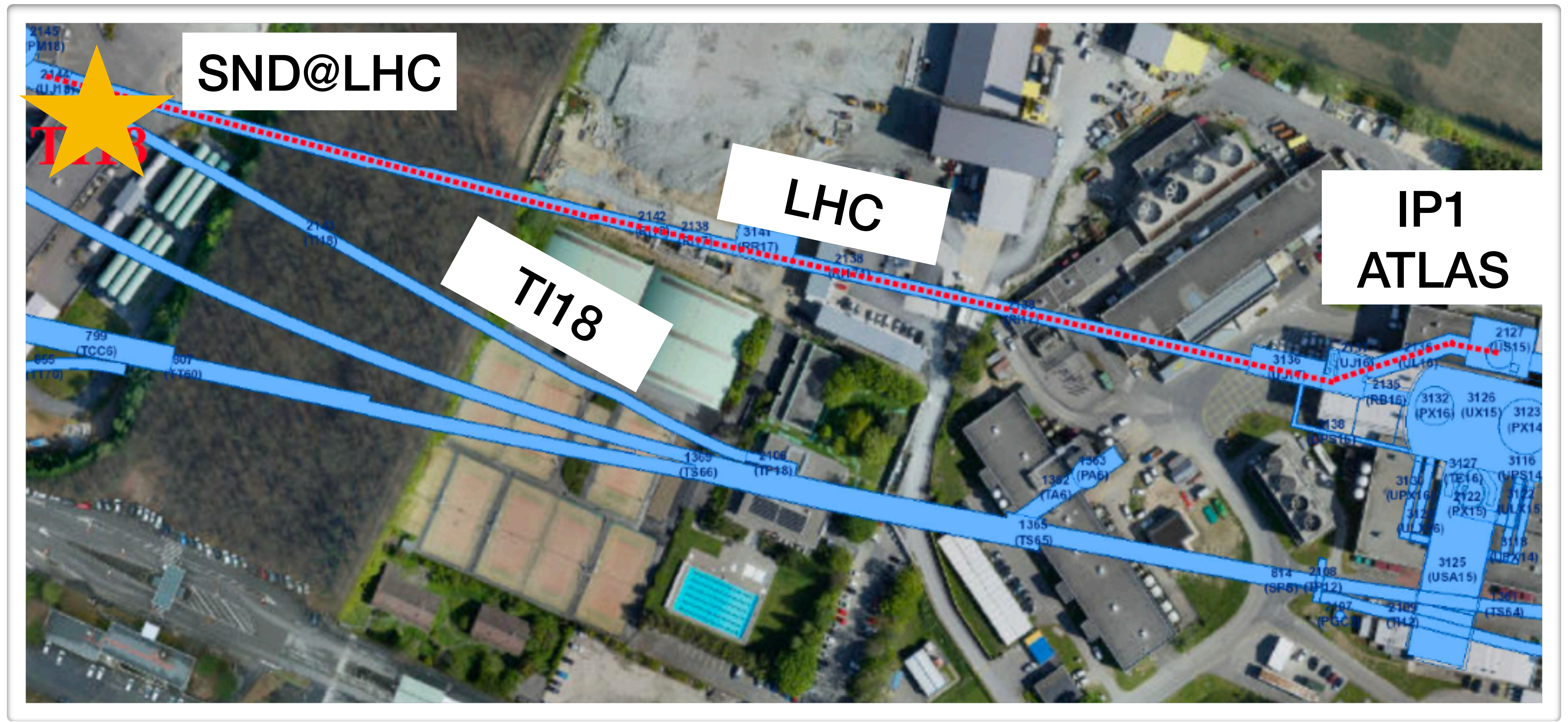
# SND@LHC UPGRADE TOWARDS HL-LHC

A. Di Crescenzo
*CERN, Università Federico II and INFN*

5th Forward Facility Meeting - 2022 November 16th

# LOCATION






- About 480 m away from the ATLAS IP
- Tunnel TI18: former service tunnel connecting SPS to LEP
- Symmetric to TI12 tunnel where FASER is located


*SND@LHC in the TI18 tunnel*

- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock
- Angular acceptance: 7.2<$\eta$< 8.4
- First phase: operation in Run 3

# THE SND@LHC CONCEPT

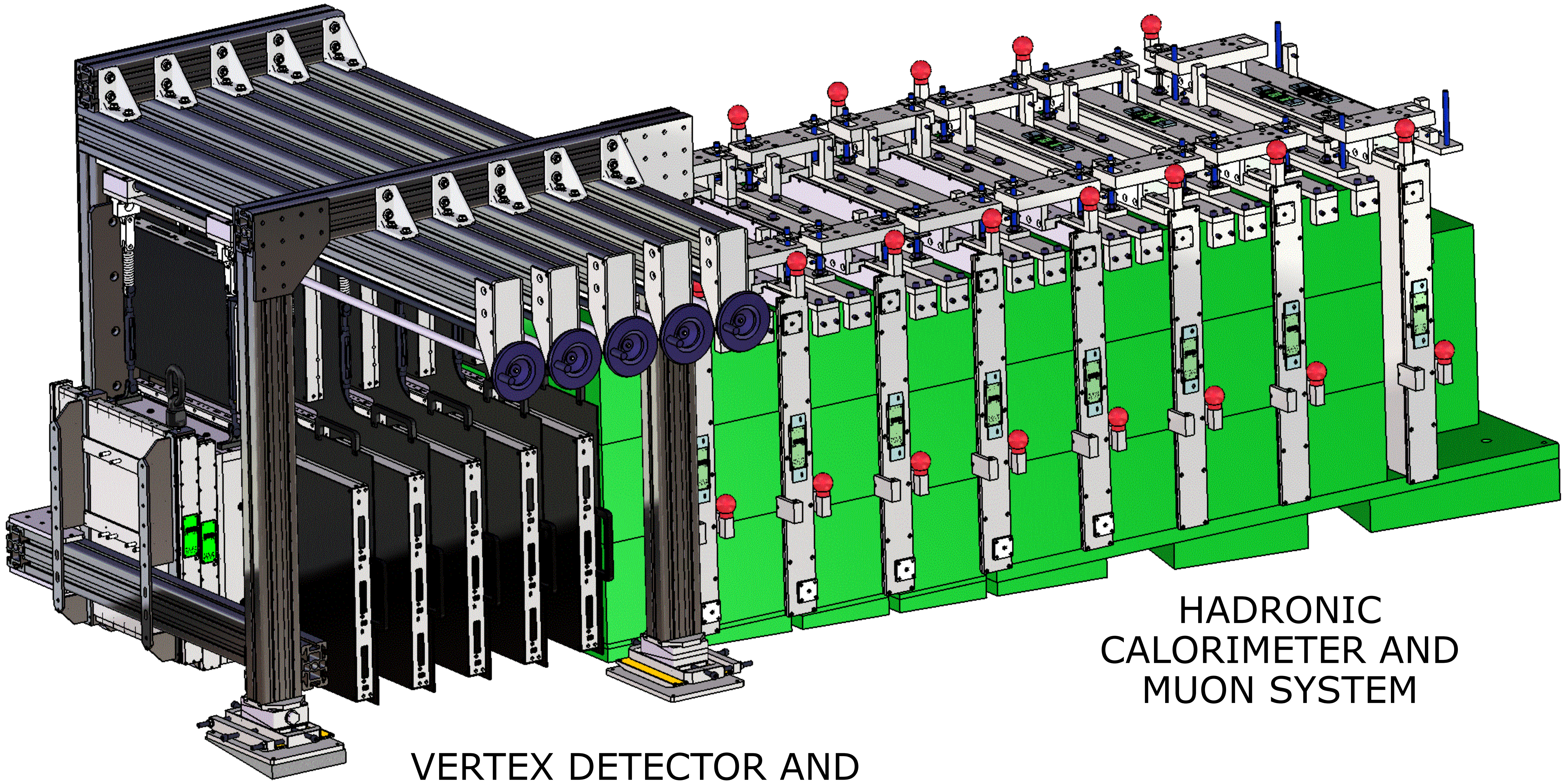
Hybrid detector optimised for the identification of three neutrino flavours and for the detection of feebly interacting particles

Angular acceptance: $7.2 < \eta < 8.6$
Target material: Tungsten
Target mass: 830 kg
Surface: 390x390 $mm^2$

VETO PLANE:
tag penetrating muons

TARGET REGION + ECAL:
- Emulsion cloud chambers (Emulsion+Tungsten) for neutrino interaction detection
- Scintillating fibers for timing information and energy measurement

MUON SYSTEM + HCAL:
iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement




Electromagnetic calorimeter
$\sim 40\ X_0$

Hadronic calorimeter
$\sim 10\ \lambda$

# PHYSICS PROGRAM IN RUN 3



**Physics with neutrinos:**

1. Measurement of the $pp \longrightarrow \nu_e X$ cross-section
2. Heavy flavour production in pp collisions
3. Lepton flavour universality in neutrino interactions
4. Measurement of the NC/CC ratio as consistency check

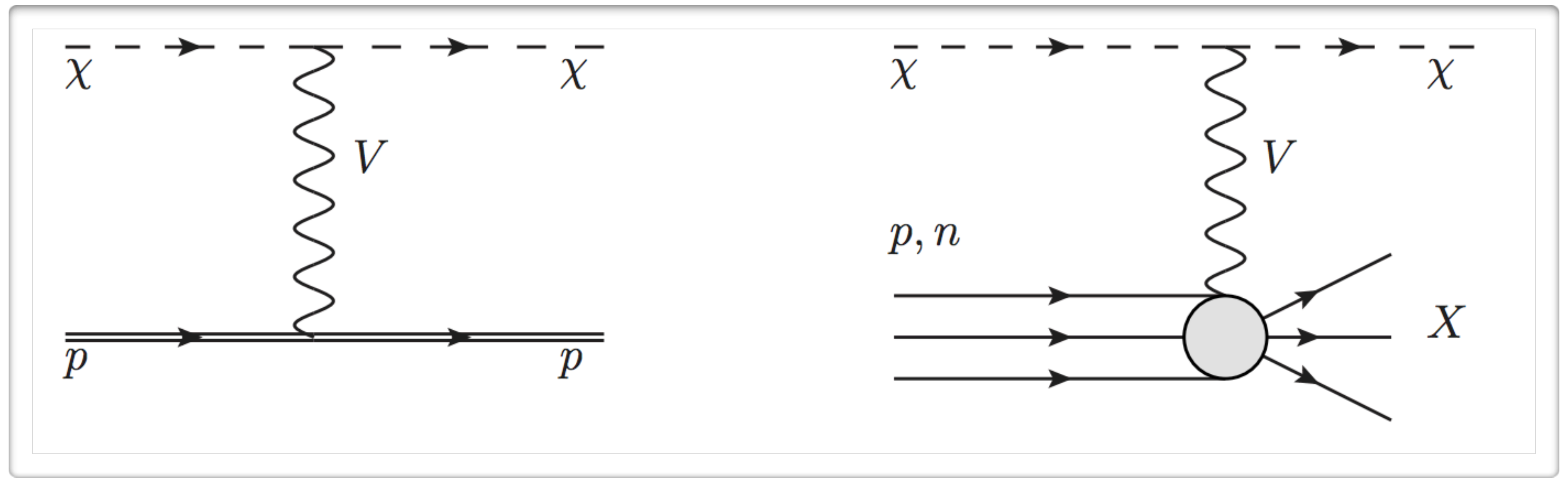
| Measurement | Uncertainty Stat. | Uncertainty Sys. |
|---|---|---|
| $pp \to \nu_e X$ cross-section | 5% | 15% |
| Charmed hadron yield | 5% | 35% |
| $\nu_e/\nu_\tau$ ratio for LFU test | 30% | 20% |
| $\nu_e/\nu_\mu$ ratio for LFU test | 10% | 10% |

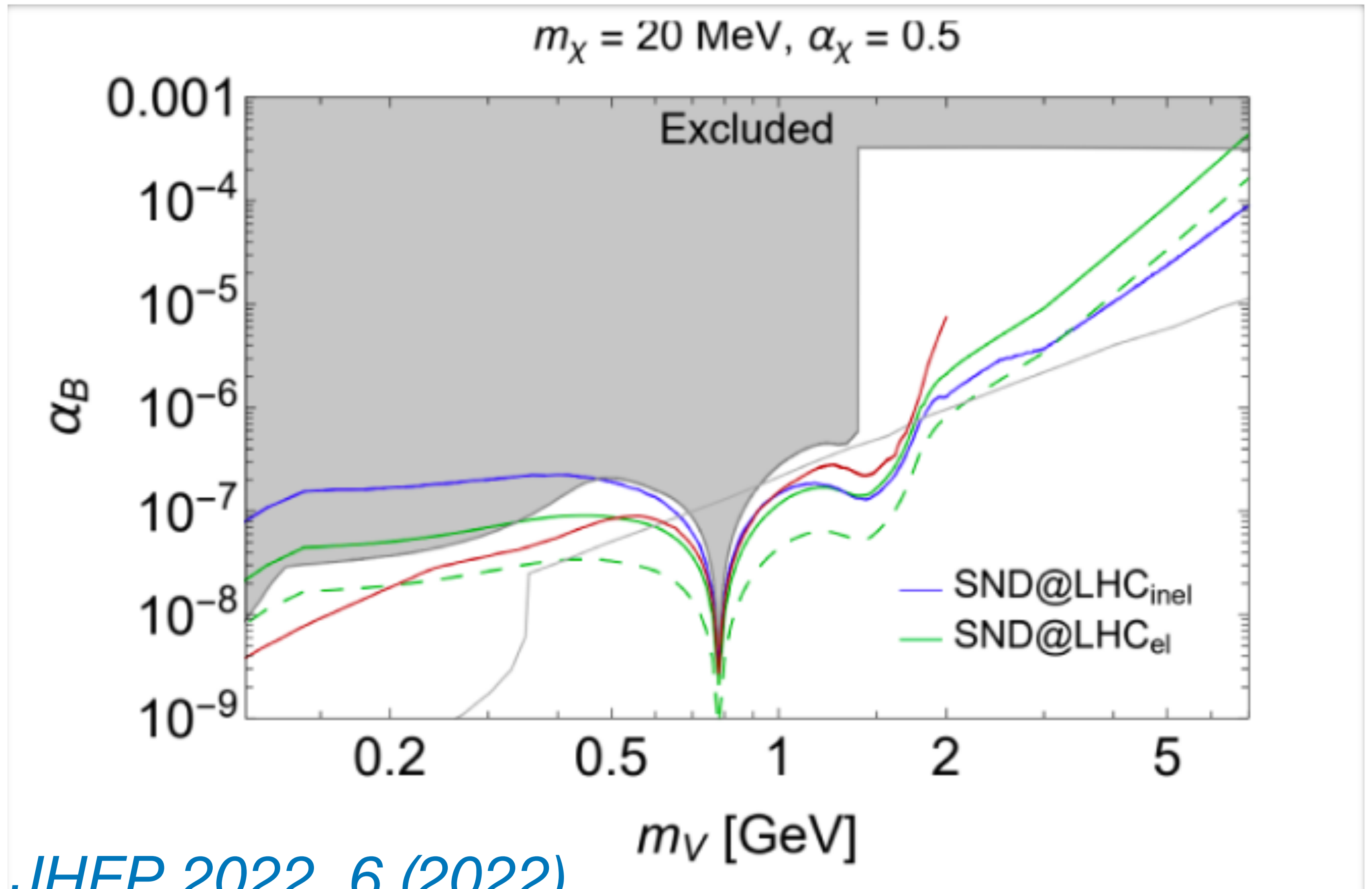
**Beyond Standard Model physics:**

Large variety of BSM scenarios describing Hidden Sector

**Production:** scalar $\chi$ particle coupled to the Standard Model via a leptophobic portal

**Detection:** $\chi$ elastic/inelastic scattering off nucleons of the target

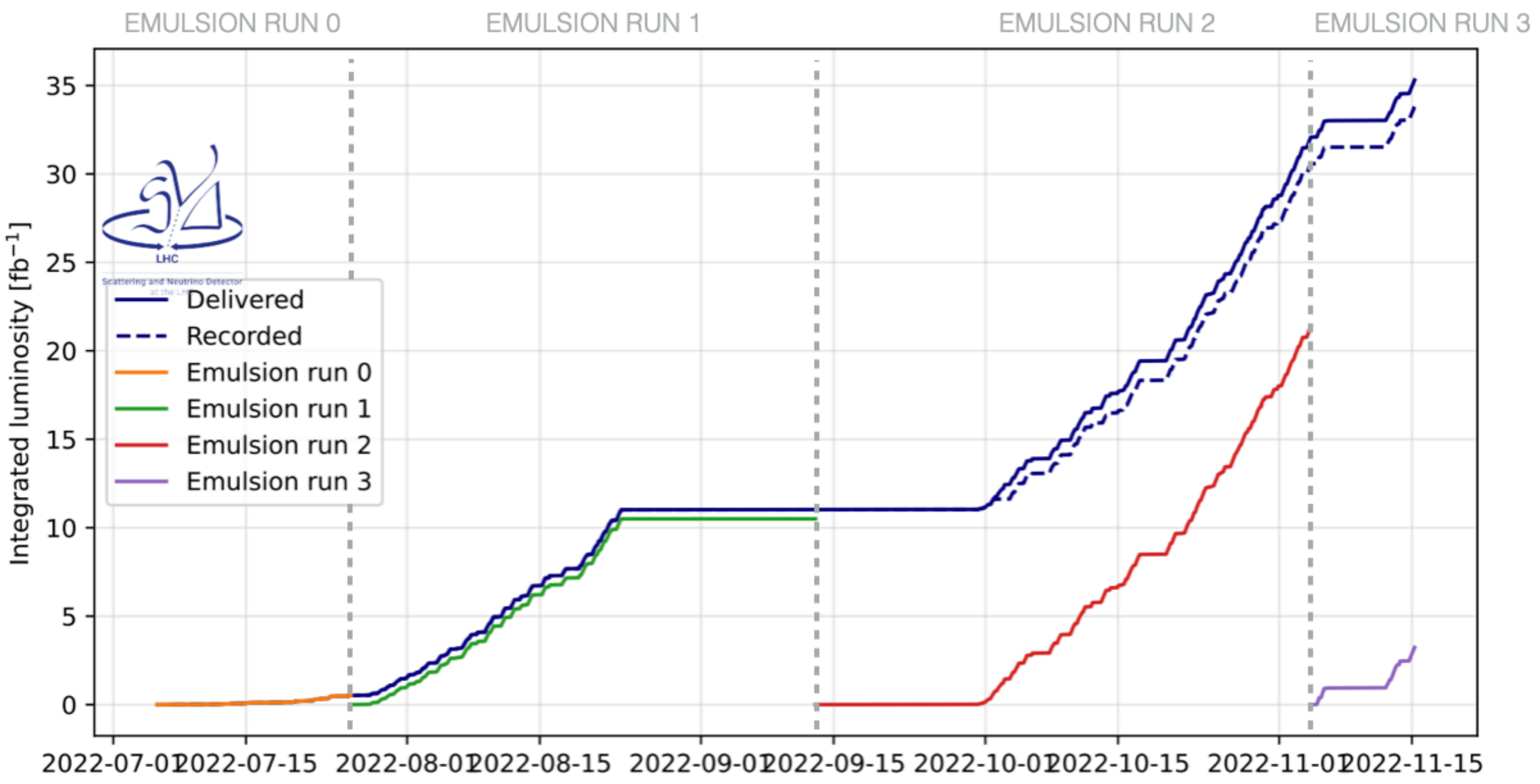


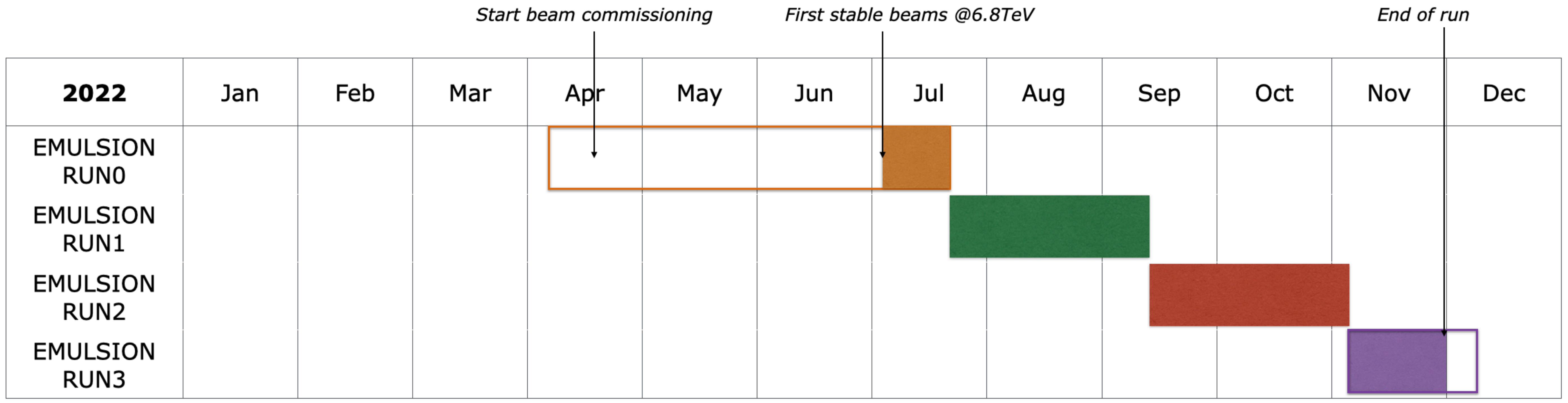




JHEP 2022, 6 (2022)

# RUN3 DATA TAKING

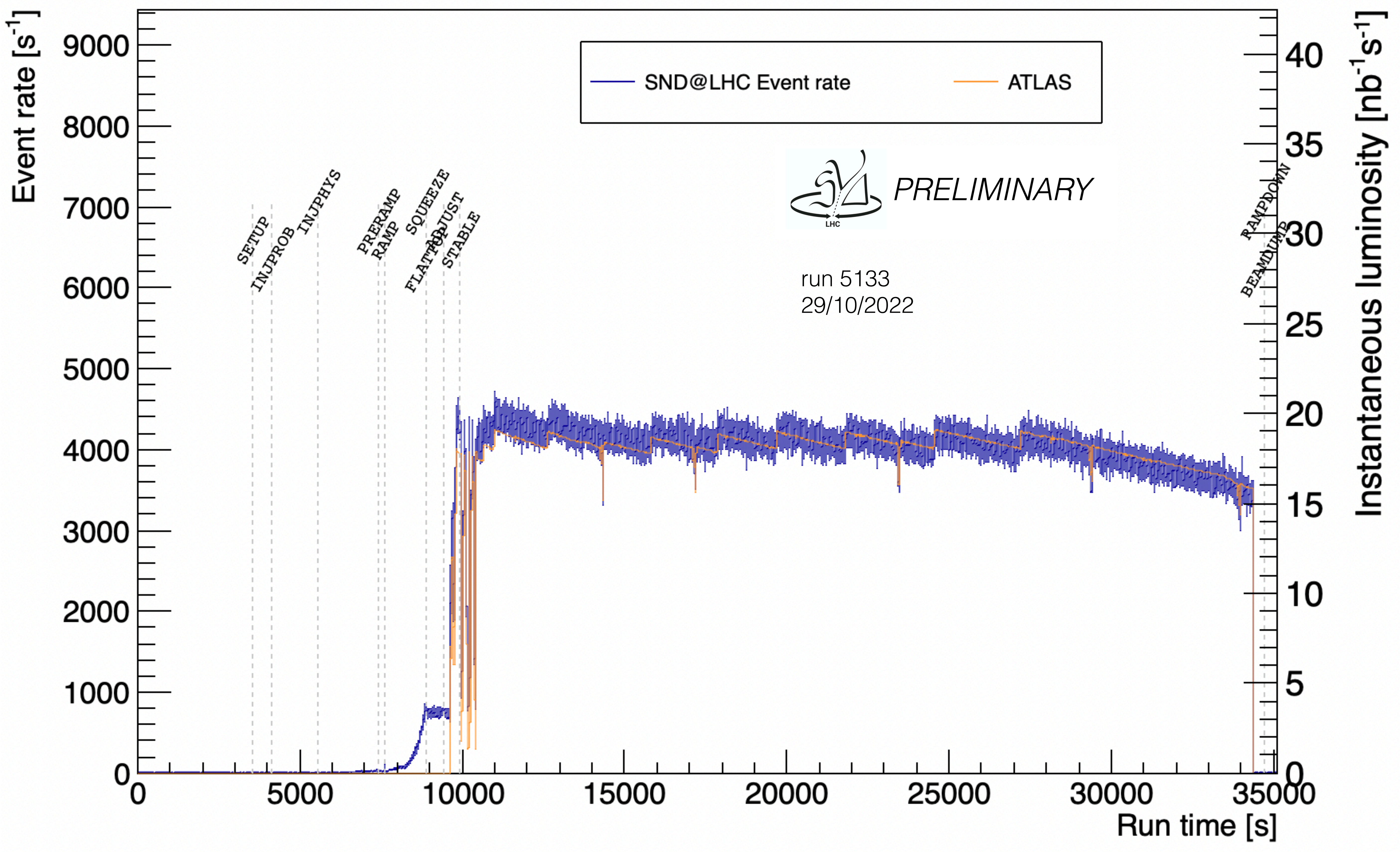


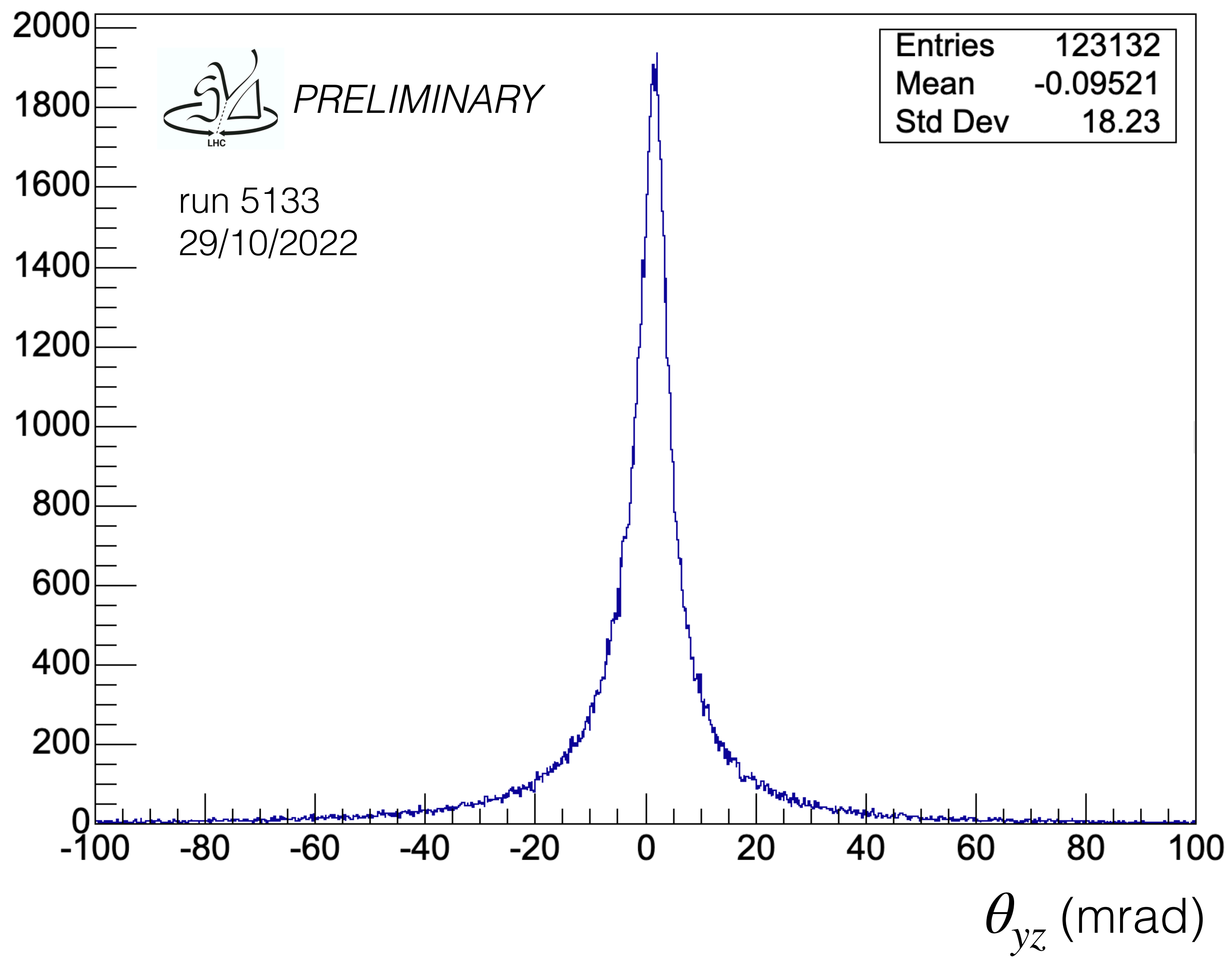


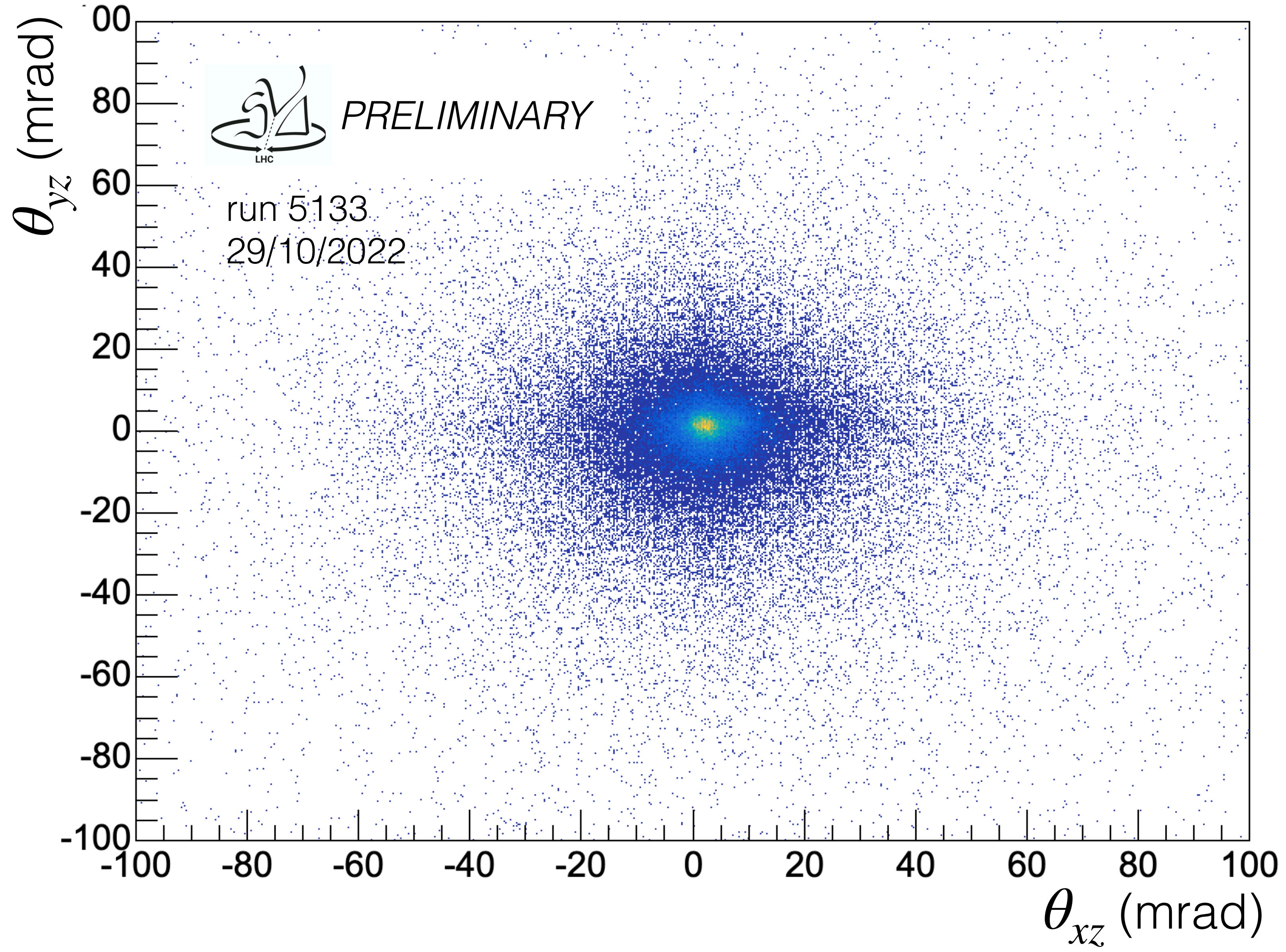




| INTEGRATED LUMINOSITY |
|---|
| 0.5 fb$^{-1}$ |
| 10.5 fb$^{-1}$ |
| 21.4 fb$^{-1}$ |
| running |

# RUN3 DATA TAKING

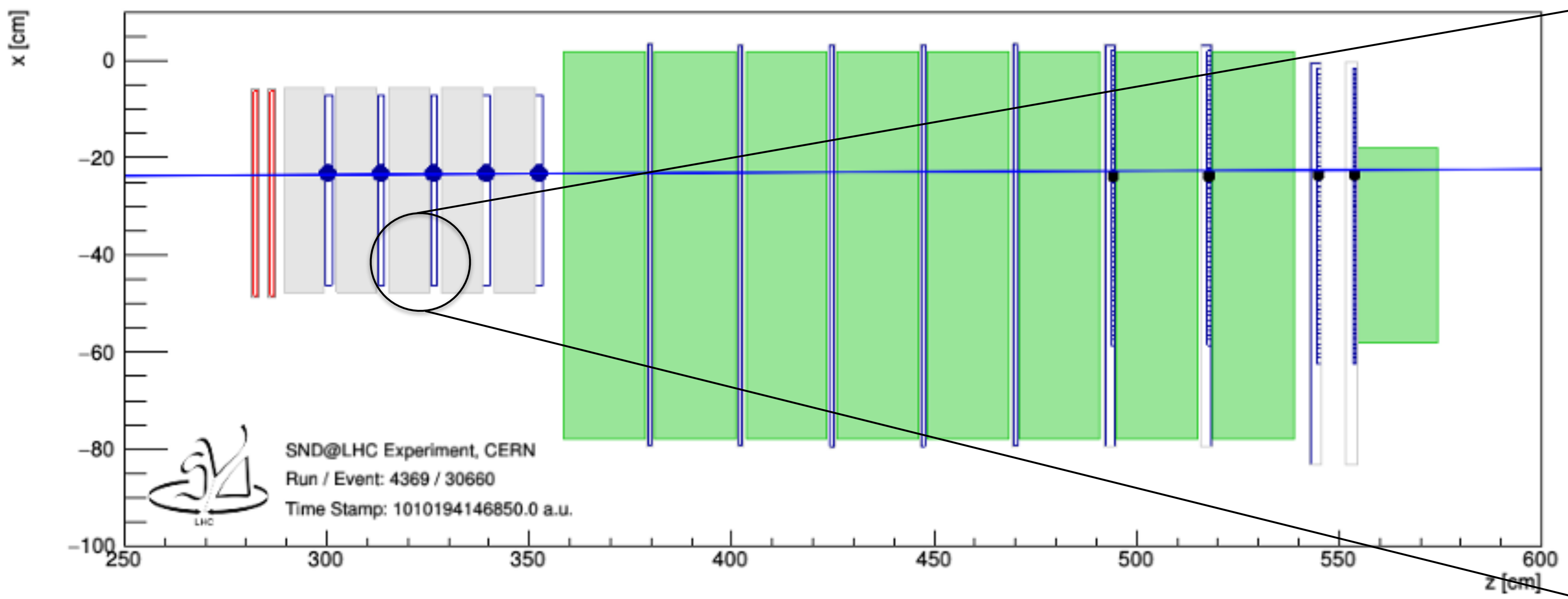


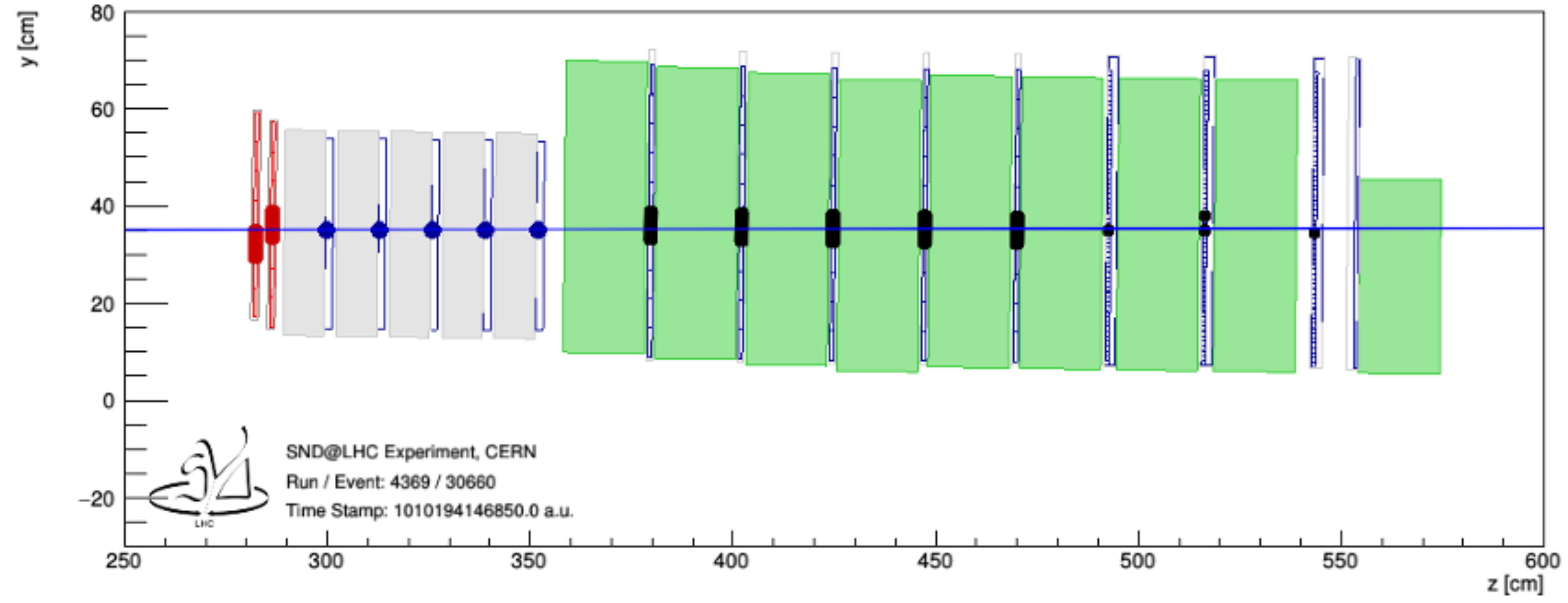



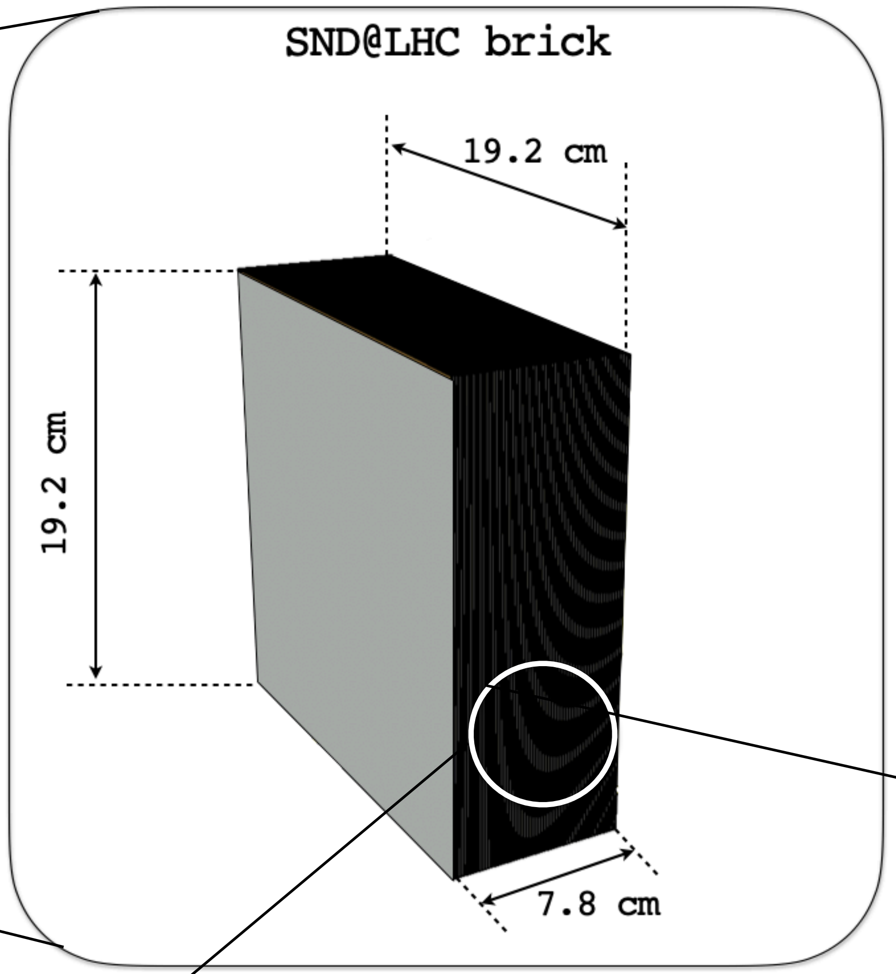



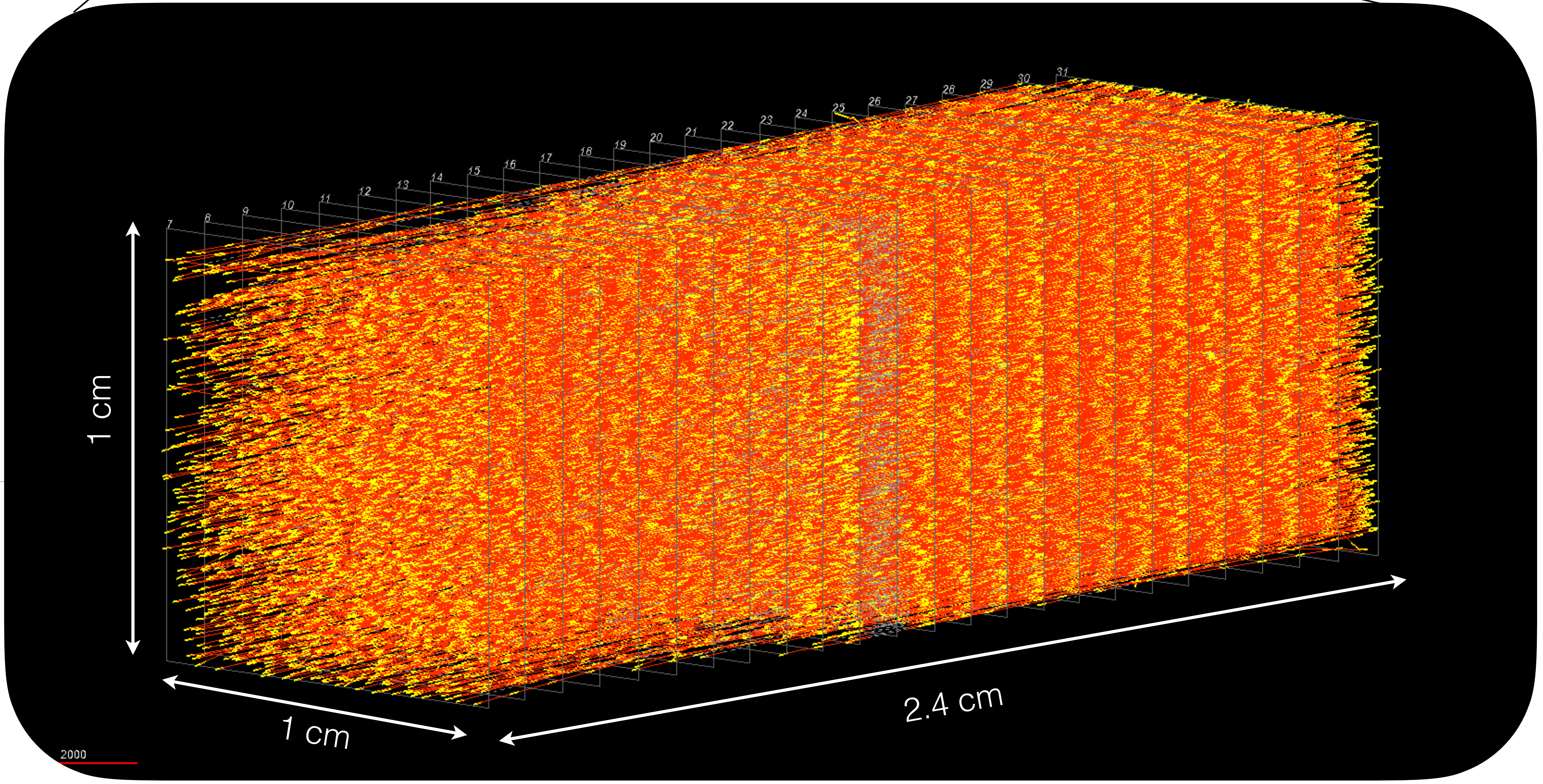
# TRACK RECONSTRUCTION

RUN0 emulsion target: April 7th - July 26th (0.51 $fb^{-1}$)




Emulsion reconstruction:
muon tracks in 1x1 $cm^2$ integrated in EMULSION RUN0

Measured rate in SciFi tracker (39x39 $cm^2$):
$1.9 \times 10^4$ /$cm^2$/$fb^{-1}$
Compatible with track density in the emulsion target

Electronic detector reconstruction:
muon track from pp collisions @13.6 TeV (July 6th 2022)

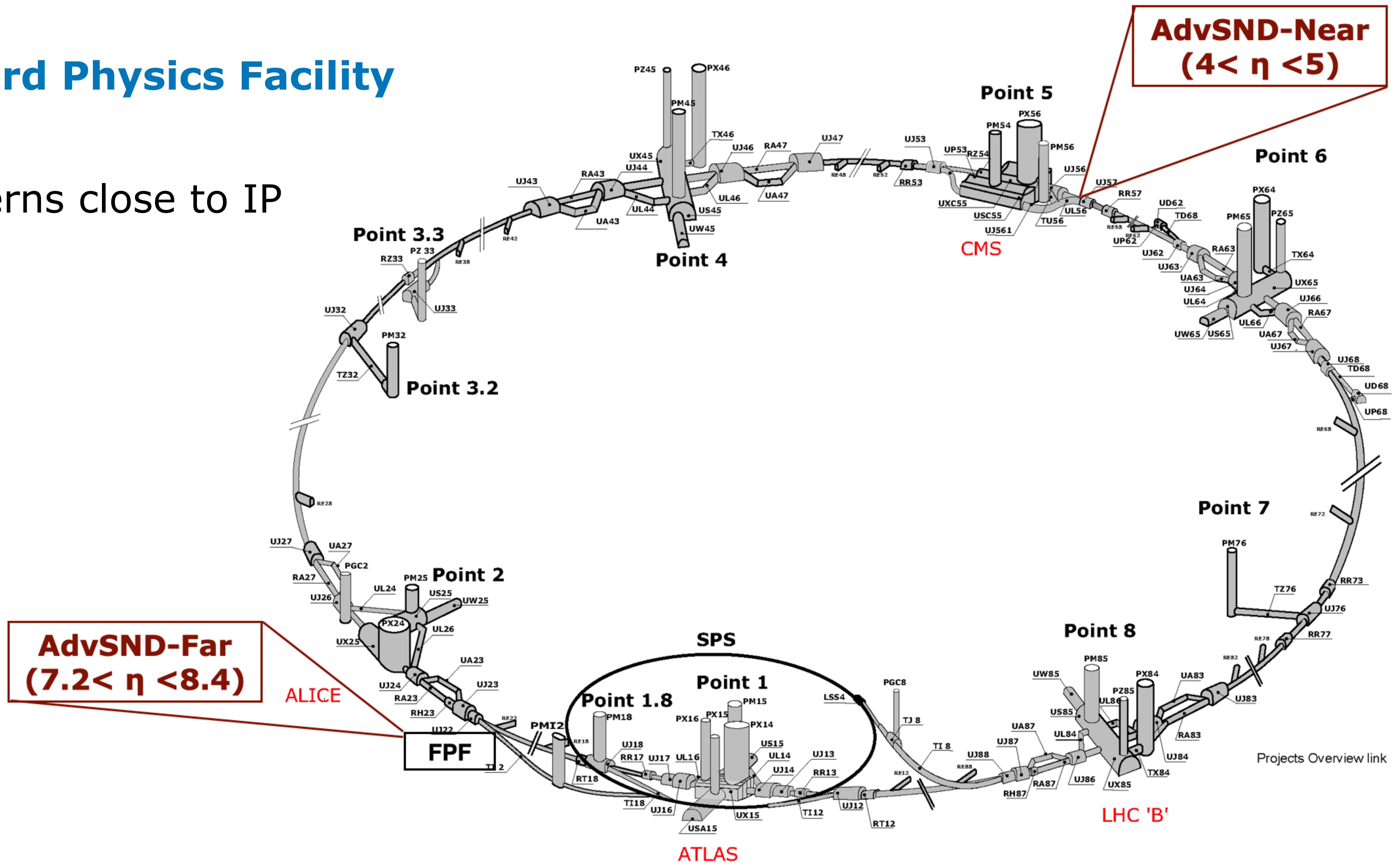
# ADVANCED SND@LHC



- Upgrade of SND@LHC in view of an extended run during Run 4:
  - Extension of the physics case
  - New technologies and detector layout
  - Two detectors
    - **AdvSND-Far** ($7.2<\eta<8.4$)

      Possible locations: TI18, **Forward Physics Facility**
    - **AdvSND-Near** ($4<\eta<5$)

      Possible locations: existing caverns close to IP



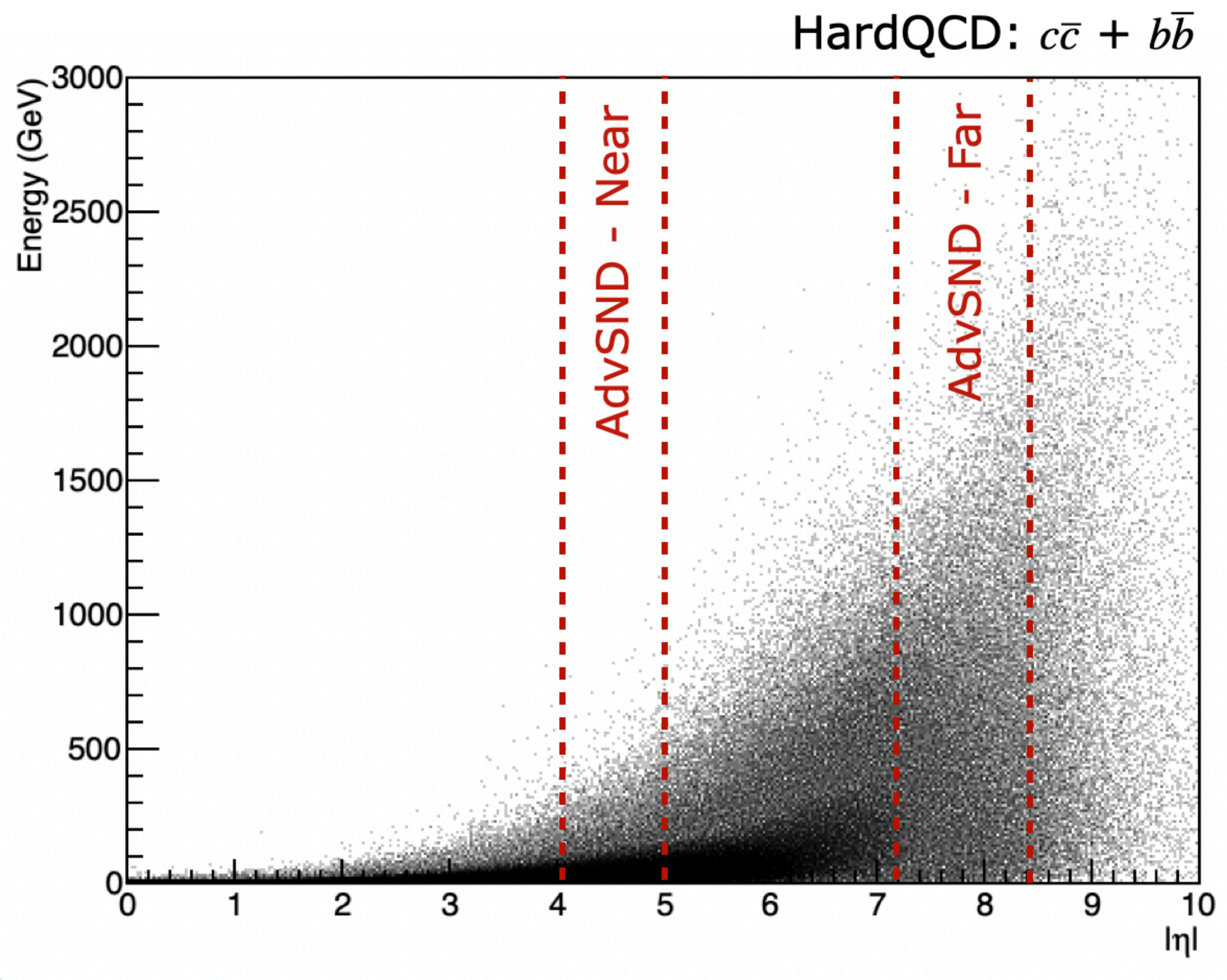
# ADVANCED SND@LHC



- Upgrade of the detector in view of an extended run during Run 4:
- **Two** off-axis forward detectors:

- **AdvSND-Near:** $4<\eta<5$
  - Overlap with LHCb pseudo-rapidity coverage
  - Reduction of systematic uncertainties
  - Neutrino cross-section measurement
  - charm measurements in the region of interest for prompt ν fluxes

- **AdvSND-Far**: $7.2<\eta<8.4$
  - Acceptance similar to SND@LHC
  - Charm production measurements
  - Lepton flavour universality

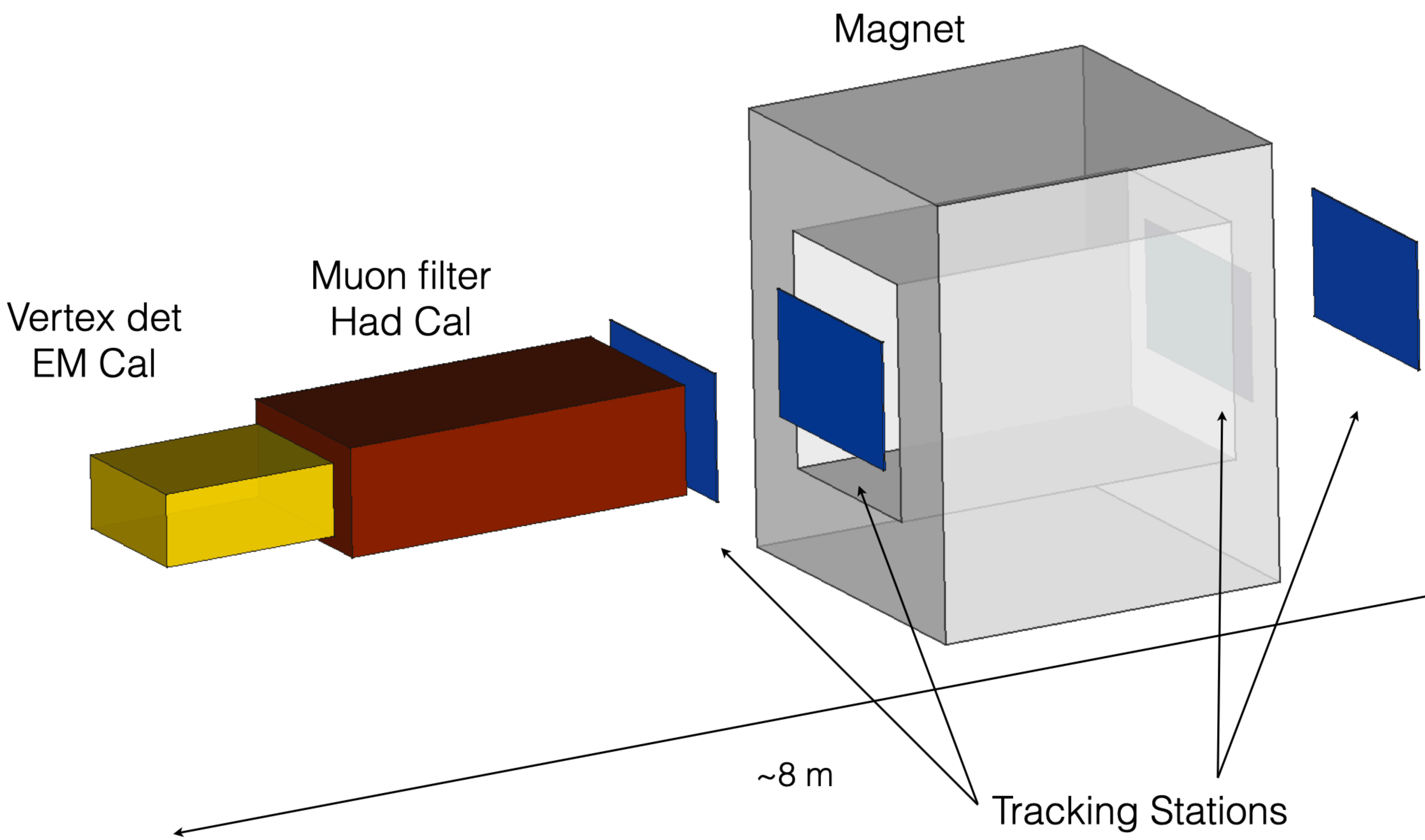


# ADVANCED SND@LHC: Detector layout



1) Target region:
   - Vertex identification and electromagnetic calorimeter
   - Thin sensitive layers interleaved with Tungsten plates
   - Replace emulsions with compact electronic trackers to cope with high intensity muon rates
2) Muon ID system and hadronic calorimeter
   - 10 interaction lengths
3) Magnetic spectrometer
   - measure charge of the muon ($\nu_\mu$/anti-$\nu_\mu$, $\nu_\tau$/anti-$\nu_\tau$ in the $\tau \longrightarrow \mu$ channel)
   - 2 tracking stations, each made of 2 planes
   - Magnet: 1 Tesla over 2 meters

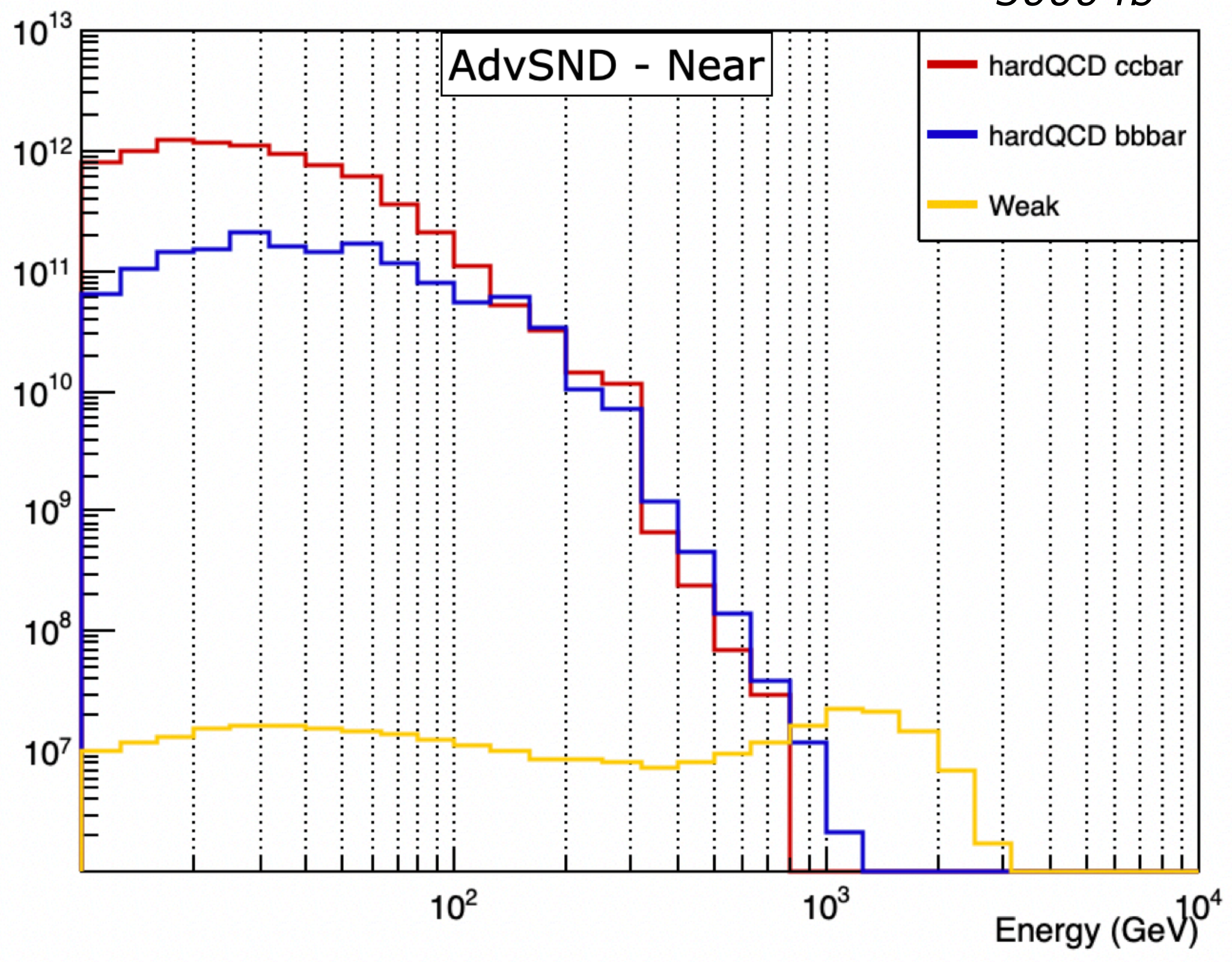
| | AdvSND - NEAR | AdvSND - FAR |
|---|---|---|
| $\eta$ | [4.0, 5.0] | [7.2,8.4] |
| mass (ton) | 5 | 5 |
| surface (cm$^2$) | $120 \times 120$ | $100 \times 40$ |
| distance (m) | 55 | 630 |



# ADVANCED SND@LHC - Near detector



*Neutrinos in AdvSDN-Near acceptance*
*3000 fb$^{-1}$*




**AdvSND-Near:**

| | |
|---|---|
| $\eta$ | [4.0, 5.0] |
| mass (ton) | 5 |
| surface (cm$^2$) | $120 \times 120$ |
| distance (m) | 55 |

AdvSND - NEAR

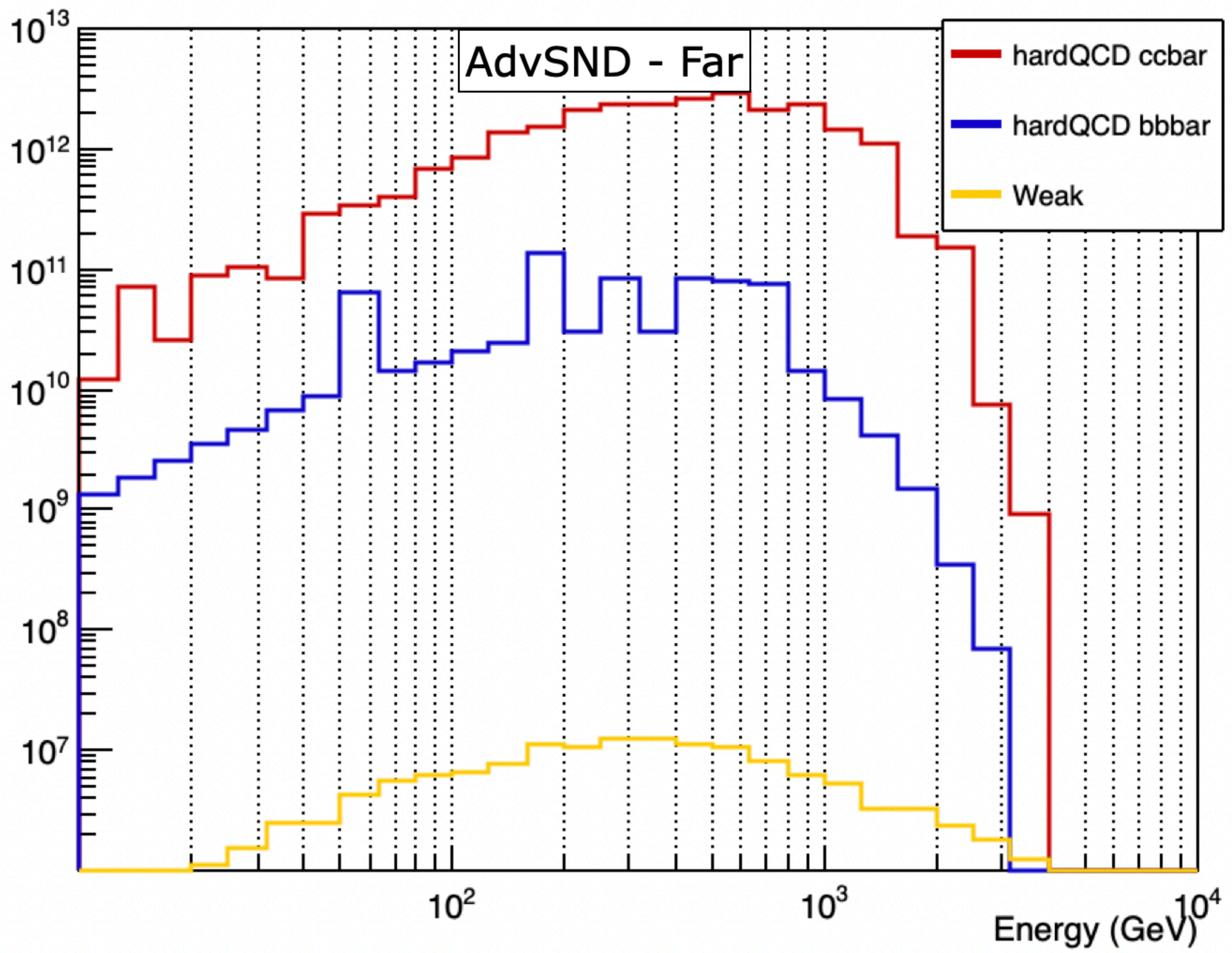
| Flavour | $\nu$ in acceptance hardQCD: $c\bar{c}$ | $\nu$ in acceptance hardQCD: $b\bar{b}$ | CC DIS hardQCD: $c\bar{c}$ | CC DIS hardQCD: $b\bar{b}$ |
|---|---|---|---|---|
| $\nu_\mu + \bar{\nu}_\mu$ | $2.1 \times 10^{12}$ | $3.3 \times 10^{11}$ | 980 | 200 |
| $\nu_e + \bar{\nu}_e$ | $2.2 \times 10^{12}$ | $3.3 \times 10^{11}$ | 1000 | 200 |
| $\nu_\tau + \bar{\nu}_\tau$ | $2.7 \times 10^{11}$ | $1.4 \times 10^{11}$ | 80 | 50 |
| Tot | $5.4 \times 10^{12}$ | | $2.5 \times 10^3$ | |

Expectations in **3000 fb$^{-1}$**
Generator: Pythia8

- Average energy for neutrinos form charm and beauty decays: ~30 GeV
- Measurement of **neutrino cross-section** for three flavours, given the measurement of the neutrino flux provided by LHCb
- Expected statistical error: a few % for electron and muon neutrinos, ~10% for tau neutrinos

# ADVANCED SND@LHC - Far detector

*Neutrinos in AdvSDN-Far acceptance*
*3000 fb$^{-1}$*




**AdvSND-Far:**

| | |
|---|---|
| $\eta$ | [7.2,8.4] |
| mass (ton) | 5 |
| surface (cm$^2$) | $100 \times 40$ |
| distance (m) | 630 |

| Flavour | $\nu$ in acceptance hardQCD: $c\bar{c}$ | $\nu$ in acceptance hardQCD: $b\bar{b}$ | CC DIS hardQCD: $c\bar{c}$ | CC DIS hardQCD: $b\bar{b}$ |
|---|---|---|---|---|
| $\nu_\mu + \bar{\nu}_\mu$ | $6.3 \times 10^{12}$ | $1.5 \times 10^{11}$ | $1.2 \times 10^4$ | 200 |
| $\nu_e + \bar{\nu}_e$ | $6.7 \times 10^{12}$ | $1.7 \times 10^{11}$ | $1.2 \times 10^4$ | 220 |
| $\nu_\tau + \bar{\nu}_\tau$ | $7.1 \times 10^{11}$ | $4.7 \times 10^{10}$ | 880 | 40 |
| Tot | $1.4 \times 10^{13}$ | | $2.5 \times 10^4$ | |

Expectations in **3000 fb$^{-1}$**
Generator: Pythia8

- Contribution from W/Z decays negligible
- Average energy for neutrinos form charm and beauty decays: ~400 GeV

- Test of **lepton flavour universality** measuring there ratio **R$_{13}$**
- Statistical uncertainty reduced to 5%
- Systematic uncertainty given by charm quark hadronisation factor: 20%

$$R_{13} = \frac{N_{\nu_e+\bar{\nu}_e}}{N_{\nu_\tau+\bar{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)}$$

- Test of **lepton flavour universality** measuring there ratio **R$_{12}$**
- Statistical uncertainty: a few %
- Systematic uncertainty given by contamination of pion/kaons

$$R_{12} = \frac{N_{\nu_e+\bar{\nu}_e}}{N_{\nu_\mu+\bar{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

# QCD MEASUREMENTS

- Electron neutrinos mostly produced by charm decays
- $\nu_e$ ca be used as a probe of **charm production** in a region where charm yield has large uncertainties

- Electron neutrinos measurements can constraint the uncertainty on the gluon PDF in $x<10^{-5}$ region

- Extraction of gluon PDF in very small x-region relevant for:
  1. Future Circular Colliders
  2. Reduction of uncertainty on the flux of very-high-energy atmospheric neutrinos

- **AdvSND-Near:** $4<\eta<5$:
  reduce systematic uncertainties in the correlation between neutrinos and charmed mesons comparing with LHCb direct charm measurements

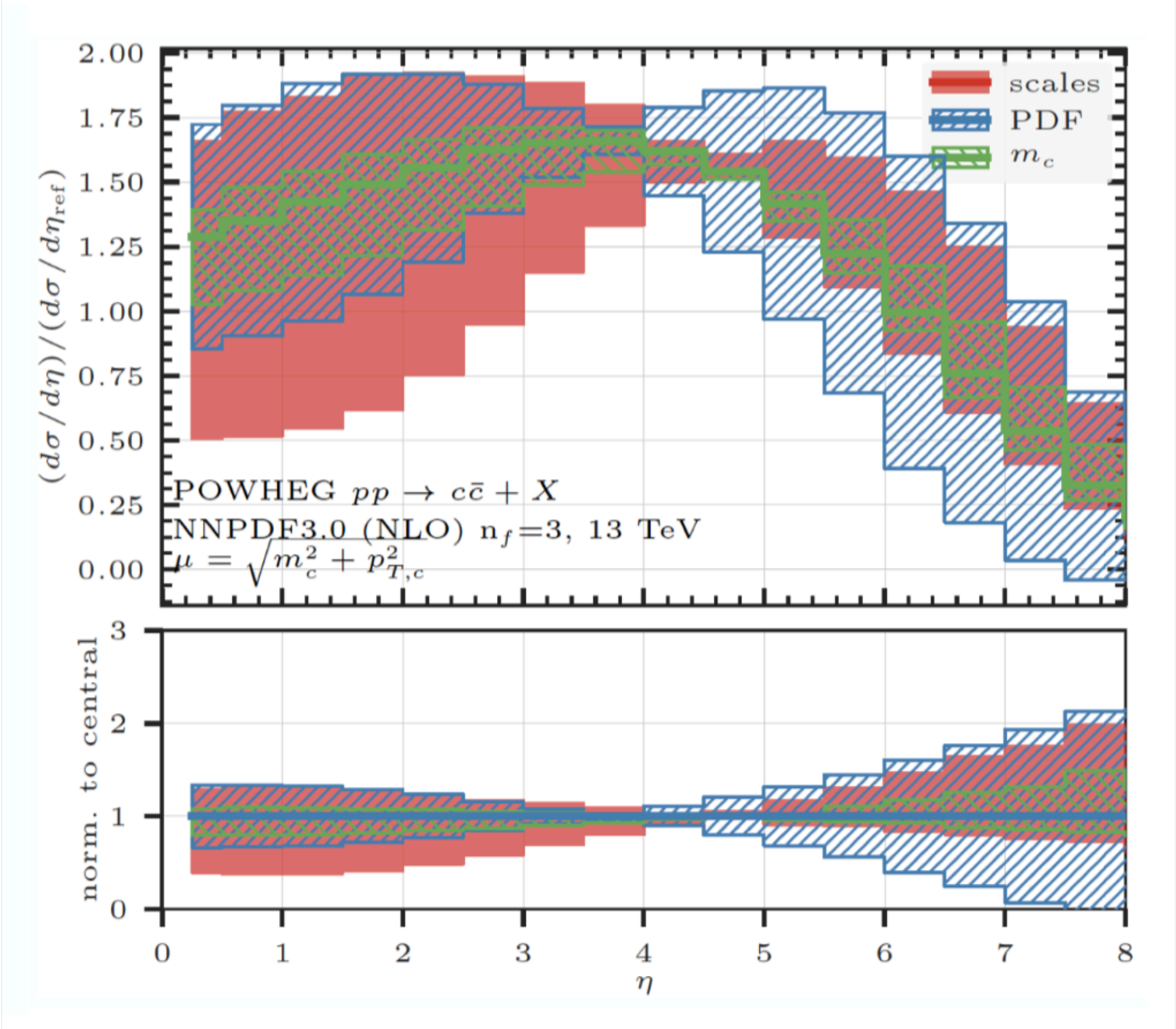
- **AdvSND-Far:** $7.2<\eta<8.4$:
  reduce statistical uncertainties

Ratio between the cross-section measurements at different pseudo-rapidities, normalised to LHCb measurements

$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$$

$\eta_{ref} = [4,4.5]$

arxiv:1510.01707



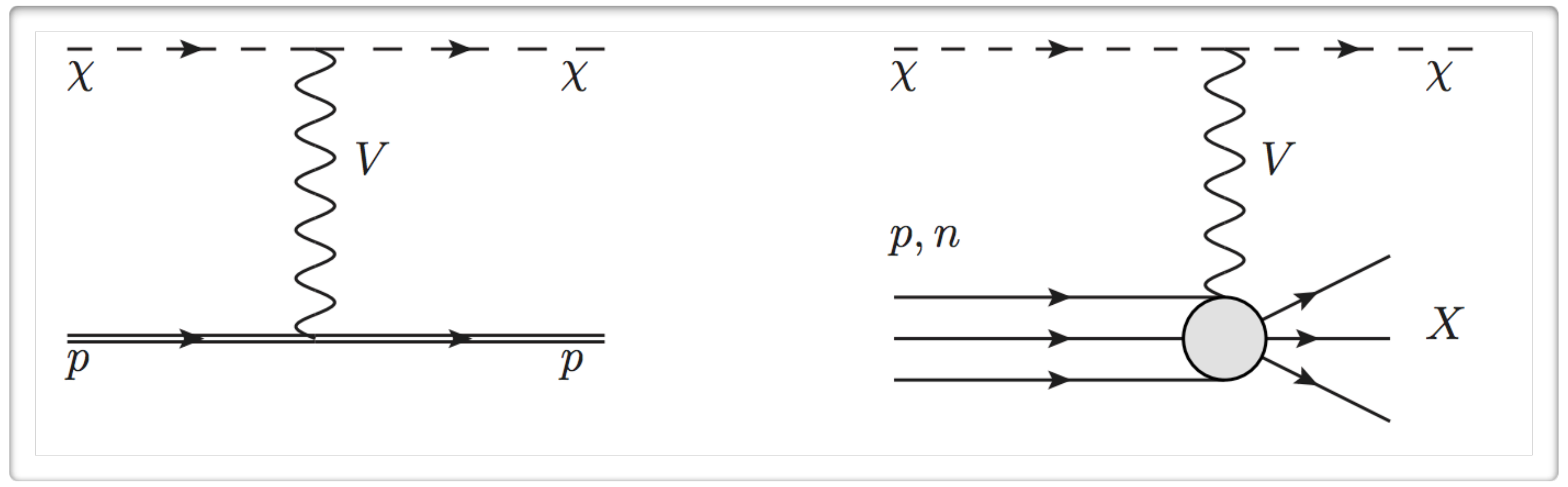
# BEYOND STANDARD MODEL

Large variety of BSM scenarios describing Hidden Sector

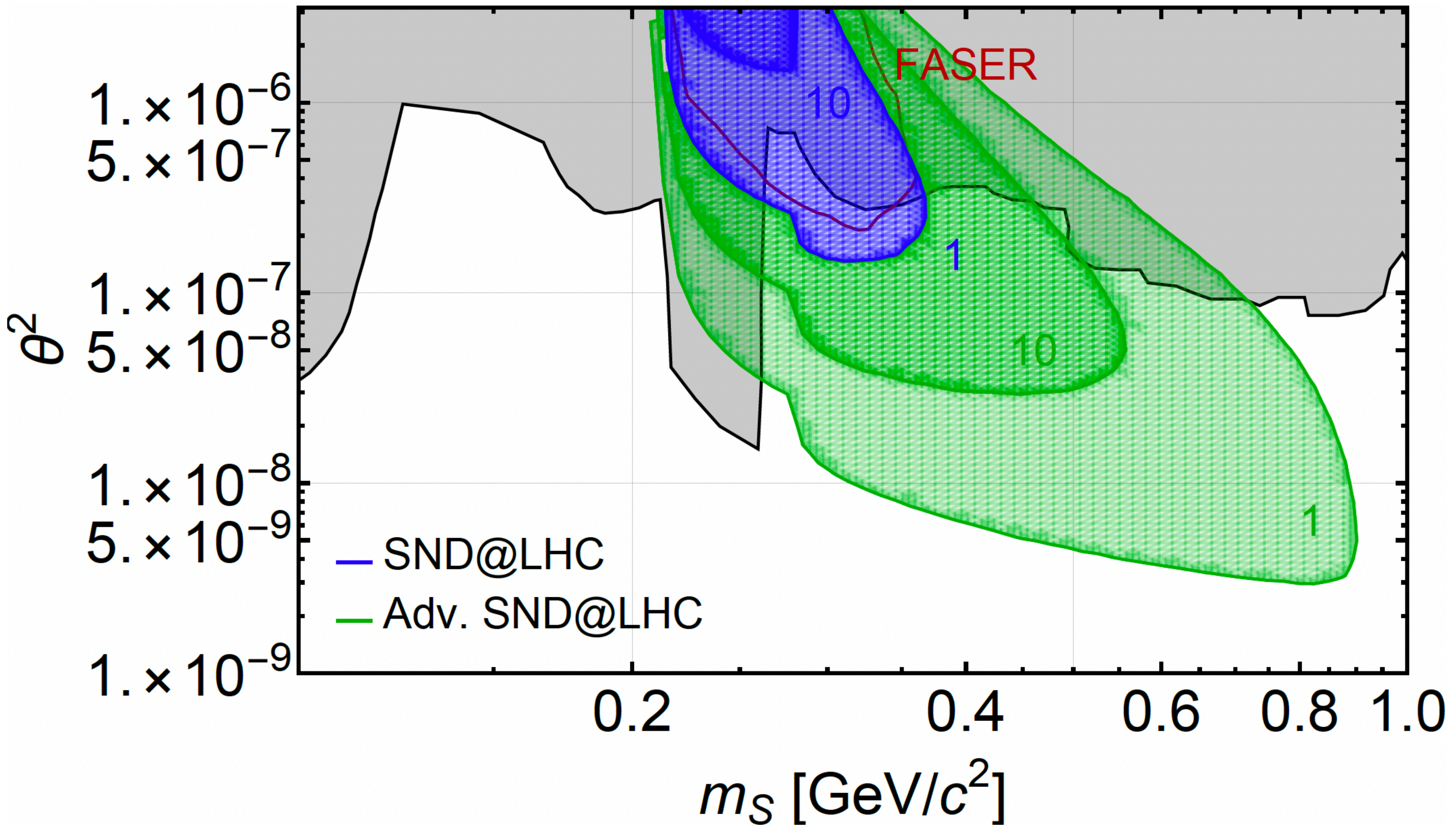
**1. Scattering**

**Production:** scalar $\chi$ particle coupled to the Standard Model via a leptophobic portal

**Detection:** $\chi$ elastic/inelastic scattering off nucleons of the target




*JHEP 2022, 6 (2022)*



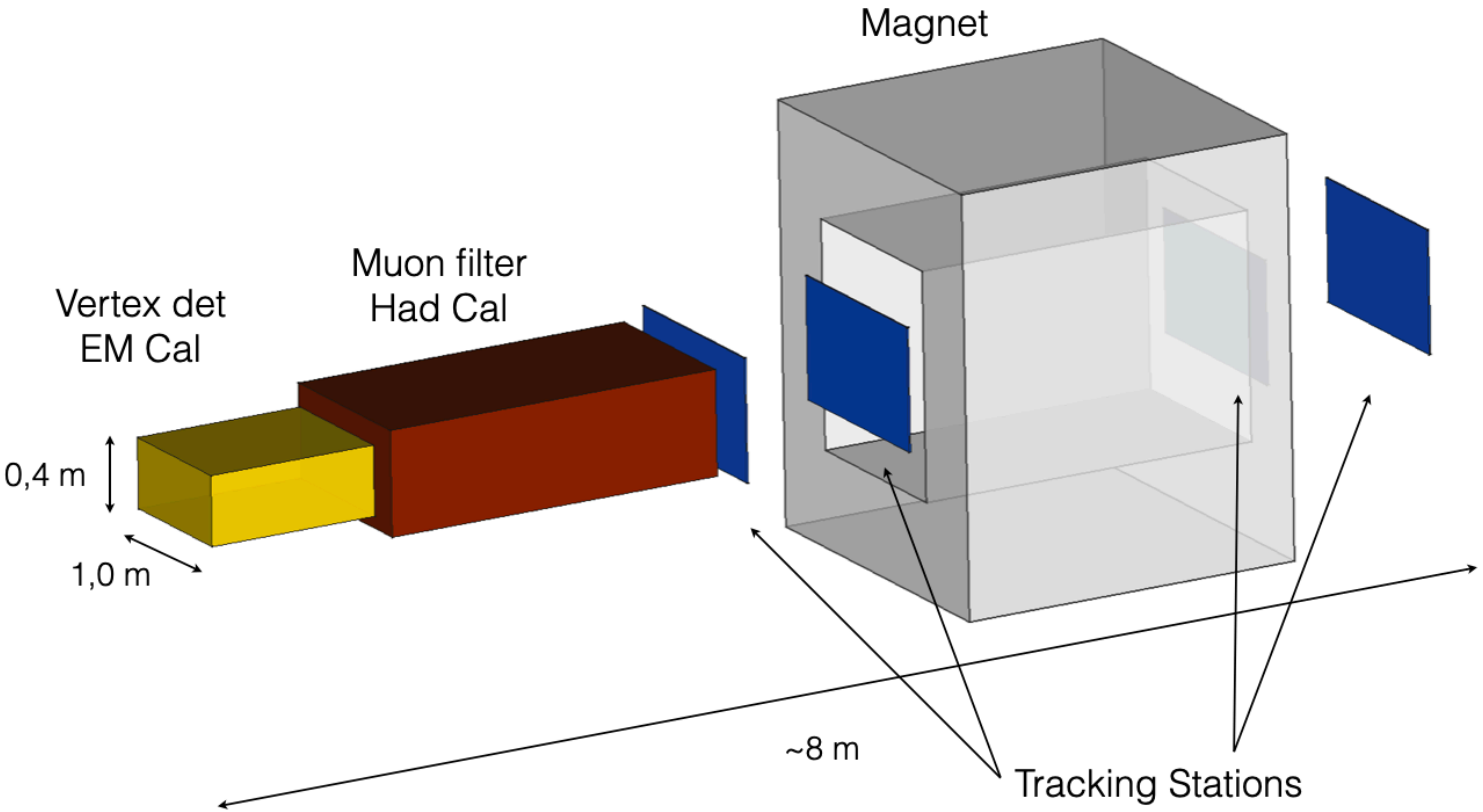

**2. Decay of dark scalars, HNLs, dark photons**

**Production:** dark scalars produced in the decay of B mesons, HLNs in the decay of B and D mesons, dark photons via leptophobic mediator

**Detection:** Decays in a pair of charged tracks or monophotons

# DETECTOR LAYOUT (Option1)



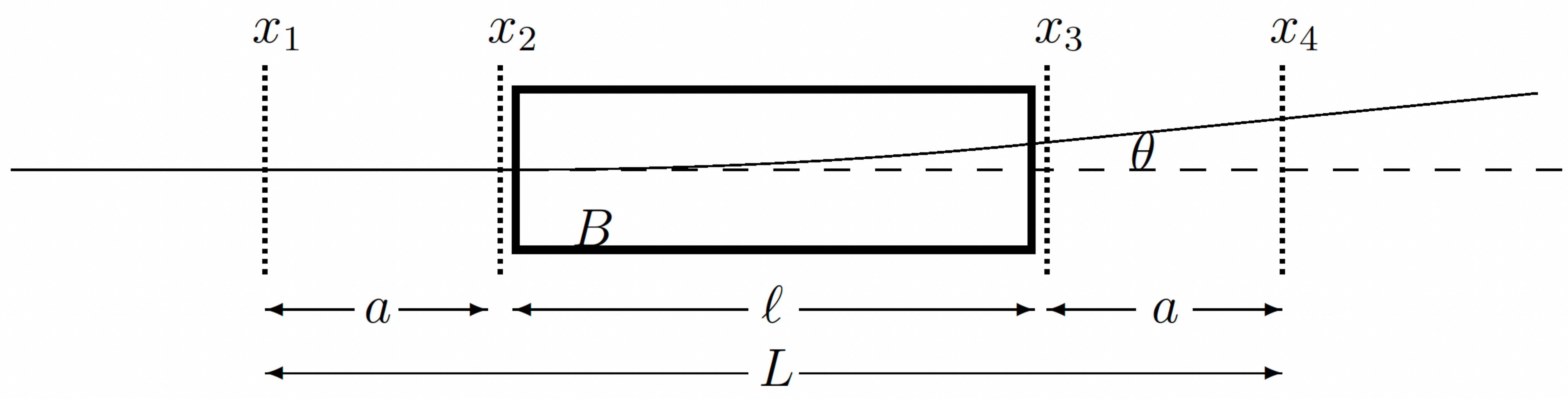


# SPECTROMETER LAYOUT (Option1)



Requirements for the spectrometer:

- measure bending angle of charged muons produced in neutrino interactions in the target
- bending angle given by $\theta = \frac{\ell}{r} = \frac{eB\ell}{p}$
- two upstream tracking stations (*x1* and *x2*) to measure the incoming angle of the track
- two downstream tracking stations (*x3* and *x4*) to measure the exiting angle of the track
- each pair of stations is separated by the lever arm *a*



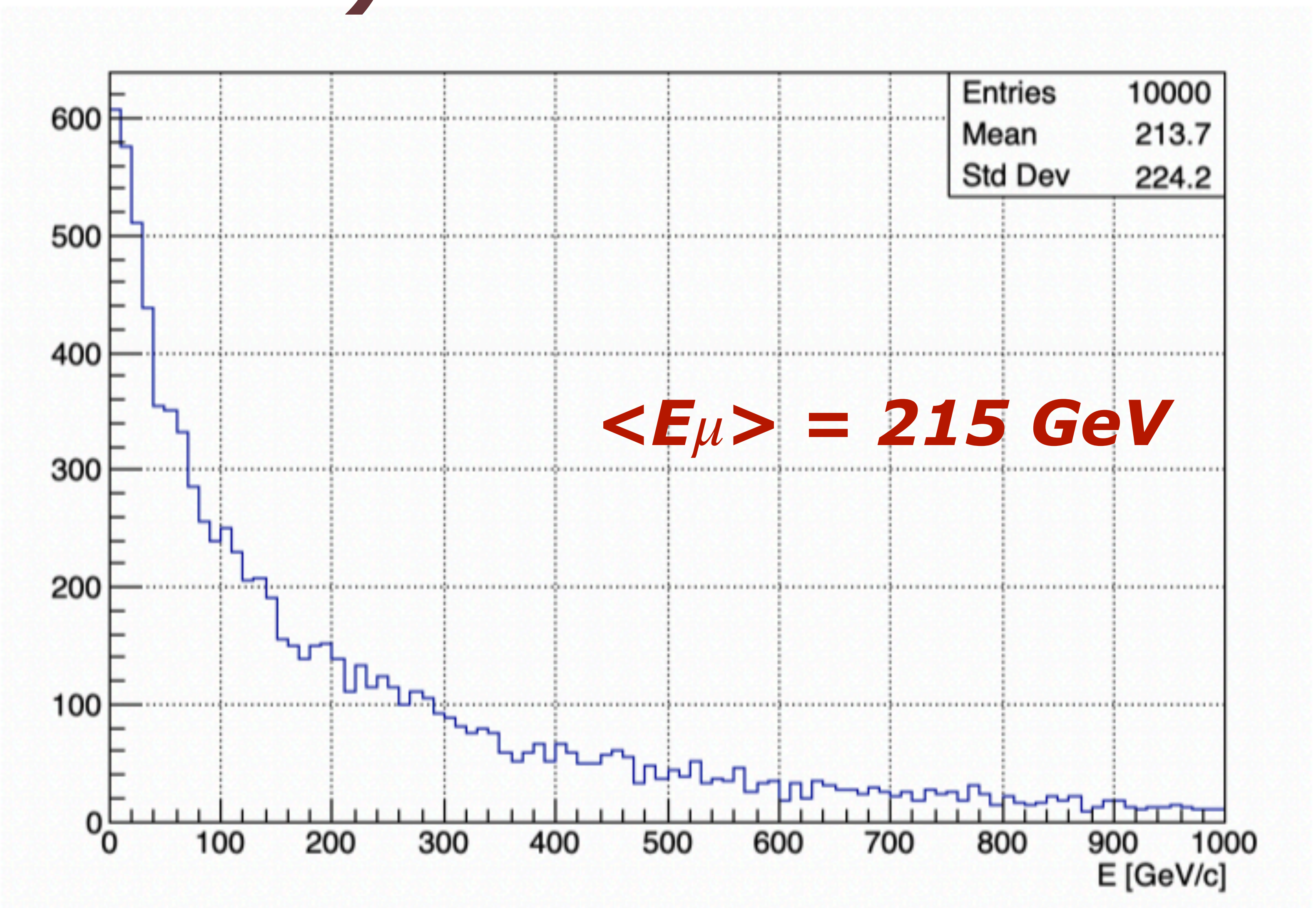

- choice of the length *l* of the magnet and of the lever arm *a*, which results in the best momentum resolution

$$a = \frac{L}{4} = \frac{\ell}{2}$$

# SPECTROMETER LAYOUT (Option1)

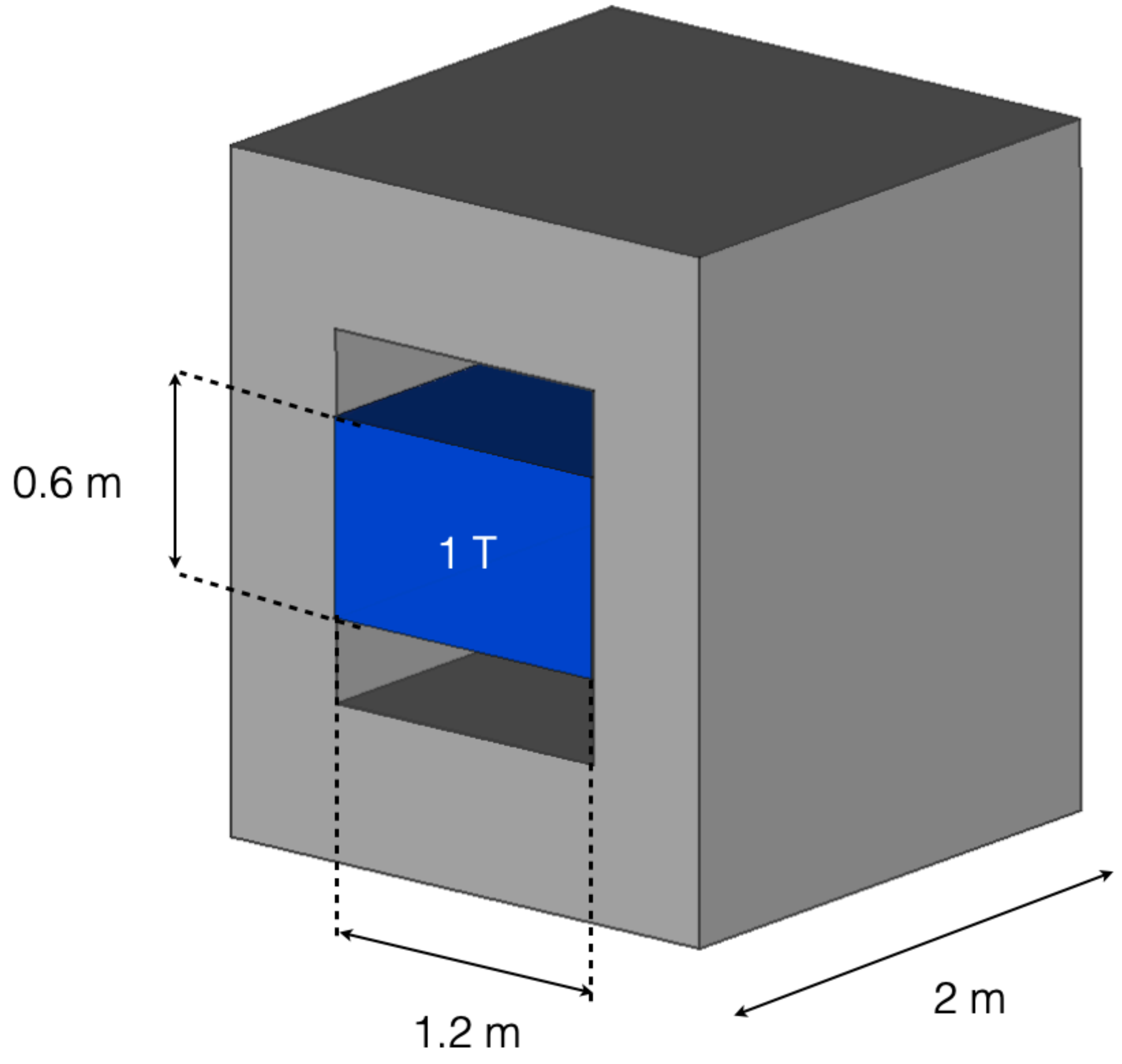


The choice of the spectrometer parameters depends on:
- energy spectrum of charged particles
- position resolution of tracking stations
- transverse dimensions of target region




*Muon energy at the FAR location*

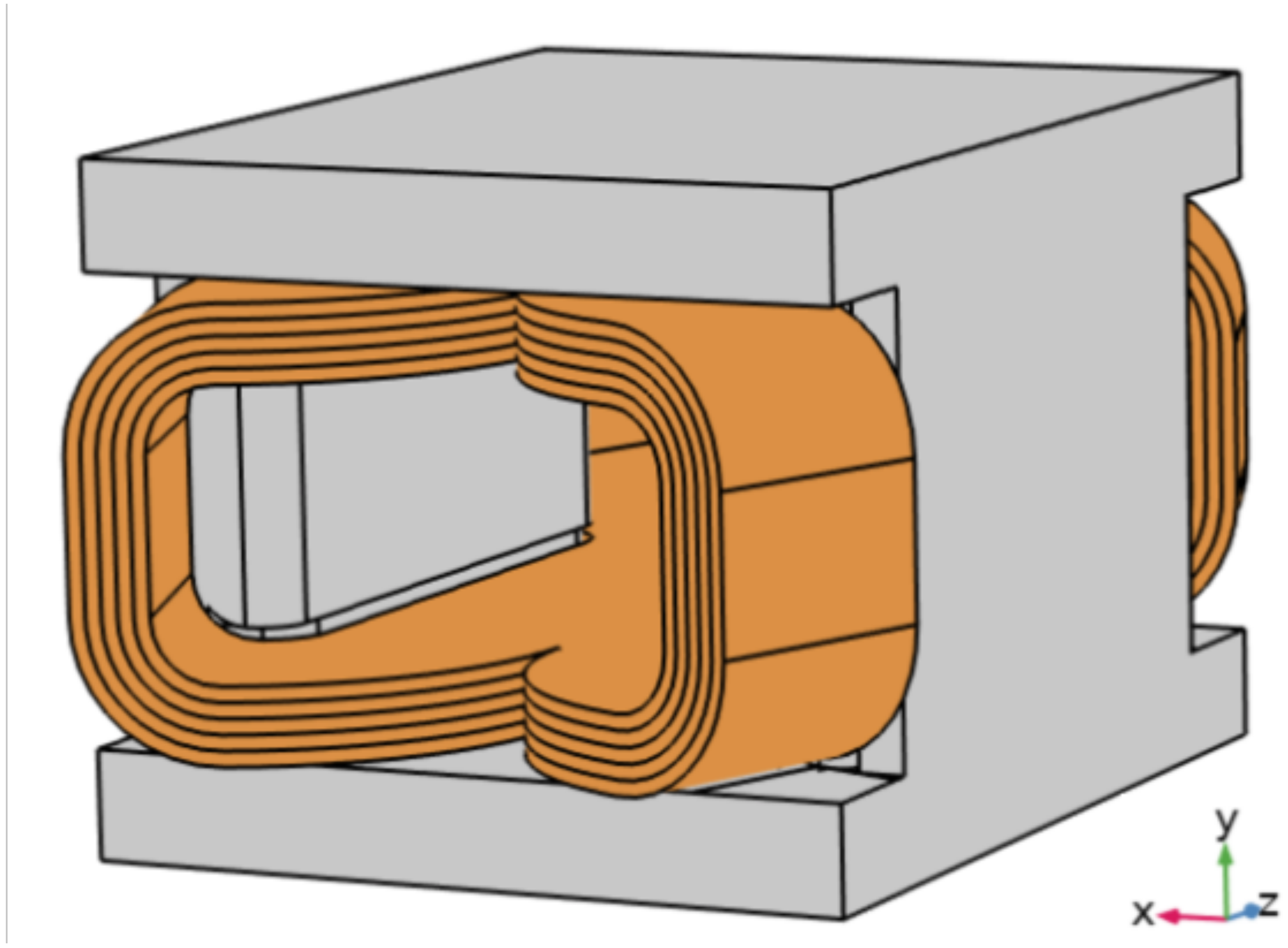
Requirements for the magnet:
- Magnetic field: 1 T
- Length of magnetised region: 2 m
- Transverse size of magnetised region: 1.2 x 0.6 $m^2$

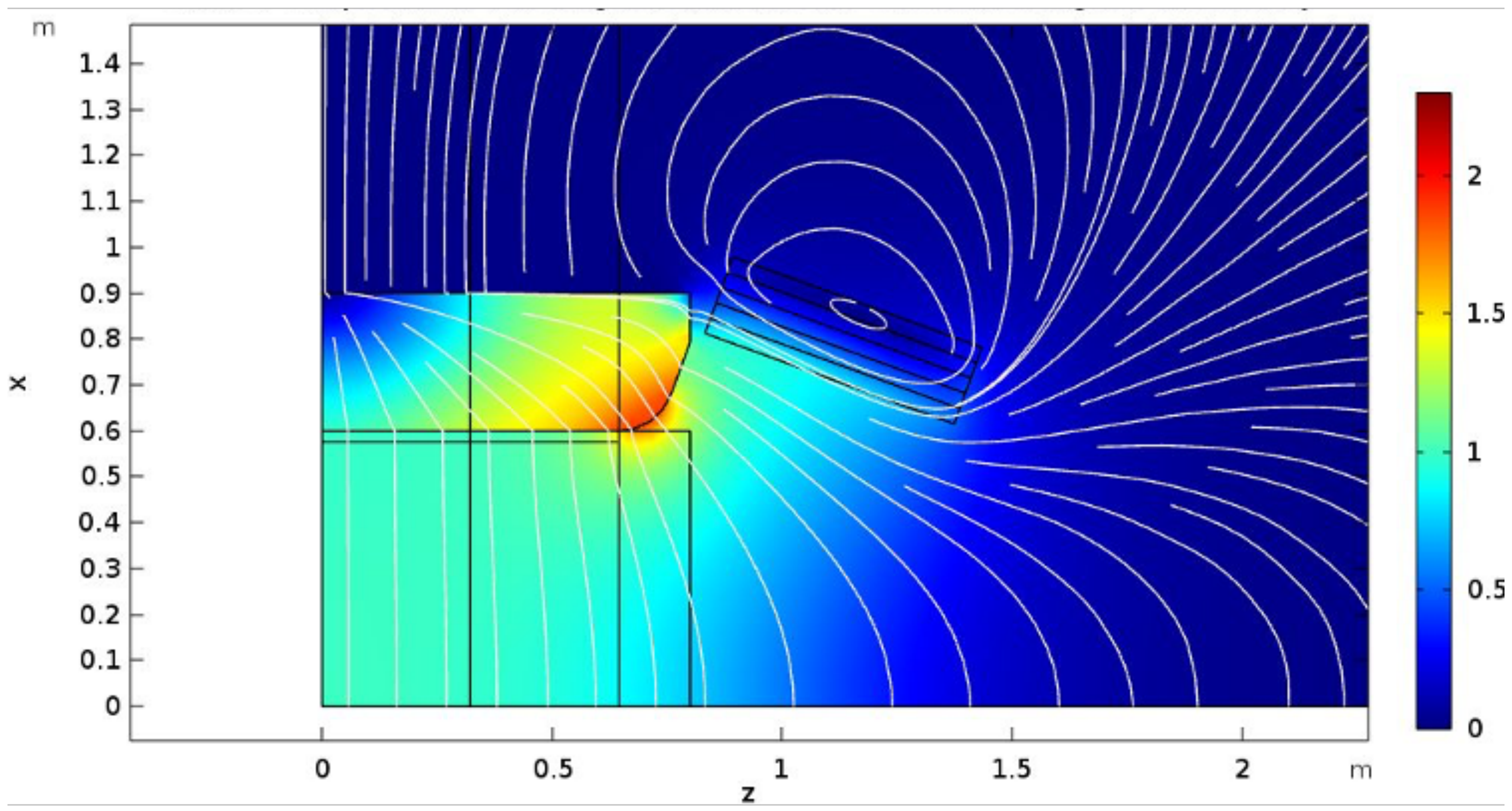


# MAGNET DESIGN (Option1)

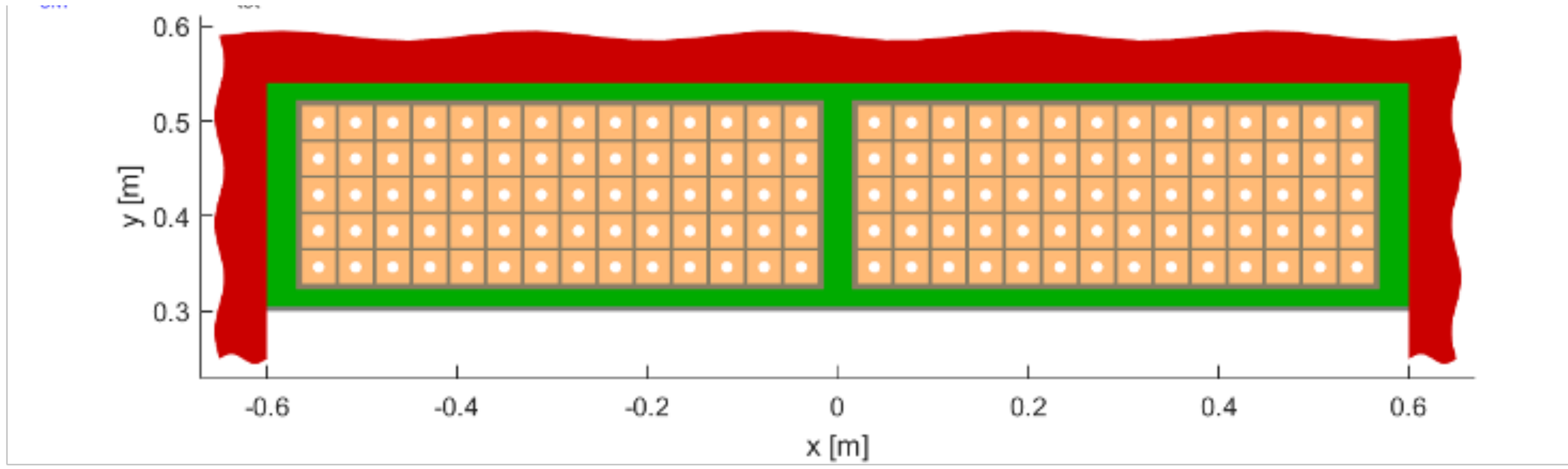


Baseline option:
-open ends air (warm) magnet
-single pancake coil
-complying CERN power supply and cooling standards




*FEM 3D simulation of B-field distribution*




*Coil design*

# MAGNET DESIGN (Option1)

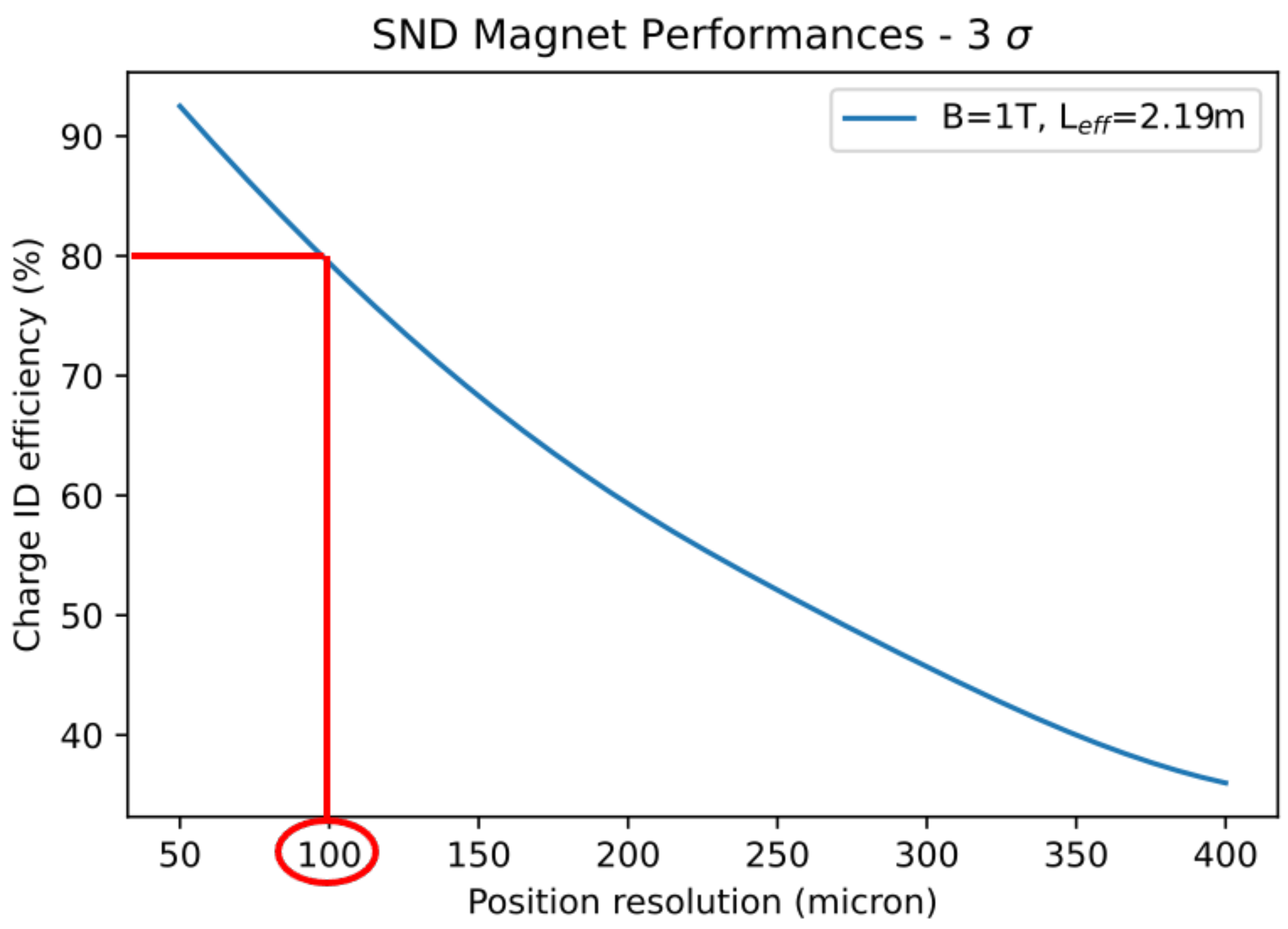


- Main figures:

magnetic length $\ell_{mag} = \frac{\int_{-\infty}^{\infty} B(0,0,z)dz}{B(0,0,0)} = 2.19\ \mathrm{m}$

| **reference B field** | **[T]** | **1.0** |
|---|---|---|
| overall volume | [m³] | 1.80x1.58x3.01 |
| magnetic length | [m] | 2.19 |
| coil total turns | [-] | 140 |
| magnetic efficiency | [-] | 987 |
| electrical power | [MW] | 0.77 |
| B_stray_max | [mT] | 20 |

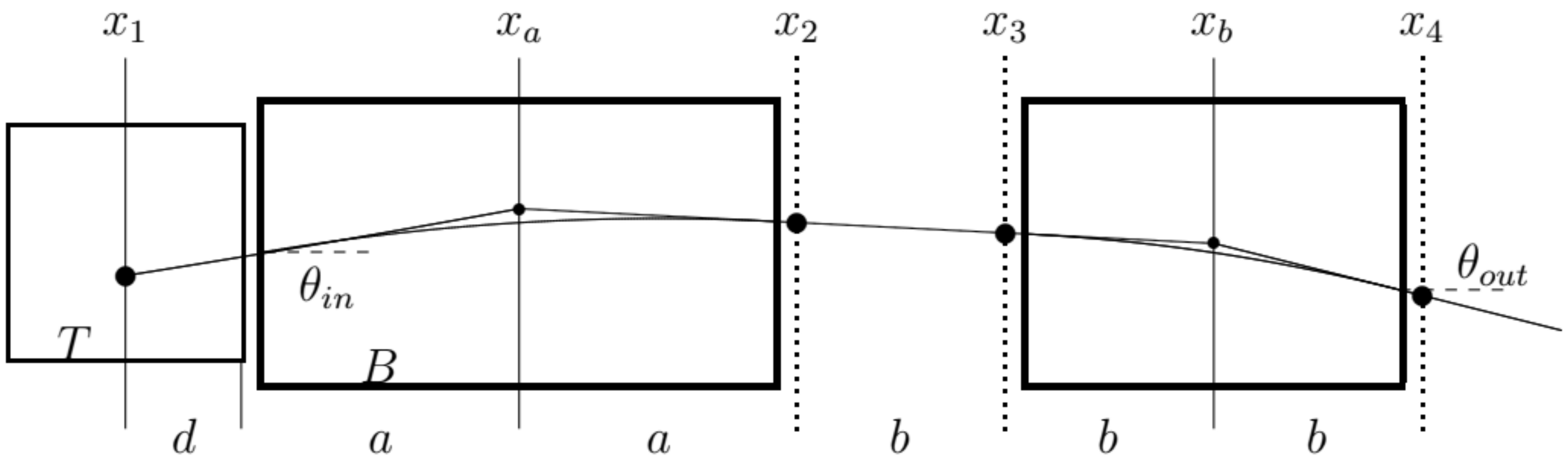
- Charge ID performances as a function of the tracker position resolution




Required position resolution for tracking stations
**100 $\mu$m**

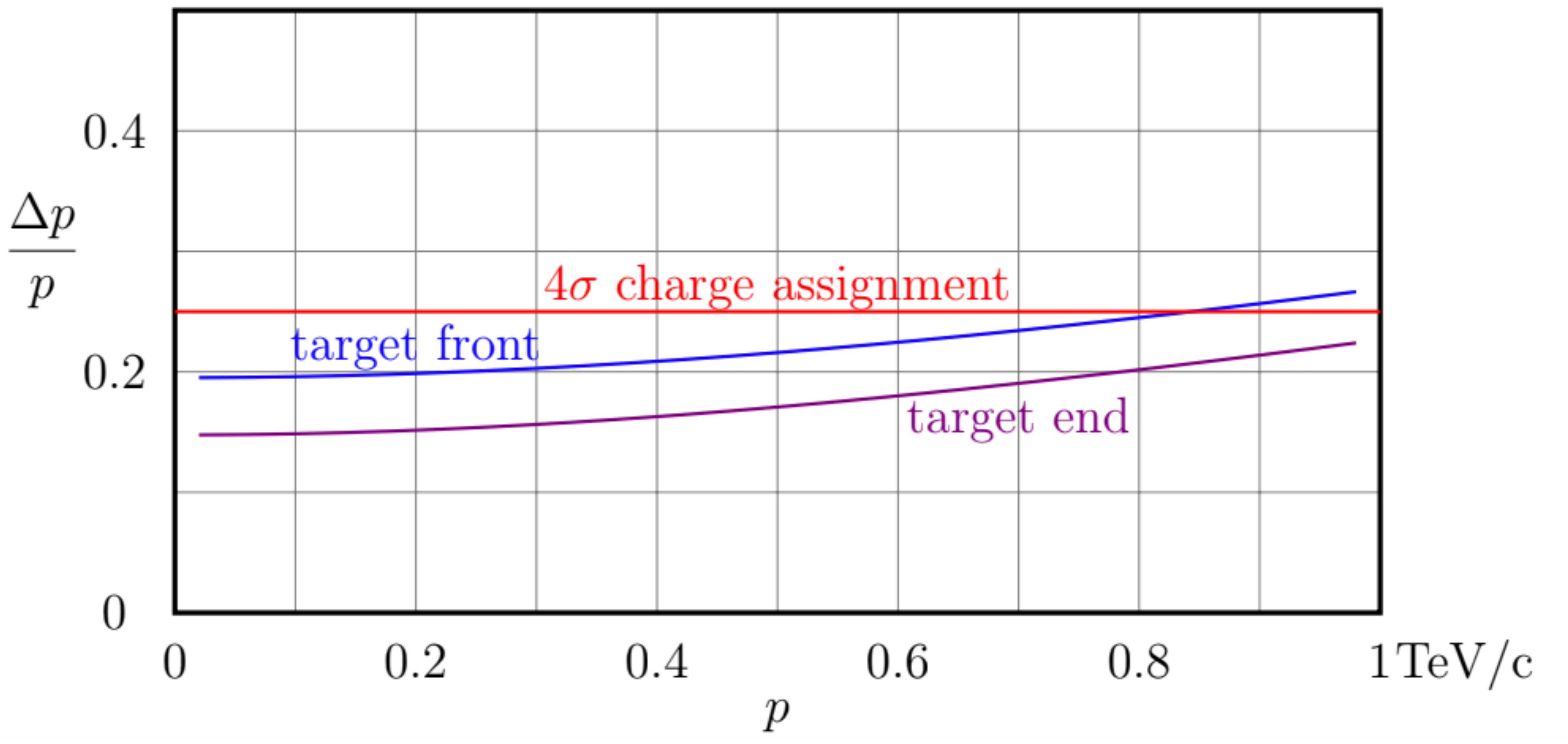
# SPECTROMETER LAYOUT (Option2)

Iron core magnet

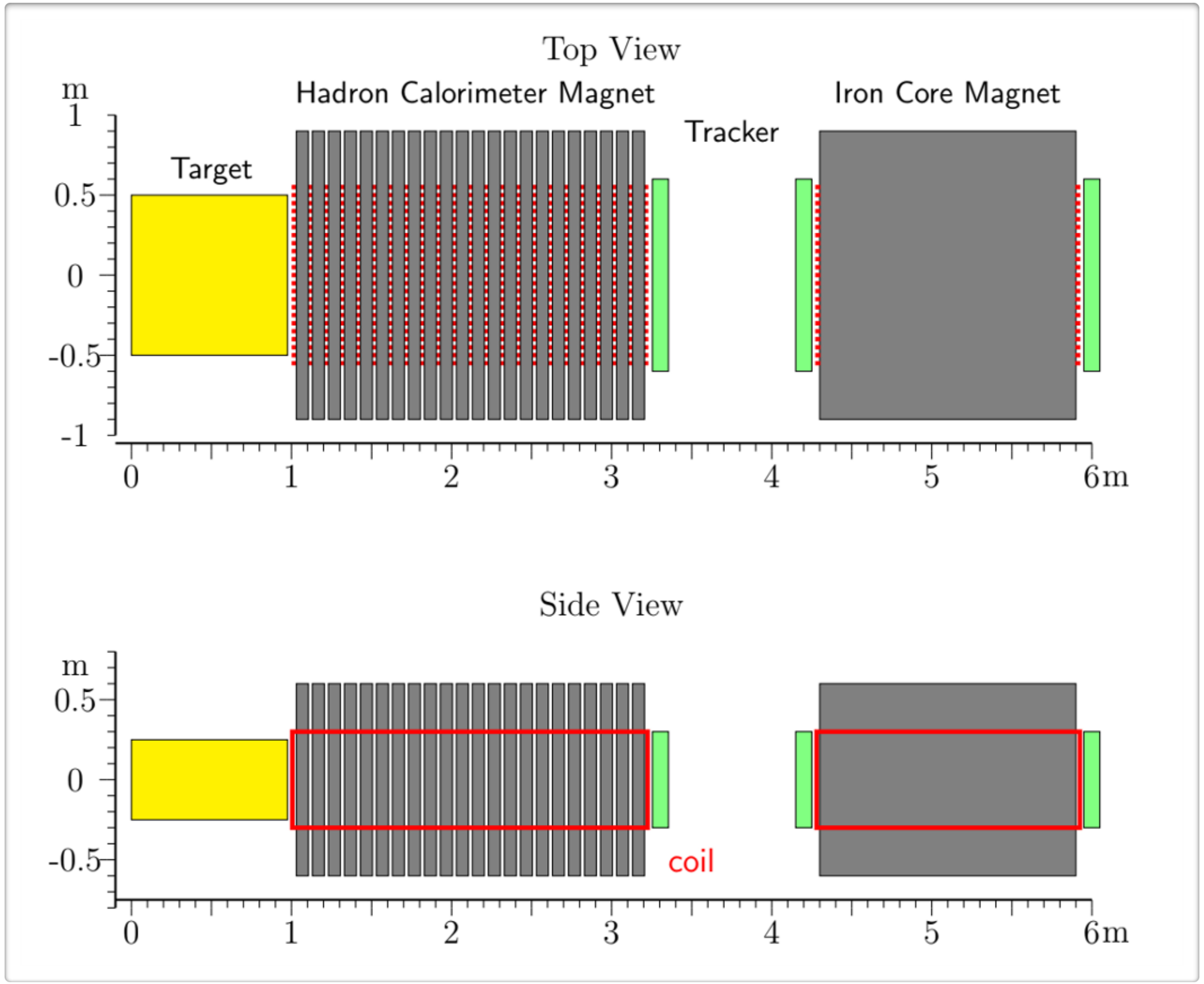


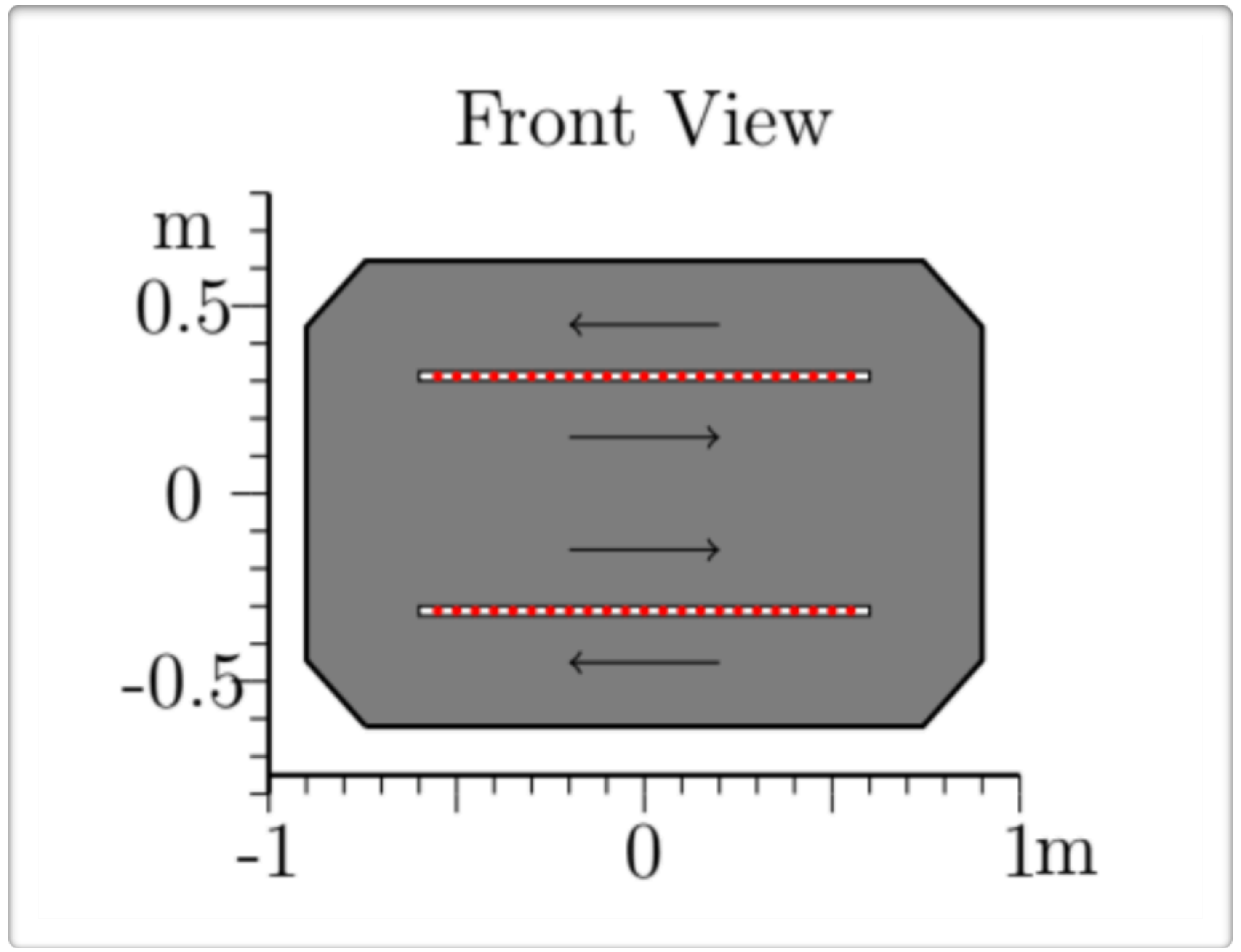

- Two magnetised volumes:
  - One as hadronic calorimeter
  - One as magnetic spectrometer
- Three drift chambers to measure muon track coordinates
- B = 1.5 T
- Total iron mass: 57 t
- Power consumption: 1kW

$$\frac{\Delta p}{p} = \frac{\sqrt{\Delta\theta_C^2 + \Delta\theta_{MS}^2}}{\theta} = \frac{1}{eB\ell}\sqrt{(\Delta\theta_C\, p)^2 + \frac{4}{3}\,(14\,\mathrm{MeV/c})^2\left(\frac{0.5d}{X_W} + \frac{\ell}{X_{Fe}}\right)} \qquad (10)$$



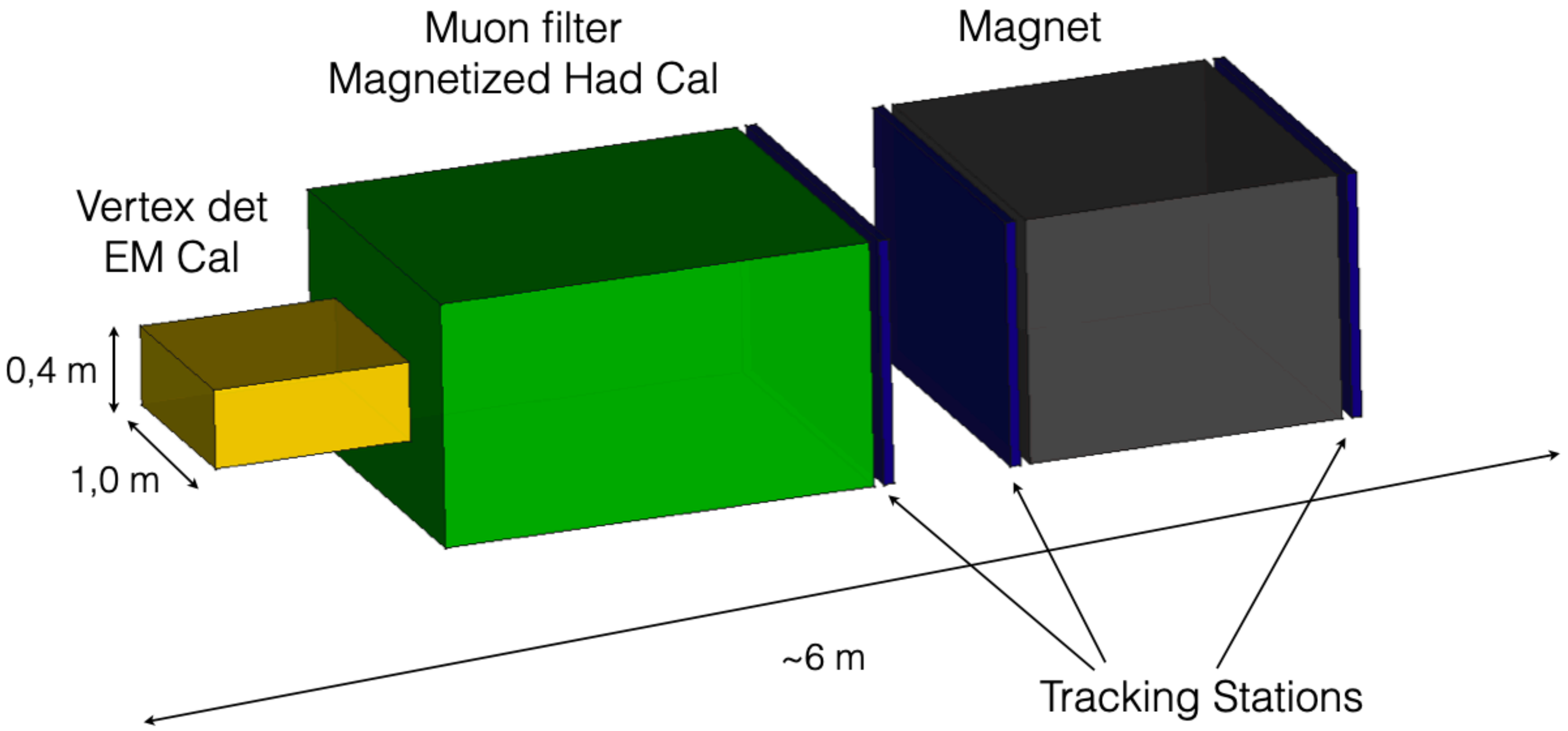
# SPECTROMETER LAYOUT (Option2)



# SPECTROMETER LAYOUT (Option2)



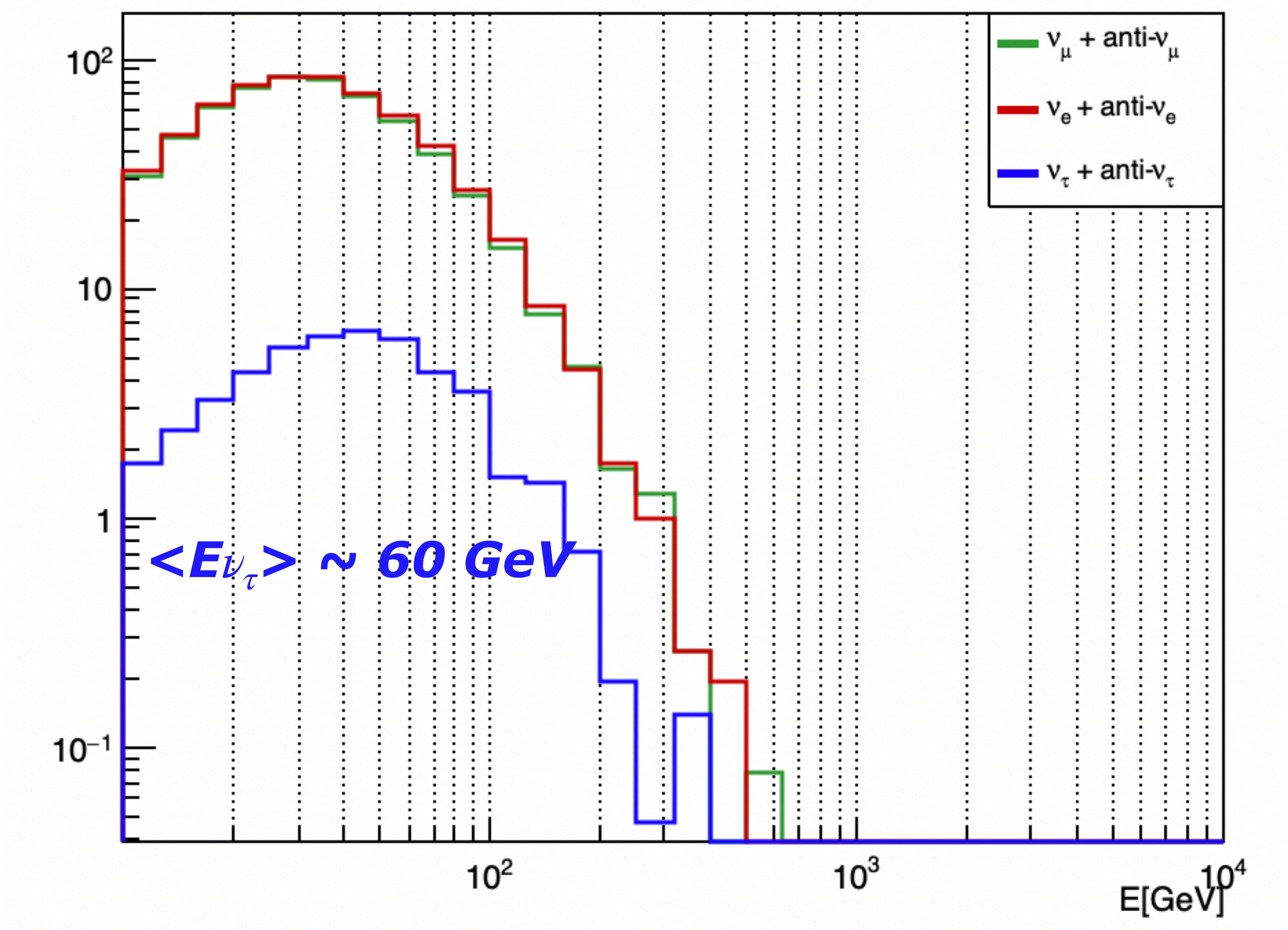


# VERTEX DETECTOR



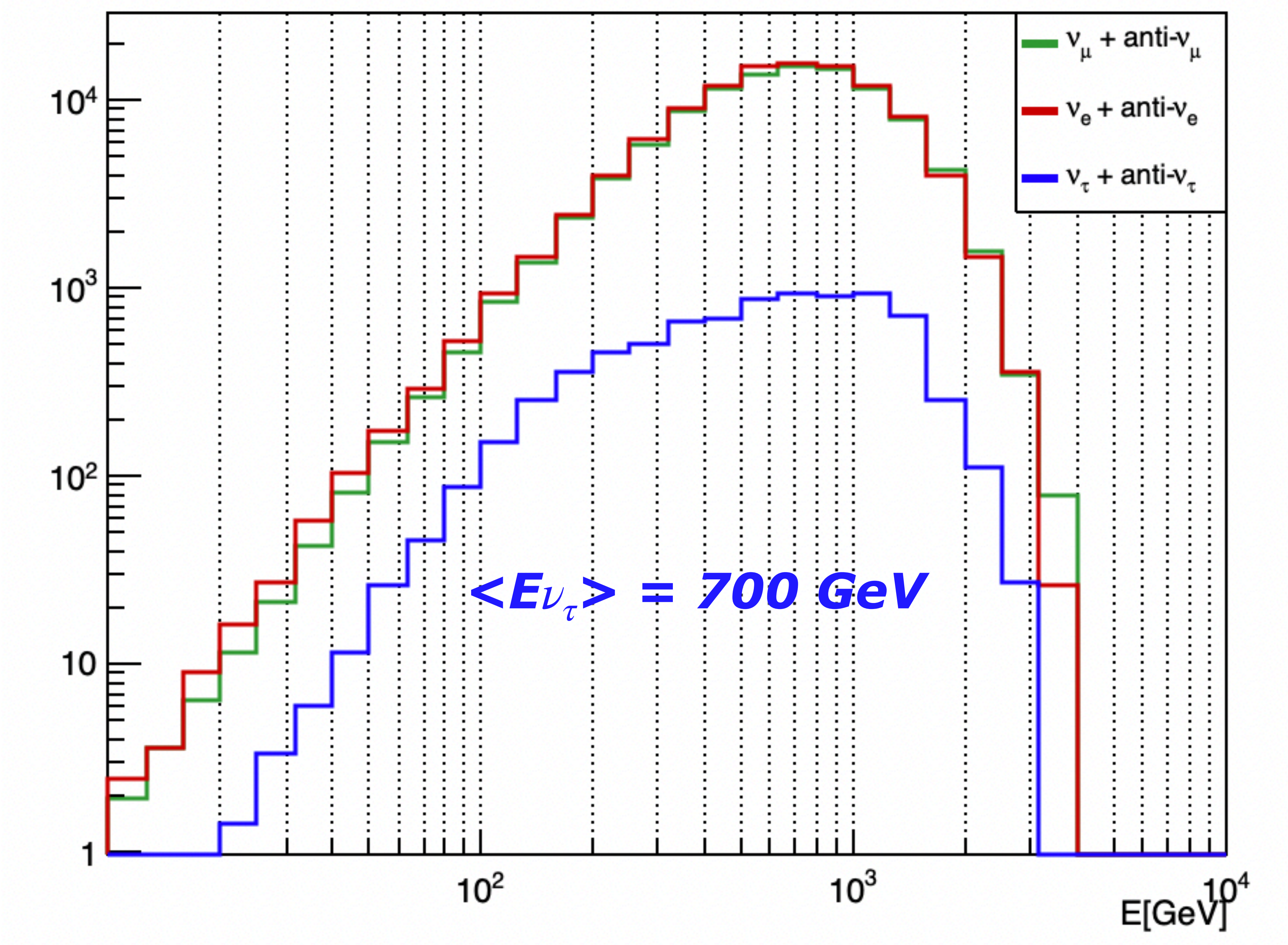
- Main task of vertex detector:
  - Reconstruction of neutrino interaction vertex
  - Identification of **tau lepton** decay vertex

*Neutrino CC interactions* ***@AdvSND-Near***
hardQCD: cc + bb
*3000 fb$^{-1}$*




Average tau neutrino energy $\langle E\nu_\tau \rangle$ ~ 60 GeV
Average tau lepton $\langle E\tau \rangle$ ~ 30 GeV
Average tau lepton decay length **$\langle L\tau \rangle$ ~ 3 mm**

*Neutrino CC interactions* ***@AdvSND-Far***
hardQCD: cc + bb
*3000 fb$^{-1}$*




Average tau neutrino energy $\langle E\nu_\tau \rangle$ ~ 700 GeV
Average tau lepton $\langle E\tau \rangle$ ~ 350 GeV
Average tau lepton decay length **$\langle L\tau \rangle$ ~ 3.5 cm**

# VERTEX DETECTOR

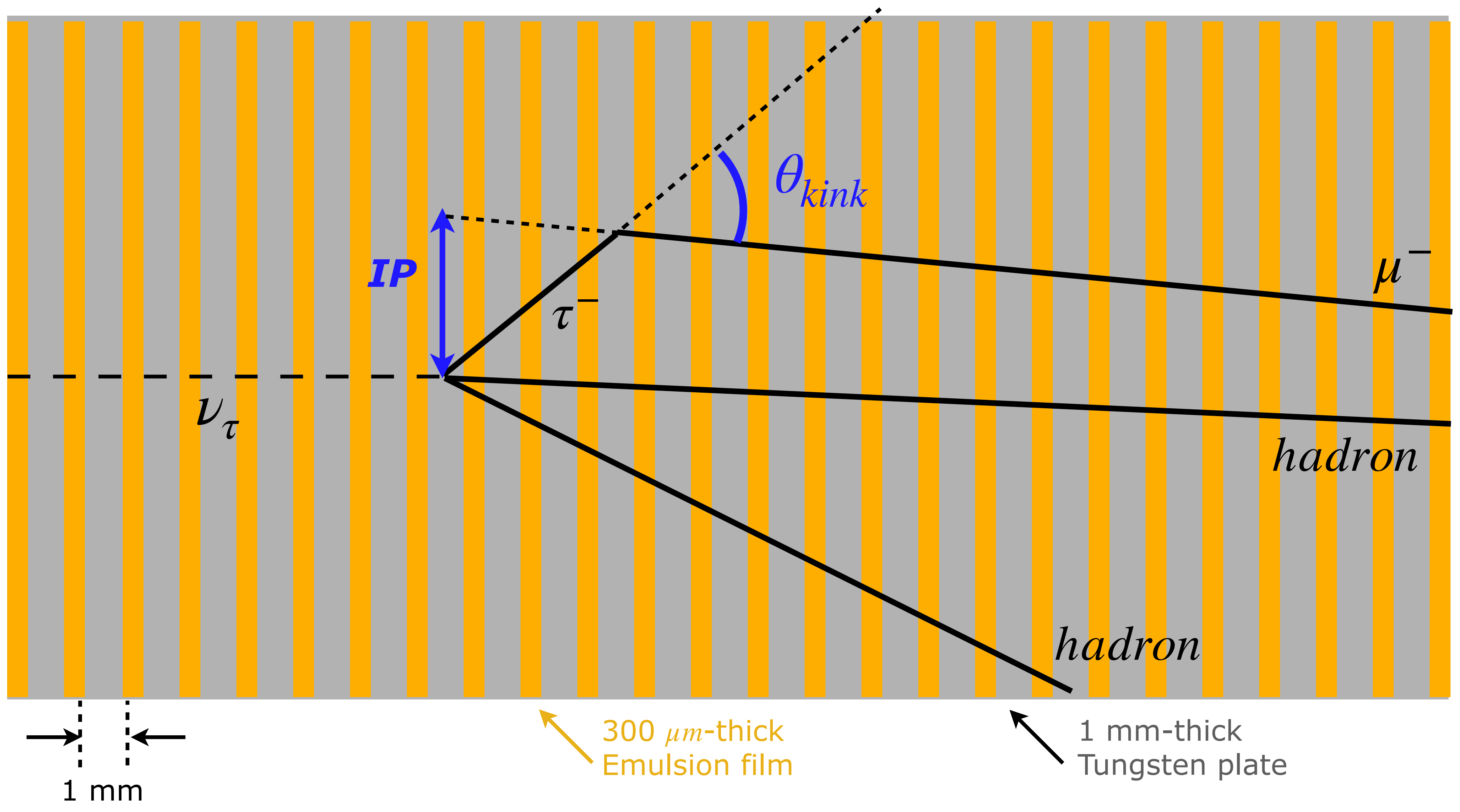


- Decay vertex identification performed by searching for:
  - large kink angle
  - large impact parameter

*Average impact parameter* ***<IP> ~ 100 $\mu$m***

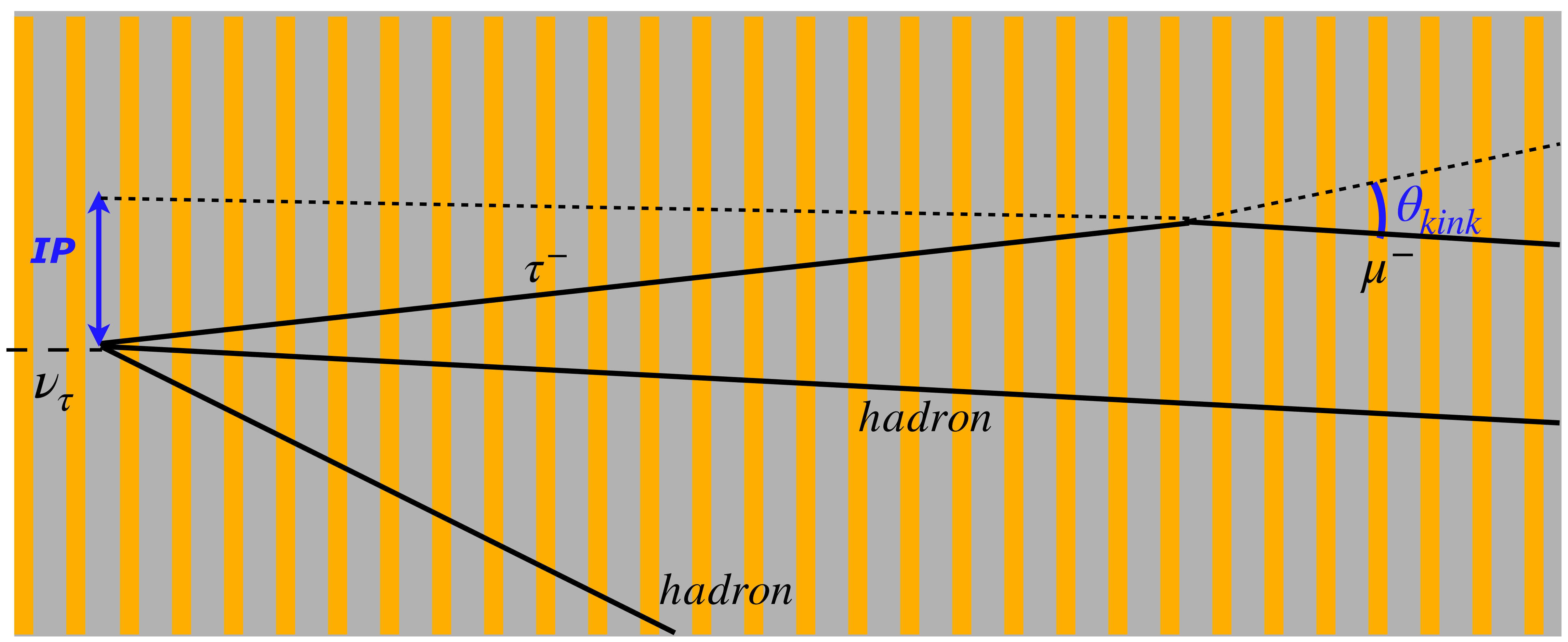
**AdvSND-Near**

*Average tau lepton decay length* ***$<L_\tau>$ ~ 3 mm***
*Average kink angle* ***$<\theta_{kink}>$ ~ 30 mrad***




**AdvSND-Far**

*Average tau lepton decay length* ***$<L_\tau>$ ~ 3.5 cm***
*Average kink angle* ***$<\theta_{kink}>$ ~ 3 mrad***




SND@LHC Emulsion Cloud Chamber

# VERTEX DETECTOR: Near Detector

- Monolithic Active Pixel Sensors (MAPS)
  Sensor and readout on the same piece of silicon
  Advantages
  - High granularity/precision
  - Minimal material/thickness
  - Low power density

  Limitations
  - Radiation tolerance
  - Rate capability

**Based on high resistivity epi layer MAPS**

**3** Inner Barrel layers (IB)
**4** Outer Barrel layers (OB)

Radial coverage: 21-400 mm

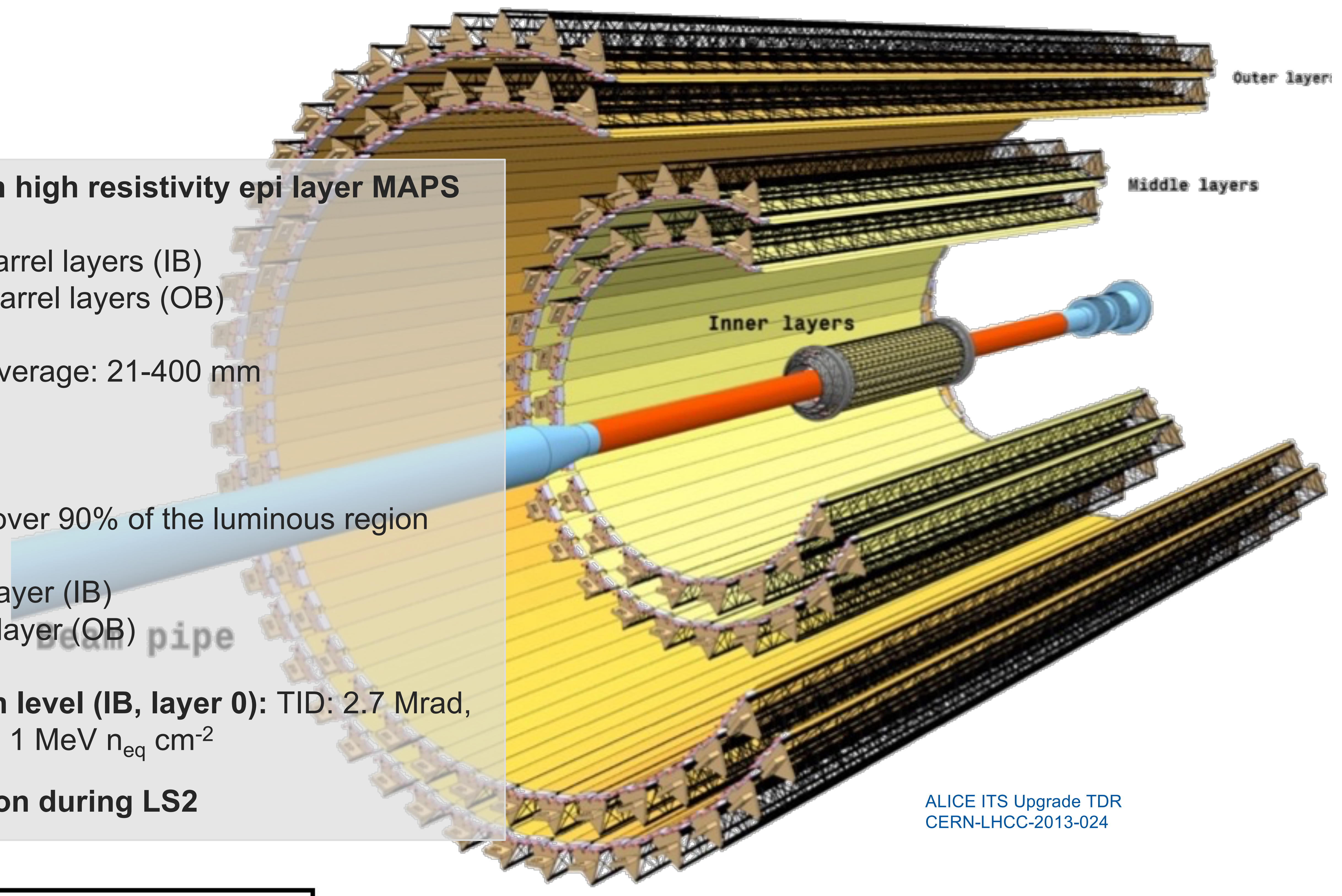
**~ 10 m$^2$**

**|η|<1.22** over 90% of the luminous region

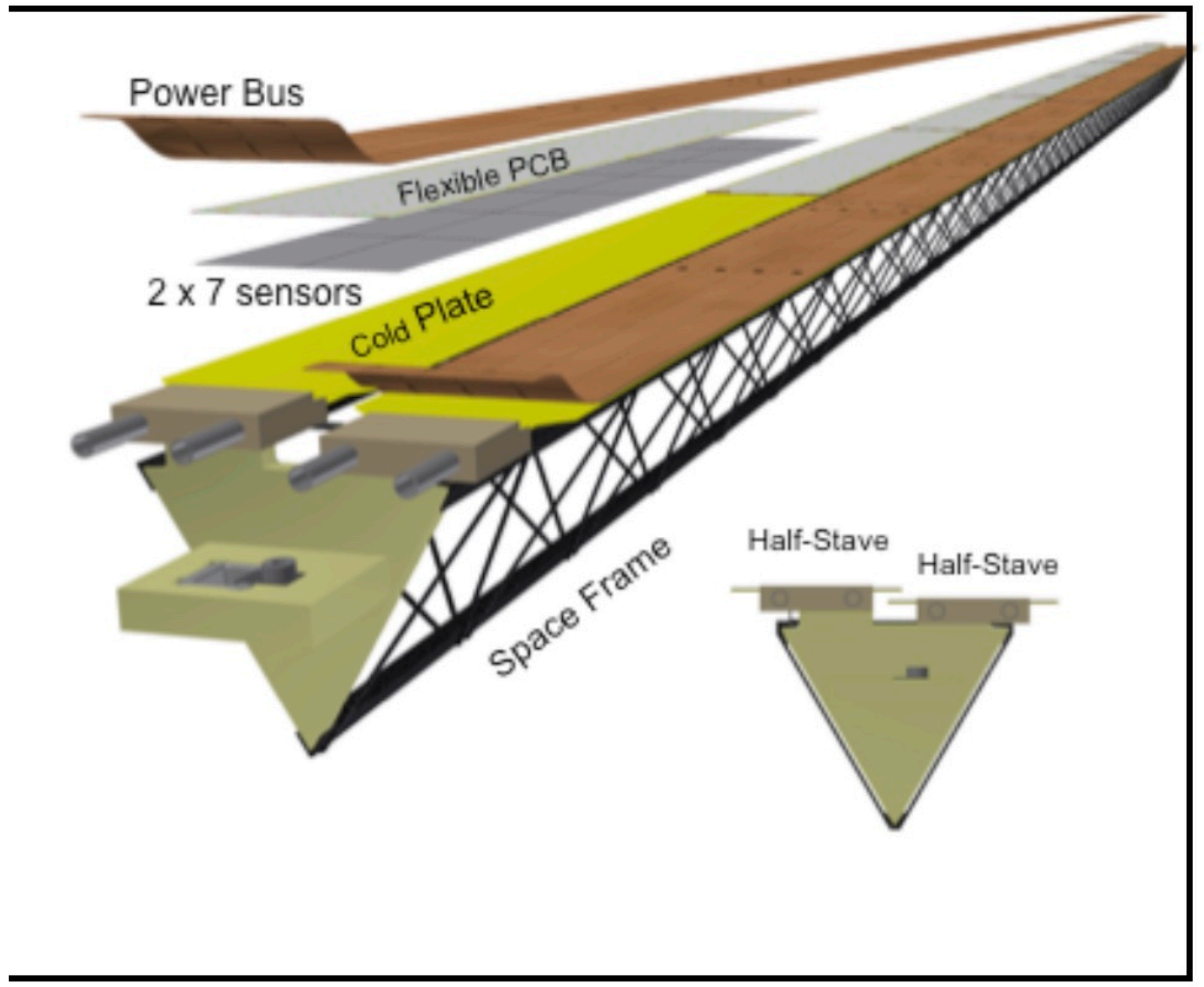
**0.3% $X_0$/layer** (IB)
0.8 % $X_0$/layer (OB)

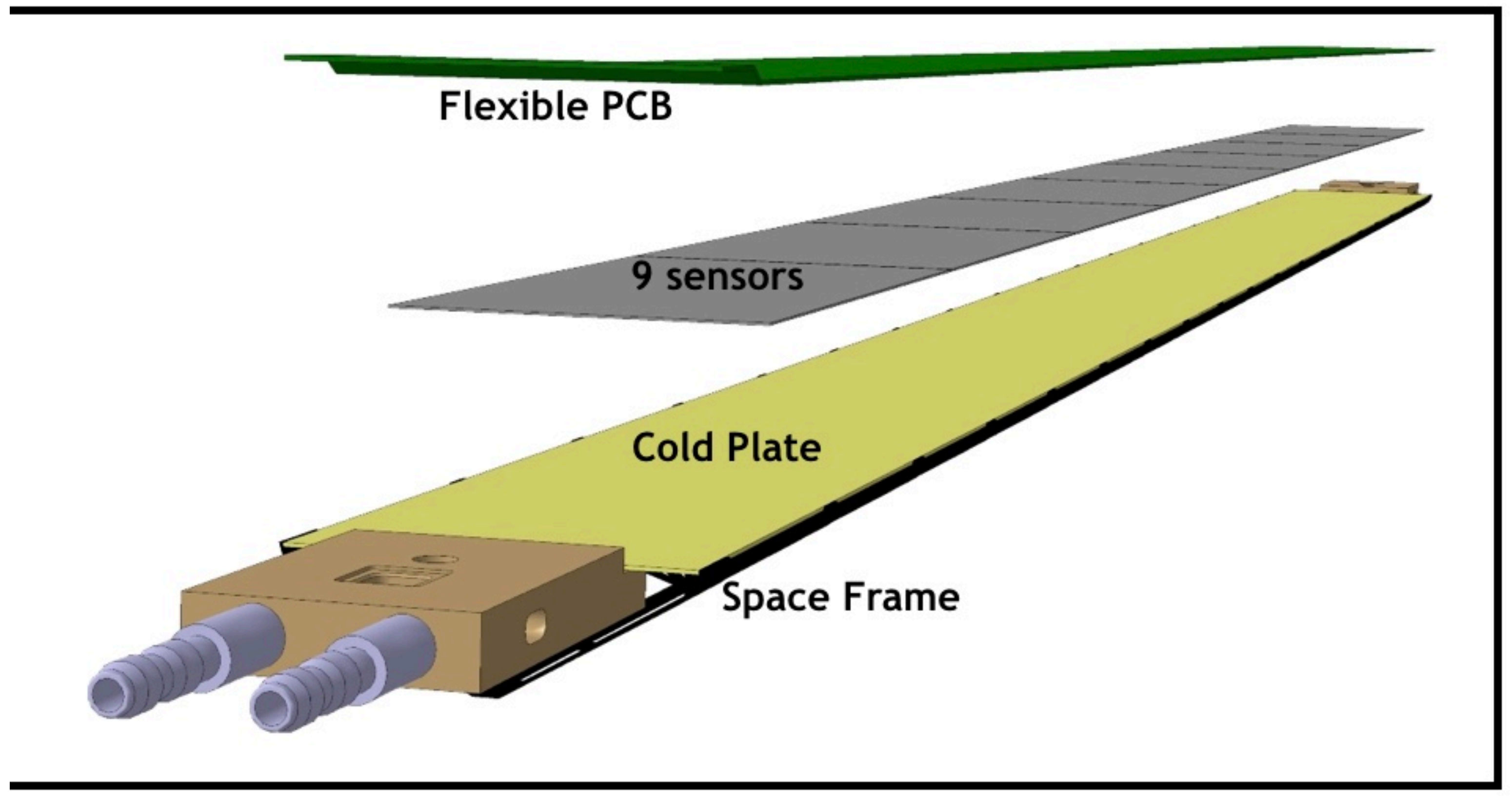
**Radiation level (IB, layer 0):** TID: 2.7 Mrad, 1.7 x $10^{13}$ 1 MeV $n_{eq}$ $cm^{-2}$

**Installation during LS2**




ALICE ITS Upgrade TDR
CERN-LHCC-2013-024



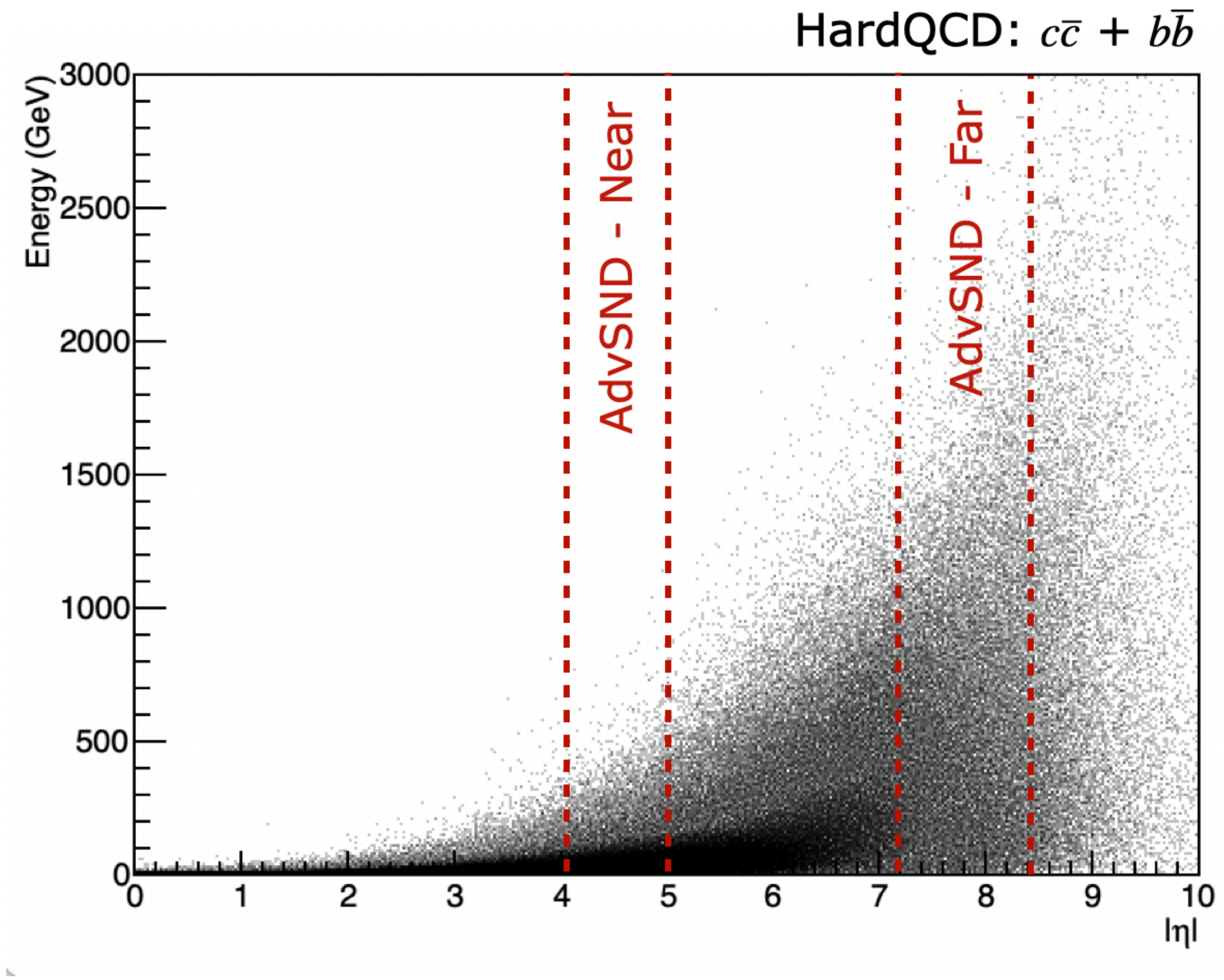



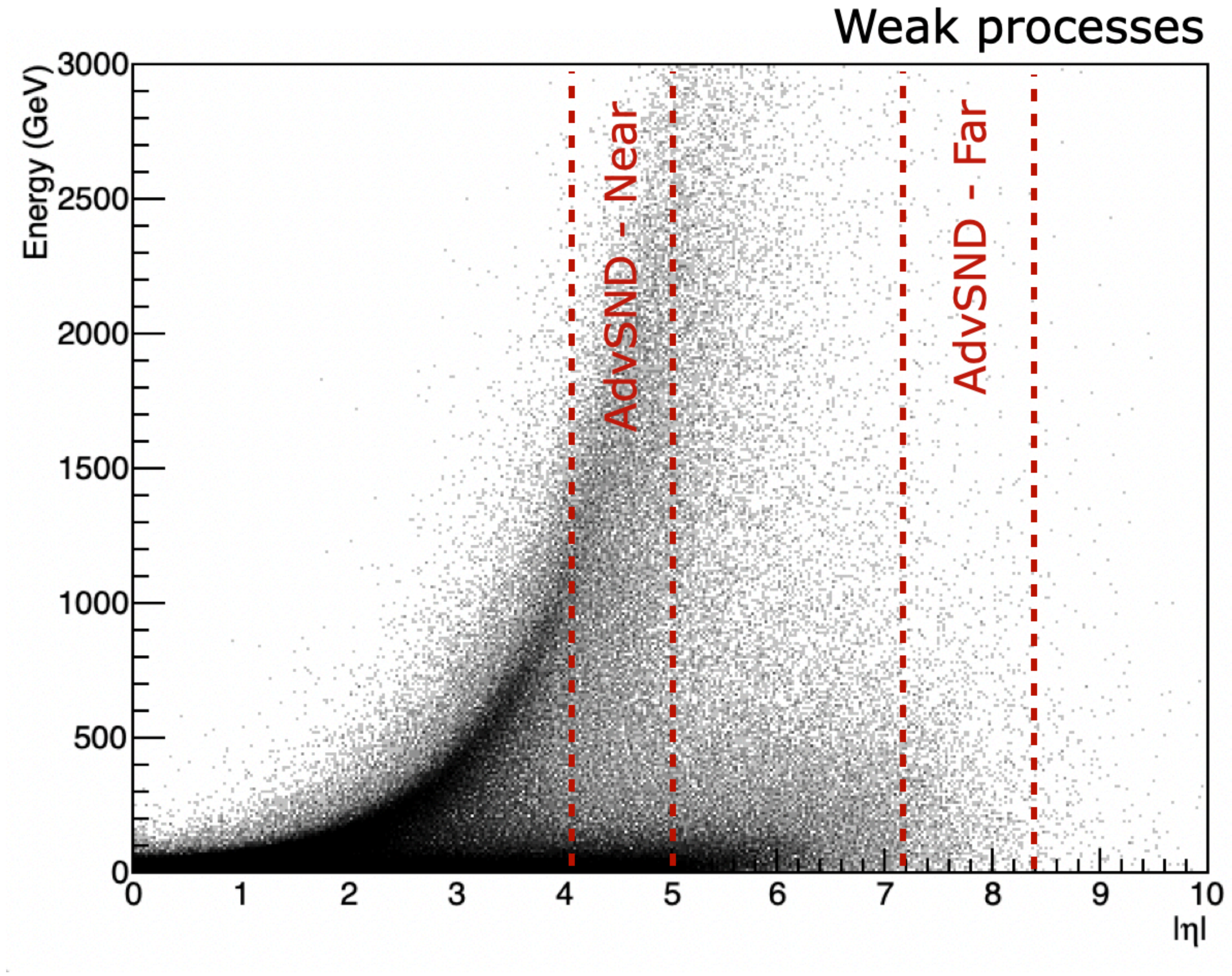
# CONCLUSIONS



- Upgrade of SND@LHC in view of an extended run during Run 4:
  - Extension of the physics case
  - Two detectors
    - AdvSND-Far ($7.2<\eta<8.4$)
    - AdvSND-Near ($4<\eta<5$)
  - New technologies and detector layout
    - Magnetic spectrometer
    - New technologies for vertex detector

# BACKUP SLIDES


HardQCD: $c\bar{c}$ + $b\bar{b}$
Energy (GeV)
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
7
8
9
10
|η|
AdvSND - Near
AdvSND - Far


Weak processes
Energy (GeV)
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
7
8
9
10
|η|
AdvSND - Near
AdvSND - Far

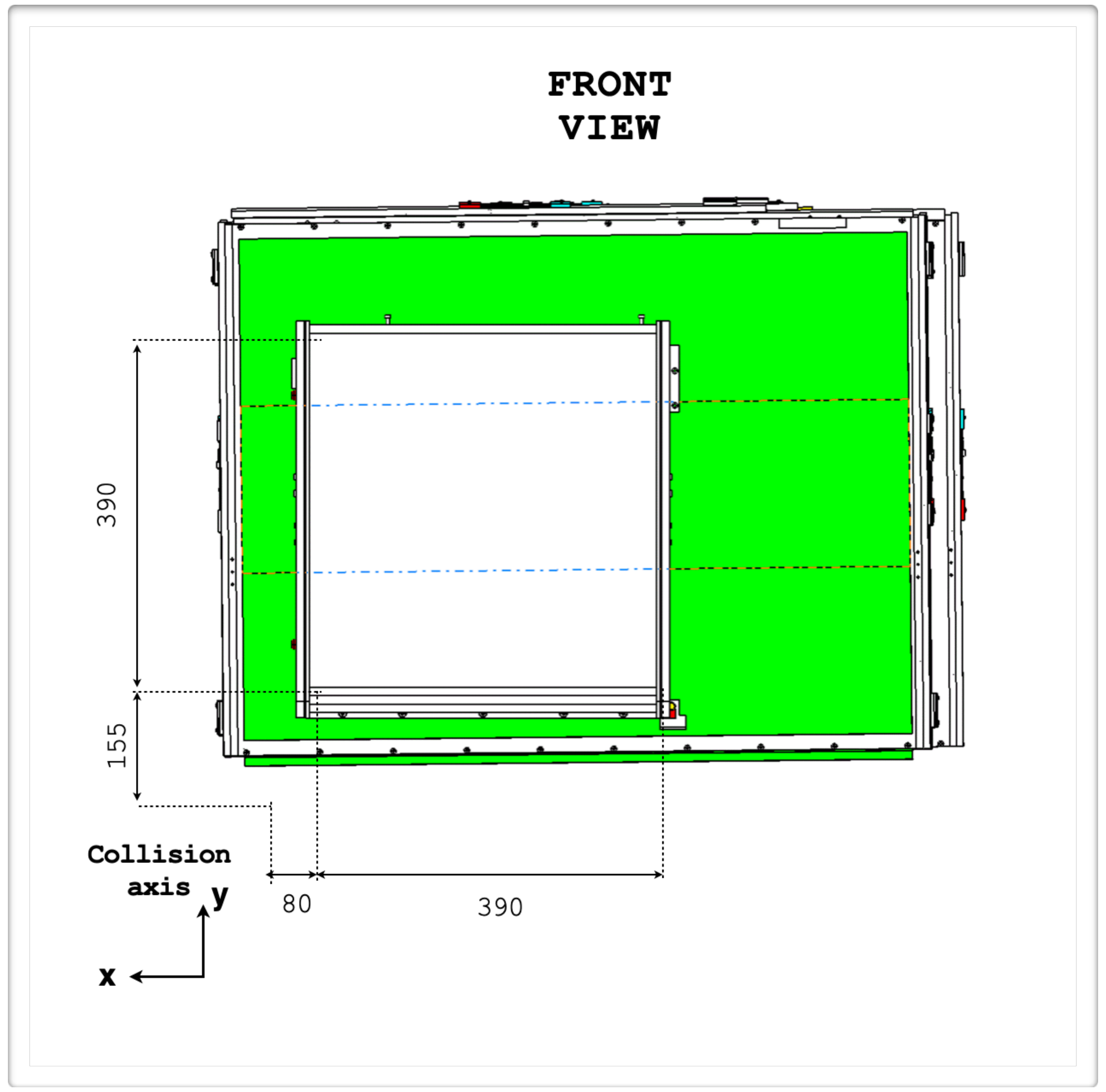
# THE SND@LHC DETECTOR LAYOUT

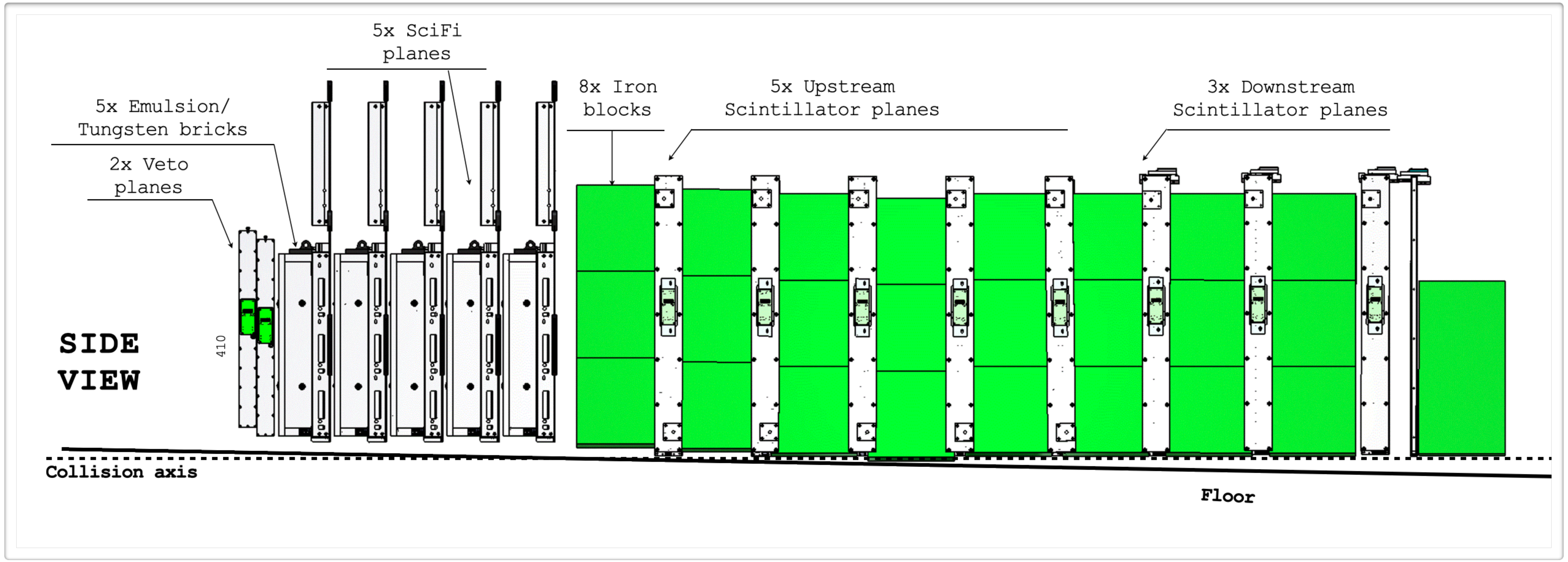
- Angular acceptance: $7.2 < \eta < 8.4$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm²

Off axis location

Electromagnetic calorimeter
~40 $X_0$

Hadronic calorimeter
~10 λ



# SND@LHC INSTALLATION IN TI18



- Detector commissioning on surface (North Area @CERN) in September and October 2021
- Installation in TI18 started on November 1st 2021

- Electronic detector installation completed on December 3rd 2021
- Installation of the neutron shield completed on March 15th 2022
- Installation of the first emulsion wall on April 7th 2022

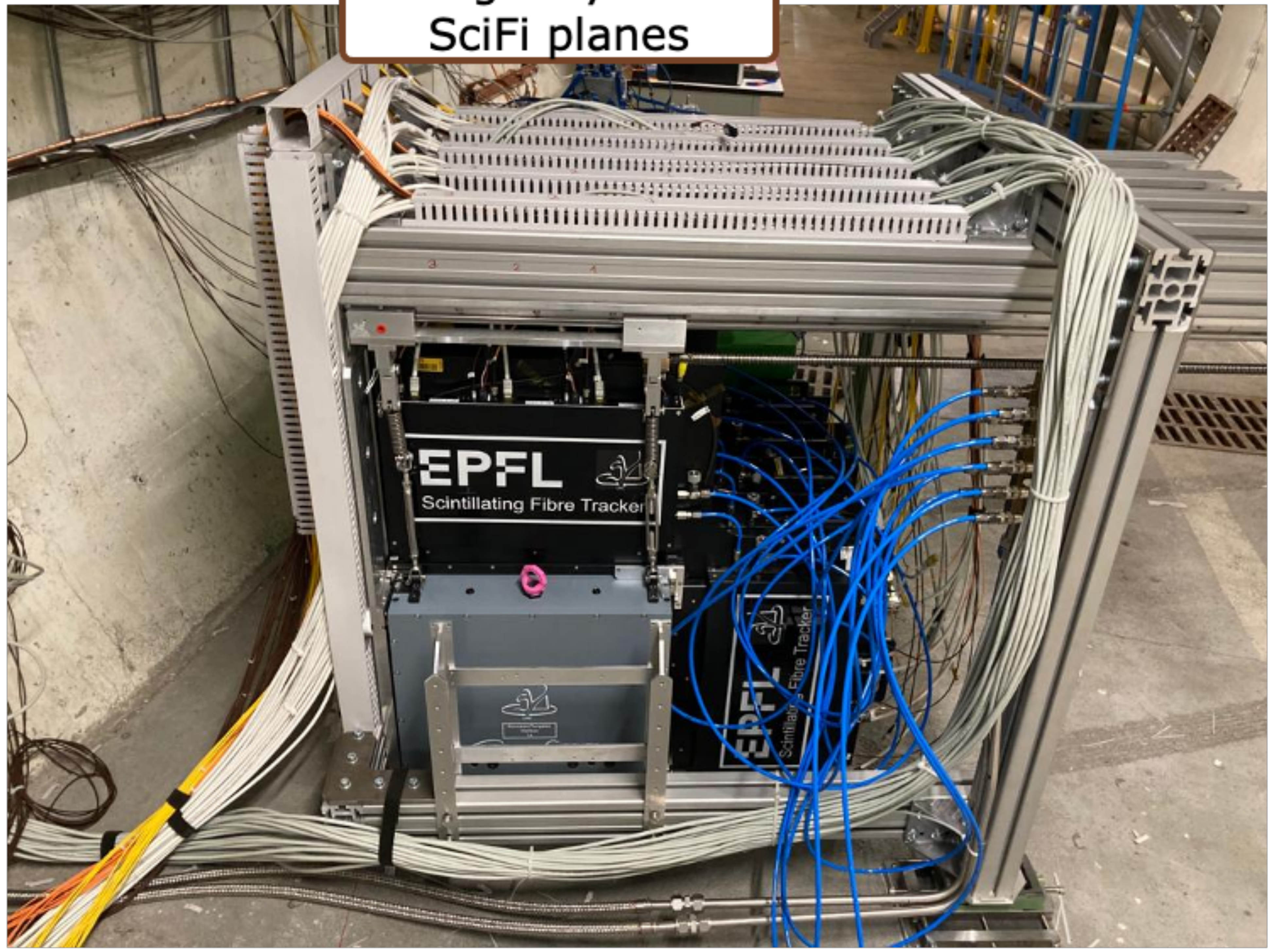
September 2021

December 2021

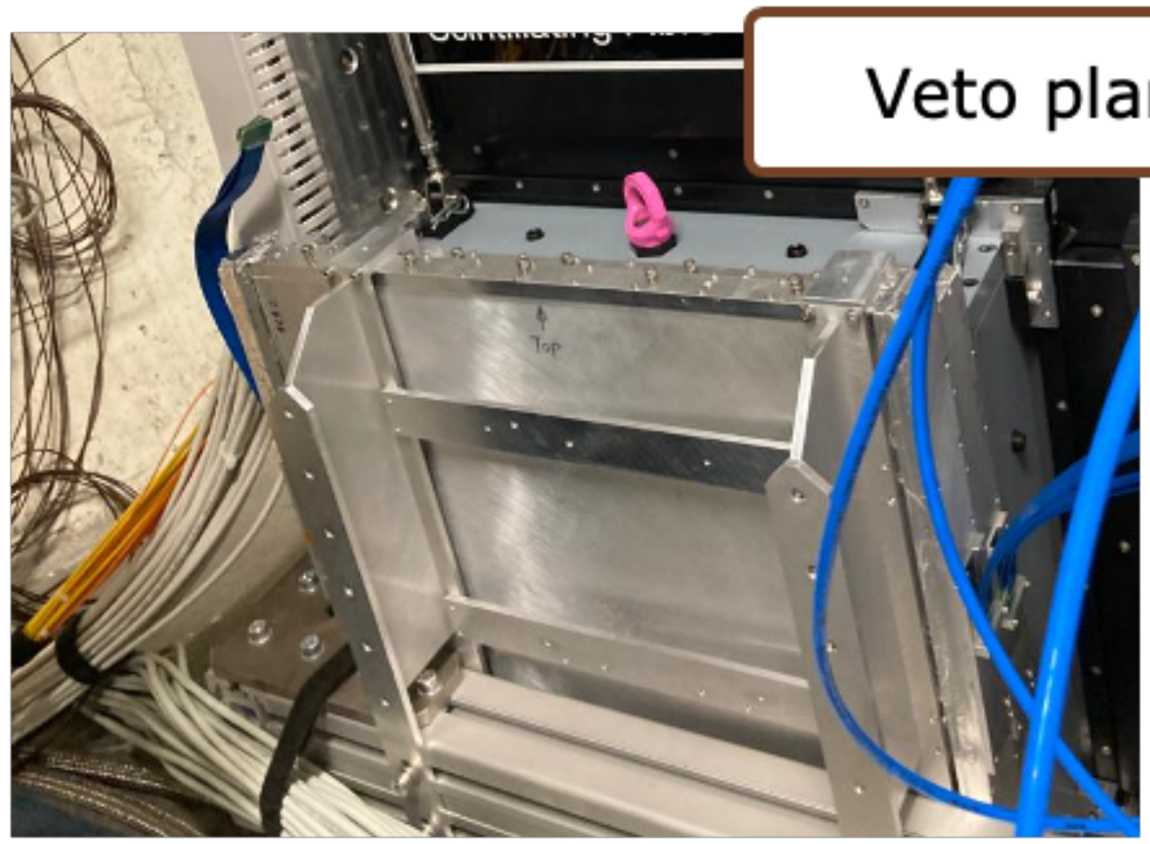
March 2022

# SND@LHC INSTALLATION IN TI18


Target wall



Target system
SciFi planes


Veto plane

Muon system