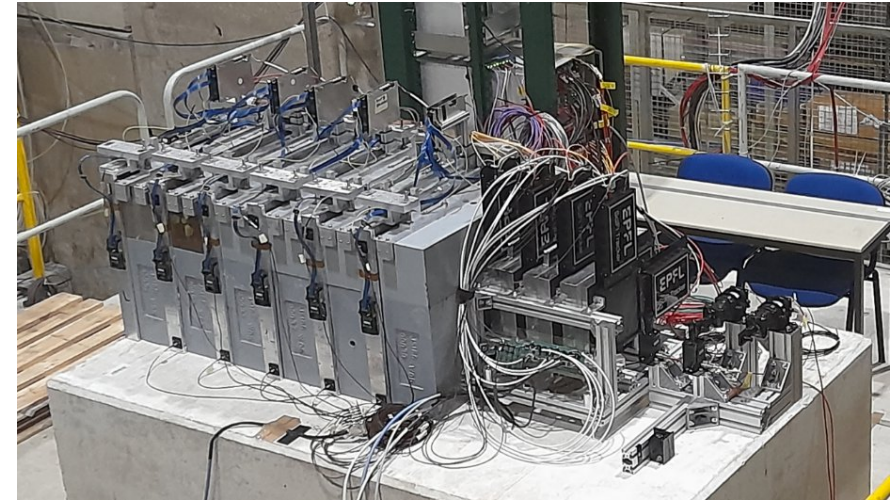
- Осем 20 см Fe блока + сцинтилационни равнини.
- Последни 3 равнини с по-финна разделимост.
- $9.5 \lambda_{int}$

**НОВО от 2025:** Равнина от дрейфови тръби.

# Калибровка по енергия

## Тестови снопове от пиони с известна енергия (SPS, Август 2023)

- Идентично копие на адронния калориметър и смалена мишена



# Мюонен поток

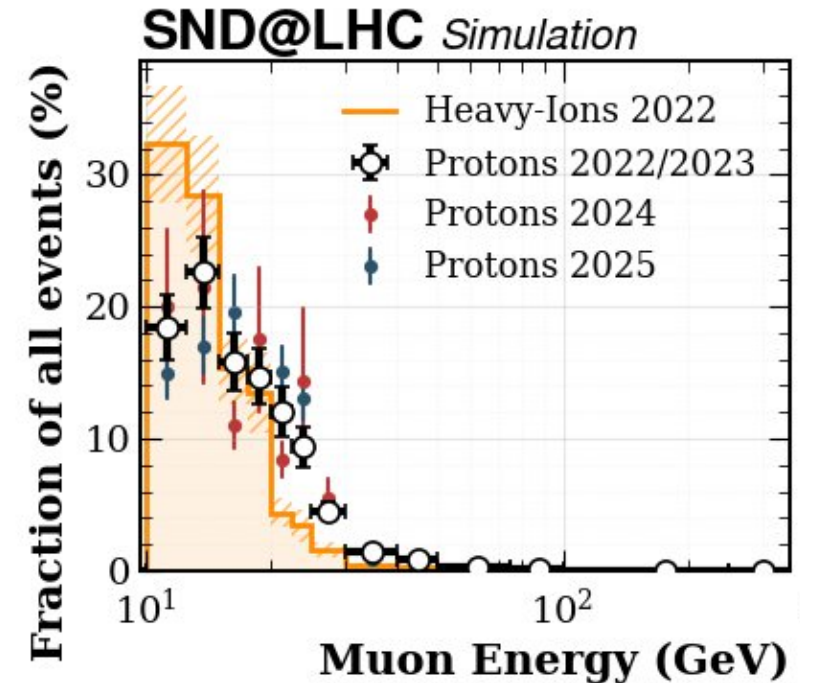
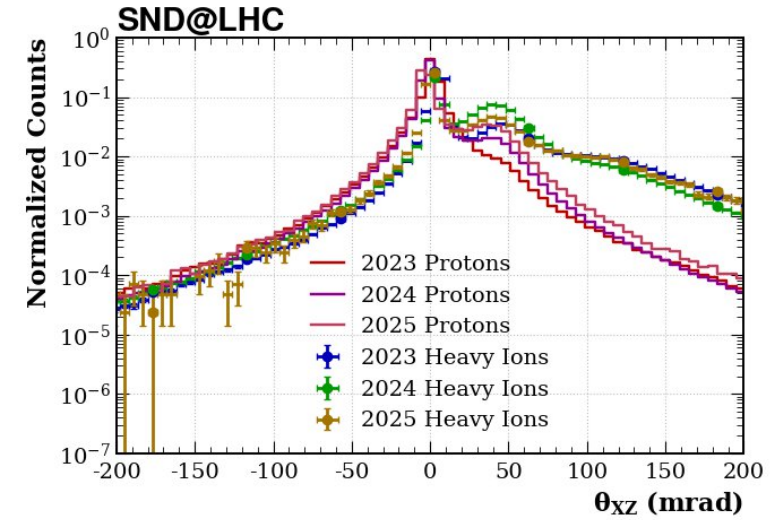
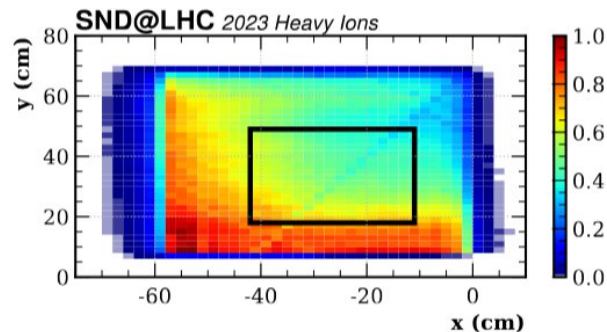
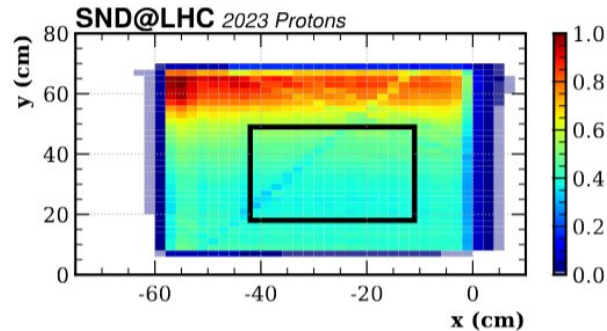
## Повечето събития в SND са на преминаващи мюони

- Главен шум за неутринни СС взаимодействия
- Основна причина за честата смяна на емулсите

Dataset	Muon Flux
<i>Heavy-Ion Collisions (<math>10^4</math> nb/cm<sup>2</sup>)</i>	
Data (2023)	$3.11 \pm 0.12$
Data (2024)	$5.53 \pm 0.22$
Data (2025)	$3.24 \pm 0.13$
Monte Carlo (2022)	$2.99 \pm 0.09$
<i>Proton Collisions (<math>10^{-2}</math> nb/cm<sup>2</sup>)</i>	
Data (2023)	$1.90 \pm 0.04$
Monte Carlo (2023)	$1.67 \pm 0.05$
Data (2024)	$3.76 \pm 0.09$
Monte Carlo (2024)	$3.34 \pm 0.12$
Data (2025)	$2.42 \pm 0.05$
Monte Carlo (2025)	$3.13 \pm 0.14$
Data (2022)	$2.06 \pm 0.12$

[Eur. Phys. J. C 84, 90 \(2024\)](#)

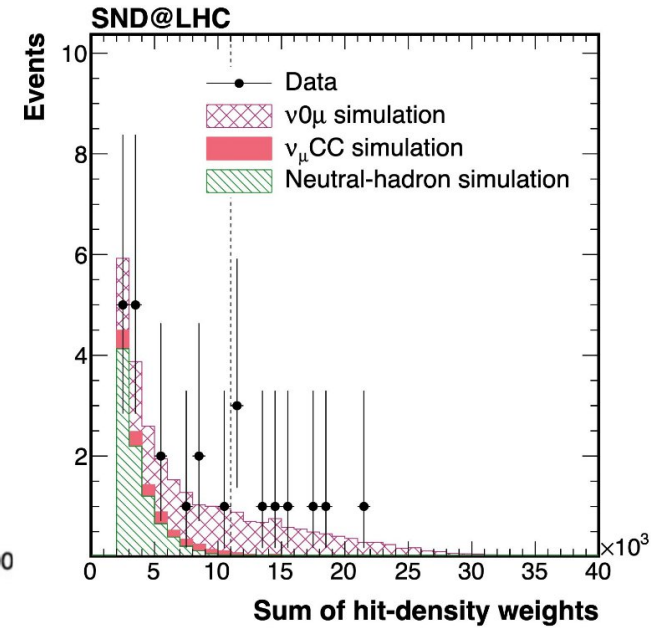
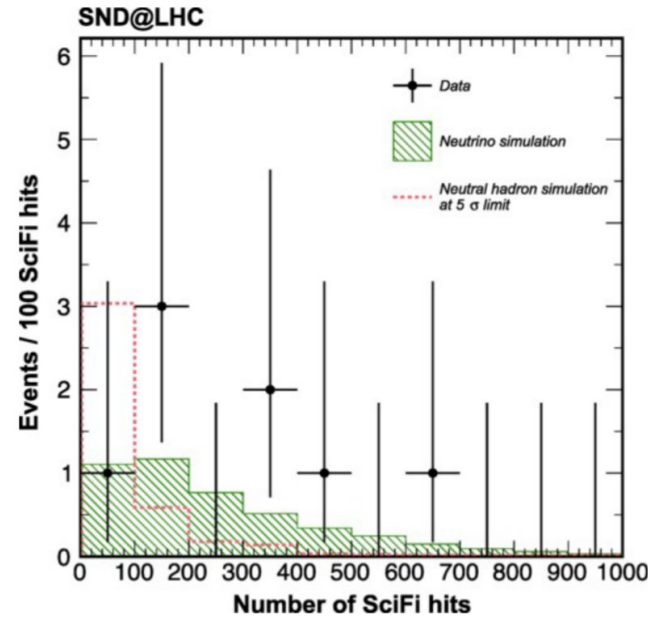
Submitted to EPJC



# Неутринни взаимодействия

## Мюонно неутрино ([Phys. Rev. Lett. 131](#))

- ✓ 8 кандидати в данни от 2022 ( $6.8 \sigma$ ,  $36.8 \text{ fb}^{-1}$ )
- ✓ 31 нови събития с включени данни от 2023 (В съответствие с Монте Карло симулации)



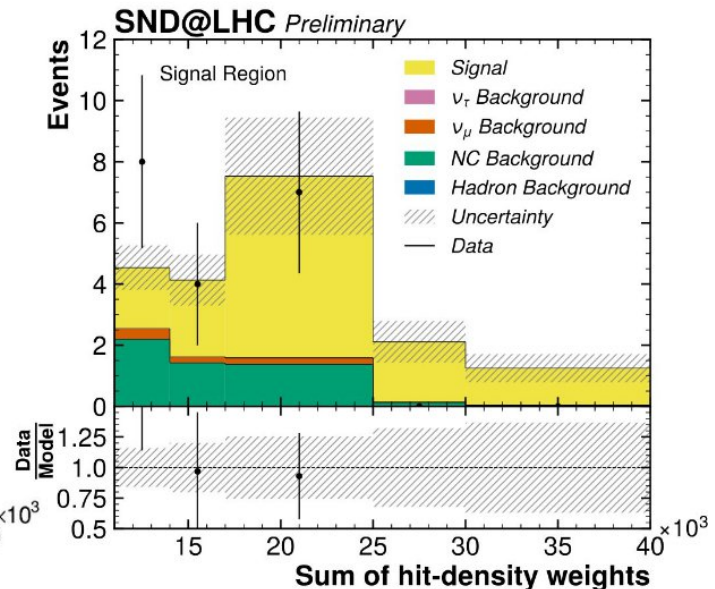
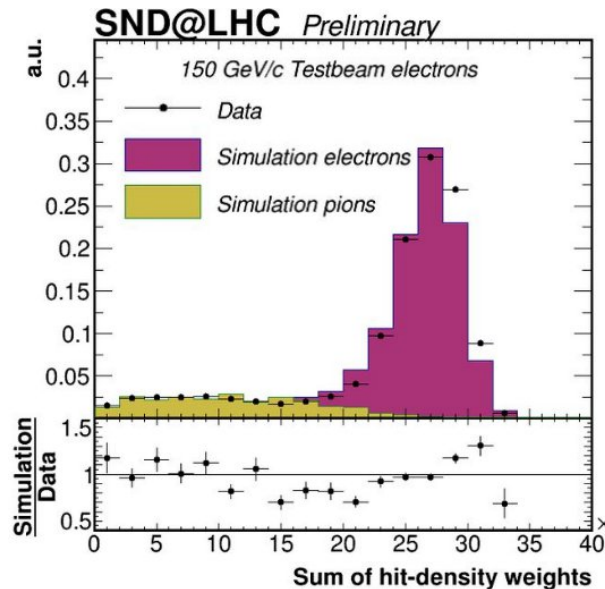
## Събития без мюон (NC and $\nu_e \text{ CC}$ )

### [PRL 134 231802 \(2025\)](#)

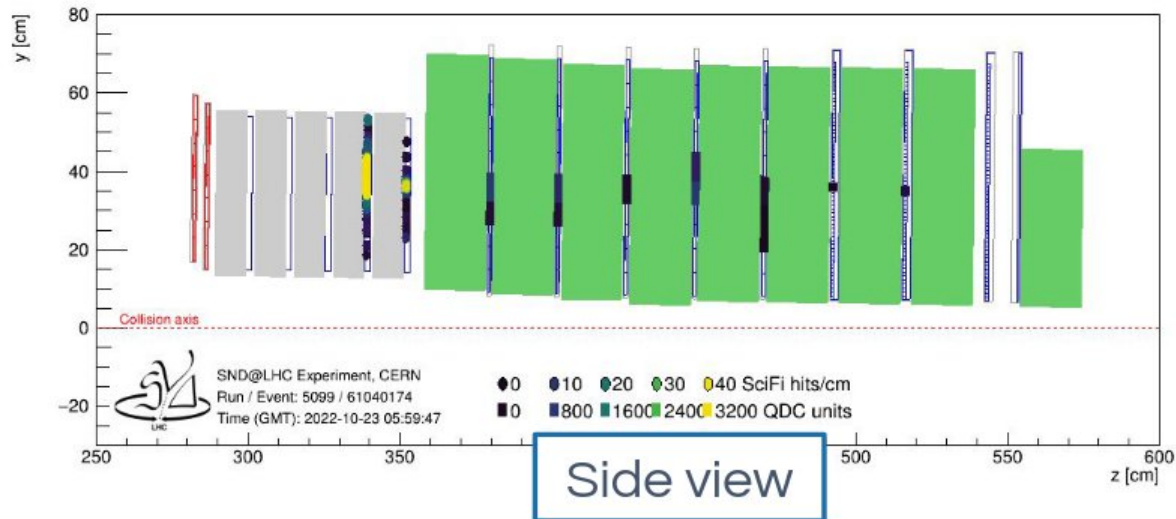
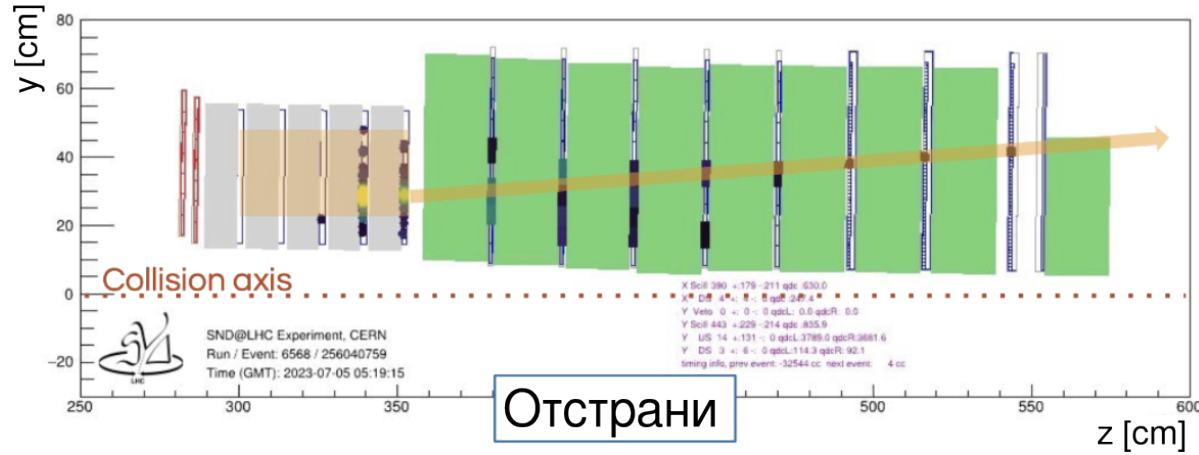
- ✓ 7.2  $\nu_0\mu$  събития с ниво на увереност  $6.4 \sigma$
- ✓ (4.9  $\nu_e \text{ CC}$  + 2.2 NC + 0.1  $\nu_e \text{ CC}$  събития)

## Електронно неутрино (Preliminary)

- ✓ 19 кандидати в данни 2022-2024 [ $2.7 \sigma$  ( $3.6 \sigma$  unbinned),  $170.6 \text{ fb}^{-1}$ ]
- ✓ Предсказани  $19 \pm 5$  събития, ниво  $4.5 \sigma$



# Неутринни взаимодействия



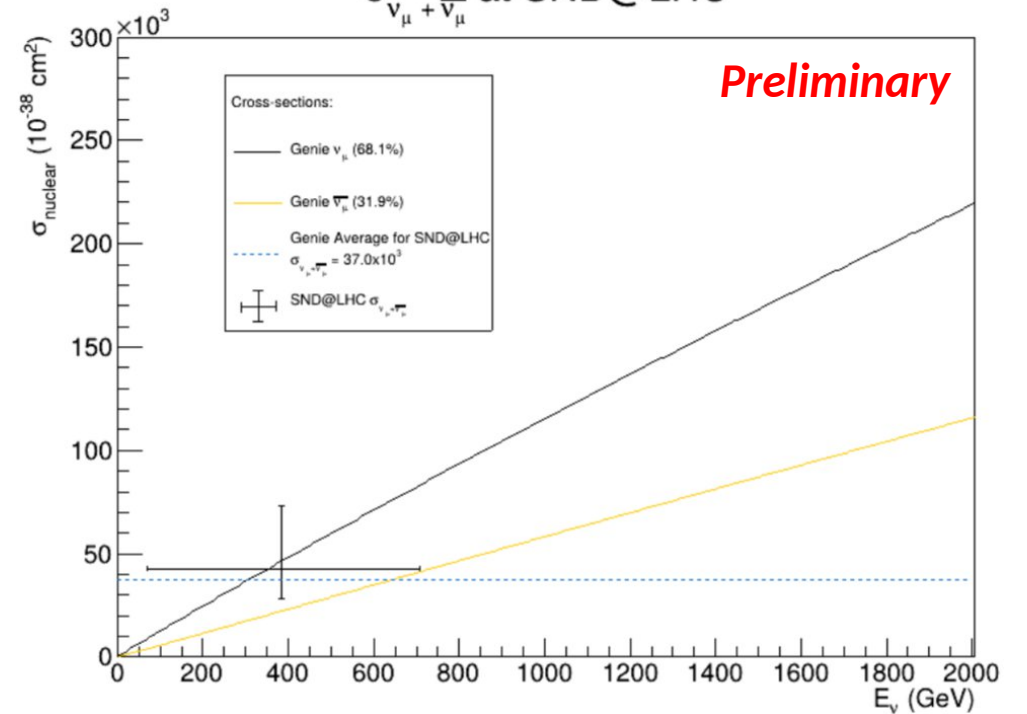
**Preliminary**

Сечения за нзаемодействие на  $\nu_\mu + \bar{\nu}_\mu$

Осреднявайки енергиите

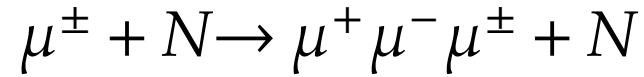
- Очаквано  $34 \times 10^{-35} \text{ cm}^2$
- Измерено  $37_{-12}^{+24} \times 10^{-35} \text{ cm}^2$

$\sigma_{\nu_\mu + \bar{\nu}_\mu}$  at SND@LHC



# Производ на три мюона

*SND@LHC* е способен да разпознае събития с три мюона

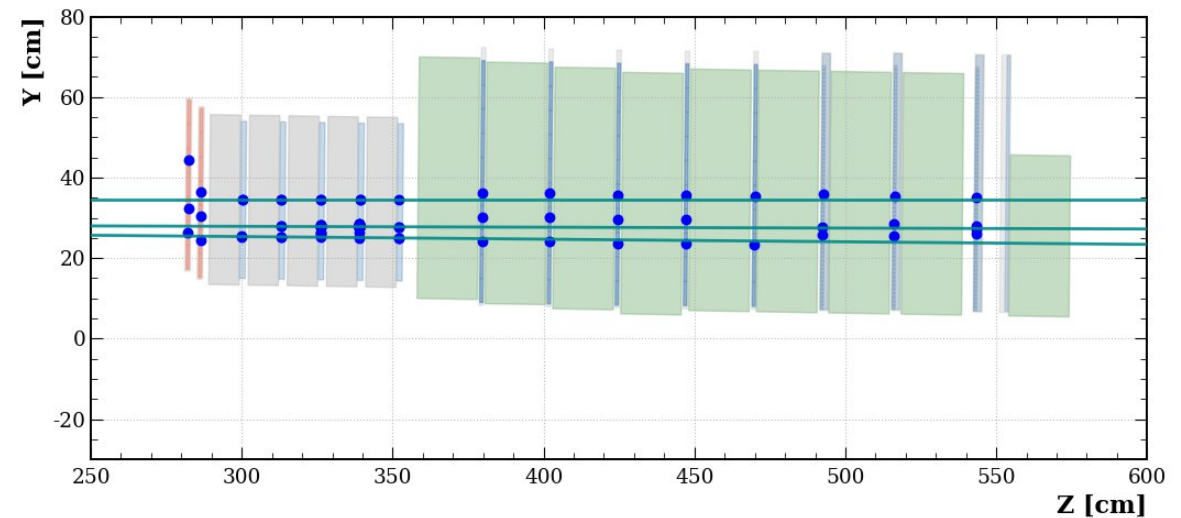
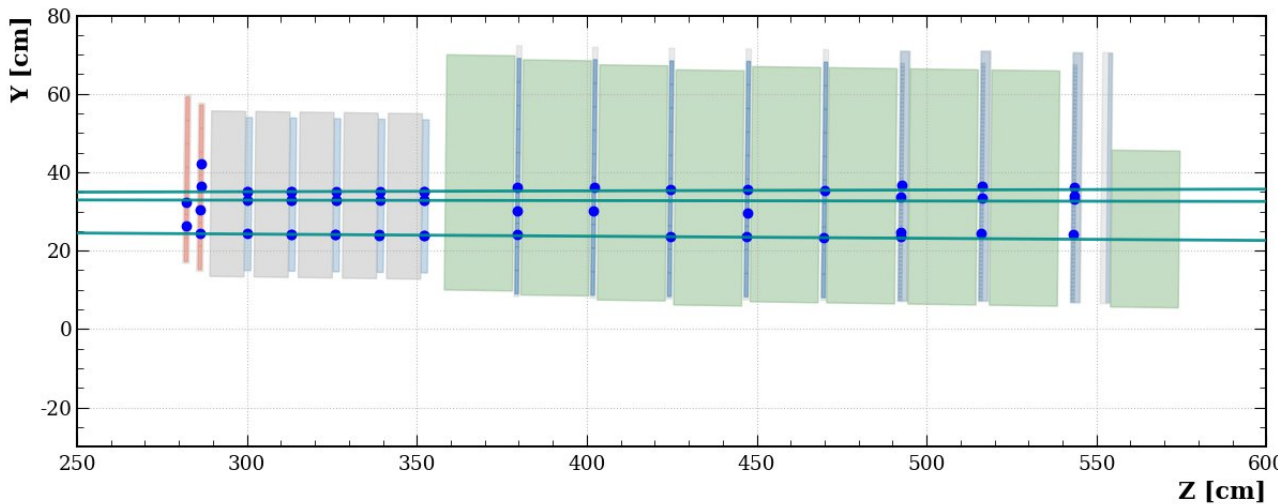


Изследват се несъответствия  
между данни и симлации

- Geant4 и MESMER

**Липса на измервания на този процес**

- Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) in 1971  
10.5-GeV muon beam impinging on a lead target (*Rev. Lett.*, vol. 26, no. 2, p. 2, 1971.)
- CosmoALEPH with cosmics in 2006  
*Phys. Rev. Lett.*, vol. 96, p. 021801, 2006



# Мюонно нееластично разсейване в емулсии

Preliminary

Дълбоко нееластични процеси на мюони с мишената.

Observed: **288 ± 17**

Expected: **341 ± 16**

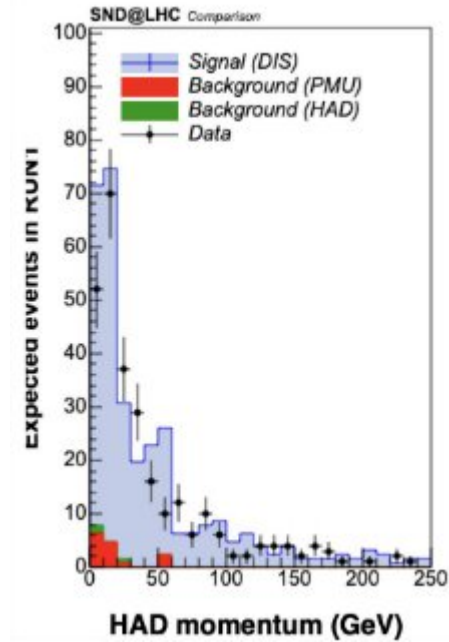
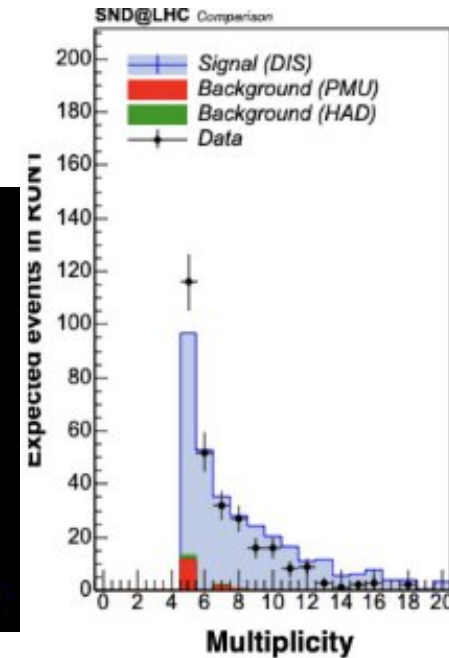
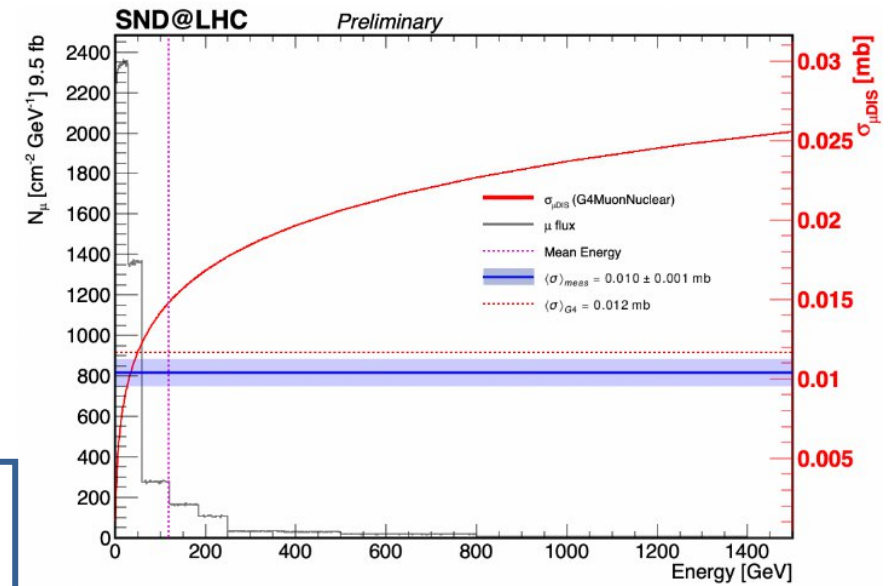
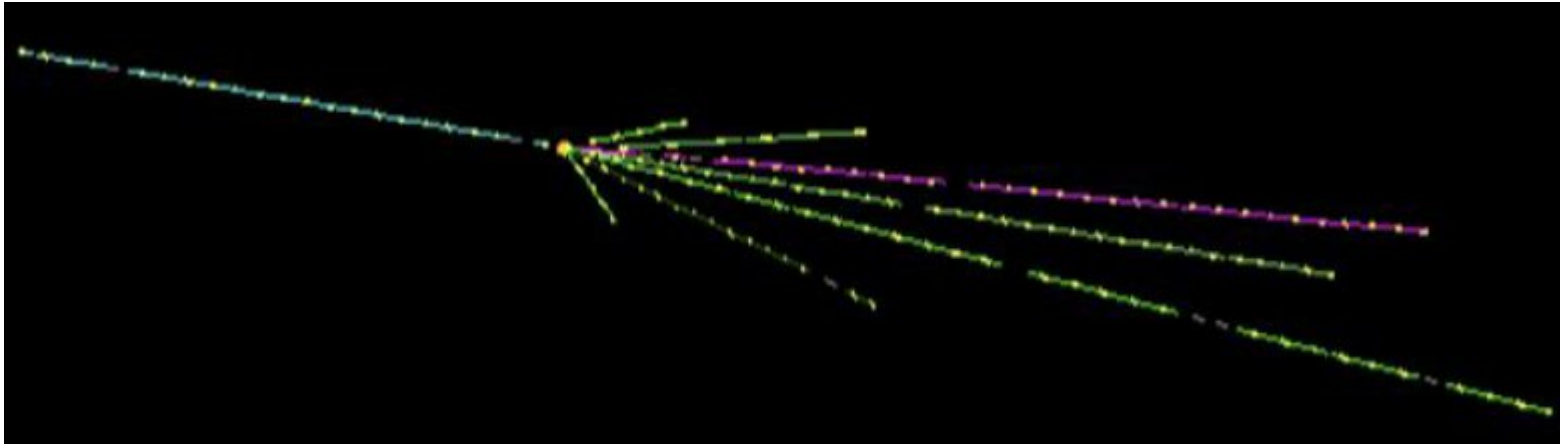
(Signal muonDIS 325 ± 16)

(Background had interact 2 ± 1)

(Background muon passing 14 ± 3)

$$\sigma(\mu_{DIS})^{meas} = (0.010 \pm 0.001) \text{ mb}$$

$$\sigma(\mu_{DIS})^{exp} = 0.012 \text{ mb}$$



# Отвъд Стандартния Модел (BSM)

*SND@LHC има чувствителност към нови, слабо взаимодействащи частици.*

- Големите експерименти нямат възможност да изследват леки и дългоживущи леки частици.
- В зависимост от времето им на живот, може да се търсят признаци за разсейване или разпад в обема на детектора.
- Експерименти за директно търсене на тъмна материя не ограничават фазовото пространство на лептофобна тъмна материя (свързва се с барионен разяд)

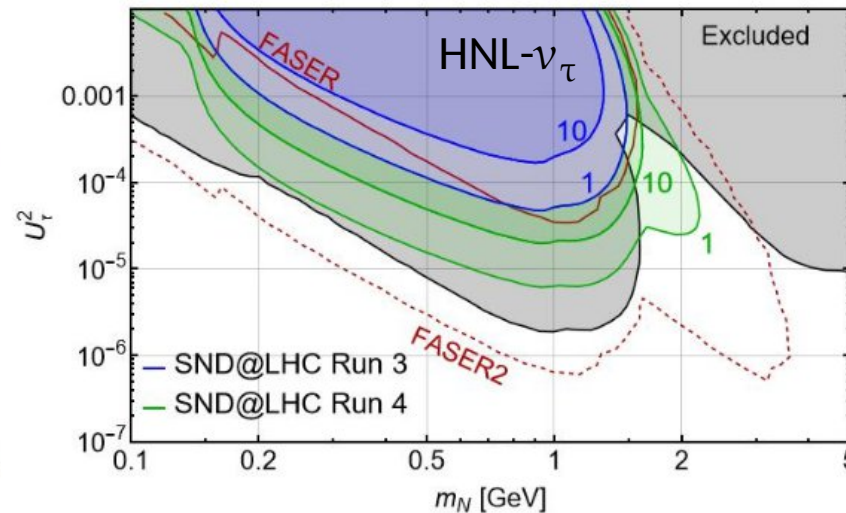
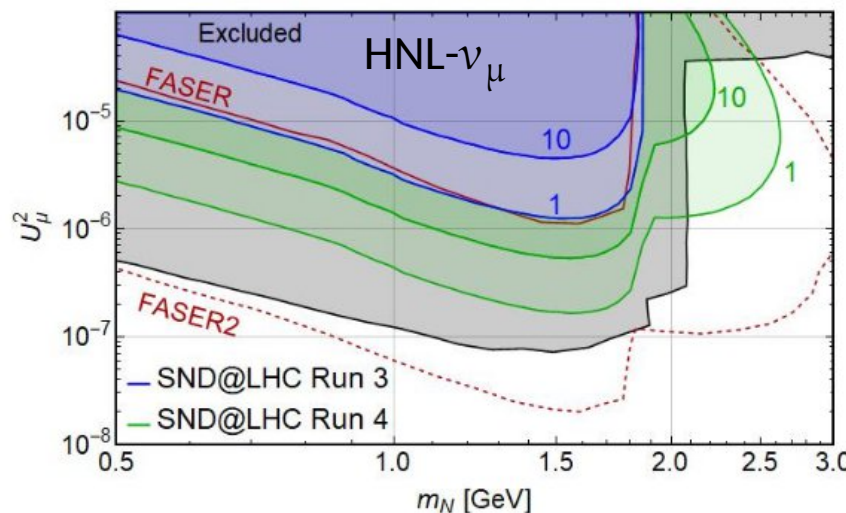
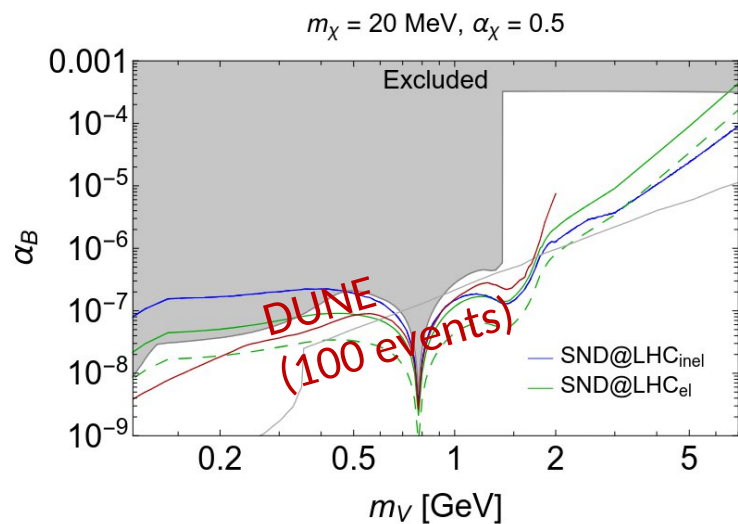
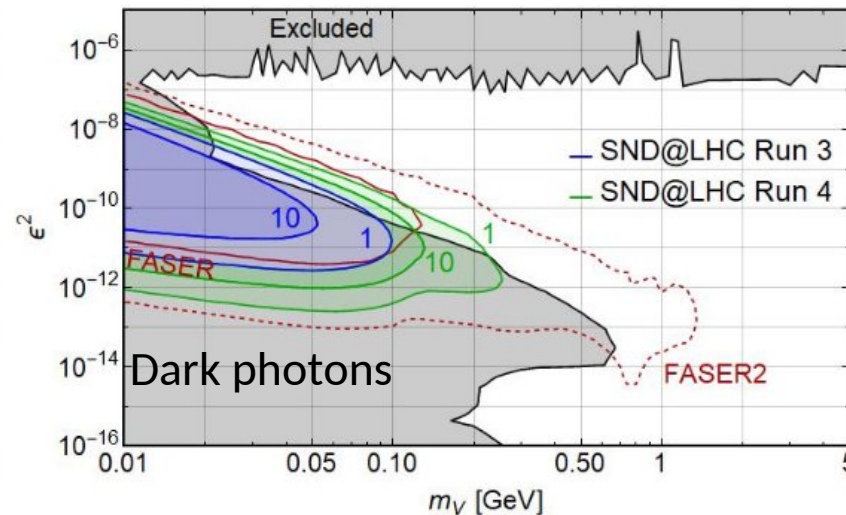
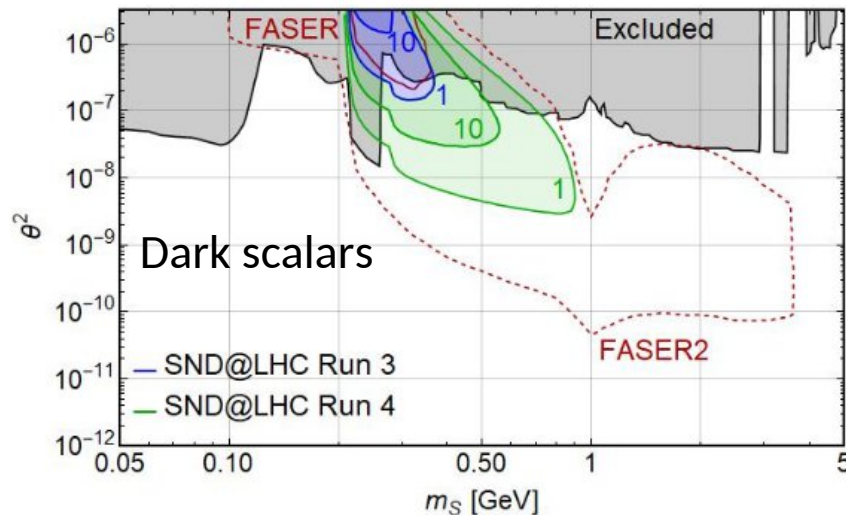
$$\mathcal{L}_{leptophobic} = -g_B V^\mu J_\mu^B + g_\chi V^\mu (\partial_\mu \chi^\dagger \chi - \chi^\dagger \partial_\mu \chi), \quad J_\mu^B = \frac{1}{3} \sum_q \bar{q} \gamma_\mu q$$

# Разпади на нови частици

Limited sensitivity by  
SND@LHC Run 3

Comparable to FASER

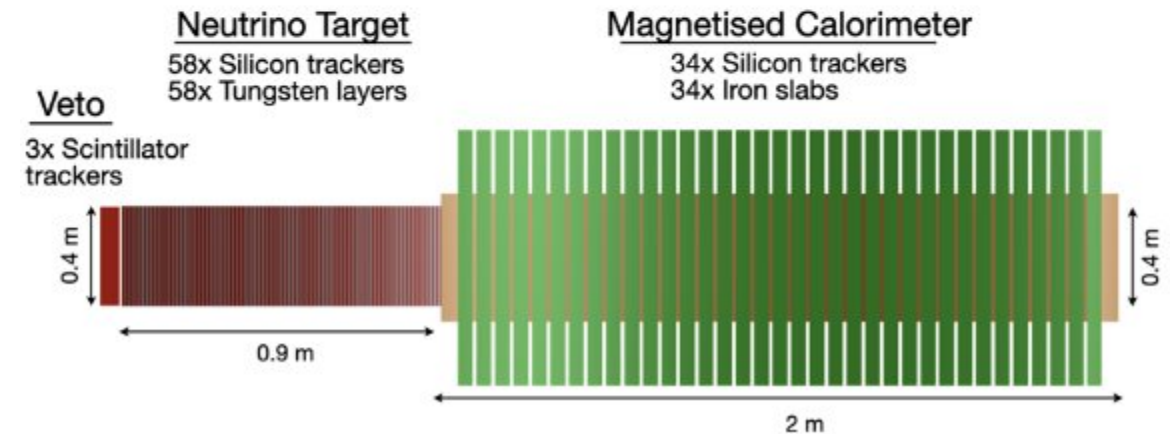
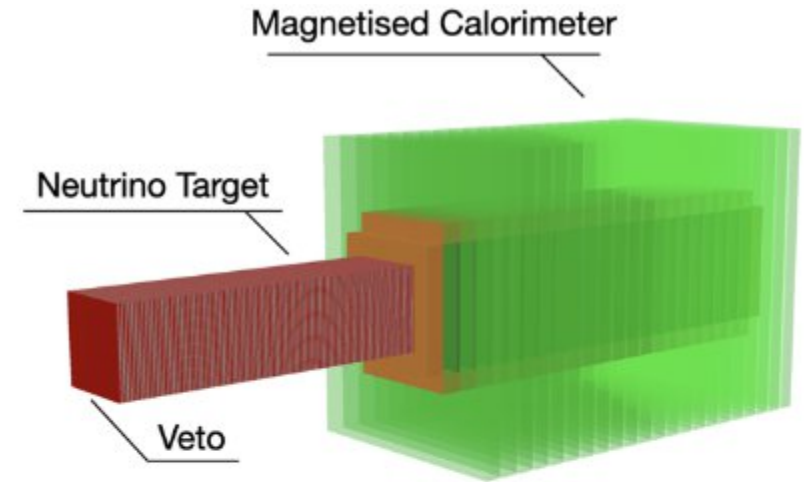
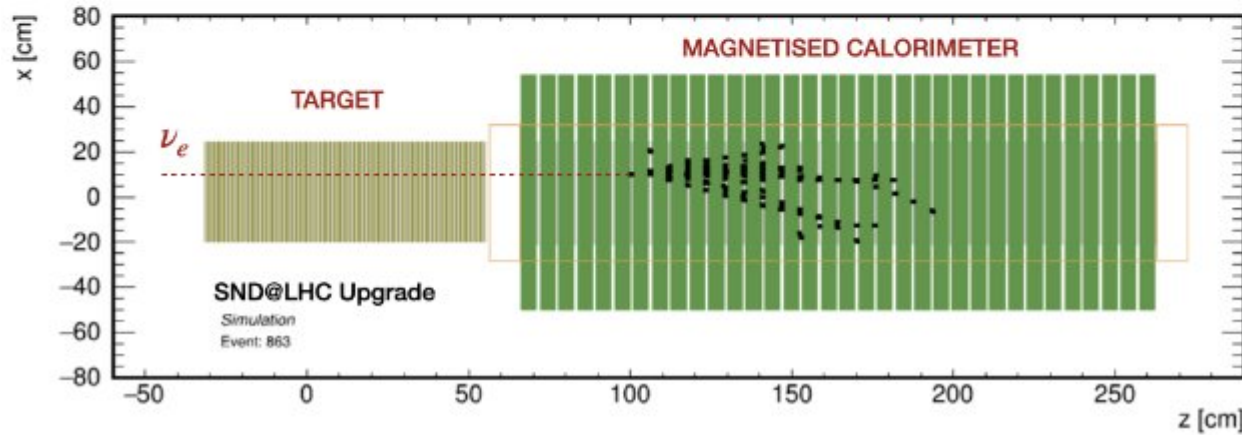
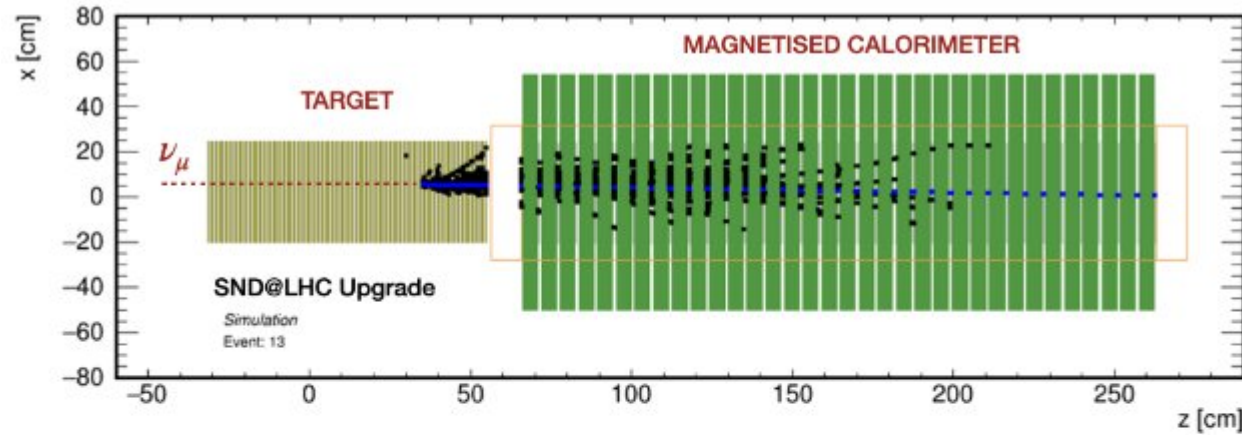
Promising parameter  
space exclusion from a  
Run 4 upgrade



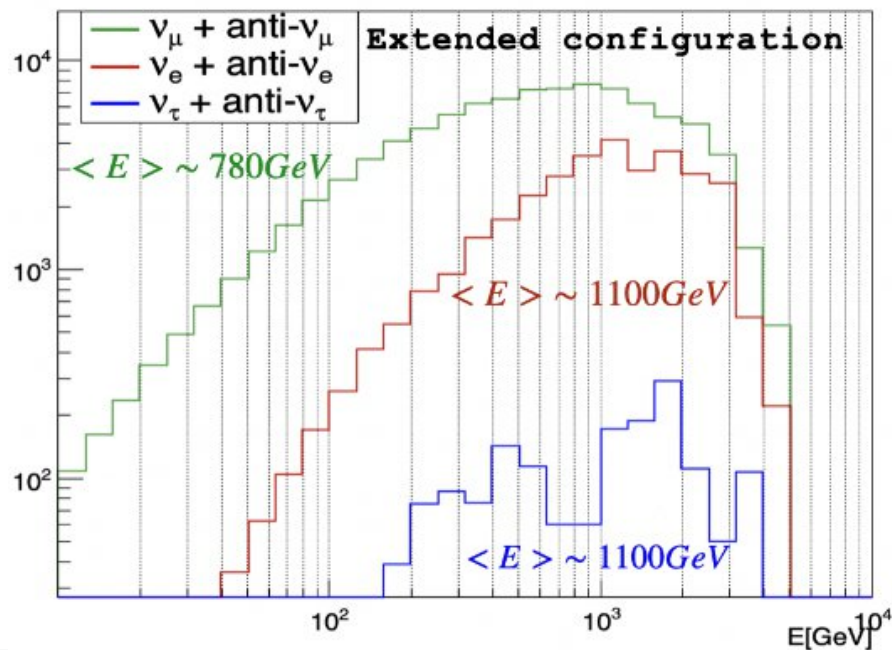
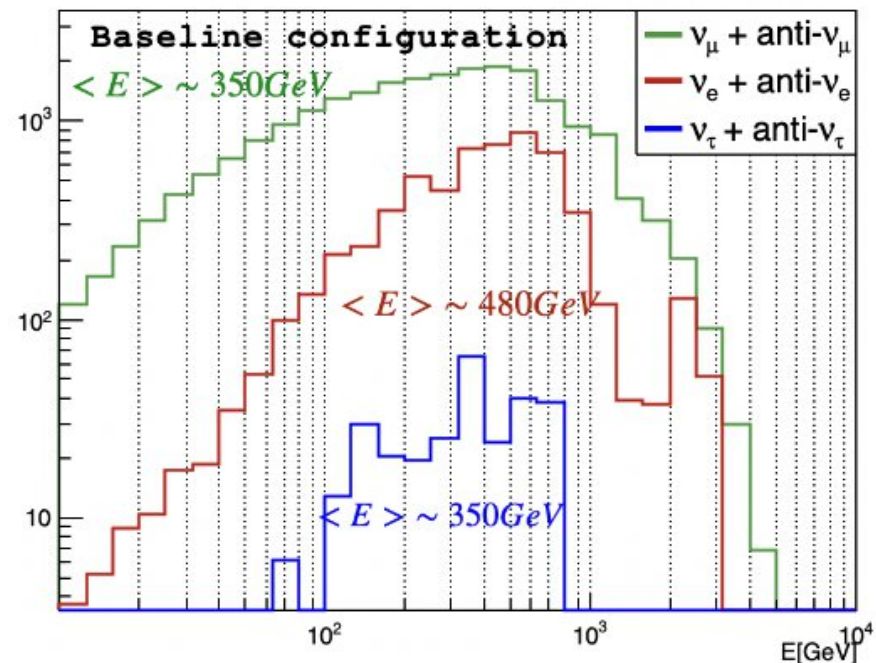
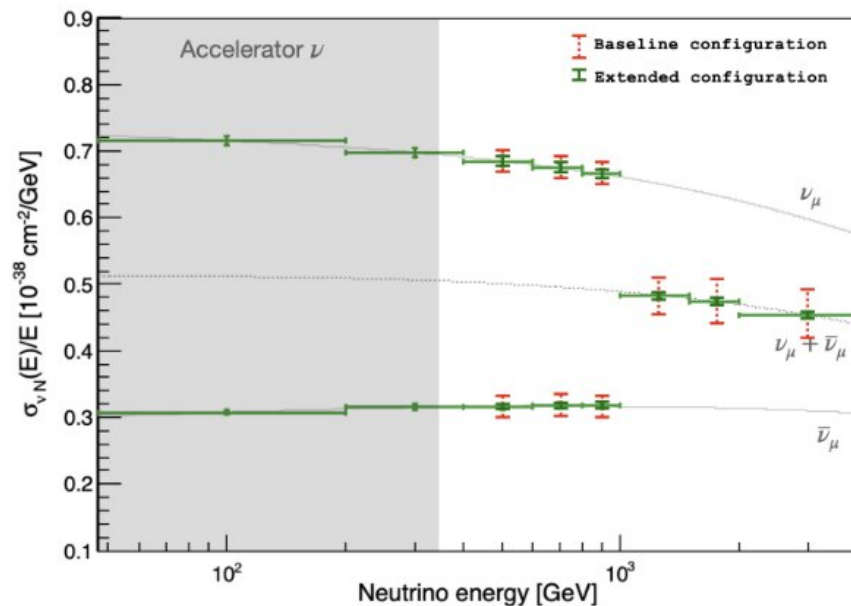
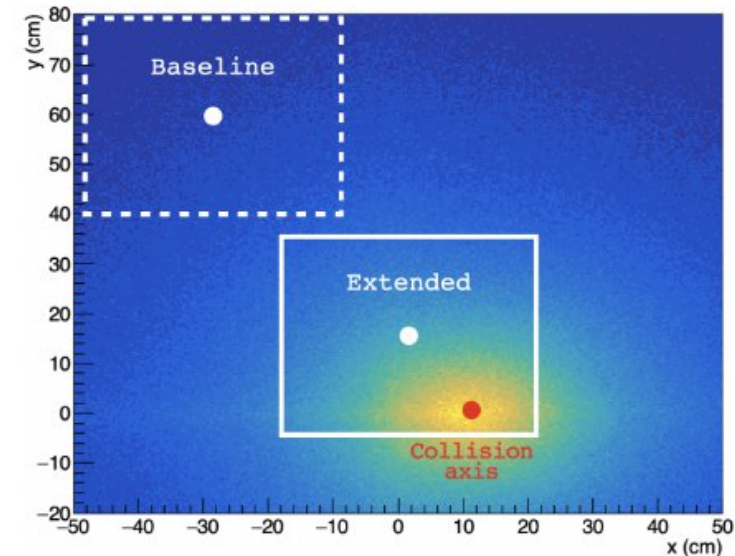
[2004.10996](https://arxiv.org/abs/2004.10996)

# SND@LHC Run 4 (HL-LHC)

[2602.21881 \(Submitted to EPJC\)](#)



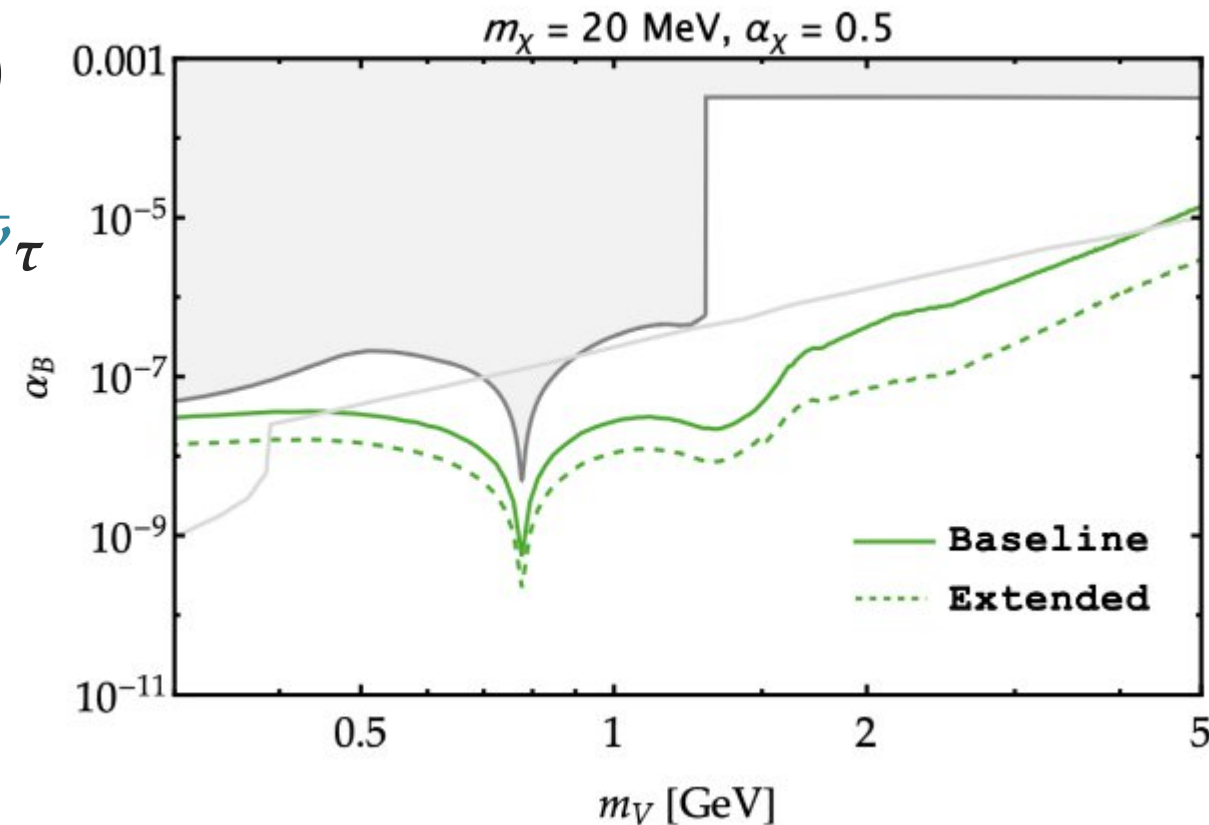
# SND@HL-LHC Конфигурации



Flavour	Baseline		Extended	
	Target	Target+HCAL	Target	Target+HCAL
$\nu_\mu$	$1.1 \times 10^4$	$1.7 \times 10^4$	$5.4 \times 10^4$	$7.5 \times 10^4$
$\bar{\nu}_\mu$	$3.6 \times 10^3$	$6.1 \times 10^3$	$1.7 \times 10^4$	$2.3 \times 10^4$
$\nu_e$	$1.7 \times 10^3$	$2.8 \times 10^3$	$7.3 \times 10^3$	$9.7 \times 10^3$
$\bar{\nu}_e$	$7.6 \times 10^2$	$1.2 \times 10^3$	$2.7 \times 10^3$	$4.4 \times 10^3$
$\nu_\tau$	$1.0 \times 10^2$	$1.7 \times 10^2$	$2.4 \times 10^2$	$3.4 \times 10^2$
$\bar{\nu}_\tau$	$5.0 \times 10^1$	$8.9 \times 10^1$	$1.2 \times 10^2$	$1.7 \times 10^2$
<b>Total</b>	<b><math>1.7 \times 10^4</math></b>	<b><math>2.7 \times 10^4</math></b>	<b><math>8.1 \times 10^4</math></b>	<b><math>1.1 \times 10^5</math></b>

# Възможности на SND@HL-LHC

- **Constraints on the gluon parton distribution function (gPDF) at large Bjorken-x**
  - От съществено значение за бъдещи ускорители като FCC
- **Lepton flavour universality (LFU)**
  - с точност от 3% (6%) за baseline (extended) конфигурация (вместо 30% за Run 3 SND)
- **Първото експериментално наблюдение на  $\bar{\nu}_\tau$** 
  - 120 (50) събития с baseline (extended)
- **Feebly Interacting Particles (FIPs)**



# Заключение

- **Неутрина** — Активно развитие с неутринните изследвания и първи измервания на сечения за взаимодействие.
- **Мюони** — Изверен мюонен поток и първи резултати за сечения за взаимодействие на muonDIS.
- **Отвъд Стандартен модел** — Потенциал за търсене на нови слабо взаимодействащи частици.
  - ✓  $\nu_\tau$  magnetic moment
  - ✓ *emulsion matching*
  - ✓ *momentum from multiple scattering*
  - ✓ *shower tagging* и др.
  - ✓  $\nu_e$  в емулсии
- **SND@HL-LHC (Run 4 Upgrade)**
  - Две различни възможни конфигурации.
  - Значително по-голям брой неутринни събития.
  - По-добра чувствителност към нови частици.

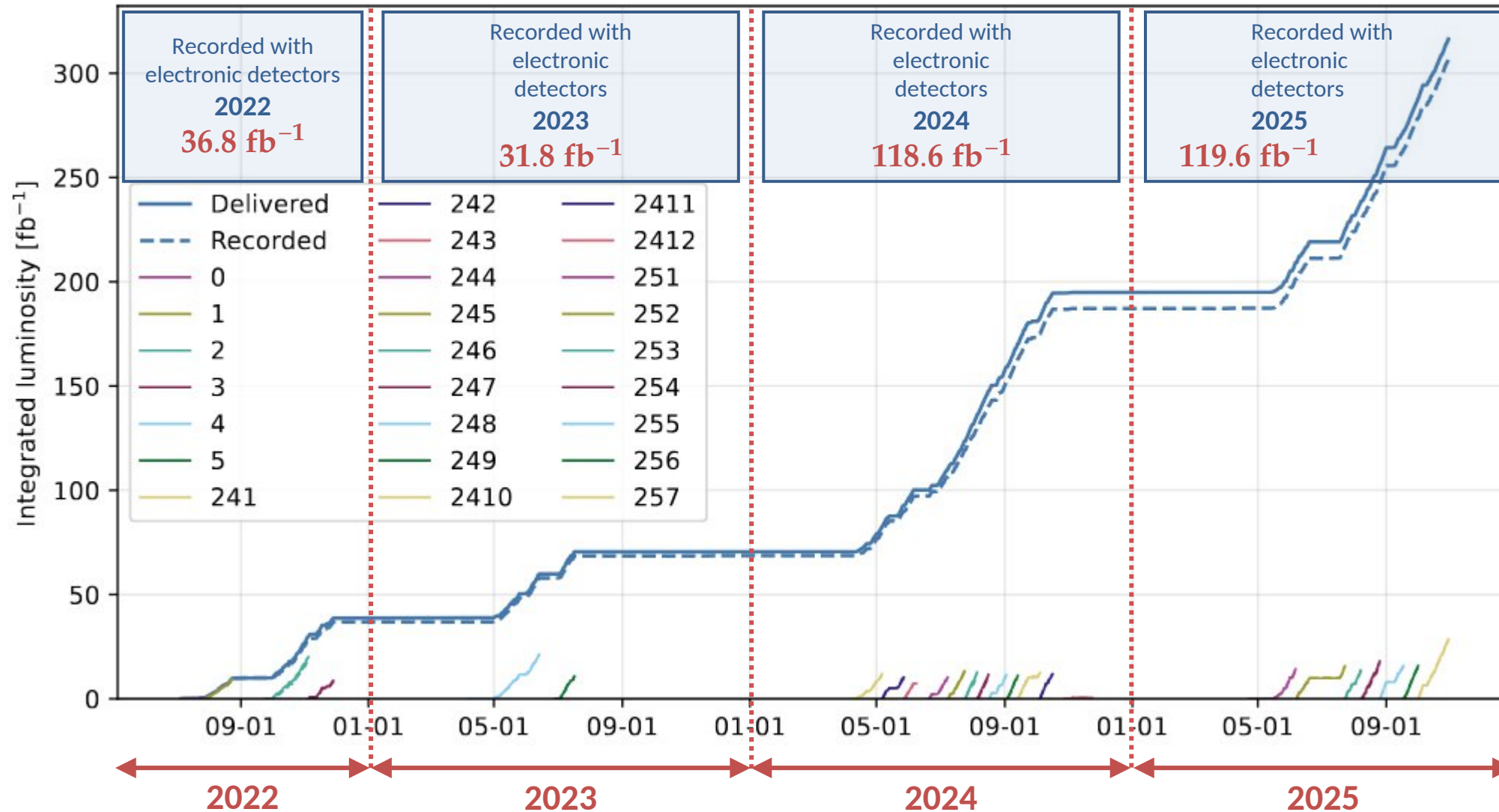


**Благодаря за вниманието!**



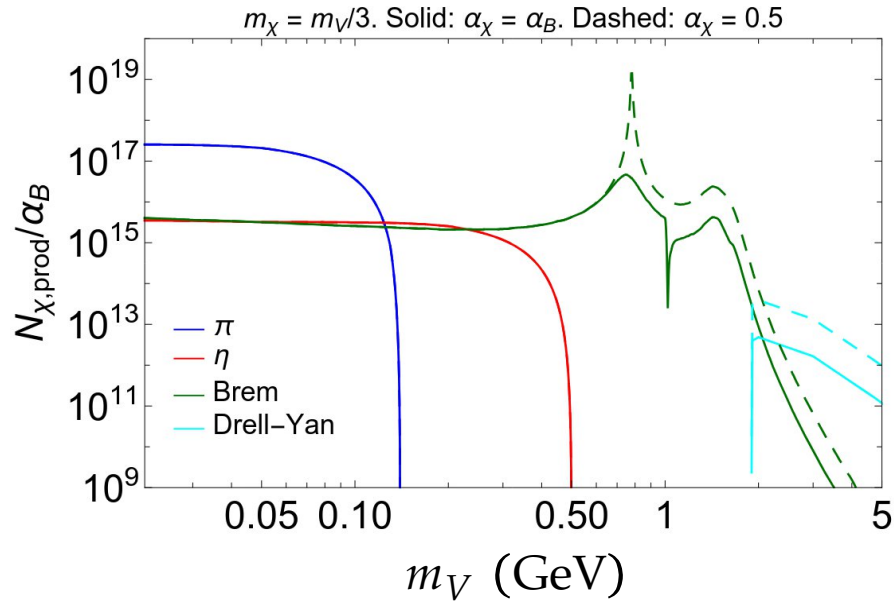
# Supplementary Slides

# Recorded Luminosity



# Leptophobic DM

## Production of $V$

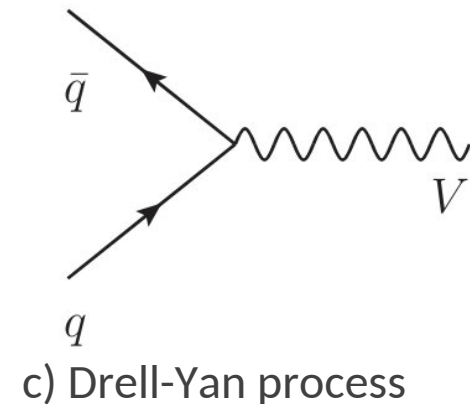
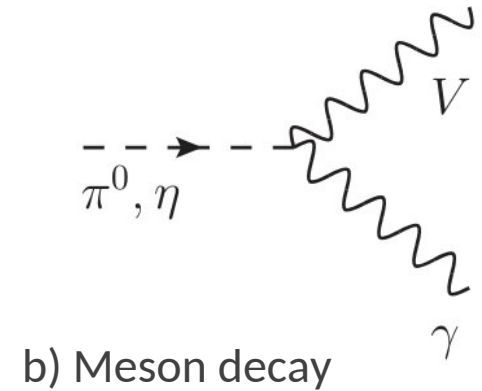
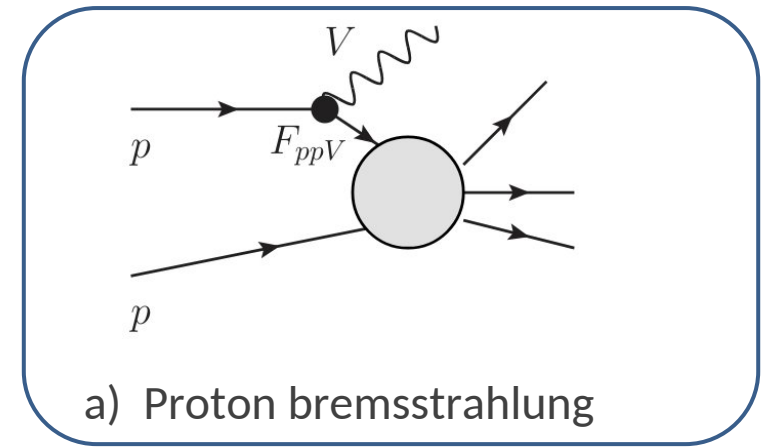


$$F_{ppV}(q^2) = \sum_{\omega} \frac{f_{\omega}/m_{\omega}^2}{m_{\omega}^2 - q^2 - im_{\omega}\Gamma_{\omega}}$$

**Resonance propagator** —  $F_{ppV}$  blows up when  $q^2 \approx m_{\omega}^2$

**Omega-like states**

$\omega(782)$ ,  
 $\omega(1420)$ ,  
 $\omega(1680)$ .

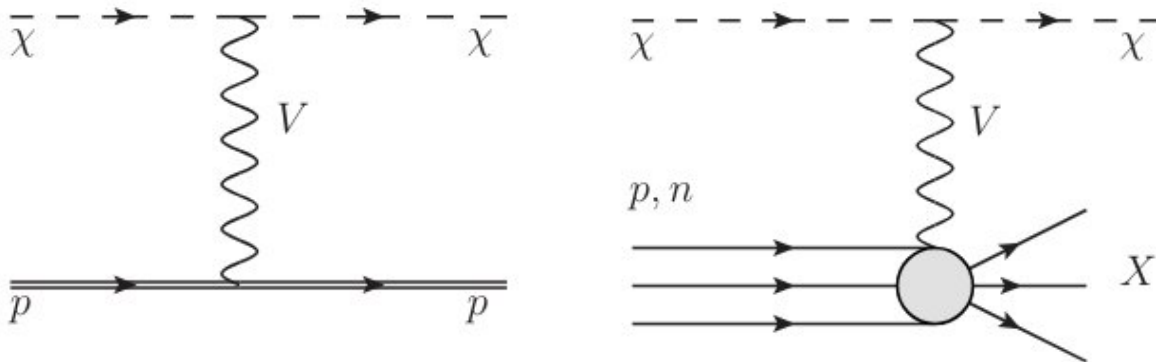


# Scattering Signatures

## 1) Elastic/inelastic ratio

- The ratio  $N_{el}/N_{inel}$  is different from that of NC neutrino interactions.
- Both decreases with the growth of the mass of the mediator  $m_V$ .
- Proton form factor — enhancement of low- $Q^2$  interactions  
 $Q^2 \lesssim r_p^{-2} \sim 1 \text{ GeV}^2$

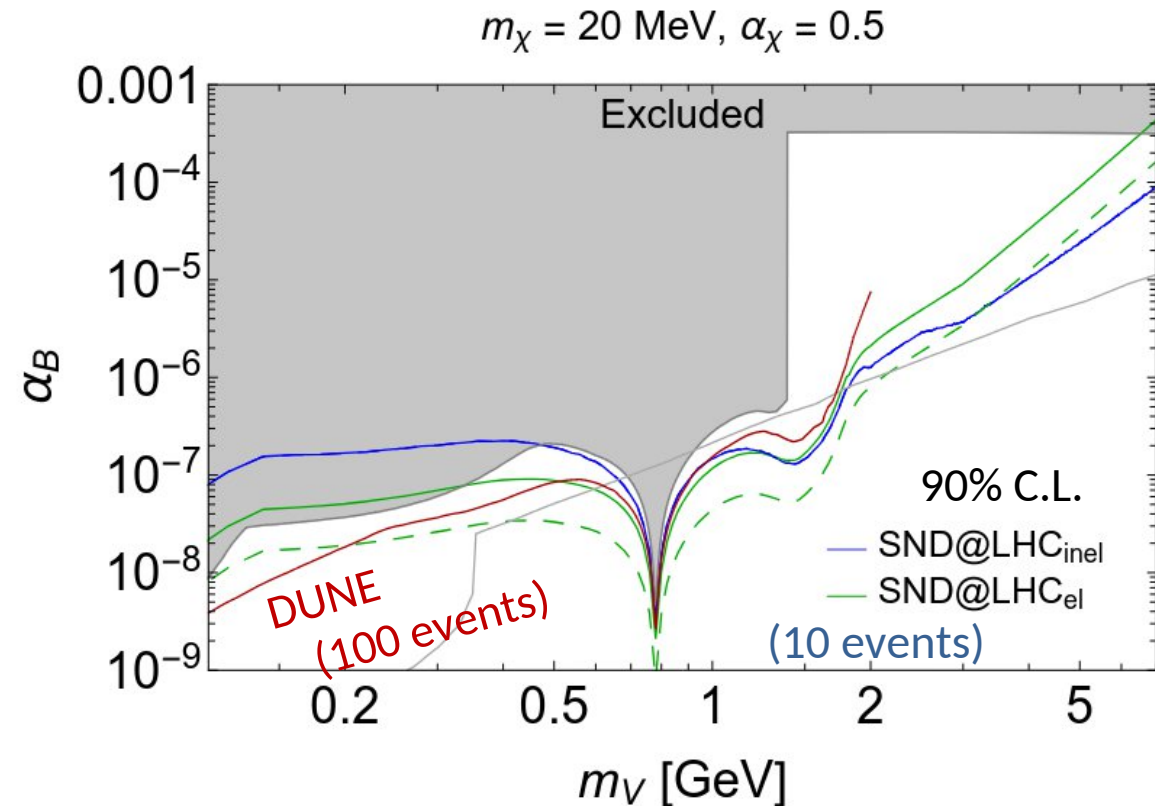
$$F_{ppV}(q^2) = \sum_{\omega} \frac{f_{\omega}/m_{\omega}^2}{m_{\omega}^2 - q^2 - im_{\omega}\Gamma_{\omega}}$$



## Elastic vs Inelastic interactions

### Elastic

- *Knockout proton starts a shower* — Low- $Q^2$  transfer, shower fully contained,
- *$\nu$ DIS* — High- $Q^2$  transfer, larger energy deposit, shower spill into multiple layers

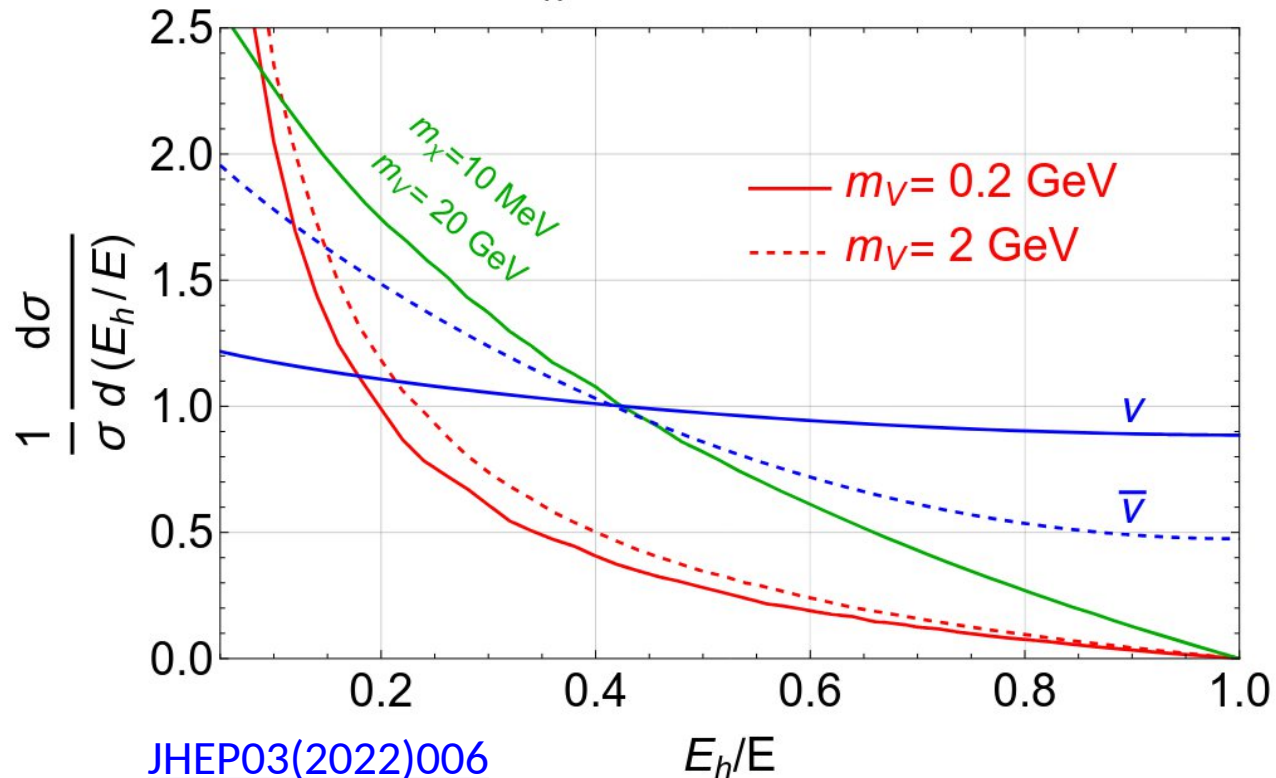


# Scattering Signatures

## 2) NC/CC ratio

- Uniquely determined for neutrinos to be 1/3
- Kinematics and topology

$$m_\chi = m_\nu/3, E = 1 \text{ TeV}$$



## Main challenge

*Neutrino NC interactions can be very similar to LDM scattering*

- Shower without outgoing muon
- Knockout protons from elastic LDM interactions cannot be traced

## Key difference

*LDM scattering enhanced for low momentum transfer*

- Softer hadronic energy fraction

*Open question* — Perhaps a neural network can be trained to use energy deposit and shower properties to identify different types of neutrino and/or LDM interactions.

# Probability of Scattering vs Decay

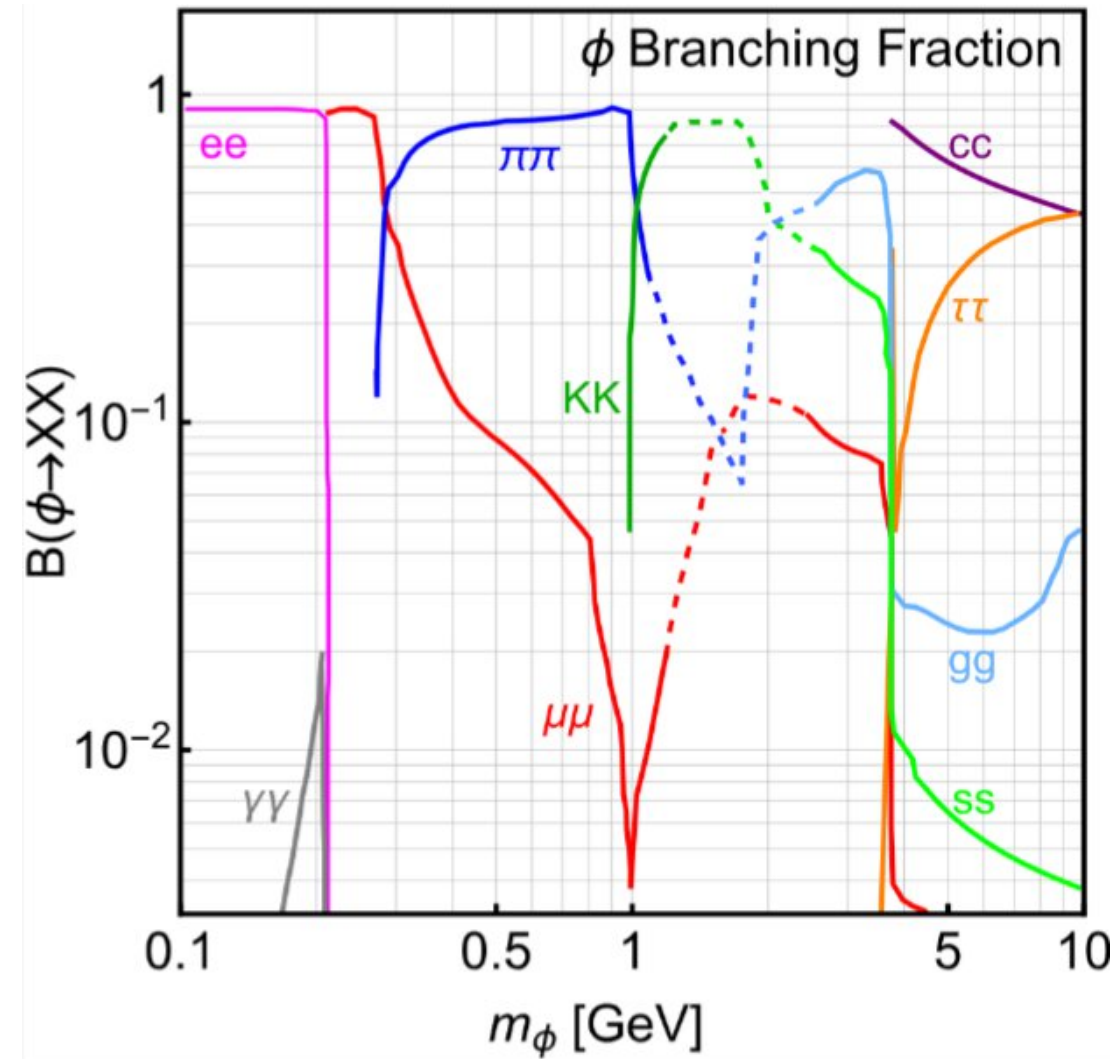
$$\frac{P_{\text{scat}}}{P_{\text{dec}}} \sim \gamma \alpha_{S\chi\chi} y_N^2 \left( \frac{v}{m_S} \right)^2 \frac{n_{\text{atom}}}{m_S m_N E_\chi} \text{ (scalar)}, \quad \frac{P_{\text{scat}}}{P_{\text{dec}}} \sim \gamma \alpha_D \frac{n_{\text{atom}}}{m_V^3} \text{ (vector)}$$

- Decay width — favors large coupling, but large  $m_\chi$
- Scattering rate — favors large coupling, small  $m_\chi$

# Dark Higgs

$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin \theta \frac{m_f}{v} \phi \bar{f} f - \lambda v h \phi \phi + \dots$$

- Dark Higgs  $\phi$  (mass  $m_\phi$ )
- SM Higgs  $h$  with vacuum expectation value  $v$
- Mixing angle  $\theta$
- Trilinear coupling ( $\lambda$ ) to SM Higgs



[Phys. Rev. D 97, 055034](#)

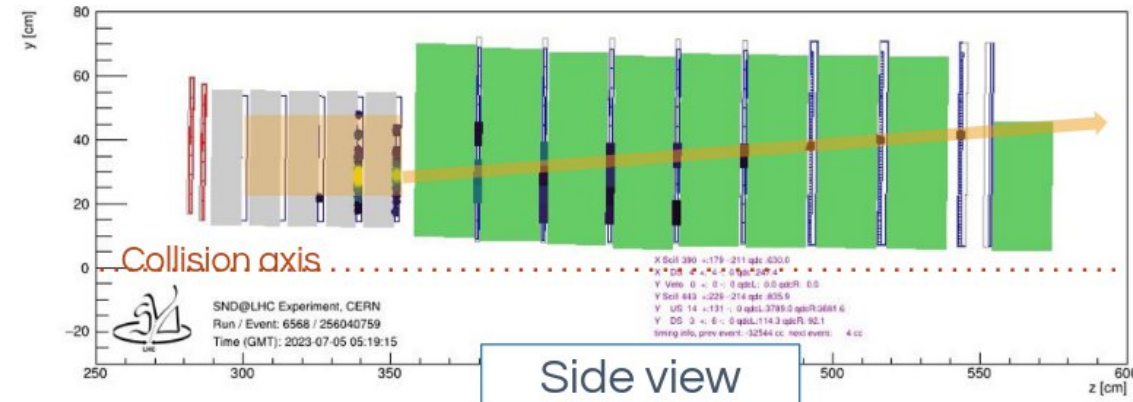
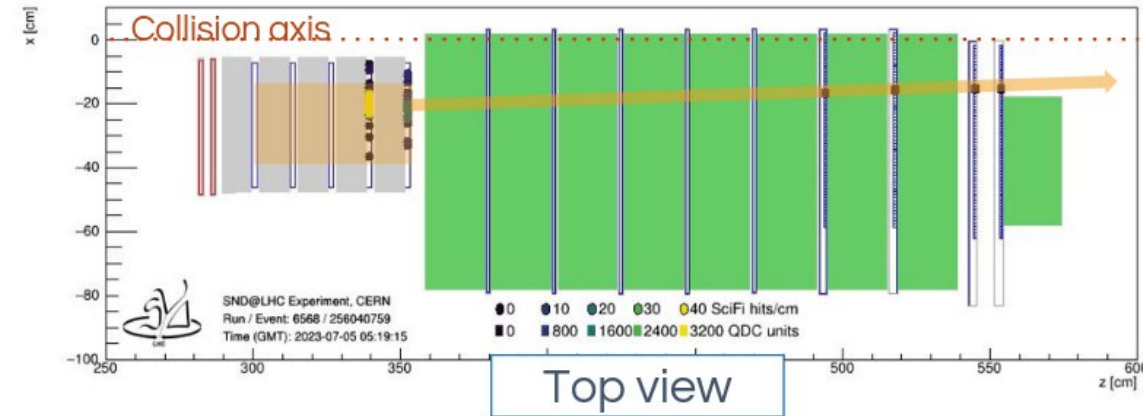
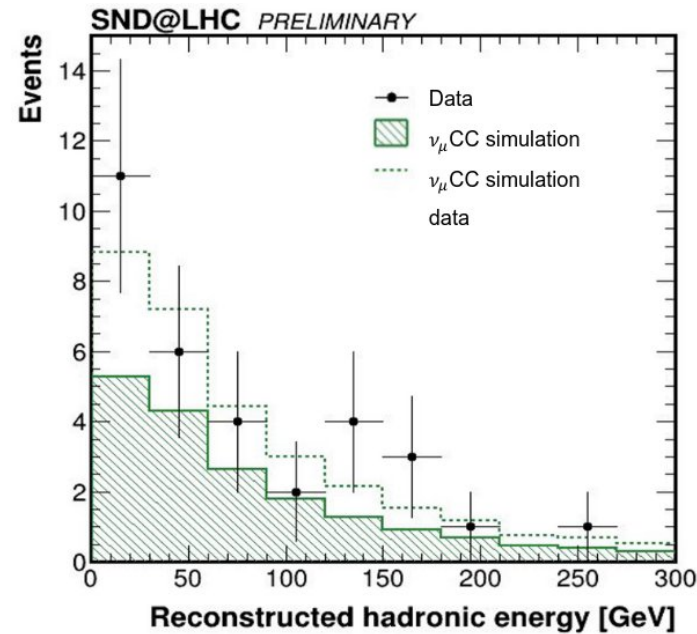
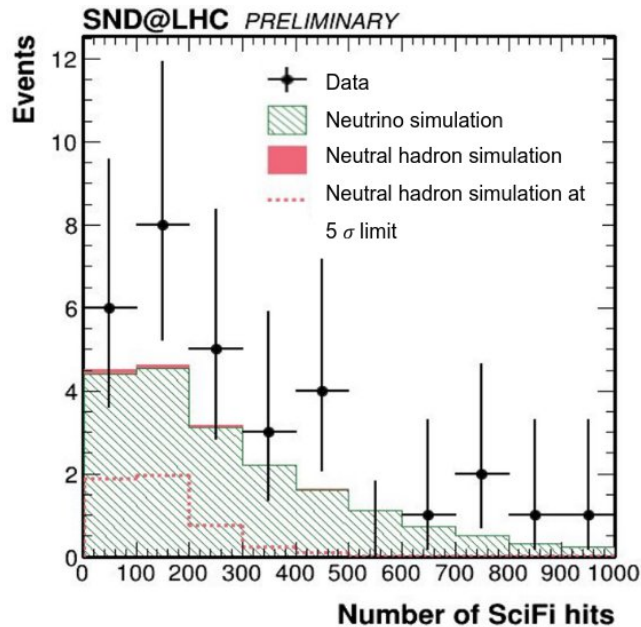
# $\nu_\mu$ Observation

Expected in  $68.6 \text{ fb}^{-1}$

- Signal:  $19.1 \pm 4.1$  (syst)
- Neutral hadrons:  $0.25 \pm 0.06$

**Observed:** 32 events

[Phys. Rev. Lett. 131, 031802](#)



# $0\nu\mu$ Observation

[Phys. Rev. Lett. 134, 231802](#)

- Expected signal: 7.2 events
- Expected background:  $0.32 \pm 0.06$
- 4.9  $\nu_e$  CC, 2.2 NC, 0.1  $\nu_\tau$  CC
- Expected significance:  $5.5\sigma$

✓ **Number of events observed: 9**

✓ **Observation significance:  $6.4\sigma$**

