Precision theory for high energy collider physics

Thomas Gehrmann (Universität Zürich)

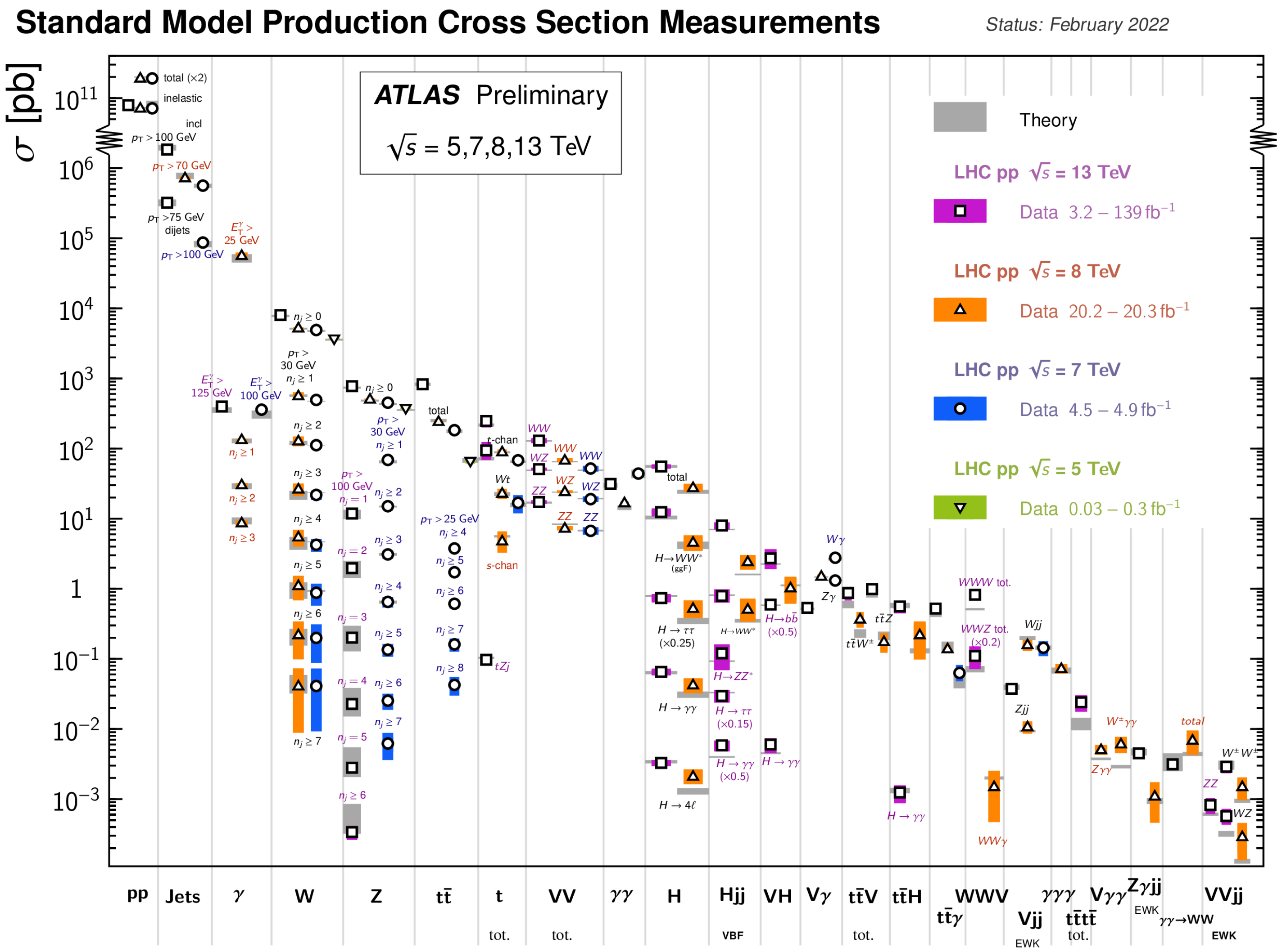
Seminar DESY Zeuthen, 21.03.2024

Swiss National Science Foundation

European Research Council
Established by the European Commission

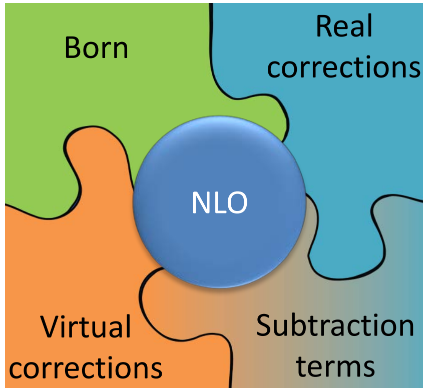
Precision physics at hadron colliders

- Precision tests of the Standard Model
  - Measurements of masses and couplings
- Interplay of calculations and measurements
  - Accuracy on many cross sections now ≈(1..5)%
- Ultimate precision frontier at hadron colliders: 1%
  - Require theory predictions accurate at this level



State-of-the-art

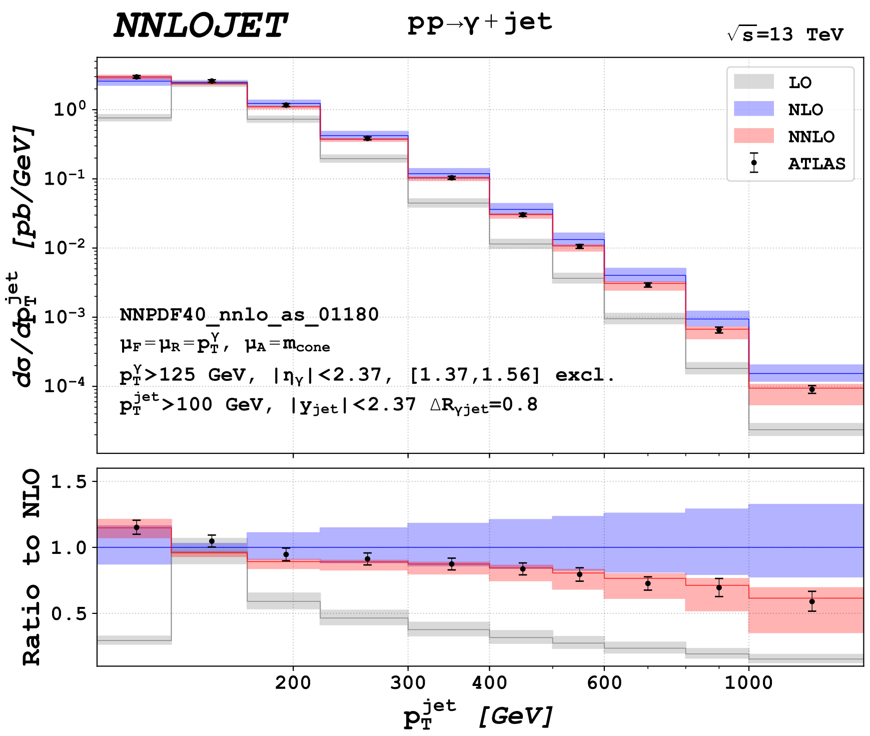
- Precise predictions: perturbation theory expansion of observables
- Experimental measurements: fiducial cross sections
  - theory predictions account for experimental cuts and definition of final state
- Automated tools for LO and NLO QCD and electroweak (2010's)
  - infrastructure from event generator programs
    - HERWIG, PYTHIA, SHERPA, aMC@NLO
  - standard interface to one-loop amplitude providers
    - BlackHat, GoSam, Recola, OpenLoops, NJet, MadLoop, CutTools



- Combined with parton shower
  - full event properties with NLO accuracy on differential cross sections

State-of-the-art

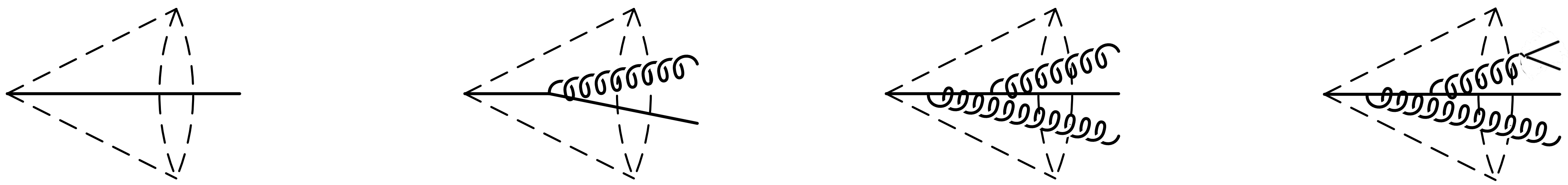
- NNLO QCD predictions for 2 ⟶ 2 processes (NNLO revolution, 2015 ⟶)
  - accomplished during past 10 years on case-by-case basis
  - as parton-level event generators (full final state information)
  - computationally expensive
  - current frontier at NNLO: 2 ⟶ 3



- Typical size of corrections and uncertainty
  - NLO corrections: 10..100%, uncertainty: 10..30%
  - NNLO corrections: 2..15%, uncertainty: 3..8%
  - expect N3LO to yield uncertainty at level of 1%.

Fixed-order perturbation theory

- One extra parton per order in perturbation series
- Partons are combined into jets using same algorithm as in experiment



LO NLO NNLO N3LO

  - No algorithm dependence at leading order
  - Theoretical description more accurate with increasing order
- Parton shower: multiple emissions, approximate description

Ingredients to fixed order calculations

- Matrix elements with extra real (R) or virtual (V) partons

	Matrix elements	Parton evolution
LO	Born	1-loop
NLO	R, V	2-loop
NNLO	RR, RV, VV	3-loop
N3LO	RRR, RRV, RVV, VVV	4-loop

- Infrared singularities in all R-type and V-type subprocesses
  - sum of all subprocesses finite
  - require procedure to arrange IR cancellations between subprocesses
- Incoming hadrons: parton distributions
  - mass factorization of initial-state radiation and parton evolution

Ingredients to fixed order calculations

- Different final state multiplicity for real and virtual corrections
  - R: n+1 particles; V: n particles
  - application of event selection, fiducial cuts: evaluate separately
- Upcycling of lower-order calculations
  - only purely virtual correction (V, VV, VVV, ...) genuinely new
  - real radiation corrections from higher-multiplicity calculations at lower order
  - e.g. Higgs boson production: NNLO RV contribution = NLO V contribution to H+jet
  - stability: use analytic one-loop amplitudes if available

- Cancellation of infrared singularities between subprocesses
  - must evaluate integrals of type [Z.Kunszt, D.Soper]

$$\mathcal{I} = \lim_{\epsilon \to 0} \left[\int_0^1 \frac{dx}{x} x^{\epsilon} F(x) - \frac{1}{\epsilon} F(0) \right]$$

Methods

$$\mathcal{I} = \lim_{\epsilon \to 0} \left[\int_0^1 \frac{dx}{x} x^\epsilon F(x) - \frac{1}{\epsilon} F(0) \right]$$

- Subtraction
  - subtract singular (soft and/or collinear behavior) from R, integrate and add back

$$\mathcal{I} = \lim_{\epsilon \to 0} \left[\int_0^1 \frac{dx}{x} x^\epsilon \left(F(x) - F(0)\right) + F(0) \int_0^1 \frac{dx}{x} x^\epsilon - \frac{1}{\epsilon} F(0) \right]$$

  - many variants at NLO and NNLO: dipole, FKS, antenna, residue, sector-improved,.....
    [S.Catani, M.Seymour; S.Frixione, Z.Kunszt, A.Signer; A.Gehrmann-De Ridder, N.Glover, TG; M.Czakon; F.Caola, K.Melnikov, R.Röntsch; V.del Duca, C.Duhr, A.Kardos, Z.Trocsanyi, G.Somogyi; G.Bertolotti, L.Magnea, G.Pelliccioli, A.Ratti, C.Signorile-Signorile, P.Torrielli, S.Uccirati]
- Slicing
  - cut off singular region from phase space integral, add integrated below-cut contribution

$$\mathcal{I} \approx \lim_{\epsilon \to 0} \left[\int_\delta^1 \frac{dx}{x} x^\epsilon F(x) + F(0) \int_0^\delta \frac{dx}{x} x^\epsilon - \frac{1}{\epsilon} F(0) \right] = \int_\delta^1 \frac{dx}{x} x^\epsilon F(x) + F(0) \ln \delta$$

  - variants up to N3LO, depending on slicing variable: q_T, N-jettiness
    [S.Catani, M.Grazzini; R.Boughezal, X.Liu, F.Petriello; J.Gaunt, M.Stahlhofen, F.Tackmann, J.Walsh]

NNLO subtraction

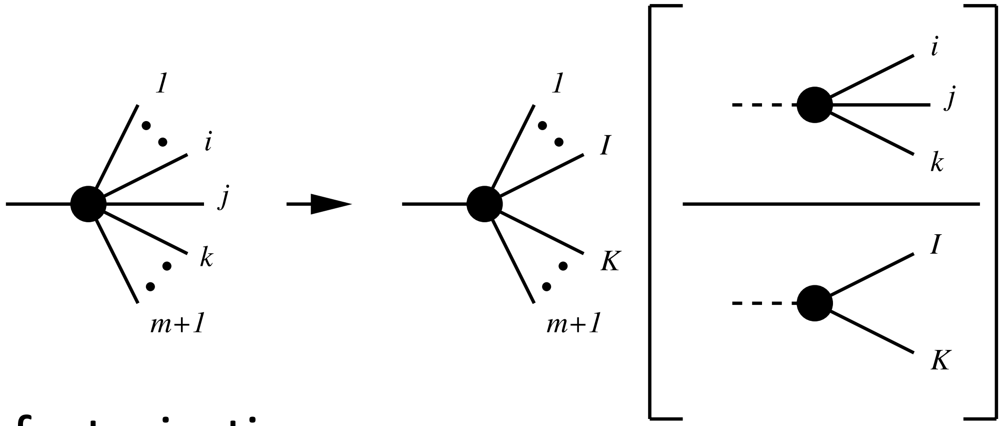
- Structure of NNLO cross section

$$\begin{aligned}\mathrm{d}\sigma_{NNLO} = &\int_{\mathrm{d}\Phi_{m+2}} \left(\mathrm{d}\sigma^R_{NNLO} - \mathrm{d}\sigma^S_{NNLO}\right) \\ &+ \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{V,1}_{NNLO} - \mathrm{d}\sigma^{VS,1}_{NNLO}\right) + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma^{MF,1}_{NNLO} \\ &+ \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\sigma^{V,2}_{NNLO} + \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\sigma^{S}_{NNLO} + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma^{VS,1}_{NNLO} + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\sigma^{MF,2}_{NNLO}\end{aligned}$$

  - Real and virtual contributions: $\mathrm{d}\sigma^R_{NNLO}, \mathrm{d}\sigma^{V,1}_{NNLO}, \mathrm{d}\sigma^{V,2}_{NNLO}$
  - Subtraction term for double real radiation: $\mathrm{d}\sigma^S_{NNLO}$
  - Subtraction term for one-loop single real radiation: $\mathrm{d}\sigma^{VS,1}_{NNLO}$
  - Mass factorization terms: $\mathrm{d}\sigma^{MF,1}_{NNLO}, \mathrm{d}\sigma^{MF,2}_{NNLO}$
- Each line finite and free of poles → numerical implementation

Antenna subtraction

- Subtraction terms constructed from antenna functions
  - Antenna function contains all emission between two partons



  - Phase space factorization

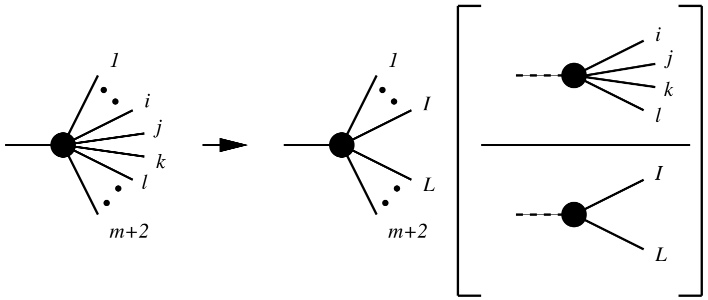
$$d\Phi_{m+1}(p_1, \ldots, p_{m+1}; q) = d\Phi_m(p_1, \ldots, \tilde{p}_I, \tilde{p}_K, \ldots, p_{m+1}; q) \cdot d\Phi_{X_{ijk}}(p_i, p_j, p_k; \tilde{p}_I + \tilde{p}_K)$$

  - Integrated subtraction term

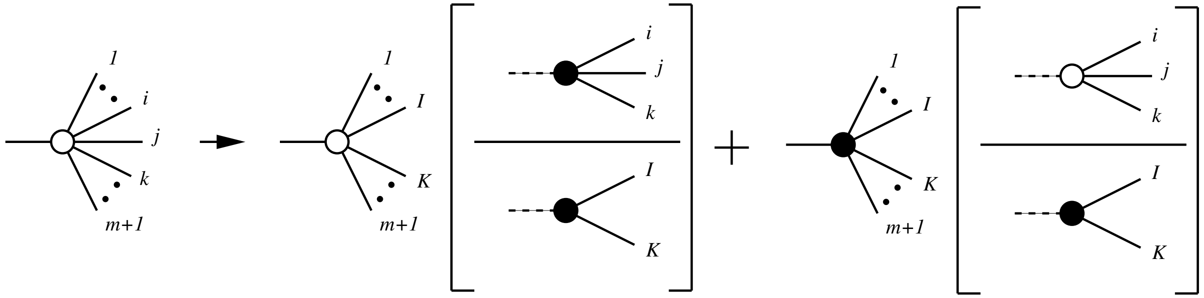
$$\mathcal{X}_{ijk} = \int d\Phi_{X_{ijk}} X_{ijk}$$

Antenna subtraction

- Colour-ordered pair of hard partons (radiators)
  - Hard quark-antiquark pair
  - Hard quark-gluon pair
  - Hard gluon-gluon pair
- NLO [D. Kosower; J. Campbell, M. Cullen, E.W.N. Glover]
  - Three-parton antenna: one unresolved parton

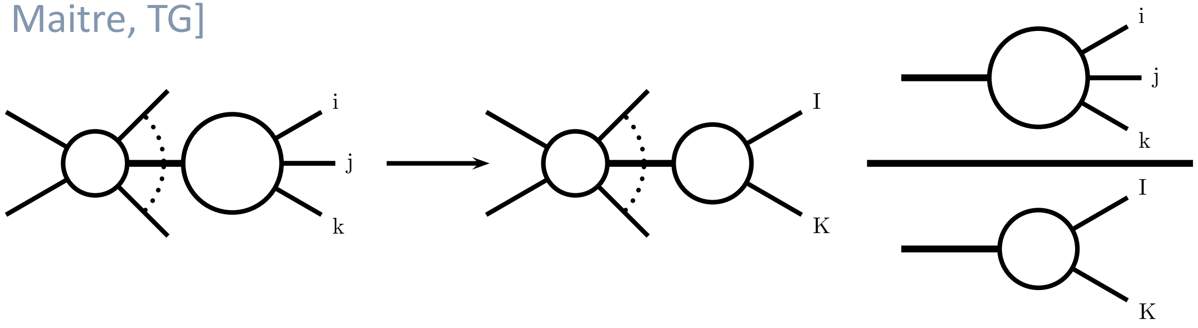


- NNLO [A. Gehrmann-De Ridder, E.W.N. Glover, TG]
  - Four-parton antenna: two unresolved partons
  - Three-parton antenna at one loop
  - Products of NLO antenna functions
  - Soft antenna function

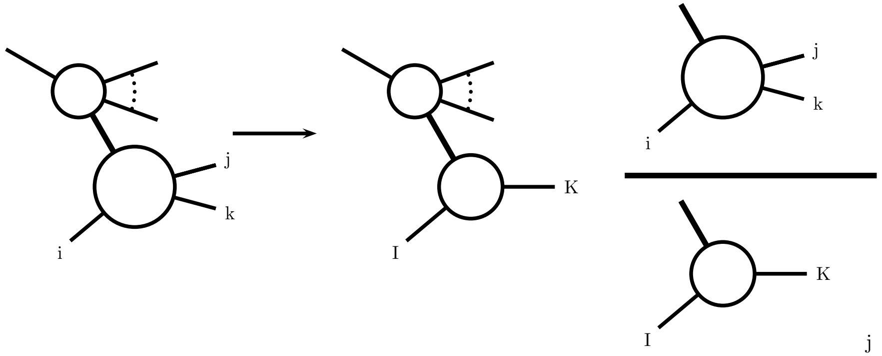


Antenna subtraction: incoming hadrons

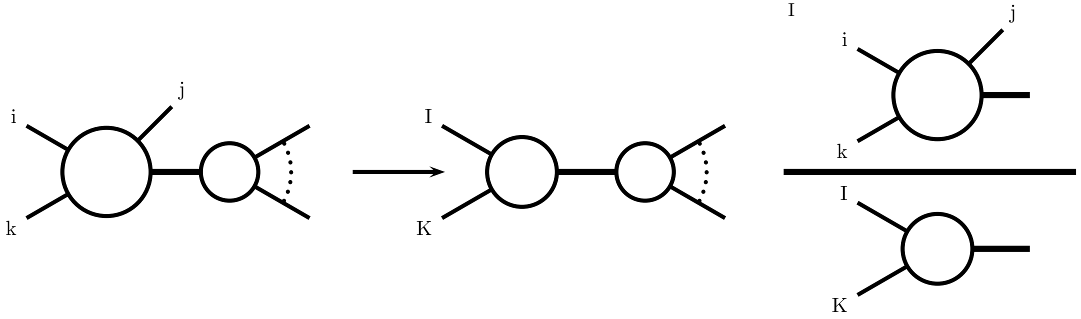
- Three antenna types [A. Daleo, D. Maitre, TG]
  - Final-final antenna



  - Initial-final antenna



  - Initial-intial antenna

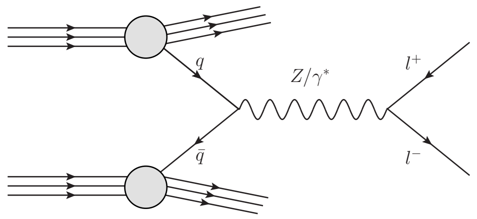


NNLOJET code

NNLOJET project:
X. Chen, J. Cruz-Martinez, J, Currie,
R. Gauld, A. Gehrmann-De Ridder,
E.W.N. Glover, M. Höfer, A. Huss,
F. Lorkowski, I. Majer, M. Marcoli, J. Mo,
T. Morgan, J. Niehues, J. Pires, C.Preuss,
A. Rodriguez-Gracia, R. Schürmann,
G. Stagnitto, D. Walker, J. Whitehead, TG

- NNLO parton level event generator
  - Based on antenna subtraction
- Provides infrastructure
  - Process management
  - Phase space, histogram routines
  - Validation and testing
  - Parallel computing (MPI) support for warm-up and production
  - ApplGrid/fastNLO interfaces in development
- Processes implemented at NNLO
  - Z+(0,1)jet, γ+1 jet, H+(0,1)jet, W+(0,1)jet, H+2jet (VBF)
  - DIS-2j, LHC-2j
  - Typical runtimes: 60’000-250’000 core-hours

Triple-differential Drell-Yan cross section

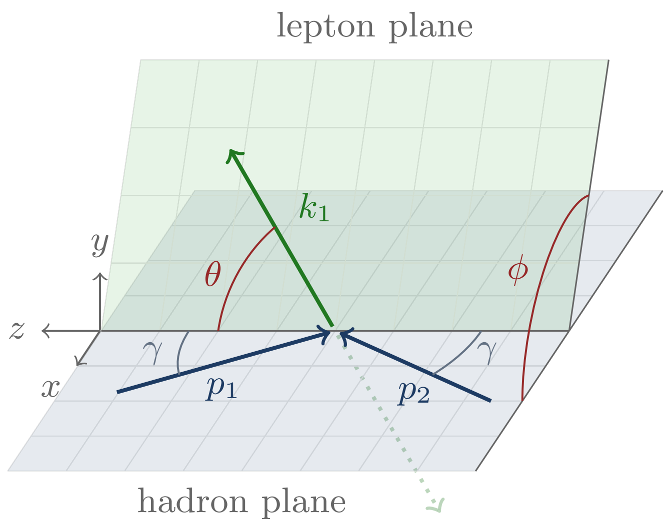


- Lepton pair production: EW precision observable

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

- 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]
$\|y_{ll}\|$	[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

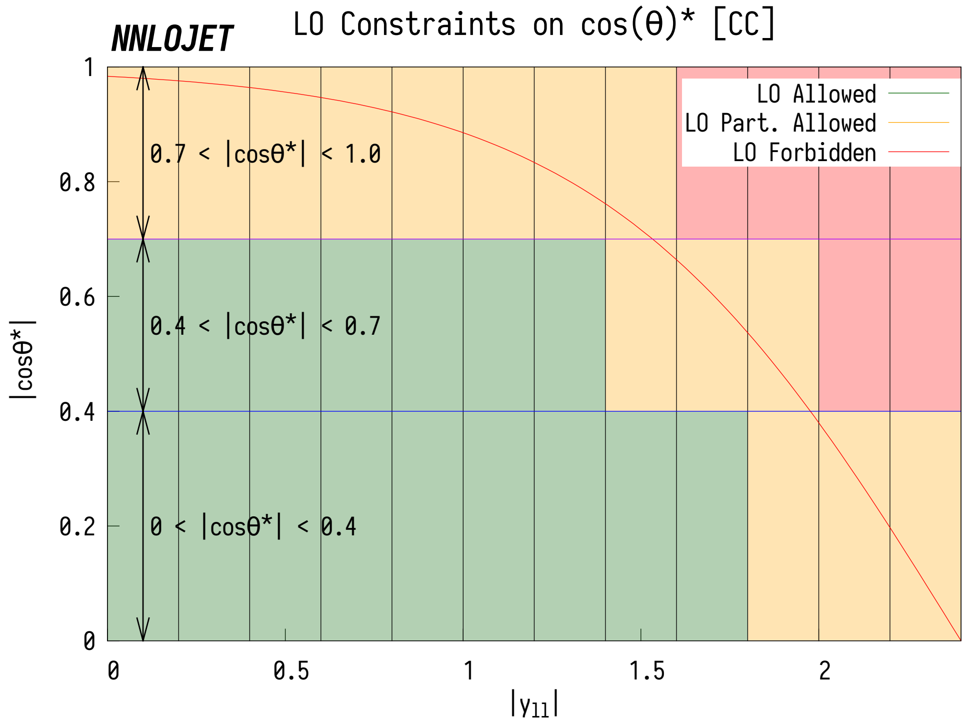
- Measured with fiducial event selection cuts (on single leptons)

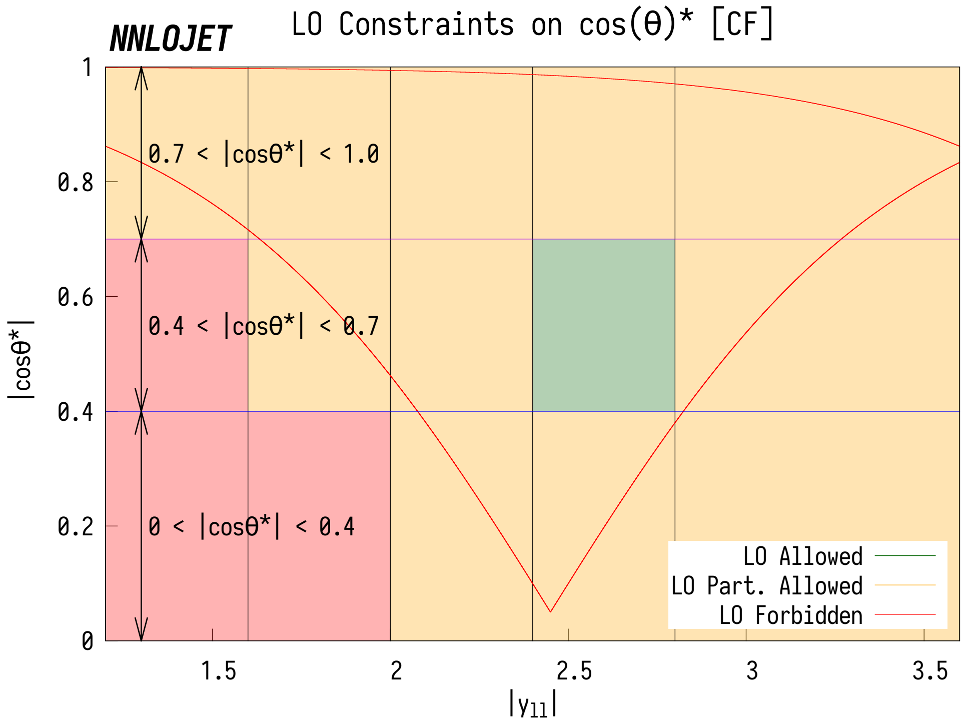
Central-Central	Central-Forward	
$p_T^l > 20$ GeV	$p_{T,F}^l > 20$ GeV	$p_{T,C}^l > 25$ GeV
$\lvert y^l \rvert < 2.4$	$2.5 < \lvert y_F^l \rvert < 4.9$	$\lvert y_C^l \rvert < 2.4$
$46\ \text{GeV} < m_{ll} < 200\ \text{GeV}$	$66\ \text{GeV} < m_{ll} < 150\ \text{GeV}$	

- 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]

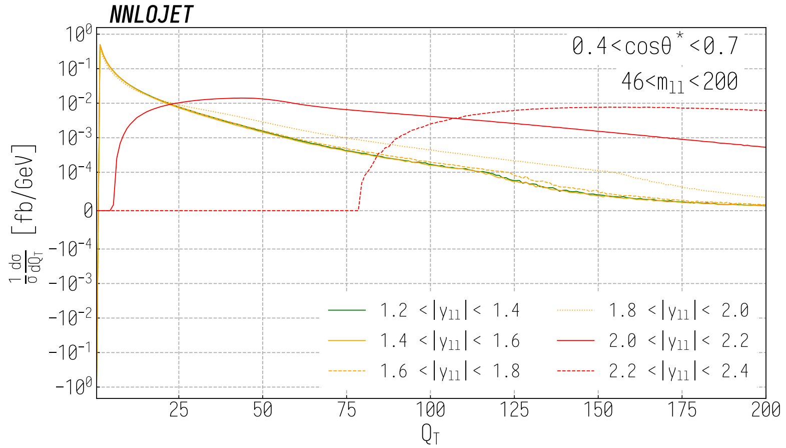


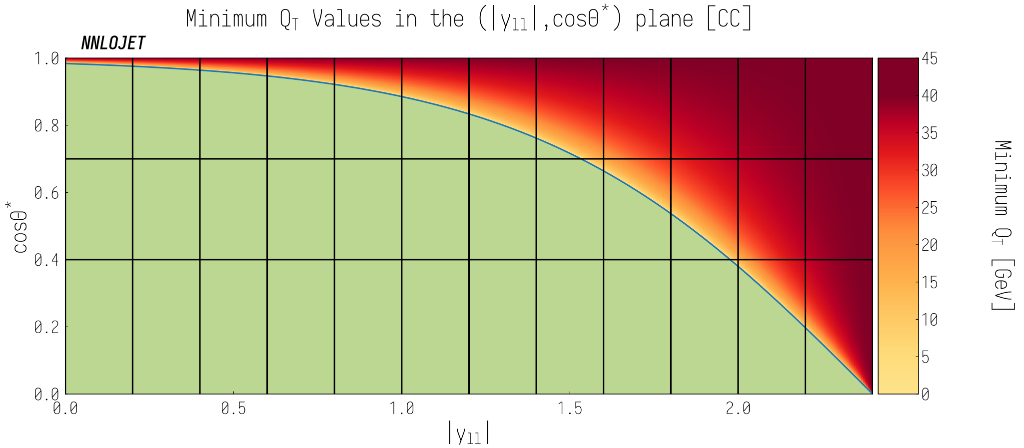


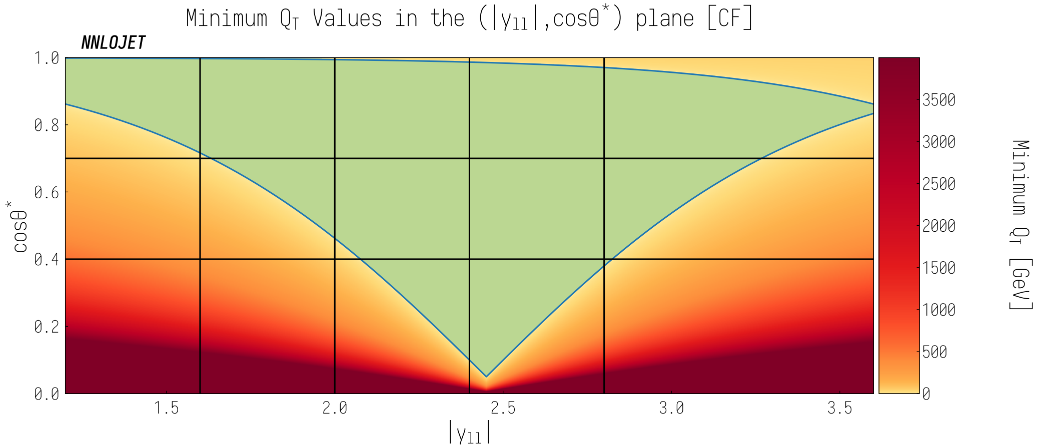
Triple-differential Drell-Yan cross section

- 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



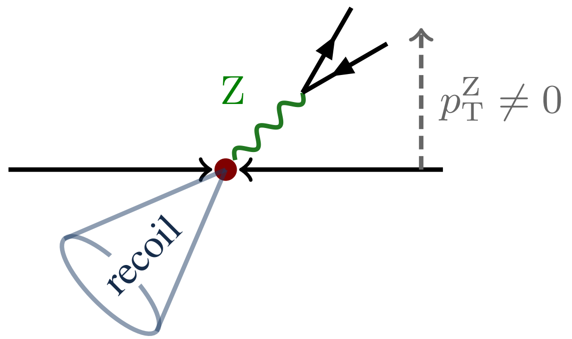




Triple-differential Drell-Yan cross section

Forbidden bins at leading order

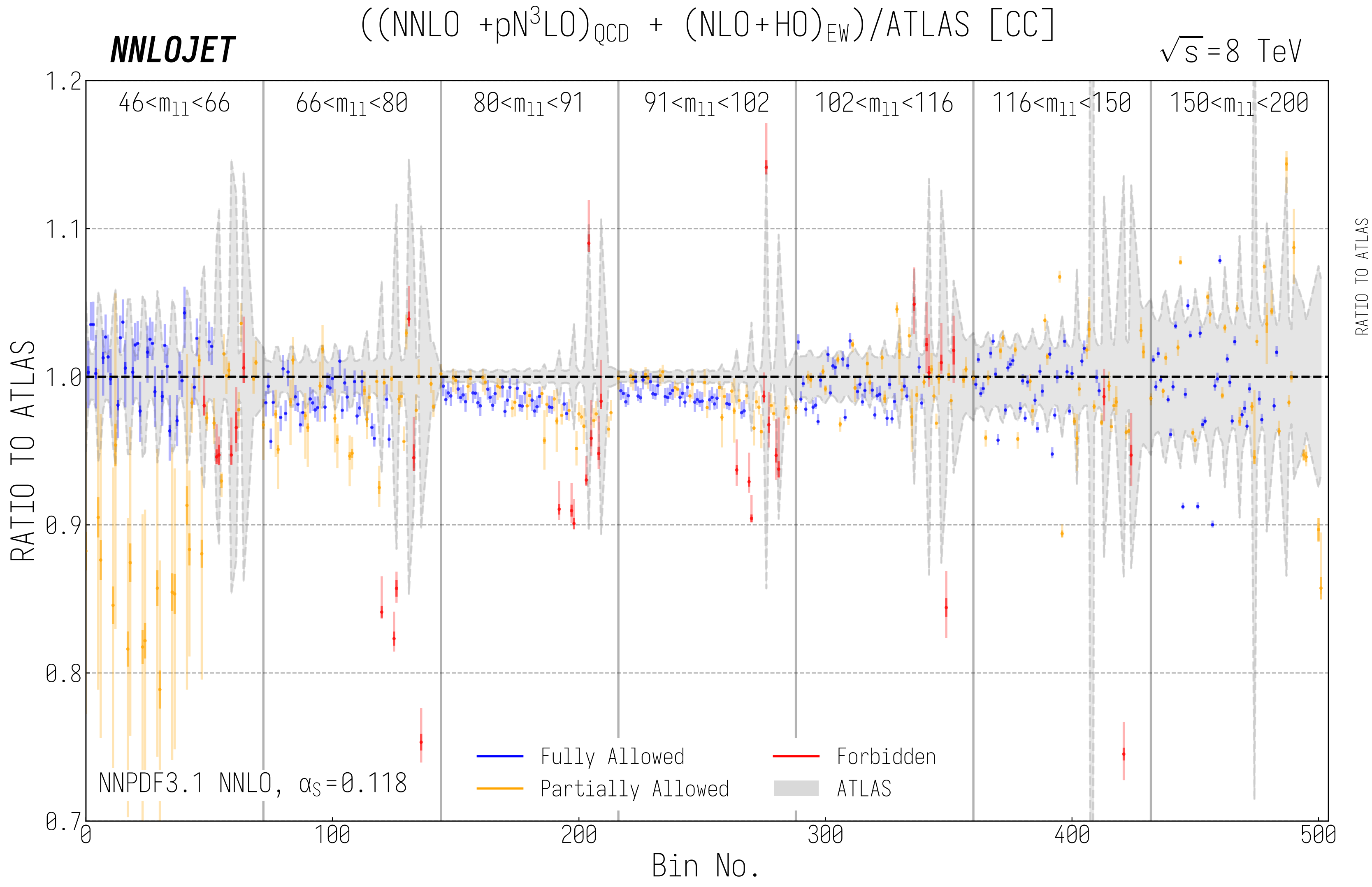
- large theory uncertainty, poor agreement with data
- $O(\alpha_s^3)$ corrections (Drell-Yan N^3LO) obtained from V+jet at NNLO
  [R.Boughezal, J.Campbell, K.Ellis, C.Focke, W.Giele, X.Liu, F.Petriello; MCFM: T.Neumann, J.Campbell; NNLOJET: A.Gehrmann-De Ridder, N.Glover, A.Huss, T.Morgan, D.Walker, TG]
  - use NNLOJET implementation
  - replace jet requirement by (small) Q_T cut
  - numerical convergence at small Q_T challenging

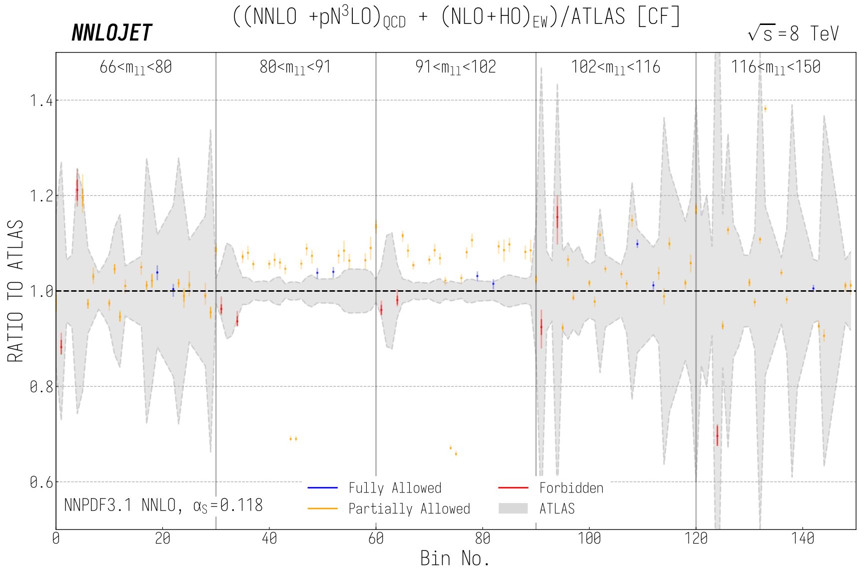


State-of-the-art theory prediction

- 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



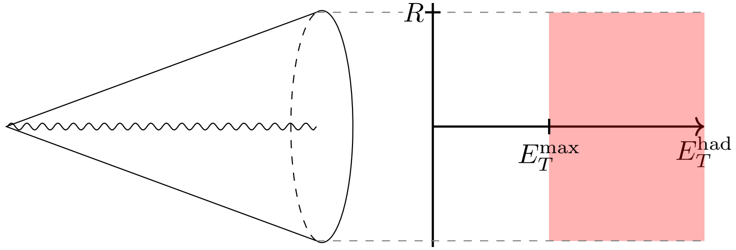


Future applications

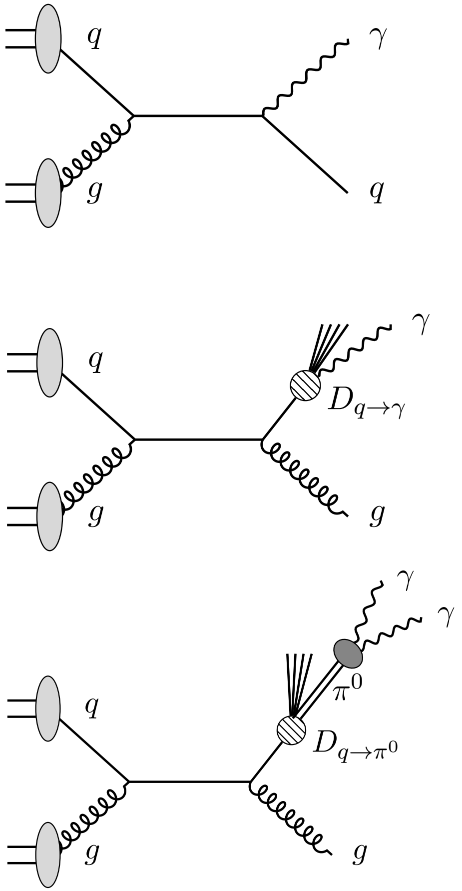
- measurement of $\sin^2\Theta_W$
- determination of parton distributions

Photon+jet production at NNLO

- Photon+jet production
  - multi-differential measurements
  - probe of gluon distribution
  - several production modes: direct, fragmentation, secondary
- Photon isolation
  - required for photon identification
  - sensitive on photon fragmentation function
  - extension of NNLO antenna subtraction: identified particles
    [R. Schürmann, TG]

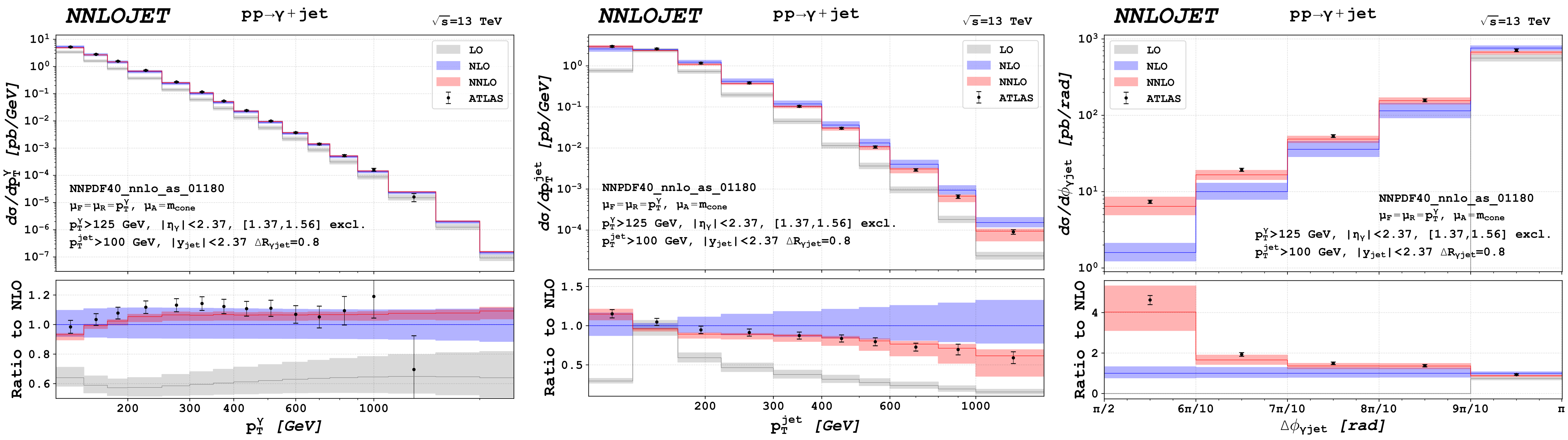


fixed cone: $E_{had} < \varepsilon E_\gamma + E_0$



Photon+jet production at NNLO

- NNLO corrections [X. Chen, E.W.N. Glover, A. Huss, M. Höfer, R. Schürmann, TG]
  - reduce theory uncertainty to ~5% level
  - considerably improve description of kinematical shapes



Identified hadrons at NNLO

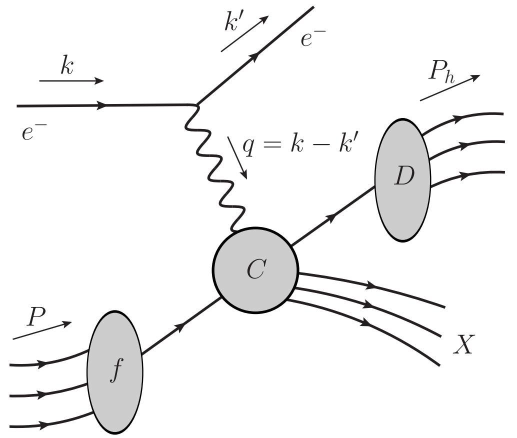
- Fragmentation antenna functions
  - antenna functions (final-final or initial-final) differential in the momentum fraction z of one hard final-state radiator
- Computation of integrated fragmentation antennae

  [L.Bonino, R.Schürmann, G.Stagnitto, TG]
  - NLO and NNLO real-virtual: no integration needed, expansion in distributions
  - NNLO double-real: phase space integration (2⟶3 phase space with constraints)
    - reduction to phase space master integrals
    - computation from differential equations
    - boundary conditions from integration over z

family	master	deepest pole	at $x=1$	at $z=1$
	$I[0]$	ϵ^0	$(1-x)^{1-2\epsilon}$	$(1-z)^{1-2\epsilon}$
A	$I[5]$	ϵ^{-1}	$(1-x)^{-2\epsilon}$	$(1-z)^{1-2\epsilon}$
	$I[2,3,5]$	ϵ^{-2}	$(1-x)^{-1-2\epsilon}$	$(1-z)^{-1-2\epsilon}$
B	$I[7]$	ϵ^0	$(1-x)^{1-2\epsilon}$	$(1-z)^{1-2\epsilon}$
	$I[-2,7]$	ϵ^0	$(1-x)^{1-2\epsilon}$	$(1-z)^{1-2\epsilon}$
	$I[-3,7]$	ϵ^0	$(1-x)^{1-2\epsilon}$	$(1-z)^{1-2\epsilon}$
	$I[2,3,7]$	ϵ^{-2}	$(1-x)^{-2\epsilon}$	$(1-z)^{-1-2\epsilon}$
C	$I[5,7]$	ϵ^{-1}	$(1-x)^{-2\epsilon}$	$(1-z)^{1-2\epsilon}$
	$I[3,5,7]$	ϵ^{-2}	$(1-x)^{-2\epsilon}$	$(1-z)^{-2\epsilon}$
D	$I[1]$	ϵ^0	$(1-x)^{-2\epsilon}$	$(1-z)^{-2\epsilon}$
	$I[1,4]$	ϵ^0	$(1-x)^{-2\epsilon}$	$(1-z)^{-2\epsilon}$
	$I[1,3,4]$	ϵ^{-1}	$(1-x)^{-2\epsilon}$	$(1-z)^{-1-2\epsilon}$
E	$I[1,3,5]$	ϵ^{-2}	$(1-x)^{-2\epsilon}$	$(1-z)^{-1-2\epsilon}$
G	$I[1,3,8]$	ϵ^{-2}	$(1-x)^{-2\epsilon}$	$(1-z)^{-1-2\epsilon}$
H	$I[1,4,5]$	ϵ^{-1}	$(1-x)^{-1-2\epsilon}$	$(1-z)^{-2\epsilon}$
I	$I[2,4,5]$	ϵ^{-2}	$(1-x)^{-1-2\epsilon}$	$(1-z)^{-2\epsilon}$
J	$I[4,7]$	ϵ^0	$(1-x)^{-2\epsilon}$	$(1-z)^{-2\epsilon}$
	$I[3,4,7]$	ϵ^{-1}	$(1-x)^{-2\epsilon}$	$(1-z)^{-2\epsilon}$
K	$I[3,5,8]$	ϵ^{-2}	$(1-x)^{-1-2\epsilon}$	$(1-z)^{-2\epsilon}$
L	$I[4,5,7]$	ϵ^{-1}	$(1-x)^{-1-2\epsilon}$	$(1-z)^{-2\epsilon}$
M	$I[4,5,8]$	ϵ^{-1}	$(1-x)^{-1-2\epsilon}$	$(1-z)^{-2\epsilon}$

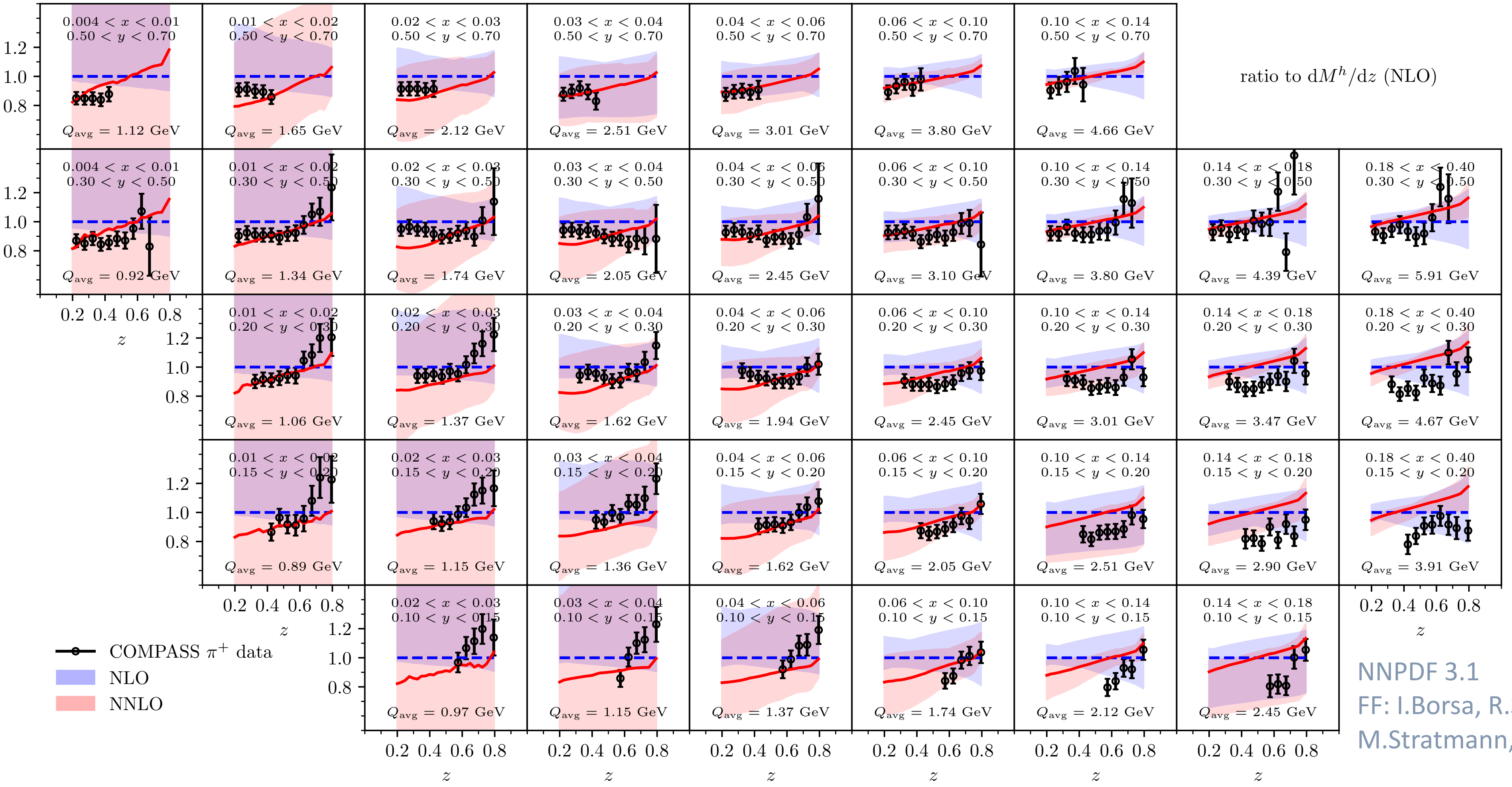
Identified hadrons at NNLO

- Semi-inclusive DIS (SIDIS)
  - resolve flavour structure of light quark sea (π, K production)
  - tag heavy flavours (D production)
  - important process in polarized DIS (spin structure of the proton)
  - studied at EMC, SMC, HERMES, COMPASS
  - will be probed extensively at BNL Electron-Ion Collider (EIC)



- NNLO SIDIS coefficient functions [L.Bonino, R.Schürmann, G.Stagnitto, TG]
  - computation very similar to initial-final fragmentation antenna functions
  - confirm earlier partial results and approximations [D.Anderle, D.de Florian, W. Vogelsang]
  - on non-singlet leading colour: agree with independent results [S.Goyal, S.Moch, V.Pathak, N.Rana, V.Ravindran]

Identified hadrons at NNLO: SIDIS



NNPDF 3.1
FF: I.Borsa, R.Sassot, D.de Florian, M.Stratmann, W.Vogelsang

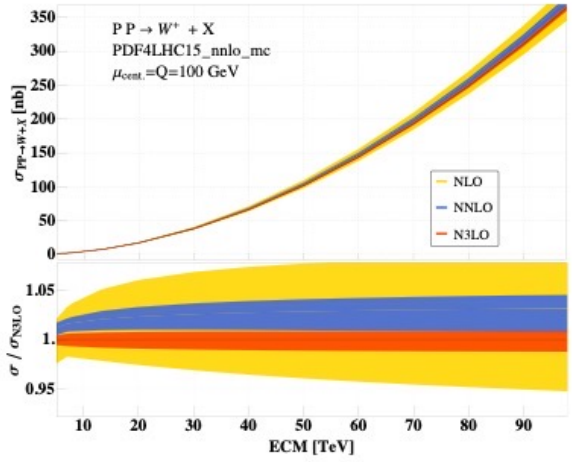
Towards N3LO for fiducial cross sections

Inclusive coefficient functions (total cross section) at N3LO

- computed analytically
- three-loop form factors (VVV)
- inclusive phase space up to triple emission (RRR,RRV,RVV)
- 100s of loop and phase-space master integrals

Results

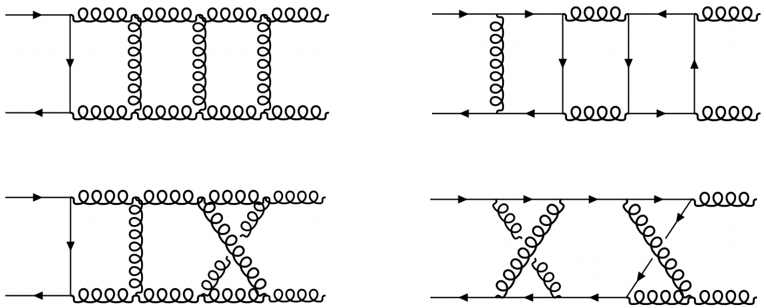
- Deep inelastic structure functions
  [S.Moch, J.Vermaseren, A.Vogt; J.Blümlein, P.Marquard, C.Schneider, K.Schönwald]
- Higgs boson production [C.Anastasiou, C.Duhr, F.Dulat, F.Herzog, B.Mistlberger]
- Higgs boson rapidity distribution [B.Mistlberger]
- Drell-Yan production: $\gamma^*/Z^0,W^\pm$ [C.Duhr, F.Dulat, B.Mistlberger]
- associated VH production [n3loxs: J.Baglio, C.Duhr, B.Mistlberger, R.Szafron]



Towards N3LO for fiducial cross sections

Three-loop amplitudes for 2 $\rightarrow$ 2 processes (VVV)

- algebraic complexity of integral reduction, computation of master integrals
- recent innovations
  - finite-field methods [A.von Manteuffel, R.Schabinger; T.Peraro]
  - canonical integral basis [J.Henn]
  - minimal tensor decomposition [T.Peraro, L.Tancredi]
- first results
  - four-parton amplitudes
    [F.Caola, A.Chakraborty, G.Gambuti, A.von Manteuffel, L.Tancredi]
  - parton-photon amplitudes
    [P.Bargiela, F.Caola, A.Chakraborty, G.Gambuti, A.von Manteuffel, L.Tancredi]
  - V+3-parton amplitudes (planar)
    [P.Jakubcik, C.Mella, N.Syrrakos, L.Tancredi, TG]



Towards N3LO for fiducial cross sections

Infrared singularity structure of real radiation understood

- RRR: four-parton collinear factors [V.del Duca, C.Duhr, R.Haindl, A.Lazopoulos, M.Michel]
- RRR: triple-soft current [S.Catani, L.Cieri, D.Colferai, F.Coradeschi, A.Torrini; V.del Duca, C.Duhr, R.Haindl, Z.Liu]
- RRV: three-parton collinear factors at one loop [S.Catani, D.de Florian, G.Rodrigo; M.Czakon, S.Sapeta]
- RRV: one-loop double-soft current [S.Catani, L.Cieri; Y.Zhu; M.Czakon, F.Eschment, T.Schellenberger]
- RVV: simple collinear factors at two loops [C.Duhr, M.Jaquier, TG]
- RVV: two-loop soft current [Y.Li, H.X.Zhu; C.Duhr, TG; L.Dixon, E.Herrmann, K.Yan, H.X.Zhu]

Require scheme for infrared cancellations

Towards N3LO for fiducial cross sections

Infrared cancellations: challenges

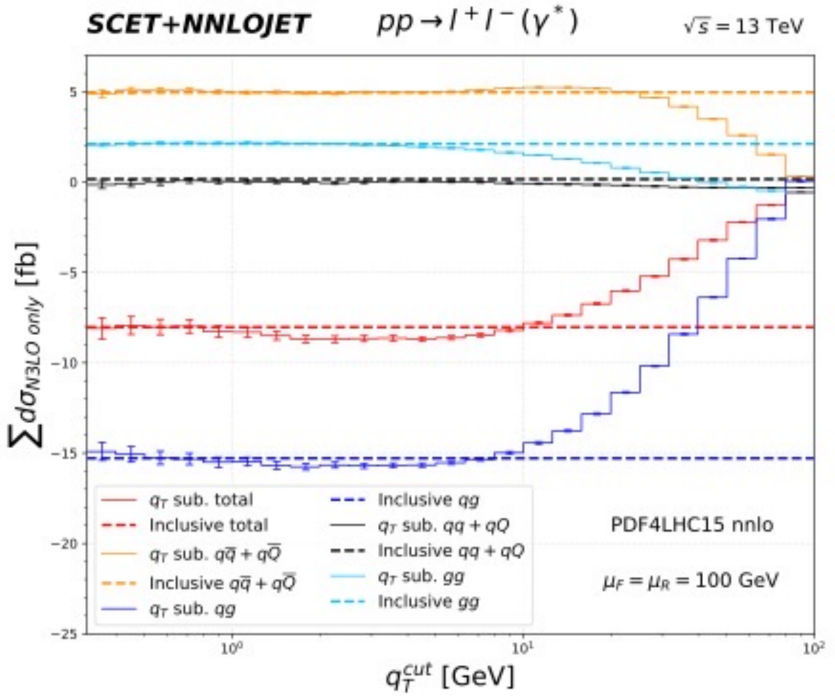
- subtraction $$\mathcal{I} = \lim_{\epsilon\to 0}\left[\int_0^1 \frac{dx}{x} x^\epsilon \left(F(x) - F(0)\right) + F(0)\int_0^1 \frac{dx}{x} x^\epsilon - \frac{1}{\epsilon}F(0)\right]$$
  - construction of subtraction term (completeness, overcompensation)
  - integration of building blocks (analytical or numerical)
- slicing $$\mathcal{I} \approx \lim_{\epsilon\to 0}\left[\int_\delta^1 \frac{dx}{x} x^\epsilon F(x) + F(0)\int_0^\delta \frac{dx}{x} x^\epsilon - \frac{1}{\epsilon}F(0)\right]$$
  - analytic computation of below-cut contribution
  - numerical importance of power-suppressed terms, value of slicing parameter

N3LO for Drell-Yan observables

Slicing parameter: transverse momentum (q_T slicing) [S.Catani, M.Grazzini]

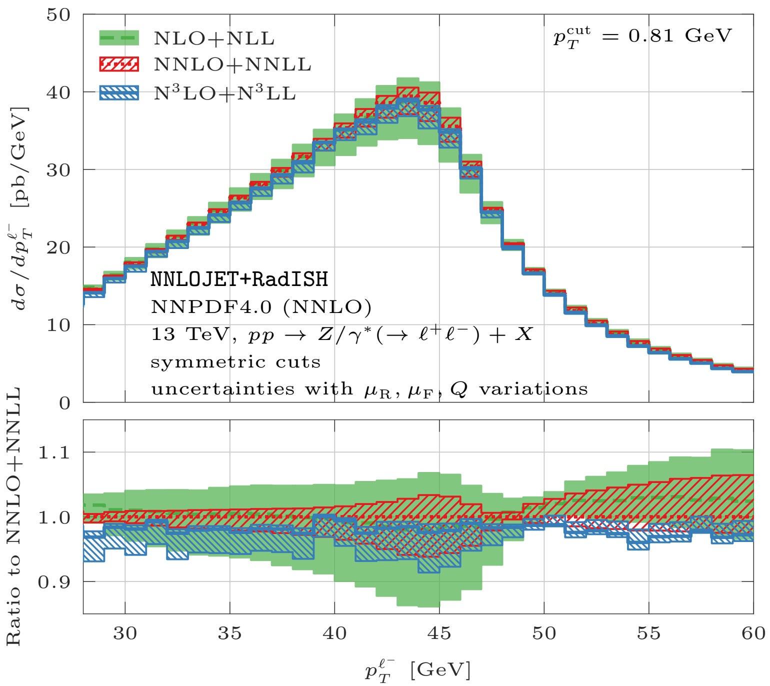
$$\frac{d\sigma_X^{N3LO}}{dO} = \mathcal{H}_{N3LO} \otimes \frac{d\sigma_X^{LO}}{dO} + \left[\int_{q_{T,X}} \frac{d\sigma_{X+j}^{NNLO}}{dO} - \frac{d\sigma_{X,CT}^{NNLO}}{dO}(q_T) \right]$$

- below-cut contribution from expansion of N3LL q_T resummation to $O(\alpha_s^3)$ [W.Bizon, P.Monni, E.Re, P.Torrielli; S.Camrada, L.Cieri, G.Ferrera;T.Becher, T.Neumann; W.L.Ju, M.Schönherr]
- ingredients: three-loop soft and beam functions [Y.Li, H.X.Zhu; M.Ebert, B.Mistlberger, G.Vita; M.X.Luo, 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!) [X.Chen, E.W.N.Glover, A.Huss, T.Z.Yang, H.X.Zhu, TG]



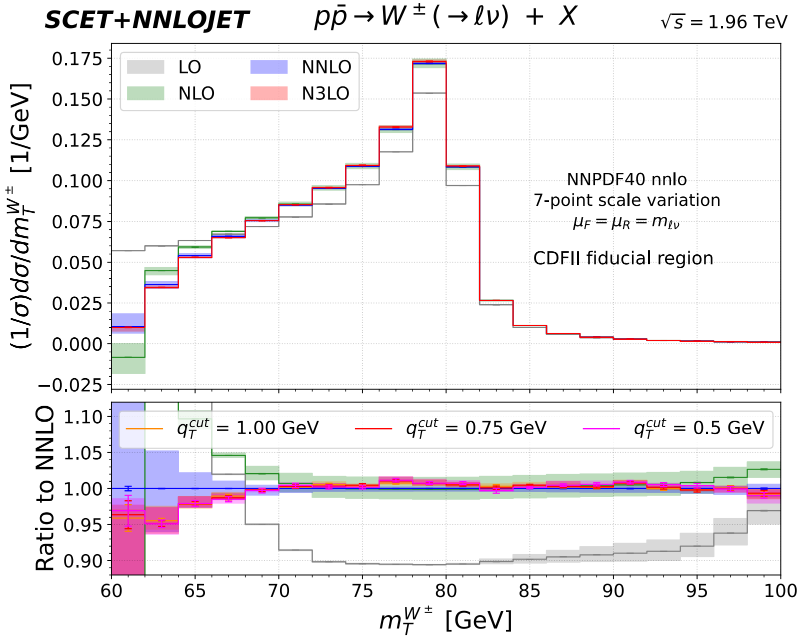
N3LO for Drell-Yan observables

Results: fiducial distributions



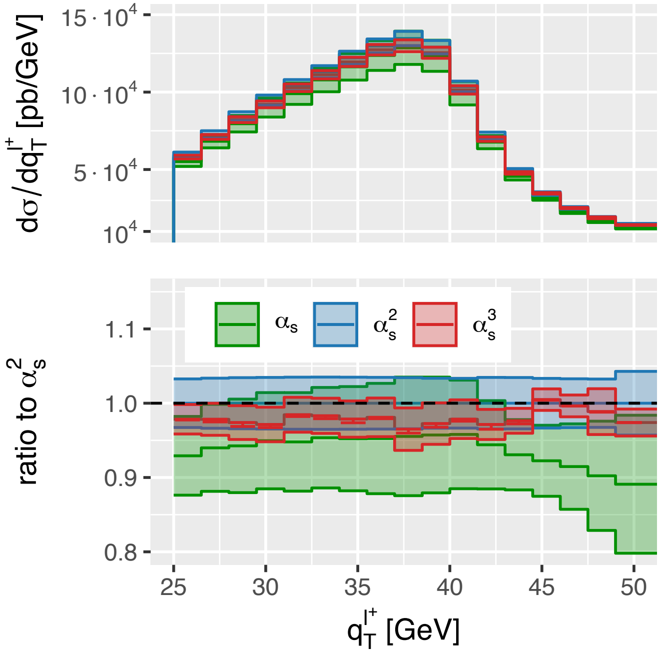
single lepton distribution in NC Drell-Yan, matched to N3LL resummation (RadISH)

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



transverse mass distribution in W boson production (CDF II cuts)

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



charged lepton distribution in W boson production (ATLAS 5.02 TeV)

[J.Campbell, T.Neumann]

Towards N3LO for fiducial cross sections

Subtraction methods at N3LO: work in progress

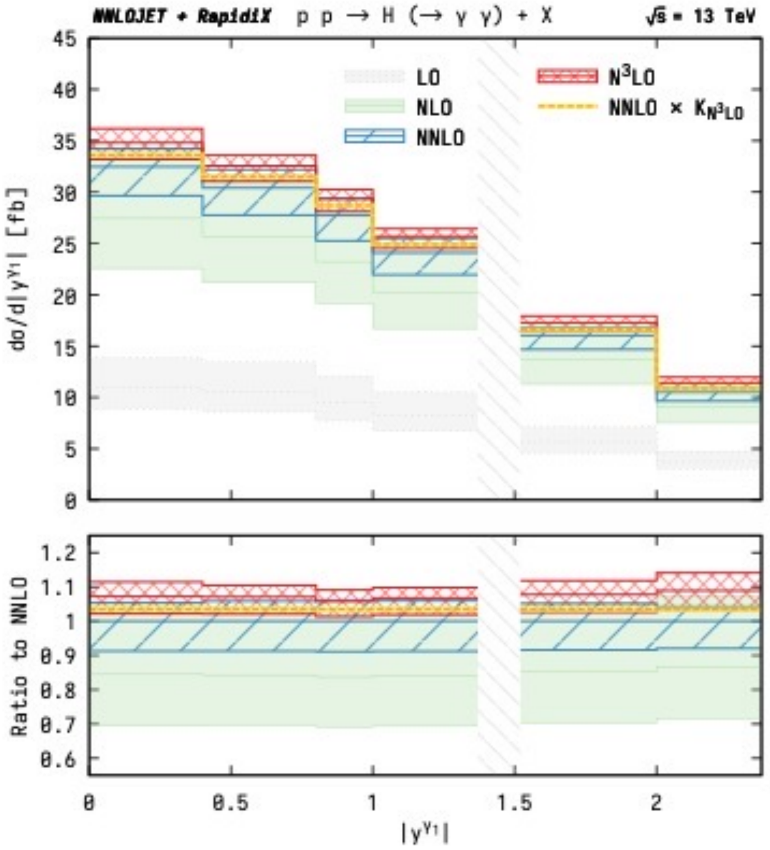
- integrating N3LO antenna functions
  - final-final kinematics [X.Chen, M.Marcoli, P.Jakubcik, G.Stagnitto]
  - initial-final kinematics [G.Fontana, K.Schönwald, TG]

Shortcut for simple processes: Projection to Born

[M.Cacciari, F.Dreyer, A.Karlberg, G.Salam, G.Zanderighi]

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

- Higgs production in vector boson fusion [F.Dreyer, A.Karlberg]
- Higgs production in gluon fusion, including $H \longrightarrow \gamma\gamma$
  [X.Chen, N.Glover, A.Huss, B.Mistlberger, A.Pelloni]



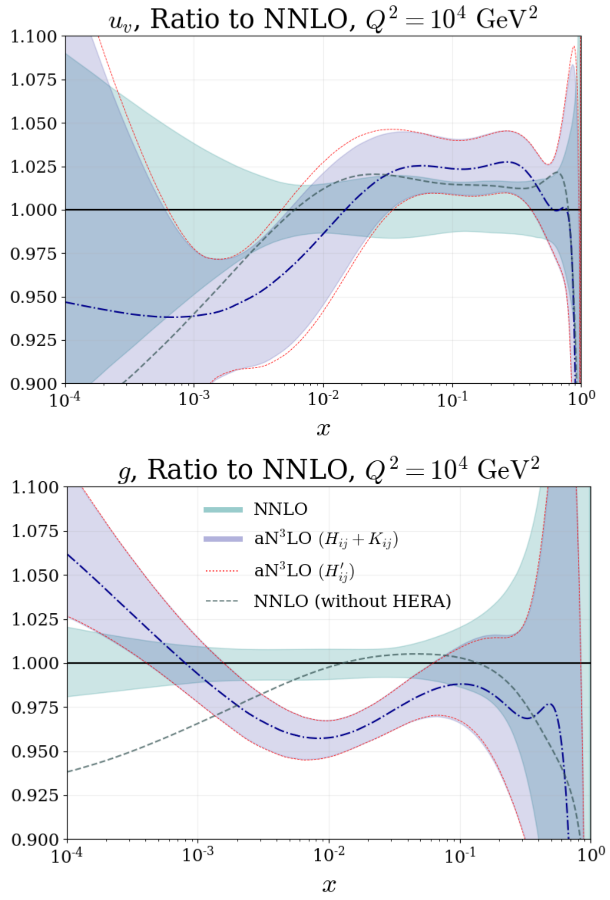
Parton distributions at N3LO

Caveat: current N3LO predictions use NNLO parton distributions

- inherent inconsistency, difficult to quantify

N3LO parton distributions require

- four-loop Altarelli-Parisi splitting functions
  - use four-loop OPE, haunted by ghosts
  - ongoing: lower Mellin moments, specific color and flavor combinations [G.Falcioni, F.Herzog, S.Moch, A.Vogt; A.von Manteuffel, V.Sotnikov, T.Z.Yang, TG]
- N3LO coefficient functions for relevant observables
  - DIS and inclusive DY known [S.Moch, J.Vermaseren, A.Vogt; J.Blümlein, P.Marquard, C.Schneider, K.Schönwald; C.Duhr, B.Mistlberger]
  - fiducial cross sections next frontier



First approximate N3LO parton distribution fits

[MSHT: J.McGowan, T.Cridge, L.Harland-Lang, R.Thorne]

Summary

- LHC embarks on a decade-long program of precision physics
- Ultimate precision challenge for QCD
  - predictions for complex final states at per-cent level accuracy
- Theory ready to face this challenge
  - NNLO predictions becoming the new standard
  - N3LO concepts, techniques and tools developing rapidly
- Stay tuned