Discussion and Aspects of Vector-Boson p_T Spectrum.

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Outline

1. Introduction
2. Resummation
3. Known Unknowns

Introduction.

Introduction (or early summary).

- Theory uncertainties for Z p_T spectrum cannot compete with per-mille experimental precision (at least not anytime soon)
- At sub-percent level many things matter
  (and which we normally like to sweep under the rug)

“Calibrating” W predictions with Z data

- One way to think about it

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

- Another way: Use common theory framework and tune to fit Z data
  - Tuning Pythia to Z data improves *description* for Z but not automatically *prediction* for W
  - Still relies on how well Pythia predicts the ratio
    (and not just for p_T spectrum but ultimately multi-differentially)

Introduction (or early summary).

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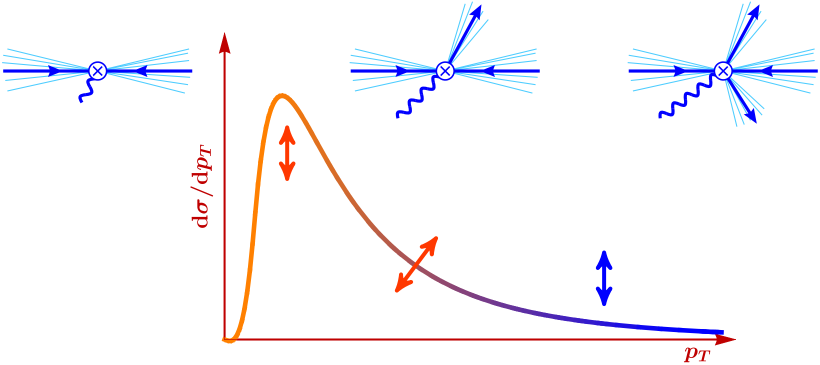
“Calibrating” W predictions with Z data

⇒ *Either way*, correlations of theory uncertainties between $\mathrm{d}\sigma(W)/\mathrm{d}p_T$ and $\mathrm{d}\sigma(Z)/\mathrm{d}p_T$ are crucial

- Correlations (only) come from common sources of uncertainties
  - In principle straightforward for parametric uncertainties (PDFs)
  - More tricky for theory uncertainties but also not impossible:
    E.g. try to probe (largely) independent perturbative effects/series by independent scale variations

The p_T Spectrum.



Spectrum transitions between different kinematic regimes

- Precise prediction requires consistent treatment of theory uncertainties across differential spectrum
  - *quite nontrivial* because it requires nontrivial correlations, which are not going to be captured by simple factor-2 scale variations

Perturbative Structure – Singular vs. Nonsingular.

Consider both differential and cumulative distribution

- Define scaling variable $\tau \equiv p_T^2/Q^2$ and $\sigma(\tau^{\mathrm{cut}}) = \int^{\tau^{\mathrm{cut}}} \mathrm{d}\tau \frac{\mathrm{d}\sigma}{\mathrm{d}\tau}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \sum_k \alpha_s^k \Big\{ \underbrace{c_{k,-1}\delta(\tau) + \sum_{n=0}^{2k-1} c_{kn} \Big[\frac{\ln^n \tau}{\tau}\Big]_+}_{\text{“singular”}} \quad + \quad \underbrace{f_k^{\mathrm{nons}}(\tau)}_{\text{“nonsingular”}} \Big\}$$

$$\sigma(\tau^{\mathrm{cut}}) = \sum_k \alpha_s^k \Big\{ \underbrace{c_{k,-1} + \sum_{n=0}^{2k-1} c_{kn} \frac{\ln^{n+1}\tau^{\mathrm{cut}}}{n+1}}_{\text{“singular”}} \quad + \quad \underbrace{F_k^{\mathrm{nons}}(\tau^{\mathrm{cut}})}_{\text{“nonsingular”}} \Big\}$$

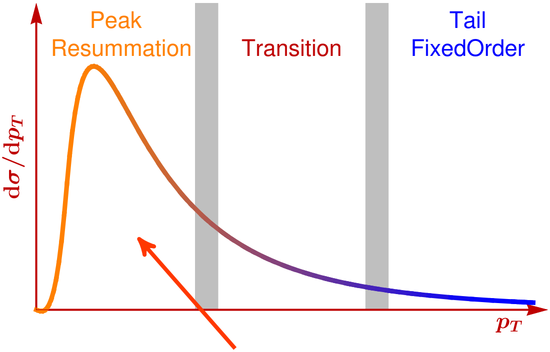
singular: leading-power terms

- to be resummed
- $c_{k,-1}$ contains k-loop virtuals
  (i.e. finite remainder after real-virtual cancellation)

nonsingular: power corrections

- suppressed by relative $\mathcal{O}(\tau)$
- $\tau f_k^{\mathrm{nons}}(\tau)$ and $F_k^{\mathrm{nons}}(\tau^{\mathrm{cut}})$ vanish for $\tau^{(\mathrm{cut})} \to 0$

Different Regions Require Different Theory.



There are no strict boundaries

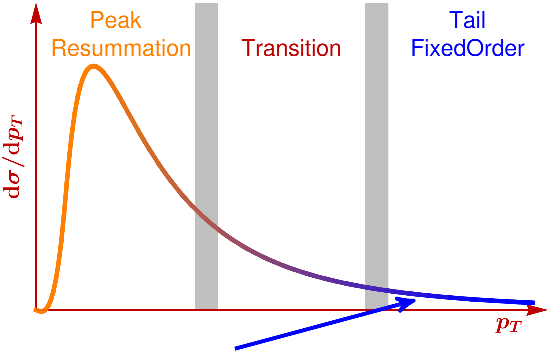
$p_T \to 0$:
only soft or collinear emissions

$p_T \sim Q$:
additional hard emissions

Resummation region

- Spectrum at low $p_T \ll Q$ and cross section with cut $p_T^{\mathrm{cut}} \ll Q$
  - Singular dominate and must be resummed (nonsingular are power-suppressed)
  - Fixed-order by itself becomes meaningless here
  - In MC: Parton shower regime

Different Regions Require Different Theory.



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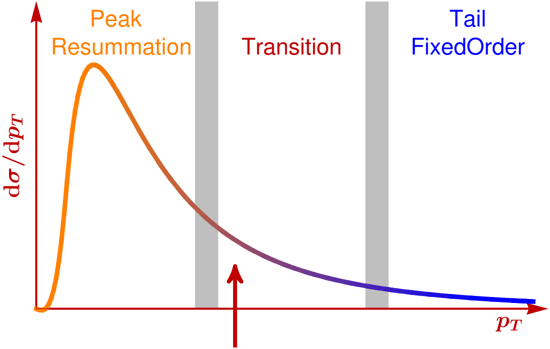
Fixed-order region

- Spectrum at high $p_T \sim Q$
  - Fixed-order calculation for inclusive V+1-jet process
  - In MC: Fixed-order matrix elements
- Integral over $p_T \leq p_T^{\mathrm{cut}} \sim Q$
  - → inclusive Drell-Yan cross section

Different Regions Require Different Theory.



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$p_T \sim Q$:
additional hard emissions

Transition region

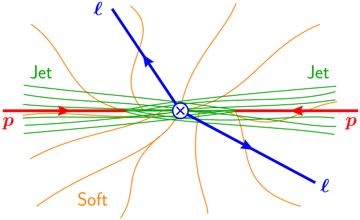
- Experimentally often the most relevant: $p_T \sim 20 - 30\,\mathrm{GeV}$
- While theoretically the most subtle
  - Requires consistent combination of resummation (singular) and fixed-order (nonsingular) pieces
  - In MC: This is where ME+PS matching/merging comes in

Resummation.

Resummation.

Singular terms of the p_T spectrum factorize into hard, collinear, and soft contributions

$$\frac{d\sigma^{\rm sing}}{d\vec{p}_T} = \sigma_0\, H(Q,\mu) \int d^2\vec{k}_a\, d^2\vec{k}_b\, d^2\vec{k}_s \times B_a(\vec{k}_a,\mu,\nu)\, B_b(\vec{k}_b,\mu,\nu) \times S(\vec{k}_s,\mu,\nu)\, \delta(\vec{p}_T - \vec{k}_a - \vec{k}_b - \vec{k}_s)$$



All-order structure of singular terms is fully determined by coupled system of differential equations (including their boundary conditions)

- in virtuality scale μ

$$\mu\frac{dH(Q,\mu)}{d\mu} = \gamma_H(Q,\mu)\, H(Q,\mu)$$

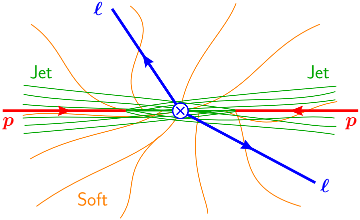
$$\mu\frac{dB(\vec{p}_T,\mu,\nu)}{d\mu} = \gamma_B(\mu,\nu)\, B(\vec{p}_T,\mu,\nu)$$

$$\mu\frac{dS(\vec{p}_T,\mu,\nu)}{d\mu} = \gamma_S(\mu,\nu)\, S(\vec{p}_T,\mu,\nu)$$

Resummation.

Singular terms of the p_T spectrum factorize into hard, collinear, and soft contributions

$$\frac{d\sigma^{\rm sing}}{d\vec{p}_T} = \sigma_0\, H(Q,\mu) \int d^2\vec{k}_a\, d^2\vec{k}_b\, d^2\vec{k}_s$$
$$\times\, B_a(\vec{k}_a,\mu,\nu)\, B_b(\vec{k}_b,\mu,\nu)$$
$$\times\, S(\vec{k}_s,\mu,\nu)\, \delta(\vec{p}_T - \vec{k}_a - \vec{k}_b - \vec{k}_s)$$



All-order structure of singular terms is fully determined by coupled system of differential equations (including their boundary conditions)

- and rapidity scale ν (or ζ)

$$\nu\frac{dB(\vec{p}_T,\mu,\nu)}{d\nu} = -\frac{1}{2}\int d^2\vec{k}_T\, \gamma_\nu(\vec{k}_T,\mu)\, B(\vec{p}_T - \vec{k}_T,\mu,\nu)$$

$$\nu\frac{dS(\vec{p}_T,\mu,\nu)}{d\nu} = \int d^2\vec{k}_T\, \gamma_\nu(\vec{k}_T,\mu)\, S(\vec{p}_T - \vec{k}_T,\mu,\nu)$$

$$\mu\frac{d}{d\mu}\gamma_\nu(\vec{k}_T,\mu) = \nu\frac{d}{d\nu}\gamma_S(\mu,\nu)\delta(\vec{k}_T) = -4\Gamma_{\rm cusp}[\alpha_s(\mu)]\delta(\vec{k}_T)$$

Resummation Orders.

Analytic resummation amounts to solving this system of differential equations

- Formal resummation accuracy is fundamentally defined by perturbative input used for anomalous dimensions and boundary conditions
  - When performed in Fourier space (as in standard CSS), solution is an exponential, and resummation orders map onto the common counting of logarithms in the exponent
  - However, counting logarithms in physical p_T space turns out to be a very slippery slope that should be avoided (and can be [see Ebert, FT '16])

	Boundary conditions	Anomalous dimensions		FO matching
	(singular)	$\gamma_{H,B,S,\nu}$	$\Gamma_{\rm cusp},\ \beta$	(nonsingular)
NLL	1	1-loop	2-loop	-
$\mathrm{NLL}^{(\prime)}+\mathrm{NLO}$	α_s	1-loop	2-loop	α_s
NNLL+NLO	α_s	2-loop	3-loop	α_s
$\mathrm{NNLL}^{(\prime)}+\mathrm{NNLO}$	α_s^2	2-loop	3-loop	α_s^2
$\mathrm{N}^3\mathrm{LL}+\mathrm{NNLO}$	α_s^2	3-loop	4-loop	α_s^2
$\mathrm{N}^3\mathrm{LL}^{(\prime)}+\mathrm{N}^3\mathrm{LO}$	α_s^3	3-loop	4-loop	α_s^3

Perturbative Accuracy (Oversimplified).

Terms in the cross section that are reproduced at some resummation order (not the definition of the order) with $\tau = p_T^2/Q^2$, $L = \ln\tau$, $L_{\mathrm{cut}} = \ln\tau^{\mathrm{cut}}$

$$
\begin{array}{llcccccccll}
 & & \text{LL} & & \text{NLL} & & \text{NLL}' & & \text{NNLL} & & \\
\frac{\sigma(\tau^{\mathrm{cut}})}{\sigma_B} = & & 1 & & & & & & & & \text{LO} \\
+ & \alpha_s\Big[& \frac{c_{11}}{2}L_{\mathrm{cut}}^2 & + & c_{10}L_{\mathrm{cut}} & + & c_{1,-1} & + & & F_1^{\mathrm{nons}}(\tau^{\mathrm{cut}})\Big] & \text{NLO} \\
+ & \alpha_s^2\Big[& \vdots & + & \vdots & + & \vdots & + & \vdots & &
\end{array}
$$

$$
\begin{array}{llcccccccll}
\frac{1}{\sigma_B}\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = & \alpha_s/\tau\Big[& c_{11}L & + & c_{10} & + & & & & \tau f_1^{\mathrm{nons}}(\tau)\Big] & \text{LO}_1 \\
+ & \alpha_s^2/\tau\Big[& c_{23}L^3 & + & c_{22}L^2 & + & c_{21}L & + & c_{20} & + \; \tau f_2^{\mathrm{nons}}(\tau)\Big] & \text{NLO}_1 \\
+ & \alpha_s^3/\tau\Big[& \vdots & + & \vdots & + & \vdots & + & \vdots & &
\end{array}
$$

- Lowest perturbative accuracy at all p_T requires (N)LL+LO$_1$
  - Provided by LO ME+PS, also plain Pythia (has full ME for first emission)
  - LO is naturally part of LL and so automatically included

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 & +\;\alpha_s^2\big[& \vdots & + & \vdots & + & \vdots & + & \vdots & & \\
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 & +\alpha_s^3/\tau\big[& \vdots & + & \vdots & + & \vdots & + & \vdots & &
\end{array}
$$

- NLO+PS matching (MC@NLO, POWHEG) adds full NLO to $\sigma(\tau^{\rm cut})$
  - Improves accuracy for $\sigma(\tau^{\rm cut} \sim 1)$ (incl. cross section) to NLO
  - Does not automatically improve formal accuracy of spectrum beyond ME+PS

Perturbative Accuracy (Oversimplified).

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+\,\alpha_s^3/\tau\big[& \vdots & + & \vdots & + & \vdots & + & \vdots & &
\end{array}$$

- NLL′ and NNLL fully incorporate 1-loop virtuals ($c_{1,-1}$) into resummation and therefore naturally match to NLO
- Similarly NNLL′ and N^{3}LL incorporate 2-loop virtuals and match to NNLO

Variety of Approaches/Implementations.

[Collins, Soper, Sterman], [Balazs, Nadolsky, Yuan], [Bozzi, Catani, de Florian, Ferrera, Grazzini], [Becher, Luebbert, Neubert, Wilhelm], [Neill, Rothstein, Vaidya], [D'Alesio, Echevarria, Idilbi, Melis, Scimemi, Vladimirov], [...]

- Differences are mainly in precise choice of
  - Boundary conditions to the solution (starting point of the evolution)
  - Precise choice of how resummation is turned off (endpoint of the evolution)
  - Various approximations along the way
- These choices determine the actual form of logarithms that are being resummed
  - Canonical Fourier (b) space: $\ln(bm_Z)$
  - Modified b space: $\ln(1 + bQ)$
  - Canonical p_T space: $\ln(p_T/m_Z)$
  - p_T space with profile scales: $\ln(\mu_T(p_T)/\mu_H)$
  - ...
  - Can matter for numerical results and perturbative uncertainties/precision
- In the end, precision is given by the size of the perturbative uncertainties, *only if* they are estimated to that purpose (e.g. to cover the all-order result)

Interlude: What is a Scale Variation?

It is not automagically a theory uncertainty!

Interlude: 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 $+\cdots$ terms, but it also *might not*
- μ (or ϵ) is not a physical quantity that has an uncertainty that is being propagated (unlike physical parameters like quark masses, PDFs, etc.)
  - A priori, scale variations do not imply anything about correlations, e.g., among different processes
  - Asymmetric variations have no meaning in terms of uncertainties

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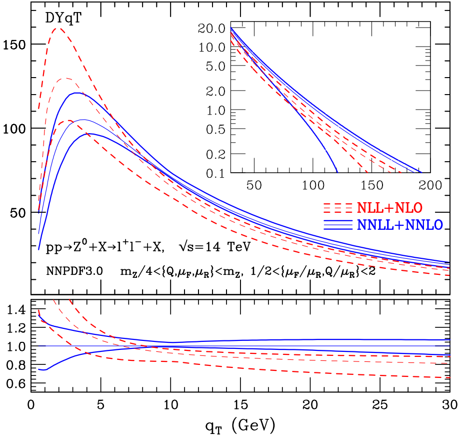
$$\tilde{\epsilon} = \alpha_s(\tilde{\mu}) \qquad \to \qquad \sigma = c_0 + \tilde{\epsilon}\, \tilde{c}_1 + \tilde{\epsilon}^2\, \tilde{c}_2 + \cdots$$

Extra care is required for differential spectra

- Additional reasons why they might not capture uncertainty
  - Resummation scales often have quadratic dependence from double logs
  - Scale variations can cross each other or the central result at some point in the spectrum
- A priori, estimate uncertainty at given point in the spectrum
  - Uncertainties at nearby points are clearly strongly correlated
  - Do not imply or encode long-range correlations across spectrum (i.e. between different kinematic regions)

Resummation Precision.

- Current perturbative uncertainties at NNLL′+NNLO are ∼ 5-10%
- N^{3}LL has recently become available
  [Li, Zhu '16; Vladimirov '16]
  - Expect some (but not huge) improvement
- More substantial improvement can be expected at N^{3}LL′
  - Requires 3-loop p_T beam function (TMD PDF) (not easy ...)
  - Hard to imagine that it will realistically get below 2%



[Catani, de Florian, Ferrera, Grazzini '15]

- Compare: Thrust spectrum in $e^+e^- \to q\bar{q}$ at $Q = m_Z$ has ≃ 2% precision at N^{3}LL′+N^{3}LO

Known Unknowns.

Resummation for W/Z Ratio.

Most ingredients are the same, so expect substantial cancellations, *but*

- At higher order intrinsic differences between W and Z start to appear
  - Vector and axial currents differ by singlet terms starting at NNLL′
    They are often neglected since tiny in inclusive cross section
  - Gluon PDF can have different relative contributions to sea-quark vs. valence-quark beam functions so different flavor mix can leave remnants
- $Q = m_W < Q = m_Z$ causes the p_T spectra to be slightly shifted already for dominant valence-quark partonic channels
  - Induces a shape in W/Z ratio sensitive to exact peak position and shape
  - Analytic resummations are (mostly) in b space and only indirectly get the resummed p_T spectrum by Fourier-transforming the resummed b-spectrum
  - In contrast, p_T-ordered parton shower is much closer to performing the resummation directly in physical p_T space [Monni, Re, Torrielli '16; Ebert, FT '16]
  - Unclear to what extent different resummation approaches could induce a small bias that would normally be irrelevant but get amplified in ratio
    (I wouldn't think so but wouldn't be surprised either)

$\Rightarrow$ At sub-% level precision would really require a dedicated analysis

Power Corrections.

$$\mathrm{d}\sigma^{\mathrm{FO}}(\mu_{\mathrm{FO}}) = \underbrace{\mathrm{d}\sigma^{\mathrm{sing}(\mu_{\mathrm{FO}})}} + \mathrm{d}\sigma^{\mathrm{nons}}(\mu_{\mathrm{FO}})$$

$$\Rightarrow \qquad \mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{resum}} \qquad + \mathrm{d}\sigma^{\mathrm{nons}}(\mu_{\mathrm{FO}})$$

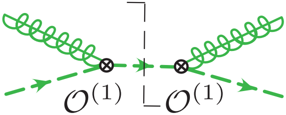
- Analytic resummation only captures leading-power singular terms
- Power-suppressed nonsingular terms are added in fixed order
  - They also contain large logarithms ($\tau = p_T^2/Q^2$)

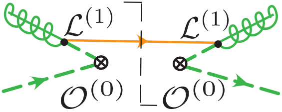
$$\tau\frac{\mathrm{d}\sigma^{\mathrm{nons}}}{\mathrm{d}\tau} \sim \tau\Big[\alpha_s(1+\ln\tau) + \alpha_s^2(\quad 1 \quad + \ln\tau\ + \ln^2\tau + \ln^3\tau) + \cdots\Big] + \mathcal{O}(\tau^2)$$

e.g. for $\tau = 0.01$ $\quad \sim \alpha_s^2(0.01 + 0.05 + 0.21\ + 0.98)$

  - Relative to *resummed* singular they are actually only power-suppressed if they are being resummed as well
  - p_T resummation at subleading power is much more complicated and currently not available even at LL (but it is not impossible either)

Power Corrections.





Explicit calculation of $\alpha_s \ln$ and $\alpha_s^2 \ln^3$ next-to-leading power terms

(for (beam)thrust but general conclusions also apply to p_T) [Moult, Rothen, Stewart, FT, Zhu '16]

- New channels appear at subleading power (e.g. soft quarks) that have no leading-power analog
    - Different color structure already at LL: C_F^2 vs. $T_F(C_F + C_A)$
    - Multiplying nonsingular by leading-power Sudakov exponent is not correct even at LL
- Numerically important type of contribution are “kinematic” power corrections that depend on PDF derivatives $x f_q'(x)$
    - Become less likely to cancel in W/Z ratio
    - Might in fact be captured reasonably well in Pythia due to it enforcing momentum conservation at each splitting

⇒ Warrants a dedicated analysis

Nonperturbative Effects.

Nonperturbative corrections can be treated in field theory based on singular factorization theorem

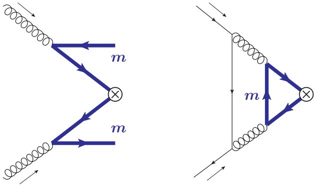
- In principle there are flavor-independent and flavor-dependent effects (though the latter are often neglected)
  - Cause few-% uncertainty at $p_T = 5\,\mathrm{GeV}$, quickly increase below that
  - Should at least partially cancel in W/Z ratio
- For $\Lambda_{\mathrm{QCD}}^2 \ll p_T^2$ (peak and above)
  - Can be expanded in powers of $\Lambda_{\mathrm{QCD}}^2/p_T^2 \sim \Lambda_{\mathrm{QCD}}^2 b^2$ and parametrized by nonperturbative coefficients of first correction
  - Typically done in b space, but equivalently possible in physical p_T space
  - Parameters can be fitted from DY data, including low-energy data [see e.g. Echevarria, Idilbi, Kang, Vitev '14; Su, Isaacson, C-P Yuan, F Yuan '14; D'Alesio, Echevarria, Melis, Scimemi '14; ...]
- For $\Lambda_{\mathrm{QCD}}^2 \sim p_T^2$ (below peak)
  - Requires full shape of nonperturbative TMDPDF
- In Pythia modelled primarily through primordial/intrinsic k_T (flavor-blind)
  - Also nontrivial interplay with ISR shower parameters (cutoff, α_s^{ISR})

$\Rightarrow$ More work needed to draw firm conclusions for W/Z ratio

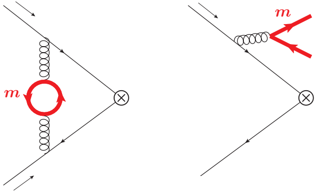
Massive Quark Effects.

(→ see talk by Daniel tomorrow)

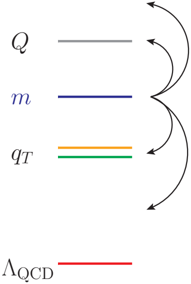
“Primary” mass effects



“Secondary” mass effects



Multi-scale problem with several possible scale hierarchies



- $m_b \simeq 5\,\mathrm{GeV}$ is right around peak so p_T distribution sweeps through different regimes
  - $\Lambda_{\mathrm{QCD}} \ll m_b \ll p_T \ll Q$
  - $\Lambda_{\mathrm{QCD}} \ll m_b \sim p_T \ll Q$
  - $\Lambda_{\mathrm{QCD}} \ll p_T \ll m_b \ll Q$
- Massless (5FS) treatment only applies in the first case
- Mass effects enter at NNLL′ for $b\bar{b} \to Z$ and at NLL′ for $c\bar{s} \to W$

⇒ Expect few-% level effects, primary do not cancel in W/Z ratio

QED Corrections.

Many studies on QED/EW and mixed QCD-QED/EW effects
(→ see previous talk by Stefan and talks tomorrow by Zbigniew, Fulvio, Scott)

I'm not actually aware of a dedicated study of QED effects in analytic resummed calculations (could just be my own ignorance)

- All resummation ingredients (boundary conditions, anomalous dimensions) receive corrections from soft and collinear photon radiation
  - Relative parametric size of $\mathcal{O}(\alpha_{\mathrm{em}}/\alpha_s) \sim \mathcal{O}(\%)$
  - Effects will clearly not drop out of W/Z ratio
- QCD+QED shower in Pythia presumably captures this?
  (again my ignorance ...)

⇒ Should be straightforward to evaluate/incorporate
(certainly when one ignores initial-final-state interference)

PDFs and α_s.

PDFs: Not much for me to say (→ see talks by Jan and Sergey tomorrow)

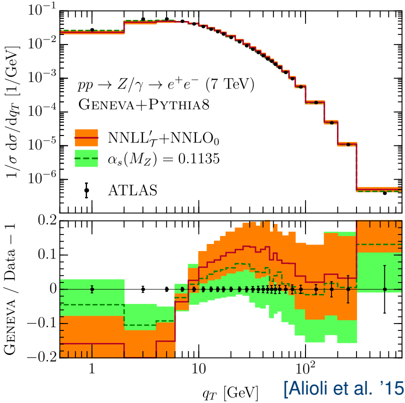
- ∼ 2% uncertainty at low p_T, mostly affect normalization and not shape

⇒ Physical parameters so in principle straightforward to take into account correlations for W/Z ratio

To be aware of: $\alpha_s(m_Z)$

- p_T tail is $\sim \alpha_s$ and α_s also appears in resummation
- Various extractions clearly favor much lower values than PDG average
  - In particular thrust in e^+e^- with high resummation
- Changing $\alpha_s(m_Z) = 0.118 \to 0.114$ has ∼ 5% effect on p_T spectrum

⇒ Should drop out of W/Z ratio
(and also easy to propagate through)



[Alioli et al. '15]

Summary.

	Uncertainty or size	Analytic resummation	Pythia	Leftover effect on W/Z
Singular resummation	5-10%	$\checkmark\checkmark\checkmark$	$\checkmark$	$\lesssim$ % (?)
Power corrections	few %	($\times$)	($\checkmark$)?	?
Nonperturbative	few %	($\checkmark$)	($\checkmark$)	?
Massive quarks	few % (?)	$\times$ ($\rightarrow$ $\checkmark$)	?	few % (?)
QED	$\lesssim$ % (?)	$\times$	$\checkmark$ (?)	$\lesssim$ % (?)
PDFs	2%	$\checkmark$	$\checkmark$	$\checkmark$
$\alpha_s(m_Z)$	up to 5%??	$\checkmark$	$\checkmark$	$\checkmark$

- Most ? could be addressed (some just mean that I don't know ...)
- Though it is a bit unsettling it is not unbelievable that in the end plain Pythia currently seems to describe the W/Z ratio best
  - Question of the uncertainty when used as prediction remains