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Search for doubly charged Higgs using Tau leptons with ATLAS at $\sqrt{s}$ =13 TeV

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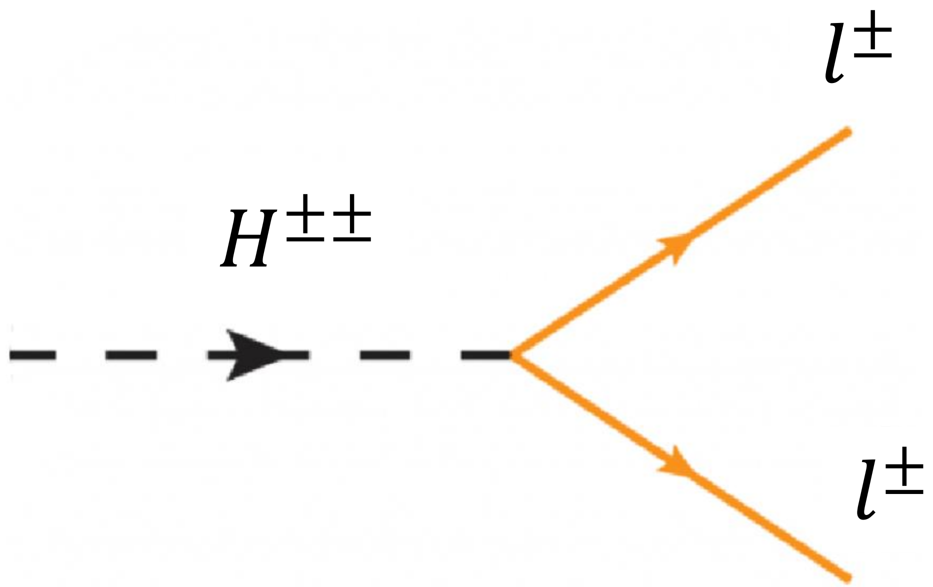
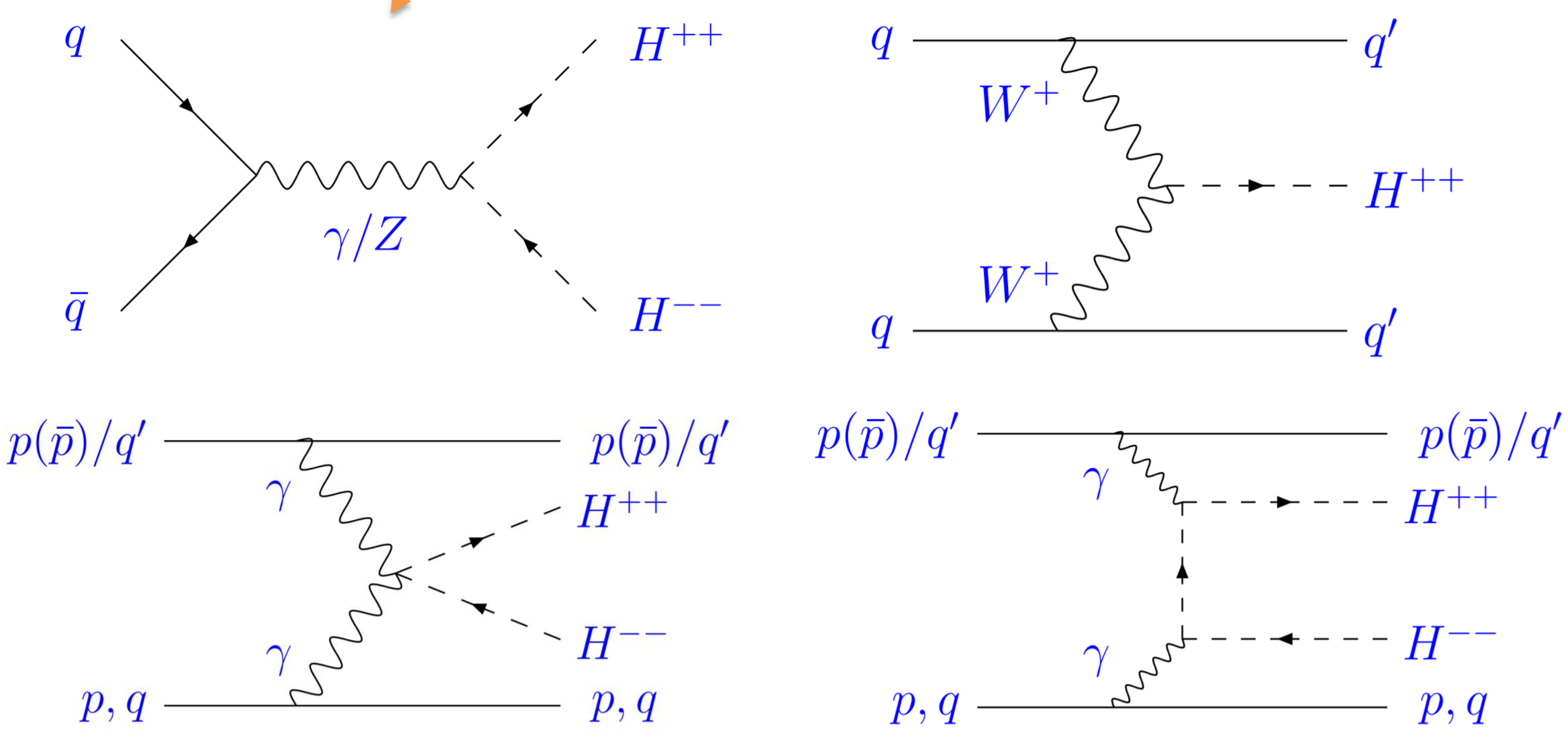
Why search for doubly charged Higgs?

- Standard Model Higgs Boson is a spinless neutral particle with a vacuum expectation value v_0
- Neutrino oscillation → Neutrino must have mass → **Origin**??
- Doubly charged Higgs bosons can be introduced to explain the origin of neutrino mass!
- Can decay to a pair of same-sign leptons
  - violation of lepton flavour by two units



Dominant Drell-Yan pair production



Feynman diagrams for several doubly charged Higgs production channel. arXiv:1105.1379v1

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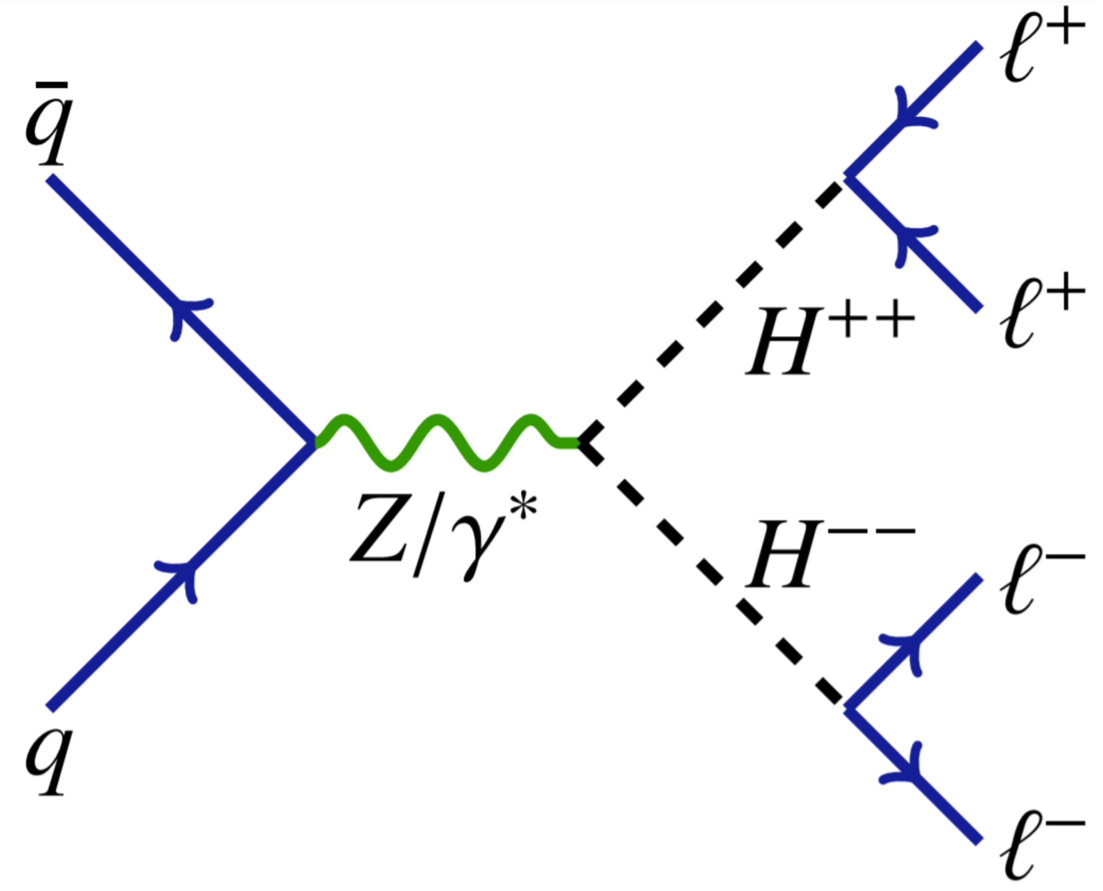
Previous study by ATLAS on $H^{\pm\pm} \to l^{\pm}l'^{\pm}$

- Used pp data sample with Integrated luminosity 36.1 fb^{-1} collected in 2015 and 2016 by the ATLAS detector at the LHC at $\sqrt{s}$=13 TeV.
- Only pair production via the Drell–Yan process was considered.
- Masses studied: $200 \le m_{H^{\pm\pm}} \le 1300$ GeV
- Only e and μ were considered.
- No significant excess was observed, but lower mass limits were presented (450 GeV for $B(H^{\pm\pm} \to l^{\pm}l'^{\pm}) = 10\%$).
- Only thing that has not been done is **hadronic decay of τ** (leptonic decay of τ is reconstructed as e or μ).

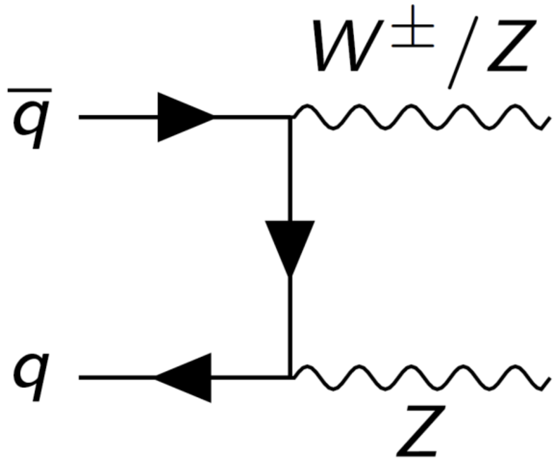


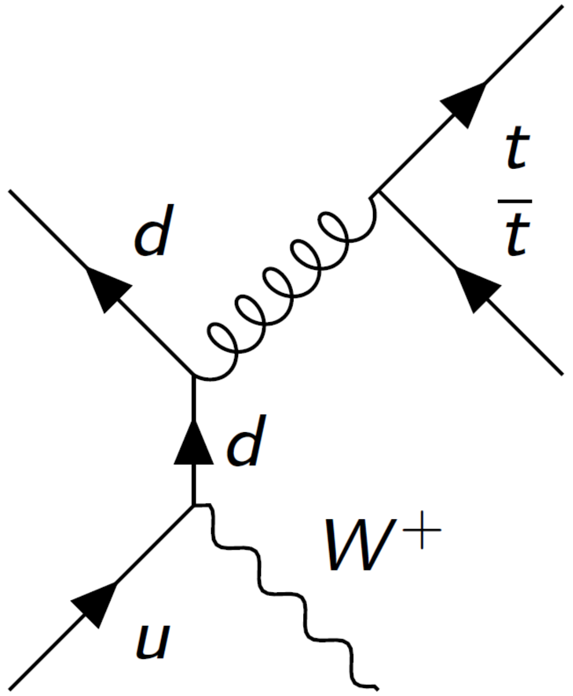
Drell-Yan pair production

Backgrounds of same-charge hadronic tau

Prompt

Same-charge taus from SM processes: diboson ($W^{\pm}W^{\pm}/ZZ/WZ$) and $t\bar{t}X$ processes ($t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$)

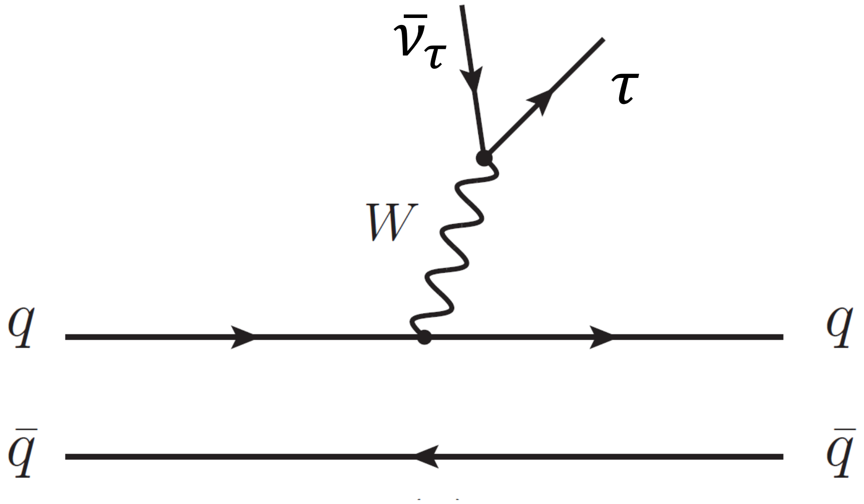


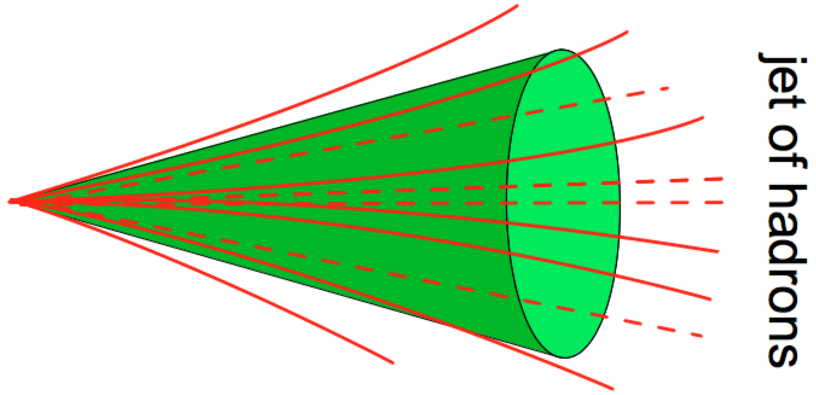


Non-prompt

Real taus from non-prompt decays, e.g. from heavy flavored mesons

Jets mis-reconstructed as taus



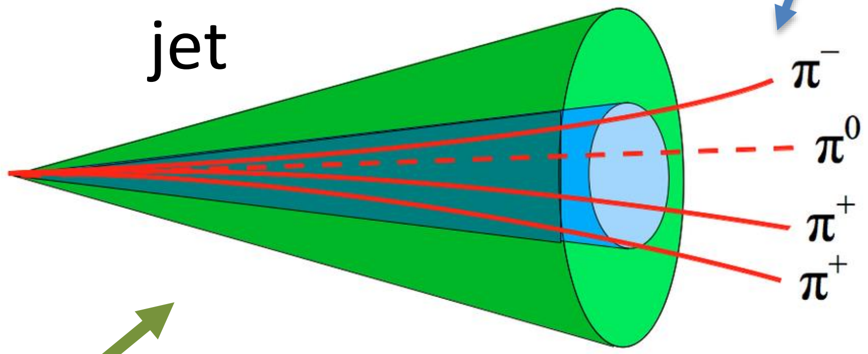


Charge-flip

Oppositely charged leptons with charge of tau misidentified: Z/γ^{*}, $t\bar{t}$, tW, $W^{\pm}W^{\mp}$

Narrow jet with 1 or 3 prongs (charged particles)

Hadronic tau jet

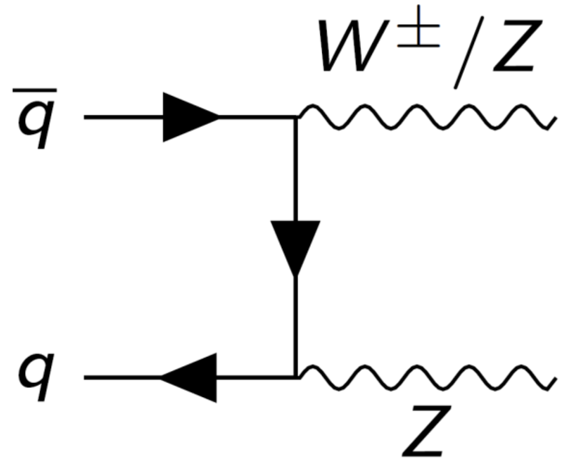


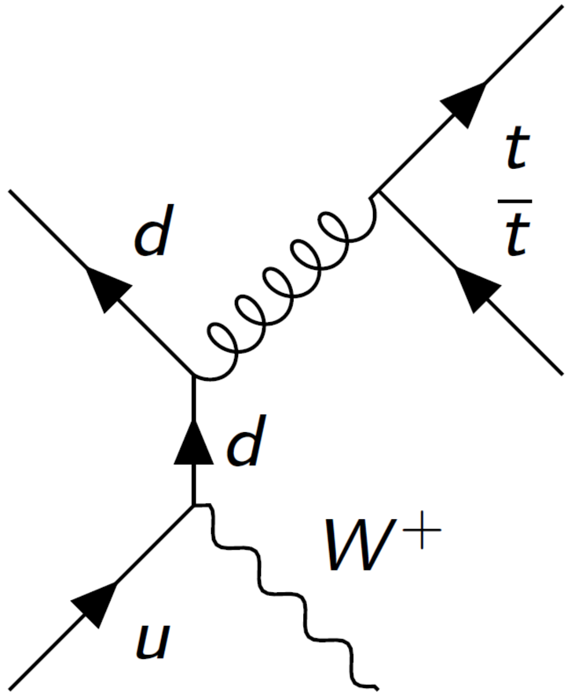
Can be distinguished, but there is some chance of mis-reconstruction.

Backgrounds

Prompt

Same-charge taus from SM processes: diboson ($W^{\pm}W^{\pm}/ZZ/WZ$) and $t\bar{t}X$ processes ($t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$)





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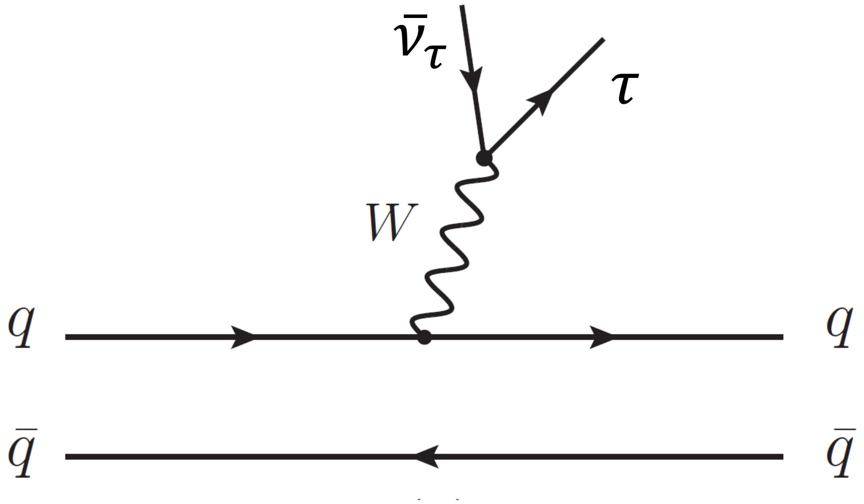

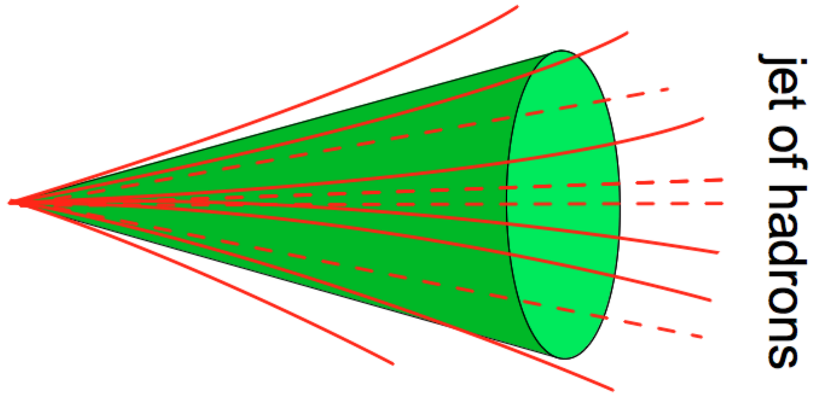

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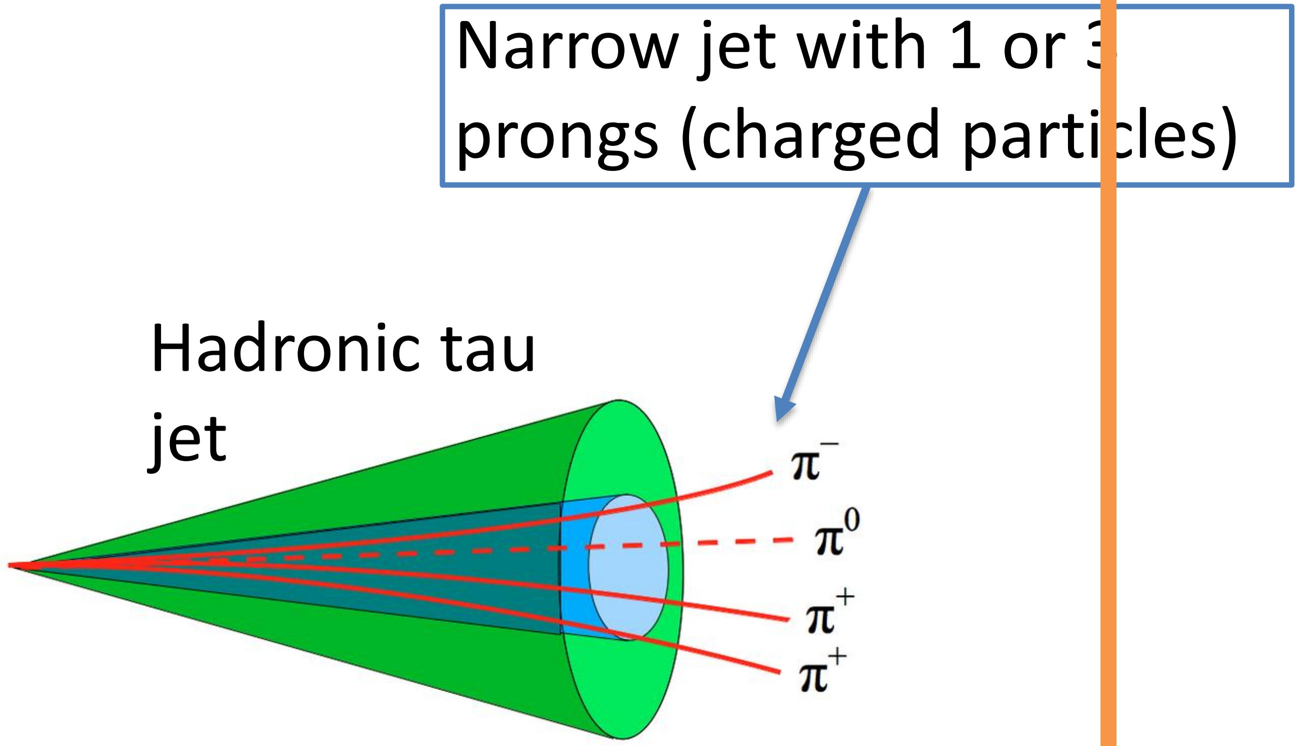

What I work on!

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Hadronic tau charge-flip background studies

- Using three methods to perform charge-flip rate study of tau for MC and data.
- What we want at the end?
    - **scale factor**: ratio of the charge-flip rate between MC and data
    - apply the scale factor to the simulated events to compensate for the differences
- **Data-drive** and **tag-and-probe** method
    - used in previous charge-flip study on electron for MC and data.
    - not working for tau data due to heavily contaminated background
- **Template fit** method
    - a new method designed for studying the hadronic tau charge-flip rate of data

Type	Method	Samples	Channel
MC	Data-driven	Ztautau ttbar	Ditau $(\tau_{had}\tau_{had})$
	Tag-and-probe	Ztautau ttbar	muTau $(\tau_{\mu}\tau_{had})$
Data	Template fit	2015-2017	muTau $(\tau_{\mu}\tau_{had})$

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Data-driven method

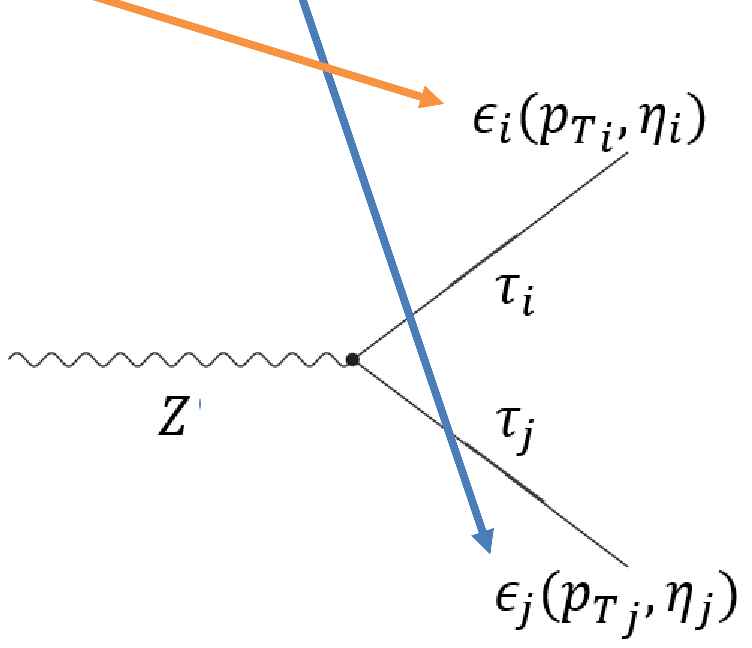
- Assume **Poissonian distribution** for expected number of charge flipped events $\boldsymbol{\lambda}$

$$P(N_{SS};\lambda) = \frac{\lambda^{N_{SS}} e^{-\lambda}}{N_{SS}!}$$

where λ is a function of the charge flip probability $\boldsymbol{\epsilon(p_T,\eta) = f(\eta)\cdot\sigma(p_T)}$.

- The expected number of charge flipped events:

$$\lambda_{i,j} = \epsilon_i(1-\epsilon_j)N_{AS}^{ij} + (1-\epsilon_i)\epsilon_j N_{AS}^{ij}$$



	Selections
Baseline	Di-tau trigger
	Two taus (BDT medium working point). Electron and muon veto
	Tau $p_T > 30$ GeV, truth matched
ttbar sample	At least one b-jet
Ztautau sample	No extra cuts for MC samples

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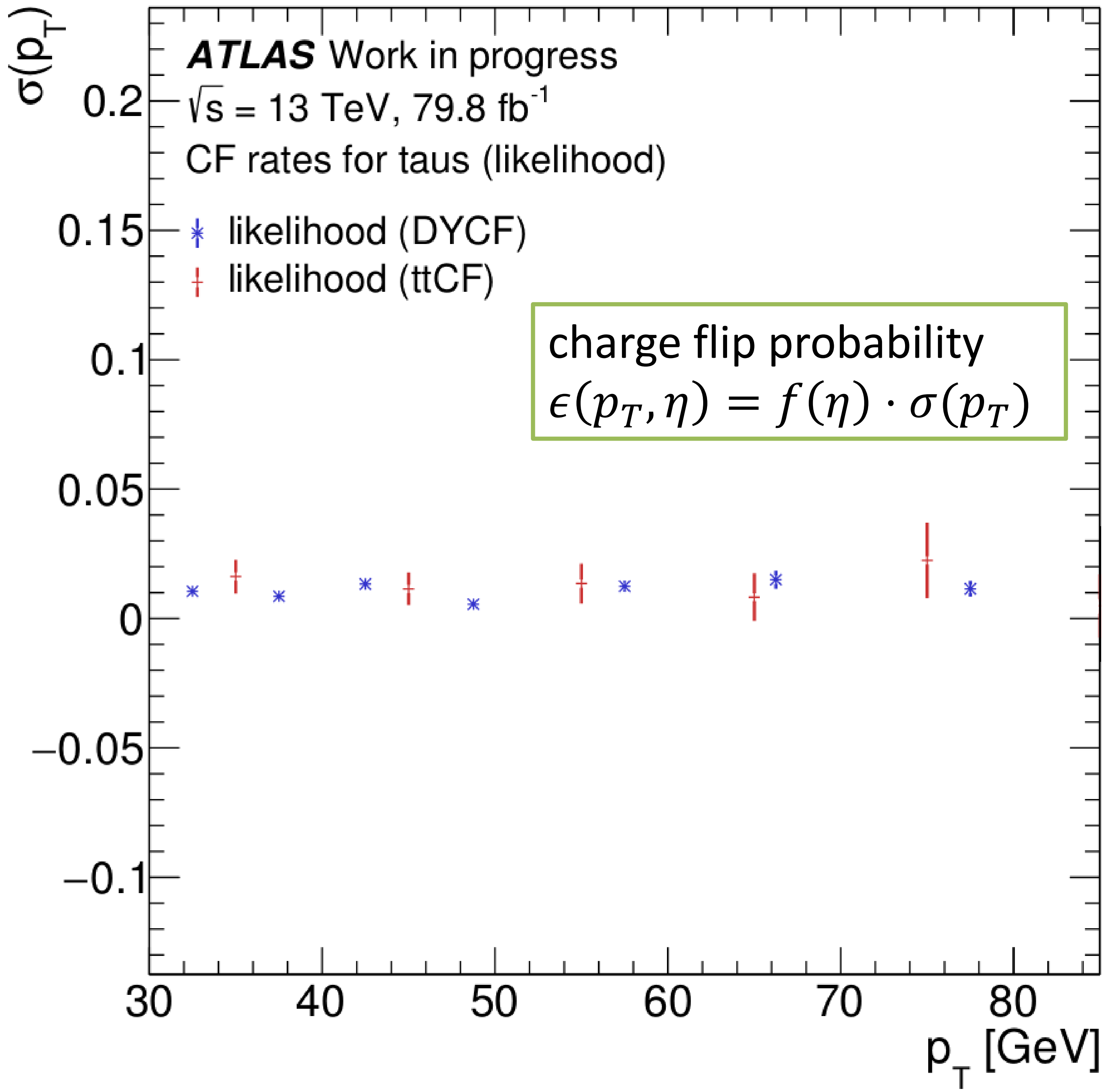
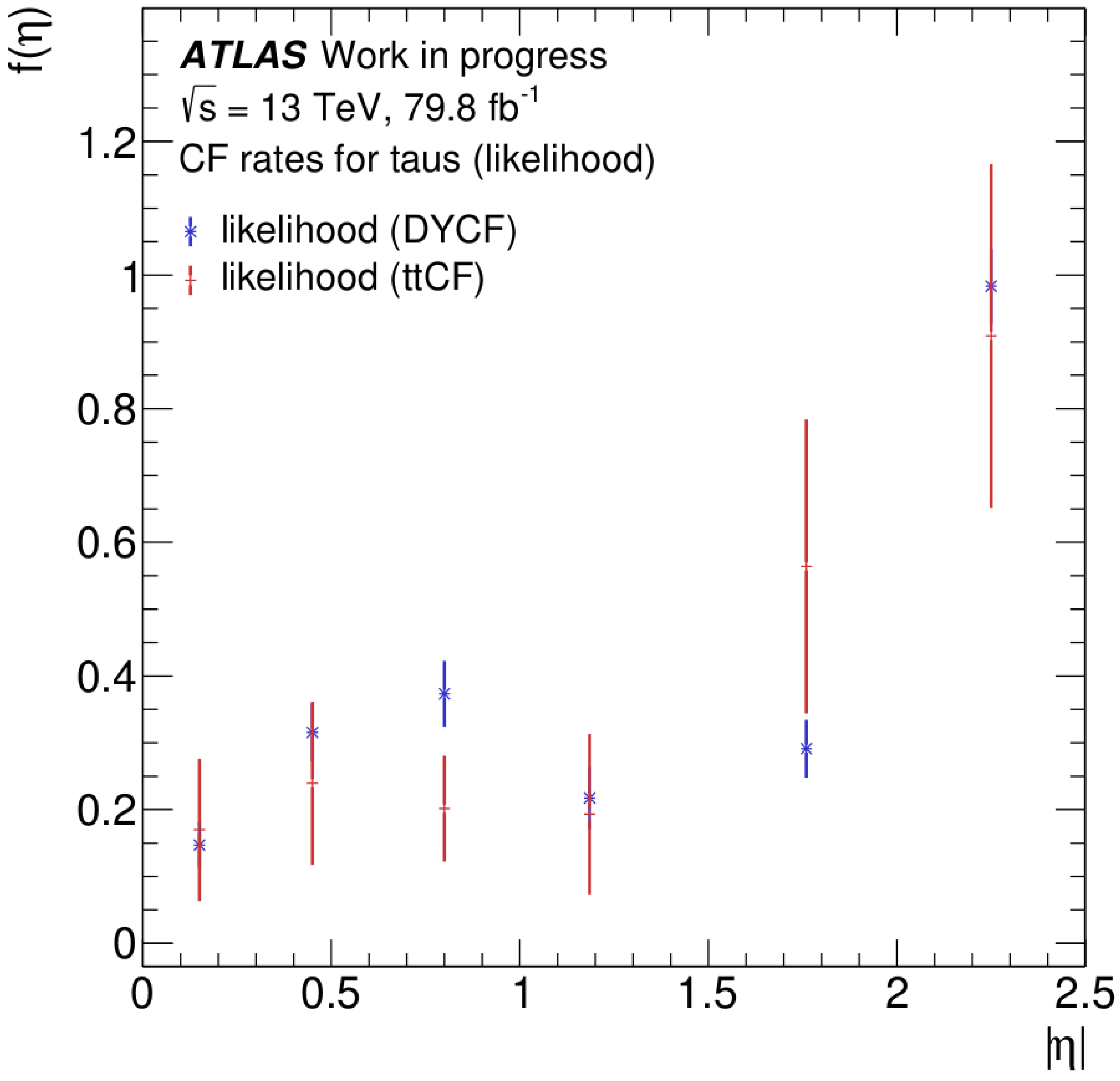
Charge-flip rate for MC estimated by data-driven method





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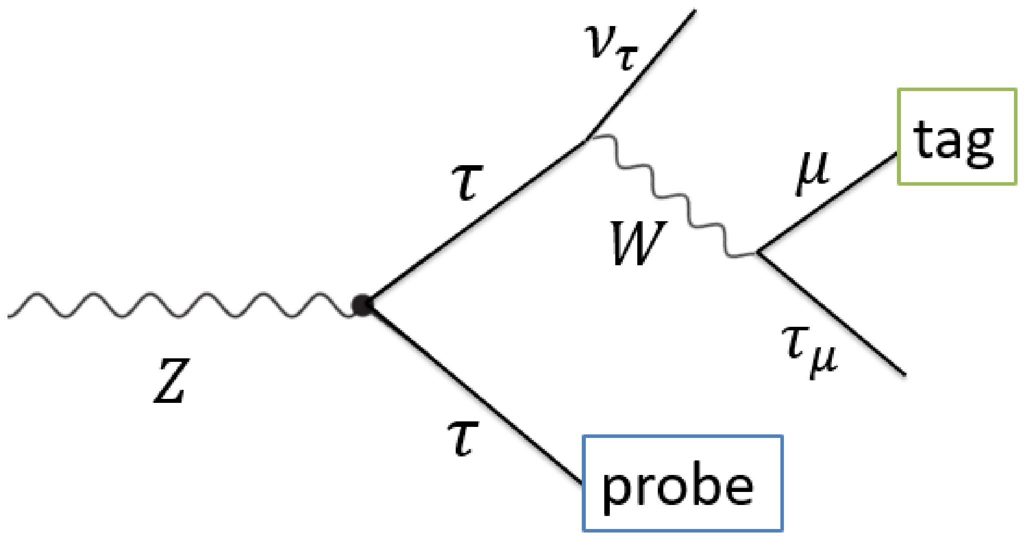
Tag-and-probe method

- Estimate the charge flip rate using following decay
$$Z/t\bar{t} \to \tau\tau \to \tau_{had}\tau_{\mu}$$
- Muon charge (the tag) is assumed to be reliably reconstructed to estimate the charge flip rate of tau (the probe)
$$\epsilon_{\tau_{had}} = \frac{N_{SS}}{N_{AS}}$$
- $\epsilon_{\tau_{had}}$ depends only on p_T **or** η due to consideration of statistics



	Selections
Baseline	Single muon trigger:
	One muon and one tau (BDT medium working point). Electron veto
	Muon: $p_T > 30$ GeV, z0sintheta < 0.5, d0sig < 3.0 Tau: $p_T > 30$ GeV, truth matched
ttbar sample	At least one b-jet
Ztautau	No extra cuts for MC samples

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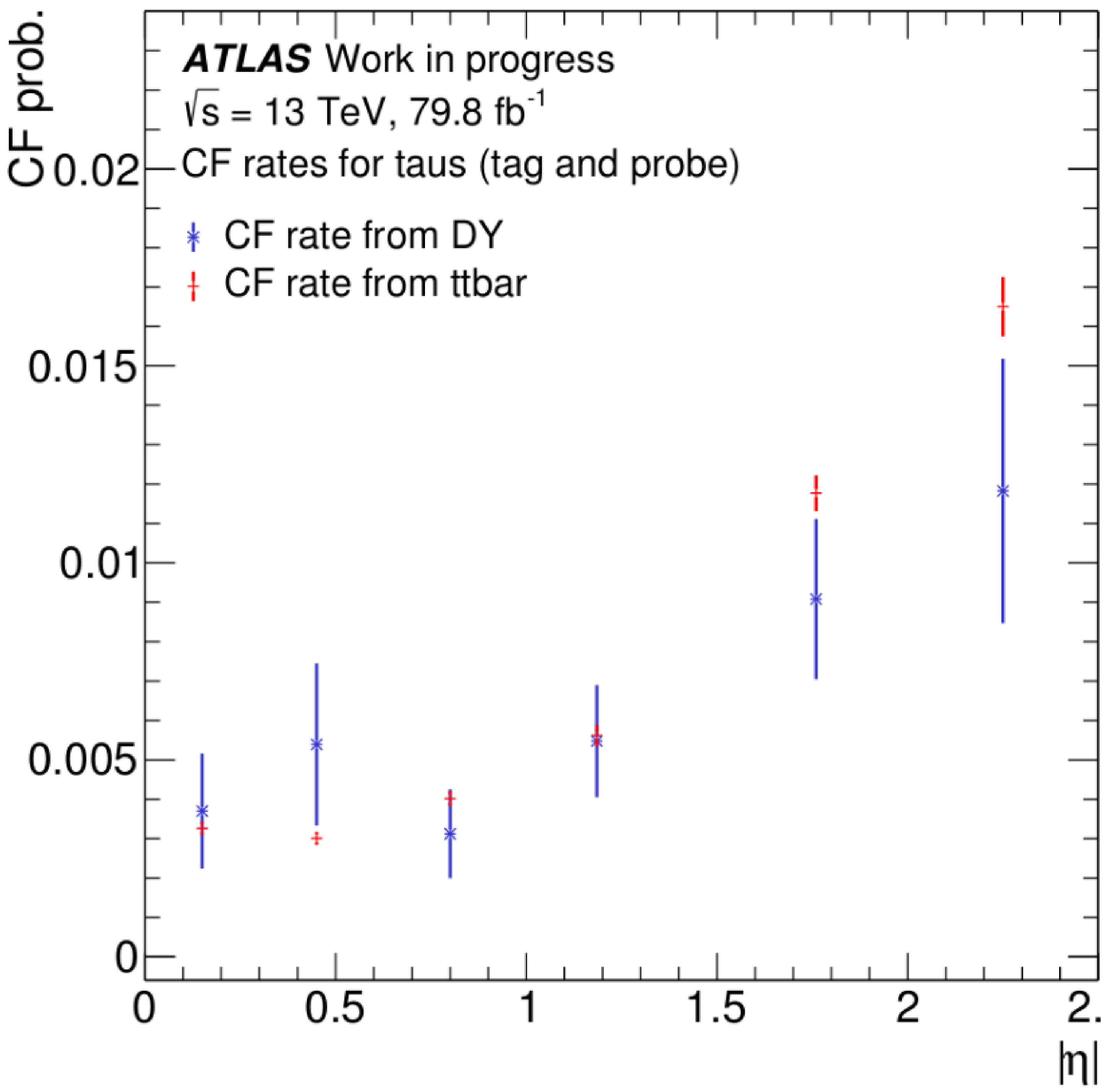
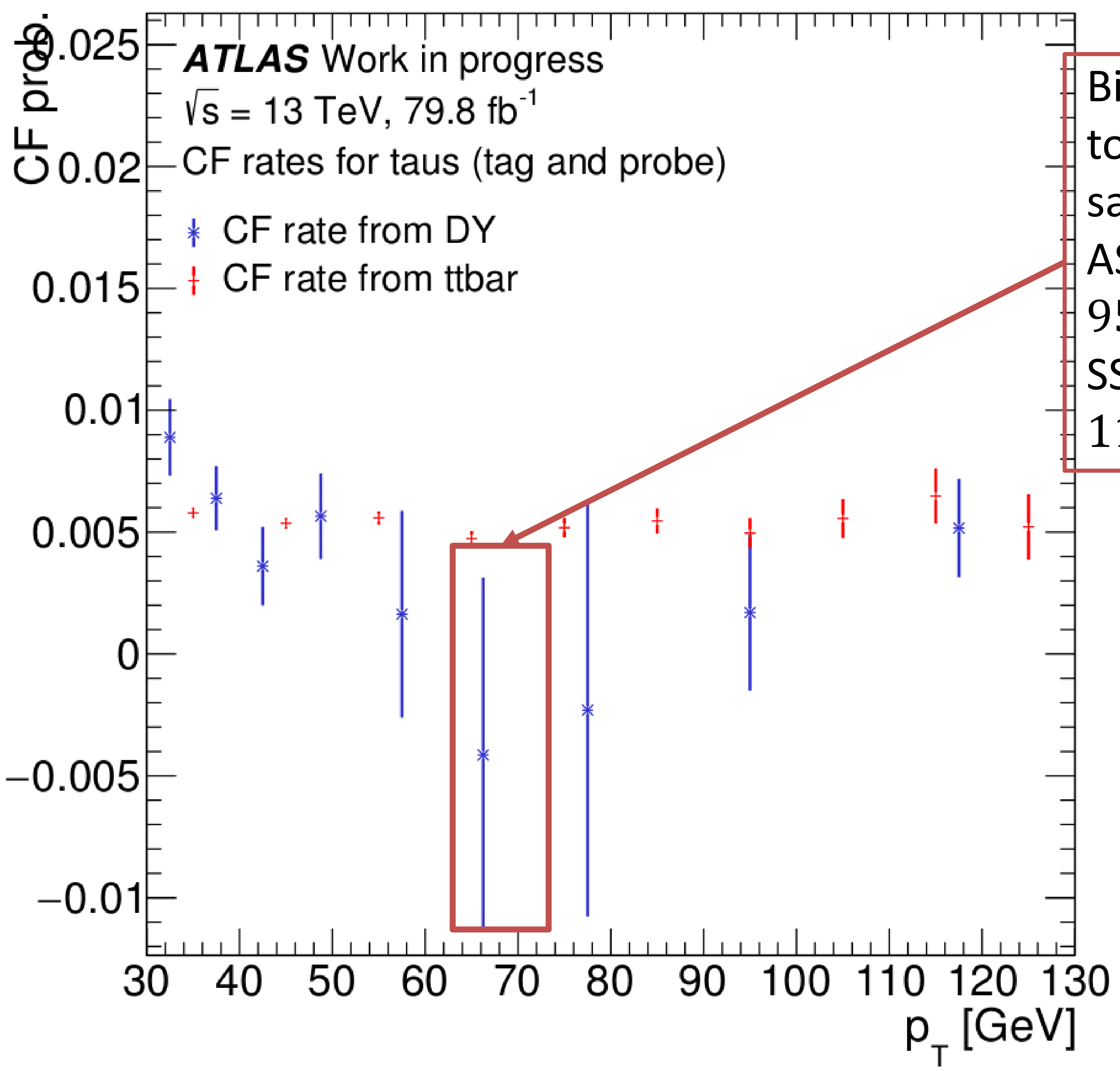
Charge-flip rate from tag-and-probe method

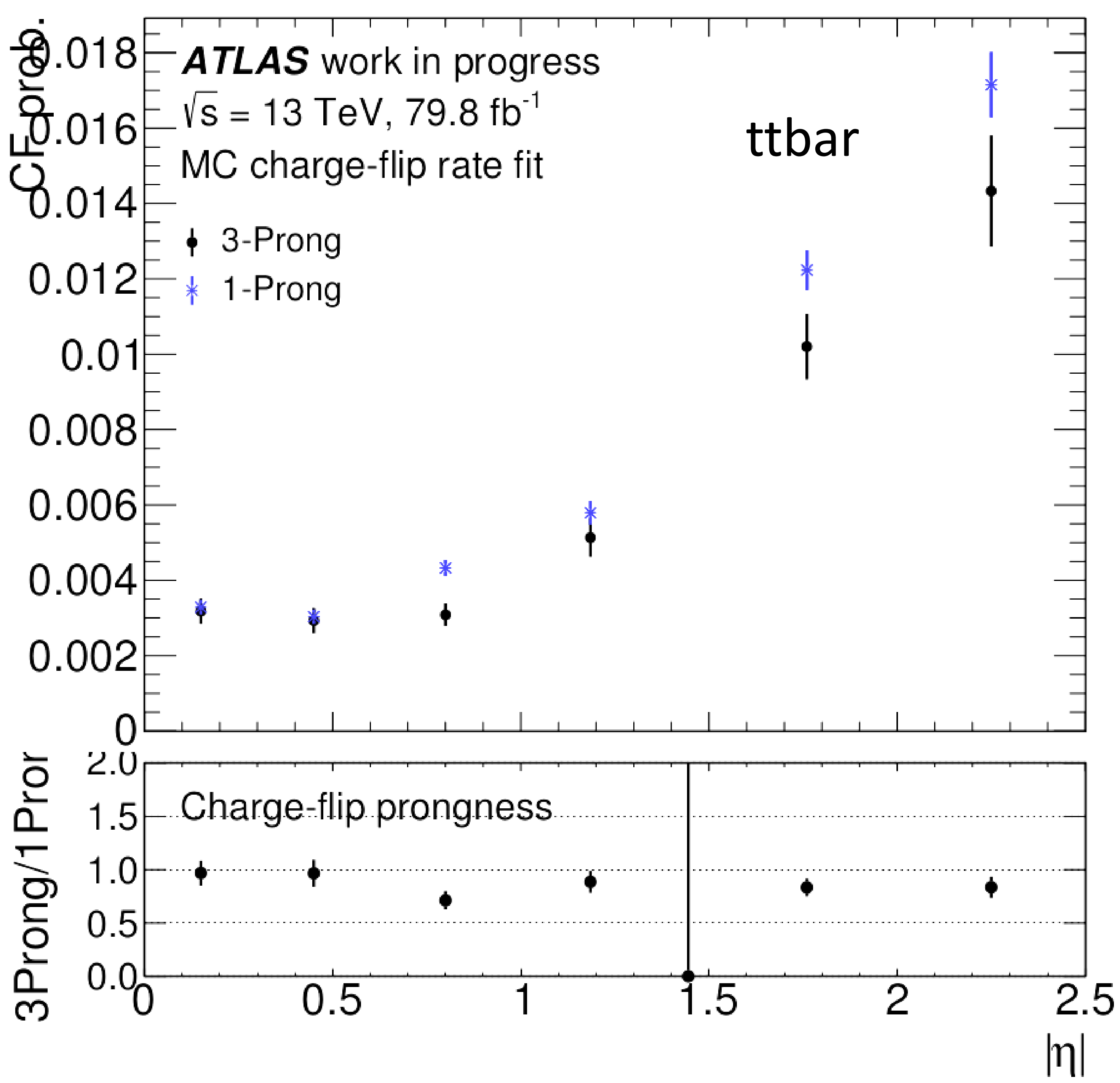


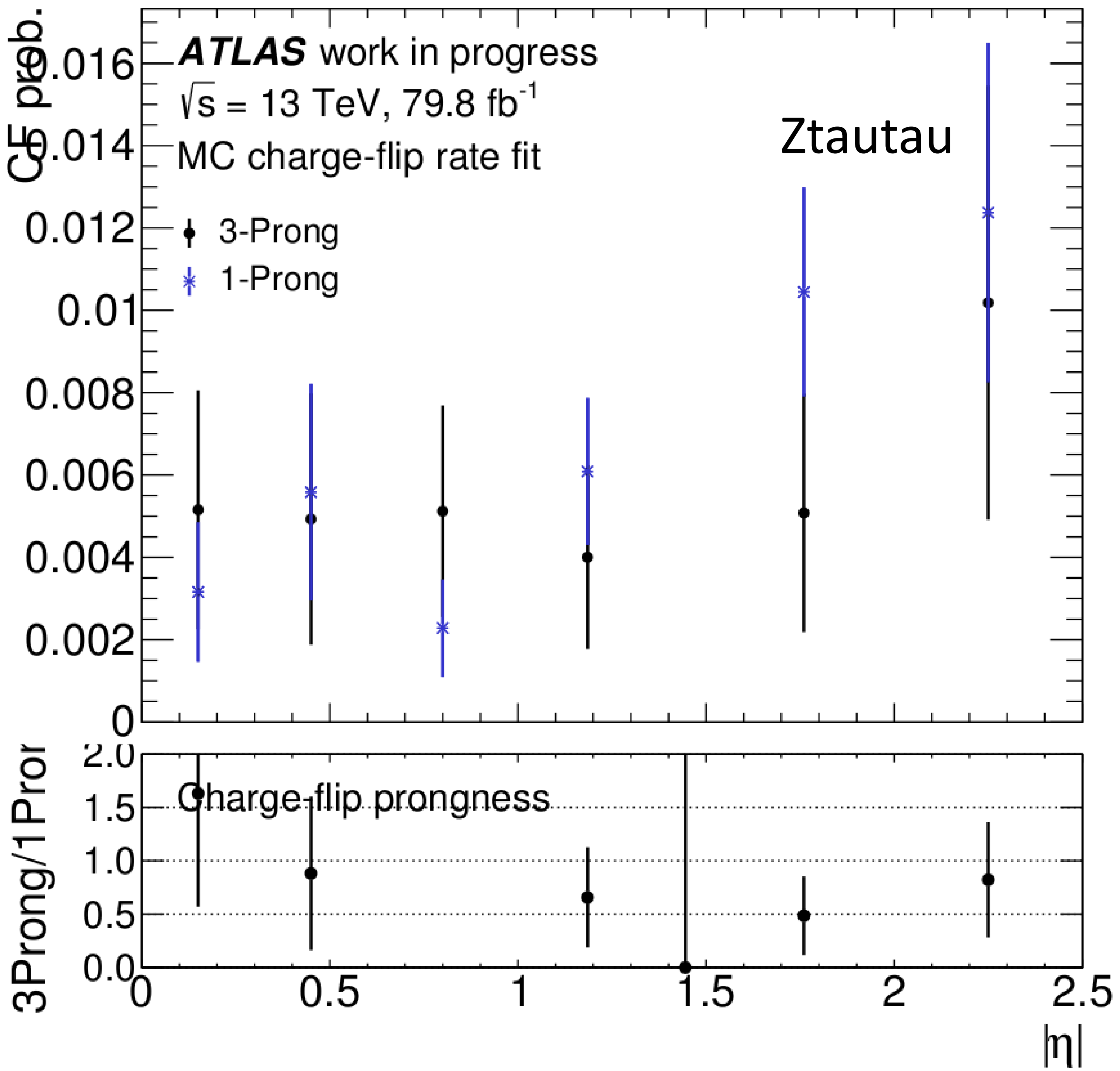


Big error bar due to large error in same sign fill:
AS_pt = 1538 ± 95
SS_pt = −6.37 ± 11.19

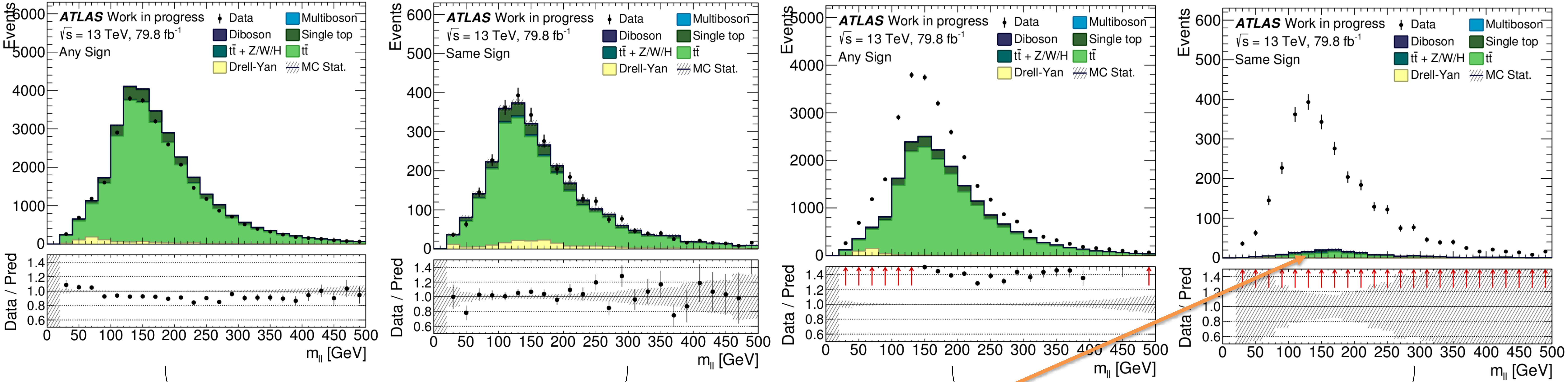
Weak dependence on pT

Comparison of charge-flip rate $\epsilon_{\tau_{had}}(\eta)$ between 1-prong and 3-prong





Difficulties in studying hadronic tau charge-flip rate for data illustrated using ttbar control region

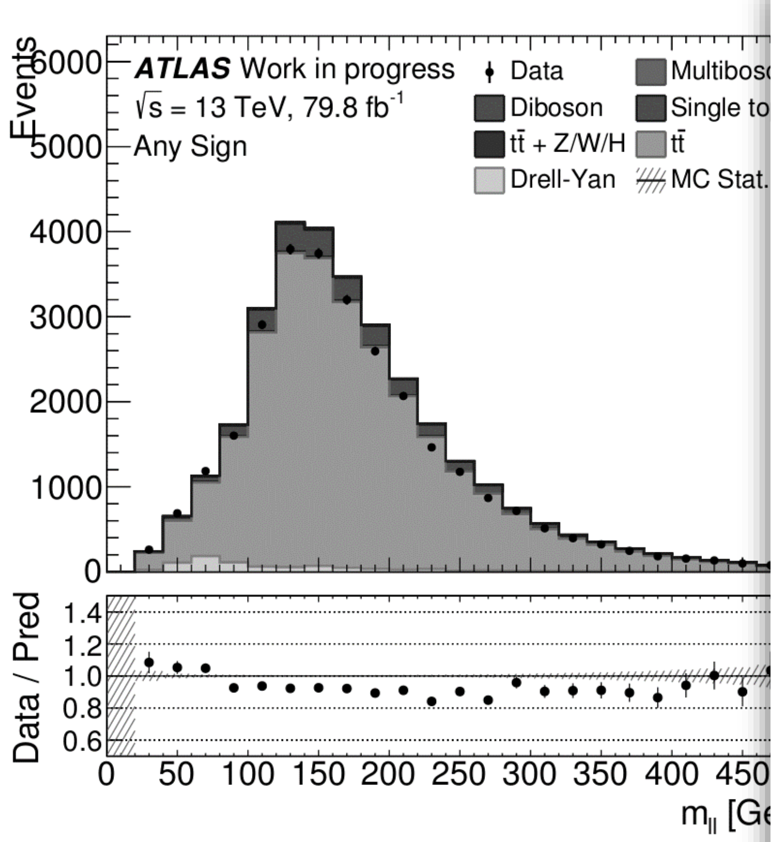


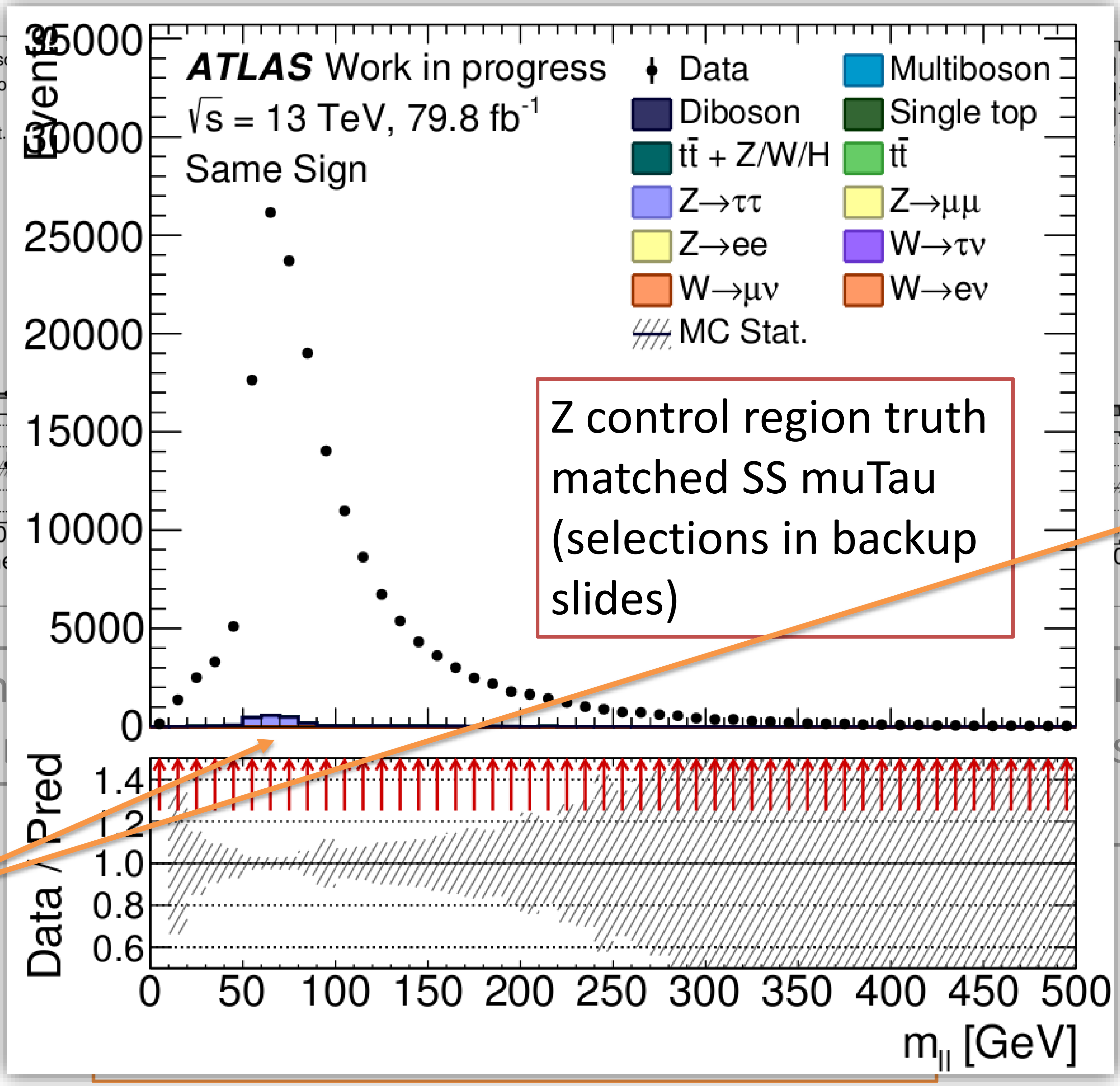
Inclusive: no truth matching of taus and muons

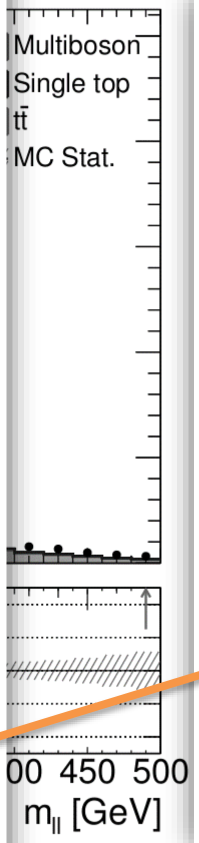
Truth matched: taus and muons are matched to their origin

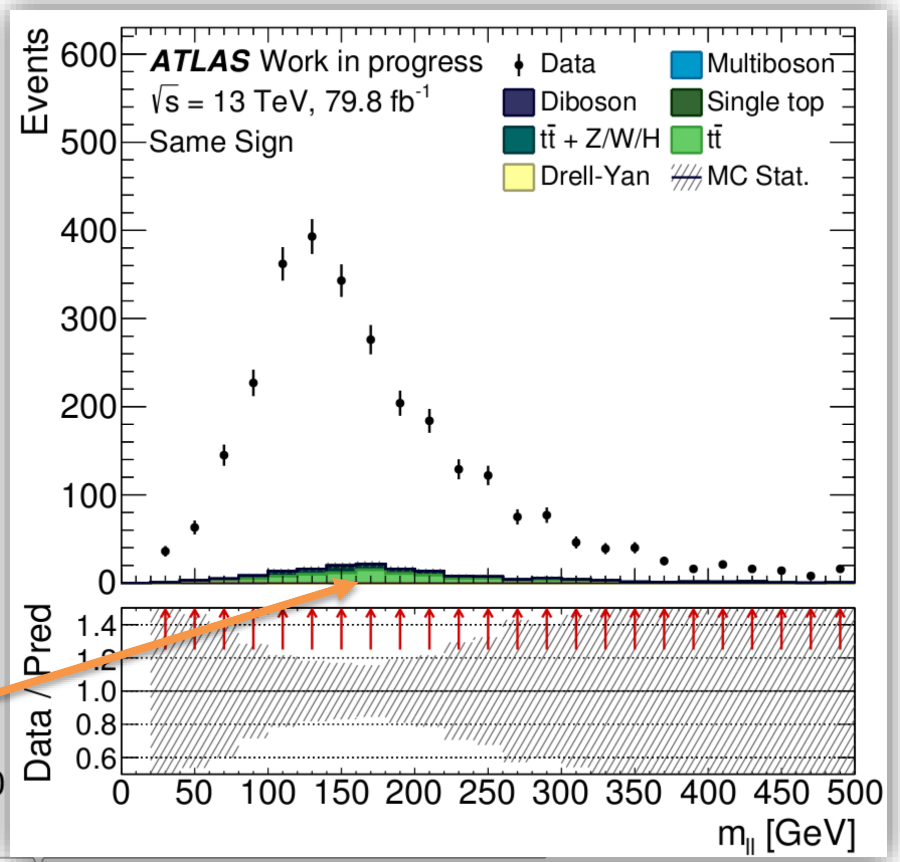
MC plot shows that the number of true SS muon tau events is very small. The SS data are **heavily contaminated by fake taus**

Ztautau control region has worse statistics









Z control region truth matched SS muTau (selections in backup slides)

Inclusive: n... of tau and ...

...matched: taus and ...s are matched to their

More events in ttbar in comparing to Z control region

Template fit method

- Choose to use **ttbar sample** and **muTau** ($\tau_{\mu}\tau_{had}$) channel to build the templates due the highest statistics it has
- **$\epsilon_{\tau_{had}}$ depends only on η**
- Using muTau channel means that tau is always assumed to be the one with wrong charge, just like the tag-and-probe
  $$\left(N_{data}^{AS}(\eta)\right)_{signal} \times \epsilon_{had}(\eta) = \left(N_{data}^{SS}(\eta)\right)_{signal}$$
- The compositions of AS and SS raw data can be separate to two parts
  $$N_{data}^{AS}(\eta_i) = N_{signal}^{AS}(\eta_i) + N_{bck}^{AS}(\eta_i)$$
  $$N_{data}^{SS}(\eta_i) = N_{signal}^{SS}(\eta_i) + N_{bck}^{SS}(\eta_i)$$

	Selections
Baseline	Single muon trigger
	One muon and one tau (BDT medium working point). Electron veto
	Muon: $p_T > 30$ GeV, z0sintheta < 0.5, d0sig < 3.0 Tau: $p_T > 30$ GeV, medium wp, isoTau, hadronic tau
ttbar control region	Tau: $p_T > 50$ GeV, muon: $p_T > 50$ GeV
	At least one b-jet

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Template fit method

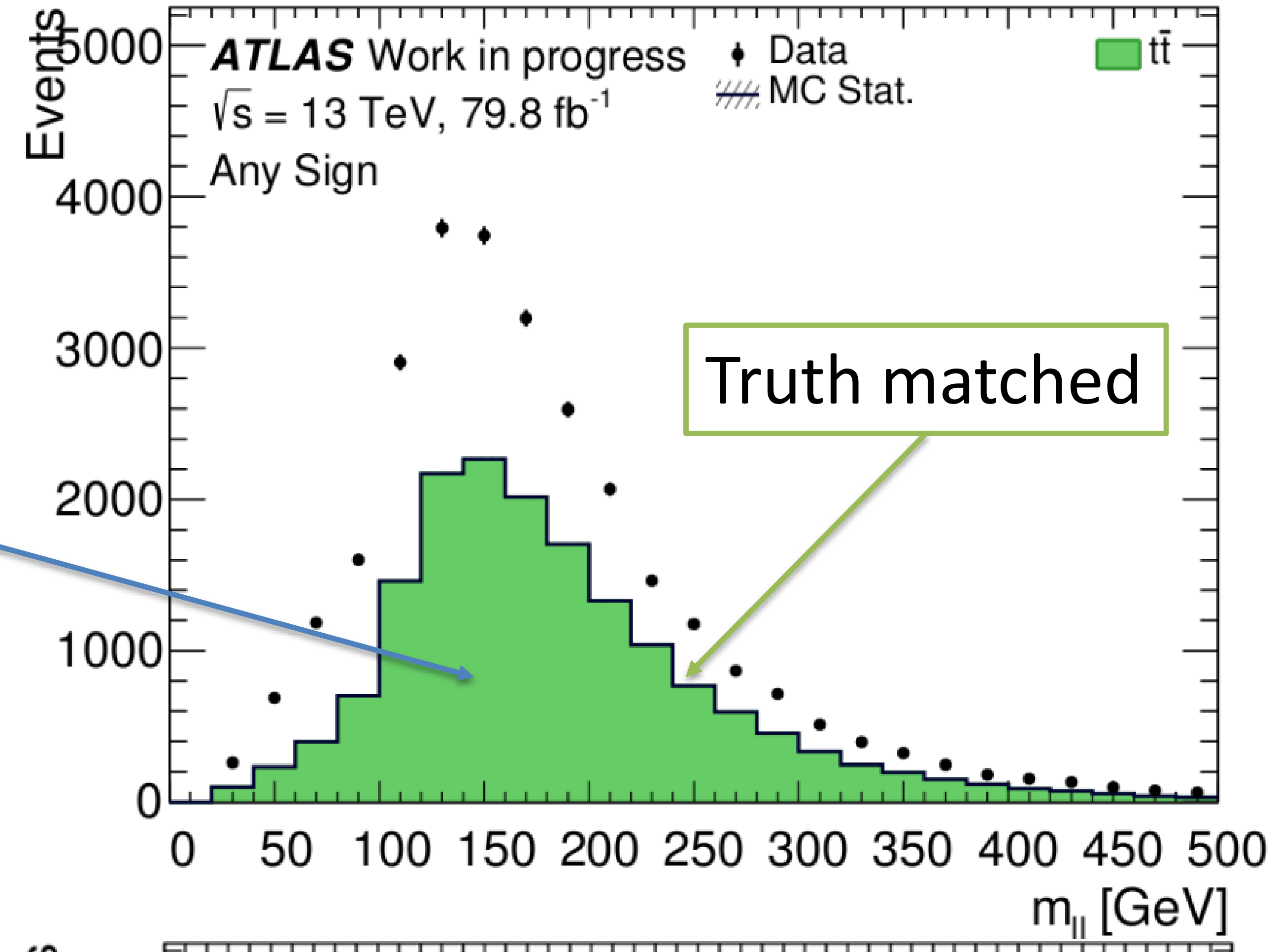
- Four templates are required:
  - $TMPL(N^{AS}_{signal})$ comes from $N^{AS}_{truth\ MC}$
  - $TMPL(N^{AS}_{bck})$ comes from $N^{AS}_{inc.\ MC} - N^{AS}_{truth\ MC}$
  - $TMPL(N^{SS}_{signal})$ comes from $N^{SS}_{truth\ MC}$
  - $TMPL(N^{SS}_{bck})$ comes from $N^{SS}_{inc.\ MC} - N^{SS}_{truth\ MC}$
- Need to find optimum values for the parameter a, b, c, d:

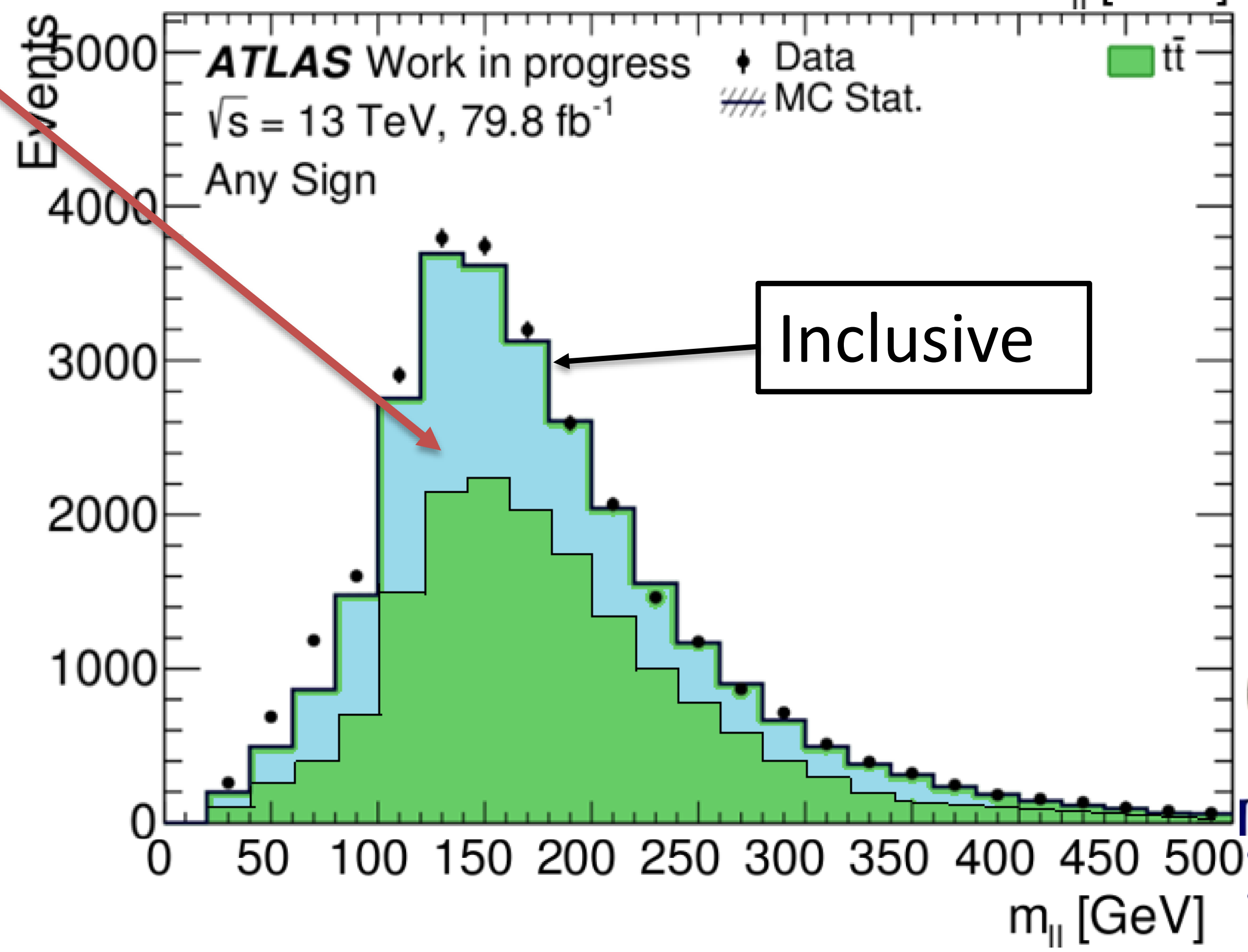
$$N^{AS}_{data}(\eta_i) = a \cdot TMPL\left(N^{AS}_{signal}(\eta_i)\right) + b \cdot TMPL\left(N^{AS}_{bck}(\eta_i)\right)$$
$$N^{SS}_{data}(\eta_i) = c \cdot TMPL\left(N^{SS}_{signal}(\eta_i)\right) + d \cdot TMPL\left(N^{SS}_{bck}(\eta_i)\right)$$

Parameter	a	b	c	d
Best fit value	0.820 $\pm$ 0.045	1.377 $\pm$ 0.070	1.364 $\pm$ 1.862	1.223 $\pm$ 0.078

- The charge flip rate is

$$\epsilon_{had}(\eta_i) = \frac{c \cdot TMPL\left(N^{SS}_{signal}(\eta_i)\right)}{a \cdot TMPL\left(N^{AS}_{signal}(\eta_i)\right)}$$





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Template fit method

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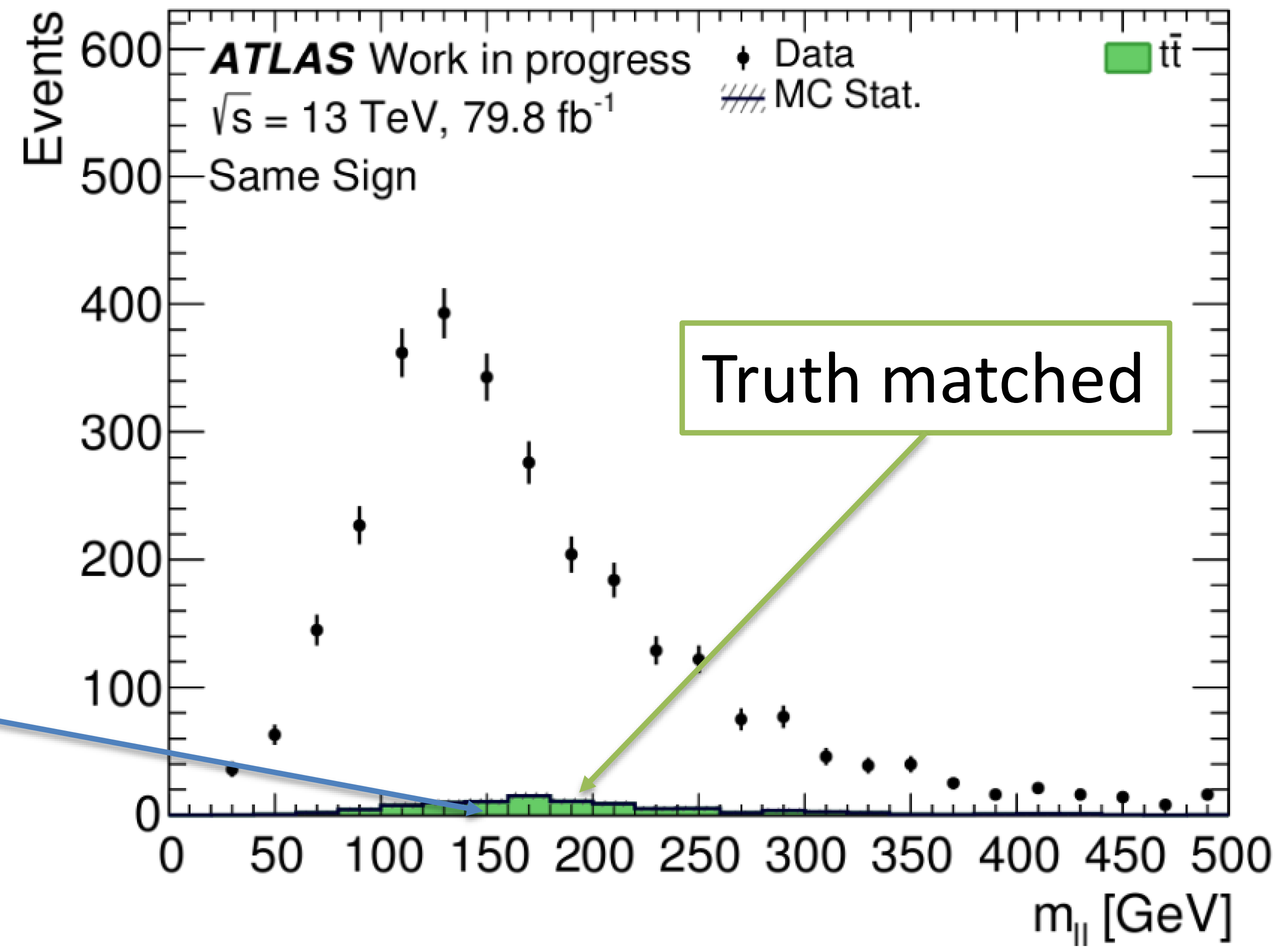
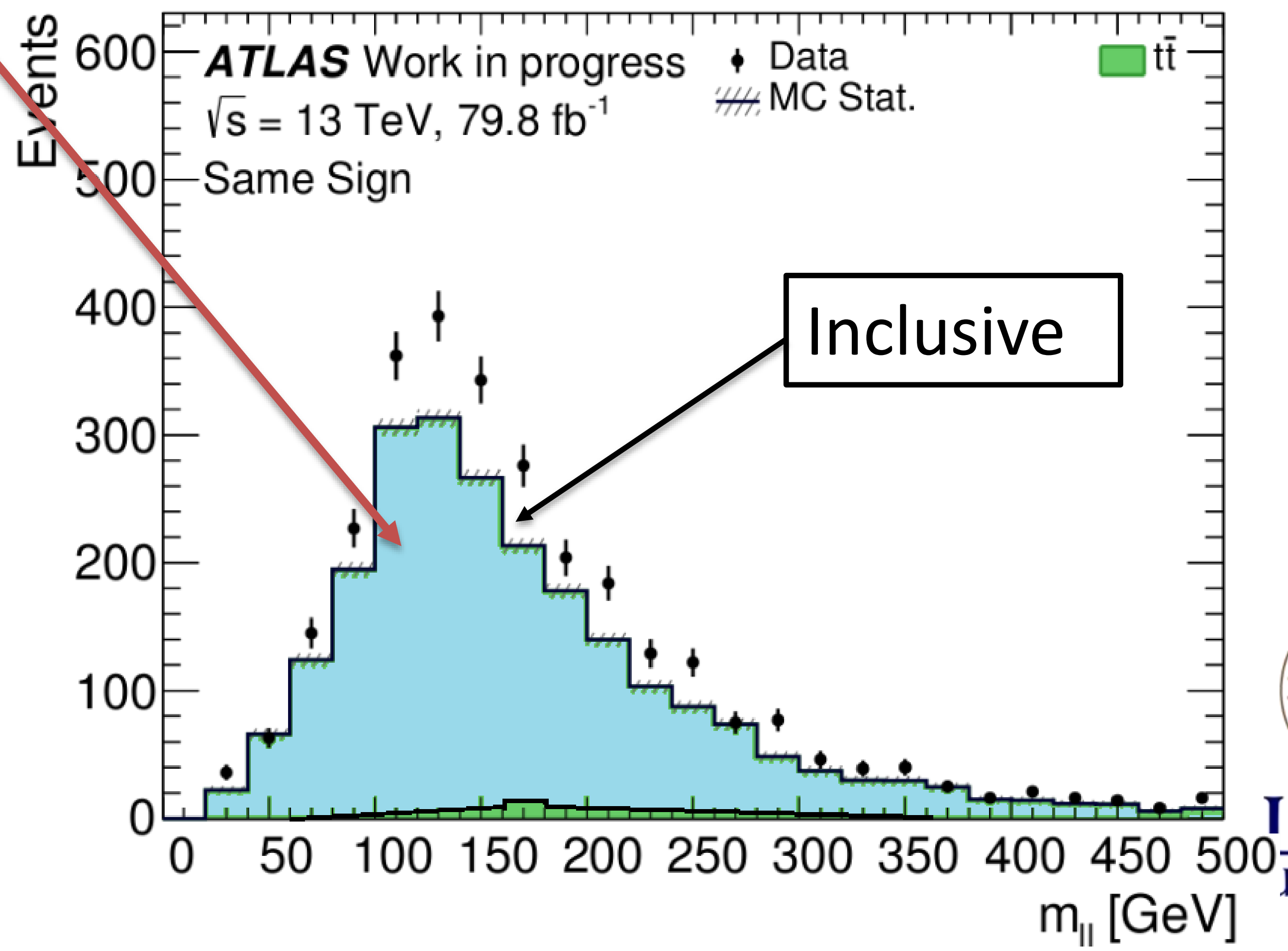
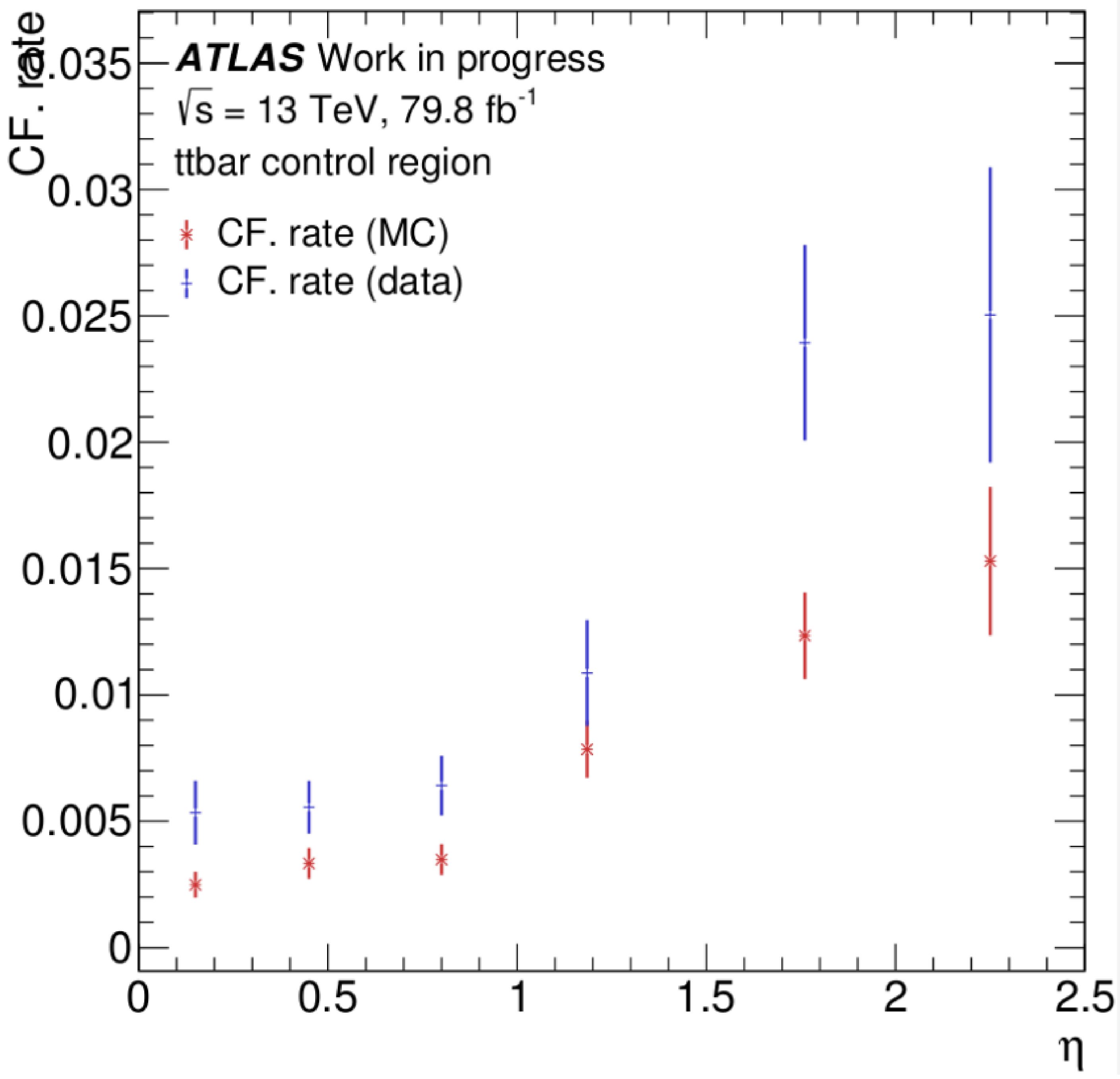
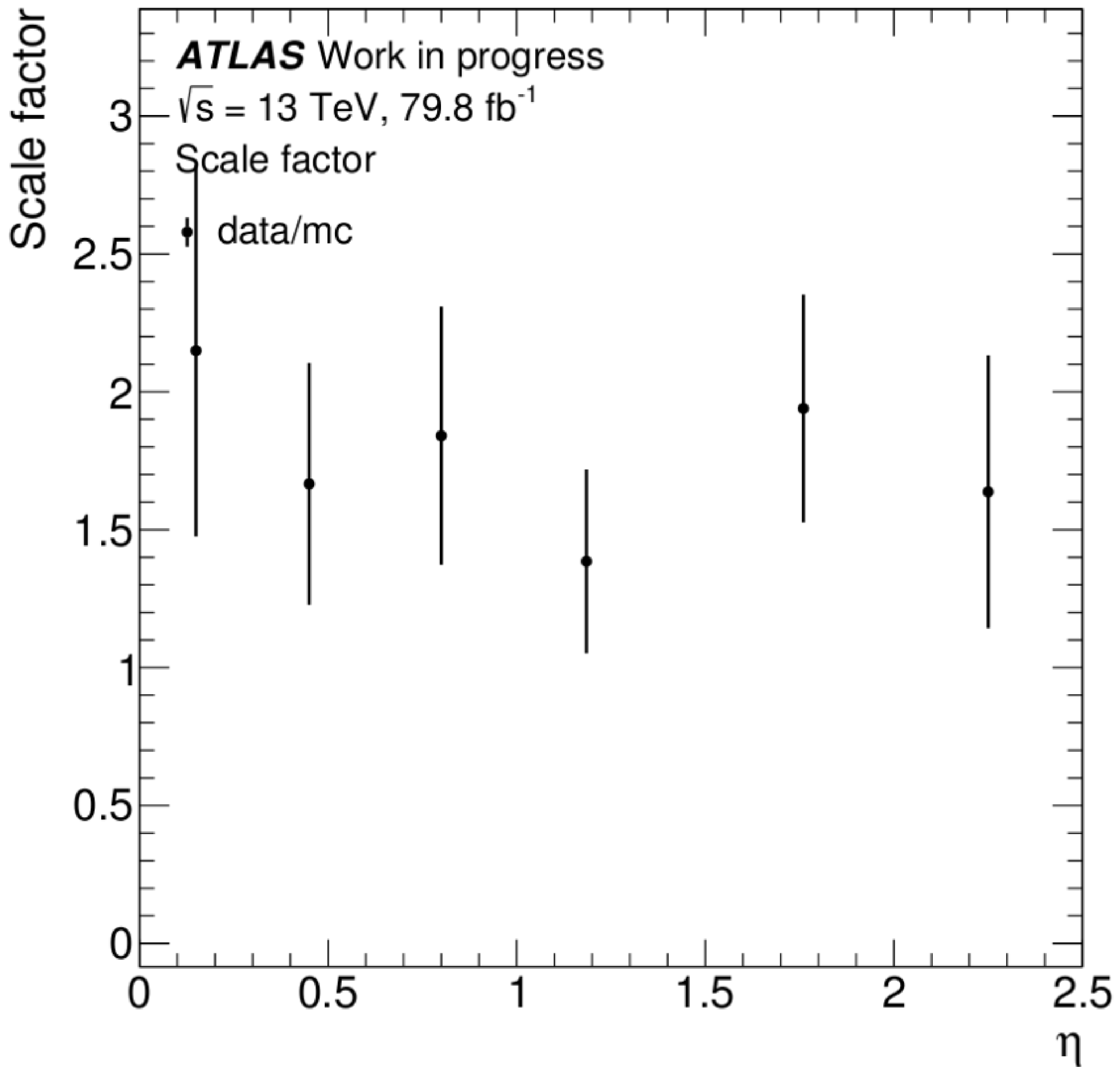




Charge flip rate for data and scale factor





Conclusion and current status

- The ATLAS detector at LHC is currently used to search for doubly charged Higgs bosons using same-charge hadronic tau channel.
- Charge-flip rate of hadronic tau ϵ_{had} for MC and data have been studied.
- ϵ_{had} depends weakly on p_T and strongly on η.
- The charge-flip background is not a dominant background. Only $0.5 - 2\%$ for $|\eta|$ ranging from 0 to 2.5.
- The scale factor is derived to be around 2 ± 0.5.

- Currently study the cause of charge-flip rate using event display

Backup slides

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Why search for doubly charged Higgs?

- Doubly charged Higgs bosons can arise in various BSM theories
  - Left-right symmetric models, little Higgs model, type-II seesaw models, …
- Appear in $SU(2)_L$ triplet for almost all the models studied

$$\Delta = \begin{pmatrix} H^+/\sqrt{2} & H^{++} \\ H^0 = \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta) & -H^+/\sqrt{2} \end{pmatrix}$$

- The Yukawa interaction term

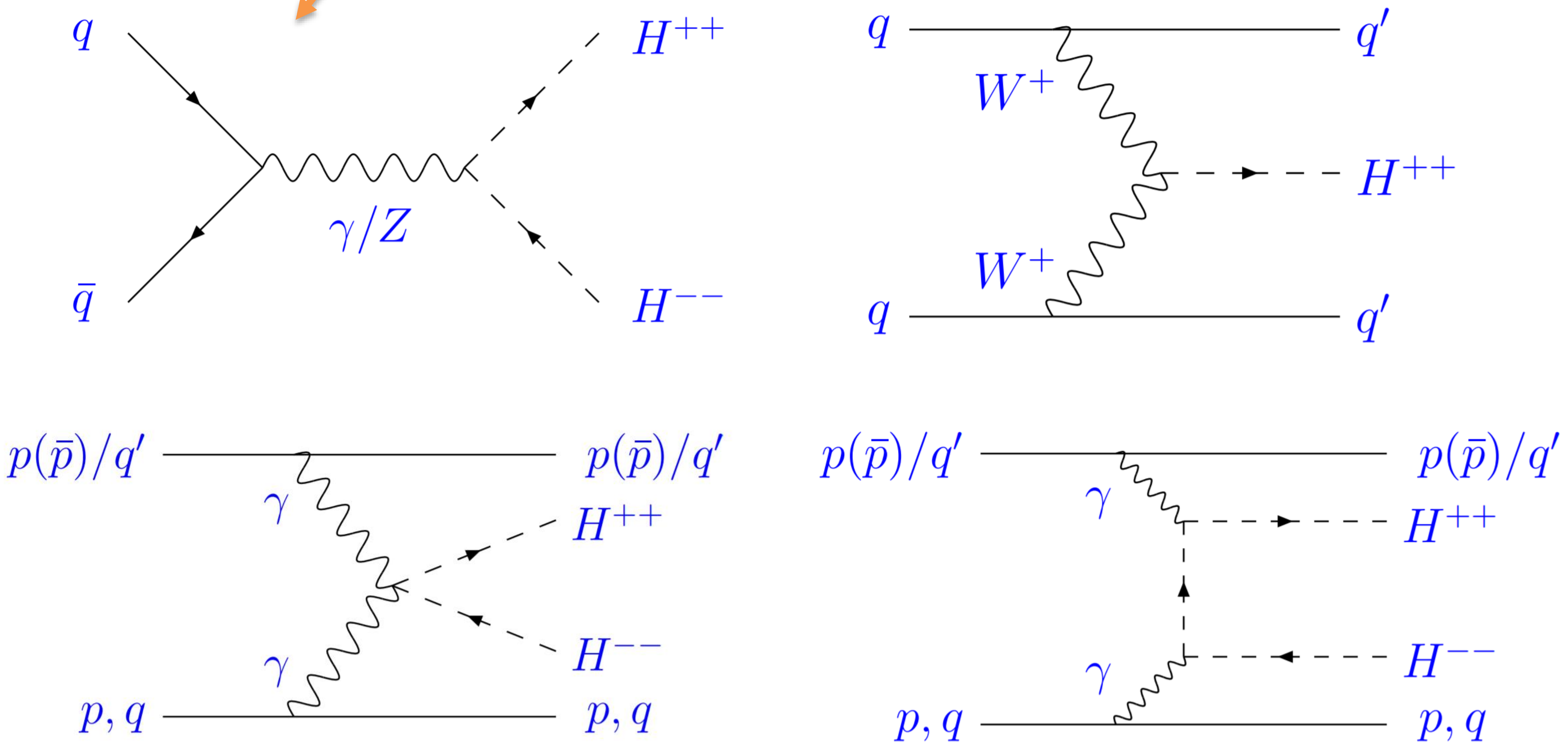
$$-Y_\nu \overline{l_L^c} i\sigma_2 \Delta l_L + h.c.$$

and the neutrinos acquire a Majorana mass

$$M_\nu = \sqrt{2} Y_\nu v_\Delta \approx Y_\nu \frac{\mu v_0^2}{M_\Delta^2}$$

- Can decay to a pair of same-sign leptons which are rare in SM
  - Signal violation of lepton flavour by two units

Dominant Drell-Yan pair production



Feynman diagrams for several doubly charged Higgs production channel. arXiv:1105.1379v1

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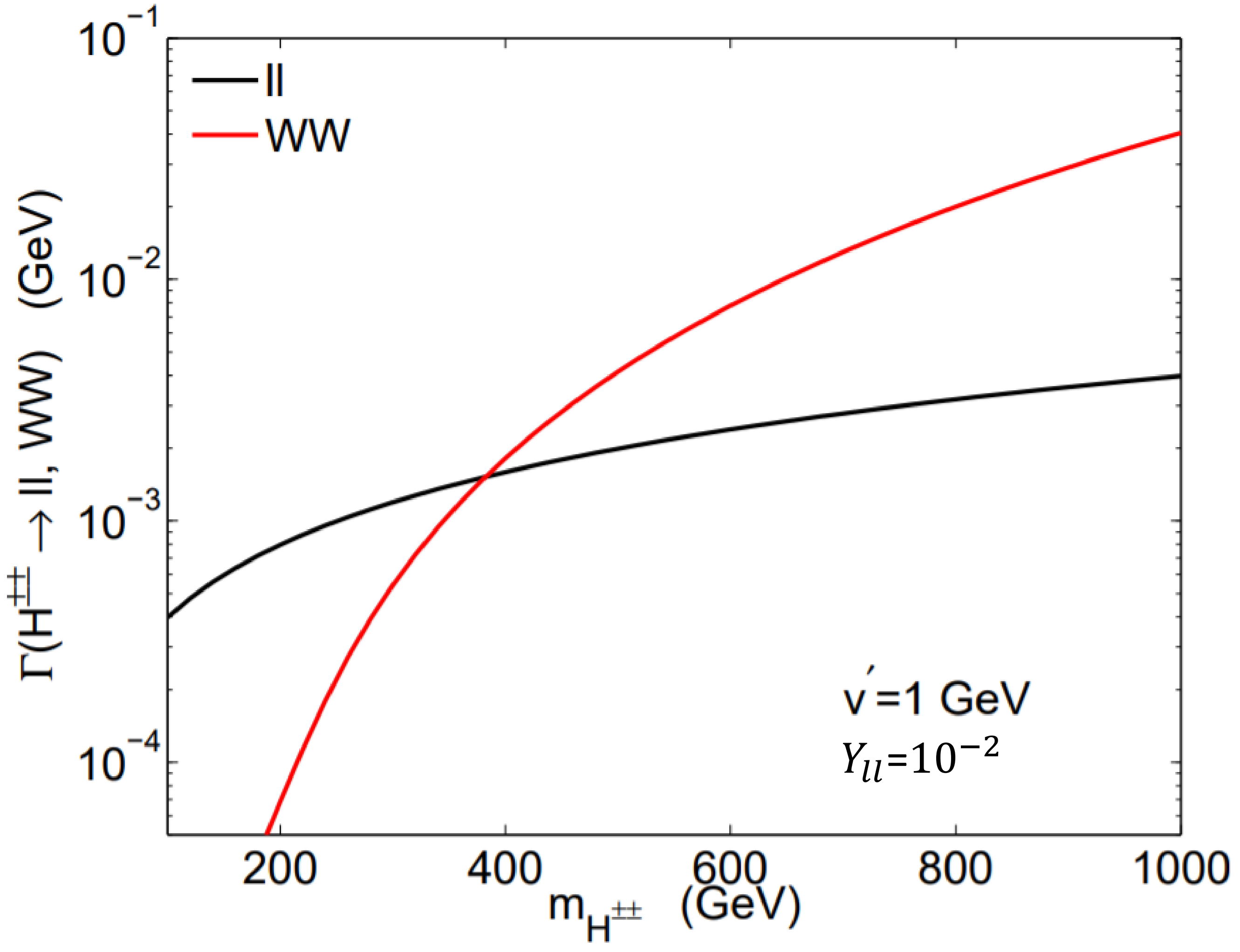
Previous study by ATLAS on $H^{\pm\pm} \rightarrow l^{\pm}l'^{\pm}$

- Used pp data sample with Integrated luminosity 36.1 fb^{-1} collected in 2015 and 2016 by the ATLAS detector at the LHC at $\sqrt{s}$=13 TeV
- Only pair production via the Drell–Yan process was considered
- Total assumed branching ratio of $H^{\pm\pm}$ is $B(H^{\pm\pm} \rightarrow l^{\pm}l'^{\pm}) + B(H^{\pm\pm} \rightarrow X) = 100\%$, while "$X$" does not enter any of the SRs. Only e and μ were considered.
- Partial decay width of $H^{\pm\pm}$ to leptons is given by:

$$\Gamma(H^{\pm\pm} \rightarrow l^{\pm}l'^{\pm}) = \frac{1}{1+\delta_{ll'}} \frac{\left|\tilde{Y}_{ll'}\right|^2 m_{H^{\pm\pm}}}{16\pi}, \quad \tilde{Y}_{ll'} = \begin{cases} 2Y_{ll'} & l = l' \\ Y_{ll'} & l \neq l' \end{cases}$$

$$\left|\tilde{Y}_{ll'}\right|^2 = 2\left|m_\nu^{ij}\right|^2 / v_\Delta^2$$

- Masses studied: $200 \leq m_{H^{\pm\pm}} \leq 1300$ GeV



Branching ratios of $H^{\pm\pm}$ into different final states vs. mass of $H^{\pm\pm}$ for $v_\Delta = 1$ GeV, $Y_{ll} = 0.01$. arXiv:1105.1379v1

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Previous study by ATLAS on $H^{\pm\pm} \to l^{\pm}l'^{\pm}$

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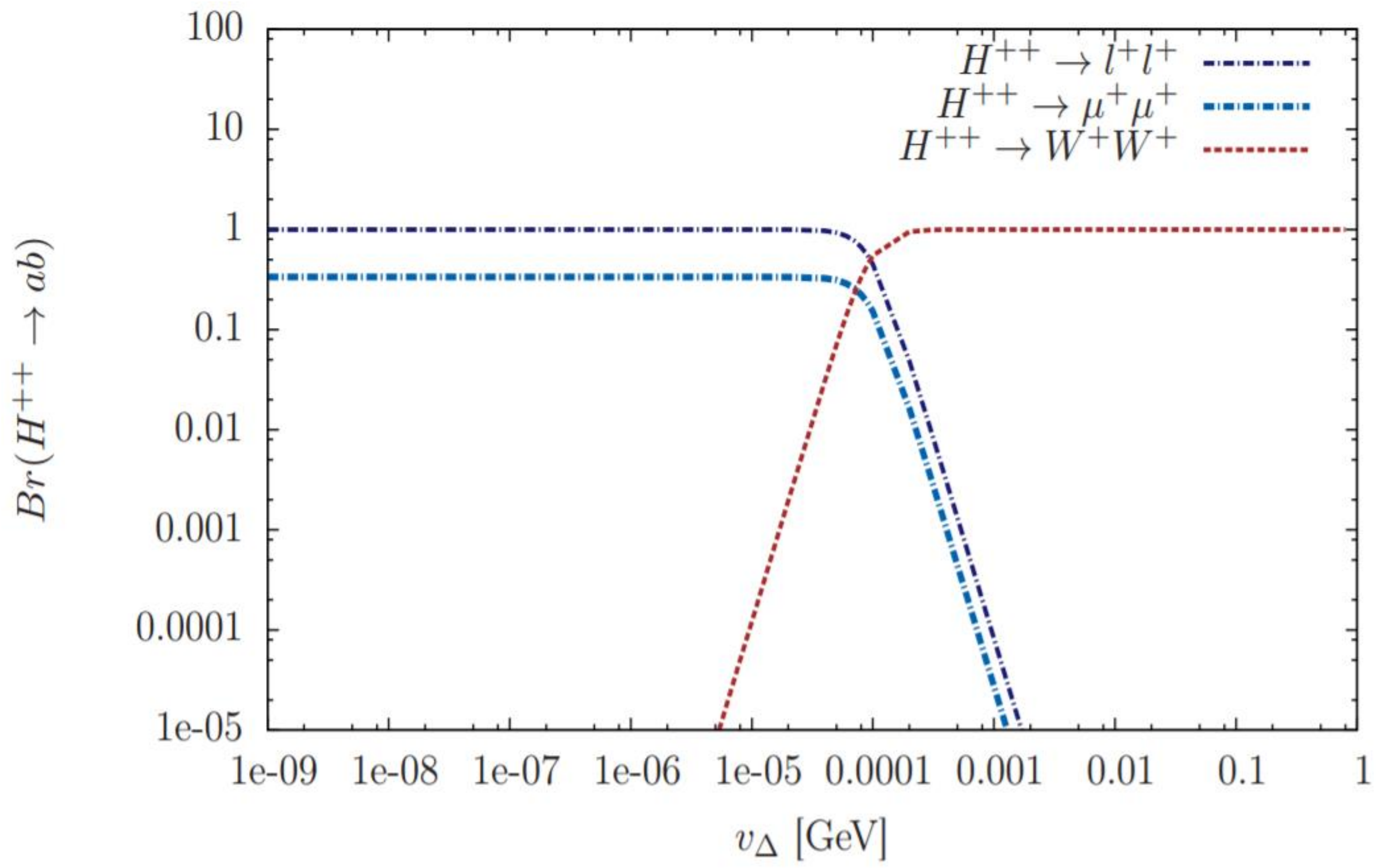

Branching ratios of $H^{\pm\pm}$ into different final states vs. vacuum expectation value. arXiv:1611.09594v2

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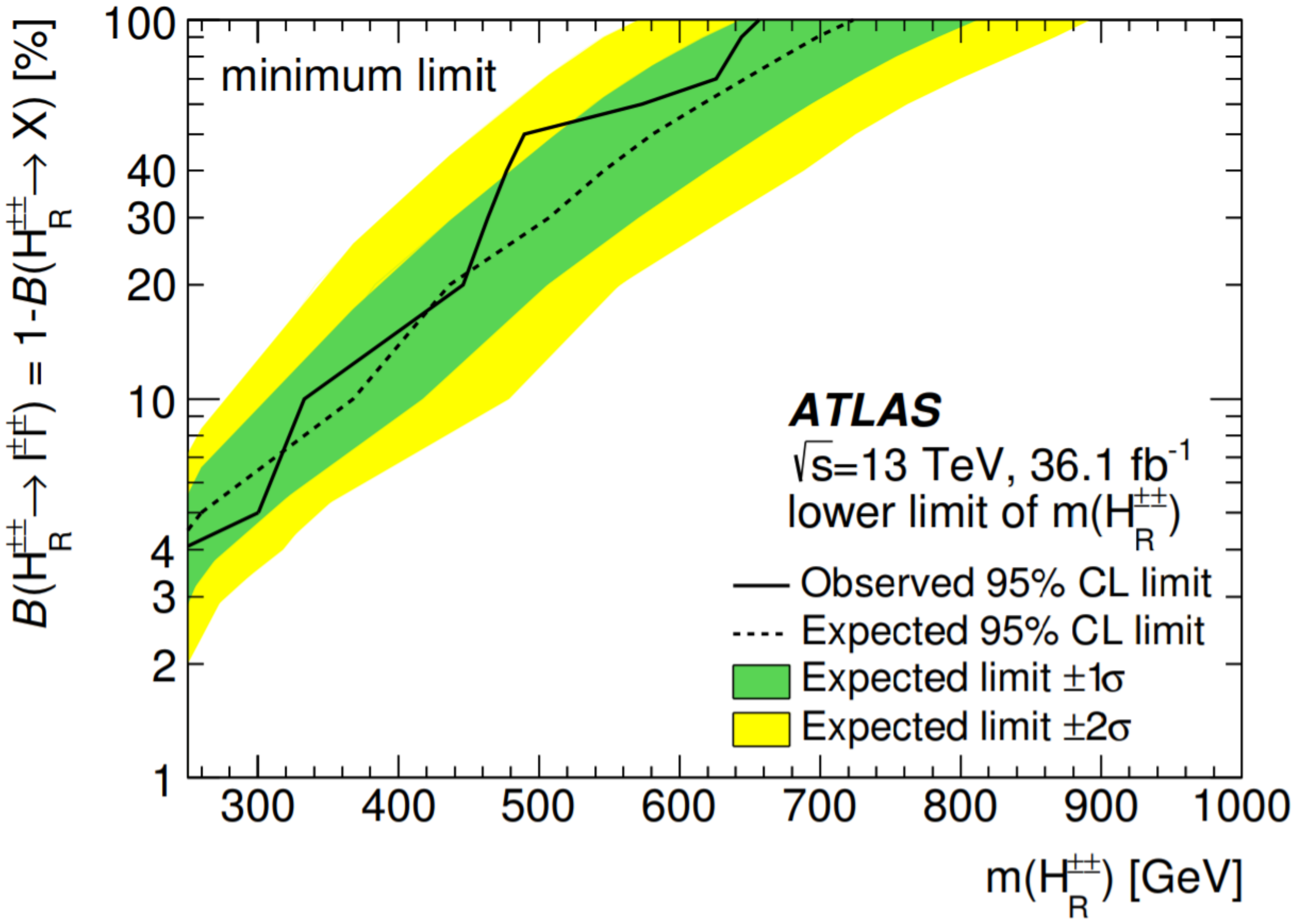
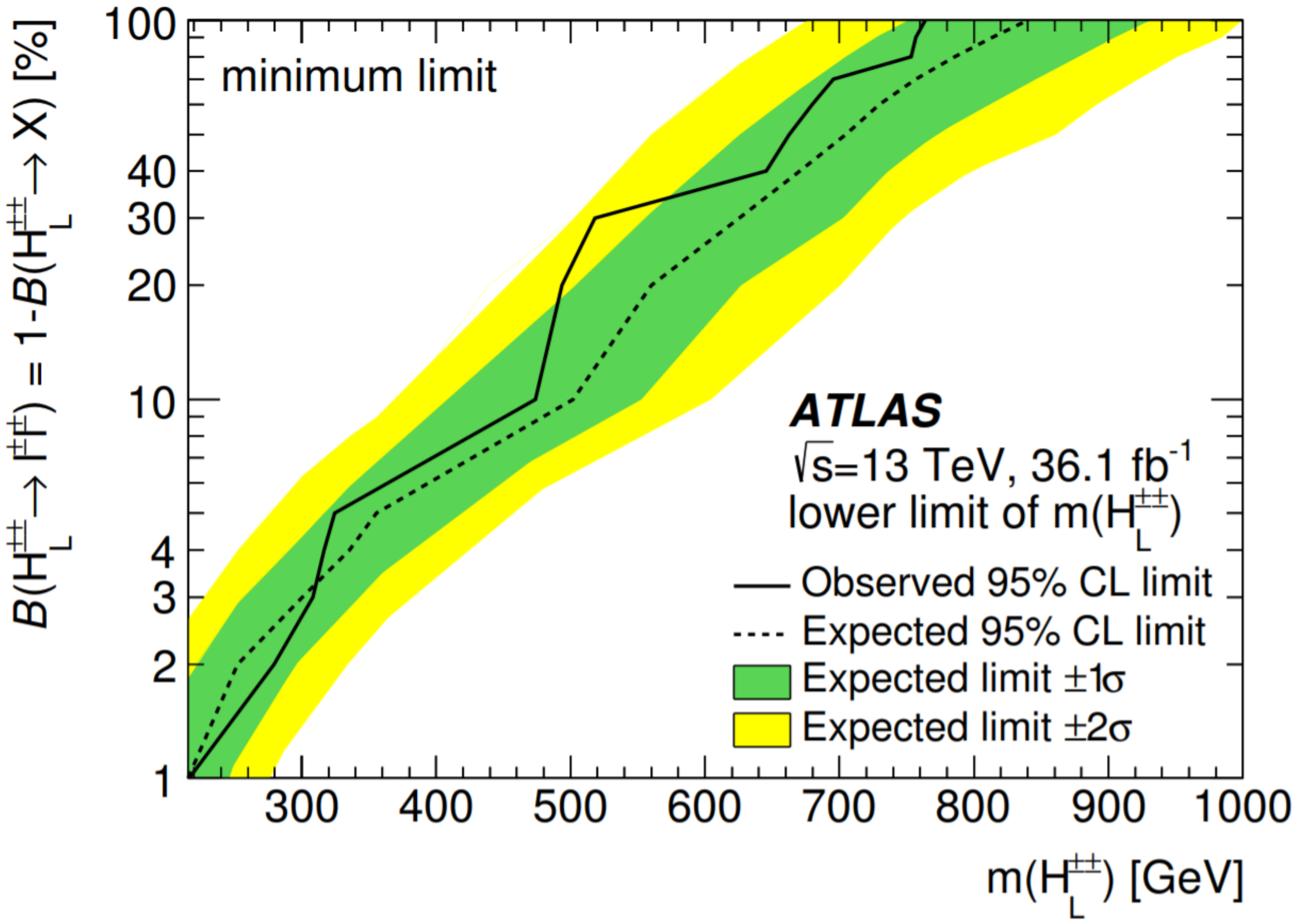
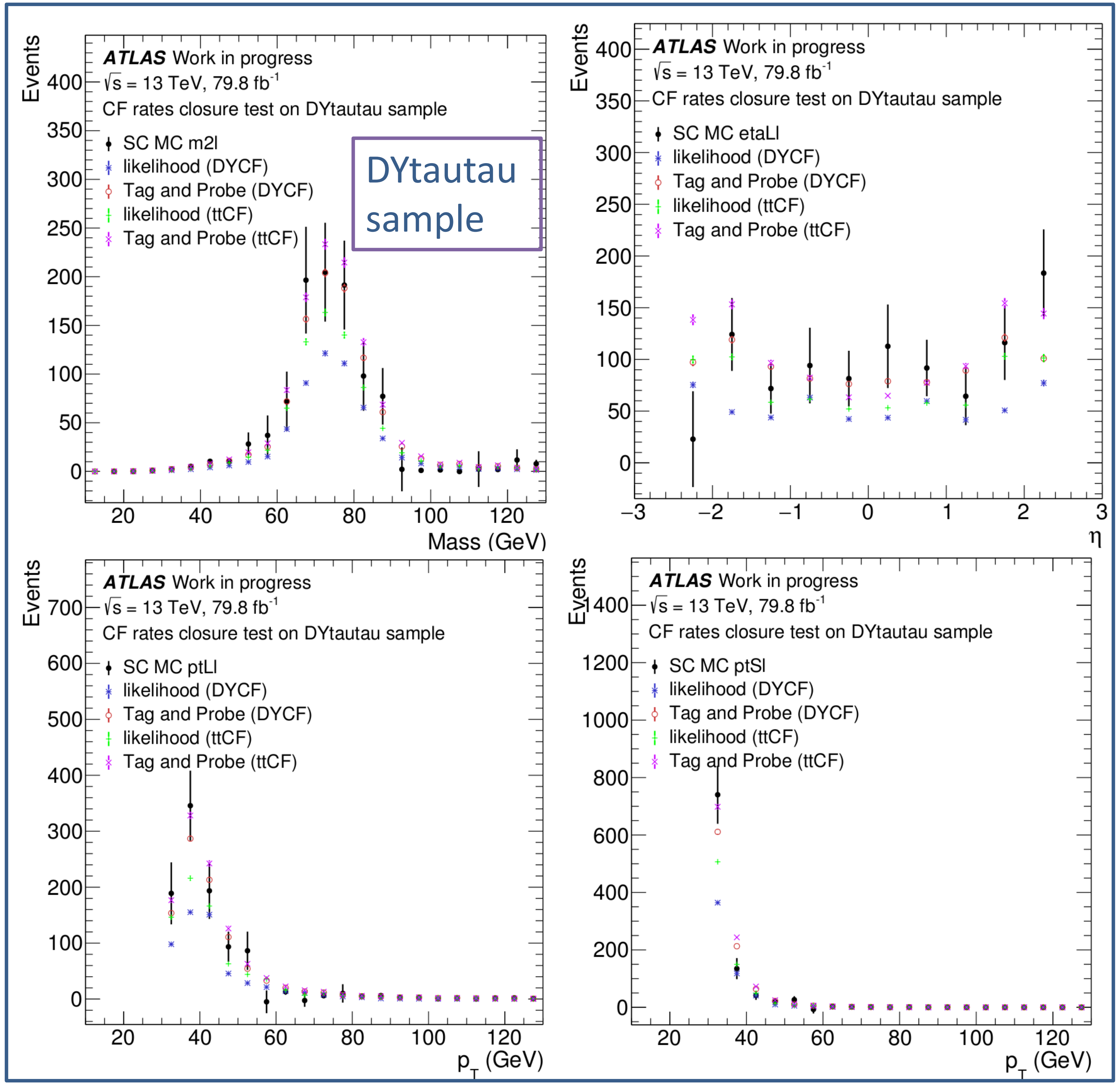
Lower-limit plots on $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ mass

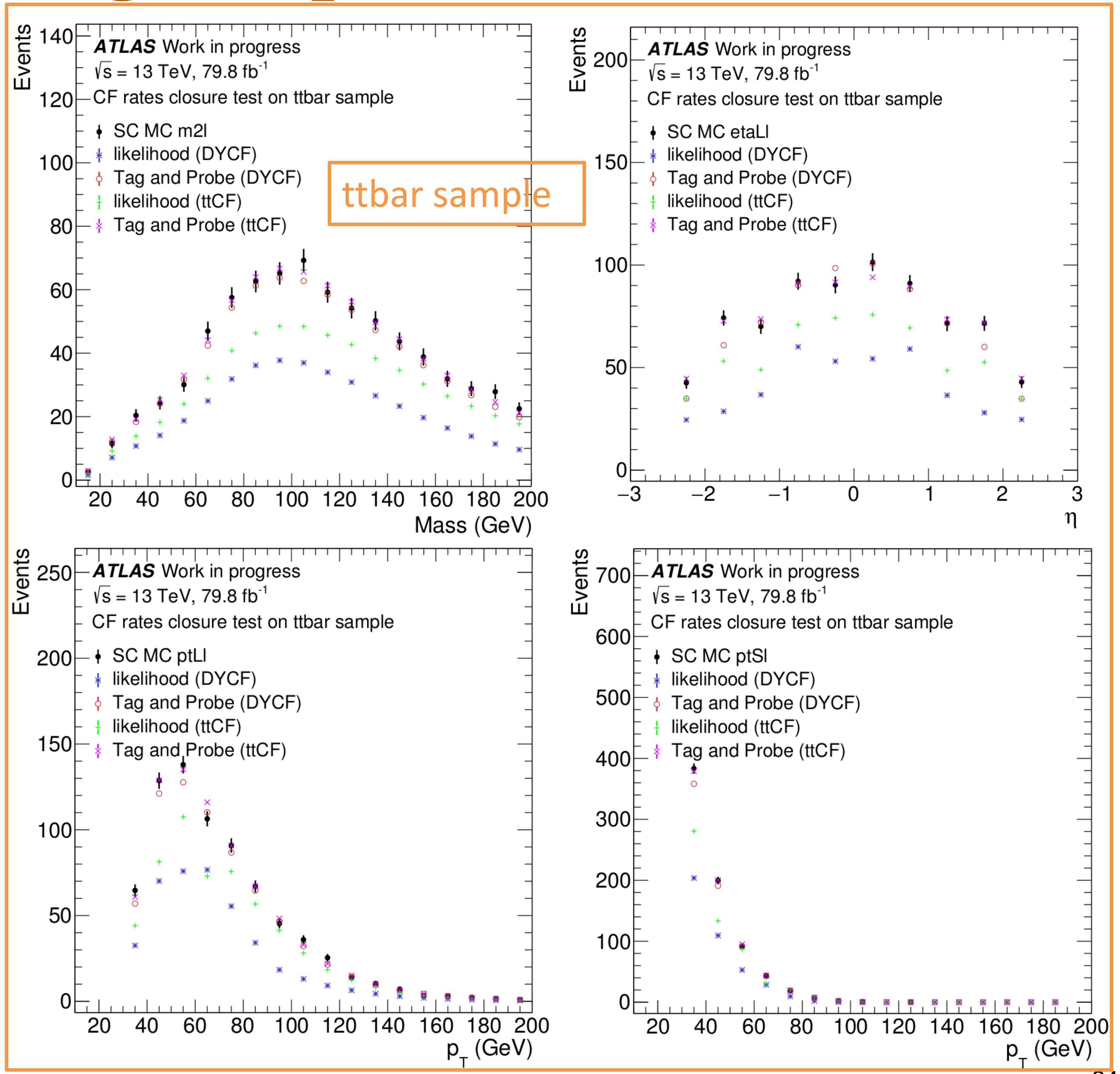




arXiv: 1710.09748v1

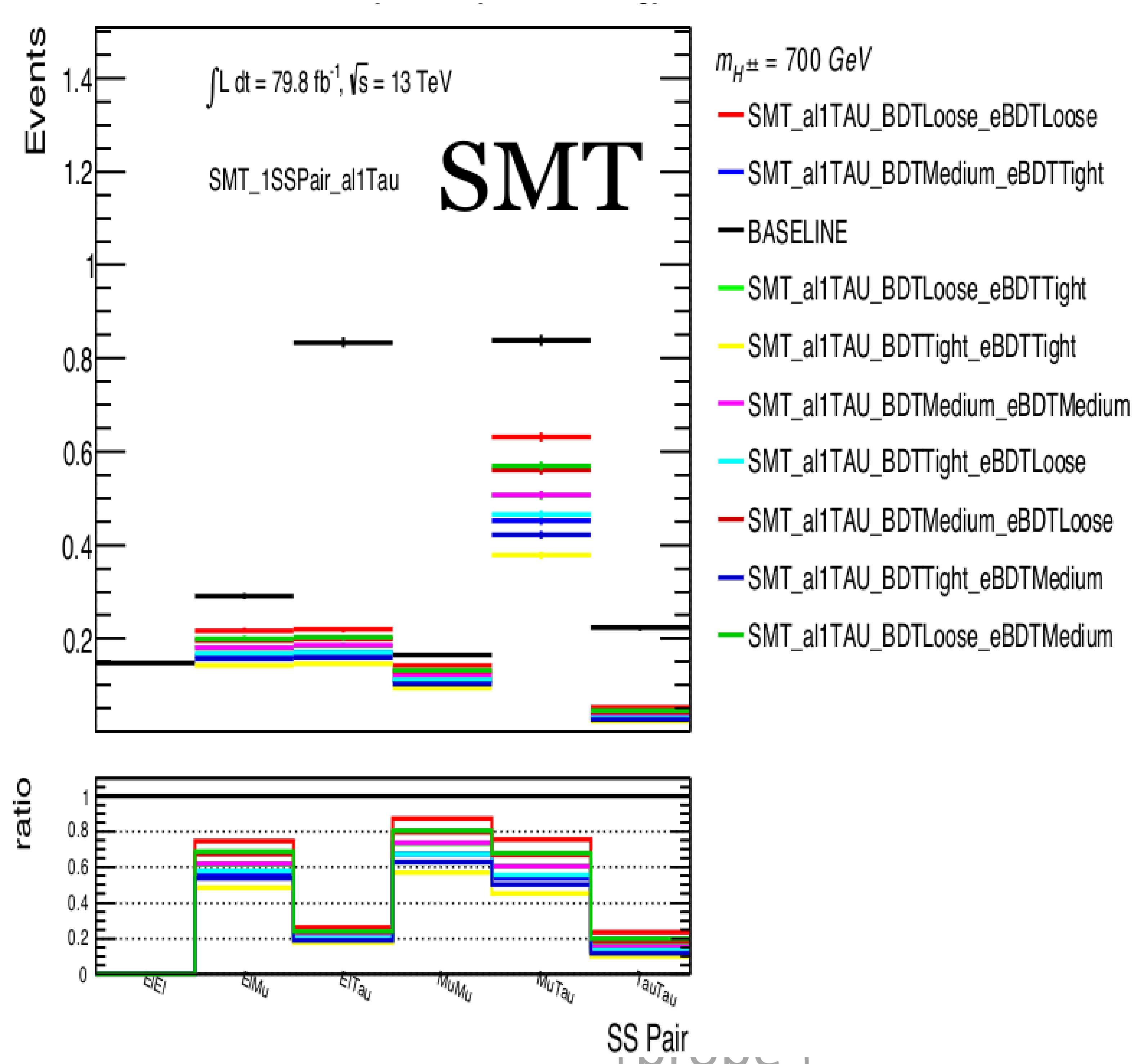
Closure test for the MC charge flip rate

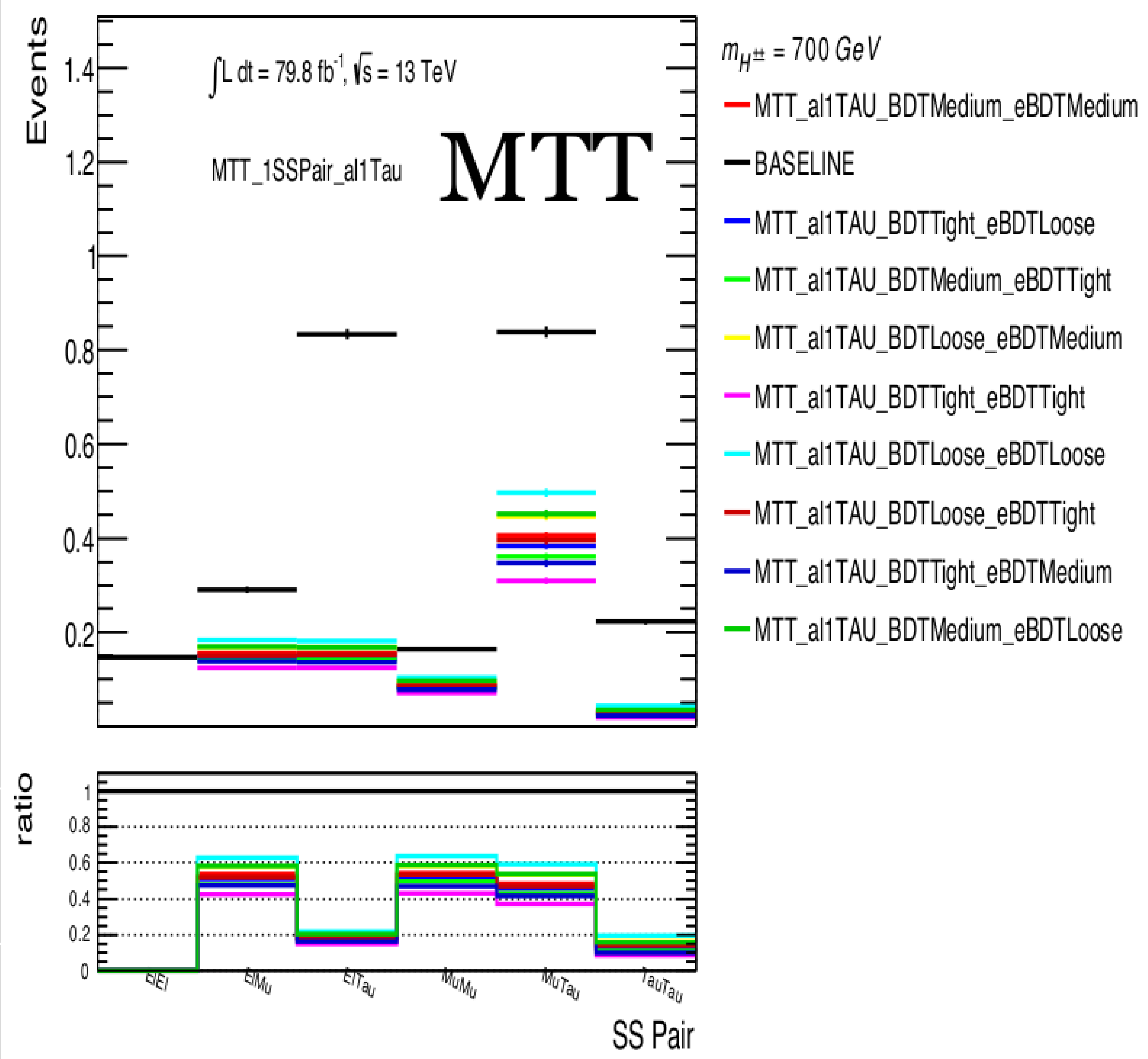




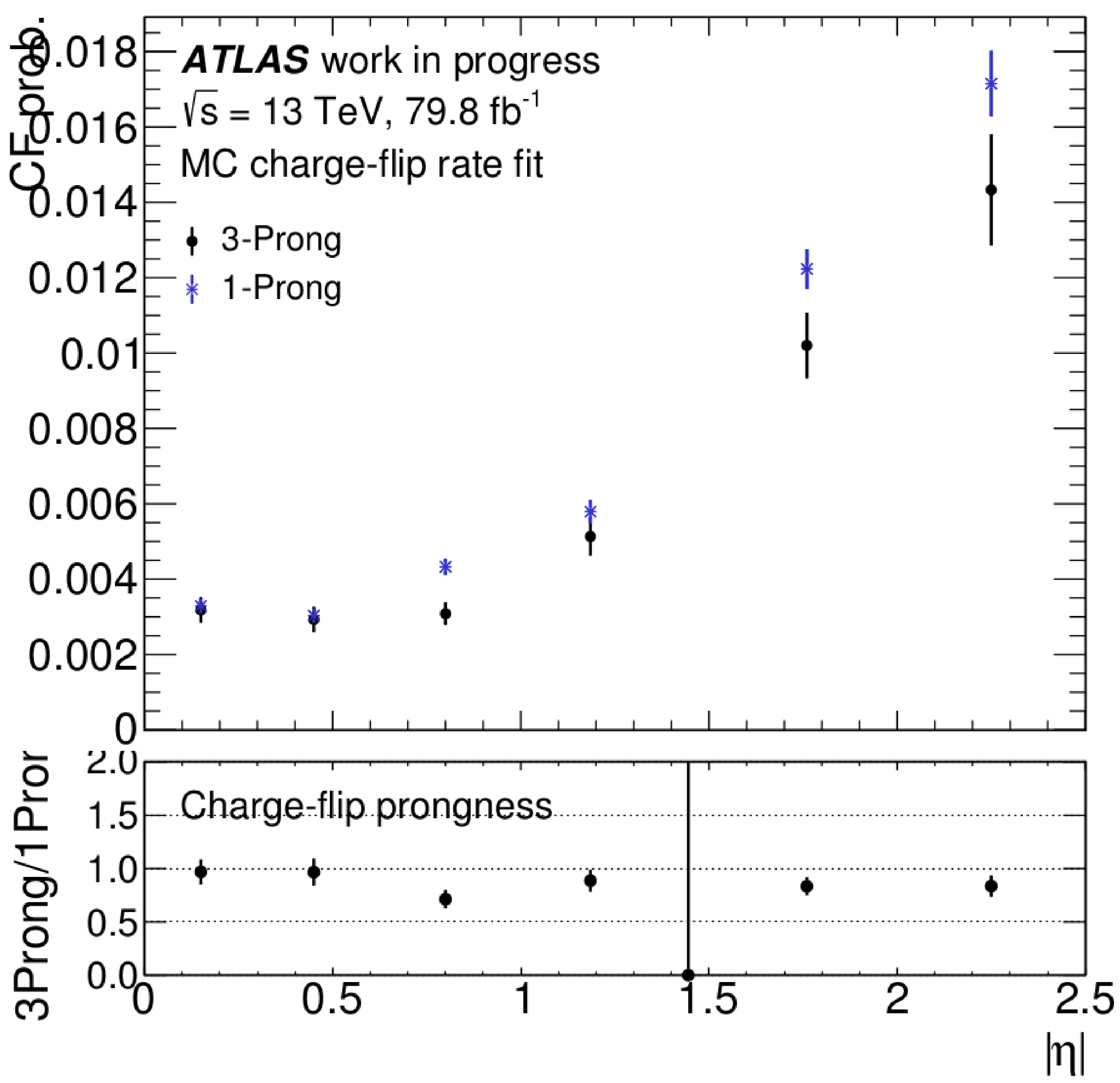
Tag-and-probe method

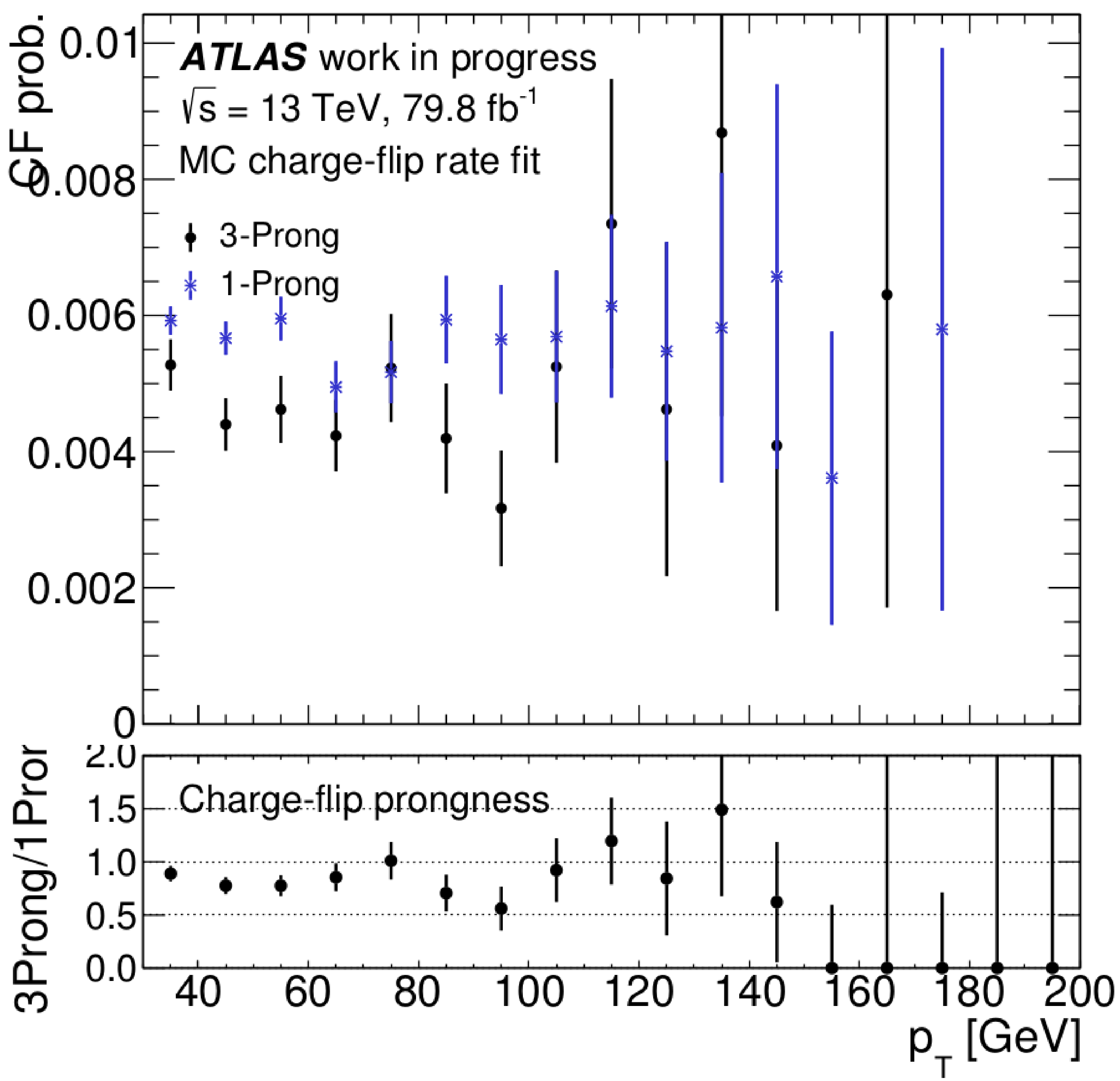
	Selections
	Single muon trigger:





1D charge-flip rate with prongness from ttbar





Tau Charge-flip rate for data

- Use recommended selections for Z and ttbar control regions

	Selections
Baseline	Single muon trigger
	One muon and one tau. Electron veto
	Muon: $p_T > 30$ GeV, medium wp, FixedCutTightTrackOnly, z0sintheta < 0.5, d0sig < 3.0 Tau: $p_T > 30$ GeV, medium wp, isoTau, hadronic tau
Z control region	$m_T(\mu, E_T^{miss}) = \sqrt{2p_T(\mu)E_T^{miss}(1-\cos\Delta\Phi(\mu, E_T^{miss}))} < 50$ GeV
	$\cos\Delta\Phi(\mu, E_T^{miss}) + \cos\Delta\Phi(\tau, E_T^{miss}) > 0.5$
ttbar control region	Tau: $p_T > 50$ GeV, muon: $p_T > 50$ GeV
	At least one b-jet

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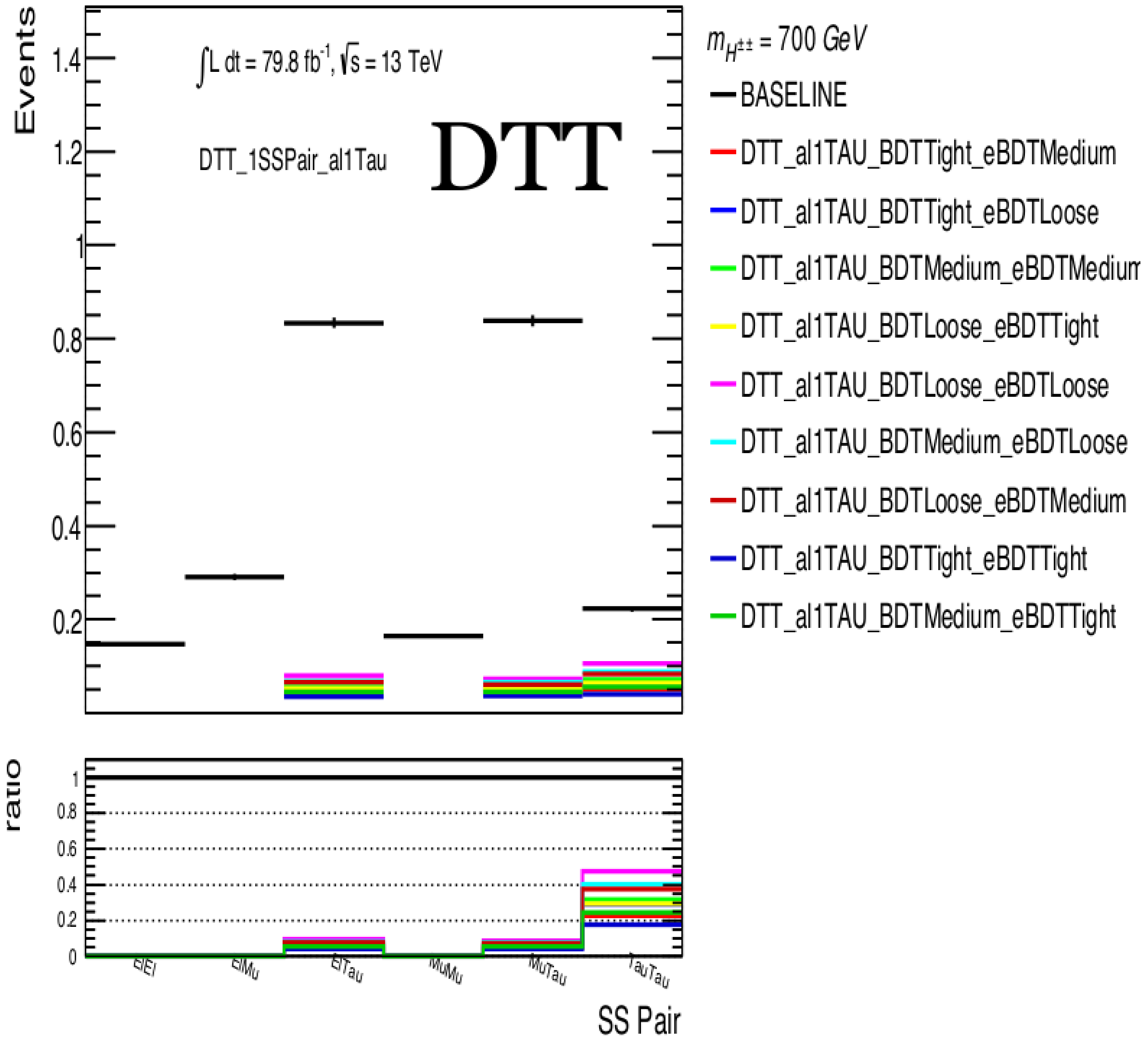
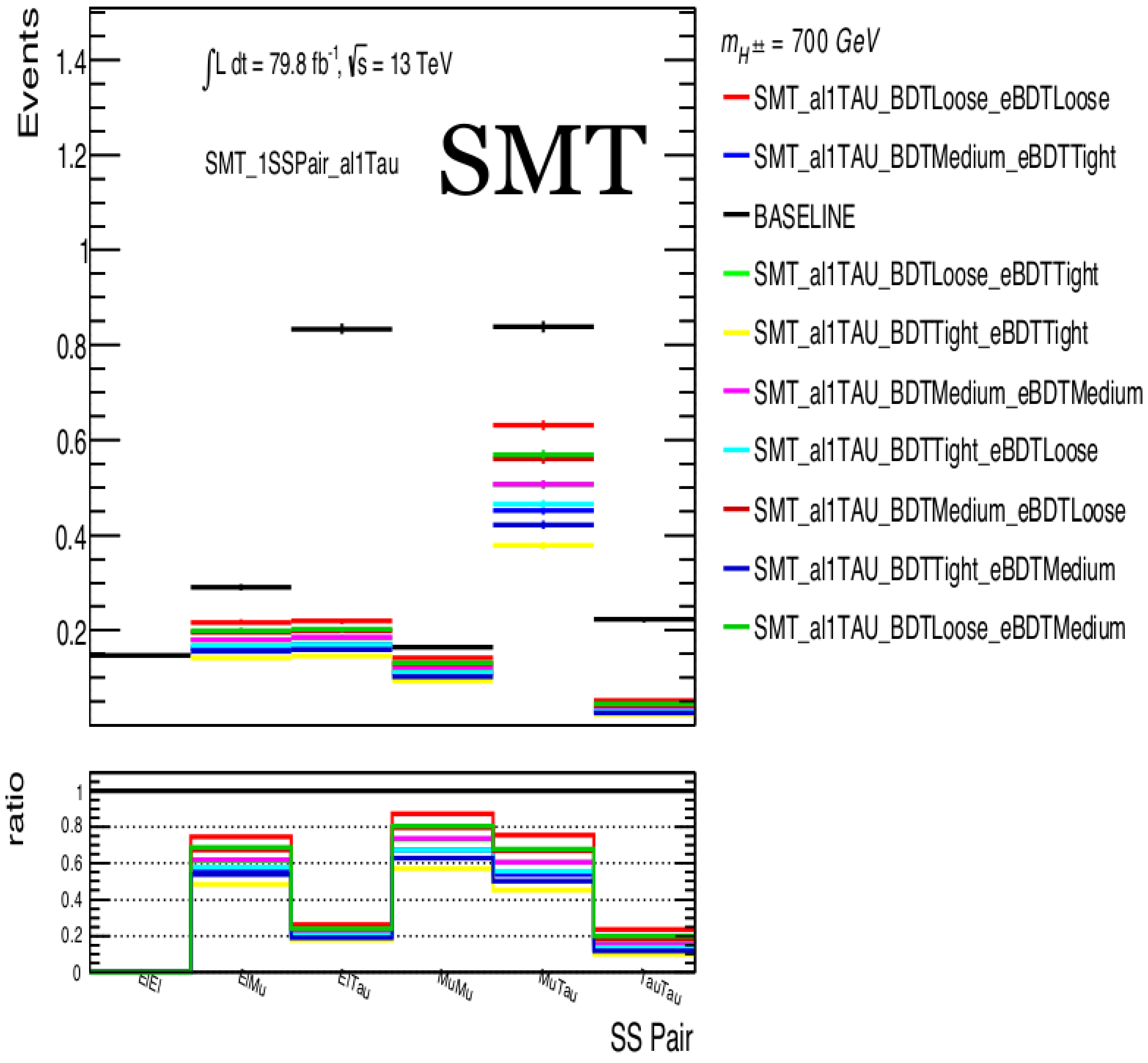
Why choose mu tau channel for template fit





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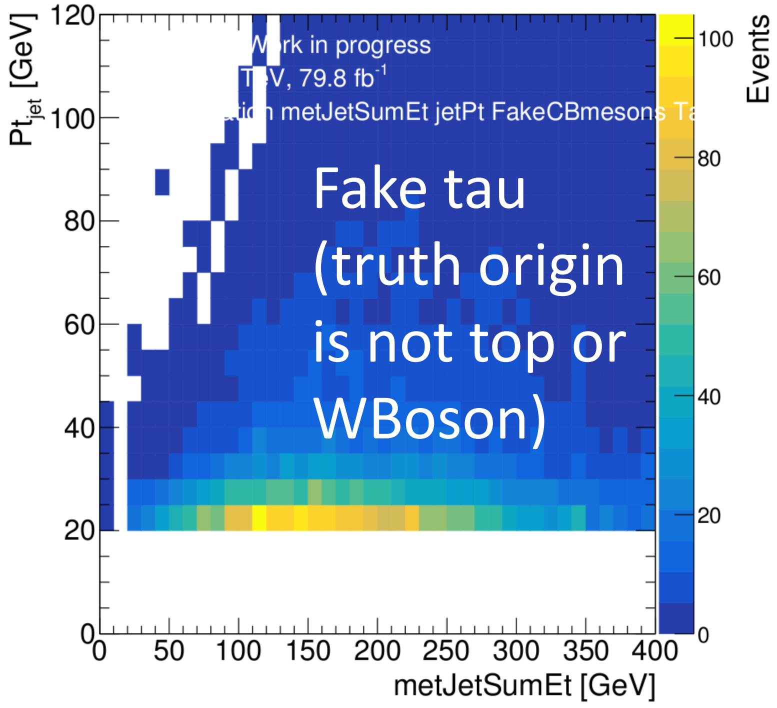
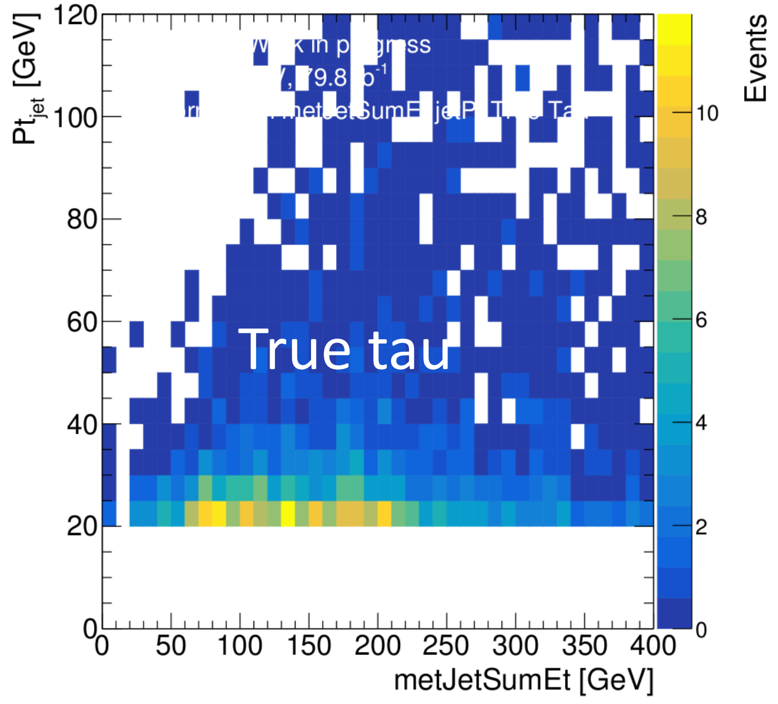
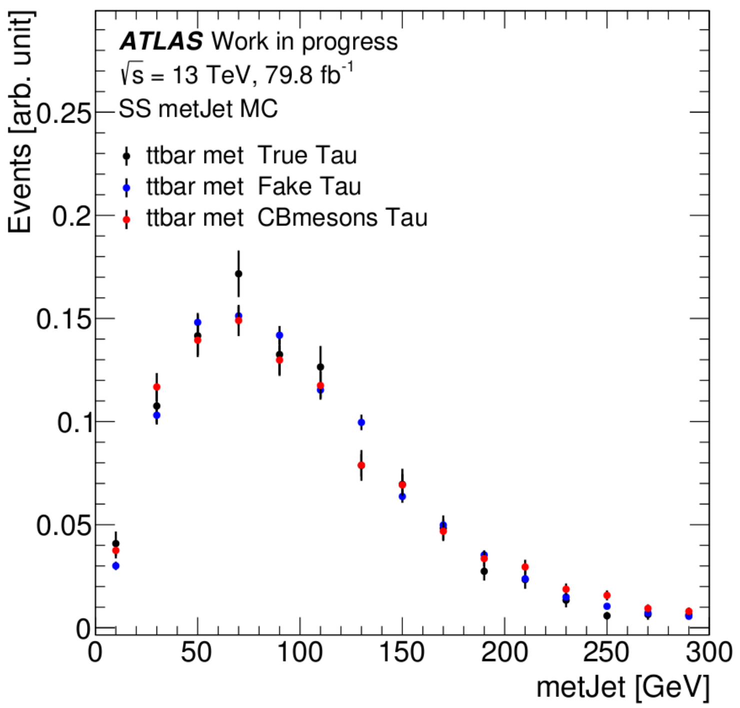
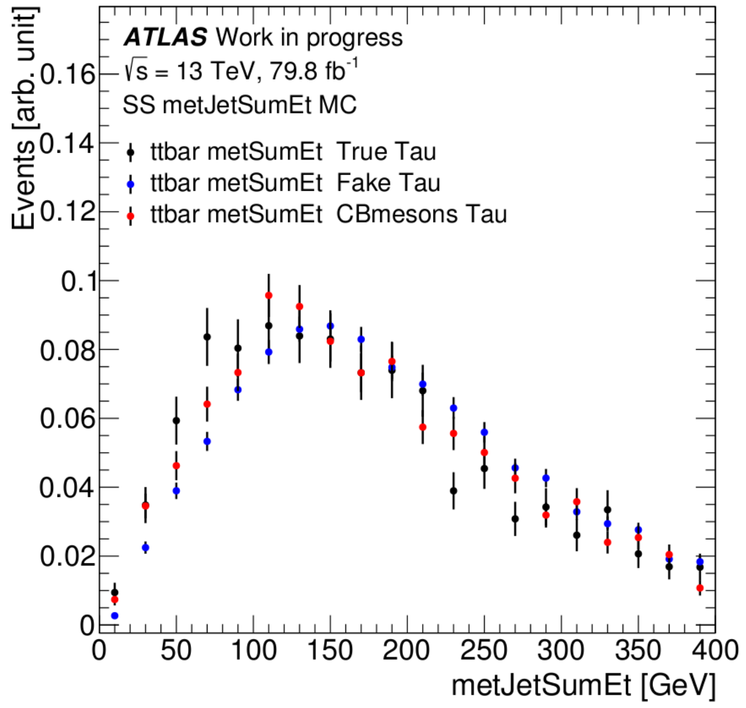
Attempts to reduce the background

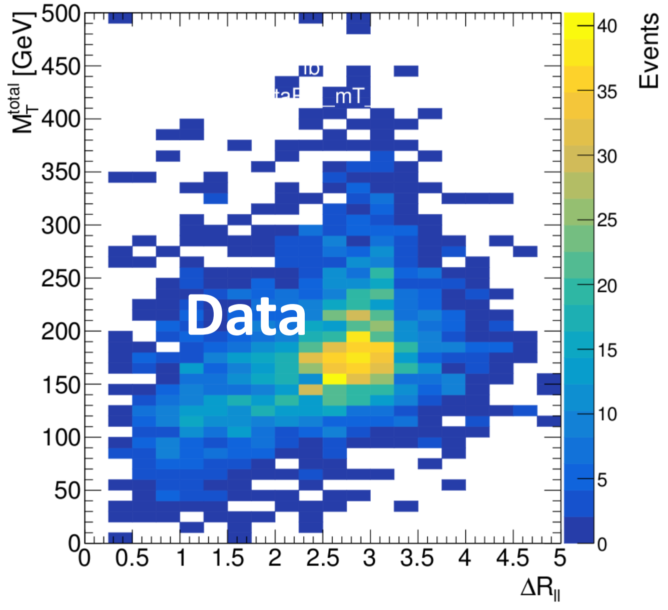
- A lot of efforts were spent on studying the correlations and distributions of tau and jet kinematic variables, but it seems that the BDT has already done a good job with selecting events with same topology

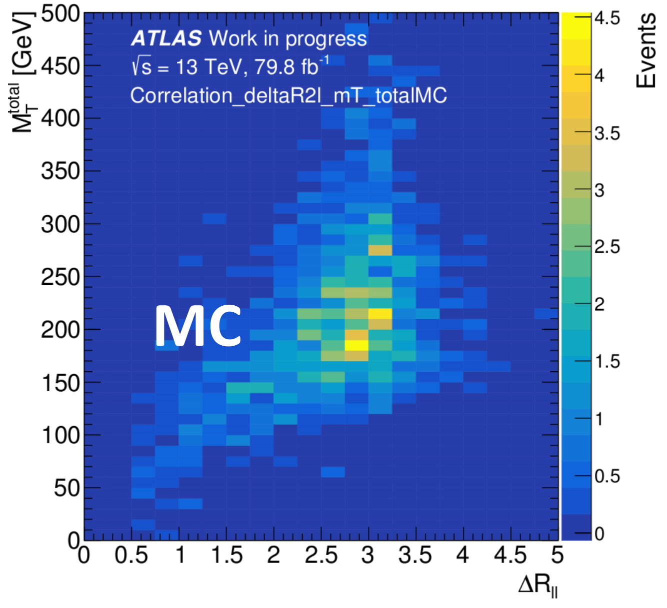












No significant difference. It is not easy to reduce fake tau SS background.

Template fit method

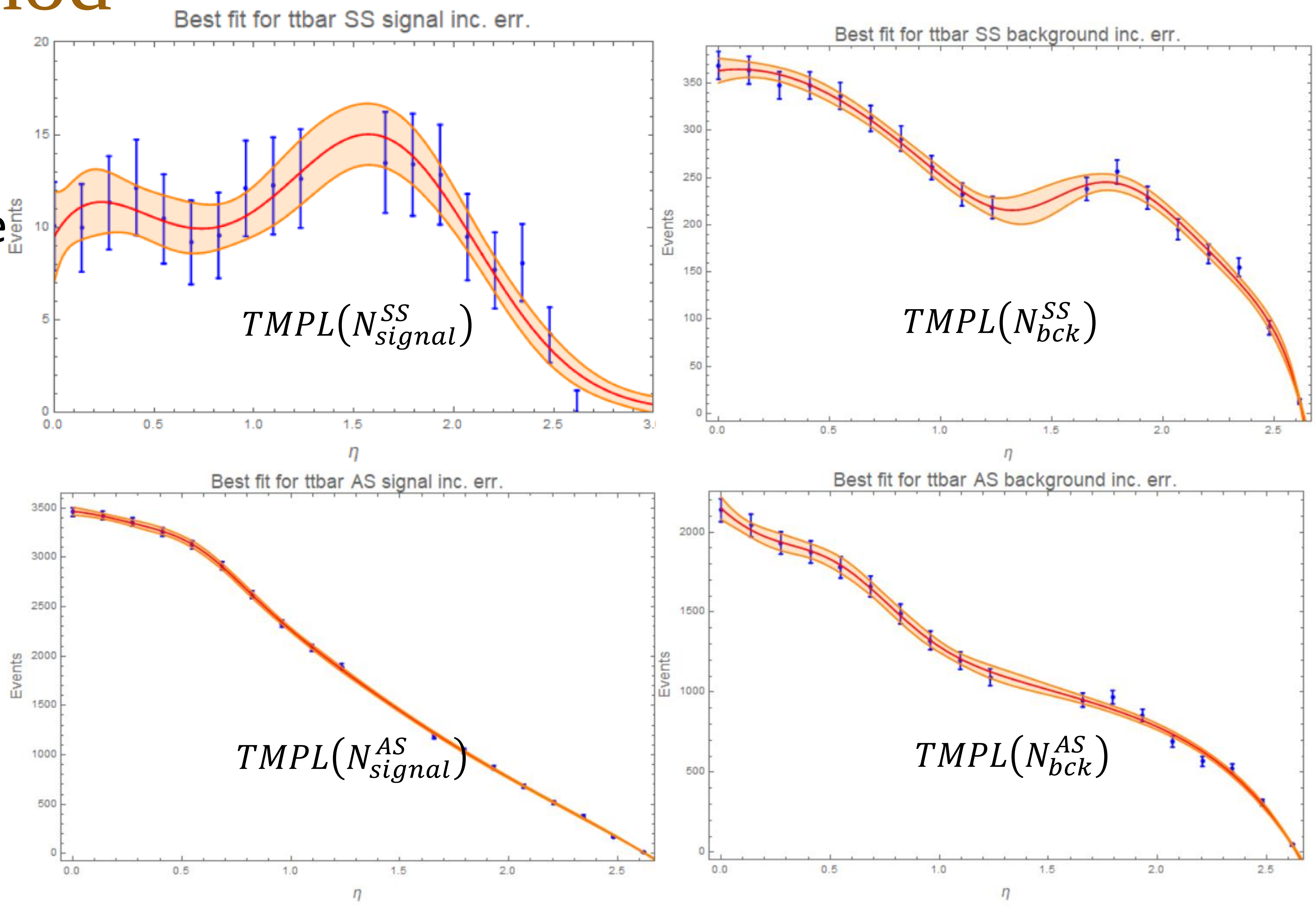
- Perform fitting in Mathematica 11.1
- The models generally have the form:

$$\frac{(ax+b)}{e^{f(x)}}$$

or

$$\frac{(ax+b)}{e^{f(x)}} + Gaussian(x)$$

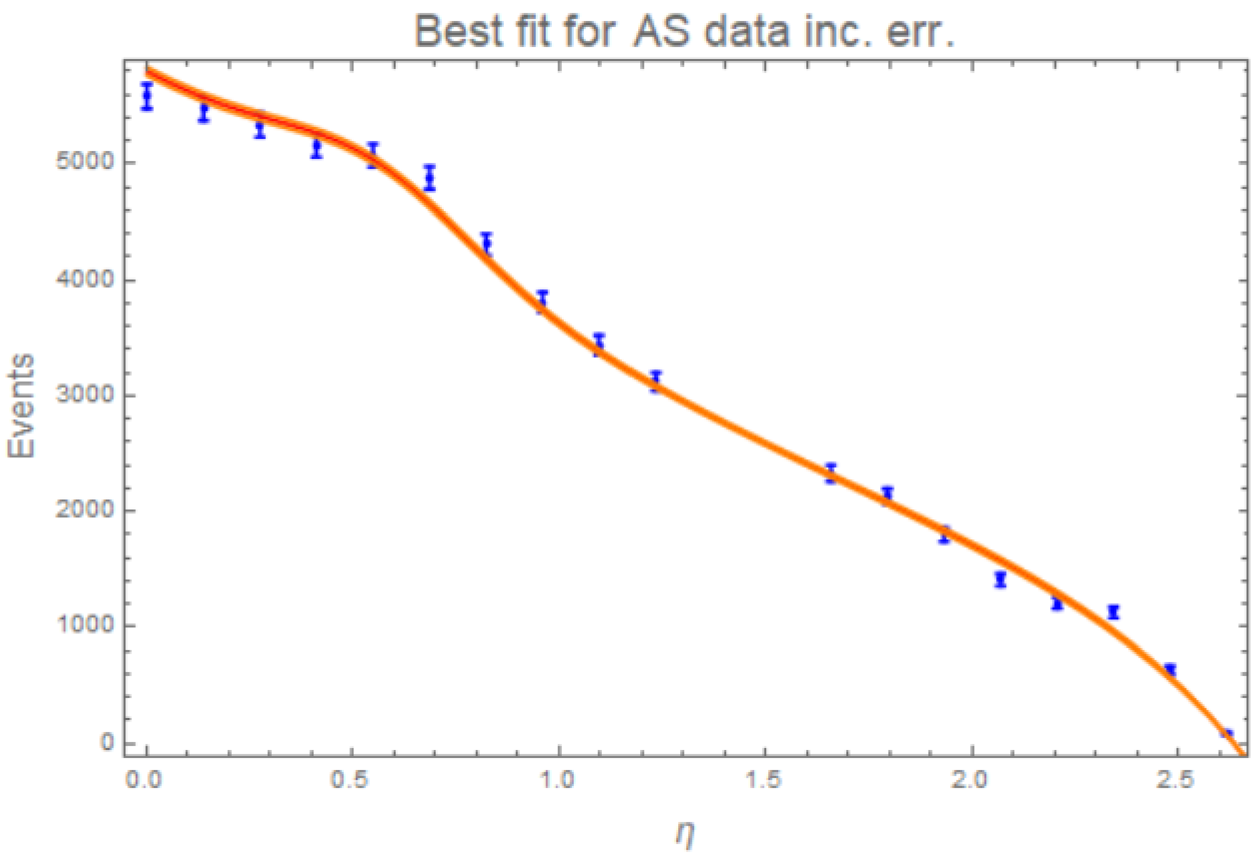
where $f(x)$ is a polynomial of x

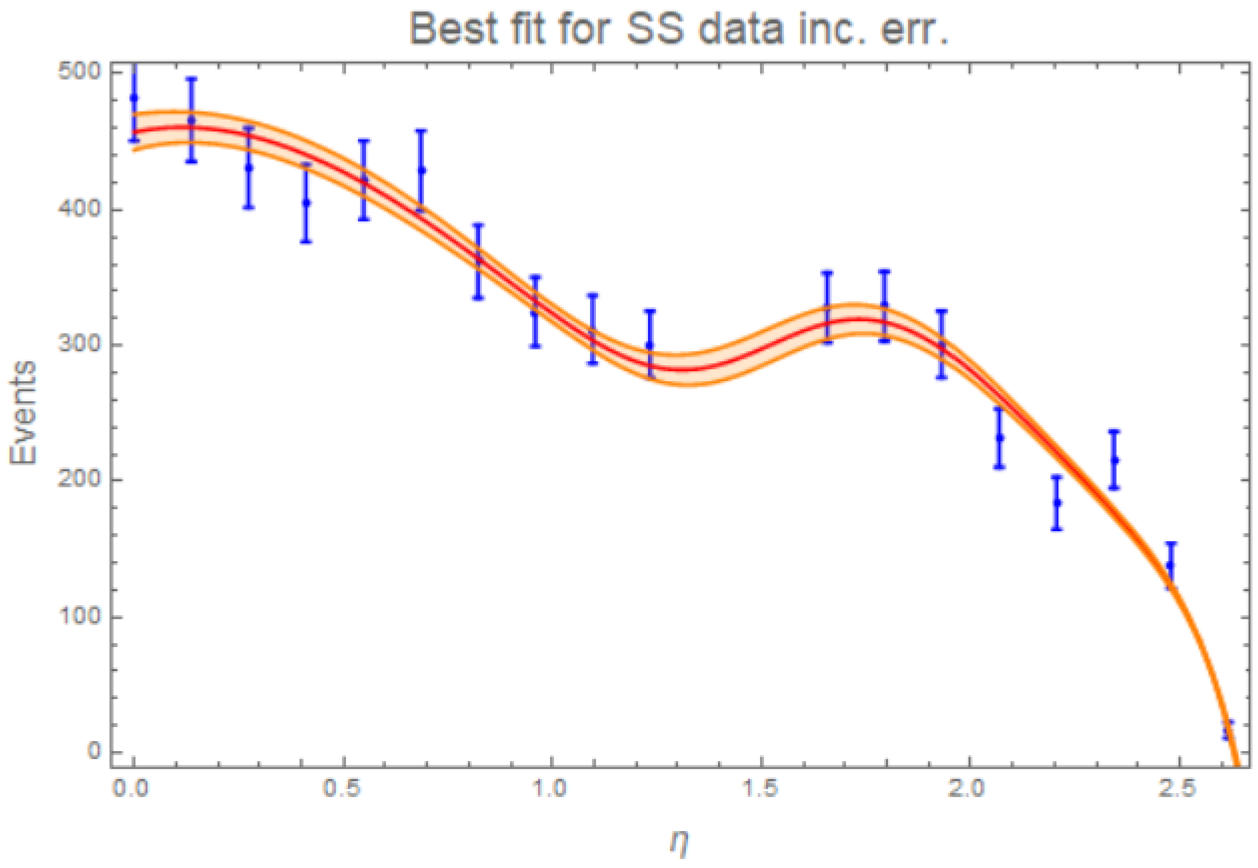


Template fit method

- Need to find optimum values for the parameter a, b, c, d:

$$N_{data}^{AS}(\eta_i) = a \cdot TMPL\left(N_{signal}^{AS}(\eta_i)\right) + b \cdot TMPL\left(N_{bck}^{AS}(\eta_i)\right)$$
$$N_{data}^{SS}(\eta_i) = c \cdot TMPL\left(N_{signal}^{SS}(\eta_i)\right) + d \cdot TMPL\left(N_{bck}^{SS}(\eta_i)\right)$$





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