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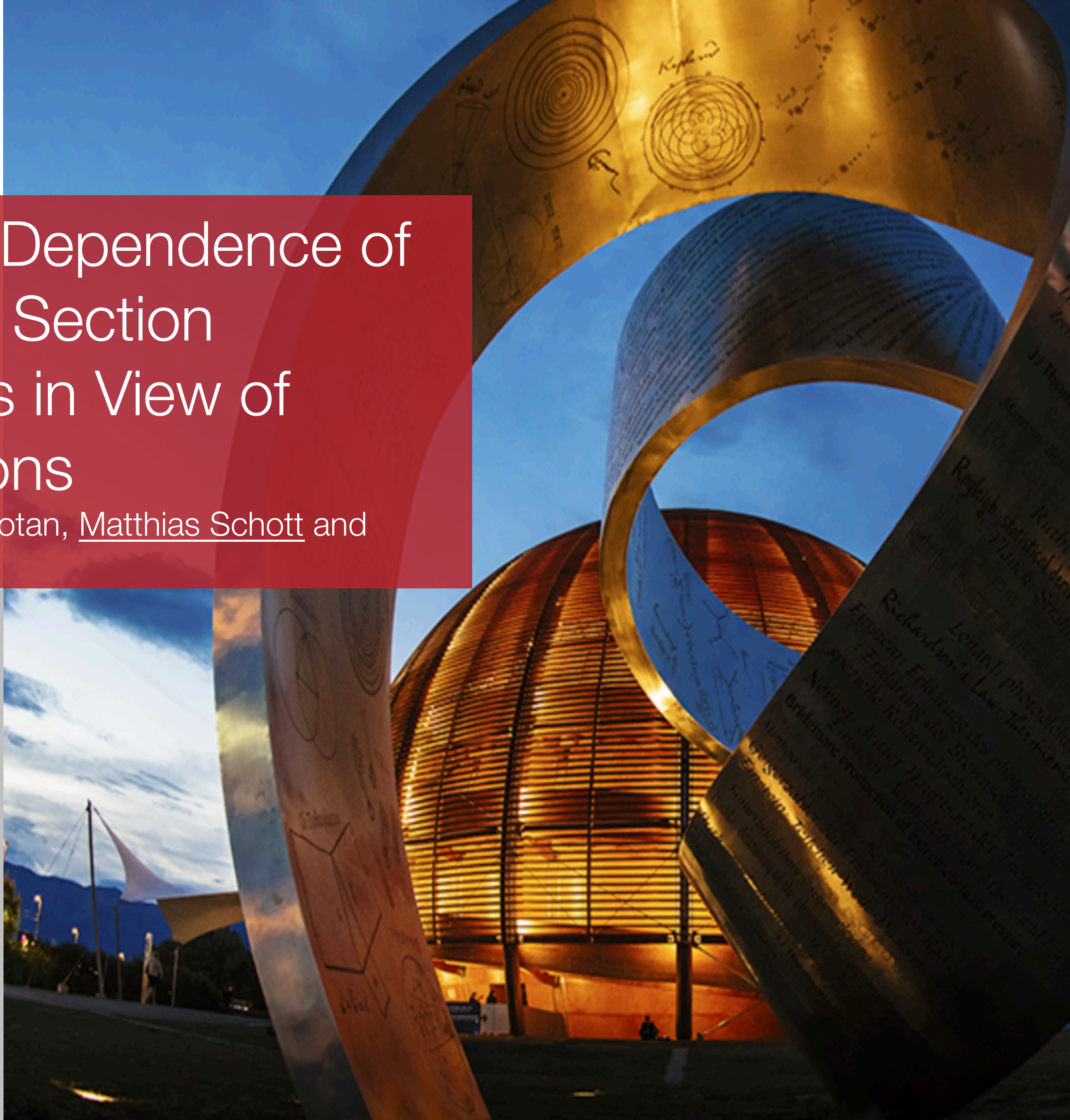
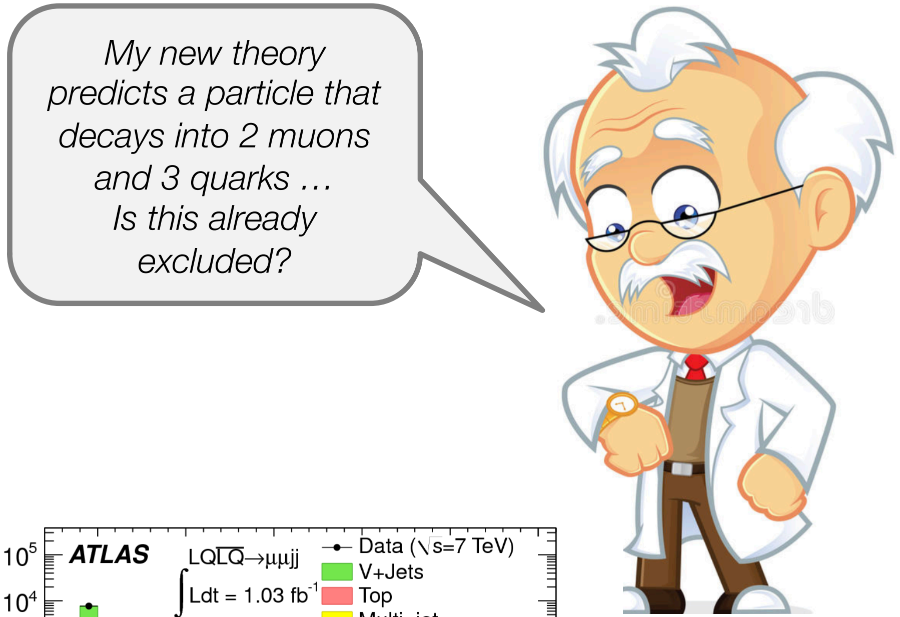


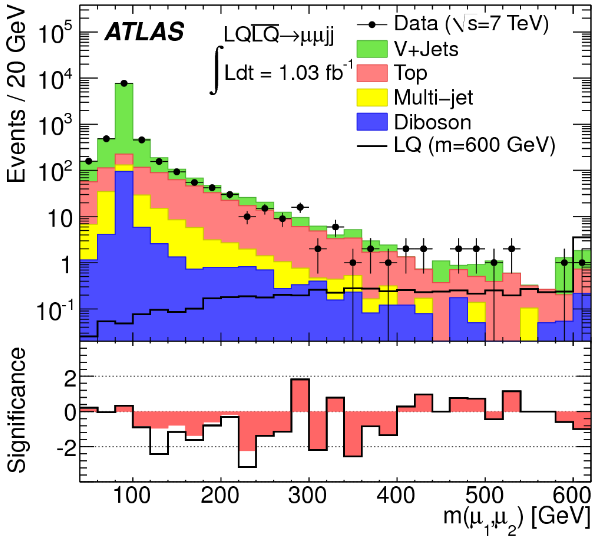
On the Model Dependence of Fiducial Cross Section Measurements in View of Reinterpretations

Gabriel Facini, Kyrylo Merkotan, Matthias Schott and Alexander Sydorenko

How to test a new model?

- Four options for a theoretician to test a new model with available LHC data
- Option 1: Ask the LHC Collaborations
- Option 2: Use LHC Open Data
  - Possible but far from trivial
- Option 3: Use published reconstructed data plots with Standard Model predictions
  - Problem: You absolutely need a detector simulation for your signal
- Option 4: Use detector-corrected (unfolded) data
  - Problem: there is a model bias
  - Question: How big is this bias?





Unfolded data and Fiducial Cross-Sections

- Option 4 becomes more and more popular!
  - EFT fits or direct BSM constrains on unfolded data (see for example the latest 4 lepton measurement of ATLAS)
- Simplest form of “removing” detector effects is a fiducial cross section measurement

$$\sigma_{fid} = \frac{N_{\text{Cand}} - N_B}{C \cdot \int L dt}$$

  - with

$$C = \frac{N^{\text{fid}}_{\text{MC-Detector-Level}}}{N^{\text{fid}}_{\text{MC-Particle-Level}}}$$

- Unfolding is somewhat equivalent fiducial cross section measurement in fine bins
  - E.g. simple bin-by-bin unfolding is nothing else than fiducial cross sections

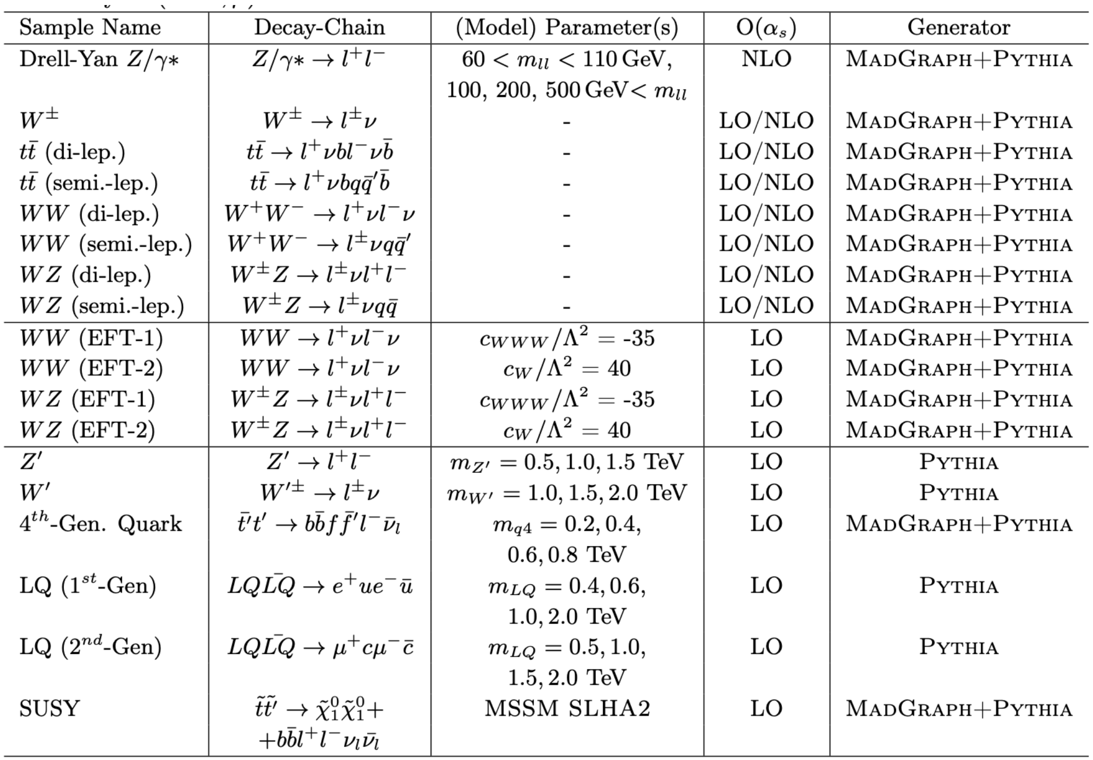
Example

- 800 observed events for the SM process X in a 100 pb^{-1} data set
- $C_X=0.8 \rightarrow \sigma_X=800/(0.8\cdot100)=10$ pb.
- Assume SM prediction of $\sigma_X=8$ pb
- Which limit can we place on BSM process Y, that has a similar final state?
  - Assume $C_X = C_Y$
    - → naive 95% CL is 4 pb
  - Problem: we typically do not know C_Y
  - If $C_Y = 0.4$ then the limit will be wrong by a factor of 2
- In other words: All measured cross-sections (inclusive, fiducial, differential) assume the SM

Methodology of this study and MC Samples

- Basic idea of this study
  - Implement many different signal regions (i.e. signal selections)
  - Simulate many processes (SM+BSM)
  - Estimate the model dependence for each case (reduces to the comparison of the C factors)

- Processes are simulated with Pythia8 or MadGraph
  - 8 SM Processes
  - 4 EFT scenarios
  - 6 BSM scenarios with 3-4 different model parameter choices



Sample Name	Decay-Chain	(Model) Parameter(s)	O(α_s)	Generator
Drell-Yan $Z/\gamma*$	$Z/\gamma* \rightarrow l^+l^-$	$60 < m_{ll} < 110\,\mathrm{GeV}$, 100, 200, 500 GeV$< m_{ll}$	NLO	MadGraph+Pythia
$W^\pm$	$W^\pm \rightarrow l^\pm\nu$	-	LO/NLO	MadGraph+Pythia
$t\bar{t}$ (di-lep.)	$t\bar{t} \rightarrow l^+\nu b l^-\nu\bar{b}$	-	LO/NLO	MadGraph+Pythia
$t\bar{t}$ (semi.-lep.)	$t\bar{t} \rightarrow l^+\nu b q\bar{q}'\bar{b}$	-	LO/NLO	MadGraph+Pythia
WW (di-lep.)	$W^+W^- \rightarrow l^+\nu l^-\nu$	-	LO/NLO	MadGraph+Pythia
WW (semi.-lep.)	$W^+W^- \rightarrow l^\pm\nu q\bar{q}'$	-	LO/NLO	MadGraph+Pythia
WZ (di-lep.)	$W^\pm Z \rightarrow l^\pm\nu l^+l^-$	-	LO/NLO	MadGraph+Pythia
WZ (semi.-lep.)	$W^\pm Z \rightarrow l^\pm\nu q\bar{q}$	-	LO/NLO	MadGraph+Pythia
WW (EFT-1)	$WW \rightarrow l^+\nu l^-\nu$	$c_{WWW}/\Lambda^2 =$ -35	LO	MadGraph+Pythia
WW (EFT-2)	$WW \rightarrow l^+\nu l^-\nu$	$c_W/\Lambda^2 =$ 40	LO	MadGraph+Pythia
WZ (EFT-1)	$W^\pm Z \rightarrow l^\pm\nu l^+l^-$	$c_{WWW}/\Lambda^2 =$ -35	LO	MadGraph+Pythia
WZ (EFT-2)	$W^\pm Z \rightarrow l^\pm\nu l^+l^-$	$c_W/\Lambda^2 =$ 40	LO	MadGraph+Pythia
Z'	$Z' \rightarrow l^+l^-$	$m_{Z'} = 0.5, 1.0, 1.5$ TeV	LO	Pythia
W'	$W'^\pm \rightarrow l^\pm\nu$	$m_{W'} = 1.0, 1.5, 2.0$ TeV	LO	Pythia
4^{th}-Gen. Quark	$\bar{t}'t' \rightarrow b\bar{b}f\bar{f}'l^-\bar{\nu}_l$	$m_{q4} = 0.2, 0.4,$ $0.6, 0.8$ TeV	LO	MadGraph+Pythia
LQ (1^{st}-Gen)	$LQ\bar{LQ} \rightarrow e^+ue^-\bar{u}$	$m_{LQ} = 0.4, 0.6,$ $1.0, 2.0$ TeV	LO	Pythia
LQ (2^{nd}-Gen)	$LQ\bar{LQ} \rightarrow \mu^+c\mu^-\bar{c}$	$m_{LQ} = 0.5, 1.0,$ $1.5, 2.0$ TeV	LO	Pythia
SUSY	$\tilde{t}\tilde{t}' \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0+$ $+b\bar{b}l^+l^-\nu_l\bar{\nu}_l$	MSSM SLHA2	LO	MadGraph+Pythia

What will certainly go wrong …

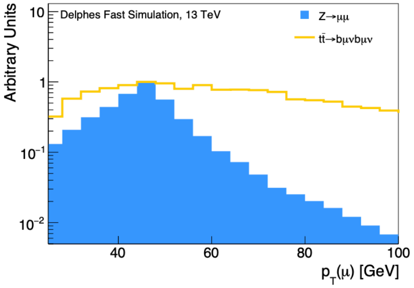
- Trivial, but crucial pre-requirement for any reinterpretation of unfolded data
  - one ought only reinterpret a measurement in terms of BSM processes which have the same final state objects multiplicity as the measured SM process

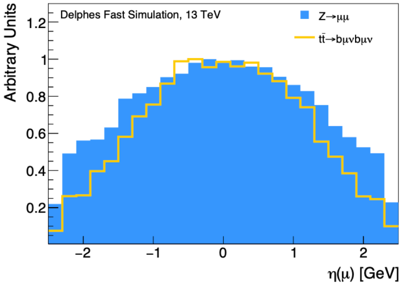
- Example
  - Assume a Drell-Yan measurement (Z→μμ) that has 2 muons on particle level and reconstruction level
  - Compare the C factor of this process to background processes, e.g. WZ or ZZ
    - Large differences due to the different number of truth leptons (even outside of the acceptance)

- Also the hadronic activity in the event plays a role due to isolation

Process	C-factor (tight iso.)	C-factor (loose iso.)
$Z/\gamma* \rightarrow \mu^+\mu^-$	0.826 ± 0.001	0.827 ± 0.001
$t\bar{t} \rightarrow \mu^+\nu b\mu^-\nu b$	0.826 ± 0.005	0.834 ± 0.005
$W^+W^- \rightarrow \mu^+\nu\mu^-\nu$	0.825 ± 0.017	0.826 ± 0.017
$W^\pm Z \rightarrow \mu^\pm\nu\mu^+\mu^-$	1.037 ± 0.012	1.033 ± 0.012
$ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$	1.129 ± 0.032	1.131 ± 0.032

Process	C-factor (tight iso.)	C-factor (loose iso.)
$Z/\gamma* \rightarrow e^+e^-$	0.696 ± 0.002	0.697 ± 0.002
$t\bar{t} \rightarrow e^+\nu be^-\nu b$	0.708 ± 0.007	0.715 ± 0.007
$W^+W^- \rightarrow e^+\nu e^-\nu$	0.686 ± 0.022	0.687 ± 0.022
$W^\pm Z \rightarrow e^\pm\nu e^+e^-$	0.872 ± 0.09	0.874 ± 0.09
$ZZ \rightarrow e^+e^-e^+e^-$	1.232 ± 0.051	1.235 ± 0.051

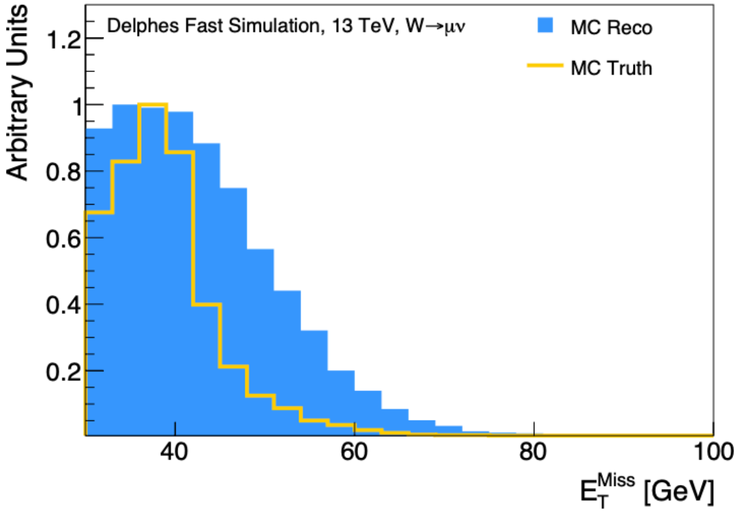


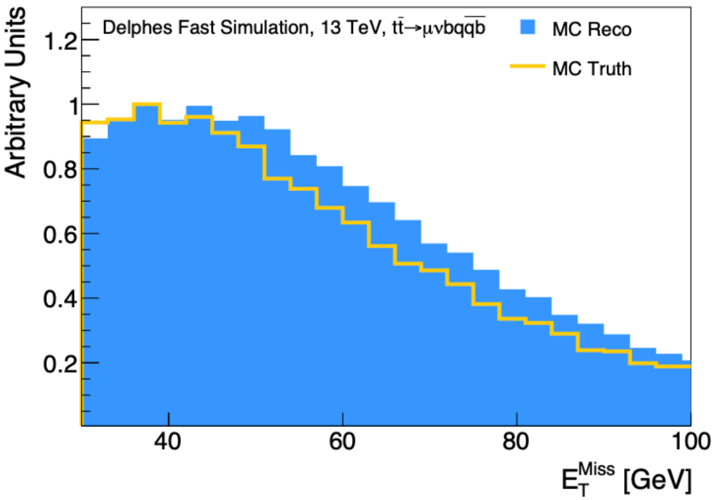


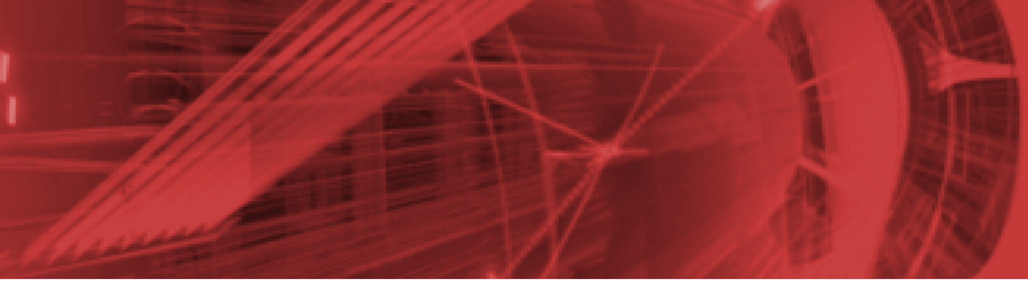
MC Samples and Detector Simulation

- The detector effects for all MC Samples are simulated via the DELPHES framework
- Typical systematic uncertainties on various object are applied
    - Lepton efficiencies
    - Scale and resolution uncertainties
    - …
- Important for the reinterpretation
    - Observables that tend to have large tails, i.e. imply large migration effects

Quantity	Relative eff. uncertainty	Quantity	Relative scale uncertainty
Electron/Photon eff.	0.5%	Electron/Photon energy scale	0.1%
Muon efficiency	0.5%	Muon momentum scale	0.1%
Lepton isolation eff.	0.3%	Jet energy scale	4% (for E_T <40 GeV)
b-tagging efficiency	4.0%		2% (for E_T >40 GeV)
		$\not\!\!E_T$ scale	4% (for E_T <40 GeV)
			2% (for E_T >40,GeV)





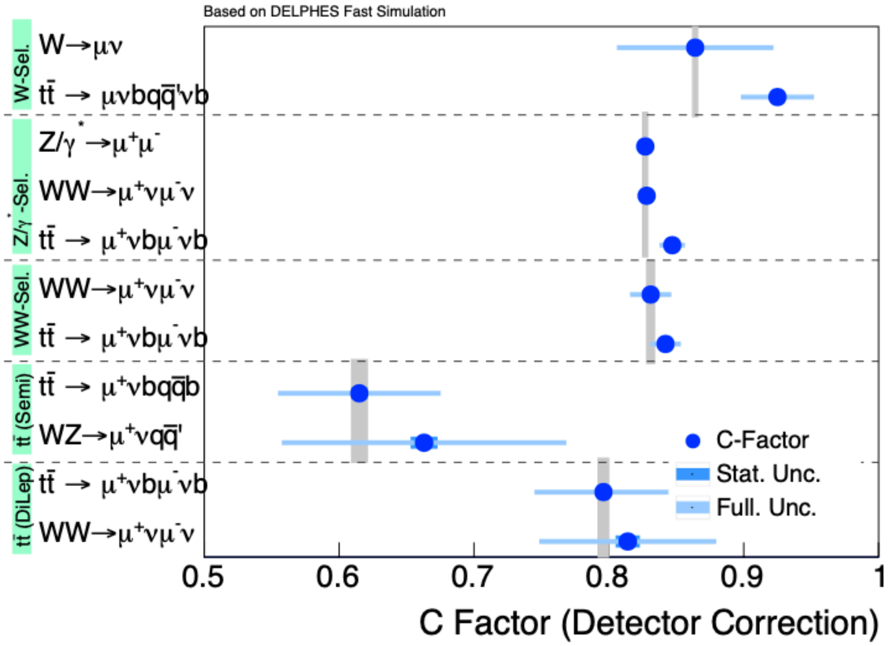


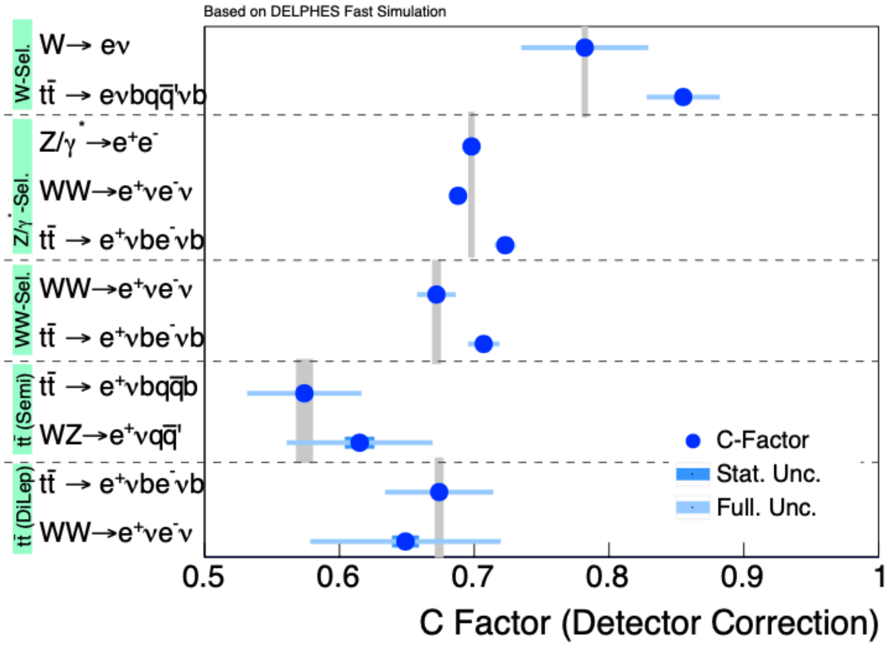
Signal Regions

- We studied 15 different selections for typical SM and BSM processes
- Each selection is applied on particle level (i.e. MC Truth) and reconstruction level
  - defines fiducial volume
  - defines the C factors
- Apply selections on all available MC samples
  - As long as number of final state objects are the same

	Standard Model regions
Scenario/Process	Fiducial phase-space definitions
Z/γ^*	$n_l = 2$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $70 < m_{ll} < 110\,\mathrm{GeV}$
$W^\pm$	$n_l = 1$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $\not\!\!E_{\mathrm{T}} > 30\,\mathrm{GeV}$, $m_{\mathrm{T}} > 40\,\mathrm{GeV}$
W^+W^- (di lep.)	$n_l = 2$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $\not\!\!E_{\mathrm{T}} > 30\,\mathrm{GeV}$, $p_{\mathrm{T}}(ll) > 30\,\mathrm{GeV}$, $m_{ll} - m_Z > 30\,\mathrm{GeV}$
$W^\pm Z$ (di lep.)	$n_l = 3$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $\not\!\!E_{\mathrm{T}} > 25\,\mathrm{GeV}$, $m_{\mathrm{T}}(W) > 30\,\mathrm{GeV}$
$t\bar{t}$ (semi. lep.)	$n_l = 1$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $\not\!\!E_{\mathrm{T}} > 40\,\mathrm{GeV}$ $n_{b-\mathrm{jet}} \geq 1$, $n_{\mathrm{jet}} \geq 3$, $p_{\mathrm{T}}(\mathrm{jet}) > 30\,\mathrm{GeV}$, $\lvert\eta(\mathrm{jet})\rvert < 4.0$
$t\bar{t}$ (di lep.)	$n_l = 2$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $\not\!\!E_{\mathrm{T}} > 60\,\mathrm{GeV}$, $\lvert m_{ll} - m_Z\rvert > 30\,\mathrm{GeV}$, $m_{ll} > 10\,\mathrm{GeV}$, $n_{b-\mathrm{jet}} \geq 1$, $n_{\mathrm{jet}} \geq 2$, $p_{\mathrm{T}}(\mathrm{jet}) > 30\,\mathrm{GeV}$, $\lvert\eta(\mathrm{jet})\rvert < 4.0$
	BSM search regions
Z'	$n_l = 2$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $m_{ll} > 200\,\mathrm{GeV}$
$W'^\pm$	$n_l = 1$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $\not\!\!E_{\mathrm{T}} > 60\,\mathrm{GeV}$, $m_{\mathrm{T}} > 500\,\mathrm{GeV}$
LQ	$n_l = 2$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $\not\!\!E_{\mathrm{T}} > 25\,\mathrm{GeV}$, $S_{\mathrm{T}} > 400\,\mathrm{GeV}$ $n_{\mathrm{jet}} \geq 2$, $p_{\mathrm{T}}(\mathrm{jet}) > 30\,\mathrm{GeV}$, $\lvert\eta(\mathrm{jet})\rvert < 4.0$, $m_{l,\mathrm{jet}} > 300\,\mathrm{GeV}$
4th Generation	$n_l = 1$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$, $\not\!\!E_{\mathrm{T}} > 35\,\mathrm{GeV}$, $\not\!\!E_{\mathrm{T}} + m_{\mathrm{T}} > 60\,\mathrm{GeV}$ $n_{b-\mathrm{jet}} \geq 1$, $n_{\mathrm{jet}} \geq 3$, $p_{\mathrm{T}}(\mathrm{jet}) > 30\,\mathrm{GeV}$, $\lvert\eta(\mathrm{jet})\rvert < 4.0$, $p_{\mathrm{T}}(\mathrm{jet}^{\mathrm{lead}}) > 60\,\mathrm{GeV}$, $S_{\mathrm{T}} > 400\,\mathrm{GeV}$
SUSY	$n_l = 2$, $p_{\mathrm{T}}(l) > 25\,\mathrm{GeV}$, $\lvert\eta(l)\rvert < 2.4$ $p_{\mathrm{T}}(\mathrm{jet}) > 30\,\mathrm{GeV}$, $\lvert\eta(\mathrm{jet})\rvert < 4.0$, $n_{\mathrm{jet}} \geq 2$, $\not\!\!E_{\mathrm{T}} > 150\,\mathrm{GeV}$
	EFT sensitive regions
W^+W^- (EFT-1 Sel.)	Standard W^+W^- (di lep.) $+\ p_{\mathrm{T}}(\mathrm{lep}^{\mathrm{lead}}) > 100\,\mathrm{GeV}$
W^+W^- (EFT-2 Sel.)	Standard W^+W^- (di lep.) $+\ m_{\mathrm{T}}(WW) > 200\,\mathrm{GeV}$
$W^\pm Z$ (EFT-1 Sel.)	Standard $W^\pm Z$ (di lep.) $+\ p_{\mathrm{T}}(\mathrm{lep}^{\mathrm{lead}}) > 80\,\mathrm{GeV}$
$W^\pm Z$ (EFT-2 Sel.)	Standard $W^\pm Z$ (di lep.) $+\ m_{\mathrm{T}}(WZ) > 250\,\mathrm{GeV}$

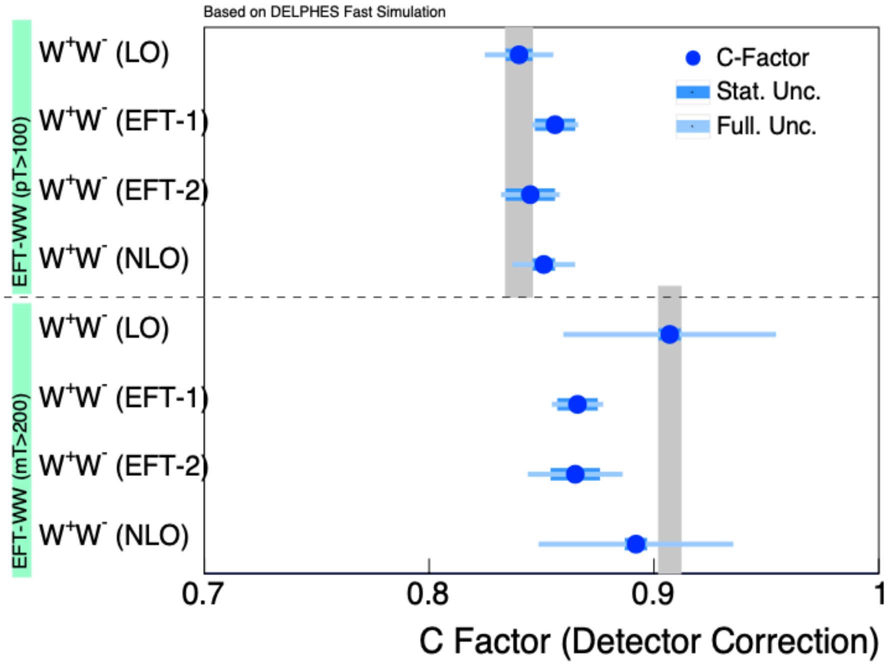
Results for Standard Model Processes

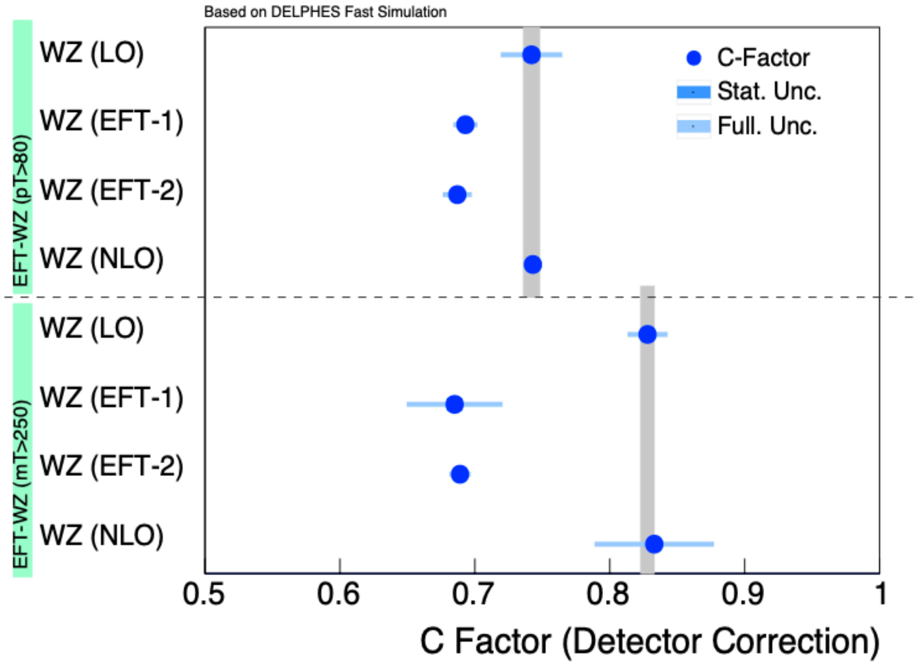




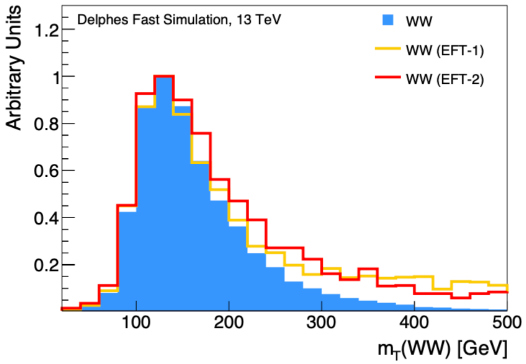
- Typical C factors are between 0.6 and 1.0
  - lower values reflect typically the inclusion of an acceptance effect
- The C factors for SM Processes in different fiducial volumes agree within 5-10%
  - In most cases smaller than the actual experimental uncertainties

EFT Interpretations

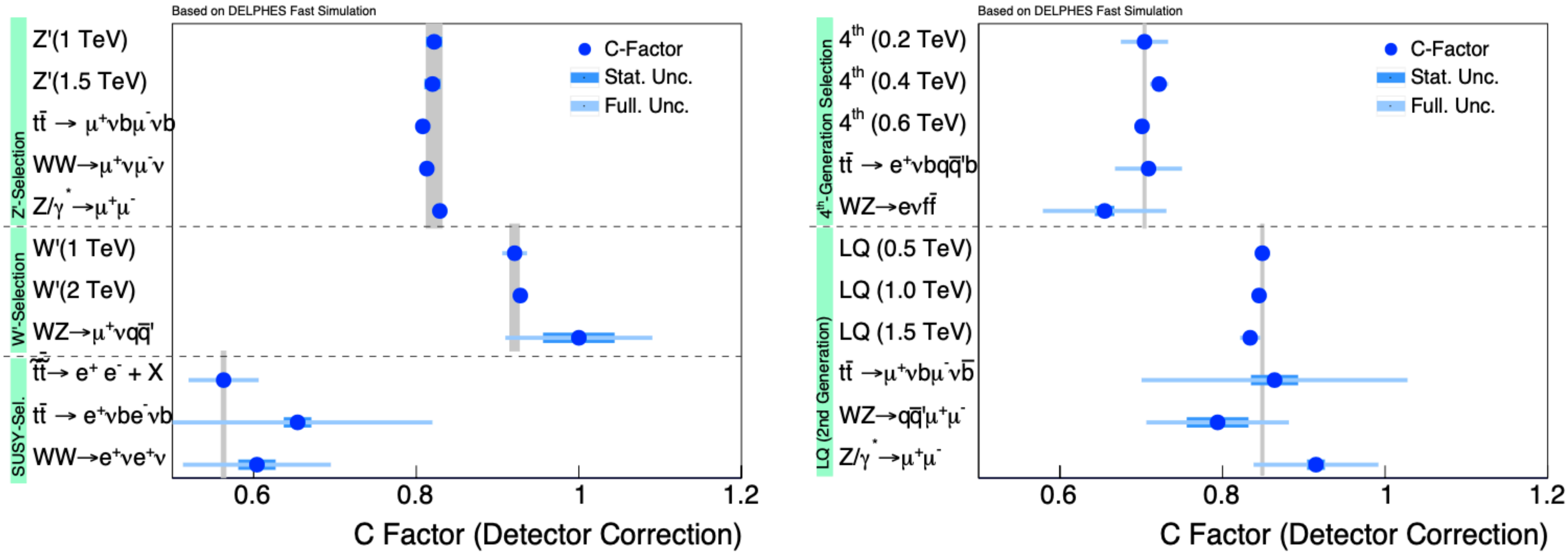




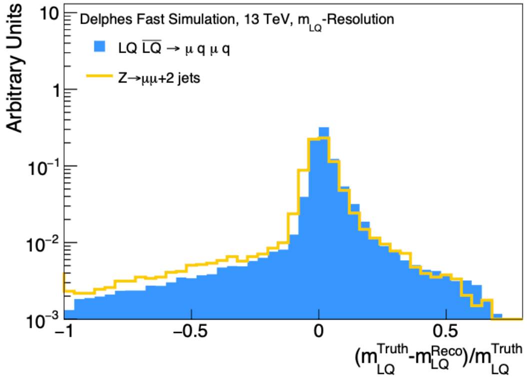
- We observe consistent C-factors with a maximal deviation of 10% for most cases
  - Observed differences can be explained by migration effects
  - E.g. a high transverse mass requirement on reconstruction level might be less efficient that the same requirement of particle level



BSM Model Selections



- C-factors are consistent for all BSM fiducial volumes, when systematic uncertainties are taken into account
- Remaining differences can be again explained by migration effects due to limited detector resolutions

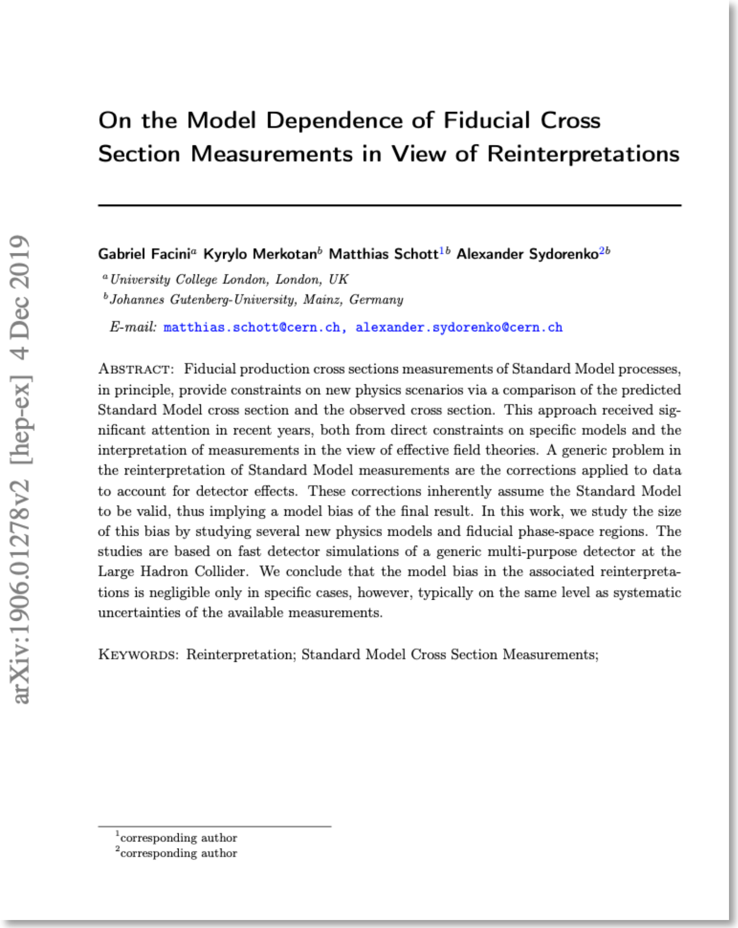


Results, Caveats and “a new rule of thumb”

- The full study is published in
  - Mod.Phys.Lett.A 34 (2019) 38
  - e-Print: 1906.01278 [hep-ex]

- Caveat: Reinterpretation of cross-section measurements that
  - do not agree in the number of final state objects
  - are subject to large migration effects
  - …should be avoided

- For all others: Add a 5-10% (correlated/uncorrelated) uncertainty, cite our paper and you should be fine
  - Clearly this only works, if you want to get a preliminary exclusion limit on your model



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On the Model Dependence of Fiducial Cross Section Measurements in View of Reinterpretations

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ABSTRACT: Fiducial production cross sections measurements of Standard Model processes, in principle, provide constraints on new physics scenarios via a comparison of the predicted Standard Model cross section and the observed cross section. This approach received significant attention in recent years, both from direct constraints on specific models and the interpretation of measurements in the view of effective field theories. A generic problem in the reinterpretation of Standard Model measurements are the corrections applied to data to account for detector effects. These corrections inherently assume the Standard Model to be valid, thus implying a model bias of the final result. In this work, we study the size of this bias by studying several new physics models and fiducial phase-space regions. The studies are based on fast detector simulations of a generic multi-purpose detector at the Large Hadron Collider. We conclude that the model bias in the associated reinterpretations is negligible only in specific cases, however, typically on the same level as systematic uncertainties of the available measurements.

KEYWORDS: Reinterpretation; Standard Model Cross Section Measurements;

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Summary

- Comprehensive study on the modelling bias of fiducial cross sections using 15 fiducial regions and more than 20 signal processes
- Significant biases are expected when observables are subject to migration effects due to limited detector resolution (e.g. E_T^{Miss}) or difference in the number of final state objects
- In all other cases: Assign a 5-10% additional uncertainty before constraining a new BSM Model using existing measurements