Motivation:

Modelling of transverse momentum distributions in Z/W production relevant for extraction of SM parameters such as

- PDFs
- α_s
- m_W
- Tune of event generators
- modelling of MPI (2307.05623)

PDFs:

→ reduction on gluon uncertainty in the intermediate x region (10^{-3} - 10^{-2})
1705.00343
+ complementary reduction on singlet

α_s

position of Sudakov peak sensitive to α_s

$$\langle p_T^2 \rangle \sim C_F \alpha_s(M_Z) M_Z \qquad 0508068$$

exploited to bound α_s (NNPDF, fitted alongside other data + PDFs)
a direct extraction (ATLAS)

m_W

Modelling of p_T^Z/p_T^W distribution crucial as full event reconstruction not accessible for m_W ⇒ measurement of m_W performed looking at observables in the transverse plane

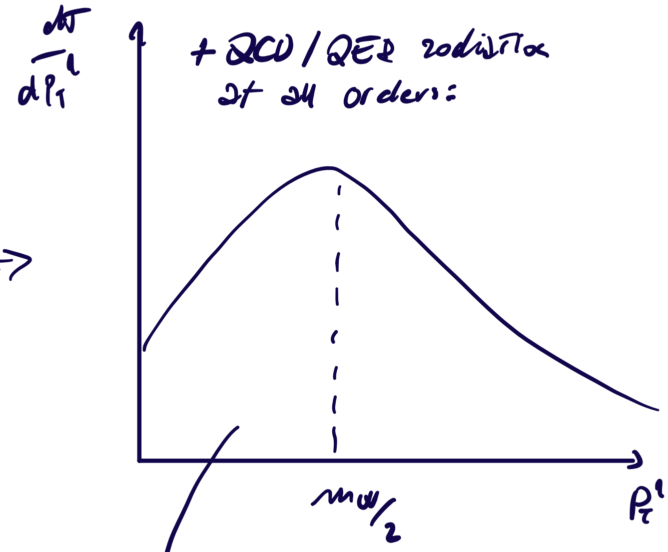
Sensitivity to m_W related to presence of "Jacobian peak" in p_T^ℓ / M_T distribution

$$\Rightarrow \frac{d\sigma}{d|p_T|^2} \sim \frac{4}{\hat{s}}\left(1 - \frac{2|\vec{p}_T|^2}{\hat{s}}\right)\left(1 - \frac{4|\vec{p}_T|^2}{\hat{s}}\right)^{-1/2}$$

divergence at $\hat{s} \sim 4|p_T|^2$.

Presence of Jacobian peak at $p_T \sim \frac{m_W}{2}$. Variations of m_W shift position of the peak

$\Rightarrow$

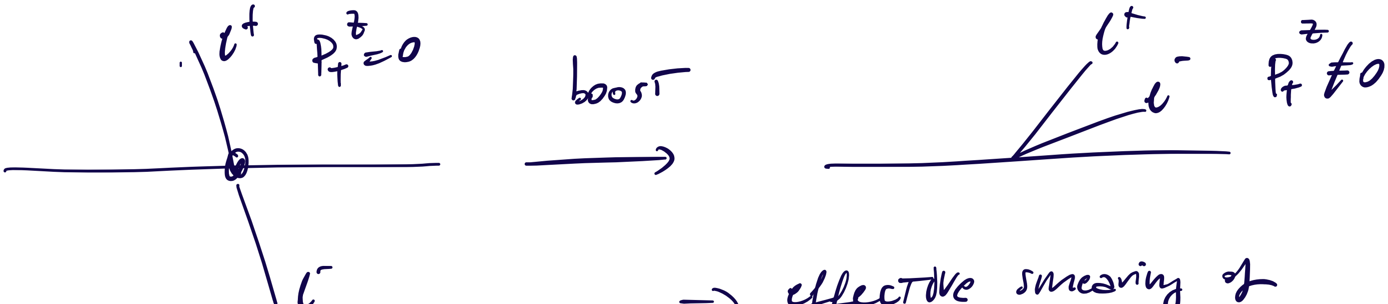


underlying mechanism governing sensitivity of $\frac{d\sigma}{dp_T^\ell}$ on m_W remains after effect of all order radiation

measurement strategy:

- Construction of templates ($p_T^\ell(m_W)$, $M_T(m_W)$) using theoretical tool,
- Similarities between Z, W production used to tune theoretical tool
  $\downarrow$
  strong dependence on W p_T modelling
- Template vs data determine best value for m_W.

Effects on transverse observables thanks to inclusion of recoil in analytical resummation codes



$\Rightarrow$ effective smearing of p_T^ℓ / M_T distributions.

Theoretical predictions for p_T^W/p_T^Z ratio

Cross-section at low q_T plagued by the presence of large logarithms $\ln\frac{Q}{p_T}$
All-order resummation needed to rescue perturbation theory.

Singular cross-section factorizes in b-space

$$\frac{d\sigma}{dQ_T^2} = \sigma^{Born}_{cc\to F}\int dx_1\int dx_2\int_0^\infty db\,\frac{b}{2}\,J_0(bQ_T)\,S_c(b,Q)$$
$$\times\int dz_1\int dz_2\;\delta\left(1-z_1 z_2\frac{x_1 x_2 S}{Q^2}\right)$$
$$\times\left[H^F_{cc}(\alpha_s(Q))\,C_{ca_1}\left(z_1,\alpha_s\left(\frac{b_0}{b}\right)\right)C_{ca_2}\left(z_2,\alpha_s\left(\frac{b_0}{b}\right)\right)\right.$$
$$\left.\times f_{a_1}\left(x_1,\frac{b_0}{b}\right)f_{a_2}\left(x_2,\frac{b_0}{b}\right)\right] \qquad b_0=2^{-\gamma_E}$$

S_c : Sudakov form factor (no-emission probability)

$$S_c \sim \exp\Big[-\big(\underbrace{L g_1(\alpha_s L)}_{LL} + \underbrace{g_2(\alpha_s L)}_{NLL} + \underbrace{\tfrac{\alpha_s}{\pi} g_3(\alpha_s L)}_{NNLL} + \dots\big)\Big]$$

C_{ab}, H^F_{ab} : perturbative functions

- All ingredients for N^3LL' resummation now available
- Some ingredients for N^4LL also available

Many formalisms nowadays available at high logarithmic accuracy (N^3LL' or N^4LL_{app}).

Perturbative Sudakov form factor often supplemented by a non-perturbative Gaussian form factor

$$S_{NP} = \exp(-g b^2)$$

usually fitted to experimental data.

$N^3LL' + NNLO$ ($\mathcal{O}(\alpha_s^3)$) predictions offer excellent description of Z_{p_T} spectra (2203.01565) down to values of 1-2 GeV, where inclusion of NP corrections becomes relevant. Inclusion of NP corrections fitted to data further improve agreement with data (2207.07056)

Relevance for m_W determination

Use of higher order computations in LHC analysis hampered by difficulty in comparing parton-level simulation results with exp. data (accurate modelling of detector simulation needed)

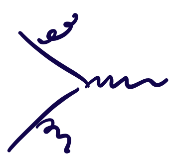
Predictions typically included via reweighting

$$\frac{1}{\sigma^W}\frac{d\sigma^W}{dp_T^W} \sim \frac{1}{\sigma^Z_{MC}}\frac{d\sigma^Z_{MC}}{dp_T^Z} \cdot \underbrace{\frac{\frac{1}{\sigma^W_{theory}}\frac{d\sigma^W_{theory}}{dp_T}}{\frac{1}{\sigma^Z_{theory}}\frac{d\sigma^Z_{theory}}{dp_T}}}_{\sigma^W/\sigma^Z \text{ modelling crucial to perform satisfactorily reweighting step}}$$

N.B. different strategy in LHCb analysis (no ratio involved but DYTurbo tuned on Z data)

Theory predictions for σ^W/σ_Z ratio

- Usually high level of correlation assumed between the two processes

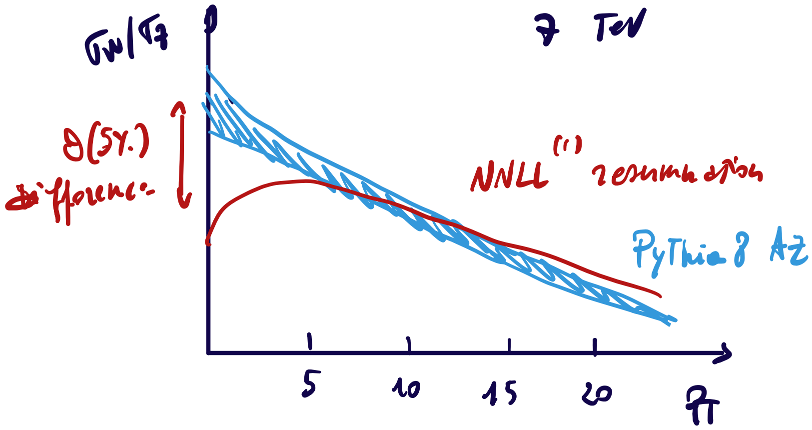


$\Rightarrow$ QCD corrections largely independent on the charge of EW boson

$\to$ main differences driven by initial state flavour (PDF dependence)

$+$ $m_W \neq m_Z$

Results discussed in ATLAS 2017 paper seem to disfavor predictions computed in pQCD



→ discrepancy disfavours the use of formally more accurate codes as it leads to mismodelling of transverse obs. relevant in m_W extraction.

⟹ Treatment of heavy flavour?

2019 results by RadISH reduce the discrepancy (N^{3}LL vs Pythia 8 AZ).

Comparison with Pythia 8 AZ tune suggests that assuming full correlation may be too strong an assumption. De-correlation of factorization scale μ_F reduces (small) tensions still present even with higher-order computations.

⟹ Recent results by MCFM show good agreement for W^+/W^- ratio against low-pileup results at 5.06 TeV.

Several codes (MCFM, RadISH + NNLOJET, SCETLib, DYTurbo...) offer now the possibility of comparing N^{3}LL' results against data/MC tunes.

Paramount to understand pattern of correlation and understanding whether the discrepancies remain.

→ Caveats

- QED effects: modelling of QED FSR essential for a comparison of QCD predictions against data.

QED FSR is <u>large</u>: shifts induced in m_W extraction from p_T^ℓ, m_T $O(350$ MeV$)$.

To what extent QED FSR is fully understood / subtracted using Pythia / Photos / Herwig, etc? Could differences between Γ_W/Γ_Z be related to partial undermodel of QED FSR, which affects W/Z production differently? (4 vs 3 radiators?)

Can Pythia tuning re-absorb these genuine effects?

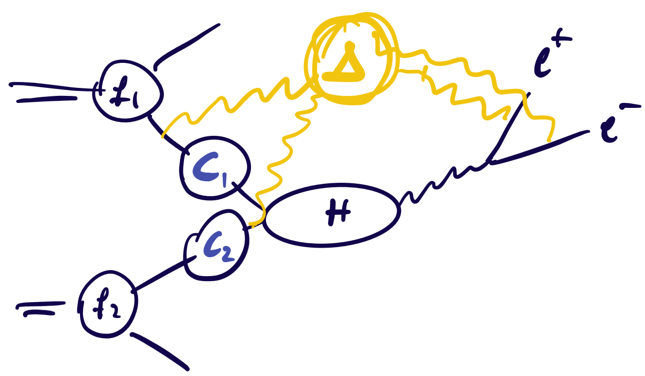
Should we worry about impacts on m_W if state-of-the art codes are not capable of describing data with sufficient precision?

→ Inclusion of QED effects in analytical resummation codes may help to shed light on these issues

$$\exp(-R_{QCD}) \longrightarrow \exp(-R_{QCD}) \times \exp(-R_{QED})$$

for on-shell Z production

more complicated structure (3/4 radiators) when including FSR effects



$$\frac{d\sigma}{dq_T} \sim \int d^2\vec{b}\, e^{i\vec{b}\cdot\vec{q}_T} S(Q,b) \int \frac{dz_1}{z_1}\frac{dz_2}{z_2} [H \Delta C_1 C_2] f\left(\frac{x_1}{z_1}, \frac{b_0}{b}\right) f\left(\frac{x_2}{z_2}, \frac{b_0}{b}\right)$$

→ Formalism akin to the resummation of $t\bar{t}$ pair

all ingredients available for full NLL' resummation
(+ some ingredients for NNLL' resummation
including $\mathcal{O}(\alpha_s \alpha_{EW})$ terms)

- Recent years have seen improvement in the description of processes with NNLO+PS accuracy (MiNNLO, GENEVA$_{q_T}$) and optimal description of p_T observables (albeit with lower formal logarithmic accuracy).

Tunes performed at the level of LO (+ ME corrections) typically underperform when using NLO+PS, NNLO+PS event generators.

$\Rightarrow$ need to rethink approach to tuning when using codes which includes (partial) tower of terms beyond LL accuracy.