FASER

The Forward Search Experiment

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IBS

SLAC NATIONAL ACCELERATOR LABORATORY

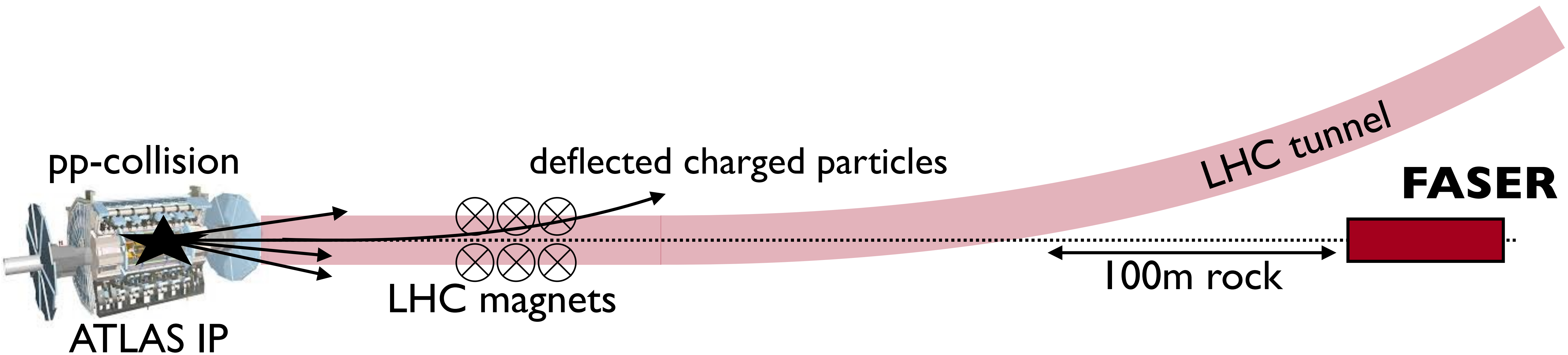
HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

Review

- Large production rate in the **forward region** along the beam line
  * many hadrons: 10^{17} π, 10^{16} K, 10^{15} D, 10^{14} B with E~TeV
  * even extremely weakly-coupled particles may be produced sufficiently
  * low pT ~ Λ_{QCD} → particles are collimated $\theta \sim \Lambda_{QCD}/E$ ~ mrad

- FASER is located 480m downstream along beam collision axis
  * placed in beam of light weakly interacting particles
  * well shielded from ATLAS IP
  * small, fast and relatively cheap detector design
  * sensitive to LLP decays and **neutrinos**



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Part 3

Detecting and Studying High-Energy Collider Neutrinos at FASERν

Motivation

Neutrino Flux and Interactions

The FASERν Detector

Background and Measurements

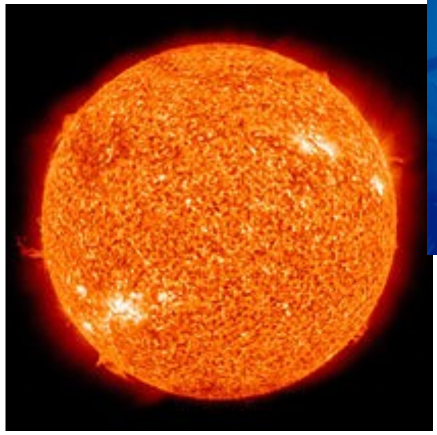
Physics Potential

Motivation

FASERν Motivation

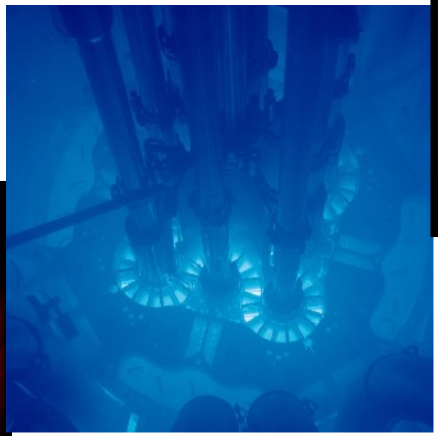
- neutrinos detected from many sources, but not from colliders

Solar



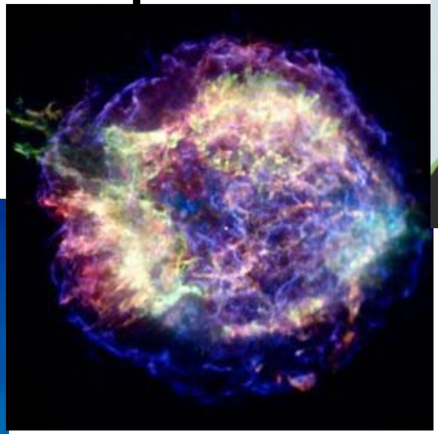
keV-MeV

Reactor



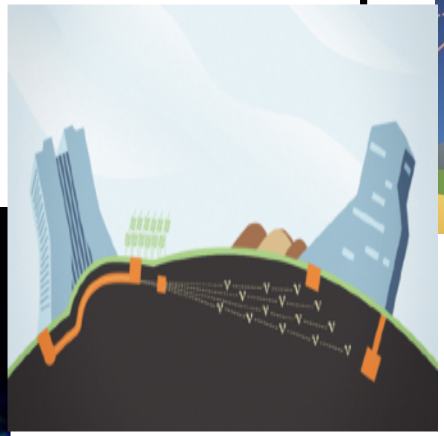
~MeV

Supernova



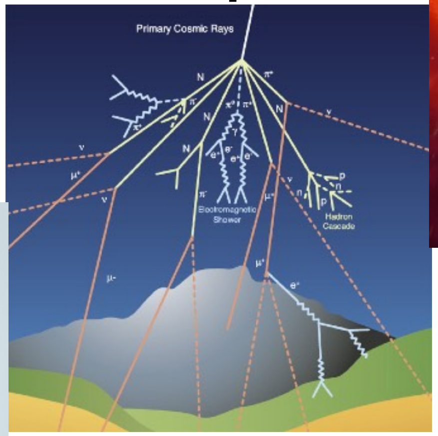
~MeV

Beam Dumps



GeV-subTeV

Atmospheric

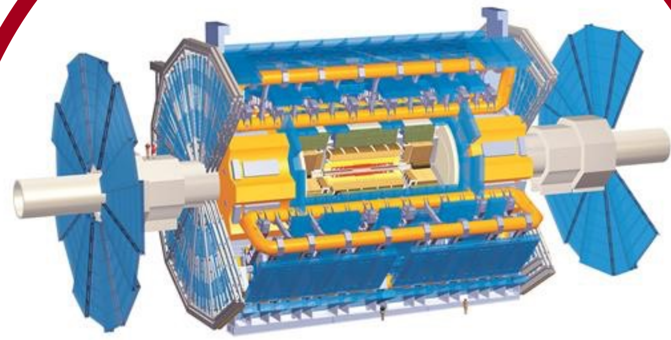


subGeV-PeV

Cosmic

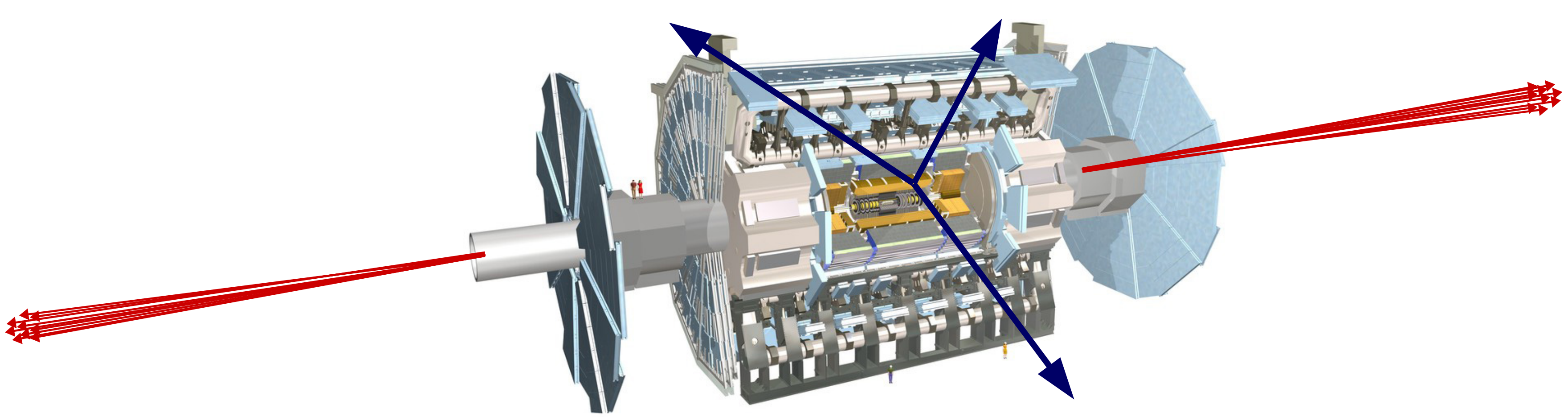
TeV-EeV

Collider



100GeV-multiTeV

- neutrinos detected from many sources, but not from colliders
- many neutrinos at LHC produced in π, K, D meson decay
  → ATLAS provides intense energetic collimated neutrino beam towards FASER
    * intense: ~10^{12} neutrino in LHC Run 3
    * energetic: E~TeV
    * collimated: $\theta \sim \Lambda_{QCD}/E \sim$ mrad



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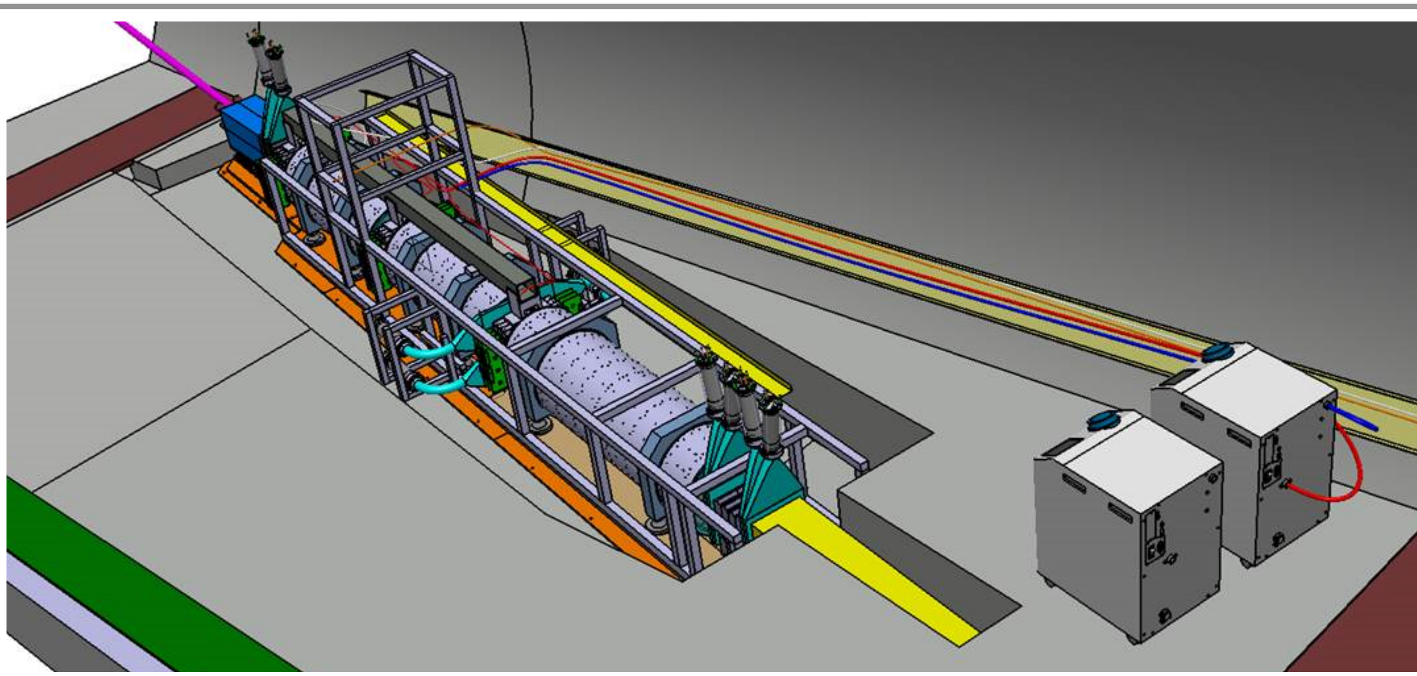
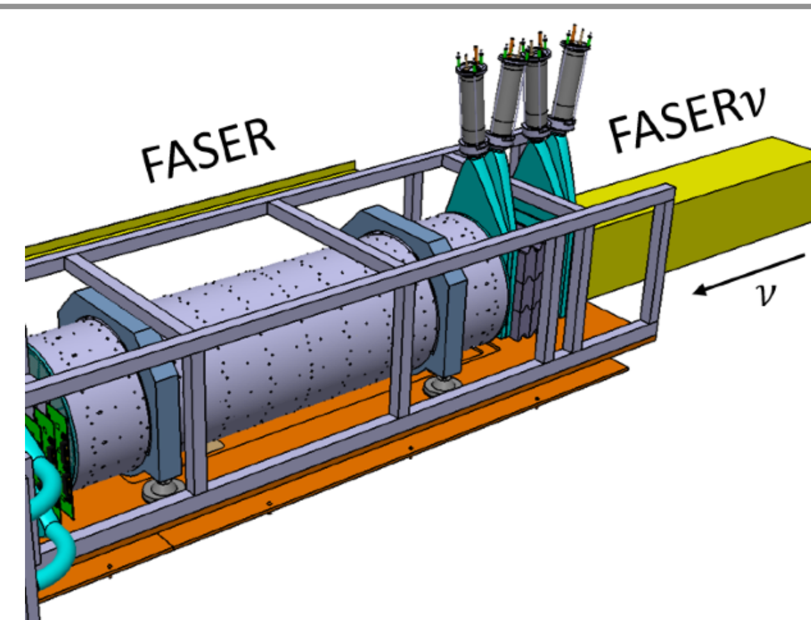
- dedicated FASERν neutrino detector in front of FASER
  * small: 25cm x 25cm x 1m emulsion detector
  * tungsten target with 1.2 ton mass
  * expected interaction rate during LHC Run 3

  * ~ 20000 ν_μ
  * ~ 2000 ν_e
  * ~ 20 ν_τ





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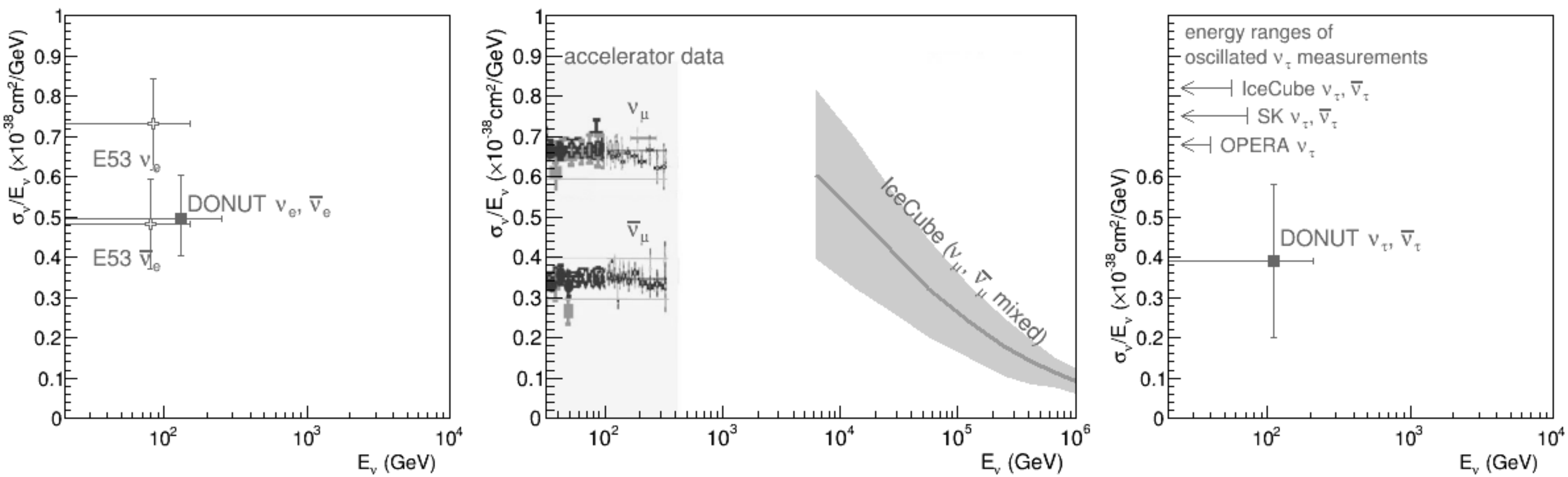
- TeV energy range currently unconstrained



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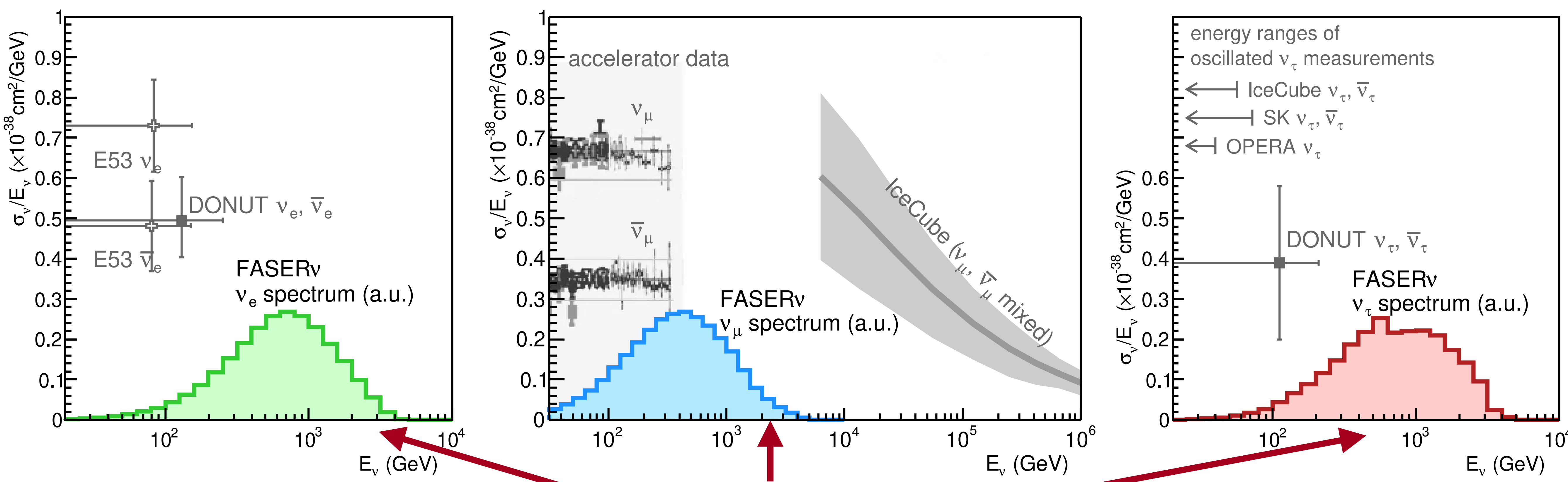
- TeV energy range currently unconstrained
  * FASERν allows to probe neutrino cross sections at TeV for all 3 flavors

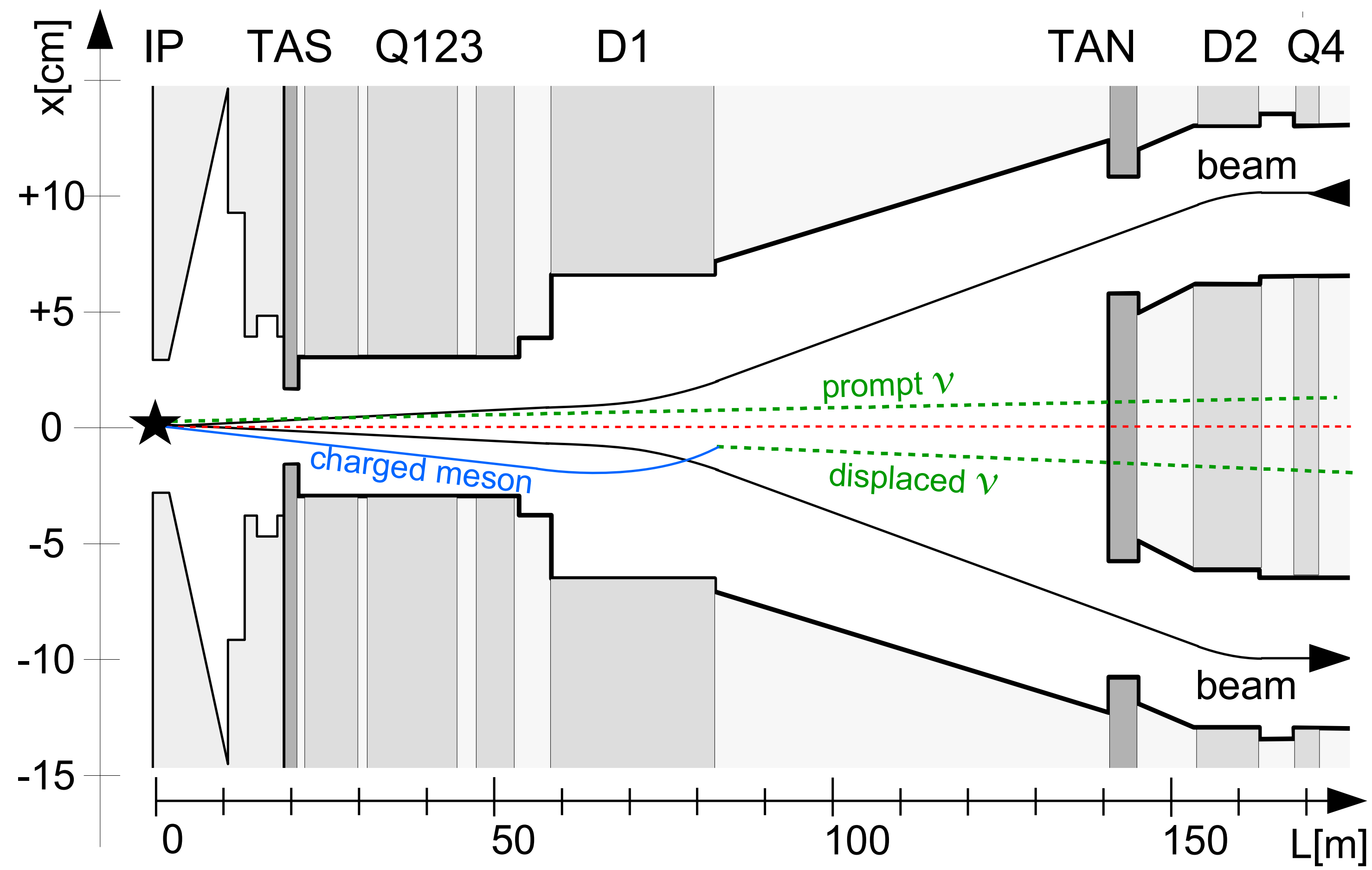


expected spectrum in FASER

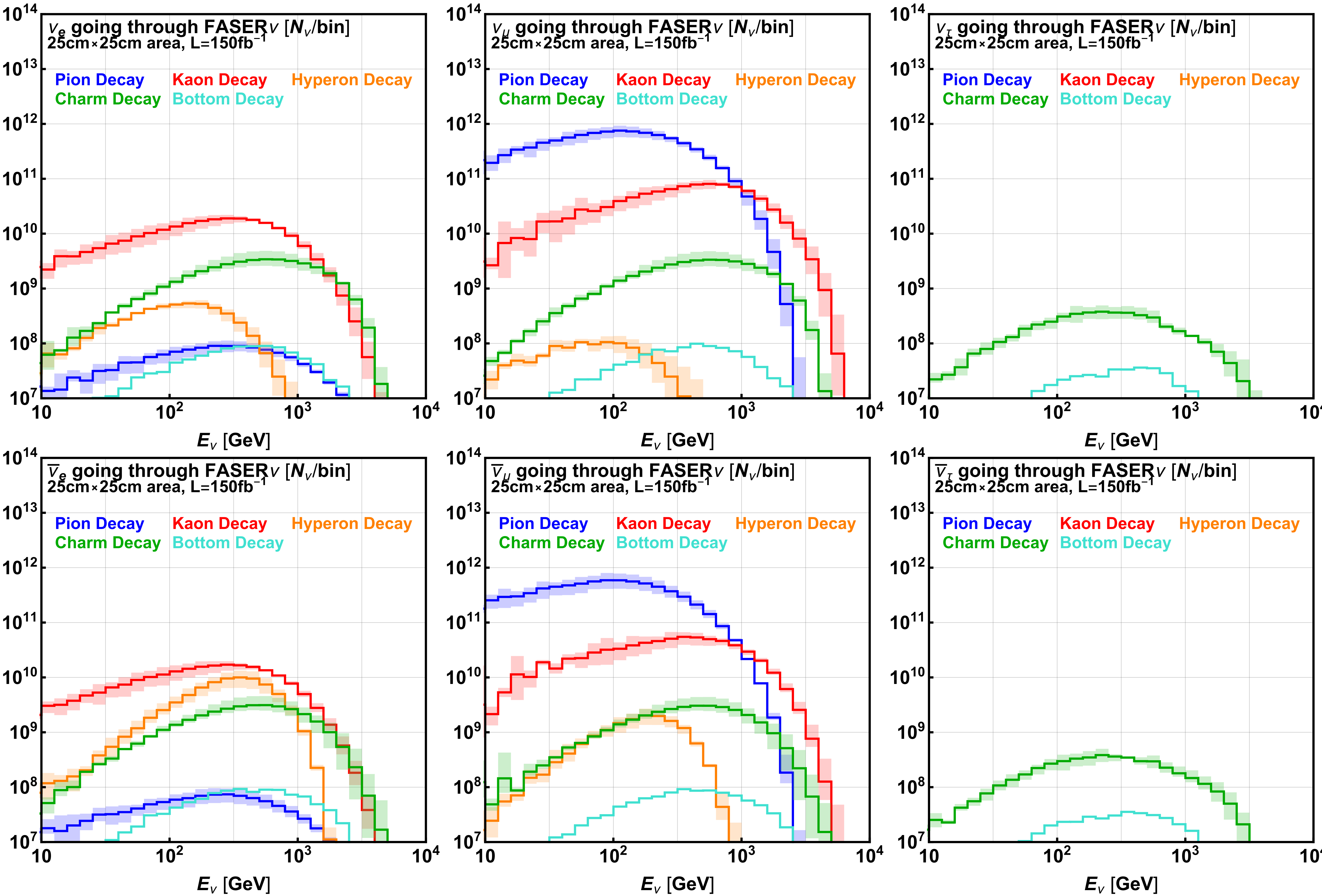
Neutrino Flux and Interactions

First Neutrino Flux Estimate

- neutrinos at FASER produced in forward hadron decays
- prompt neutrinos from heavy hadrons decay
  * charm, bottom
  * simulated using SIBYLL, PYTHIA8
- displaced neutrinos from light hadron decay
  * pions, kaons, hyperons
  * simulated using EPOS-LHC, QGSJET, SIBYLL
- long lived hadrons: modeling propagation through LHC
  * deflection by magnets
  * absorption in beam pipe
  * use simplified simulation
- obtained neutrino flux through FASERν
- first estimate of flux uncertainties
  * range of simulator predictions

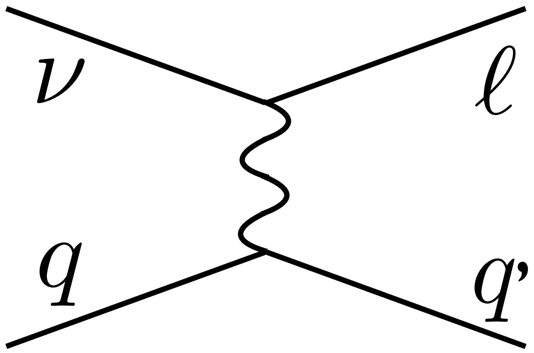


Neutrino Flux and Interactions



Neutrino Interaction Rate

- for E_ν>100GeV: deep inelastic scattering $q\nu \rightarrow q'\ell$



$$\frac{d\sigma_{\nu p}}{dx\ dy} = \frac{G_F^2 m_p E_\nu}{\pi} \frac{m_{W,Z}^4}{(Q^2 + m_{W,Z}^2)^2} \times \left[x f_q(x, Q^2) + x f_{\bar{q}}(x, Q^2)(1-y)^2\right]$$

* proton momentum carried by the quark q: $x \sim 0.1$
* fraction of the neutrino energy transferred: $y \sim 0.5$
* transferred four-momentum: $Q^2 \sim (10\text{ GeV})^2$
* cross section grows linear with energy: $\sigma \sim E$

Neutrino Flux and Interactions

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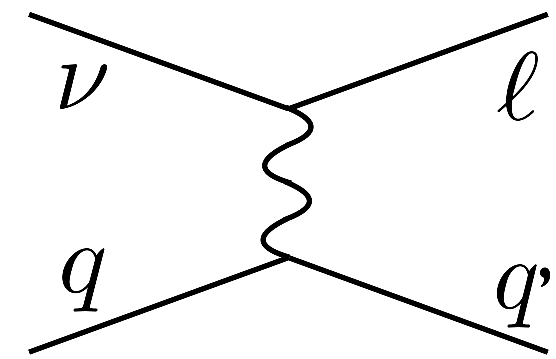
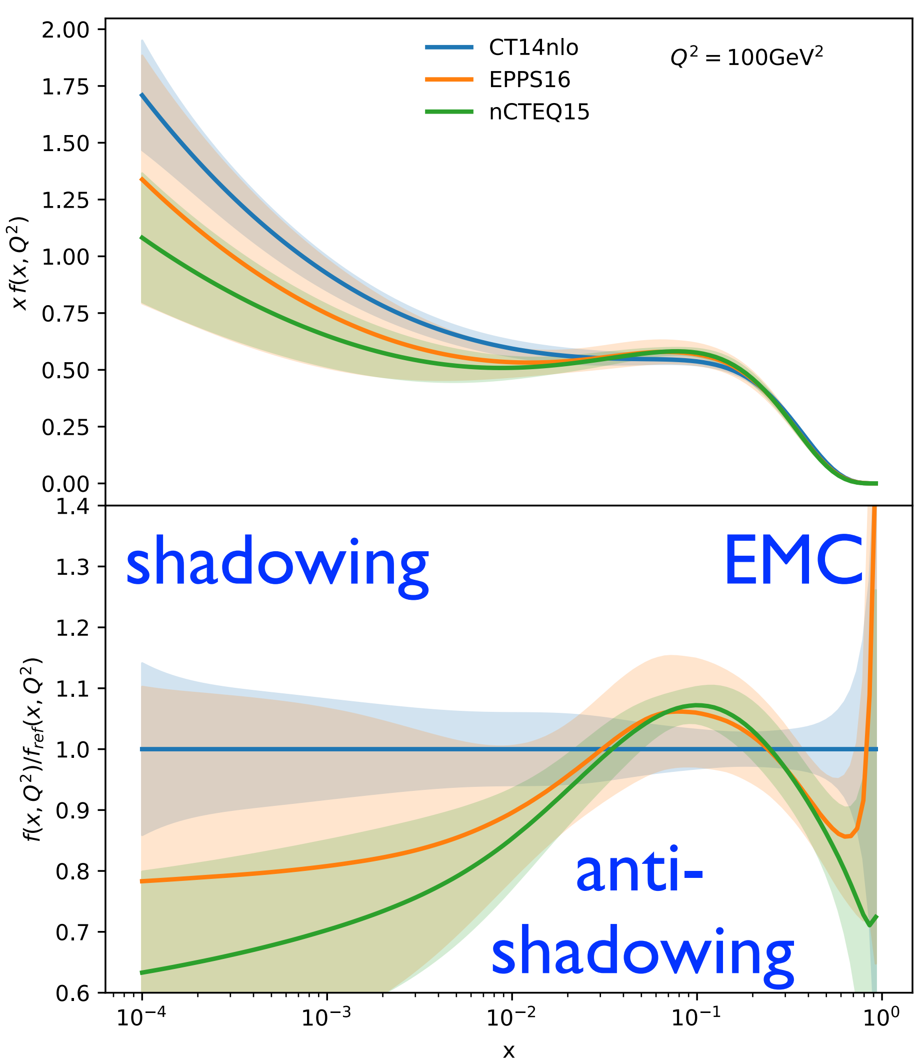
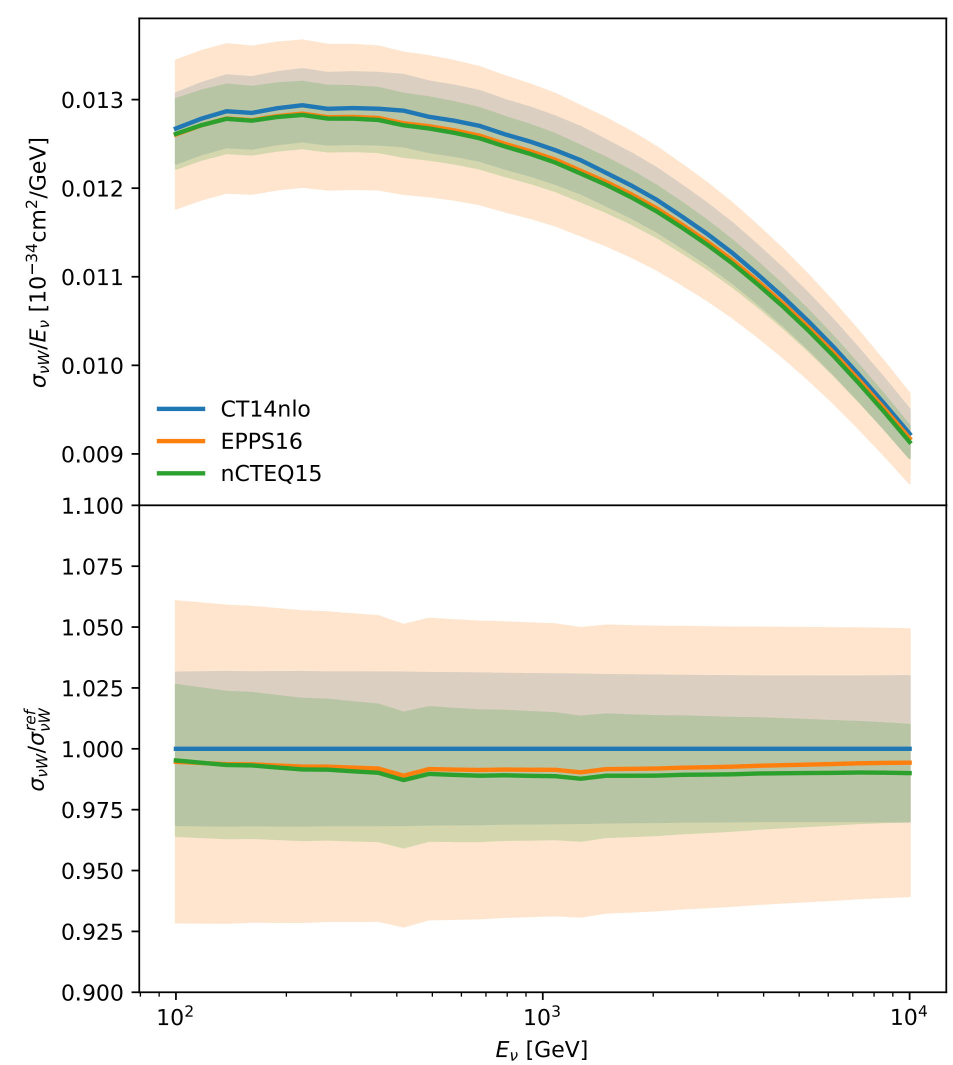


- FASER measures scattering on tungsten (Z=74, A=184)
  * without nuclear effects: $\sigma_{\nu N} = Z\sigma_{\nu p} + (A\text{-}Z)\sigma_{\nu n}$
  * for heavy nuclei, nuclear effects become important
  * treated using nuclear PDFs → only mild changes in cross section





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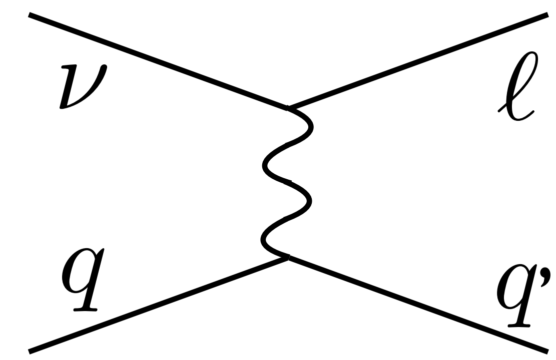

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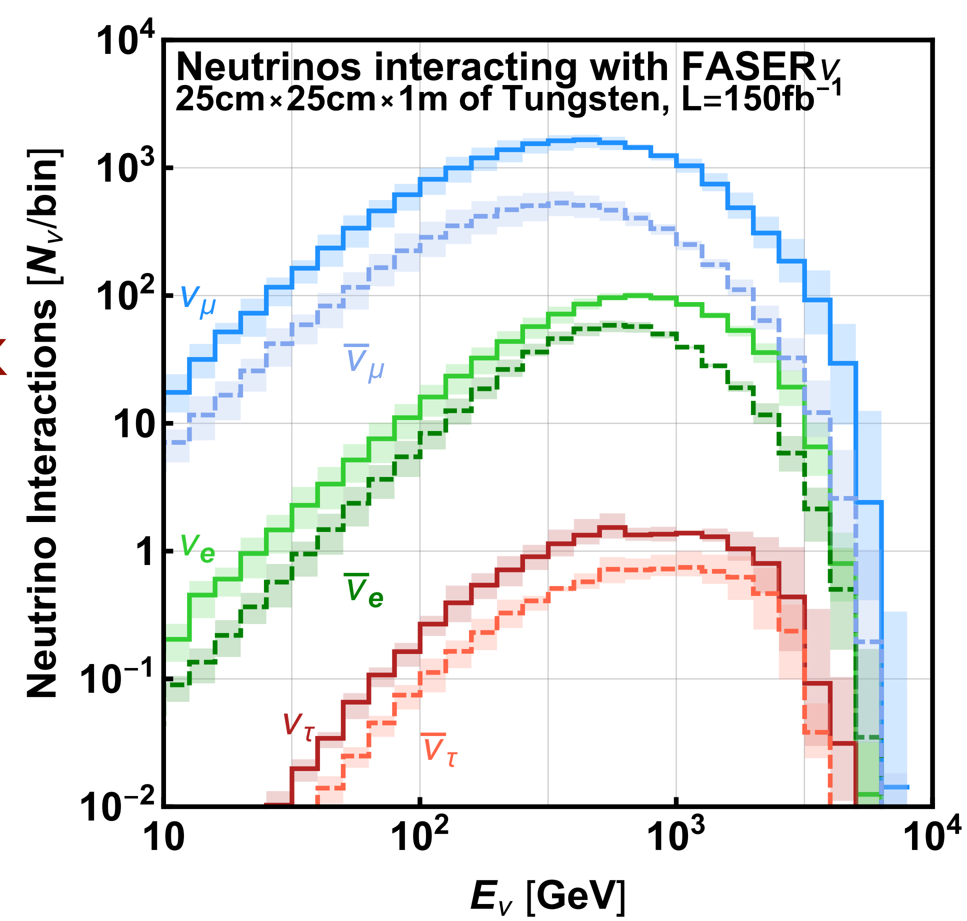
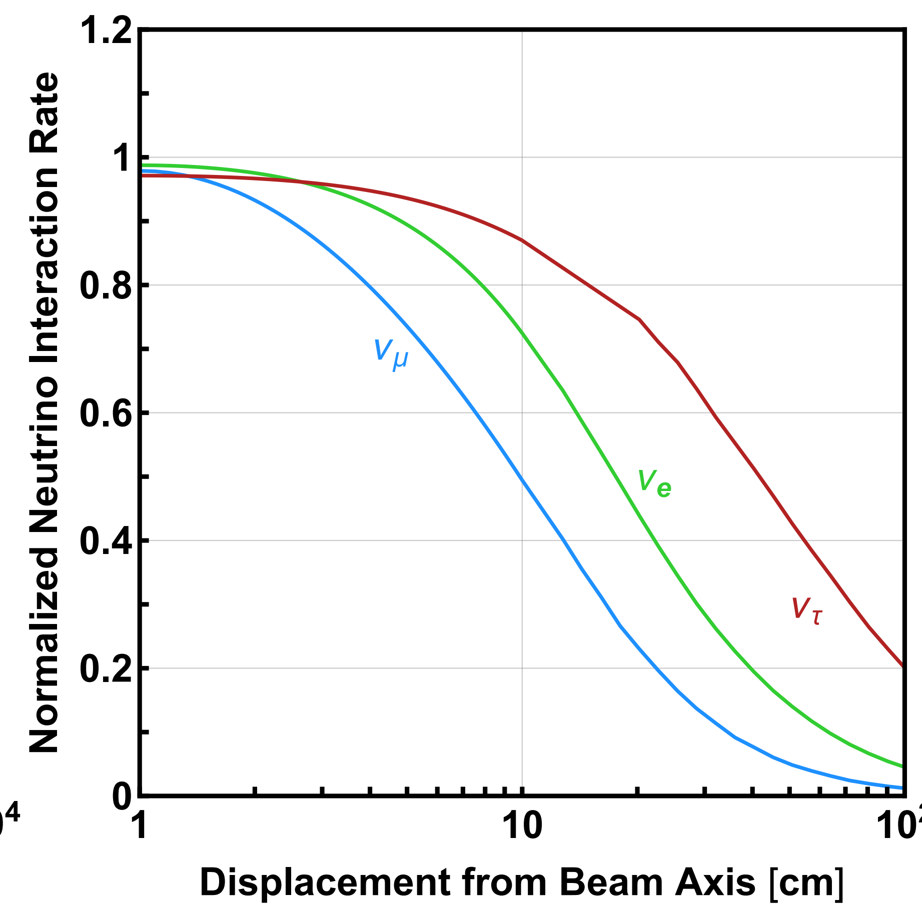
- FASER measures scattering on tungsten (Z=74, A=184)
  * without nuclear effects: $\sigma_{\nu N} = Z\sigma_{\nu p} + (A-Z)\sigma_{\nu n}$
- calculate events rate at FASERν during LHC Run 3 (150 fb^{-1})
  * interaction probability = $\sigma_{\nu N}$ * (Number of Nuclei) / (Detector Area)
  * average energy ~TeV
  * ~ 20000 ν_μ
  * ~ 2000 ν_e
  * ~ 20 ν_τ
  * highest neutrino flux along beam axis

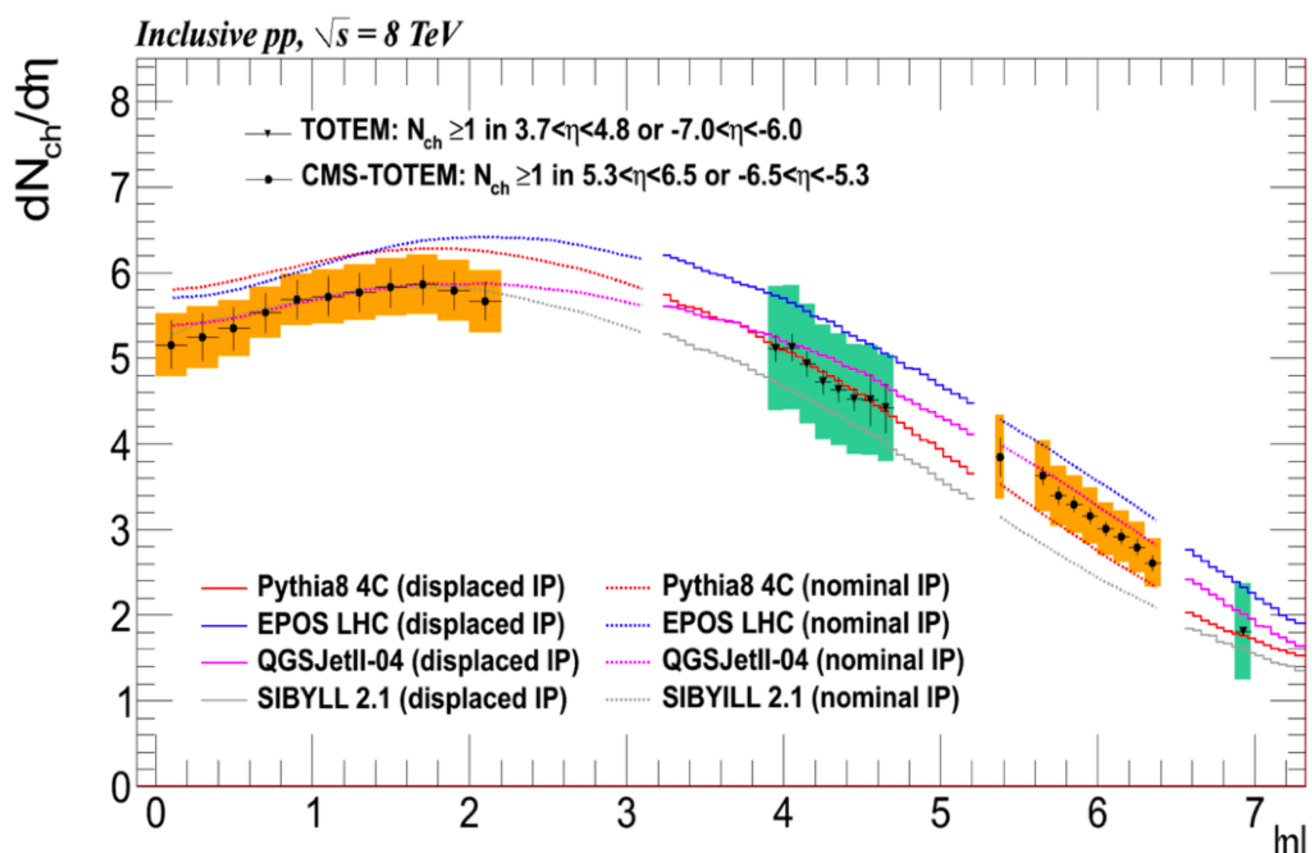




Neutrino Flux Modelling Uncertainties

- cross section measurements limited by neutrino flux uncertainty
  * we need to quantify and reduce these uncertainties
- forward particle production not described by pQCD, but soft physics
  * use hadronic interaction models
- simulators based on sophisticated modeling of microscopic physics
  * phenomenological parameters need to be tuned
  * include tuning uncertainties (similar to PDFs)

    → develop dedicated forward physics tune using forward data



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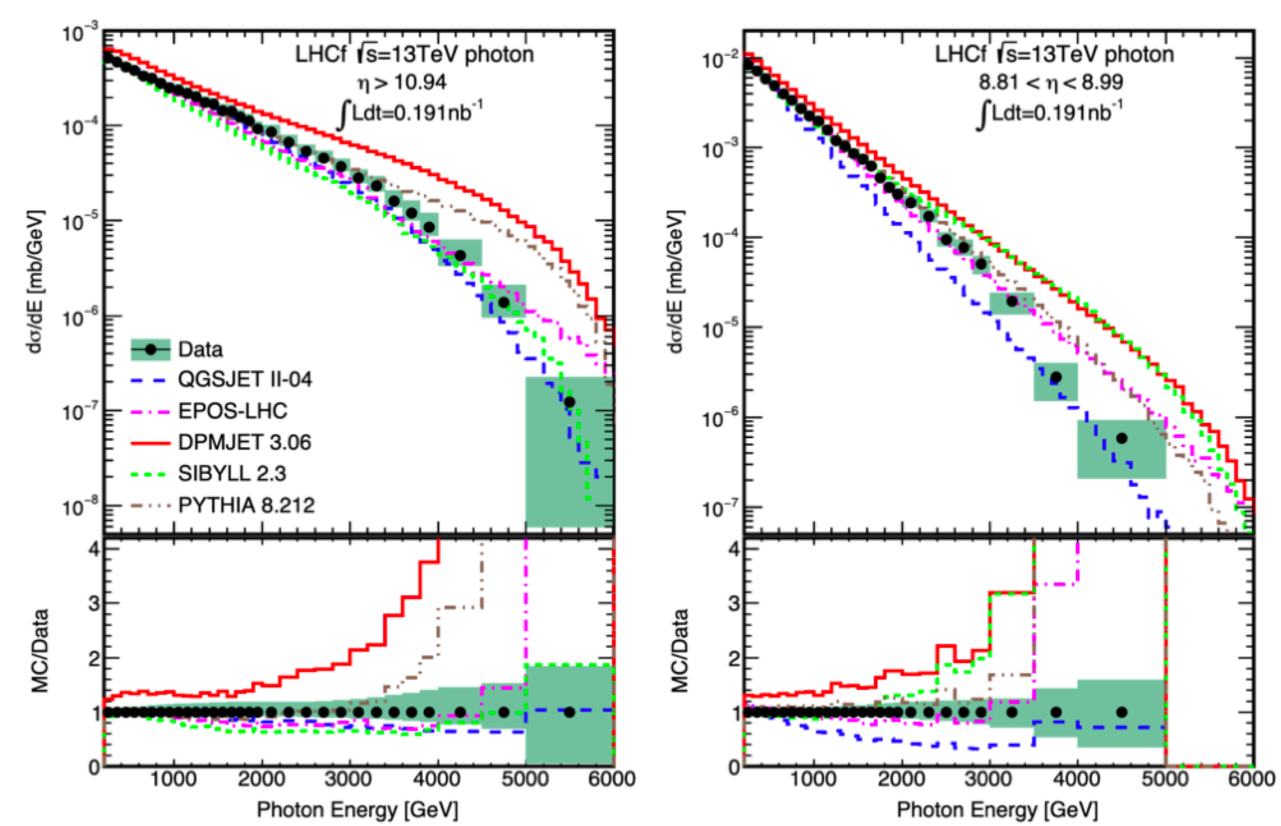

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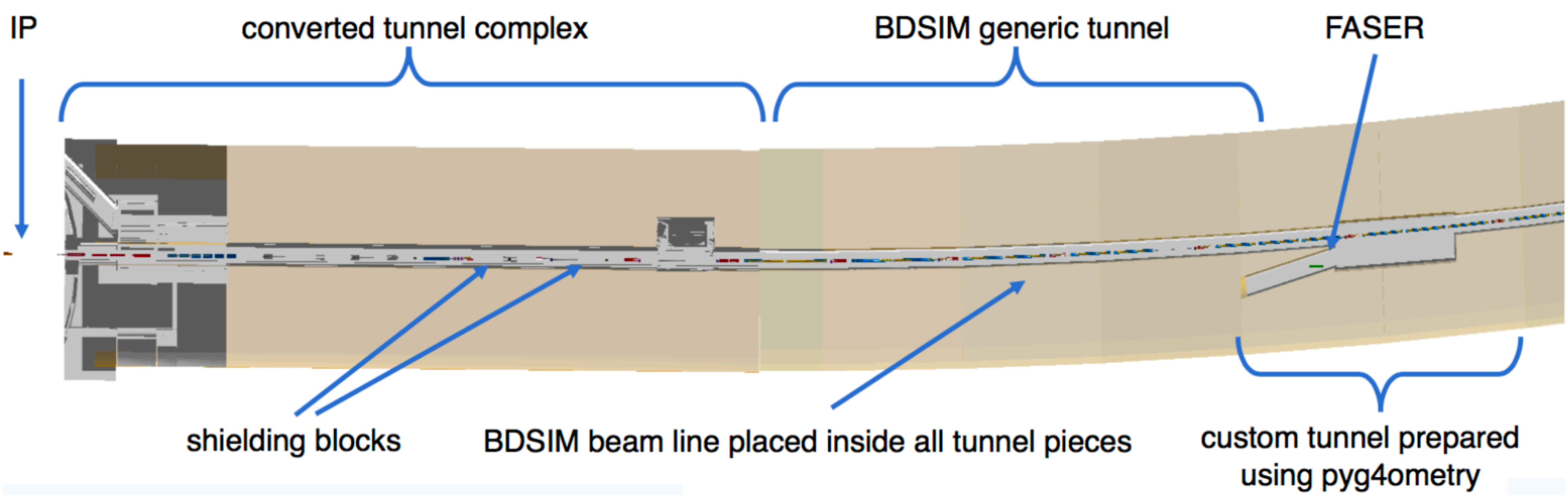
Neutrino Flux and Interactions

Dedicated LHC simulations: Beam Delivery Simulation

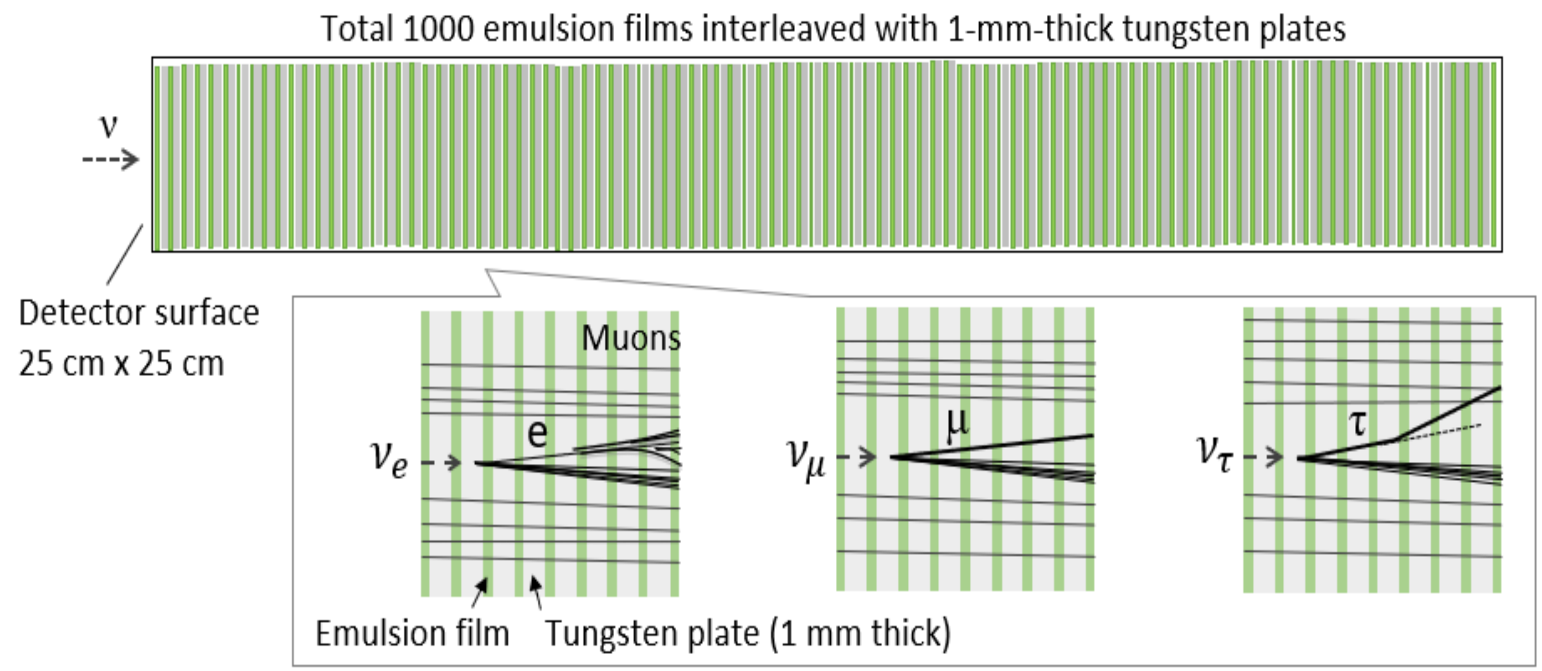
- full Geant4 based LHC simulation: BDSIM
- allows to study
  * effect of beam configurations, crossing angle
  * additional secondary neutrino production (for example in TAN)
  * sources of uncertainties associated with the simulation
  * muon flux at FASER
- study ongoing

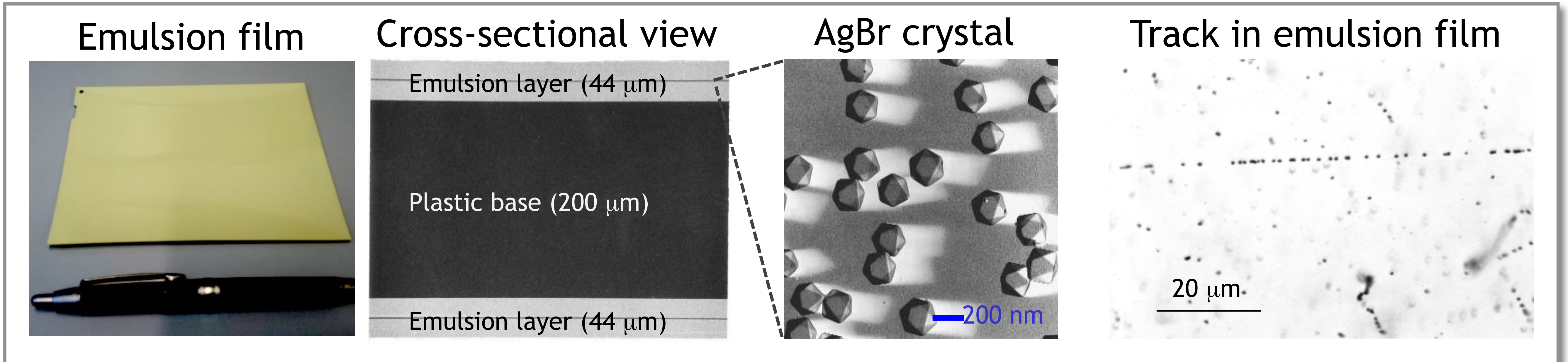


The FASERν Detector

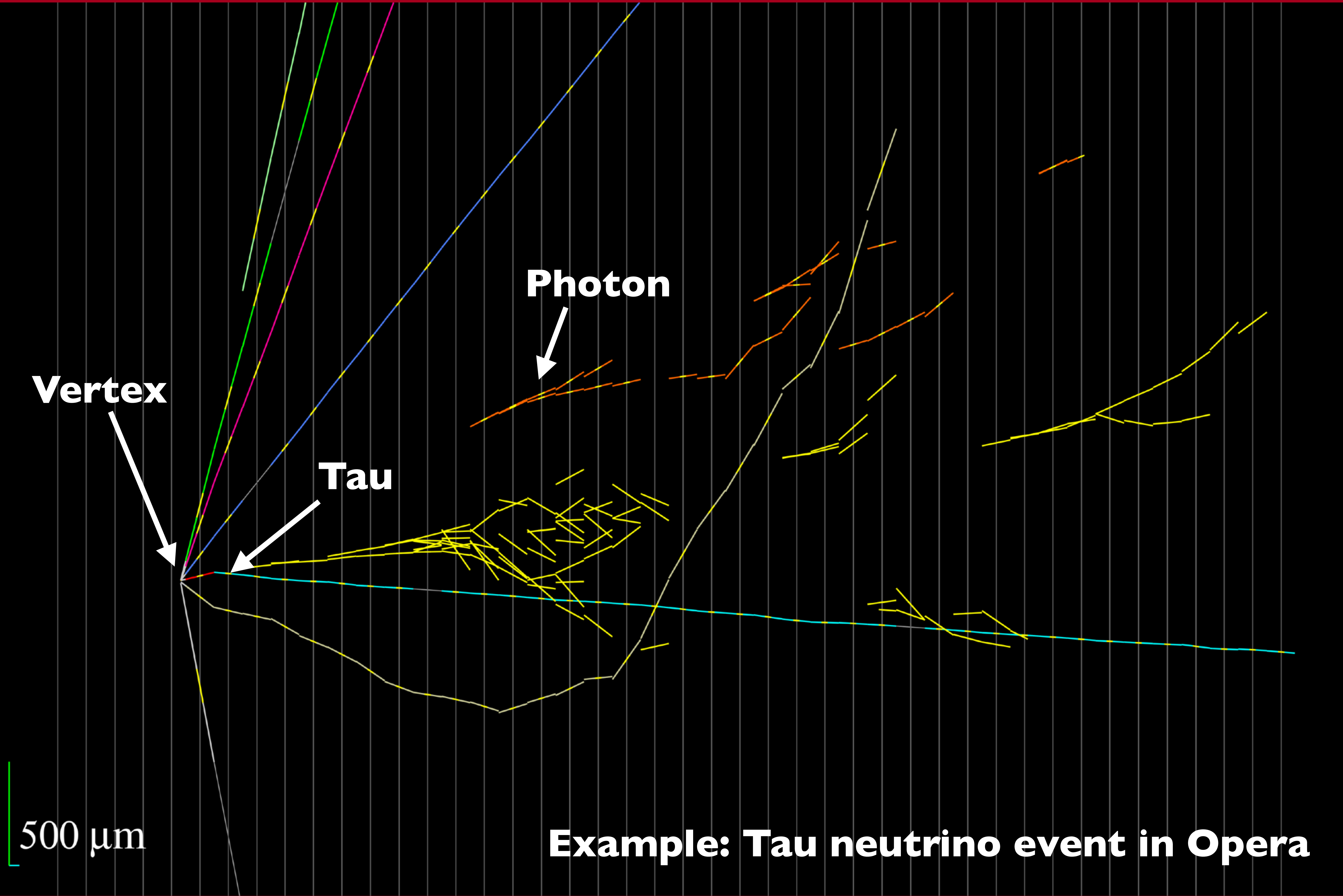
Detector Technology

- emulsion detector
  - 3D tracking device with 50 nm precision
  - no time resolution
- 1000 emulsion films interleaved with 1mm tungsten plates
  - allows flavor identification
  - vertex finding efficiency about 80%





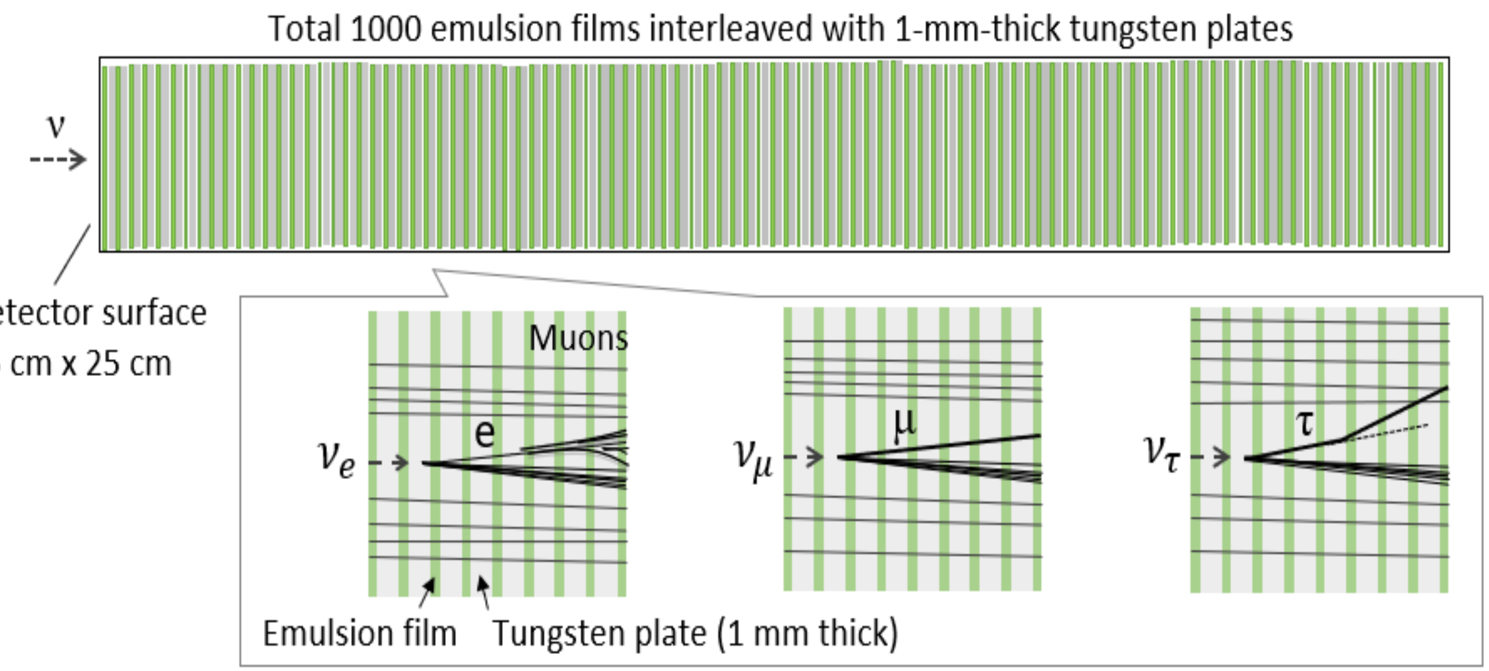
FASERν Detector



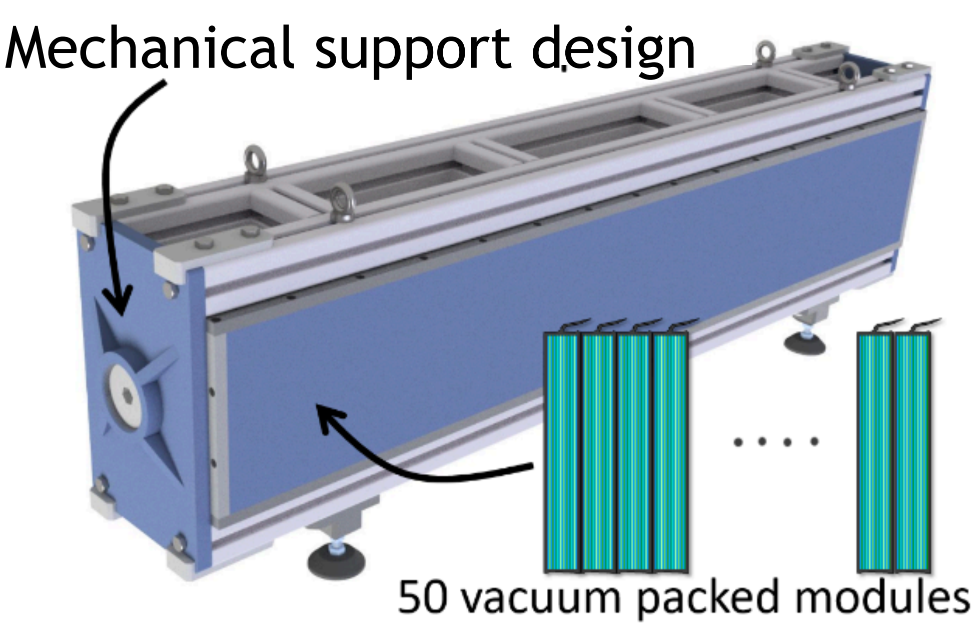
Example: Tau neutrino event in Opera

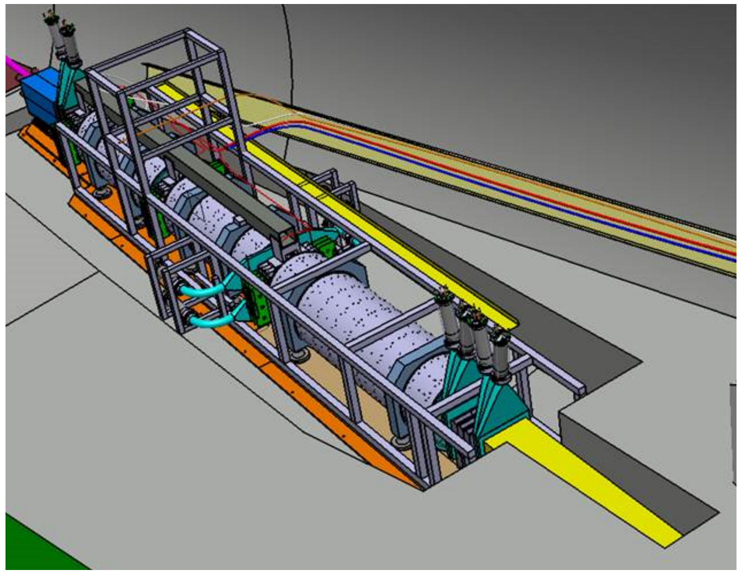
Detector Technology

- emulsion detector
  * 3D tracking device with 50 nm precision
  * no time resolution
- 1000 emulsion films interleaved with 1mm tungsten plates
  * allows flavor identification
  * vertex finding efficiency about 80%
- replace every 15-30 fb^{-1} to maintain track low density



Vacuum-packed module





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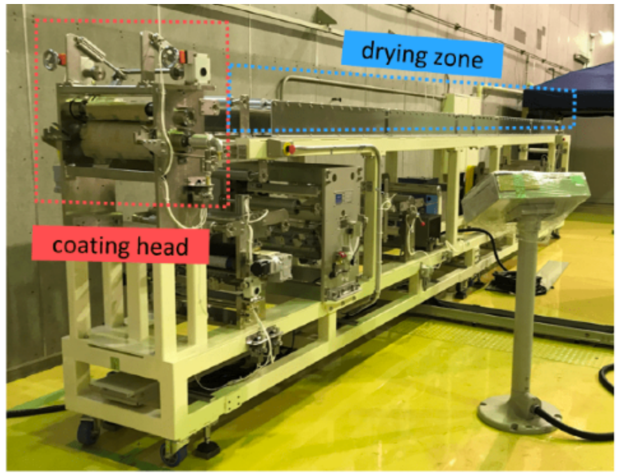
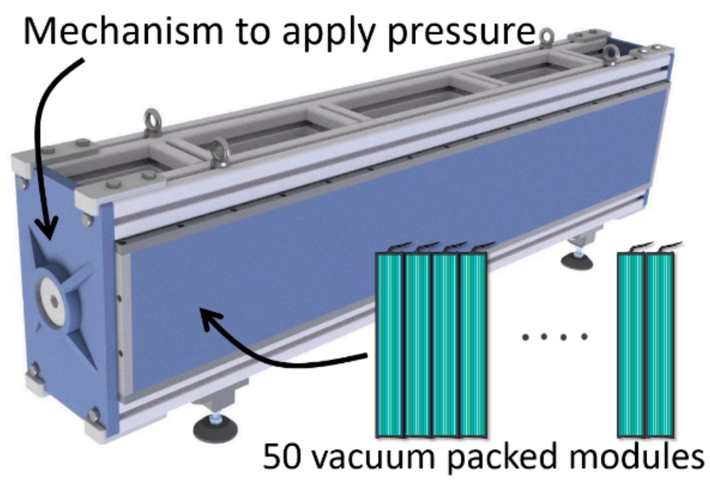
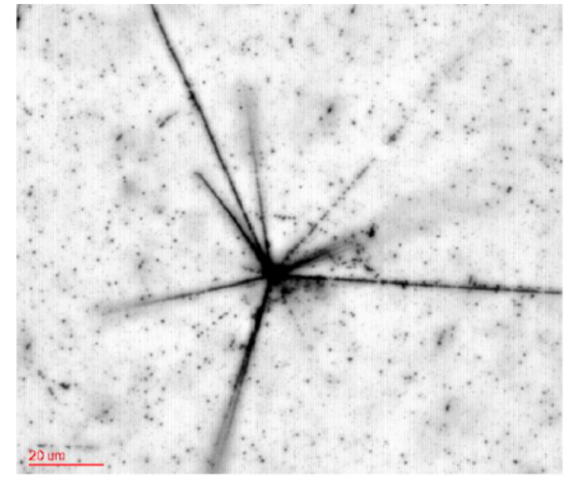
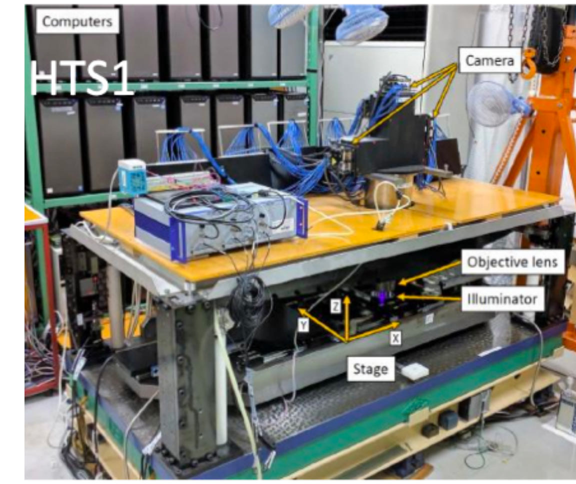


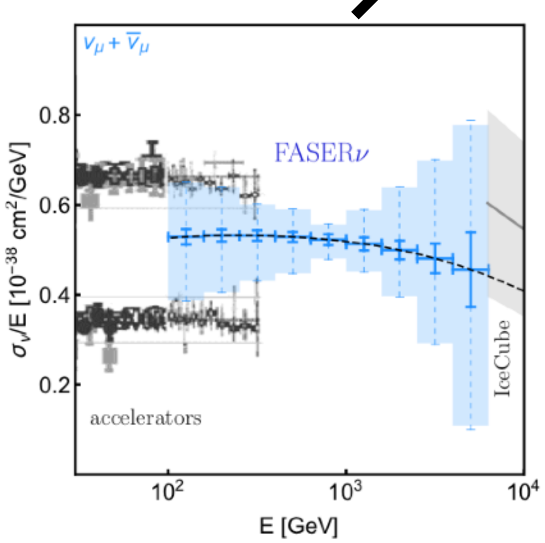


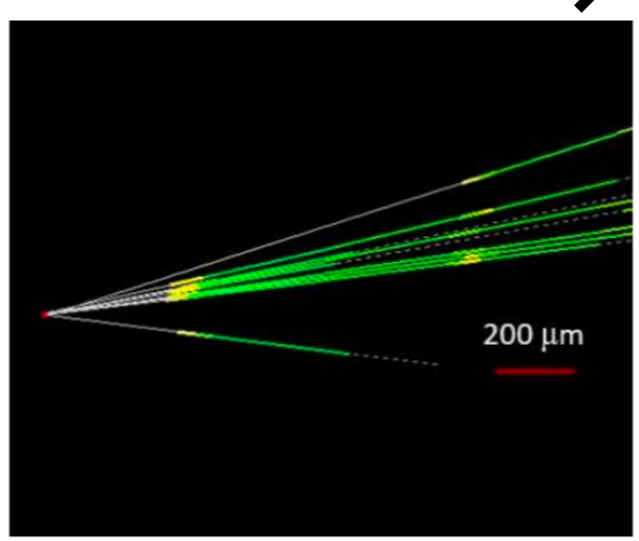


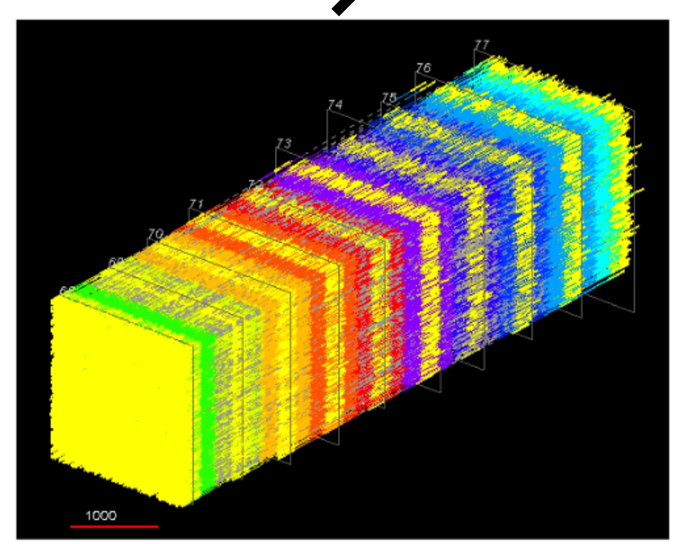


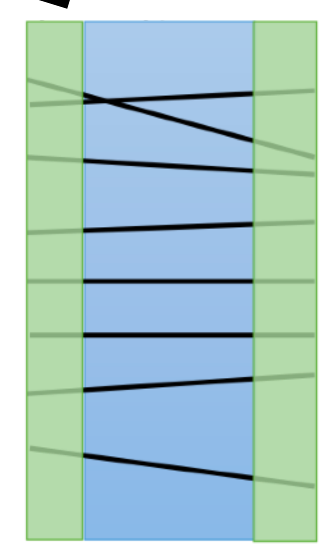
In Japan: **Emulsion film production** → At CERN: **Detector assembling** → **Exposure** → **Disassembling** → **Development** → In Japan: **Full area Readout**

Off-line analysis: **Alignment** → **Track reconstruction** → **Vertex reconstruction** → **μ / e ID** → **Search for tau/charm decays** → **Kinematical analysis**









FASERν Detector

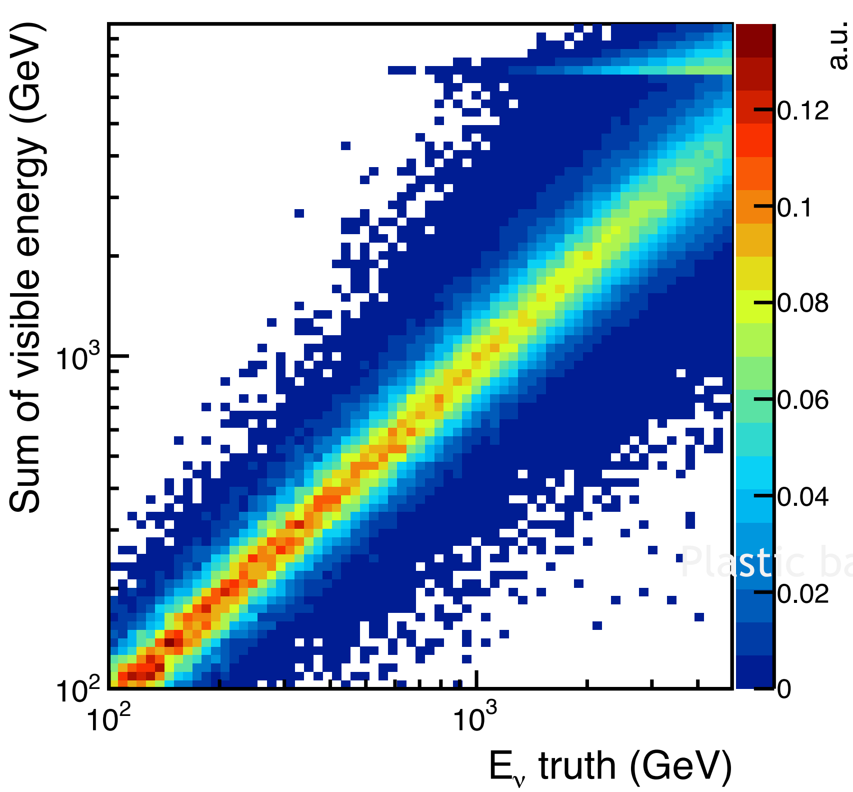
Neutrino Energy Reconstruction

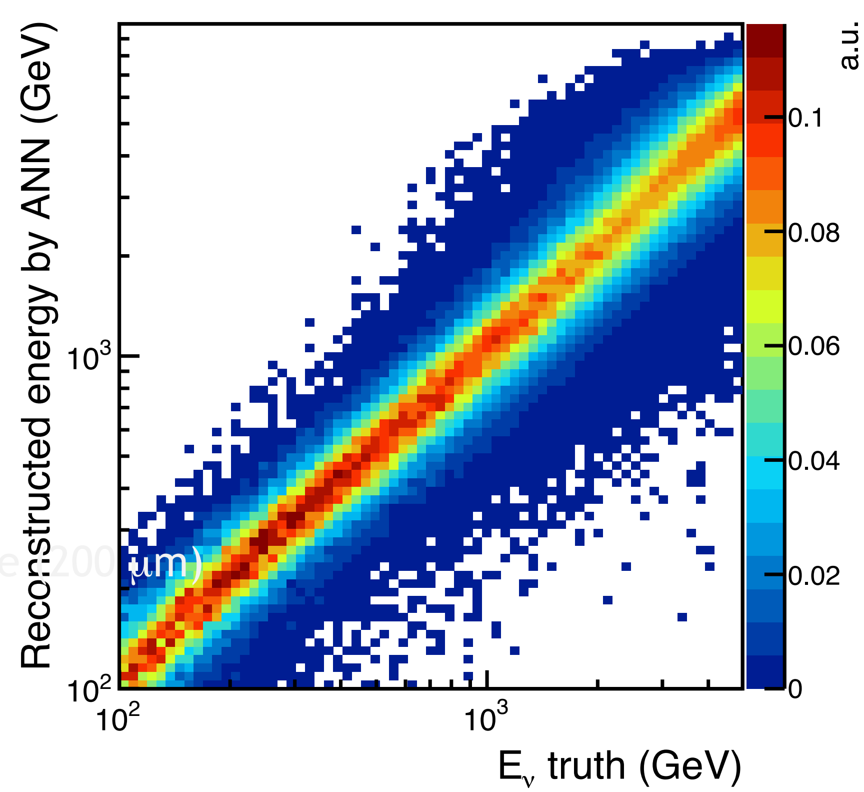
i) use visible energy measurement
  * track: multiple coulomb scattering
  * γ/e: EM shower

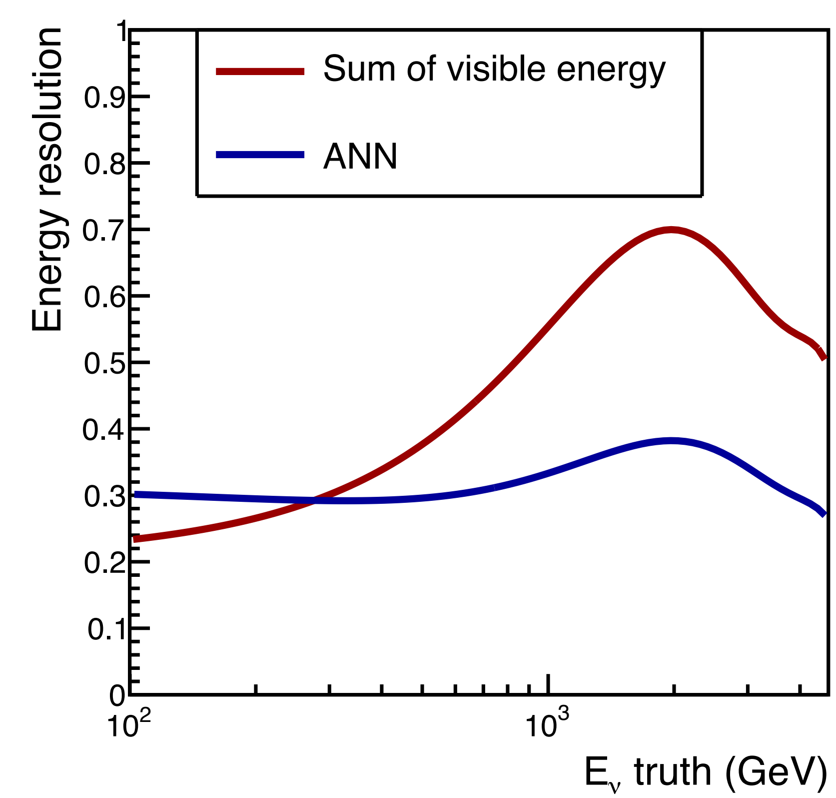
ii) multivariate analysis
  * topological + kinematic observables
  * use ANN

30% energy resolution achievable

Topological Variables		related to
$n_{\rm tr}$	charged tracks multiplicity	$E_{\rm had}$
n_γ	photon multiplicity	$E_{\rm had}$
$\lvert 1/\theta_\ell \rvert$	lepton angle	E_ℓ
$\sum \lvert 1/\theta_{\rm had} \rvert$	sum of inverse hadron track angles	$E_{\rm had}$
$1/\theta_{\rm median}$	inverse of median of all track angles	$E_{\rm had}, E_\ell$
Kinematical Variables		
$p_\ell^{\rm MCS}$	lepton momentum from MCS	E_ℓ
$\sum p_{\rm had}^{\rm MCS}$	charged hadron momenta from MCS	$E_{\rm had}$
$\sum E_\gamma$	energy in photon showers	$E_{\rm had}$



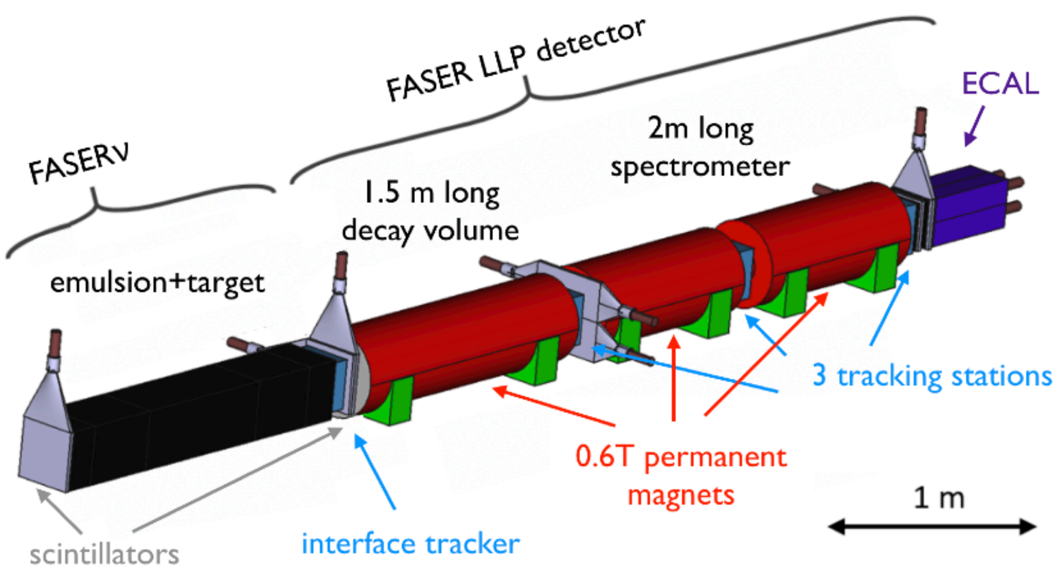


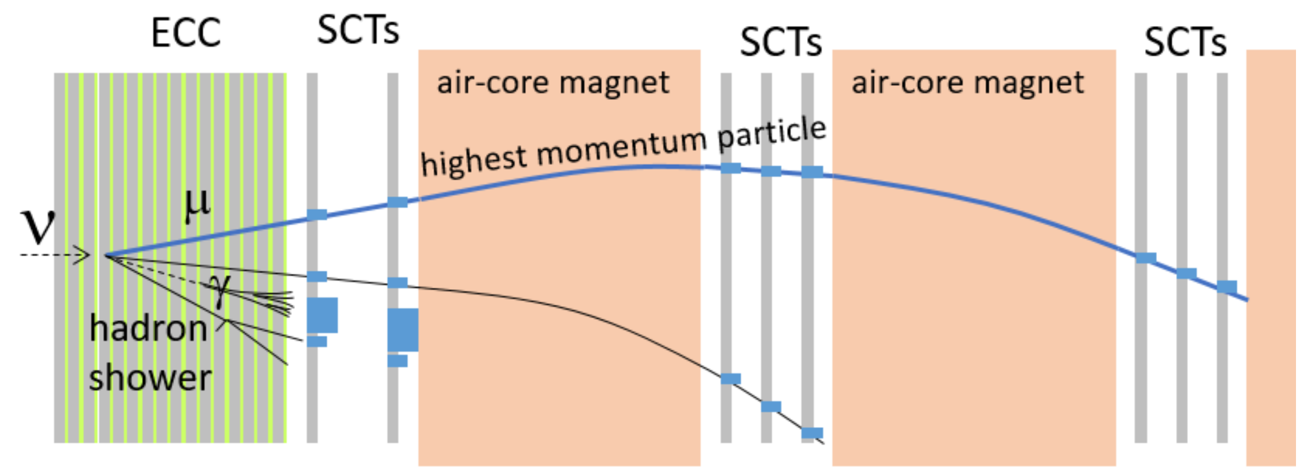


FASERν Detector

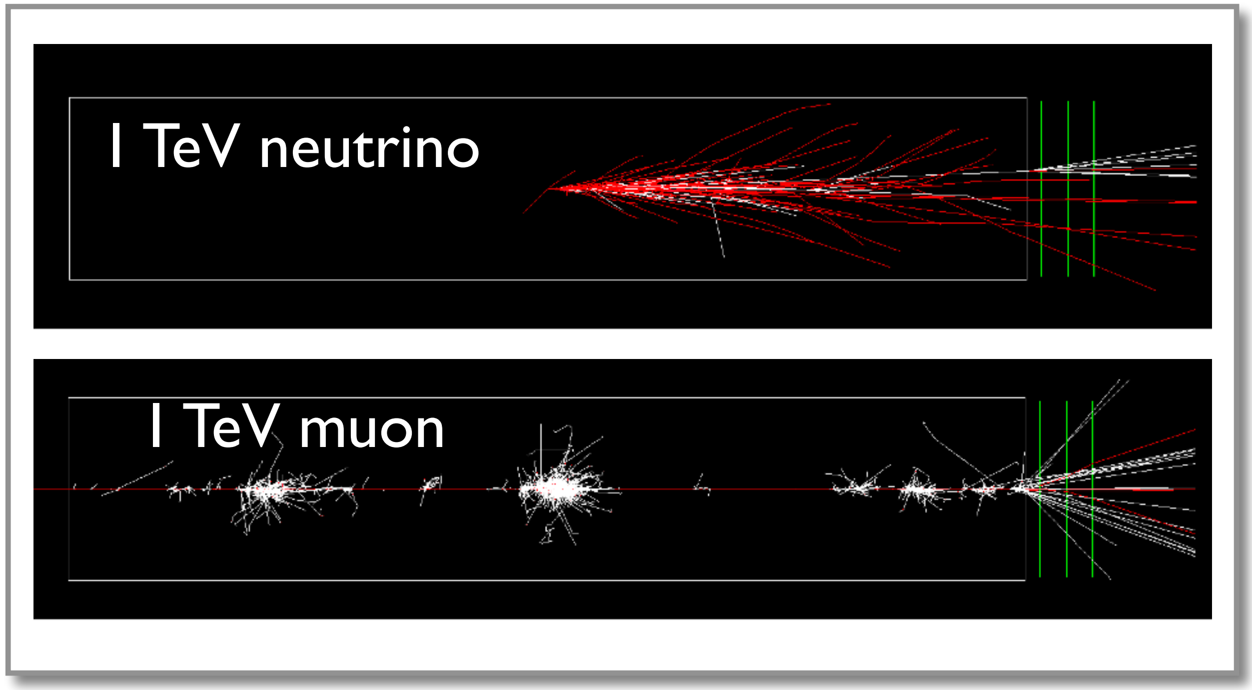
Interface Detector

- possibility for future: global reconstruction with the FASER detector
  * interface FASERν to the FASER spectrometer
  * additional tracking layer to allow matching





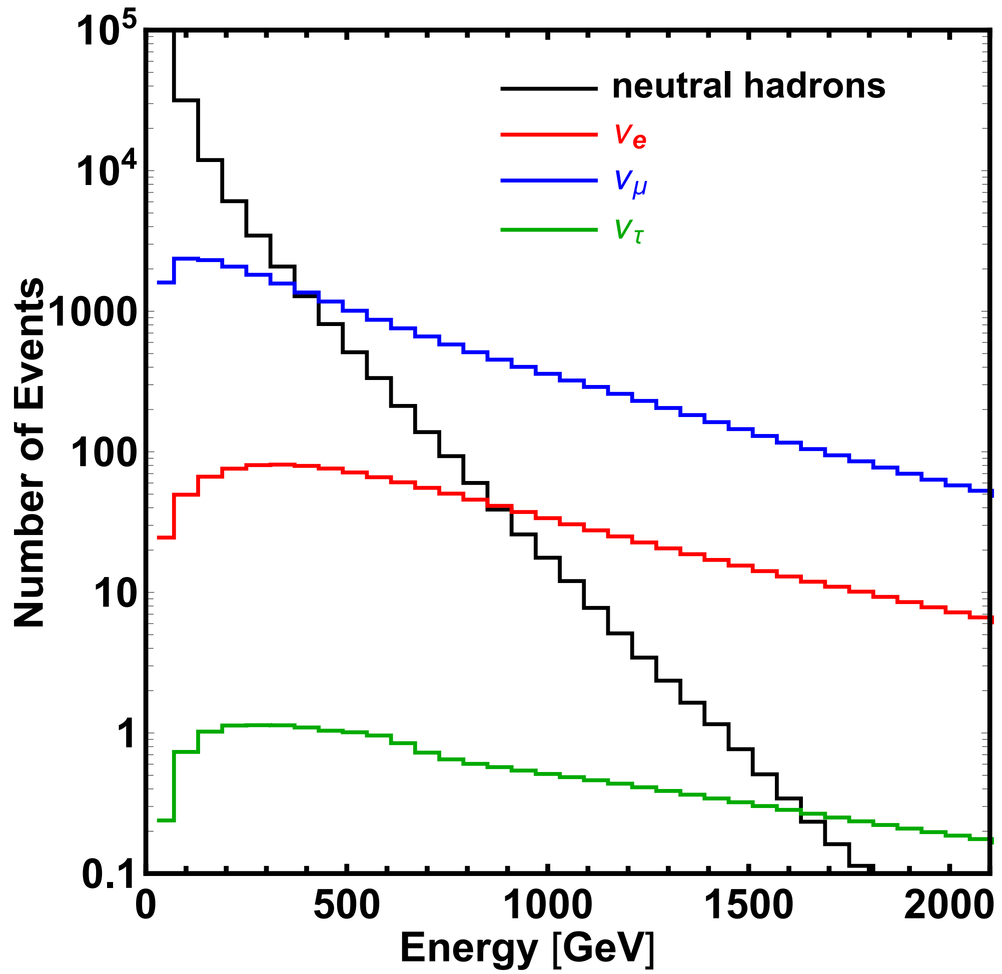
- muon charge identification
  → distinguish neutrino / anti-neutrino
- momentum of charged tracks
  → improve neutrino energy reconstruction
- timestamp events and identify additional activity (muon)
  → background rejection

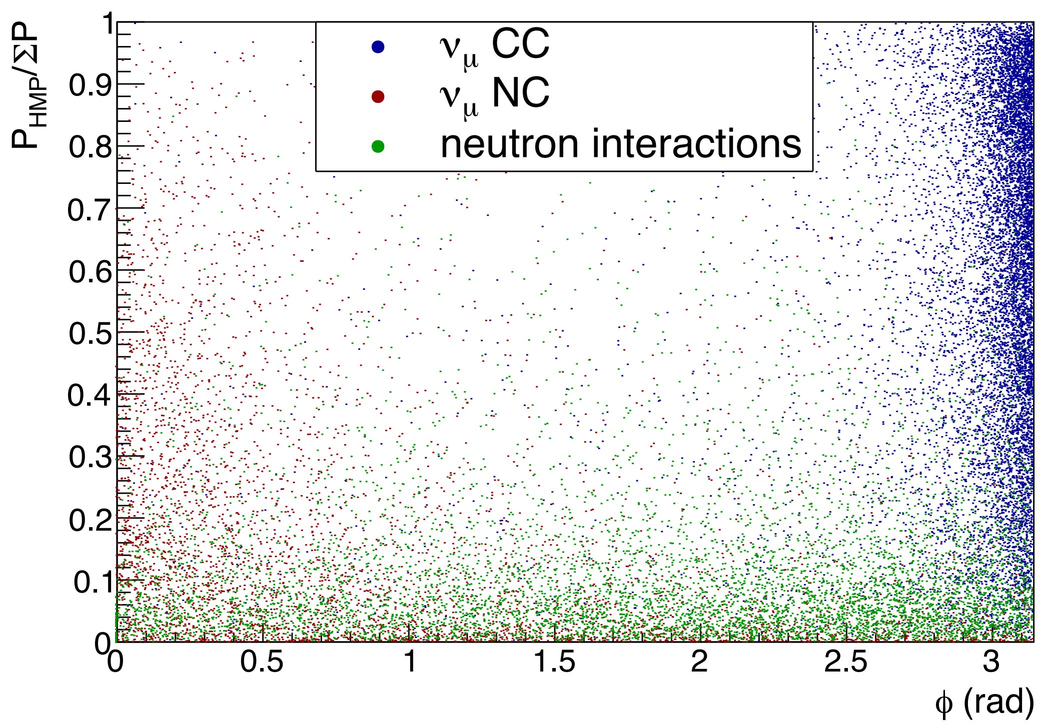


Backgrounds and Measurements

FASERν Backgrounds

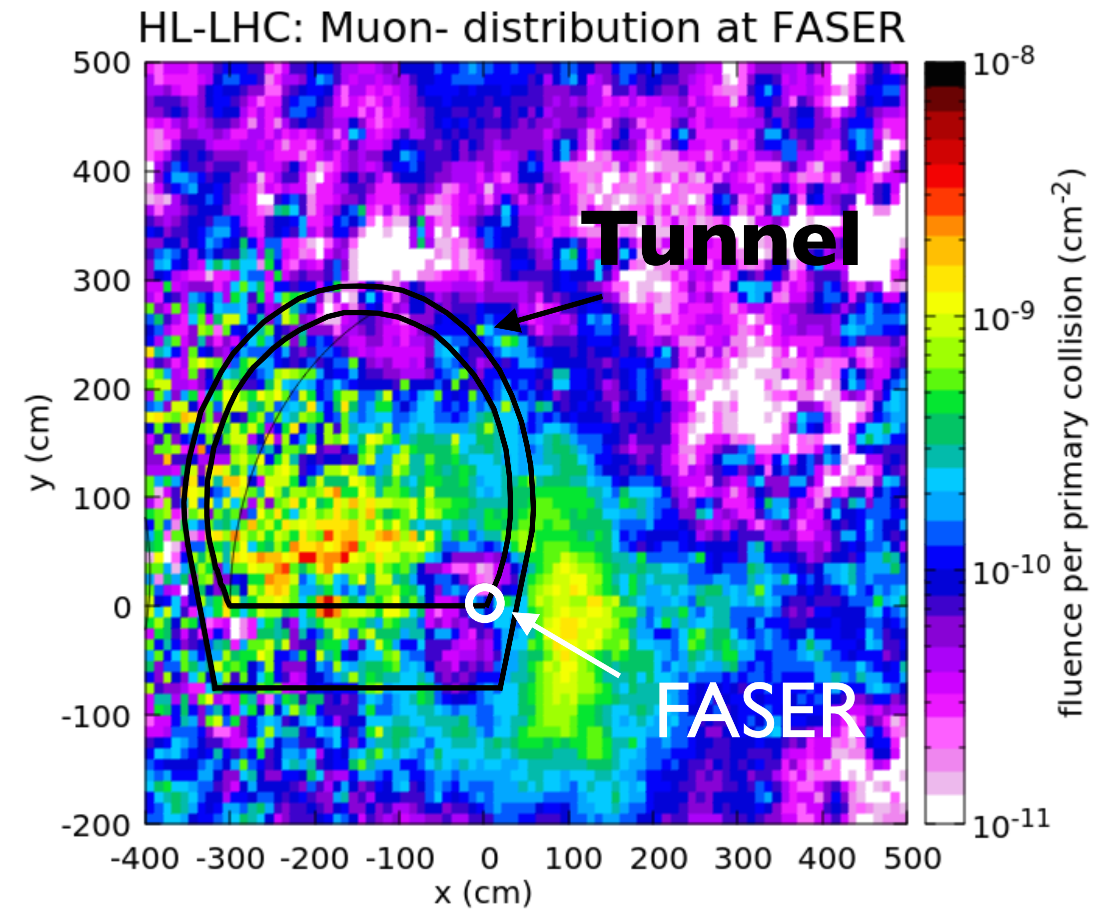
- neutrino interaction signal is striking
  * neutral vertex identified with >5 tracks
  * points back to IP
  * high energy event
  * charged lepton identified
- neutral hadrons could mimic neutrino signal
  * simulated with FLUKA
  * rejection based on energy, lepton ID and kinematics
- lepton identification
  * ν_μ: highest momentum particle without interactions
  * ν_e: single-electron initiated EM shower
  * ν_τ: kink from displaced τ-decay vertex



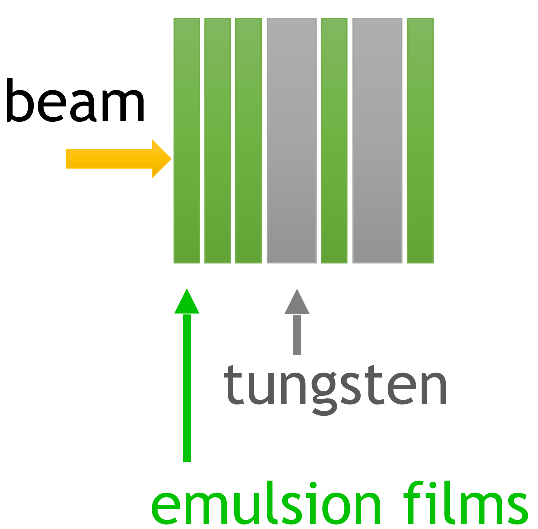


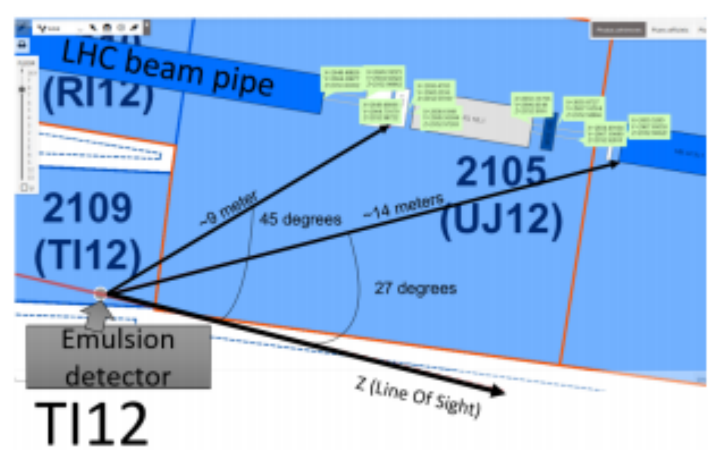
FLUKA Simulation
- only muons/neutrinos can pass 100m rock
- muon flux simulated by CERN STI group
- FASER in “shadow of LHC magnets“

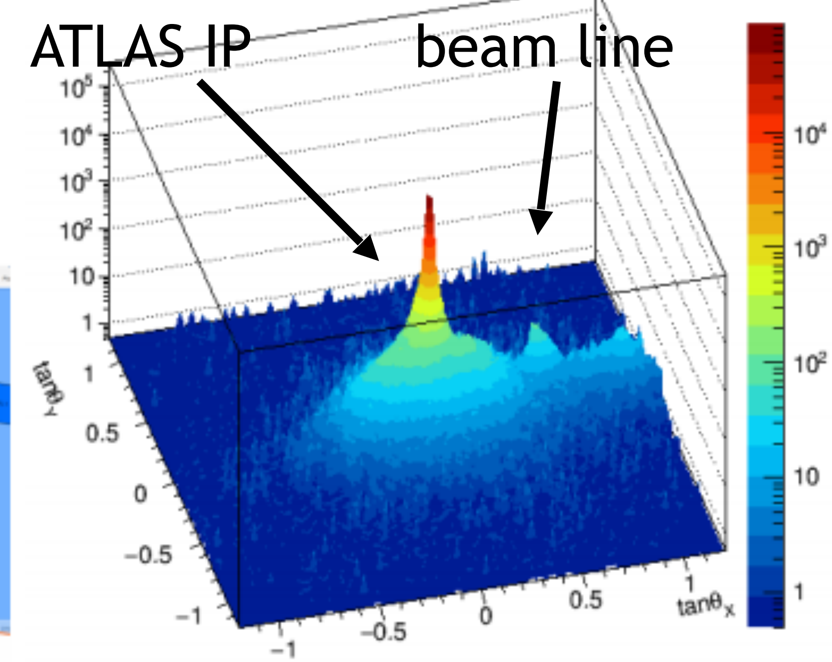
2018 In Situ Measurements
- test of detector environment in TI12 and TI18
- flux and angular measurements
- data/simulation agree



detector structure



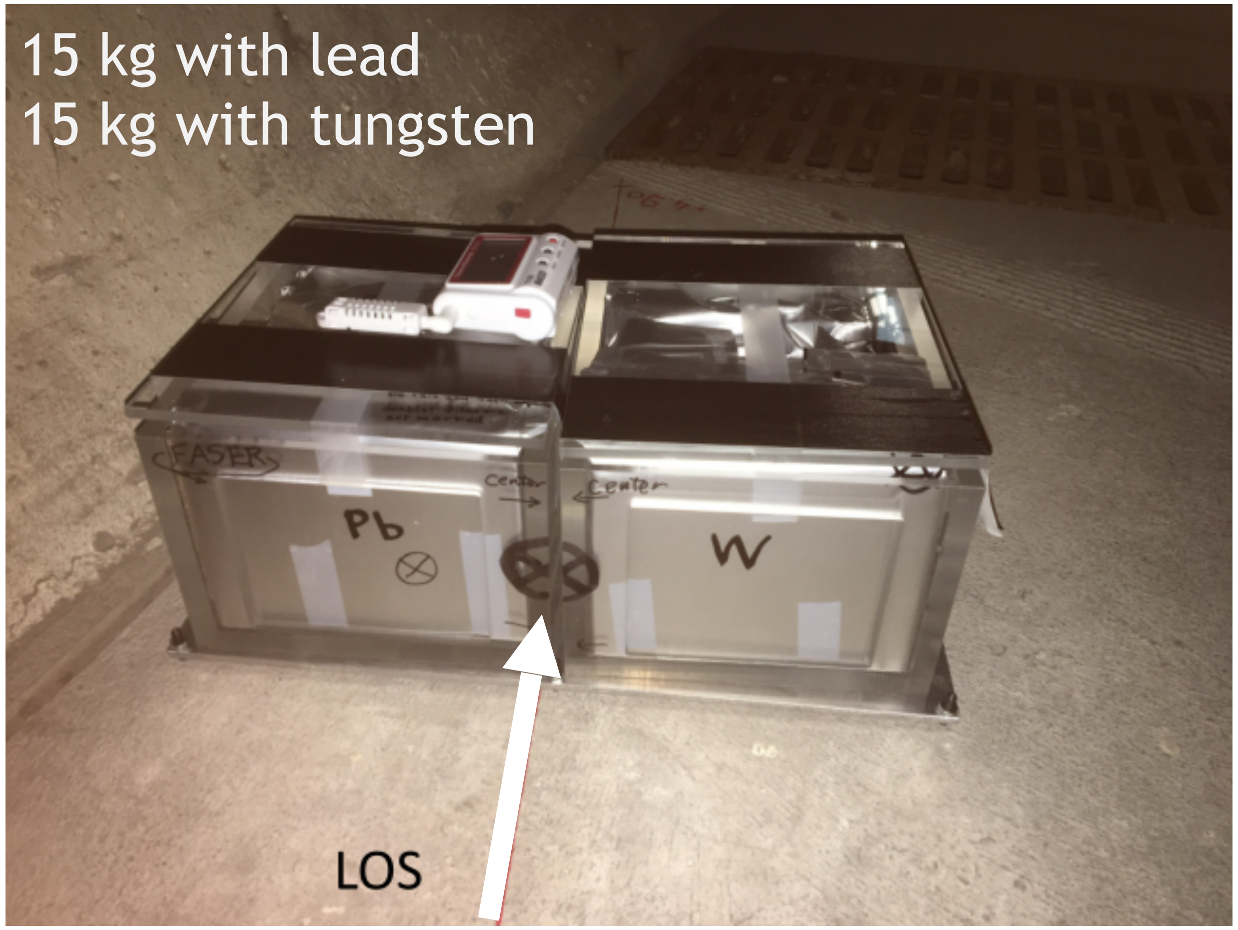




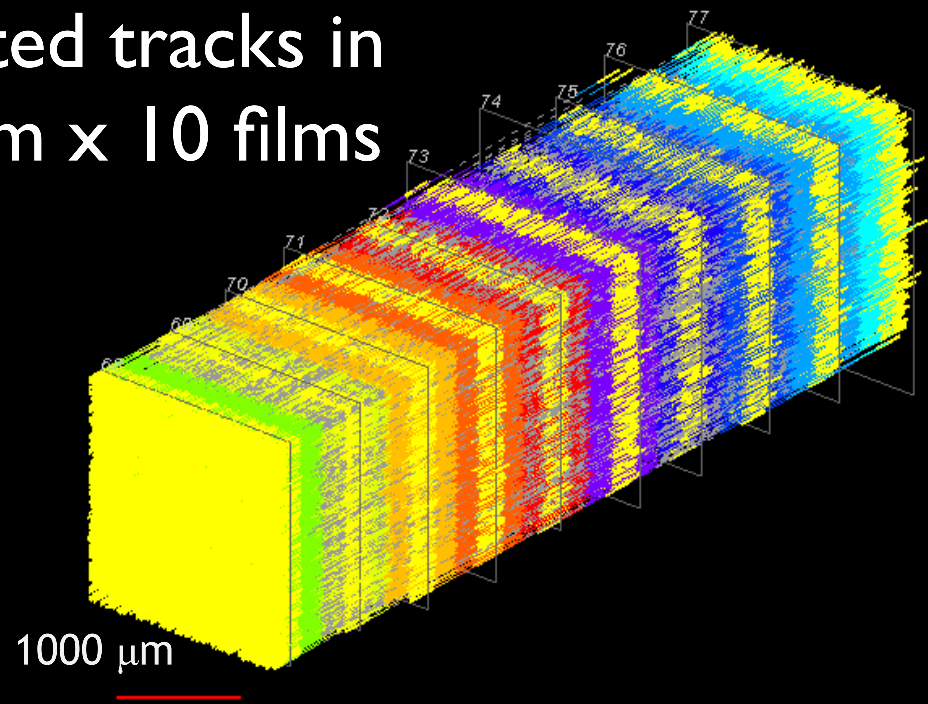
Backgrounds and Measurements

2018 Pilot Detector Run

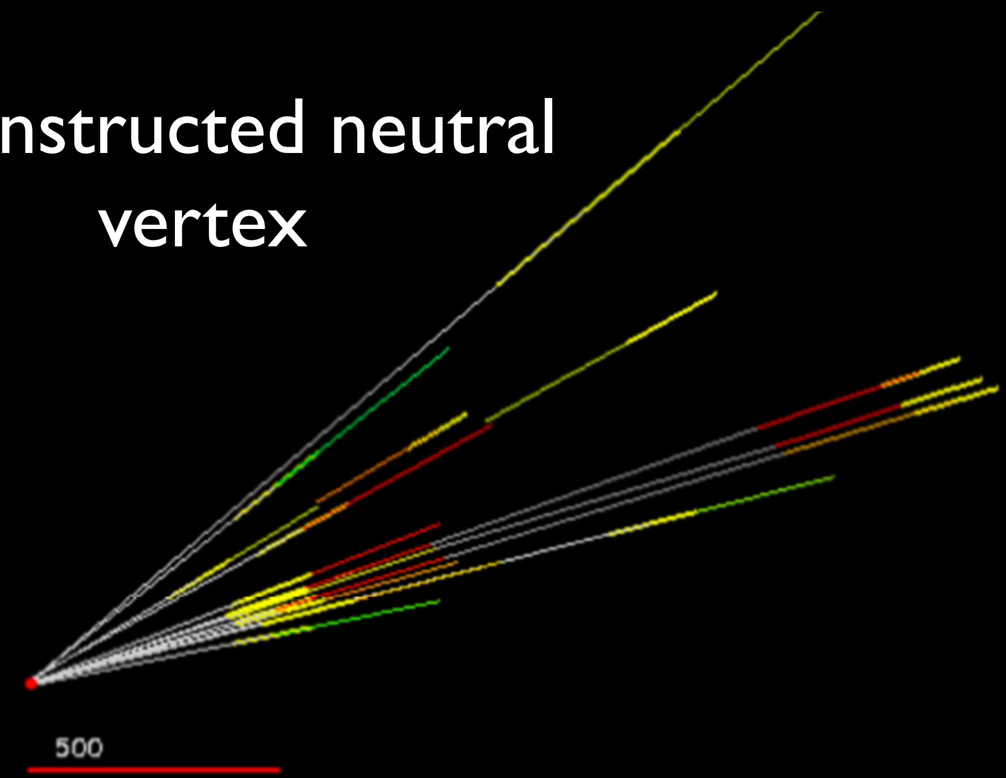
- 30 kg detector was installed in TI18
- it collected 12.5 fb^{-1} of data collected in Sep./Oct. 2018
- ~30 neutrino events expected



reconstructed tracks in
2mm x 2mm x 10 films



reconstructed neutral
vertex



- most readout performed
- emulsion detector works in actual environment
- several vertex candidates found so far

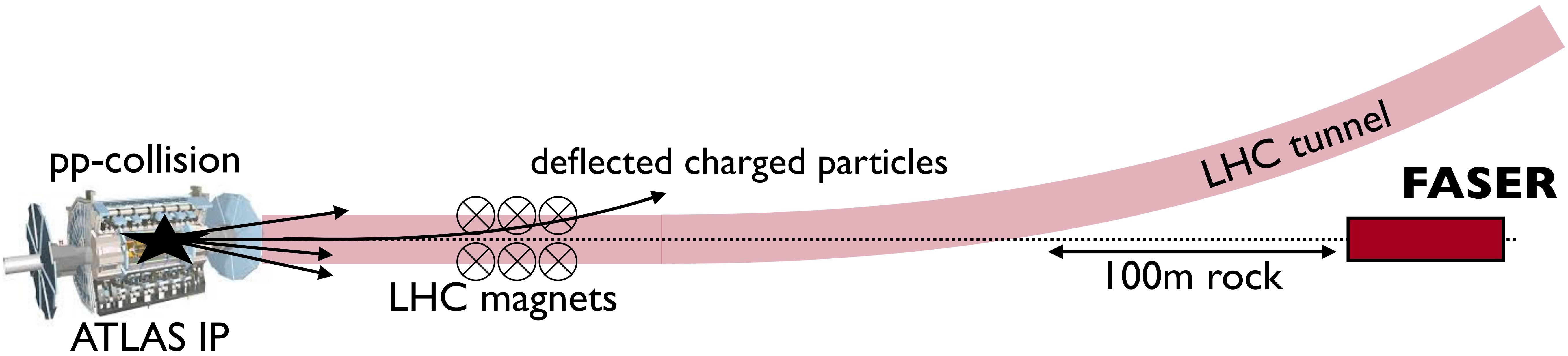
- no muon ID in pilot detector
  → more background than in FASERν due to neutral hadrons

- analysis is on-going
- goal: first detection of neutrinos from the LHC

FASERv Physics Potential

FASERν Physics Potential

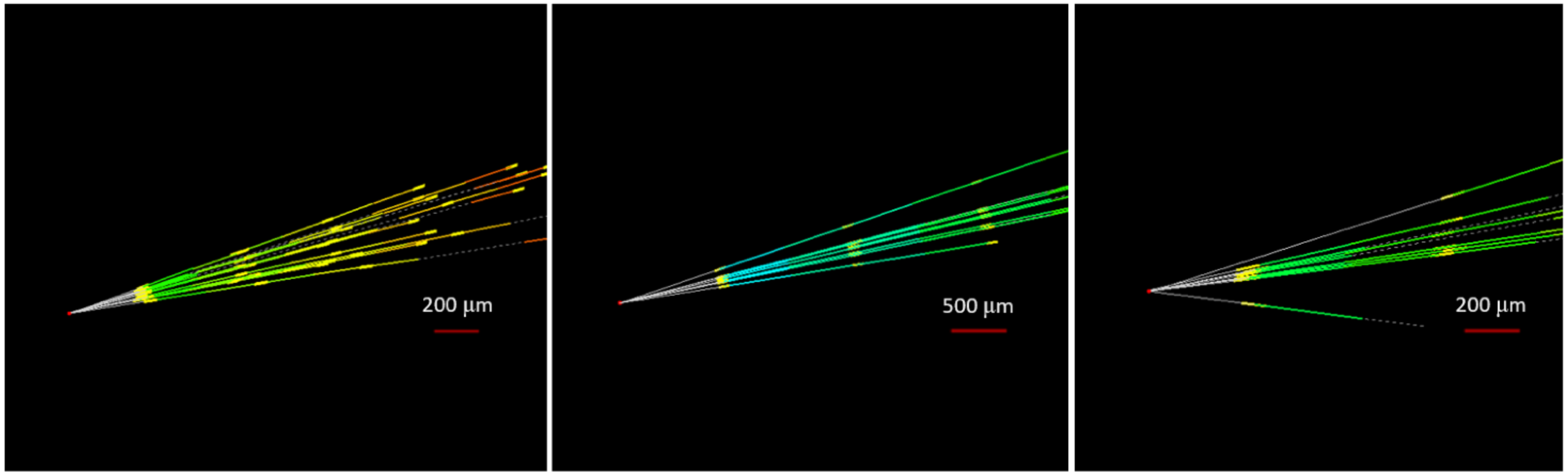
Many Physics Opportunities for FASERν



Neutrino Production	Neutrino Propagation	Neutrino Interactions
test/validate hadronic interaction models	neutrino oscillations	cross section measurements events shapes and kinematics

FASERν Physics Potential

First Goal: Observe first Neutrino at the LHC
- no collider neutrino observed so far
- ongoing analysis of pilot neutrino detector used in 2018



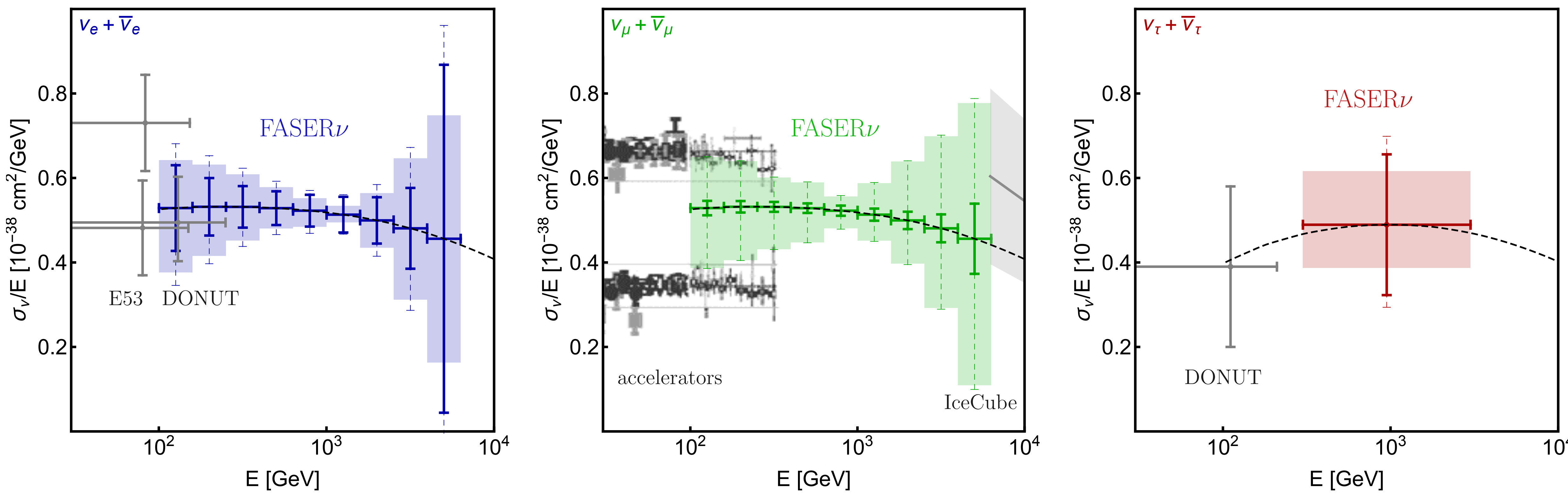
Study Tau Neutrinos
- only ~10 have been directly measured at DONuT and OPERA,
- ~20 events expected at FASERν in LHC Run 3

Neutrino Event Shapes and Kinematics
- high spatial resolution: FASERν resolves shape of neutrino events
  * multiplicity, charged particles momentum distributions, …
- use as input to tune MC tools

Measure Neutrino Interaction XS

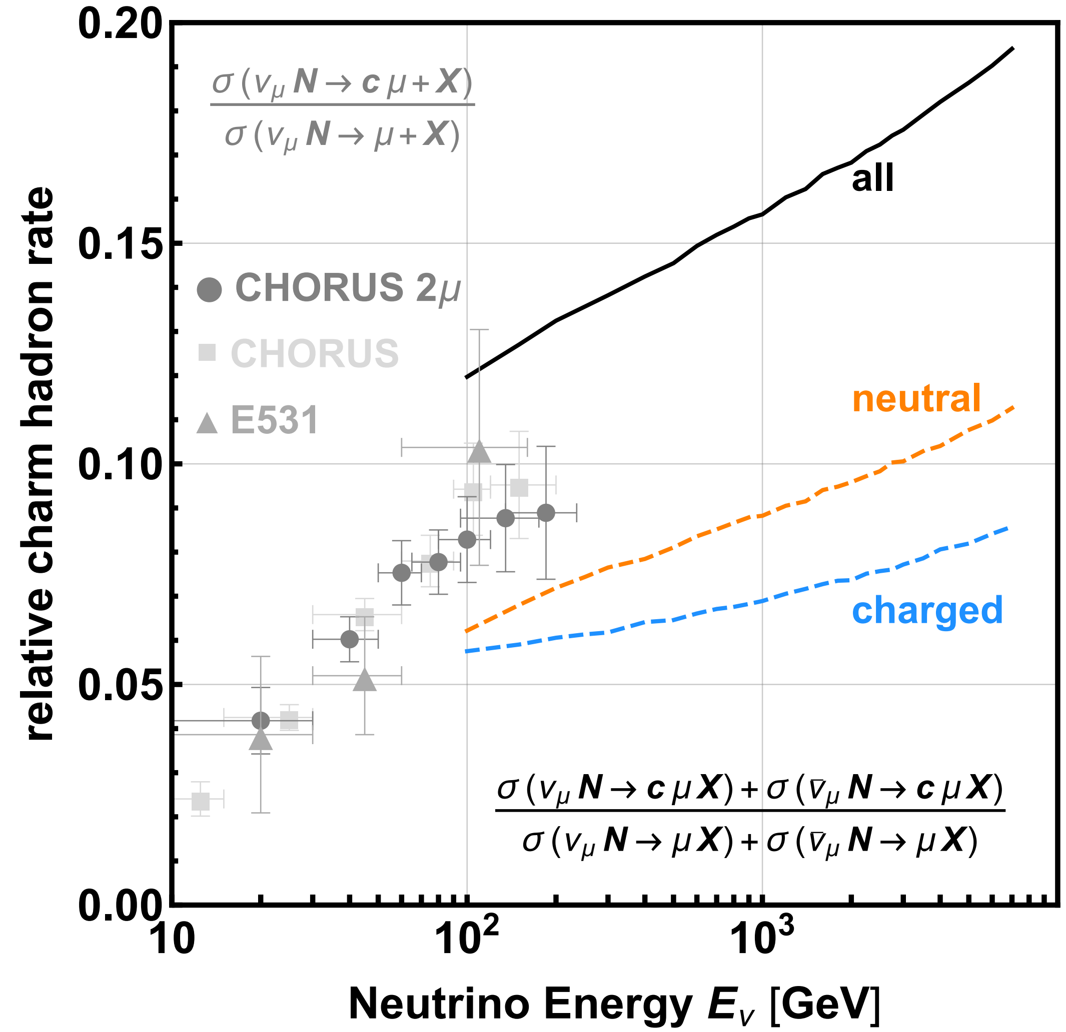
- use observed neutrino spectrum to measure neutrino interaction XS
- sensitive to all 3 neutrino flavors
- broad beam, unique reach around E~TeV

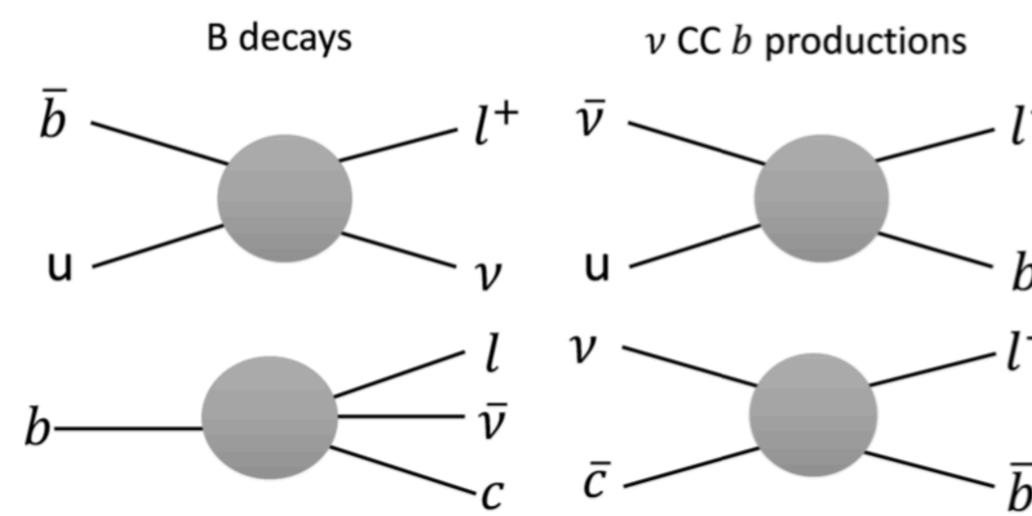
- first sensitivity estimate
  * systematic uncertainty: range of simulator predictions
  * applies: geometrical acceptance, vertex detection and lepton ID efficiency
  * assumes background free environment



Heavy Flavor associated Processes

- FASERν is sensitive to heavy flavor
- study charm associated neutrino interactions
  * ~10% of events have charm in final state
  * was used at CHORUS to
    - probe strange PDF
    - measure V_{dc}
    - measure charm fragmentation functions
  * sensitivity to NP?
- bottom associated neutrino interactions
  * strongly suppressed in SM
  * O(0.1) events expected
  * sensitivity to NP?
  → motivated by BSM models (W', H$^+$, LQ) and b-physics anomalies

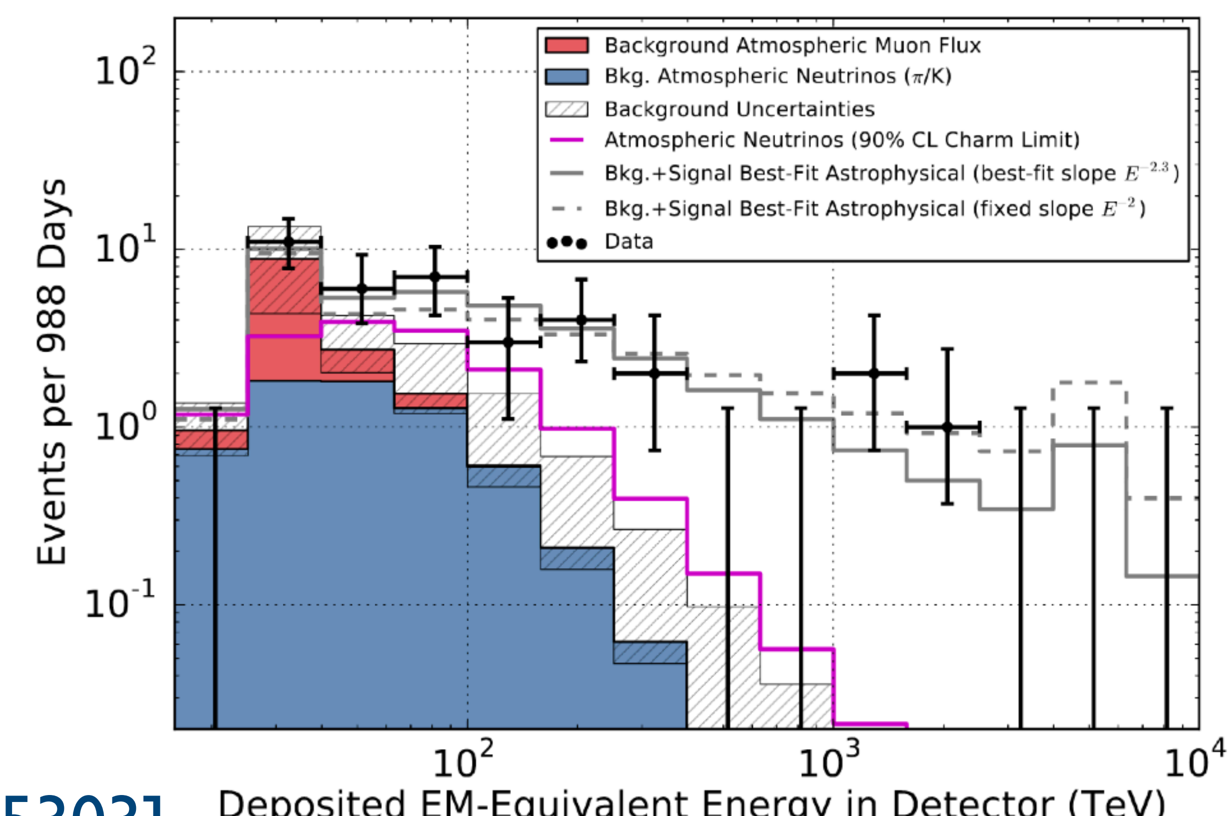




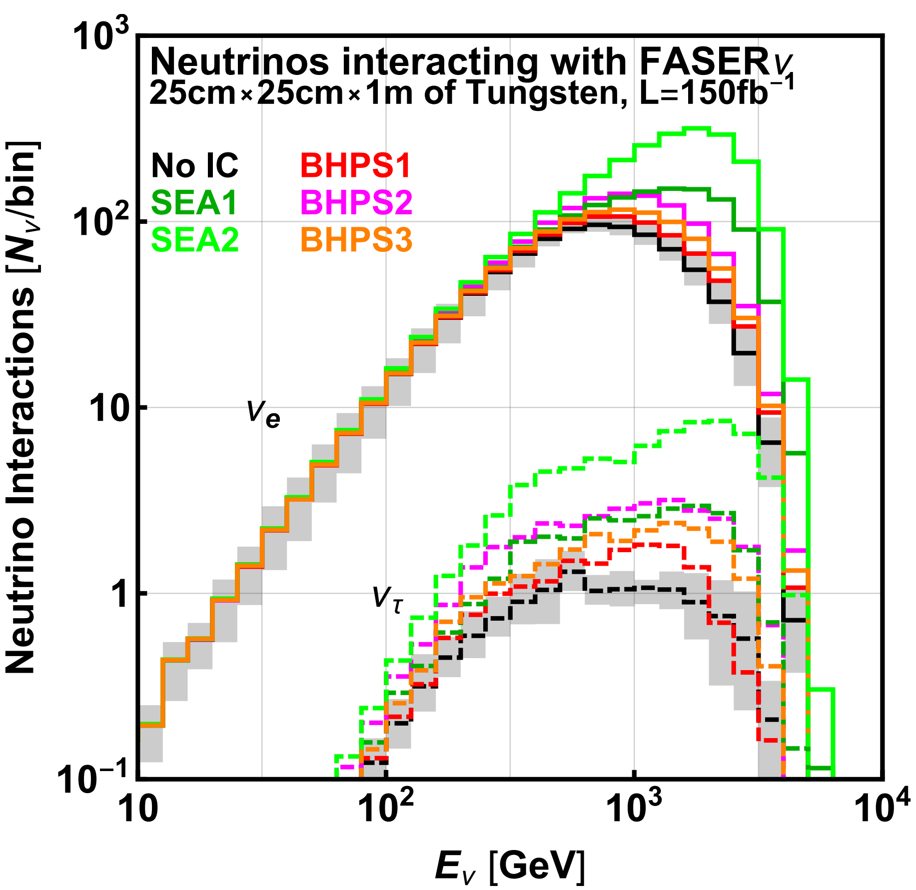
Measure Neutrino Production Rate

- use observed neutrino spectrum to measure neutrino production rate
- validate/improve/constrain hadronic interaction models or PDFs
  * used for LHC and cosmic rays physics
  * example: intrinsic charm
- important input for HE neutrino observatories

IceCube: atmospheric neutrino uncertainty

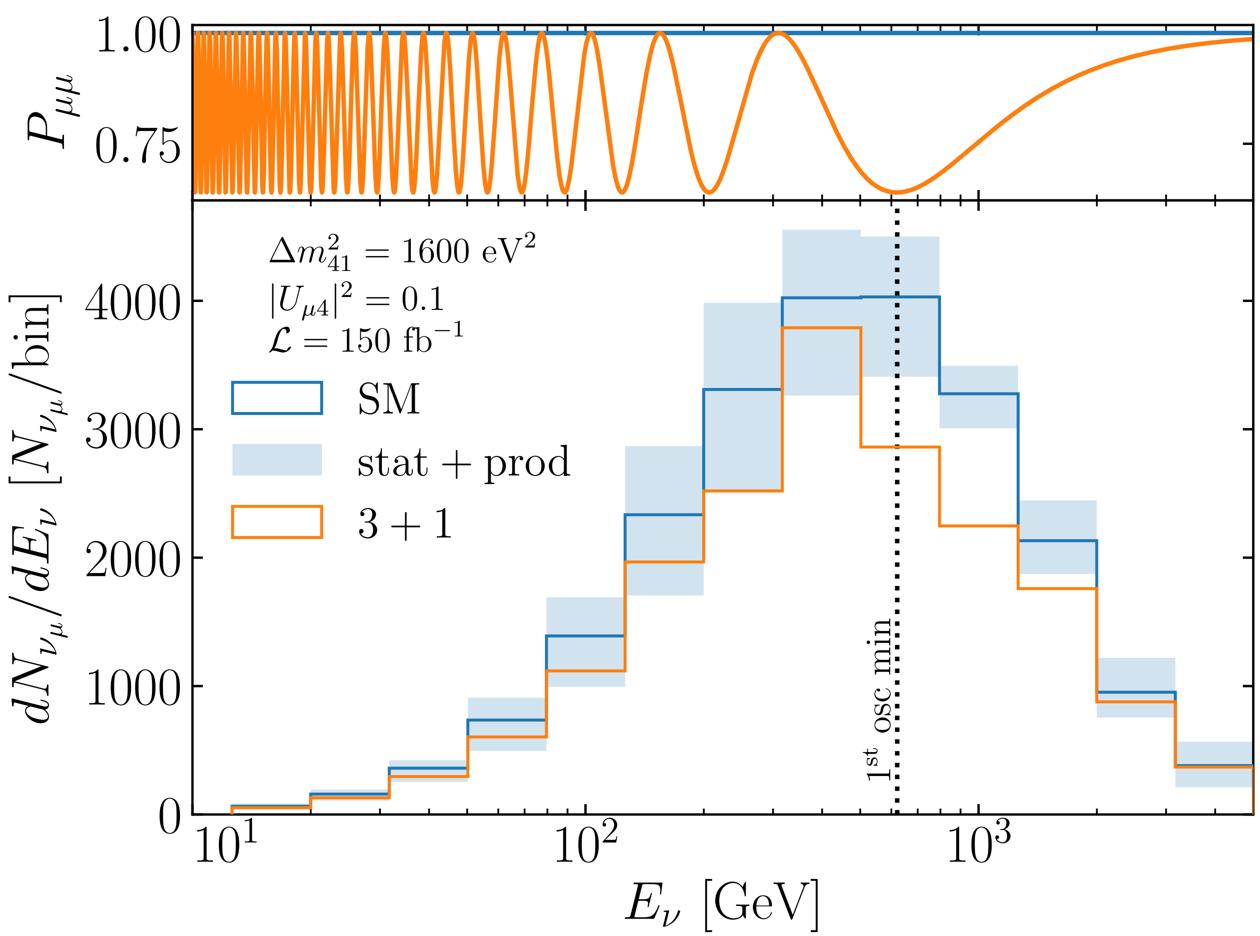


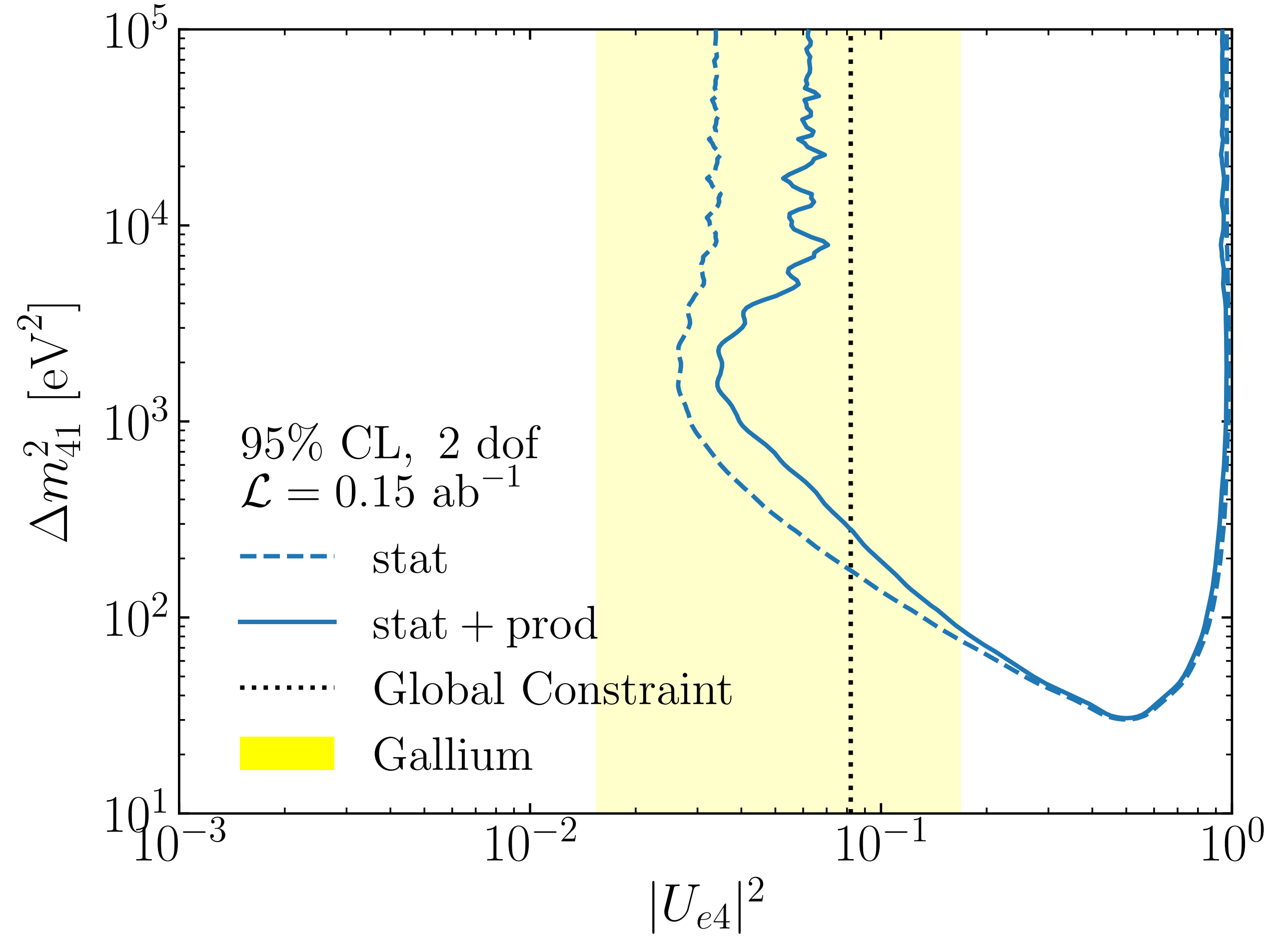
[IceCube: 1405.5303]



Sterile neutrino oscillations

- no oscillations in SM
- use FASERν as short-baseline experiment
- ~40 eV sterile neutrino can cause oscillations
  * changes shape of energy spectrum





FASERν Physics Potential

Neutrinos at the LHC
- LHC produces intense high energy neutrino beam
- no neutrino detected so far
- all 3 flavors, E~TeV

FASERν
- emulsion based detector
- 25cm x 25cm x 1m with 1.2 ton target mass
- take data during Run 3 (2021-23, 150 fb^{-1})
- expect ~ 20000 ν_μ, 2000 ν_e and 20 ν_τ

Physics Applications
- neutrino cross section measurement at TeV energies
- neutrino production rate measurements
- flavor physics, neutrino oscillations
- probably more unexplored opportunities!

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We look forward to feedback and suggestions