Machine learning techniques for cross-section measurements for the vector-boson-fusion production of the Higgs boson in the $H \to WW^* \to e\nu\mu\nu$ decay channel with the ATLAS detector

57th Recontres de Moriond

23rd March, 2023

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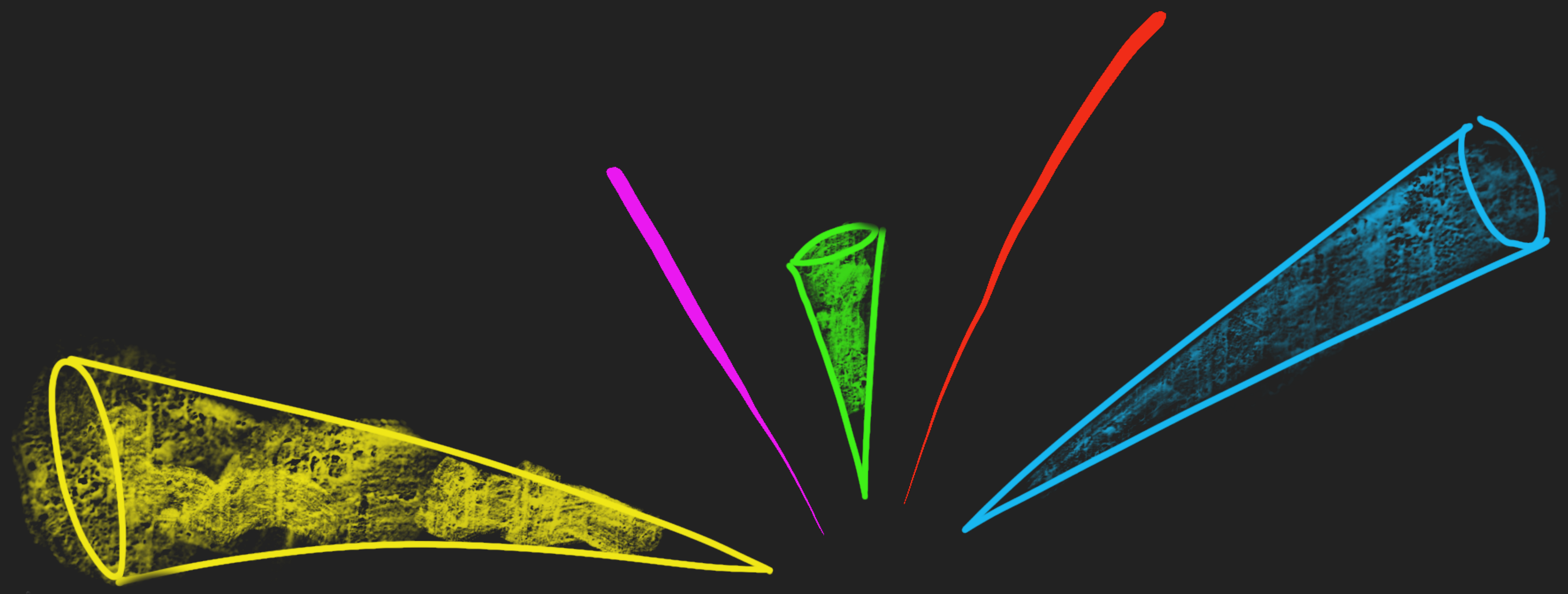

Brandeis

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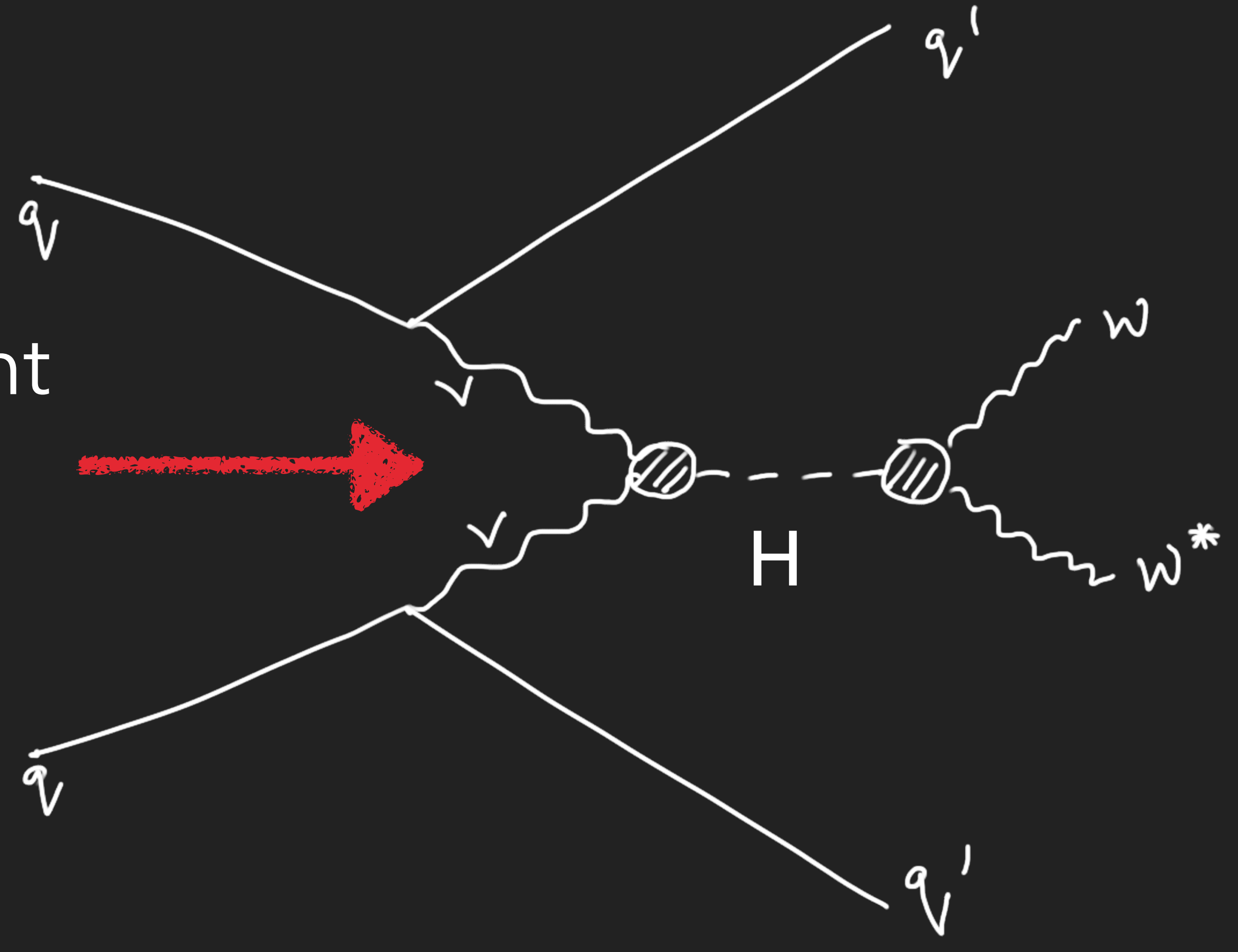
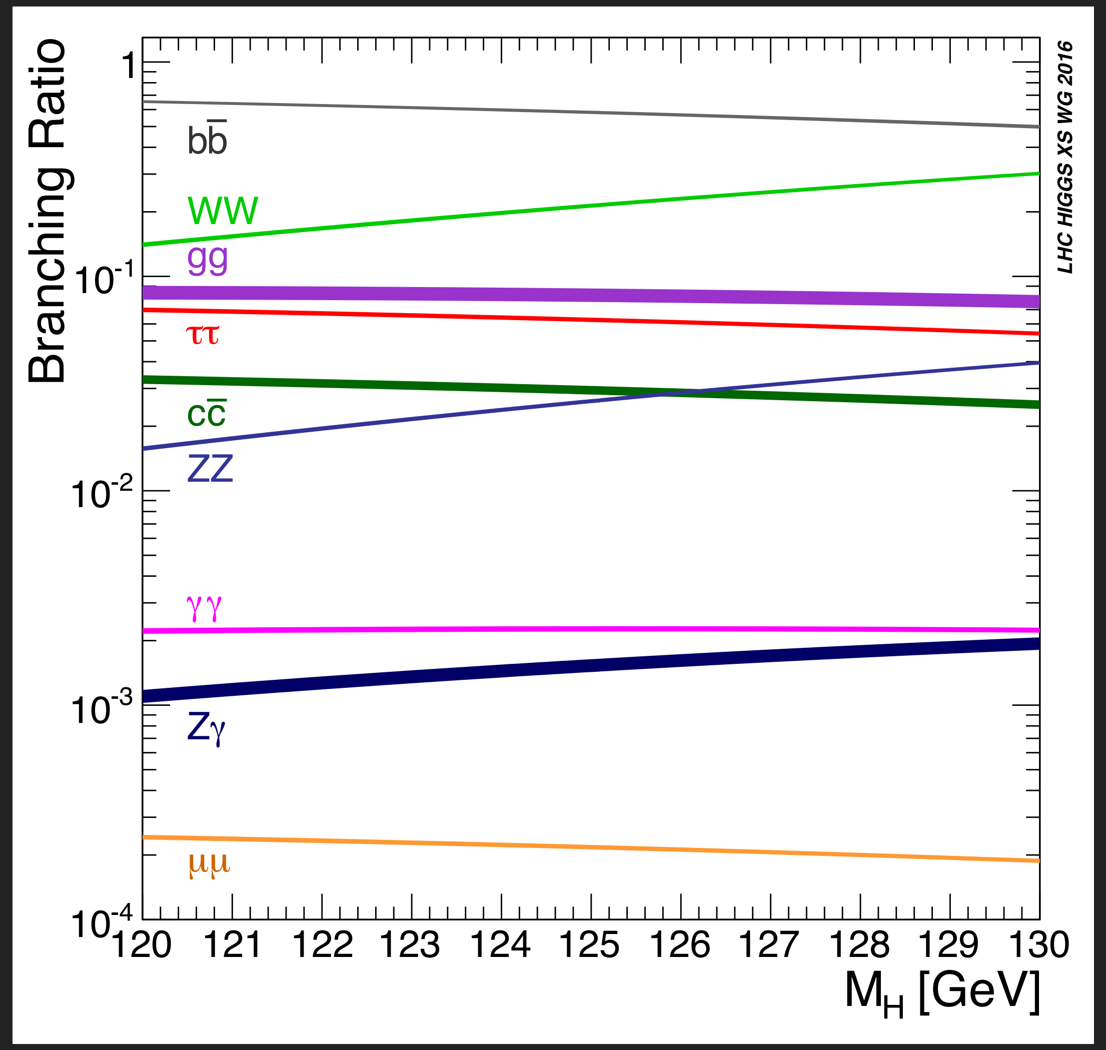
ATLAS EXPERIMENT

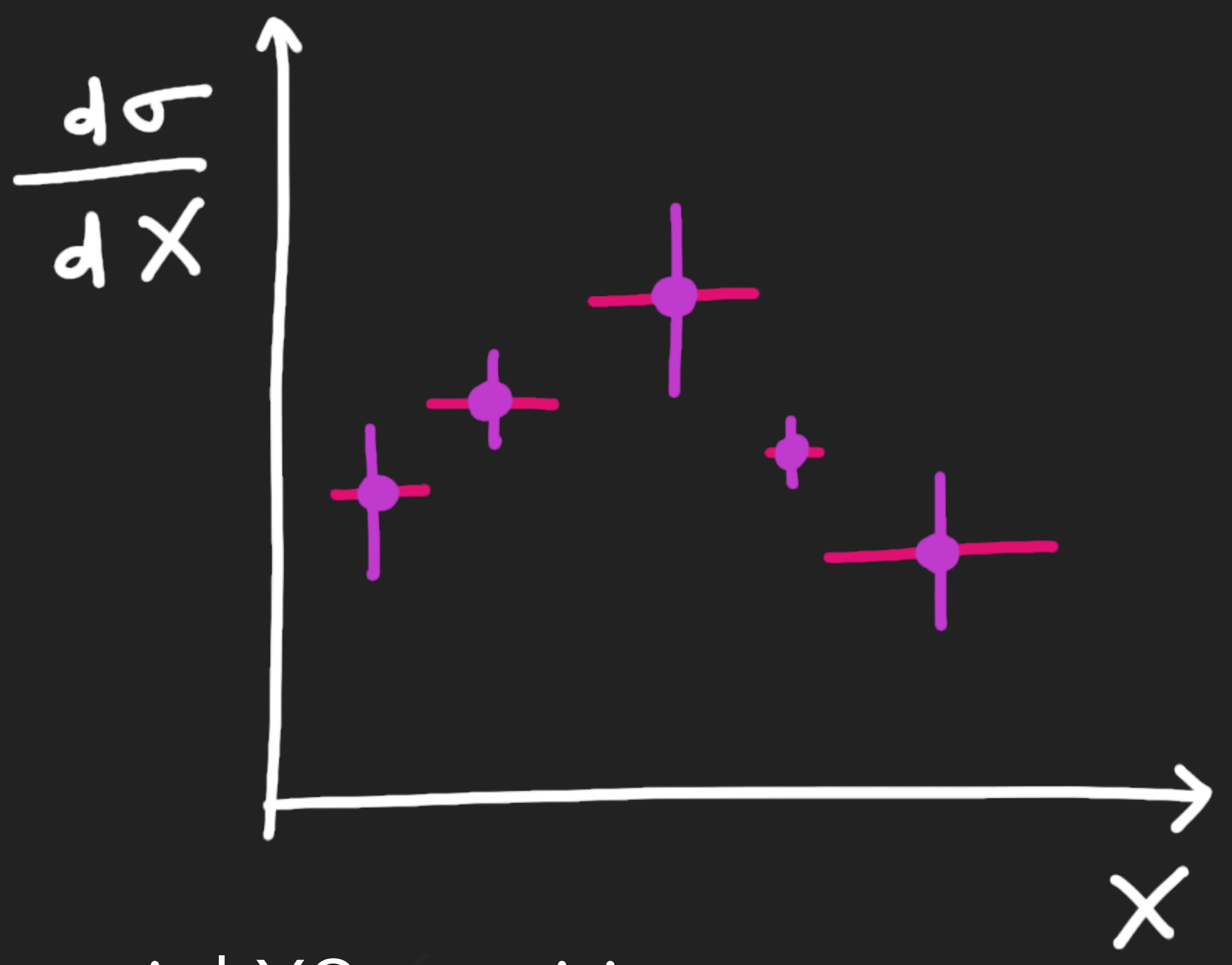
Understanding the fundamental properties of the Higgs boson is one of the main goals of the physics programme at the LHC.

VBF cross-section measurement probes directly the Higgs coupling to W and Z bosons.

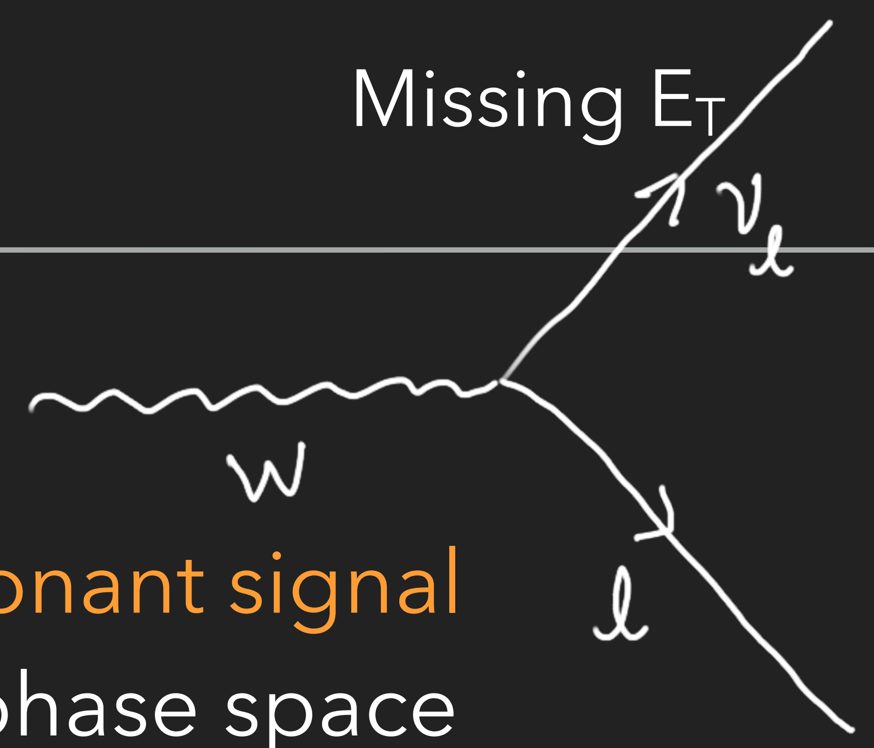




$H \to WW^*$ has a high BR (~20%) and good signal purity



Differential XS sensitive to many properties of the Higgs – spin & CP structure, anomalous couplings.



Measurement extremely challenging:

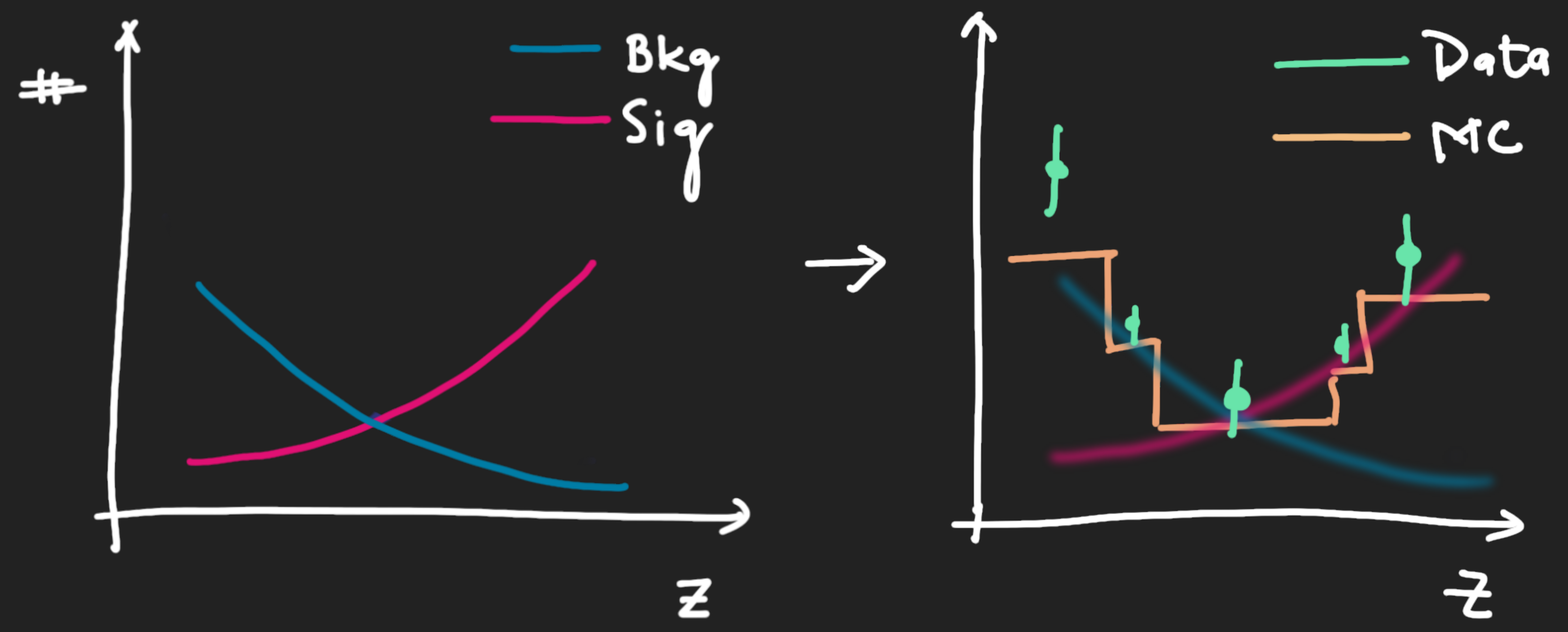
- Final state not fully reconstructed – non-resonant signal
- Signal/Background of 0.13 in the targeted phase space

To maximize signal sensitivity:

- Boosted Decision Trees output used as classifiers
- Classifiers used as templates in the multi-dimensional fit

To minimize model dependency with BDTs:

- BDTs trained in a broader phase space than what is measured
- Retrained with a smaller set of variables for each differential XS measurement

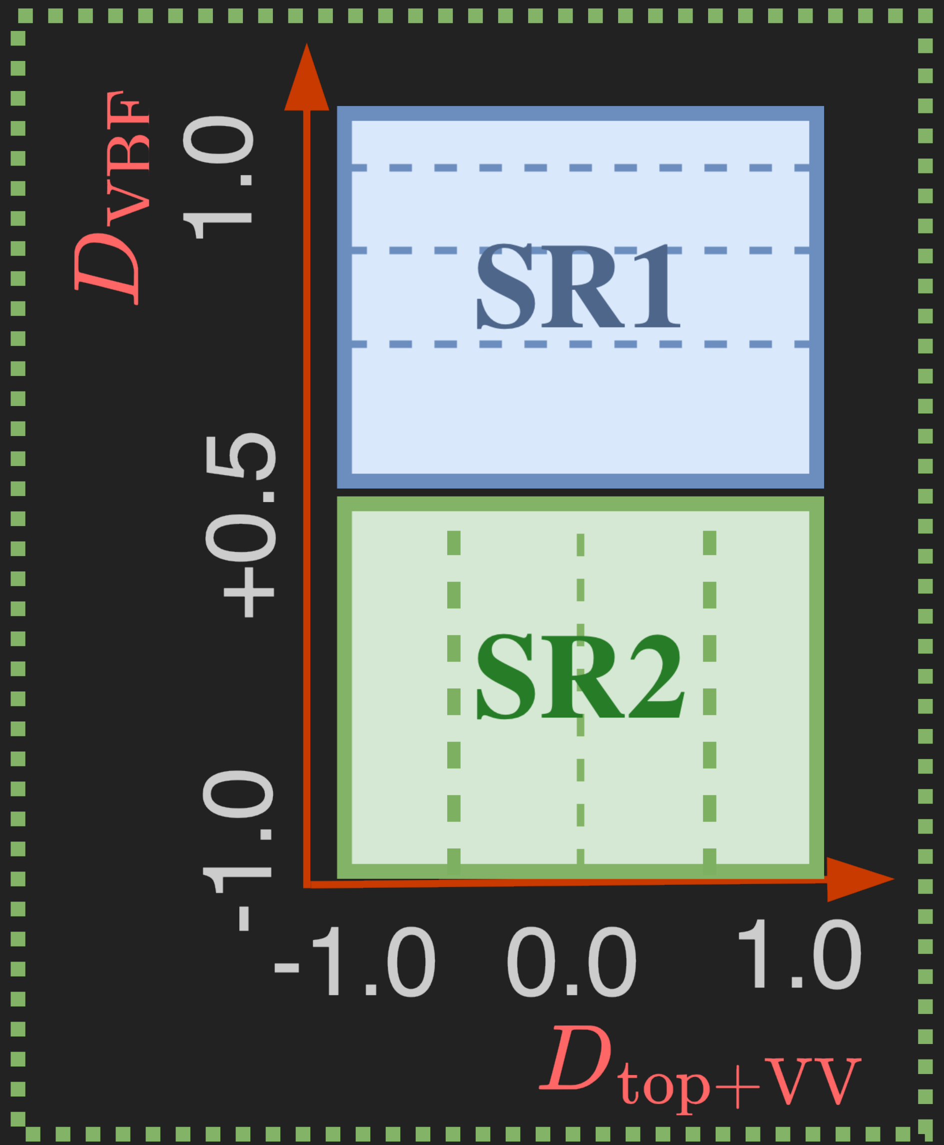


Multi-dimensional fit using a multivariate discriminant

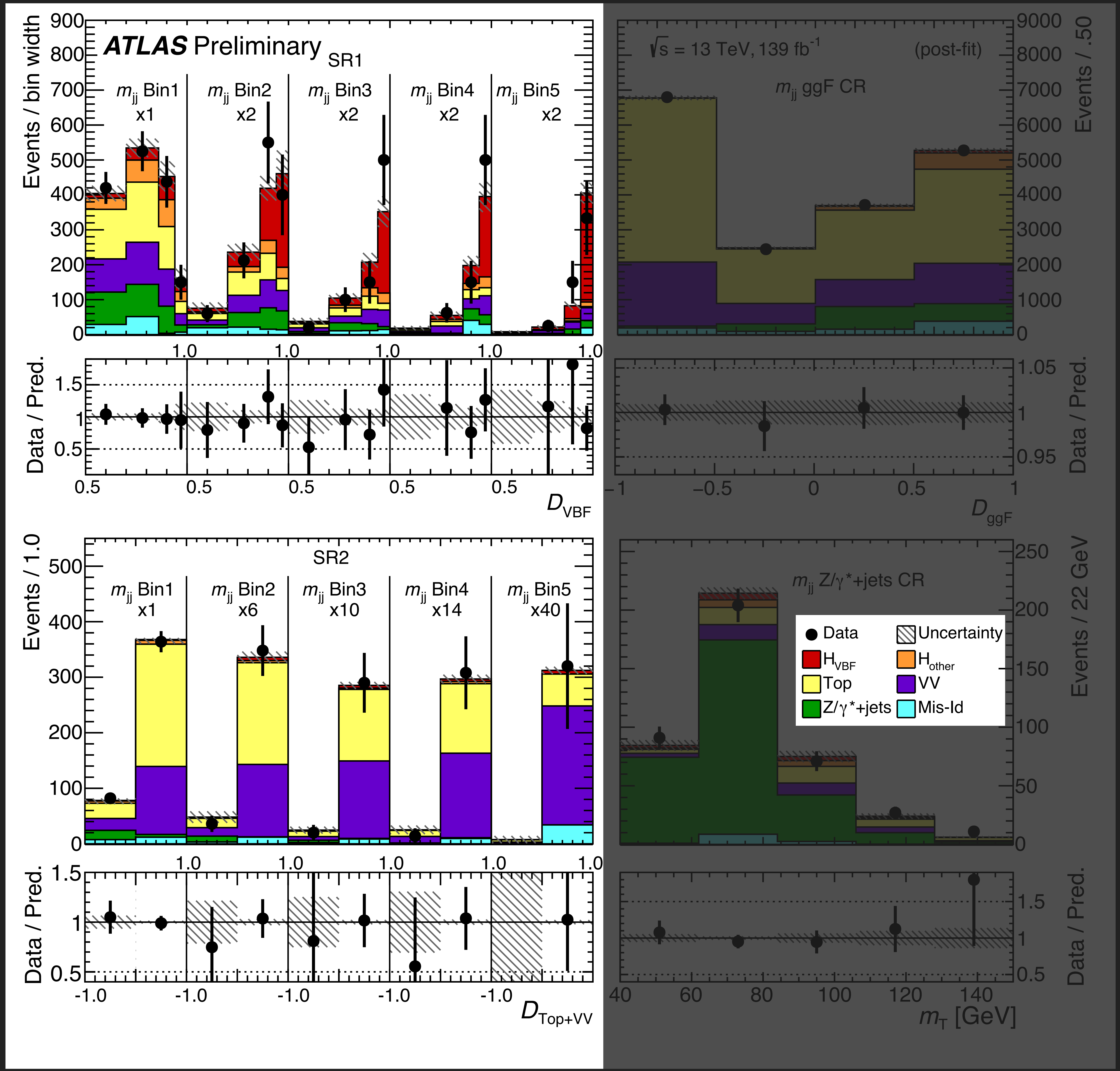
SR split in the fit template:

- SR1 rich in VBF signal.
- SR2 rich in top and VV.

D_{VBF} - VBF signal against Top+VV.



D_{top+VV} - Top+VV against all other processes.



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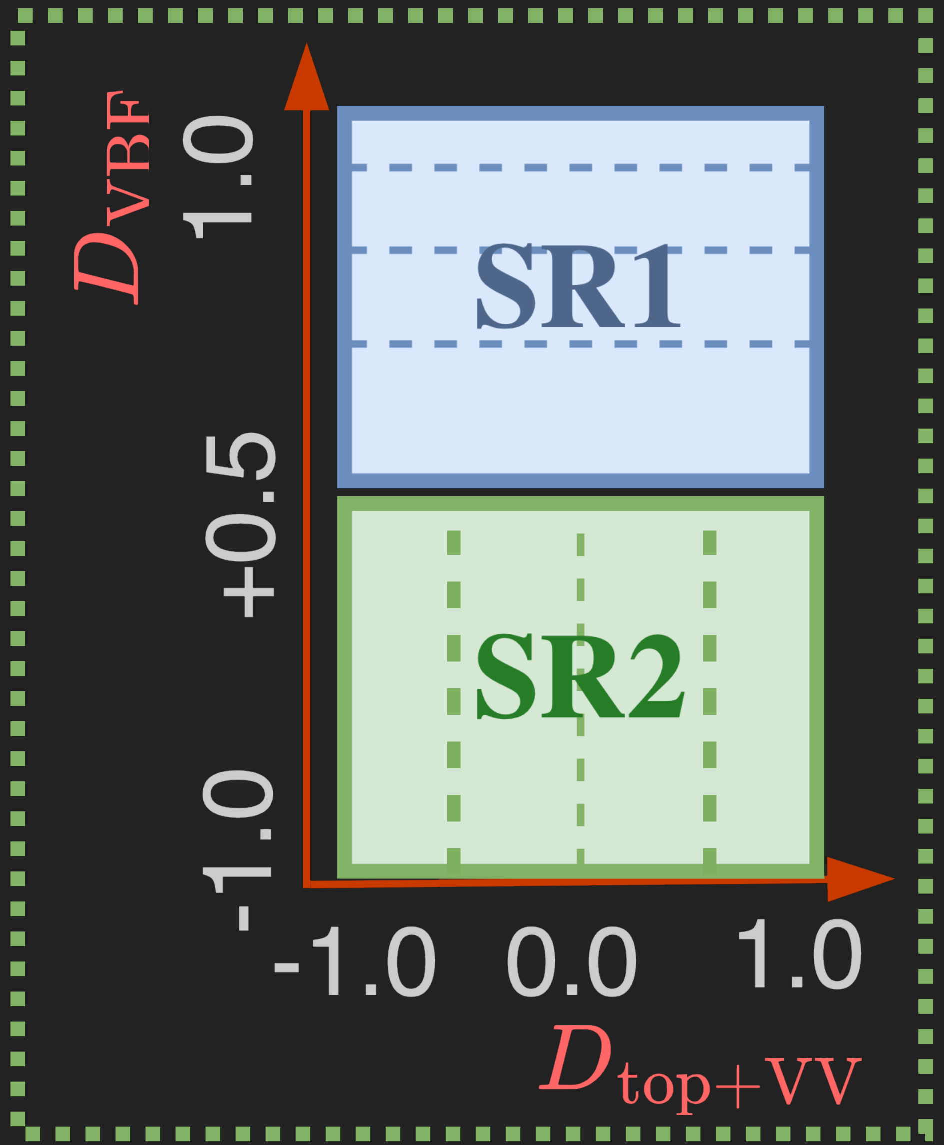

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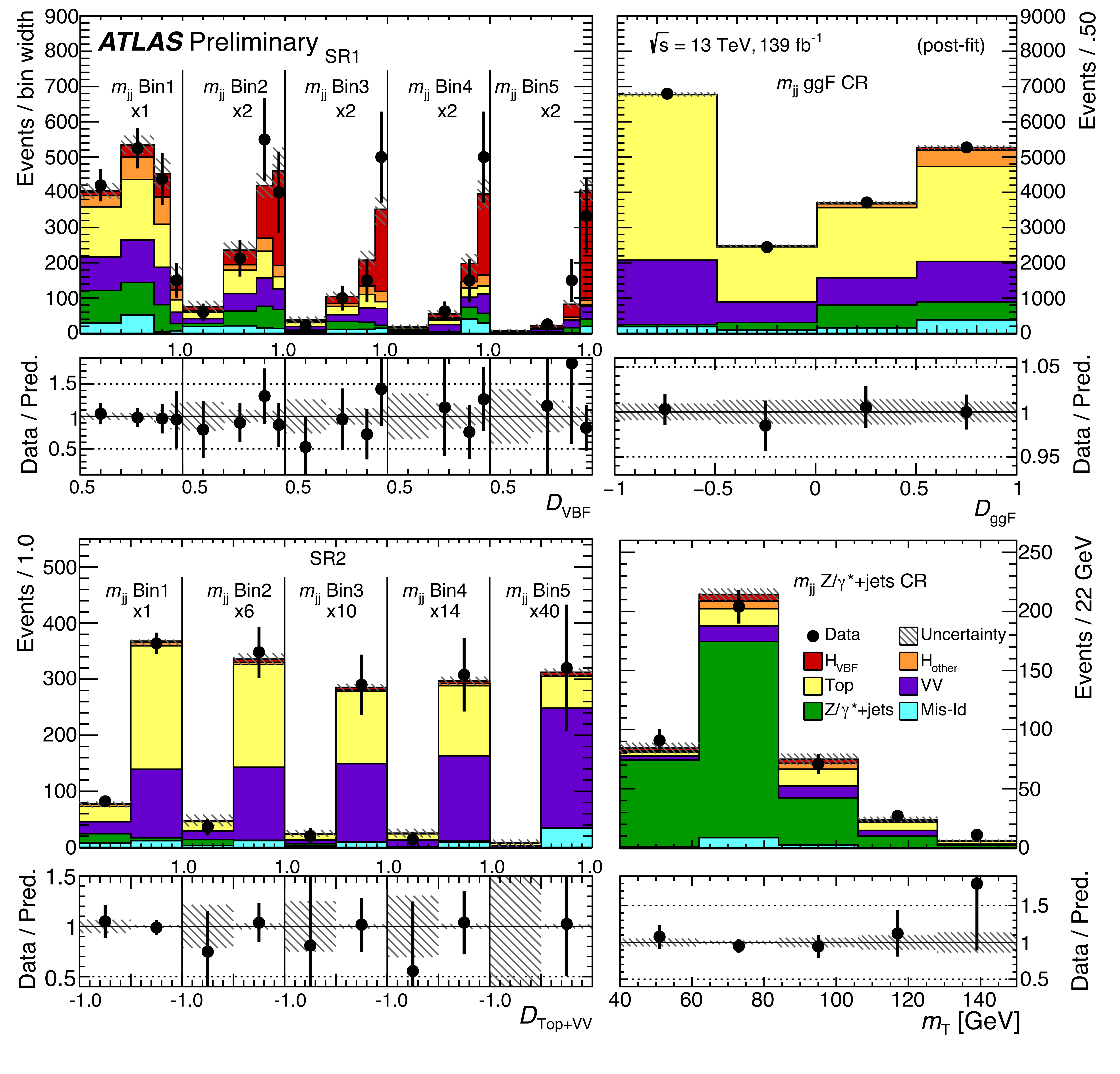
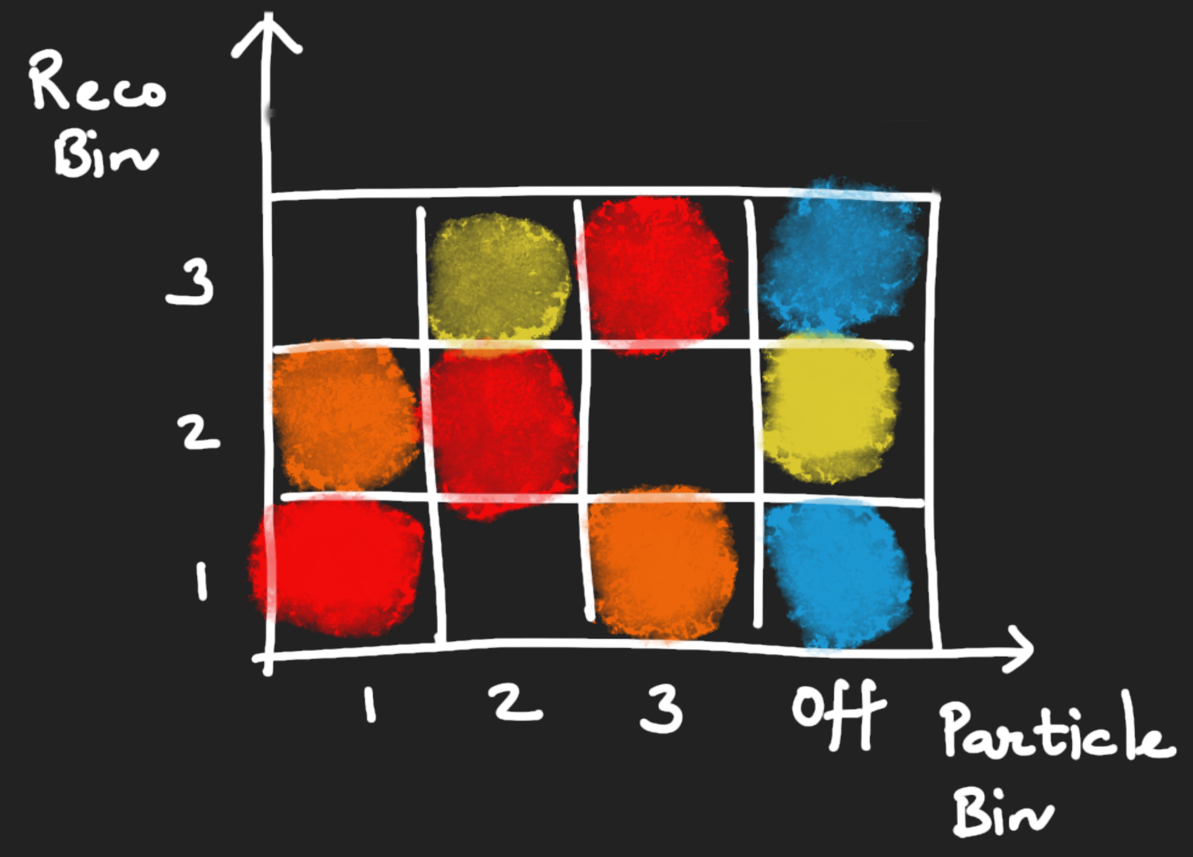


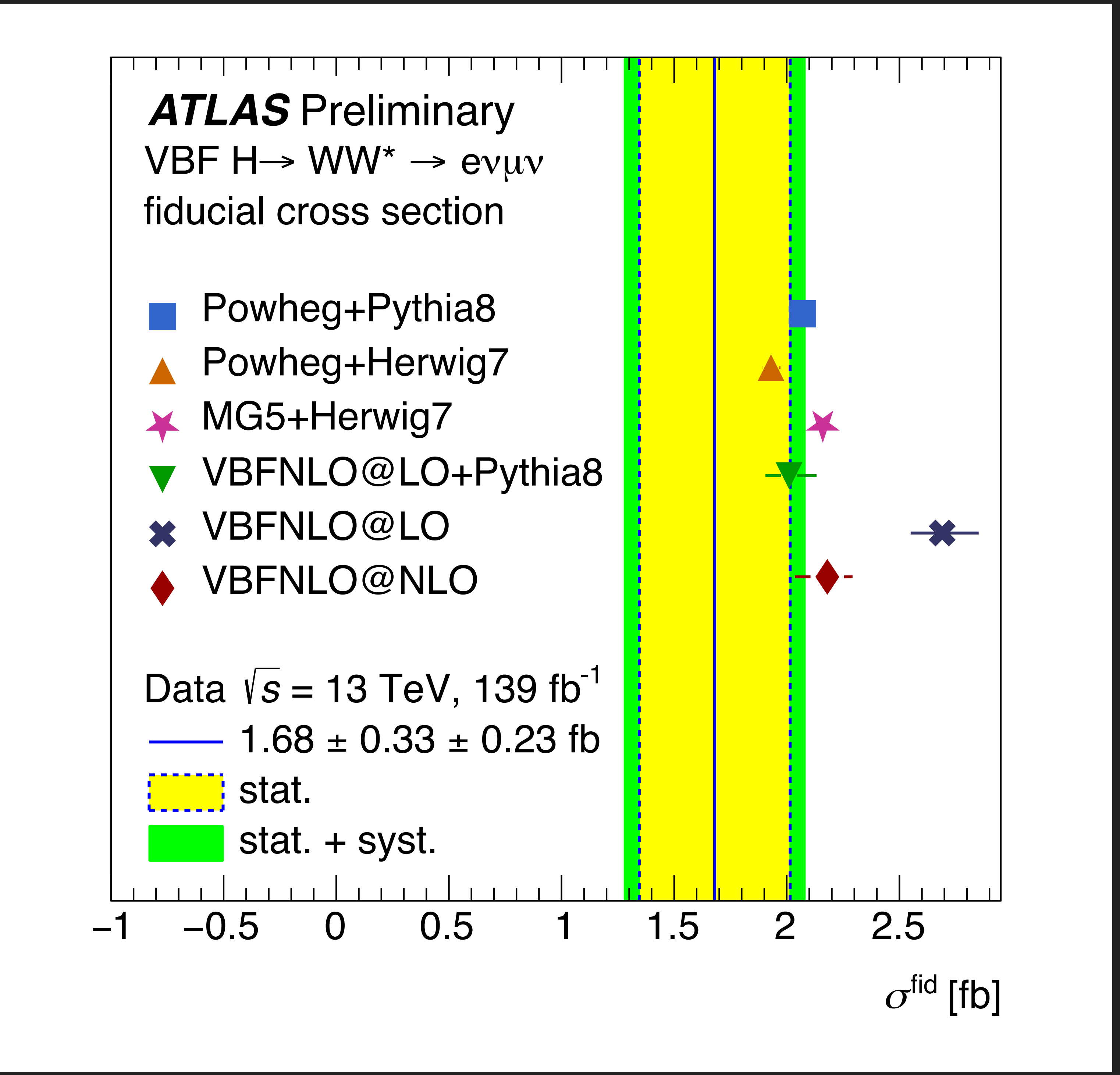
D_{ggF} - ggF background against all other processes.

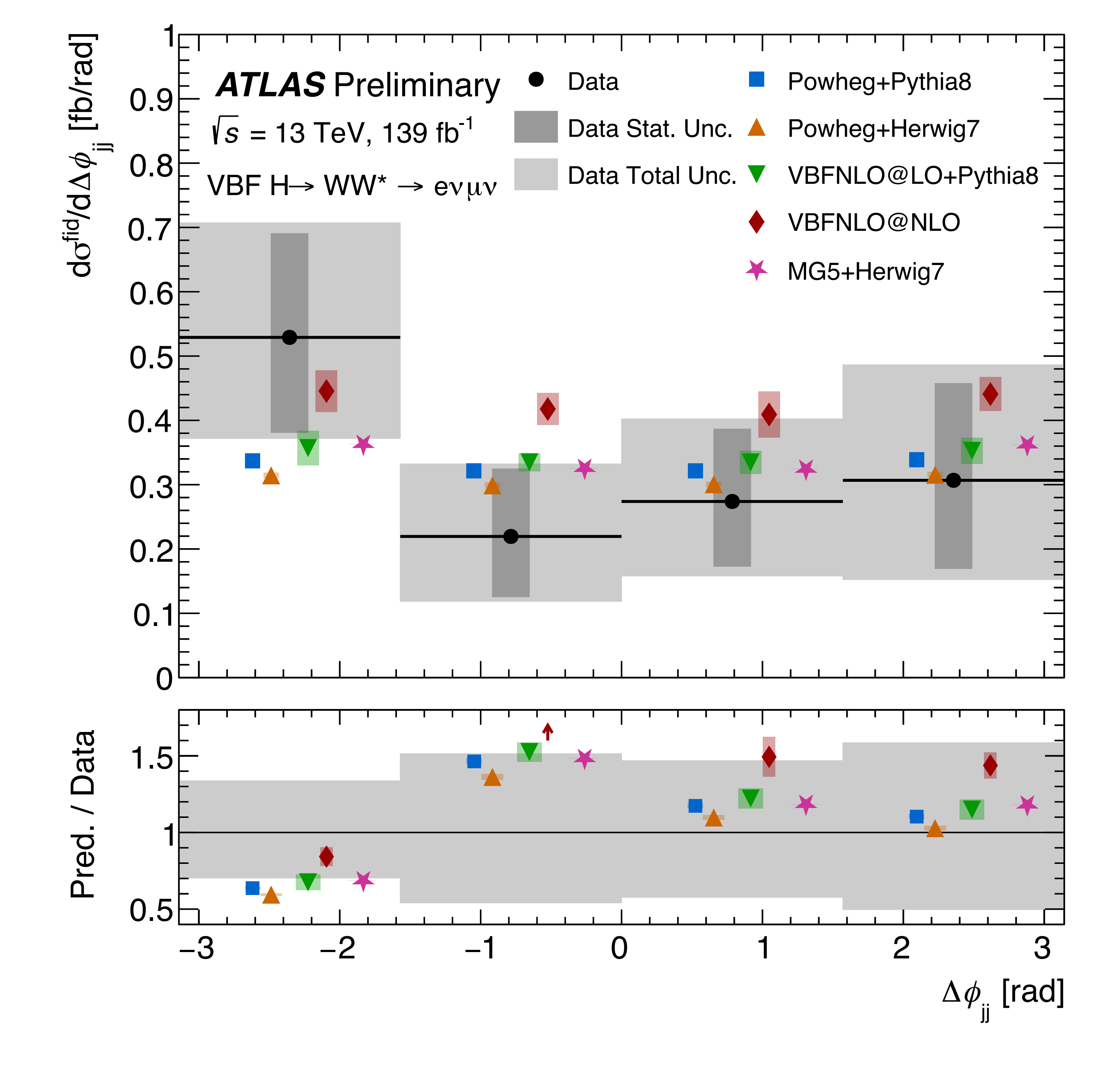
Data driven estimates also for ggH and Z/γ^*+jets bkgs.

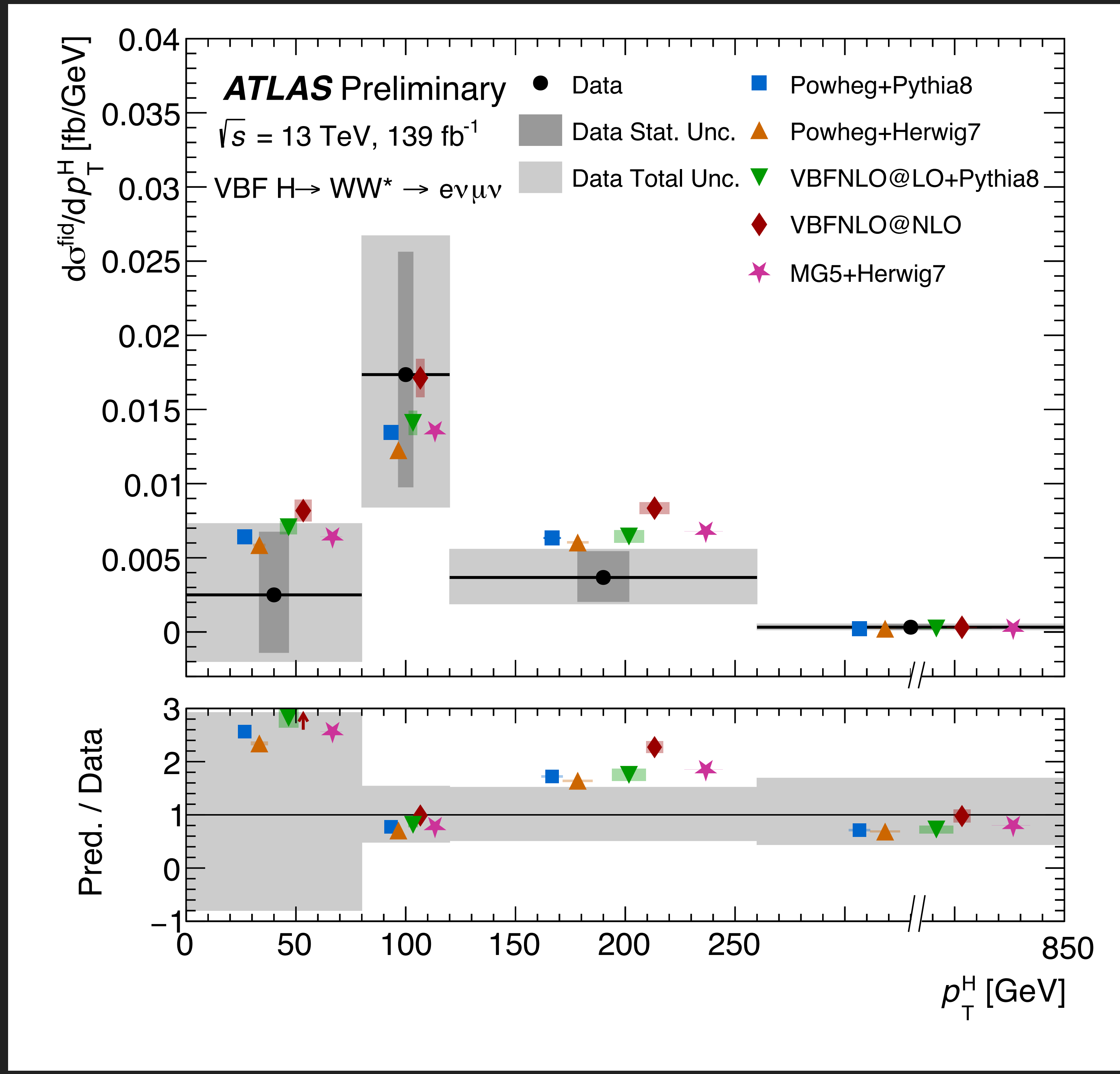


Unregularized matrix-based unfolding in the same step as the likelihood fit

13 differential cross-sections measured – lepton kinematics, jet kinematics, and combined







Results compatible with SM predictions, limited by statistical uncertainty.

INTERPRETATION - EFT

- Constraints are set on mass dim-6 Wilson coefficients (7 CP-even, 3 CP-odd) within the SMEFT formalism.

- One parameter constrained at a time.

$$\sigma - \sigma_{\text{SM}} \propto 2 \sum_i \frac{c_i}{\Lambda^2} \text{Re}\left(\mathcal{M}^*_{\text{SM}} \mathcal{M}_i\right) + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} \text{Re}\left(\mathcal{M}^*_i \mathcal{M}_j\right)$$

1 TeV — Linear Term — Quadratic Term

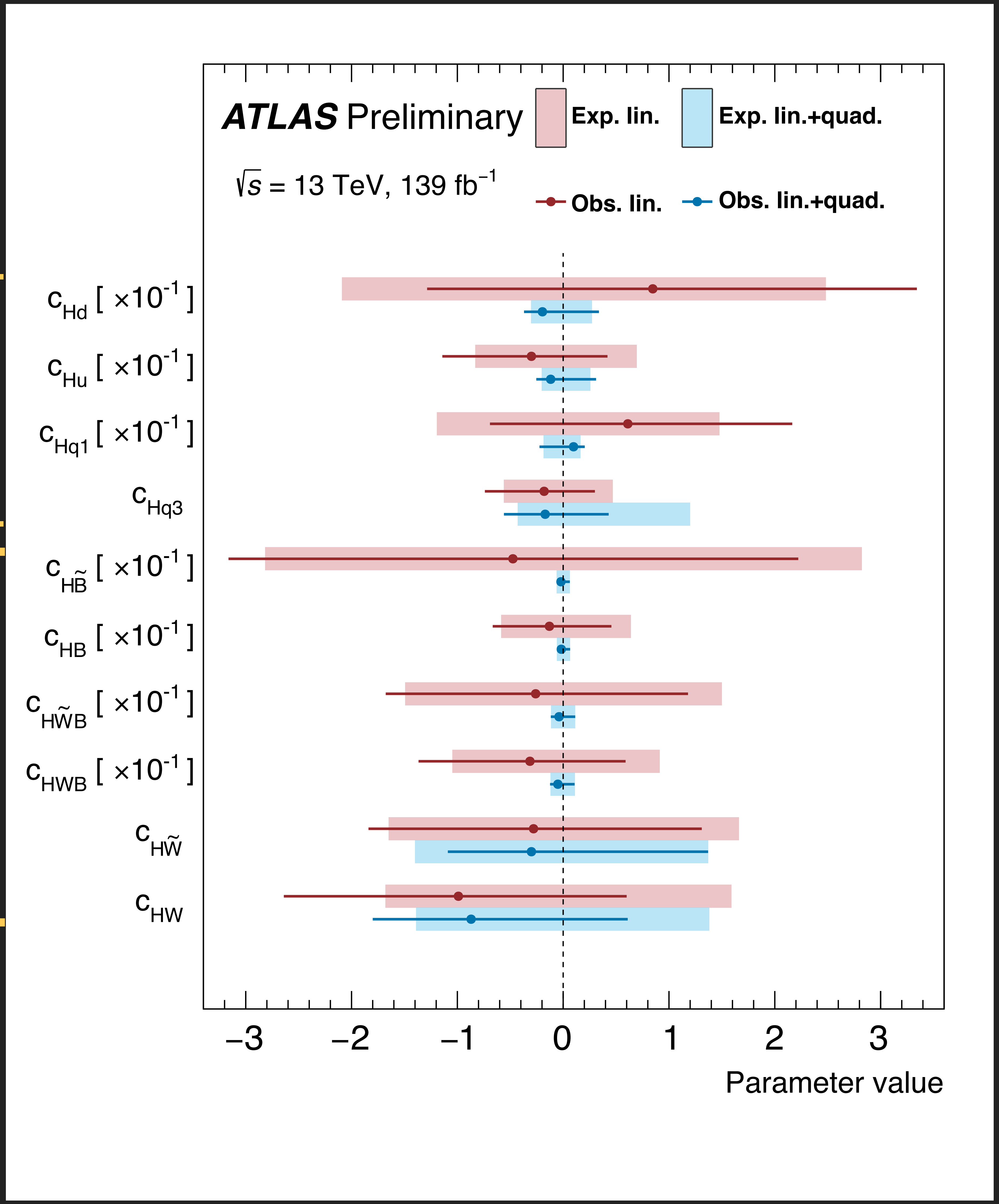
- Stronger limits from the linear+quadratic parameterization compared to linear only.

- Shows the impact of the quadratic term (and hence possible sensitivity to higher mass dimension terms).

Observable Used

$p_{\text{T}}^{j_1}$

$\Delta\phi_{jj}$

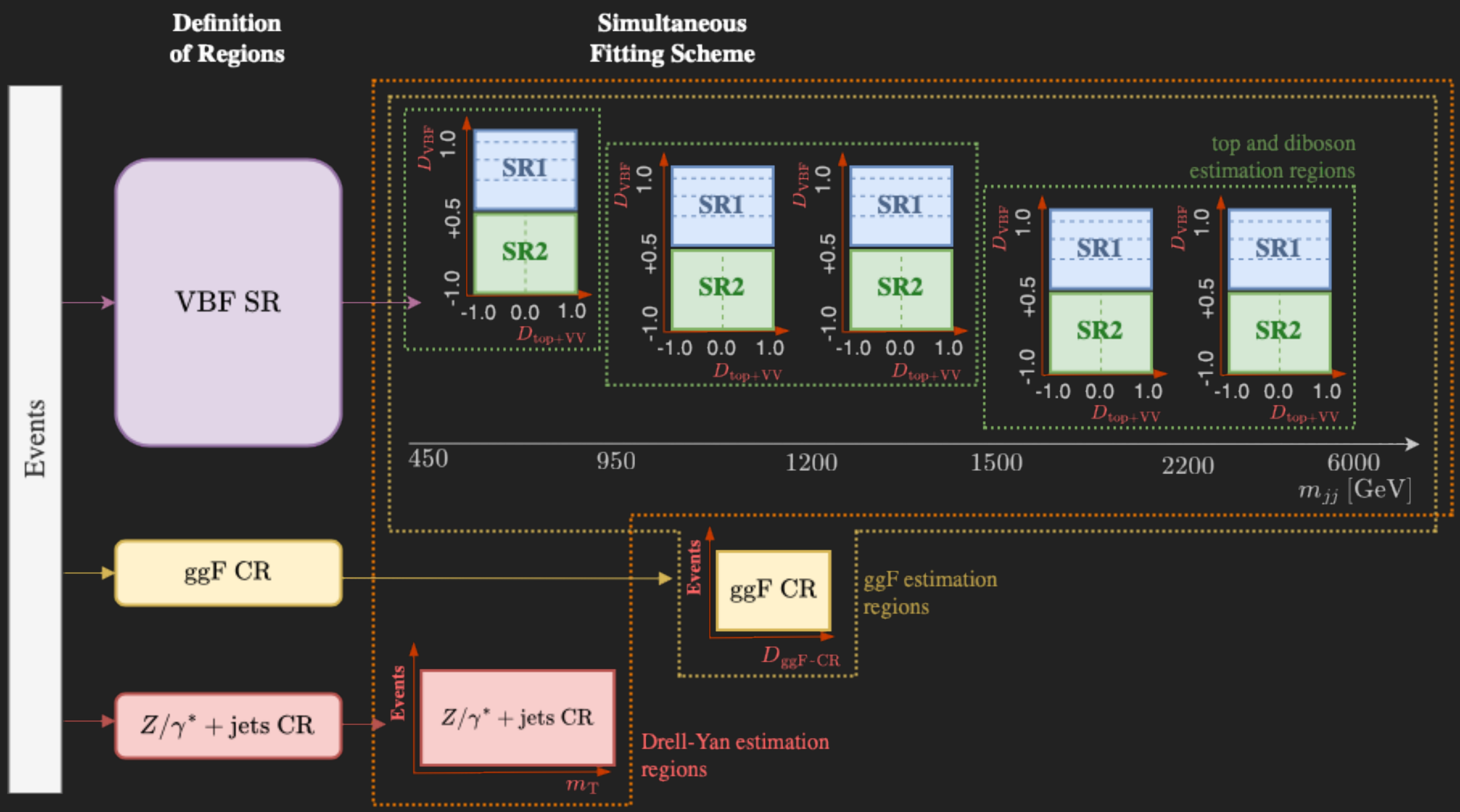


Thank you for listening!

CERN-EP-2023-25

ADDITIONAL MATERIAL

Selection Requirements	Signal Region	Fiducial Region
Lepton pair flavors	e-μ	
Lepton pair charge	0	
Leading (subleading) lepton p_{T}	> 22 GeV (> 15 GeV)	
Lepton η^{ℓ}	$\lvert\eta^{\mu}\rvert < 2.5$	
	$0 < \lvert\eta^{e}\rvert < 1.37$ or $1.52 < \lvert\eta^{e}\rvert < 2.47$	$\lvert\eta^{e}\rvert < 2.5$
No. of additional leptons	0	
$\Delta R(\ell, \ell)$	overlap removal	> 0.1
$m_{\ell\ell}$	> 10 GeV	
$\Delta R(\ell, \mathrm{jet})$	overlap removal	> 0.4
No. of jets ($p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 4.5$)	≥ 2	
No. of b-jets ($p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.5$)	0	
$m_{\tau\tau}$	$< m_Z - 25$ GeV	
Central jet veto ($p_{\mathrm{T}} > 20$ GeV)	✓	
Outside lepton veto	✓	
m_{jj}	> 450 GeV	
$\lvert\Delta y_{jj}\rvert$	> 2.1	
$\lvert\Delta\phi_{\ell\ell}\rvert$	< 1.4 rad	



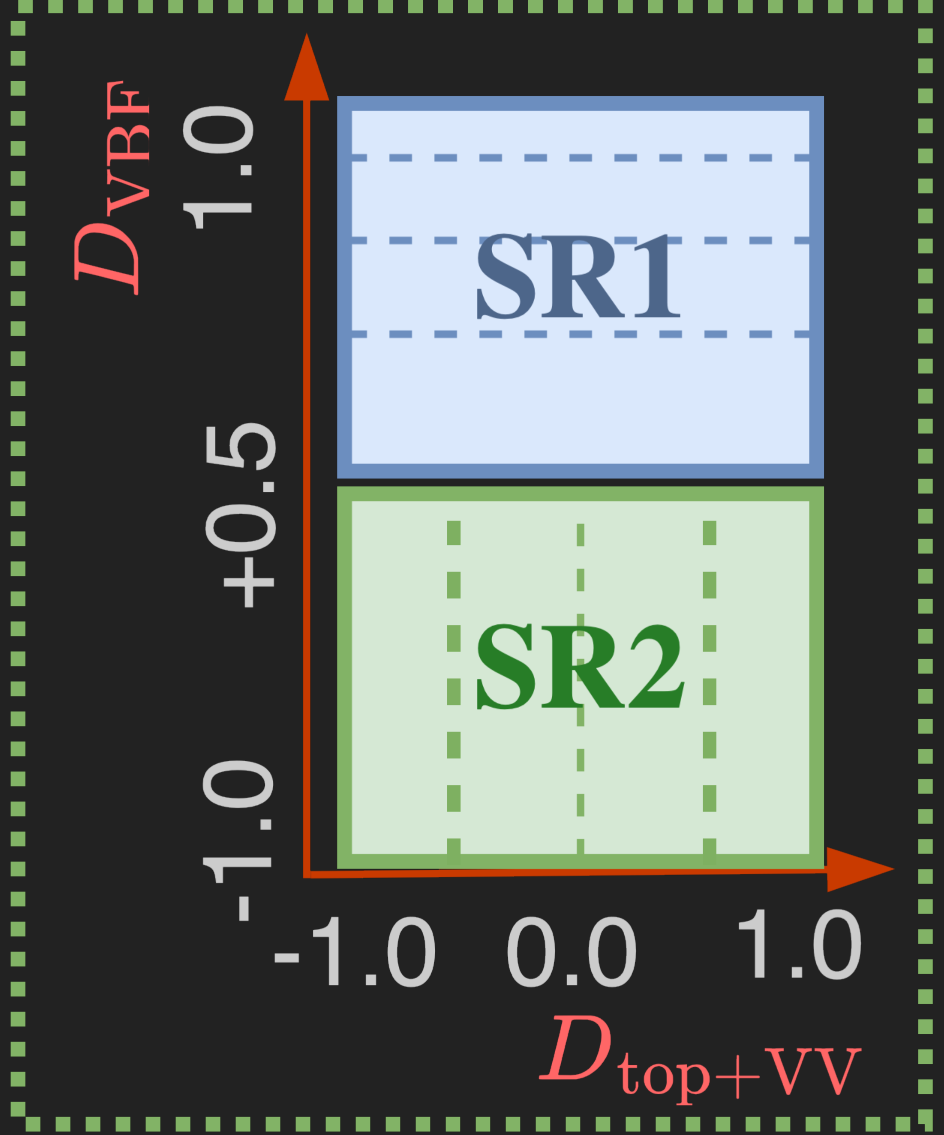
Background	Estimation
Diboson	Data-driven
Top Induced	Data-driven
ggF H	Data-driven
Z+Jets	Data-driven
W+Jets (Mis-Id)	Data-driven
Vγ	MC
Htt, VH	MC

Scheme designed to **minimize total uncertainty**.
Comes at a cost of slight increase in stat. unc., but significant reduction in syst. unc.

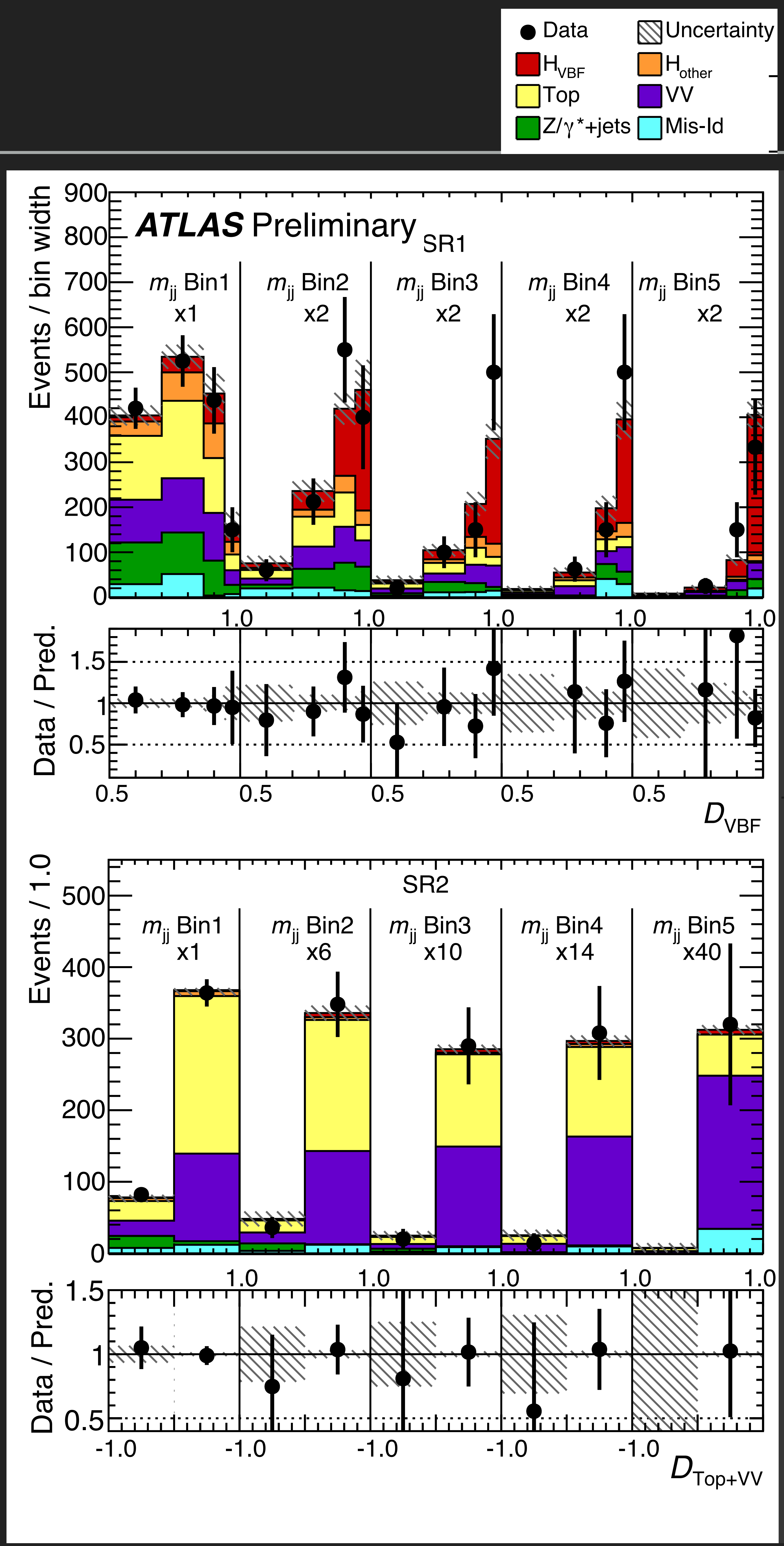
SR split in the fit template:

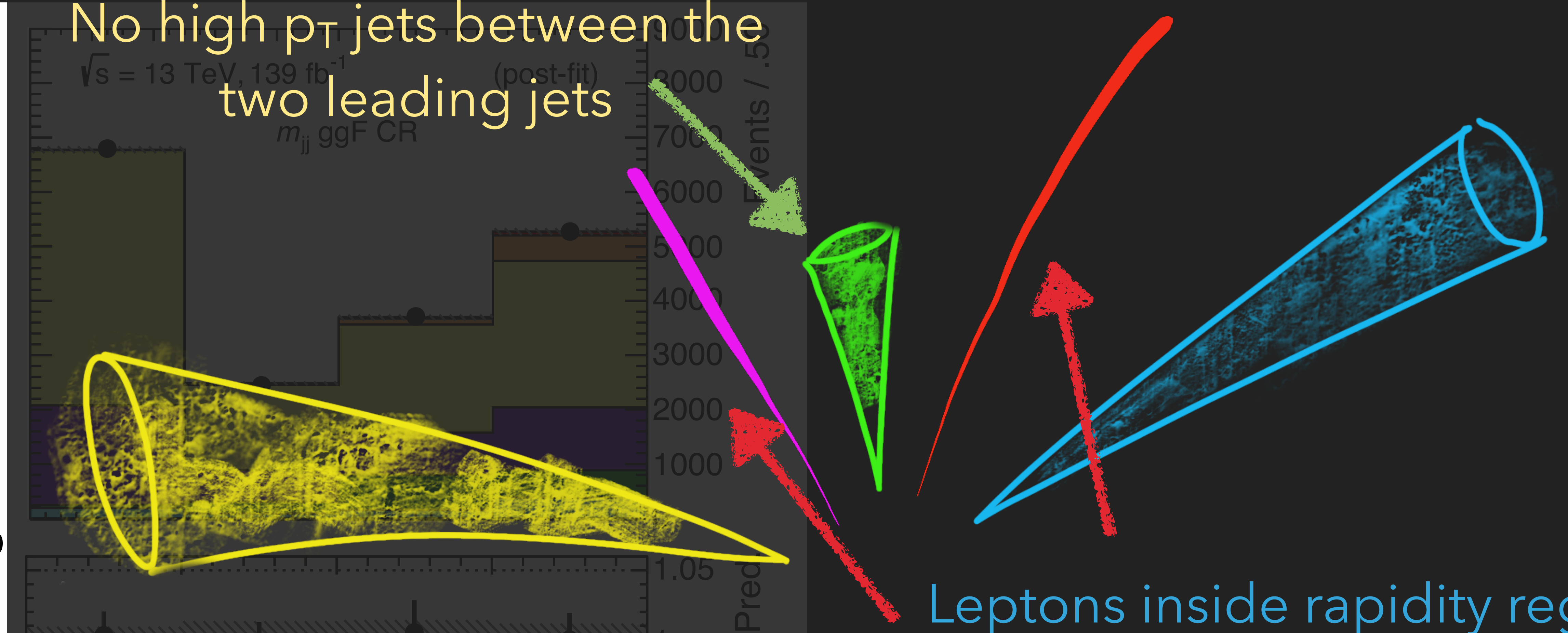
- SR1 rich in VBF signal.
- SR2 rich in top and VV.

D_{VBF} - VBF signal against Top+VV.



D_{top+VV} - Top+VV against all other processes.





Estimating bkg from the same phase space of the measurement significantly reduces extrapolation unc.

$m_{\tau\tau}$	$< m_Z - 25$ GeV
Central jet veto ($p_T > 20$GeV)	yes
Outside lepton veto	yes
m_{jj}	> 450 GeV
$\lvert\Delta y_{jj}\rvert$	> 2.1
$\lvert\Delta\phi_{\ell\ell}\rvert$	< 1.4 rad

Reconstruction-level cuts in the SR

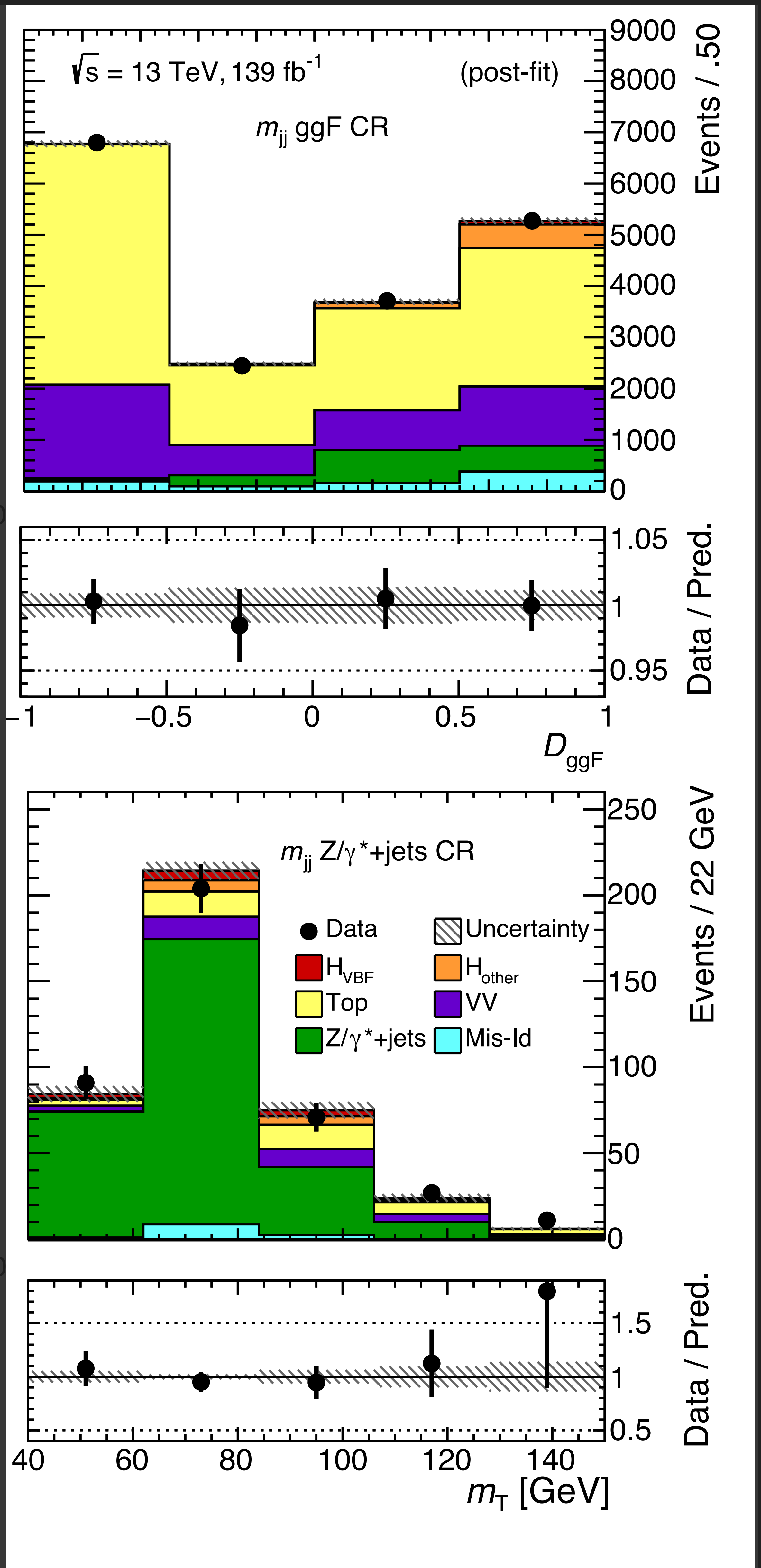
$m_{\tau\tau}$	$< m_Z - 25$ GeV
Central jet veto ($p_T > 20$GeV)	Exactly 1 fails
Outside lepton veto	
$\lvert\Delta\phi_{\ell\ell}\rvert$	< 1.4 rad

ggF CR definition

Sample	SR	Z/γ^*+jets CR	ggF CR
Signal (Powheg+Pythia 8)	110	13	86
ggF Higgs	39	4	450
Other Higgs	3	10	78
Top	420	41	11 000
Z/γ^*+jets	79	320	1 400
VV	280	32	4 300
$V\gamma$	13	14	210
Mis-Id	47	12	810
Total Signal+Background	1 000 ± 120	450 ± 160	18 800 ± 2 600
Data	916	406	18 228

$m_{\tau\tau}$	66.2 GeV $< m_{\tau\tau} <$ 116.2 GeV
Central jet veto ($p_T > 20$GeV)	yes
Outside lepton veto	yes
m_{jj}	> 450 GeV
$m_{\ell\ell}$	< 80 GeV

Z/γ^*+jets CR definition



D_{ggF} - ggF background against all other processes.

μ_{ggF} estimated in ggF CR and SR

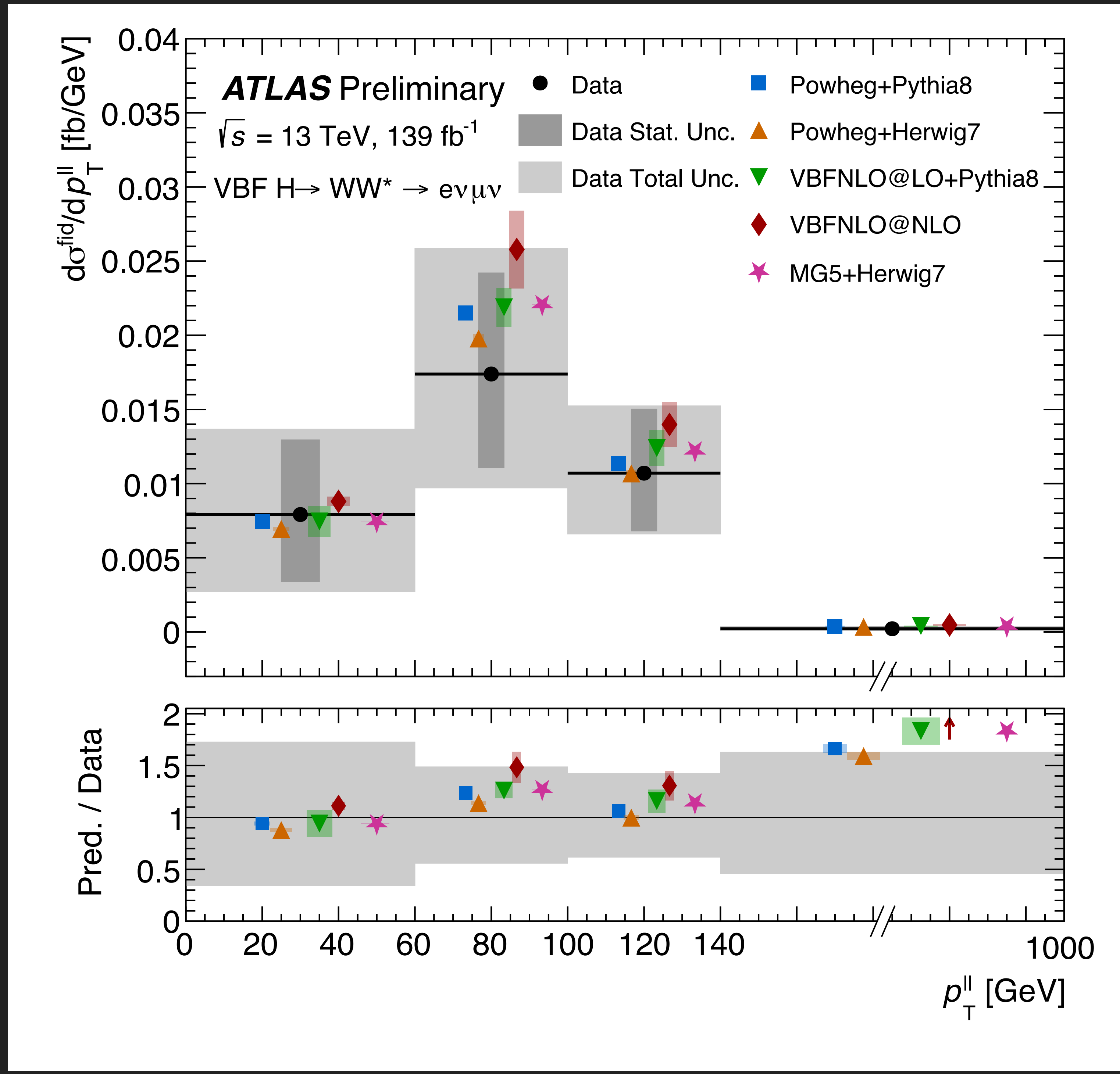
W+jets CR used to estimate the contribution from jets mis-reconstructed as leptons.

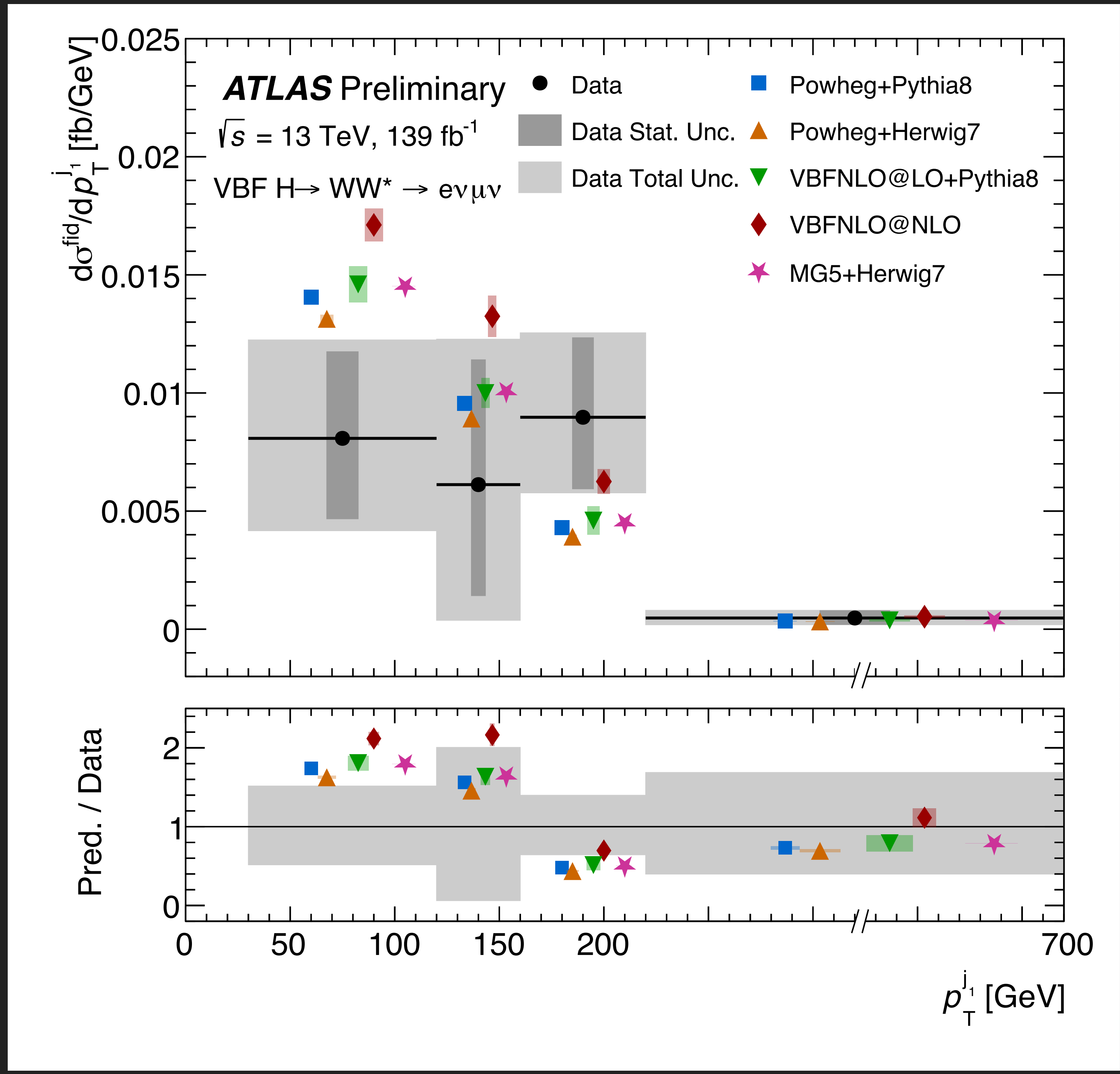
μ_{Z+jets} estimated in Z/γ^*+jets CR and SR

- Measurements limited by data statistics.
- Inclusive XS measurement limited by (in order) -
    - Data statistics,
    - Background modeling ($t\bar{t}$ PS/UE and matching),
    - Signal modeling (generator),
    - Jets (JER), pileup, and MET,
    - MC stats.

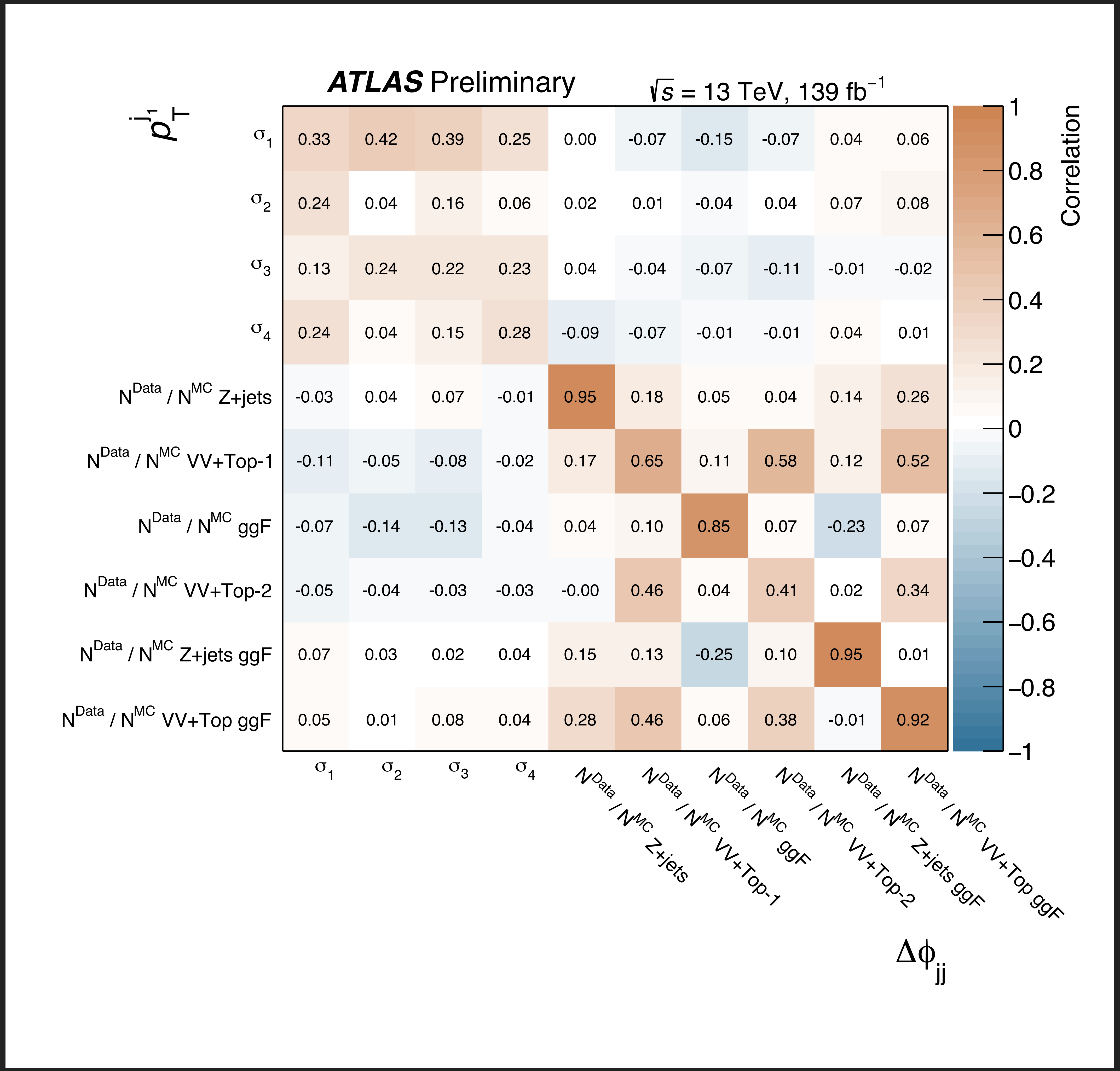
Source	Uncertainty [%] σ^{fid}	Uncertainty range [%] p_{T}^{H}	$p_{\mathrm{T}}^{\ell\ell}$, $p_{\mathrm{T}}^{\ell_1}$, $p_{\mathrm{T}}^{\ell_2}$, $\lvert\Delta y_{\ell\ell}\rvert$, $\lvert\Delta\phi_{\ell\ell}\rvert$, $cos(\theta^*_\eta)$	$m_{\ell\ell}$	$p_{\mathrm{T}}^{j_1}$, $p_{\mathrm{T}}^{j_2}$, $\lvert\Delta y_{jj}\rvert$, $\Delta\phi_{jj}$	m_{jj}
Signal modelling	5	< 1 – 7	< 1 – 7	< 1 – 19	< 1 – 8	2 – 7
Signal parton shower	< 1	< 1 – 2	< 1 – 1.8	< 1 – 10	< 1 – 1.8	< 1 – 7
$t\bar{t}$ modelling	6	1.7 – 30	3 – 13	3 – 80	3 – 10	1.2 – 70
WW modelling	4	< 1 – 12	3 – 11	2 – 90	3 – 10	3 – 40
Z/γ^*+jets modelling	4	< 1 – 19	2 – 18	4 – 30	3 – 13	2 – 50
ggF modelling	5	4.0 – 28	3.4 – 10	2.6 – 12	2.3 – 9.0	1.4 – 86
Mis-Id. background	< 1	< 1 – 12	1.1 – 5	< 1 – 19	1 – 3	< 1 – 40
Jets & Pile-up & $E_{\mathrm{T}}^{\mathrm{miss}}$	5	8 – 60	6 – 30	6 – 120	9 – 30	9 – 130
b-tagging	< 1	< 1 – 9	< 1 – 3	< 1 – 19	1.1 – 3	< 1 – 40
Leptons	1.5	3 – 17	2 – 9	1.2 – 13	1.7 – 7	< 1 – 16
Luminosity	1.5	1.7 – 2	1.3 – 1.9	< 1 – 4	1.5 – 2	< 1 – 1.9
MC statistics	5	10 – 40	6 – 30	6 – 180	8 – 30	7 – 90
Total systematics	13	19 – 90	13 – 60	12 – 180	15 – 50	15 – 200
Data statistics	20	50 – 160	30 – 110	30 – 400	40 – 100	50 – 300
Total uncertainty	23	50 – 190	40 – 120	30 – 500	40 – 100	50 – 400

Post-fit uncertainty range for all the measurements


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
VBF H→ WW* → eνμν
Data
Data Stat. Unc.
Data Total Unc.
Powheg+Pythia8
Powheg+Herwig7
VBFNLO@LO+Pythia8
VBFNLO@NLO
MG5+Herwig7
dσfid/dpTll [fb/GeV]
Pred. / Data
pTll [GeV]


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
VBF H→ WW* → eνμν
Data
Data Stat. Unc.
Data Total Unc.
Powheg+Pythia8
Powheg+Herwig7
VBFNLO@LO+Pythia8
VBFNLO@NLO
MG5+Herwig7
dσfid/dpTj1 [fb/GeV]
Pred. / Data
pTj1 [GeV]

- Correlations between differential XS and background normalizations for all observables measured evaluated using the bootstrapping technique.
- Same procedure also used to evaluate correlations between central values of EFT operators.
- Correlations extremely useful for future global fits and EFT interpretations using more than one observable.
- All correlations as well as all individual correlated measurements published on HepData.



Wilson Coeff.	Operator Structure	Fit distr.
c_{HW}	$H^\dagger H\, W^n_{\mu\nu} W^{n\mu\nu}$	$\Delta\phi_{jj}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$
c_{HWB}	$H^\dagger \tau^n H\, W^n_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$
c_{Hq1}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	p_{T}^{j1}
c_{Hq3}	$(H^\dagger i \overleftrightarrow{D}^n_\mu H)(\bar{q}\tau^n\gamma^\mu q)$	p_{T}^{j1}
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	p_{T}^{j1}
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	p_{T}^{j1}
$c_{H\tilde{W}}$	$H^\dagger H\, \tilde{W}^n_{\mu\nu} W^{n\mu\nu}$	$\Delta\phi_{jj}$
$c_{H\tilde{B}}$	$H^\dagger H\, \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$
$c_{H\tilde{W}B}$	$H^\dagger \tau^n H\, \tilde{W}^n_{\mu\nu} B^{\mu\nu}$	$\Delta\phi_{jj}$

Operator structure corresponding to the constrained Wilson coefficients