The Drell-Yan q_T Spectrum and Its Uncertainty at $\mathrm{N^3LL'}$

Johannes Michel
MIT Center for Theoretical Physics

SCET 2022
University of Bern, April 21

The Drell-Yan q_T Spectrum and Its Uncertainty at $\mathrm{N^3LL'}$

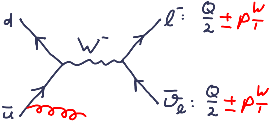
[to appear soon]

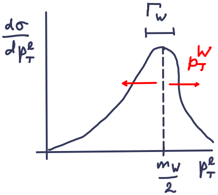
in collaboration with

G. Billis, M. Ebert, F. Tackmann



Want to measure m_W, but too much information about the neutrino is lost:





⇒ Need precise theory predictions for $\mathrm{d}\sigma/\mathrm{d}p_T^Z$ and $\mathrm{d}\sigma/\mathrm{d}p_T^W$ to model the p_T^W spectrum using precisely measured p_T^Z as input

$$m_W^{\mathrm{ATLAS}} = 80370 \pm 7_{\text{stat.}} \pm 11_{\text{exp. syst.}} \pm 14_{\text{theory}}\,\mathrm{MeV} = 80370 \pm 19\,\mathrm{MeV}$$

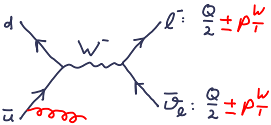
[ATLAS, 1701.07240]

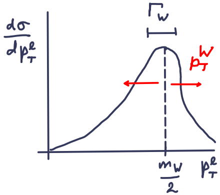
$$m_W^{\mathrm{LHCb}} = 80354 \pm 23_{\text{stat.}} \pm 10_{\text{exp. syst.}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\,\mathrm{MeV} = 80354 \pm 32\,\mathrm{MeV}$$

[LHCb, 2109.01113]

Motivation: Measuring m_W at ~~the LHC~~ any hadron collider

Want to measure m_W, but too much information about the neutrino is lost:





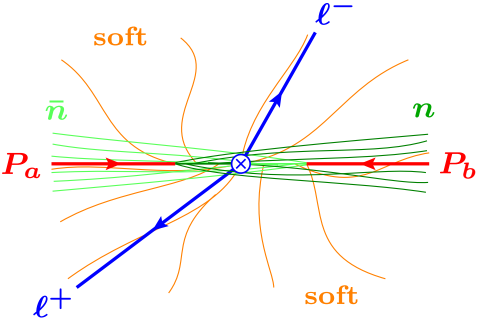
$\Rightarrow$ Need precise theory predictions for $\mathrm{d}\sigma/\mathrm{d}p_T^Z$ and $\mathrm{d}\sigma/\mathrm{d}p_T^W$ to model the p_T^W spectrum using precisely measured p_T^Z as input

~~Challenges~~ Opportunities for theory

- Need sub-percent precision on $\mathrm{d}\sigma/\mathrm{d}p_T^Z$ and $\mathrm{d}\sigma/\mathrm{d}p_T^W$
  - Leave no stone unturned: QCD three-loop corrections, QED radiative corrections, quark mass effects, parametric and nonperturbative uncertainties
- Resum singular terms & large logarithms $\dfrac{\alpha_s^n}{q_T}\left(\ln\dfrac{q_T}{Q}\right)^{2n-1}$ to all orders in α_s

$$\frac{d\sigma}{dq_T} = \frac{d\sigma^{\rm res}_{\rm sing}}{dq_T} + \frac{d\sigma^{\rm FO}_{\rm nons}}{dq_T} = \frac{d\sigma^{\rm res}_{\rm sing}}{dq_T} + \left[\frac{d\sigma^{\rm FO}_{\rm full}}{dq_T} - \frac{d\sigma^{\rm FO}_{\rm sing}}{dq_T}\right]$$

$$\frac{d\sigma_{\rm sing}}{dQ\,dY\,dq_T} = \sum_q H_{q\bar q}(Q,\mu)\;\; q_T \int_0^\infty db_T\, b_T\, J_0(q_T b_T) \times B_q(x_a, b_T, \mu, Q/\nu)\, B_{\bar q}(x_b, b_T, \mu, Q/\nu)\, S(b_T, \mu, \nu) + (q \leftrightarrow \bar q)$$



Perturbative ingredients: Factorized singular cross section at N^{3}LL$'$

$$\frac{d\sigma}{dq_T} = \frac{d\sigma^{\rm res}_{\rm sing}}{dq_T} + \frac{d\sigma^{\rm FO}_{\rm nons}}{dq_T} = \frac{d\sigma^{\rm res}_{\rm sing}}{dq_T} + \left[\frac{d\sigma^{\rm FO}_{\rm full}}{dq_T} - \frac{d\sigma^{\rm FO}_{\rm sing}}{dq_T}\right]$$

$$\frac{d\sigma_{\rm sing}}{dQ\,dY\,dq_T} = \sum_q H_{q\bar q}(Q,\mu)\; q_T \int_0^\infty db_T\, b_T\, J_0(q_T b_T) \times B_q(x_a, b_T, \mu, Q/\nu)\, B_{\bar q}(x_b, b_T, \mu, Q/\nu)\, S(b_T, \mu, \nu) + (q \leftrightarrow \bar q)$$

Implemented in `SCETlib` C++ numerical library [Ebert, JKLM, Tackmann]:

- Three-loop hard function [Baikov et al. ’09; Lee et al. ’10; Gehrmann et al. ’10, ’20; Czakon et al. ’21]
- Three-loop matching of beam functions onto PDFs
  [Luo, Yang, Zhu, Zhu ’19; Ebert, Mistlberger, Vita ’20]
- Three-loop perturbative soft function for exponential regulator
  [Li, Zhu, Neill ’16; Li, Zhu, ’16]
- Four-loop cusp, three-loop noncusp anomalous dimensions
  [Brüser, Grozin, Henn, Stahlhofen ’19; Henn, Korchemsky, Mistlberger ’20; v. Manteuffel, Panzer, Schabinger ’20] [Moch, Vermaseren, Vogt ’05; Idilbi, Ma, Yuan ’06; Li, Zhu, ’16; Vladimirov ’16]
- Fiducial power corrections $\mathcal{O}(q_T/Q)$ resummed through exact acceptance
  [Ebert, JKLM, Stewart, Tackmann ’20]

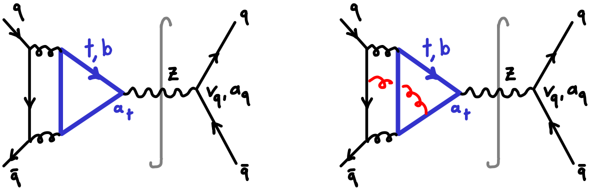
Perturbative ingredients: Factorized singular cross section at N^{3}LL$'$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} = \frac{\mathrm{d}\sigma^{\mathrm{res}}_{\mathrm{sing}}}{\mathrm{d}q_T} + \frac{\mathrm{d}\sigma^{\mathrm{FO}}_{\mathrm{nons}}}{\mathrm{d}q_T} = \frac{\mathrm{d}\sigma^{\mathrm{res}}_{\mathrm{sing}}}{\mathrm{d}q_T} + \left[\frac{\mathrm{d}\sigma^{\mathrm{FO}}_{\mathrm{full}}}{\mathrm{d}q_T} - \frac{\mathrm{d}\sigma^{\mathrm{FO}}_{\mathrm{sing}}}{\mathrm{d}q_T}\right]$$

$$\frac{\mathrm{d}\sigma_{\mathrm{sing}}}{\mathrm{d}Q\,\mathrm{d}Y\,\mathrm{d}q_T} = \sum_q H_{q\bar{q}}(Q,\mu)\ \ q_T \int_0^\infty \mathrm{d}b_T\, b_T\, J_0(q_T b_T)$$
$$\times\, B_q(x_a, b_T, \mu, Q/\nu)\, B_{\bar{q}}(x_b, b_T, \mu, Q/\nu)\, S(b_T, \mu, \nu) + (q \leftrightarrow \bar{q})$$

Implemented in SCETlib C++ numerical library [Ebert, JKLM, Tackmann]:

- Three-loop hard function [Baikov et al. '09; Lee et al. '10; Gehrmann et al. '10, '20; Czakon et al. '21]



Perturbative ingredients: Factorized singular cross section at N^{3}LL$'$

$$\frac{d\sigma}{dq_T} = \frac{d\sigma^{\rm res}_{\rm sing}}{dq_T} + \frac{d\sigma^{\rm FO}_{\rm nons}}{dq_T} = \frac{d\sigma^{\rm res}_{\rm sing}}{dq_T} + \left[\frac{d\sigma^{\rm FO}_{\rm full}}{dq_T} - \frac{d\sigma^{\rm FO}_{\rm sing}}{dq_T}\right]$$

$$\frac{d\sigma_{\rm sing}}{dQ\,dY\,dq_T} = \sum_q H_{q\bar{q}}(Q,\mu)\;\; q_T \int_0^\infty db_T\, b_T\, J_0(q_T b_T) \times B_q(x_a, b_T, \mu, Q/\nu)\, B_{\bar{q}}(x_b, b_T, \mu, Q/\nu)\, S(b_T, \mu, \nu) + (q \leftrightarrow \bar{q})$$

Implemented in SCETlib C++ numerical library [Ebert, JKLM, Tackmann]:

- Three-loop hard function [Baikov et al. ’09; Lee et al. ’10; Gehrmann et al. ’10, ’20; Czakon et al. ’21]
- Three-loop matching of beam functions onto PDFs
  [Luo, Yang, Zhu, Zhu ’19; Ebert, Mistlberger, Vita ’20]
- Three-loop perturbative soft function for exponential regulator
  [Li, Zhu, Neill ’16; Li, Zhu, ’16]
- Four-loop cusp, three-loop noncusp anomalous dimensions
  [Brüser, Grozin, Henn, Stahlhofen ’19; Henn, Korchemsky, Mistlberger ’20; v. Manteuffel, Panzer, Schabinger ’20] [Moch, Vermaseren, Vogt ’05; Idilbi, Ma, Yuan ’06; Li, Zhu, ’16; Vladimirov ’16]
- Fiducial power corrections $\mathcal{O}(q_T/Q)$ resummed through exact acceptance
  [Ebert, JKLM, Stewart, Tackmann ’20]

- Use exact analytic solutions of virtuality and rapidity RG equation, combined with fast numerically exact solution of β function [Ebert '21]

  ...will come back to this

- Choose RG boundary scales as *hybrid profile scales* $\mu_X(b_T, q_T, Q)$:
  [Lustermans, JKLM, Tackmann, Waalewijn '19]

$$\mu_X(b_T, q_T \ll Q) = \frac{b_0}{b_T} \quad \text{but} \quad \mu_X(b_T, q_T \to Q) \to \mu_{\rm FO} = Q$$

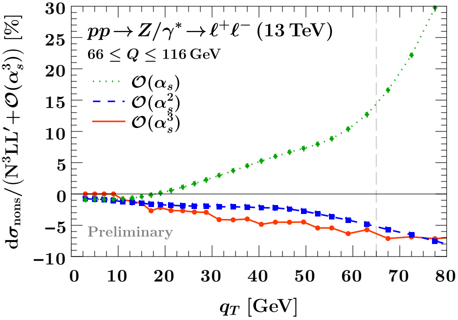
- Apply "local" b^* prescription starting at $\mathcal{O}(b_T^4)$ to virtuality scales *only*:

$$\mu_X \to \mu_X^* = \Big[\big(\mu_X^{\min}\big)^4 + \Big(\frac{b_0}{b_T}\Big)^4\Big]^{1/4} = \frac{b_0}{b_T}\Big\{1 + \mathcal{O}\Big[\big(\mu_i^{\min} b_T\big)^4\Big]\Big\}$$

  - Avoids contaminating nonperturbative corrections at quadratic order
    [Conflict with b_T-space renormalon structure: Scimemi, Vladimirov '18]
    [Translation back to momentum space: Ebert, JKLM, Stewart, Sun '22]

- For PDFs inside beam functions, use $\mu_f^{\min} = \min\{Q_0, m_c\}$

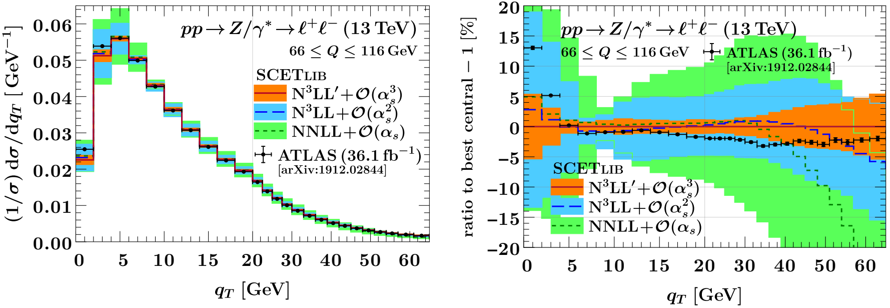
$$\frac{d\sigma_{\rm nons}}{dq_T} = \frac{d\sigma^{\rm FO}_{\rm full}}{dq_T} - \frac{d\sigma^{\rm FO}_{\rm sing}}{dq_T} = \frac{1}{q_T}\mathcal{O}\Big(\frac{q_T^2}{Q^2}\Big)$$



- In-house analytic implementation of all helicity structure functions at $\mathcal{O}(\alpha_s)$
- Fiducial Z+jet MC data at $\mathcal{O}(\alpha_s^2)$ from MCFM
  [Campbell, Ellis, et al. '99, '15]
- Very recently: Precise fiducial Z+jet MC data at $\mathcal{O}(\alpha_s^3)$ from NNLOjet
  [Chen et al., 2203.01565 – many thanks to the NNLOjet collaboration for providing the raw data.]
- Use that $\left|\int_0^{8\,\mathrm{GeV}} dq_T \, \frac{d\sigma^{(3)}_{\rm nons}}{dq_T}\right| \le 1\mathrm{pb}$ to drop $d\sigma^{(3)}_{\rm nons}$ below $8\,\mathrm{GeV}$

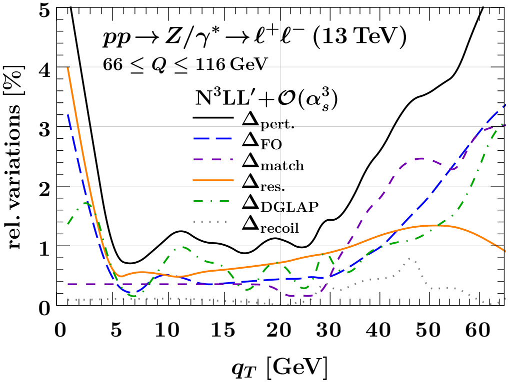
Results: Central prediction and perturbative convergence for $Z \to \ell^+\ell^-$

- Central results use MSHT20nnlo with $\alpha_s(m_Z) = 0.118$, $n_f = 5$
- NNLO (= three-loop!) PDF evolution formally sufficient at N^{3}LL′:
  - DGLAP kernels are a noncusp anomalous dimension
  - Scale dependence cancels within three-loop beam function
  - Separate question whether PDFs should have been extracted using three-loop $\hat{\sigma}_{ij}$



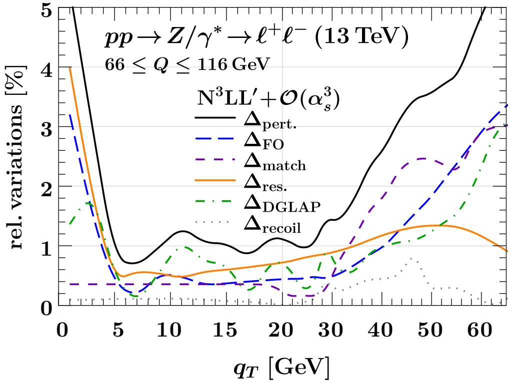
- Excellent perturbative convergence towards three-loop result
- Higher orders are covered by uncertainty estimate at lower orders
  …see next five slides for how they are estimated

Breakdown of perturbative uncertainties



$$\Delta_{\rm pert.} = \Delta_{\rm FO} \oplus \Delta_{\rm match} \oplus \Delta_{\rm res} \oplus \Delta_{\rm DGLAP} \oplus \Delta_{\rm recoil}$$

- Fixed-order uncertainty, keeps resummed logarithms unchanged
- Estimated by standard variations of overall $\mu_R = \mu_{\rm FO}$
- All scales (except μ_f) are chosen $\propto \mu_{\rm FO}$, so e.g. μ_H/μ_S unchanged
- Frozen out at $b_T \lesssim 1/\Lambda_{\rm QCD}$ by μ_X^* prescription $\Rightarrow$ disentangled from NP

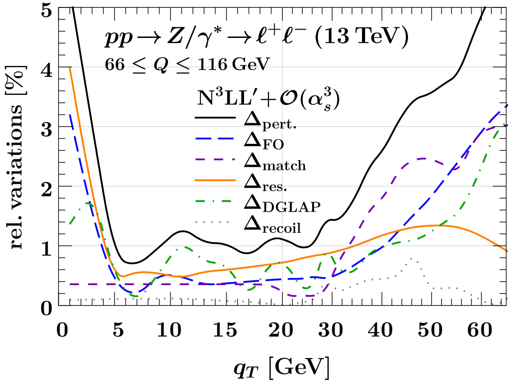


$$\Delta_{\text{pert.}} = \Delta_{\text{FO}} \oplus \Delta_{\text{match}} \oplus \Delta_{\text{res}} \oplus \Delta_{\text{DGLAP}} \oplus \Delta_{\text{recoil}}$$

- Uncertainty from matching scheme between resummed peak and fixed-order tail
- Estimated by varying the $x = q_T/Q$ transition points in hybrid profile as

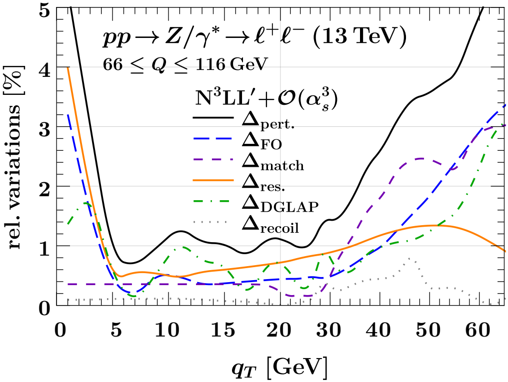
$$\{x_1, x_2, x_3\} = \{0.3, 0.6, 0.9\} \pm \{0.1, 0.15, 0.2\}$$

- Checked that *inclusive* integrated cross section is recovered within Δ_{match}



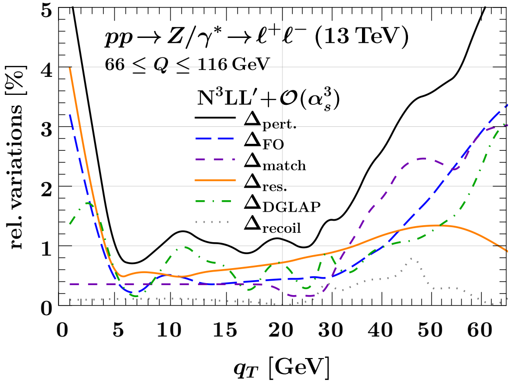
$$\Delta_{\text{pert.}} = \Delta_{\text{FO}} \oplus \Delta_{\text{match}} \oplus \Delta_{\text{res}} \oplus \Delta_{\text{DGLAP}} \oplus \Delta_{\text{recoil}}$$

- Probes higher-order resummed logarithms
- Estimated by envelope of 36 different combinations of independently varying $\{\mu_B, \mu_S, \nu_B, \dots\}$ in $\sigma^{(0)} = H\, B \otimes B \otimes S$
- Also frozen out at $b_T \lesssim 1/\Lambda_{\text{QCD}}$ by μ_X^* prescription $\Rightarrow$ disentangled from NP



$$\Delta_{\mathrm{pert.}} = \Delta_{\mathrm{FO}} \oplus \Delta_{\mathrm{match}} \oplus \Delta_{\mathrm{res}} \oplus \Delta_{\mathrm{DGLAP}} \oplus \Delta_{\mathrm{recoil}}$$

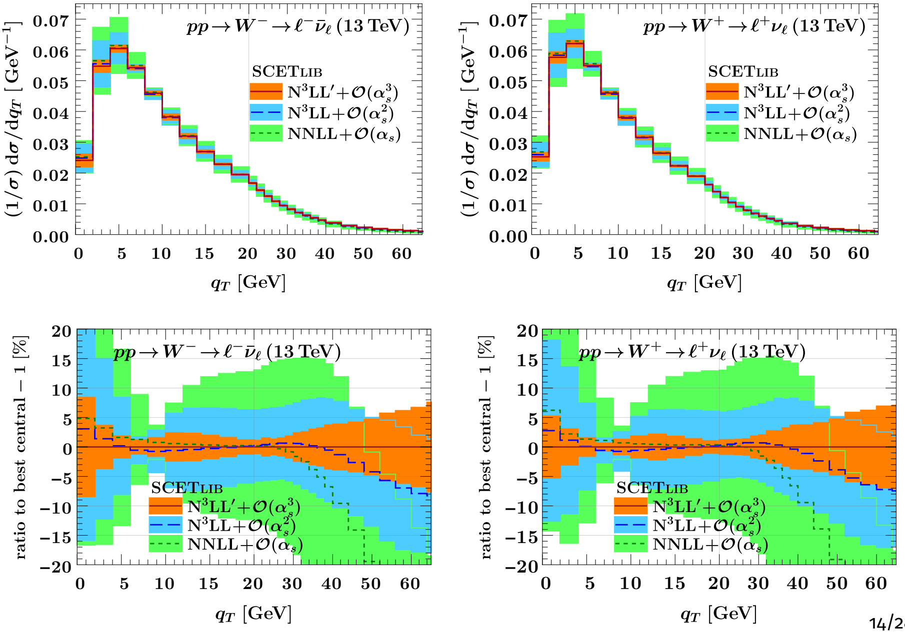
- Estimate of missing higher orders (four loops) in DGLAP running
- Estimated both in peak and tail by joint variations of $\mu_f(b_T, q_T, Q)$ and $\mu_F(Q)$
- Oscillatory due to b_T-space features at uncancelled m_b threshold



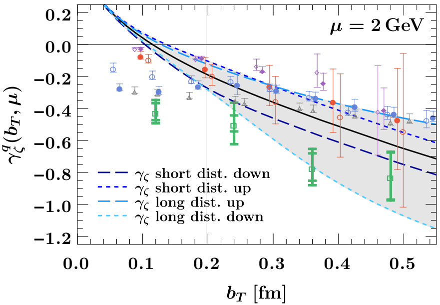
$$\Delta_{\text{pert.}} = \Delta_{\text{FO}} \oplus \Delta_{\text{match}} \oplus \Delta_{\text{res}} \oplus \Delta_{\text{DGLAP}} \oplus \Delta_{\text{recoil}}$$

- RPI-I transformation of n_a^μ, n_b^μ in $W_{\text{LP}}^{\mu\nu} \sim g_\perp^{\mu\nu}(n_a, n_b)$
- Induces $O(q_T^2/Q^2)$ change in spectrum due to fiducial cuts on $L_{\mu\nu}$
  [Ebert, JKLM, Stewart, Tackmann '20]
- Equivalent to changing "recoil prescription"/choice of Z rest frame by $\mathcal{O}(q_T/Q)$

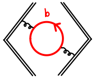
Results: Predictions for $W^\pm \to \ell\nu$



$$\frac{1}{2}\gamma^q_{\nu,\mathrm{NP}}(b_T) = \gamma^q_{\zeta\,\mathrm{NP}}(b_T) = c^i_\zeta \tanh\left(\frac{\omega^2_{\zeta,i}}{|c_\zeta|} b_T^2\right) = \mathrm{sgn}(c^i_\nu)\,\omega^2_{\zeta,i} b_T^2 + \mathcal{O}(b_T^4)$$



- Vary either ω_ζ ("short distance") or c_ζ ("long distance") to cover lattice results
  [Collection of lattice data reproduced from Shanahan, Wagman, Zhao, 2107.11930]
- Pick central value of $\mathrm{sgn}(c^i_\nu)\,\omega^2_{\zeta,i}(1 \pm 2)$ to serve as bias correction for known leading (NNLL) bottom quark mass effect in γ^q_ζ:



$$\Delta\gamma^q_\zeta(b_T, m_b, \mu) = \frac{\alpha_s^2}{\pi^2} C_F T_F (m_b b_T)^2 \left(\ln \frac{b_T^2 m_b^2}{4e^{-2\gamma_E}} - 1\right) \approx -(0.25\,\mathrm{GeV})^2 b_T^2$$

NOTE Compatible with [Scimemi, Vladimirov '19; Bacchetta et al. '19], but aim for a-priori prediction

Nonperturbative model for the TMD PDF $= B_i(x, b_T, \mu, \nu/\omega)\sqrt{S(b_T, \mu, \nu)}$

- Most general structure of leading NP correction $b_T^2 \Lambda_i^{(2)}(x)$ is complicated
- However, can show that for a given process and fiducial volume, only *a single average coefficient* $\overline{\Lambda}$ remains after the integral over hard phase space Φ_B:
  [Ebert, JKLM, Stewart, Sun '22]

$$\tilde{\sigma}(b_T) = \tilde{\sigma}^{(0)}(b_T)\Big\{1 + b_T^2\Big(2\overline{\Lambda}^{(2)} + \gamma_{\zeta,q}^{(2)} L_{Q^2}\Big)\Big\} + \mathcal{O}\big[(\Lambda_{\rm QCD} b_T)^4\big]$$

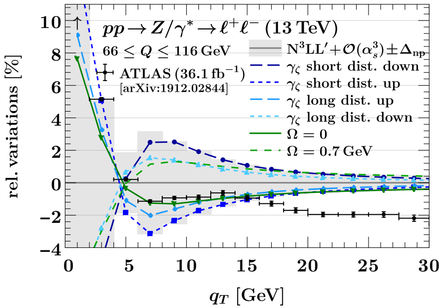
$$\overline{\Lambda}^{(2)} = \frac{\int \mathrm{d}\Phi_B\, A(\Phi_B)\, \sum_{i,j} \sigma_{ij}^B(Q)\, f_i^{(0)}(x_a, \mu_0)\, f_j^{(0)}(x_b, \mu_0)\big[\Lambda_i^{(2)}(x_a) + \Lambda_j^{(2)}(x_b)\big]}{2\int \mathrm{d}\Phi_B\, A(\Phi_B)\, \sum_{i,j} \sigma_{ij}^B(Q)\, f_i^{(0)}(x_a, \mu_0)\, f_j^{(0)}(x_b, \mu_0)}$$

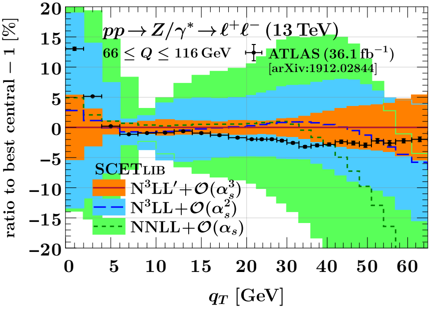
- ▶ Idea: Promote $\overline{\Lambda}^{(2)}$ to a single-parameter Gaussian model

$$f_i^{\rm NP}(x, b_T) = \exp(-\Omega^2 b_T^2) \quad \text{with} \quad \overline{\Lambda}^{(2)} = -\Omega^2$$

- Take central $\Omega = 0.5\,\mathrm{GeV}$ and vary it as $\Omega = \{0, 0.7\}\,\mathrm{GeV}$
- ▶ For $q_T \gg \Lambda_{\rm QCD}$, this captures the most general form of the leading NP correction to the rapidity-integrated q_T spectrum

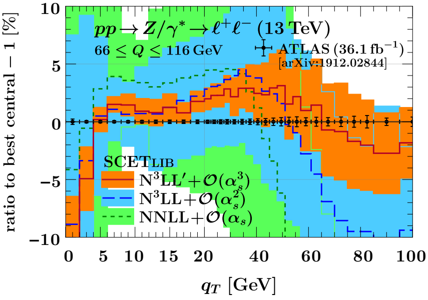
Results: Nonperturbative contributions



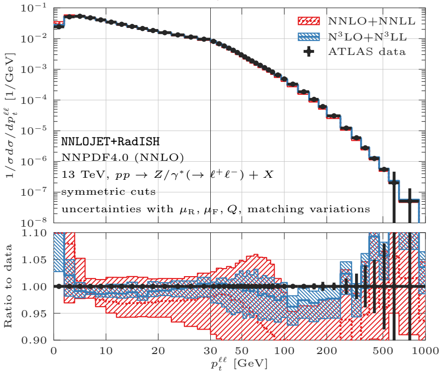


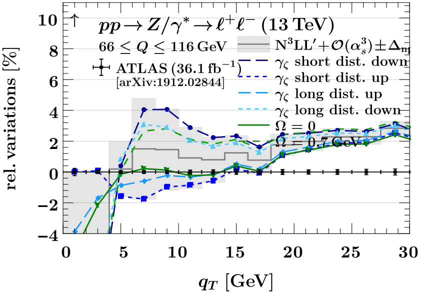
- Taken at face value, the lowest bins seem to prefer *weaker* NP effects
- N^{3}LL closer to data for $q_T \le 15\,\mathrm{GeV}$ with our default NP parameters, suggesting that three-loop and NP corrections can be traded off for one another
- Overshoot data at $q_T = 20 - 30\,\mathrm{GeV}$, way outside NP effect strength

Comparison with RadISH (using identical NNLOjet fixed-order matching)



[Chen et al., 2203.01565]





- Can recover the data for $q_T \leq 4\,\mathrm{GeV}$ with NP model ≈ *off*
- To recover the RadISH result at $\leq 4\,\mathrm{GeV}$, would need large positive $\gamma_\zeta^{(2)}$ or $\bar{\Lambda}^{(2)}$
- In either case, cannot recover $\geq 20\,\mathrm{GeV}$ due to $\Lambda_{\mathrm{QCD}}^2/q_T^2$ scaling imposed by TMD factorization & OPE

Comparison with RadISH (using identical NNLOjet fixed-order matching)

- Common ingredient: Sudakov evolution kernels from $\mu_0 \sim Q$ to $\mu \sim 1/b_T, q_T$

  e.g.: $$K_\Gamma(\mu_0, \mu) = \int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \Gamma[\alpha_s(\mu')] \ln \frac{\mu'}{\mu_0}$$

- Implementation of Sudakov kernels in SCETlib is exactly equal to numerical solution of β function + numerical μ' integral
  - $\beta(\alpha_s)$ and $\Gamma(\alpha_s)$ truncated after α_s^4, no additional approximations or assumptions
  - Exact RGE closure $U(\mu_0, \mu)\, U(\mu, \mu_0) = 1$
  - Exact path independence in (μ, ν) or (μ, ζ) plane
- …but much faster, thanks to closed-form results in [Ebert, 2110.11360] in terms of a single polynomial root-finding problem

Comparison with RadISH (using identical NNLOjet fixed-order matching)

- Common ingredient: Sudakov evolution kernels from $\mu_0 \sim Q$ to $\mu \sim 1/b_T, q_T$

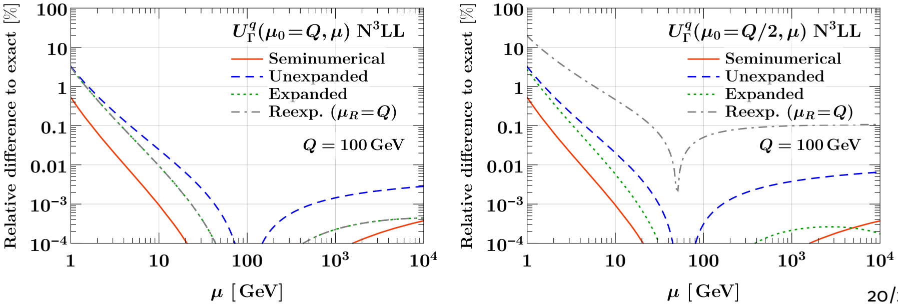
  e.g.: $$K_\Gamma(\mu_0, \mu) = \int_{\mu_0}^{\mu} \frac{\mathrm{d}\mu'}{\mu'} \Gamma[\alpha_s(\mu')] \ln \frac{\mu'}{\mu_0}$$

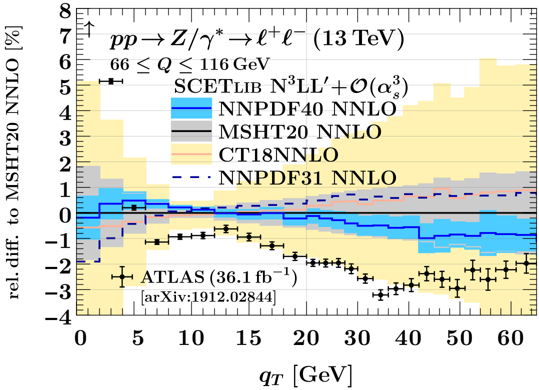
- Common to expand $K_\Gamma(\mu_0, \mu)$ in terms of $\alpha_s(\mu_0)$ throughout instead

  $\Rightarrow$ simpler analytic solution with $g^{(1)}$ a function of an $\mathcal{O}(1)$ argument:

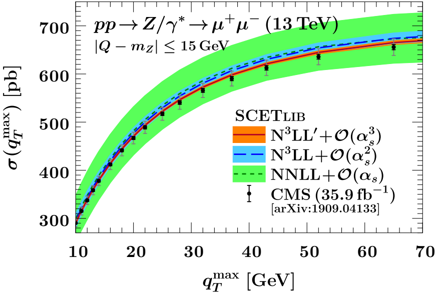
  $$K_\Gamma^{\mathrm{exp.}}(\mu_0, \mu) = L g^{(1)}\big(\alpha_s(\mu_0) L\big) + \text{NLL}\,, \qquad L = \ln \frac{\mu_0}{\mu}$$

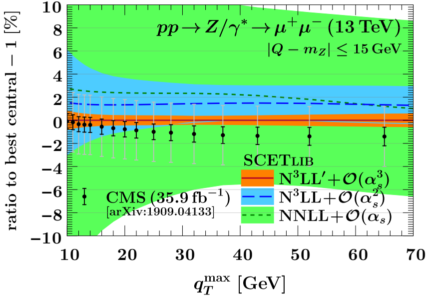
- However, reexpanding in terms of $\alpha_s(\mu_R)$, $\mu_R \neq \mu_0$ (read: μ_0 = resummation scale) leads to large truncation errors [Billis, Tackmann, Talbert, 1907.02971]

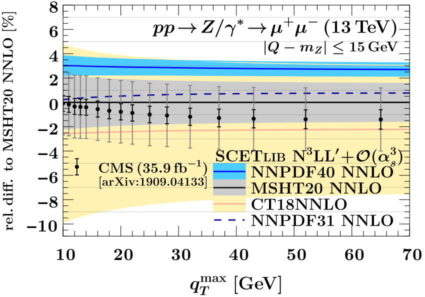




- PDF uncertainty largely cancels in normalized spectrum
- Cannot explain overshoot at $q_T = 20 - 30\,\mathrm{GeV}$

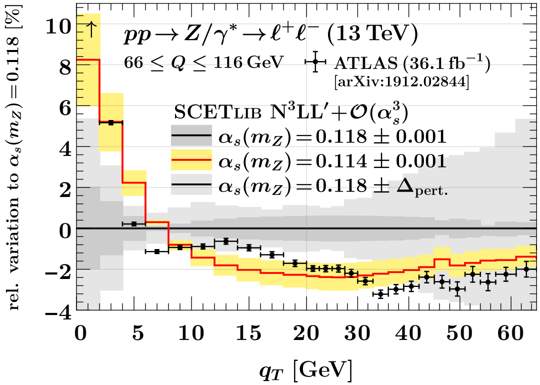






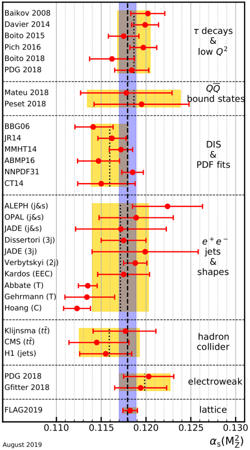
- Cumulative cross section distinguishes recent PDF sets
- $\mathcal{O}(b_T^2 \Lambda_{QCD}^2)$ effects $\leq 0.1\%$ past $q_T^{max} \sim 20\,\mathrm{GeV}$
- Hold small $\alpha_s^{2,3}$ nonsingular fixed
  - Whole figure at few 100 CPUh
- Promising target for N^{3}LO PDF fits

Results: Impact of α_s on normalized Z spectrum



- Parametric uncertainty due to $\alpha_s(m_Z)$ on par with perturbative uncertainty
- Overshoot at $q_T = 20 - 30\,\text{GeV}$ is naturally explained by lower $\alpha_s(m_Z)$

This is not unprecedented …



- Lower values of $\alpha_s(m_Z)$ have previously been reported in fits to e^+e^- event shapes (thrust and C parameter)

  DISCLAIMER: This was *not* an actual fit to $\{\alpha_s(m_Z), \Omega, \omega_\zeta^{(2)}\}$.

- Like $p_T^{Z/W}$, these are driven by all-order resummation …

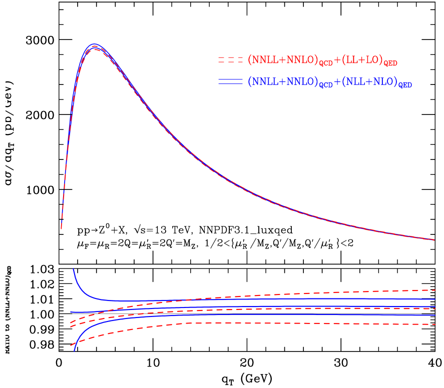
T. Rex Might Have Had Close Cousins

New York Times, March 1, 2022

"That's not the kind of thing you should be doing based on femur robusticity and the presence or absence of a tooth," Dr. Hone added. "If you're going to shoot for the king, don't miss."

Outlook: Systematics at the theory frontier

- QED effects for on-shell Z well understood
  [Bacchetta, Echevarria '18; Cieri, Ferrera, Sborlini '18; Billis, Tackmann, Talbert '19]
  - Expected to be $\sim 1\%$, but would bring the tail up *more*

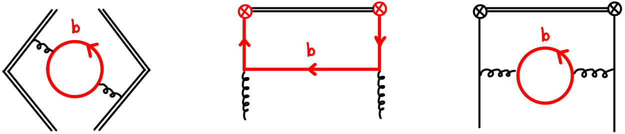


[Cieri, Ferrera, Sborlini 1805.11948]

…but many caveats remain

Outlook: Systematics at the theory frontier

- QED effects for on-shell Z well understood
  [Bacchetta, Echevarria ’18; Cieri, Ferrera, Sborlini ’18; Billis, Tackmann, Talbert ’19]
  - Expected to be $\sim 1\%$, but would bring the tail up *more*
- QED corrections to full process with realistic lepton definitions *challenging* to interface with resummation [see talk by G. Billis at SCET ’20]
- Subleading power resummation & factorization for *nonsingular* cross section
  [Progress towards doing this at least for $\mathcal{O}(q_T/Q)$ azimuthal correlations!]
  [Moos, Scimemi, Rodini, Vladimirov ’21-’22; Ebert, Gao, Stewart ’21 $\longrightarrow$ see yesterday’s session]
- Full resummed treatment of mass effects/flavor thresholds
  - Expect impact on spectrum (and cumulative cross section) to be suppressed by $\# \, m_b^2/q_T^2$?



The Drell-Yan q_T Spectrum at N^{3}LL$'$ and Its Uncertainty:

- Presented third-order predictions for Z and $W^\pm$ q_T spectra at the LHC
  - Residual perturbative uncertainty at percent level in the peak
- Three-loop resummed `SCETlib` predictions are analytic & fast also with cuts
  - Assessing PDF and α_s uncertainties possible *directly at three loops*
  - Cumulative cross sections up to $q_T^{\max} \approx 40\,\mathrm{GeV}$ promising targets for N^{3}LO PDF fits (or reweighting)
- Even small changes $\alpha_s(m_Z) \pm 0.001$ strongly impact the peak shape
  - Effect for $q_T \le 20\,\mathrm{GeV}$ as relevant for TMD fits as collinear PDF uncertainty
- Intriguing hints that the data may prefer a lower value of $\alpha_s(m_Z)$ – stay tuned

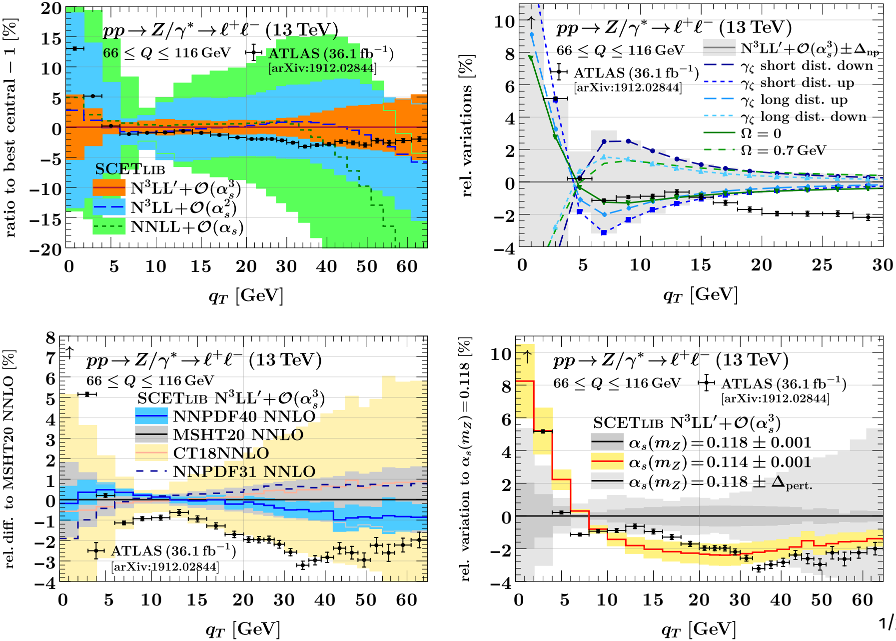
The Drell-Yan q_T Spectrum at N^{3}LL′ and Its Uncertainty:

- Presented third-order predictions for Z and $W^\pm$ q_T spectra at the LHC
  - Residual perturbative uncertainty at percent level in the peak
- Three-loop resummed `SCETlib` predictions are analytic & fast also with cuts
  - Assessing PDF and α_s uncertainties possible *directly at three loops*
  - Cumulative cross sections up to $q_T^{\max} \approx 40\,\mathrm{GeV}$ promising targets for N^{3}LO PDF fits (or reweighting)
- Even small changes $\alpha_s(m_Z) \pm 0.001$ strongly impact the peak shape
  - Effect for $q_T \leq 20\,\mathrm{GeV}$ as relevant for TMD fits as collinear PDF uncertainty
- Intriguing hints that the data may prefer a lower value of $\alpha_s(m_Z)$ – stay tuned

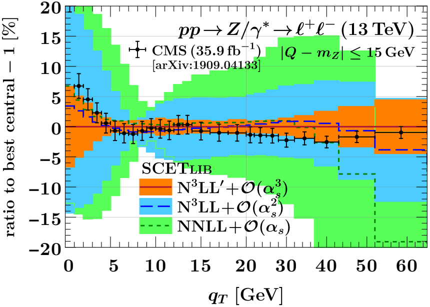
Thank you for your attention!

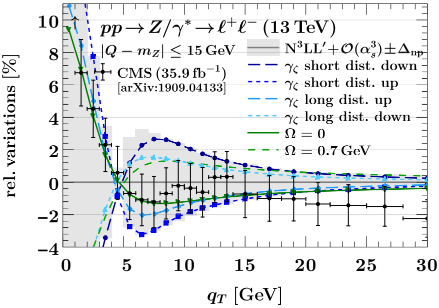
Backup

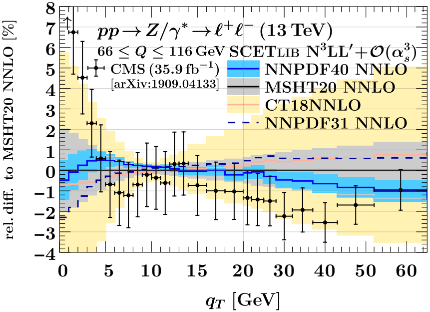
ATLAS normalized spectrum (Born leptons)

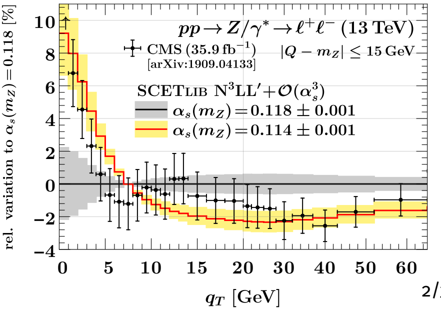


CMS normalized spectrum (dressed leptons)









$\mathcal{O}(\alpha_s^3)$ nonsingular interpolations