Precision phenomenology in the Drell-Yan process

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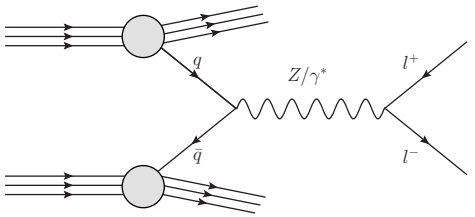
based on: 2107.09085, 2203.01565, 2205.11426, 2301.11827

Drell-Yan process



- Drell-Yan lepton pair (neutral-current or charged-current) production
  - Benchmark observable: multi-differential measurements
  - Precision measurements of EW parameters and parton distributions
- Standard Model theory well understood
  - NLO EW [C.Carloni Calame, G.Motagna, A.Nicrosini, A.Vicini; S.Dittmaier, M.Huber]
  - NNLO QCD and NNLO QCD+EW (+ total cross section to N3LO QCD)
    [K.Melnikov, F.Petriello; S.Catani, L.Cieri, G.Ferrera, D.de Florian, M.Grazzini; C.Duhr, F.Dulat, B.Mistlberger; R.Bonciani, L.Buonocore, M.Grazzini, S.Kallweit, N.Rana, F.Tramontano, A.Vicini; F.Buccioni, F.Caola, H.Chawdhry, F.Devoto, M.Heller, A.von Manteuffel, K.Melnikov, R.Röntsch, C.Signorile-Signorile]
  - transverse momentum resummation to N3LL QCD
    [W.Bizon, P.F.Monni, E.Re, L.Rottoli, P.Torrielli]
- Precision Tools: FEWZ, DYNNLO, DYturbo, POWHEG, ...

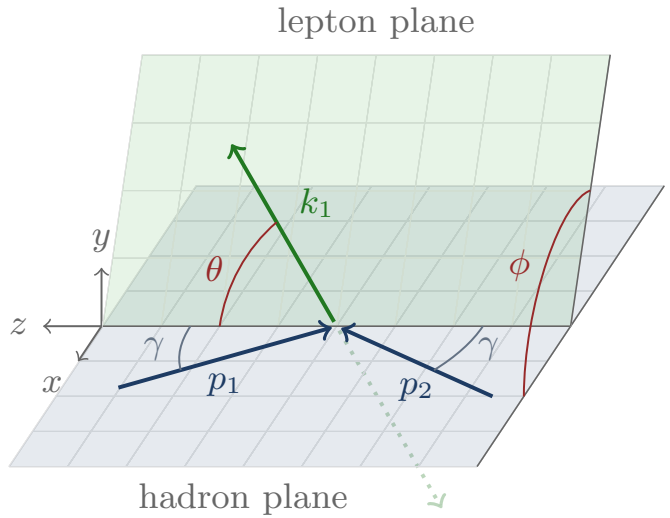
Triple-differential Drell-Yan cross section

- Lepton pair production: EW precision observable

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{ll}\mathrm{d}y_{ll}\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{ll}s}\sum_q P_q(\cos\theta^*)\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2) + (q \leftrightarrow \bar{q})\right]$$

- ATLAS 8 TeV measurement [1710.05167]

Observable	Central-Central	Central-Forward
m_{ll} [GeV]	[46,66,80,91,102,116,150,200]	[66,80,91,102,116,150]
$\lvert y_{ll}\rvert$	[0,0.2,0.4,0.6,0.8,1,1.2, 1.4,1.6,1.8,2,2.2,2.4]	[1.2,1.6,2,2.4,2.8,3.6]
$\cos\theta^*$	[-1,-0.7,-0.4,0,0.4,0.7,1]	[-1,-0.7,-0.4,0,0.4,0.7,1]
Total Bin Count:	504	150



Triple-differential Drell-Yan cross section

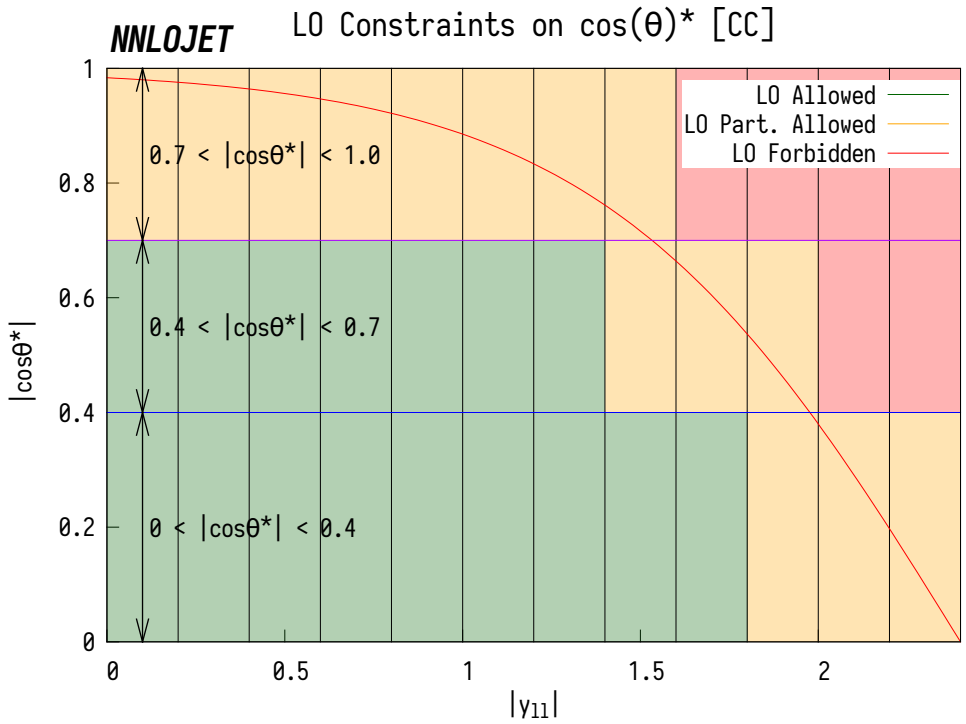
- Measured with fiducial event selection cuts (on single leptons)

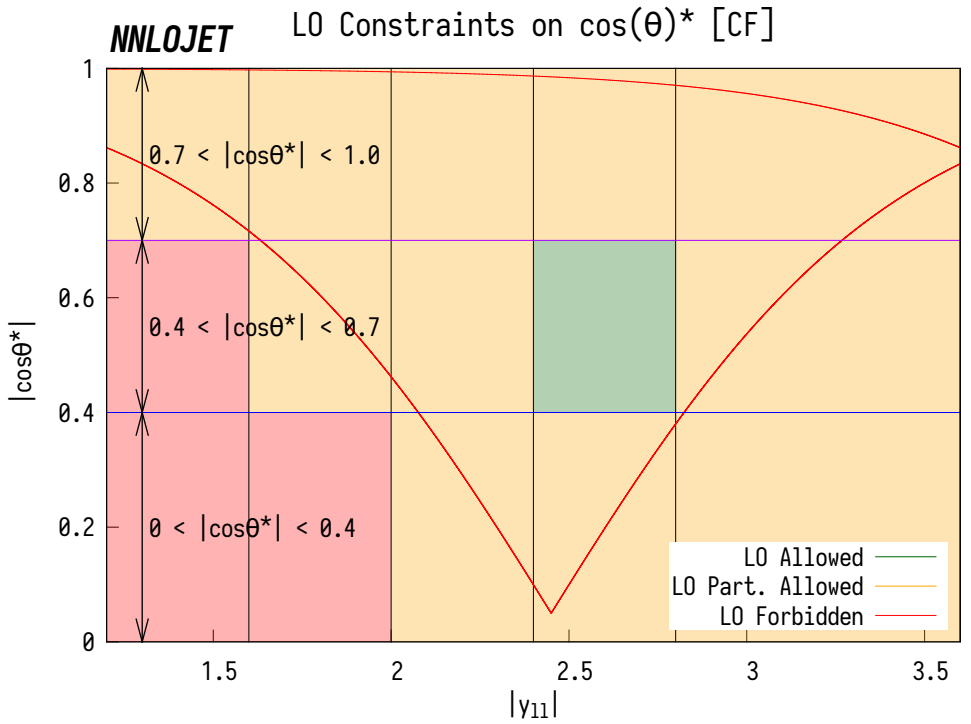
Central-Central	Central-Forward	
$p_T^l > 20$ GeV	$p_{T,F}^l > 20$ GeV	$p_{T,C}^l > 25$ GeV
$\lvert y^l \rvert < 2.4$	$2.5 < \lvert y_F^l \rvert < 4.9$	$\lvert y_C^l \rvert < 2.4$
46 GeV $< m_{ll} <$ 200 GeV	66 GeV $< m_{ll} <$ 150 GeV	

- Fiducial cuts influence acceptances in triple-differential bins

Triple-differential Drell-Yan cross section

- Leading order: fiducial cuts intersect bin definitions
  [A.Gehrmann-De Ridder, E.W.N.Glover, A.Huss, C.Preuss, D.Walker, TG: 2301.11827]



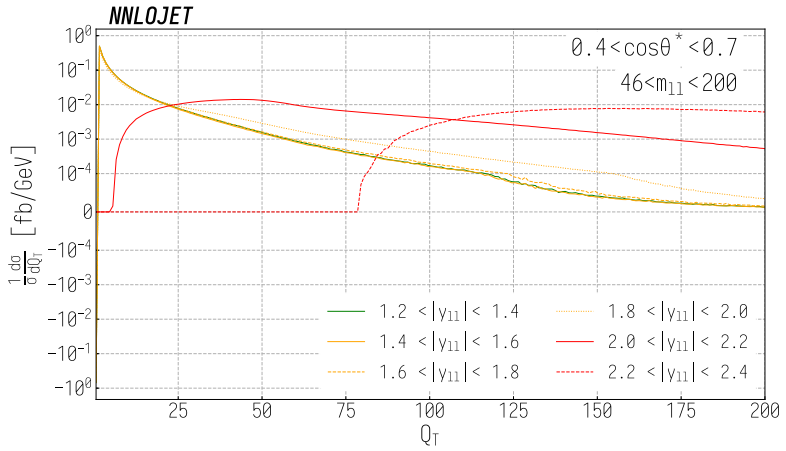


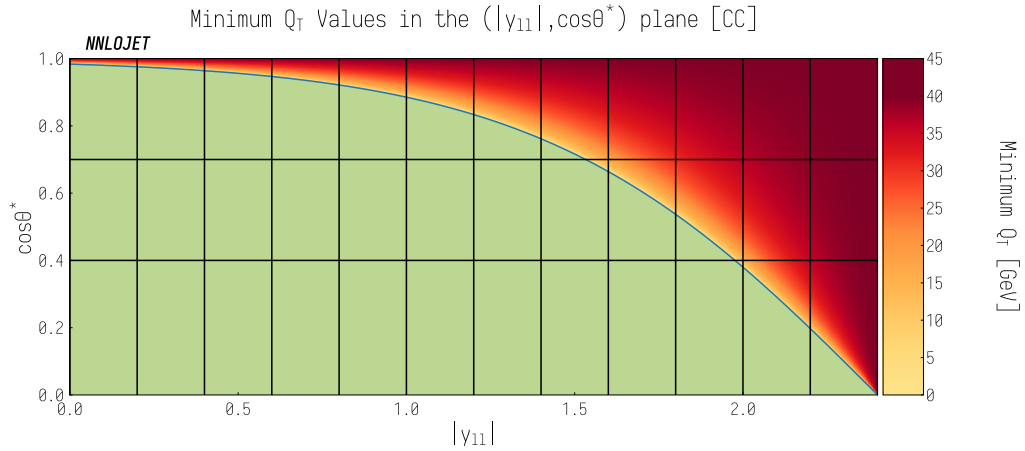
Triple-differential Drell-Yan cross section

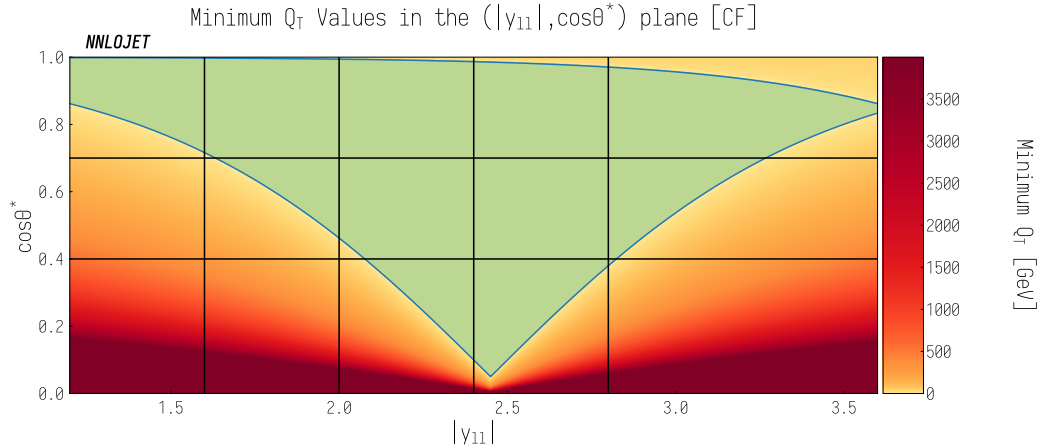
- Leading-order forbidden bins
  - require finite Q_T of lepton pair
  - shown here: symmetric lepton pair

→ prediction starts only at NLO

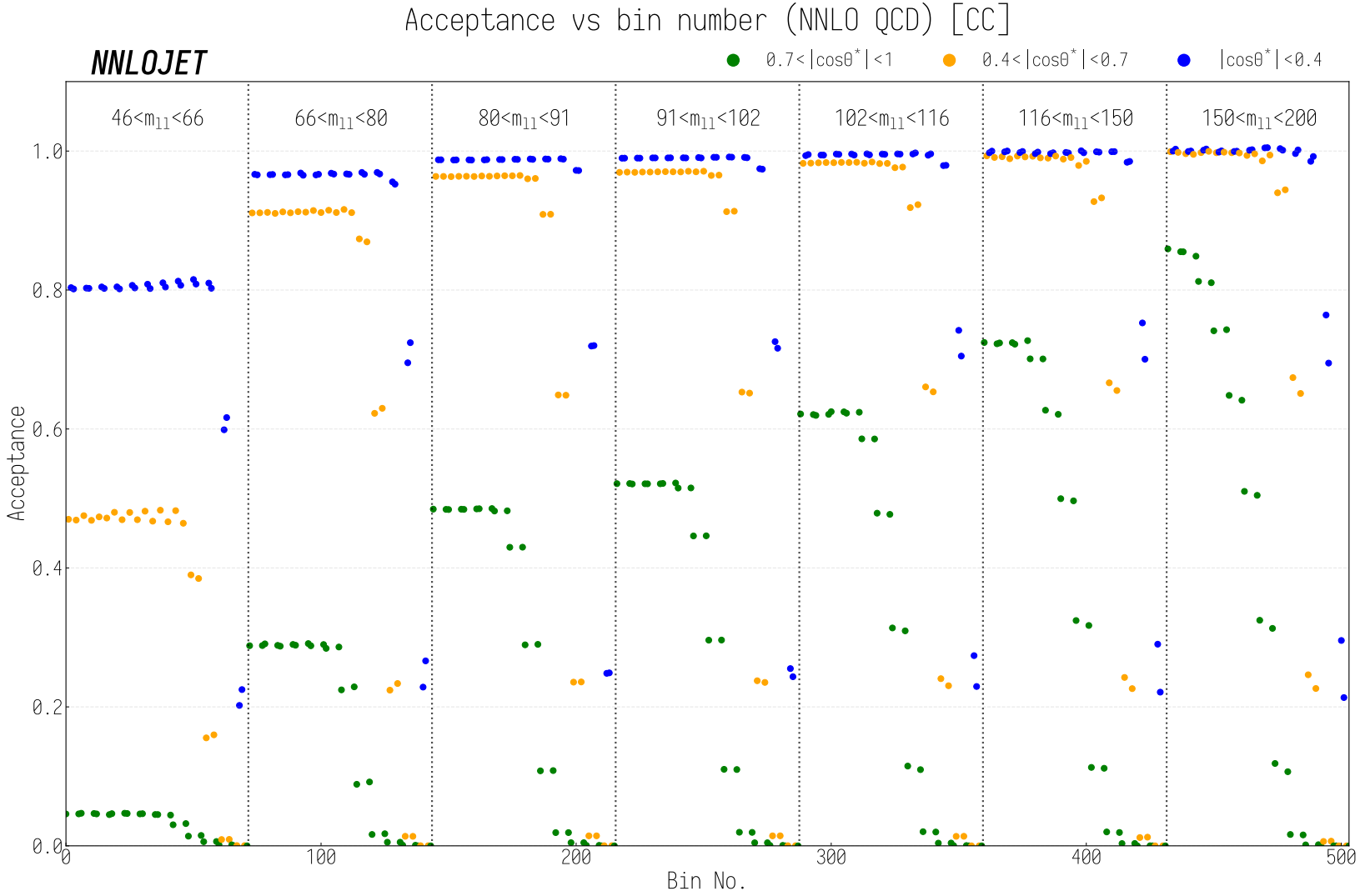
  - lower accuracy
  - potential perturbative instabilities







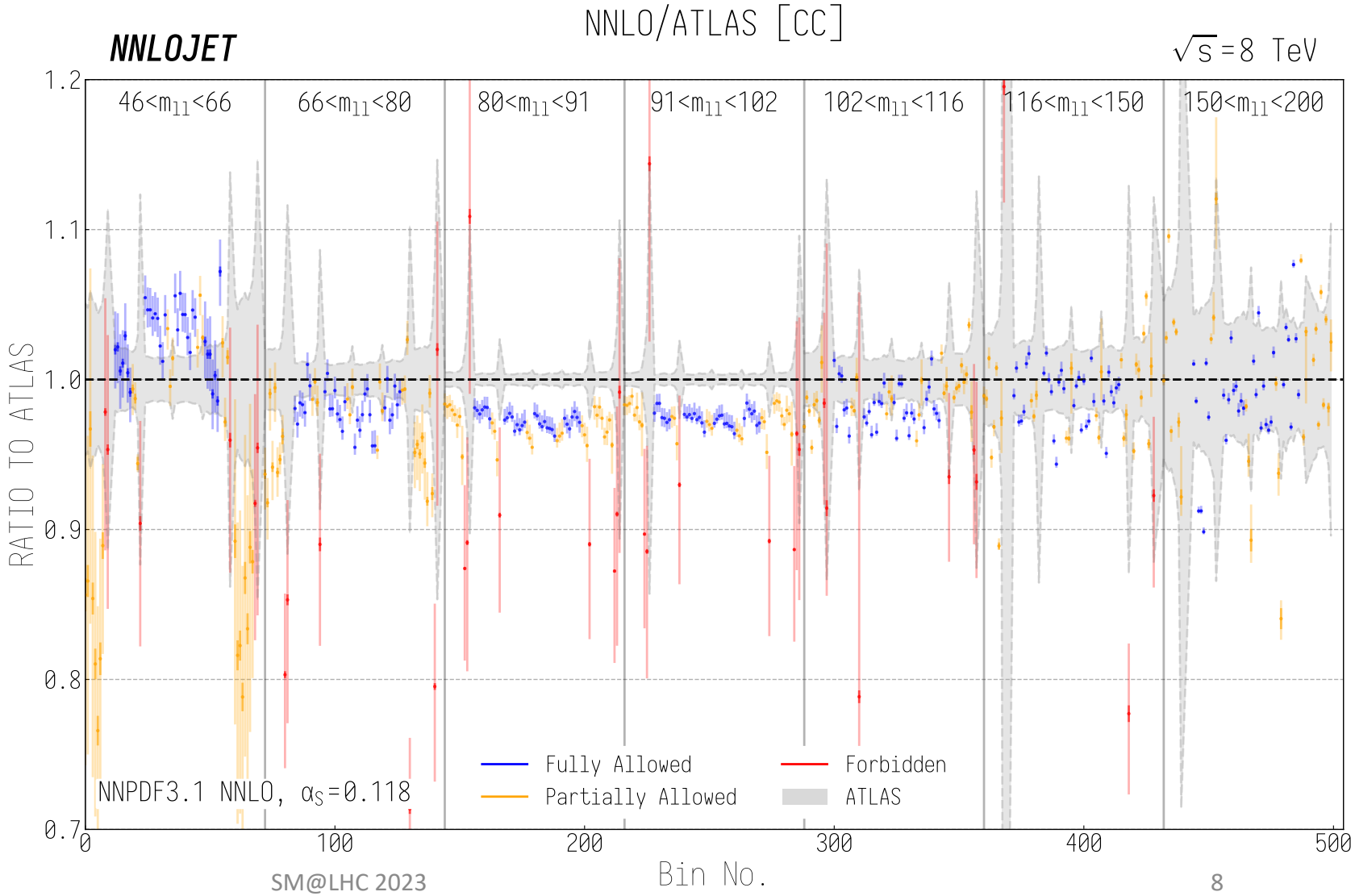
Triple-differential Drell-Yan cross section



Triple-differential Drell-Yan cross section

In forbidden bins

- large theory uncertainty
- poor agreement with data



Triple-differential Drell-Yan cross section

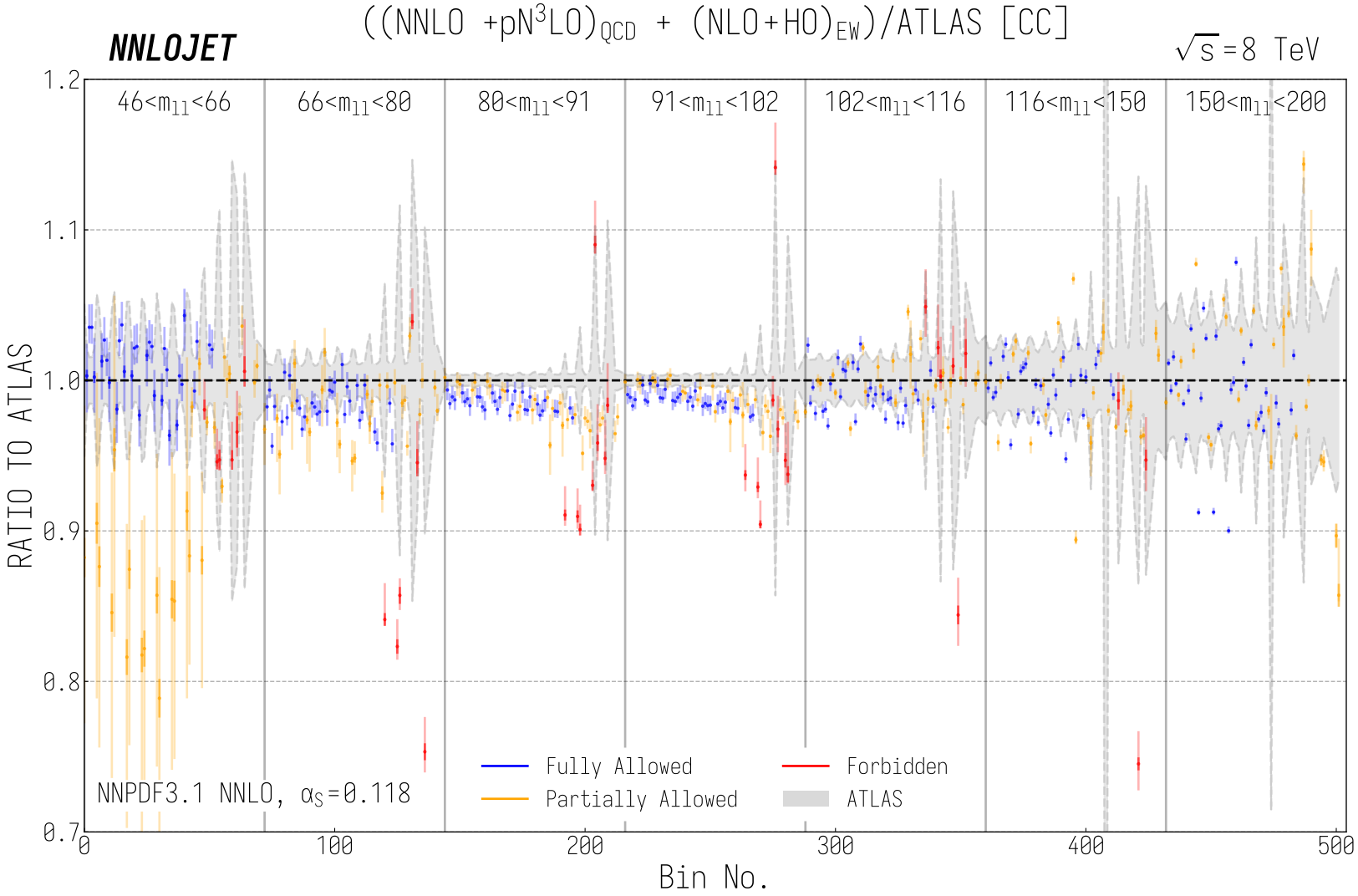
Forbidden bins at leading order

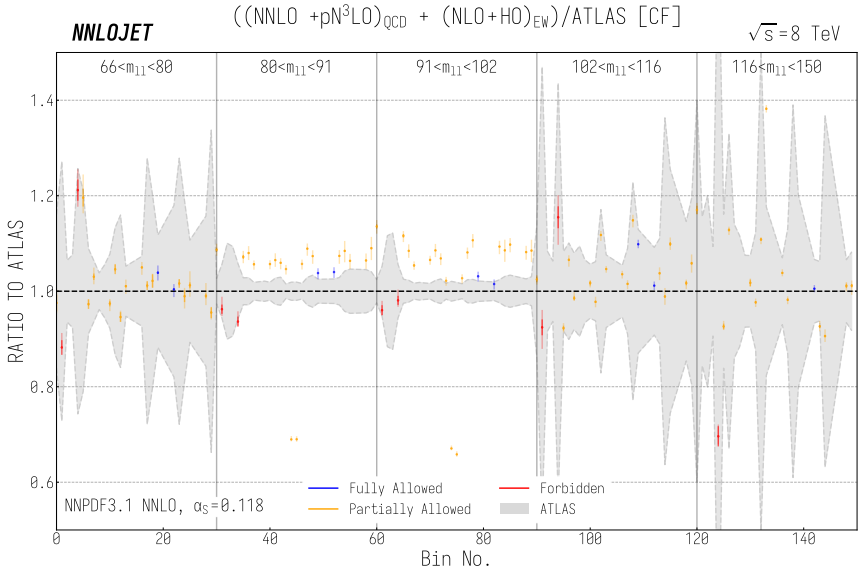
- $O(\alpha_s^3)$ corrections (Drell-Yan N^{3}LO) obtained from V+jet at NNLO
  [MCFM: T.Neumann, J.Campbell; NNLOJET: A.Gehrmann-De Ridder, N.Glover, A.Huss, T.Morgan, D.Walker, TG]
  - implemented in NNLOJET using antenna subtraction
  - replace jet requirement by (small) Q_T cut
  - numerical convergence at small Q_T challenging

State-of-the-art theory prediction

- QCD NNLO (α_s^2) plus N3LO (α_s^3) in LO-forbidden bins
- combined with (NLO+HO) EW corrections [C.Carloni Calame, G.Motagna, A.Nicrosini, A.Vicini]

Triple-differential Drell-Yan cross section





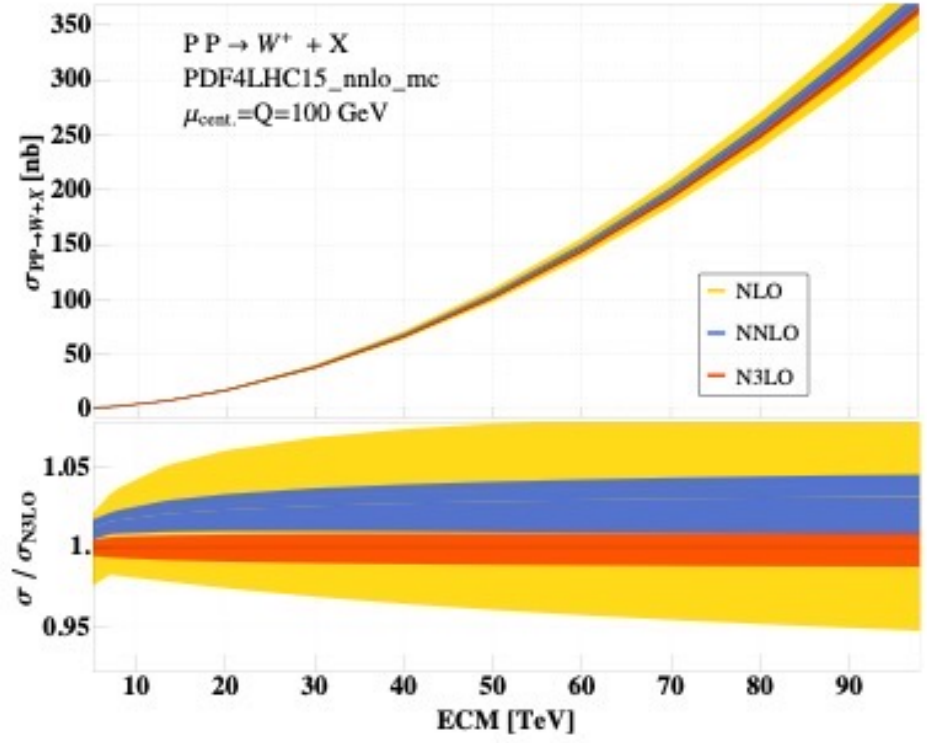
Future applications

- measurement of $\sin^2\Theta w$
- determination of parton distributions

Towards full N3LO in Drell-Yan observables

Inclusive coefficient functions (total cross section) at N3LO

- computed analytically
  - three-loop form factors
  - inclusive phase space up to triple emission
  - 100s of loop and phase-space master integrals
- Results
  - virtual photon exchange [C.Duhr, F.Dulat, B.Mistlberger]
  - charged-current Drell-Yan: $W^{\pm}$ production [C.Duhr, F.Dulat, B.Mistlberger]
  - neutral-current Drell-Yan: γ^*/Z^0 production [C.Duhr, B.Mistlberger]
  - associated VH production [n3loxs: J.Baglio, C.Duhr, B.Mistlberger, R.Szafron]



Towards full N3LO in Drell-Yan observables

Differential distributions at N3LO

- parton-level implementation of all V+jet processes at NNLO
- combined with three-loop virtual corrections (form factor)
- subtraction scheme for handling of infrared-singular contributions

Subtraction methods applicable at N3LO

- Projection to Born [M.Cacciari, F.Dreyer, A.Karlberg, G.Salam, G.Zanderighi]

$$\frac{d\sigma_X^{N3LO}}{dO} = \frac{d\sigma_{X+j}^{NNLO}}{dO} - \frac{d\sigma_{X+j}^{NNLO}}{dO_B} + \frac{d\sigma_X^{N3LO,\,incl}}{dO_B}$$

- q_T subtraction [S.Catani, M.Grazzini]

$$\frac{d\sigma_X^{N3LO}}{dO} = \mathcal{H}_{N3LO} \otimes \frac{d\sigma_X^{LO}}{dO} + \left[\int_{q_T,X} \frac{d\sigma_{X+j}^{NNLO}}{dO} - \frac{d\sigma_{X,CT}^{NNLO}}{dO}(q_T) \right]$$

Towards full N3LO in Drell-Yan observables

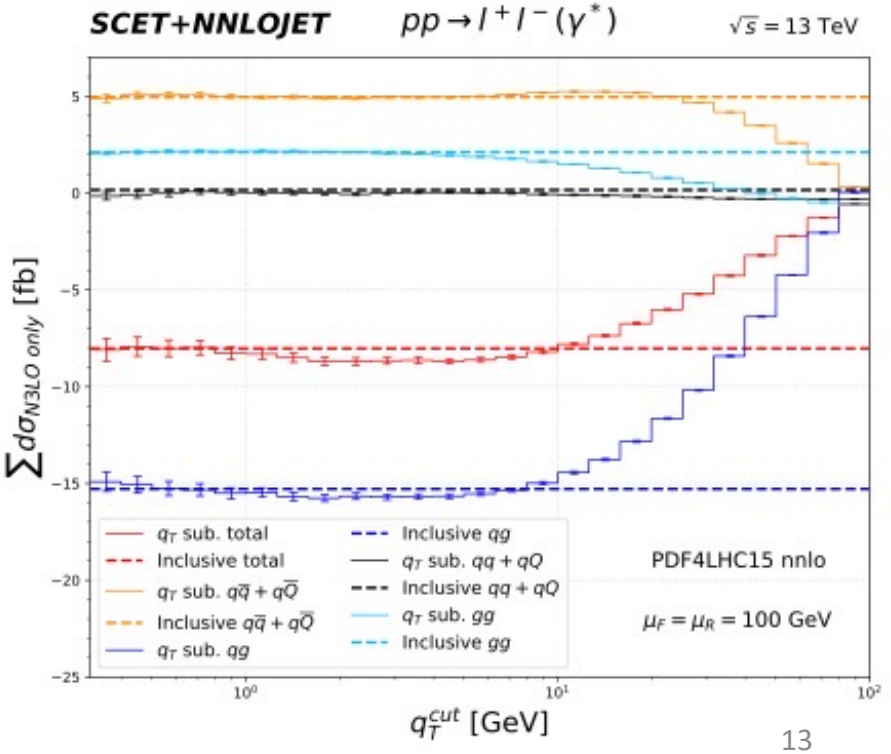
NNLOJET implementation of Drell-Yan processes at N3LO

[X.Chen, E.W.N.Glover, A.Huss, T.Z.Yang, H.X.Zhu, TG: 2107.09085]

- based on V+jet at NNLO
- using antenna subtraction for infrared subtraction at NNLO

Genuine N3LO singularities: q_T subtraction

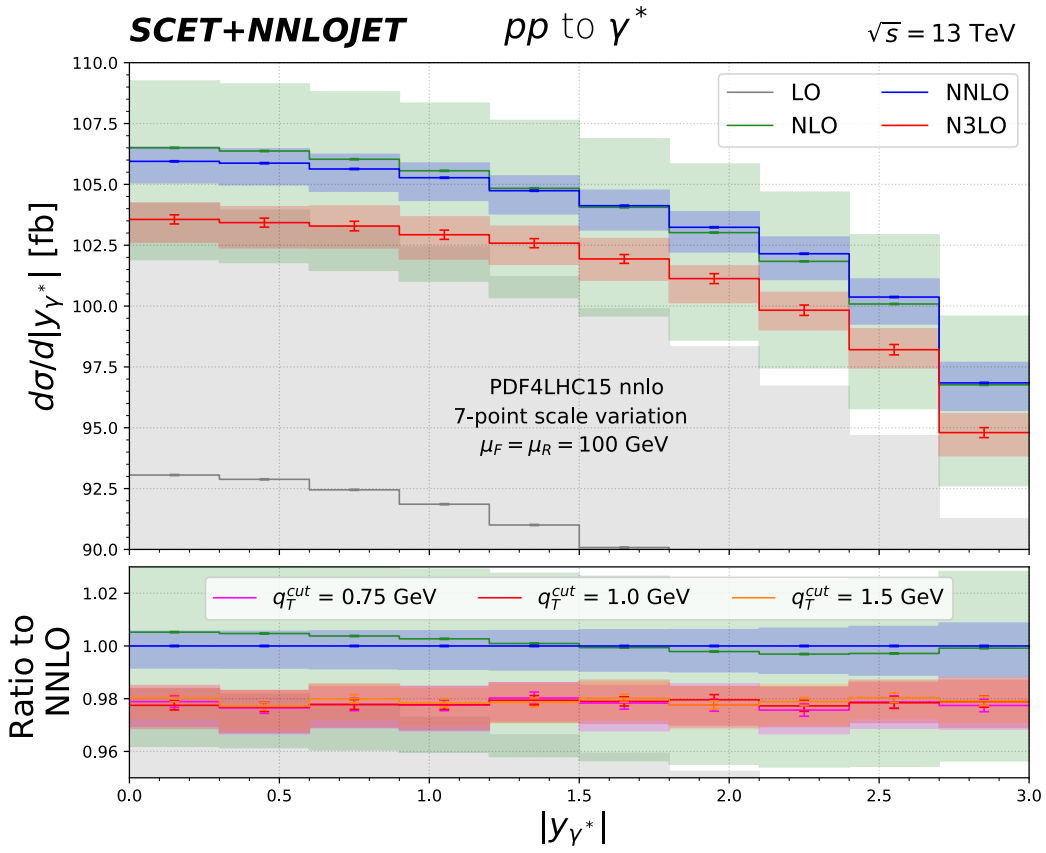
- obtain q_T counterterm from expansion of N3LL q_T resummation to $O(\alpha_s^3)$
- ingredients: three-loop soft and beam functions
  [Y.Li, H.X.Zhu; M.Ebert, B.Mistlberger, G.Vita; M.X.Luo, H.X.Zhu, T.Z.Yang, Y.J.Zhu]
- check: independence on $q_{T,cut}$ slicing parameter
- check: reproduce inclusive coefficient functions (no ingredients or methodology in common!)



N3LO in Drell-Yan observables

Rapidity distribution of lepton pair

- N3LO corrections uniform in y
- same size as inclusive N3LO K-factor
- N3LO outside NNLO scale uncertainty
- scale uncertainty remains at 1% level
- still: inclusive in lepton kinematics

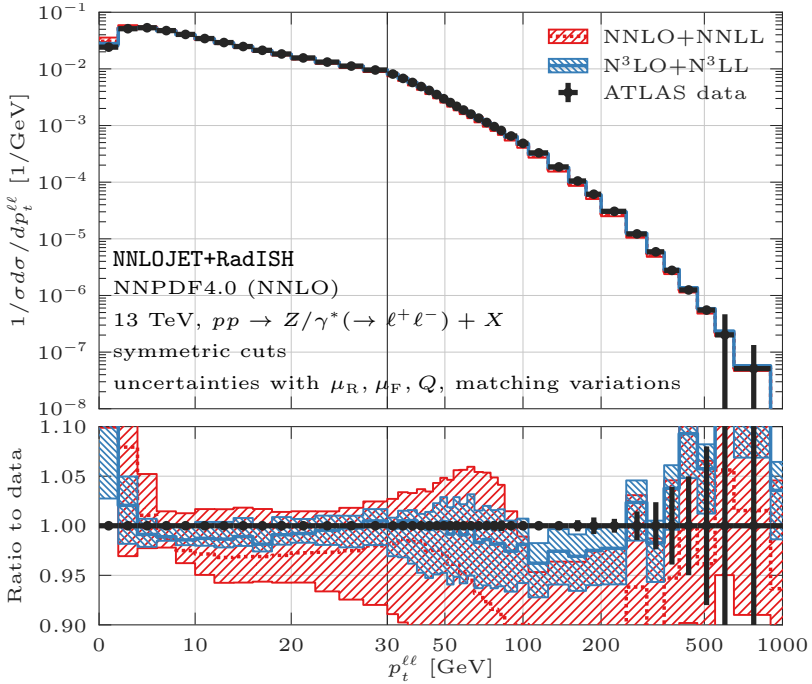


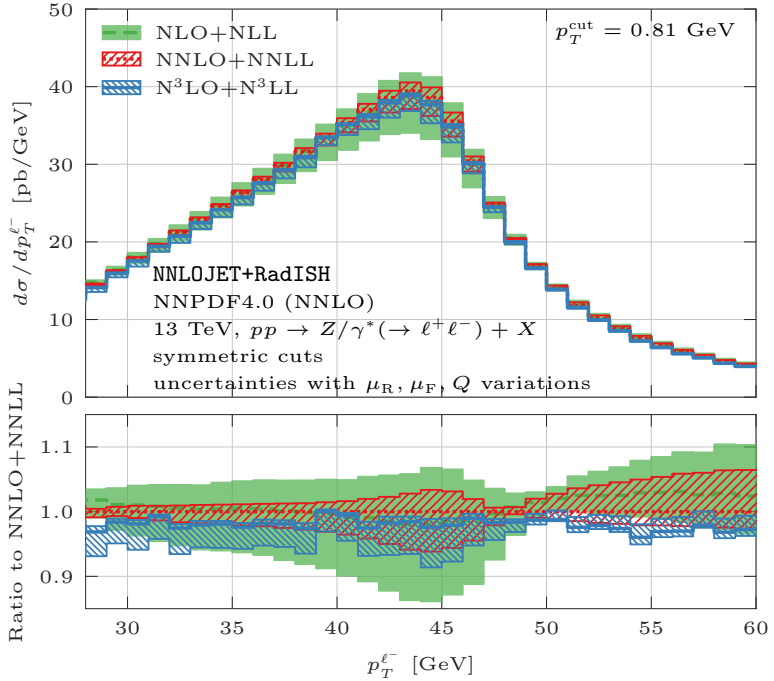
N3LO in Drell-Yan observables

Matching of N3LO with N3LL resummation

[X.Chen, E.W.N.Glover, A.Huss, P.F.Monni, E.Re, L.Rottoli, P.Torrielli, TG: 2203.01565]

- resummation in momentum space (RadISH)
- fiducial cross sections: lepton pair and single lepton distributions in NC Drell-Yan process
- improved perturbative convergence: uncertainty on NNLO+NNLL larger than NNLO-only





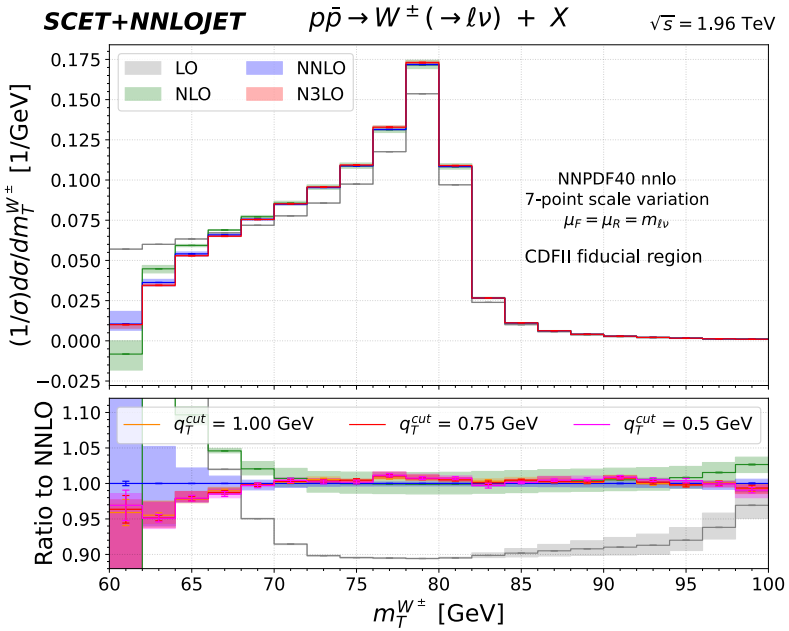
N3LO in Drell-Yan observables

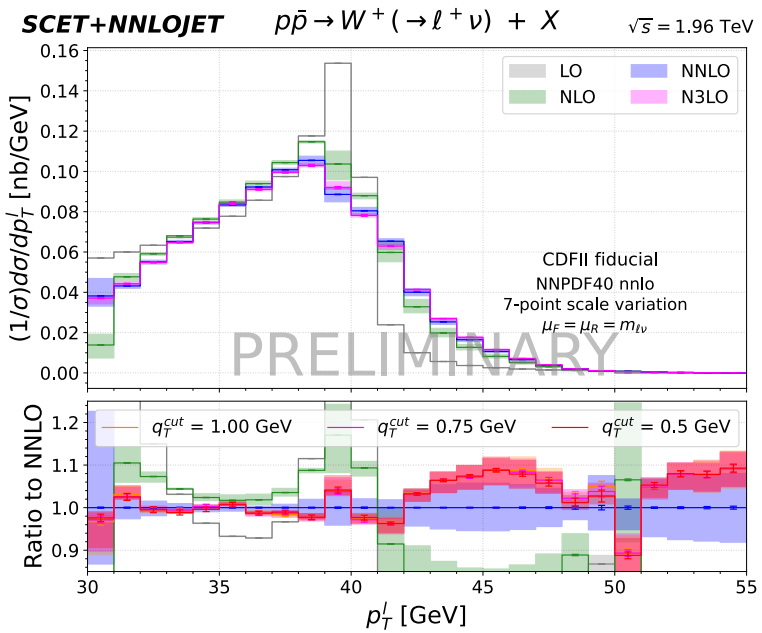
[G.Fontana]

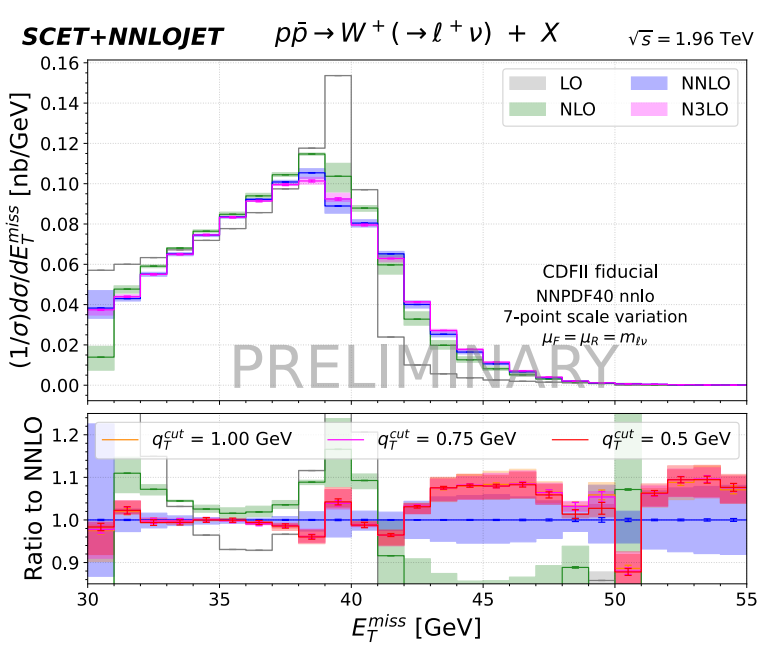
Normalized fiducial distributions in W production

[X.Chen, E.W.N.Glover, A.Huss, T.Z.Yang, H.X.Zhu, TG: 2205.11426 and work in progress]

- relevant for W mass extraction (CDF II, future LHC measurements)
- N3LO corrections for CDFII kinematics flat in m_T, but non-trivial shape in p_T^l, E_T^{miss}







Summary

- Drell-Yan process enables broad range of precision studies
- Complex interplay between observable definitions and fiducial cuts
- Demands ultimate per-cent level precision on fiducial distributions
  - NNLO and N3LO fixed-order, matched on N3LL resummation
  - combined with higher-order electroweak corrections
- First results, enabled by important computational advances
  - Triple-differential Drell-Yan cross sections at NNLO^{+} QCD + NLO EW
  - Single-differential N3LO corrections uniform in inclusive observables
  - non-trivial shape deformations for some fiducial distributions
- Preparing for LHC phenomenology at ultimate precision