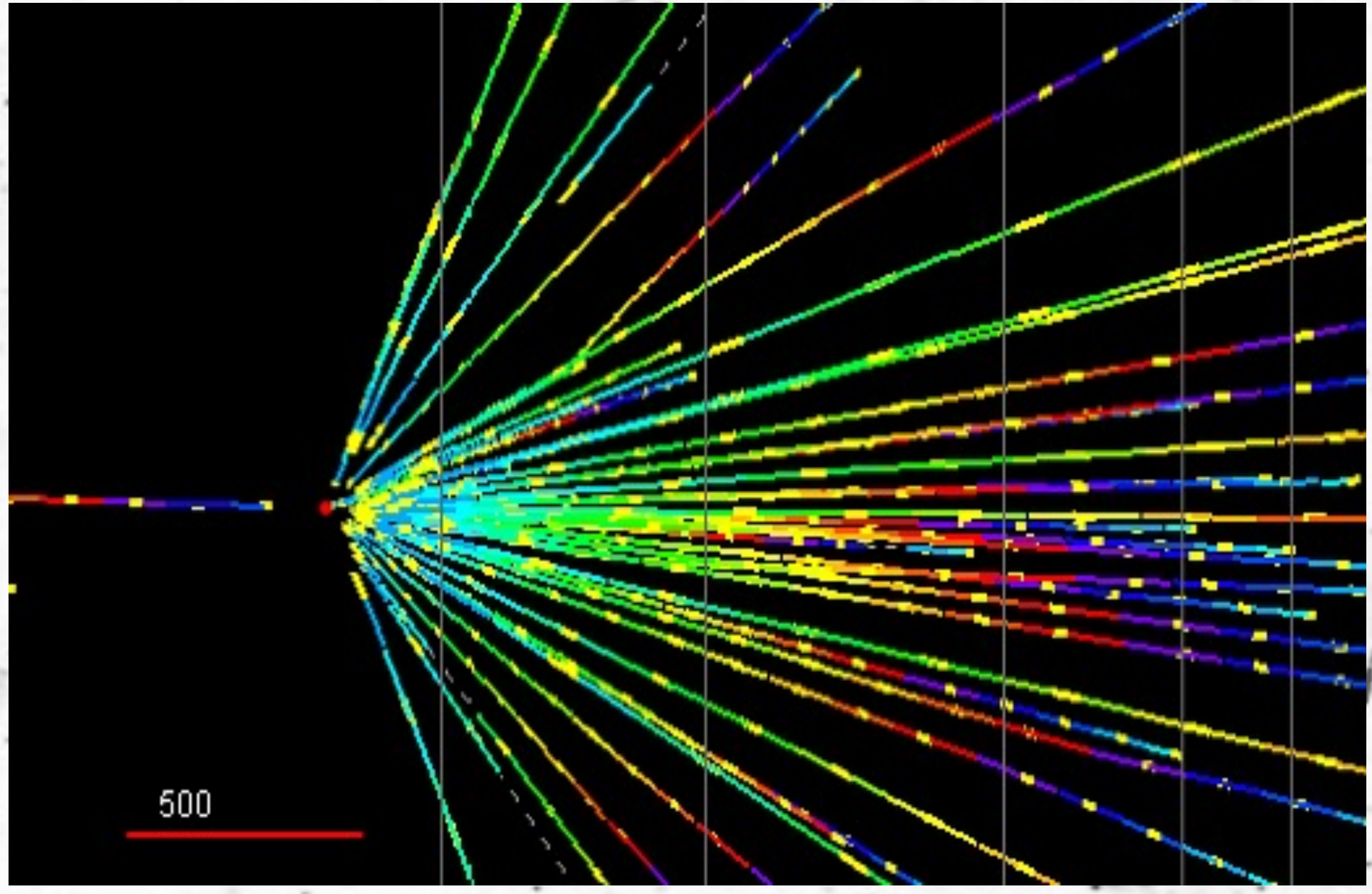
Study of tau neutrino production in NA65 experiment at CERN SPS

Yury Gornushkin (JINR, Dubna)
For DsTau Collaboration



Outline

- Motivation
- Technique description
- Analysis status
- Summary and Prospects

TWENTIETH LOMONOSOV CONFERENCE August, 19-25, 2021 ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Tau neutrino interaction cross-section

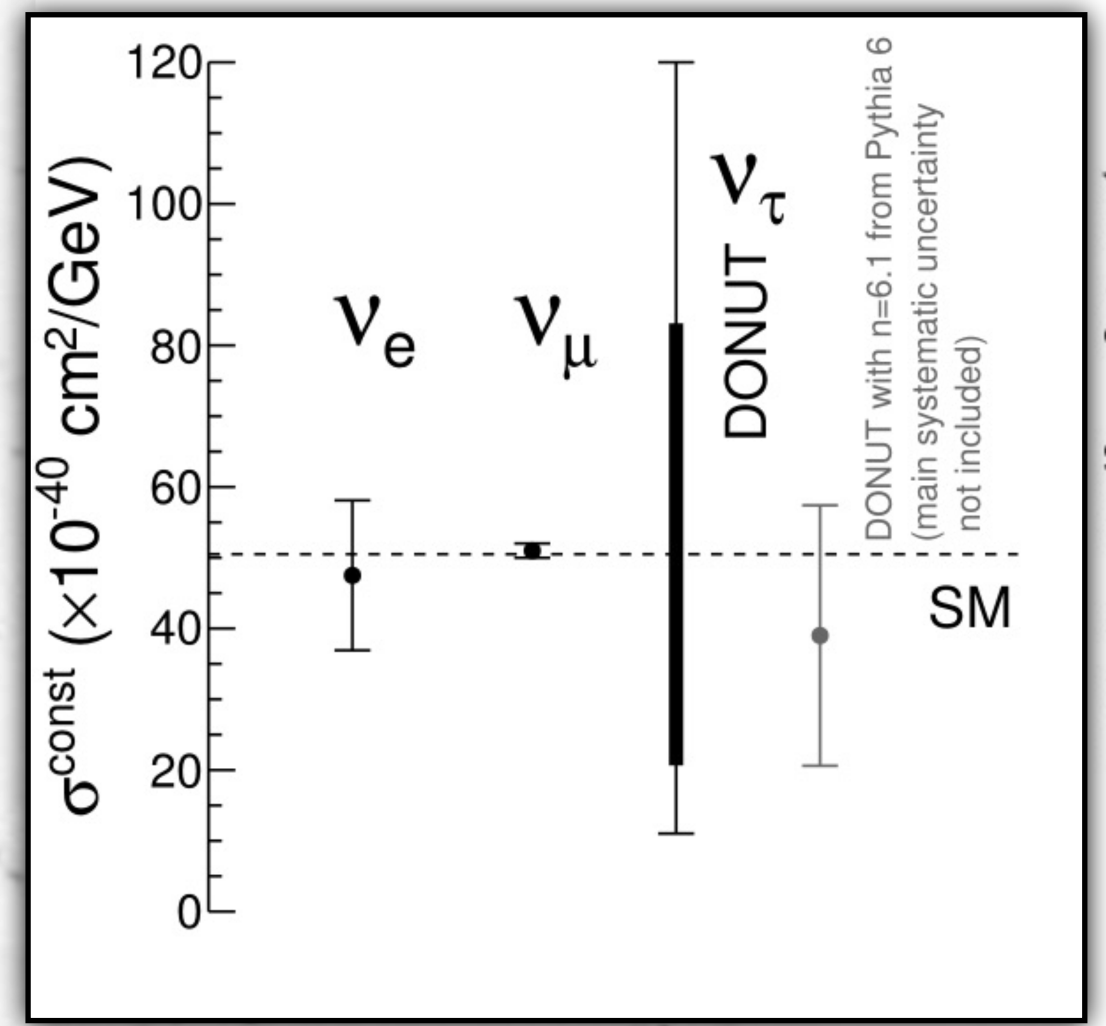
Tau neutrino is the least studied particle at the moment

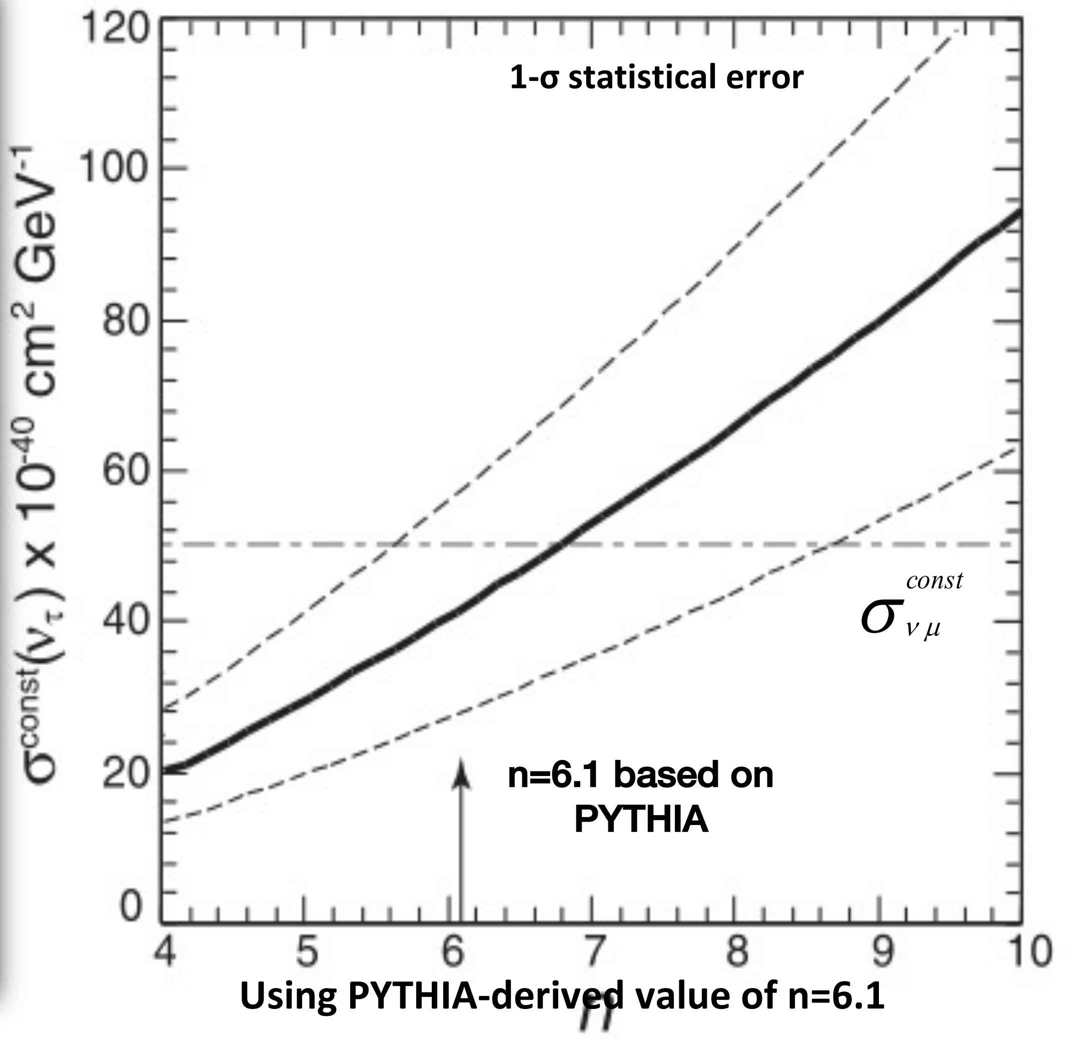
Only a few measurements:

Direct detection in beam-dump: **DONuT** (DIS) – 9 events

Oscillated : **OPERA** (DIS), **Super-K** (QE), **IceCube**(DIS)

Cross section by DONuT: statistical error 33%
systematic error >50%
due to uncertainty in ν_τ flux



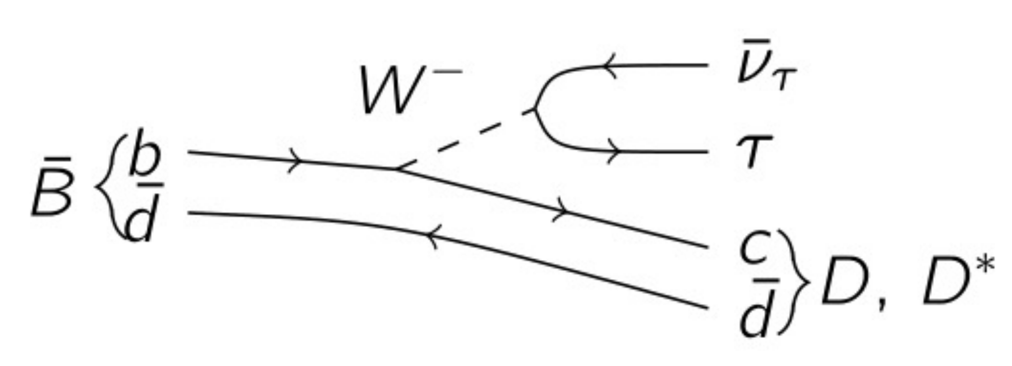


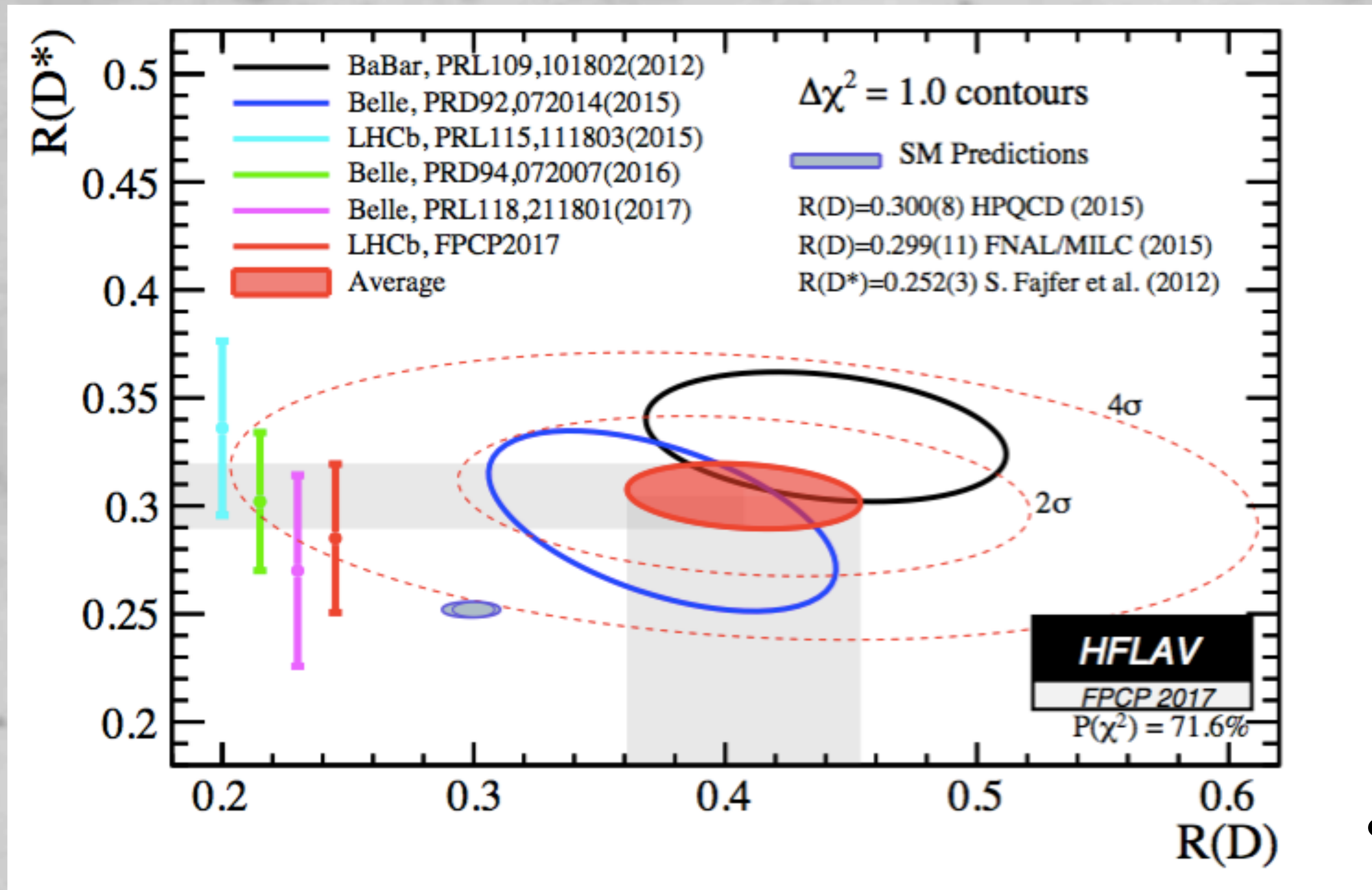
More accurate measurement of ν_τ cross-section would provide a complementary test of LU in neutrino scattering

Hints of Lepton Universality Violation

- Semi-leptonic decays of B meson prefers to decay into τ and ν_τ

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\mu\bar{\nu}_\mu)}$$





BaBar:
- hadronic tag, leptonic τ

Belle:
- hadronic tag, leptonic τ
- semileptonic tag, leptonic τ
- hadronic tag, hadronic τ

LHCb:
- leptonic τ (only muons)
- hadronic τ (3-prongs)

- Experimental results and SM prediction disagree by 4 σ
- $B_C \rightarrow J/\Psi + \tau + \nu_\tau$ also has similar tendency (2 σ)
- Flavour Anomaly?

The NA65/DsTau experiment at the CERN SPS

- Study of ν_τ production for future tau neutrino experiments.
- D_s **double differential production cross section** measurement as 95% of ν_τ are produced in $D_s \rightarrow \tau \rightarrow X$ decays

$$\frac{d^2\sigma}{dx_F dp_T^2} \propto (1-|x_F|)^n \exp(-bp_T^2)$$

To reduce ν_τ flux uncertainty from >50% to 10%

Fundamental input for future ν_τ experiment: SHiP, and indirectly FASER, SND@LHC

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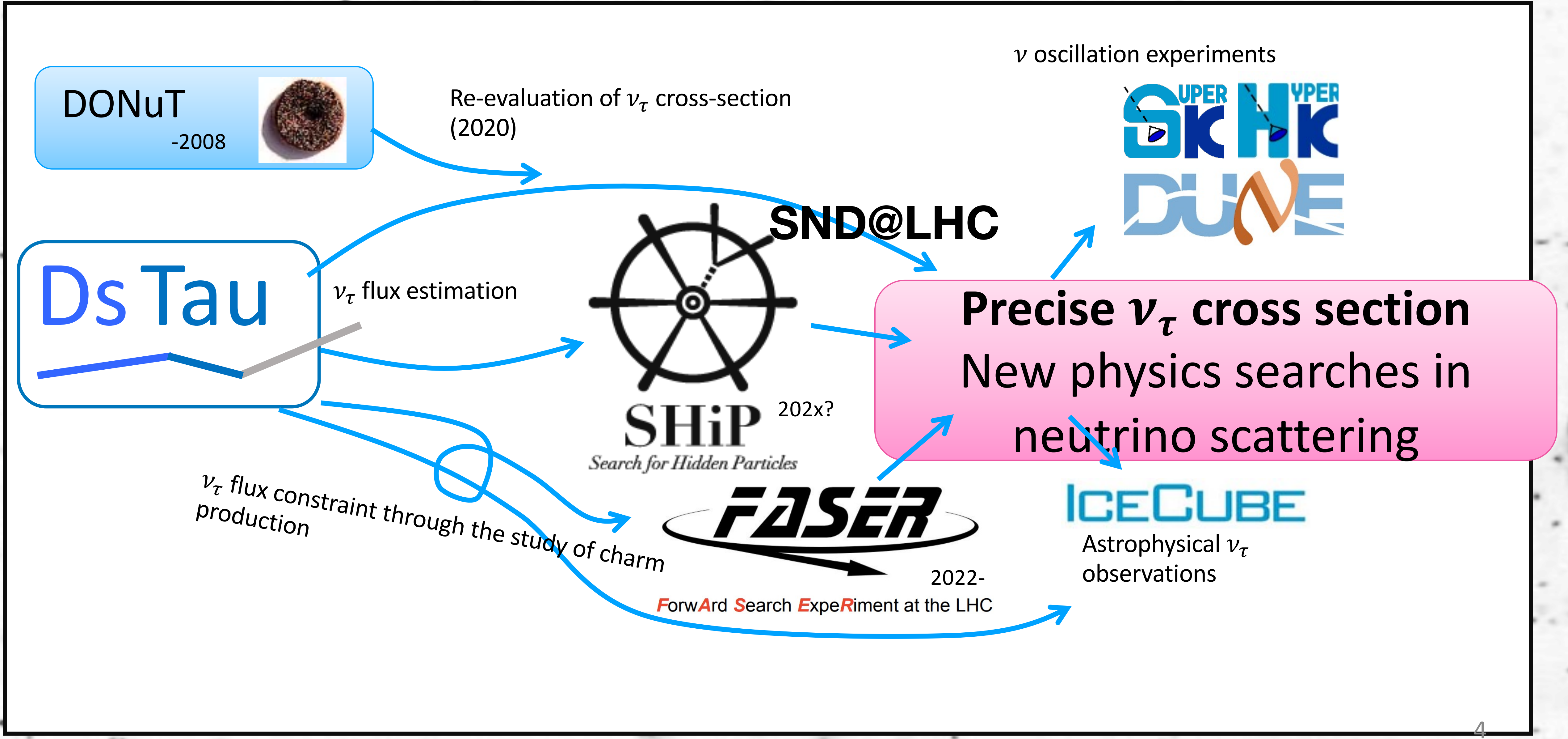
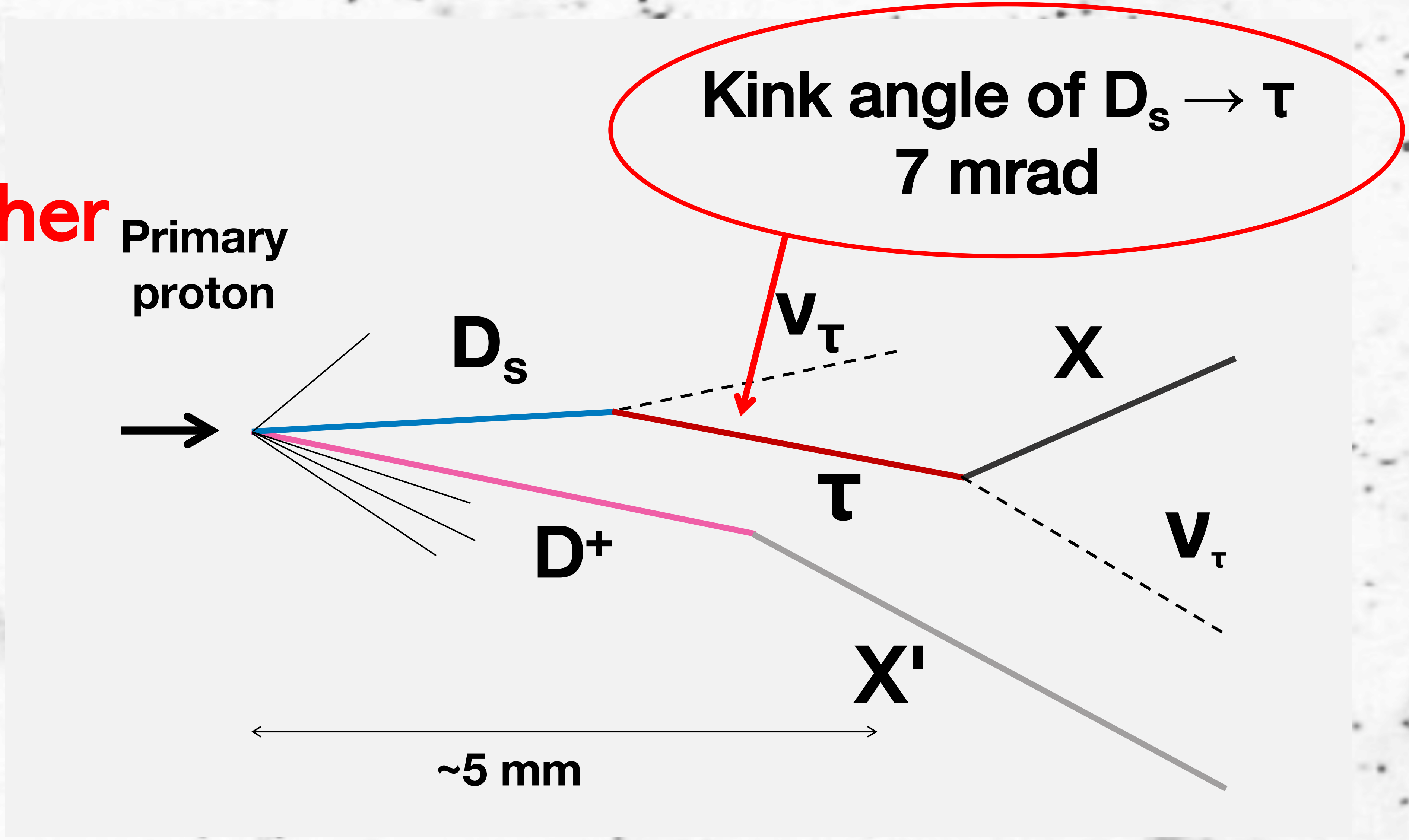


Principle of the experiment

Detection of double-kink + another decay topology within a few mm with emulsion detector



DsTau Collaboration

- Letter of Intent submitted to the CERN-SPSC in 2016
- Test Beam Studies in November 2016 and May 2017
- **Technical Proposal in 2017**
- Pilot run 2018
  - 1/10 of the full-scale experiment with tungsten target
  - 30 % uncertainty on ν_τ flux
  - Revise the DONUT result
  - Charm physics
- **Approved as NA65 in 2019**
- DsTau paper: JHEP 01(2020)033
- **Physics run 2021-2022**
  - Full scale experiment with tungsten and molybdenum targets

Japan:
Aichi
Chiba
Kobe
Kyushu
Nagoya

Switzerland:
Bern

Romania:
Bucharest

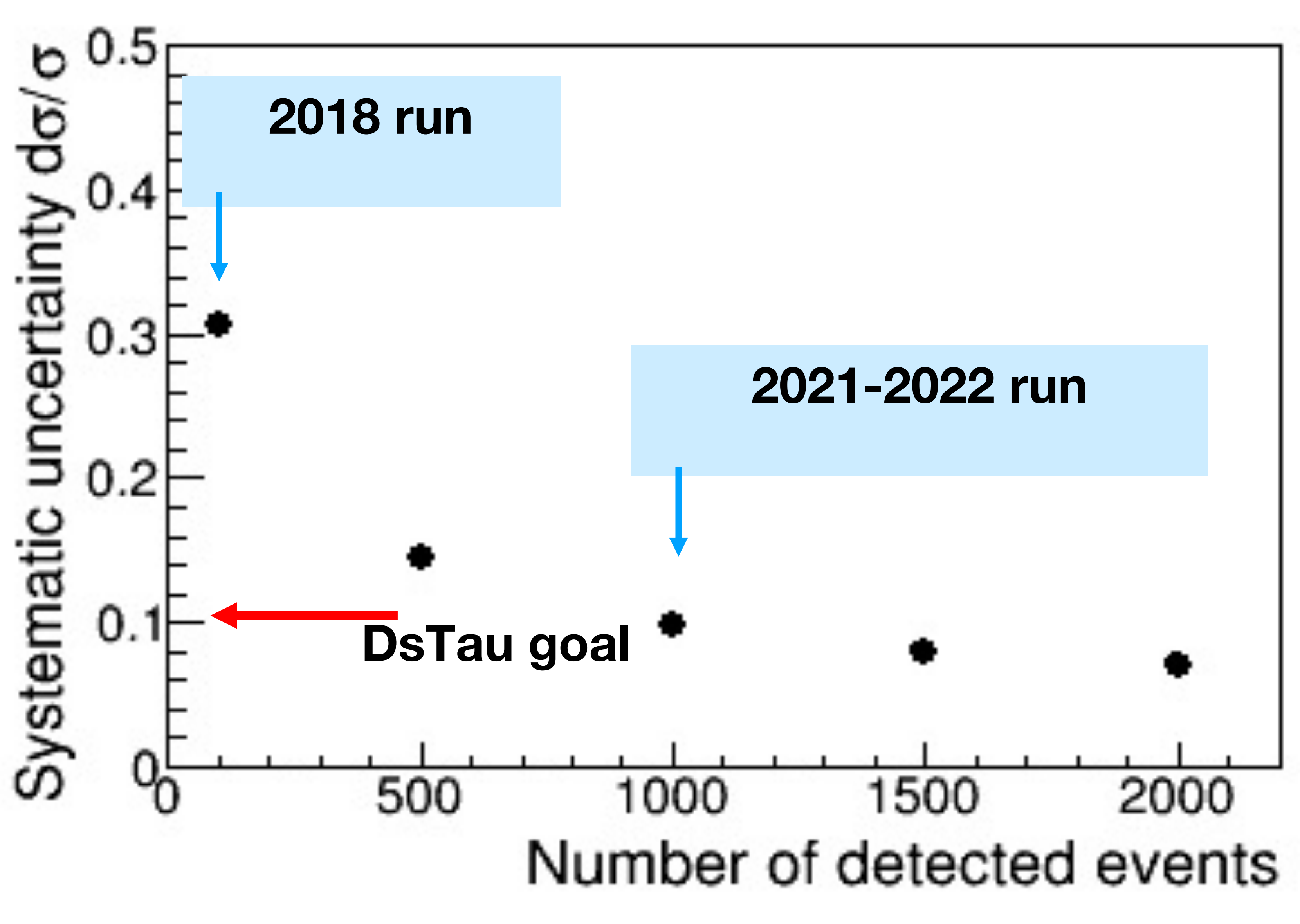
Russia:
Dubna

Turkey:
METU

DsTau web site: https://na65.web.cern.ch/

Expected performance

Run	Beam time	Emulsion surface	Systematic uncertainty for the cross section measurement
2018 pilot run	1 week	48 m² (30 modules)	30% → Re-evaluation of the DONUT result
2021 physics run	2 weeks	545 m² (338 modules)	10% → Input for future measurement
2022 physics run	2 weeks		

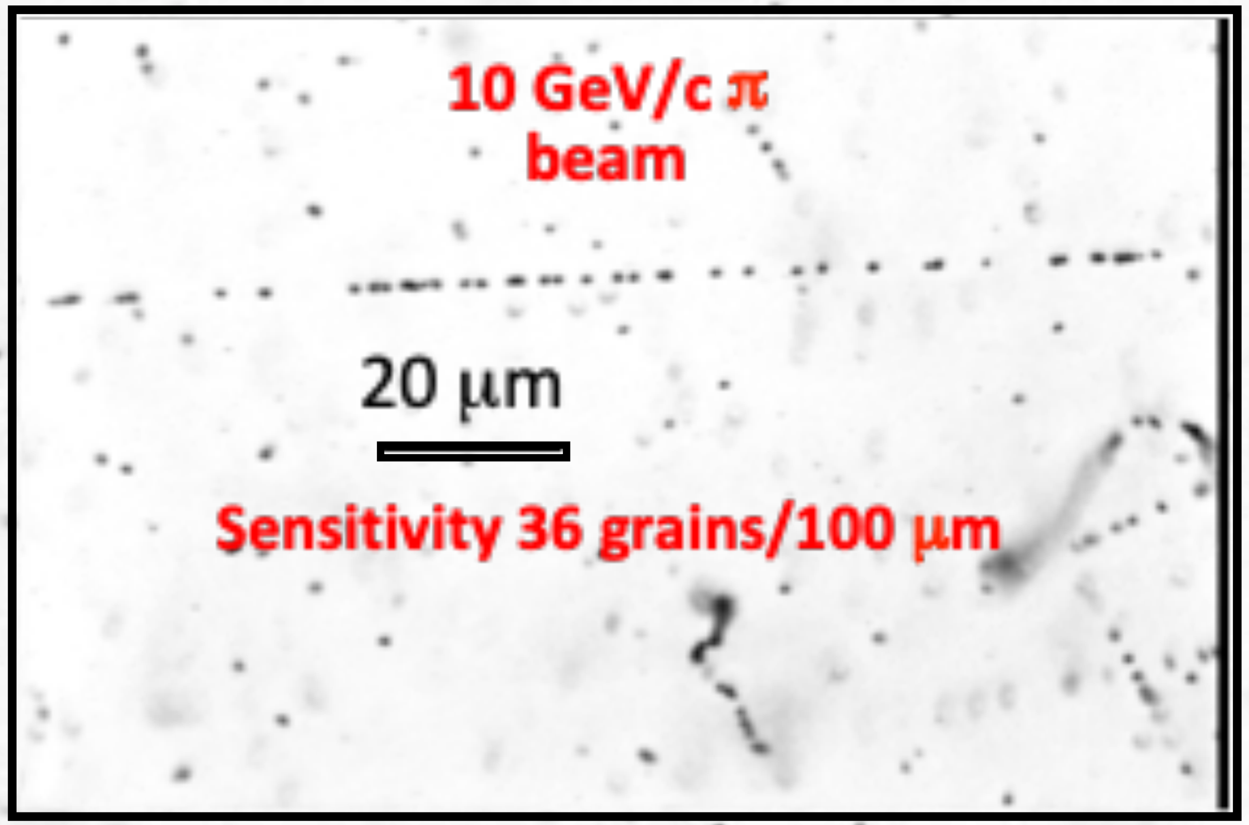


Systematic uncertainties	DONUT	With DsTau
D_s differential cross section (x_F dependence)	~0.5	0.1
Charm production cross section	0.17	0.05
Decay branching ratio	0.23	
Target atomic mass effects (A dependence)	0.14	

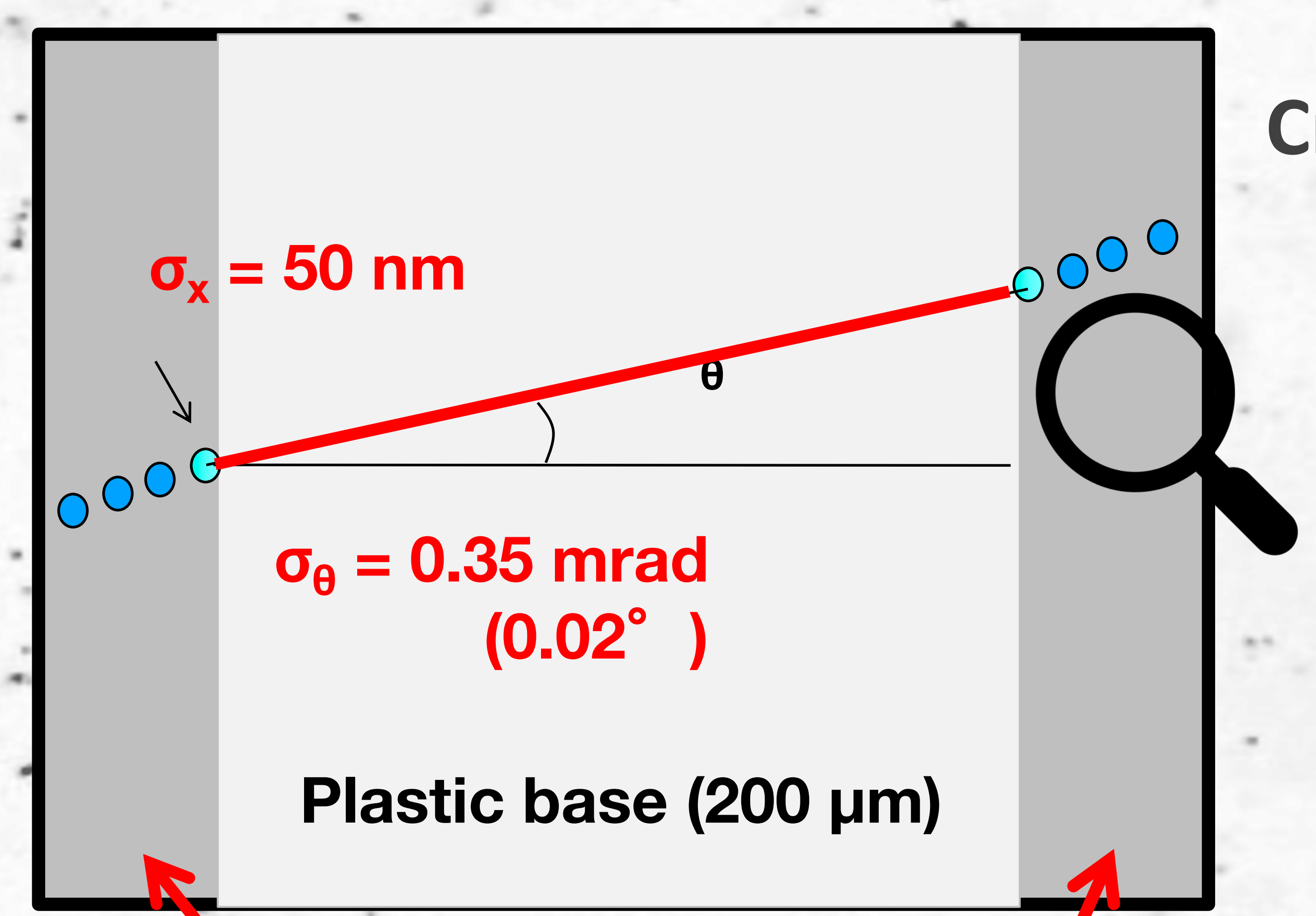
Nuclear Emulsion detectors have highest spatial resolution

Nucl.Instrum.Meth.A 556 (2006) 80-86

Emulsion film

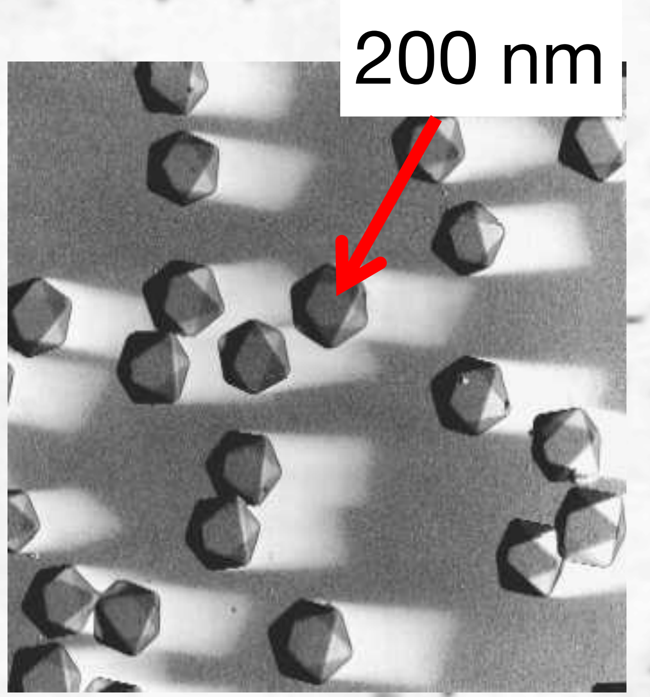


Single emulsion film is high angular resolution tracker



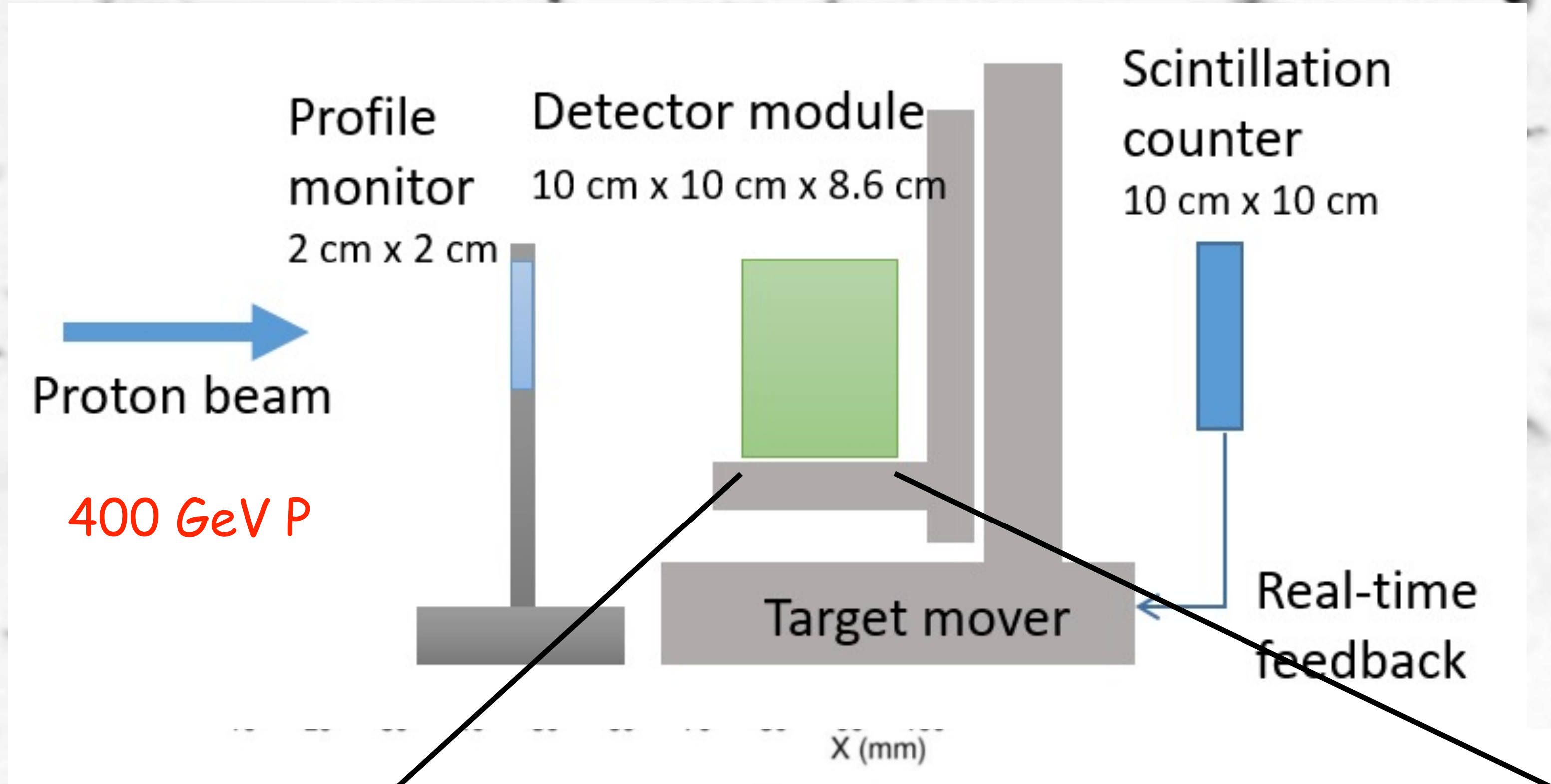
Emulsion layers (70 μm)

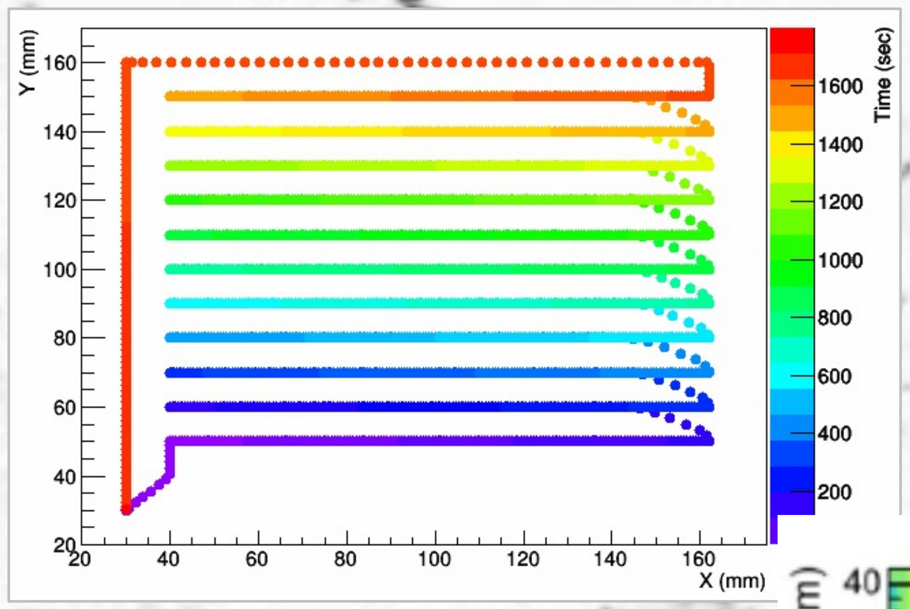
Cross-sectional view



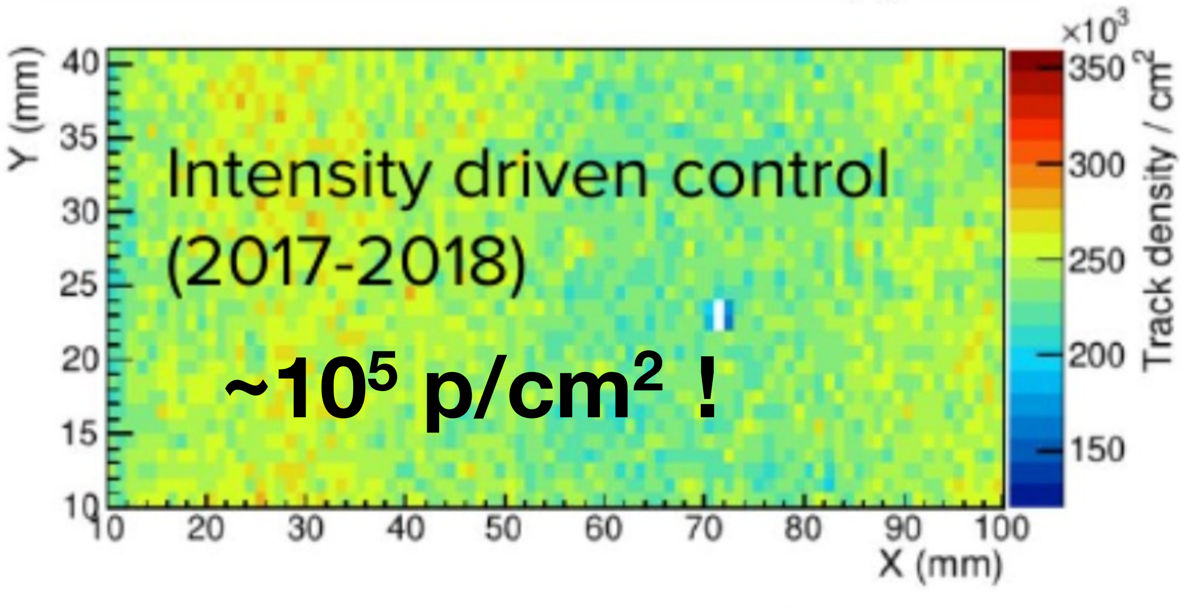
- 10^{14} AgBr crystals per film
- Volume occupancy 30%
- Detection efficiency per crystal 16%

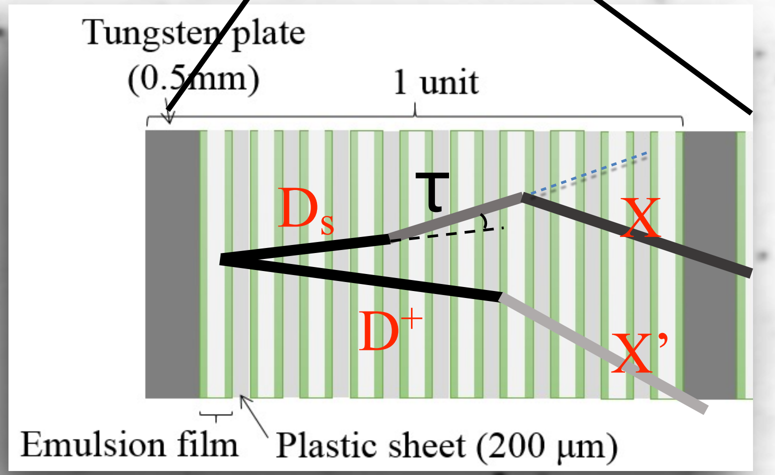
Principle of DsTau experiment





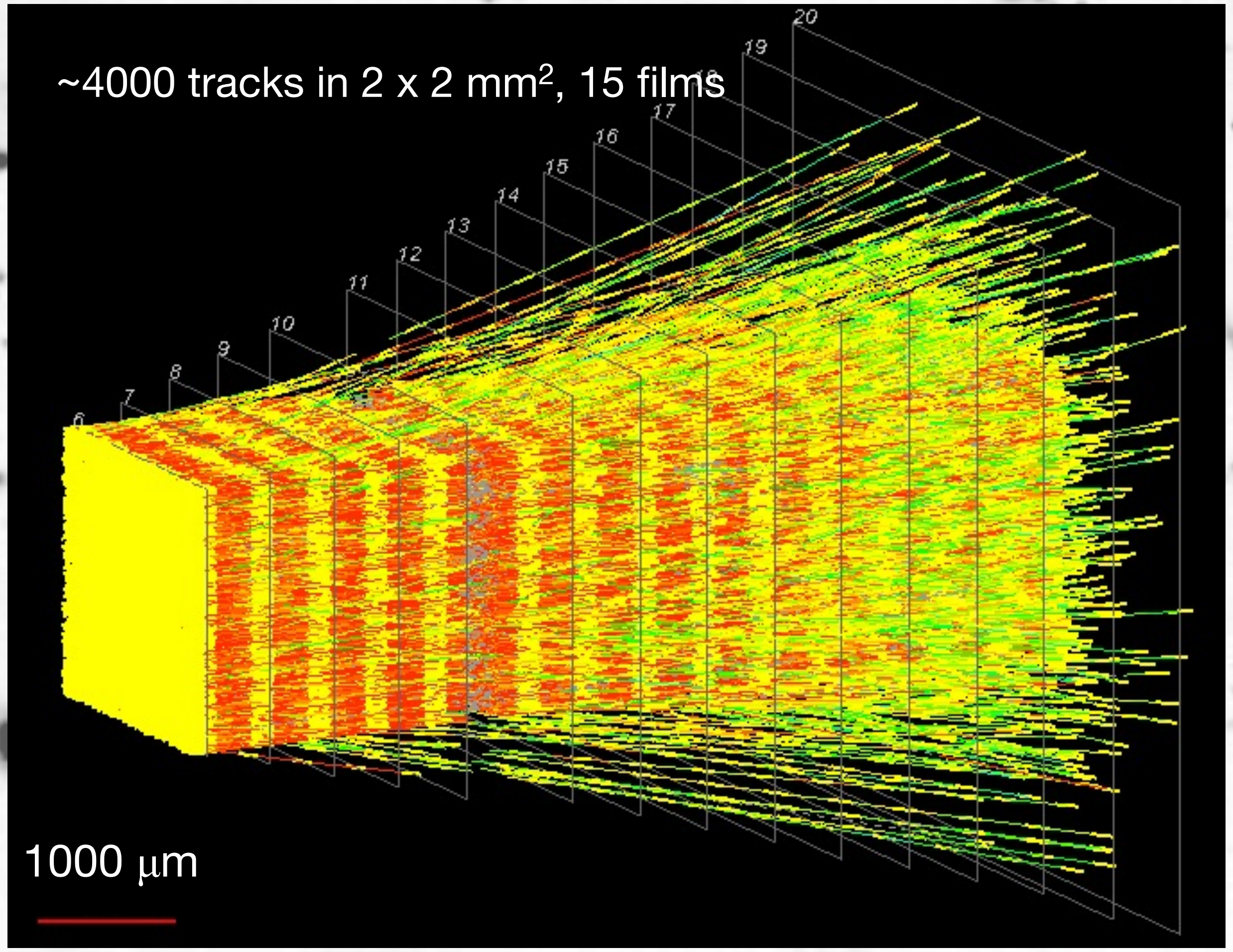
A target instrumented with high resolution detectors uniformly exposed to the proton beam at SPS

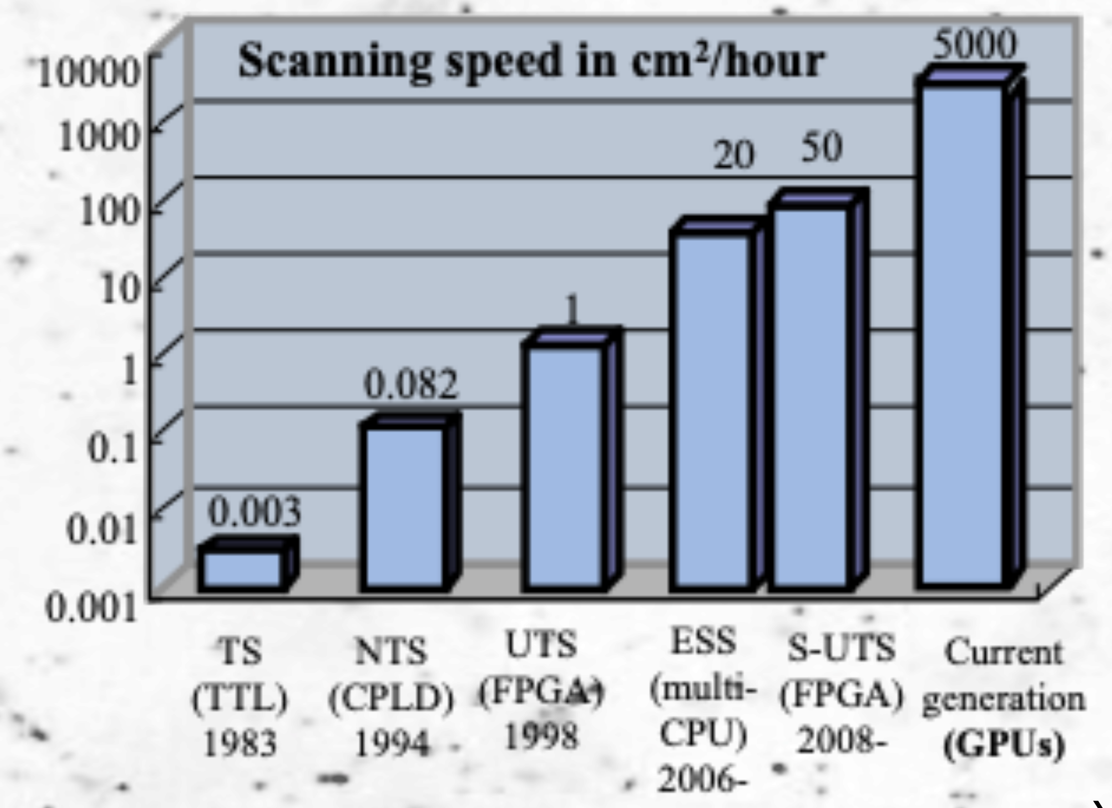


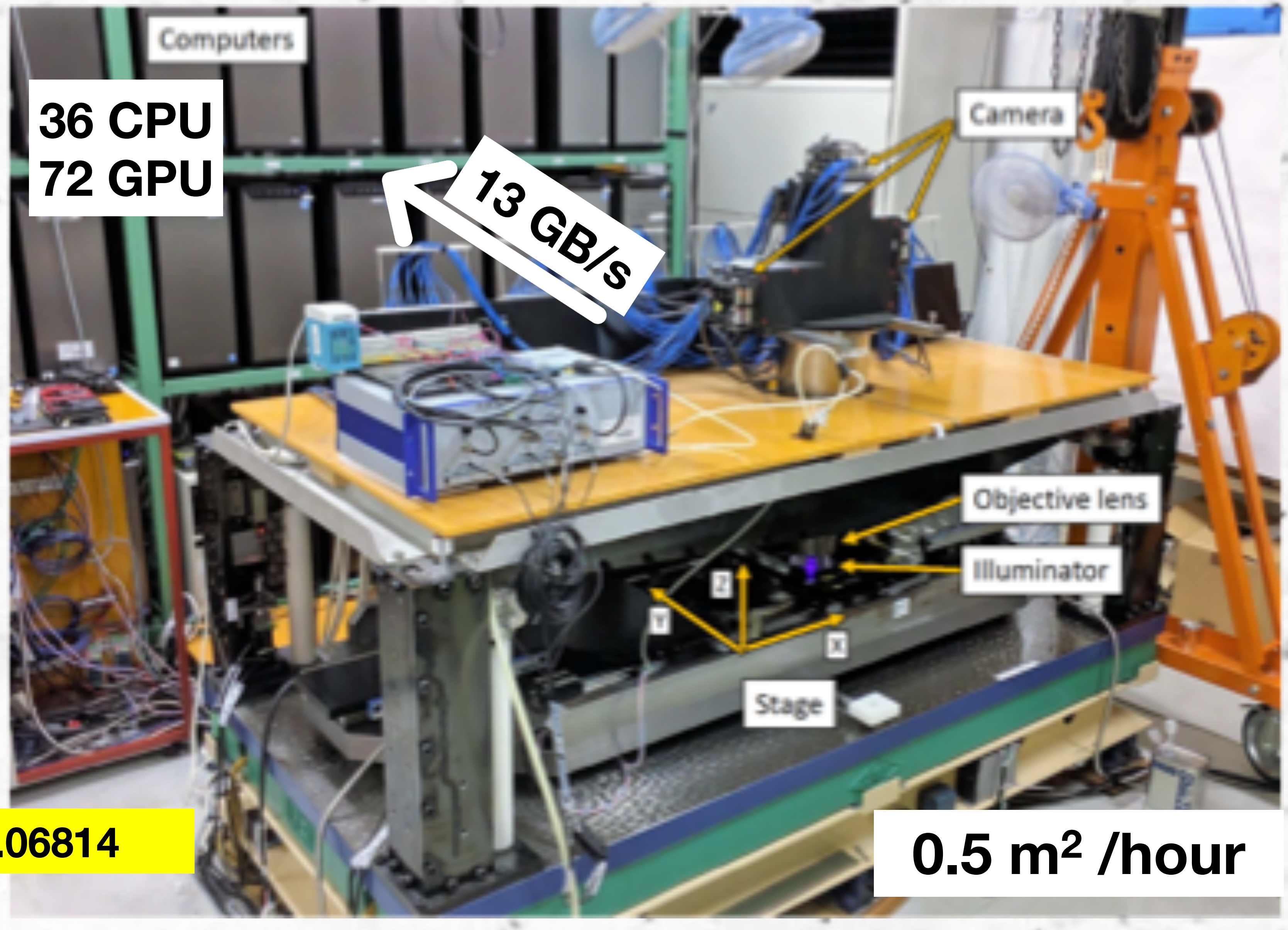


In 2021-2022: 300 modules will be exposed to 4.9×10^9 protons to accumulate $\sim2.3\times10^8$ interactions with $\sim10^5$ charmed particles pairs and ~1000 $D_s \rightarrow \tau + X$ events

Progress in automatic emulsion readout technique







arxiv:1704.06814

HTS - fastest emulsion data readout system - wide field lens, multi-sensors, GPU. 20 GB/s or 2 PB/day with capability to process 1000 m² of emulsion per year

Data stored after scanning – 3D coordinates and direction of track segments

Pilot run data processing

Scanning -> track segments (vectors) in each plate

Tracking -> segments combined to tracks

Precise alignment of the emulsion plates with reconstructed tracks

Tracking with improved geometry of the setup after the alignment

Search for the vertexes

Decay search

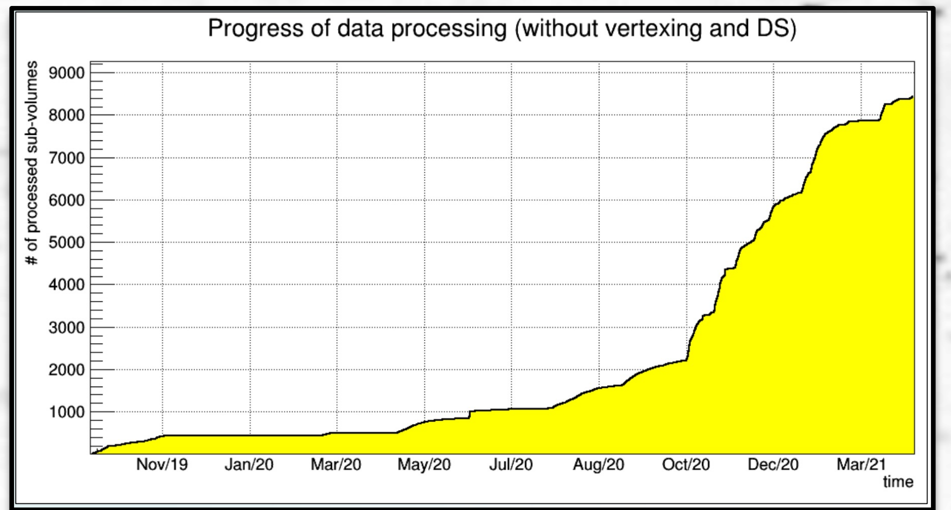
Japan (Nagoya/Kyushu):
2 servers
CPU, GPU, 128/256 GB RAM
Storage : ~100 TB

Russia (JINR):
1 processing server
CPU, GPU, 256 GB RAM
Storage: ~40 TB

CERN EOS
100 TB (data)
20 TB (MC)

Turkey (METU):
TRUBA Computing Center resources
CPU, GPU, 128 GB RAM
Storage capacity: 100+ TB

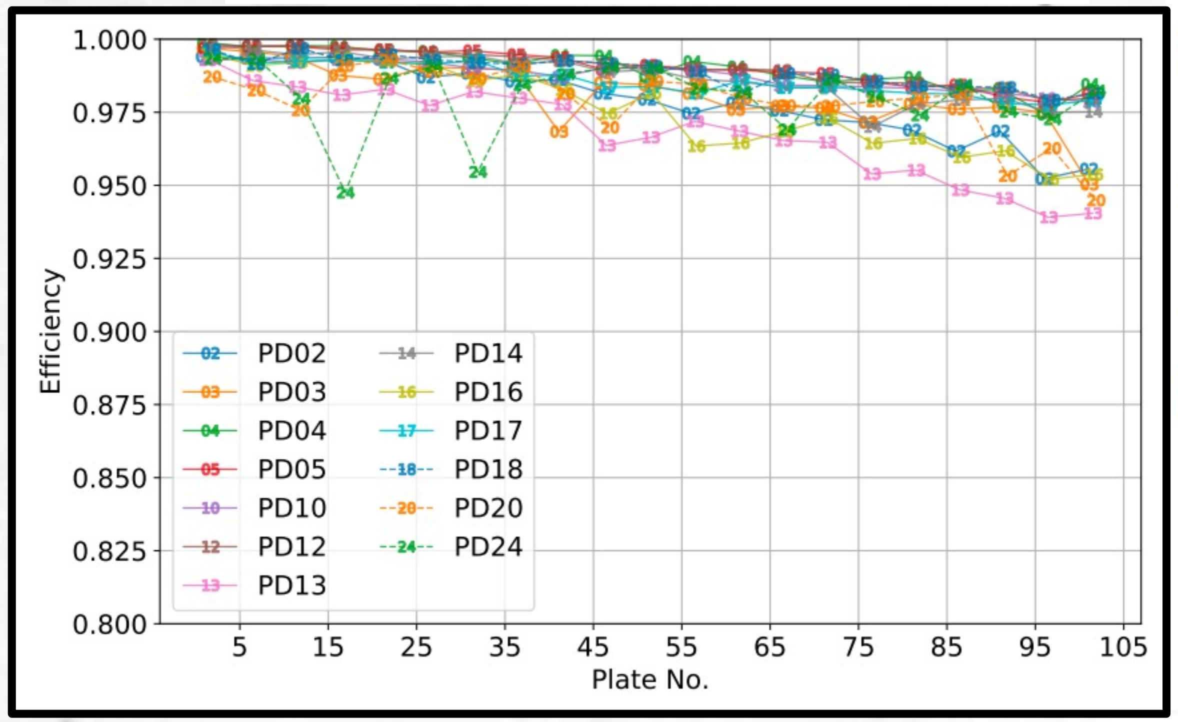
Romania (ISS):
1 processing server
CPU, GPU, 128 GB RAM
Storage: ~40 TB



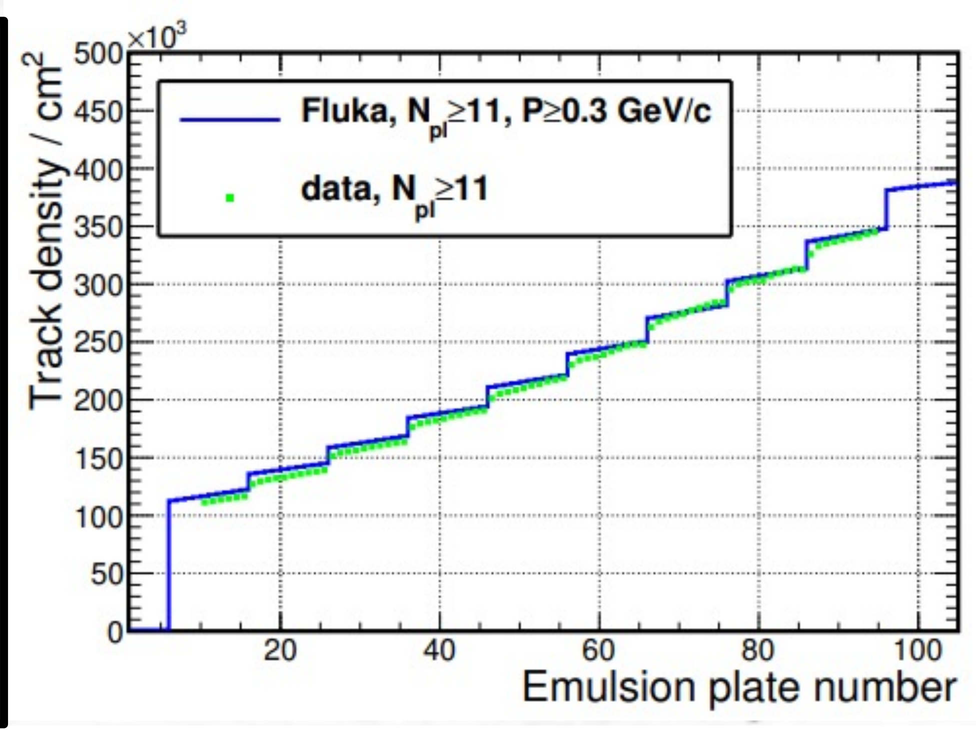
- **16 / 30 modules reconstructed, 2-4 months to process the rest.**

Pilot run data reconstruction performance:

Track registration **efficiency >95%**

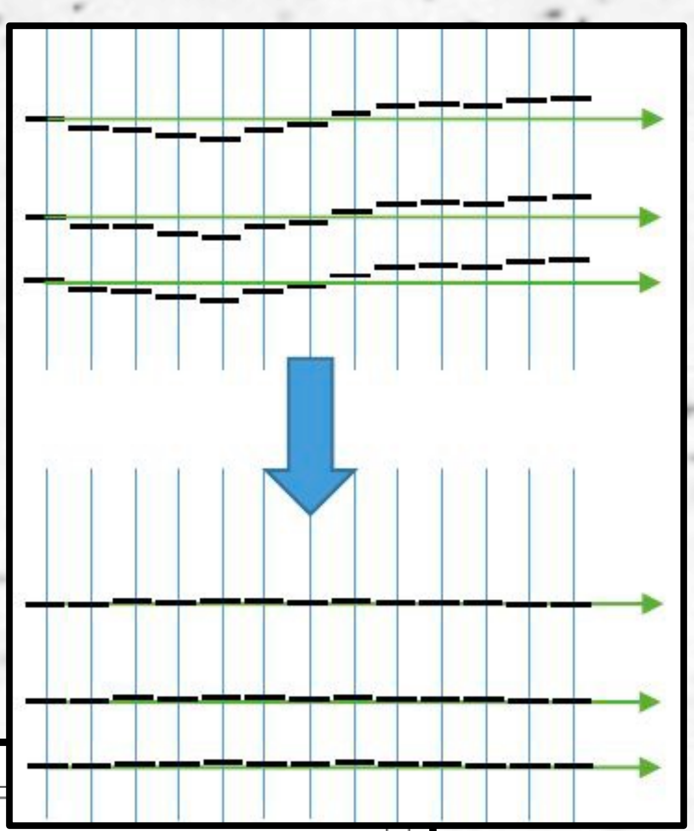


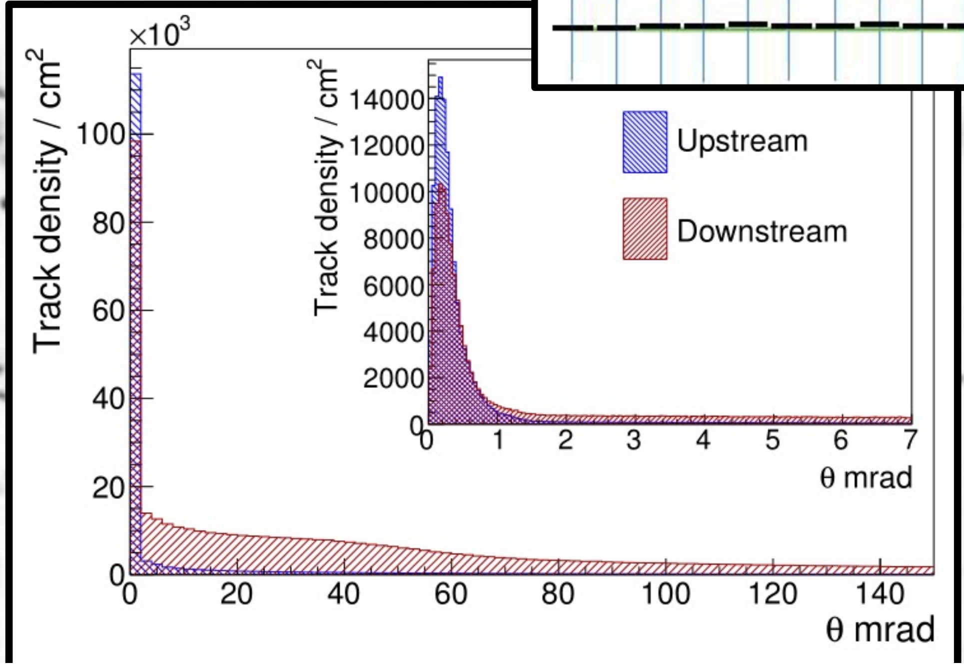
Track density according to simulation

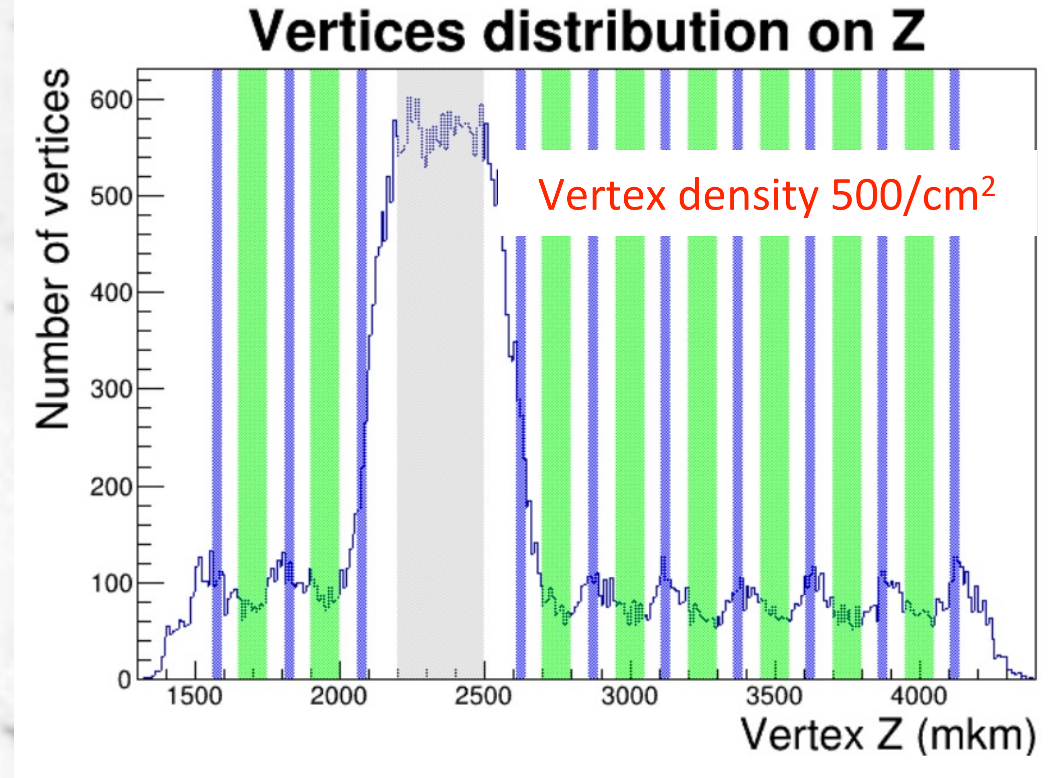


Alignment with proton beam tracks, 100 tracks/mm^2

Residual of track segments to fitted line (RMS) $\simeq$ **0.4 μm**

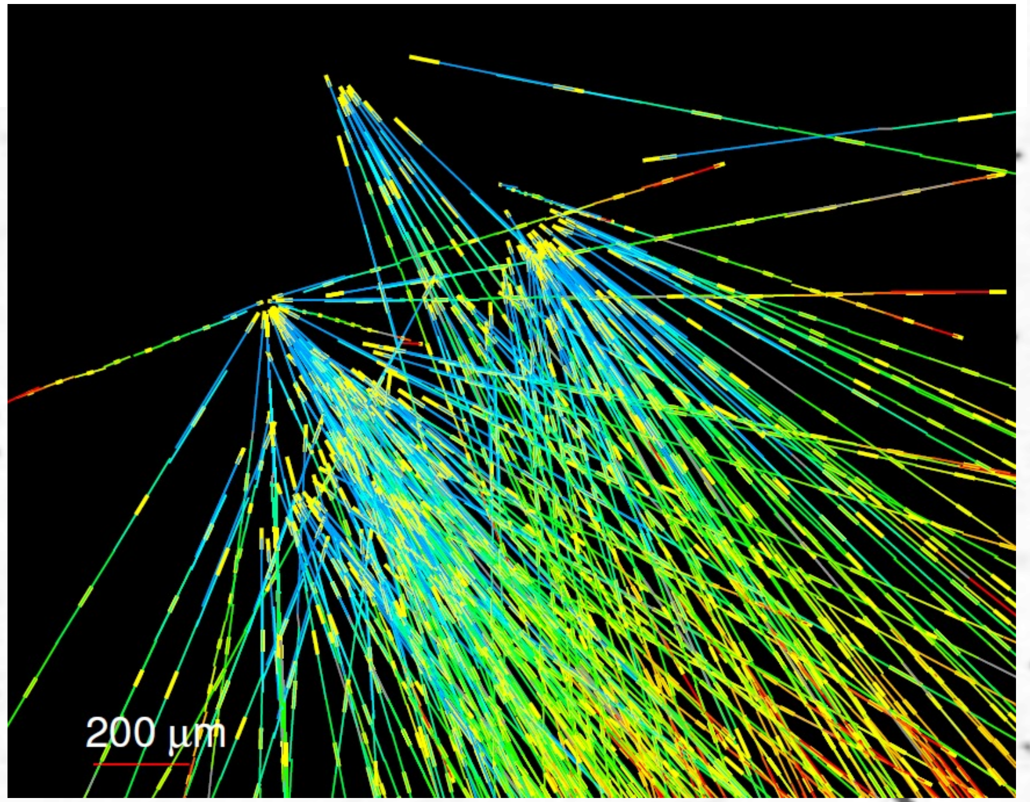






Reconstructed vertex position in the detector

Tracks emerging from tungsten



Observed tracks and vertexes density, secondary tracks multiplicity and angular distribution are consistent with FLUKA and Geant4 simulation

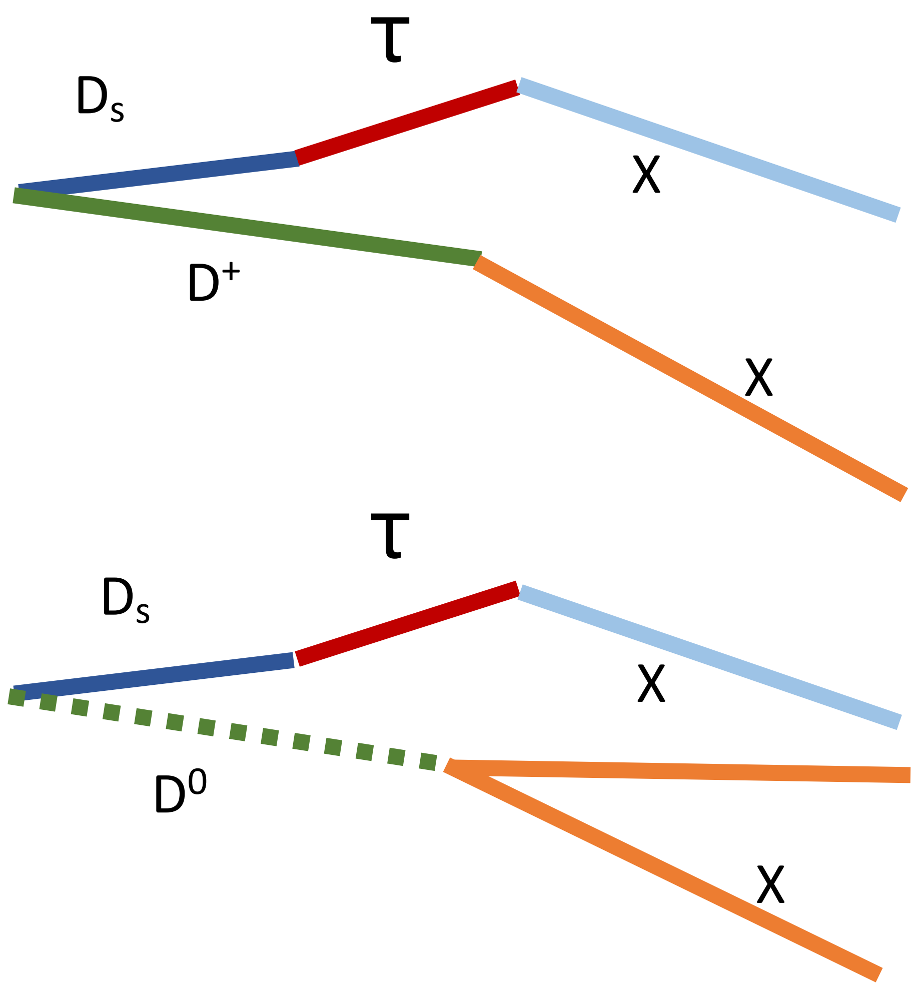
Efficiency of $D_s \rightarrow \tau \rightarrow X$ detection

Selection	Total efficiency (%)
(1) Flight length of $D_s \geq 2$ emulsion layers	77
(2) Flight length of $\tau \geq 2$ layers & $\Delta\theta(D_s \rightarrow \tau) \geq 2$ mrad	43
(3) Flight length of D_s < 5 mm & flight length of τ < 5 mm	31
(4) $\Delta\theta(\tau) \geq 15$mrad	28
(5) Pair charm: 0.1 mm < flight length < 5 mm (charged decays with $\Delta\theta$ > 15 mrad or neutral decays)	20

Background estimation

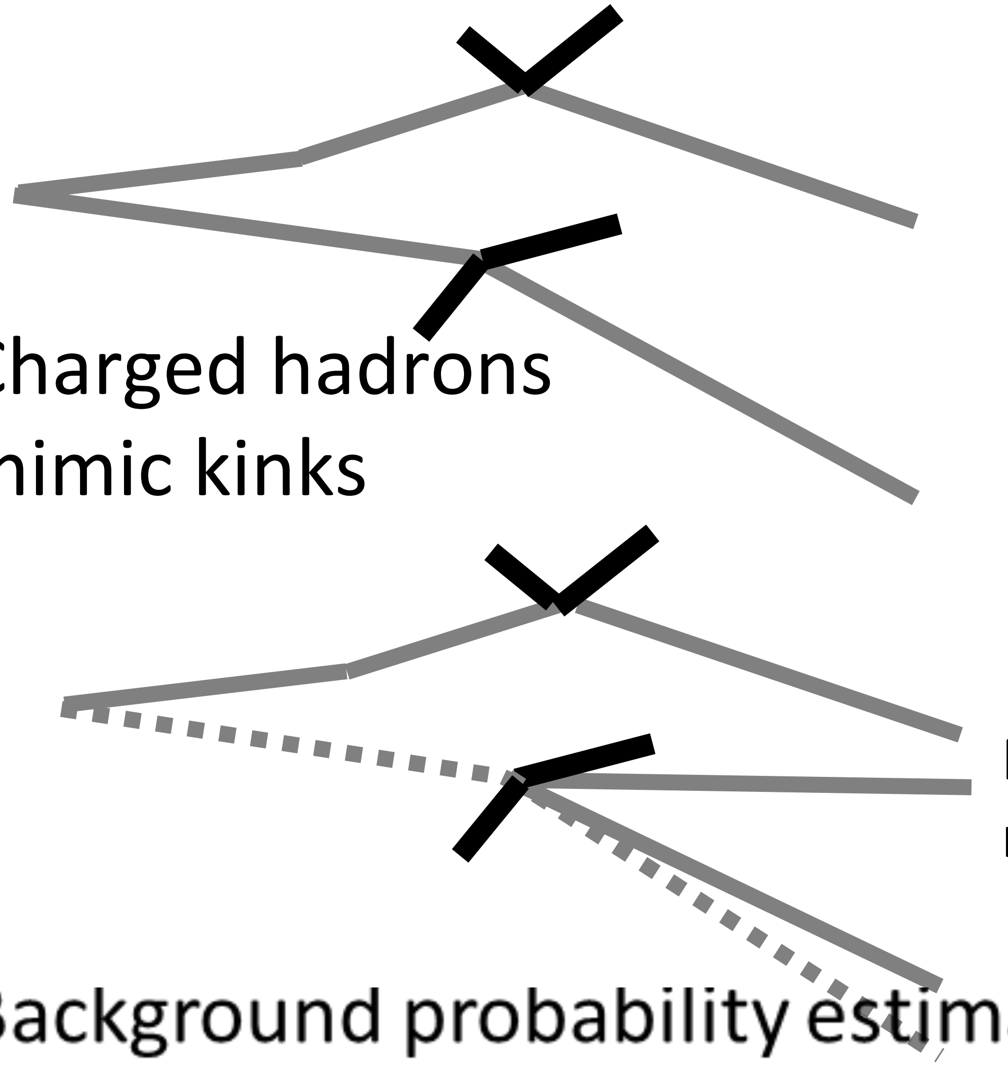
- **Signal:**

$D_s \rightarrow \tau$ decay: small kink
~7 mrad



Signal probability 2.2x10^-7^/proton

- **Main background**: Hadron interactions of secondary hadrons of proton interactions

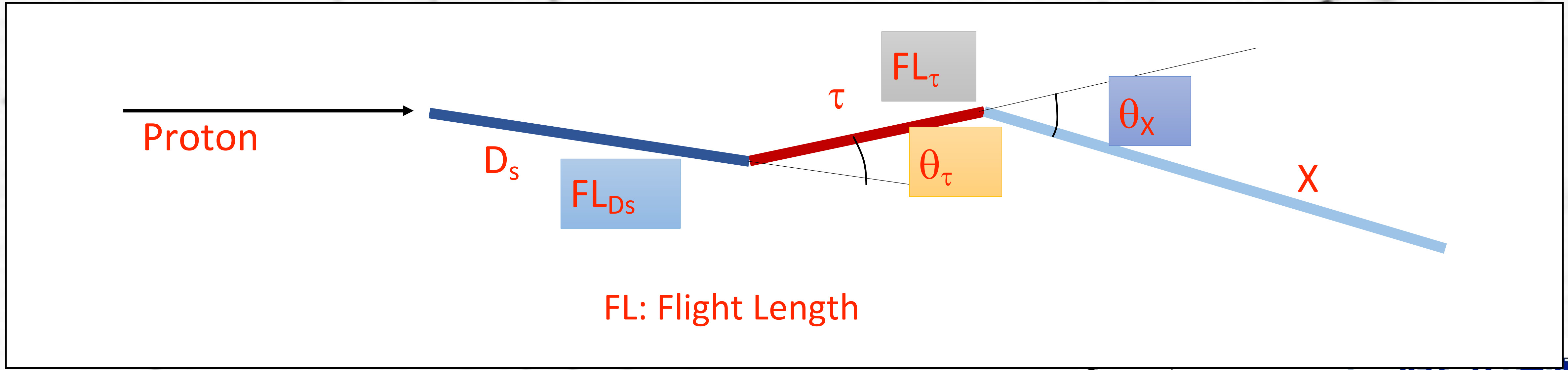


Background probability estimated by FLUKA.

$P_{BG}^{charged} = 1.3 \pm 0.4 \times 10^{-9}$/ proton

$P_{BG}^{neutral} = 2.7 \pm 0.8 \times 10^{-9}$/ proton

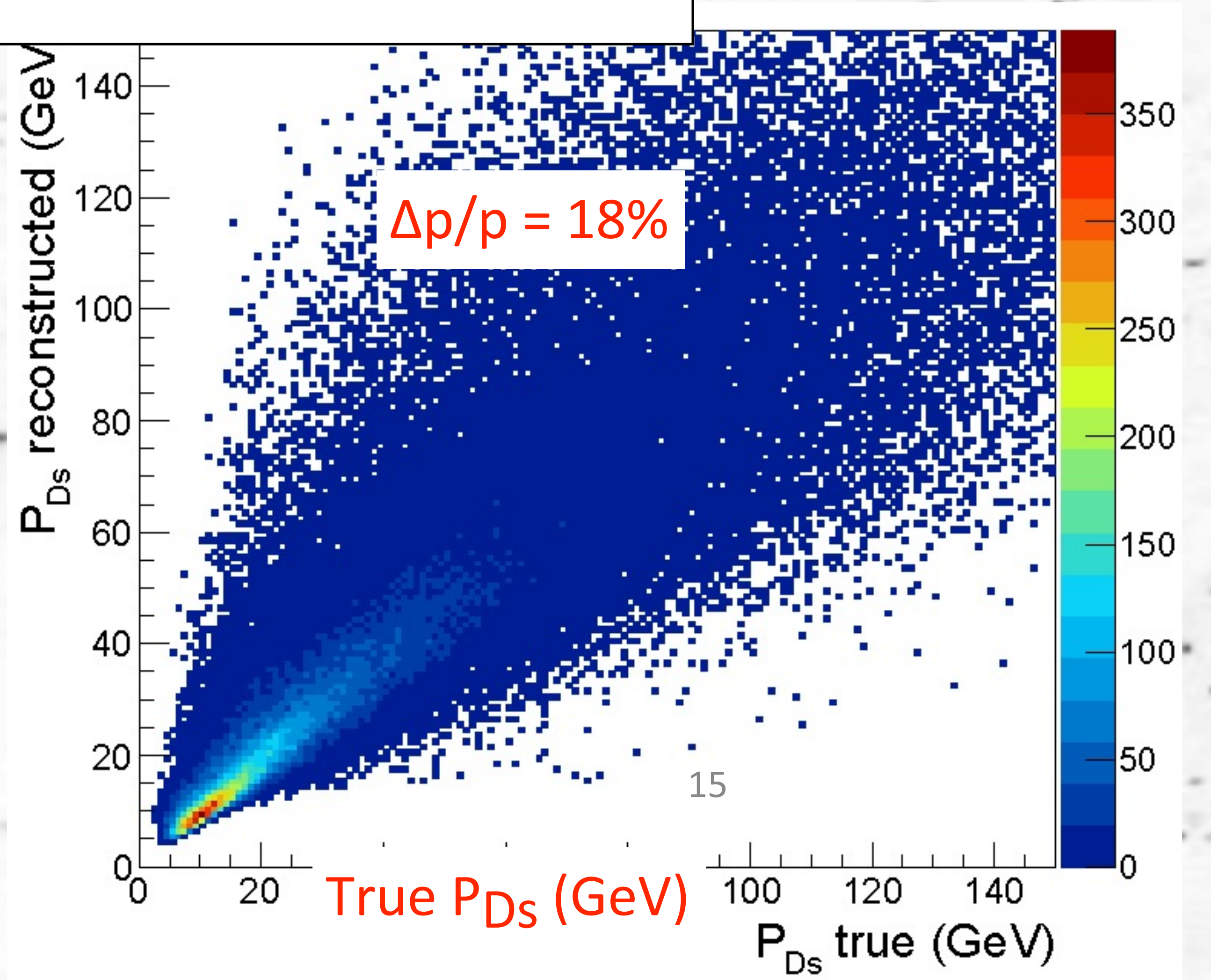
D_s momentum reconstruction
by Artificial Neural Network using topological variables



- Difficult to measure D_s momentum directly due to short lifetime

→ D_s momentum reconstruction by topological variables

- A Neural Network with 4 variables was trained with MC events
- Momentum resolution for $\tau \to 1$ prong decays $\Delta p/p = 18\%$



15

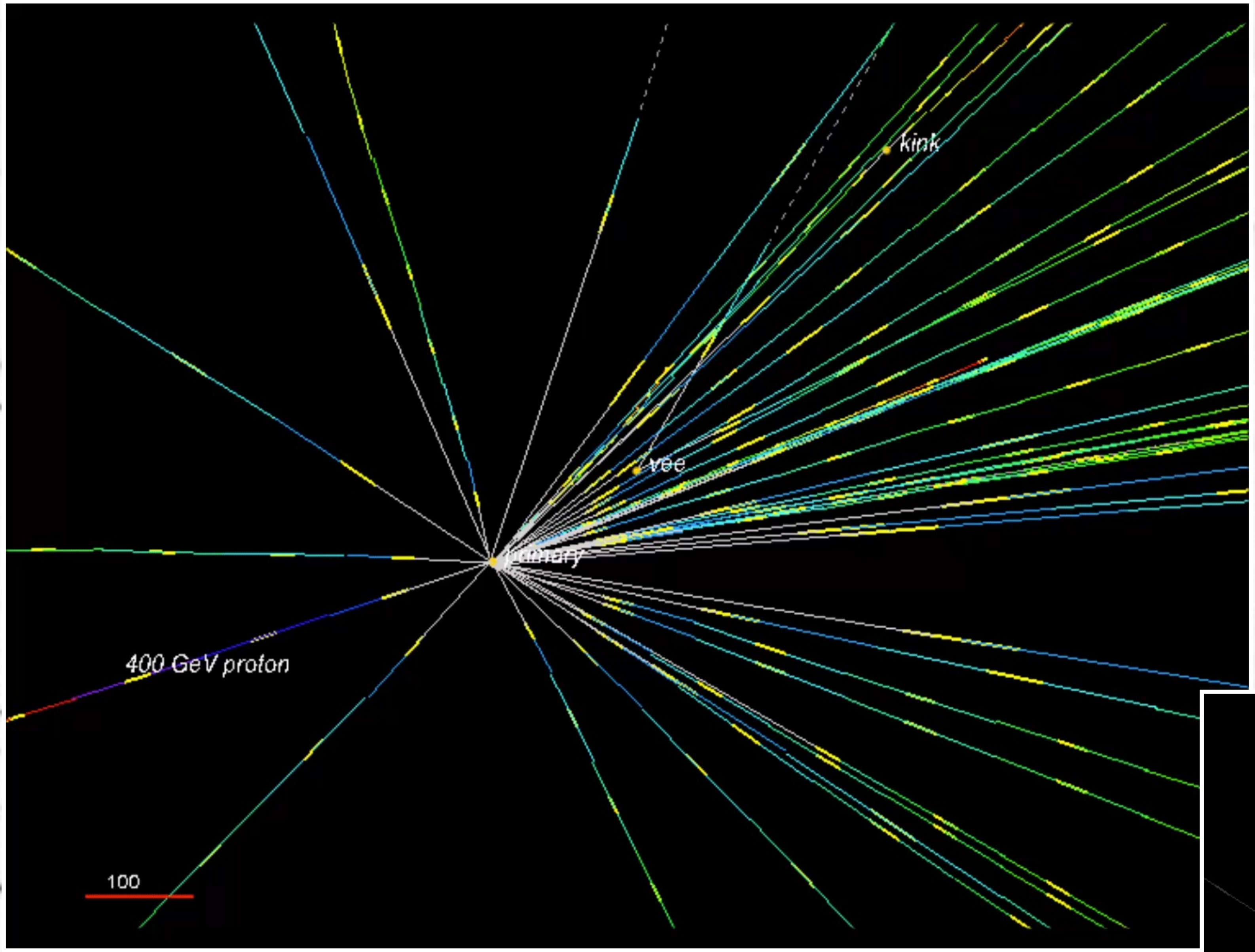
Double-decay topology events search

About 23% of the data sample processed with vertex search and decay search programs.

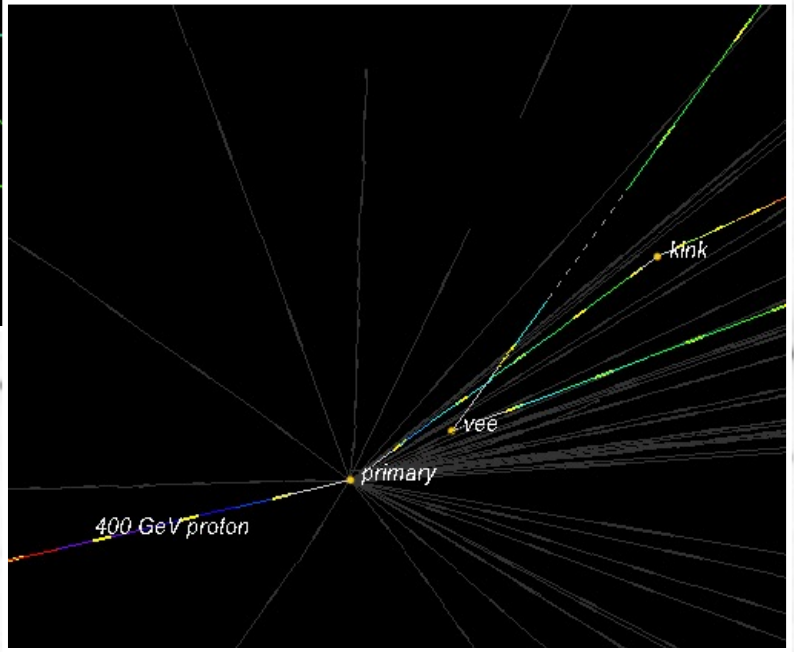
August 2021

Analyzed sample/Total	22.2%
Protons on tungsten plate	486,137,516
Vertices in tungsten	2,653,846
Double decay topology vertex candidates	17,574

- **Work now is focused on the software optimization and upgrade to make it faster and more efficient.**

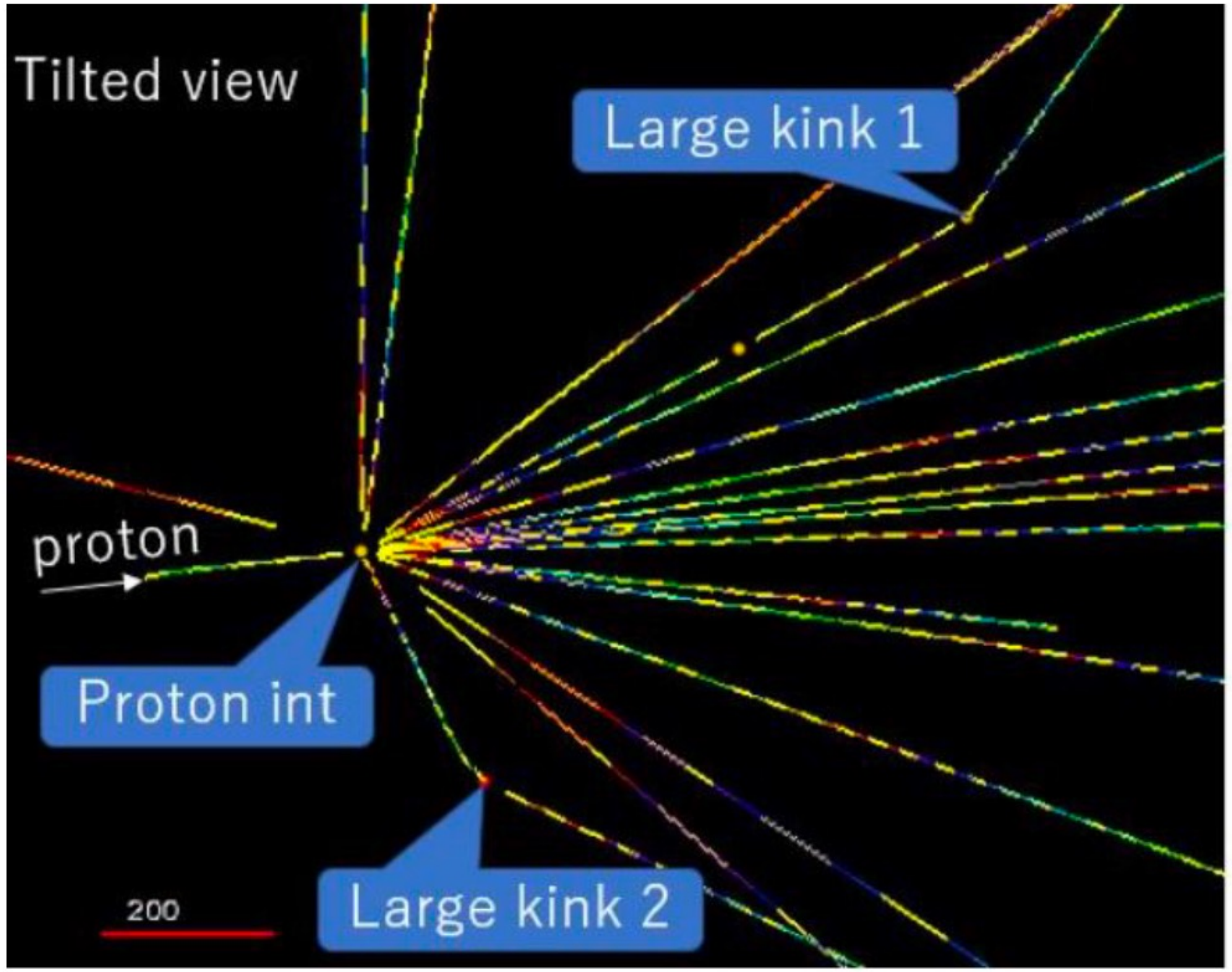


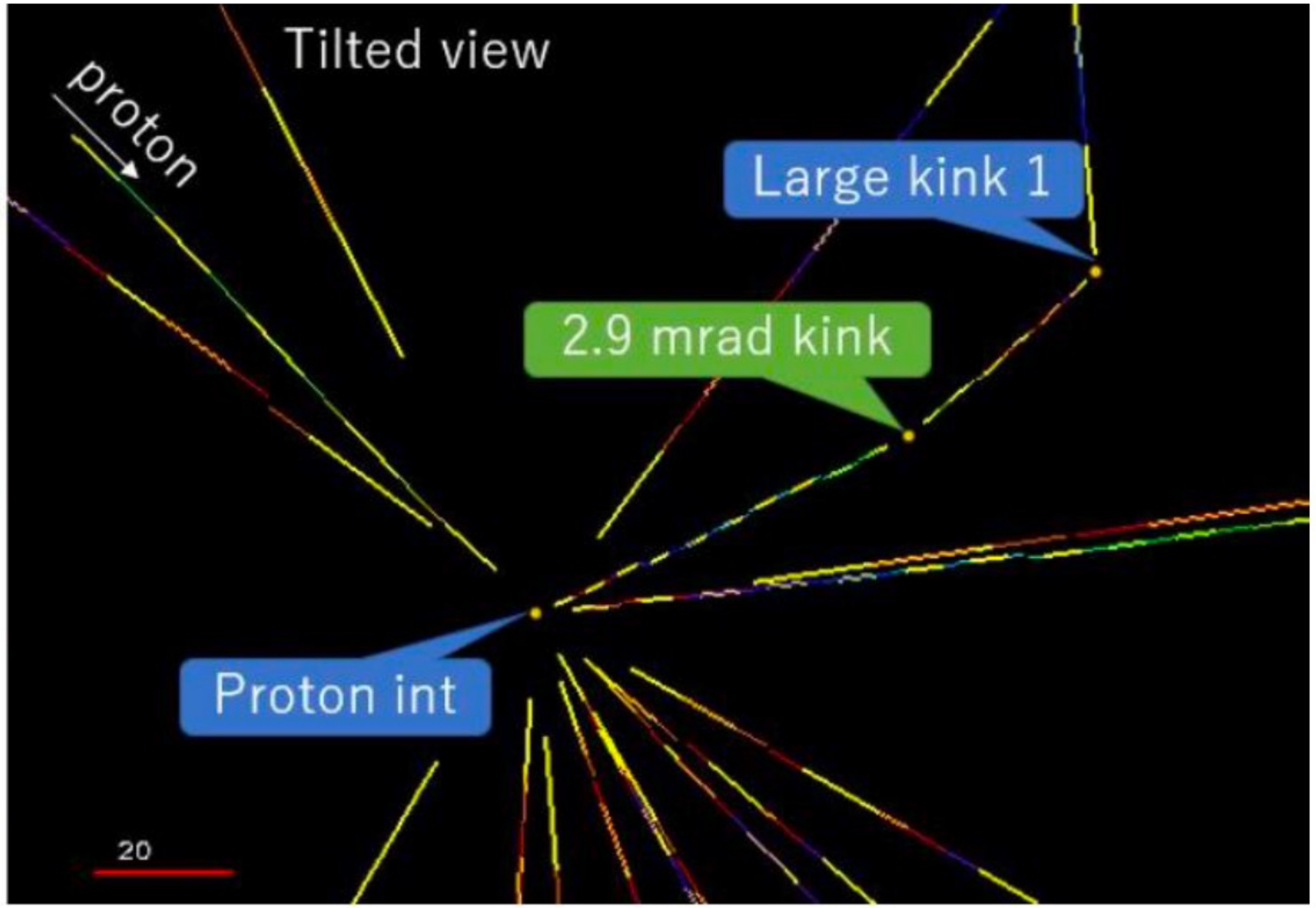
- Kink
  - IP of daughter 291.6 μm
  - FL 2536.6 μm
  - kink angle 118 mrad
- Vee
  - IP of daughters 20.9, 109.7 μm
  - FL 554.5 μm
  - opening angle 242 mrad



100 μm

New algorithm of small kink search



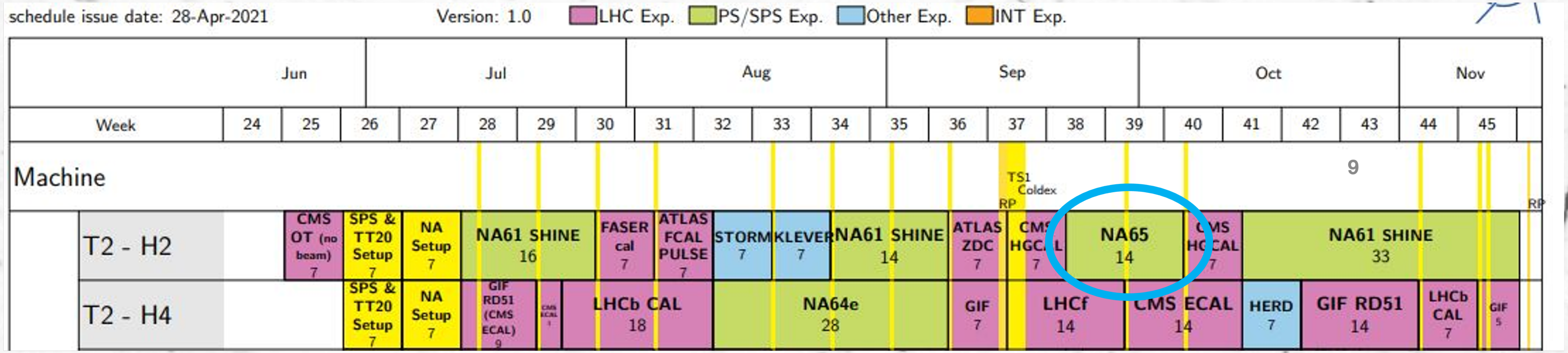


An event with 2 large kinks was selected in data sample

One of the kink parents has a small kink of 2.9 mrad.

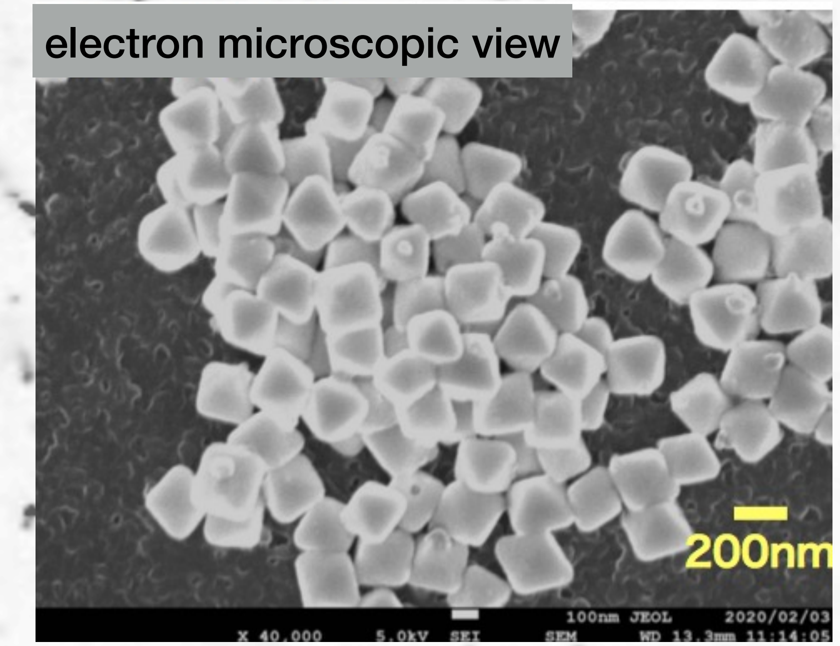
Preparation for 2021 physics run

- Beam time is schedule in Sep-Oct 2021
- 20% of full statistics (30% including the pilot run)
- Scaled down due to COVID - 100 modules



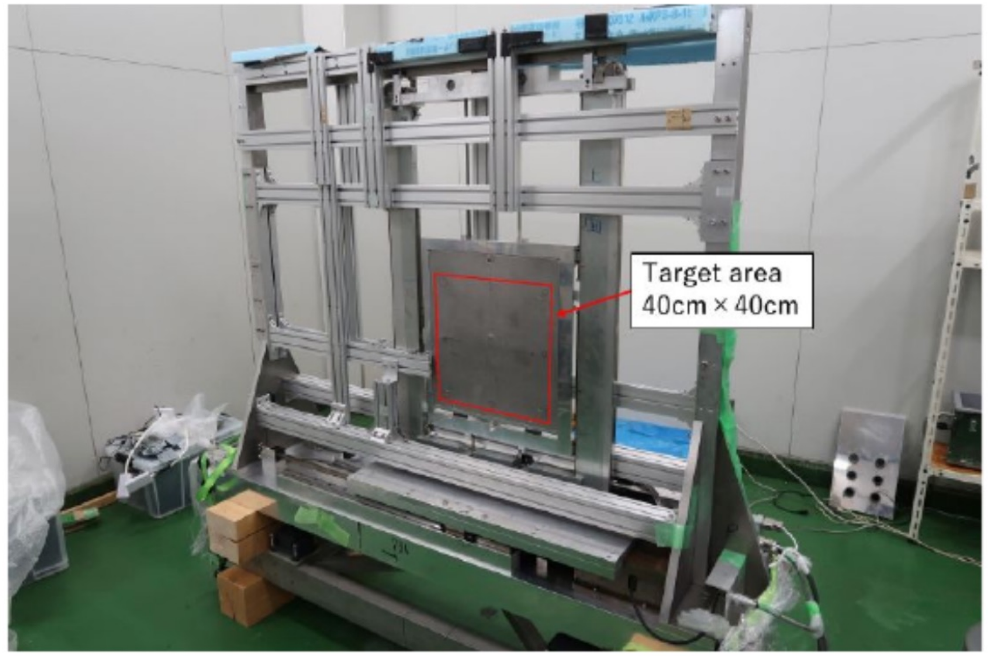
Preparation for the main physics runs

New gel production facility

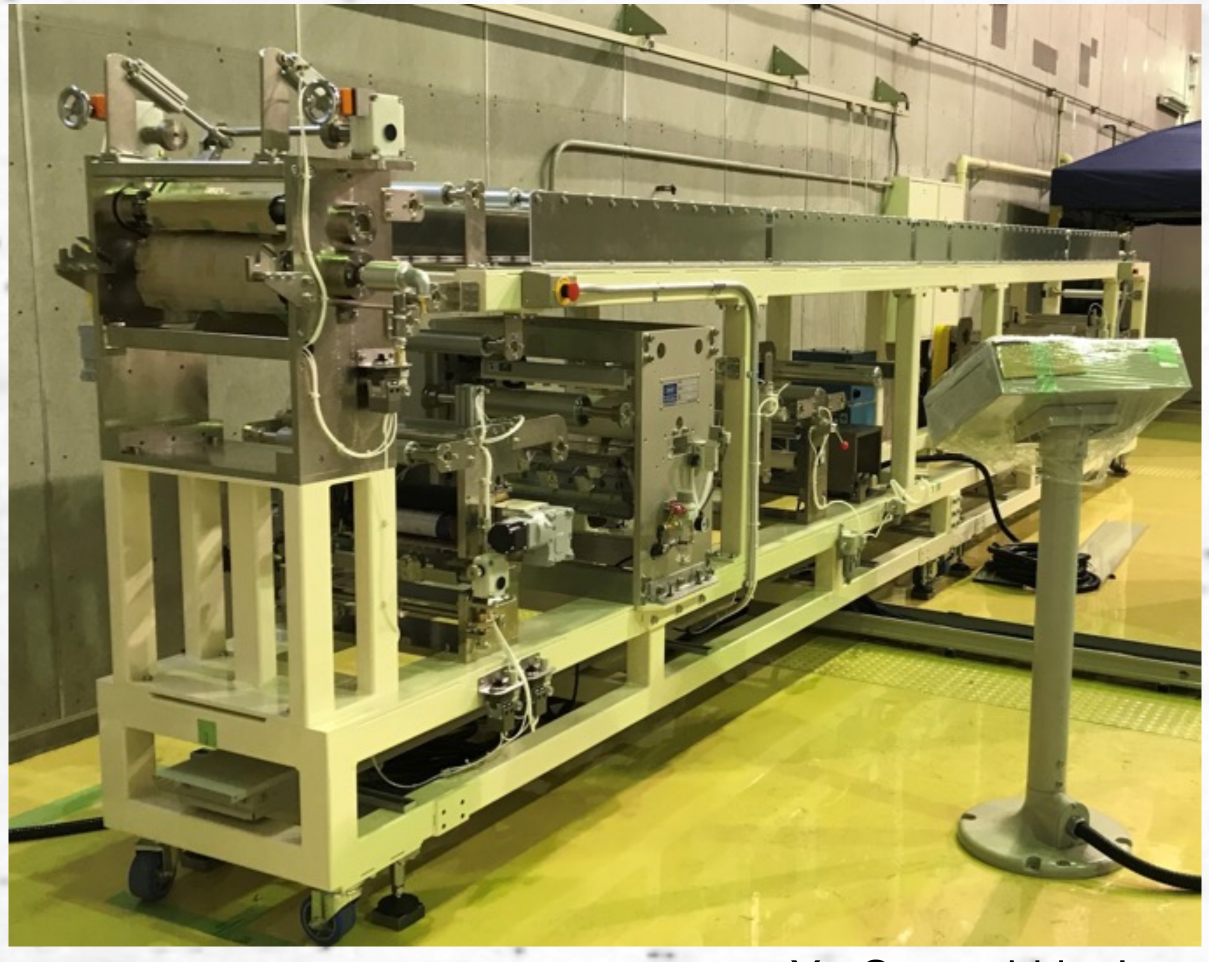


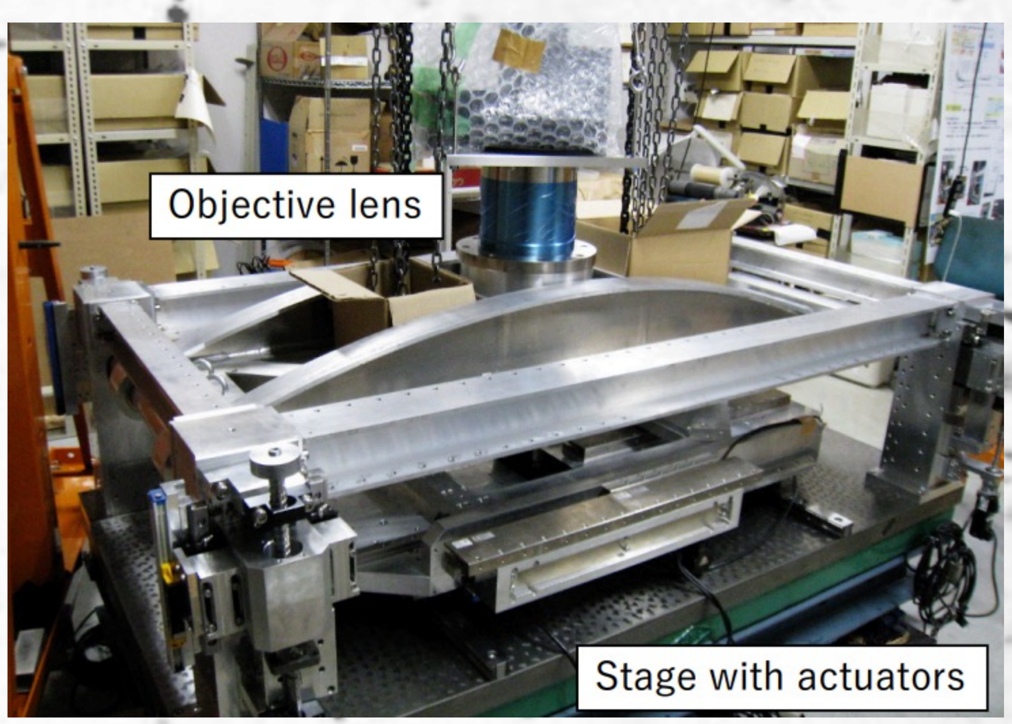
Larger film size
10x12.5 → 25 cm x 20 cm

Target mover for 2021-2022 runs



Film production facility – 15 m^2 per day





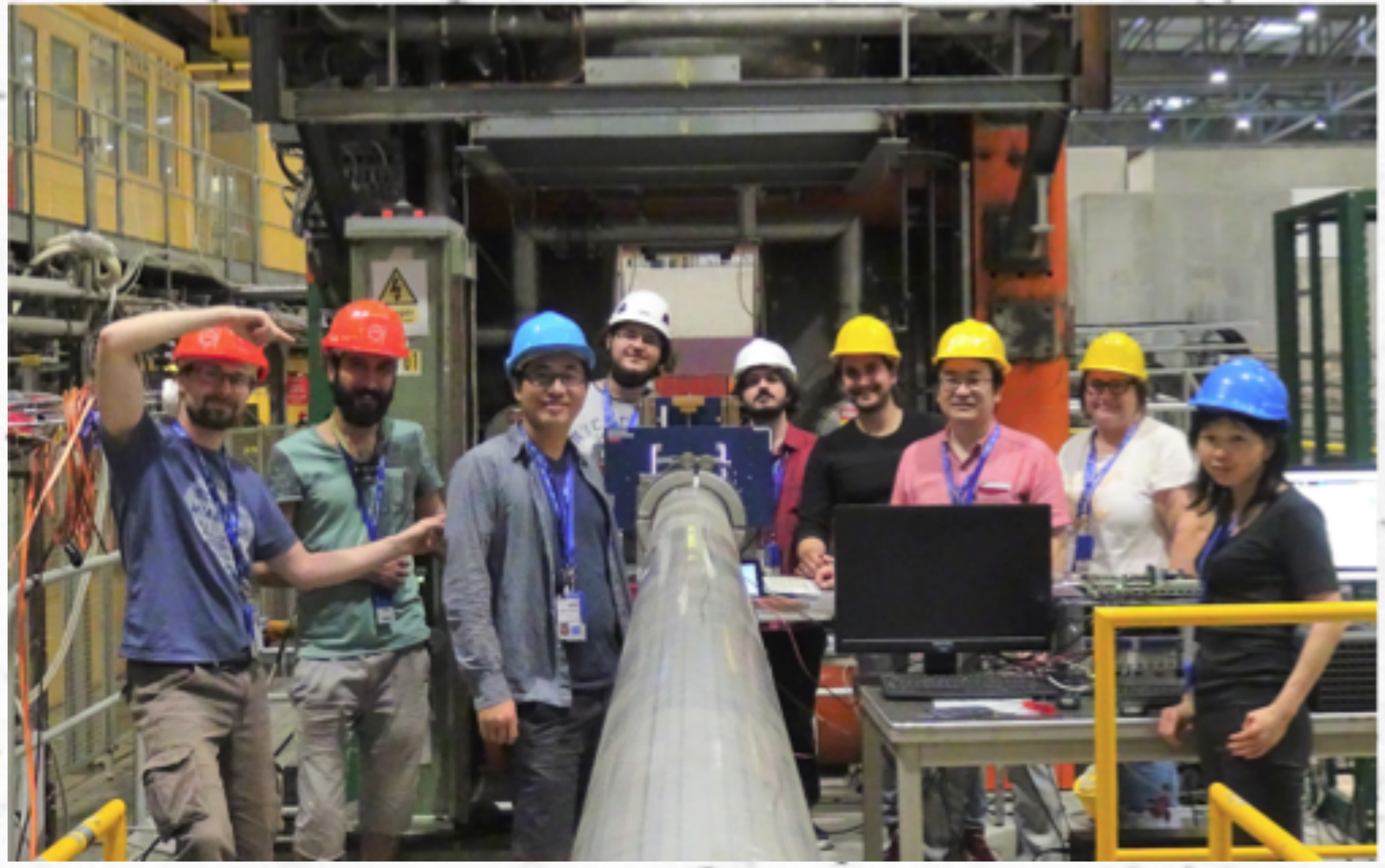
HTS (0.5 m^2/h) → HTS II (2.5 m^2/h)

Summary and outlook

- Progress in nuclear emulsion readout made possible new generation of the experiments
- DsTau aims to measure double differential cross section of $D_s \rightarrow \tau$ production in proton-nuclei interactions to reduce uncertainty of tau neutrino flux in future experiments down to 10% .
- The analysis of the pilot run data is ongoing, very high track density requires upgrading software instruments and increasing computing resources.
- The physics run in September of 2021 is under preparation. Both hardware and software have been revised to meet very challenging experimental conditions.

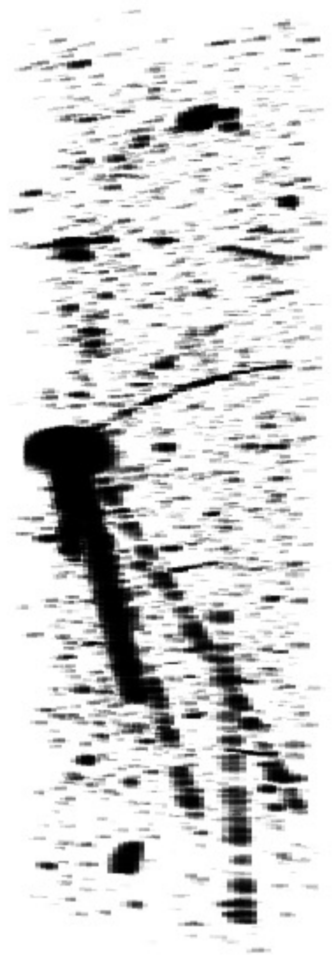
DsTau paper: JHEP 01(2020)033
DsTau web site: https://na65.web.cern.ch/

Thank you!



Backup

Emulsion = a detector with high detection channel density



150 μm x 120 μm x 50 μm

1.2×10^{8} channels (crystals) in this volume.

10^{14} channels in a film (12.5 cm x 10

ATLAS-IBL pixel sensor FE-14

1 pixel =

250 μm x 50 μm x 200 μm

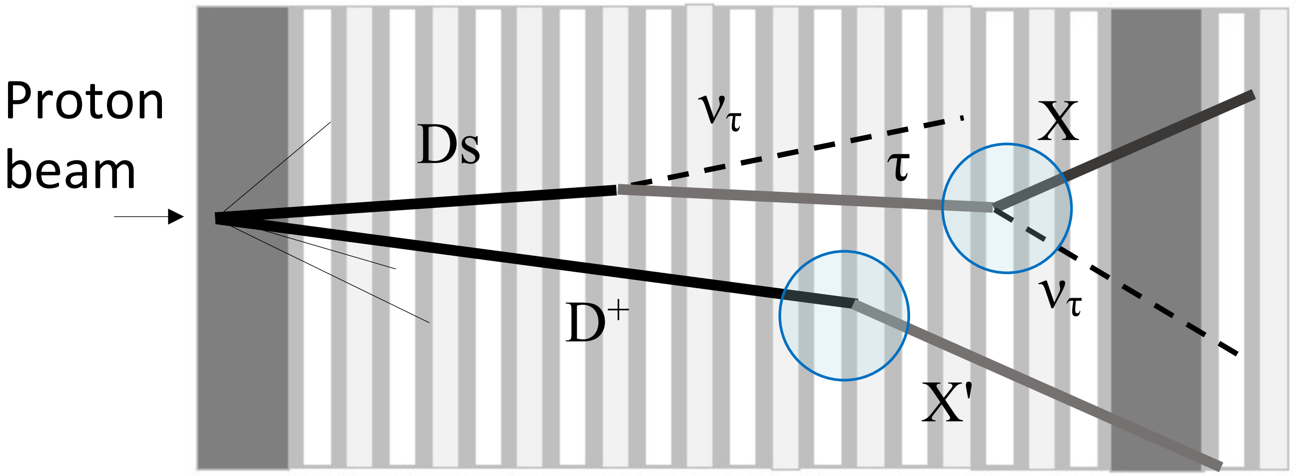
Sum of all channels in ATLAS = ~10^{8}

High density of detection channels, O(10^{14}) channels/cc, makes emulsion attractive for many purposes.

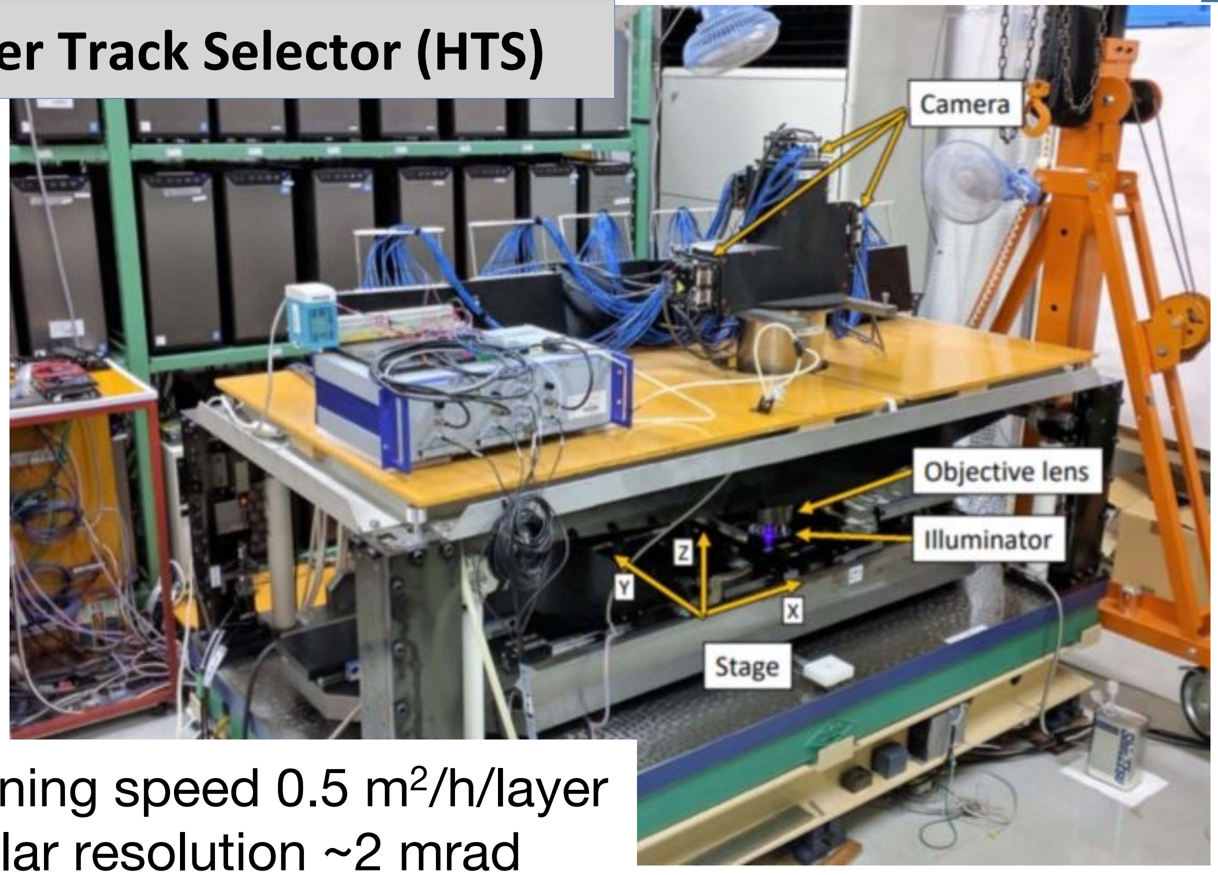
Analysis scheme of double-kink search

Step 1

- Full area scanning by the fast scanning system
- Select decays with $\Delta\theta$ > 20 mrad



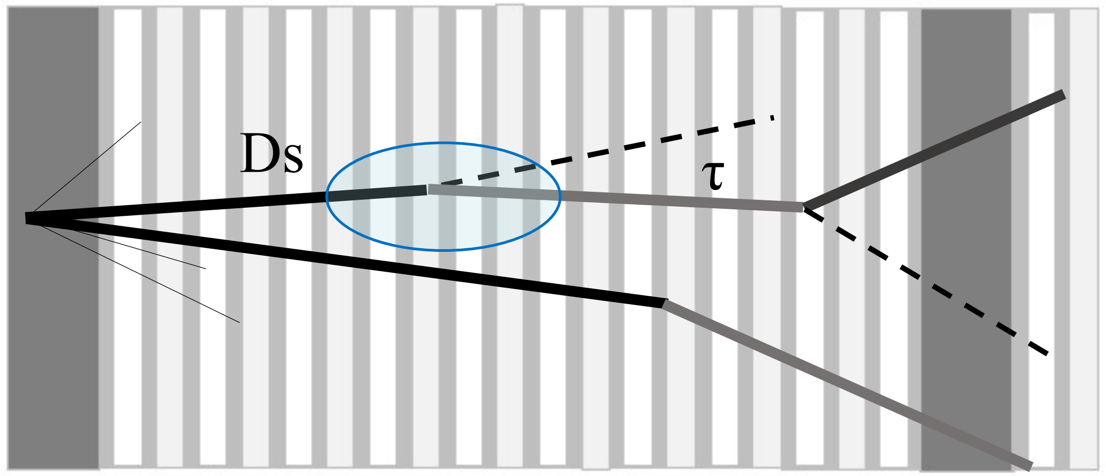
Hyper Track Selector (HTS)



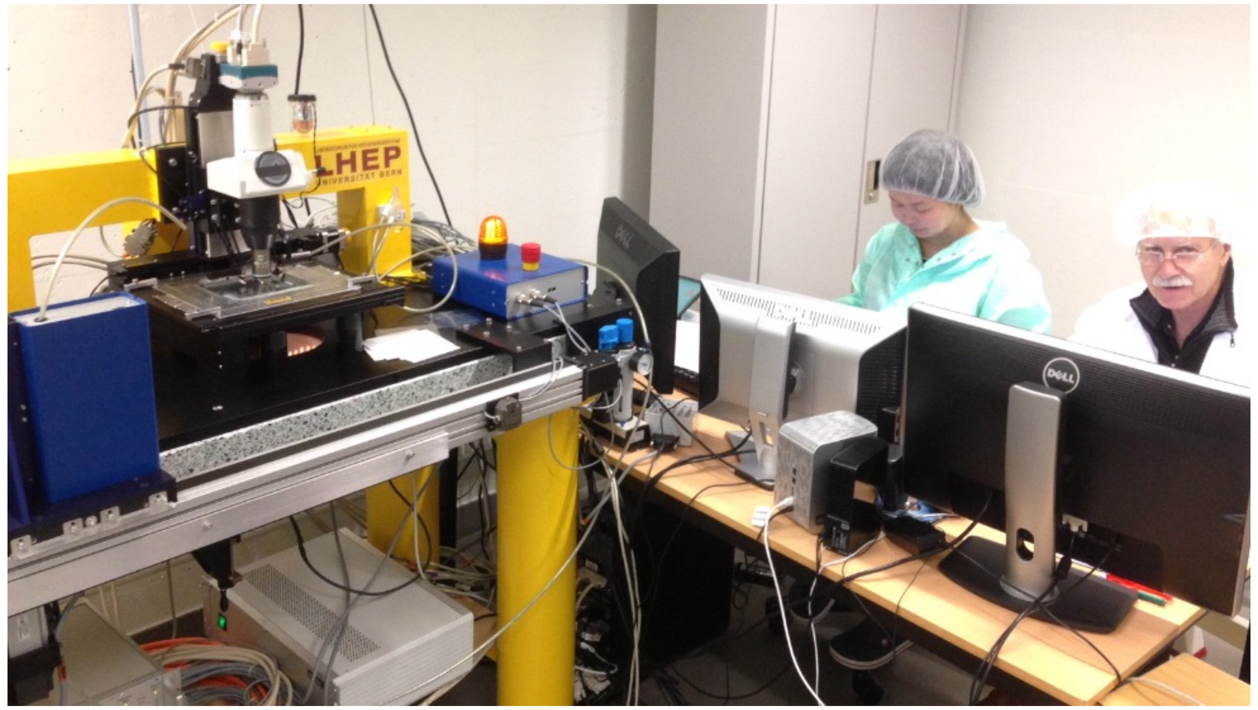
Scanning speed 0.5 m^2/h/layer
Angular resolution ~2 mrad

Step 2

- Precise measurement to detect Ds -> τ decay (a few mrad)



Dedicated high-precision systems (Bern, Dubna)



Angular resolution ~0.3 mrad

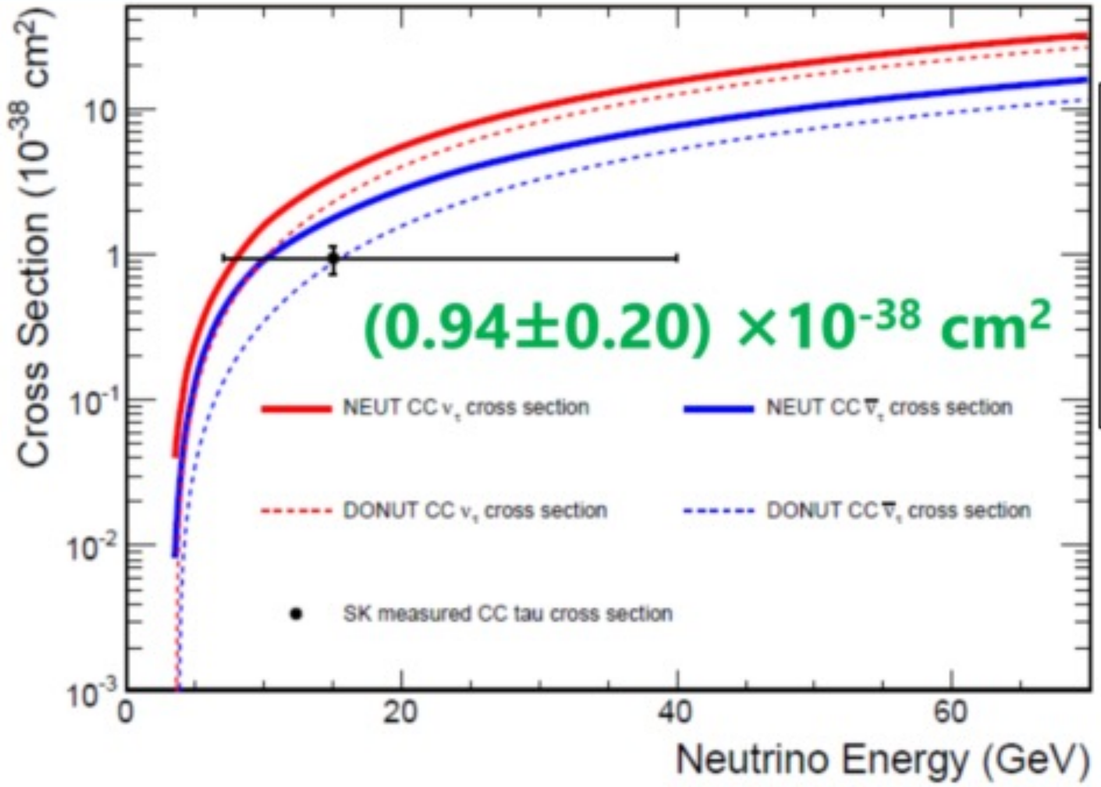
ν_τ cross section measurement by oscillated neutrinos

SK

Atmospheric

$\nu_\mu \rightarrow \nu_\tau$ & $\overline{\nu_\mu} \rightarrow \overline{\nu_\tau}$

$\sigma_{meas}=(1.47\pm0.32)\ \sigma_{theory}$



arXiv:1711.09436

Presented 1st day by Guillaume Pronost

OPERA

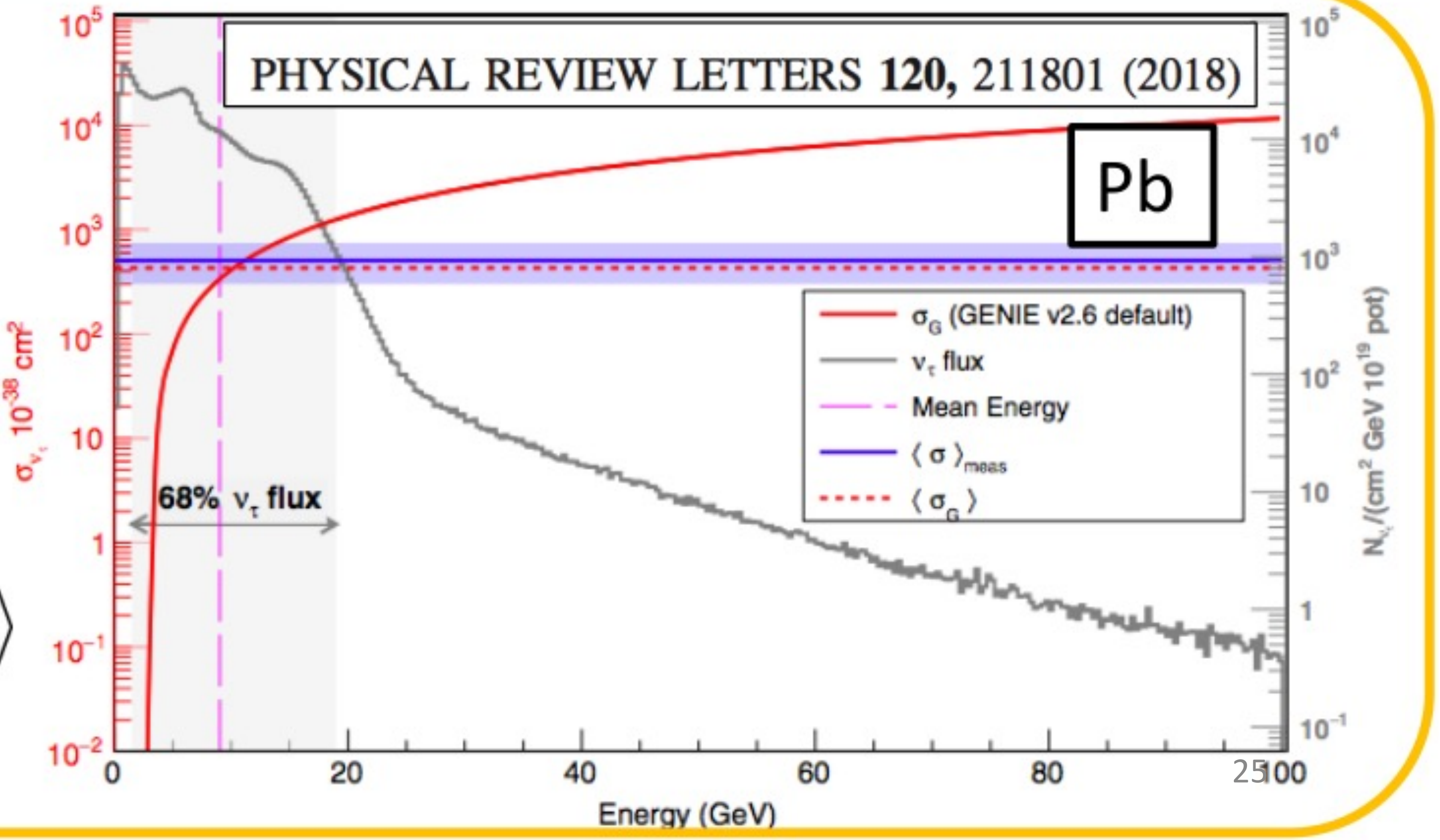
CNGS ν_μ beam

$\nu_\mu \rightarrow \nu_\tau$

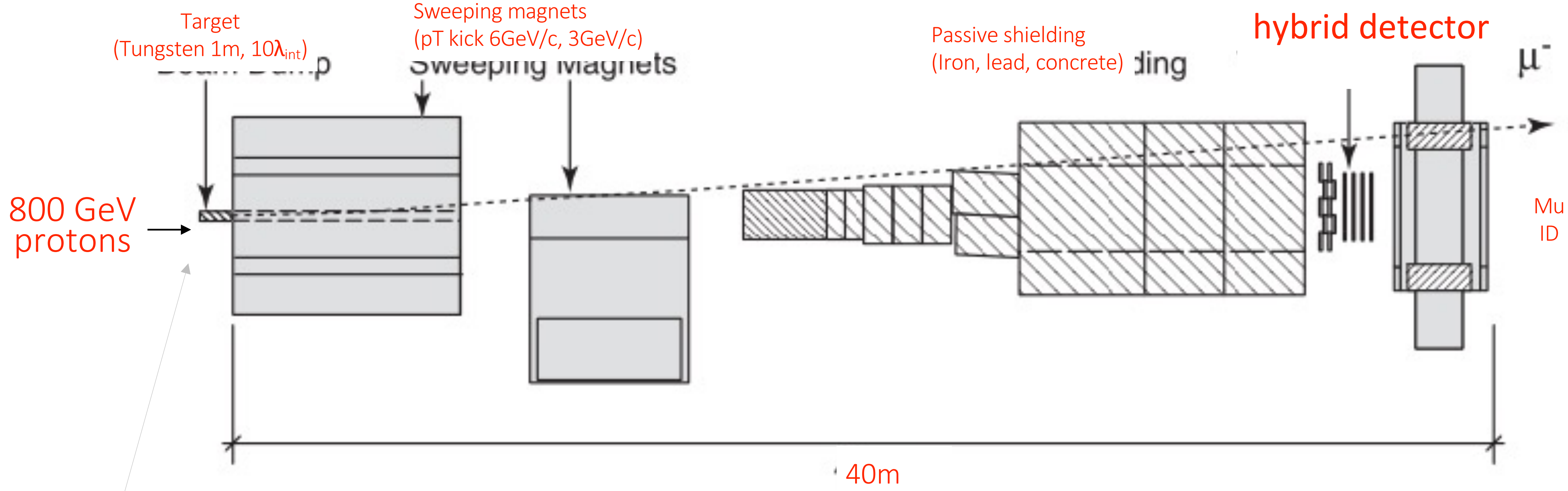
σ with a Pb nucleus

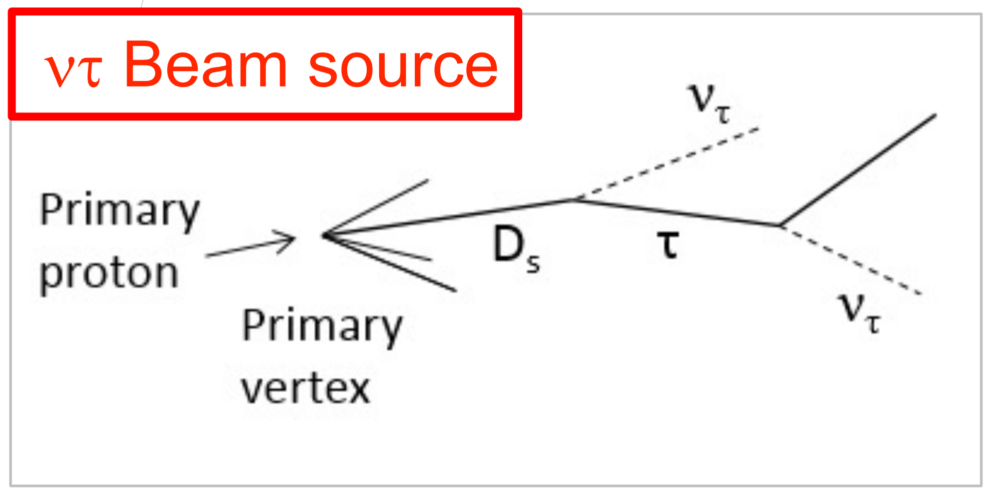
$\langle\sigma\rangle_{\rm meas} = (5.1^{+2.4}_{-2.0}) \times 10^{-36}\ {\rm cm}^2$

$$\langle\sigma\rangle_{meas} = (1.2^{+0.6}_{-0.5})\ \langle\sigma_G\rangle$$

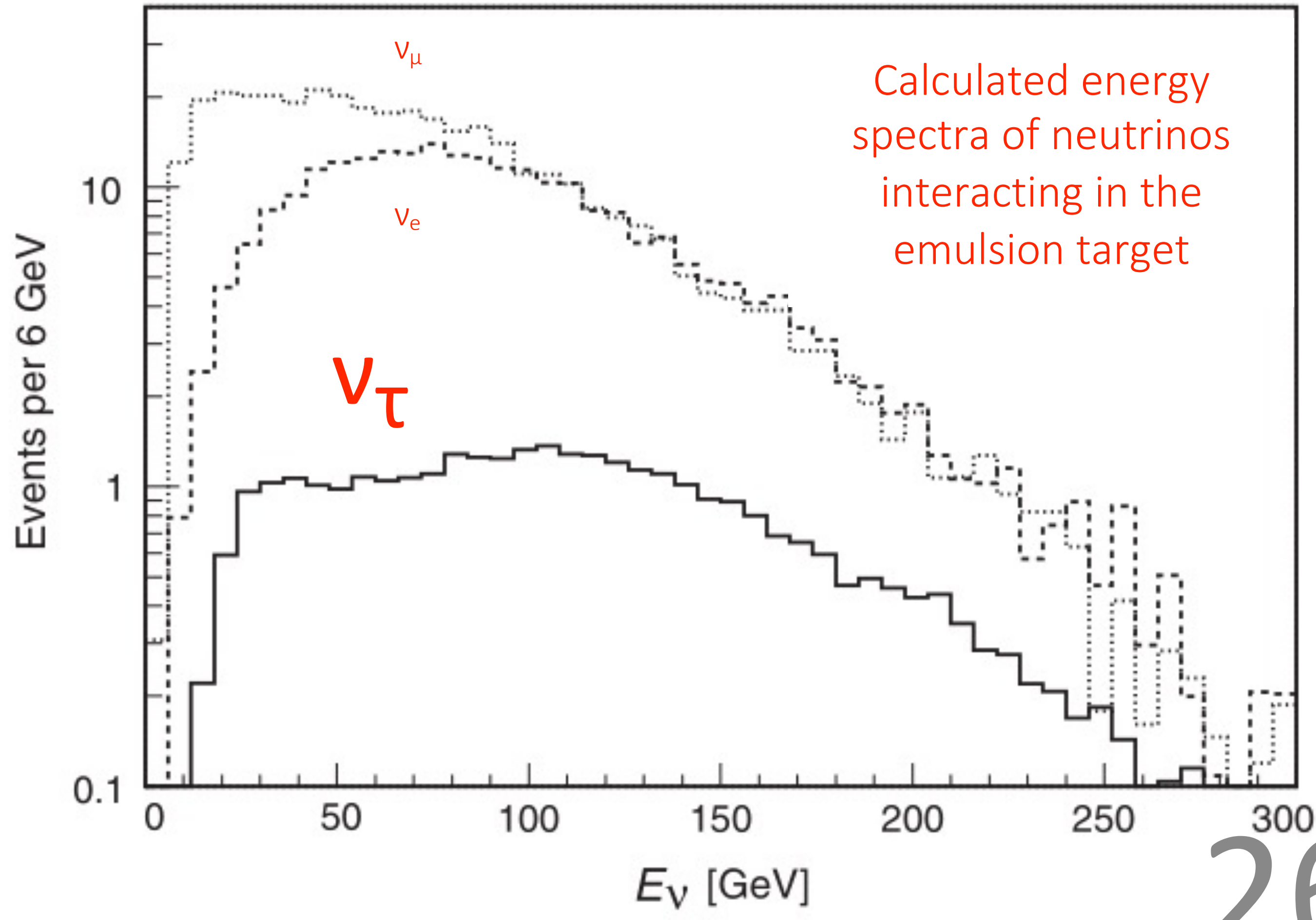


Neutrino beam line in DONuT

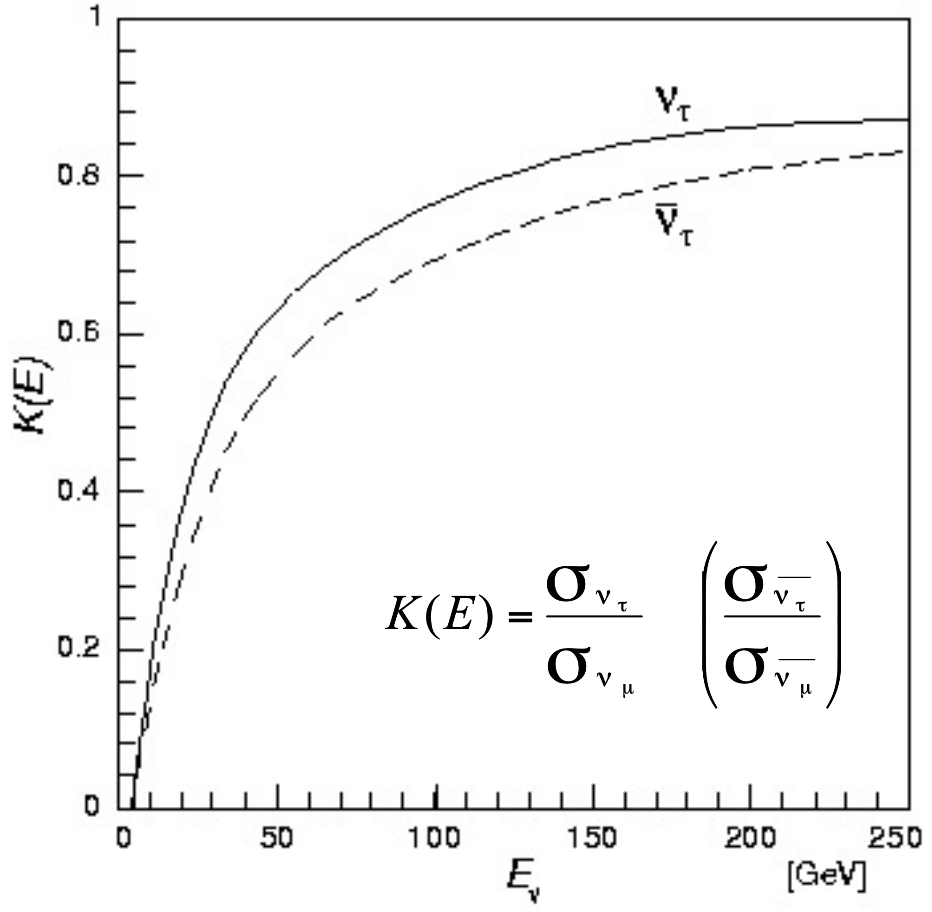




	Main source
ν_e	D^0 , $D^\pm$, D_s , Λ_c
ν_μ	D^0 , $D^\pm$, D_s , Λ_c , π, K
ν_τ	D_s



Results from DONuT



ν_τ CC cross section

$$\sigma_{\nu\tau}(E) = \sigma_{\nu\tau}^{const} \times E_{\nu\tau} \times K_\tau(E)$$

ν_τ CC cross section was calculated as a function of one parameter. The energy-independent part was parameterized as

$$\sigma_{\nu\tau}^{const} = 7.5(0.335\,n^{1.52}) \times 10^{-40}\, cm^2 GeV^{-1}$$

where n is the parameter controlling the longitudinal part of the D_s differential cross section

Phenomenological formula

$$\frac{d^2\sigma}{dx_F\,dp_T^2} \propto \underbrace{(1-|x_F|)^n}_{\text{longitudinal dependence}} \underbrace{\exp(-bp_T^2)}_{\text{transverse dependence}}$$

x_F is Feynman x ($x_F = 2p^{CM}_Z/\sqrt{s}$) and p_T is transverse momentum