Extrapolating Between Electroweak Bosons.

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LHC Physics Discussion
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Outline

1. Introduction: V_2/V_1
2. Mono-jet Backgrounds: Z/W and Z/γ at high p_T
3. Higgs $\to$ Invisible
4. Fun Things to Explore

Introduction: V_2/V_1

Extrapolating from V_1 to V_2

Goal: Use precise measurement for V_1 to get an improved prediction for V_2

$$\frac{d\sigma(V_2)}{dp_T} = \left[\frac{d\sigma(V_2)/dp_T}{d\sigma(V_1)/dp_T}\right]_{\text{theory}} \times \left[\frac{d\sigma(V_1)}{dp_T}\right]_{\text{measured}}$$

- Whenever $d\sigma(V_1)$ is measured (much) more precisely than $d\sigma(V_2)$ can be measured or calculated
- Requires theory prediction for V_2/V_1 to be much more precise than for individual processes
  - This is equivalent to the theory uncertainties being strongly correlated between processes
  - Resulting theory uncertainty is entirely driven by correlation model

Typical examples

- NP and DM mono-jet searches: Z/W and Z/γ at high p_T
- Higgs $\to$ invisible: Z/W in VBF topology and high p_T
- mono-Z and Z+Higgs $\to$ invisible: ZZ/V_1V_2
- m_W measurement: W/Z at low p_T

Theory Uncertainties and Correlations.

$$\frac{\mathrm{d}\sigma(V_2)}{\mathrm{d}p_T} = \left[\frac{\mathrm{d}\sigma(V_2)/\mathrm{d}p_T}{\mathrm{d}\sigma(V_1)/\mathrm{d}p_T}\right]_{\text{theory}} \times \left[\frac{\mathrm{d}\sigma(V_1)}{\mathrm{d}p_T}\right]_{\text{measured}}$$

⇒ Extrapolation hinges entirely on correlations of theory uncertainties between $\mathrm{d}\sigma(V_1)$ and $\mathrm{d}\sigma(V_2)$

- Irrespectively of how it is implemented, whether by taking explicit ratio or combined fit to signal and control regions or ...
- Correlations, hm? Often we don't even know what our theory uncertainties really mean ...

Correlations (only) come from common sources of uncertainties

- In principle straightforward for parametric uncertainties (PDFs, ...)
- More tricky for theory uncertainties (missing higher orders, ...)
  - Scale variations are intrinsically ill-suited for this
  - Not impossible either, but has to be studied case by case, e.g.
    - Use differences between known corrections as correlation model
    - Try to identify largely (in)dependent perturbative series

What is a Scale Variation?

It is not automagically a theory uncertainty!

So What is a Scale Variation?

It is an easy way to obtain (slightly) different expansions for the same quantity

$$\epsilon = \alpha_s(\mu) \qquad \to \qquad \sigma = c_0 + \epsilon\, c_1 + \epsilon^2\, c_2 + \cdots$$

$$\tilde{\epsilon} = \alpha_s(\tilde{\mu}) \qquad \to \qquad \sigma = c_0 + \tilde{\epsilon}\, \tilde{c}_1 + \tilde{\epsilon}^2\, \tilde{c}_2 + \cdots$$

- The full result is the same and independent of the choice of ϵ vs. $\tilde{\epsilon}$
  - We only know the first few orders, which do depend on the choice
  - Comparing both expansions *might* provide a way to estimate the typical size of the missing $\epsilon^3 c_3 + \cdots$ terms
  - It also *might not*, because it only knows about the structures present in c_1 and c_2 and so cannot estimate the effect of possible new structures appearing in c_3 and beyond
- QCD scales are not physical parameters
  - They do not have an uncertainty that can be propagated
  - They also cannot be regarded as the fundamental sources of uncertainties, i.e. they cannot be used as nuisance parameters to imply correlations
  - A priori, scale variations do not imply anything about correlations among different processes or different kinematic regions

Uncertainties in Ratio.

$$\left[\frac{d\sigma(V_2)/dp_T}{d\sigma(V_1)/dp_T}\right]_{\text{theory}} = \frac{c_0(p_T) + \epsilon\, c_1(p_T) + (\epsilon^2\, c_2(p_T) + \cdots)}{d_0(p_T) + \epsilon\, d_1(p_T) + (\epsilon^2\, d_2(p_T) + \cdots)}$$

QCD corrections for W, Z, γ are *largely* the same but also *not entirely*

- Using correlated scale variations between numerator and denominator
  - Scale dependence will largely cancel, can easily reduce by factor 10 or more
  - Possible differences between processes at higher order are precisely not probed by scale variations

  $\Rightarrow$ The resulting residual scale dependence has little to no meaning in terms of uncertainties
- Crucial to identify and separately probe intrinsic differences
  - At minimum, explicitly include some uncorrelated uncertainty components
  - E.g. separately treat heavy-flavor channels

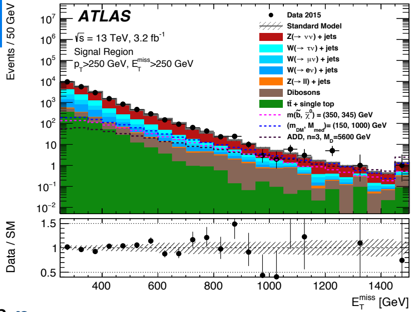
EW corrections for W, Z, γ will generally be different

- There are also important corrections that are common (EW Sudakov logs)

Z/W and Z/γ at high p_T

Mono-jet + MET Search.

[ATLAS EXOT-2015-03; arXiv:1604.07773]



Need precise predictions for $Z(\to \nu\bar{\nu})$+jets and also $W(\to \tau\bar{\nu})$+jets backgrounds

- Combined fit to several control regions
  - $Z(\to \ell\bar{\ell})$+jets: very precise at low p_T, statistics-limited at high p_T
  - $W(\to \ell\bar{\nu})$+jets: much larger statistics
  - γ+jets: clean and large statistics at high p_T
- Effectively amounts to

$$\frac{d\sigma(Z)}{dp_T} = \left[\frac{d\sigma(Z)/dp_T}{d\sigma(W,\gamma)/dp_T}\right]_{\text{theory}} \times \left[\frac{d\sigma(W,\gamma)}{dp_T}\right]_{\text{measured}}$$

- $10 - 20\%$ scale dependence cancels to $< 1\%$ if taken fully correlated
  - Add additional 3% for $Z(\to \nu\bar{\nu})$+jets
  - NLO EW effects taken as uncertainty: $2 - 4\%$ for $Z(\to \nu\bar{\nu})$+jets
  - Total background uncertainty $4 - 12\%$ from lowest to highest E_T^{miss}

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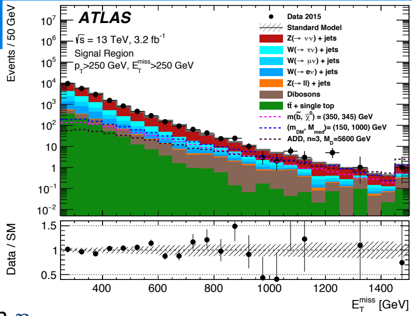

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⇒ Q: Do you think this is realistic, too conservative, or too aggressive?

QCD Corrections.

Recent analysis of theory uncertainties of V+jet ratios at high p_T [Lindert et al. 1705.04664]

Consider 3 uncertainty sources

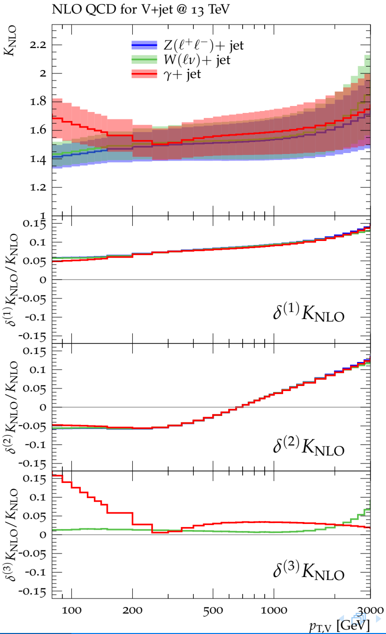
- $\delta^{(1)} K^{(V)}$: from 7-point $\{\mu_R, \mu_F\}$ variation
  - Determines absolute unc. for individual processes, taken as fully correlated
- $\delta^{(2)} K^{(V)}$: p_T-shape uncertainty

$$\frac{p_T^2 - p_{T,0}^2}{p_T^2 + p_{T,0}^2}\,\delta^{(1)} K^{(V)}$$

  - Size still proportional to scale variation
  - Fixed crossing point $p_{T,0} = 600\,\mathrm{GeV}$
- $\delta^{(3)} K^{(V)}$: differences of relative (N)NLO corrections between processes

$$\frac{\sigma^{(V)}_{\mathrm{(N)NLO}}}{\sigma^{(V)}_{\mathrm{(N)LO}}} - \frac{\sigma^{(Z)}_{\mathrm{(N)NLO}}}{\sigma^{(Z)}_{\mathrm{(N)LO}}}$$

  - Serves to decorrelate processes



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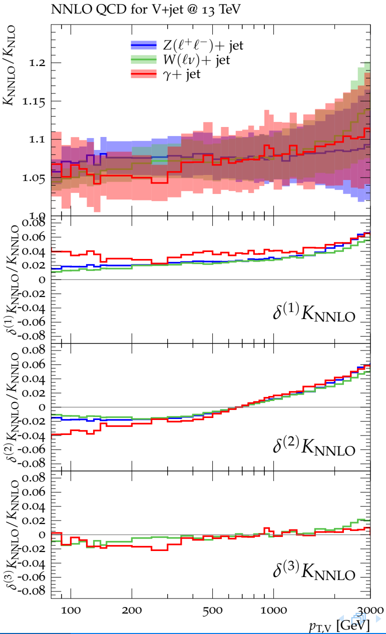
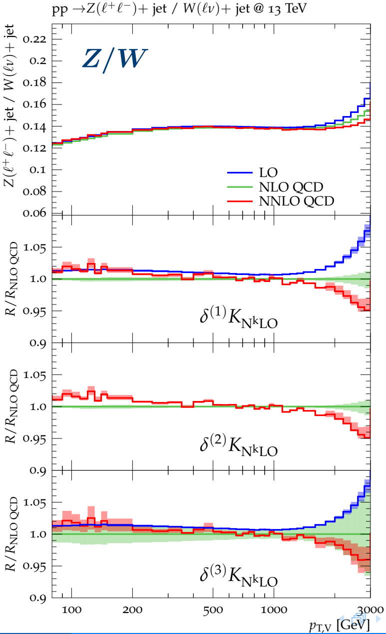


QCD Corrections: Impact on Ratio.

- $\delta^{(1)}K$ and $\delta^{(2)}K$ cancel (by construction)
  - As expected do not capture higher-order effects in ratio
- Process-dependent $\delta^{(3)}K$ drives the overall uncertainty of ratio
  - Sign change in relative correction inevitably leads to a p_T region where uncertainty becomes unreliable



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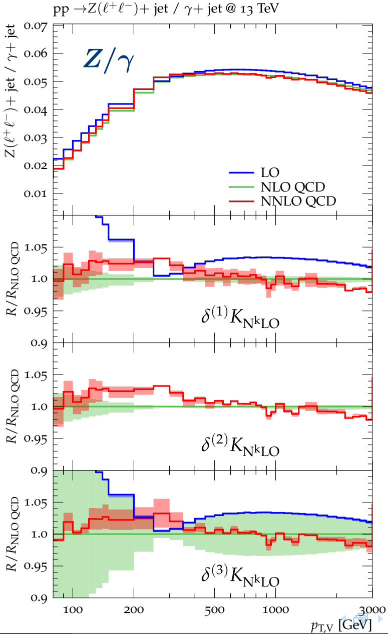
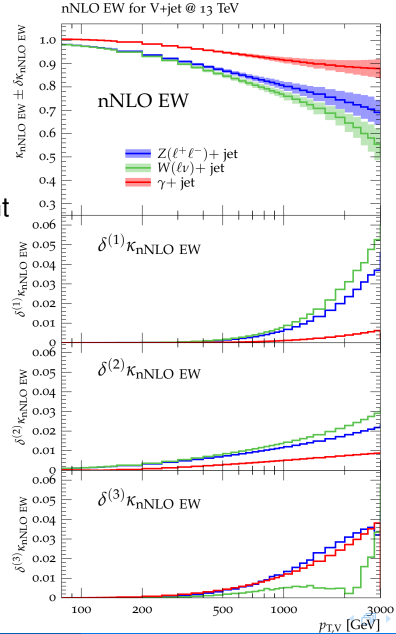
- Important caveat for γ
  - Relies on p_T-dependent smooth isolation to force effective "photon jet" to have invariant mass around m_Z
    - Needs additional uncertainty to account for realistic experimental isolation
  - Fails for $p_T < 200\,\mathrm{GeV}$ where $\delta^{(3)}K$ becomes meaningless



Electroweak Corrections.

EW corrections get large for $m_V \ll p_T$

- Due to (virtual) EW Sudakov logs
  - Can get NNLO estimate from known leading two-loop Sudakov logs
- 3 uncertainty sources to estimate different types of EW effects
  - $\delta^{(1)}\kappa_{\mathrm{EW}}$: higher-order Sudakov logs (treated as correlated)
  - $\delta^{(2)}\kappa_{\mathrm{EW}}$: non-log NNLO effects (treated as uncorrelated)
  - $\delta^{(3)}\kappa_{\mathrm{EW}}$: NLO² cross terms (treated as uncorrelated)
- Mixed QCD-EW corrections
  - Factorize for dominant Sudakov terms
  - $\delta_{\mathrm{mix}} = (0.1\ldots0.4)(\sigma_{\mathrm{QCD+EW}} - \sigma_{\mathrm{QCD\times EW}})$



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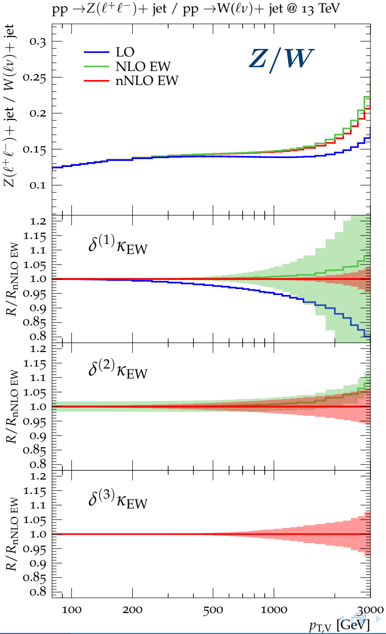

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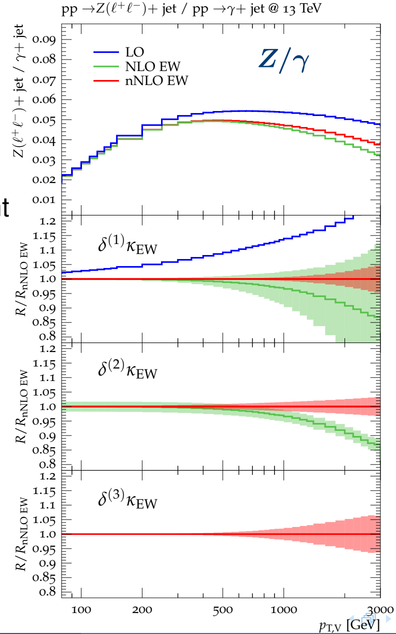
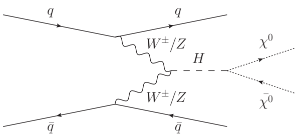


Higgs $\to$ Invisible.

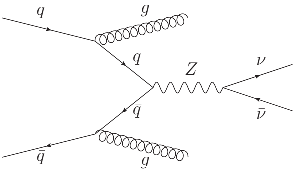
Higgs $\to$ Invisible in VBF.

[ATLAS HIGG-2013-16; arXiv:1508.07869]

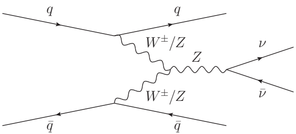
Signal



QCD $Z(\to \nu\bar{\nu})$+jets



EW $Z(\to \nu\bar{\nu})$+jets



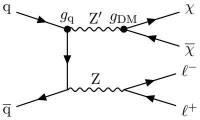
- Simultaneous fit to both signal region and $W(\to \ell\bar{\nu})$+jets and $Z(\to \ell\bar{\ell})$+jets control regions

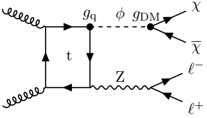
$$\frac{d\sigma^{\mathrm{QCD+EW}}(Z)}{dp_T} = \left[\frac{d\sigma^{\mathrm{QCD+EW}}(Z)/dp_T}{d\sigma^{\mathrm{QCD+EW}}(W)/dp_T}\right]_{\mathrm{theory}} \times \left[\frac{d\sigma^{\mathrm{QCD+EW}}(W)}{dp_T}\right]_{\mathrm{meas.}}$$

  - Effective extrapolation for the sum of QCD and EW production processes
  - In the presence of nontrivial VBF cuts and veto on 3rd jet
- Uses common QCD scale and parton shower variations

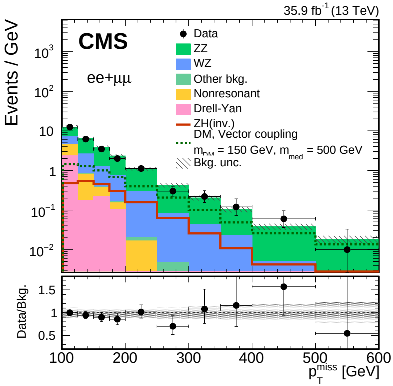
  $\Rightarrow$ Should be very cautious to trust any substantially reduced scale dependence to provide meaningful uncertainty estimate

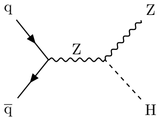
Z+Higgs → Invisible.

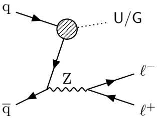




[CMS-EXO-16-052; arXiv:1711.00431]







- Dominant backgrounds:
  - $ZZ \to \ell\bar{\ell}\nu\bar{\nu}$ and $ZW \to \ell\bar{\ell}\ell\bar{\nu}$
- Control regions:
  - $ZZ \to \ell\bar{\ell}\ell\bar{\ell}$ and $ZW \to \ell\bar{\ell}\ell\bar{\nu}$

- Simultaneous fit to signal and control regions with single normalization for all ZZ and ZW channels with ratios taken from theory
  - EW uncertainties assumed anticorrelated between ZZ and ZW
  - QCD uncertainties from scale variations (not sure about correlation assumption)

⇒ Total background uncertainty 15% entirely dominated by theory

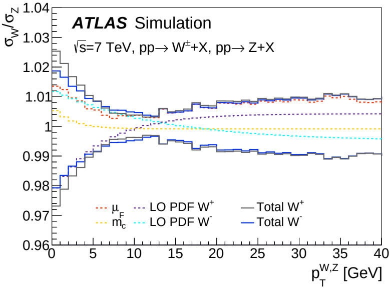
Fun Things to Explore.

m_W Measurement.

Crucially relies on precise modelling of W kinematics at low $p_T^W \lesssim 30\,\mathrm{GeV}$

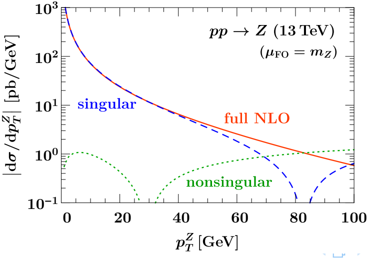
- $\simeq 2\%$ uncertainties in p_T^W translate into $\simeq 10\,\mathrm{MeV}$ uncertainty in m_W

$\Rightarrow$ Use precise low-p_T^Z measurement to get best possible prediction for p_T^W



$$\frac{\mathrm{d}\sigma(W)}{\mathrm{d}p_T} = \left[\frac{\mathrm{d}\sigma(W)/\mathrm{d}p_T}{\mathrm{d}\sigma(Z)/\mathrm{d}p_T}\right]_{\text{theory}} \times \left[\frac{\mathrm{d}\sigma(Z)}{\mathrm{d}p_T}\right]_{\text{measured}}$$

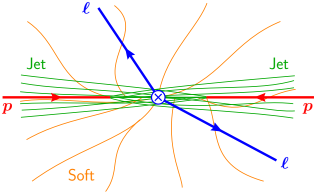
- At first sight, low-p_T region seems more complicated due to large logarithms $\ln(p_T/Q)$ that need to be resummed
- But, cross section is dominated by leading singular terms in p_T/Q
  - They are much less process dependent
  - They can be predicted by p_T resummation



Embrace the Resummation Region.

Leading terms at low p_T factorize

$$\frac{d\sigma(X)}{d\vec{p}_T^{\,X}} = \sum_{a,b} H_{ab\to X}(Q) \int d^2\vec{k}_a\, d^2\vec{k}_b \times B_a(\vec{k}_a)\, B_b(\vec{k}_b)\, S_{ab}(\vec{p}_T^{\,X} - \vec{k}_a - \vec{k}_b) \times \left[1 + \mathcal{O}(p_T^2/Q^2)\right]$$



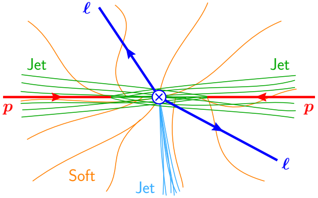
- Hard function $H_{ab\to X}$: Encodes all dependence on hard process
  - Contains all Born and virtual $ab \to X$ matrix elements
- Beam and soft functions: Independent of hard process
  - Only depend on color channel (q vs. g)
  - Determine the all-order p_T dependence

⇒ For $p_T^X \ll Q \equiv \sqrt{p_X^2}$ all color-singlet X are to some degree related

- I really mean *all*: Z, W, Higgs, but also V_1V_2, VH, $V\chi\bar{\chi}$, ...
- True "mono-V" limit (where also most of cross section is)
- It is well-defined to consider different parton channels $ab \to X$ separately
- Allows to develop a quantitative theory correlation model [wip ...]

Can Be Extended to $V+$ jet.

$$\frac{\mathrm{d}\sigma(Vj)}{\mathrm{d}p_T^{Vj}} = \sum_{a,b,j} H_{ab\to Vj}(p_T^V) \times [B_a \otimes B_b \otimes J_j \otimes S_{abj}](p_T^{Vj}) \times \left[1 + \mathcal{O}(p_T^{Vj}/p_T^V)\right]$$



Can increase universality by (in)directly vetoing additional hard emissions

- In a theoretically well-controlled way, i.e. using factorizeable/resummable jet resolution variable, e.g. p_T^{j2} or $p_T^{Vj} \ll Q \sim p_T^V \sim p_T^j$
  - True "mono-jet" limit
- In this limit it makes again sense to separate different partonic channels
  - Dependence on hard Vj process is isolated into hard function $H_{ab\to Vj}$, which contains all Born and virtual $ab \to Vj$ matrix elements
  - Beam, jet, and soft functions are again process independent and only depend on partonic channel and color representation

$\Rightarrow$ Would be worth exploring

Summary.

Extrapolation between different processes (or different kinematic regions of the same process) intrinsically requires understanding correlations in theory uncertainties

- Theory uncertainties are tricky business to begin with
  - A theory prediction without an uncertainty is about as useful as an experimental measurement without uncertainties
  - Precision requires meaningful uncertainties, small is not enough ...
  - Providing a knob is not the same as providing an uncertainty estimate
- QCD scales are not physical parameters
  - They should not be regarded as the fundamental sources of uncertainties

$\Rightarrow$ There is no general procedure for this

- Only general advice: Be careful

$\Rightarrow$ Good news: There are various avenues for improvement and we are starting to explore them