Impact of theory uncertainties in the extraction of precise EW parameters at the LHC

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Outline

1. **Introduction**: the Drell-Yan process experimentally and theoretically

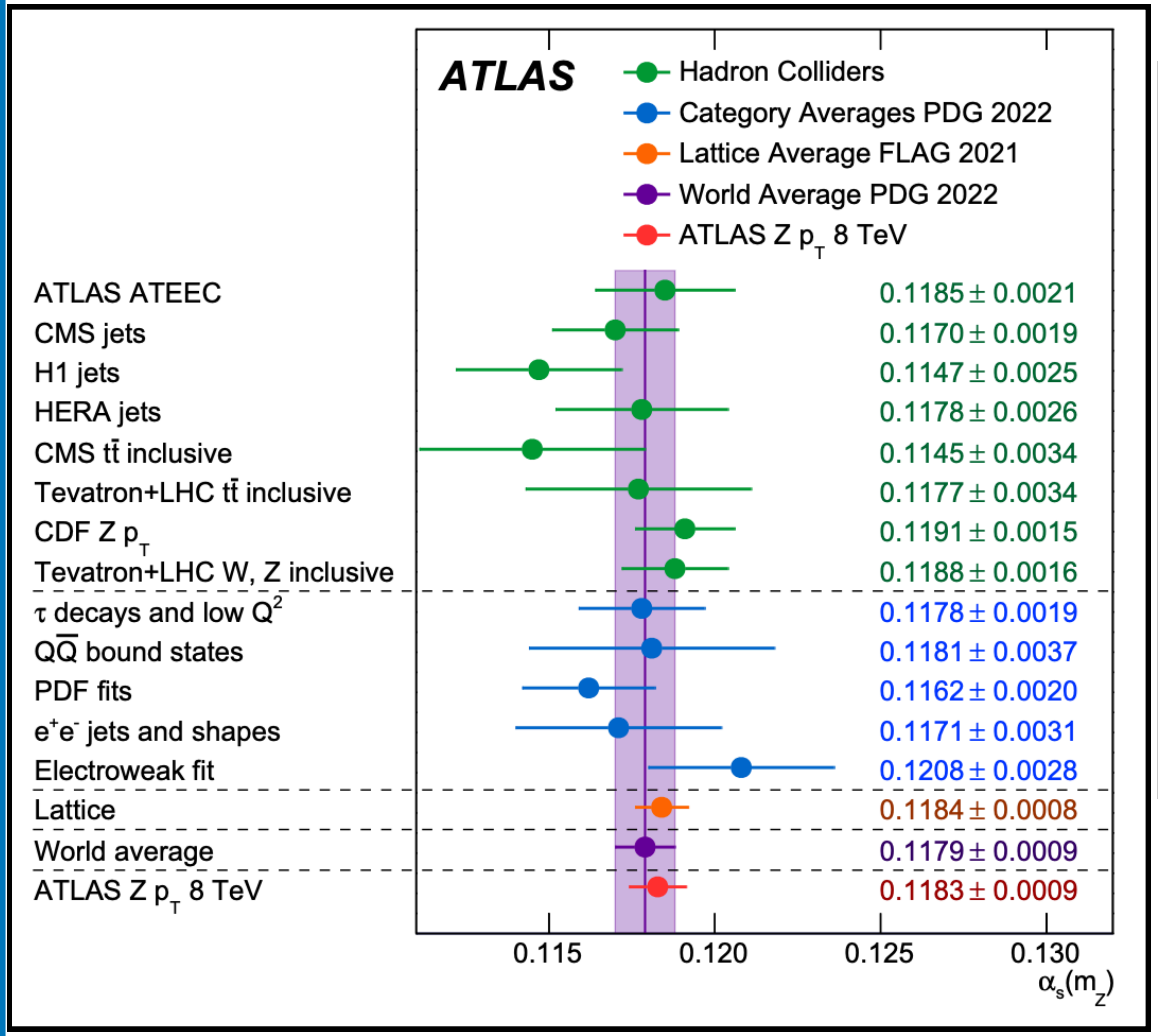
2. **Theory Uncertainties** and how to propagate them
   - Scanning or off-setting
   - Profiling

3. $\alpha_s(m_Z)$ and m_W extractions as examples

Drell-Yan: the EW standard candle of the LHC

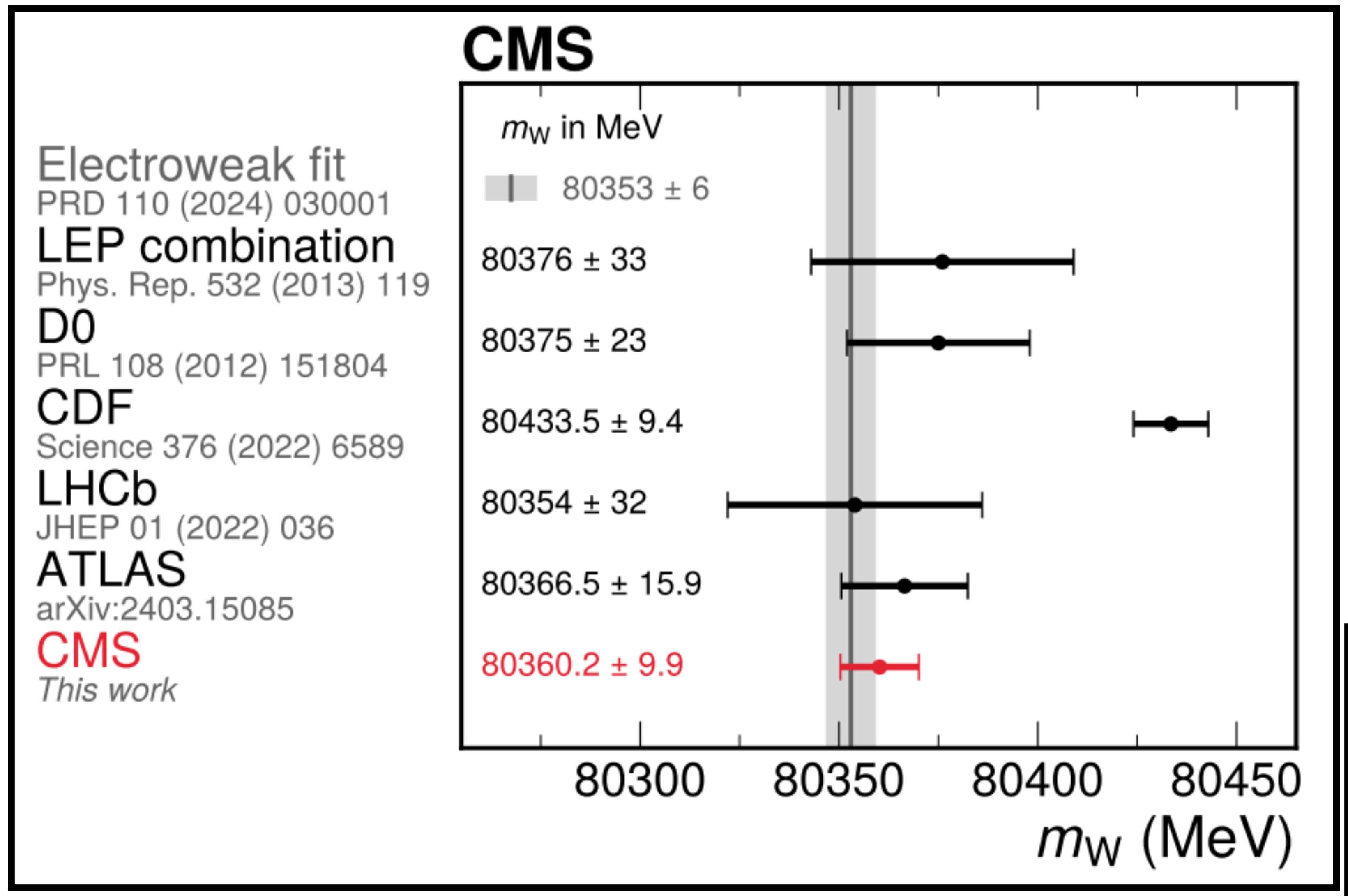
LHC not only discovery machine, but also a **precision machine!**

Drell-Yan process (*mostly its color singlet q_T spectrum*) has a special role:

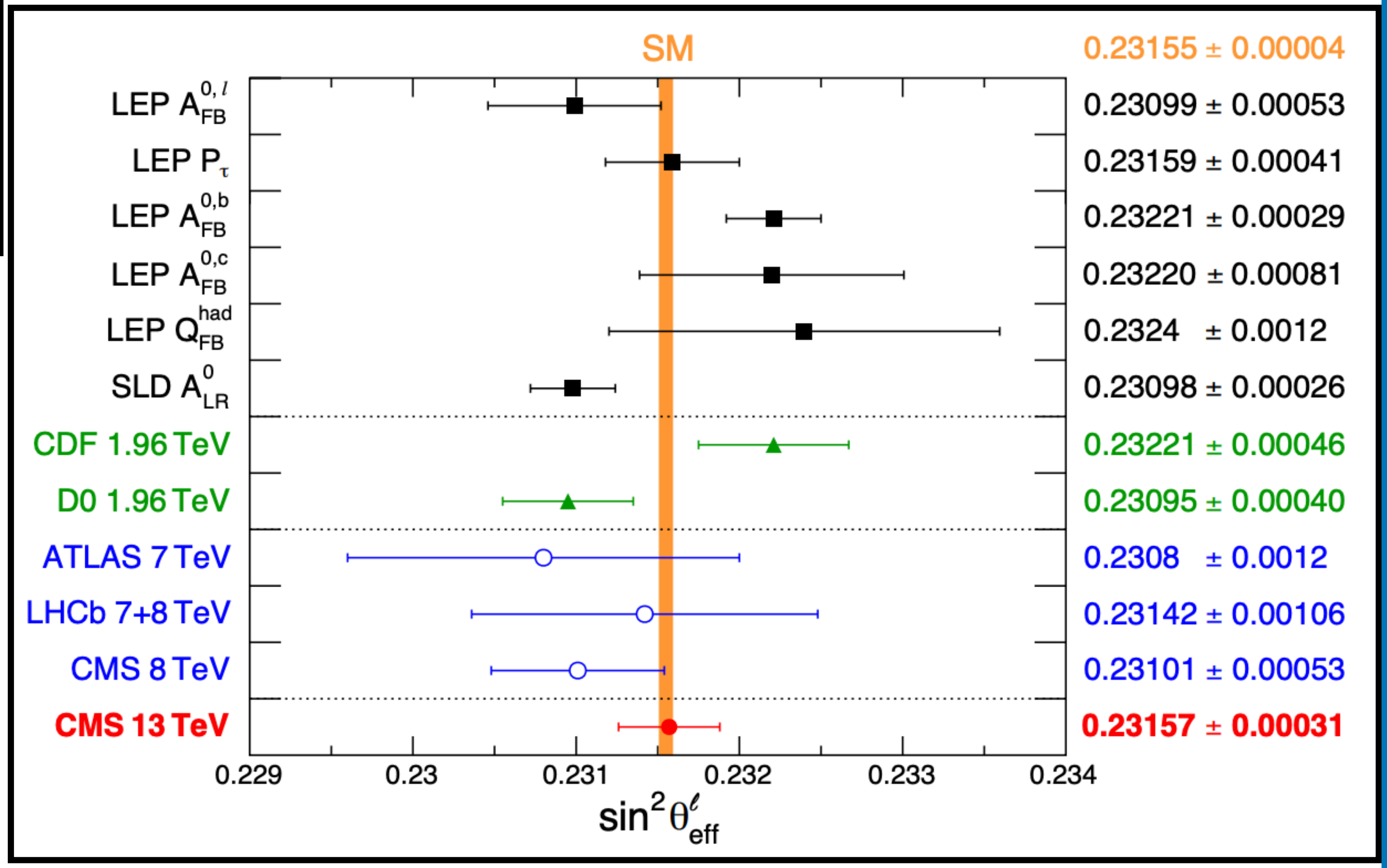


$\alpha_s(m_Z)$

[ATLAS '23, '24]



m_W [CMS '24]



$\sin^2\theta^\ell_{\mathrm{eff}}$

[CMS '24]

Drell-Yan: the EW standard candle of the LHC

- Wide-ranging applications, many precise **measurements**:

  ATLAS '20, ATLAS '24, CMS '17, CMS '19, LHCb '16, ...

  experimental precision $\sim \mathcal{O}(1\,\%)$

- Many **theory** requirements to reach the same level of precision:

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\text{resum}}$$ resummation

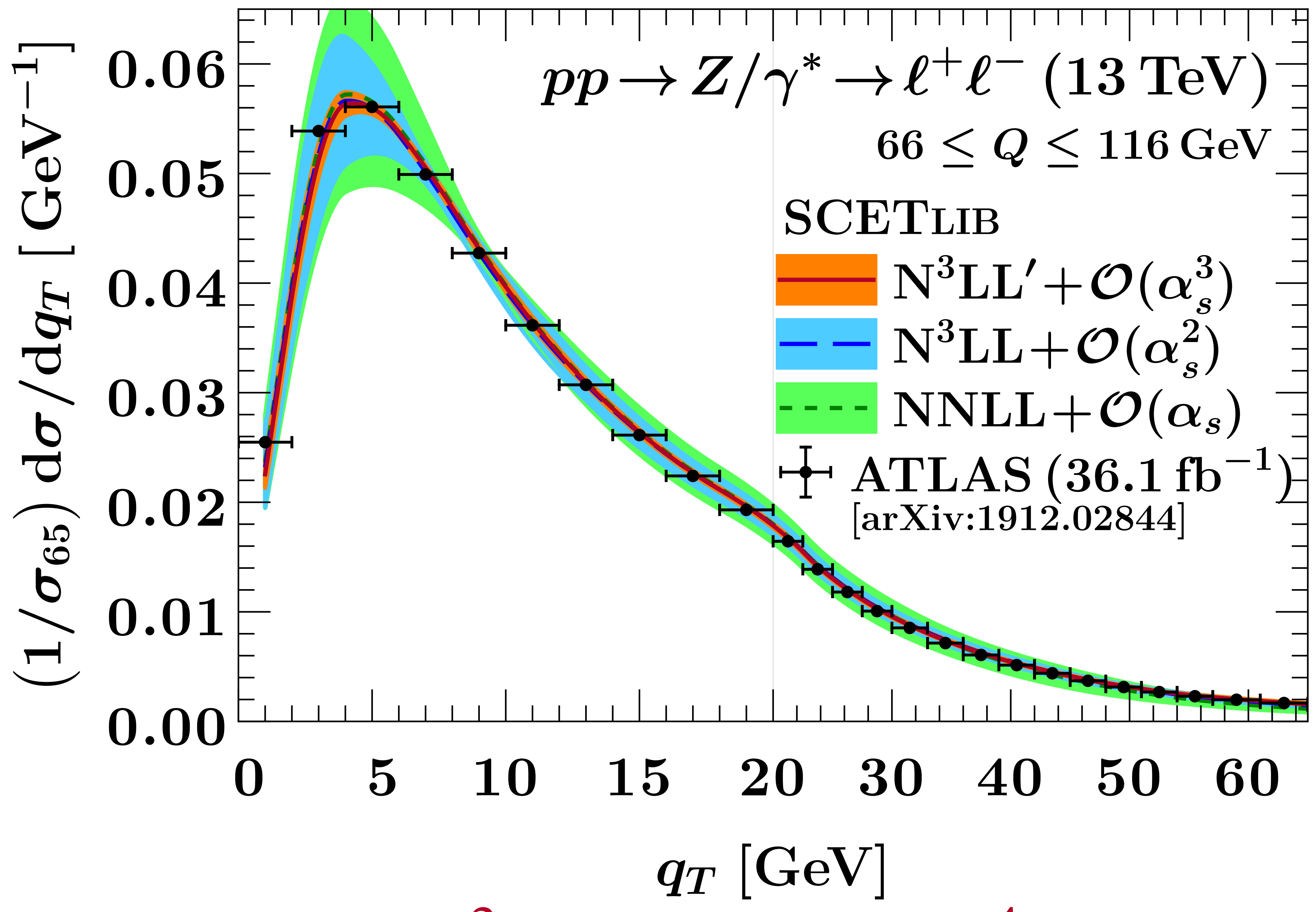
$$+\mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$ pert. power corrections

$$+\mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{q_T^2}\right)$$ nonpert. effects

$$+\mathcal{O}\left(\frac{m_q^2}{q_T^2}\right)$$ quark mass corrections

$$+\mathcal{O}(\alpha^{\text{ISR/EW}}) + \mathcal{O}(\alpha_{\text{em}}^{\text{FSR}})$$ EW corrections

+ Parton Distribution Functions (PDFs)



N^{3}LL$'$/ approx N^{4}LL

Camarda, Cieri, Ferrera '23
Moos, Scimeni, Vladimirov, Zurita '24
Billis, Michel, Tackmann '25

Theory vs Data

Given a measured observable f:

$$\left[f \pm \Delta f_{\text{stat}} \pm \Delta f_{\text{sys}}\right]_{\text{exp}} \stackrel{?}{=} \left[f(p) \pm \Delta f\right]_{\text{theo}}$$

✓ ✓ ?

Δf theory uncertainty due to inexactness of theory prediction, usually dependent on a PoI p

taken from Tackmann's EW-WG '26

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Meaningful Theory Uncertainties:

1. must reflect our degree of knowledge (or ignorance) of $f(p)$
2. provide correct **correlations** for different predictions
3. have a statistical meaning needed for the interpretation of experimental measurements

» High-precision measurements often deal with $\Delta f \gg \Delta f_{\text{stat}} \gg \Delta f_{\text{sys}}$

taken from Tackmann's EW-WG '26

Theory vs Data: propagate uncertainty

More *delicate* treatment when extracting a PoI :

$$\left[f \pm \Delta f_{\text{stat}} \pm \Delta f_{\text{sys}}\right]_{\text{exp}} = \left[f(p) \pm \Delta f\right]_{\text{theo}} \dashrightarrow \quad p \pm \Delta p$$

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1 **Scanning (off-set):** $f_{i,\text{exp}} = f_i(p) + \theta \Delta f_i \rightarrow p \pm \Delta p$ usually multiple quantities f_i (different bins, processes, ...)

Solve for p at fixed θ: $\theta = 0 \rightarrow p, \quad \theta = \pm c \rightarrow \pm \Delta p$ 0 central value, c value of the variation

- using a common θ means treat all Δf_i as 100% correlated
- using separate θ_i for each Δf_i means treat all Δf_i as uncorrelated

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2 Profiling: $f_{i,\text{exp}} = f_i(p) + \theta \Delta f_i \rightarrow p \pm \Delta p_{\text{fit}}$ and $\theta \pm \Delta \theta_{\text{fit}}$

Solve (fit) both p and θ:

- fit move theory prediction along fixed trajectories given by $\theta \Delta f_i$
- relies on knowing correlation of Δf_i

correlation of Δf_i is fundamental!

taken from Tackmann's EW-WG '26

Uncertainty: approaches for MHO uncertainty

$$d\sigma = d\sigma^{\text{resum}} + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{q_T^2}\right) + \mathcal{O}\left(\frac{m_q^2}{q_T^2}\right) + \mathcal{O}(\alpha^{\text{ISR/EW}}) + \mathcal{O}(\alpha_{\text{em}}^{\text{FSR}}) + \text{PDFs}$$

missing higher orders (MHOs) or perturbative uncertainty

Major source of uncertainty

$$f(\alpha) = f_0 + \alpha f_1 + \alpha^2 f_2 + \mathcal{O}(\alpha^3) \longrightarrow \text{NLO}: f(\alpha) = \hat{f}_0 + \alpha \hat{f}_1 \pm \Delta f$$

Δf is due to the series of the unknown true values $\hat{f}_n$

Can be determined through:

- **scale variations** $\Delta f = \max_{\text{vary}} | f(\mu_{\text{vary}}) - f(\mu_{\text{central}}) |$
- scale variation with bayesian approach
- series acceleration
- using reference processes

Cacciari, Houdeau '11 - Bonvini '20
Duhr, Huss et al. '21 - David, Passarino '13
Ghosh, Nachman et al. '22

- Theory Nuisance Parameters (**TNPs**) Tackmann '24 - Poncelet, Lim '24

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Can be determined through:

- **scale variations** $\Delta f = \max_{\text{vary}} | f(\mu_{\text{vary}}) - f(\mu_{\text{central}}) |$ — many **known** limitations

- scale variation with bayesian approach
- series acceleration
- using reference processes

Cacciari, Houdeau '11 - Bonvini '20
Duhr, Huss et al. '21 - David, Passarino '13
Ghosh, Nachman et al. '22

improved, but still sharing some limitations of scale vars.

- Theory Nuisance Parameters (**TNPs**) Tackmann '24 - Poncelet, Lim '24 — new approach

Theory Nuisance Parameters (TNPs) in a nutshell

Tackmann '24

1 **Parametrize** the uncertainty by the missing highest piece

$$\mathrm{N}^{2+1}\mathrm{LO}: \; f^{\mathrm{pred}}(x, \theta_3) = \hat{f}_0(x) + \alpha\, \hat{f}_1(x) + \alpha^2\, \hat{f}_2(x) + \alpha^3 f_3\,(x, \theta_3)$$

nuisance parameters θ_n

key condition : $\hat{f}_n(x) = f_n(x, \hat{\theta}_n)$

- true values $\hat{\theta}_n$ must satisfy this relation
- $f_n(x, \theta)$ encodes correct x dependence —— correlation structure in x
- once θ_3 becomes well constrained/known, move to θ_4

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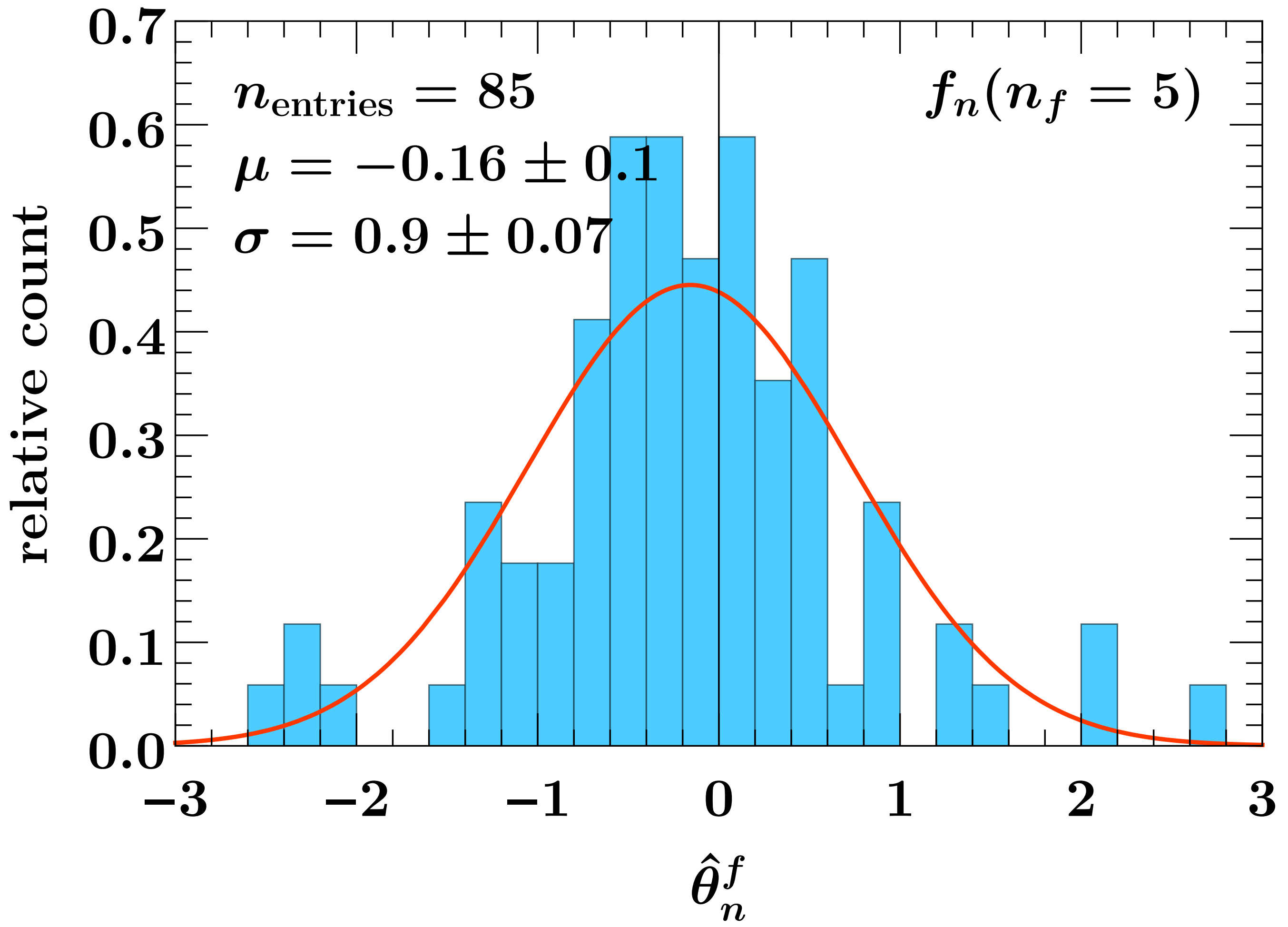
2 **Define** θ_n: account for the internal structure of $f_3(x,\theta_3)$ and find a **suitable parameterization**

3 Obtain **suitable constraints** on TNPs: $\theta_n = \theta_n^{\mathrm{central}} \pm \Delta\theta_n$

theory judgement

- needed for off-set or as prefit constraint when profiling
- θ_n normalized such that default theory constraint is $\theta_n = 0 \pm 1$

68% theory CL



Applications

1 $\alpha_s(m_Z)$ from DY q_T spectrum [α_s **is** a %-level **shape effect** $\rightarrow$ bin-by-bin correlation is crucial]

- using toy/Asimov standard χ^2 fits:
  central theory prediction at $\alpha_s(m_Z) = 0.118$ as pseudodata, uncertainty assigned from **ATLAS 8 TeV** meas.
- study only the dominant source of uncertainty (MHO), neglecting power corrections, mass effects, etc..

2 CMS m_W determination from DY q_T spectrum [first modeling p_T^W to then propagate uncertainty on p_T^ℓ and m_W]

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2 CMS m_W determination from DY q_T spectrum [first modeling p_T^W to then propagate uncertainty on p_T^ℓ and m_W]

Drell-Yan resummed q_T ($\equiv x$) spectrum case: [considering SCET factorization]

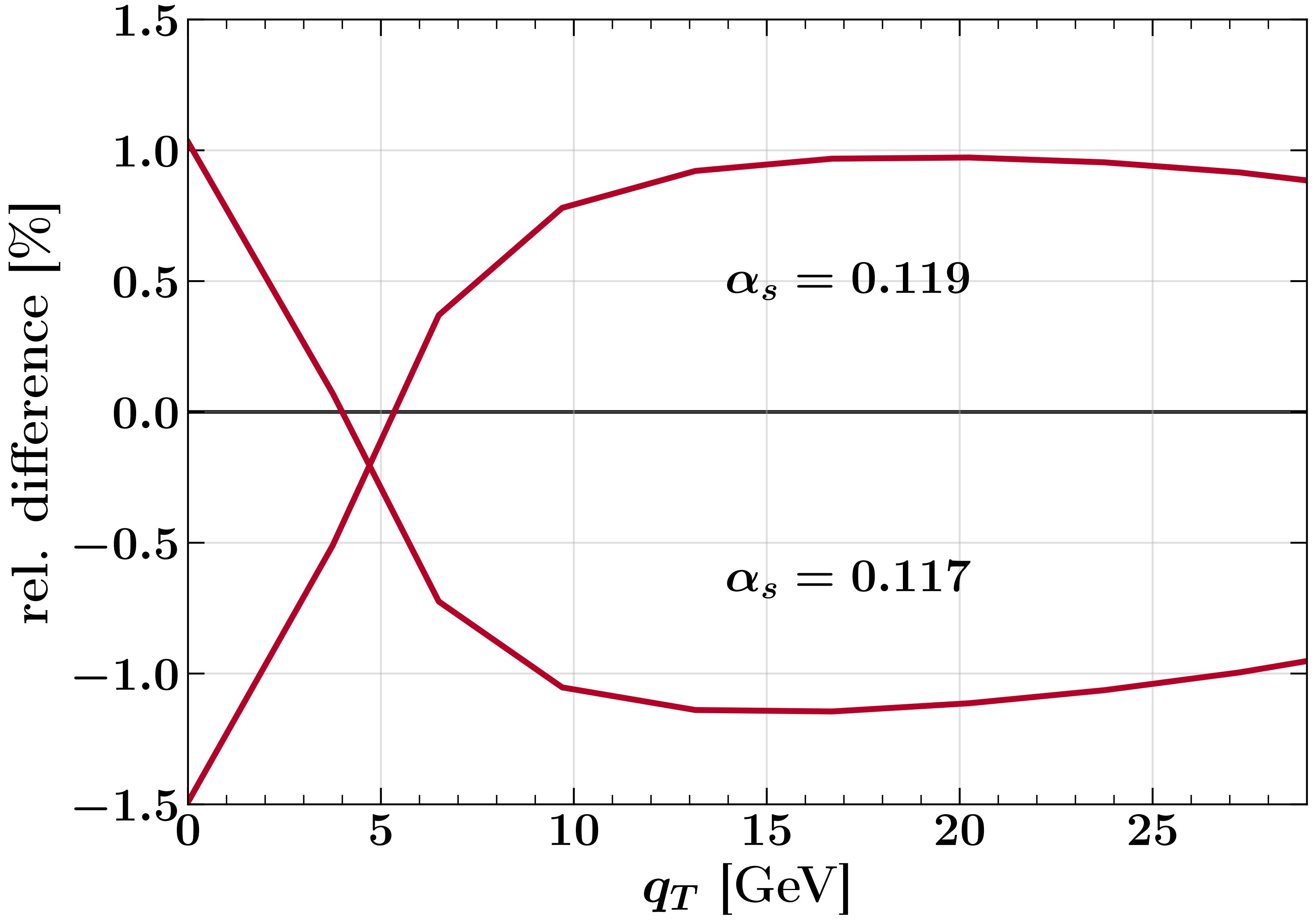
$$q_T \frac{d\sigma}{dq_T} = \left[H \times B_a \otimes B_b \otimes S \right] (\alpha_S, L \equiv \ln q_T/m_Z) + \mathcal{O}\left(\frac{q_T^2}{m_Z^2}\right)$$

leading power q_T dependence known to all orders

- Described by seven TNPs: $\Gamma_{\rm cusp}$, γ_μ , γ_ν , $H(\alpha_s)$, $S(\alpha_s)$, B_{qq} , B_{qg}
- Nomenclature used: N^{n+k}LL, with $k = 0{,}1$
  Full N^{n+k} structure, including TNPs for beyond N^{n}LL ingredients

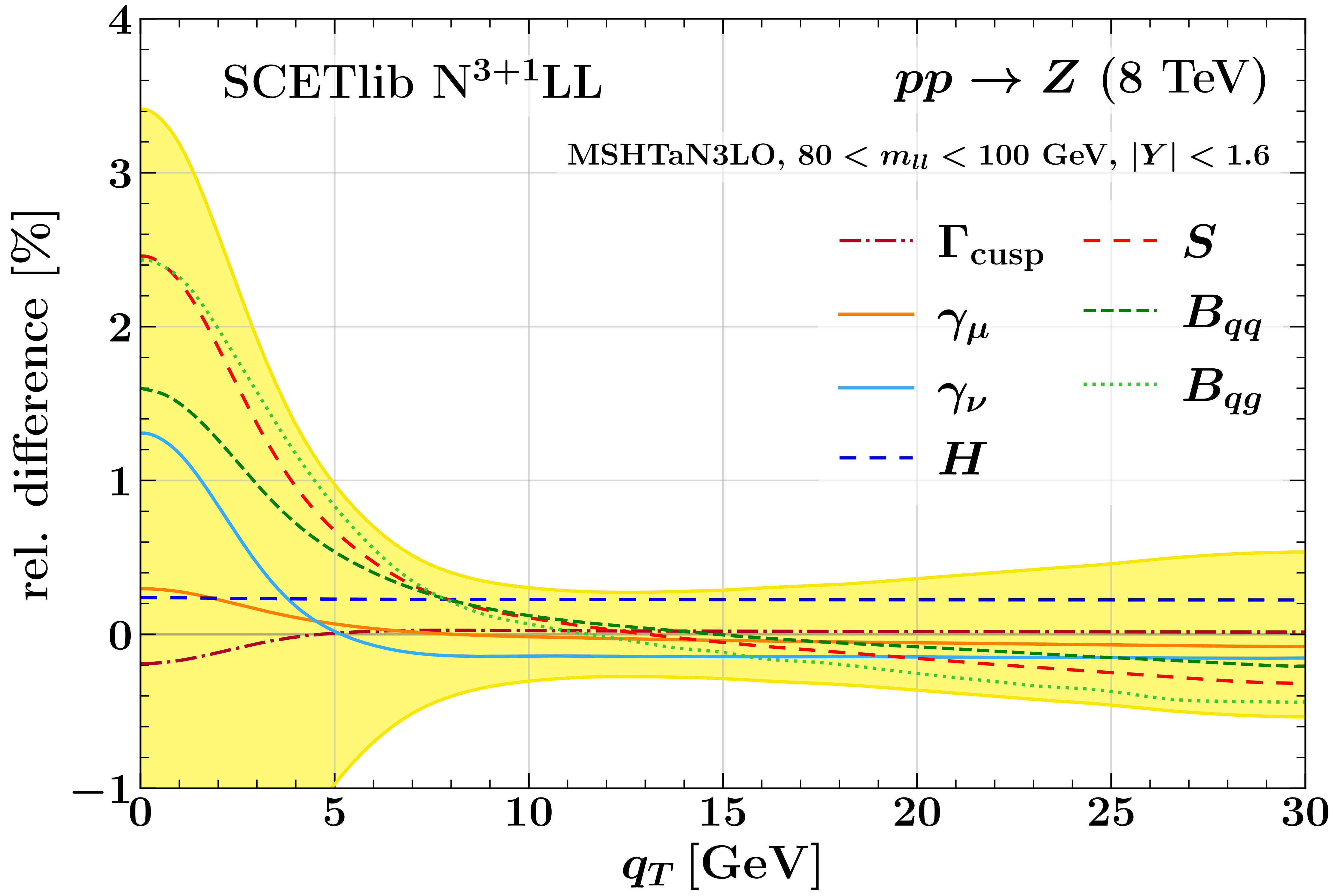
$\alpha_s(m_Z)$ from DY q_T spectrum

%-level **shape effect**



Perturbative uncertainty: TNP scanning Cridge, GM, Tackmann '25

Data as $\mathrm{N^{3+1}LL}$ at $\alpha_s = 0.118$ against $\mathrm{N^{3+1}LL}$ theory model



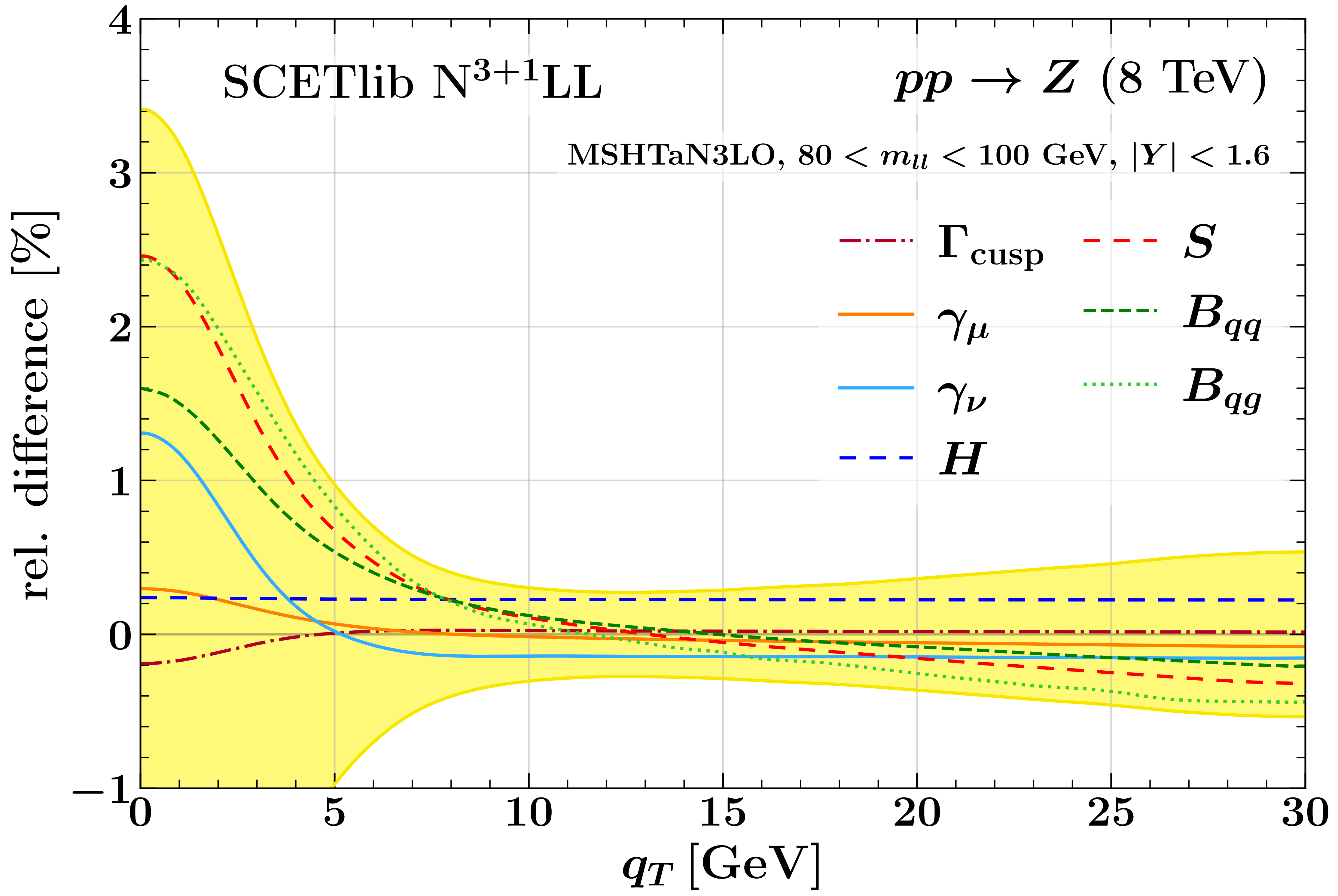
- Breakdown into independent sources of uncertainty with correct shape (correlation) in q_T, varying each TNP by $\Delta\theta_n = \pm 1$

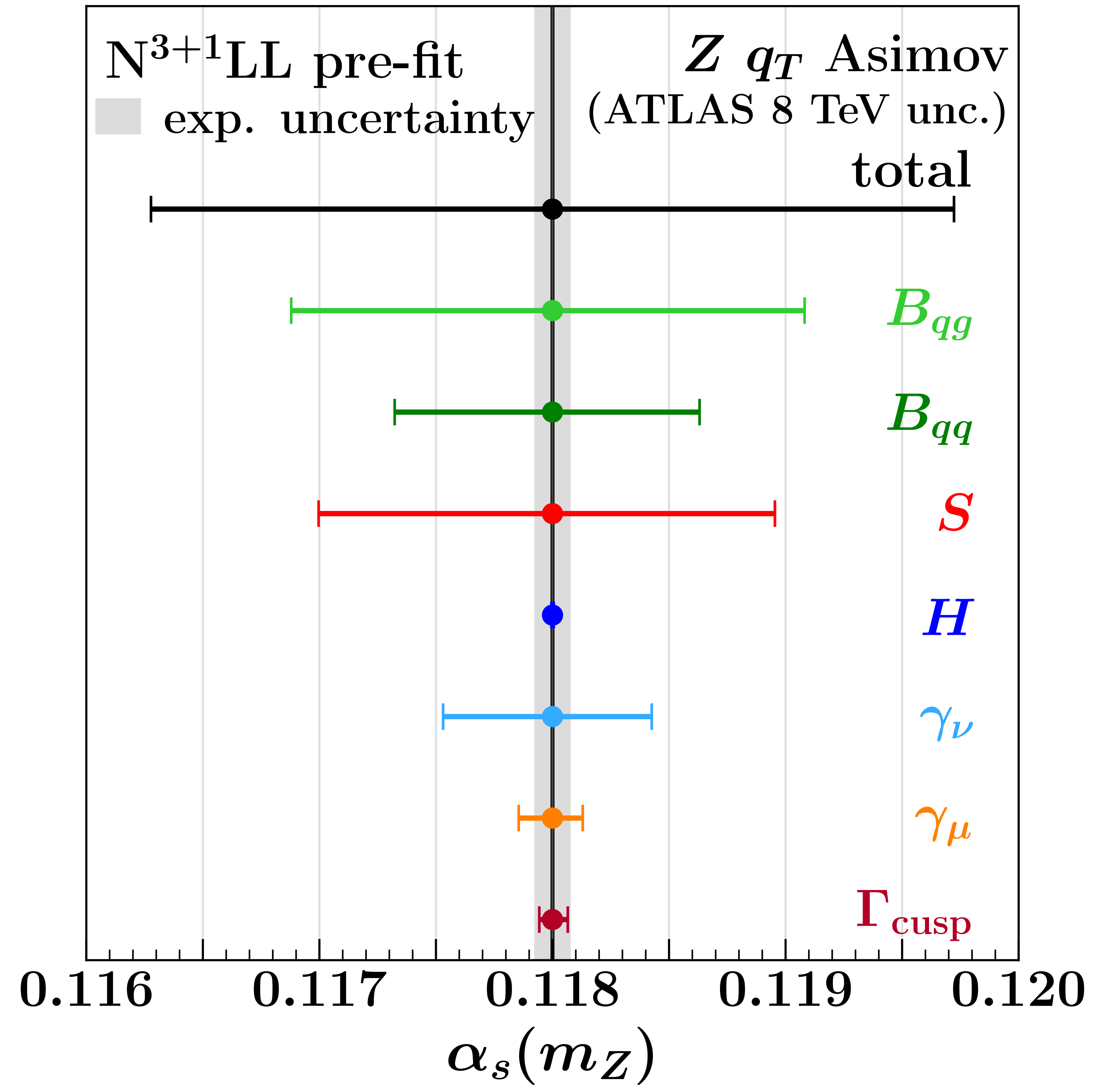
Perturbative uncertainty: TNP scanning

Cridge, GM, Tackmann '25

Data as N^{3+1}LL at $\alpha_s = 0.118$ against N^{3+1}LL theory model

$$\chi^2_{\text{total}} = \sum_{ij} (y_i - \lambda_i)^T C^{-1}_{ij} (y_j - \lambda_j)$$





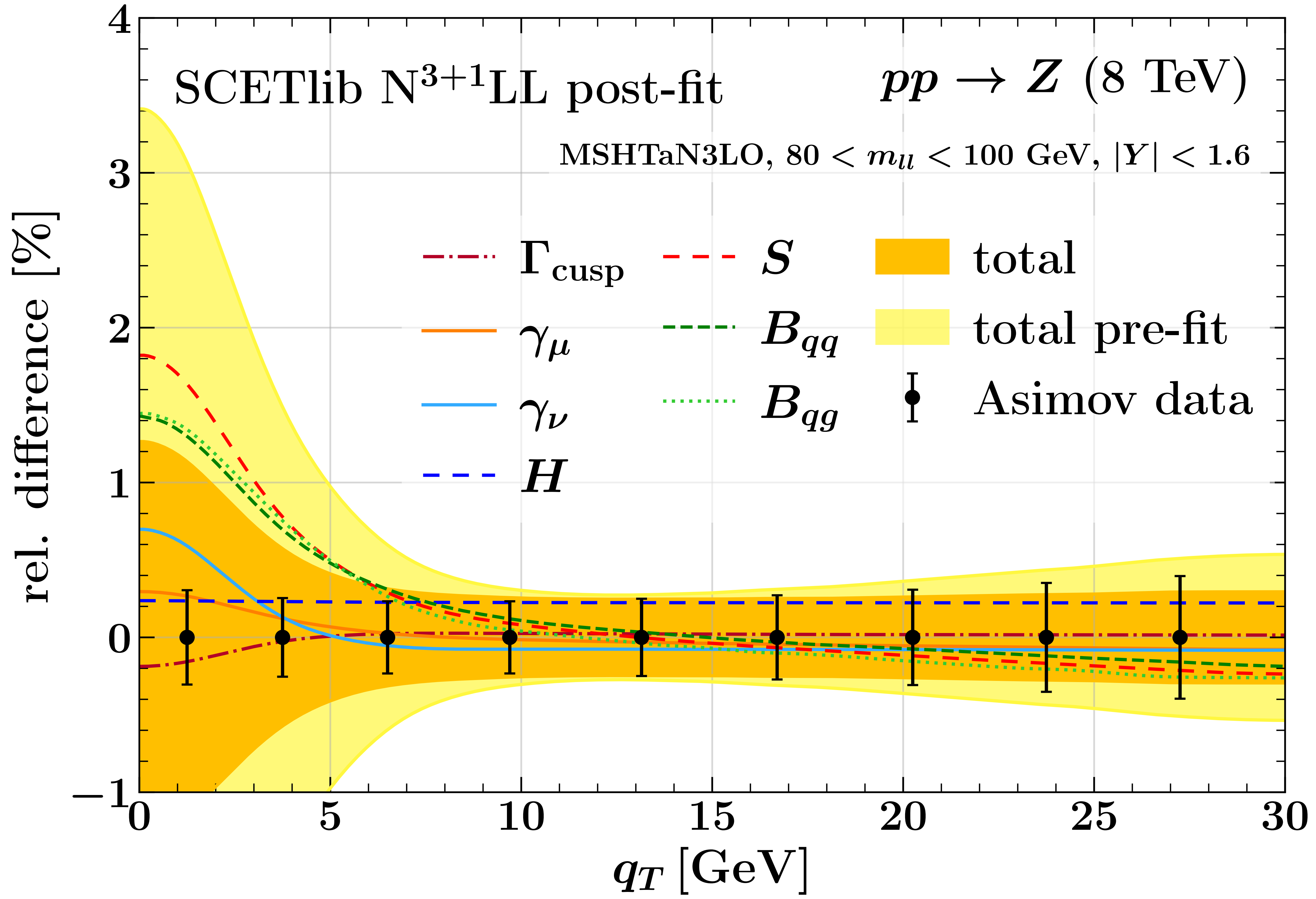
- Breakdown into independent sources of uncertainty with correct shape (correlation) in q_T, varying each TNP by $\Delta\theta_n = \pm 1$
- Repeat α_s fit for every TNP variation: sum in quadrature $\to \Delta_{\text{pert}} = 1.75 \times 10^{-3}$

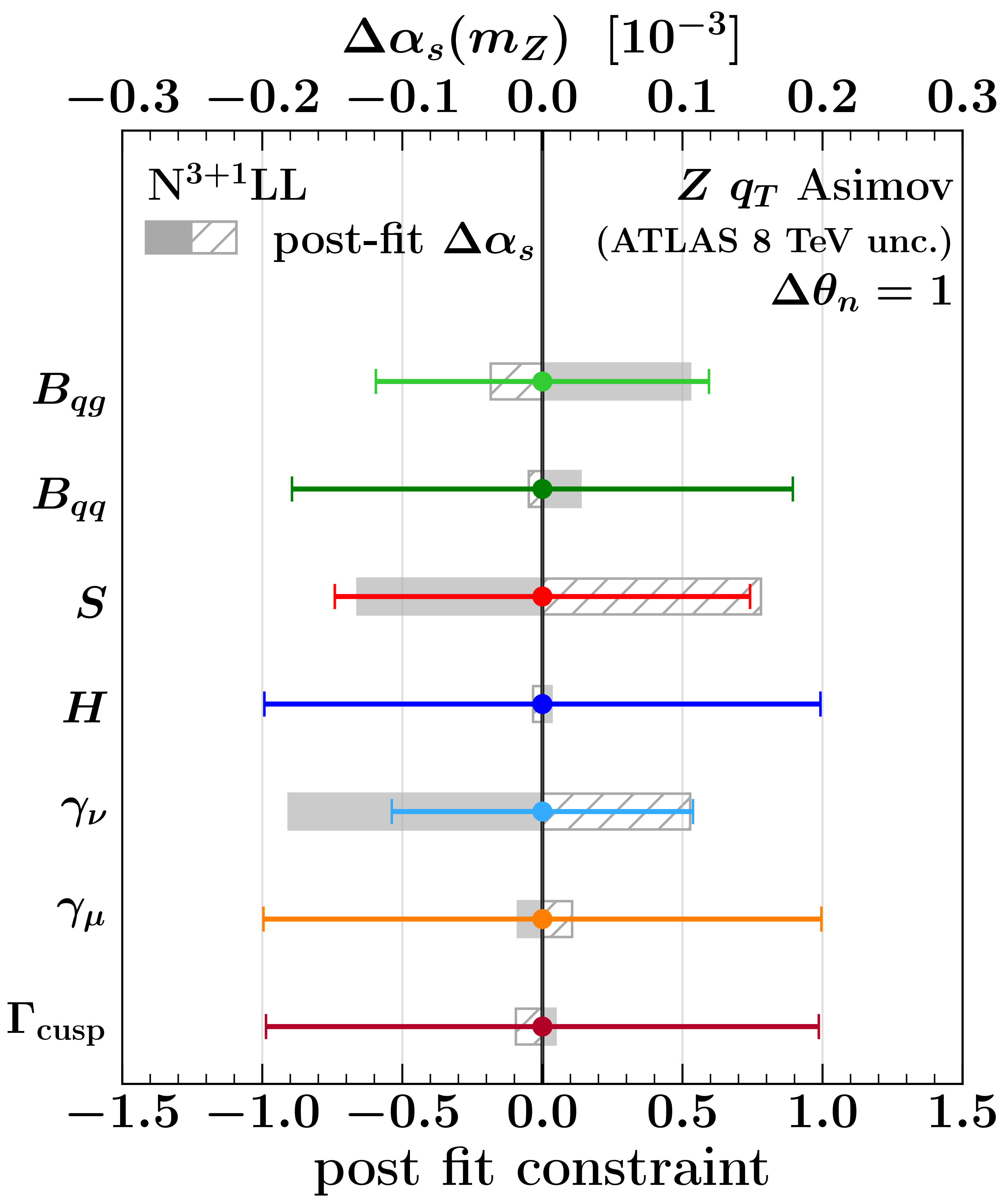
Perturbative uncertainty: TNP profiling

Cridge, GM, Tackmann '25

Data as N^{3+1}LL at $\alpha_s = 0.118$ against N^{3+1}LL theory model

$$\chi^2_{\text{total}} = \sum_{ij} (y_i - \lambda_i)^T C^{-1}_{ij} (y_j - \lambda_j) + \sum_i \frac{(\theta_i - 0)^2}{\Delta\theta_i^2}$$





- Fit α_s *together* with all TNPs, included with Gaussian constraint $\theta_n = 0 \pm 1$
- Nontrivial data constraints on TNPs and reduced theory uncertainty

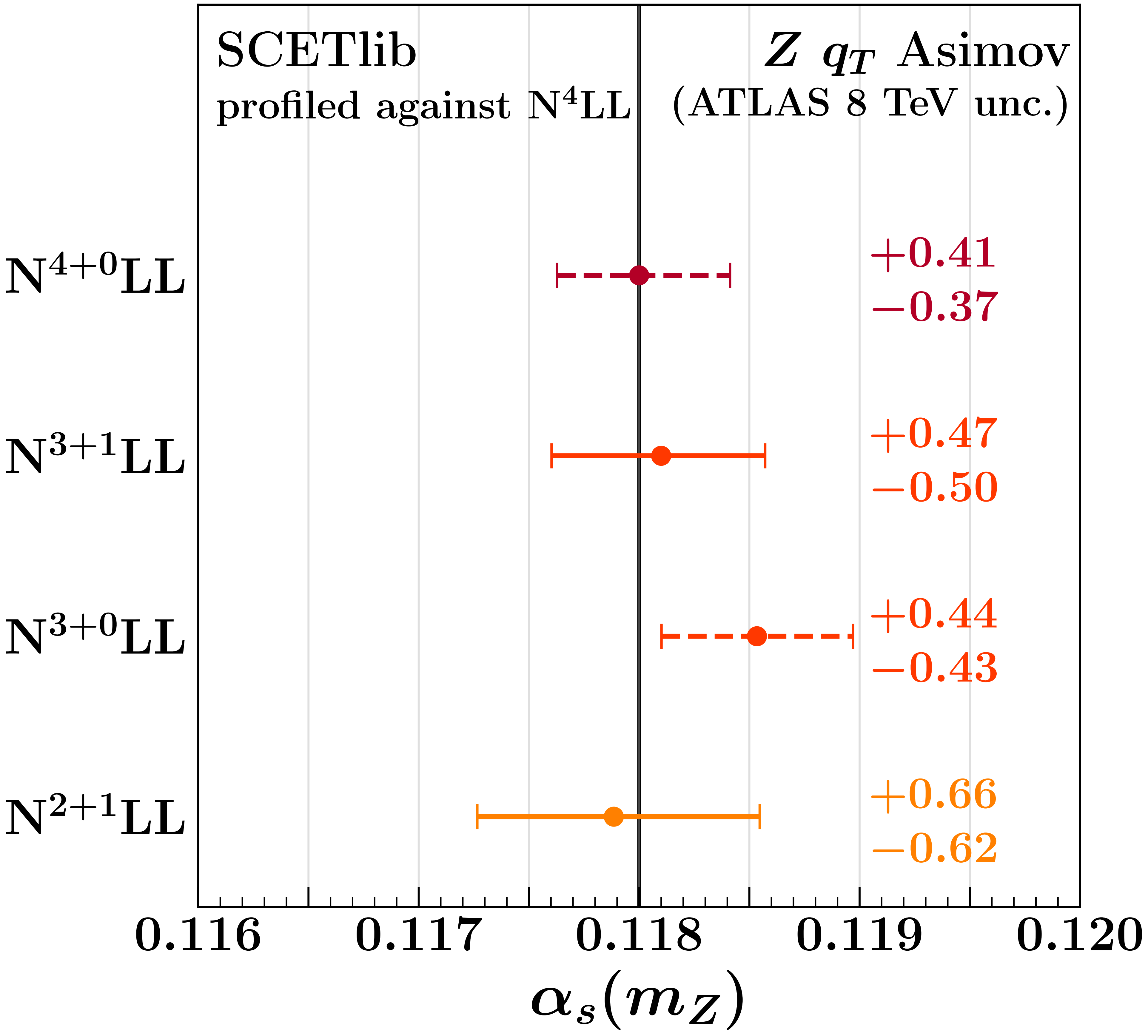
$\Delta_{\text{pert}} = 0.45 \times 10^{-3}$

TNP profiling against different orders

Cridge, GM, Tackmann '25

Data as N^4LL at $\alpha_s = 0.118$ against different orders

simulates the fit to real data, which contains the all-order result!



- $N^{3+0}LL$ approx of $N^{3+1}LL$ as N^{4+0} of $N^{4+1}LL$
  absorb the $N^{k+1}LL$ TNPs uncert. term into the N^kLL structure
- Uncertainty decreases with increasing perturbative order

*uncertainties in units of 10^{-3}

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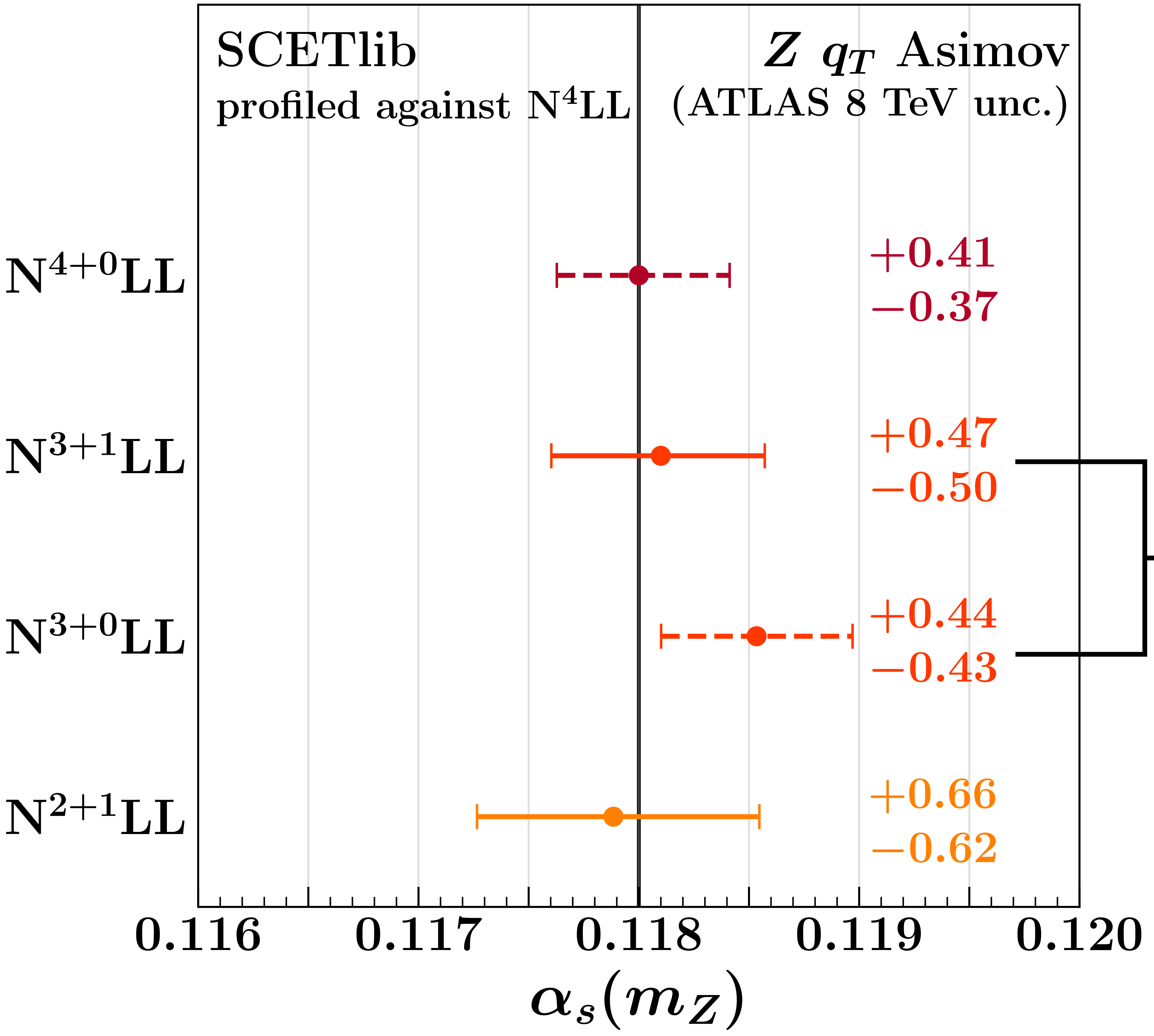

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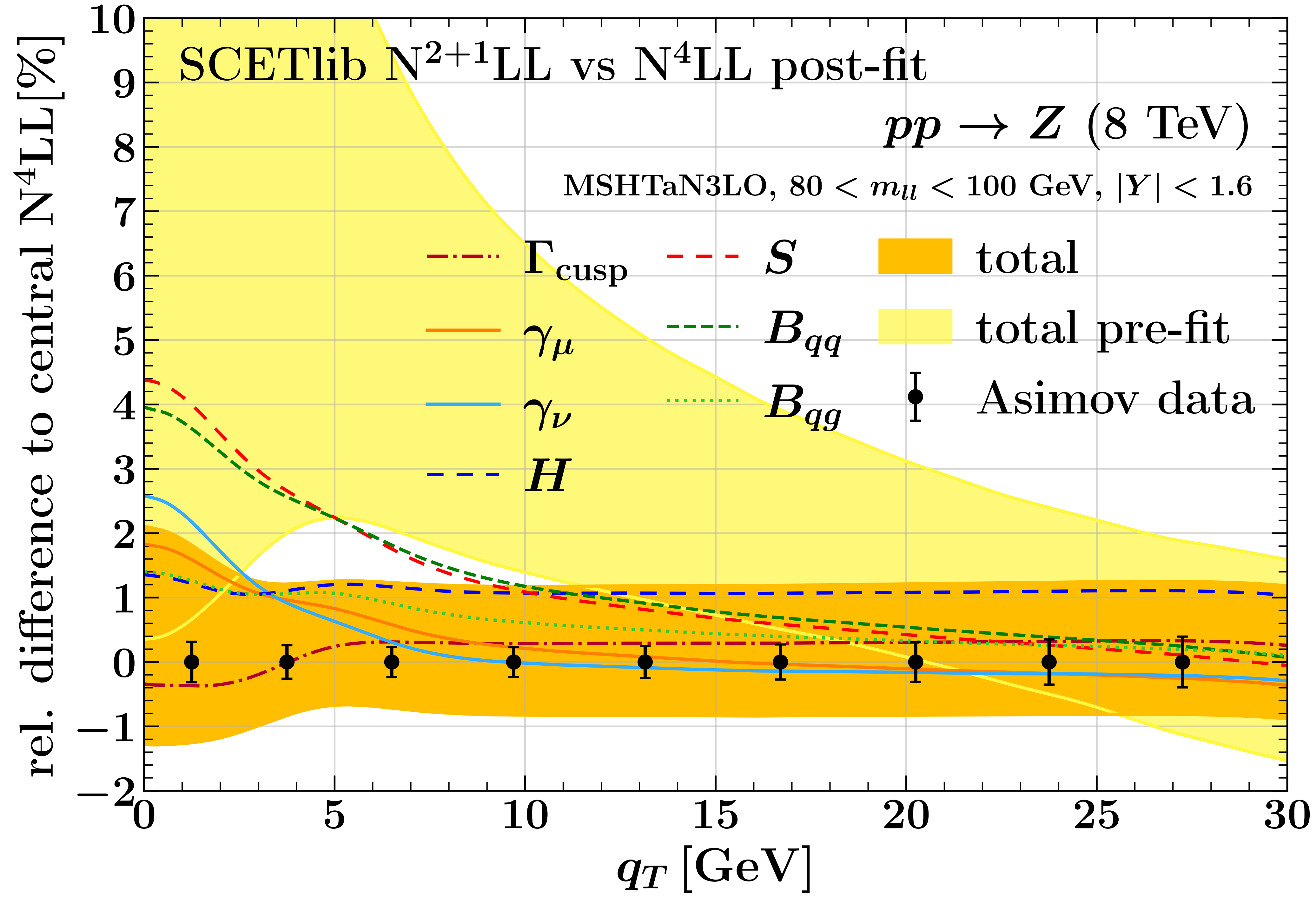
  absorb the N^{k+1}LL TNPs uncert. term into the N^{k}LL structure
- Uncertainty decreases with increasing perturbative order
- Uncertainty size alone can be misleading
  Investigate looking at the TNP pulls
- Reduction on the uncertainty depends on the constraining power of the data

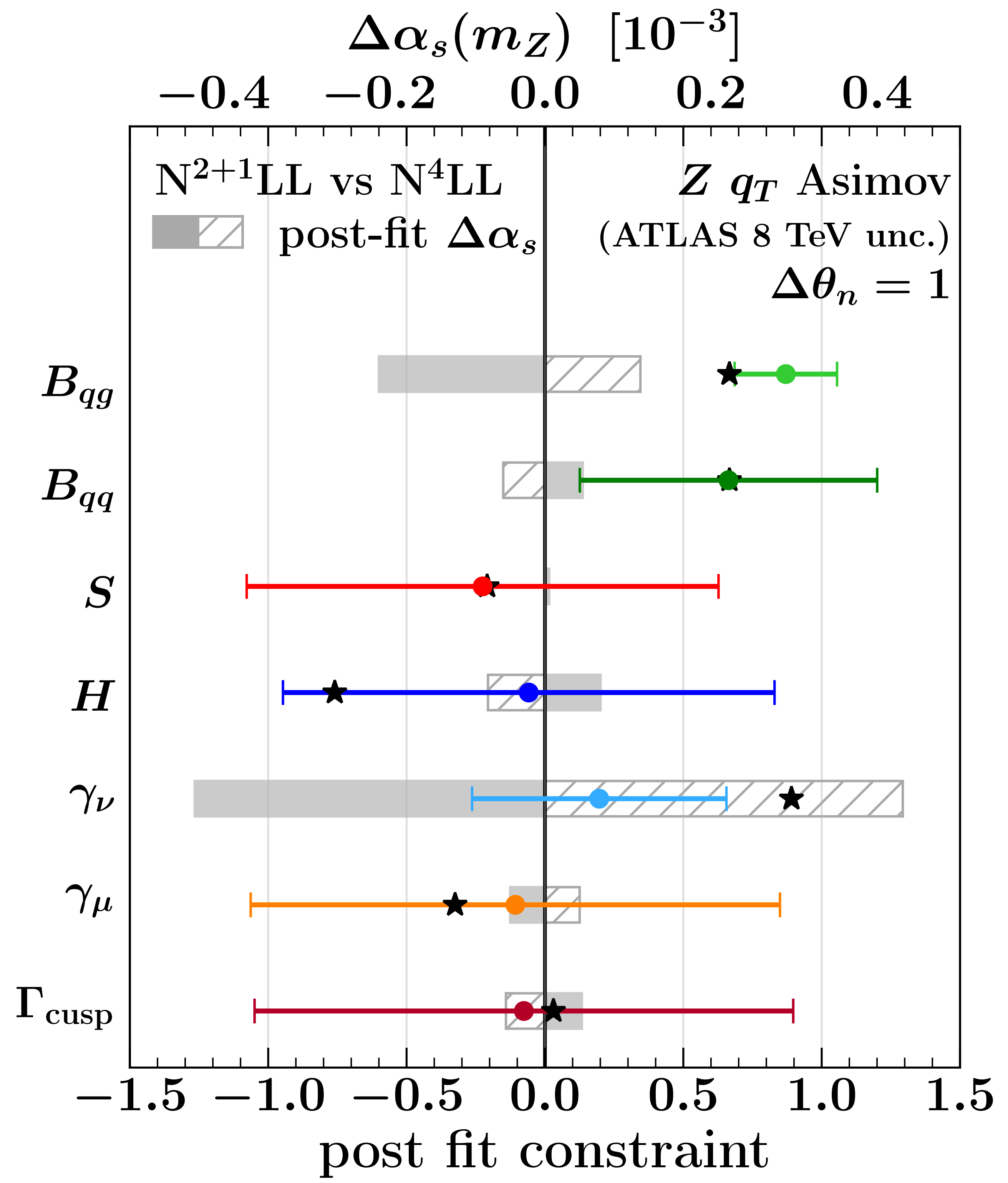
N^{3+1}LL is our prefered and reference perturbative order

*uncertainties in units of 10^{-3}

TNP profiling against different orders: $N^{2+1}LL$ Cridge, GM, Tackmann '25

Data as N^4LL at $\alpha_s = 0.118$ against $N^{2+1}LL$ theory model



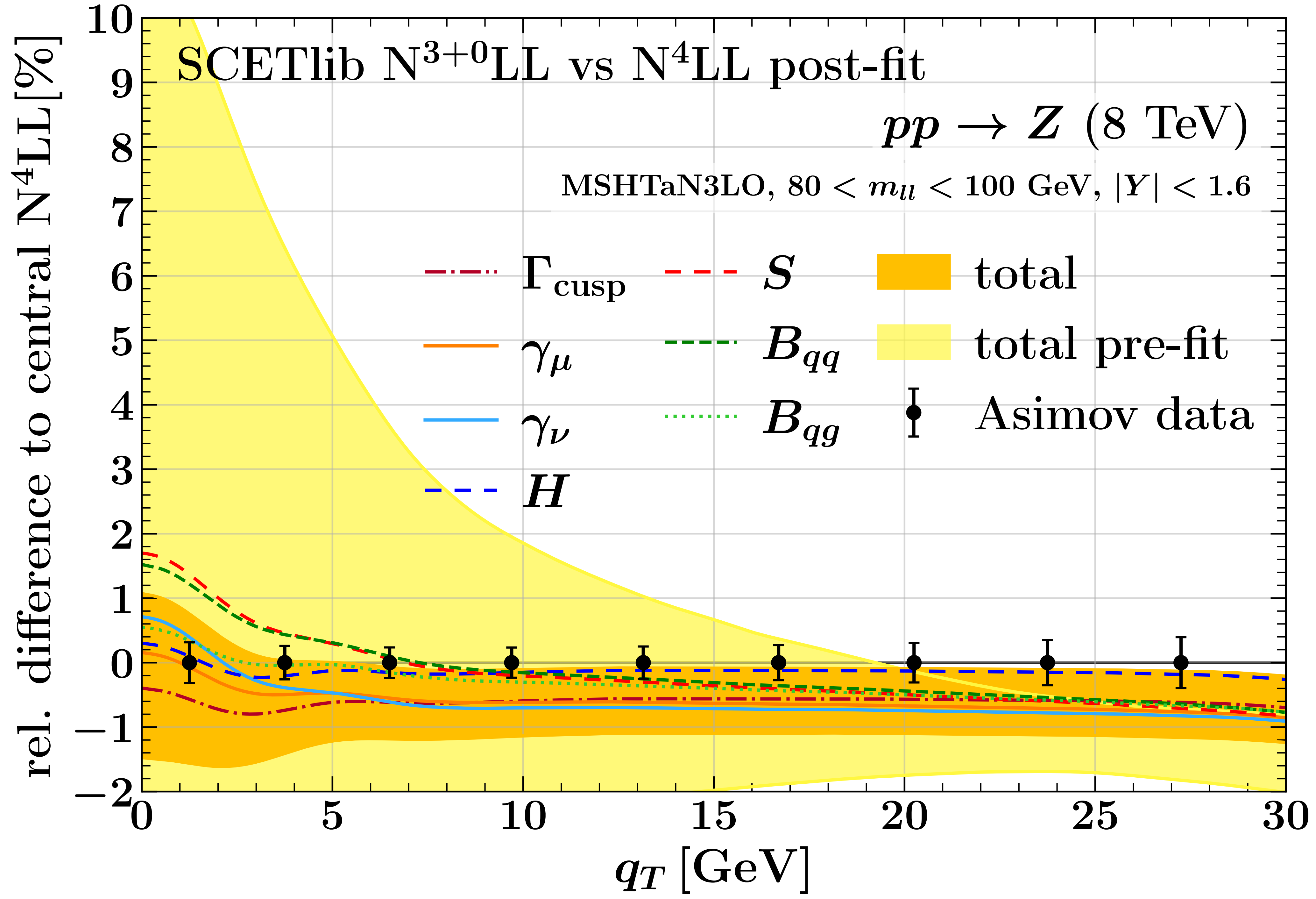


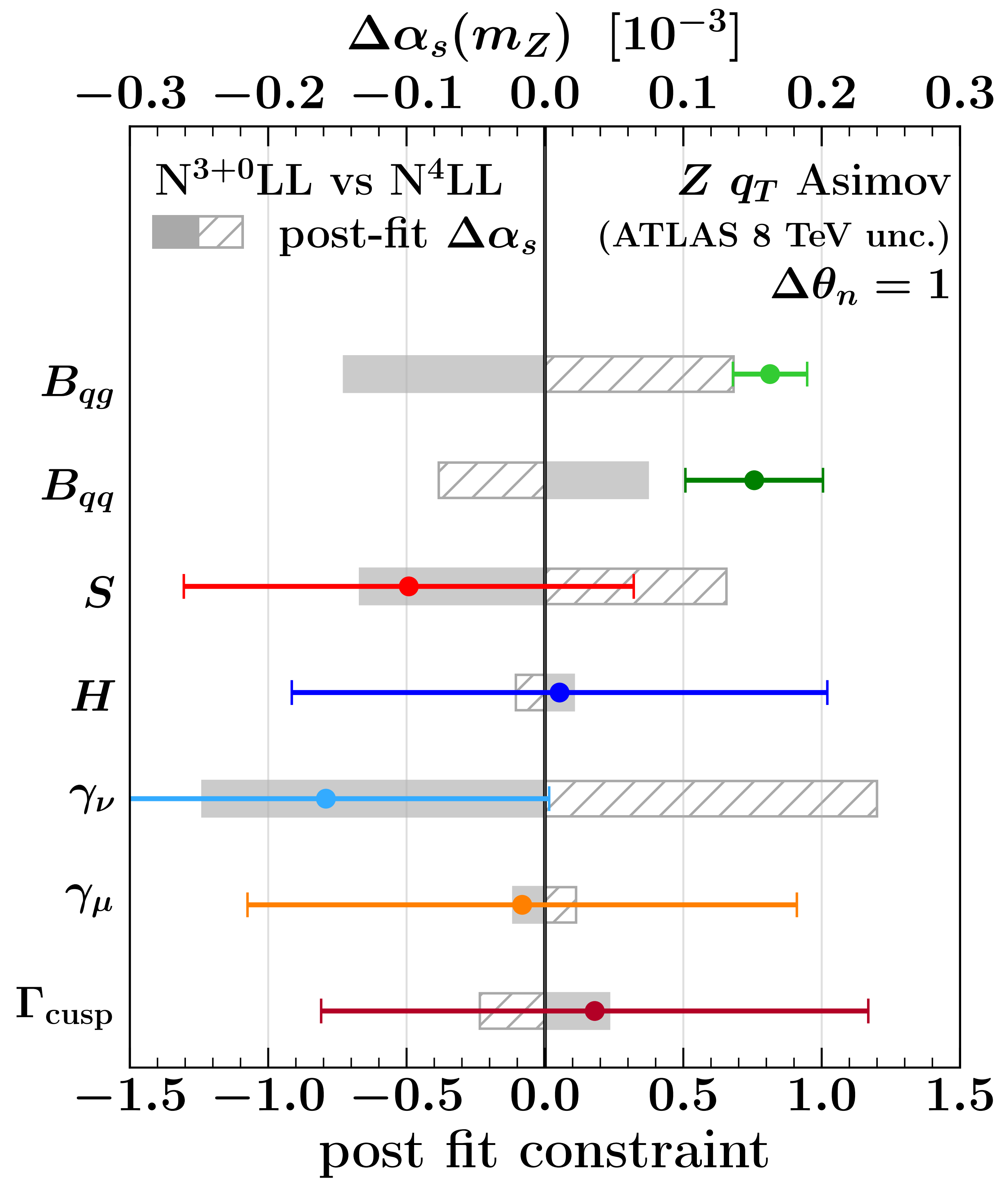
- $N^{2+1}LL$ **strongly** pulled toward correct true values [★] —— indication that the order is not enough for the data
- post-fit prediction for q_T spectrum driven by constraints from data

$\Delta_{pert} =^{+0.66}_{-0.62} \times 10^{-3}$

TNP profiling against different orders: $N^{3+0}LL$ Cridge, GM, Tackmann '25

Data as N^4LL at $\alpha_s = 0.118$ against $N^{3+0}LL$ theory model





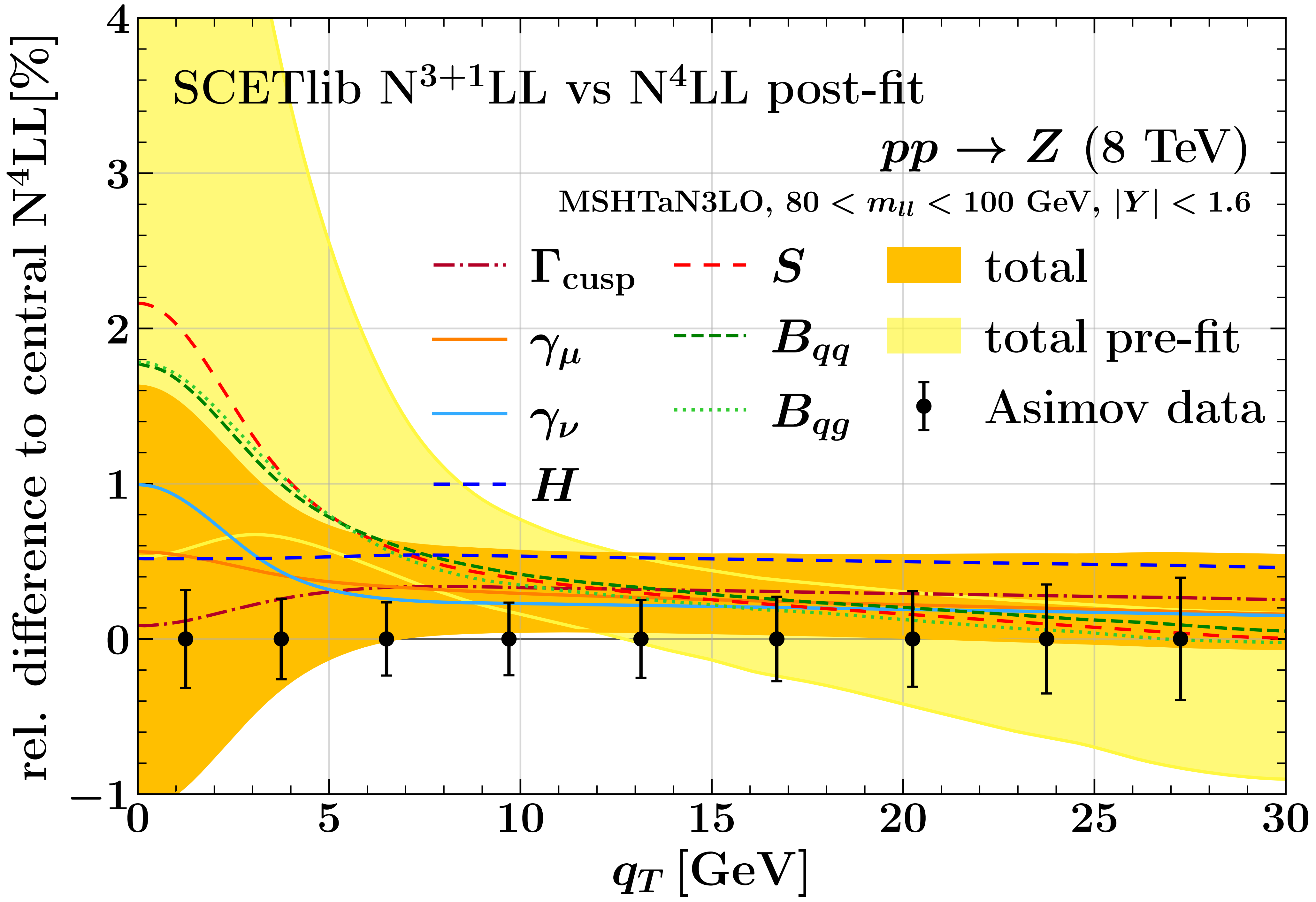
- significant reduction in uncertainty in the post-fit prediction — suspicious, insights in the pull plot
- some TNPs are strongly constrained by the data: B_{qq} , B_{qg}

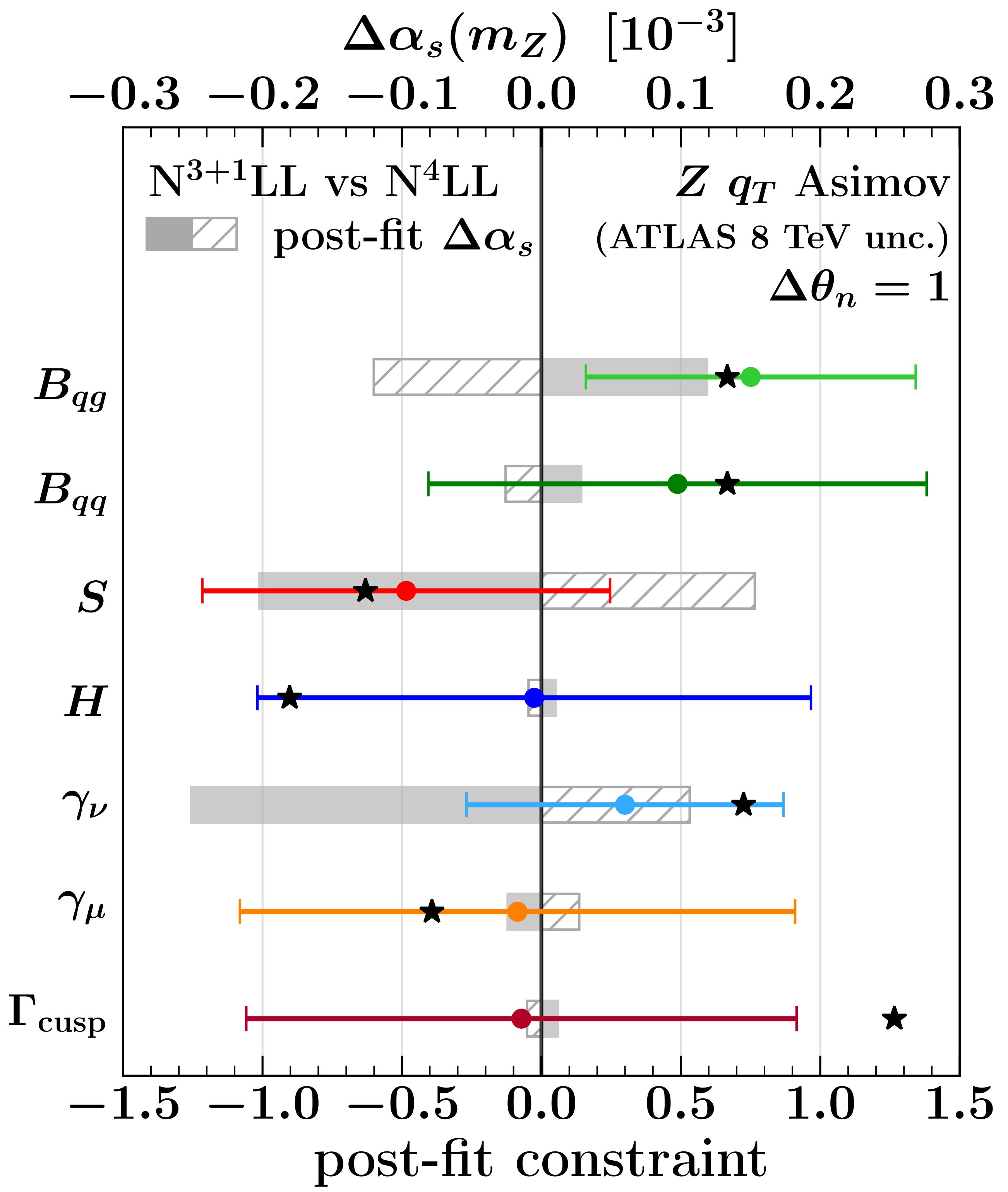
$\Delta_{pert} =^{+0.44}_{-0.43} \times 10^{-3}$

TNP profiling against different orders: N^{3+1}LL

Cridge, GM, Tackmann '25

Data as N^{4}LL at $\alpha_s = 0.118$ against N^{3+1}LL theory model



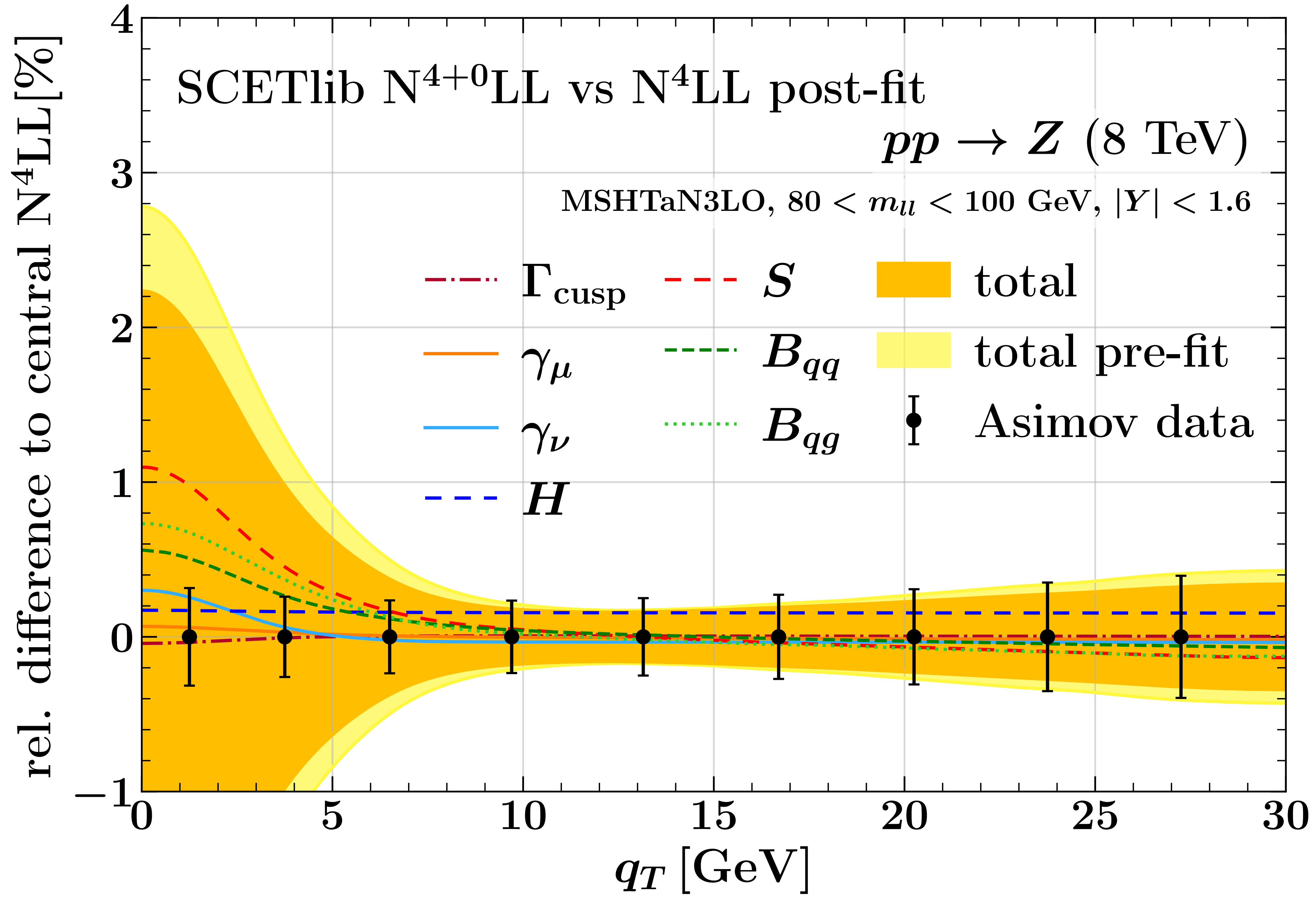


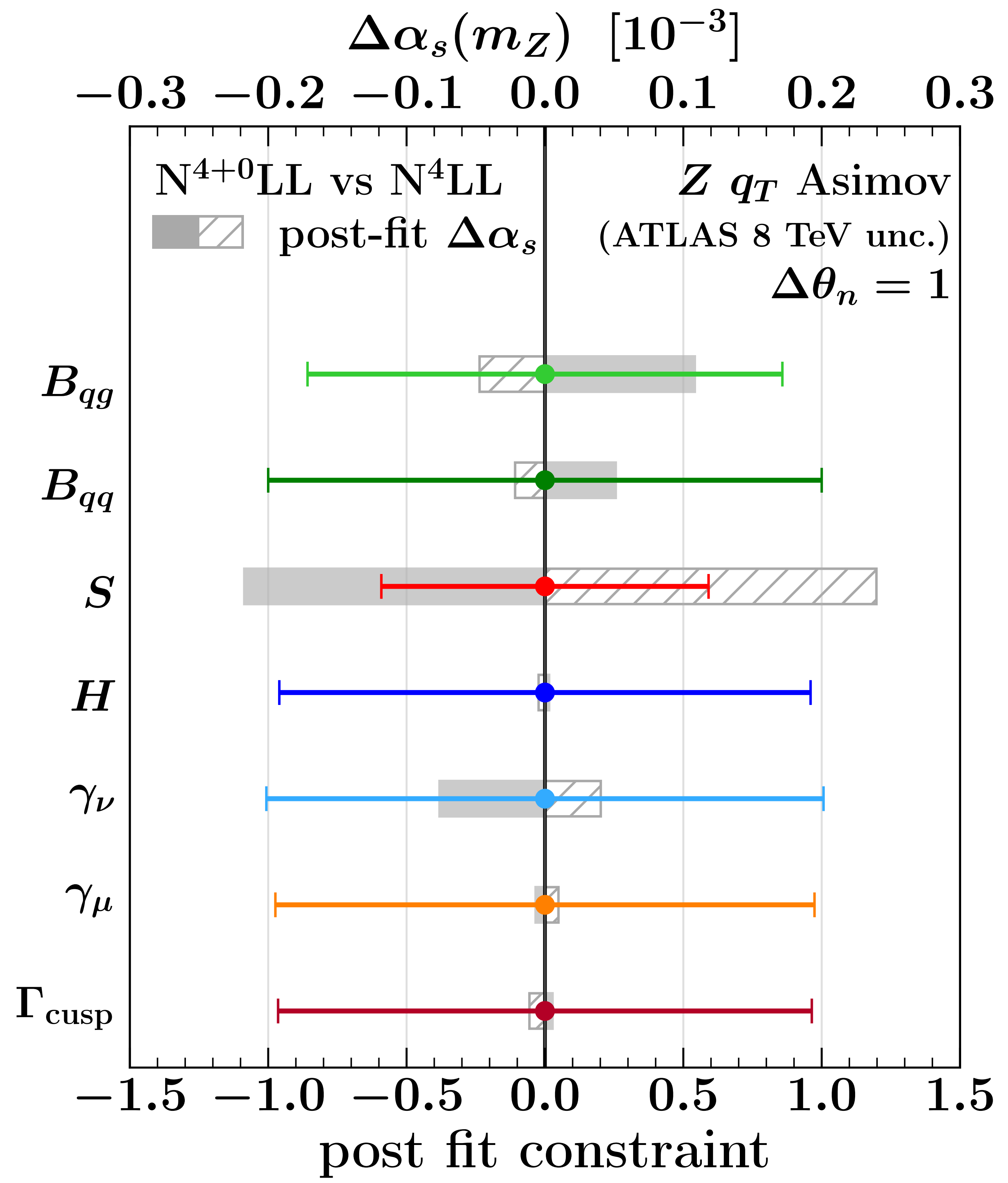
- N^{3+1}LL pulled toward correct true values [★]
- post-fit prediction for q_T spectrum driven by constraints from data

$\Delta_{\rm pert} = ^{+0.47}_{-0.50} \times 10^{-3}$

TNP profiling against different orders: $N^{4+0}LL$ Cridge, GM, Tackmann '25

Data as N^4LL at $\alpha_s = 0.118$ against $N^{4+0}LL$ theory model





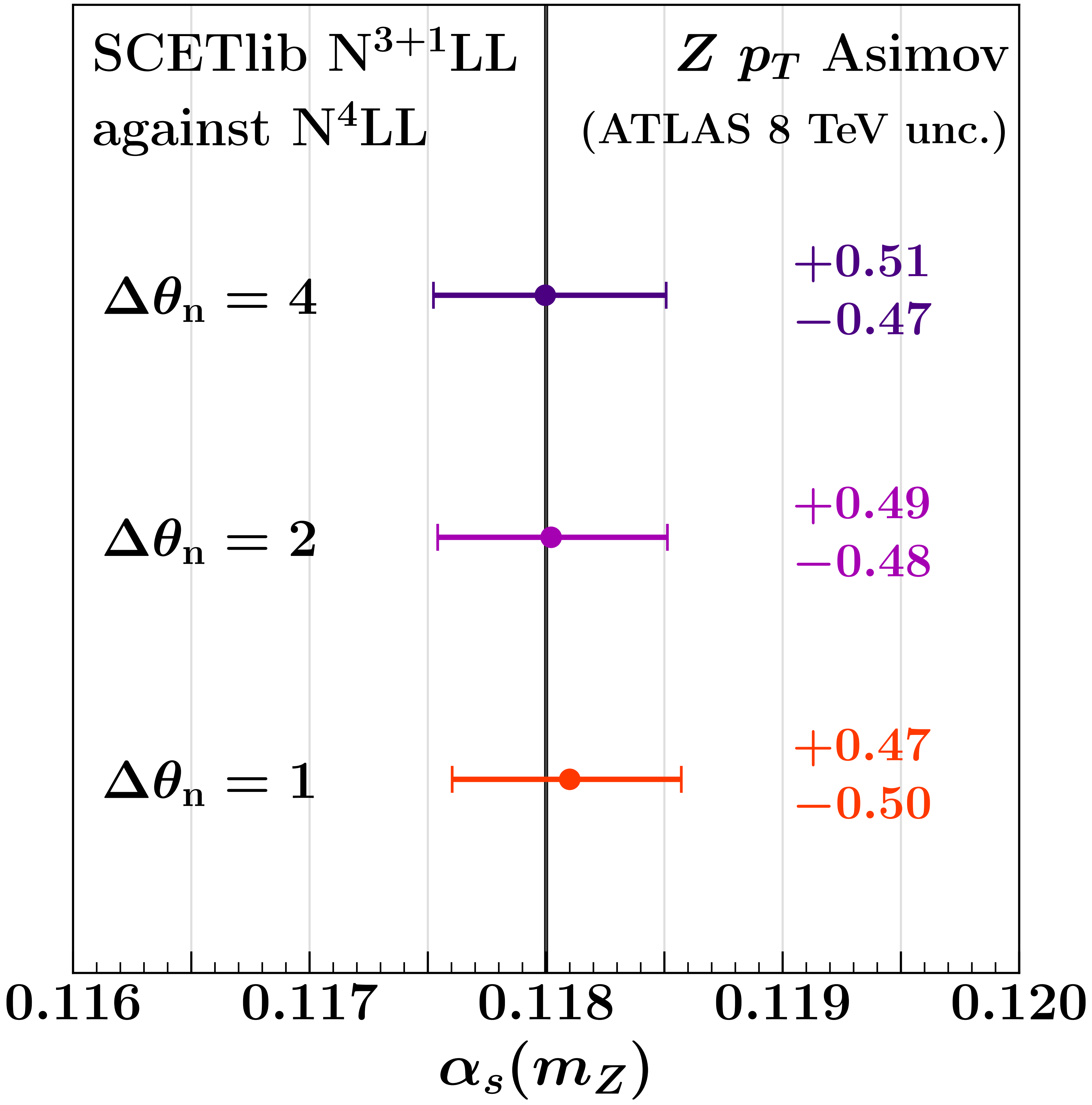
- central $N^{4+0}LL$ identical to that of N^4LL by construction
- reduction in the uncertainty less pronounced than $N^{3+0}LL$ case

$\Delta_{\text{pert}} = ^{+0.41}_{-0.37} \times 10^{-3}$

TNP profiling with different $\Delta\theta_n$: $N^{3+1}LL$ Cridge, GM, Tackmann '25

Data as N^4LL at $\alpha_s = 0.118$ against $N^{3+1}LL$ theory model

- Change the prior theory constraint: using now $\theta_n = 0 \pm \Delta\theta_n$ with $\Delta\theta_n = 1, 2, 4$ and fit again



1. effect of the theory constraint strongly depends on the power of the experimental constraint
2. data reduces dependence on theory constraint and associated potential bias
3. only slight difference in the uncertainties when relaxing the TNP constraint

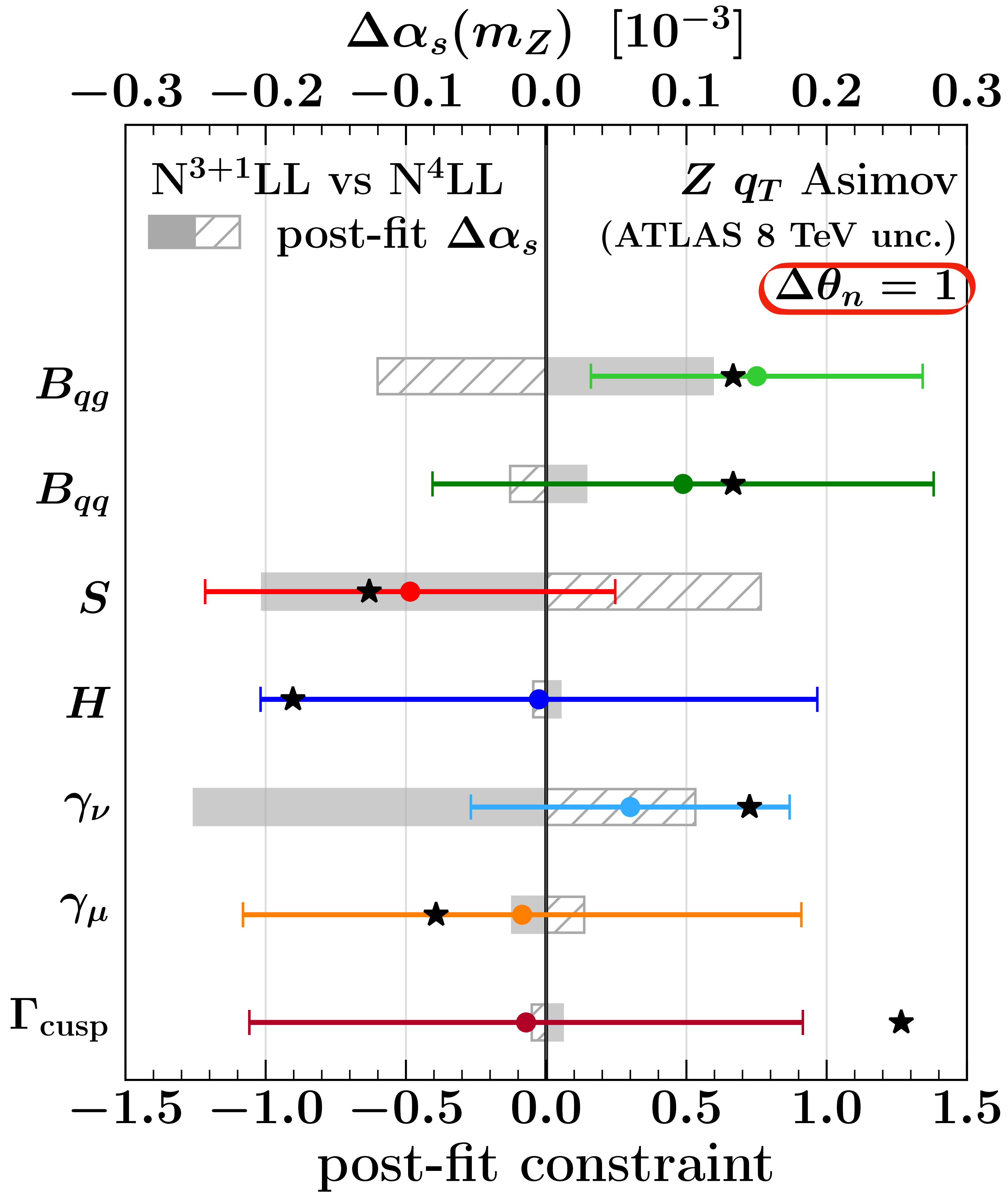
Precise theory constraint does not matter here

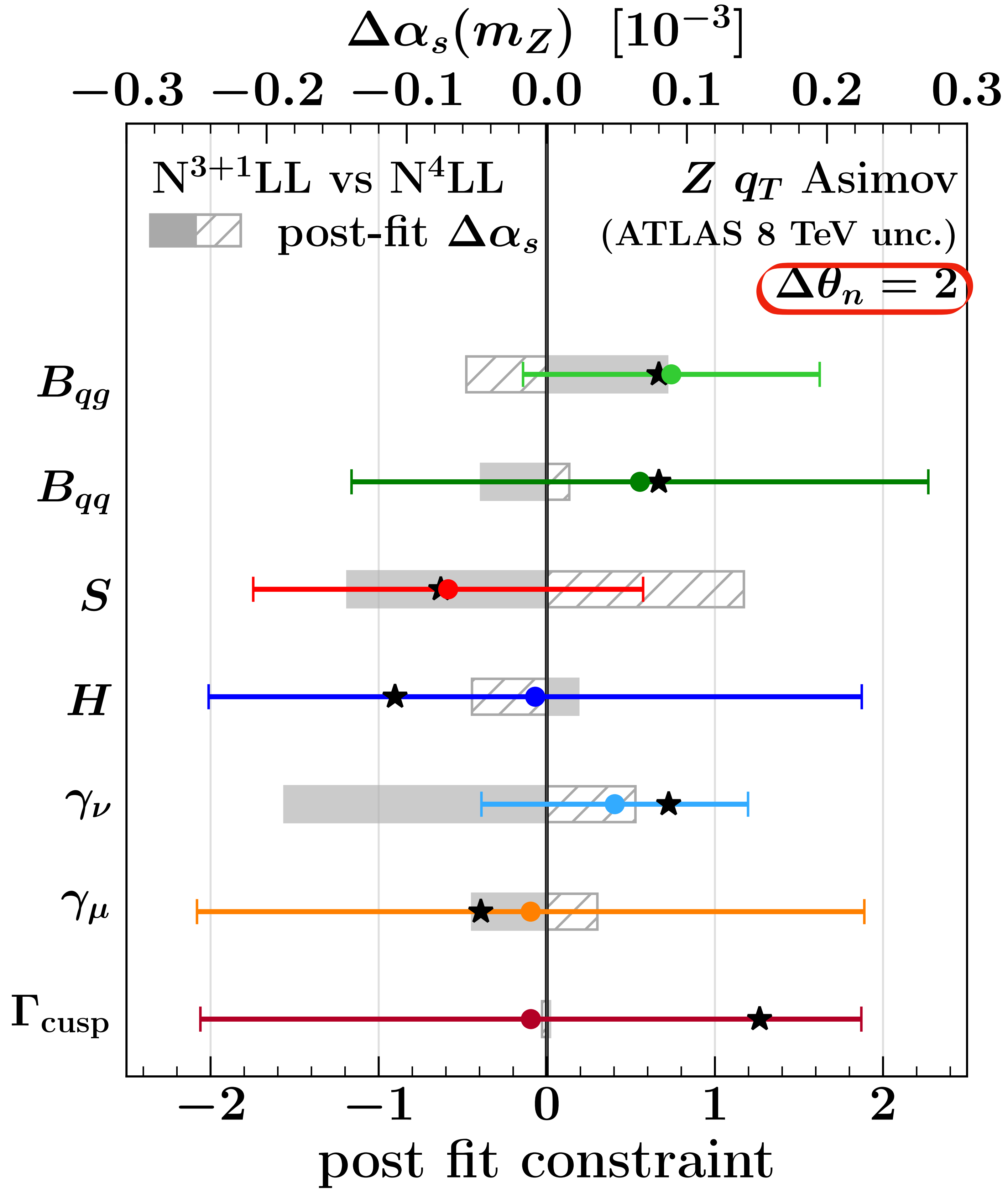
*uncertainties in units of 10^{-3}

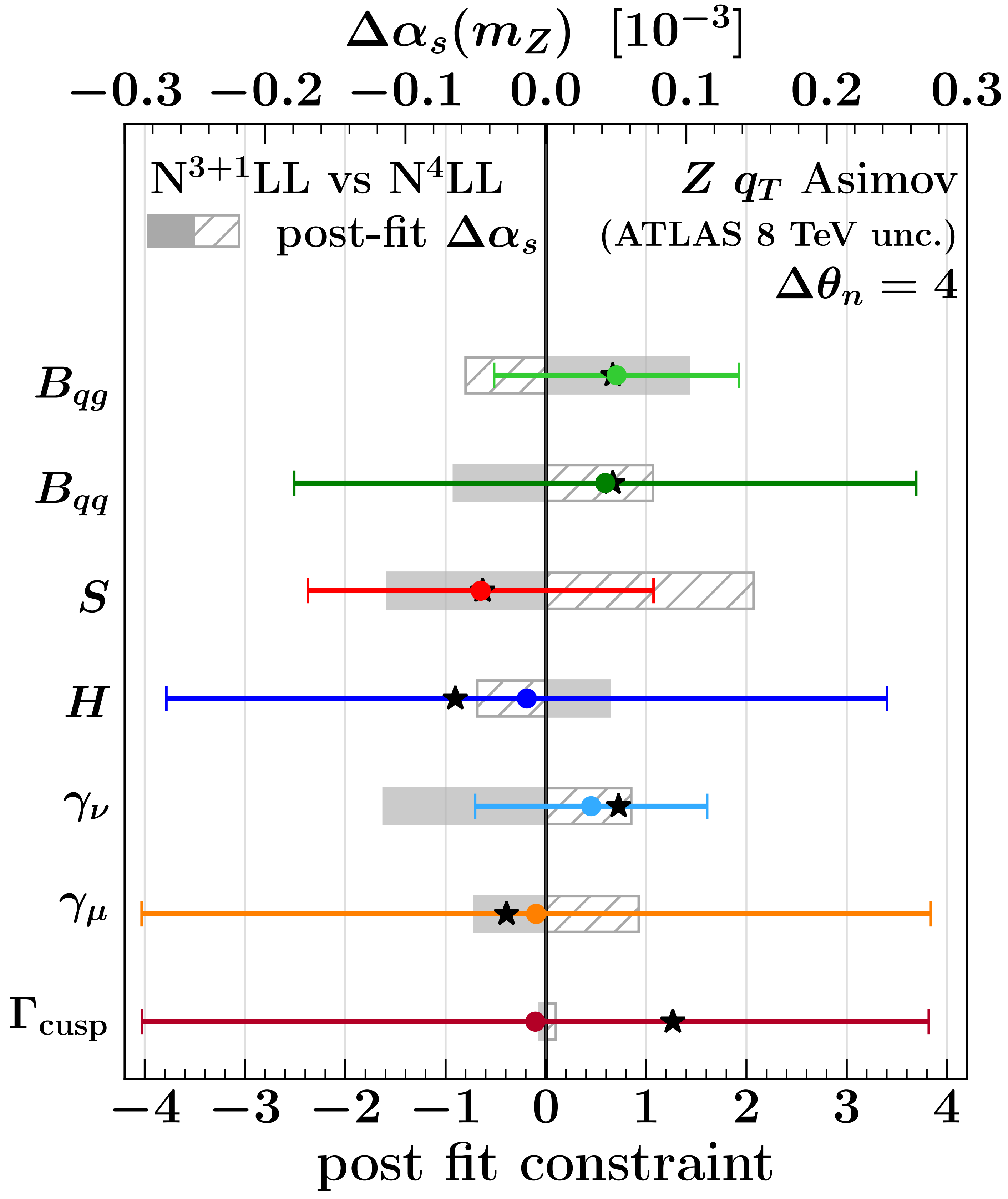
TNP profiling with different $\Delta\theta_n$: N^{3+1}LL

Cridge, GM, Tackmann '25

Data as N^{4}LL at $\alpha_s = 0.118$ against N^{3+1}LL theory model







Post-fit constraints on TNPs become even more consistent with true values!

CMS m_W determination

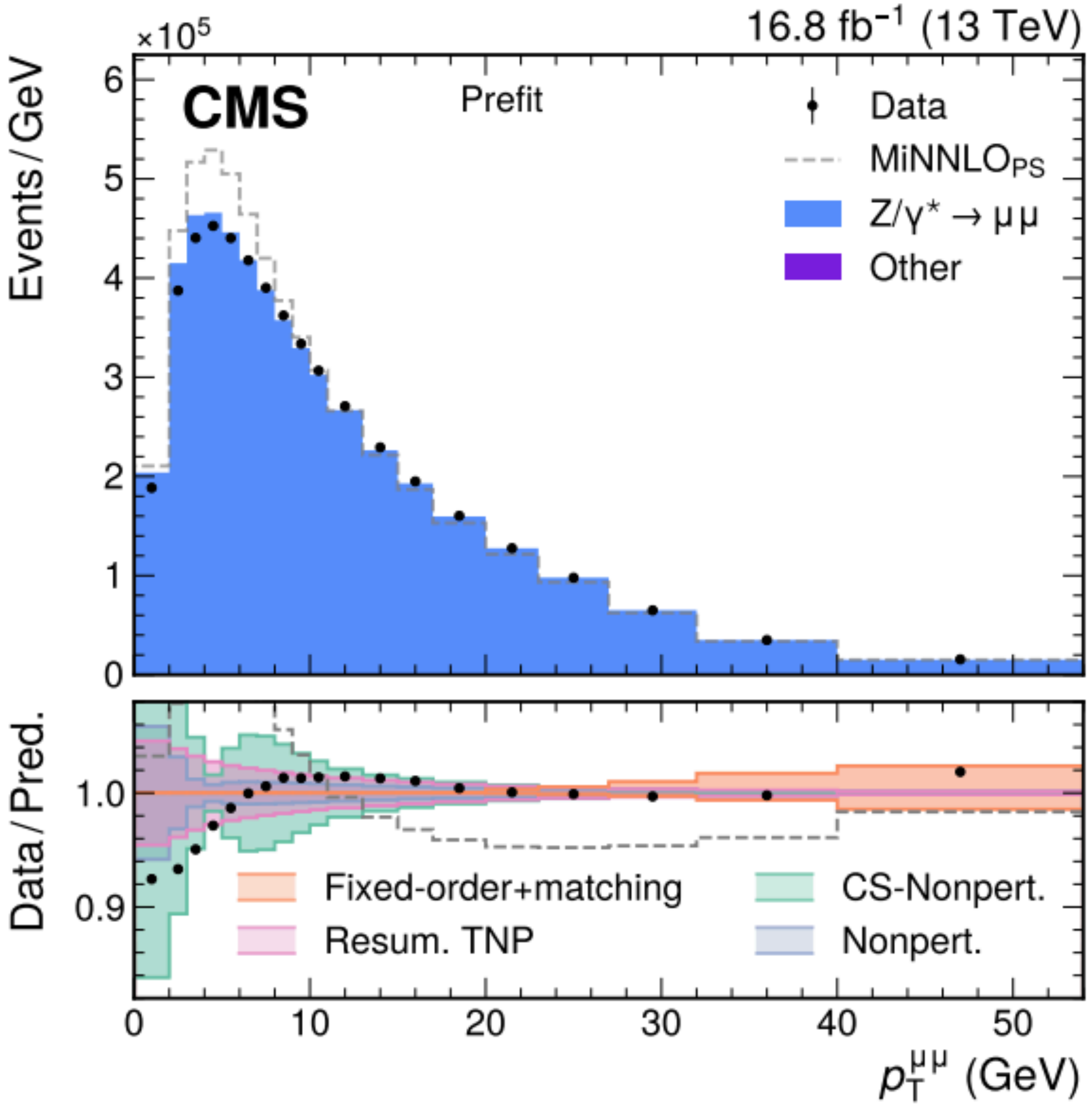
CMS W mass measurement CMS-SMP-23-002

Perturbative uncertainties in the resummed prediction: N^{3+0}LL SCETlib

$$f(\alpha, \theta_4) = \hat{f}_0 + \hat{f}_1\alpha + \hat{f}_2\alpha^2 + [\hat{f}_3 + \alpha_0 f_4(\theta_4)]\alpha^3$$

consider the N^{3}LL structure but absorb the N^{3+1}LL TNPs uncert. term into the N^{3}LL structure

limited effect on the overall size of theory uncert. but correlation approximated by lower order structure



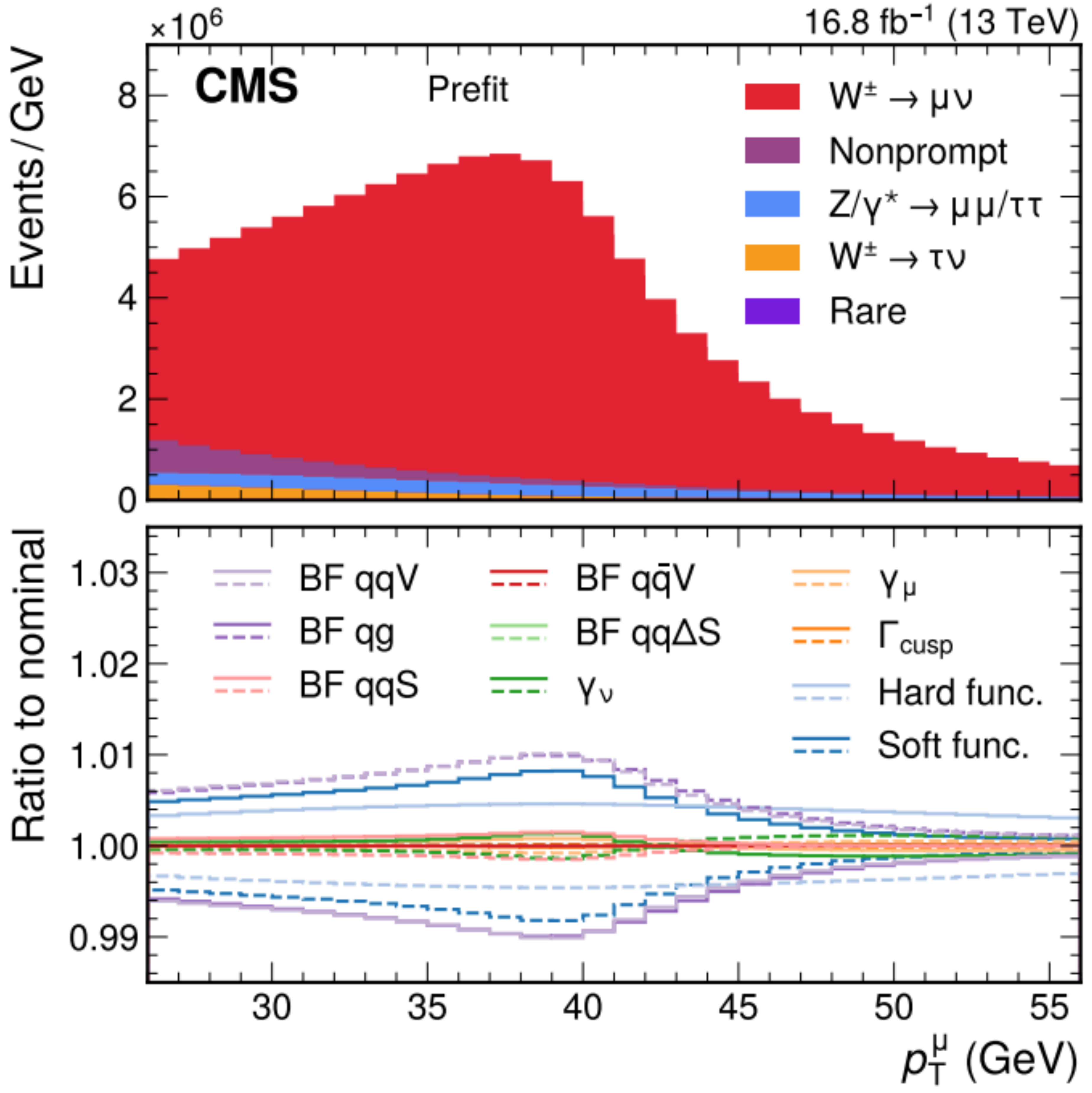
- p_T^W modeling fundamental: uncertainties in the low p_T region affect the shape as m_W variation
- theory correlations are crucial: uncertainty propagated from p_T^W to p_T^ℓ to m_W!

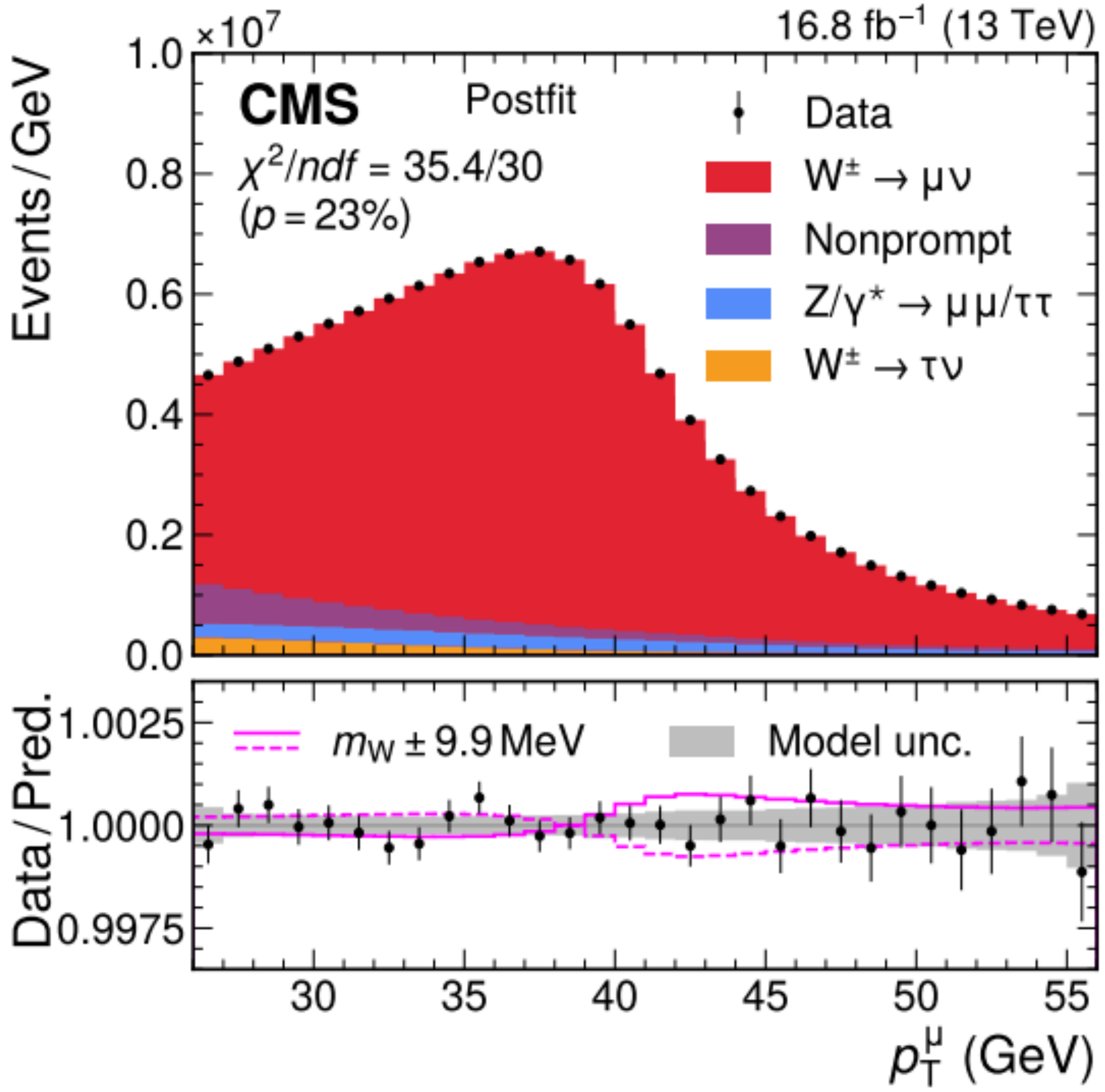
TNPs enable consistent W-only fits by allowing in-situ profiling of theory uncertainties

CMS *W* mass measurement CMS-SMP-23-002

Perturbative uncertainties in the resummed prediction: N^{3+0}LL SCETlib

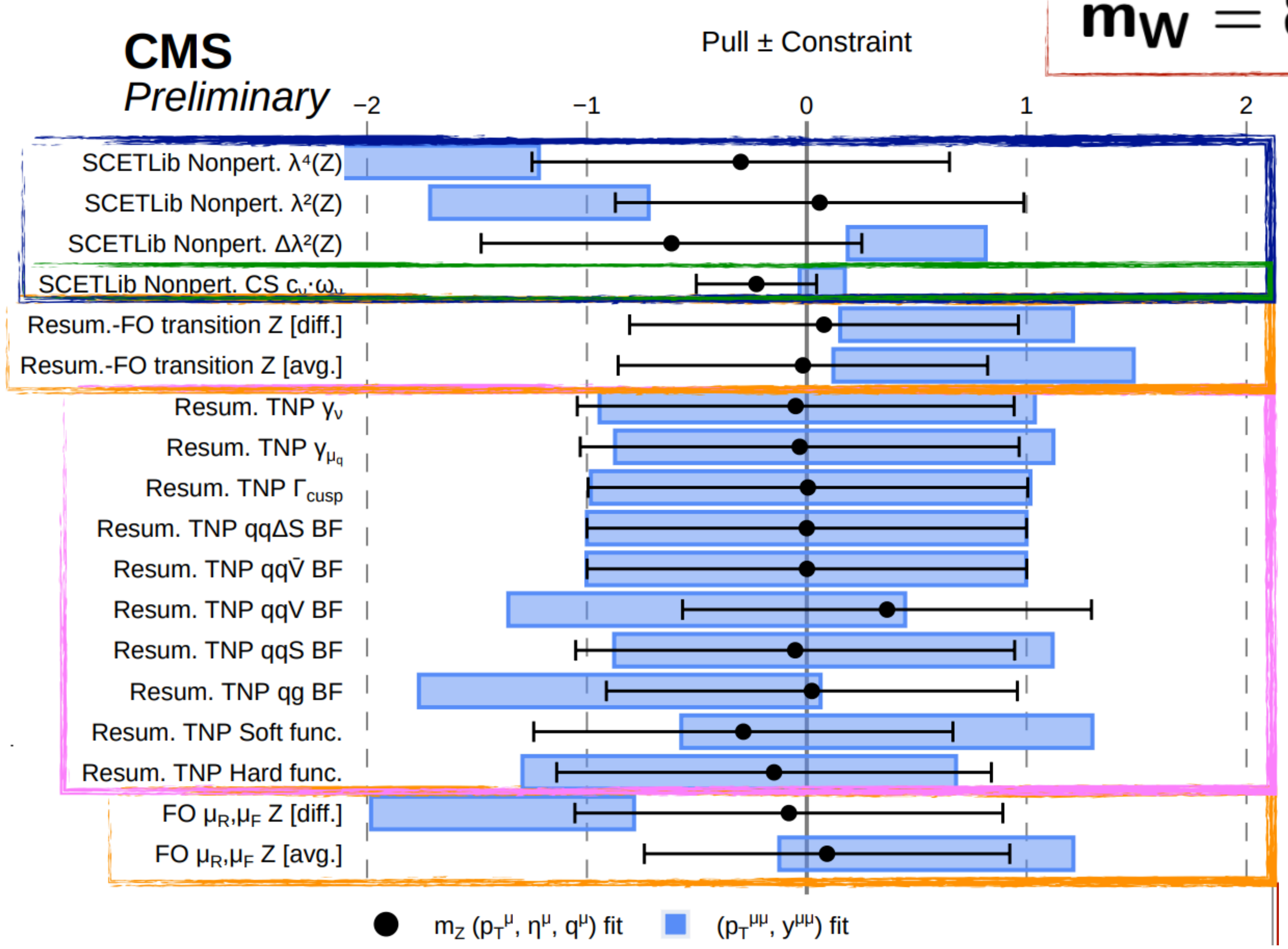
contribution of all theoretical and experimental uncert. before and after profiling





CMS W mass measurement CMS-SMP-23-002

$m_W = 80360.2 \pm 9.9\text{MeV}$



Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4	6.0
Total uncertainty	9.9	9.9

TNPs ideal for future m_W combinations: allow to have a common treatment of theory uncertainties!

Still *some* work on the theory side:

1. FO contributions and specifically nonsingular TNPs for p_T^W (and not only...)
2. Look into $\sin^2\theta_W$

from Long's talk

Summary

Correlations are fundamental for the interpretation of precision measurements:
having meaningful theory uncertainty is as important as having meaningful experimental one!

1. Theory Nuisance Parameters perfect candidate to describe theory uncertainty and *correlations*
   - correlation encoded in those x dependences that have been parameterized
   - can be consistently used for profiling: done with care! Checking pulls and constraints on TNPs

2. Highly relevant for the extraction of EW measurements (and not only at LHC!)
   - toy studies for α_s work as advertised, lots of effort on the extraction against real data...
   - m_W extraction "real" example of TNPs at work

THANK YOU!

Backup slides

Scale variations approach

Method: given $f(\alpha)$, make a variable transformation

$$\tilde{\alpha}(\alpha) = \alpha[1 + b_0\alpha + b_1\alpha^2 + \mathcal{O}(\alpha^3)]$$ defining a different prediction $$\tilde{f}(\tilde{\alpha}) = \tilde{f}_0 + \tilde{f}_1\tilde{\alpha} + \tilde{f}_2\tilde{\alpha}^2 + \mathcal{O}(\tilde{\alpha}^3)$$

LO : $\tilde{f}(\tilde{\alpha}) = \tilde{f}_0 = \hat{f}_0$

NLO : $\tilde{f}(\tilde{\alpha}) = \hat{f}_0 + \tilde{\alpha}\hat{f}_1 = \hat{f}_0 + \hat{f}_1\alpha^2 + b_0\hat{f}_1\alpha^2 + b_1\hat{f}_1\alpha^3 + \dots$

LO : $f(\alpha) = \hat{f}_0 \pm \Delta f$

NLO : $f(\alpha) = \hat{f}_0 + \alpha\hat{f}_1 \pm \Delta f$

Take the difference between the two "schemes":

LO : $\Delta f(\alpha) = 0$

NLO : $\Delta f(\alpha) = b_0\hat{f}_1\alpha^2 + b_1\hat{f}_1\alpha^3 + \mathcal{O}(\alpha^4)$

Estimating MHOs uncertainty by approximating them by some linear combination of known lower-order terms $[f_2 \approx b_0\, \hat{f}_1]$

✅ $\Delta f(\alpha)$ is genuinely of higher order

Scale variations approach

Estimating MHOs uncertainty by approximating them by some linear combination of known lower-order terms $[f_2 \approx b_0 \hat{f}_1]$

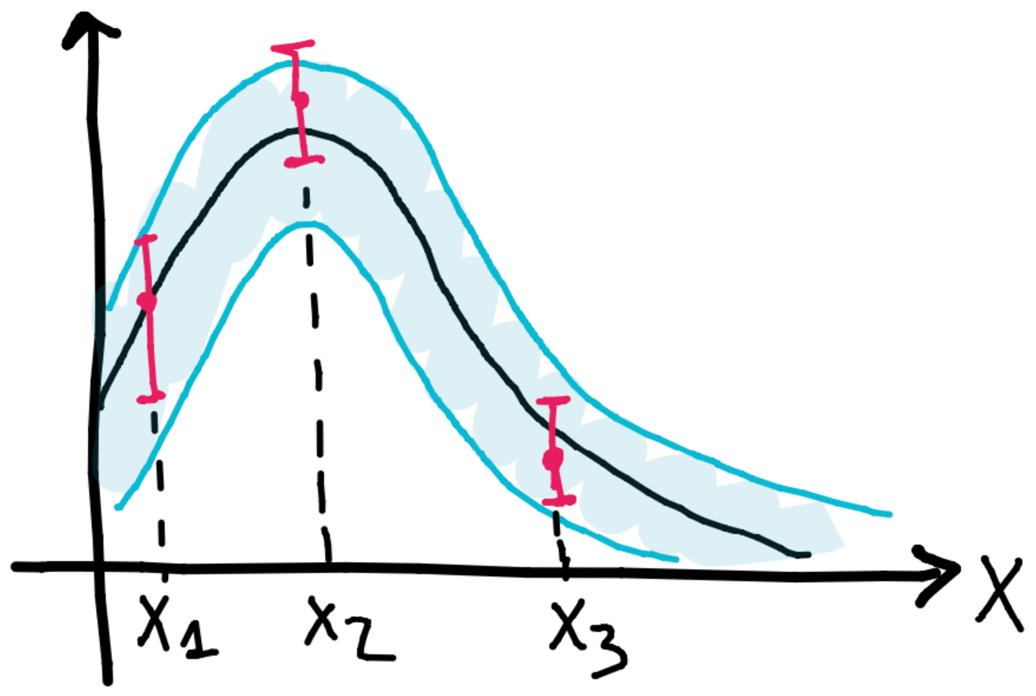
- ✗ nothing guarantees this is any good
- ✗ f_{n+1} generally more complex internal structure than $f_{\leq n}$
- ✗ b_0 (b_n) are just arbitrary constants and usually the same for any f
- ✗ b_n are not actual physical parameter with a true value
- ✗ correlation and shape uncertainties?

Now imagine $\alpha \equiv \alpha_s(\mu_0)$ and $\tilde{\alpha} \equiv \alpha_s(\mu)$: $b_0 = \frac{\beta_0}{2\pi} \ln \frac{\mu}{\mu_0}$, and why vary μ by 2?

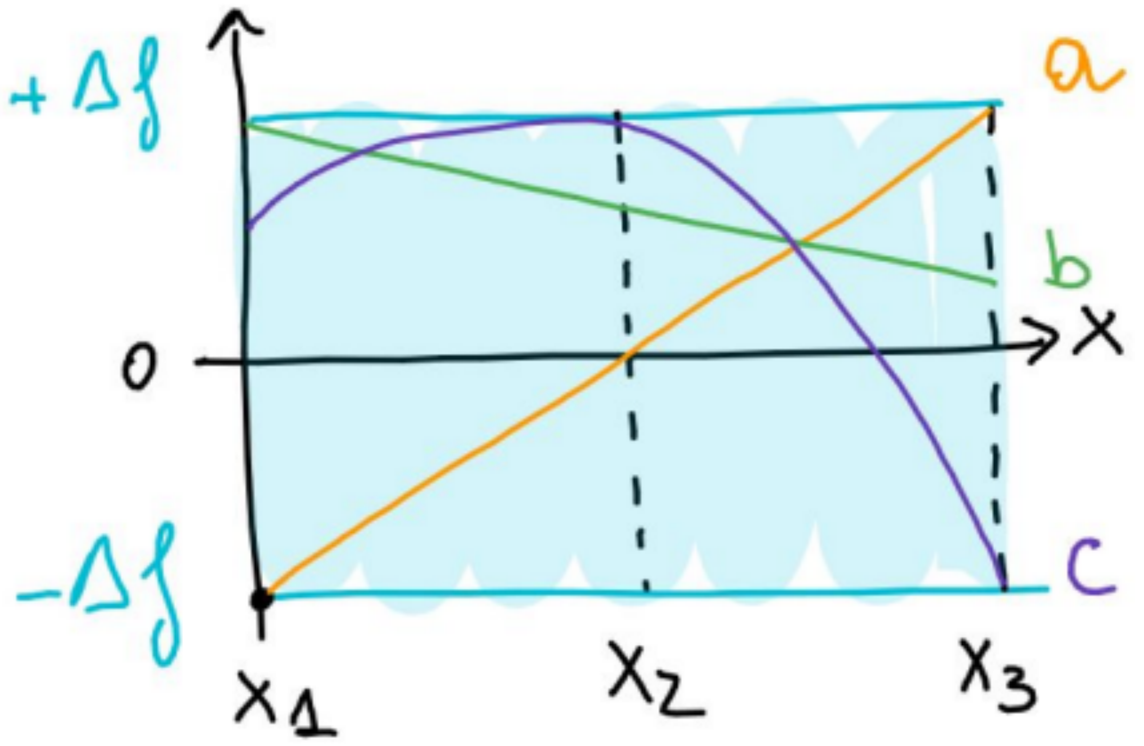
Correlation with Scale Variations

For a differential spectrum, each bin is a separate prediction as it is a separate measurement!

With scale variations:



scanning over scales →



? ~~correlation~~ ?

? shape ?

	ρ_{12}	ρ_{13}	ρ_{23}
a	0	−1	0
b	1	1	1
c	1	−1	−1

» Scanning over scale variations that fill the band is like scanning over several *ad hoc* correlation models

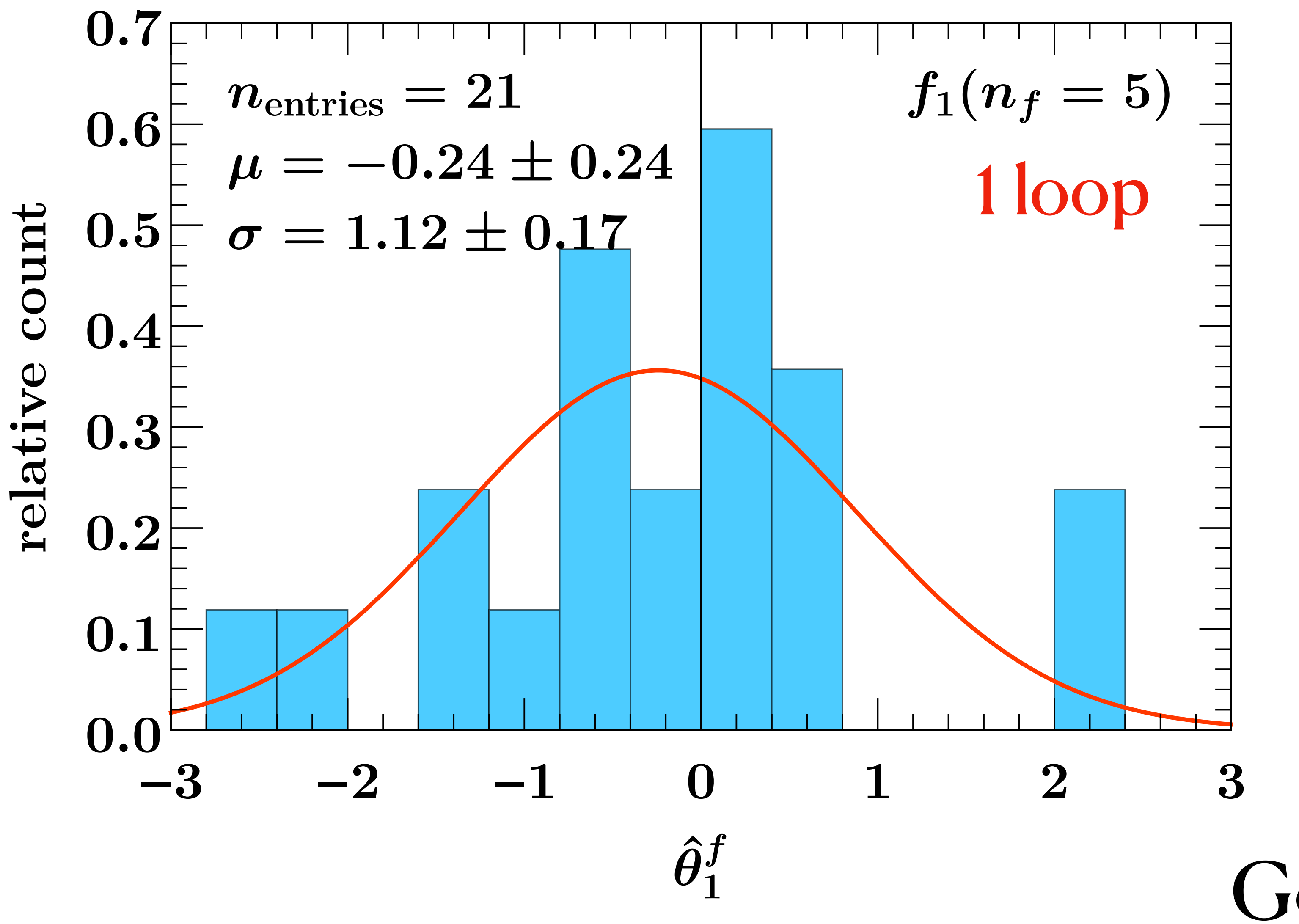
→ scale variations cannot give the correct shape (and therefore correlation): that's why we take envelopes!

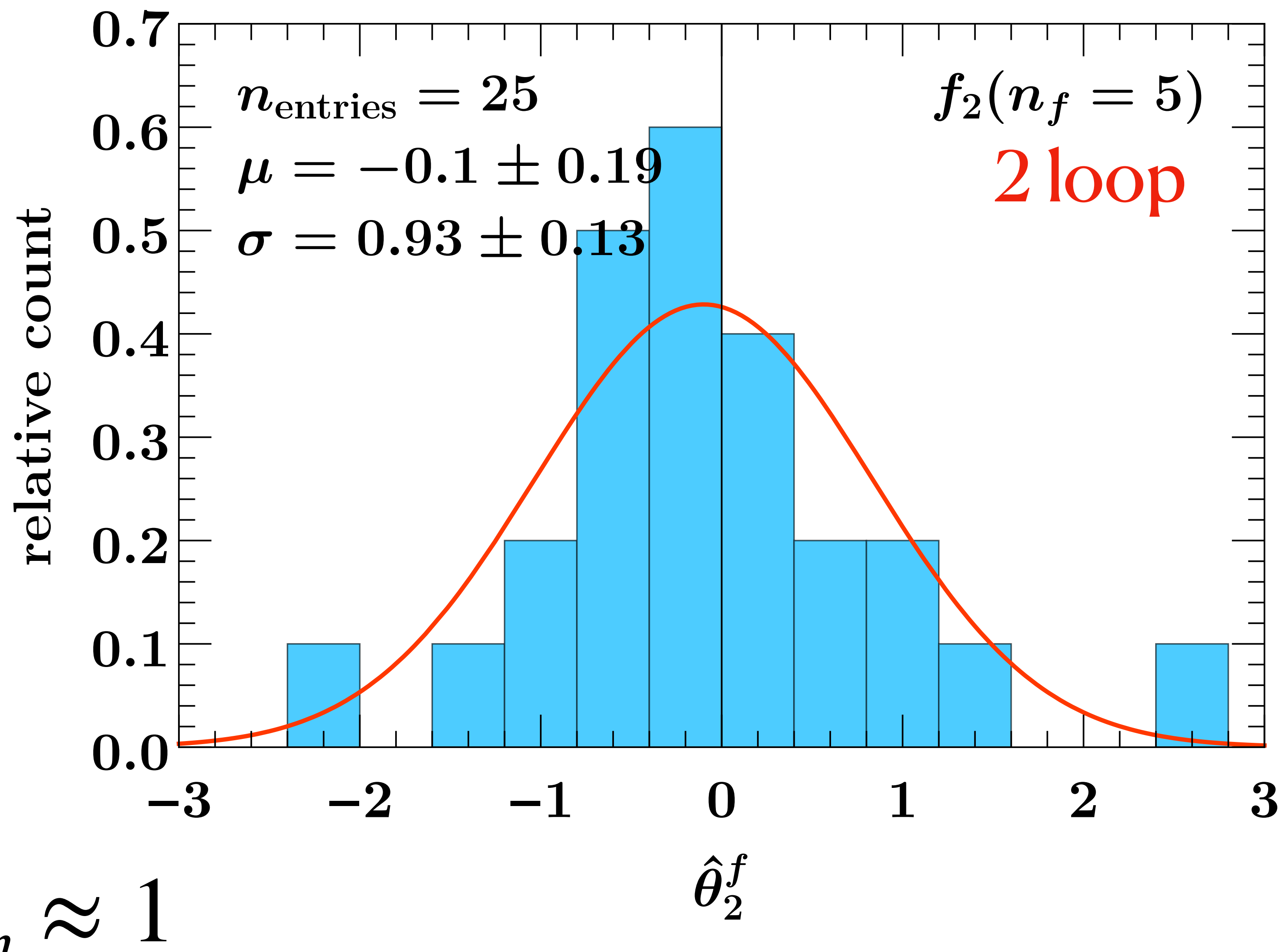
→ to get correct correlation: breakdown into *independent uncertainty components* required

TNPs for Boundary Conditions

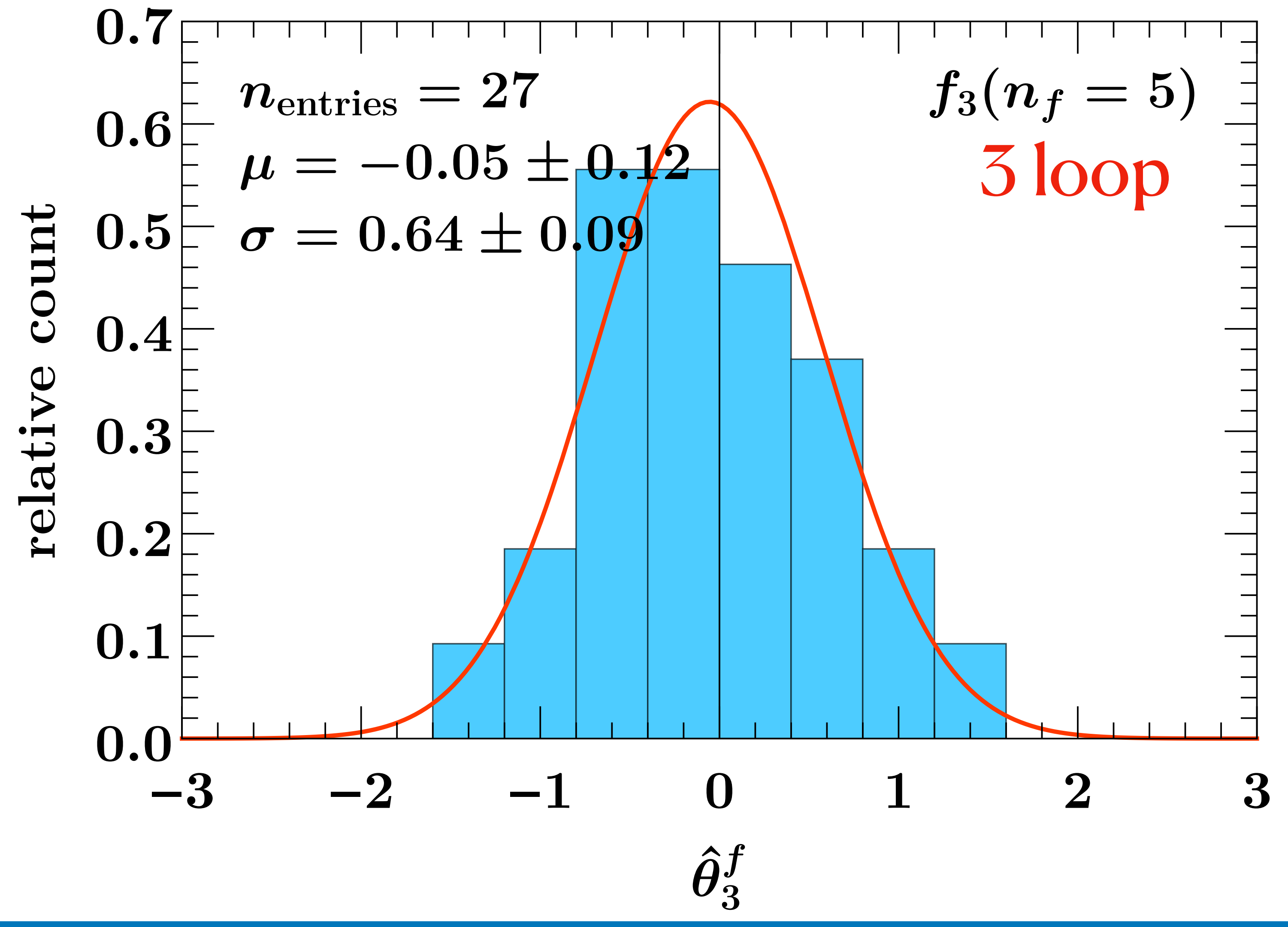
$$F(\alpha_s) = 1 + \sum_{n=1} \left(\frac{\alpha_S}{4\pi}\right)^n F_n$$

$$F_n(\theta_n) = 4C_r(4C_A)^{n-1}(n-1)!\,\theta_n^f$$

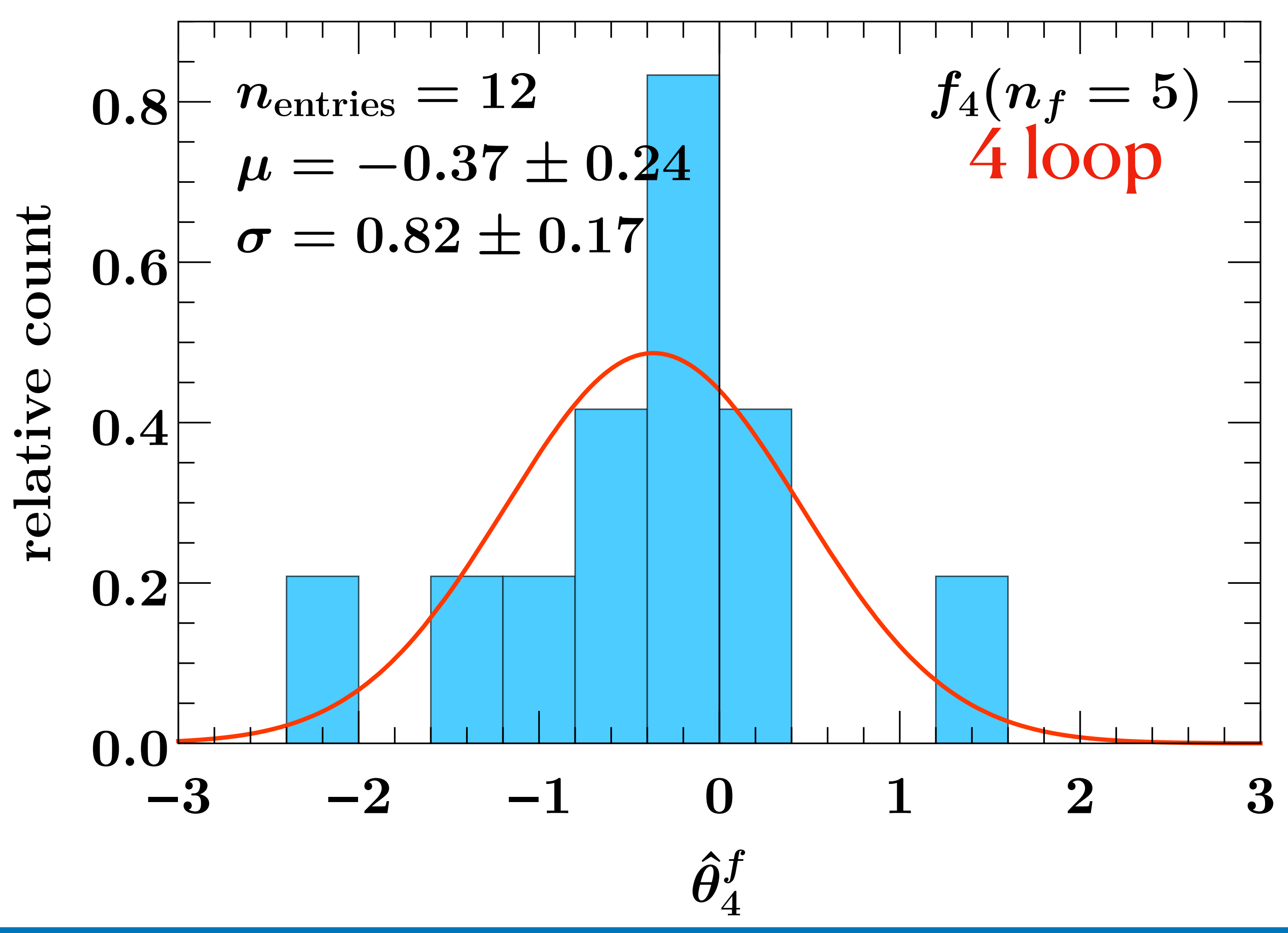




Good fit to a Gaussian with $\theta_n \approx 0$ and $\Delta\theta_n \approx 1$



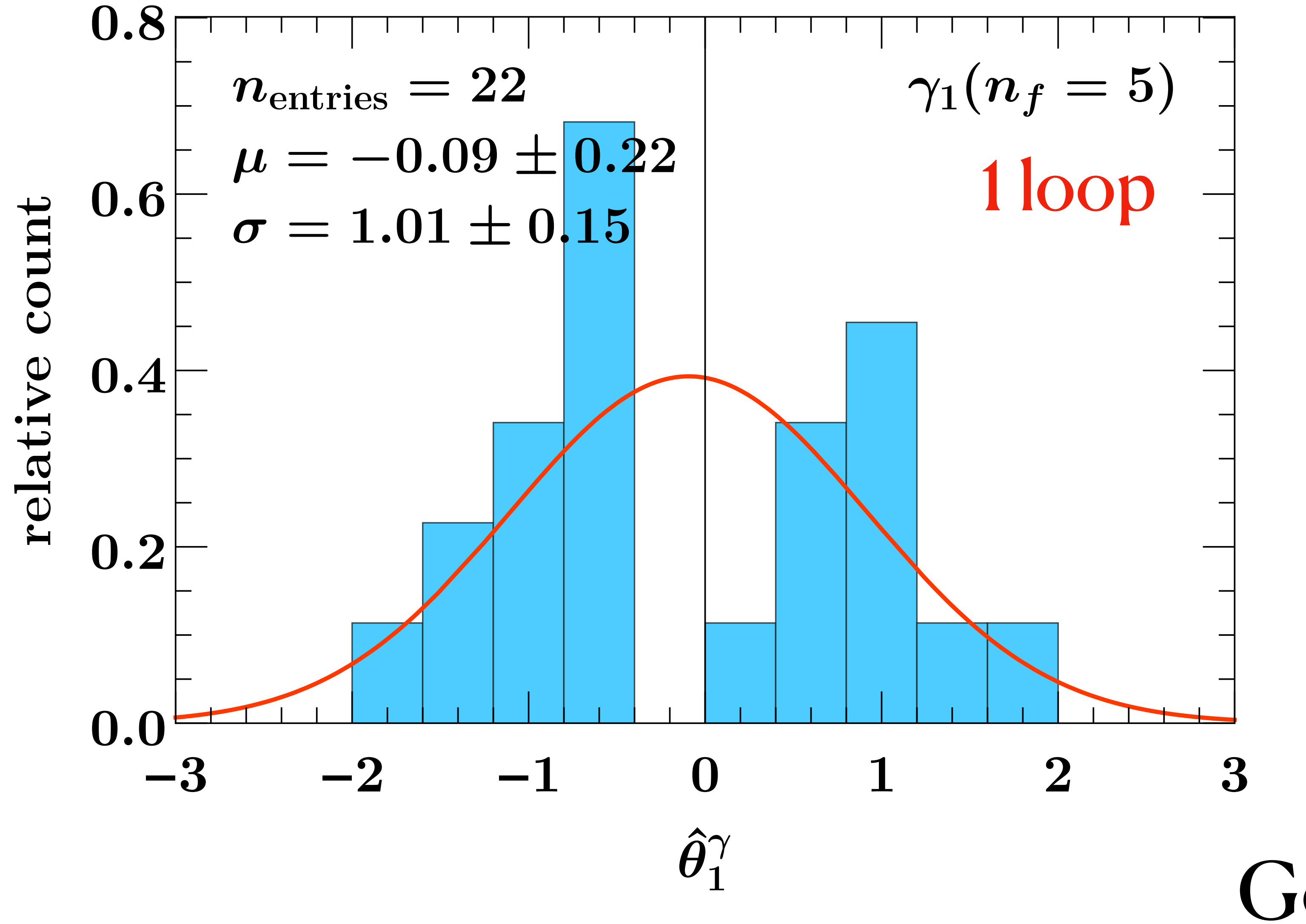
✓

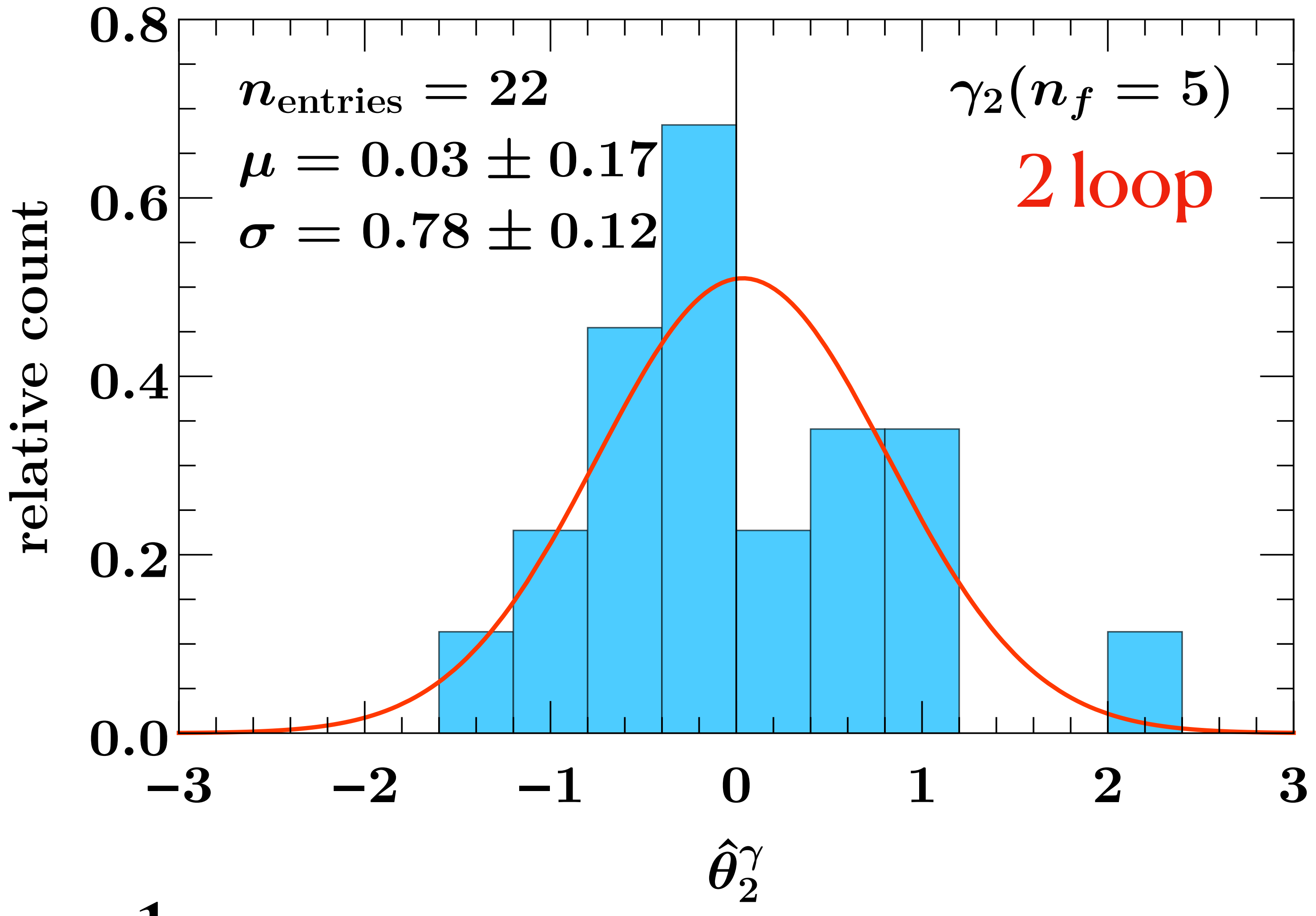


TNPs for Anomalous Dimensions

$$\gamma(\alpha_s) = \sum_{n=0} \left(\frac{\alpha_S}{4\pi}\right)^{n+1} \gamma_n$$

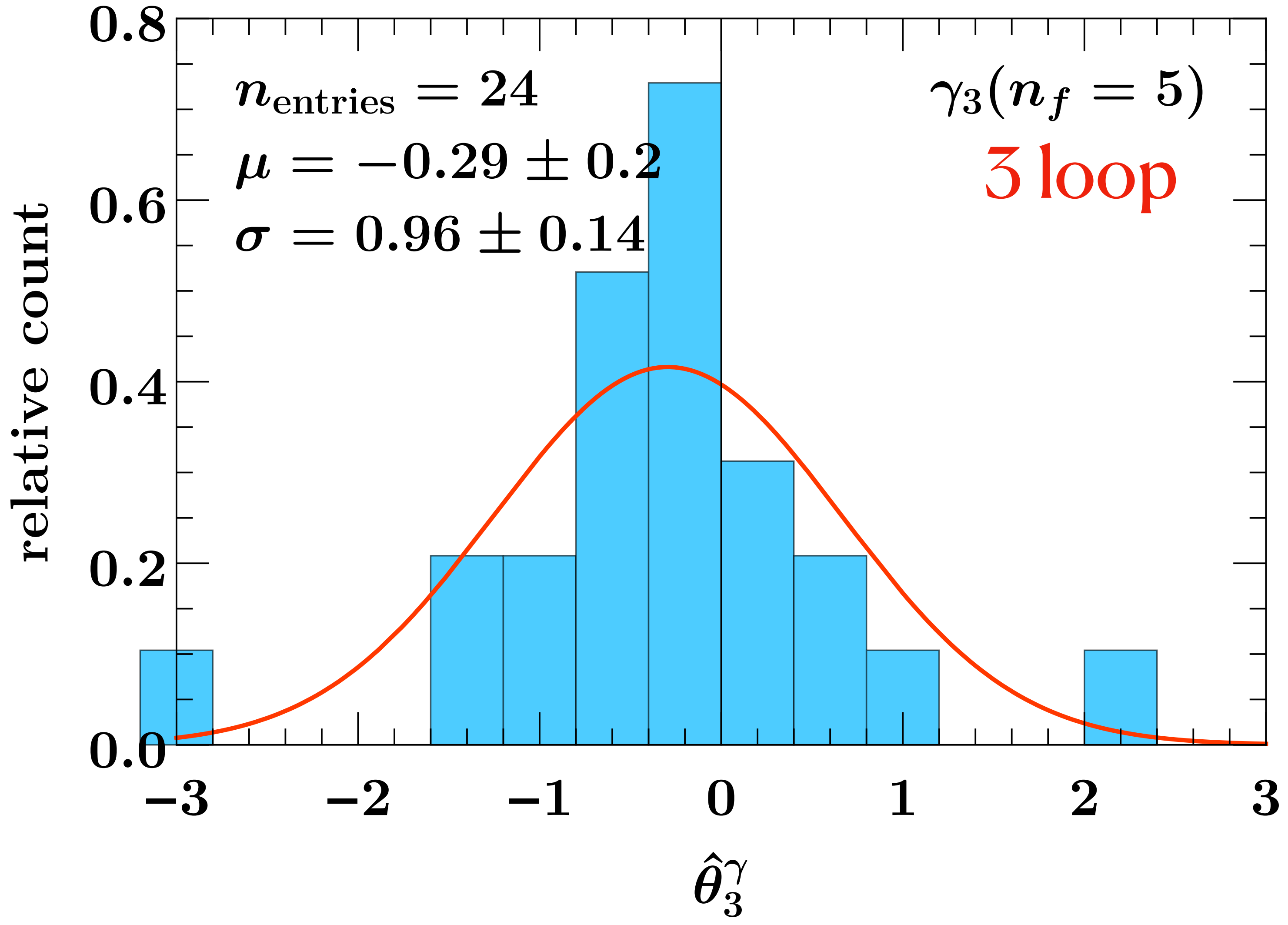
$$\gamma_n(\theta_n) = 4C_r(4C_A)^n\,\theta_n^\gamma$$

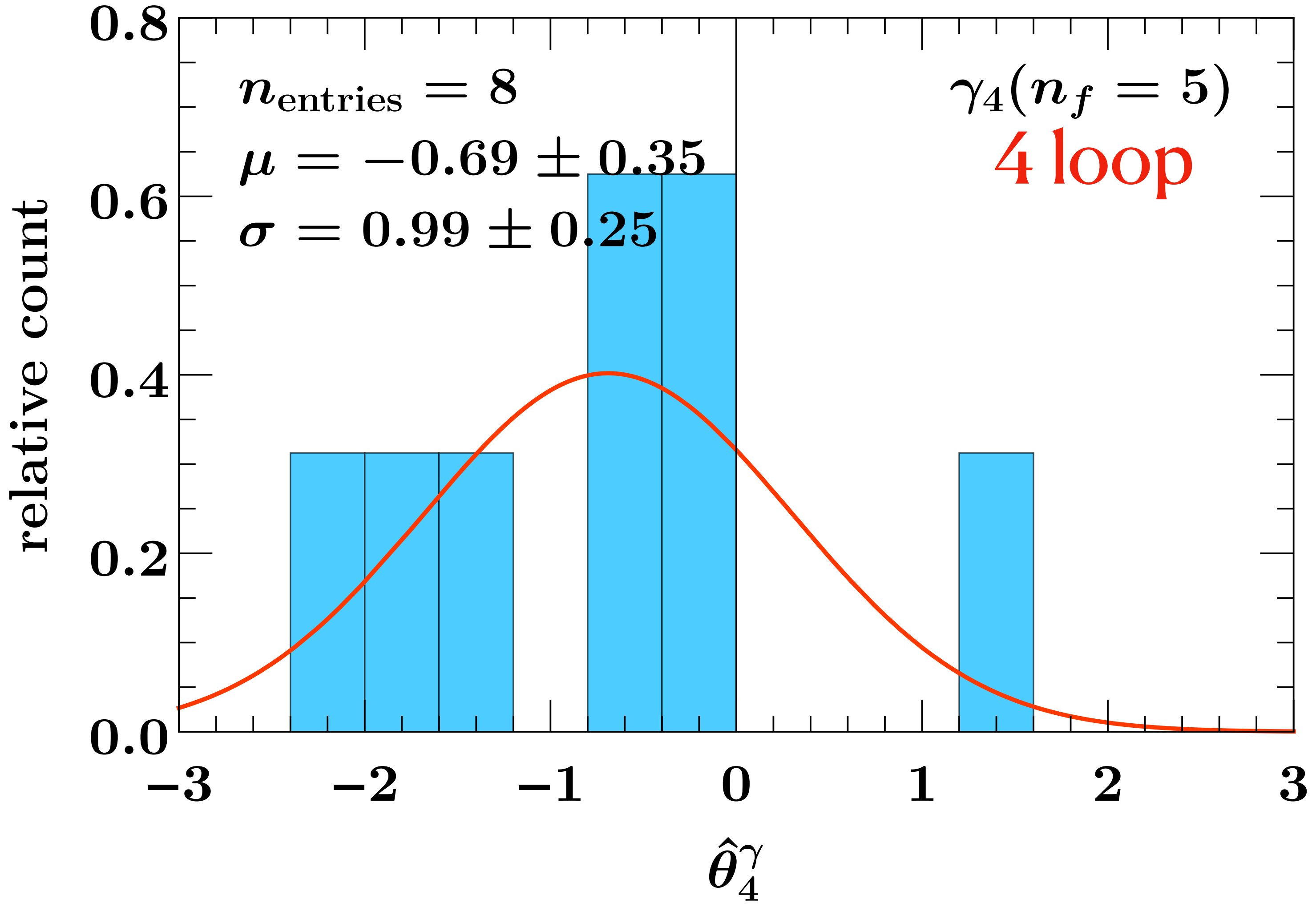




Good fit to a Gaussian with $\theta_n \approx 0$ and $\Delta\theta_n \approx 1$

✓





TNPs for Drell-Yan q_T spectrum

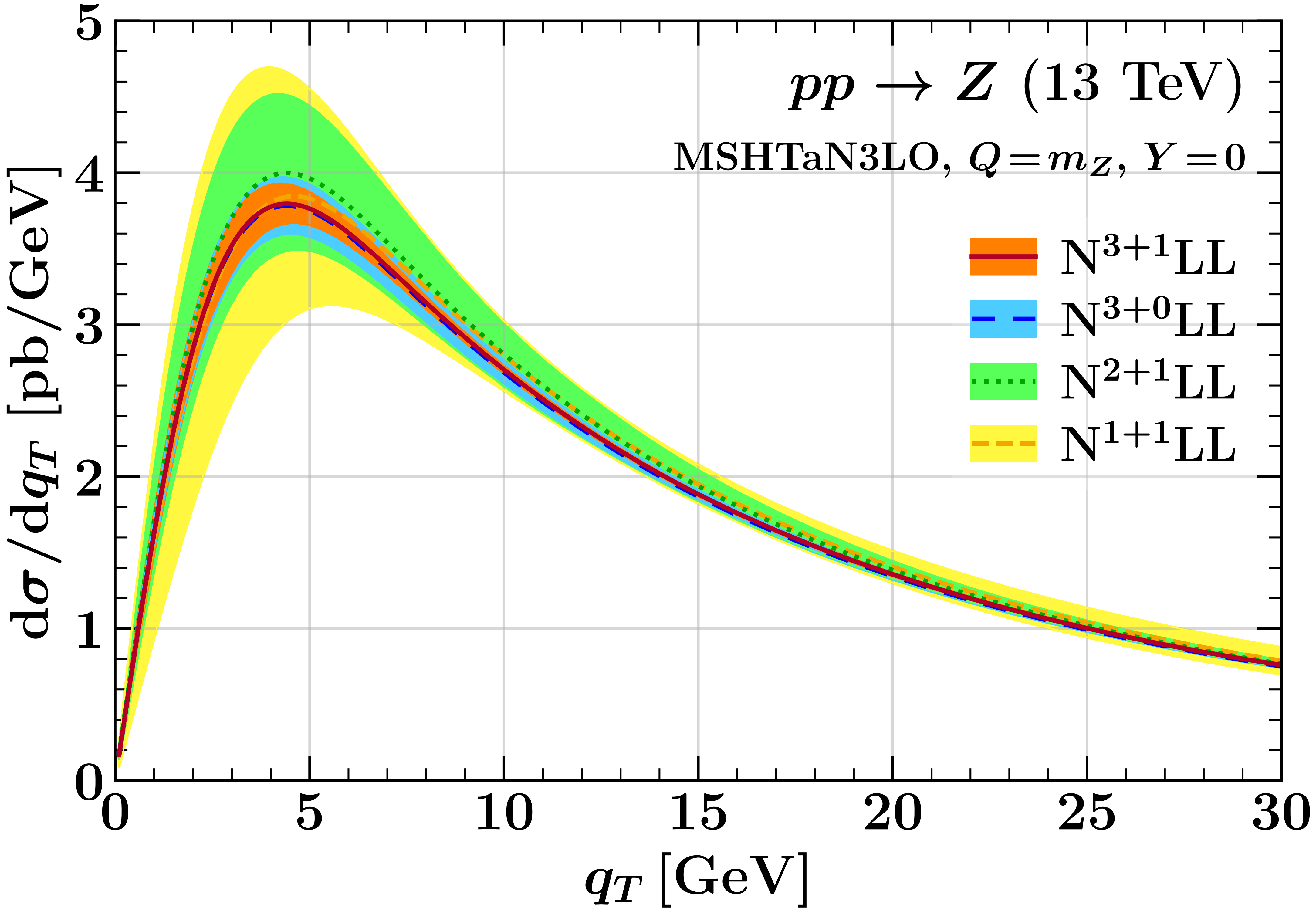
$$q_T \frac{\mathrm{d}\sigma}{\mathrm{d}q_T} = \left[H \times B_a \otimes B_b \otimes S \right] (\alpha_S, L \equiv \ln q_T/m_Z) + \mathcal{O}\left(\frac{q_T^2}{m_Z^2}\right)$$

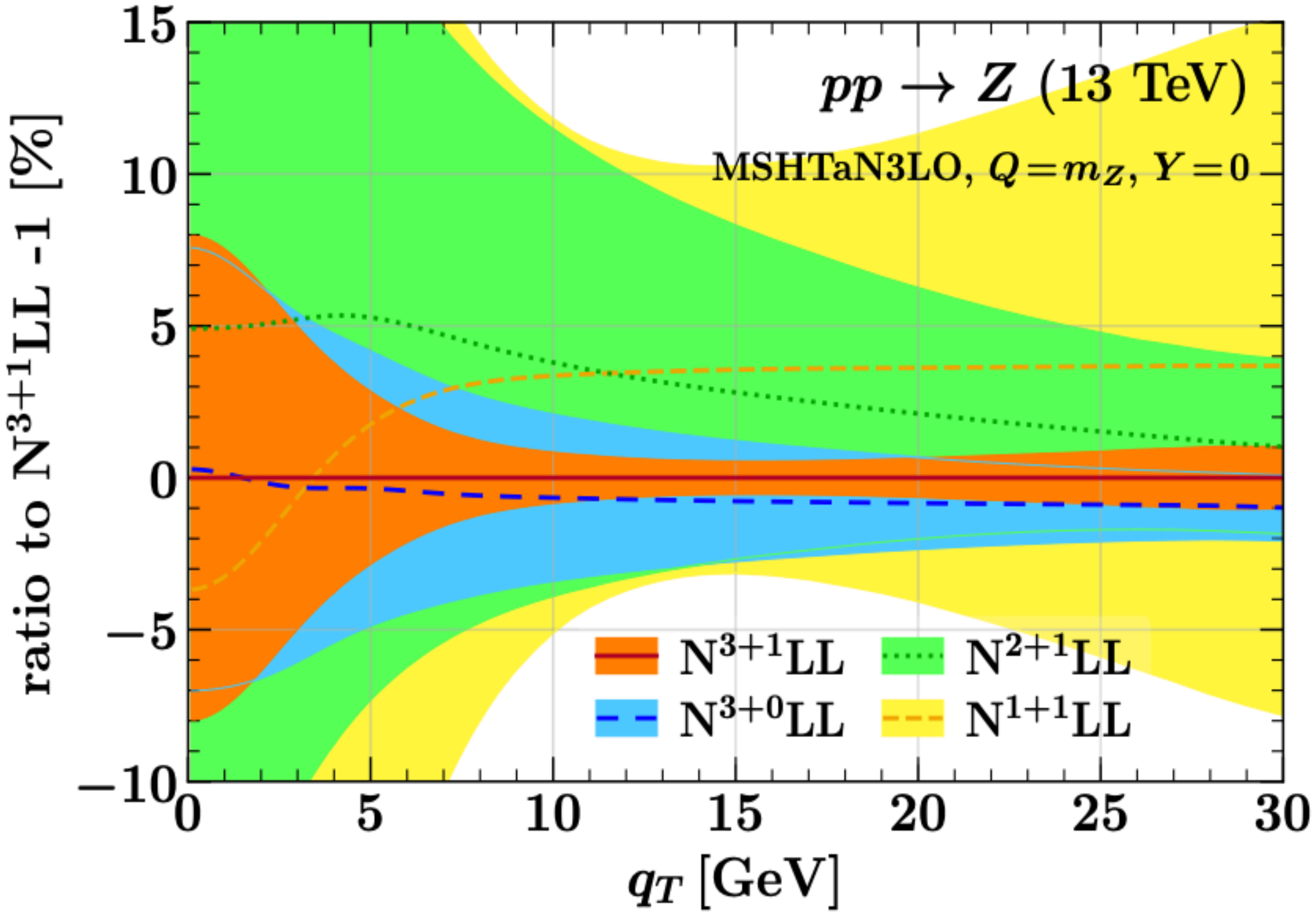
$F = \{H, B, S\}$ solution to RGE equations

$$F(\alpha_S, L) = F(\alpha_S) \exp \int_0^L \mathrm{d}L' \{ \Gamma[\alpha_S(L')] L' + \gamma_F[\alpha_S(L')] \}$$

boundary conditions — anomalous dimensions

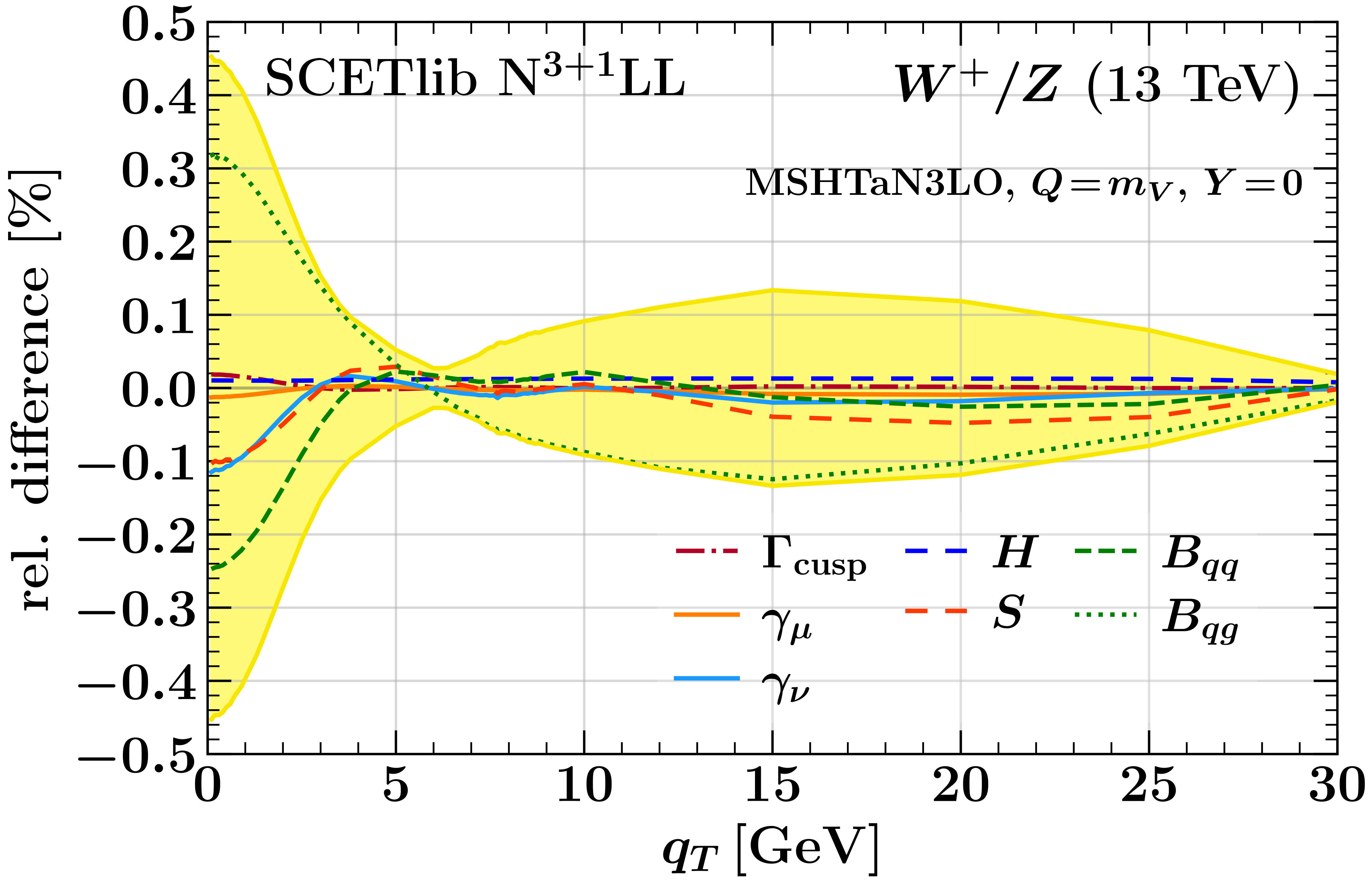
Different orders at **95% theory CL** ($\Delta\theta_n = \pm 2$)





TNPs correlation for Drell-Yan q_T spectrum

Relative impacts on W/Z*:



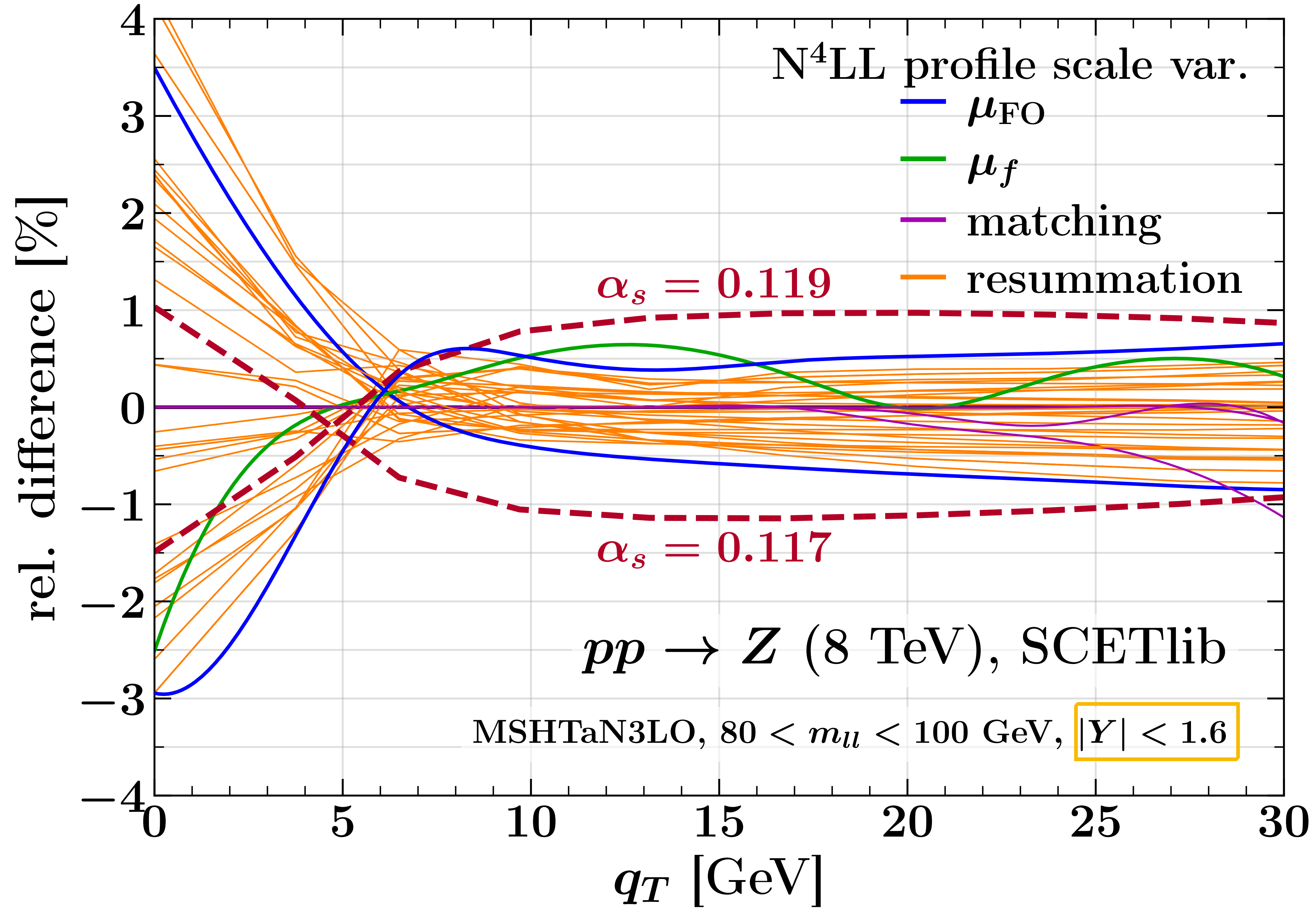
» uncertainties very similar for Z and W processes: same TNPs for both

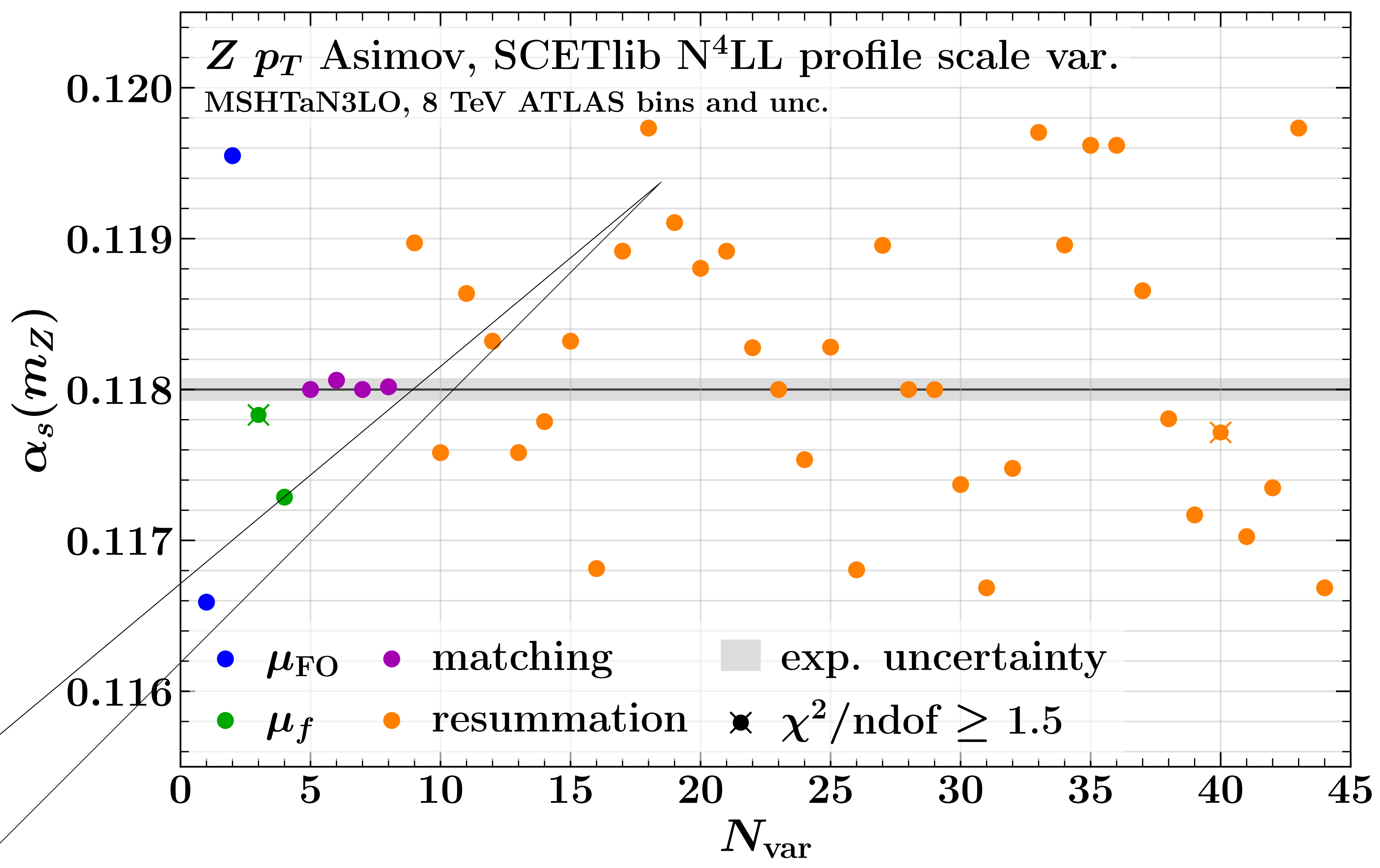
→ each TNP impacts are 100% correlated between the processes: nice cancellation in the ratio!

*just for illustration: only leading **massless** contribution

Perturbative uncertainty: scale variations

Fitting only $\alpha_s(m_Z)$: Data as N^{4}LL against N^{4}LL theory model





Sum envelopes of different types: $\Delta_{scale} = 2.43$

Naive envelope: $\Delta_{scale} = 1.73$

Perturbative uncertainty	Absolute uncertainty on $\alpha_s(m_Z)$ in units of 10^{-3}	
	ATLAS '23	Our estimate of expected size
Scale variations	± 0.42	± 2.43

❌ Scale variations are just insufficient for this purpose!

*uncertainties in units of 10^{-3}

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