Treatment of Fiducial Acceptance Cuts in q_T Resummation.

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Work in collaboration with M. Ebert, I. Stewart, and F. Tackmann
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Recap of inclusive Drell-Yan.

Consider $p(P_a^\mu)p(P_b^\mu) \to Z/\gamma^*(q^\mu) \to \ell^-(k_1^\mu)\ell^+(k_1^\mu)$:

- Cross section factorizes into leptonic/hadronic tensor, $q^\mu L_{\mu\nu} = q^\mu W_{\mu\nu} = 0$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4 q} = L^{\mu\nu}(q^\mu) W_{\mu\nu}(q^\mu, P_a^\mu, P_b^\mu)$$

- Leptonic tensor is simple, by convention includes line-shape (here: photon case)

$$L^{\mu\nu}(q^\mu) \equiv L(q^2)(q^2 g^{\mu\nu} - q^\mu q^\nu)\,, \qquad L(q^2) \sim \frac{\alpha_{\mathrm{em}}^2}{q^4}$$

  - $\mathrm{d}\sigma/\mathrm{d}^4 q = L(q^2) W(q^\mu, P_a^\mu, P_b^\mu)$ proportional to trace $W \equiv g_{\mu\nu} W^{\mu\nu}$

- W is scalar, so only depends on $q^2 \equiv Q^2$ and $P_{a,b} \cdot q = E_{\mathrm{cm}} \sqrt{Q^2 + q_T^2}\, e^{\pm Y}$

  - Resummation limit $q_T \to 0$ of W receives only quadratic power corrections:

$$W = \Big\{ \delta(q_T^2) + \alpha_s \Big[\frac{\ln q_T^2/Q^2}{q_T^2} + \frac{1}{q_T^2} + \delta(q_T^2) \Big] + \ldots \Big\} \Big[1 + \mathcal{O}\Big(\frac{q_T^2}{Q^2}\Big) \Big]$$

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Leptonic observables & tensor decomposition.

Consider $p(P_a^\mu)p(P_b^\mu) \to Z/\gamma^*(q^\mu) \to \ell^-(k_1^\mu)\ell^+(k_1^\mu)$ and measure $k_{1,2}^\mu$:

- Parametrize decay phase space by two rest-frame angles $\cos\theta, \varphi$:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4 q\, \mathrm{d}\cos\theta \mathrm{d}\varphi} = L^{\mu\nu}(q^\mu, \cos\theta, \varphi) W_{\mu\nu}(q^\mu, P_a^\mu, P_b^\mu)$$

- Leptonic tensor carries dependence on lepton momenta (shown: P-even case)

$$L^{\mu\nu}(q^\mu, \cos\theta, \varphi) \sim \frac{\alpha_{\mathrm{em}}^2}{q^4}(k_1^\mu k_2^\nu + k_2^\mu k_1^\nu - g^{\mu\nu} k_1 \cdot k_2)$$

- Decompose $W^{\mu\nu}$ into nine allowed orthogonal tensor structures $K_i^{\mu\nu}$:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4 q\, \mathrm{d}\cos\theta \mathrm{d}\varphi} = \sum_{i=-1}^{7} (L \cdot K_i)(K_i \cdot W) \equiv \sum_{i=-1}^{7} L_i W_i$$

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$$= \frac{\mathrm{d}\sigma}{\mathrm{d}^4q}\Big[1 + \cos^2\theta + \sum_{i=0}^{7} A_i f_i(\cos\theta, \varphi)\Big]$$

▶ K_i map onto spherical harmonics $f_i(\cos\theta, \varphi)$ with angular coefficients A_i

Resummation in the strict $q_T \to 0$ limit.

What are the leading singular terms as $q_T \to 0$ that must be resummed?

- Expand hadronic structure functions as $W_i \to W_i^{\rm res}$

▶ All* vanish except for $W_{-1}^{\rm res} \leftrightarrow \mathrm{d}\sigma^{\rm res}/\mathrm{d}q_T$ and $W_4^{\rm res} \leftrightarrow \mathrm{d}A_{FB}^{\rm res}/\mathrm{d}q_T$

*Up to intrinsically nonperturbative effects

- Expand leptonic tensor as $L_i(q_T, \cos\theta, \varphi) \to L_i(q_T = 0, \cos\theta, \varphi)$
  - ▶ Leptons are exactly back to back, $p_T^{\ell^-} = p_T^{\ell^+}$
  - ▶ No distinguished transverse direction anymore, so $L_i(\not{\varphi})$

▶ $$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\cos\theta\,\mathrm{d}\varphi} \sim \frac{1}{2\pi}\Big[(1+\cos^2\theta)W_{-1}^{\rm res} + \cos\theta\, W_4^{\rm res}\Big] \quad \text{as} \quad q_T \to 0$$

- Underappreaciated fact: $W_{-1}^{\rm res} \neq W_4^{\rm res}$, easy to see from FO expansion:

$$W_i^{\rm res} = \delta(q_T)\sum_q Q_q^{\rm EW}(i) f_q f_{\bar q} + \mathcal{O}(\alpha_s)$$

  - ▶ Calculating $A_4^{\rm FO} \times \mathrm{d}\sigma^{\rm res}/\mathrm{d}q_T$ does not recover $A_{\rm FB}^{\rm res}/\mathrm{d}q_T$ at small q_T

Resumming fiducial power corrections.

What are the power corrections to $\sum_i L_i(q_T = 0)\, W_i^{\rm res}$?

- Hadronic structure functions are scalar, so $W_i = W_i^{\rm res}\big[1 + \mathcal{O}(q_T^2/Q^2)\big]$
- L_i are also scalar, but $L_i(q_T) = L_i(0)\big[1 + \mathcal{O}(q_T/Q)\big]$
  in the presence of practically any measurements on the decay products

WHY? Boosting back into lab frame from rest frame (say: Collins-Soper frame), we have

$$p_{\ell^-}^\mu = \frac{Q}{2}\Big(\gamma + \frac{q_T}{Q} s_\theta c_\varphi, \gamma s_\theta c_\varphi + \frac{q_T}{Q}, s_\theta s_\varphi, c_\theta\Big)\,, \quad \gamma = \frac{\sqrt{Q^2 + q_T^2}}{Q}$$

- ▶ Measuring p_T^ℓ and/or η_ℓ results in a linear dependence on q_T

- We can fix this – we can even exploit it!

  By restoring the exact q_T dependence of the L_i,
  we resum all linear power corrections to all orders in α_s:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4 q\, \mathrm{d}\cos\theta\, \mathrm{d}\varphi} = \Big[L_{-1}(q_T) W_{-1}^{\rm res} + L_4(q_T) W_4^{\rm res}\Big]\Big[1 + \mathcal{O}(q_T^2/Q^2)\Big]$$

Relation to literature.

- Keeping $L_i(q_T)$ exact allows for nonzero recoil in the resummation
  ... see numerics on the next slides for examples of this

- Equivalent to evaluating tree-level matrix element in a (sensibly) boosted frame, as done e.g. in ResBos or DyRes

- One-parameter ambiguity in how to distribute p_T between annihilating partons
  [Catani, Ferrera, de Florian, Grazzini '15]

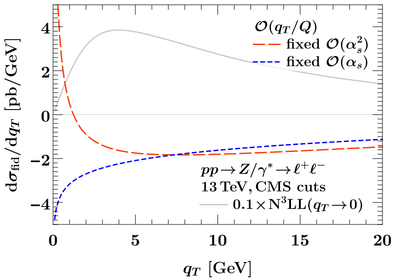
  - Corresponds to slightly rotated basis choice for the $K_i^{\mu\nu}$

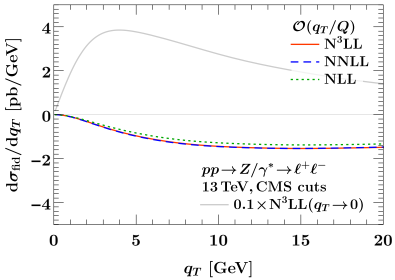
- Can show using $K_i^{\mu\nu}$ that the difference is strictly $\mathcal{O}(q_T^2/Q^2)$

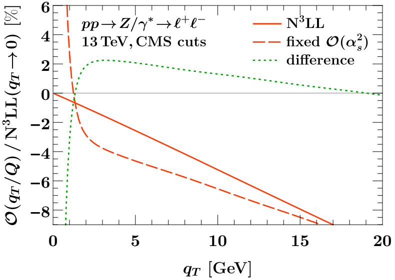
  - Change of basis for P-even structure functions is known
    [Boer, Vogelsang '06]

- Linear power corrections to fiducial q_T spectrum are unique

Numerical impact: $\mathrm{d}\sigma_{\mathrm{fid}}/\mathrm{d}q_T$





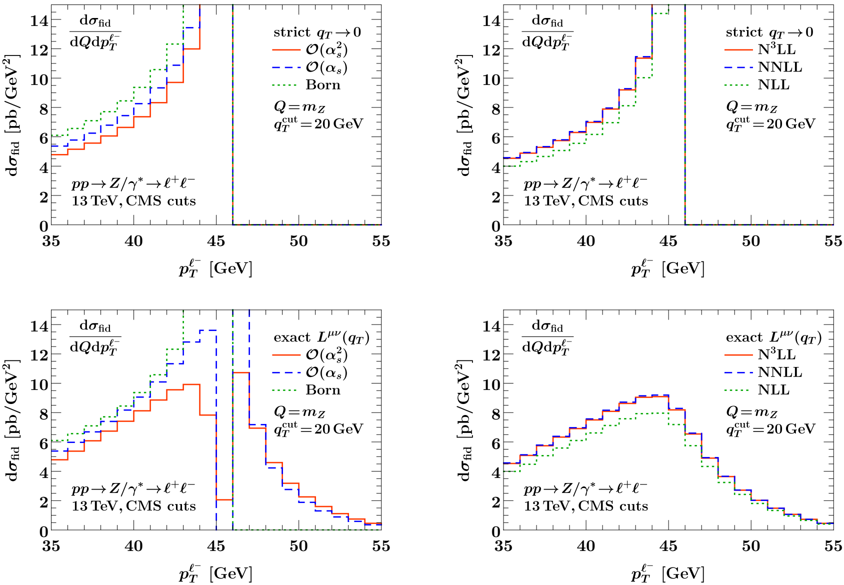


Shorthand for fiducial power corrections:

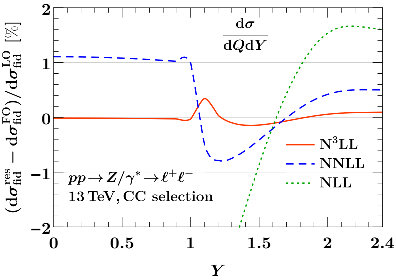
$$\mathcal{O}(q_T/Q) \equiv \sum_i \Big[L_i(q_T) - L_i(0)\Big] W_i^{\mathrm{res}}$$

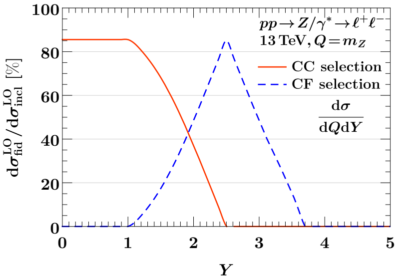
CMS cuts: $p_T^{\min} = 25\,\mathrm{GeV}, |\eta_\ell| < 2.4$

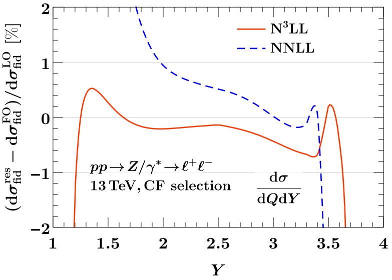
Numerical impact: $\mathrm{d}\sigma_{\mathrm{fid}}/\mathrm{d}p_T^{\ell^-}$



Application: Resummation effects in $\mathrm{d}\sigma_{\text{fid}}/\mathrm{d}Y$







Question: Is the fiducial rapidity spectrum sensitive to resummation effects?
[see also talk by M. Boonekamp in Durham]

Note: Requires care to ensure

$$\int \mathrm{d}q_T \left[\sigma^{\text{incl}}_{\text{res}} - \sigma^{\text{incl}}_{\text{sing}}\right] = 0$$

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- Demonstrated that linear power corrections in the fiducial q_T spectrum arise (only) from the cuts on leptonic phase space
- Enables their resummation at N^{3}LL, including the physical effect of recoil
- Showed first results for the lepton p_T spectrum at N^{3}LL
- Confirmed presence of resummation effects
in the fiducial Z rapidity spectrum – stay tuned for LH study

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Thank you for your attention!