Search for Higgs Boson Decays into Collimated Tau Lepton Pairs

ATLAS EXPERIMENT
est. 2022
13.6 TeV

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General Exam
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Introduction

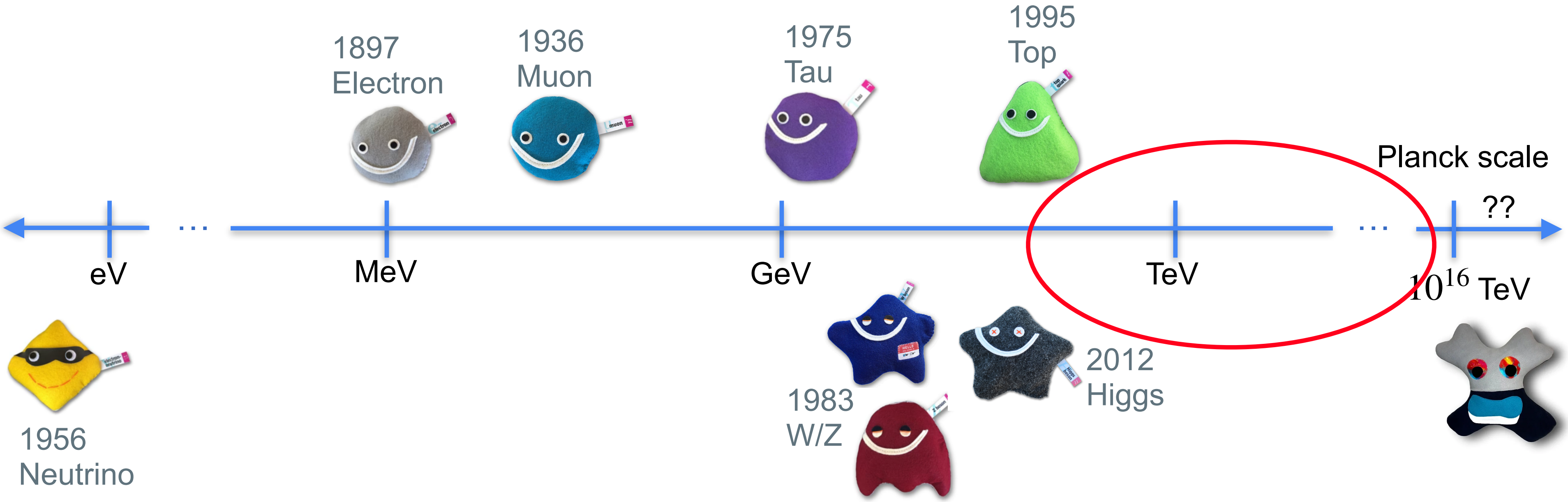
Major projects:

- **FASER experiment**: Contributed to the software alignment of the tracking detectors and neutrino studies with emulsion detector
- **ATLAS experiment**: Reconstruction and identification of $H \rightarrow \tau\tau$ and its measurement **(focus of this talk)**

Outline:

1. **Why** are we doing it?
    i. The Standard Model
    ii. Motivation for new physics
    iii. Role of experiment
2. **How** are we doing it?
    i. ATLAS detector
    ii. Reconstruction and identification of collimated tau pairs
    iii. Higgs to $\tau\tau$ analysis

Particle Mass Range



1897
Electron

1936
Muon

1975
Tau

1995
Top

Planck scale

??

eV

…

MeV

GeV

TeV

…

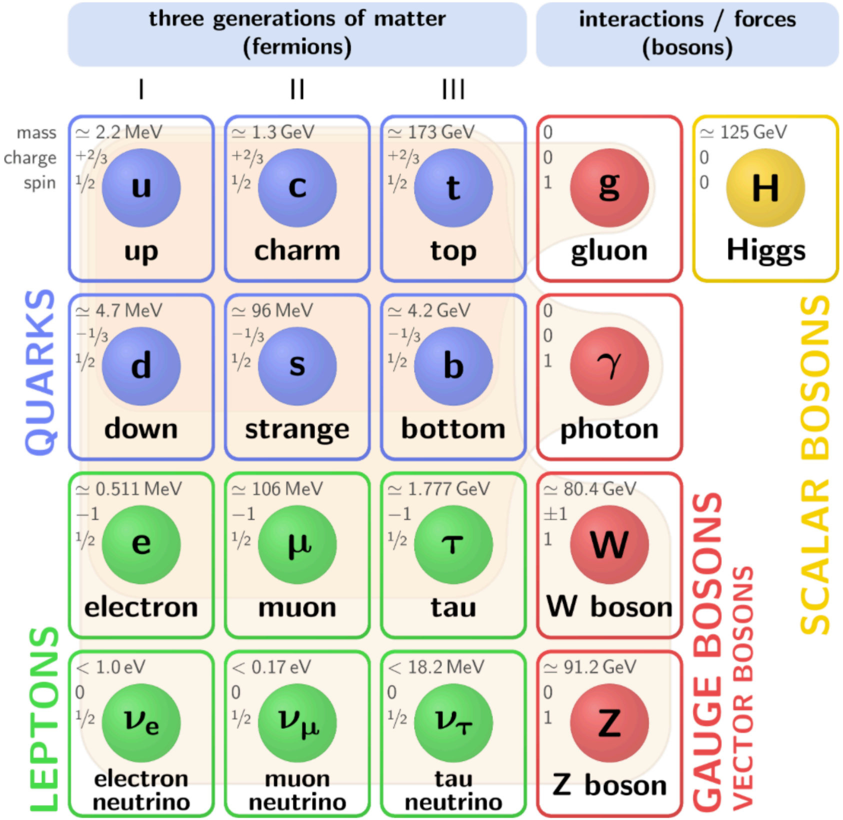
10^{16} TeV

1956
Neutrino

1983
W/Z

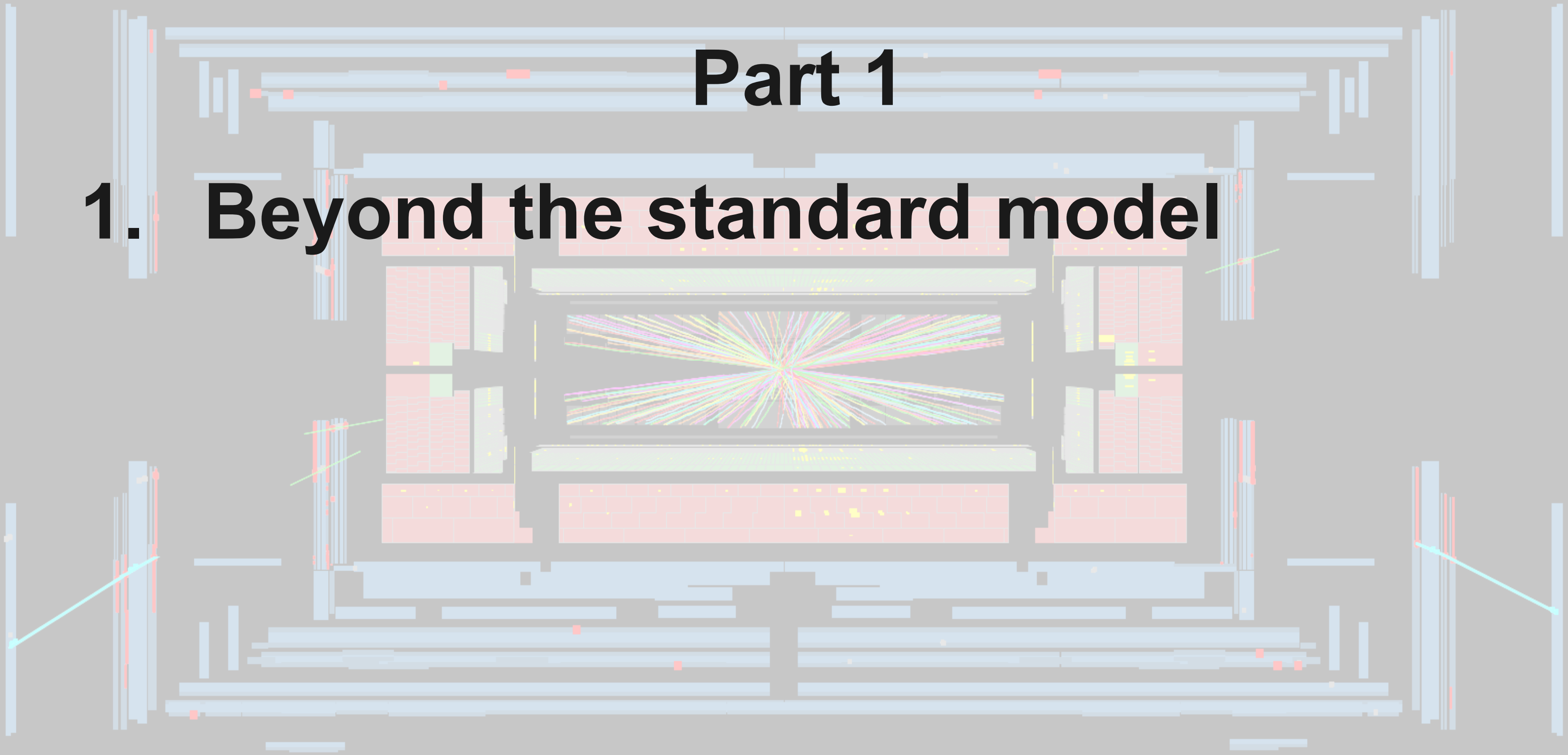
2012
Higgs

The Standard Model



The standard model describes the fundamental particle interaction via the electroweak and strong forces

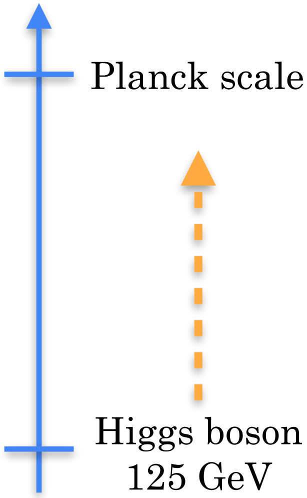
- 6 quarks and 6 leptons (matter particles)
- 4 vector bosons (force mediators)
- 1 scalar boson (mass generator)



Part 1

1. Beyond the standard model

Hierarchy Problems



Planck scale

Higgs boson
125 GeV

Yukawa couplings

$$\lambda_{electron} = 2.9 \times 10^{-6}$$

$$\lambda_{muon} = 6.1 \times 10^{-4}$$

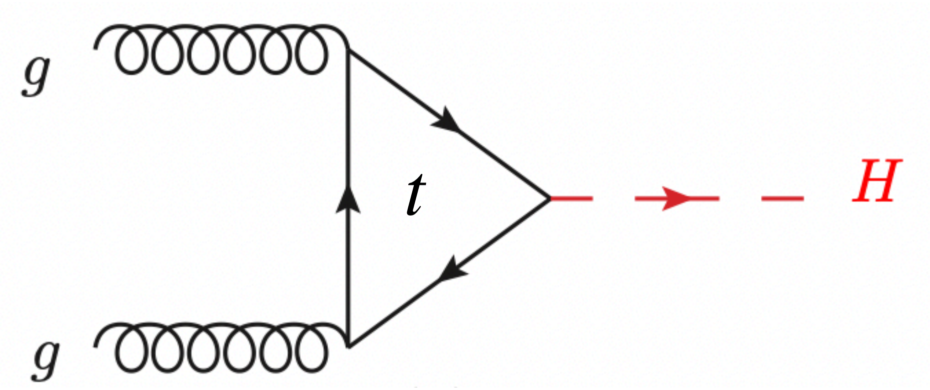
$$M_f = \lambda_f \frac{246GeV}{\sqrt{2}}$$

$$\lambda_{tau} = 1 \times 10^{-2}$$

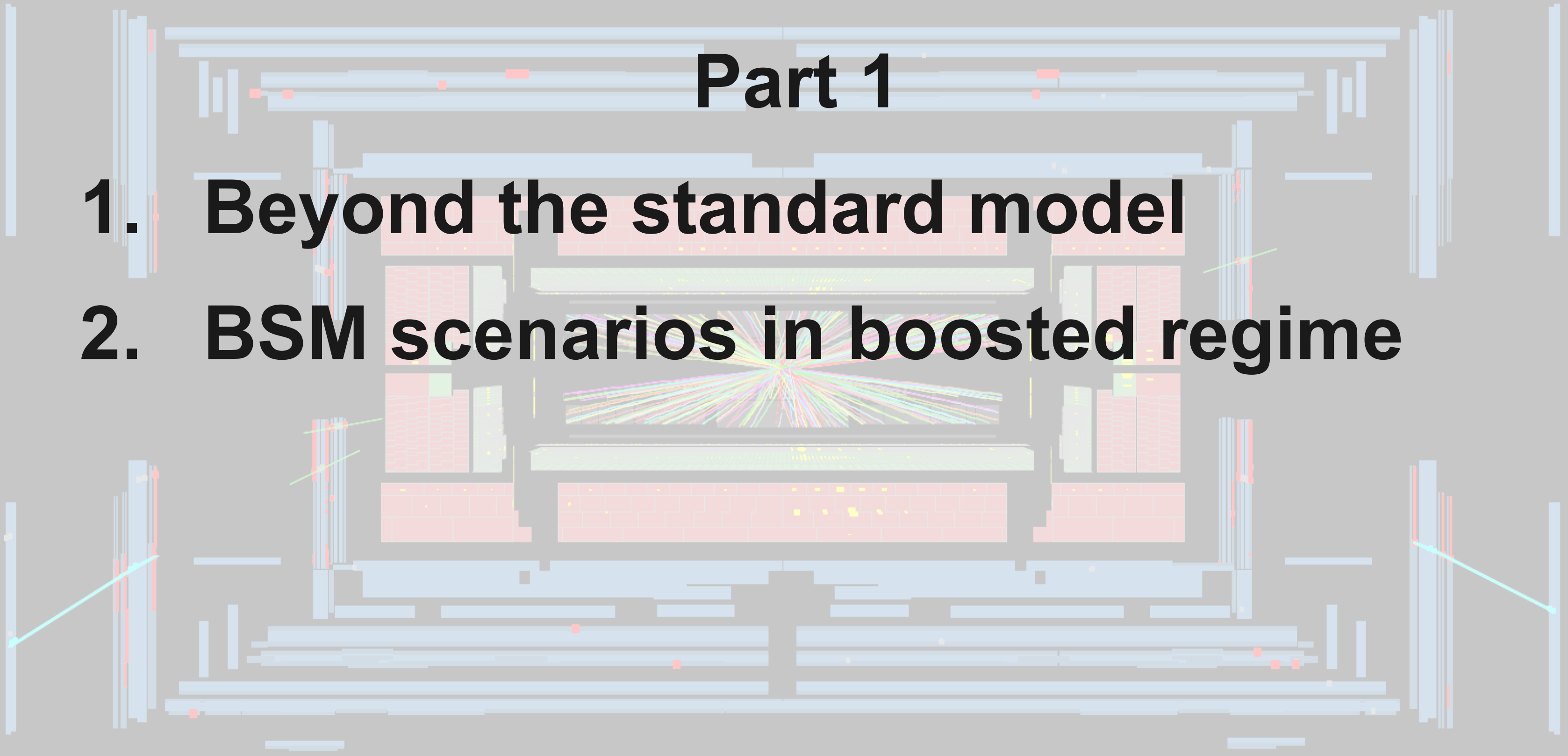
$$\lambda_{top} = 1$$

- Many Empirical and theoretical motivations exist for physics Beyond the Standard Model (BSM)
- Higgs hierarchy: SM doesn’t stop the Higgs mass from reaching the Planck scale
- Yukawa coupling hierarchy: Higgs-fermion interaction strengths span a wide range

Higgs Production at the LHC



- 88% of Higgs production at the LHC is through gluon fusion mediated by a top quark
- Any modifications to the top Yukawa coupling or gluon fusion process will modify the Higgs production
- New physics that explains hierarchy problems can be probed in this process



Part 1

1. Beyond the standard model
2. BSM scenarios in boosted regime

EFT Interpretation

We consider extensions of the SM with dimension-6 operators

$$\mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

Extract most important terms relevant to gluon fusion process

$$\mathcal{L}_{\text{eff}} = -\boxed{\kappa_t} \frac{m_t}{v} \bar{t} t h + \boxed{\kappa_g} \frac{\alpha_s}{12\pi} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu\, a} + \mathcal{L}_{\text{QCD}}$$

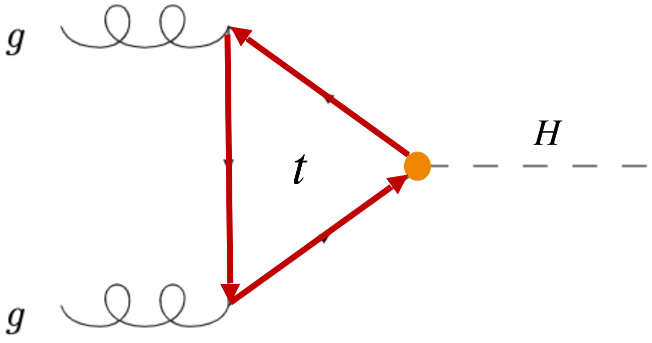
κ_t modifies the top Yukawa coupling

κ_g modifies the gluon-Higgs interaction

arXiv:1405.4295, arXiv:1312.3317

In the SM $\kappa_t = 1$ and $\kappa_g = 0$. New physics will change these values

Cross Section



Low Momentum

$$\frac{\sigma(\kappa_t,\kappa_g)}{\sigma^{\mathrm{SM}}} \simeq \left(\underline{\kappa_t} + \underline{\kappa_g}\right)^2$$

↓

High Momentum (boosted)

$$\frac{\sigma(p_T^{\mathrm{cut}})}{\sigma^{SM}(p_T^{\mathrm{cut}})} = \left(\underline{\kappa_t} + \underline{\kappa_g}\right)^2 + \underline{\delta(p_T^{\mathrm{cut}})}\,\underline{\kappa_t}\,\underline{\kappa_g} + \underline{\epsilon(p_T^{\mathrm{cut}})}\,\underline{\kappa_g^2}$$

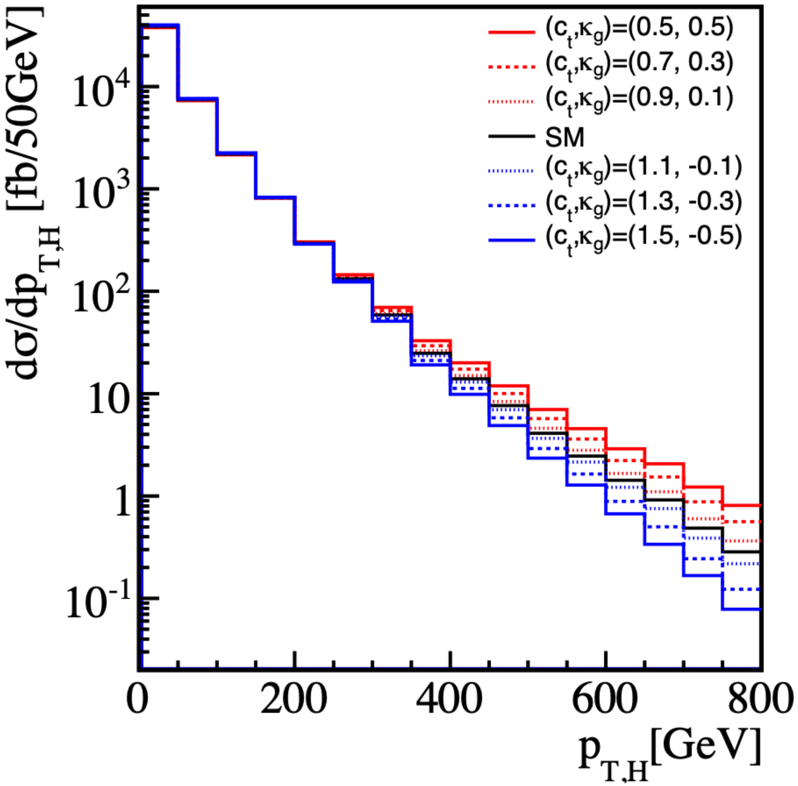
Where δ and ϵ capture different physics processes. Both are small at low p_t where the SM dominates, and grow to $\mathcal{O}(1)$ at $p_T^{cut} > 300$ GeV

Models like MCHM and SUSY can predict specific values for these factors, enhancing their detection by probing κ_g and κ_t separately

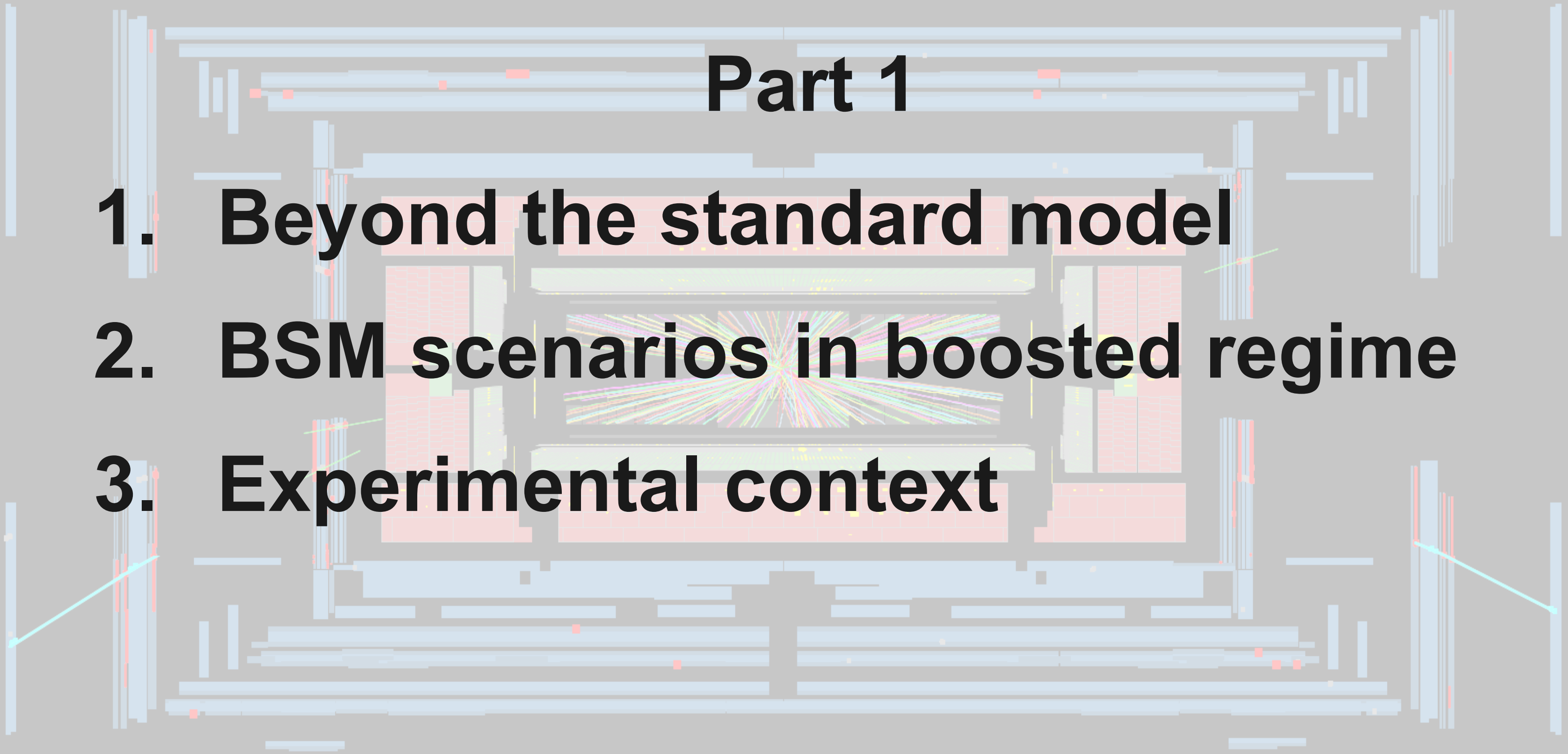
arXiv:1405.4295, arXiv:1312.3317

Model Specific Enhancements

- Here $c_t = \kappa_t = 1 - \kappa_g$
- Several hypothetical points are shown, at higher momenta the degeneracy between the distributions breaks
- There is about 20% difference from SM for $\sigma(p_{T,H} > 300GeV)$



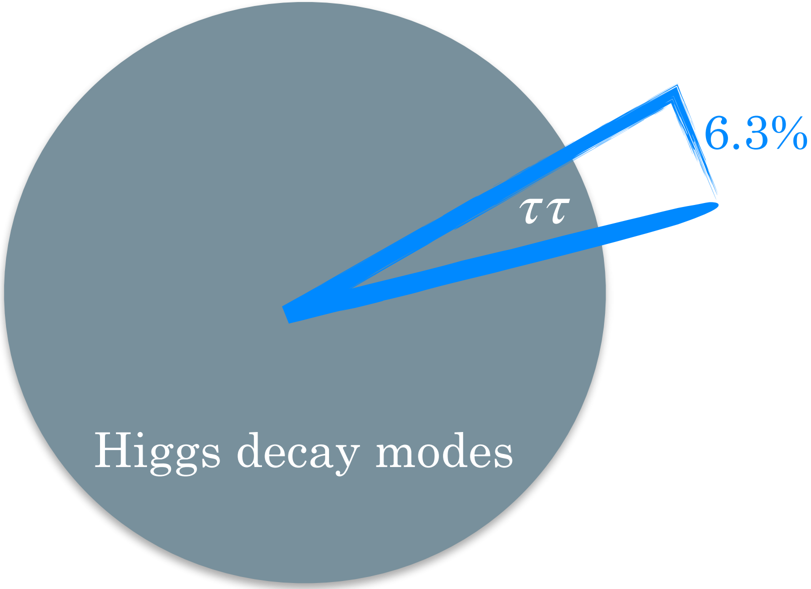
arXiv:1405.4295



Part 1

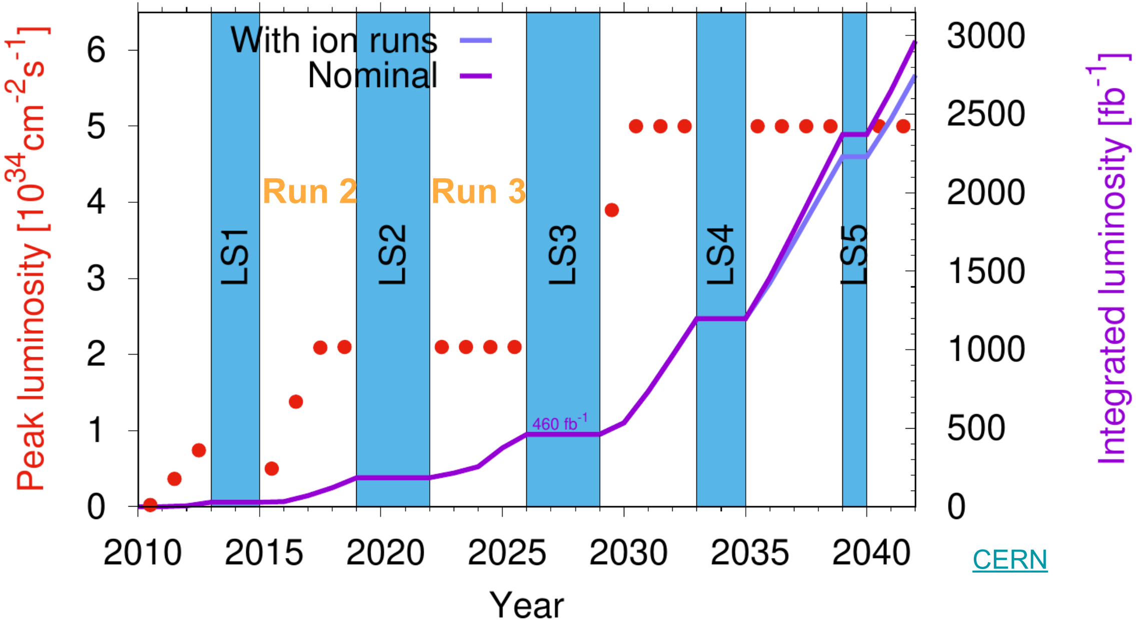
1. Beyond the standard model
2. BSM scenarios in boosted regime
3. Experimental context

Higgs Measurement



- We want to **measure the Higgs boson** production cross section as best as we can, specially in the high momentum regime
- Focusing on Higgs **decay to Taus**

Higgs Production at the LHC



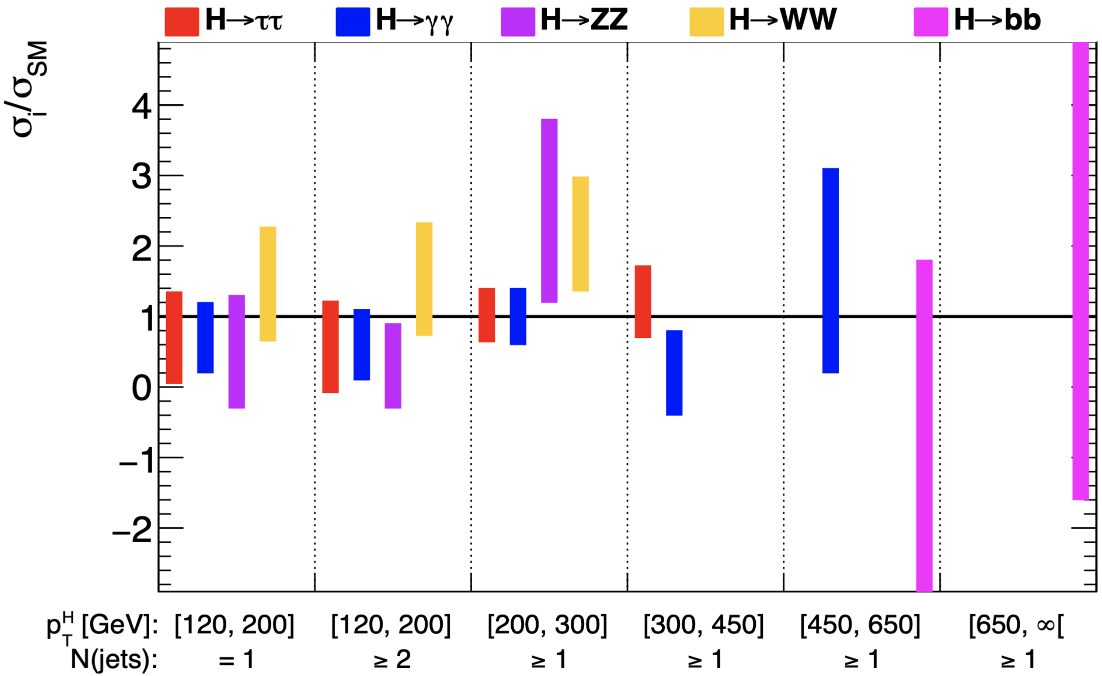
CERN

$$N = \underline{\sigma} \times \underline{L} \times \underline{BR(H \to \tau\tau)}$$

- Higgs production cross section (52 pb)
- Integrated luminosity (485 fb^{-1})
- Branching ratio (6.3%)

In Run 2 and Run 3 we expect about 1 million Higgs to $\tau\tau$ events while in HL-LHC we expect about 10 million of such events

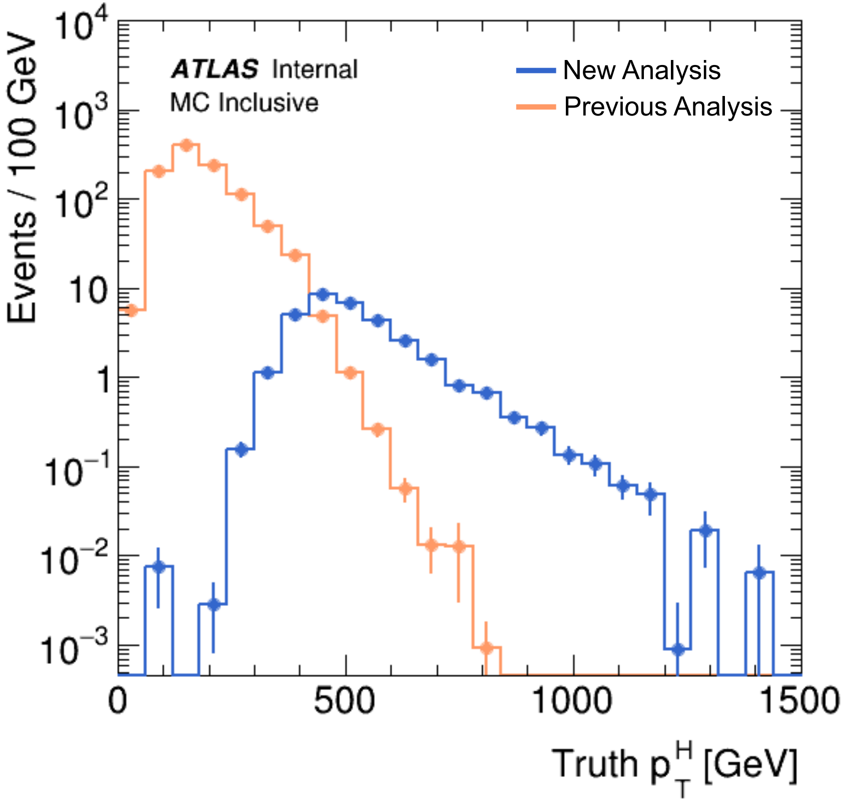
Importance of Boosted Higgs Decay to Taus



In the $p_T > 450\ GeV$ phase space the $\tau\tau$ channel is unexplored

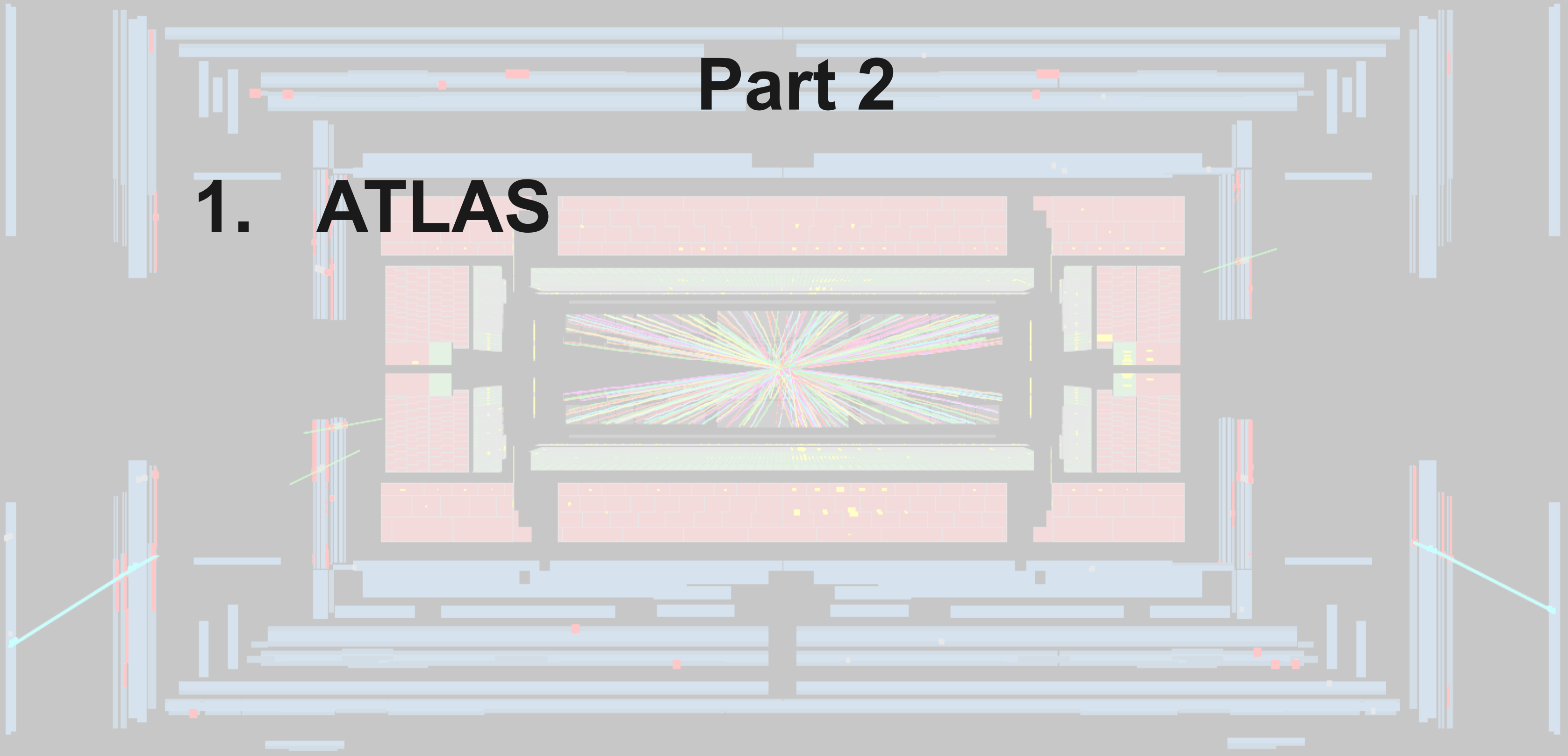
Probing a New Higgs Phase Space

- The boosted di-τ analysis will be the first in ATLAS to explore this phase-space
- Probing the higher p_T tail of the old analysis
- New analysis reconstructs seven times more events at $p_T^H > 450$ GeV



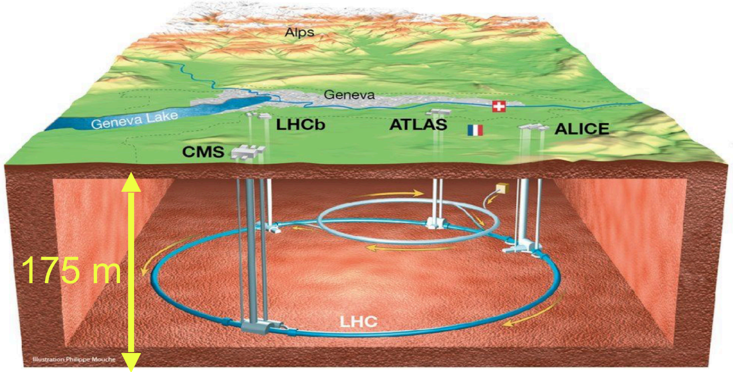
Part 2

1. ATLAS

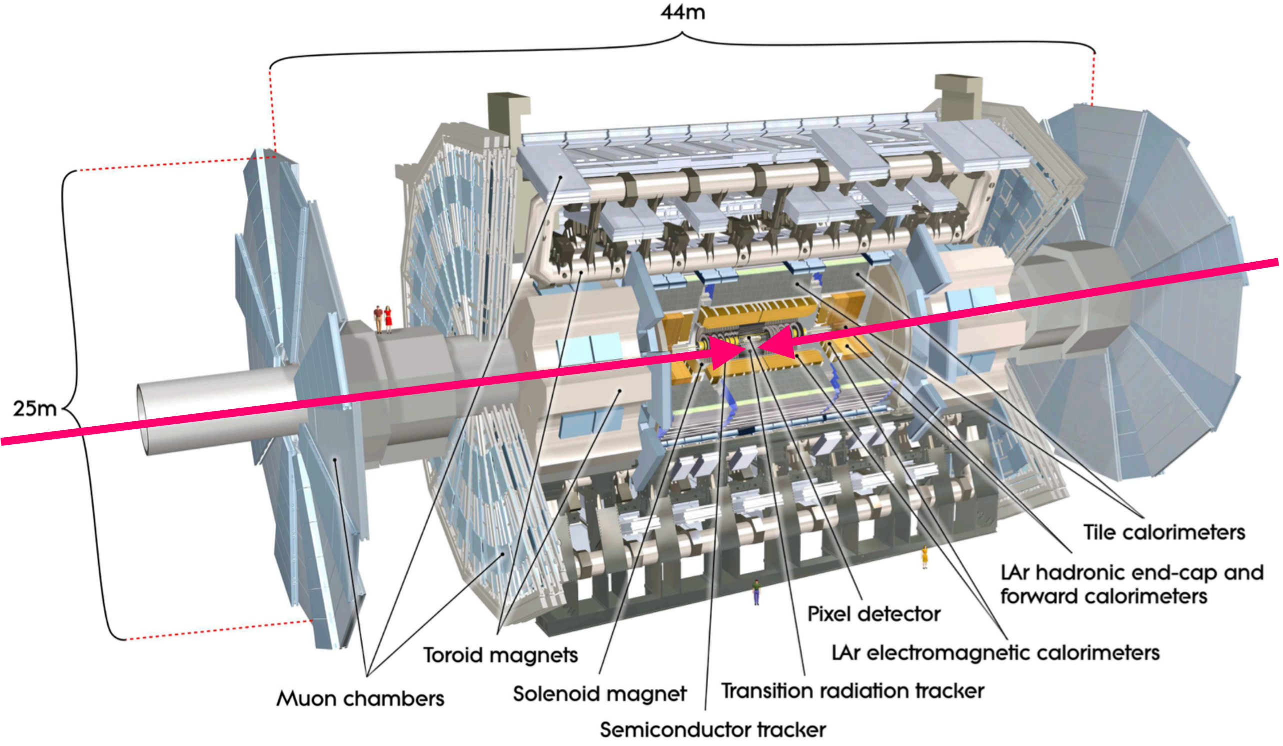


CERN


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km


Alps
Geneva
Geneva Lake
LHCb
ATLAS
ALICE
CMS
175 m
LHC
Illustration Philippe Mouche

ATLAS Detector



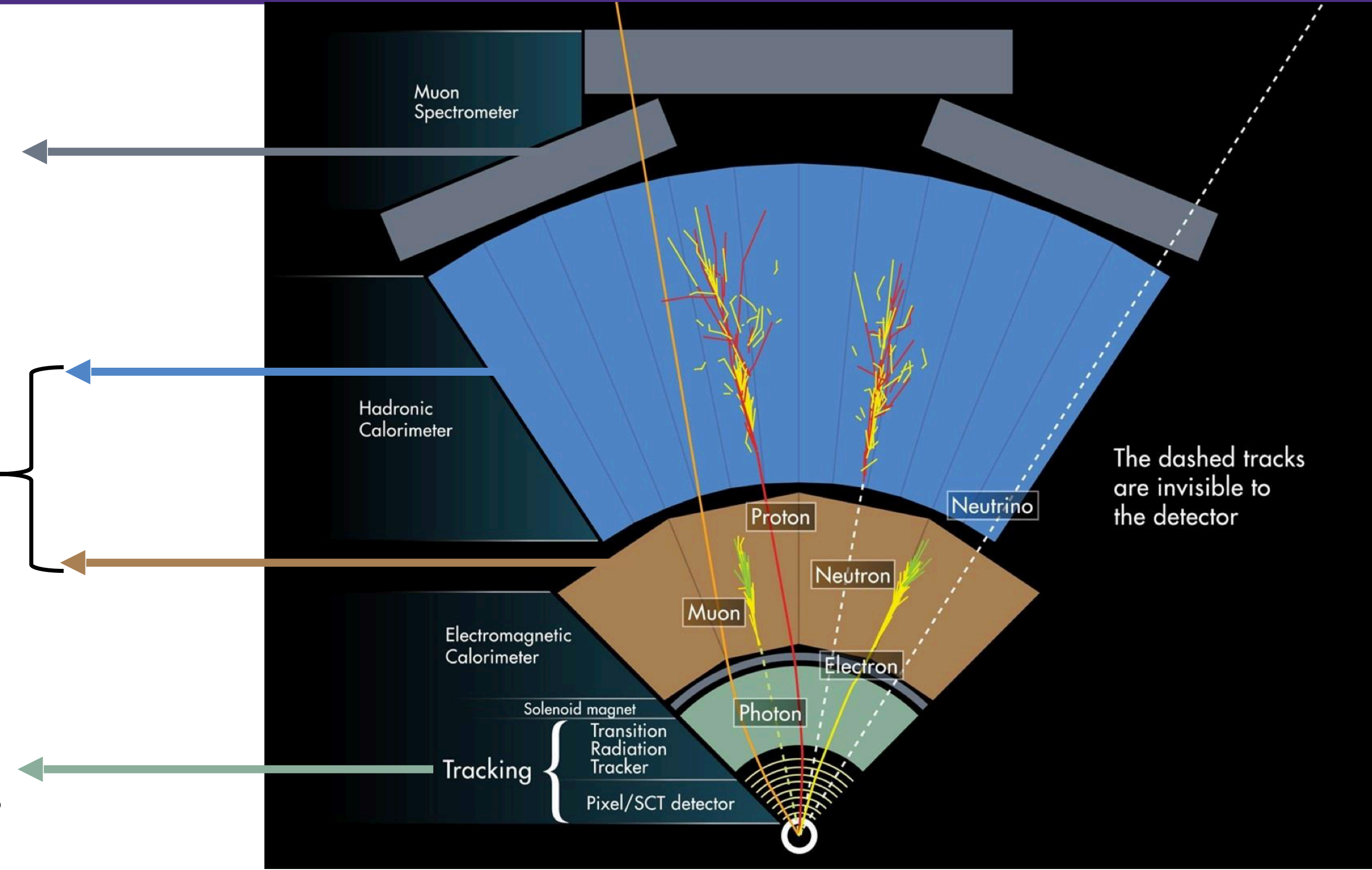
- The ATLAS experiment is one of the two general purpose detectors at the LHC constructed to probe proton-proton collisions
- designed to look for new physics and precision measurements of the Standard Model

ATLAS Sub-Detectors

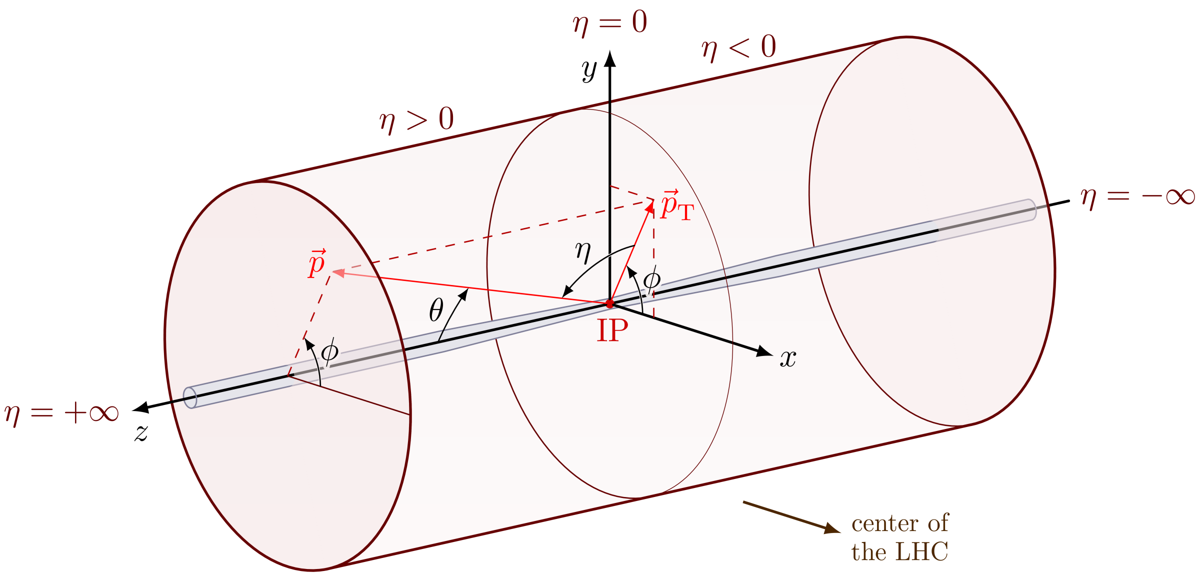
Muon spectrometer: used to measure the momentum and position of muons

Calorimeters: captures incoming particles energy

Inner detector: for tracking charged particles



ATLAS Coordinate System



- ATLAS is a cylindrical detector
- The transverse plane, which is perpendicular to the beam line, is essential as it is the plane where momentum is conserved
- Based on these the coordinate system uses η and ϕ

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

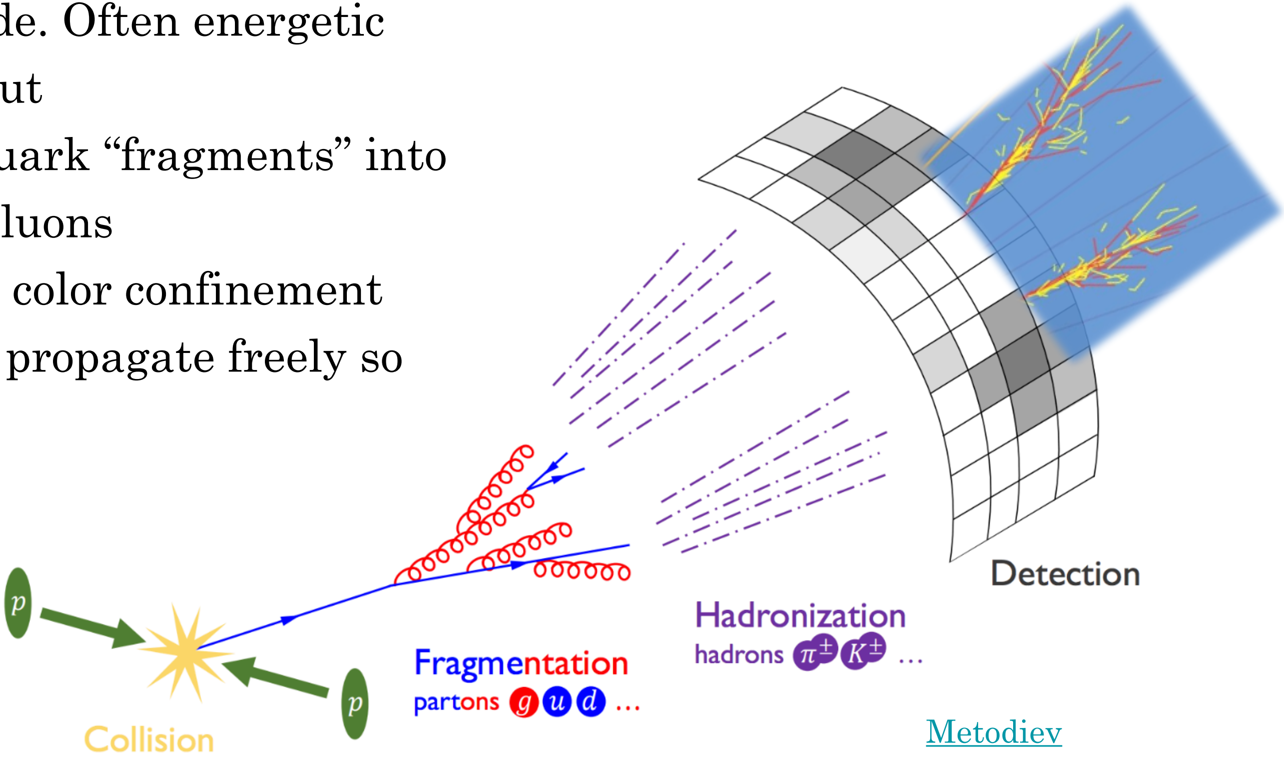
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

QCD Background

Collision: Protons collide. Often energetic quarks or gluons come out

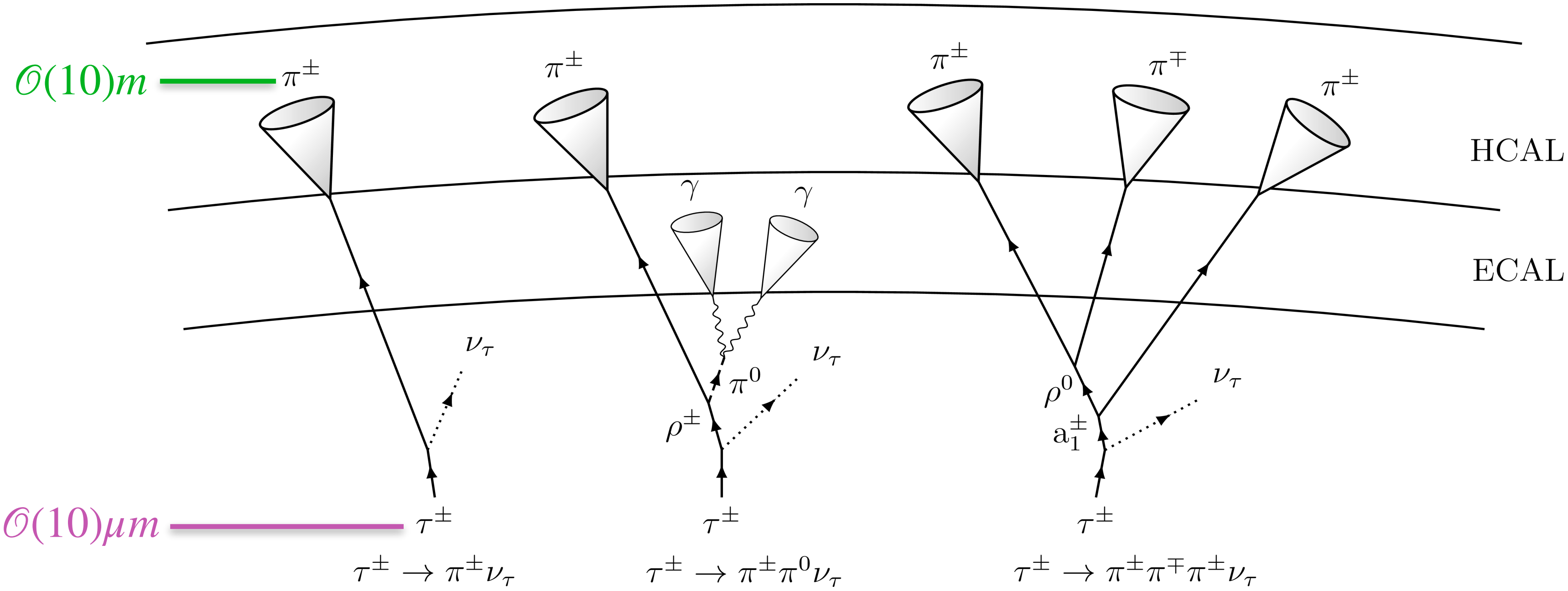
Fragmentation: The quark “fragments” into a “soup” of quarks and gluons

Hadronization: Due to color confinement quarks and gluons can’t propagate freely so they “hadronize”



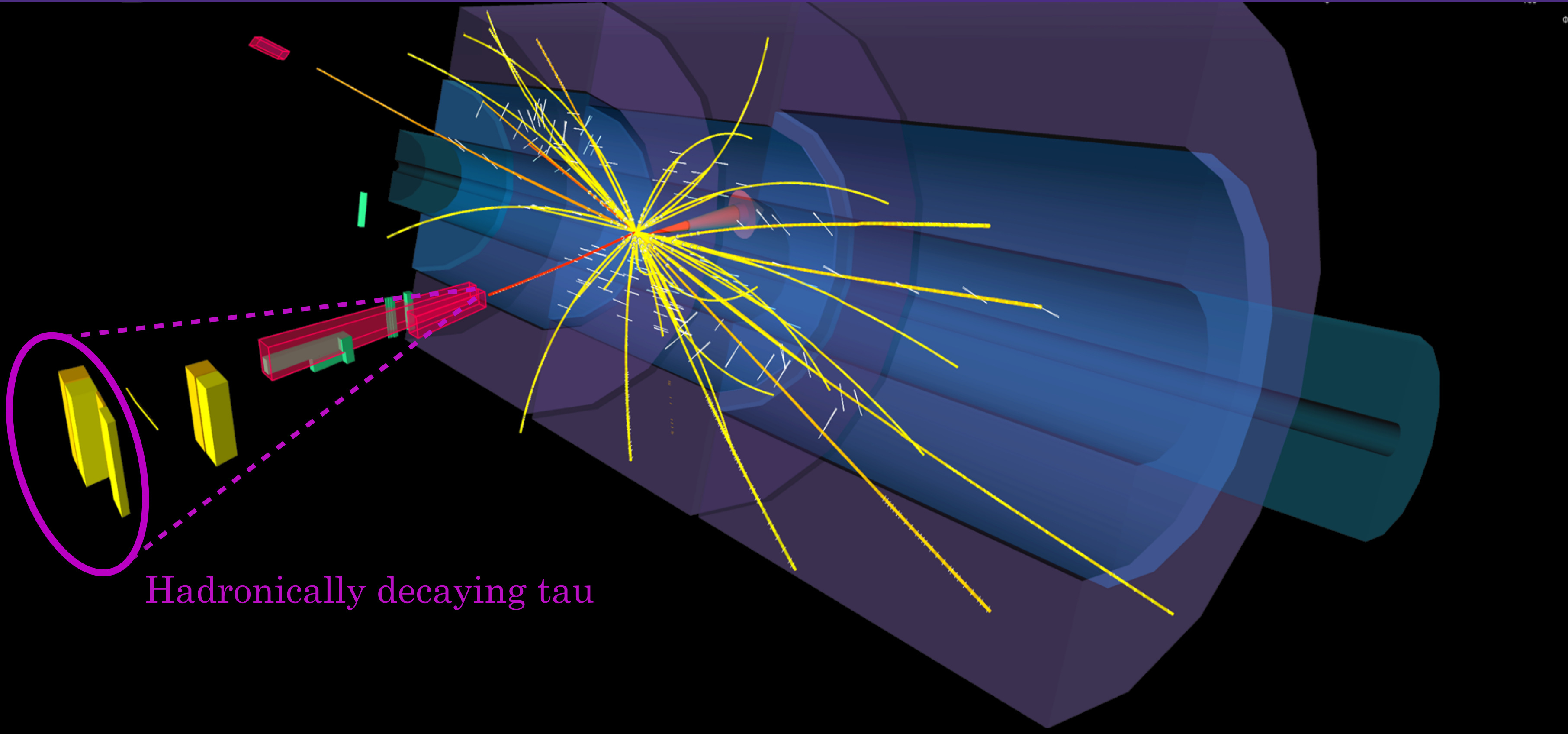
Metodiev

Taus at the LHC

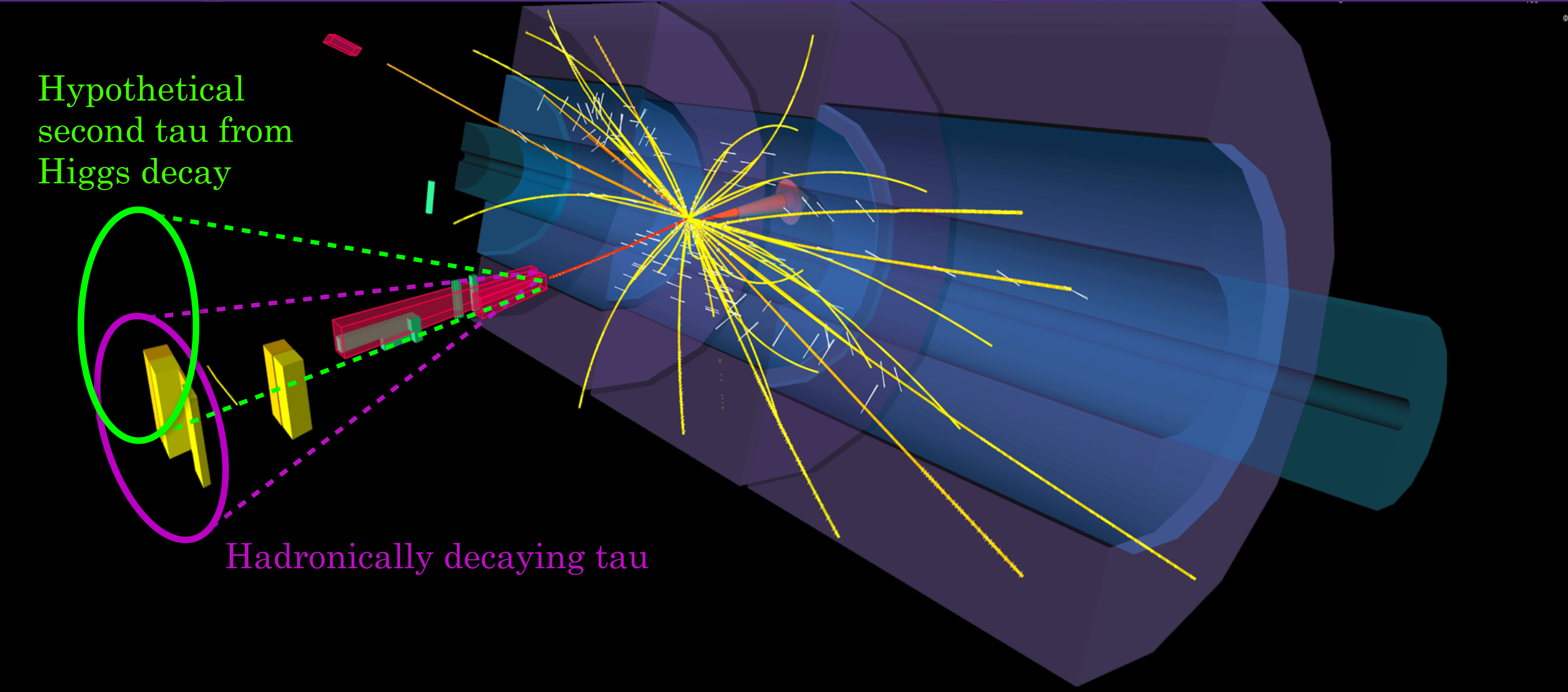


- Currently focusing on the fully hadronic final state
- Taus decay before reaching the detector

Hadronic Tau Decay

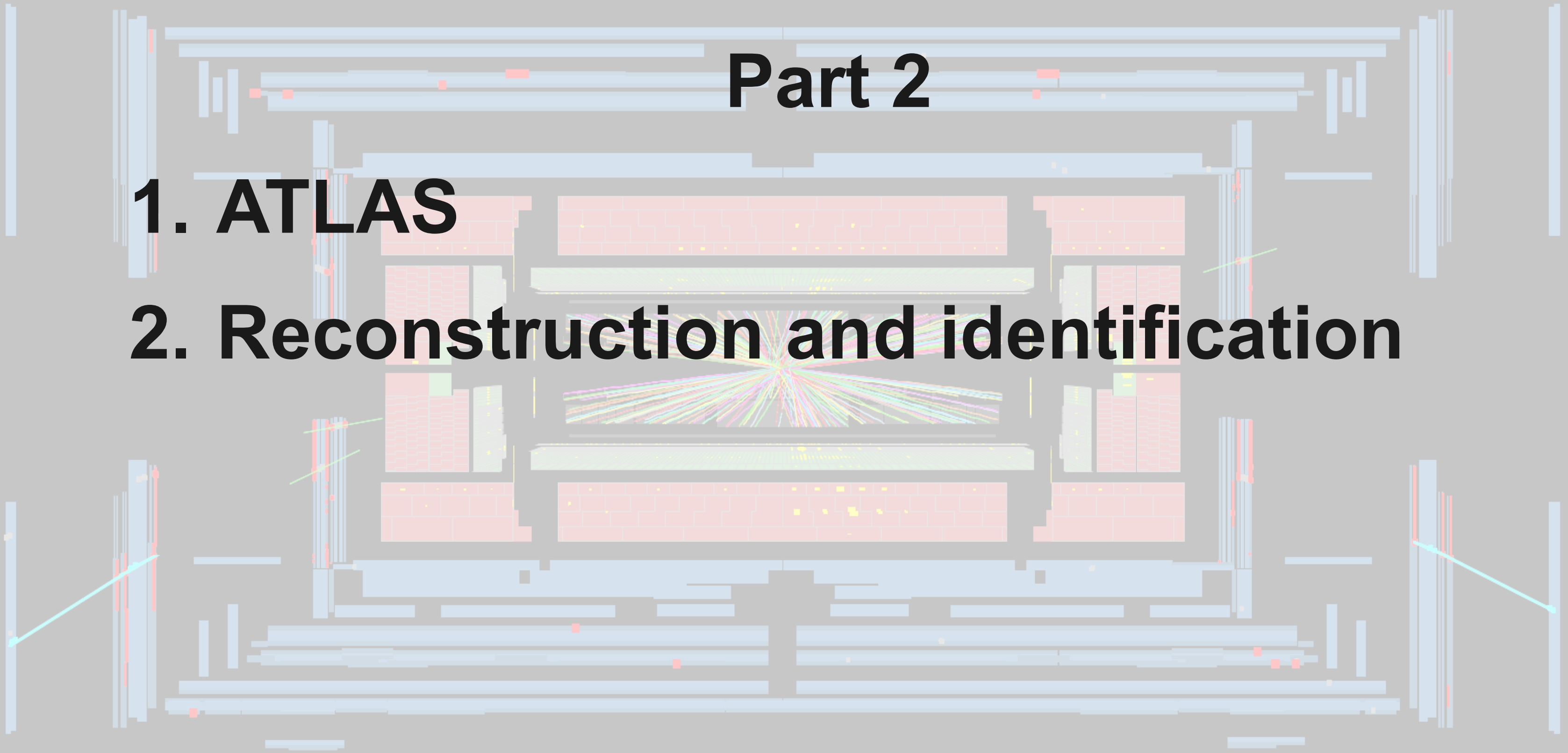


Hadronic Decays of a Pair of Collimated Taus



Hypothetical second tau from Higgs decay

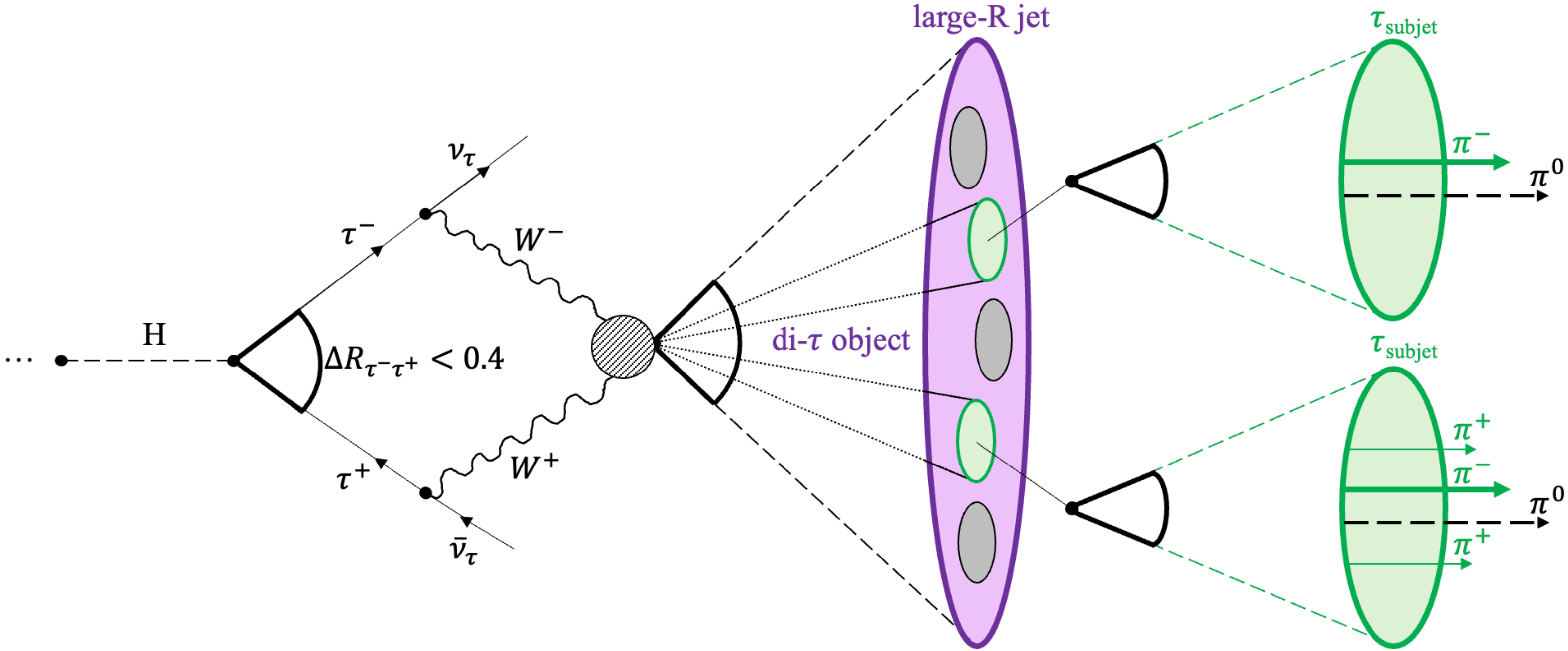
Hadronically decaying tau



Part 2

1. ATLAS
2. Reconstruction and identification

DiTau Object

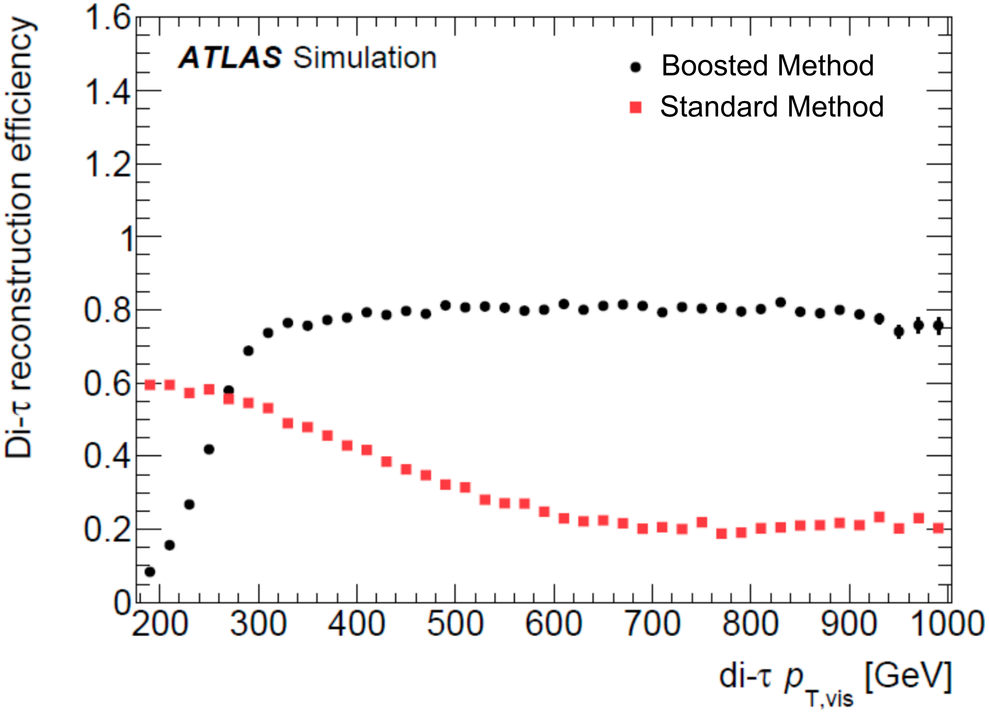


The boosted taus are reconstructed from a large-R jet (R = 1.0). The subjets are reclustered within a smaller (R = 0.2) jet

DiTau Reconstruction

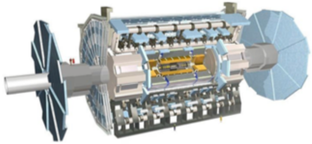
Boosted Di-τ reconstruction extends reconstruction efficiency down to $\Delta R(\tau_1, \tau_2) \approx 0.2$

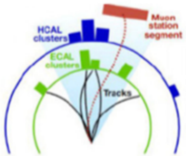
$$\Delta R_{\tau_1\tau_2} = \frac{2m^H}{p_t^H}$$

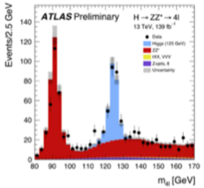


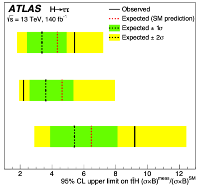
arXiv:2407.16320

Analysis Workflow





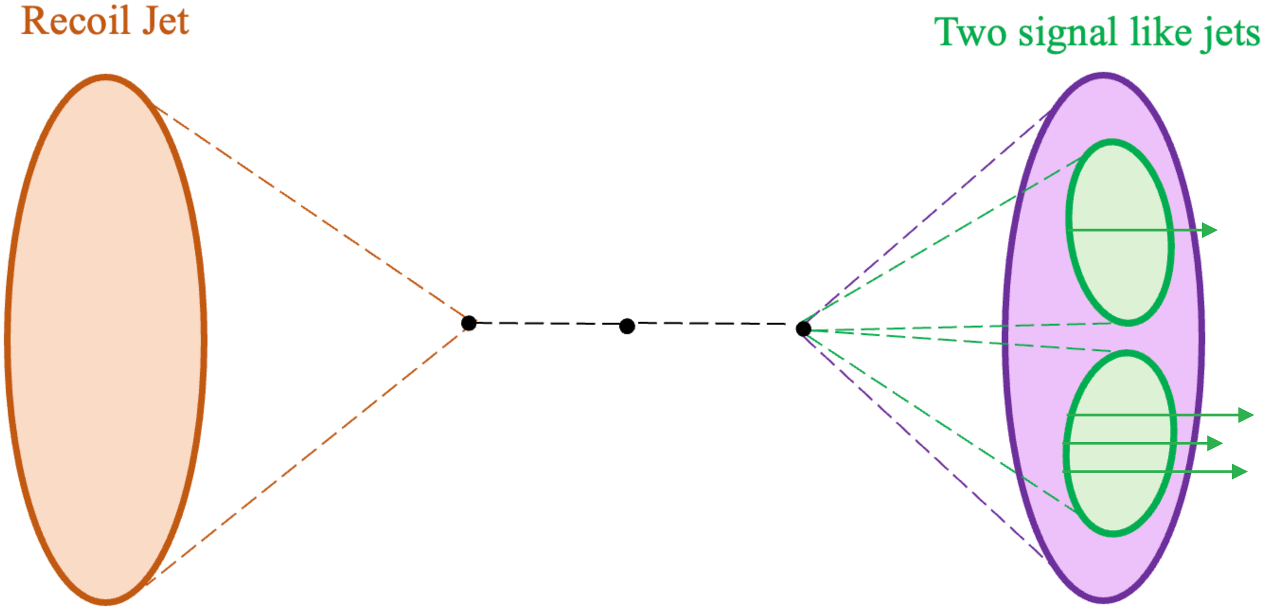




Collision → Detection → Event Reconstruction → Event Selection → Statistical Analysis

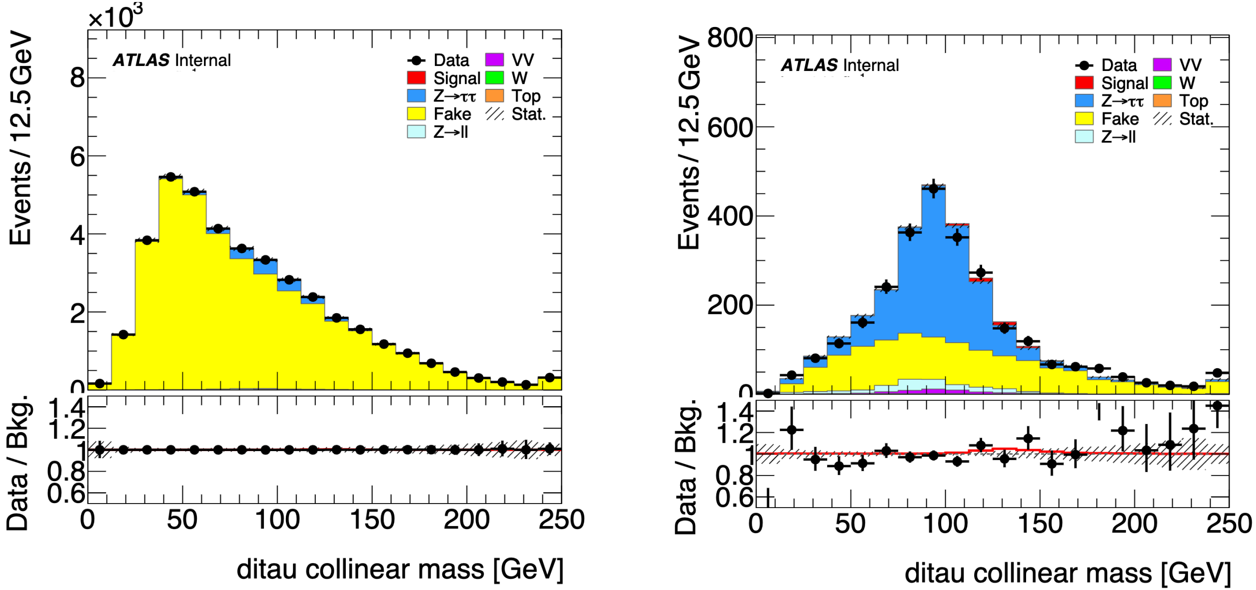
We have so far discussed the first three steps and now move to the last two steps

Event Selection



- Veto any muons or electrons that can fake the two taus
- Require p_T of DiTau object to be bigger than 300 GeV
- Require 1 or 3 tracks in each Tau jet

Event Selection: DiTau Identification



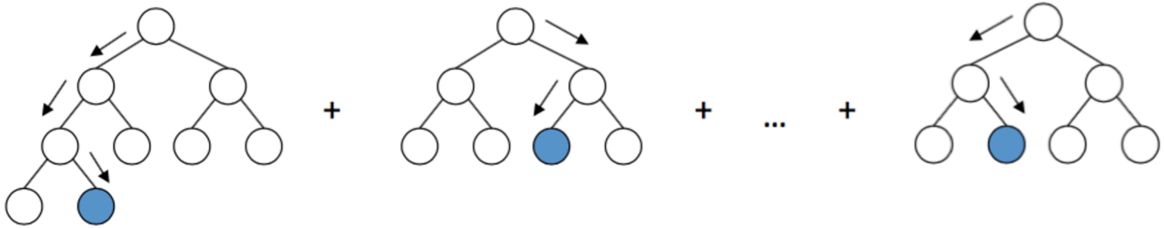
Without DiTau ID

With DiTau ID

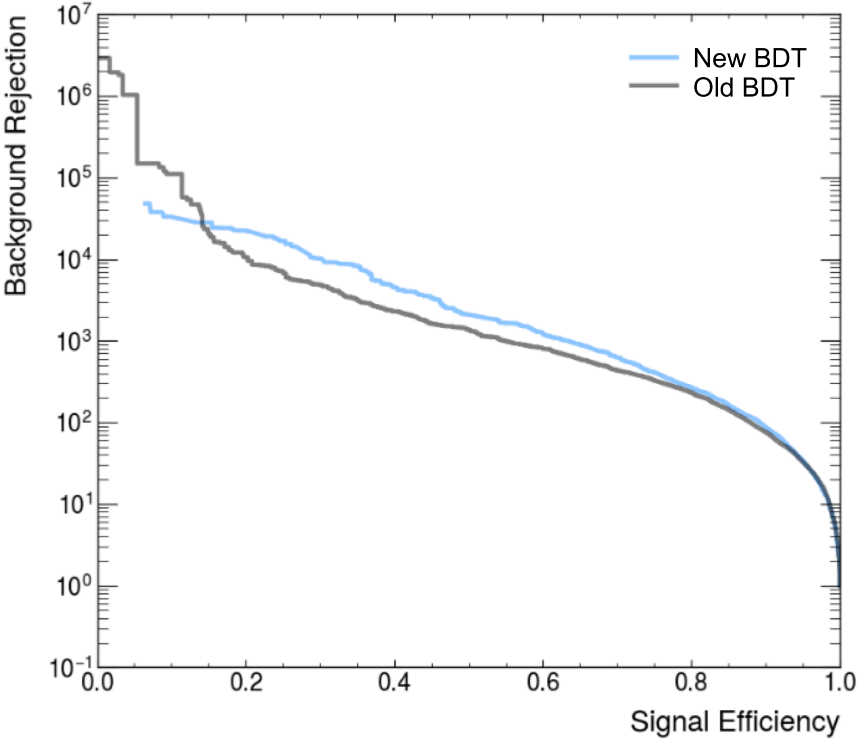
DiTau identification cut plays a significant role in reducing QCD background

DiTau Identification

- My qualification task focused on the DiTau Identification step
- Original DiTau tagger used a Boosted Decision Tree (BDT) and was developed for early Run 2
- This task updated the tagger for all of Run 2 and incorporated Run 3
- Also explored more advanced algorithms



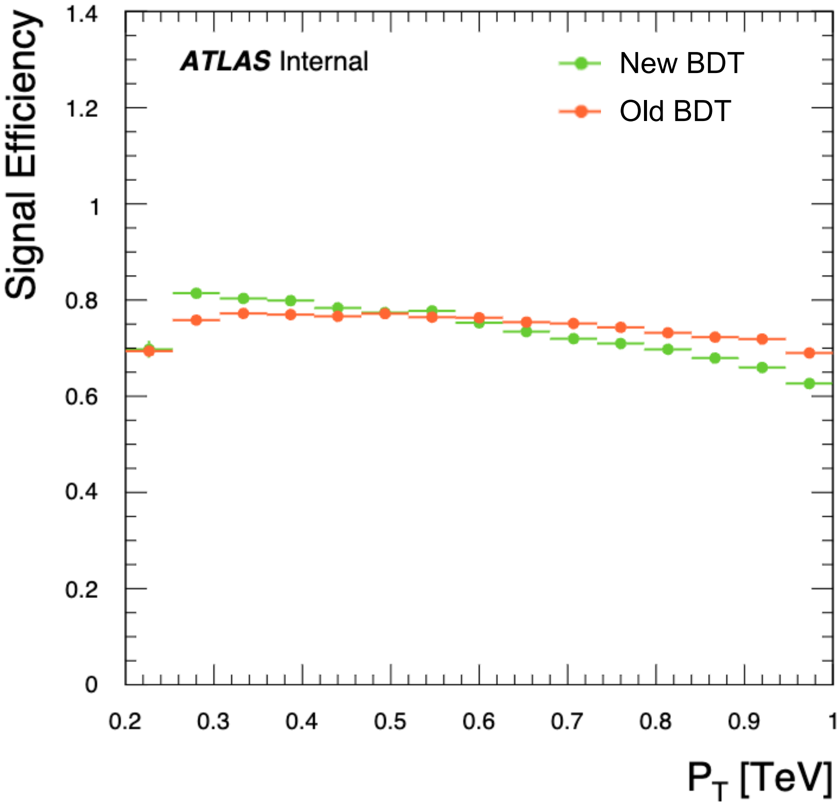
BDT Results



- We use the Receiver Operating Characteristic (ROC) curve as one metric to measure performance
- We see **improved performance** from the new BDT

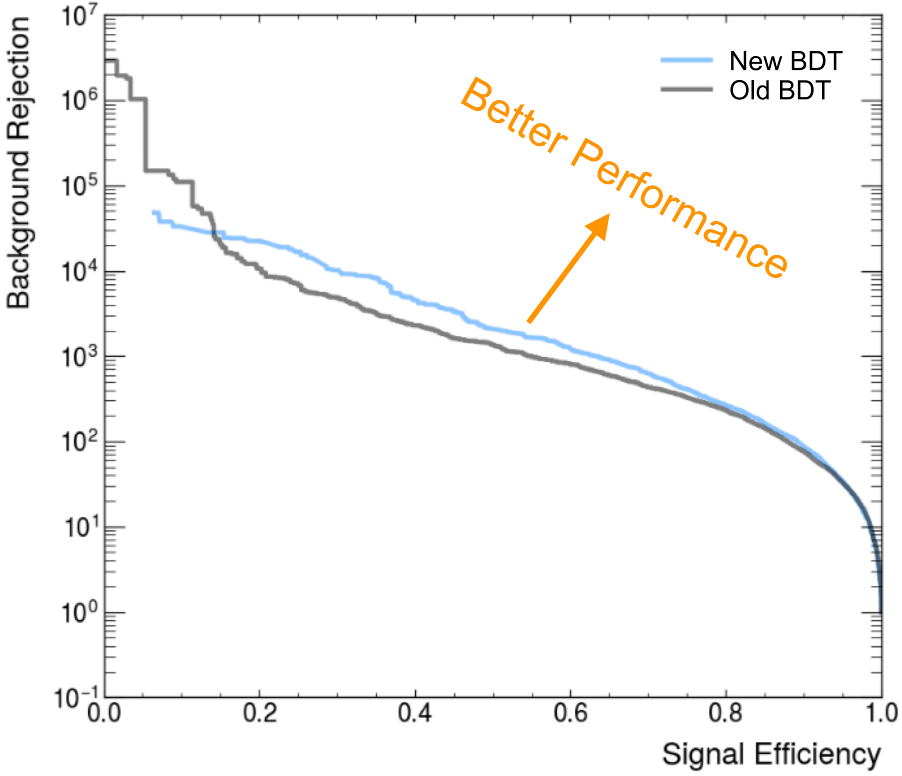
BDT Signal Efficiency

- Signal efficiency as a function of *transverse momentum*
- The **flatter the better** as we do not want our classifier to be dependent on kinematics

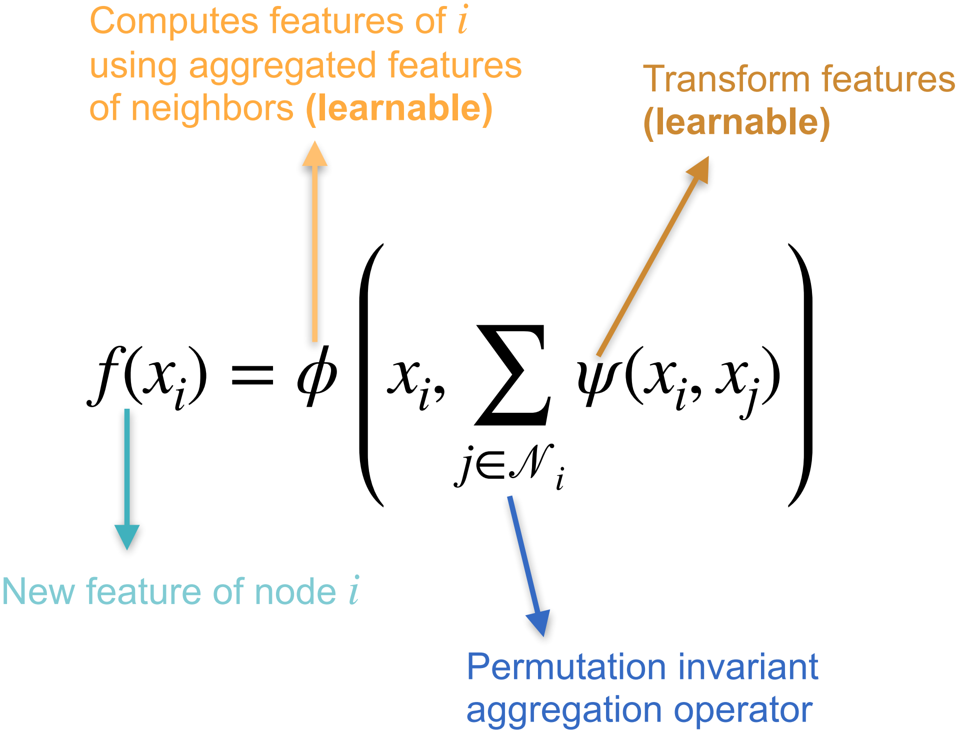


How to Improve the Measurement?

Performance Improvements in the Ditau tagger will directly improve our measurement



Role of Graphs in Jet Identification



Computes features of i using aggregated features of neighbors **(learnable)**

Transform features **(learnable)**

$$f(x_i) = \phi\left(x_i, \sum_{j\in\mathcal{N}_i} \psi(x_i, x_j)\right)$$

New feature of node i

Permutation invariant aggregation operator

arXiv:2104.13478

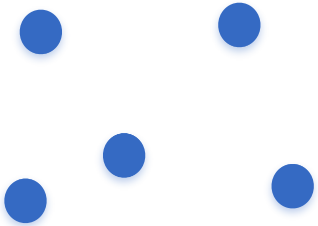
- Graph Neural Net (GNN)
- GNN and transformer architectures have been shown to perform very well in HEP applications
- Looking at neural networks trough the lens of graph can reveal underlying features like **permutation invariants** of the networks
  - Ordering of clusters and tracks is not important in identifying different kinds of jets

Machine Learning Architectures

DeepSets

$$f(x_i) = \phi\left(x_i, \sum_{j \in \mathcal{N}_i} \psi(x_j)\right)$$

We assume fully connected graphs but no coefficients of interaction

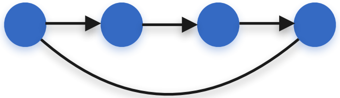


arXiv:1703.06114

Convolution

$$f(x_i) = \phi\left(x_i, \sum_{j \in \mathcal{N}_i} c_{ij}\psi(x_j)\right)$$

Here a constant is added that specifies importance of node j to node $i's$ transformation. Order matters here.

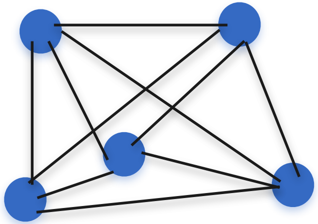


arXiv:1609.02907

Attention

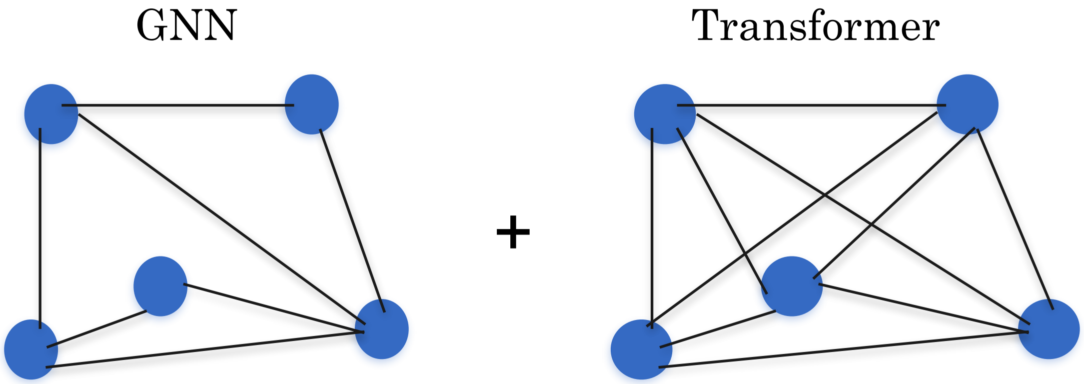
$$f(x_i) = \phi\left(x_i, \sum_{j \in \mathcal{N}_i} a(x_i, x_j)\psi(x_j)\right)$$

Here a is a learnable importance constant "self-attention mechanism"



arXiv:1710.10903

OmniLearn



Low Level Features
e.g. track p_t

High Level Features
e.g. $p_T^{sj_2}/p_T^{LRJ}$

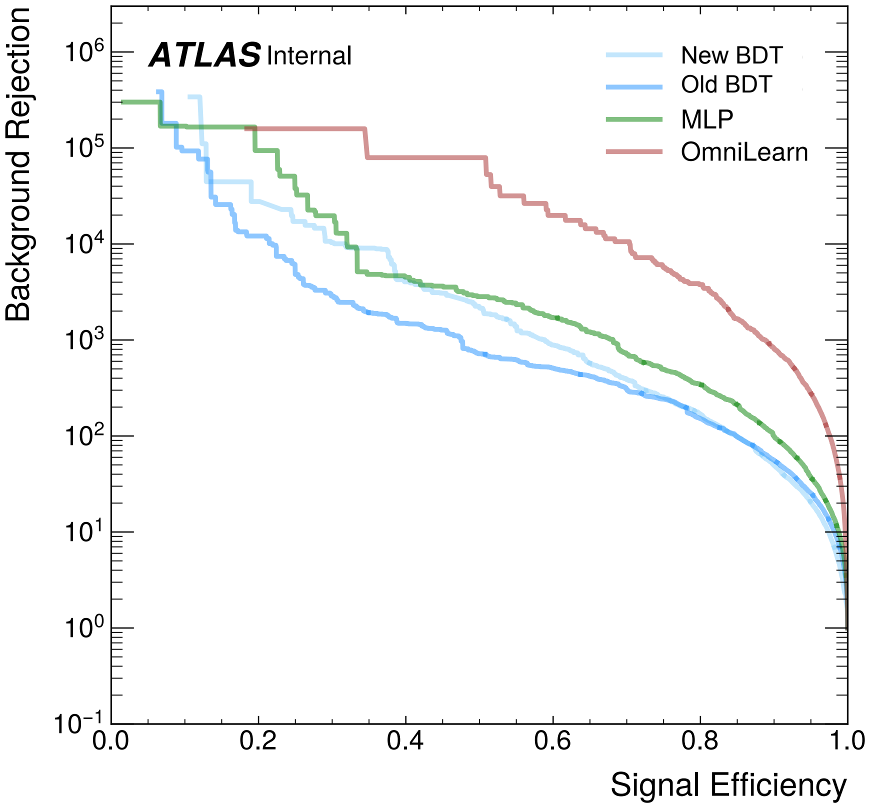
arXiv:2404.16091

This framework combines both GNNs and transformers

1. First a GNN is built using low level features
2. High level features are added into transformer blocks along with the low level features to further enhance performance

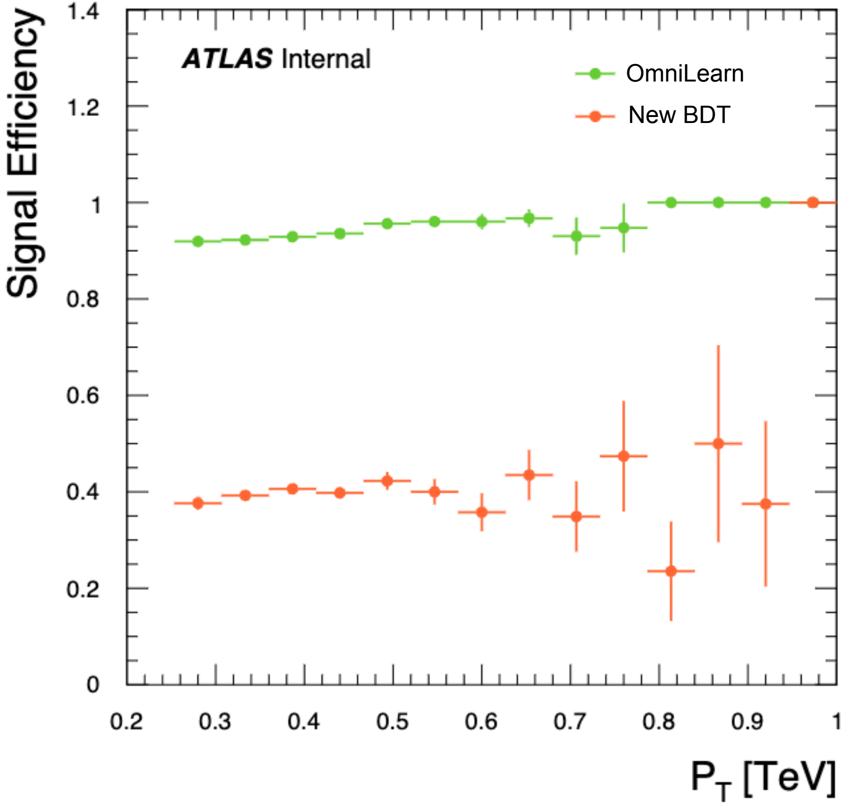
Performance Improvements

- We see large improvement over the current BDT
- Back of the envelope estimate indicates a ~60% improvement in significance for the analysis
- Implemented in analysis framework and ready for wider adoption



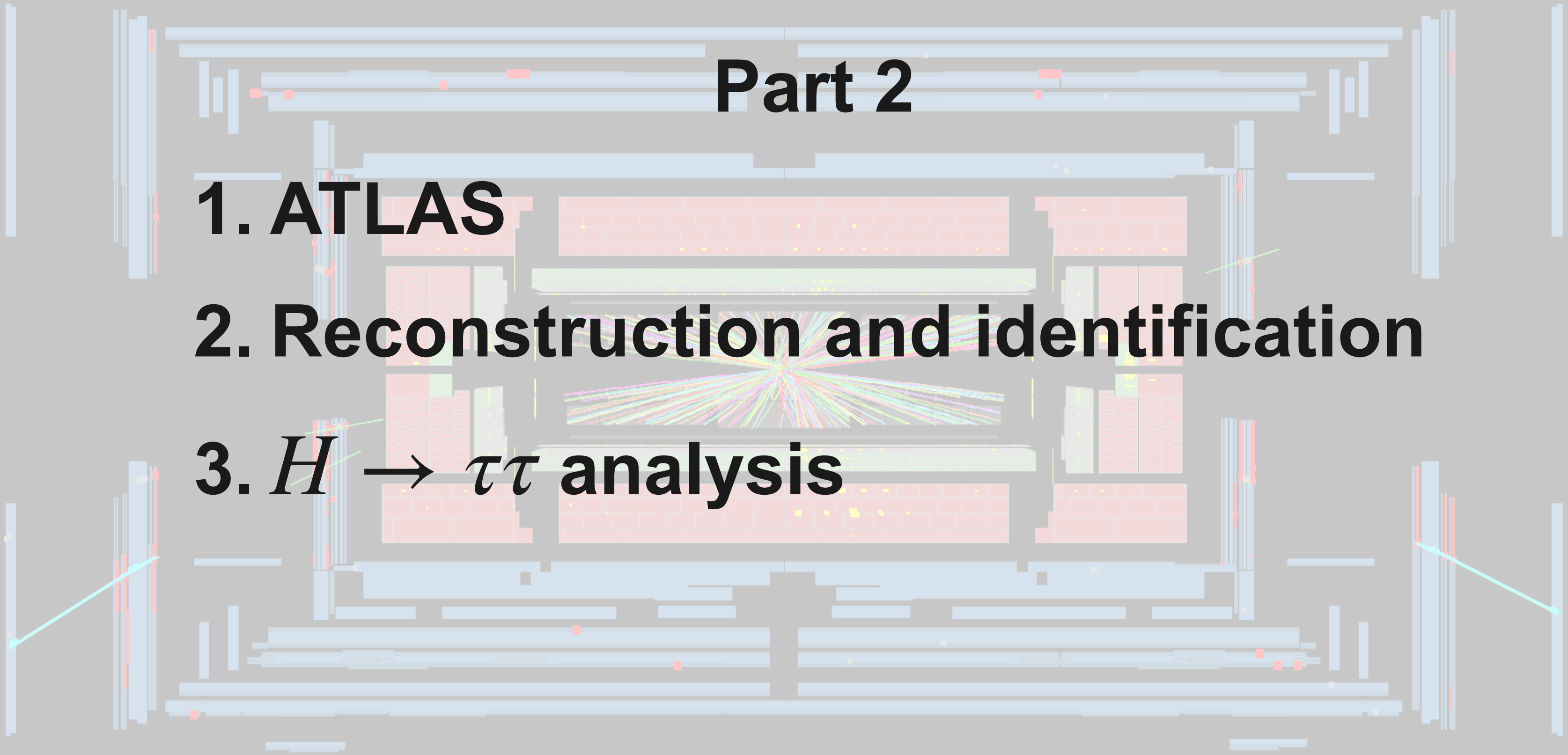
OmniLearn Performance in Analysis

An initial test with analysis signal samples shows a **doubling of signal efficiency** at a fixed background rejection rate using the new architecture compared to the BDT



Summary of DiTau Identification

- Trained and tuned a new Di-τ tagger for Run 2/3
- Available in Athena for use in all ATLAS analyses
- ATLAS note available here
- Results shown in multiple ATLAS meetings and the TauCP + HLeptons Workshop
- ATLAS author
- New architecture is expected to substantially improve analysis performance

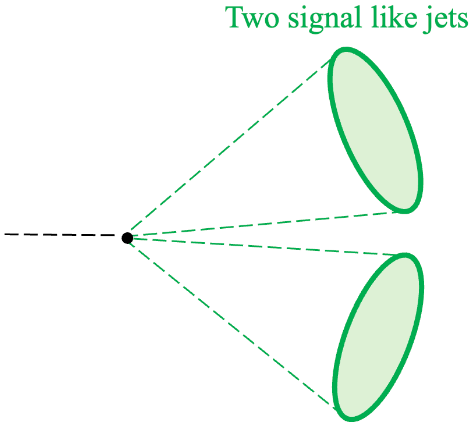


Part 2

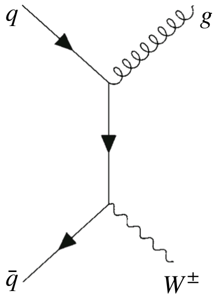
1. **ATLAS**
2. **Reconstruction and identification**
3. **$H \rightarrow \tau\tau$ analysis**

Backgrounds

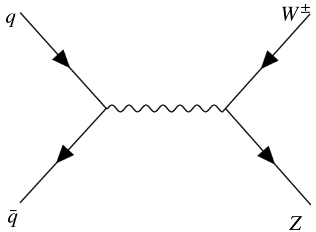
Final State



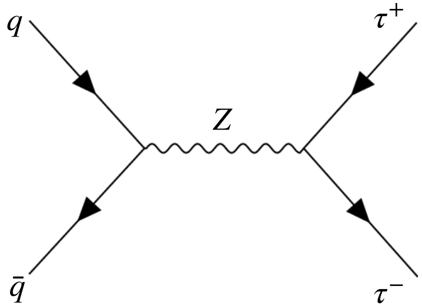
Non Higgs Processes



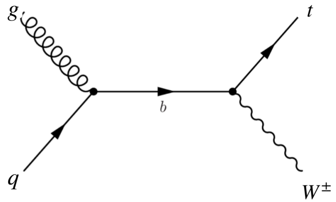
W + jet



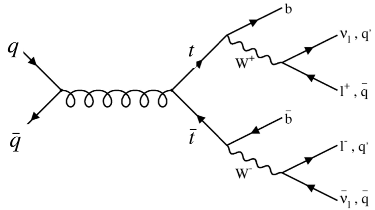
Di-boson



Irreducible background



Single top



Di-top

Backgrounds: Data Driven

Backgrounds estimated using simulations:

SM events with two true taus

Z(→ττ) + jets, ttbar + single top, Di-boson, Z(→ll)+jets

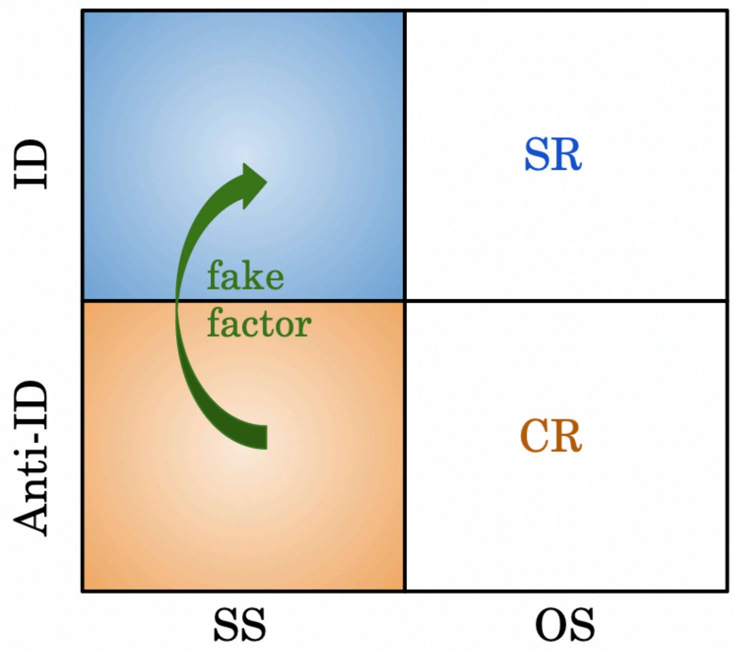
Fakes estimated using a data-driven technique:

Events with at least one subjet coming from a jet faking an hadronic tau (QCD, W+jets)

Fake-Factor technique

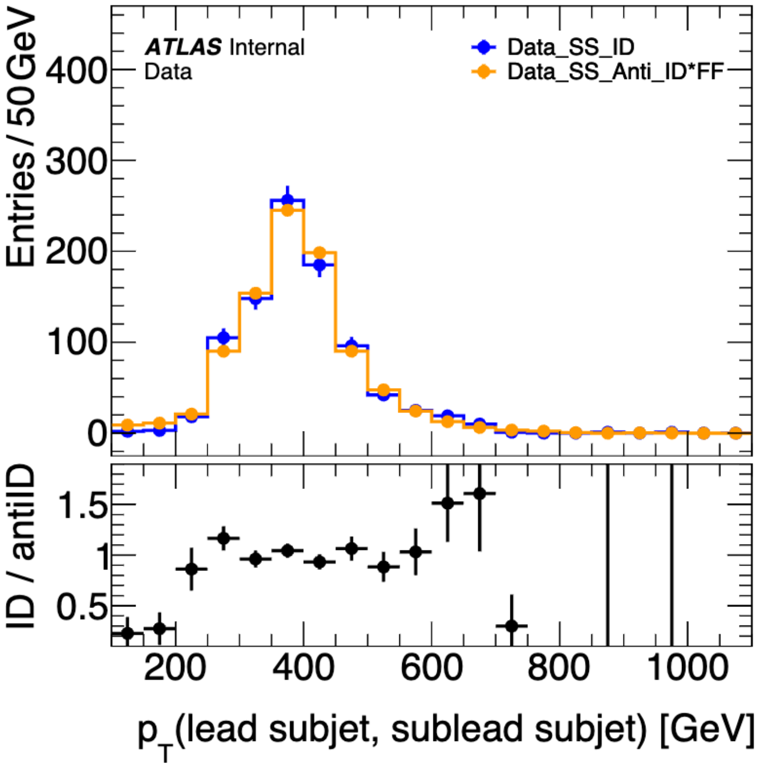
Fake Factor Method

- Same Sign (SS):
  Jet1 charge × Jet2 charge is positive
- Opposite Sign (OS):
  Jet1 charge × Jet2 charge is negative
- Fake factors: (SS and Anti-ID data) / (SS and ID data)

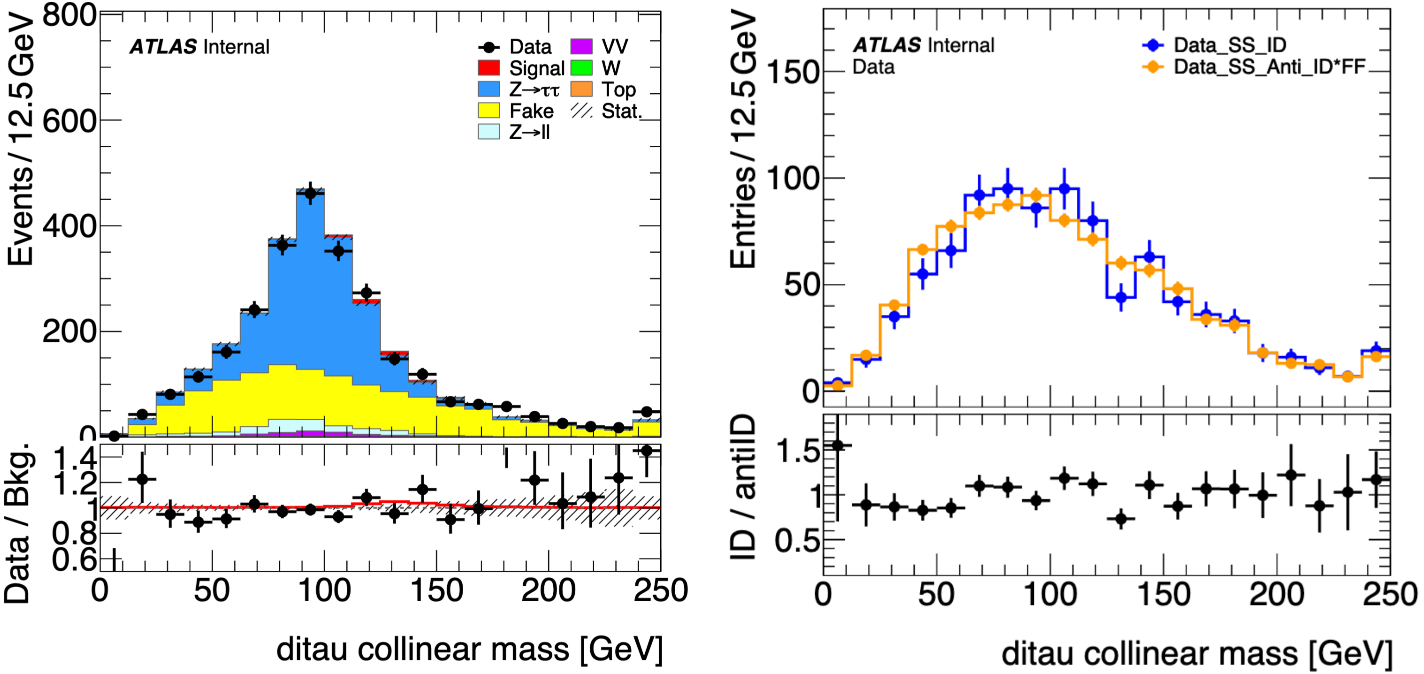


Closure Test

- Plotting (SS&ID region) vs (SS&anti-ID region * **FF**)
- See good agreement in p_T distribution



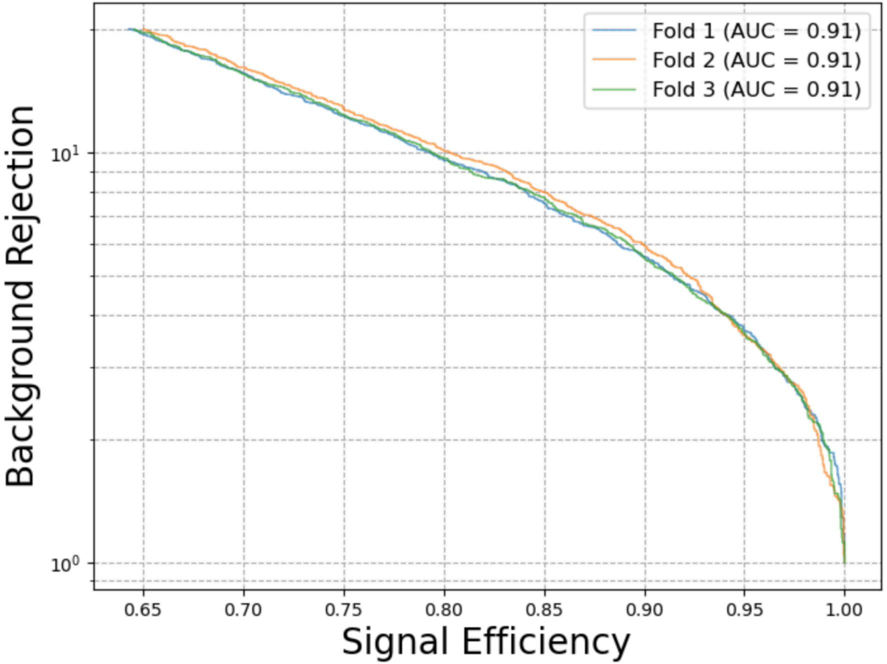
Modeling Performance: Collinear Mass



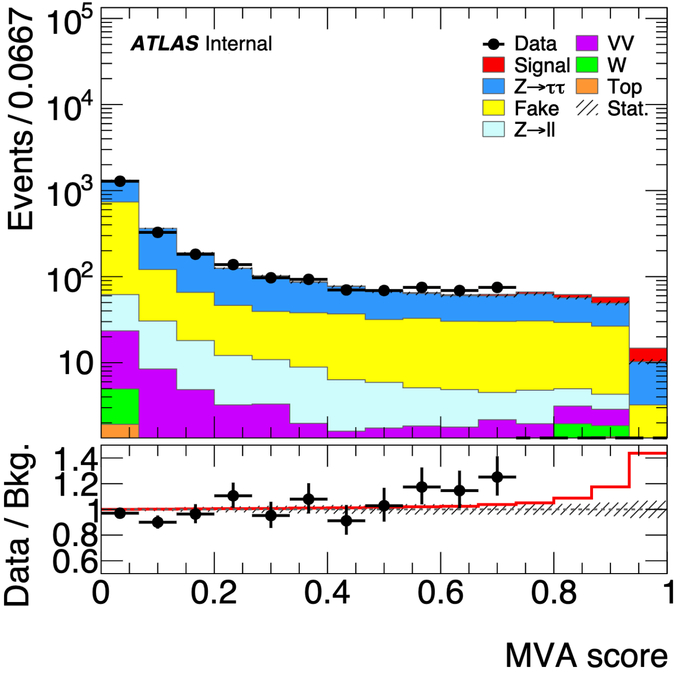
We see good agreement in the collinear mass. Which means good kinematic modeling of di-τ and MET object.

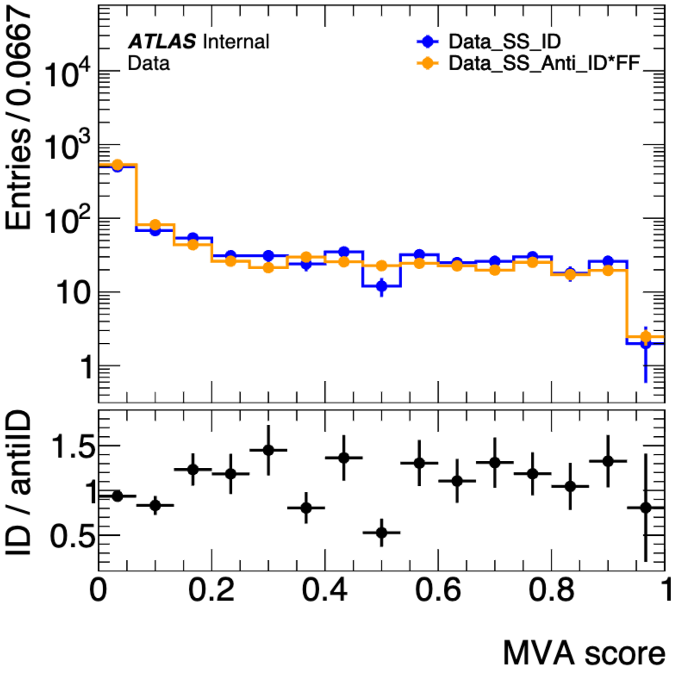
MultiVariate Analysis (MVA)

- While a single variable provides some discrimination power, a multivariate approach allows us to exploit the combined discriminative power of multiple variables.
- A BDT is trained on the full Run 2 dataset using nine features

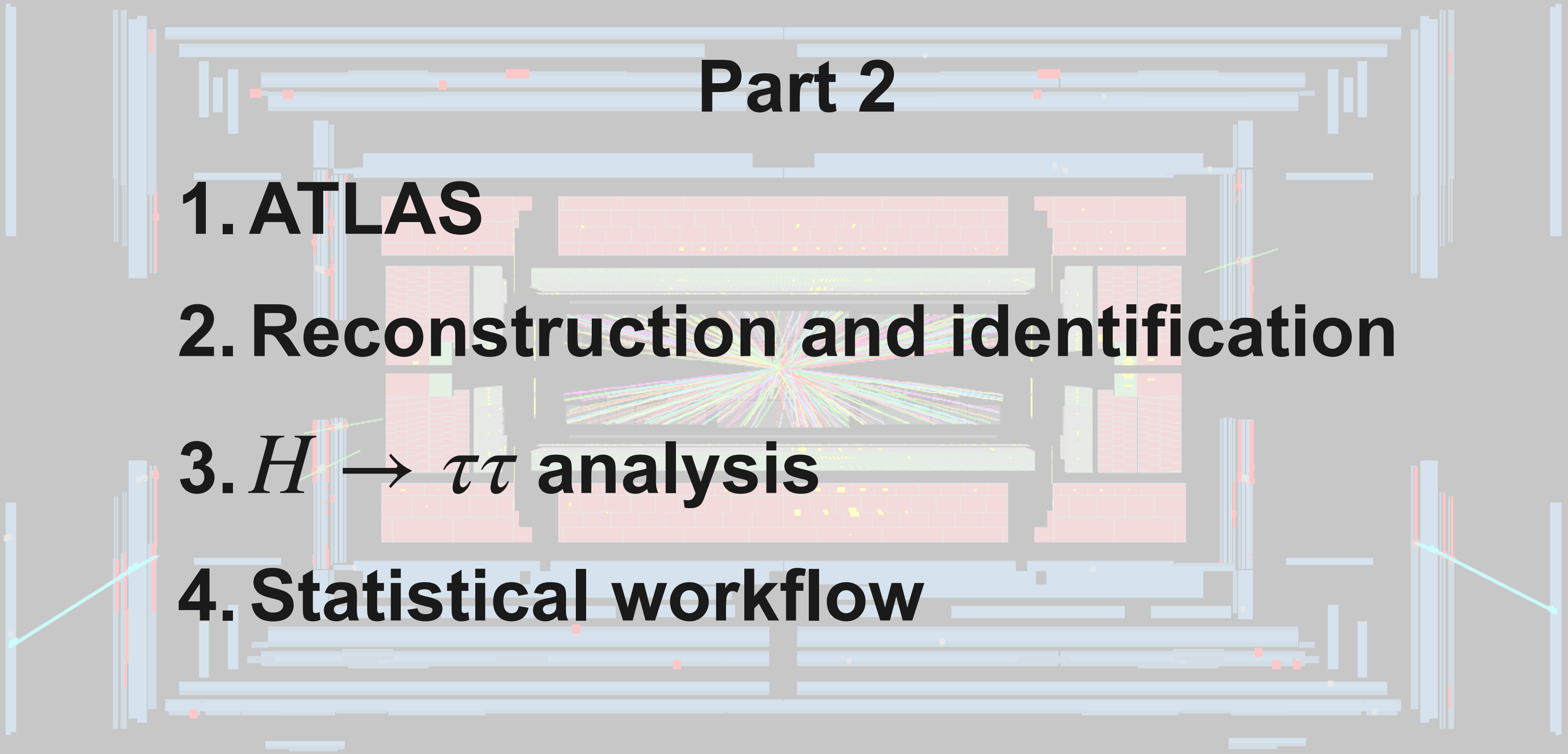


Modeling Performance: MVA





MVA agreement between background and data looks good, work in progress to improve

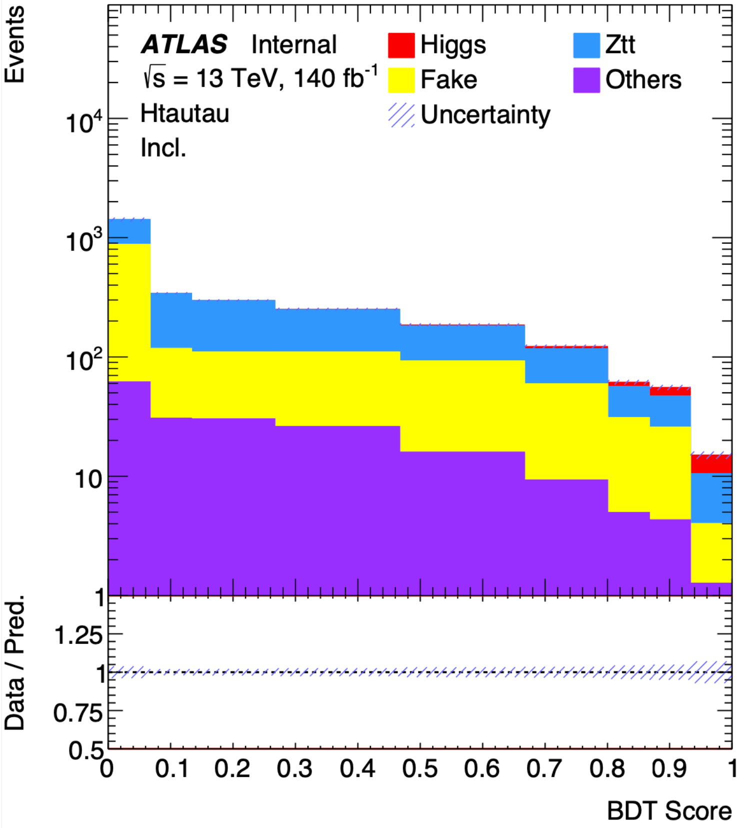


Part 2

1. ATLAS
2. Reconstruction and identification
3. $H \rightarrow \tau\tau$ analysis
4. Statistical workflow

Signal Significance

- Significance: sum in quadrature of σ in each bin where $\sigma = \dfrac{S}{\sqrt{B}}$
- MVA distribution has a significance of 2.11. While collinear mass gives 0.94
- This includes all of Run 2



Fit Result

Signal strength $\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$ is extracted from the fit along with an extensive set of systematic uncertainties

signal strength: $\mu = 1^{+0.63}_{-0.55}$

significance for $\mu = 1$**:** 2.097

From this we can calculate the cross section of Higgs boson production to taus

Analysis Outlook

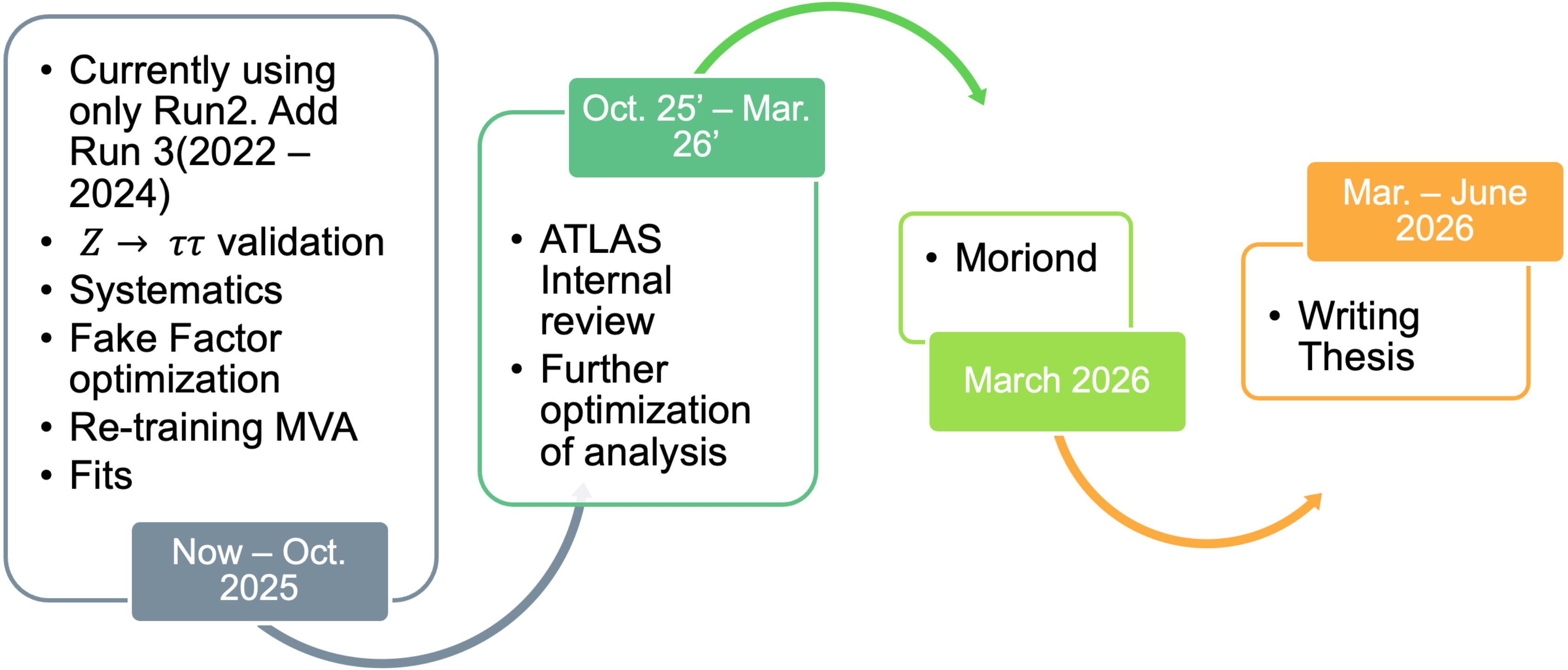
	Integrated Luminosity (fb^{-1})	Number of measured events $N = L\sigma$	Significance $\sigma_{i+1} \approx \sigma_i\sqrt{\frac{L_{i+1}}{L_i}}$	Expected Significance with OmniLearn
Run 2	140	33	2	**~3.2**
Run 2 + (partial) 3	140+200	~80	~3.1	**~4.9**
Run 2 + 3	140+345	~114	~3.7	**~5.8**
Run 2 + 3 + HL-LHC	140+345+3000	~819	~10	**~16**

Expect improvement with Run 3 data, but much more with HL-LHC

Summary

- Di-τ tagger as part of ATLAS qualification task was completed
- Leading the Boosted $H \rightarrow \tau\tau$ analysis
  - Background studies
  - MVA development
  - A new and improved Di-τ tagger
  - Work presented multiple ATLAS meetings including in Tau | Leptons meetings
  - Analysis progressing well

Timeline



- Currently using only Run2. Add Run 3(2022 – 2024)
- $Z \rightarrow \tau\tau$ validation
- Systematics
- Fake Factor optimization
- Re-training MVA
- Fits

Now – Oct. 2025

Oct. 25' – Mar. 26'

- ATLAS Internal review
- Further optimization of analysis

- Moriond

March 2026

Mar. – June 2026

- Writing Thesis

Acknowledgments

- Advisor - Quentin Buat
- Committee members - Isabel Garcia-Garcia, Shih-Chieh Hsu, Max Parsons, Gordon Watts
- Physics staff and faculty
- CERN collaboration

Thank You

Okazaki

BackUp

Importance of ML Tools

“**New directions in science are launched by new tools much more often than by new concepts.** The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained” - Freeman Dyson

Anomaly Detection

Uncertainty Aware ML

_____ as a Service

Foundation Models

Object Tagger

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.

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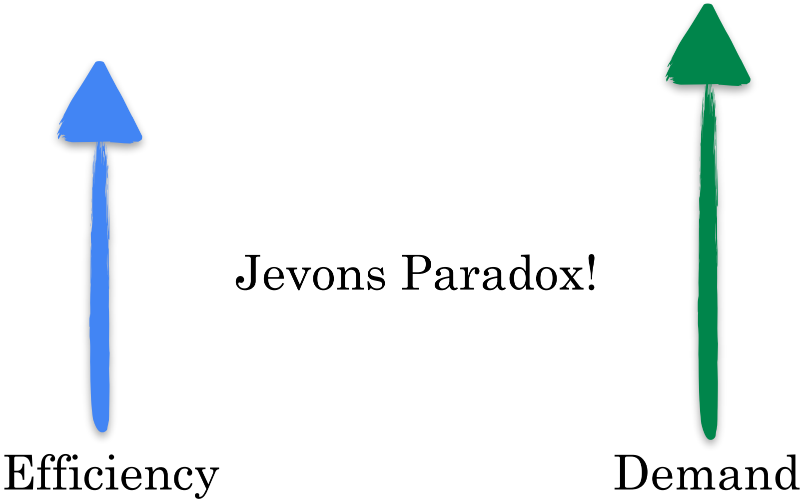


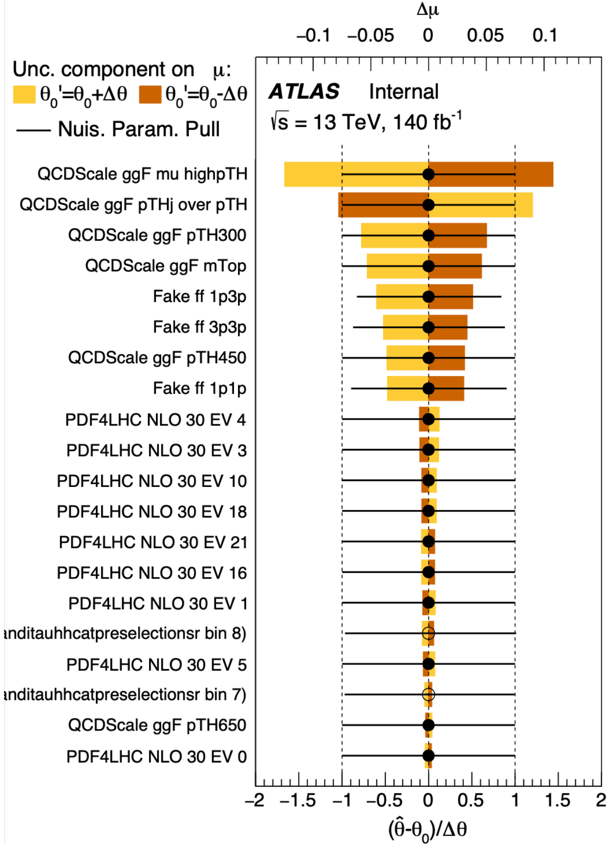
Jevons Paradox!

Fit Result

- We have the infrastructure ready for fitting
- Fit significance in agreement with estimate
- Pull plot performance is as expected

$$\textbf{signal strength: } \mu = 1^{+0.63}_{-0.55}$$

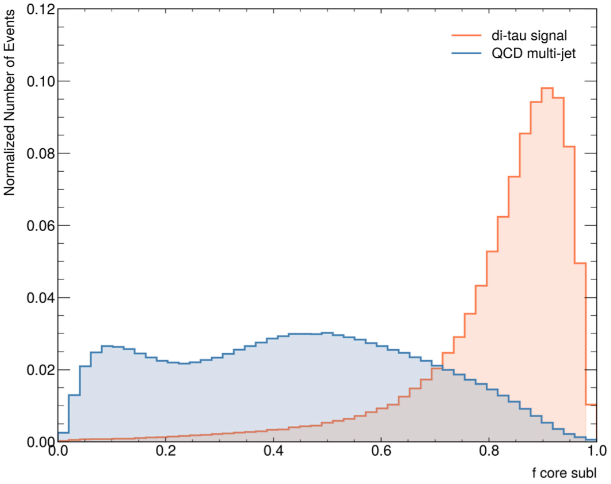
$$\textbf{significance for } \mu = 1 : 2.097$$

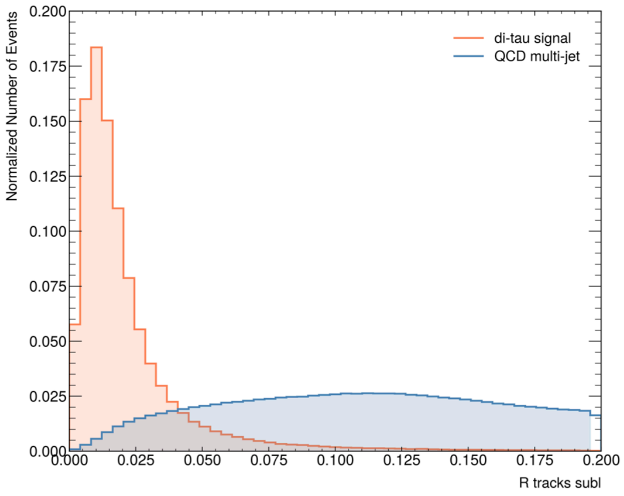


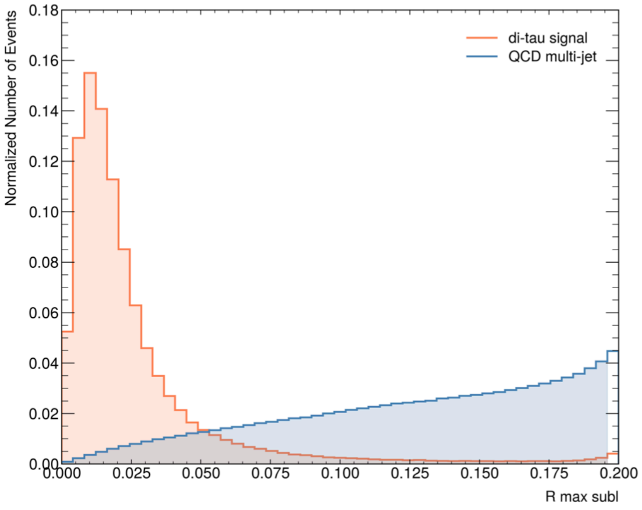
Full Event Selection

- Electrons (used for veto):
  - loose working point
  - $|\eta_{\mathrm{cluster}}| < 2.47$ (excl. $1.37 < |\eta_{\mathrm{cluster}}| < 1.52$)
  - $p_T > 15$ GeV
- Muons (used for veto):
  - loose working point
  - $|\eta| < 2.5$
  - $p_T > 10$ GeV
- Jets:
  - collection: EMPFlow
  - $p_T > 20$ GeV
  - pass (f)JVT cut
  - btagging WP: DL1d 70%
- Single taus (only used for ORL)
  - $p_T > 20$ GeV
  - nTracks = {1, 3}
  - tau ID: RNN score > 0.01
- Ditau (at least 1):
  - collection: DiTauJets
  - $p_T > 300$ GeV
  - nTracks: {1,3} on (sub)lead subjet
  - ID cut: BDT score > 0.96
- Missing Transverse Energy (MET): A modified version of MET HPTO, with Di-τ and all other jets in the event is used, with $\Delta R(\mathrm{jet, ditau}) > 1.0$
- Triggers:
  - Single jet (0.4) or large-R jet

BDT Training



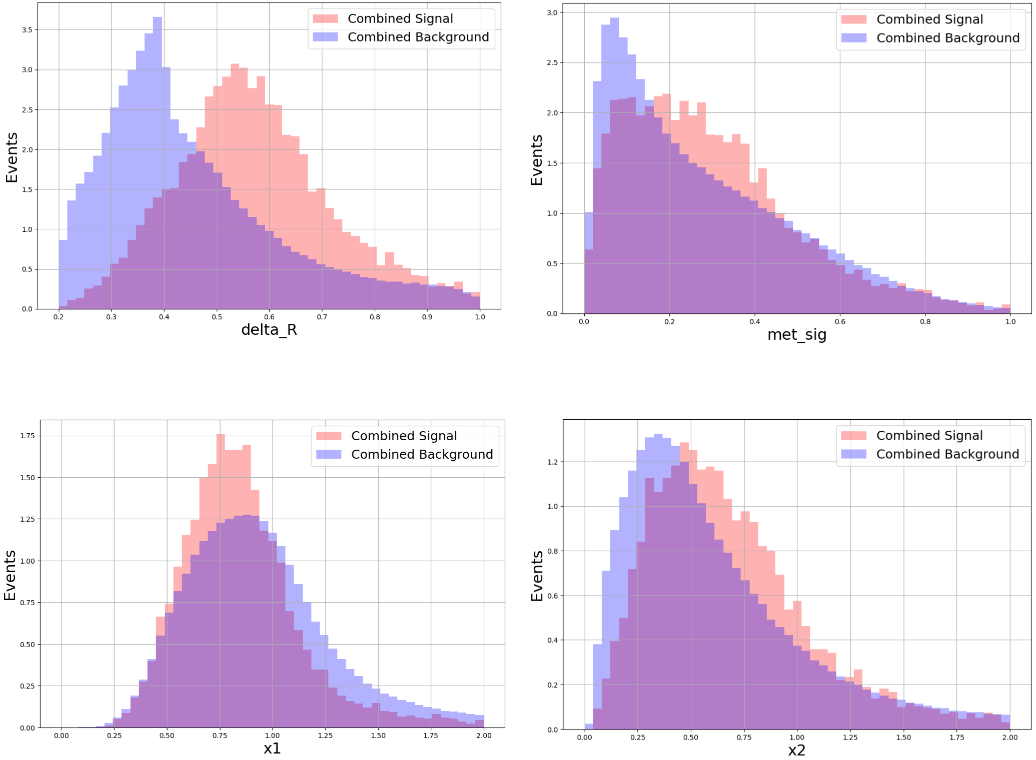




- The background in this classification task is QCD multi-jet events and the signal is different particles decaying to taus
- Seventeen variables are used in training, chosen from a set of kinematic and geometric variables of the Di-τ objects that show the best classification power

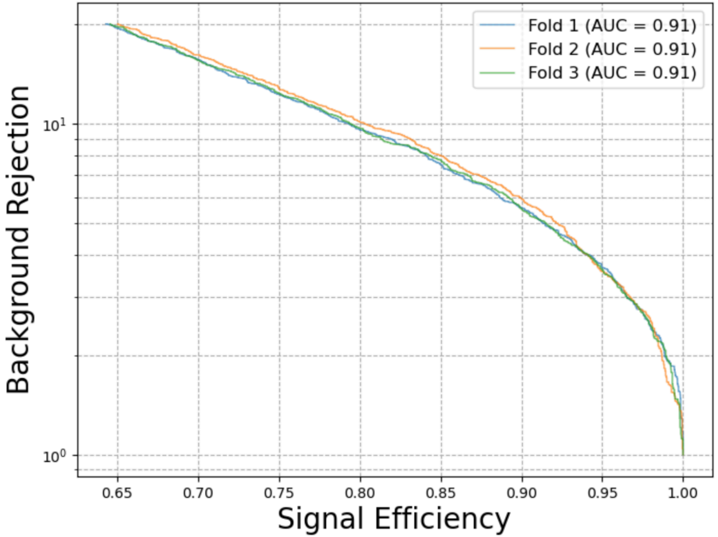
MVA Training

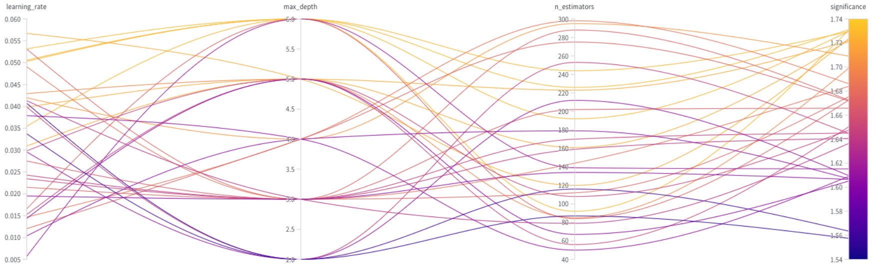
- MVA BDT Features:
  - ○ leading subjet p_T
  - ○ subleading subjet p_T
  - ○ Visible Mass
  - ○ Collinear Mass
  - ○ ΔR
  - ○ MET
  - ○ MET significance
  - ○ MET centrality
  - ○ x_1 and x_2 collinear variables



MVA Optimization

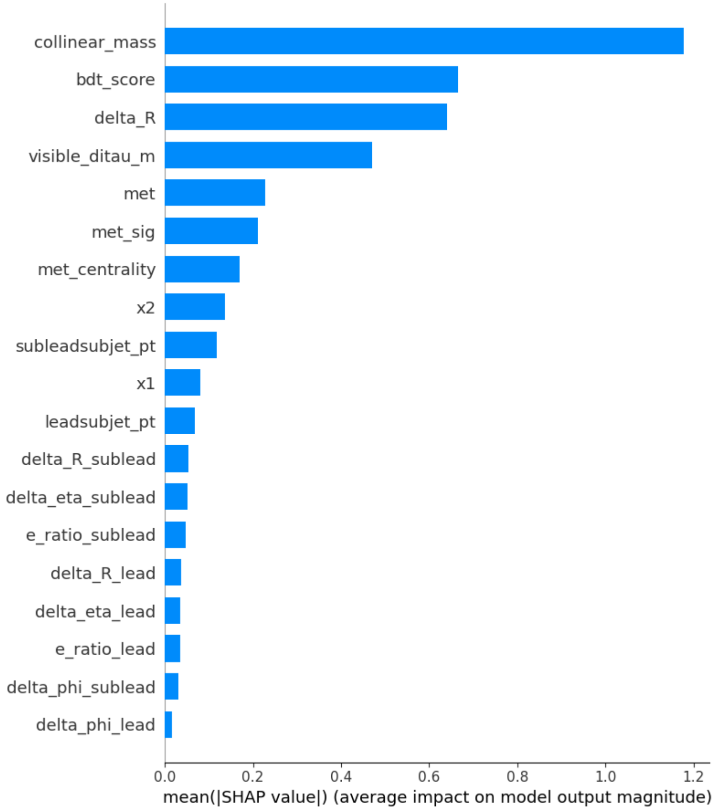
- Using 3-fold training
  - Splitting the training and testing data this way allows for usage of all data at inference time
- Hyper parameter (learning rate, depth, # of estimators) tuning of the BDT is done to maximize significance



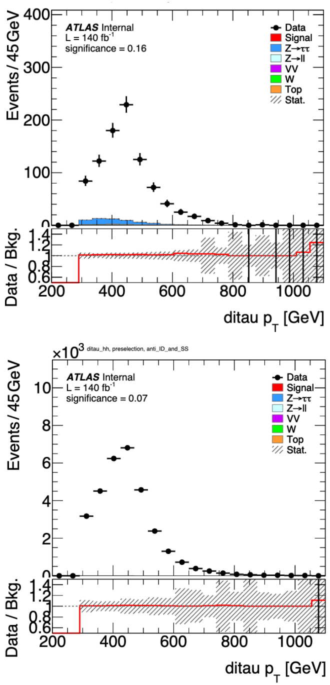


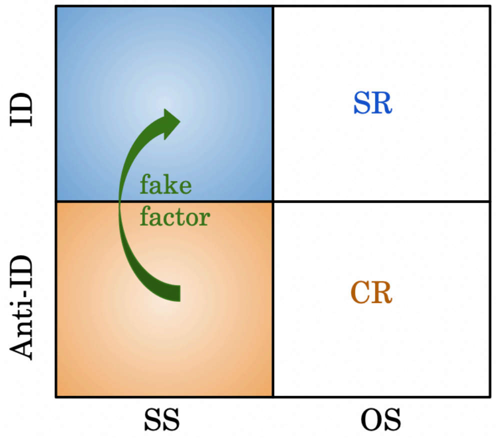
MVA Feature Importance Study

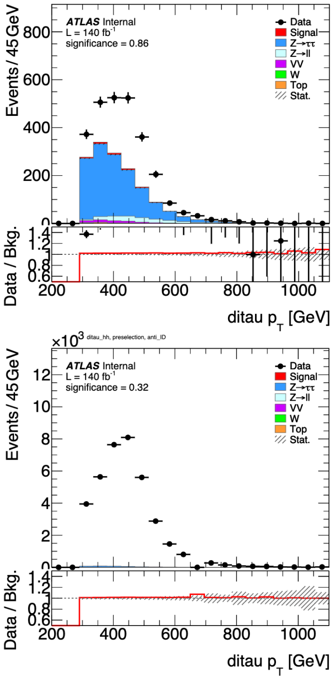
- Also performed feature importance studies
- Choose most relevant set of features and asses importance of each to the model
- Only the top performing ones are chosen for final BDT



Fake Factor Method

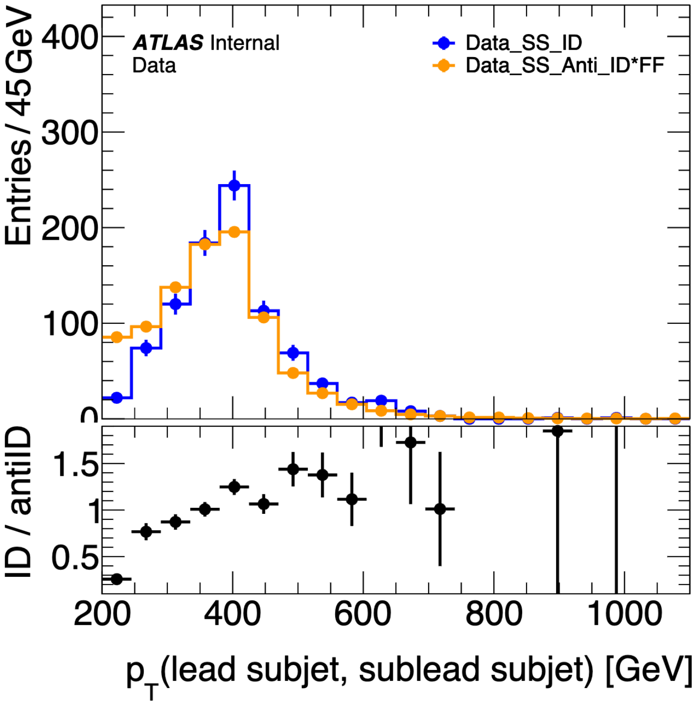


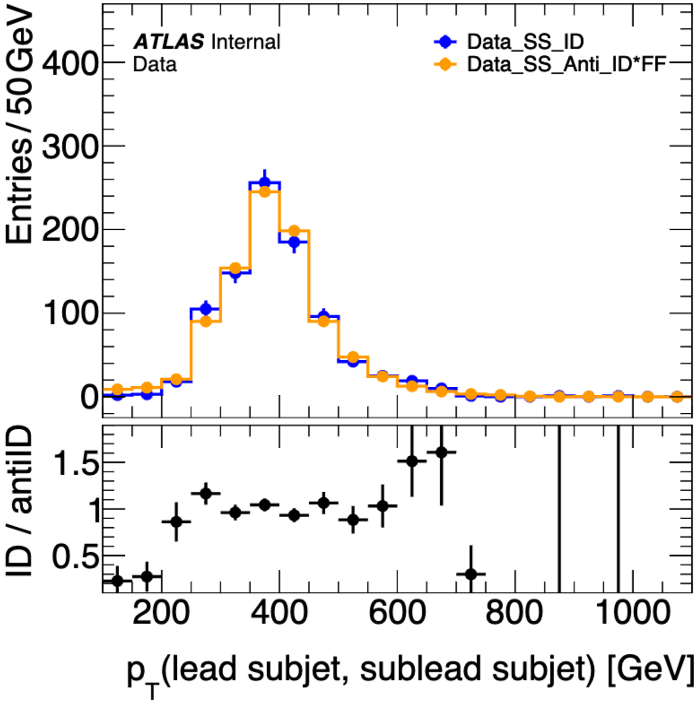




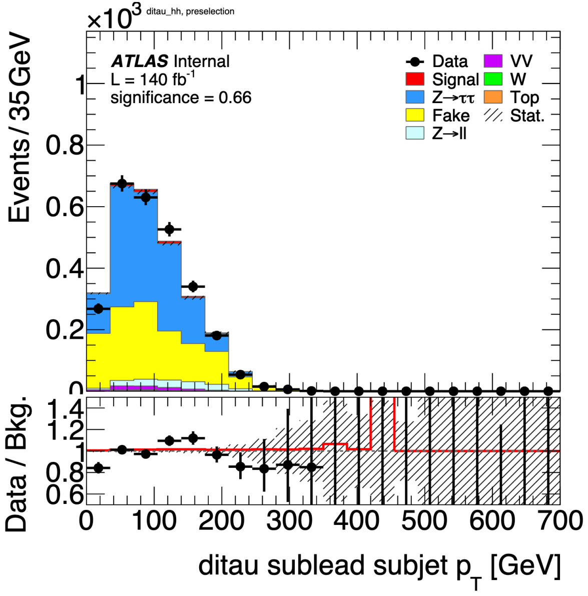
- Fake factors: (Same-Sign (SS) and Anti-ID data) / (SS and ID data)
- Monte Carlo contributions are subtracted from the data in each region

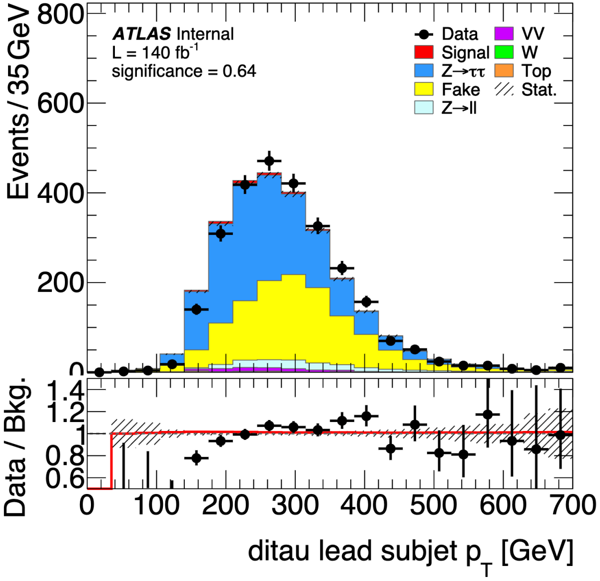
Closure Test Improvement

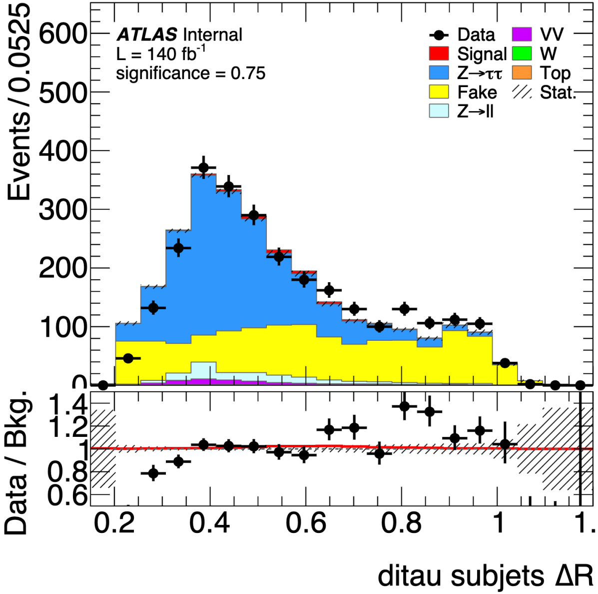




More Modeling Performance Plots

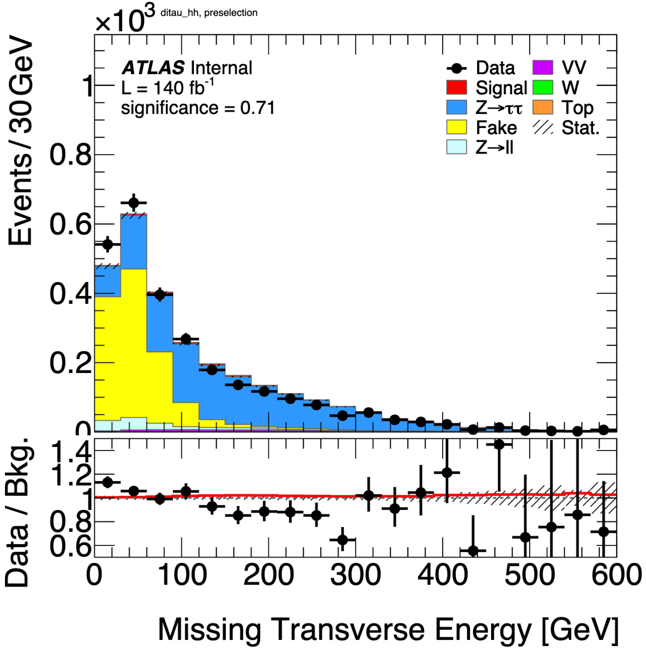


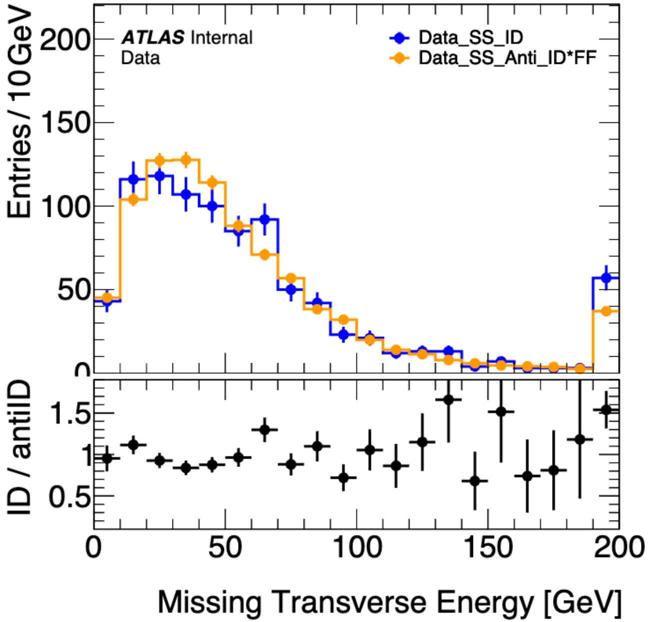




Also see reasonably good modeling in subjet kinematics

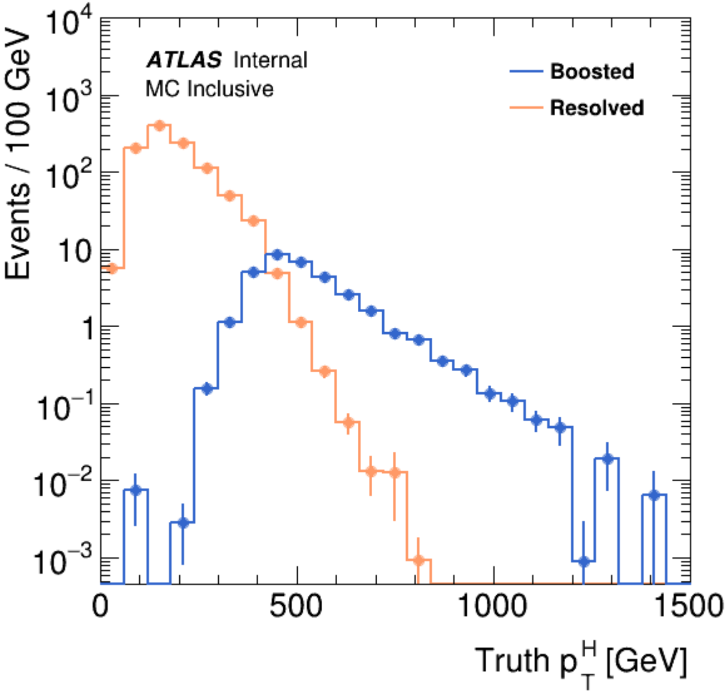
Modeling Performance: MET

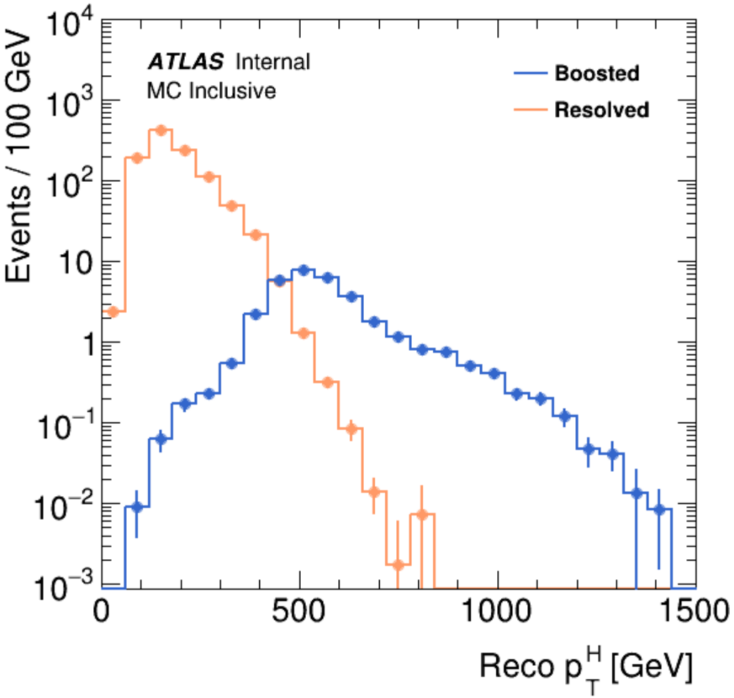




Good modeling at higher tail of MET, while a bit of mis-modeling and lower end.

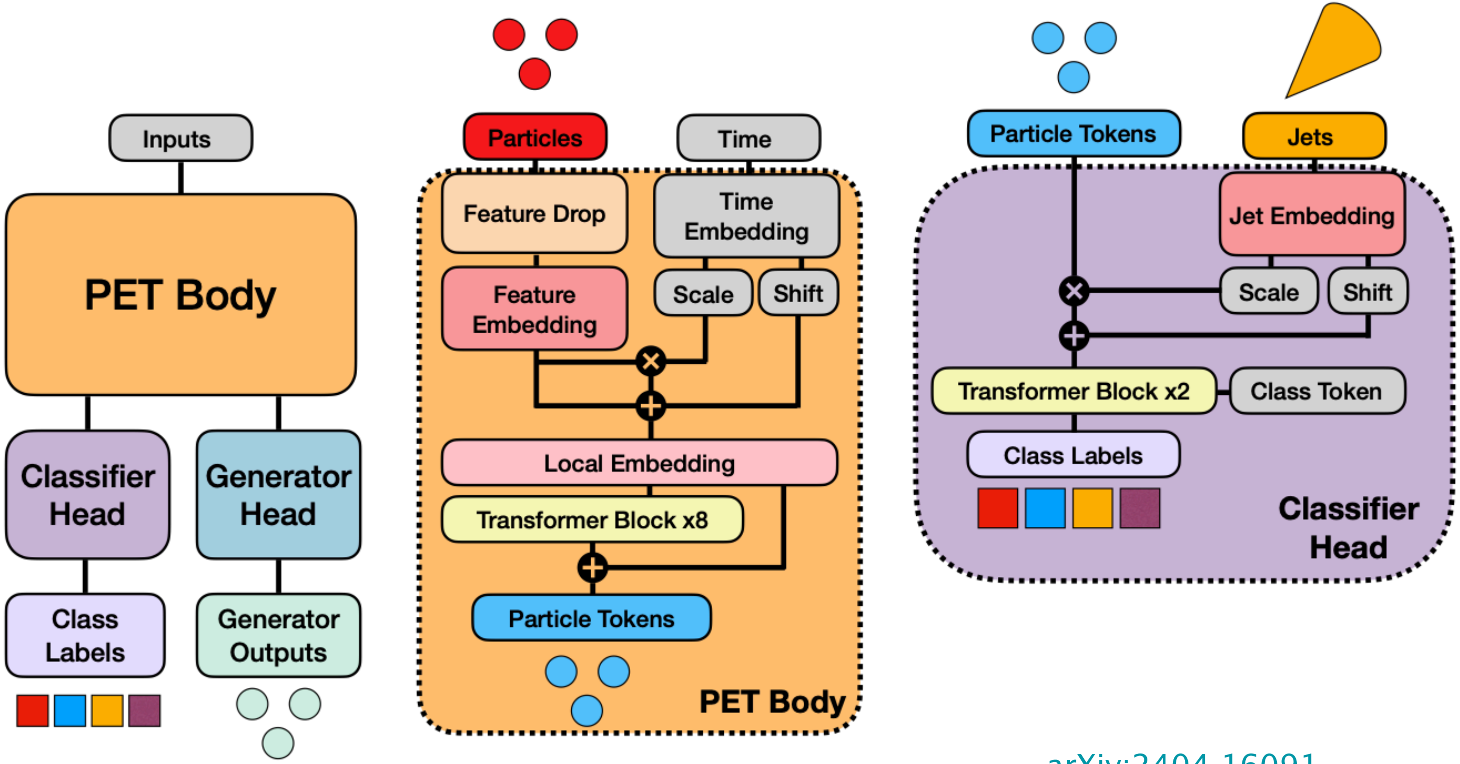
Probing a New Higgs Phase Space





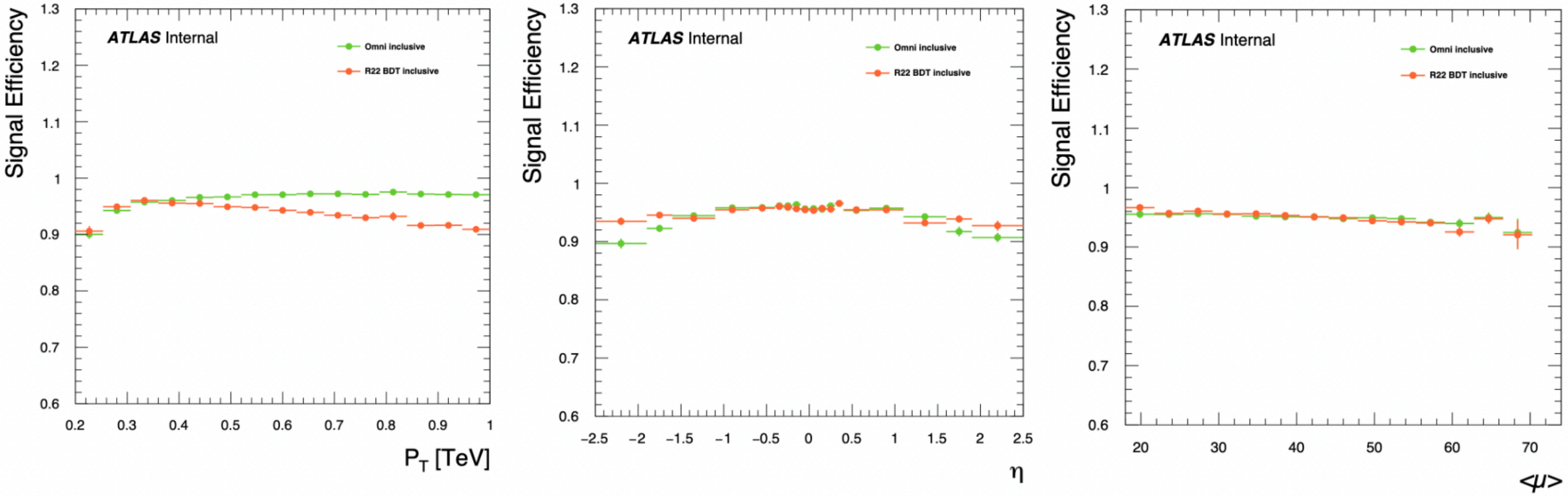
- The boosted di-τ analysis will be the first one in ATLAS to explore this phase-space
- Probing the higher p_T tail of the resolved analysis

OmniLearn Workflow



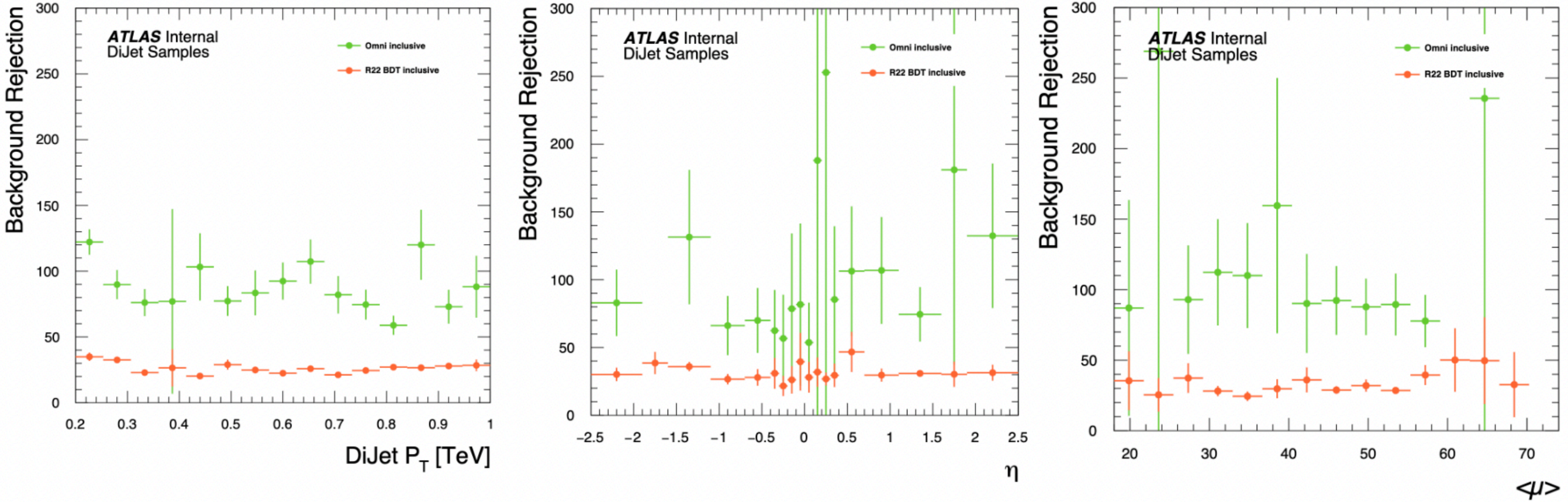
arXiv:2404.16091

OmniLearn: Signal Efficiency



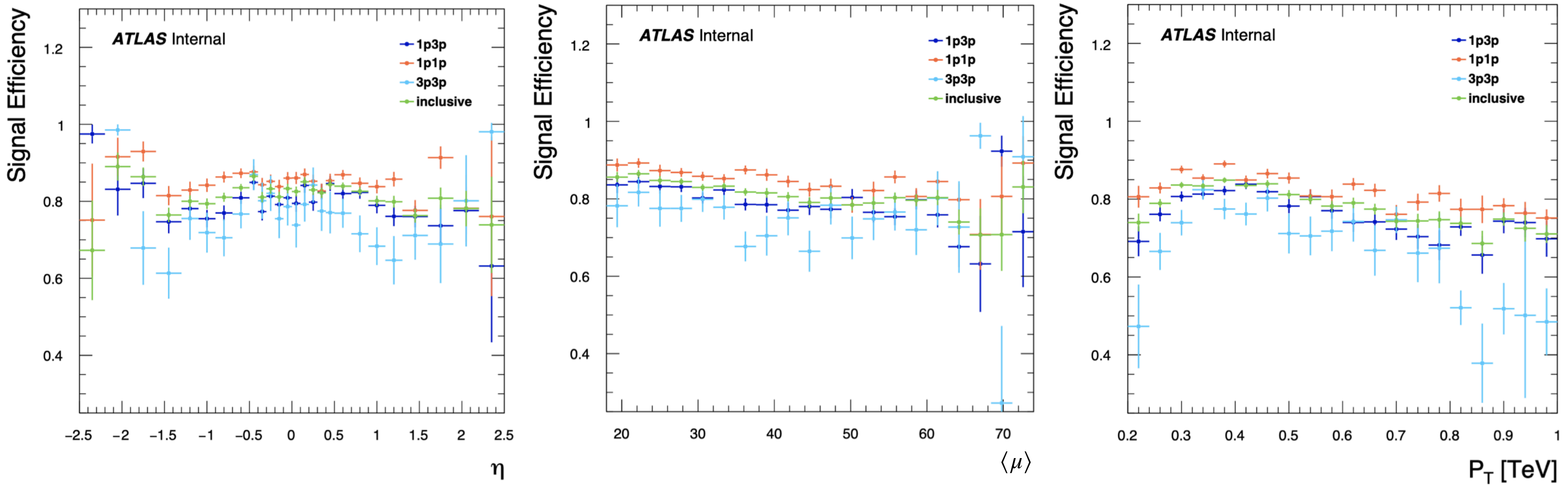
- The working point used to define signal efficiency was selected to ensure that both models have the same efficiency
- We observe that OmniLearn exhibits a consistent response across the plotted features even without weights in training

OmniLearn: Background Rejection



- Since by construction the signal efficiency is supposed to be the same, we expect and observe stronger background rejection in OmniLearn compared to the BDT
- The limited statistics in OmniLearn are a result of the working point effectively rejecting a substantial portion of the background

BDT Signal Efficiency



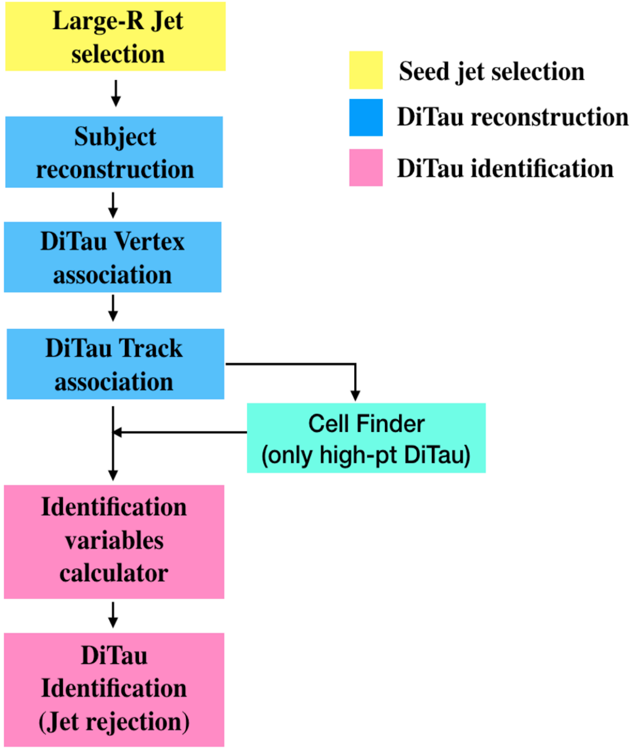
- Signal efficiency as a function of *pseudo-rapidity*, *average interactions per bunch crossing* and *transverse momentum*
- The **flatter the better** as we do not want our classifier to be dependent on these parameters

OmniLearn Training Dataset

- Using the same signal sample as GN2X
  - mc23_13p6TeV.802168.Py8EG_A14NNPDF23LO_VHtautau_flatmasspTFilt_**hadhad**.recon.AOD.e8558_s4162_r14622
- Only the JZ samples as GN2X, will add others soon.
  - mc23_13p6TeV:mc23_13p6TeV.*.Py8EG_A14NNPDF23LO_jj_JZ*.recon.AOD.e8514_s4162_r14622
- THOR is used to process the AOD's and outputs nTuples with di-tau jet and track information.
  - Cuts: # subjets >= 2, 1 or 3 tracks in leading and subleading subjets.
- **Jet variables:** ditau_R_max_lead, ditau_R_max_subl, ditau_R_tracks_subl, ditau_R_isotrack, ditau_d0_leadtrack_lead, ditau_d0_leadtrack_subl, ditau_f_core_lead, ditau_f_core_subl, ditau_f_subjet_subl, ditau_f_subjets, ditau_f_isotracks, ditau_m_core_lead, ditau_m_core_subl, ditau_m_tracks_lead, ditau_n_trac
- **Track variables:** trackDeltaEta, trackDeltaPhi, track_pT, d0TJVA, z0TJVA, dR, numberOfInnermostPixelLayerHits, numberOfPixelHits, numberOfSCTHits, charge

ATLAS Qualification Task

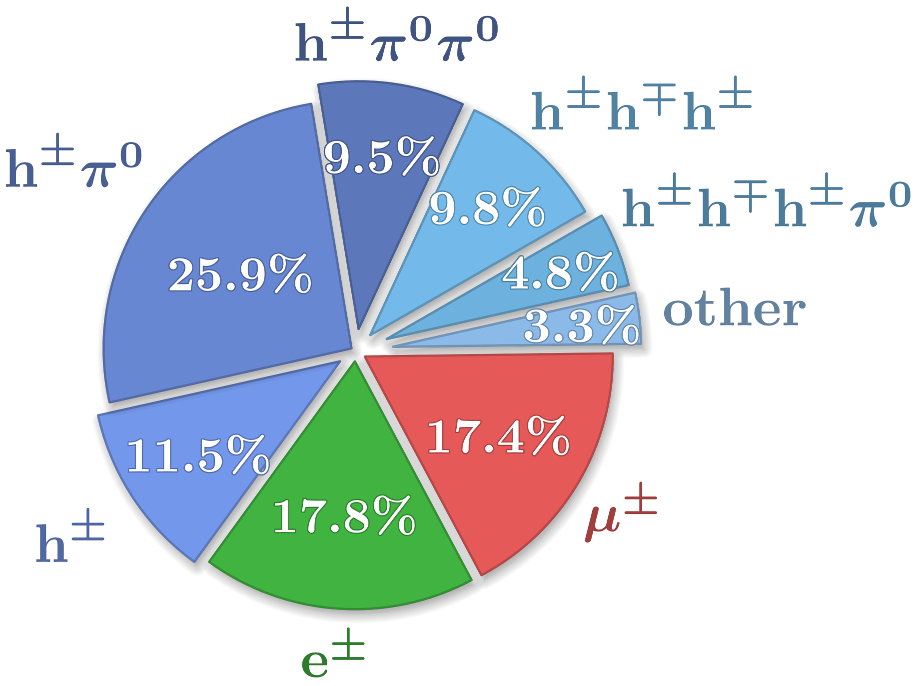
- BDT are just a series of cuts. This methods has traditionally been used in HEX to select events. BDT is just a automation and improvement of this cut based method
- Boosted comes from fact that in decision trees are NP Complete so need to run approximation algorithms which could lead to suboptimal cuts that lead to a optimal end result so want a ensemble of trees and averaging of them to find optimal result



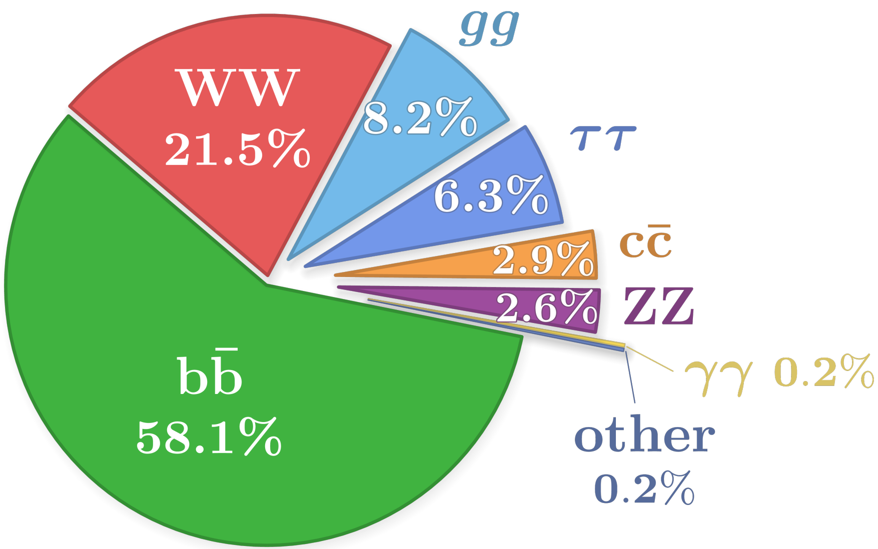
ATLAS Trigger

1. **Level-1 (Hardware Trigger):**
   - First stage of event selection
   - Uses custom hardware (FPGAs and ASICs)
   - 40 MHz to 100 kHz
   - Makes fast decisions based on limited detector information
   - Focuses on identifying high-energy objects like electrons, muons, jets, and missing transverse energy
2. **High-Level Trigger (HLT) - Level-2 and Event Filter:**
   - Software-based trigger running on a large computing farm
   - Operates in two stages: Level-2 and Event Filter
   - 100 kHz to 4 kHz
   - Performs more sophisticated and computationally intensive event reconstruction
   - Uses more detailed detector information compared to Level-1
   - Applies more complex selection criteria for physics analysis

Branching Ratios

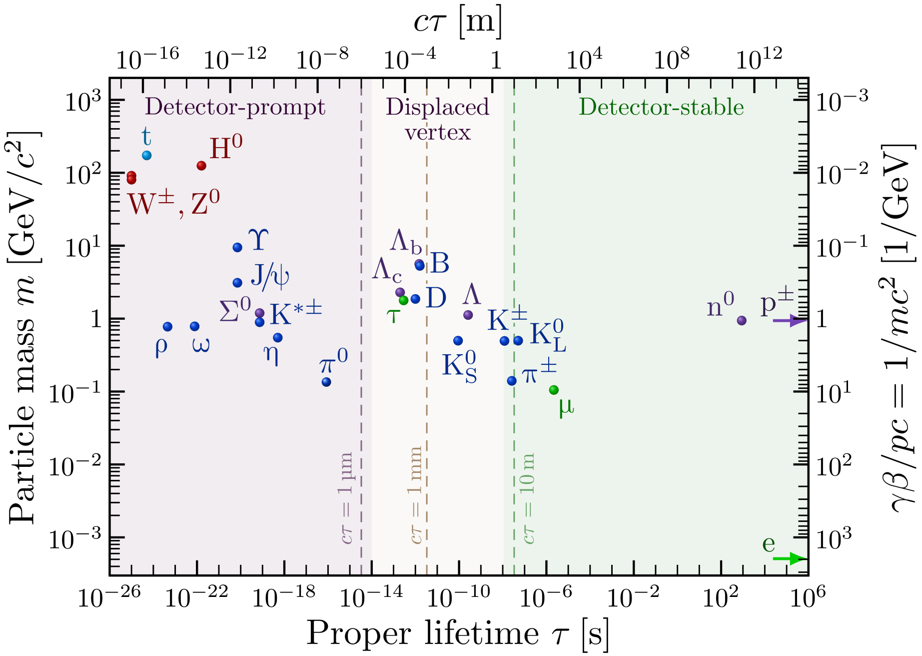


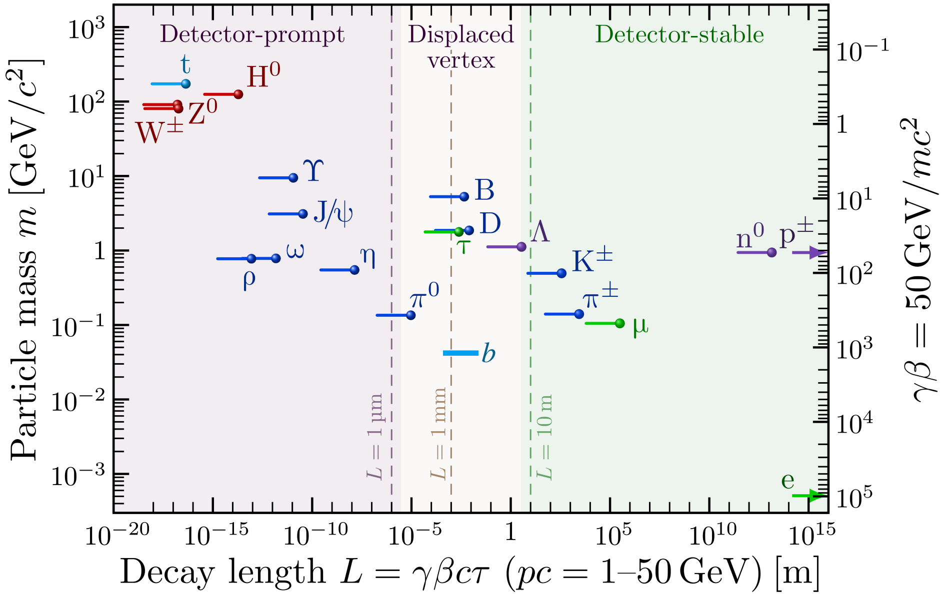
Tau decay



Higgs decay

Particle Lifetimes





Izaak Neutelings

$$\gamma\beta c\tau(\Delta R = 0.4) = \frac{pc}{mc^2}c\tau = \frac{300GeV}{1.7GeV}87\mu m = 15mm$$

The Higgs Boson

The standard model described in terms of groups:

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$\downarrow$

How do particles get their masses?

$\downarrow$

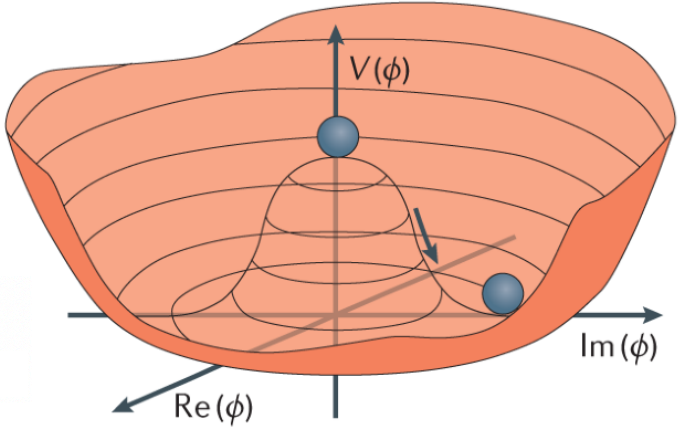
Simplified version of EWSB with just $U(1)$:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |\, D_\mu \phi \,|^2 - V(\phi)$$

$$D_\mu = \partial_\mu - ieA_\mu$$

$$V(\phi) = \mu^2 |\phi|^2 + \lambda(|\phi|)^2$$

$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4 + O(5)$$



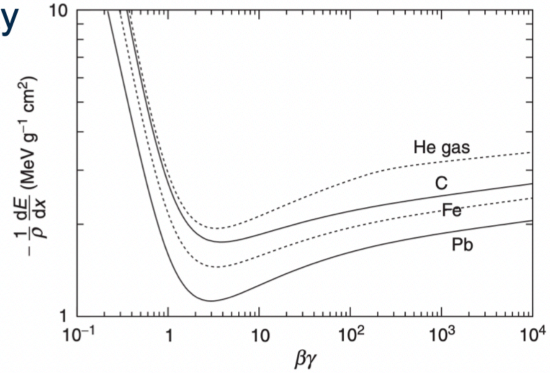
1.) $\mu^2 > 0$: potential perseveres symmetries of the Lagrangian with lowest energy state at $\phi = 0$

2.) $\mu^2 < 0$: now lowest every state is at $\langle\phi\rangle = \sqrt{-\frac{\mu^2}{2\lambda}}$

$\langle\phi\rangle$ breaks global U(1) symmetry. This gives rise to a massive photon and a scalar field h, called the Higgs boson

Jet Reconstruction

- Unstable particles produced in high-energy collisions **decay after distance** $\gamma v \tau$
  - **Long-lived particles** ($\mu^{\pm}, n, \pi^{\pm}, K^{\pm}$) can travel several meters in detectors before decaying
- All **charged particles** lose energy via **ionization**, with energy loss $\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \approx -\frac{4\pi\hbar^2c^2\alpha^2}{m_e v^2 m_u}\frac{Z}{A}\left\{\ln\left[\frac{2\beta^2\gamma^2 m_e c^2}{I_e}\right]-\beta^2\right\}$
  - Energy loss doesn't depend strongly on material except density
  - **Muons** lose energy almost entirely through ionization making them **highly penetrating**

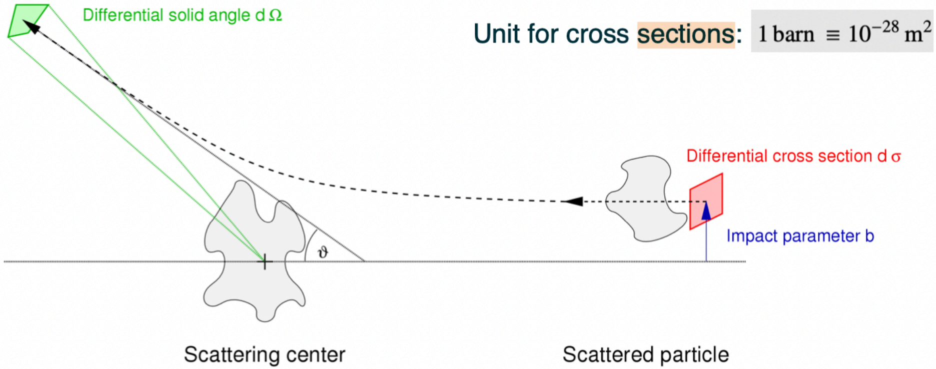


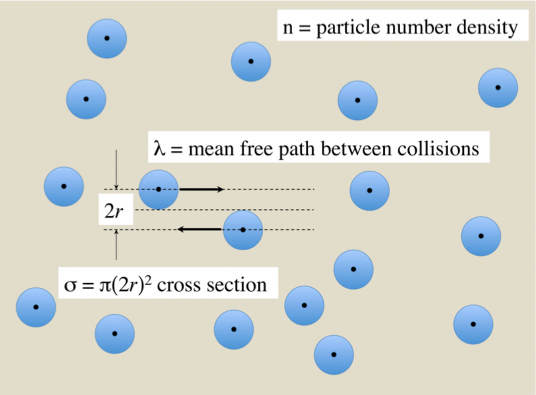
- High-energy **electrons** and **photons** lose energy through **EM cascades** (bremsstrahlung and e^+e^- pair production)
  - Dominant for electrons at $E_c \sim \frac{800}{Z}\,\mathrm{MeV}$ and photons at $E_\gamma > 10\,\mathrm{MeV}$
  - Energy reduced by 1/e after radiation length $X_0 \approx \frac{1}{4\alpha n Z^2 r_e^2 \ln(287/Z^{1/2})}$
- **Charged hadrons** can interact with nuclei via strong force, creating **hadronic cascades** which can vary in structure depending on interaction
  - Often contain **EM component** via production of $\pi^0 \rightarrow \gamma\gamma$.

Luminosity and Cross Section

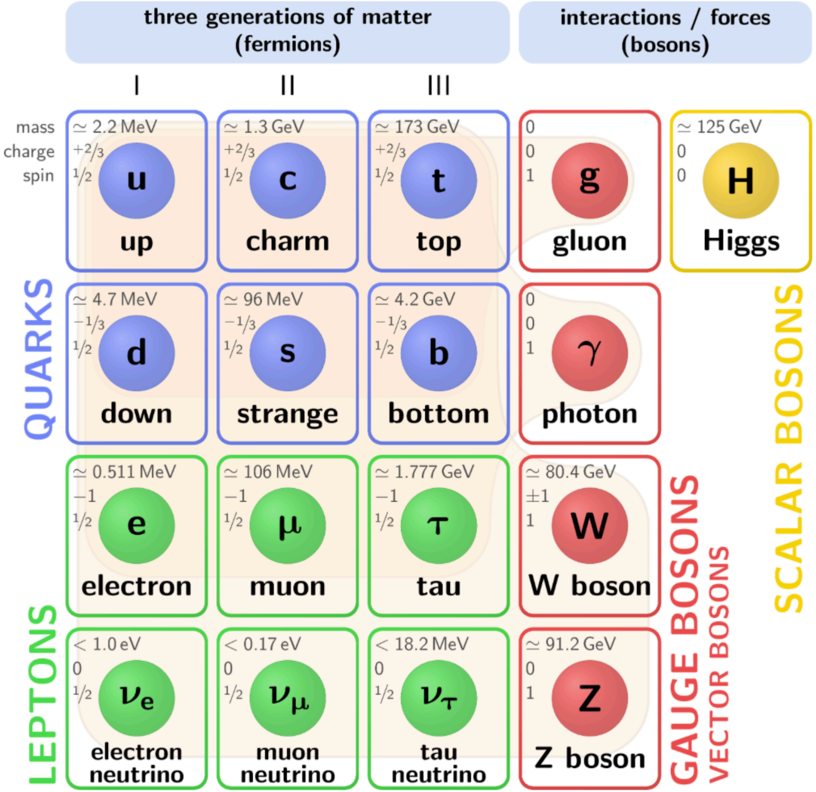
- **Partial decay rates** (or widths) describe rate at which initial state particle decays to particular final state which **sum to the total decay width** $\Gamma = \sum_j \Gamma_j$, related to the lifetime $\tau = \frac{1}{\Gamma}$
  - **Branching ratios** are given by $BR(j) = \frac{\Gamma_j}{\Gamma}$.
- Cross sections are **ratio between interaction rate** per target particle and **incident particle flux**
  - Differential cross sections can express angular/energy dependence as $\frac{d\sigma}{d\Omega}$, or $\frac{d\sigma}{dE}$
- **Instantaneous luminosity** relates interaction rate to cross section in colliders $\frac{dN}{dt} = \mathscr{L}_{\text{inst}} \times \sigma$ where $\mathscr{L}_{\text{inst}} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$

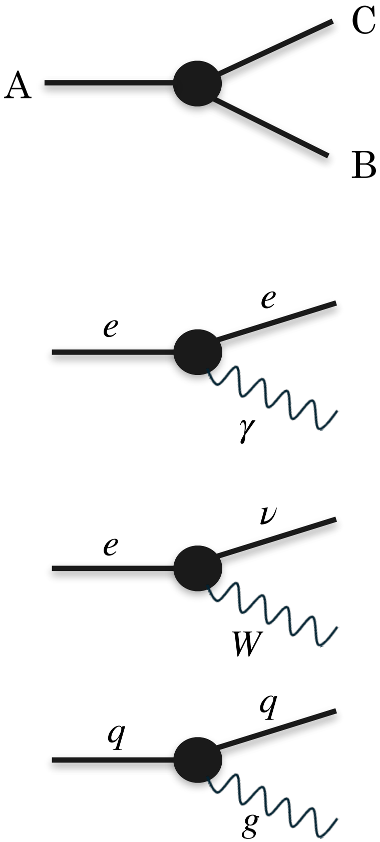
Unit for cross sections: $1\,\text{barn} \equiv 10^{-28}\,\text{m}^2$





The Standard Model





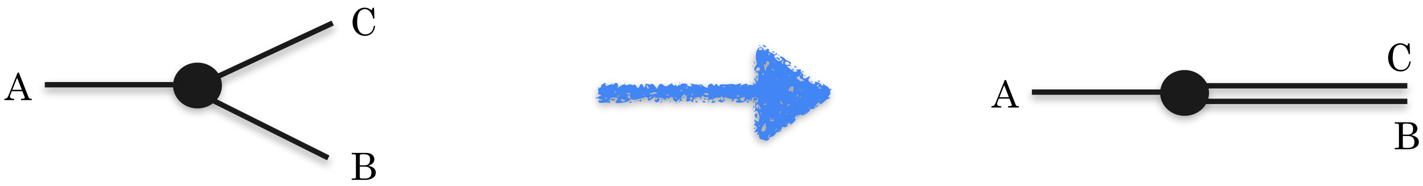
α_{EM}

α_{weak}

α_{strong}

$3 \neq 2$

Focusing on very small scales (high energies)
In this limit $E \approx p \implies m = 0$

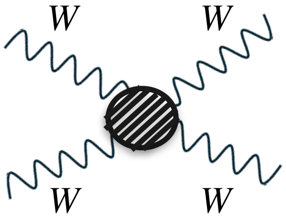


Massive particle has Spin with **3 degrees of freedom**

Massless particle also has spin (helicity) but with **2 degrees of freedom**

Divergences

We consider the scattering of W bosons. Again assuming they are near this **massless** limit.



$$Amplitude = |probability|^2 \propto \alpha^2 \left(\frac{E}{m_W} \right)^2$$

At around energy values of **1000 GeV this breaks**. Meaning we need new physics to avoid this.

The Need for New Physics

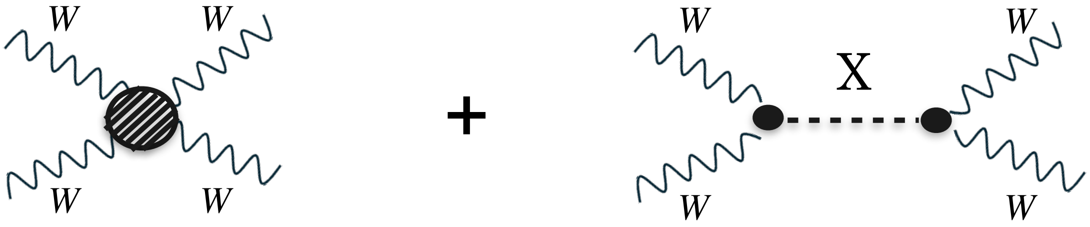
We need something new in this range
Within range of LHC!

…

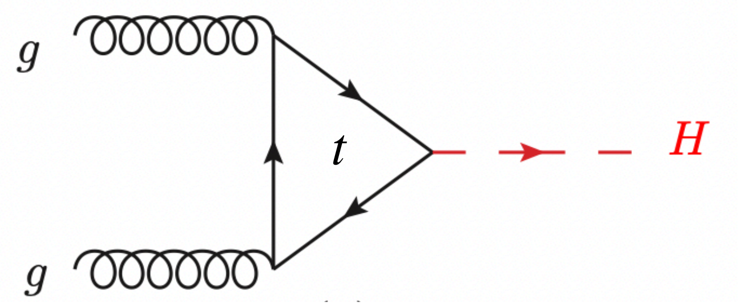
80 GeV

1000 GeV

Planck scale



$1 = 1$



Higgs Spin = 0
Massless degrees of freedom = 1

Higgs Spin = 0
Massive degrees of freedom = 1

Why isn't the Higgs mass enormous?

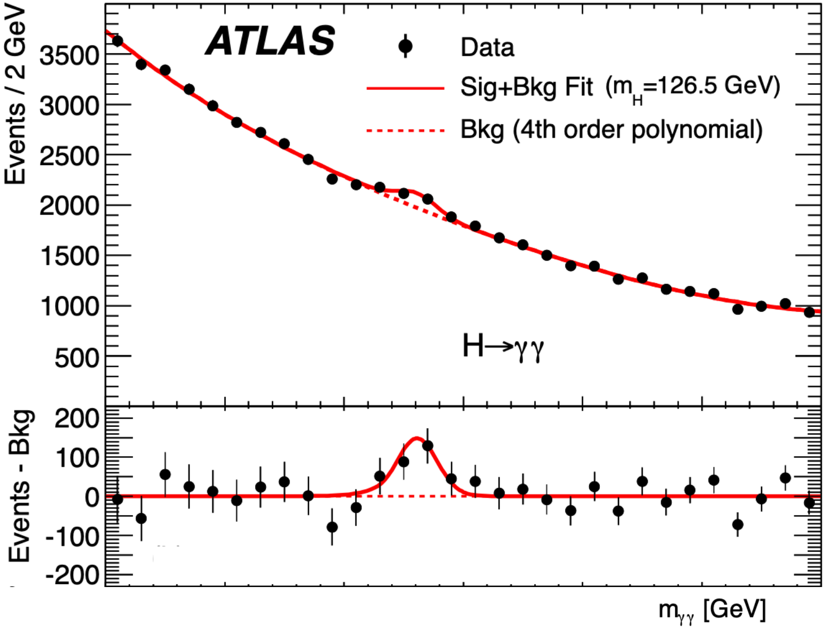
S = 0

What options do we have?

At long distances we have spin choices of
$(0, 1/2, 1, 3/2, 2)$

$$X_{spin=0} = Higgs$$

We first measured the Higgs mass in 2012 at 125 GeV

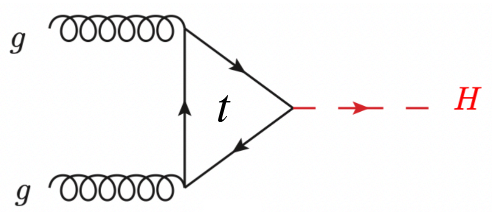


arXiv:1207.7214

Higgs Production at the LHC

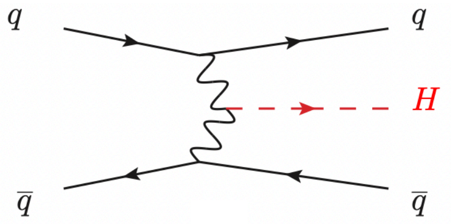
Gluon Fusion (ggF)

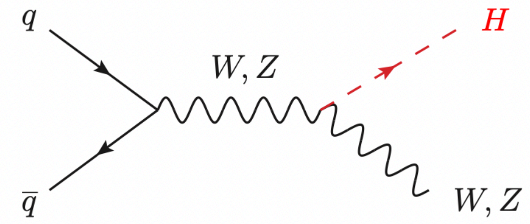
~ 88%



Vector Boson Fusion (VBF)

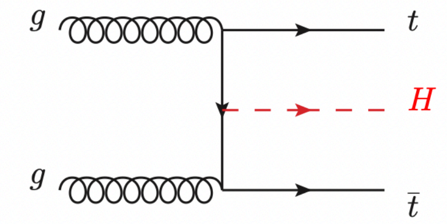
~7%





Higgs-strahlung (VH)

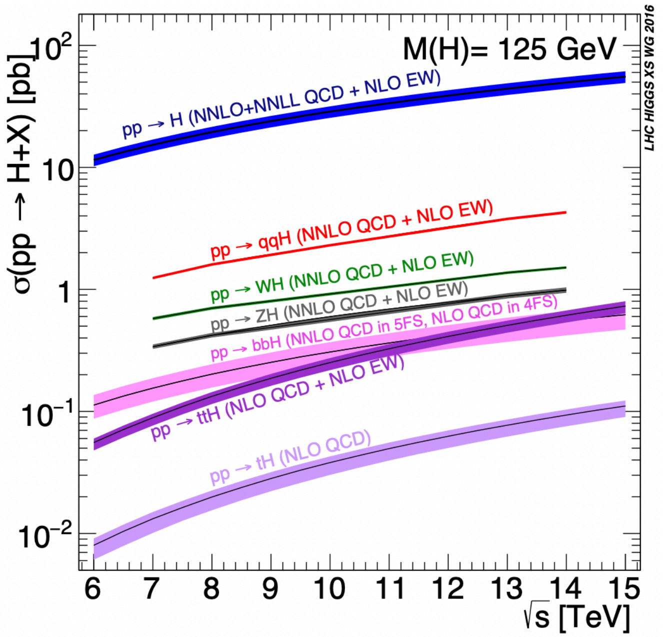
~4%



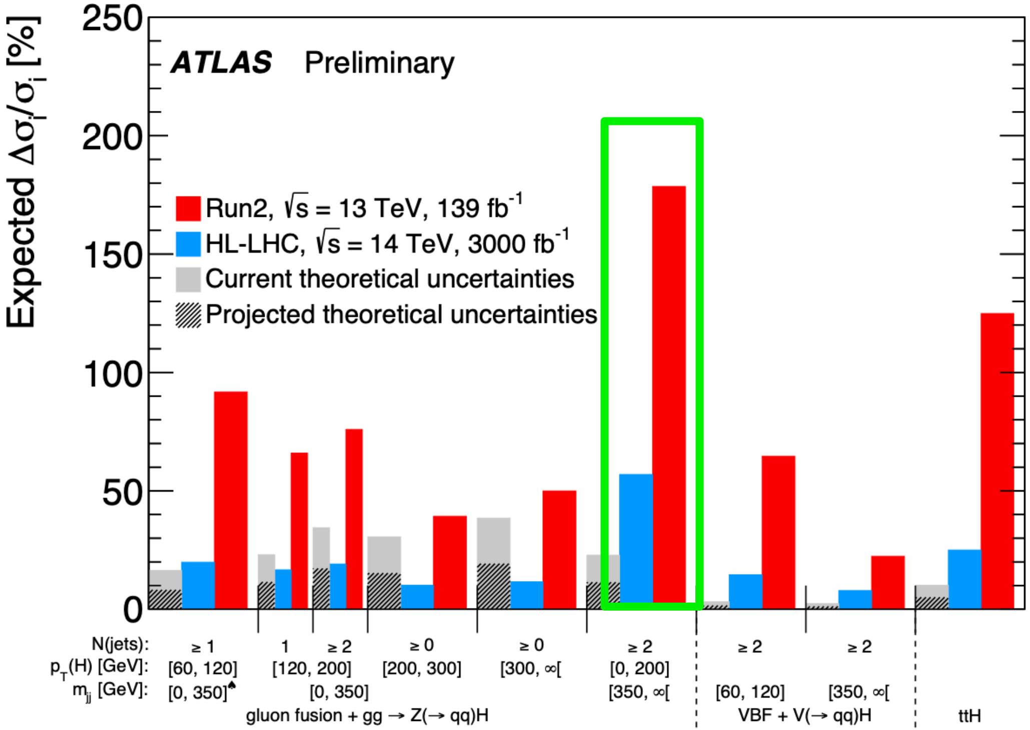
Top-Higgs Production (ttH)

~1%

PDG



Higgs Measurement Improvements at HL-LHC



arXiv:2307.07772

Expect a 120% reduction in cross-section uncertainty in ggH channel at p_T values

All Dimension-6 Operators Considered

All the operators that are considered in the papers:

y: modify Top Yukawa,
H: modify kinematic terms of the Higgs field,
g: introduce direct coupling between Higgs and gluon,
~g: introduce CP-violating coupling between Higgs and gluon

But in the papers only consider CP-conserving effects are considered so the last term drop out.

$$\mathcal{O}_y = \frac{y_t}{v^2}|H|^2\bar{Q}_L\tilde{H}t_R\ , \qquad \mathcal{O}_H = \frac{1}{2v^2}\partial_\mu|H|^2\partial^\mu|H|^2\,,$$

$$\mathcal{O}_g = \frac{\alpha_s}{12\pi v^2}|H|^2G^a_{\mu\nu}G^{a\,\mu\nu}\,, \qquad \widetilde{\mathcal{O}}_g = \frac{\alpha_s}{8\pi v^2}|H|^2G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu}\,,$$

$$\kappa_t = 1 - \mathrm{Re}(C_y) - C_H/2 \qquad \kappa_g = C_g$$

Details of δ and ϵ

1. **Matrix Element Structure:** The total matrix element for Higgs production is a sum of the SM (top-Yukawa dominated) contribution M_{IR} and the new physics (direct gluon-Higgs interaction) contribution M_{UV}:

$$M_{\text{total}} = c_t M_{\text{IR}} + \kappa_g M_{\text{UV}}.$$

2. **Cross-Section:** The cross-section depends on the **squared modulus** of M_{total}:

$$|M_{\text{total}}|^2 = |c_t M_{\text{IR}}|^2 + |\kappa_g M_{\text{UV}}|^2 + 2\text{Re}(c_t M_{\text{IR}} \kappa_g^* M_{\text{UV}}^*).$$

   - The first term is the pure SM contribution ($|M_{\text{IR}}|^2$).
   - The second term is the pure new physics contribution ($|M_{\text{UV}}|^2$).
   - The third term is the interference ($\text{Re}(M_{\text{IR}} M_{\text{UV}}^*)$).

3. **Normalized Cross-Section:** When normalizing by the SM cross-section, you divide by $|M_{\text{IR}}|^2$. This introduces:
   - $\delta(p_T^{\text{cut}})$ to capture the interference's relative importance.
   - $\epsilon(p_T^{\text{cut}})$ to capture the quadratic term's relative importance.

4. **Dependence on p_T^{cut}:** Both δ and ϵ are integrals over p_T above a certain threshold p_T^{cut}. At high p_T, the relative contributions of M_{IR} and M_{UV} change, leading to increasing sensitivity to κ_g.

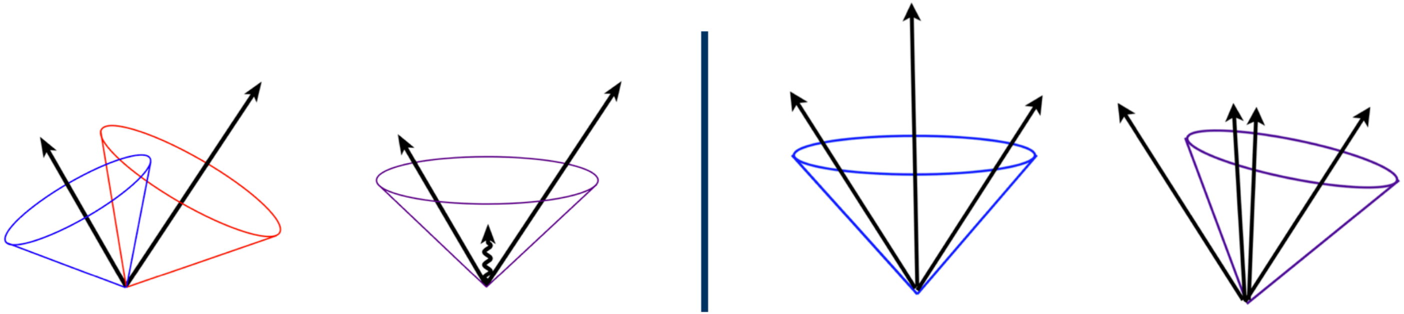
$$\delta(p_T^{\text{cut}}) = \frac{2\int_{p_T^{\text{cut}}}^{\infty} dp_T d\Omega Re(\mathcal{M}_{IR}(m_t)\mathcal{M}_{UV}^*)}{\int_{p_T^{\text{cut}}}^{\infty} dp_T d\Omega |\mathcal{M}_{IR}(m_t)|^2} - 2,$$

$$\epsilon(p_T^{\text{cut}}) = \frac{\int_{p_T^{\text{cut}}}^{\infty} dp_T d\Omega |\mathcal{M}_{UV}|^2}{\int_{p_T^{\text{cut}}}^{\infty} dp_T d\Omega |\mathcal{M}_{IR}(m_t)|^2} - 1.$$

Anti-Kt Algorithm

- Jet reconstruction should not be affected by additional soft radiation or collinear splitting (**infrared** and **collinear safety** - or IRC safety) which is common in higher order QCD
- **Sequential recombination algorithms** build jets by calculating inter-particle $d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$ and beam distances $d_{iB} = k_{ti}^{2p}$ where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and R, p are parameters
  - If d_{ij} is the smallest of these, i and j are combined and process repeats
  - If d_{iB} is the smallest of these, the item i is called a jet and removed

$k_t = p_T$
y = *rapidity*



Infrared unsafety

Collinear unsafety

How SUSY can Effect the Kappas

1. Supersymmetry (SUSY):

- **Stop Quarks:**
  - In SUSY, the stop quarks ($\tilde{t}_1$ and $\tilde{t}_2$) appear in the gluon-Higgs loop and modify the gluon fusion cross-section.
  - Their contribution affects both c_t (through changes in the top Yukawa coupling) and κ_g (by adding a new loop-induced interaction).
- **Implications for EFT:**
  - SUSY predicts specific relations between c_t, κ_g, and the stop masses $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, and mixing parameters like A_t:

$$\Delta c_t \propto \frac{\mu A_t}{m_{\tilde{t}_1}^2}, \quad \Delta \kappa_g \propto \frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2}.$$

  - This means the EFT coefficients are calculable from SUSY parameters.

How MCHM can Effect the Kappas

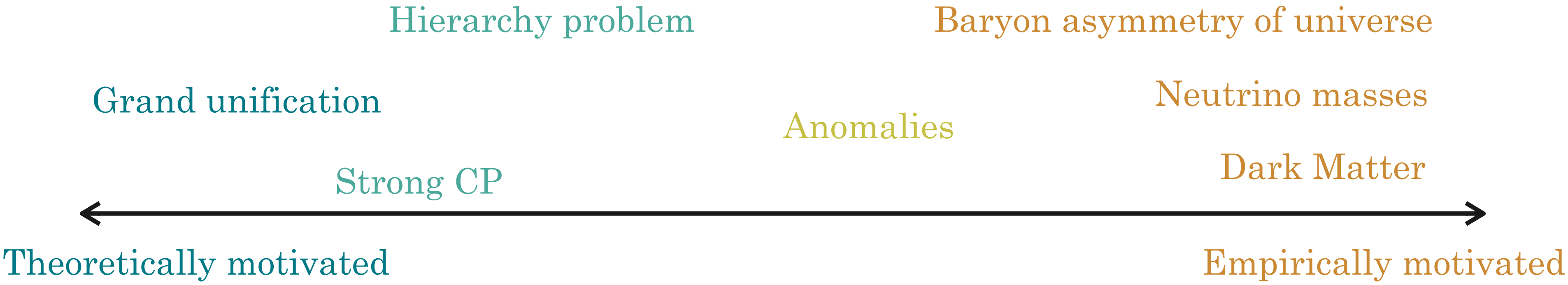
2. Minimal Composite Higgs Model (MCHM):

- **Top Compositeness:**
  - In MCHM, the top quark is partially composite, leading to modified top Yukawa couplings. This affects c_t, which deviates from its SM value of 1.
- **Heavy Resonances:**
  - MCHM introduces new fermionic resonances that contribute to the gluon fusion loop, modifying κ_g.
- **Implications for EFT:**
  - MCHM predicts specific forms for the EFT coefficients. For example:

    $$c_t \sim 1 - \xi, \quad \kappa_g \sim \xi,$$

    where $\xi = v^2/f^2$ is a parameter describing the Higgs compositeness scale (f is the decay constant of the composite sector).

Beyond The Standard Model



Hierarchy problem

Baryon asymmetry of universe

Grand unification

Neutrino masses

Anomalies

Dark Matter

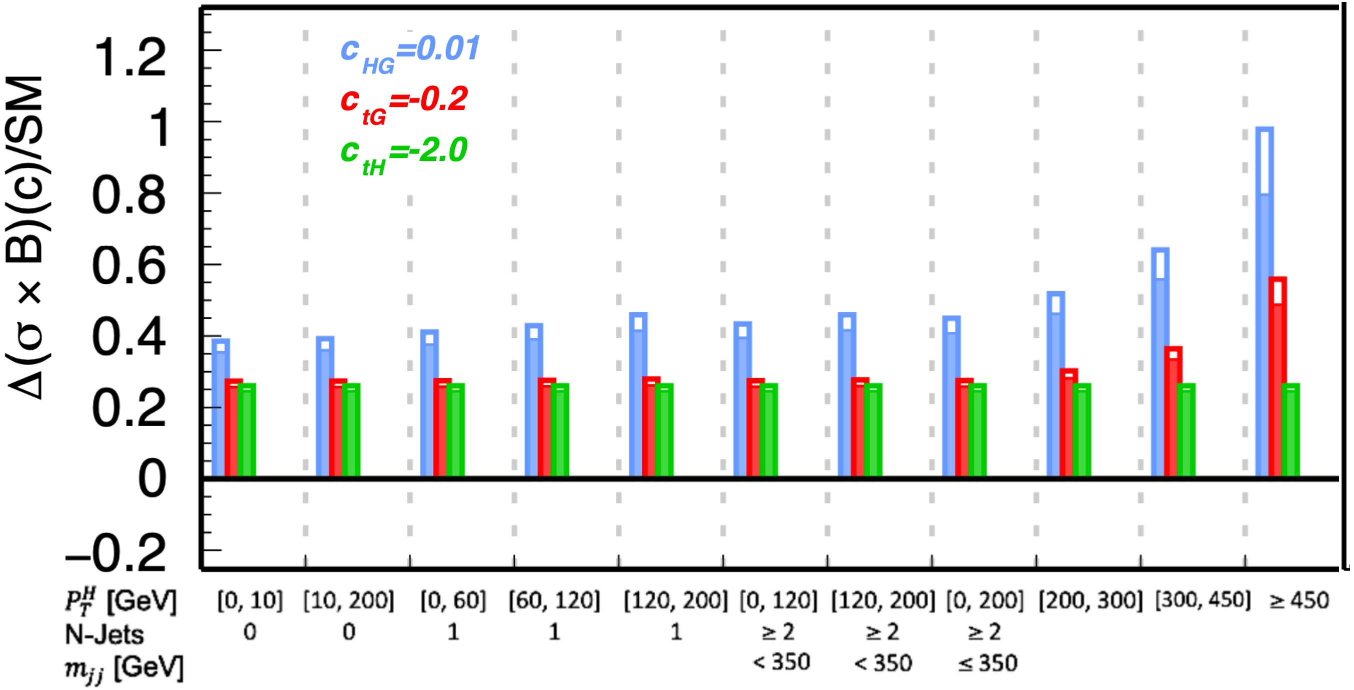
Strong CP

Theoretically motivated

Empirically motivated

Many motivations for new physics beyond the standard model

EFT Enhancements



arXiv:2402.05742

In EFT interpretation large p_T^H regions show enhanced sensitivity to c_{HG}