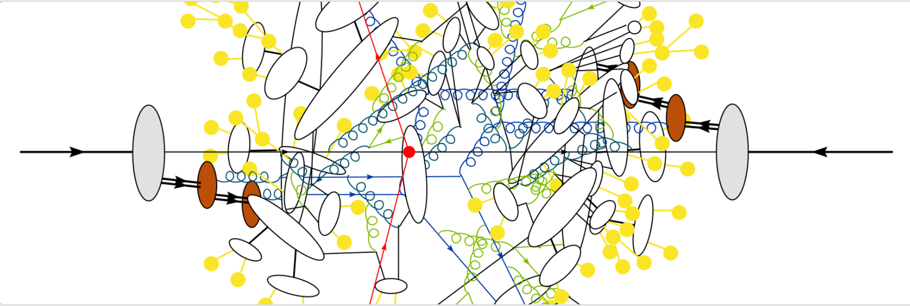
Triple-Differential Z+Jet Production at 13 TeV

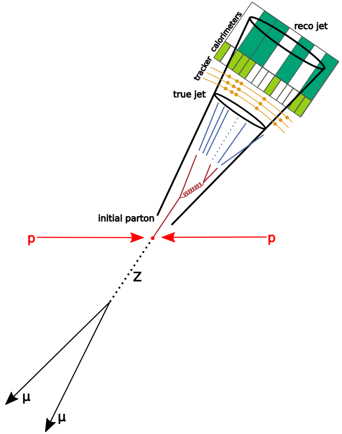
10th KSETA Plenary Workshop 2023

Robin Hofsaess, **Maximilian Horzela**, Günter Quast, Klaus Rabbertz, Cedric Verstege | 29. March 2023



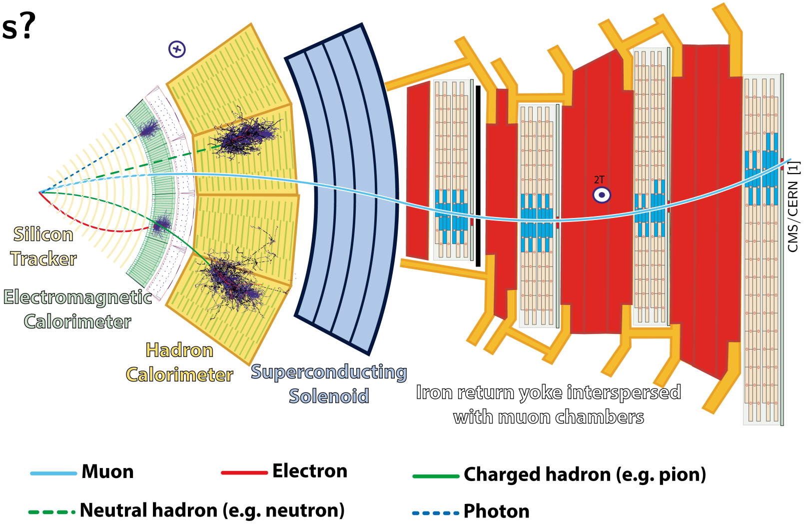
S. Gieseke

Why Z+Jets?

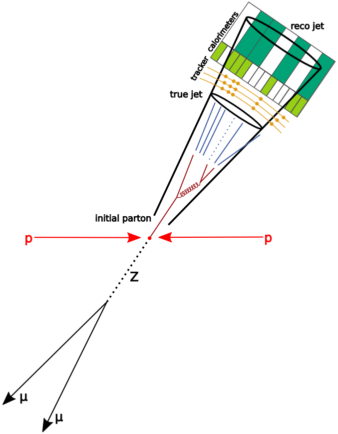


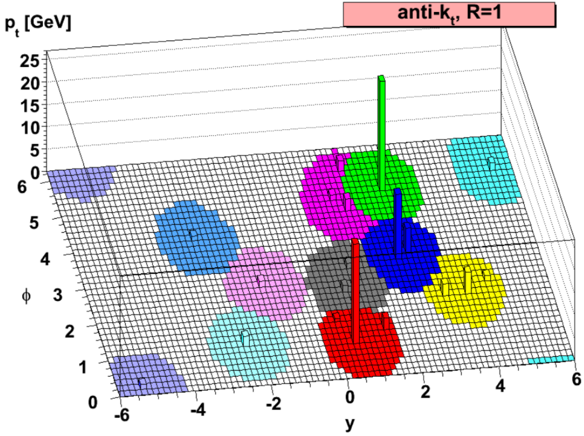
- Goal
  - Constraints on gluon (and other) parton distribution functions (PDFs)
  - Input for α_s fits
- $Z \to \mu^+\mu^-$
  - Good number of signal events
  - Low number of background events
  - Precise muon reconstruction and identification with CMS

Why Muons?


2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with muon chambers
CMS/CERN [1]
Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

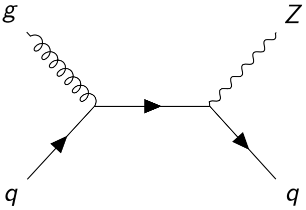
What is a Jet?



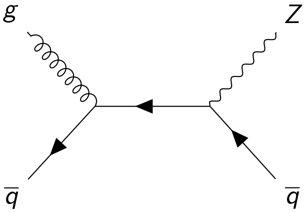


JHEP04(2008)063 [3]

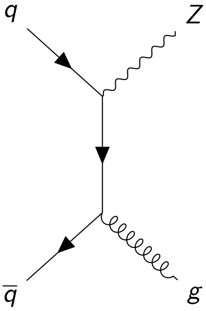
Why plus Jet?



(a) quark-gluon

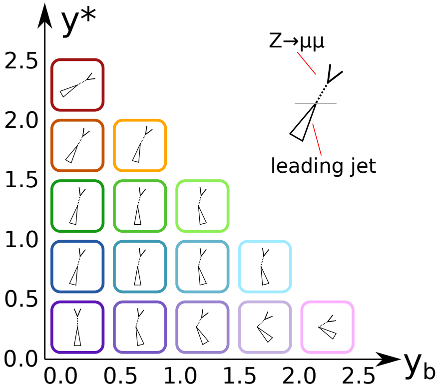


(b) antiquark-gluon



(c) quark-antiquark

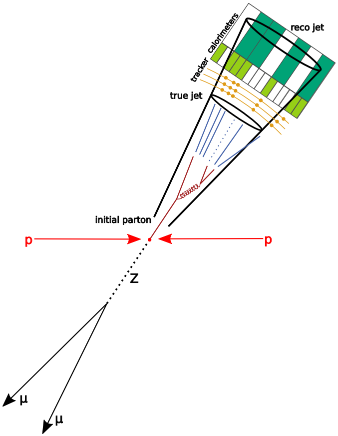
Why Triple-Differential?



M. Schnepf 2022 [5]

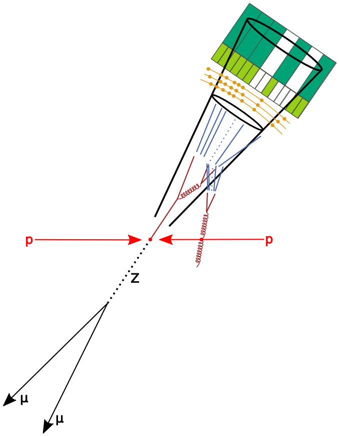
- Transverse momentum of di-muon system
  - p_{T}^{Z}
  - Scale of the hard interaction
- Boost of center-of-mass system
  - $y_b = \frac{1}{2}|y^Z + y^{\mathrm{Jet1}}|$
  - Parton momentum fractions of the protons
- Rapidity separation
  - $y^* = \frac{1}{2}|y^Z - y^{\mathrm{Jet1}}|$
  - Scattering angle in center-of-mass system

Event Selections and Corrections (Muons)



- Events passing single muon trigger
  - p_T^μ above trigger threshold
  - Corrected for trigger efficiency
- Muon selection
  - Within muon system coverage $|\eta| < 2.4$
  - Tight identification and isolation criteria
  - Cluster final state radiation (dressed muons)
- Z-boson reconstruction
  - $\mu^+\mu^-$ pair compatible with Z-boson mass

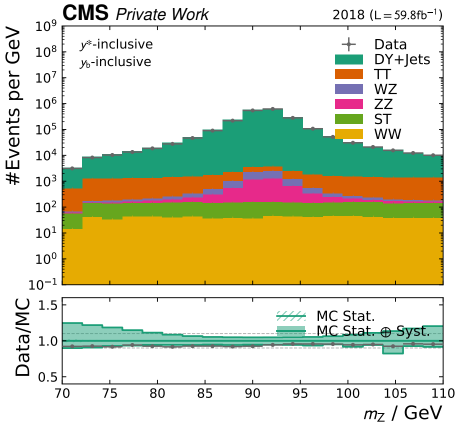
Event Selections and Corrections (Jets)



- Jet selection
  - Within similar detector coverage $|y| < 2.4$
  - Tight identification incl. lepton veto
  - Muon-jet overlap removal
  - Tight pile-up jet identification
  - p_T cut to reduce pile-up contributions

Datasets and MC

- Proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ recorded from 2016 to 2018
- Total integrated luminosity $138\,\text{fb}^{-1}$
- Signal MC:
  - $Z(\rightarrow \ell^+\ell^-) + 0, 1, 2$ jets MadGraph+Pythia8 aMC@NLO FXFX
- Background MC:
  - $t\bar{t} \rightarrow 2b2\ell2\nu$ Powheg+Pythia8 NLO
  - Single top quark t-channel and tW Powheg+MadSpin+Pythia8 NLO
  - Di-Boson WW, WZ, ZZ Pythia8 LO



Unfolding Basics

- Unfolding for detector effects of observation s to true spectrum t
  - Detector Resolution $\rightarrow$Migration between generator and reconstruction bins
  - Detector Efficiency $\rightarrow$Less events on reconstruction level than generator level

We have: $s(\vec{y}) = \int_X D(\vec{y}, \vec{x}) t(\vec{x}) \mathrm{d}\vec{x}$

We want: $t(\vec{x}) = \int_Y D'^{-1}(\vec{x}, \vec{y}) s(\vec{y}) \mathrm{d}\vec{y}$

Unfolding Basics

Karlsruhe Institute of Technology

- Unfolding for detector effects of observation s to true spectrum t
  - Detector Resolution $\rightarrow$Migration between generator and reconstruction bins
  - Detector Efficiency $\rightarrow$Less events on reconstruction level than generator level
- Variations below finite resolution $\leftrightarrow$ Ill-posed problem
- Usually s and t discretized in histograms $\rightarrow$ "invert" Response Matrix $\mathbf{R}$ (i.e. `TUnfold` [4])
  - Estimate Response Matrix from MC $\rightarrow$ Systematic and statistical uncertainties
  - If matrix ill-conditioned $\rightarrow$ Regularize "unphysical" oscillations

We have: $s(\vec{y}) = \int_X D(\vec{y}, \vec{x}) t(\vec{x}) \mathrm{d}\vec{x}$

We want: $t(\vec{x}) = \int_Y D'^{-1}(\vec{x}, \vec{y}) s(\vec{y}) \mathrm{d}\vec{y}$

$$s^i = \mathbf{R}^i_j t_j \rightarrow t_j = \mathbf{R^{-1}}^i_j s^i$$

$$\text{with} \quad \mathbf{R}^i_j = \frac{\int_{Y_i} \int_{X^j} D(\vec{y}, \vec{x}) t(\vec{x}) \mathrm{d}\vec{x} \mathrm{d}\vec{y}}{\int_{X^j} t(\vec{x}) \mathrm{d}\vec{x}}$$

TUnfold

- Algorithm for estimating truth $\mathbf{t}$ from measured observables $\mathbf{s}$
- Assumes Gaussian distribution of $\mathbf{s}$ with average $\tilde{\mathbf{s}} = \mathbf{R}\tilde{\mathbf{t}} \rightarrow$ least-square method
- Maximize likelihood

$$\mathcal{L} = (\mathbf{s} - \mathbf{Rt})^T \mathbf{V_{ss}} (\mathbf{s} - \mathbf{Rt}) + \mathcal{L}_{\text{reg}} + \mathcal{L}_{\text{norm}}$$

  with covariance matrix $\mathbf{V_{ss}}$

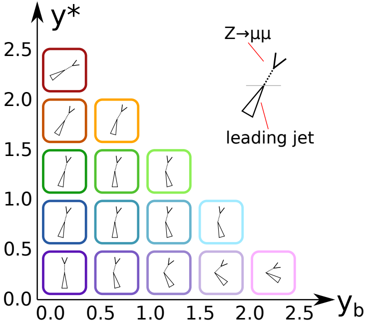
$\rightarrow$ General analytical solution $\mathbf{t_0}(\mathbf{s}, \mathbf{R}, \mathbf{V_{ss}})$ and covariance $\mathbf{V_{tt}}(\frac{\partial \mathbf{t_0}}{\partial \mathbf{s}}, \mathbf{R}, \mathbf{V_{ss}}) \rightarrow$ plug in and do the linear algebra

$\rightarrow$ Similar for contributions to $\mathbf{V_{tt}}$ due to statistical uncertainties on $\mathbf{R}$

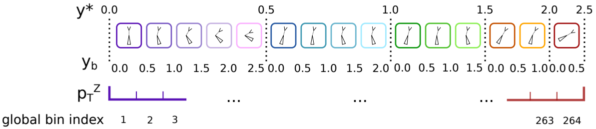
- Avoid regularization $\mathcal{L}_{\text{reg}}$, when $\mathbf{R}$ well-conditioned ($\delta\mathbf{s} \approx$ resolution)
- Avoid normalization $\mathcal{L}_{\text{norm}}$, when Gaussian approximation holds $\rightarrow$ true in this analysis

Bin Unraveling

3D phase-space → 1D visualization

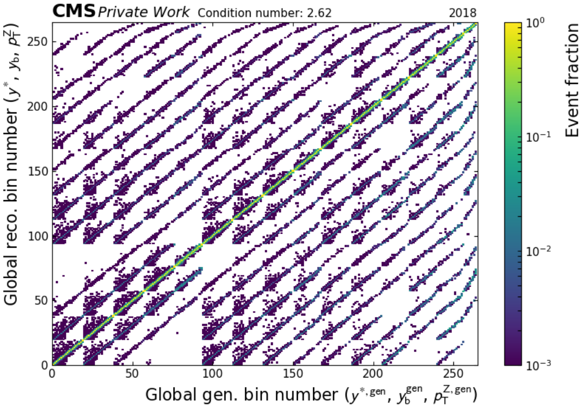


→



M. Schnepf 2022 [5]

Response Matrix



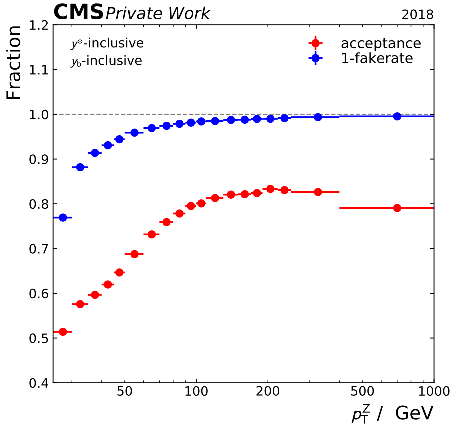
- Migrations from truth level to observation level due to detector effects

$$\mathcal{P}(\text{event in reco bin } i | \text{event in gen bin } j)$$

→ Fill MC events passing selections on reco- and gen-level for each analysis bin and normalize

- Small condition number, well-conditioned → Regularization not necessary
- Found to be similar for all data taking years

Acceptance & Fake rate

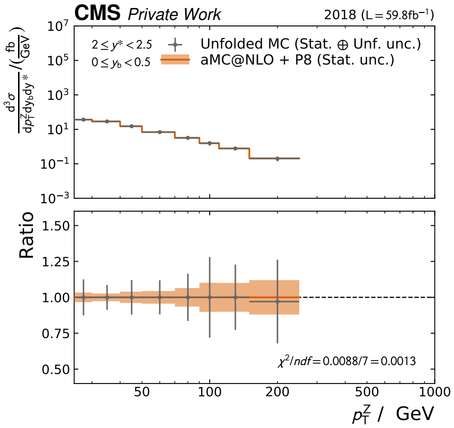


- Some events reconstructed in underflow or overflow of Response Matrix
- Acceptance
  - Events passing cuts on generator level but not on reconstruction level
  - Including detector & reconstruction inefficiencies

  → Treat as inefficiencies
- Fake rate
  - Events passing cuts on reconstruction level but not on generator level

  → Subtract as background
- Accounted for during unfolding

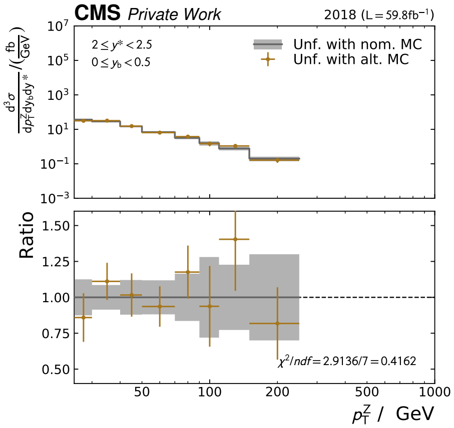
Unfolding Closure



- Consistency check
- Unfold simulated distribution with response using the same MC events
- Perfect agreement between unfolded MC and generator level

→ Unfolding works as expected

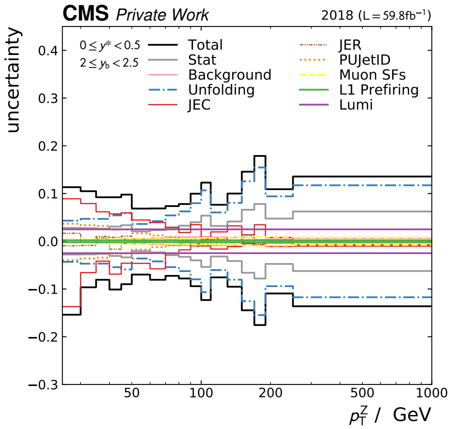
Model Dependence of Unfolding



- Choice of MC to fill Response Matrix might bias the results
- Estimate effect of alternative MC simulation
- Compare unfolded distribution using nominal & alternative response matrices
- Agreement within statistical uncertainties

→ No significant model dependence

Systematic Uncertainties

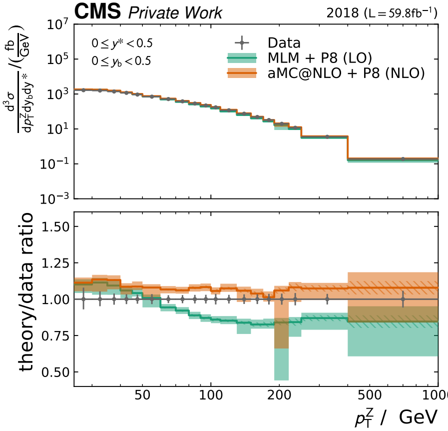


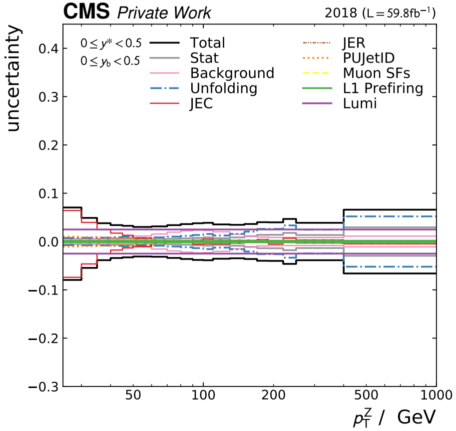
- Various systematic effects impacting unfolded event yields, e.g.
  - Jet energy calibration (JEC) and resolution correction on MC (JER)
  - Measured Luminosity
  - Limited number of events for creation of Response Matrix for Unfolding
  - Estimated Background contributions
  - ...
- Subject to systematical uncertainties

→ Adapt response matrix, acceptance, and fake rate for each systematical variation

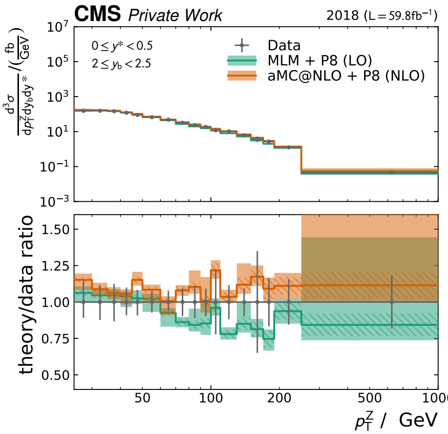
→ New unfolding for each uncertainty

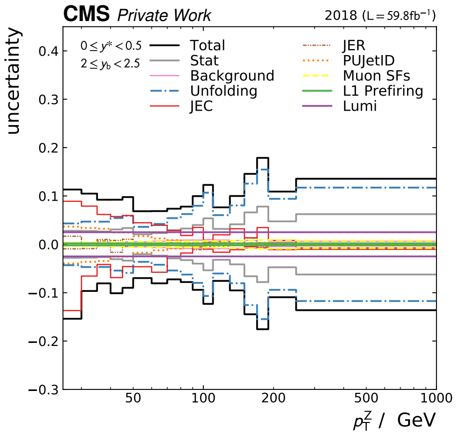
Unfolded Cross-Sections 2018: Central Region





Unfolded Cross-sections 2018: High Boost





Comparison to NNLO Predictions and QCD Analysis

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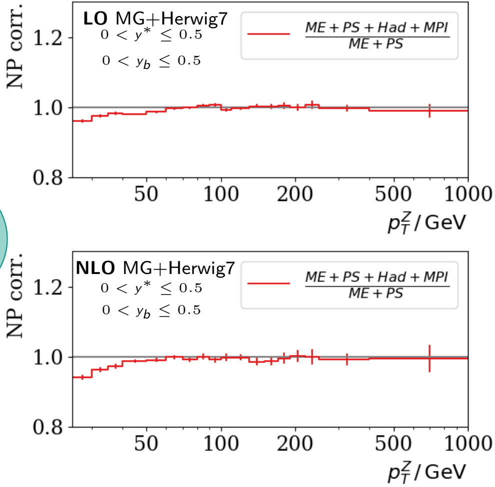
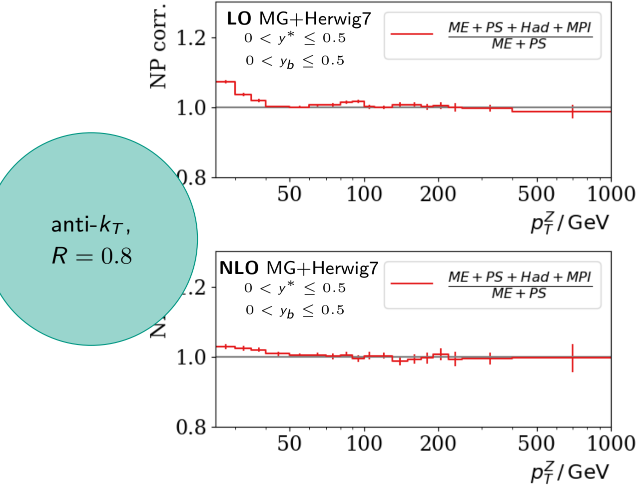


anti-k_T, $R = 0.4$

- TBD: Compare and fit measured cross-sections to state-of-the-art theory predictions for Z+Jet $\rightarrow$ NNLO QCD $\otimes$ NLO-EWK $\otimes$ **non-perturbative (NP) corrections**
- NP corrections $\frac{ME+PS+Had+MPI}{ME+PS}$
  - dimish towards higher p_T^Z
  - change to slightly lower values from LO to NLO perturbative QCD

Comparison to NNLO Predictions and QCD Analysis

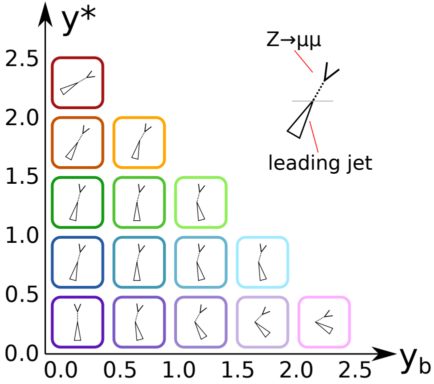


- TBD: Compare and fit measured cross-sections to state-of-the-art theory predictions for Z+Jet $\rightarrow$ NNLO QCD $\otimes$ NLO-EWK $\otimes$ **non-perturbative (NP) corrections**
- NP corrections $\frac{ME+PS+Had+MPI}{ME+PS}$
  - dimish towards higher p_T^Z
  - change to slightly lower values from LO to NLO perturbative QCD
  - depend on the jet type

Outlook

- First Z+Jet triple-differential cross-section measurement at $13\,\mathrm{TeV}$ with full Run II CMS data in progress
  - Combination of all data-taking periods from 2016 to 2018 into single measurement
  - Comparison to NNLO fixed-order predictions including electroweak and non-perturbative corrections
  - PDF and α_S fits

→ Aiming for publication early 2024



Backup

Detailed Event Selection

One $Z \to \mu\mu$ candidate with the following criteria

Selection	Value
Trigger	2016: HLT_IsoMu24 or HLT_TkMu24 2017: HLT_IsoMu27 2018: HLT_IsoMu24
Muon ID	Tight
Muon PF ISO	Tight
Muon p_T	> 29 GeV
Muon $\lvert\eta\rvert$	< 2.4
Z mass	$m_Z \pm 20$ GeV
Z p_T	> 25 GeV

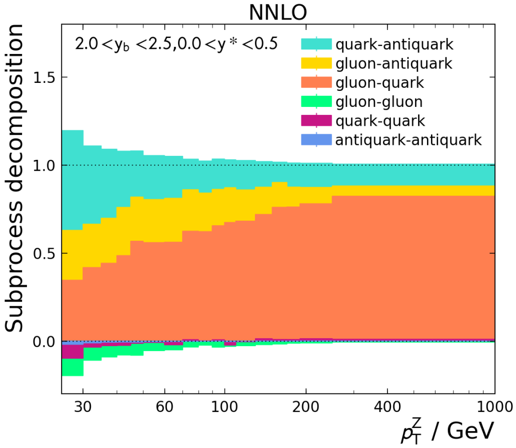
At least one Jet with the following criteria

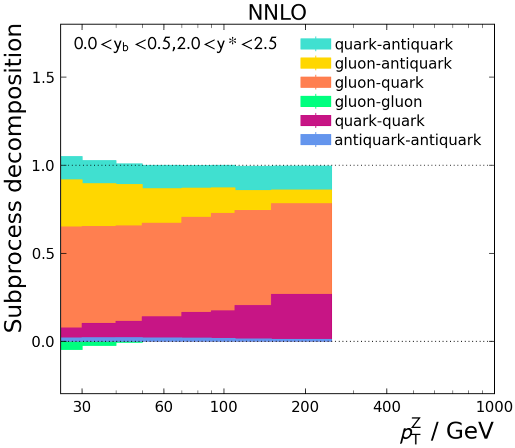
Selection	Value
Jet ID	Tight + Lepveto
PUJetID	Tight
$\Delta R(\mu_Z, \mathrm{Jet})$	> 0.4
Jet p_T	> 20 GeV
Jet $\lvert y\rvert$	< 2.4
Jet Veto Maps	✓

Corrections

Correction/SF	2016preVFP	2016postVFP	2017	2018
Muon RECO SFs	✓	✓	✓	✓
Muon ISO SFs	✓	✓	✓	✓
Muon ID SFs	✓	✓	✓	✓
Muon Trigger SFs	✓	✓	✓	✓
Muon Rochester	Data (kScaleDT) + MC (kSpreadMC)			
Muon Dressing	Data + MC with $\Delta R(\mu, \gamma) < 0.1$			
Muon L1Prefiring	✓	✓	✓	✓
ECAL L1Prefiring	✓	✓	✓	not needed
METFilters	Data + MC (All recommended for each year)			
PuJetID SFs	✓	✓	✓	✓
JEC	V7	V7	V5	V5
JER (hybrid)	V3	V3	V2	V2

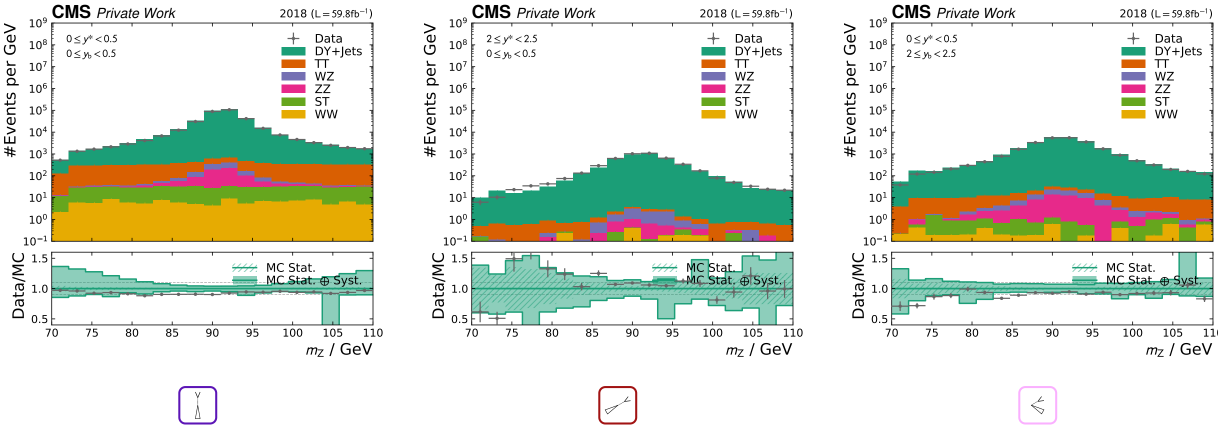
Dependence of Parton Luminosities on Phase-Space





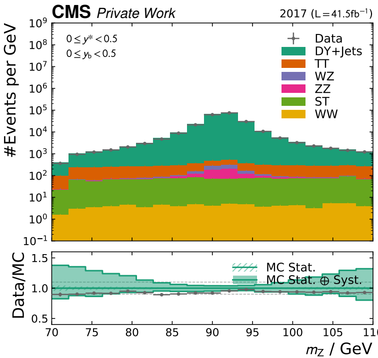
T. Berger 2019 [2]

Data/MC 2018

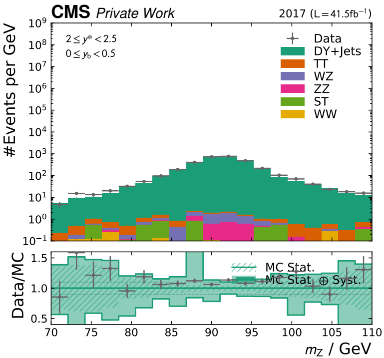


CMS Private Work
2018 (L = 59.8fb⁻¹)
0 ≤ y* < 0.5
0 ≤ y_b < 0.5
2 ≤ y* < 2.5
0 ≤ y_b < 0.5
0 ≤ y* < 0.5
2 ≤ y_b < 2.5
Data
DY+Jets
TT
WZ
ZZ
ST
WW
#Events per GeV
Data/MC
MC Stat.
MC Stat. ⊕ Syst.
m_Z / GeV

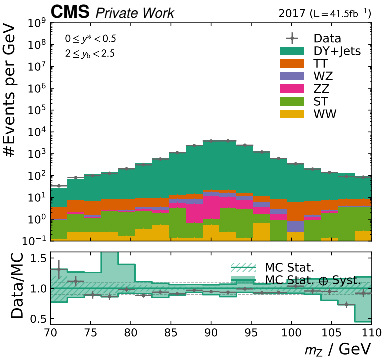
Data/MC 2017



CMS Private Work
2017 (L = 41.5fb⁻¹)
0 ≤ y* < 0.5
0 ≤ y_b < 0.5
Data
DY+Jets
TT
WZ
ZZ
ST
WW
#Events per GeV
Data/MC
MC Stat.
MC Stat. ⊕ Syst.
m_Z / GeV



CMS Private Work
2017 (L = 41.5fb⁻¹)
2 ≤ y* < 2.5
0 ≤ y_b < 0.5
Data
DY+Jets
TT
WZ
ZZ
ST
WW
#Events per GeV
Data/MC
MC Stat.
MC Stat. ⊕ Syst.
m_Z / GeV



CMS Private Work
2017 (L = 41.5fb⁻¹)
0 ≤ y* < 0.5
2 ≤ y_b < 2.5
Data
DY+Jets
TT
WZ
ZZ
ST
WW
#Events per GeV
Data/MC
MC Stat.
MC Stat. ⊕ Syst.
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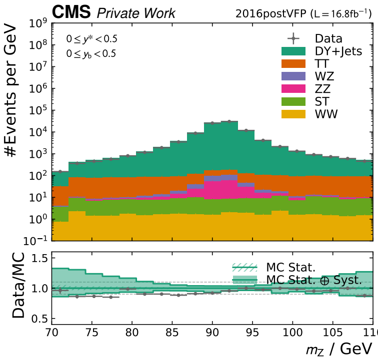
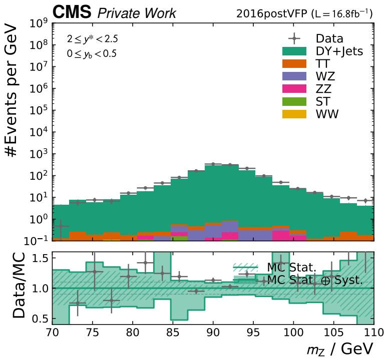
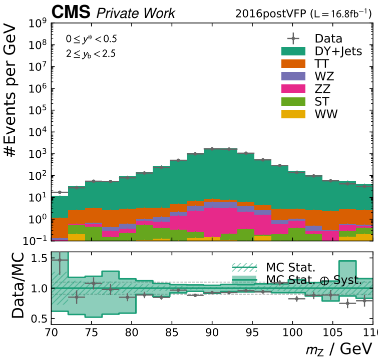
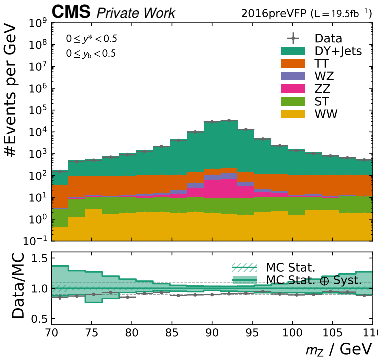
Data/MC 2016postVFP

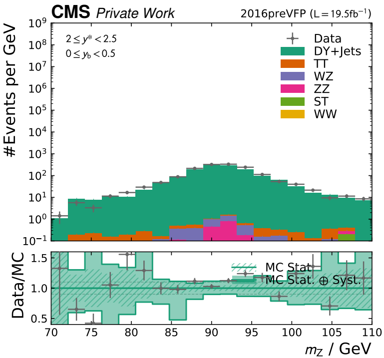


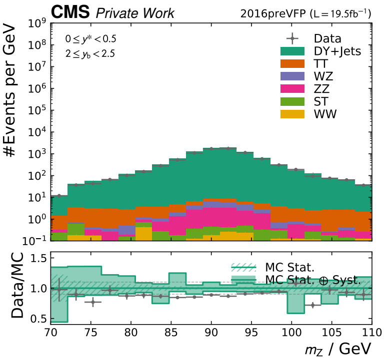




Data/MC 2016preVFP

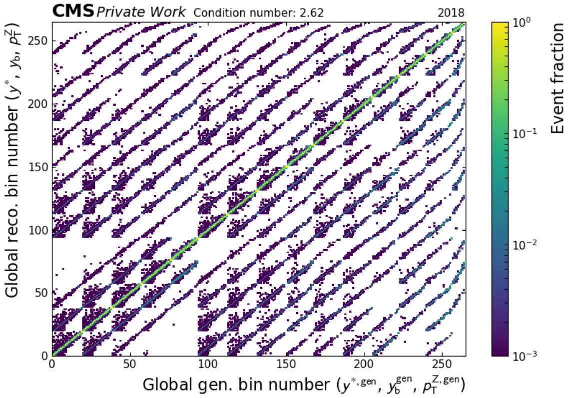




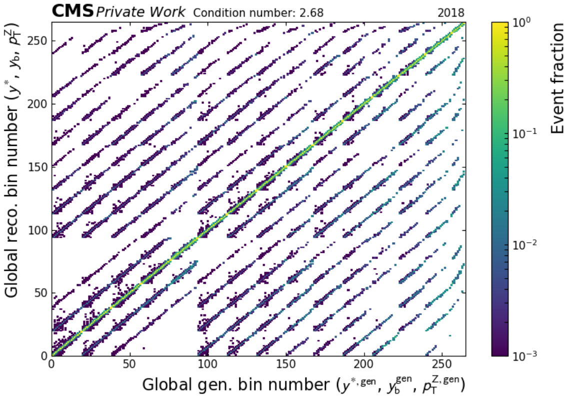


Response Matrices 2018

NLO

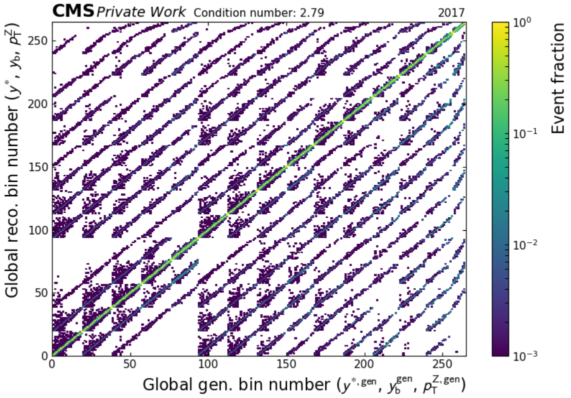


LO

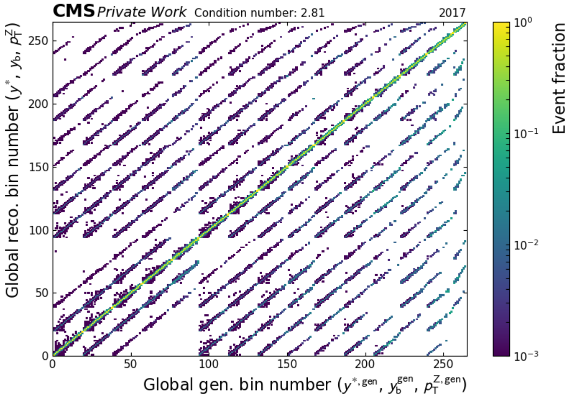


Response Matrices 2017

NLO

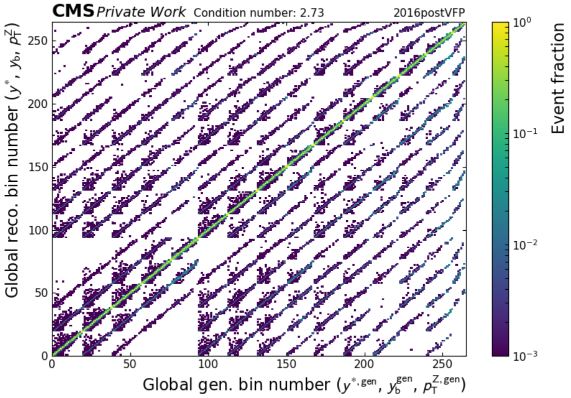


LO

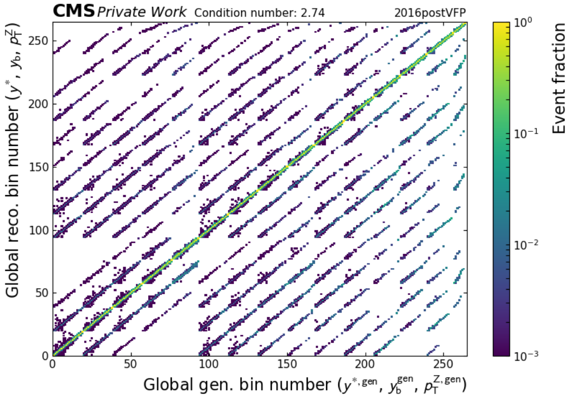


Response Matrices 2016postVFP

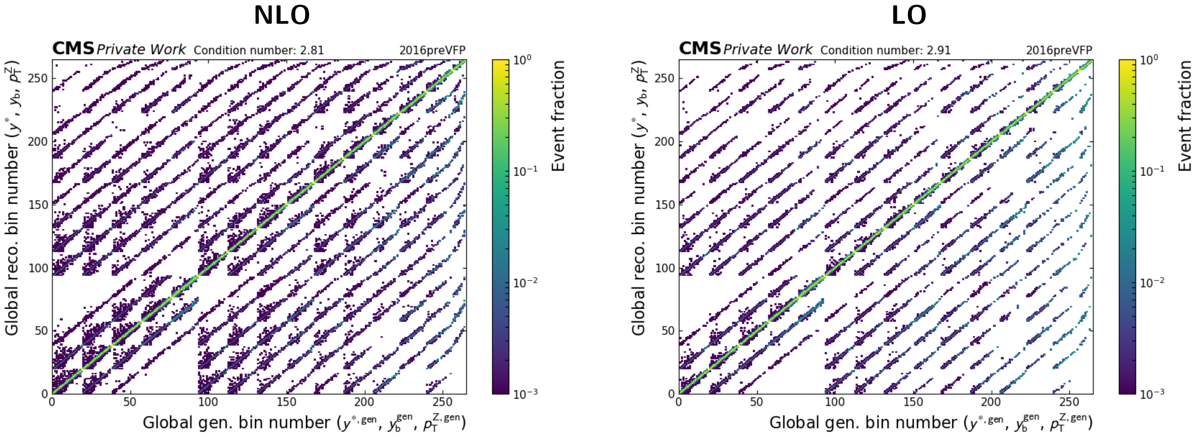
NLO



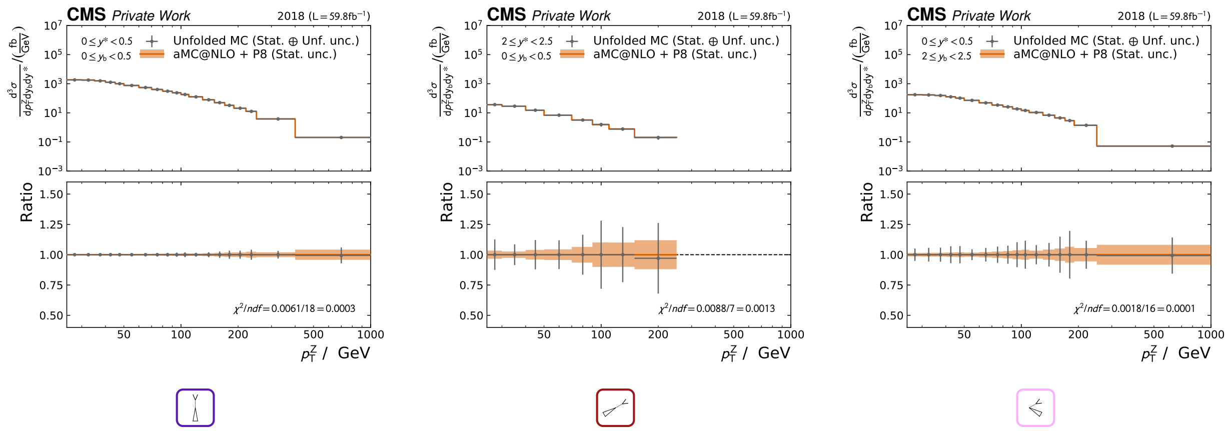
LO



Response Matrices 2016preVFP



Unfolding Closure 2018



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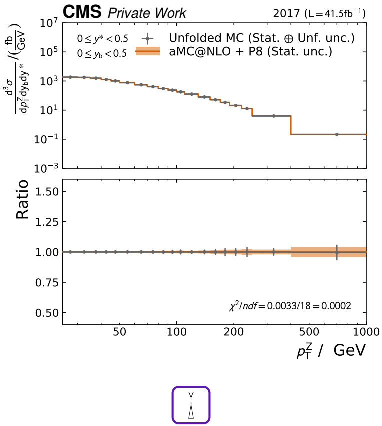
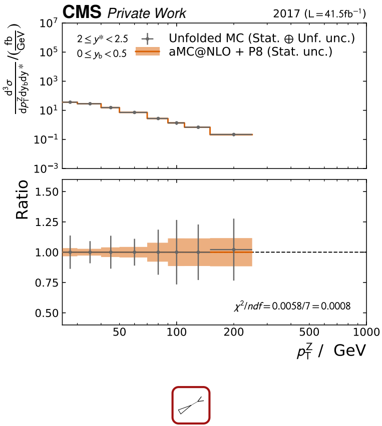
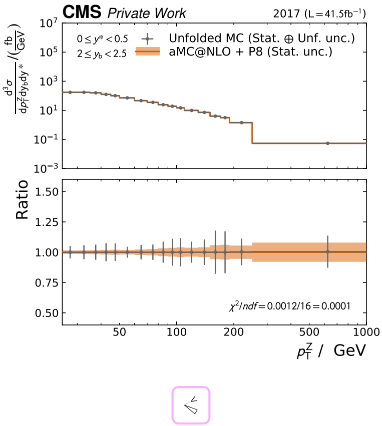
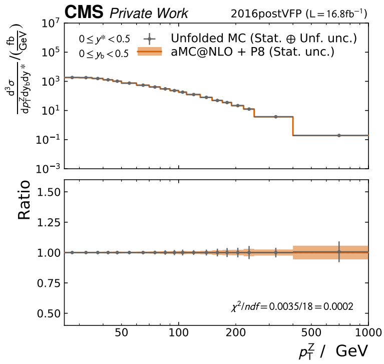
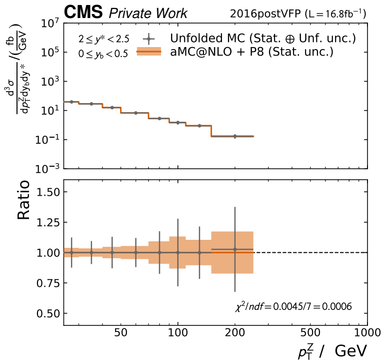


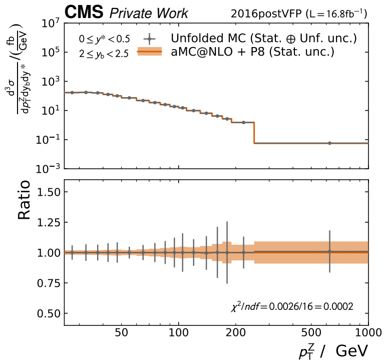




Unfolding Closure 2016postVFP

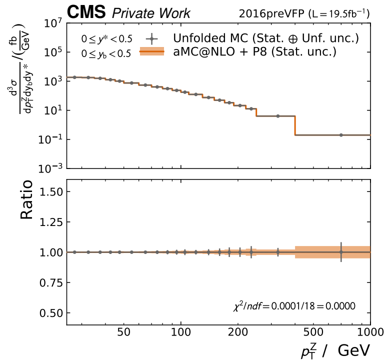


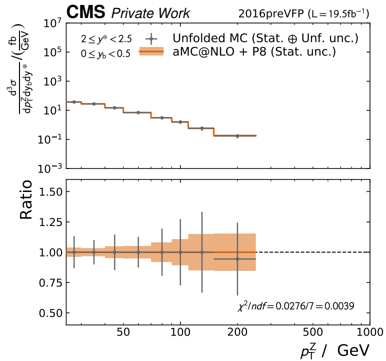


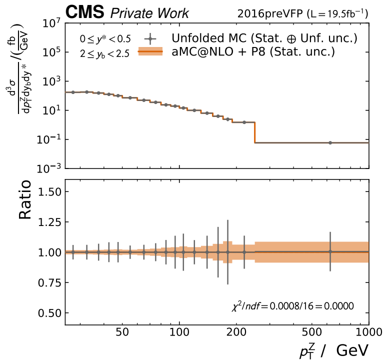




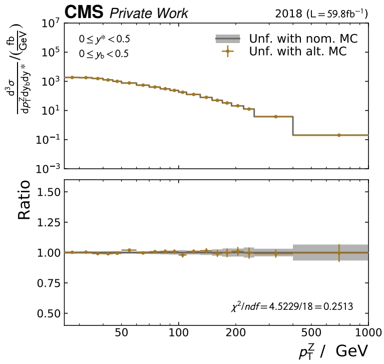
Unfolding Closure 2016preVFP

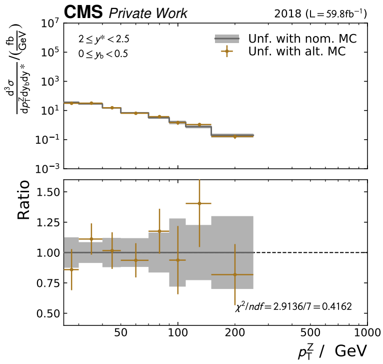


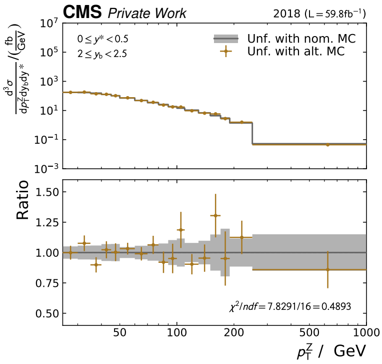




Unfolding Model Dependence 2018







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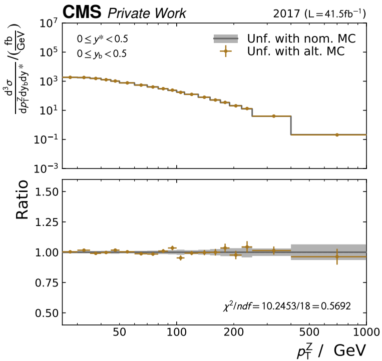
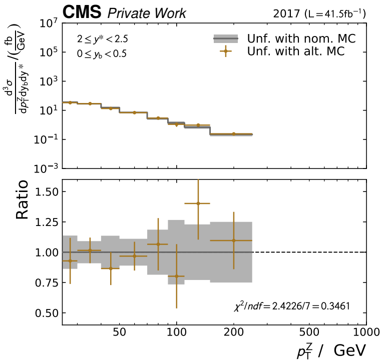
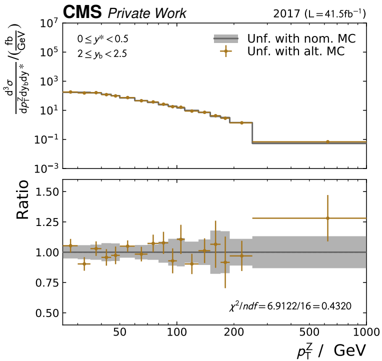
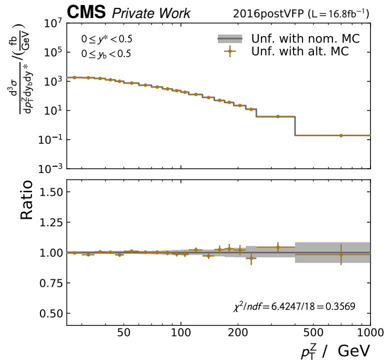
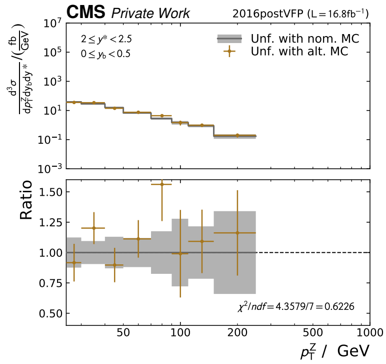


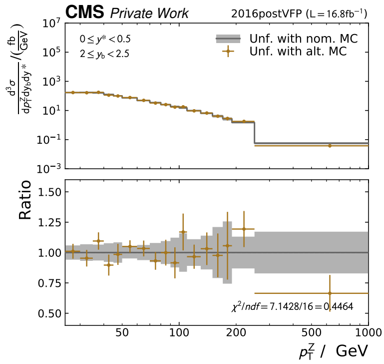




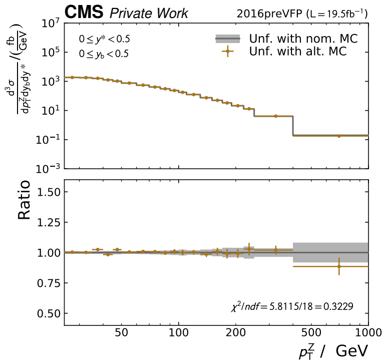
Unfolding Model Dependence 2016postVFP

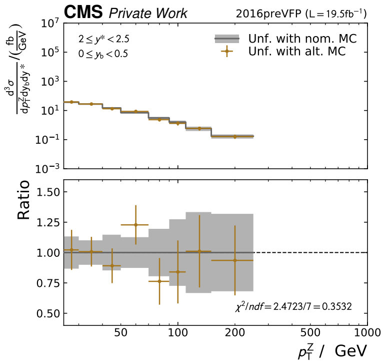


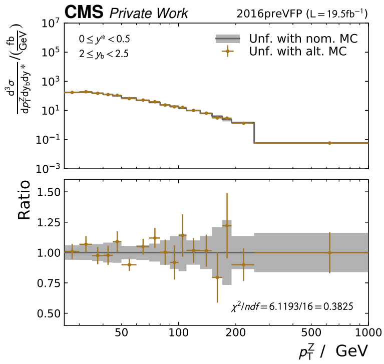




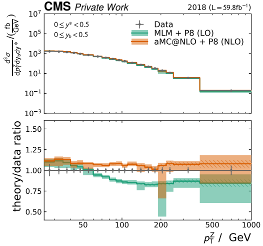
Unfolding Model Dependence 2016preVFP

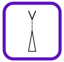


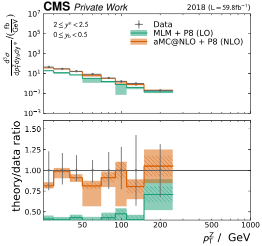


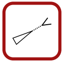


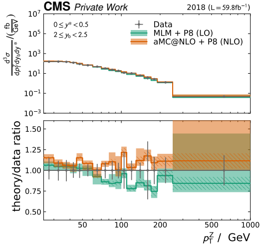
Unfolded Cross-Sections 2018

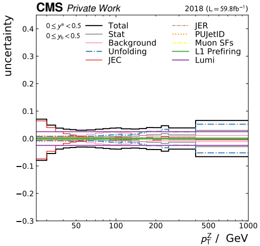


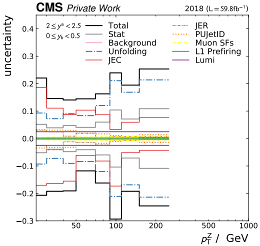


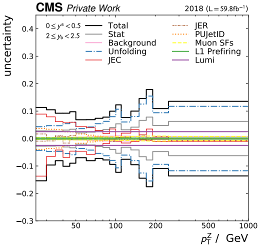












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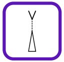
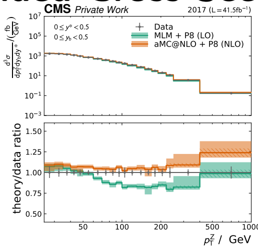
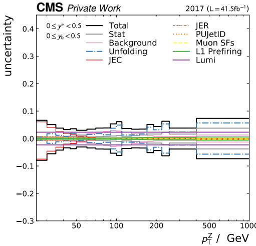
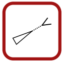
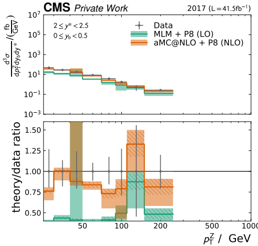
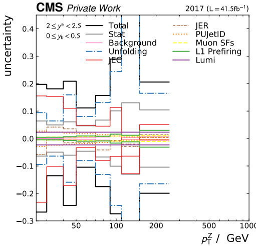


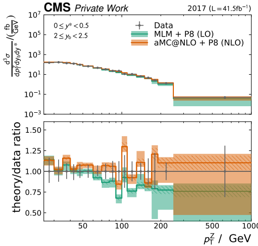


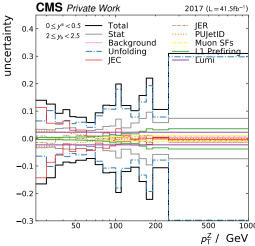




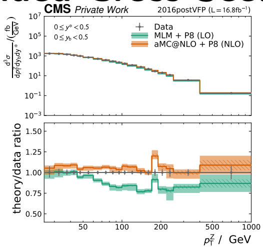


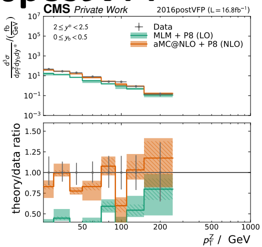


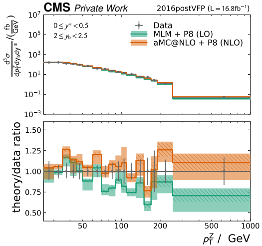


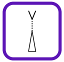


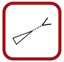
Unfolded Cross-Sections 2016postVFP

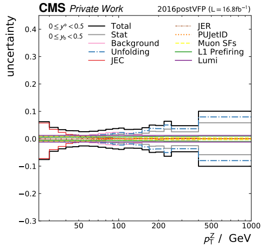


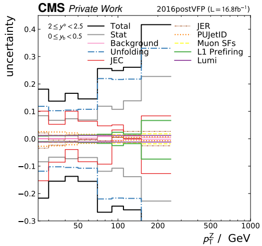


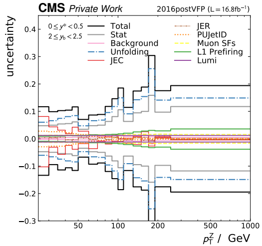




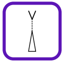


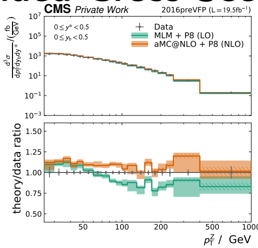


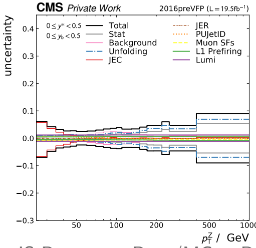


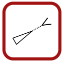


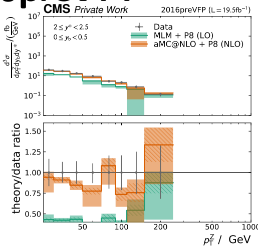
Unfolded Cross-Sections 2016preVFP

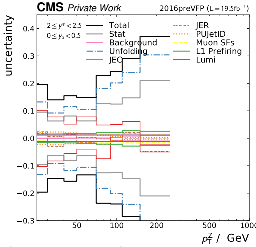


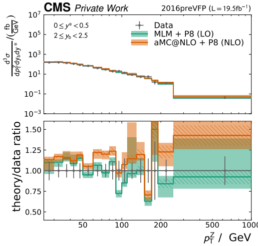


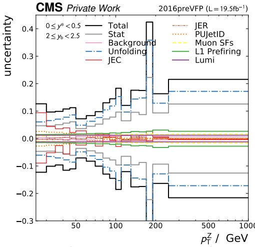




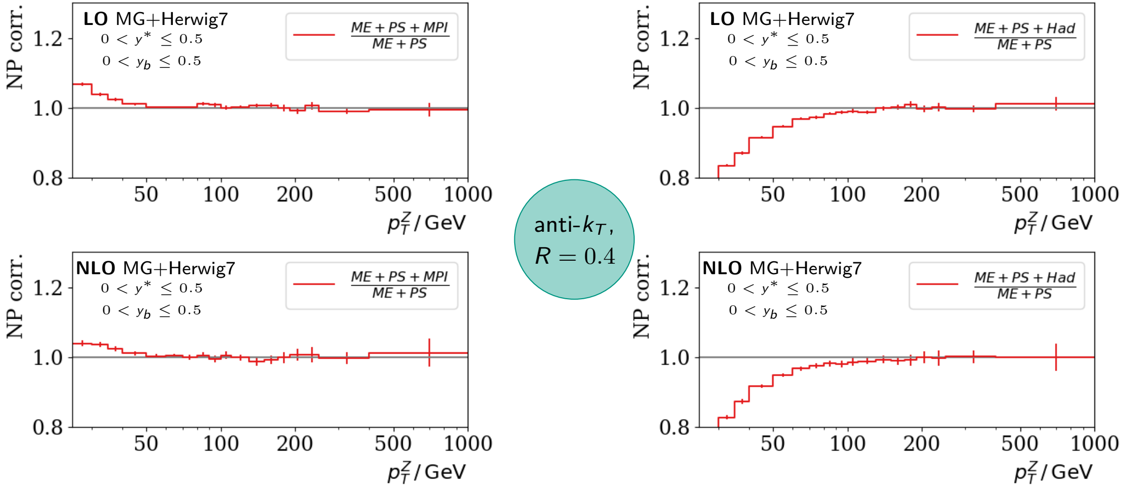




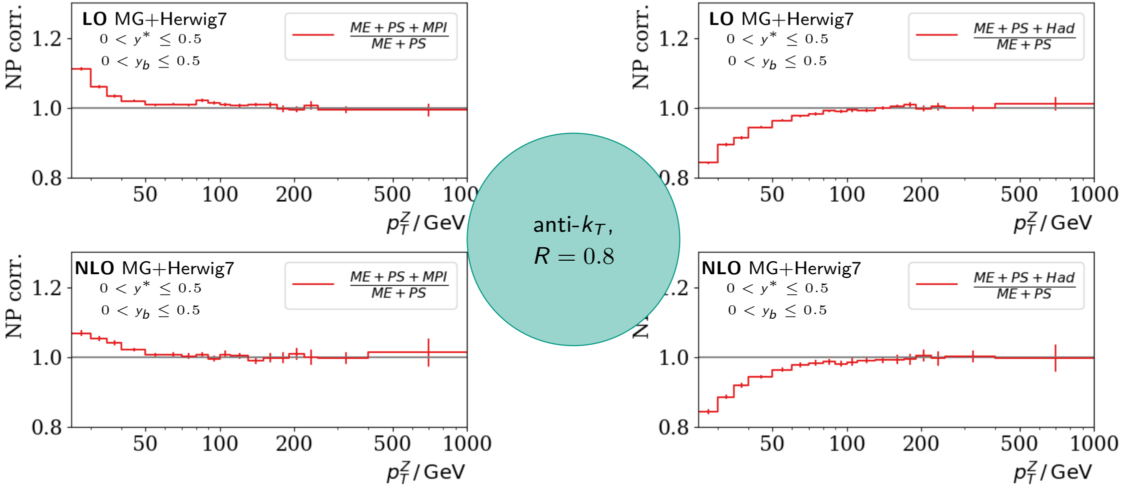




MPI and Hadronization effects



MPI and Hadronization effects



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[3] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. "The anti-kt jet clustering algorithm". *Journal of High Energy Physics* 2008.04 (Apr. 2008), p. 063. DOI: 10.1088/1126-6708/2008/04/063. URL: https://dx.doi.org/10.1088/1126-6708/2008/04/063.

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