

# The spectrum of electro-weak gauge bosons at $N^3LL+NNLO$

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Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, LR, Walker, 190x.xxxx

***NNLOJET***



# Transverse observables in colour-singlet production

Clean experimental and theoretical environment for precision physics

Parameterized as

$$V(k) = \left( \frac{k_t}{M} \right)^a f(\phi)$$

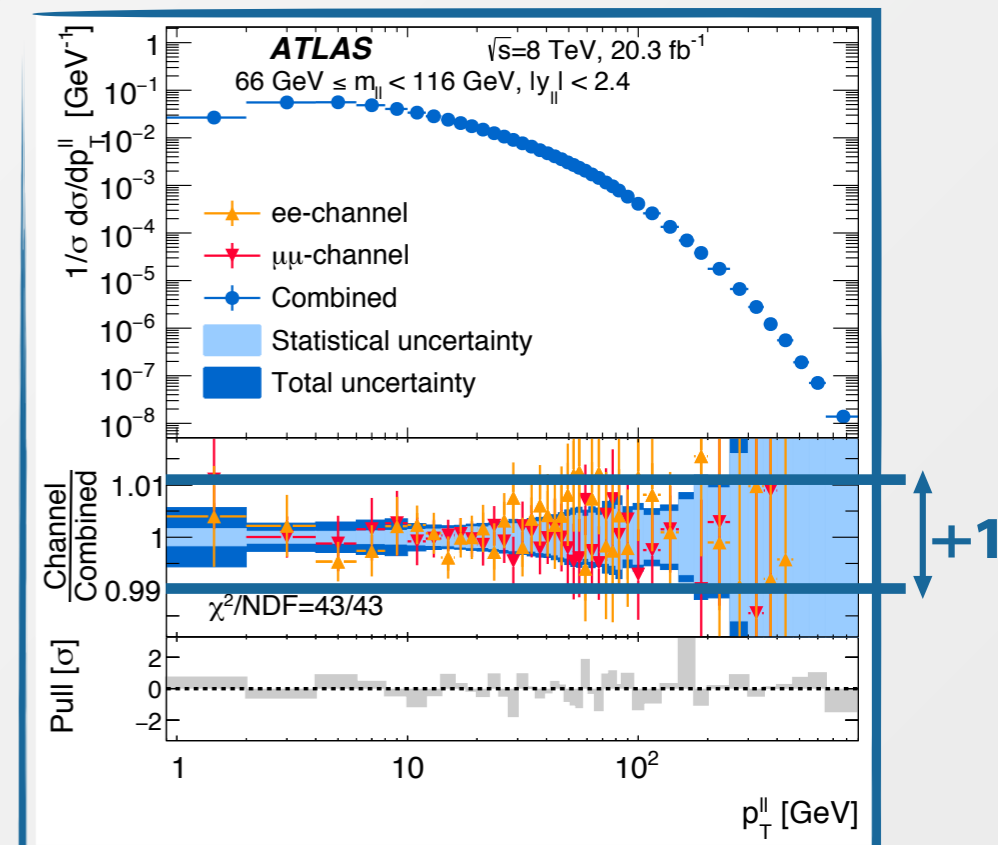
for a **single soft** QCD emission  $k$  **collinear** to incoming leg. Independent of the rapidity of radiation.  $V \rightarrow 0$  for soft/collinear radiation.

**Inclusive observables** (e.g. transverse momentum  $p_t$ ) probe directly the kinematics of the colour singlet

$$V(k_1, \dots, k_n) = V(k_1 + \dots + k_n)$$

- negligible or no sensitivity to multi-parton interactions
- reduced sensitivity to non-perturbative effects
- measured extremely precisely at experiments

**Very accurate theoretical predictions needed**



# Precision physics at the LHC: theoretical predictions

$$\sigma(s, Q^2) = \sum_{a,b} \int dx_1 dx_2 f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) \hat{\sigma}_{ab \rightarrow X}(Q^2, x_1 x_2 s) + \mathcal{O}(\Lambda_{\text{QCD}}^p / Q^p)$$

Input parameters:

**strong coupling**  
**PDFs**

$\alpha_s$   
 $f$

few percent  
uncertainty;  
improvable

**Non-perturbative effects**

percent effect;  
not yet under  
control

# Precision physics at the LHC: theoretical predictions

$$\sigma(s, Q^2) = \sum_{a,b} \int dx_1 dx_2 f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) \hat{\sigma}_{ab \rightarrow X}(Q^2, x_1 x_2 s) + \mathcal{O}(\Lambda_{\text{QCD}}^p / Q^p)$$



$$\hat{\sigma} = \hat{\sigma}_0(1 + \alpha_s C_1 + \alpha_s^2 C_2 + \alpha_s^3 C_3 + \dots)$$

**LO    NLO    NNLO    N<sup>3</sup>LO**

$\alpha_s \sim 0.1$

$\delta \sim 10\text{-}20\%$

**NLO**

$\delta \sim 1\text{-}5\%$

**NNLO** (or even **N<sup>3</sup>LO**)

# All-order resummation

**Cumulative** cross section

$$\Sigma(v) = \int_0^v dV \frac{d\sigma}{dV} \sim \sigma_0 [1 + \alpha_s \# + \alpha_s^2 \# + \dots]$$

**Fixed-order** prediction: reliable for **inclusive enough** observables and in regions not marred by **soft/collinear radiation** ( $v \rightarrow 0$ )

Real and virtual contributions can become **highly unbalanced** in processes where the real radiation is strongly constrained by kinematics

**Large logarithms** appear at **all order** as a left-over of the real-virtual cancellation of IRC divergences

$$\ln \Sigma(v) = \sum_n \left\{ \underbrace{\mathcal{O}(\alpha_s^n L^{n+1})}_{\text{LL}} + \underbrace{\mathcal{O}(\alpha_s^n L^n)}_{\text{NLL}} + \underbrace{\mathcal{O}(\alpha_s^n L^{n-1})}_{\text{NNLL}} + \dots \right\} \quad \begin{array}{l} L = \ln 1/v \\ v = p_t/M \text{ in the transverse} \\ \text{momentum case} \end{array}$$

**Fixed order predictions no longer reliable:  
all-order resummation of the perturbative series**

# Case study: transverse momentum $p_t$

Resummation of transverse momentum is particularly delicate because  $p_t$  is a **vectorial quantity**

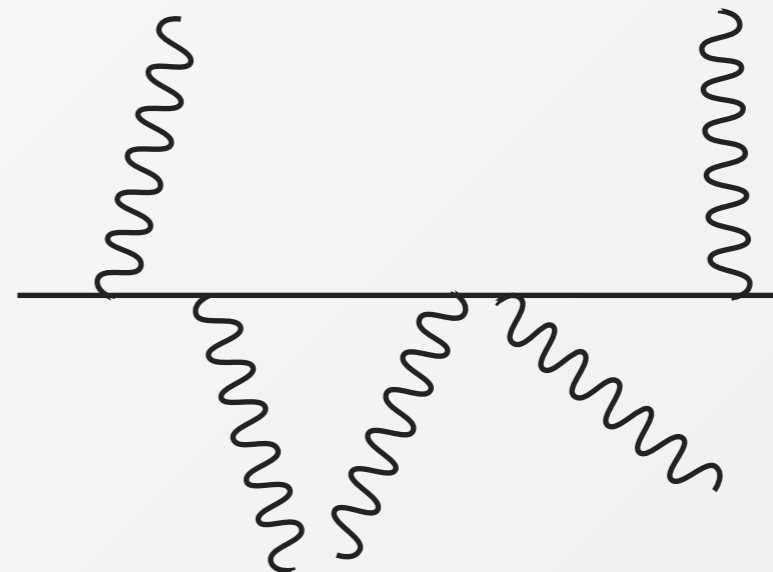
**Two concurring mechanisms** leading to a system with small  $p_t$



$$p_t^2 \sim k_{t,i}^2 \ll M^2$$

cross section naturally suppressed as there is no phase space left for gluon emission  
(Sudakov limit)

**Exponential suppression**



$$\sum_{i=1}^n \vec{k}_{t,i} \simeq 0$$

**Large kinematic cancellations**

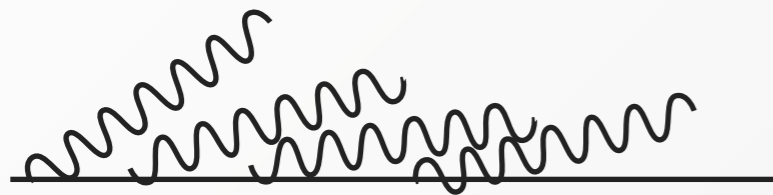
$p_t \sim 0$  far from the Sudakov limit

**Power suppression**

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$$p_t^2 \sim k_{t,i}^2 \ll M^2$$

cross section naturally suppressed as there is no phase space left for gluon emission (Sudakov limit)

**Exponential suppression**

**Dominant at small  $p_t$**



$$\sum_{i=1}^n \vec{k}_{t,i} \simeq 0$$

**Large kinematic cancellations**

$p_t \sim 0$  far from the Sudakov limit

**Power suppression**

# Resummation in direct and in conjugate space

Phase-space constraints do not usually factorize in **direct space**

Resummation usually performed in impact-parameter ( $b$ ) space where the two competing mechanisms are handled through a **Fourier transform**. **Transverse-momentum conservation** is respected

$$\delta\left(\vec{p}_t - \sum_{i=1}^n \vec{k}_{t,i}\right) = \int d^2b \frac{1}{4\pi^2} e^{i\vec{b}\cdot\vec{p}_t} \prod_{i=1}^n e^{-i\vec{b}\cdot\vec{k}_{t,i}}$$

[Parisi, Petronzio '78; Collins, Soper, Sterman '85]

## Resummation in direct space: RadISH

[Monni, Re, Torrielli '16, Bizon, Monni, Re, LR, Torielli '17]

single-particle phase space

matrix element for  $n$  real emissions

$$\Sigma(v) = \int d\Phi_B \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^n [dk_i] |\mathcal{M}(\Phi_B, k_1, \dots, k_n)|^2 \Theta(v - V(\{\Phi_B\}, k_1, \dots, k_n))$$

$$v = p_t/M$$

all-order form factor  
(virtuals)

see also [Ebert, Tackmann '16][Kang, Lee, Vaidya '17]  
for alternative approaches within SCET formalism



# Transverse observable resummation with RadISH

[Monni, Re, Torrielli '16, Bizon, Monni, Re, LR, Torielli '17]

1. Establish a **logarithmic counting** for the squared matrix element  $|\mathcal{M}(\Phi_B, k_1, \dots, k_n)|^2$

Decompose the squared amplitude in terms of  **$n$ -particle correlated blocks**, denoted by  $|\tilde{\mathcal{M}}(k_1, \dots, k_n)|^2$  ( $|\tilde{\mathcal{M}}(k_1)|^2 = |\mathcal{M}(k_1)|^2$ )

$$\sum_{n=0}^{\infty} |\mathcal{M}(\Phi_B, k_1, \dots, k_n)|^2 = |\mathcal{M}_B(\Phi_B)|^2$$

\*expression valid for inclusive observables

$$\times \sum_{n=0}^{\infty} \frac{1}{n!} \left\{ \prod_{i=1}^n \left( |\mathcal{M}(k_i)|^2 + \int [dk_a][dk_b] |\tilde{\mathcal{M}}(k_a, k_b)|^2 \delta^{(2)}(\vec{k}_{ta} + \vec{k}_{tb} - \vec{k}_{ti}) \delta(Y_{ab} - Y_i) \right. \right.$$

LL
NLL

$$+ \int [dk_a][dk_b][dk_c] |\tilde{\mathcal{M}}(k_a, k_b, k_c)|^2 \delta^{(2)}(\vec{k}_{ta} + \vec{k}_{tb} + \vec{k}_{tc} - \vec{k}_{ti}) \delta(Y_{abc} - Y_i) + \dots \left. \right\}$$

NNLL

$$\equiv |\mathcal{M}_B(\Phi_B)|^2 \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^n |\mathcal{M}(k_i)|_{\text{inc}}^2$$

Upon integration over the phase space, the expansion can be put in a **one to one correspondence** with the logarithmic structure

Systematic recipe to include terms up to the desired logarithmic accuracy

# Transverse observable resummation with RadISH

[Monni, Re, Torrielli '16, Bizon, Monni, Re, LR, Torielli '17]

2. Exploit rIRC safety to single out the IRC singularities of the real matrix element and achieve the cancellation of the exponentiated divergences of virtual origin

Introduce a slicing parameter  $\epsilon \ll 1$  such that all inclusive blocks with  $k_{t,i} < \epsilon k_{t,1}$ , with  $k_{t,1}$  hardest emission, can be neglected in the computation of the observable

$$\Sigma(v) = \int d\Phi_B |\mathcal{M}_B(\Phi_B)|^2 \mathcal{V}(\Phi_B) \quad \text{unresolved emissions}$$

$$\times \int [dk_1] |\mathcal{M}(k_1)|_{\text{inc}}^2 \left( \sum_{l=0}^{\infty} \frac{1}{l!} \int \prod_{i=2}^{l+1} [dk_j] |\mathcal{M}(k_j)|_{\text{inc}}^2 \Theta(\epsilon V(k_1) - V(k_j)) \right)$$

$$\times \left( \sum_{m=0}^{\infty} \frac{1}{m!} \int \prod_{i=2}^{m+1} [dk_i] |\mathcal{M}(k_i)|_{\text{inc}}^2 \Theta(V(k_i) - \epsilon V(k_1)) \Theta(v - V(\Phi_B, k_1, \dots, k_{m+1})) \right) \quad \text{resolved emissions}$$

**Unresolved emission** doesn't contribute to the evaluation of the observable: it can be exponentiated directly and employed to cancel the virtual divergences, giving rise to a Sudakov radiator

$$\mathcal{V}(\Phi_B) \exp \left\{ \int [dk] |\mathcal{M}(k)|_{\text{inc}}^2 \Theta(\epsilon V(k_1) - V(k)) \right\} \simeq e^{-R(\epsilon V(k_1))}$$

# Transverse observable resummation with RadISH

[Monni, Re, Torrielli '16, Bizon, Monni, Re, LR, Torielli '17]

Final result at NLL

$$\begin{aligned} \frac{d\Sigma(v)}{d\Phi_B} &= \int \frac{dk_{t,1}}{k_{t,1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(k_{t,1})} e^{R'(k_{t,1})} \mathcal{L}_{\text{NLL}}(k_{t,1}) R'(k_{t,1}) \\ &\times \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_{\epsilon}^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'(\zeta_i k_{t,1}) \Theta(v - V(\Phi_B, k_1, \dots, k_{n+1})) \end{aligned}$$

Parton luminosity at NLL reads

$$\mathcal{L}_{\text{NLL}}(k_{t,1}) = \sum_c \frac{d|M_B|_{c\bar{c}}^2}{d\Phi_B} f_c(x_1, k_{t,1}^2) f_{\bar{c}}(x_2, k_{t,1}^2)$$

At higher logarithmic accuracy, it includes **coefficient functions** and **hard-virtual** corrections

All ingredients to perform resummation at **N<sup>3</sup>LL accuracy** are now available

[Catani *et al.* '11, '12][Gehrmann *et al.* '14][Li, Zhu '16, Vladimirov '16][Moch *et al.* '18, Lee *et al.* '19]

Fixed-order predictions now available at **NNLO**

[A. Gehrmann-De Ridder *et al.* '15, 16, '17][Boughezal *et al.* '15, 16]

# Matching to fixed order: multiplicative matching

Cumulative cross section should reduce to the fixed order at large  $v$

$$\Sigma_{\text{matched}}^{\text{mult}}(v) \sim \Sigma_{\text{res}}(v) \left[ \frac{\Sigma_{\text{f.o.}}(v)}{\Sigma_{\text{res}}(v)} \right]_{\text{expanded}} *$$

- allows to include constant terms from NNLO (if N<sup>3</sup>LO total xs available)
- physical suppression at small  $v$  cures potential instabilities

\*actual scheme slightly more involved, see backup slides

To ensure that resummation does not affect the hard region of the spectrum when the matching is performed we introduce **modified logarithms**

This corresponds to restrict the rapidity phase space at large  $k_t$

$$\ln(Q/k_{t1}) \rightarrow \frac{1}{p} \ln \left( 1 + \left( \frac{Q}{k_{t1}} \right)^p \right)$$

$Q$  : **perturbative resummation scale**  
used to probe the size of subleading logarithmic corrections

$p$  : arbitrary matching parameter

# Theoretical predictions for $Z$ and $W$ observables at 13 TeV

Results obtained using the following fiducial cuts (agreed with ATLAS)

$$Z \quad p_t^{\ell^\pm} > 25 \text{ GeV}, \quad |\eta^{\ell^\pm}| < 2.5, \quad 66 \text{ GeV} < M_{\ell\ell} < 116 \text{ GeV}$$

$$W \quad p_t^\ell > 25 \text{ GeV}, \quad |\eta^\ell| < 2.5, \quad \cancel{E}_T^{\nu_\ell} > 25 \text{ GeV}, \quad m_T > 50 \text{ GeV}$$

using NNPDF3.1 with  $\alpha_s(M_Z)=0.118$  and setting the central scales to

$$\mu_R = \mu_F = M_T = \sqrt{M_{\ell\ell'}^2 + p_T^2}, \quad Q = \frac{M_{\ell\ell'}}{2}$$

5 flavour (massless) scheme: no HQ effects and no PDF thresholds

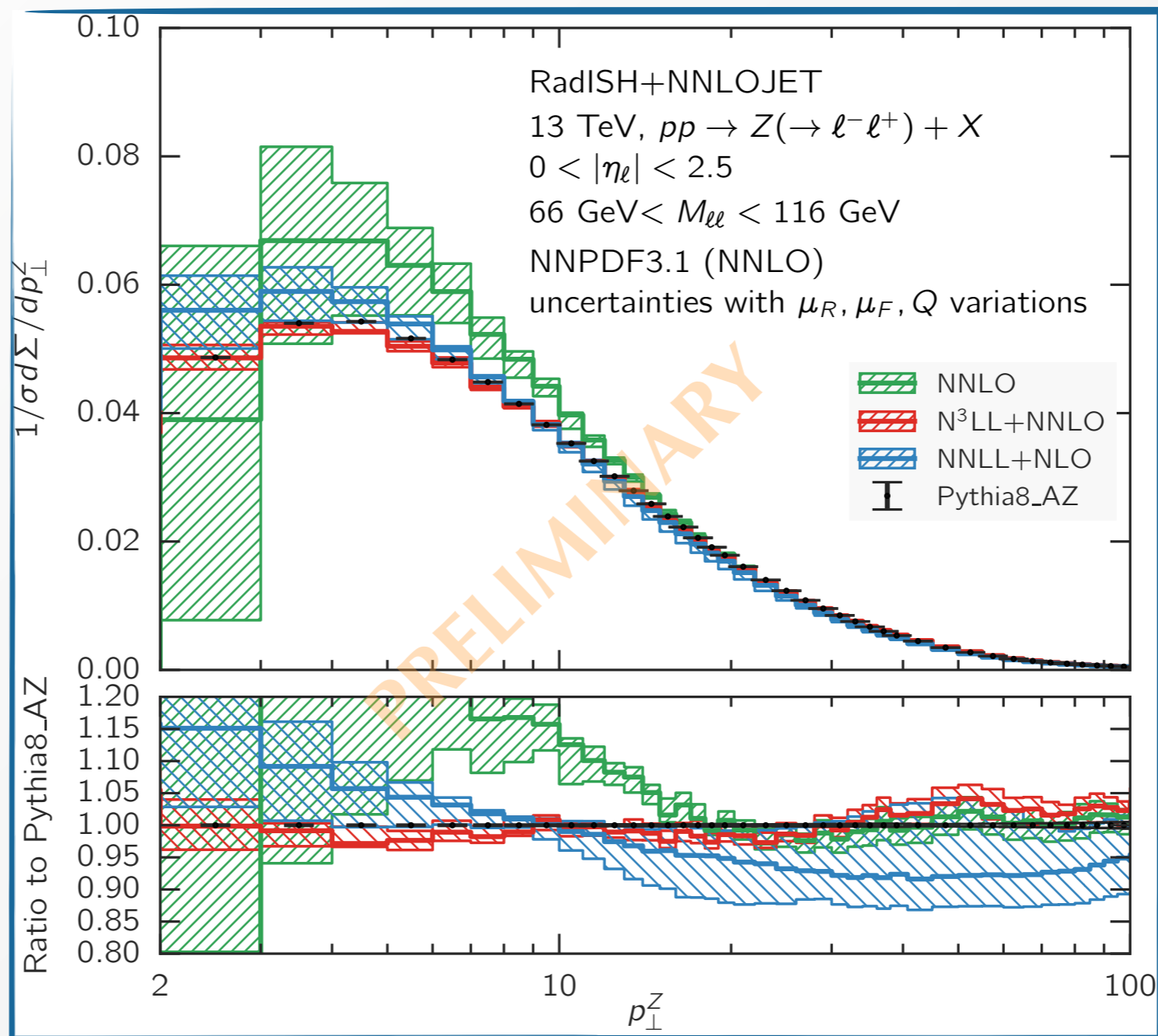
**NB: quark thresholds now implemented in the resummation, not turned on in the following results**

Scale uncertainties estimated by varying **renormalization** and **factorization** scale by a factor of two around their central value (**7 point variation**) and varying the **resummation** scale by a factor of 2 around its central value for factorization and renormalization scales set to their central value: **9 point envelope**

Matching parameter  $p$  set to 4 as a default

**No non perturbative parameters included** in the following

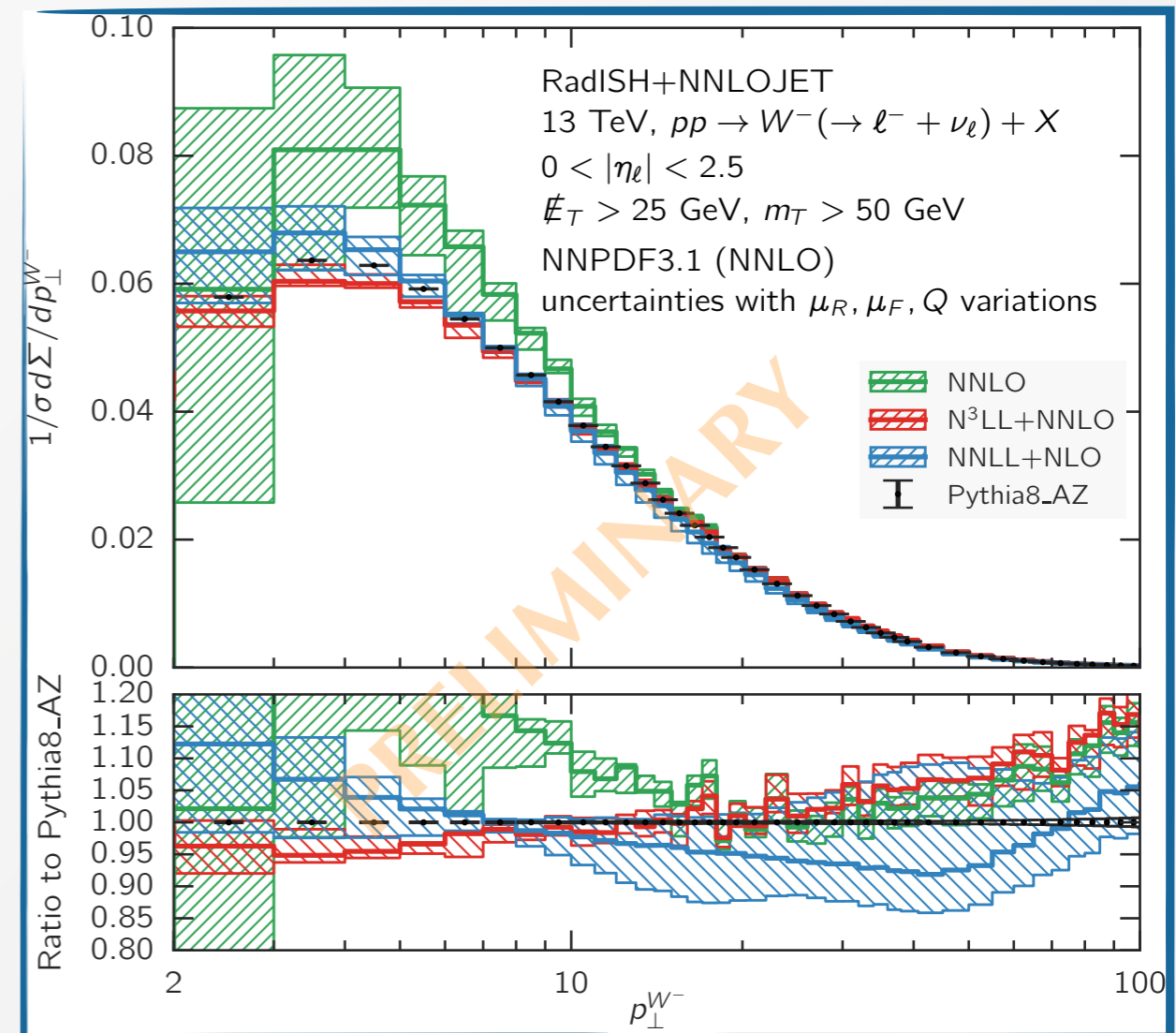
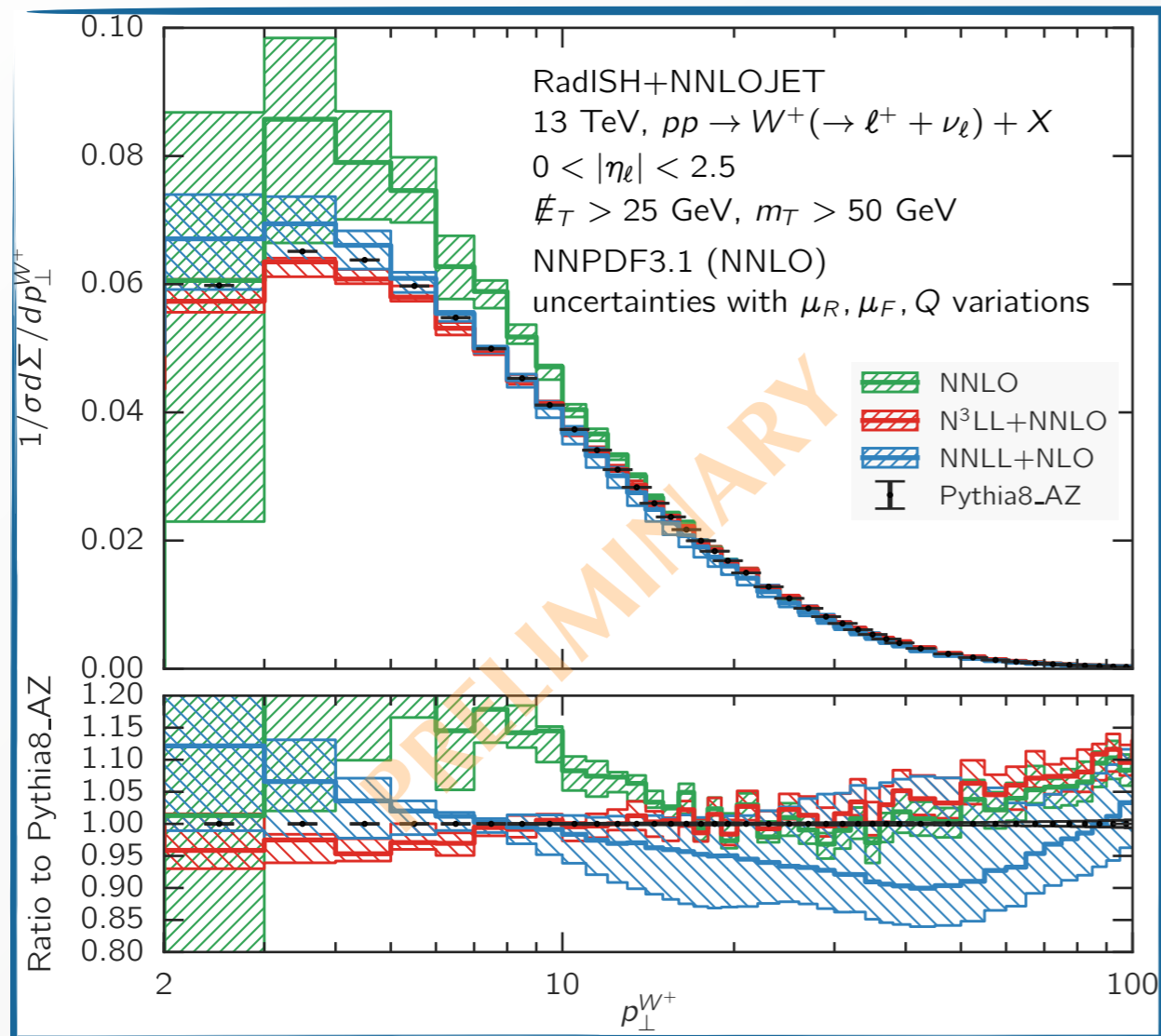
# Results for the $p_{\perp}^Z$ distribution



*Thanks to Jan Kretzschmar for providing the Pythia8 AZ tune results*



# Results for the $p_{\perp}^{W^{\pm}}$ distribution

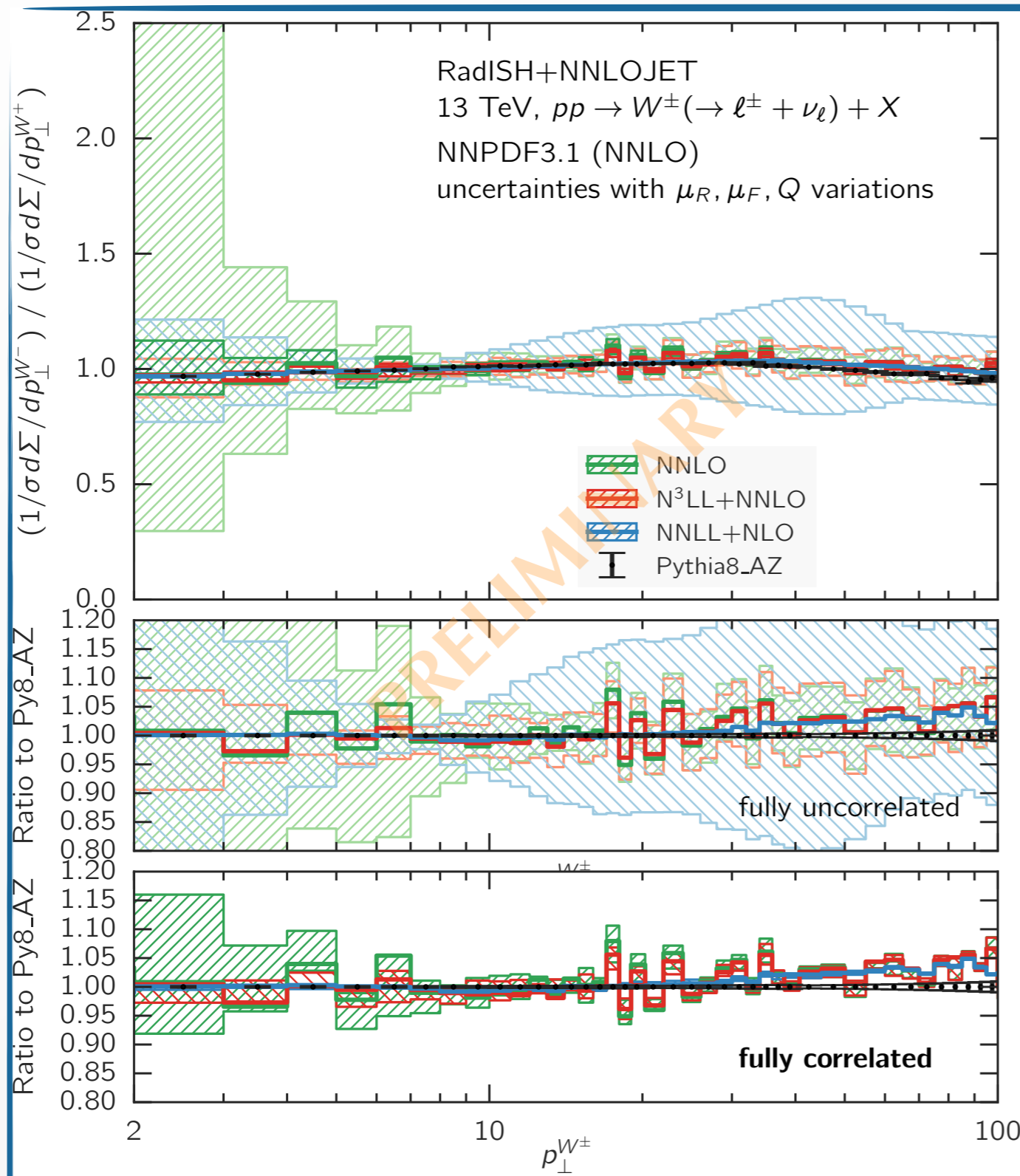


Discrepancies with MC still needs some further understanding (does the tune work out of the box at 13 TeV?)

*Thanks to Jan Kretzschmar for providing the Pythia8 AZ tune results*

Precision EW workshop, April 2, Durham

# Results for the $p_{\perp}^{W^-}/p_{\perp}^{W^+}$ distribution



N<sup>3</sup>LL+NNLO and NNLL+NLO description of the spectrum almost identical: virtually no change if theoretical accuracy changes

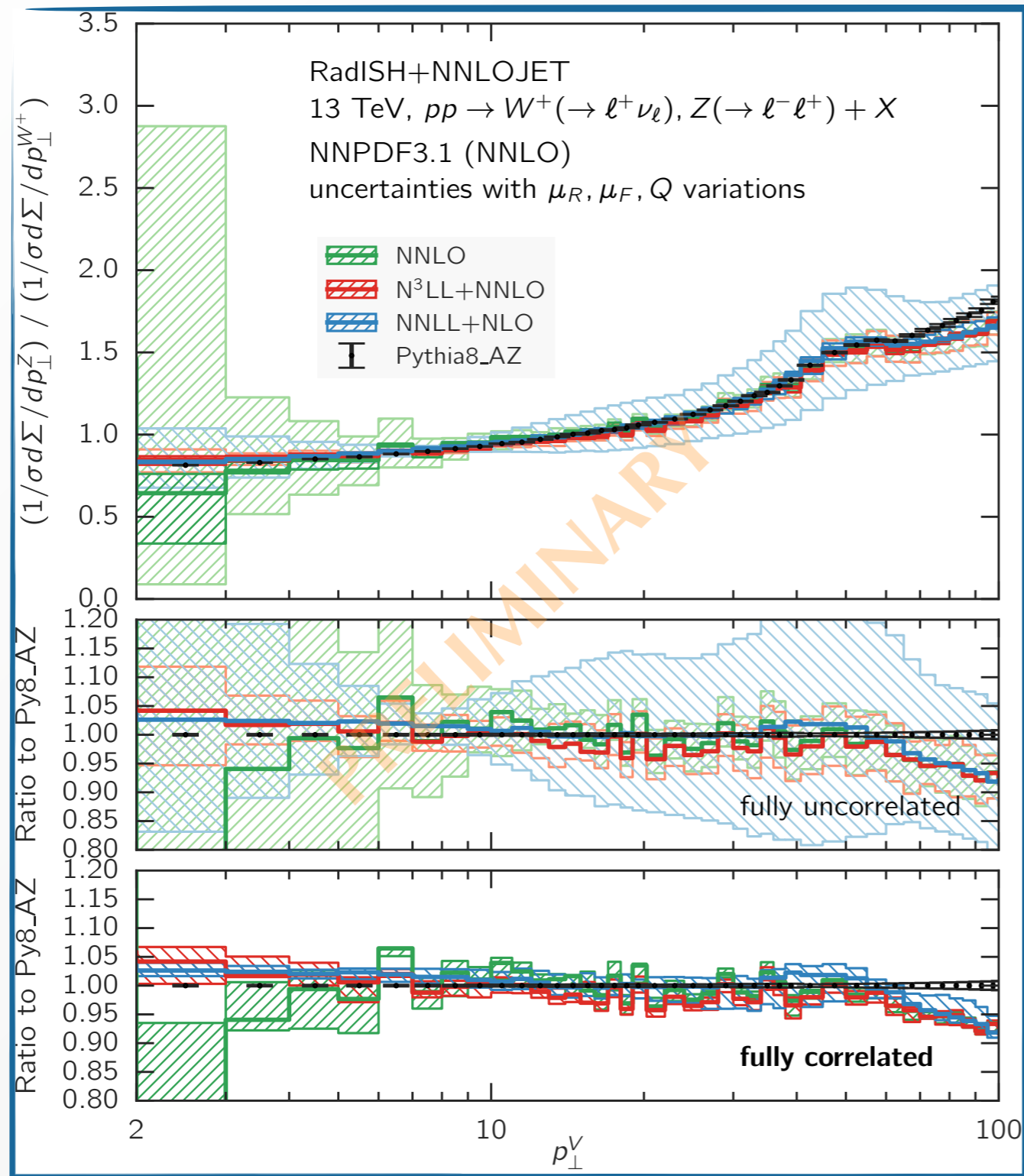
This may suggest that **fully correlated uncertainties** are appropriate (massless QCD description)

Non necessarily the case for extra sources of uncertainty (mass effects, EW corrections...)

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# Results for the $p_{\perp}^Z/p_{\perp}^{W^+}$ distribution



N<sup>3</sup>LL+NNLO and NNLL+NLO description of the spectrum almost identical: virtually no change if theoretical accuracy changes

This supports the use of **fully correlated uncertainties** (massless QCD description)

Non necessarily the case for extra sources of uncertainty (mass effects, EW corrections...)

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# Benchmarking among different resummation codes

At this level of accuracy, it becomes increasingly important to compare different resummed result with the **same formal accuracy** to quantify the effect of **subleading** differences and to assess the so-called '**algorithmic**' uncertainties (e.g. matching, modified logarithms, scale variations, etc)

The roadmap for benchmark exercise is now (almost) final

## Step 1

### Setup:

- a) On-shell ( $Q=M_Z$ ) at  $\sqrt{s} = 13$  TeV (integrated over  $y$ )
- b) five generations, all massless
- c) PDF choice: NNPDF31\_nnlo\_as\_0118 with evolution from LHAPDF. Evolve from  $\alpha_s(m_Z)=0.118$  as relevant for each resummation order.
- d) Include 2 levels of resummation results: 1. canonical logarithms (as much as possible,  $\ln(Qb_T/b_0), \ln(q_T/Q)$ ) in  $b$  (if possible) and  $q_T$  space, 2. Nominal logarithms in  $q_T$  space. Summarized in Frank's slide 4.
- e) Order of resummation: LL and NLL('). Other points can be added in parallel (NNLL('), N3LL (if possible)) for step 2 (see 1\_c above).
- f) Binning in  $q_T$  and in  $b_T$  space for  $b_0/b_T$  (if possible),  $\{1, 2, 3, \dots, 39, 40, 45, \dots, 95, 100\}$ . Also include the log binning for  $q_T$ :  $\log_{10} q_T \{-1, -0.9, \dots, 1.9, 2\}$ .

### Results:

- g) With Z couplings to all five generations
- h) Limit the Z couplings to the first generation, and then add also the second generation
- i)  $Q=M_Z$  and two fixed  $y$  values: 0 and 2.4. To be done for both g) and h) above

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We plan to start with the following:

## Step 1

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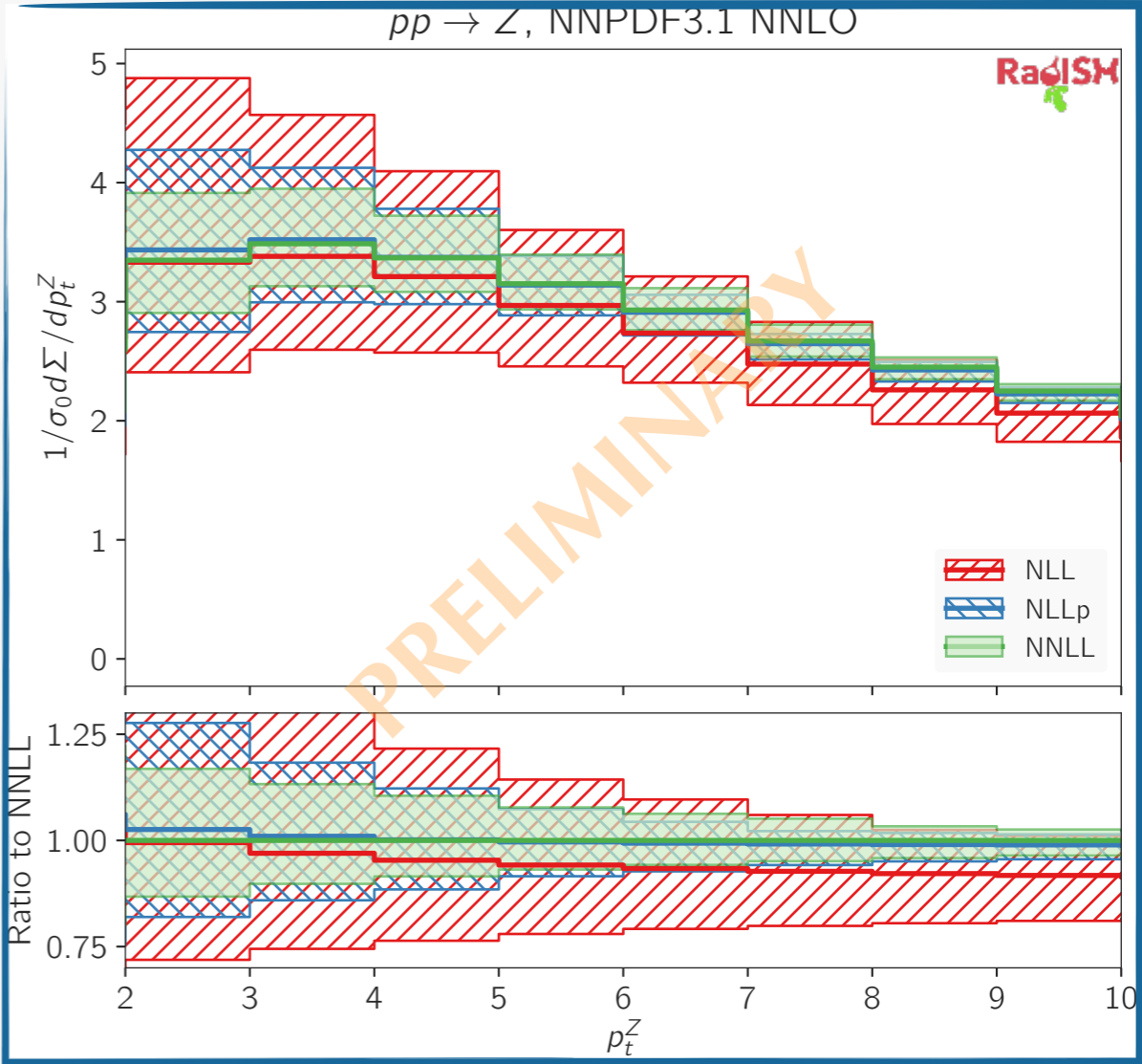
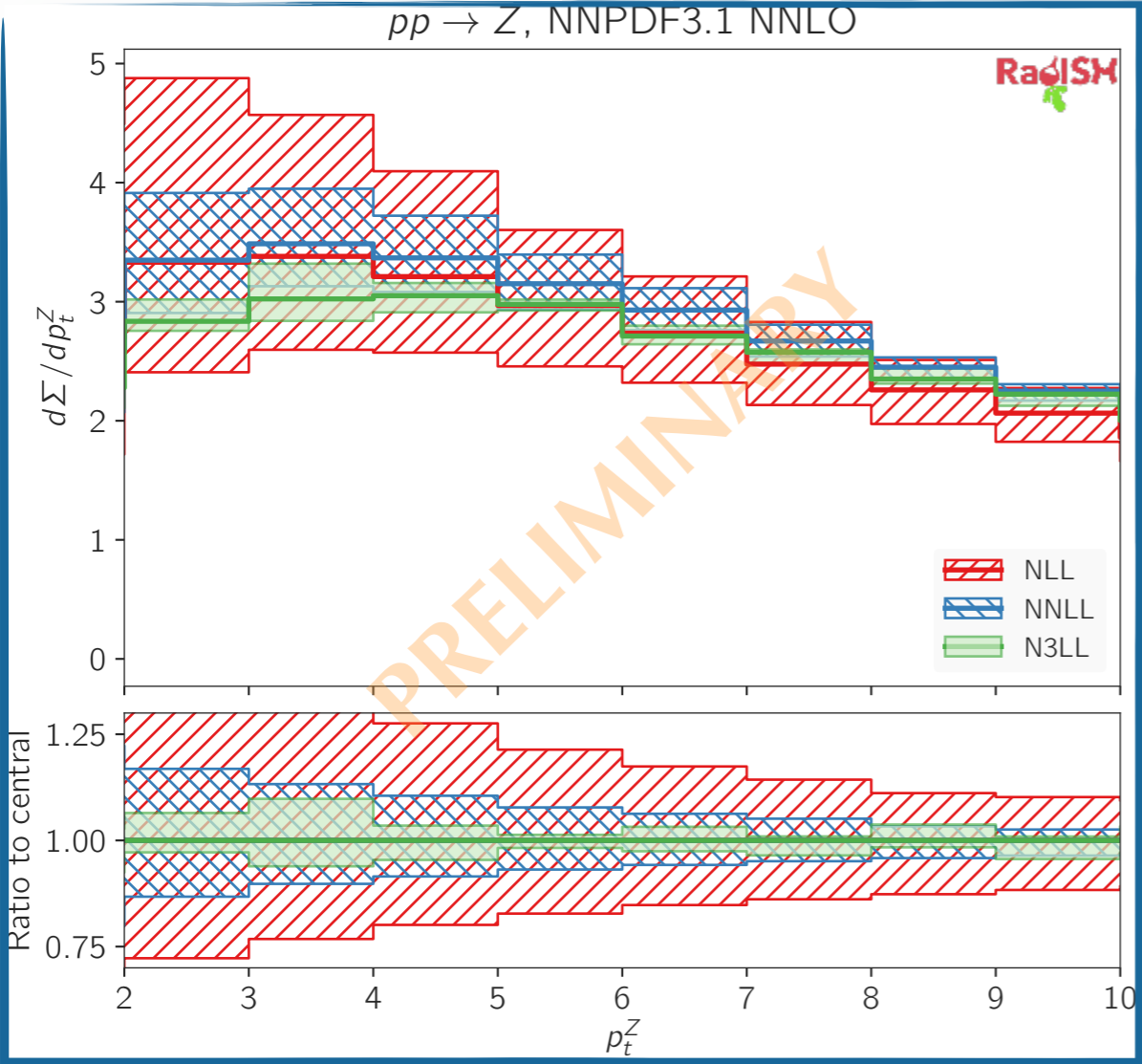
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\*RadISH uses HOPPET for PDF evolution

# Benchmarking among different resummation codes



# Recapitulation

- No sign of NP at the LHC so far - necessary to perform detailed theory/experimental comparisons, to look for deviations from SM. Perturbation theory must be pushed to its limit
- New formalism formulated in **direct space** for all-order resummation up to **N<sup>3</sup>LL accuracy** for inclusive, transverse observables.
- Preliminary results at NNLO+N<sup>3</sup>LL for  $W$  and  $Z$  differential distributions with **uncertainties at the few percent level**. Some discrepancies with the Pythia8 AZ tune results to be understood.
- Preliminary results on the  $W^+/W^-$  ratios and  $Z/W$  ratios. Uncertainty <5-10% even if the error is taken as fully uncorrelated. The excellent convergence of the perturbative corrections supports **fully correlated** scale variations, with uncertainties **at the 1-2% level**.

# Backup



# Transverse observable resummation with RadISH

Result at NLL accuracy can be written as

$$\Sigma(v) = \sigma^{(0)} \int \frac{dv_1}{v_1} \int_0^{2\pi} \frac{d\phi_1}{2\pi} e^{-R(\epsilon v_1)} R'(v_1) \quad v_i = V(k_i), \quad \zeta_i = v_i/v_1$$

$$\times \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_{\epsilon}^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'(\zeta_i v_1) \Theta(v - V(\Phi_B, k_1, \dots, k_{n+1}))$$

Formula can be evaluated with Monte Carlo method; dependence on  $\epsilon$  vanishes exactly and result is finite in four dimensions

It contains **subleading effect** which in the original CAESAR approach are disposed of by expanding  $R$  and  $R'$  around  $v$

~~$$R(\epsilon v_1) = R(v) + \frac{dR(v)}{d \ln(1/v)} \ln \frac{v}{\epsilon v_1} + \mathcal{O}\left(\ln^2 \frac{v}{\epsilon v_1}\right)$$

$$R'(v_i) = R'(v) + \mathcal{O}\left(\ln \frac{v}{v_i}\right)$$~~

**Not possible!** valid only if the ratio  $v_i/v$  remains of order one in the whole emission phase space, but for observables which feature kinematic cancellations there are configurations with  $v_i \gg v$ . **Subleading effects necessary**

# Transverse observable resummation with RadISH

[Monni, Re, Torrielli '16, Bizon, Monni, Re, LR, Torielli '17]

Translate the resummability of the observable into properties of the observable in the presence of multiple radiation: **recursive infrared and collinear (rIRC) safety**

[Banfi, Salam, Zanderighi '01, '03, '04]

Existence of a **resolution scale**  $q_0$ , **independent of the observable**, such that emissions below  $q_0$  (**unresolved**) do not contribute significantly to the observable's value.

Starting point: all-order cumulative cross section

$$\Sigma(v) = \int d\Phi_B \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^n [dk_i] |\mathcal{M}(\Phi_B, k_1, \dots, k_n)|^2 \Theta(v - V(\{\Phi_B\}, k_1, \dots, k_n))$$

single-particle phase space

matrix element for  $n$  real emissions

all-order form factor (virtuals)

$v = p_t/M$



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Formula can be evaluated with Monte Carlo method; dependence on  $\epsilon$  vanishes exactly and result is finite in four dimensions

Convenient to perform an expansion around  $k_{t1}$  (more efficient and simpler implementation)

$$\begin{aligned} R(\epsilon k_{t1}) &= R(k_{t1}) + \frac{dR(k_{t1})}{d \ln(1/k_{t1})} \ln \frac{1}{\epsilon} + \mathcal{O}\left(\ln^2 \frac{1}{\epsilon}\right) \\ R'(k_{ti}) &= R'(k_{t1}) + \mathcal{O}\left(\ln \frac{k_{t1}}{k_{ti}}\right) \end{aligned}$$



**Subleading effects retained:** no divergence at small  $v$ , power-like behaviour respected

**Logarithmic accuracy** defined in terms of  $\ln(M/k_{t1})$

Result formally equivalent to the  $b$ -space formulation

# Matching to fixed order: multiplicative matching

Cumulative cross section should reduce to the fixed order at large  $v$

$$\Sigma_{\text{matched}}^{\text{mult}}(v) = \Sigma_{\text{res}}(v) \left[ \frac{\Sigma_{\text{f.o.}}(v)}{\Sigma_{\text{res}}(v)} \right]_{\text{expanded}}$$

- allows to include constant terms from NNLO
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To ensure that resummation does not affect the hard region of the spectrum when the matching is performed we introduce **modified logarithms**

This corresponds to restrict the rapidity phase space at large  $k_t$

$$\ln(Q/k_{t1}) \rightarrow \frac{1}{p} \ln \left( 1 + \left( \frac{Q}{k_{t1}} \right)^p \right)$$

$Q$  : perturbative **resummation scale** used to probe the size of subleading logarithmic corrections

$p$  : arbitrary matching parameter

Matching improved by normalizing to the **asymptotic value** to avoid **spurious**  $\mathcal{O}(\alpha_s^4)$  **contributions**

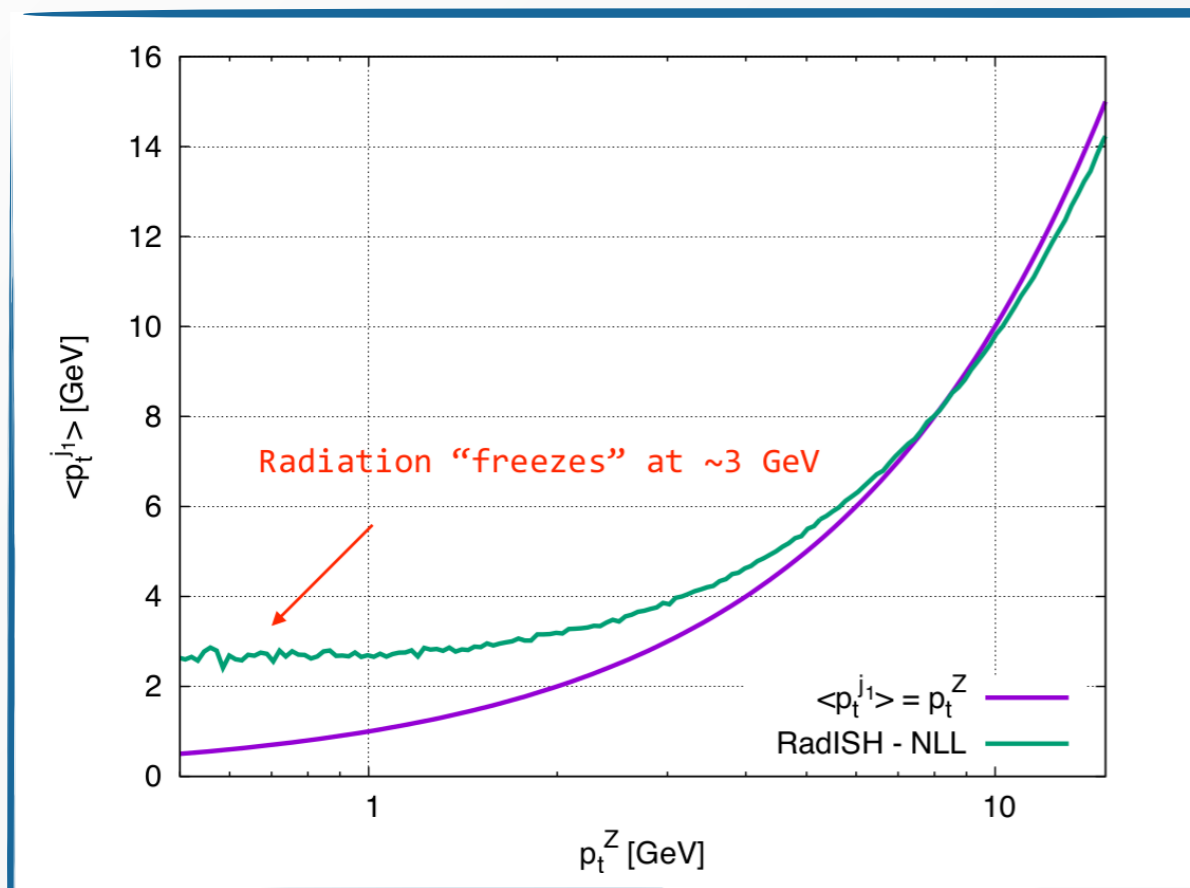
$$\Sigma_{\text{mult}}^{\text{matched}}(v) = \frac{\Sigma_{\text{res}}(v)}{\Sigma_{\text{asym.}}^{\text{res}}} \left[ \Sigma_{\text{asym.}}^{\text{res}} \frac{\Sigma^{\text{f.o.}}(v)}{\Sigma^{\text{exp}}(v)} \right]_{\text{expanded}} \quad \Sigma_{\text{asym.}}^{\text{res}} = \int_{\text{with cuts}} d\Phi_B \left( \lim_{L \rightarrow 0} \mathcal{L}_{\text{N}^{\text{kLL}}} \right)$$

# The Landau pole and the small- $p_t$ limit

Running coupling  $\alpha_s(k_{t1}^2)$  and Sudakov radiator hit Landau pole at

$$\alpha_s(\mu_R^2)\beta_0 \ln Q/k_{t1} = \frac{1}{2} \quad k_{t1} \sim 0.01 \text{ GeV}, \quad \mu_R = Q = m_Z$$

Only real cutoff in the calculation: emission probability is set to zero below this scale and parton densities are frozen.



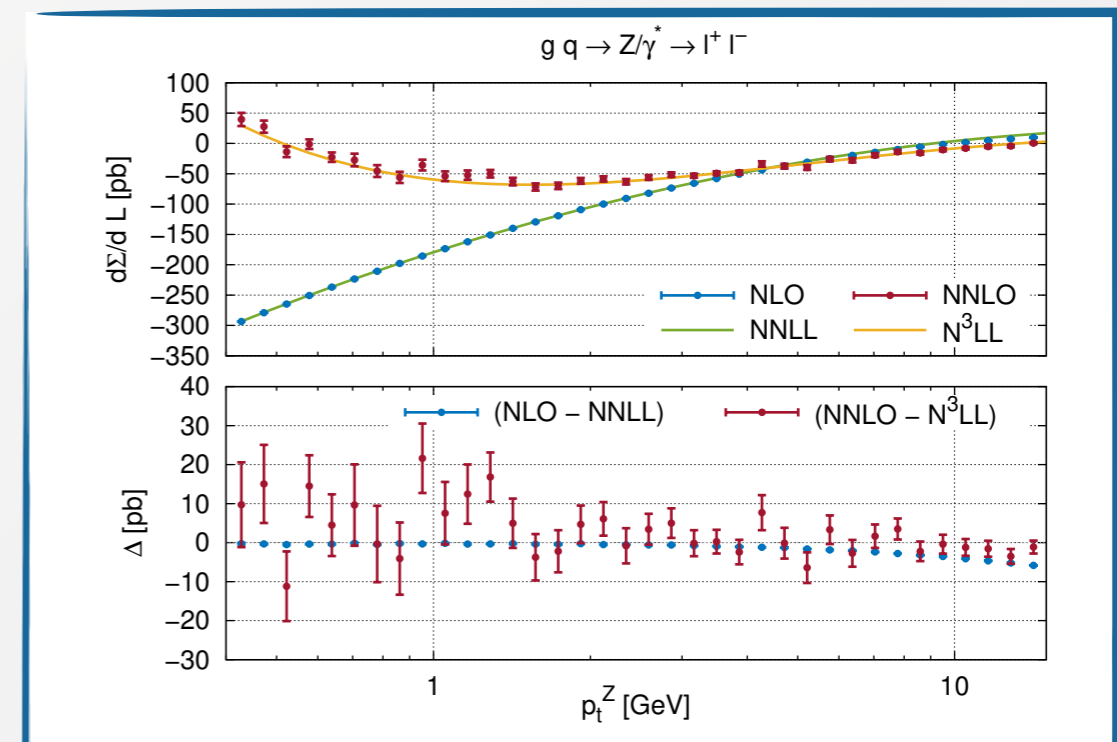
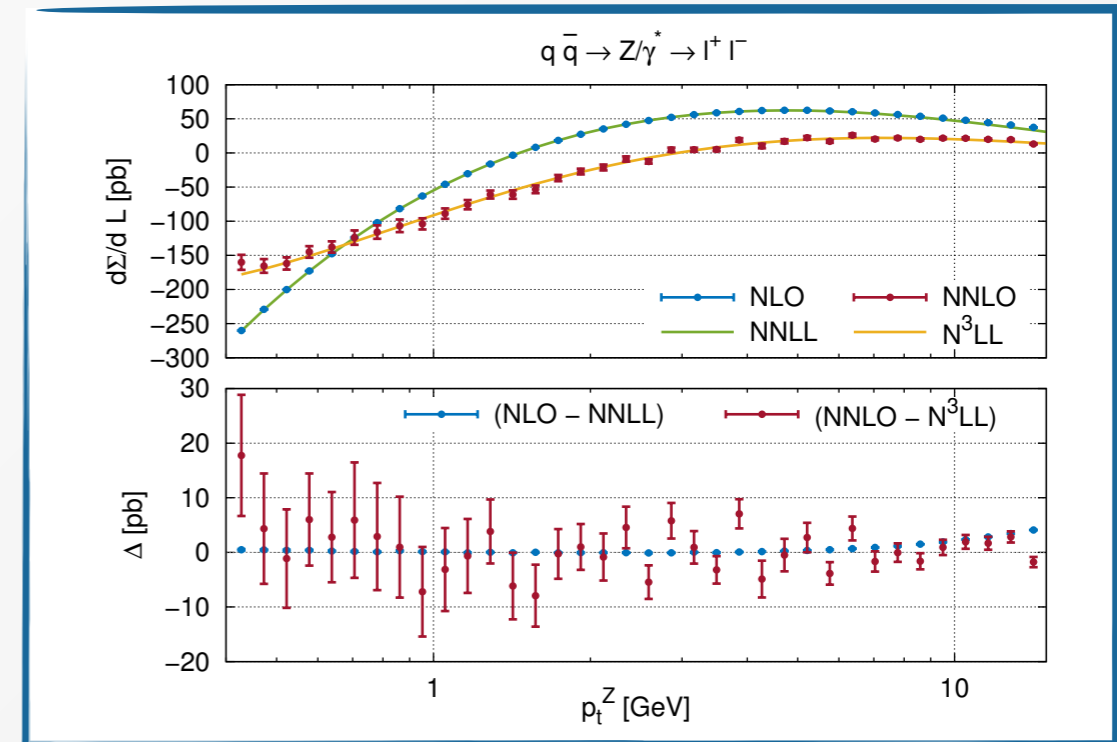
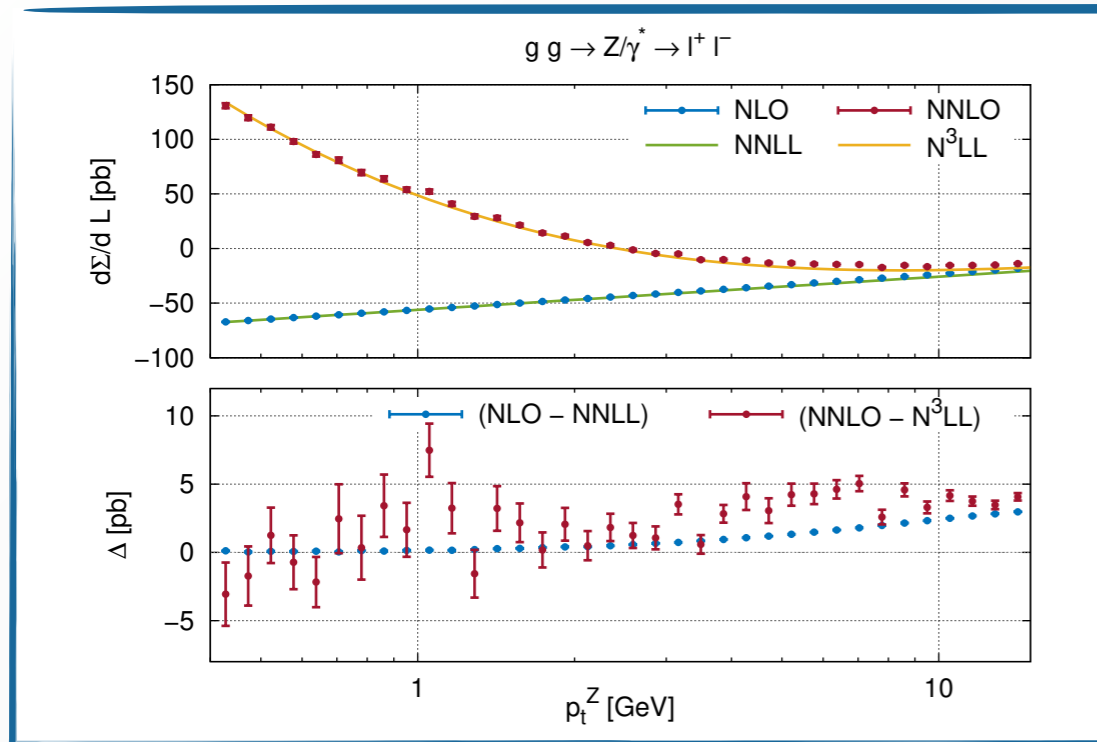
At small  $p_t$  the large azimuthal cancellations dominate over the Sudakov suppression: the cutoff is never an issue in practice

$$\frac{d^2\Sigma(v)}{dp_t d\Phi_B} \simeq 2\sigma^{(0)}(\Phi_B)p_t \left( \frac{\Lambda_{\text{QCD}}^2}{M^2} \right)^{\frac{16}{25} \ln \frac{41}{16}}$$

**No NP parameters included in the following**

# Fixed order vs. resummation

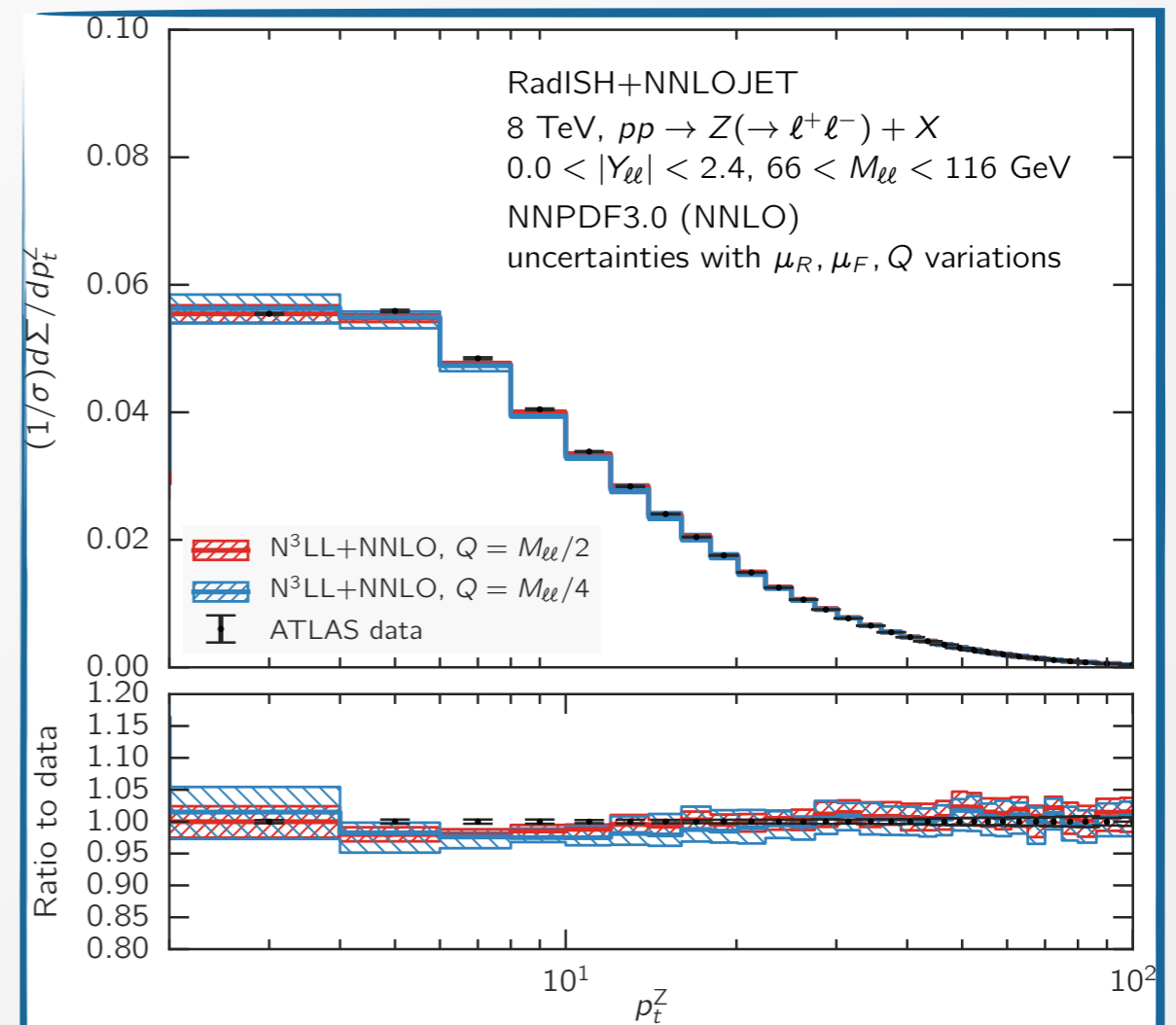
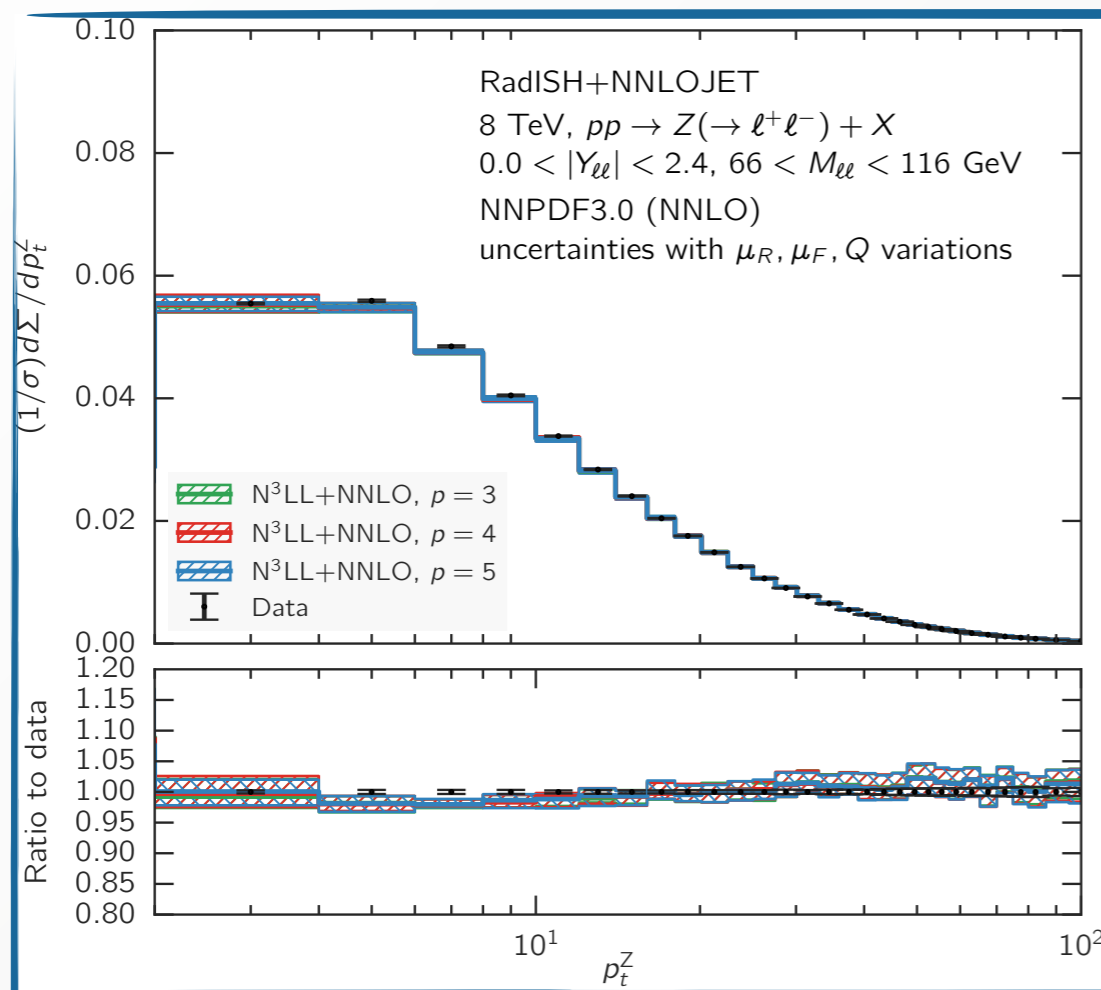
[Bizon, Chen et al. 1805.05916]



- Very good agreement with the fixed order at small  $p_t$
- Very strong validation of both calculations
- Fixed an implementational error in the fixed order computation

# Resummation and matching uncertainties

[data from ATLAS 1512.02192]  
[Bizon, Chen et al. 1805.05916]

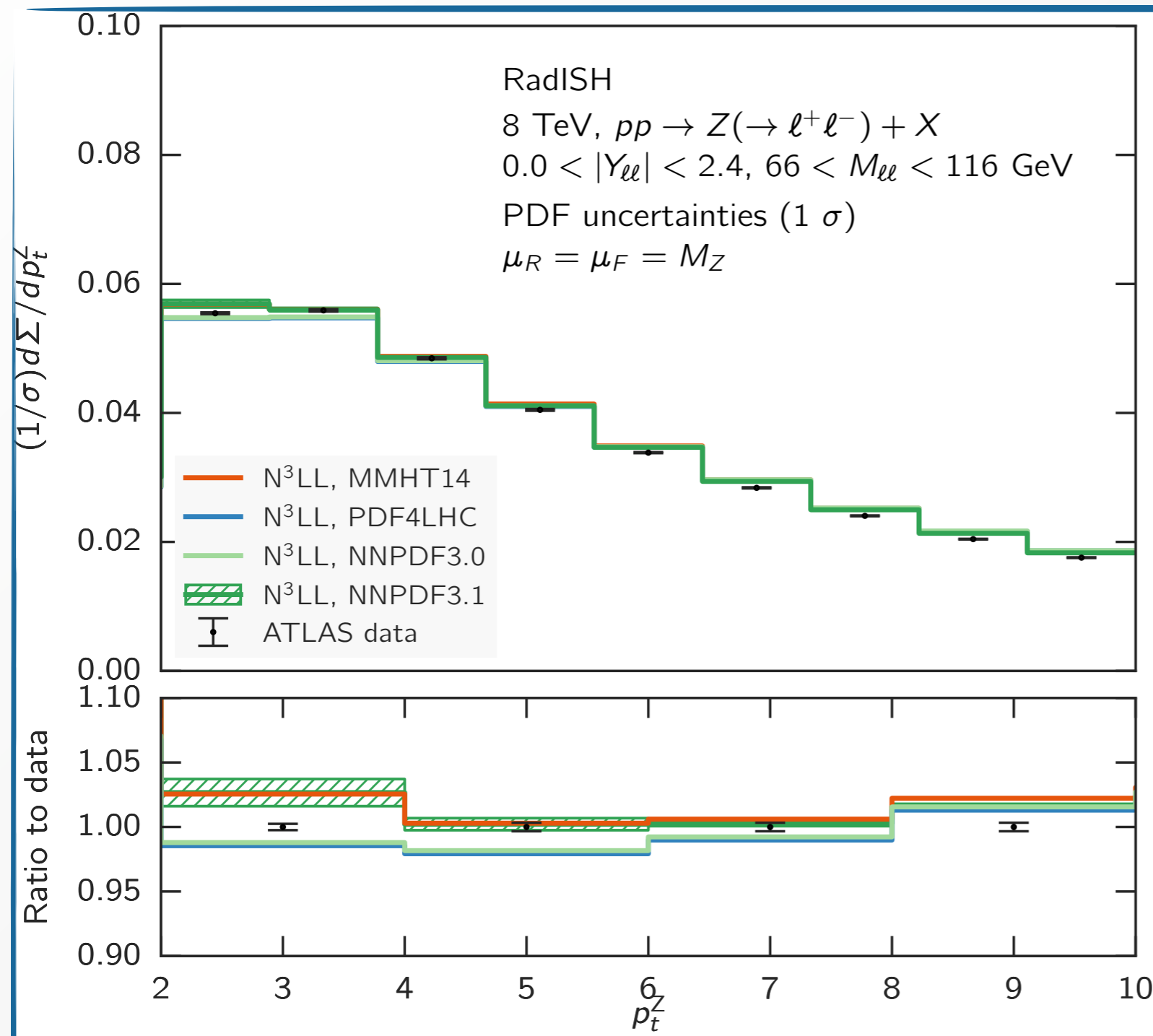


- Matching uncertainties at the sub percent level

- Predictions stable wrt variation of central value of the resummation scale

# PDF uncertainties

Beware of different PDFs and central scales



- Uncertainty with state-of-the-art PDFs at the 1-2% level
- Spectrum gets slightly harder than NNPDF3.0 (used in our current studies)