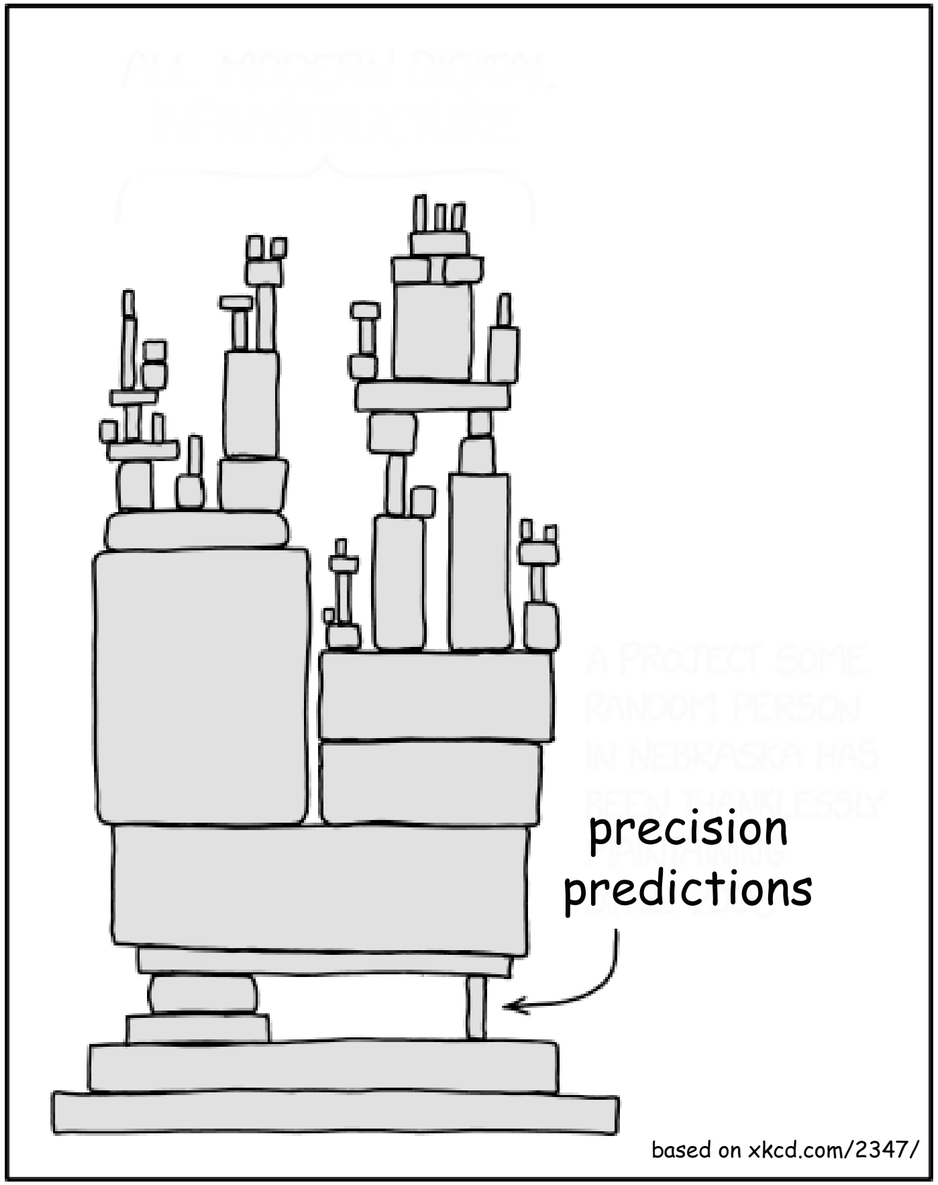
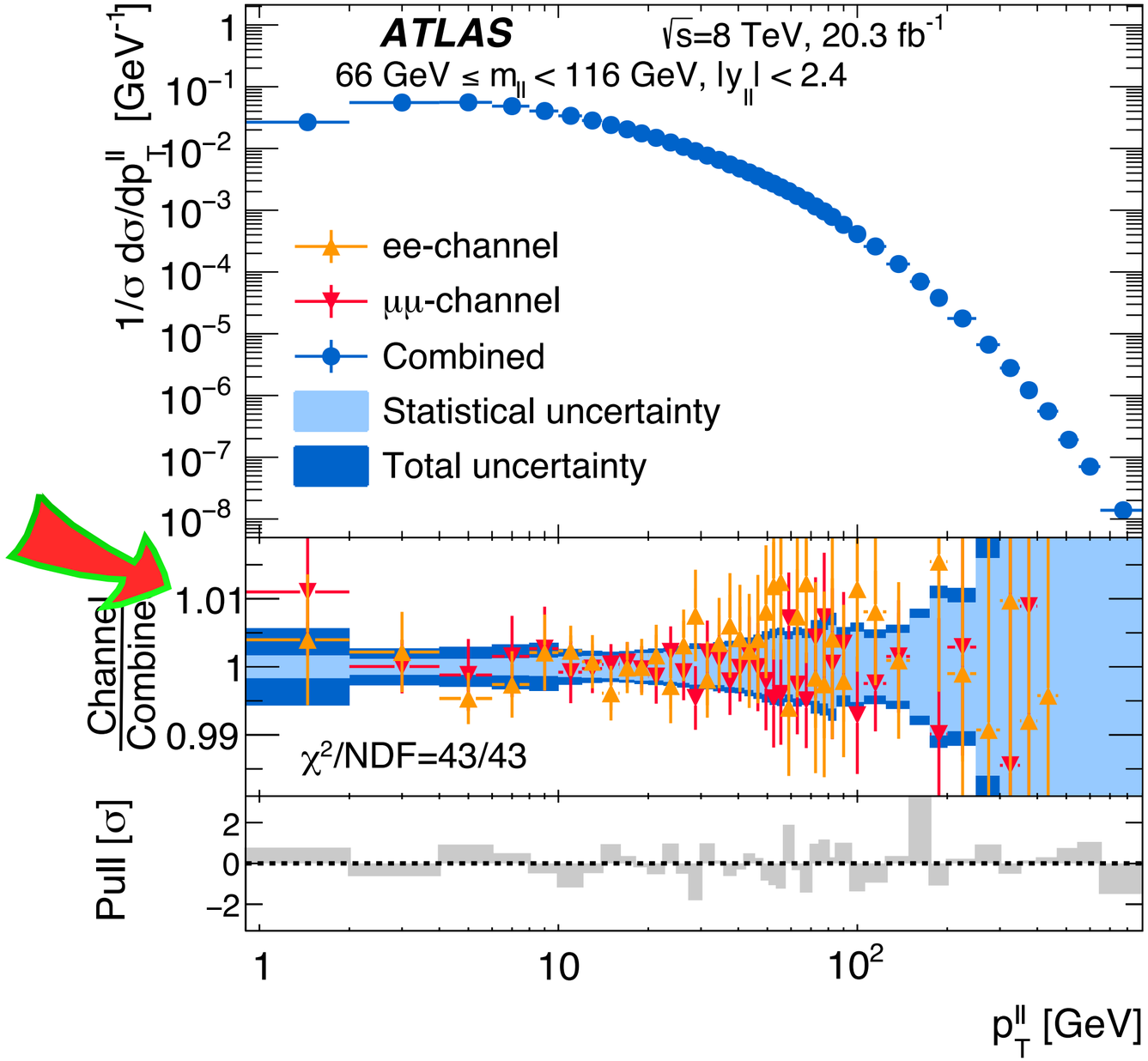
Precision calculations in boson and diboson processes with transverse-momentum and jet-veto resummation

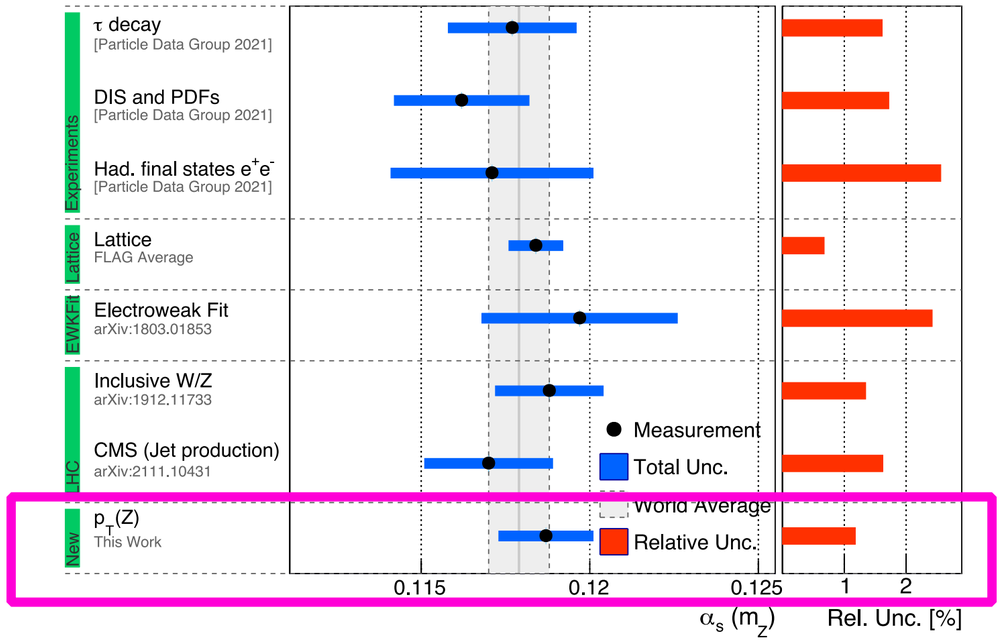
Tobias Neumann, Brookhaven National Lab


precision
predictions
based on xkcd.com/2347/


ATLAS
√s=8 TeV, 20.3 fb-1
66 GeV ≤ m_ll < 116 GeV, |y_ll| < 2.4
ee-channel
μμ-channel
Combined
Statistical uncertainty
Total uncertainty
1/σ dσ/dp_T^ll [GeV-1]
Channel/Combine
χ2/NDF=43/43
Pull [σ]
p_T^ll [GeV]

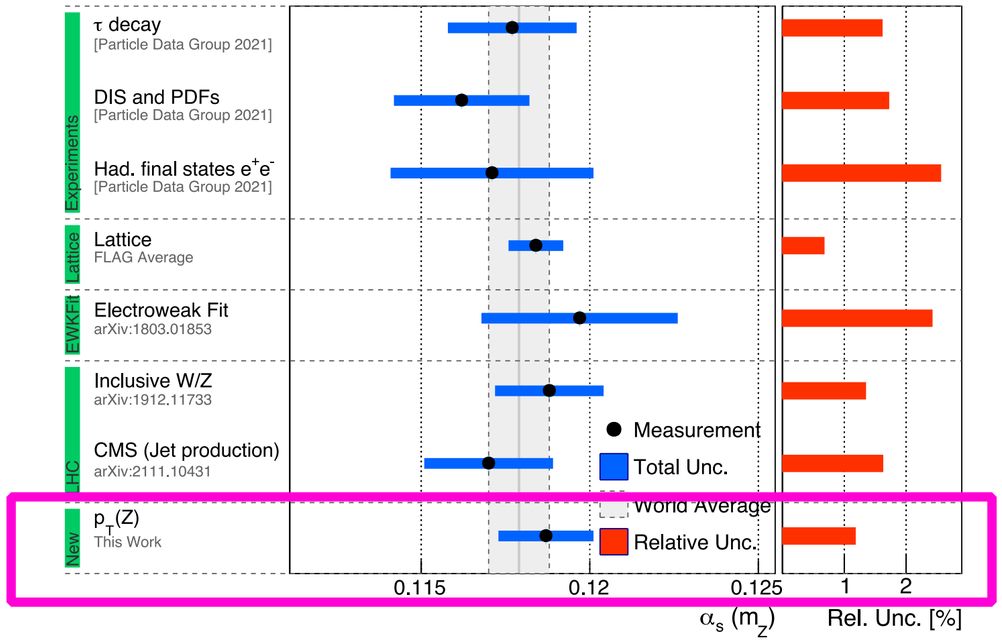
Pythia tunes....
(e.g. ATLAS AZ)

Camarda, Ferrera, Schott 2203.05394



Pythia tunes....
(e.g. ATLAS AZ)

Camarda, Ferrera, Schott 2203.05394

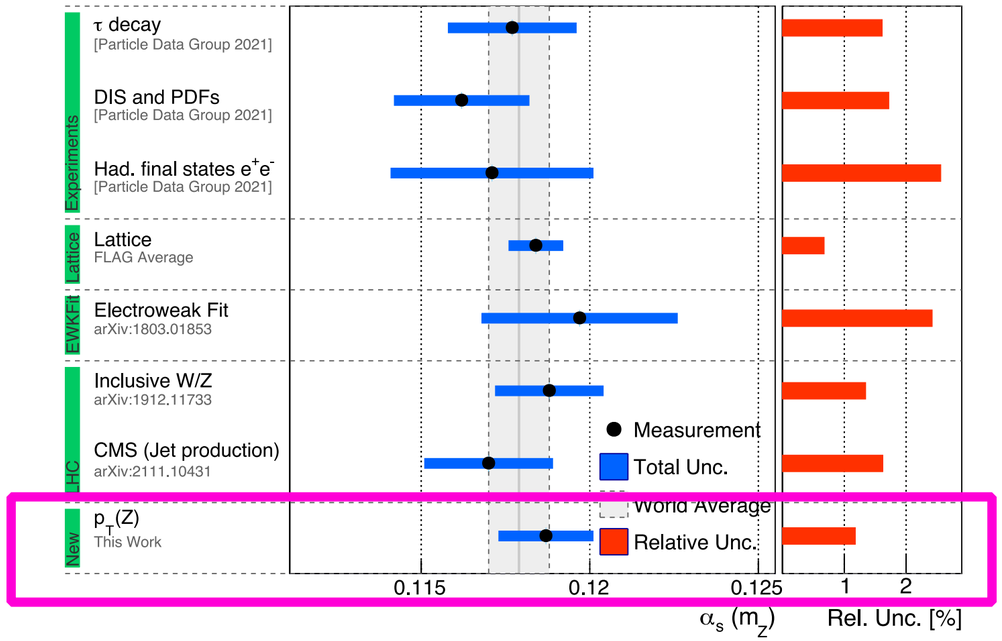


Calibration/Tuning

Illustration: Gaia Fontana

Pythia tunes....
(e.g. ATLAS AZ)

Camarda, Ferrera, Schott 2203.05394



Calibration/Tuning

Illustration: Gaia Fontana

Pythia tunes....
(e.g. ATLAS AZ)

PDFs , e.g. Boughezal, Guffanti, Petriello, Ubiali '17
now also in modern PDF sets (e.g. NNPDF 4.0, MSHT 20, CT18)

Fixed-order expansion in α_s

Improved expansion in α_s:

$$\log(m_Z/q_T) \sim 1/\alpha_s$$

Resummation at α_s^3

- via small-q_T factorization

$$\mathrm{d}\sigma_{ij} \sim \int \mathrm{d}\xi_1 \mathrm{d}\xi_2 \, \mathrm{d}\sigma_{ij}^0 \cdot H(\xi_1 p_1, \xi_2 p_2, \mu) \cdot$$

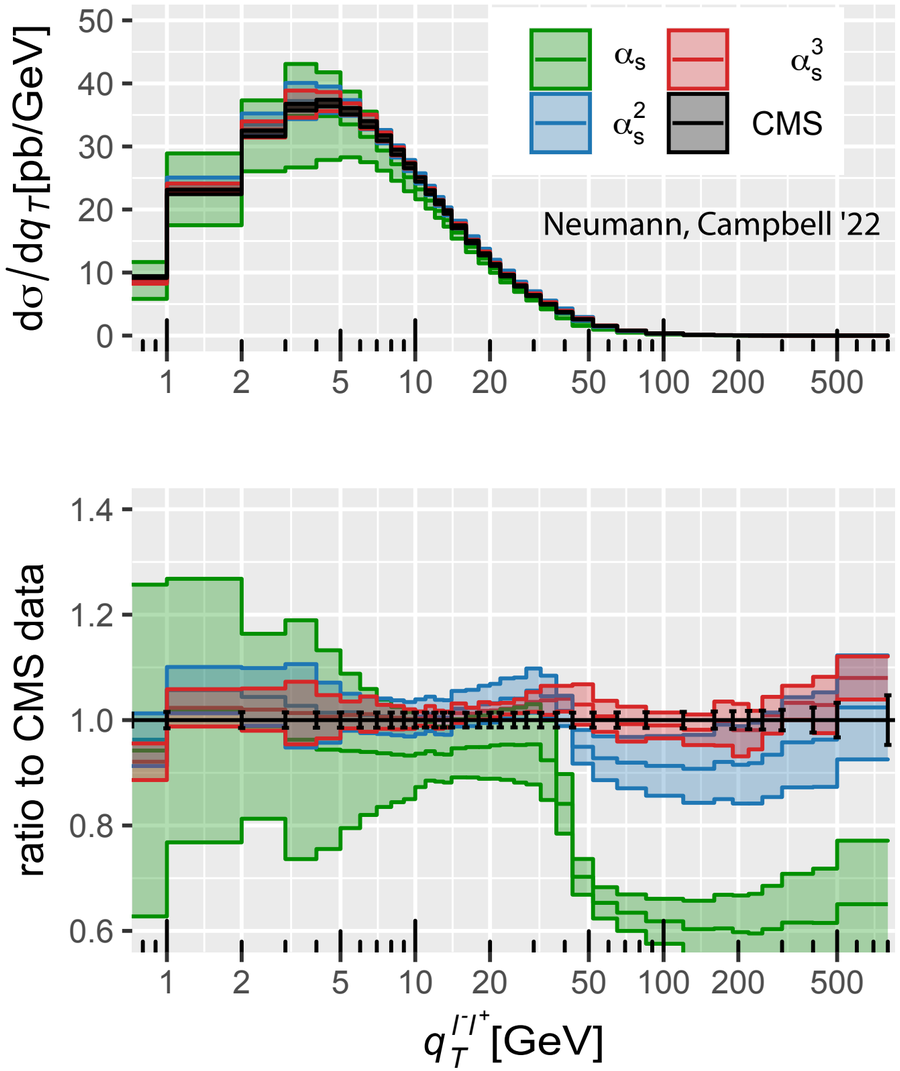
$$\cdot \int \mathrm{d}^2 x_\perp e^{-iq_\perp x_\perp} (x_T^2 Q^2)^{-F(x_\perp,\mu)} \cdot B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu)$$

based on formalism of Becher, Neubert '10; Becher, Neubert, Wilhelm '11; Becher, Hager '19
implemented in CuTe-MCFM (Becher, Neumann '19)

- three-loop beam functions
  M.-x. Luo, T.-Z. Yang, H. X. Zhu, Y. J. Zhu '19, '20; Ebert, Mistlberger, Vita '20
- Z+jet NNLO calculation (via 1-jettiness slicing)
  Boughezal, Focke, Liu, Petriello; Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello '15
- N^4LL: Four loop rapidity anomalous dimension
  Duhr, Mistlberger, Vita '22; Moult, H.X. Zhu, Y. J. Zhu '22
- e.g. Four-loop collinear anomalous dimension
  Agarwal, von Manteuffel, Panzer, Schabinger '21
- Massive three-loop axial singlet contributions
  Chen, Czakon, Niggetiedt '22

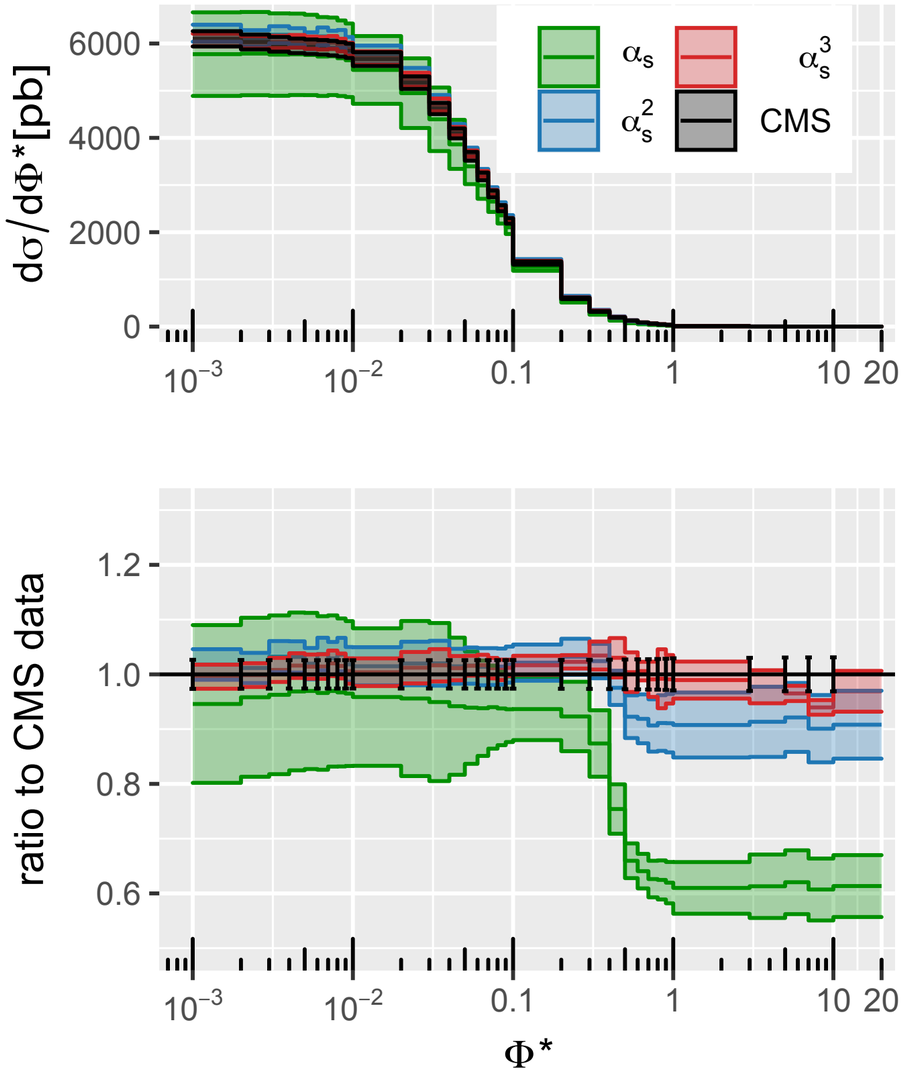
are *some* ingredients

Fiducial results in comparison with CMS 13 TeV data

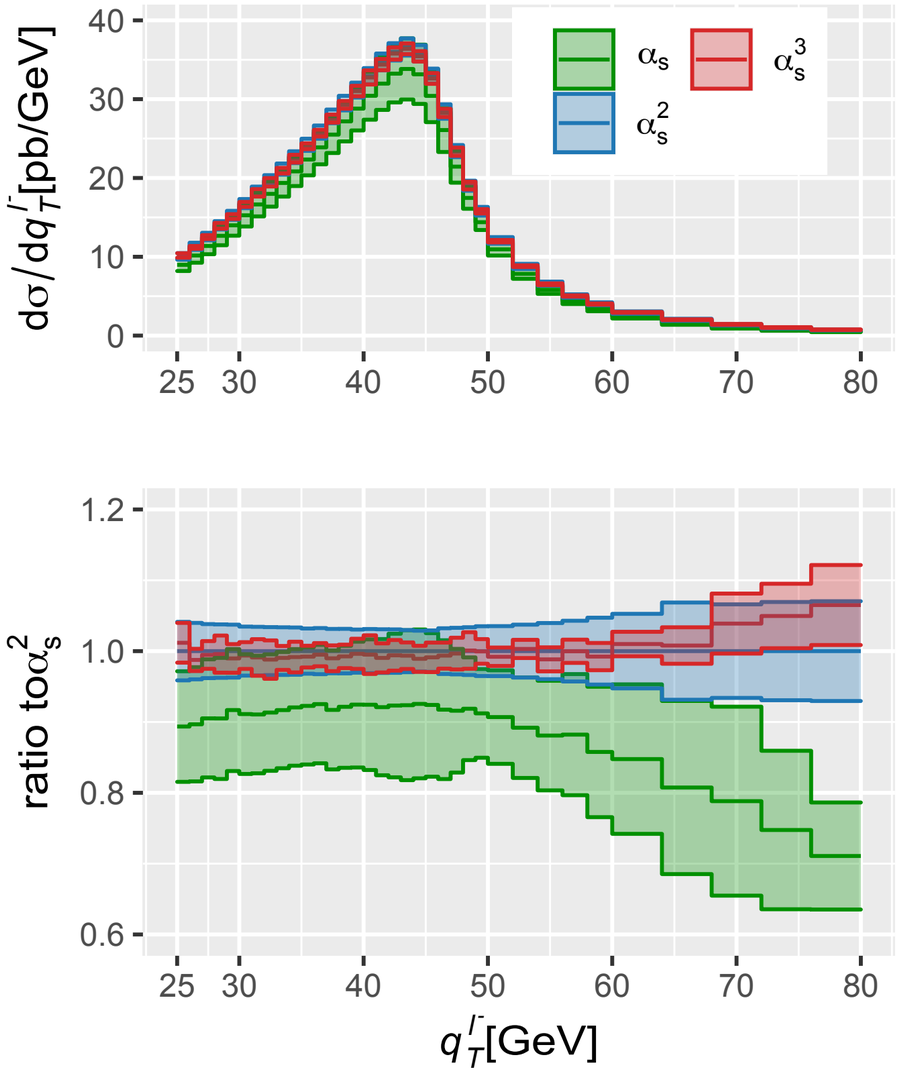


CMS measurement: 1909.04133

Fiducial results in comparison with CMS 13 TeV data



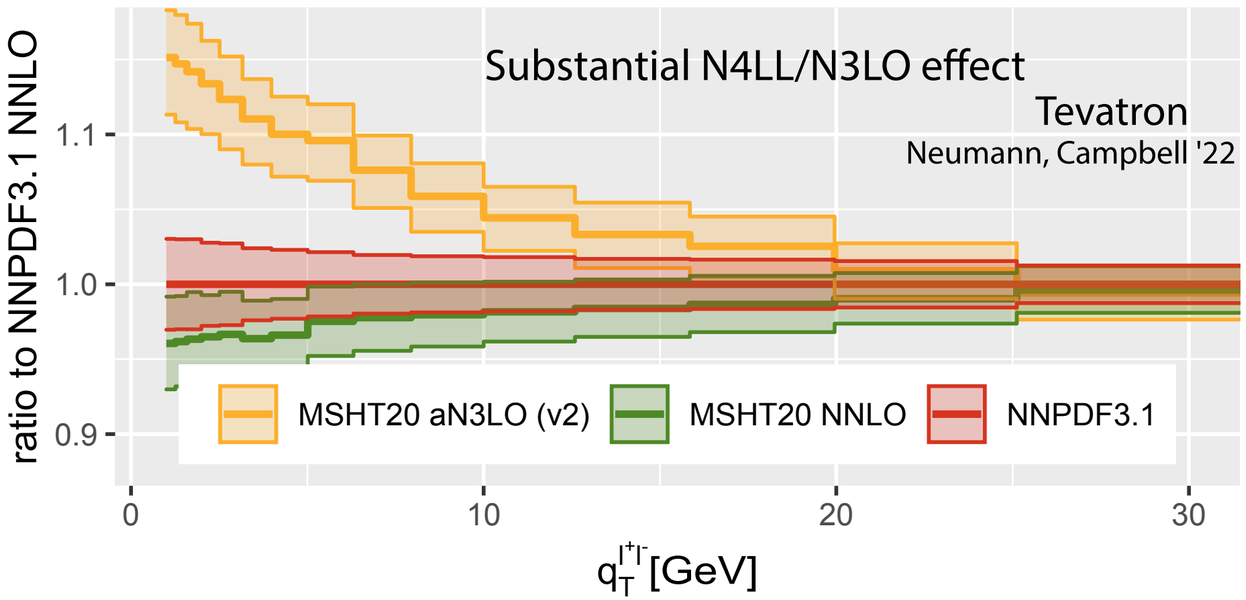
Cure for Jacobian peak in lepton q_T

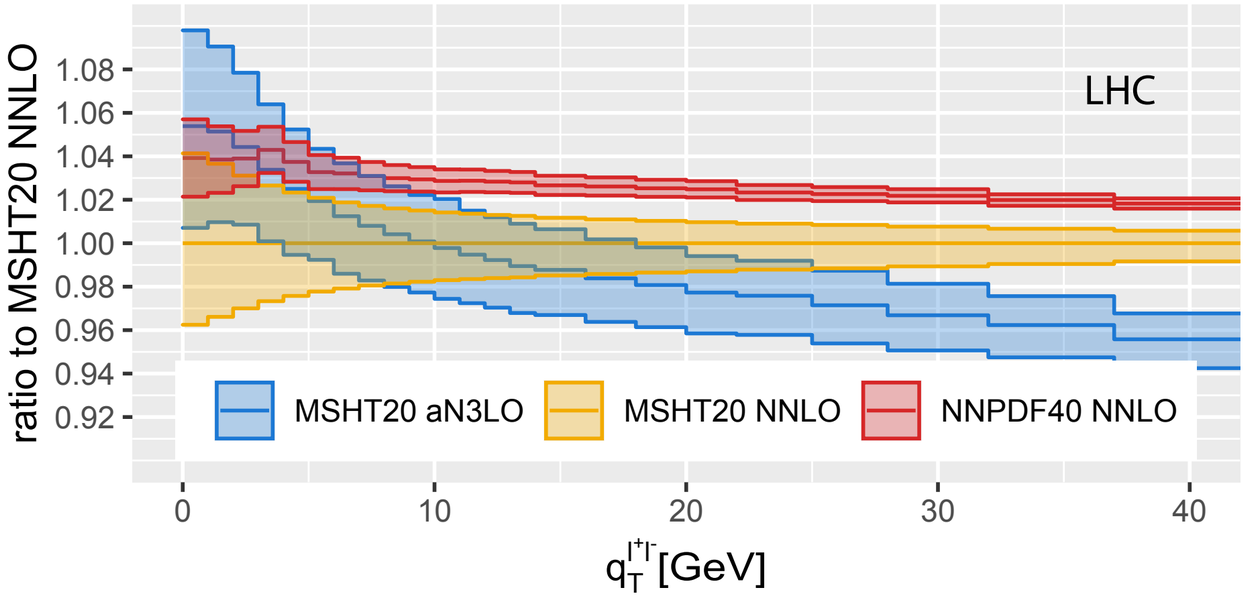


Total fiducial cross-sections

Order k	fixed-order α_s^k	res. improved α_s^k
0	694^{+85}_{-92}	—
1	732^{+19}_{-30}	$637 \pm 8_{\text{mat.}} \pm 70_{\text{sc.}}$
2	720^{+4}_{-3}	$707 \pm 3_{\text{mat.}} \pm 29_{\text{sc.}}$
3	$700^{+4}_{-6} \pm 1_{\text{slicing}}$	$702 \pm 1_{\text{mat.}} \pm 17_{\text{sc.}}$

$699 \pm 5\,(\text{syst.}) \pm 17\,(\text{lumi.})$ (e, μ combined) [3]


Substantial N4LL/N3LO effect
Tevatron
Neumann, Campbell '22
ratio to NNPDF3.1 NNLO
1.1
1.0
0.9
MSHT20 aN3LO (v2)
MSHT20 NNLO
NNPDF3.1
0
10
20
30
$q_T^{l^+l^-}$ [GeV]


LHC
ratio to MSHT20 NNLO
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
MSHT20 aN3LO
MSHT20 NNLO
NNPDF40 NNLO
0
10
20
30
40
$q_T^{l^+l^-}$ [GeV]

Public and well supported (you tell me)!

CuTe-MCFM

mcfm.fnal.gov

"If a theoretical calculation is done, but it can not be used by any experimentalist, does it make a sound?"

— Joey Huston

See also "Computational Challenges for Multi-loop Collider Phenomenology: A Snowmass 2021 White Paper"

Febres Cordero, von Manteuffel, Neumann '22

Jet-veto

e.g. W^+W^- to veto $t\bar{t}$ background with energetic jets

Improved expansion in α_s: $\log(m_Z/p_T^{\text{veto}}) \sim 1/\alpha_s$

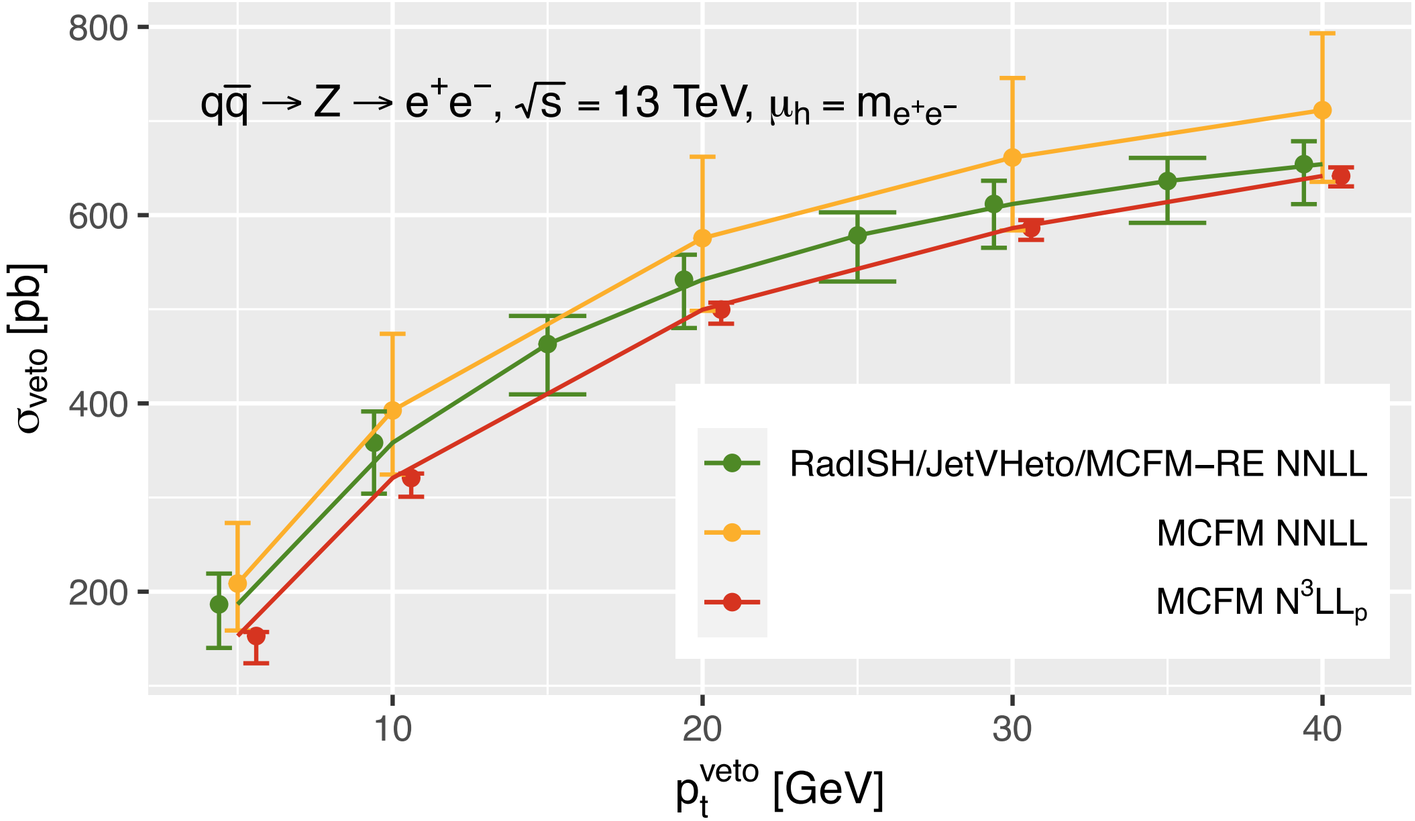
Jet-veto resummation at α_s^2

- via small-p_T factorization
  Becher, Neubert '12; Becher, Neubert, Rothen '12; Stewart, Tackmann, Walsh, Zuberi '13
- two-loop soft function
  Abreu, Gaunt, Monni, Szafron '22
- two-loop beam functions
  Abreu, Gaunt, Monni, Rottoli, Szafron '22
- collinear anomaly (approximation for three-loop so far!)
  Banfi, Caola, Dreyer, Monni, Salam, Zanderighi '15
- NNLO diboson calculations in MCFM, e.g. WW, WZ and ZZ
  Campbell, Ellis, Seth '22

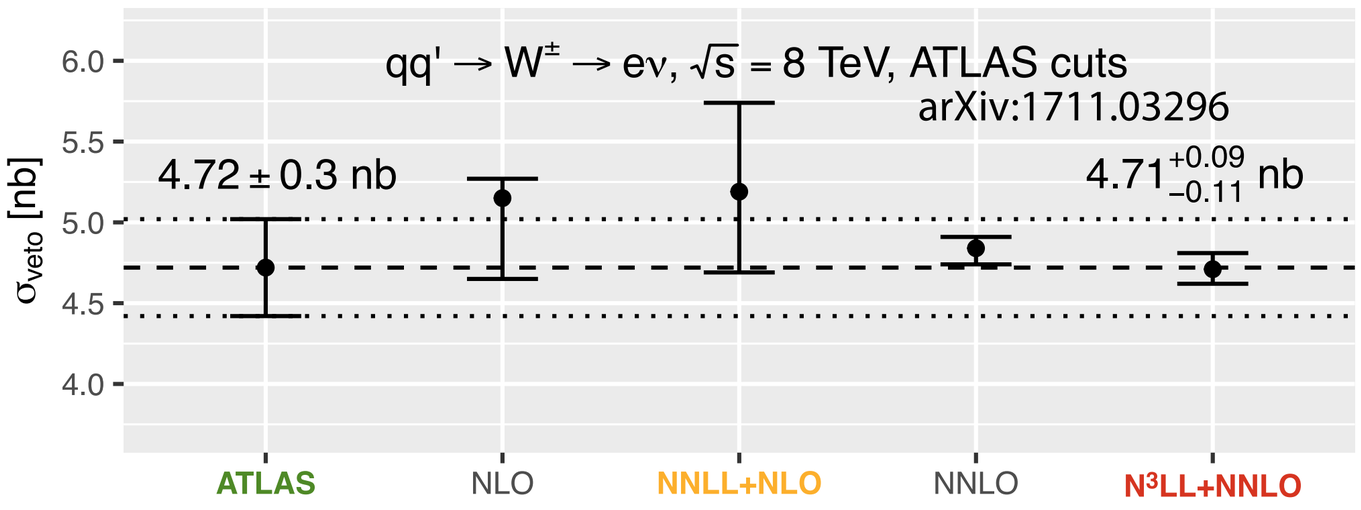
We recently implemented this in MCFM

Campbell, Ellis, Neumann, Seth '23

Campbell, Ellis, Neumann, Seth '23



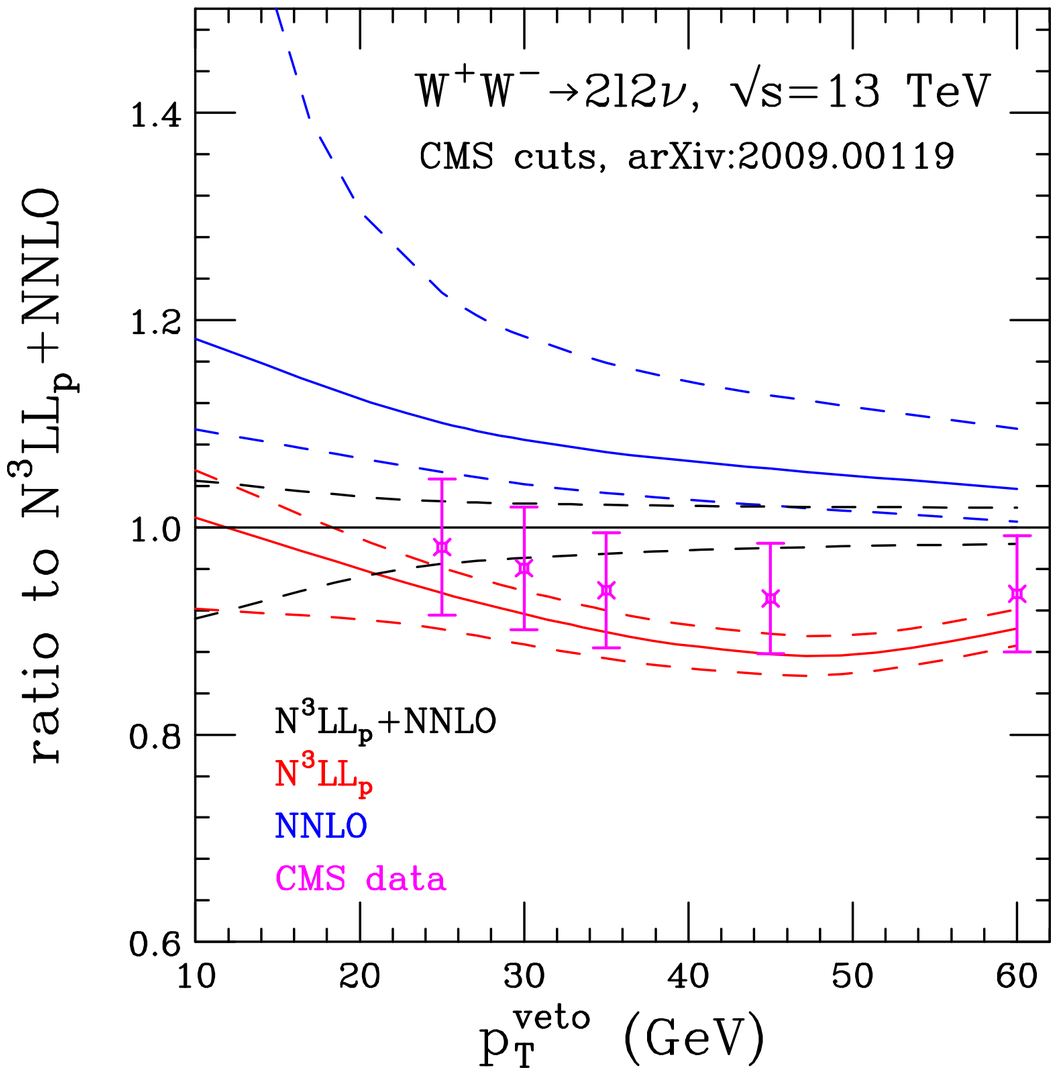
JetVHeto: Banfi, Salam, Zanderighi '05, '12; Banfi, Monni, Salam, Zanderighi '12



$$\log(p_T^{\rm veto}/m_Z),\ p_T^{\rm veto} = 30\,{\rm GeV}$$

Something heavier: $\log(p_T^{\text{veto}}/m_{W^+W^-})$

Campbell, Ellis, Neumann, Seth '23



Conclusions and outlook

- CuTe-MCFM fixed-order and q_T-resummed α_s^3 predictions for Z
- α_s^2 for all other boson and diboson processes, $W, H, \gamma\gamma, Z\gamma, W\gamma, ZH, WH, ZZ, WZ, WW$
- MCFM: Jet-veto resummation at α_s^2 for all boson and diboson processes

Download and documentation at mcfm.fnal.gov
Any requests or questions: tneumann@bnl.gov

- Given that DY is regaining popularity... an outlook..
- W @ N^{3}LO and N^{4}LL
- Inclusion of non-perturbative effects (Gaussian model, TMDs?)
- Inclusion of QED effects (HORACE?)
- Fully differential event(!) generator at α_s^3