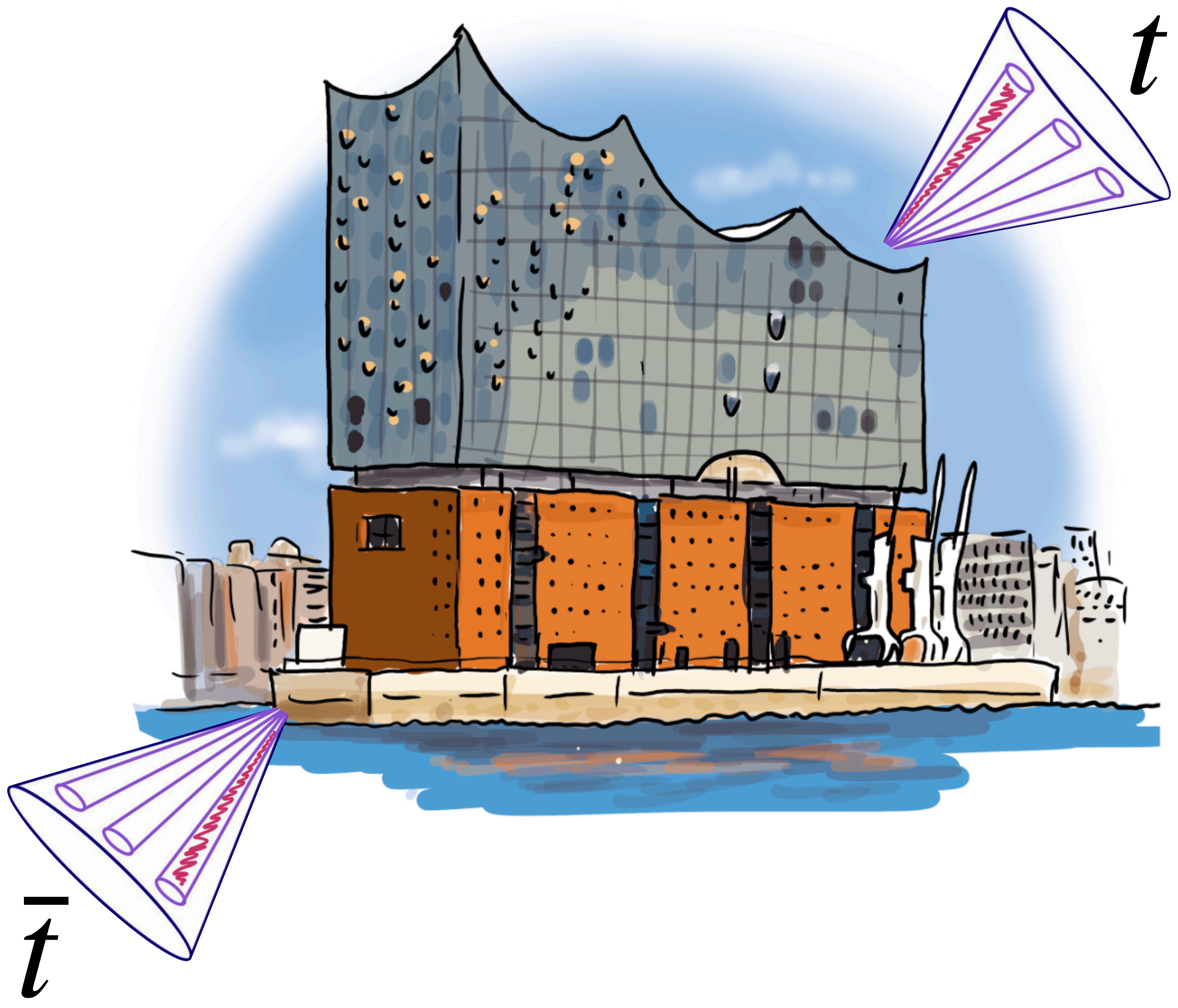
Top-quark charge asymmetry in $t\bar{t} + jets$ events

Hugo Alberto Becerril Gonzalez, Maria Aldaya, Andreas Meyer, An Ying, Abideh Jafari



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New observables for the top charge asymmetry at the LHC

In contrast to AC in $t\bar{t}$ production, the asymmetry in $t\bar{t}$ + j final states has the advantage that it is non-vanishing at LO and NLO calculations are available

1. The incline asymmetry tests the charge asymmetry of the qq-channel with expected asymmetries of up to −4% (depending of the phase space definition)

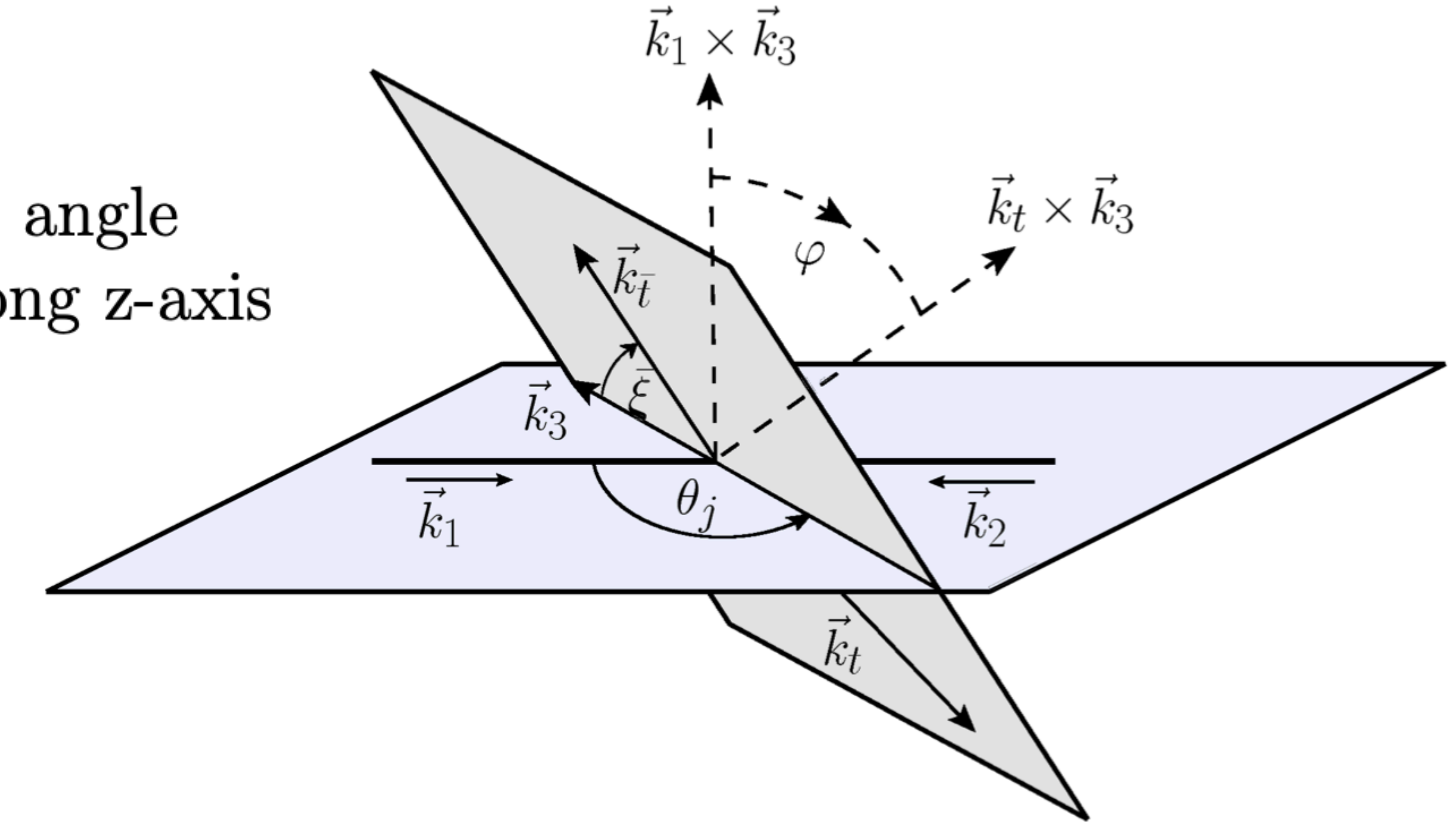
2. The energy asymmetry tests the charge asymmetry of the qg-channel with expected asymmetries of up to −11%

Incline Asymmetry at the LHC

Incline asymmetry $A^{\varphi,q}$ tests the charge asymmetry of the $q\bar{q}$-channel

$$A^{\varphi,q} \equiv \frac{\sigma_A^{\varphi}(y_{t\bar{t}j} > 0) - \sigma_A^{\varphi}(y_{t\bar{t}j} < 0)}{\sigma_S}$$

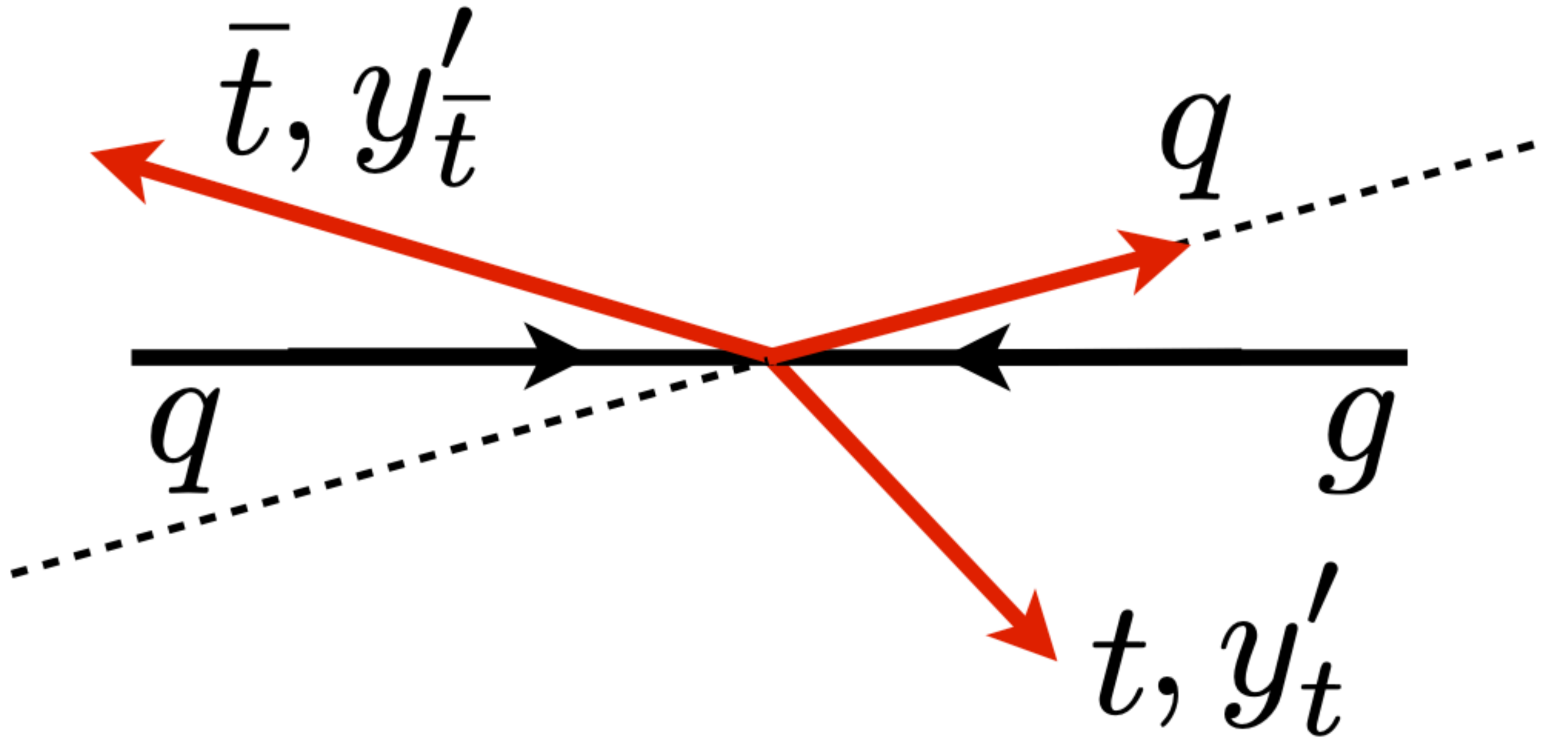
φ ... inclination angle
y_{ttj} ... boost along z-axis



Energy Asymmetry at the LHC

Energy asymmetry AE tests the charge asymmetry of the qg-channel $q\bar{q}$ contribution to A^E is exactly zero

$$A^E = \frac{\sigma_A(\Delta E \geq 0)}{\sigma_S} \qquad \Delta E = E_t - E_{\bar{t}}$$

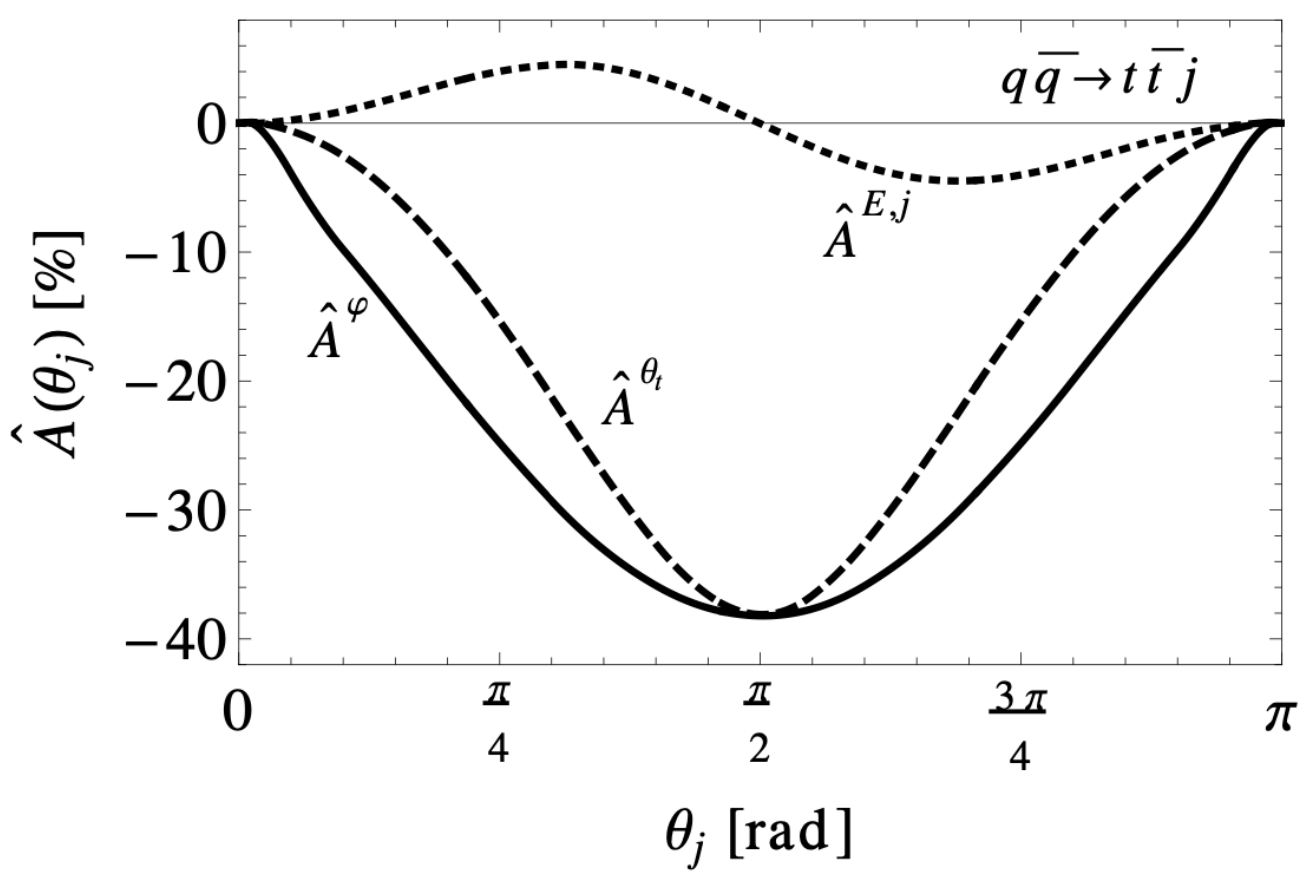


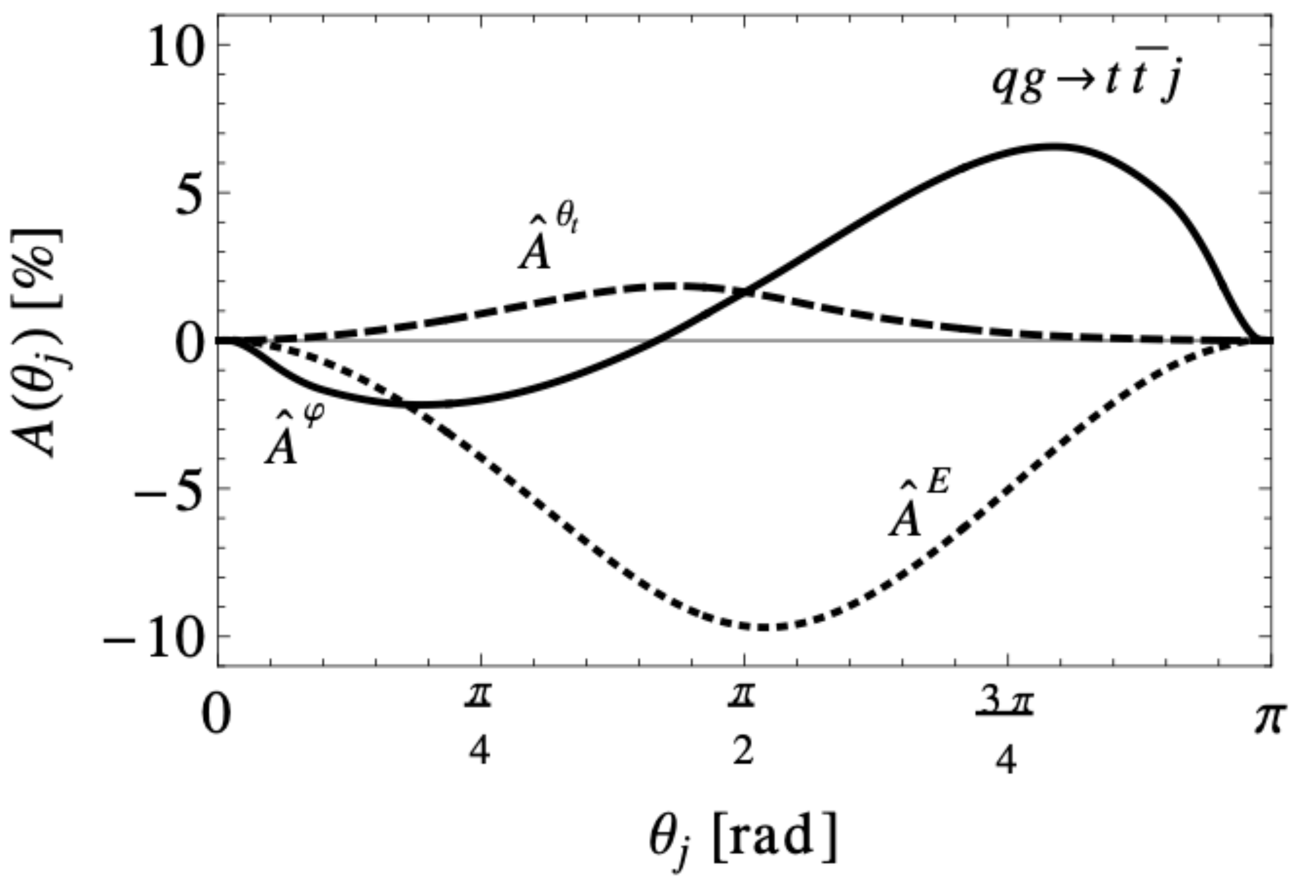
$\Delta E, \varphi, y_{ttj}$ are all defined in the ttj CM rest frame

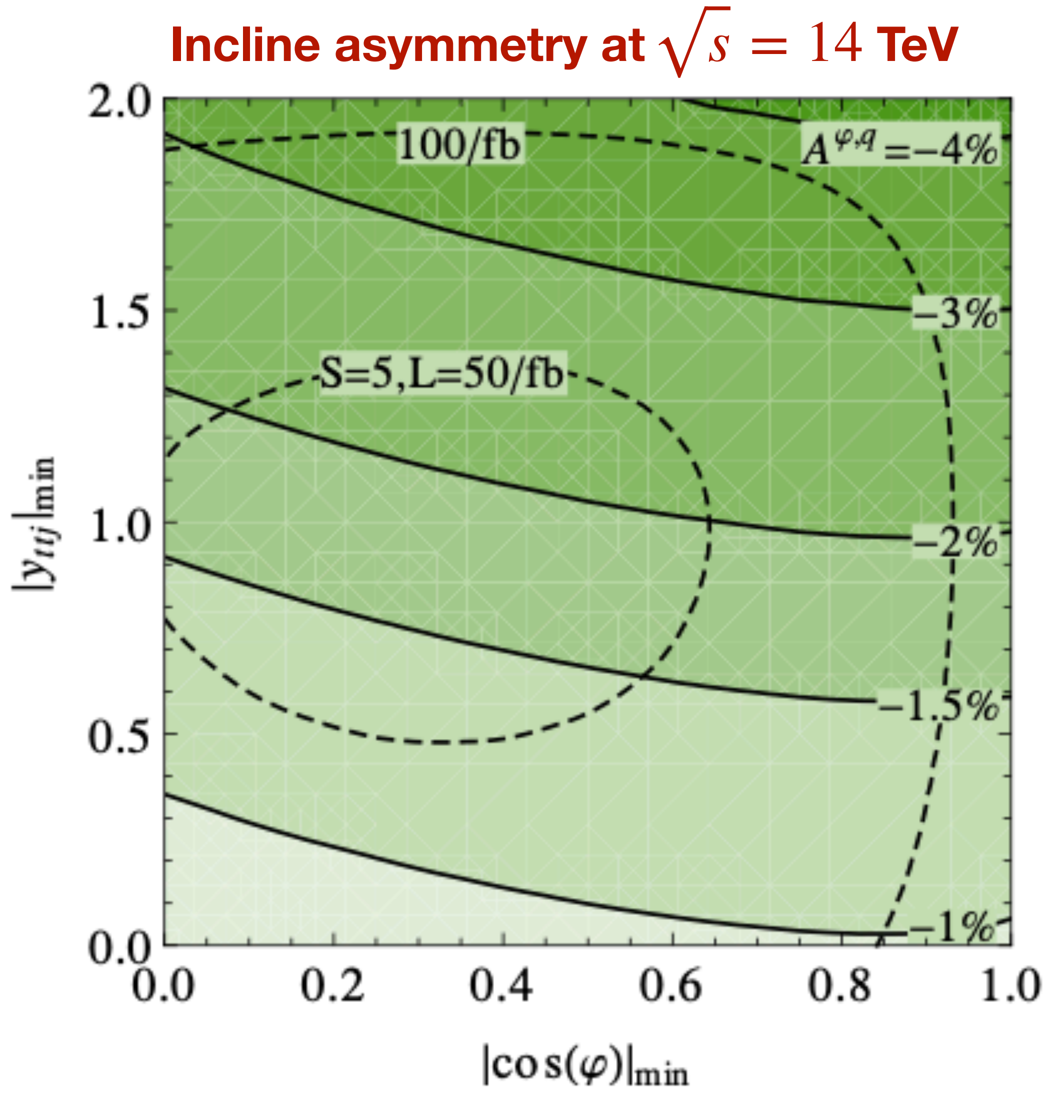
https://doi.org/10.1007/JHEP07%282013%29179

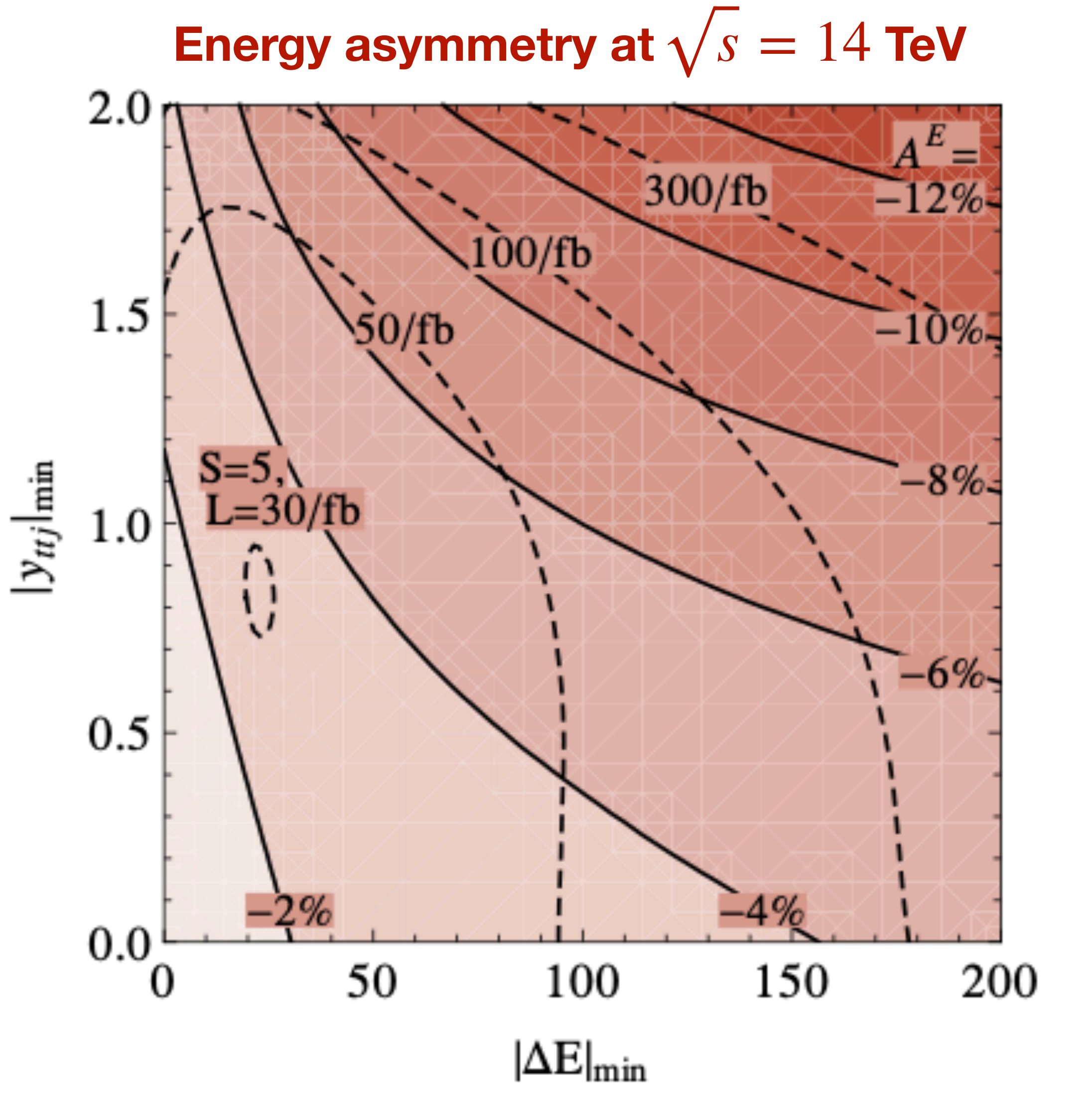
Charge asymmetry in $t\bar{t}$+jets

Partonic asymmetries as function of the jet scattering angle at $\sqrt{s}$ = 1TeV









$\lvert\hat{y}_j\rvert_{\max}$	—	—	0.5	—	0.5	0.5	0.25
$\lvert y_{t\bar{t}j}\rvert_{\min}$	—	1.5	—	—	1.3	1.85	1.9
$\lvert\cos\varphi\rvert_{\min}$	—	—	—	0.8	0.5	0.7	0.9
$A^{\varphi,q}$ [%]	−0.41	−1.4	−0.77	−0.54	−2.4	−3.7	−4.2
σ_S [pb]	458	41.3	117	217	17.6	3.6	1.0
$\mathcal{S}(50\,\mathrm{fb}^{-1})$	4.4	4.4	4.2	4.0	5.0	3.5	2.1
$\mathcal{S}(100\,\mathrm{fb}^{-1})$	6.2	6.3	5.9	5.7	7.1	5.0	3.0

$\lvert\hat{y}_j\rvert_{\max}$	—	—	0.2	—	0.5	0.5	0.5
$\lvert y_{t\bar{t}j}\rvert_{\min}$	—	1.5	—	—	1.4	1.7	1.8
$\lvert\Delta E\rvert_{\min}$ [GeV]	—	—	—	160	61	80	130
$p^j_{T,\min}$ [GeV]	25	25	25	25	80	100	160
A^E [%]	−0.48	−1.5	−1.1	−0.86	−6.5	−8.8	−11
σ_S [pb]	458	41.3	46.4	47.6	2.4	0.64	0.14
$\mathcal{S}(50\,\mathrm{fb}^{-1})$	5.2	4.9	3.6	3.0	5.0	3.5	2.0
$\mathcal{S}(100\,\mathrm{fb}^{-1})$	7.3	6.9	5.1	4.2	7.1	5.0	2.9
$\mathcal{S}(300\,\mathrm{fb}^{-1})$	12.7	11.9	8.8	7.3	12.3	8.6	5.0

- As shown above, the incline asymmetry is as good as charge asymmetry in the maximum $\theta_j = \pi/2$ in the $q\bar{q}$ channel
- The incline asymmetry and energy asymmetry are simple superior than the charge asymmetry in the qg channel

Partonic contributions at $\sqrt{s} = 8[14]$ TeV: 65%[75%] (gg), 27%[21%] (qg+q̄g) and 8%[4%] (qq̄).

Expected maximal incline asymmetry 4%, but with different sets of cuts a significance > 5 σ can be achieved with enough statistics

Similar to incline asymmetry, higher luminosities allows to achieve a good statistical significance.

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Datasets and conditions

The analysis uses the full Run 2 UL dataset with the following GTs:

- Data: 106X_dataRun2_v37
- MC 2016APV: 106X_mcRun2_asymptotic_preVFP_v11
- MC 2016: 106X_mcRun2_asymptotic_v17
- MC 2017: 106X_mc2017_realistic_v10
- MC 2018: 106X_upgrade2018_realistic_v16_L1v1

Golden JSON files:

- Cert_271036-284044_13TeV_Legacy2016_Collisions16_JSON.txt
- Cert_294927-306462_13TeV_UL2017_Collisions17_GoldenJSON.txt
- Cert_314472-325175_13TeV_Legacy2018_Collisions18_JSON.txt

MC samples

Signal

- TTToSemiLeptonic_CP5_powheg-pythia8
- TTToHadronic_CP5_powheg-pythia8
- TTTo2L2Nu_CP5_powheg-pythia8

Bkg

- WJetsToLNu_HT-XToX_CP5_madgraphMLM-pythia8
- DYJetsToLL_M-50_HT-70to100_CP5_PSweights_madgraphMLM-pythia8
- WZ_CP5_pythia8_Summer20UL18
- WW_CP5_pythia8_Summer20UL18
- ZZ_CP5_pythia8
- ST_tW_antitop_5f_NoFullyHadronicDecays_CP5_powheg-pythia8
- ST_tW_top_5f_NoFullyHadronicDecays_CP5_powheg-pythia8
- ST_t-channel_top_4f_InclusiveDecays_CP5_powheg-madspin-pythia8
- ST_s-channel_4f_leptonDecays_CP5_amcatnlo-pythia8
- ST_t-channel_antitop_4f_InclusiveDecays_CP5_powheg-madspin-pythia8
- QCD_HTXtoX_CP5_PSWeights_madgraph-pythia8

*V+jets reweighted to account for NLO QCD and EWK effects

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Scale Factors and corrections

Centrally provided SFs and corrections:

- Pileup ID
- L1 Prefiring fro 2016 and 2017
- muon ID, iso, reco, trigger SFs
- electron ID+iso, reco SFs
- JEC/JER
- b-tagging SFs
- t-tagging SFs
- top-pt-rew

Correction derived for analysis (B2G-22-006):

electron trigger SFs derived with orthogonal dataset method and approved by EGM POG

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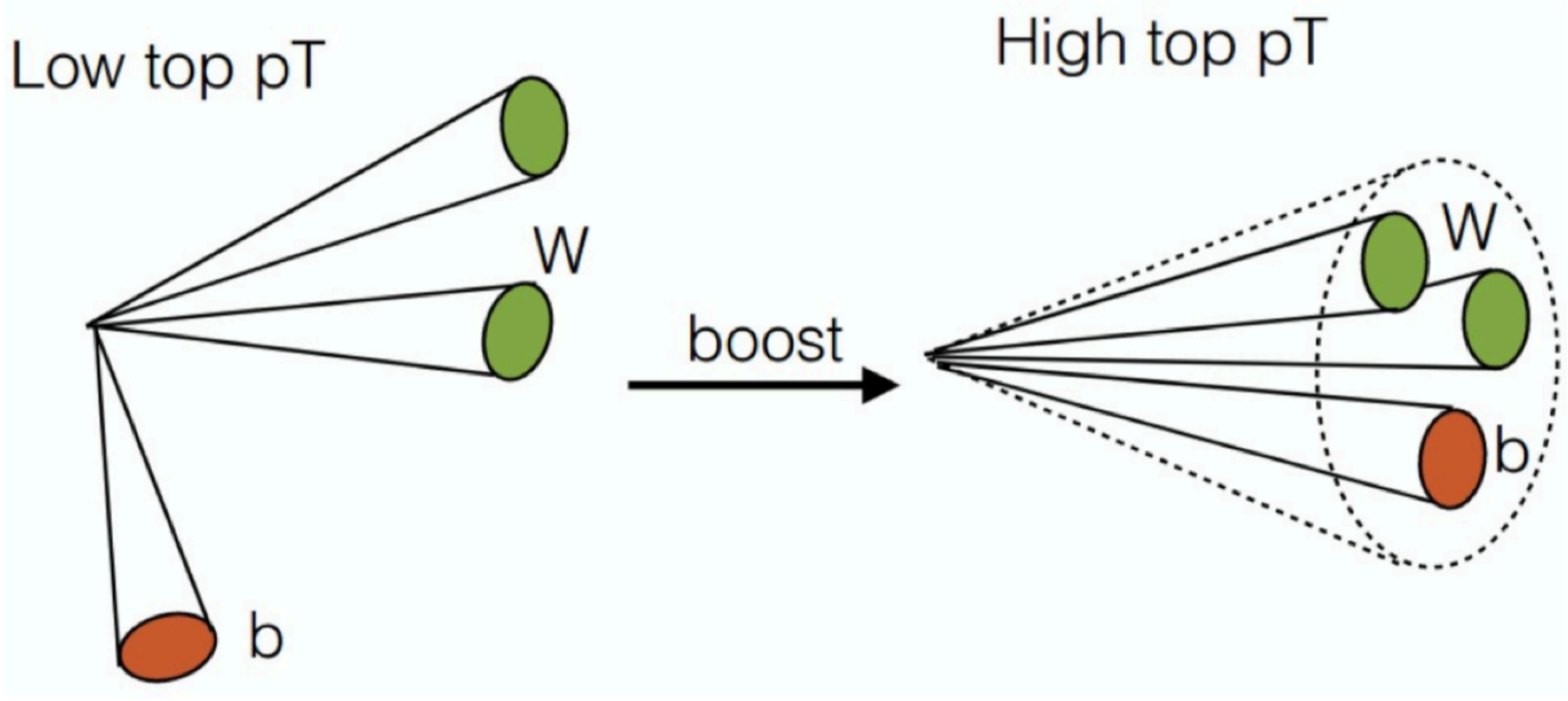
Baseline selection for semileptonic channel

- HLT_Mu50_v* / HLT_Ele50_WPTight_Gsf_v* or HLT_Ele115_CaloIdVT_GsfTrkIdT_v* (No isolation requirement!)
- 2D kinematic cut:
  - $\Delta R(l, j) > 0.4$ **OR**
  - $p_T^{rel}(l, j) > 25$ GeV
- Exactly one muon(electron)
  - Tight identification requirements for both e and μ channels
  - $p_T^{lep} > 55(80)$ GeV and $|\eta| < 2.4$
- MET > 50 GeV; $H_T^{lep} > 150$ GeV
- At least three high p_T AK4 jets with $|\eta| < 2.4$
  - p_T(jet1) >150 GeV & p_T(jet2) > 50 GeV, p_T(add) > 100 GeV
- At least 1 b-jet identified with the medium criteria of the CMS DeepJet algorithm
- $M_{t\bar{t}} > 500$ GeV, $\frac{1}{4}\pi < \theta_j^{opt} < \frac{3}{5}\pi$, $\chi^2 < 30$

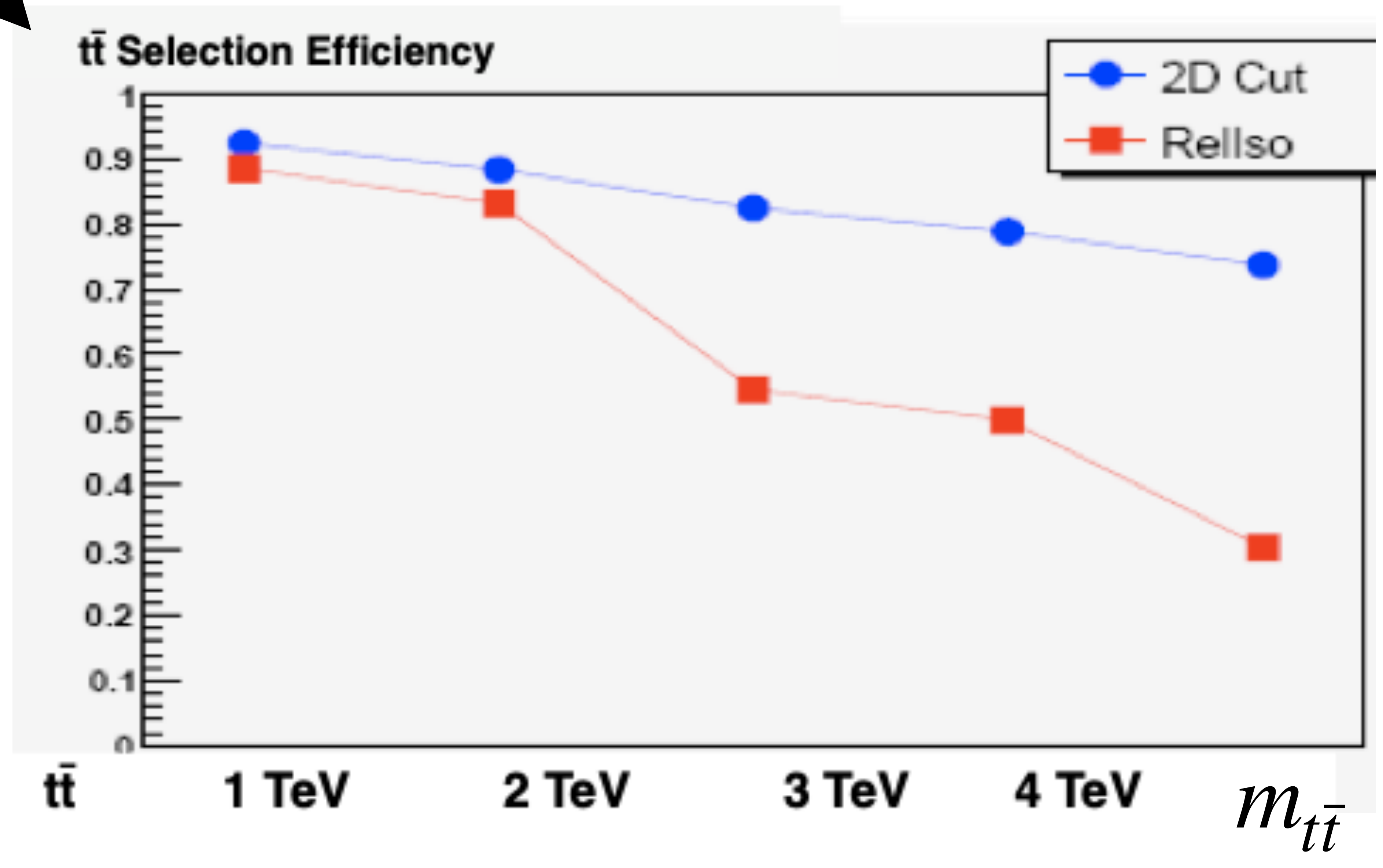
$$\theta_j^{\mathrm{opt}} = \begin{cases} \theta_j & if\ \ y_{t\bar{t}j} > 0 \\ \pi - \theta_j & if\ \ y_{t\bar{t}j} < 0 \end{cases}$$

- AK8 PUPPI jets with $p_T > 400$ GeV and $|\eta| < 2.4$ (in case of Boosted or Semi-Resolved reconstruction)



For boosted reconstruction:

At least one top/W tagged jet (DeepAK8)



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Events reconstruction

Start with reconstruction of $t\bar{t}$ system and then add additional jet

$$\chi^2 = \chi^2_{lep} + \chi^2_{had} = [\frac{M_{lep} - \bar{M}_{lep}}{\sigma_{M_{lep}}}]^2 + [\frac{M_{had} - \bar{M}_{had}}{\sigma_{M_{had}}}]^2$$

The kinematic reconstruction of the top and antitop quark four-momenta is performed for each event according to the following strategy

Boosted/Semi-resolved: Events with exactly 1 top tag or 1 WTag jet:

- Top/W tagged jet is assigned to hadronic top
- Lepton, MET and only well separated AK4 jets are considered to leptonic side

Resolved: Events with no top tagged or Wtag jet:

- All possible combinations for each AK4 jets to either hadronic or leptonic top leg
- Lepton, MET assigned to leptonic top.

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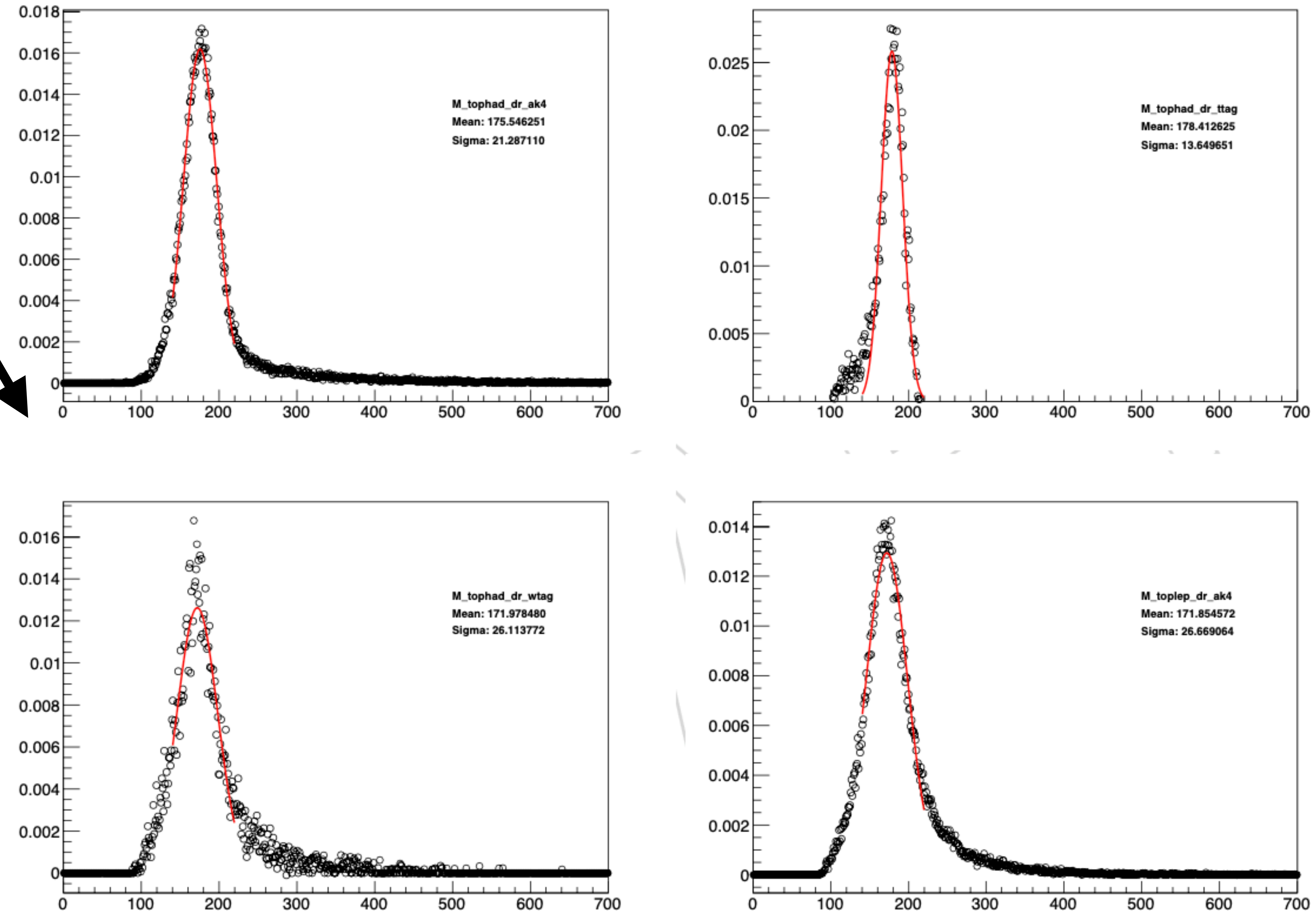
- **Tuning of Mass Reconstruction Parameters**



- $M_{\text{lep}} = 172$ GeV, $\sigma_{M_{\text{lep}}} = 26$ GeV
- $M_{\text{had}} = 175$ GeV, $\sigma_{M_{\text{had}}} = 21$ GeV (when no t/W tag jet)
- $M_{\text{had}} = 178$ GeV, $\sigma_{M_{\text{had}}} = 14$ GeV (for ttag reconstruction)
- $M_{\text{had}} = 171$ GeV, $\sigma_{M_{\text{had}}} = 25$ GeV (for wtag reconstruction)

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Start with reconstruction of $t\bar{t}$ system and then add additional jet

$$\chi^2 = \chi^2_{lep} + \chi^2_{had} = [\frac{M_{lep} - \bar{M}_{lep}}{\sigma_{M_{lep}}}]^2 + [\frac{M_{had} - \bar{M}_{had}}{\sigma_{M_{had}}}]^2$$

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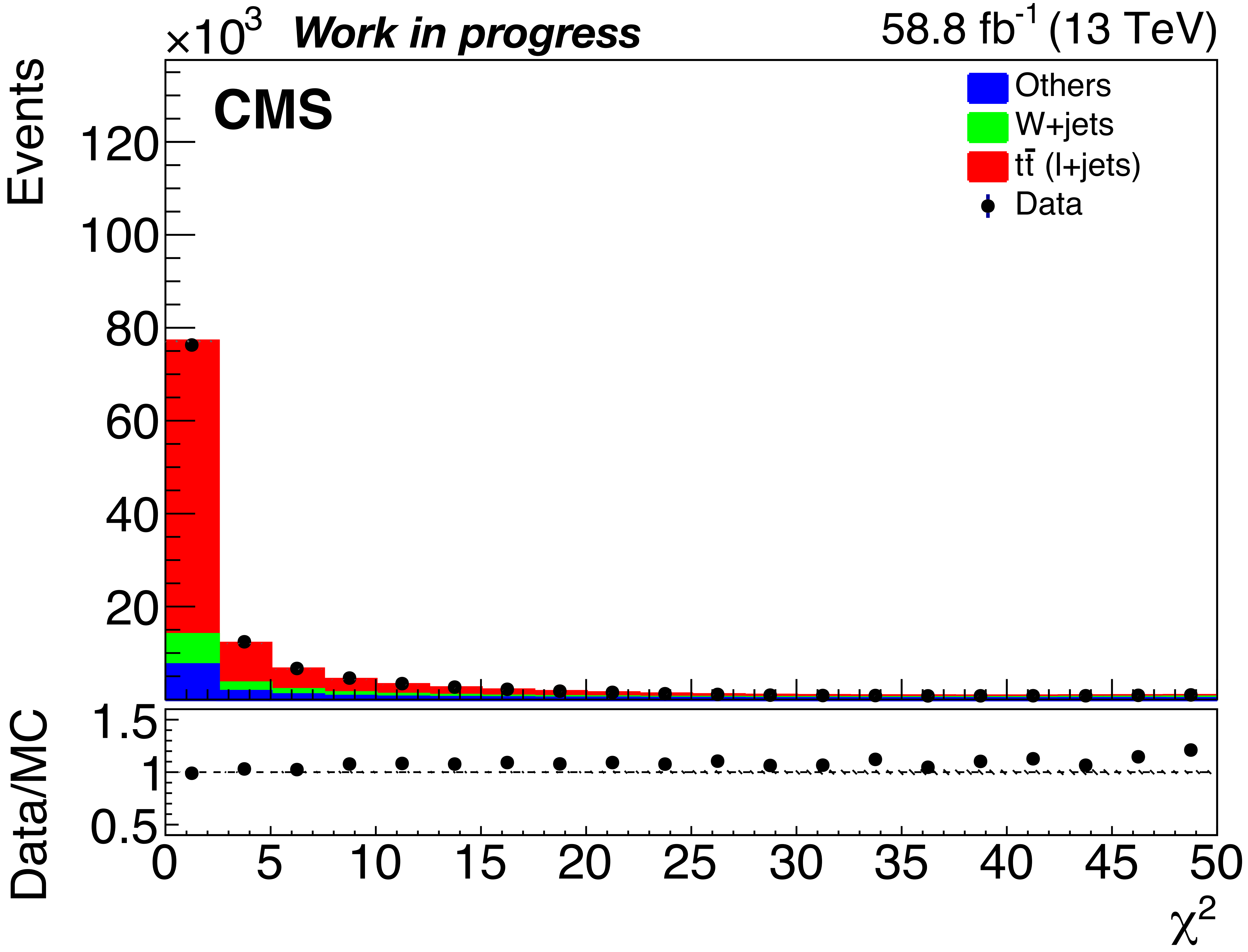
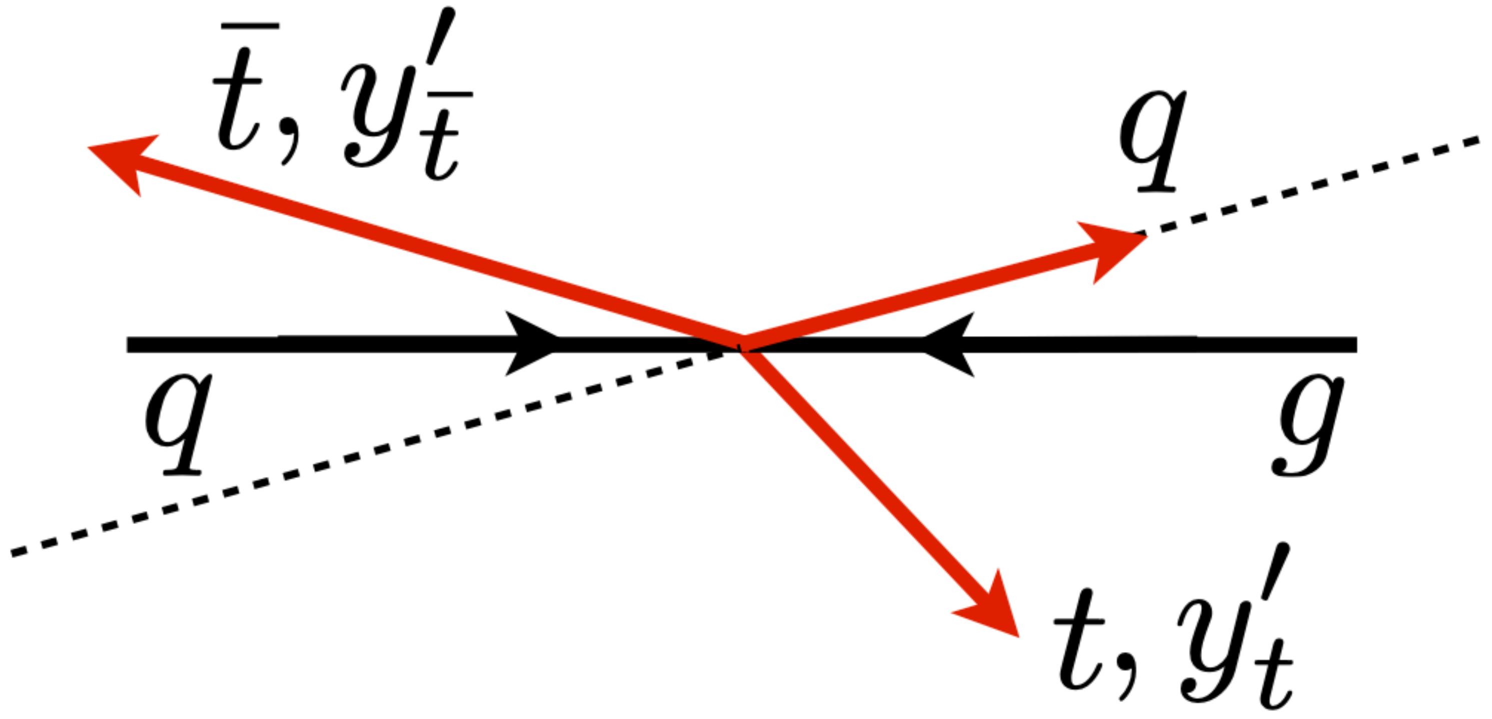


Additional jet

Only events with a successful $t\bar{t}$ reconstruction are considered in the subsequent steps. The additional jet has not to be part of any the top quarks and have a p_T greater than 100 GeV

- $p_T(j_{add})$>100 GeV, $|\eta_{j_{add}}|$<2.4, $\Delta R(t, j_{add})$>1.5, $\Delta R(\bar{t}, j_{add}) > 1.5$
- If there is more than one candidate, the one with the highest traverse momentum is selected



Parton level information

Top and anti-top quark are already defined at Parton level, additional jet is selected using the following criteria

- $p_T(j_{add})$>100 GeV, $|\eta_{j_{add}}|$<2.4, $\Delta R(t, j_{add})$>1.2, $\Delta R(\bar{t}, j_{add}) > 1.2$
- $p_T(j_{add})$>100 GeV, $|\eta_{j_{add}}|$<2.4, $\Delta R(t, j_{add})$>0.8, $\Delta R(\bar{t}, j_{add}) > 0.8$
- $|\eta_{j_{add}}|$<2.4, $\Delta R(t, j_{add})$>0.8, $\Delta R(\bar{t}, j_{add}) > 0.8$
- $\Delta R(t, j_{add})$> 0.8, $\Delta R(\bar{t}, j_{add}) > 0.8$
- $\Delta R(t, j_{add})$> 0.4, $\Delta R(\bar{t}, j_{add}) > 0.4$

If no additional jet is found at Parton level, the event is rejected (This was not observed)

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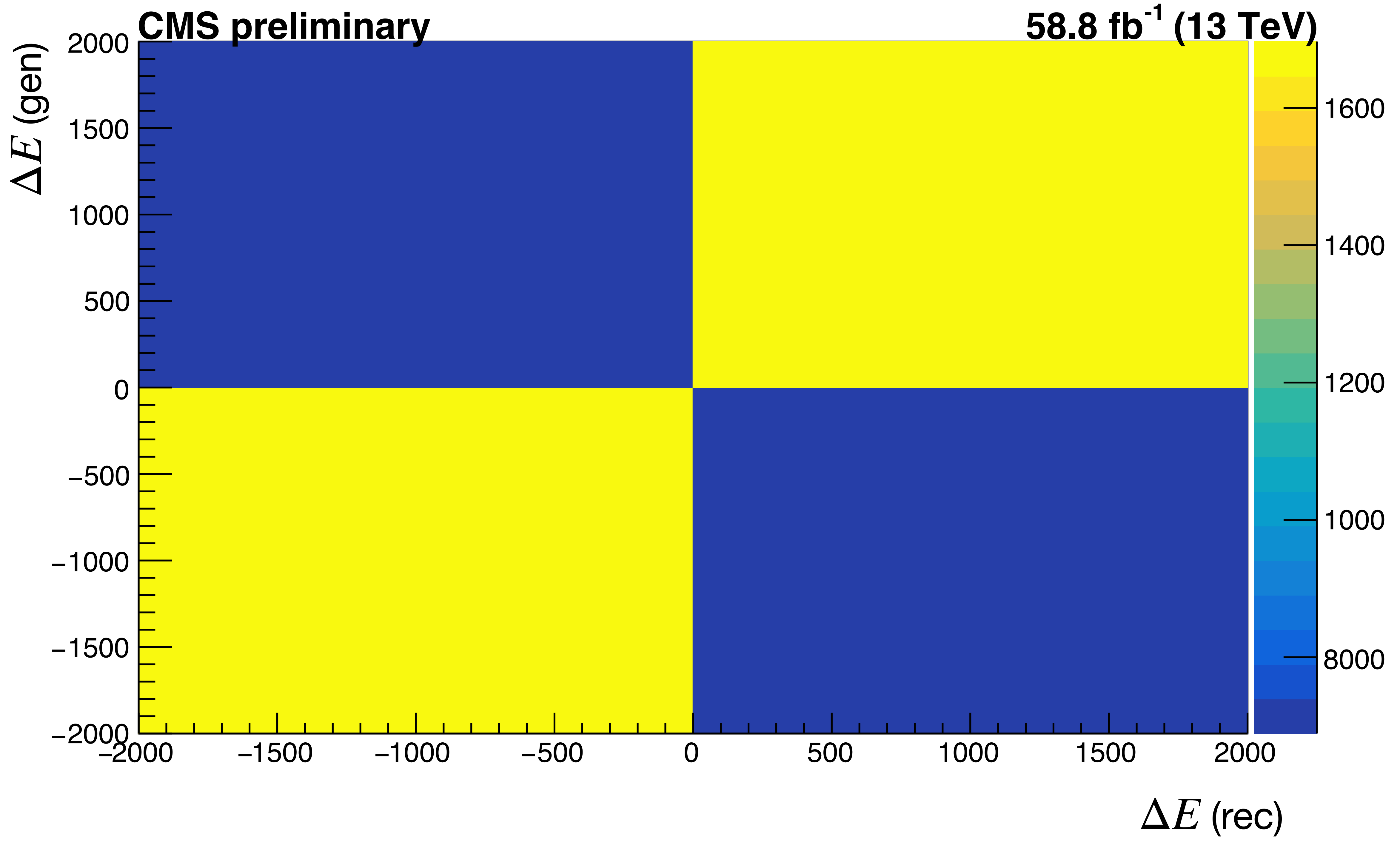
Control Plots

More Control Plots

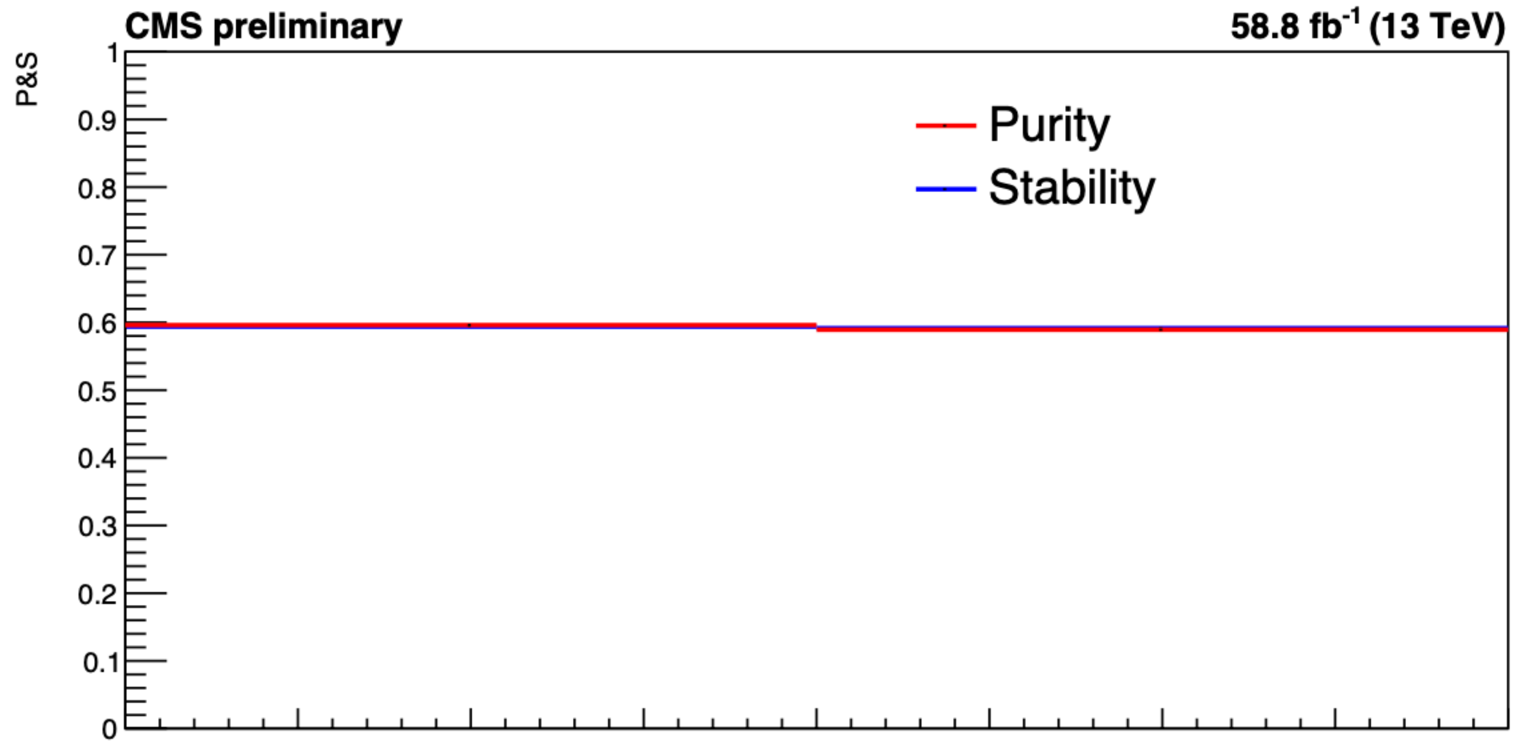
Response matrices

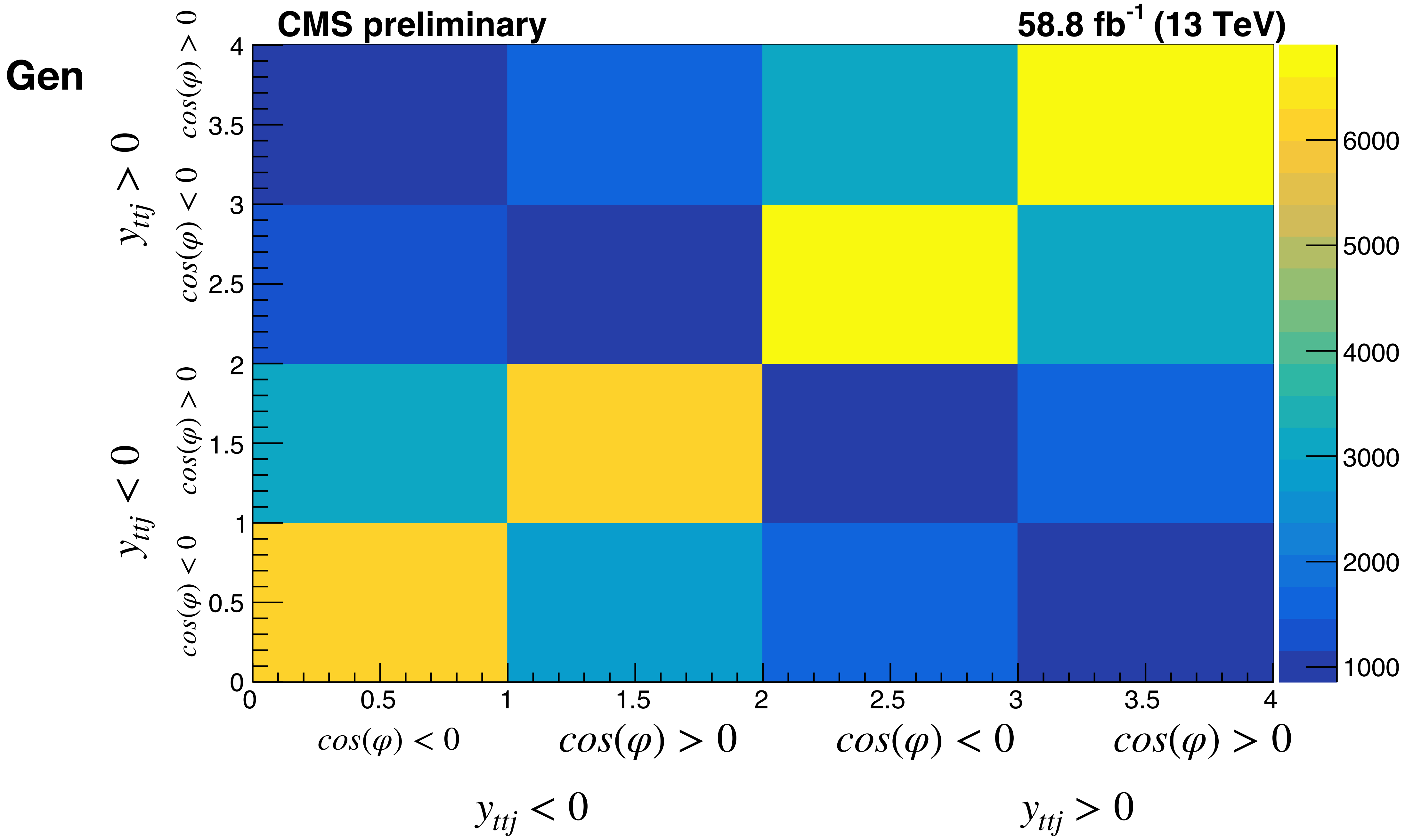
The binning is chosen such that the minimum number of bins is used. All matrix are fairly diagonal so no need of regularized unfolding

Year	Conditional number (AE)	Conditional number (AI)
2018	1.52	3.42
2017	1.54	3.51
2016preVFP	1.65	3.76
2016postVFP	1.67	3.74



Purity and stability values are also calculated and documented in the note.





Extracting the asymmetry directly from Combine

Unfolding with the Combine tool enables us to extract the asymmetries directly from the maximum likelihood fit that is performed, hence all error propagation is taken care of:

$$A_E = \frac{r_1 * N_{unf}(\Delta E > 0) - r_2 * N_{unf}(\Delta E < 0)}{r_1 * N_{unf}(\Delta E > 0) + r_2 * N_{unf}(\Delta E < 0)}$$

After few simple steps, we can introduce the asymmetry directly in the fit by resolving the equation as function of one of the signal strength:

$$r_1 = \frac{N_{unf}(\Delta E < 0)}{N_{unf}(\Delta E > 0)} * r_2 * \frac{1 - A_E}{1 + A_E}$$

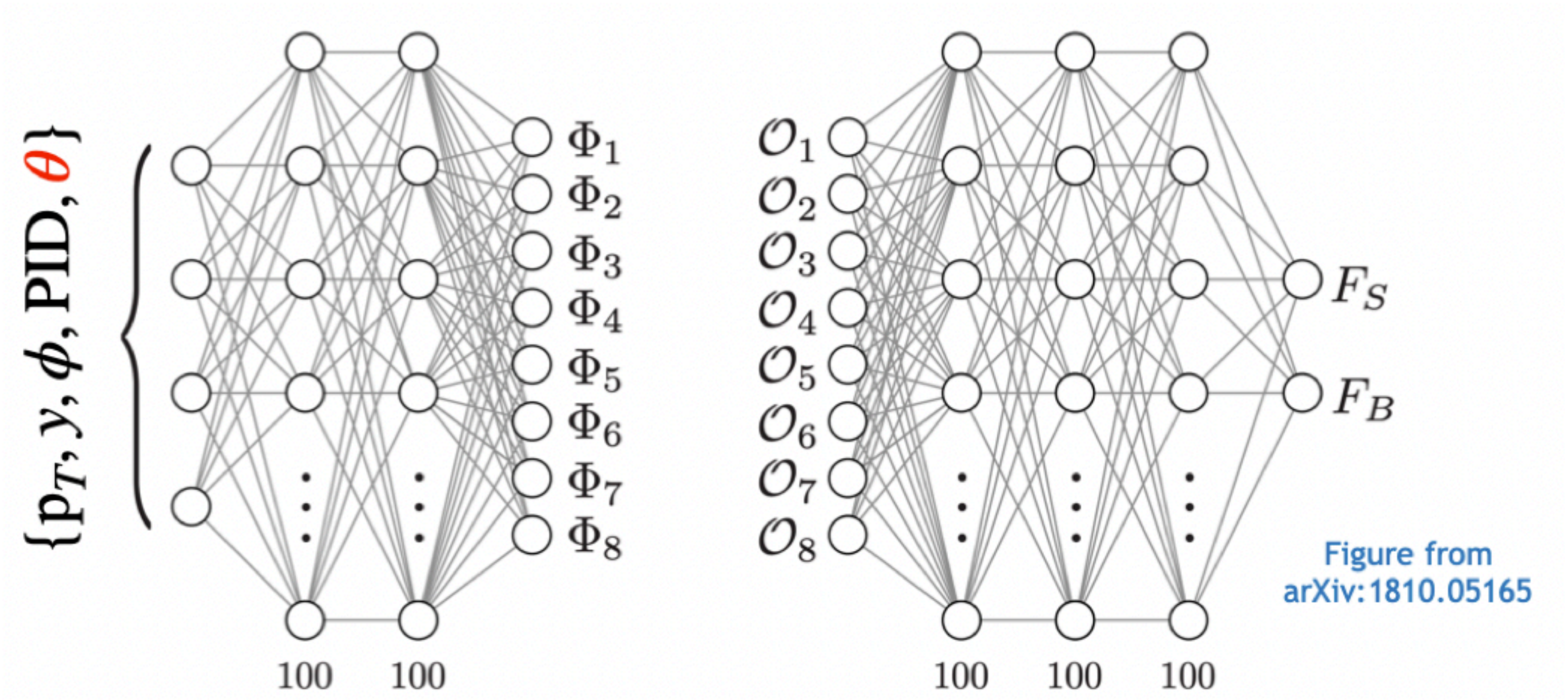
Similarly for A_I

$$\begin{aligned} r_4 = r_2 * \frac{N_{truth}(cos\phi > 0 | y_{ttj} < 0)}{N_{truth}(cos\phi > 0 | y_{ttj} > 0)} * \frac{1 + A_I}{1 - A_I} \\ + r_3 * \frac{N_{truth}(cos\phi > 0 | y_{ttj} < 0)}{N_{truth}(cos\phi < 0 | y_{ttj} > 0)} * \frac{1 + A_I}{1 - A_I} \\ - r_1 * \frac{N_{truth}(cos\phi < 0 | y_{ttj} < 0)}{N_{truth}(cos\phi > 0 | y_{ttj} > 0)} \end{aligned}$$

Systematic uncertainties

source	uncertainty	type	process
luminosity	±1% - 2%	norm	all
$t\bar{t}$ cross section	±5%	norm	$t\bar{t}$
single t cross section	±30%	norm	single t
W+jets cross section	±30%	norm	W+Jets
other bkg cross section	±50%	norm	DY,Diboson,QCD
Pileup reweighting	$\pm 1\sigma$	norm & shape	all
Muon reconstruction	$\pm 1\sigma$	norm & shape	all
Muon isolation	$\pm 1\sigma$	norm & shape	all
HLT muon	$\pm 1\sigma$	norm & shape	all
electron ID+isolation	$\pm 1\sigma$	norm & shape	all
electron reconstruction	$\pm 1\sigma$	norm & shape	all
HLT trigger	$\pm 1\sigma$	norm & shape	all
b-tagging	$\pm 1\sigma$	norm & shape	all
L1prefiring	$\pm 1\sigma$	norm & shape	all(2016,2017)
PDFs	$\pm 1\sigma$	shape	all
μ_R and μ_F	$\pm 1\sigma$	norm & shape	all
JES	$\pm 1\sigma$	norm & shape	all
JER	$\pm 1\sigma$	norm & shape	all
t-tagging	unconstrained	norm & shape	all
FSR	$\pm 1\sigma$	shape	$t\bar{t}$
ISR	$\pm 1\sigma$	shape	$t\bar{t}$
h_{damp}	$\pm 1\sigma$	shape	$t\bar{t}$
top-p_T reweighing	$\pm 1\sigma$	shape	$t\bar{t}$

ML for reweighting



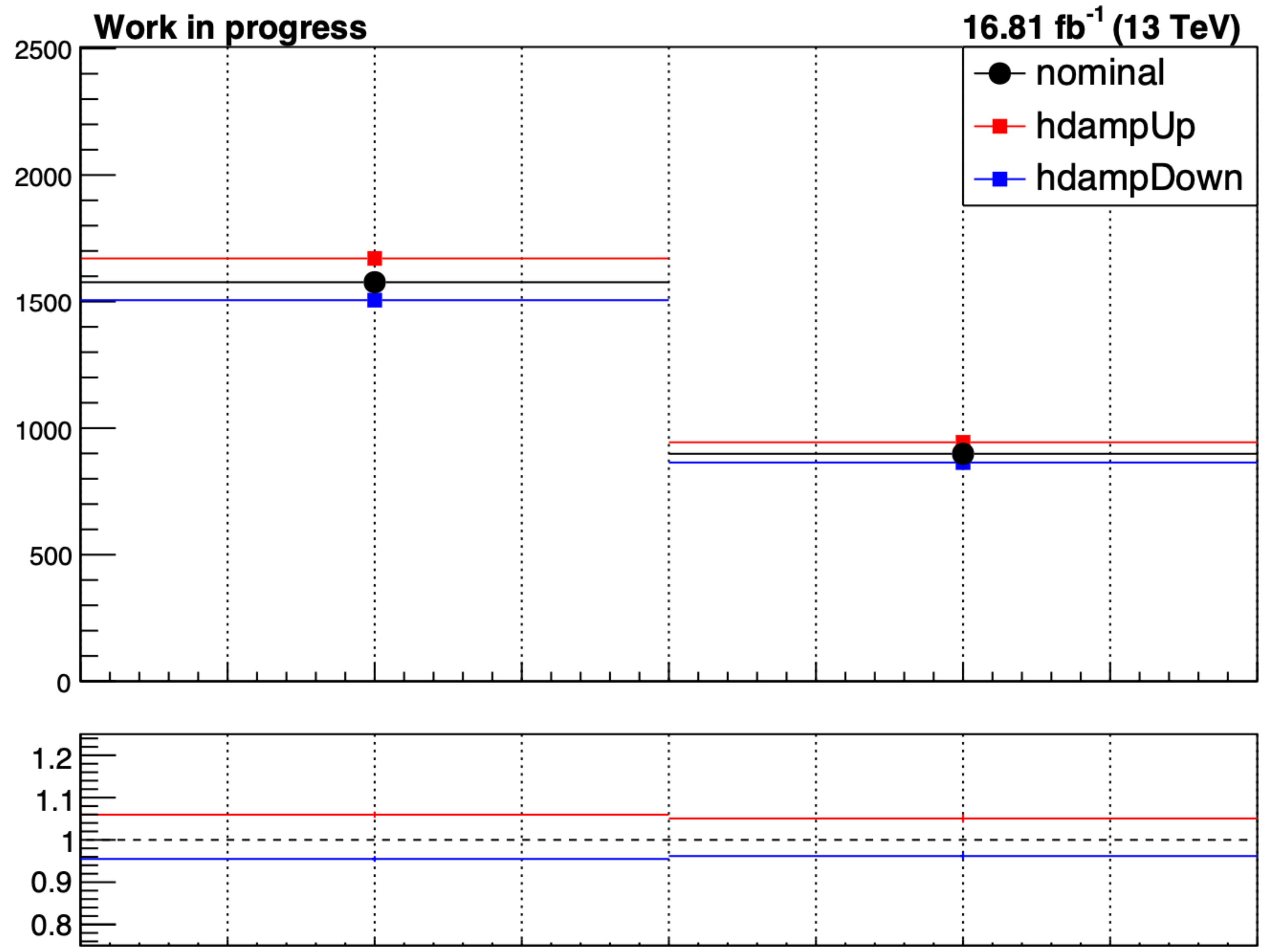
2 NN models to reweighs sample with CMS nominal value of hdamp:

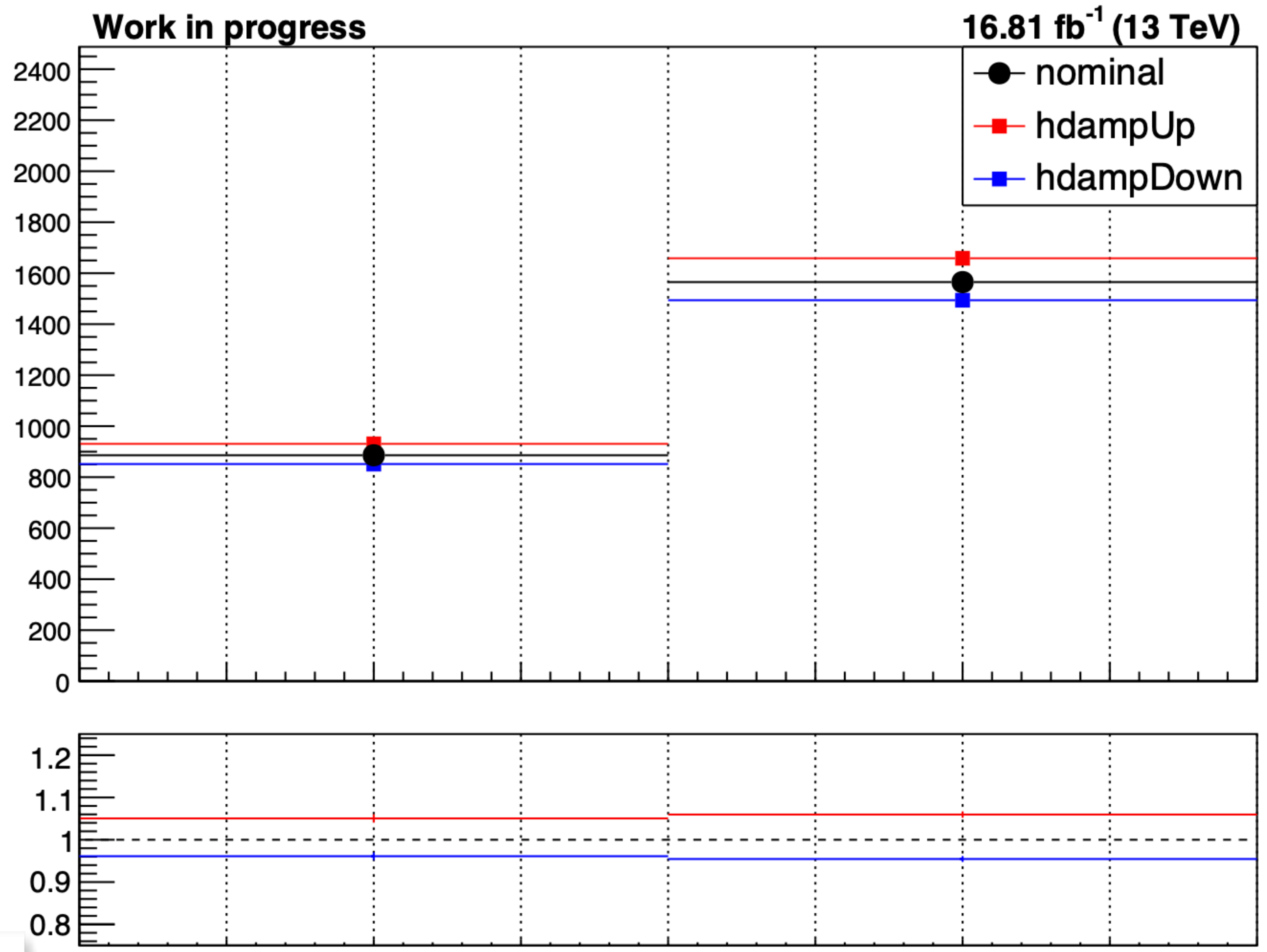
- Nominal to up CMS variation of h_{damp}: $(1.379 \rightarrow 2.305) \cdot m_t$
- Nominal to down CMS variation of h_{damp}: $(1.379 \rightarrow 0.8739) \cdot m_t$

- **Parton level information as inputs to the PFN:**
  - 4-vector (p_T, y, ϕ, m) and PID [t, $\bar{t}$, $t\bar{t}$ system]

Reweighting closure of ~2% up to 1 TeV

I include this as a new syst. Uncertainty





https://indico.cern.ch/event/1402978/contributions/5905049/attachments/2834281/4960603/Meeting-16-4-24.pdf

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JEC Uncertainty Correlation and Grouping for Run2

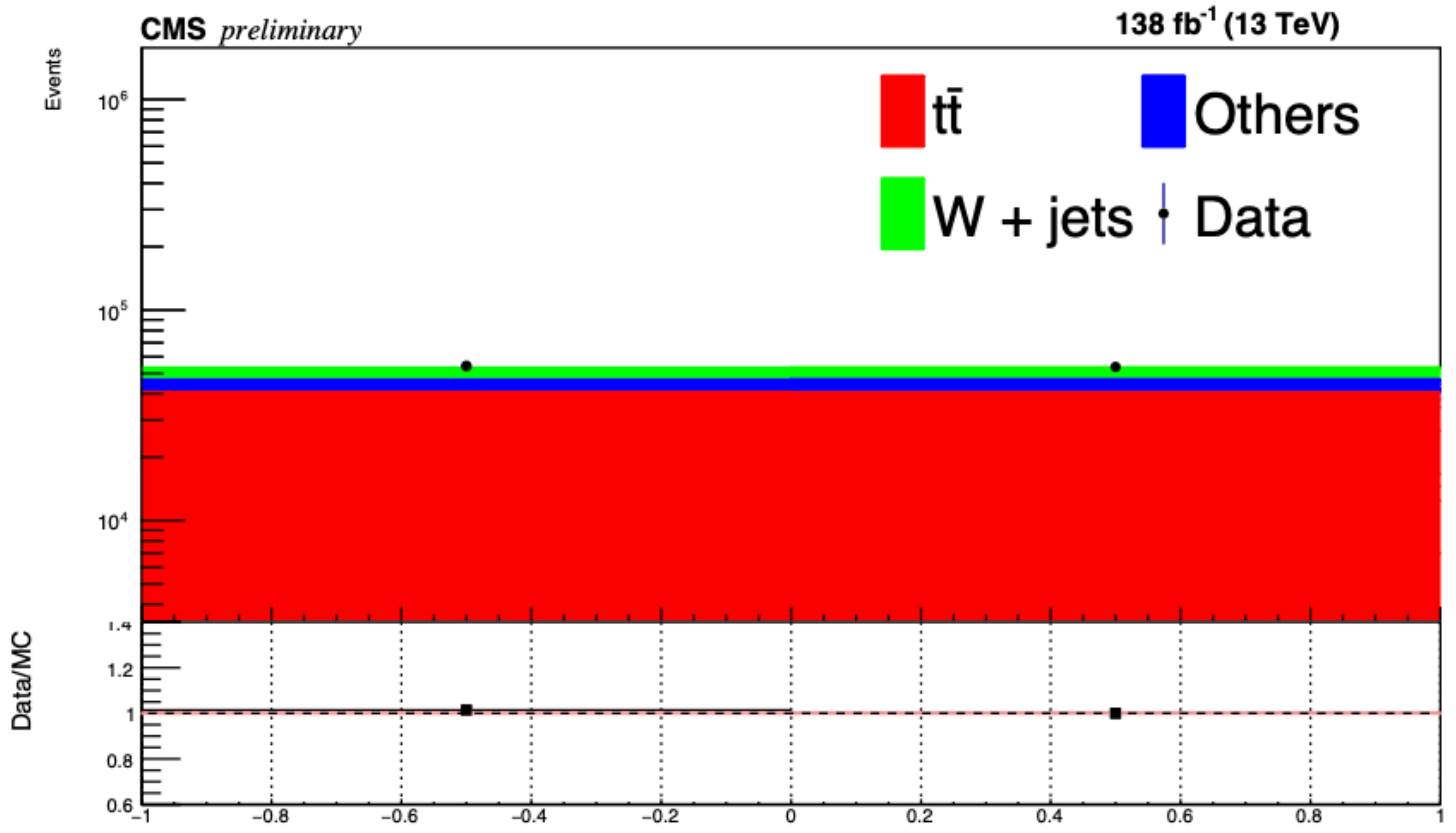
The recommended 11 sources (per year) consist of 6 uncertainty sources that are fully correlated across all 4 years and 5 uncertainties that are uncorrelated across years.

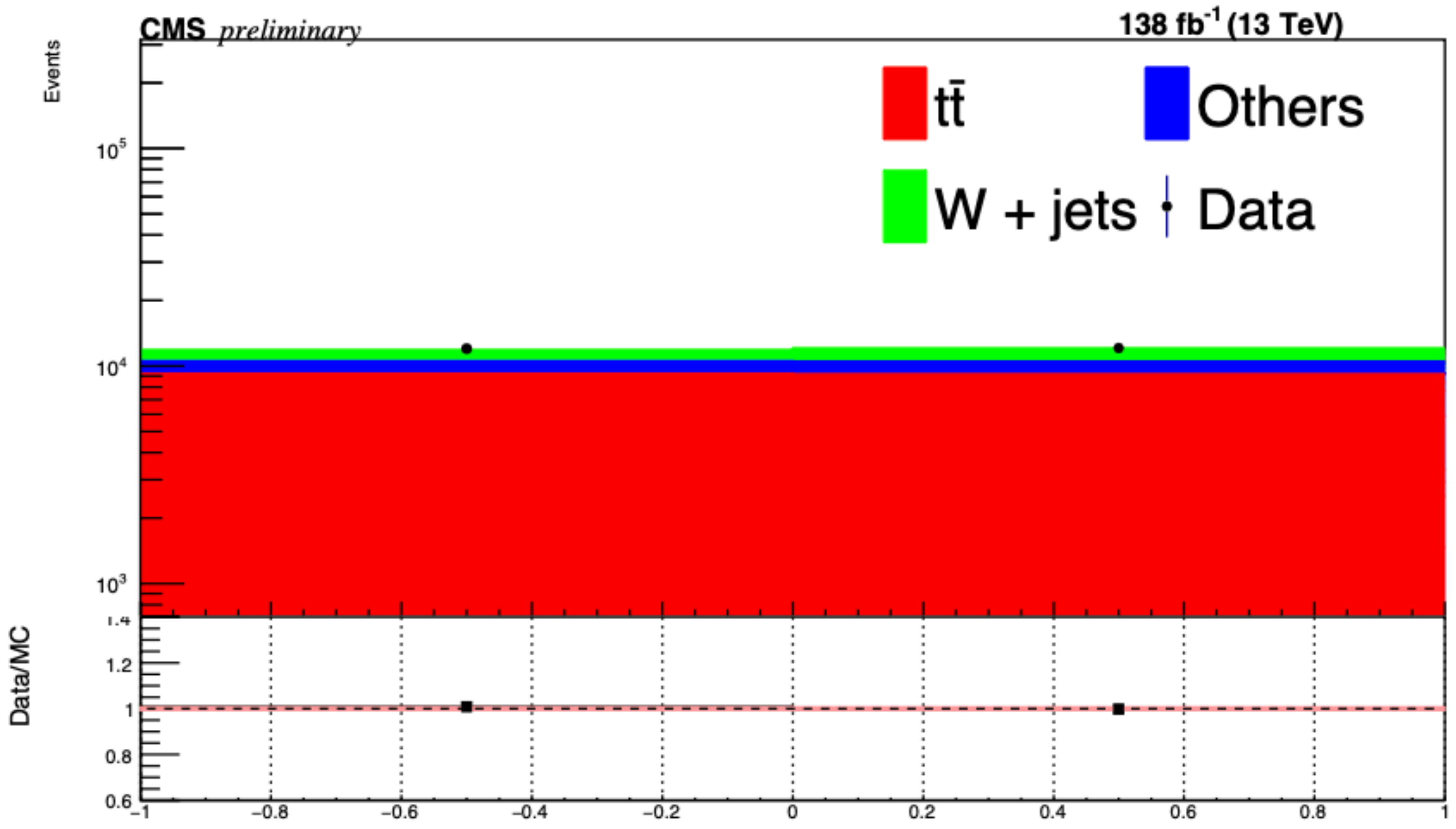
Find the information in this table: table

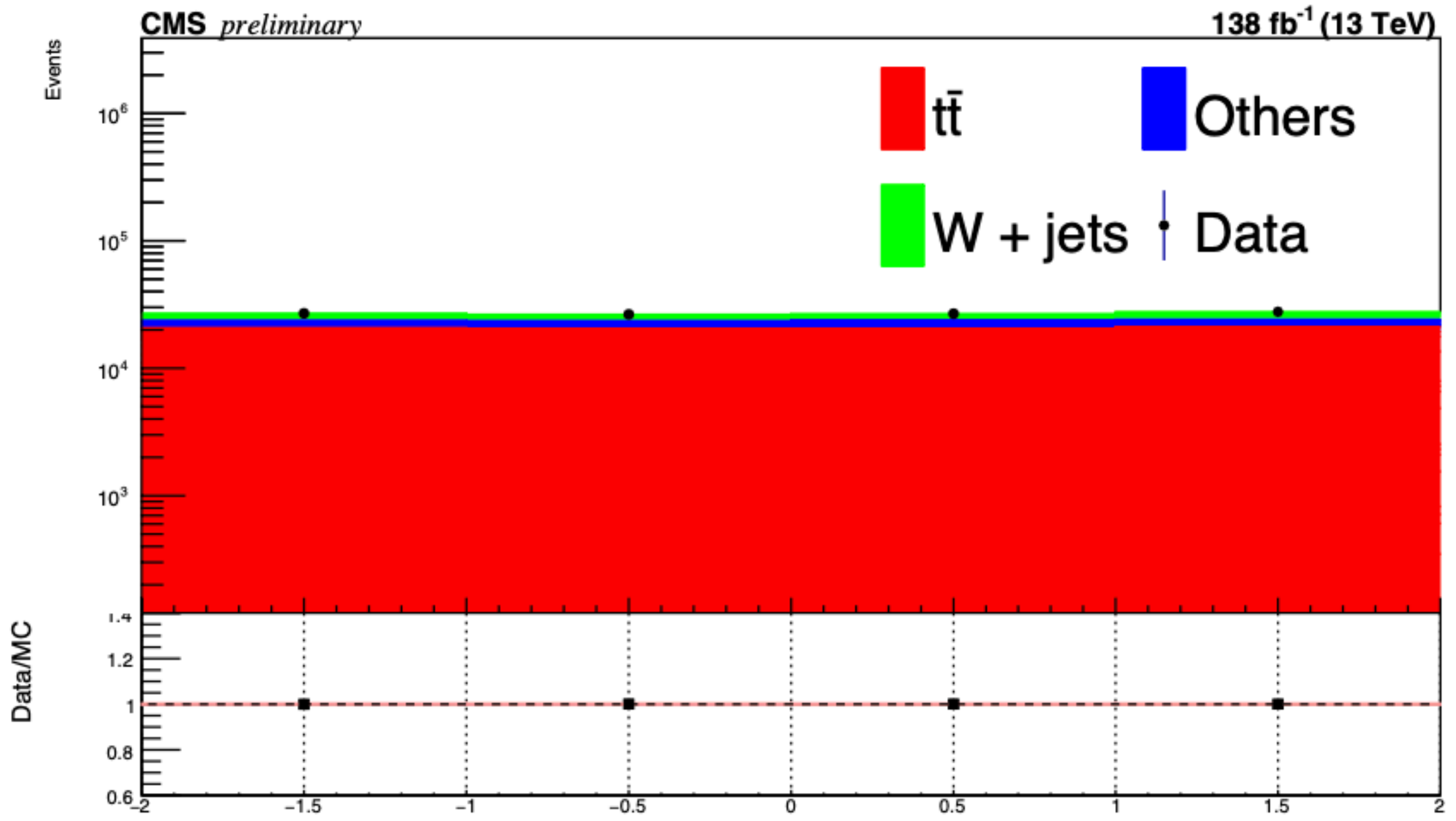
Already implemented in the fit

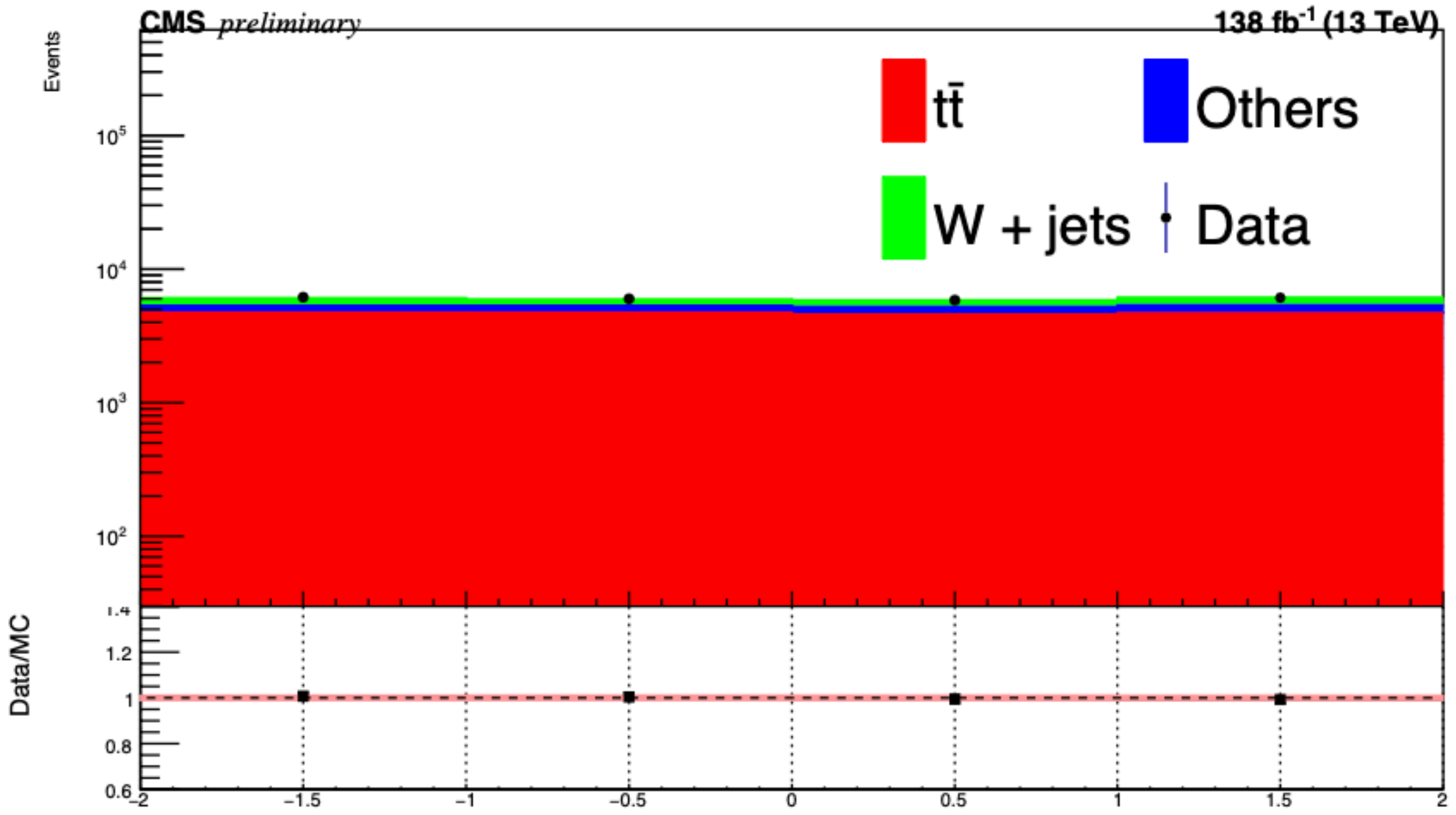
Uncertainty Source	JetMET grouping and correlation
	_year indicates a nuisance parameter uncorrelated across 3 years
Number of nuisances	4xAbsolute+4xBBEC1+4xEC2+4xHF+RelativeBal+3xRelativeSample+FlavorQCD = 21
AbsoluteMPFBias	Absolute
AbsoluteScale	Absolute
AbsoluteStat	Absolute_year
FlavorQCD	FlavorQCD
Fragmentation	Absolute
PileUpDataMC	Absolute
PileUpPtBB	BBEC1
PileUpPtEC1	BBEC1
PileUpPtEC2	EC2
PileUpPtHF	HF
PileUpPtRef	Absolute
RelativeFSR	Absolute
RelativeJEREC1	BBEC1_year
RelativeJEREC2	EC2_year
RelativeJERHF	HF
RelativePtBB	BBEC1
RelativePtEC1	BBEC1_year
RelativePtEC2	EC2_year
RelativePtHF	HF
RelativeBal	RelativeBal
RelativeSample	RelativeSample_year
RelativeStatEC	BBEC1_year
RelativeStatFSR	Absolute_year
RelativeStatHF	HF_year
SinglePionECAL	Absolute
SinglePionHCAL	Absolute
TimePtEta	Absolute_year

Perfil distribution of unfolded variable









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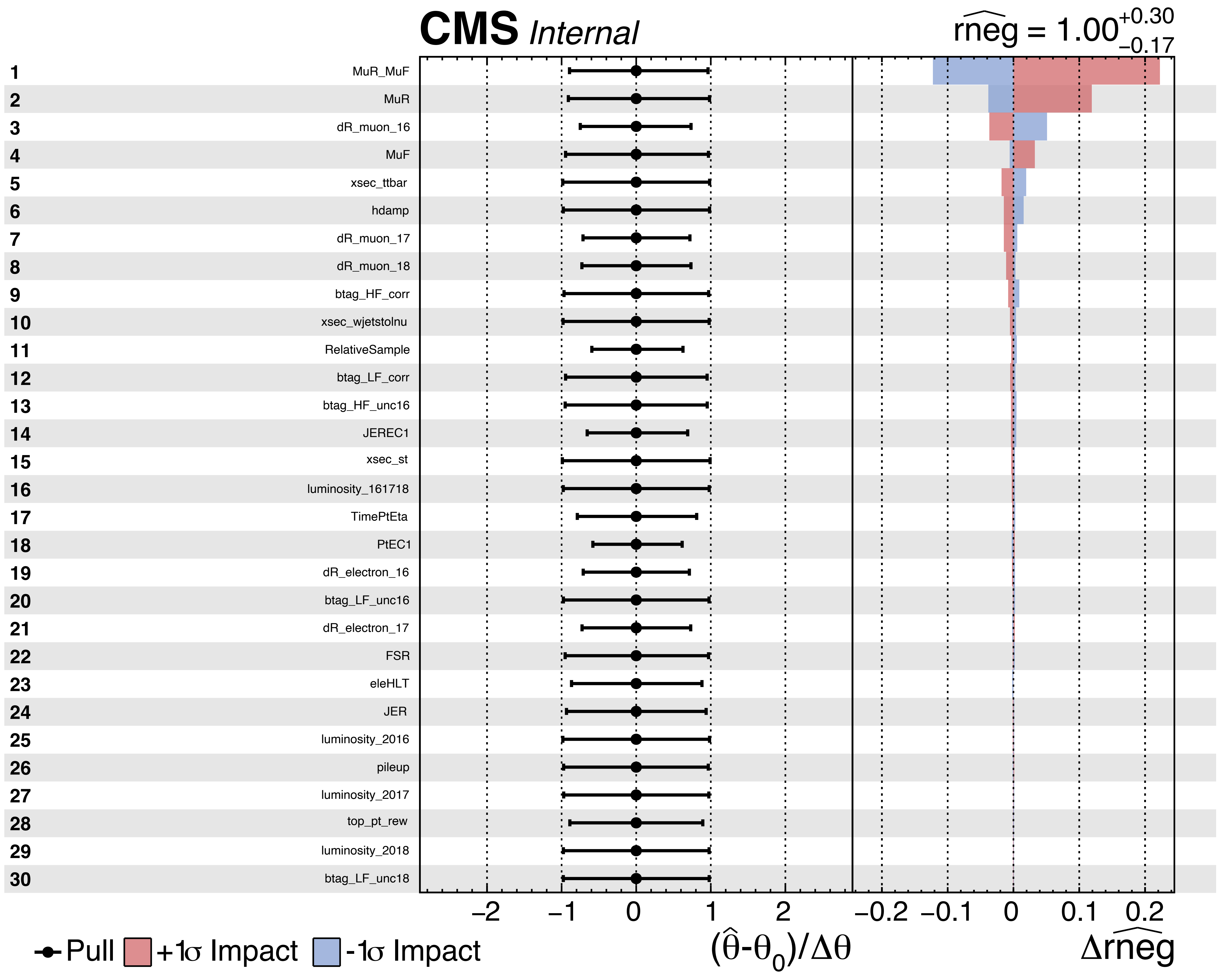
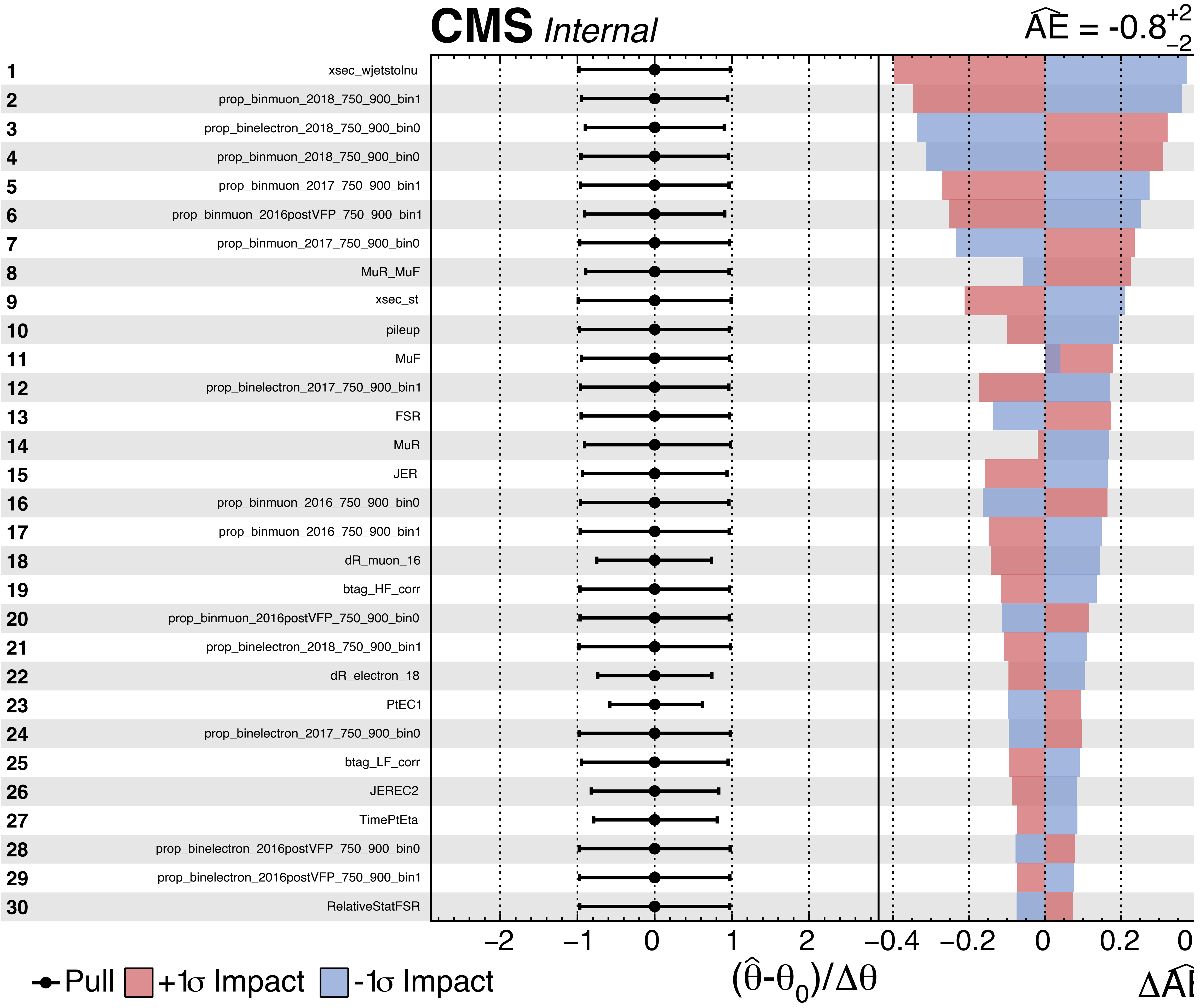
Blinded results (AE)





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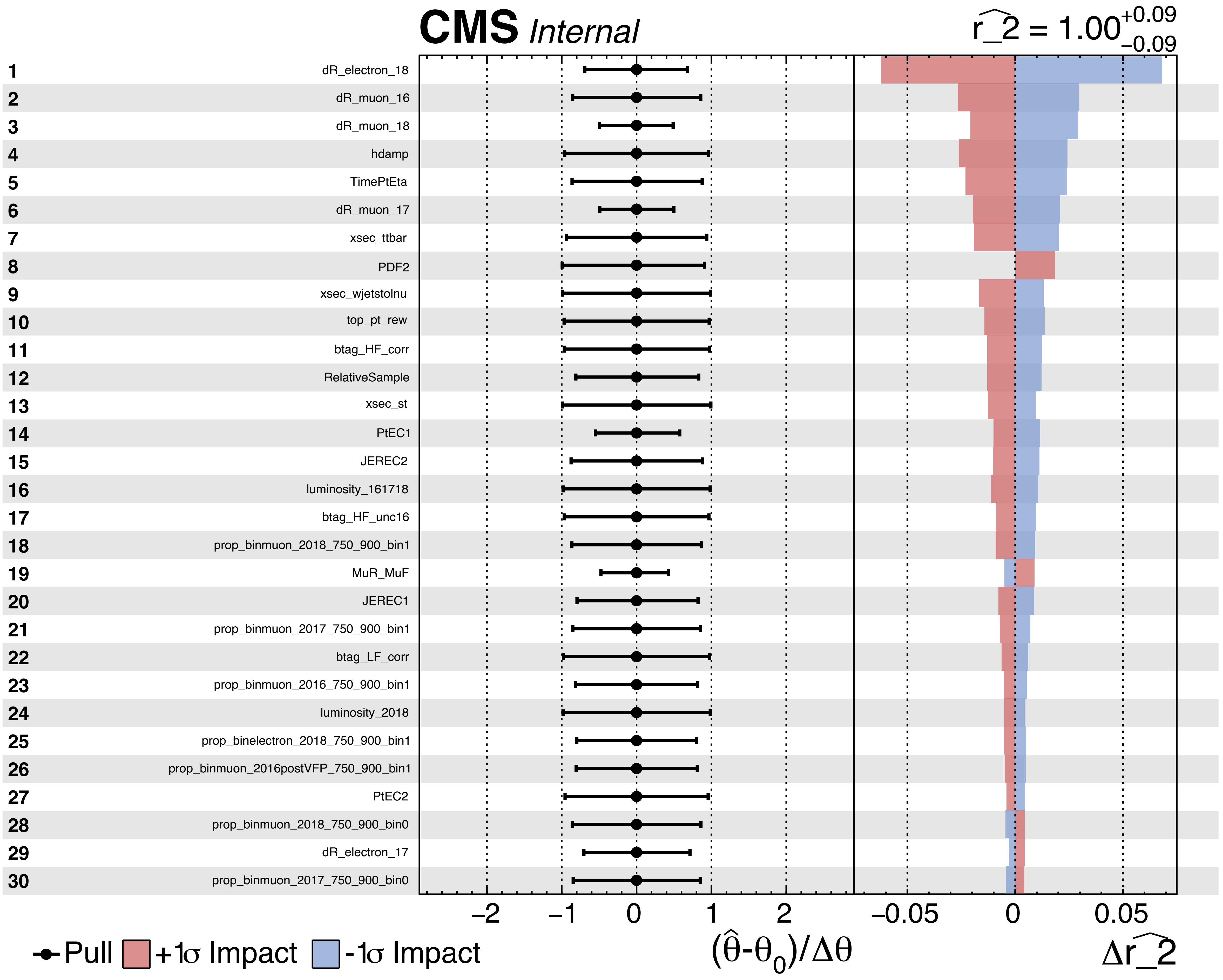
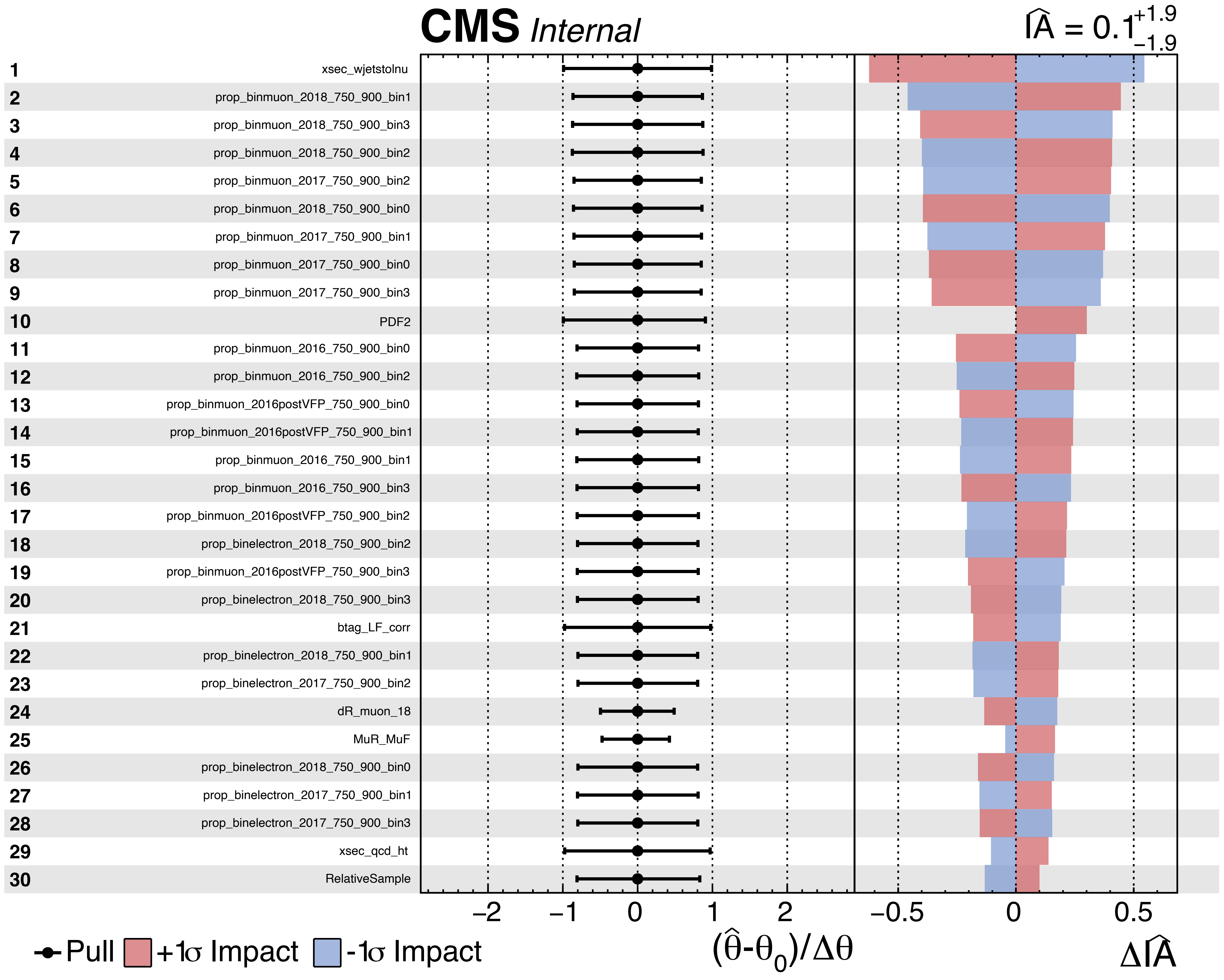
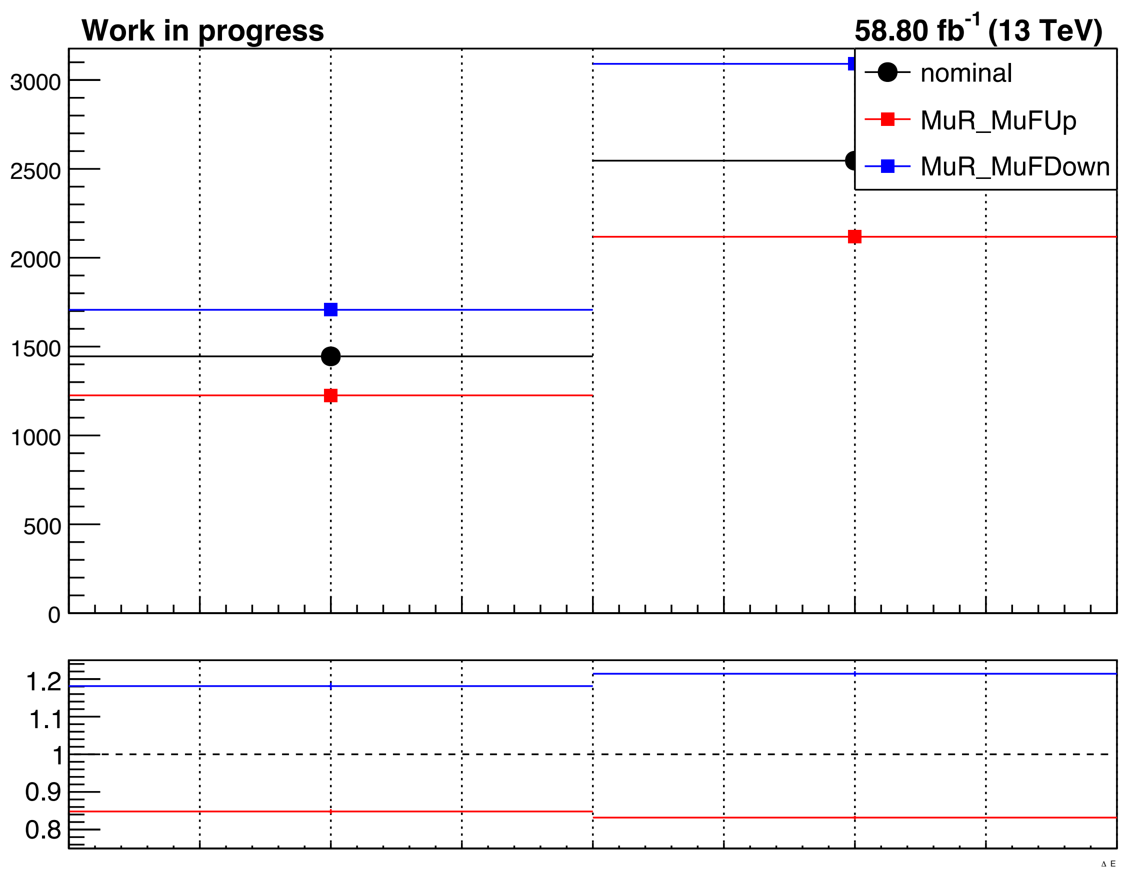
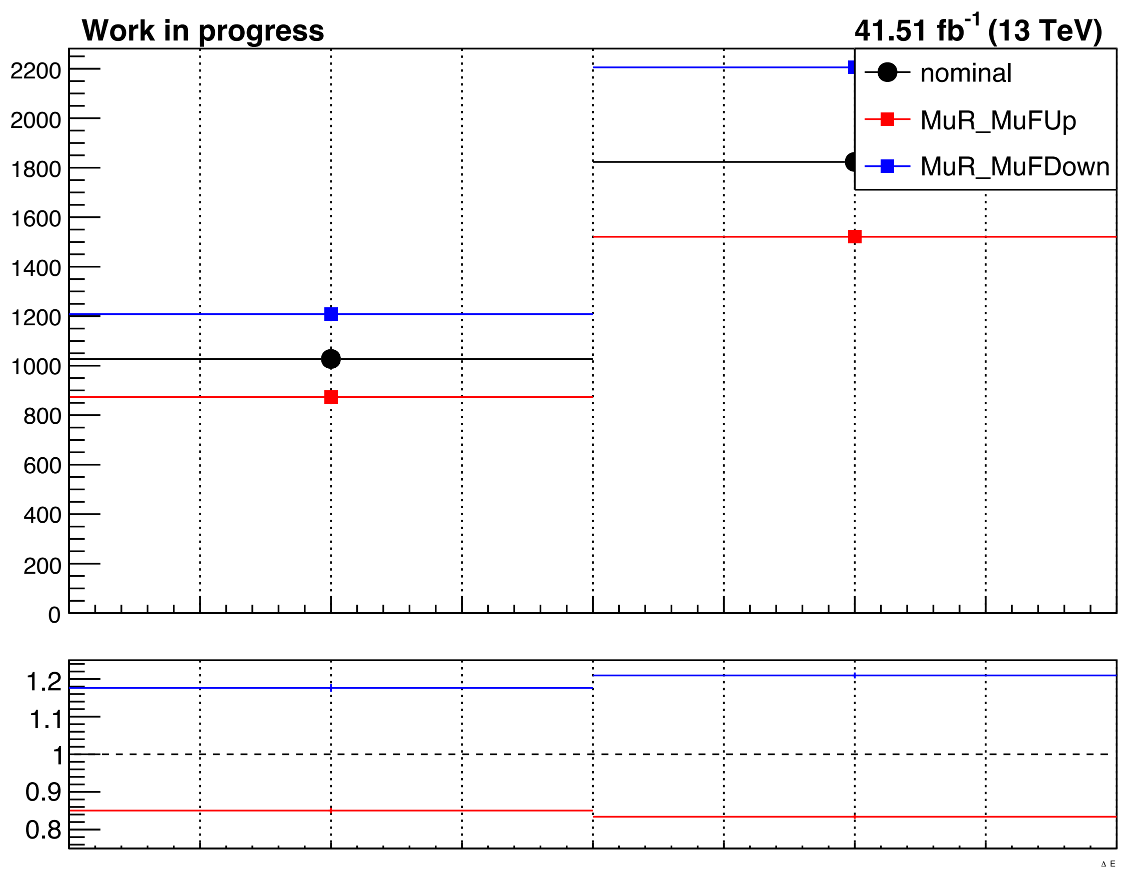
Blinded results (AI)

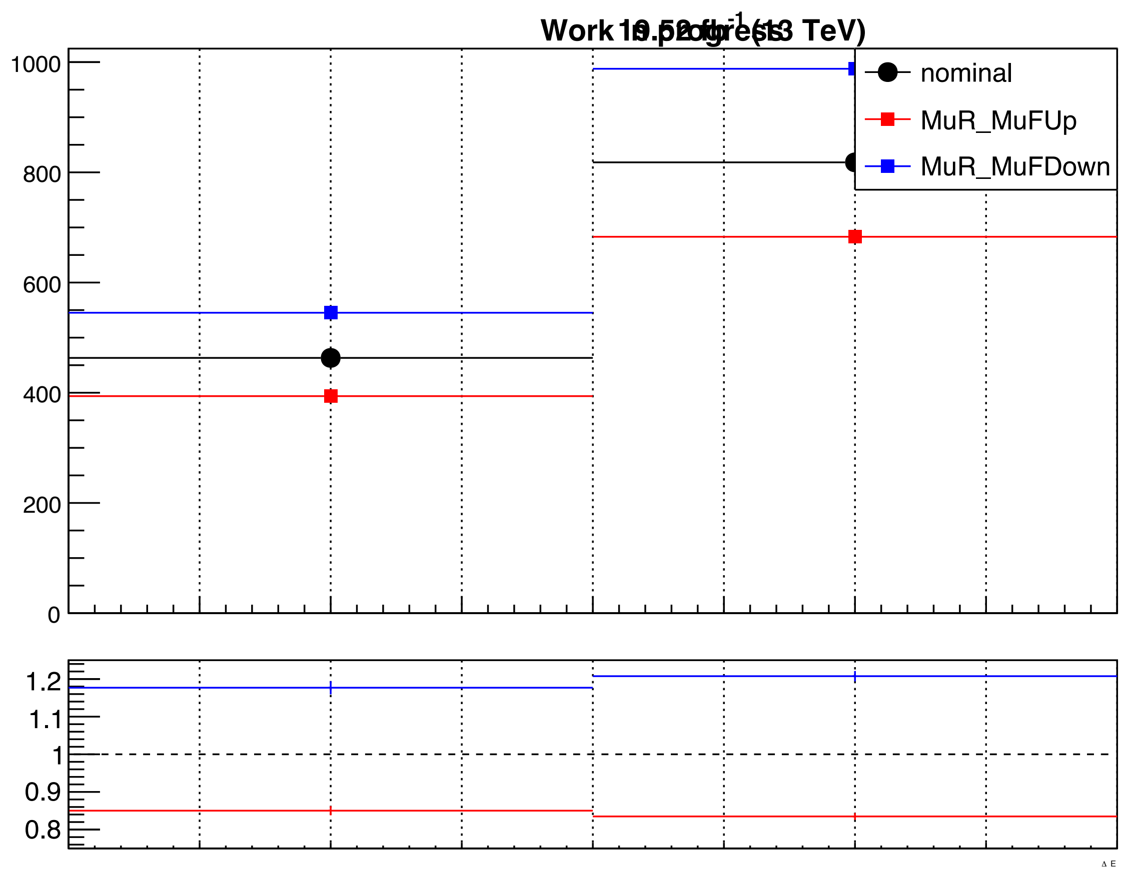


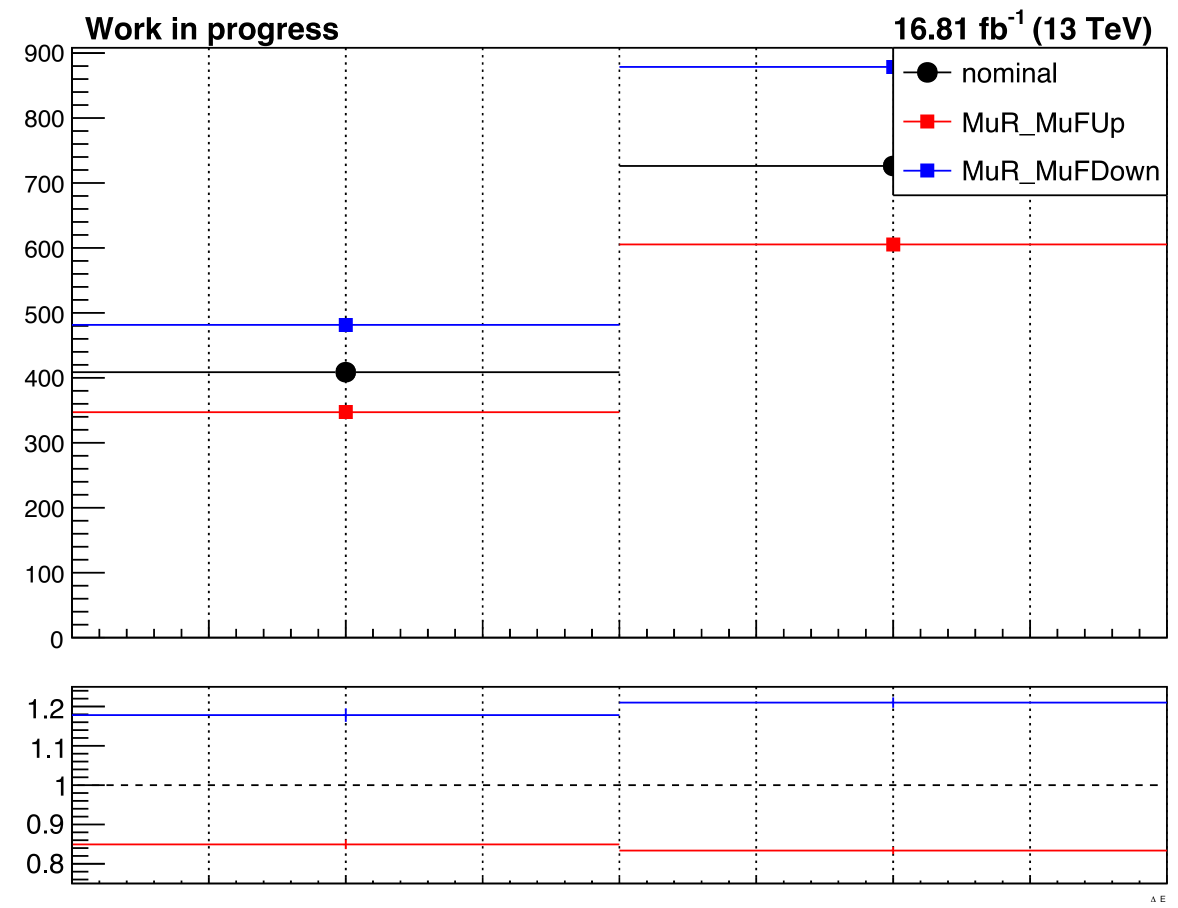


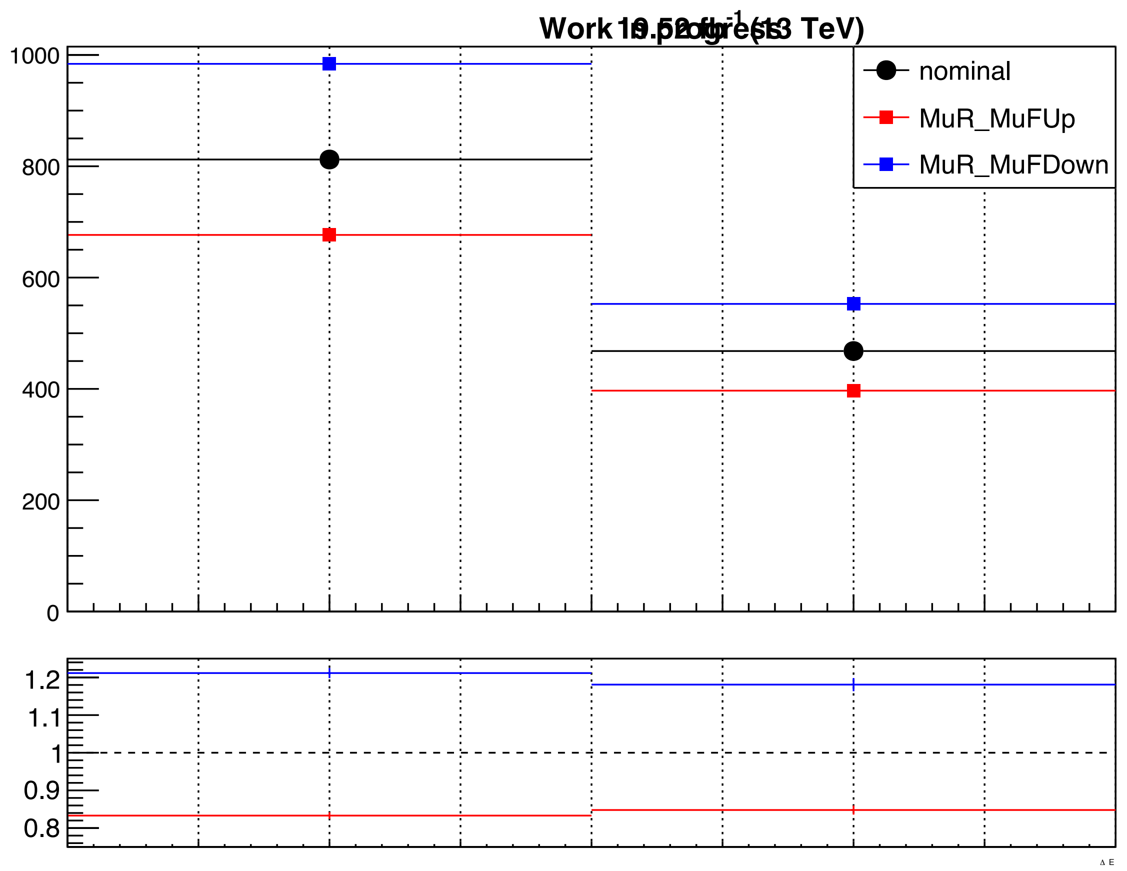
e + jets channel

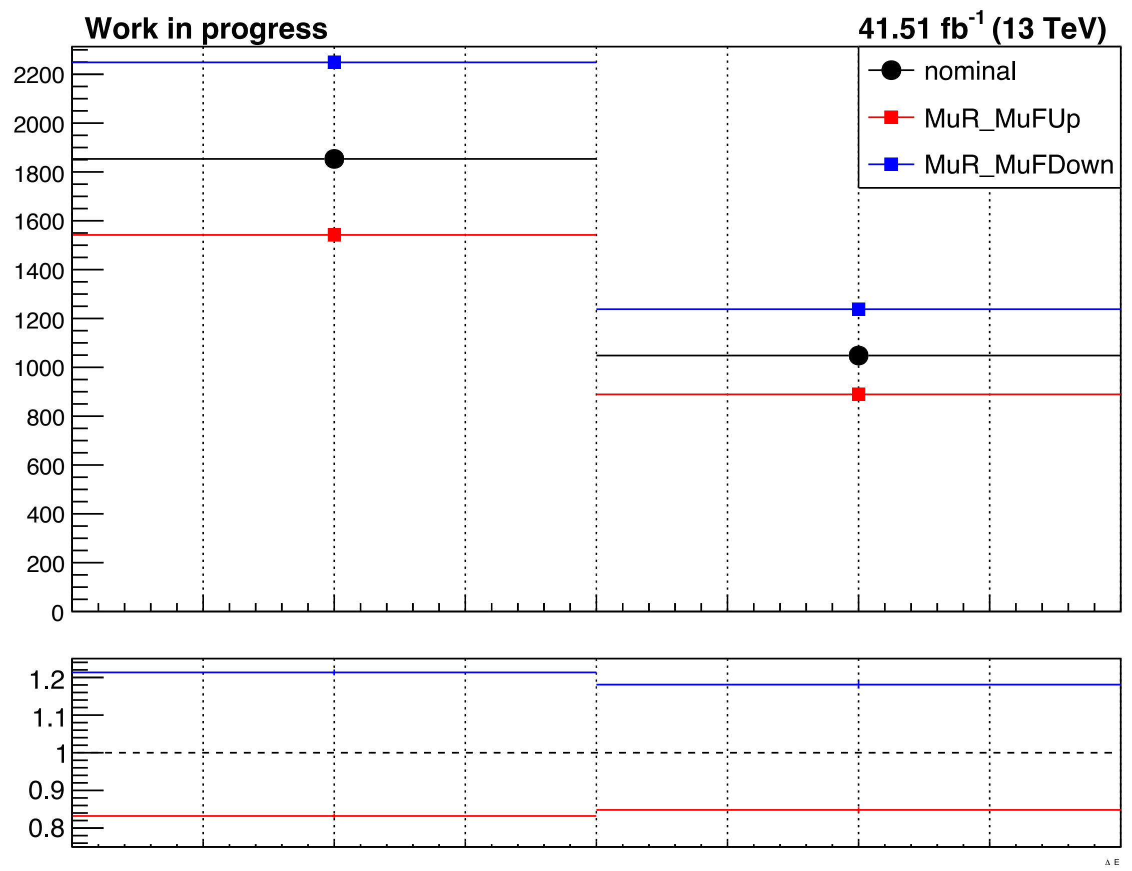


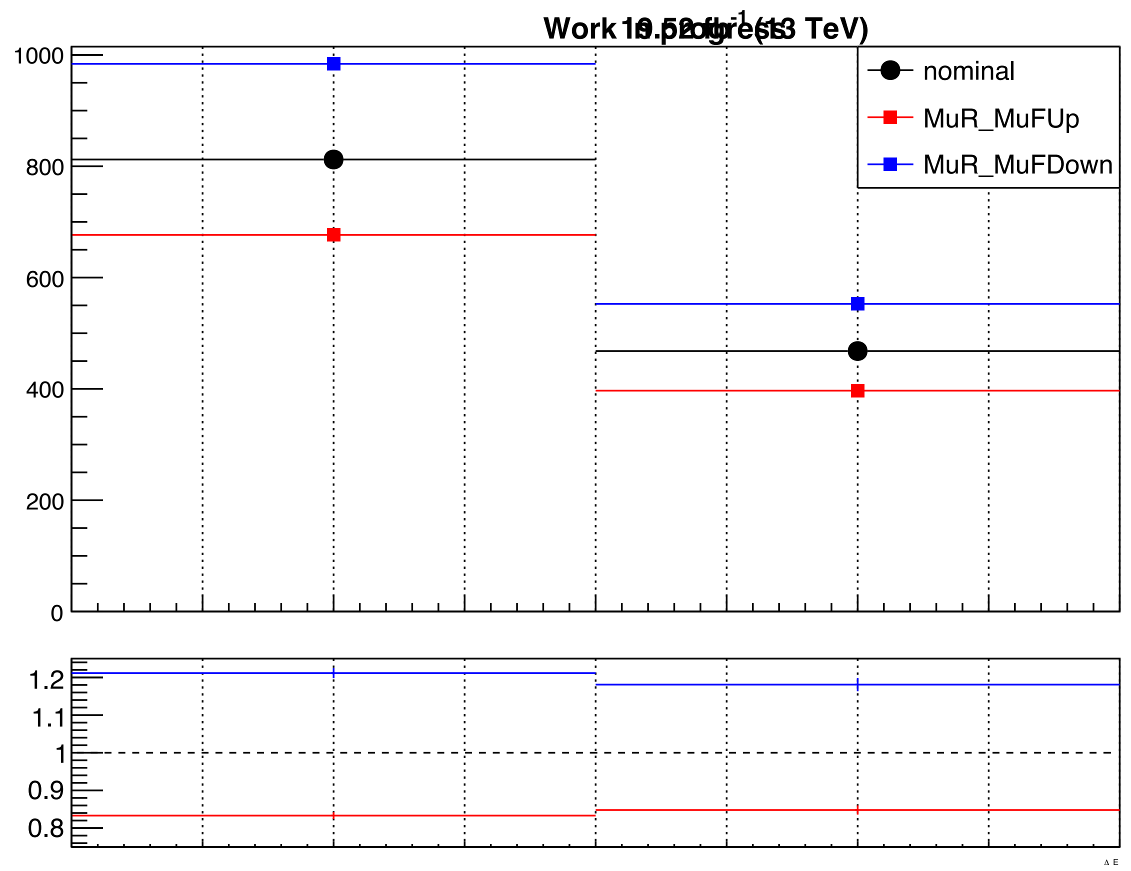


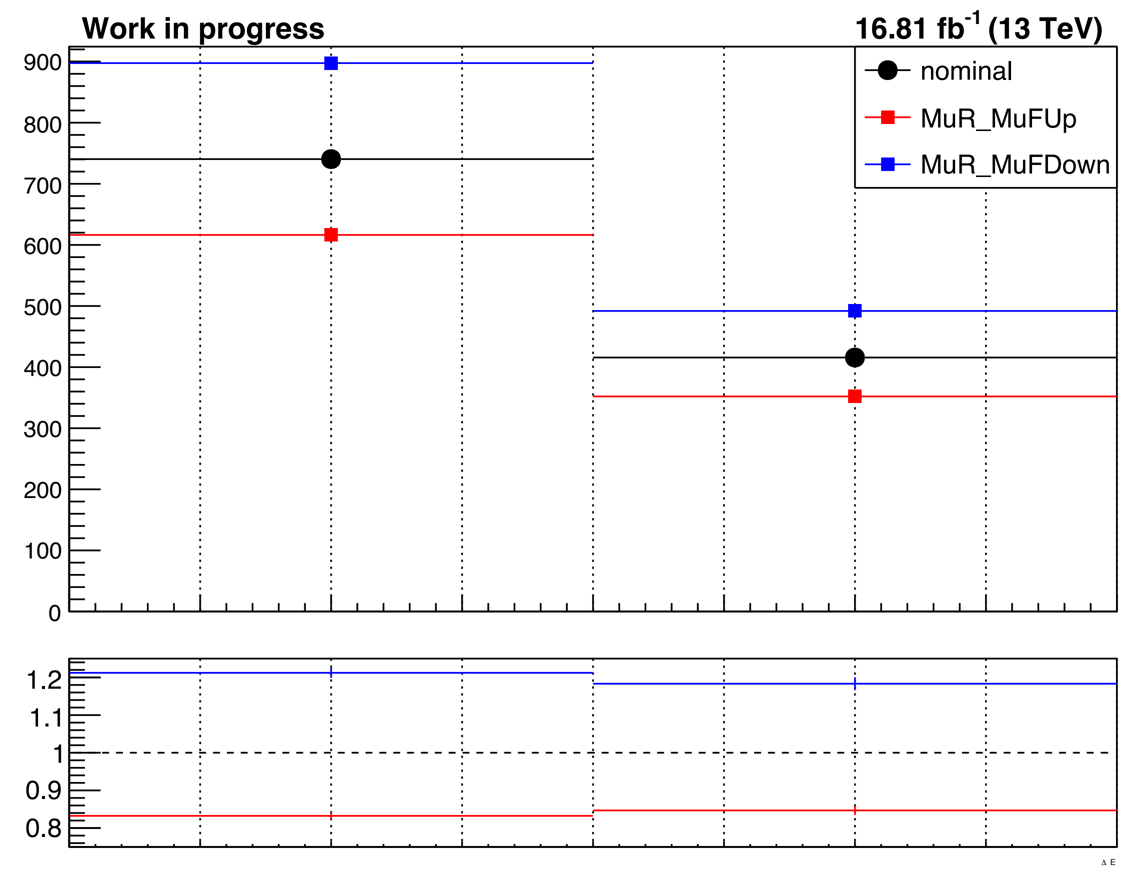












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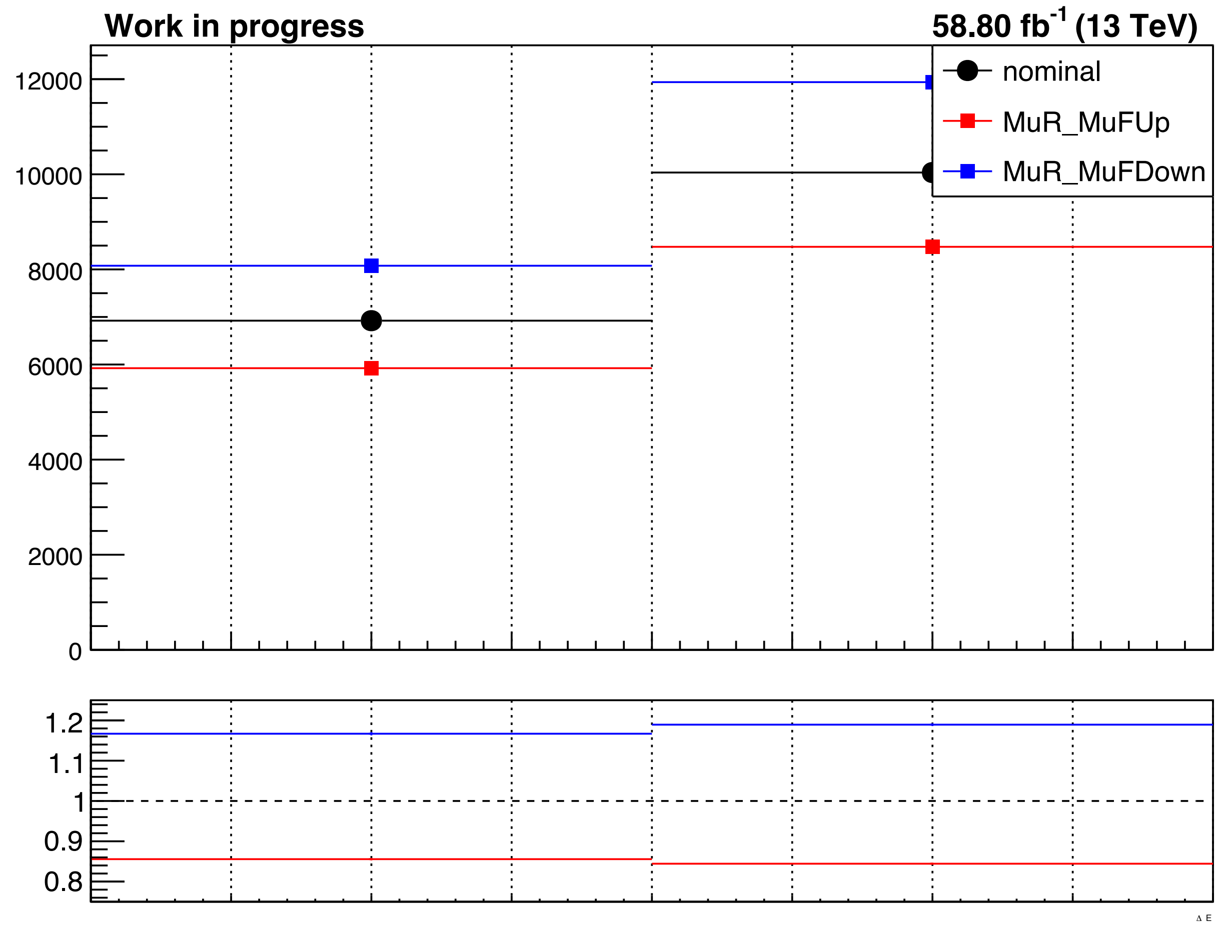
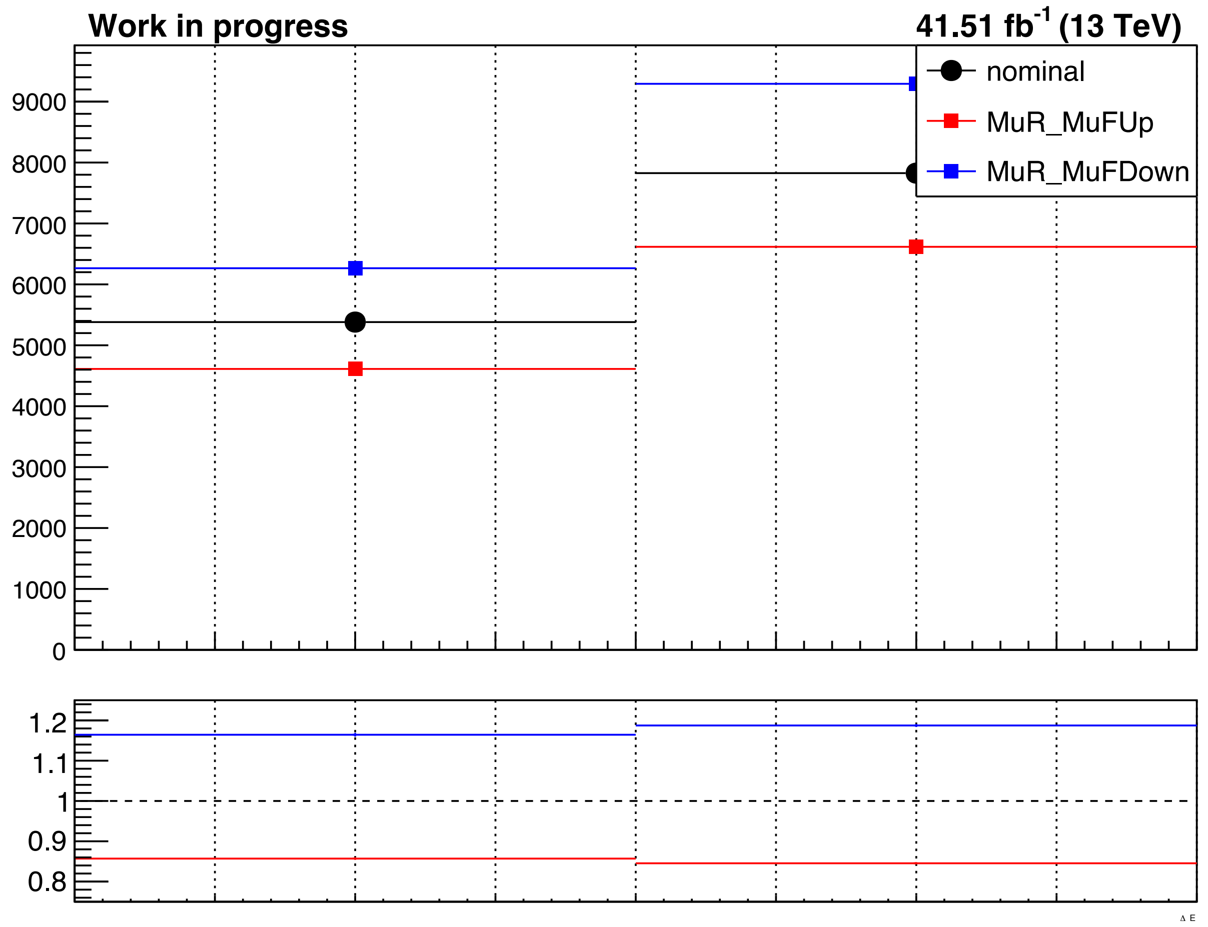
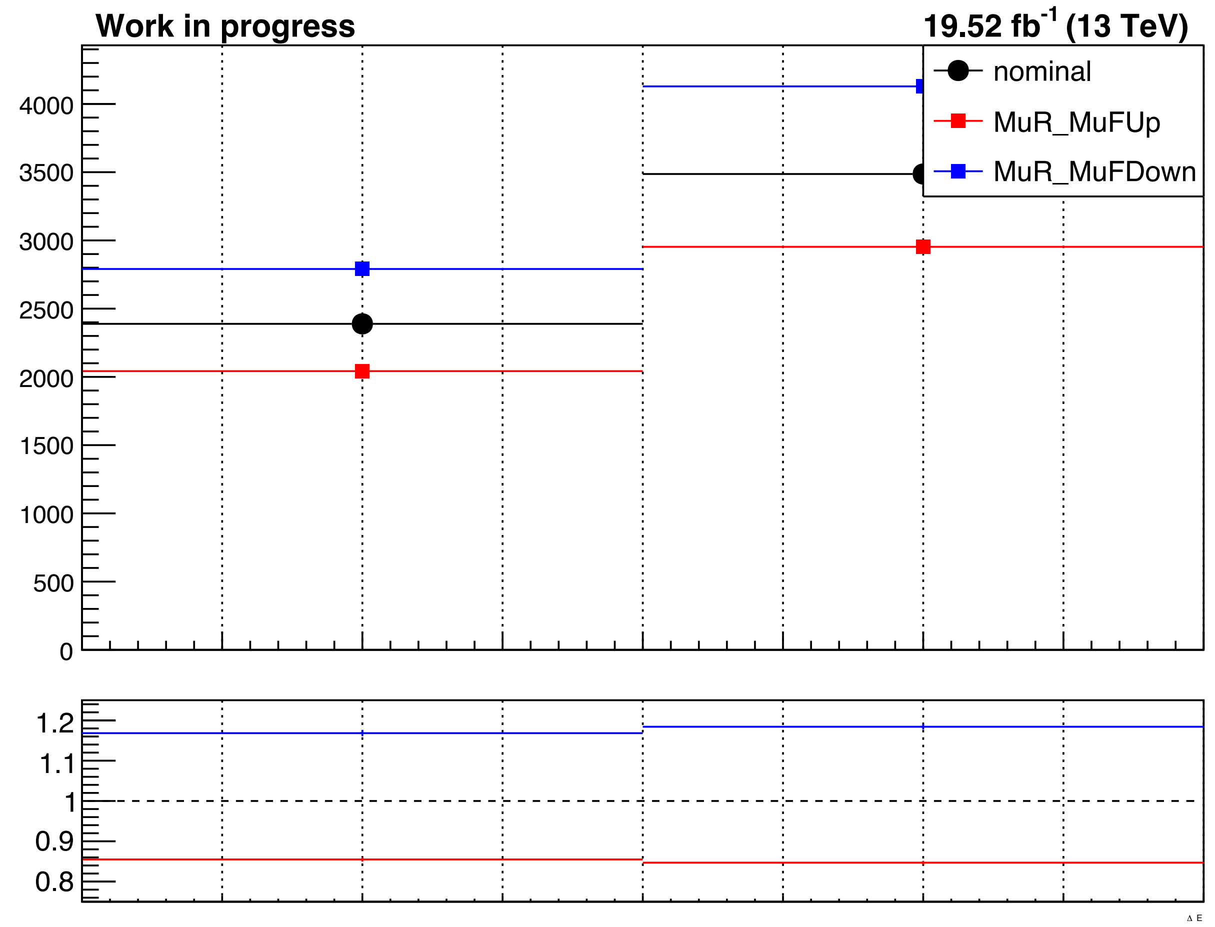
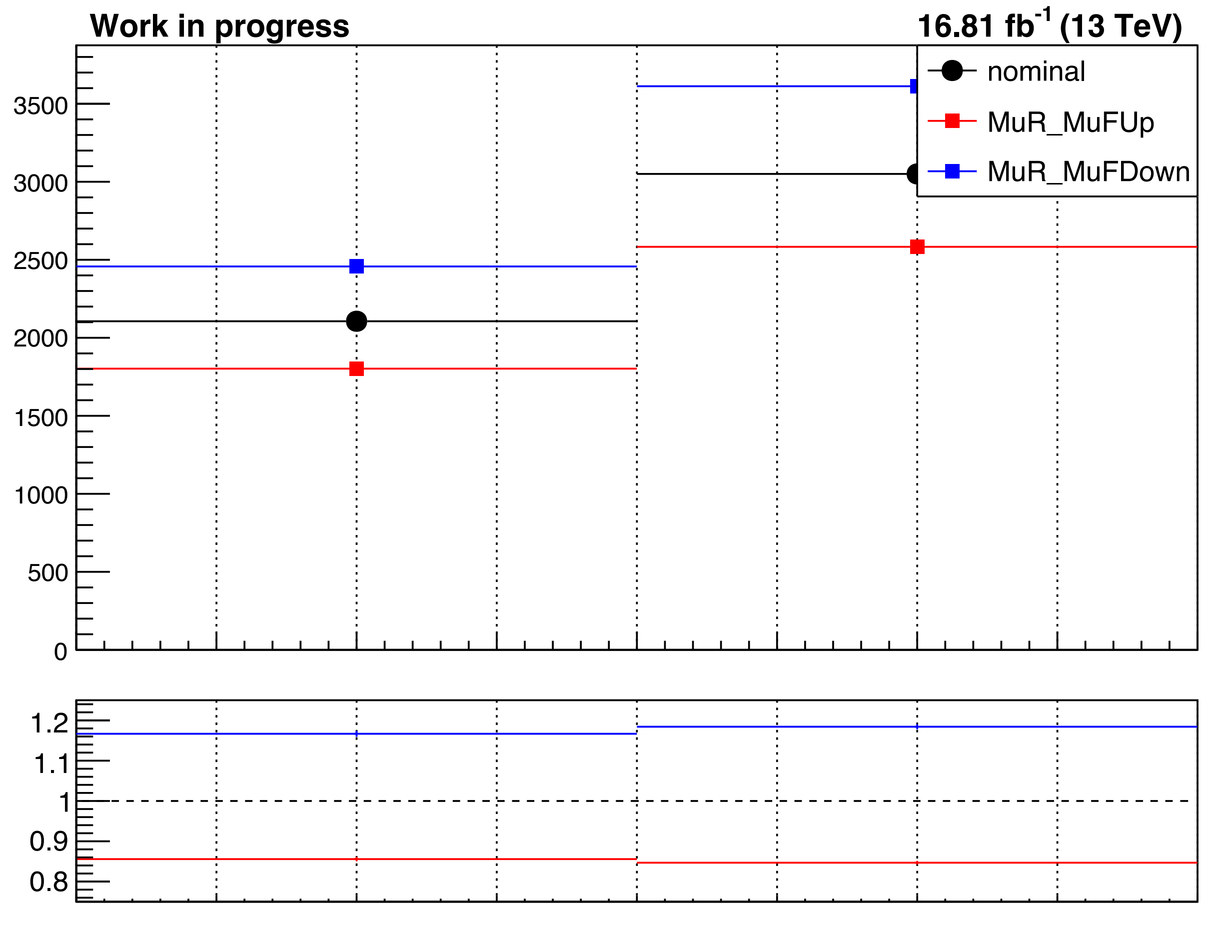
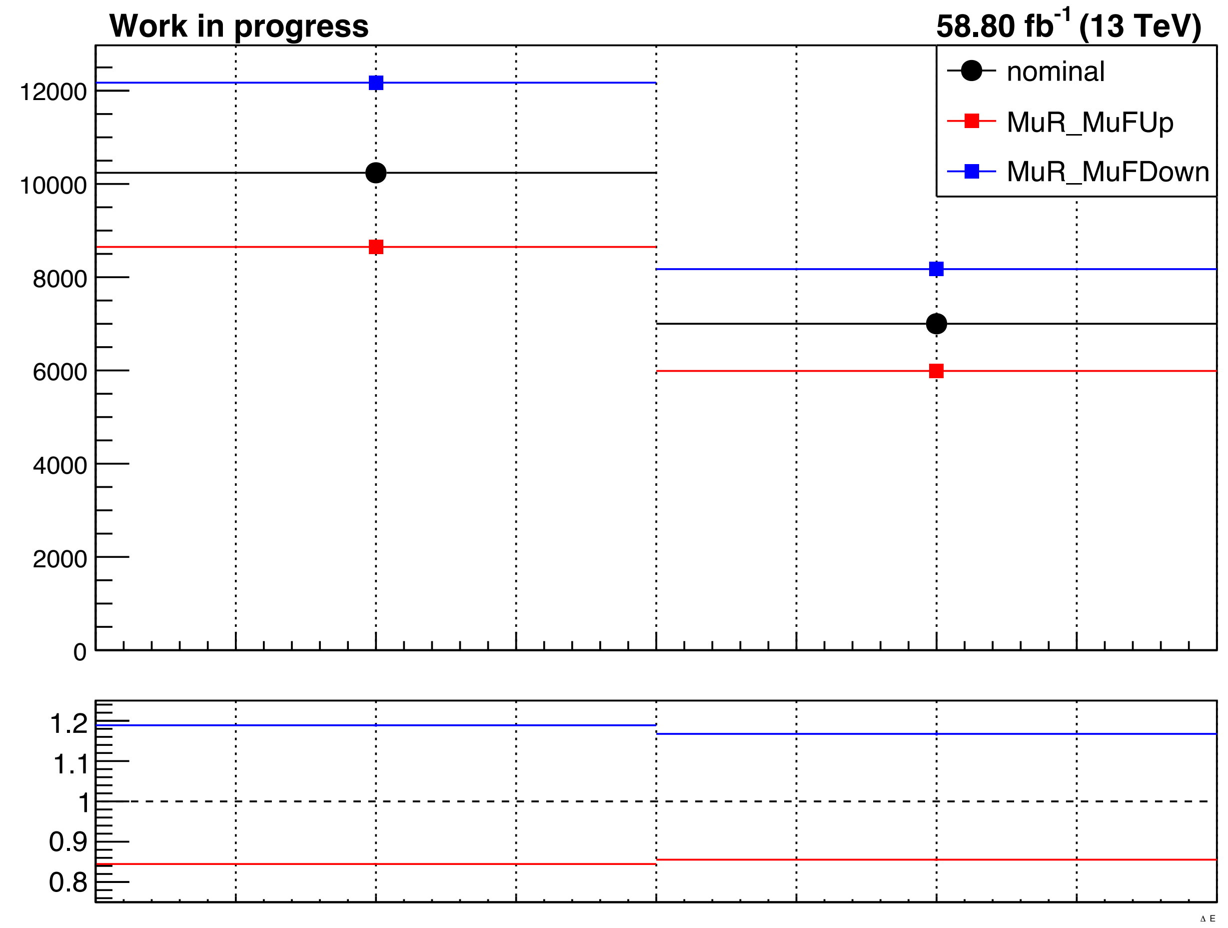
μ + jets channel

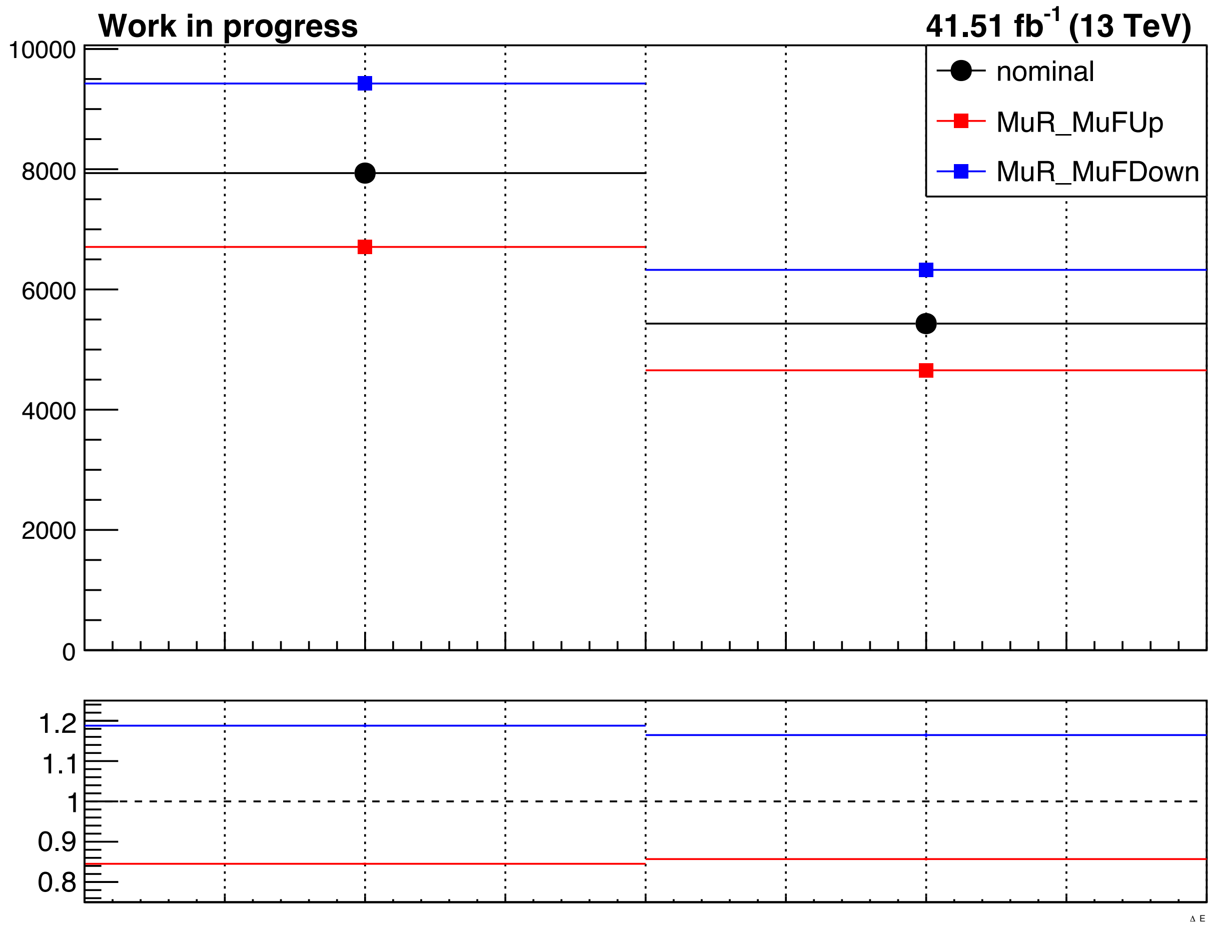


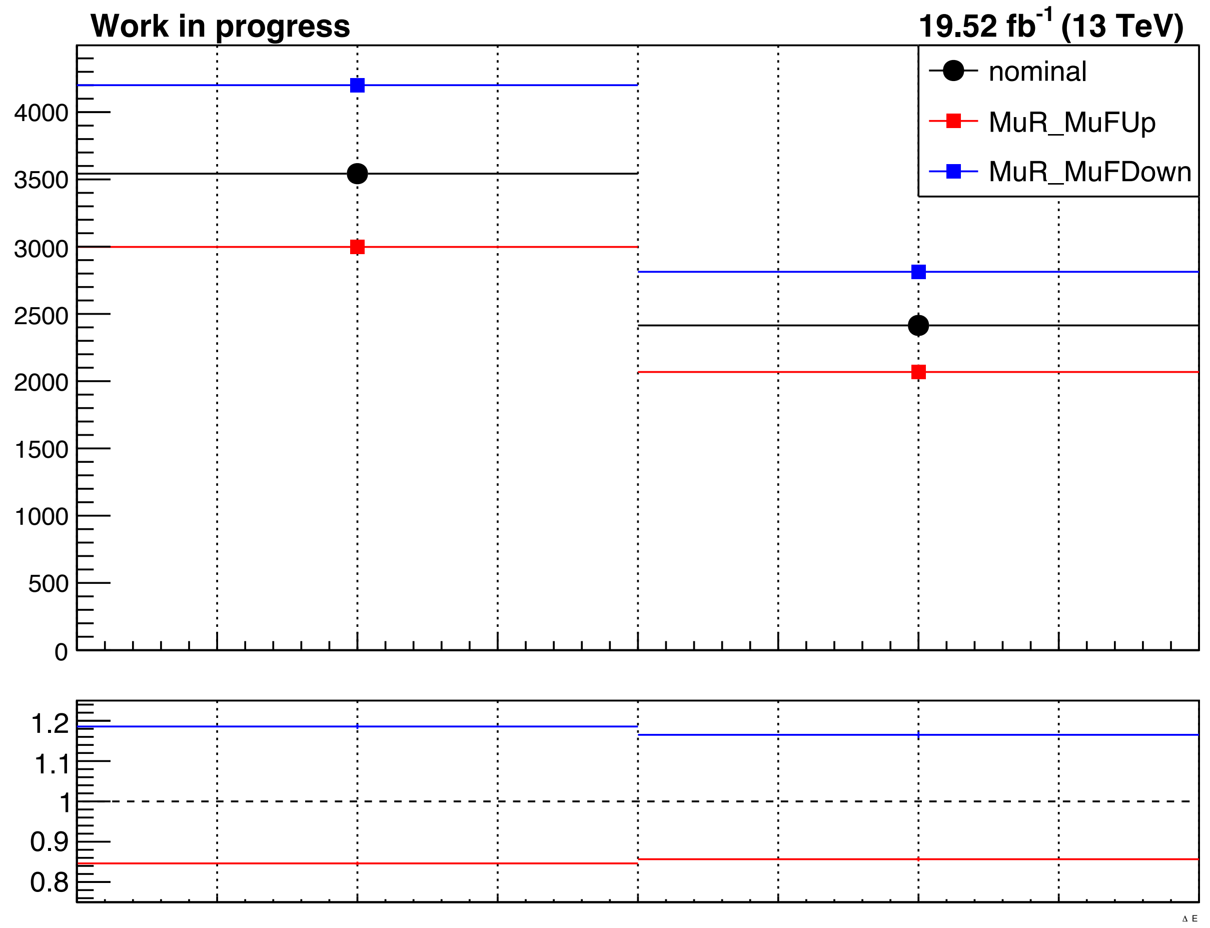


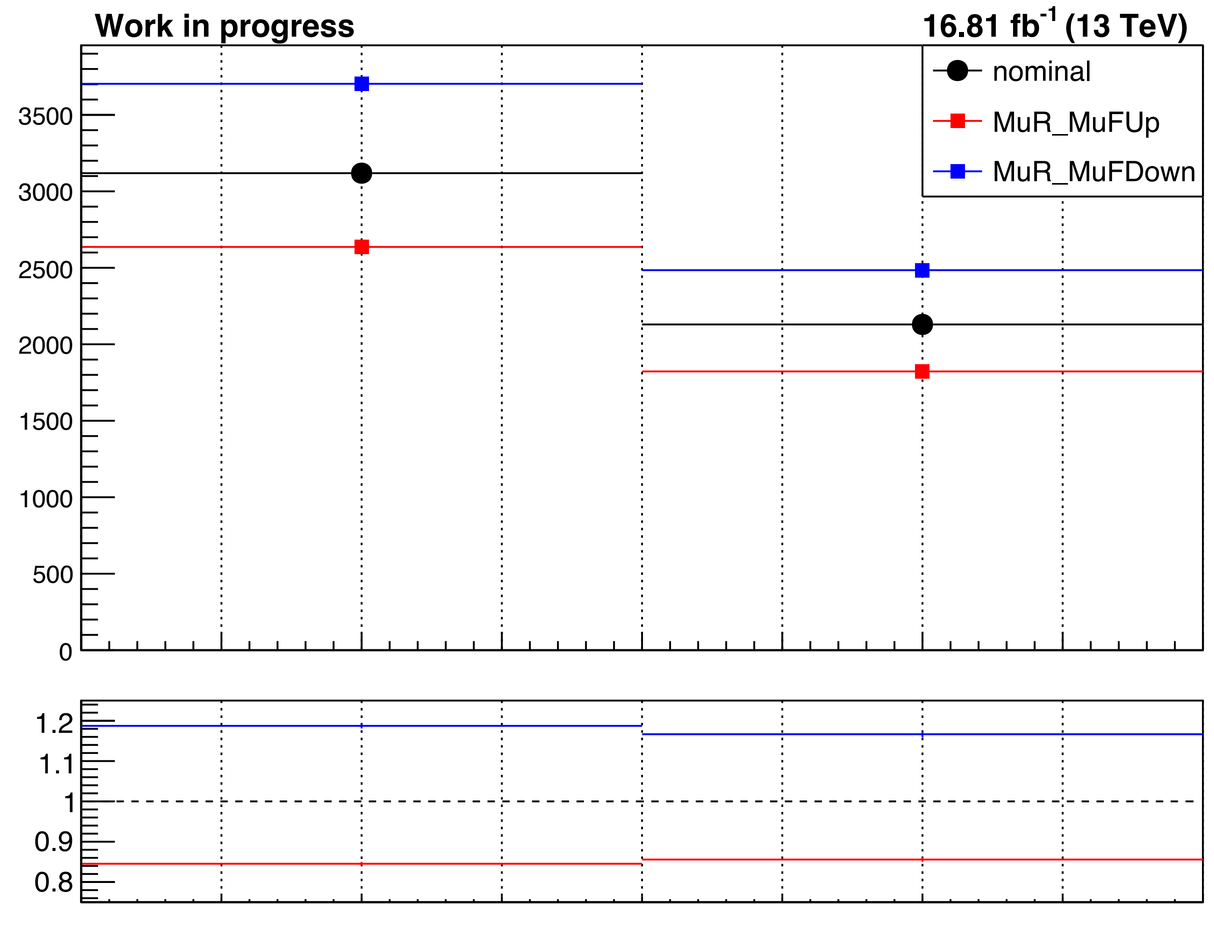












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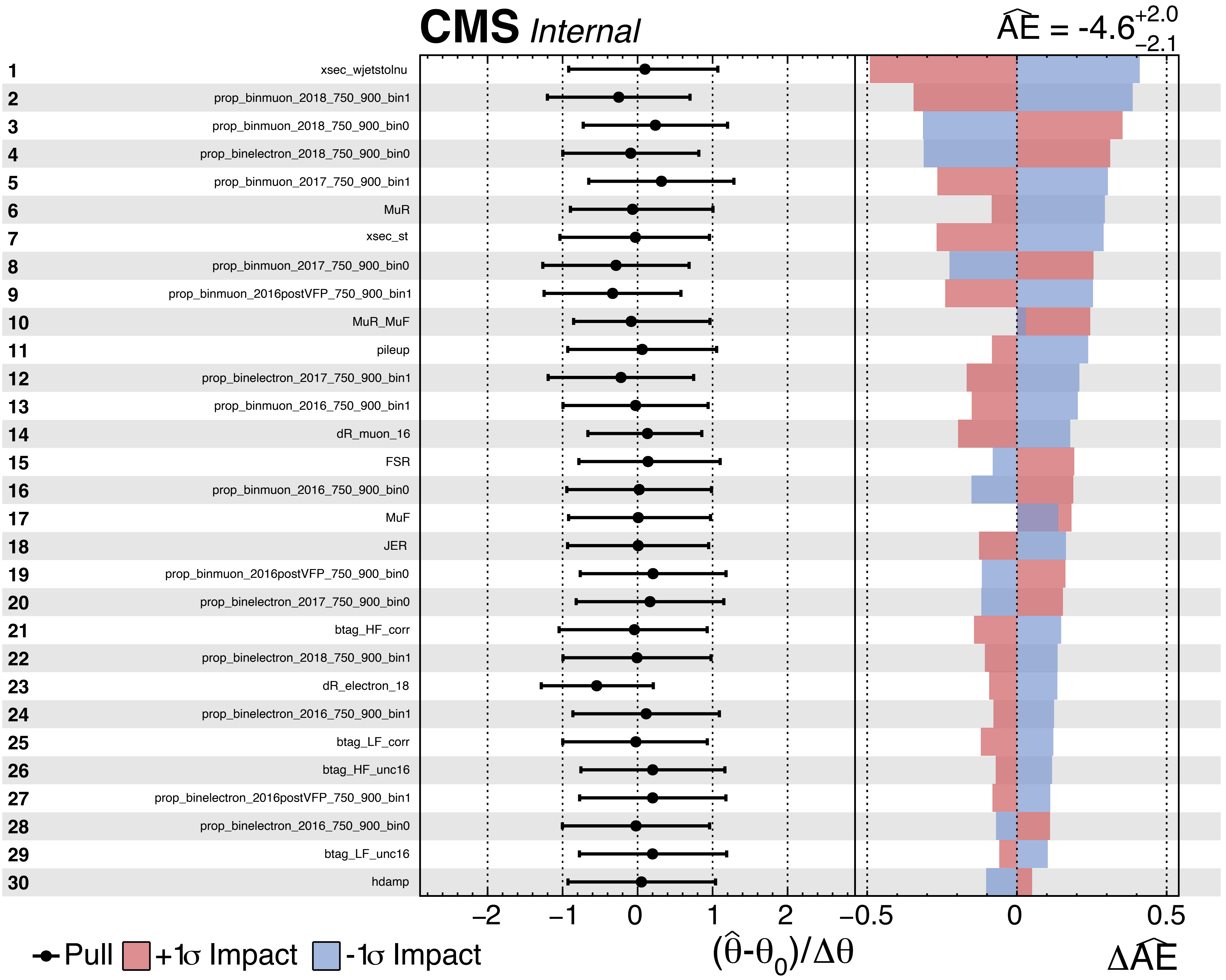
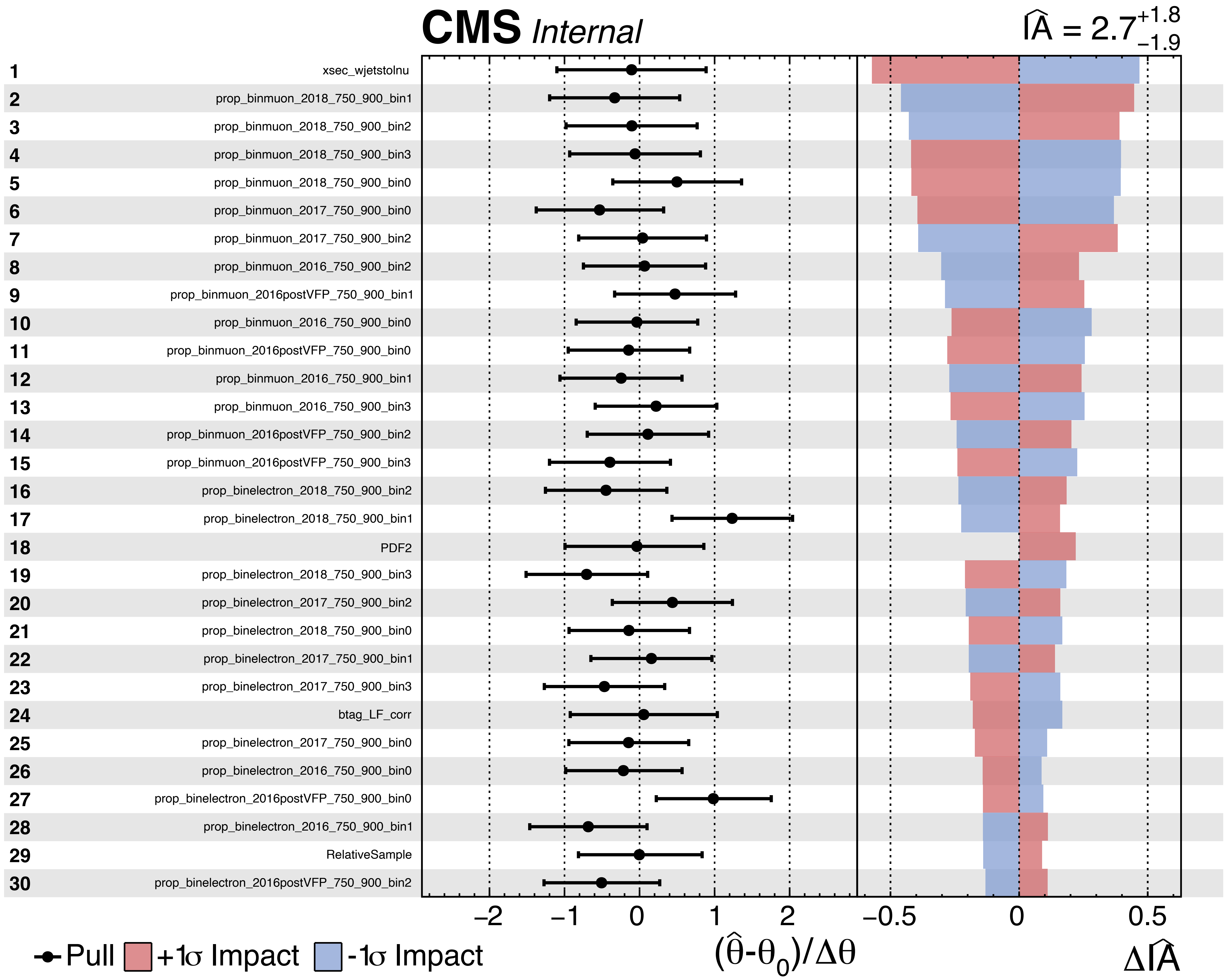
Unblinded results





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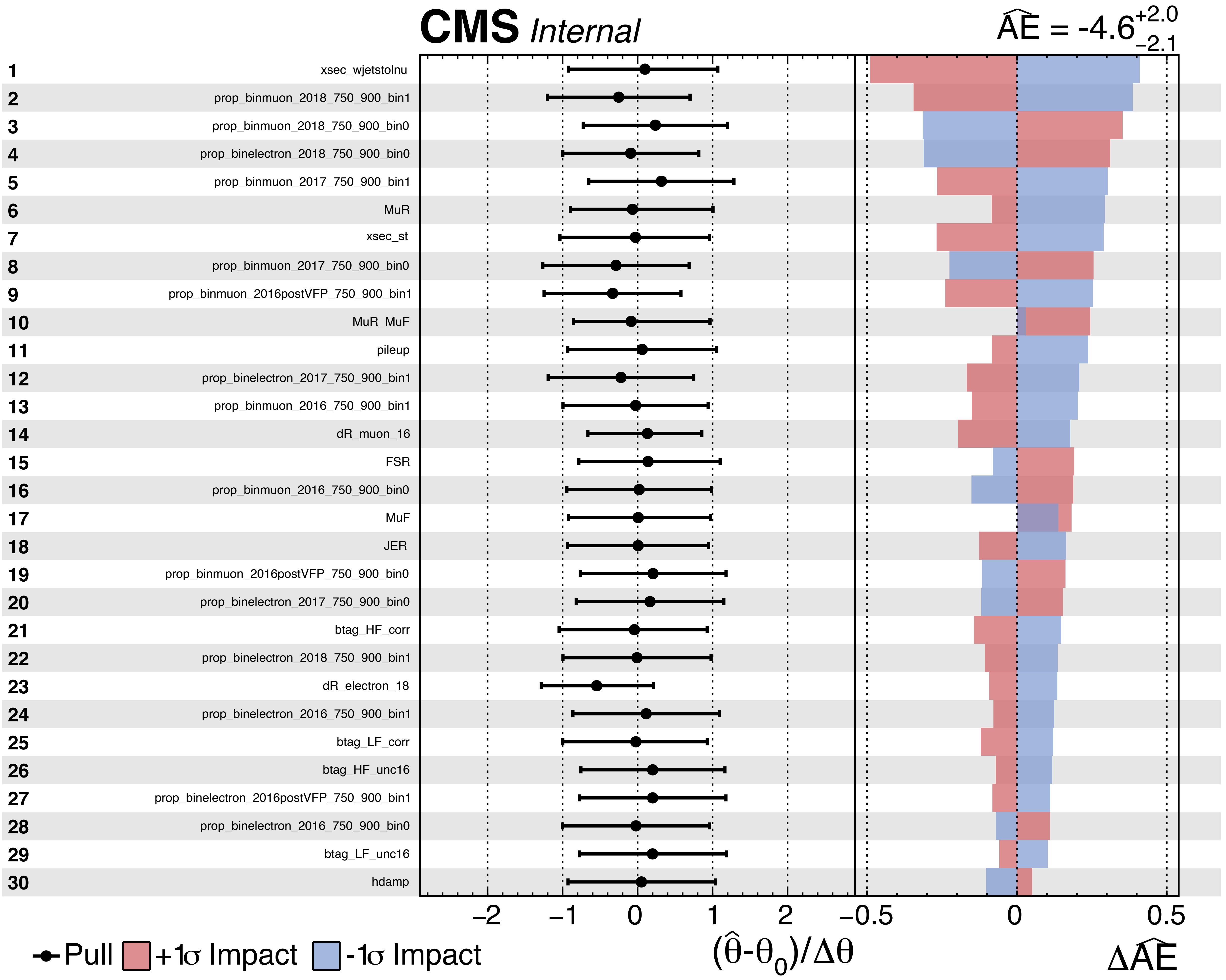
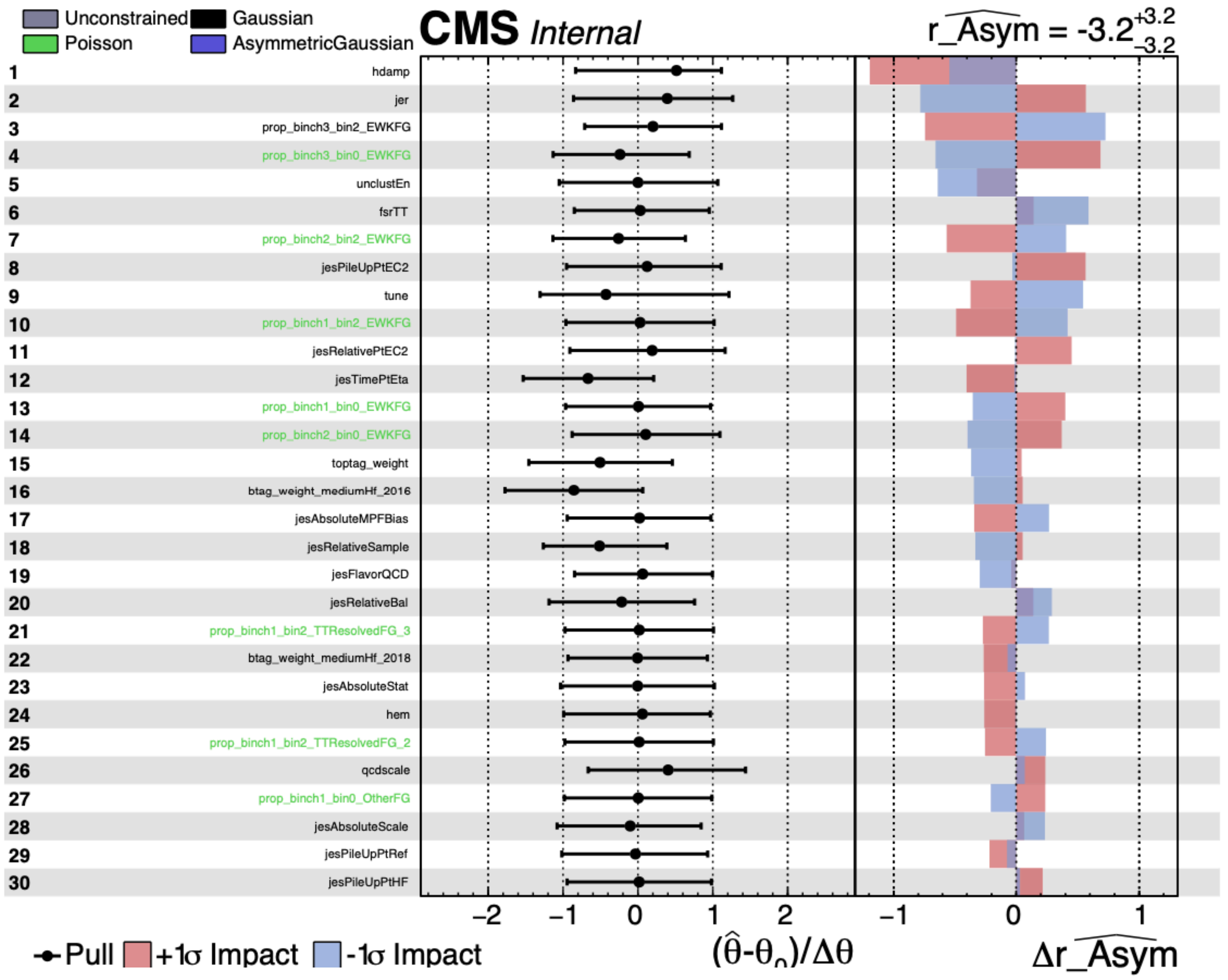
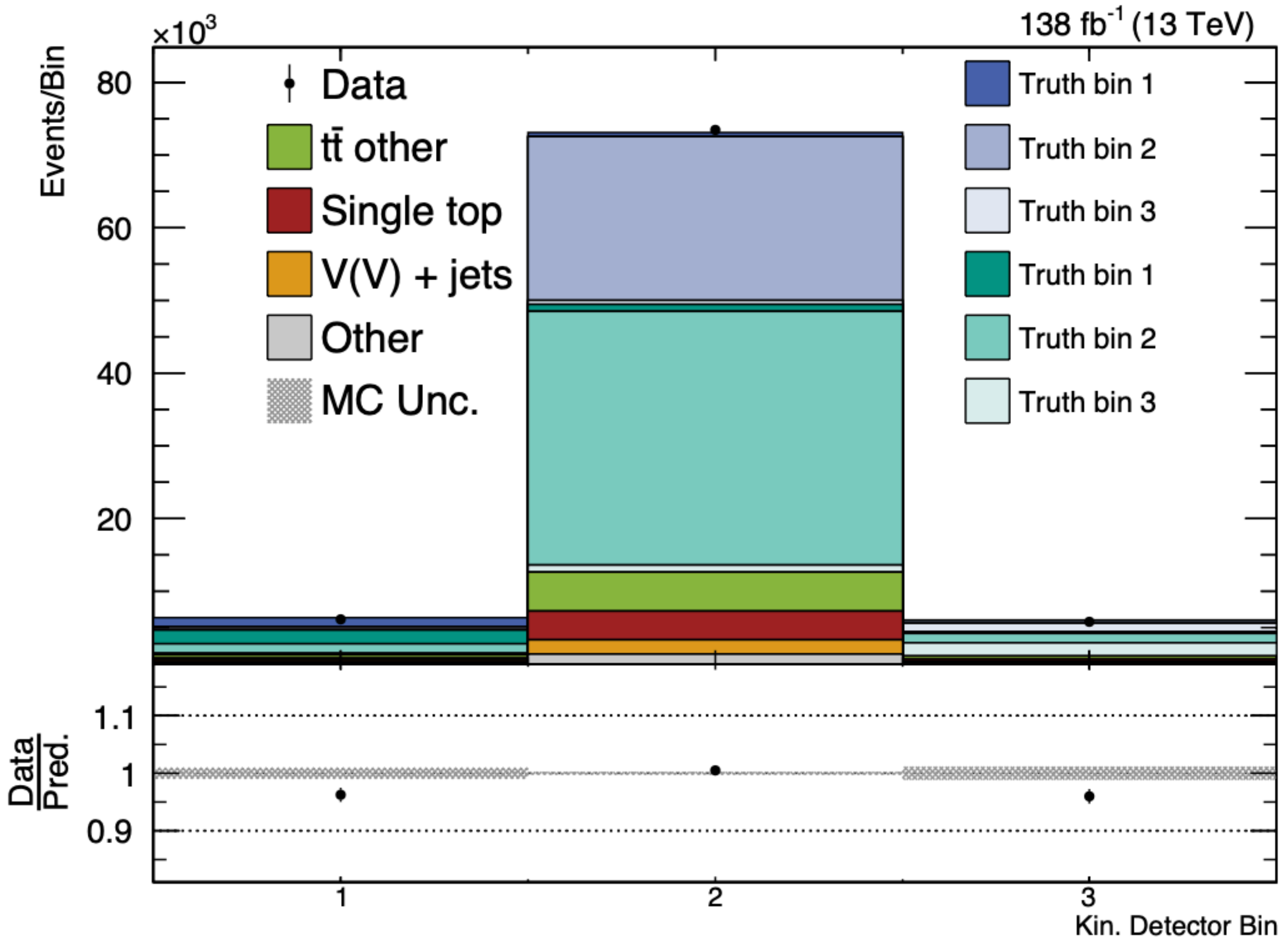
Unblinded results

Measurement of energy asymmetry in ttbar events: TOP-21-006



$$\mathbf{r}_{\text{neg}} = 0.79^{+0.25}_{-0.19},$$
$$\mathbf{r}_{t\bar{t}} = 0.86^{+0.25}_{-0.20},$$
$$\mathbf{r}_{\text{Asym}} = -0.0315^{+0.0321}_{-0.0319}.$$





To do:

- The results section in the analysis note is in progress
- Start the object review.
- Look into EFT interpretations

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Backup

Control Region

Same selection as SR but:

- $\chi^2 > 30$
- $N_{jets} < 4$

CR region included on the fit ($M_{t\bar{t}}$) to try to constrain the W+jets normalization factor

Maybe train a BDT?