



A measurement of $D^{*\pm} \rightarrow \pi^{\pm} (K^{\mp} \pi^{\pm} \pi^0)$ decay channel as pertaining to the production of a charm quark in associations with a W boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

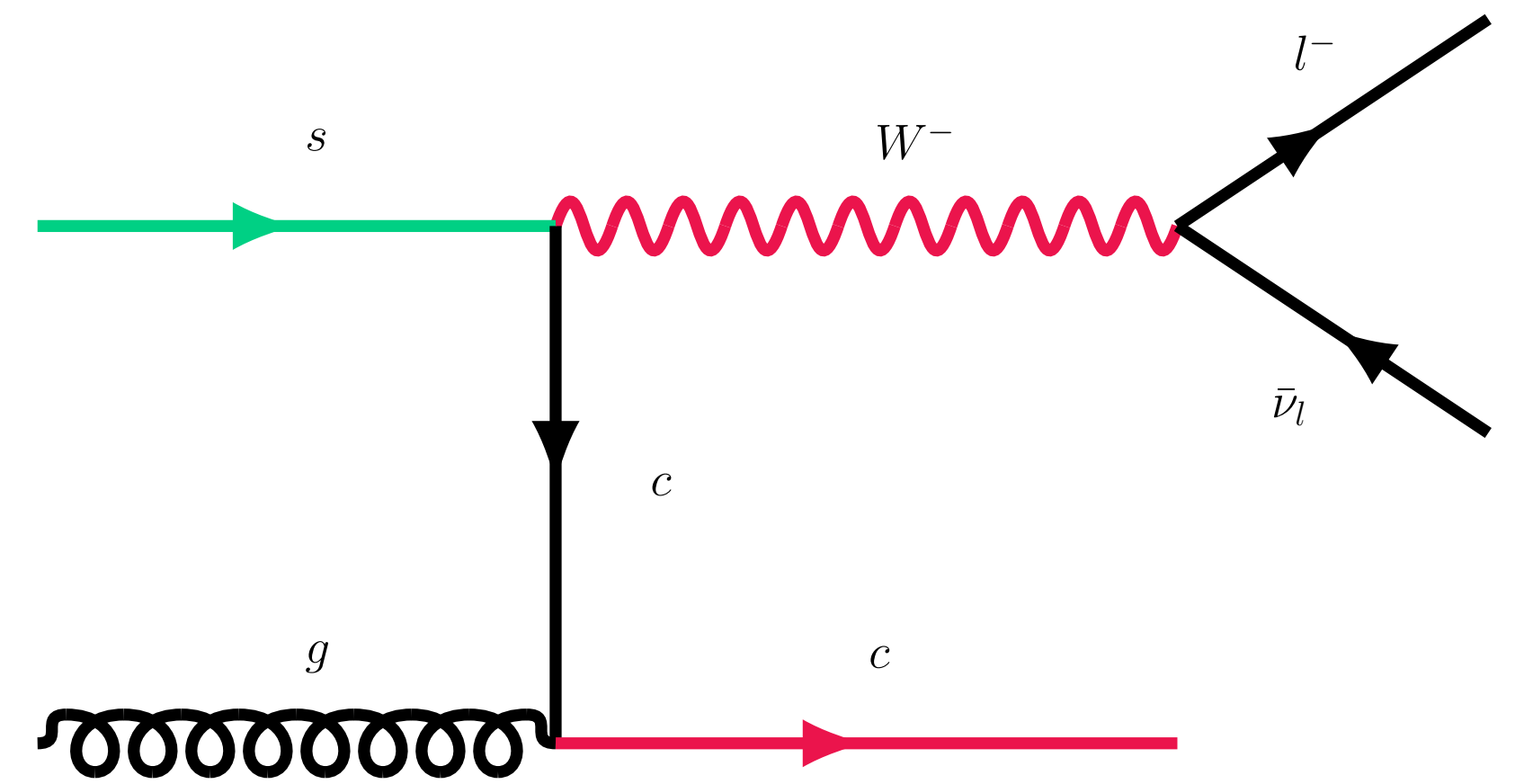
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General Overview

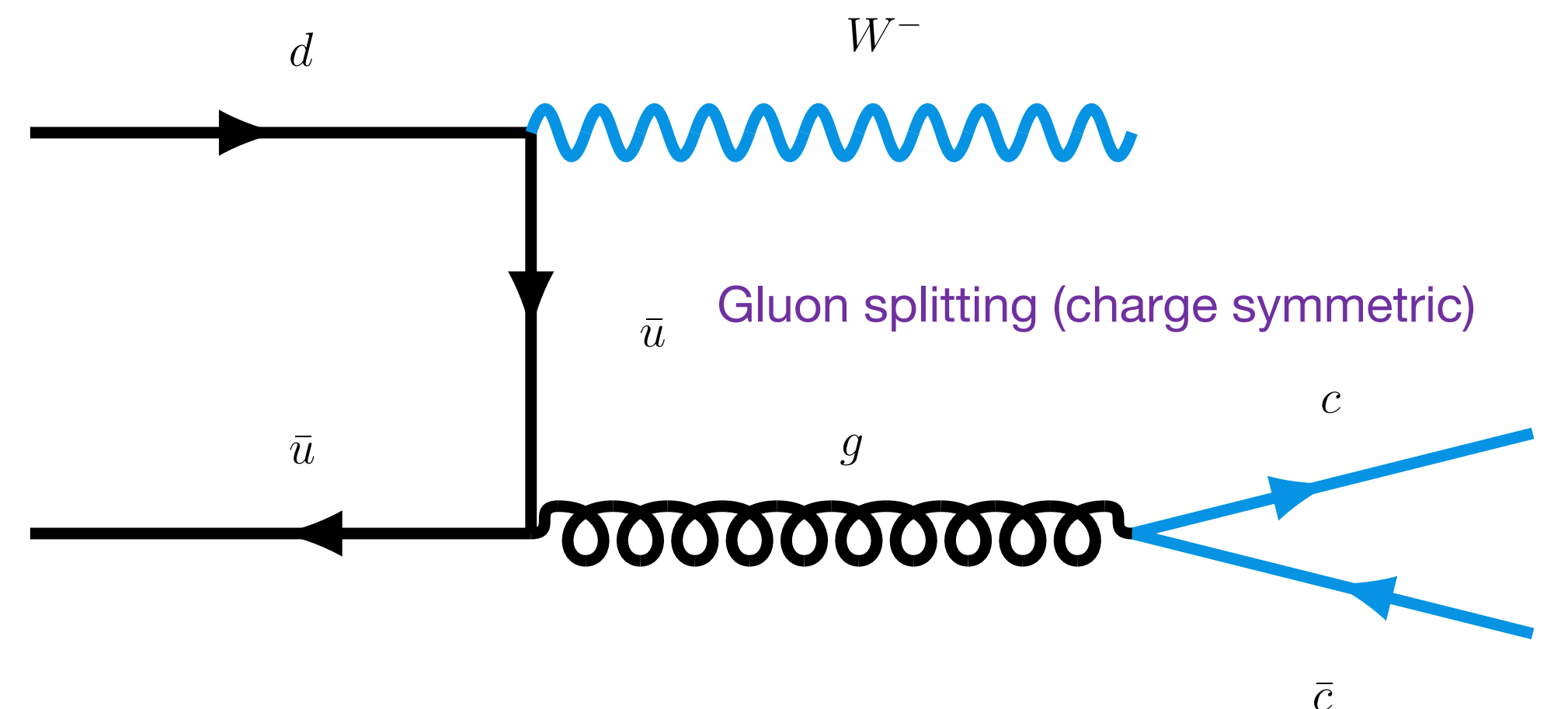
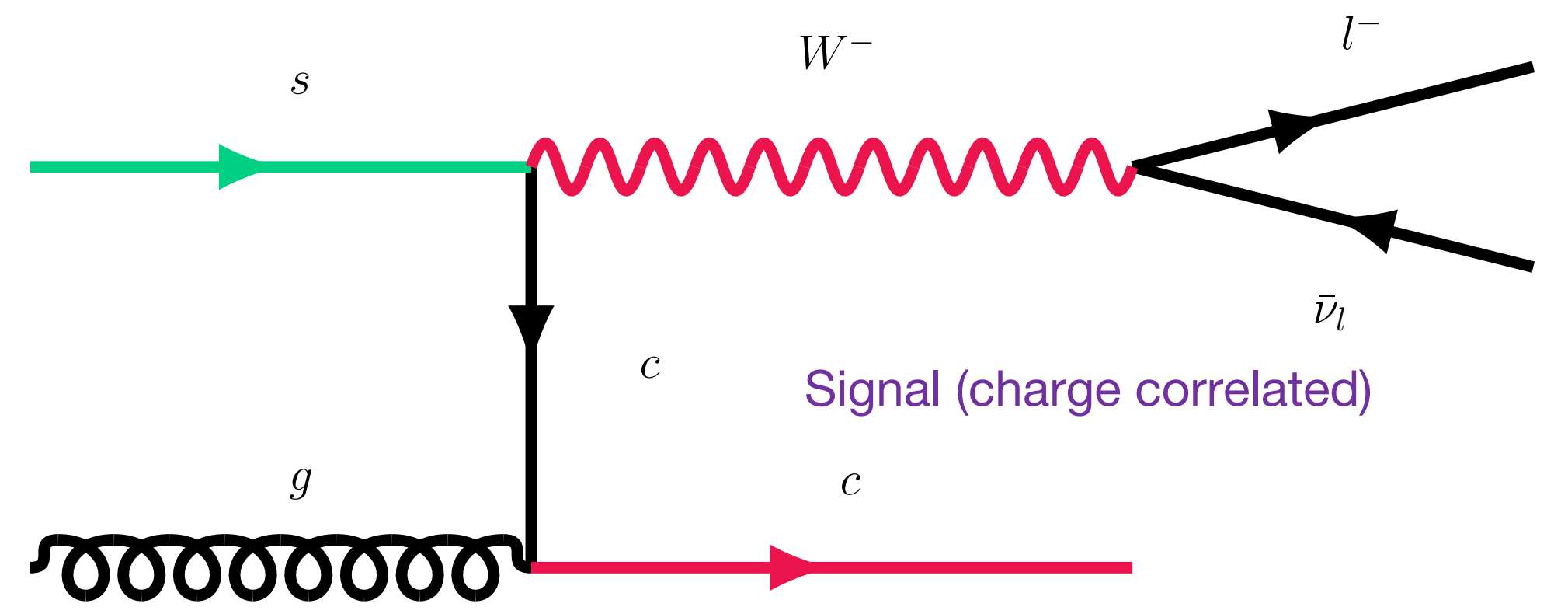
- A measurement of $W + c$ process at the LHC
 - Measurement of cross section is sensitive to s quark PDF and $s - \bar{s}$ ratio
- Measured through semi-leptonic channel or through presence of charmed hadron (D meson)
 - We choose latter route, making our analysis $W + D$ analysis
- Our analysis spans many D mesons decay channels (using Run 2 data to measure same quantities as measured in Run 1), but here we only look at the decay channel $D^{*\pm} \rightarrow \pi^\pm (K^\mp \pi^\pm \pi^0)$
 - Termed the *Satellite* mode; π^0 is not reconstructed
 - Other modes:
 - $D^{*\pm} \rightarrow \pi^\pm (K^\mp \pi^\pm)$
 - $D^{*\pm} \rightarrow \pi^\pm (K^\mp \pi^\pm \pi^\mp \pi^\pm)$



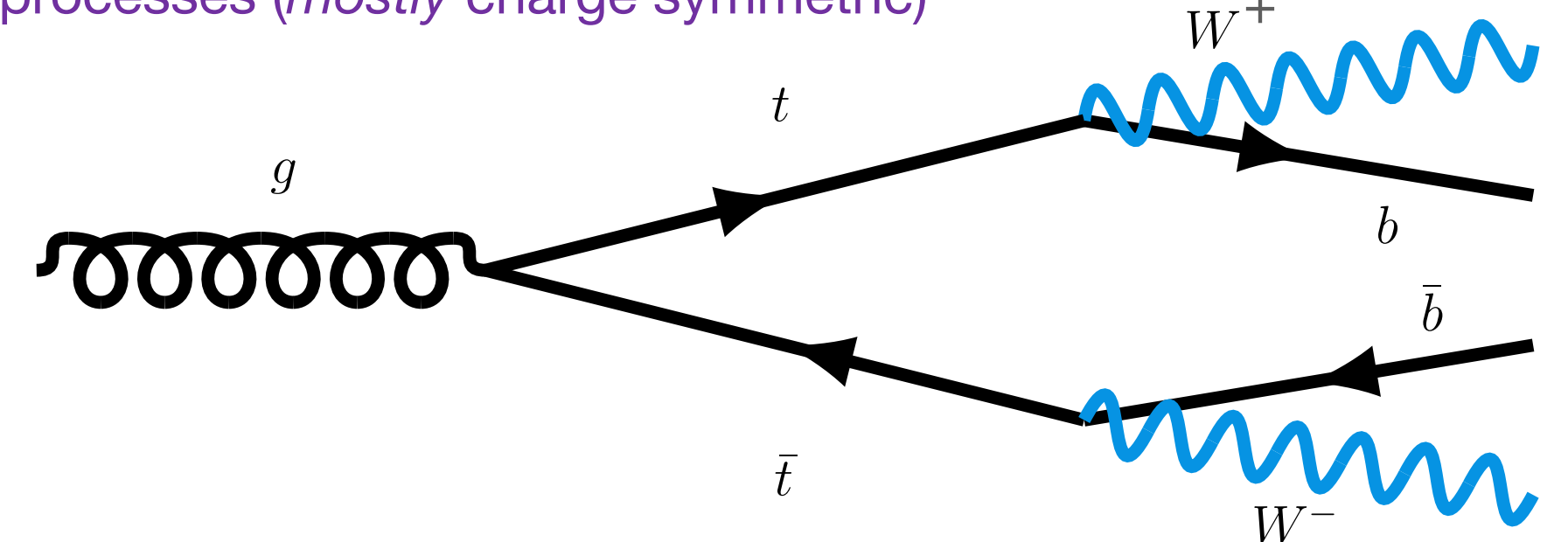
Overview

General measurement procedure

- Goal: separate signal events from background events
- Signal events must have W bosons and D mesons of opposite sign charge (OS)
 - Charge correlation between W boson and c quark
- Several background processes have W bosons and D mesons with no charge correlation (OS or SS)
 - Charm quarks produced in quark-anti quark pairs and other charge symmetric processes (gluon splitting and most $t\bar{t}$ processes)
- The signal in the events we analyze are greatly enhanced by looking at opposite sign (OS) minus same sign (SS) profiles (OS-SS)
 - Charge asymmetric $t\bar{t}$ processes contain $W \rightarrow c\bar{s}$ and remain in background



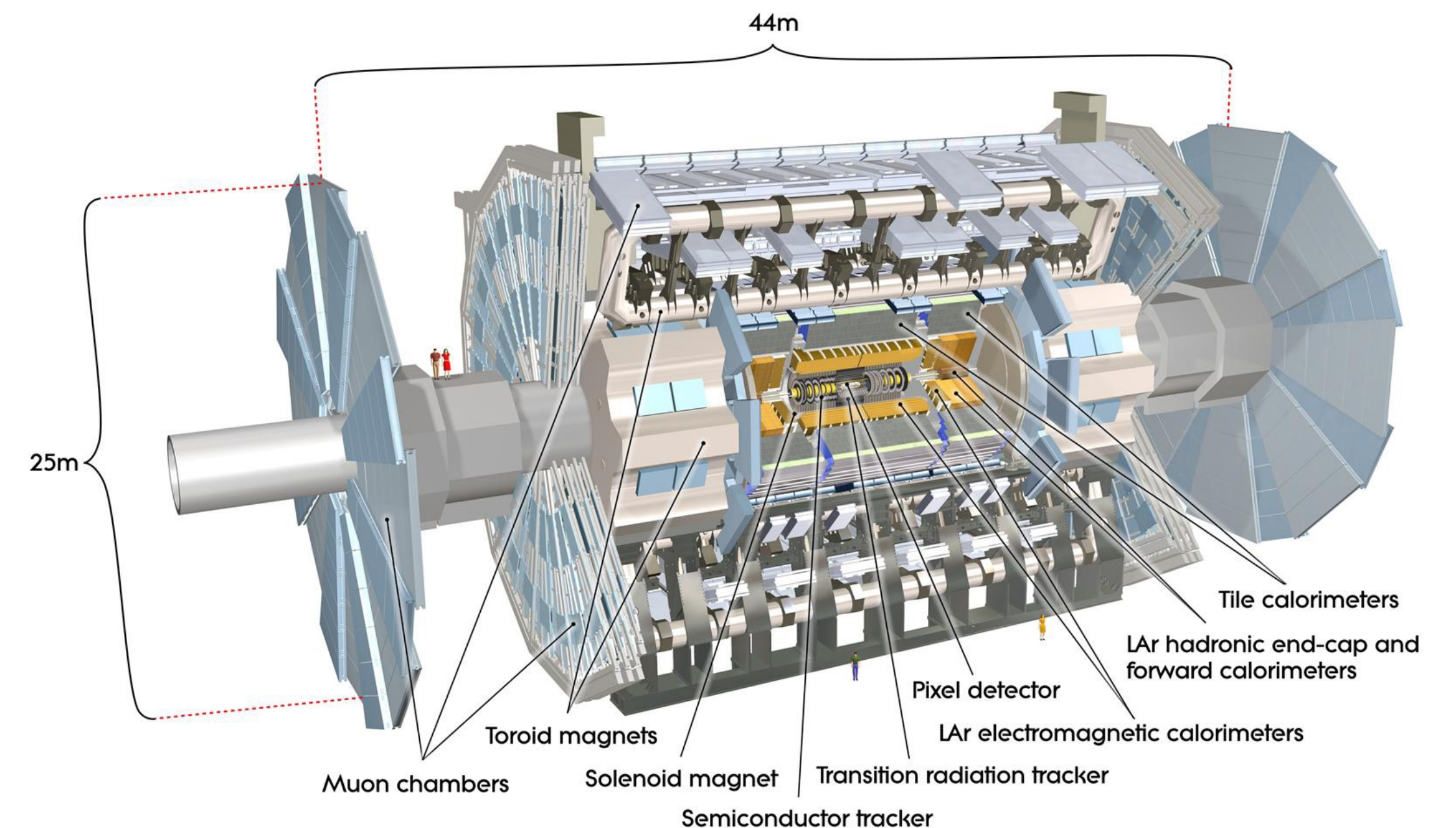
$t\bar{t}$ processes (mostly charge symmetric)



Data and Monte Carlo Samples Used

- Data
 - Entire Run 2 data set (2015-2018)
 - Total integrated luminosity $\mathcal{L} = 139.0\text{fb}^{-1}$ (Uncertainty of 1.7%)
- MC Samples
 - Produced with GEANT4 based ATLAS detector simulations
 - Signal event generators
 - MadGraph LO (hard scattering)
 - Pythia8 (parton showers)
 - PDF sets include NNPDF3.0NLO set

The ATLAS Detector



<https://cds.cern.ch/record/1095924>

Truth Definition of Satellite Decay Mode

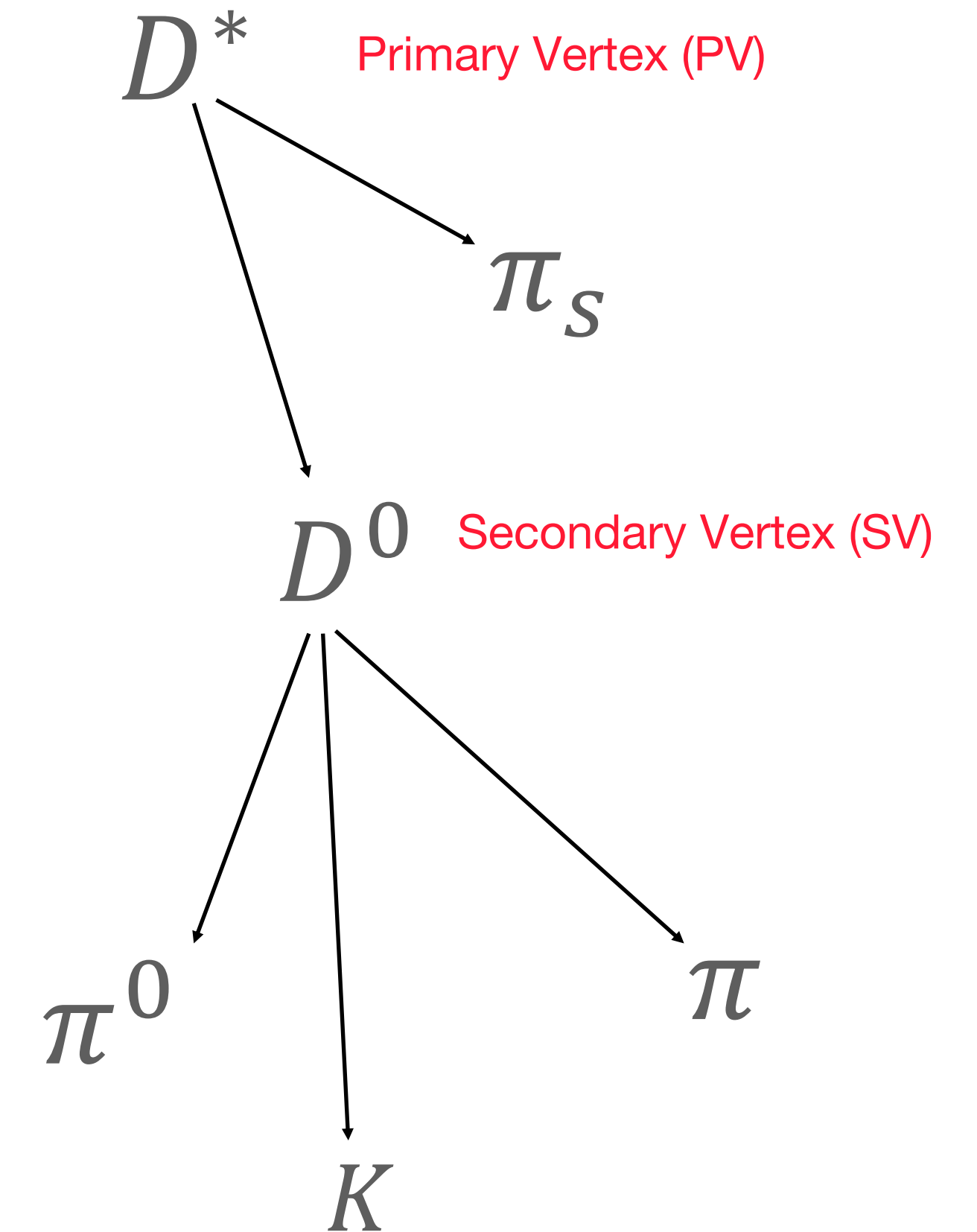
Fiducial Event Selection

- Require $D^{*\pm} \rightarrow \pi^\pm (K^\mp \pi^\pm \pi^0)$ decay at truth level
- We place *fiducial* cuts on our truth level events
 - For W boson: $p_T^l > 30$ GeV and $|\eta^l| < 2.5$
 - For D meson: $p_T(D) > 8$ GeV and $|\eta(D)| < 2.5$

Reconstructing the D^* Meson, W Boson

Overview

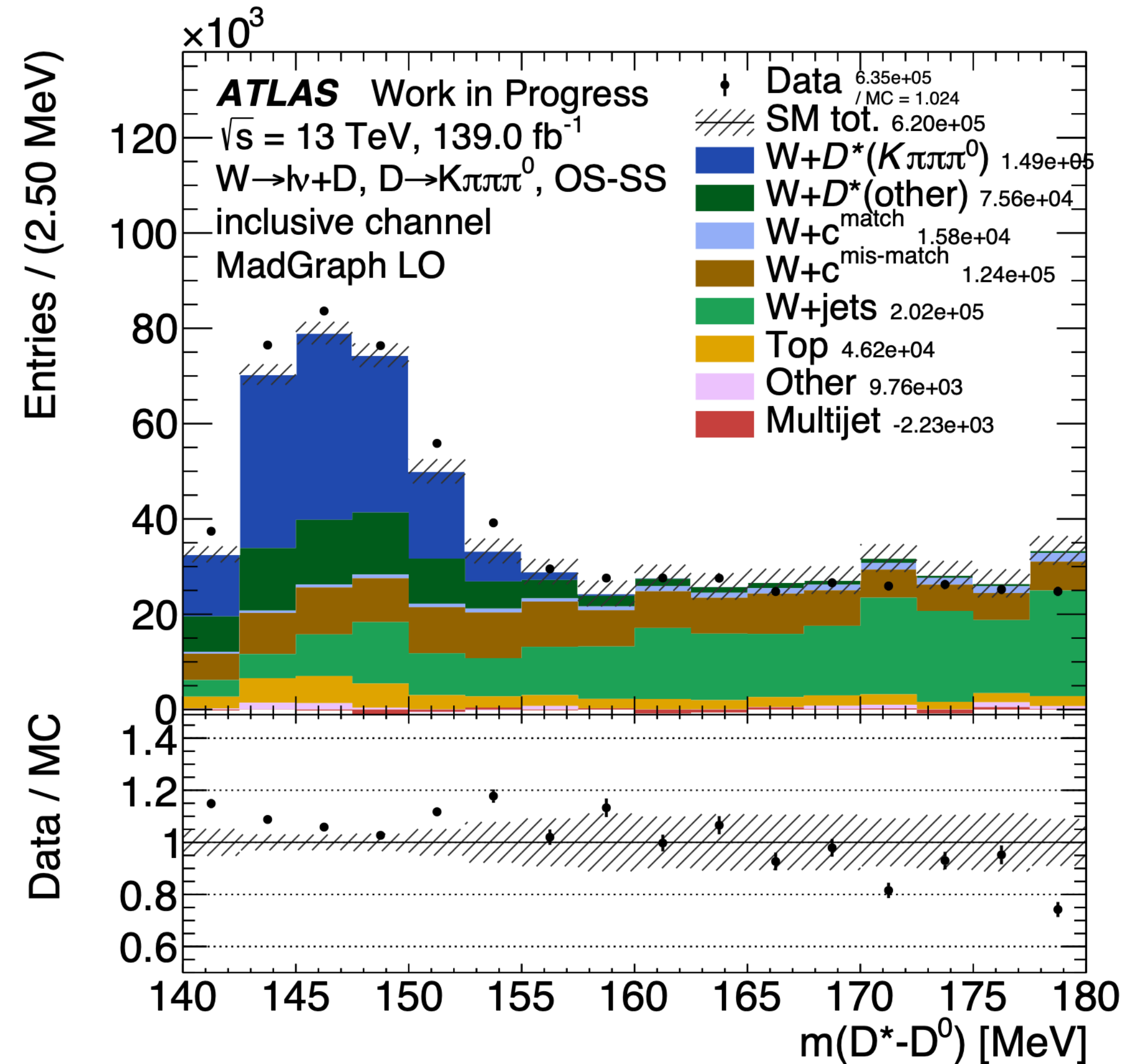
- D^* decays to a soft pion and D^0
 - Require D^*, D^0 to originate from PV, SV
 - D^* and D^0 differ in mass by 6%
 - Analyze mass difference $m(D^* - D^0)$ rather than mass
- Vertices reconstructed with Kalman Filter which fits best intersection of reconstructed tracks
- We require that $E_T^{\text{miss}} > 30 \text{ GeV}$ and $m_T > 60 \text{ GeV}$ for reconstructed events (for W boson)
 - Reduce multi-jet background
- Further require one charged lepton with $p_T > 30 \text{ GeV}$ and $|\eta| < 2.5$



Reconstructing the D^* Meson

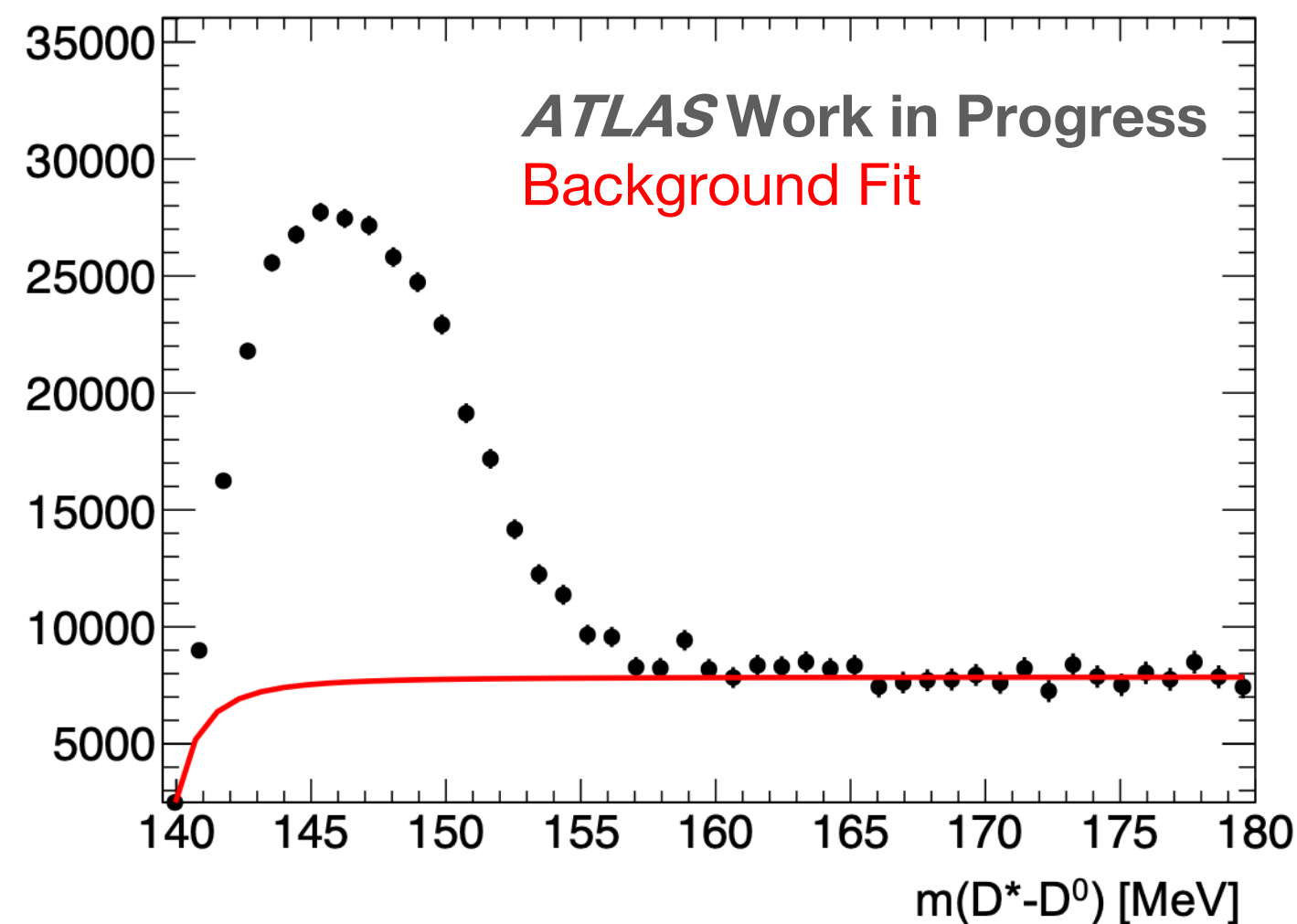
Signal vs Background Categories

- Signal MC samples: $W + D(K\pi\pi\pi^0)$
- Mis-matched D^* decays: $W + D^*(\text{other})$
- $W + c^{\text{match}}$: All tracks matched to D meson, but not to D^*
- $W + c^{\text{mis-match}}$: At least 1 track matched to D meson
- $W + jets$: All other processes resulting from a $W + jets$ interaction
- *Other*: All $Z + jets$ and Diboson events
- *Top*: Top quark ($t\bar{t}$) events
- *Multijet*: Uses data-driven matrix method (currently computed for D^+ meson and applied to D^* meson)



Cut optimized event selection

- Need to optimize our $m(D^* - D^0)$ signal significance, while maintaining a signal efficiency close to 1
 - Signal Region (SR): 135 MeV to 165 MeV
 - Significance: $Z = \frac{S}{\delta_S}$
 - Signal efficiency: $\frac{\text{Data} - \text{subtracted Background Profile}}{\text{Scaled Monte Carlo Signal}}$
- Include all points except those in the SR in a background fit

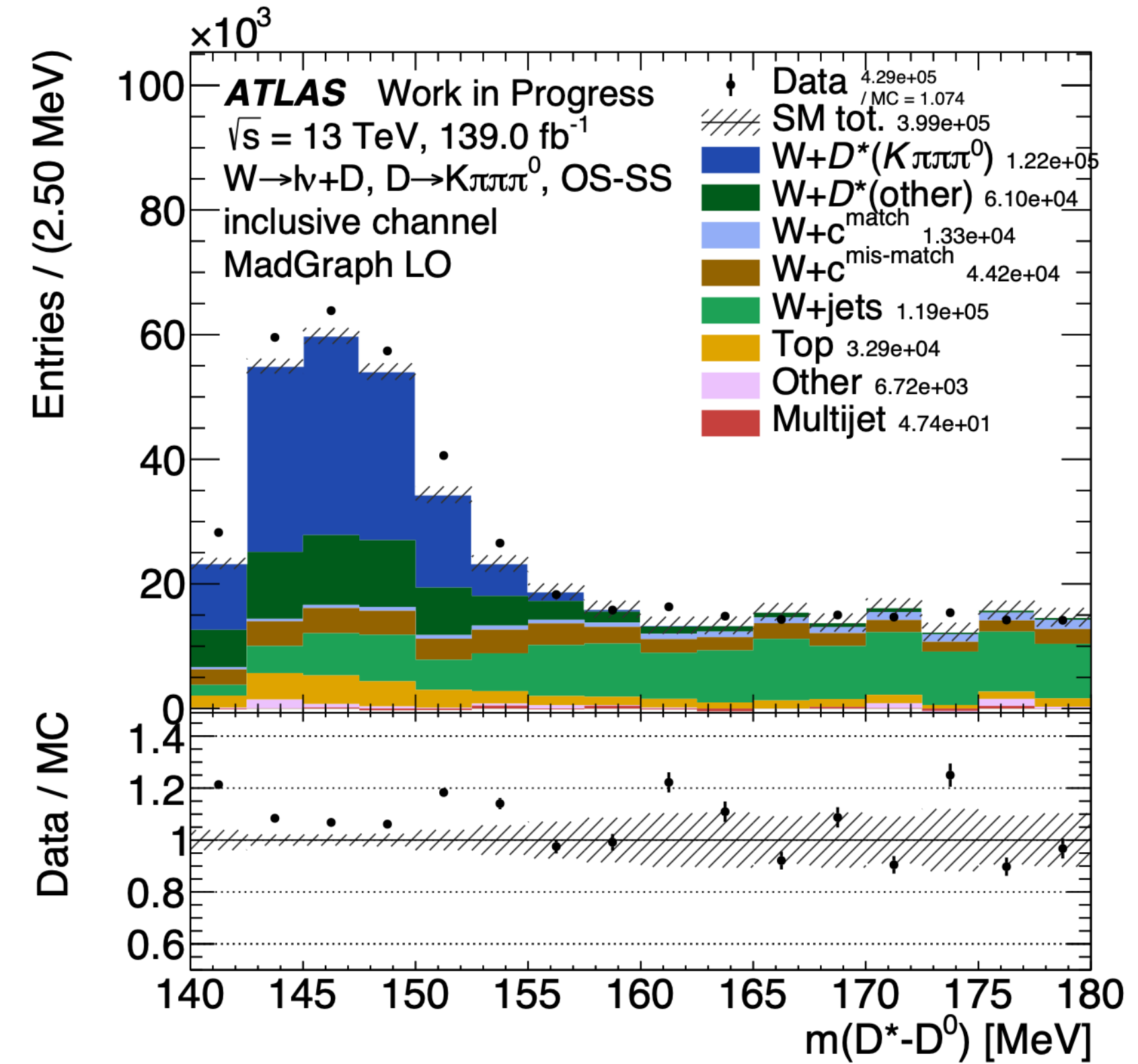
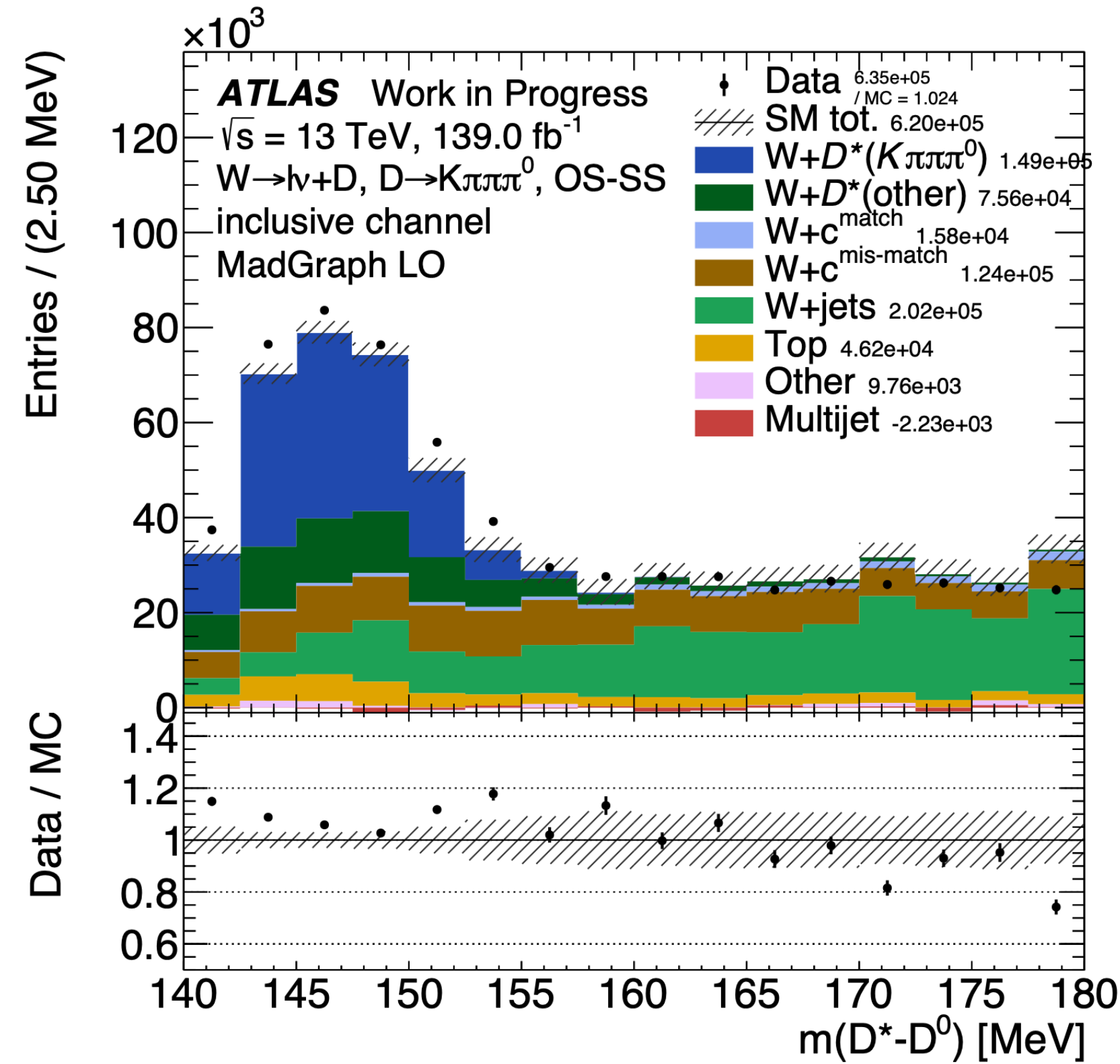


$$y_{\text{bgd}}(x) = A + B \tanh(\log(x - (m_\pi - e^{-A/B})))$$

*CO = Variable that has been cut optimized

N_{tracks} at SV	2
SV Charge	0
CO SV Probability	$\chi^2 < 8$
CO SV Track p_T	$p_T > 800 \text{ GeV}$
Track angular separation	$\Delta R < 0.6$
CO Min. Flight length	$L_{xy} > 0.3 \text{ mm}$
Max. flight length	$L_{xy} < 2 \text{ mm}$
CO SV 3D impact parameter significance	$\sigma^{3D} < 6.0$
CO Isolation	$\frac{p_T(D^*)}{\sum p_{T \text{ tracks}}^{\Delta R < 0.4}} < 2.0$
SV impact parameter	$ d_0 < 10 \text{ mm}$
D^0 mass	$1.5 \text{ GeV} < m_{K\pi} < 1.7 \text{ GeV}$
$\pi_s p_T$	$p_T > 500 \text{ MeV}$
π_s angular separation	$\Delta R(\pi_{\text{slow}}, D^0) < 0.3$
$\pi_s d_0$	$ d_0 > 1 \text{ mm}$
QCD background rejection	$\Delta R(l, D^*) > 0.3$
Phase space	$D^* p_T > 8 \text{ GeV}, \eta < 2.2$

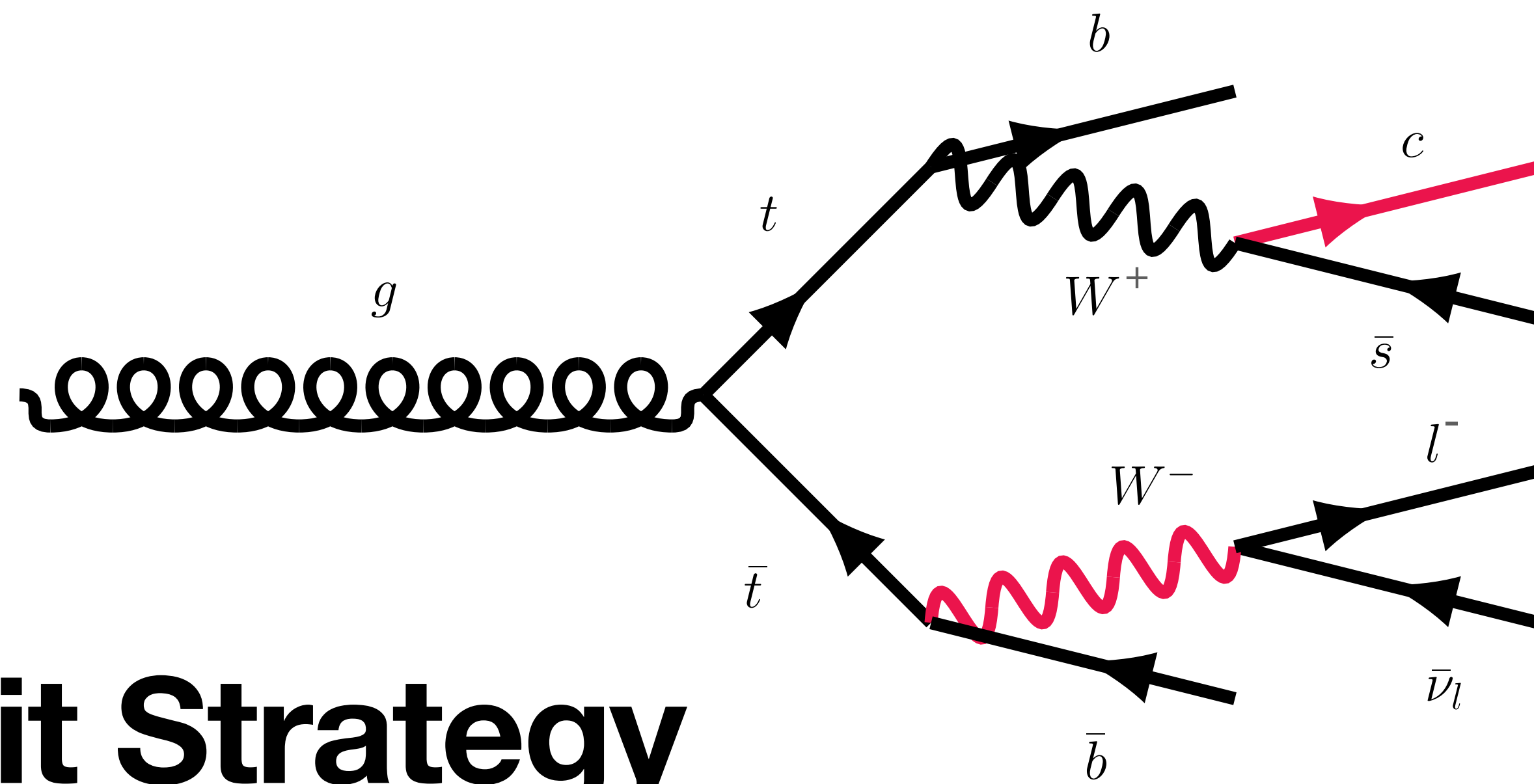
Cut optimized event selection



- Rudimentary definition of Monte Carlo-only relative significance for both OS+SS regions: $Z = \frac{S_{OS+SS}}{\sqrt{S_{OS+SS} + B_{OS+SS}}}$, within SR
- $Z(\text{pre} - \text{opt}) \approx 78 \rightarrow Z(\text{opt}) \approx 103$ (32% increase)

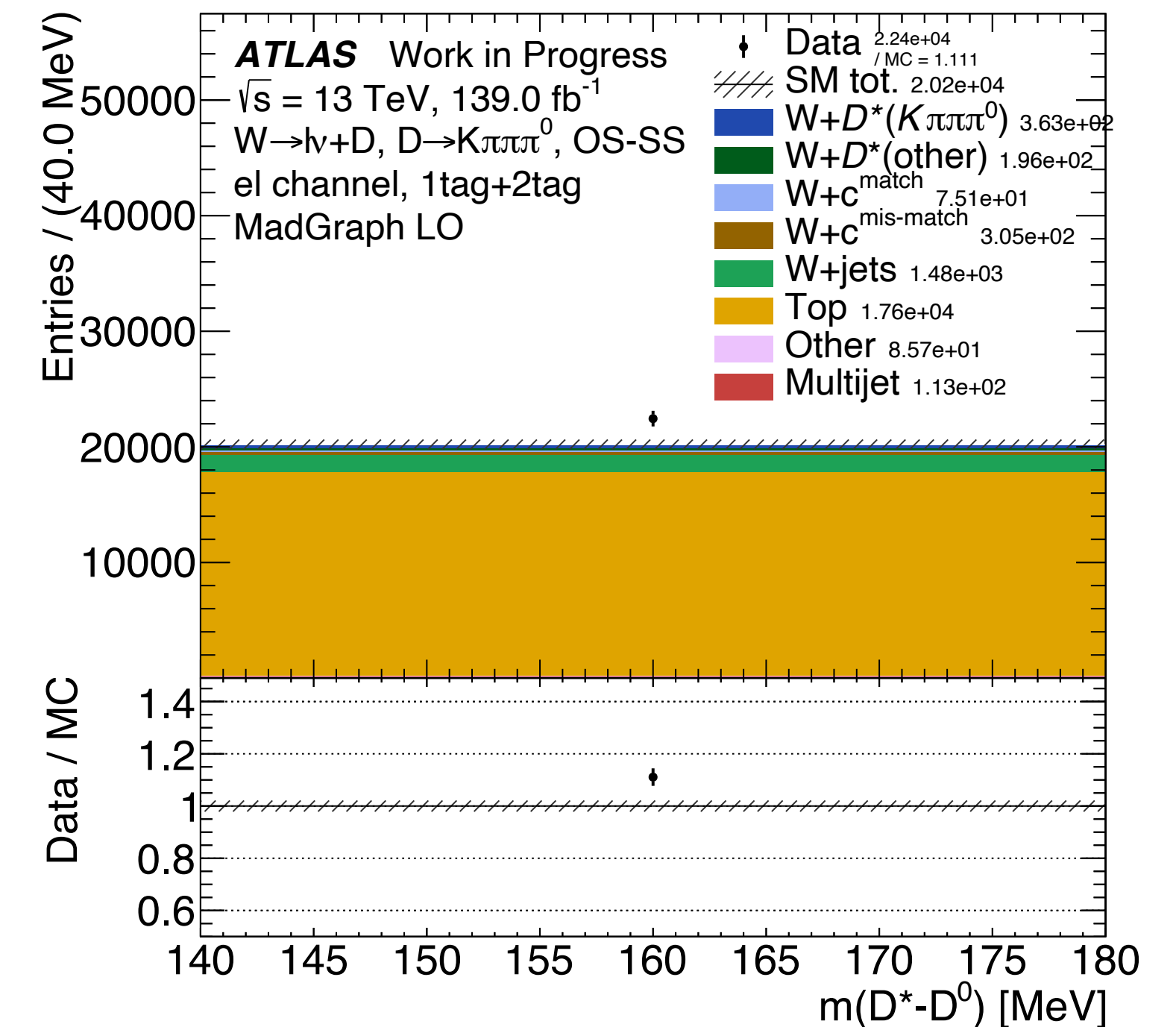
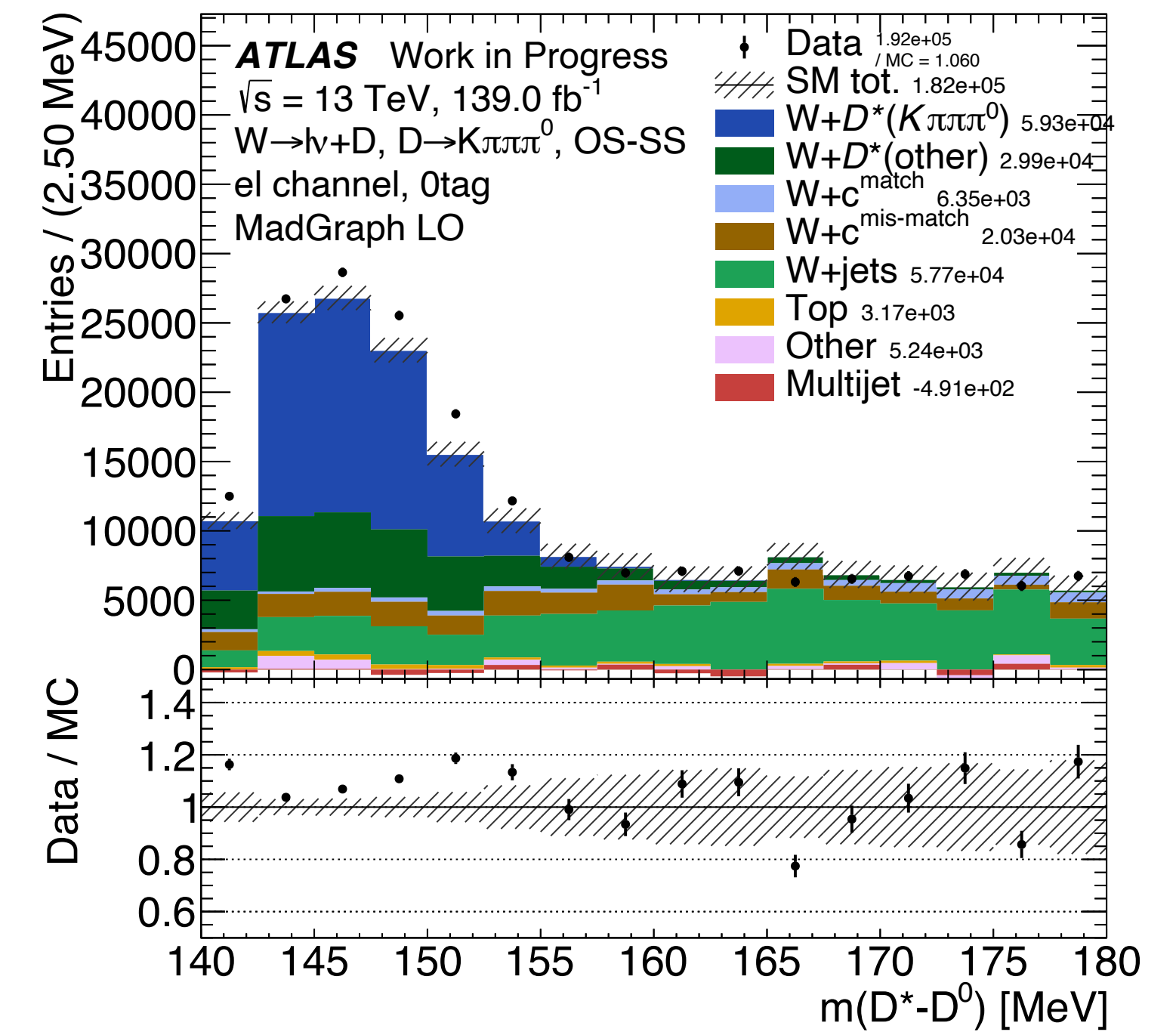
Systematic Uncertainties

- Affect normalization and shape of samples in our fit
- Broadly broken into Experimental and Theoretical systematics
- Examples of Experimental Uncertainties
 - Luminosity (1.7% uncertainty)
 - PDG measured $D^* \rightarrow \pi(K\pi\pi^0)$ branching ratio (BR) ($\sim 3.5\%$ uncertainty)
 - Tracking Efficiency ($\sim 2\%$ uncertainty)
- Examples of Theory Uncertainties (Background)
 - PDF variations
 - QCD Scaling (Renormalization and Factorization)



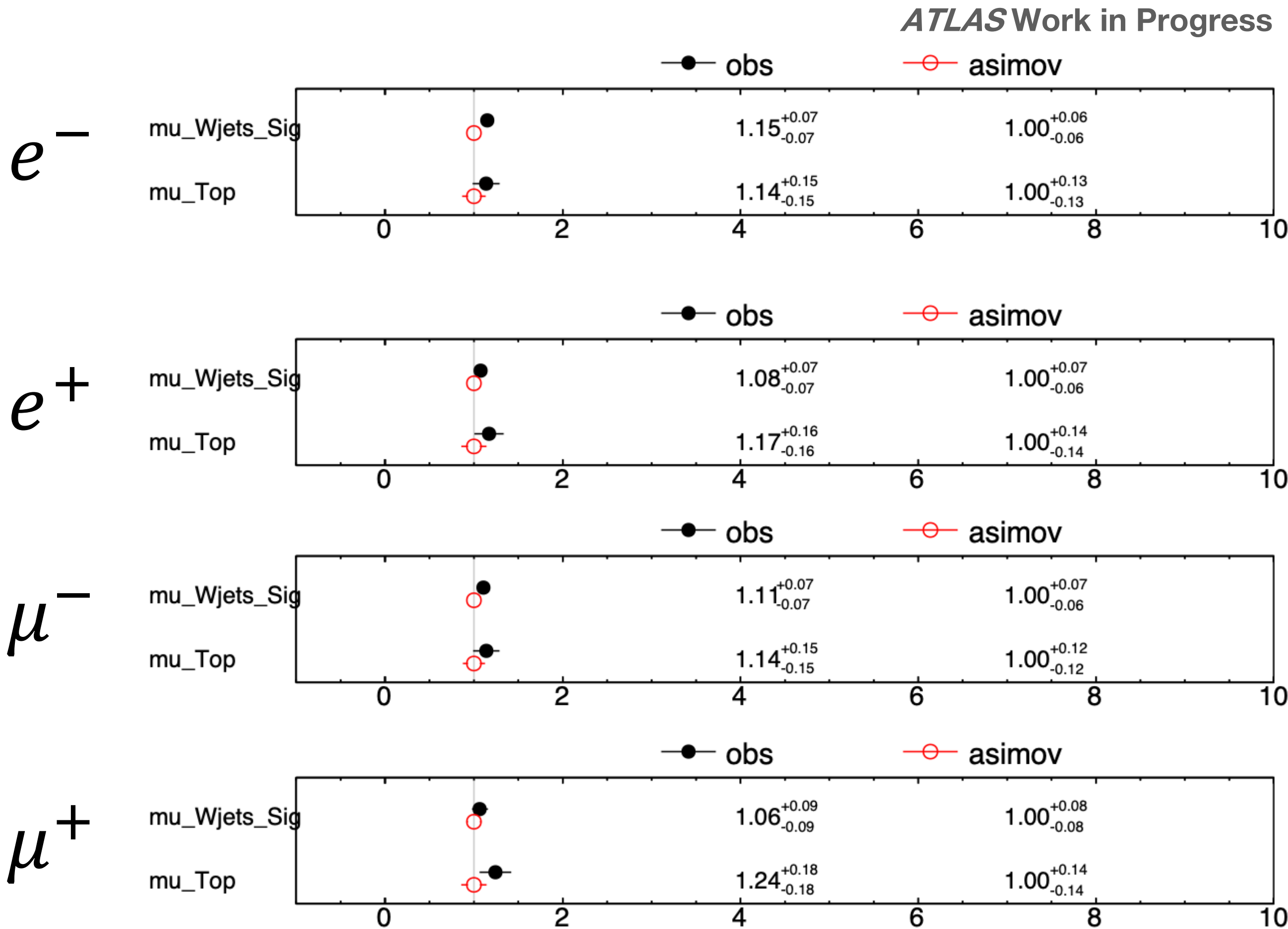
Fit Strategy

- We separate our $m(D^* - D^0)$ profiles into charged electron and muon channels.
- Maximize the OS-SS likelihood by fitting OS and SS regions in a combined fit with a common floating point component correlated bin-by-bin between both regions
- We further split our profiles into regions where 0 and ≥ 1 b quarks have been tagged
 - Better discrimination between $W + jets$ and $t\bar{t}$ regions
- Subsequently perform two binned likelihood fitting routines (observed and Asimov)



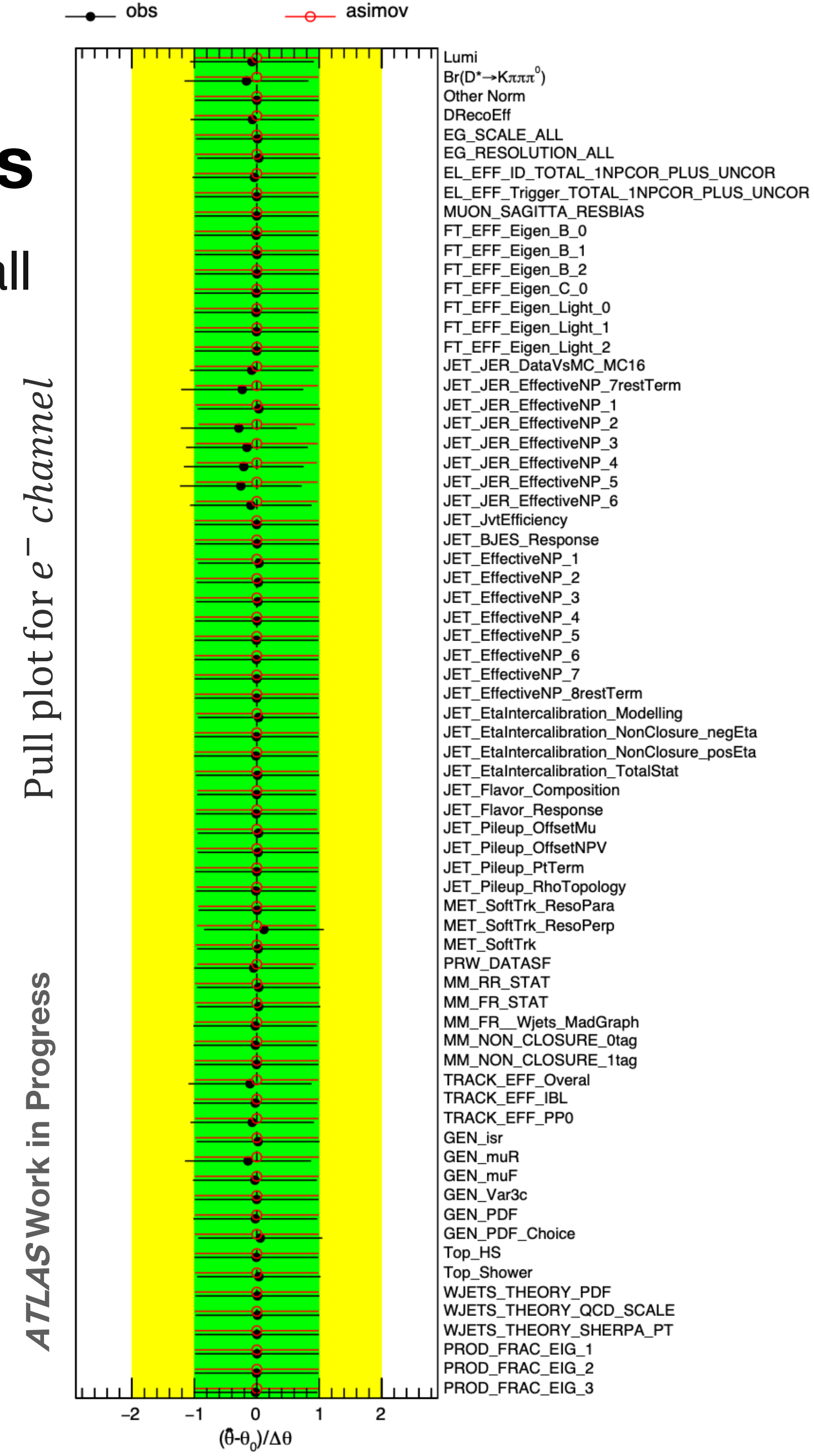
Fitting results

Normalization factors



Pull plots

Very good results in all channels ($\approx 0 \pm 1$)

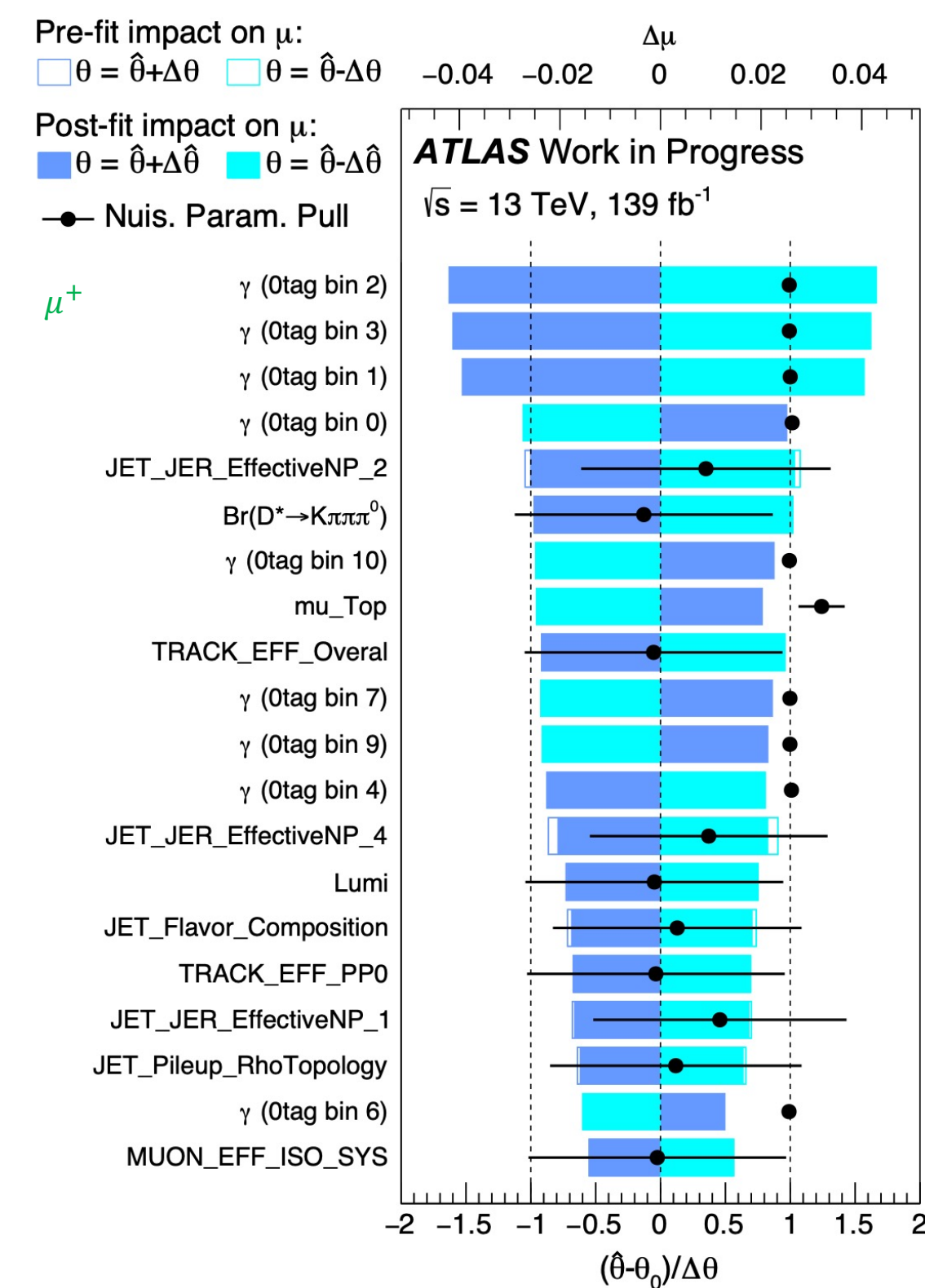
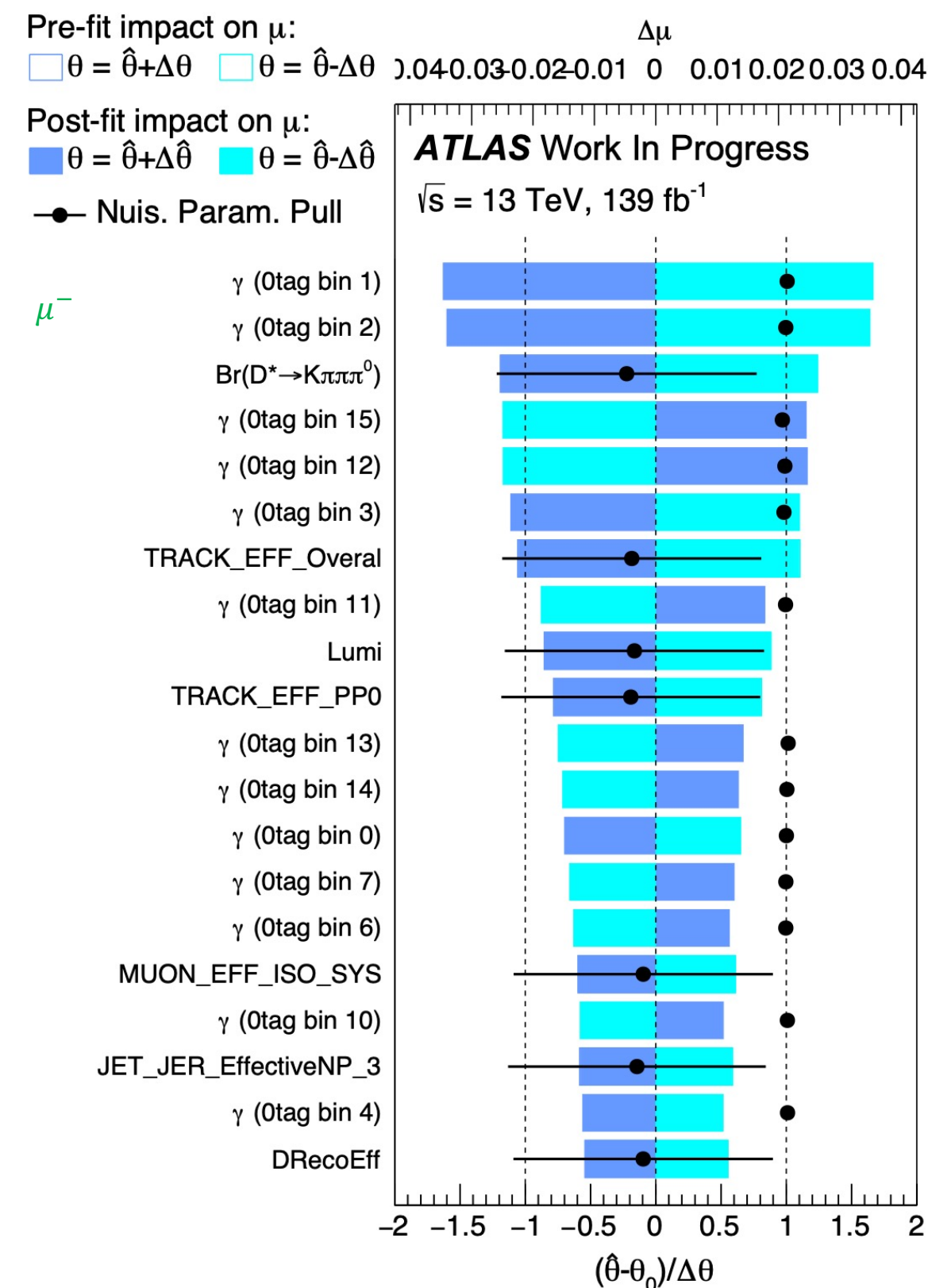
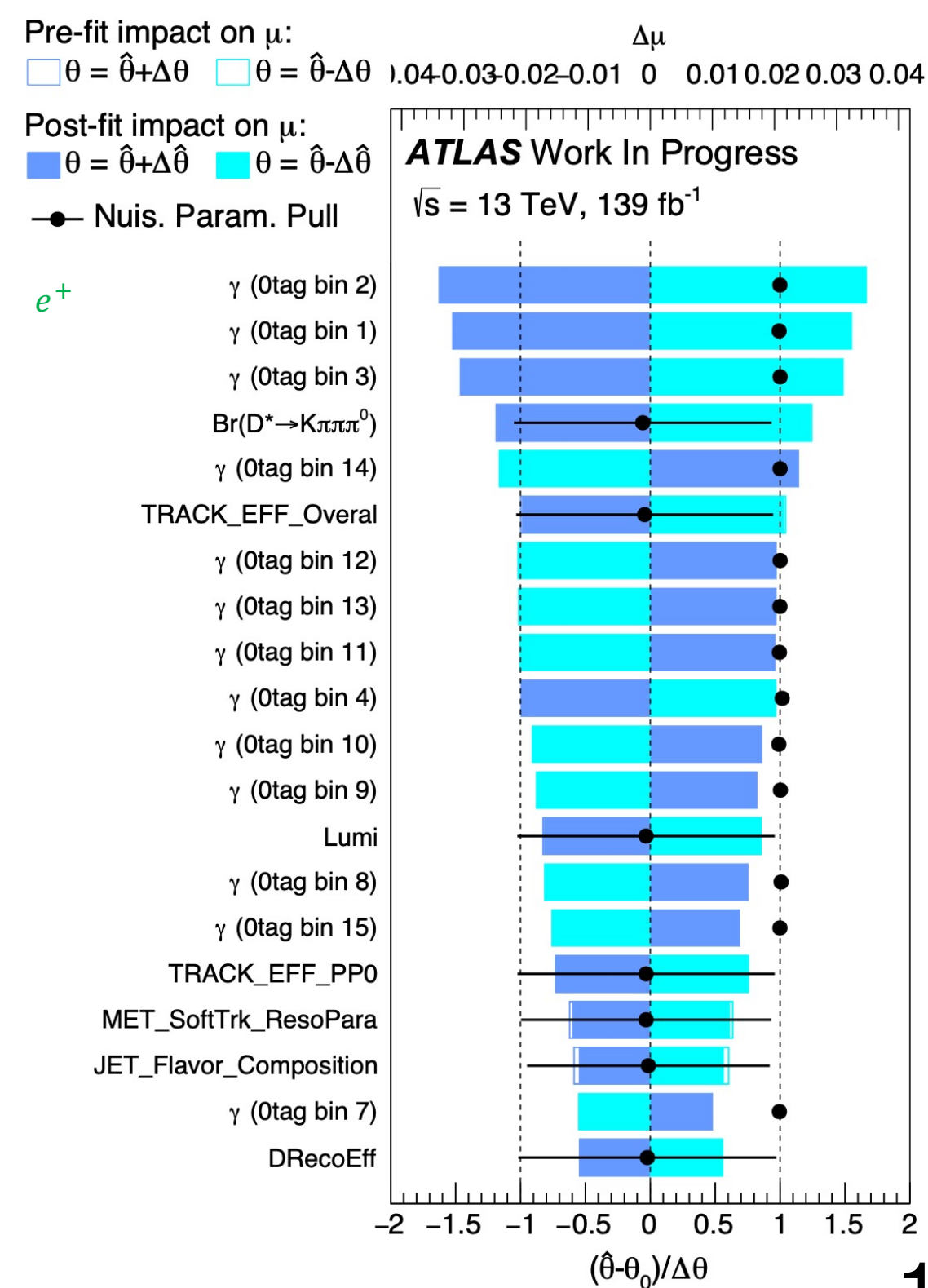
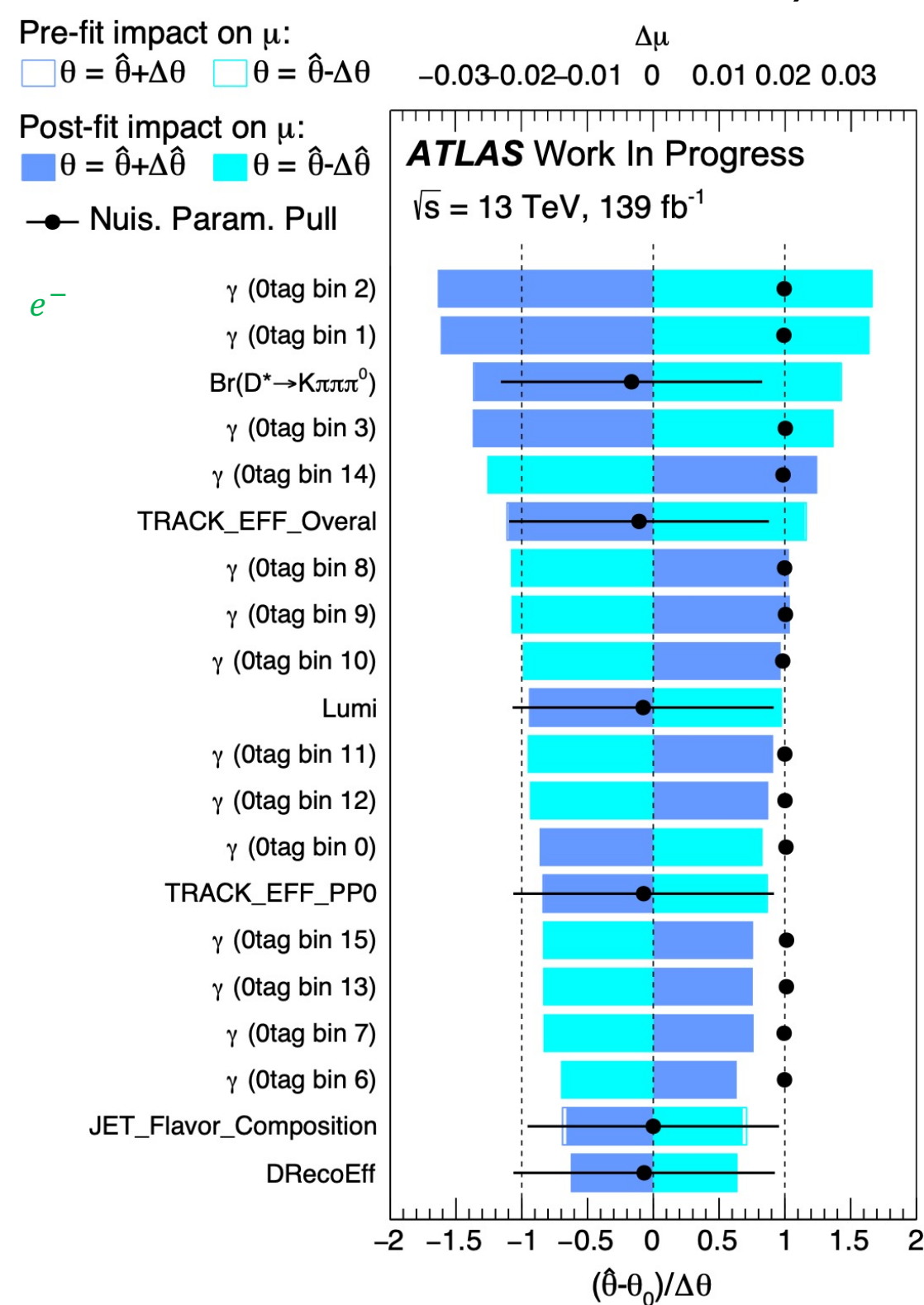


Calculating $R_c^\pm(WD^*)$

- Cross sections computed by scaling MadGraph Standard Model predictions by μ factors derived from fit
- Combine cross sections into positive/negative channels
- $R_c^\pm(WD^*) = \frac{\sigma^{\text{fid}}(W^+ + D^{*-})}{\sigma^{\text{fid}}(W^- + D^{*+})}$
- Errors (statistical and systematic) combined assuming no correlations
- $R_c^\pm(WD^*) = 0.92$ (In agreement with theory).
- Calculate uncorrelated error (upper bound)
- $\sigma(R_c^\pm(WD^*)) < 0.06$

Ranking plots

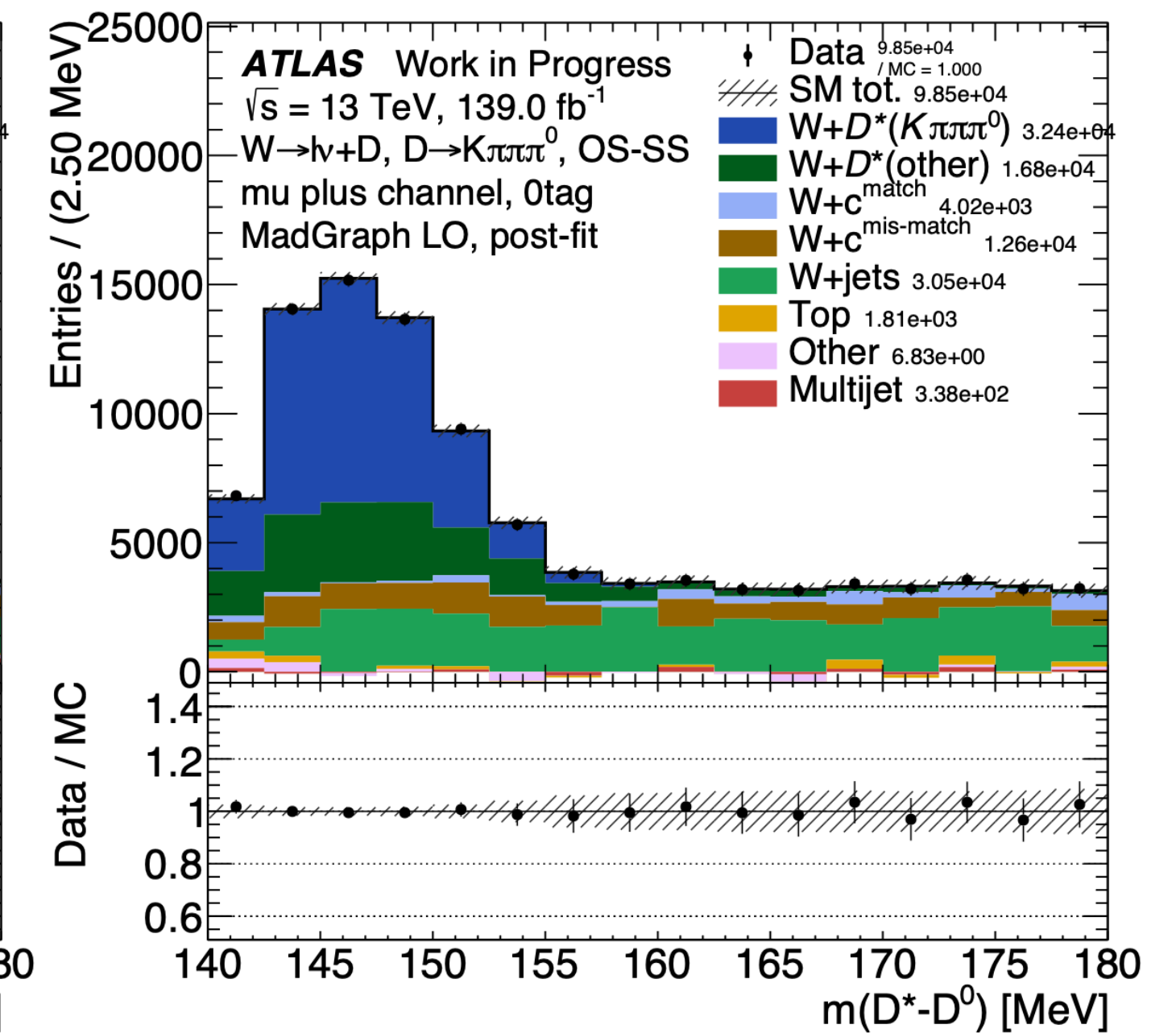
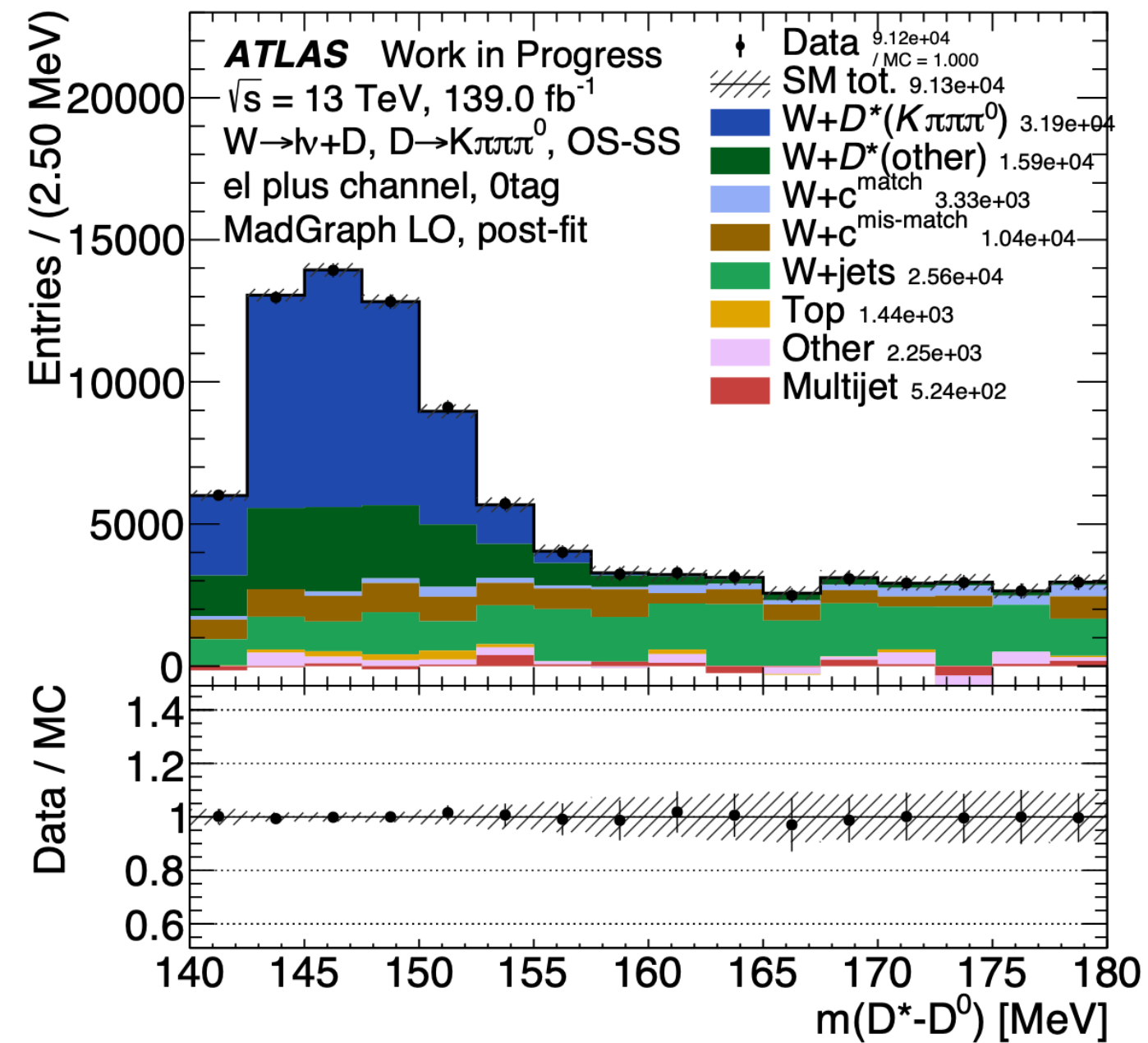
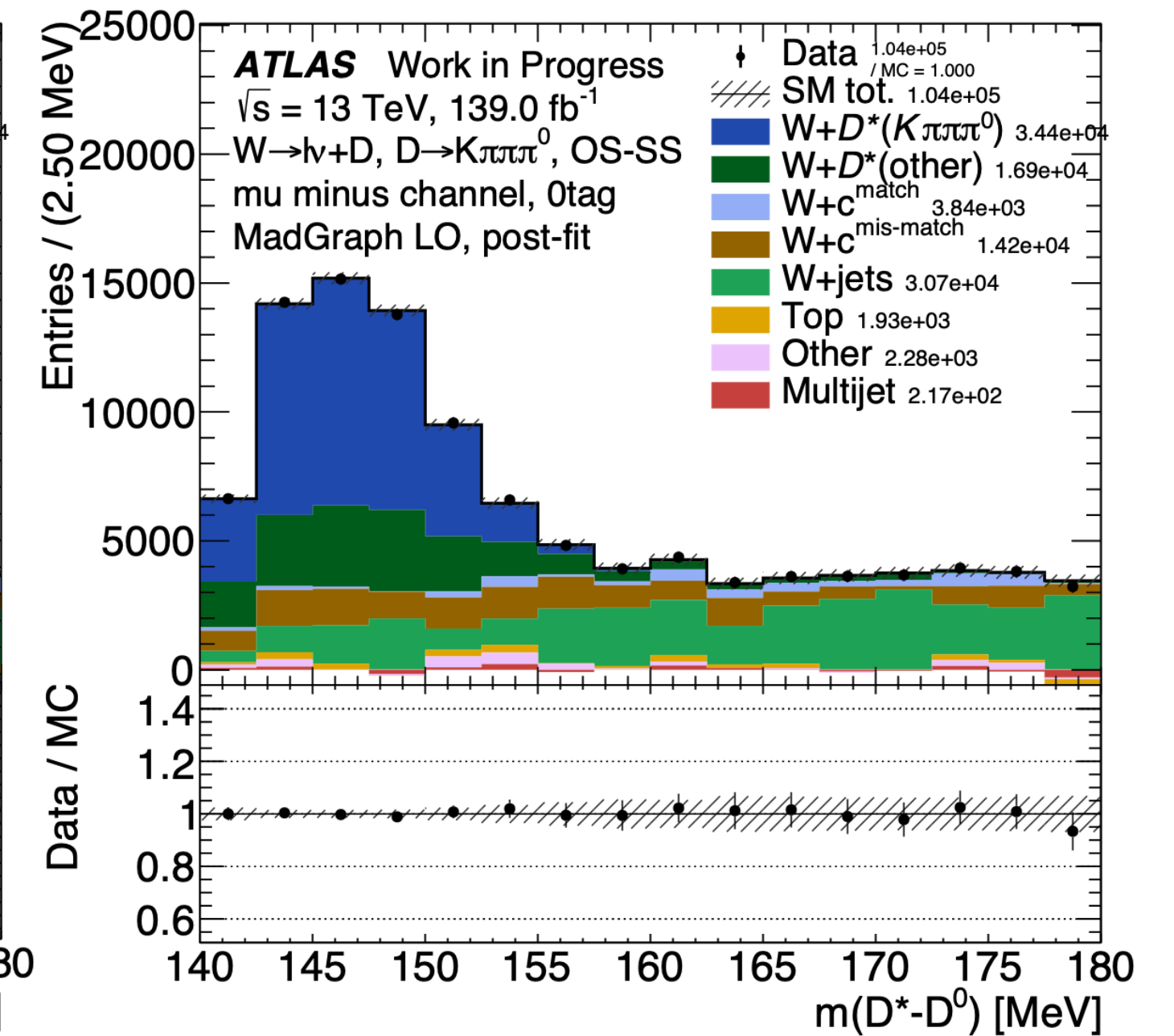
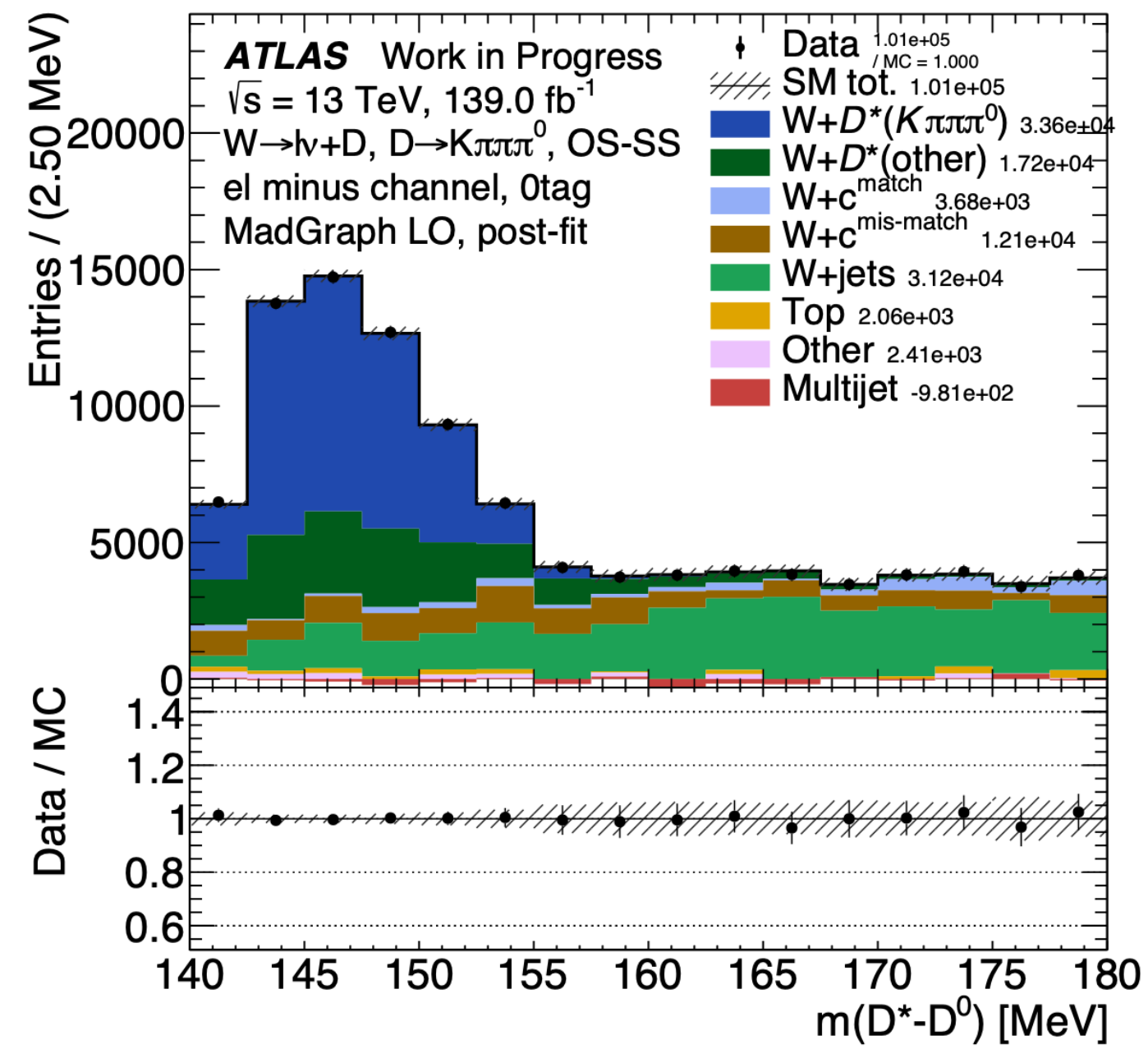
- See which errors are most dominant in our fit
- Ranking plots vary each NP by 1σ and redo the fit, measuring pull and pre/post fit impact
- Overall largest systematic uncertainties
 - Branching ratio of $D^* \rightarrow \pi(K\pi\pi^0)$
 - Overall track efficiency
 - Luminosity
- Dominated by MC statistical uncertainties from first 3 bins
- Able to achieve (already for D^+) better statistical uncertainty with methods like ParticleGun (single hadron decays with unlimited statistics)



Results and Conclusion

Measurement of $\sigma_{\text{fid}}(WD^*)$ in Satellite Mode with 139.0 fb^{-1}

- $e^-: \mu = 1.15_{-0.07}^{+0.07}$
- $e^+: \mu = 1.08_{-0.07}^{+0.07}$
- $\mu^-: \mu = 1.11_{-0.07}^{+0.07}$
- $\mu^+: \mu = 1.06_{-0.09}^{+0.09}$
- $R_c^\pm(WD^*) = 0.92$
- $\sigma(R_c^\pm(WD^*)) < 0.06$
- Satellite mode precision *alone* roughly equal to Run 1 study measured R with a precision of 6% with all modes (CERN-PH-EP-2014-007)
- Unprecedented precision of complete Run 2 $W + D$ study



BACKUP SLIDES

Trigger Selection & Object Selection (BACKUP)

- We use single lepton triggers
- 2015 Electron trigger:
 - e24_lhmedium_L1EM20VH
 - e60_lhmedium
 - e120_lhloose
- 2016-2018 Electron trigger
 - e26_lhtight_nod0_ivarloose
 - e60_lhmedium_nod0
 - e140_lhloose_nod0
- 2015 Muon trigger
 - mu20_iloose_L1MU15
 - HLT_mu50
- 2016-2018 Muon trigger
 - mu26_ivarmedium
 - HLT_mu50
- Electron selection:
 - LHTight ID
 - FCTight isolation
- Muon selection:
 - Tight quality
 - PflowTight_VarRad
- Jets selection:
 - $p_T > 20\text{GeV}$
 - $|\eta| < 5.0$
 - DL1r_FixedCutBEff_70 *b*-tag WP

Cut optimization (BACKUP)

Background Fit

- Need to optimize our $m(D^* - D^0)$ signal significance, while maintaining a signal efficiency close to 1

- Signal Region (SR): 135 MeV to 165 MeV

- Significance: $Z = \frac{S}{\delta_S}$

- Signal efficiency: $\frac{\text{Background-subtracted Data Signal}}{\text{Scaled Monte Carlo Signal}}$

- Include all points except those in the SR in a background fit B_{Fit}

- Our total Monte Carlo signal within the SR is termed MC_S

- Scale Factor: $SF = \frac{\sum_{SR} \text{Data} - B_{Fit}}{\sum_{SR} MC_S}$

- sig. eff. = $\frac{\sum_{SR} \text{Data} - B_{Fit}}{SF \cdot \sum_{SR} MC_S}$

- Signal: $S = SF \cdot \sum_{SR} MC_S$

- $\delta_S = \sqrt{(\delta B_{Fit})^2 + (\delta \text{Data})^2}$

- $Z = \frac{S}{\delta_S}$

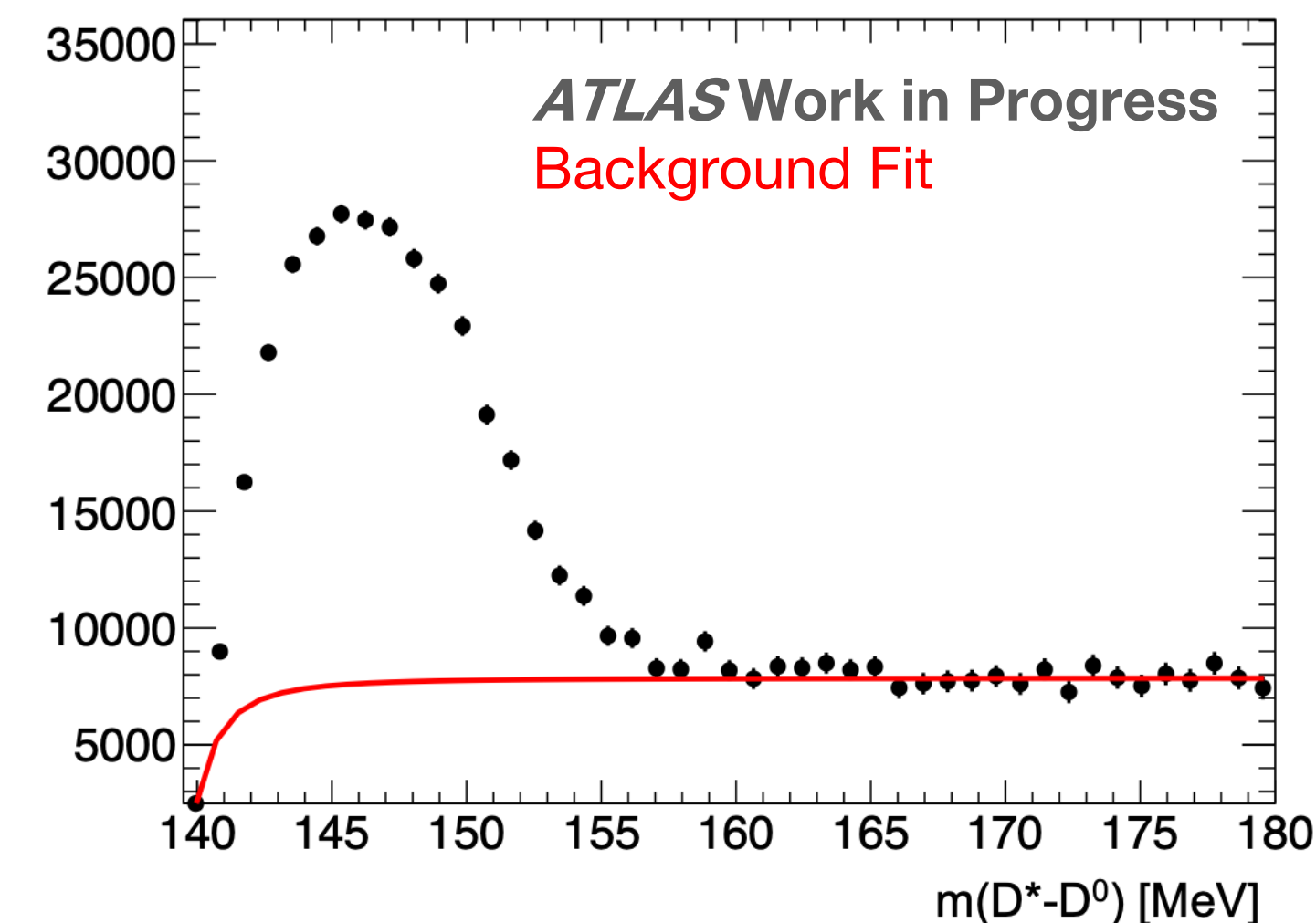
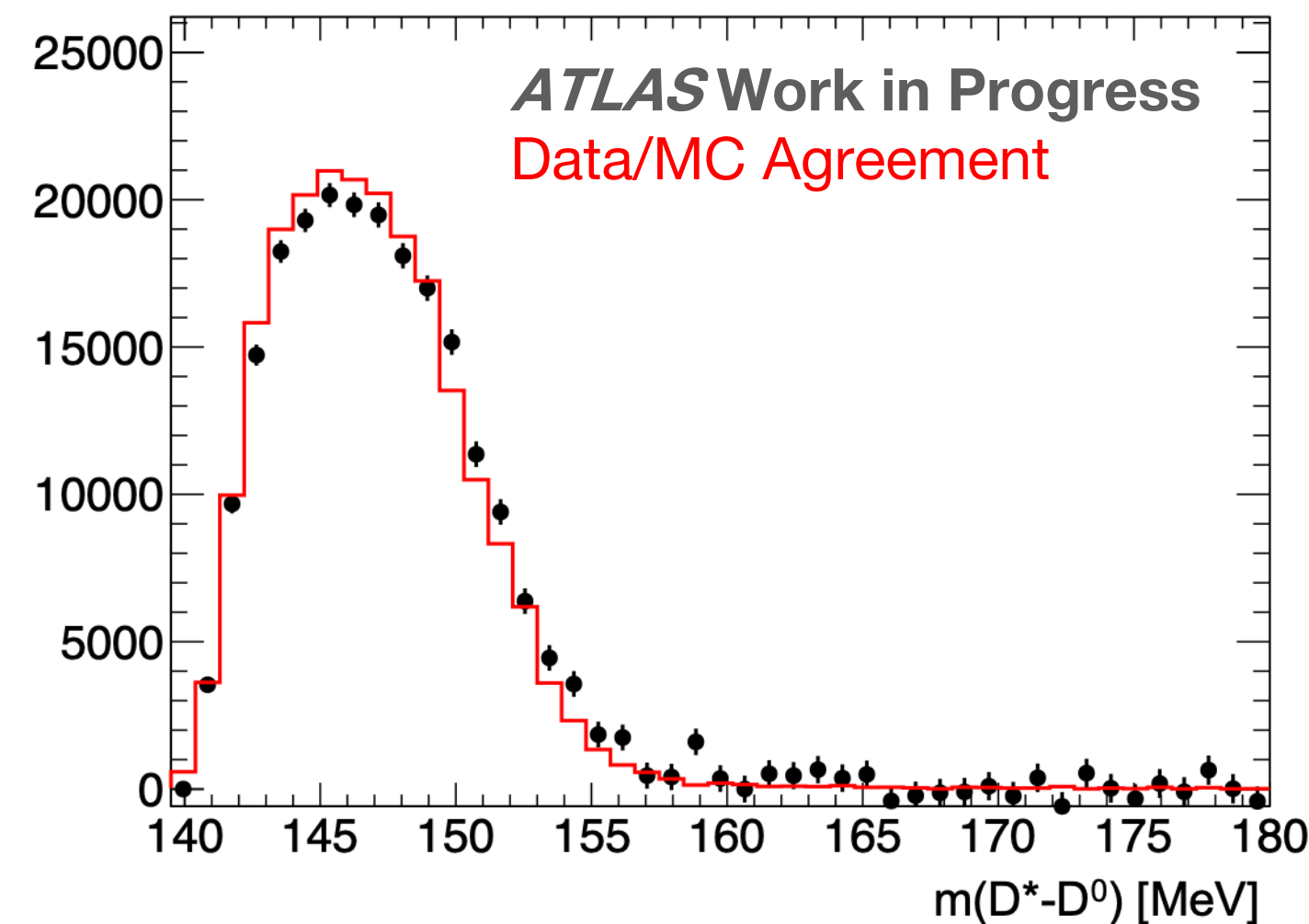
- Noticing that background looks logarithmic, we can make rudimentary fit

- $y_{\text{bkgd}}(x) = A + B \log(x - C)$

- We can fix the x-intercept of our fit to be at m_π (reducing degrees of freedom by 1)

- We additionally take tanh of our fit, flattening our curve

- $y_{\text{bkgd}}(x) = A + B \tanh(\log(x - (m_\pi - e^{-A/B})))$



Cut optimization (BACKUP)

- SV fit variables that we will use in cut optimization
 - 3D Impact Significance
 - $SV \chi^2$
 - Isolation
 - Min. L_{xy}
 - Daughter Tracks p_T
- Sig. Eff. Set to 1.0 for loosest cut
- Original (red), Optimized (blue)

Variable	Cut Scan Values
3D Impact Significance	100,14,12,10,9,8,7,6,5,4
$SV \chi^2$	100000,20,18,15,12,10,8,7,6,5
Isolation	100.0,4.5,4.0,3.5,3.0,2.5,2.0,1.5,1.0,0.5
Min L_{xy} (mm)	0.0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9
Daughter Tracks p_T (MeV)	500,550,600,650,700,750,800,850,900,950

Variable	Z	Z	Sig. Eff.	Sig. Eff.
3D Impact Significance	48.51	58.31	1.01	1.01
$SV \chi^2$	58.02	58.03	1.01	1.02
Isolation	89.12	61.73	1.09	1.05
Min L_{xy} (mm)	58.78	71.18	1.00	1.04
Daughter Tracks p_T (MeV)	71.6	-	0.96	-

Fitting procedure (BACKUP)

$$\mathcal{L} = \prod_i f(N_i | \mu \cdot \sigma_{fid}^{pred} \cdot \epsilon_{fid}(\boldsymbol{\theta}) \cdot \mathcal{S}_i(\boldsymbol{\theta}) \cdot L(\theta_{lumi}) \cdot \gamma_i + \mathcal{B}_i(\boldsymbol{\theta}, \mu_{Top}) \cdot \gamma_i) \times \prod_t g(\theta_0 | \theta_t, \Delta\theta_t) \times \prod_i f(N_{MC_i} | \tau \cdot \gamma_i \cdot (S_i + B_i))$$

- Aim: performed a binned likelihood fit that will scale our Standard Model MC predictions to data by maximizing likelihood function \mathcal{L}
 - Use RooStats and TRexFitter frameworks
- We represent our $D^* \rightarrow \pi(K\pi\pi^0)$ signal as well as Top background as normalization factors μ and μ_{Top}
 - Ideally, we would include other regions as normalization factors provided control regions
- Systematic and statistical uncertainties as represented as a vector of nuisance parameters $\boldsymbol{\theta}$ and $\boldsymbol{\gamma}$
- Other backgrounds' uncertainties are also included in $\boldsymbol{\theta}$ using the Beeston-Barlow technique
- We perform two fits
 - *Obs: Fits the MC profile to Observed profile*
 - *Asimov: Replaces Data with MC profiles; used to calculate expected uncertainties of nuisance parameters*

Likelihood Function Overview (BACKUP)

In short, we condition the number of observed events on the expected signal + background events

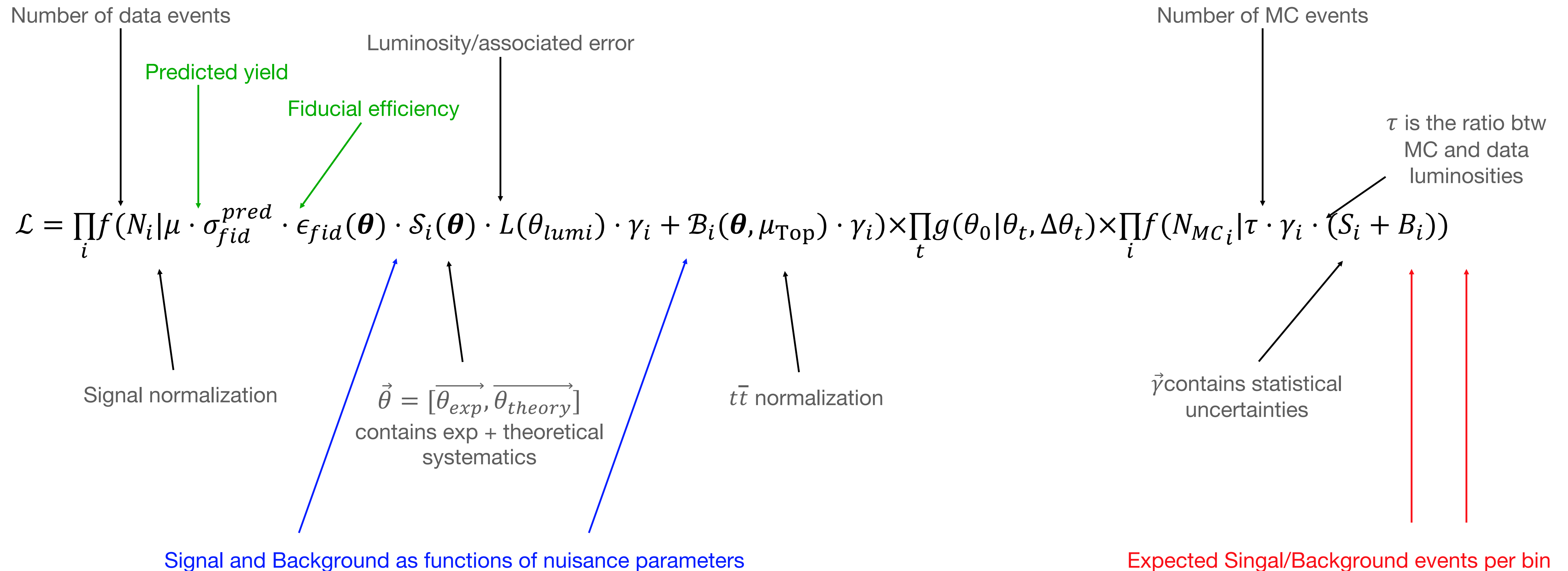
We constrain each parameter in θ by g , a Gaussian function: $g(\theta_0|\theta_t, \Delta\theta_t) = \frac{1}{\Delta\theta_t\sqrt{2\pi}} \exp(-\frac{1}{2}(\frac{\theta_t-\theta_0}{\Delta\theta_t})^2)$

$$\mathcal{L} = \prod_i f(N_i | \mu \cdot \sigma_{fid}^{pred} \cdot \epsilon_{fid}(\boldsymbol{\theta}) \cdot \mathcal{S}_i(\boldsymbol{\theta}) \cdot L(\theta_{lumi}) \cdot \gamma_i + \mathcal{B}_i(\boldsymbol{\theta}, \mu_{Top}) \cdot \gamma_i) \times \prod_t g(\theta_0 | \theta_t, \Delta\theta_t) \times \prod_i f(N_{MC_i} | \tau \cdot \gamma_i \cdot (S_i + B_i))$$

By convention, we set $\theta_0 = 0$ and $\Delta\theta_t = 1$. The quantity $\frac{\theta_t - \theta_0}{\Delta\theta_t}$ and its error is known as a parameter's *pull*

f is a Poisson probability function: $f(N|\lambda) = \frac{\lambda^N e^{-\lambda}}{N!}$

Likelihood Function Details (BACKUP)



Completing the Likelihood Fit (BACKUP)

- We perform two fits
 - *Obs*: Fits the Mc profile to Observed profile
 - *Asimov*: Replaces Data with MC profiles; used to calculate expected uncertainties of nuisance parameters
- After fits are performed, we have our optimal values/parameters:
 - $\mu \rightarrow \hat{\mu}$
 - $\vec{\Theta} \equiv [\vec{\theta}, \vec{\gamma}, \mu_{\text{Top}}] \rightarrow \hat{\vec{\Theta}}$
- Uncertainty on μ is computed using the likelihood ratio $q_{\mu} = -2 \ln \frac{\mathcal{L}(\mu, \hat{\vec{\Theta}}_{\mu})}{\mathcal{L}(\hat{\mu}, \hat{\vec{\Theta}})}$
 - $\hat{\vec{\Theta}}_{\mu}$ is optimal value of $\vec{\Theta}$ as a function of floating parameter μ
 - $\Delta\mu$ is obtained by varying μ in both directions until q_{μ} changes by ± 1 unit
- Uncertainty on $\Theta_i \in \vec{\Theta}$, computed in exactly same way, using likelihood ratio q_{Θ_i}

Fitting results (BACKUP)

Pull plots

