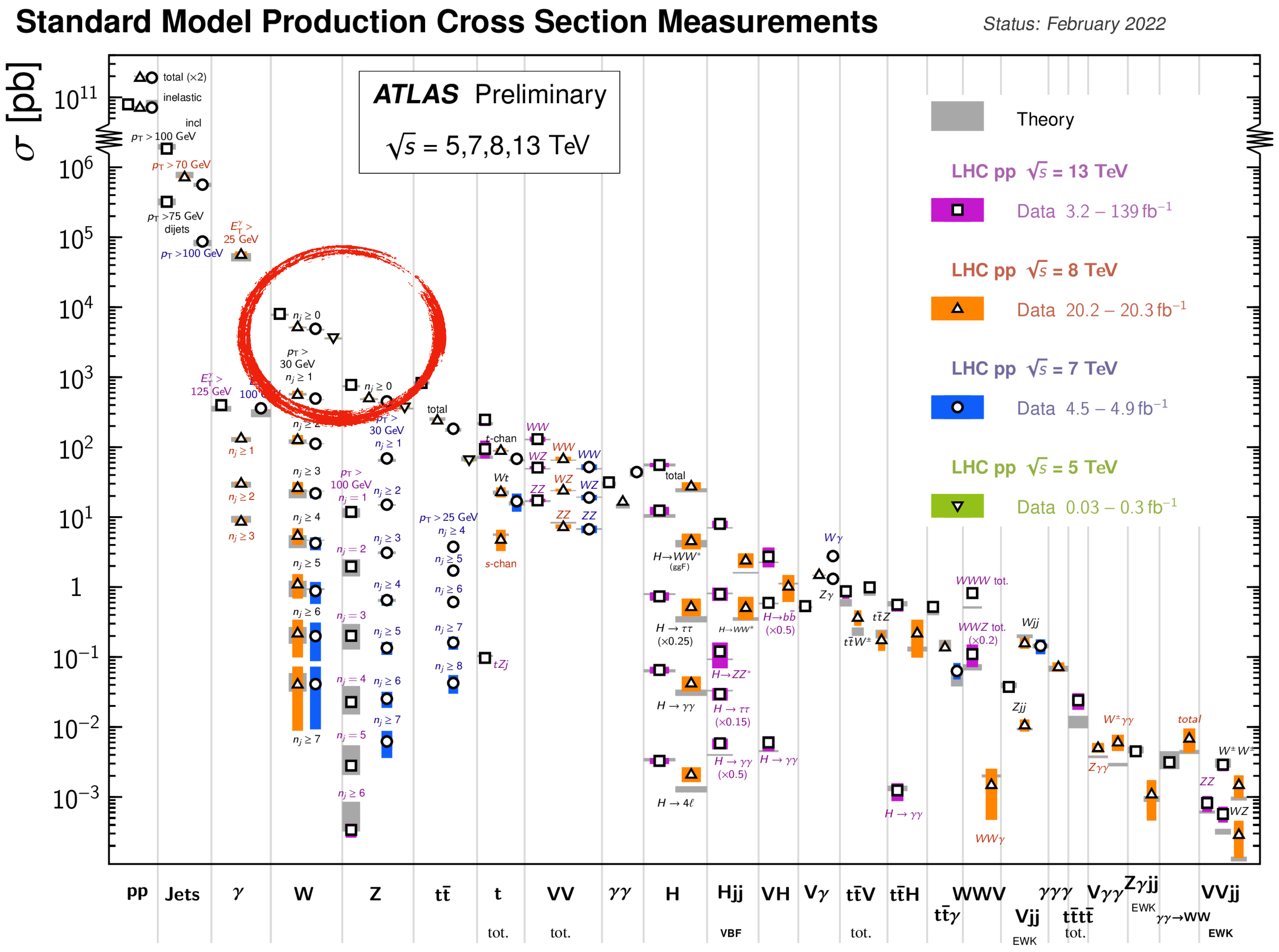
p_T resummation in Drell-Yan and determination of the W mass at hadron colliders

Paolo Torrielli
Università di Torino and INFN

QCD Evolution 2024

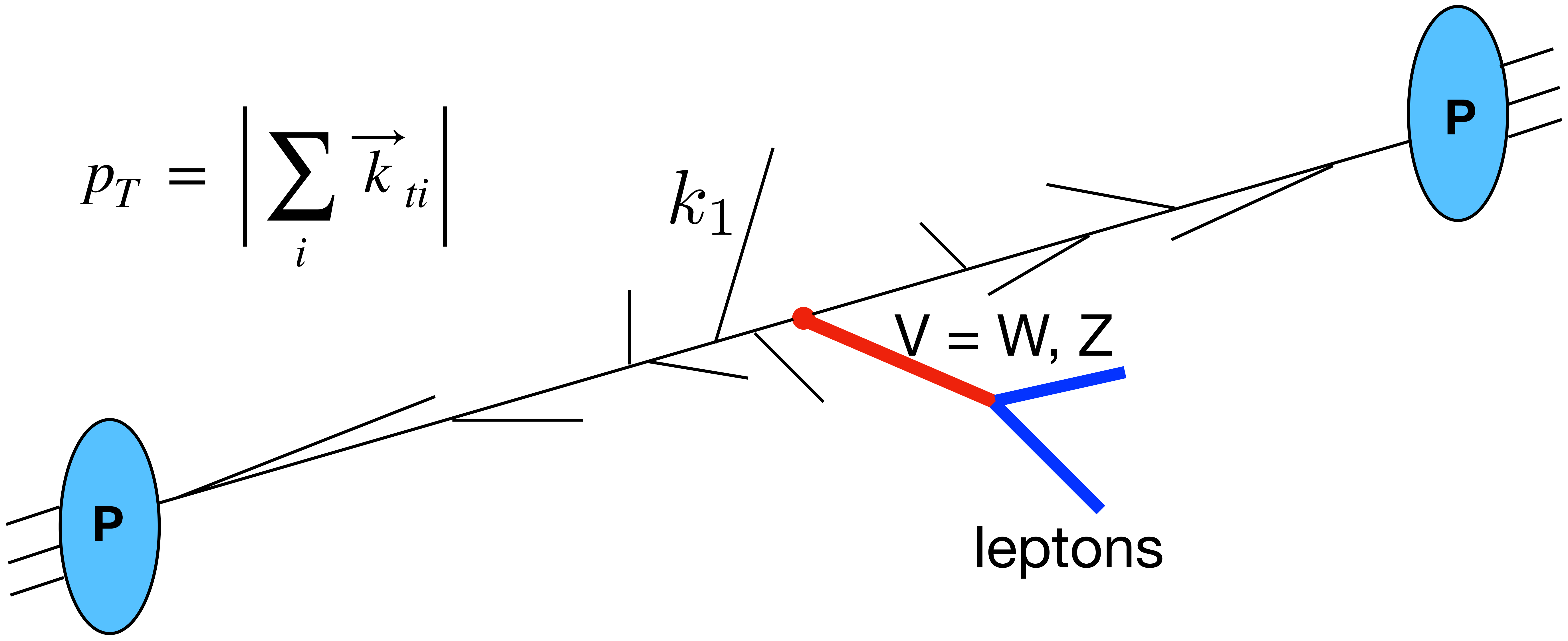
Pavia, May 27th 2024

Drell-Yan at the LHC



- DY: the LHC standard candle
- Large cross section and clean signature due to hard charged lepton(s) in the final state
- Allows experimental measurements and theoretical predictions of the highest precision

Drell-Yan at the LHC



- Fixed-order DY computations reliable only for large values of $p_T \sim M$
- Large soft/collinear $\log(p_T/M)$ arising when $p_T \ll M$
- All-order resummation of $\log(p_T/M)$ needed

Outline

- State-of-the-art p_T resummation in QCD
- Inclusion of EW effects in p_T resummation
- Implications for m_W determination

- State-of-the-art p_T resummation in QCD
- Inclusion of EW effects in p_T resummation
- Implications for m_W determination

p_T resummation in Drell-Yan

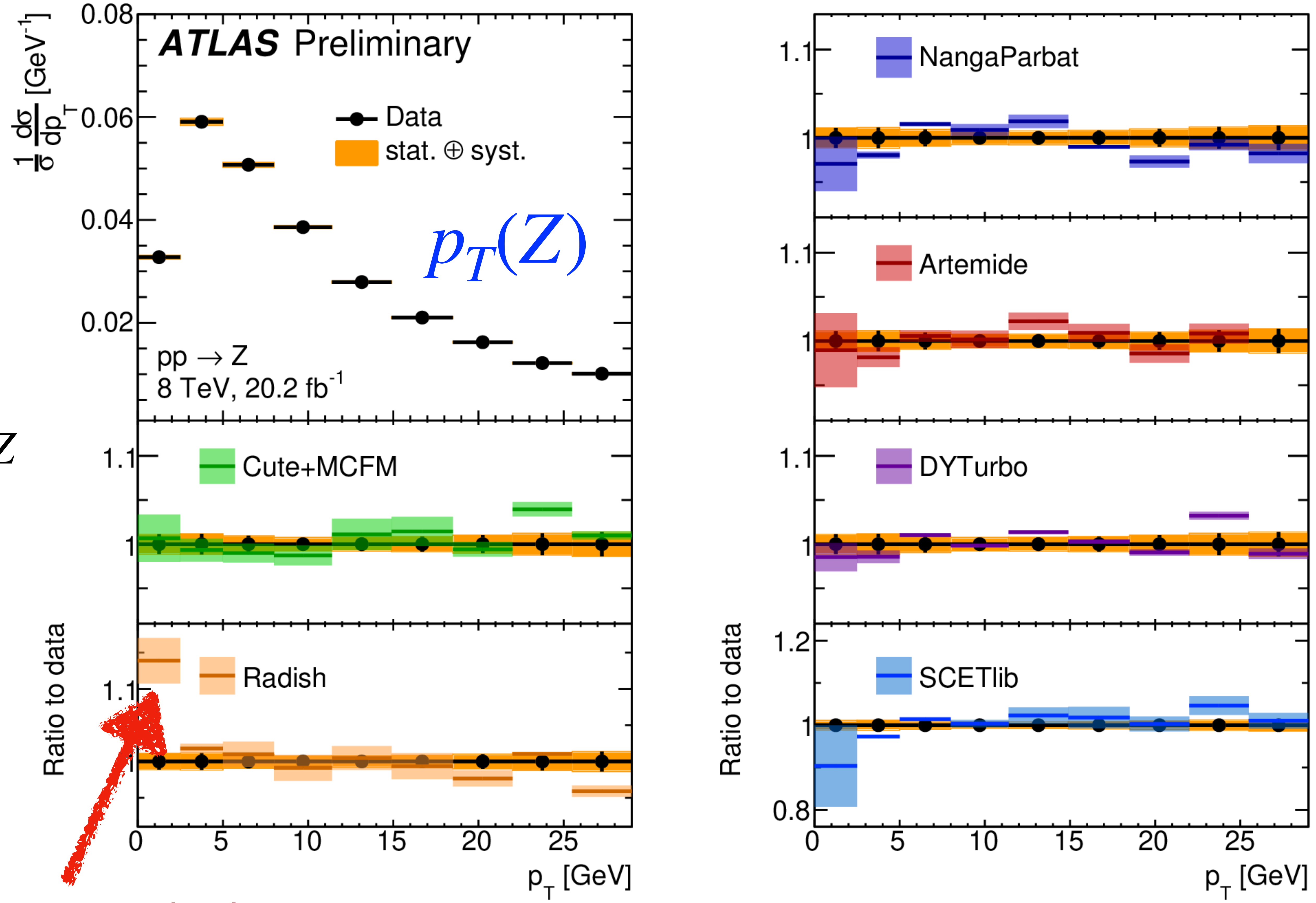
- Variety of frameworks to perform p_T resummation: b-space / momentum space, QCD / SCET, TMD
- Nowadays full N3LL' QCD accuracy, i.e. $\alpha_s^n \log(p_T/M)^{n-2}$ and $\alpha_s^n \log(p_T/M)^{2n-6}$
- Ingredients known for N4LL in QCD, i.e. $\alpha_s^n \log(p_T/M)^{n-3}$, included in some of the frameworks

[Artemide: Scimemi, Vladimirov
Cute+MCFM: Becher, Campbell, Neumann, et al.
DYTurbo: Camarda, Catani, Cieri, Ferrera, Grazzini, et al.
NangaParbat: Bacchetta, Bertone, Bozzi, et al.
RadISH: Monni, Re, Rottoli, PT
Resbos: Isaacson, Yuan, et al.
reSolve: Coradeschi, Cridge
SCETlib: Billis, Ebert, Michel, Tackmann, et al.
…]

p_T spectrum in Drell-Yan at the LHC

- $p_T(Z)$ comparison at N3LL’ / approx N4LL QCD against ATLAS 8 TeV data
- A success for the community: remarkable agreement with data and few-% QCD residual uncertainty in the resummation region $p_T(Z) \ll m_Z$
- Impact of aN3LO PDFs to be carefully assessed
- Non-perturbative developments important to improve description below 5 GeV

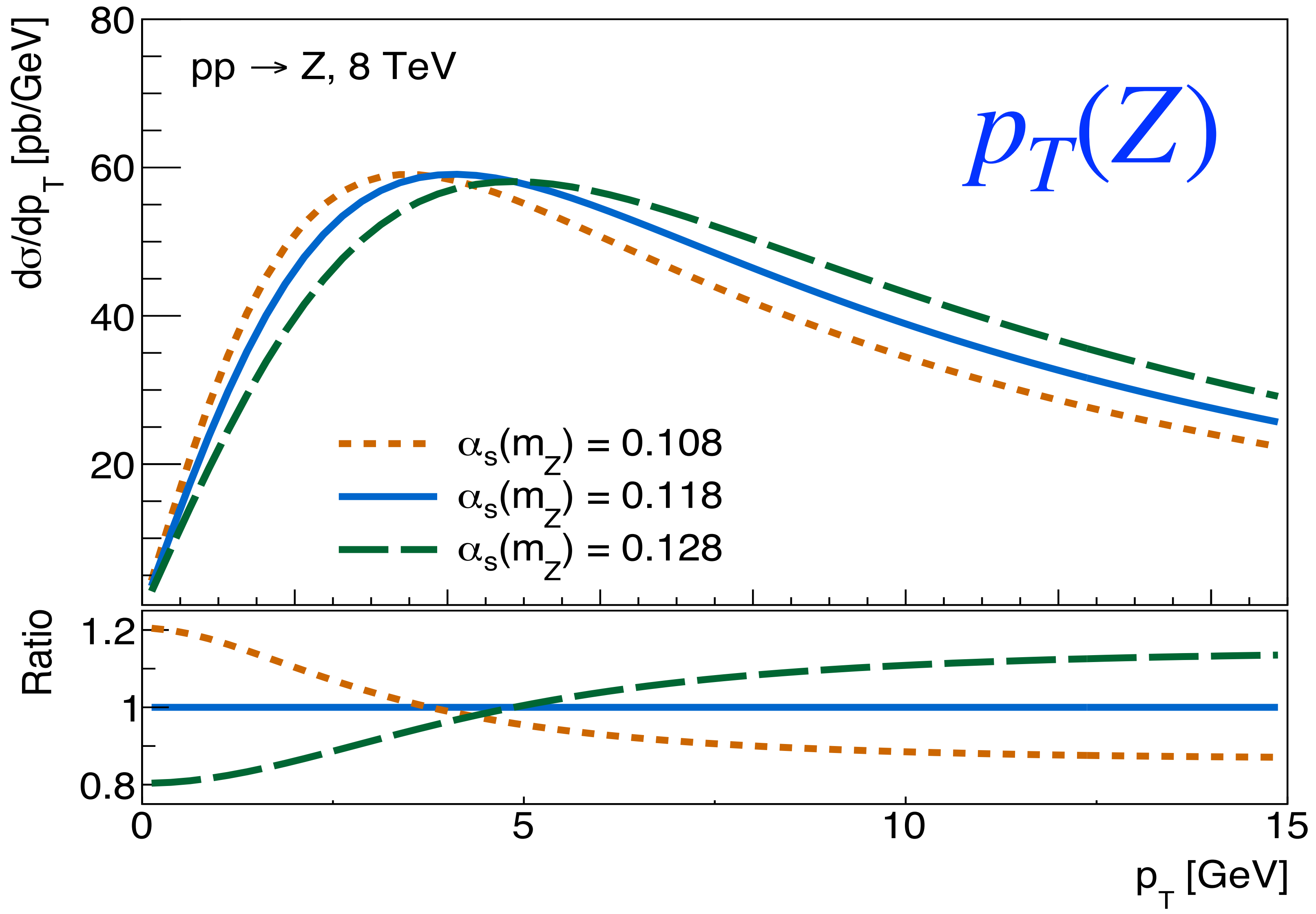
[ATLAS-CONF-2023-013]

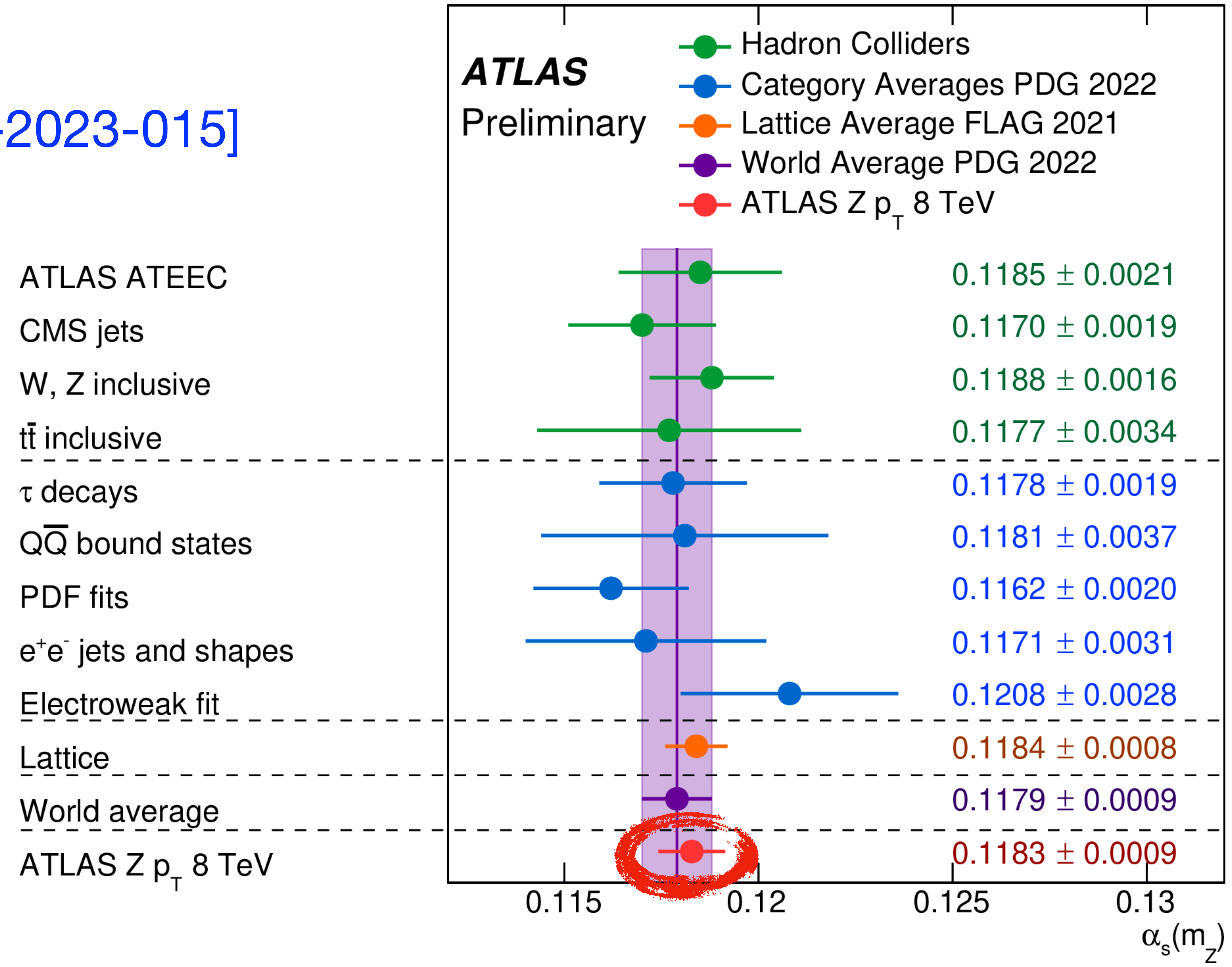


No non-perturbative modelling in RadISH

α_s from resummed $p_T(Z)$ in Drell-Yan

[ATLAS-CONF-2023-015]





- α_s precisely extracted from resummed $p_T(Z)$ spectrum by ATLAS
- Uses aN3LO MSHT20 PDFs [MSHT 2207.04739]
- Studies on correlation of α_s with PDFs and non-perturbative modelling important to build confidence in the quoted uncertainty

p_T resummation for differential distributions

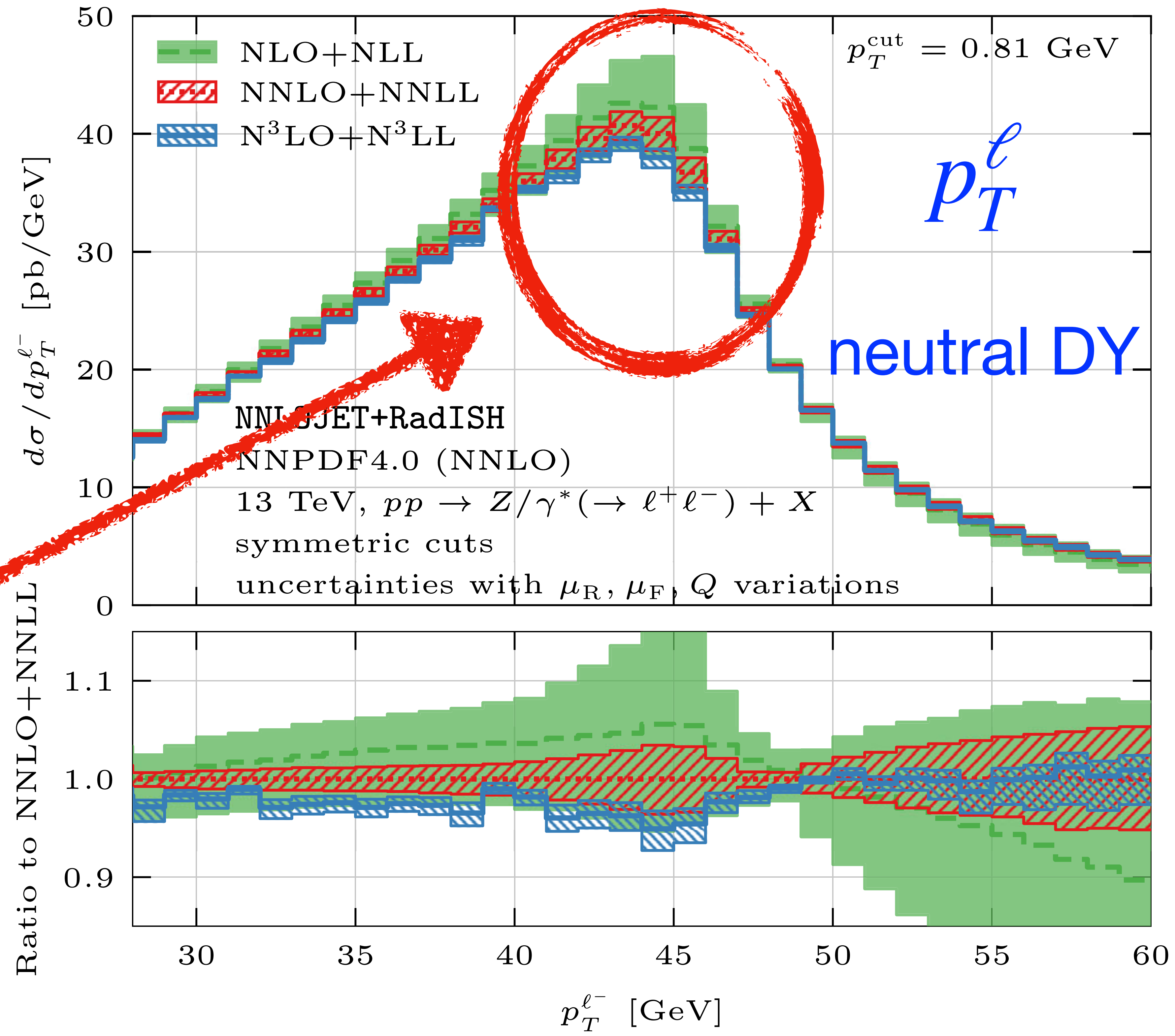
- Some crucial leptonic observables for DY phenomenology cannot be described at fixed order

- Lepton transverse momentum: at $p_T^\ell \sim m_Z/2$ jacobian peak sensitive to multiple IR radiation beyond LO [Catani, Webber, 9710333]: integrable singularity at fixed order

- Physical behaviour recovered resumming linear power corrections through kinematical recoil [Catani et al. 1507.06937, Ebert et al. 2006.11382]

- q_T subtraction formula [Catani, Grazzini, 0703012] with recoil

$$d\sigma_{\rm DY}^{\rm N3LO+N3LL} = \mathscr{H}_{\rm DY}^{\rm N3LL+recoil} \otimes d\sigma_{\rm DY}^{\rm LO} + d\sigma_{\rm DY+1\,jet}^{\rm NNLO} - \left[d\sigma_{\rm DY}^{\rm N3LL+recoil} \right]_{\mathcal{O}(\alpha_s^3)}$$



[RadISH+NNLOJET, 2203.01565]

ATLAS symmetric cuts:
$p_T^\ell > 27$ GeV, $|\eta^\ell| < 2.5$
66 GeV < $M_{\ell\ell}$ < 116 GeV

- State-of-the-art p_T resummation in QCD
- Inclusion of EW effects in p_T resummation
- Implications for m_W determination

p_T resummation in Drell-Yan and determination of the W mass at hadron colliders

Paolo Torrielli
Università di Torino and INFN

+ QED

QCD Evolution 2024

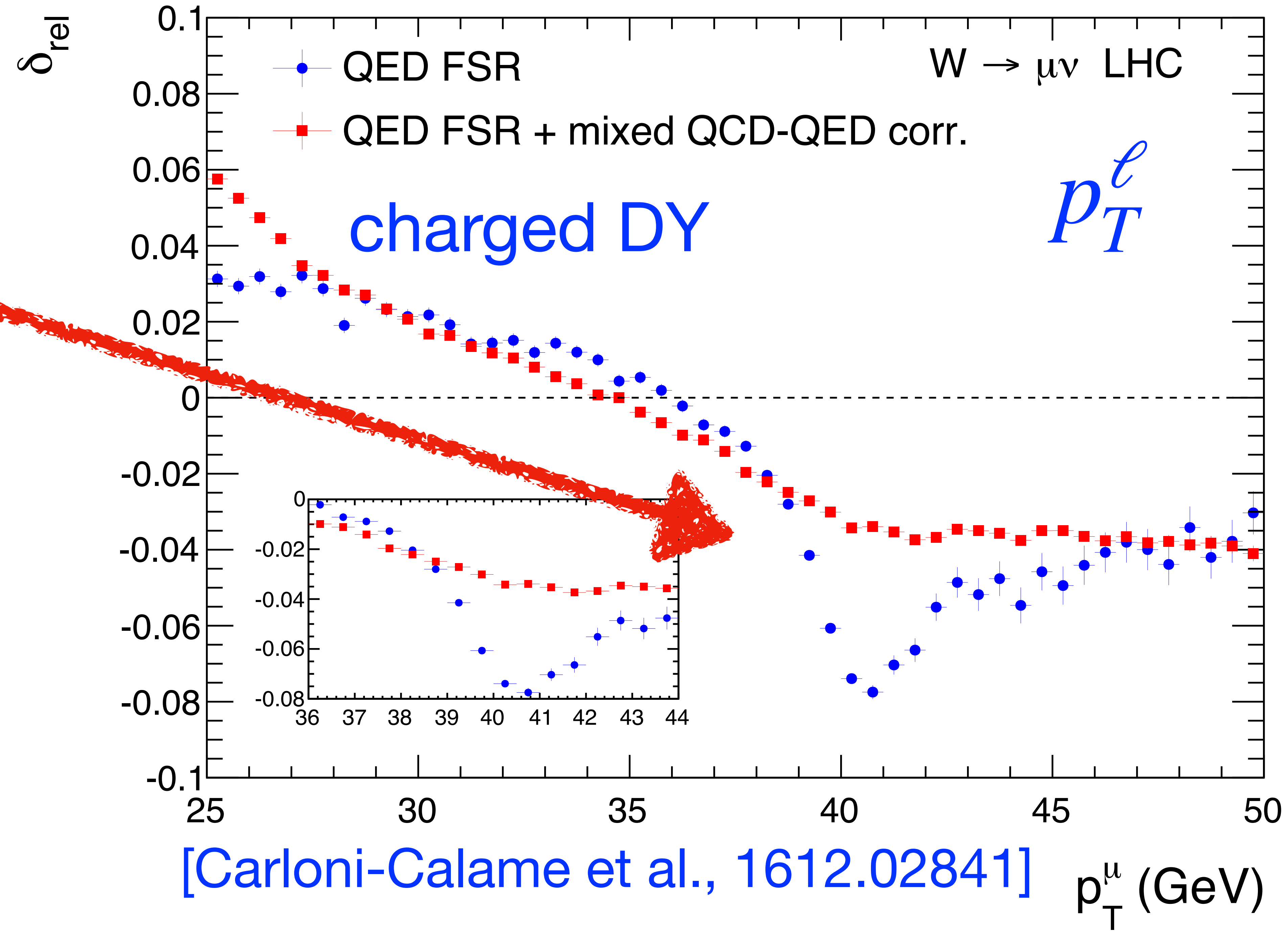
Pavia, May 27th 2024

EW effects on precision DY observables

- Sizeable impact of QED radiation from final-state leptons and mixed QCD-EW corrections on precision DY observables

- Resummation of EW effects at the level of fiducial leptons obtained with dedicated codes [Horace, Photos], up to NLO+PS with POWHEG-EW [Bernaciak, Wakeroth, 1201.4804, Barzè et al., 1202.0465, 1302.4606, …]

- NLL QED and mixed QCD-EW effects for inclusive on-shell W and Z production in [Cieri et al. 1805.11948, Autieri et al. 2302.05403]



[Carloni-Calame et al., 1612.02841]

Accurate resummation of QED and mixed QCD-EW effects with RadISH

[Buonocore, Rottoli, PT, 2404.15112]

Schematic RadISH resummation differential over leptons phase space (massive bare muons)

$$\frac{\mathrm{d}\sigma(p_T)}{\mathrm{d}\Phi_B} = \int \frac{\mathrm{d}k_{t1}}{k_{t1}} \mathscr{L}(k_{t1})\, \mathrm{e}^{-R(k_{t1})}\, \mathscr{F}(p_T, \Phi_B, k_{t1})$$

- Inclusion of QED and mixed QCD-EW effects in RadISH at NLL, i.e. $O(\alpha_s^n \alpha^m L^{n+m})$ + subleading

Accurate resummation of QED and mixed QCD-EW effects with RadISH

[Buonocore, Rottoli, PT, 2404.15112]

Schematic RadISH resummation differential over leptons phase space (massive bare muons)

$$\frac{d\sigma(p_T)}{d\Phi_B} = \int \frac{dk_{t1}}{k_{t1}} \mathscr{L}(k_{t1})\, e^{-R(k_{t1})} \mathscr{F}(p_T, \Phi_B, k_{t1})$$

- Inclusion of QED and mixed QCD-EW effects in RadISH at NLL, i.e. $O(\alpha_s^n \alpha^m L^{n+m})$ + subleading

Luminosity $\mathscr{L}(k_{t1}) = |\mathscr{M}_B|^2_{cd} \left[C_{ci} \otimes f_i(k_{t1})\right] \left[C_{dj} \otimes f_j(k_{t1})\right] H(\mu_R)$ including $O(\alpha)$ and $O(\alpha_s \alpha)$ corrections to coefficient functions, hard function:

$$C_{ab} = C_{ab}^{\rm QCD} + \frac{\alpha}{2\pi} C_{ab}^{'(1)} + \frac{\alpha_s}{2\pi}\frac{\alpha}{2\pi} C_{ab}^{(1,1)} \qquad + \qquad \text{DGLAP } P_{ab}^{'(1)} \text{ and } P_{ab}^{(1,1)}$$

$$H = H^{\rm QCD} + \frac{\alpha}{2\pi} H^{'(1)} + \frac{\alpha}{2\pi} F^{'(1)}(\Phi_B) + \frac{\alpha_s}{2\pi}\frac{\alpha}{2\pi} H^{(1,1)}$$

Accurate resummation of QED and mixed QCD-EW effects with RadISH

[Buonocore, Rottoli, PT, 2404.15112]

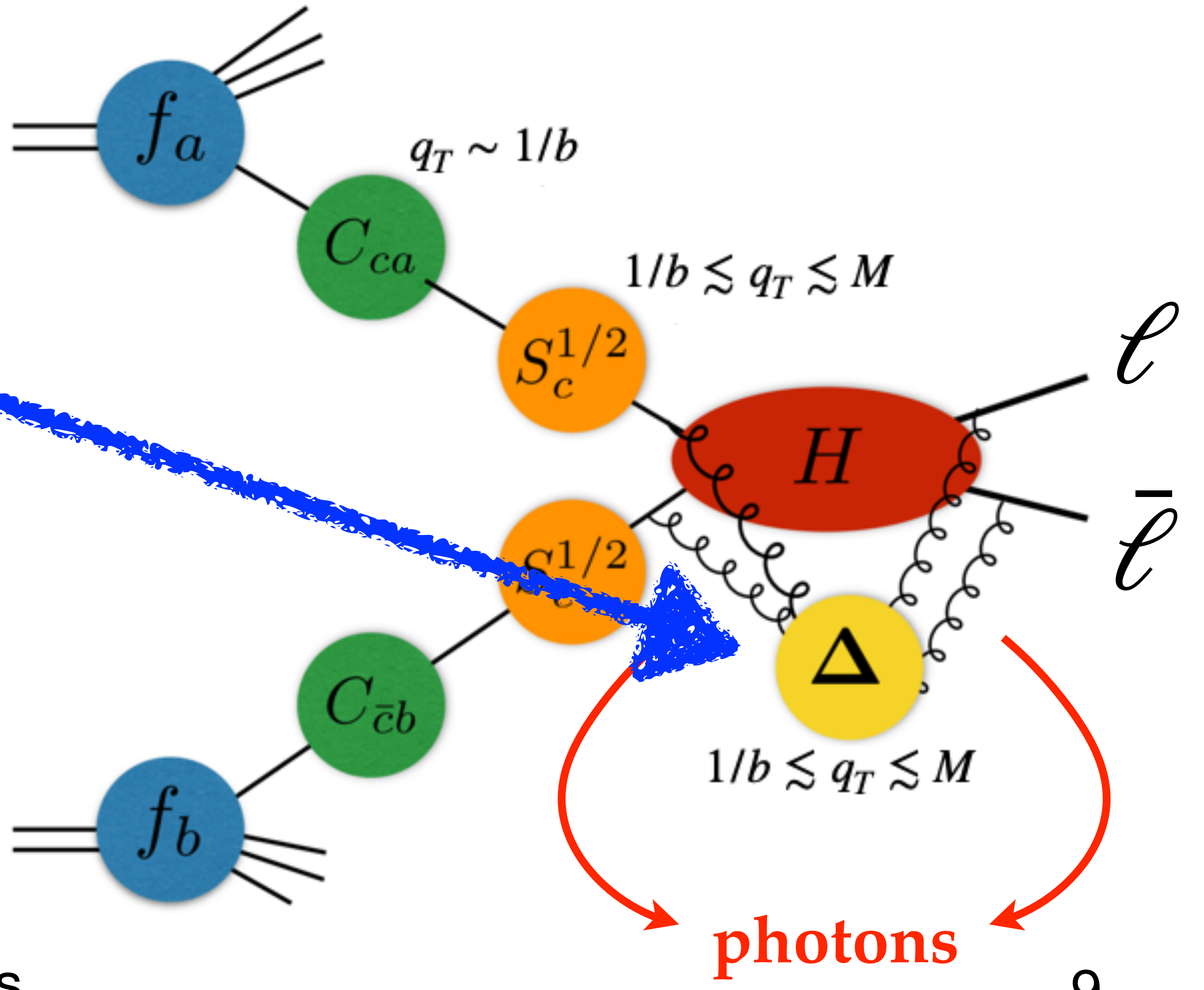
Schematic RadISH resummation differential over leptons phase space (massive bare muons)

$$\frac{d\sigma(p_T)}{d\Phi_B} = \int \frac{dk_{t1}}{k_{t1}} \mathcal{L}(k_{t1})\, e^{-R(k_{t1})} \mathcal{F}(p_T, \Phi_B, k_{t1})$$

- Inclusion of QED and mixed QCD-EW effects in RadISH at NLL, i.e. $O(\alpha_s^n \alpha^m L^{n+m})$ + subleading

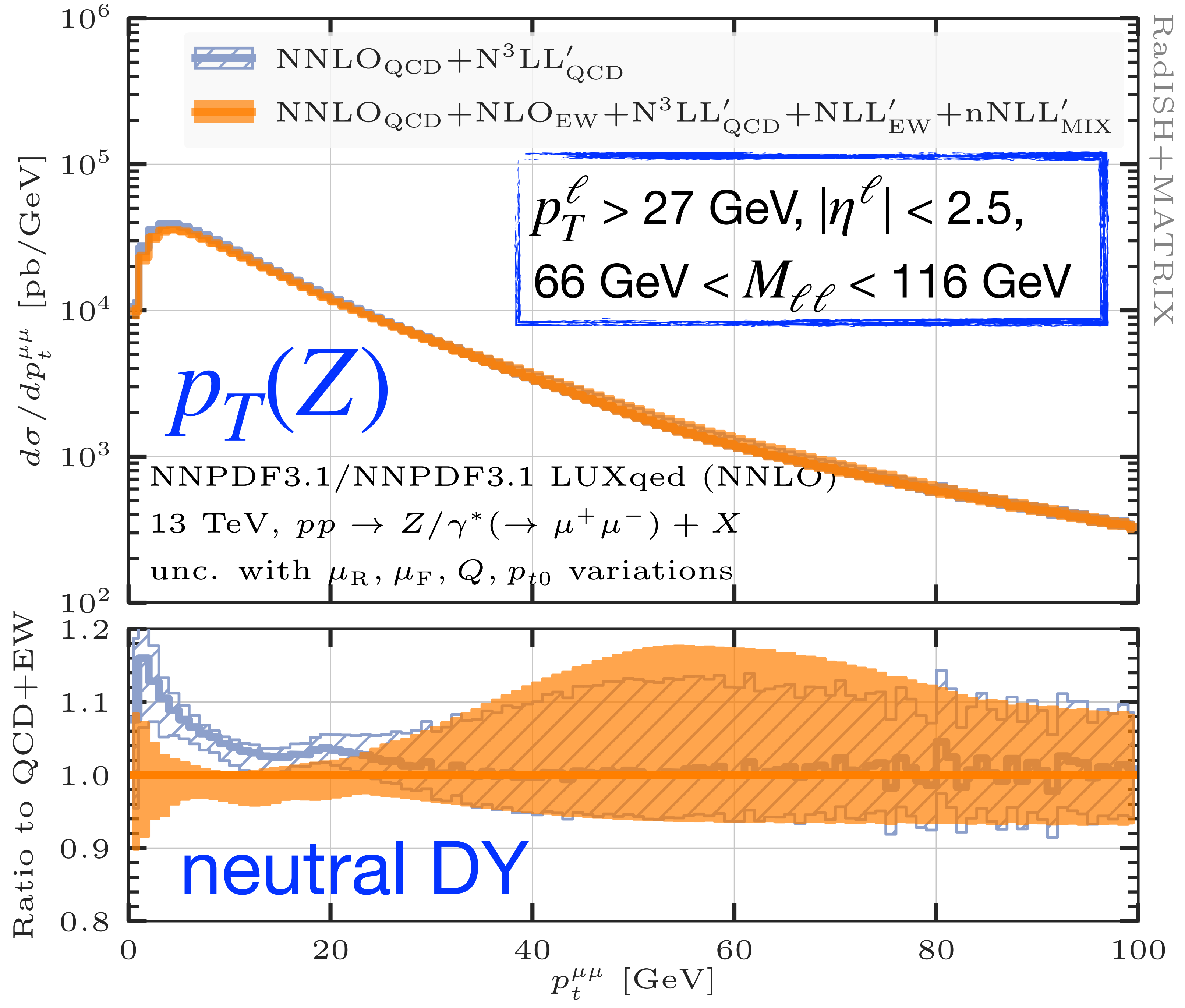
Sudakov radiator $R(k_{t1})$ including QED NLL $L\, g_1(\alpha L) + g_2(\alpha L)$, QED (QCD) running of QCD (QED) coupling $g_{11}(\alpha_s L, \alpha L)$, and soft wide-angle QED radiation from leptons (Φ_B dependence)

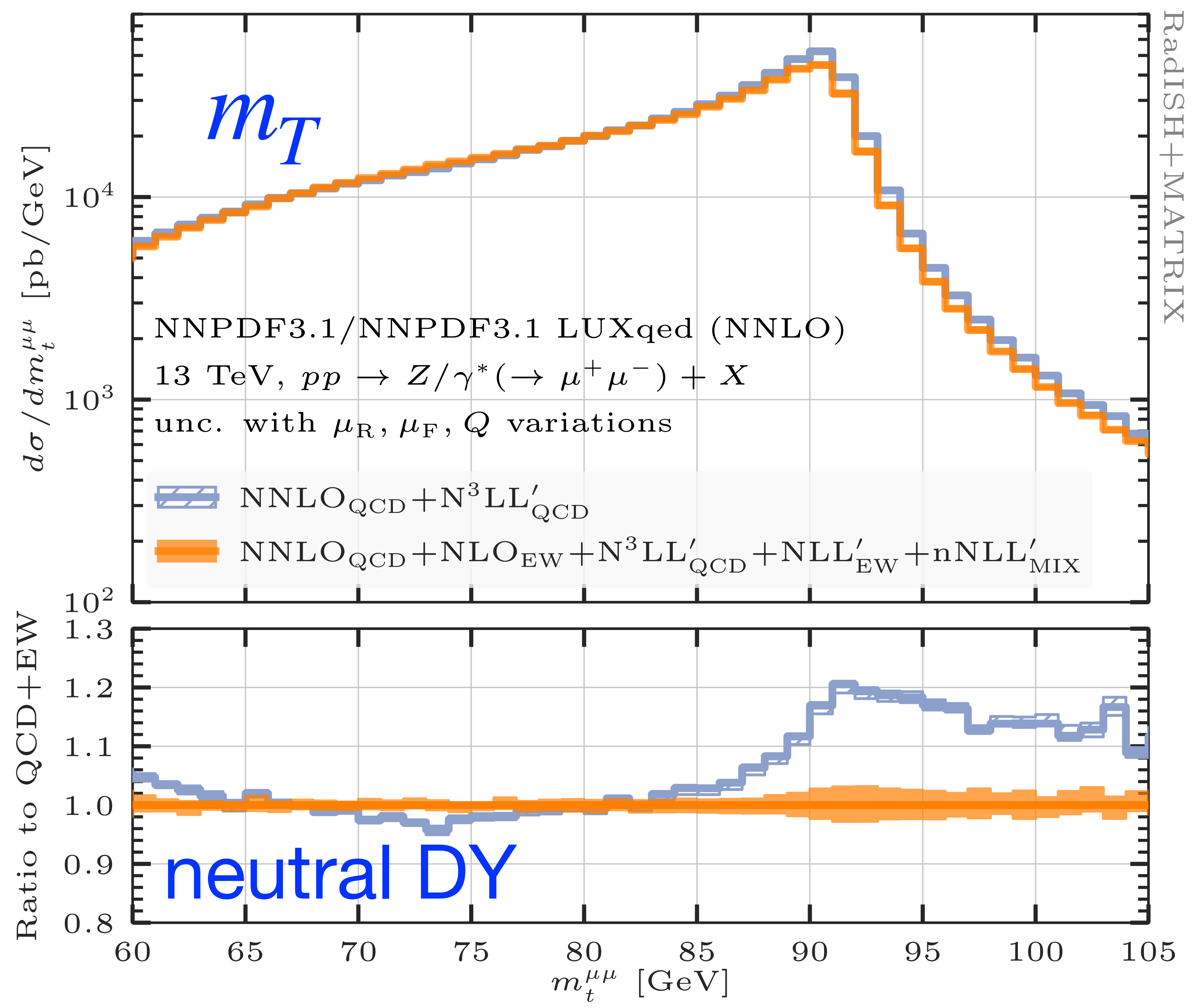
$$R = R^{\rm QCD} + R^{\rm QED}(\Phi_B) + R^{\rm MIX} + \frac{\alpha_s}{2\pi}\frac{\alpha}{2\pi} B^{(1,1)} L$$

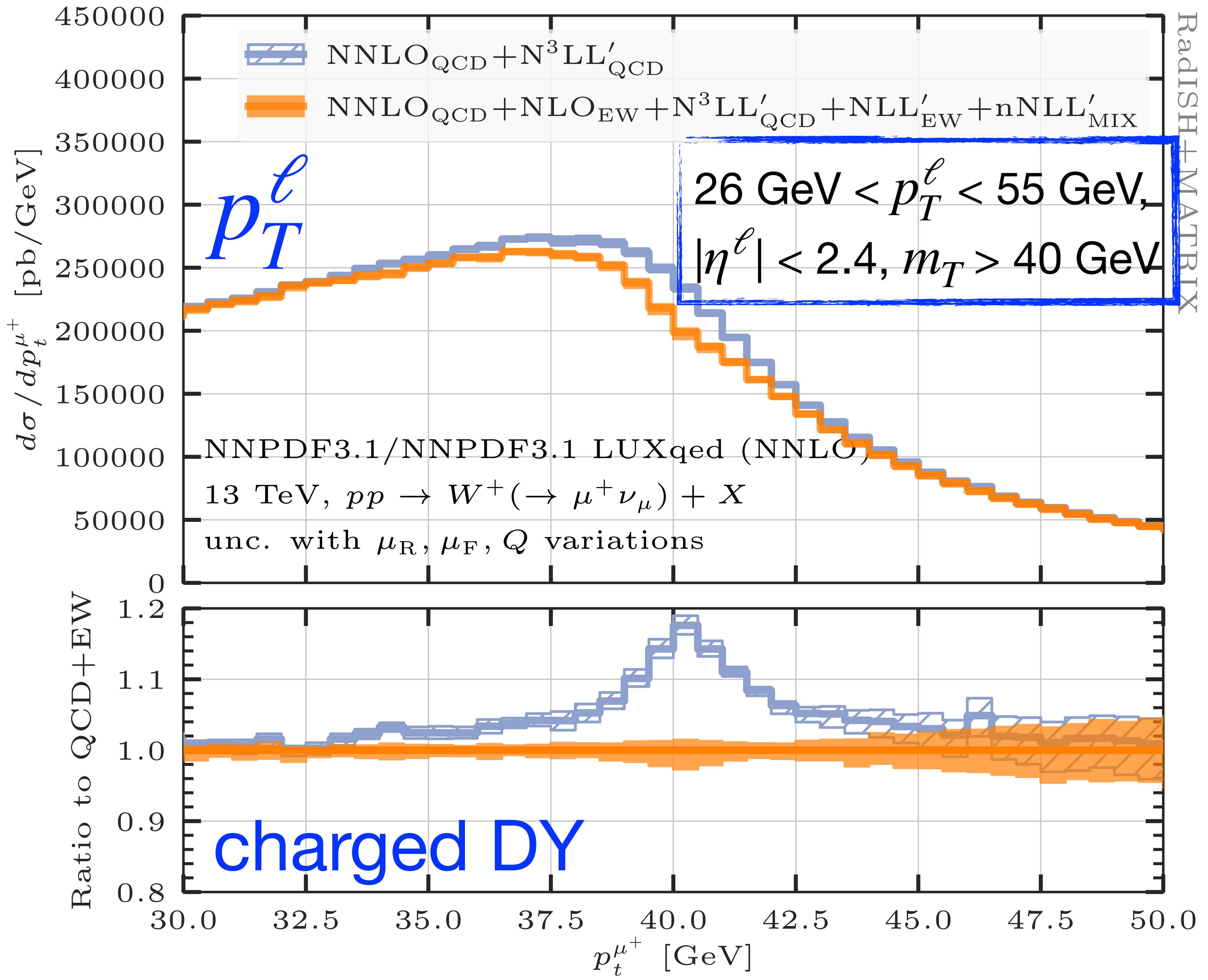


First pheno results with QED and mixed QCD-EW effects in RadISH

[Buonocore, Rottoli, PT, 2404.15112]

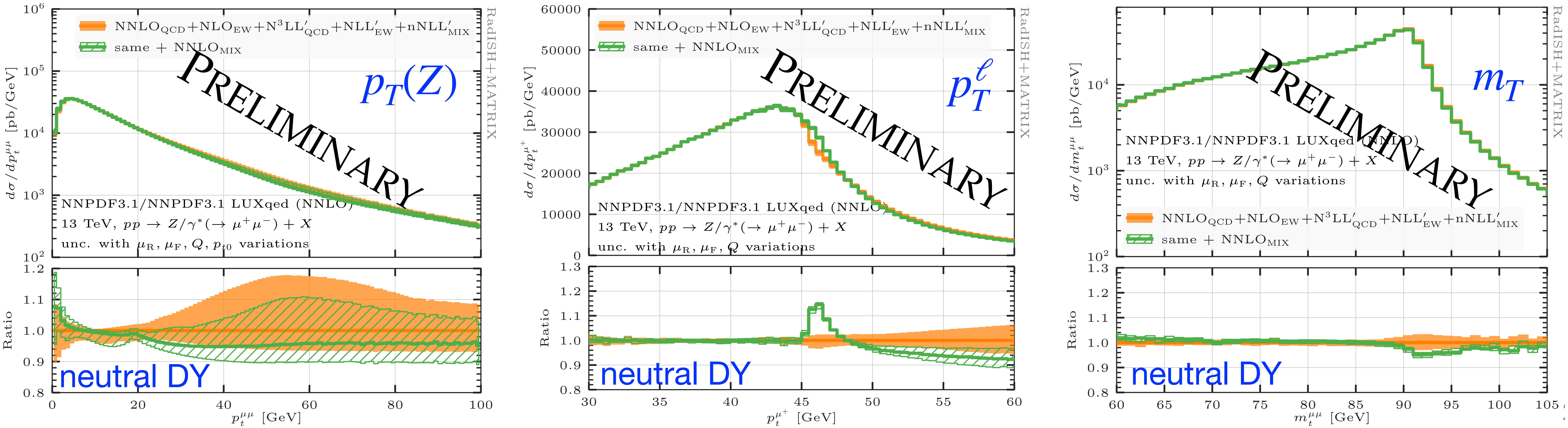






- Large EW effects at small $p_T(Z)$ and around jacobian peak of m_T and p_T^ℓ, mostly driven by QED FSR
- Towards accurate comparison with data without subtraction of EW effects from the latter ('Born' leptons)
- Mixed $O(\alpha_s\alpha)$ terms from fixed order not included in these plots

Impact of matching at $O(\alpha_s \alpha)$



- We work with massive bare muons: $O(\alpha_s \alpha)$ terms enhanced by large $\log(m_\mu/M)$ in the resummation, largely absorbed by matching to fixed order
- Expected numerical impact of matching on precision observables. After matching, residual m_μ dependence should be under control
- Interest in developing formalism to resum all $\log(m_\mu)$ terms (soft wide-angle + quasi-collinear)

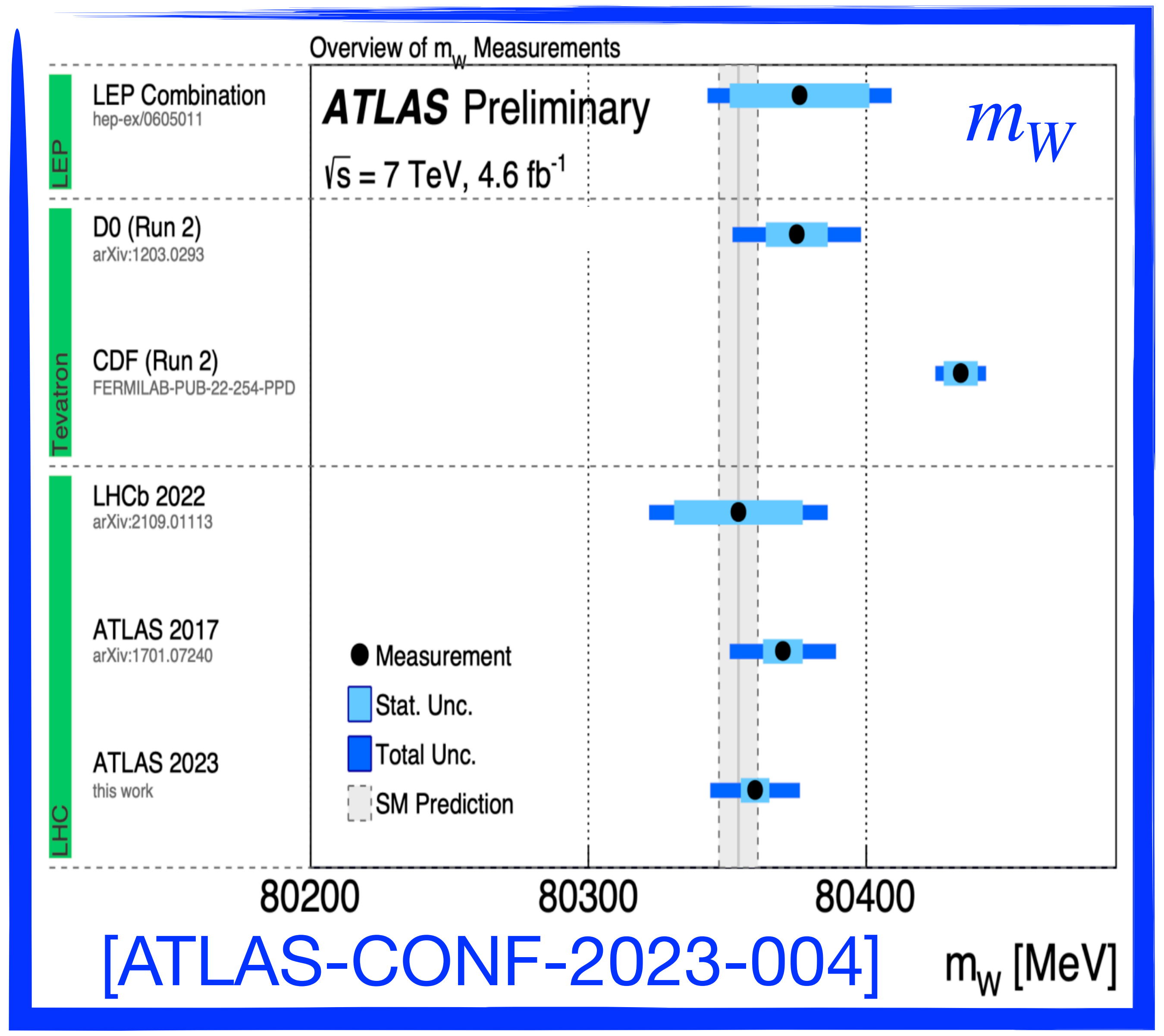
- State-of-the-art p_T resummation in QCD
- Inclusion of EW effects in p_T resummation
- Implications for m_W determination

Experimental determination of m_W

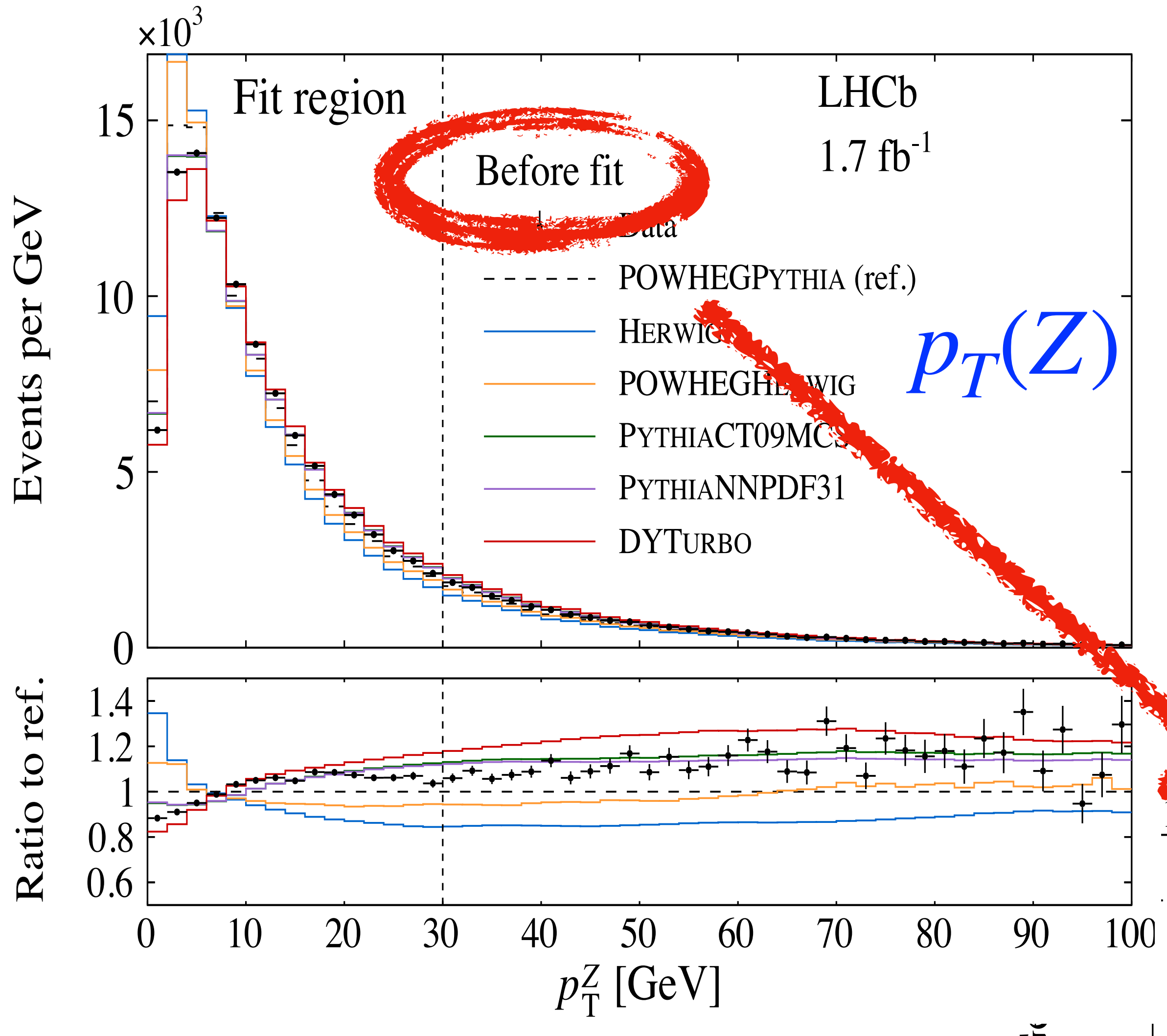
- Current experimental procedure for m_W is to fit template p_T^ℓ and m_T distributions to data in charged DY

- Templates are generated with (quite low accuracy) parton shower, after crucial calibration (tuning) to $p_T(Z)$ neutral DY

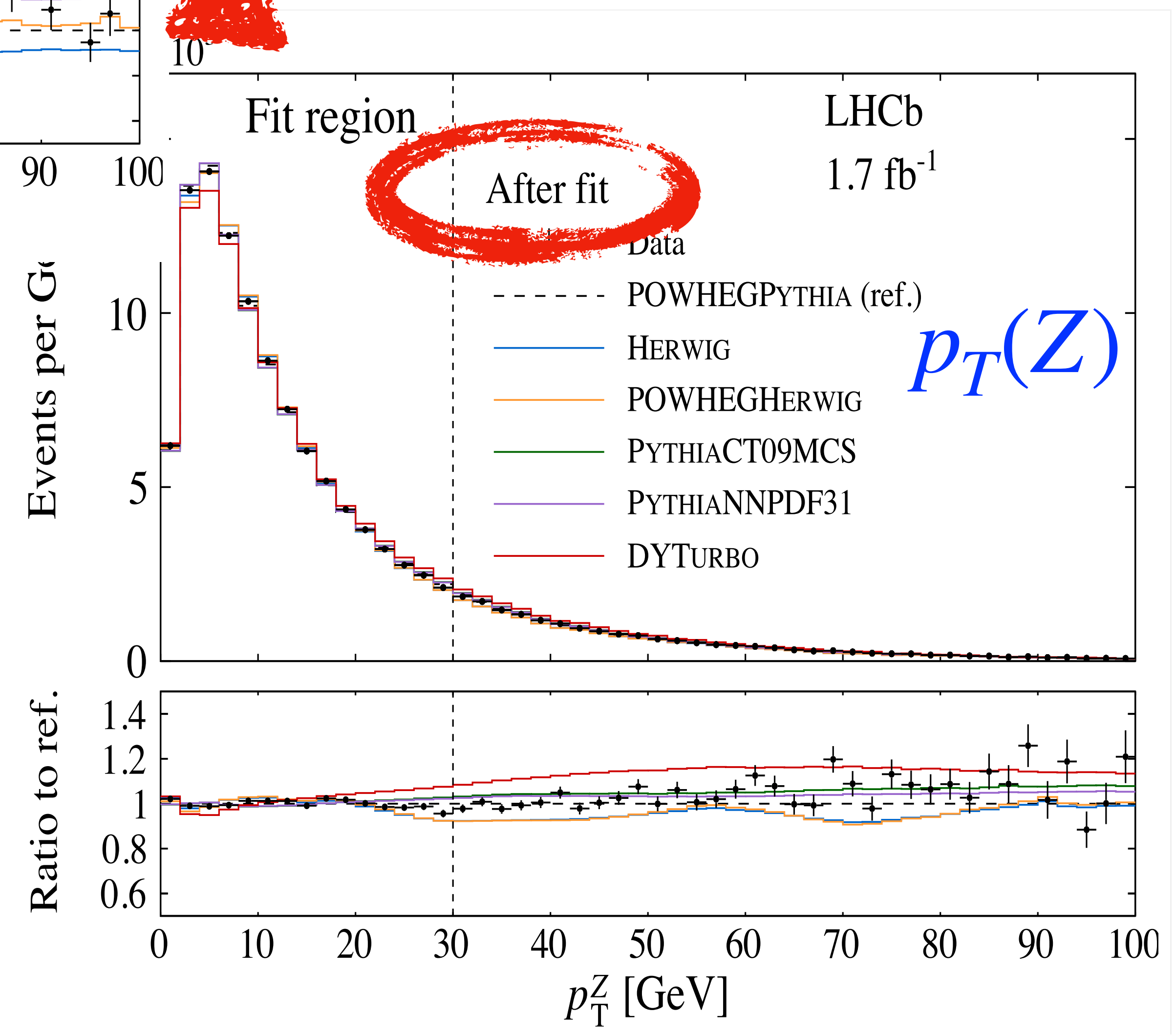
- Transfer of information from neutral to charged DY: subtle to assess systematics



[ATLAS-CONF-2023-004]

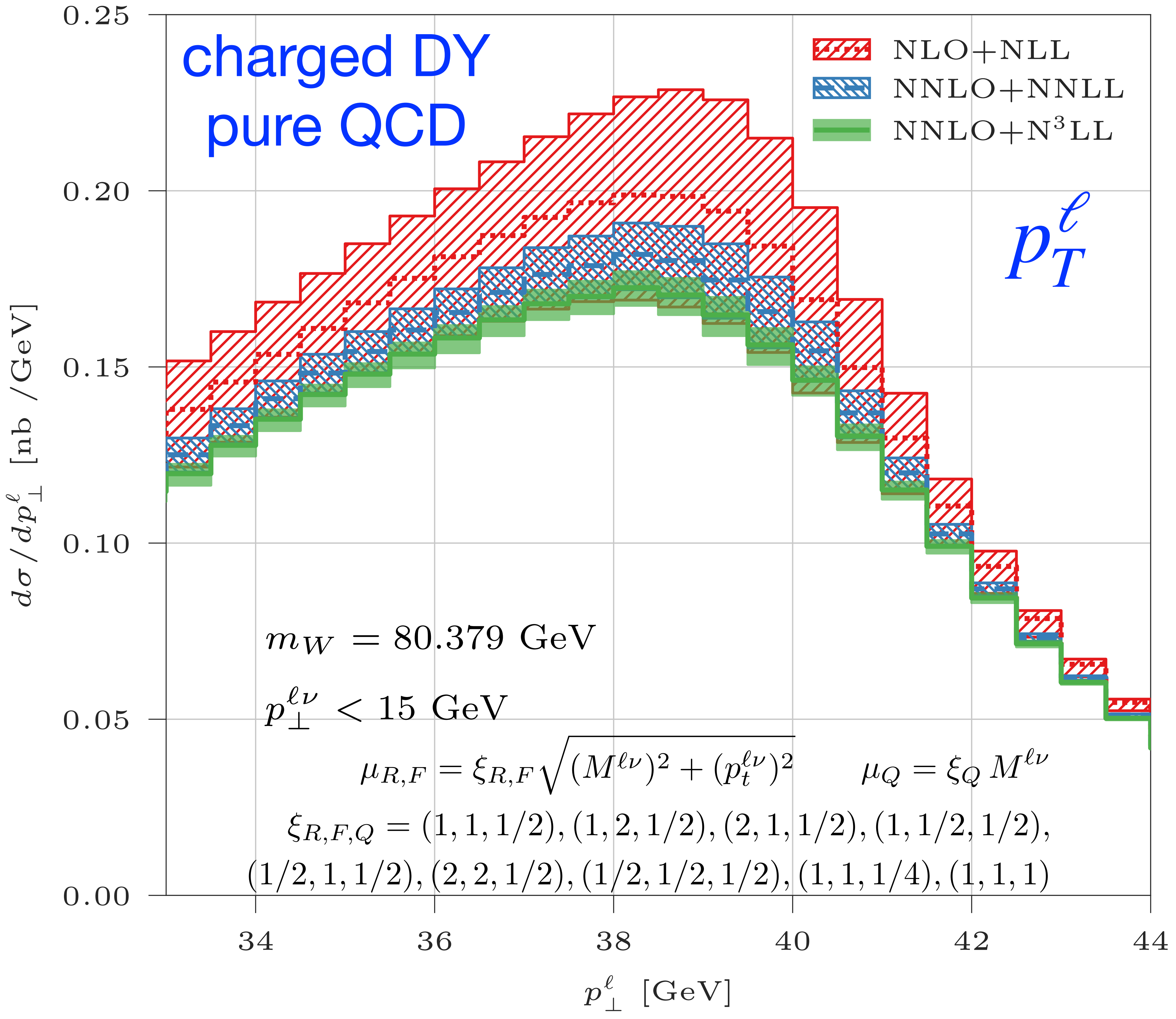


[LHCb 2109.01113]



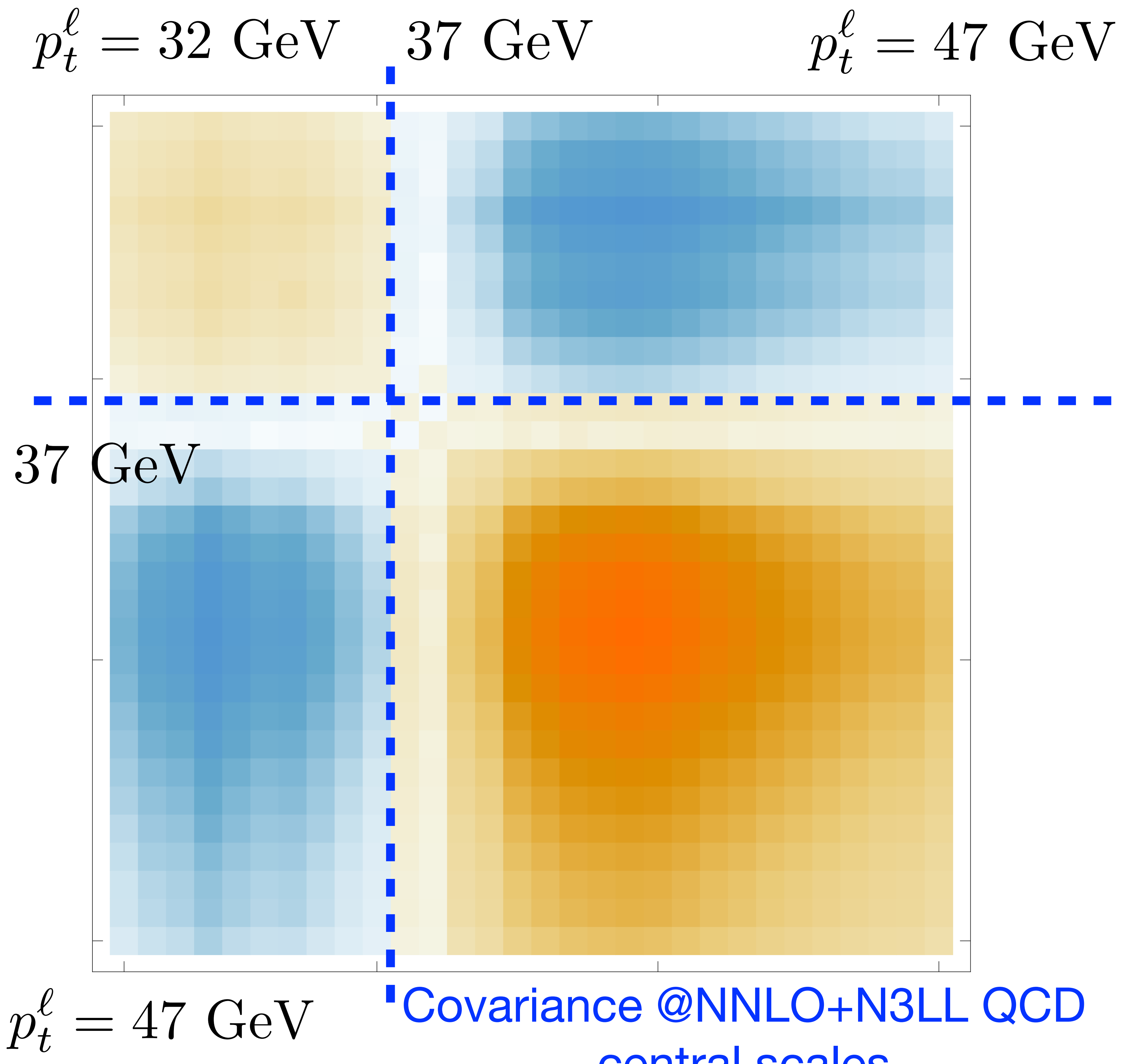
New variable for m_W determination

[Rottoli, PT, Vicini, 2301.04059]

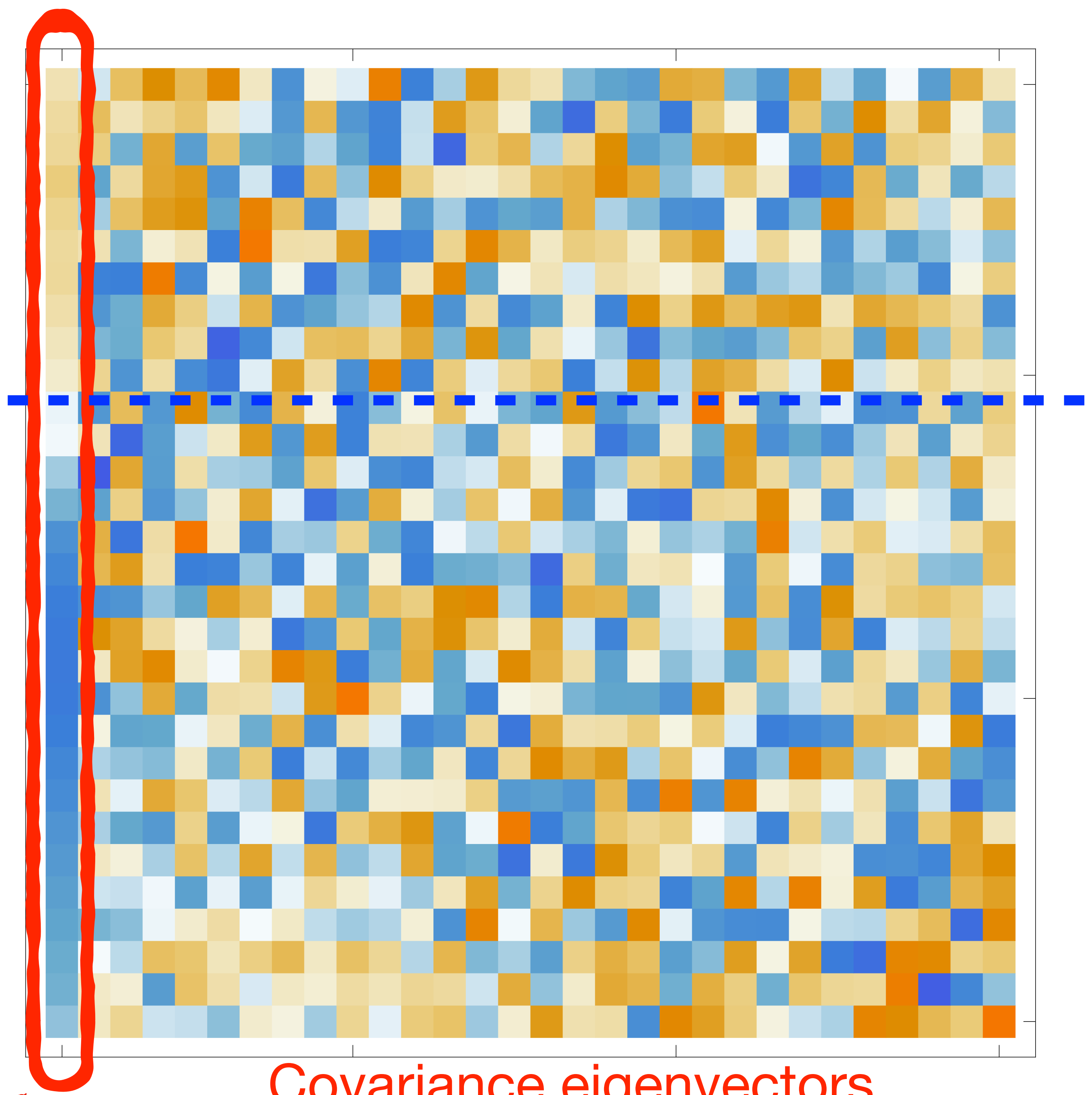


- p_T^ℓ jacobian peak at ~ $m_W/2$
- Sensitivity to m_W of p_T^ℓ bins σ_i through the covariance matrix: $C_{ij} = \langle \sigma_i \sigma_j \rangle - \langle \sigma_i \rangle \langle \sigma_j \rangle$
  $\langle .. \rangle$ = average over different m_W values
- Eigenvalues of C_{ij} yield eigenvectors' sensitivity to m_W

New variable for m_W determination [Rottoli, PT, Vicini, 2301.04059]



Covariance @NNLO+N3LL QCD central scales

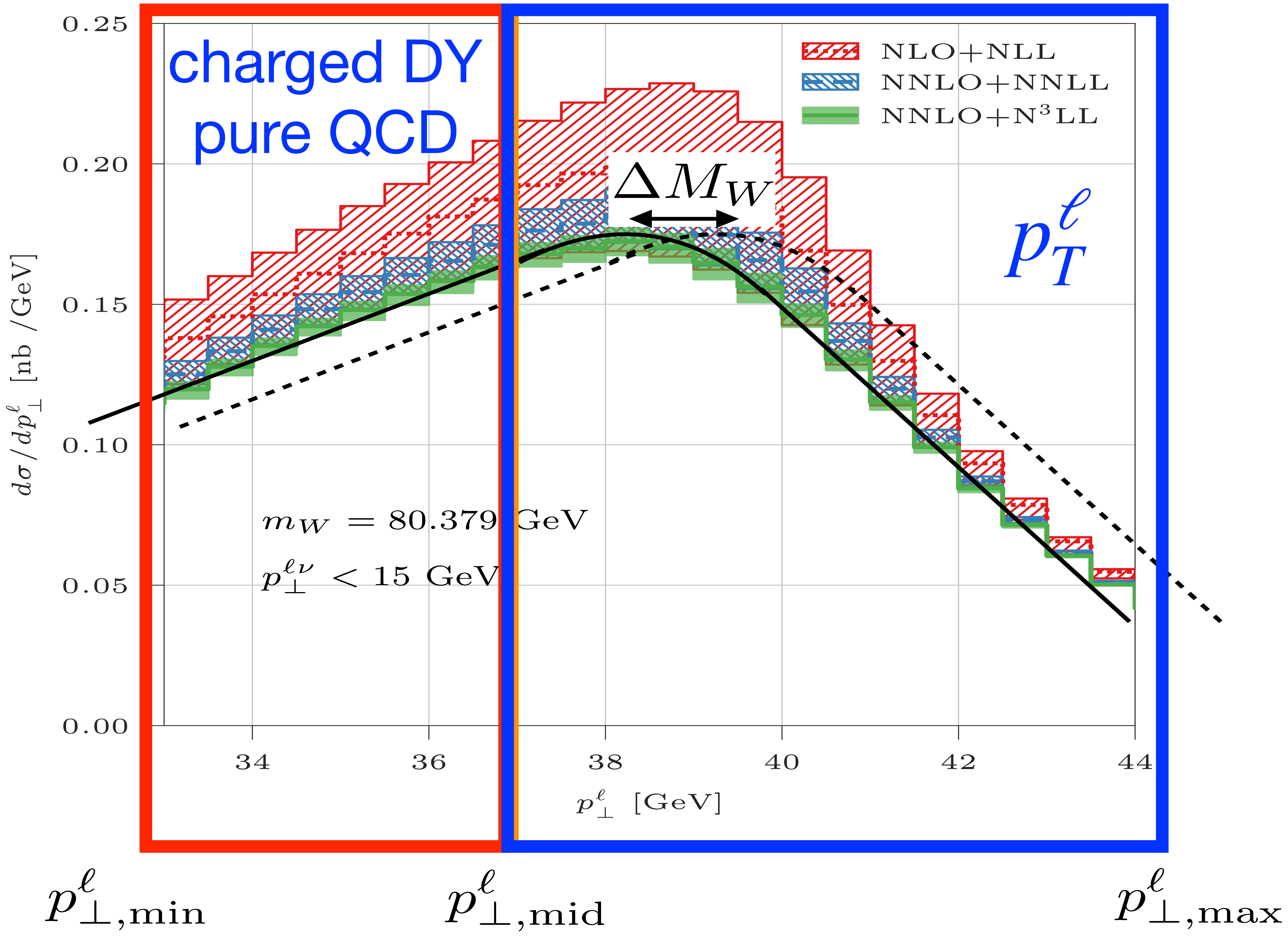


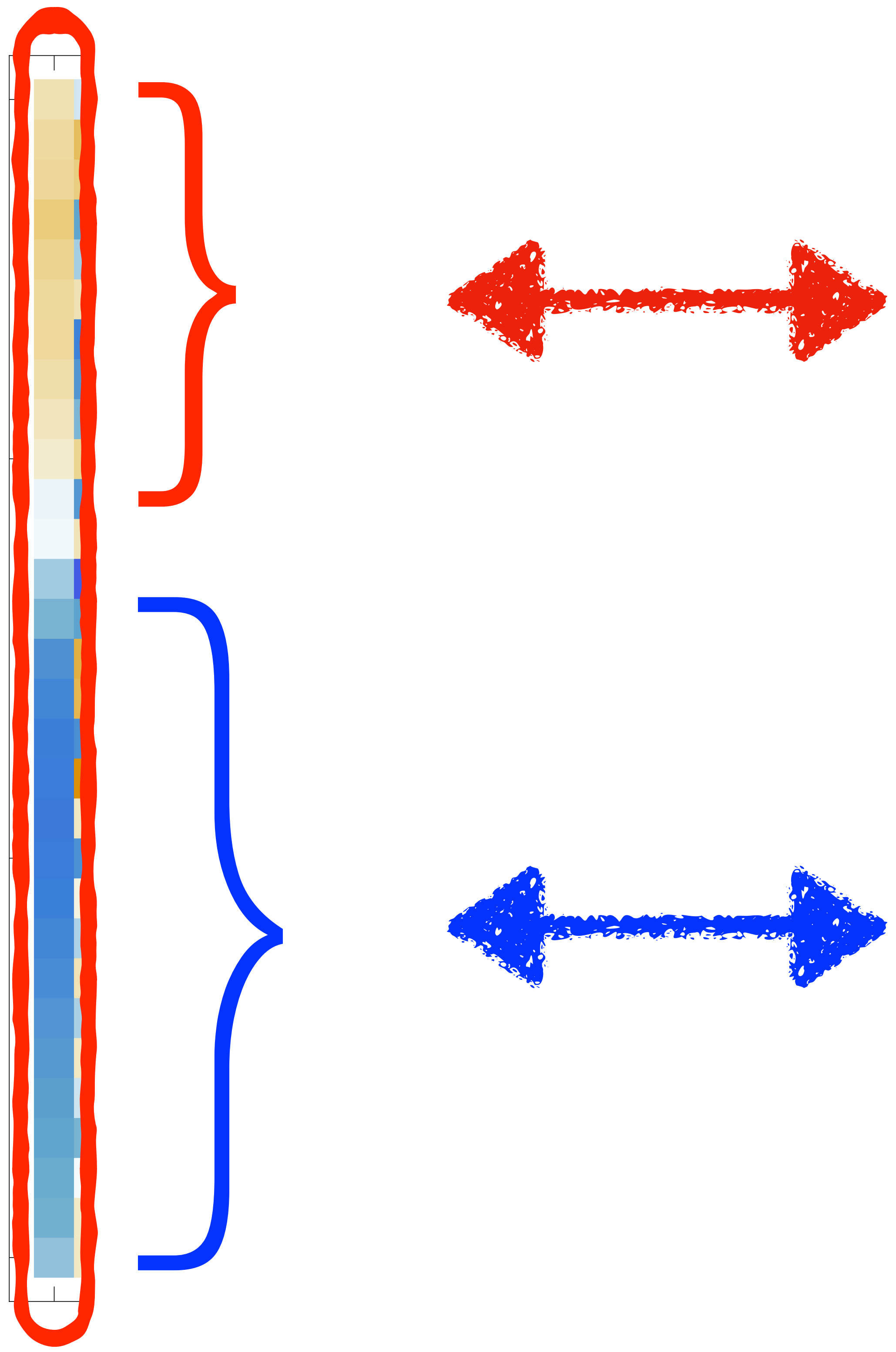
Covariance eigenvectors

- First eigenvalue is ~ 99% of the C_{ij} trace
- Sensitivity to m_W in a single bin combination: Δm_W just causes p_T^ℓ spectrum to shift by $\Delta m_W/2$
- Define a new observable as a proxy for the dominant C_{ij} eigenvector: jacobian asymmetry

Jacobian asymmetry

[Rottoli, PT, Vicini, 2301.04059]





$$L = \int_{p^\ell_{T,min}}^{p^\ell_{T,mid}} \mathrm{d}p_T^\ell \, \frac{\mathrm{d}\sigma}{\mathrm{d}p_T^\ell}$$

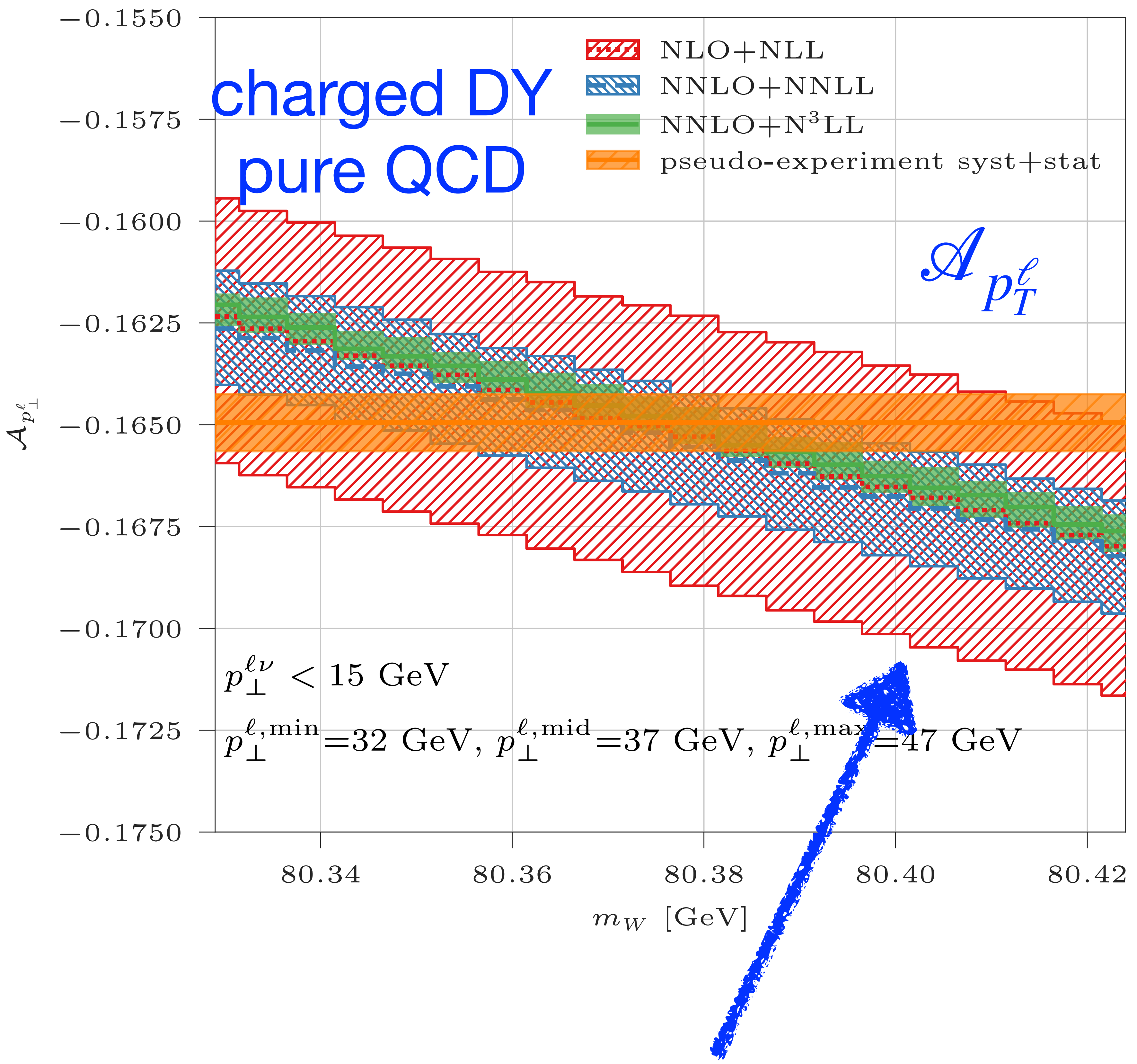
$$U = \int_{p^\ell_{T,mid}}^{p^\ell_{T,max}} \mathrm{d}p_T^\ell \, \frac{\mathrm{d}\sigma}{\mathrm{d}p_T^\ell}$$

$$\mathscr{A}_{p_T^\ell} = \frac{L - U}{L + U}$$

- L / U sum bins below / above ~ 37GeV with + / — sign, mimicking dominant C_{ij} eigenvector

Jacobian asymmetry in perturbative QCD

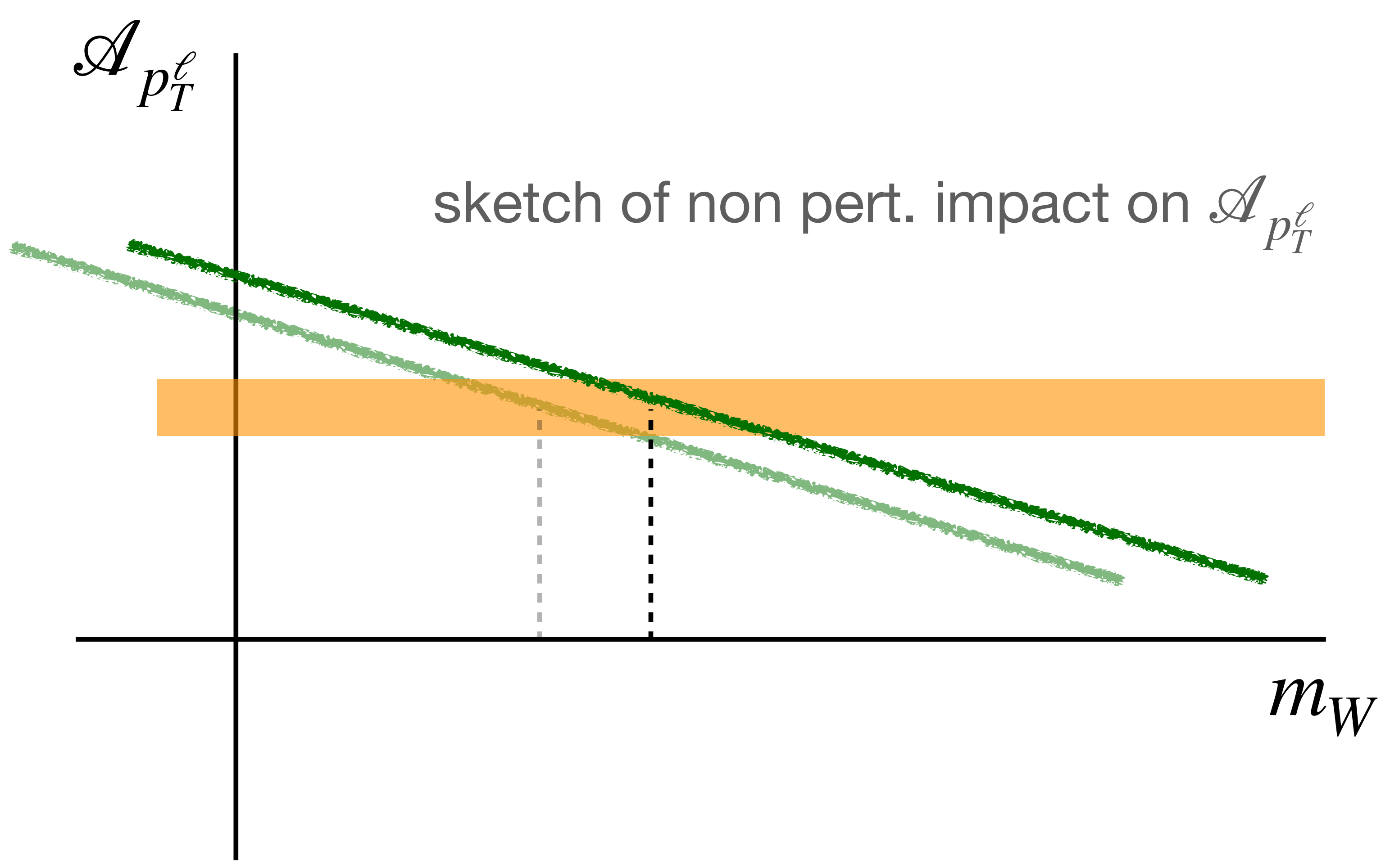
[Rottoli, PT, Vicini, 2301.04059]

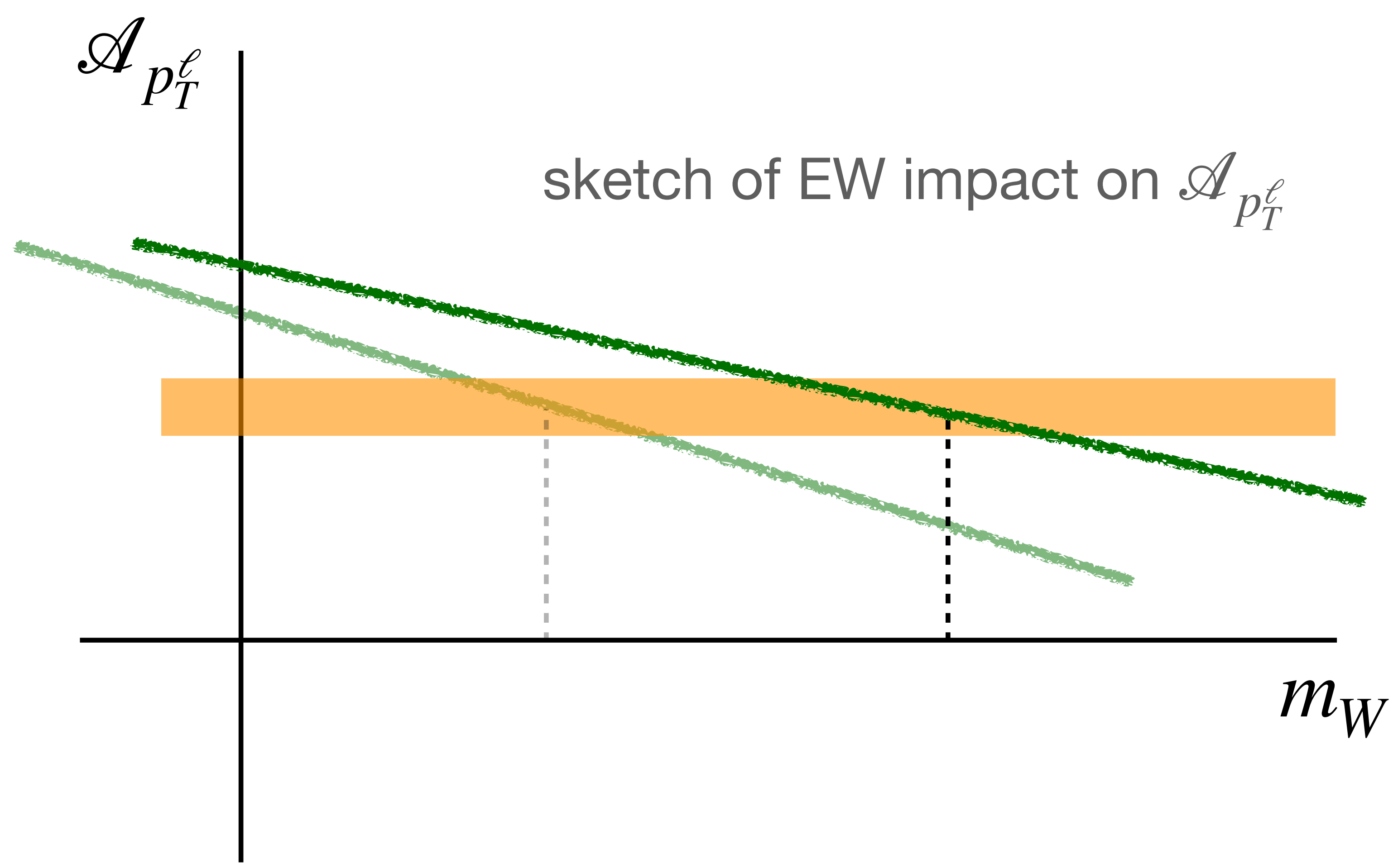


Slope independent of QCD approx / scale choice: QCD ISR factorised from m_W-sensitive propagation / decay

- Excellent perturbative QCD convergence
- Simple combination of fiducial p_T^ℓ rates integrated in wide bins: small systematic/statistical experimental error, viability to unfold detector effects
- Naive estimate: $\Delta m_W \sim \pm$ 15 MeV experimental (syst.), $\Delta m_W \sim \pm$ 5 MeV in perturbative QCD
- m_W determined as the intersection of theo. / expt. straight lines, with their error bands
- Calculated from charged DY: minimal reliance on neutral DY (only via non-perturbative QCD model, when included)

Jacobian asymmetry: expected impact of EW and non-perturbative





- $\mathscr{A}_{p_T^\ell}$ allows to disentangle the impact of non-pert. QCD and of EW effects on m_W extraction
- Non-pert. QCD expected to have a moderate impact on $\mathscr{A}_{p_T^\ell}$ values without affecting slope
- EW effects (mainly QED FSR) expected to significantly affect $\mathscr{A}_{p_T^\ell}$ value (O (100 MeV)) and, less so, its slope

$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: LO Pseudo–data accuracy		M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	 p_T^ℓ	 $W^+ \to e^+\nu$ M_T	 p_T^ℓ
1	HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2	HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3	HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
5	PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

Outlook

- p_T resummation at N3LL' / approx. N4LL in perturbative QCD, accurate comparison with data.
  Non pert. and PDF advances important for $p_T(Z) \to 0$ and for α_s measurement from $p_T(Z)$

- Importance of EW effects for leptonic DY observables.
  High accuracy resummation of QCD+EW effects at the level of fiducial leptons in RadISH

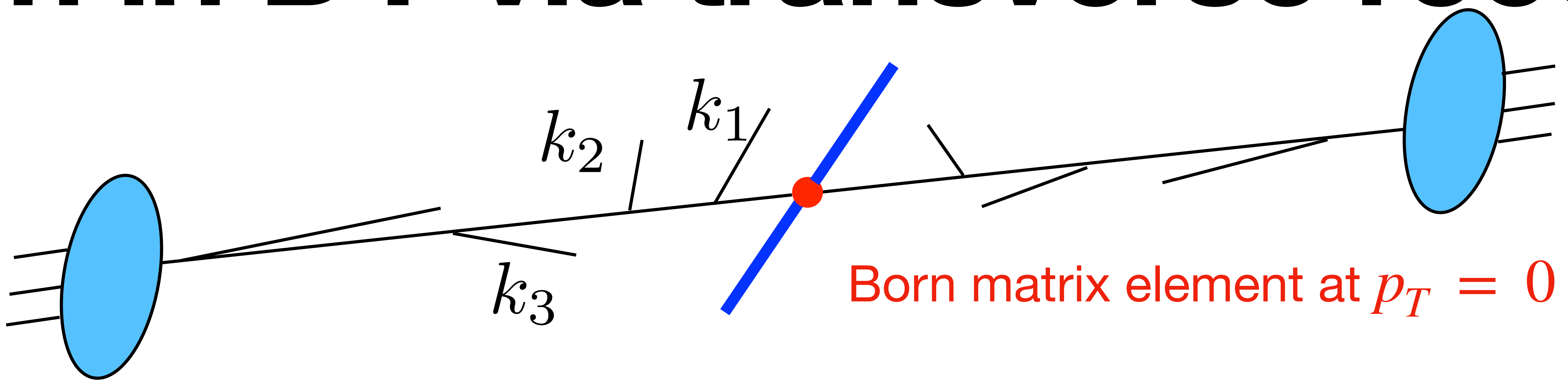
- Jacobian asymmetry for m_W determination.
  Minimal reliance on neutral DY (i.e. no tuning), clean disentangling of different effects contributing to m_W dependence

Thank you for your attention

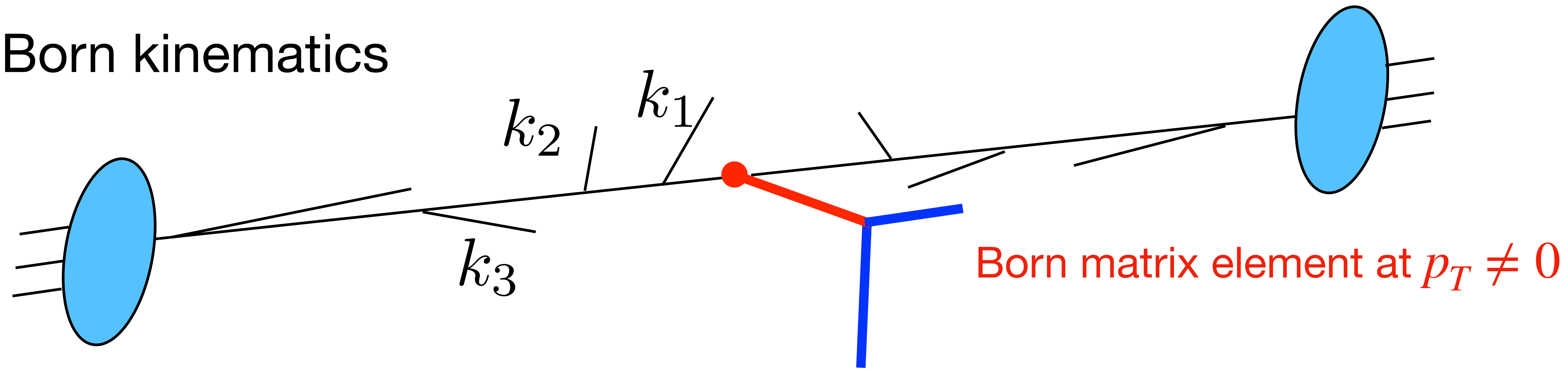
Backup

NLP resummation in DY via transverse recoil

- Leading-power p_T resummation



- Including next-to-leading power: recoil prescription [Catani et al., 1507.06937]
  - generate p_T by QCD initial-state radiation
  - boost Born kinematics from V rest frame to frame with that p_T
  - apply fiducial cuts on boosted Born kinematics



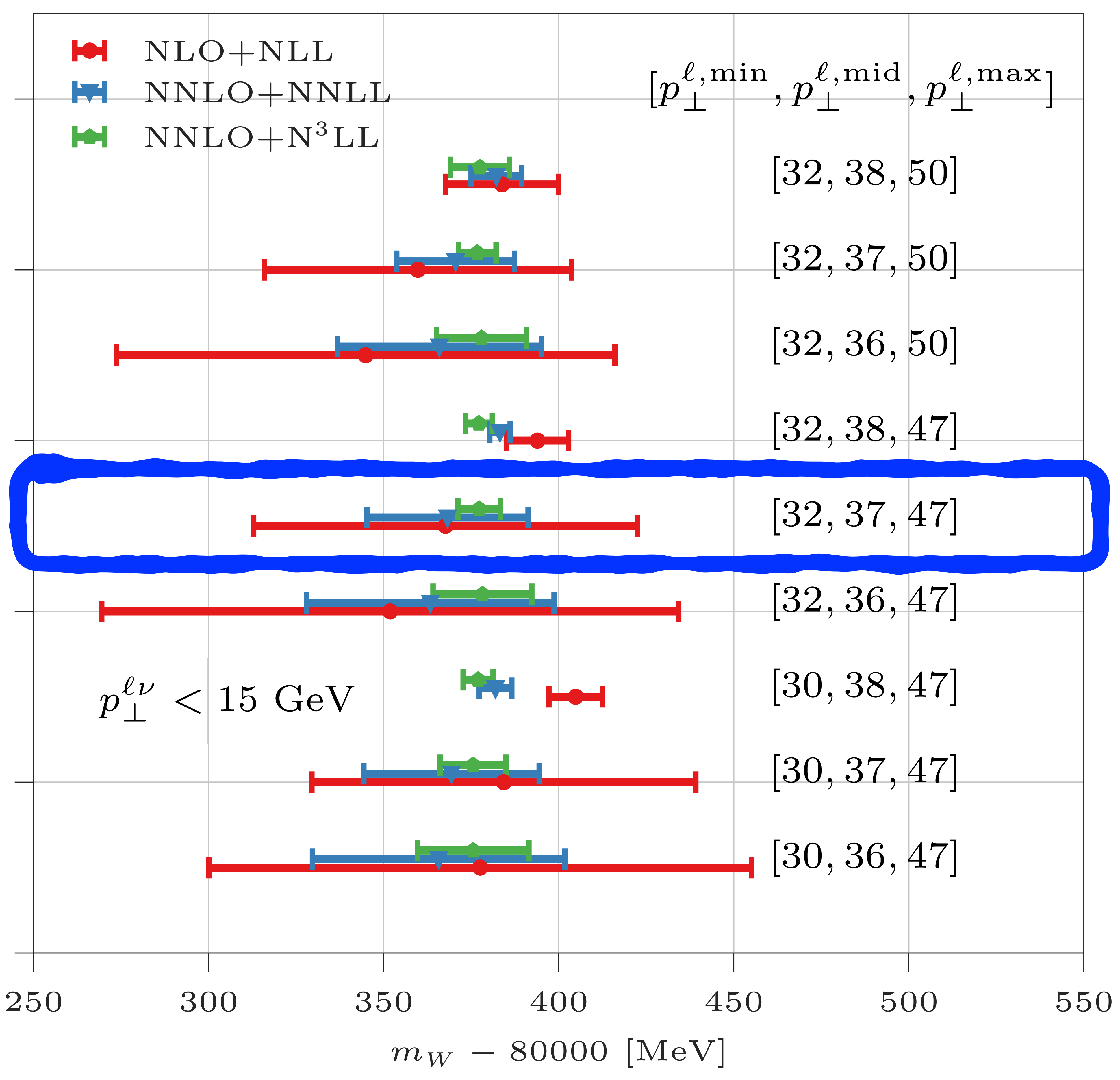
- Sufficient to resum all linear fiducial power corrections in p_T in the QCD corrections to DY [Ebert et al., 2006.11382]

RadISH vs POWHEG-EW

[Buonocore, Rottoli, PT, 2404.15112]

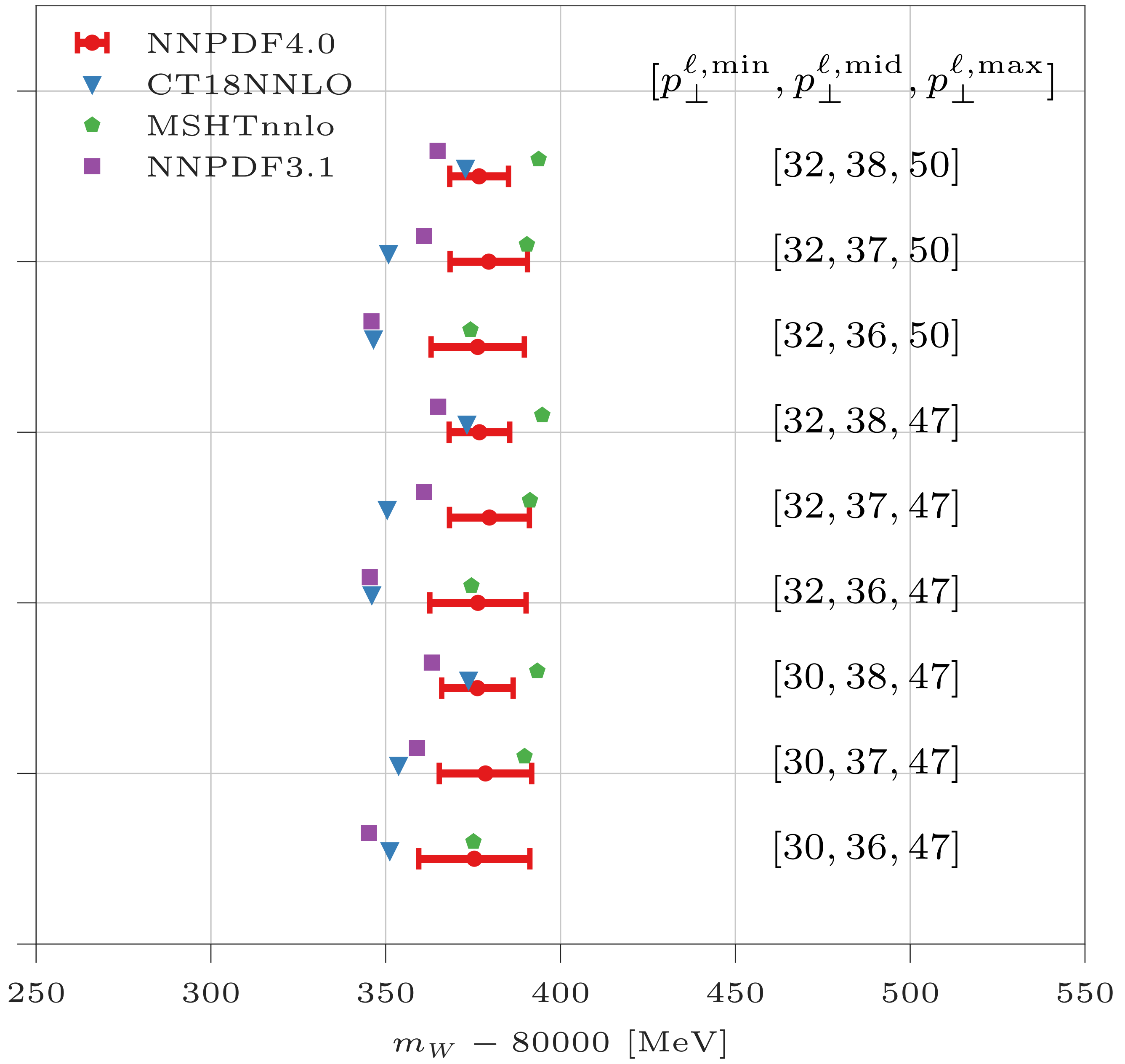
- POWHEG-EW ([Barzè et al., 1202.0465, 1302.4606, …], pink) at approx. NLL’+NLO QCD+EW. General agreement with RadISH but some shape distortion at the jacobian peak $p_T^\ell \sim m_W/2$ and no matching systematics
- Ratio observable (crucial for m_W): nice perturbative stability from RadISH, similar to POWHEGBOX+QED shower (brown), while POWHEG-EW displays more significant discrepancy

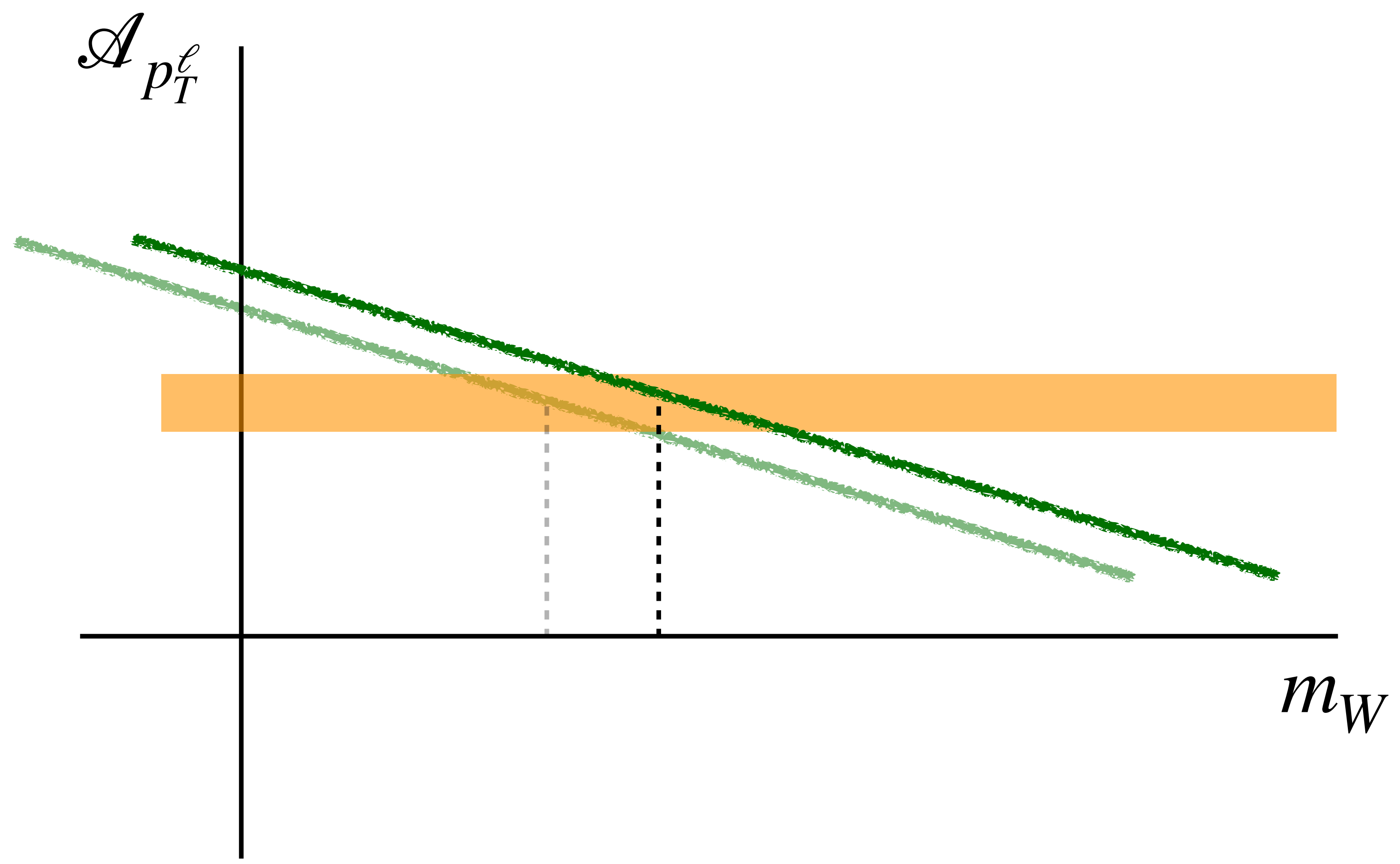
Jacobian asymmetry: dependence on bin edges



- Very good perturbative QCD convergence across different bin-edge choices
- Importance of N3LL resummation to establish perturbative convergence beyond mere scale variations
- Trade-off between sensitivity (improving at higher $p_\perp^{\ell,\mathrm{mid}}$) and perturbative convergence (improving at lower $p_\perp^{\ell,\mathrm{mid}}$)

Jacobian asymmetry: dependence on PDFs





- Variations from 100 NNPDF4.0 NNLO replicas on NLL+NLO result: $\Delta m_W \sim \pm 12$ MeV
  Spread from 3 other NNLO PDF sets (central replica) on N3LL+NNLO: $\Delta m_W \sim$ 30 MeV
- Asymmetry slope unaffected: factorisation of initial-state effects from W propagation / decay
- PDF spread can be reduced to few MeV using additional p_T^ℓ bins, anti-correlation of different rapidity windows [Bozzi, Citelli, Vesterinen, Vicini, 2015; Bagnaschi, Vicini 2019], combination of W^+ / W^-

Jacobian asymmetry: toy non perturbative study

- $p_T(Z)$ K-factors from NNLL (templates) to N3LL (pseudo-data): mimic tuning. One K-factor per scale variation
- Reweigh NNLL $p_T(W)$ templates with those K-factors and compare with N3LL $p_T(W)$ pseudo-data
- Uncertainty on m_W is not reduced after reweighing
- Importance of accurate perturbative starting point to assess impact of tuning on m_W extraction
- Asymmetry allows to study non-pert. impact separately from other sources (e.g. EW). Slope unaffected