pT resummation in Dell-Yan production and a new observable for mW measurements

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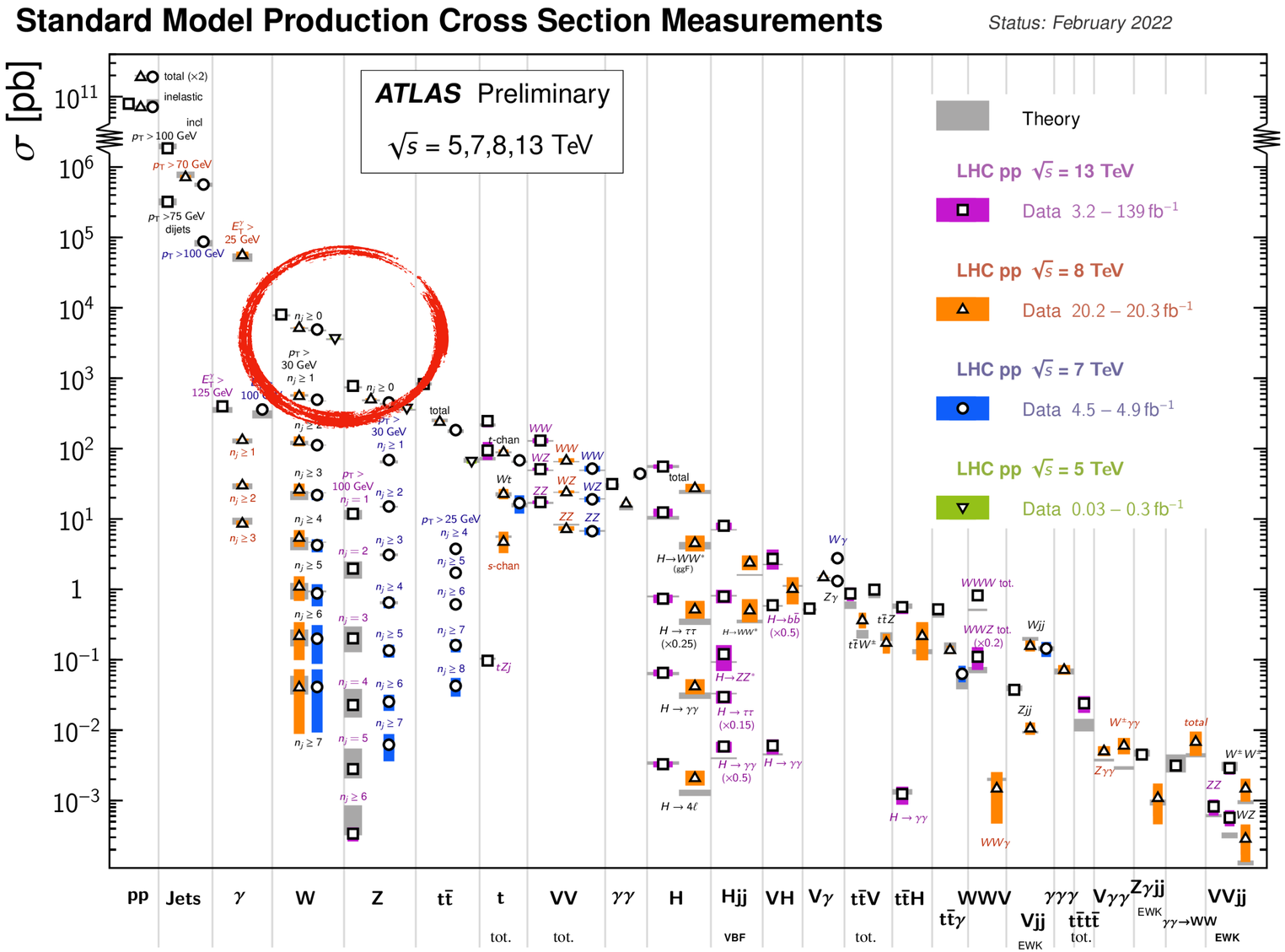
Drell-Yan @LHC



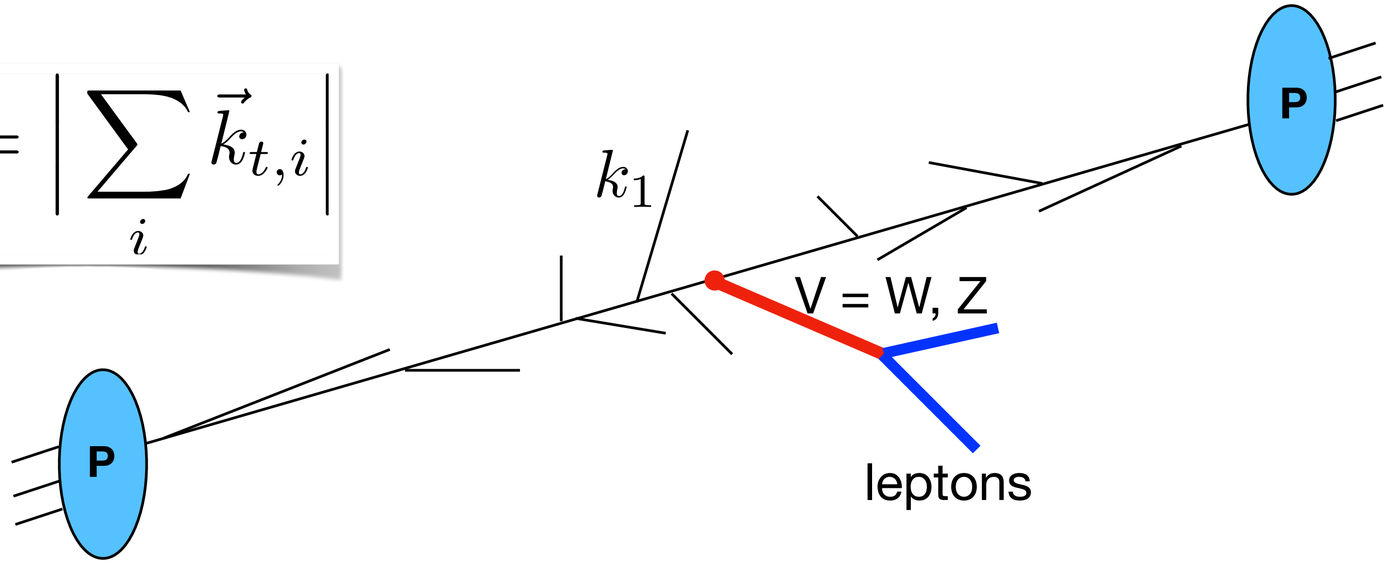
Standard candle process at the LHC

Large cross section and clean signature due to hard charged lepton

Allows experimental measurements and theoretical predictions of the highest precision

Drell-Yan @LHC

$$p_T = \left| \sum_i \vec{k}_{t,i} \right|$$



- Fixed-order DY computations reliable only for large values of pT ~ M
- Large soft/collinear log(pT/M) arising when pT << M
- All-order resummation of log(pT/M) needed

Outline

- State-of-the-art pT resummation in QCD
- Fiducial N3LO DY cross sections from pT resummation
- Inclusion of EW effects in pT resummation
- New observable for mW determination

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pT resummation in Drell-Yan

- Variety of frameworks to perform pT resummation: b-space / momentum space, QCD / SCET, TMD
- Nowadays N3LL' QCD accuracy, i.e. $\alpha s^{n} \log(pT/M)^{n-2}$ and $\alpha s^{n} \log(pT/M)^{2n-6}$
- Some ingredients known at N4LL QCD, i.e. $\alpha s^{n} \log(pT/M)^{n-3}$

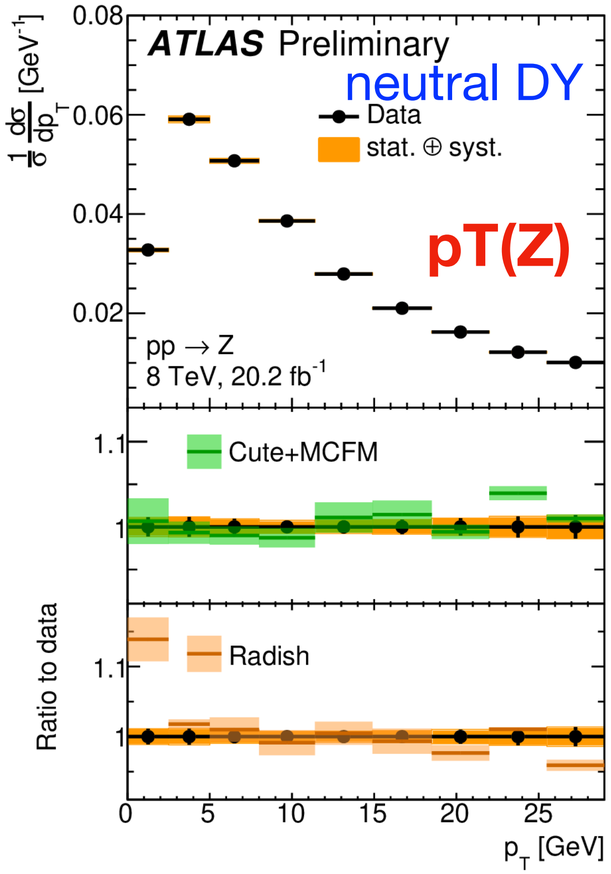
[Cute+MCFM: Becher, Campbell, Neumann, et al.; RadISH: Monni, Re, Rottoli, PT; NangaParbat: Bacchetta, Bertone, Bozzi, et al.; Artemide: Scimemi, Vladimirov; DYTurbo: Catani, Grazzini, Ferrera, Cieri, Camarda, et al.; SCETlib: Billis, Ebert, Michel, Tackmann, et al.; reSolve: Coradeschi, Cridge; Resbos: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

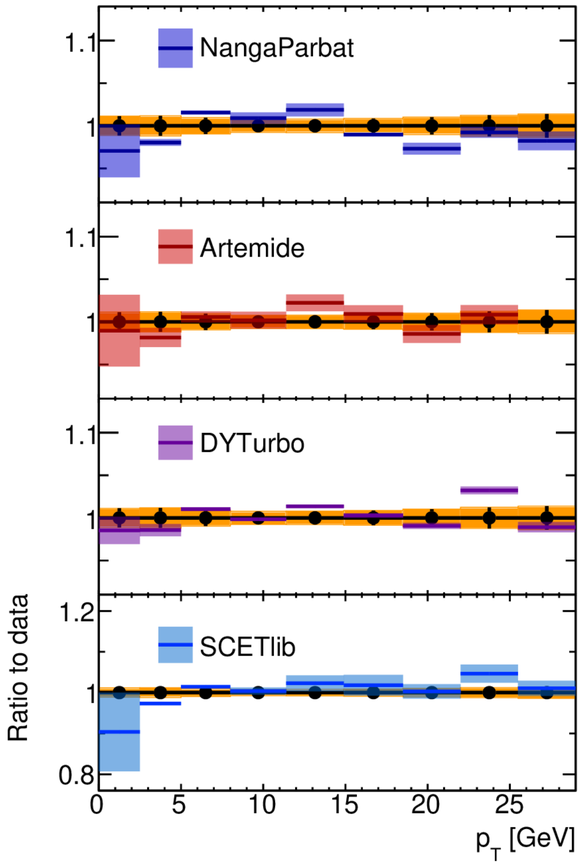
pT spectrum in Drell-Yan @LHC

- pT(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
- Non-perturbative advances would be needed to improve description below 5 GeV
- Impact of aN3LO PDFs to be carefully assessed

-> see also T. Cridge's talk

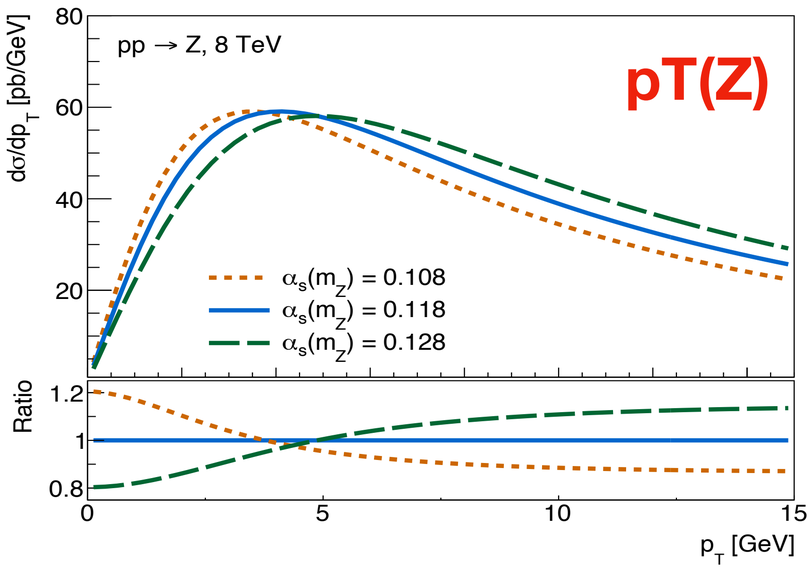
[ATLAS-CONF-2023-013]

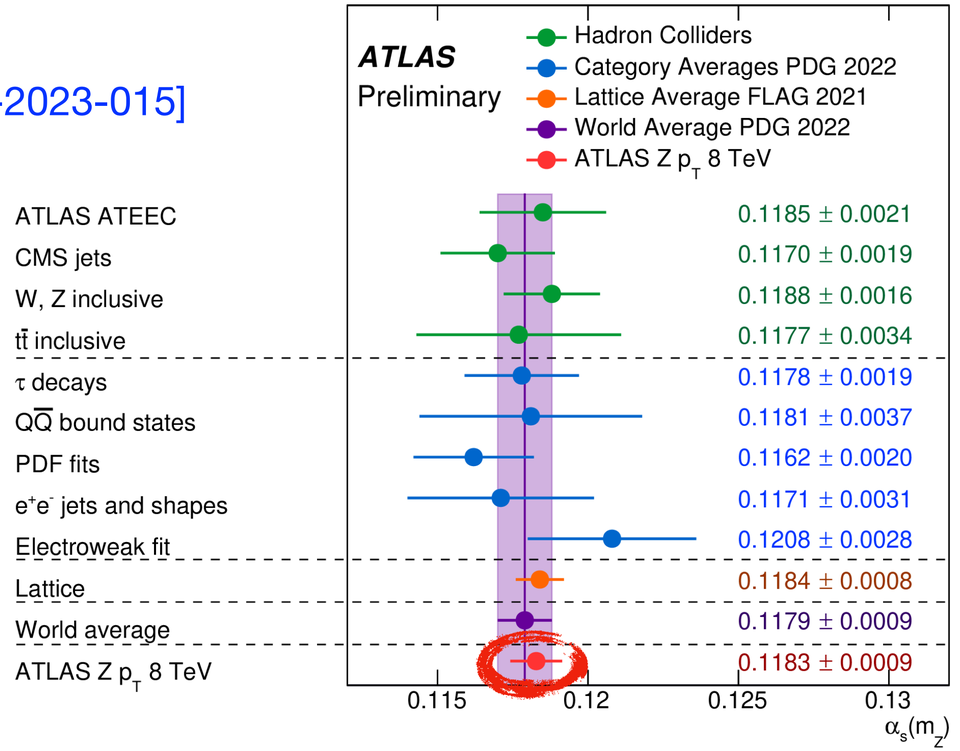




alphas from resummed pT in Drell Yan

[ATLAS-CONF-2023-015]





- αs precisely extracted from resummed pT(Z) spectrum by ATLAS

-> see also M. Corradi's talk

- Uses aN3LO MSHT20 PDFs [MSHT 2207.04739]

- Studies on PDF and non-pert. correlations with αs needed to build confidence in the quoted uncertainty

- State-of-the-art pT resummation in QCD
- Fiducial N3LO DY cross sections from pT resummation
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- New observable for mW determination

qT subtraction [Catani, Grazzini, 0703012]

differential pT spectrum at NNLO QCD

$O(\alpha s^3)$ expansion of pT resummation

$$d\sigma_{DY}^{\mathrm{N^3LO}} = \mathcal{H}_{DY}^{\mathrm{N^3LO}} \otimes d\sigma_{DY}^{\mathrm{LO}} + \left(d\sigma_{DY+1j}^{\mathrm{NNLO}} - \left[d\sigma_{DY}^{\mathrm{N^3LL}} \right]_{\alpha_s^3} \right) \Theta(p_t > p_t^{cut}) + \mathcal{O}\left((p_t^{cut}/M)^n \right)$$

$O(\alpha s^3)$ δ(pT) terms from N3LL' pT resummation

Power corrections

- Linear fiducial power corrections with standard experimental cuts, numerically challenging

qT subtraction [Catani, Grazzini, 0703012]

differential pT spectrum at O(αs^3)

O(αs^3) expansion of pT resummation

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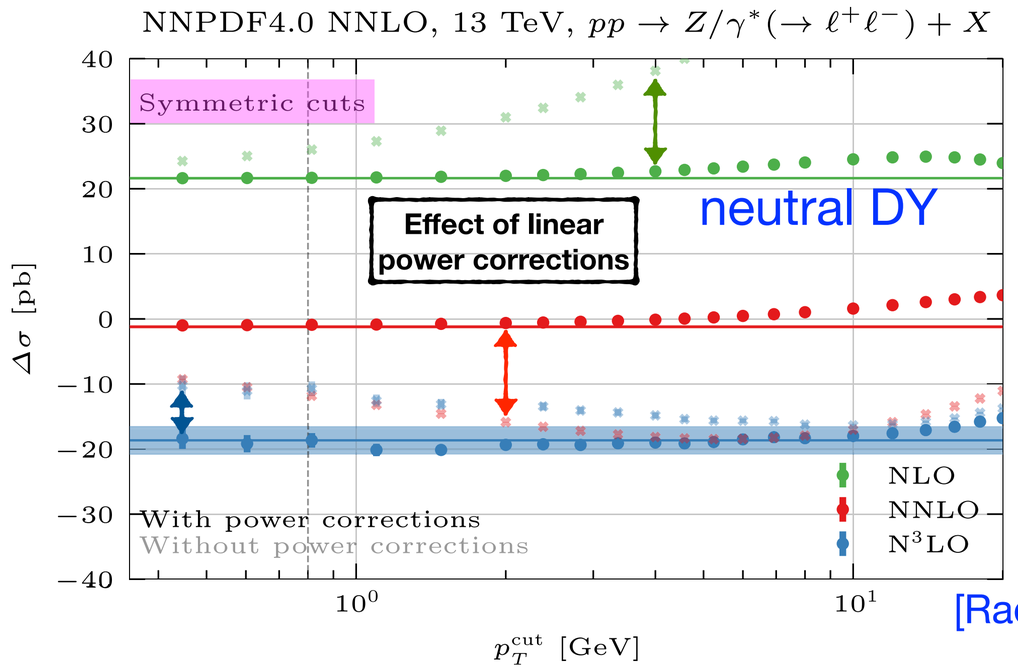
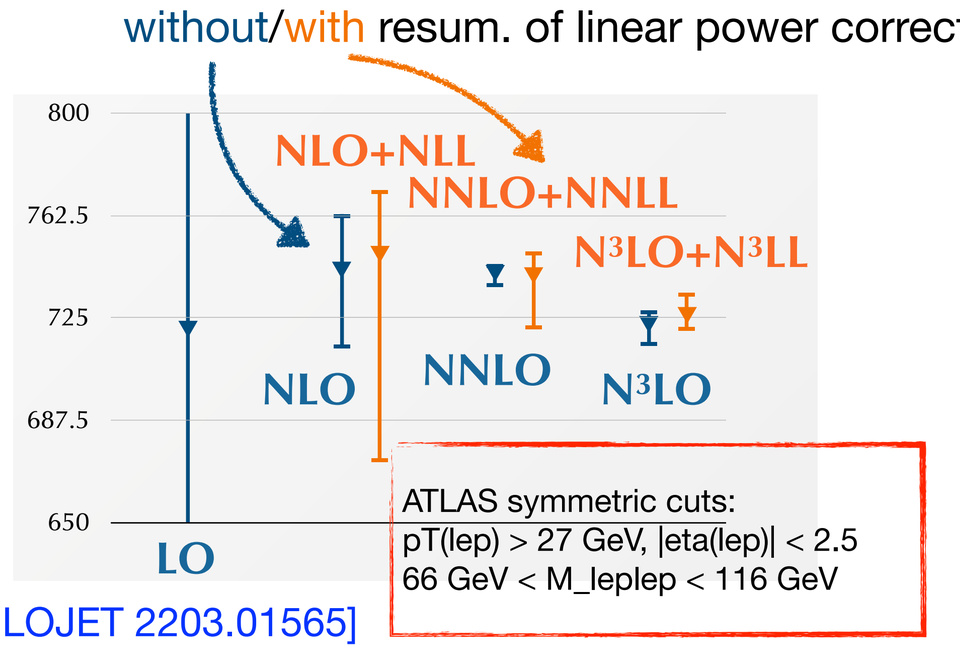
O(αs^3) δ(pT) terms from N3LL' pT resummation

Power corrections

- Linear fiducial power corrections with standard experimental cuts, numerically challenging
- Can be reduced to quadratic $(pTcut/M)^2$ by using different cuts: staggered [Grazzini, Kallweit, Wiesemann, 1711.06631], product [Salam, Slade, 2106.08329]
- Alternatively, include transverse recoil in the resummation [Catani et al. 1507.06937, Ebert et al. 2006.11382] or in the expansion [Buonocore, et al. 2111.13661, Camarda, Cieri, Ferrera, 2111.14509]

N3LO QCD DY fiducial





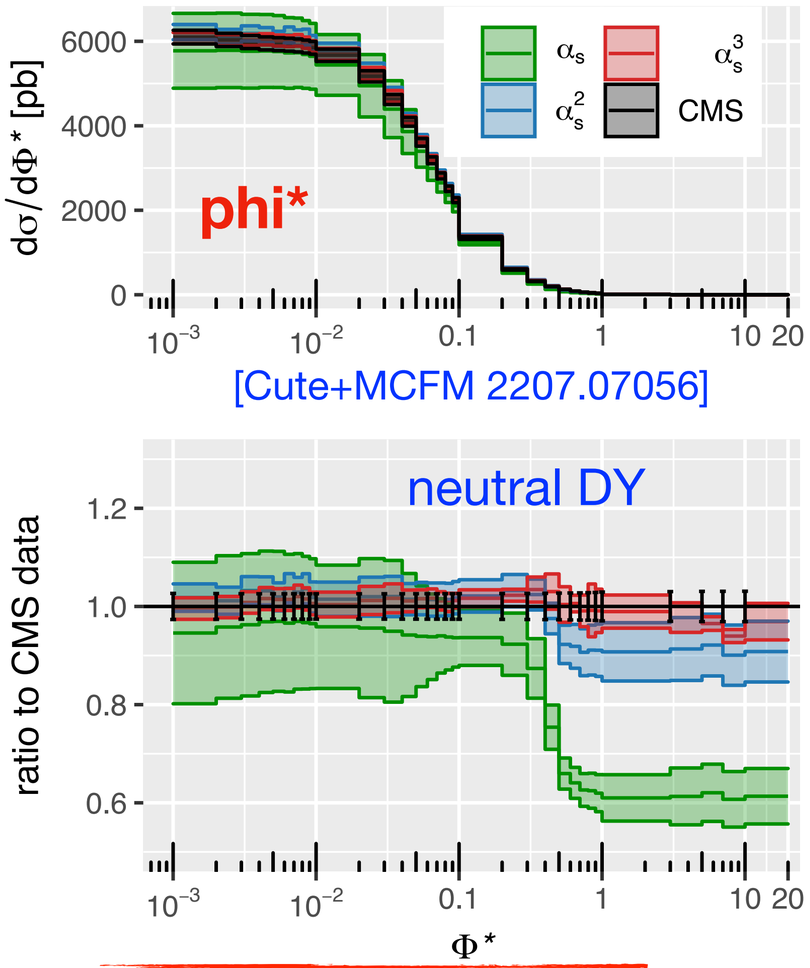
[RadISH+NNLOJET 2203.01565]

- Recoil crucial to tame linear power corrections
- Resummation of linear power corrections through recoil yields robust uncertainty estimate
- Results here with NNLO PDFs, impact of aN3LO PDF [MSHT 2207.04739, NNPDF 2402.18635]

-> see also M. Grazzini's talk

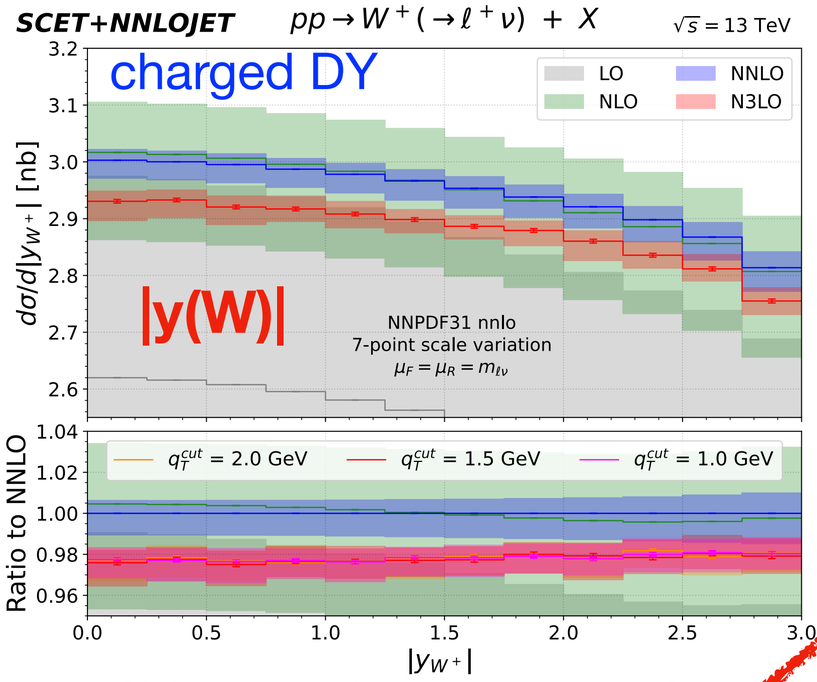
- N3LO QCD fiducial DY results nowadays available in different frameworks, see e.g. [DYTurbo 2103.04974, SCET+NNLOJET 2107.09085, Cute+MCFM 2207.07056]

N3LO QCD DY differential

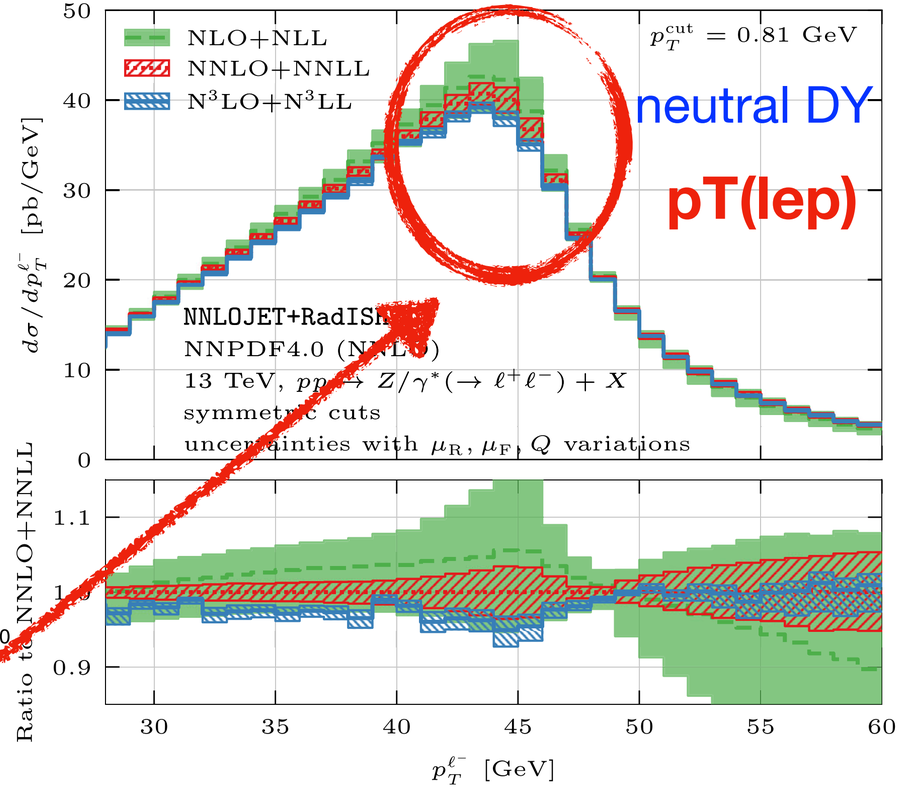


[Cute+MCFM 2207.07056]

CMS symmetric cuts:
pT(lep) > 25 GeV, |eta(lep)| < 2.4
76.2 GeV < M_leplep < 106.2 GeV
|y_leplep| < 2.4



[SCET+NNLOJET, 2205.11426]



[RadISH+NNLOJET, 2203.01565]

ATLAS symmetric cuts:
pT(lep) > 27 GeV, |eta(lep)| < 2.5
66 GeV < M_leplep < 116 GeV

Fixed-order integrable singularity at pT(lep) ~ mZ/2 cured by resummation

[Catani, Webber, 9710333]: no sensible fixed-order description!

- State-of-the-art pT resummation in QCD
- Fiducial N3LO DY cross sections from pT resummation
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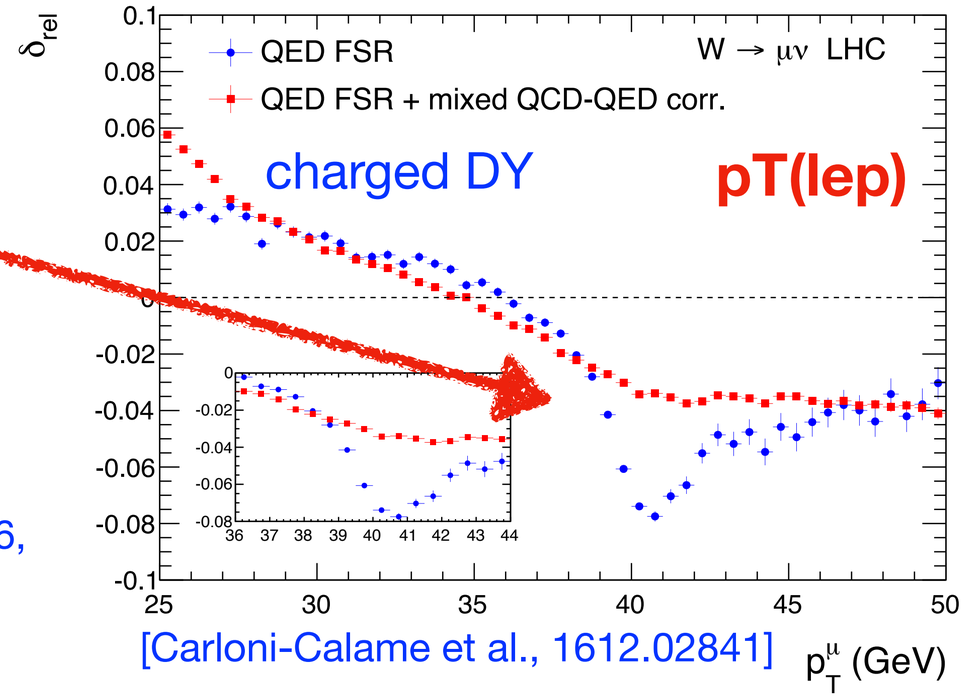
EW effects on precision DY observables

- 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, …], general LO+PS event generators, NLO+PS POWHEG-EW [Bernaciak, Wakeroth, 1201.4804, Barzè et al., 1202.0465, 1302.4606, …]



[Carloni-Calame et al., 1612.02841]

-> see also S. Schumann's talk

-> see also A. Vicini's talk

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)

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

Luminosity: now including O(α) and O(αs α) constants + photon-initiated channel

Radiator: now with all $\alpha s^{m} \alpha^{n} \log(pT/M)^{n+m}$ terms (+ some subleading), including also soft wide-angle radiation from leptons, acquiring dependence on Φ_B

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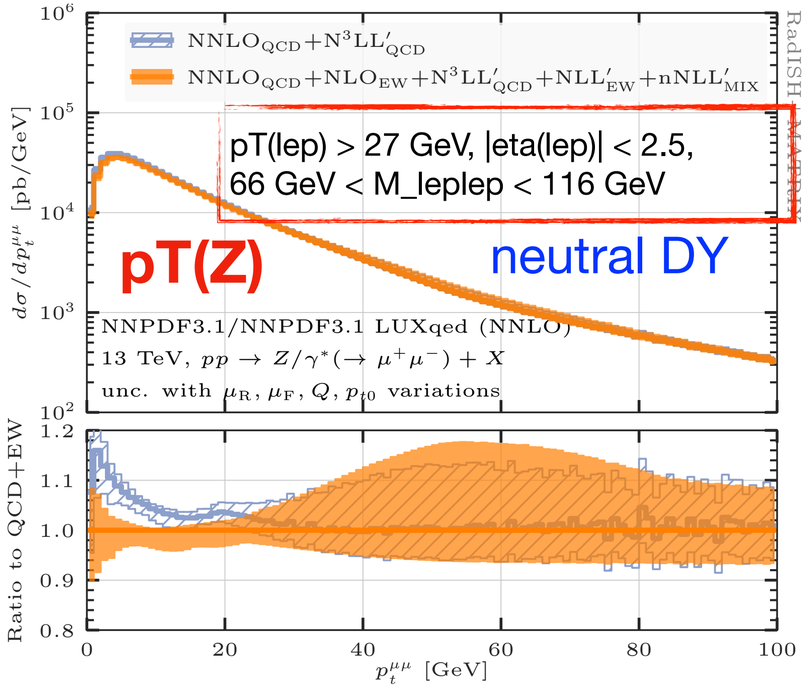

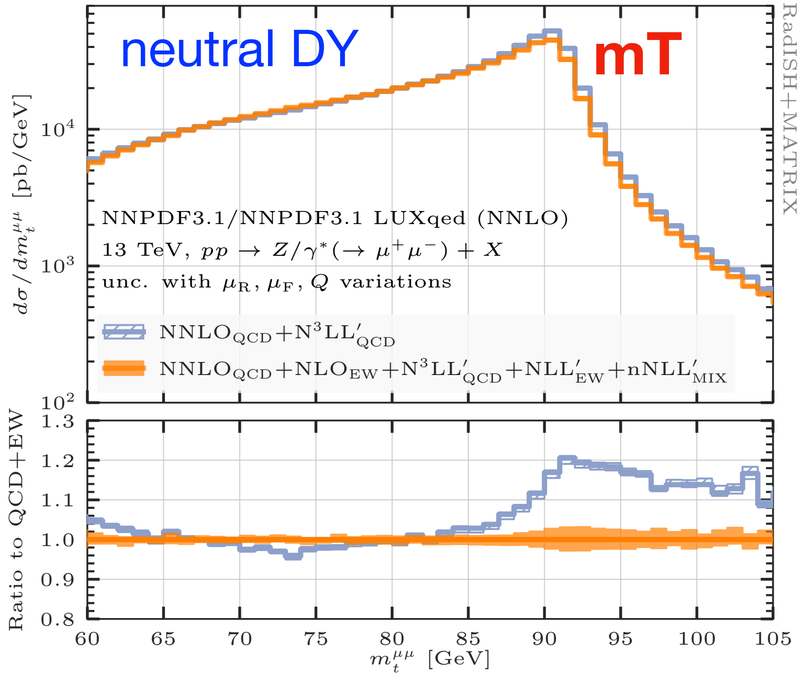

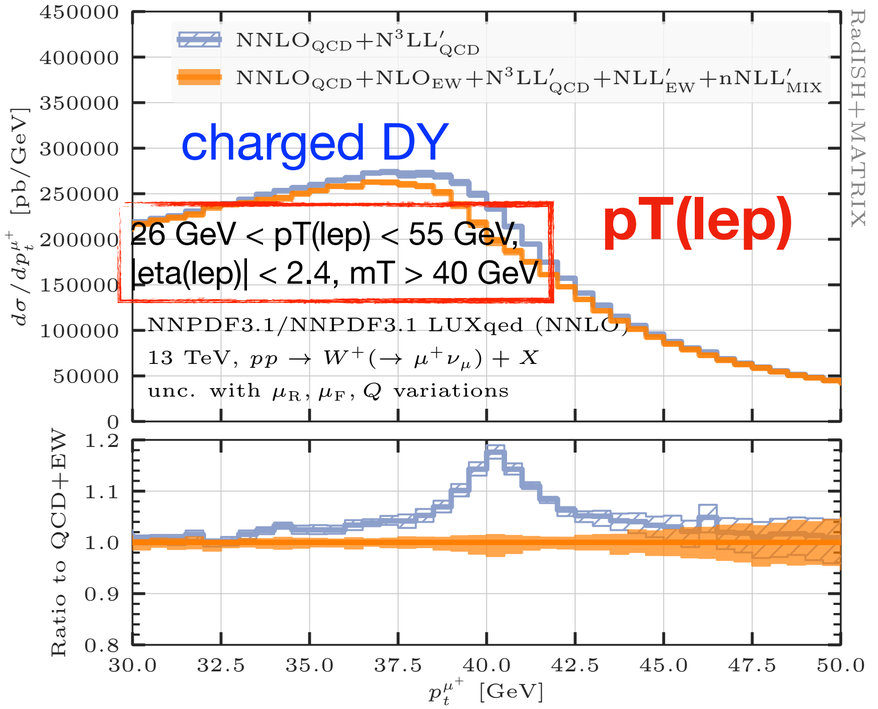

- Large EW effects on top of QCD at small pT(Z) and around jacobian peak of mT and pT(lep)
- Accurate comparison with data possible without subtraction of EW effects from the latter
- Mixed O(αs α) from fixed order not included: it will have a numerical effect (bare muons)

- State-of-the-art pT resummation in QCD
- Fiducial N3LO DY cross sections from pT resummation
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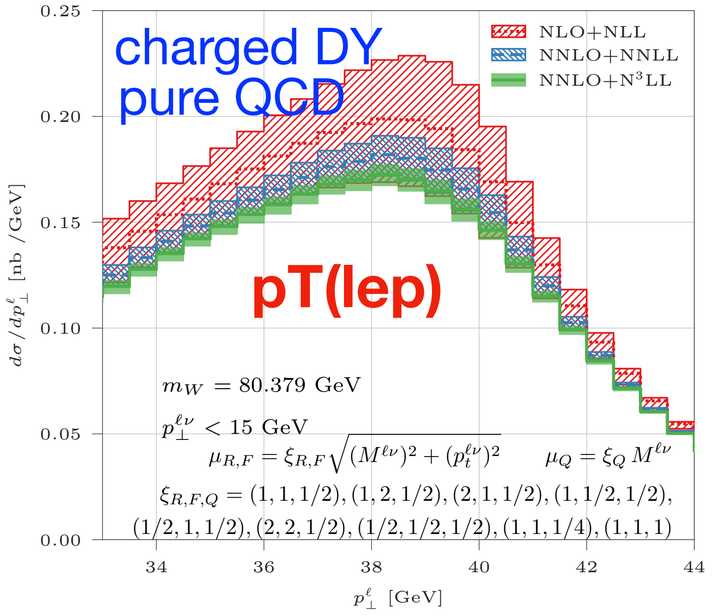
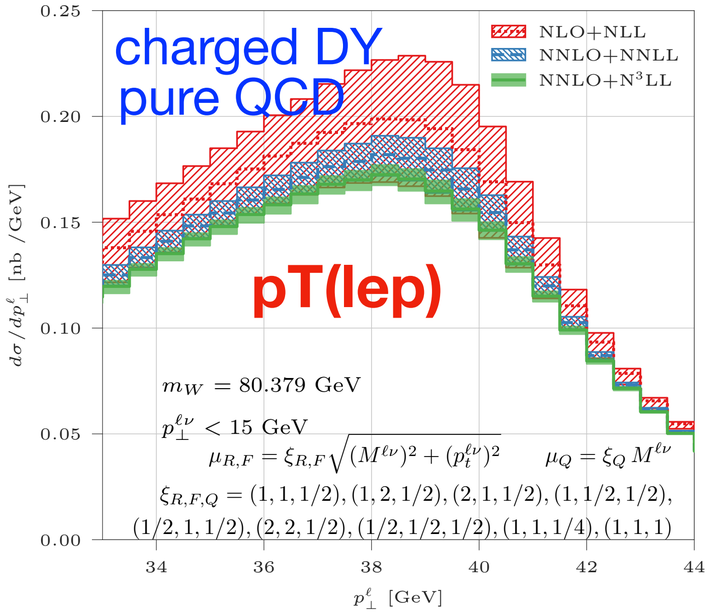
- New observable for mW determination

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



- pT(lep) jacobian peak at ~ mW/2
- Sensitivity to mW of pT(lep) bins σi through covariance matrix: Cij = <σi σj> - <σi> <σj>, with <..> = average over mW values
- Eigenvalues of Cij yield eigenvectors' sensitivity to mW

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



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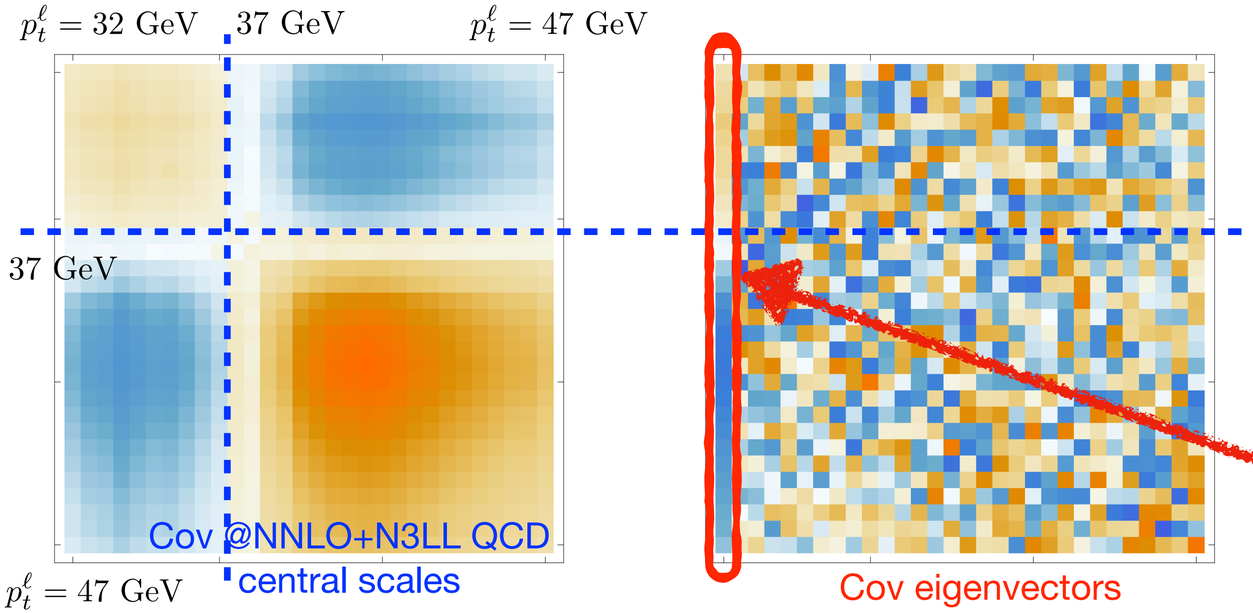
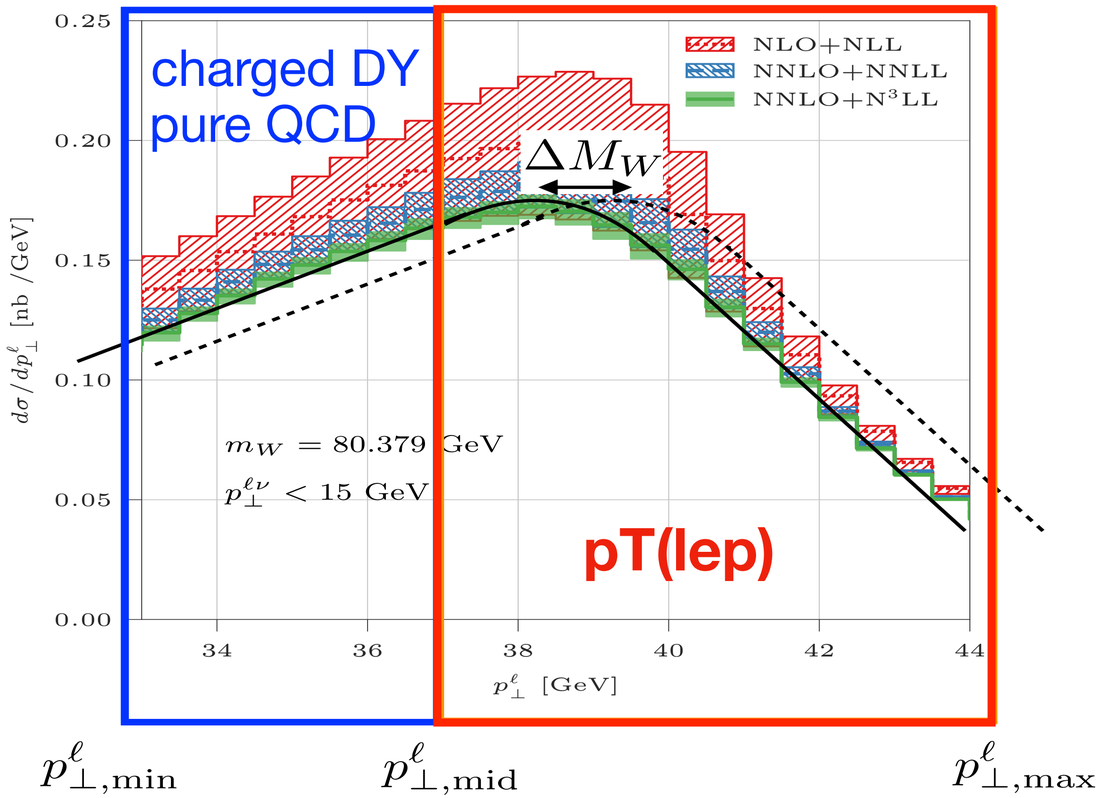


- First eigenvalue ~ 99% of Cij trace
- Sensitivity in a single bin combination: ΔmW just causes spectrum to shift by ΔmW/2
- Jacobian asymmetry: a proxy for the dominant Cij eigenvector

Jacobian asymmetry [Rottoli, PT, Vicini, 2301.04059]

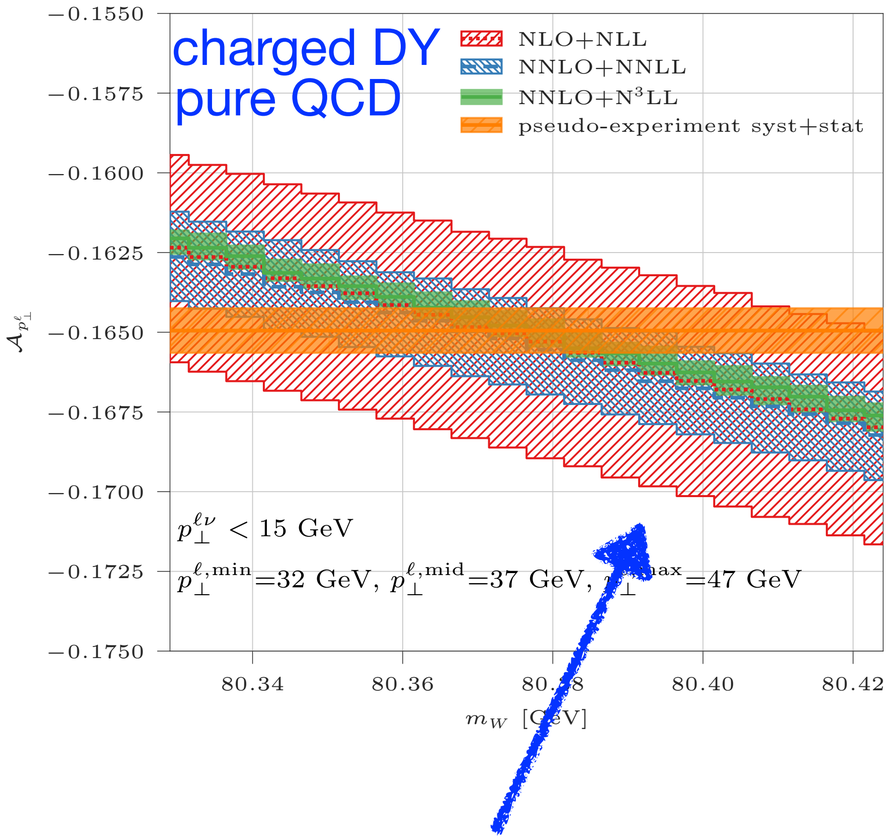


$$\mathcal{A}_{p_t^\ell} = \frac{L - U}{L + U}$$

$$L = \int_{p_{\perp,\mathrm{min}}^\ell}^{p_{\perp,\mathrm{mid}}^\ell} \mathrm{d}p_t^\ell \, \frac{\mathrm{d}\sigma}{\mathrm{d}p_t^\ell} \qquad U = \int_{p_{\perp,\mathrm{mid}}^\ell}^{p_{\perp,\mathrm{max}}^\ell} \mathrm{d}p_t^\ell \, \frac{\mathrm{d}\sigma}{\mathrm{d}p_t^\ell}$$

- L / U sum bins below / above ~ 37GeV with + / — sign, mimicking dominant Cij eigenvector

Jacobian asymmetry [Rottoli, PT, Vicini, 2301.04059]



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

- Excellent perturbative QCD convergence
- Simple combination of fiducial pT(lep) rates integrated in wide bins: small systematic/statistical experimental error, viability to unfold detector effects
- Naive estimate: ΔmW ~ ± 15 MeV experimental (syst), ΔmW ~ ± 5 MeV in perturbative QCD
- Impact of EW and non-perturbative QCD to be separately assessed, clean disentangling of effects, minimal reliance on neutral DY

Outlook

- pT resummation at N3LL’ / approx. N4LL QCD resummation, successful comparison with data

- pT resummation for fixed-order N3LO fiducial, resummation of linear power corrections

- High accuracy resummation of QCD+EW effects in RadISH, impact on precision Drell-Yan leptonic observables

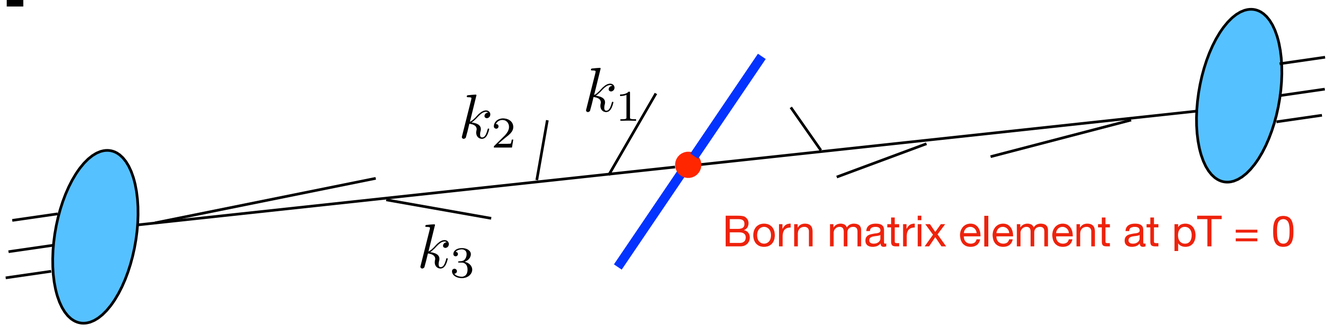
- Jacobian asymmetry for mW determination, with good theo./expt. properties and clean disentangling of different effects

Thank you for your attention

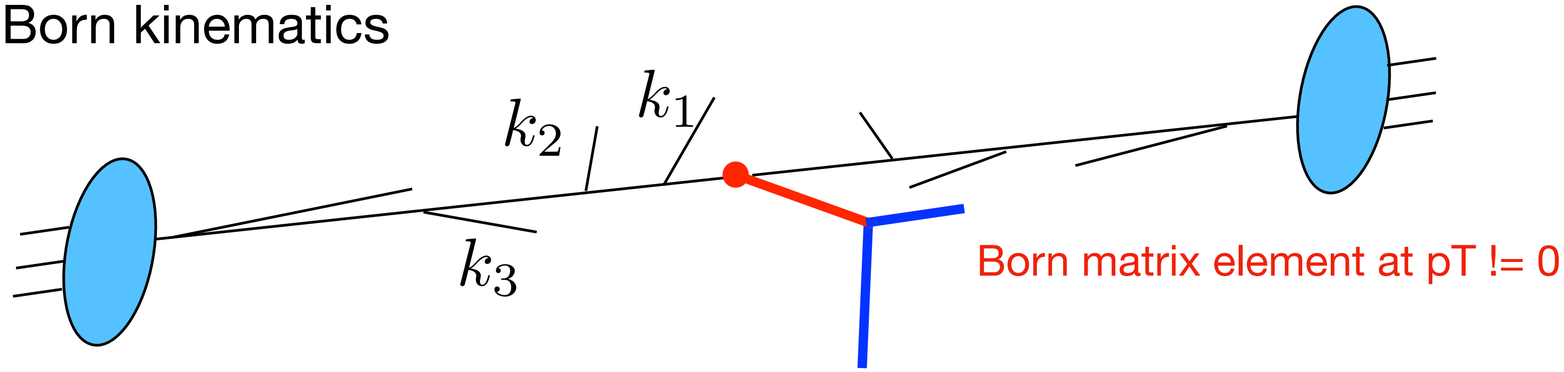
Backup

Transverse recoil

- Leading-power pT resummation



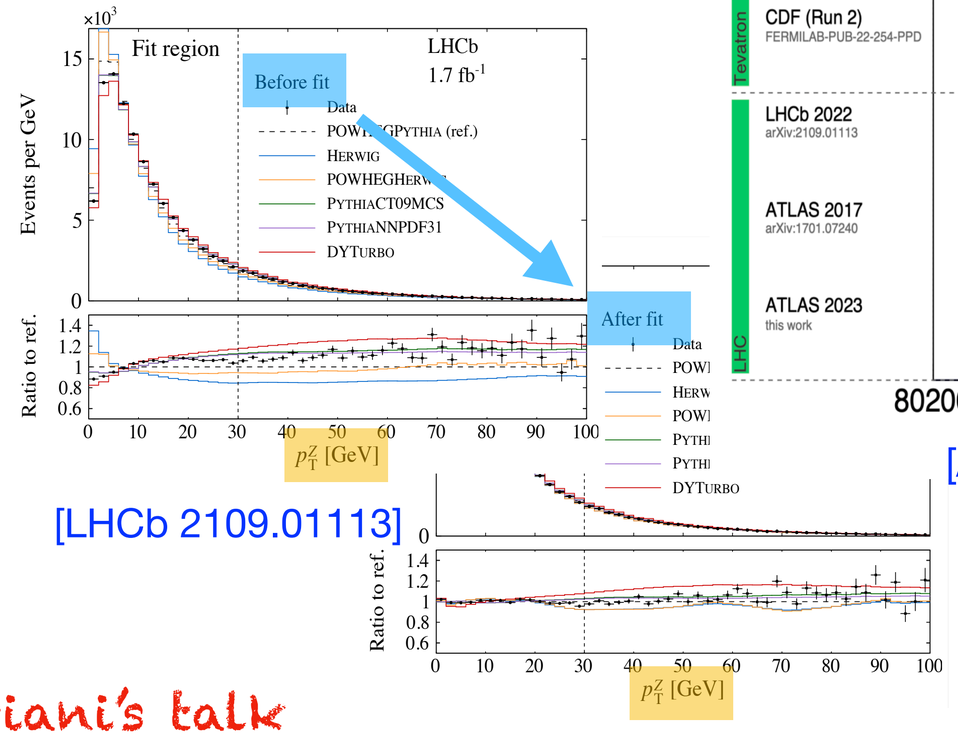
- Including next-to-leading power: recoil prescription [Catani et al., 1507.06937]
  - generate pT by QCD initial-state radiation
  - boost Born kinematics from V rest frame to frame with that pT
  - apply fiducial cuts on boosted Born kinematics



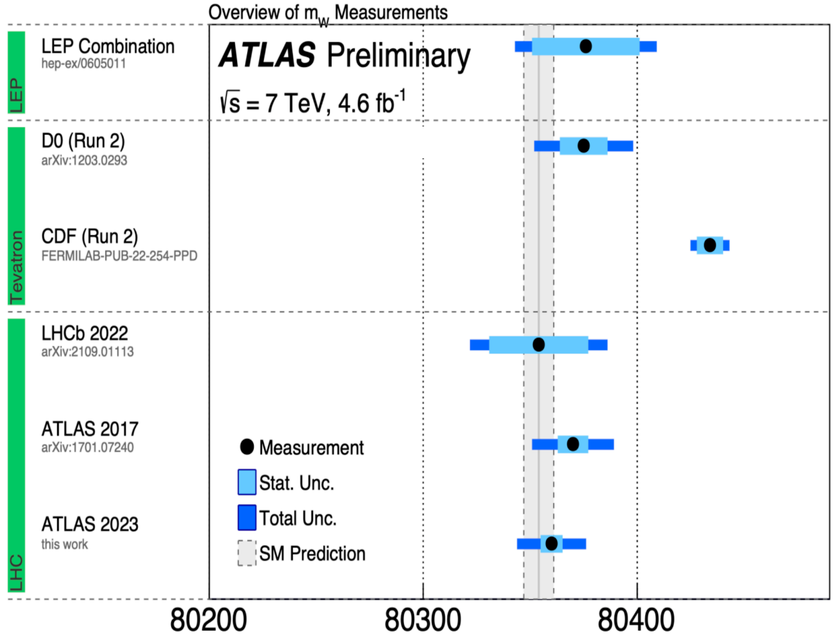
- Sufficient to resum all linear fiducial power corrections for pT in DY [Ebert et al., 2006.11382]

Experimental determination of mW

- Fit template pT(lep) and mT distributions to charged DY data
- Templates generated with (low accuracy) Monte Carlos, after crucial calibration to pT(Z) neutral DY data
- Transfer of information from neutral to charged DY: subtle to assess systematics



[LHCb 2109.01113]



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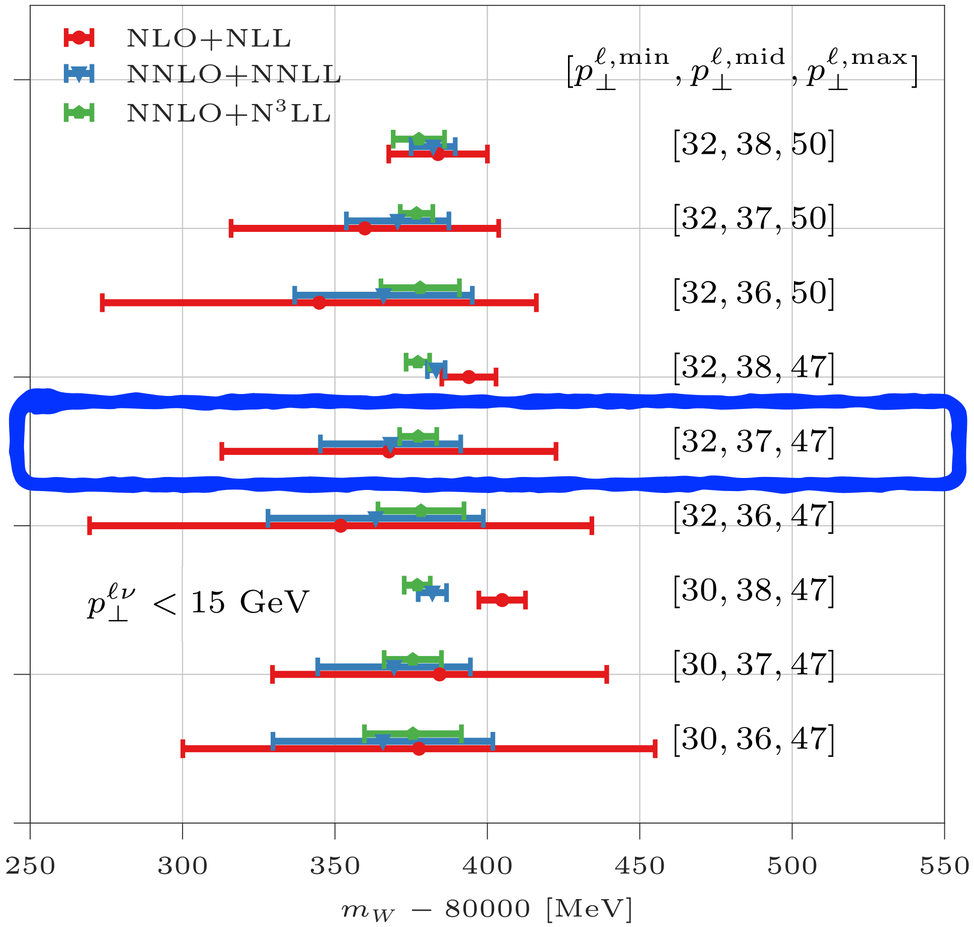
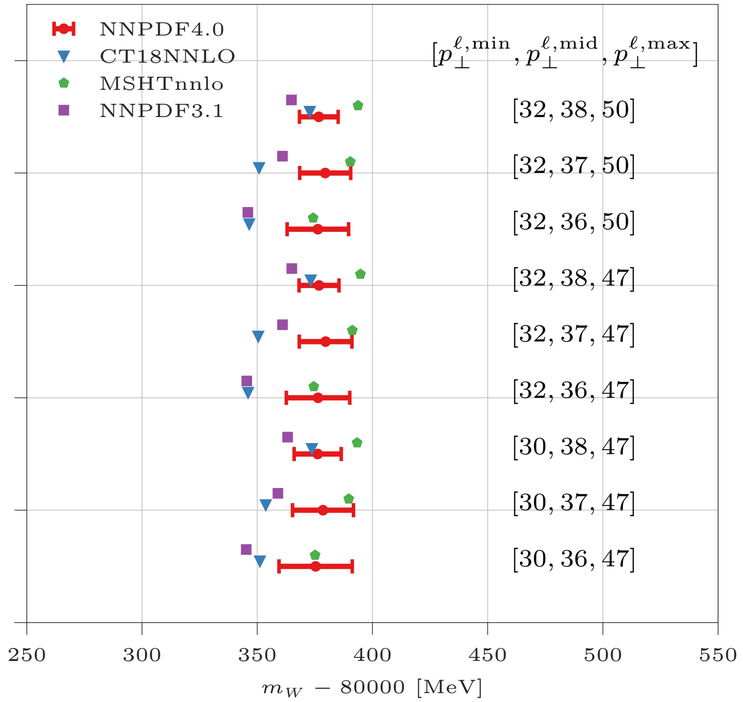
-> see also M. Cipriani's talk

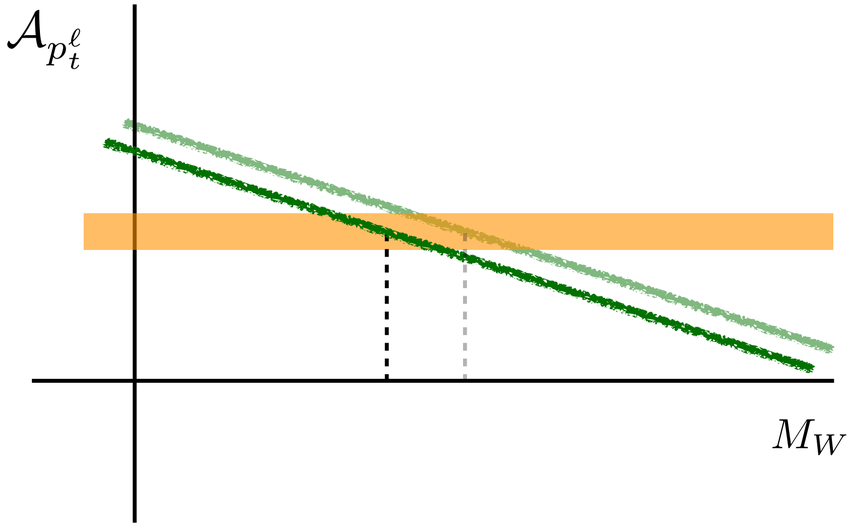
Jacobian asymmetry: dependence on bin edges



- 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 pTmid) and perturbative convergence (improving at lower pTmid)

Jacobian asymmetry: dependence on PDFs





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