Measurement of $\mathrm{D}^{\pm}/\mathrm{D}_s^{\pm}$ differential production cross-section and search for LFV decays in $\tau \rightarrow \mu\mu\mu$

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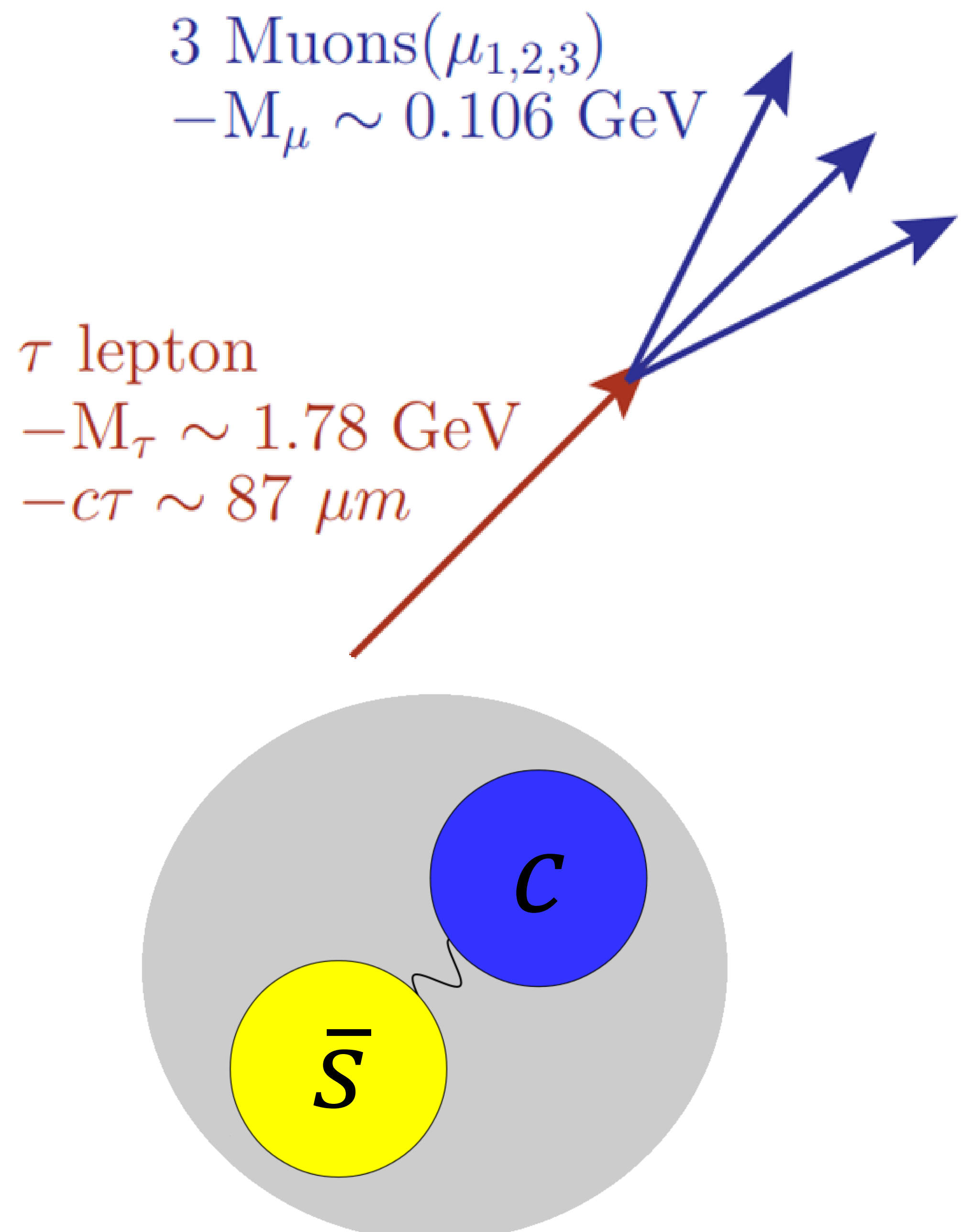
Motivation

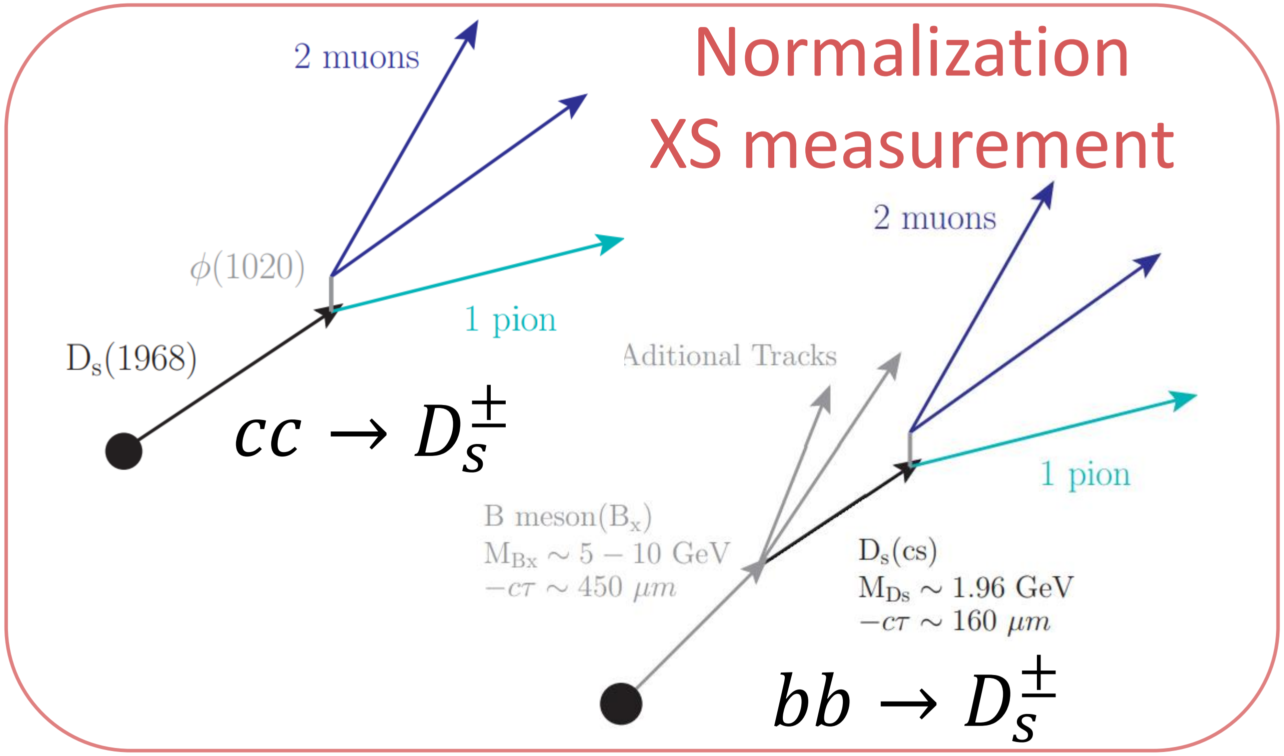
- Why $\tau \rightarrow 3\mu$?
  - LFV decay
  - Rare in SM with neutrino mixing (BR < 10^{-14})
  - Predicted by some SUSY model (BR ~ 10^{-10} - 10^{-8})
- How?
  - LHC produces lots of D mesons
  - $\mathrm{BR}\left(\mathrm{D}_s^{\pm} \rightarrow \tau\nu\right) \sim 5\%$
  - Measure $\mathrm{D}_s^{\pm}$ production rate and $N_{\tau\rightarrow 3\mu}$ originating from $\mathrm{D}_s^{\pm}$ → compute $\mathrm{BR}(\tau \rightarrow 3\mu)$

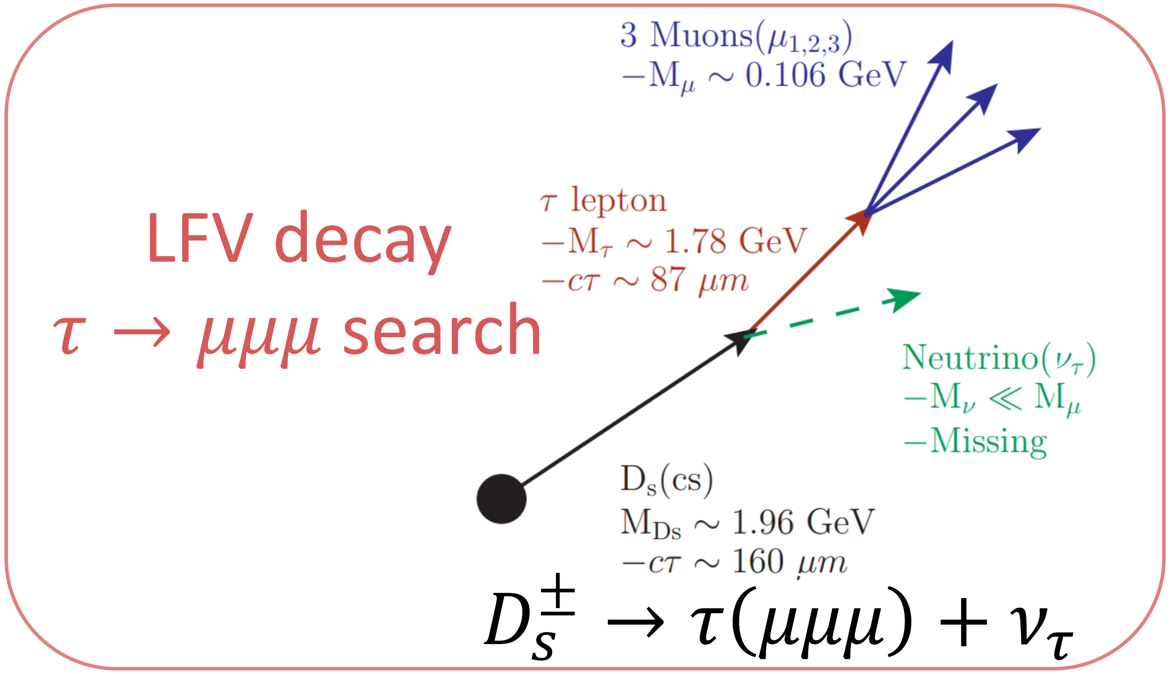


D_s^+ meson

Analysis Goal

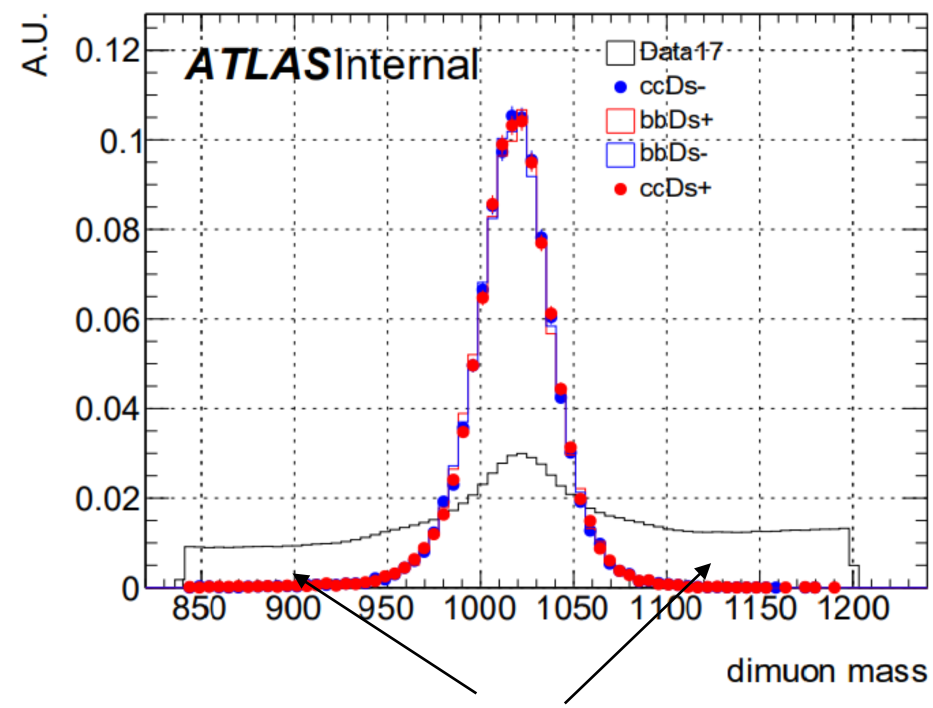
- Channel
  - $D_s^{\pm} \to \phi\pi \to \mu\mu\pi$
  - Doublet($\mu\mu$) and triplet($\mu\mu\pi$) built
- Goal 1: Non-prompt fraction measurement
  - $cc \to D_s^{\pm}$
    prompt production
  - $bb \to D_s^{\pm}$
    non-prompt production
    through B-mesons, more detached vertex
- Goal 2: Cross section measurement
  - Extract signal and efficiencies
  - Differential cross section in p_T
- Goal 3: Search for $\tau \to \mu\mu\mu$ rare decay
  - Take $D_s^{\pm} \to \phi\pi$ as normalization
  - Acquire Neural Networks approach





Selection

- Strategy for $D_s^{\pm} \rightarrow \phi\pi \rightarrow \mu\mu\pi$
  - Basic selection
  - Build analytic fit models
  - Extract parameters by fitting to data
- Key selection
  - Doublet(ϕ) mass
  - Detached secondary vertex
  - $p_T^{\mu} > 4$ GeV and $p_T^{\pi} > 1$ GeV
  - One candidate per event
- Triggers
  - Dimuon triggers
  - Lowest p_T trigger is 2mu6 (2 muons with $p_T > 6$GeV)
  - Run out of stats below 12 GeV Trigger is the main limitation

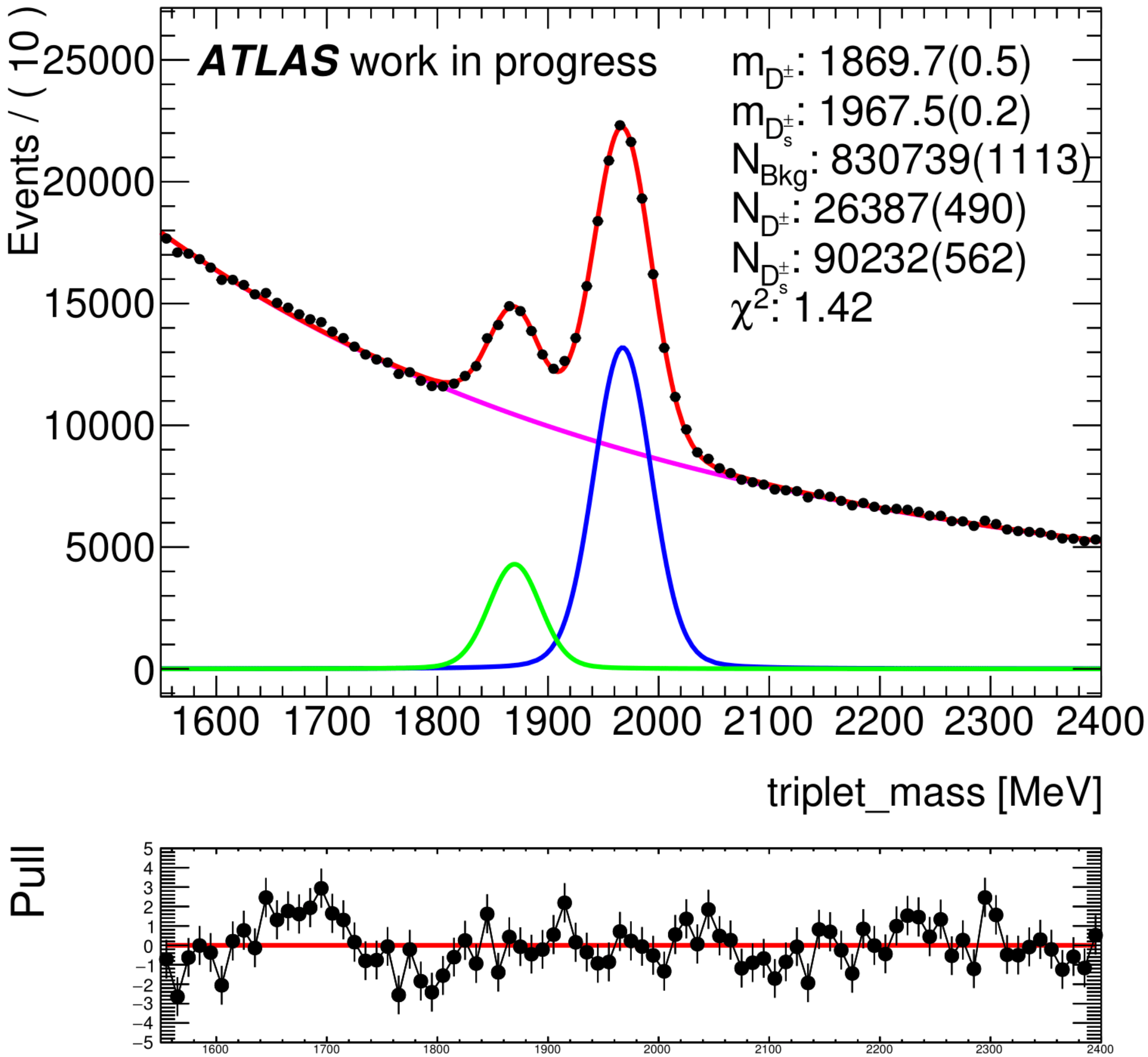


Side band used for background study

2017	
HLT_mu11_mu6_bDimu2700	BLS
HLT_mu11_mu6_bTau	BLS
HLT_mu11_mu6_bPhi	BLS
HLT_mu20_mu6noL1_bTau	BLS
2018	
HLT_2mu6_bPhi_L1LFV-MU6	BLS
HLT_mu11_mu6_bTau	BLS
HLT_mu11_mu6_bPhi	BLS
HLT_mu20_mu6noL1_bTau	BLS

Triplet Mass Fit

- Model components
  - Voigtian peaks verified in MC
  - Quadratic exponential verified in ϕ mass side band
- Combined model
  - $N_{D_s^\pm}$ Voigtian + $N_{D^\pm}$ Voigtian + $N_{bkg}\text{Exp}(c_2 m^2 + c_1 m)$
- Result
  - $m_{D_s^\pm}$ and $m_{D^\pm}$ extracted roughly matches with PDG
  - Full run-II $N_{D_s^\pm}$ is 90k (post-selection)

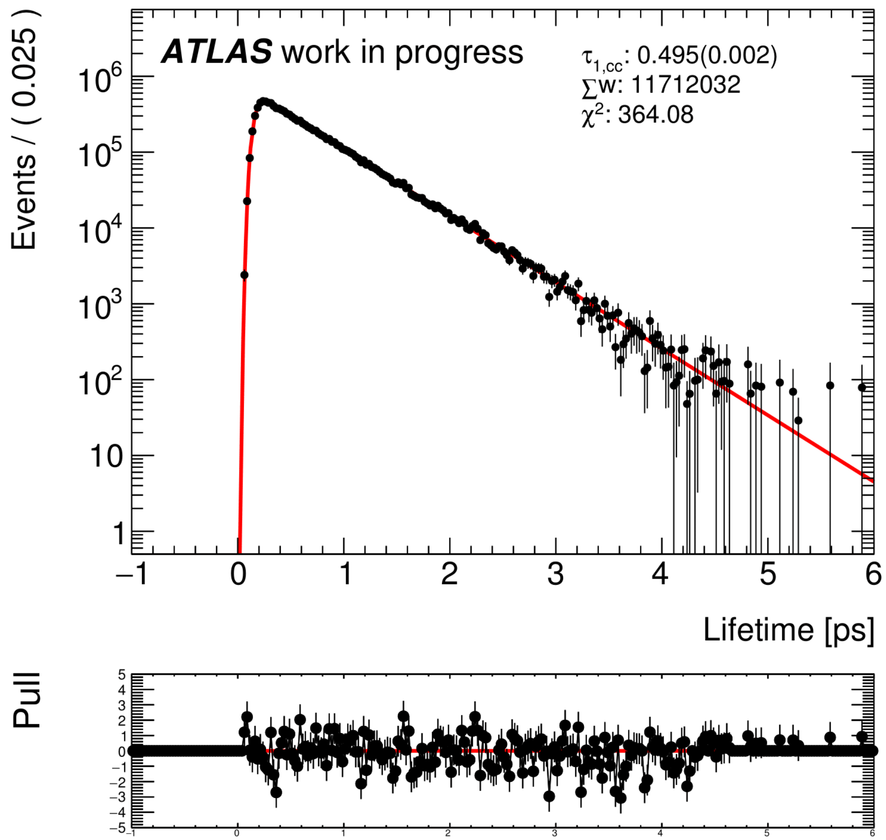


Lifetime Templates

- Analytic function fitted to bb/cc MC samples
- Template parameter extracted and fixed

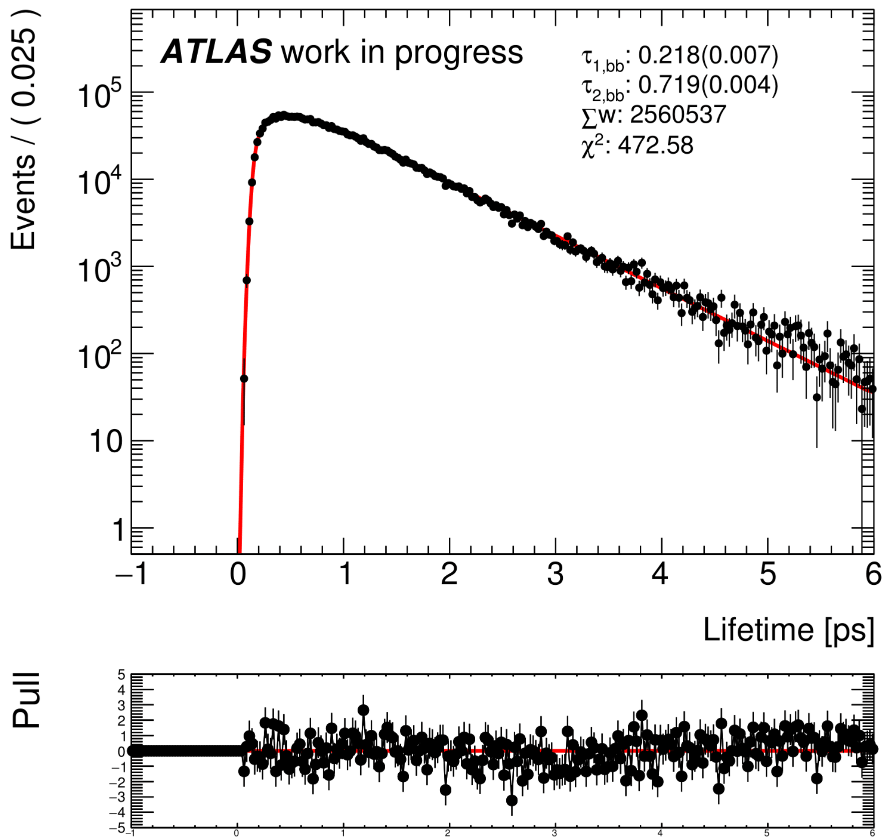
$cc \rightarrow D_s + X \rightarrow \phi\pi + X$

$\mathrm{PDF}_{\mathrm{prompt}} = \mathrm{Exp} \otimes \mathrm{Gaussian} \otimes \mathrm{Erf}$



$bb \rightarrow B + X_1 \rightarrow D_s + X_2 \rightarrow \phi\pi + X_2$

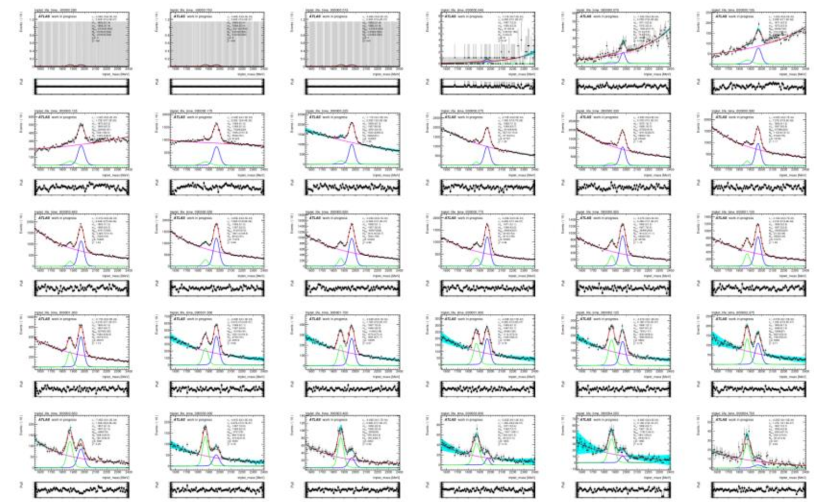
$\mathrm{PDF}_{\mathrm{non\text{-}prompt}} = \mathrm{Exp1} \otimes \mathrm{Exp2} \otimes \mathrm{Gaussian} \otimes \mathrm{Erf}$

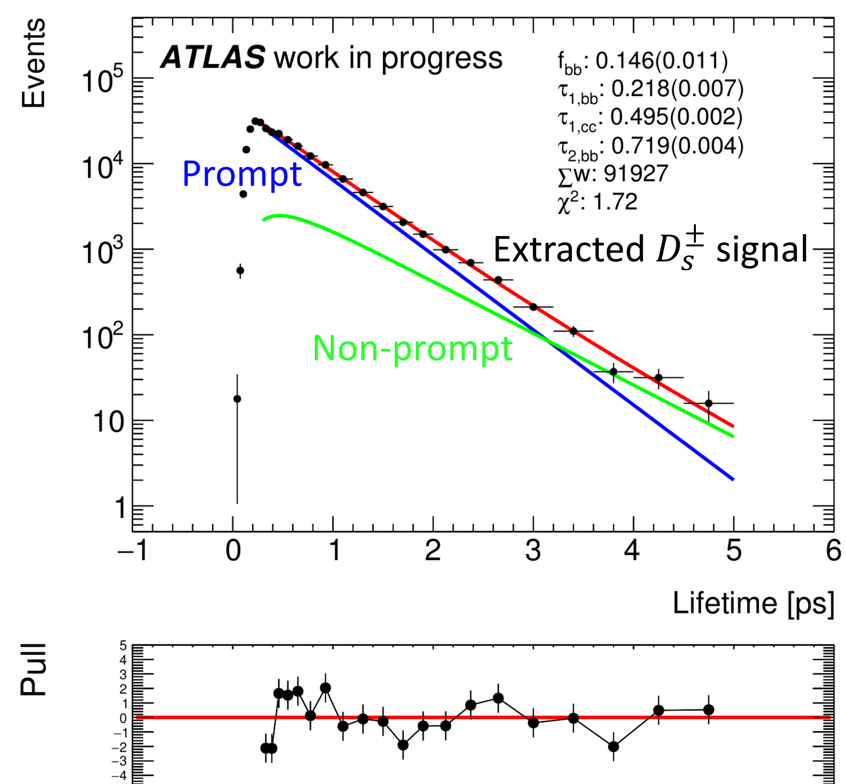


Lifetime Fit

- Signal extraction
  - Slice the dataset per lifetime
  - Extract number of signal in each slice
  - Plot as a function of lifetime for signal shape
- Combined model
  - $N_{sig}\, f\, \mathrm{PDF}_{\mathrm{Non-prompt}} + N_{sig}\, (1 - f)\, \mathrm{PDF}_{\mathrm{Prompt}}$
  - Individual PDF parameters set to extracted values
  - Peak region and rising slope at low lifetime excluded (vulnerable to mis-modelling)
- Result
  - Number of signal matches (~90k)
  - Directly at fit level
    $f_{NP,\,fit} = 14.6 \pm 1.1$ %
  - With known selection efficiencies for prompt and non-prompt processes, scaling back to production level
    $f_{NP,\,prod} = 17.2 \pm 1.3$ %

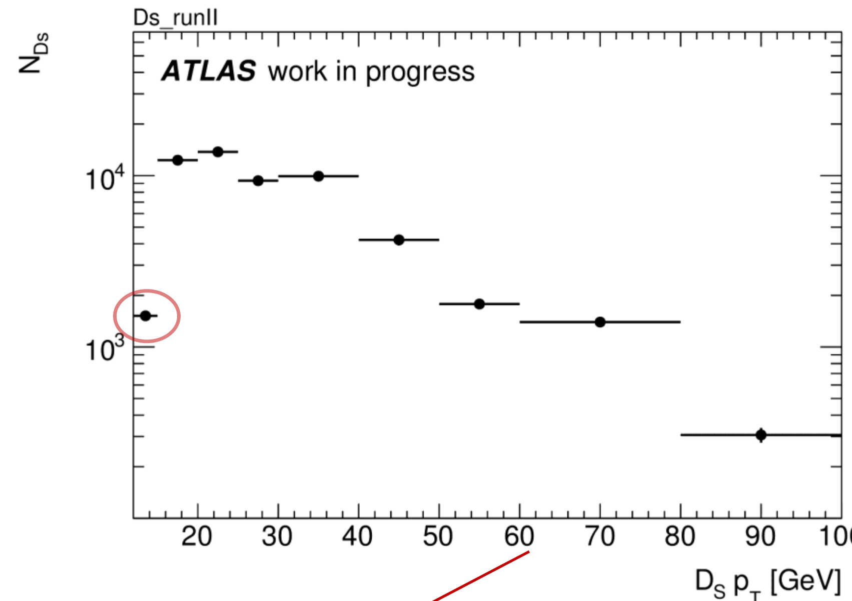
30 mass fits for signal extraction



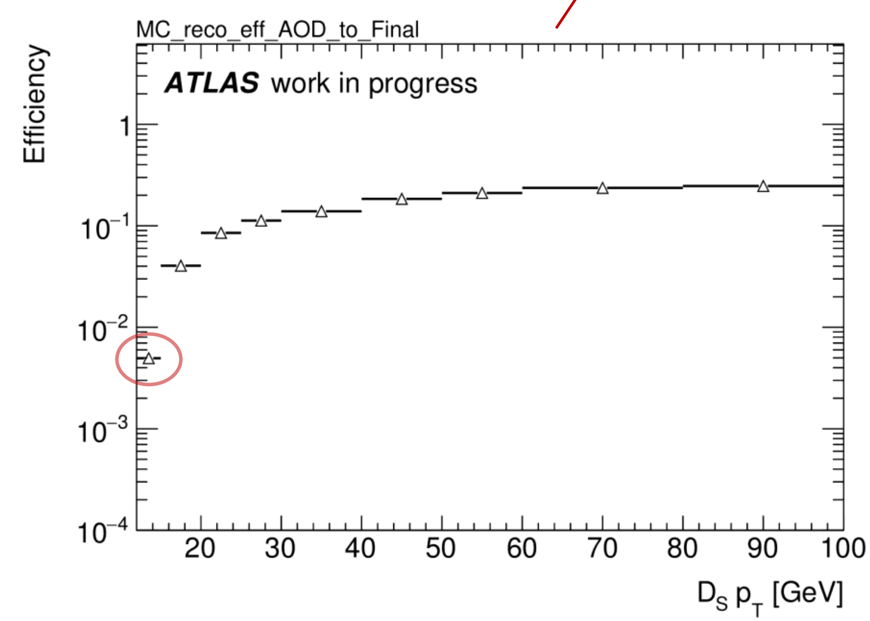


Differential Cross Section

- Ingredients
  - Signal shape extracted by mass fit
  - Efficiency obtained by simulation (weighted with measured f_{NP})
  - Luminosity
  - Branching ratio
- Main limitation
  - Trigger threshold
  - Low efficiency for low p_T
  - Signal starts from around 12 GeV

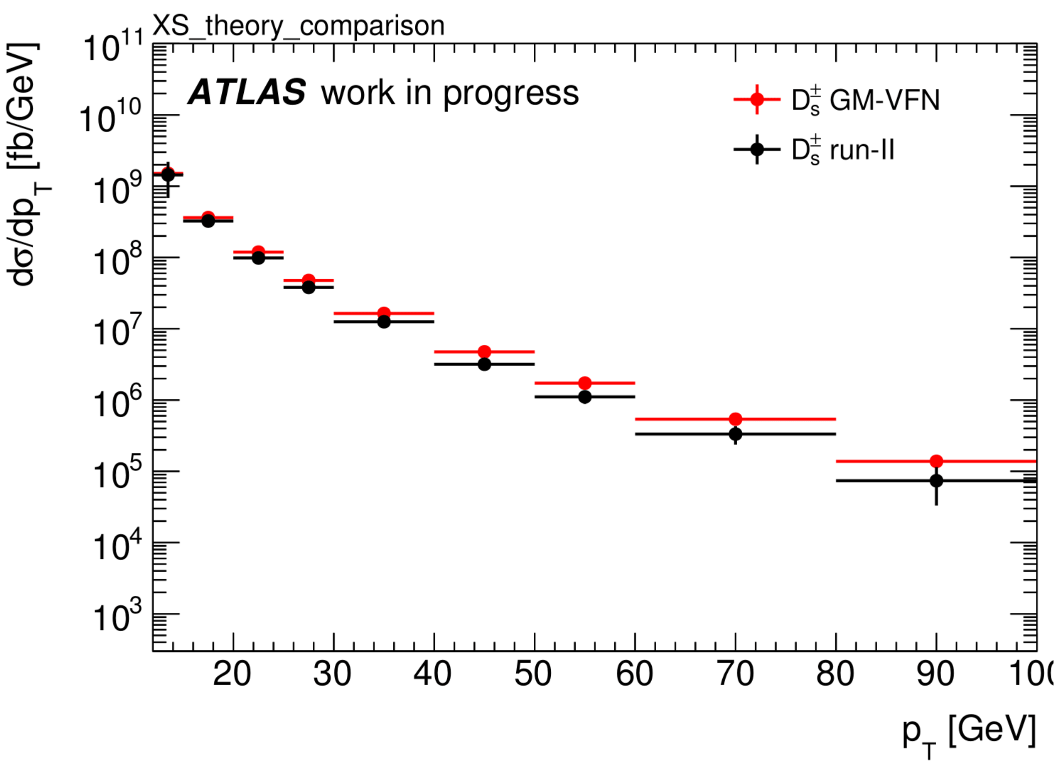


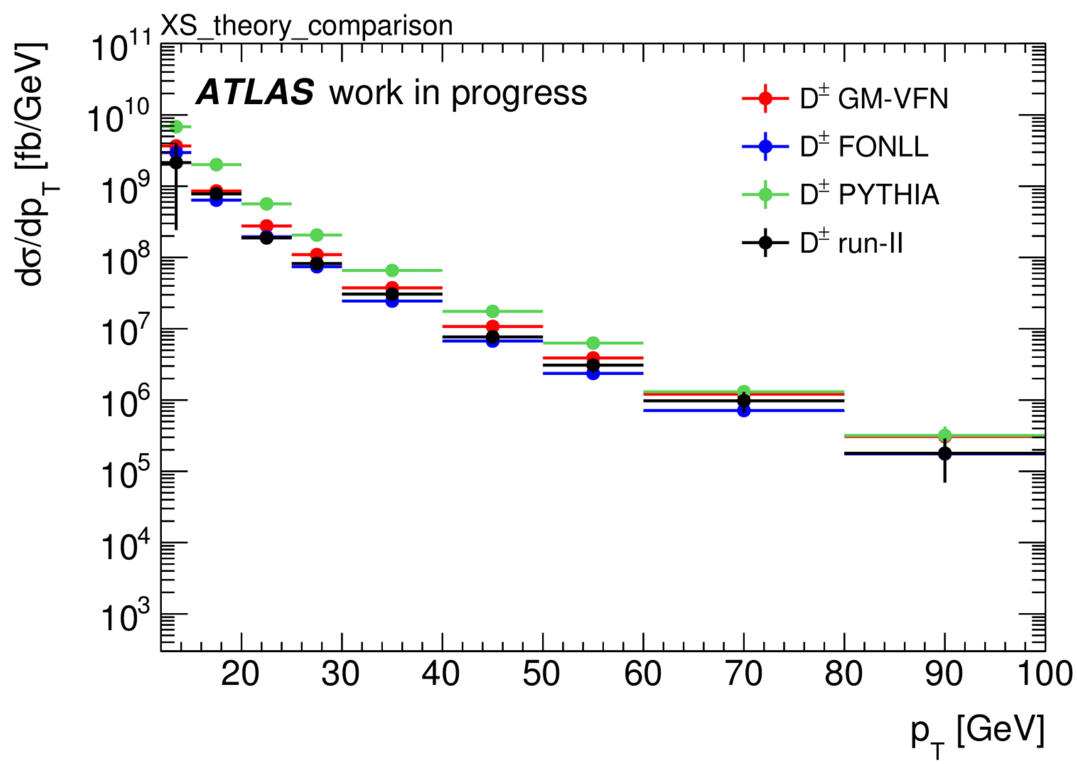
$$\frac{d\sigma_{D_s}}{dp_T} = \frac{N_{D_S^{\pm}}\text{(extracted from fit)}}{\int Ldt \;\; BR(D_s \to \phi\pi \to \mu\mu\pi) \;\; \epsilon \;\; BinWidth(p_T)}$$



Cross Section Result

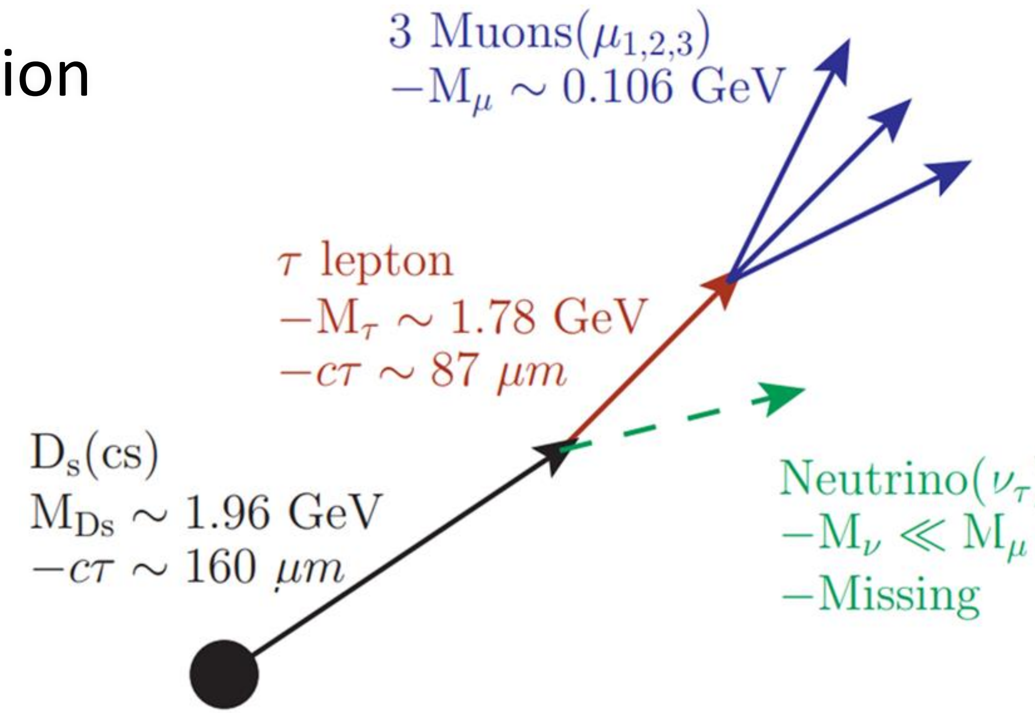
- Same procedure done for $D^{\pm}$ and $D_s^{\pm}$
- Theory prediction from FONLL and GM-VFN included
- Run-II vs Run-I comparison
  - Inclusive values obtained by integrating over p_T
  - For $D_s^{\pm}$: $\sigma_{\text{inclusive}}^{\text{run-II}} = 1.6 \pm 0.2\ \ \sigma_{\text{inclusive}}^{\text{run-I}}$
  - For $D^{\pm}$: $\sigma_{\text{inclusive}}^{\text{run-II}} = 1.9 \pm 0.2\ \ \sigma_{\text{inclusive}}^{\text{run-I}}$

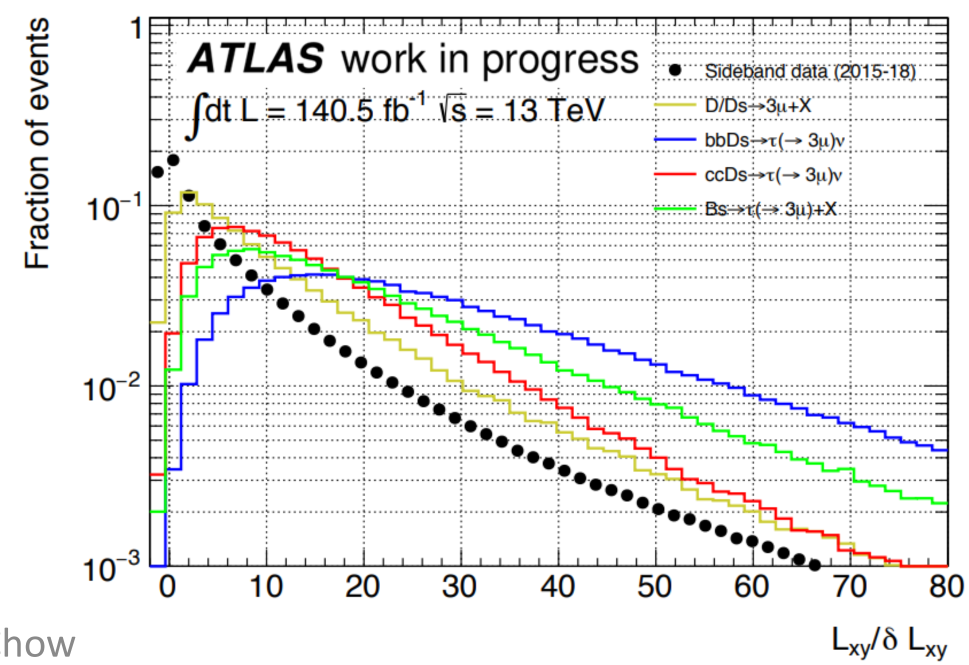


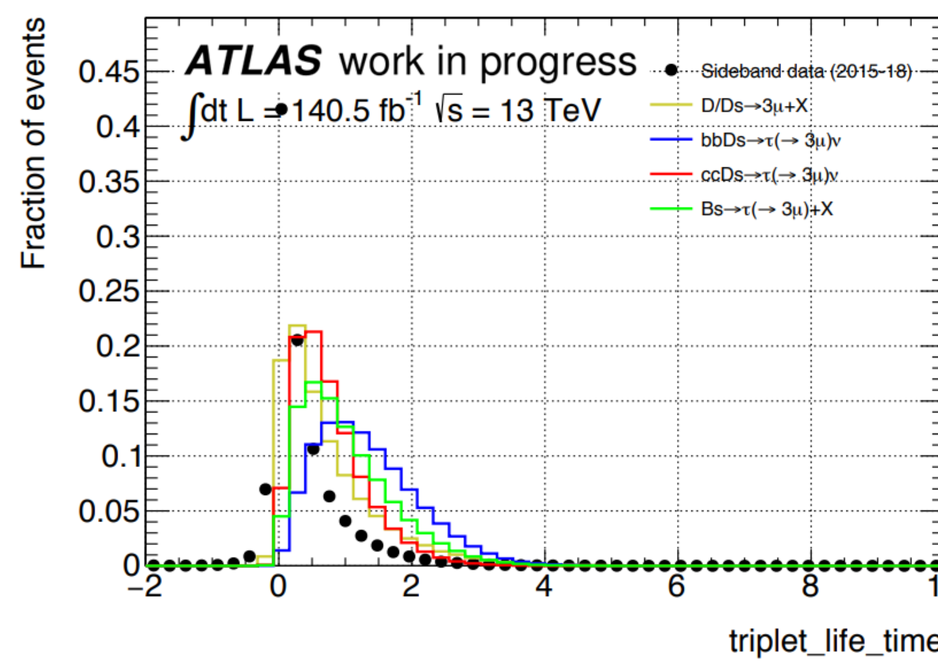


LFV Search in $\tau \to \mu\mu\mu$

- Using D_s measurement as normalization
  - $BR(\tau \to \mu\mu\mu) = \frac{N_{sig}}{(\epsilon \times A)\, N_{D_s} \times BR(D_s \to \tau + X)}$
  - Directly impacted by the precision of $\sigma_{D_s^\pm}$
  - Some systematic error can be cancelled
- Key variables:
  - Lifetime
  - Vertex distances (L_{XY}, A_{0XY})

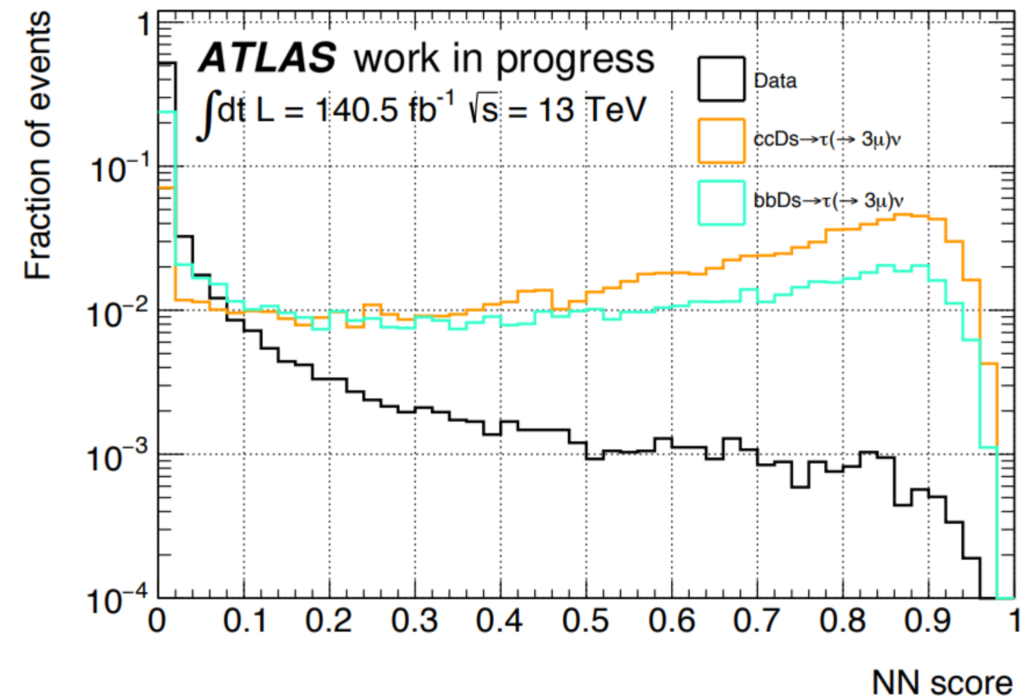


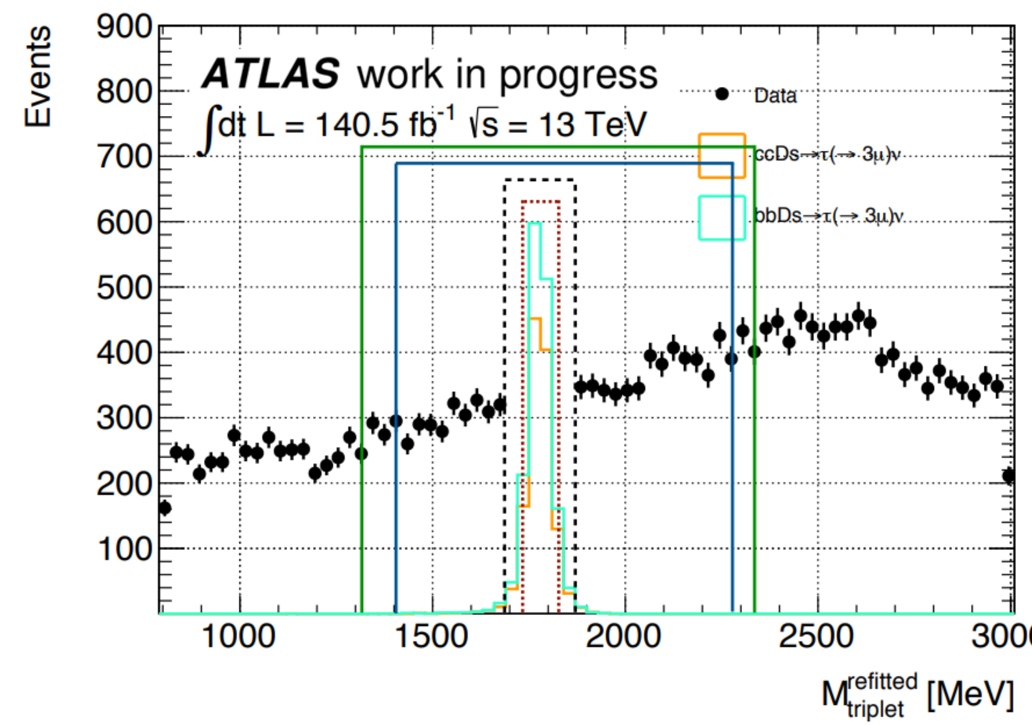




Neural Network Approach

- Procedure
  - Basic selection
  - Build a neural network (NN) to distinguish signal from background
  - Perform a cut on the NN score
  - Fit on triplet mass to extract yield
- No significant signal?
  - Calculate the upper limit of $\mathrm{BR}(\tau \to \mu\mu\mu)$
- Current status
  - optimizing NN and fit
  - Aiming at few times 10^{-8}
  - Newest limit from CMS study with 2016 dataset is 8.8×10^{-8}





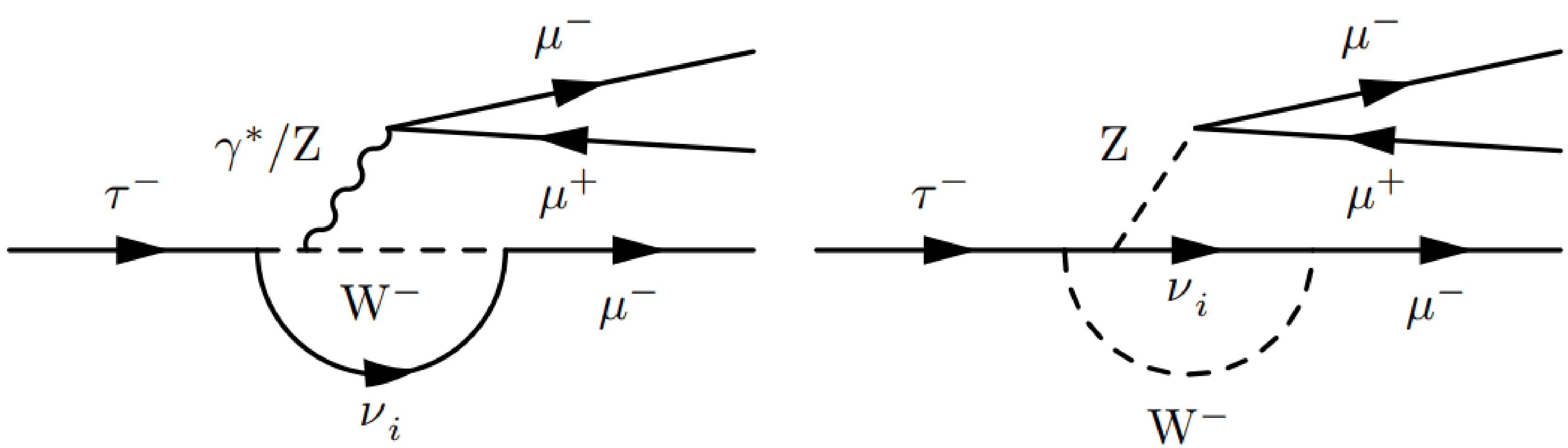
Summary

- Two parallel analysis on-going
- Measurement of $D^{\pm}/D_s^{\pm}$
  - Preliminary values obtained
  - Fine tuning on-going
  - Target to publish in 1st quarter of 2020
- Search for $\tau \to \mu\mu\mu$
  - Optimization still on-going
  - Expect to be competitive with a limit at few times 10^{-8}
  - Target to publish late 2020
- B physics and low energy searches in ATLAS can be competitive

Back up

Feynmann diagram

- Lepton mixing
  - $\tau \to 3\mu$ is allowed by the SM (with neutrino mixing)
  - Constraint to lepton mixing angle and neutrino mass ratio



- Constraint / rule out BSM theories
  - BR($\tau \to 3\mu$)
    Standard Model : < 10^{-14} (EPJC May 1999)
    Minimal SUSY : 10^{-10} - 10^{-8} (arxiv: 0801.1826)
    Current best measurement : 2.1×10^{-8} (arxiv: 1001.3221)

Lifetime Definition

- Definition in Athena standard tool

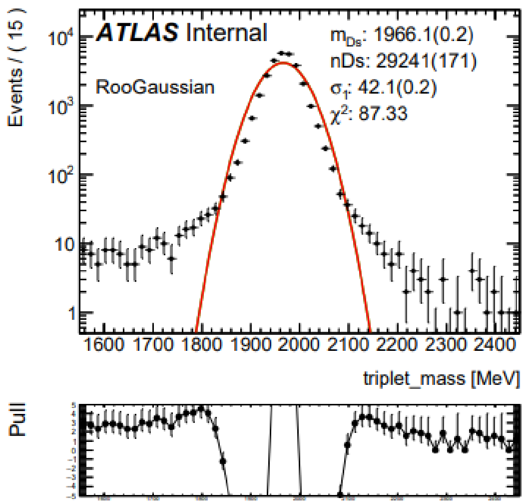
```
double V0Tools::tau(const xAOD::Vertex * vxCandidate, const xAOD::Vertex* vertex, const std::vector<double> &masses) const
{
  unsigned int NTrk = vxCandidate->vxTrackAtVertex().size();
  if (masses.size() != NTrk) {
    ATH_MSG_DEBUG("The provided number of masses does not match the number of tracks in the vertex");
    return -999999.;
  }
  //double CONST = 1000./CLHEP::c_light;
  double CONST = 1000./299.792;
  double M = invariantMass(vxCandidate, masses);
  double LXY = lxy(vxCandidate,vertex);
  double PT = V0Momentum(vxCandidate).perp();
  return CONST*M*LXY/PT;
}
```

- Formula
  - $\mathrm{L_{xy}} = (\overrightarrow{r_{SV}} - \overrightarrow{r_{PV}}) \cdot \widehat{p_T}$
  - $\tau = \frac{\mathrm{ML_{xy}}}{\mathrm{p_T}}$

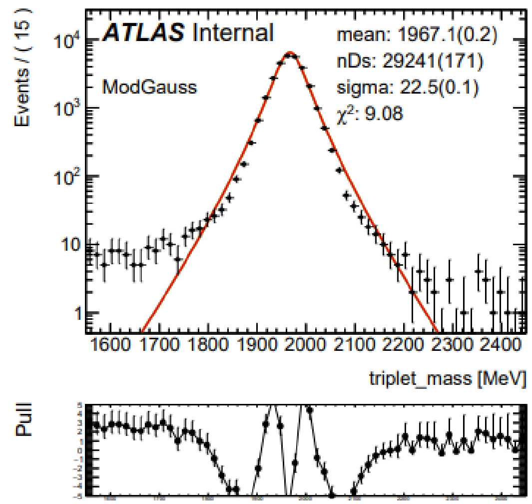
Trigger

Trigger	Periods online	stream
	2015	
Data15 is not used		
	2016	
HLT_mu20_l2idonly_mu6noL1_nscan03		Main
HLT_2mu6_nomucomb_bPhi		Main
	2017	
HLT_mu11_mu6_bDimu2700		BLS
HLT_mu11_mu6_bTau		BLS
HLT_mu11_mu6_bPhi		BLS
HLT_mu20_mu6noL1_bTau		BLS
	2018	
HLT_2mu6_bPhi_L1LFV-MU6		BLS
HLT_mu11_mu6_bTau		BLS
HLT_mu11_mu6_bPhi		BLS
HLT_mu20_mu6noL1_bTau		BLS

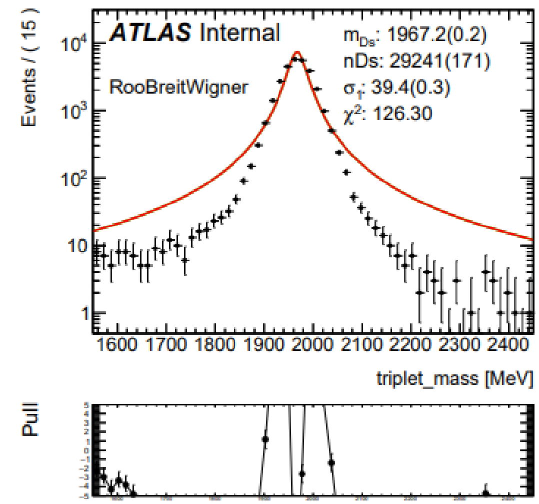
Signal model study



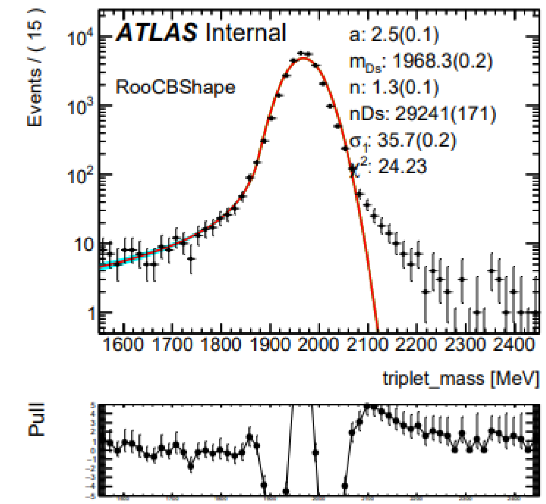
(a) Gaussian



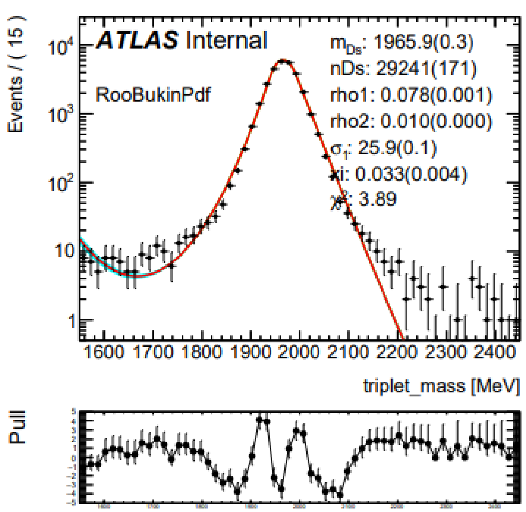
(b) Modified Gaussian



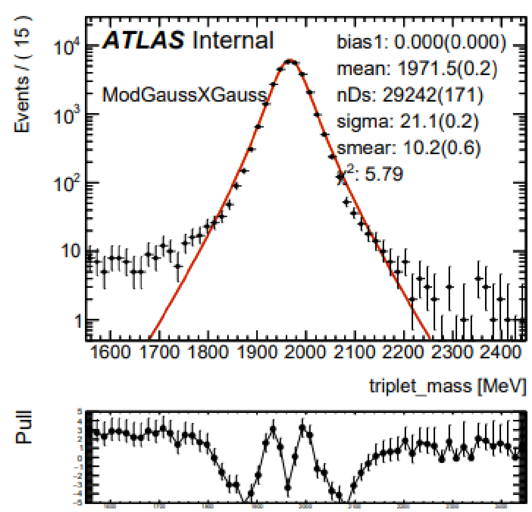
(c) Breit-Wigner



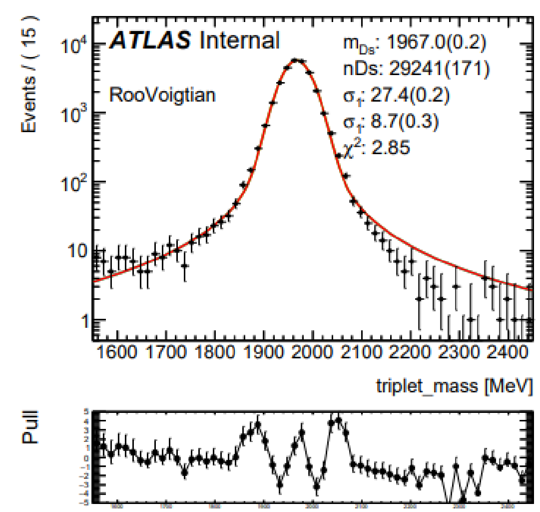
(d) Crystal Ball



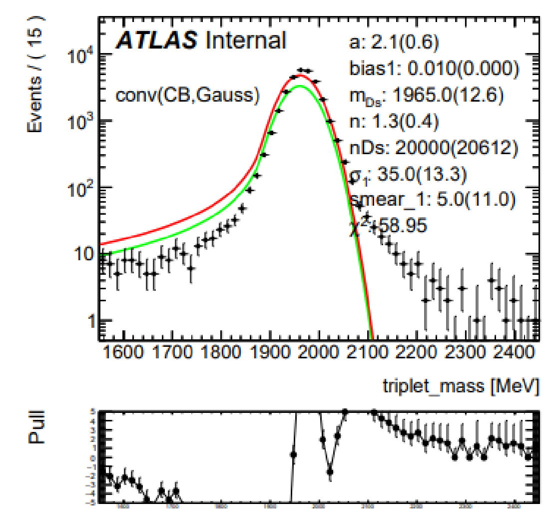
(e) Bukin



(f) Modified Gaussian conv Gaussian

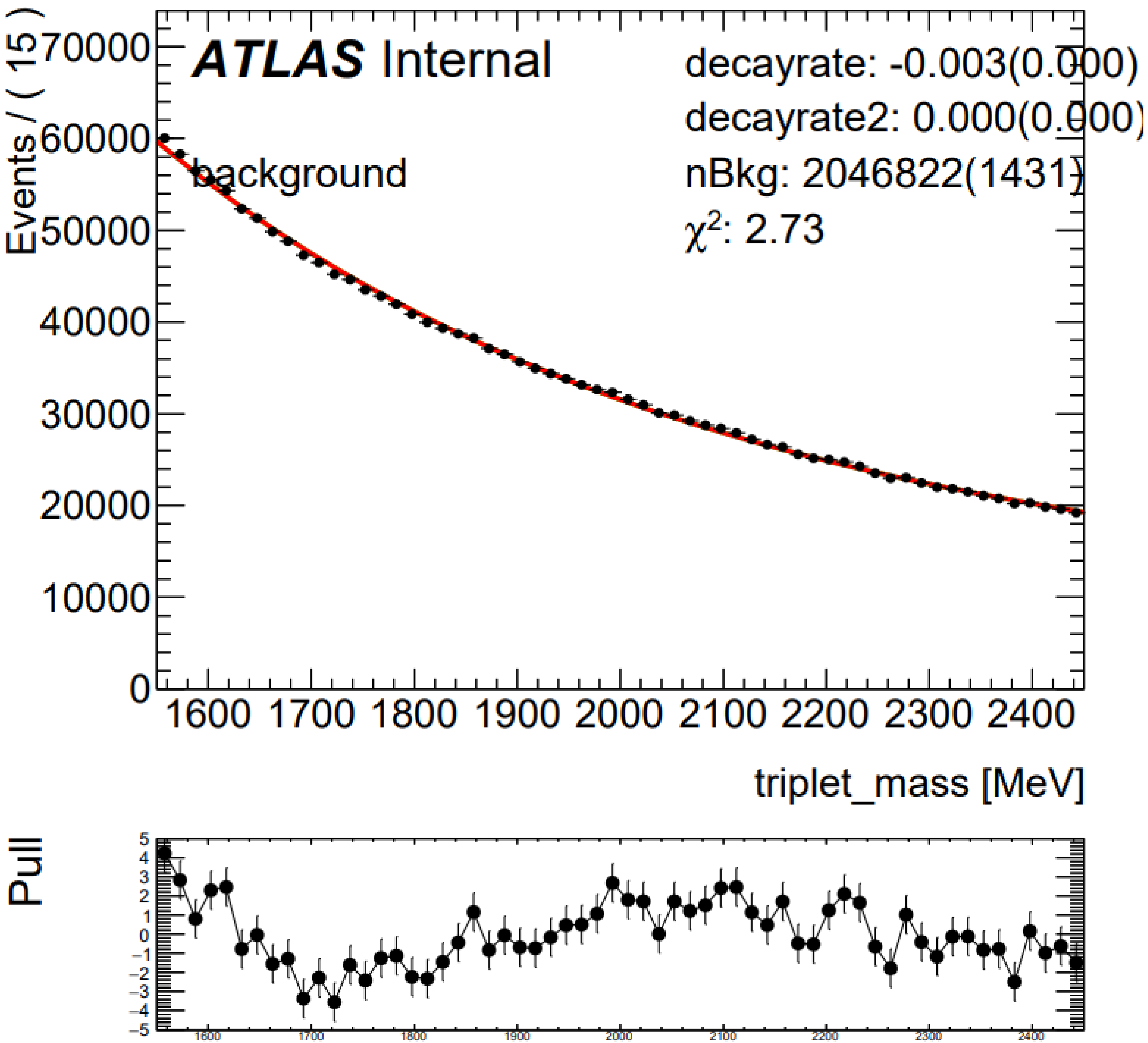


(g) Voigtian



(h) Crystal Ball conv Gaussian

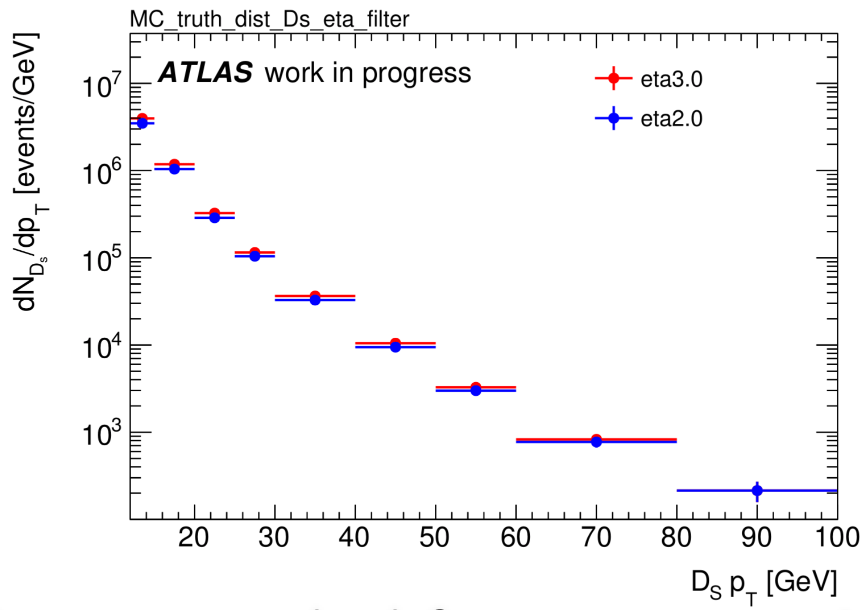
Background model study

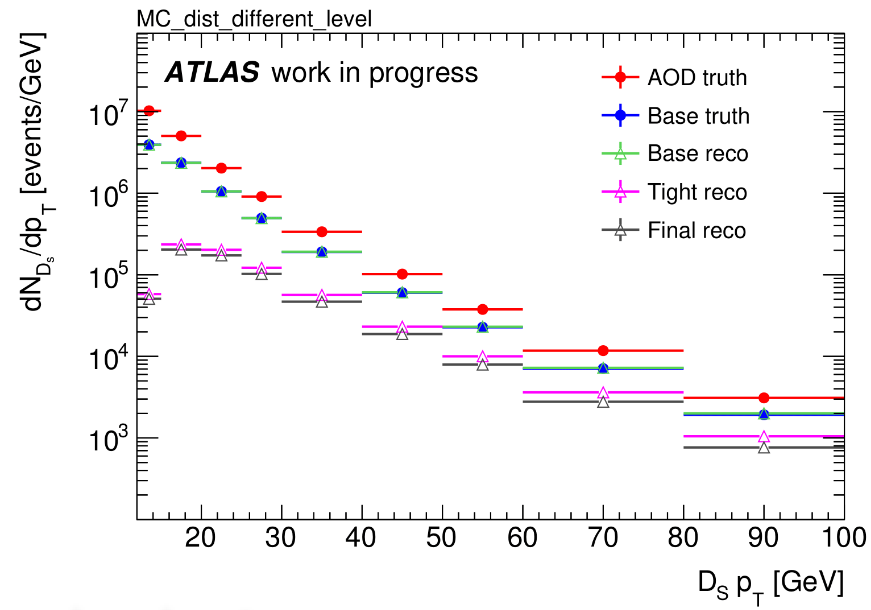


Unfolding non-prompt fraction

- Ingredients
  - For prompt events in MC:
    1.25M events → 60k events
    Selection efficiency $\alpha = 4.8\%$
  - For non-prompt events in MC:
    1.25M events → 47.8k events
    Selection efficiency $\beta = 3.8\%$
  - In data:
    Measured non-prompt fraction is f
- Consider the non-prompt to prompt ratio
  - $\frac{0.17}{\beta} / \frac{0.83}{\alpha} = \frac{f}{\beta} / \frac{1-f}{\alpha} = \frac{\alpha f}{\beta(1-f)} / 1$
- Formula
  - Weight $\frac{\alpha f}{\beta(1-f)}$ needed for non-prompt MC samples
  - $f_{\text{unfolded}} = \frac{1}{1+\frac{\beta(1-f)}{\alpha f}} = 20\%$

Efficiency Study





- Efficiency needed for cross-section calculation
- Distribution at different levels obtained
  (bb/cc samples mixed with non-prompt fraction of 20%)

New calculation with unfolding

AOD (1M) → Normal Derivation → DAOD (0.7M) → Base → Ntuple (0.5M) → Tight → NTuple (0.05M)

AOD truth p_T

Unfolding matrix
Base reco p_T
Base truth p_T

Ntuple reco p_T

$$\epsilon_{\text{Deriv+Base}} = \frac{\text{Base truth pT}}{\text{AOD truth pT}}$$

$$\epsilon_{\text{Tight}} = \frac{\text{Ntuple reco pT}}{\text{Base reco pT}}$$

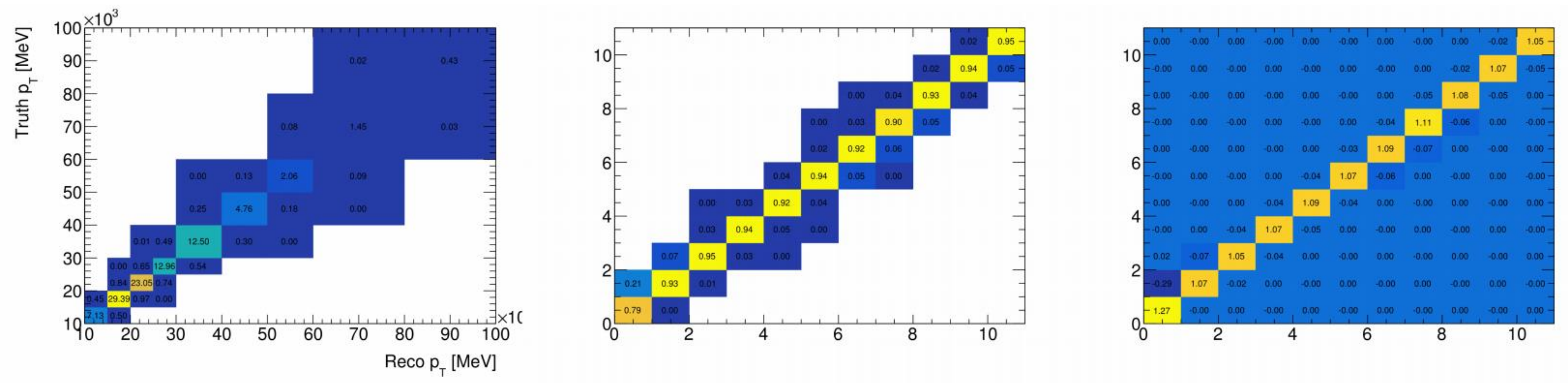
$$\sigma = \frac{1}{Lumi \times BR} * \frac{1}{\epsilon_{3.5,3.5,0.7}} * \frac{1}{\epsilon_{\text{Deriv+Base}}} * M_{\text{unfold}} * \frac{N_{Ds}}{\epsilon_{\text{Tight}}}$$

reco

Truth

Unfolded Reco (Truth)

Resolution and Unfolding



(a) Migration matrix (b) Response matrix (c) Inverted response matrix

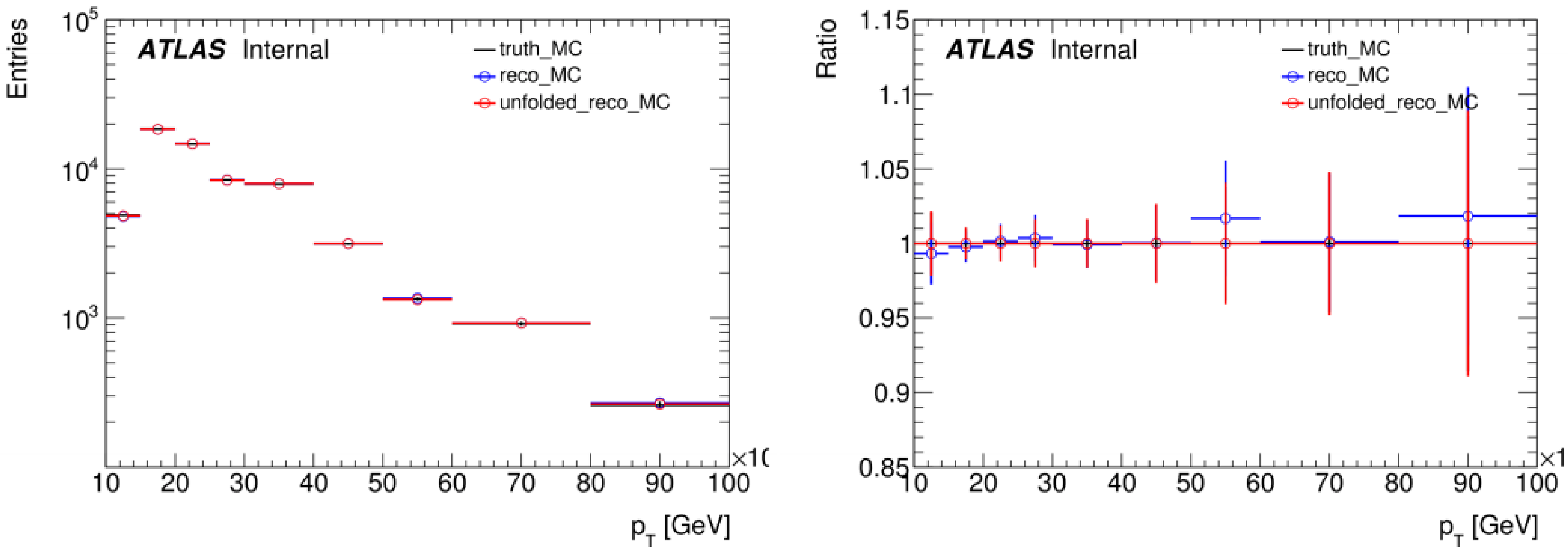


Figure 16: Closure test of the matrix inversion technique applied for unfolding in MC simulation. Left: Transverse momentum of the triplet system at generated (black) and reconstructed (blue) level. In red the unfolded distribution is overlaid. Right: ratio of reconstructed and unfolded distribution w.r.t truth.

Links

- Ds Internal Note
- BPHY7 Derivation
- Twiki – MC information
- FONLL
- LHCb thesis
- Kohei data16
- 7TeV Run-I measurement paper
- 7TeV Run-I internal notes
- CMS newest result