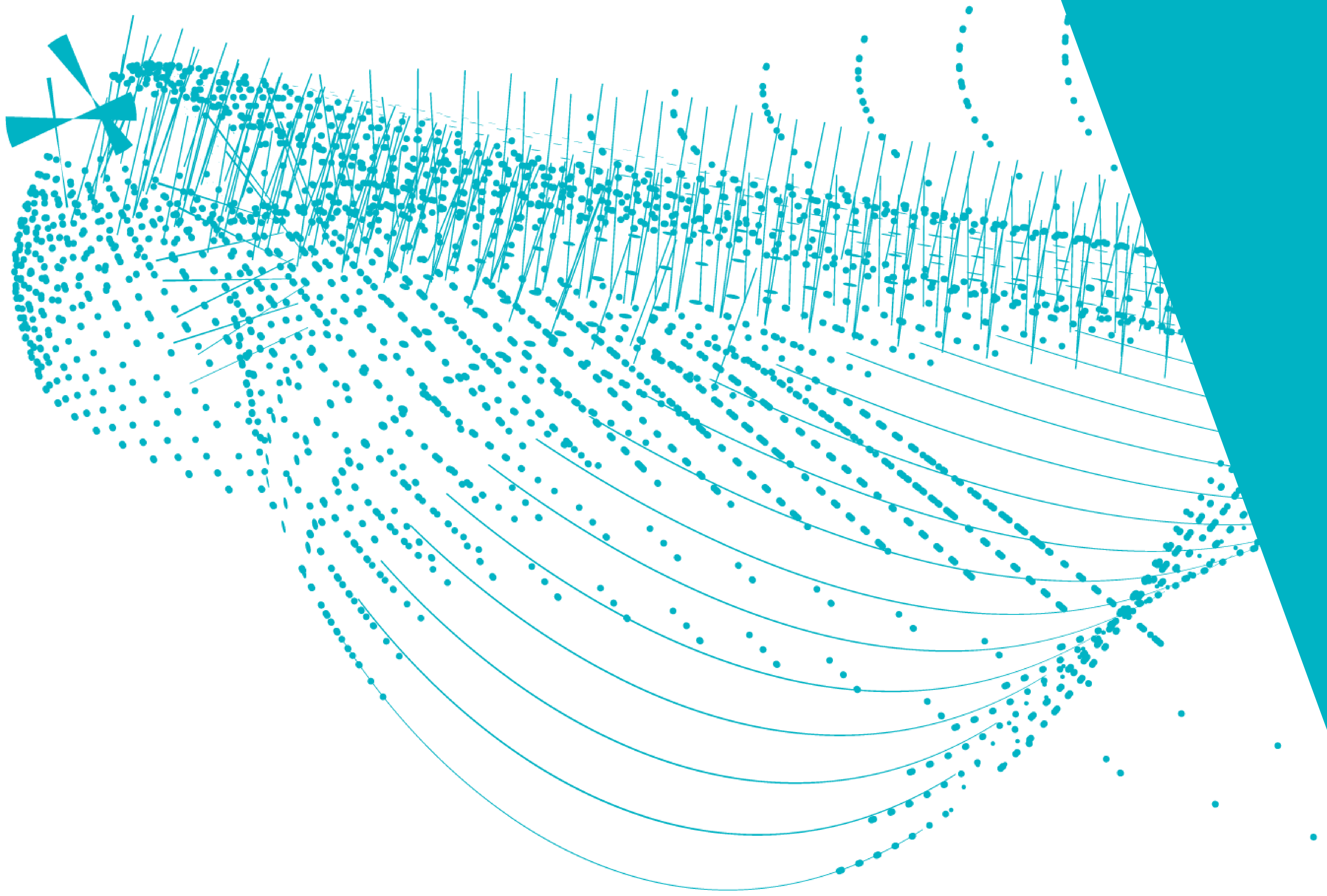
ATLAS EXPERIMENT Radboud University Nikhef

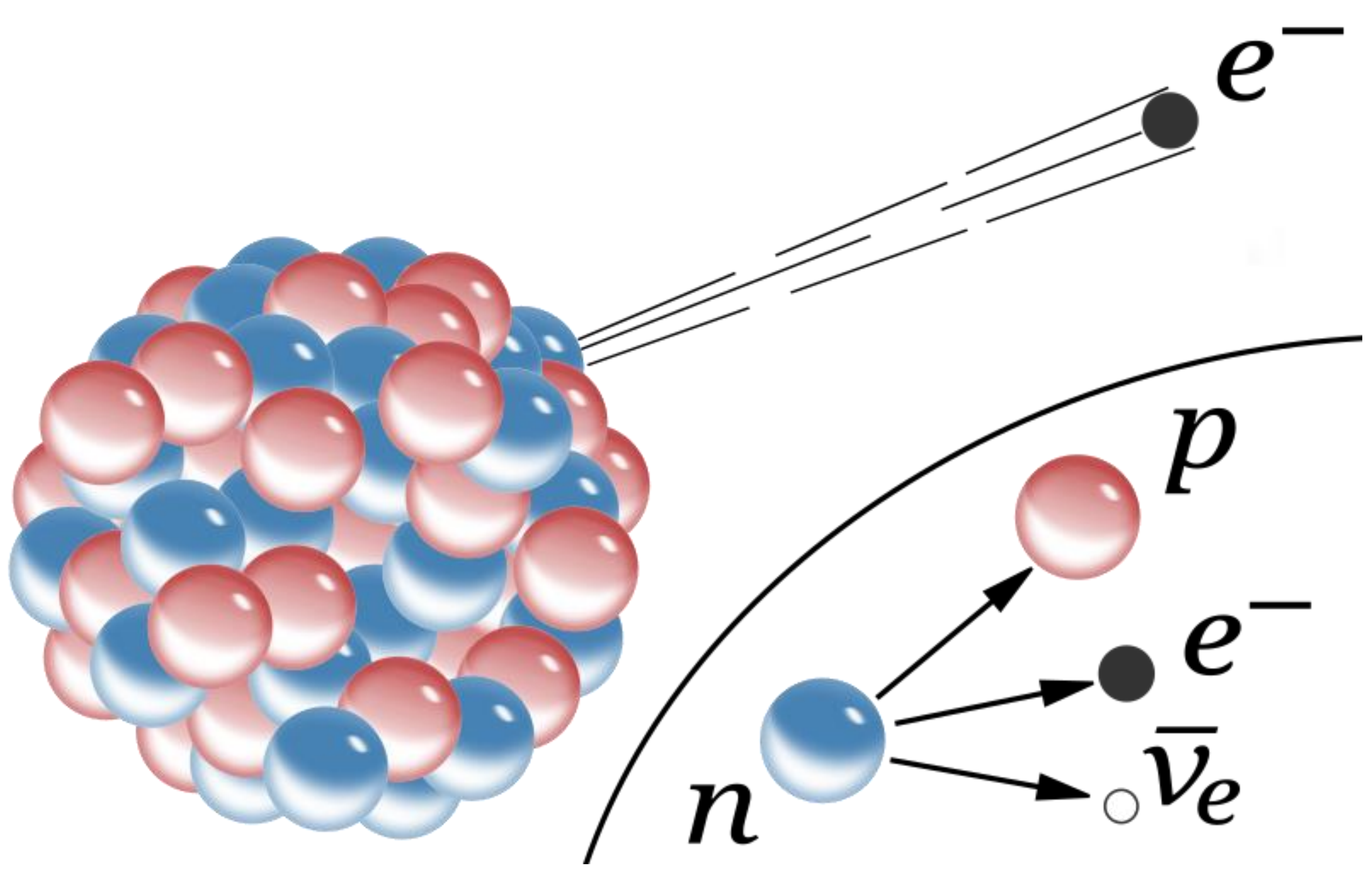


NNV FALL CONFERENCE
7TH NOVEMBER 2024

SEARCHES FOR HEAVY NEUTRAL LEPTONS IN THE ATLAS EXPERIMENT

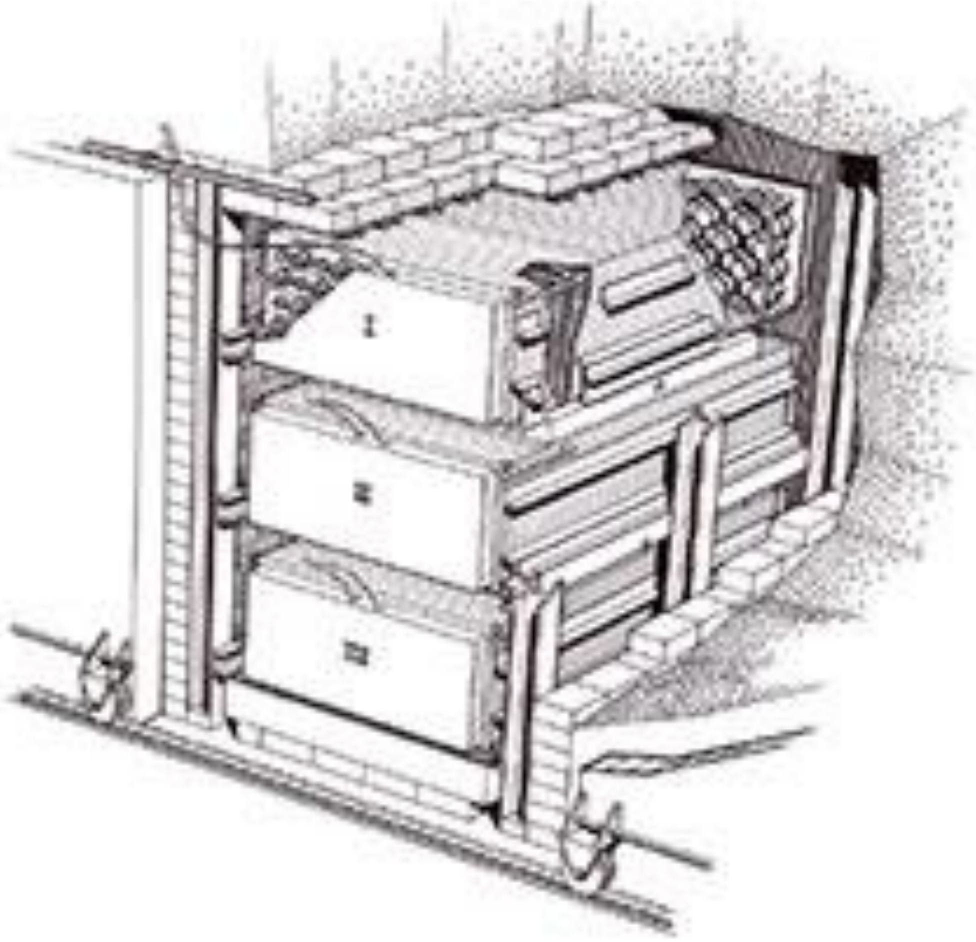
Edwin Chow

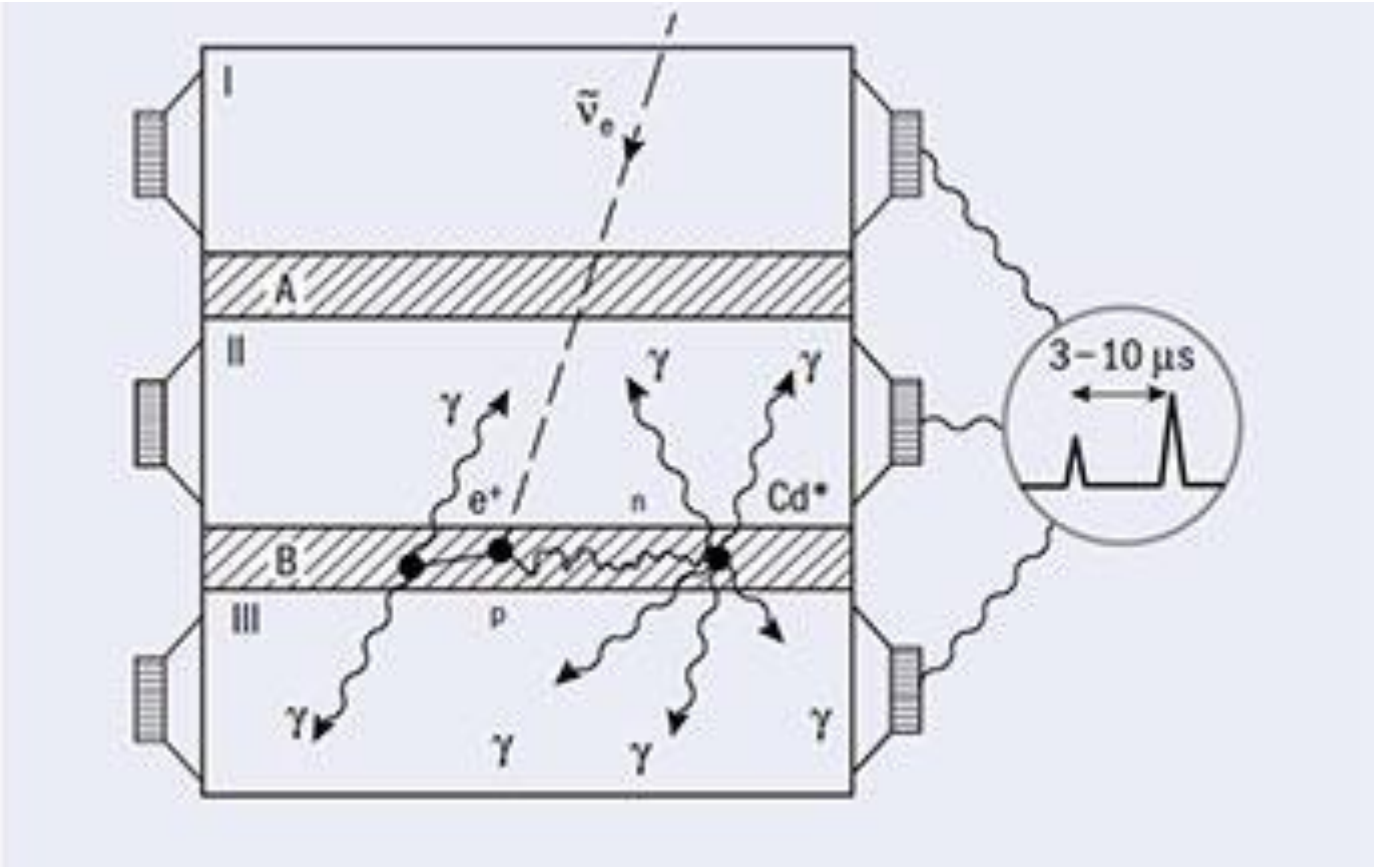
Early neutrino physics



$$(A, Z) \rightarrow (A, Z \pm 1) + e^{\mp} + \text{nothing else visible}$$

Beta decay

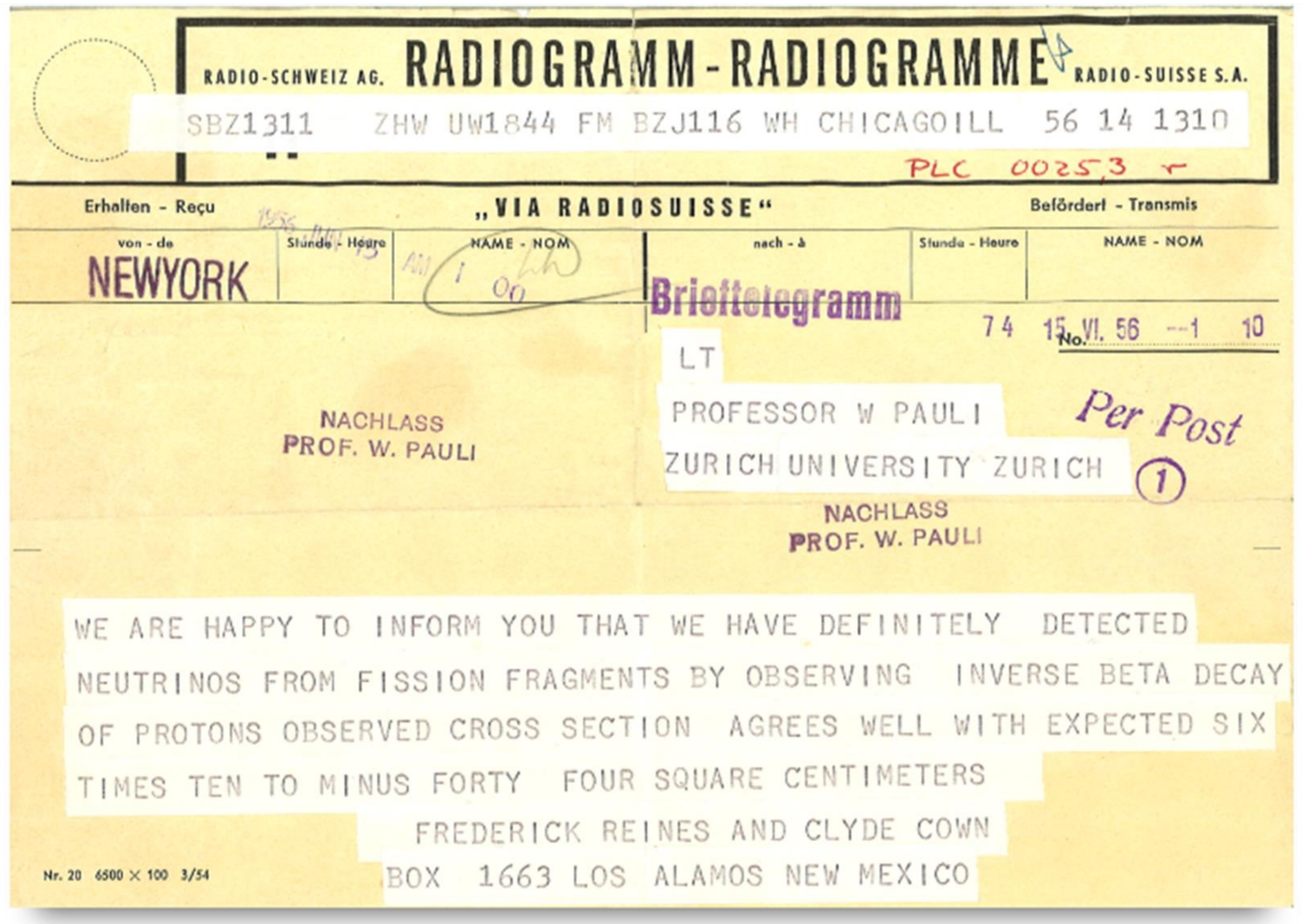




1934

NEUTRINO NAMED

Enrico Fermi, father of the world's first nuclear reactor, popularized the term "neutrino." It is Italian for "little neutral one," summing up key properties of the neutrino: it's lack of charge and it's incredibly tiny size. Fermi proposed a theory that included Pauli's hypothesized particle; this was the first theory of one of the four fundamental forces, the weak force.



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LT

NACHLASS PROF. W. PAULI

PROFESSOR W PAULI Per Post

ZURICH UNIVERSITY ZURICH

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN BOX 1663 LOS ALAMOS NEW MEXICO

CERN

1956

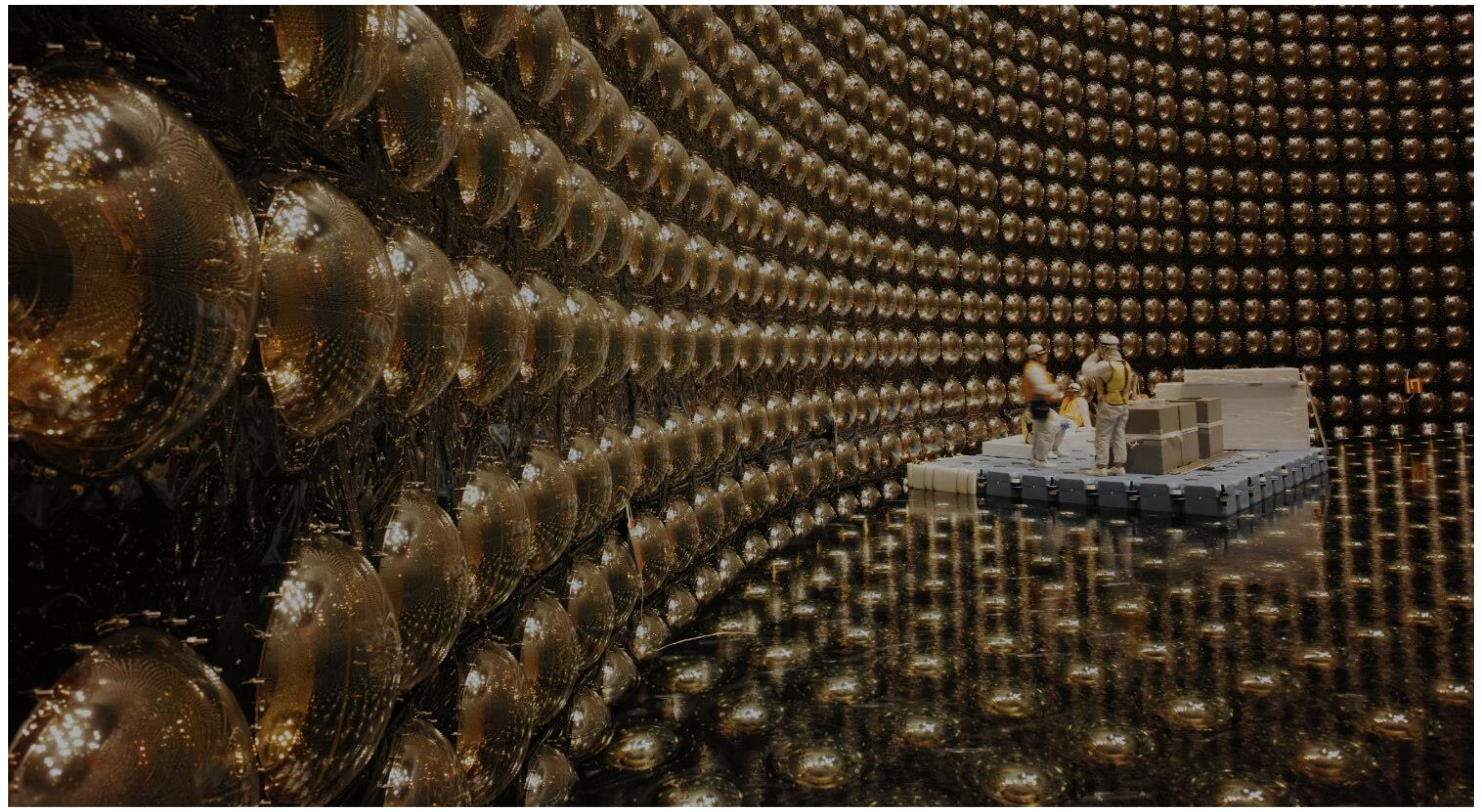
FIRST EXPERIMENTAL EVIDENCE

A team of scientists led by Los Alamos National Laboratory physicists Frederick Reines and Clyde Cowan observed the first evidence of neutrinos as part of Project Poltergeist. The neutrino was then, as it still is now, considered a "ghostly" particle, flitting through matter without leaving much of a trace. The scientists used a nuclear reactor, an incredibly dense source of neutrinos, to finally catch the ghost. For five months, they collected data with a 10-ton detector placed next to a fission reactor at the Savannah River Plant. They announced their success in a 1956 telegram to Wolfgang Pauli: "We are happy to inform you that we have definitively detected neutrinos."

Next decades – physicists in caves and mountains

Homestake

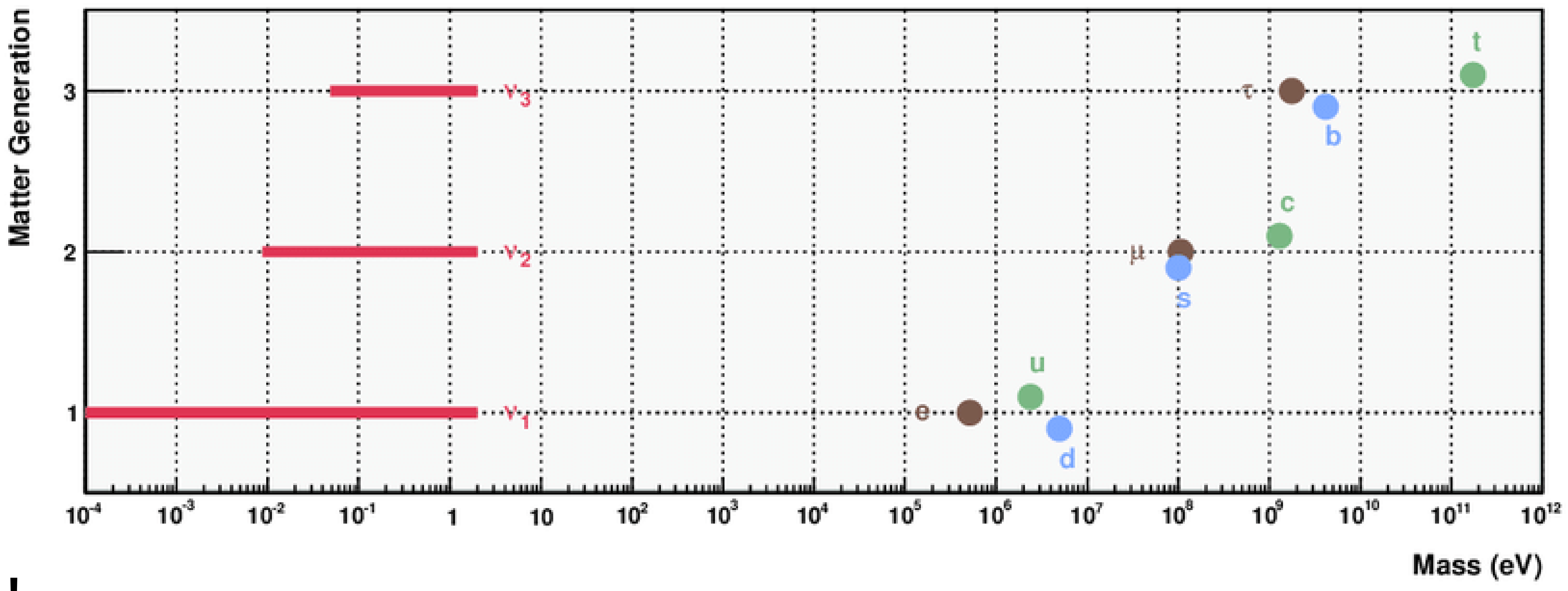
Kamiokande



What have they found?

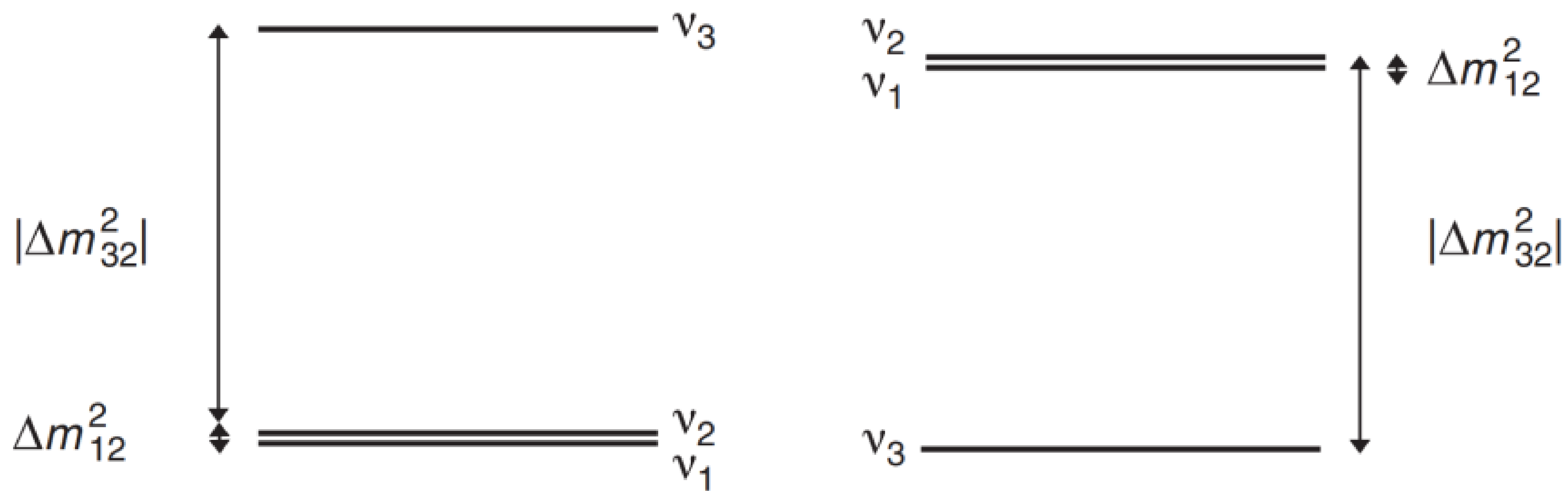
Neutrinos do MIXING!

- Flavors
  - 3 types of flavors
  - Corresponding to leptons
- Masses
  - Very tiny
  - Mass ordering unknown



Extra parameters in the SM!

How can we explain the masses?

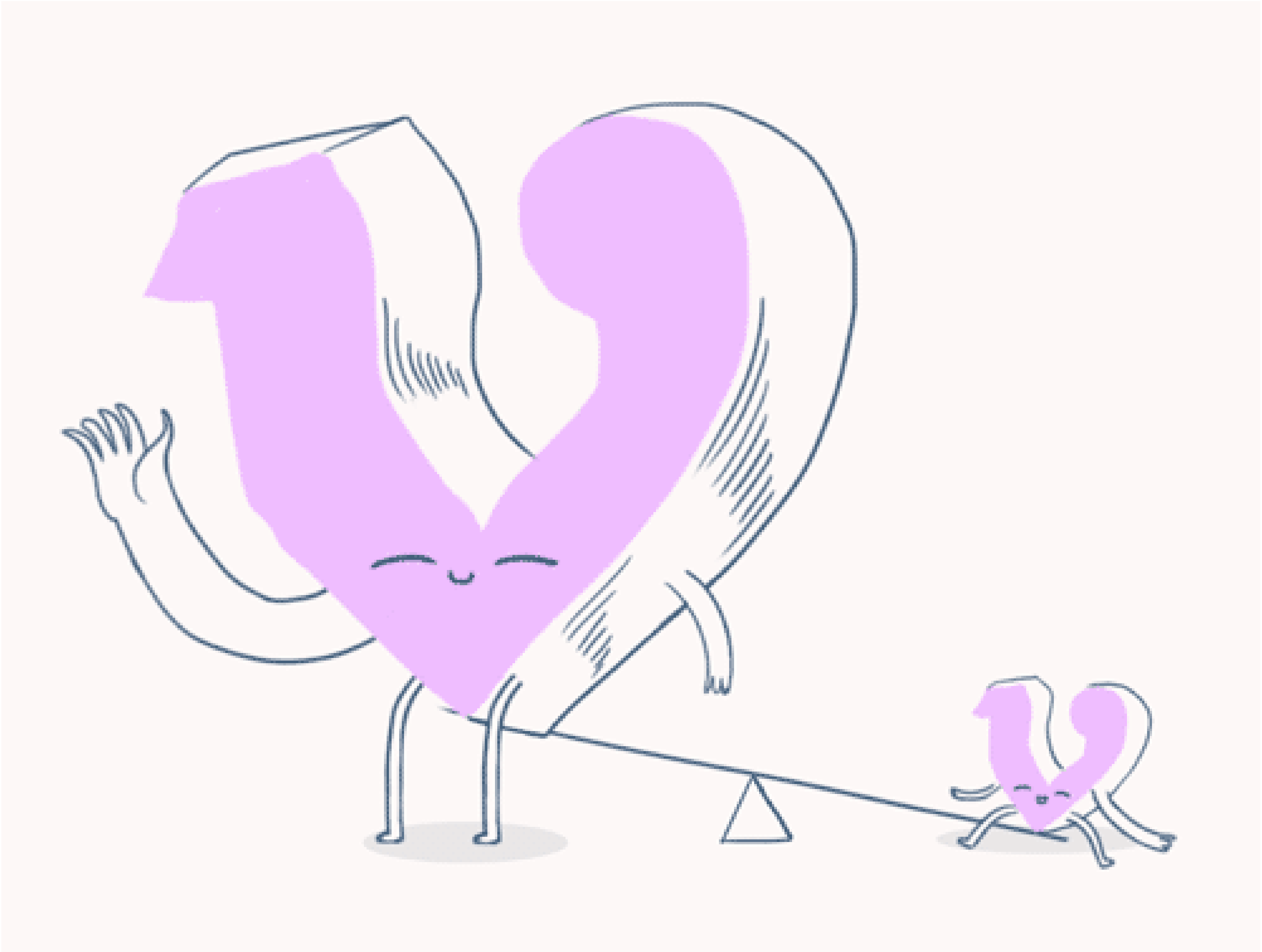


Type-I seesaw mechanism

One way to explain the tiny masses
We can add Majorana neutrinos to the SM

$$-\mathcal{L}_{M\nu} = \frac{1}{2}\bar{\nu}_l M^l \nu_l + \frac{1}{2}\bar{\nu}_h M^h \nu_h$$

$$M_\nu \to \begin{bmatrix} -V^T M_D^T M_N^{-1} M_D V & 0 \\ 0 & U^T M_N U \end{bmatrix} \equiv \begin{bmatrix} M^l & 0 \\ 0 & M^h \end{bmatrix}$$

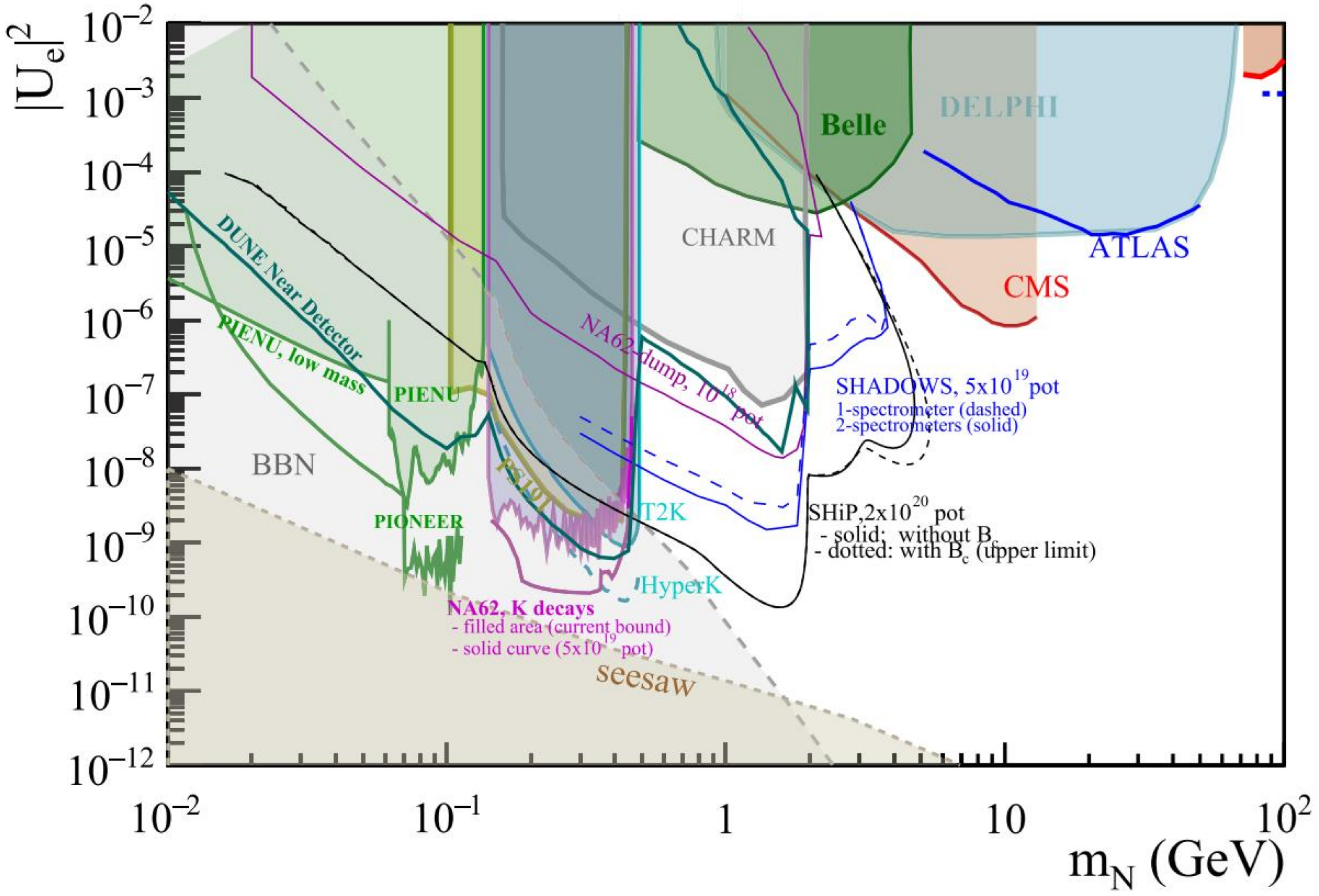


We have

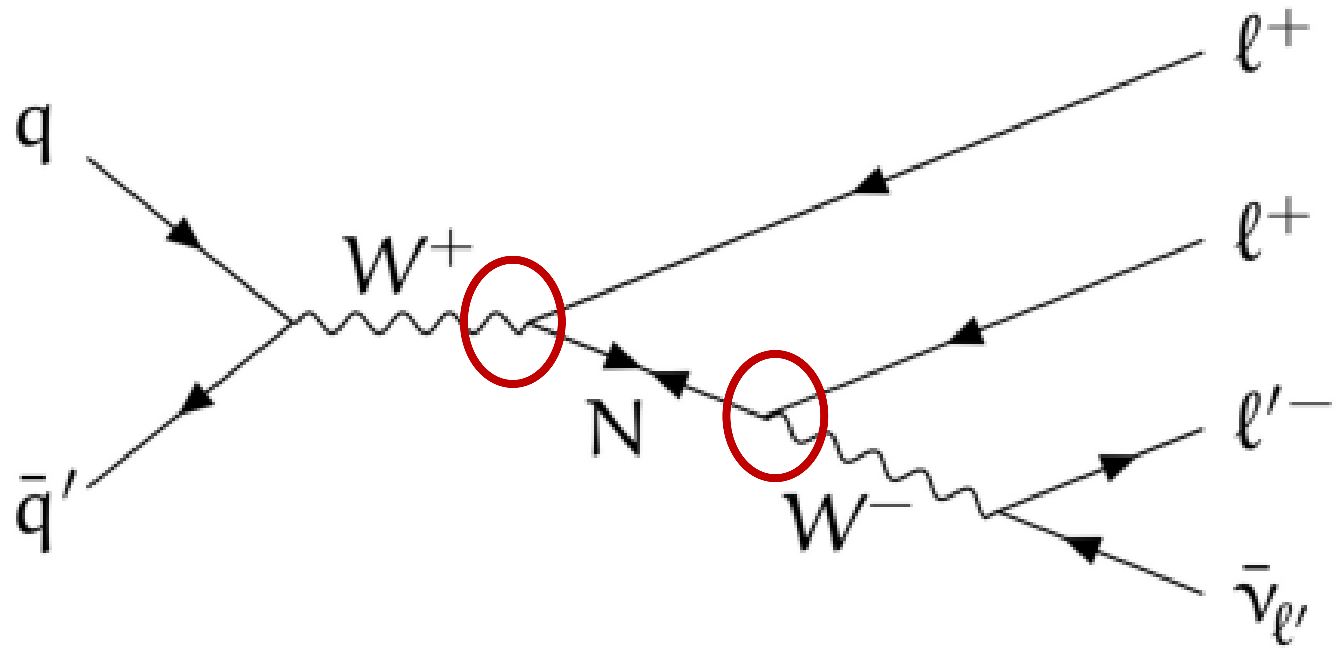
- Light neutrino mass ~ M_N^{-1}
- Heavy neutrino mass ~ M_N

Simple, minimal assumption!
Heavy particles, that's what we can search for in the LHC!

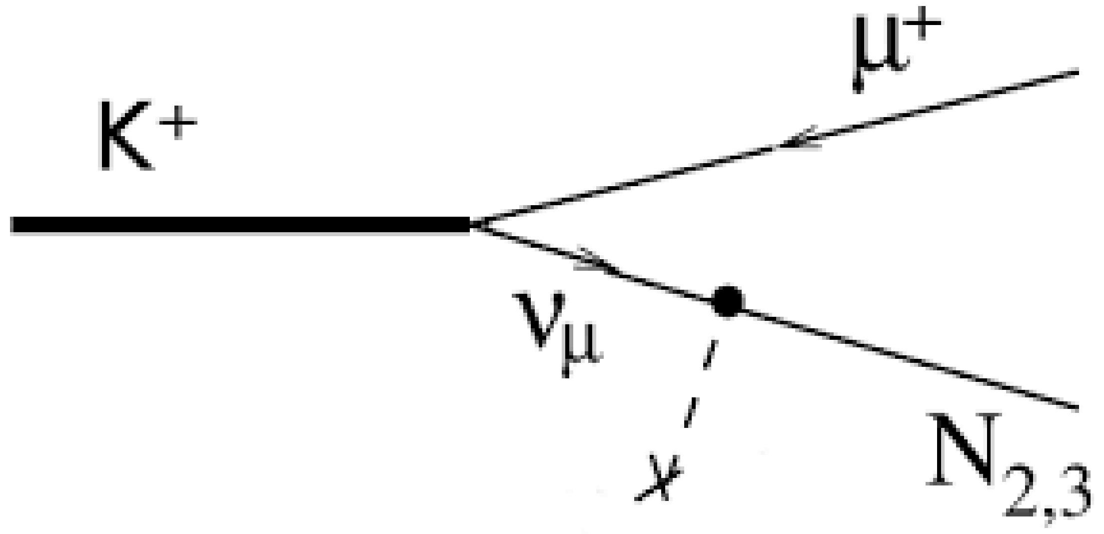
Current status and exclusion limits



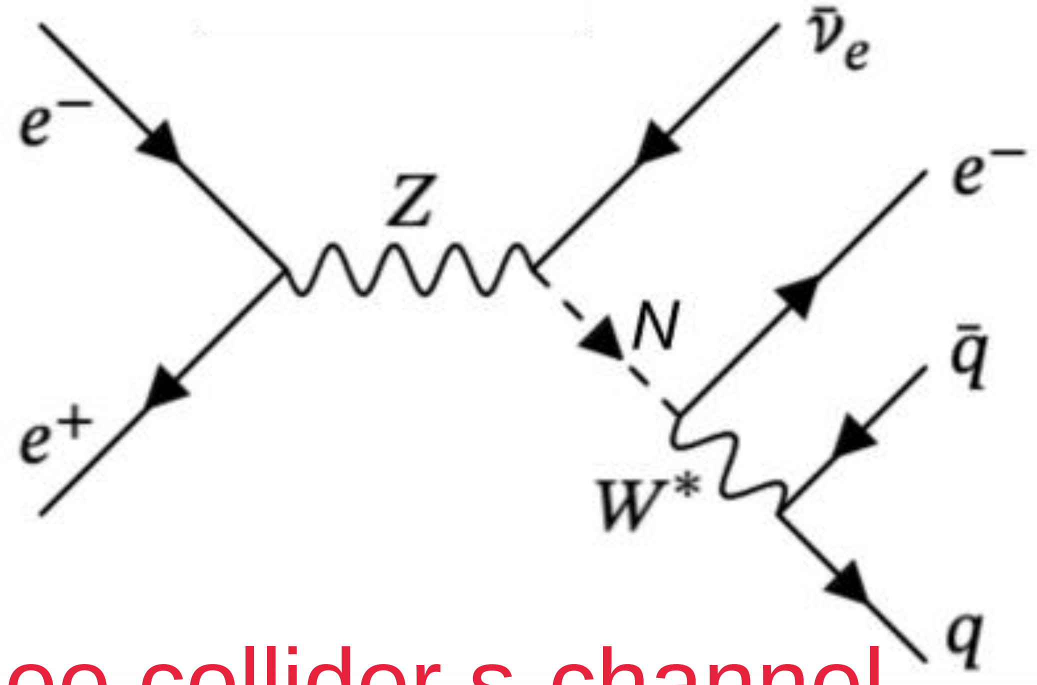
Heavy Neutrino coupling often described by U_{e} or V_{eN}



pp collider s-channel



Kaon decay

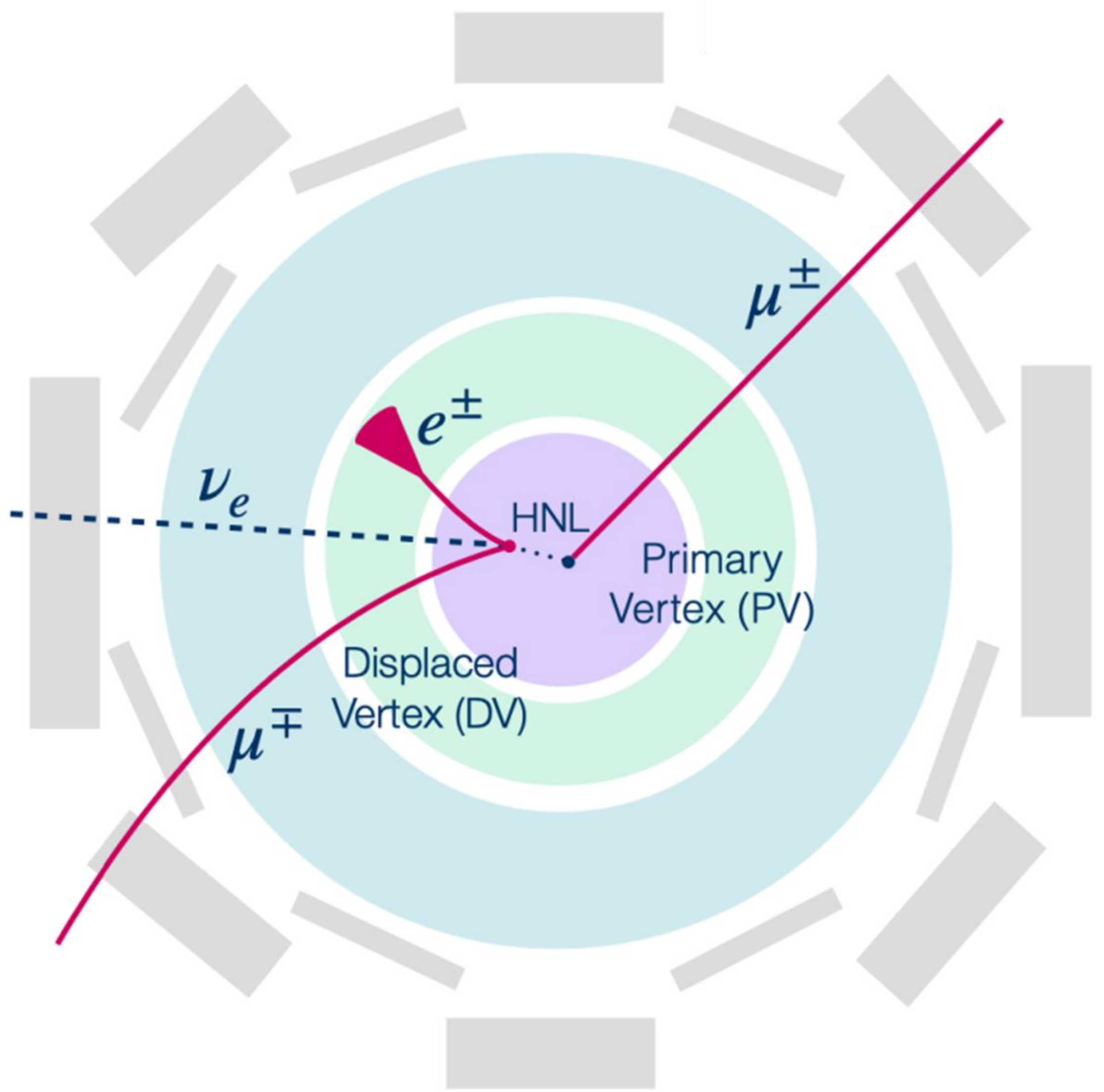


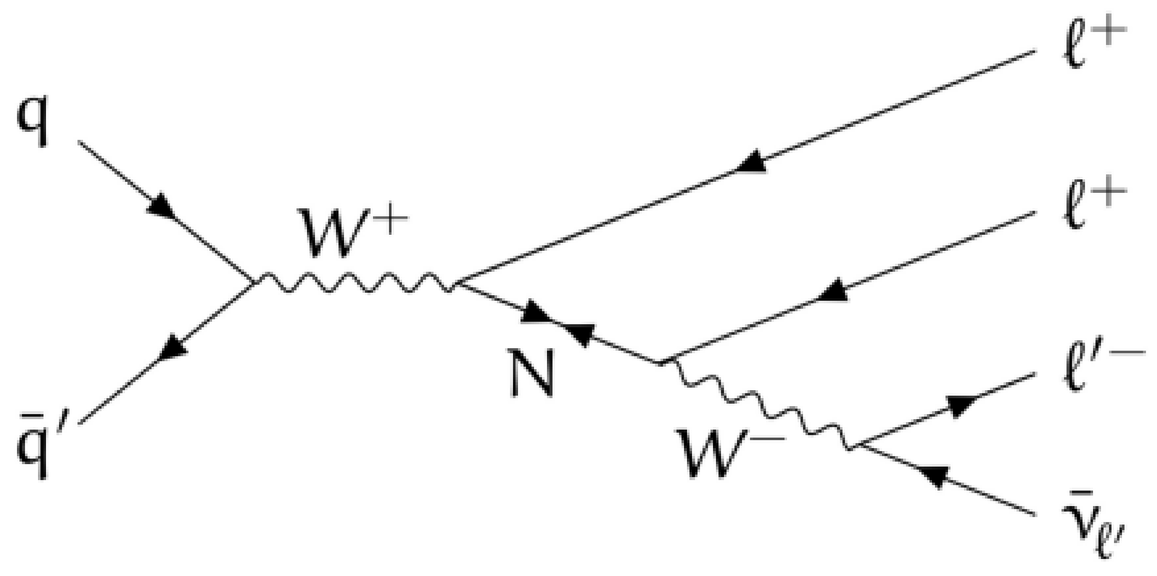
ee collider s-channel

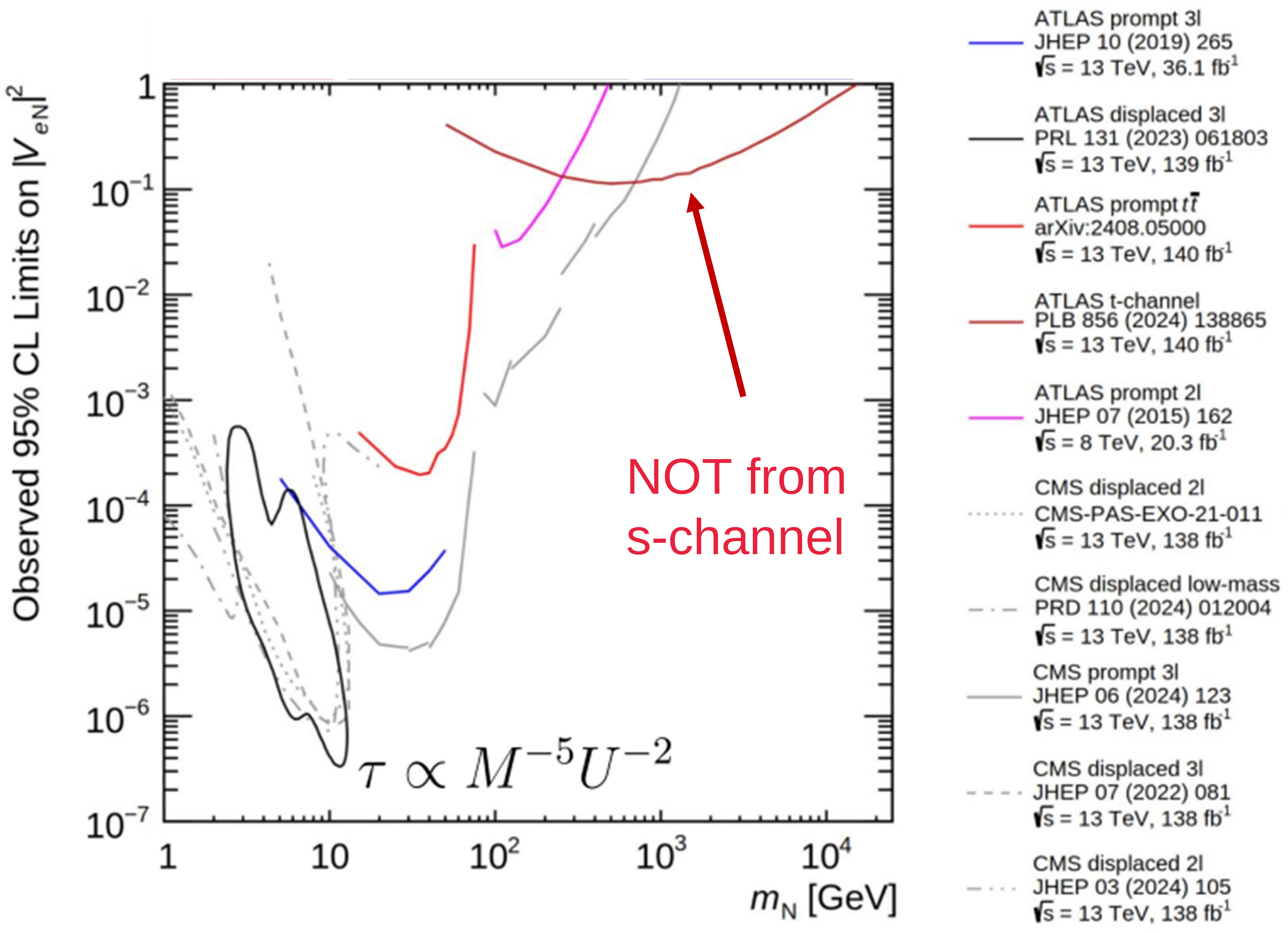
HNL in ATLAS

What about ATLAS?

Our multi-layered detector can identify different leptons/hadrons reasonably





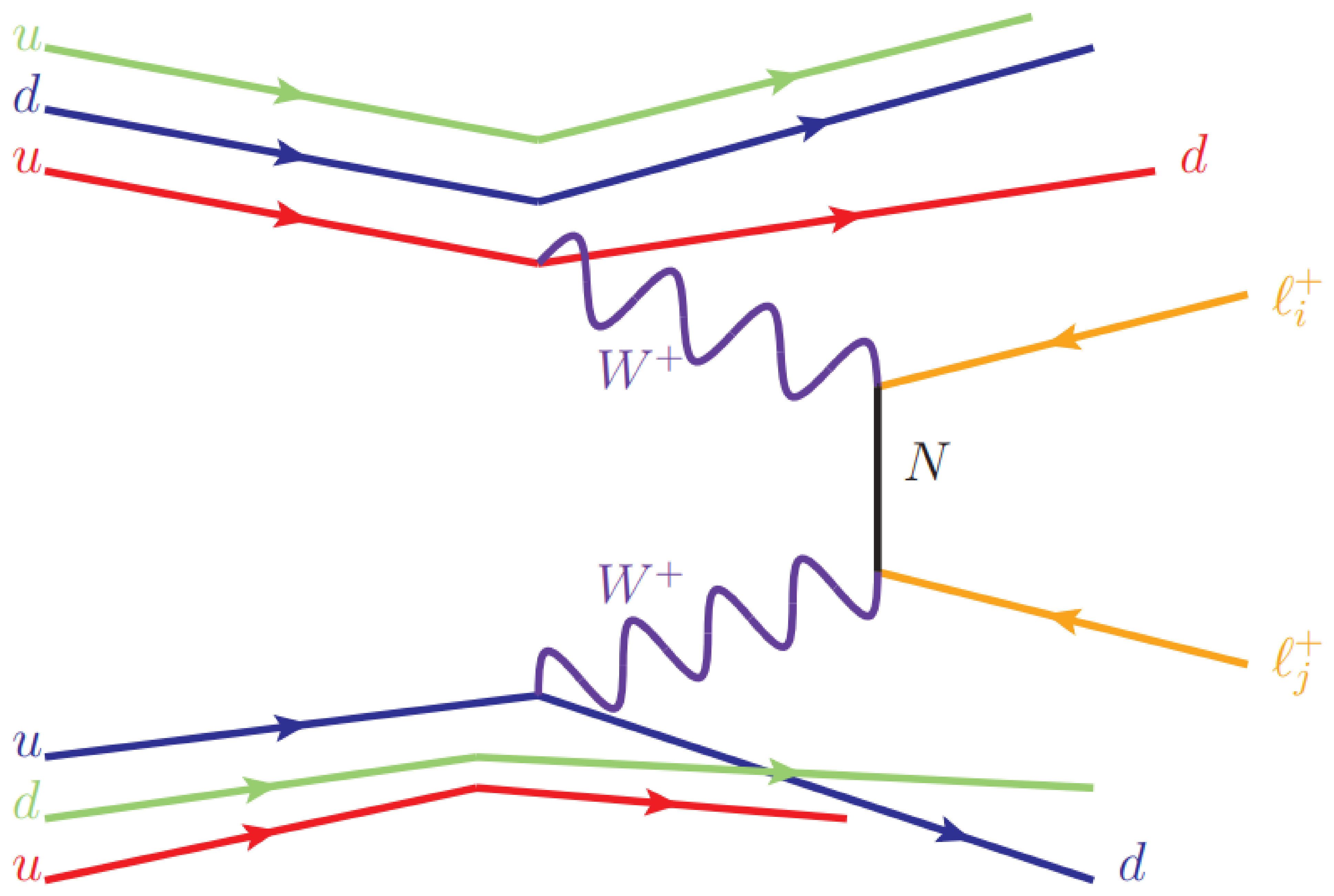


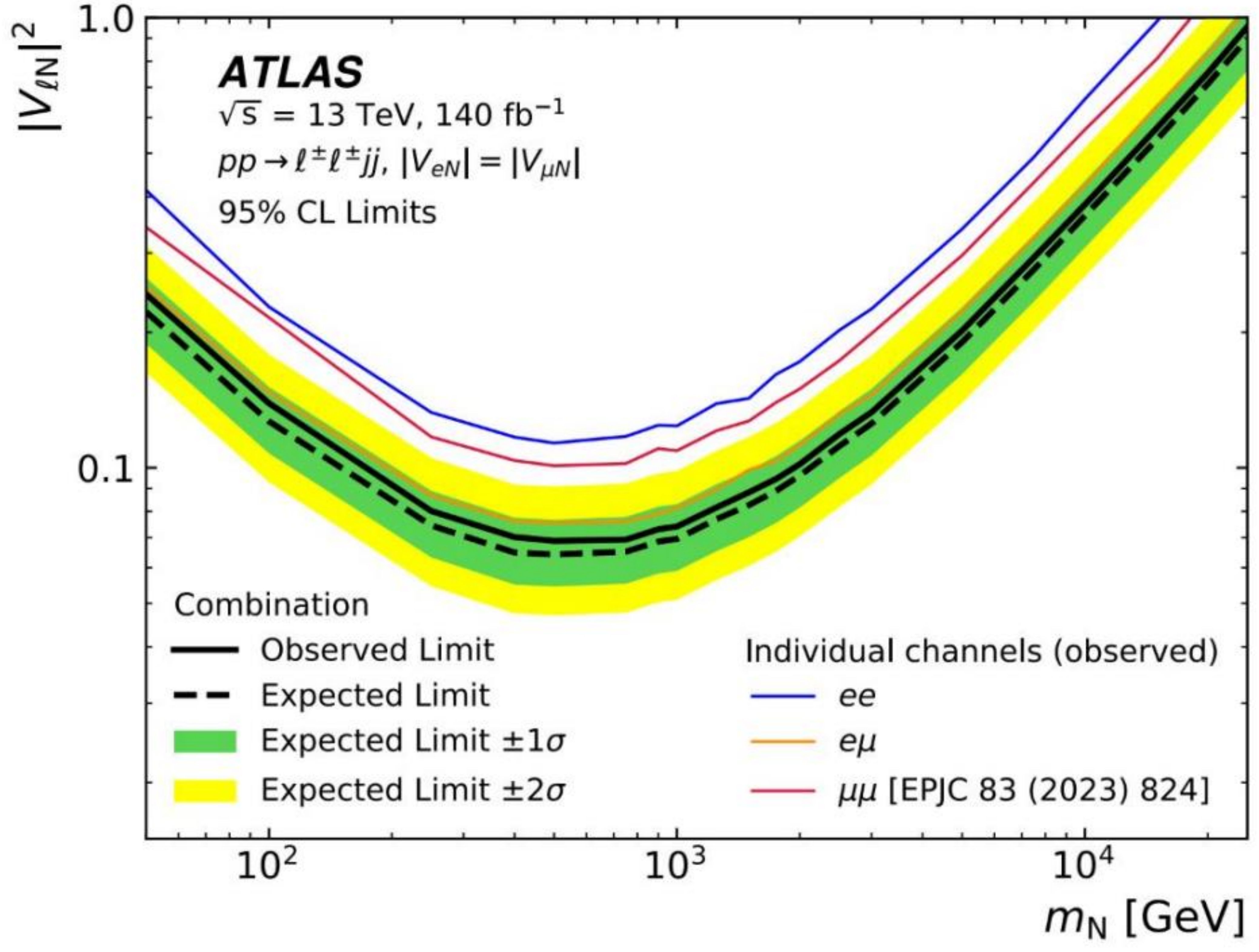
Multiple teams looking for

- Displaced HNL
- s-channel
  - Good result for μ and e

s-channel contributes up to m_N~100 GeV

t-channel HNL in ATLAS





Many interesting physics keywords

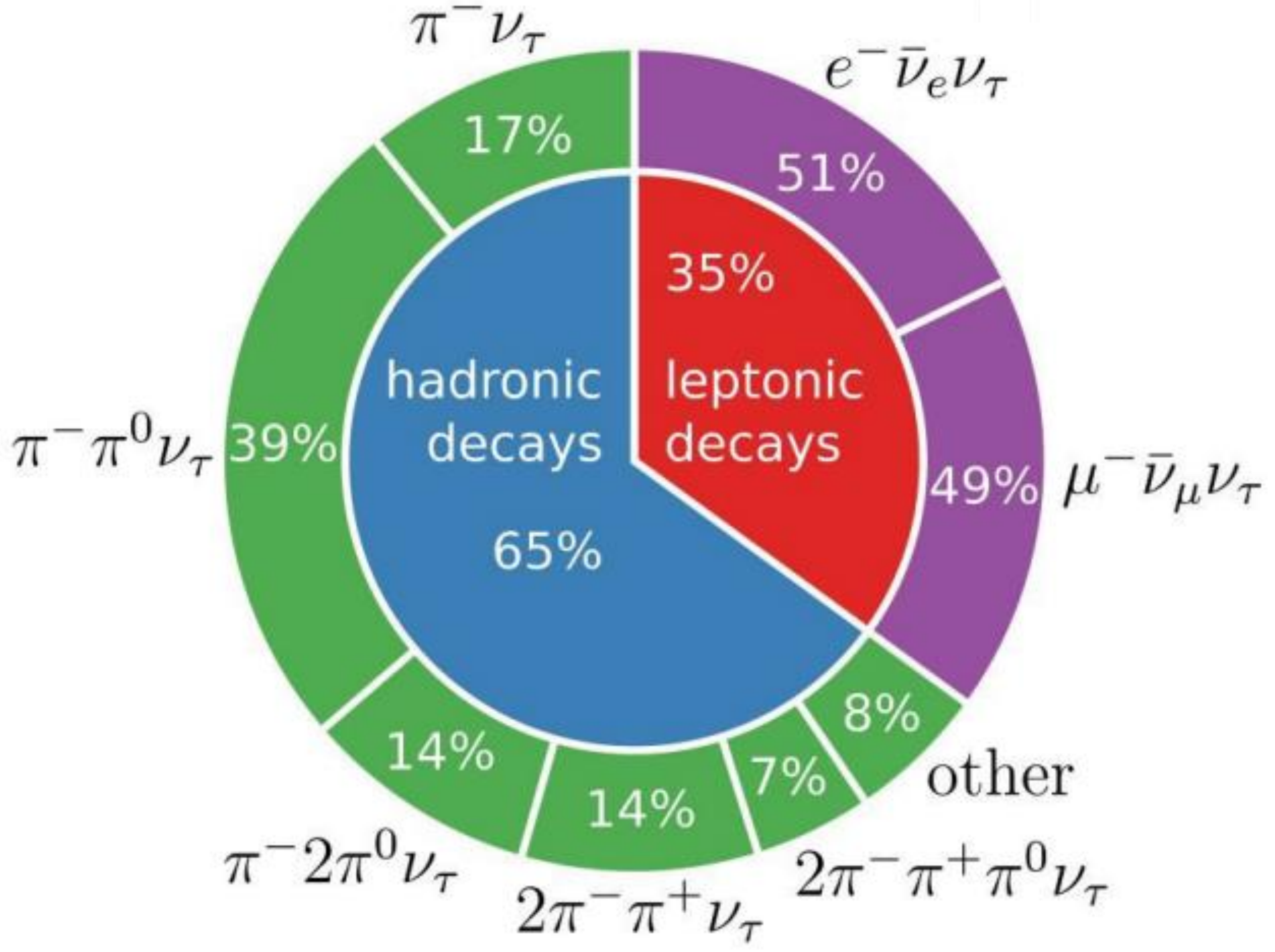
- VBS, HNL, LFV, Majorana neutrino
- May solve many problems at once!

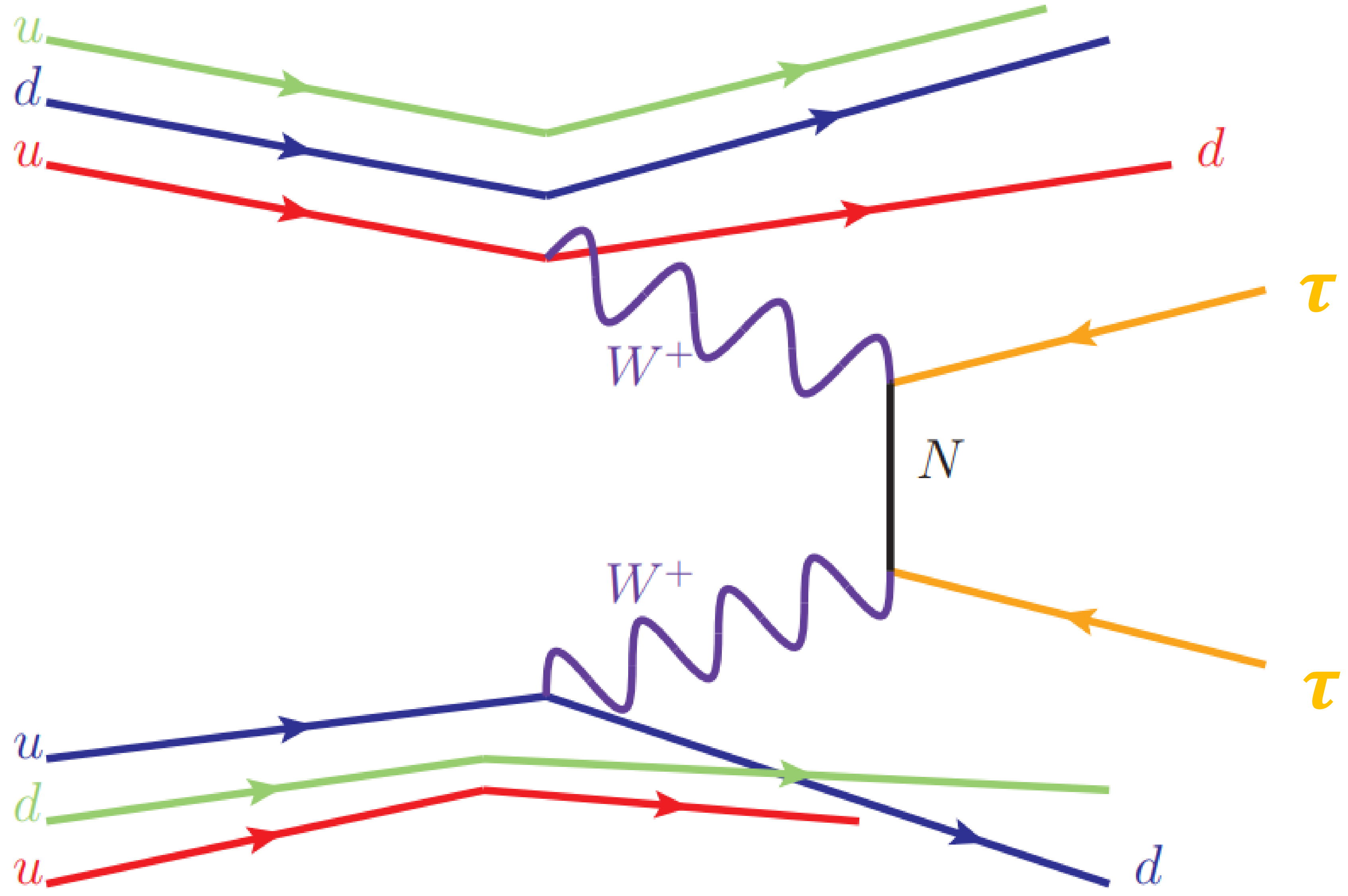
Although no signal for e/μ,
But best limit is set at ~0.05 for 1TeV

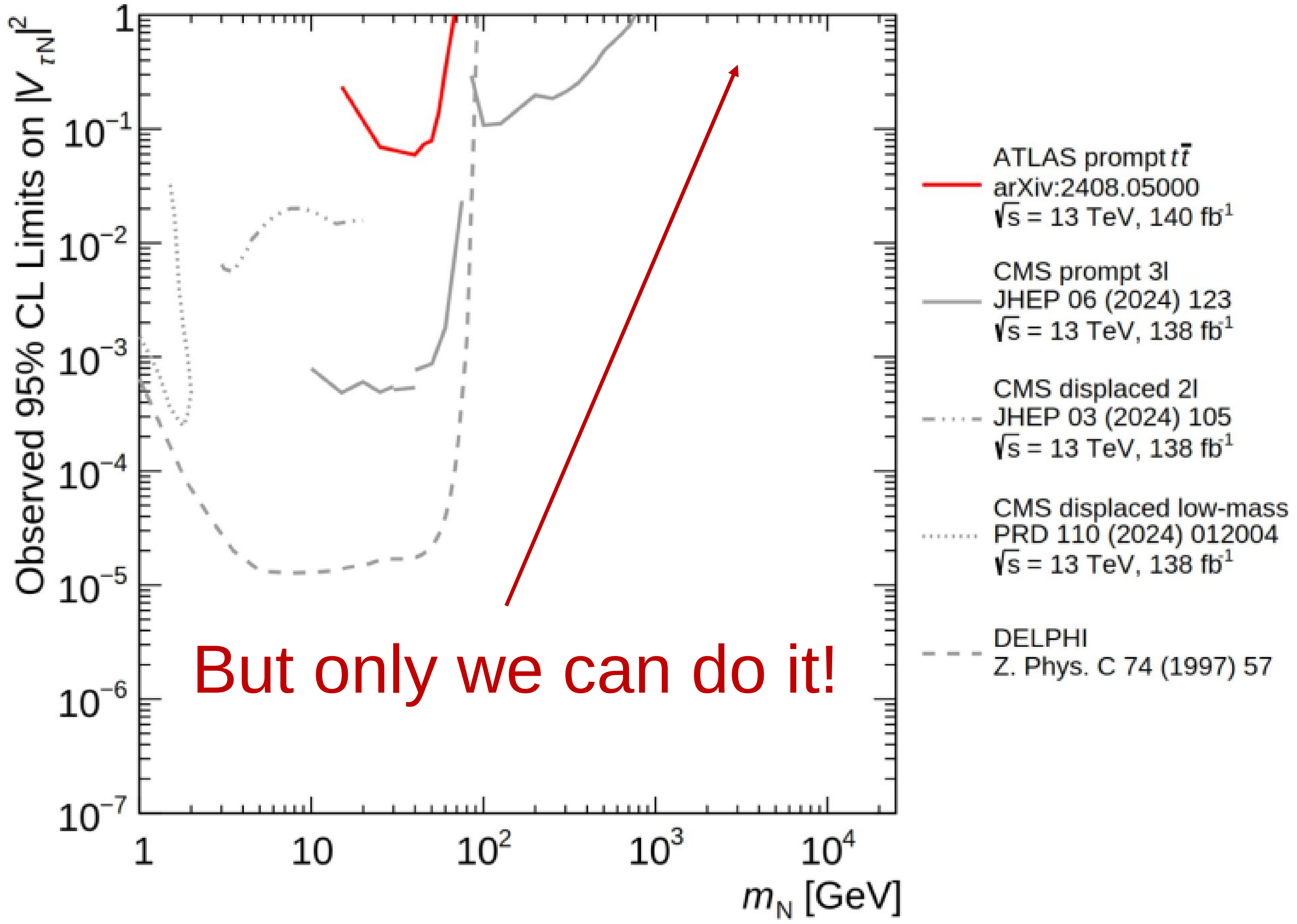
t-channel with τ

Uncovered τ channel

- Much harder channel
- Worse reconstruction
- More fakes
- Complicated decays
  (2 τ means many combinations…)







t-channel basic strategy

Some terminologies

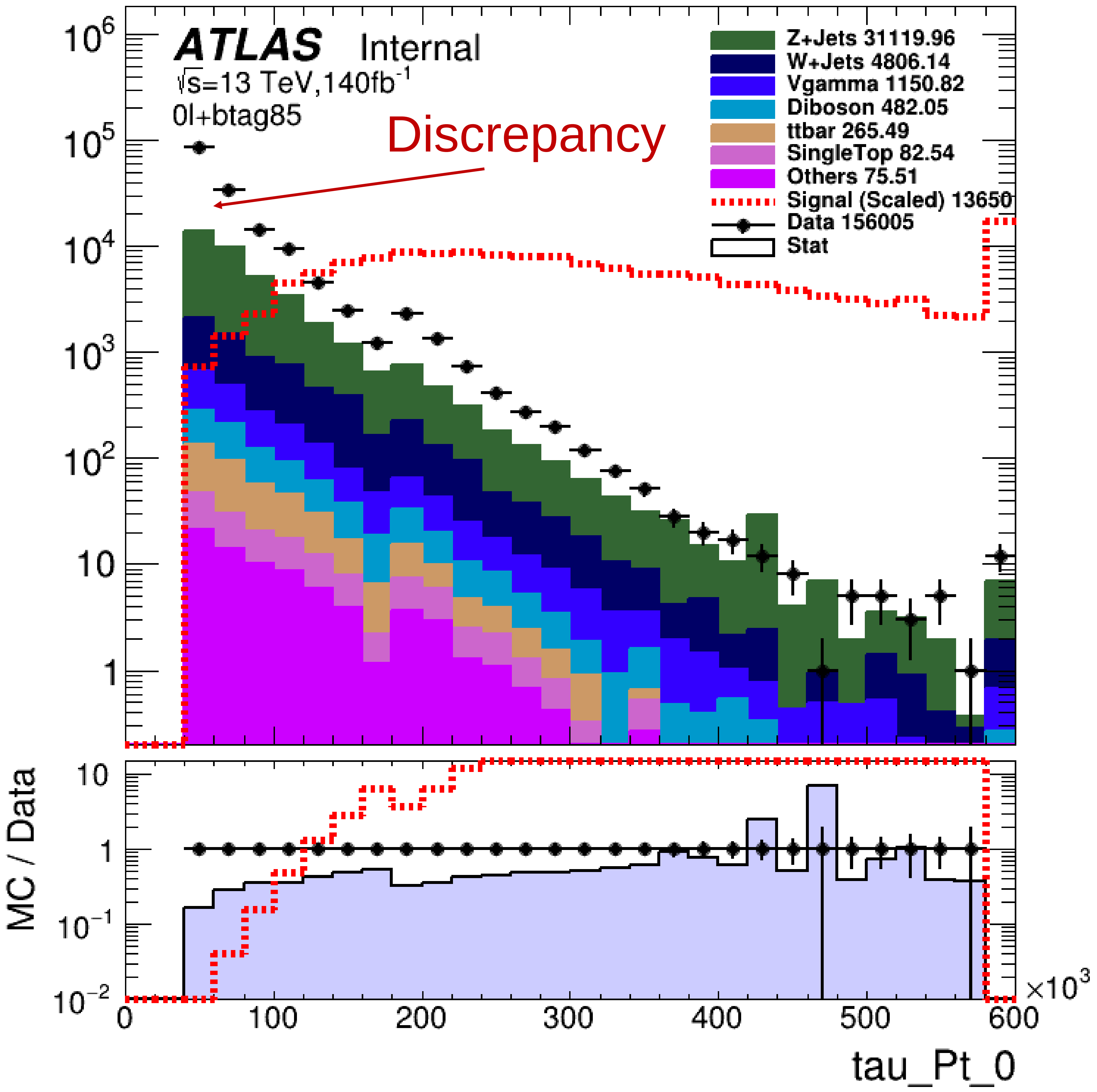
- SS = same sign pair
- OS = opposite sign pair
- MC = simulation

Regions

- $SS\tau\tau$ regions blinded
- $OS\tau\tau$ regions for validation (as a proxy for $SS\tau\tau$ background)

First look

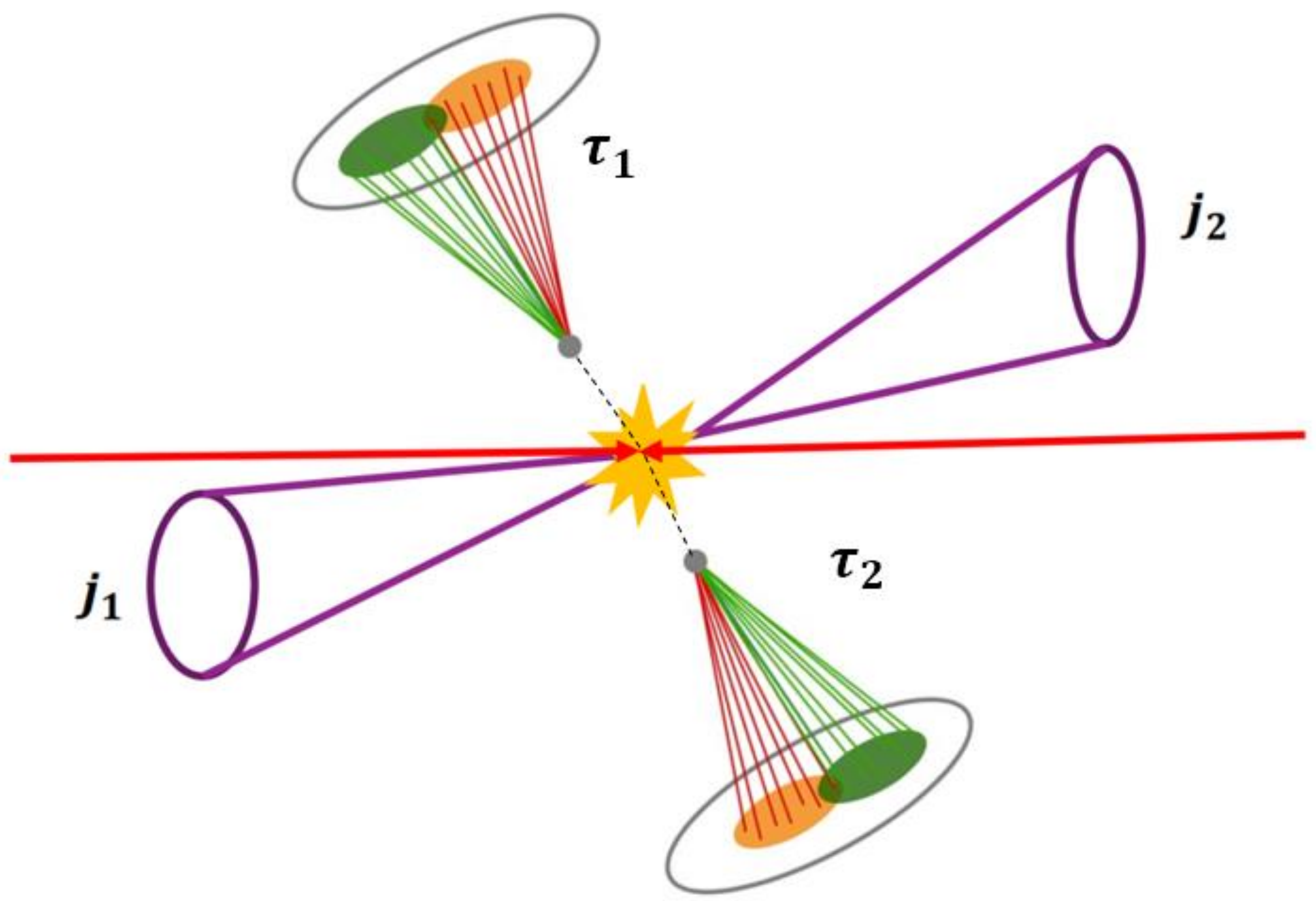
- Simply selecting events with 2 jets and 2 τ
- Comparison to data in $OS\tau\tau$ region
- Very high p_T signature
- A huge discrepancy…

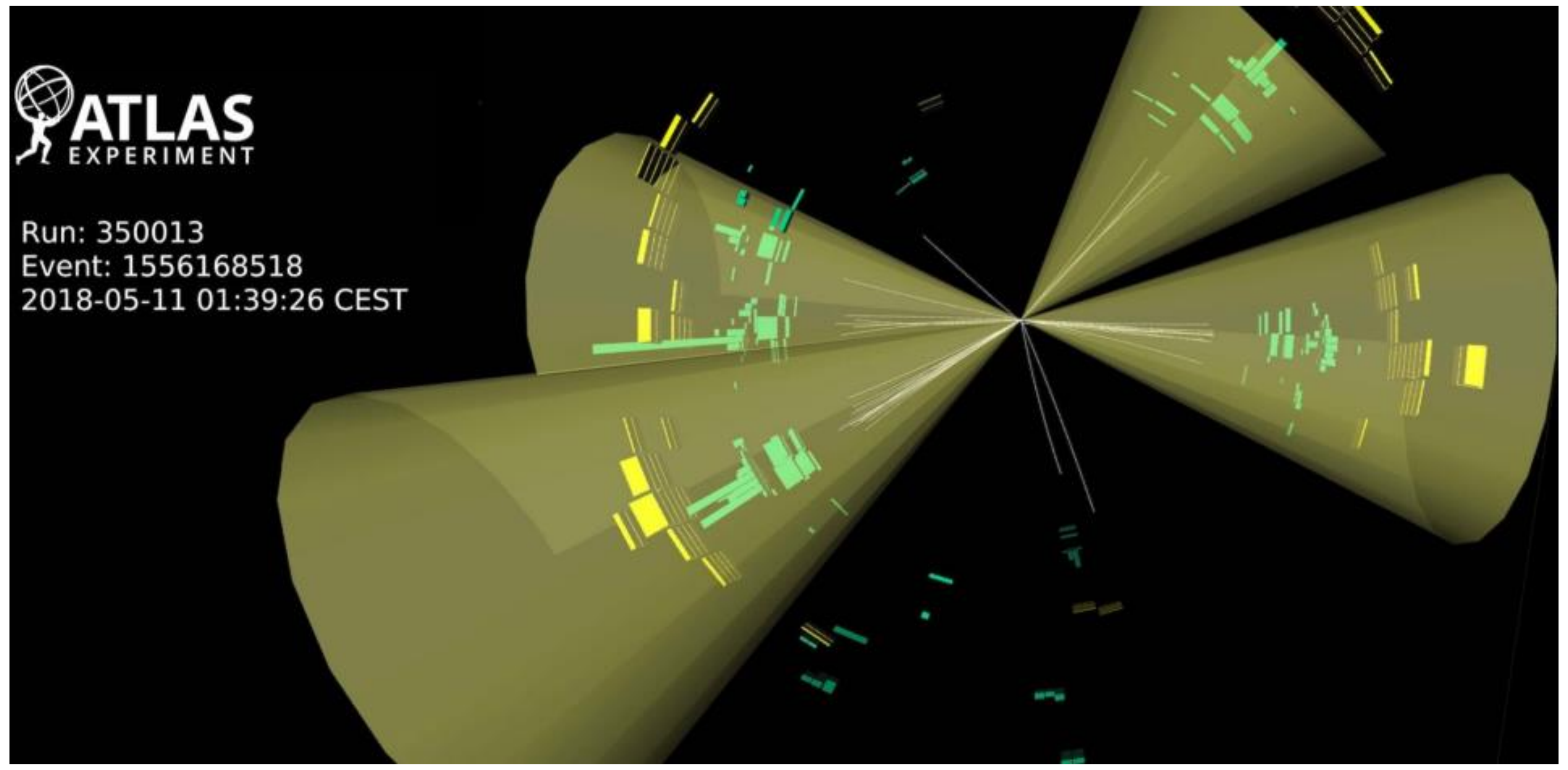


$OS\tau\tau$ (data, MC) vs $SS\tau\tau$ (signal)

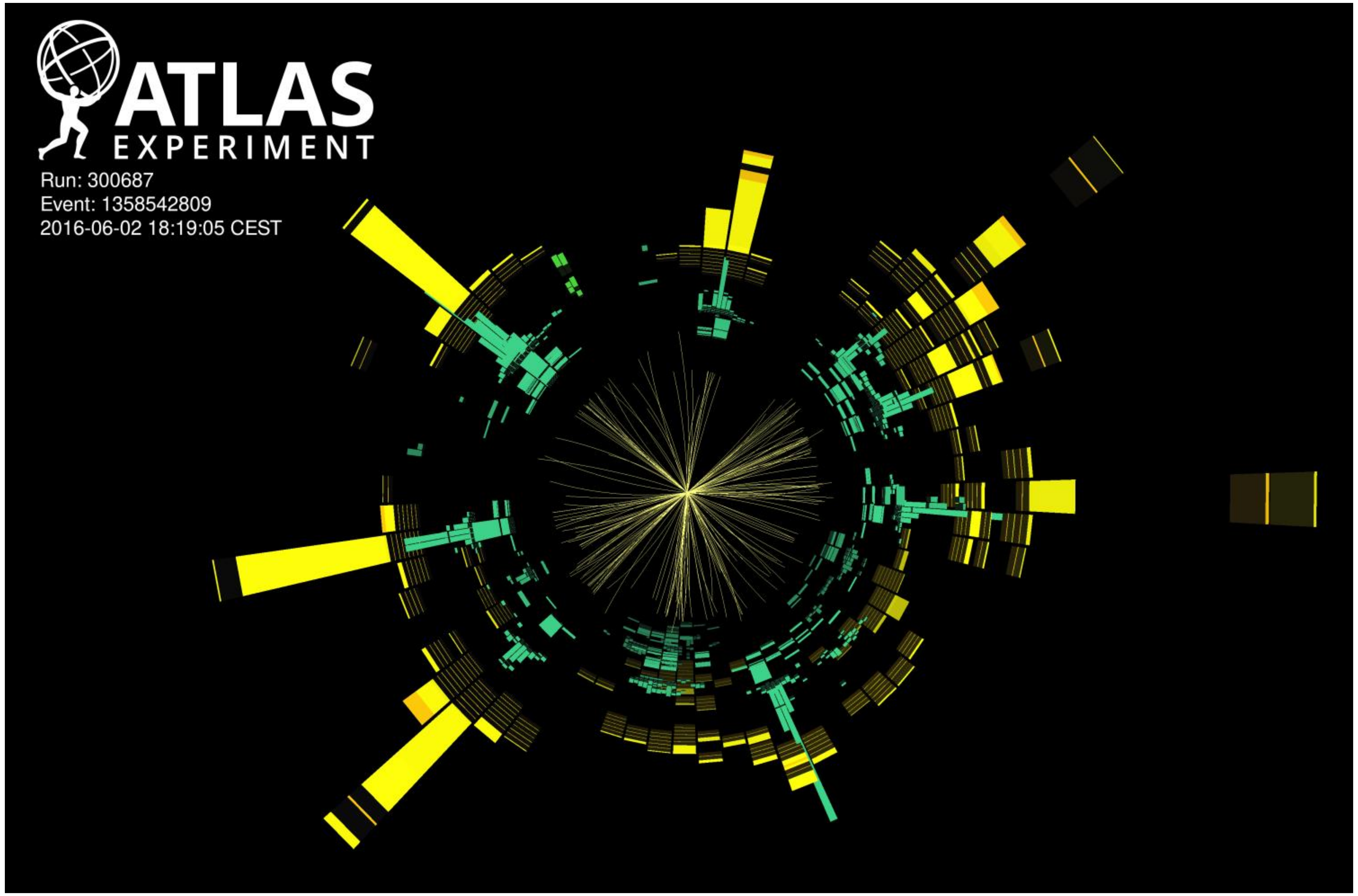
Explaining the discrepancy

The reason is FAKES from QCD
(mislabeling j → τ)





We want 2 τ and 2 jets



But we often record this, how do we tell which is which?
This is also hard to simulate correctly…

Quality selection

OS$\tau\tau$ and SS$\tau\tau$ regions could be complicated
Let's look at 1 reconstructed τ first.

What about using data to estimate the fakes?
Use ID Score of τ!

What is ID Score?

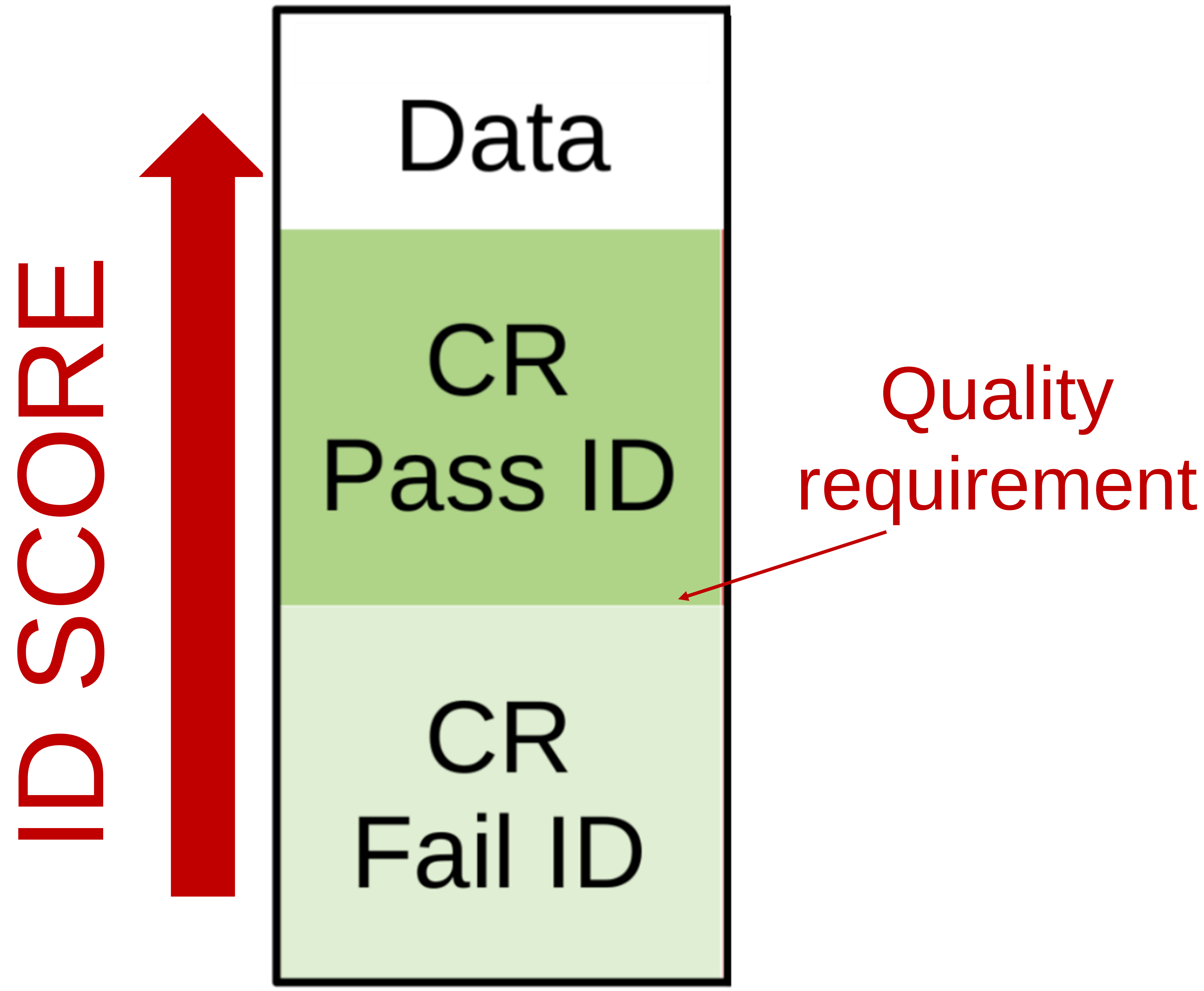
- RNN based Identification score
  (take into account tracks, calorimeter deposition, and more…)
- Quality measurement of reconstructed τ

Cutting at higher quality

- tighter selection, fewer fakes, fewer data

Cutting at lower quality

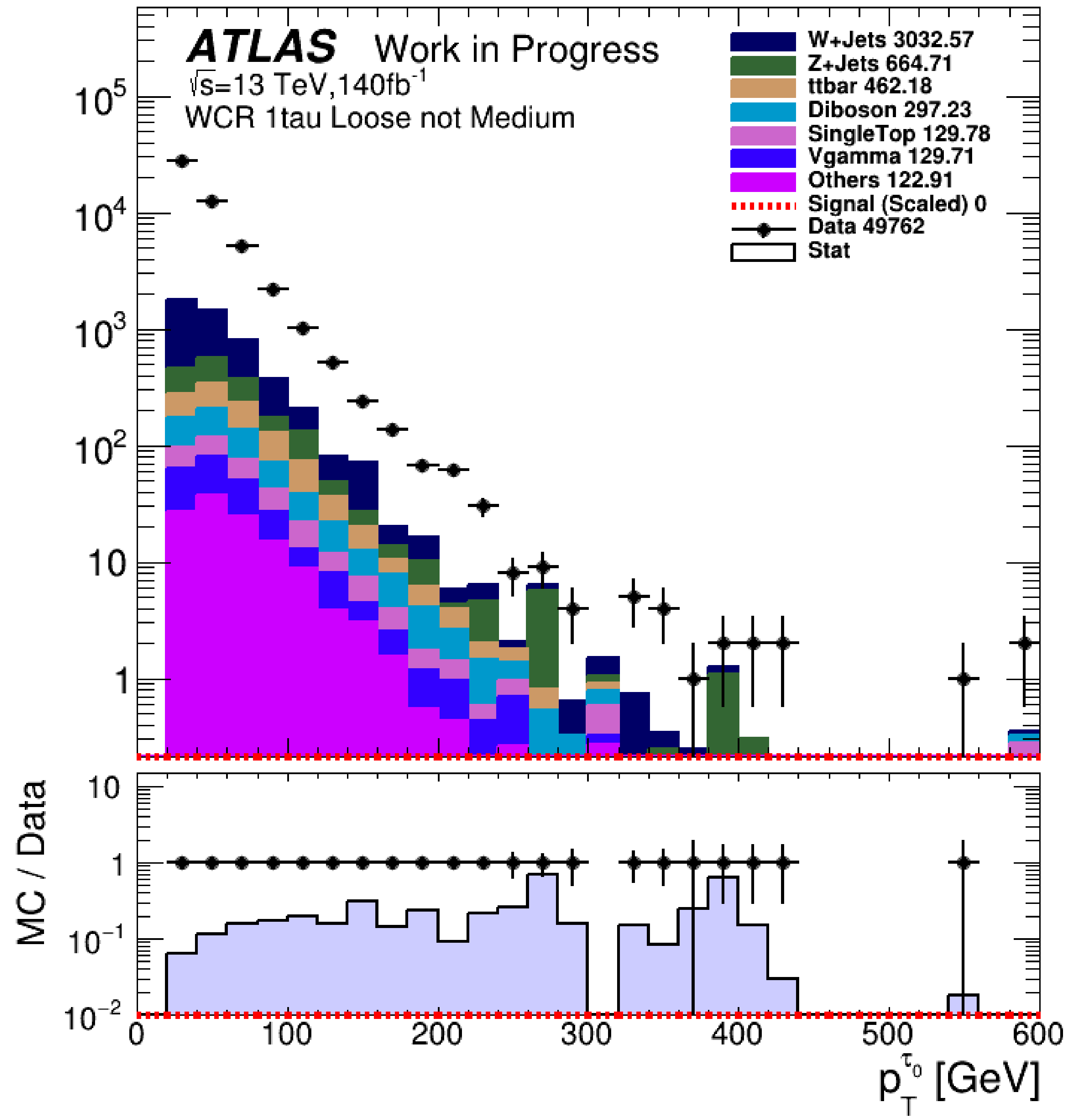
- looser selection, more fakes, more data



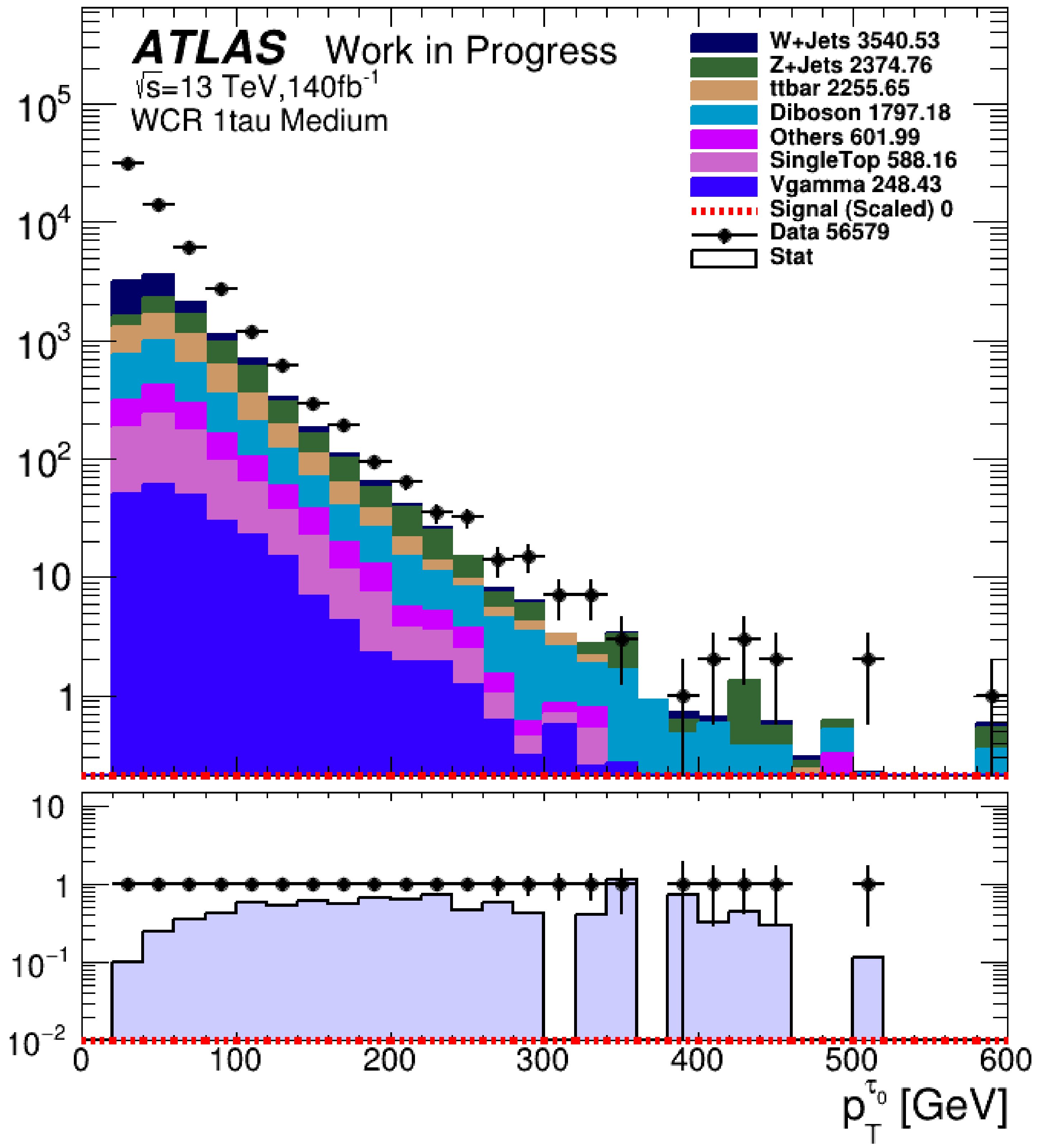
Control Region
1τCR

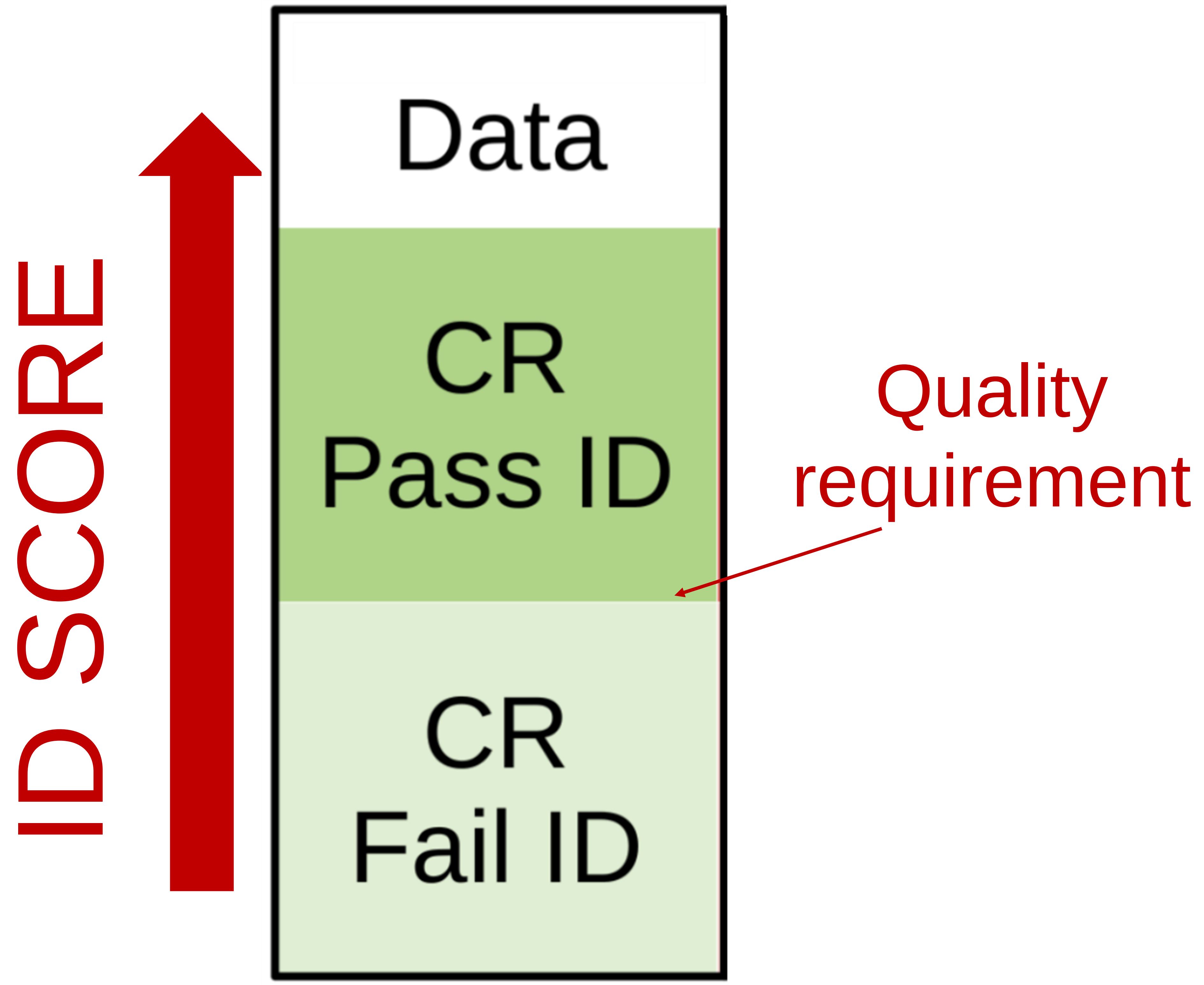
Quality selection

1τ Fail ID Region



1τ Pass ID Region



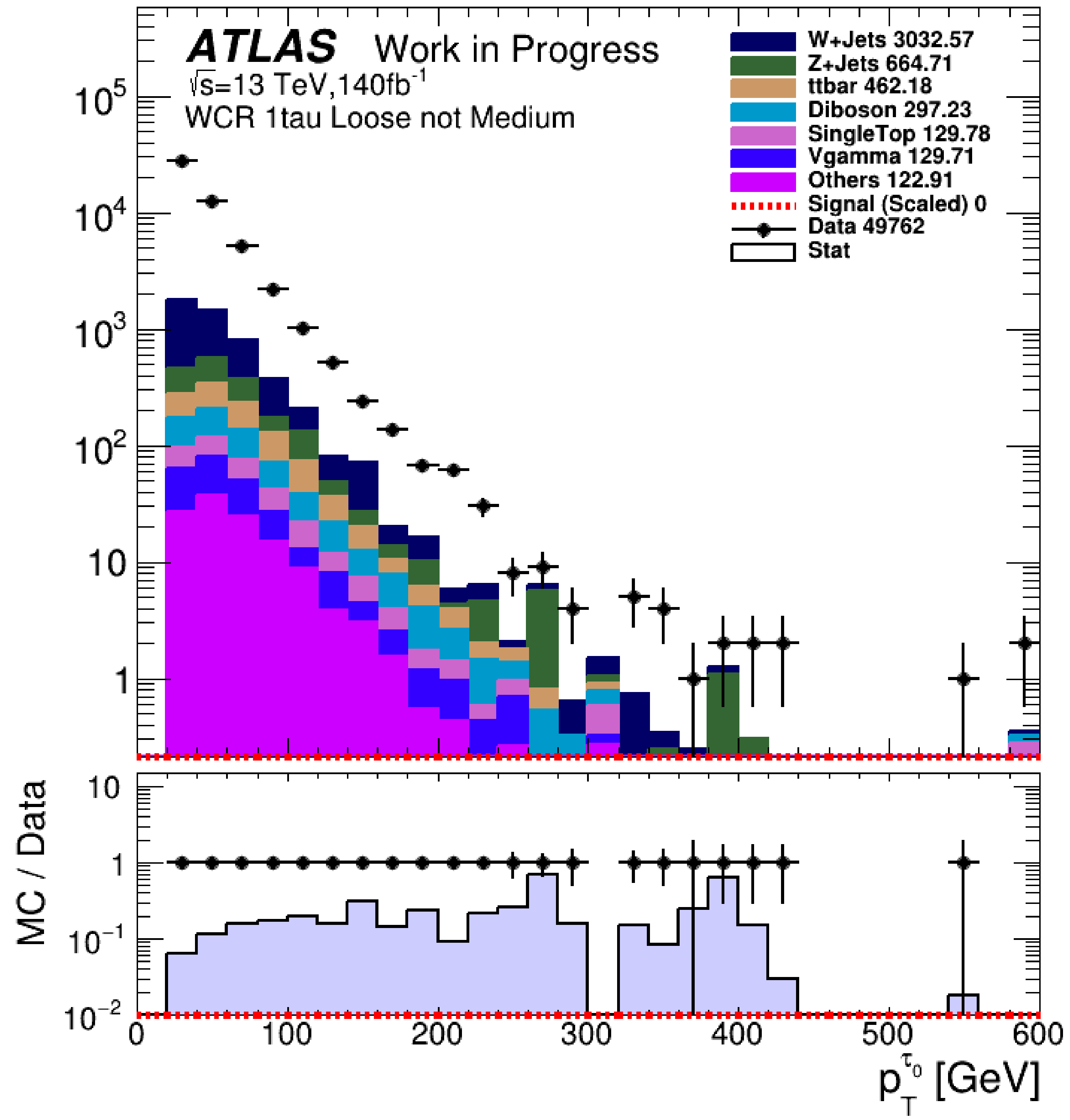


Control Region
1τCR

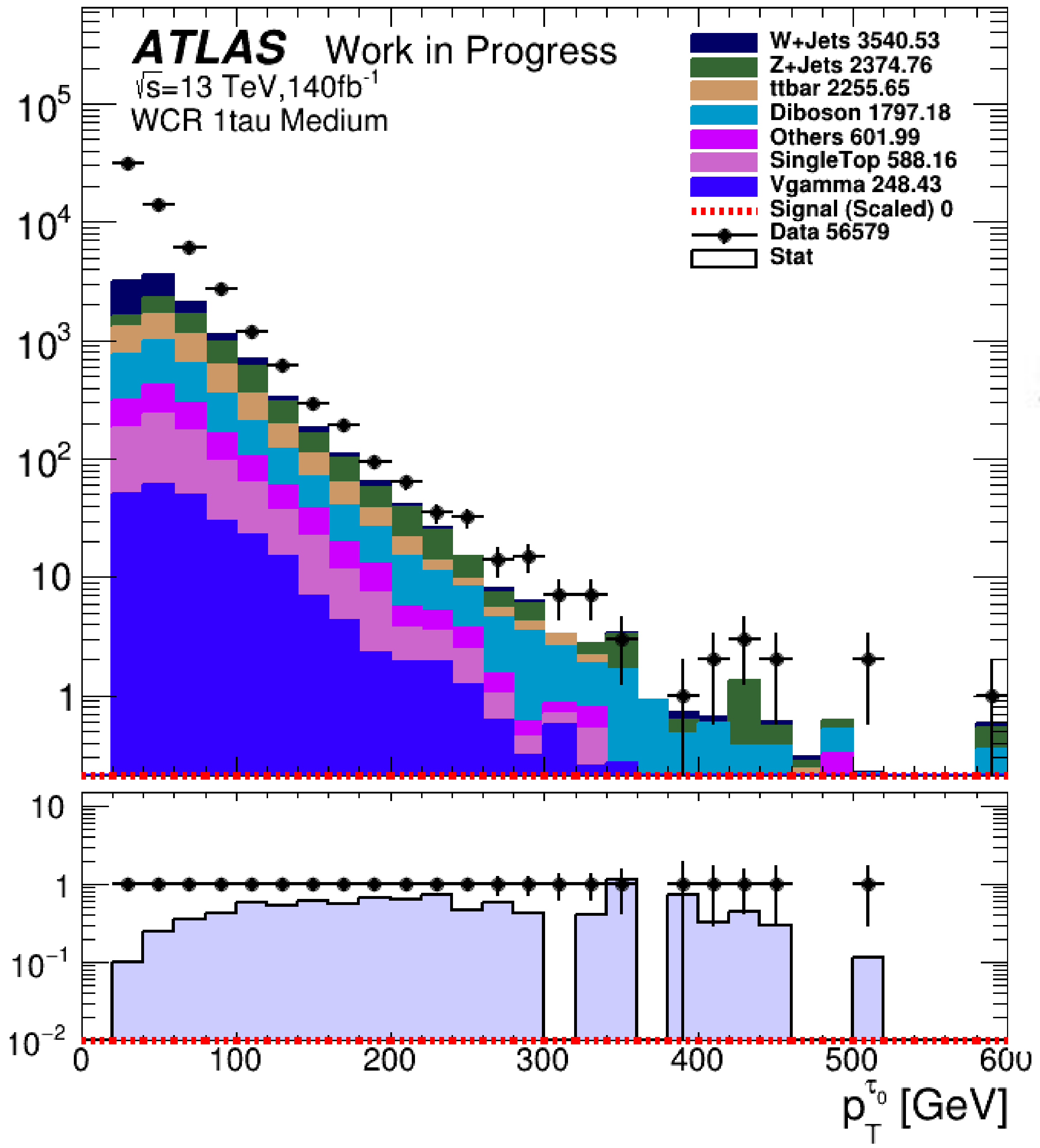
Higher score → lower discrepancy!
Maybe we just cut tighter?
But we still have discrepancies…

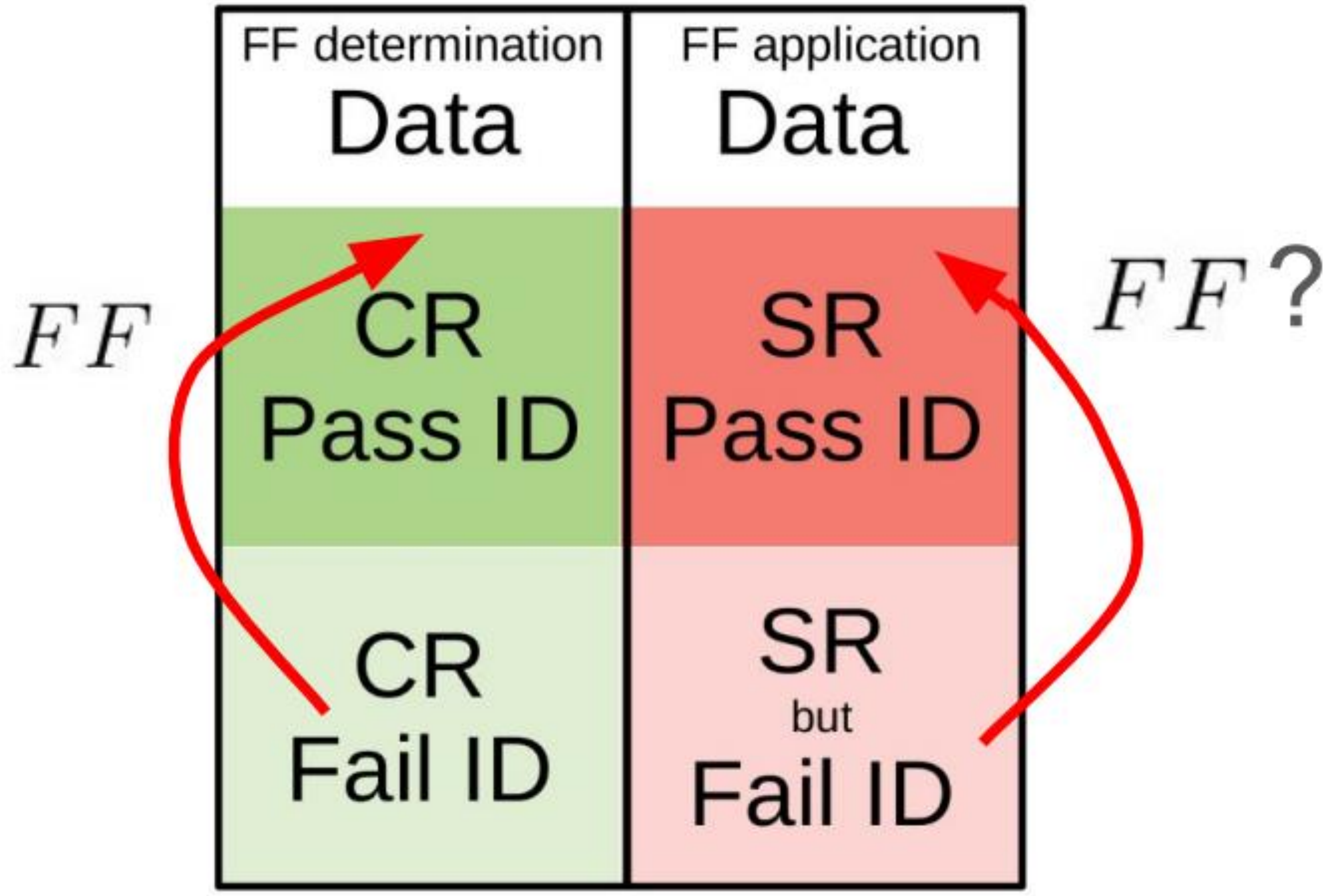
Fake Factors definition

1τ Fail ID Region



1τ Pass ID Region





Control Region 1τCR

Signal Region e.g. SS$\tau\tau$

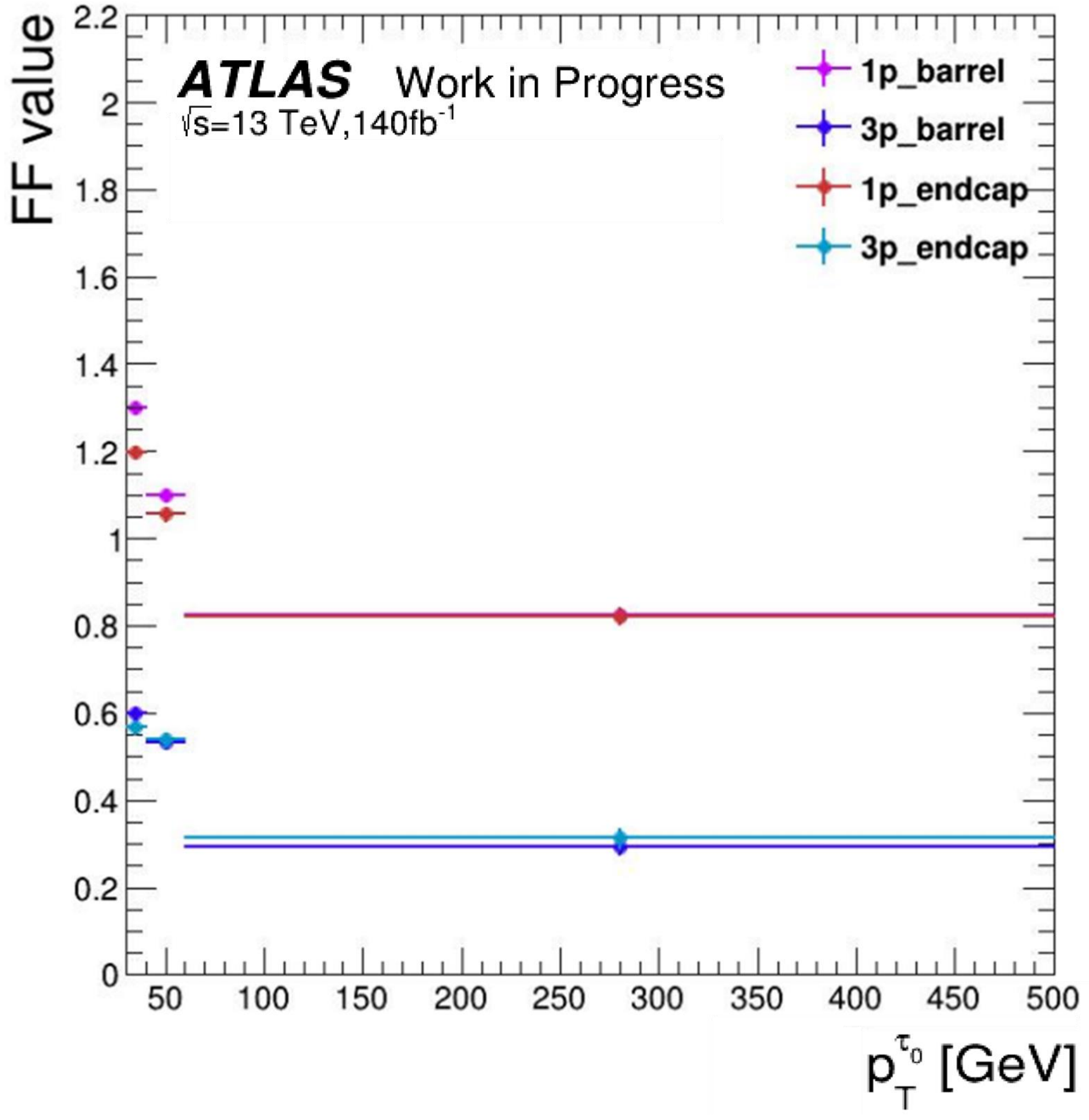
$$FF = \frac{N^{data}_{Pass\ ID\ \tau} - N^{MC}_{Pass\ ID\ \tau}}{N^{data}_{Fail\ ID\ \tau} - N^{MC}_{Fail\ ID\ \tau}} = \frac{Discrepancy\ on\ the\ right\ plot}{Discrepancy\ on\ the\ left\ plot}$$

While we cannot predict the amount of fakes from pure simulation, this is a data-driven ratio!

Fake Factor application

Measured FF

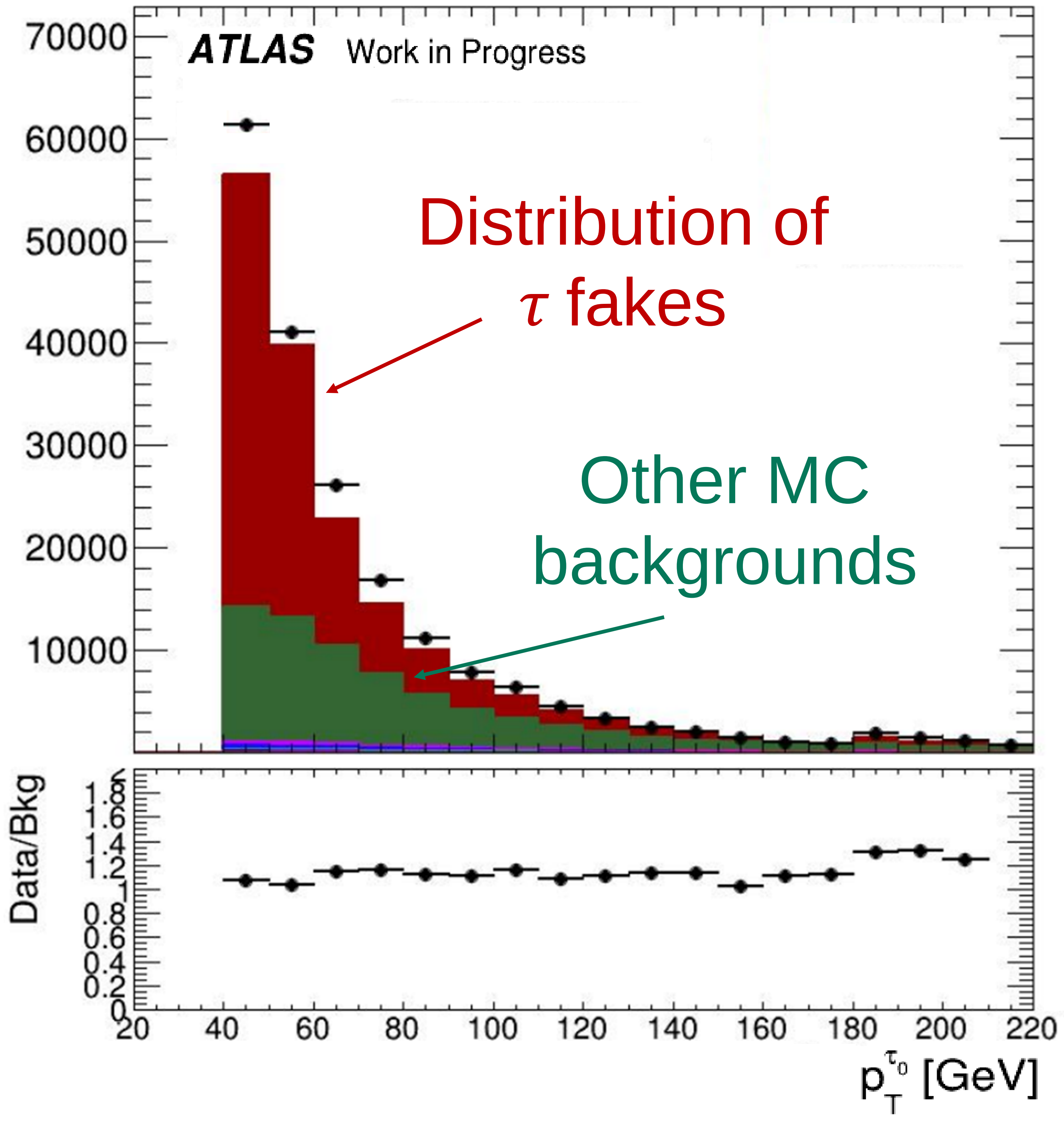
- First trial, binned in coarse p_T, τ prongs, η



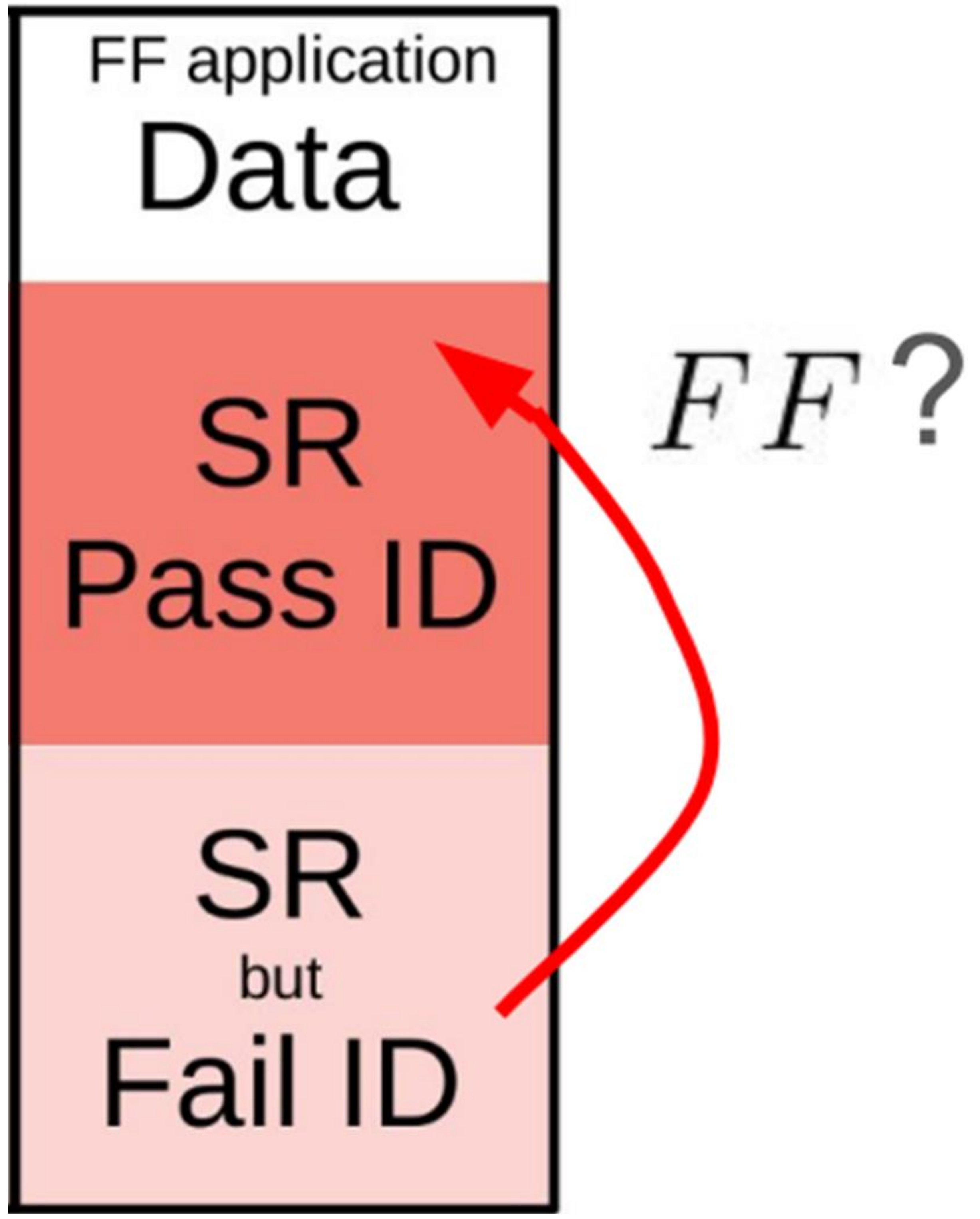
FF measured in bins of p_T

Applied to OS$\tau\tau$ (keep SS $\tau\tau$ still blinded)

- Much improved Data-MC agreements
- Only ~20% deviation



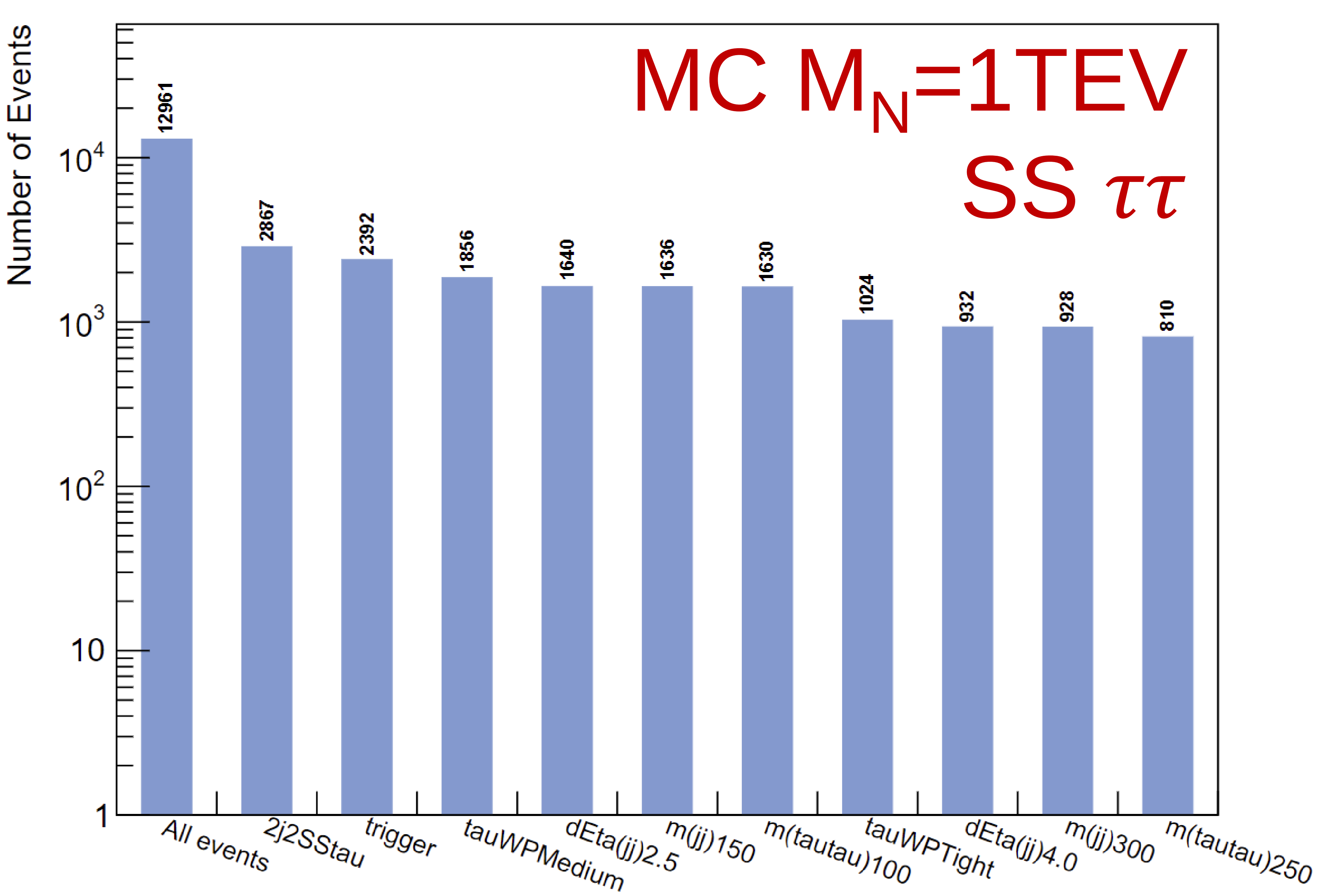
FF testing is OS$\tau\tau$ Pass ID Region (FF × OS Fail ID)

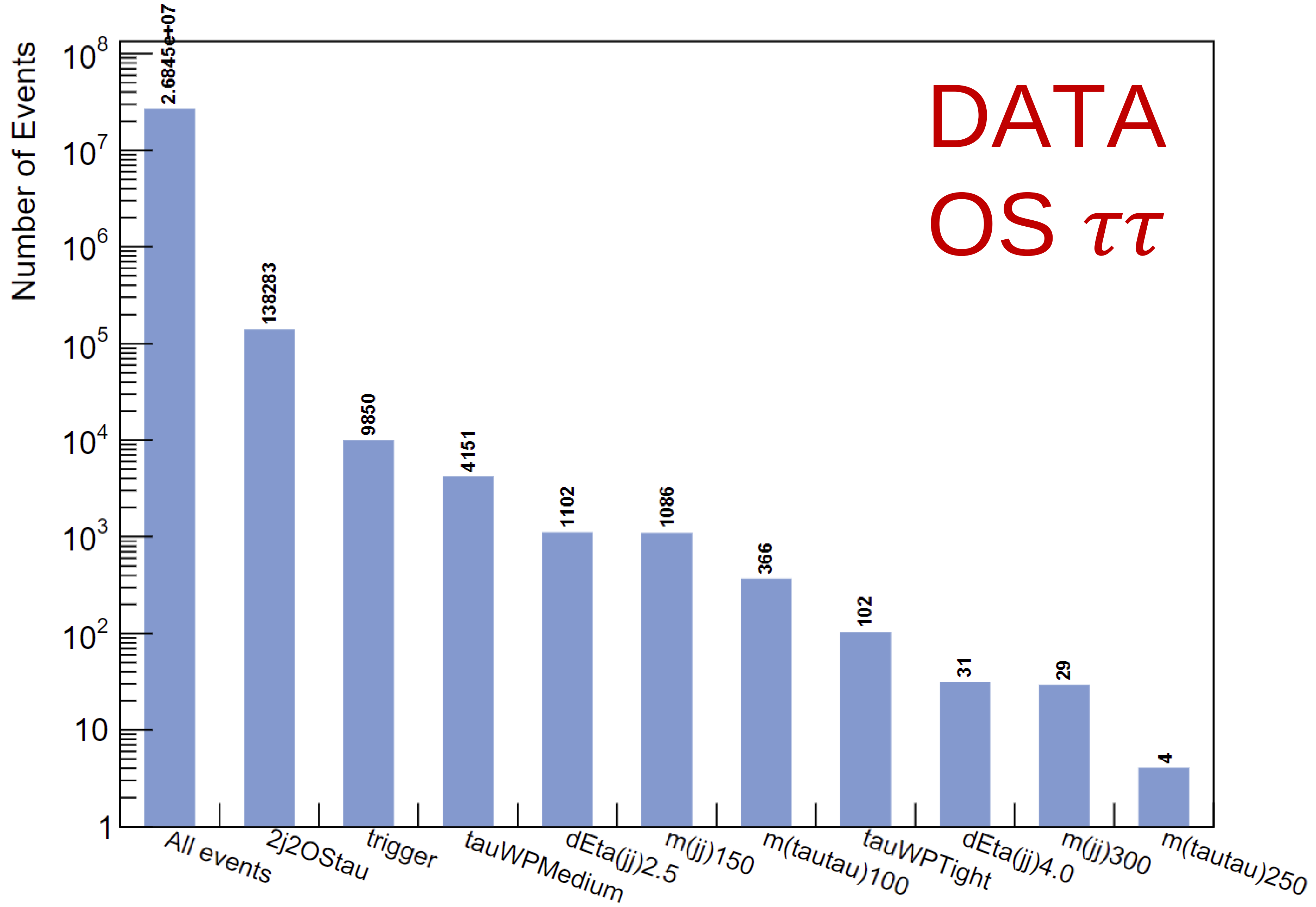


Sensitivity estimate

Fake Factor is not entirely ready…
Can we estimate our sensitivity?
Testing our selections

- SS region is fully blinded → Use OS distributions as proxy of our background
- Place progressive cuts on kinematics
- S/B ratio goes from 10^{-3} to 10^{-2}
  (raw MC yields vs data events)
- Assume data is all background → statistical test on $|V_{\tau N}|$





Summary

- Heavy neutral lepton above TeV scale is something unique in LHC
- Our team is working directly with theorists for both predictions and measurements
- Currently all the channels $\{s\ t\} \times \{e\ \mu\ \tau\}$ are limited by statistics, significant improvement guaranteed for run 3 and HL-LHC