Pablo Martínez Agulló
PhD thesis defence
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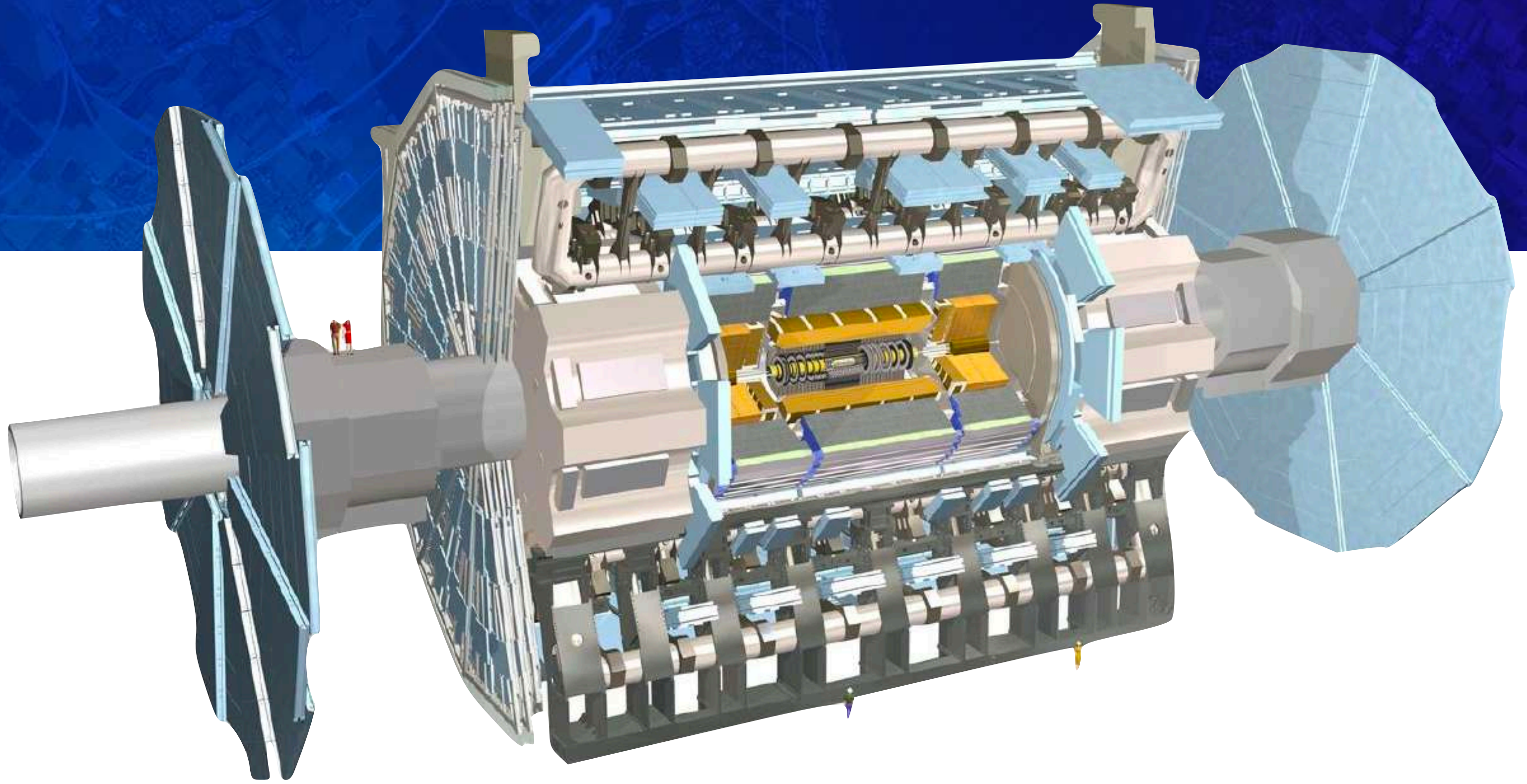
Search for the Higgs boson produced in association with a top quark using τ leptons with ATLAS

INSTITUT DE FÍSICA CORPUSCULAR · CSIC Consejo Superior de Investigaciones Científicas · Vniversitat de València · Gobierno de España · Ministerio de Ciencia e Innovación · ATLAS Experiment

Outline



1. Introduction
2. Experimental setup
3. Analysis & results
4. Summary & conclusions

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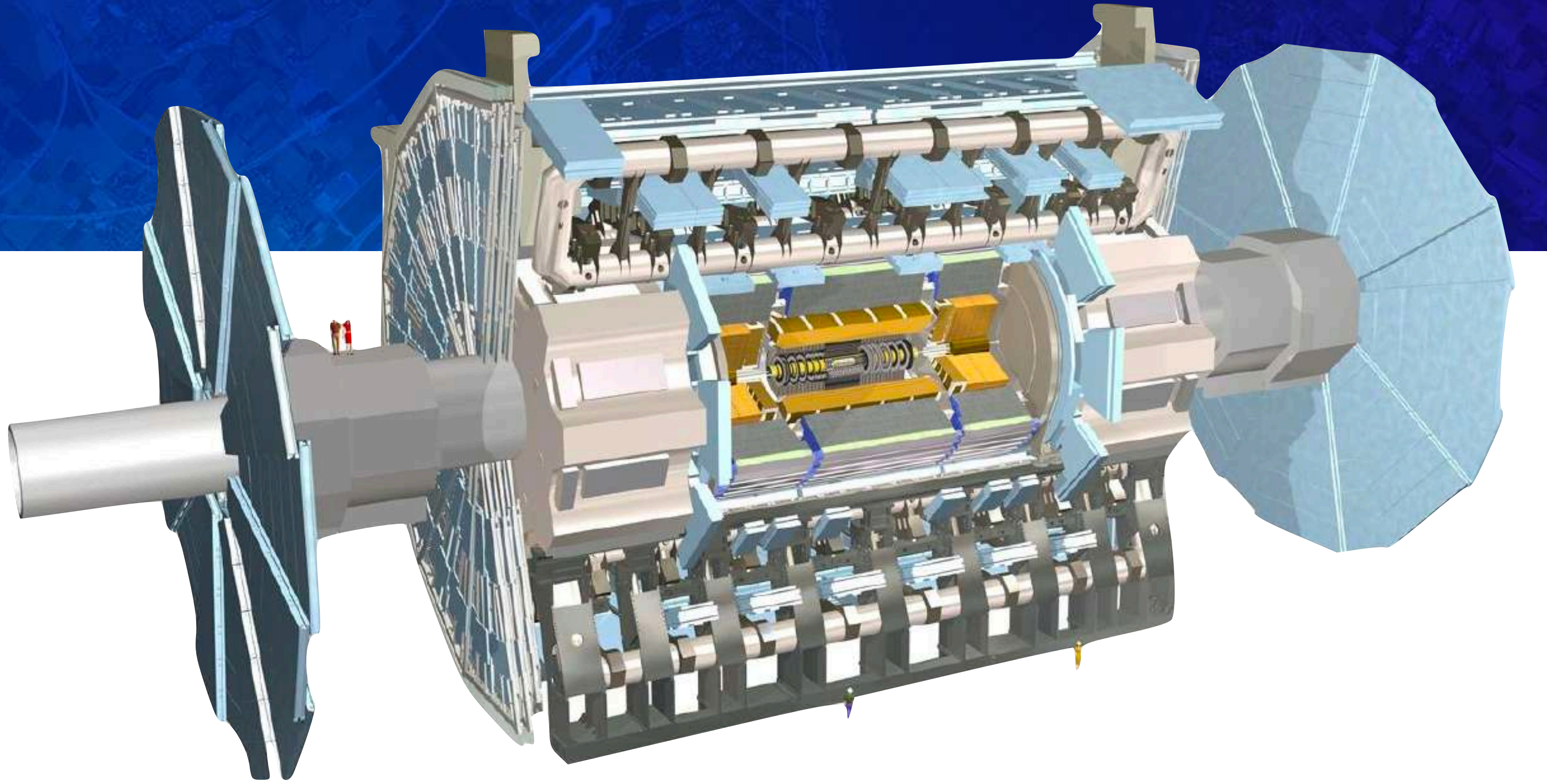

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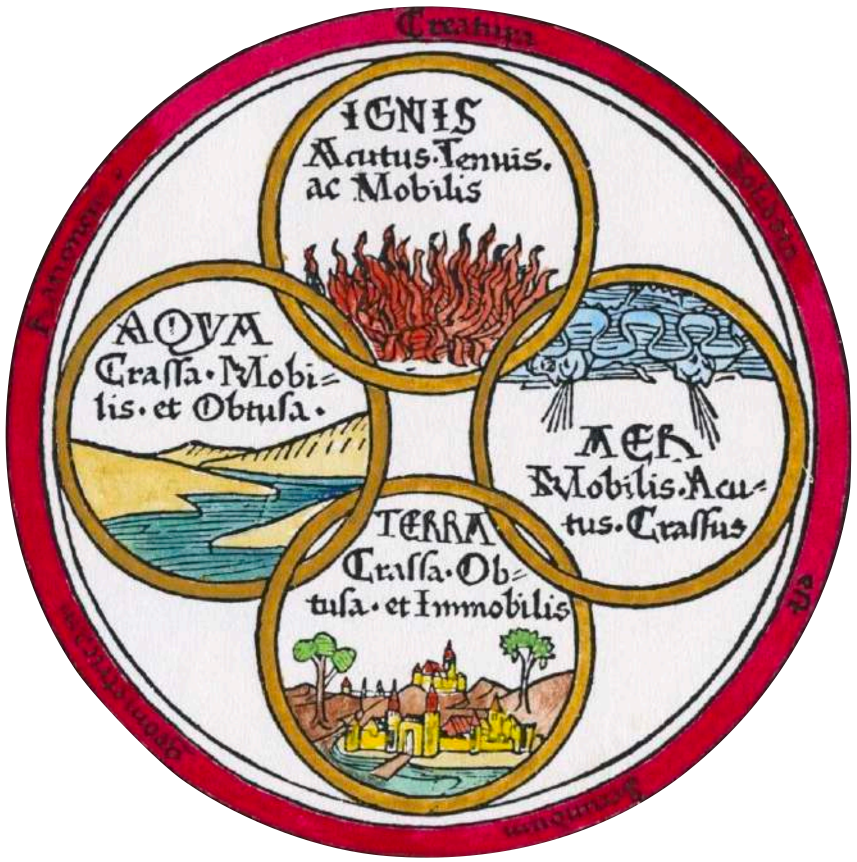
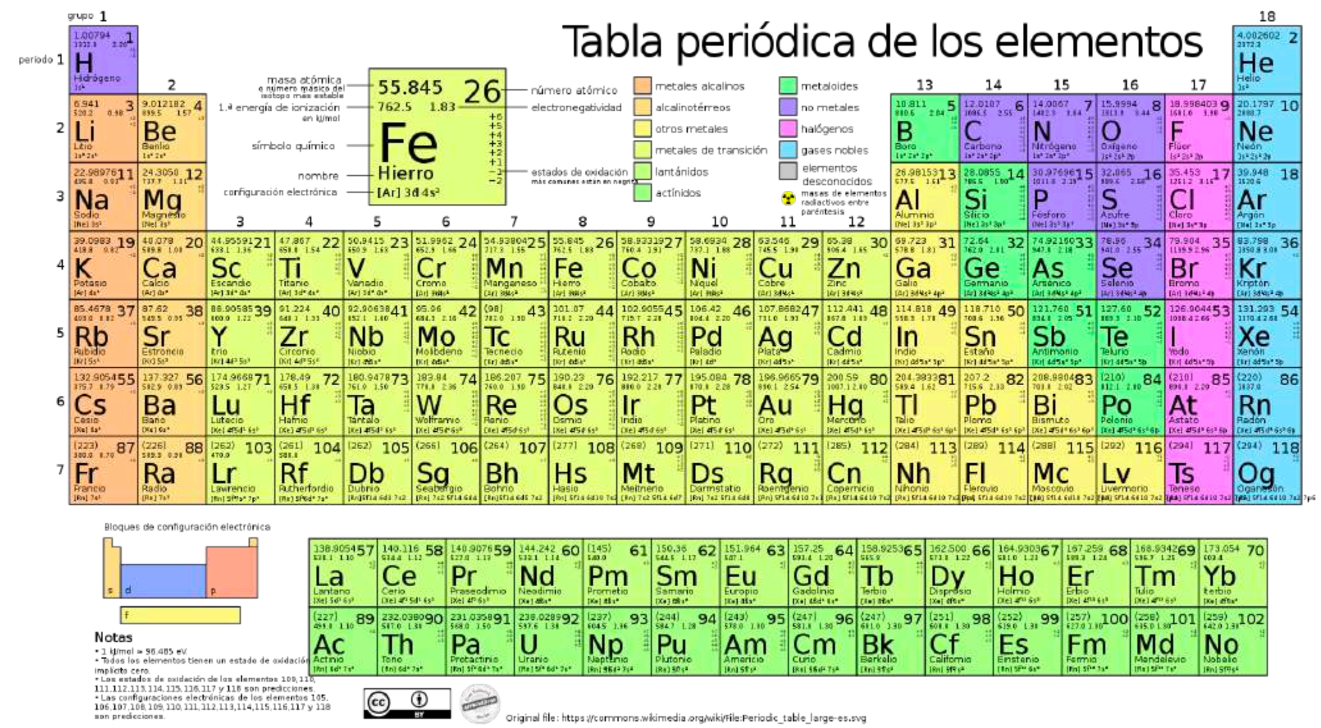
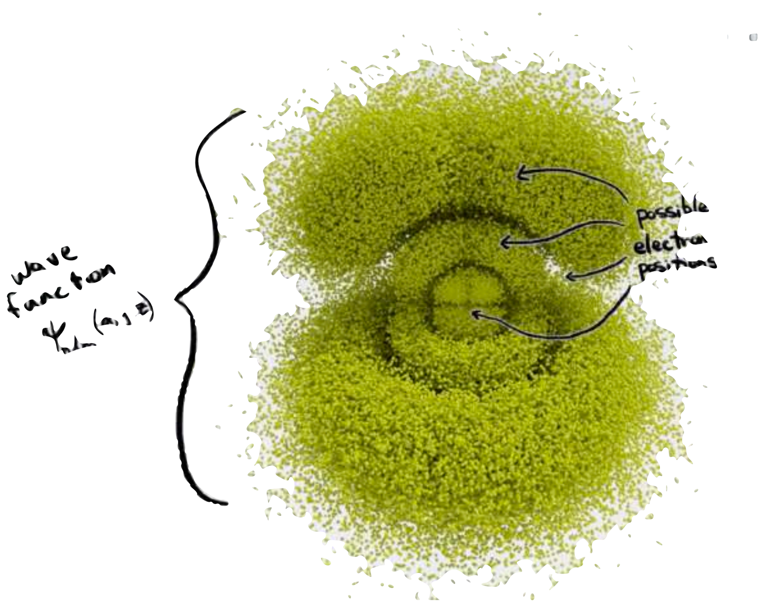
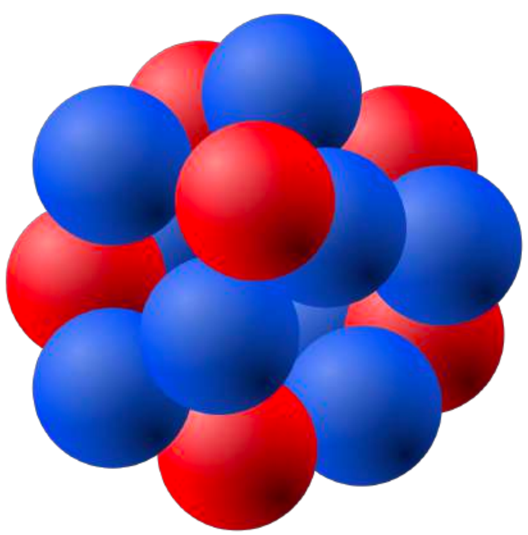
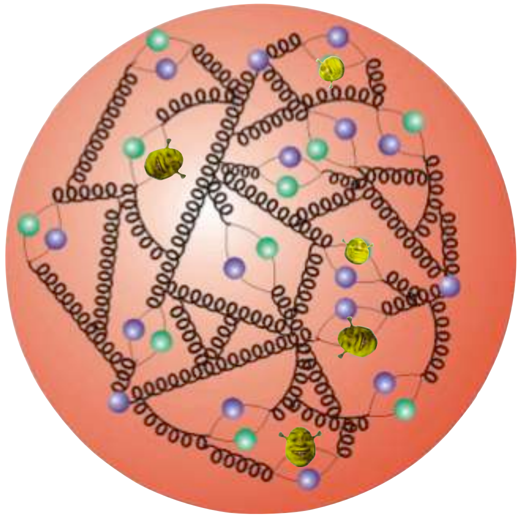
The pursue of knowledge





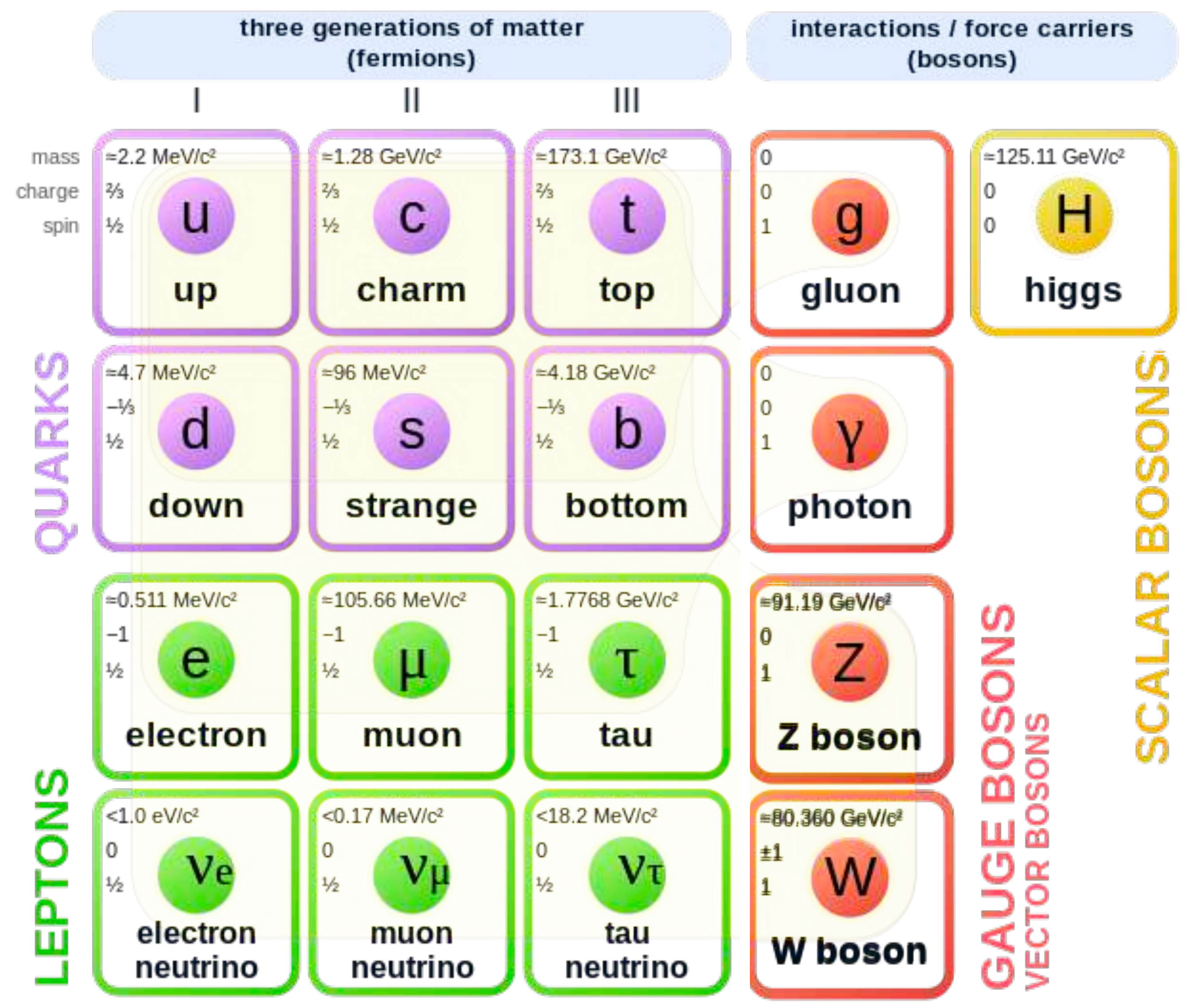






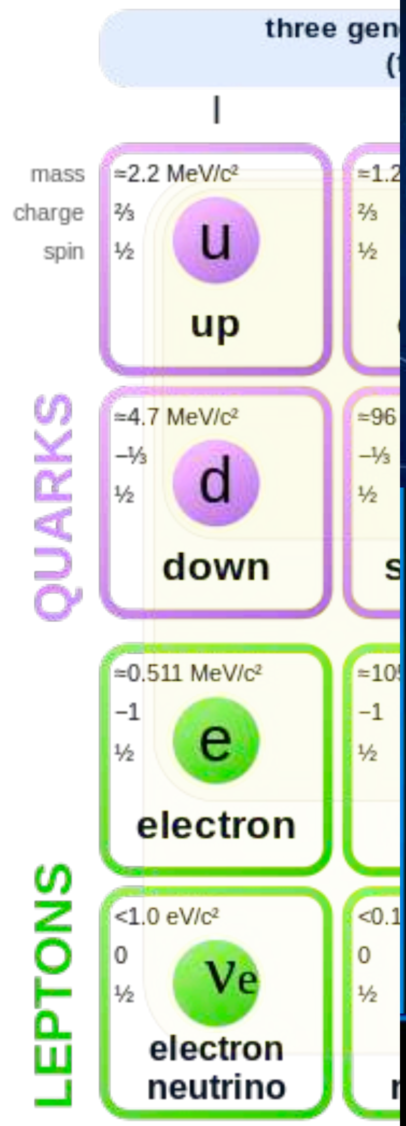
The Standard Model

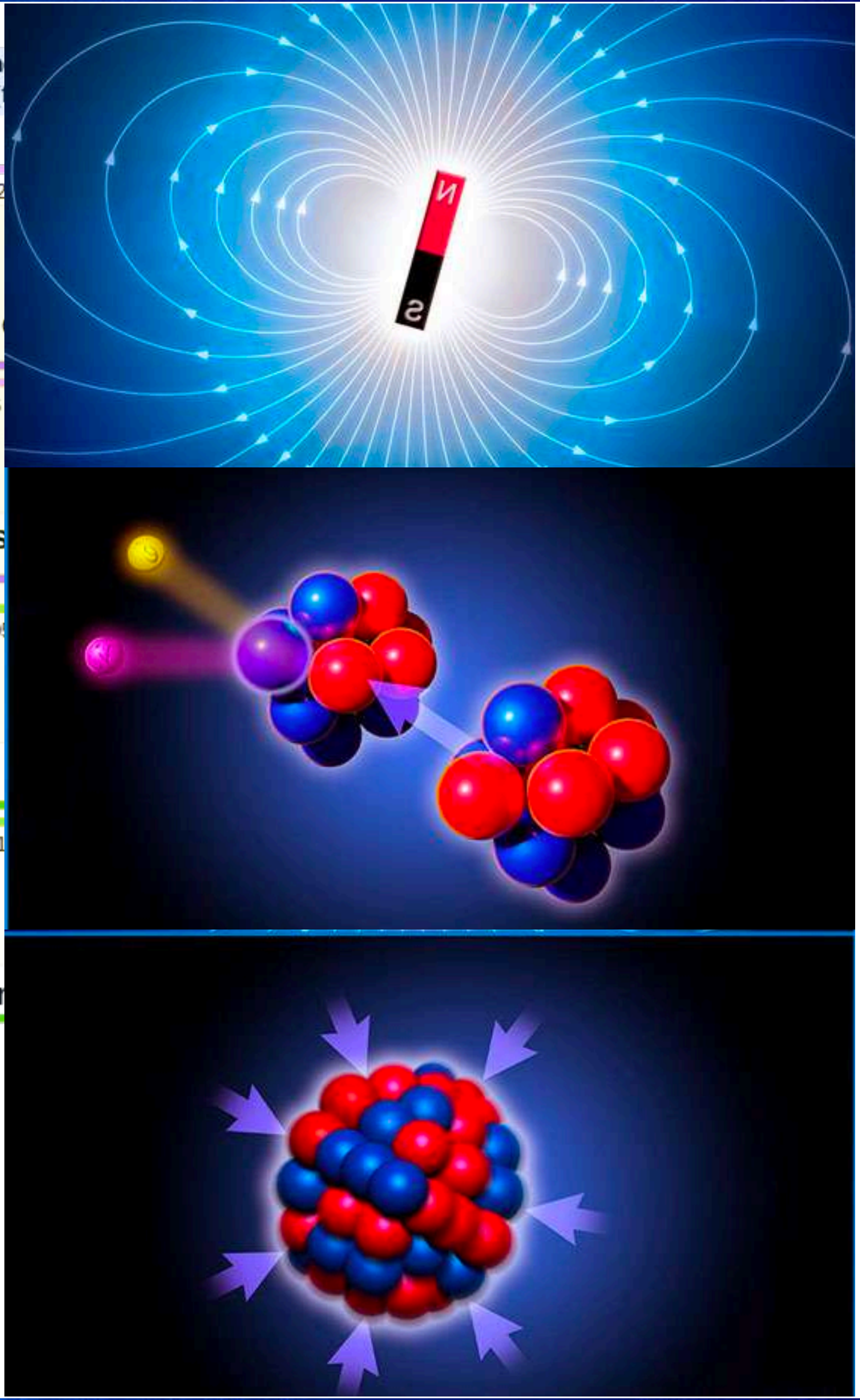
- Fundamental particles:
    - Fermions <— Matter
    - Gauge bosons <—Force carriers
    - Higgs boson <— Mass provider



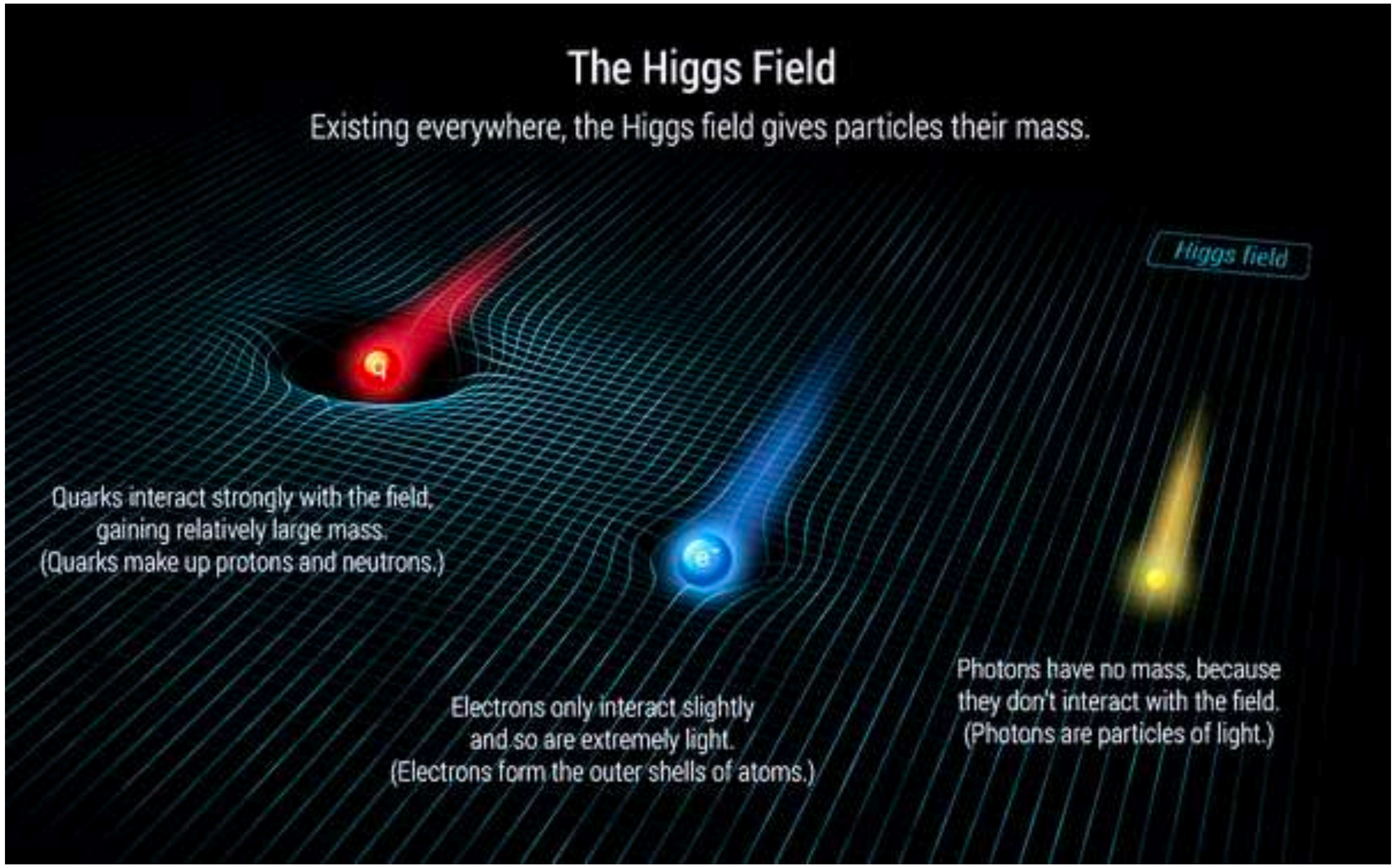
The Standard Model

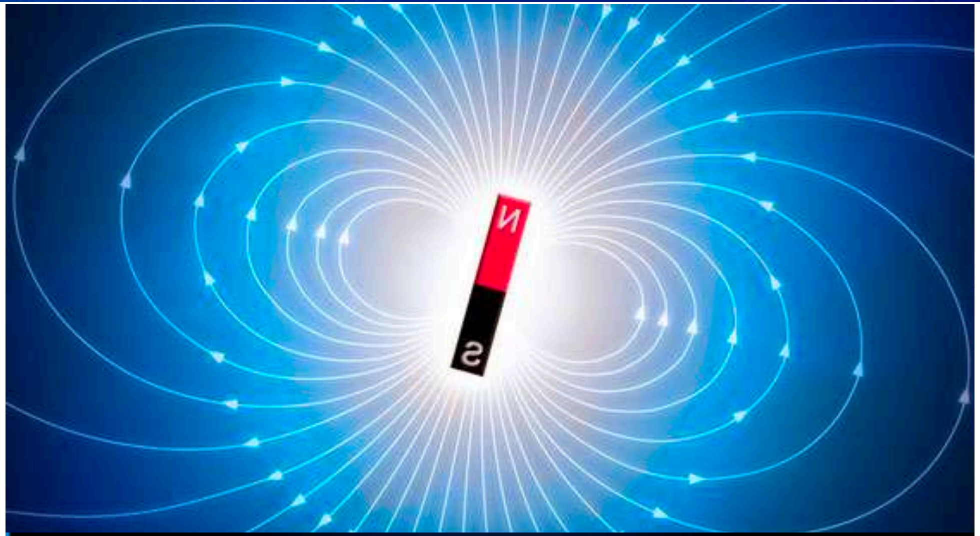
- Fundamental particles:
  - Fermions <— Matter
  - Gauge bosons <—Force carriers
  - Higgs boson <— Mass provider
- Describes all interactions except gravity
  - Electromagnetic <—γ
  - Weak <— $Z, W^{\pm}$
  - Strong <— g

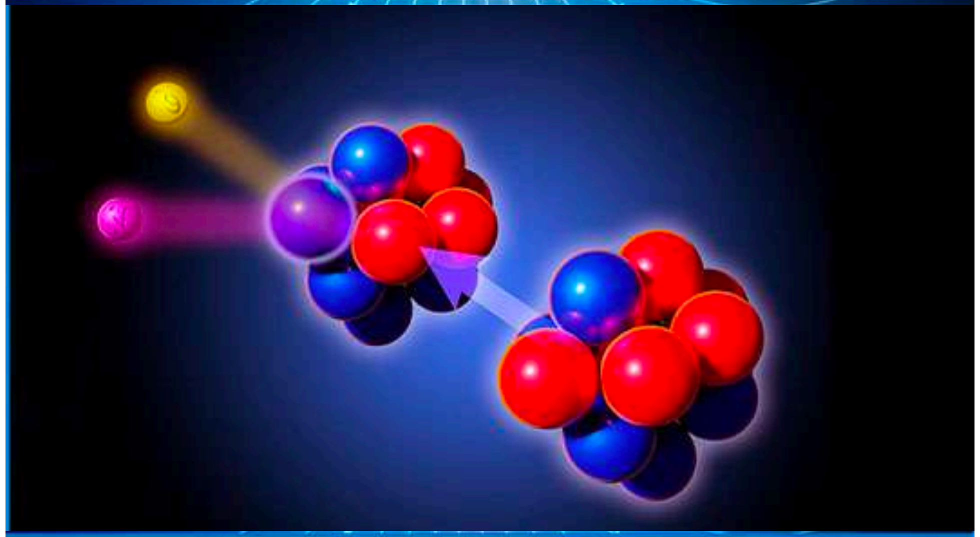


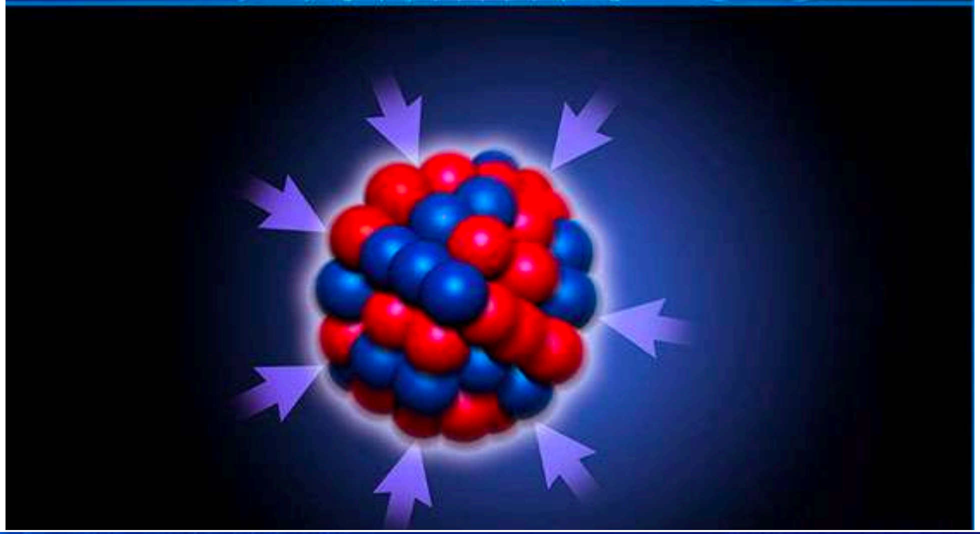


The Standard Model









- Mass:
    - Higgs field

Open question in the SM

Standard Model

Open question in the SM

Phenomena not explained

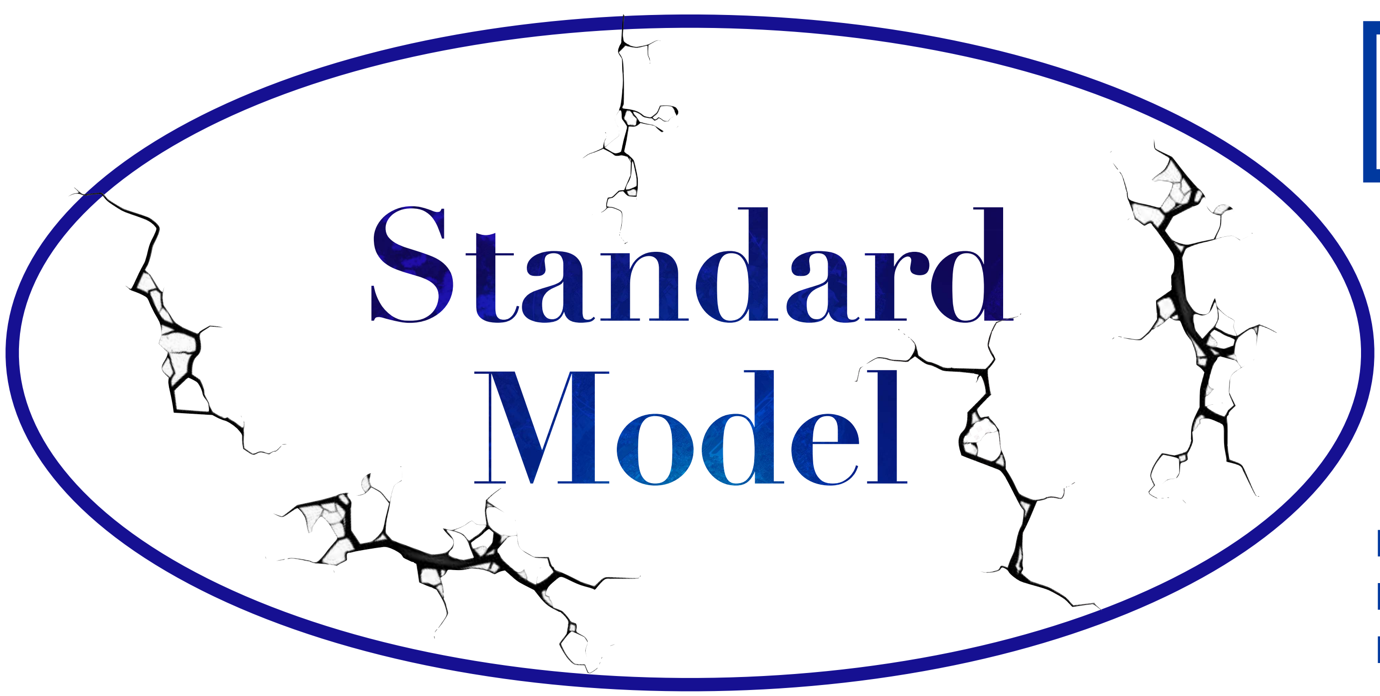
Theoretical problems

Neutrino masses and oscillations

Dark matter

Dark energy

Gravity



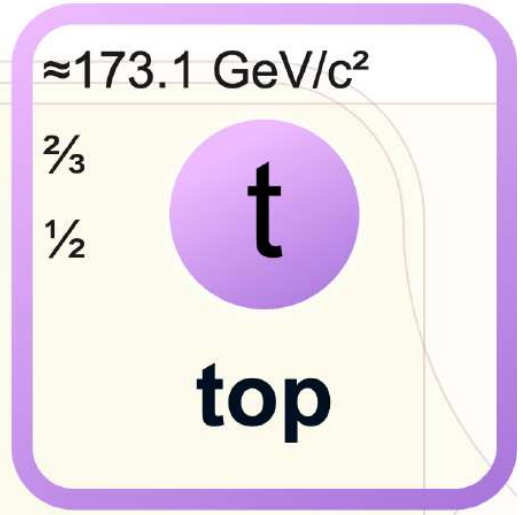
Flavour puzzle

Matter-antimatter asymmetry
(CP violation)

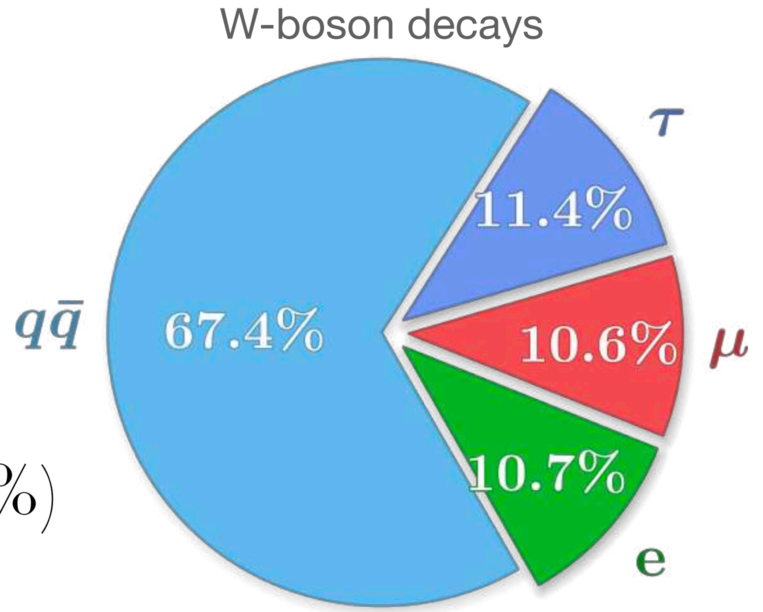
Hierarchy problem

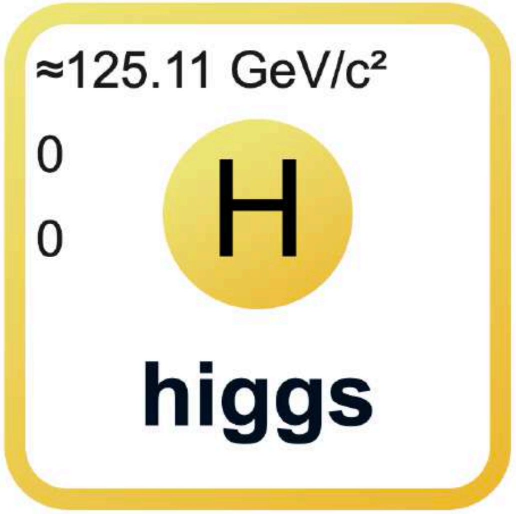
Strong CP problem

Top quark and Higgs boson

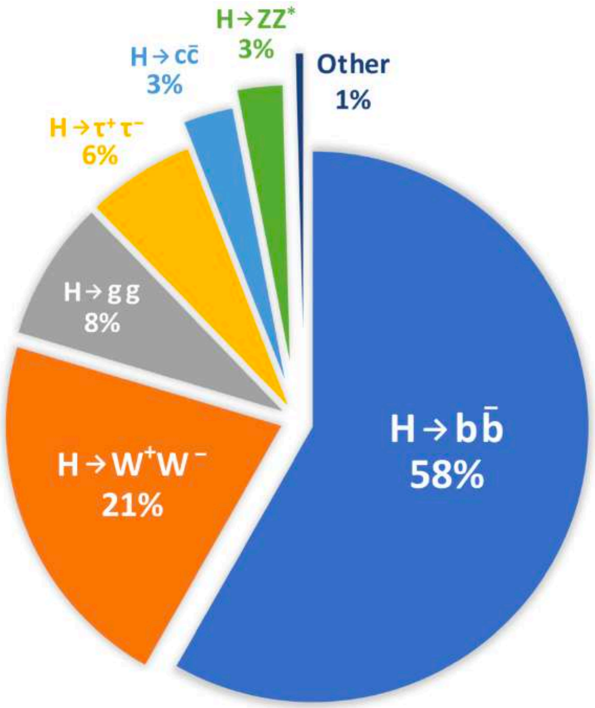


- Discovered in 1995 at Tevatron (Fermilab)
- Heaviest known elementary particle
- Very short lifetime $\tau_t = 5 \times 10^{-25}$ s
  - Decays before hadronising
  - Decays to W boson and a b quark (99%)
- Largest Yukawa coupling to Higgs boson





- Discovered in 2012 at LHC (CERN)
- Higgs field, SSB
- The mass elementary particles: Uniquely determined by its **coupling** strength to Higgs
- Short lifetime $\tau_H = 1.6 \times 10^{-22}$ s

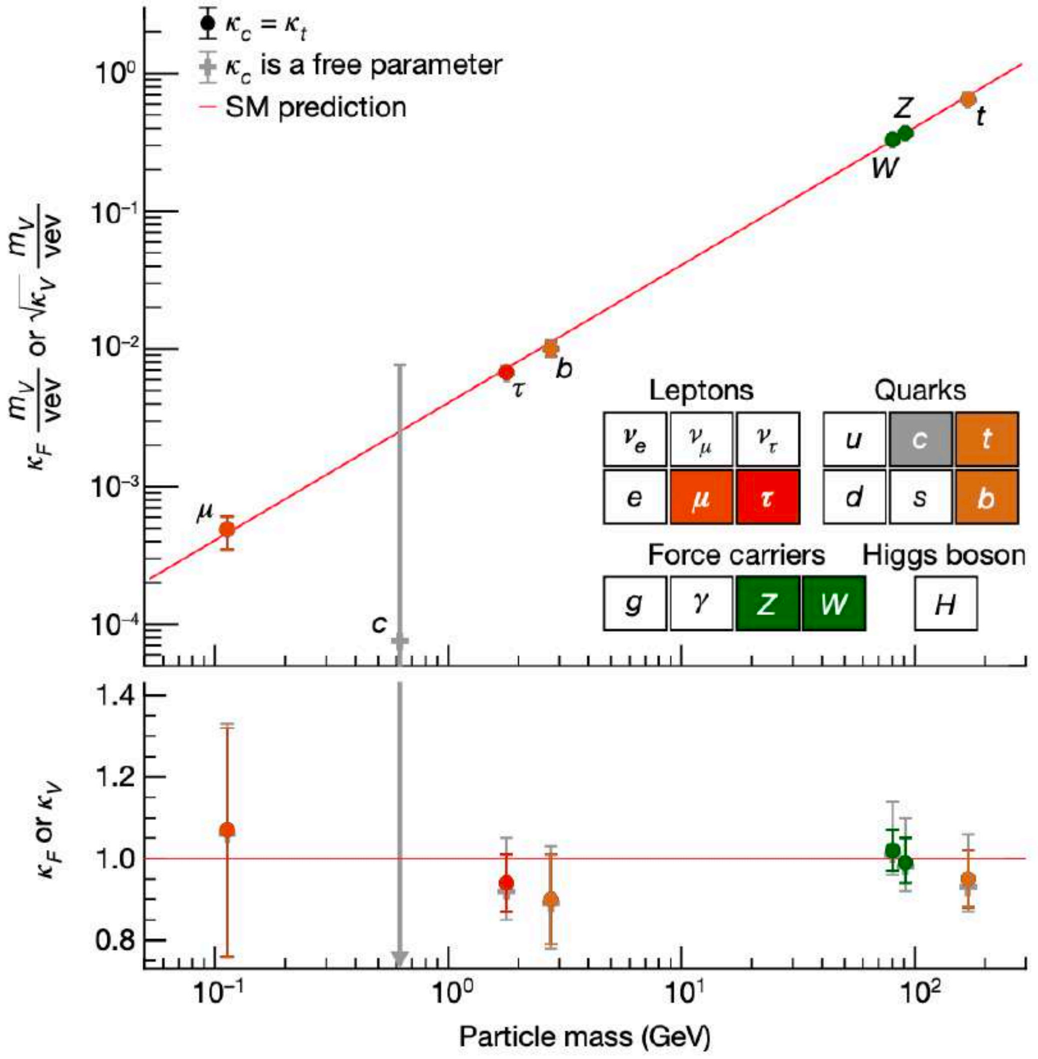


Top-Higgs interplay

- The mass of elementary particles: Determined by its **coupling** strength to Higgs

- Particular interest: The **Yukawa coupling to top quarks** ($y_t \simeq 1$)

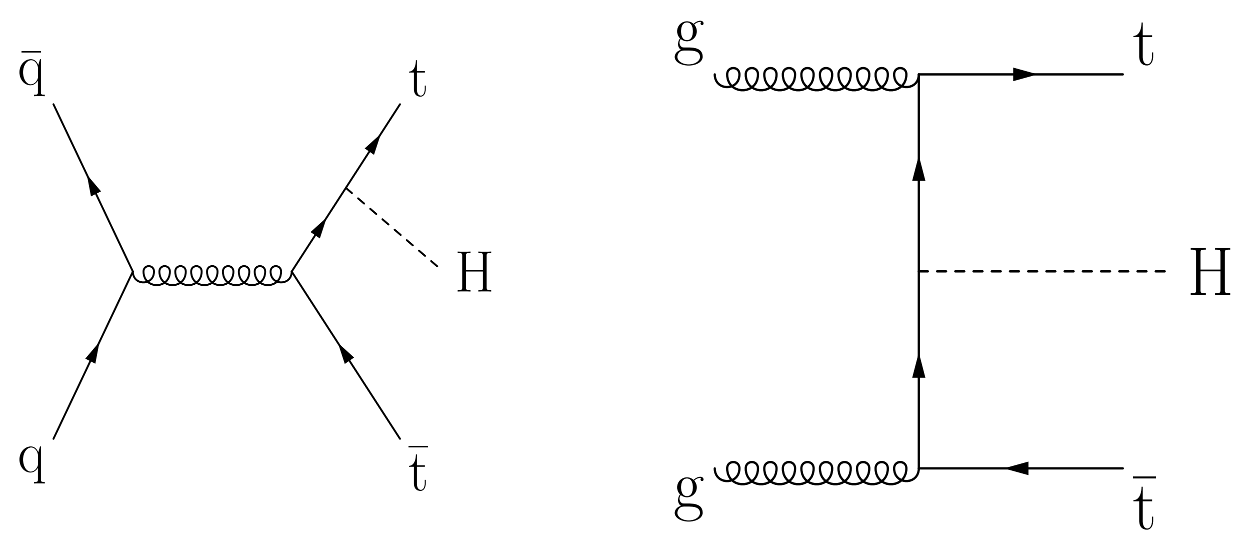
$$y_t = \frac{\sqrt{2} m_t}{v} \simeq 1$$



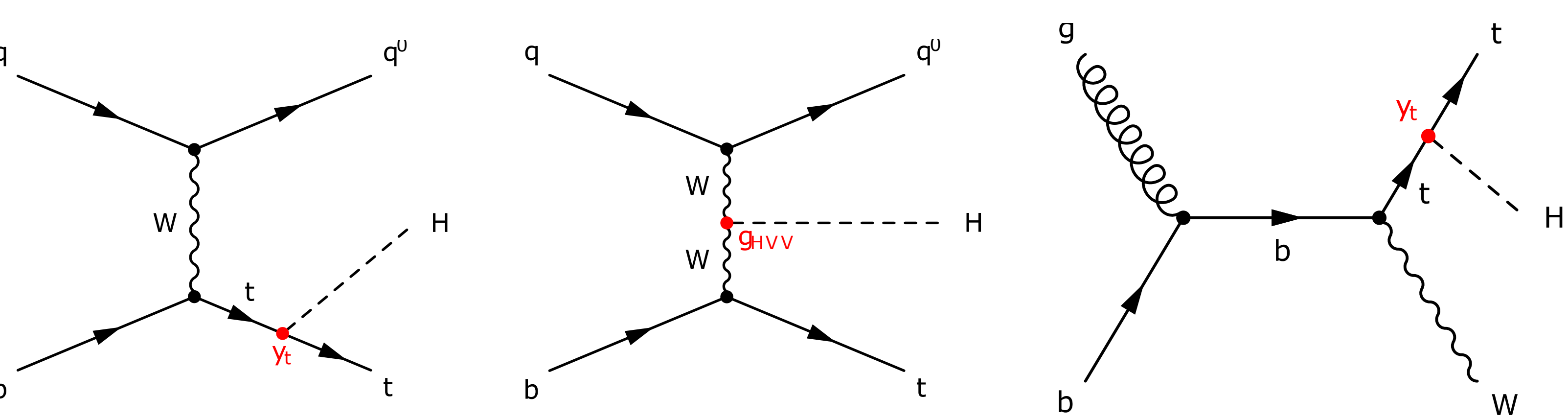
- Measurements of y_t via **Higgs** production with:
  - A pair of top quarks ($t\bar{t}H$)
    $\sigma(t\bar{t}) \simeq 500$ fb
    Sensitive to the **magnitude** of y_t
  - A single top quark (tH)
    $\sigma(tHq) \simeq 74$ fb
    Sensitive to y_t **magnitude** and **sign**

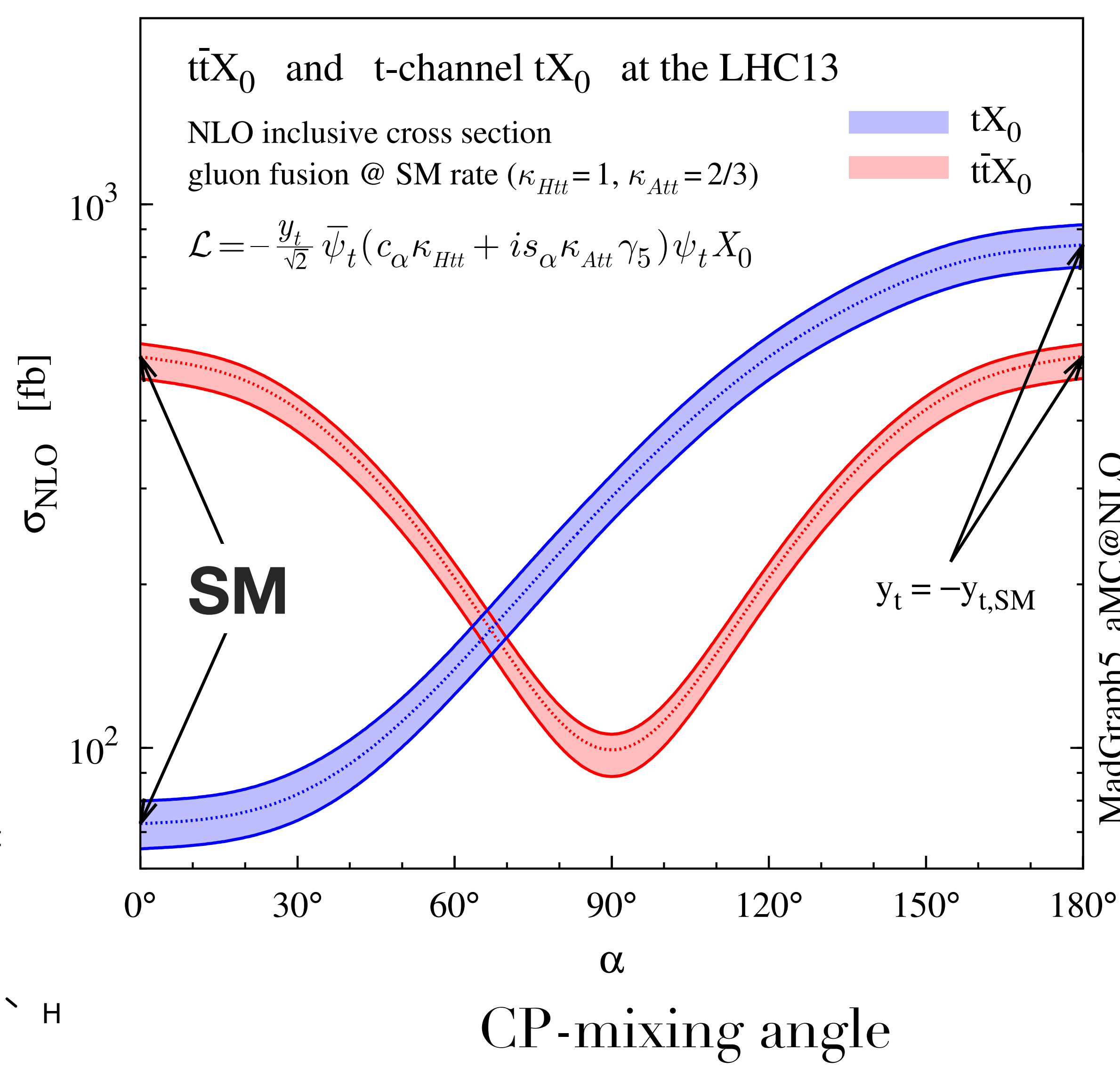
Measuring the Yukawa coupling y_t

$$\sigma(t\bar{t}H) \propto |y_t|^2\kappa^2(A\cos^2\alpha + B\sin^2\alpha)$$



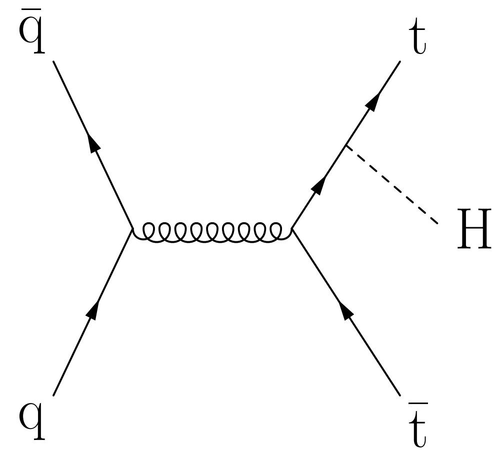
$$\sigma(tH) \propto |y_t|^2\kappa^2(A\cos^2\alpha + B\sin^2\alpha) + \boxed{Cy_t\kappa^2\cos^2\alpha + Dy_t\kappa^2\sin^2\alpha} + E\ldots$$

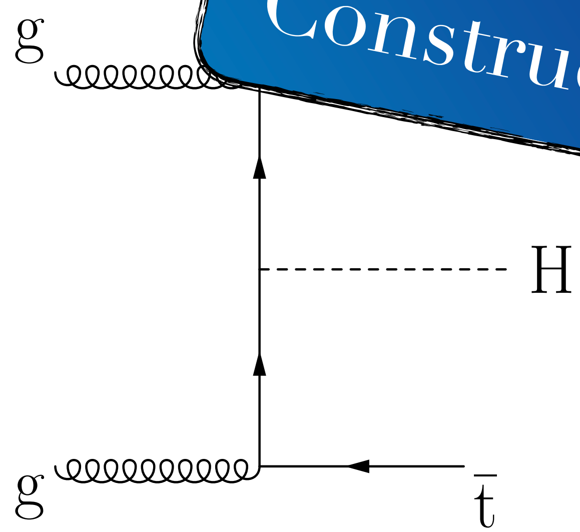




Measuring the Yukawa coupling y_t

$$\sigma(t\bar{t}H) \propto |y_t|^2 \kappa^2 (A\cos^2\alpha + B\sin^2\alpha)$$

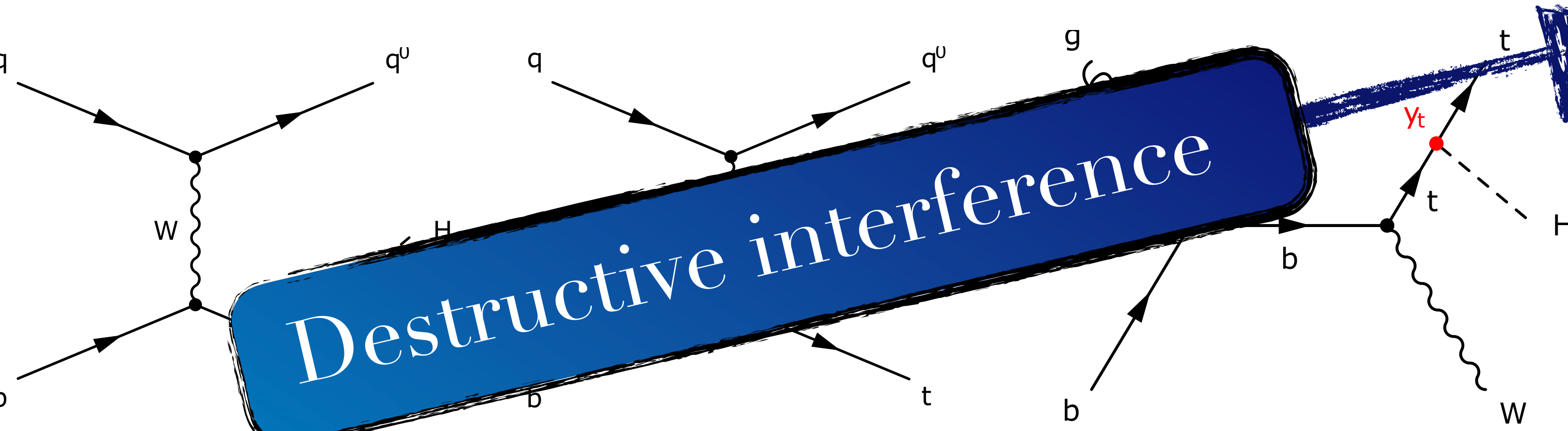




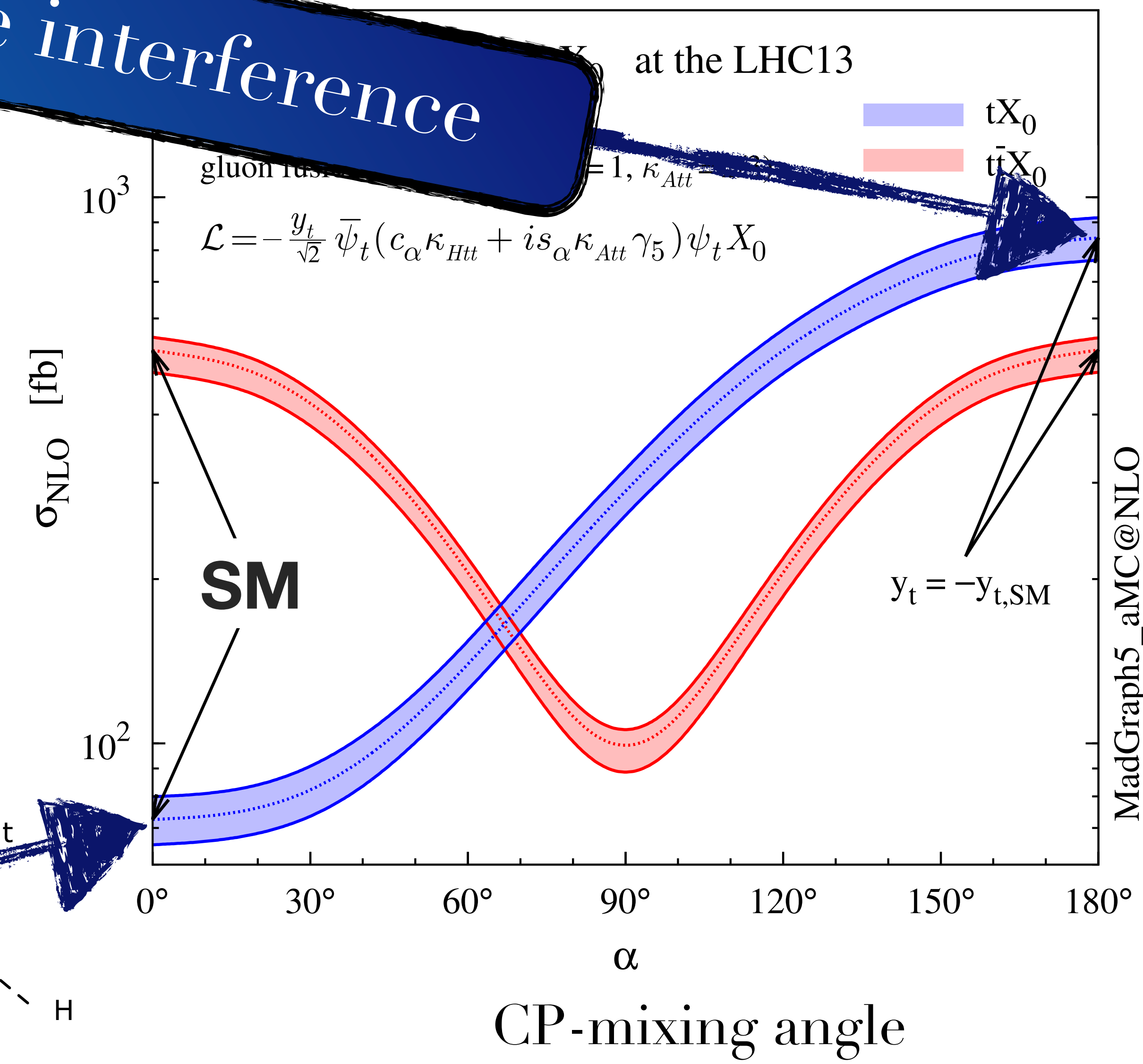
Constructive interference

$$\sigma(tH) \propto |y_t|^2 \kappa^2 (\mathrm{A}\cos^2\alpha + \mathrm{B}\sin^2\alpha) +$$

$$\boxed{\mathrm{C} y_t \kappa^2 \cos^2\alpha + \mathrm{D} y_t \kappa^2 \sin^2\alpha} + \mathrm{E} \ldots$$



Destructive interference



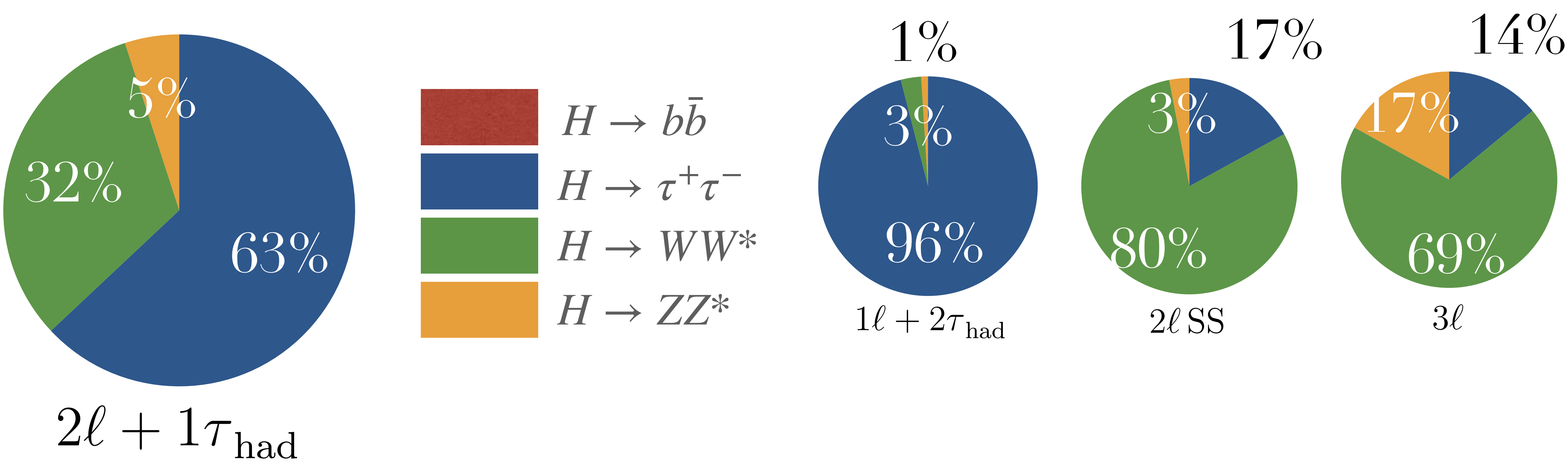
Previous results

- Current experimental constrains favour the SM predictions
but and opposite sign with respect to the expectations has not been excluded yet

Analysis	Luminosity (fb^{-1})	Collaboration	μ_{tH}
tH (2018)	35.9	CMS	limit$\sim$ 25(obs.) 12(exp.)
$t\bar{t}H/tH$ multilepton (2019)	137	CMS	$5.7^{+2.8}_{-2.7}$ (stat.) $\pm$ 3.0(syst.)
$t\bar{t}H/tH,\ H \to \gamma\gamma$ (2020)	139	ATLAS	$0.85^{+3.13}_{-2.21}$ (stat.) $^{+0.97}_{-0.98}$(stat.)
$t\bar{t}H/tH$ (2023)	138	CMS	$\mathrm{limit}_{95\mathrm{CL}} = 14.6$(obs.)$19.3^{+9.2}_{-6.0}$(exp.)

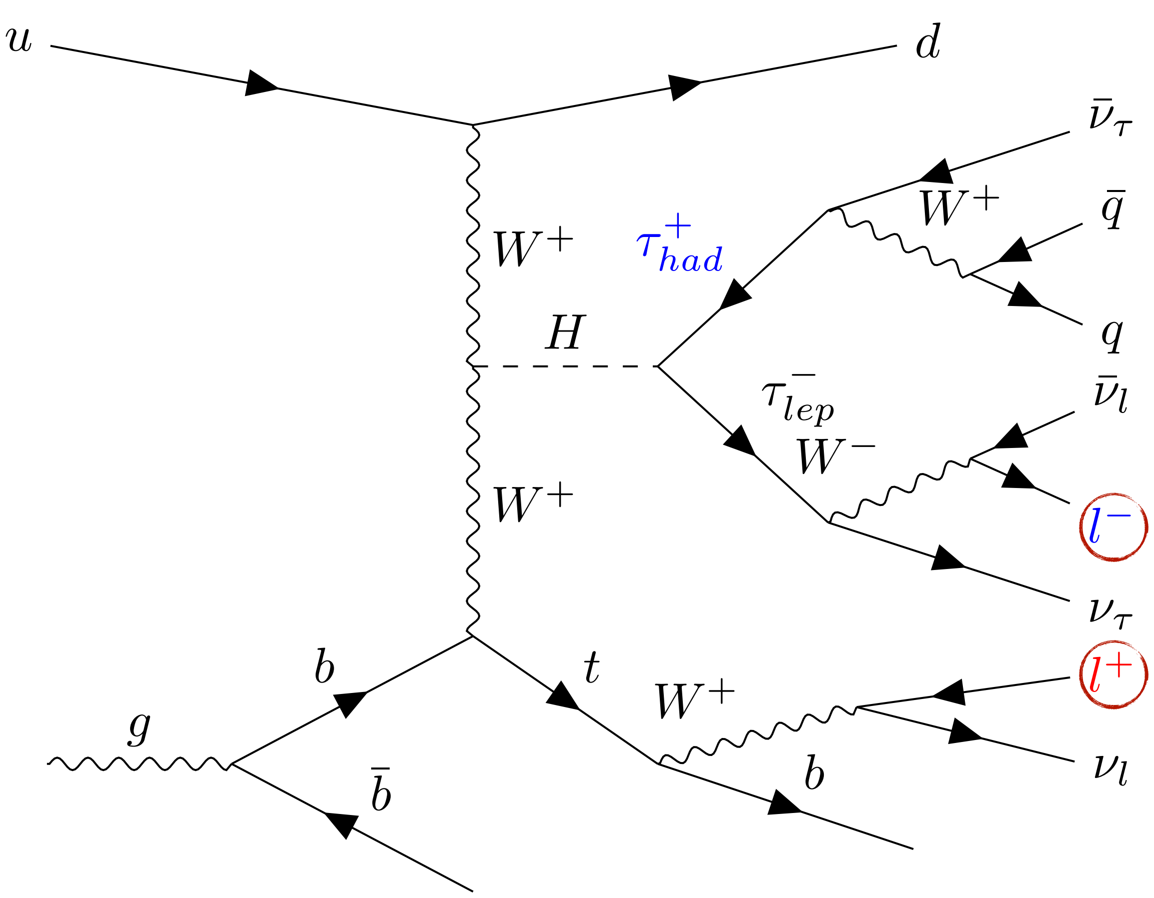
Search channels

	0τ	1τ	2τ
1L	1ℓ		$1\ell + 2\tau_{\text{had}}$
2L	2ℓ SS	$\boxed{2\ell + 1\tau_{\text{had}}}$	
3L	3ℓ		

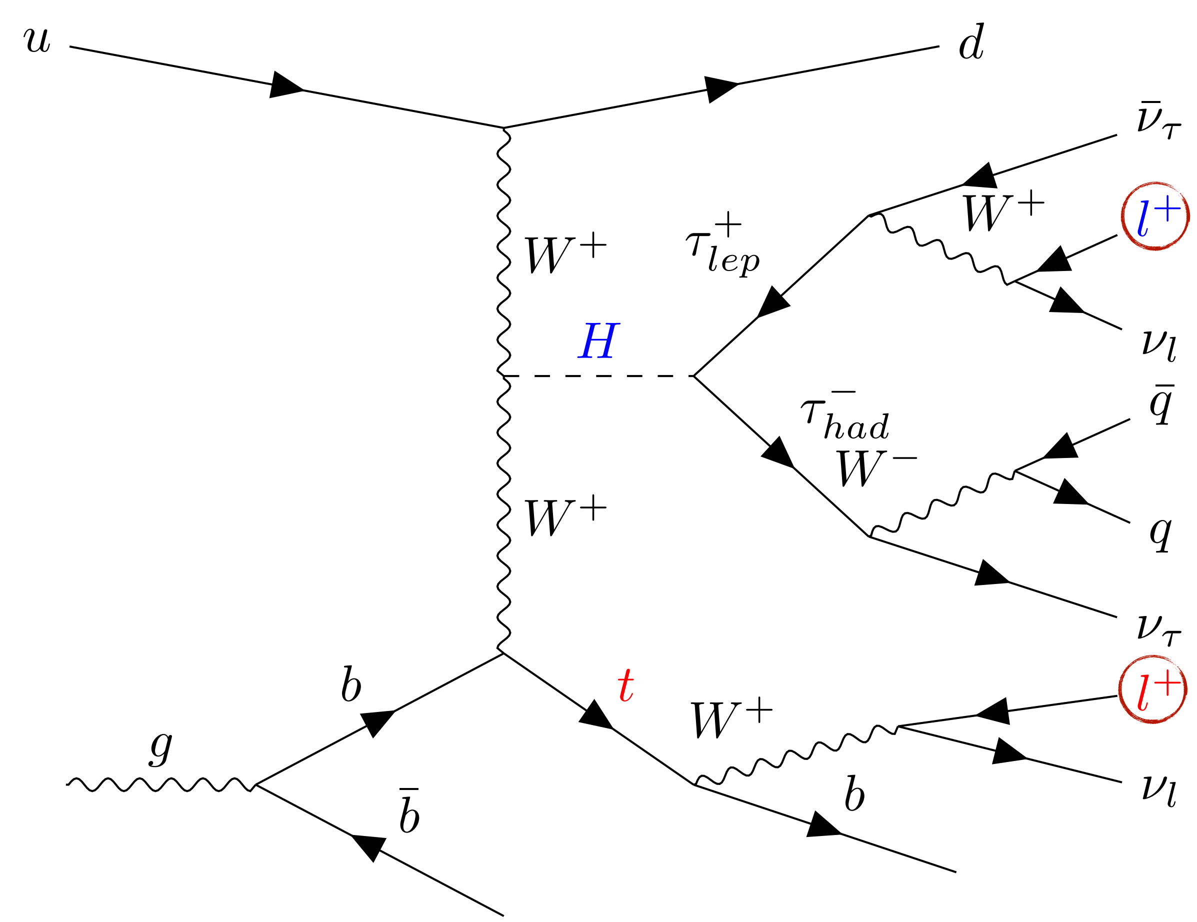


$2\ell + 1\tau_{had}$ channel

- Signal divided due to different background contributions

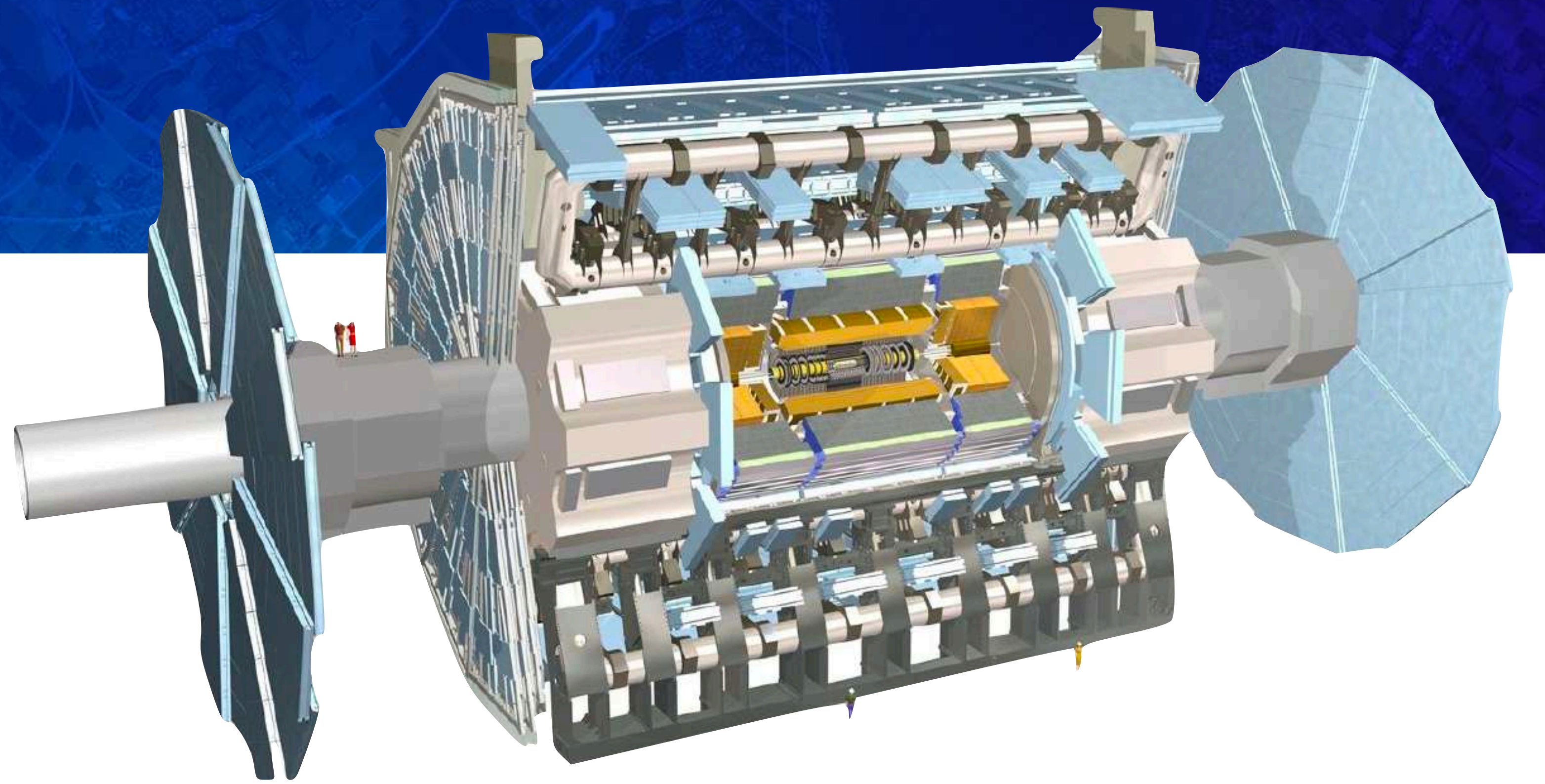


$2\ell OS + \tau_{had}$



$2\ell SS + \tau_{had}$

Outline



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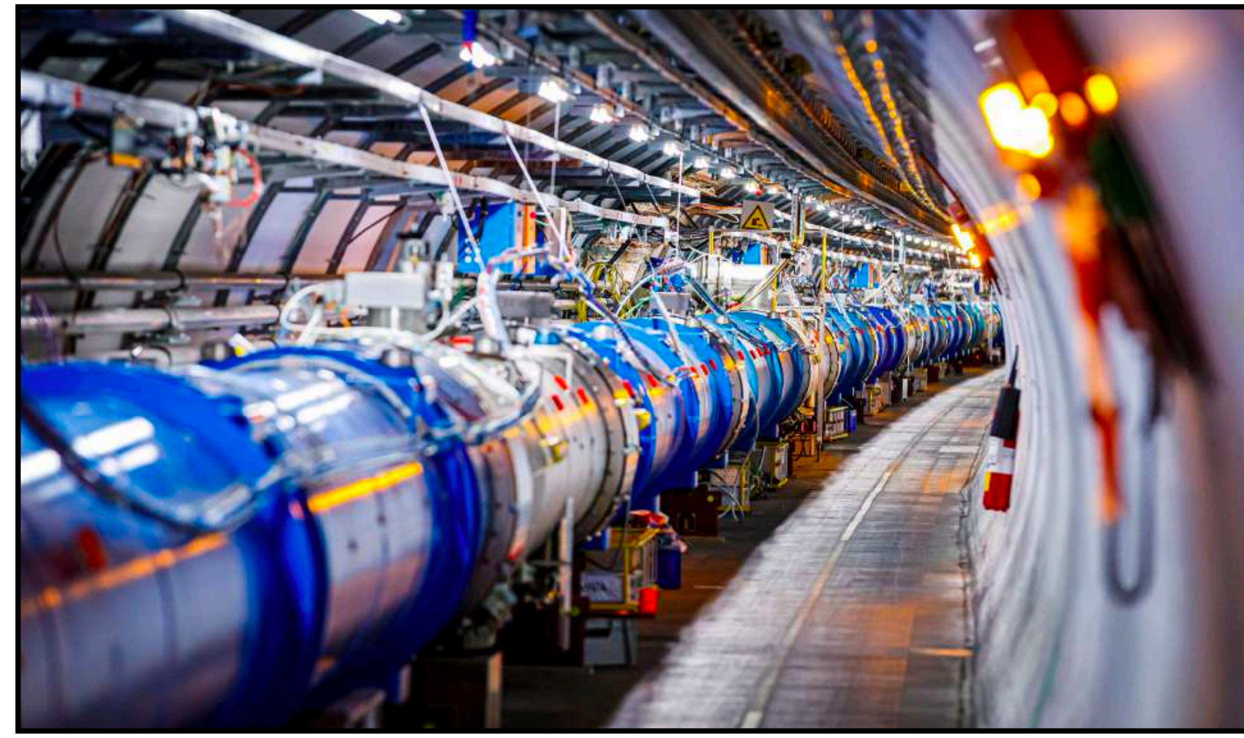
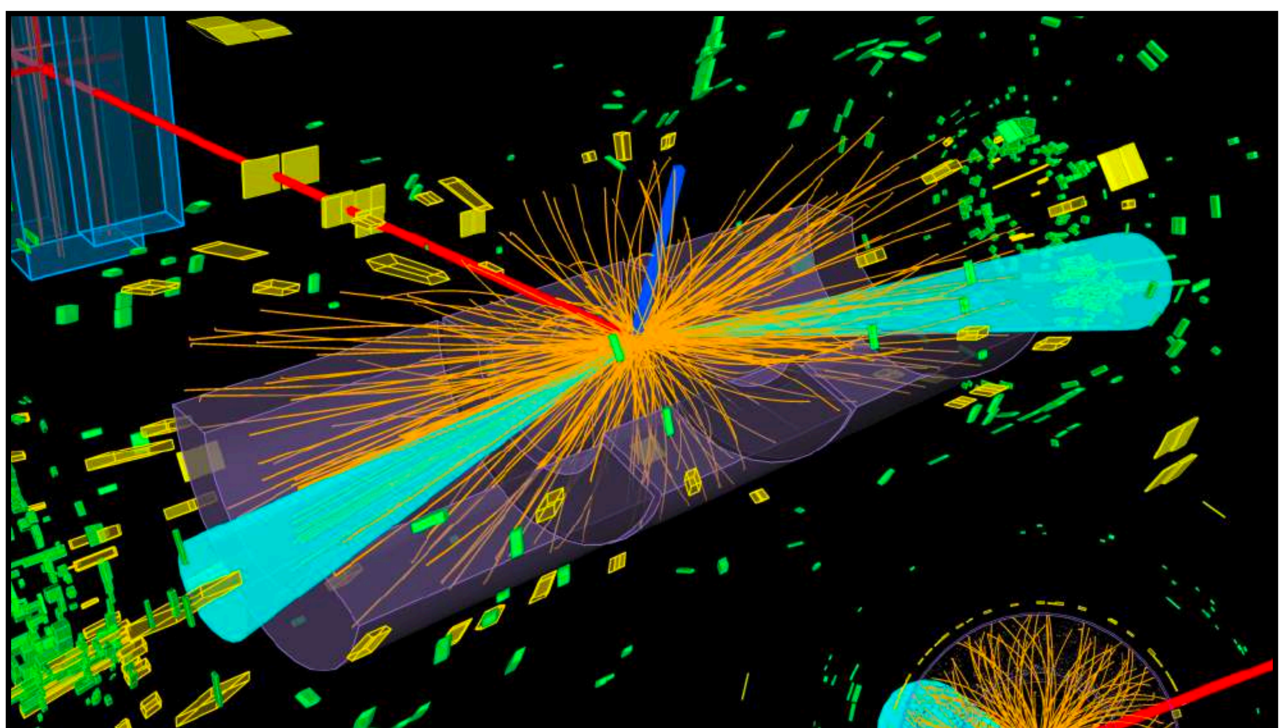
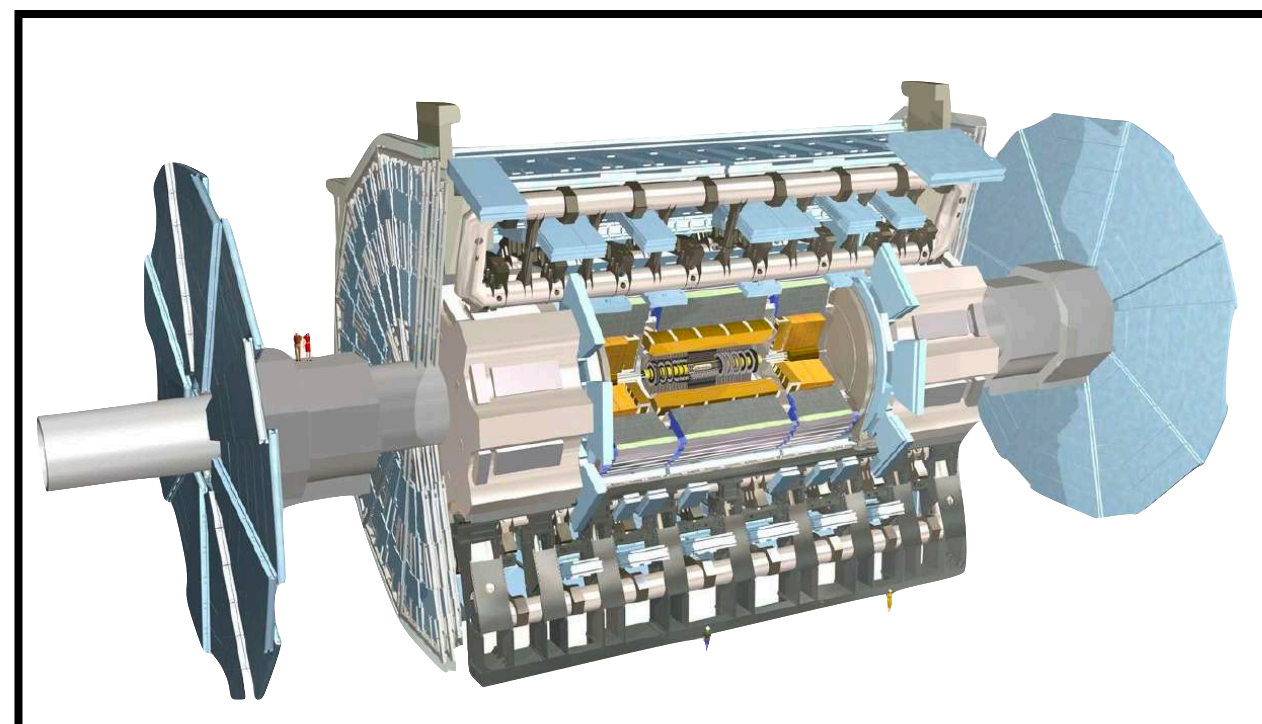
Experimental setup







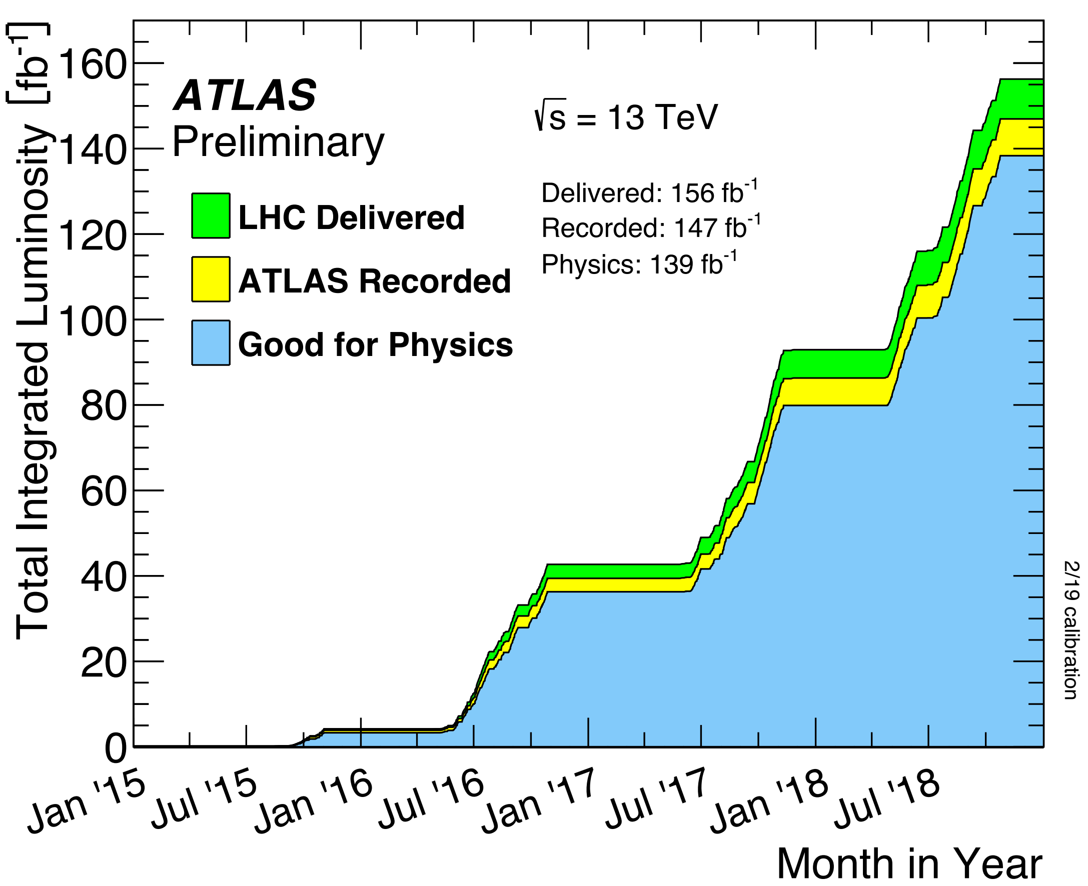
The Large Hadron Collider

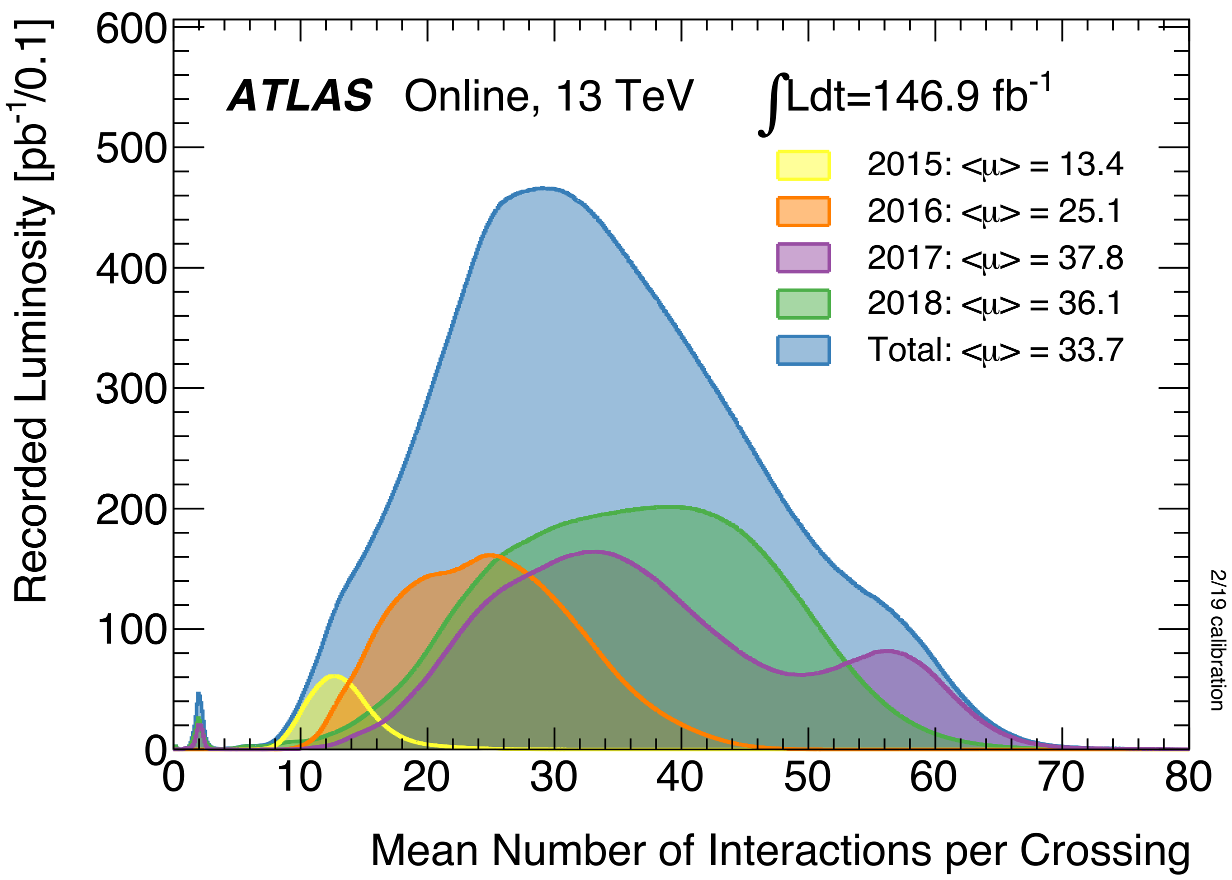
The LHC is the most powerful particle accelerator in the world: Up to 13.6 TeV

- Located at CERN, 100 m underground
- 27 km collider where two beams go in opposite directions
- Top quark factory

Proton-proton collisions at LHC

- During Run 2 (2015-2018) ATLAS recorded 140 fb^{-1} of pp collisions
  - This thesis uses the data collected by ATLAS during this period
  - Large pile-up :: 33.7

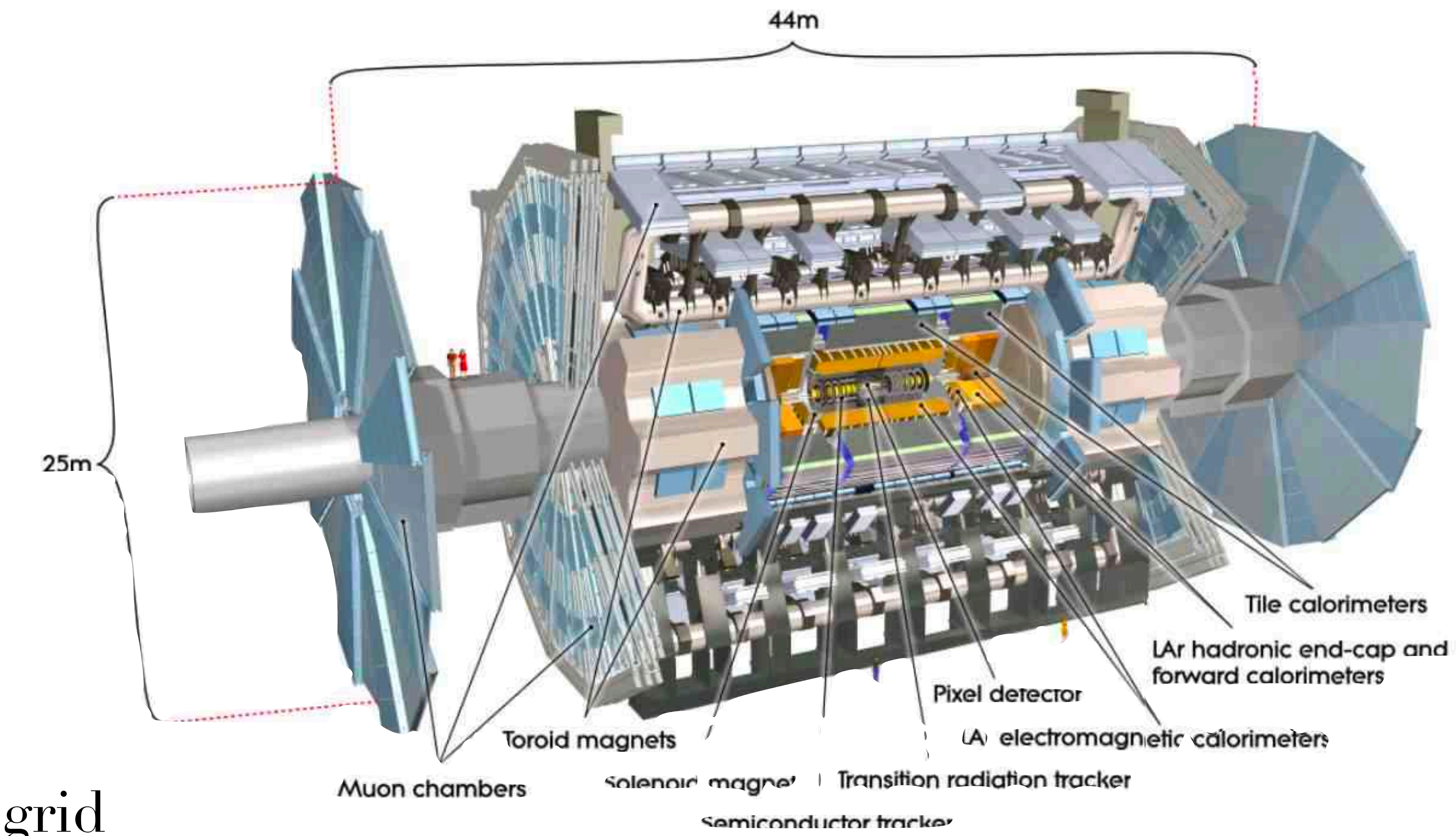




The ATLAS detector

A Toroidal LHC ApparatuS (ATLAS)

- Forward/backward-symmetric cylindrical detector covering almost the entire solid angle.
- Largest detector located at LHC: 44m length, 25m diameter and 7000 Tones
- Subdetectors:
  - Tracker
  - Calorimeters
  - Muon spectrometer
- Magnetic system
- Two level trigger system
  - 40 MHz —> 1 kHz
- Worldwide LHC computing grid



The ATLAS detector

Inner Detector (ID): Reconstructs the tracks of the charged particles. Closest detector to the collision point. 2T axial magnetic field

Made of:

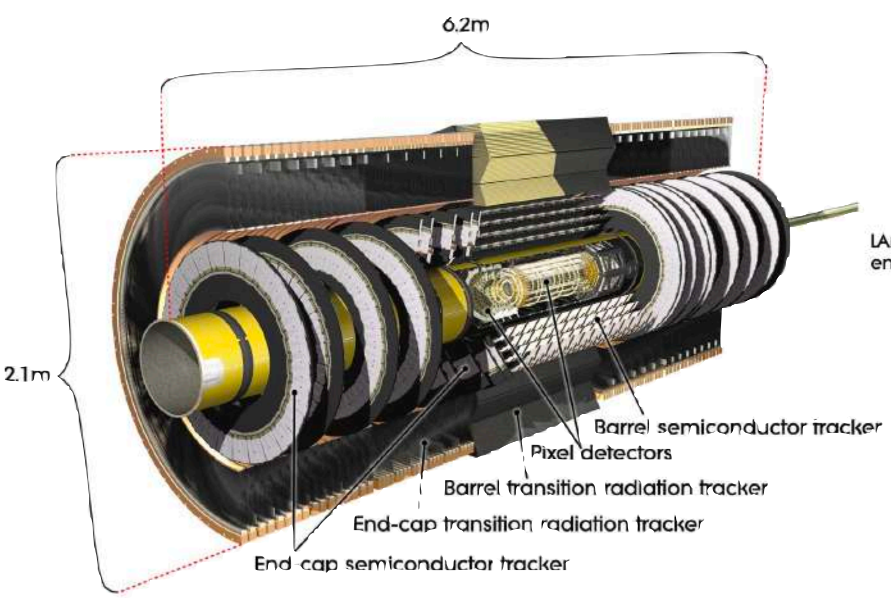
- IBL+Pixel
- SCT
- TRT

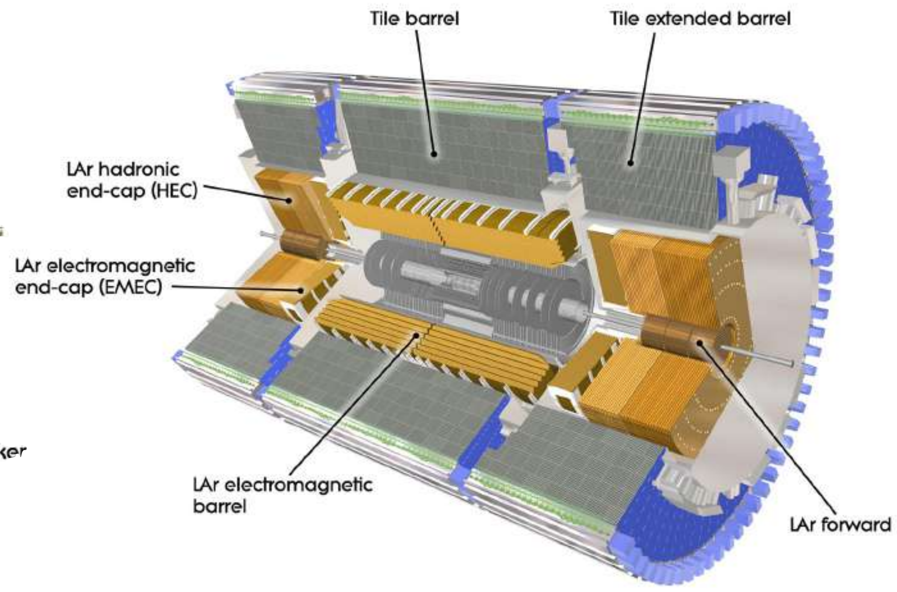
Calorimeters: Measures the energy of particles.

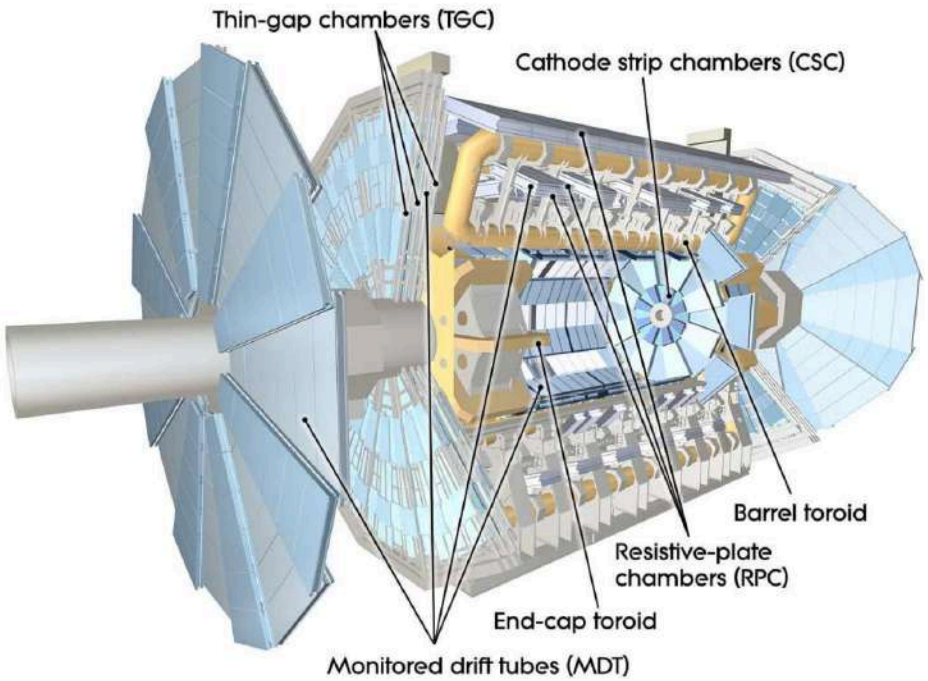
- ECAL: Electrons and photons. LAr
- HCAL: jets, τ, E_T^{miss} . Steel/Scintillator

Muon Spectrometer: Outermost layer. Tracks of muons. Up to 6T toroidal magnetic field.

- MDT
- CSC
- RPC
- TGC



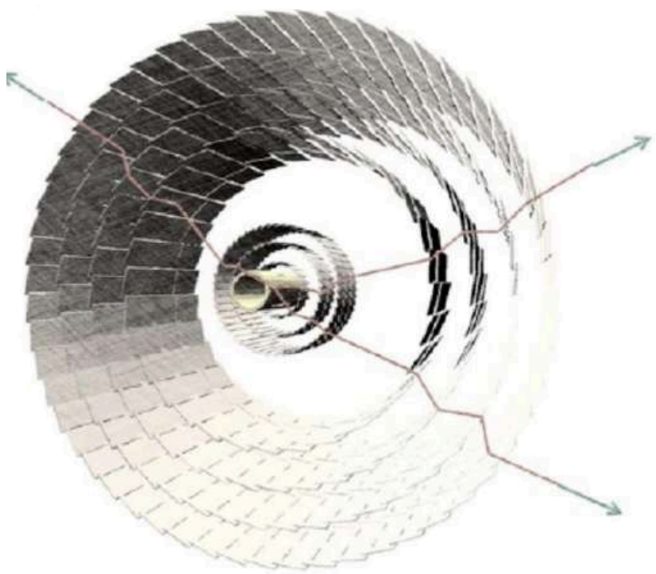




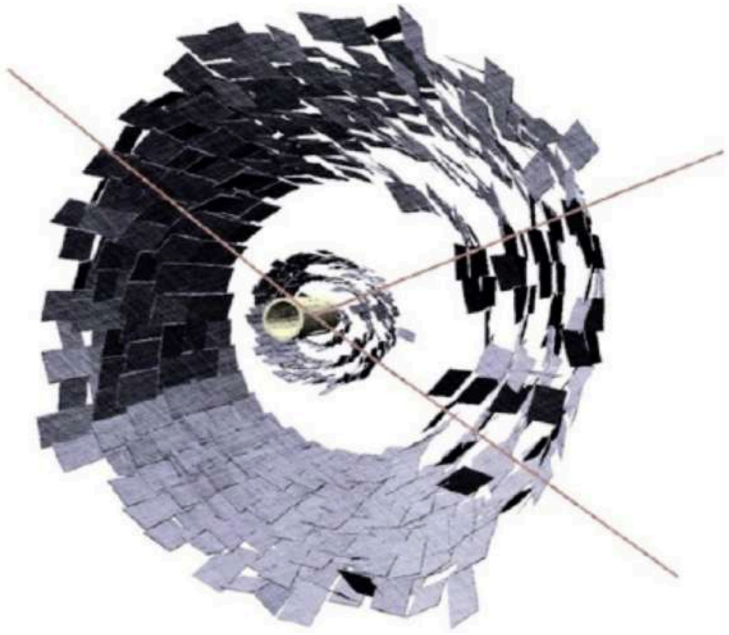
Performance of the ATLAS detector

Excellent detector performance

- A good performance of the track reconstruction is a key ingredient for the success of physics analysis
- ID Alignment is concerned with determining the actual geometry of the tracking system and following its eventual changes in time
- Limited knowledge of alignment parameters must not lead to significant degradation of the track params.



Nominal (ideal) geometry



Aligned geometry (exaggerated)

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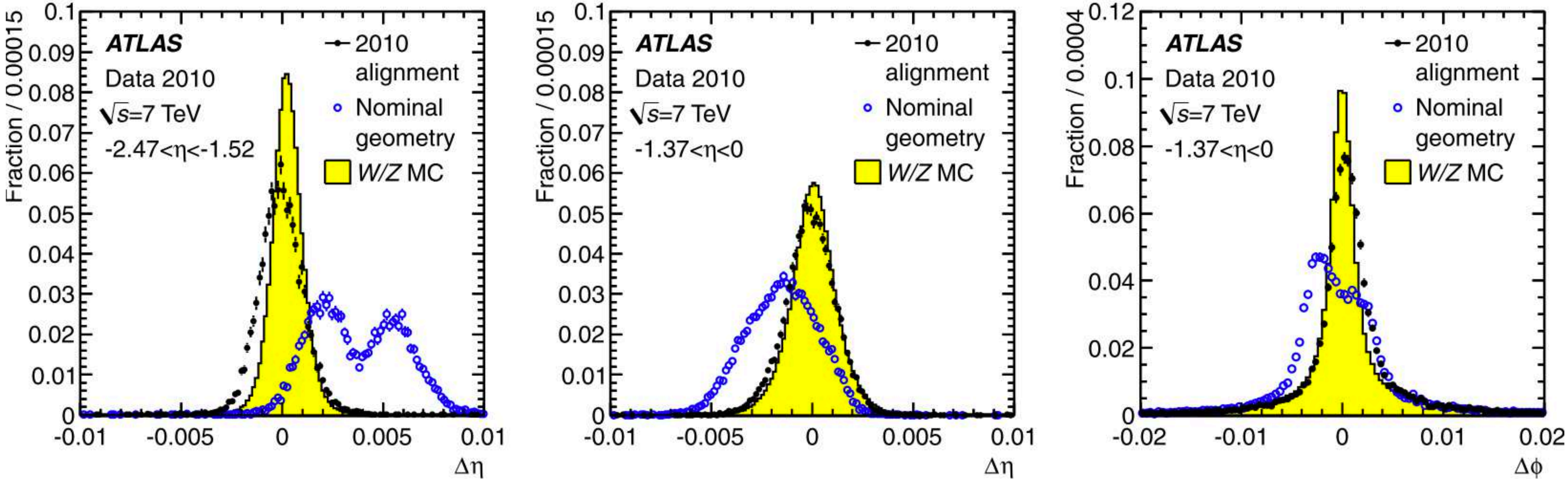
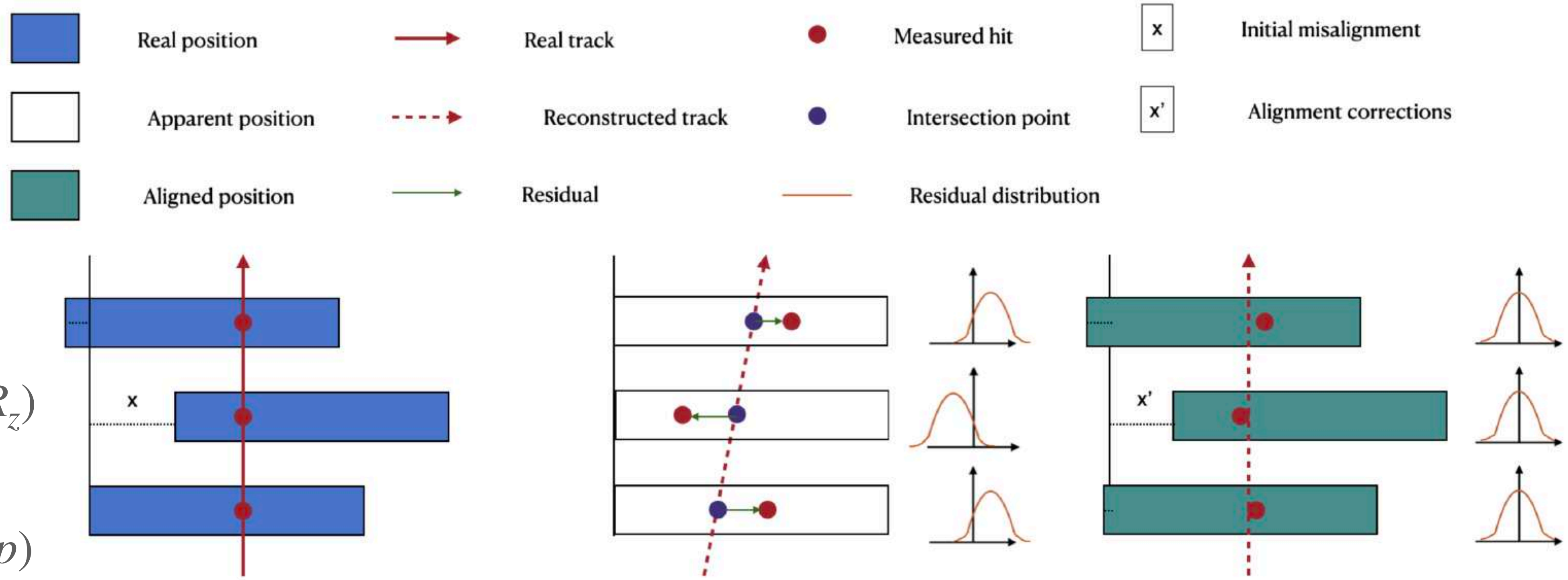


Inner Detector alignment

- Track based alignment
- Track fit residuals are defined as the distance between the measured hits and the extrapolated fits
  - The alignment consists on the minimisation of a global χ^2 function of residuals (r)
  - $r_i \neq 0$ indicate displacements of the detector from the nominal geometry <—> Misalignment
  - Done from large structures to modules

Alignment parameters:
3 Rotations + 3 Translations
$\alpha = (T_x, T_y, T_z, R_x, R_y, R_z)$

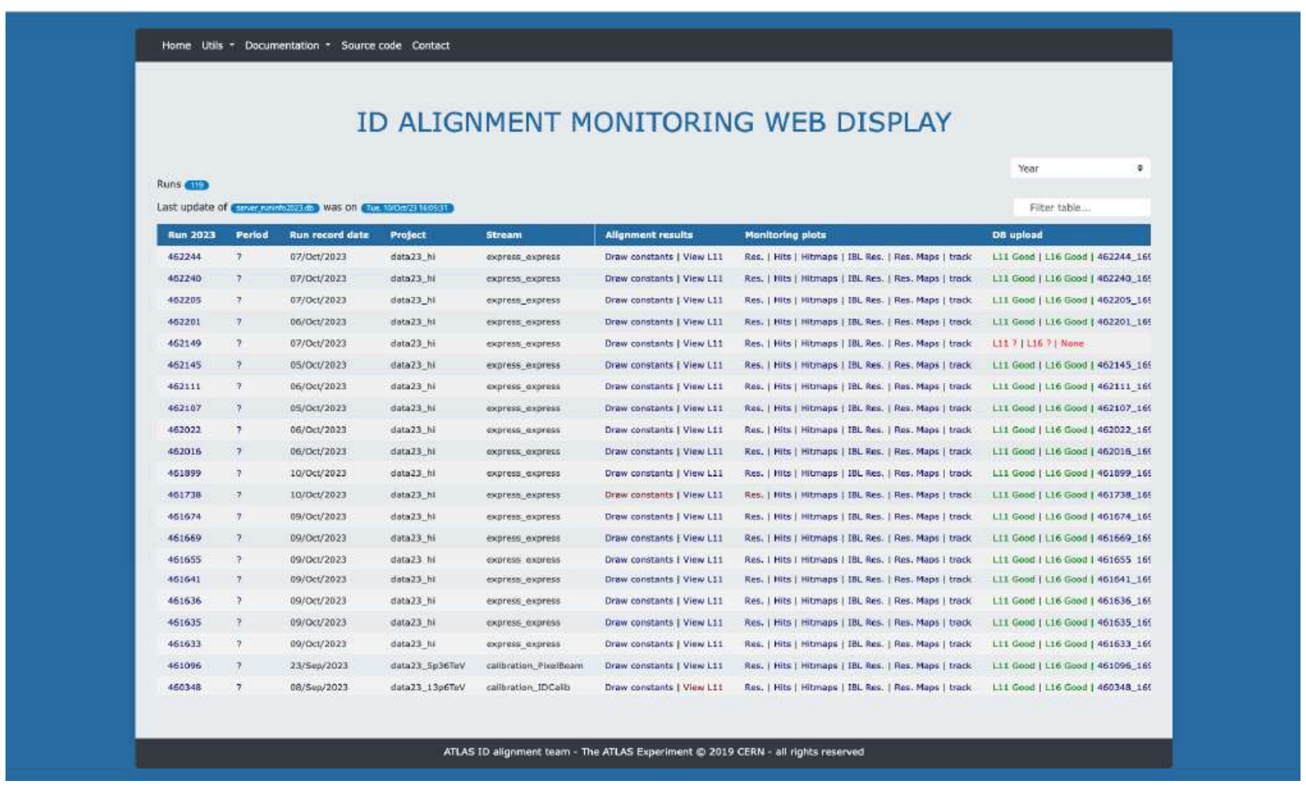
Track parameters:
$\tau = (d_0, z_0, \phi_0, \theta_0, q/p)$

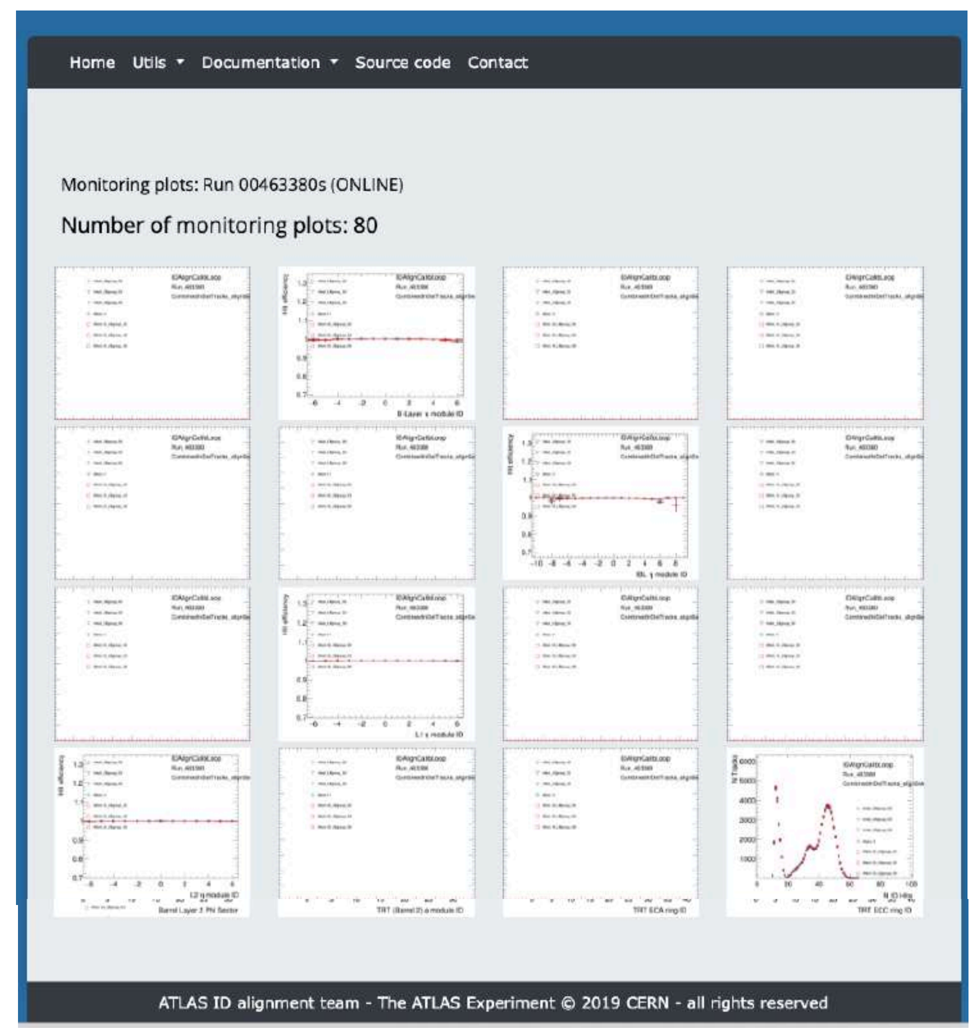


ID Alignment Monitoring Web

- The alignment provides the good performance that allow us to study the objects of our analysis
- ID Alignment Web Display
  - Monitors the alignment results obtained during the calibration loop
  - Allows to spot misalignments and take action asap.
- All detector levels

https://atlasalignment-dev.cern.ch/webapp/





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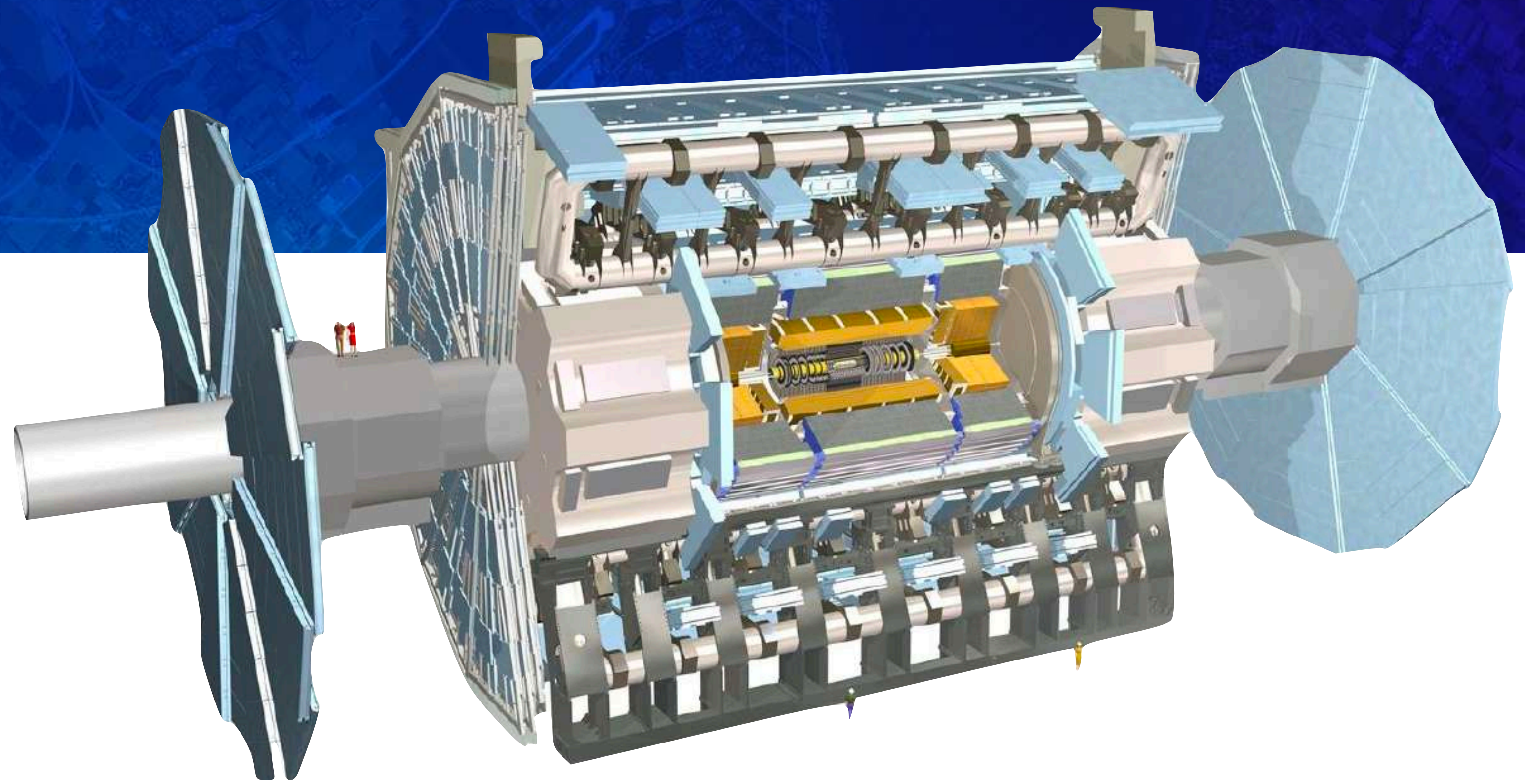

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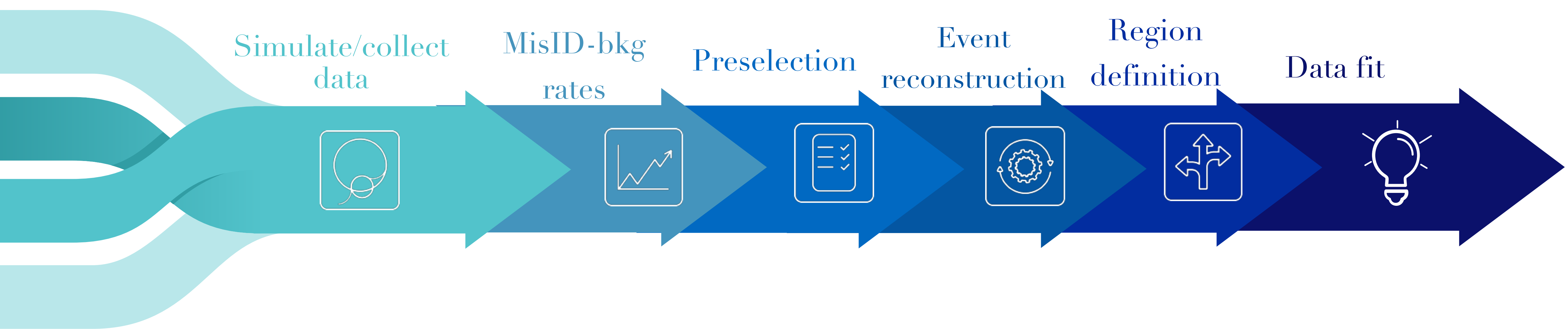
Steps of the search

Steps

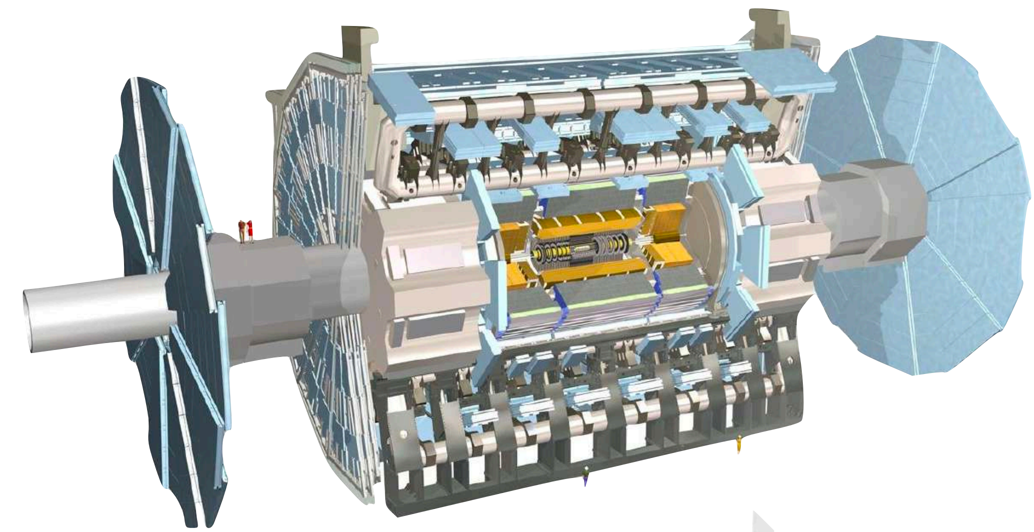
- Estimate the background contributions
- Apply preselection requirements
- Reconstruct the event
- Define regions for the analysis
- Fit to data



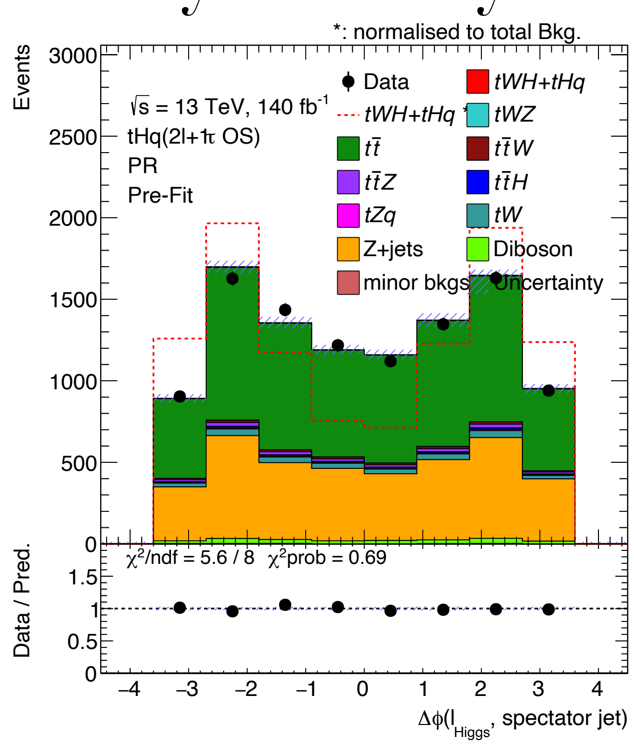
Data collection

LHC real collision data

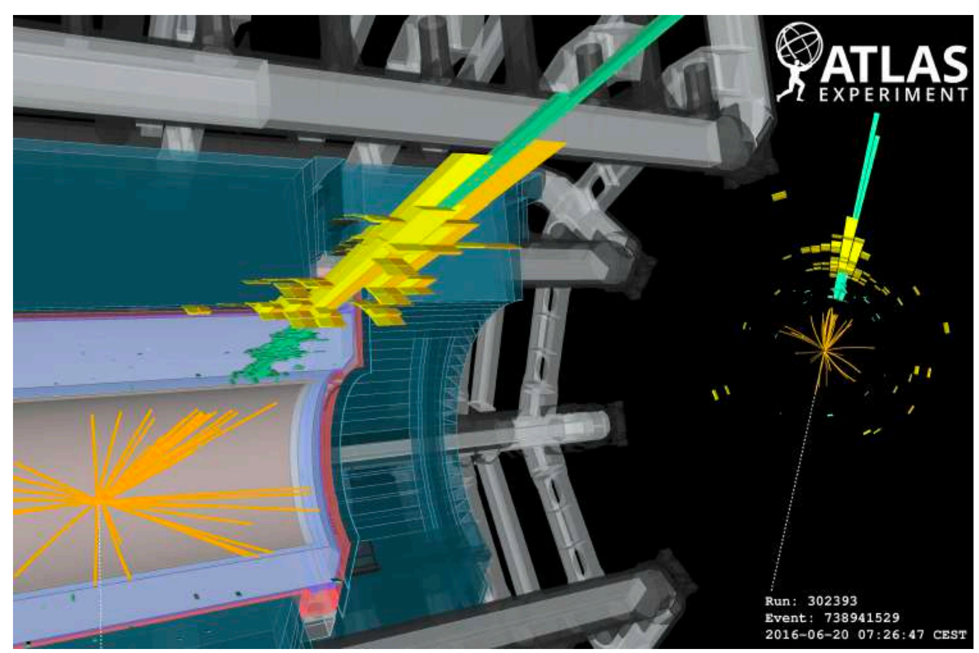
ATLAS detector



Physics analysis



Reconstruction of physic objects



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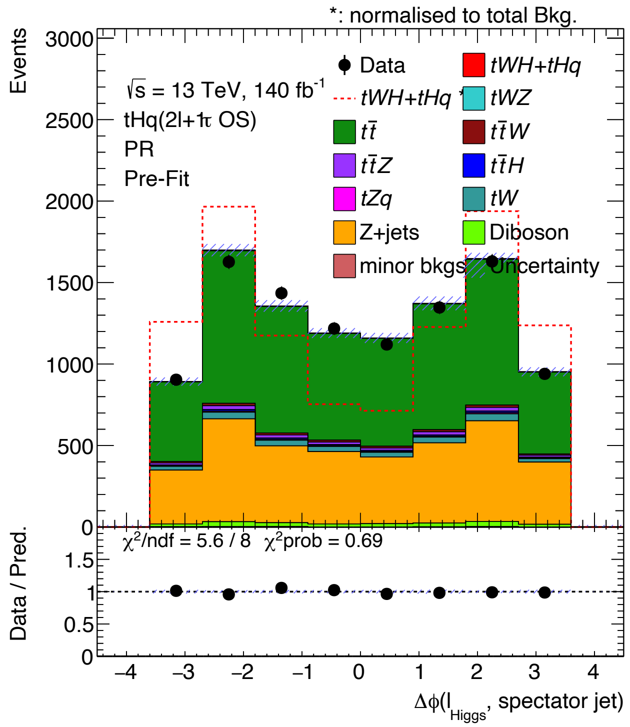

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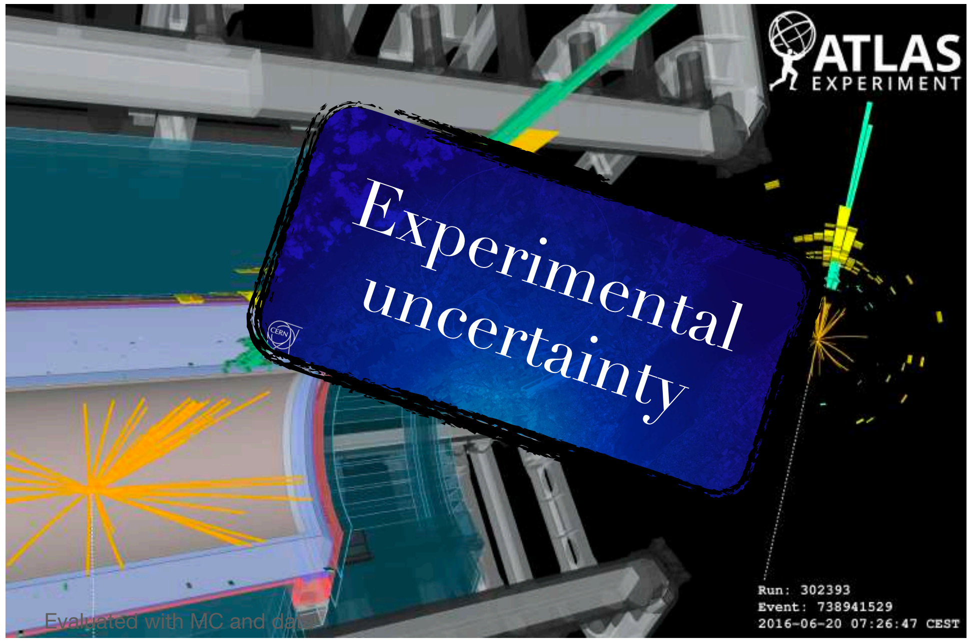
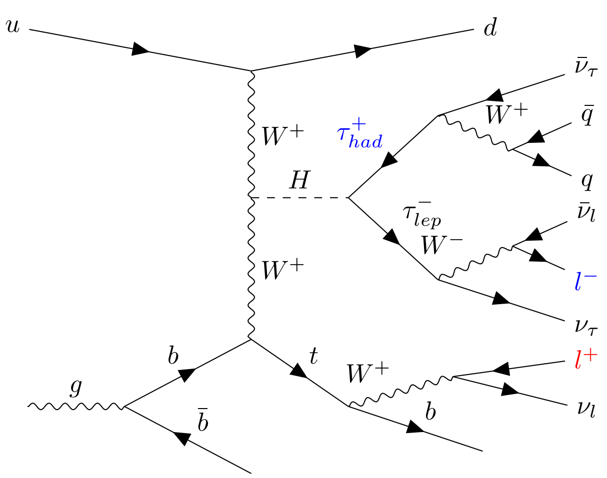
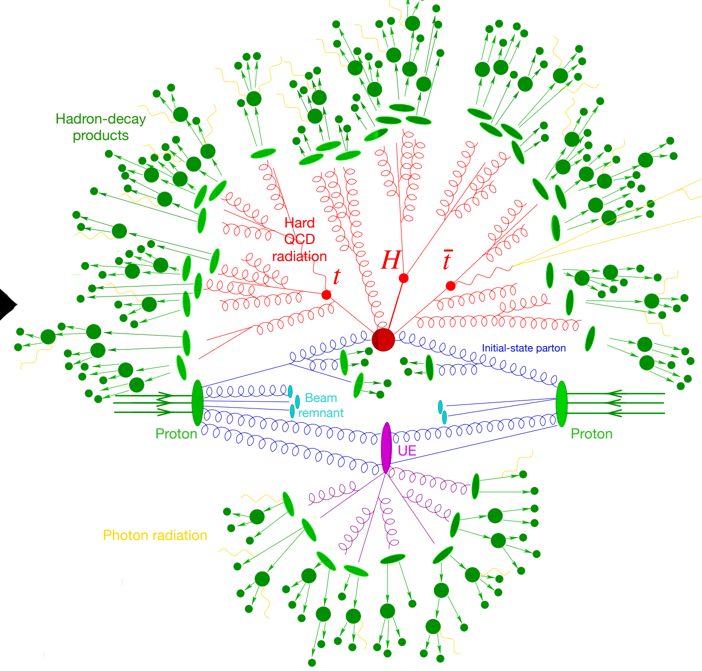


Simulation workflow

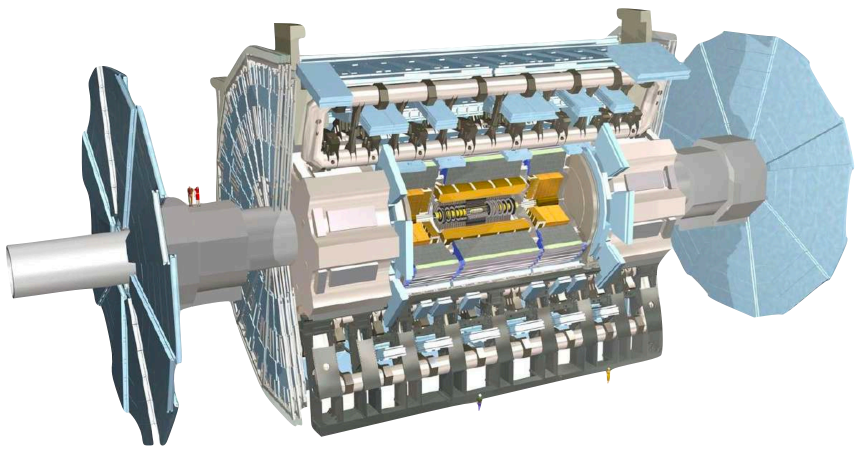
Simulation of the hard scattering process



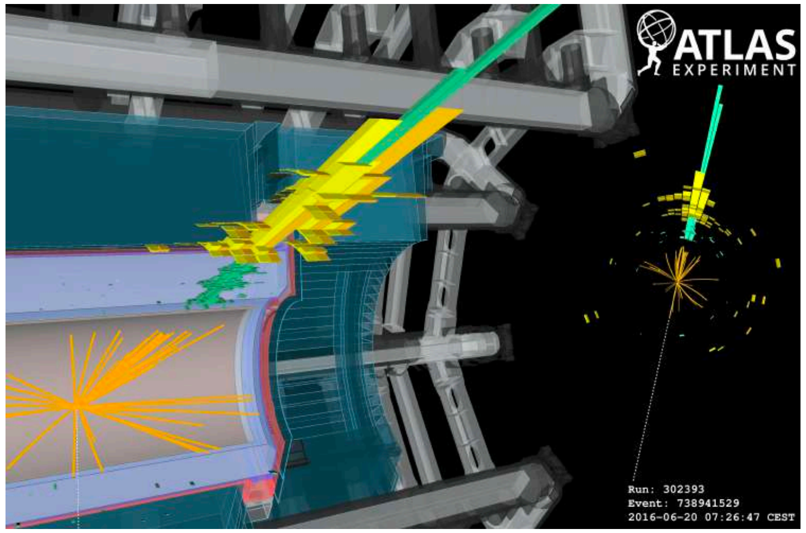
Simulation of soft physics



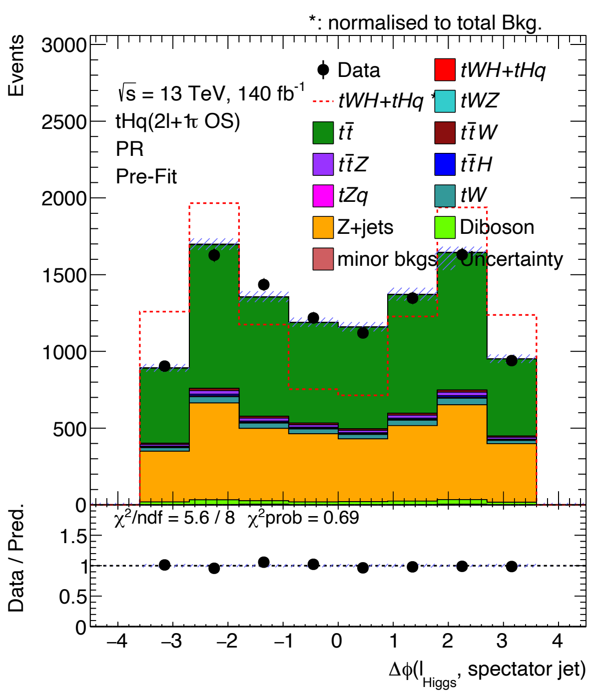
Simulation of the ATLAS detector



Reconstruction of physics objects

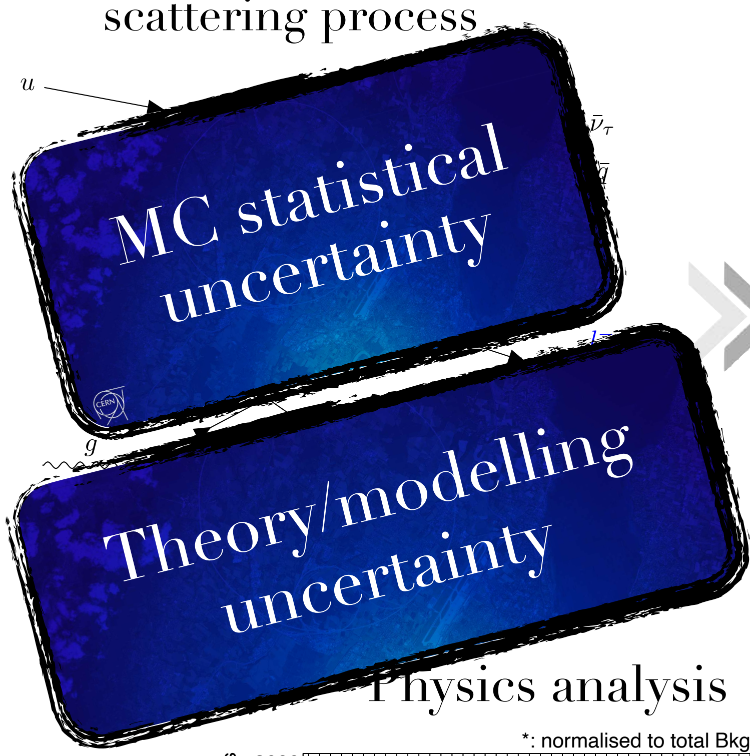


Physics analysis

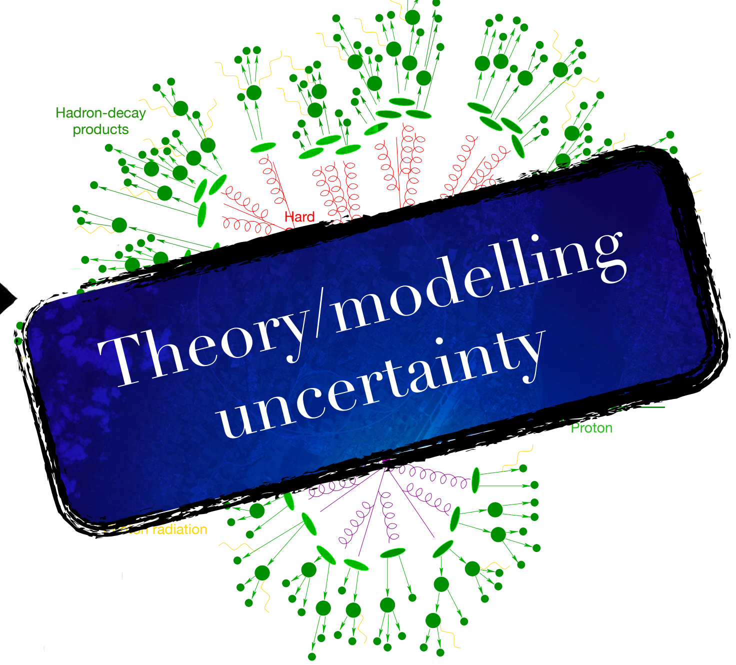


Simulation workflow

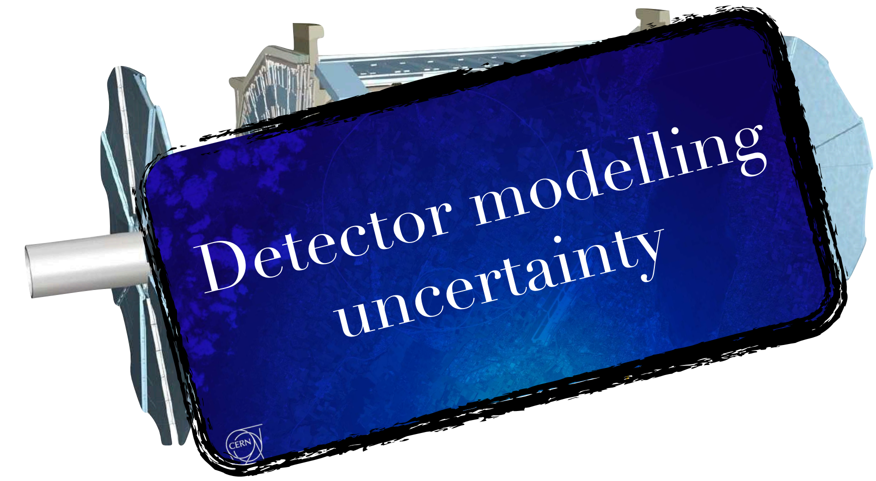
Simulation of the hard scattering process



Simulation of soft physics

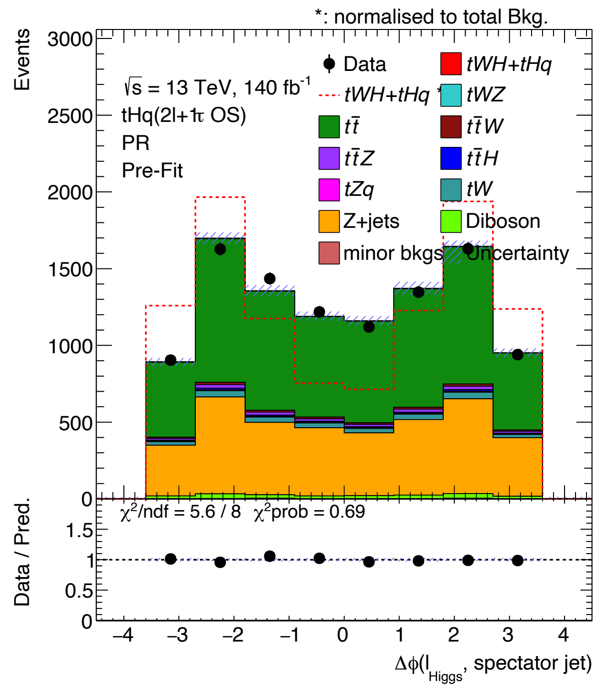


Simulation of the ATLAS detector



Reconstruction of physics objects

Physics analysis



Analysis context

- Analysis performed in these two channels: $2\ell\text{OS} + 1\tau_{had}$ and $2\ell\text{SS} + 1\tau_{had}$
- Data: ATLAS Run 2 140 fb^{-1} of pp collisions
- Simulated processes:

Process	Generator	Order (scheme)	PDF set	Parton shower	PDF set (tune)
			Signal		
tHq	MadGraph5_aMC@NLO 2.6.2	NLO (4FS)	NNPDF3.0nlo nf4	Pythia 8.230	NNPDF2.3lo (A14 tune)
			Backgrounds		
$t\bar{t}$	Powheg Box v2	NLO (5FS)	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
V+jets	Sherpa 2.2.1	NLO+LO	NNPDF3.0nnlo	-	-
Diboson	Sherpa 2.2.1-2	NLO+LO	NNPDF3.0nnlo	-	-
Triboson	Sherpa 2.2.2	NLO+LO	NNPDF3.0nnlo	-	-
$t\bar{t}Z$	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.0nlo	Pythia 8.210	NNPDF2.3lo (A14 tune)
$t\bar{t}W$	Sherpa 2.2.10	NLO	NNPDF3.0nnlo	-	-
$t\bar{t}H$	Powheg Box v2	NLO (5FS)	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
t-channel	Powheg Box v2	NLO (4FS)	NNPDF3.0nlo nf4	Pythia 8.230	NNPDF2.3lo (A14 tune)
tW	Powheg Box v2	NLO (5FS, DR)	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
s-channel	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
tZq	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
$\boxed{tWH}$	MadGraph5_aMC@NLO 2.8.1	NLO (5FS, DR)	NNPDF3.0nlo	Pythia 8.245p3	NNPDF2.3lo (A14 tune)
tWZ	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.0nlo	Pythia 8.212	NNPDF2.3lo (A14 tune)
ttt	MadGraph5_aMC@NLO 2.2.2	NLO	NNPDF3.1nlo	Pythia 8.186	NNPDF2.3lo (A14 tune)
$t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.1nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
ggH	Powheg Box v2	NLO	CT10	Pythia 8.210	CTEQ6L1 (AZNLO tune)
qqH	Powheg Box v1	NLO	CT10	Pythia 8.186	CTEQ6L1 (AZNLO tune)
WH	Pythia 8.186	LO	NNPDF2.3lo	-	-
ZH	Pythia 8.186	LO	NNPDF2.3lo	-	-

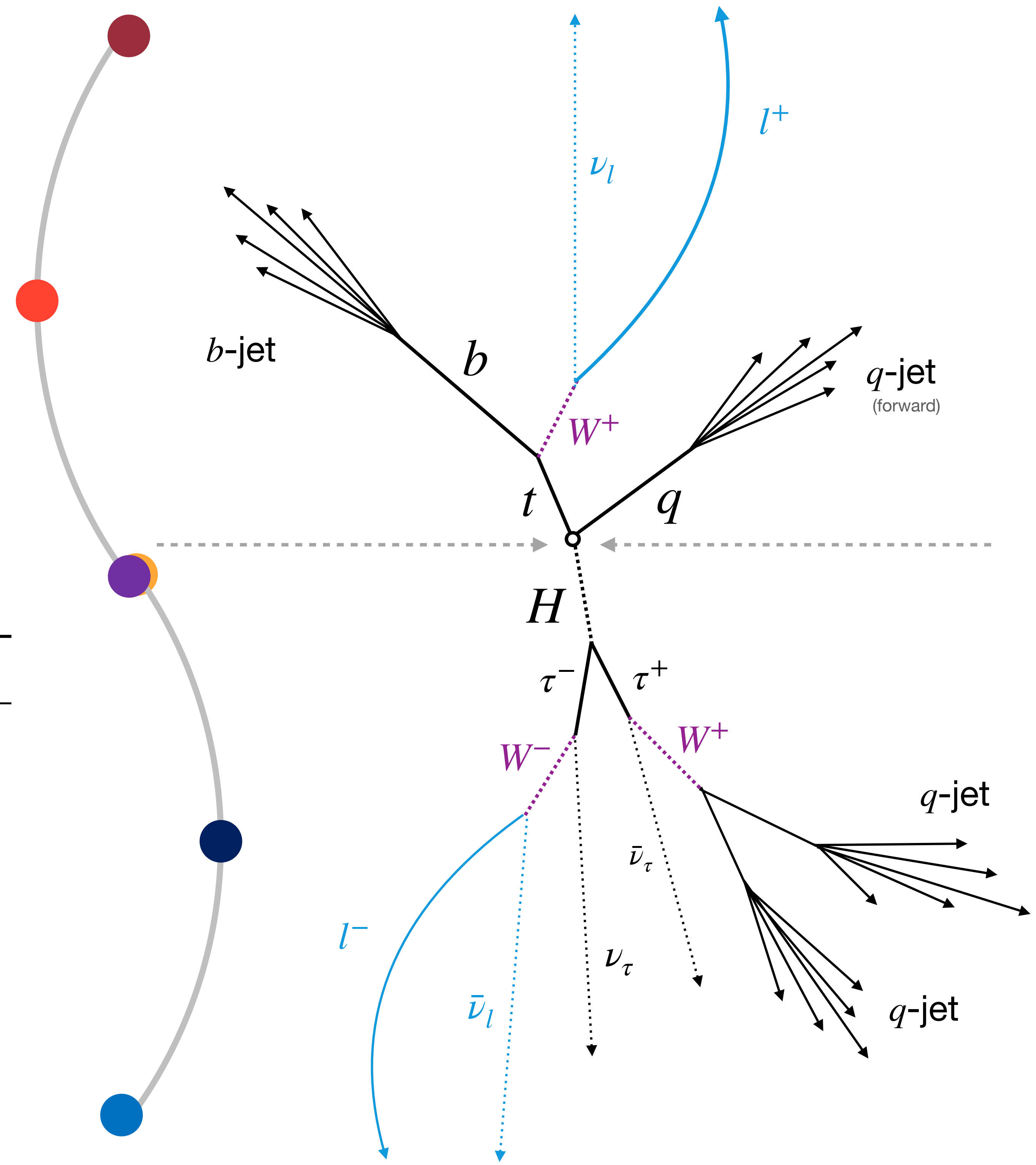
Preselection requirements

Year	Single-electron trigger	Single-muon trigger
2015	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose	HLT_mu20_iloose_L1MU15 HLT_mu50
2016–2018	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0	HLT_mu26_ivarmedium HLT_mu50

Object	Multiplicity	Momentum
Light leptons	$n(e/\mu) = 2$	$p_{\mathrm{T}}(e) > 14$ GeV $p_{\mathrm{T}}(\mu) > 14$ GeV
Hadronic tau	$n(\tau_{\mathrm{had}}) = 1$	$p_{\mathrm{T}}(\tau_{\mathrm{had}}) > 20$ GeV
Jets	$n(\mathrm{jet}) = [2,\ 6]$	$p_{\mathrm{T}}(\mathrm{jet}) > 20$ GeV
b-tagged jets	$n(b\text{-jet}) = [1,\ 2]$	$p_{\mathrm{T}}(b\text{-jet}) > 20$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$		$p_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}}) \in [5,\ 800]$ GeV

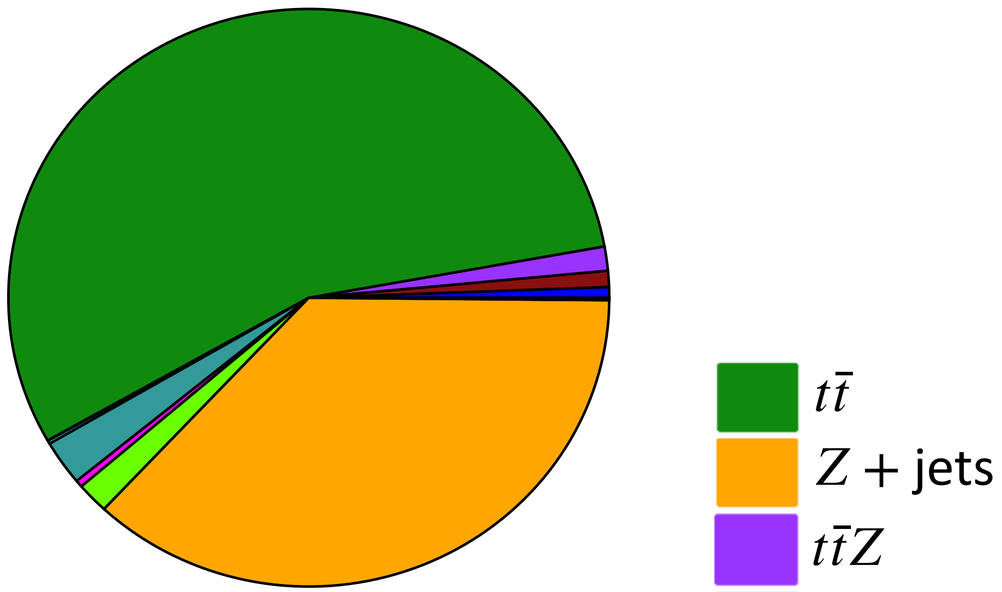
$p_{\mathrm{T}}(\text{lep}1) > 27$ GeV

$p_{\mathrm{T}}(\text{lep}2) > 20$ GeV

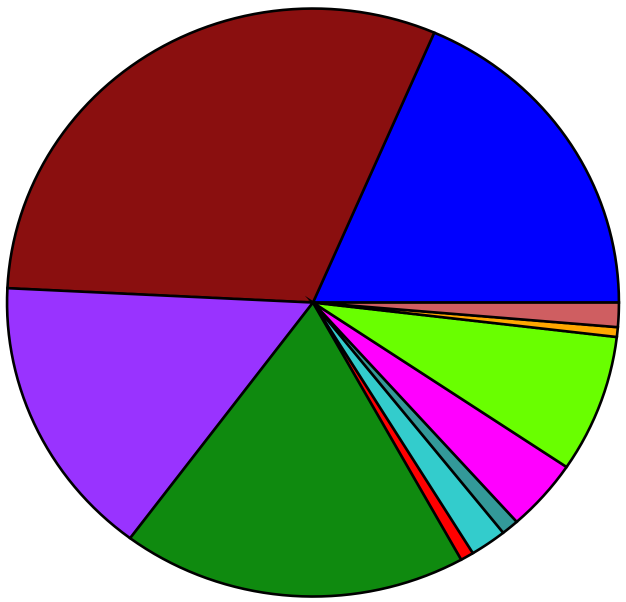


Preselection: 2ℓOS/SS + $1\tau_{had}$

Process	2ℓ OS + $1\tau_{\text{had}}$	2ℓ SS + $1\tau_{\text{had}}$
tHq	1.93 ± 0.11	1.22 ± 0.09
tWH	2.4 ± 1.1	0.95 ± 0.22
$t\bar{t}$	5690 ± 160	24.8 ± 1.7
$Z+$jets	3800 ± 400	0.7 ± 0.4
$t\bar{t}H$	61 ± 13	25.2 ± 1.3
$t\bar{t}W$	92 ± 23	42 ± 9
$t\bar{t}Z$	139 ± 26	21.2 ± 1.0
tWZ	19 ± 10	2.6 ± 1.7
tZq	40 ± 6	5.4 ± 0.9
tW	260 ± 40	1.2 ± 1.0
Diboson	180 ± 130	10 ± 6
minor bkgs	14 ± 8	1.8 ± 1.0
Total background	10300 ± 500	137 ± 12
Data	10221	102
S/B (%)	0.019	0.89
Significance	0.019	0.104



2ℓOS + τ_{had}



2ℓSS + τ_{had}

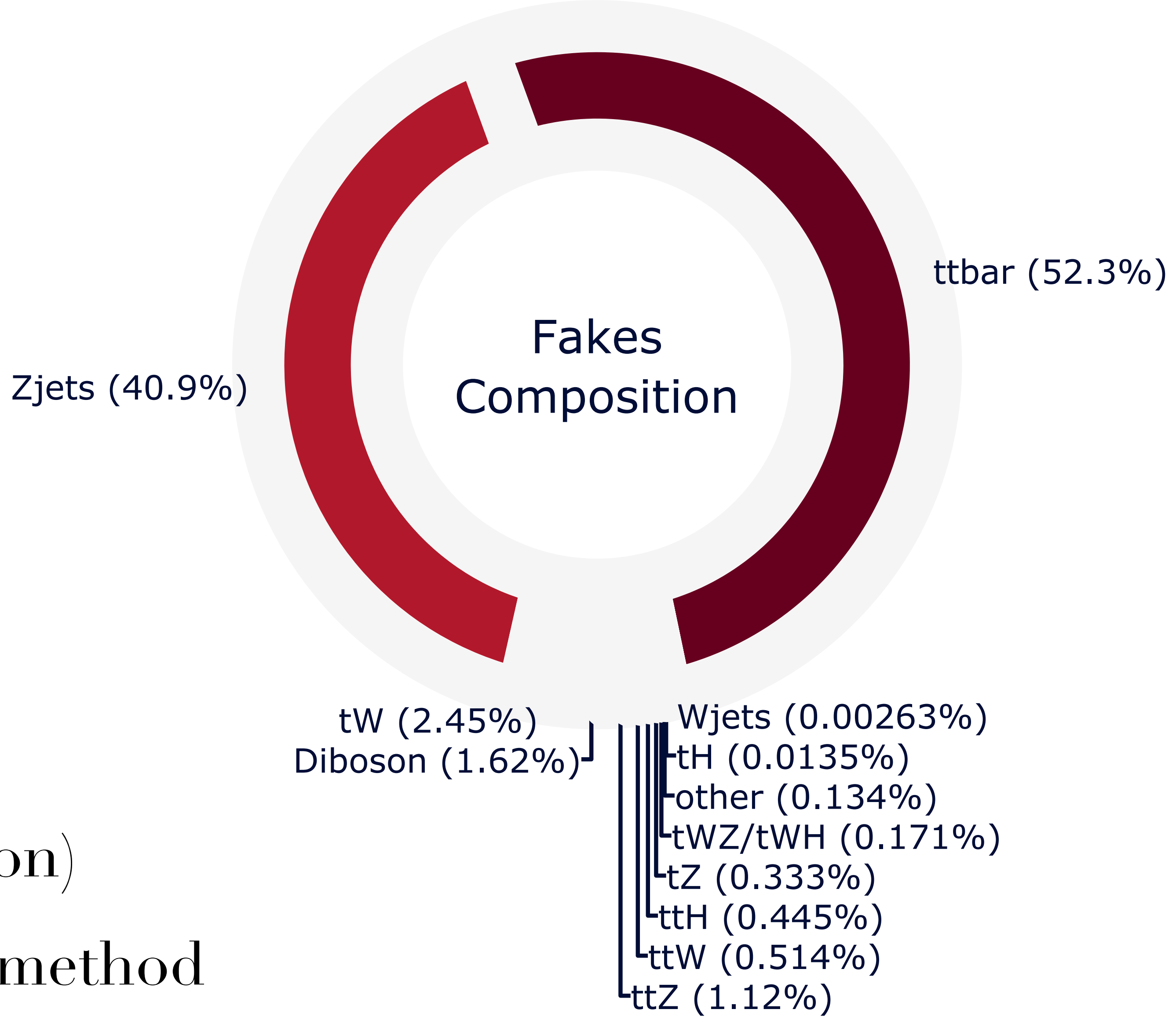
Background contribution

Two kinds of background processes according to their sources

- Irreducible: Same final-state objects
- Reducible: Arising from misidentification of physical objects
  - Misidentification of light leptons (e/μ)
  - Misidentification of τ_{had}

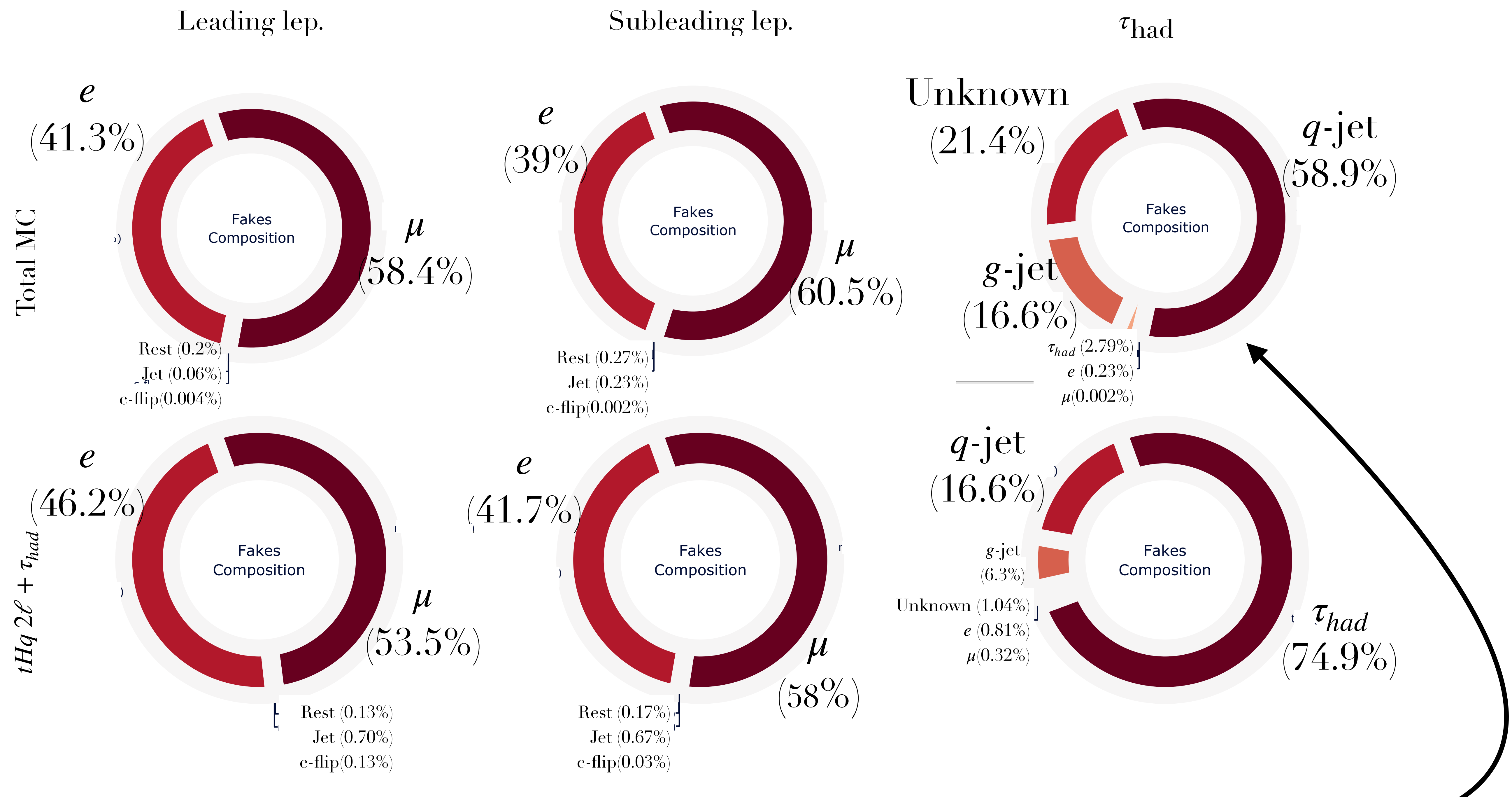
Estimation of τ_{had} misidentification

- Our MC simulations do not describe the misidentification **rates**
- Template fit method —> Scale Factors
- MisId regions: Fail medium RNN(τ-ID)
- Templates separated by
  - p_T bins
  - b-jet multiplicity (1 or 2)
  - Prongness (1-prong, 3-prong)
- Fit to
  - JetTrackWidth (1 b-jet region)
  - LightGBM BDT score (2 b-jet region)
- Derive Scale Factors with template fit method
- Uncertainty —> Counting method



Estimation of τ_{had} misidentification

- All $2\ell + \tau_{had}$



- Jets faking τ_{had} **dominate the background**

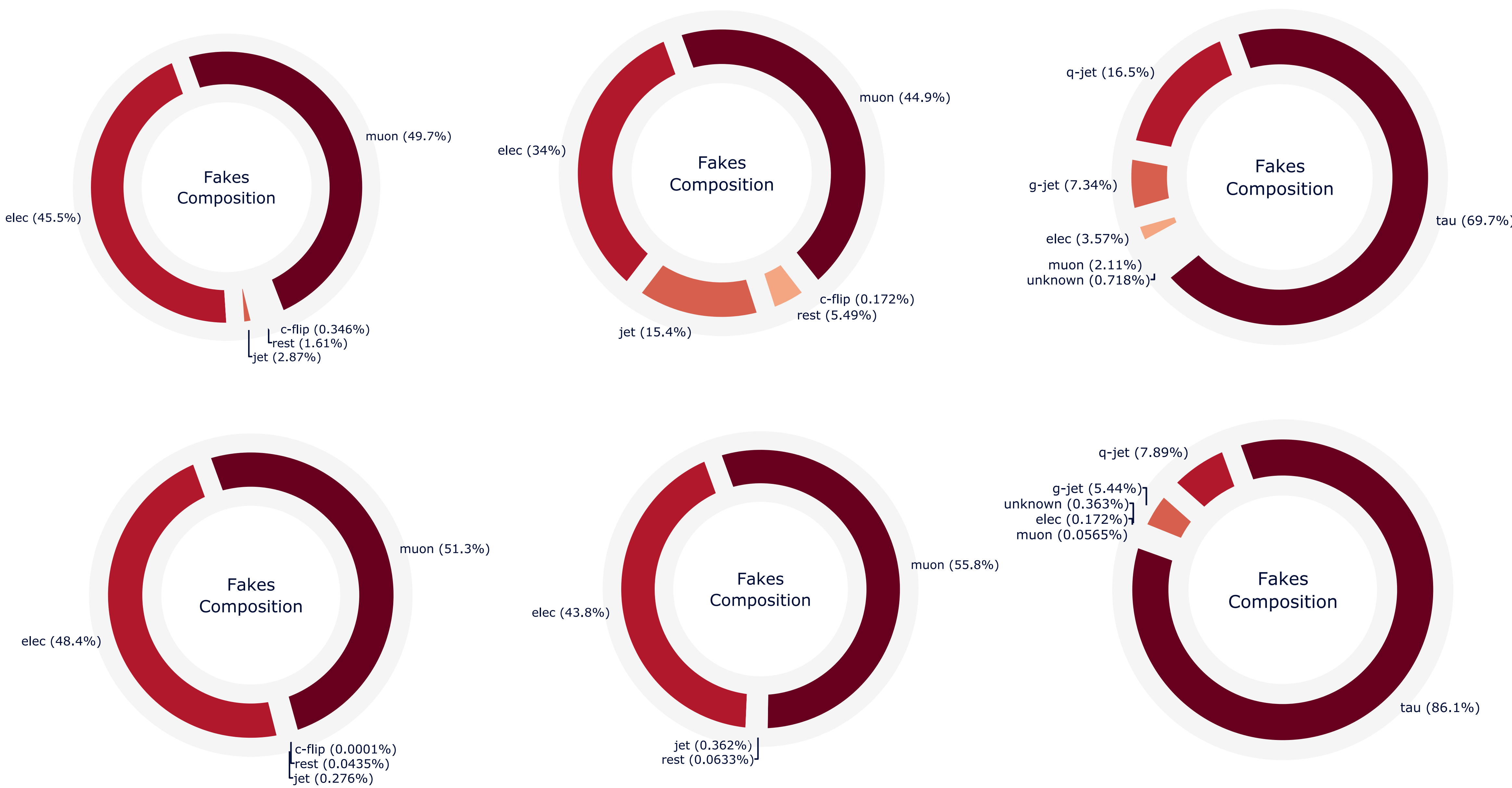
Estimation of τ_{had} misidentification

- $2\ell SS + \tau_{had}$ channel

Leading lep. | Subleading lep. | τ_{had}

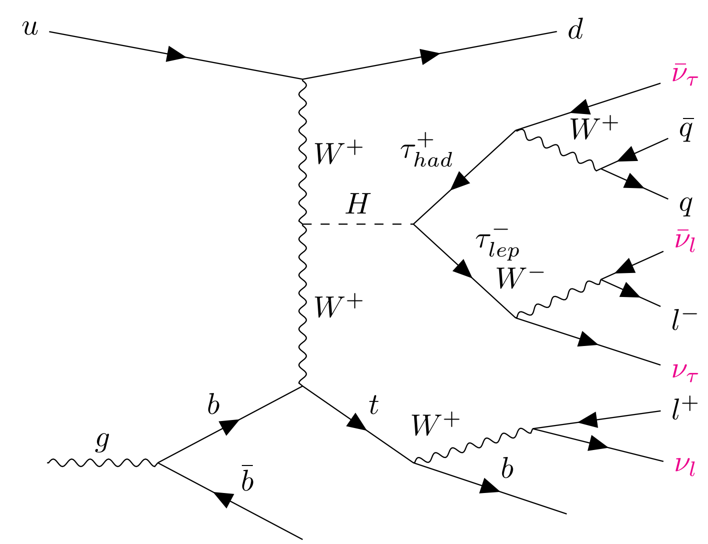
Total MC

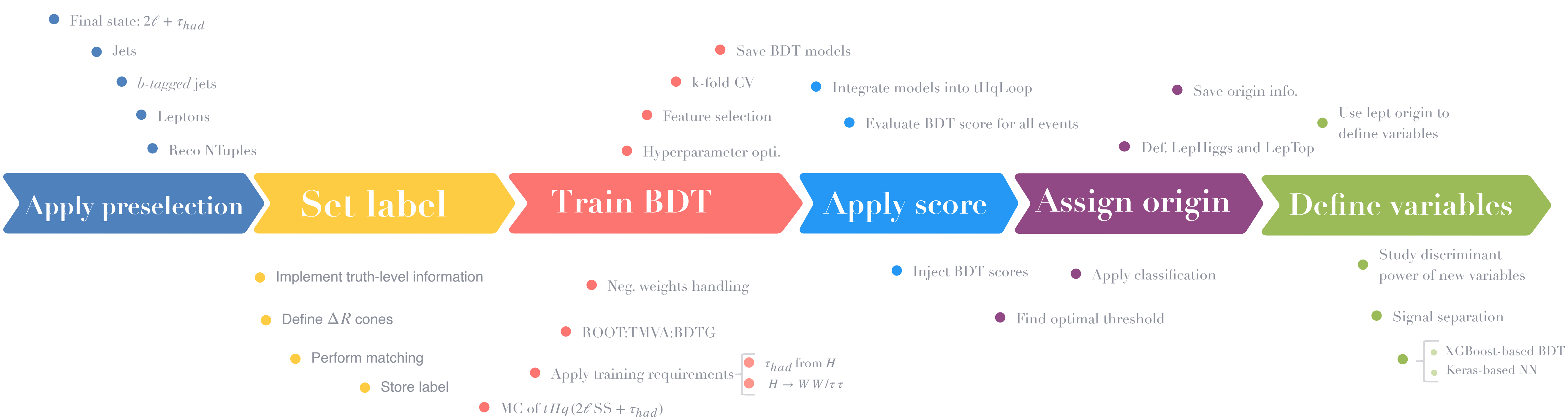
$tHq\ 2\ell SS + \tau_{had}$



Event reconstruction

- Reconstructing the four momentum of H and t can be used to suppress background.
- Difficult: **at least** four neutrinos in the final state
- First step: Assign the origin of light leptons:
  - Trivial for the 2ℓOS $+ \tau_{had}$ channel
  - MVA method for the 2ℓSS $+ \tau_{had}$ channel



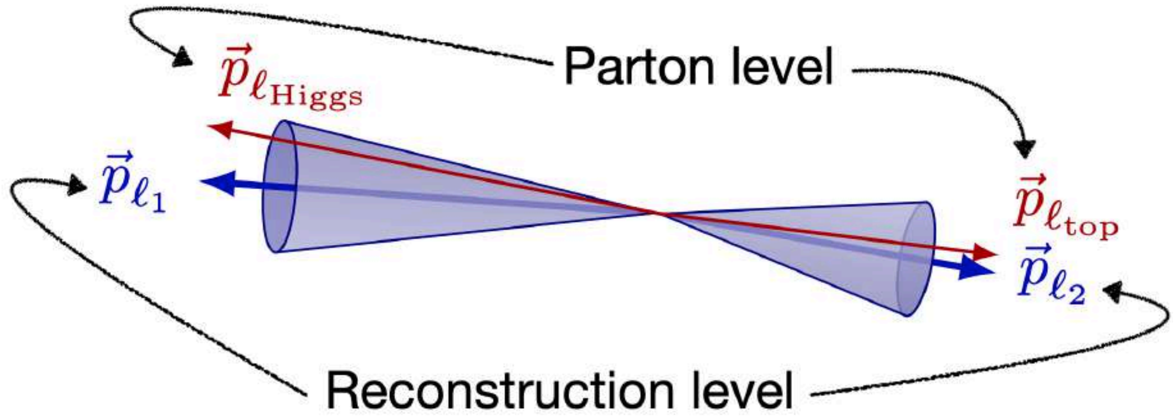


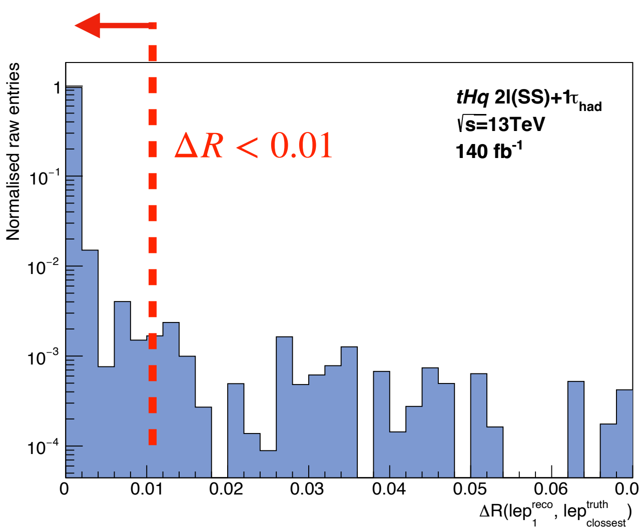
Assignment lepton origin - Label

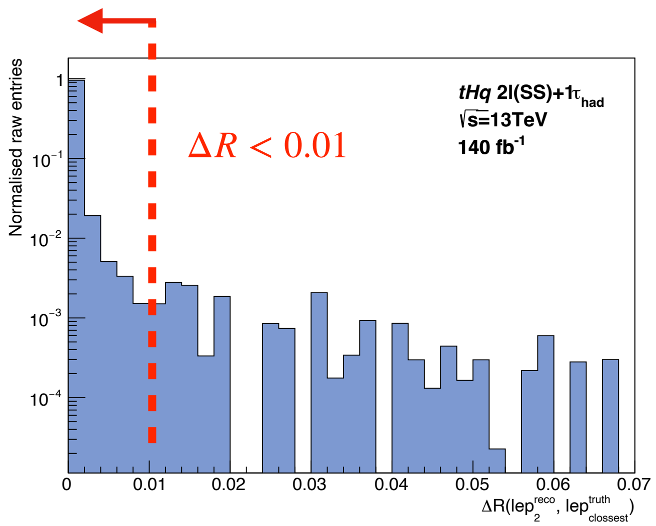
- Label the date comparing the parton-level with reco-level in simulation:
  - **Parton-level**: Before the detector simulation. The origin of the particles is known.
  - **Reconstruction-level**: Objects as identified by the detector. Origin of particles unknown

- Requirements:
  - $2\ell SS + \tau_{had}$
  - τ_{had} from Higgs
  - $H \to \tau\tau/WW$

- Draw $\Delta R < 0.01$ cones around the of the leptons.



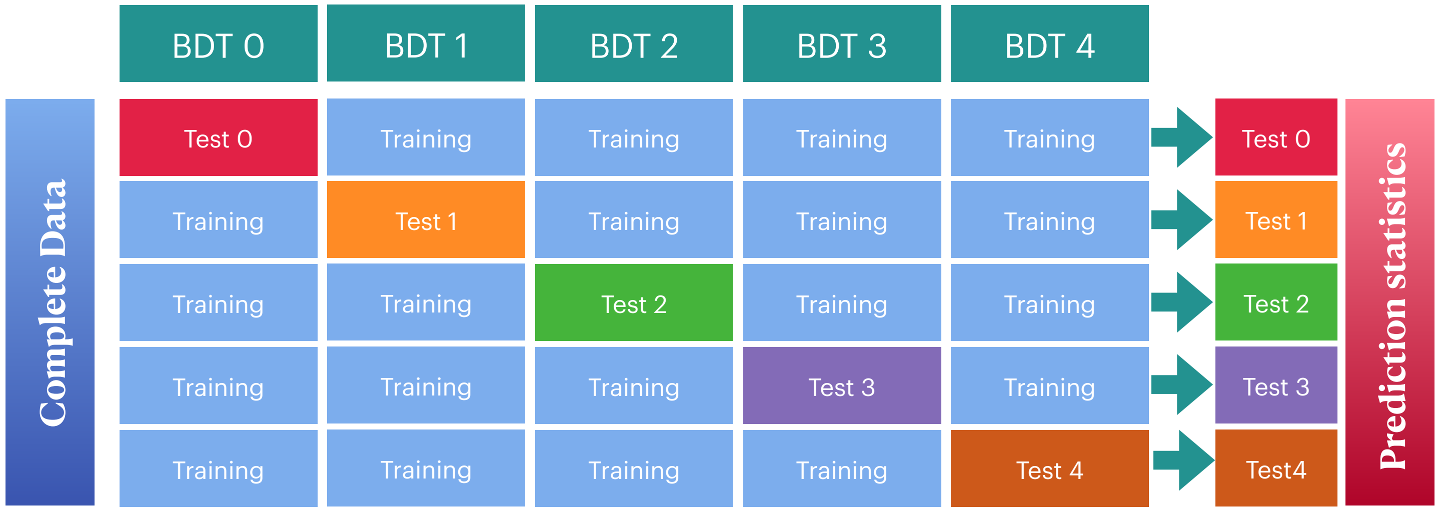


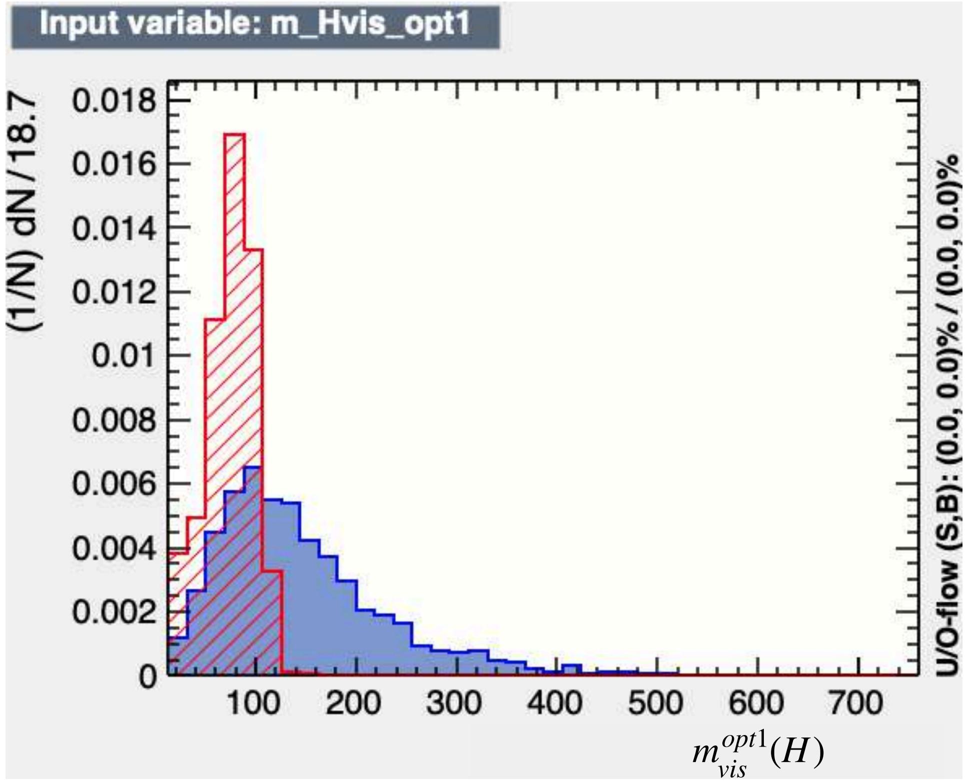


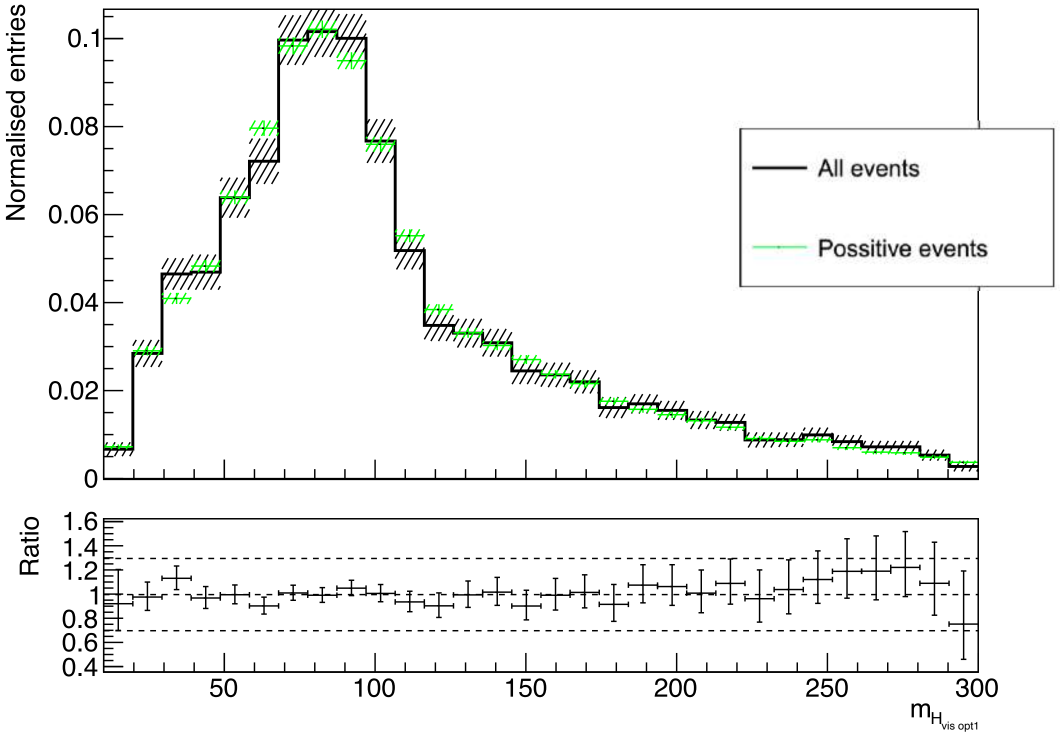
- Two categories:
  - **Type 1**: $\ell_1^{reco} = \ell_t$ and $\ell_2^{reco} = \ell_H$: 61.1%
  - **Type 2**: $\ell_1^{reco} = \ell_H$ and $\ell_2^{reco} = \ell_t$: 38.9%

BDT lepton origin - Configuration

- Truth info used to obtain the label
- TMVA-based Gradient BDT: One score
  - Variable optimisation
  - Negative weight strategy (~36% of neg)
    - Same profiles (all vs pos-only)? Yes
    - Same fraction of negative weights in both categories? Yes
  - Hyperparameter optimisation: Grid search
  - k-folding for training ($k = 5$)



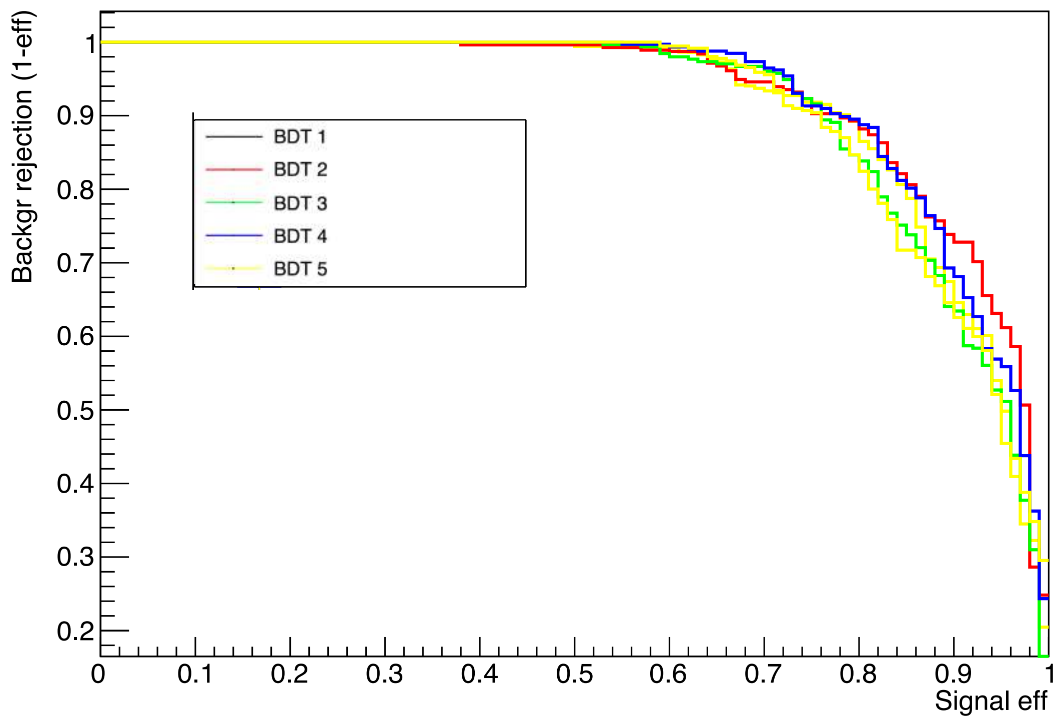


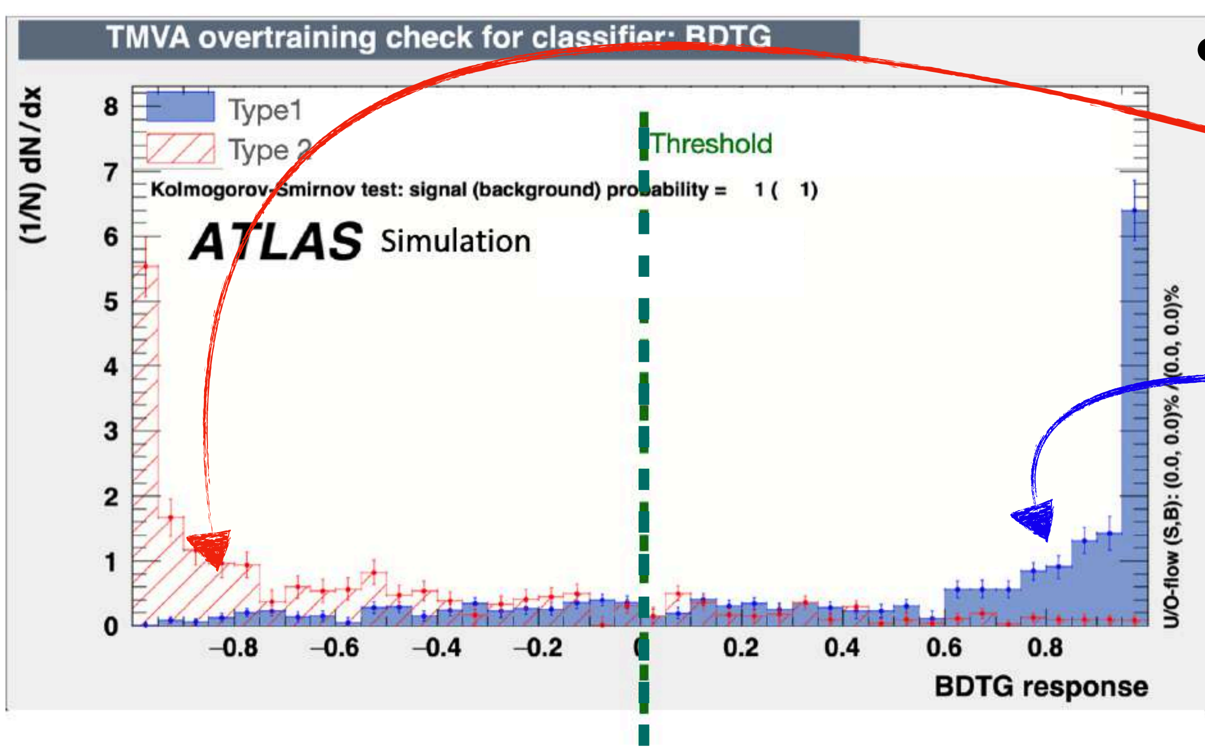


BDT lepton origin - Model

Ranked variables

1. $m_{vis}^{opt1}(H)$
2. $\Delta\eta(\tau_{had}, \ell_1)$
3. $m_{vis}^{opt2}(H)$
4. $\Delta\eta(\tau_{had}, \ell_2)$
5. $m_{pred}^{opt1}(t)$
6. ΔR(leading b-tagged jet, ℓ_1)
7. $m_{pred}^{opt2}(t)$
8. ΔR(b-tagged jet, ℓ_2)
9. $\Delta\eta$(closest b-tagged jet, ℓ_1)





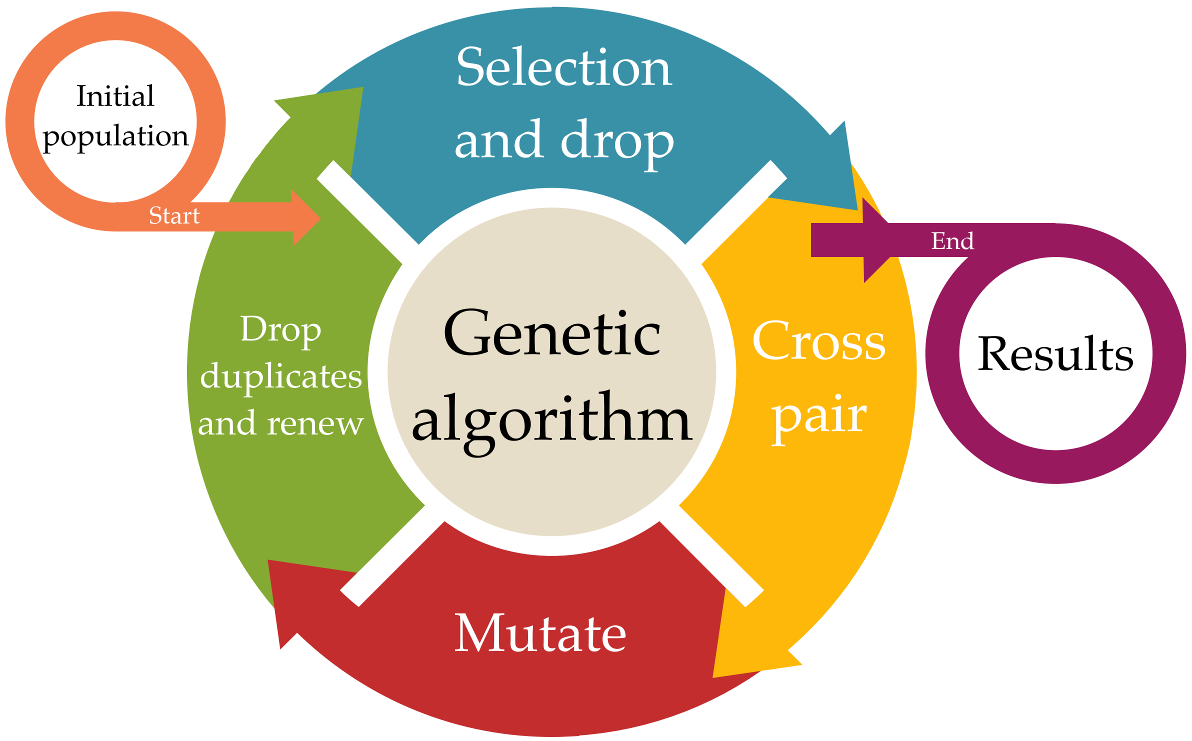
- Optimised threshold

ℓ_1 from H and ℓ_2 from t

ℓ_1 from t and ℓ_2 from H

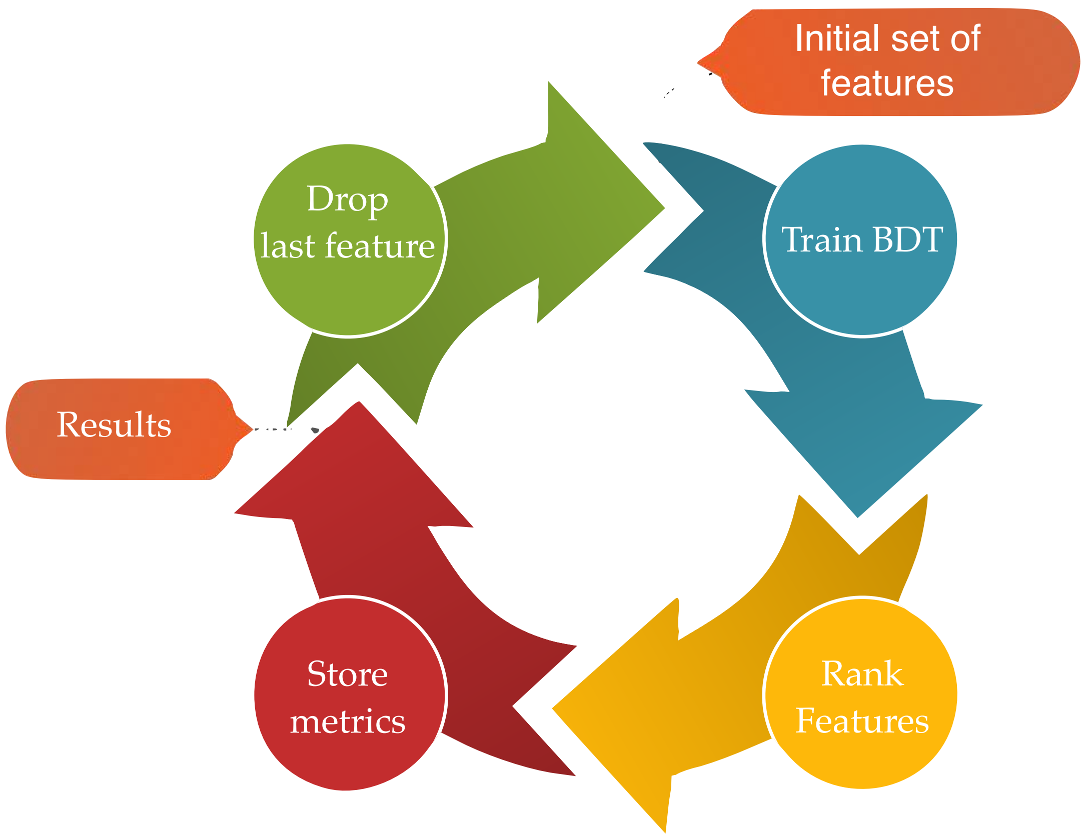
BDTs for process separation

- Improve signal sensitivity using MVA method
- The XGBoost classifier has been used to enhance the signal-to-background separation due to its high performance.
  - k-folding method for training ($k = 5$)
  - Negative weights strategy: Only positive or Absolute weights
  - Iterative algorithm for variable optimisation
  - Genetic algorithm for hyperparameter optimisation
- Trained on events that pass the PR requirements.
- Three different binary BDTs are used:
  - $\mathrm{BDT}(tHq\,|\,\mathrm{OS})$
  - $\mathrm{BDT}(t\bar{t}\,|\,\mathrm{OS})$
  - $\mathrm{BDT}(tHq\,|\,\mathrm{SS})$



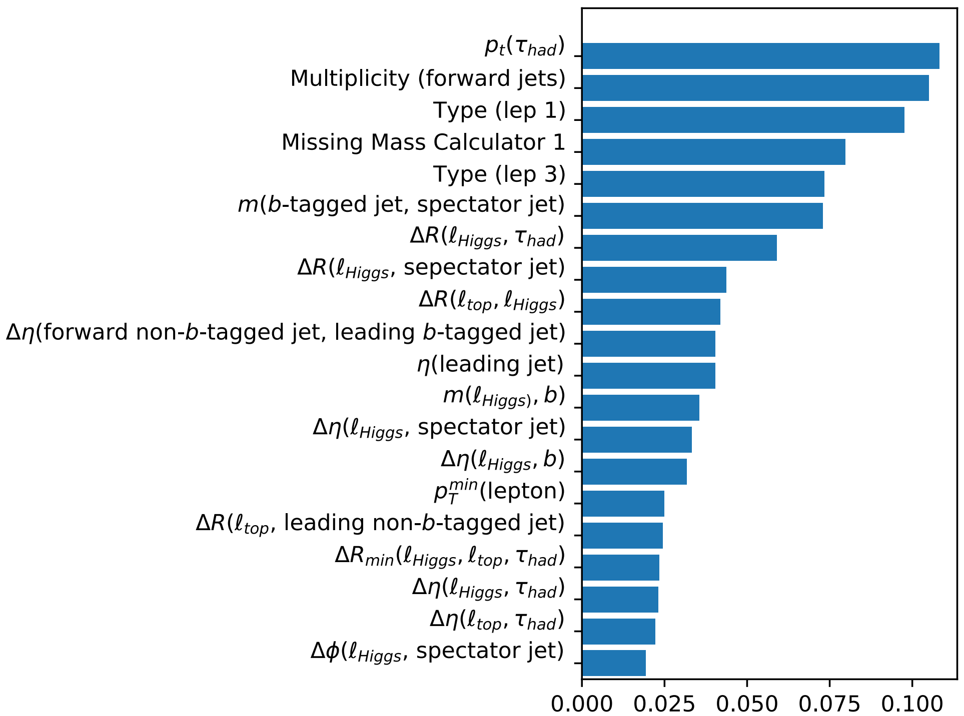
BDTs for region def - Variables

Variable name	BDT($tHq\|_{\mathrm{OS}}$)	BDT($t\bar{t}\|_{\mathrm{OS}}$)	BDT($tHq\|_{\mathrm{SS}}$)
$\Delta\eta(\ell_{\texttt{Higgs}}, \tau_{\mathrm{had}})$	✓	-	✓
$\Delta R(\ell_{\mathrm{top}}$, leading non-$b$-tagged jet)	✓	-	-
$\Delta\eta$(forward non-b-tagged jet, leading b-tagged jet)	✓	-	✓
Visible mass (top quark)	-	✓	-
p_{T} (b-tagged jet)	-	✓	-
$m(\ell_{\texttt{Higgs}}, b\text{-tagged} jet)$	✓	✓	-
Missing Mass Calculator 1	✓	-	-
$p_{\mathrm{T}}(\ell_{\mathrm{top}})$	-	-	✓
$\mathrm{E}(\ell_{\mathrm{top}})$	-	-	✓
$\Delta R_{min}(\ell_{\texttt{Higgs}}, \ell_{\mathrm{top}}, \tau_{\mathrm{had}})$	✓	-	-
m(b-tagged jet, spectator jet)	✓	-	-
$\Delta\eta$(forward non-b-tagged jet, subleading b-tagged jet)	-	✓	-
DL1R calibrated score of subleading b-tagged jet	-	✓	-
DL1R calibrated score of leading b-tagged jet	-	✓	-
$\Delta\phi(\ell_{\texttt{Higgs}}$, spectator jet)	✓	-	✓
$\Delta R(\ell_{\mathrm{top}}, \ell_{\texttt{Higgs}})$	✓	-	✓
Multiplicity (forward jets)	✓	-	-
$\Delta\eta$(leading lepton, closest b-tagged jet)	-	✓	-
$\Delta\eta(\ell_{\mathrm{top}}, \ell_{\texttt{Higgs}})$	-	✓	✓
$\Delta R(\ell_{\texttt{Higgs}}, \tau_{\mathrm{had}})$	✓	-	-
$p_{\mathrm{T}}^{\mathrm{min}}$(lepton) || p_{T} of the softest lepton	✓	-	-
$\Delta R(\ell_{\texttt{Higgs}}$, spectator jet)	✓	-	-
Type (ℓ_1)	✓	-	-
Type (ℓ_3)	✓	-	-
$m_{\mathrm{T}}(\ell_{\mathrm{top}}$ + leading b-tagged jet)	-	-	✓
$\Delta\eta(\ell_{\mathrm{top}}$, leading non-$b$-tagged jet)	-	-	✓
$\Delta\eta(\ell_{\texttt{Higgs}}$, leading b-tagged jet)	✓	-	-
$m(\ell_{\texttt{Higgs}} + \ell_{\mathrm{top}})$	-	✓	-
p_{T} (τ_{had})	✓	-	✓
p_{T} (jet 3)	-	✓	-
η(leading jet)	✓	-	-
$\Delta\eta(\ell_{\texttt{Higgs}}$, spectator jet)	✓	-	-
E_T^{miss}	-	✓	-
$\Delta\eta(\ell_{\mathrm{top}}, \tau_{\mathrm{had}})$	✓	-	-
Multiplicity central jets	-	-	✓

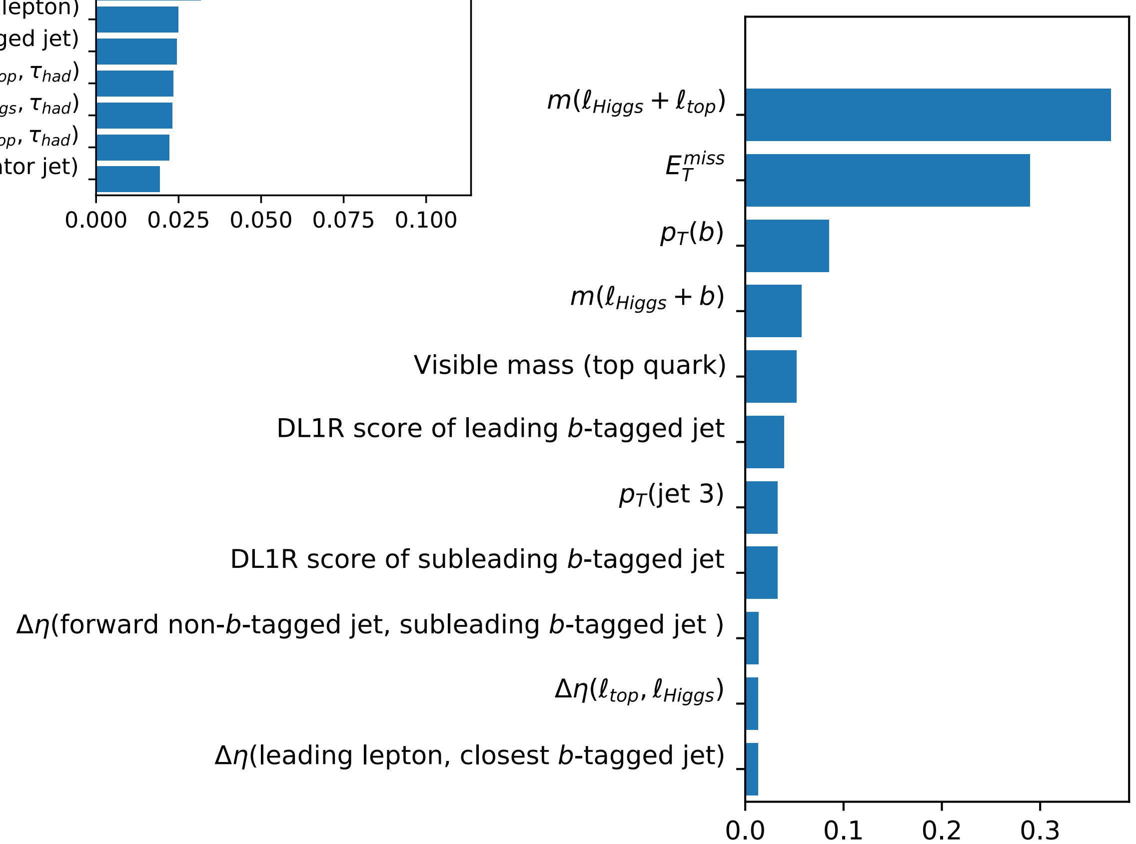


BDTs for region def - Variables

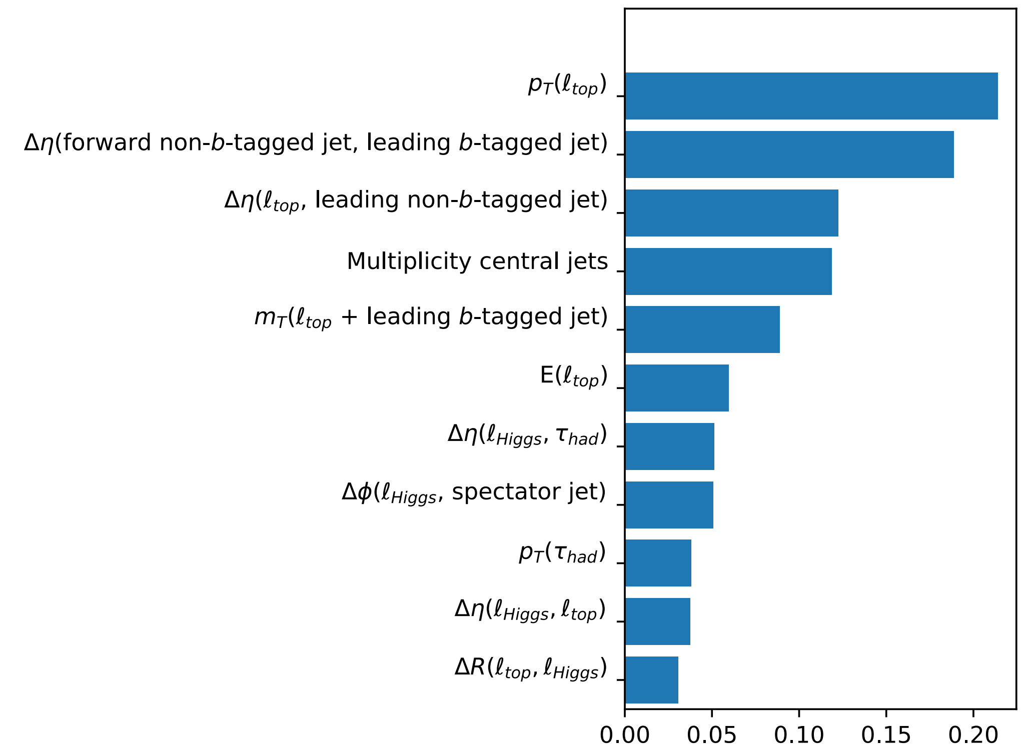
BDT(tHq | OS)



BDT($t\bar{t}$ | OS)



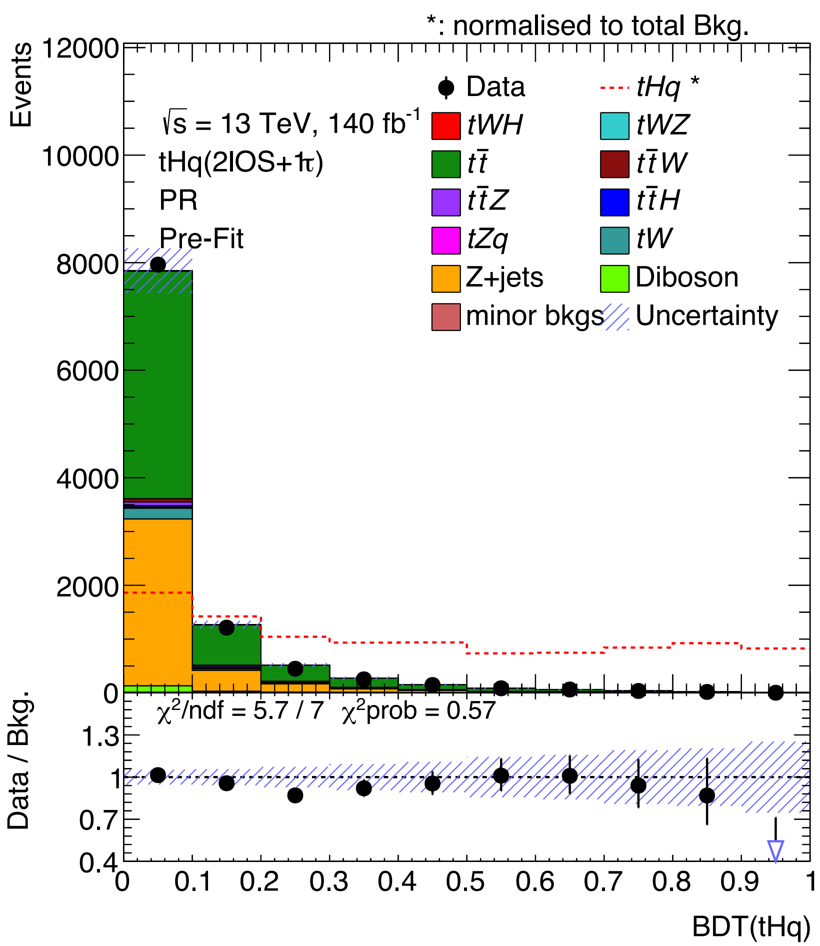
BDT(tHq | SS)



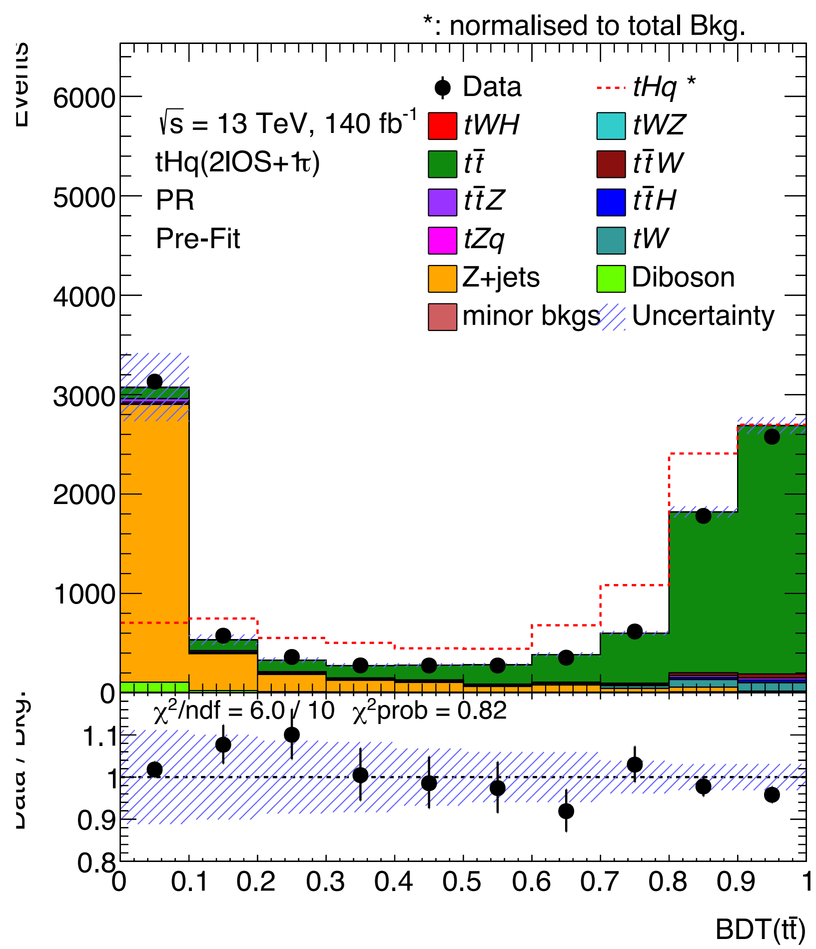
Ranking allows for interpretability

BDTs for region def - Scores

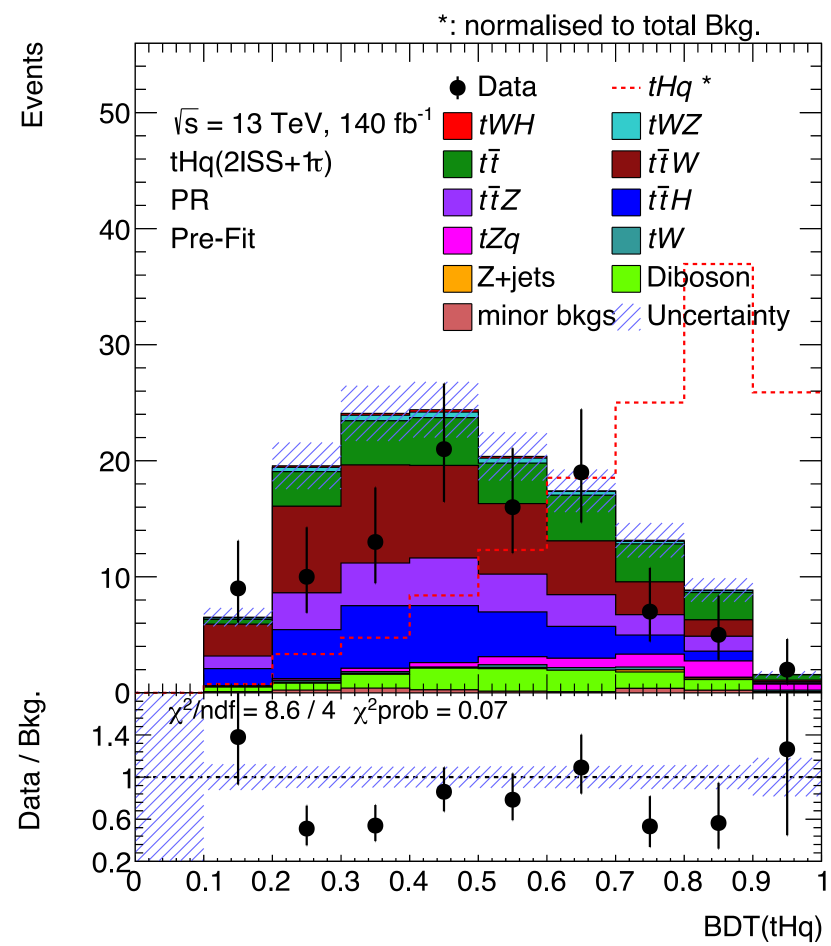
$\mathrm{BDT}(tHq\,|\,\mathrm{OS})$



$\mathrm{BDT}(t\bar{t}\,|\,\mathrm{OS})$



$\mathrm{BDT}(tHq\,|\,\mathrm{SS})$

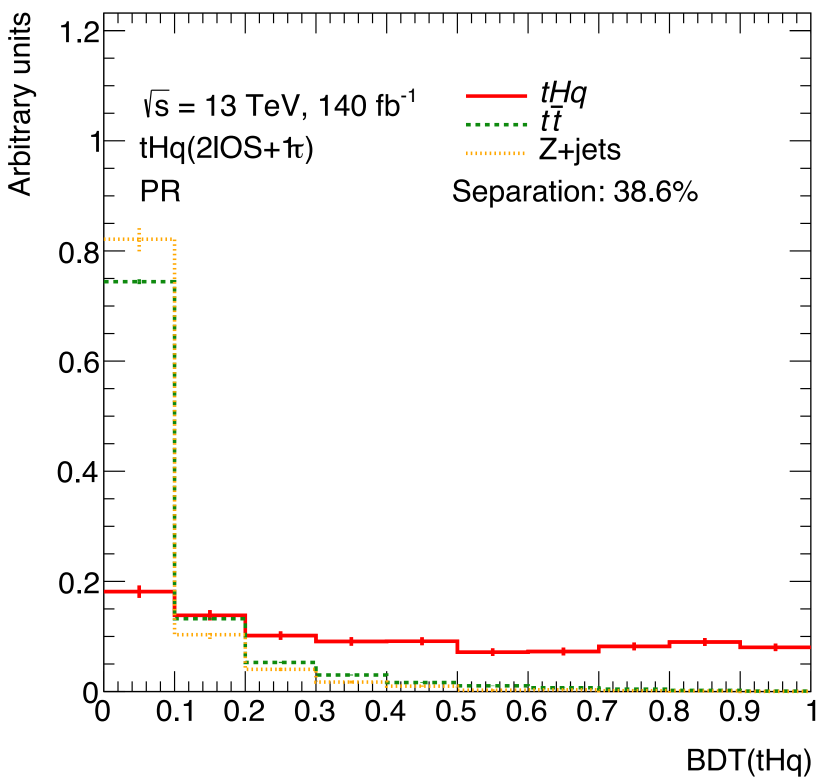


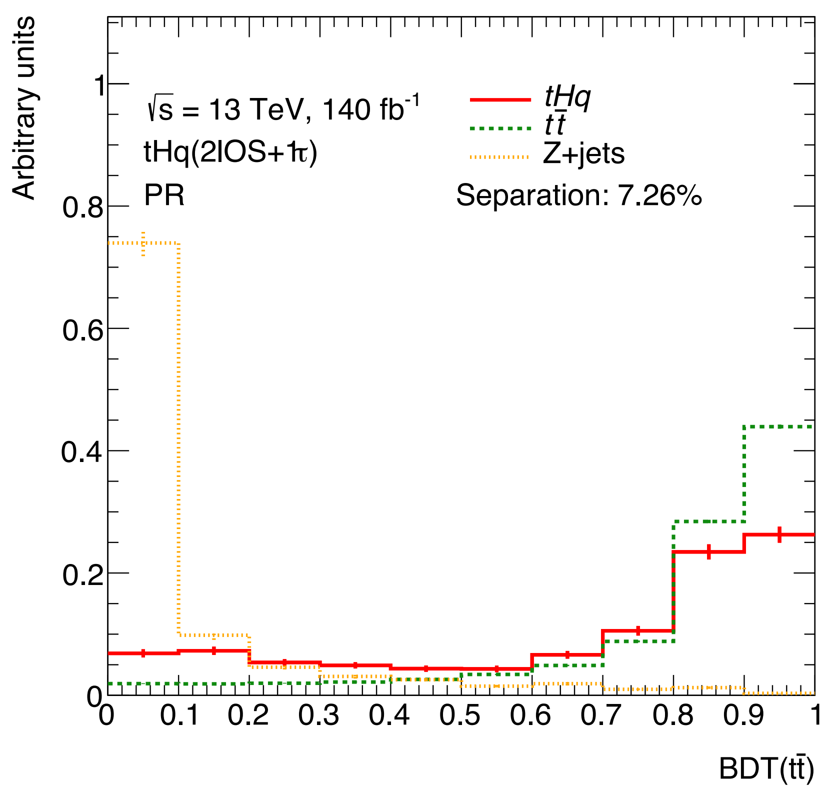
$2\ell\mathrm{OS} + \tau_{had}$

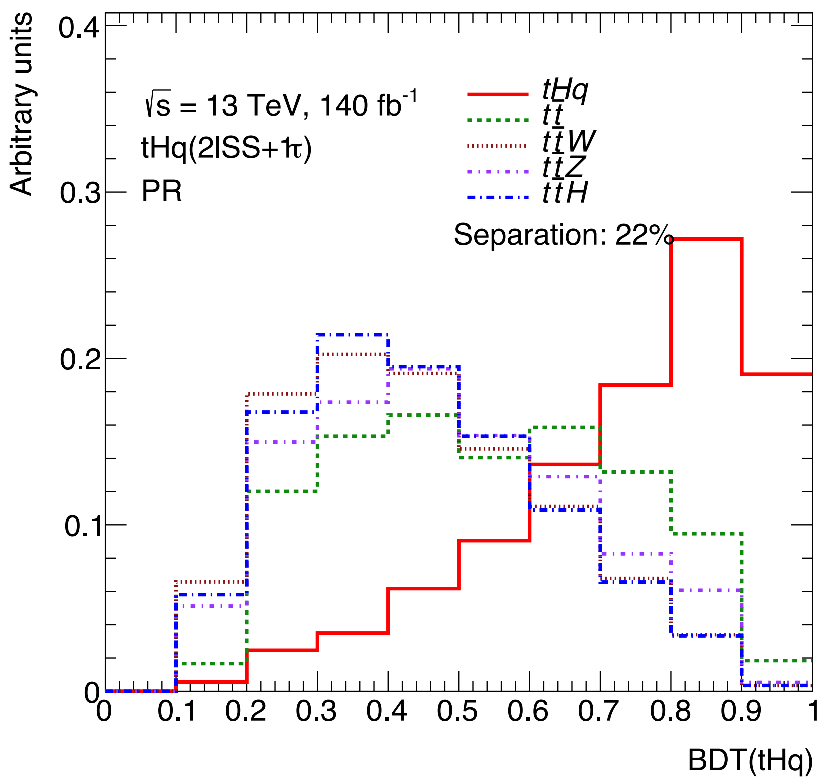
$2\ell\mathrm{SS} + \tau_{had}$

BDTs for region def - Scores

$\mathrm{BDT}(tHq\,|\,\mathrm{OS})$ $\mathrm{BDT}(t\bar{t}\,|\,\mathrm{OS})$ $\mathrm{BDT}(tHq\,|\,\mathrm{SS})$





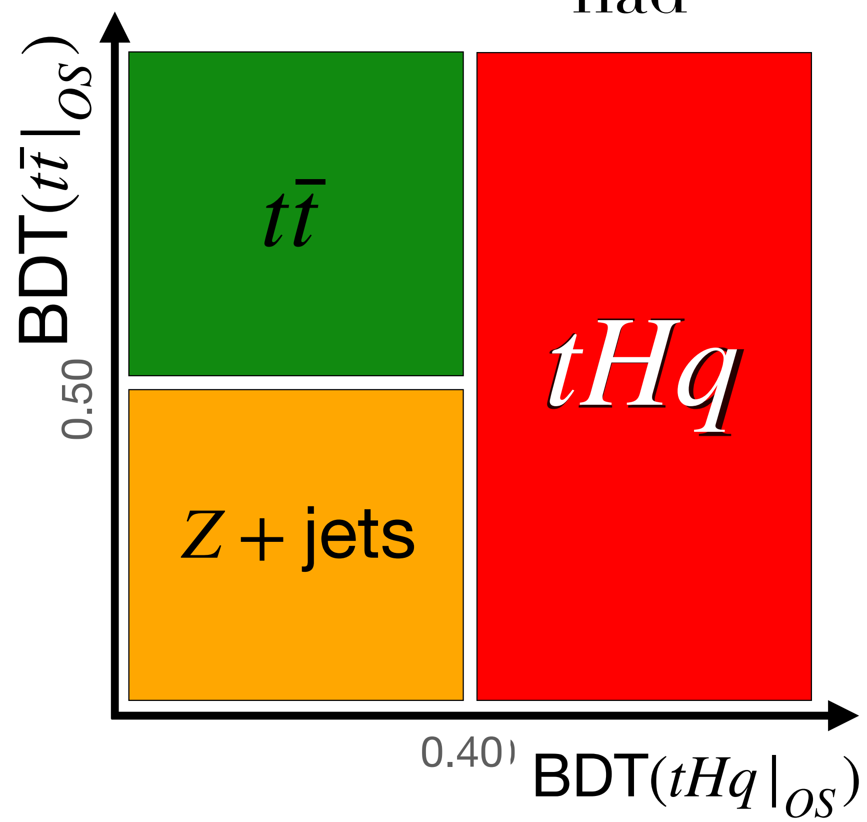


$2\ell\mathrm{OS} + \tau_{had}$

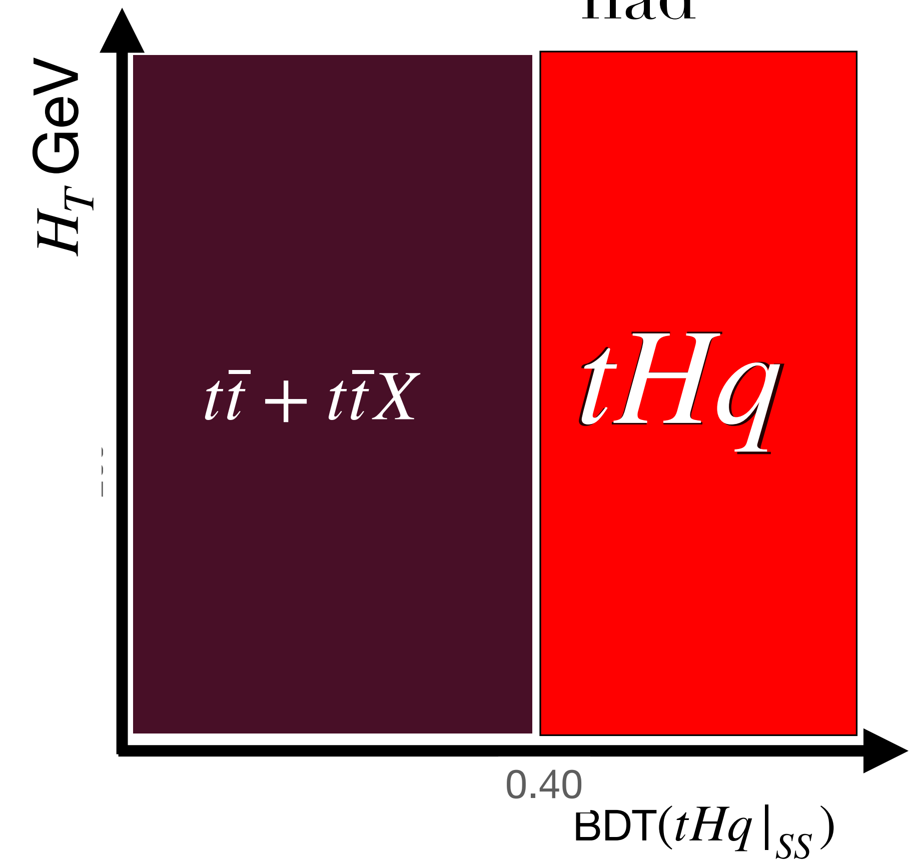
$2\ell\mathrm{SS} + \tau_{had}$

Region definition

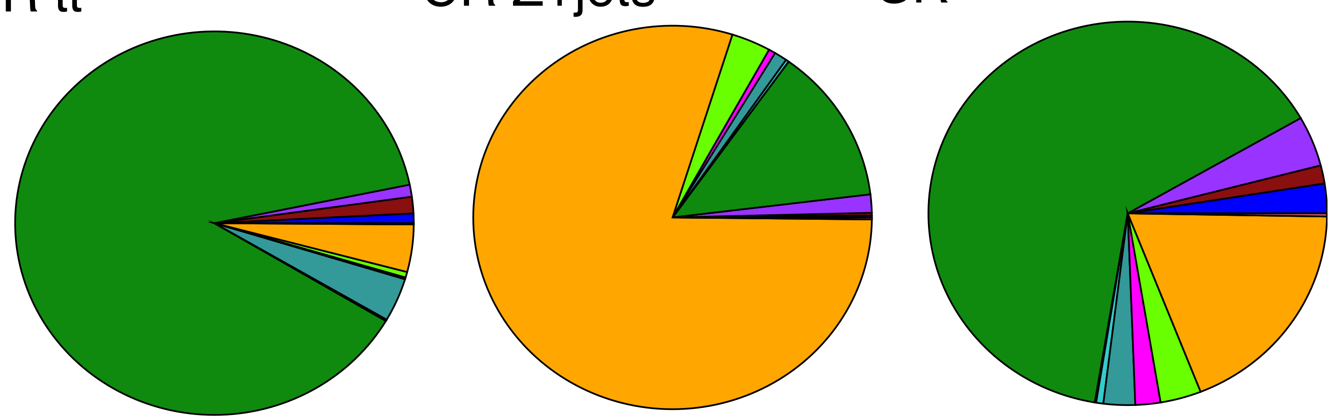
$2\ell\mathrm{OS} + 1\tau_{\mathrm{had}}$



$2\ell\mathrm{SS} + 1\tau_{\mathrm{had}}$

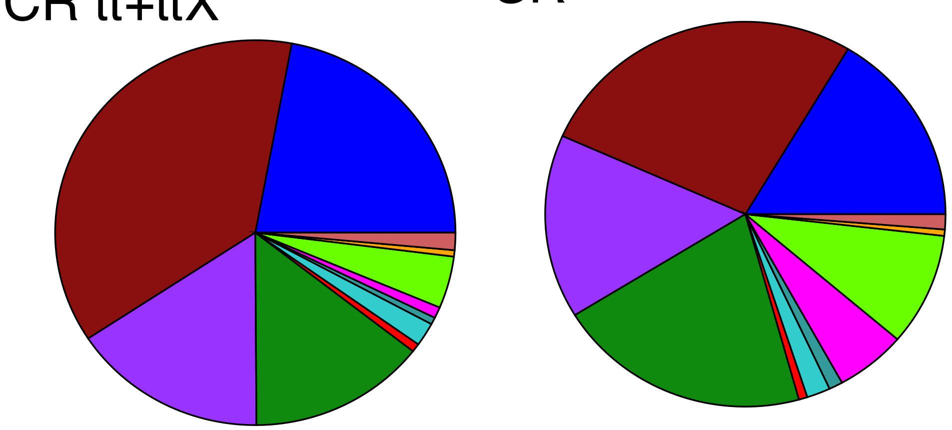


CR $t\bar{t}$ | CR Z+jets | SR



88.5% | 79.7% | 0.019% —> 0.261%

CR $t\bar{t}$+$t\bar{t}$X | SR



0.89% —> 1.26%

The Binned Profile Likelihood fit

- Profile likelihood binned fit to test the experimental confirmation of the *tHq* process
- Shape analysis, based on distributions of continuous observables
- Signal and background predictions depend on parameters: $\mu(tHq)$ and k_p
- Build a global likelihood function: $$L(\vec{n}|\mu,\vec{\theta}) = \prod_{i\in\text{bins}} \mathcal{P}\left(n_i^{\text{obs}}|\mu\cdot s_i^{\text{exp}}(\vec{\theta}) + b_i^{\text{exp}}(\vec{\theta})\right) \times \prod_{j\in\text{syst}} \mathcal{G}(\theta_j^0|\theta_j,\Delta\theta_j) \times \prod_{s\in\gamma} \mathcal{P}(\theta_s^0|\theta_s,\Delta\theta_s)$$
- Solving for
  - **Parameters if interest:** $\mu_{tHq}^{2\ell OS+1\tau}$ and $\mu_{tHq}^{2\ell SS+1\tau}$
  - **Free-floating normalisations**: $k_{t\bar{t}}^{2\ell OS+1\tau}$, $k_{Z+jets}^{2\ell OS+1\tau}$ and $k_{t\bar{t}+t\bar{t}X}^{2\ell SS+1\tau}$
- All systematics included
- Systematic pruning: shape 1%, normalisation 0.5%

Systematics

Detector uncertainties:

- Luminosity, Pile-up rew., Electron, Muon, Tau, Jet [JES, JER, FTAG, JVT, fJVT], MET

Modelling Uncertainties:

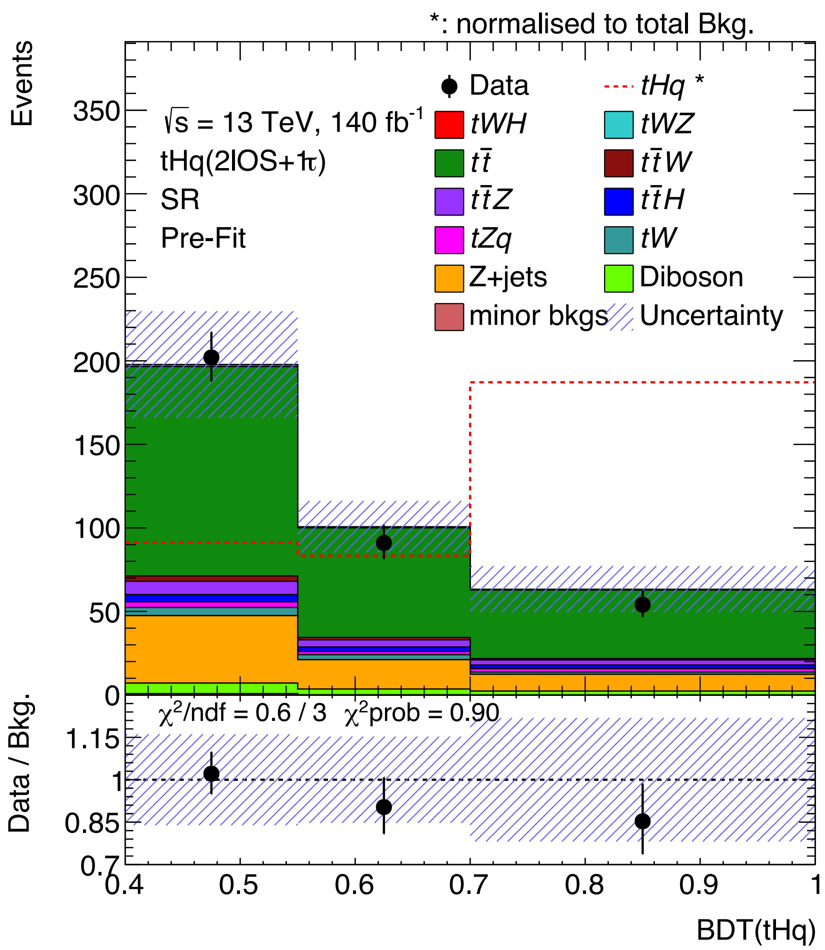
- tHq: PS
- $t\bar{t}$: ME, PS, ISR, FSR, hdamp
- Single top-quark: ME, PS, ISR, FSR
- $t\bar{t}H$: ME, PS, ISR, FSR
- tZq , ttZ, ttW: PS, ME, ISR
- Diboson: MEPS
- tWH: PS
- μ_R and μ_F variations for tHq, $t\bar{t}$, $t\bar{t}H$, $t\bar{t}V$, tZq, tWH, diboson, V+jets
- Cross-section uncertainty for all processes (except for processes being fitted)
- PDF uncertainties: tHq, $t\bar{t}$, $t\bar{t}H$, $t\bar{t}V$, tZq, tWH and diboson

Light lepton fakes and Tau fakes (template fit / counting method)

The Binned Profile Likelihood fit

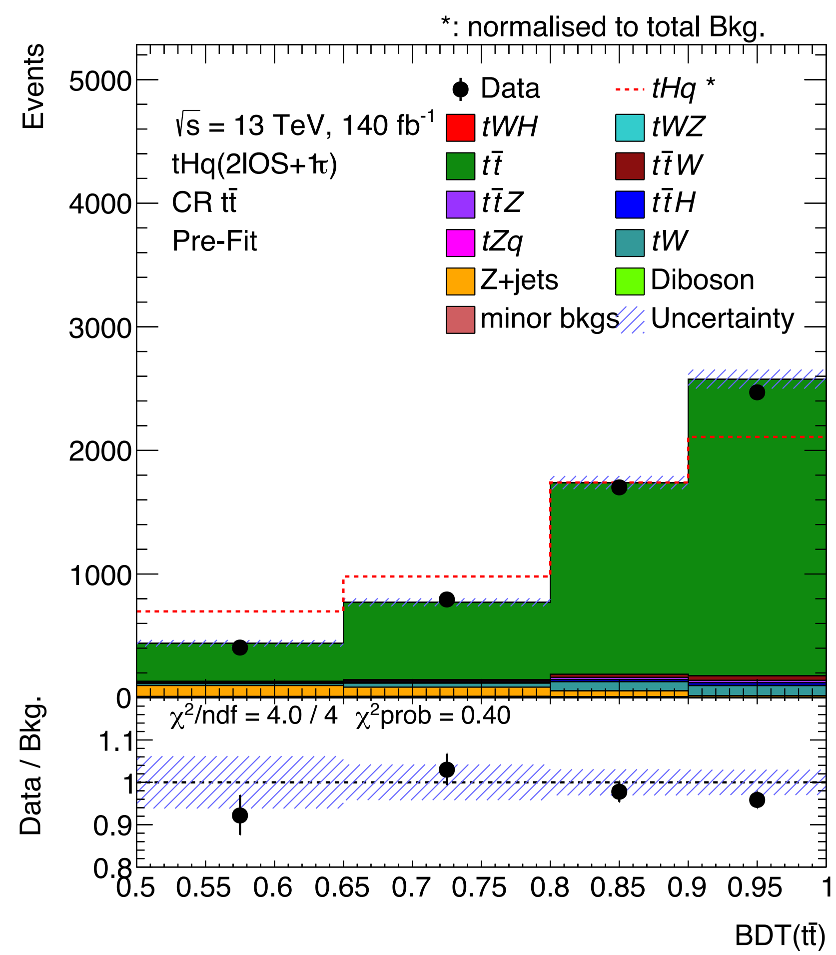
$2\ell OS + 1\tau_{\text{had}}$

Floating normalisations: $\mu_{tHq}^{2\ell OS+1\tau}$ $k_{t\bar{t}}^{2\ell OS+1\tau}$ $k_{Z+jets}^{2\ell OS+1\tau}$



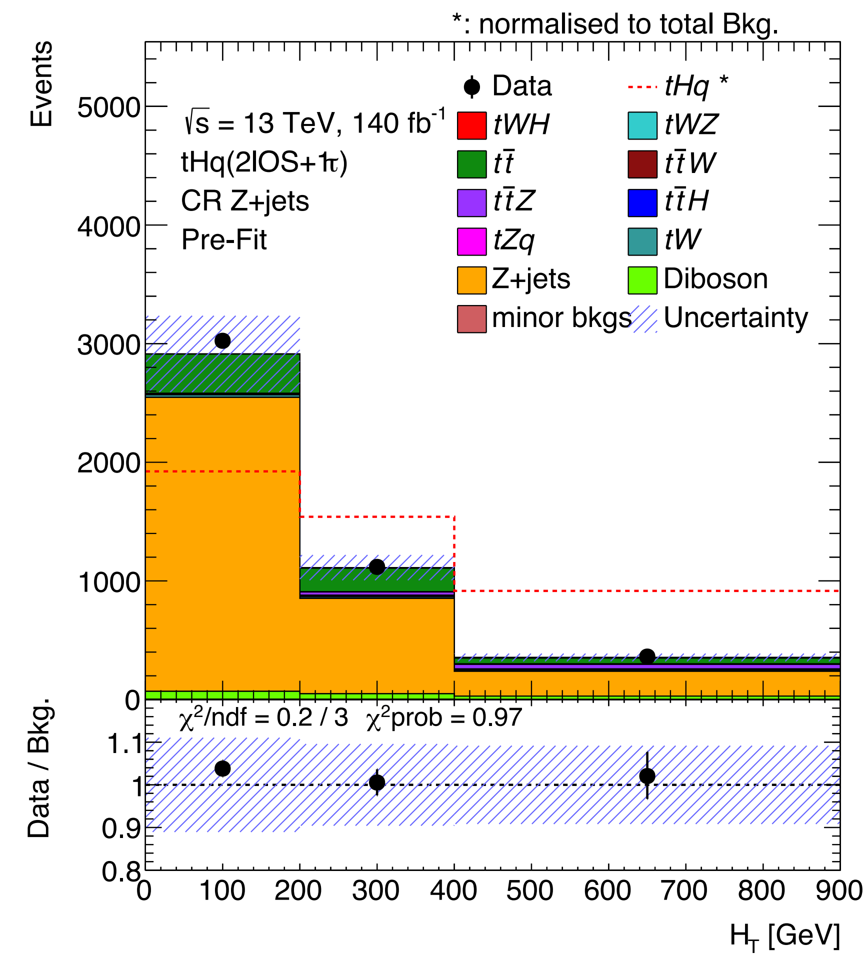
SR

- $\text{BDT}(tHq) \geq 0.4$



CR($t\bar{t}$)

- $\text{BDT}(tHq) < 0.4$
- $\text{BDT}(t\bar{t}) \geq 0.5$



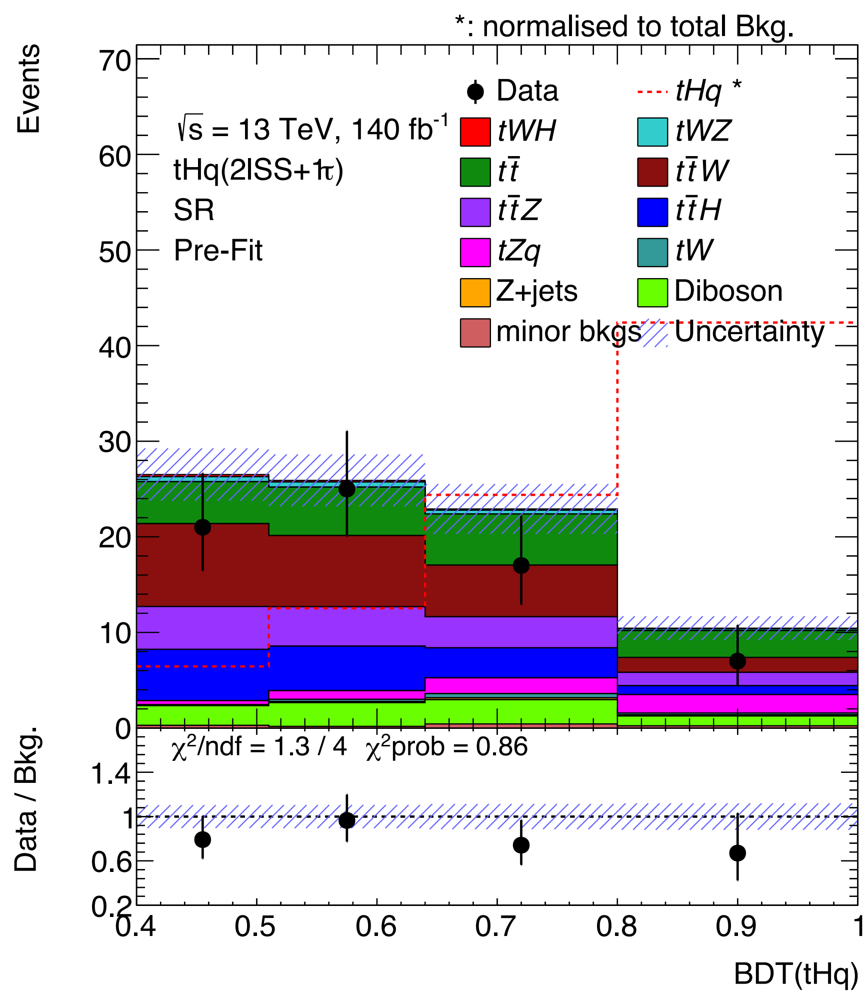
CR(Z+jets)

- $\text{BDT}(tHq) < 0.4$
- $\text{BDT}(t\bar{t}) < 0.5$

The Binned Profile Likelihood fit

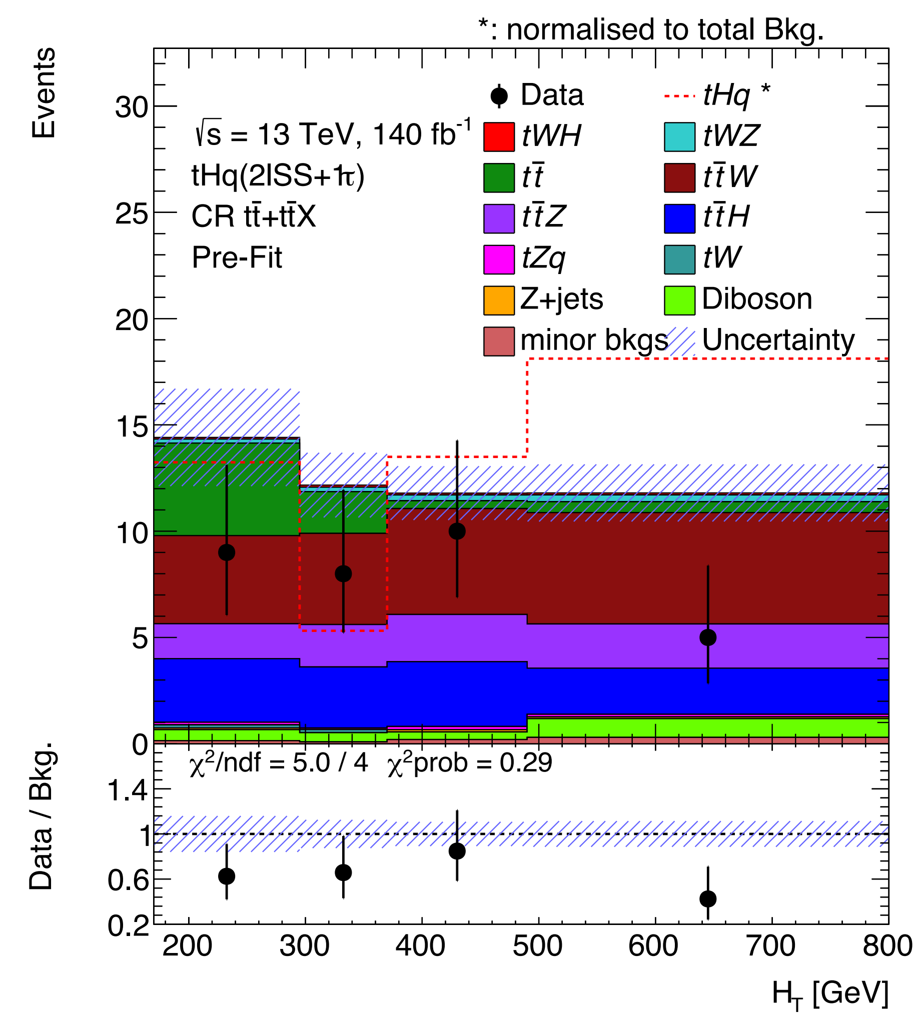
$2\ell SS + 1\tau_{had}$

Floating normalisations: $\mu_{tHq}^{2\ell SS+1\tau}$ $k_{t\bar{t}+t\bar{t}X}^{2\ell SS+1\tau}$



SR

- $\mathrm{BDT}(tHq) \geq 0.4$



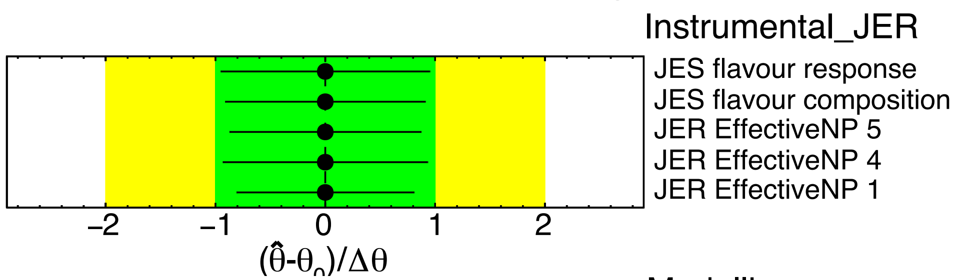
$\mathrm{CR}(t\bar{t} + t\bar{t}X)$

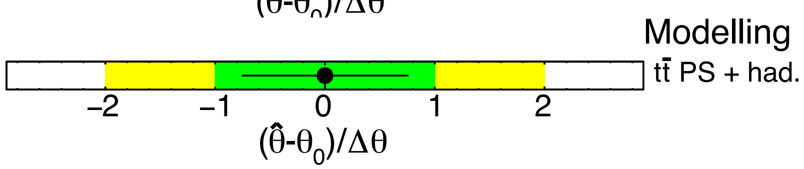
- $\mathrm{BDT}(tHq) < 0.4$

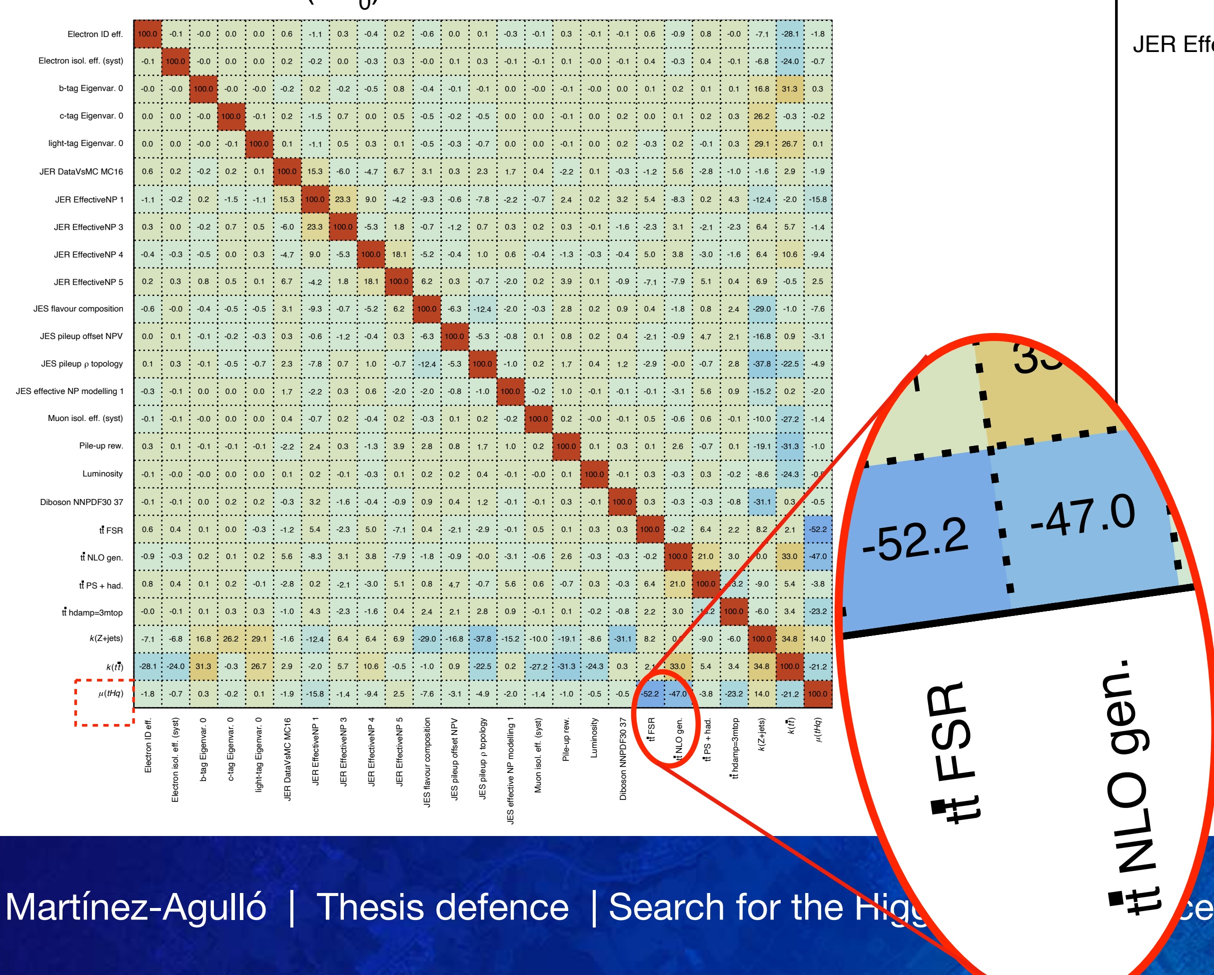
Asimov Fit - NPs

$2\ell OS + 1\tau_{had}$

- No significant constraints except: JES/JER || $t\bar{t}$ Modelling

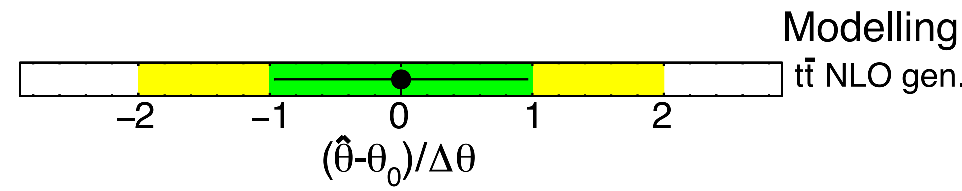






$2\ell SS + 1\tau_{had}$

- No constraints



	JER DataVsMC MC16	JER EffectiveNP 1	JER EffectiveNP 10	JER EffectiveNP 12restTerm	JER EffectiveNP 3	JER EffectiveNP 4	JER EffectiveNP 5	JER EffectiveNP 9	$k(t\bar{t}+t\bar{t}X)$	$\mu(tHq)$
JER DataVsMC MC16	100.0	-0.2	-0.0	-0.0	-0.1	-0.0	-0.1	0.0	15.4	-1.4
JER EffectiveNP 1	-0.2	100.0	0.1	-0.2	-0.6	-0.3	-0.4	-0.2	19.7	-5.0
JER EffectiveNP 10	-0.0	0.1	100.0	0.0	0.3	0.2	0.2	0.1	15.2	-0.0
JER EffectiveNP 12restTerm	-0.0	-0.2	0.0	100.0	-0.1	-0.1	-0.1	-0.0	15.2	-2.3
JER EffectiveNP 3	-0.1	-0.6	0.3	-0.1	100.0	-0.3	-0.4	-0.1	18.4	-4.3
JER EffectiveNP 4	-0.0	-0.3	0.2	-0.1	-0.3	100.0	-0.2	-0.1	17.5	-2.9
JER EffectiveNP 5	-0.1	-0.4	0.2	-0.1	-0.4	-0.2	100.0	-0.1	16.2	-1.0
JER EffectiveNP 9	0.0	-0.2	0.1	-0.0	-0.1	-0.1	-0.1	100.0	15.2	-2.2
$k(t\bar{t}+t\bar{t}X)$	15.4	19.7	15.2	15.2	18.4	17.5	16.2	15.2	100.0	-35.7
$\mu(tHq)$	-1.4	-5.0	-0.0	-2.3	-4.3	-2.9	-1.0	-2.2	-35.7	100.0

Asimov fit - Grouped impact

$2\ell\mathrm{OS} + 1\tau_{\mathrm{had}}$

Expected

Uncertainty source	Grouped impact
MC uncertainty	±7.845
Modelling	
Theoretical uncertainties	±11.917
PDF uncertainty	±7.895
Experimental	
Instrumental	±4.917
Flavour tagging	±0.439
JES/JER	±10.851
NormFactors	±10.493
Total systematic uncertainty	±28.511

$2\ell\mathrm{SS} + 1\tau_{\mathrm{had}}$

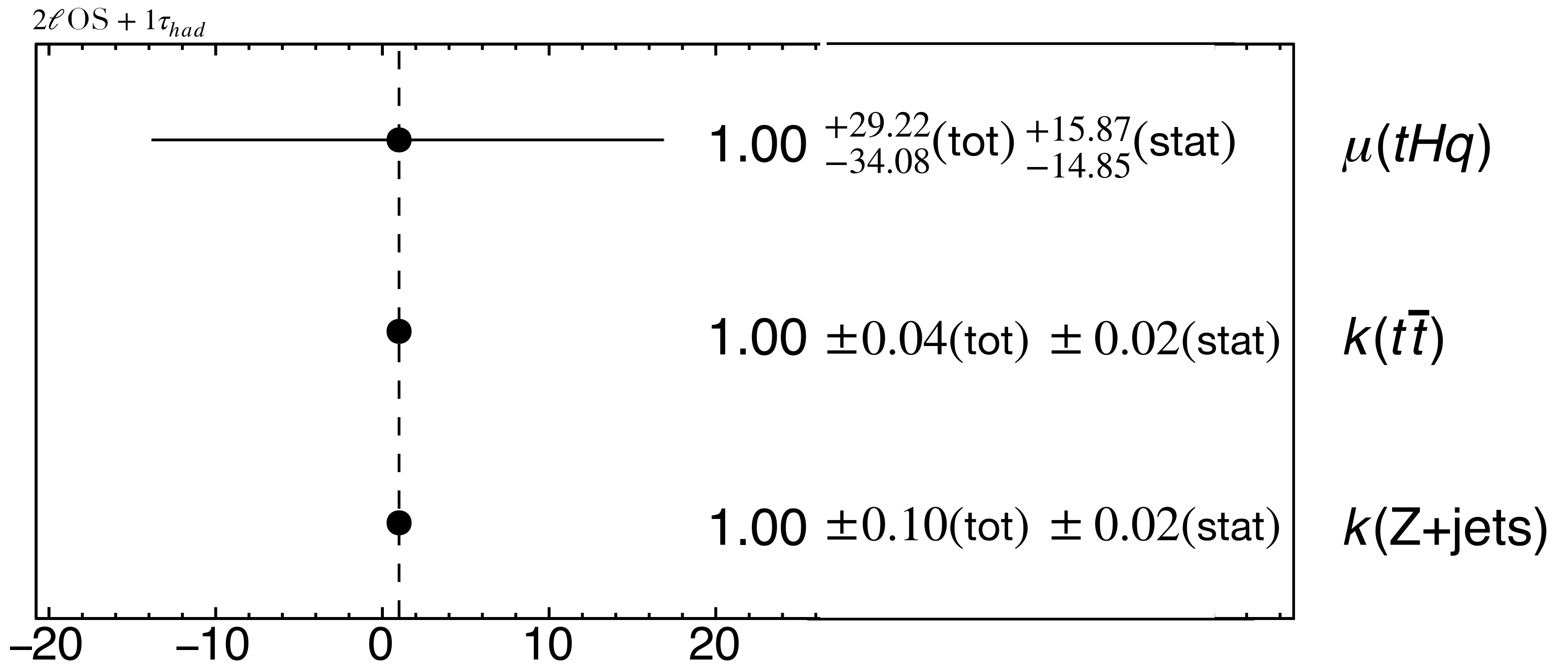
Expected

Uncertainty source	Grouped impact
MC uncertainty	±1.376
Modelling	
Theoretical uncertainties	±1.262
PDF uncertainty	±0.839
Experimental	
Instrumental	±0.793
Flavour tagging	±0.163
JES/JER	±2.877
NormFactors	±2.725
Total systematic uncertainty	±4.614

Asimov fit - Expected sensitivity

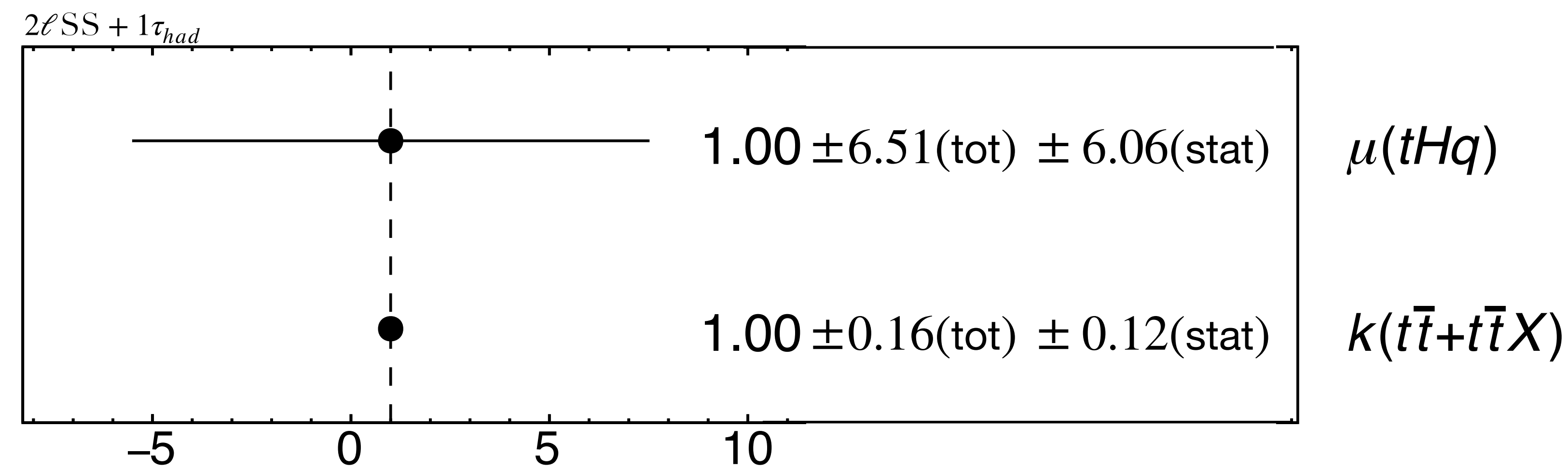
$2\ell\mathrm{OS} + 1\tau_{had}$

- Dominated by systematic uncertainty



$2\ell\mathrm{SS} + 1\tau_{had}$

- Dominated by statistical uncertainty
- Most sensitive

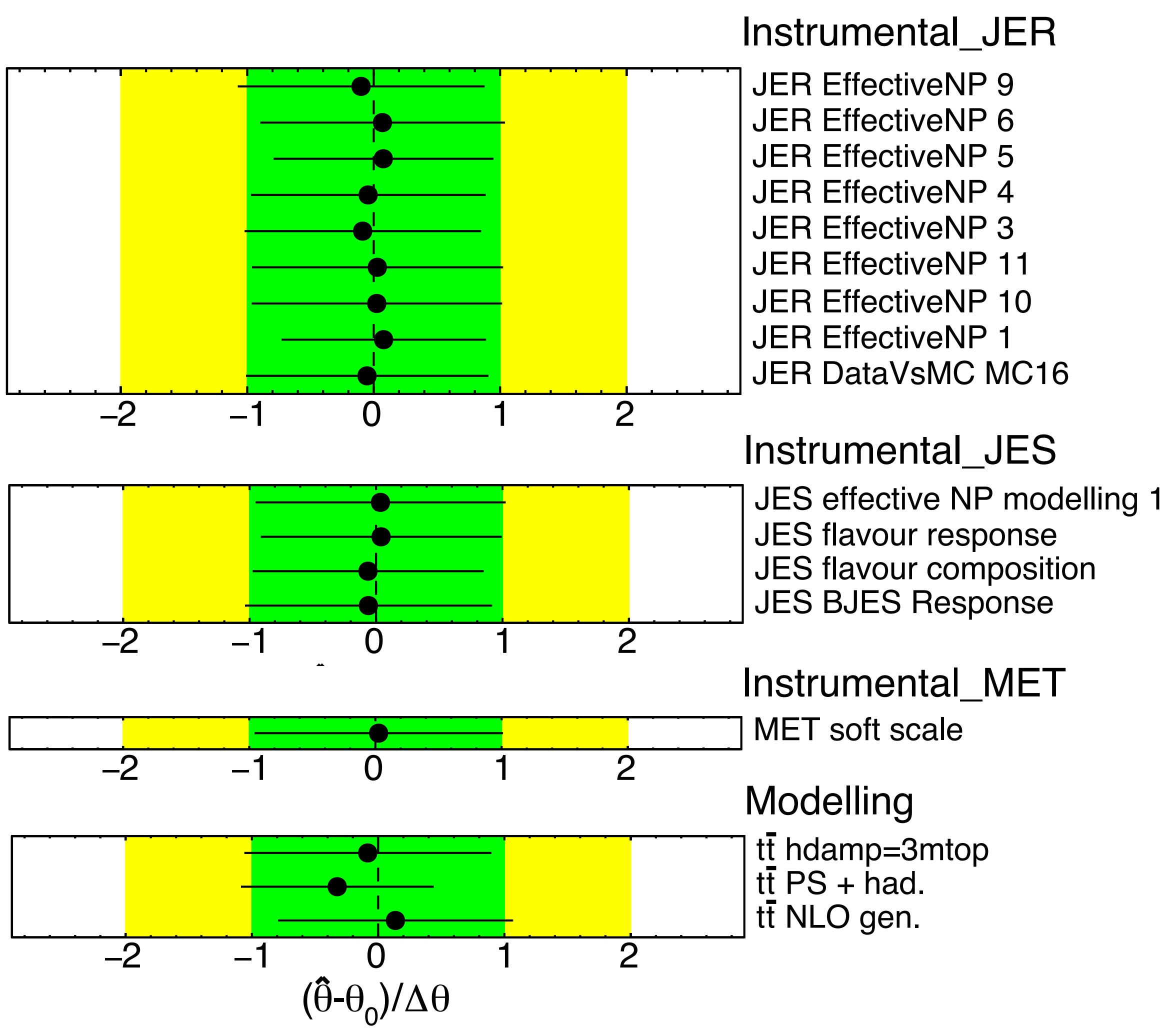


$$\mu_{tHq} = \frac{\sigma_{tHq}}{\sigma_{tHq}^{SM}}$$

Fit - Pulled NPs

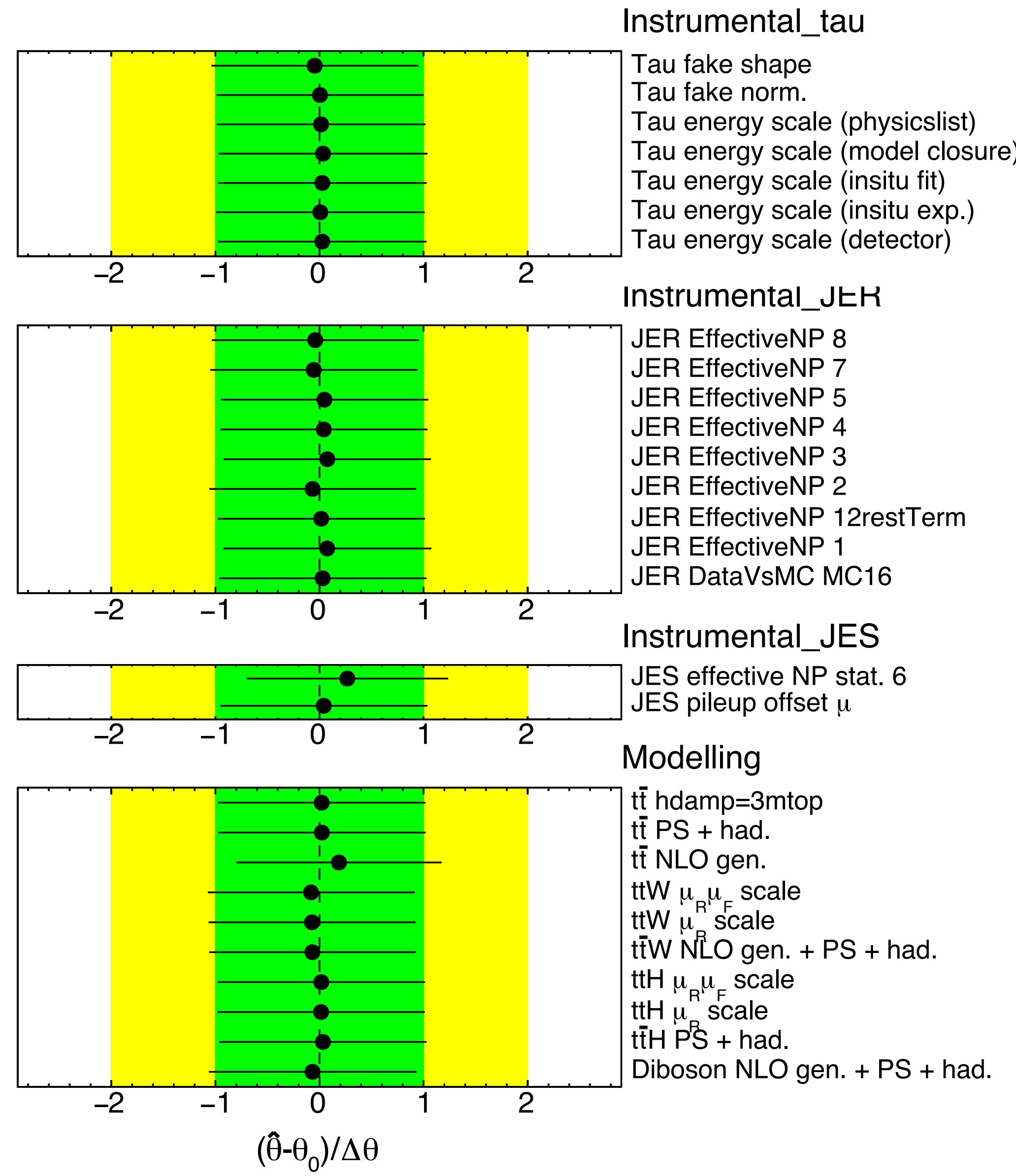
$2\ell OS + 1\tau_{\rm had}$

- No significant pulls except:
  - $t\bar{t}$ Modelling, JES/JER



$2\ell SS + 1\tau_{\rm had}$

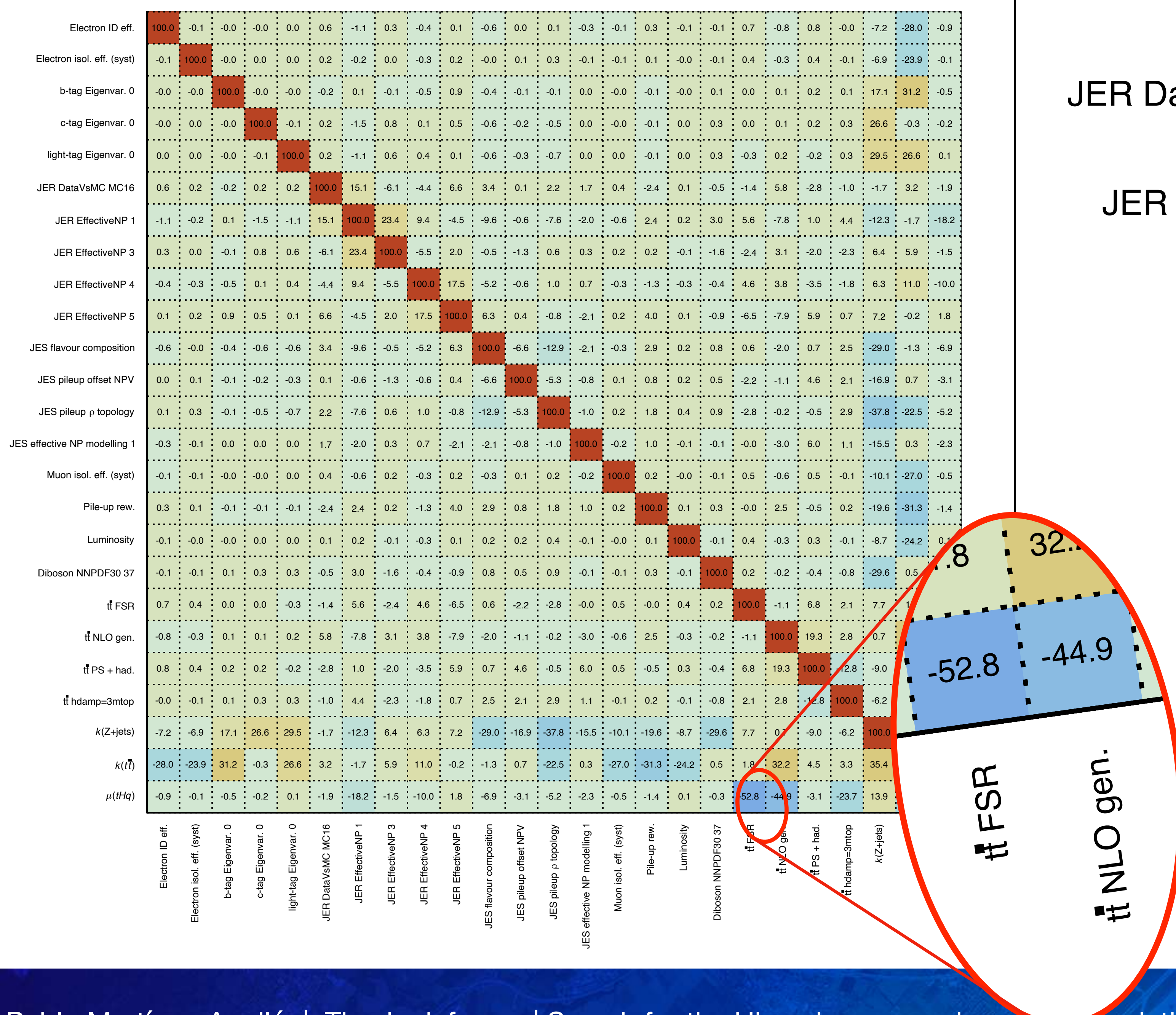
- No significant constraints except:
  - $t\bar{t}$ Modelling, JES/JER, τ-misID



Fit - Correlation matrices

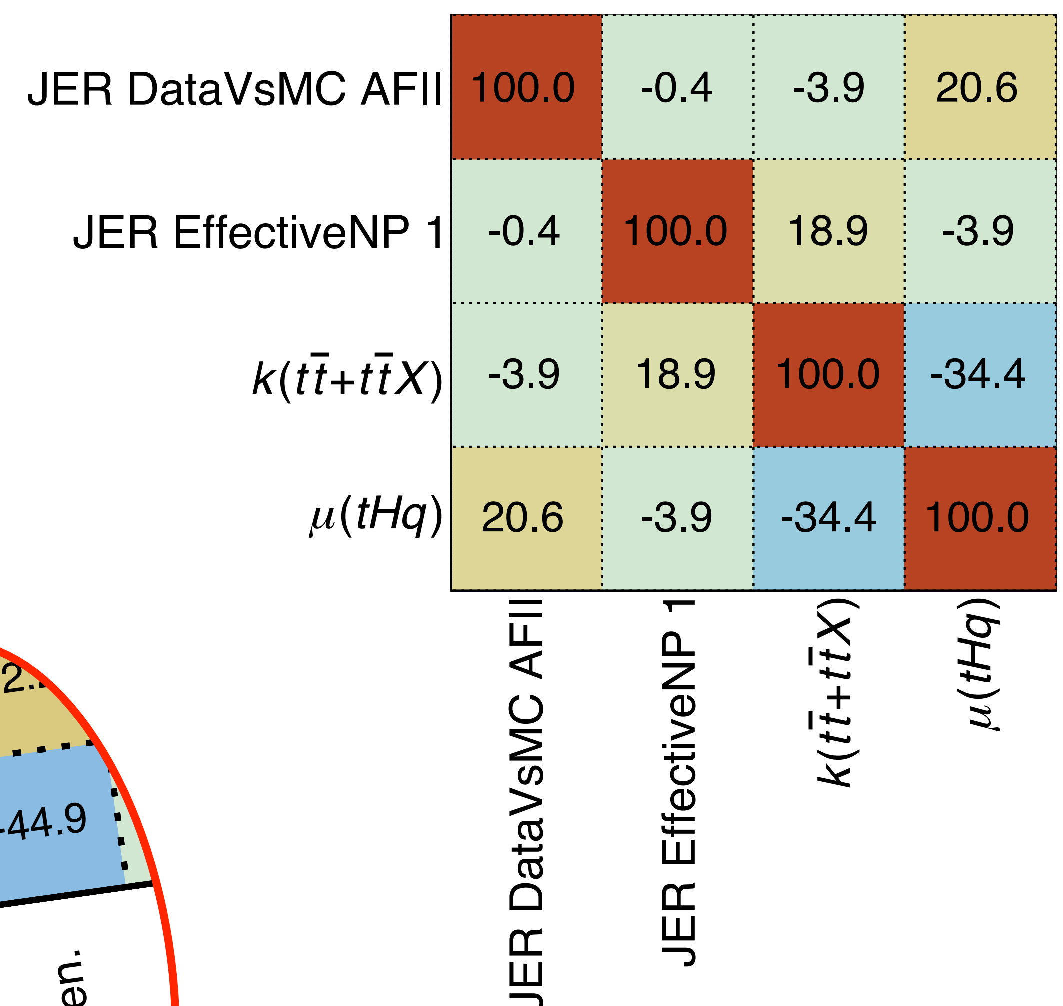
$2\ell\mathrm{OS} + 1\tau_{\mathrm{had}}$

- $t\bar{t}$ modelling with μ_{tHq}



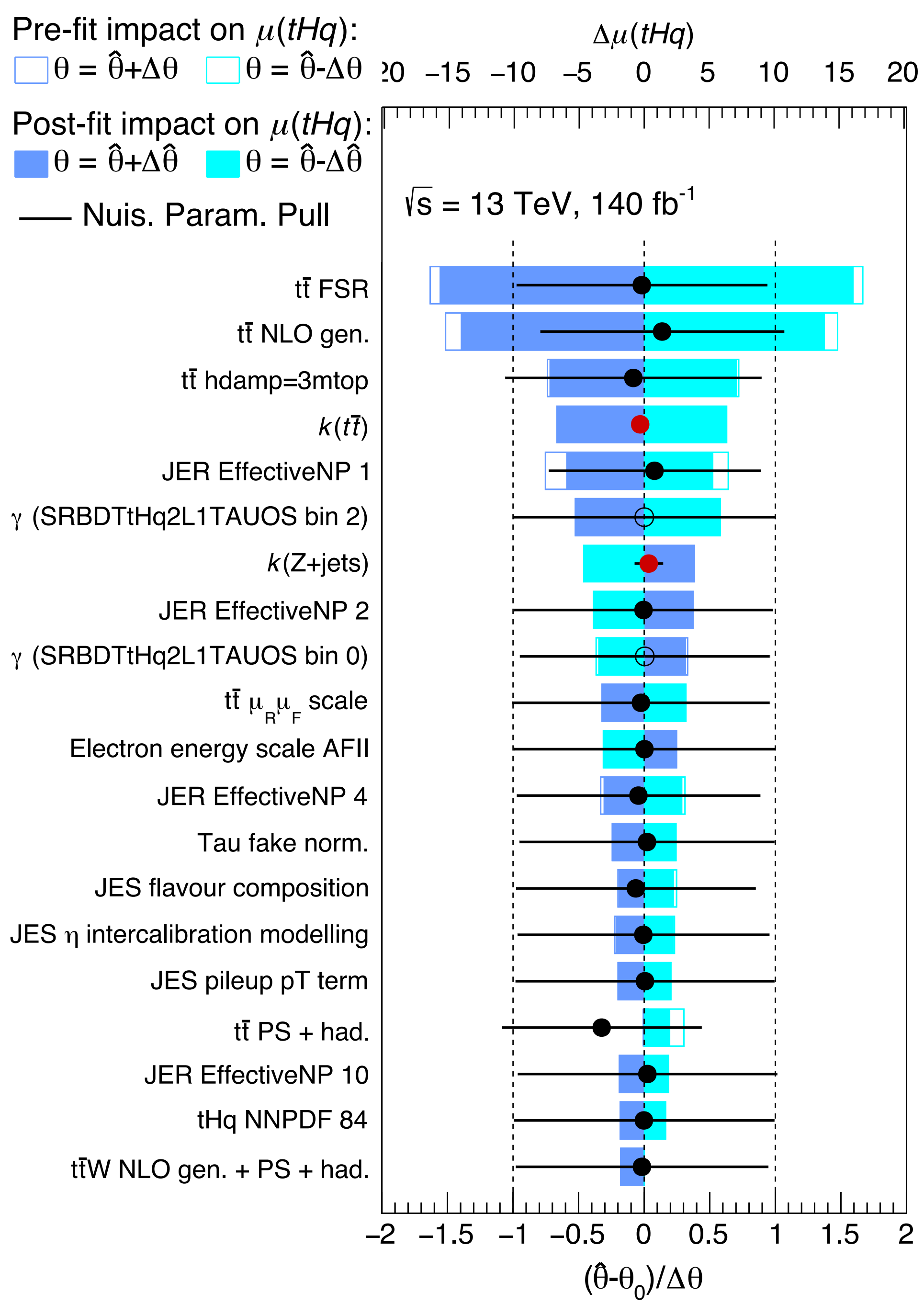
$2\ell\mathrm{SS} + 1\tau_{\mathrm{had}}$

- No significant correlation

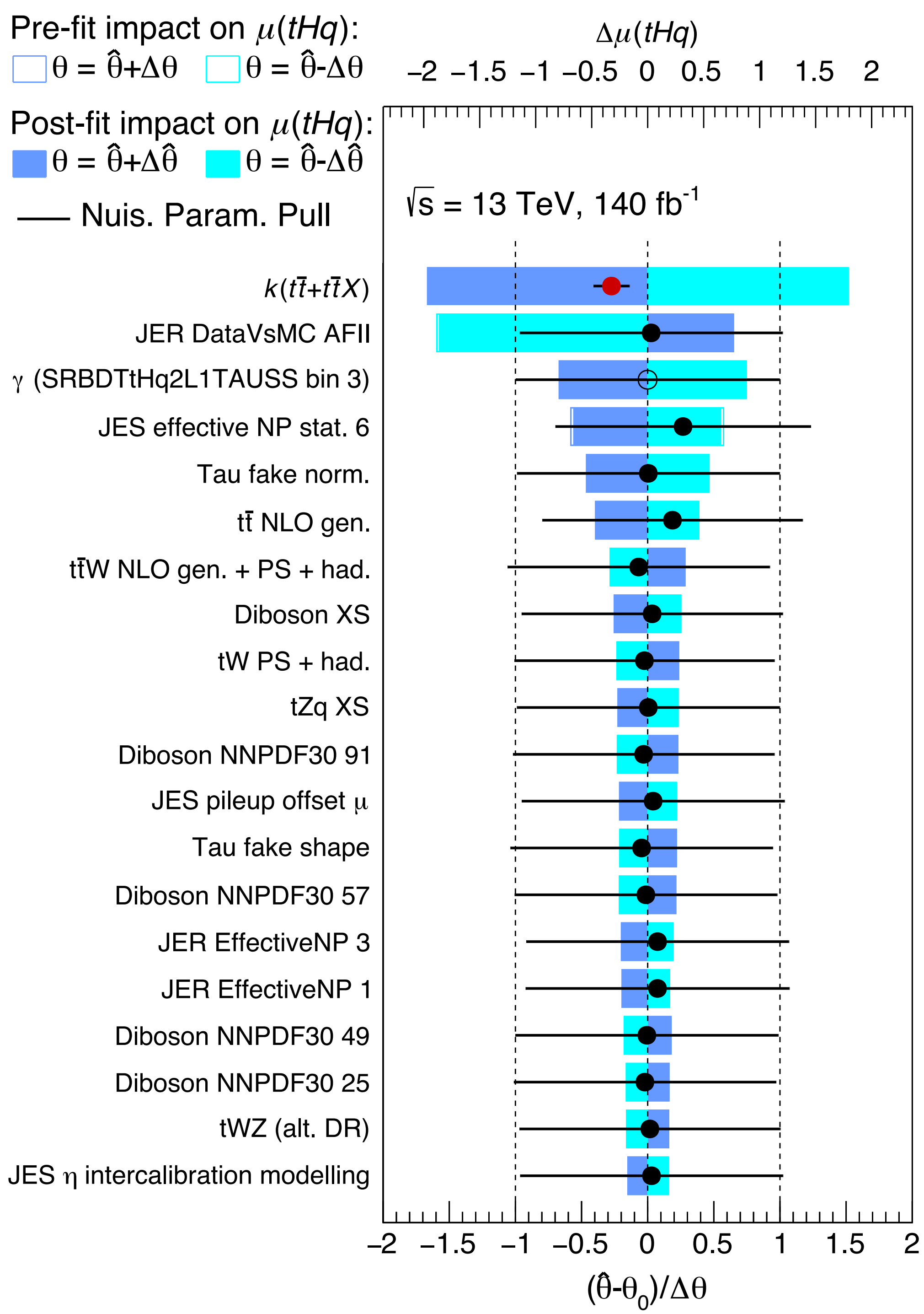


Fit - Ranking

$2\ell\mathrm{OS} + 1\tau_{\mathrm{had}}$



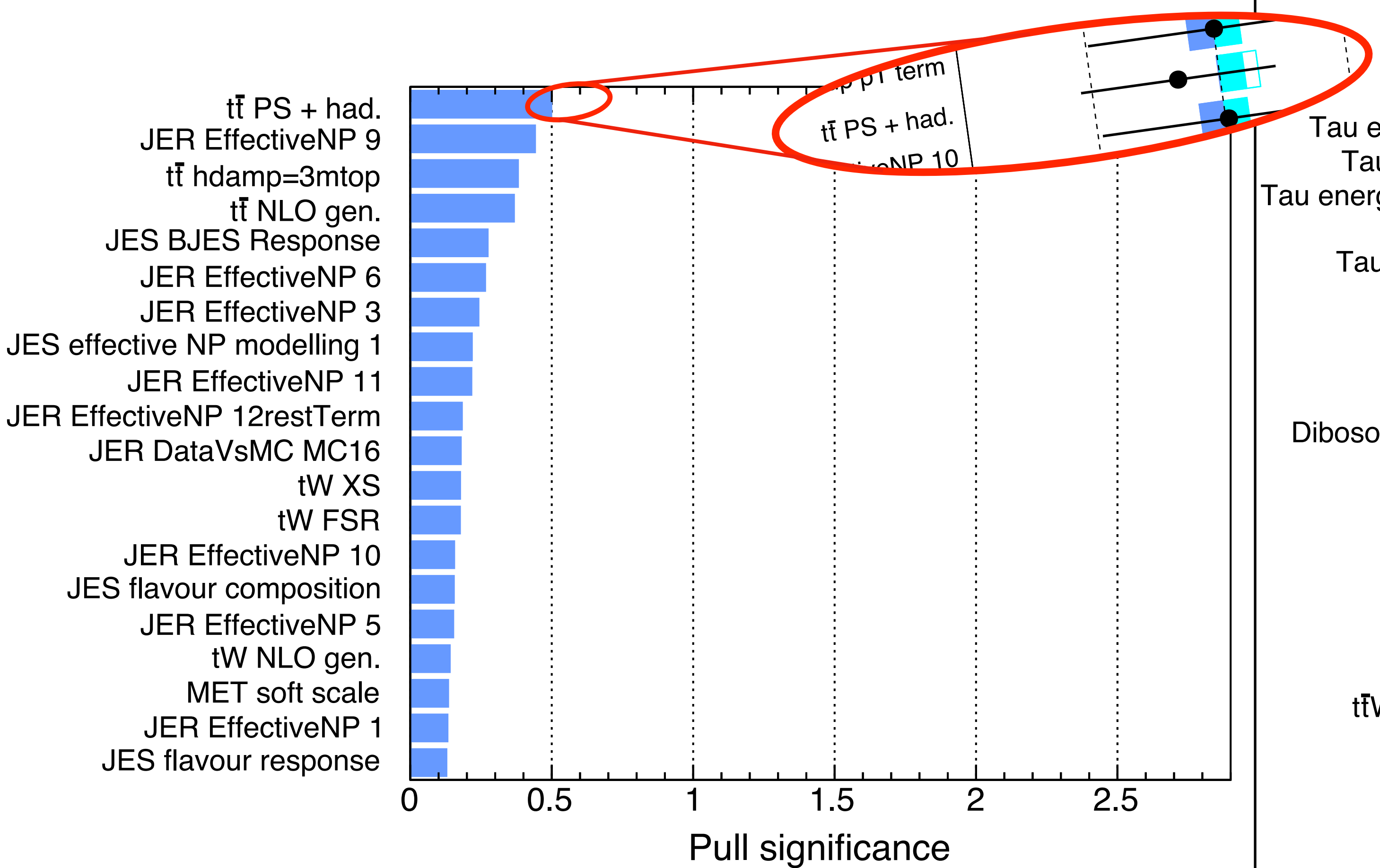
$2\ell\mathrm{SS} + 1\tau_{\mathrm{had}}$



Fit - Pulls

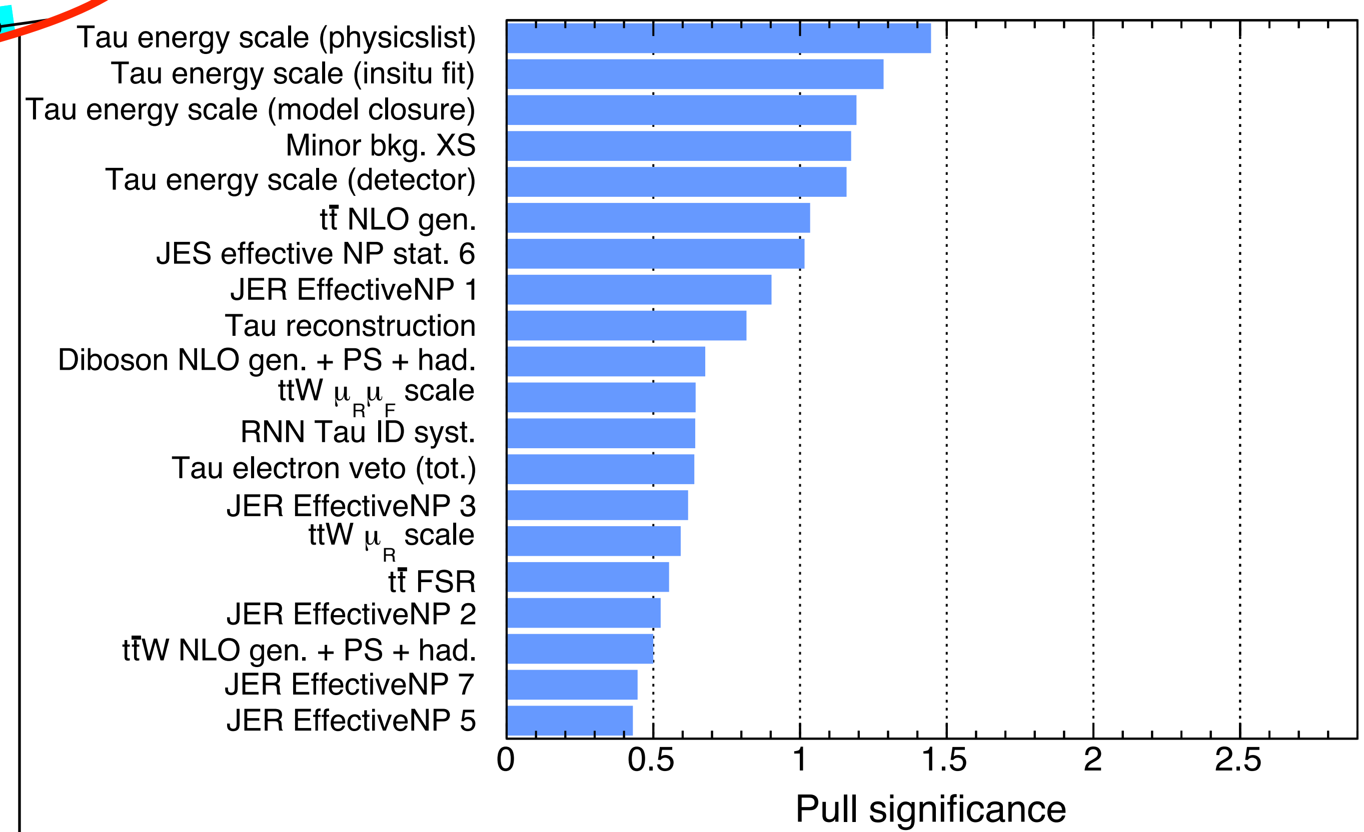
$2\ell OS + 1\tau_{had}$

- Most significant: $t\bar{t}$ Modelling



$2\ell SS + 1\tau_{had}$

- Most significant: τ energy scale



$$\text{pull significance} = \frac{|\text{post fit value}|}{\sqrt{1 - (\text{postfit error})^2}}$$

Fit - Grouped impact

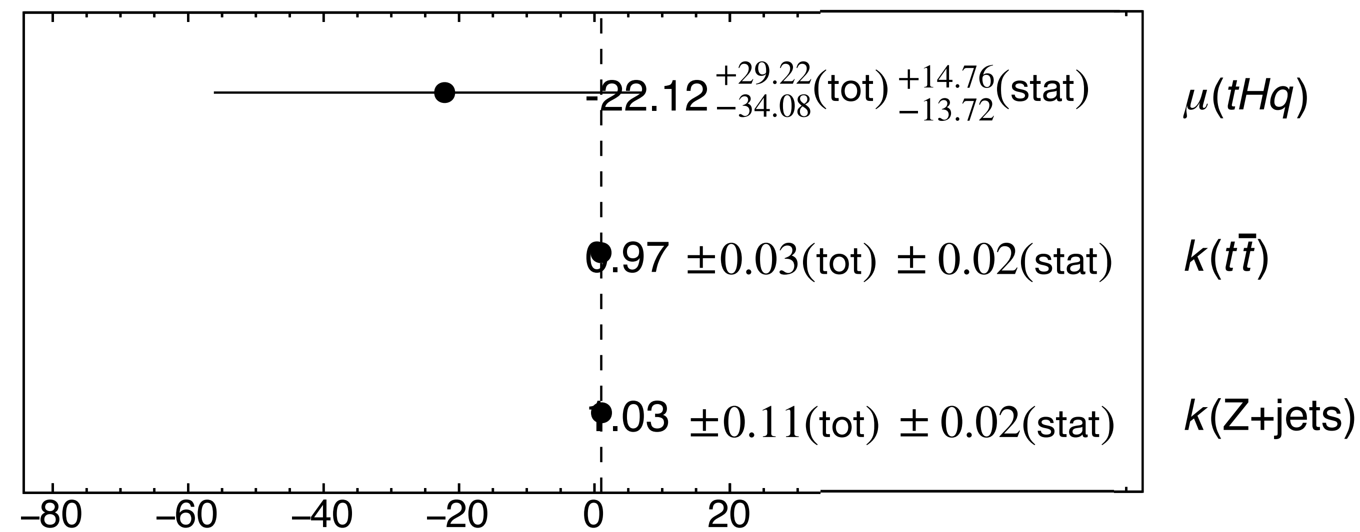
	$2\ell OS + 1\tau_{had}$	$2\ell SS + 1\tau_{had}$
Uncertainty source	Grouped impact	Grouped impact
MC uncertainty	± 7.136	± 0.983
Modelling		
Theoretical uncertainties	± 24.041	± 1.105
PDF uncertainty	± 9.624	± 0.817
Experimental		
Instrumental	± 5.408	± 0.716
Flavour tagging	± 0.455	± 0.126
JES/JER	± 11.377	± 2.727
NormFactors	± 10.527	± 2.235
Total systematic uncertainty	± 28.543	± 4.081

Fit - Results

$2\ell\mathrm{OS} + 1\tau_{had}$

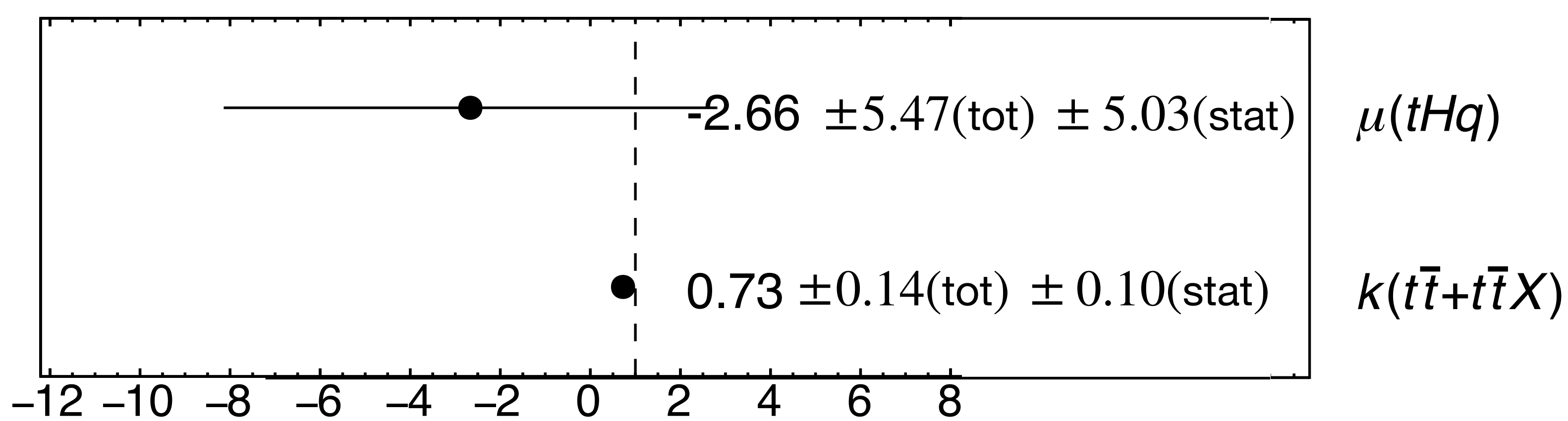
Observed

- Compatible with the SM
- Dominated by systematic uncertainty: $t\bar{t}$ modelling



$2\ell\mathrm{SS} + 1\tau_{had}$

Observed



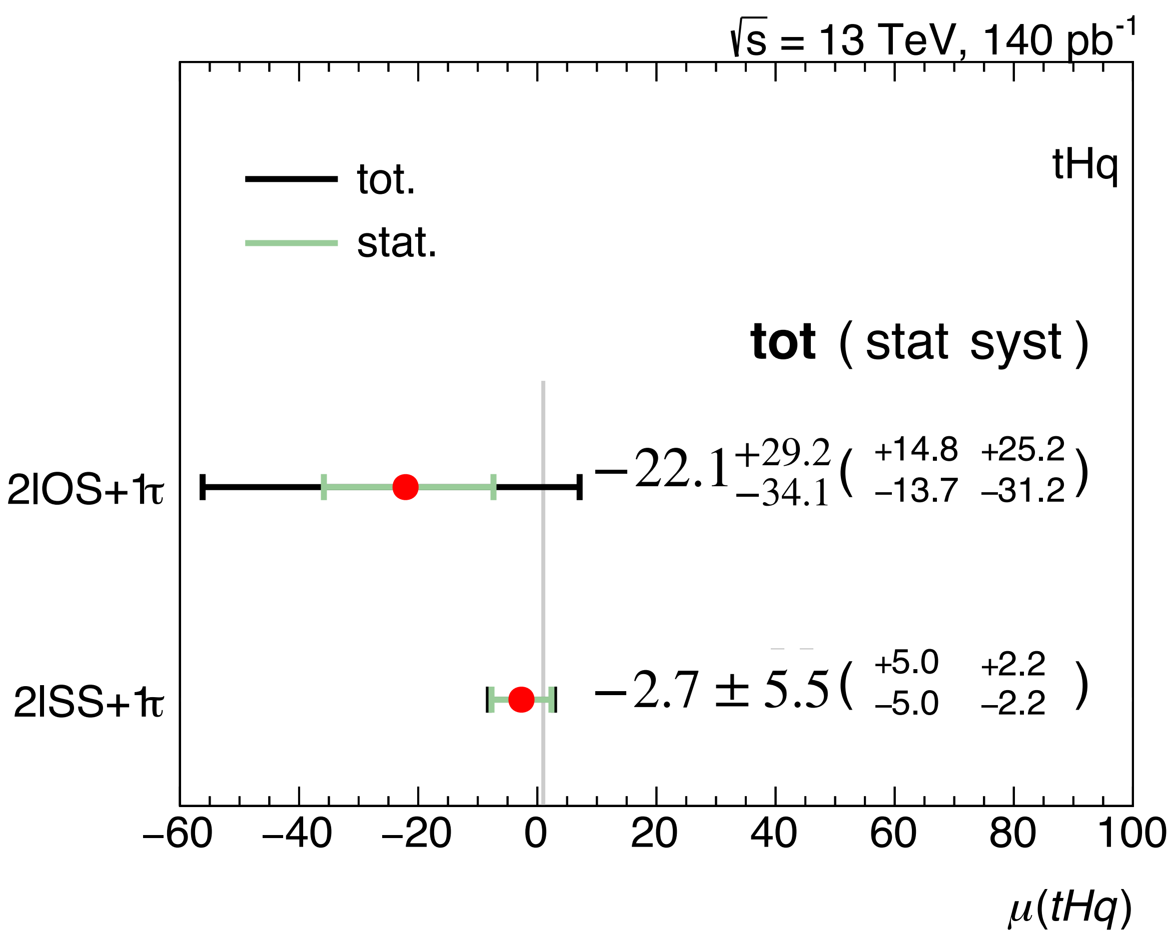
- μ_{tHq} compatible with the SM
- $k_{t\bar{t}+t\bar{t}X}$ not compatible with the SM within 1std
  - Systematics for template fit to be derived
  - The τ SFs are known to not be fully correct
  - $t\bar{t}W$ mild tension in $t\bar{t}W$ xsec measurements

$$\mu_{tHq} = \frac{\sigma_{tHq}}{\sigma_{tHq}^{SM}}$$

Fit - Results

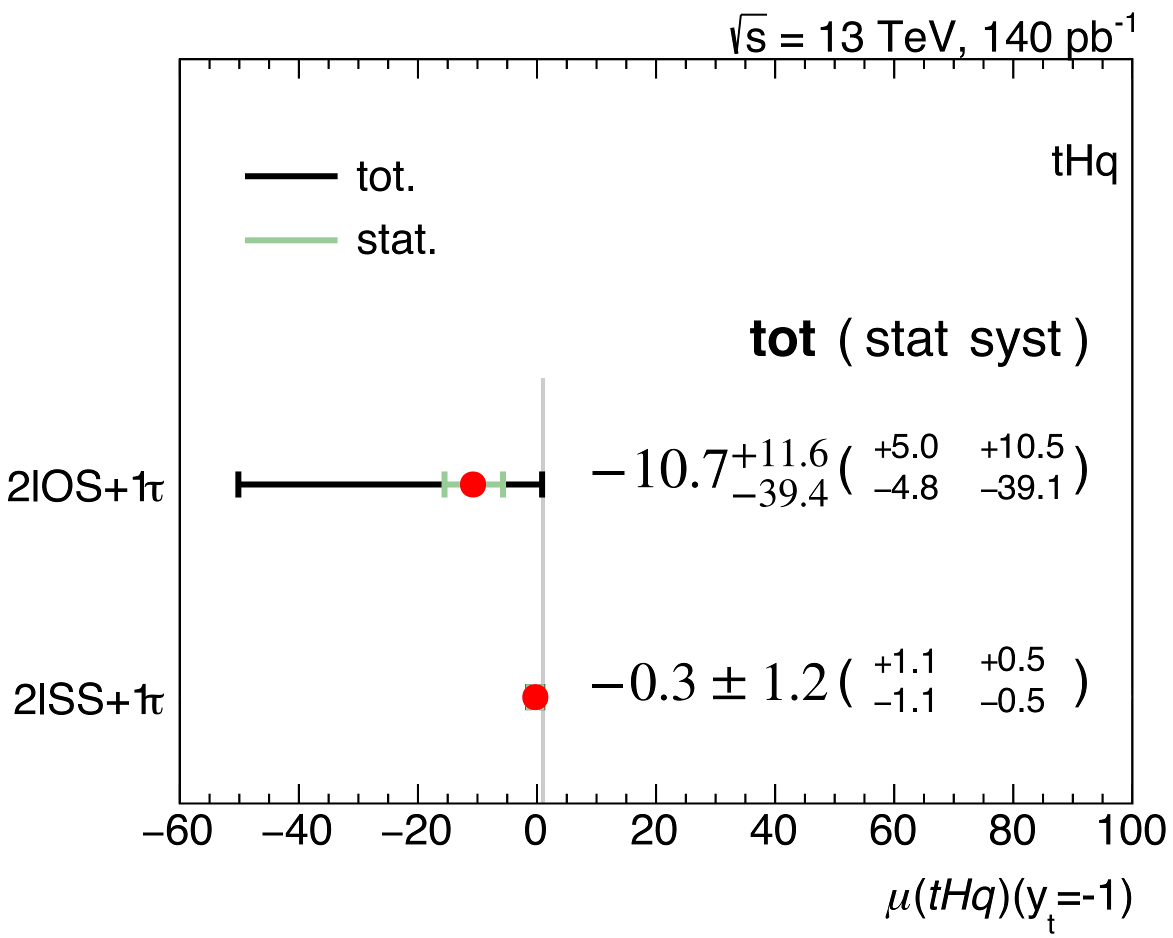
Standard model

- Compatible with SM
- The $2\ell SS + 1\tau_{had}$ is the most sensitive channel



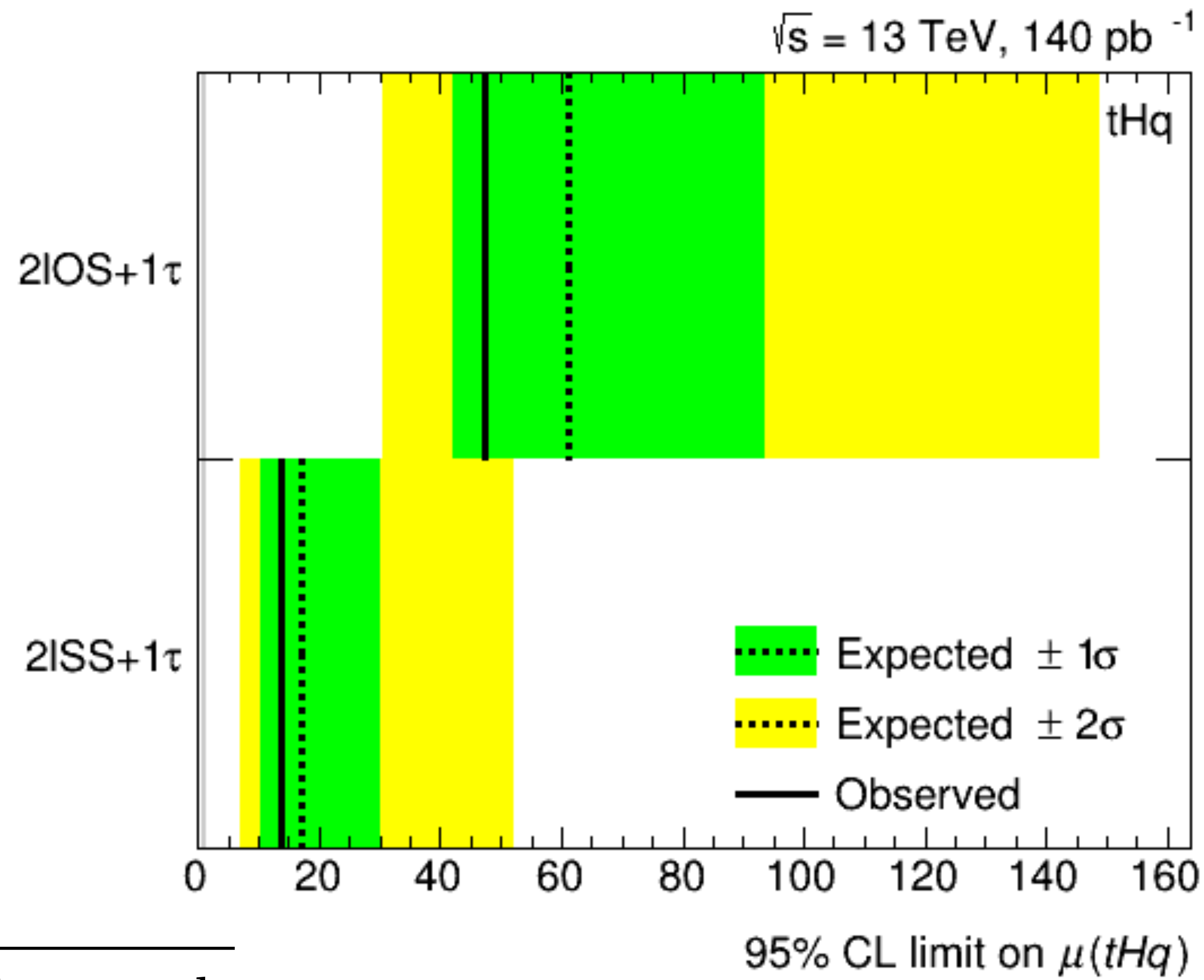
$$y_t = -y_t^{SM}$$

Alternative signal samples simulated using $y_t = -y_t^{SM}$



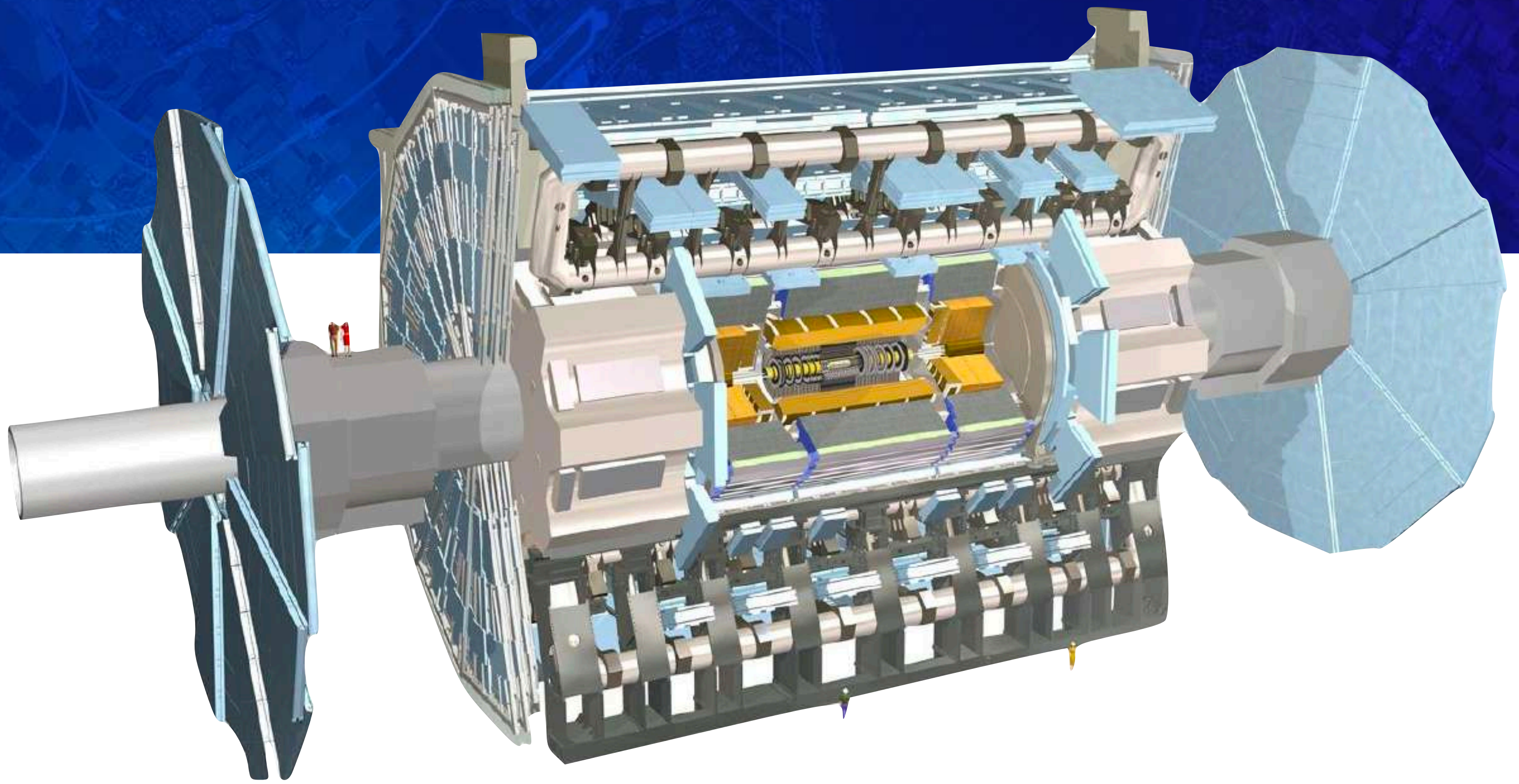
Upper limits on μ_{tHq}

When the cross section is not measured, upper exclusion limits are set using the CL method



Channel	Observed	Expected
$2\ell\,\mathrm{OS} + 1\tau_{\mathrm{had}}$	47.51	61.2
$2\ell\,\mathrm{SS} + 1\tau_{\mathrm{had}}$	13.83	16.94

Outline



1. Introduction
2. Experimental setup
3. Analysis & results
4. Summary & conclusions

Conclusion

- Contributed to detector performance (ID alignment monitoring web page)
- The tHq process is an excellent test of the SM and for the search of new physics
- Performed a dedicated search for the tHq process in two final states: $2\ell OS + 21\tau_{had}$ and $2\ell SS + 21\tau_{had}$
- Successful MVA strategy for lepton-origin assignment (Labels def., High acc)
- Successful MVA strategy for region definition:
  - Feature and hyperparameter optimisation algorithms
  - Significant improvement in the S/B ratio in the SRs
- The observed μ_{tHq} is compatible with the SM
- Dominated by systematic uncertainty in the $2\ell OS + 1\tau_{had}$ and stat uncertainty in the $2\ell SS + 1\tau_{had}$

Conclusion

Channel	Observed	Expected
$2\ell\,\mathrm{OS} + 1\tau_{\mathrm{had}}$	47.51	61.2
$2\ell\,\mathrm{SS} + 1\tau_{\mathrm{had}}$	13.83	16.94

- Exclusion upper limits are established
- No exclusion of CP violation
- Prospects:
    - Extend signal to $tH = tHq + tWH$
    - Combine results with other tH channels
    - First publication of a dedicated tH search with the full Run 2 data
- Improvements:
    - Increment of luminosity in Run 3
    - Improvement on the simulation of $t\bar{t}W$
    - Improvement on the derivation of SF for misID

Gràcies

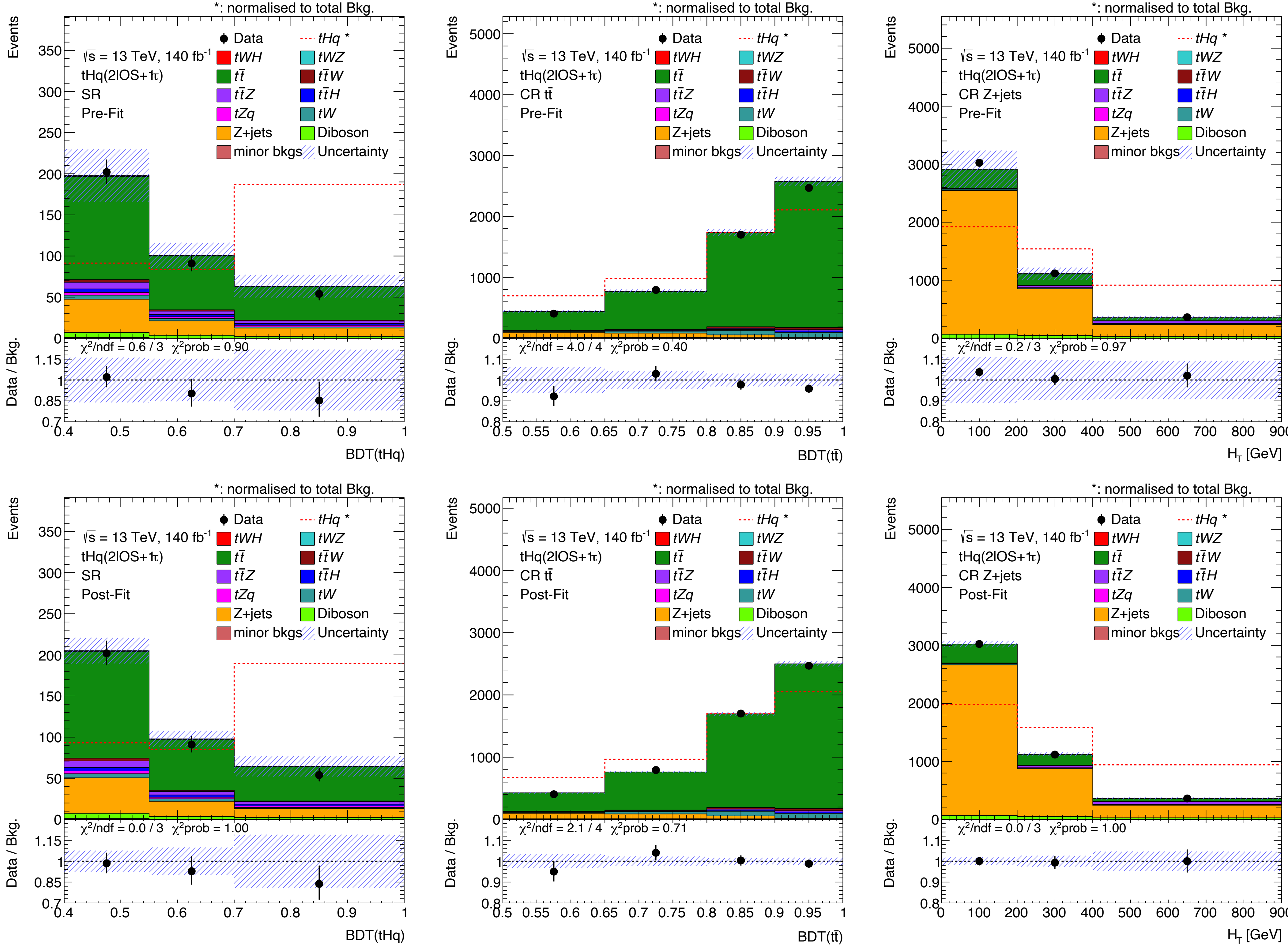
Backup

Pre- and post-fit distributions

$2\ell\mathrm{OS} + 1\tau_{had}$

Pre-fit

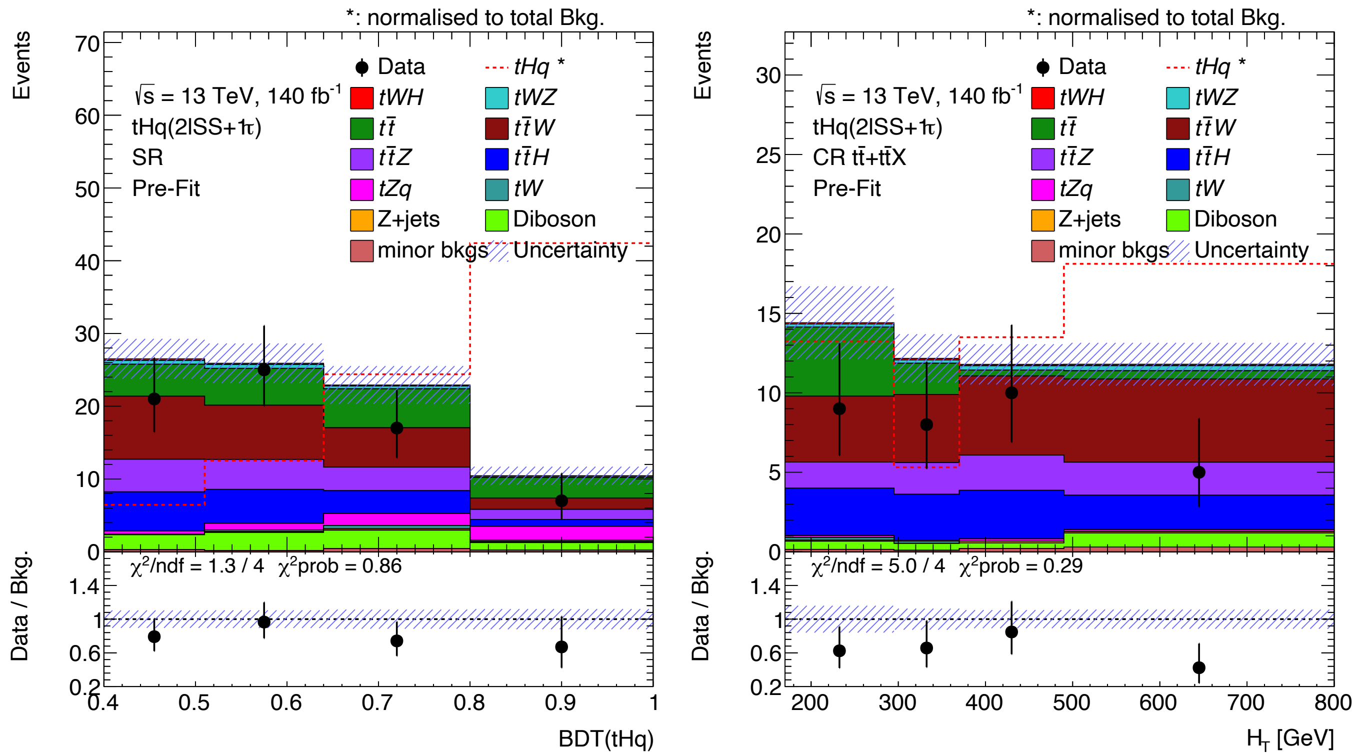
Post-fit



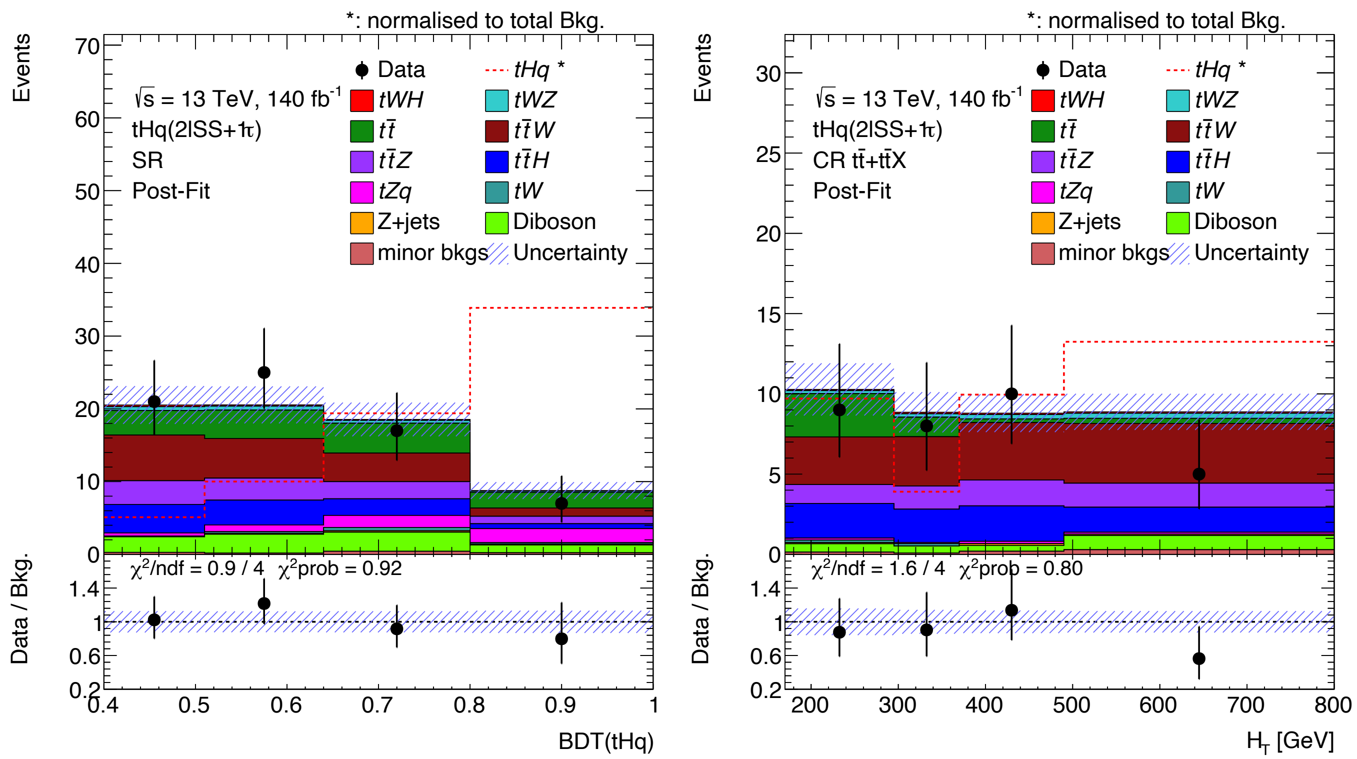
Pre- and post-fit distributions

$2\ell SS + 1\tau_{had}$

Pre-fit

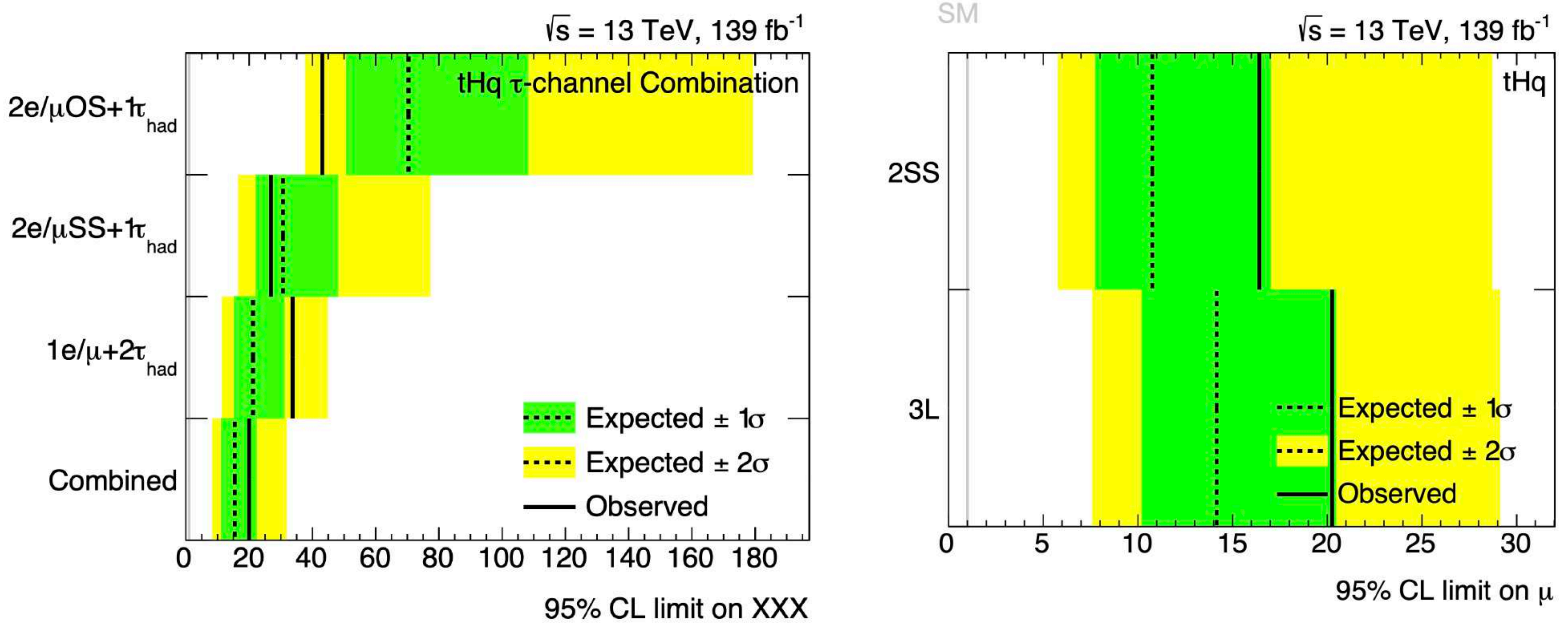


Post-fit



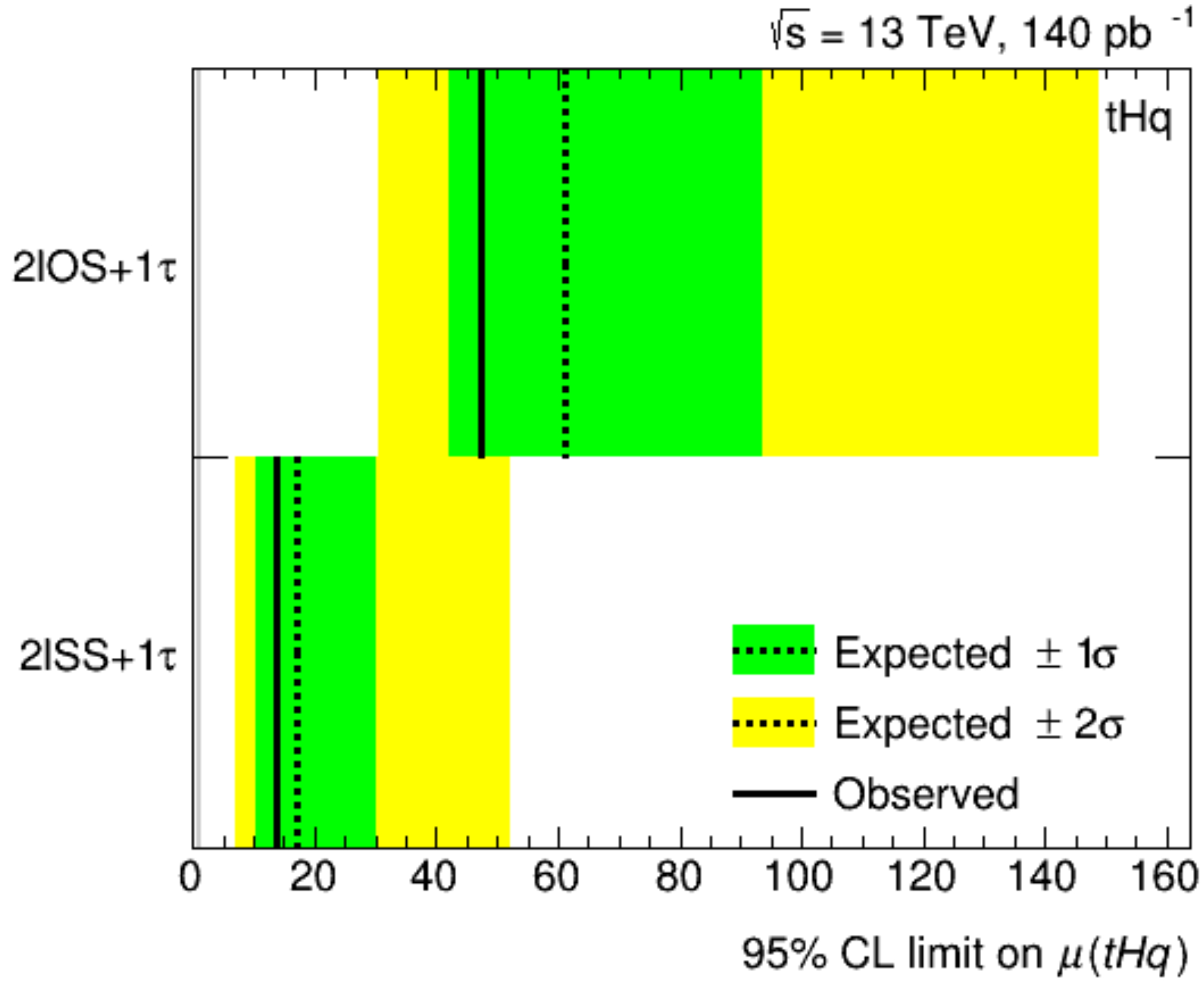
Upper limits on μ_{tHq}

- Other expulsion limits in the *tHq*multilpetonic channels



Upper limits on μ_{tHq}

When the cross section is not measured, upper exclusion limits are set using the 95% CL method

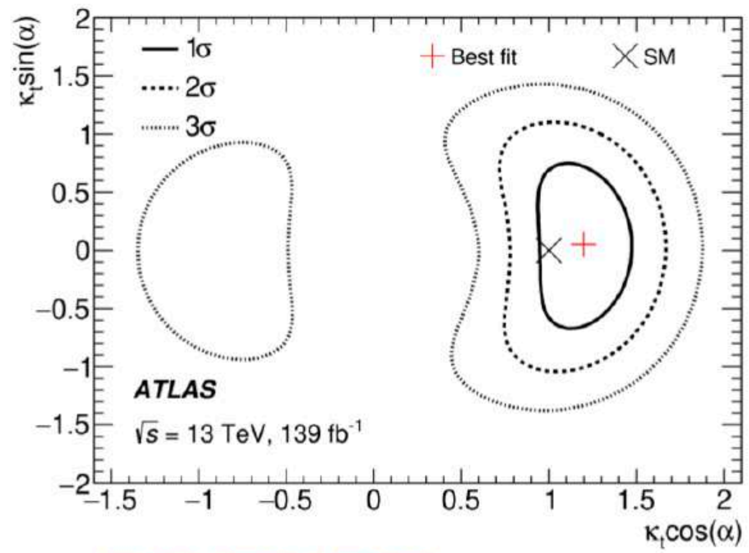


Channel	Observed	Expected	1σ CL$_{95}$	2σ CL$_{95}$
$2\ell\,\mathrm{OS} + 1\tau_{\mathrm{had}}$	47.51	61.2	[41.95, 93.48]	[30.56, 148.6]
$2\ell\,\mathrm{SS} + 1\tau_{\mathrm{had}}$	13.83	16.94	[10.33, 30.22]	[6.991, 52.24]
$2\ell\,\mathrm{OS} + 1\tau_{\mathrm{had}}$ $(y_t = -y_t^{\mathrm{SM}})$	77.95	119.6	[46.97, 284.9]	—
$2\ell\,\mathrm{SS} + 1\tau_{\mathrm{had}}$ $(y_t = -y_t^{\mathrm{SM}})$	20.79	24.07	[7.478, 112.5]	[3.197, 342.4]

Previous results on μ_{tH}

Latest results from **ATLAS**

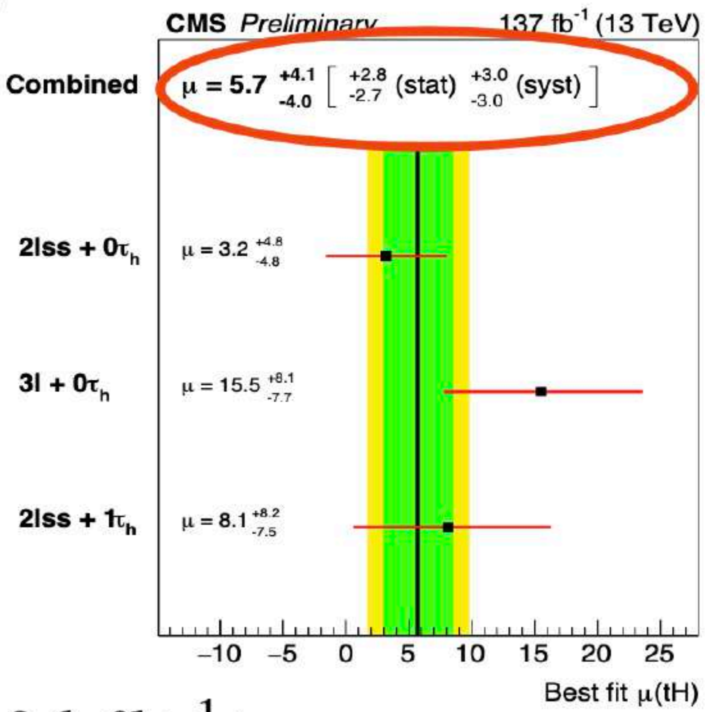
- H -> $\gamma\gamma$ ($139\ fb^{-1}$) ATLAS-CONF-2020-026
  - $\sigma(tH) < 8 \times \sigma_{SM}(tH)$ (@ 95% CL)



PRL 125 (2020) 6, 061802

Latest results from **CMS**:

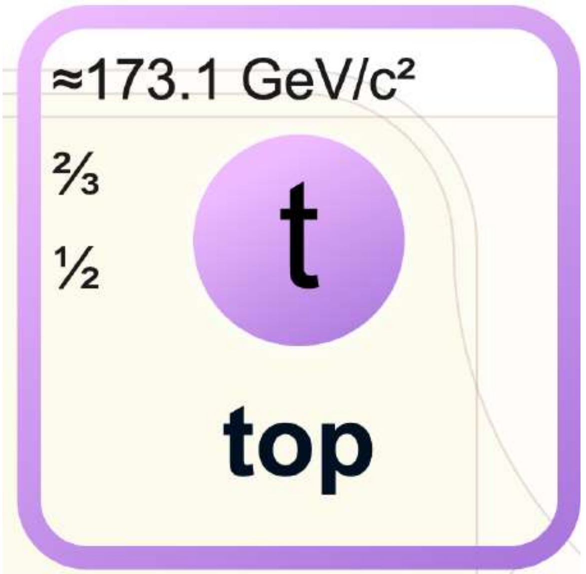
- ttH / tH multilepton ($137\ fb^{-1}$) CMS-PAS-HIG-19-008
  - $-0.7 < y_t < -0.9$ or $0.7 < y_t < 1.1$ (@ 95 % CL)



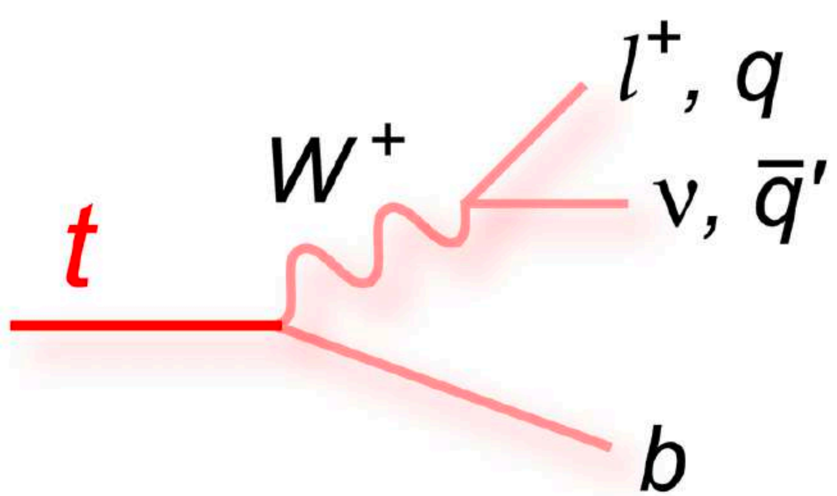
- tH ($36\ fb^{-1}$) CMS PAS HIG-18-009:
  - $\sigma(tH) < 14 \times \sigma_{SM}(tH)$ (@ 95% CL)
- H -> bb ($138\ fb^{-1}$) CMS-PAS-HIG-19-001
  - $\sigma(tH) < 14.6 \times \sigma_{SM}(tH)$ (@ 95% CL)

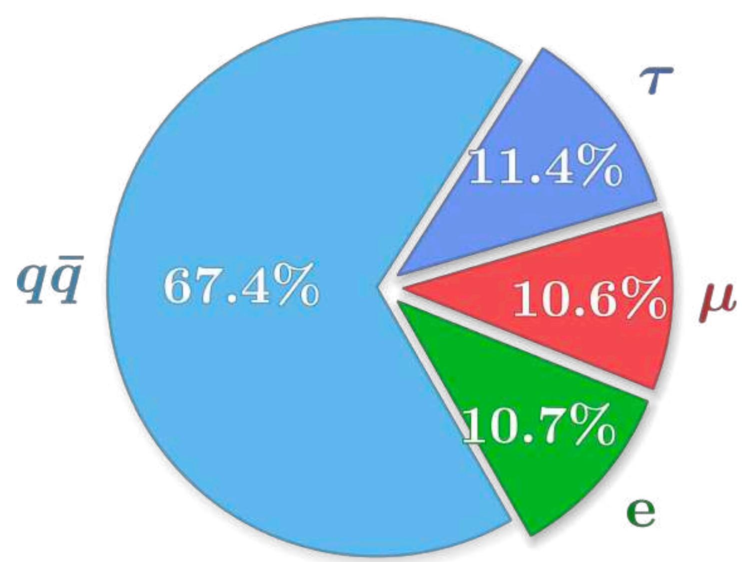
Top quark

$W^+ \to e^+\nu_e$	$(10.71 \pm 0.16)\%$,
$W^+ \to \mu^+\nu_\mu$	$(10.63 \pm 0.15)\%$,
$W^+ \to \tau^+\nu_\tau$	$(11.38 \pm 0.21)\%$,
$W^+ \to q\bar{q}$ (hadrons)	$(67.41 \pm 0.27)\%$,
$W^+ \to$ invisible	$(1.4 \pm 2.9)\%$.

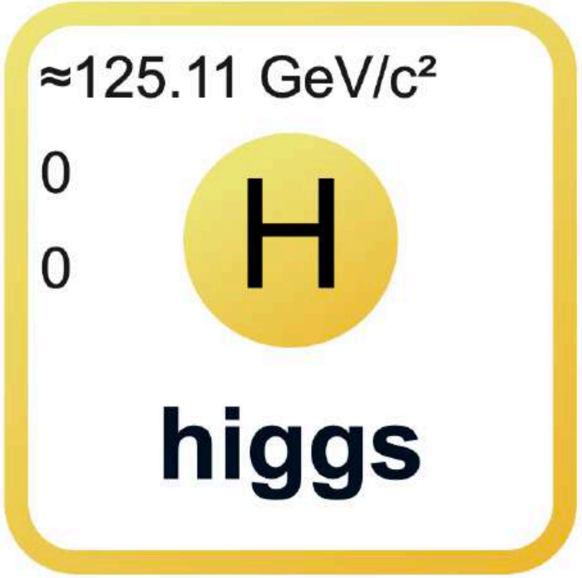


- Discovered in 1995 at Tevatron
- Heaviest known elementary particle
- Very short lifetime
  - Decays before hadronising
  - Decays almost exclusively to a W boson and a b quark
  - Largest Yukawa coupling to Higgs boson

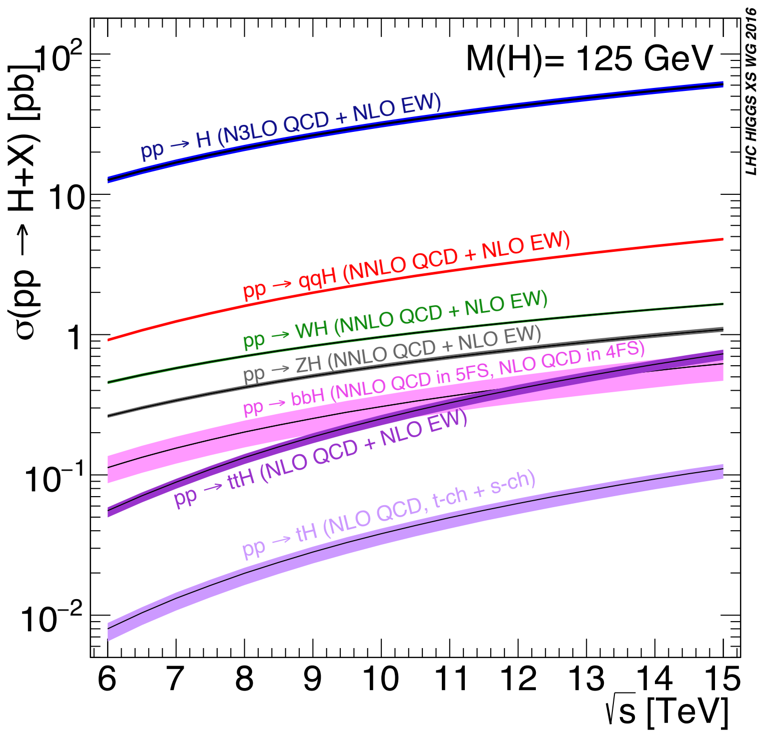


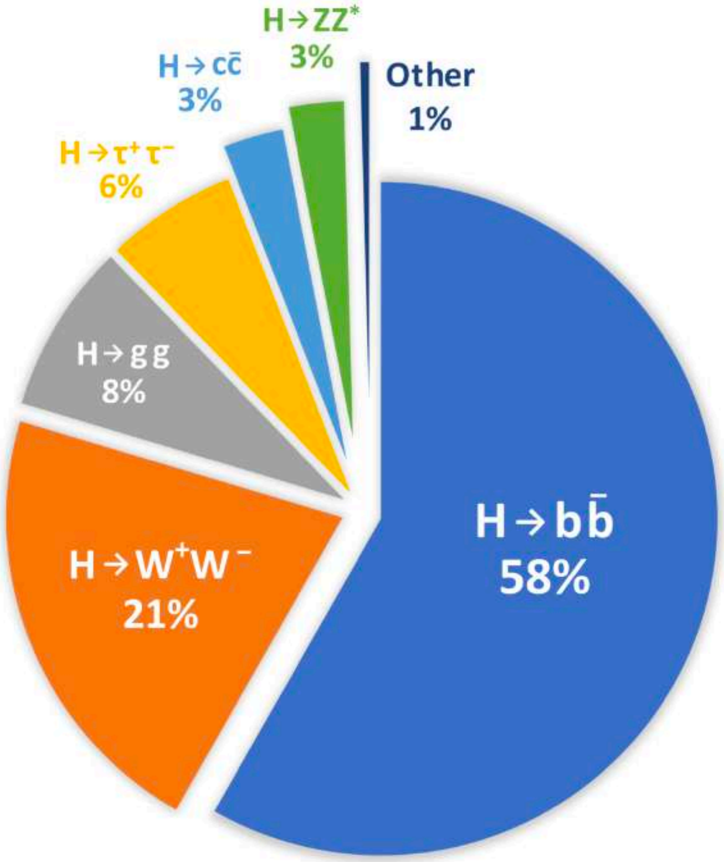


Higgs boson



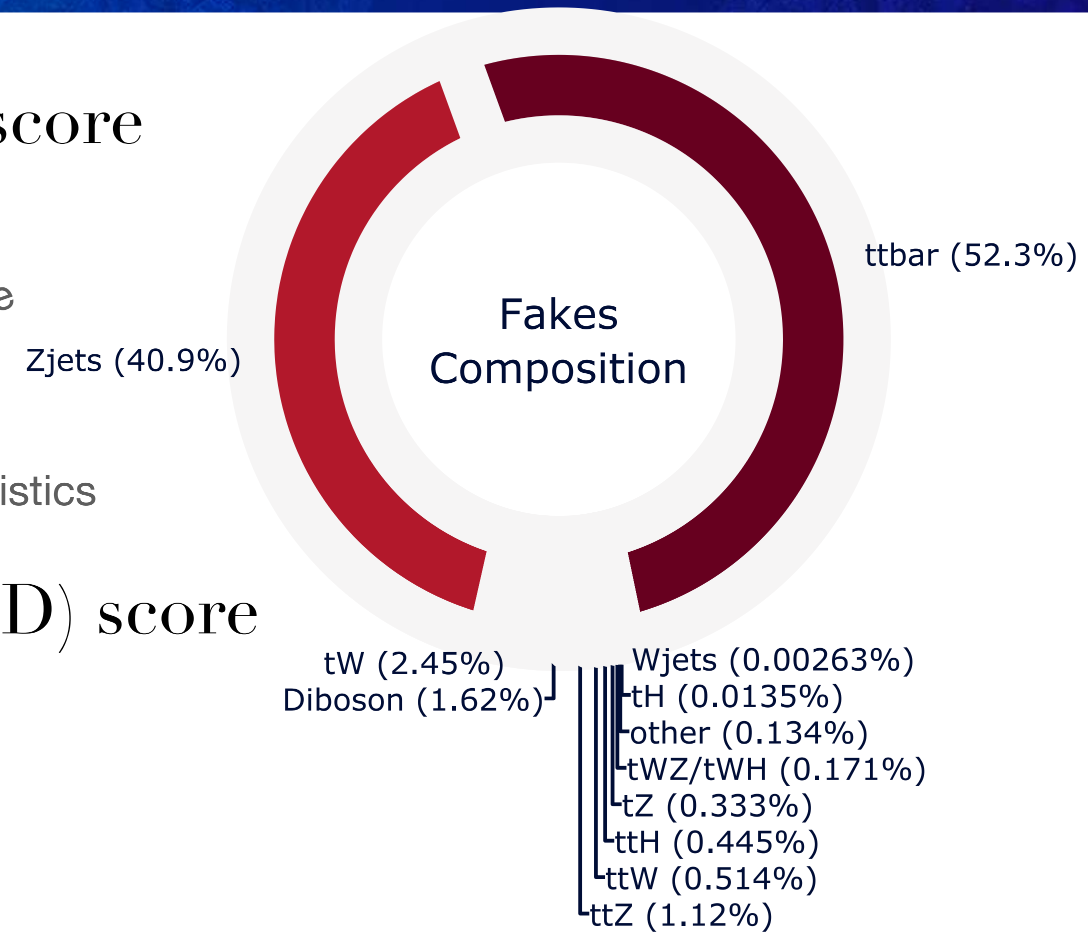
- Discovered in 2012 at CERN
- Higgs field, SSB
- The mass elementary particles: Uniquely determined by its **coupling** strength to Higgs
- Short lifetime $\tau_{\text{Higgs}} = 1.6 \times 10^{-22}$ s





Template fit metod

- The anti-tau-ID :: Not pass medium RNN(tauID) score
- Fit in two variables:
  - 1 b-jet region: JetTrackWidth <— Stronger observable
  - 2 b-jet region: LightGBM BDT <— Because low statistics
    - JetTrackWidth+JetCaloWidth+RNN(tauID) score
- Templates
  - G(x): Quark-initiated jet template
  - Q(x): Gluon-initiated jet template
  - S(x): other templates (tau, electron, and unknown)
- $M(x) = f_S \cdot S(x) + (1 - f_S) \cdot f_q \cdot Q_x + (1 - f_q) \cdot G_X)]$
- f <— SFs



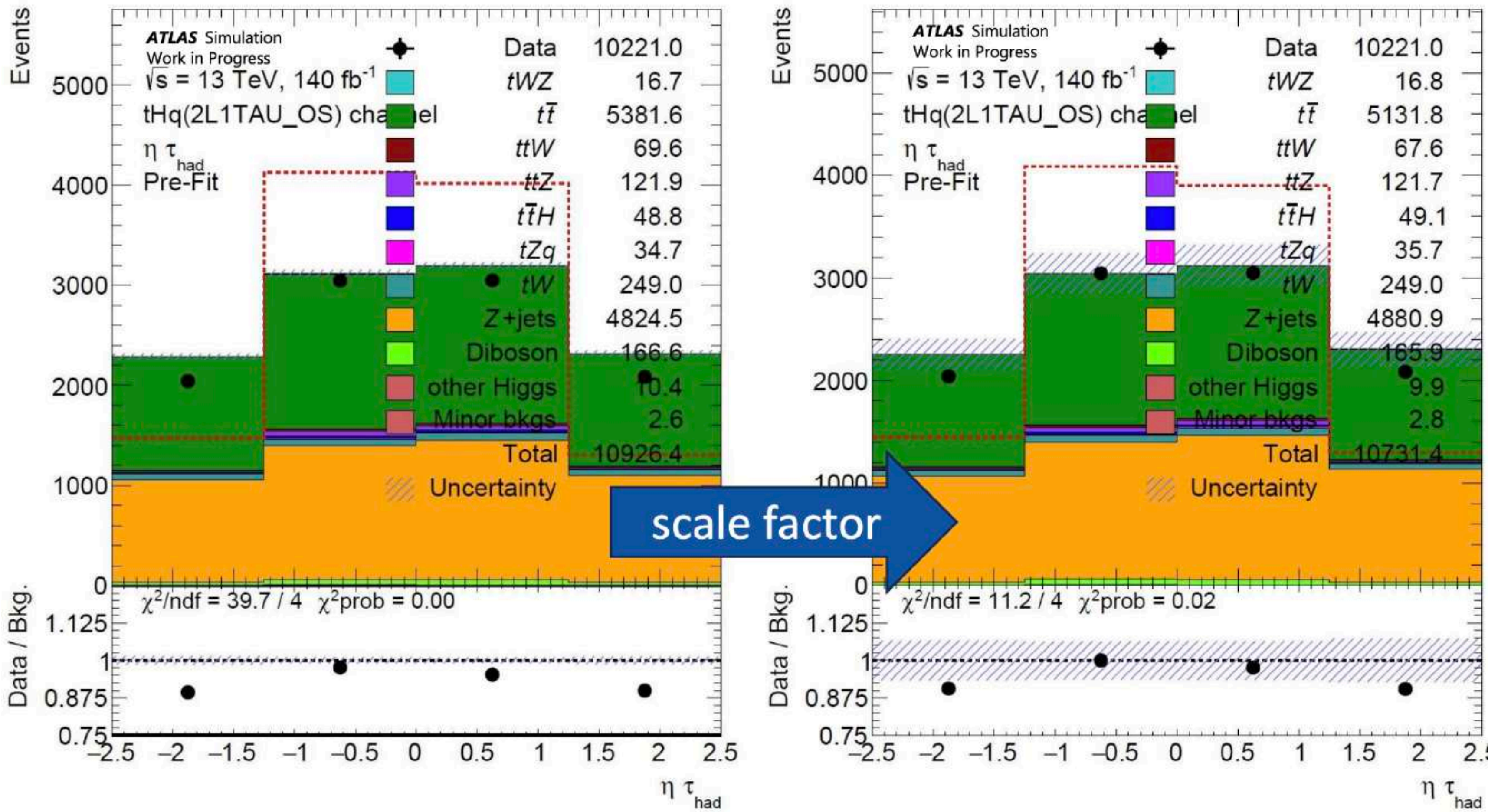
This is the current method.
In the NTuples used for my thesis just the JetTrackWidth is used

Template fit metod

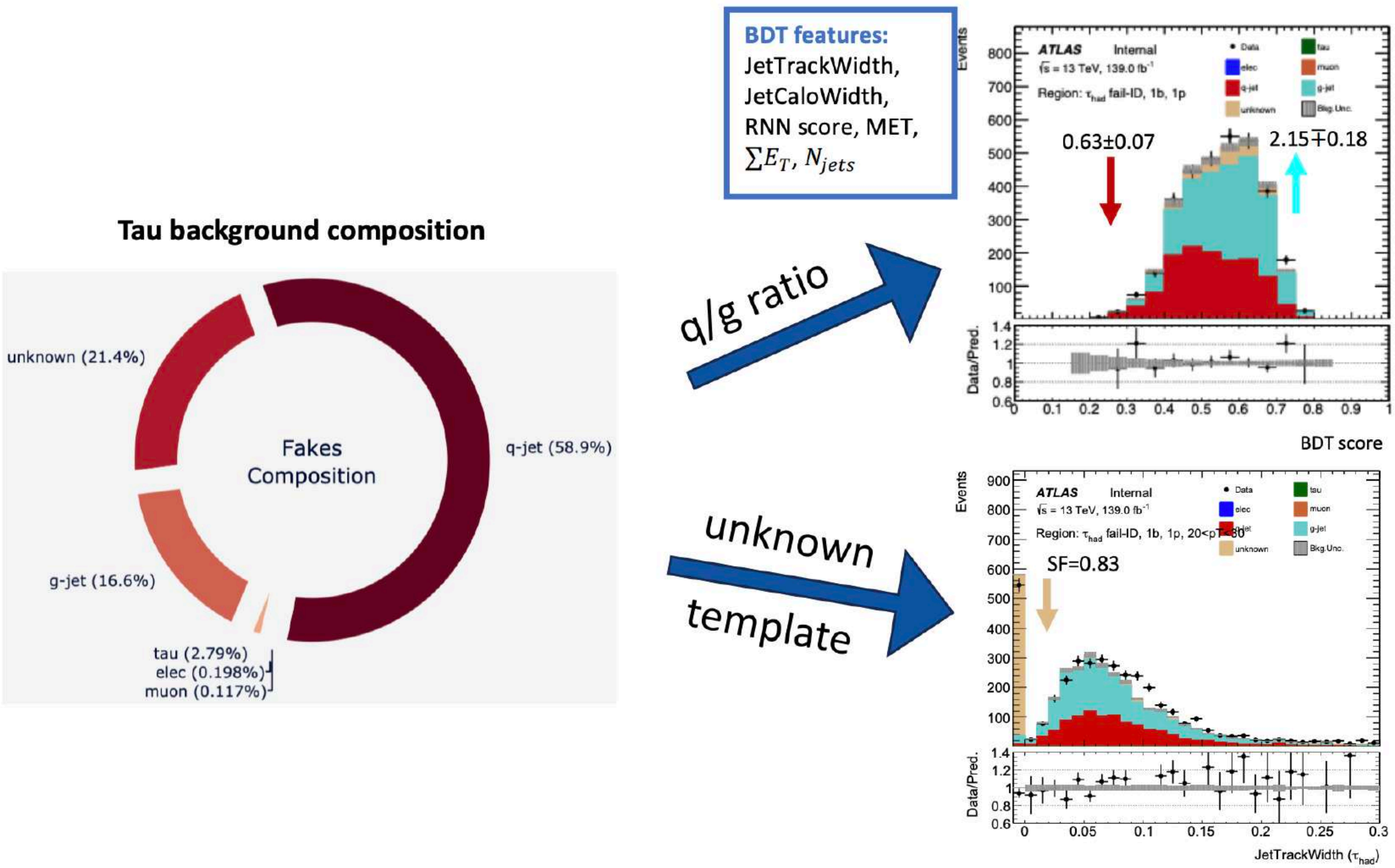
- τ fakes → primary cause of reducible backgrounds
- Assumption: MC & data disagreement from τ fakes
- Obtain scale factor in fake enriched control region (inverted RNN cuts) using template fit
- For all channels, we use the template Fit method

Definitions of control regions:

- ***τhad***: Loose!Medium RNN score
- ***e*** or ***μ***: fail ID and Isolation



Template fit metod

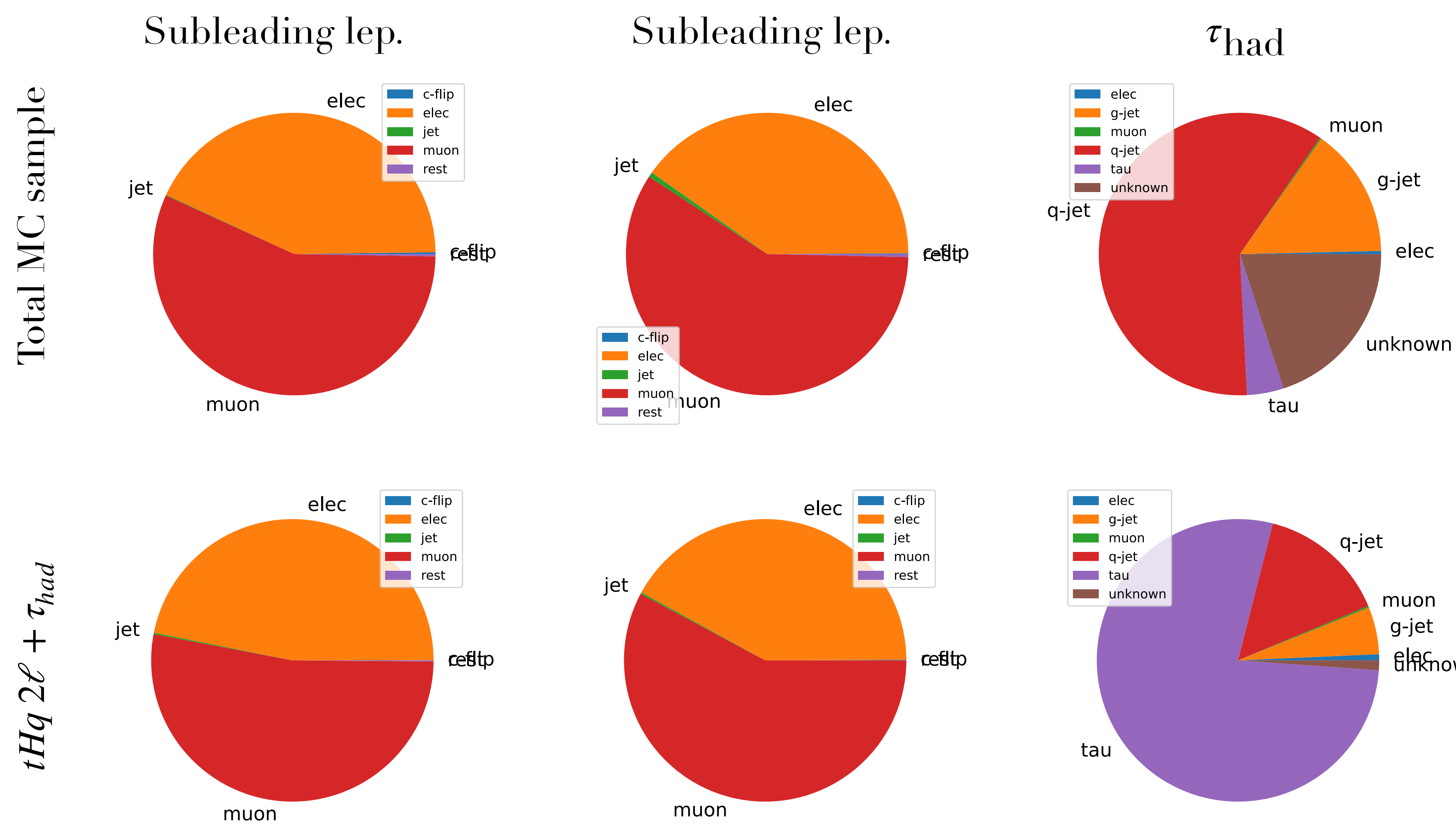


Estimation of τ_{had} misidentification

Two types of backgrounds:

- Irreducible: Same signature as signal process
- Reducible: Misidentification leads to seam signature as signal process

- Jet faking taus **dominate** the **background**.
- Fake **rates** are difficult to simulate
- Data driven method
- Estimation of fakes = to scale MC templates to match data in CRs



Estimation of τ_{had} misidentification

- Jet faking taus **dominate** the **background**.
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- Data driven method
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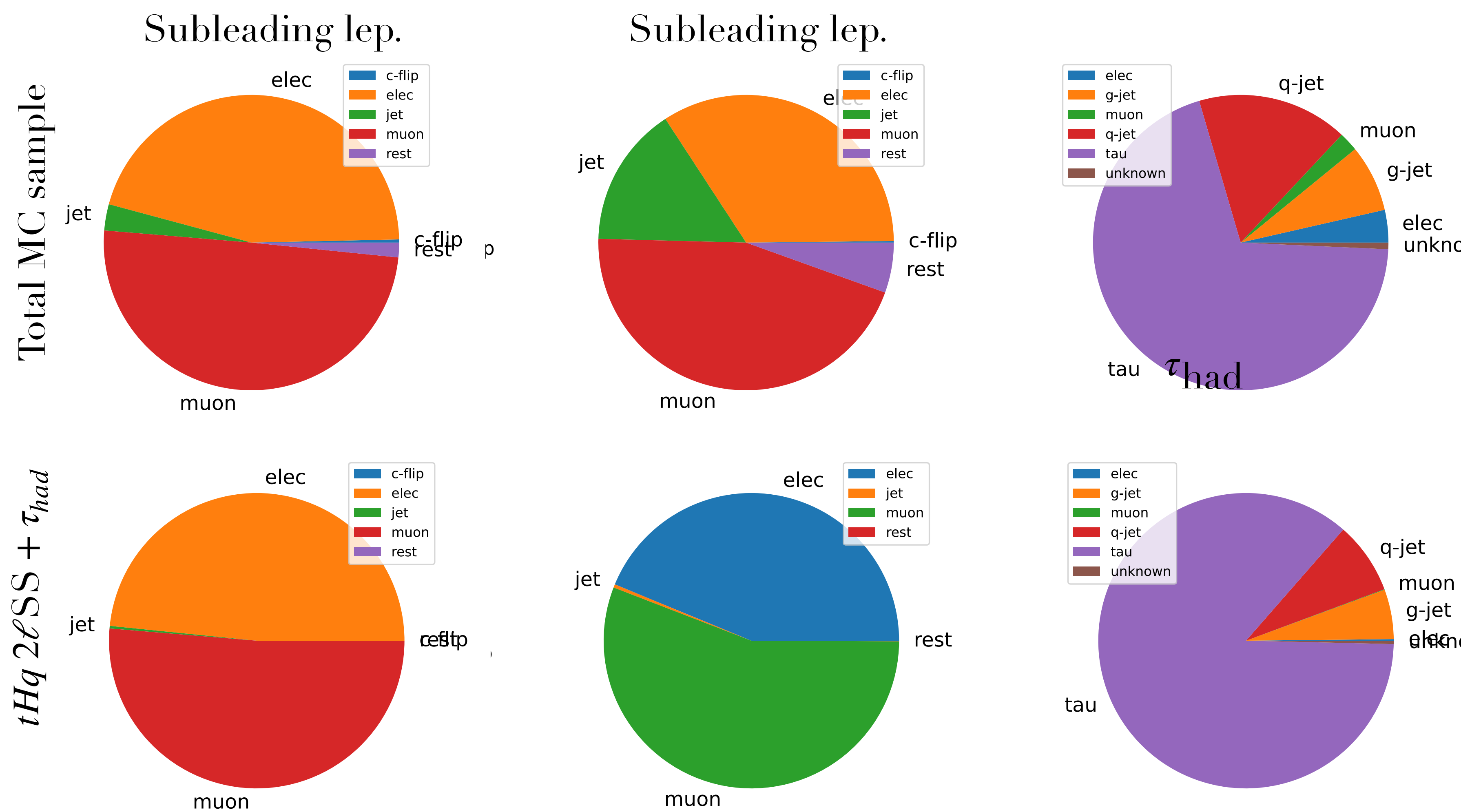


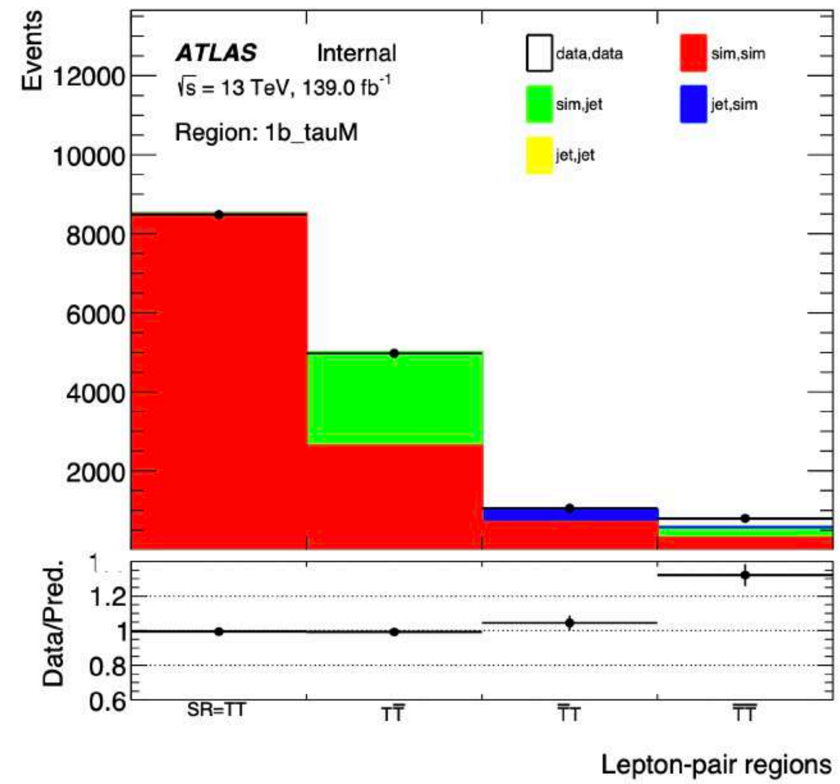
Contar xq se necesita estimar esto: MC no describe el fake rate
Decir qué templates se usan: Separar por pt, N-bjets, pongees

Fitamos una BDT(Tau_Id) distribution en unra region de control rica en fakes

Counting method para asses the uncertainty of this method

Estimation of light-lepton fakes

- Two light leptons. We define the following regions
  - [L1, L2] T = pass tight criteria
    [T , T] nT = fail to pass this criteria
    [nT, T]
    [T, n T]
    [nT, nT]



$2l1\tau$ SS - Estimating fakes

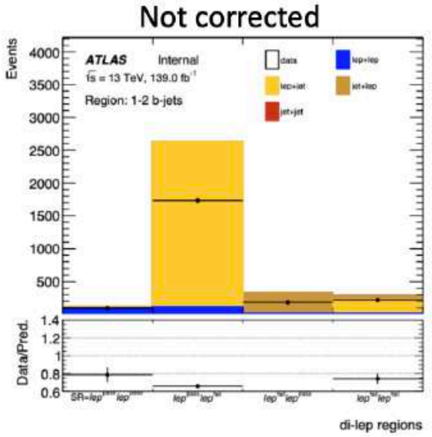
Tau fakes

- adjusting the inclusive jet template to data yields in tau CR
- bins: N_{tracks}, $p_T(\tau_{had})$

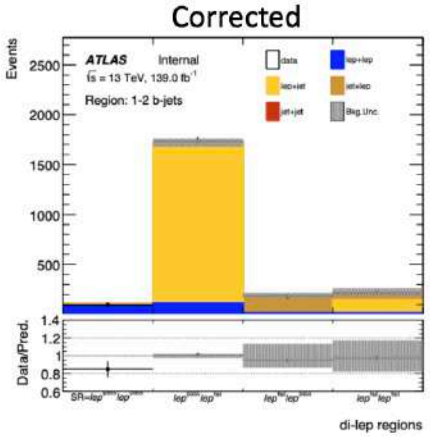
Lepton fakes

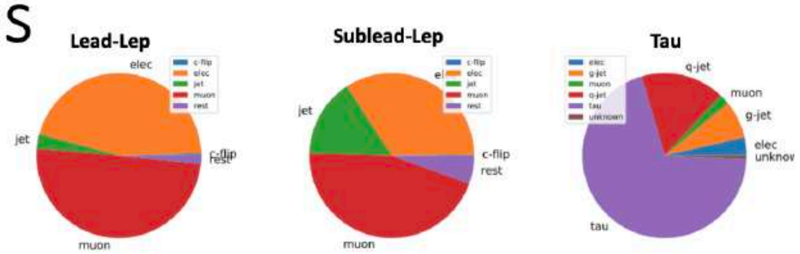
- estimated by fitting **(sim,jet)**, **(jet,sim)** & **(jet,jet)** templates in 3 control regions to data, inclusively.
- corrections: fake SFs and statistical uncertainties indicated in tables.

Not corrected



Corrected





Fake tau SFs

$p_T(\tau_{had})$ bin [GeV]	1-prong	3-prong
20-30	3.6 ± 1.2	1.1 ± 0.7
30-40	1.7 ± 1.0	3.2 ± 2.3
>40	1.6 ± 0.8	$\boxed{0.1 \pm 1.0}$

MC $\pm$ 100%

Fake lep-pair SFs

Template	1+2 b-jet
lep+jet	0.64±0.01
jet+lep	0.52±0.04
jet+jet	$\boxed{6.42\pm3.35}$

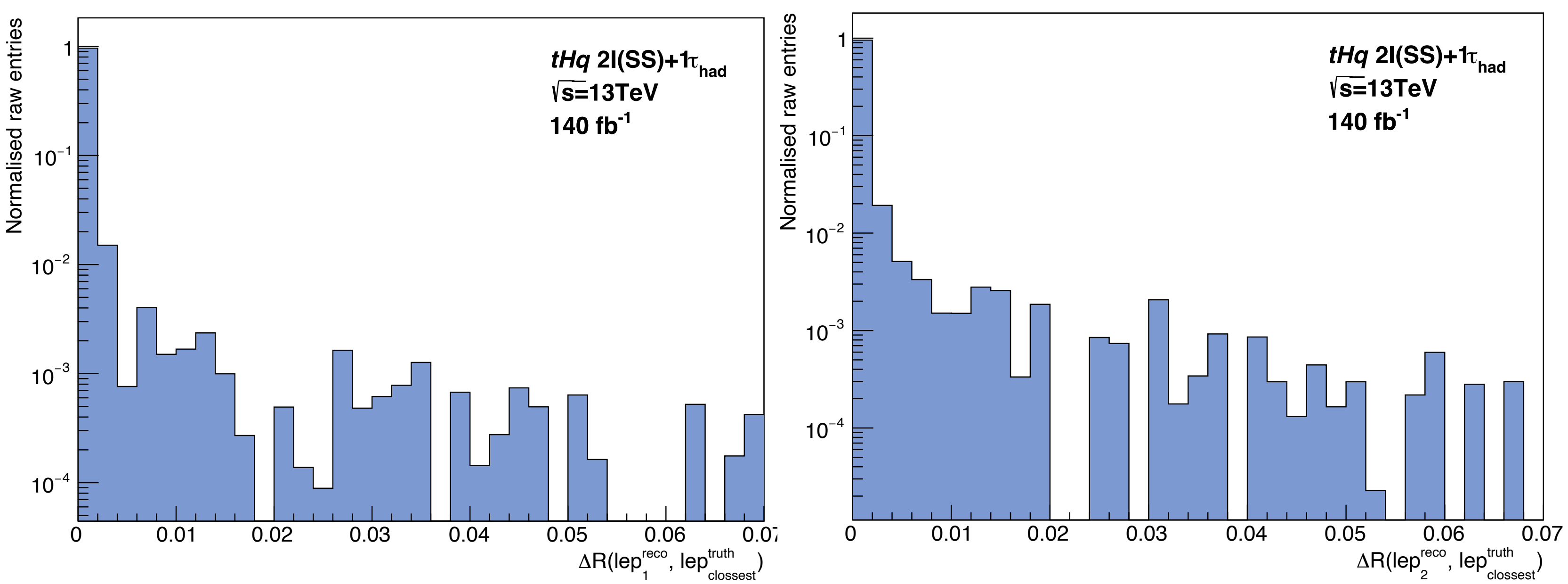
-> No SF applied

10
10

Assignment of the lepton origin

- Starting from the entire *tHq* MC sample, as conditions are imposed, the number of entries decrease
- τ_{had} from Higgs so that it makes sense to talk about ℓ_H and ℓ_t

Stage	Entries
Total tHq $(2\ell + 1\tau_{\text{had}})$ sample	43922
2ℓ SS $+ 1\tau_{\text{had}}$ sample	18140
Selection: $H \to \tau_{\text{lep}}\tau_{\text{had}}/W^+W^-$, $W \to e/\mu/\tau_{\text{lep}}$	15446
$\Delta R(\ell_1^{\text{reco}}, \ell_{\text{closest}}^{\text{truth}}) < 0.01$ and $\Delta R(\ell_2^{\text{reco}}, \ell_{\text{closest}}^{\text{truth}}) < 0.01$	14680

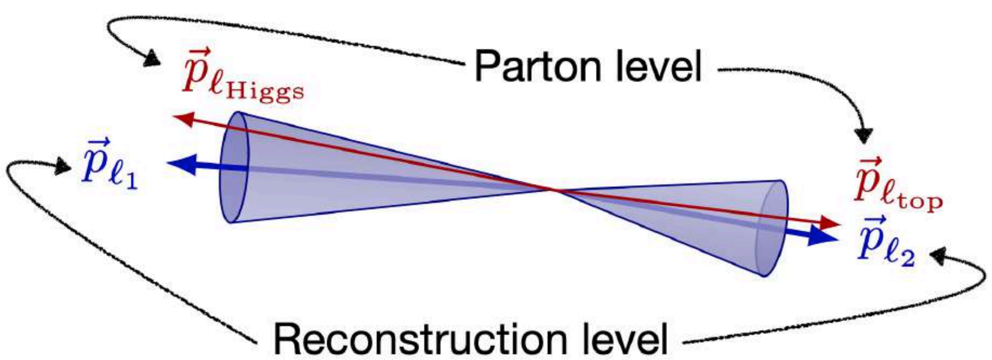


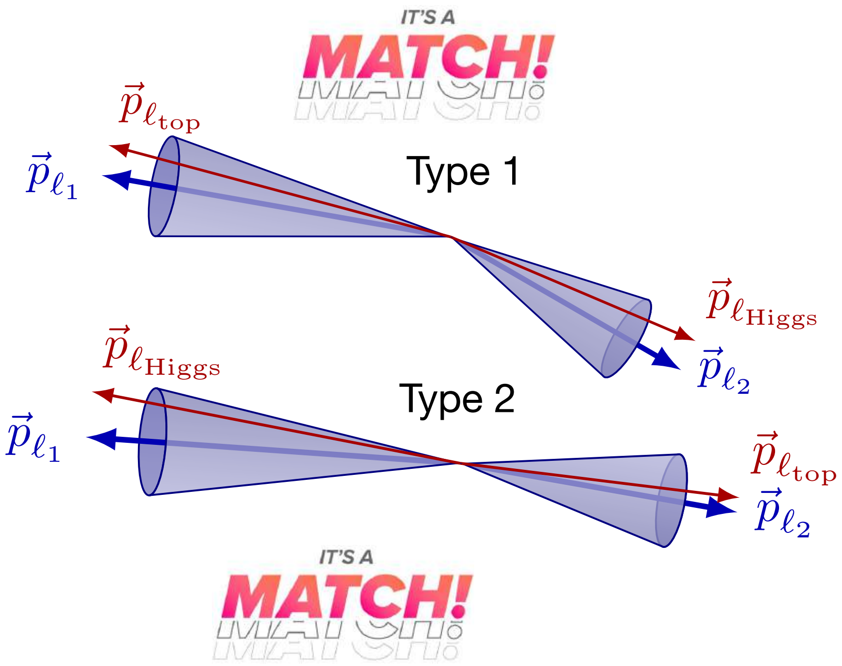
- Requirements:
  - 2ℓSS $+ \tau_{had}$
  - τ_{had} from Higgs
  - $H \to \tau\tau/WW^*$
  - Min ΔR(truth, reach)

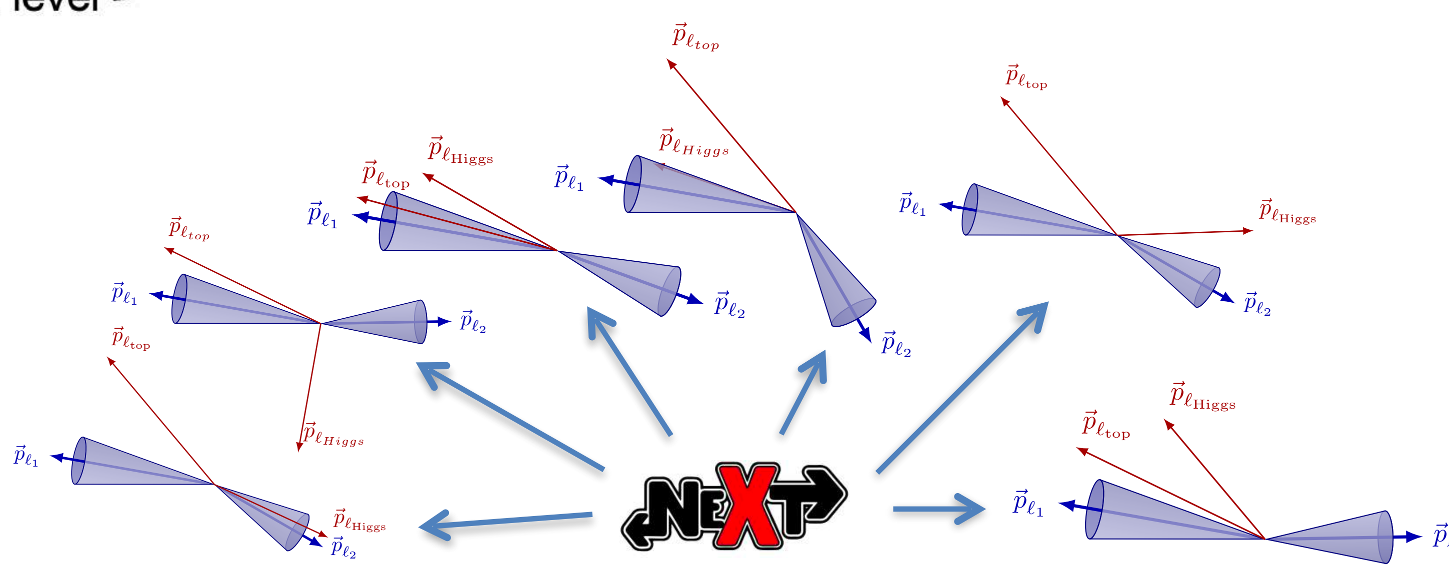
Lepton origin assignment - Label

- Label the date comparing the truth-level with reco-level:
  - **Parton-level**: Before the detector simulation. The origin of the particles is known.
  - **Reco-level**: Objects as identified by the detector. Origin of particles unknown

Draw $\Delta R < 0.1$cones around the of the leptons.

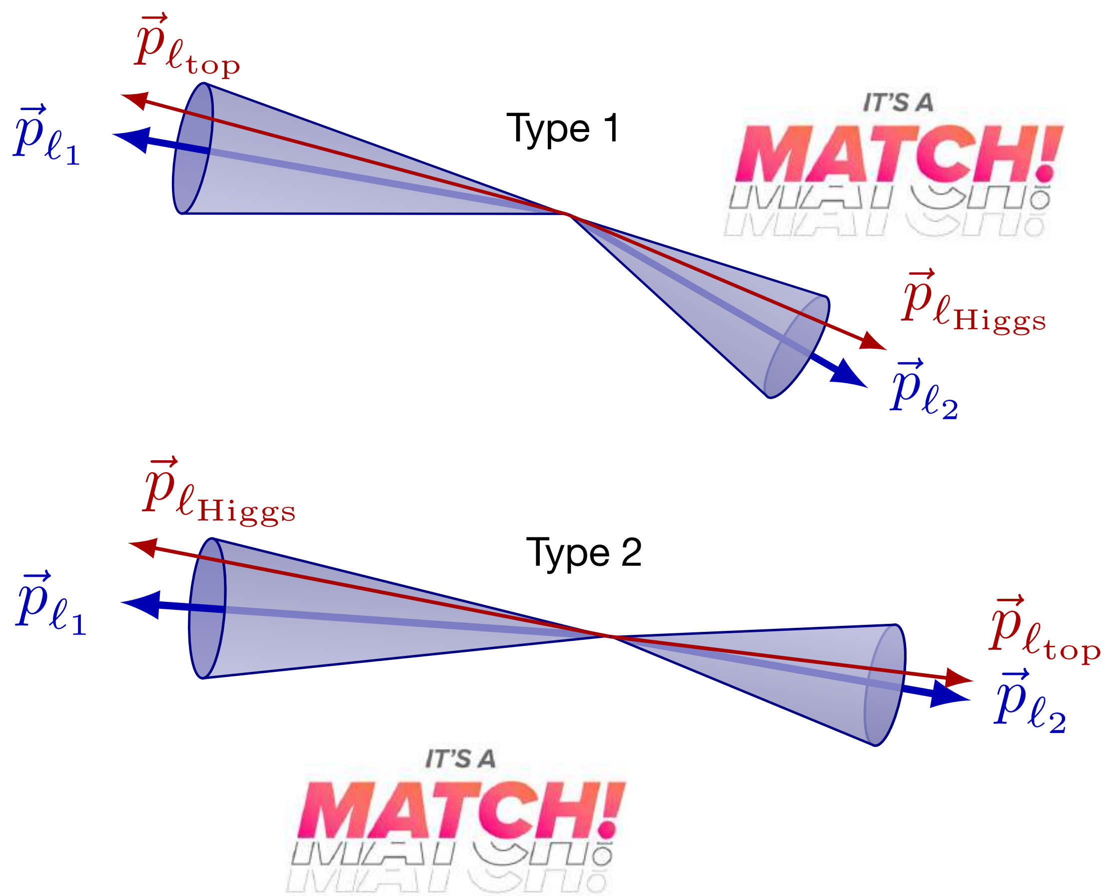


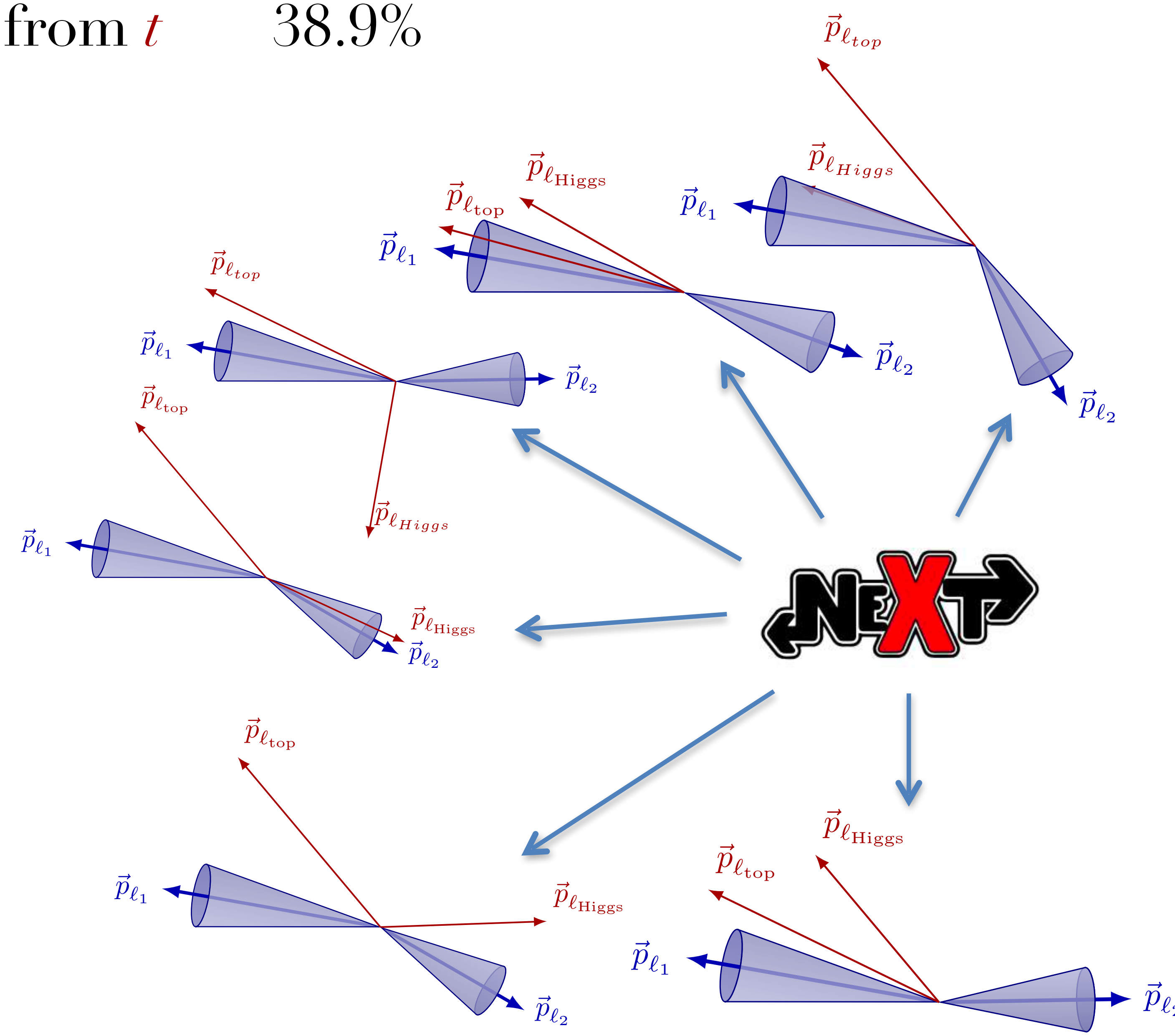




Assignment of the lepton origin

- Two categories:
  - **Type 1**: Leading lepton (ℓ_1^{reco}) form t and subleading (ℓ_2^{reco}) from H 61.1%
  - **Type 2:** ℓ_1^{reco} form H and ℓ_2^{reco} from t 38.9%

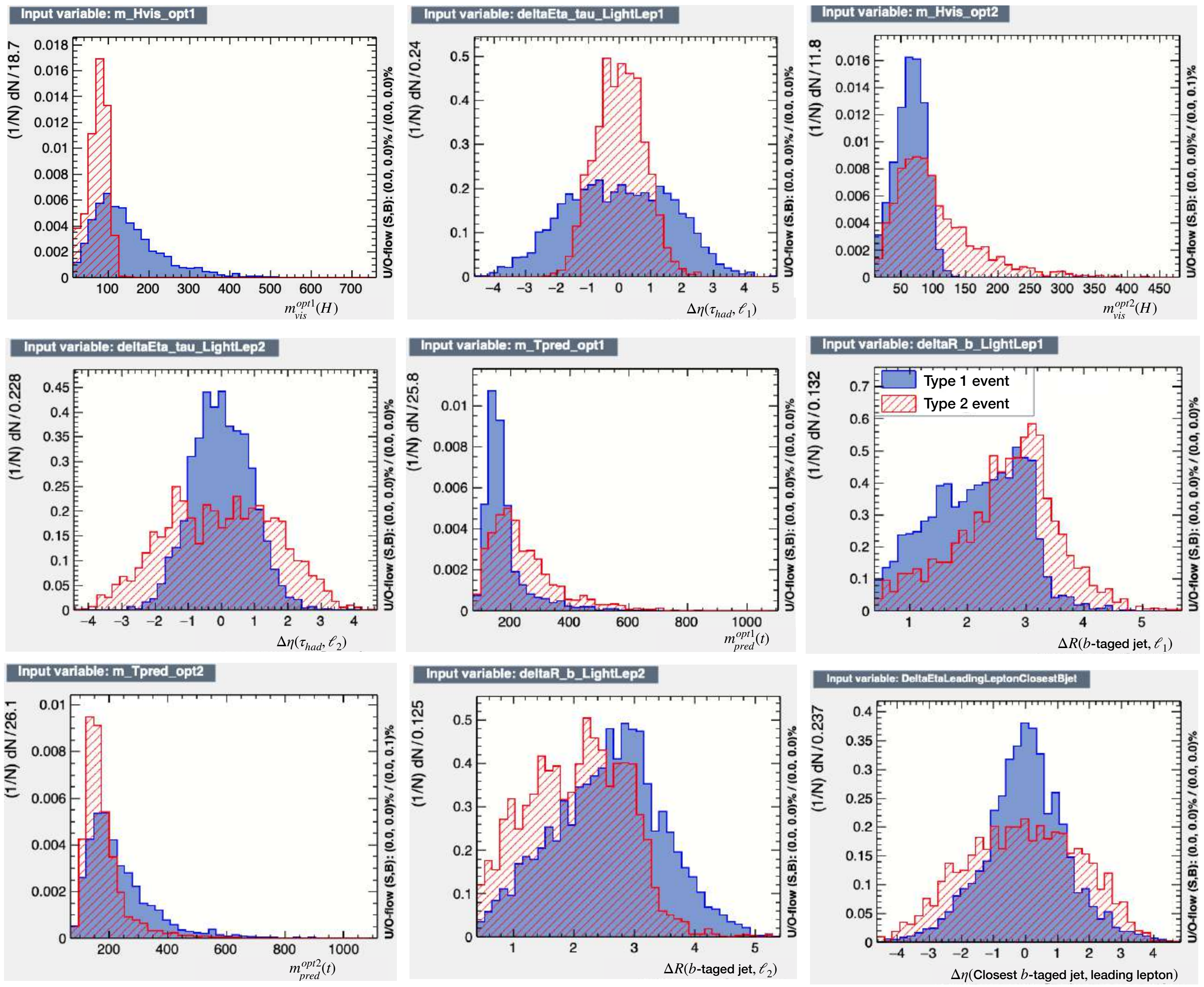




BDT lepton origin - Variables

Ranked variables

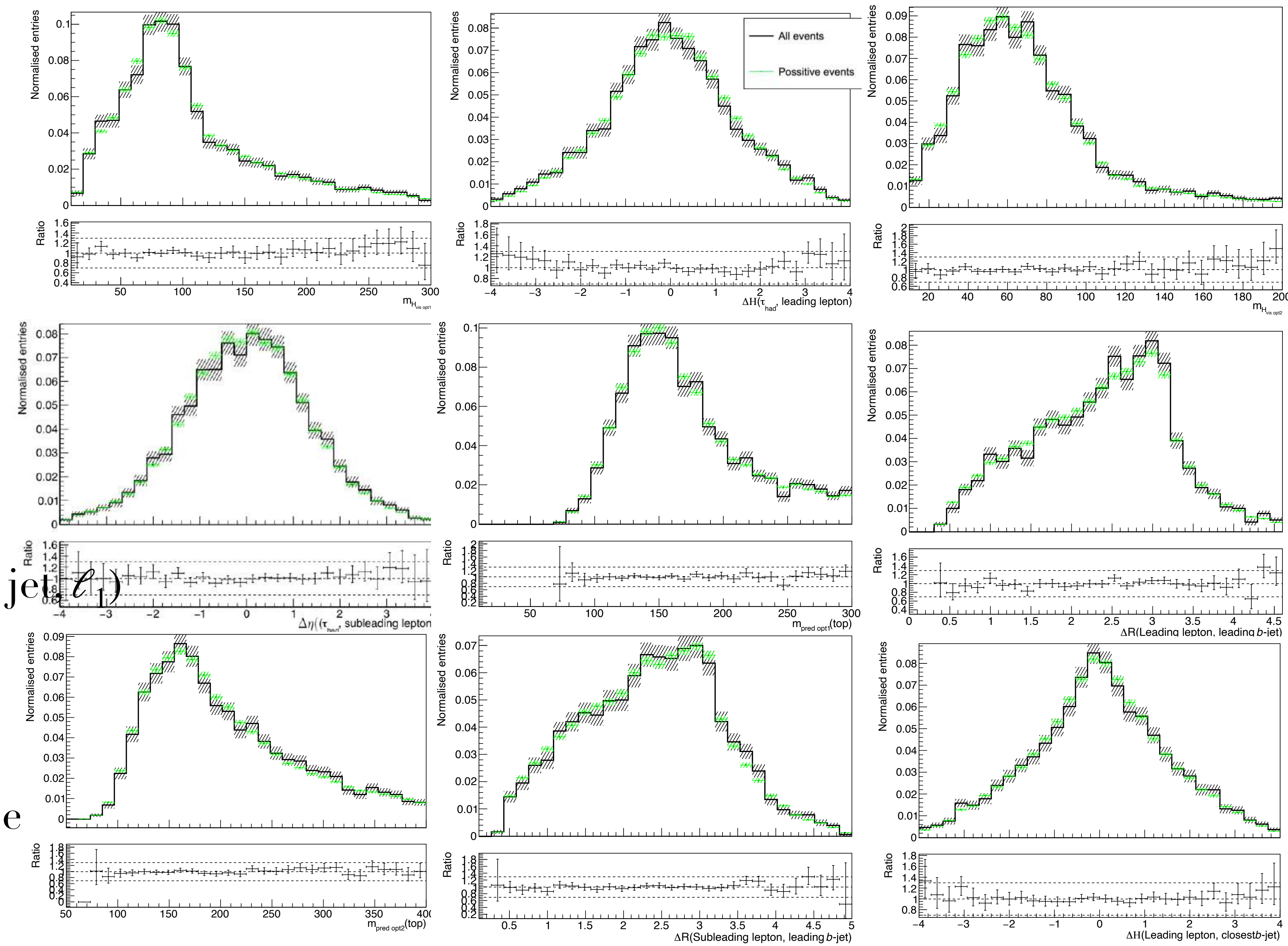
1. $m_{vis}^{opt1}(H)$
2. $\Delta\eta(\tau_{had}, \ell_1)$
3. $m_{vis}^{opt2}(H)$
4. $\Delta\eta(\tau_{had}, \ell_2)$
5. $m_{pred}^{opt1}(t)$
6. $\Delta R(\text{leading } b\text{-tagged jet}, \ell_1)$
7. $m_{pred}^{opt2}(t)$
8. $\Delta R(b\text{-tagged jet}, \ell_2)$
9. $\Delta\eta(\text{closest } b\text{-tagged jet}, \ell_1)$



BDT lepton origin - Variables

- The distributions with negative weights have the same distribution as with all the weights

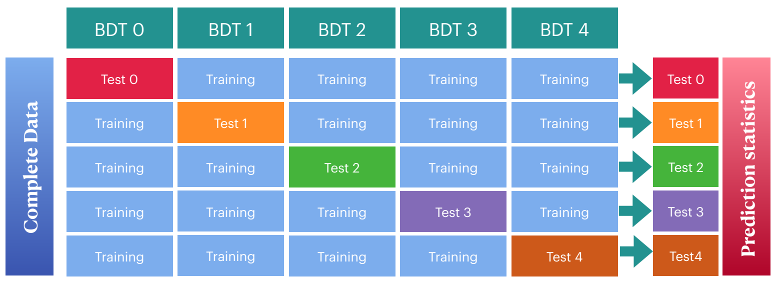
Ranked variables



1. $m_{vis}^{opt1}(H)$
2. $\Delta\eta(\tau_{had}, \ell_1)$
3. $m_{vis}^{opt2}(H)$
4. $\Delta\eta(\tau_{had}, \ell_2)$
5. $m_{pred}^{opt1}(t)$
6. ΔR(leading b-tagged jet, ℓ_1)
7. $m_{pred}^{opt2}(t)$
8. ΔR(b-tagged jet, ℓ_2)
9. $\Delta\eta$(closest b-tagged je

BDT lepton origin - Training

Hyperparam.	Value	Meaning
`Type`	Gradient	Boosting type for the trees.
`MaxDepth`	3	Maximum depth of cell tree.
`Shrinkage`	0.2	Learning rate for GradBoost algorithm.
`NTrees`	10^3	Number of trees in method.
`nCuts`	40	Number of grid points in variable range used in finding optimal cut in node splitting.

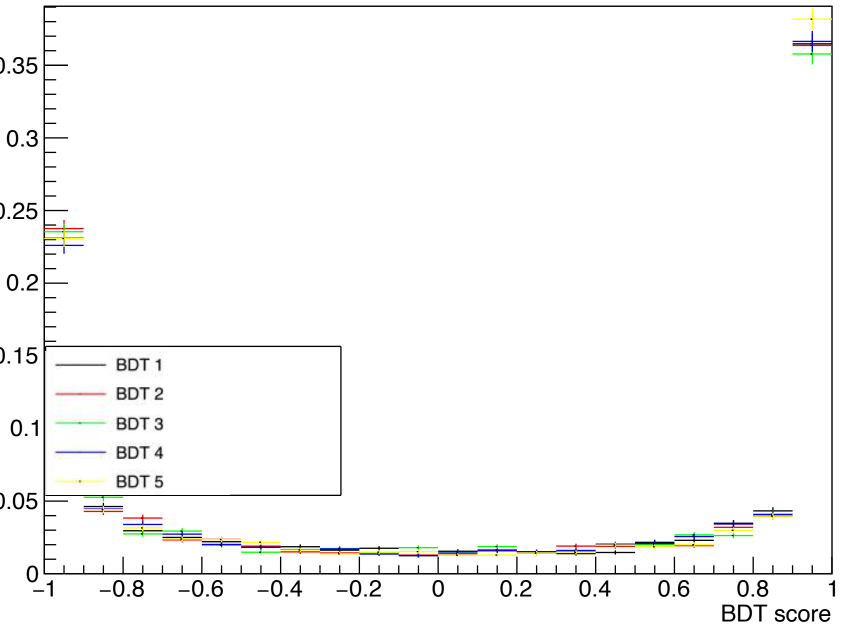


The split expression uses the event number

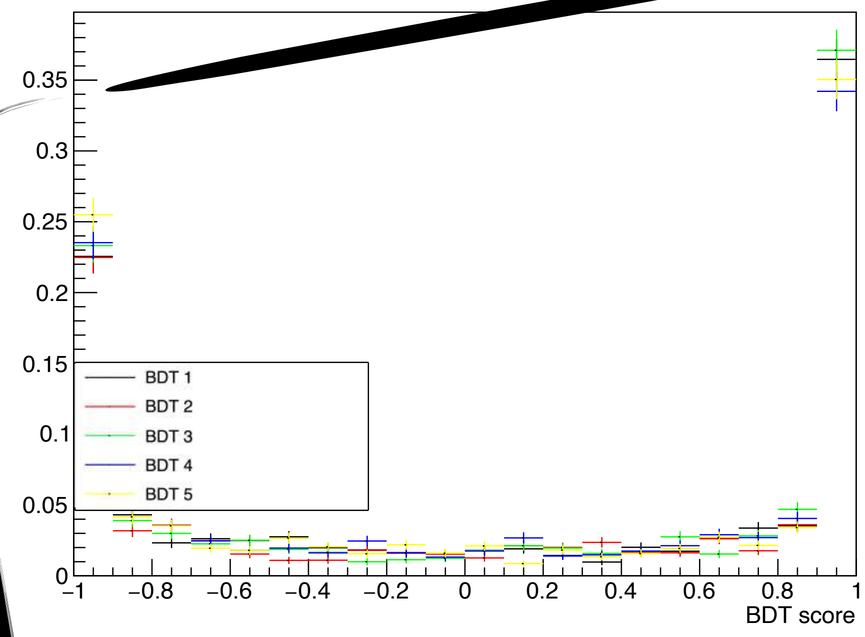
- BDT score distributions for the different models (split is a model)
- Only the scores corresponding to test samples are applied
- The model does not seem to be affected by which folds are used <—general

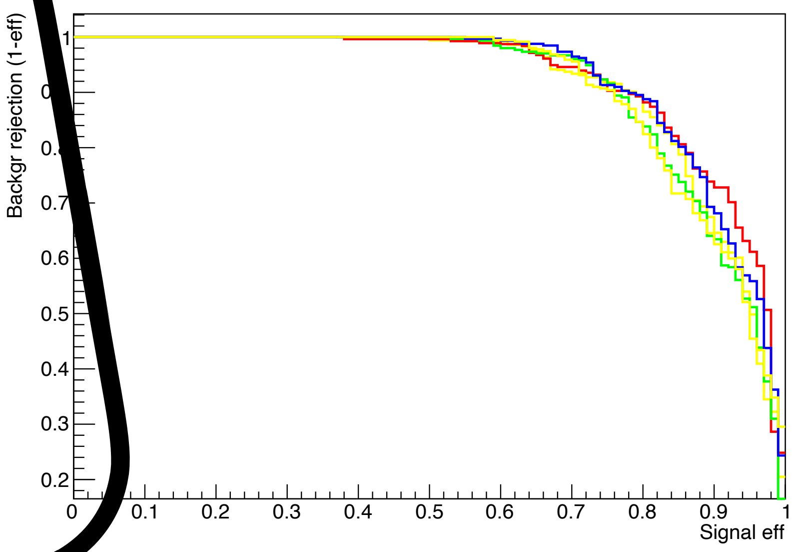
What is used!

Train samples



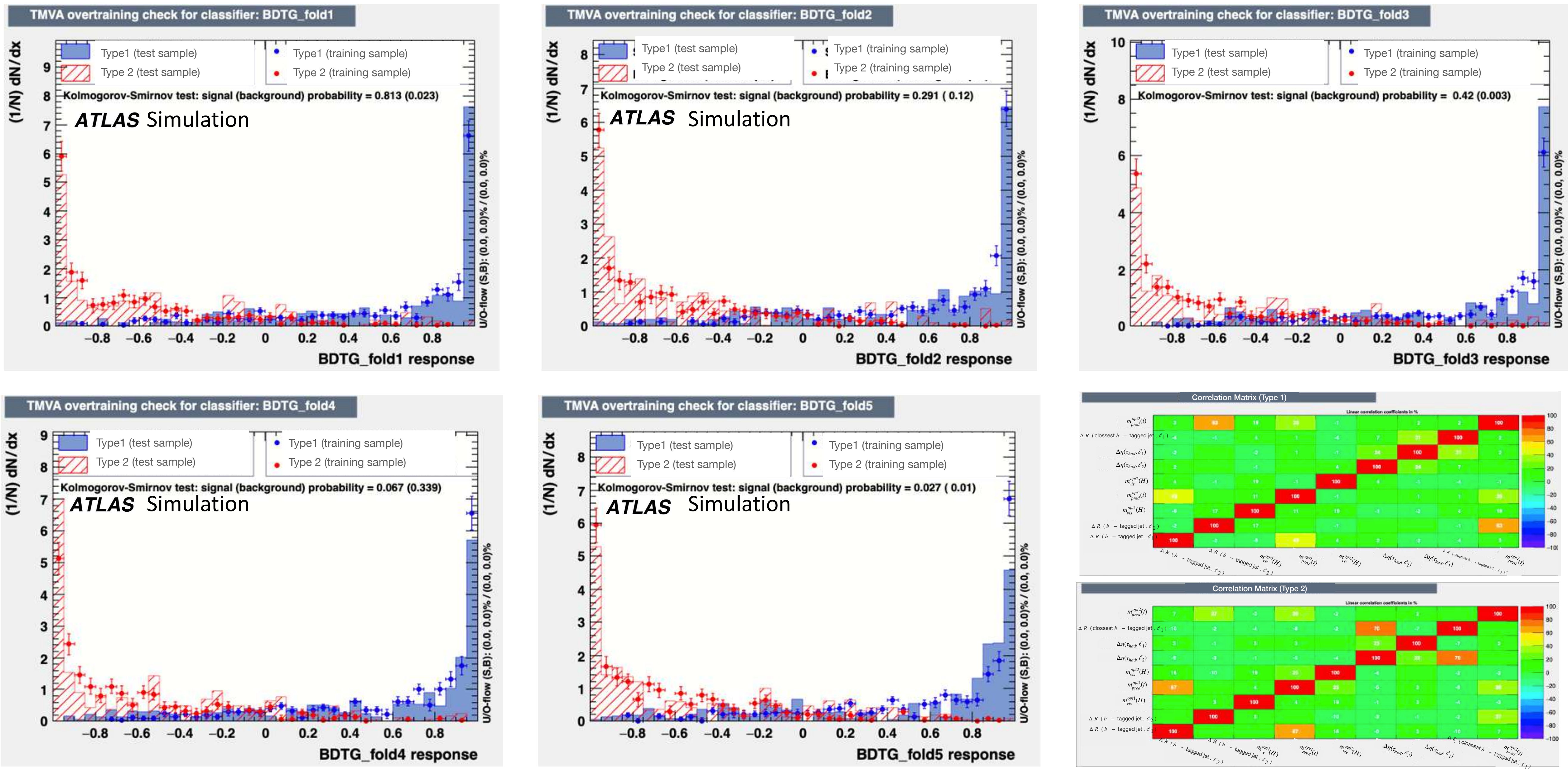
Test samples





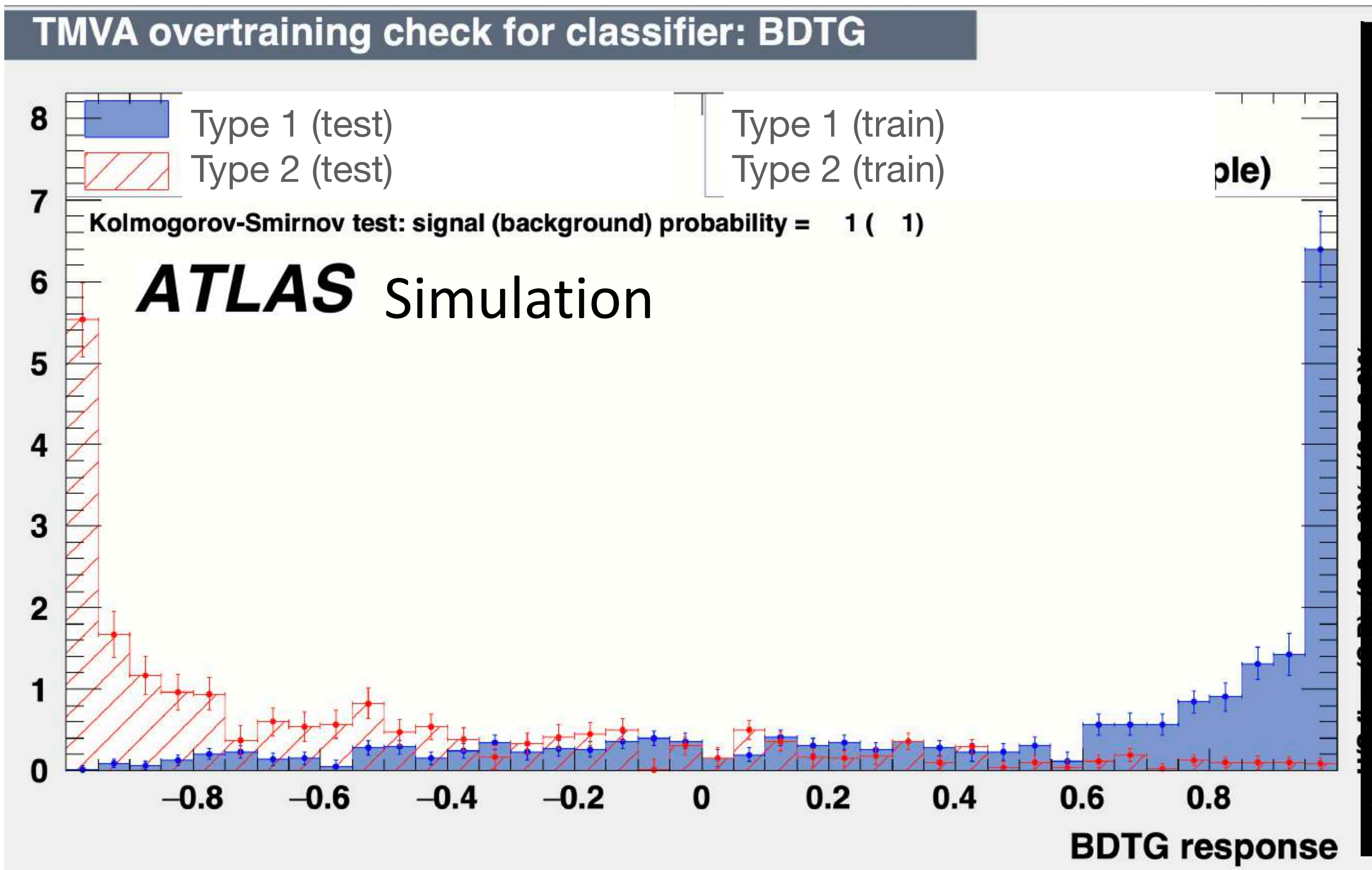
BDT lepton origin - Models

The 5-folds result in 5 BDTs. Each with its own train (80%) and test (20%) samples.



BDT lepton origin - Thereshold

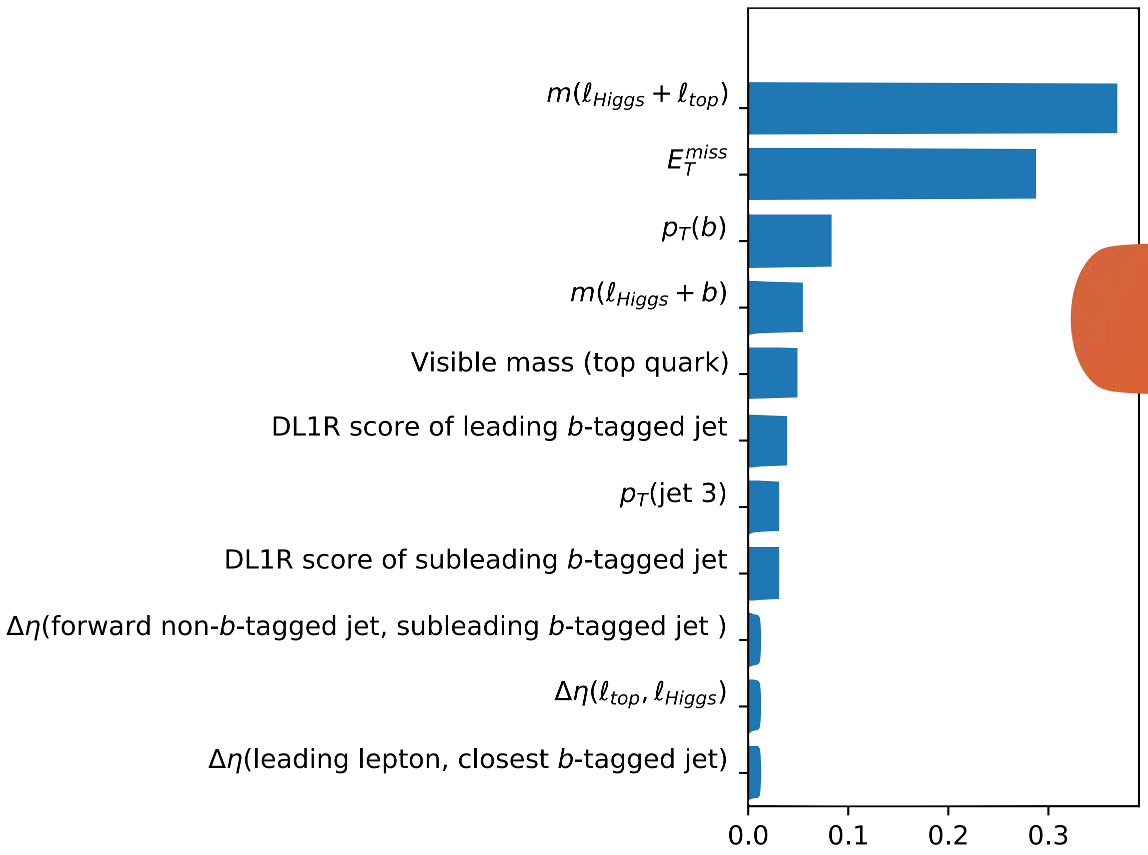
Combining the 5 BDTs:

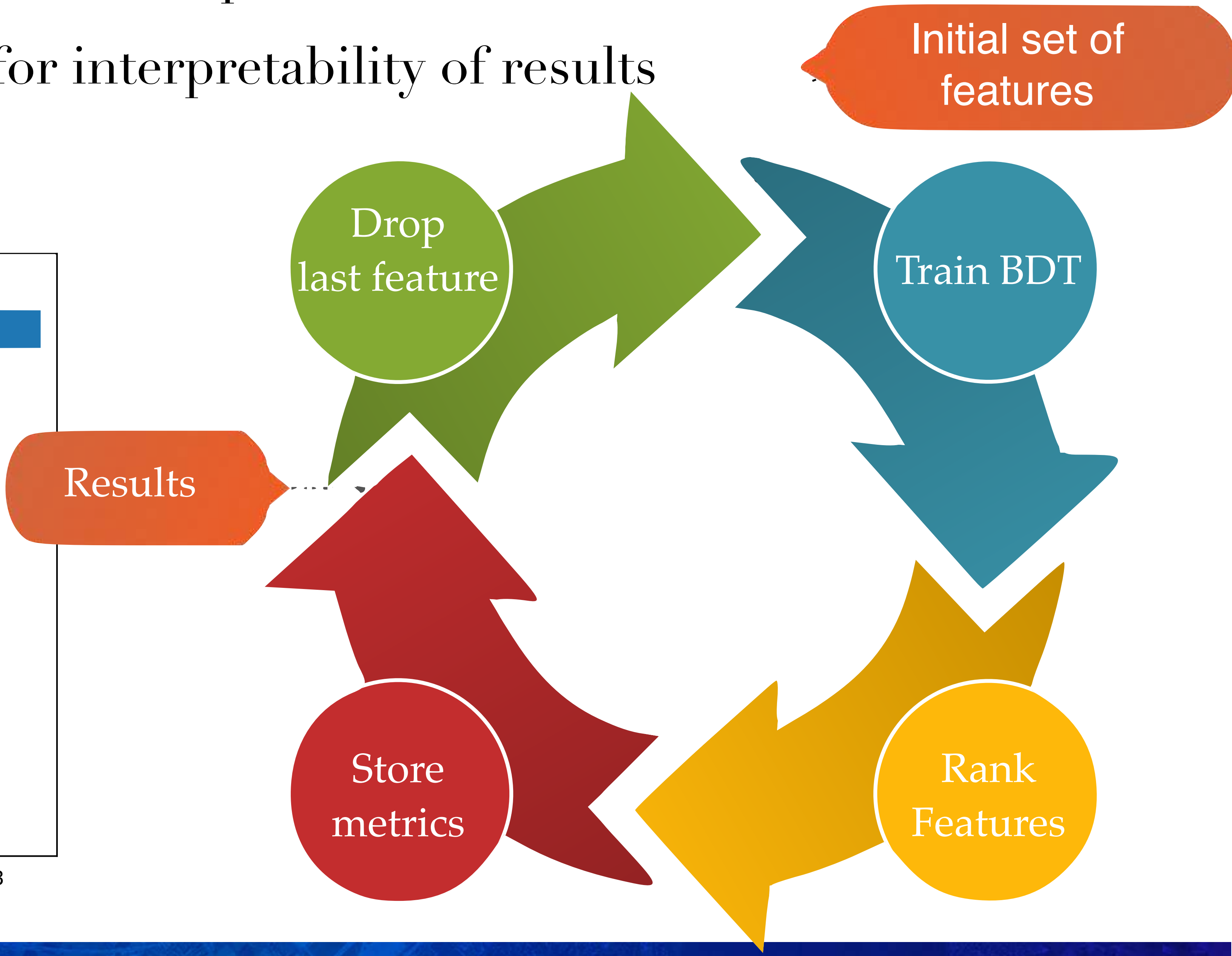



```
Cut = -0.45     => Efficiency = (83.0%) 93.04%
Cut = -0.4      => Efficiency = (84.0%) 93.39%
Cut = -0.35     => Efficiency = (84.0%) 93.77%
Cut = -0.33     => Efficiency = (84.0%) 93.92%
Cut = -0.32     => Efficiency = (84.0%) 93.9%
Cut = -0.31     => Efficiency = (84.0%) 93.78%
Cut = -0.3      => Efficiency = (84.0%) 94.02%
Cut = -0.29     => Efficiency = (84.0%) 94.31%
Cut = -0.28     => Efficiency = (84.0%) 94.31%
Cut = -0.27     => Efficiency = (84.0%) 94.29%
Cut = -0.25     => Efficiency = (84.0%) 94.59%
Cut = -0.2      => Efficiency = (84.0%) 94.93%
Cut = -0.15     => Efficiency = (84.0%) 94.95%
Cut = -0.1      => Efficiency = (84.0%) 95.18%
Cut = -0.05     => Efficiency = (85.0%) 95.28%
Cut = 0.0       => Efficiency = (85.0%) 95.14%
Cut = 0.05      => Efficiency = (85.0%) 95.31%
Cut = 0.1       => Efficiency = (85.0%) 95.11%
Cut = 0.15      => Efficiency = (85.0%) 94.6%
Cut = 0.2       => Efficiency = (85.0%) 94.26%
Cut = 0.25      => Efficiency = (85.0%) 94.59%
Cut = 0.3       => Efficiency = (85.0%) 94.28%
Cut = 0.35      => Efficiency = (85.0%) 94.04%
Cut = 0.4       => Efficiency = (85.0%) 93.69%
Cut = 0.45      => Efficiency = (85.0%) 93.71%
```

BDT - Variables Optimisation

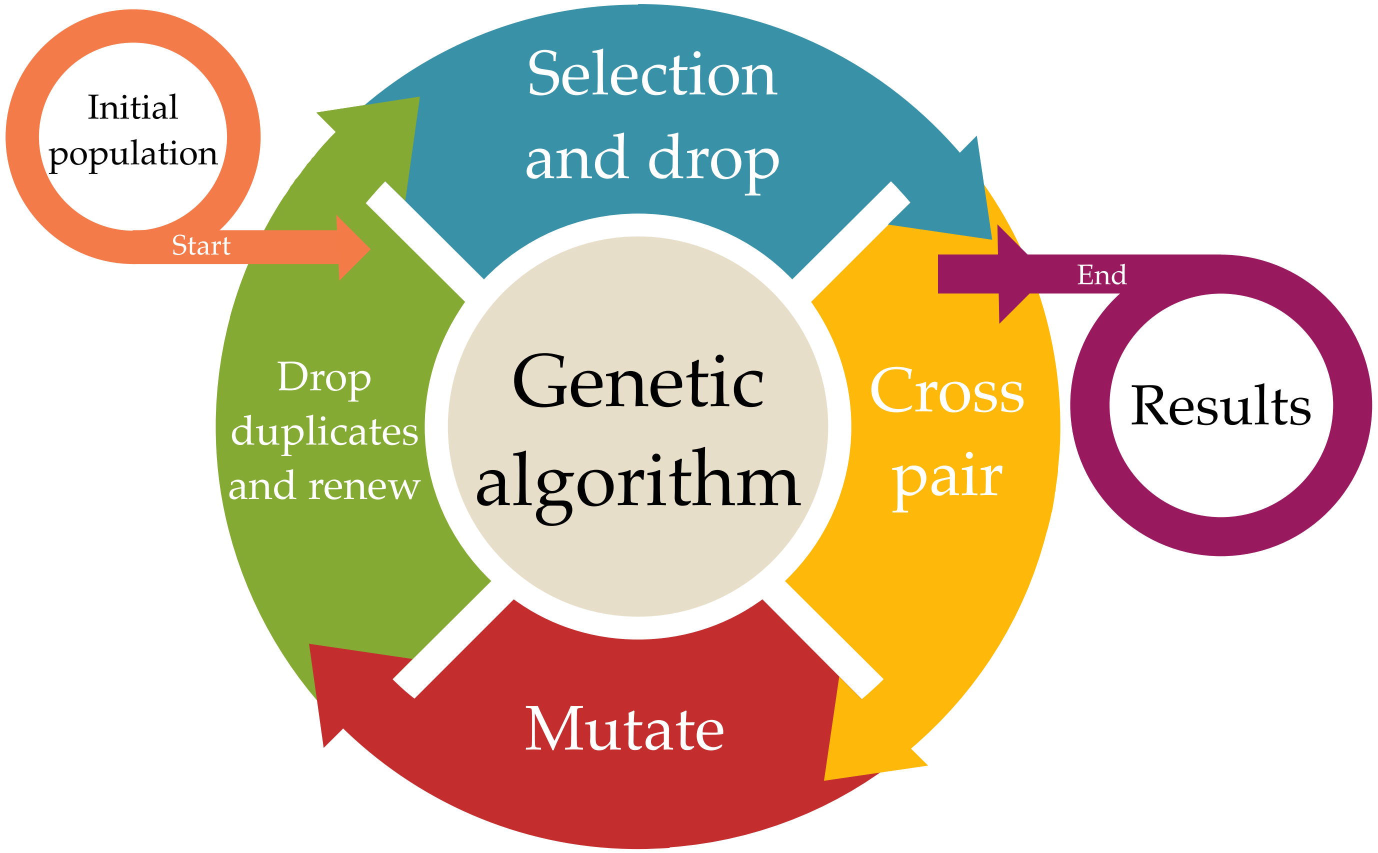
- Preliminar set of input variables selected from distributions
- Iterative algorithm to rank variables according to its impact
- Most discriminant variables selected as input variables
- The ranking of variables allows for interpretability of results





BDT - Hyperparam - GA

- The genetic algorithm is inspired in the concept of natural selection



Inject initial population
A collection of sets of hyperparameters is injected to the GA.

Selection and drop
A model is trained for each set and these are ranked. The worst half is dropped.

Cross pair
Randomly interchange values of some hyperparameters between two sets.

Mutate
Randomly mutate the values of some hyperparameters.

Drop duplicates and renew
Remove the duplicates and add the new sets to reach the initial population.

Results
To watch carefully and attentively in order to learn or gain information.

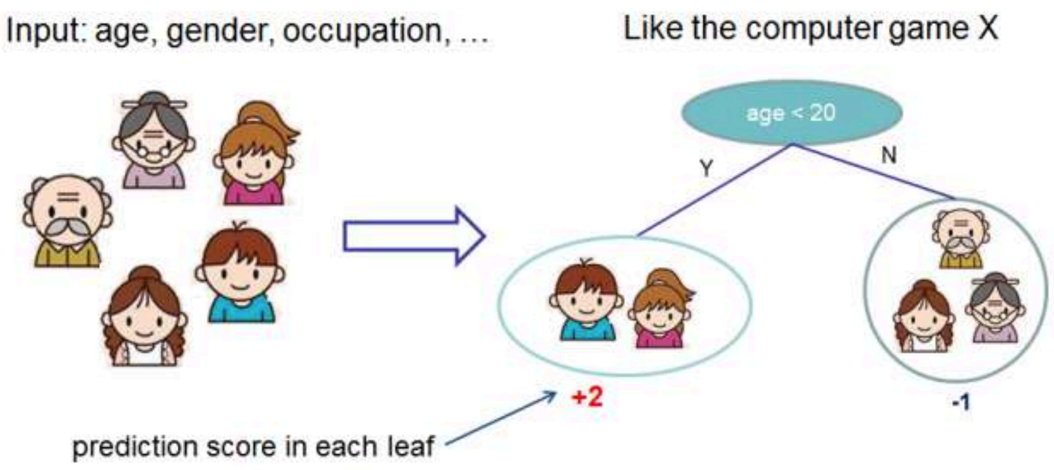
Hyperparameter	BDT($tHq|_{\mathrm{OS}}$)	BDT($t\bar{t}|_{\mathrm{OS}}$)	BDT($tHq|_{\mathrm{SS}}$)
Maximum depth	4	4	4
Learning rate	0.1237	0.0334	0.04
Number of estimators	1500	1500	1500
Minimum child weigh	0.52	0.077	0.026
Scale of positive weights	268.838	0.36	83.21
Neg. weight strategy	Only positive	Only positive	Absolute values

Boosted Decision Trees

What is a BDT?

- A BDT (Boosted Decision Tree) is a type of supervised machine learning algorithm
- Given a set of input variables, decide whether an event is signal or background
- Conceptually, nothing more than a complicated sequence of cuts

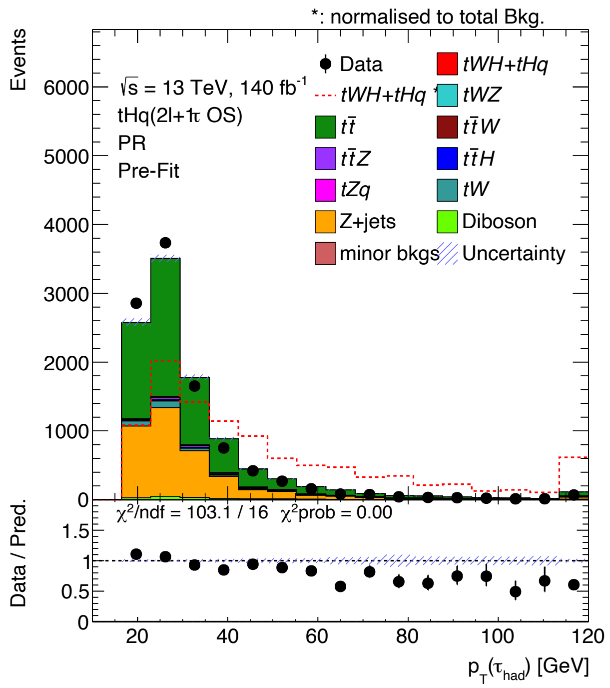
dmlc XGBoost

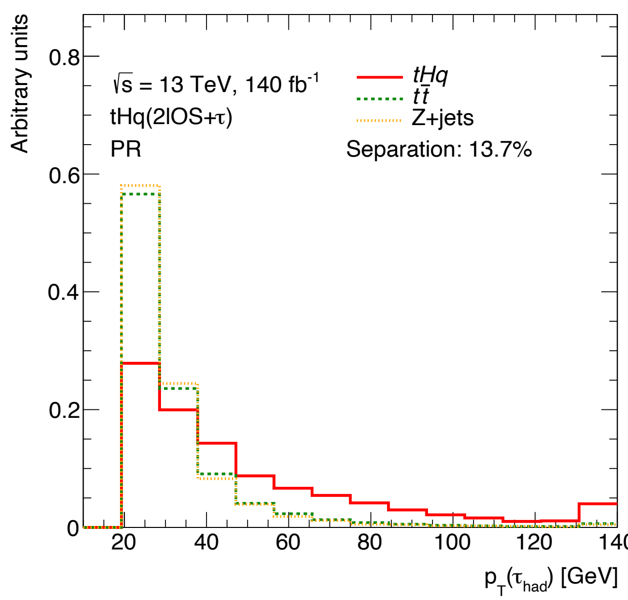


- Here use XGBoost → fast, robust performance without much hyperparameter tuning needed

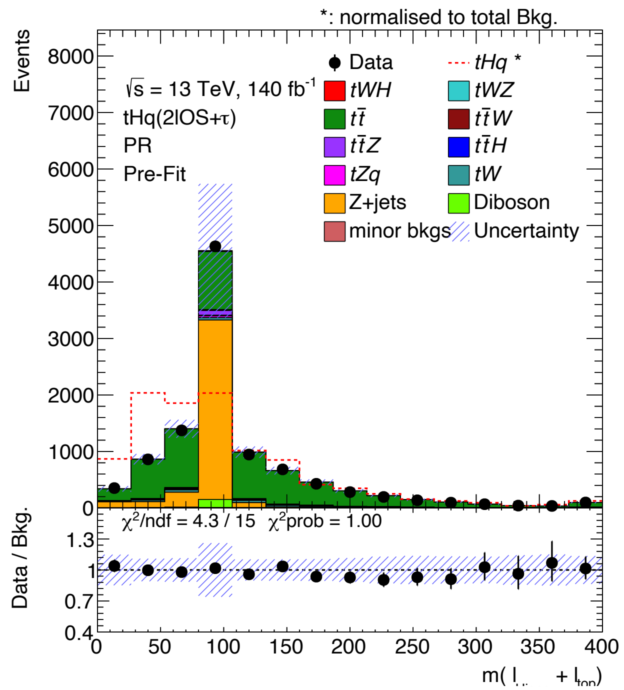
BDTs for region def - Variables

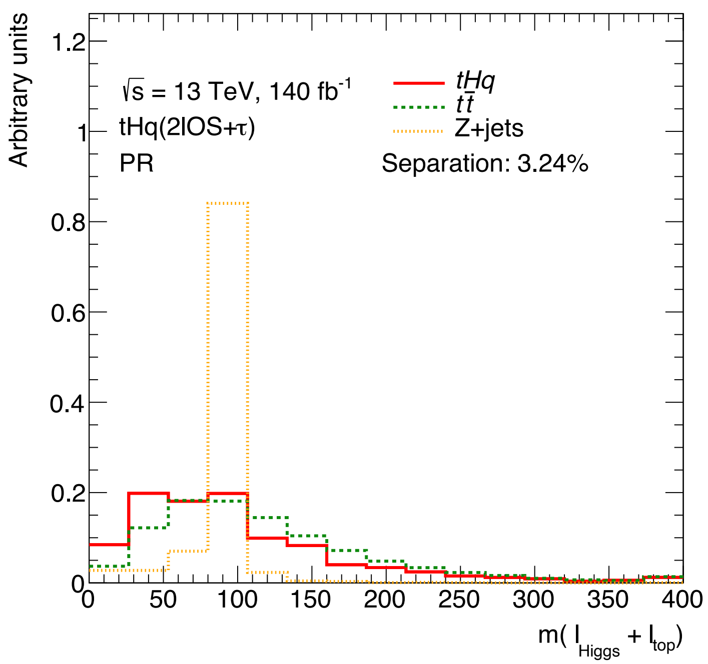
BDT$(tHq\,|\,\mathrm{OS})$



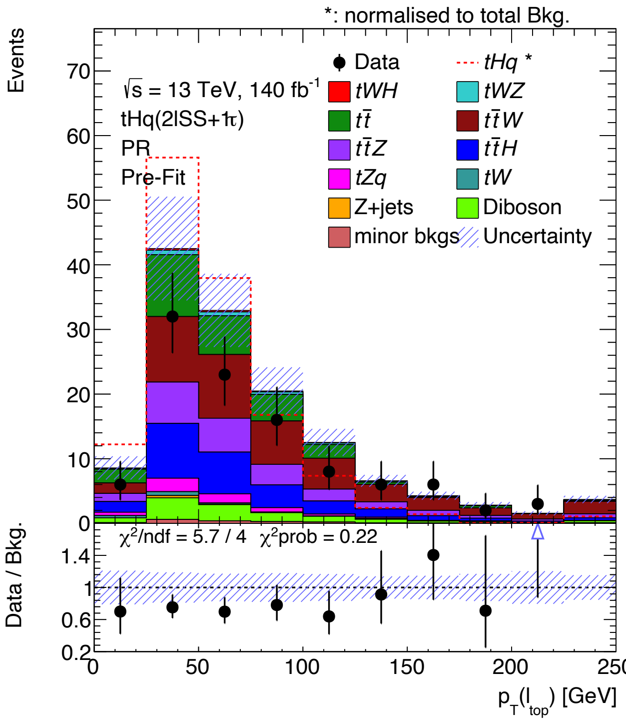


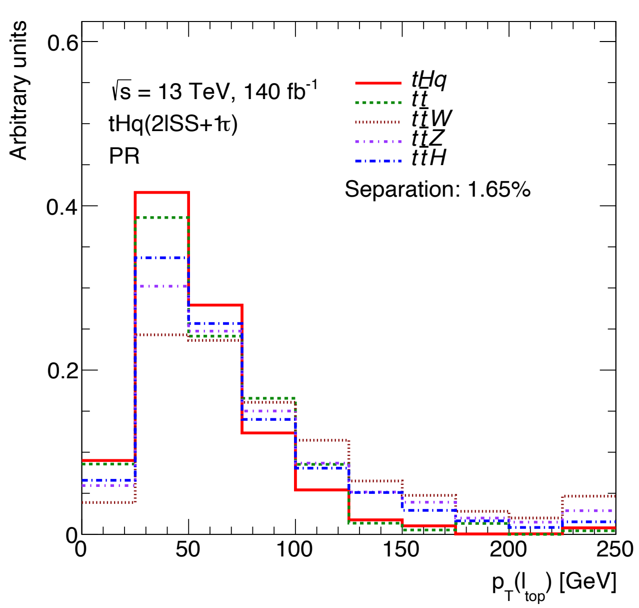
BDT$(t\bar{t}\,|\,\mathrm{OS})$





BDT$(tHq\,|\,\mathrm{SS})$





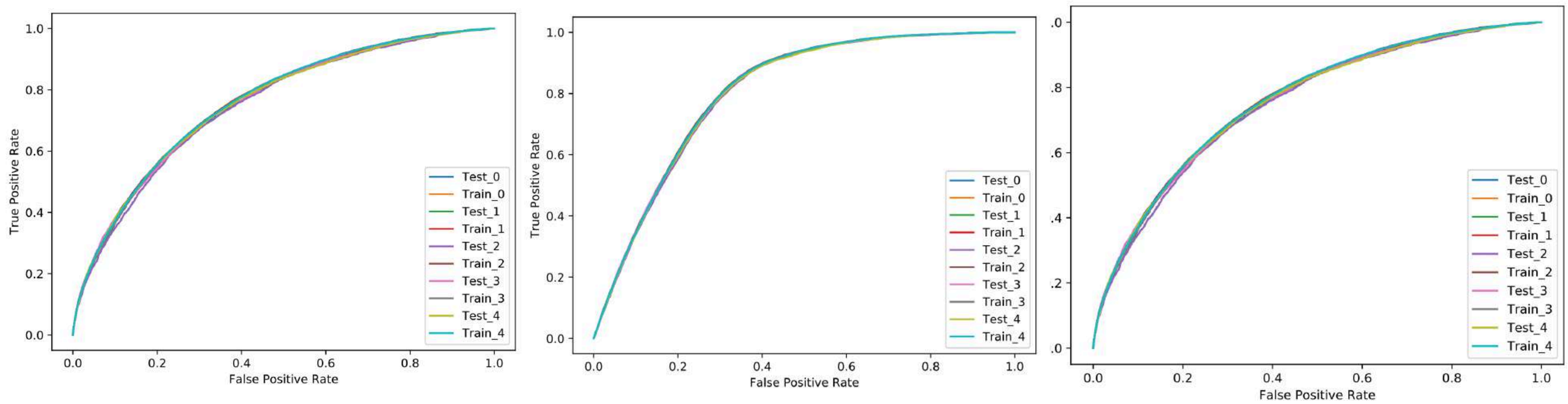
Variables, hyperparam and performance

Variable name	BDT($tHq|_{\mathrm{OS}}$)	BDT($t\bar{t}|_{\mathrm{OS}}$)	BDT($tHq|_{\mathrm{SS}}$)
$\Delta\eta(\ell_{\texttt{Higgs}}, \tau_{\mathrm{had}})$	✓	-	✓
$\Delta R(\ell_{\mathrm{top}}$, leading non-$b$-tagged jet)	✓	-	✓
$\Delta\eta$(forward non-b-tagged jet, b-tagged jet)	✓	-	✓
ΔR(leading non-b-tagged jet, b-tagged jet)	-	-	✓
Visible mass (top quark)	-	✓	-
p_{T} (b-tagged jet)	-	✓	-
$m(\ell_{\texttt{Higgs}}, b\text{-tagged}jet)$	✓	✓	-
$\Delta R(\ell_{\texttt{Higgs}}$, leading non-$b$-tagged jet)	-	-	✓
Missing Mass Calculator 1	✓	-	-
$p_{\mathrm{T}}(\ell_{\mathrm{top}})$	-	-	✓
$\mathrm{E}(\ell_{\mathrm{top}})$	-	-	✓
$\Delta R_{min}(\ell_{\texttt{Higgs}}, \ell_{\mathrm{top}}, \tau_{\mathrm{had}})$	✓	-	-
m(b-tagged jet, spectator jet)	✓	-	-
$\Delta\eta$(forward non-b-tagged jet, subleading b-tagged jet)	-	✓	-
DL1R calibrated score of subleading b-tagged jet	-	✓	-
DL1R calibrated score of leading b-tagged jet	-	✓	-
$\Delta\phi(\ell_{\texttt{Higgs}}$, spectator jet)	✓	-	✓
$\Delta R(\ell_{\mathrm{top}}, \ell_{\texttt{Higgs}})$	✓	-	✓
Multiplicity (forward jets)	✓	-	-
$\Delta\eta$(leading lepton, closest b-tagged jet)	-	✓	-
$\Delta\eta(\ell_{\mathrm{top}}, \ell_{\texttt{Higgs}})$	-	✓	✓
$\Delta R(\ell_{\texttt{Higgs}}, \tau_{\mathrm{had}})$	✓	-	-
$p_{\mathrm{T}}^{\mathrm{min}}$(lepton) || p_{T} of the softest lepton	✓	-	-
$\Delta R(\ell_{\texttt{Higgs}}$, spectator jet)	✓	-	-
Type (ℓ_1)	✓	-	-
Type (ℓ_3)	✓	-	-
$m_T(\ell_{\mathrm{top}}$, b-tagged jet)	-	-	✓
ΔR(spectator jet, leading b-tagged jet)	-	-	✓
$\Delta\eta(\ell_{\mathrm{top}}$, leading non-$b$-tagged jet)	-	-	✓
$\Delta\eta(\ell_{\texttt{Higgs}}, b\text{-tagged}jet)$	✓	-	-
$m(\ell_{\texttt{Higgs}} + \ell_{\mathrm{top}})$	-	✓	-
p_{T} (τ_{had})	✓	-	✓
p_{T} (jet 3)	-	✓	-
η(leading jet)	✓	-	-
$\Delta\eta(\ell_{\texttt{Higgs}}$, spectator jet)	✓	-	-
E_T^{miss}	-	✓	-
$\Delta R(\ell_{\texttt{Higgs}}$, b-tagged jet)	-	-	✓
$\Delta\eta(\ell_{\mathrm{top}}, \tau_{\mathrm{had}})$	✓	-	-
Multiplicity central jets	-	-	✓

Hyperparameter	BDT($tHq|_{\mathrm{OS}}$)	BDT($t\bar{t}|_{\mathrm{OS}}$)	BDT($tHq|_{\mathrm{SS}}$)
Maximum depth	4	4	4
Learning rate	0.1237	0.0334	0.04
Number of estimators	1500	1500	1500
Minimum child weigh	0.52	0.077	0.026
Scale of positive weights	268.838	0.36	83.21
Neg. weight strategy	Only positive	Only positive	Absolute values

	BDT($tHq|_{\mathrm{OS}}$)		BDT($t\bar{t}|_{\mathrm{OS}}$)		BDT($tHq|_{\mathrm{SS}}$)	
Fold	AUC	Log Loss	AUC	Log Loss	AUC	Log Loss
0	0.6334	0.1940	0.7315	0.1940	0.6685	0.588
1	0.6339	0.1979	0.7419	0.1979	0.6702	0.591
2	0.6365	0.1958	0.7257	0.1958	0.6705	0.595
3	0.6438	0.1958	0.7321	0.1958	0.6717	0.600
4	0.6352	0.1971	0.7268	0.1971	0.6723	0.599
Mean	0.637 ± 0.004	0.1961 ± 0.0013	0.730 ± 0.003	0.4381 ± 0.0006	0.6706 ± 0.0013	0.595 ± 0.004

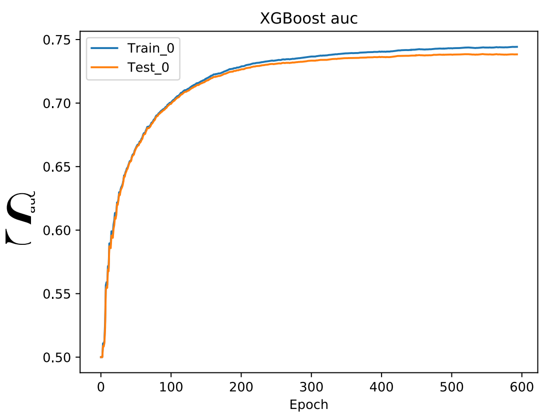
BDT - Performance



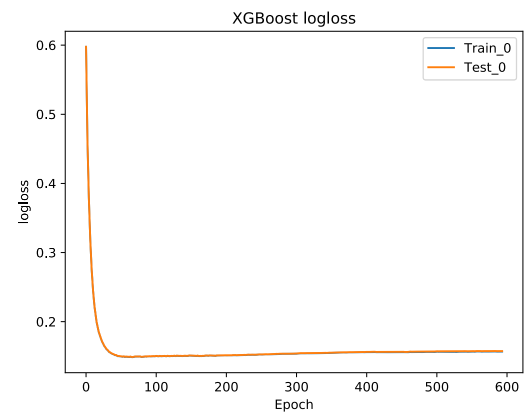
	BDT($tHq\|_{\mathrm{OS}}$)		BDT($t\bar{t}\|_{\mathrm{OS}}$)		BDT($tHq\|_{\mathrm{SS}}$)	
Fold	AUC	LogLoss	AUC	LogLoss	AUC	LogLoss
0	0.6334	0.1940	0.7315	0.4378	0.6685	0.306
1	0.6339	0.1979	0.7419	0.4381	0.6702	0.307
2	0.6365	0.1958	0.7257	0.4374	0.6705	0.309
3	0.6438	0.1958	0.7321	0.4374	0.6717	0.311
4	0.6352	0.1971	0.7268	0.4391	0.6723	0.311
Mean	0.637 ± 0.004	0.1961 ± 0.0013	0.730 ± 0.003	0.4381 ± 0.0006	0.6706 ± 0.0013	0.308 ± 0.002

BDT - Performance

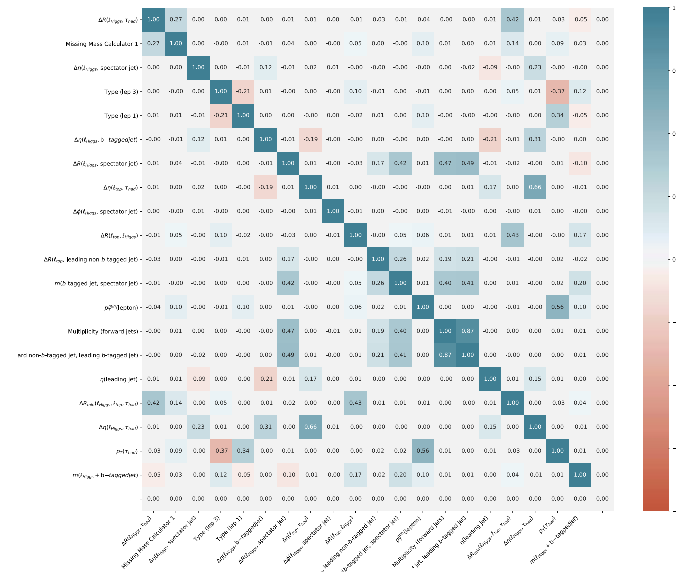
$\mathrm{BDT}(tHq\,|\,\mathrm{OS})$



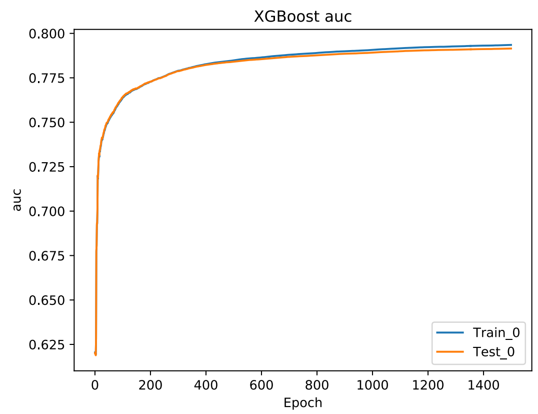
(a) Area under the ROC curve.

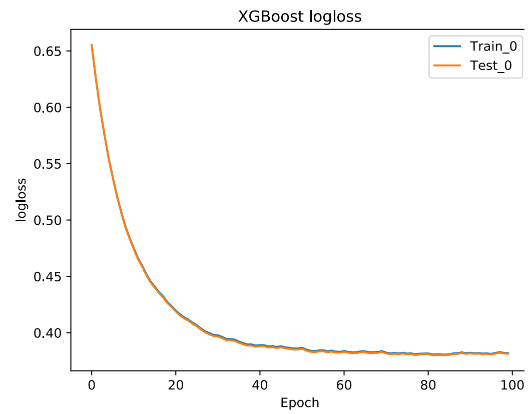


(b) Logarithm of the loss function.

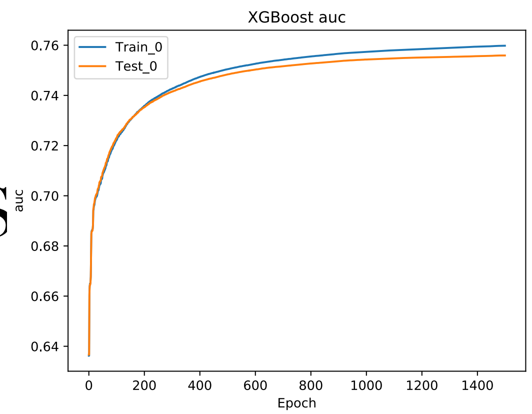


$\mathrm{BDT}(t\bar{t}\,|\,\mathrm{OS})$

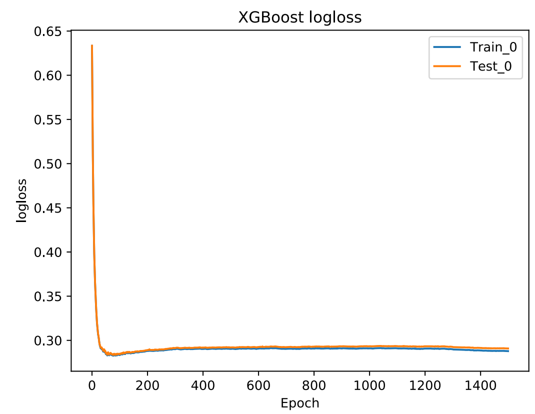




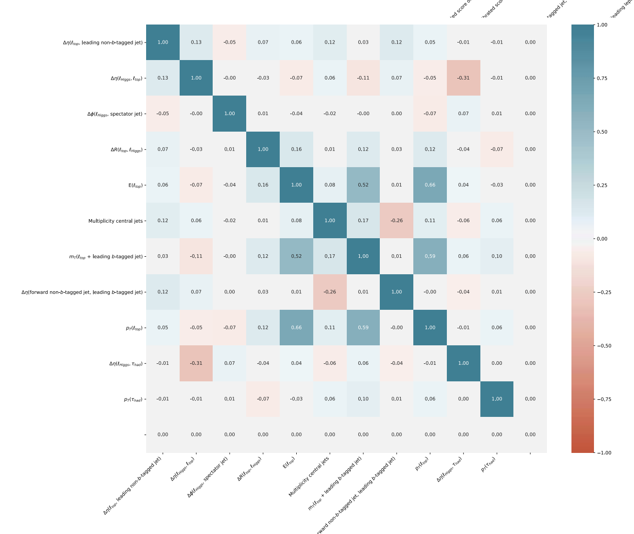
$\mathrm{BDT}(tHq\,|\,\mathrm{SS})$



(a) Area under the ROC curve.



(b) Logarithm of the loss function.

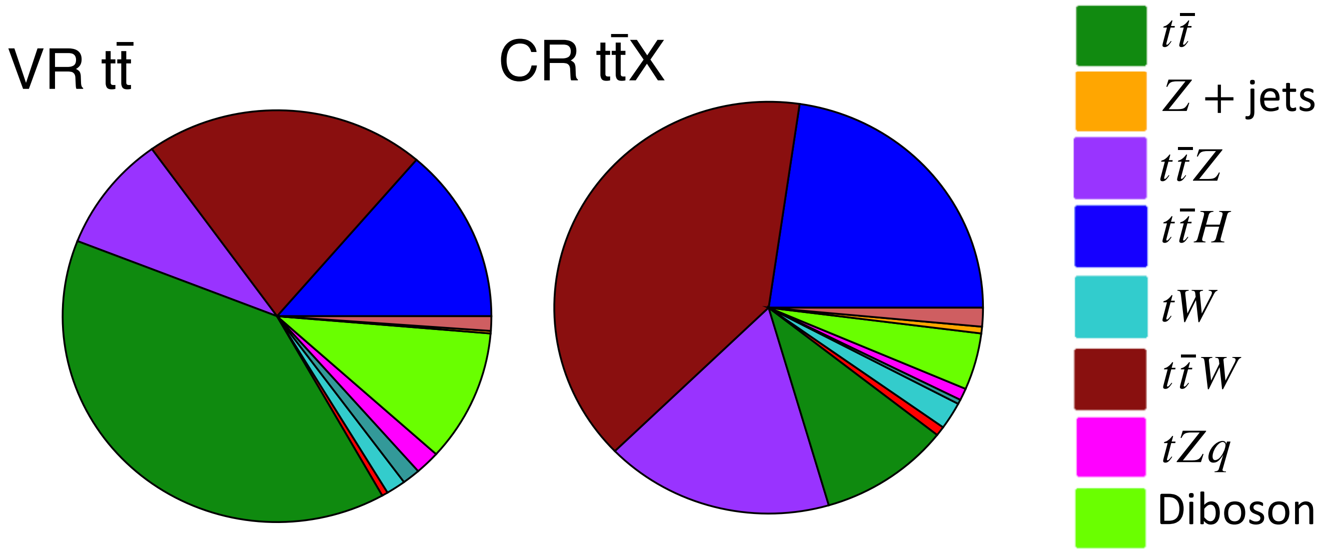


Fit strategies for the $2\ell SS + \tau_{had}$

- Different fit configurations explored
- Baseline is the one used in the thesis
- In alternatives 1 and 2 the CR(All Bkgs) is split in CR($t\bar{t}$) and CR($t\bar{t}X$)

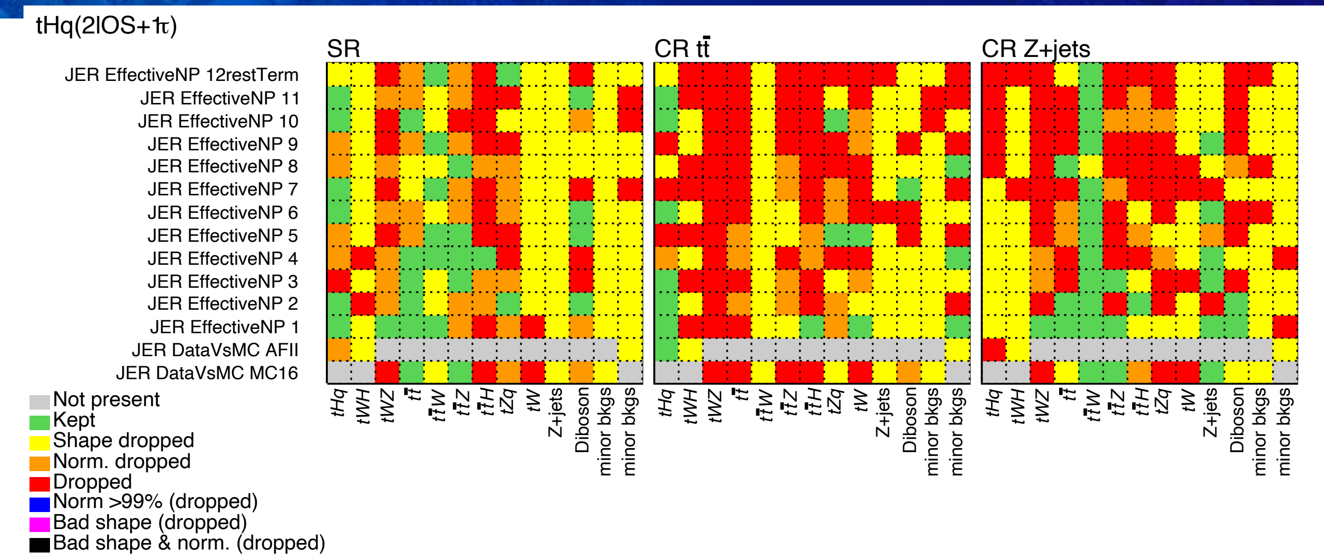
	CRs	Free k_p
Baseline	All bkgs	$k_{t\bar{t},t\bar{t}X}$
Alternative 1	$t\bar{t}$, $t\bar{t}X$	$k_{t\bar{t}}$, $k_{t\bar{t}W}$
Alternative 2	$t\bar{t}$, $t\bar{t}X$	$k_{t\bar{t}}$, $k_{t\bar{t}X}$
Alternative 3	$t\bar{t}$, $t\bar{t}X$	$k_{t\bar{t}}$, $k_{t\bar{t}W}$, $k_{t\bar{t}H}$, $k_{t\bar{t}Z}$

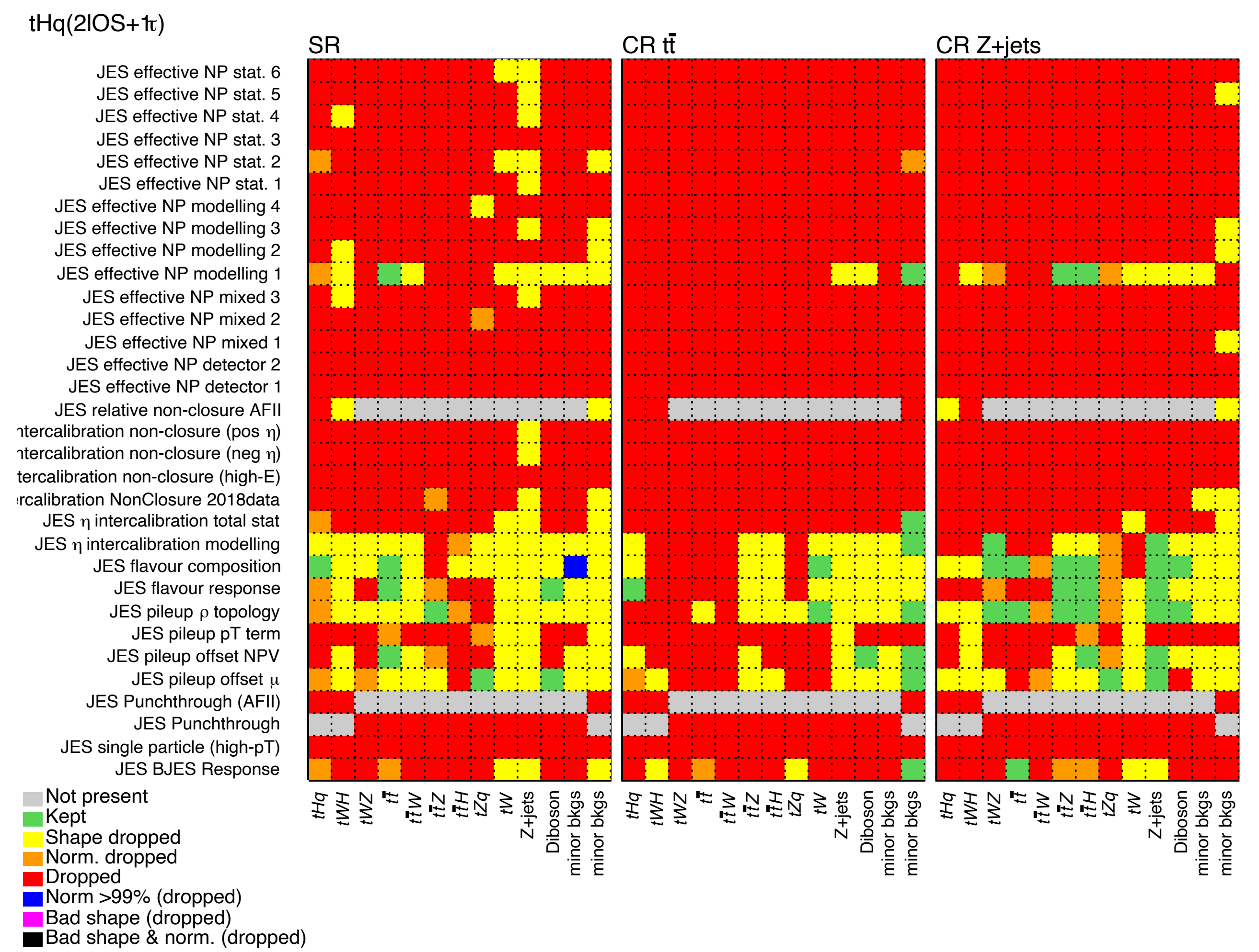
- Due to low statistics, a single CR yielded the best results



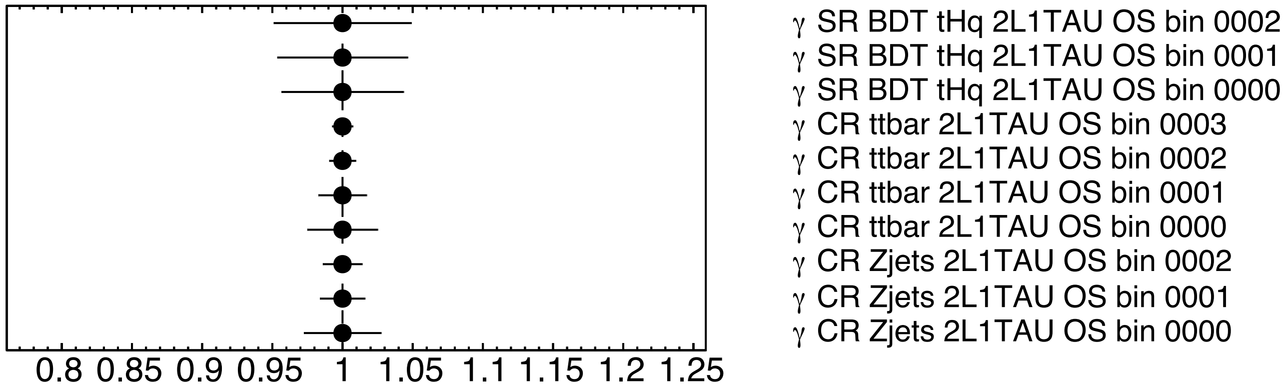
Pruning of NPs

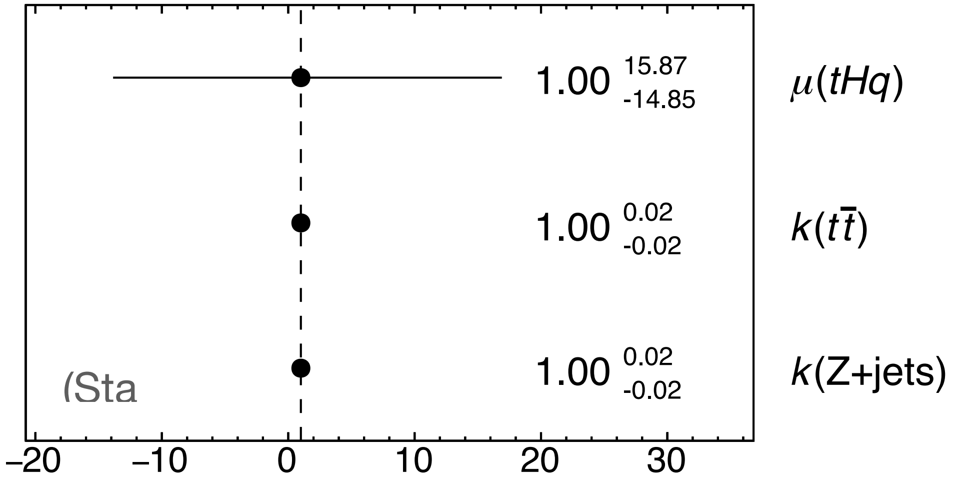
- If a NP has little impact on the fit, it can be ignored in the calculations
- Pruning: Removing the NPs that do not affect the fit
    - Shape: 1%
    - Normalisation: 0.5%
- Explored for each process and region

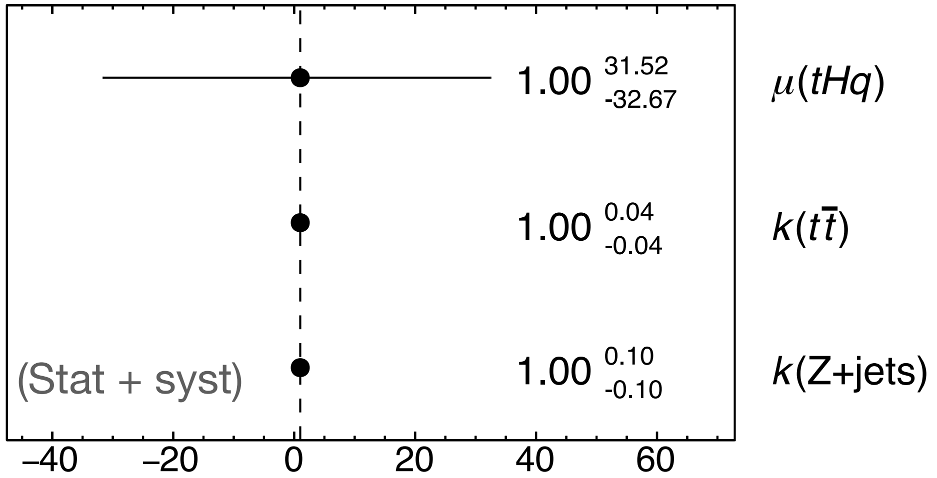


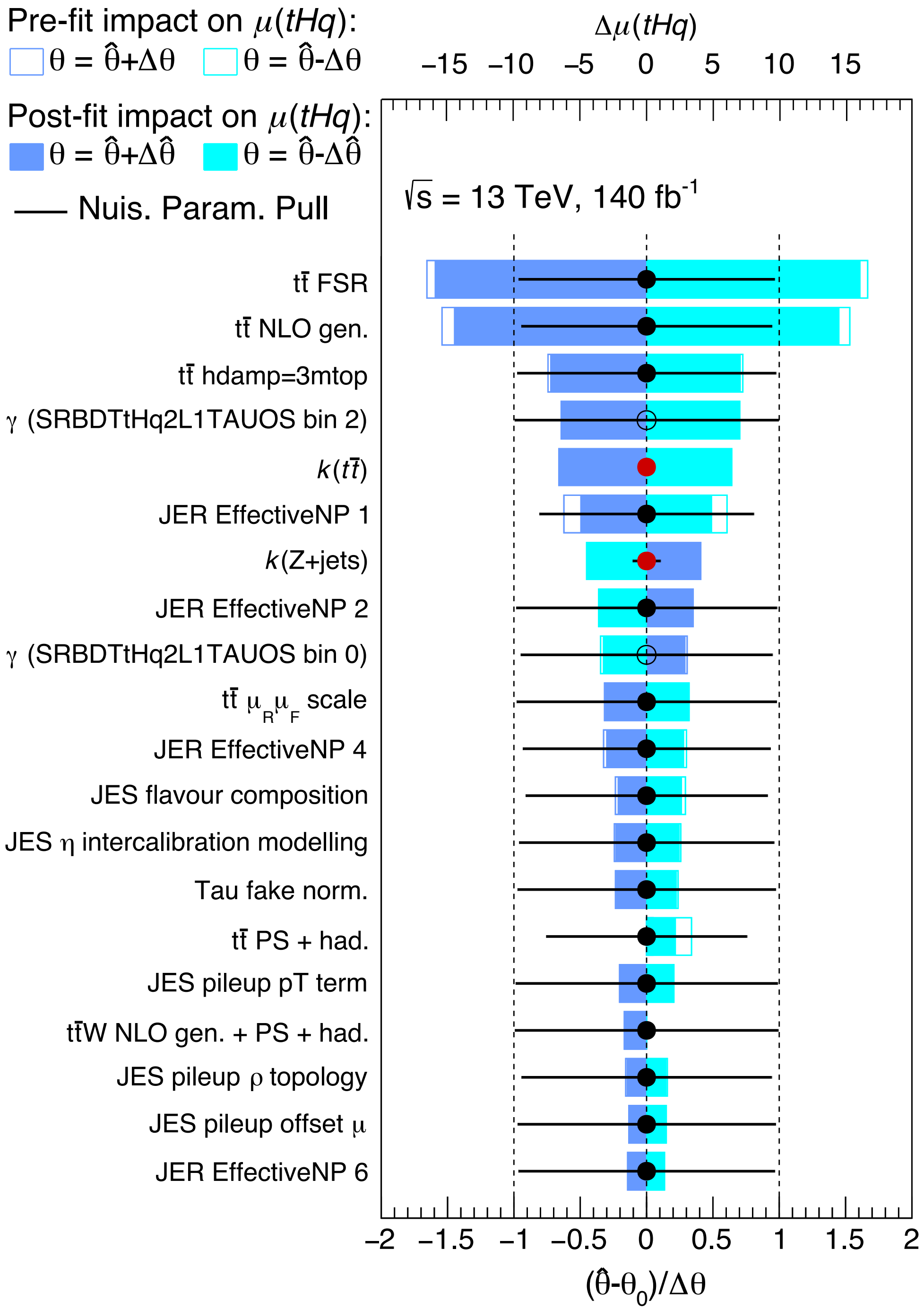


Asimov fit - $2\ell OS + \tau_{had}$

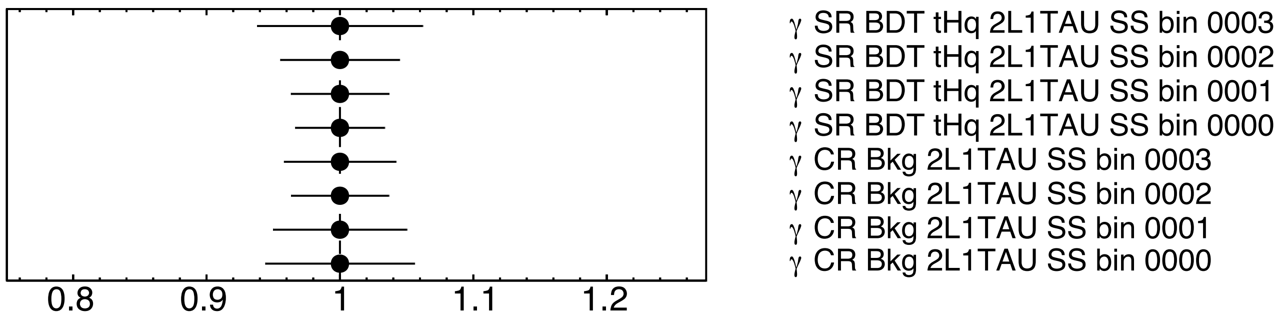


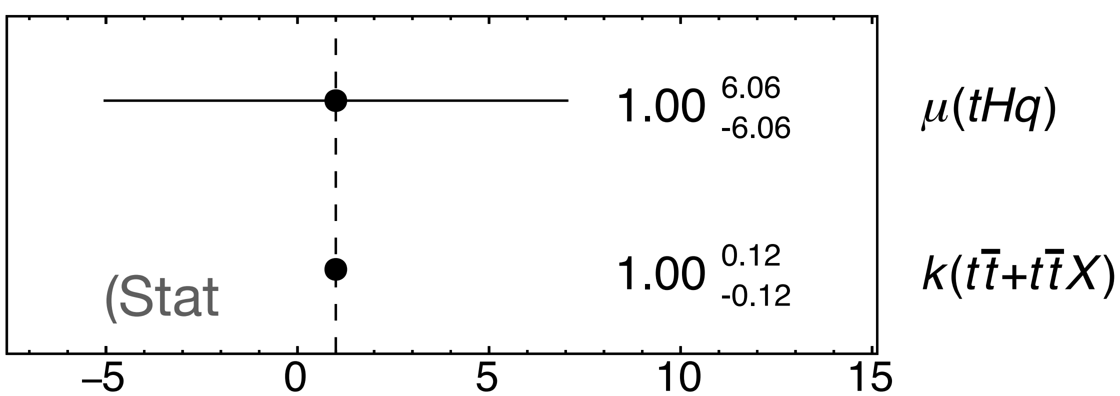


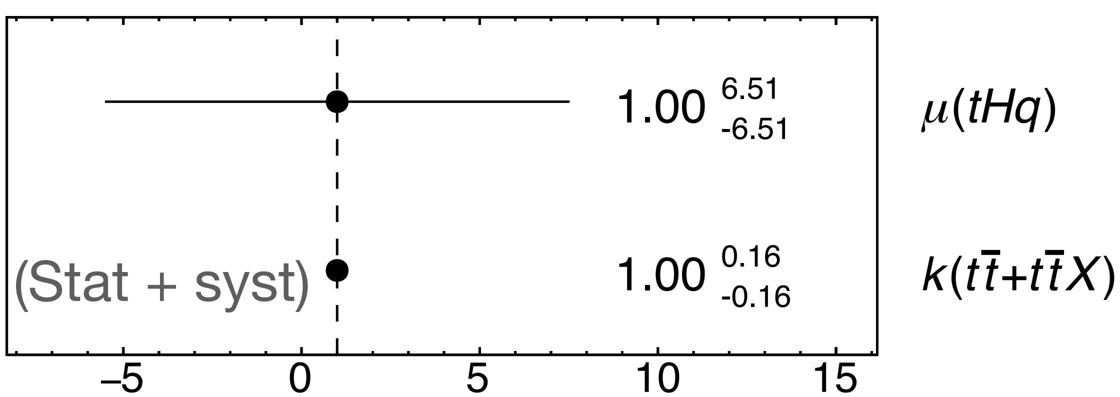


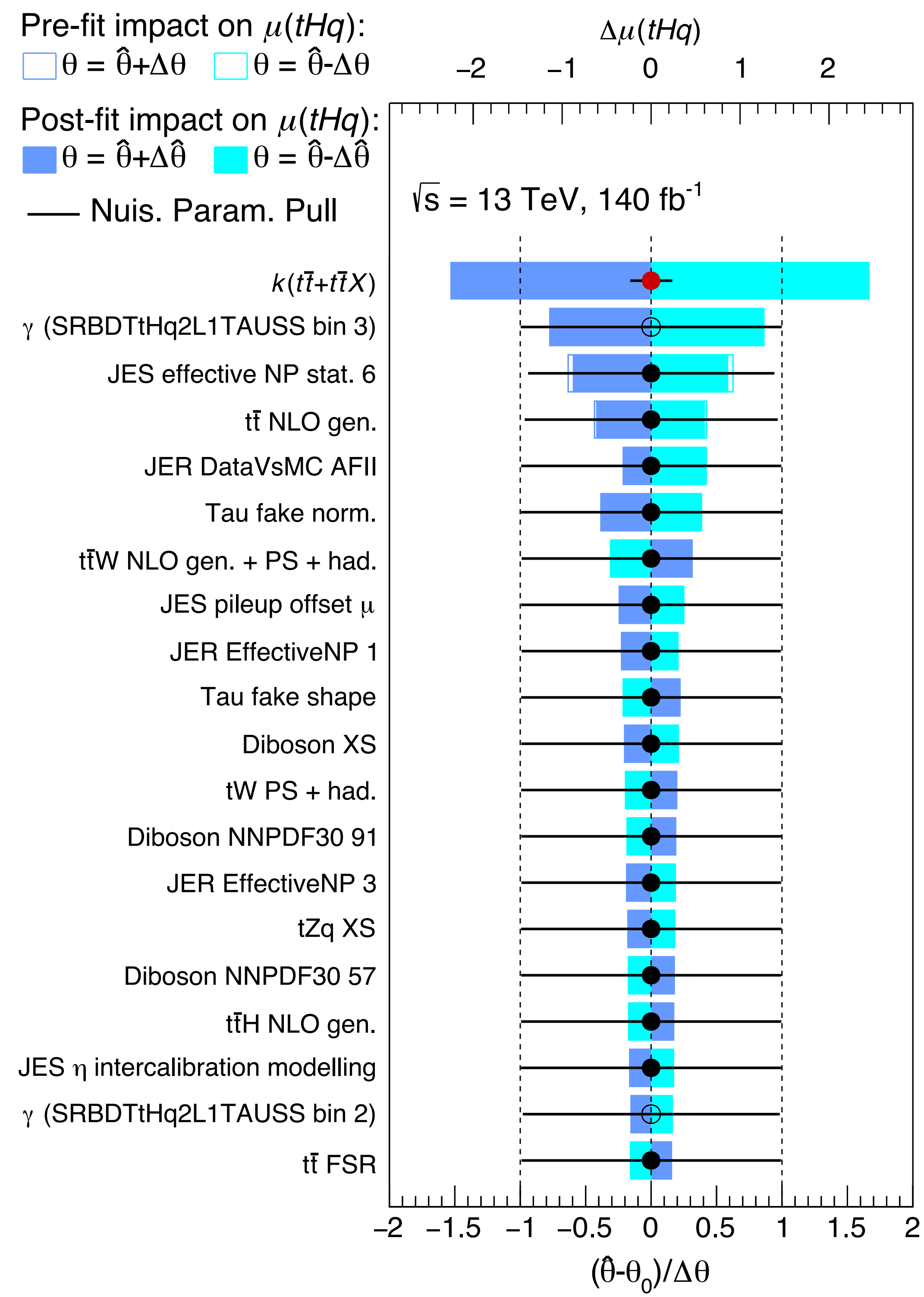


Asimov fit - $2\ell SS + \tau_{had}$

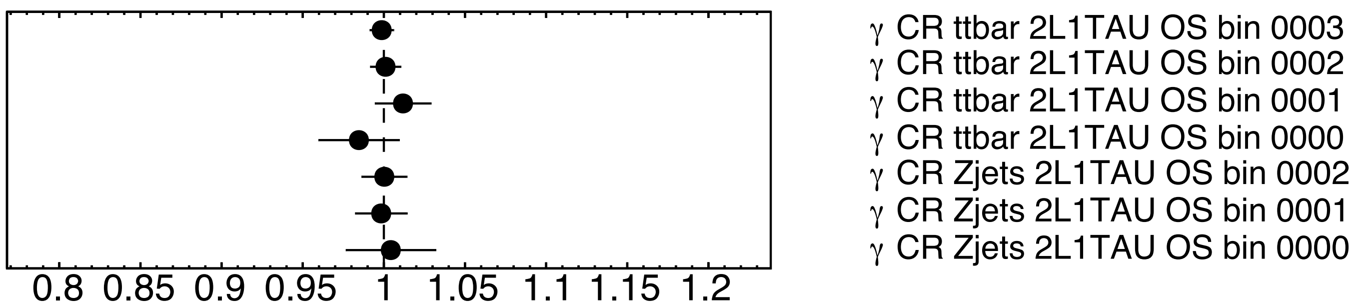


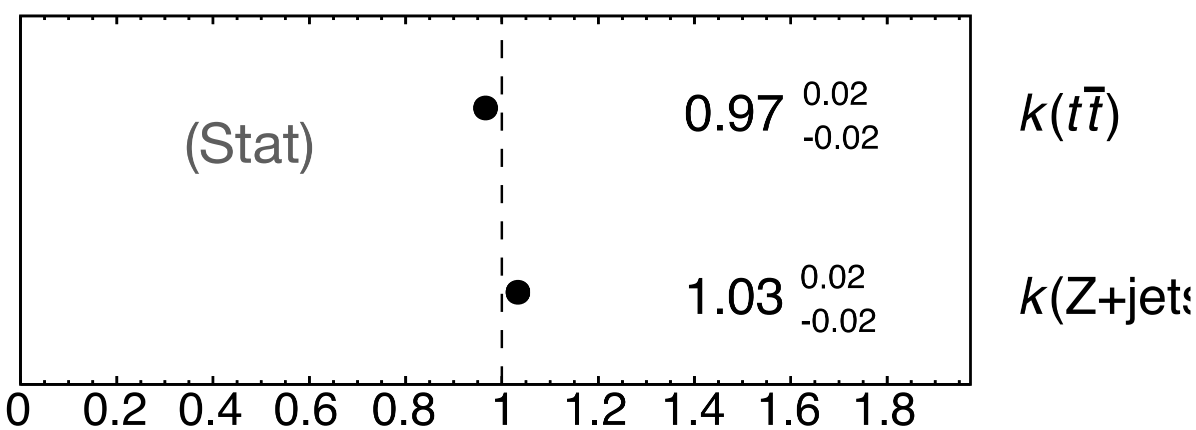


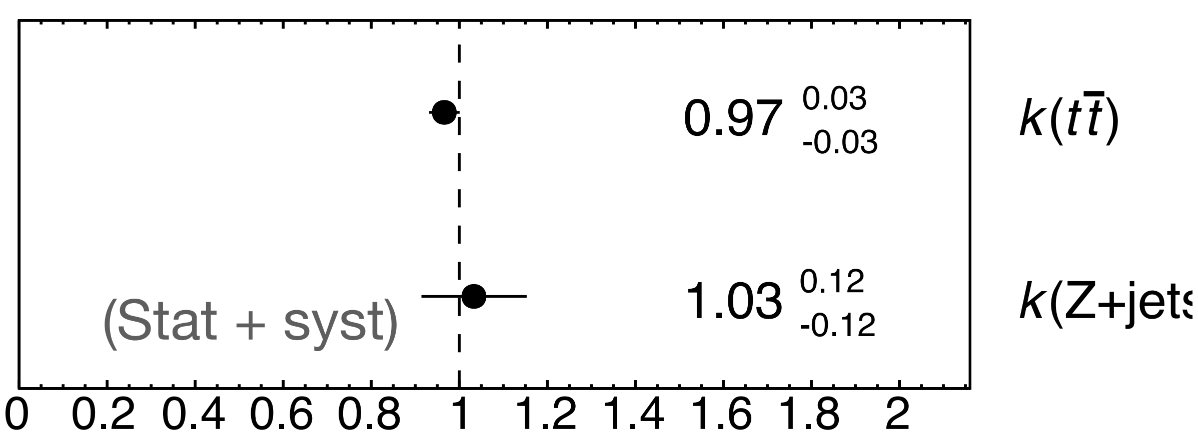


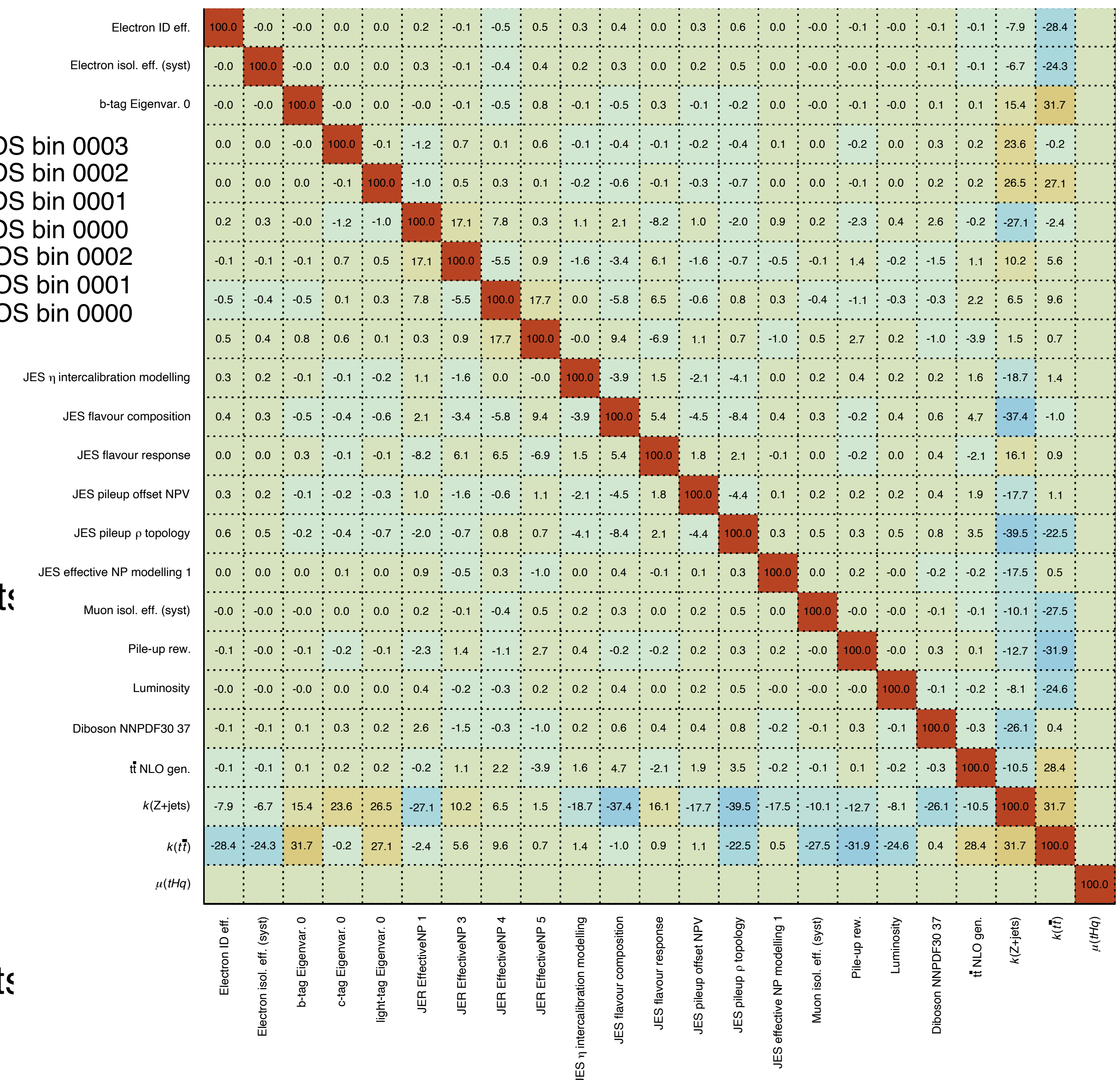


CR-only Bkg-only fit - $2\ell OS + \tau_{had}$

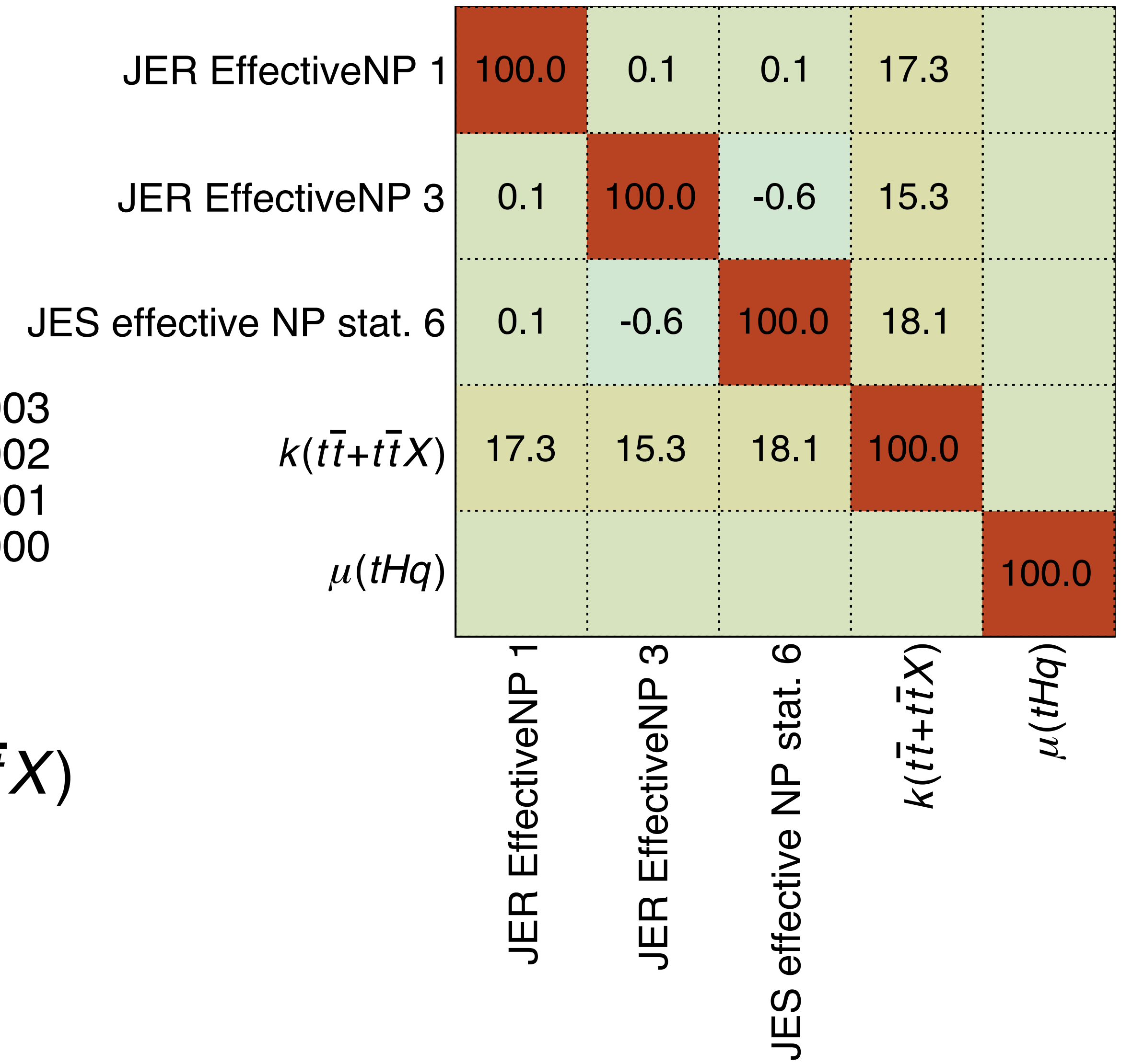


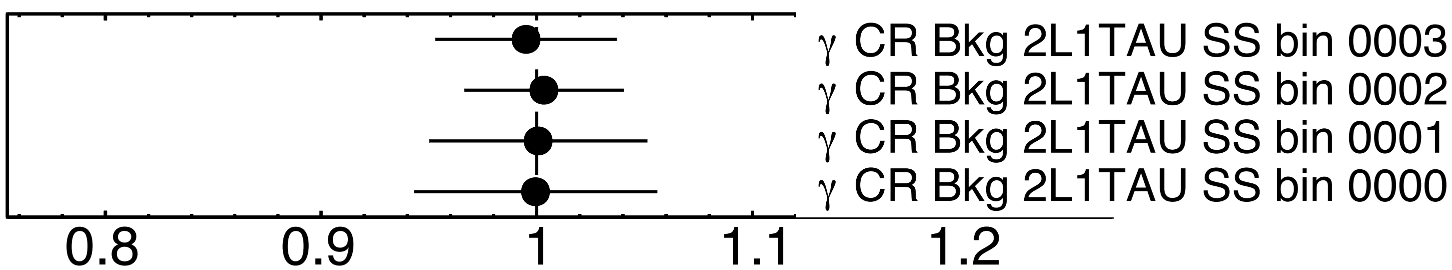


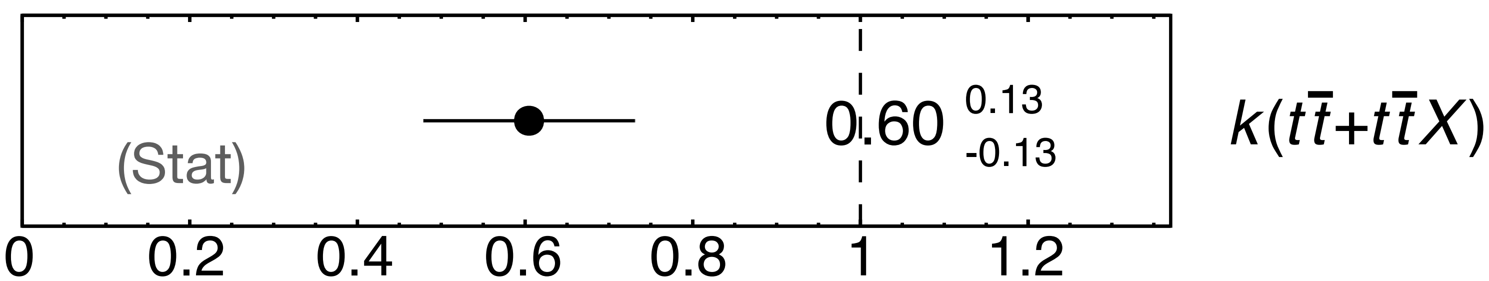


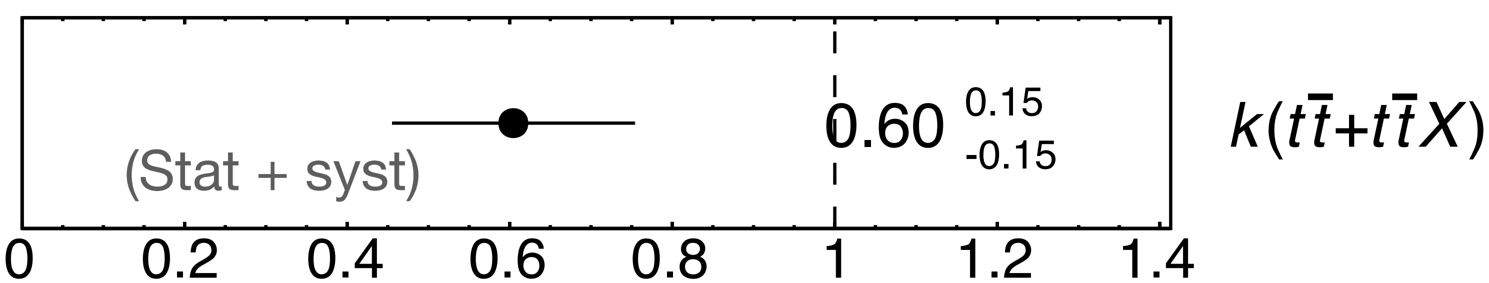


CR-only Bkg-only fit - $2\ell SS + \tau_{had}$

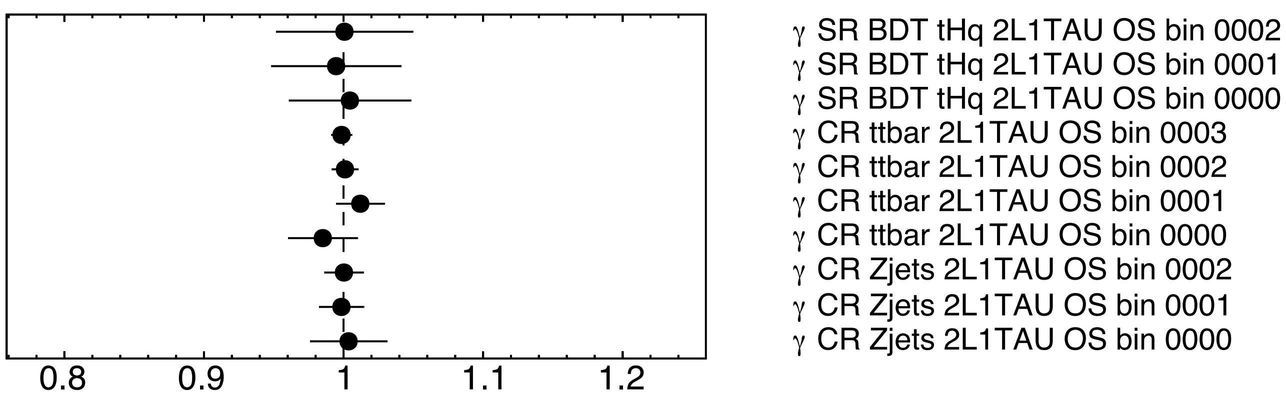


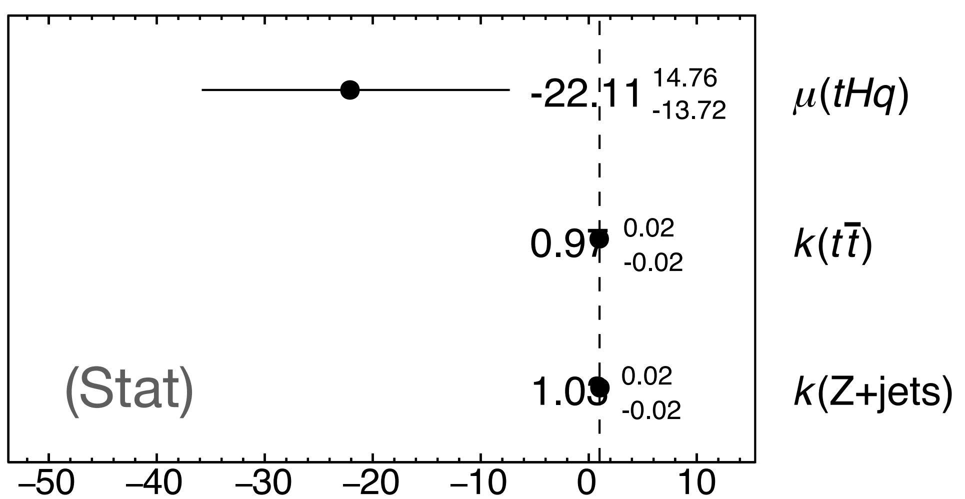


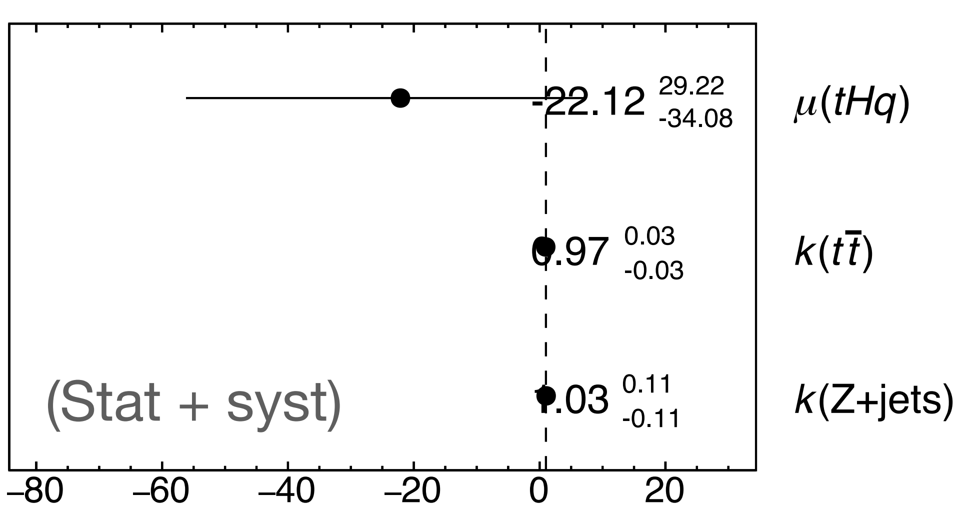


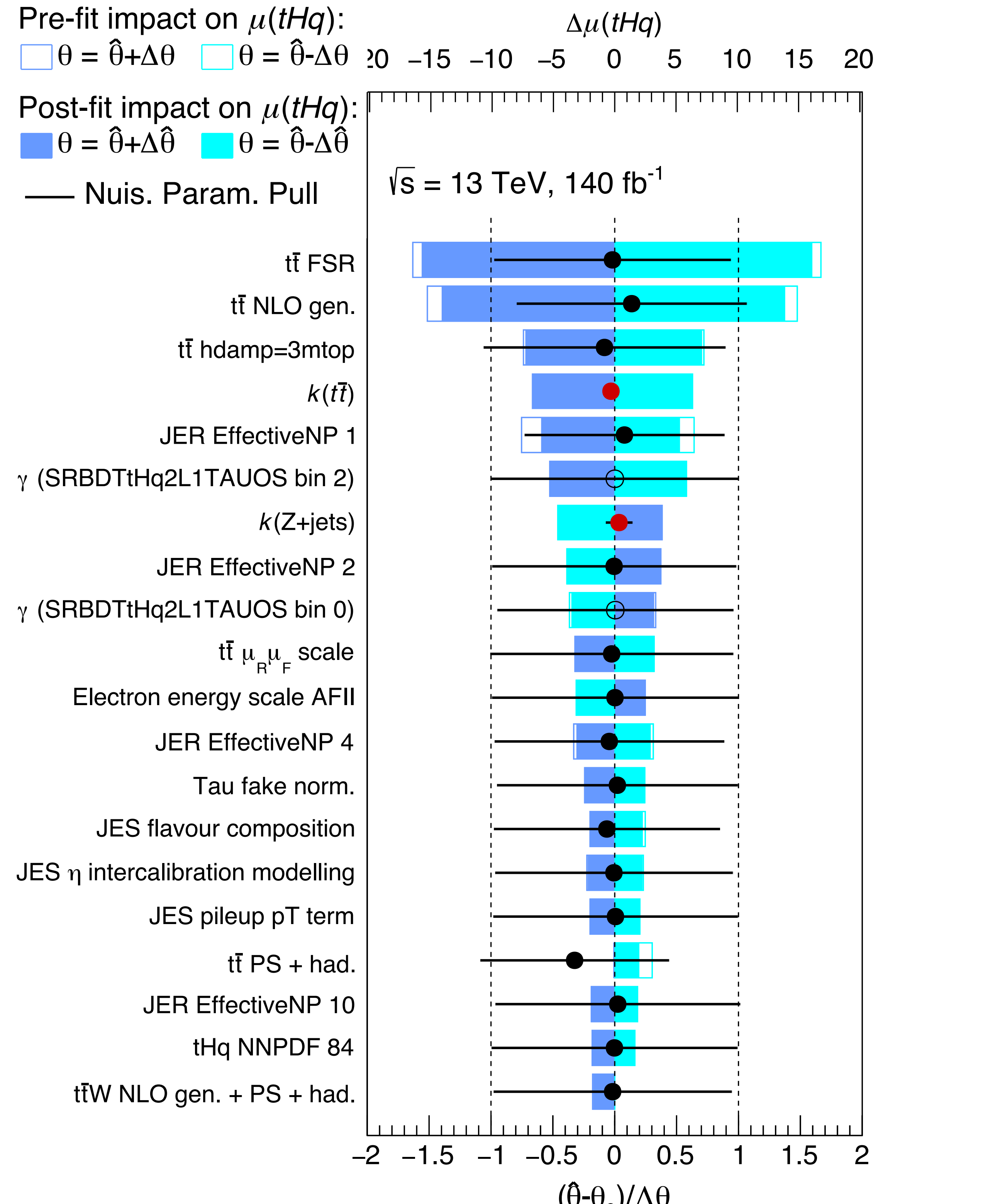


Full data fit - 2ℓOS + τ_{had}

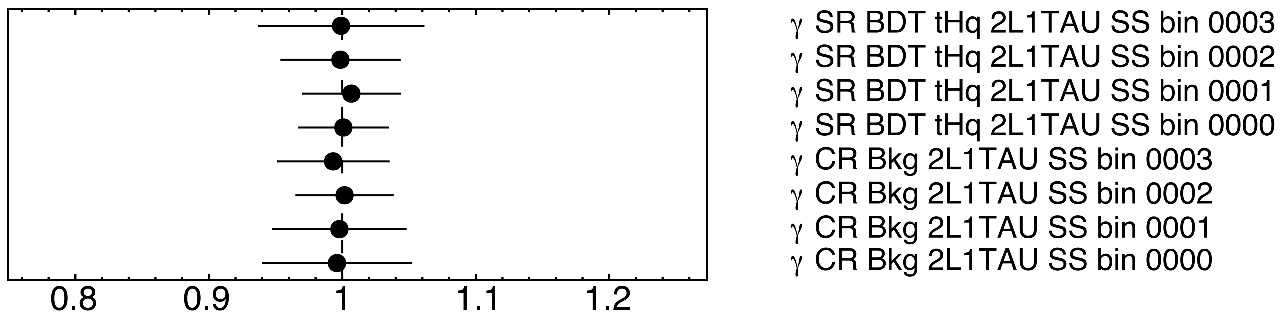


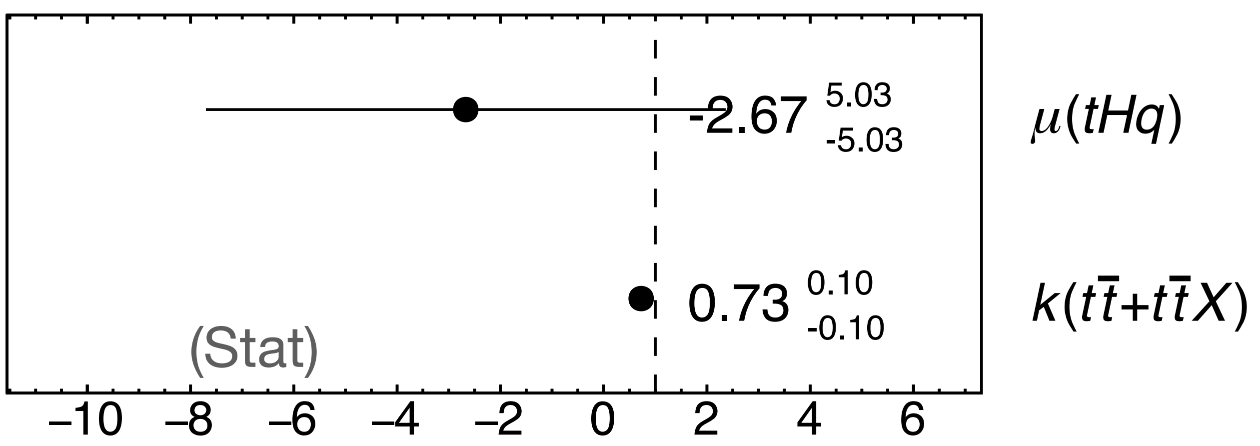


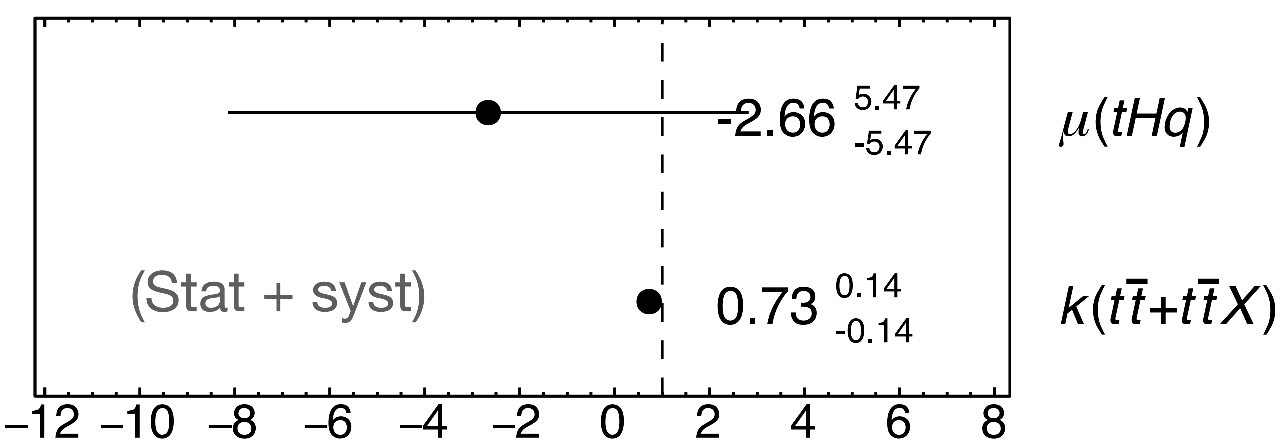


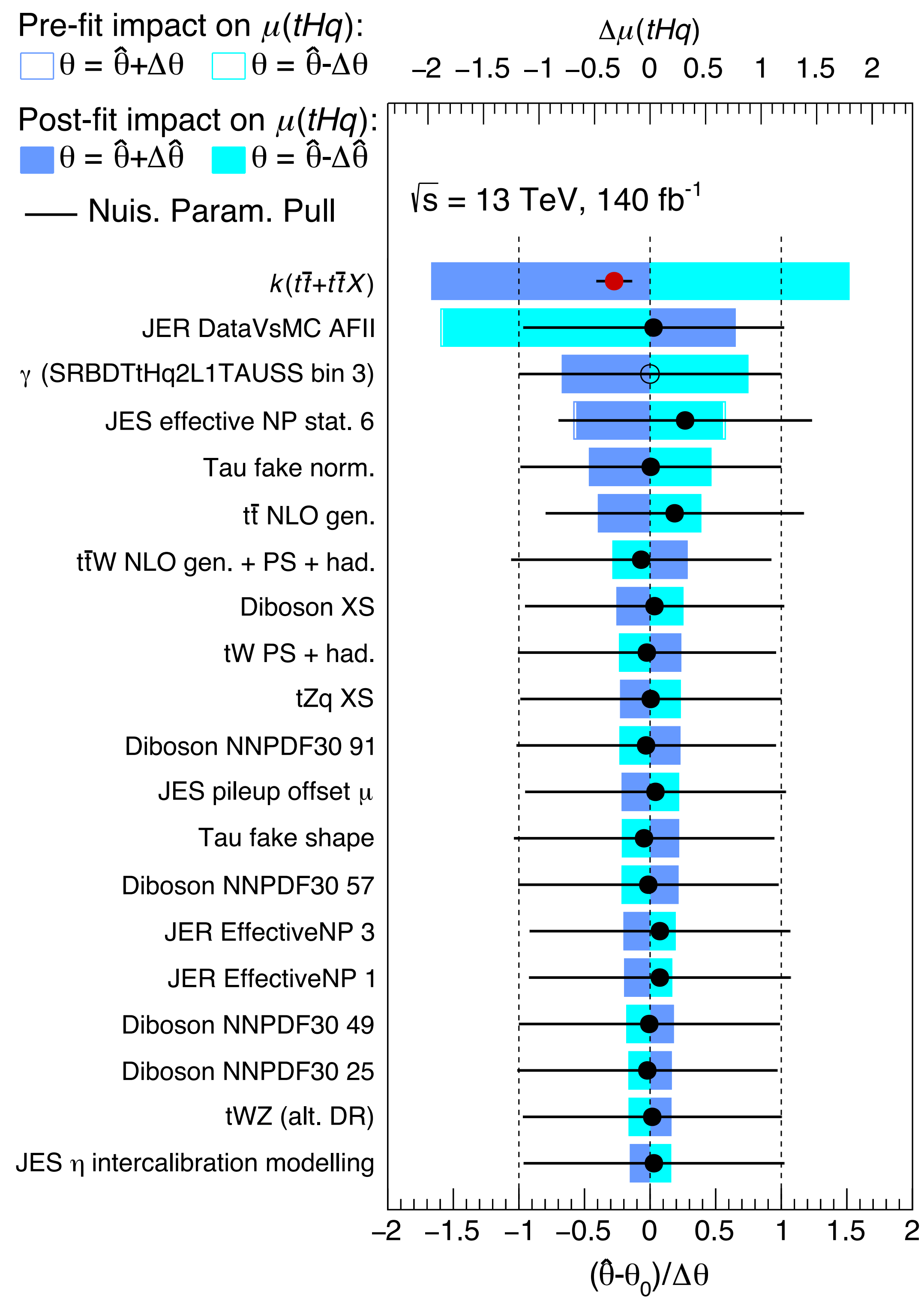


Full data fit - $2\ell SS + \tau_{had}$

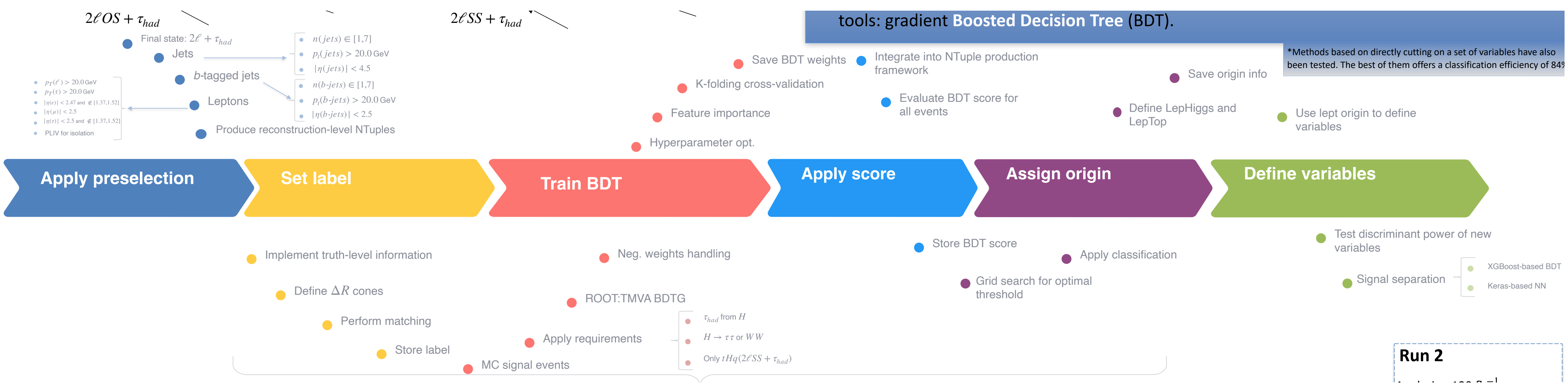








Search channels



This poster

Labelling the light leptons using truth information

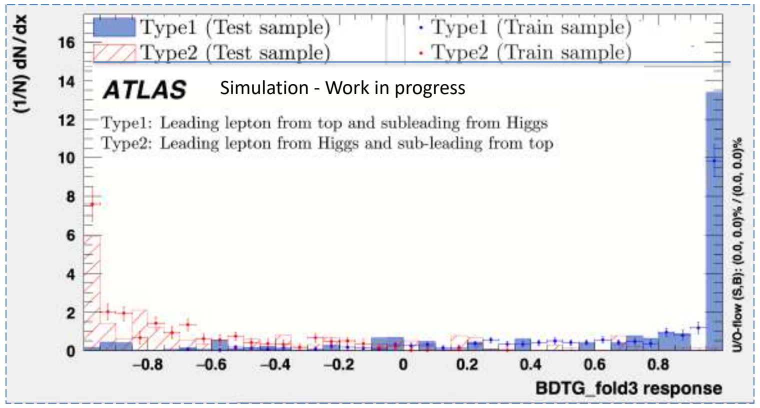
Before performing a supervised training it is necessary to **label the leptons** in the events. To do so, the **truth**-level and **reconstruction**-level information of the events is compared to determine a correspondence between the leading (ℓ_1^{reco}) and subleading (ℓ_2^{reco}) leptons and the lepton from Higgs boson ($\ell_{\text{Higgs}}^{\text{truth}}$), and the lepton from the top quark ($\ell_{\text{Top}}^{\text{truth}}$):

1. Access to parton-level information. At parton level the **origin** of the lepton is **obviously known**.
   - Requirements: τ_{had} from the Higgs decay and $H \to \tau\tau$ or $H \to WW$. The $H \to ZZ$ is neglected.
2. Define $\Delta R < 0.1$ cones around momentum of the the reconstructed lepton ($\vec{p}_{\ell_1}$).
3. Look for a parton level lepton ($\vec{p}_{\ell_{\text{reco}}}$) within each cone.
4. Perform matching:
   - Both cones are required to have one and only one lepton of each level.
5. Define type of events:
   - **Type1**: Leading lepton from the top quark and subleading from the Higgs boson (61.1%).
   - **Type2**: Leading lepton from the Higgs boson and subleading from top quark (38.9%).

Training, optimisation and evaluation of the BDT

After labelling the signal samples, a BDT can be trained to identify the origin of the light leptons:

1. Select events for training:
   i. Signal events only: The process to reconstruct is the $tHq(2\ell + \tau_{had})$.
   ii. $2\ell SS + \tau_{had}$
   iii. Demand τ_{had} from Higgs boson.
   iv. Requiere $H \to \tau\tau$ or WW.
2. Ignore negatively weighted events.
3. Rank features: Optimised by ROOT.TMVA.
4. Optimise hyperparameters: Grid serach.
5. Use k-folding for cross-validation (k=5)
   i. Avoids overtraining
   ii. Mitigates the effects of low statistics.
   iii. Results in 5 different BDTs



6. Implement and evaluate the BDT: Implemented in the NTuple software framework where the BDT score is calculated for each event.
7. Once the BDT score is saved, the optimal threshold for classification is found through a scan. Best point around 0.0

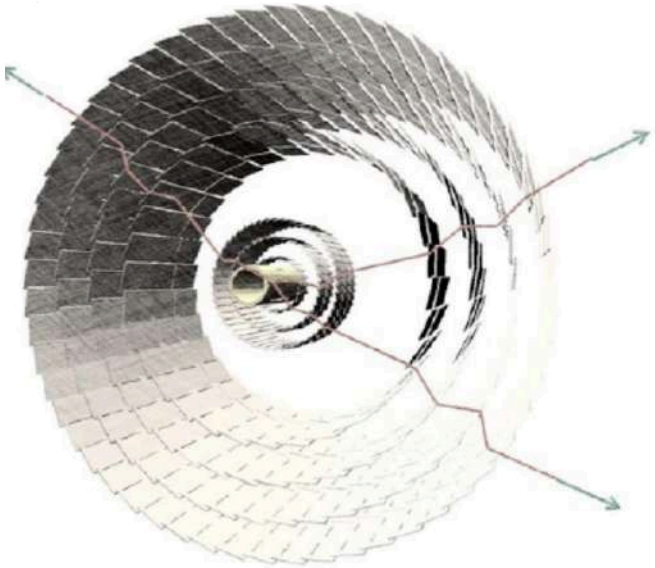
$$\text{Efficiency} = \frac{\text{Events properly assigned}}{\text{Total events}} \geq 95\,\%$$

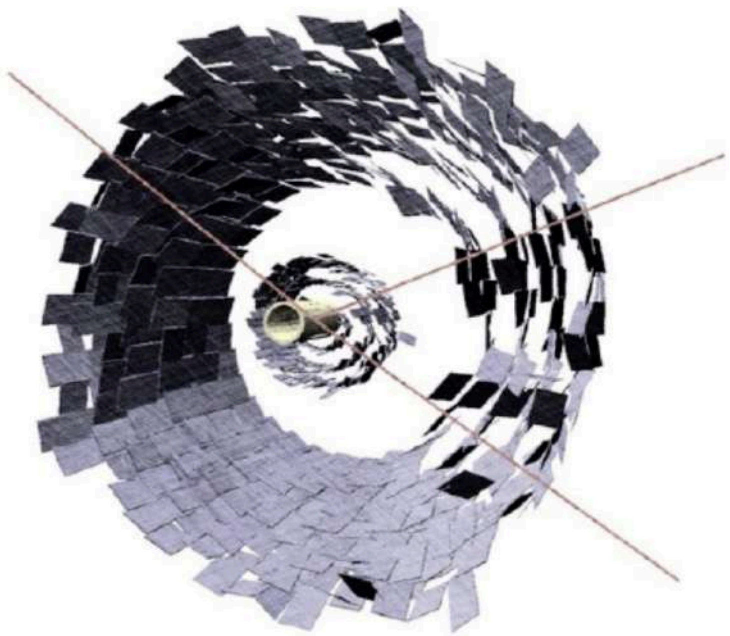
Performance of the ATLAS detector

- What is the **maximum** allowed **degradation**?

	Pixel		SCT	
	barrel	Endacp	barrel	Endacp
rΦ(μm)	7	7	12	12
z(μm)	20	100	50	200

Maximum allowed random misalignment of the silicon modules to keep degradation below the 20% of the resolution.





Inner Detector alignment

$$\chi^2 = \sum_e \sum_t \boldsymbol{r}^T \Omega^{-1} \boldsymbol{r},$$

- Ω s the covariance matrix of the corresponding measurements
- Must find the tracking parameters (α) that minimise χ^2

$$\frac{d\chi^2}{d\boldsymbol{\alpha}} = \sum_e \sum_t \left[\left(\frac{d\boldsymbol{r}}{d\boldsymbol{\alpha}} \right)^T \Omega^{-1} \boldsymbol{r} \right]^T + \sum_e \sum_t \left[(\boldsymbol{r}^T \Omega^{-1} \left(\frac{d\boldsymbol{r}}{d\boldsymbol{\alpha}} \right) \right] = 0$$

$$\left[\sum_e \sum_t \left(\frac{d\boldsymbol{r}}{d\boldsymbol{\alpha}_0} \right)^T \Omega^{-1} \left(\frac{d\boldsymbol{r}}{d\boldsymbol{\alpha}_0} \right) \right] \delta\boldsymbol{\alpha} + \sum_e \sum_t \left(\frac{d\boldsymbol{r}}{d\boldsymbol{\alpha}_0} \right)^T \Omega^{-1} \boldsymbol{r}(\boldsymbol{\tau}_0, \boldsymbol{\alpha}_0) = 0$$

Alignment corrections

Inner Detector alignment

- The ATLAS alignment proceeds from large structures to module level with increasing granularity of structures and number of degrees of freedom

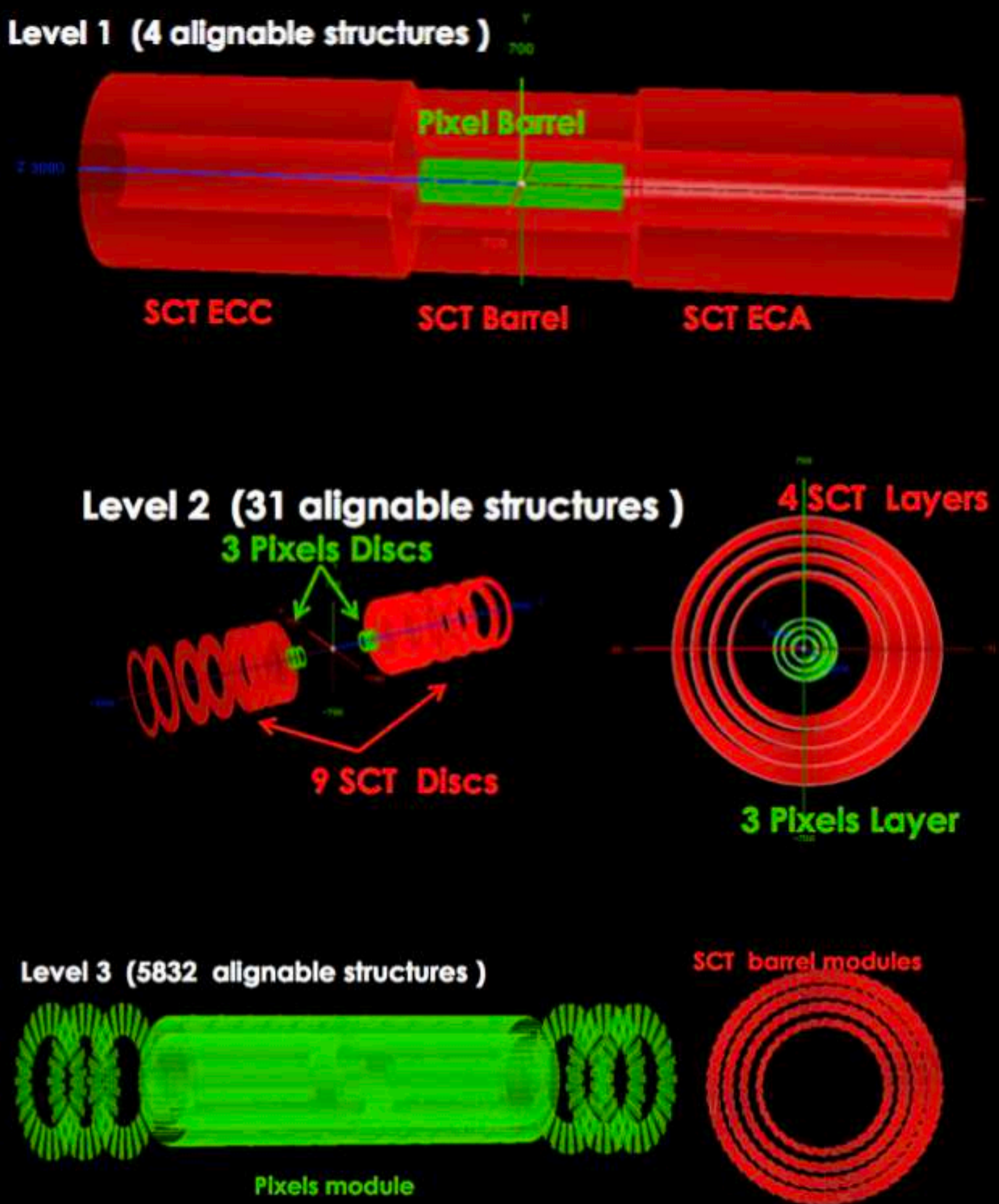
eels	structures			Corr. Size
	pixel	SCT	TRT	µm
Level 1	1+1	3	3	1000
Level 2	10	22	96	100
Level 3	2024	4088	350848	10

	structures			DoFs
	IBL	Pixels	SCT	#
Level 1	1	1	3	30+1
Level 2	1	9	22	192
Level 3	280	1744	4088	36672

	TRT		DoFs
	Barrel	End-cap	#
Level 1	1	2	18
Level 2	96	80	1056
straw	105088	245760	701696

- Real data tracks used for the alignment
- Iteratively produced at different stages
  - Prompt calibration feedback <24h (structure movements)
  - Off-line alignment: from large structures to individual modules
  - Commissioning with cosmic rays
- Six DoFs for detector location and orientations. +Extra DoFs for deformations

Inner Detector alignment



O(1) mm

Level 1: 4 structures (24 DoFs)
PIX: Whole detector
SCT: Barrel + 2 ECs

Several intermediate levels here!

Level 2: 31 structures (186 DoFs)
PIX: 3 barrel layers + 2x3 EC disks
SCT: 4 barrel layers + 2*9 EC disks

Several intermediate levels here!

Level 3: 5832 structures (34992 DoFs)
PIX: 1456 barrel mods + 2x144 EC mods
SCT: 2112 mods + 2x988 EC mods

Expected corrections

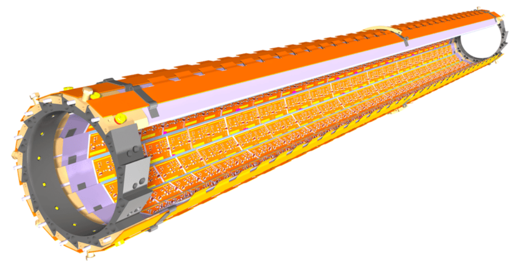
O(10) μm

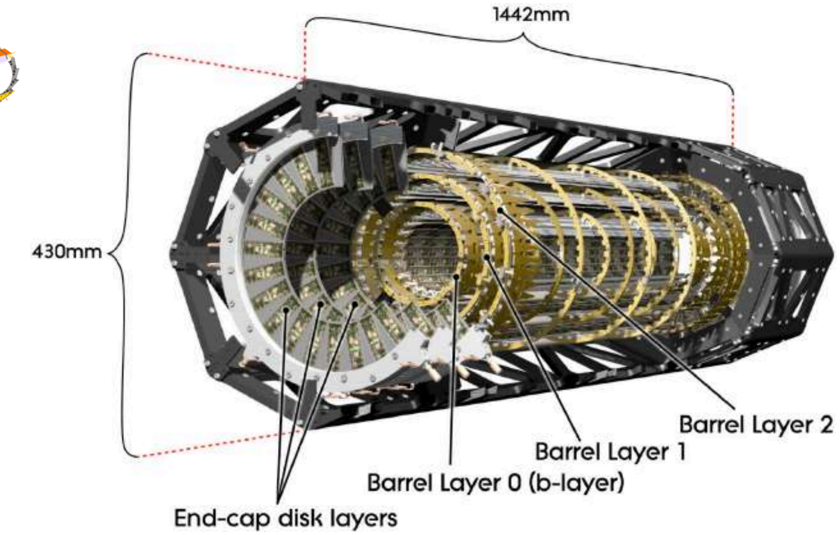
ID Alignment Monitoring Web

- The ID Alignment Monitoring Web Display is an application intended for monitoring the track-based alignment results obtained at the calibration loop for the ID. It helps to evaluate the computed alignment corrections as well as many graphical distributions directly related to the performance.
- The web application is structured with a server overseen by the ATLAS Distributed Computing. It incorporates a suite of backend scripts designed for generating distributions, refreshing the data, and managing HTTP requests from the users. The frontend allows to the user to interact with the application by requesting alignment-related information. This tool is integrated within Athena, the established software framework for ATLAS.
- Developed both: front-end and back-end

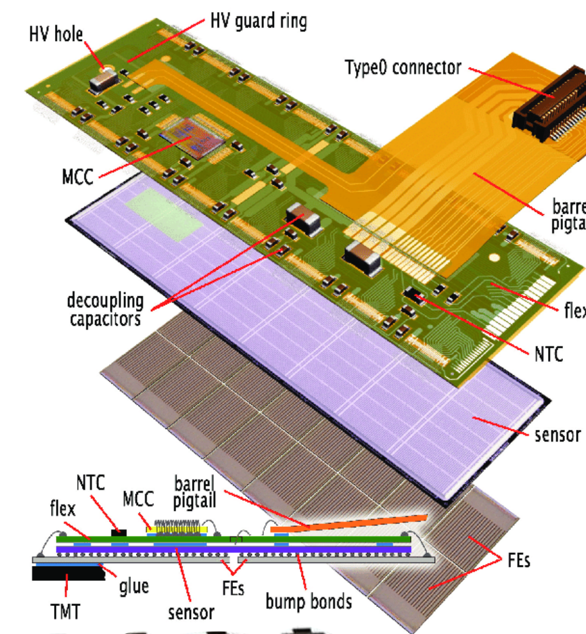
The ATLAS detector - ID

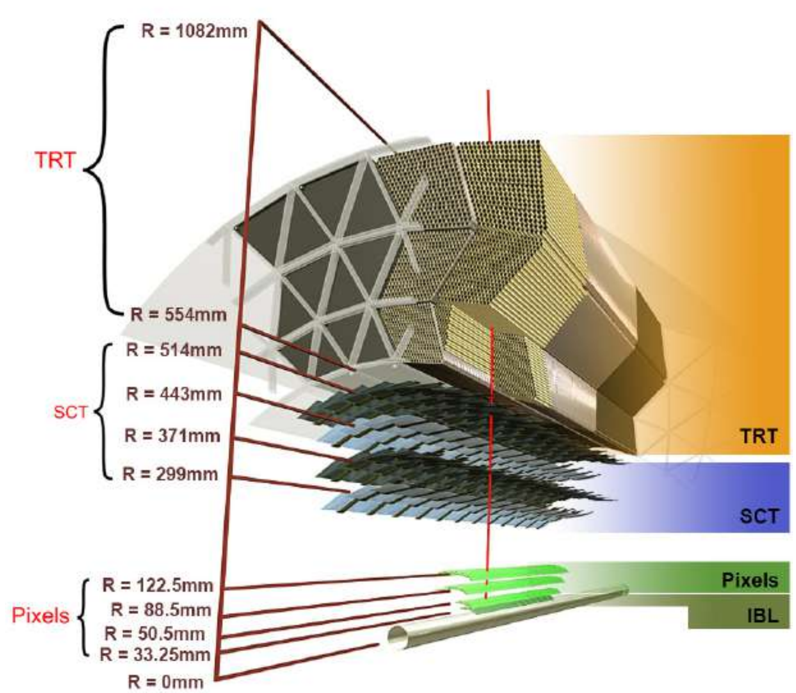
Inner Detector (ID): Reconstructs the tracks of the charged particles. Closest detector to the collision point. Characterised by its resolution

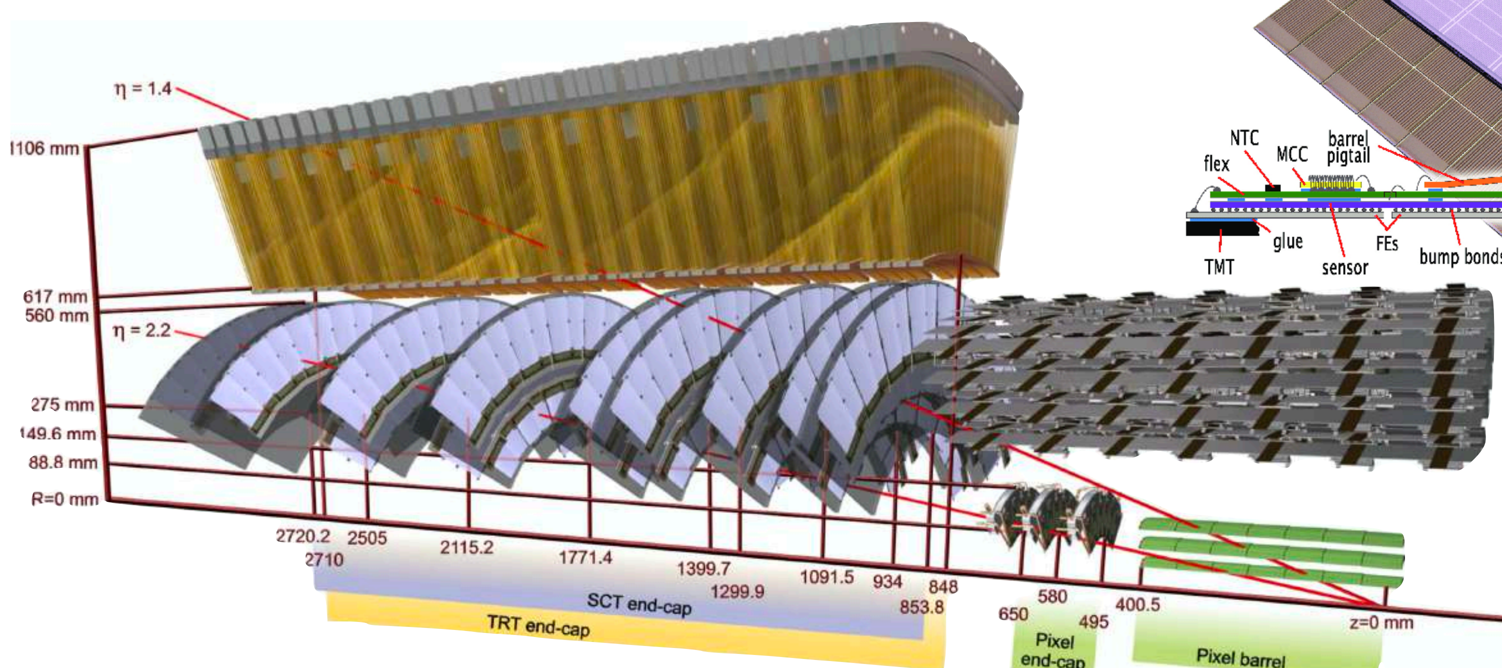




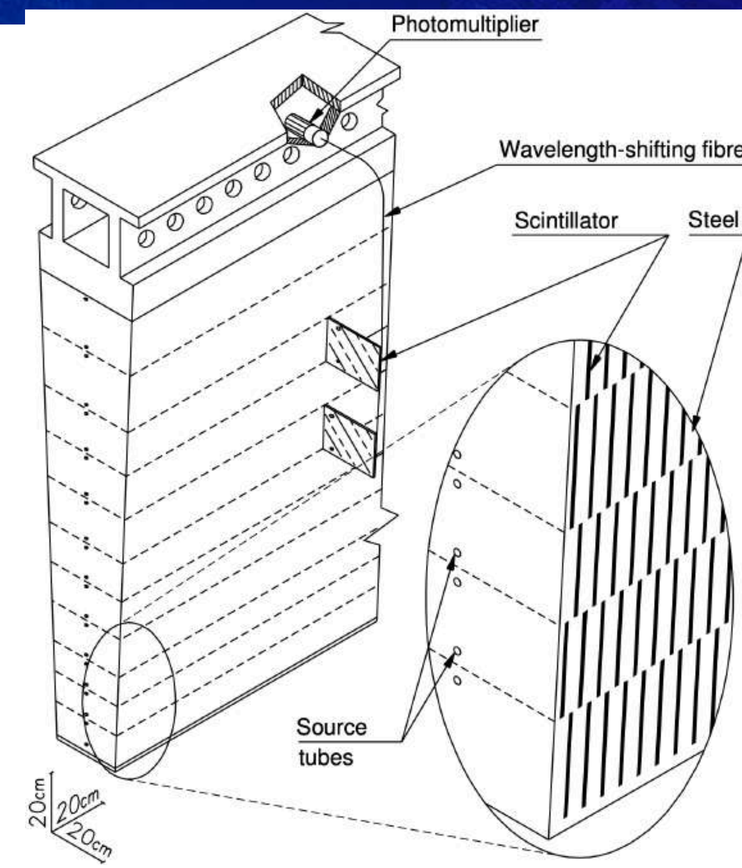
Subdetector	Element size (µm)	Intrinsic resolution (µm)
IBL	50×250	8×40
Pixel	50×400	10×115
SCT	80	17×580
TRT	4000	130





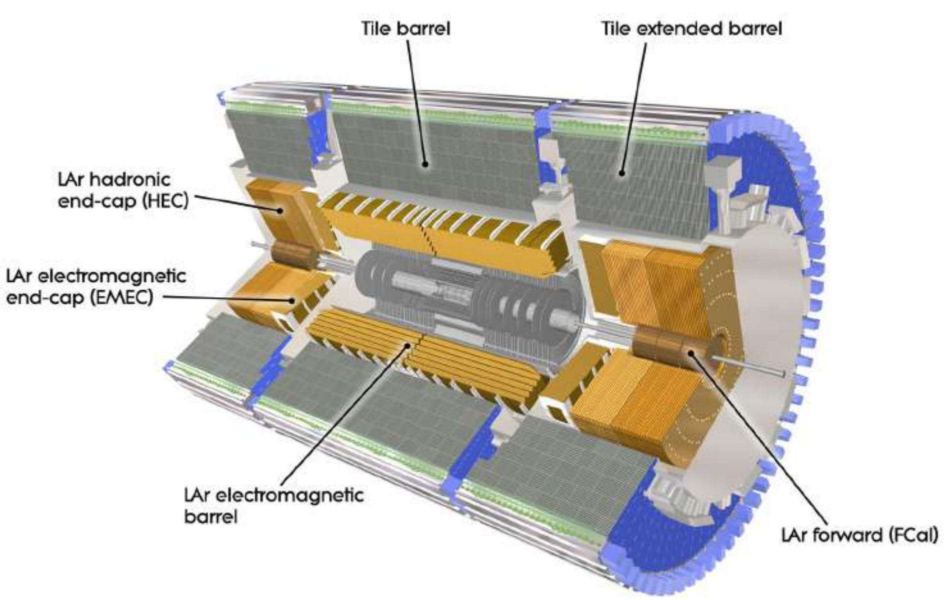


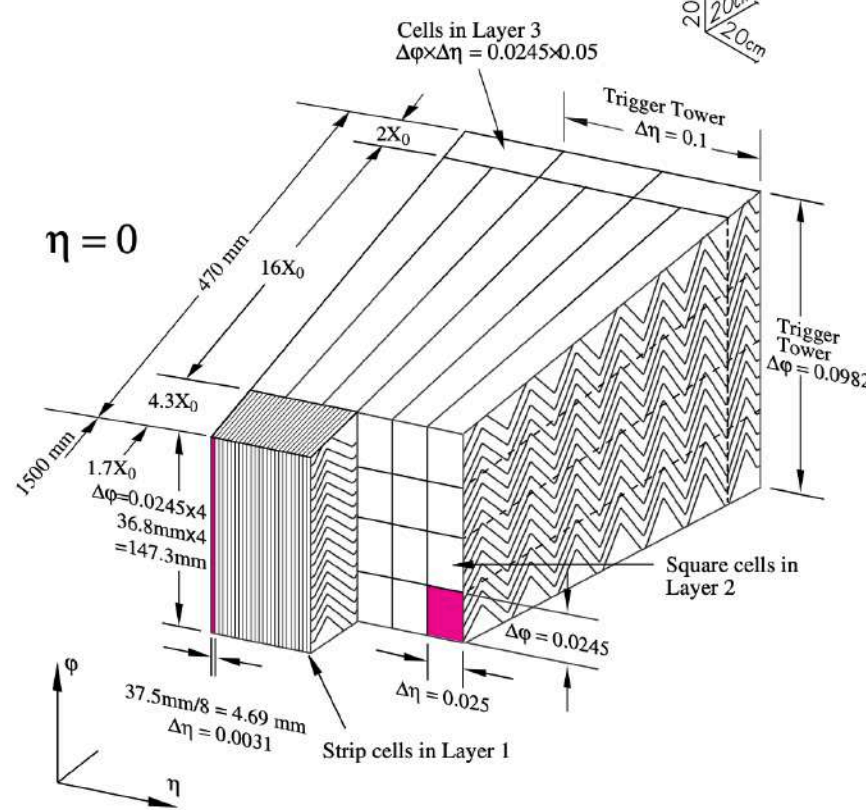
The ATLAS detector - Calorimeters



Calorimeters: Measures the energy of particles.

- ECAL:
    - Detects: Electrons and photons.
    - Made of liquid Argon $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{170\ \text{MeV}}{E} \oplus 0.7\%$
- HCAL:
    - Detects: Hardons $\frac{\sigma_E}{E} = \frac{5.9\%}{\sqrt{E}} \oplus 5.7\%$
    - Made of steel/scintillator layers

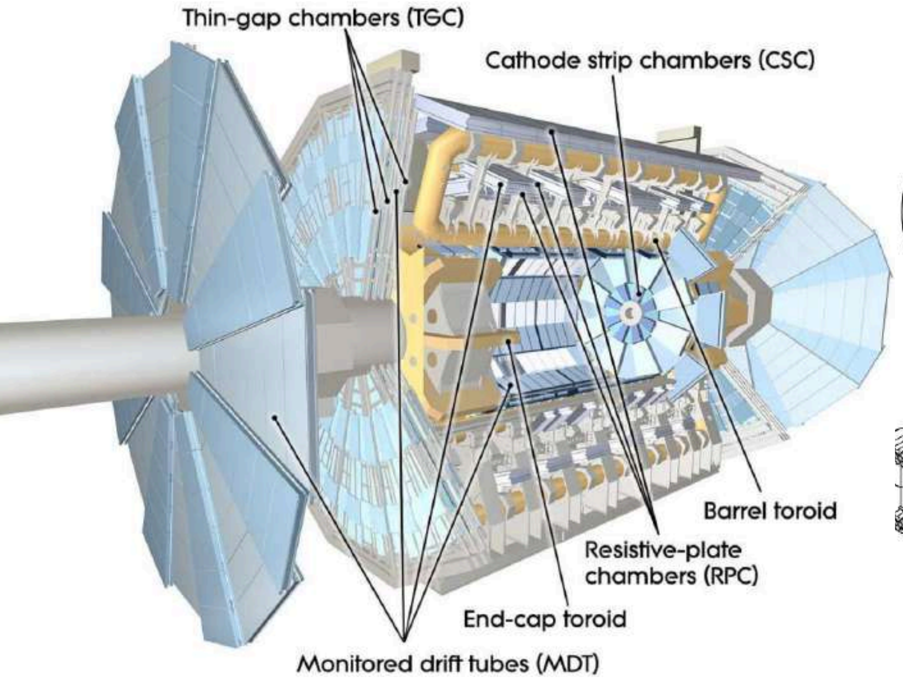


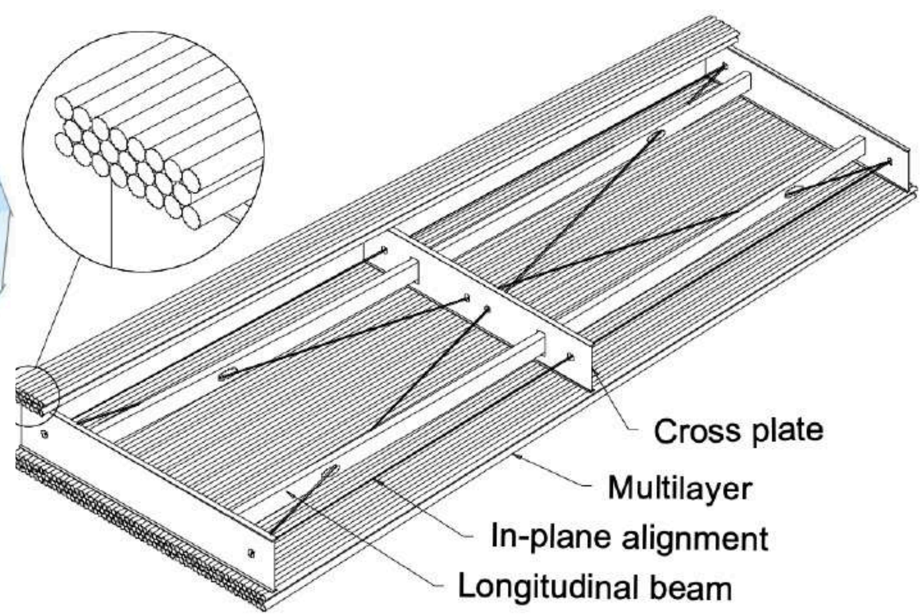


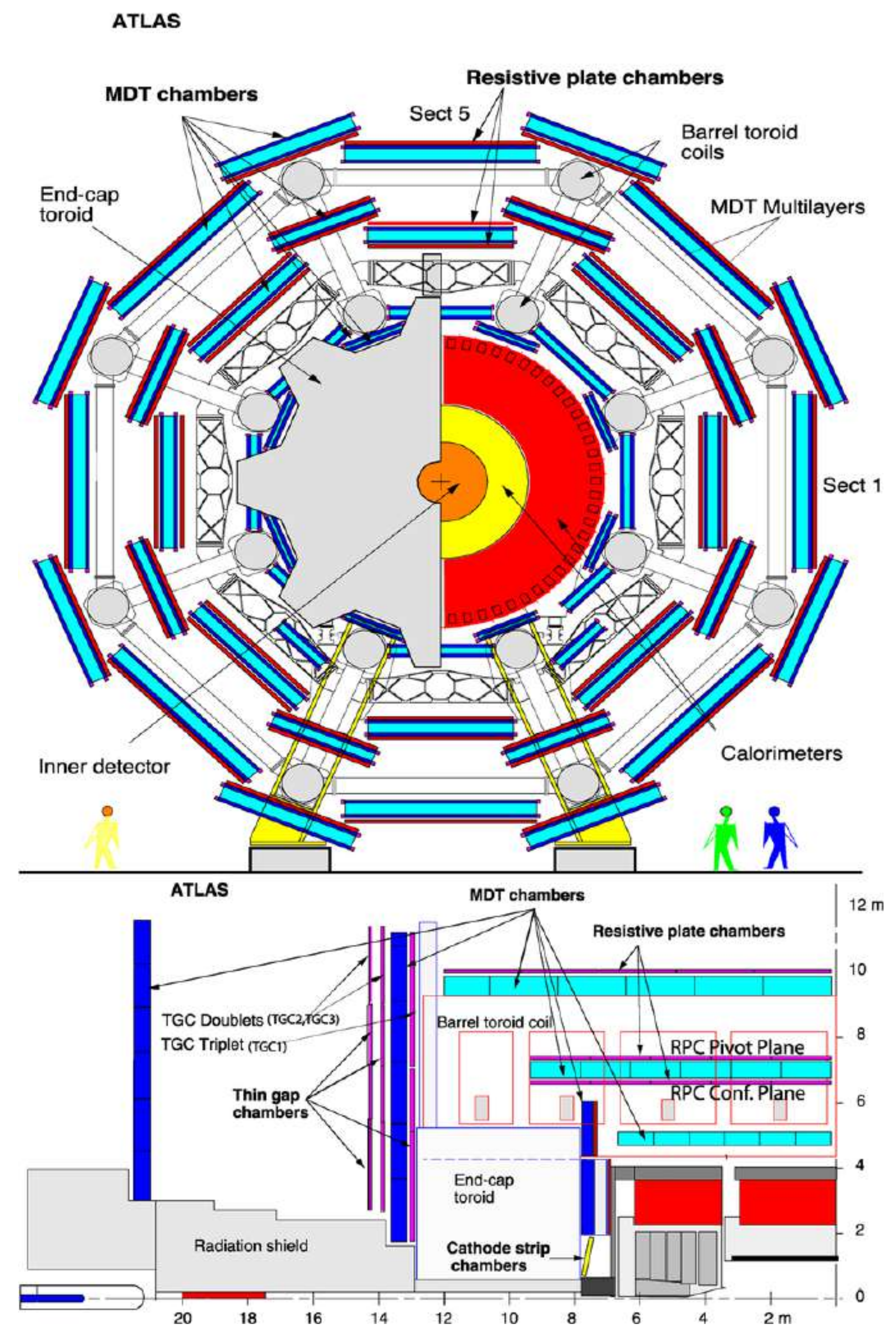
The ATLAS detector - Muon

Muon Spectrometer: Outermost layer. Detects muon. Uses the toroidal magnets to bend the path of muons. Subdetectors:

Type	Purpose	Location	Coverage
MDT	Tracking	Barrel + end-cap	$0.0 < \|\eta\| < 2.0$
CSC	Tracking	End-cap layer 1	$2.0 < \|\eta\| < 2.7$
RPC	Trigger	Barrel	$0.0 < \|\eta\| < 1.0$
TGC	Trigger	End-cap	$1.0 < \|\eta\| < 2.4$



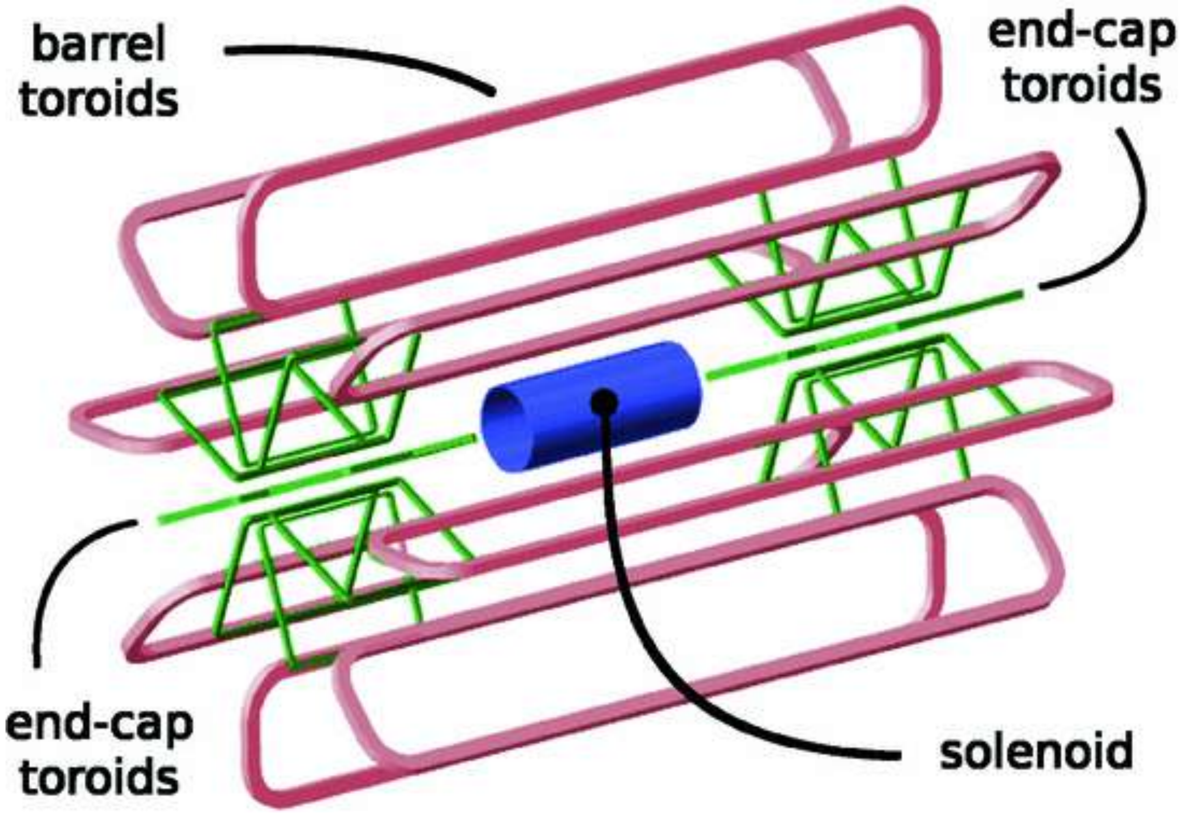


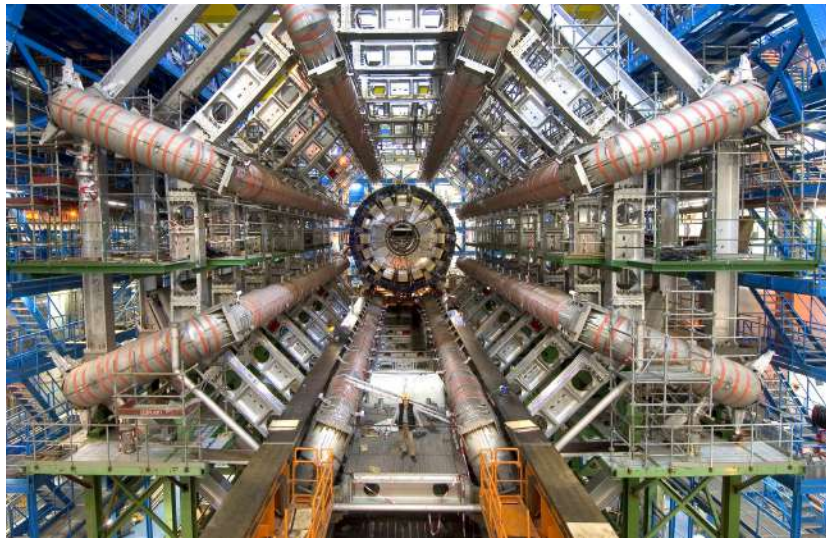


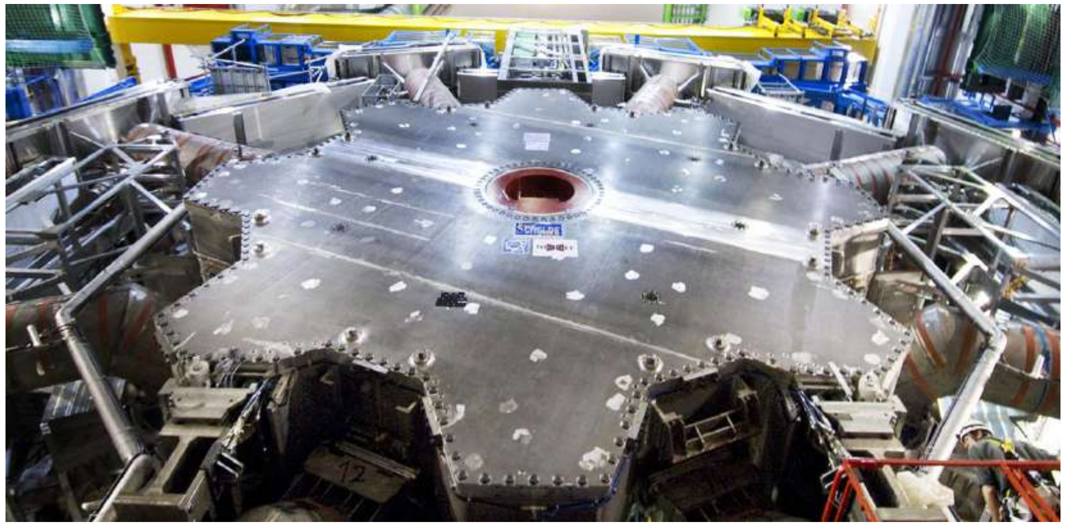
The ATLAS detector - Magnet

Magnet system: Bends the particles, allowing us to measure its momentum.

- Central solenoid: Outside the ID. Field parallel to beam axis that curves particles that move through the ID.
- Toroidal magnet: Specially designed for the muon spectrometer
  - End-cap toroids
  - Barrel toroids





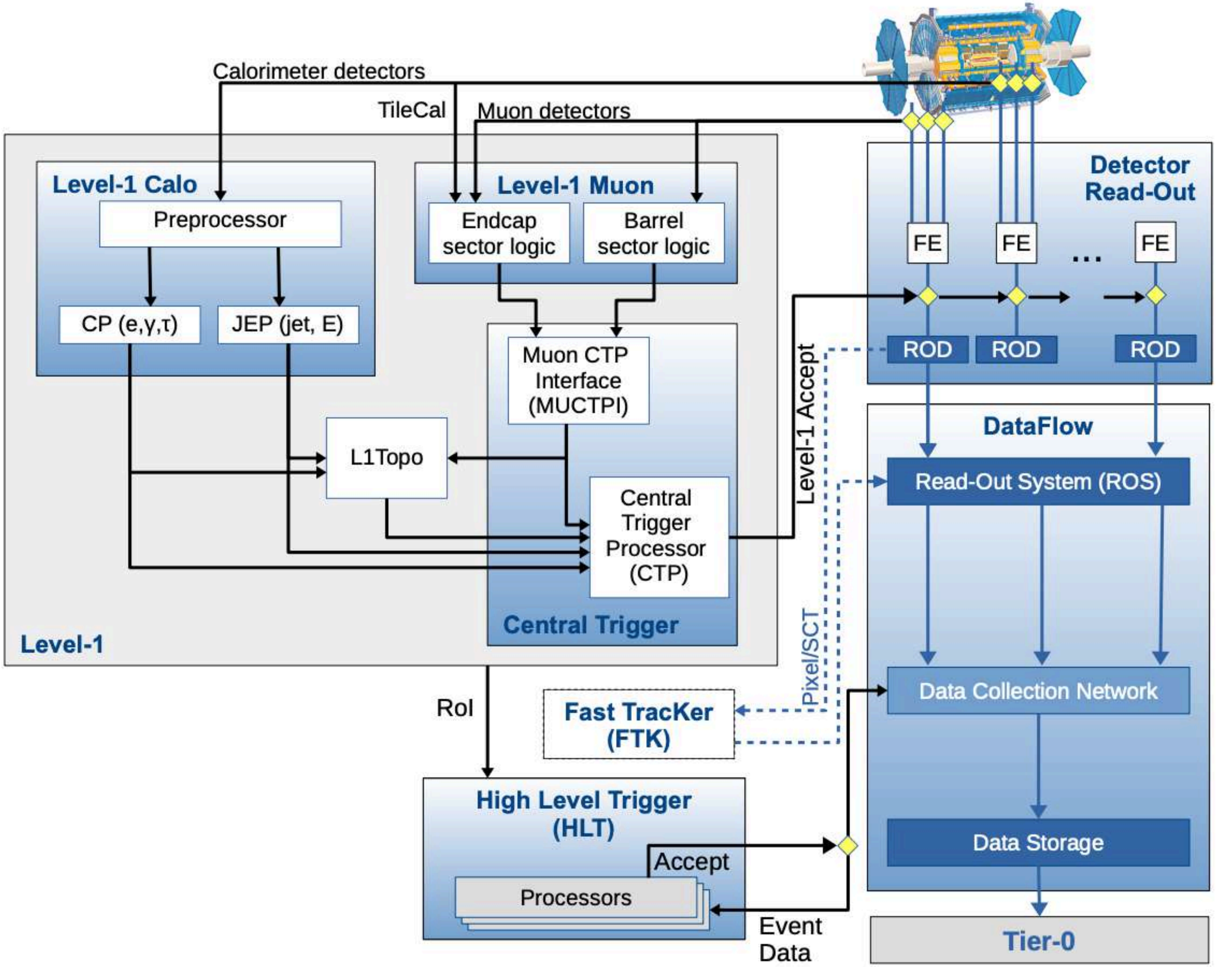


The ATLAS trigger system

- 2 level trigger to record data at an average of 1 kHz from physics collisions starting from a bunch crossing rate of 40 MHz
    - L1: hardware-based system that uses custom electronics to trigger on reduced granularity information from the calorimeter and muon detectors. From 40 MHz to 100 kHz
    - HLT: Software baed. Athena. From 100 kHz to 1 kHz
- For Run 2, 1500 individual event selections were included in a trigger menu
    - Specific physic signatures
    - Different selection algorithms for data taking
- a
- Trigger and DAQ: TDAQ <— Responsible for online processing, selecting and storing events of interest for offline analysis

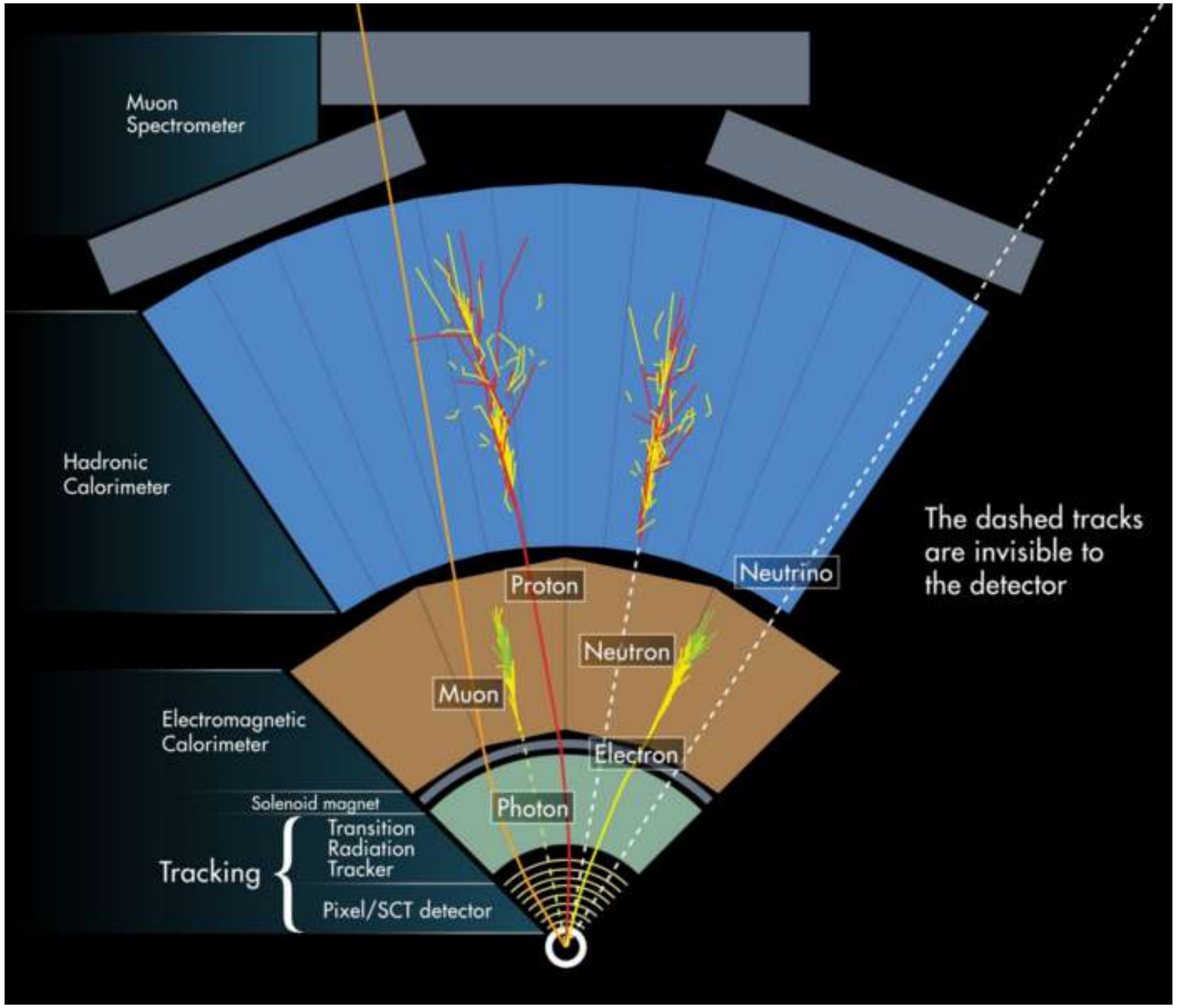
The ATLAS trigger system

- TDAQ in Run 2
- L1
- HLT



Particle reconstruction with ATLAS

Different types of particles leave different types of signal in the detectors



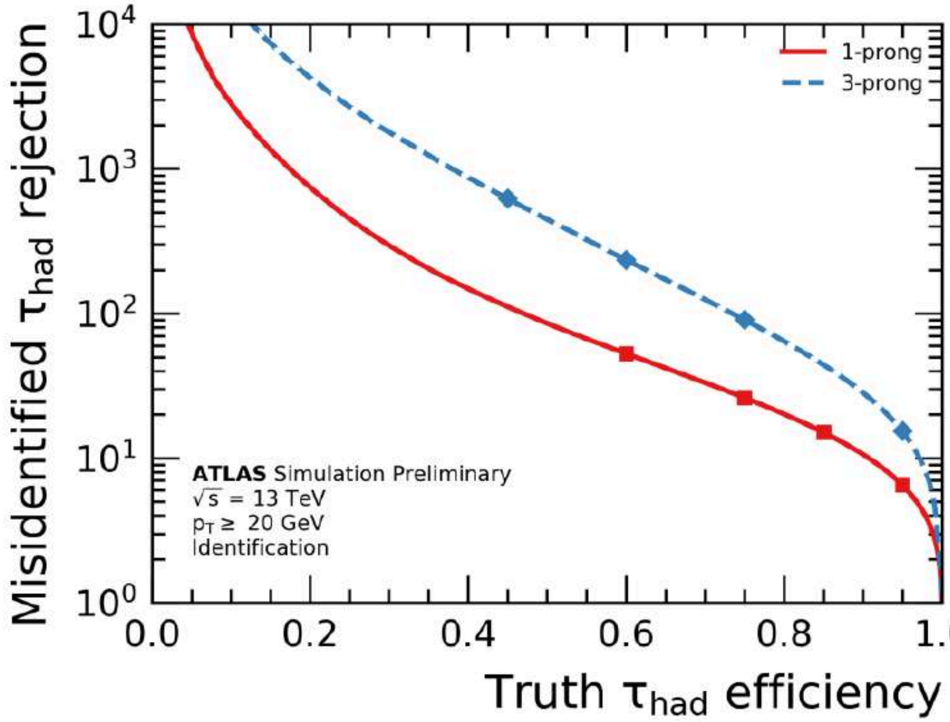
- Electrons: ID tracks + ECAL deposit
- Photon: ECAL only
- Muons: MS+ID
- Jets: HCal with anti-k_t. ID
- MET: Momentum imbalance
- τ_{had}: Characteristic narrow jets consisting in one or three tracks. ID+HCAL. Reconstructed using MVA algorithms
- b-quarks: Long lifetime = displaced from PV. ID for secondary vertices.

Hadronic tau identification

- Based on MVA methods
- The τ_{had} candidates are seeded using the anti-k_t algorithm
    - anti-k_t is a jet clustering algorithm that operates by iteratively clustering particles into jets based on their relative distances in the momentum space. In τ_{had} reconstruction, the parameters that sets the size of the jet (R) is set to R=0.4
- TopoClusters used as input for the jet algorithm. A topocluster is a 3D cluster of calorimeter cells
- As τ leptons travel away from the PV before decaying, a dedicated τ vertex association algorithm (TJVA) is employed
- Tracks are associated with the τ_{had} in they are $\Delta R < 0.25$ around it and satisfy some hit criteria in the ID
- The number and charge of the decay products of a τ are classified using a RNN (Run3) or BDT (Run2): Tau tracks, Conversion tracks, Isolation tracks and Fake tracks

Hadronic tau reconstruction

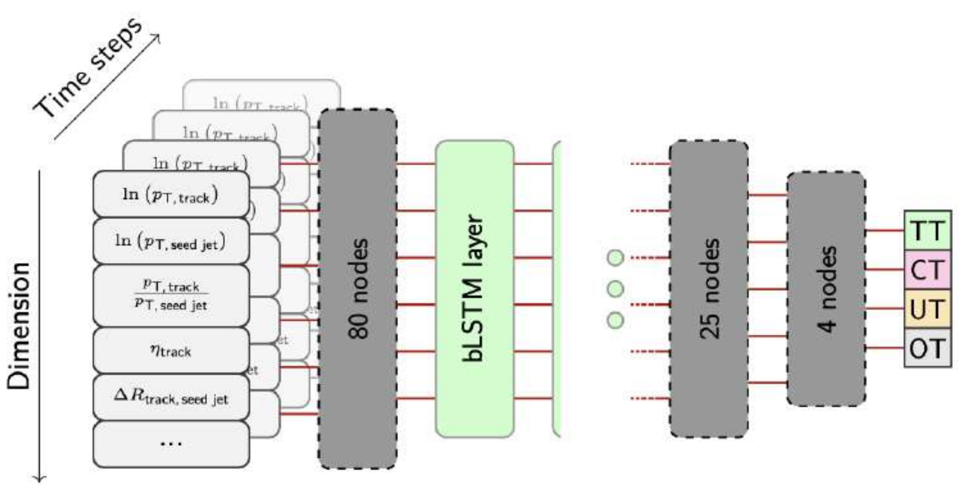
- Keras+TensorFlow RNN used to separate real from misidentified τ_{had}. The RNN is trained comparing the truth and reach level simulations of $\gamma \rightarrow \tau\tau$
- The performance of the RNN for τ_{had} is evaluated using $\gamma \rightarrow \tau\tau$ as signal and diet as background.



- Three WP defined (Figure)

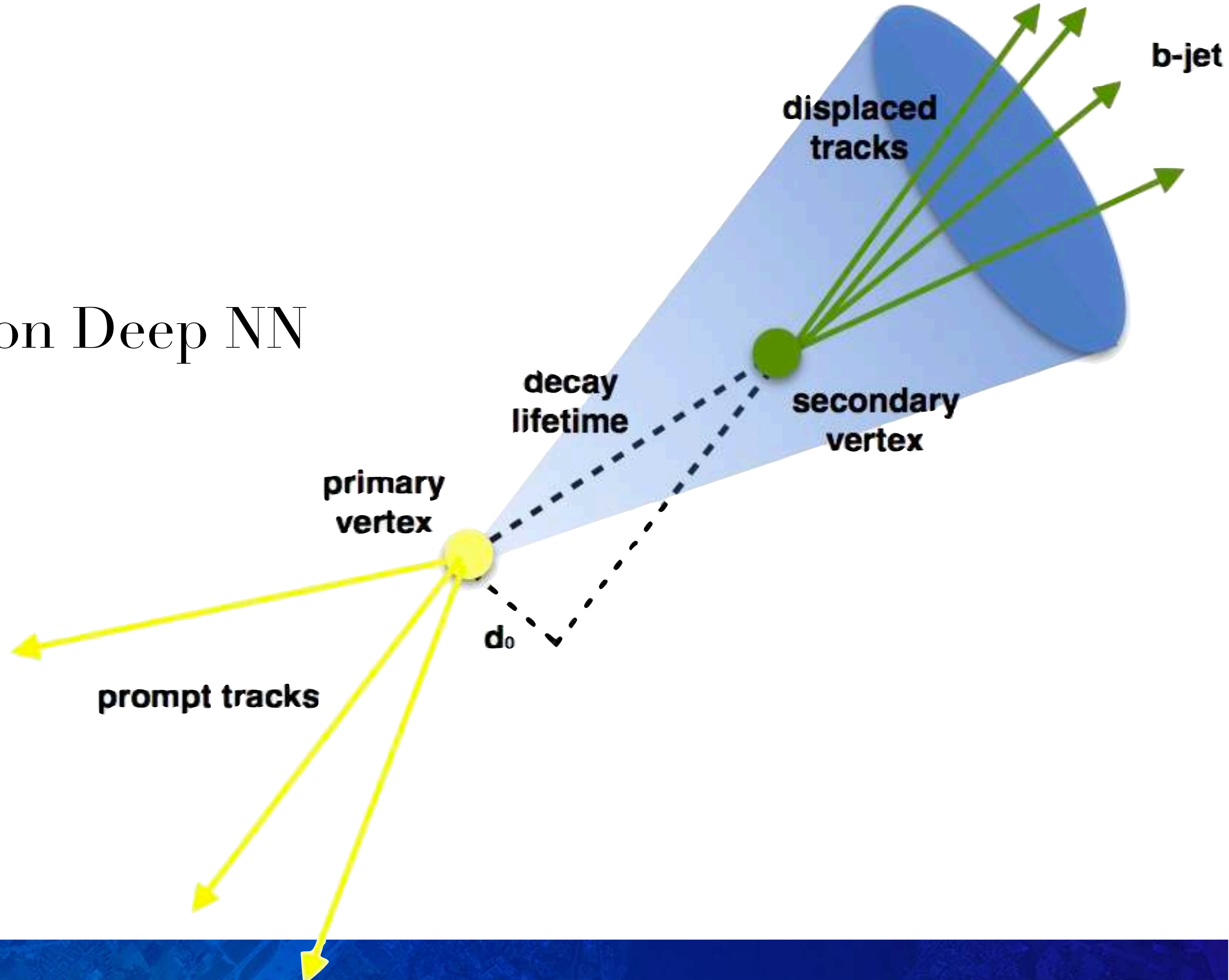
Working point	Truth τ_{had} efficiency 1-prong	3-prong
`Tight`	60%	45%
`Medium`	75%	60%
`Loose`	85%	75%
`Very Loose`	95%	95%

- BDT-based eVeto algorithm used to prevent an electro from being identified as τ_{had} with 1-prong
- Boosted Regression Tree used to reconstruct the tau energy scale



b-jet identification

- Tracks: ID. Consider $p_T > 500$ MeV for b-tag
- Primary Vertex: Reconstructed for every event. Defines the reference point for the displace vertex. At least on PV required
- Hadronic jets: From topoclusters with antikt. JetVertexTagger. Produces a MVA discriminant.
- Track-jet matching
- Jet-flavour label
- Identification DL1 algorithm based on Deep NN



ID Alignment Monitoring Web

- Old display

ID Alignment

Plots | ATLAS | conTZole | Documentation Twiki | Source code | BS Hand shake | Upload DB folder status

326 runs

Last update of server_runinfo2018.db was Mon, 04/Nov/19 00:05:56

Run 2018	Period	Date	Project	Stream	Alignment results	Monitoring plots	DB upload	BS Handshake
367384	?	02/Dec/2018 ?	data18_hi	calibration_IDTracks	Draw constants | View L11	Residuals | Hits | Hit Maps | IBL Res. | Residual Maps	L11 Good | L16 Good | 2018-12-04-11:04:13 | Summary File 367384_1543917853.log	2018-12-04-11:04:12 CRONJOB
367365	?	03/Dec/2018 ?	data18_hi	calibration_IDTracks	Draw constants | View L11	Residuals | Hits | Hit Maps | IBL Res. | Residual Maps	L11 Good | L16 Good | 2018-12-04-10:59:20 | Summary File 367365_1543917560.log	2018-12-04-10:59:19 CRONJOB
367364	?	02/Dec/2018 ?	data18_hi	calibration_IDTracks	Draw constants | View L11	Residuals | Hits | Hit Maps | IBL Res. | Residual Maps	L11 Good | L16 Good | 2018-12-02-21:35:35 | Summary File 367364_1543782935.log	2018-12-02-21:35:34 CRONJOB
367363	?	01/Dec/2018 ?	data18_hi	calibration_IDTracks	Draw constants | View L11	Residuals | Hits | Hit Maps | IBL Res. | Residual Maps	L11 Good | L16 Good | 2018-12-02-09:35:00 | Summary File 367363_1543739700.log	2018-12-02-09:35:00 CRONJOB
367321	?	01/Dec/2018 ?	data18_hi	calibration_IDTracks	Draw constants | View L11	Residuals | Hits | Hit Maps | IBL Res. | Residual Maps	L11 Good | L16 Good | 2018-12-02-06:41:12 | Summary File 367321_1543729272.log	2018-12-02-06:41:12 CRONJOB
367318	?	01/Dec/2018	data18_hi	calibration_IDTracks	Draw	Residuals | Hits	L11 Good | L16 Good |	2018-12-02-06:37:07

2018 Go!

Search

Run: 0

Period:

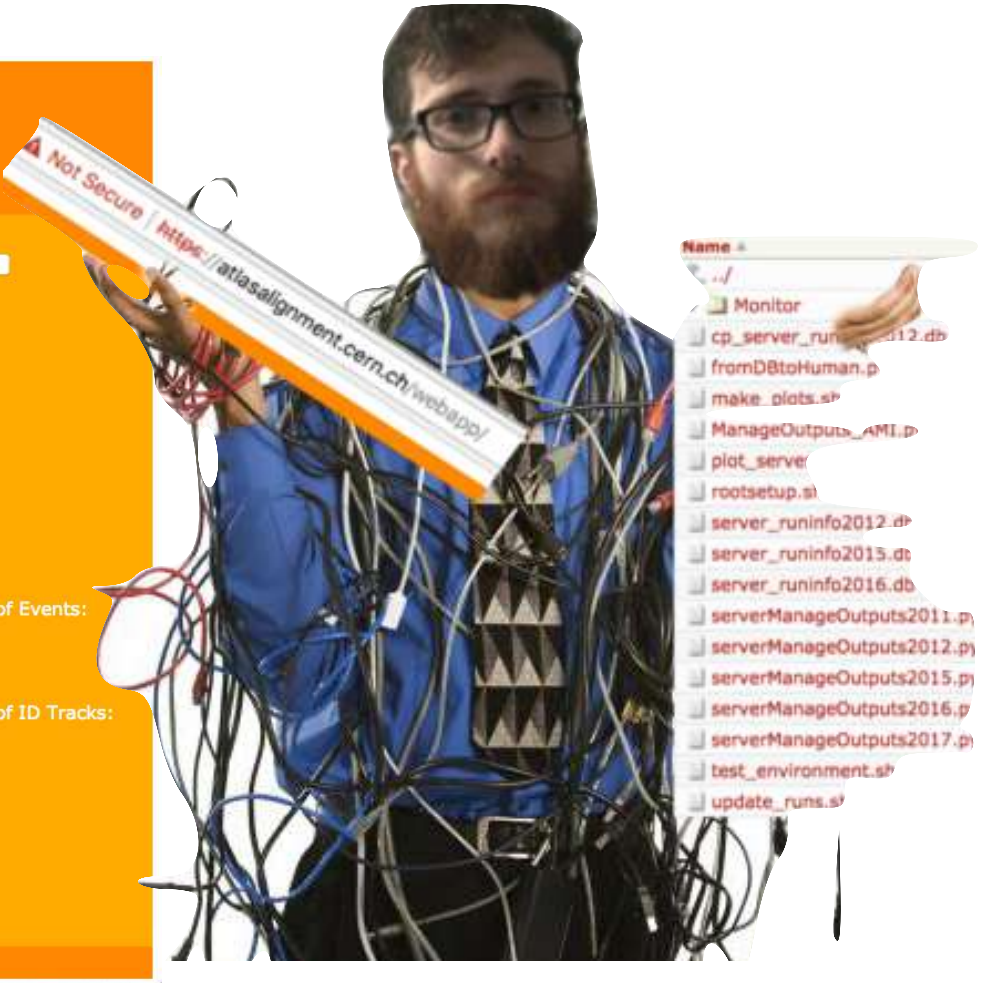
Min. number of Events: 0

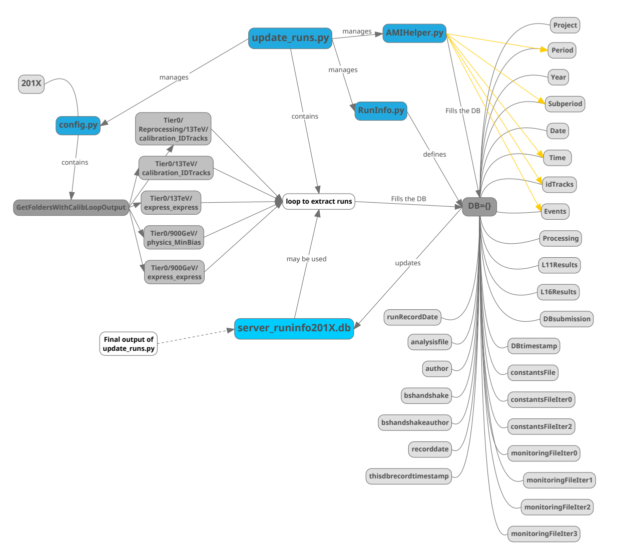
Min. number of ID Tracks: 0

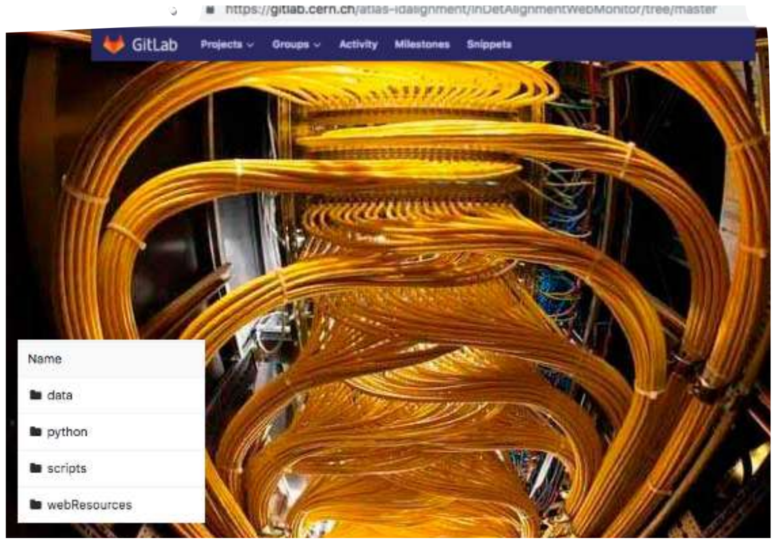
submit

reset

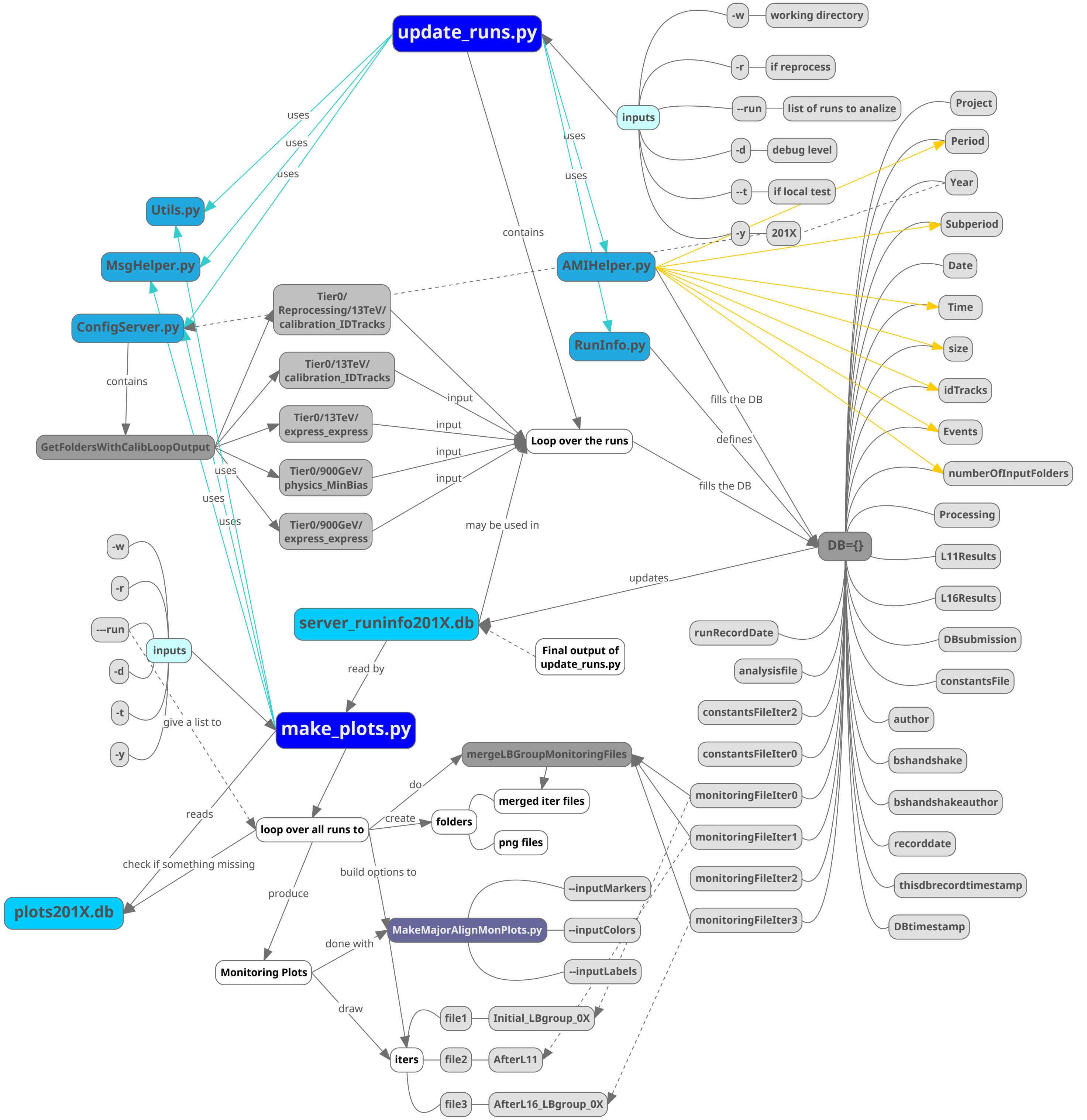
Contact

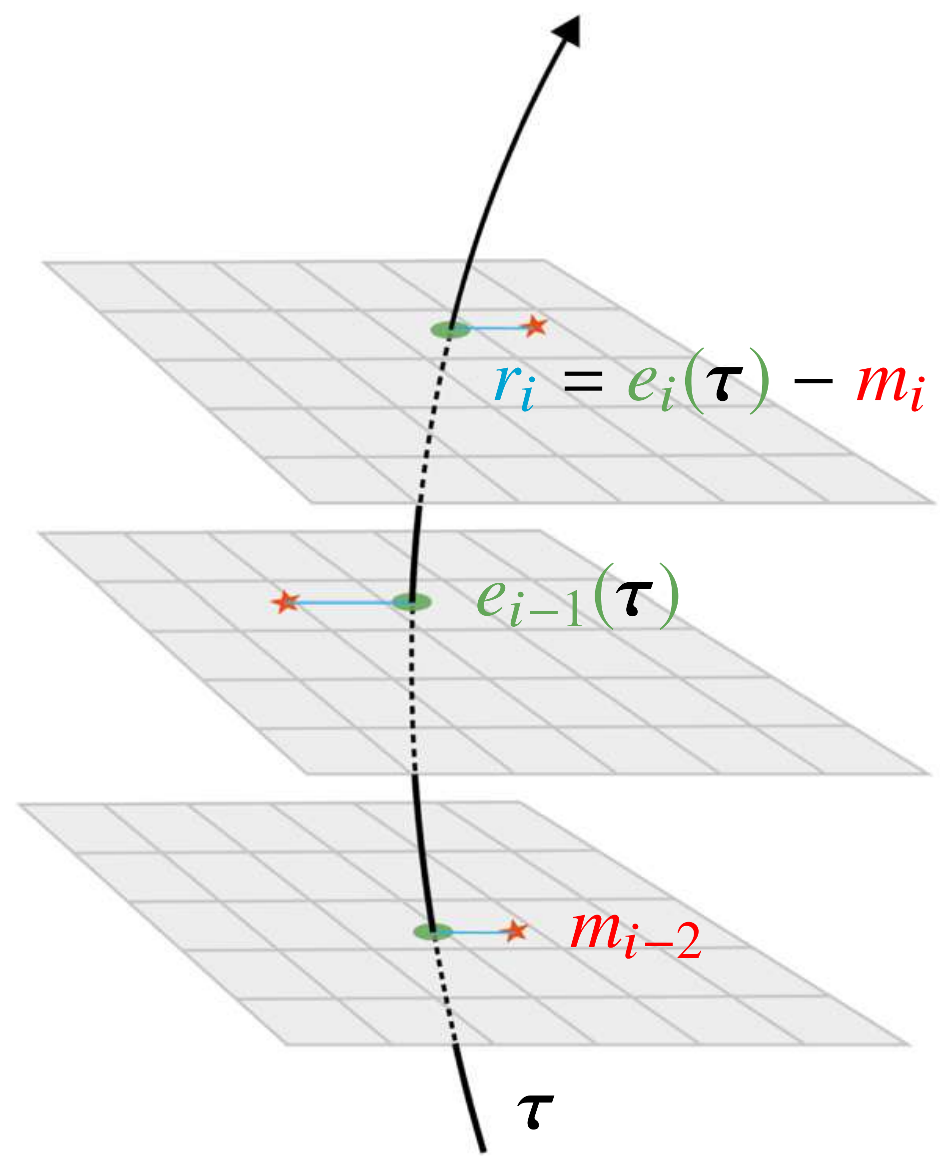




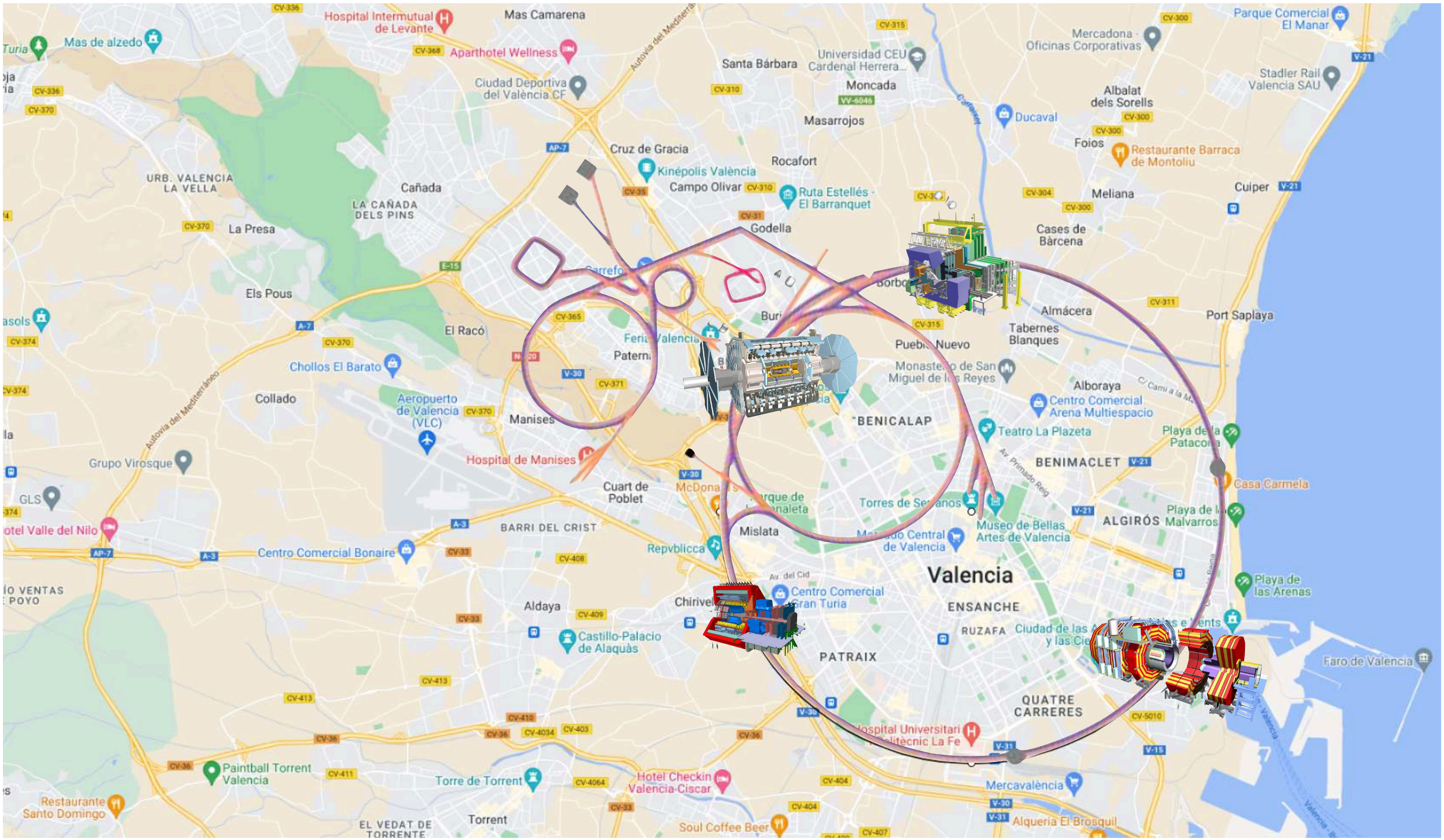


ID Alignment Monitoring Web

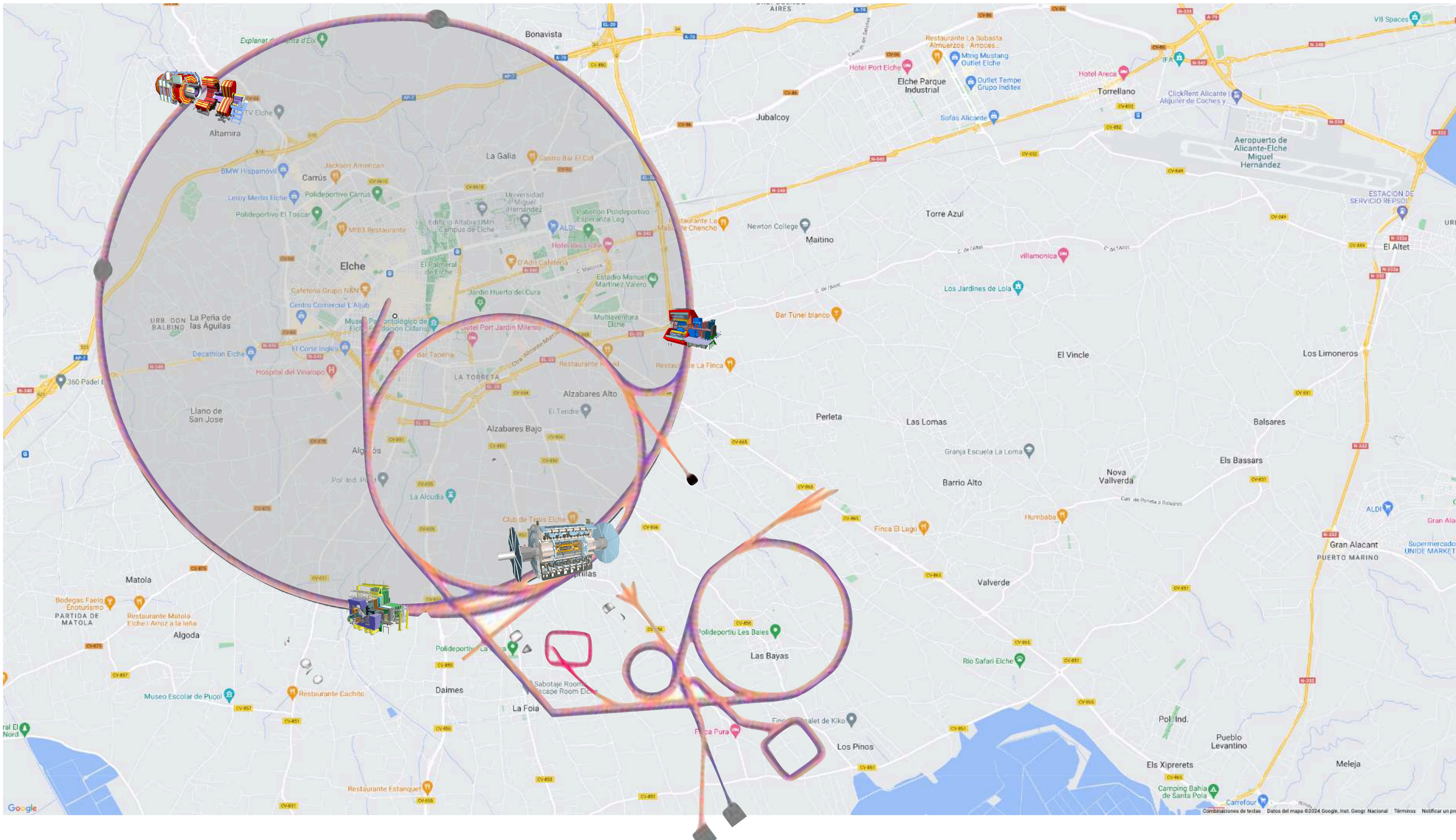




The Large Hadron Collider



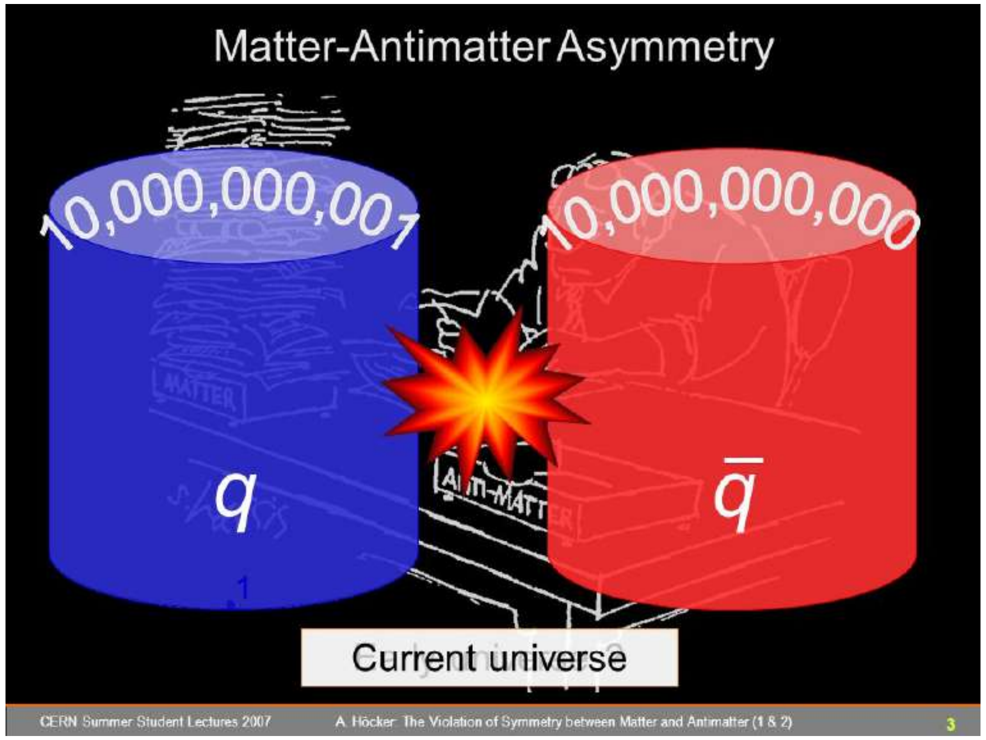
The Large Hadron Collider

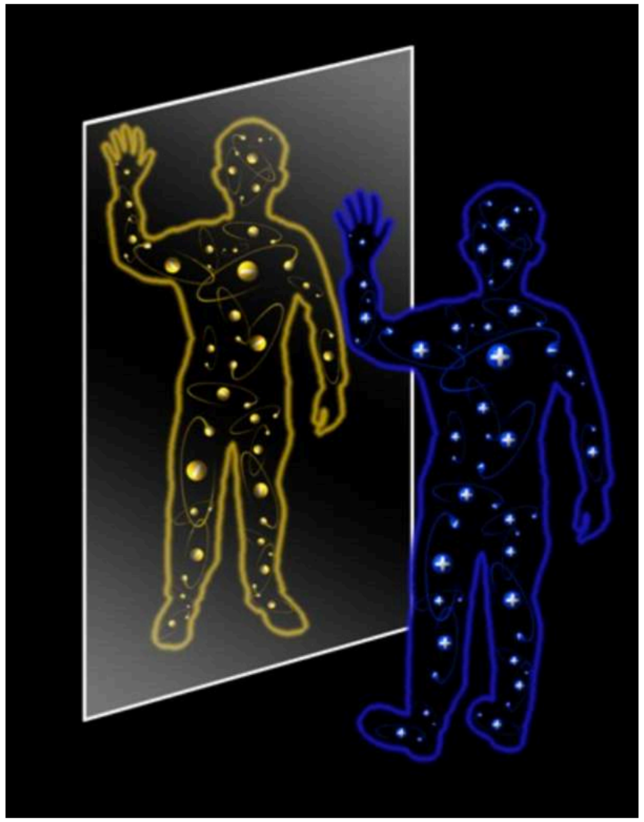


The ATLAS detector

The matter-antimatter asymmetry problem

- Known as baryon asymmetry problem
- In principle, matter and antimatter should have been created in equal quantities
- As the universe cooled, particles and antiparticles would annihilate each other, releasing energy.
- If matter = antimatter <— The annihilation would have left photons but not matter
- But our universe consists on matter



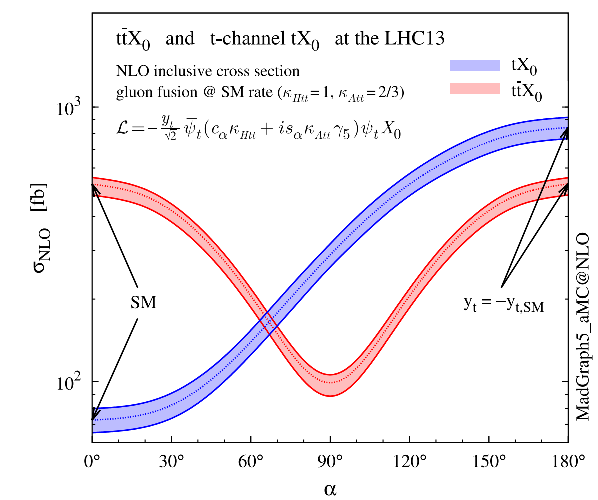


The matter-antimatter asymmetry problem

- In 1967, Sakharov outlined three conditions to this asymmetry to arise:
  - **Baryon Number Violation**: Processes must exist that result in a net change in the number of baryons
  - **C and CP Violation**: Conservation of the C symmetry and the combined CP symmetry must be violated. These violations allow for processes that can distinguish between matter and antimatter
  - **Departure from Thermal Equilibrium**: These processes must occur out of thermal equilibrium because, in thermal equilibrium, matter-antimatter creation and annihilation rates would be balanced.

The matter-antimatter asymmetry problem

- While the SM of particle physics allows for some degree of CP violation, it is insufficient to account for the observed level of matter-antimatter asymmetry
- This inadequacy suggests the need for physics beyond the SM.
- Experimental efforts continue to measure CP violation with greater precision and to search for baryon number-violating processes
- Sources of CP violation:
    - The CP-violating phase in the CKM
    - QCD Lagrangian θ term could lead to CP violation
    - CP violations on neutrino oscillations
    - Some SUSY or extradim models often include CP-violating phases
- The SM predicts the Higgs to be a CP-even scalar particle (i.e. no CP violation) but a CP-odd contribution has not been discarded yet



Alternative BDT Models

- Apart from the BDT models used in the analysis, several other models have been trained as an alternative approach to the ones that have been ultimately used in the thesis:
    - Alternative BDT for lepton assignment
    - BDT(Z+jets | OS)
    - BDT(tWH | OS) // BDT(tH | OS)
    - BDT(tWH | SS) // BDT(tH | SS)
    - BDT($t\bar{t}$ | SS)
    - BDT($t\bar{t}W$ | SS)
    - BDT($t\bar{t}X$SS)
- Some of these models are used in the ongoing ATLAS analysis
- Some other have been discarded due to their performance

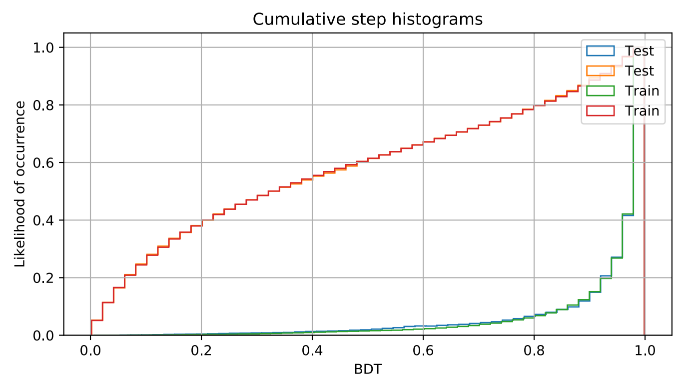
Alternative Models - Lep. Assignment

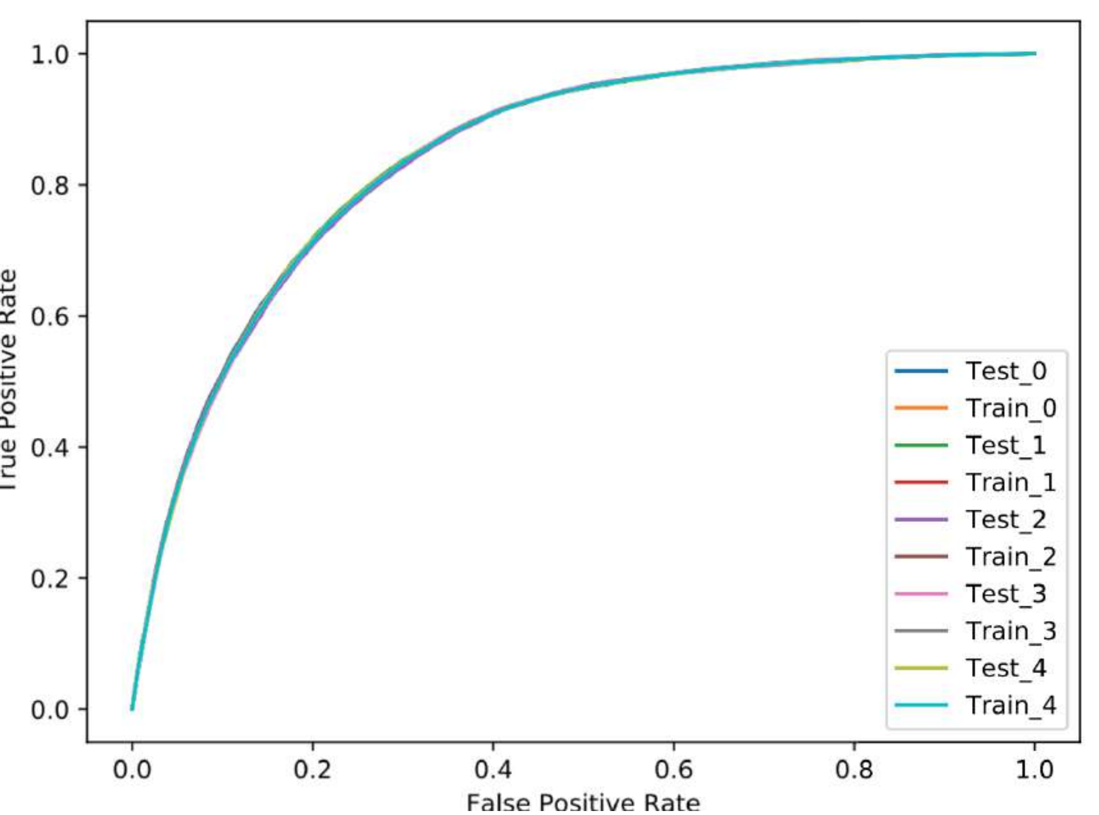
- Within the gradient BDTs, different configurations are explored regarding the number of folds, the hyperparameters and the collection of input variables. Several of these offer a similar performance to the chosen $\mathrm{BDT}^{\mathrm{Lepton\ Assignment}}$. Besides the BDTs, other algorithms such as NN and random forests have been teste and, although they showed promising performances, none of them are adopted in the final analysis.

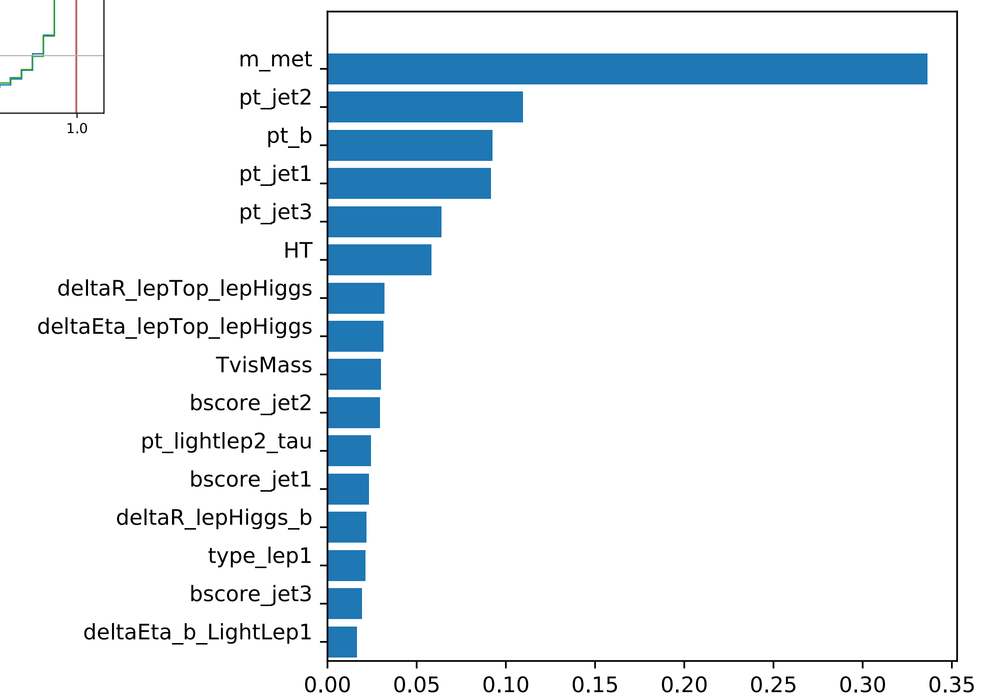
Alternative Models - BDT(Z+jets|OS)

- The production of Z bosons in association with jets is, along with $t\bar{t}$, the most important background process for the OS channel.
- To better discriminate the Z+jets background, a dedicated BDT model was trained.
- Discarded because it does the same as the model trained to discriminate $t\bar{t}$

Hyperparameter	BDT($tWH|_{\mathrm{OS}}$)
Maximum depth	5
Learning rate	0.05
Number of estimators	2500
Minimum child weight	0.7
Scale of positive weights	12
Neg. weight strategy	Pos. only



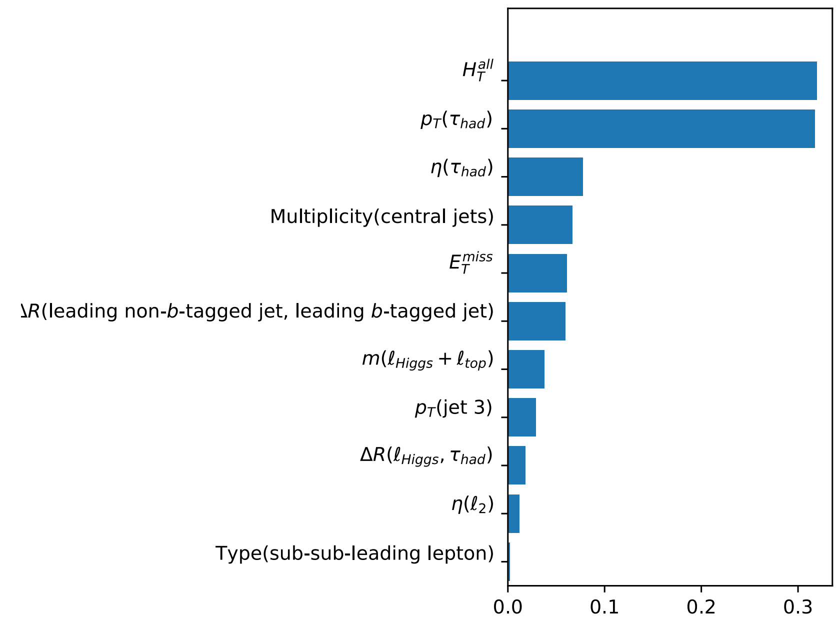


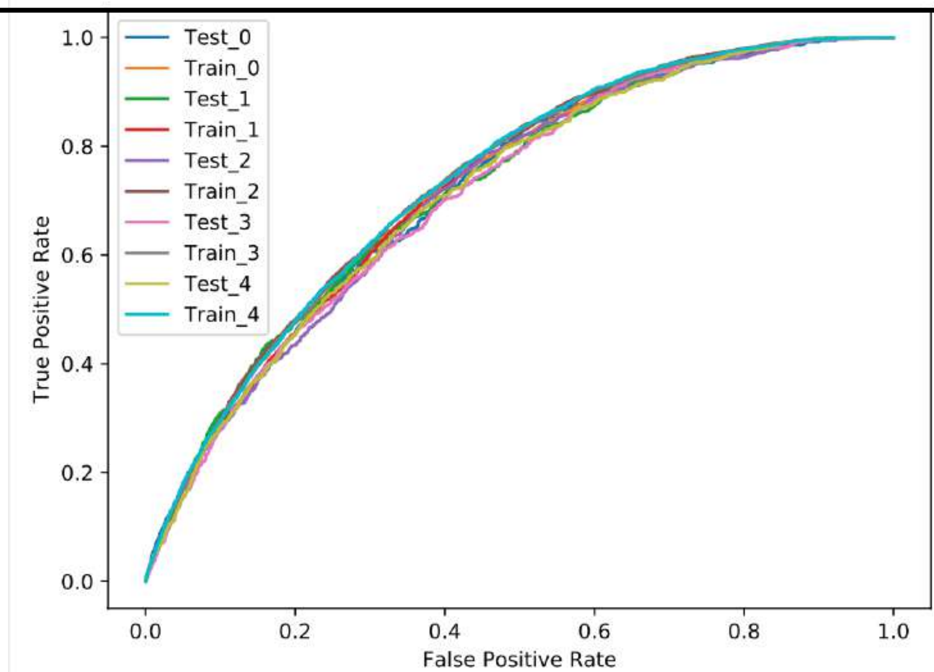


Alternative Models - BDT(tWH | OS)

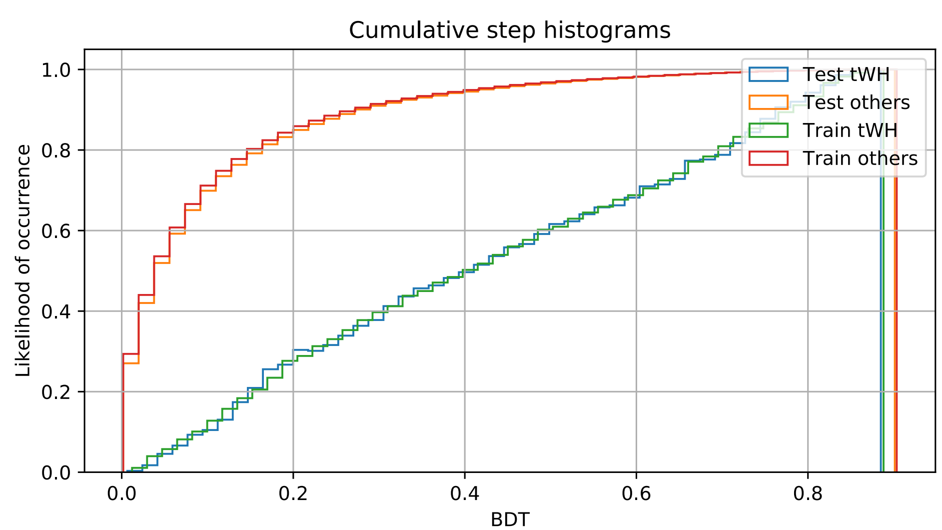
- Trained to perform the inclusive tH search
- In the ongoing ATLAS analysis a BDT targeting $tHq + tWH$ simultaneously is used

Hyperparameter	BDT(tWH|$_{\text{OS}}$)
Maximum depth	4
Learning rate	0.15
Number of estimators	1000
Minimum child weight	1.3
Scale of positive weights	400
Neg. weight strategy	All events





(a) ROC



(b) Cumulative distribution