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Experimental Lepton Flavour Physics

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HEP Herbstschule
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Who am I?

Ann-Kathrin Perrevoort

› 2014-2018
  PHD Heidelberg — Mu3e
› 2018-2021
  Postdoc Nikhef&Nijmegen — ATLAS
› 2022-2023
  Fellow KIT — Mu3e
› Since 2024
  Ass. Prof. Univ. Groningen — LHCb

› Research interests
  charged Lepton Flavour Violation
  data acquisition

Experimental Lepton Flavour Physics

- Selection of e**xperiments** that investigate **lepton flavour**
  - Focus on Lepton Flavour Violation (**LFV**)
  - Leaving out a lot of other interesting searches: Lepton Flavour Universality, (g-2) of muon, electron EDM, neutrino mass, …
- Wed: Leptons @ Collider Experiments
- Thu: Muon Experiments
- Fri: Neutrinos

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Experimental Lepton Flavour Physics

Introduction and Leptons @ Collider Experiments

Lecture 1

Today

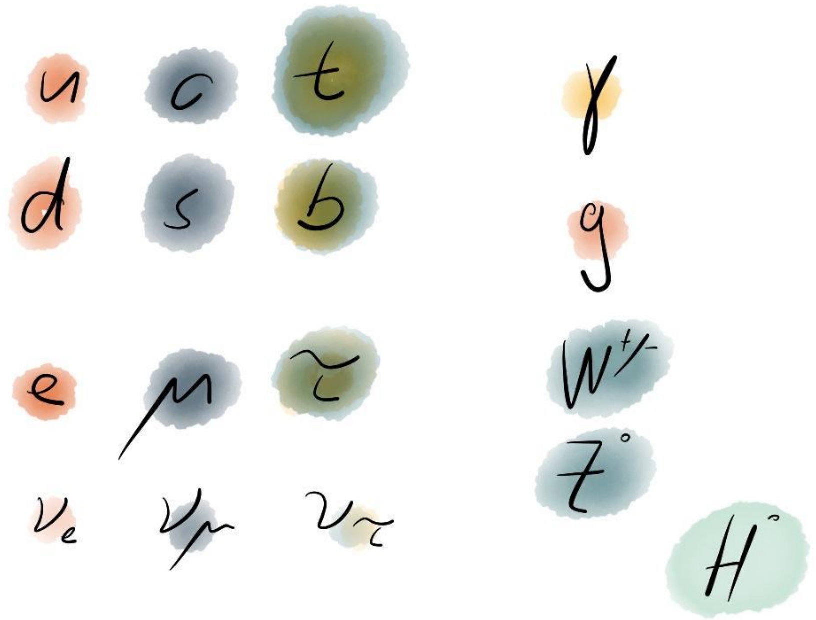
- **Indirect searches for BSM** with Leptons
  - Lepton Flavour Violation

- **Leptons @ Colliders**
  - Detection of e, μ, τ
  - Example:
    Search for Z→eτ and Z→μτ with the ATLAS Experiment

Indirect Searches for BSM with Leptons

Indirect Searches for BSM Physics

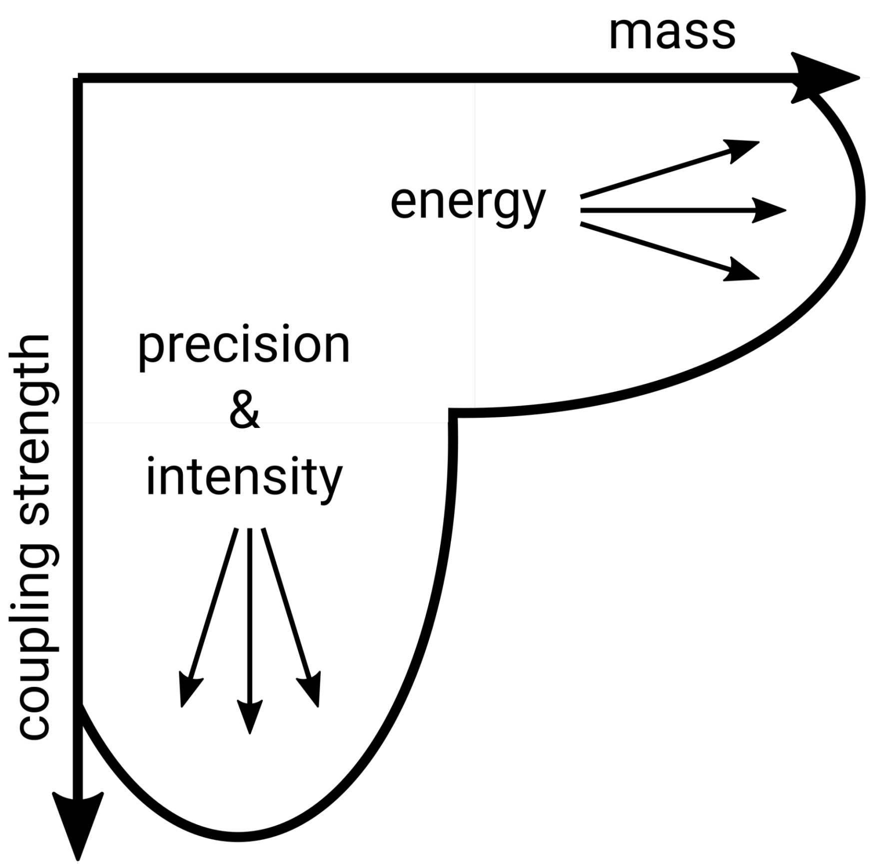
- **Standard Model** (SM) is **not** an **ultimate theory** of particle physics
- Search for signs of beyond SM (**BSM**) physics



Indirect Searches for BSM Physics

- **Standard Model** (SM) is **not** an **ultimate theory** of particle physics
- Search for signs of beyond SM (**BSM**) physics

- **Energy** frontier
  - **Direct production** of heavy BSM particles
- **Precision** / **Intensity** frontier
  - **Indirect** search for tiny **deviations** from SM predictions
  - Sensitive to **small couplings** and/or **heavy particles in loops**
  - Use processes that are rare or forbidden in the SM



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- **Standard Model** (SM) is **not** an **ultimate theory** of particle physics
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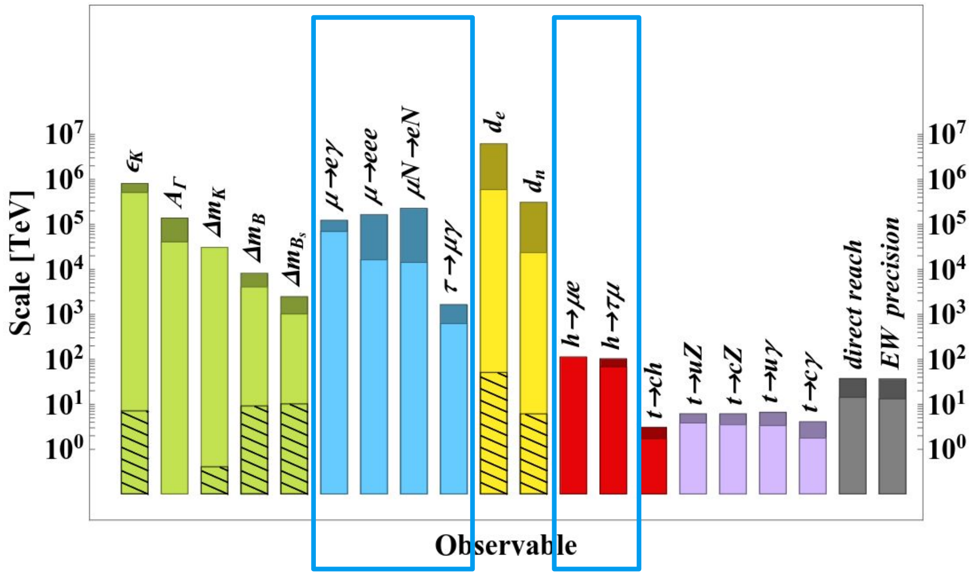
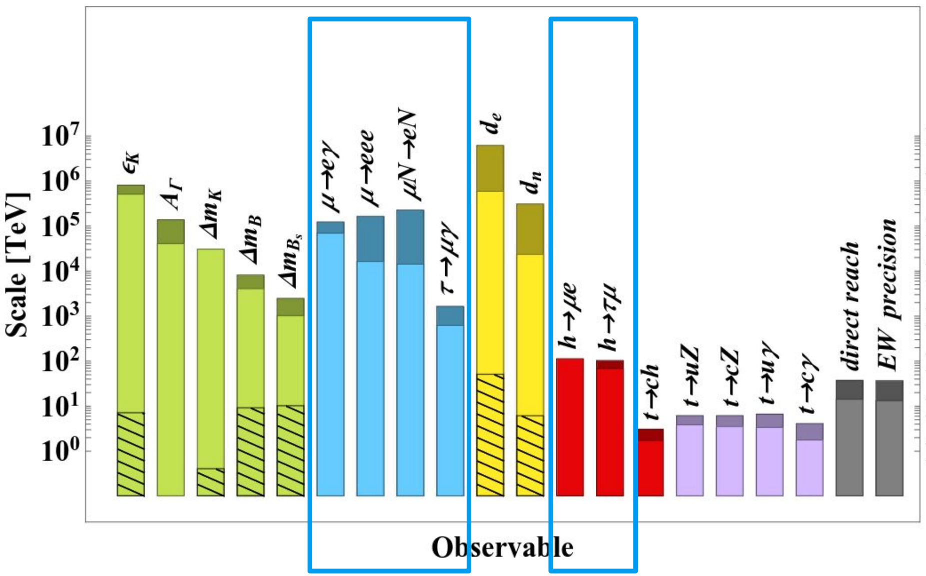


Physics Briefing Book, ESPPU2020

Lepton Flavour Violation

- **Lepton flavour** is conserved due to an **accidental symmetry** in the SM
- Lepton Flavour Violation (**LFV**) is a **forbidden** process



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Lepton Flavour Violation

› **Lepton flavour** is conserved due to an **accidental symmetry** in the SM

› Lepton Flavour Violation (**LFV**) is a **forbidden** process

› And in **BSM**?

- LFV frequently predicted
- No LFV would hint at additional symmetry

H. Murayama, Supersymmetry IV, 2005

Lepton Flavour Violation

- **Lepton flavour** is conserved due to an **accidental symmetry** in the SM
- Lepton Flavour Violation (**LFV**) is a **forbidden** process

- And in **BSM**?
  - LFV frequently predicted
  - No LFV would hint at additional symmetry

- And in **nature**?
  - **Neutrino oscillations** are LFV!
  - But what about **charged leptons**?

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

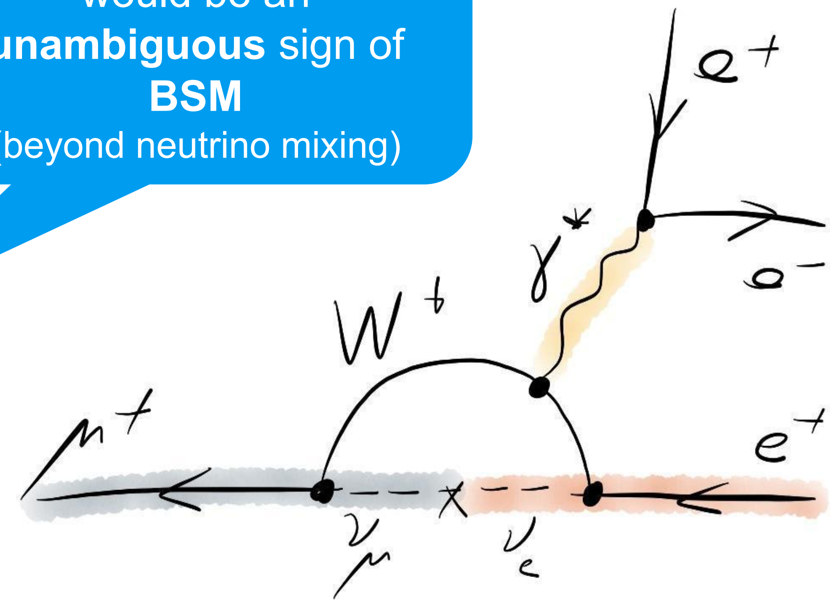
Charged Lepton Flavour Violation

- LFV with charged leptons (**cLFV**)
  - forbidden in the SM
  - predicted in BSM models
  - not (yet?) observed

Any **observation** of **cLFV** would be an **unambiguous** sign of **BSM** (beyond neutrino mixing)

- If **neutrino mixing** is added to SM, **cLFV** still heavily **suppressed**:

$$\mathcal{B}_{\mu\to eee} \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \to \mathcal{B}_{\mu\to eee} < 10^{-54}$$

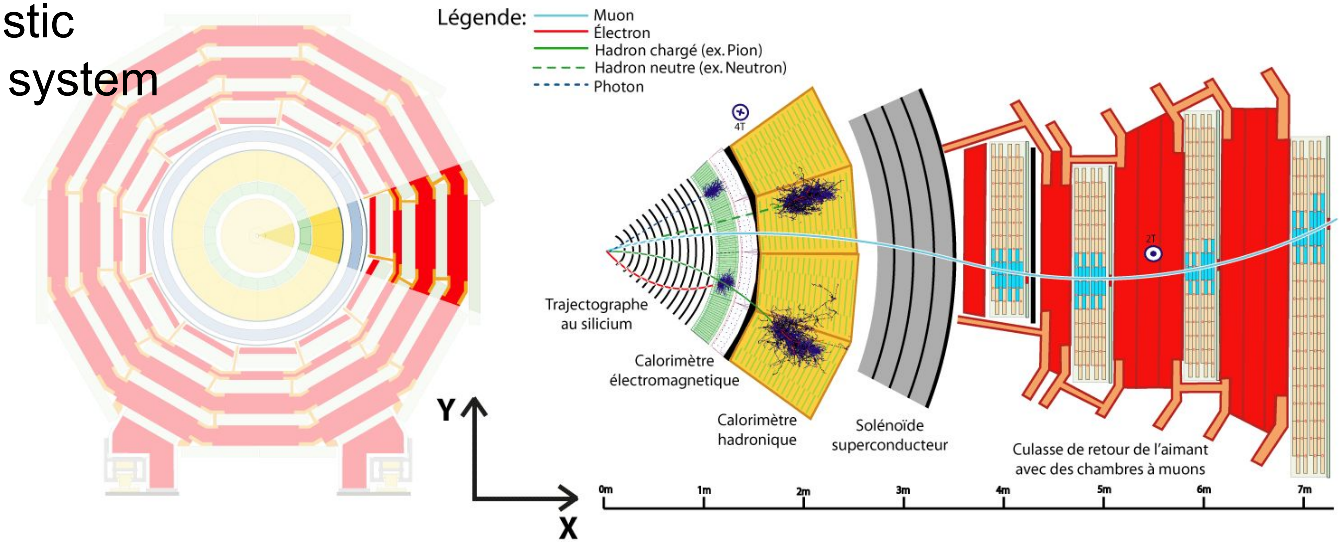


Detecting Leptons @ Collider Experiments

Detecting Leptons

- Detect
  - Charged leptons
  - Photons
  - Hadrons
  - No neutrinos
- Identify by characteristic signature in detector system

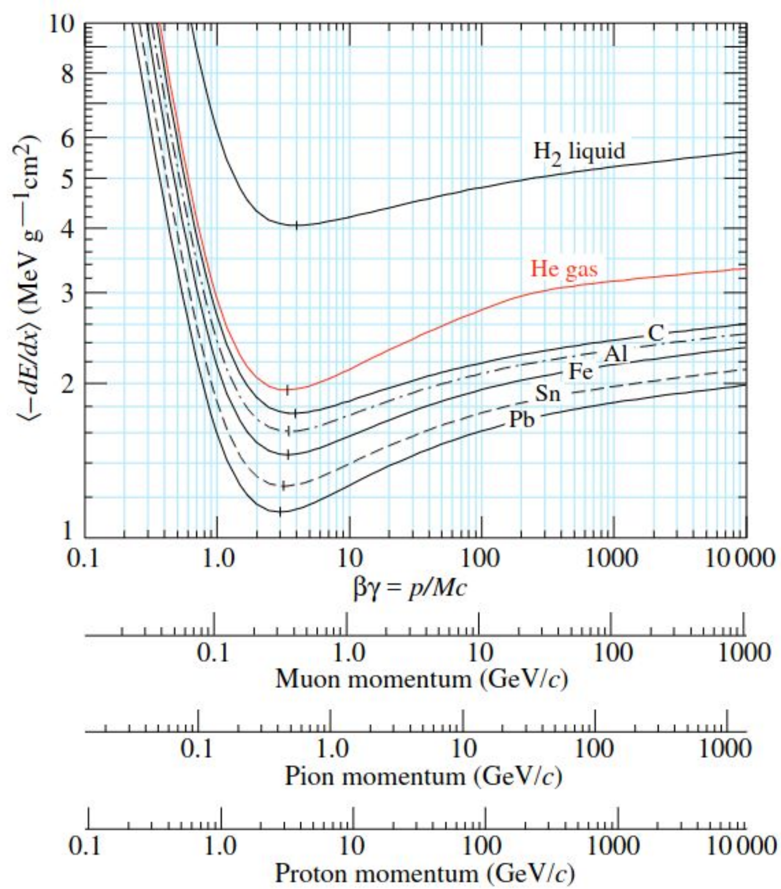
Example: CMS Experiment



Detecting Leptons: Muons

- **Muons** are rather **light**
  m = 105.66 MeV
  with rather **long lifetime**
  τ = 2.197 × 10^{-6}s
  - Decays via $\mu^\pm \rightarrow e^\pm \nu\bar{\nu}$,
    but most muons don't decay within detector

- Minimum-ionizing particle (**MIP**)
  - Passes through all detectors
  - Characteristic signal in **muon system**



Detecting Leptons: Muons

- Reconstructed from
  - Combined **tracking** and **muon system** signals
  - Also possible:
    - Tracking + calorimeter
    - Muon system alone
- Identification of prompt muons (from PV)
  - Distinguish from $K/\pi \rightarrow \mu$
    - Track fit quality
    - Mismatch of momenta measured in tracking and muon system
- Isolation
  - Reject muons produced in jets
  - Selections based on activity around reconstructed muon candidate

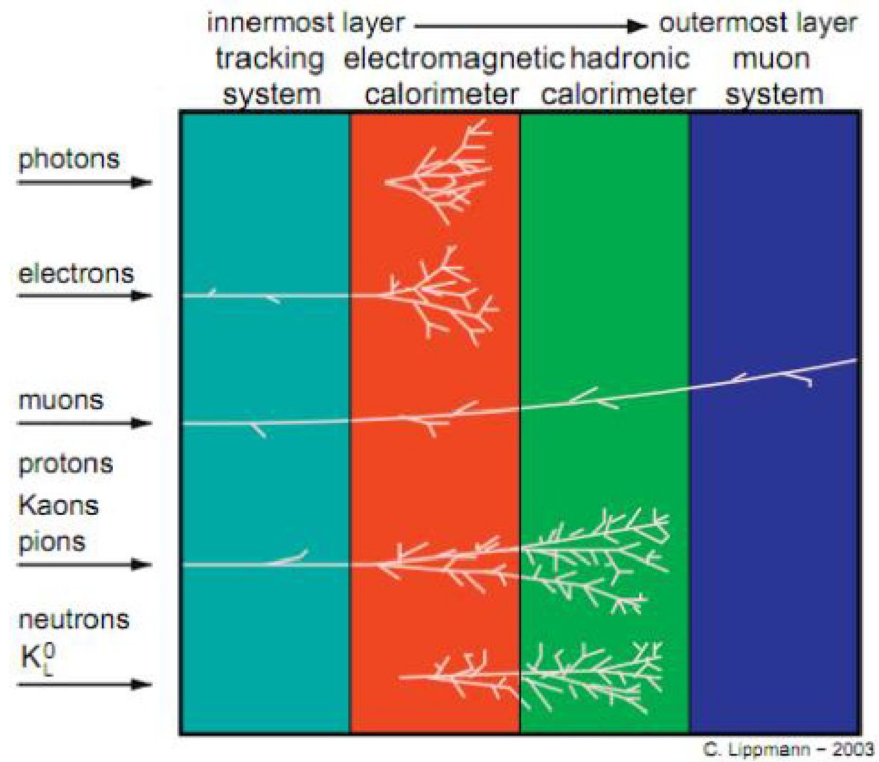
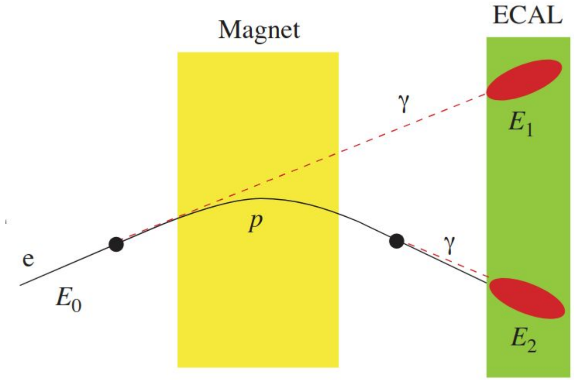


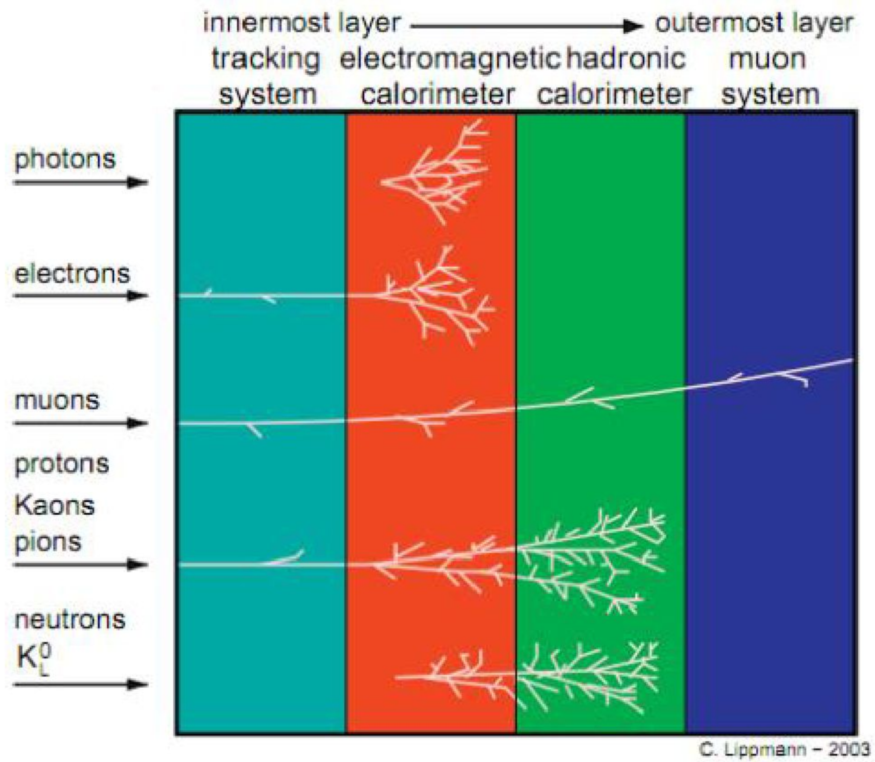
Fig. 1. Components of a "traditional" particle physics experiment. Each particle type has its own signature in the detector. For example, if a particle is detected only in the electromagnetic calorimeter, it is fairly certain that it is a photon.

Detecting Leptons: Electrons

- **Electrons** are **very light** (m = 0.511 MeV) and **stable**

- Reconstructed from
  - Signal in electromagnetic calorimeter (**ECAL**) same for electrons and photons
  - Need matching **track**
  - Recover bremsstrahlung losses





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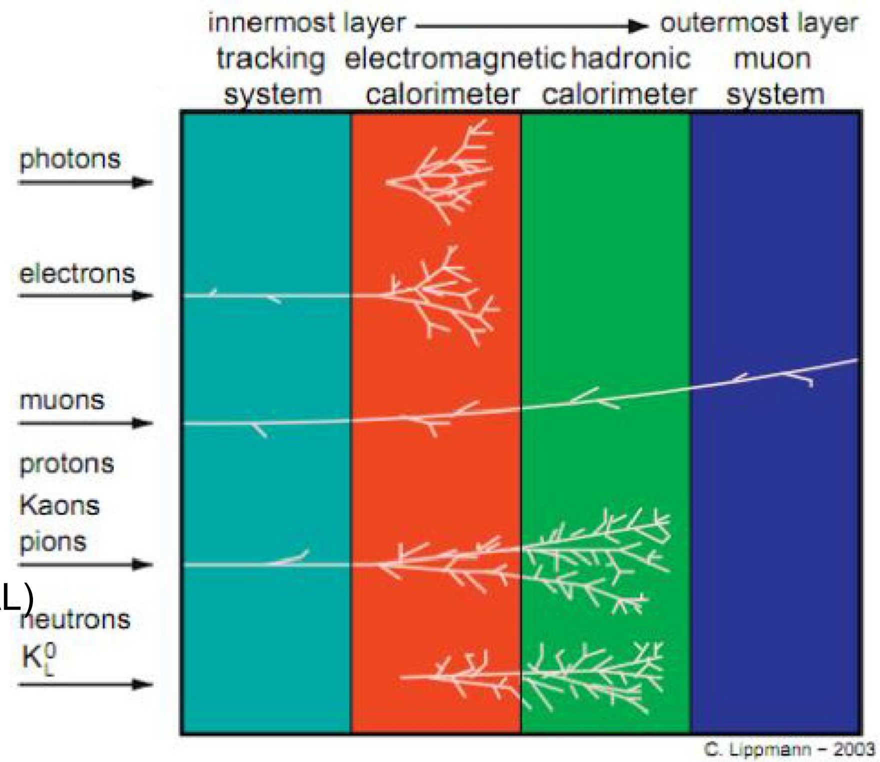
Detecting Leptons: Electrons

- **Electrons** are **very light** (m = 0.511 MeV) and **stable**
- Reconstructed from
  - Signal in **ECAL** and matching **track**
  - Recover bremsstrahlung losses
- Identification
  - Distinguish from jets
    - Shower and track parameters
    - Leakage into hadronic calorimeter (HCAL)
- Isolation
  - Reject electrons produced in jets
  - Selections based on activity around reconstructed electron candidate



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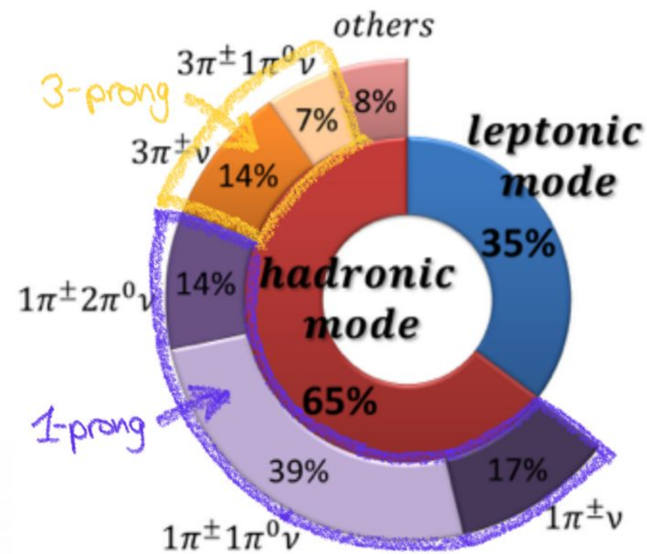
Detecting Leptons: Taus

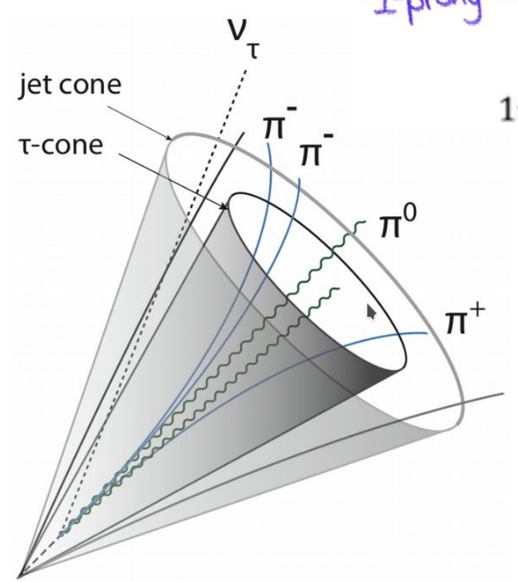
- Taus are heavy   m = 1777 MeV
  and **short-lived** τ = 2.9×10^{-13}s

- Multiple **decay modes**
  - **Leptonic** (BR ~ 35%)
    - $\tau^\pm \to \ell^\pm \nu\bar{\nu}$, ℓ = e, μ
    - Reconstruct as e, μ
  - **Hadronic** (BR ~ 65%)
    - $\tau^\pm \to \pi^\pm \nu$ or $3\pi^\pm \nu + \pi^0$s

- **Neutrinos** from tau decay not directly detected
  - Reconstruct **visible products**
  - Neutrinos partially reconstructed via missing transverse momentum

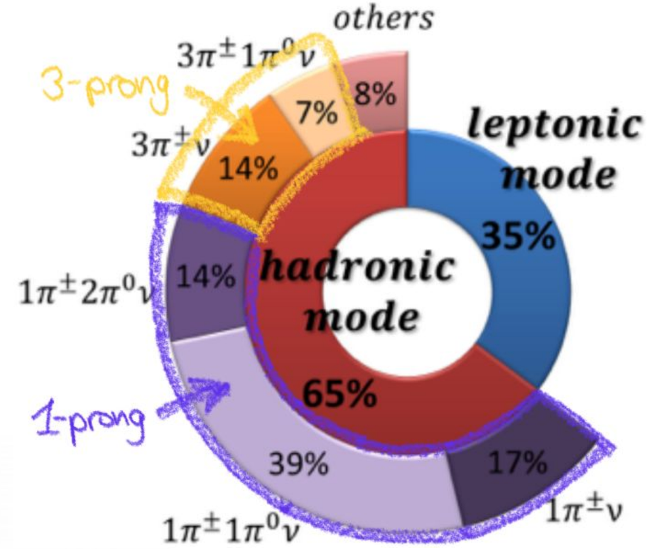
$$E_{\mathrm{T}}^{\mathrm{miss}} = \sum_{\mathrm{visible}} \vec{p}_{\mathrm{T}}$$

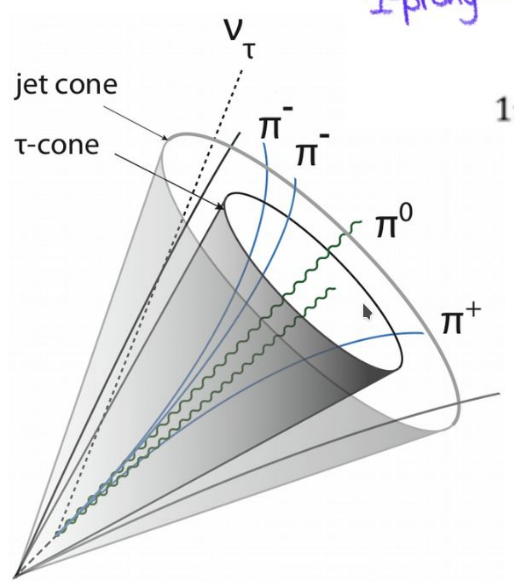




Detecting Leptons: Hadronic Taus

- Reconstruct **visible hadronic** tau decay products
  - Decay **$\tau^{\pm} \rightarrow \pi^{\pm}\nu$ or $3\pi^{\pm}\nu$ + π^0s** has 1 or 3 associated **tracks** within a cone (**1-prong / 3-prong**) + **calorimeter** activity
  - Improve by
    - Exploiting substructure: $\pi^{\pm}$ have tracks, π^0 don't
    - Jet rejection via tracking and calorimeter information, ex. displaced vertex
    - Electron rejection via activity in ECAL vs. HCAL



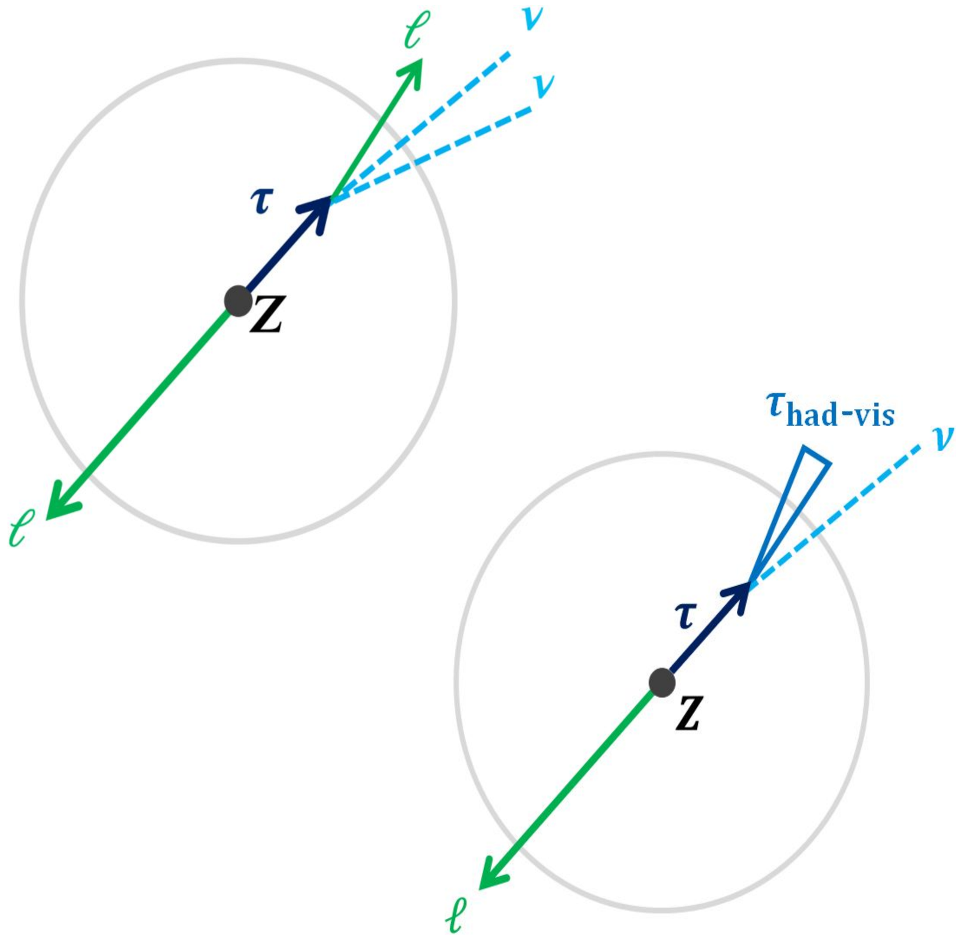


Example: Z→eτ and Z→μτ with ATLAS

Z→ℓτ with ATLAS

- ATLAS search for $Z \to \ell^{\pm}\tau^{\mp}$ (ℓ = e or μ) with full Run 2 dataset (8 billion Z)

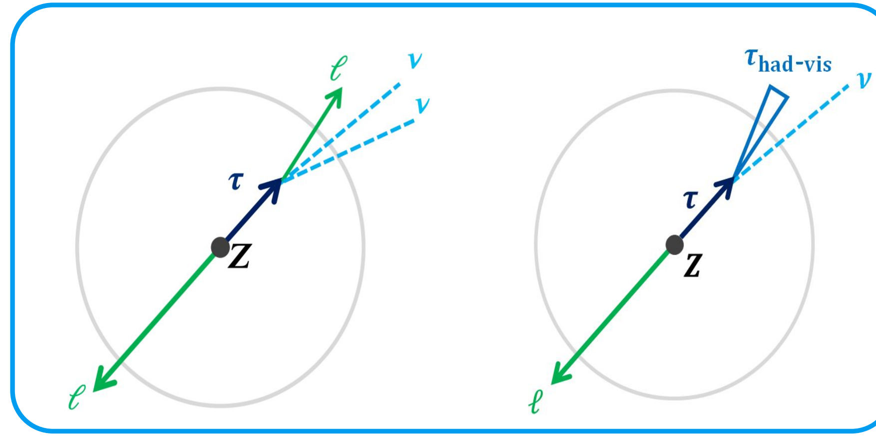
- **Signal Z→ℓτ**
  - **Opposite sign** $\ell^{\pm}\tau^{\mp}$ pair
  - **Back-to-back** in Z rest frame
  - τ_{lep} and $\tau_{had\text{-}vis}$ channel
  - **ν collinear** with $\tau_{had\text{-}vis}$ / ℓ from τ decay

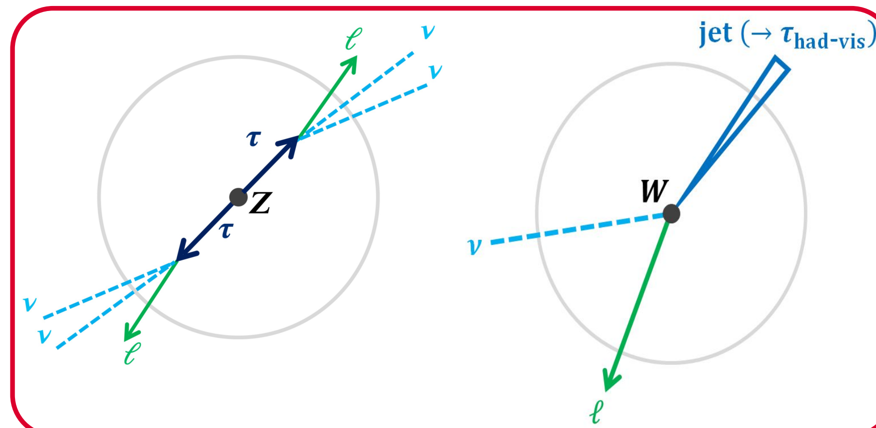


Z→ℓτ with ATLAS

- ATLAS search for $Z \to \ell^{\pm}\tau^{\mp}$ (ℓ = e or μ) with full Run 2 dataset (8 billion Z)

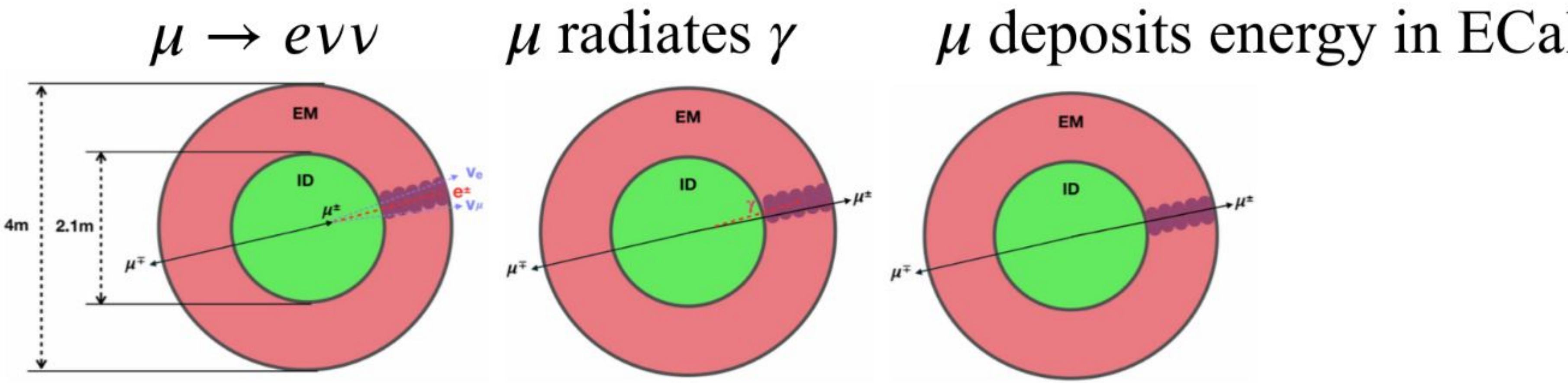
- Signal Z→ℓτ
- **Background**
  - Same final state
    - Z→ττ, Z→ℓℓ
    - Decays of ttbar, two gauge bosons, …
    - Estimate from simulation
  - Misidentification
    - μ→e in Z→ℓℓ
    - jet→ℓ / $\tau_{\text{had-vis}}$, ex. W(→ℓν)+jet
    - Data-driven estimate





Misidentification

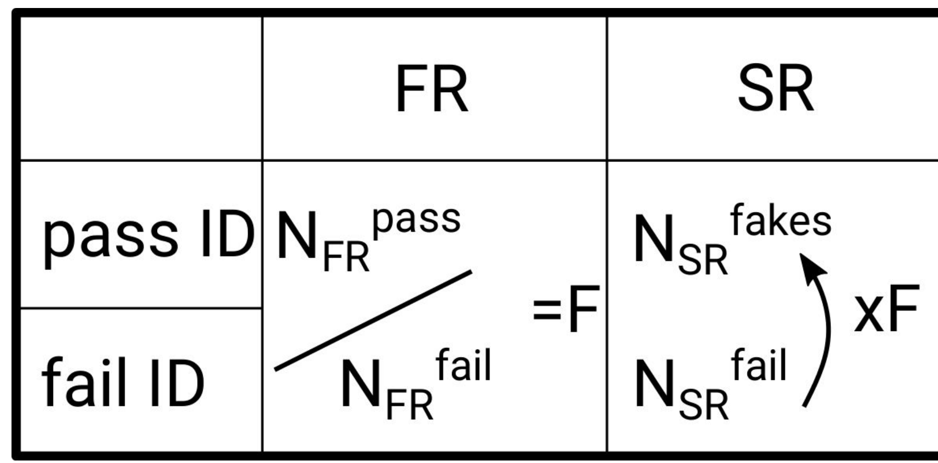
Z→ℓτ with ATLAS



- Misidentification: **μ→e** (leptonic τ decays)
  - A **Z→μμ** event can look like signal if a μ gets mistaken for an electron
  - Reasons: muon decay to electron, enhanced activity in ECAL
  - Expect mismatch of p_T measured in tracking and in ECAL

Z→ℓτ with ATLAS

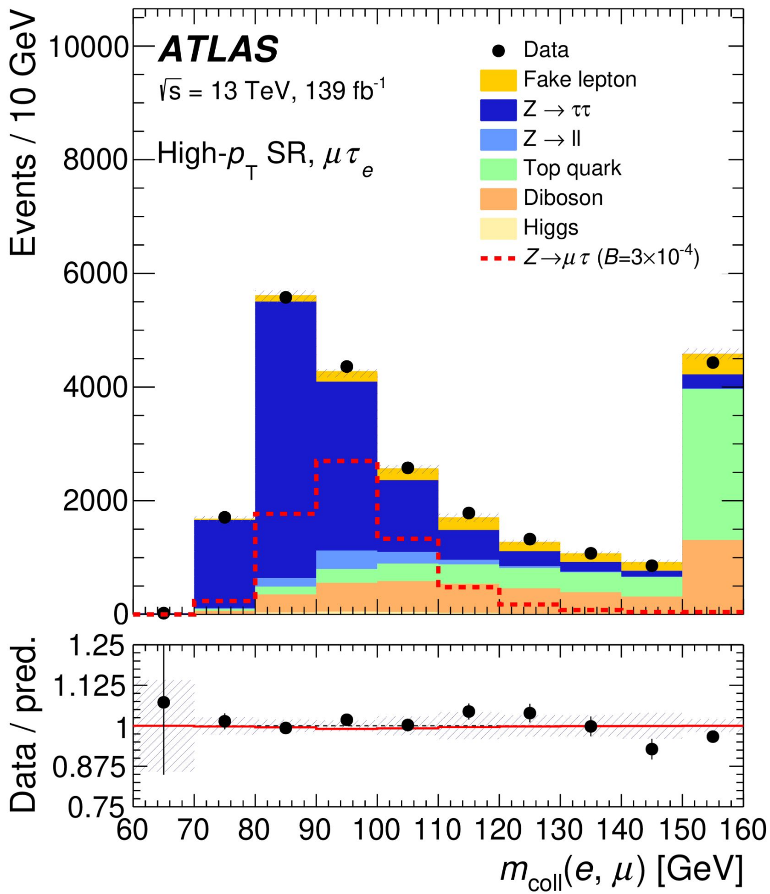
- Mis-identification background difficult to simulate
- Fakes from **jet→ℓ / τ$_{\textbf{had-vis}}$** mis-identification estimated with data-driven **Fake Factor** method
  - Count events **passing/failing quality criteria** in fake enriched (FR) region
  - Ratio is fake factor F
  - Count events failing quality criteria in signal region (SR)
  - Multiply by fake factor ⇒ Estimate of fakes in SR



Observables

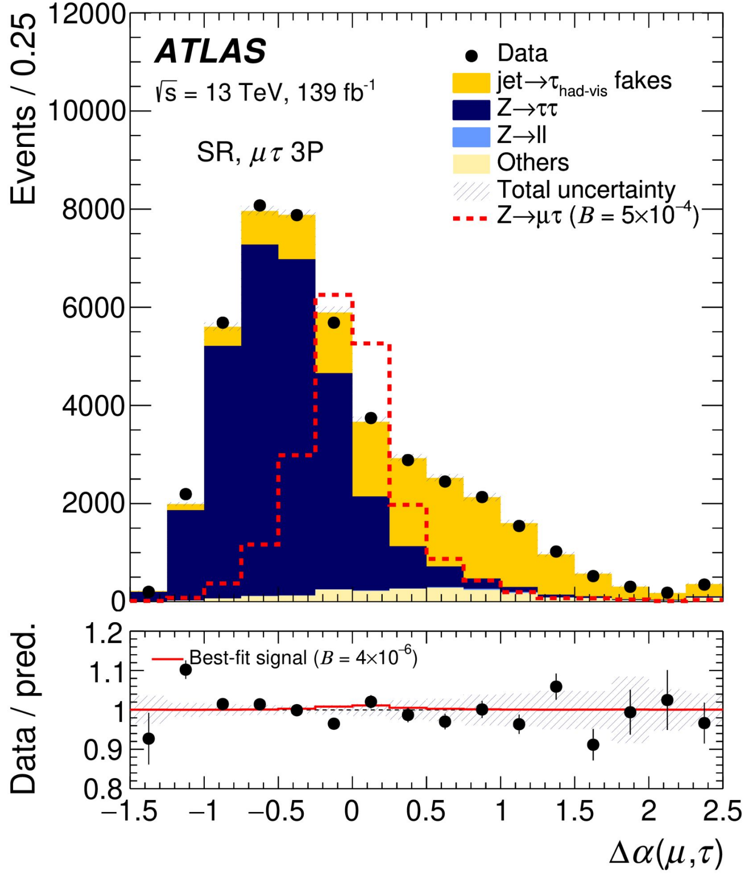
Z→ℓτ with ATLAS

- Closest **proxy to invariant mass** of ℓ-τ_{vis}-ν system is **collinear mass**
  - Invariant mass of ℓ-τ_{vis}-E_T^{miss} system
  - Assume E_T^{miss} has z-component such that $\eta(E_T^{miss}) = \eta(\tau_{vis})$



Z→ℓτ with ATLAS

›



› Kinematic discriminant **Δα**

- τ_{vis} **collinear** with τ:
  $p(\tau) = \alpha\, p(\tau_{vis})$
- Invariant mass Z→ℓτ
  $m_Z^2 - m_\tau^2 = 2p(\ell)p(\tau) = 2\alpha p(\ell)p(\tau_{vis})$
- ℓ and τ back-to-back in Z→ℓτ:
  $p_T(\ell) = p_T(\tau) = \alpha\, p_T(\tau_{vis})$
- Δα as difference
  - Close to zero for signal
  - But not for background

Z→ℓτ with ATLAS

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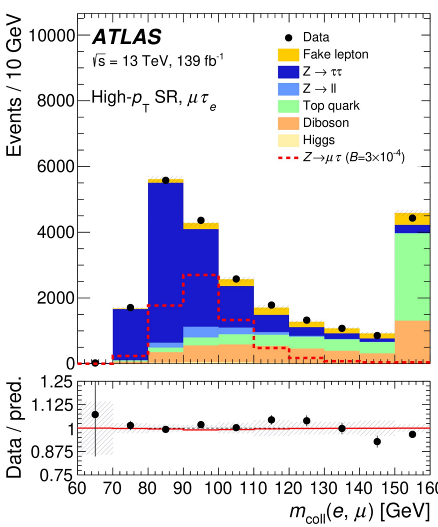

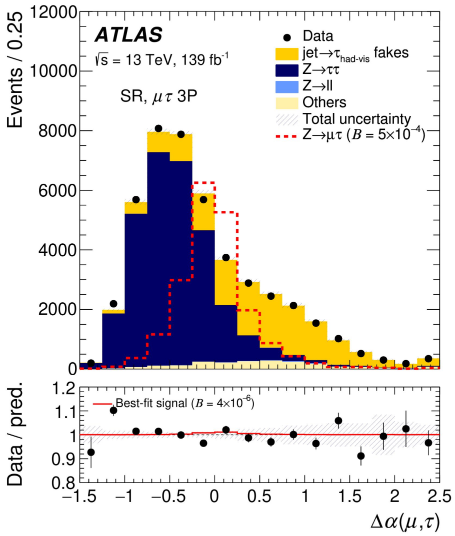

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  - Δα as difference
    - Close to zero for signal
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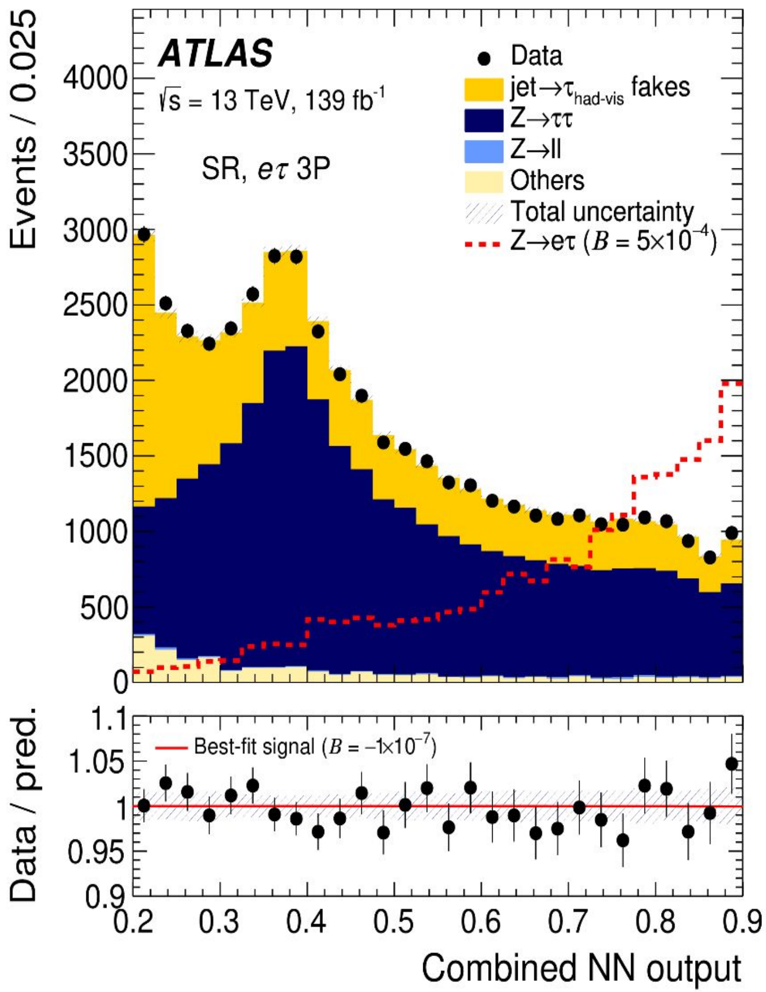
Z→ℓτ with ATLAS

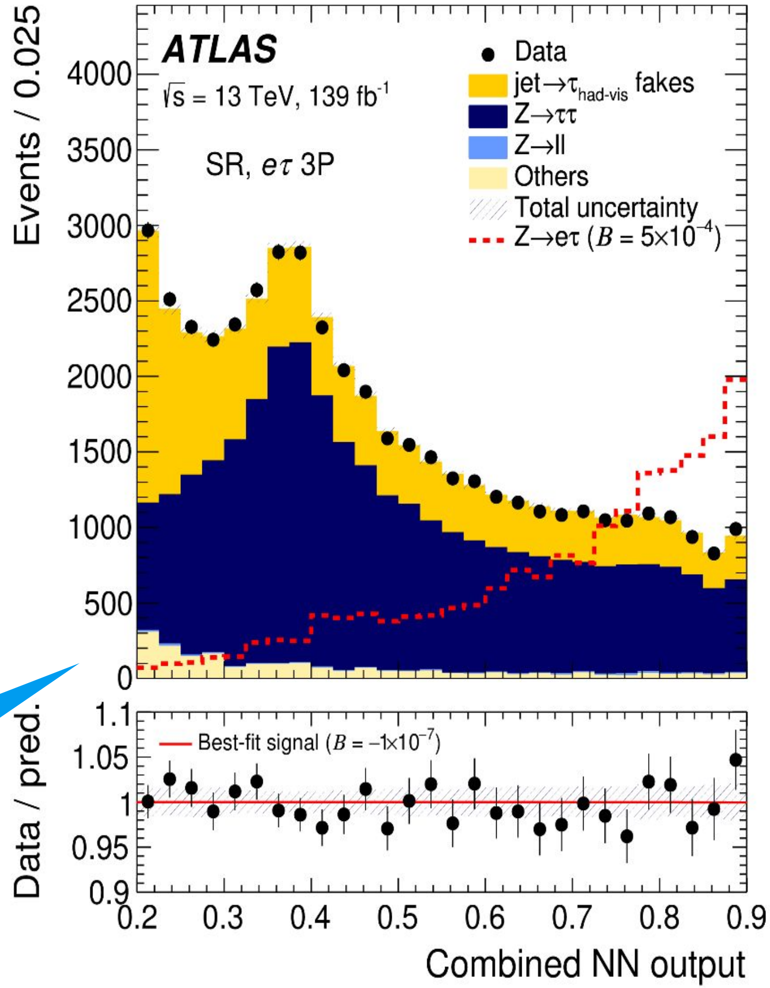
- Exploit all correlations of the ℓ - τ_{vis}- E_T^{miss} system
- **Binary neural net** (NN) classifier to discriminate against dominant backgrounds



Z→ℓτ with ATLAS

› Binned maximum likelihood fit to data of NN distribution in signal and control regions

› Extract signal branching fraction ℬ (Z→ℓτ) and background normalization



No statistically significant **deviation** observed →upper limits on ℬ (Z→ℓτ)

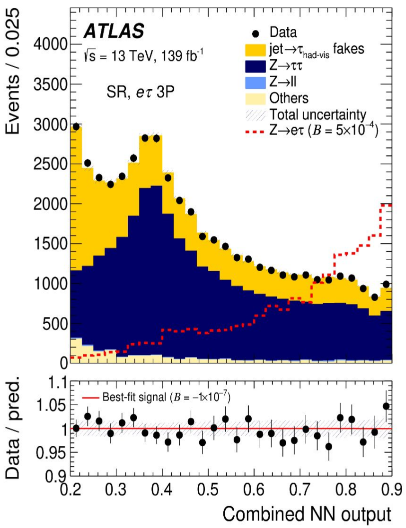
Z→ℓτ with ATLAS

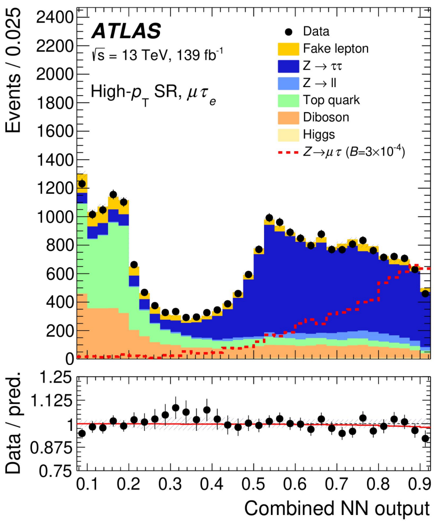
Nature Physics 17, 819–825 (2021)
Phys.Rev.Lett. 127, 271801 (2021)

Observed (expected) **upper limit on ℬ(Z→ℓτ) [×10⁻⁶] at 95% confidence level (CL)**		
Final state	**eτ**	**μτ**
Data set	Run 2	Run 1 ($\tau_{had\text{-}vis}$) + Run 2
Combined τ_{lep} and $\tau_{had\text{-}vis}$	**5.0** (6.0)	**6.5** (5.3)
OPAL & DELPHI at LEP	9.8	12

World-leading upper limit on ℬ(Z→ℓτ)

- Superseding LEP limits
  by a factor of ~2 for 1st time @ LHC
- Statistically limited





Summary

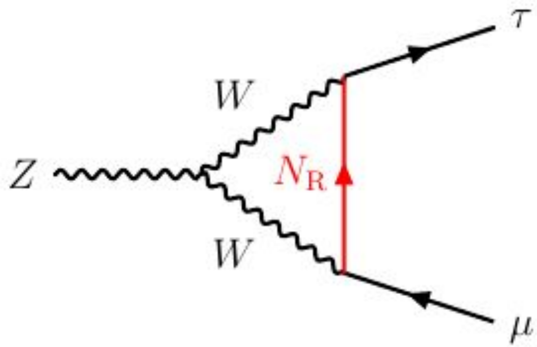
Summary

› Indirect searches for BSM
  ▪ Testing flavour symmetries in the lepton sector, ex. LFV

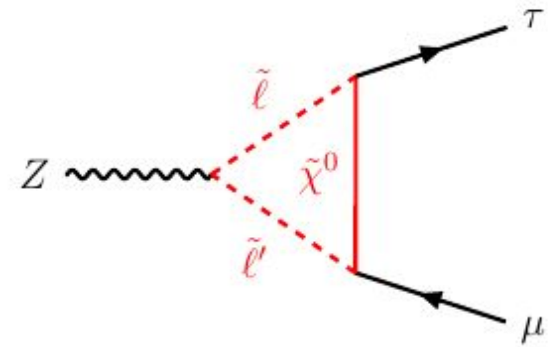
› Leptons at colliders
  ▪ Detection and reconstruction
  ▪ Several challenges
    - Bremsstrahlung
    - Neutrinos in the final state
    - Misidentification
    - …

Backup

cLFV Z→ℓτ Decays



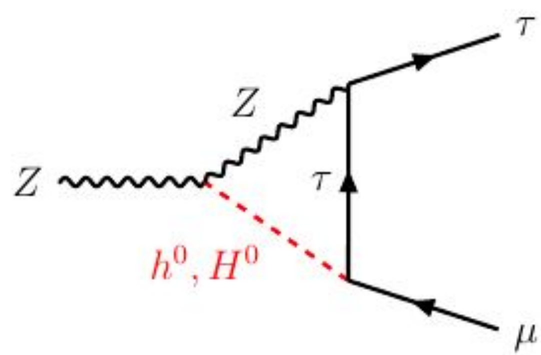
(a) Heavy right-handed neutrinos



(b) SUSY (slepton flavour mixing)

Examples for BSM in Z→ℓτ

- Heavy neutrinos
- Supersymmetry
- Extended Higgs sector



(c) Type-III 2HDM

Contact Details

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faculty of science and engineering

$Z \to \ell\tau$ with ATLAS

- ATLAS search for $Z \to \ell^{\pm}\tau^{\mp}$ (ℓ = e or μ) with full Run 2 dataset

- Signal and most backgrounds modelled with **MC simulation**
- **jet→ℓ / $\tau_{\text{had-vis}}$** misidentification estimated **Fake Factor** method

	FR		SR	
pass ID	N_{FR}^{pass}	=F	N_{SR}^{fakes}	xF
fail ID	N_{FR}^{fail}		N_{SR}^{fail}