$\sin^2\theta_W$ & m_W

DESY SM group meeting

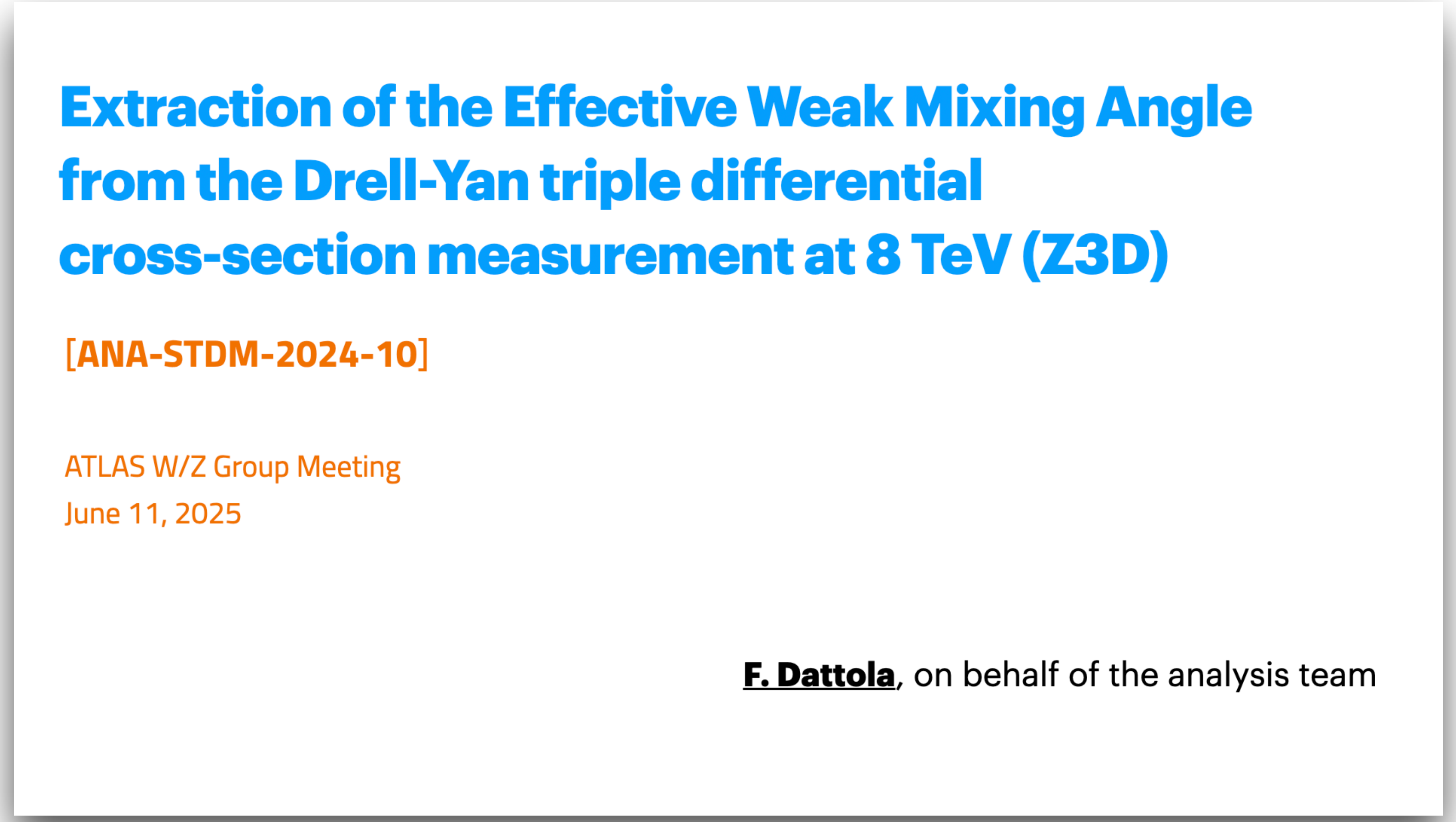
July 29, 2025

F. Dattola

Effective Weak Mixing Angle

Extraction from DY triple differential cross-section at 8 TeV (Z3D)

- Ongoing work on the sin2θW extraction from Z3D data
- Detailed status update recently presented at the SM W/Z-Physics group Meeting

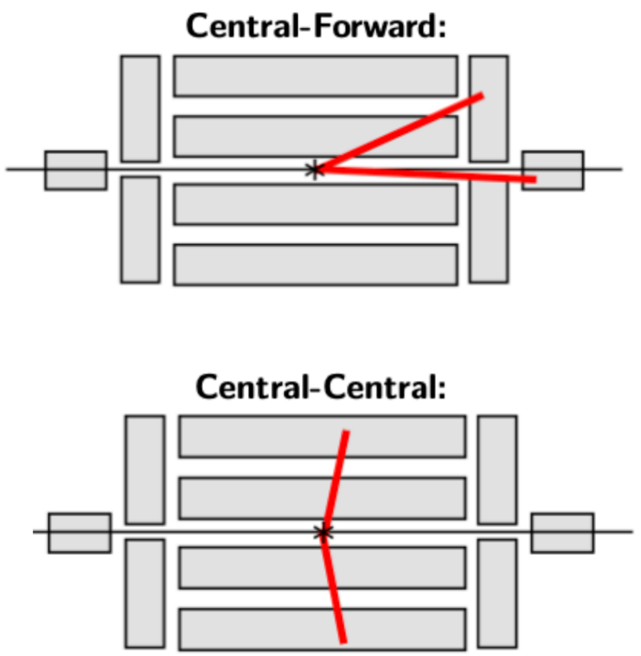


Effective Weak Mixing Angle

ATLAS Z3D at 8 TeV

- Extraction of $\sin^2\theta^f_{\text{eff}}$ builds on ATLAS 3D $(y_{ll}, M_{ll}, \cos\theta^*)$ DY cross section measurement at 8 TeV
  - $\mathrm{d}^3\sigma$ provides information on both A_{FB} and PDFs:
    $x_1 = \frac{m_{ll}}{\sqrt{s}} e^{yll}, x_2 = \frac{m_{ll}}{\sqrt{s}} e^{-yll}, Q^2 = m_{ll}^2 \;\rightarrow\; f(x, Q^2),\; \cos\theta^* \;\rightarrow\; A_{\text{FB}}(\cos\theta^*)$

- 20.2 fb^{-1} of pp data at $\sqrt{s}$ = 8 TeV
- Two measurement regions:
  - central-central (CC): electrons and muons in seven $46 < m_{ll} < 200$ GeV, twelve $|y_{ll}| < 2.4$ and six $cos\theta^*$ bins (2×504 bins)
  - central-forward (CF): one central and one forward electron in five $66 < m_{ll} < 150$ GeV, five $1.2 < |y_{ll}| < 3.6$ and six $cos\theta^*$ bins (150 bins)
- Signal MC: `POWHEG+PYTHIA` with CT10 PDFs, and with NNLO QCD+NLO EW k-factors
- Good agreement with theoretical predictions
  - $d^3\sigma$ reaches 0.5% precision near Z peak, barring luminosity uncertainty



Effective Weak Mixing Angle

My current focus: brand-new EW and QCD modelling

- Working on the production of NNLO+NNLL QCD predictions with DYTurbo and NLO + h.o. EW predictions with POWHEG Z_ew-BMNNPV (+Pythia)

- **NLO + H.O. (F.O.) EW** predictions in $\sin^2\theta^f_{\text{eff}}$ EW scheme with the **POWHEG-BOX-V2** framework
  - Use **Z_ew-BMNNPV** package at LO QCD + NLO+H.O. EW **(+ matching to QCD Parton Shower)**
  - **EW accuracy**: **NLO EW plus** leading universal **higher order radiative corrections** $(\Delta\alpha, \Delta\rho)$
  - $(G_\mu, M_Z, \sin^2\theta^l_{\text{eff}})$ **input scheme**: observables (e.g., A_{FB}) in terms of $\sin^2\theta^f_{\text{eff}}$; fast perturbative convergence
  - Resonance described using **Complex Mass Scheme (CMS)**: theoretically more rigorous, width appearing at Lagrangian level → drawback complex propagators and couplings
    - ***W,Z* masses/ (fixed) widths** converted to their **pole values:** consistent with CMS definition

- **NNLO + NNLL QCD** predictions with **DYTurbo 1.4.2**
  - Accounts for **resummation** corrections
  - LO EW in $\sin^2\theta^f_{\text{eff}}$ - like scheme
  - Fixed width + on-shell W,Z masses/widths converted to pole values: CMS not implemented

… potentially including also an "exercise" with SCETlib + Theory Nuisance Parameters (TNPs) in fiducial regions sensitive to resummation effects, against traditional scale variations for perturbative theory uncertainties

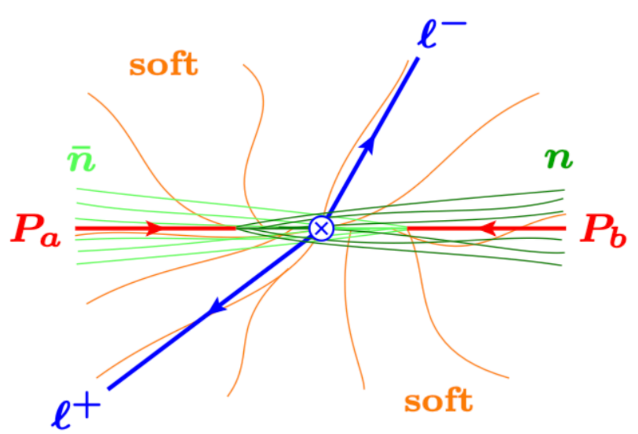
W mass

Resummed predictions with SCETlib + TNPs

- Goal is to use the new Theory Nuisance Parameter formalism designed by Frank (Tackmann) in the analysis
  - See Tackmann arXiv:2411.18606 and Cridge, Marinelli, Tackmann arXiv:2506.13874

$$\frac{d\sigma}{dq_T} = \frac{d\sigma^{\mathrm{res}}_{\mathrm{sing}}}{dq_T} + \frac{d\sigma^{\mathrm{FO}}_{\mathrm{nons}}}{dq_T} = \frac{d\sigma^{\mathrm{res}}_{\mathrm{sing}}}{dq_T} + \left[\frac{d\sigma^{\mathrm{FO}}_{\mathrm{full}}}{dq_T} - \frac{d\sigma^{\mathrm{FO}}_{\mathrm{sing}}}{dq_T}\right]$$

$$\frac{d\sigma_{\mathrm{sing}}}{dQ\,dY\,dq_T} = \sum_q H_{q\bar{q}}(Q,\mu)\; q_T \int_0^\infty db_T\, b_T\, J_0(q_T b_T) \times B_q(x_a, b_T, \mu, Q/\nu)\, B_{\bar{q}}(x_b, b_T, \mu, Q/\nu)\, S(b_T, \mu, \nu)$$



Six sources of TNPs: the **three fixed-order boundary conditions** of each of the hard (H), soft (S), and beam (B) functions, and **three anomalous dimensions** governing their renormalization group evolution, namely the cusp anomalous dimension (Γ_{cusp}) and the virtuality and rapidity noncusp anomalous dimensions (γ_μ and γ_ν)

Brake things down to independent perturbative series, e.g. at N^{2+1}LL

- 5 scalar series (plus a few more we neglect ...)

$$\Gamma(\alpha_s) = \alpha_s\,\hat{\Gamma}_0 + \alpha_s^2\,\hat{\Gamma}_1 + \alpha_s^3\,\hat{\Gamma}_2 + \alpha_s^4\,\Gamma_3(\theta_3^\Gamma) + \cdots$$
$$\gamma_\mu(\alpha_s) = \alpha_s\,\hat{\gamma}_{\mu 0} + \alpha_s^2\,\hat{\gamma}_{\mu 1} + \alpha_s^3\,\gamma_{\mu 2}(\theta_2^{\gamma_\mu}) + \cdots$$
$$\gamma_\nu(\alpha_s) = \alpha_s\,\hat{\gamma}_{\nu 0} + \alpha_s^2\,\hat{\gamma}_{\nu 1} + \alpha_s^3\,\gamma_{\nu 2}(\theta_2^{\gamma_\nu}) + \cdots$$
$$c(\alpha_s) = \hat{c}_0 + \alpha_s\,\hat{c}_1 + \alpha_s^2\,c_2(\theta_2^H) + \cdots$$
$$\tilde{S}(\alpha_s) = \hat{\tilde{S}}_0 + \alpha_s\,\hat{\tilde{S}}_1 + \alpha_s^2\,\tilde{S}_2(\theta_2^S) + \cdots$$

- Up to five one-dimensional functional series for beam functions

$$\tilde{b}_i(x,\alpha_s) = \sum_j \int \frac{dz}{z}\left[\hat{I}_{ij,0}(z) + \hat{I}_{ij,1}(z) + I_{ij,2}(z,\theta_2^{B_{ij}})\right] f_j\!\left(\frac{x}{z}\right),$$

[F. Tackmann]

> TNPs of the hard and soft functions and the three anomalous dimensions are numerical constants

> beam functions (BF) five one-dimensional functions of the Bjorken-x for the different partonic splitting channels

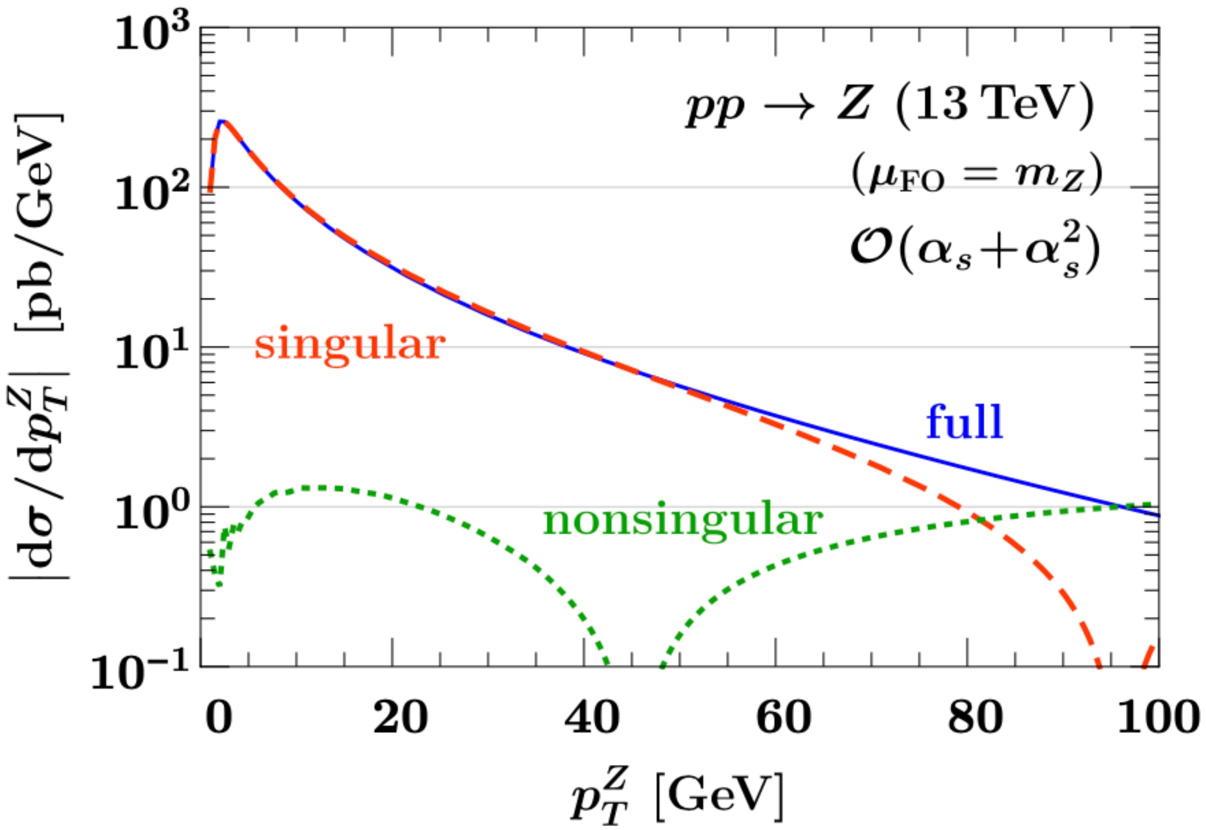
> known functional shape and treat their normalization as a scalar TNP for each partonic channel

W mass

My current focus: matching to fixed order

- Suggested prescription is to **match resummed SCETlib cross-section to DYTurbo fixed-order** to cover consistently the qT spectrum

- "singular" (or "leading-power")
  - To be resummed
- "nonsingular" (or "subleading-power")
  - Suppressed by relative p_T^2/m_Z^2
  - To be supplied by matching to full FO



W mass

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Matching to Fixed Order.

$$\mathrm{d}\sigma = \underbrace{\mathrm{d}\sigma^{(0)}(\mu_H, \mu_B, \nu_B, \mu_S, \nu_S)}_{\equiv\, \mathrm{d}\sigma^{\mathrm{resum}}(\mu_H, \mu_B, \nu_B, \mu_S, \nu_S)} + \underbrace{\left[\mathrm{d}\sigma^{\mathrm{FO}}(\mu_{\mathrm{FO}}) - \mathrm{d}\sigma^{(0)}(\mu_i, \nu_i \equiv \mu_{\mathrm{FO}})\right]}_{\mathrm{d}\sigma^{\mathrm{nons}}(\mu_{\mathrm{FO}})}$$

- σ^{resum} and σ^{nons} are *separately* scale independent (args show residual dep.)
  - In particular, σ^{nons} has no dependence (not even residual) on resum. scales
- Condition for $p_T \ll Q$: σ^{nons} must be power-suppressed by p_T/Q
  - $\mathrm{d}\sigma^{(0)}$ must exactly cancel all singular terms $\mathrm{d}\sigma^{\mathrm{FO}}$
- Condition for $p_T \sim Q$: Reproduce correct FO result $\mathrm{d}\sigma^{\mathrm{FO}}$
  - $\sigma^{\mathrm{resum}} - \mathrm{d}\sigma^{(0)}$ must vanish *exactly* (i.e. their difference must not introduce higher-order corrections, because in general they would be unphysical and can be arbitrarily large)
  - Guaranteed by profile scales $\mu_i, \nu_i \to \mu_{\mathrm{FO}}$ for $p_T \to Q$