THEORY OVERVIEW OF LHC PRECISION PHYSICS

Alexander Huss

MITP Workshop — May 4th 2026 — Johannes Gutenberg University Mainz

“LHC EW precision physics, extraction of pseudo-observables (POs) from hadron collider data, impact of PDFs”

—

so… Drell–Yan? *

* personal selection of results / concerns / …

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CERN

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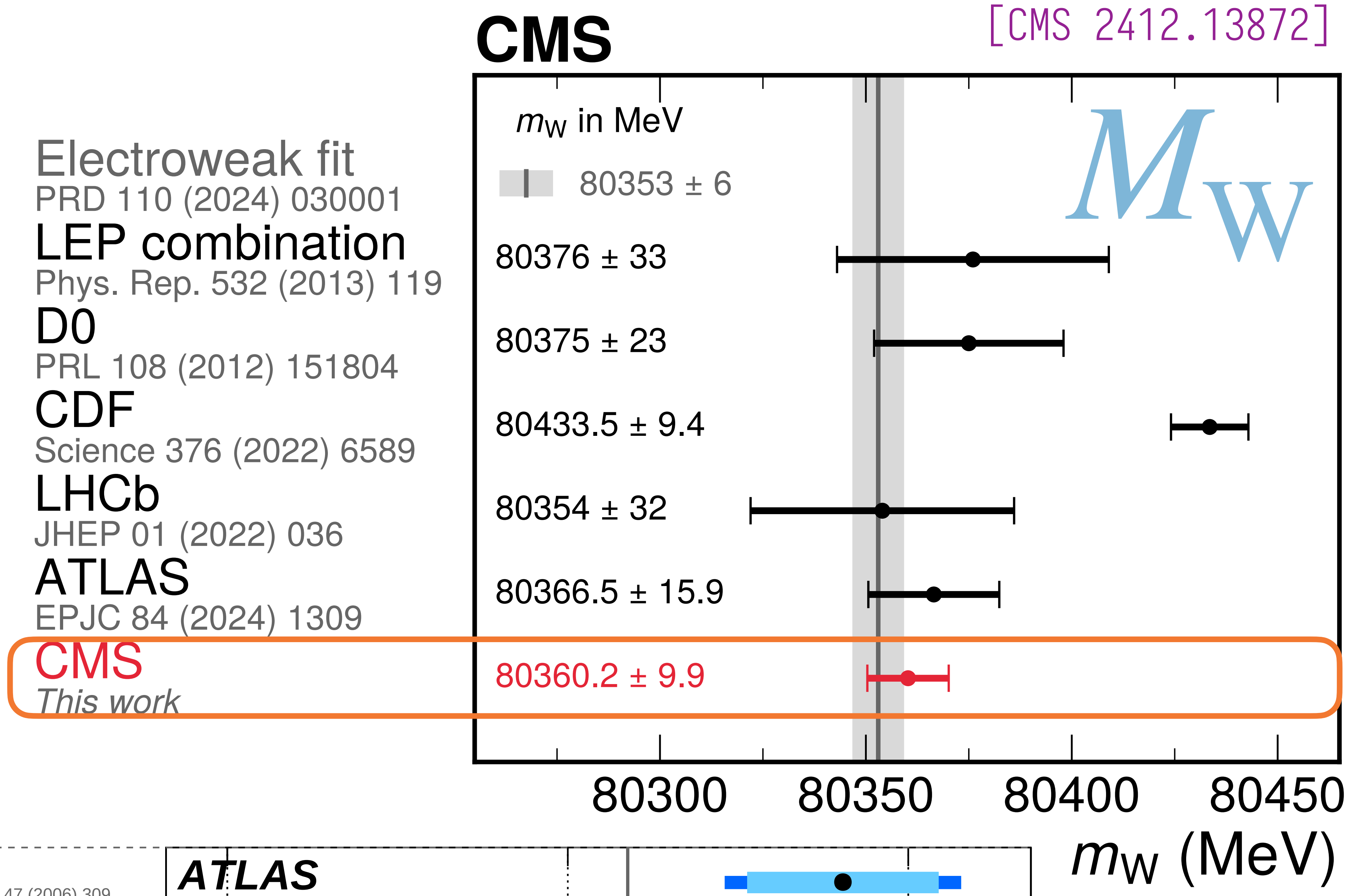
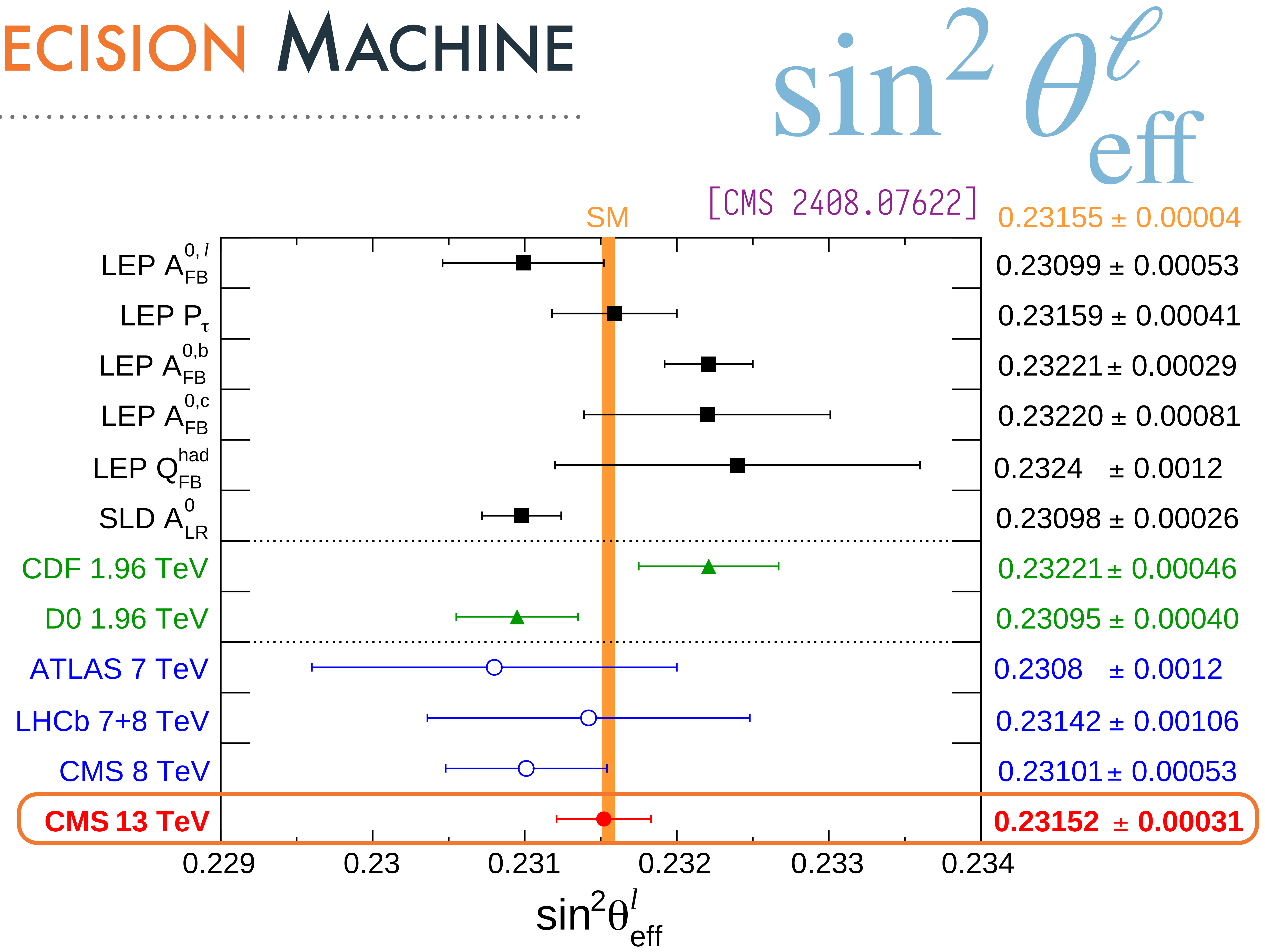
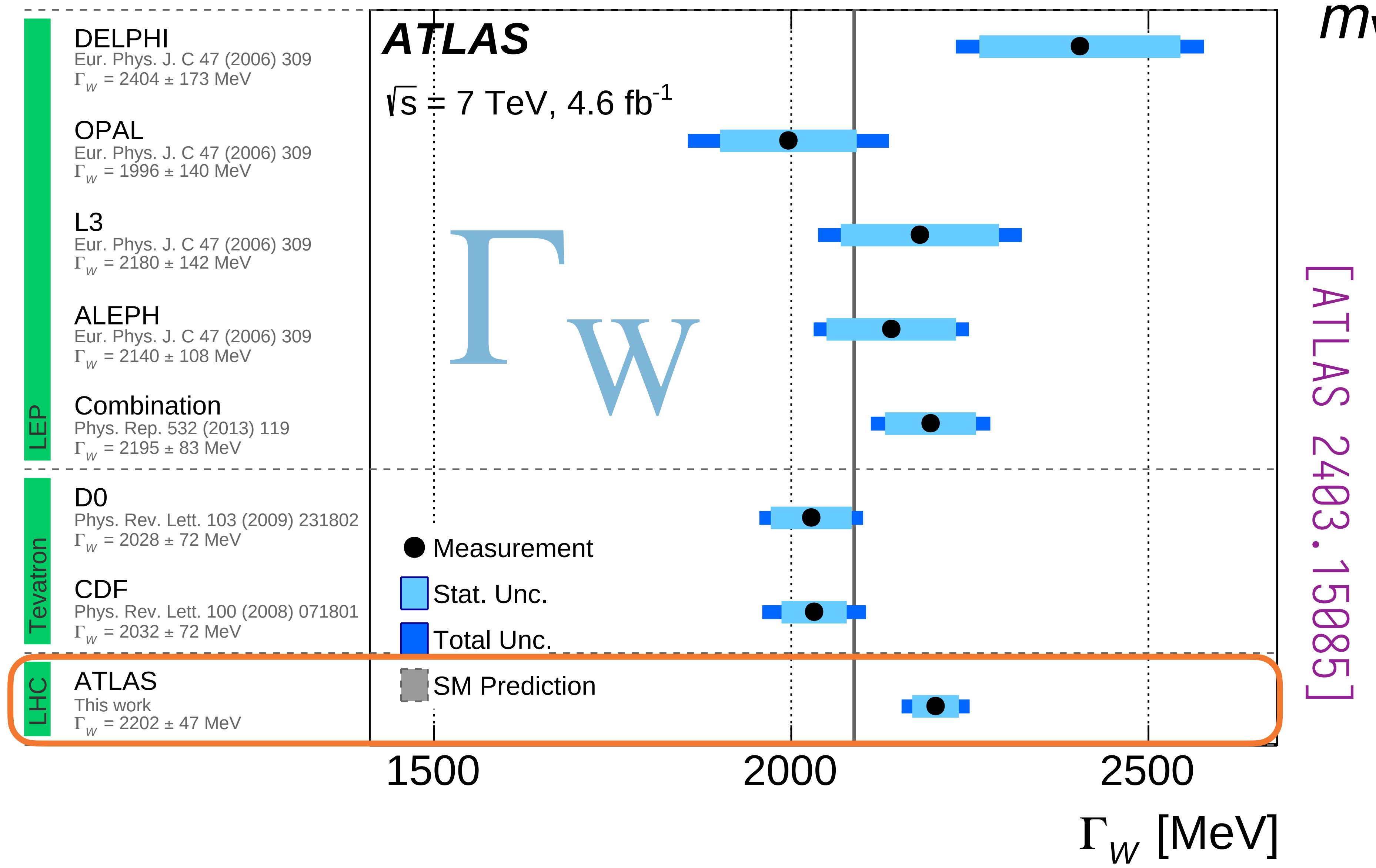
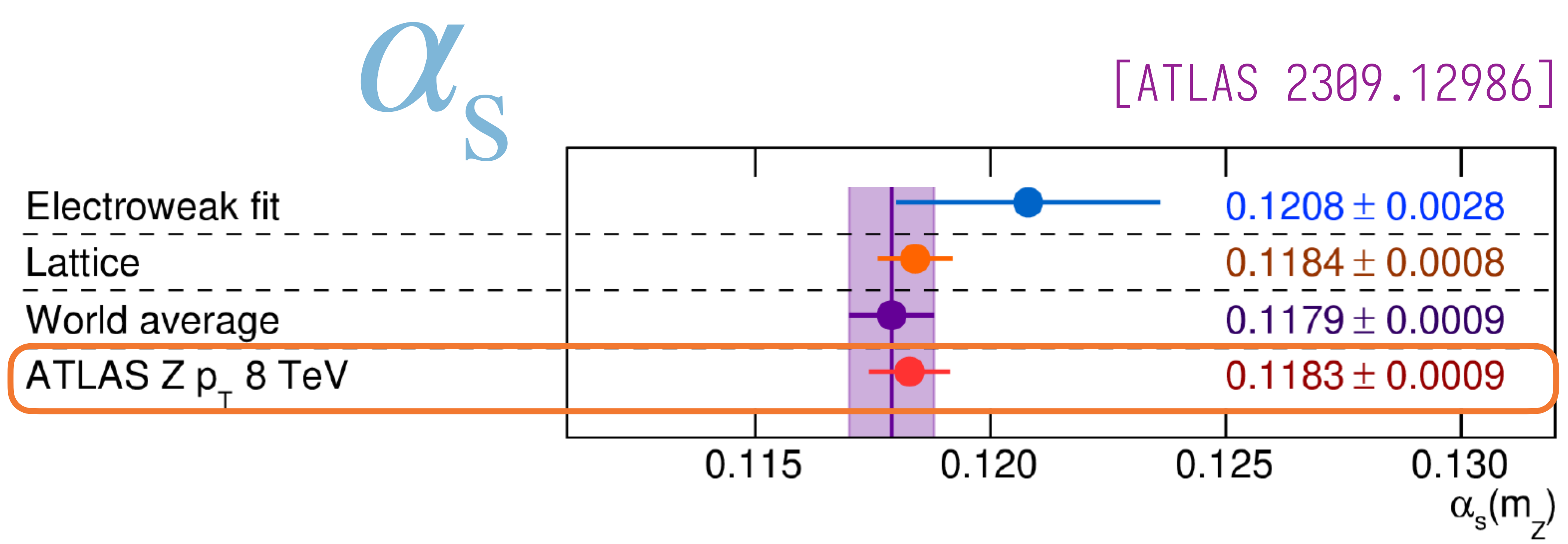
LHC – From a Discovery to a Precision Machine





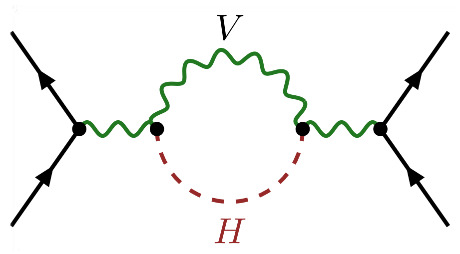


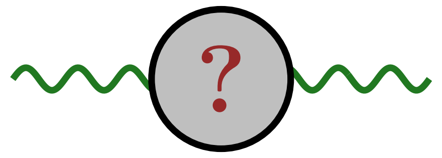


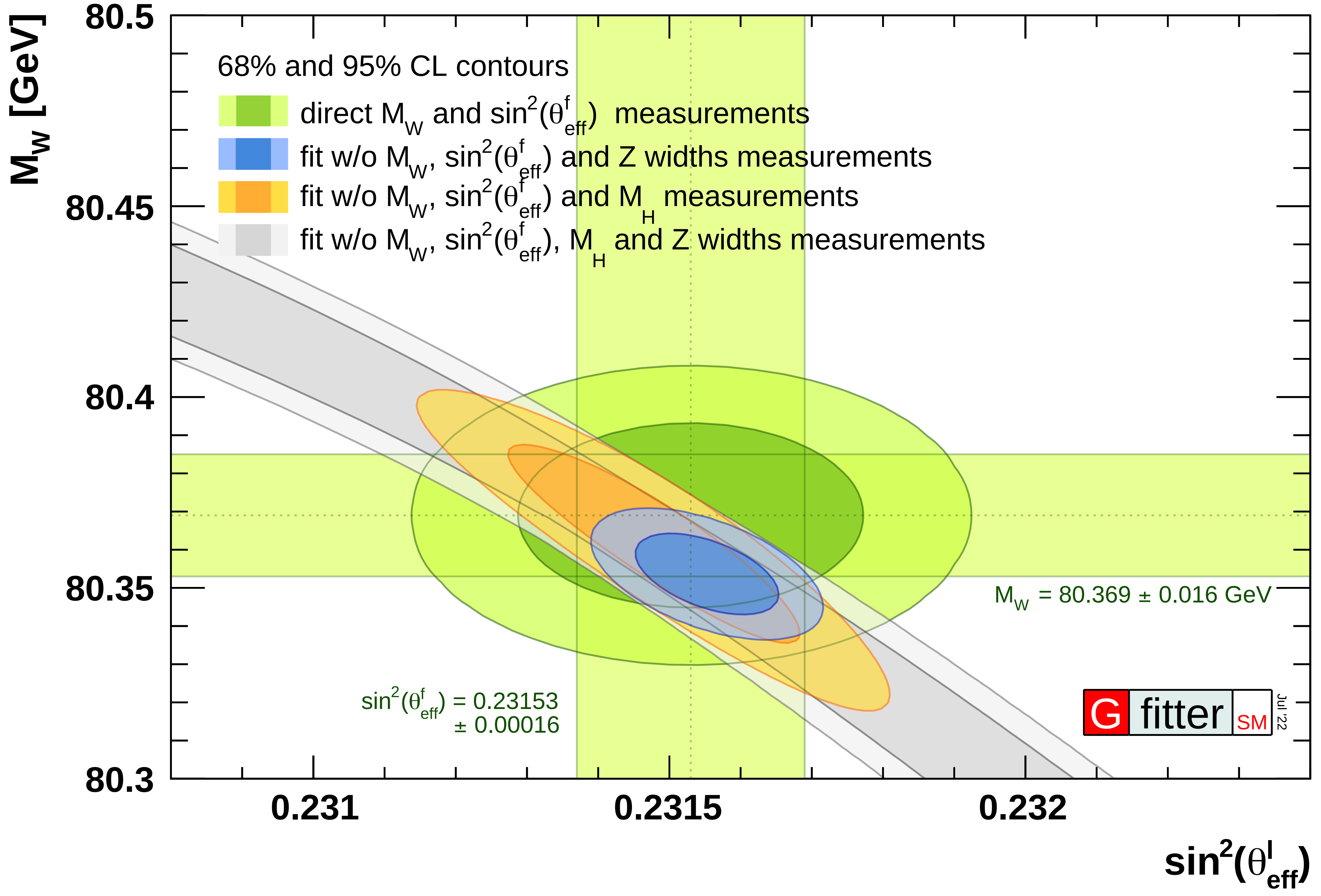
Why & What? – Global EW Fit

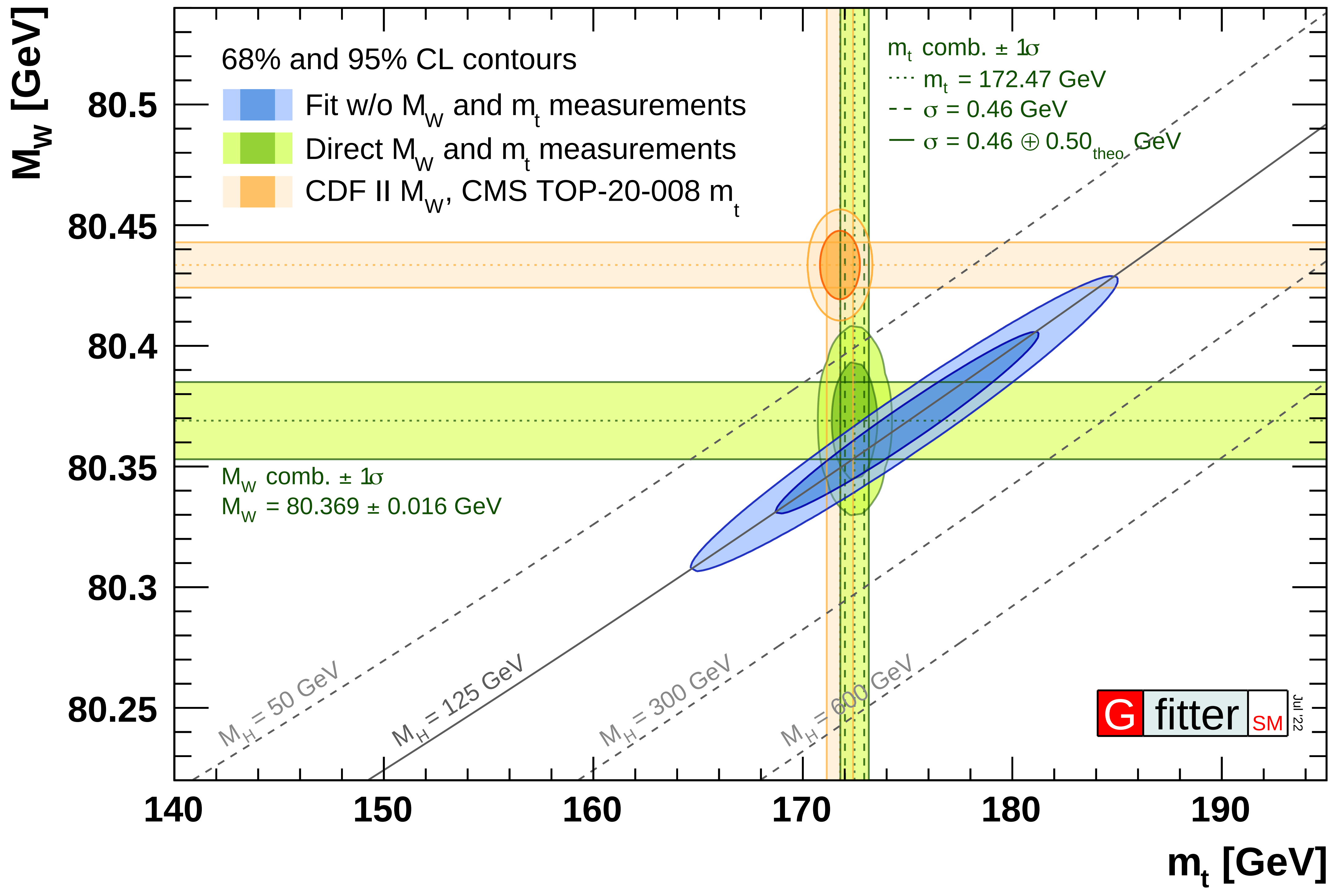
[Gfitter '22]

- SM: constrained system ⇝ is it self-consistent?
- sensitivity $\delta\mathcal{O} \sim Q^2/\Lambda_{\rm NP}^2$ ⇝ per-cent @ EW scale ⇒ probe $\Lambda_{\rm NP} \sim$ TeV









Precision Tests @ the LHC

- M_W & $\sin^2\theta^\ell_{\rm eff}$ from fit $\leftrightarrow$ smaller uncertainties than direct measurements!
  $\hookrightarrow$ high priority as most "bang for the buck"

- both are SM predictions: M_W [Freitas, Hollik, Walter, Weiglein '02] [Awramik, Czakon, Freitas, Weiglein '03] $\sin^2\theta^\ell_{\rm eff}$ [Dubovyk, Freitas, Gluza, Riemann, Usovitsch '20]
  $\hookrightarrow$ full 2-loop EW results
  + subset of even higher-order terms

talk by G. Degrassi

Parameter	Measurement	Fit w/o "input"	Theory calculation
m_t [GeV]	172.47 ± 0.68	175.2 ± 2.4	Input parameter
M_H [GeV]	125.20 ± 0.11	100^{+25}_{-21}	Input parameter
M_Z [GeV]	91.1880 ± 0.0020	91.1956 ± 0.0105	Input parameter
Γ_Z [GeV]	2.4955 ± 0.0023	2.4943 ± 0.0016	2.4942 ± 0.0004
M_W [GeV]	80.3692 ± 0.013	80.354 ± 0.007	80.353 ± 0.004
Γ_W [GeV]	2.14 ± 0.05	2.091 ± 0.001	2.090
$\sin^2\theta^\ell_{\rm eff}$	0.23153 ± 0.00016	0.23154 ± 0.00010	0.231488 ± 0.000045

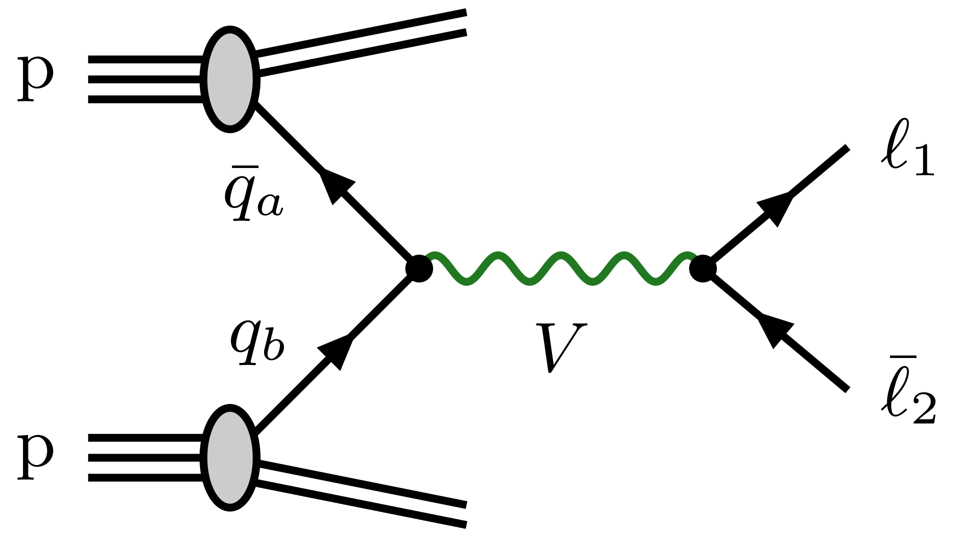
[Gfitter '22]

precision targets often limited by:
$\hookrightarrow$ TH modelling
$\hookrightarrow$ PDFs

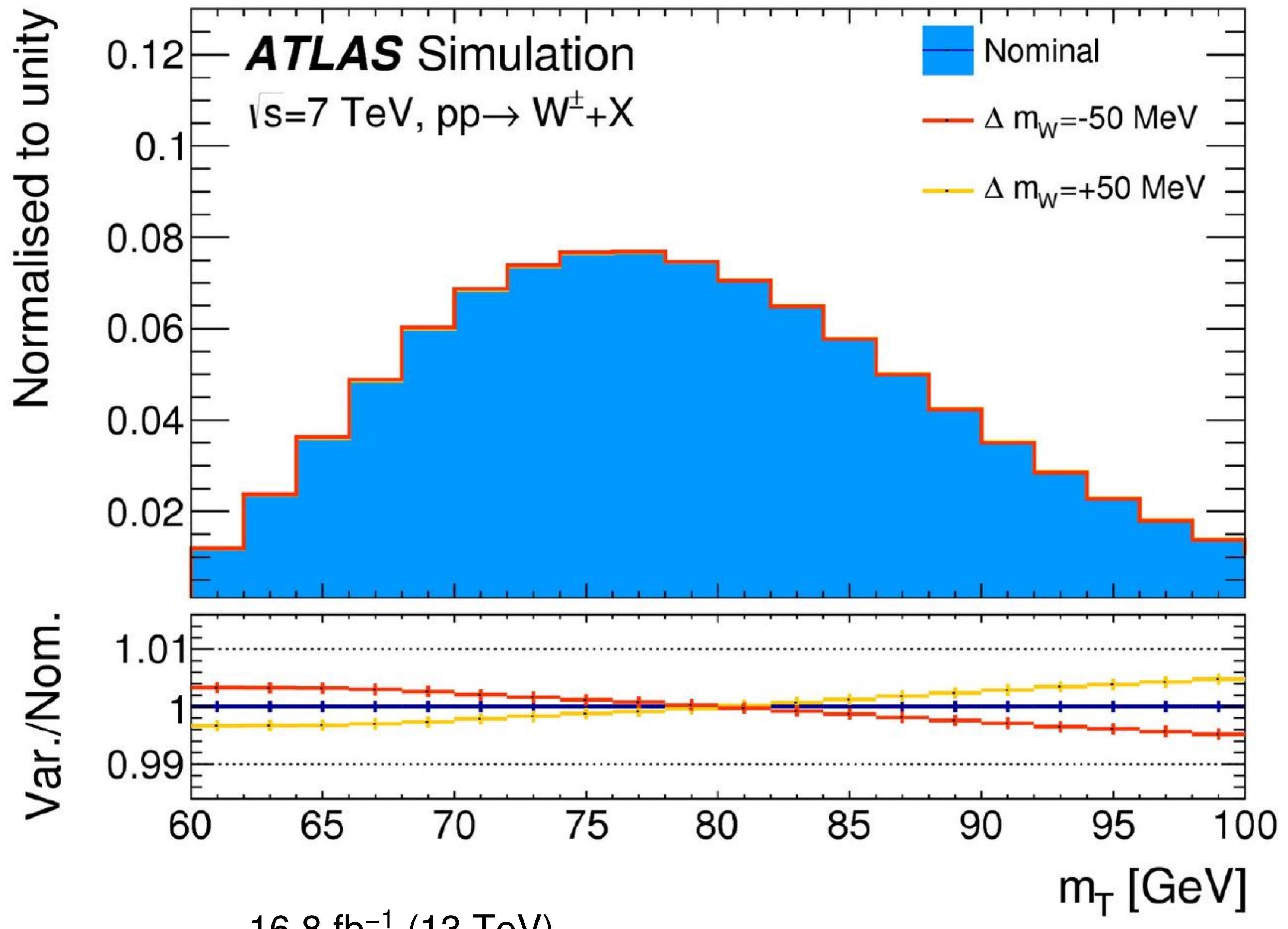
Outline

- Motivation
1. Theory Status for Single Boson Production
    1. Drell-Yan process at fixed order
    2. Transverse momentum
2. Parton Distribution Functions & More
    1. PDF uncertainties & profiling, N3LO
    2. Theory uncertainties & modelling
- Conclusions

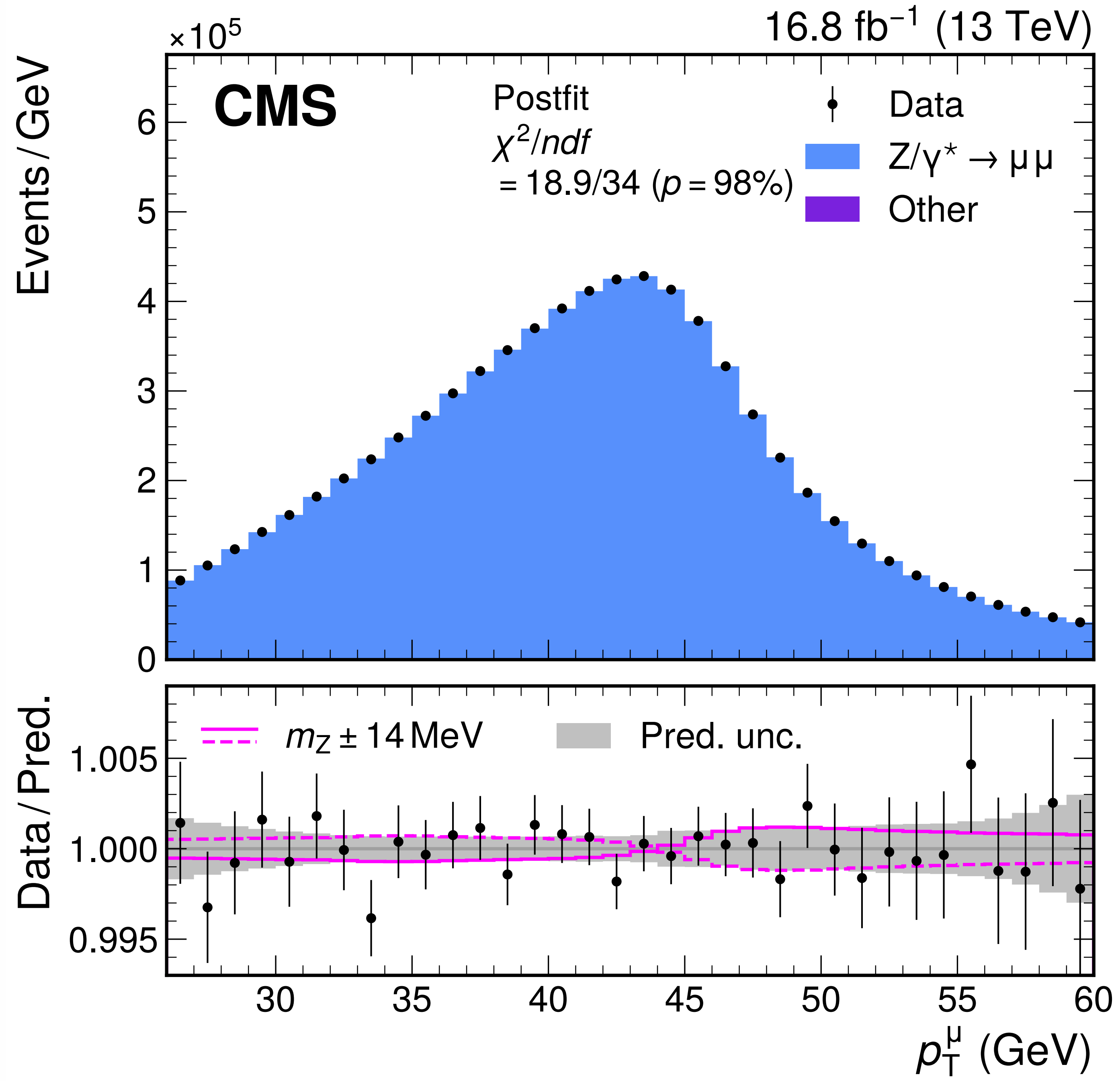
Drell–Yan — THE Standard Candle @ LHC



- clean signature $(\ell^{\pm}, E_{\mathrm{T}}^{\mathrm{miss}})$
  & large cross section:
  $(\sim 1000$ Z & ~ 4000 $\mathrm{W}^{\pm})$ / sec *
- detector calibration, BSM searches, luminosity monitor, quark PDFs, …
- precision measurements: $\sin^2(\theta_{\mathrm{w}})$, M_{W}
  ↪ $\Delta M_{\mathrm{W}} \simeq 10\,\mathrm{MeV}$
  ⇝ control *shape* at ‰



±50 MeV

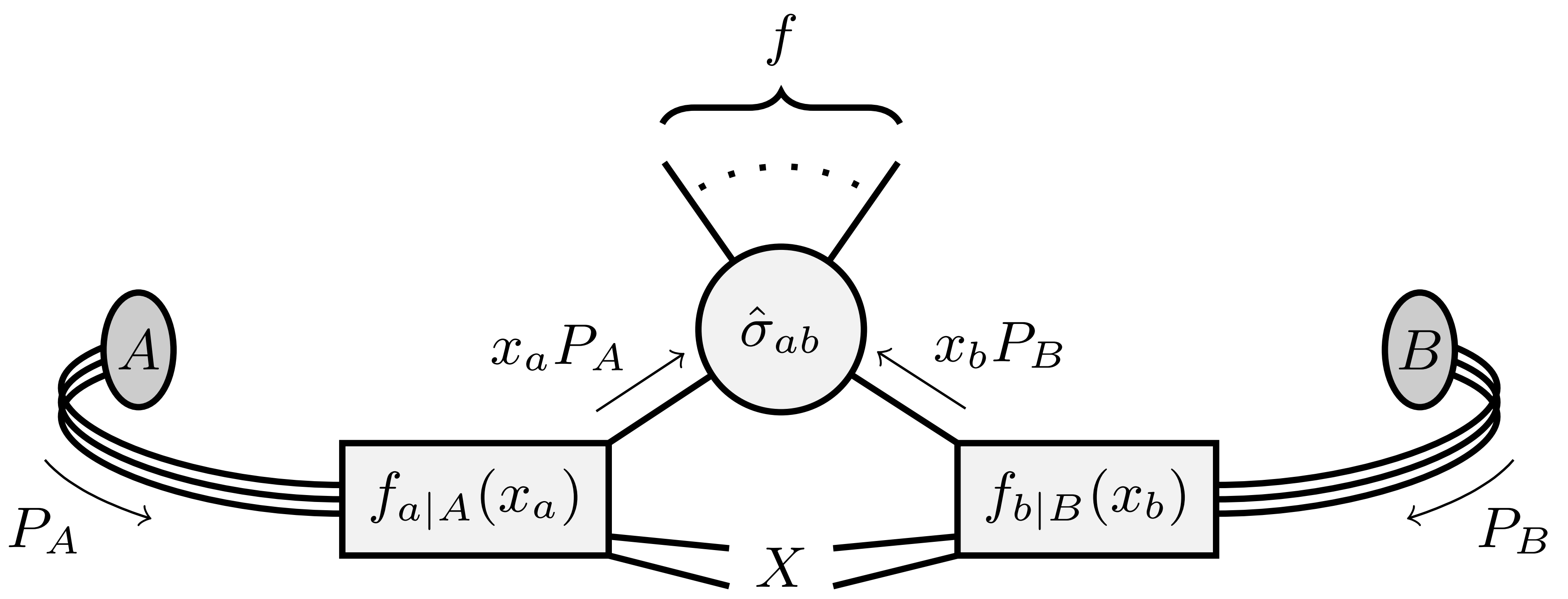


±14 MeV

c.f. target of $\mathcal{O}(5\,\mathrm{MeV})$

big TH challenge!

* $\mathscr{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_{a|A}(x_a)\; f_{b|B}(x_b)\; \hat{\sigma}_{ab}(x_a, x_b)\; \left(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}^p / Q^p)\right)$$

parton distribution functions (PDFs)
(non-perturbative, universal)

hard scattering
(perturbation theory)

non-perturbative effects
(power suppressed)

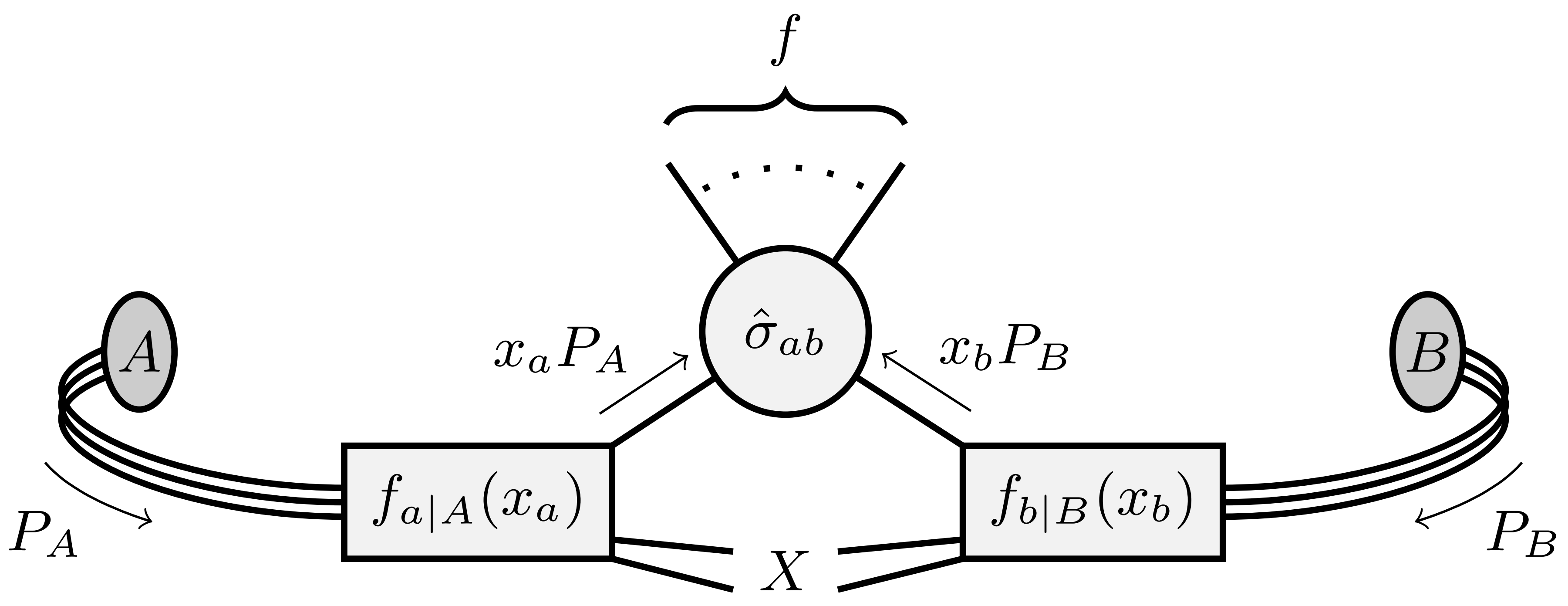
Drell–Yan:

high momentum transfer
& clean signature

Perturbation theory:

$\alpha_s \sim 0.1$ & $\alpha_{ew} \sim 0.01$

‰ target $\leftrightarrow$ $\mathcal{O}(\alpha_s^3, \alpha_s\,\alpha_{ew})$ & beyond



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(power suppressed)

- $\Lambda \lesssim 1\,\mathrm{GeV}$
- power p depends on the observable
  - ↪ σ Drell-Yan ⇝ $p = 2$
  - ↪ jets ⇝ $p = 1$ (hadronization & MPI)
- numerical impact ($Q \sim 100\,\mathrm{GeV}$)
  - ↔ $(\Lambda/Q) \sim 1\,\%$
  - ↔ $(\Lambda/Q)^2 \sim 0.01\,\%$
- for p_T^Z ↔ $\Delta_{\mathrm{exp}} \lesssim 0.3\,\%$
  - ↪ $\cancel{p = 1}$ a potential disaster
  (study based on IR renormalons)
  [Ferrario Ravasio, Limatola, Nason '21]

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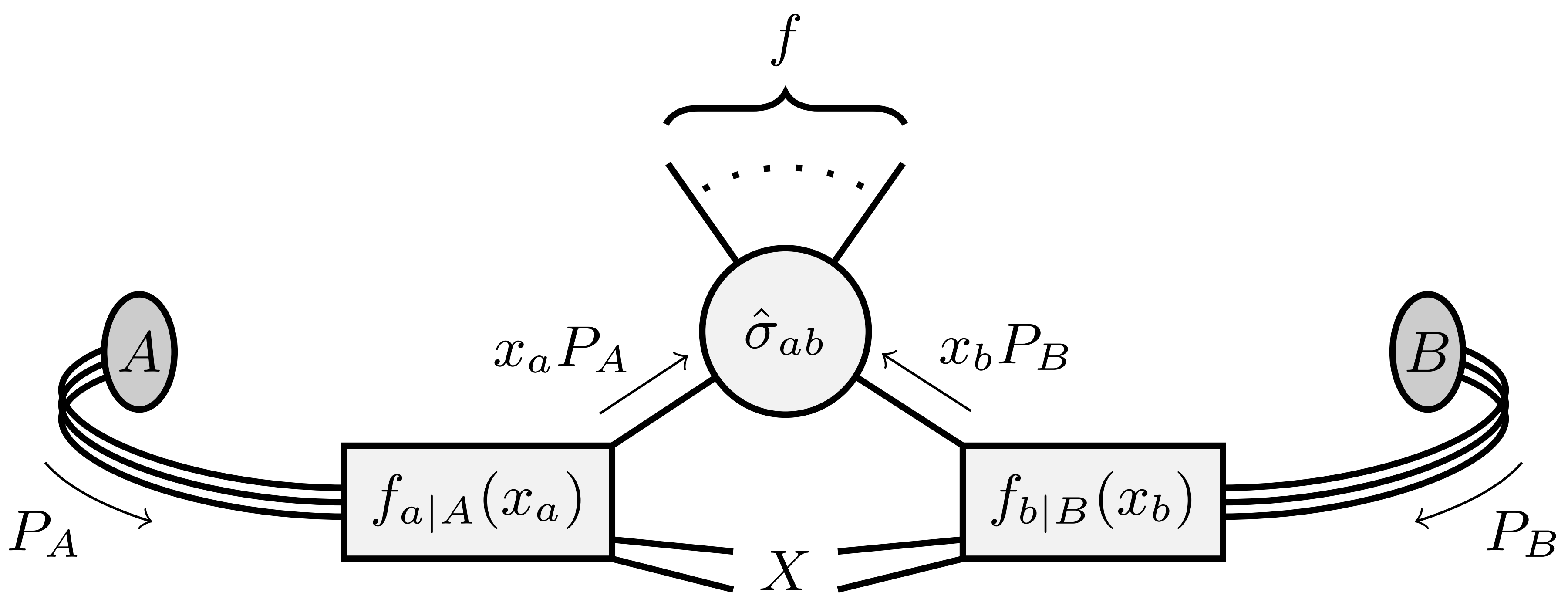
$$\sigma_{\mathrm{DY}} = \sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)} + \alpha_s^2\,\sigma^{(2,0)} + \alpha_s^3\,\sigma^{(3,0)} + \alpha_s^4\,\sigma^{(4,0)} + \ldots$$
$$+\ \alpha\,\sigma^{(0,1)} + \alpha_s\alpha\,\sigma^{(1,1)} + \alpha_s^2\alpha\,\sigma^{(2,1)} + \ldots$$
$$+\ \alpha^2\,\sigma^{(0,2)} + \ldots$$



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Drell–Yan @ Fixed Order

$$\sigma_{\mathrm{DY}} = \boxed{\sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)} + \alpha_s^2\,\sigma^{(2,0)} + \alpha_s^3\,\sigma^{(3,0)}} + \alpha_s^4\,\sigma^{(4,0)} + \ldots$$
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$$+ \alpha^2\,\sigma^{(0,2)} + \ldots$$

QCD corrections

- NNLO differential

  [Anastasiou, Dixon, Melnikov, Petriello '03],
  [Melnikov, Petriello '06], [Catani, Cieri, Ferrera, de Florian, Grazzini '09],
  [Catani, Ferrera, Grazzini '10]

  ↪ public codes: DYNNLO, DYTurbo, FEWZ, Matrix, MCFM, NNLOJET, …

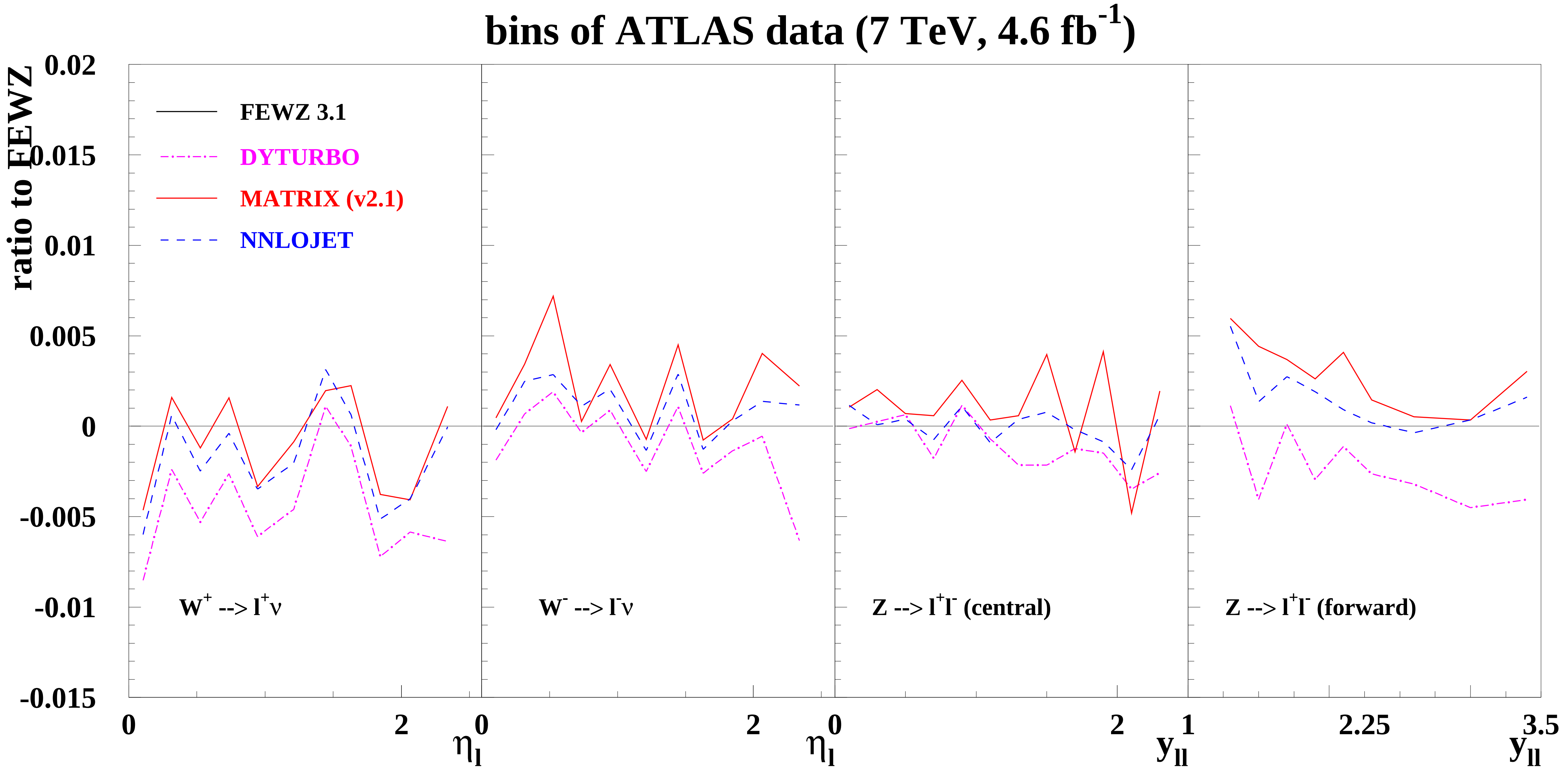
- N³LO inclusive / rapidity

  [Duhr, Dulat, Mistlberger '20], [Duhr, Mistlberger '21],
  [Chen, Gehrmann, Glover, AH, Yang, Zhu '21] (Y)

  ↪ public code: n3loxs

- N³LO differential

  [Camarda, Cieri, Ferrera '21],
  [Chen, Gehrmann, Glover, AH, Monni, Re, Rottoli, Torrielli '22],
  [Chen, Gehrmann, Glover, Huss, Yang, and Zhu '22],
  [Neumann, Campbell '22, '23], [Billis, Michel, Tackmann '24]



per-mille level agreement

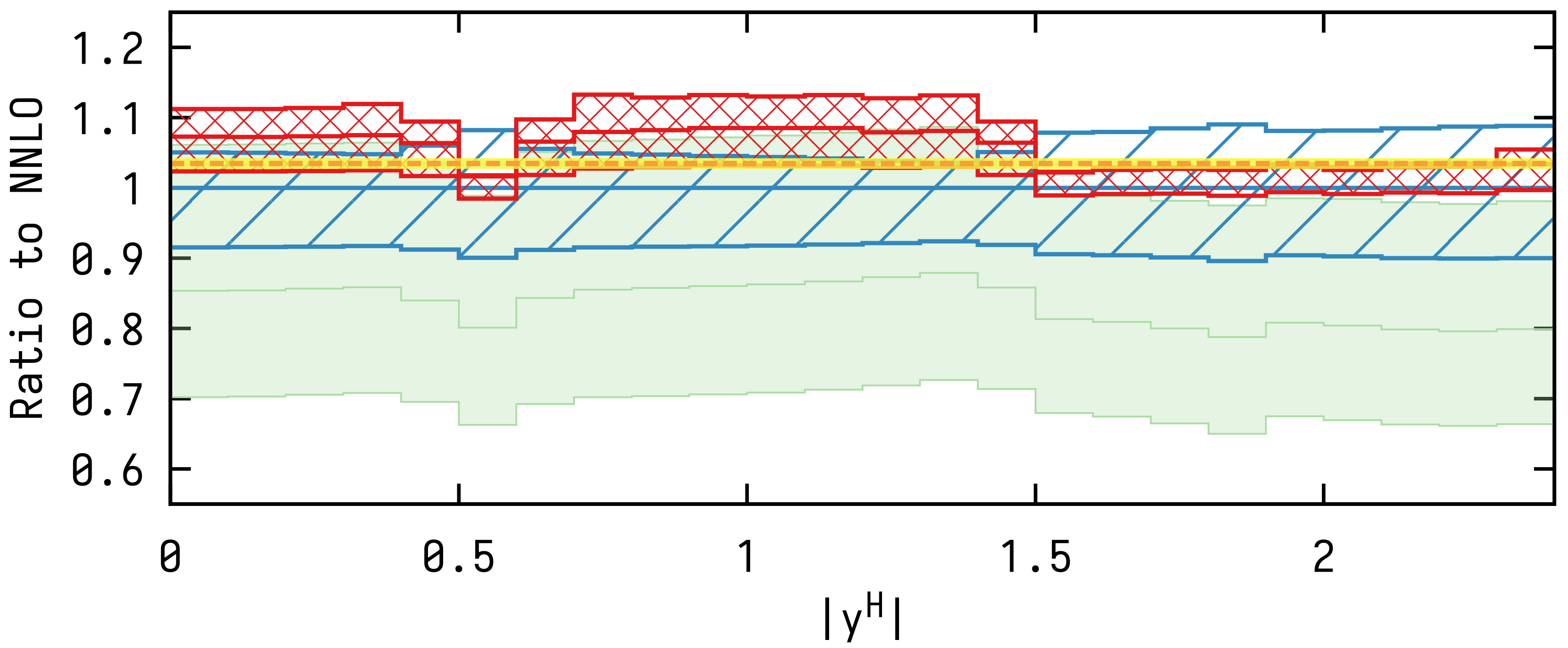
[Alekhin et al. '24]

Definition of the Fiducial Cuts

[Frixione, Ridolfi '97] [Ebert, Tackmann '19 + Michel, Stewart '21] [Alekhin et al. '21]

- symmetric/asymmetric cuts → linear acceptance ($q_T \to 0$)
  ↪ induces IR sensitivity: "fiducial power corrections"
  (perturbative instabilities with factorial growth)

Example: Higgs @ N³LO [Chen, Gehrmann, Glover, AH, Mistlberger, Pelloni '21]

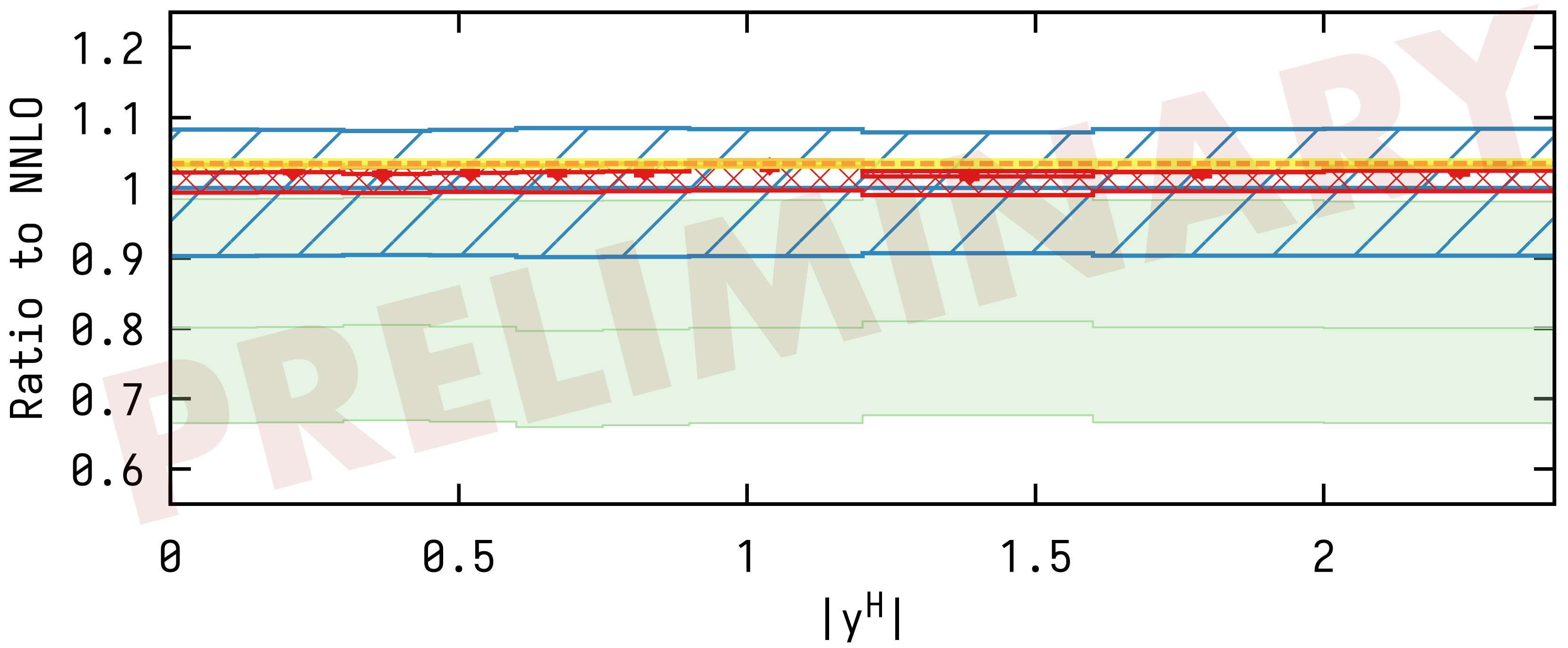


ATLAS

$p_T^{\gamma_1} \geq 0.35 \cdot M_H$

$p_T^{\gamma_2} \geq 0.25 \cdot M_H$

$f(p_T^H) = f_0 + f_1 \cdot p_T^H + \mathcal{O}((p_T^H)^2)$



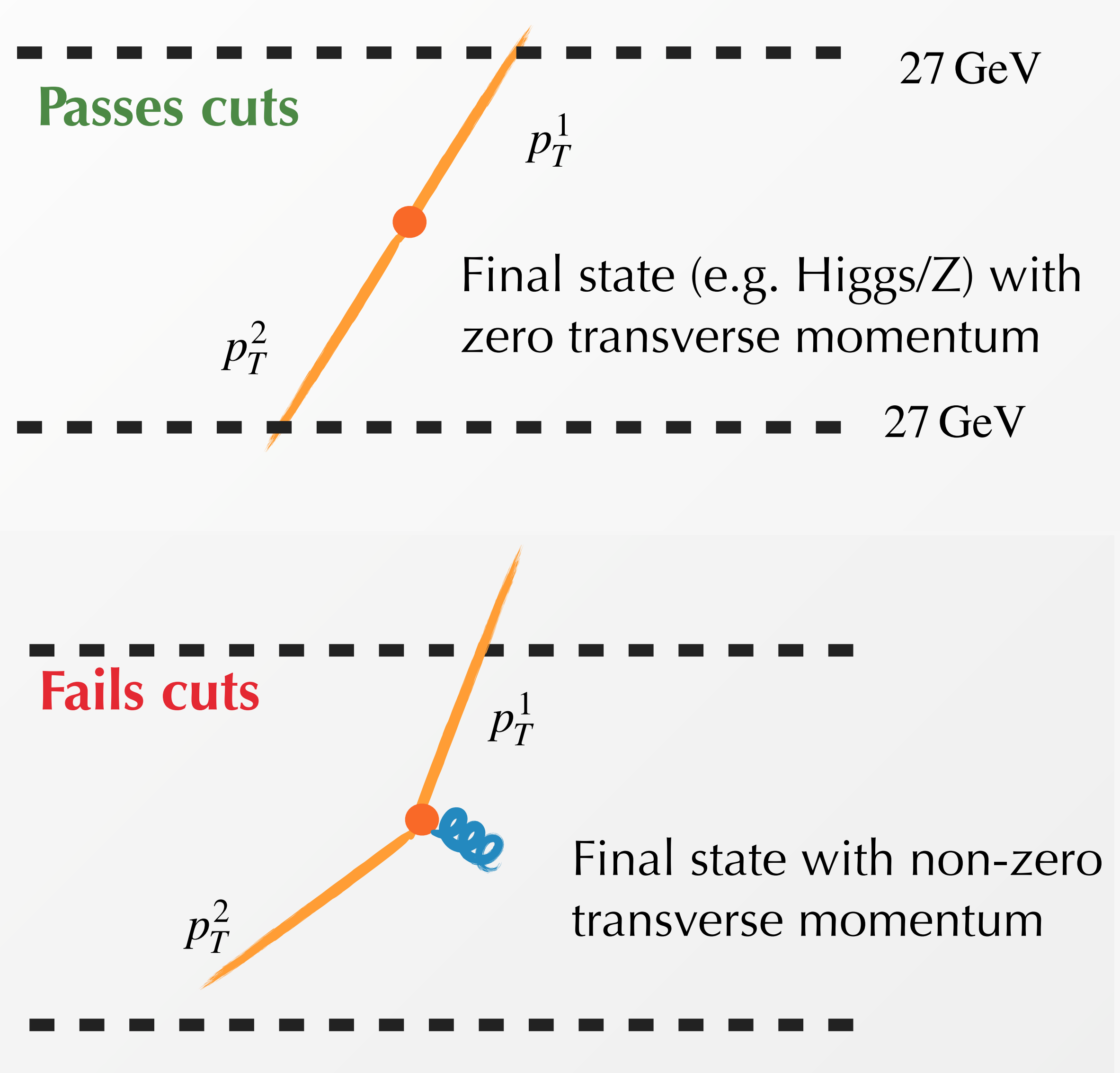
Product cuts [Salam, Slade '21]

$\sqrt{p_T^{\gamma_1} p_T^{\gamma_2}} \geq 0.35 \cdot M_H$

$p_T^{\gamma_2} \geq 0.25 \cdot M_H$

$f(p_T^H) = f_0 + \cancel{f_1 \cdot p_T^H} + f_2 \cdot (p_T^H)^2 + \mathcal{O}((p_T^H)^3)$

Symmetric lepton p_T cuts:



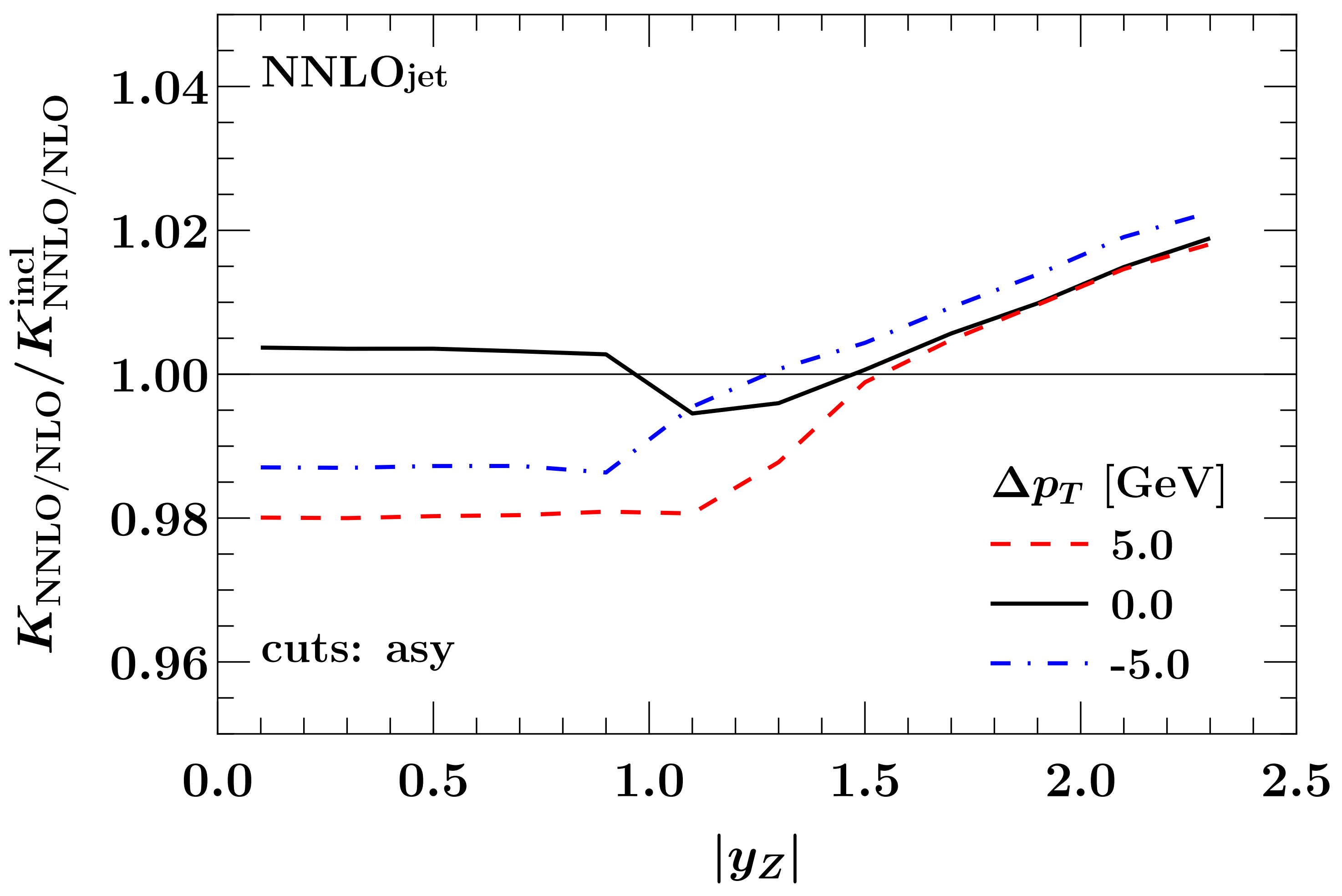
[sketch by L. Rottoli — SM@LHC '22]

- NNLO × $K_{\mathrm{N^3LO}}$ ≈ N³LO
- very flat
- no "features"
- robust (v.s. resummation)

Definition of the Fiducial Cuts

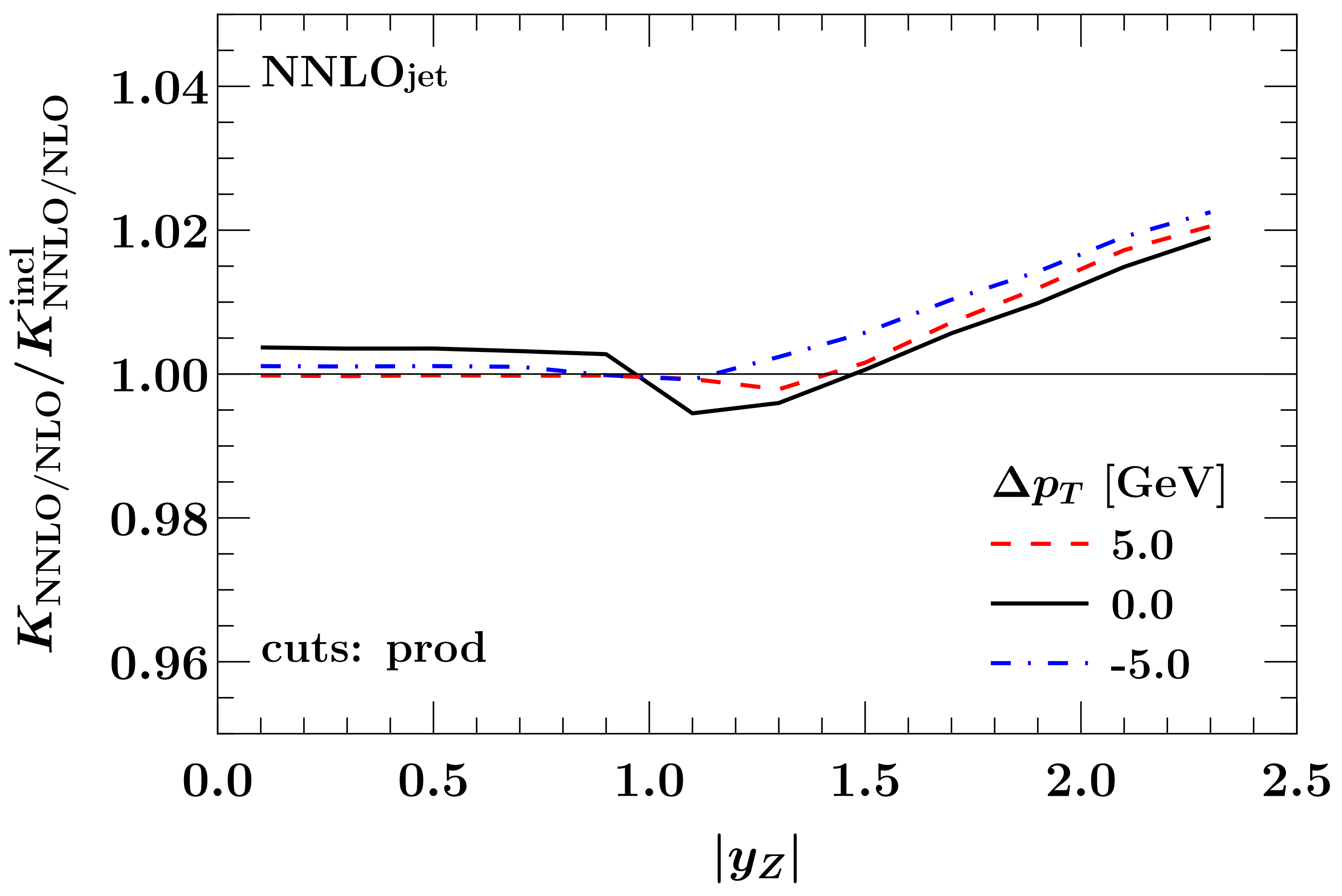
Drell–Yan @ NNLO [Alekhin et al. '24]

- $\Delta = 0$ ⇝ symmetric (black)
- ratio of K_{NNLO} w.r.t. inclusive
- smooth behaviour w/ product cuts
- smaller effect than in Higgs (Casimir, Γ_Z smearing, …)



Asymmetric cuts

$$p_T^{\ell_1} \geq p_T^{\text{cut}} + \Delta$$
$$p_T^{\ell_2} \geq p_T^{\text{cut}}$$
$$f(p_T^V) = f_0 + f_1 \cdot p_T^V + \mathcal{O}((p_T^V)^2)$$



Product cuts [Salam, Slade '21]

$$\sqrt{p_T^{\ell_1} p_T^{\ell_2}} \geq p_T^{\text{cut}} + \Delta$$
$$p_T^{\ell_2} \geq p_T^{\text{cut}}$$
$$f(p_T^V) = f_0 + \cancel{f_1 \cdot p_T^V} + f_2 \cdot (p_T^V)^2 + \mathcal{O}((p_T^V)^3)$$

impact more minor but <ins>more robust</ins> (errors) and preferable for <ins>legacy</ins> data

not the only way (studies needed): cut on $\Delta\eta_{\ell_1\ell_2}$, asymmetric on $p_T^{\ell^\pm}$, …

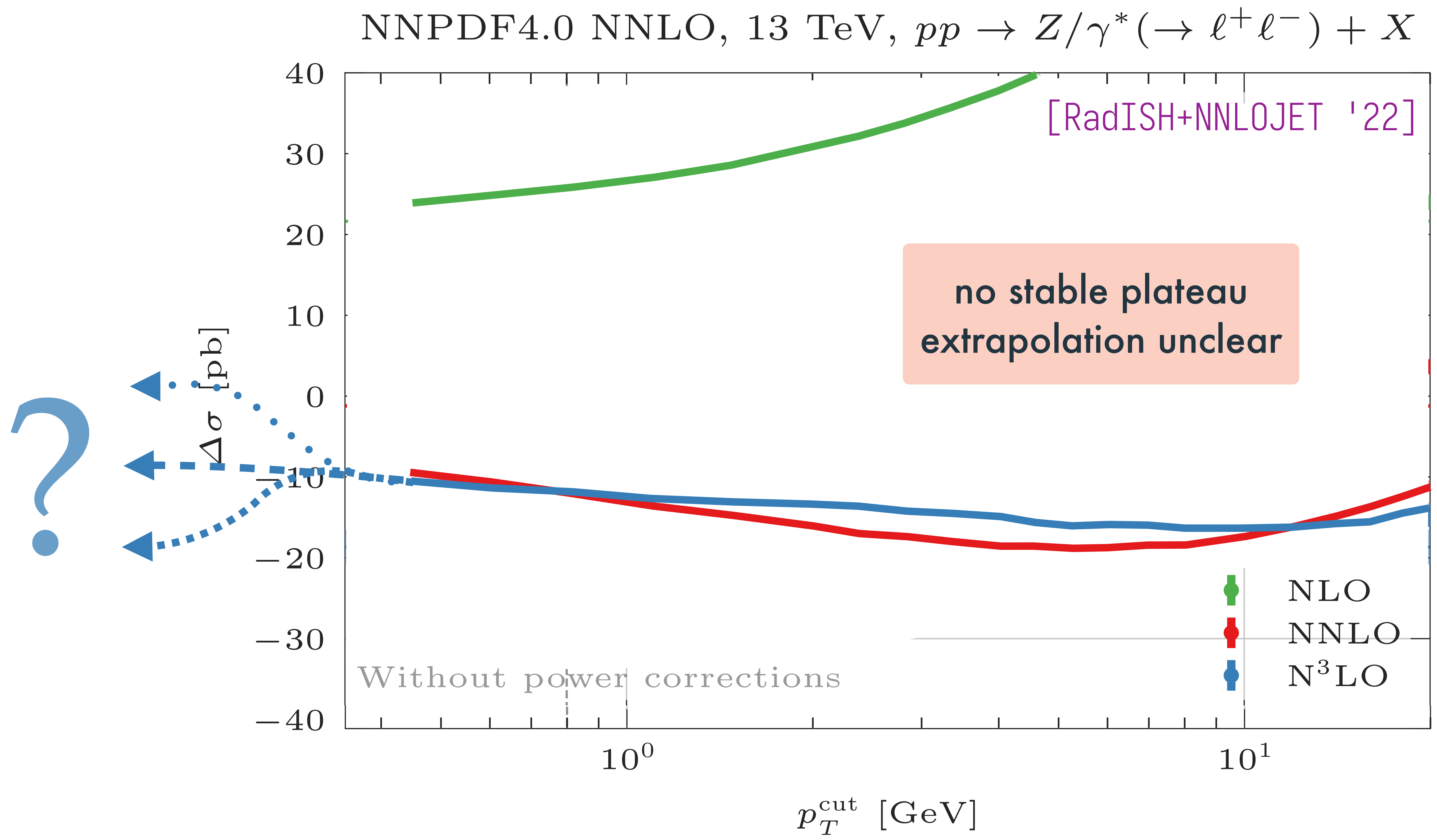
* Can also be cured through q_T resummation [Ebert, Tackmann '19]

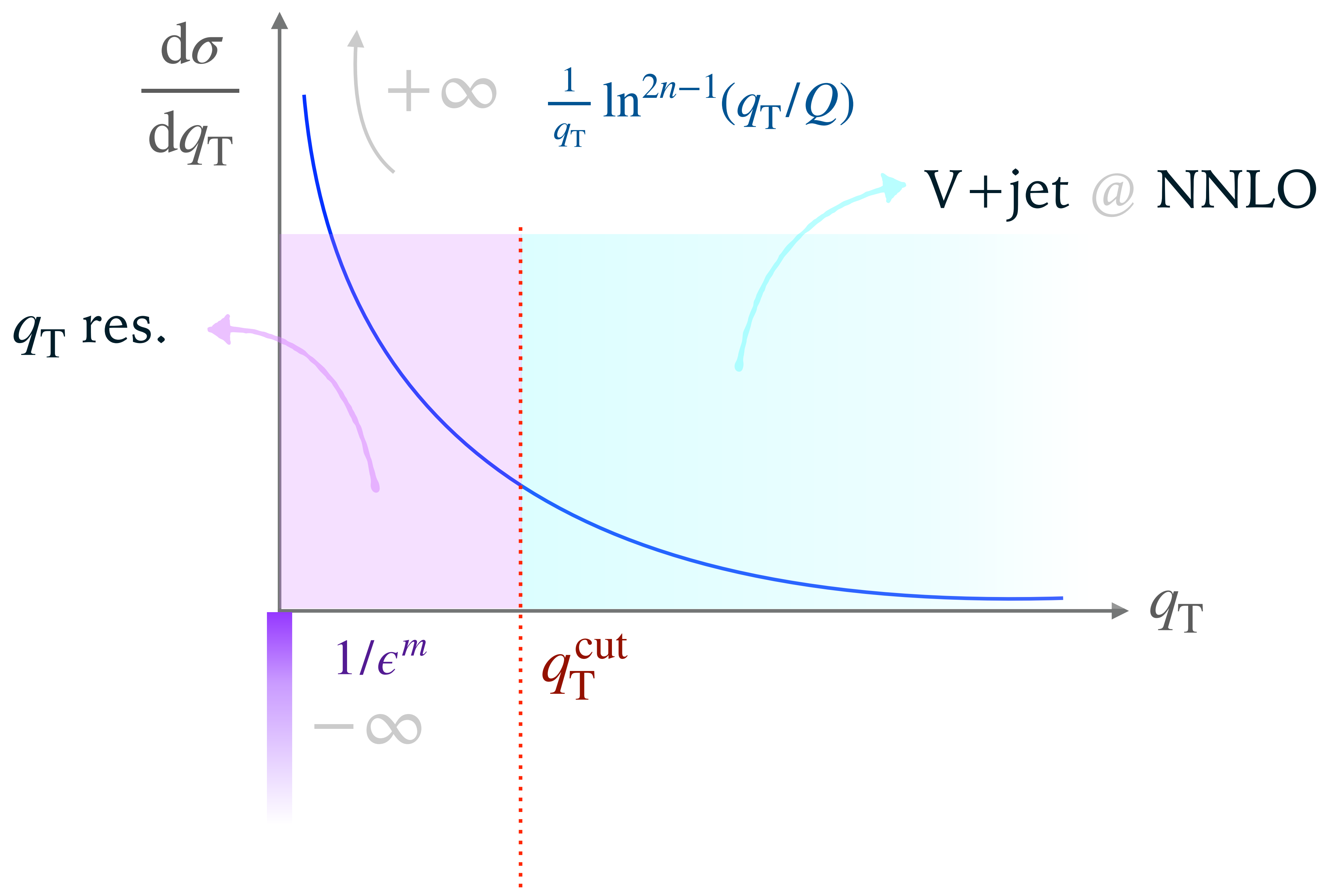
Fiducial Cuts and Linear Power Corrections — N^{3}LO Slicing

- fiducial cuts ⇝ can jeopardise q_T slicing

$$\mathcal{O}\left((q_T^{\text{cut}}/Q)^2\right) \quad \text{v.s.} \quad \mathcal{O}\left(q_T^{\text{cut}}/Q\right)$$

$[q_T^{\text{cut}} \lesssim 1\,\text{GeV}]$ $[q_T^{\text{cut}} \lesssim 10^{-2}\,\text{GeV ?!}]$



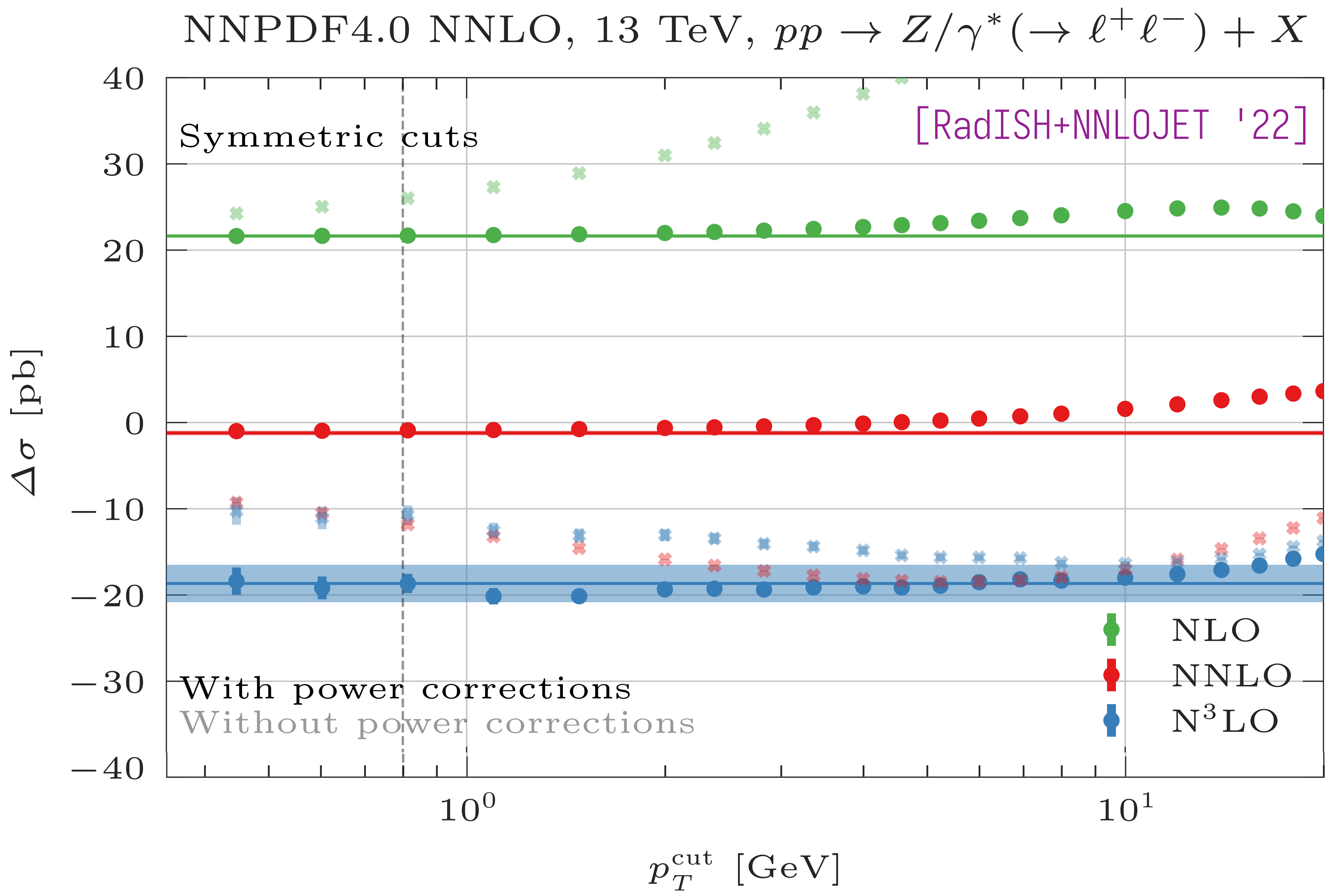


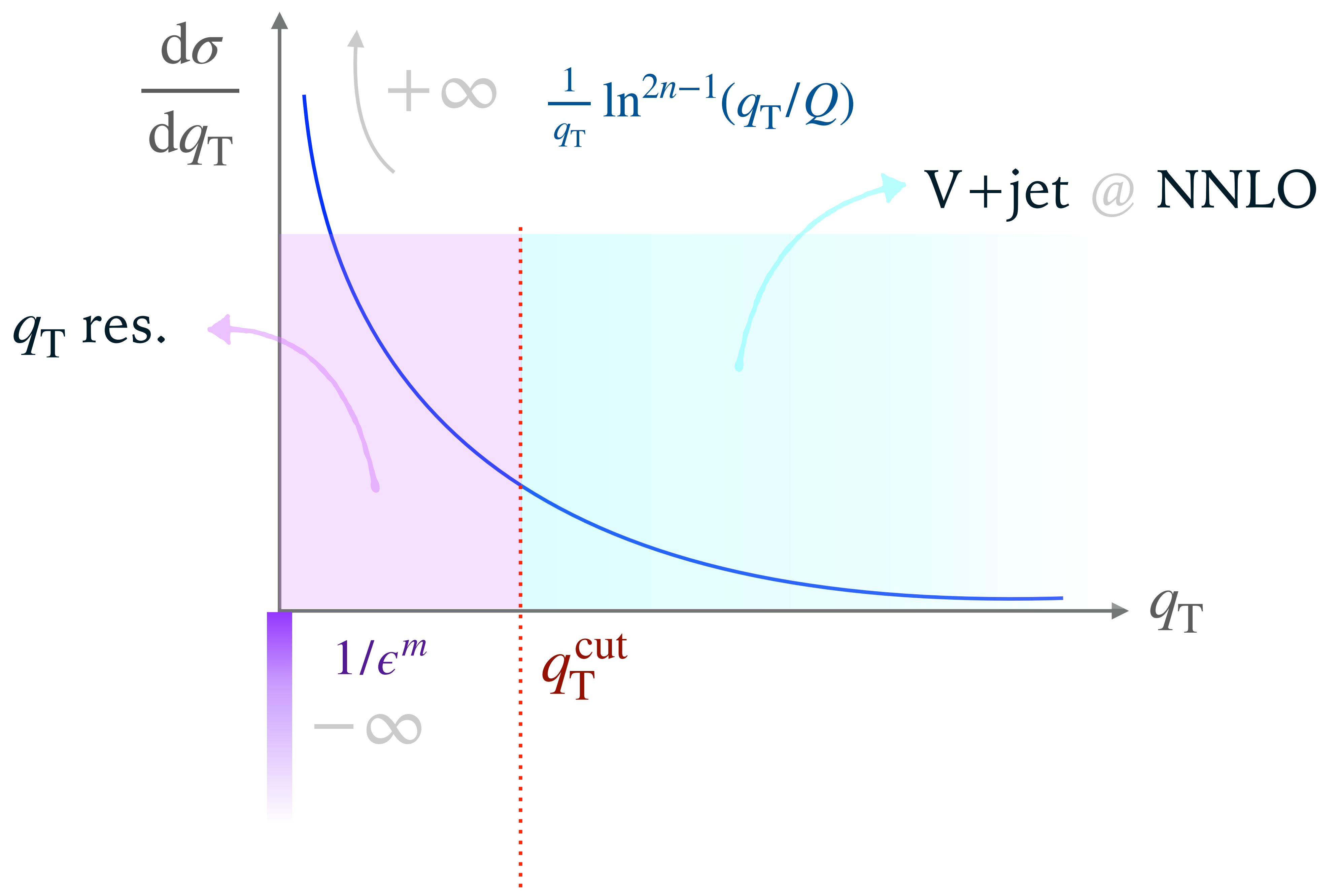
Fiducial Cuts and Linear Power Corrections — N³LO Slicing

- fiducial cuts ⇝ can jeopardise q_T slicing

$\mathcal{O}\left((q_T^{\text{cut}}/Q)^2\right)$ v.s. $\mathcal{O}\left(q_T^{\text{cut}}/Q\right)$

[$q_T^{\text{cut}} \lesssim 1\,\text{GeV}$] [$q_T^{\text{cut}} \lesssim 10^{-2}\,\text{GeV}$?!]





can *compute* & *subtract* the linear term:

↪ simple boost of $V \to \ell\bar{\ell}$ system

(pure kinematics & acceptance effect)

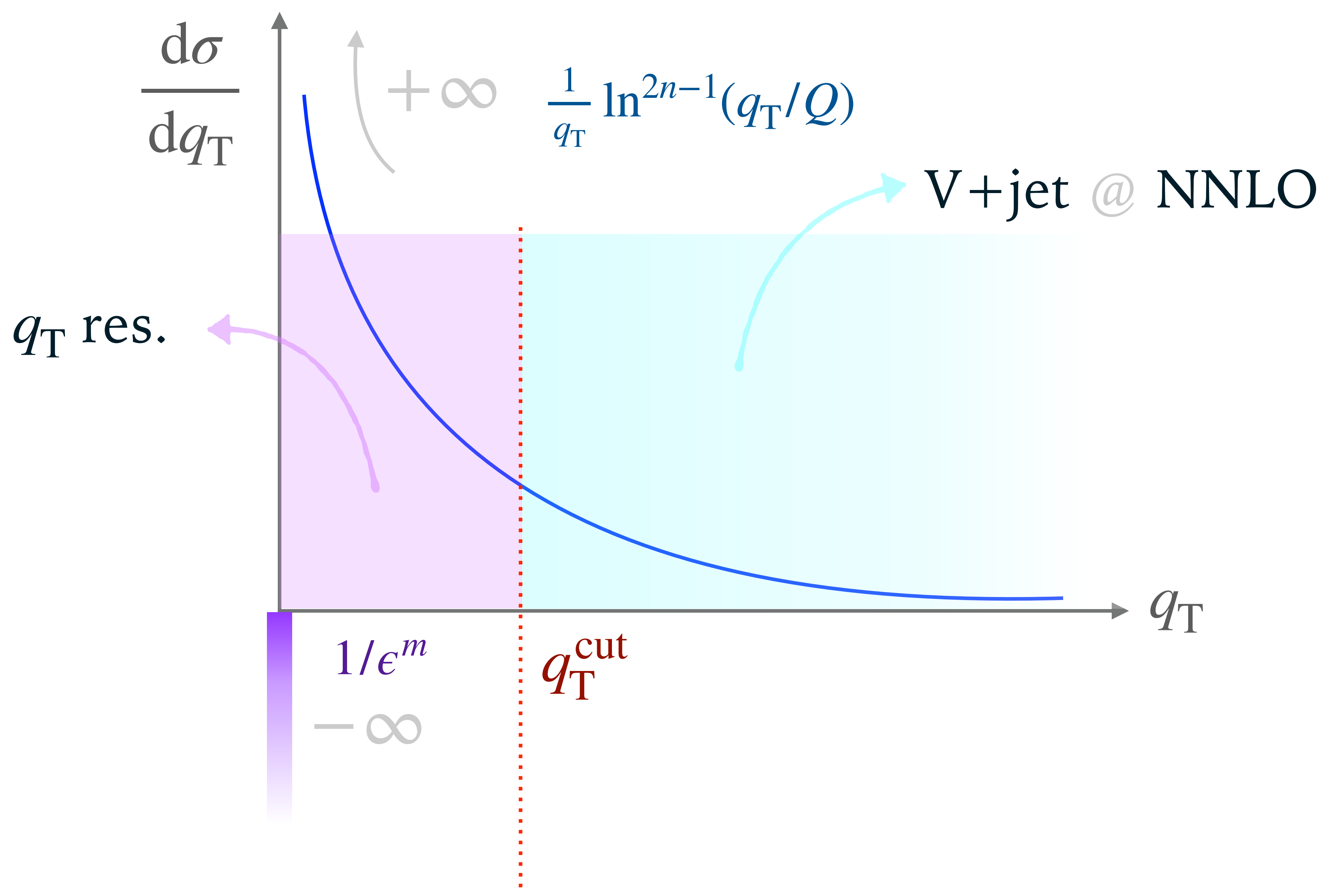
[Catani, de Florian, Ferrera, Grazzini '15]
[Ebert, Michel, Stewart, Tackmann '21]

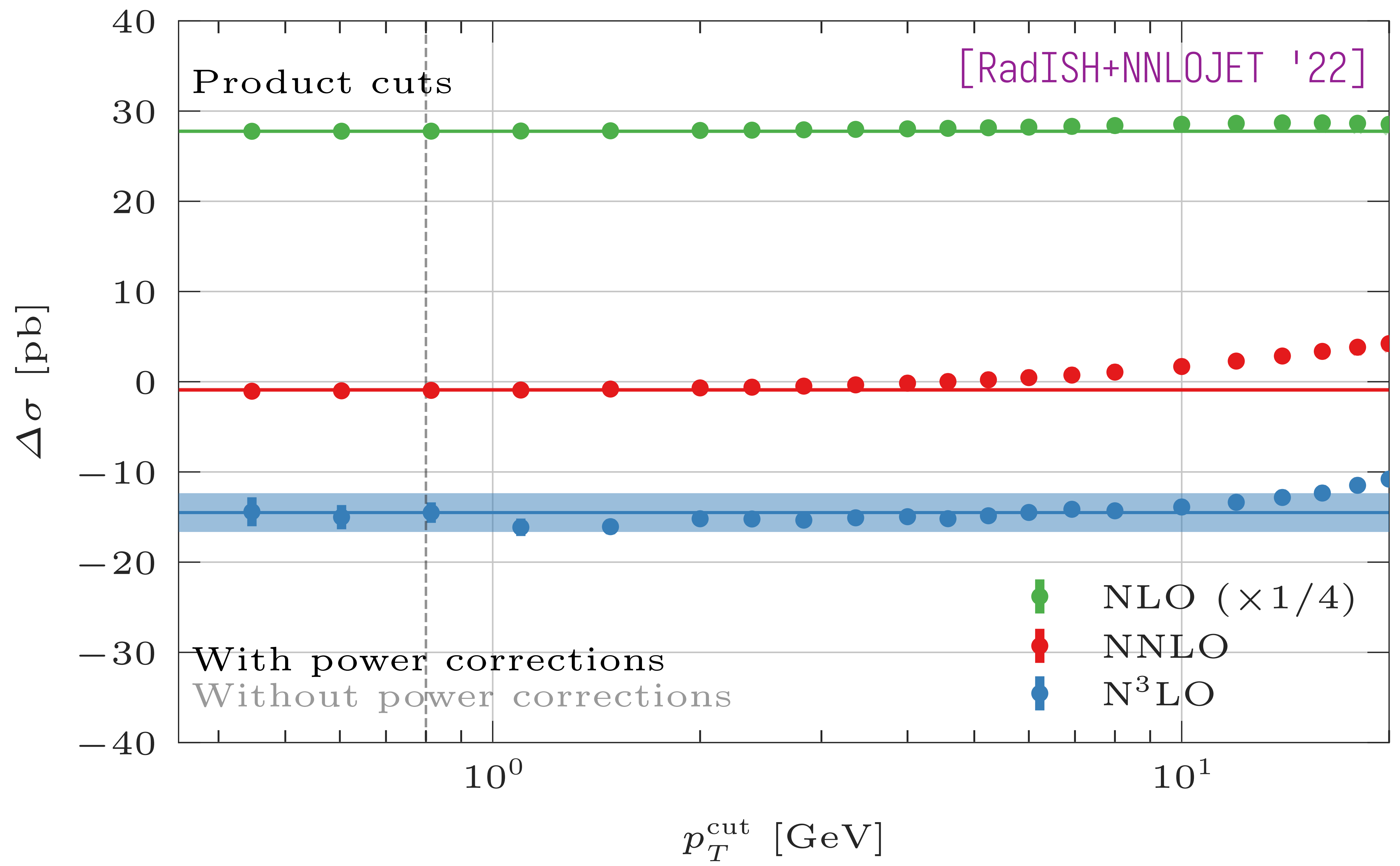
Fiducial Cuts and Linear Power Corrections — N³LO Slicing

- fiducial cuts ⇝ can jeopardise q_T slicing

$$\mathcal{O}\left((q_\mathrm{T}^\mathrm{cut}/Q)^2\right) \quad \text{v.s.} \quad \mathcal{O}\left(q_\mathrm{T}^\mathrm{cut}/Q\right)$$

$[q_\mathrm{T}^\mathrm{cut} \lesssim 1\,\mathrm{GeV}]$ $[q_\mathrm{T}^\mathrm{cut} \lesssim 10^{-2}\,\mathrm{GeV}$?!]

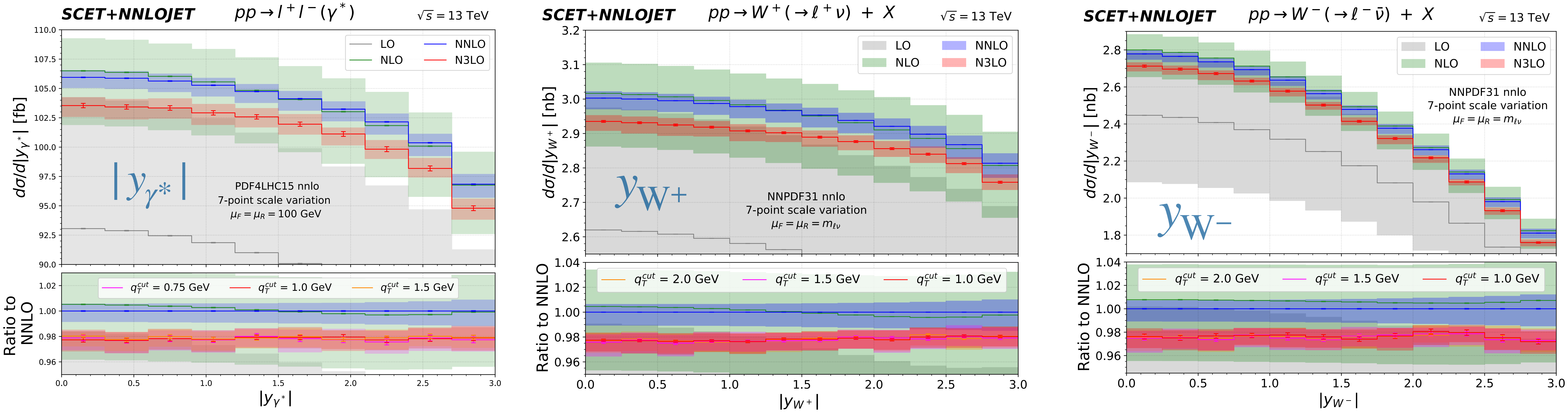




or use a setup that is not plagued by linear power corrections to start with
↪ here: product cuts

Drell–Yan @ N^{3}LO — Y_V Distributions

[Chen, Gehrmann, Glover, AH, Yang, Zhu '21,'22]

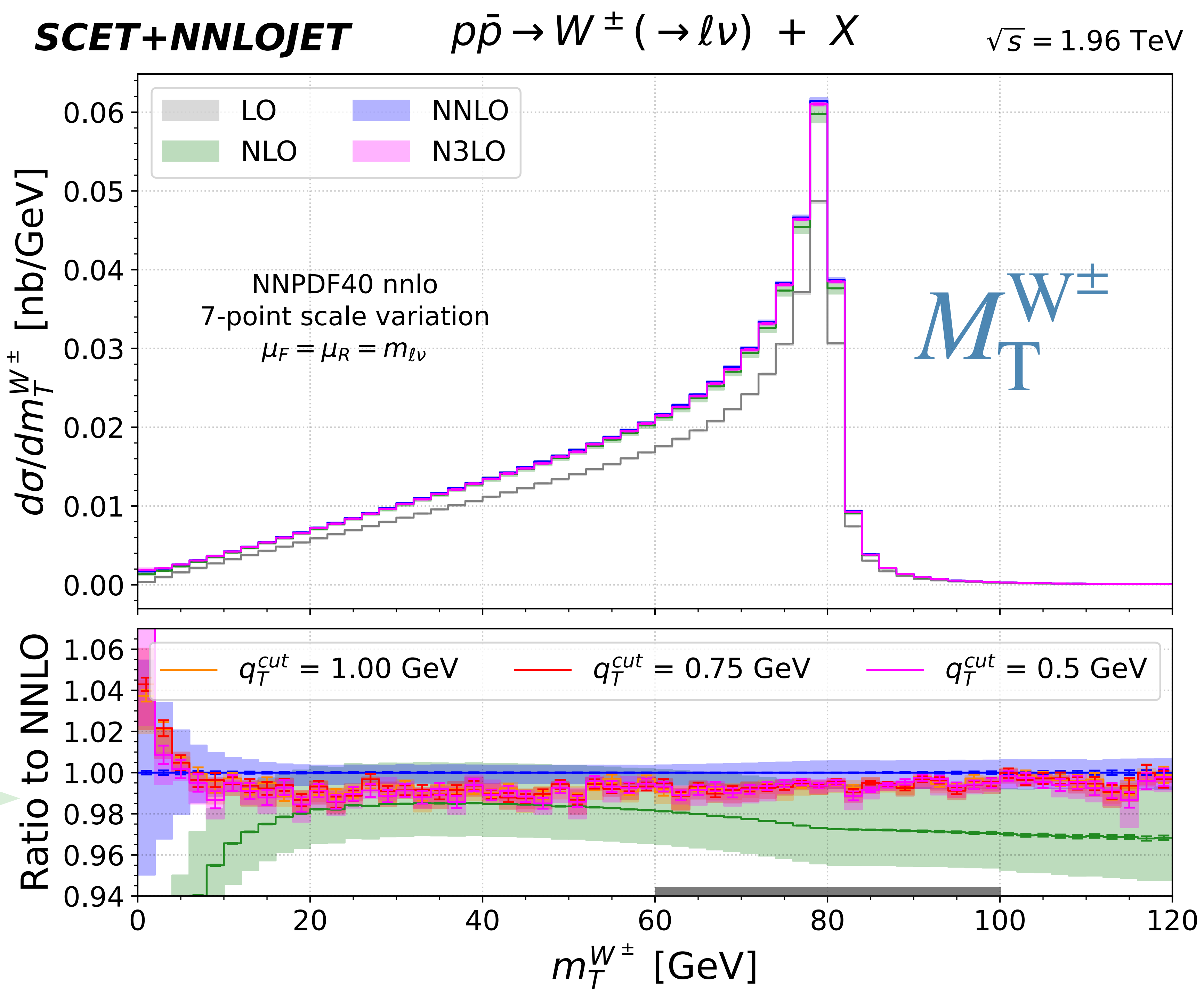


- same collider @ 13 TeV ⇝ almost universal NNLO → N^{3}LO corrections!
- NC & CC$^\pm$ processes probe different parton content across Y_V (valence u vs. d, …)

W Production — Absolute Spectrum

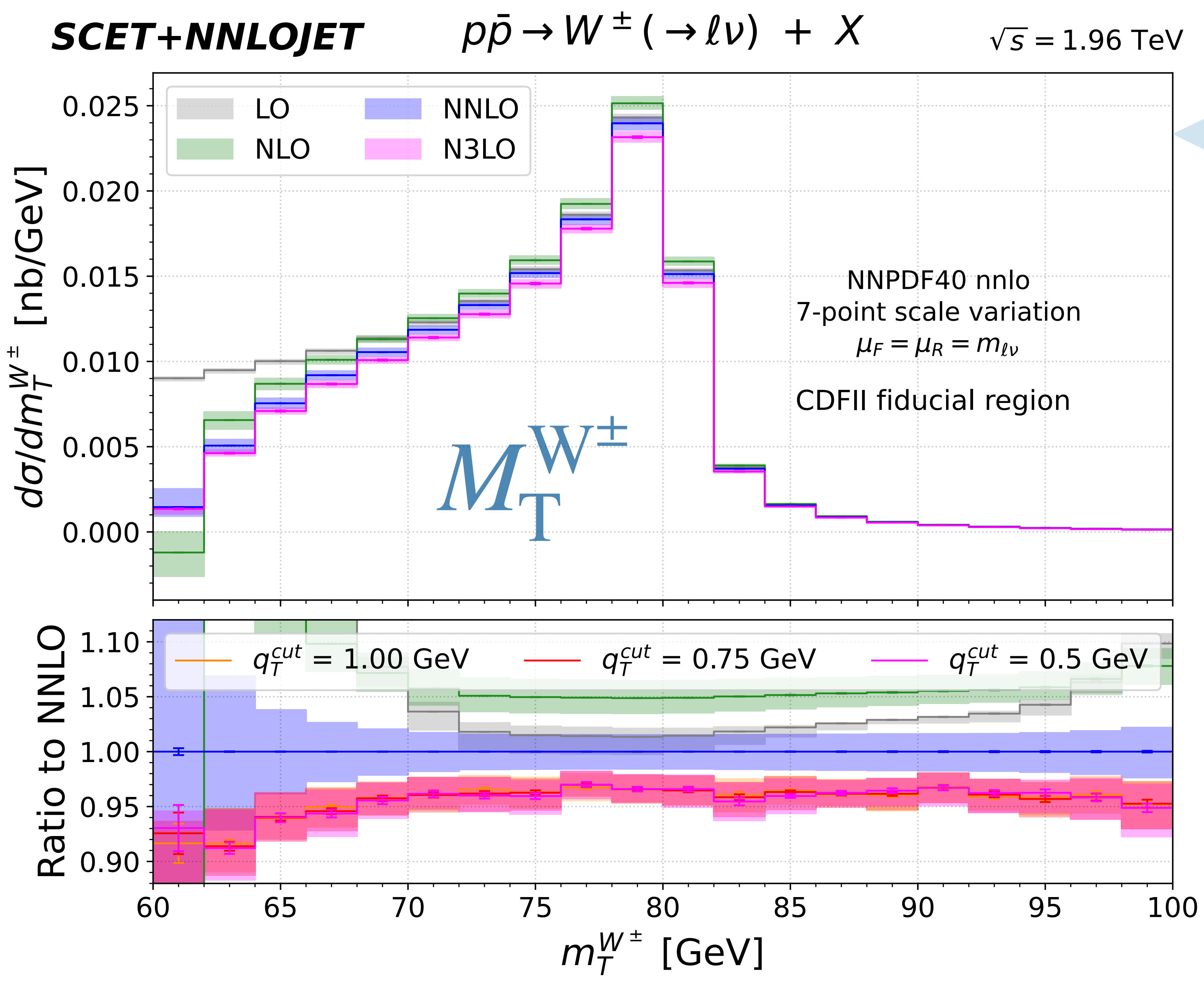
$$M_T^W \equiv \sqrt{E_T^\ell \, E_T^\nu \, (1 - \cos \Delta\varphi_{\ell\nu})}$$

Inclusive



1.96TeV – better convergence as seen in σ^{tot}

Fiducial (CDF II)



$p_T^\ell,\, E_T^{miss} \in [30, 55]$ GeV
$|\eta^\ell| < 1$
$p_T^W < 15$ GeV

LO
NLO
NNLO
N3LO

- remain largely flat around peak; larger corrections at low M_T^W
- fiducial cuts impact pattern of radiative corrections
- larger N³LO corrections ($-1\,\%$ [inc.] vs. $-4\,\%$ [fid.])

fiducial power corrections?

Drell–Yan @ Fixed Order

$$\sigma_{\mathrm{DY}} = \sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)} + \alpha_s^2\,\sigma^{(2,0)} + \alpha_s^3\,\sigma^{(3,0)} + \alpha_s^4\,\sigma^{(4,0)} + \ldots$$
$$\boxed{+\ \alpha\,\sigma^{(0,1)}} + \alpha_s\alpha\,\sigma^{(1,1)} + \alpha_s^2\alpha\,\sigma^{(2,1)} + \ldots$$
$$+\ \alpha^2\,\sigma^{(0,2)} + \ldots$$

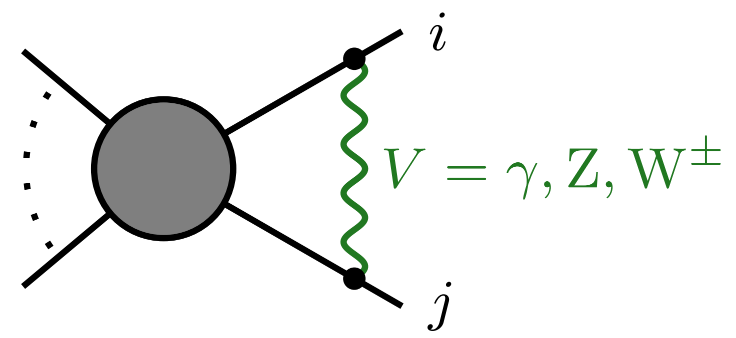
EW corrections

- NLO has been known for a long time
  [Dittmaier, Kramer '02], [Baur,Wackeroth '04], [Baur, Brein, Hollik, Schappacher, Wackeroth '02]
- automated in different generators
  ↪ comparison: [Les Houches 2017, 1803.07977]
- dictionary for EW corrections
  ↪ "Electroweak Radiative Corrections for Collider Physics" [Denner, Dittmaier '20]
- EWWG benchmark exercise
  ↪ "Precision Studies of Observables in [DY] processes at the LHC" [Alioli et al. '16: 1606.02330]

Systematic enhancements possible

Sudakov Logarithms

(kinematic tails)



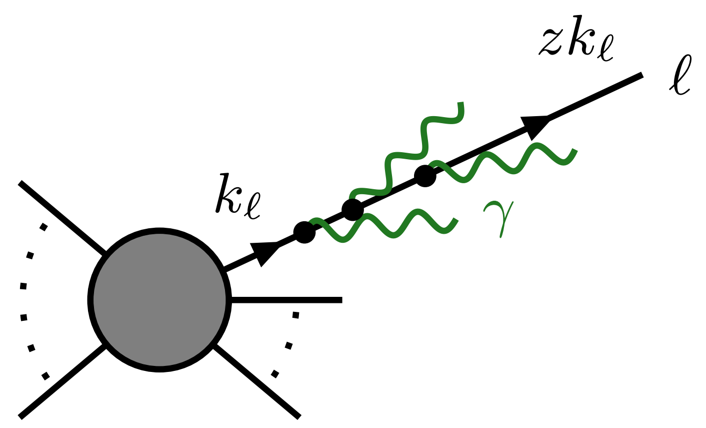
$$\sim \ln^2\left(\frac{s_{ij}}{M_{\mathrm{W}}^2}\right) + \text{sub-leading (collinear)}$$

O(10-20%) corrections!

[Kuhn, Smirnov, Penin], [Ciafaloni, Ciafaloni, Comelli], [Denner, Pozzorini '01]

Final-State Radiation

(resonances, shoulders, …)



$$\rightsquigarrow \alpha^n \ln^n\left(\frac{Q^2}{m_\ell^2}\right)$$

dressed: $\ln(R)$

O(10-100%) corrections!

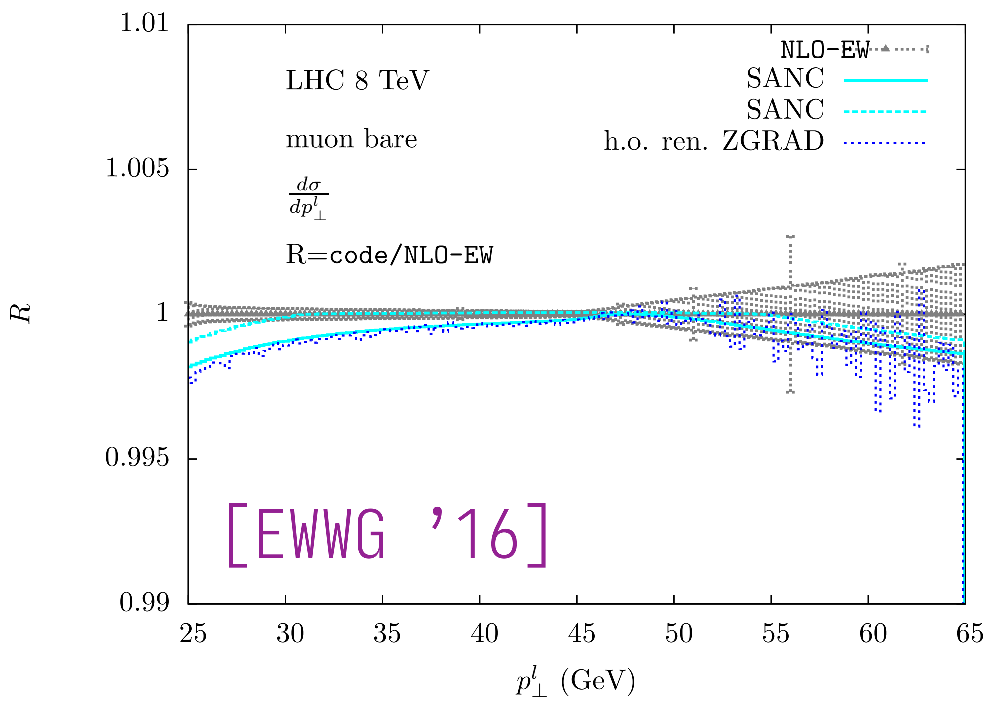
Structure function (LL up to $\mathcal{O}(\alpha^3)$), MC: Photos, Pythia, Sherpa, …

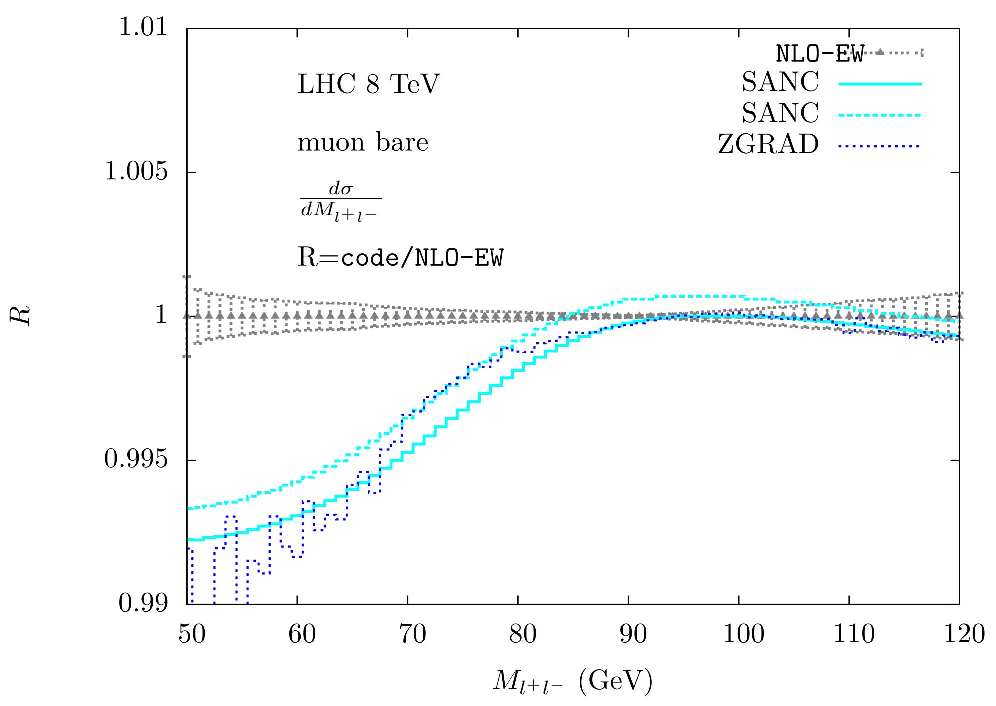
Higher-Order Radiative Effects & Scheme Choices

Universal h.o. corrections

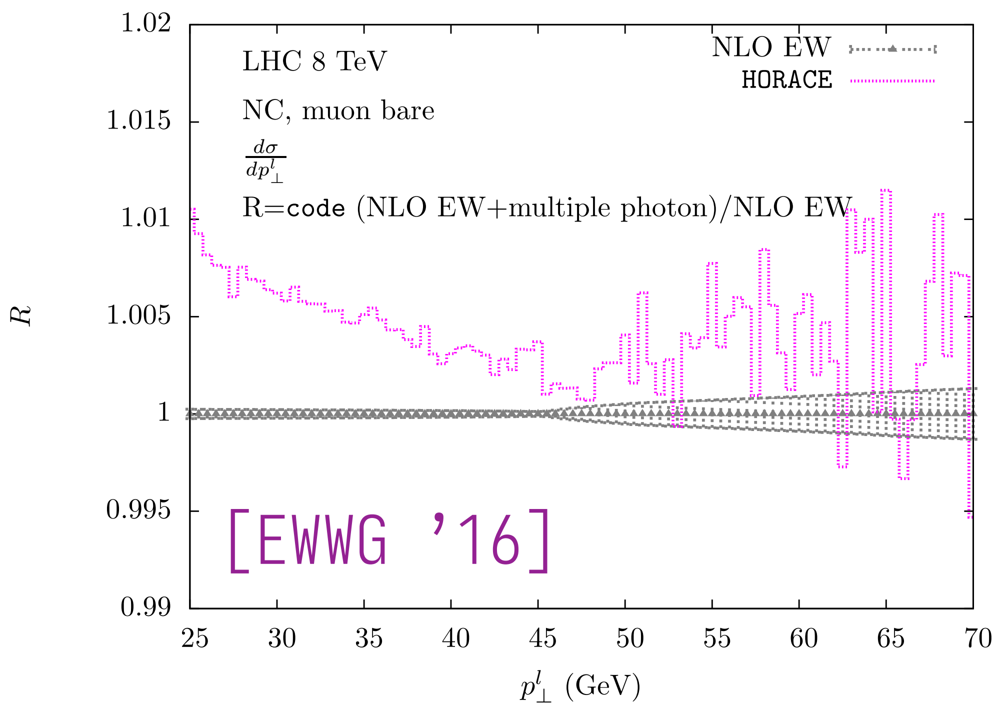
- NC in G_μ scheme: leading m_t

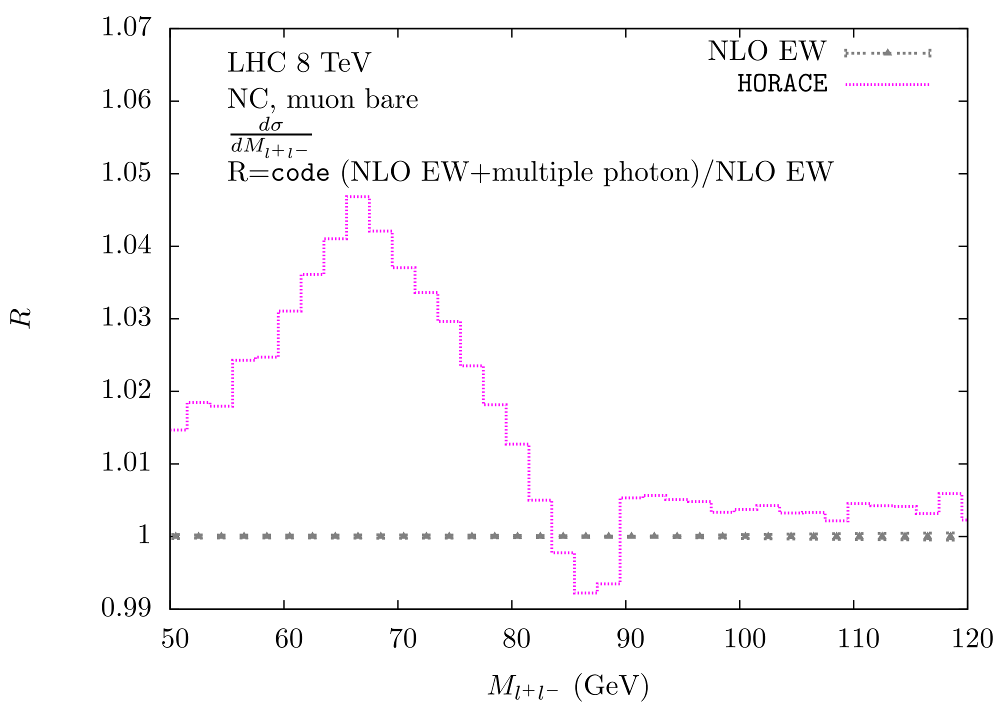
$$s_W^2 \to \bar{s}_W^2 \equiv s_W^2 + \Delta\rho\, c_W^2\,, \qquad c_W^2 \to \bar{c}_W^2 \equiv 1 - \bar{s}_W^2 = (1-\Delta\rho)\,\bar{c}_W^2$$





Higher-order QED emissions

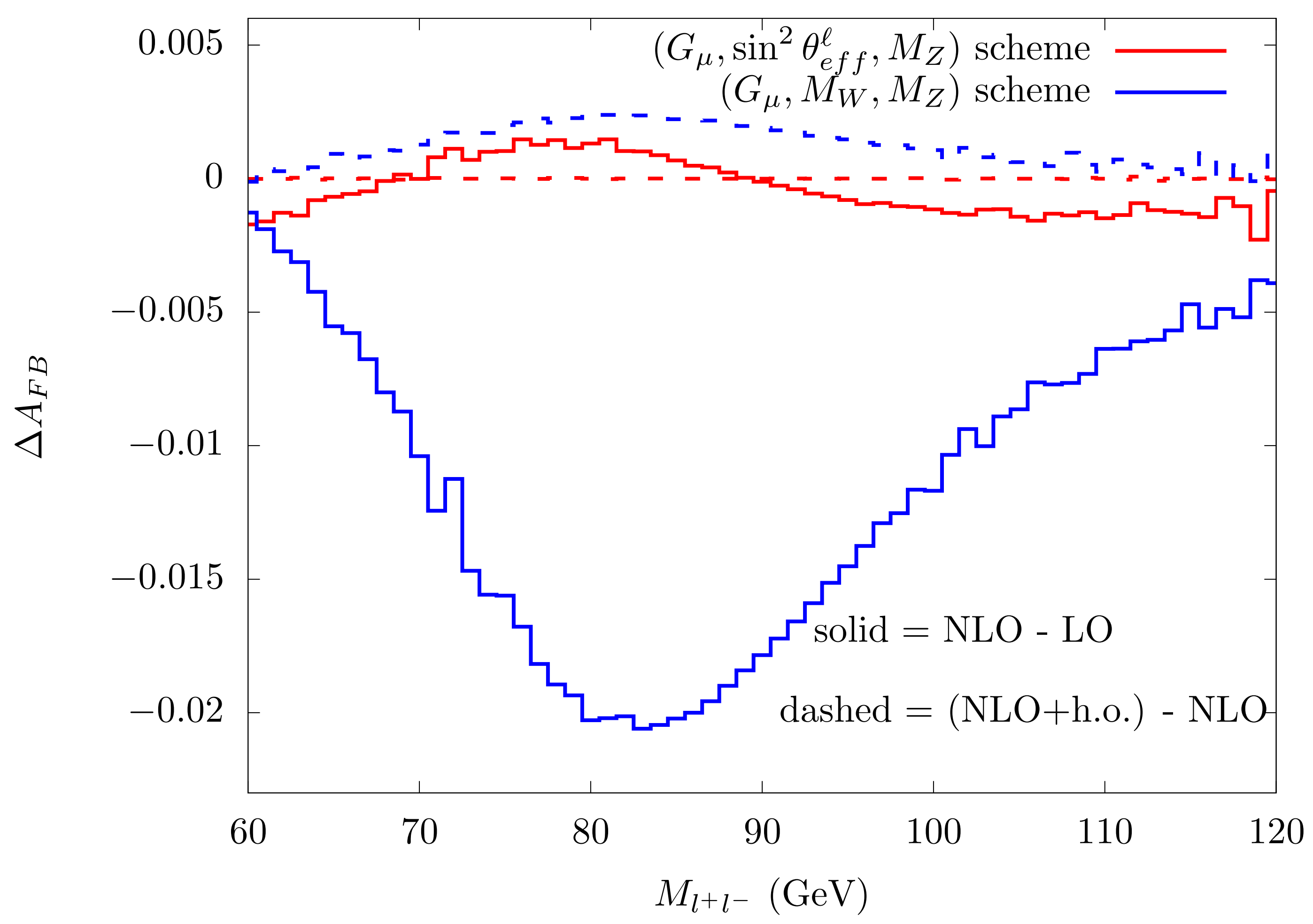




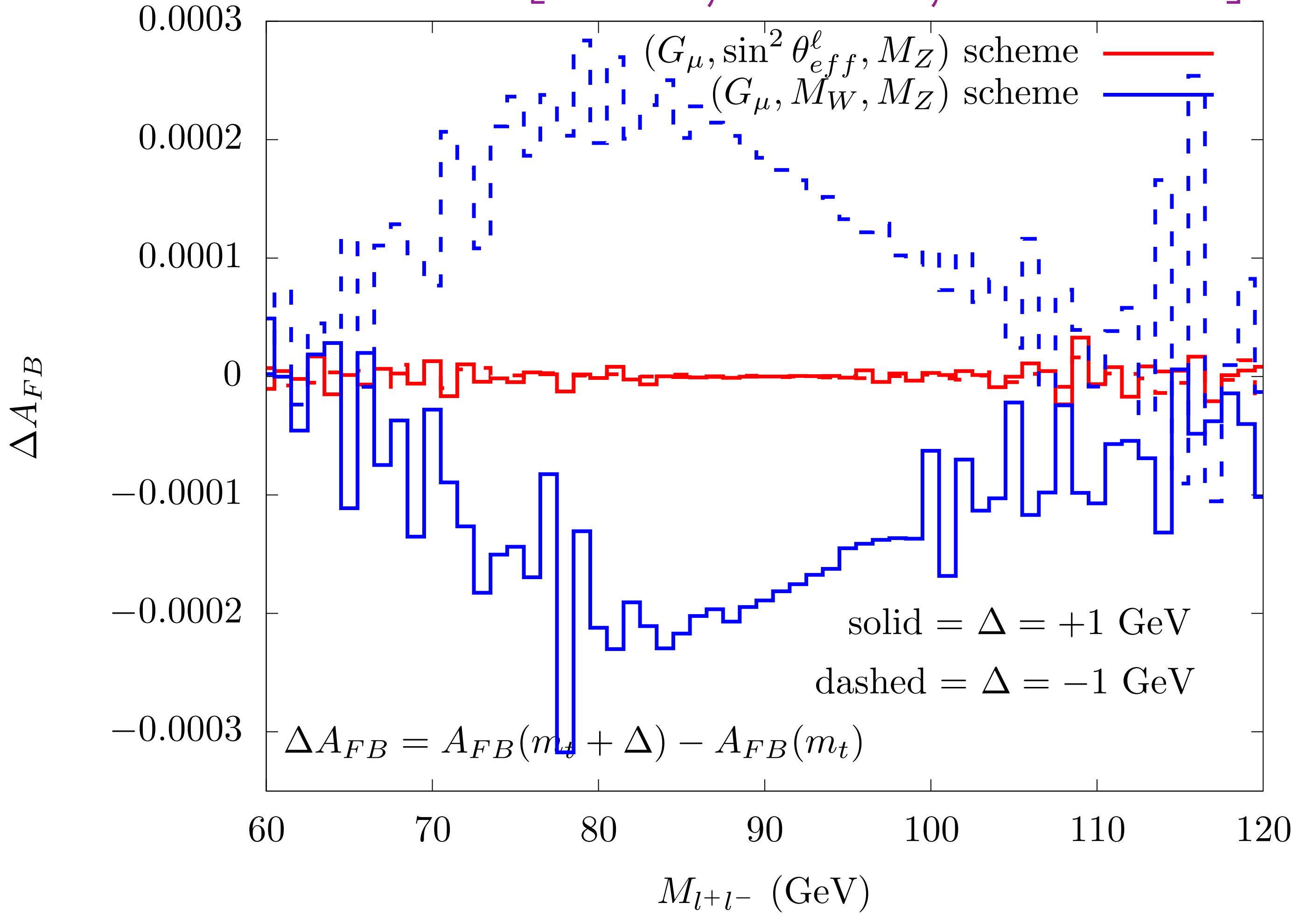
Input scheme: $\sin^2\theta^\ell_{\rm eff}$ as parameter

- (G_μ, M_W, M_Z) v.s. $(G_\mu, \sin^2\theta^\ell_{\rm eff}, M_Z)$
  - ↪ make POI an input parameter
  - ↪ leading m_t: $G_\mu \to G_\mu\,(1 + \Delta\rho^{(1)} + \Delta\rho^{(2)})$

[Chiesa, Piccini, Vicini '19]



improved pert. conv. (smaller "+h.o." effects)



smaller param. sensitivity (smaller dependence on m_t)

DRELL–YAN @ FIXED ORDER

$$\sigma_{\rm DY} = \sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)} + \alpha_s^2\,\sigma^{(2,0)} + \alpha_s^3\,\sigma^{(3,0)} + \alpha_s^4\,\sigma^{(4,0)} + \ldots$$
$$+\ \alpha\,\sigma^{(0,1)} \boxed{+\ \alpha_s\alpha\,\sigma^{(1,1)}} + \alpha_s^2\alpha\,\sigma^{(2,1)} + \ldots$$
$$+\ \alpha^2\,\sigma^{(0,2)} + \ldots$$

Mixed QCD×EW corrections

- RESONANT / ON-SHELL
  - pole expansion [Dittmaier, AH, Schwinn '14,'15] [Dittmaier, AH, Schwarz '24]
  - $\sigma_Z^{\rm tot}$ (QCD×QED) [de Florian, Der, Fabre '18]
  - on-shell Z (QCD×QED) [Delto, Jaquier, Melnikov, Röntsch '19]
  - $\sigma_Z^{\rm tot}$ [Bonciani, Buccioni, Rana, Vicini '20]
  - on-shell
    [Buccioni, Caola, Delto, Jaquier, Melnikov, Roentsch '20]
    [Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch '20]

- FULLY OFF-SHELL
  - W
    [Buonocore, Grazzini, Kallweit, Savoini, Tramontano '21]
  - Z
    [Bonciani, Buonocore, Grazzini, Kallweit, Rana, Tramontano, Vicini '21]
    [Buccioni, Caola, Chawdhry, Devoto, Heller, von Manteuffel, Melnikov, Rontsch, Signorile-Signorile '22]

q_T slicing, dressed leptons

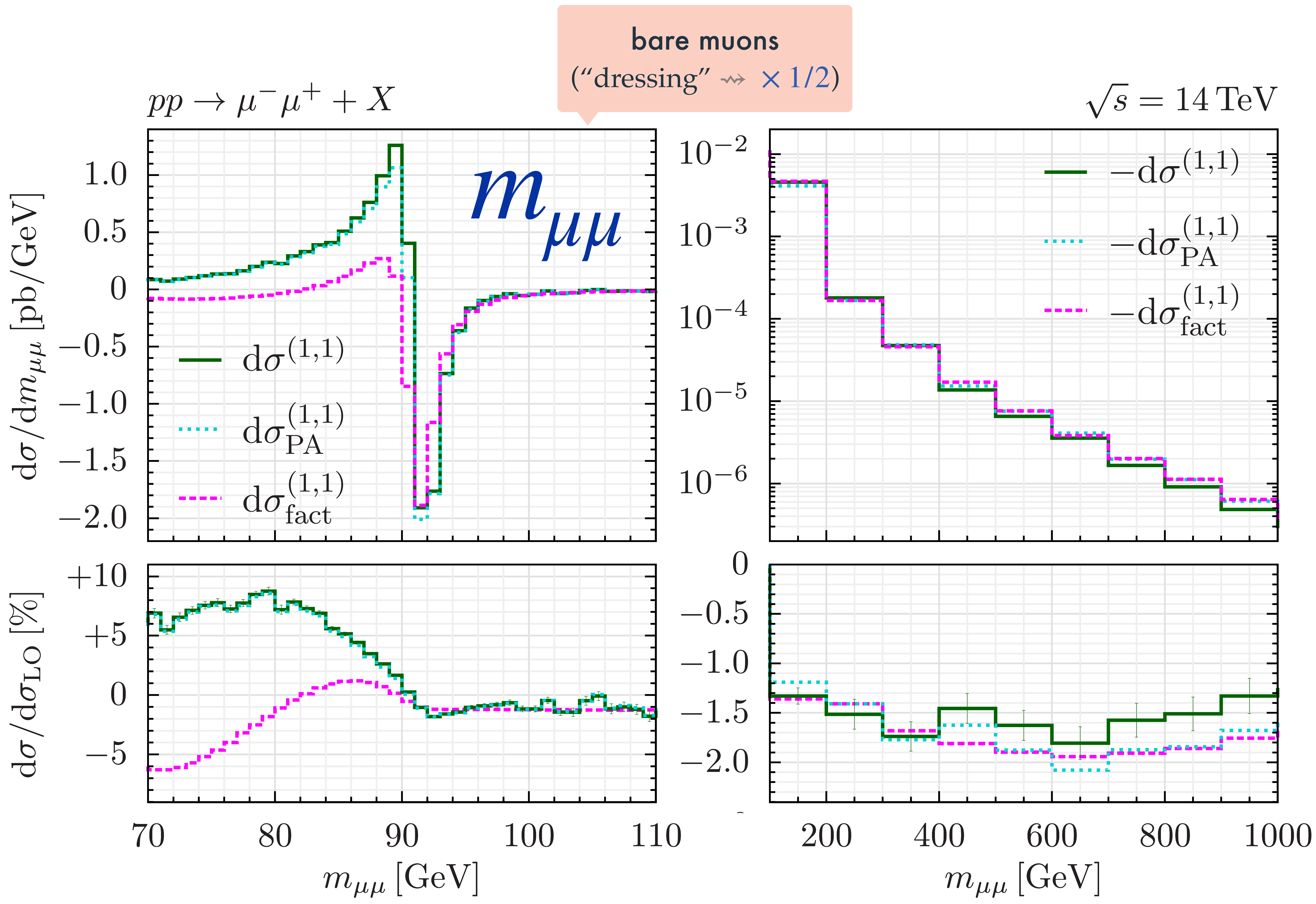
σ [pb]	$\sigma_{\rm LO}$	$\sigma^{(1,0)}$	$\sigma^{(0,1)}$	$\sigma^{(2,0)}$	$\sigma^{(1,1)}$
$q\bar{q}$	1561.52(5)	340.3(3)	−49.77(5)	44.6(4)	−15.7(7)
qg	—	0.0601(3)	—	−32.7(2)	2.15(7)
$q\gamma$	—	—	−0.30(2)	—	−0.231(9)
$g\gamma$	—	—	—	–	0.266(1)
gg	—	—	—	2.02(6)	—
$\gamma\gamma$	59.645(6)	—	3.174(9)	—	—

Nested-soft collinear, dressed leptons

σ[fb]	$\sigma^{(0,0)}$	$\delta\sigma^{(1,0)}$	$\delta\sigma^{(0,1)}$	$\delta\sigma^{(2,0)}$	$\delta\sigma^{(1,1)}$
$q\bar{q}$	1561.42	340.31	−49.907	44.60	−14.78
$\gamma\gamma$	59.645		3.166		
qg		0.060		−32.66	2.07
$q\gamma$			−0.305		−0.227
$g\gamma$					0.2668
gg				1.934	

NC-DY — Quality of Approximations

[Bonciani, Buonocore, Grazzini, Kallweit, Rana, Tramontano, Vicini '21]



- $\sigma^{\mathrm{NNLO}_{s\otimes ew}}$
- $\sigma^{\mathrm{NNLO}_{s\otimes ew}}_{\mathrm{PA}}$
- $\sigma^{\mathrm{NNLO}_{s\otimes ew}}_{\text{naive prod.}}$

- naive product not able to capture kinematic entanglement
  - ↪ fails below resonance ($m_{\ell\ell}$)
  - ↪ fails away from shoulder (p_T^μ)
- pole approximation (PA)
  - ↪ captures full result around M_Z
  - ↪ deteriorates in high-mass tails
  - ↪ *performance:* faster cal^n

NC-DY — Forward–Backward Asymmetry

- One of the main observables to measure $\sin^2\theta^{\ell}_{\mathrm{eff}}$

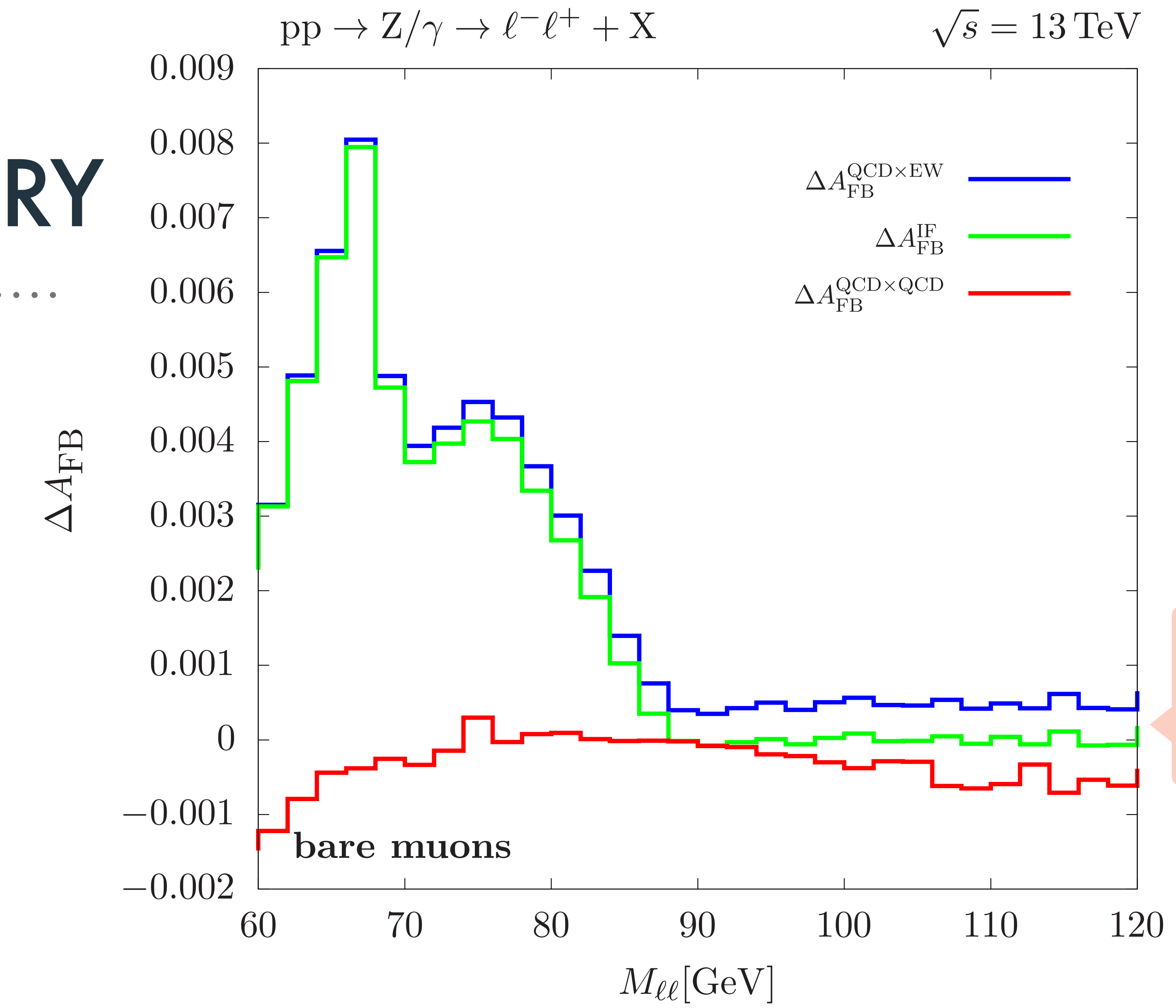
$$A_{\mathrm{FB}}(M_{\ell\ell}) = \frac{\sigma_{\mathrm{F}}(M_{\ell\ell}) - \sigma_{\mathrm{B}}(M_{\ell\ell})}{\sigma_{\mathrm{F}}(M_{\ell\ell}) + \sigma_{\mathrm{B}}(M_{\ell\ell})}$$

$$\sigma_{\mathrm{F}}(M_{\ell\ell}) = \int_0^1 \mathrm{d}\cos\theta^* \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} \qquad \sigma_{\mathrm{B}}(M_{\ell\ell}) = \int_{-1}^0 \mathrm{d}\cos\theta^* \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}$$

Impact of radiative corrections (PA)

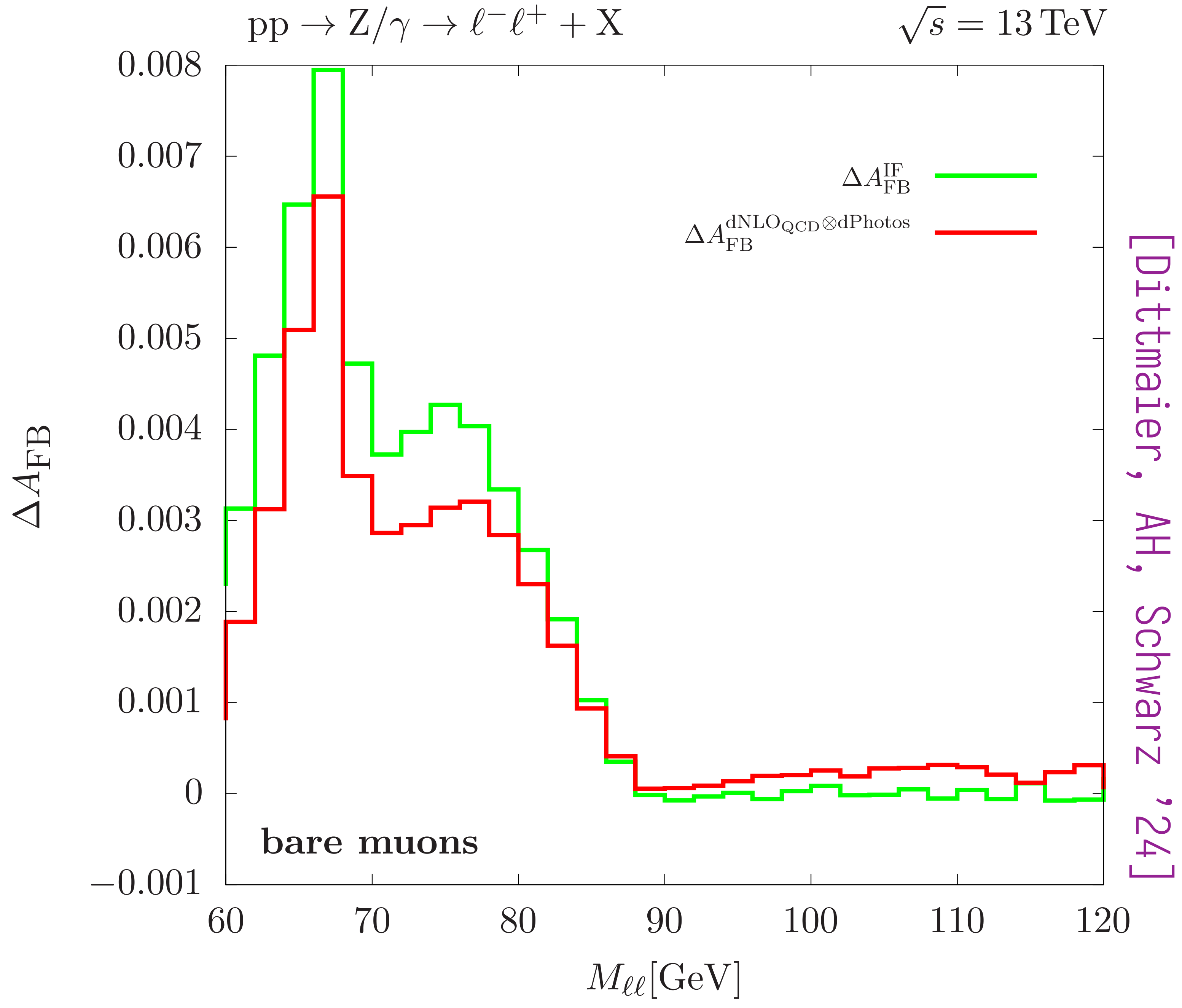
$$\Delta A^{x}_{\mathrm{FB}} = A^{\mathrm{LO}+\delta^x}_{\mathrm{FB}} - A^{\mathrm{LO}}_{\mathrm{FB}}$$

- LEP/SLC ⇝ $\Delta A_{\mathrm{FB}} \sim 10^{-3}$
  ↪ *target for LHC:* few 10^{-4} @ Z resonance
- multi-photon ~ 10^{-3}, EWHO ~ few 10^{-4}
  QCD² ~ few 10^{-4} (QCD³ likely similar),
  QCD×EW ~ few 10^{-3} (FF ~ 10^{-4}, II/NF ~ 0)
- QCD⊗Photos degrades c.f. other observables



QCD×EW
QCD$_\mathrm{I}$×EW$_\mathrm{F}$
QCD²

bare muons
("dressing" ⇝ × 1/2)



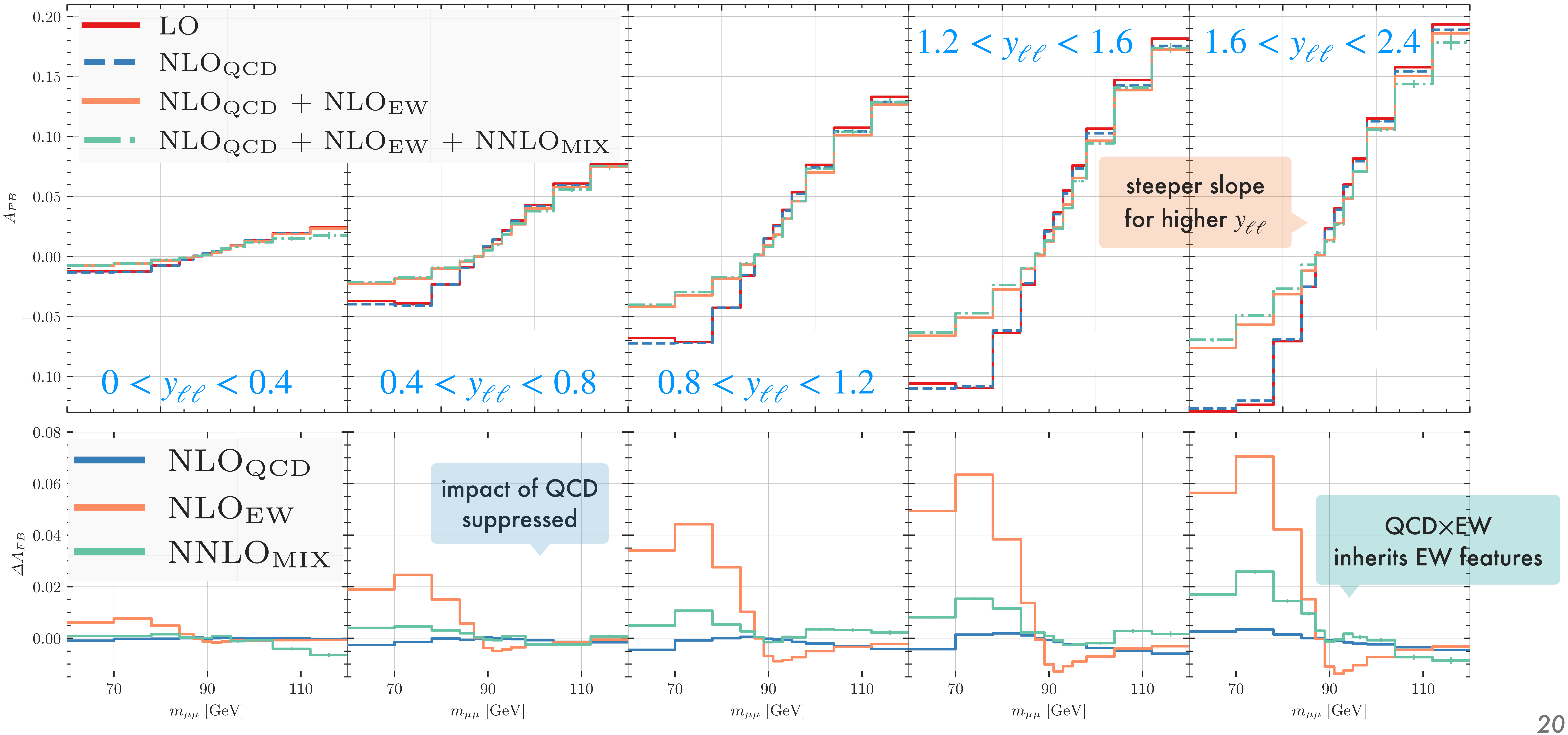
QCD$_\mathrm{I}$×EW$_\mathrm{F}$
QCD⊗Photos

[Dittmaier, AH, Schwarz '24]

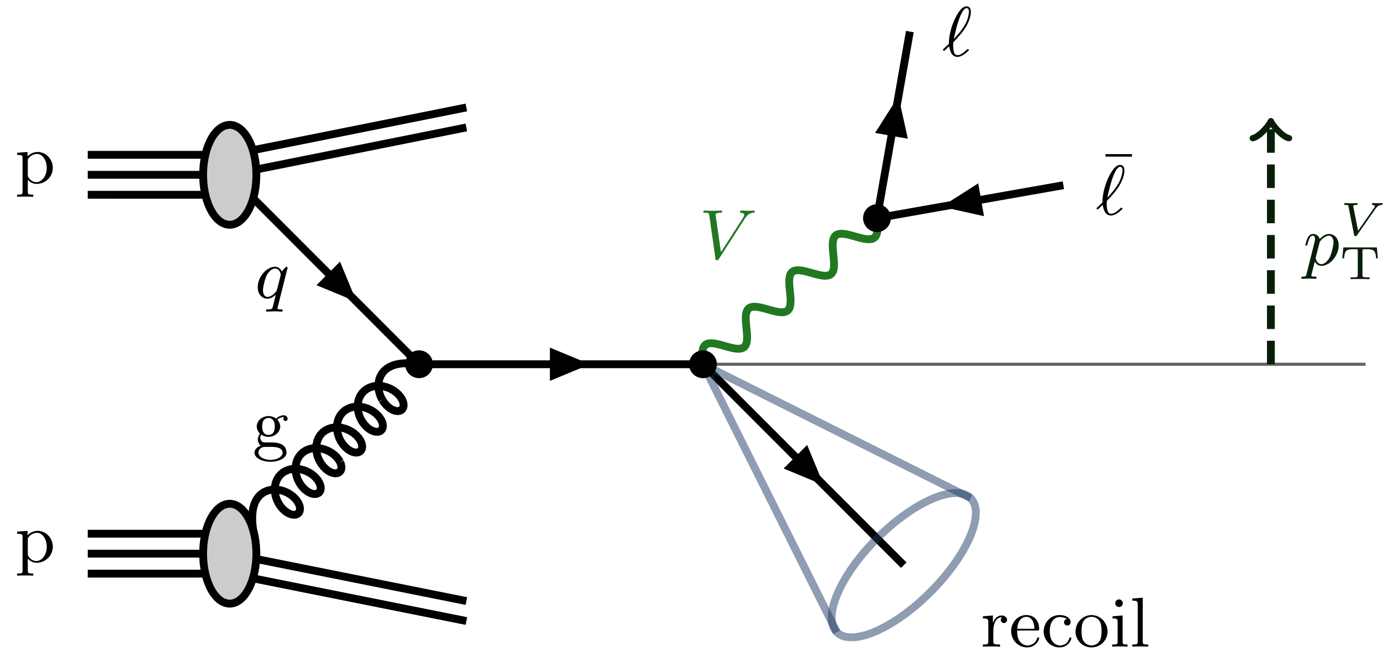
* $\cos\theta^*$ Collins-Soper angle $\cos\theta^* = \frac{|k^3_{\ell\ell}|}{k^3_{\ell\ell}} \frac{2}{M_{\ell\ell}\sqrt{M^2_{\ell\ell}+k^2_{\mathrm{T},\ell\ell}}}\left(k^+_\ell k^-_{\bar\ell} - k^+_{\bar\ell} k^-_\ell\right)$

NC-DY — Forward–Backward Asymmetry

[Armadillo, Bonciani, Buonocore, Devoto, Grazzini, Kallweit, Rana, Vicini '25]



q_T — The Transverse Momentum



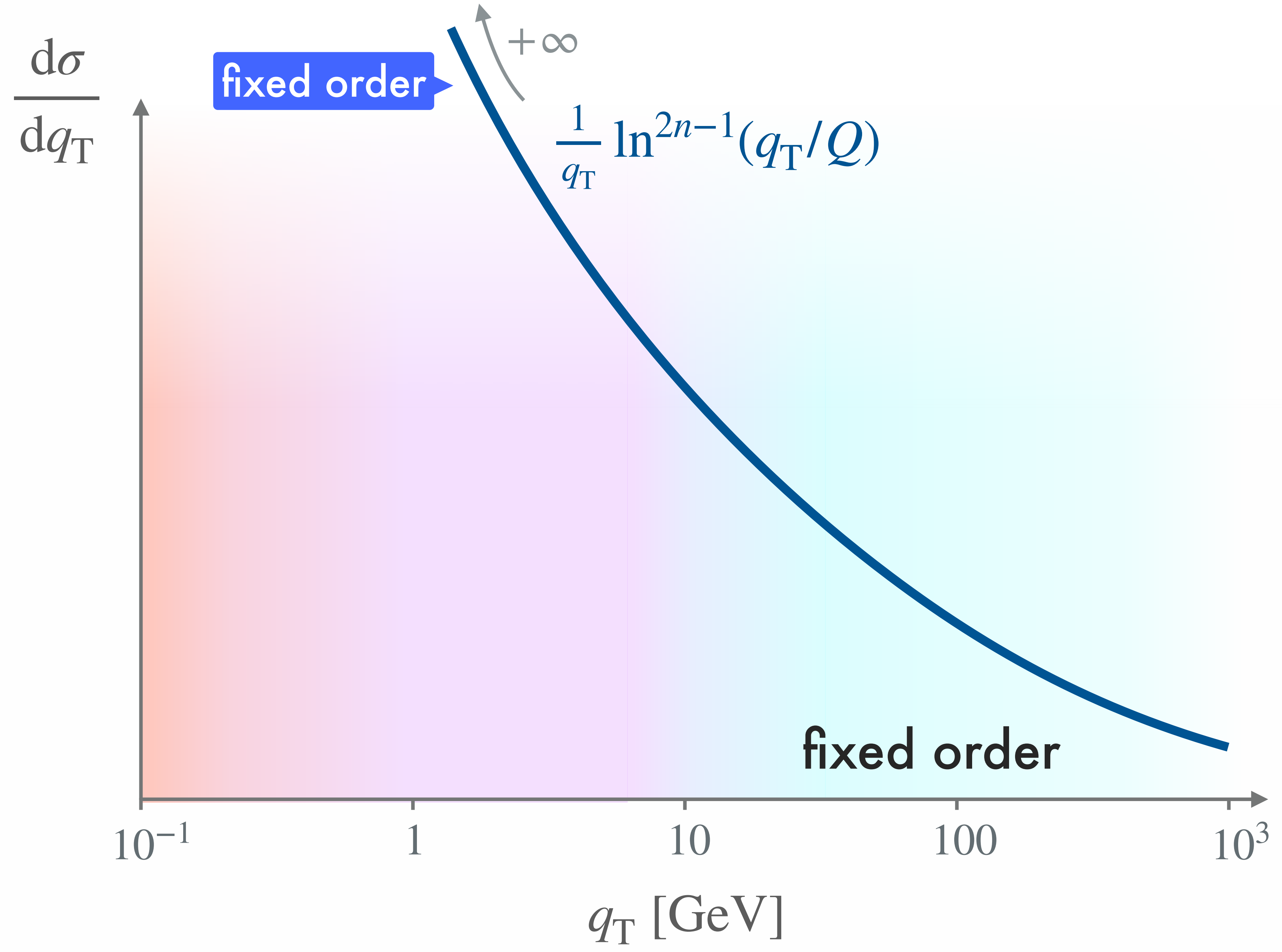
⇒ direct sensitivity to α_s

& PDFs (high-x gluon)

precision TH tests

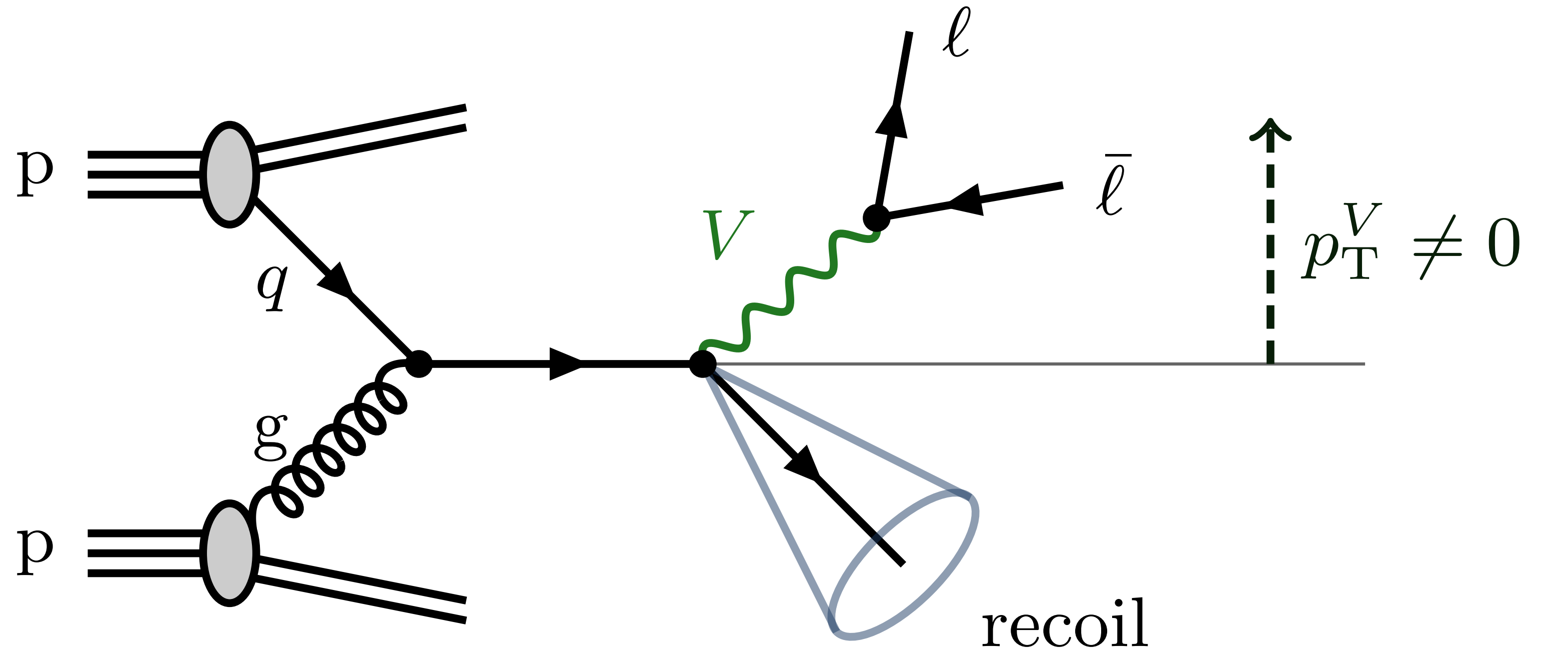
↪ non-perturbative QCD ⟩ quark masses ⟩ resummation ⟩ fixed-order ⟩ EW Sudakovs ⟩ …

↪ crucial ingredient in many precision measurements



$\mathcal{O}(\alpha_s^n)$ for Drell-Yan ⇜⇝ N^{n}LO$_0$ for e.g. σ^tot, $M_{\ell\ell}$, Y_V, p_T^ℓ, … ⇜⇝ N^{n-1}LO$_1$ for p_T^V, …

q_T – The Transverse Momentum



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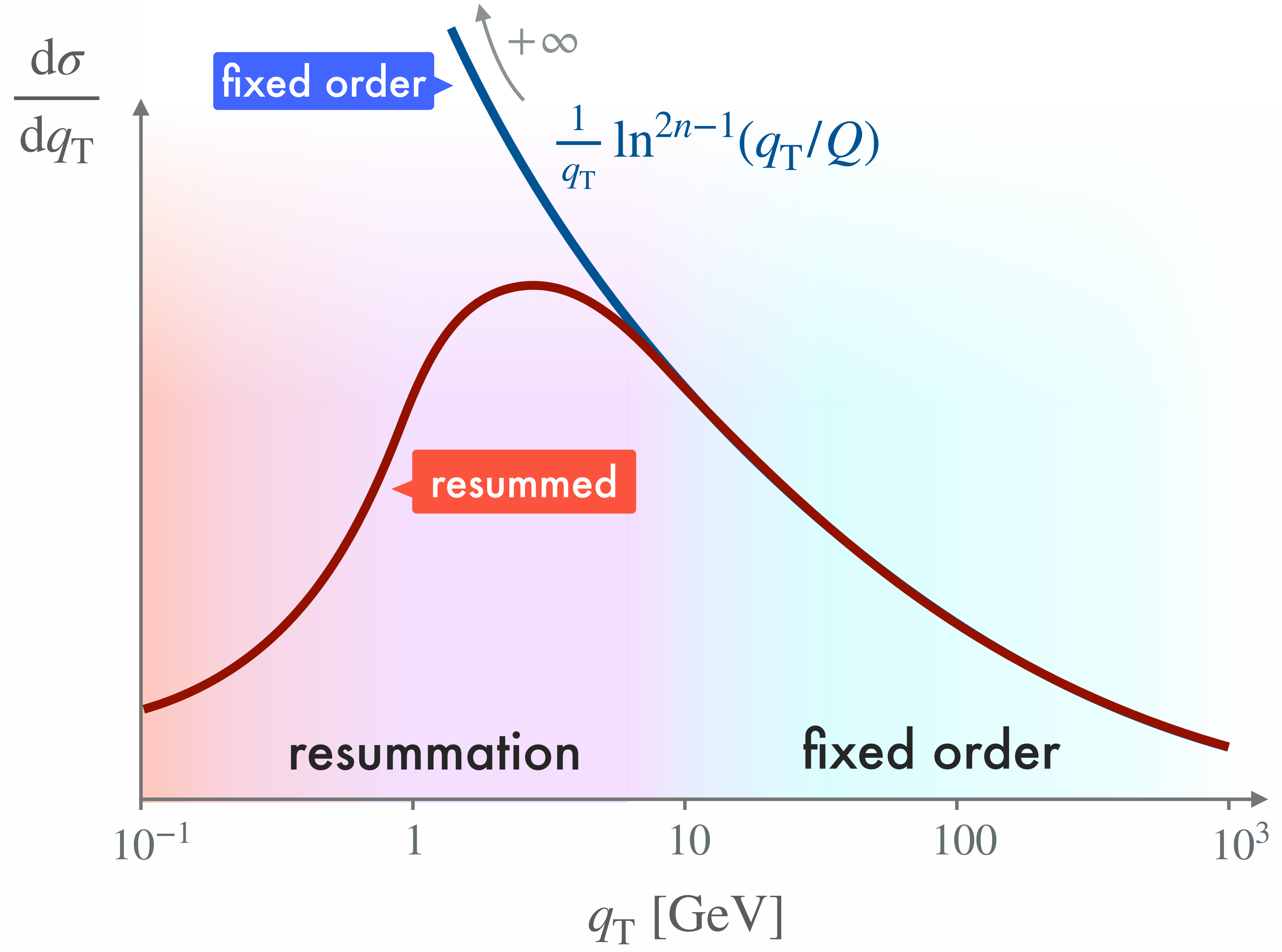
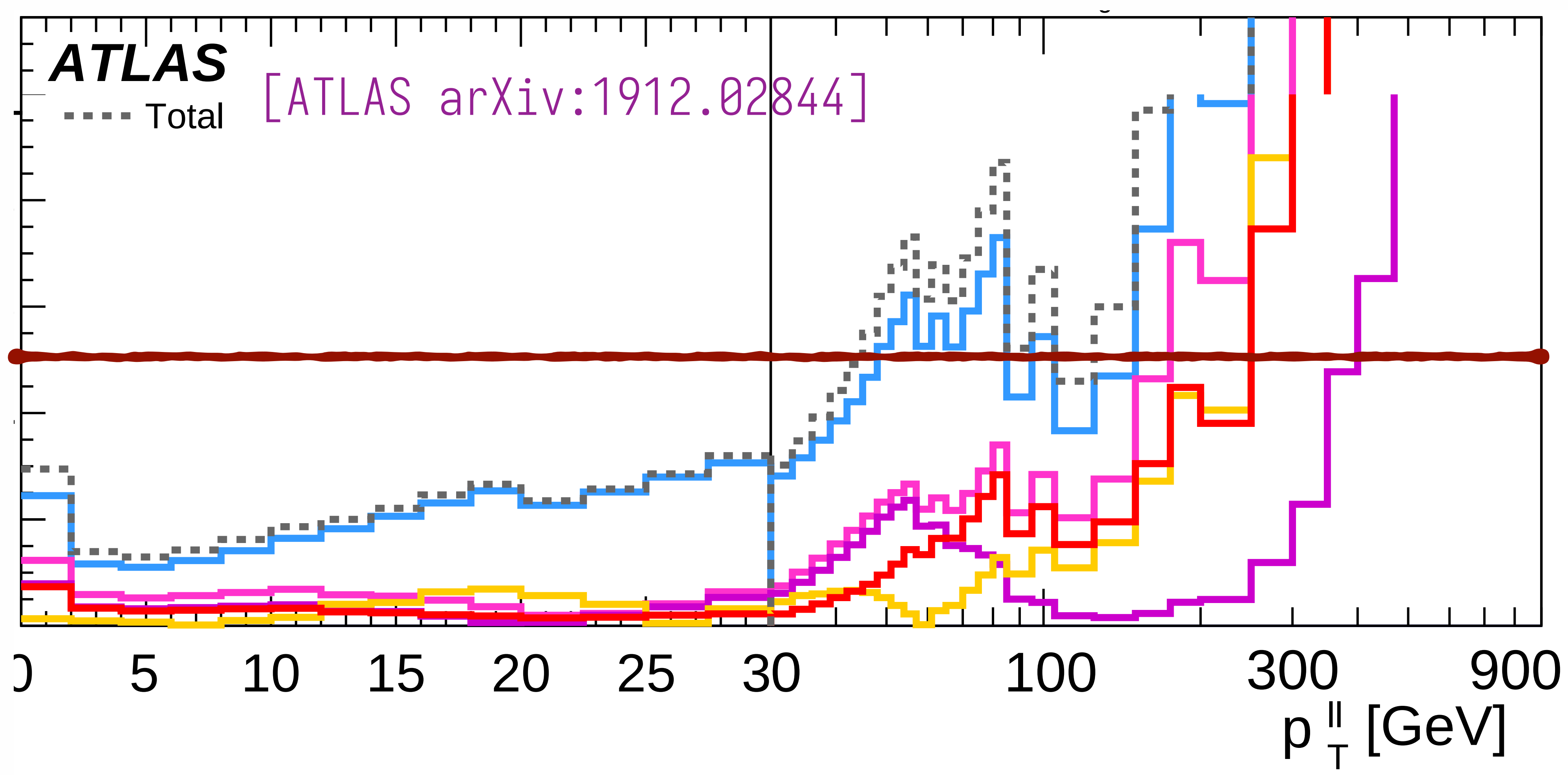
big TH challenge!

0.5%

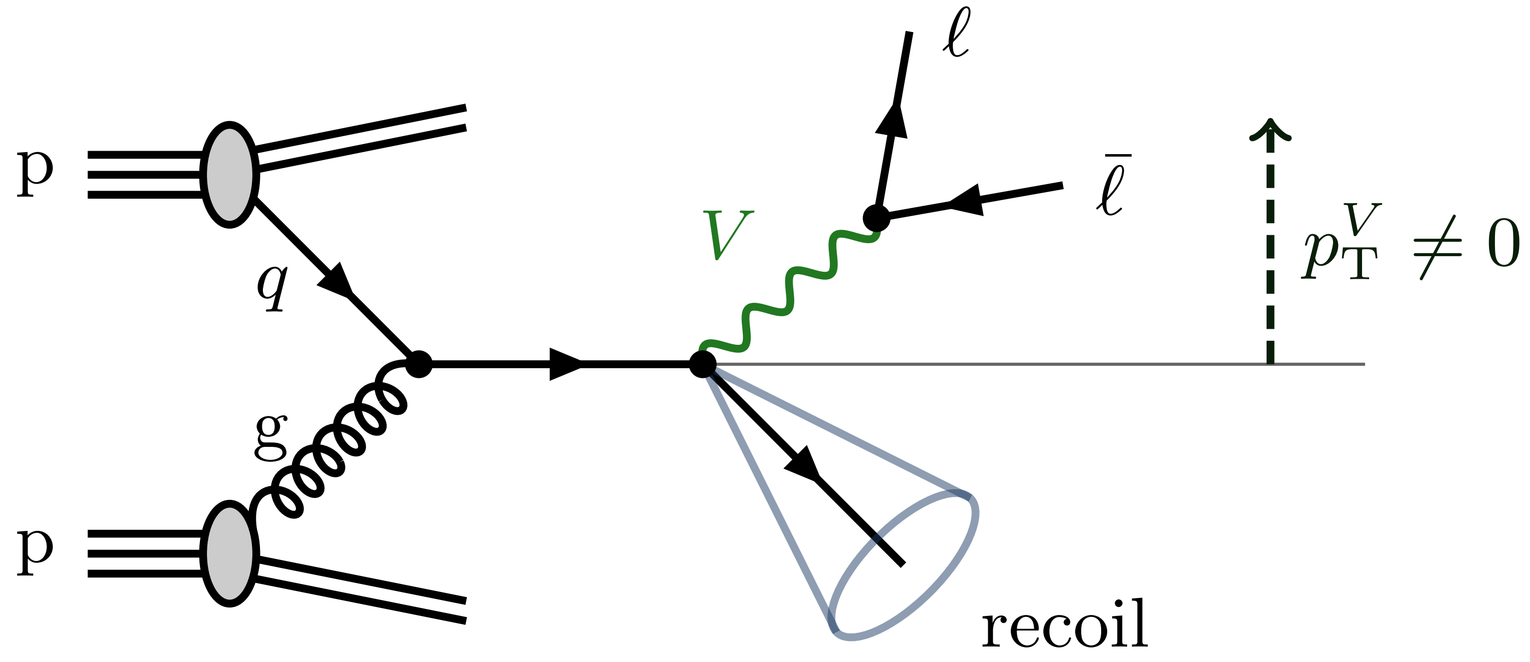


$$\sigma = \sigma_0 \cdot \exp\left(\alpha_s^n L^{n+1} + \alpha_s^n L^n + \alpha_s^n L^{n-1} + \ldots\right)$$

resummation: LL NLL NNLL …



q_T – The Transverse Momentum



⇒ direct sensitivity to α_s
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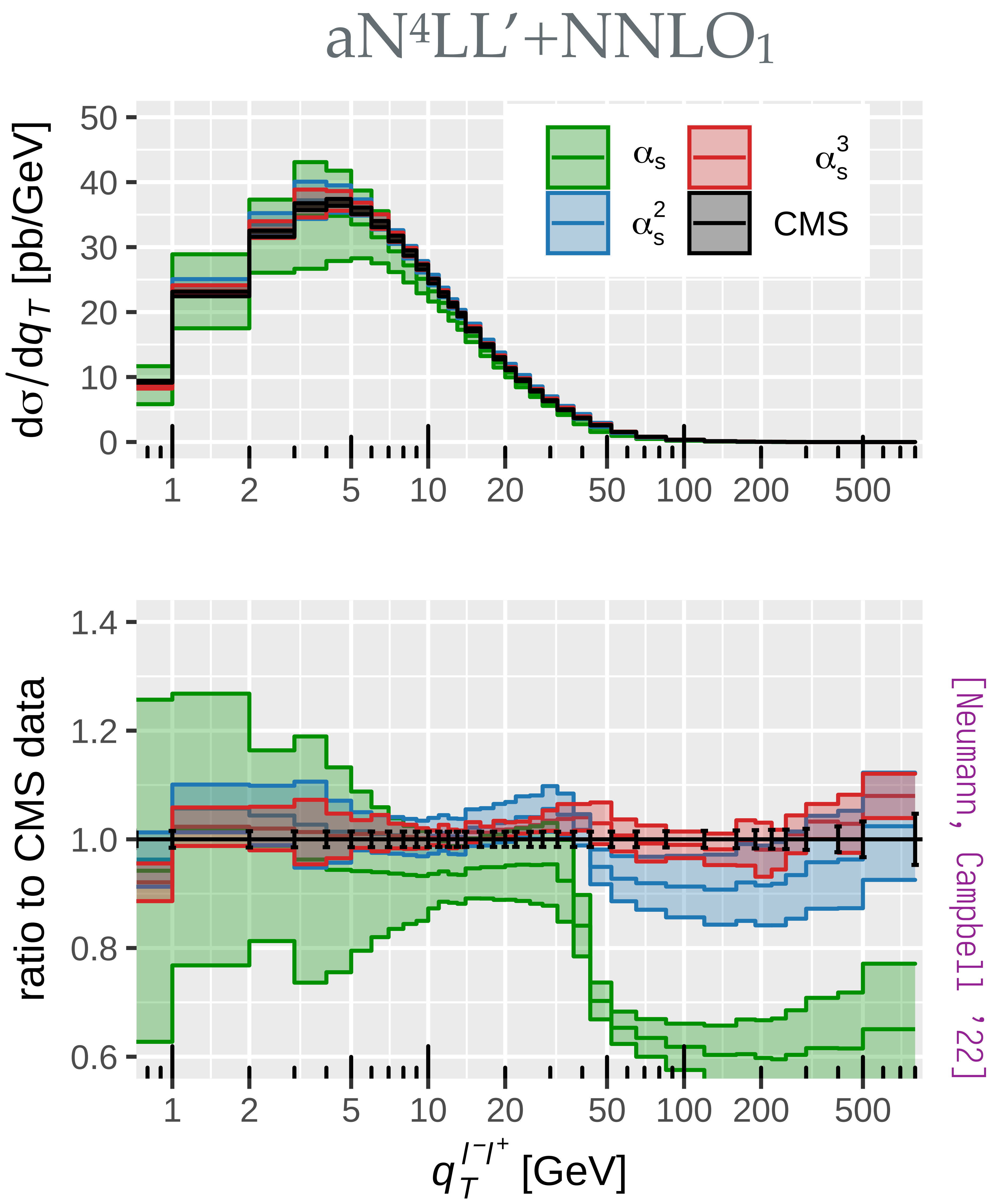


Boson Transverse Momentum Distribution

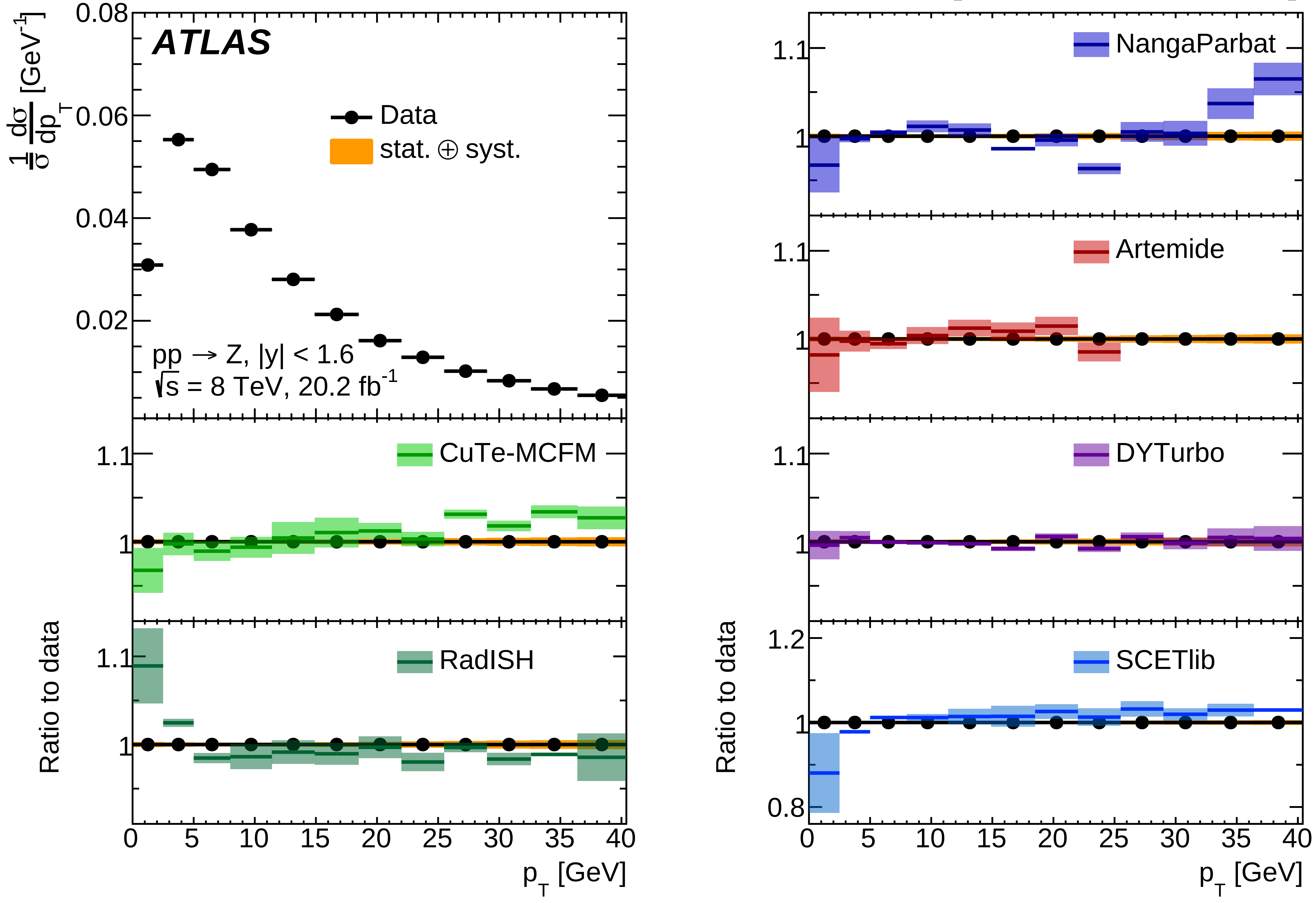
- state of the art:
  $N^3LL' / aN^4LL' + NNLO_1$
  (residual scale unc. ~ few %)

Comparison to ATLAS data

- overall good agreement w/ data
- matching ambiguities (transition)
- NP modelling ($p_T \to 0$)
- estimates for missing h.o. effects can vary significantly

ongoing benchmark exercise in EW WG 1

[ATLAS '23: 2309.09318]

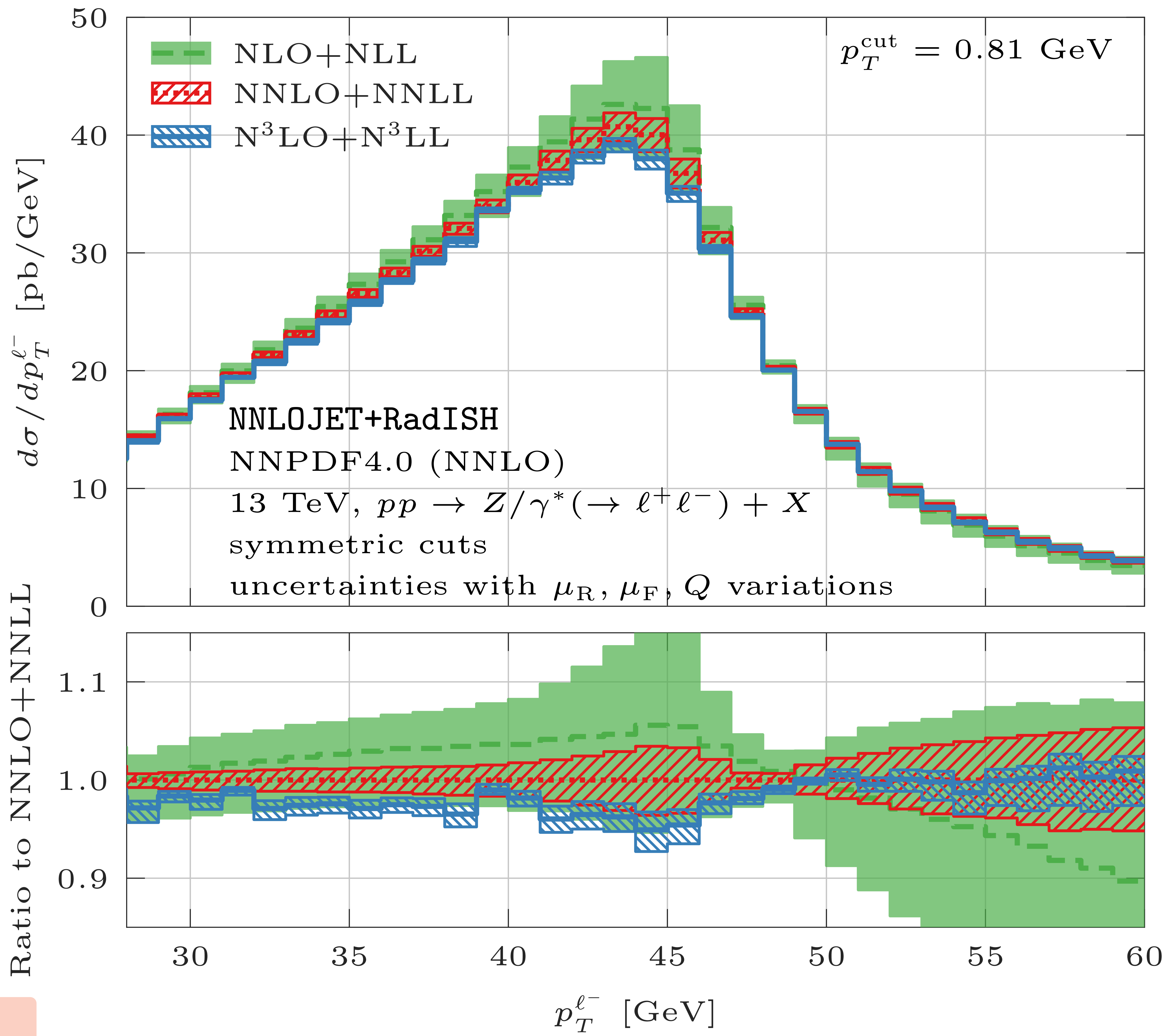


Lepton Transverse Momentum Distribution

$$\mathrm{d}\sigma_V^{\mathrm{N^3LO+N^3LL}} \equiv \mathrm{d}\sigma_V^{\mathrm{N^3LL}} + \mathrm{d}\sigma_{V+\mathrm{jet}}^{\mathrm{NNLO}} - \left[\mathrm{d}\sigma_V^{\mathrm{N^3LL}}\right]_{\mathcal{O}(\alpha_s)}$$

- fully differential calculation
  - ↪ access to fiducial observables
    - & decay kinematics
- lepton transverse momentum
  - ↪ important in *M_W extraction*
  - ↪ challenging due to Jacobian peak
    - @ $p_T^\ell \sim M_V/2$ (integrable singularity)
  - ↪ resummation mandatory
- reduced uncertainties
  - & some impact on shape

how would it translate to M_W shift in $W^\pm$ production?



[Chen, Gehrmann, Glover, AH, Monni, Rottoli, Re, Torrielli '22]

Z / W Ratio @ N³LL+NNLO₁

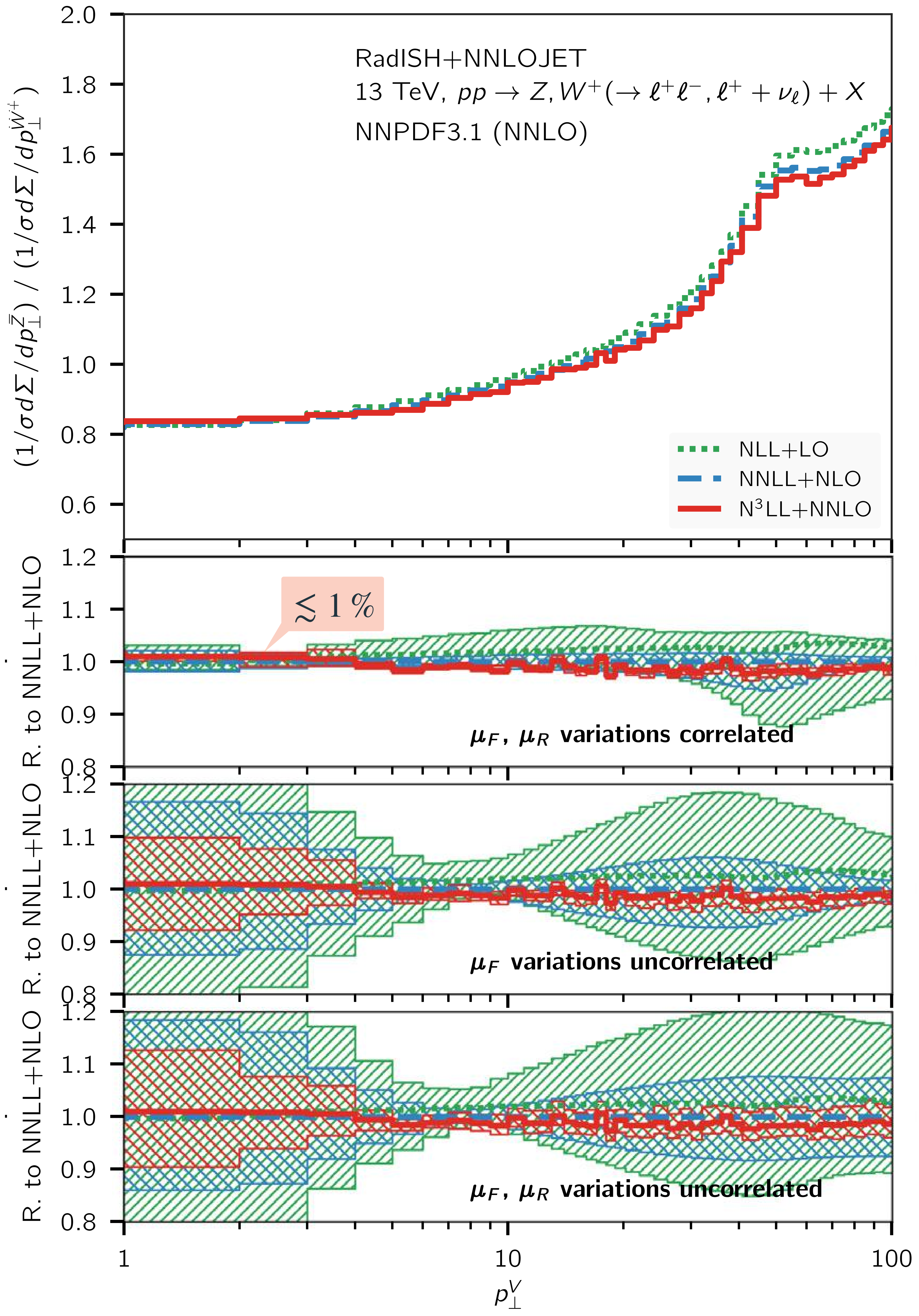
$$\frac{\frac{1}{\sigma^{Z}}\left(d\sigma^{Z}/dp_T^{Z}\right)}{\frac{1}{\sigma^{W^+}}\left(d\sigma^{W^+}/dp_T^{W^+}\right)}$$

NLL+LO
NNLL+NLO
N³LL+NNLO

- central in $p_T^Z \rightsquigarrow p_T^W$ modelling
- ratio of quantities [num / den.] (μ_F, μ_R, Q)
  ↔ how to assess perturbative uncertainties?

↪ matching scale Q — correlated (same γ_i)
↪ μ_F, μ_R — vary correlation (different PDFs)

⇒ stable ratio ⇝ strong correlation between sources of perturbative uncertainties



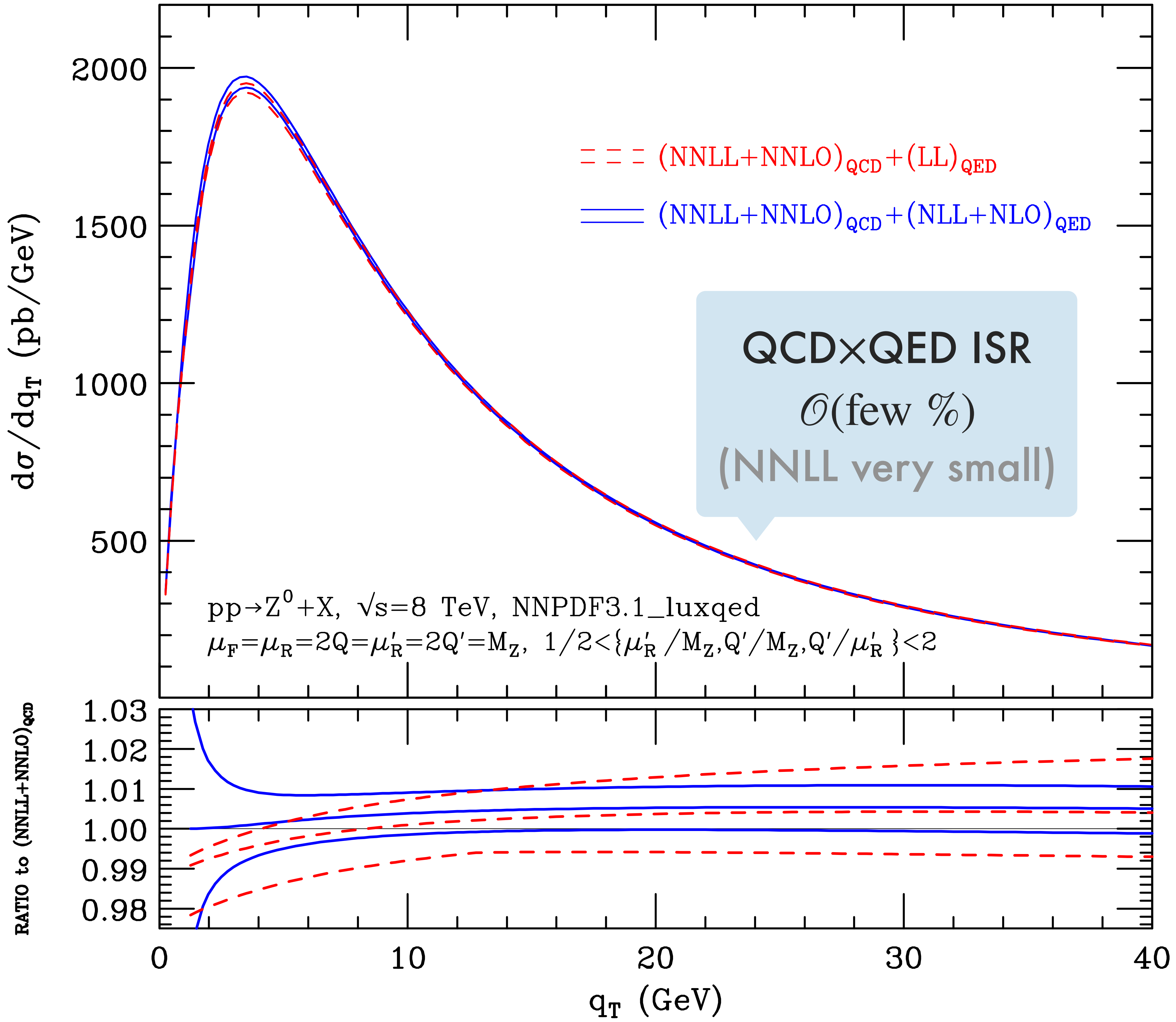
[Bizon, Gehrmann-De Ridder, Gehrmann, Glover, AH, Monni, Re, Rottoli, Walker '19]

Combined QCD×EW Resummation

on-shell gauge bosons (CC: radiation off W included)

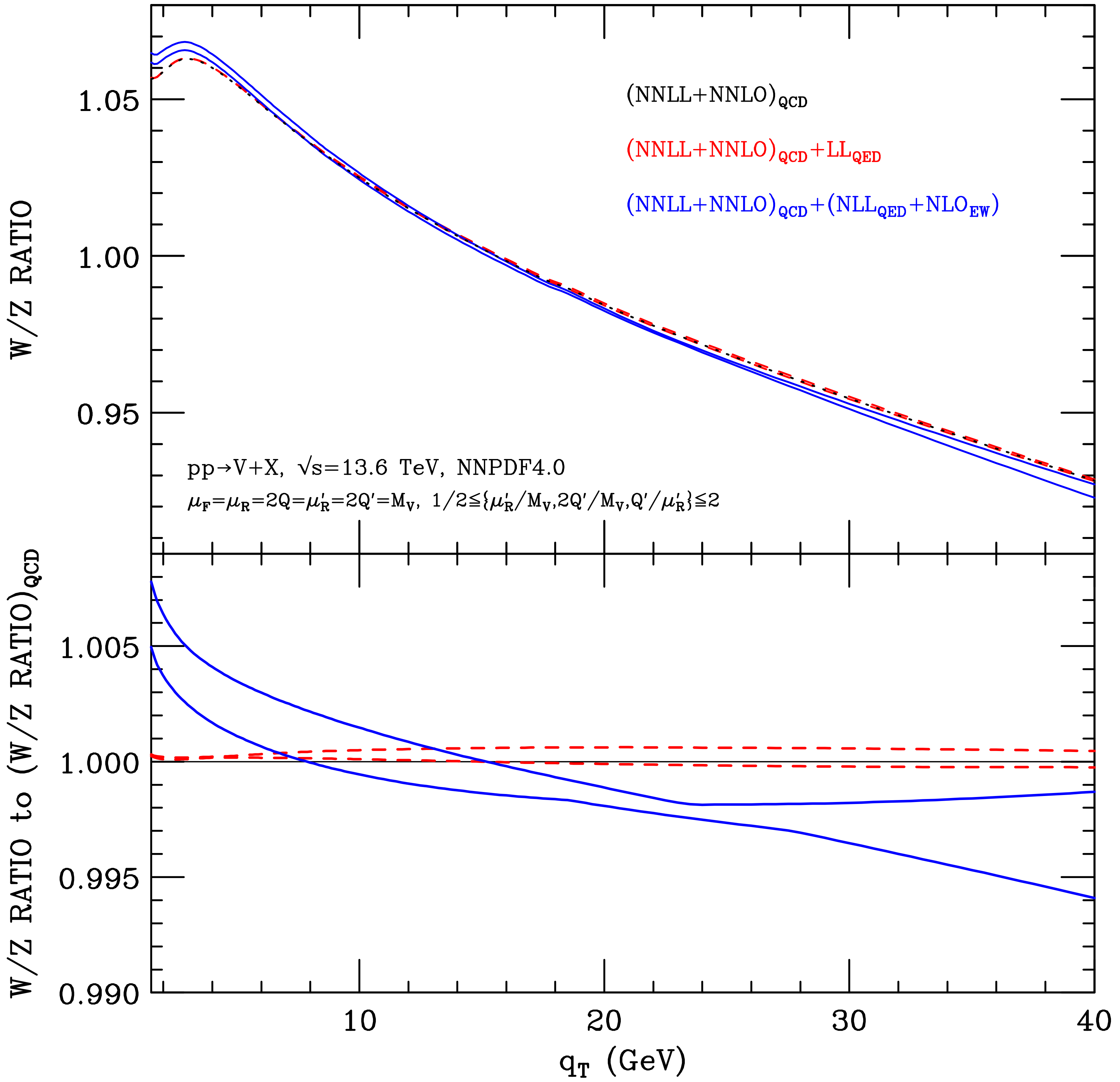
↪ NLL [Cieri, Ferrera, Sborlini '18] [Autieri, Cieri, Ferrera, Sborlini '23]

↪ NNLL (Z) [Autieri, Camarda, Cieri, Ferrera, Sborlini '25]



decorrelation between spectra

W / Z Ratio



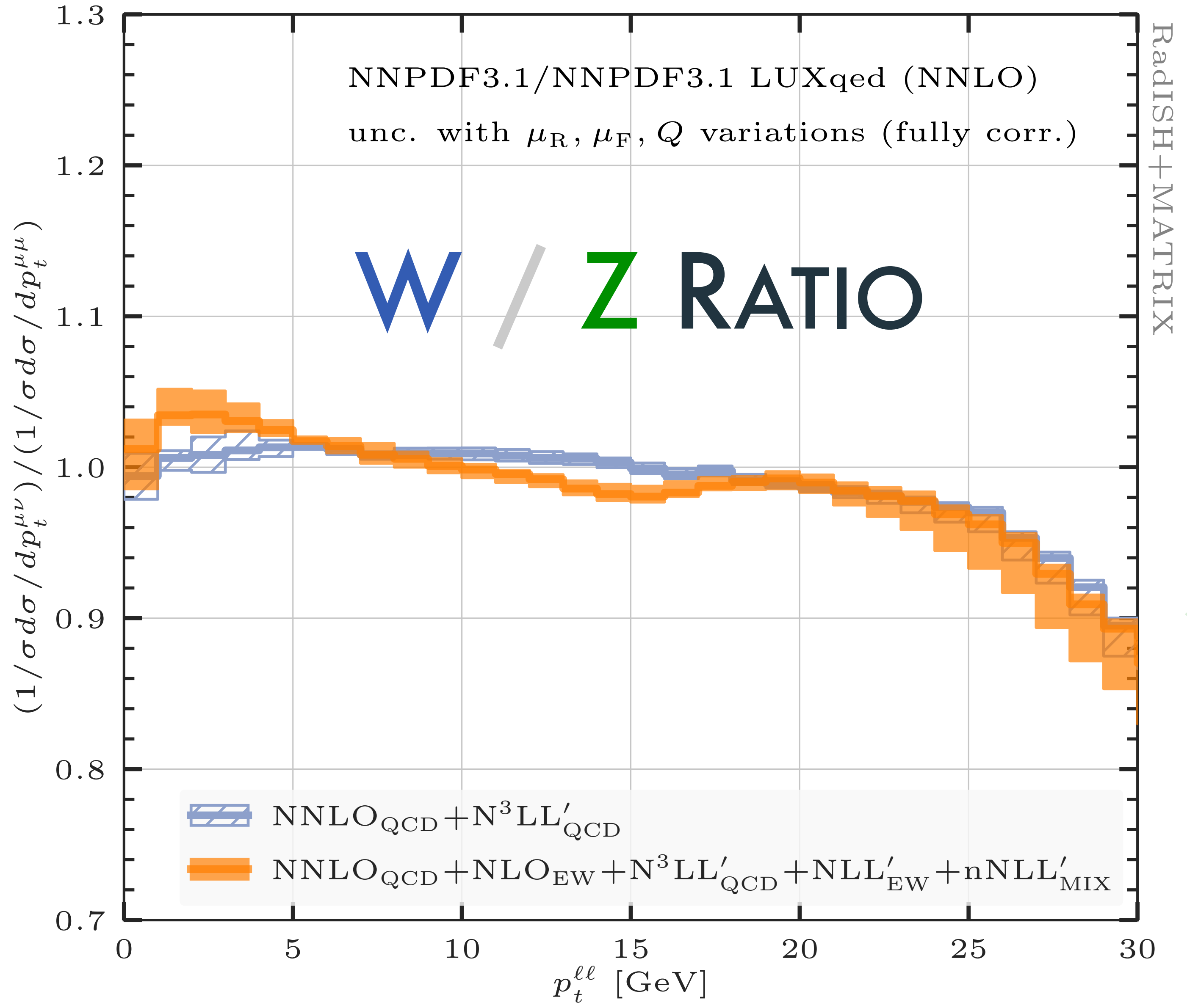
not differential in lepton kinematics!

Combined QCD×EW Resummation

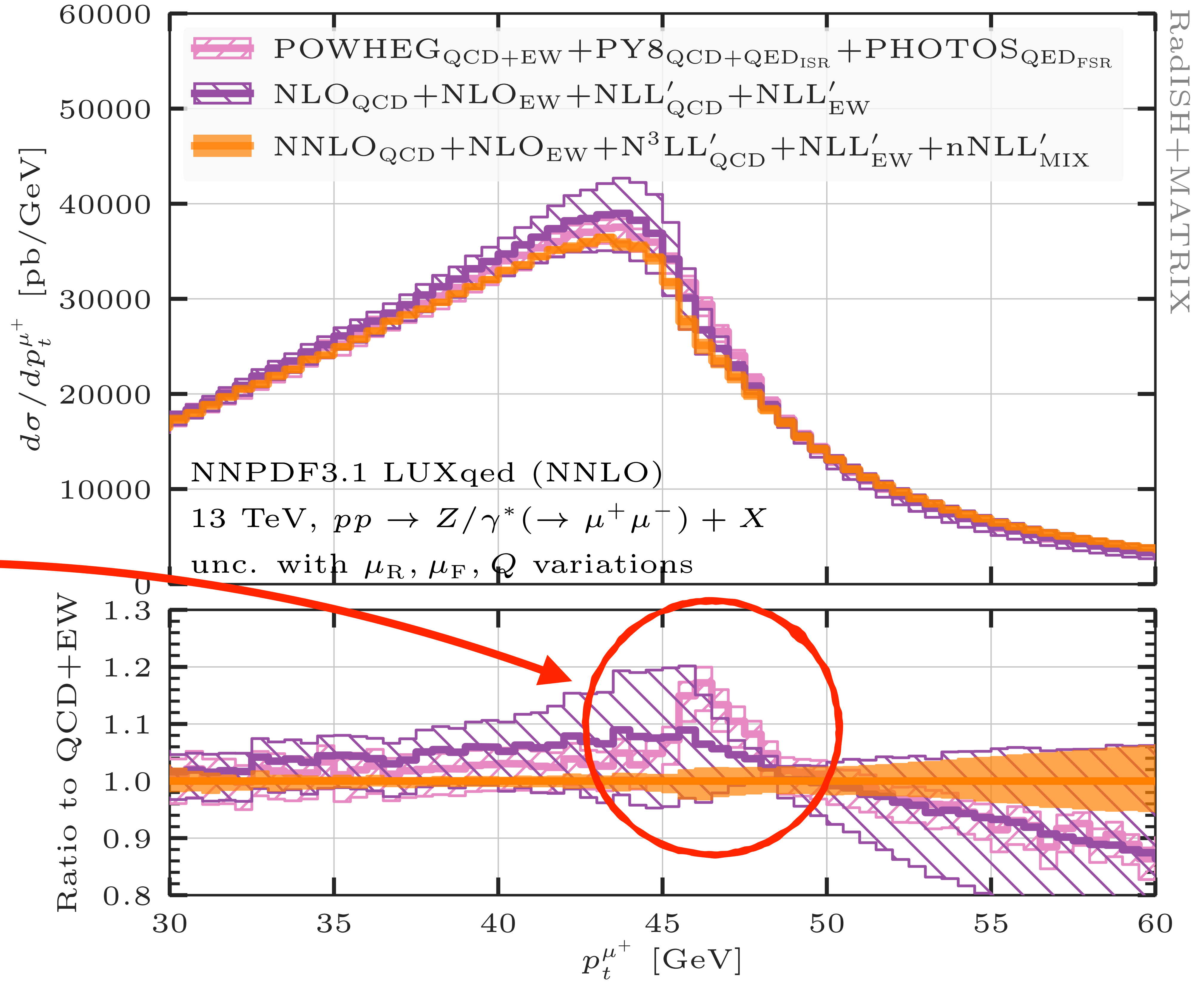
[Buonocore, Rottoli, Torrielli '24]

Extend RadISH framework w/ NLL

- ↪ abelianized heavy quark pair production
- ↪ fully differential in lepton kinematics
- ↪ **BUT**: only resummation of $p_\mathrm{T}(\ell\bar{\ell})$ *not* coll. FSR
  (FSR logs at **fixed order** via matching)
- ↪ not yet matched to mixed QCD×EW



similar effects



$\mathrm{POWHEG_{QCD+EW}+PY8_{QCD+QED_{ISR}}+PHOTOS_{QED_{FSR}}}$

$\mathrm{NNLO_{QCD}+NLO_{EW}+N^3LL'_{QCD}+NLL'_{EW}+nNLL'_{MIX}}$

Combined QCD×EW Resummation

[Buonocore, Rottoli, Torrielli '24]

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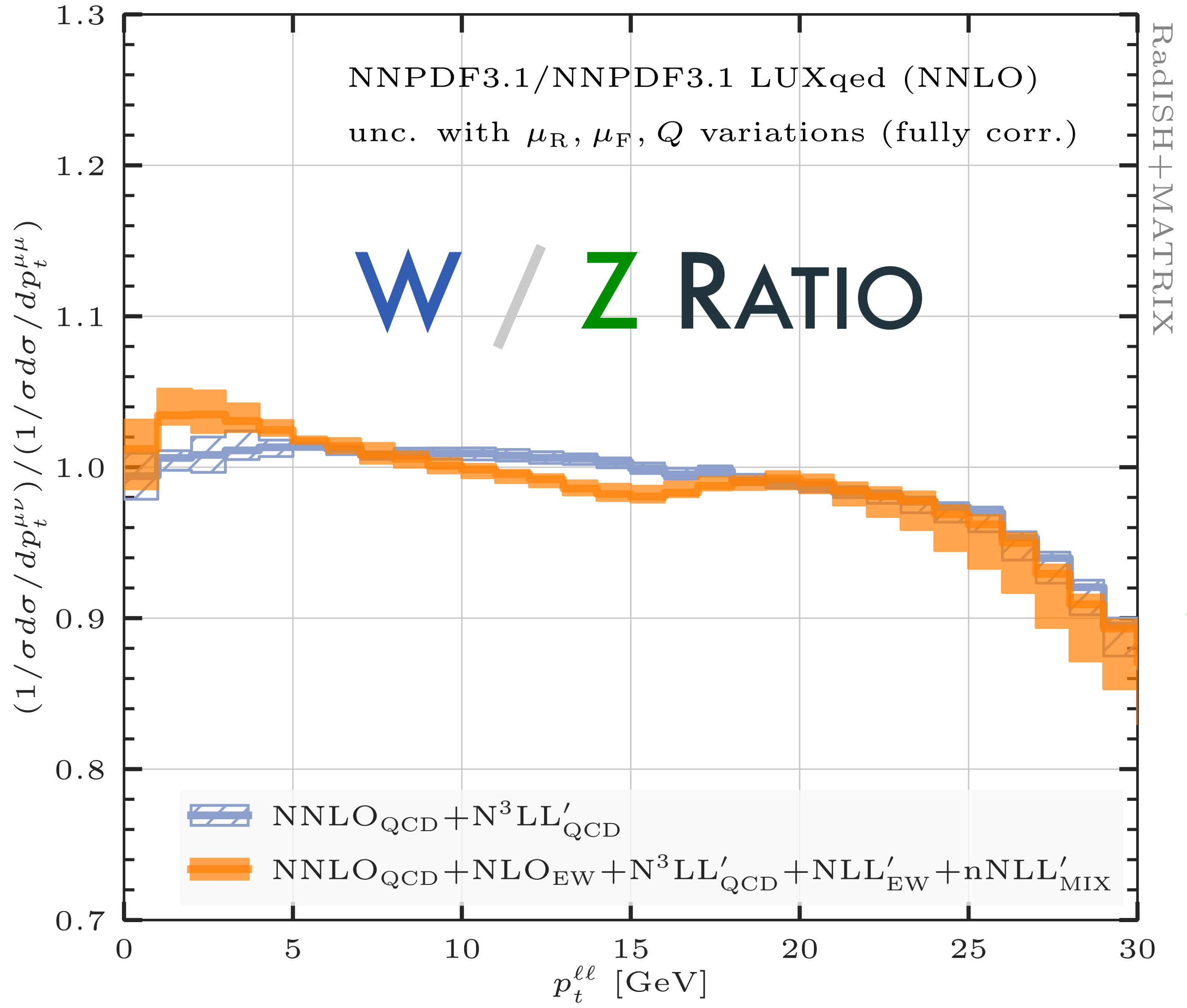

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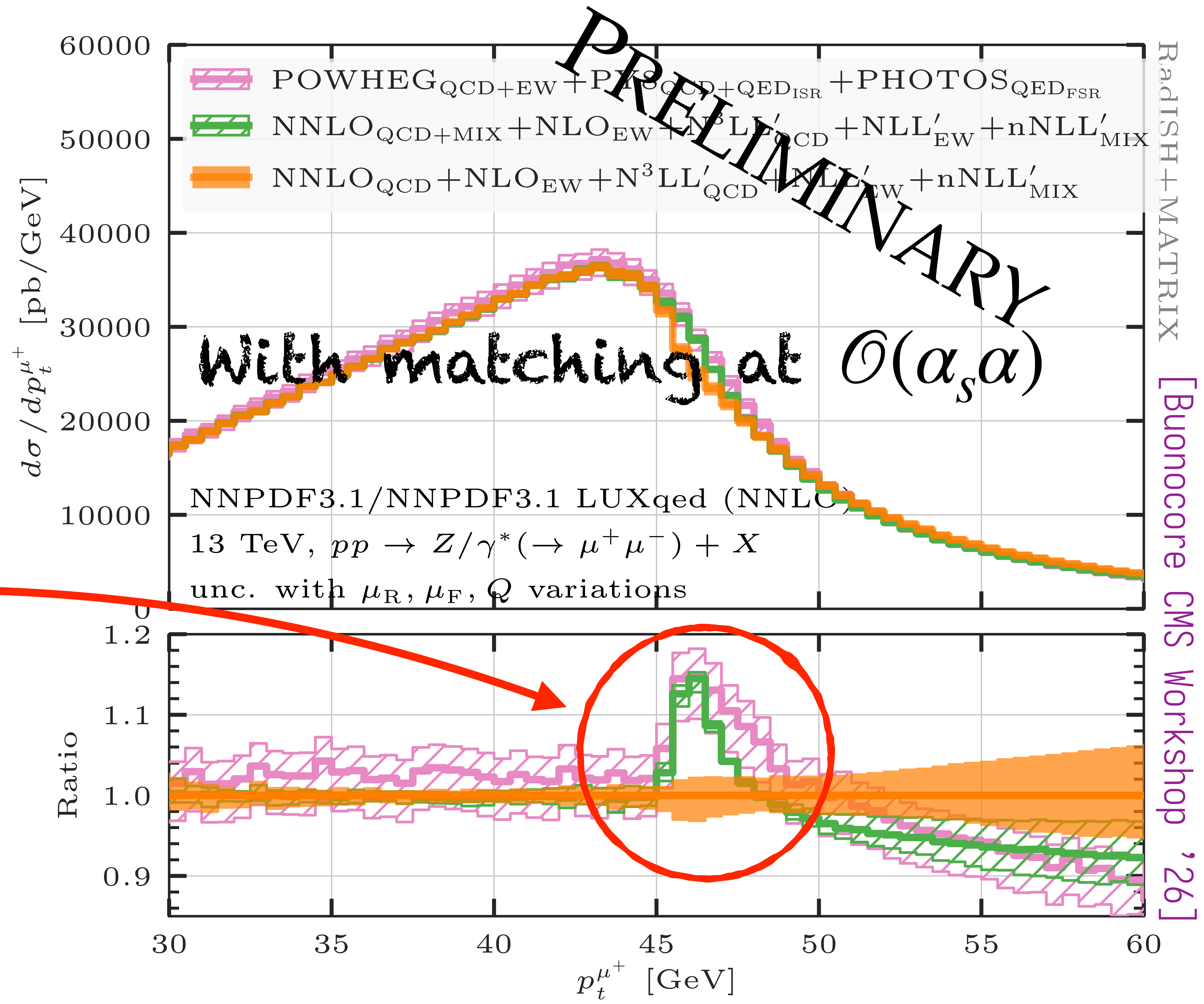


POWHEG$_{QCD+EW}$+PY8$_{QCD+QED_{ISR}}$+PHOTOS$_{QED_{FSR}}$
NNLO$_{QCD}$+NLO$_{EW}$+N^{3}LL$'_{QCD}$+NLL$'_{EW}$+nNLL$'_{MIX}$
+ mixed QCD×EW

Outline

- Motivation
1. Theory Status for Single Boson Production
   1. Drell-Yan process at fixed order
   2. Transverse momentum
2. Parton Distribution Functions & More
   1. PDF uncertainties & profiling, N3LO
   2. Theory uncertainties & modelling
- Conclusions

Parton Distribution Functions

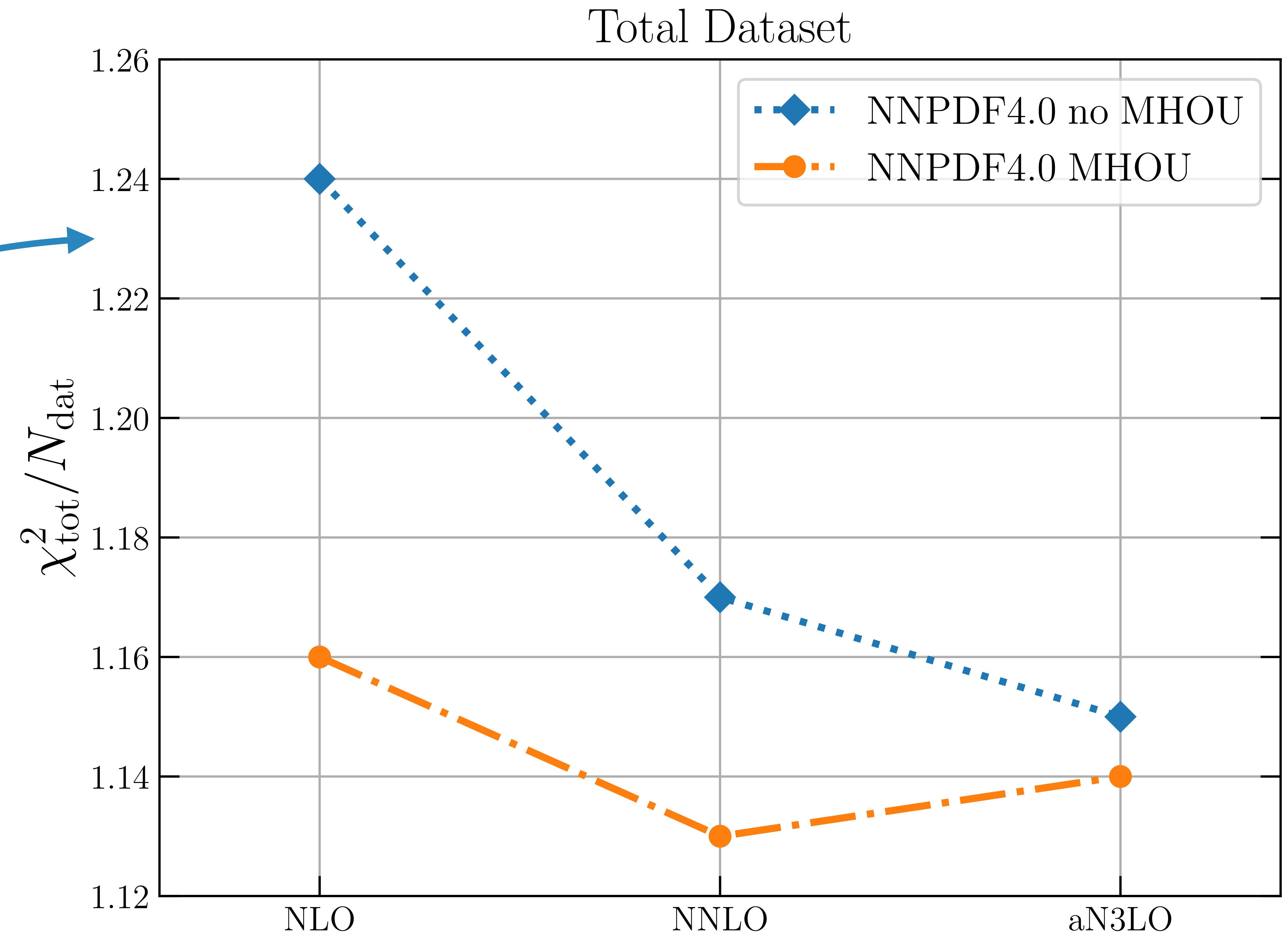
Dataset & Tolerances

- $\mathcal{O}(4000)$ datapoints in a global fits
  ↪ inconsistencies between data, unknown/underestimated EXP/TH uncertainties, model, …
- $\Delta\chi^2 = 1$ for 68% C.L. not suited
  ⇝ "tolerance" $T^2 = 10$–30

Theory Uncertainties in PDFs

- NNPDF4+ (scale variation)
  MSHT aN³LO (nuisance parameter)
- mandatory in aN³LO as (almost) no predictions available at this order

more stable χ^2 in the progression of the orders



[NNPDF 2402.18635]

PDFs in Precision Measurements

tiny deviations in spectra & control of correlations

Require *precise* & *accurate* PDFs: $\Delta_{\text{PDF}} \sim \mathcal{O}(\,\%\,) \leftrightsquigarrow \Delta_{\text{shape}} \lesssim \mathcal{O}(‰)$

Approaches

1. **Scan/offset** PDF eigenvectors: $\delta\mathcal{O} = \sqrt{\sum_{i=1}^{N_{\text{ev}}} \left[(\mathcal{O}_i^+ - \mathcal{O}_i^-)/2\right]^2}$ (how we compute Δ_{PDF} for cross sections)
   - ↪ if $\Delta_{\text{PDF}} \gg \Delta_{\text{exp}}$ "surely my data can constrain the PDFs?" (good strategy but caution advised)

2. **Profiling**: joint χ^2 of new data & PDFs ⇝ fit together
   - ↪ *issue:* global PDFs have tolerances: $\theta_i^{\text{PDF}} = \pm 1 \leftrightsquigarrow \Delta\chi^2 = T^2 > 1$
   - ↪ *assumptions:*
     - PDF uncertainties included consistently (tolerance!)
     - PDFs not altered much (central value & errors)

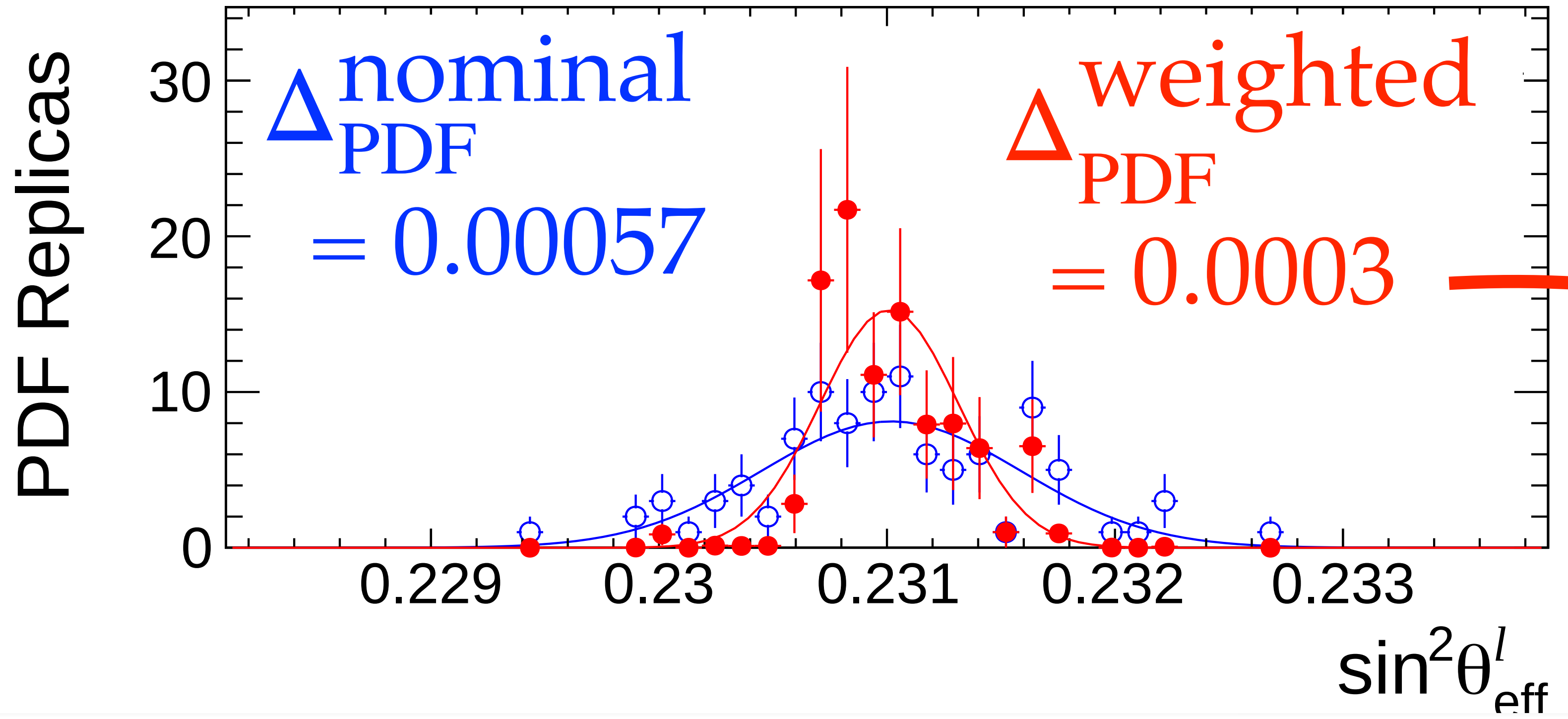
new data can overestimate pull & uncertainty reduction

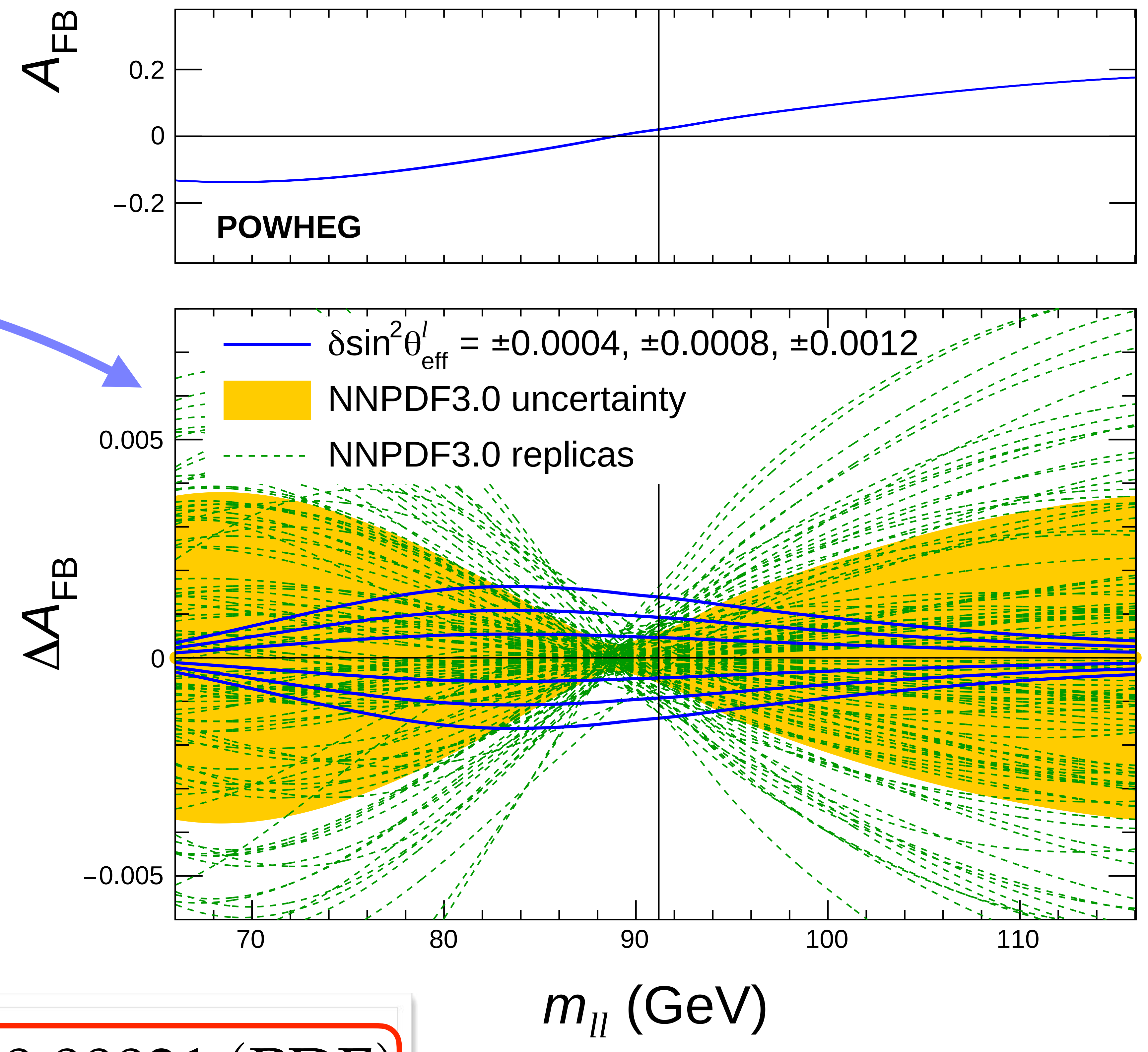
Parton Distribution Functions

[CMS 1806.00863]

Profiling / Reweighting

- PDF uncert. often among dominant sources
  - ⇝ exploit correlations to reduce impact
  - ⇒ often a huge reduction ($\sim 2\times$) in Δ_{PDF}!





$$\sin^2\theta^\ell_{\mathrm{eff}} = 0.23101 \pm 0.00036\,(\mathrm{stat}) \pm 0.00018\,(\mathrm{syst}) \pm 0.00016\,(\mathrm{theo}) \boxed{\pm 0.00031\,(\mathrm{PDF})}$$

still almost 50% of Δ_{tot}

how plausible is such a large impact from $\mathcal{O}(100)$ extra data points?
⇜ this data effectively carries a very high weight!

Parton Distribution Functions

$\alpha_s(m_Z) = 0.1183 \pm 0.0009$

[ATLAS 2309.12986]

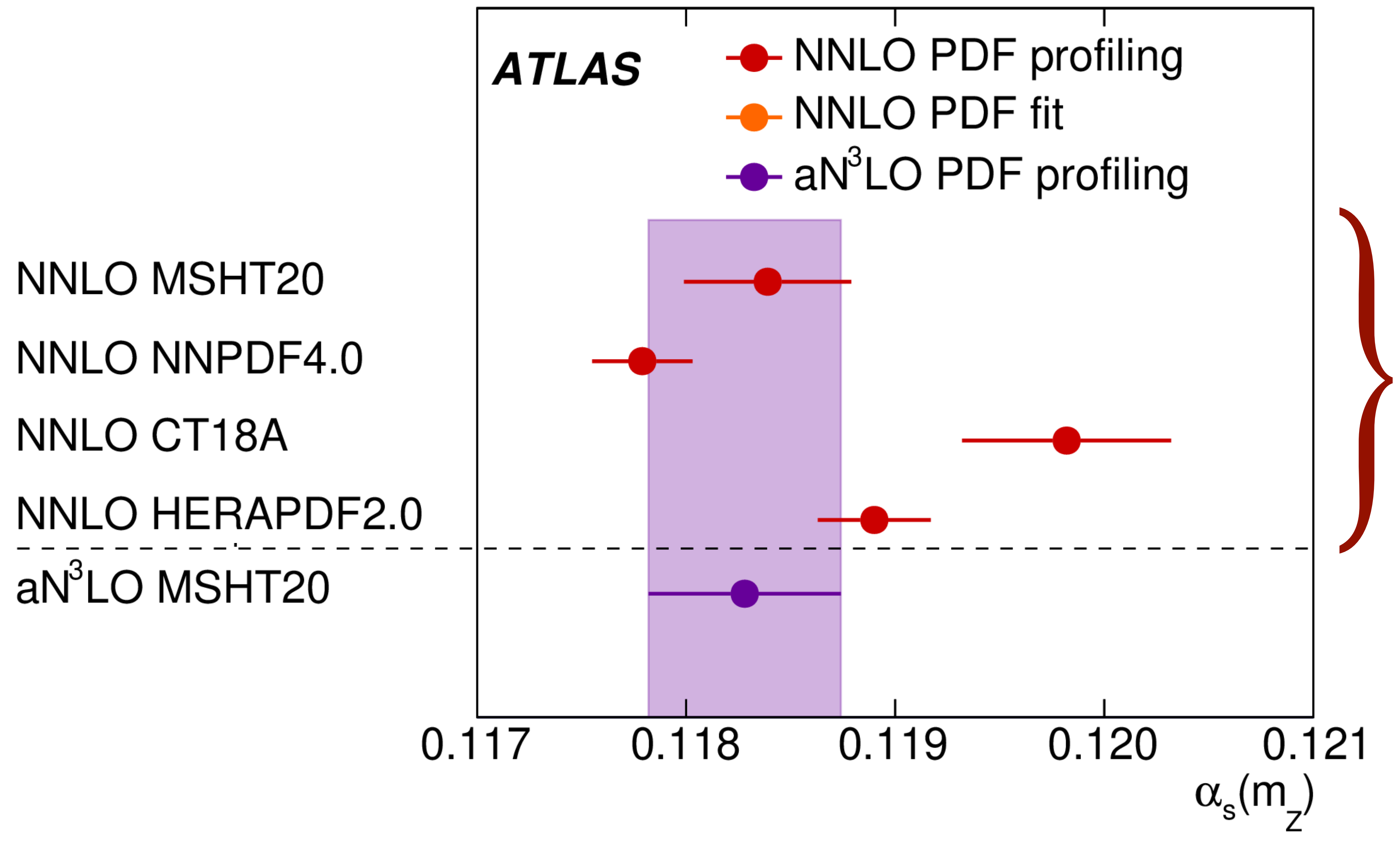
Profiling / Reweighting for α_s

- situation is even more delicate for α_s
  ⇝ strong correlations between α_s & PDFs (g)

profiling may bias probing direction of factorised approx.

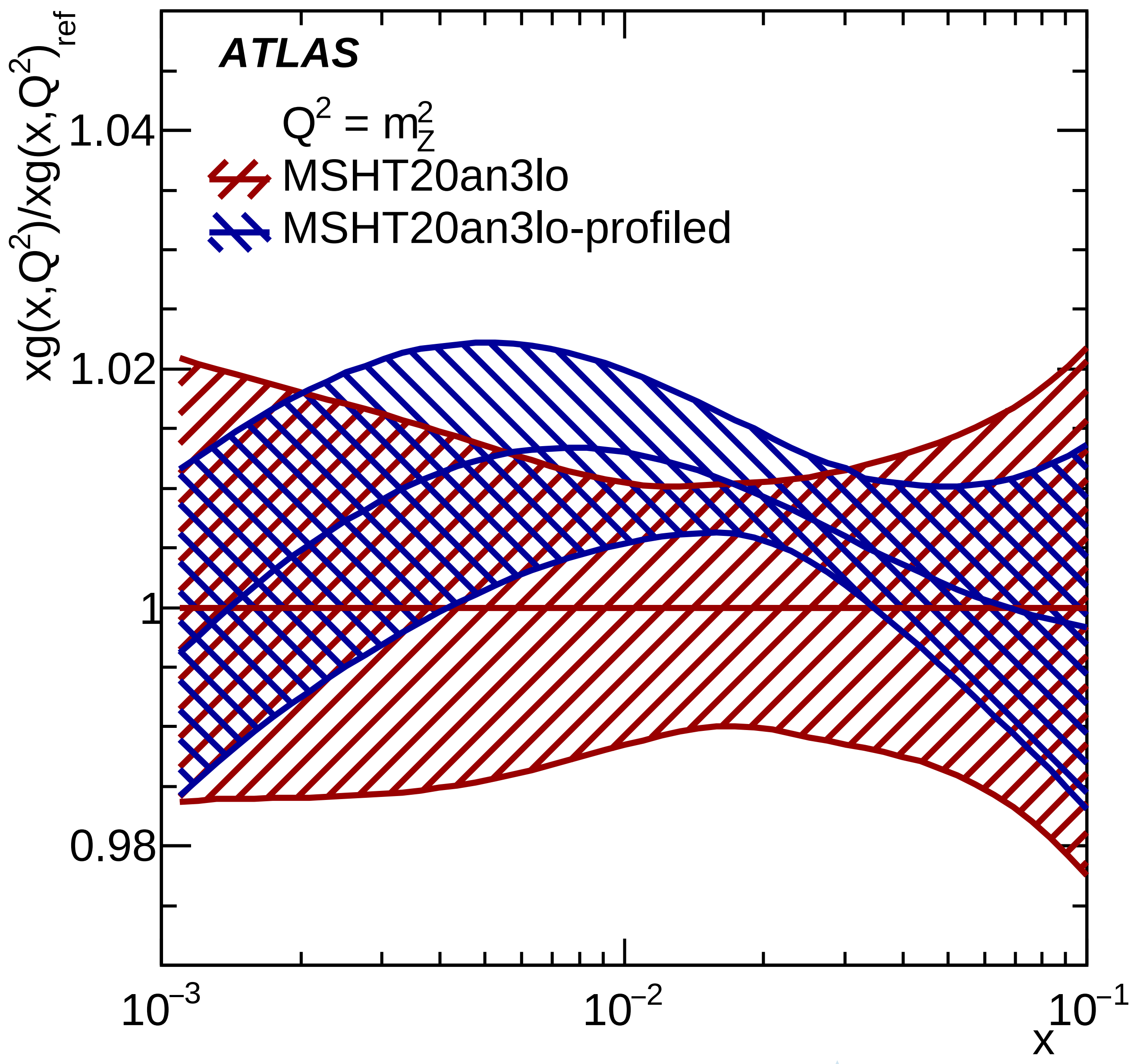
- quoted $\Delta_{\mathrm{PDF}} = \pm\, 0.00051$

$4\,\times$



spread in NNLO PDFs $\sim 0.00203 \simeq 2\Delta_{\mathrm{tot}}$

underestimated unc. / unaccounted Δ_{model}



back-reaction to other measurements in the fit?

PDFs in Precision Measurements

tiny deviations in spectra & control of correlations

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   ↪ *assumptions:*
   - PDF uncertainties included consistently (tolerance!)
   - PDFs not altered much (central value & errors)

new data can overestimate pull & uncertainty reduction

3. Two-step profiling:
   - Profile PDFs with tolerance T^2 $\rightsquigarrow$ consistently profiled PDF
   - Scan PDFs while fitting with $\Delta\chi^2 = 1$ other uncertainties

ongoing study in EW WG 1 [Thomas Cridge]

Theory Nuisance Parameters

[Tackmann '24]

- factorization in limit $p_T \to 0$ ⇝ functional dependence known

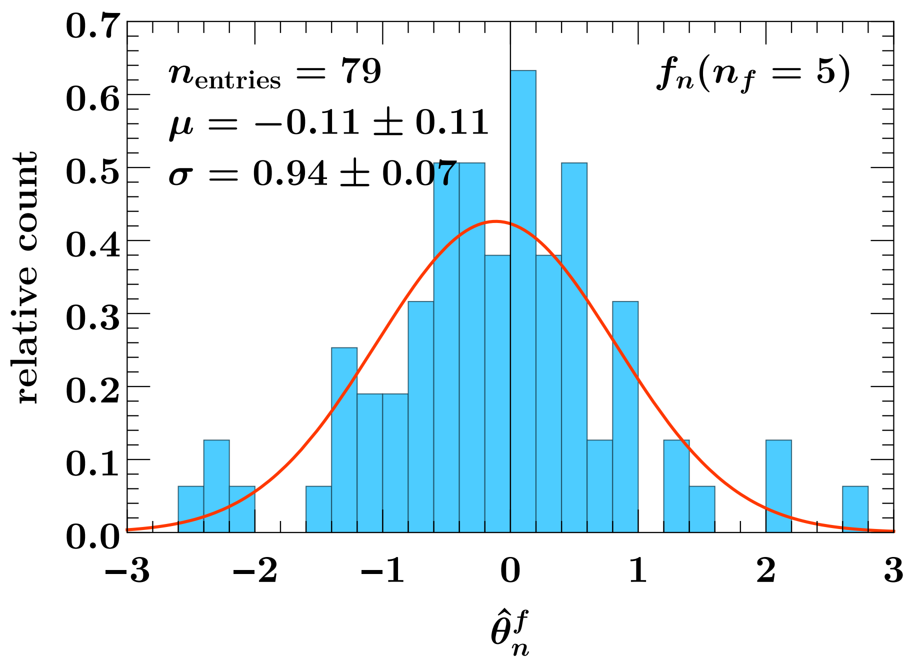
$$\frac{d\sigma}{dp_T} = \left[H \otimes B_a \otimes B_b \otimes S\right](\alpha_s;\, L) + \mathcal{O}\left(p_T/Q\right) \qquad L \equiv \ln\left(p_T/Q\right)$$

- parametrise unknown resummation ingredients using **nuisance parameters** $\vec{\theta}$

$$\mathcal{X}_n = \mathcal{N}_{\mathcal{X}}^{(n)}\, \theta_{\mathcal{X}}$$

- assign a probability distribution

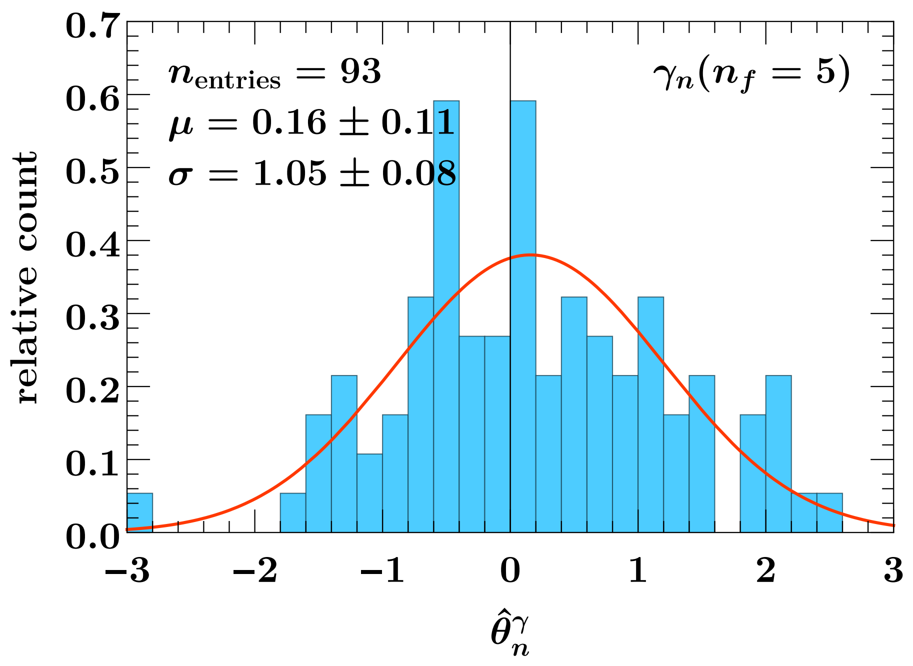
Matrix Elements



$\mathcal{N}_{\mathcal{X}}^{(n)} = 4^n\, C_r\, C_A^{n-1}\, (n-1)!$

(& $\mathcal{X} \to \mathcal{X}^\delta$ to scale like $\mathcal{M}_{1\to 1}$)

anomalous dimensions

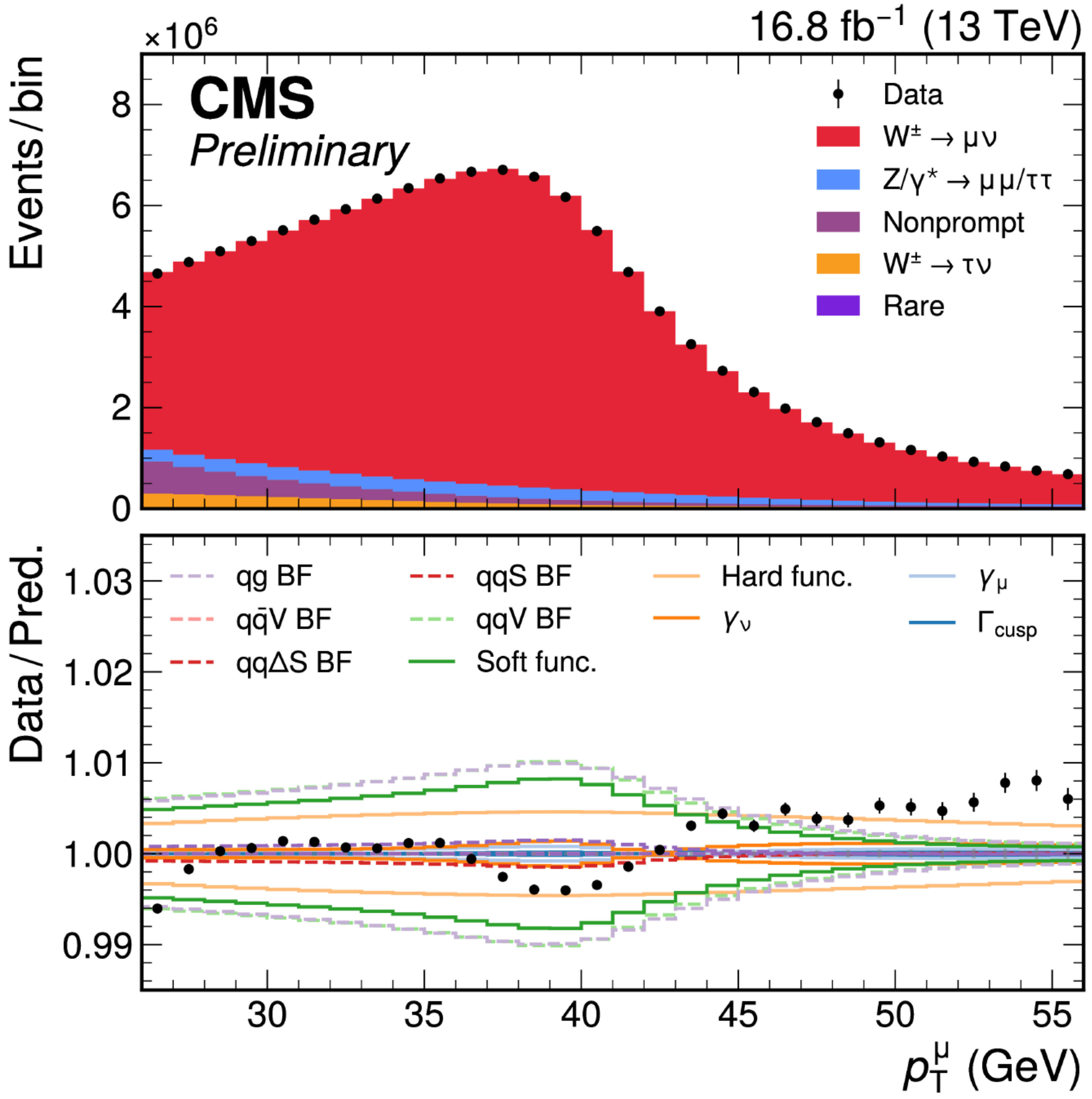


$\mathcal{N}_{\Gamma}^{(n)} = 4^n\, C_r\, C_A^n$

Theory Uncertainties & Profiling

CMS M_W Measurement

- constrain $\vec{\theta}_{TNP}$ using data



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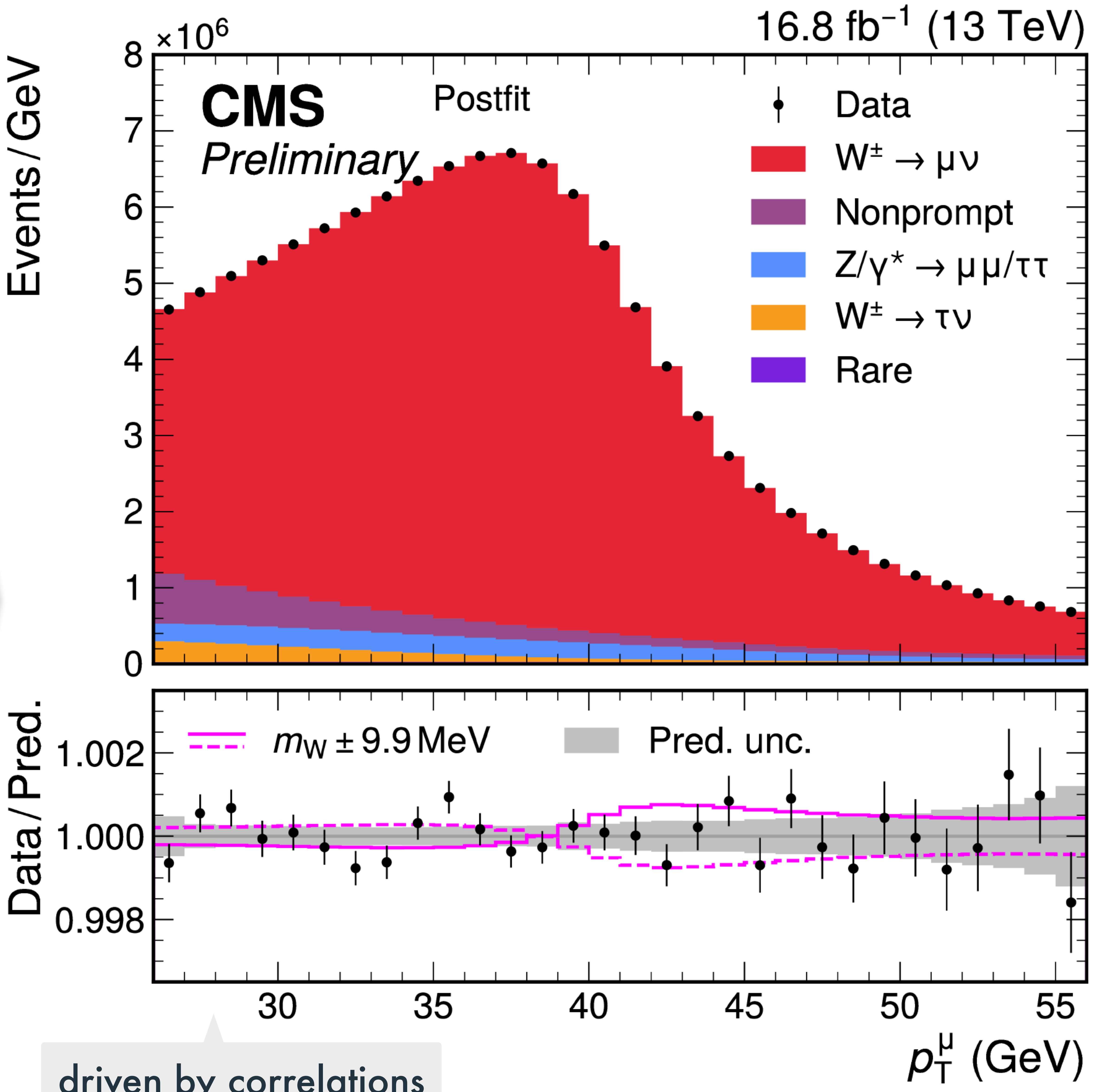

driven by correlations

[CMS arXiv:2412.13872 [hep-ex]]

Theory Uncertainties & Profiling

CMS M_W Measurement

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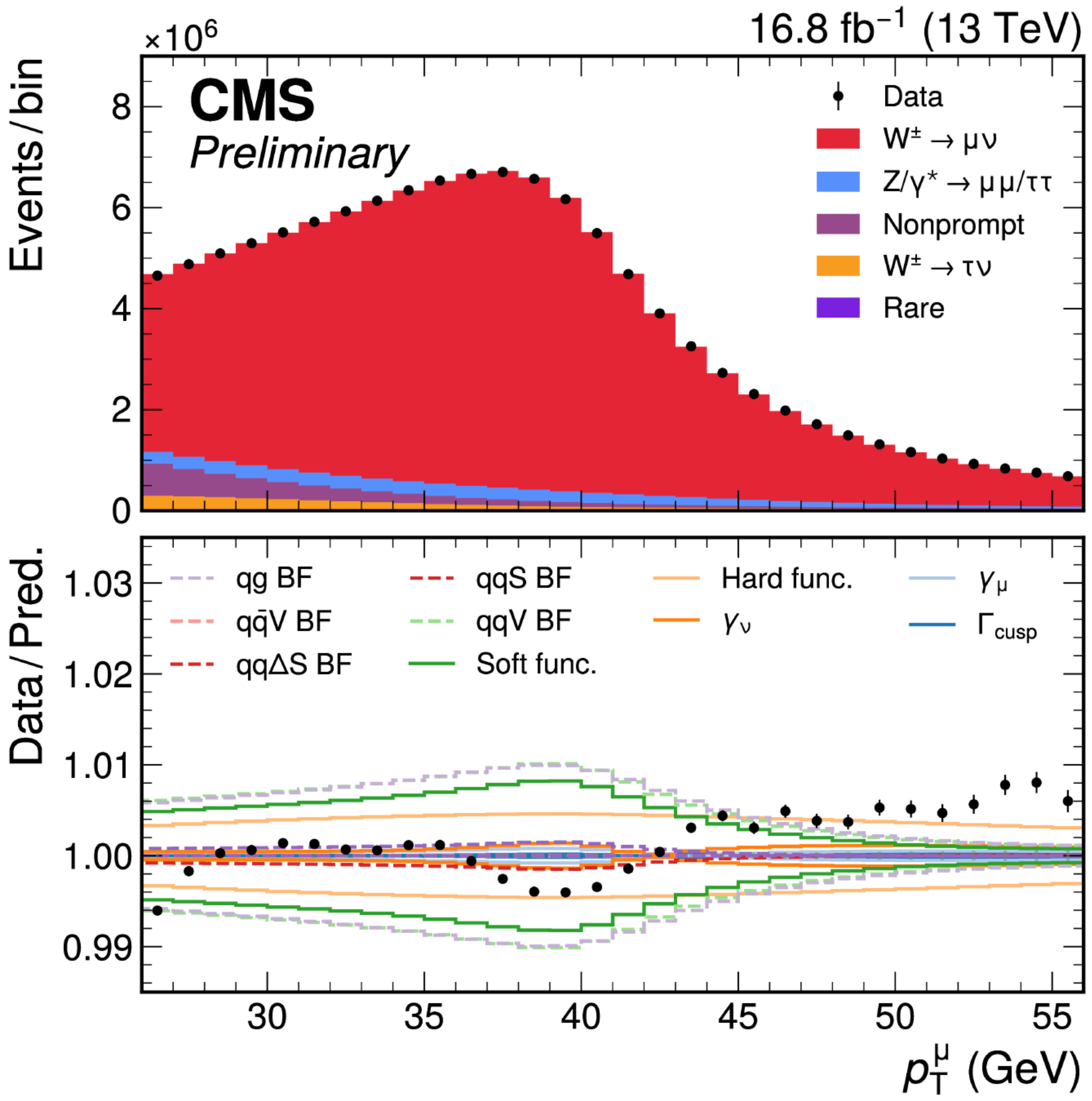

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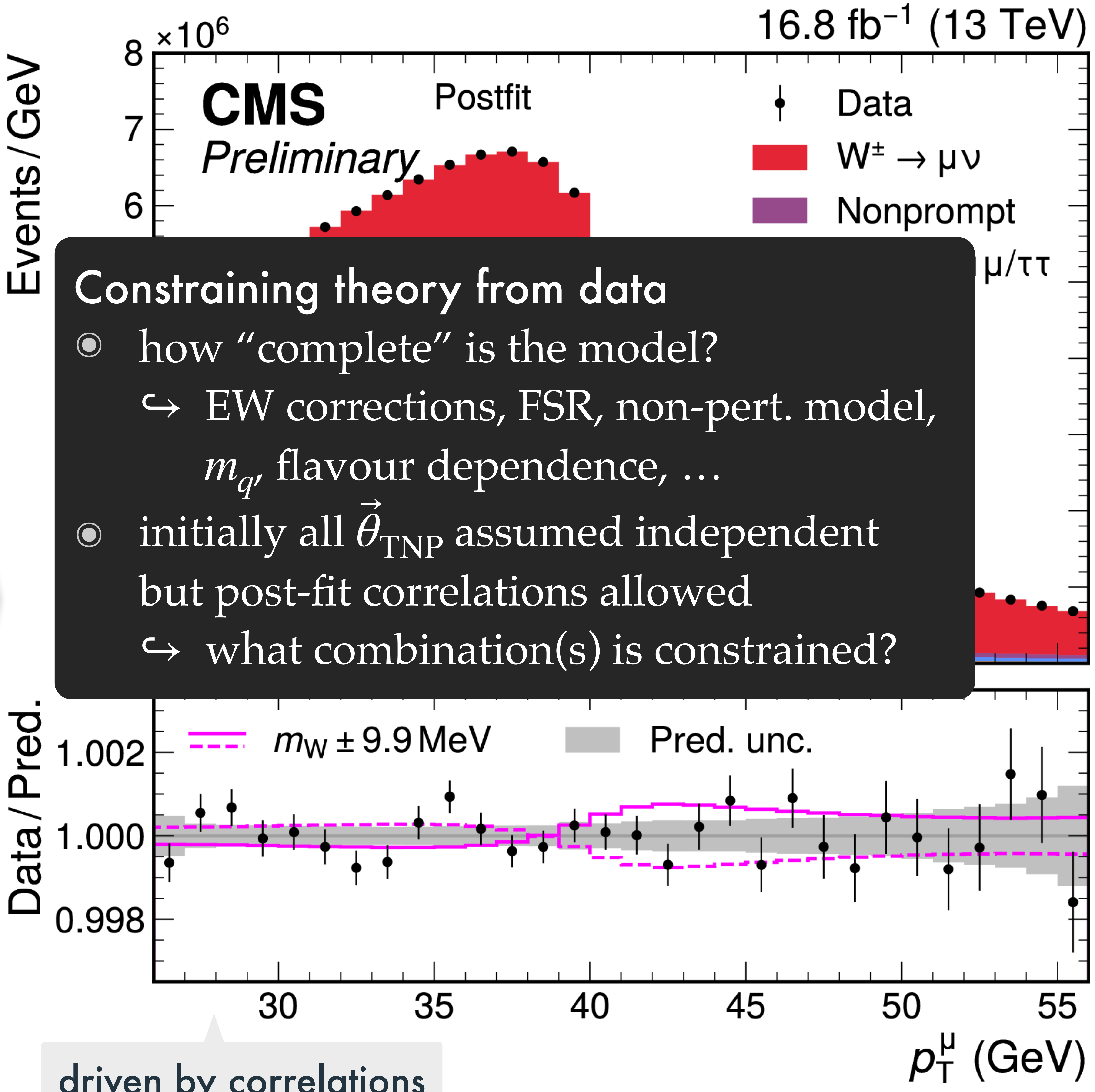

Constraining theory from data

- how "complete" is the model?
  ↪ EW corrections, FSR, non-pert. model, m_q, flavour dependence, …
- initially all $\vec{\theta}_{TNP}$ assumed independent but post-fit correlations allowed
  ↪ what combination(s) is constrained?

driven by correlations

[CMS arXiv:2412.13872 [hep-ex]]

Conclusions

- status of Drell–Yan (f.o. & resummation) reached remarkable level of precision
  - ↪ N^{3}LO QCD, NLO EW (+ h.o./FSR), NNLO QCD×EW
  - ↪ aN^{4}LL′/N^{3}LL′ QCD, NLL QCD×EW
  - ↪ generators at NNLO+PS
- and yet, we are still often facing $\Delta_{\mathrm{TH}} > \Delta_{\mathrm{exp}}$ ⇜⇝ opportunity!
  - ↪ tremendous community effort for more: loops, legs, logs, … & public tools
  - ↪ reached the state where better handle on non-perturbative physics needed
- at this level of precision, it also matters how the measurement is done
  - ↪ are there more robust definition of the fiducial volume/setup?
    (fiducial power corrections, "Born leptons", …)
  - ↪ profiling PDFs and theory uncertainties in situ
    very powerful but "with great power comes great responsibility"

Conclusions

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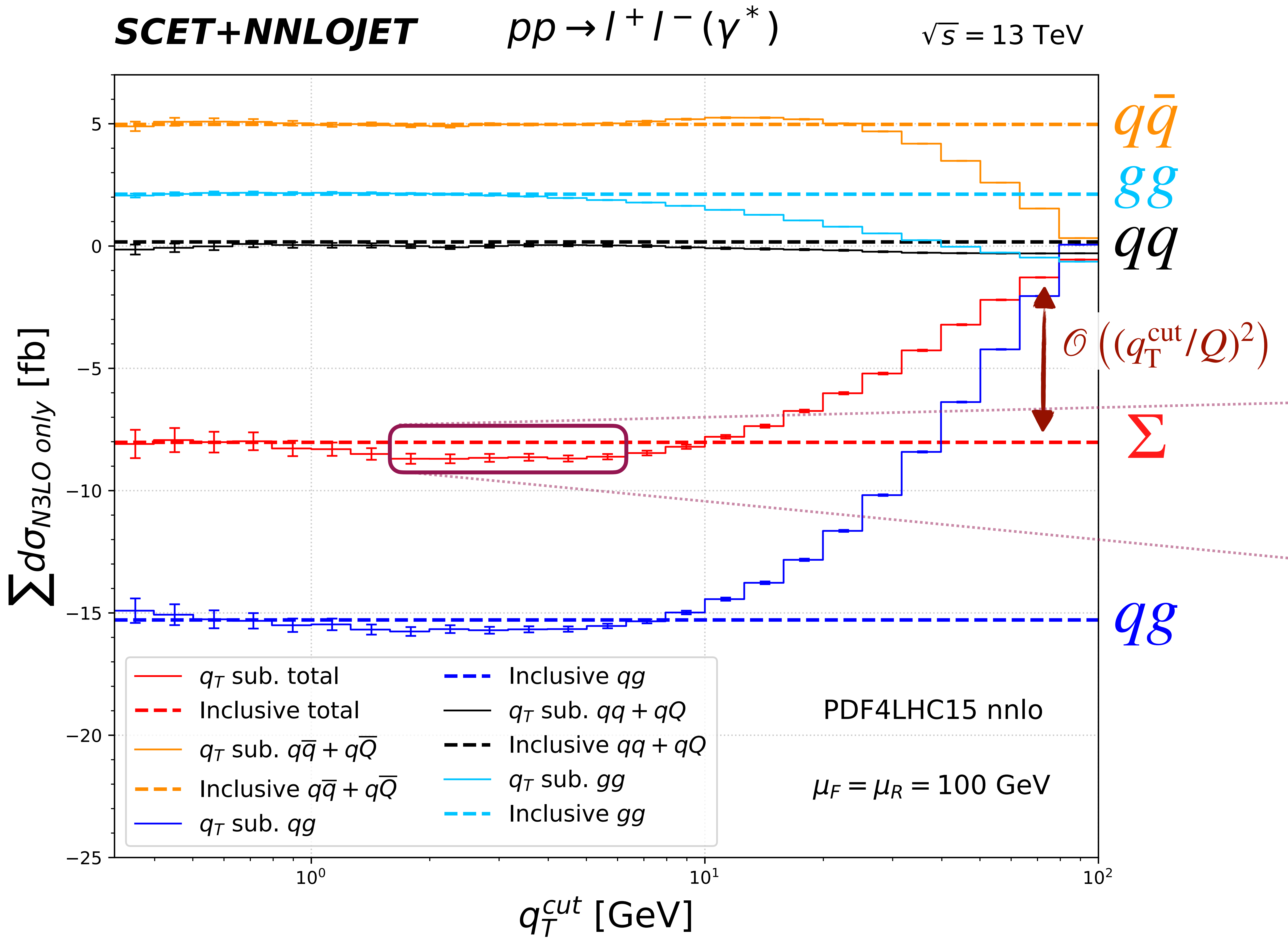
Thank you!

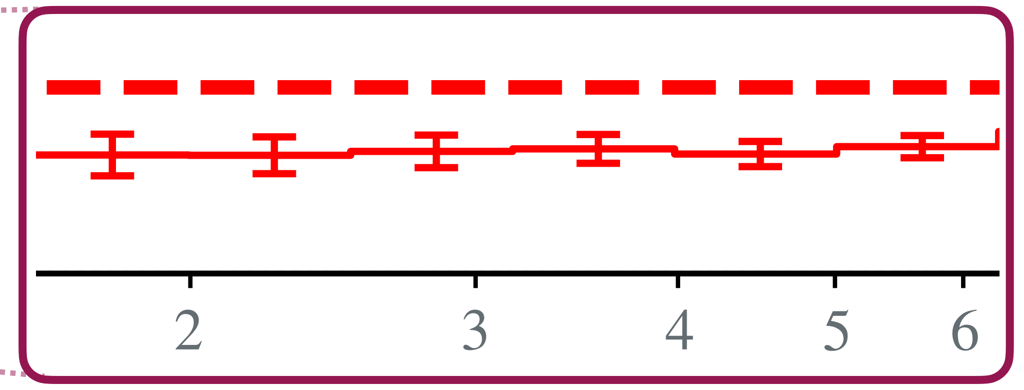
BACKUP

Inclusive N3LO Validation

[Chen, Gehrmann, Glover, AH, Yang Zhu '21, '22]



- *fully independent* calculation of the inclusive cross section
- ---- ⇝ analytic result [Duhr, Dulat, Mistlberger '20]
- "fake" plateau: $q_T^{\mathrm{cut}} \in [2, 5]\,\mathrm{GeV}$
  ↪ 12% error on $\delta\mathrm{N^3LO}$!



- converges to correct result for $q_T^{\mathrm{cut}} \lesssim 1\,\mathrm{GeV}$
- fit & extrapolate?
  ⇝ marginal gains for potentially uncontrolled systematics

Fully Differential Higgs @ N^3LO

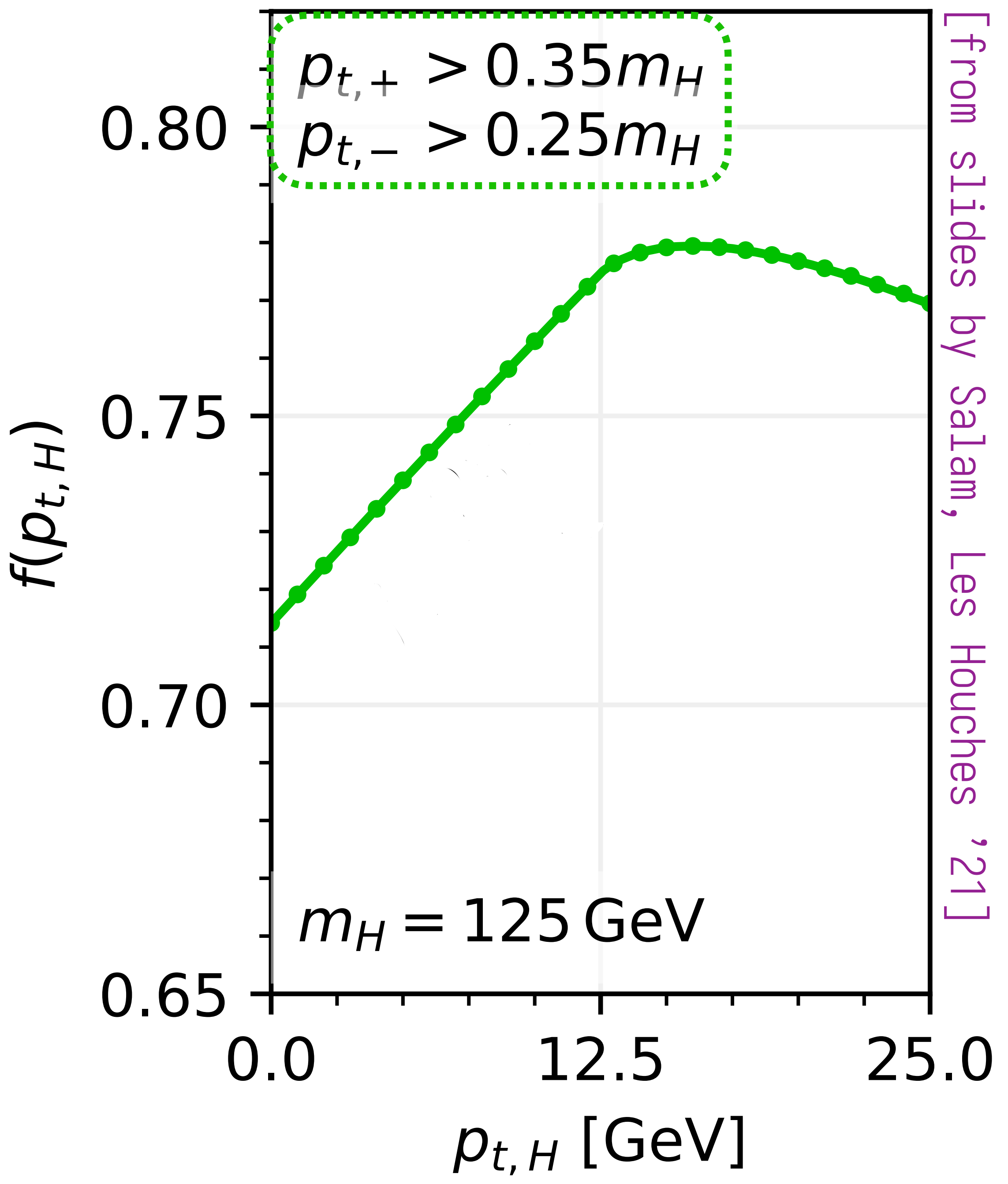
Origin: Linear acceptance ⇝ IR sensitivity

"fiducial power corrections"

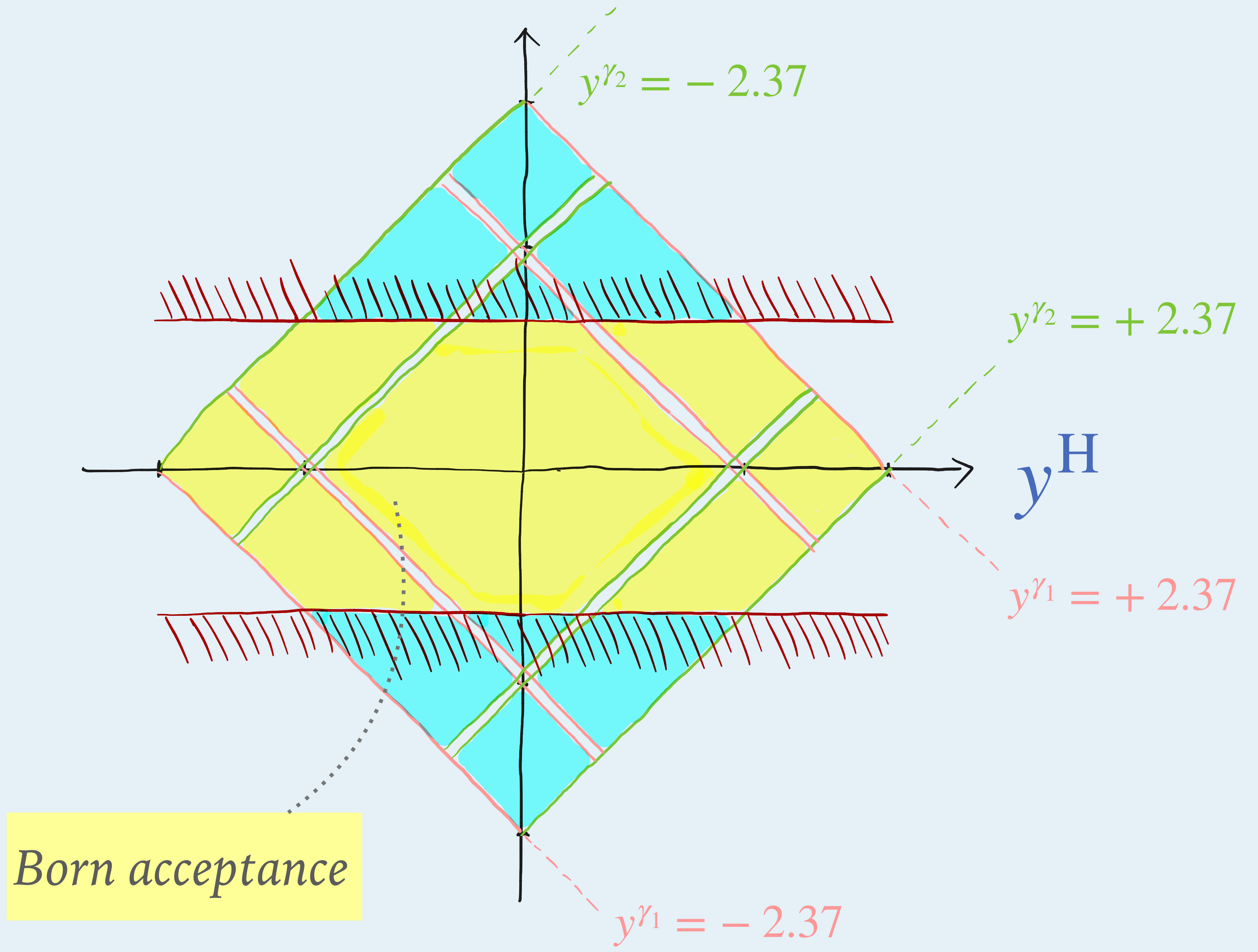
[Frixione, Ridolfi '97] [Ebert, Tackmann '19 + Michel, Stewart '21] [Alekhin et al. '21]

[Chen, Gehrmann, Glover, AH, Mistlberger, Pelloni '21]

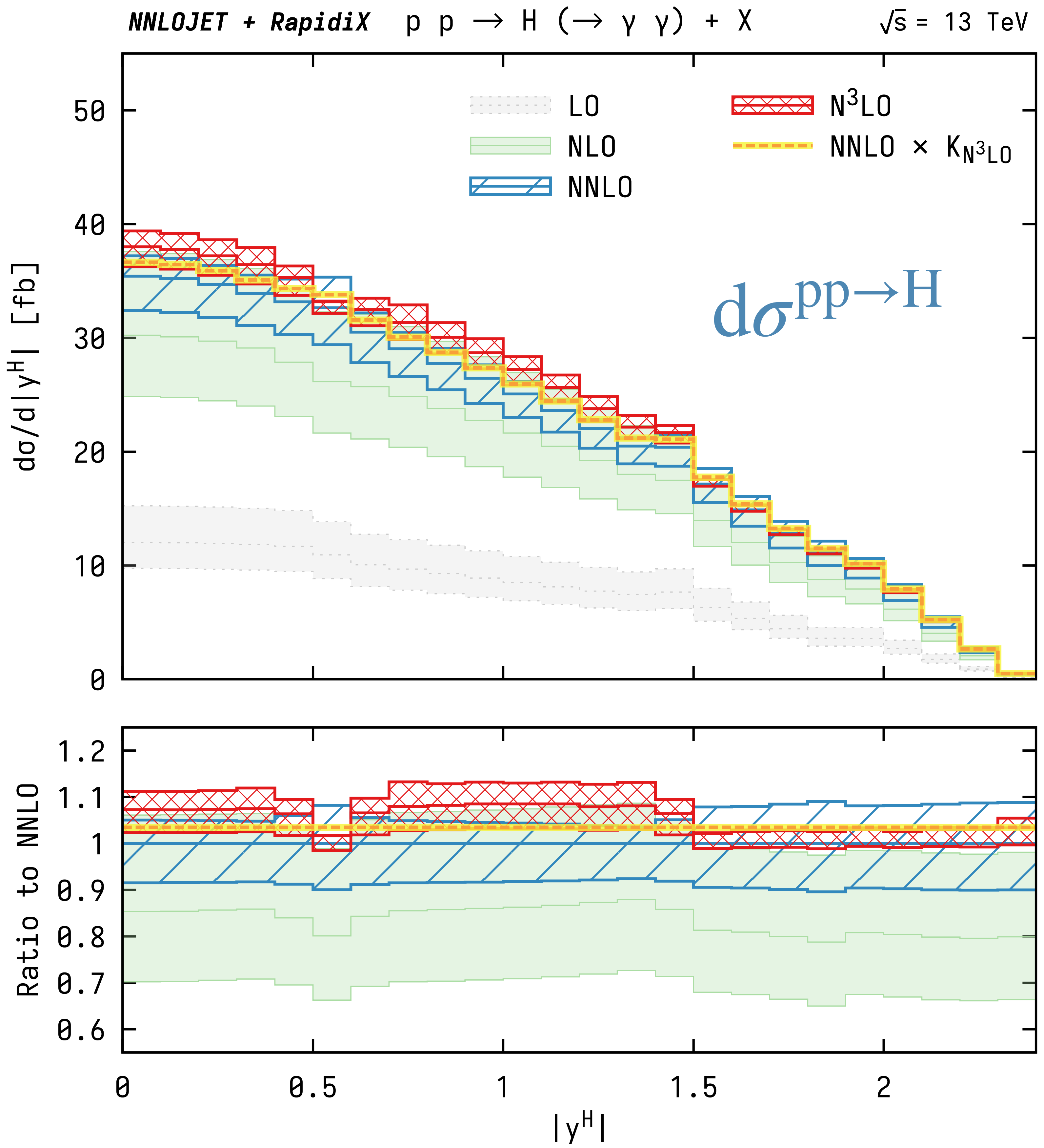
"with cuts" / "no cuts"



$\frac{1}{2}|\Delta y(\gamma_1,\gamma_2)| \lesssim 0.9$ @ $p_T^H \to 0$



Fiducial (ATLAS)



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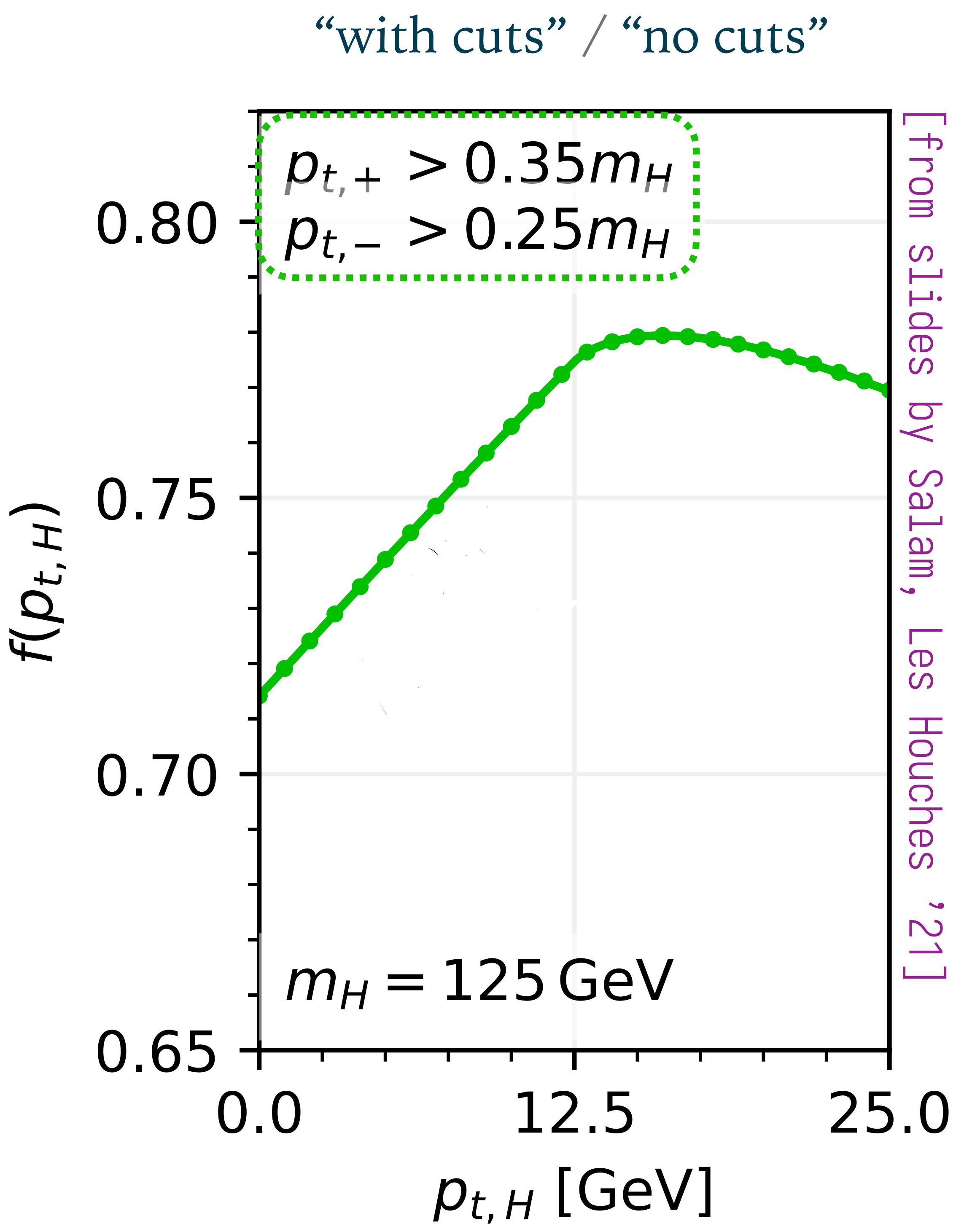
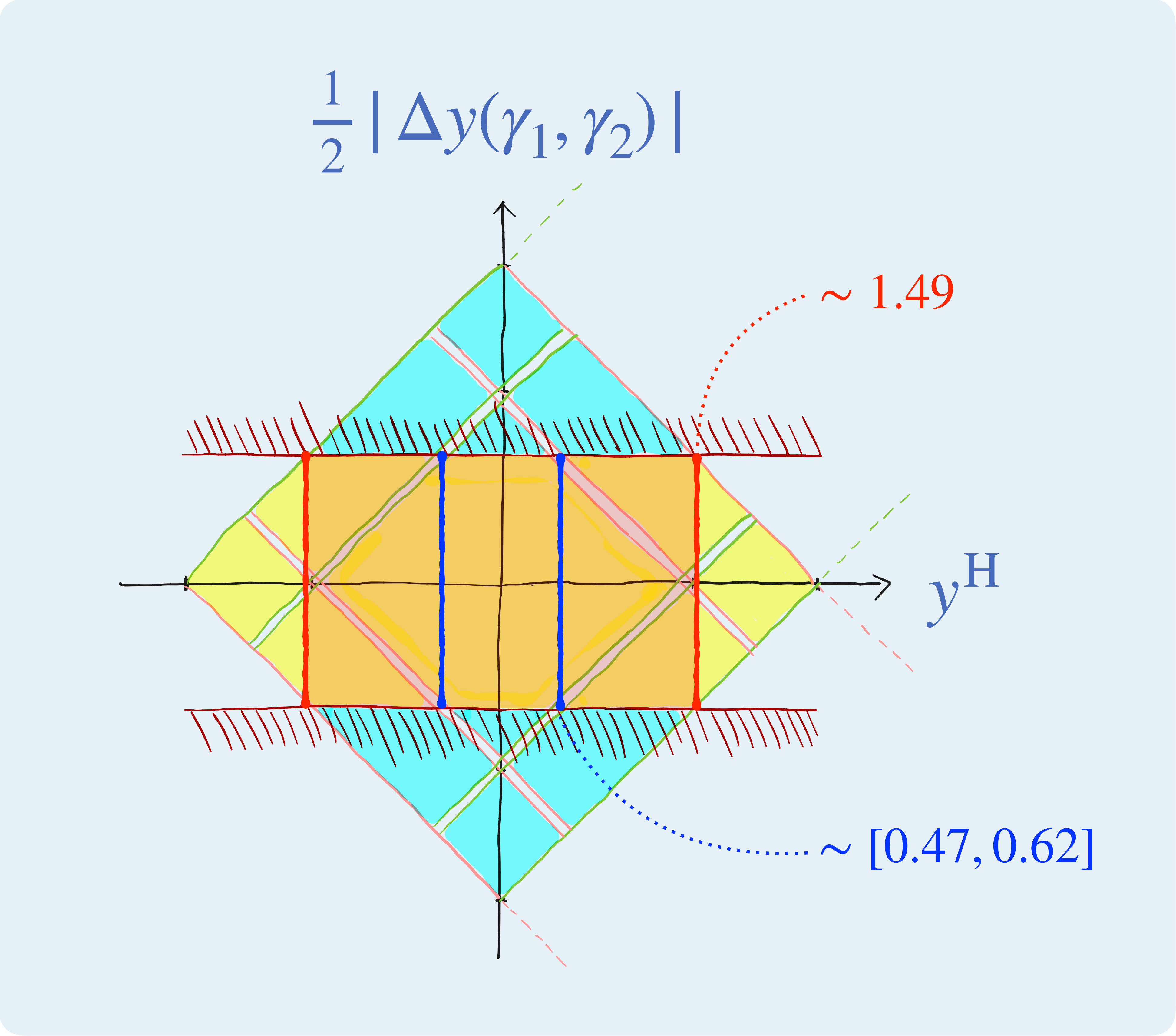
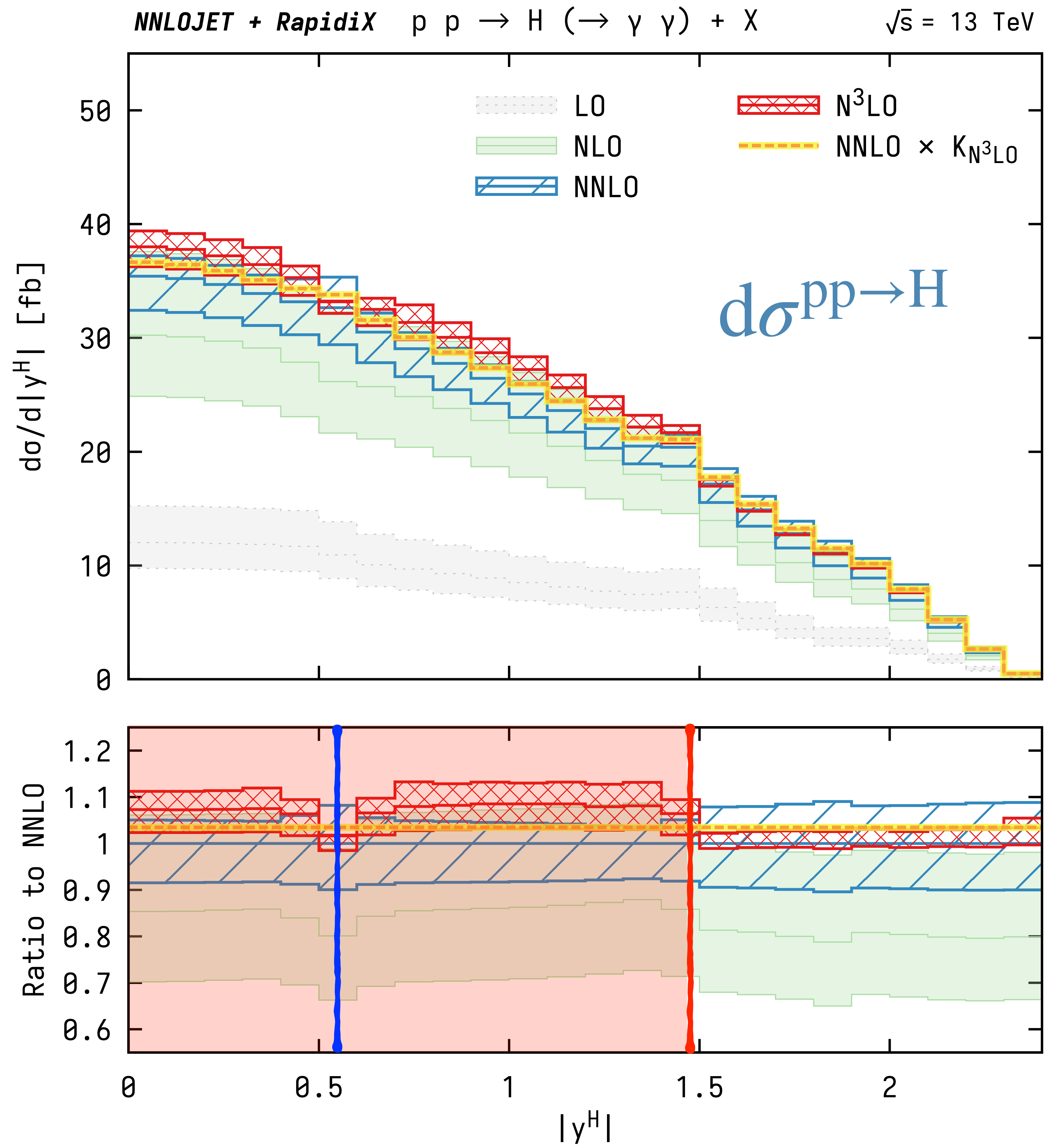






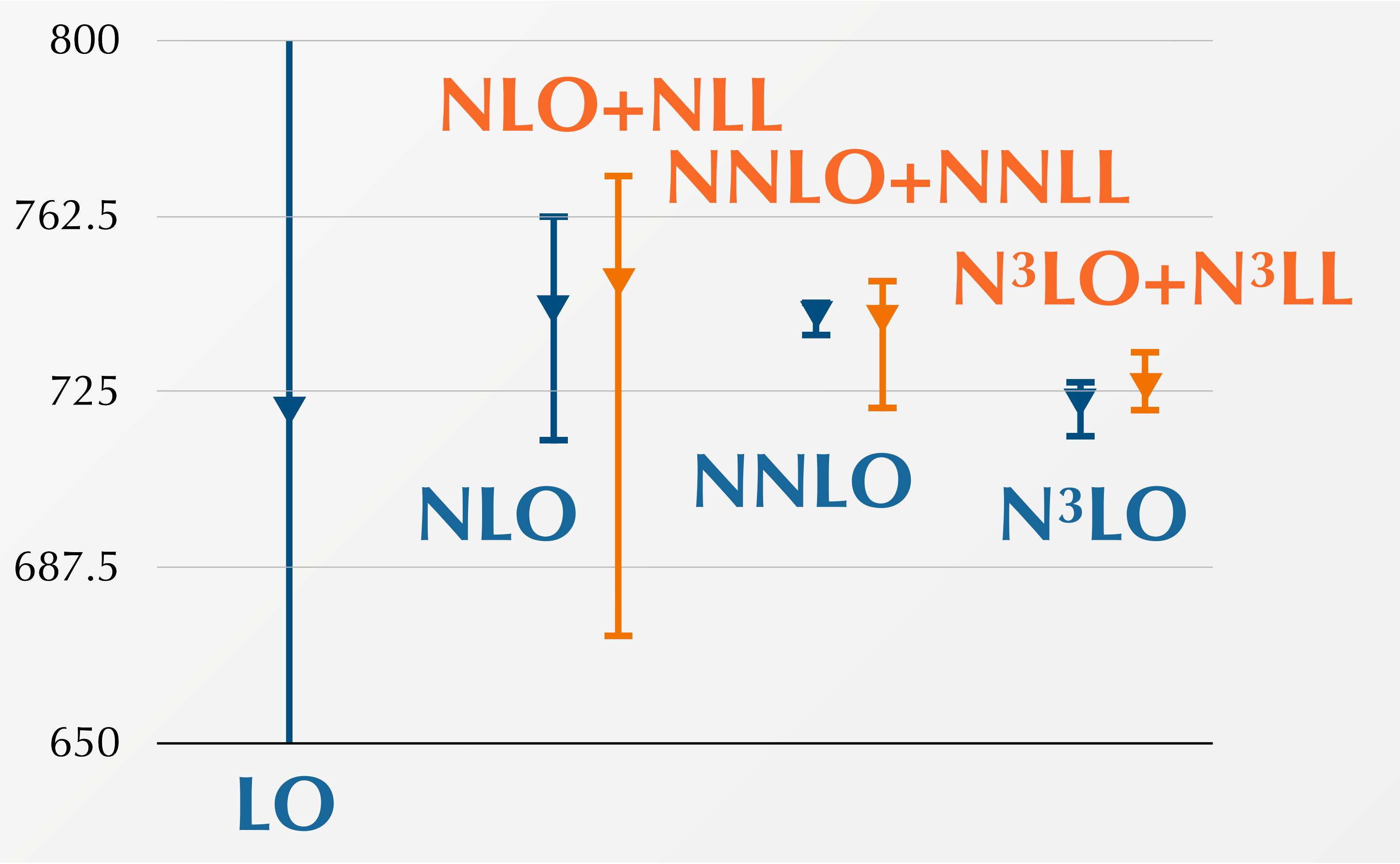
FIDUCIAL Z CROSS SECTION @ N³LO+N³LL

Symmetric cuts:

$p_T^{\ell^\pm} > 27\,\mathrm{GeV}$

[Chen, Gehrmann, Glover, AH, Monni, Rottoli, Re, Torrielli '22]

Order	σ [pb] Symmetric cuts	
k	N^{k}LO	N^{k}LO+N^{k}LL
0	$721.16^{+12.2\%}_{-13.2\%}$	—
1	$742.80(1)^{+2.7\%}_{-3.9\%}$	$748.58(3)^{+3.1\%}_{-10.2\%}$
2	$741.59(8)^{+0.42\%}_{-0.71\%}$	$740.75(5)^{+1.15\%}_{-2.66\%}$
3	$722.9(1.1)^{+0.68\%}_{-1.09\%} \pm 0.9$	$726.2(1.1)^{+1.07\%}_{-0.77\%}$



- $K_{\mathrm{N^3LO}} \sim -2.5\,\%$; outside scale bands (fixed order)
- fixed order vs. +resummation — similar central values

  Γ_V ⇝ regulator?

  ⇝ smaller fiducial power corrections than gg → H → $\gamma\gamma$; nonetheless, not negligible
- N³LO+N³LL more robust error estimate (matching scale Q)

get rid of these completely by solving the problem at its core

FIDUCIAL Z CROSS SECTION @ N³LO+N³LL

Product cuts:

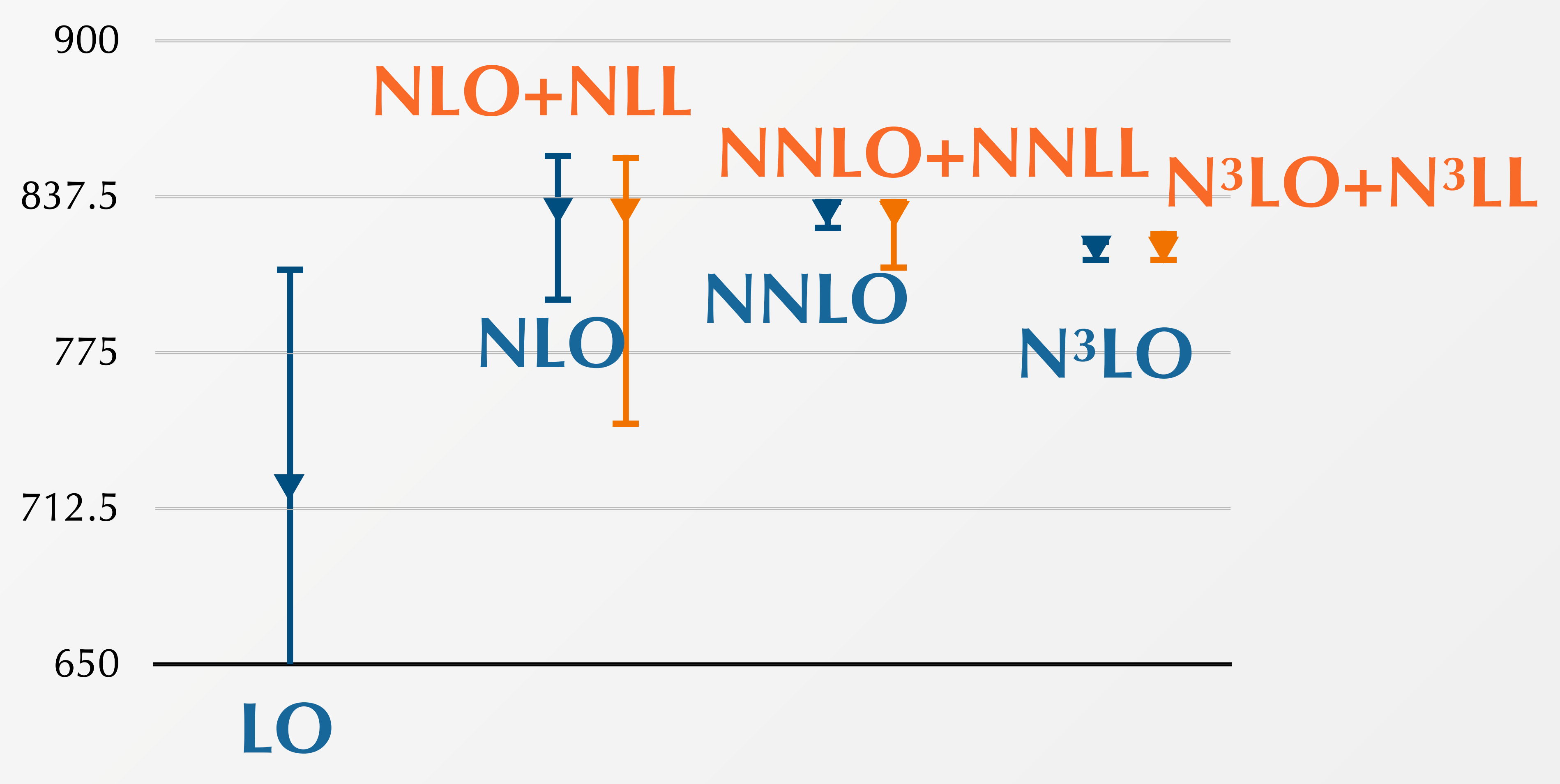
[Salam, Slade '21]

$$\sqrt{p_T^{\ell^+} p_T^{\ell^-}} > 27\,\text{GeV}$$

$$\min\left\{p_T^{\ell^\pm}\right\} > 20\,\text{GeV}$$

[Chen, Gehrmann, Glover, AH, Monni, Rottoli, Re, Torrielli '22]

Order	σ [pb] Product cuts	
k	N^{k}LO	N^{k}LO+N^{k}LL
0	$721.16^{+12.2\%}_{-13.2\%}$	—
1	$832.22(1)^{+2.7\%}_{-4.5\%}$	$831.91(2)^{+2.7\%}_{-10.4\%}$
2	$831.32(3)^{+0.59\%}_{-0.96\%}$	$830.98(4)^{+0.74\%}_{-2.73\%}$
3	$816.8(1.1)^{+0.45\%}_{-0.73\%} \pm 0.8$	$816.6(1.1)^{+0.87\%}_{-0.69\%}$



- $K_{\text{N}^3\text{LO}} \sim -2\,\%$; outside scale bands (fixed order)
- fixed order vs. +resummation — virtually identical central values
  - ⇝ basically no linear fiducial power corrections; very robust
- N³LO+N³LL more robust error estimate (matching scale Q)

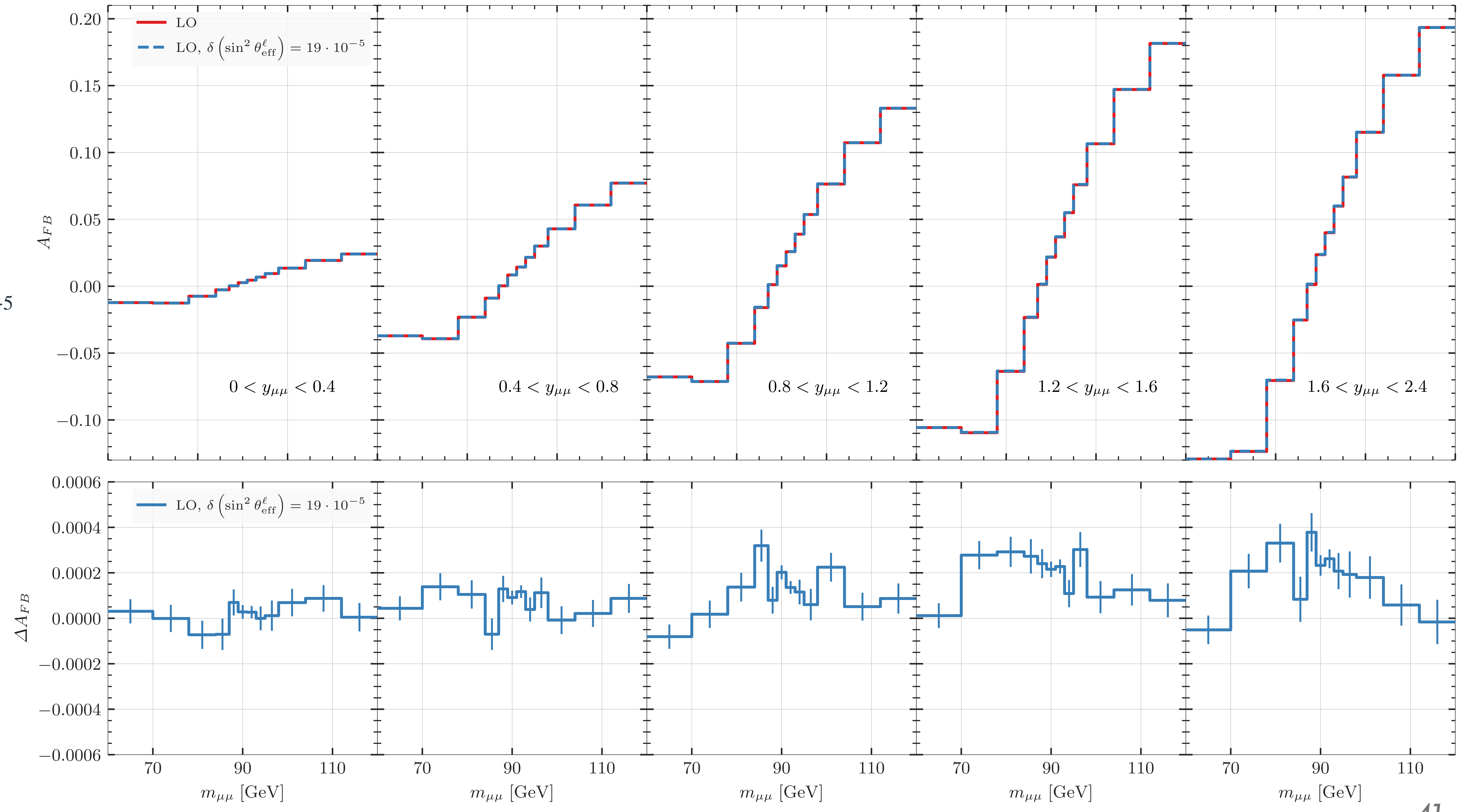
NC-DY – Forward-Backward Asymmetry

[Armadillo, Bonciani, Buonocore, Devoto, Grazzini, Kallweit, Rana, Vicini '25]

- $\delta\left(\sin^2\theta_{\text{eff}}\ell\right) \sim 19 \times 10^{-5}$

$\downarrow$

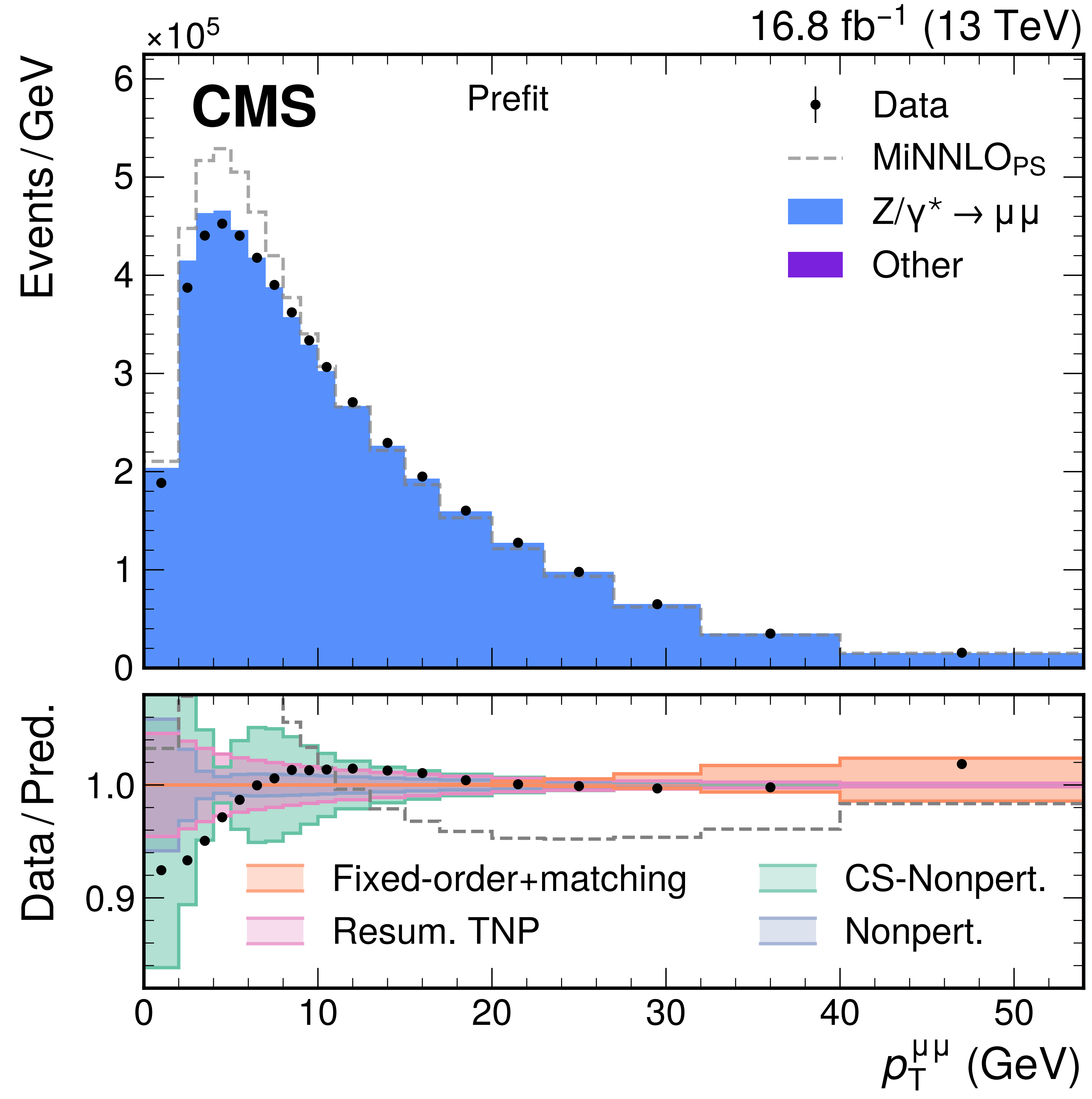
$\delta\left(A_{\text{FB}}\right) \sim \text{few } 10^{-4}$



Theory Uncertainties & Profiling

CMS M_W Measurement

- constrain $\vec{\theta}$ using data



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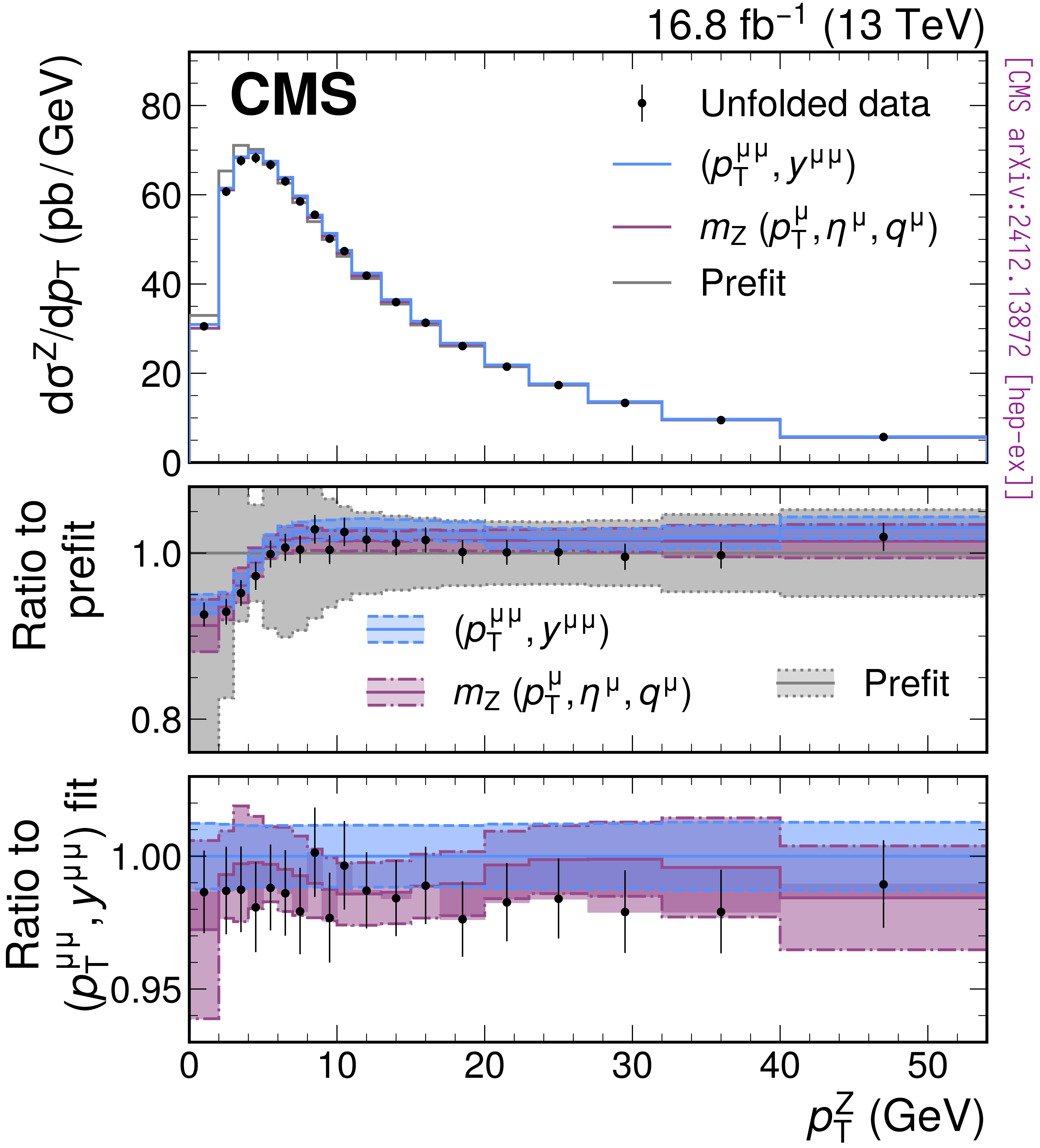
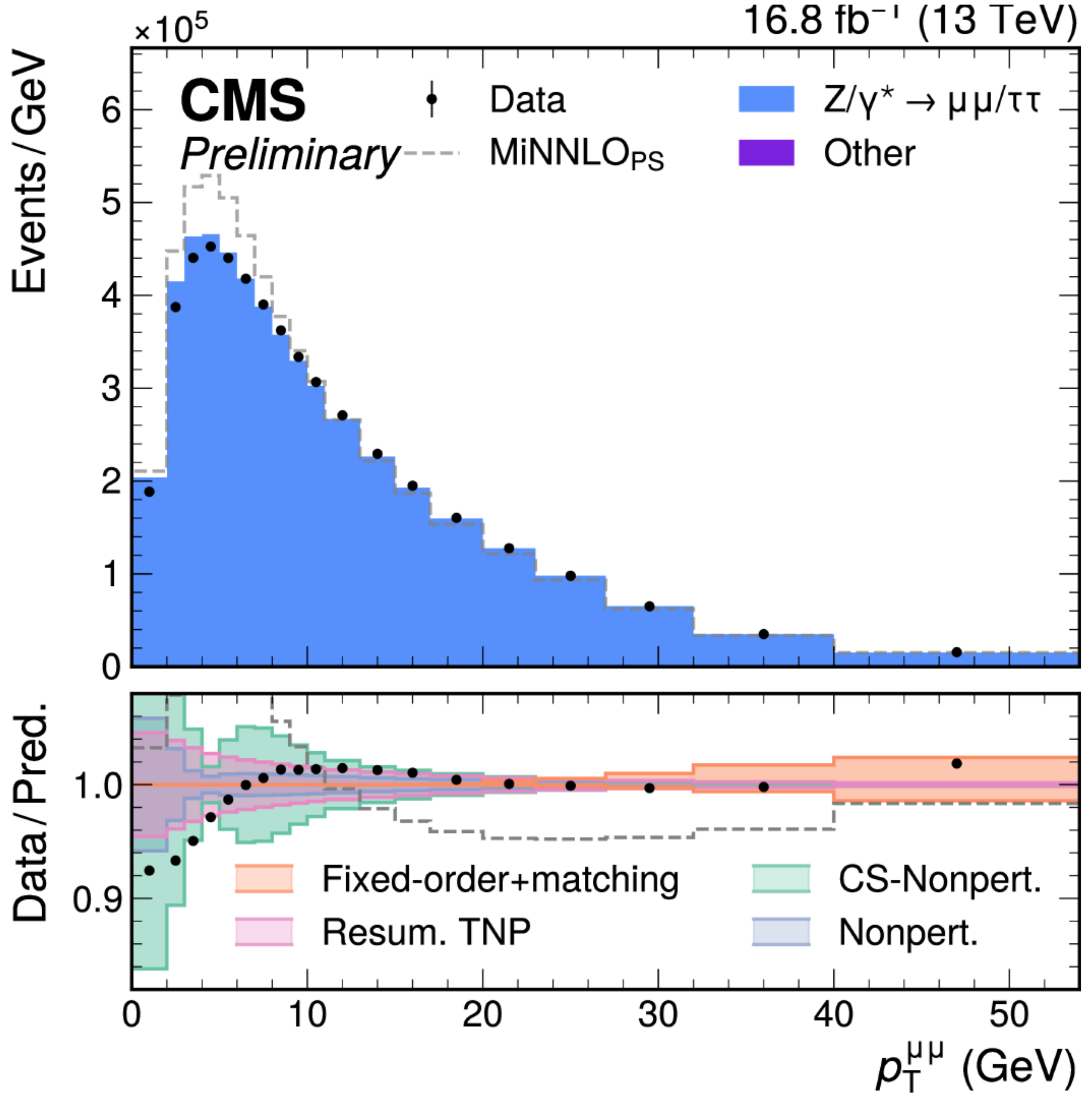
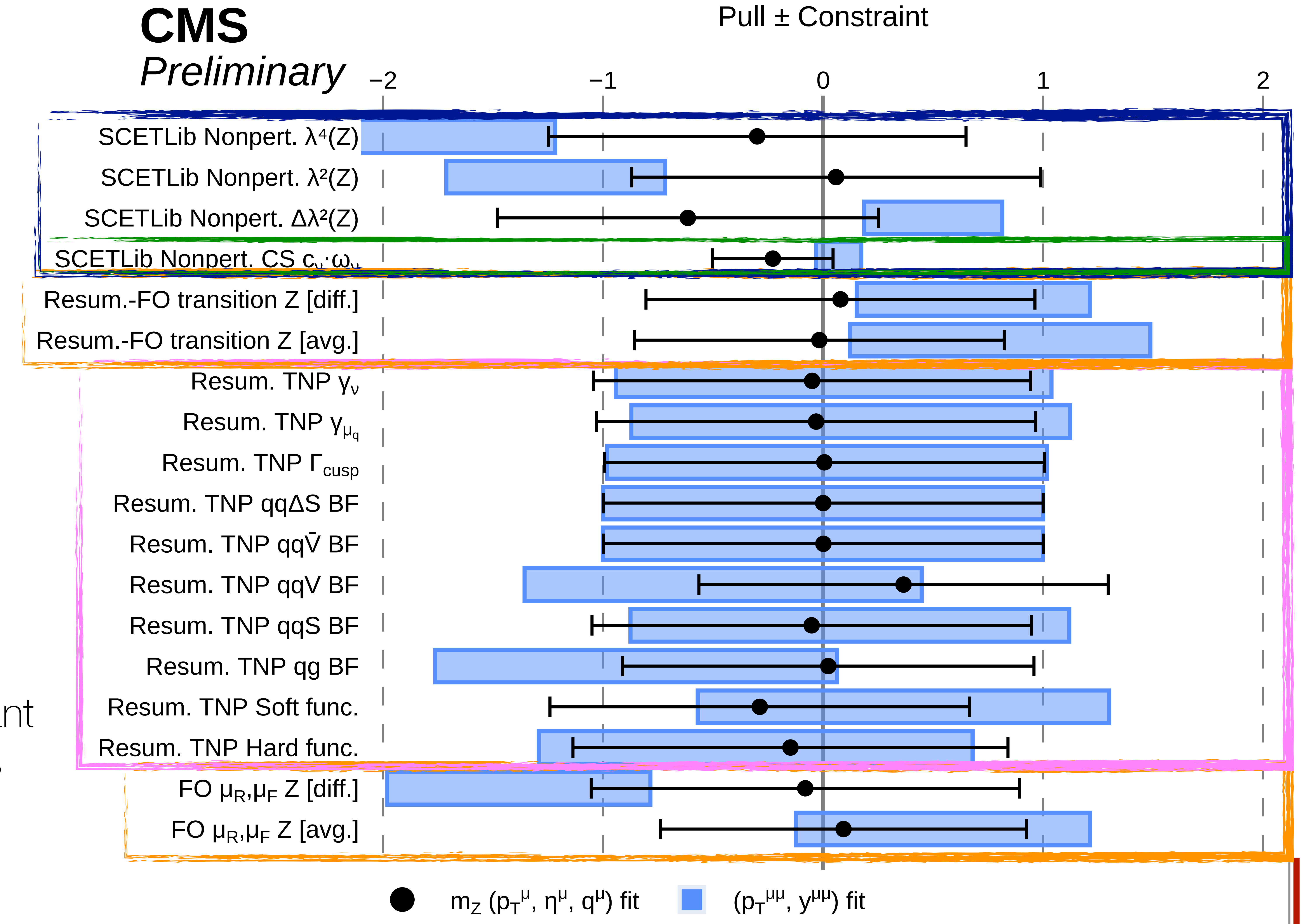


Pull ± Constraints on TNPs

[slide by K. Long]





- Small pulls/constraints on TNPs
- Nonperturbative terms most important
  - Different behaviour of $\Lambda^{(2)}$ and CS terms due to degeneracy
- **Consistent impact on p_T^Z**

Theory Nuisance Parameters

[McGowan, Cridge, Harland-Lang, Thorne '23]
[Tackmann '24], [Lim, Poncelet '24]

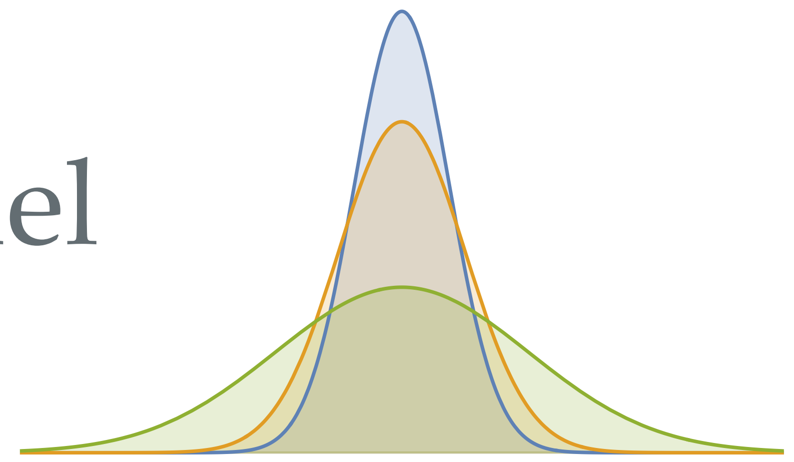
General Idea & Steps

1. parametrise the unknown order using nuisance parameters $\vec{\theta}$ (TNP)

$$d\sigma = d\sigma^{(0)} + \alpha_s\, d\sigma^{(1)} + \alpha_s^2\, d\sigma^{(2)}_{\mathrm{TNP}}(\vec{\theta})$$

$\mathcal{N}\,\theta$ (simplest case)

2. assign a probability distribution $P(\vec{\theta})$
   ↪ stat. interpretation & correlation model



3. possibility to constrain $\vec{\theta}$ using data

most interesting when we have information on the functional dependence of an observable
⇝ correlations

Theory Nuisance Parameters

[Tackmann '24]

Resummed Prediction

1. factorization in limit $p_T \to 0$ ⇝ functional dependence known

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}} = \left[H \otimes B_a \otimes B_b \otimes S\right](\alpha_s;\, L) + \mathcal{O}\left(p_T/Q\right) \qquad L \equiv \ln\left(p_T/Q\right)$$

RGE

$$\mathcal{X} \in \{H, B_a, B_b, S\} \longrightarrow \mathcal{X}(\alpha_s;\, L) = \mathcal{X}(\alpha_s)\ \exp\int_0^L \mathrm{d}L' \left\{\Gamma\left(\alpha_s(L')\right) L' + \gamma_{\mathcal{X}}\left(\alpha_s(L')\right)\right\}$$

- boundary conditions:

$$\mathcal{X}(\alpha_s) = \mathcal{X}_0 + \alpha_s\,\mathcal{X}_1 + \alpha_s^2\,\mathcal{X}_2 + \dots$$

- anomalous dimensions:

$$\Gamma(\alpha_s) = \alpha_s\left[\Gamma_0 + \alpha_s\,\Gamma_1 + \alpha_s^2\,\Gamma_2 + \dots\right] \qquad \gamma_{\mathcal{X}}(\alpha_s) = \alpha_s\left[\gamma_0 + \alpha_s\,\gamma_1 + \alpha_s^2\,\gamma_2 + \dots\right]$$

Theory Nuisance Parameters

[Tackmann '24]

Resummed Prediction

1′ parametrise unknown resummation ingredients using nuisance parameters $\vec{\theta}$

- boundary conditions: $\mathcal{X} \in \{H, \underbrace{B_a, B_b}, S\}$ → actually functions: $B_i(x_i)$

  $$\mathcal{X}_n = \mathcal{N}_{\mathcal{X}}^{(n)}\, \theta_{\mathcal{X}}$$

- anomalous dimensions:
  (+ beta function β & splitting functions $P_{a\to b}$)

  $$\Gamma_n = \mathcal{N}_{\Gamma}^{(n)}\, \theta_{\Gamma} \qquad \gamma_{\mathcal{X},n} = \mathcal{N}_{\gamma_{\mathcal{X}}}^{(n)}\, \theta_{\gamma_{\mathcal{X}}}$$

- implements a correlation model for the (low-ish) p_T spectrum

Theory Nuisance Parameters

[Tackmann '24]

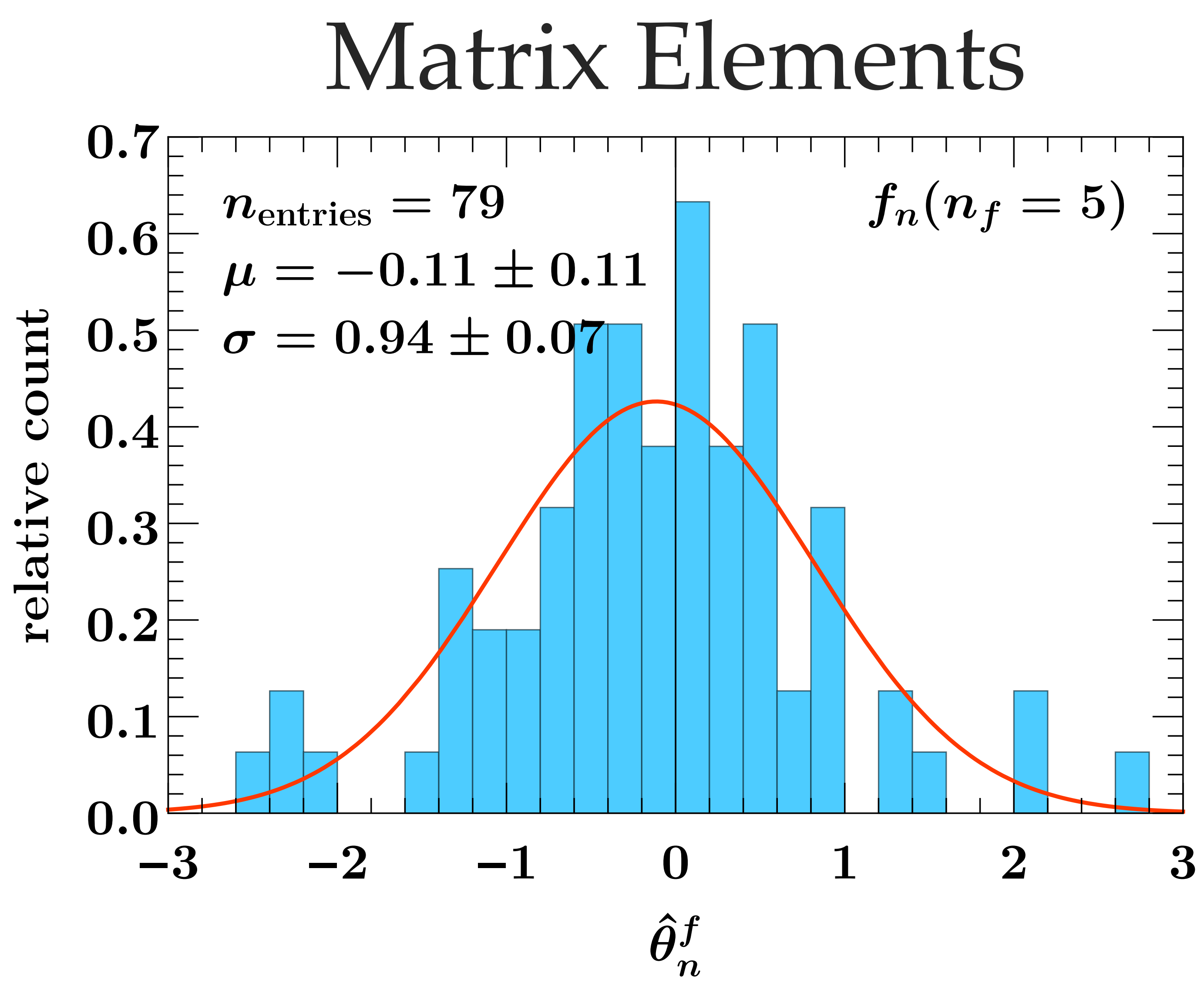
Resummed Prediction

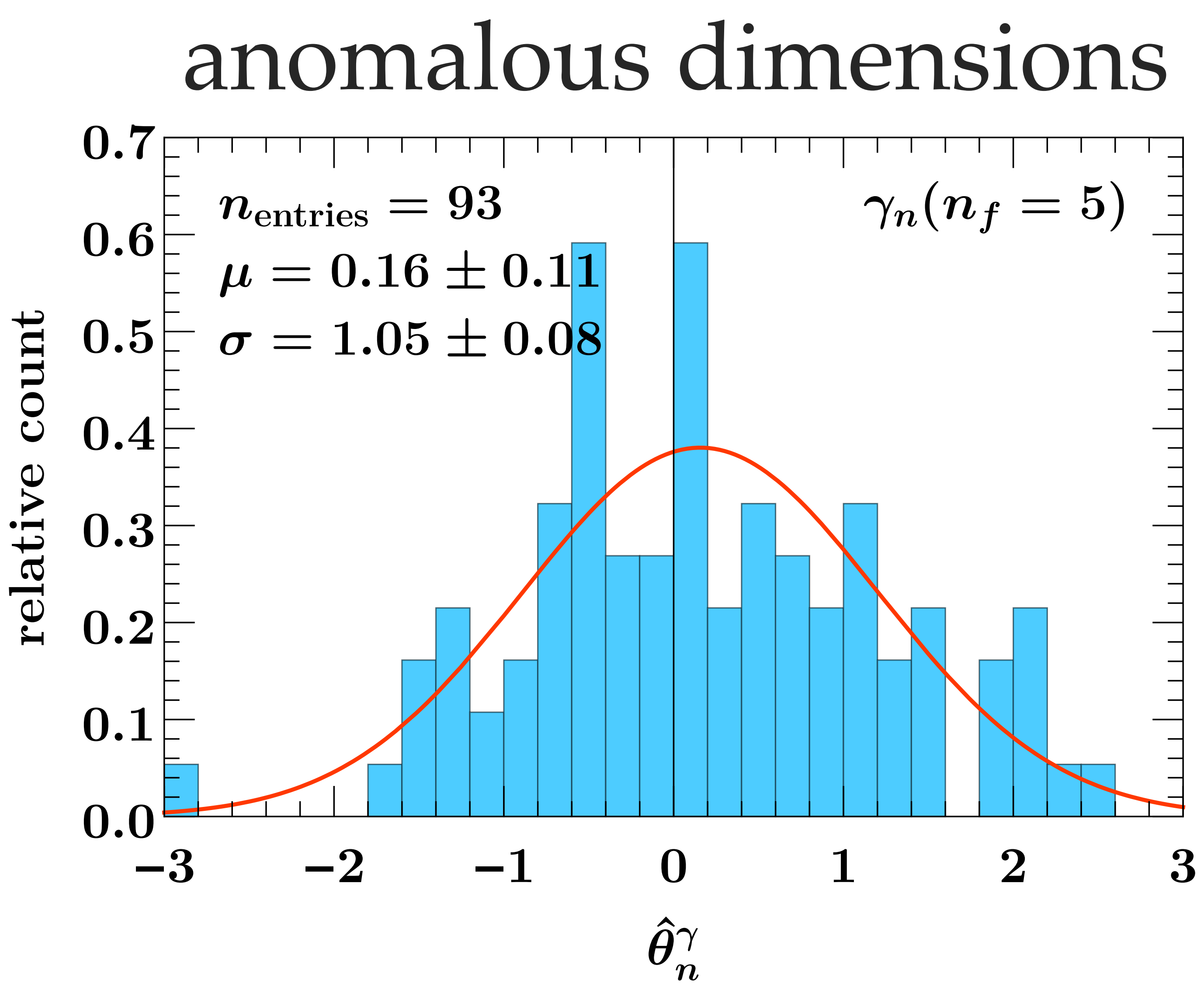
selection bias?

② assign a probability distribution (statistics over ∃ calculations)

⇝ assume universality in order n as well as processes / ingredients

valid?





$$\mathcal{N}_{\mathcal{X}}^{(n)} = 4^n\, C_r\, C_A^{n-1}\, (n-1)!$$

(& $\mathcal{X} \to \mathcal{X}^\delta$ to scale like $\mathcal{M}_{1\to1}$)

$$\mathcal{N}_{\Gamma}^{(n)} = 4^n\, C_r\, C_A^{n}$$

"massaging"

Choices (⇝ ambiguities)

- scheme dependence (scale, ren. scheme, IR subtr., …)
- parametrisation freedom ($\vec\theta \to \vec\theta'$: changes what is uncorrelated / independent)

Theory Nuisance Parameters

[Tackmann '24]

Resummed Prediction

- 2′ 100% correlation of $\vec{\theta}$
  - large cancellation in W^+/Z
  - dominant residual uncertainties from B_{ab}
- similar absolute errors to Δ_{scl}
- valid at low p_T
  ↪ requires matching @ high p_T (μ_R, μ_F)
- missing: non-pert. modelling