THEORY UNCERTAINTIES

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CERN

Zurich Phenomenology Workshop — January 8th 2025 — Zurich

THEORY UNCERTAINTIES IN HIGH-ENERGY PRECISION MEASUREMENTS AT THE LHC

* I will focus on select recent developments & trends which I find interesting / important / concerning / …

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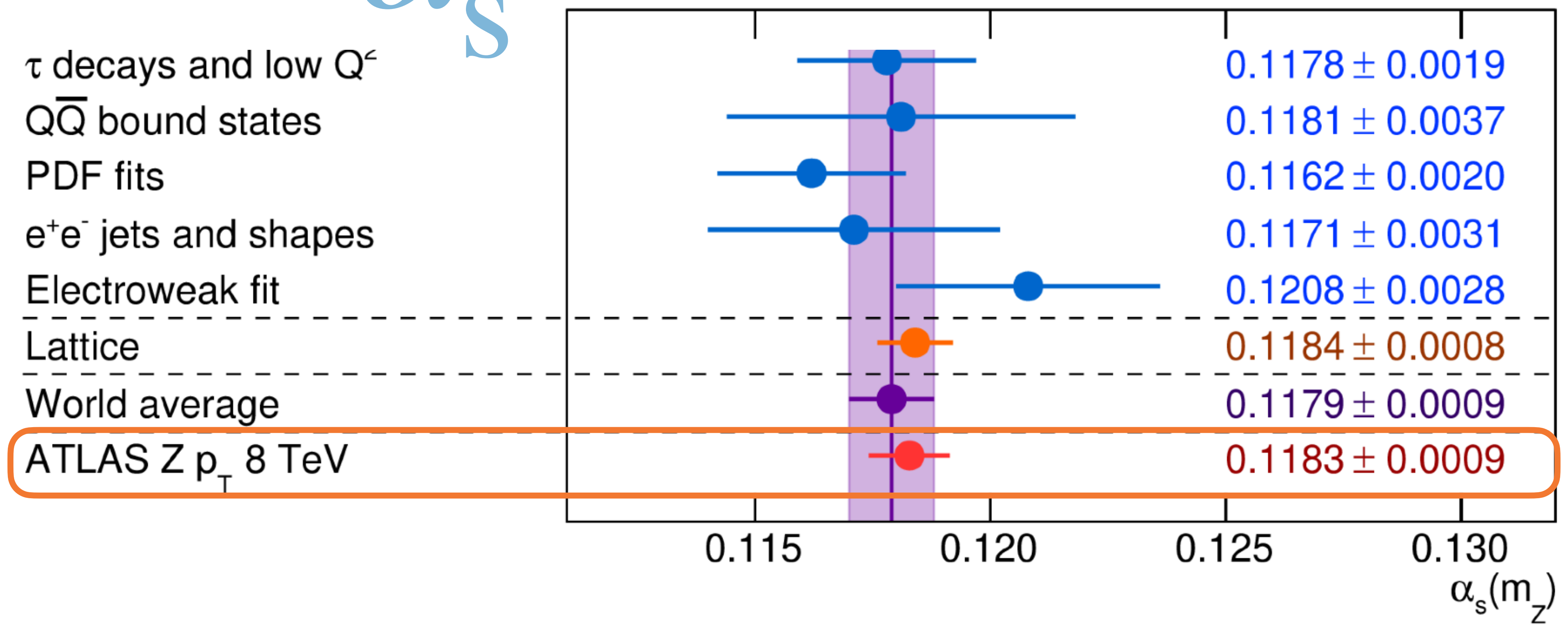
LHC – From a Discovery to a Precision Machine

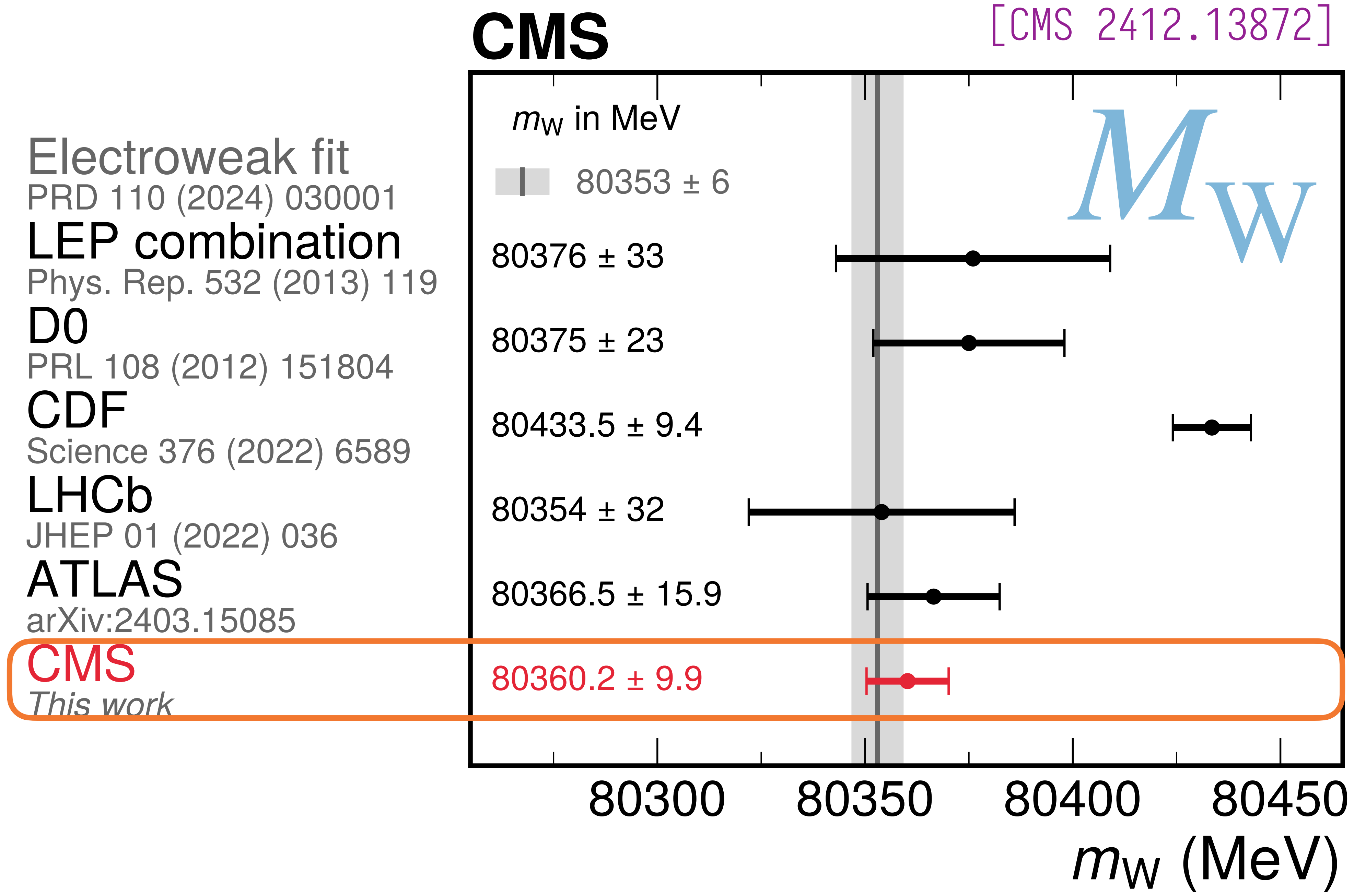
α_s

[ATLAS arXiv:2309.12986]



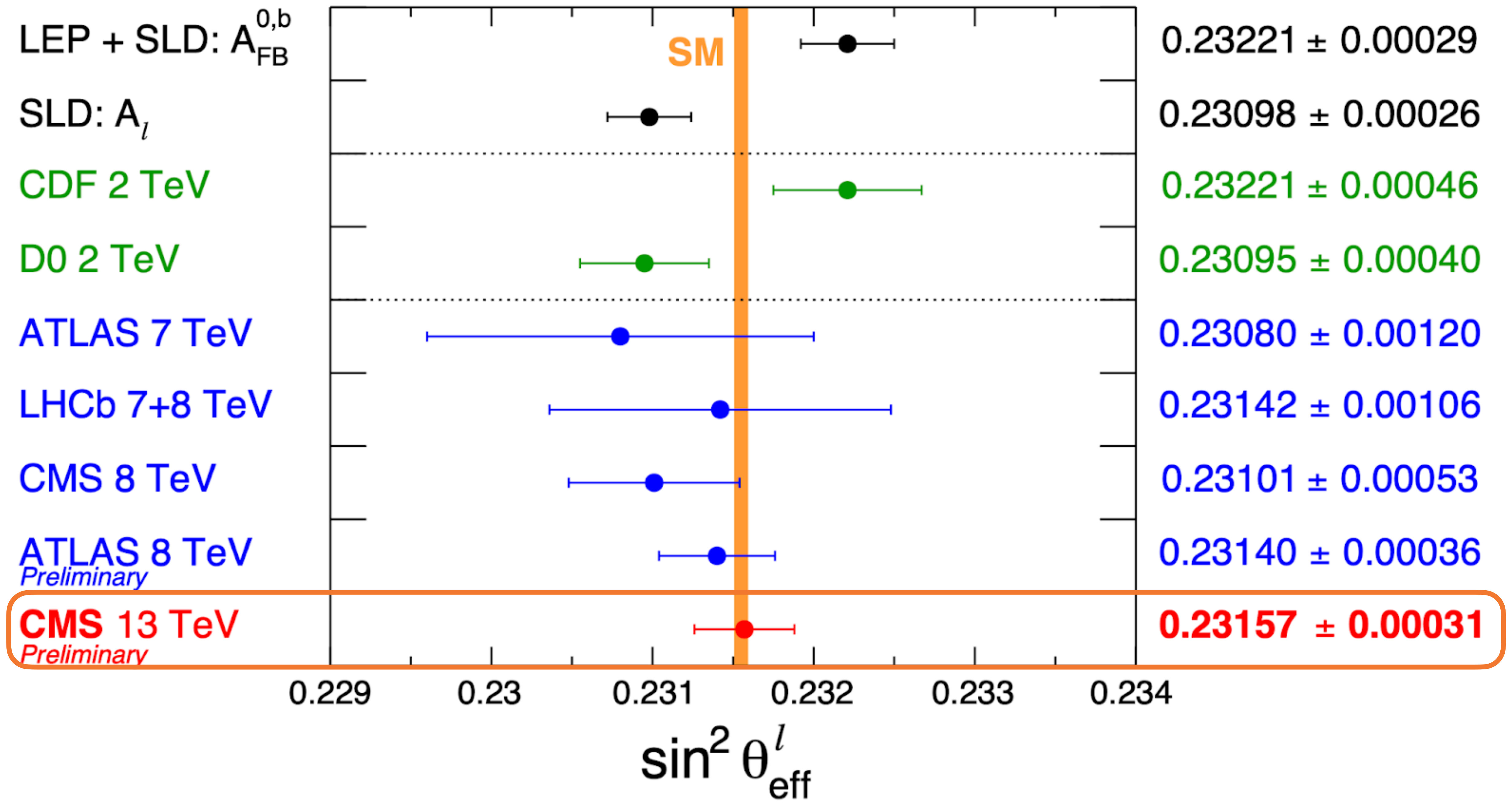
M_W

[CMS 2412.13872]



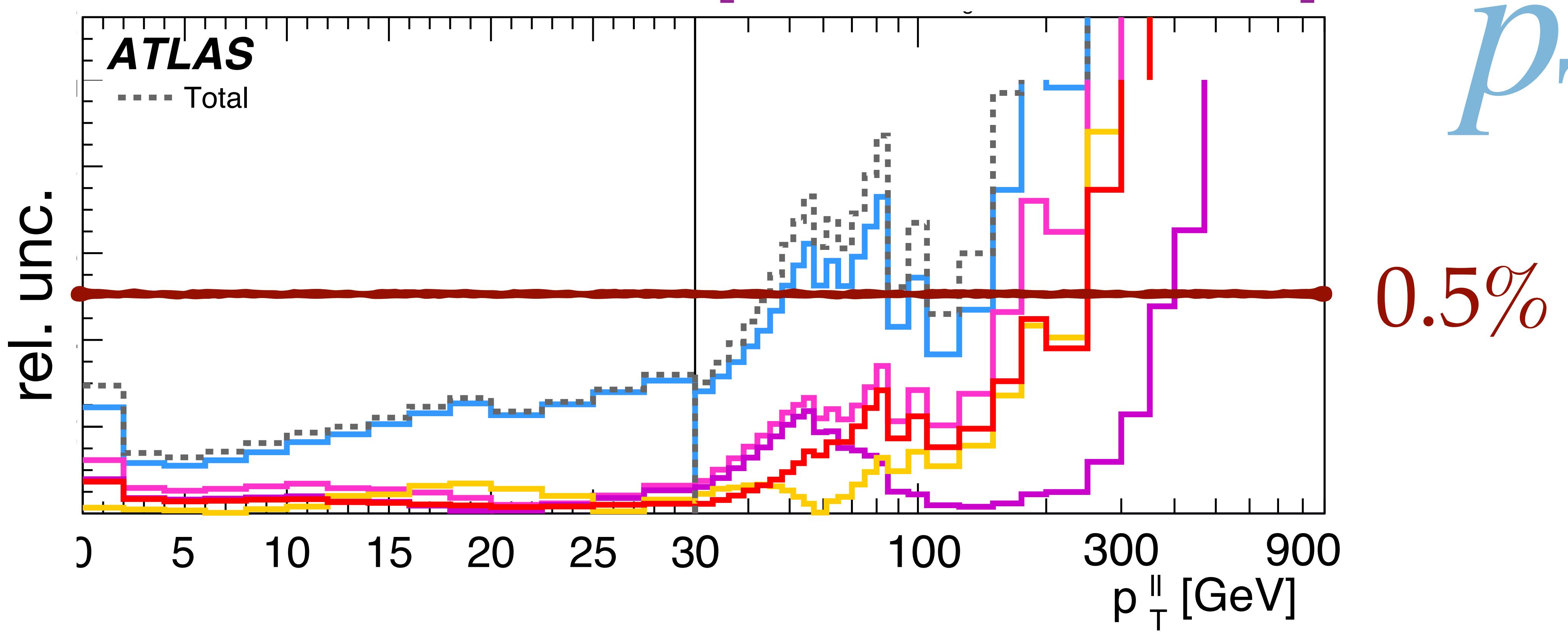
$\sin^2\theta_W$

[CMS-PAS-SMP-22-010]



p_T^Z

[ATLAS arXiv:1912.02844]



What is the Uncertainty Δ_{TH} of my Result?

- increasingly urgent to address with $\Delta_{\mathrm{EXP}} \searrow$ ($\leftrightsquigarrow$ HL-LHC)
  - what does 5σ mean if Δ_{TH} non-negligible?
  - interpretation of data in need for robust Δ_{TH}: precision measurements, PDF fits, …
- various sources that contribute to Δ_{TH}:
  - Δ_{α_s}, Δ_{param}: parametric uncertainties $\leftrightsquigarrow$ exp. extraction
  - Δ_{PDF}: parton distribution functions (PDFs) $\leftrightsquigarrow$ fits to data, lattice, …
  - $\Delta_{\text{non pert.}}$: intrinsic k_T, hadronisation, UE, … $\leftrightsquigarrow$ TMD, parton showers, …
  - $\Delta_{\text{pert.}}$: *missing higher-order* corrections $\leftrightsquigarrow$ conceptually tricky

OUTLINE

focus on dominant sources of Δ_{TH} in precision measurements

- MOTIVATION

"QCD modelling"

1. Scale Variations
2. Bayesian Estimates
3. Theory Nuisance Parameters
4. Parton Distribution Functions

- CONCLUSIONS

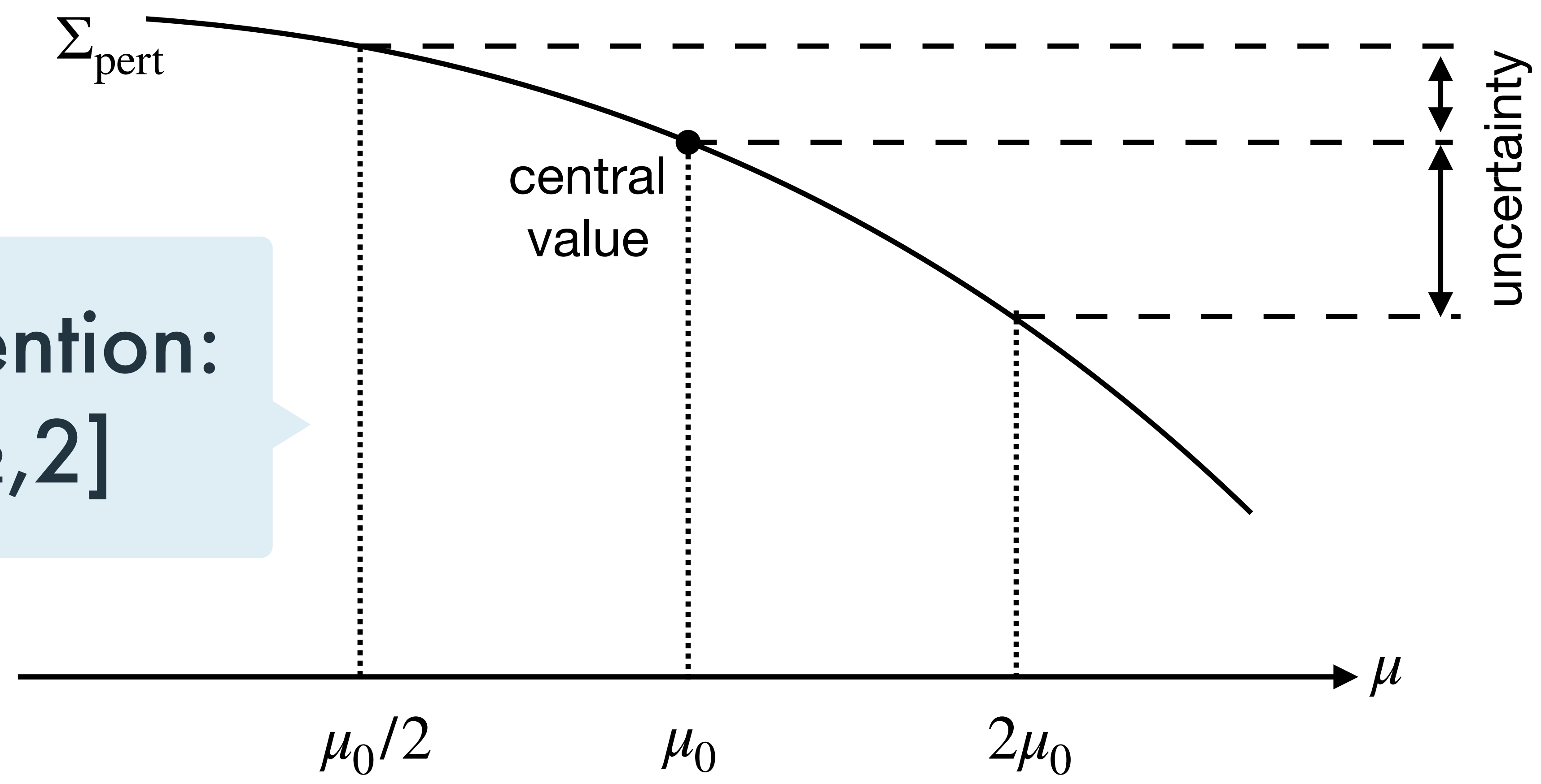
General Idea & Conventions

- approximation for an observable
  @ (next-to-)^n leading order:

$$\mathrm{d}\sigma^{\mathrm{N^nLO}} = \mathrm{d}\sigma^{(0)} + \alpha_s\,\mathrm{d}\sigma^{(1)} + \ldots + \alpha_s^n\,\mathrm{d}\sigma^{(n)}, \qquad \mathrm{d}\sigma^{(0)} \propto \alpha_s^{n_0}$$

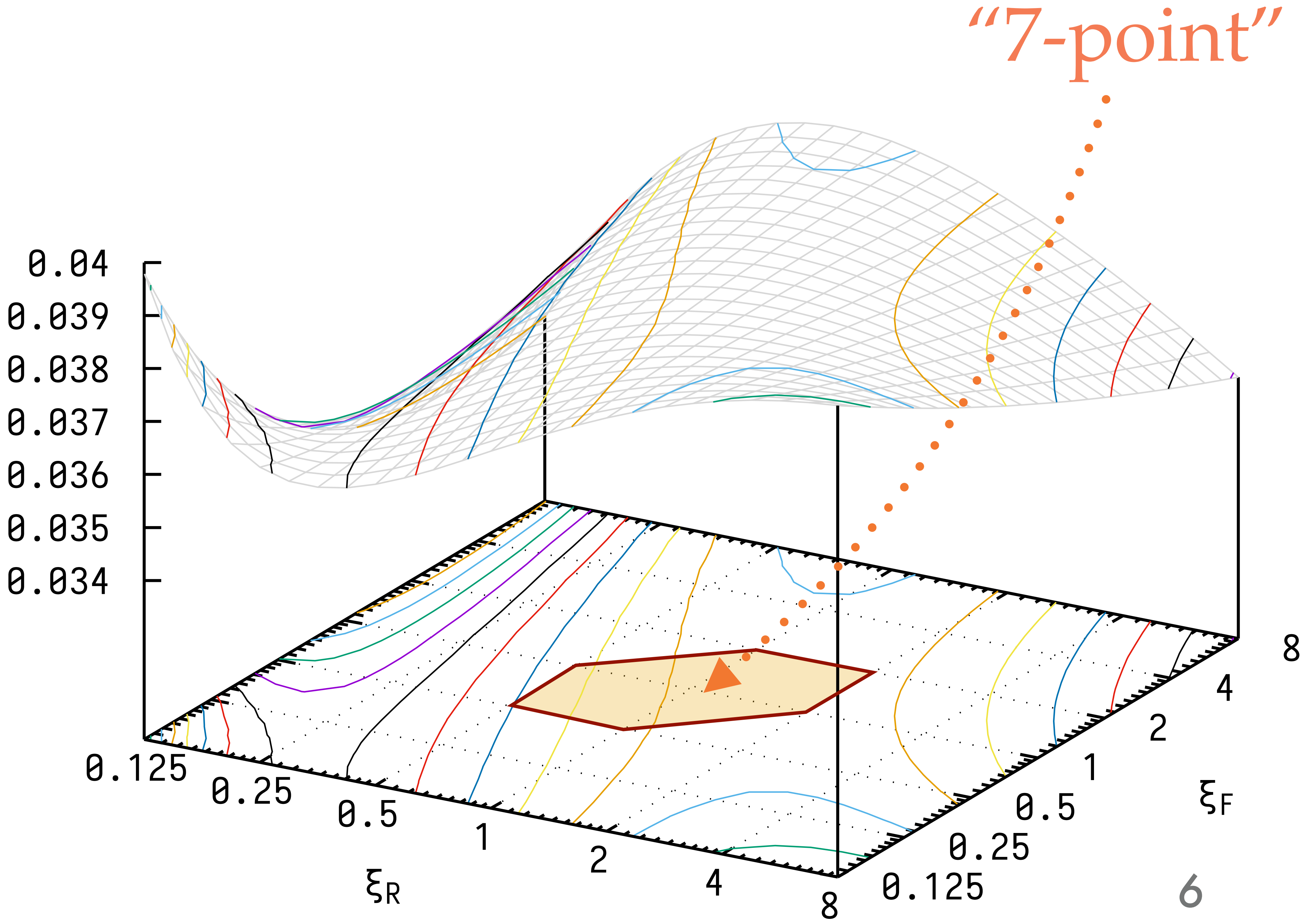
- truncation of series induces a sensitivity to terms of the next order

$$\mu\,\frac{\mathrm{d}}{\mathrm{d}\mu}\sigma^{\mathrm{N^nLO}}(\mu) = \mathcal{O}(\alpha_s^{n_0+n+1}) = \mathcal{O}(\Delta_{\mathrm{pert.}})$$



convention:
[½,2]

(μ_R, μ_F)

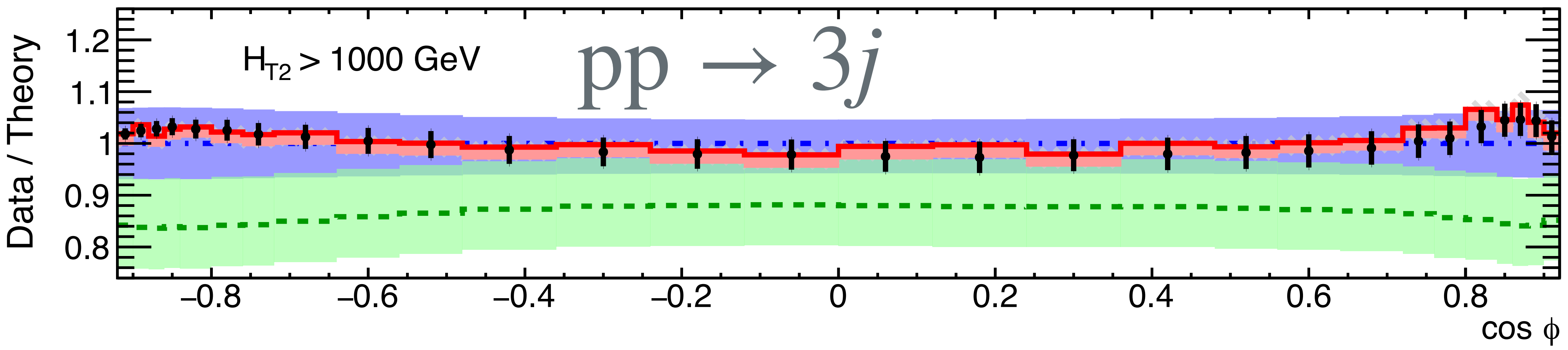


1 Scale Variation

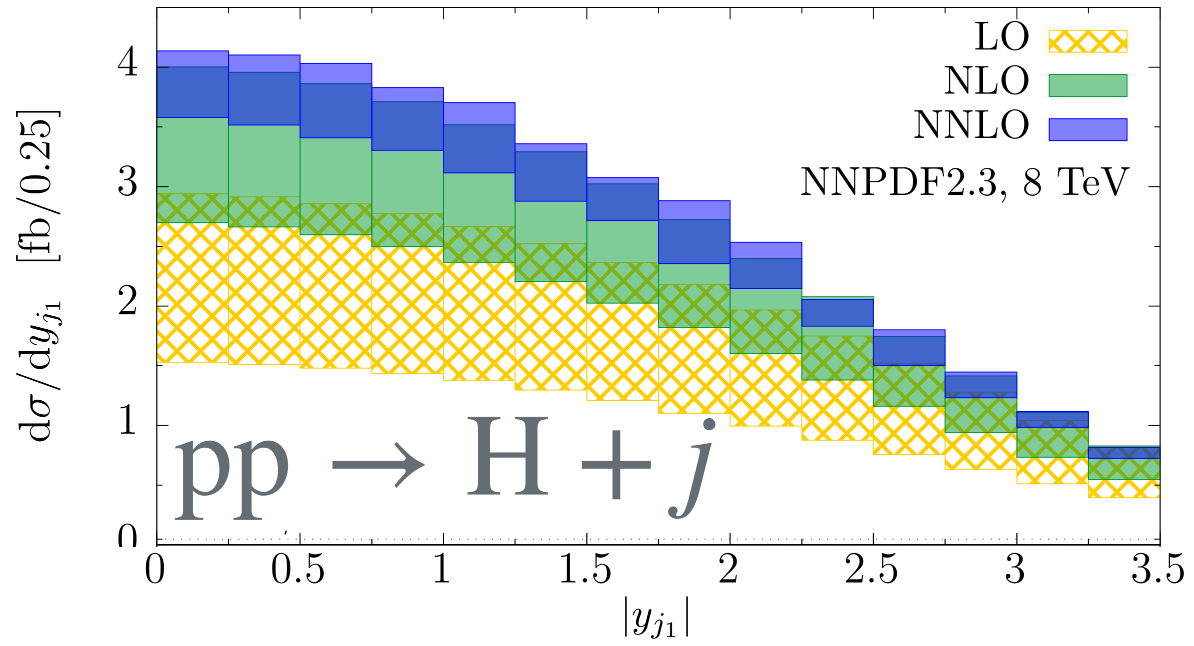
Credit where credit is due

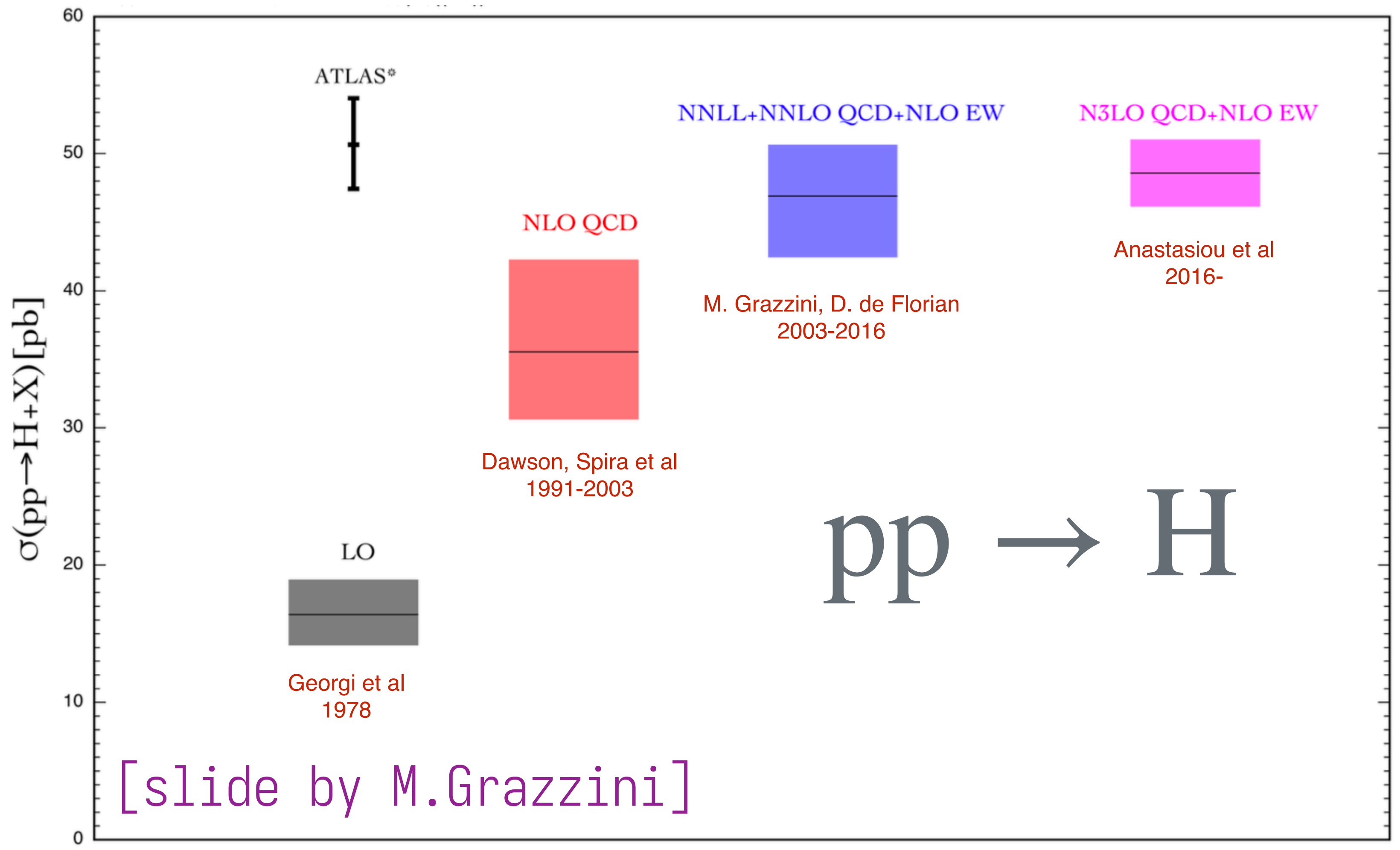
- quite neat & simple
- can work very well…
  … lot of experience if it doesn't
  - ↪ new channels, jet bins, "giant K factors", ratios, …
  - ↪ strategies to mitigate

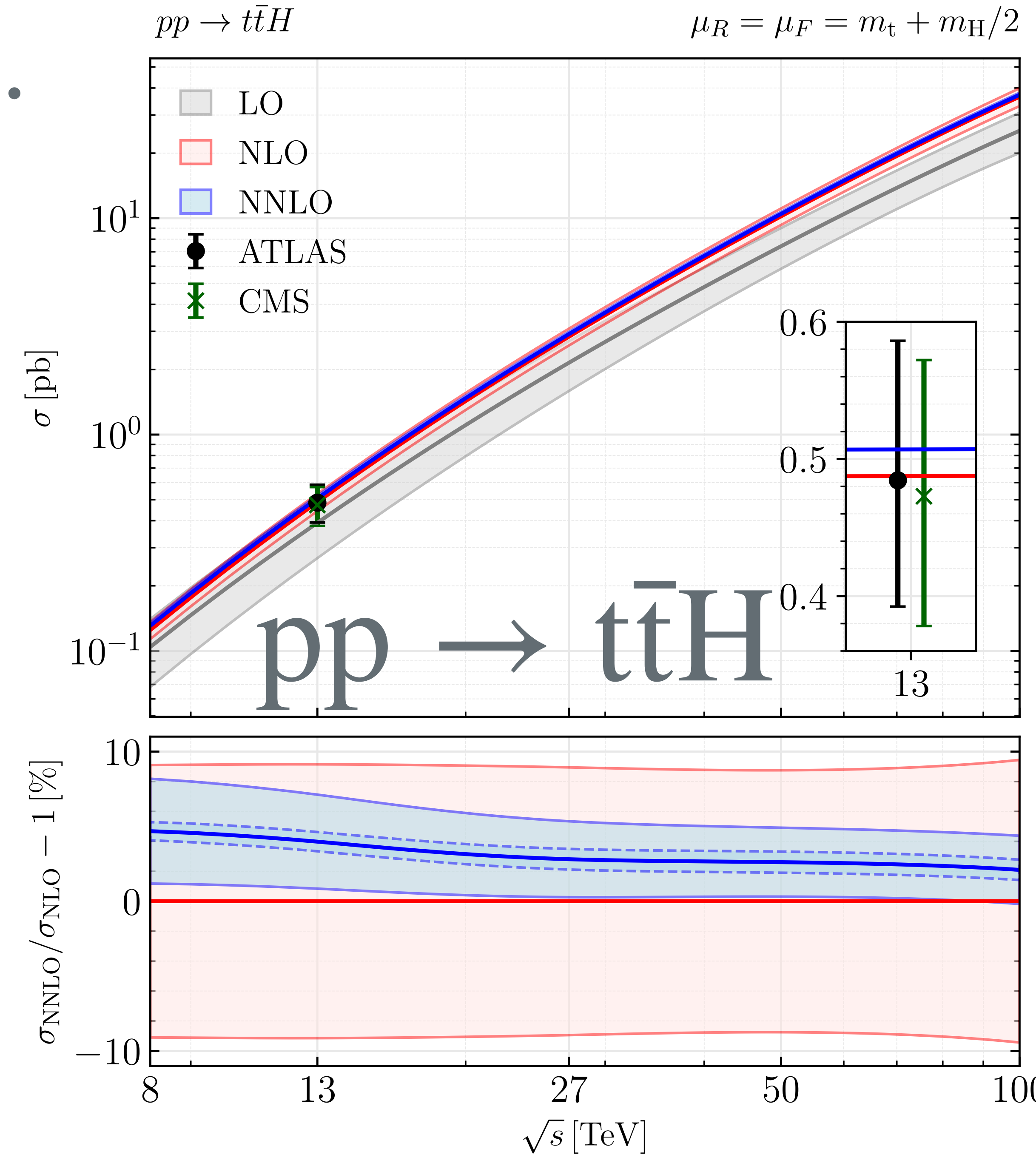
[Czakon, Mitov, Poncelet '21]



[Caola, Melnikov, Schulze, '15]

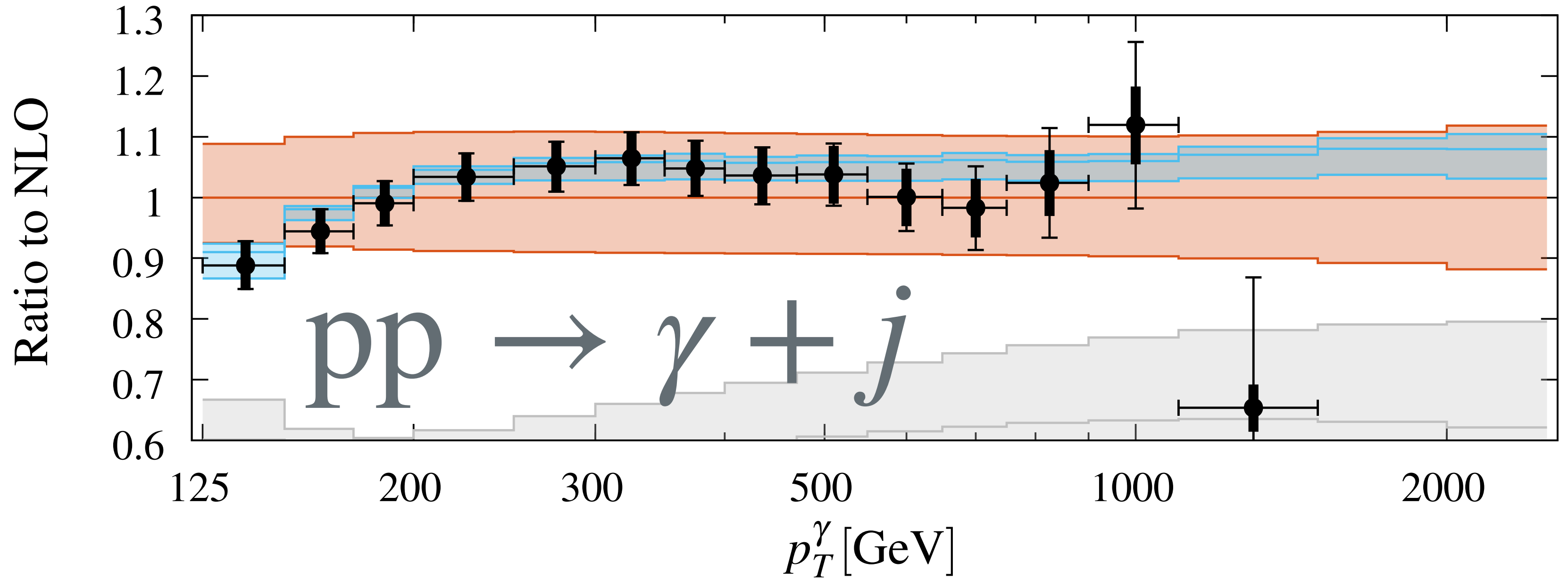






[Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini '22]

[Chen, Gehrmann, Glover, Höfer, Huss '19]



1 Scale Variation

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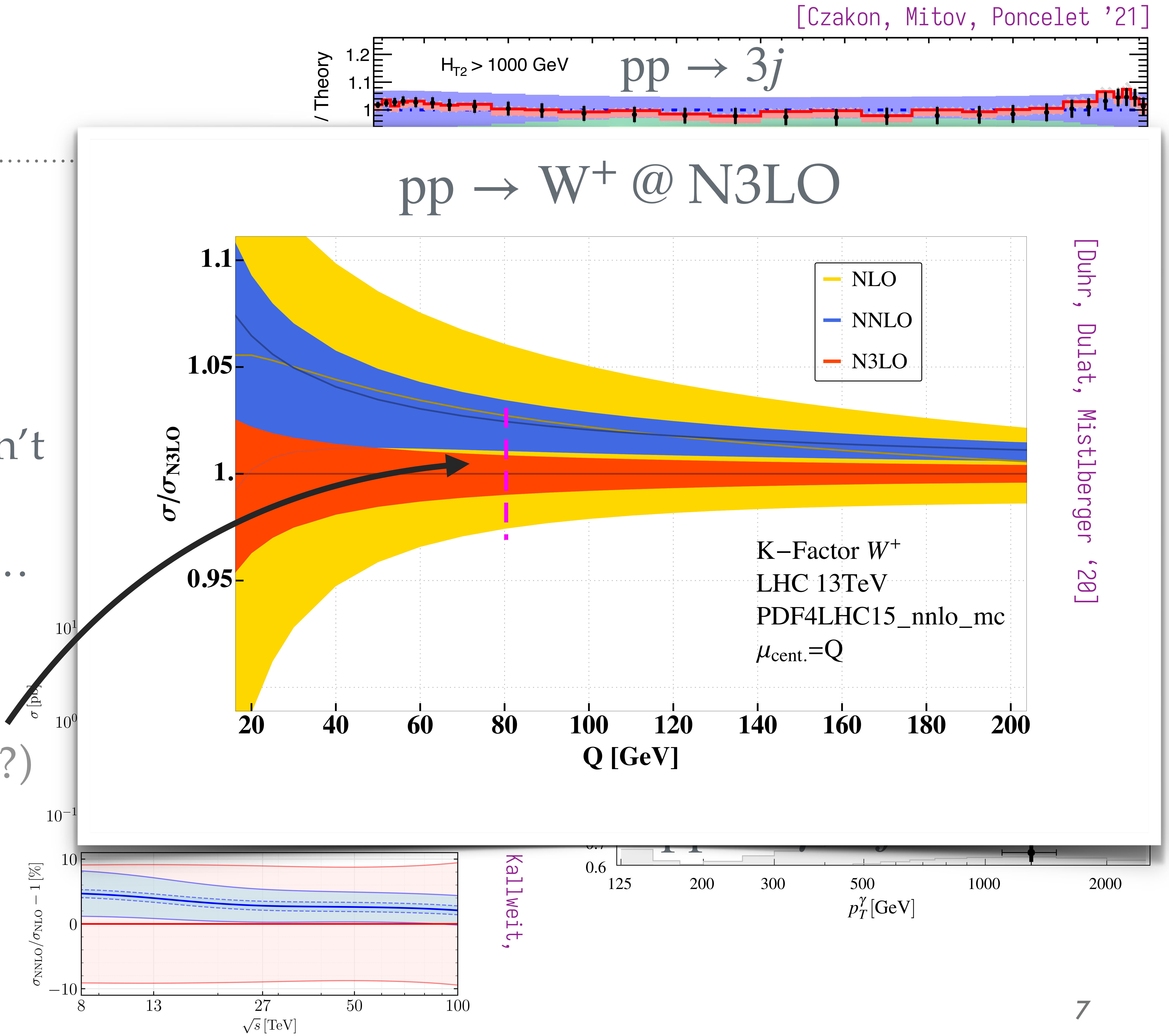
  ↪ new channels, jet bins, "giant K factors", ratios, …
  ↪ strategies to mitigate

- failure of Δ_{scl} beyond repair(?)
  ↔ difficult for any method



Scale Variation

Main Issues with Scales

1. choice of the central scale μ_0
2. no probabilistic interpretation
3. no correlation model

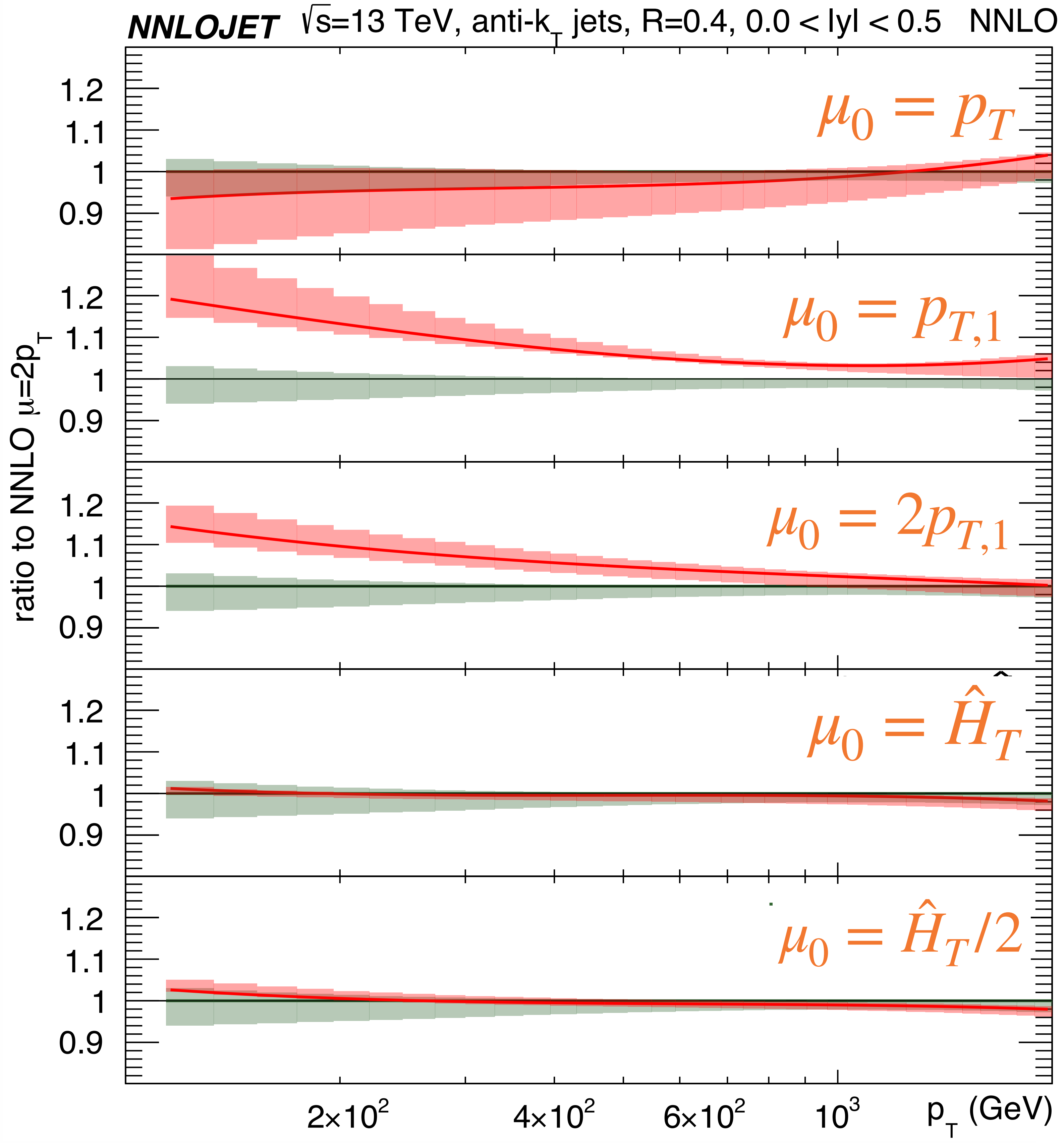
- fastest apparent convergence (FAC)
  $\hookrightarrow \; \sigma^{(n)}(\mu_{\mathrm{FAC}}) = 0$
- principle of minimal sensitivity (PMS)
  $\hookrightarrow \; \frac{\partial}{\partial\mu}\sigma^{(n)}(\mu)\Big|_{\mu_{\mathrm{PMS}}} = 0$
- BLM/PMC, …

invoke some principle

incl. jets @ NNLO
w.r.t. $\mu_0 = 2p_T$

or combination:

- convergence
- band overlap
- stability
- …



[Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Pires '18]

1 Scale Variation

Main Issues with Scales

1. choice of the central scale μ_0
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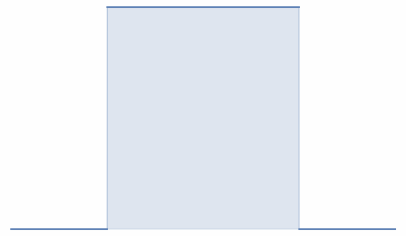
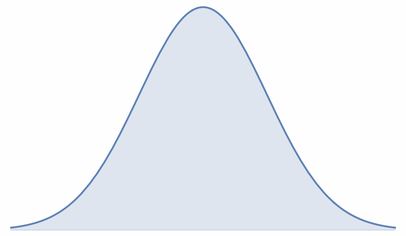
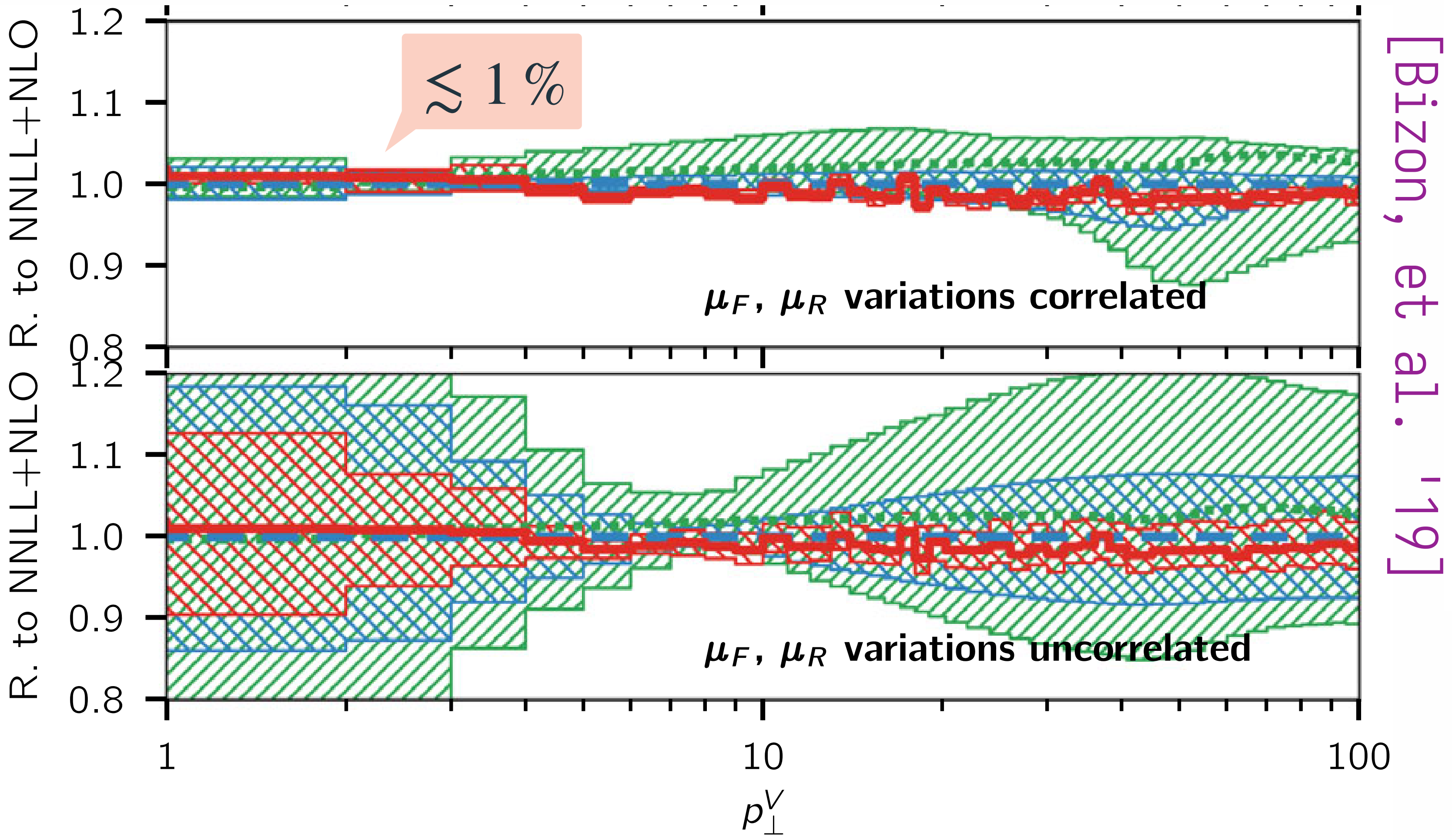
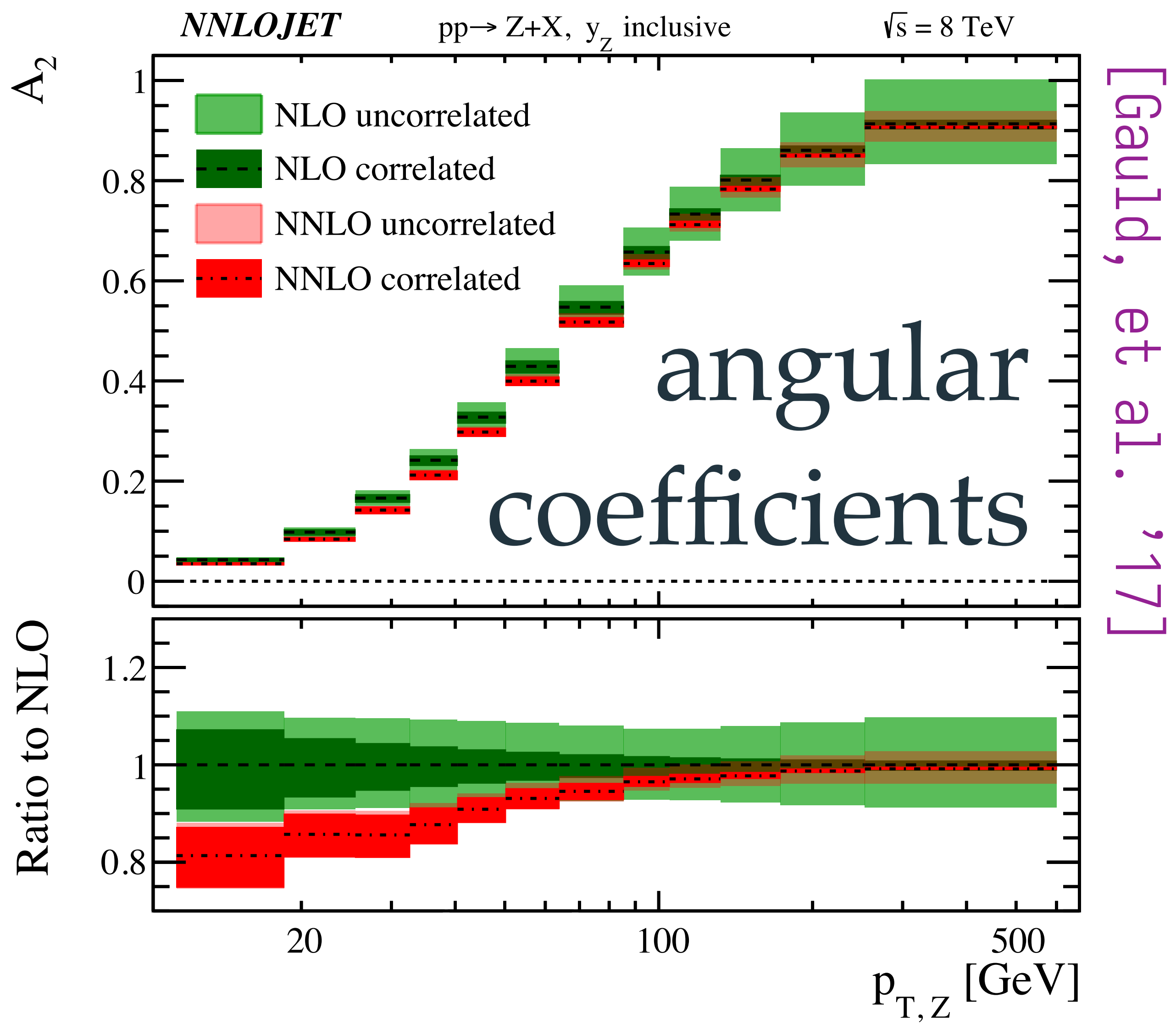
- **meaning of the envelope?**

box , Gaussian , …

- **to correlate, or not to correlate**

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





1 Scale Variation

Main Issues with Scales

1. choice of the central scale μ_0
2. no probabilistic interpretation
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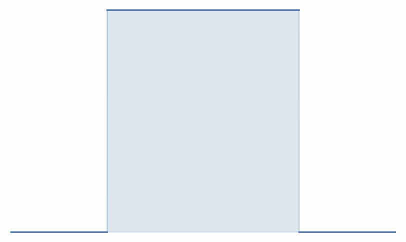
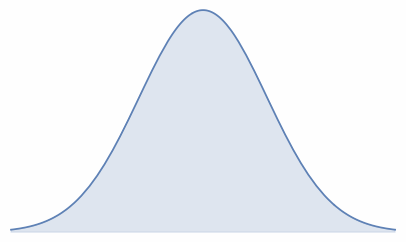
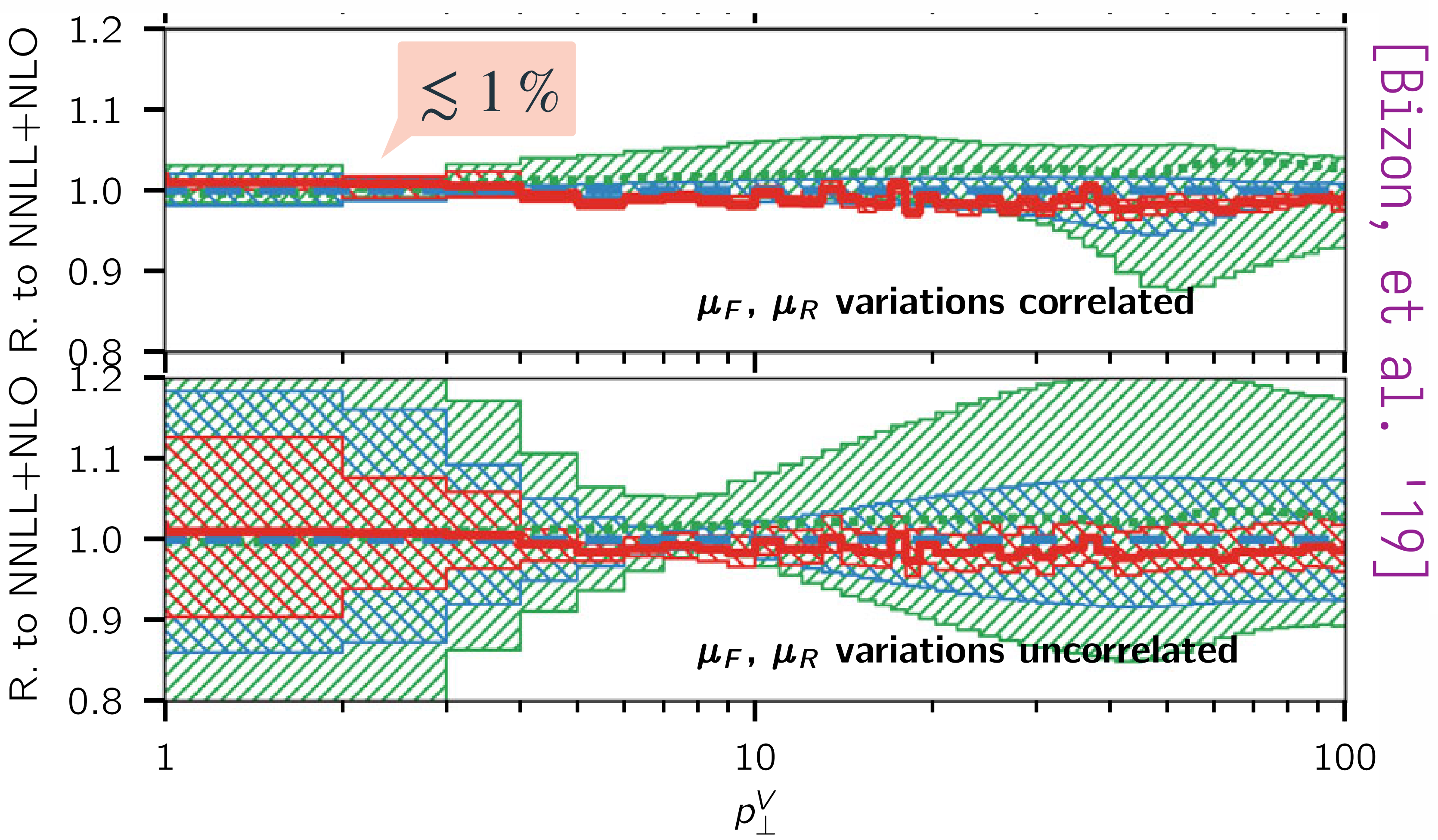
new approaches try
to mainly address 2 & 3
1 remains a challenge ∀

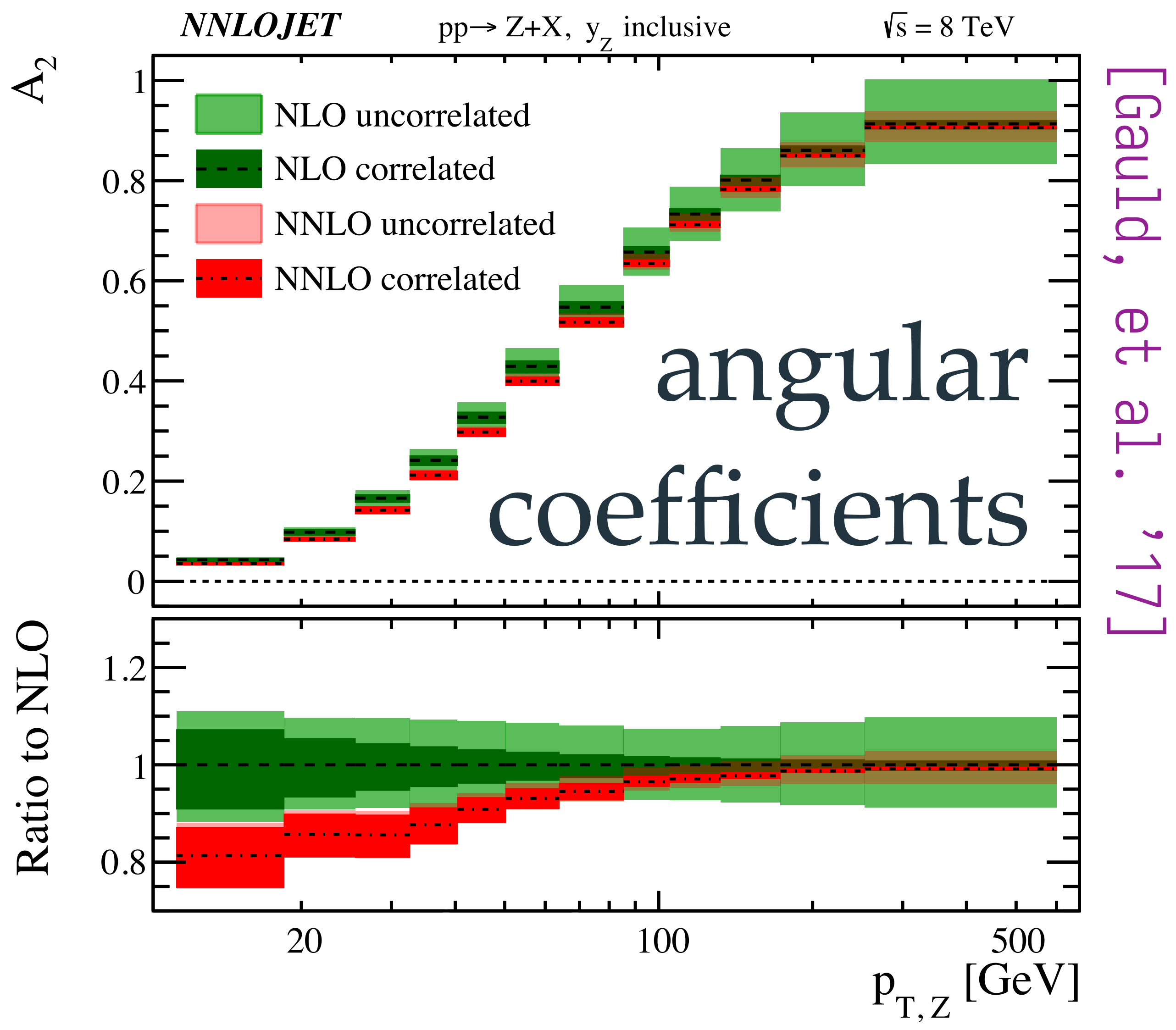
- **meaning of the envelope?**

box , Gaussian , …

- **to correlate, or not to correlate**

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





2 Bayesian Estimates

[Cacciari, Houdeau '11], [Bonvini '20]
[Duhr, Huss, Mazeliauskas, Szafron '21]

General Idea

- consider the perturbative series as a *sequence of dimensionless numbers*

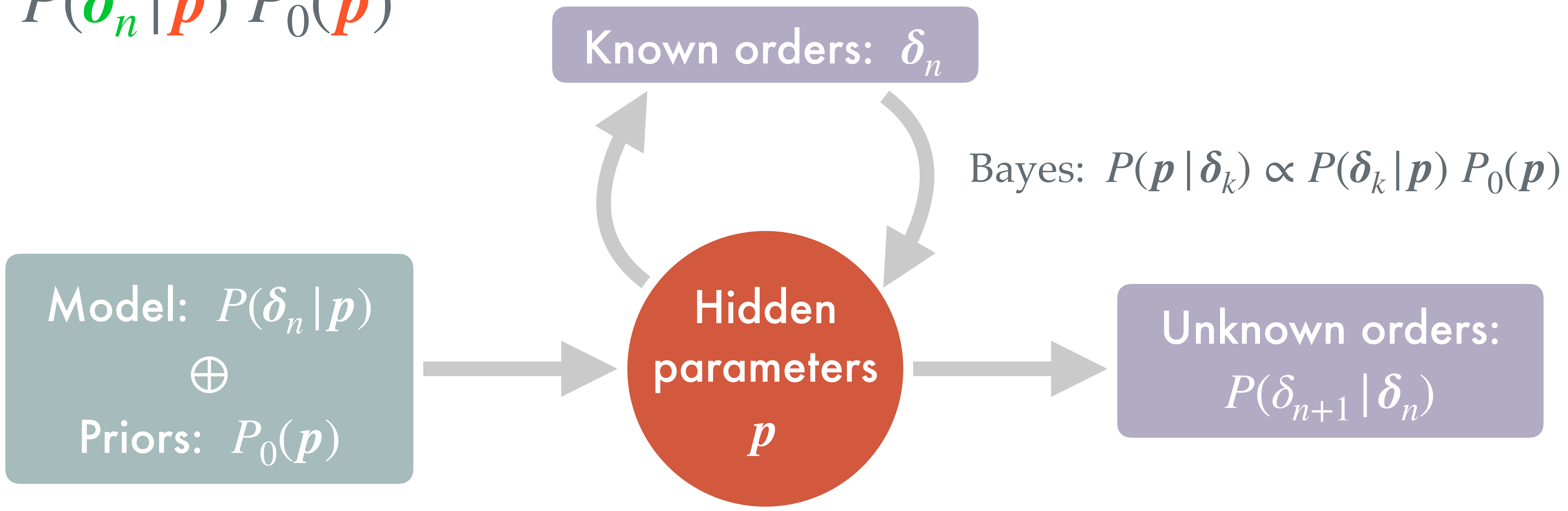
$$\mathrm{d}\sigma = \mathrm{d}\sigma^{(0)} \left[1 + \delta_1 + \delta_2 + \ldots\right] \quad \rightsquigarrow \quad \delta_k = \mathcal{O}(\alpha_s^k)$$

- *Q*: after observing $\boldsymbol{\delta}_n \equiv (\delta_0, \delta_1, \ldots, \delta_n)$, prob. to observe δ_{n+1}?

$$P(\delta_{n+1} \,|\, \boldsymbol{\delta}_n) = \frac{P(\delta_{n+1}, \boldsymbol{\delta}_n)}{P(\boldsymbol{\delta}_n)} = \frac{\int \mathrm{d}^m\boldsymbol{p}\; P(\delta_{n+1}, \boldsymbol{\delta}_n \,|\, \boldsymbol{p})\; P_0(\boldsymbol{p})}{\int \mathrm{d}^m\boldsymbol{p}\; P(\boldsymbol{\delta}_n \,|\, \boldsymbol{p})\; P_0(\boldsymbol{p})}$$

$$P(A, B) = P(A \,|\, B)\; P(B)$$

$$P(A) = \int \mathrm{d}B\; P(A, B)$$



2 Bayesian Estimates

The CH Model [Cacciari, Houdeau '11]

- pert. exp. $\delta_k = c_k\,\alpha_s^k$ bounded by geometric series: $|c_k| \le \bar{c} \quad \forall k$ $\rightsquigarrow$ 1 param: $\bar{c}$

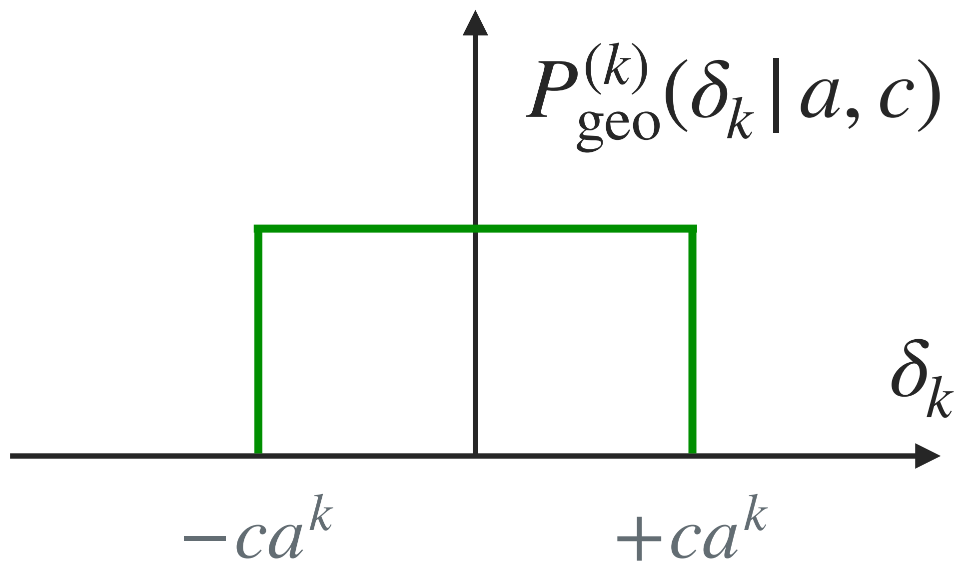
  α_s at what scale? why not: $\alpha_s/\pi,\ \alpha_s/(4\pi),\ \alpha_s \ln^2(v),\ \alpha_s \ln(v), \ldots$?

The Geometric Model [Bonvini '20]

- let the model learn the expansion parameter: $|\delta_k| \le c\,a^k \quad \forall k$ $\rightsquigarrow$ 2 params: $a,\ c$

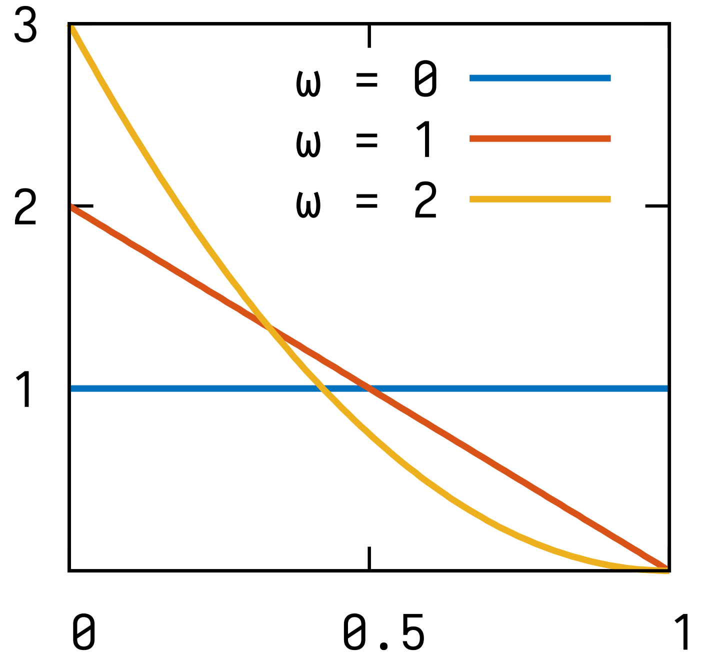
model:

$$P_{\text{geo}}^{(k)}(\delta_k\,|\,a,c) = \frac{1}{2c\,a^k}\,\Theta\!\left(c - \frac{|\delta_k|}{a^k}\right)$$



priors:

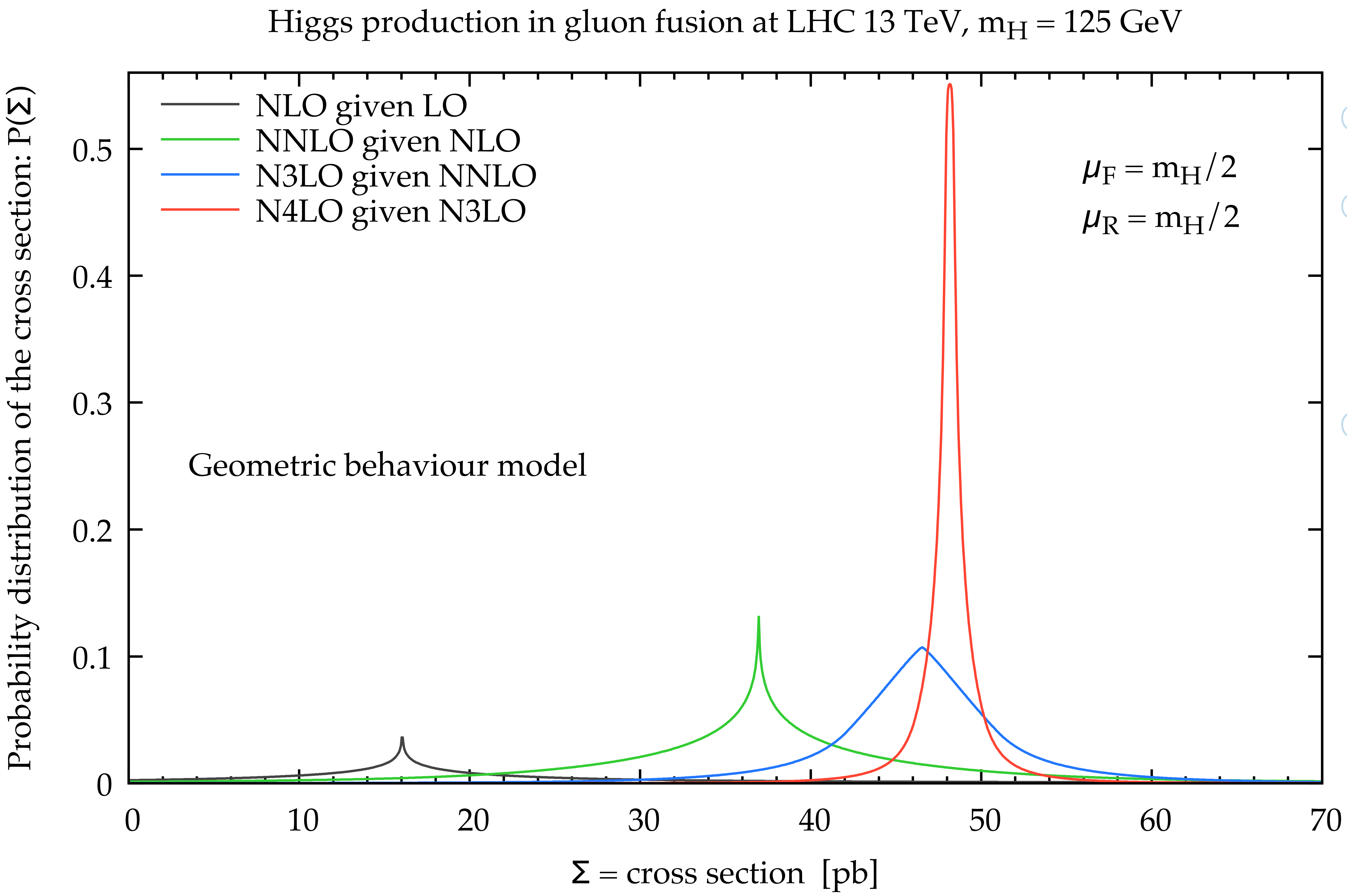
$$P_0(a) = (1+\omega)\,(1-a)^{\omega}\,\Theta(|a|<1)$$



$$P_0(c) = \frac{\varepsilon}{c^{1+\varepsilon}}\,\Theta(c-1)$$

$dc/c \sim d\ln(c)$
(ε: regulator)

[Bonvini '20]



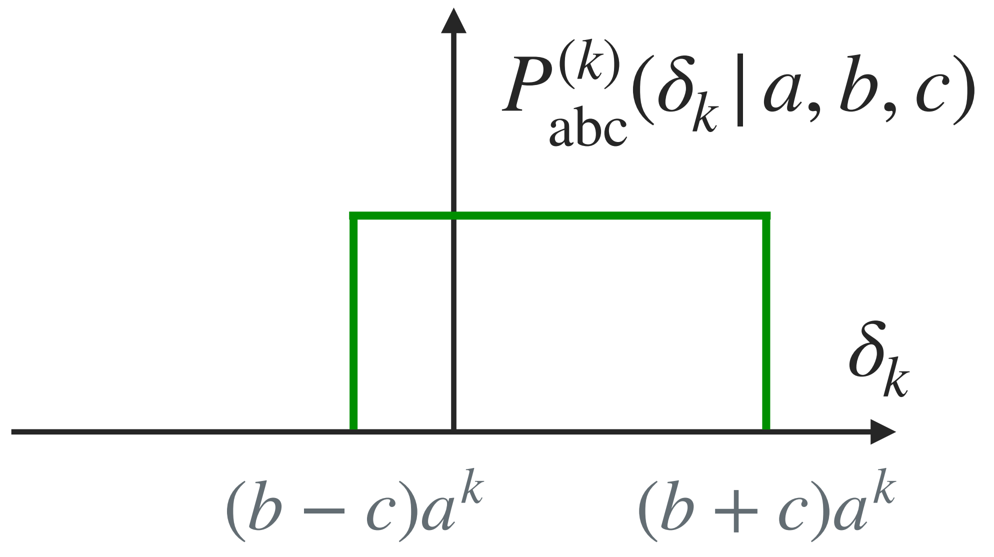
The Geometric Model

- full prob. dist. $P(\sigma)$
- *broad* lower orders:
  - ↪ stronger dependence on priors P_0
- *narrow* higher orders:
  - ↪ inference of hidden parameters

[Duhr, Huss, Mazeliauskas, Szafron '21]

The ABC Model

- allow for a bias & alt. series: $b - c \leq \frac{\delta_k}{a^k} \leq b + c \quad \forall k$



Incorporation of Scales

1. **scale marginalisation** (sm)

$$\int \mathrm{d}\mu\; P(\delta_{n+1} \,|\, \boldsymbol{\delta}_n; \mu)\; P(\mu \,|\, \boldsymbol{\delta}_n)$$

$$\propto P(\boldsymbol{\delta}_n; \mu)\; P_0(\mu)$$

prior

weight

2. **scale average** (sa)

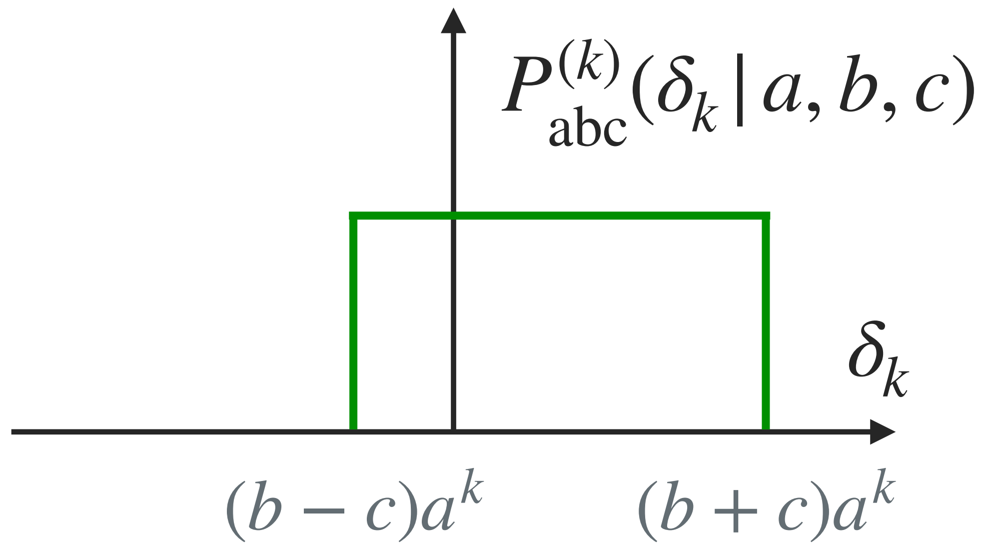
$$\int \mathrm{d}\mu\; w(\mu)\; P(\delta_{n+1} \,|\, \boldsymbol{\delta}_n; \mu)$$

$$\frac{1}{2\mu \ln F}\, \Theta\!\left(\ln F - \left|\ln\!\left(\frac{\mu}{\mu_0}\right)\right|\right)$$

[Duhr, Huss, Mazeliauskas, Szafron '21]

The ABC Model

- allow for a bias & alt. series: $b - c \leq \frac{\delta_k}{a^k} \leq b + c \quad \forall k$



Incorporation of Scales

1. **scale marginalisation** (sm)

   $\rightsquigarrow P_{\mathrm{sm}}(\delta_{n+1} \,|\, \boldsymbol{\delta}_n)$ peaks at μ_{FAC}

$$\int \mathrm{d}\mu \; P(\delta_{n+1} \,|\, \boldsymbol{\delta}_n; \mu) \; P(\mu \,|\, \boldsymbol{\delta}_n)$$

$P(\mu \,|\, \boldsymbol{\delta}_n) \propto P(\boldsymbol{\delta}_n; \mu) \; P_0(\mu)$ — $P_0(\mu)$: prior

2. **scale average** (sa)

   $\rightsquigarrow P_{\mathrm{sa}}(\delta_{n+1} \,|\, \boldsymbol{\delta}_n)$ peaks at μ_{PMS}

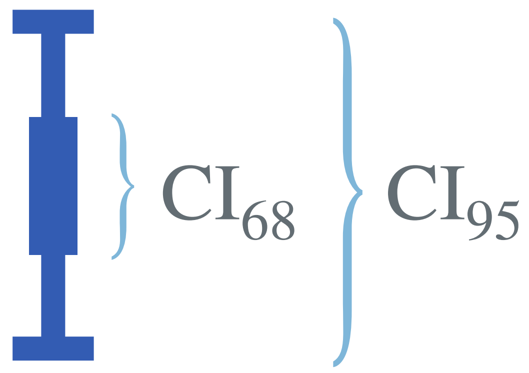
$$\int \mathrm{d}\mu \; w(\mu) \; P(\delta_{n+1} \,|\, \boldsymbol{\delta}_n; \mu)$$

$w(\mu)$: weight

prior / weight: $\frac{1}{2\mu \ln F} \, \Theta\left(\ln F - \left|\ln\left(\frac{\mu}{\mu_0}\right)\right|\right)$

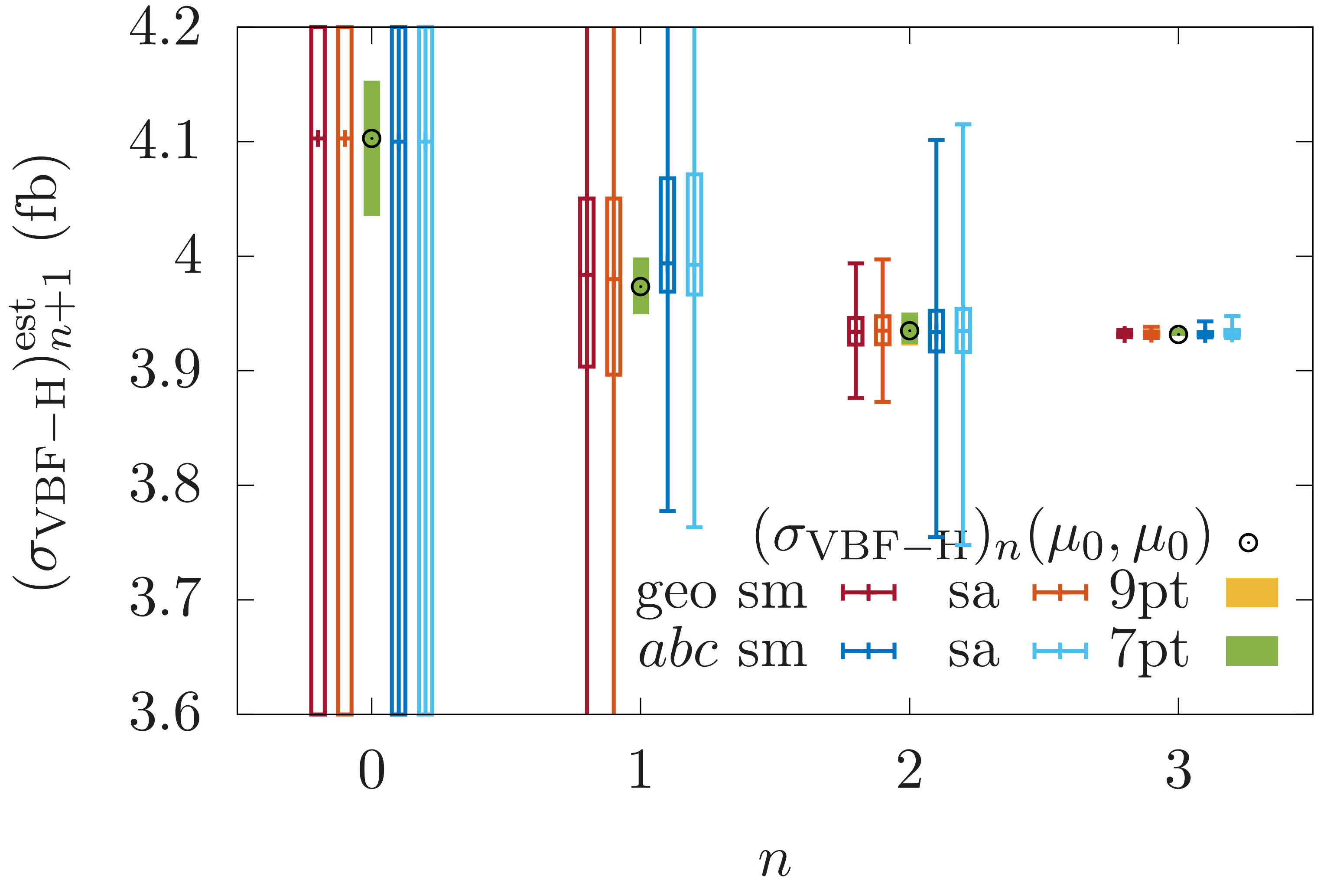
scale interpretation $\leftrightarrow$ prescription

2 Bayesian Estimates

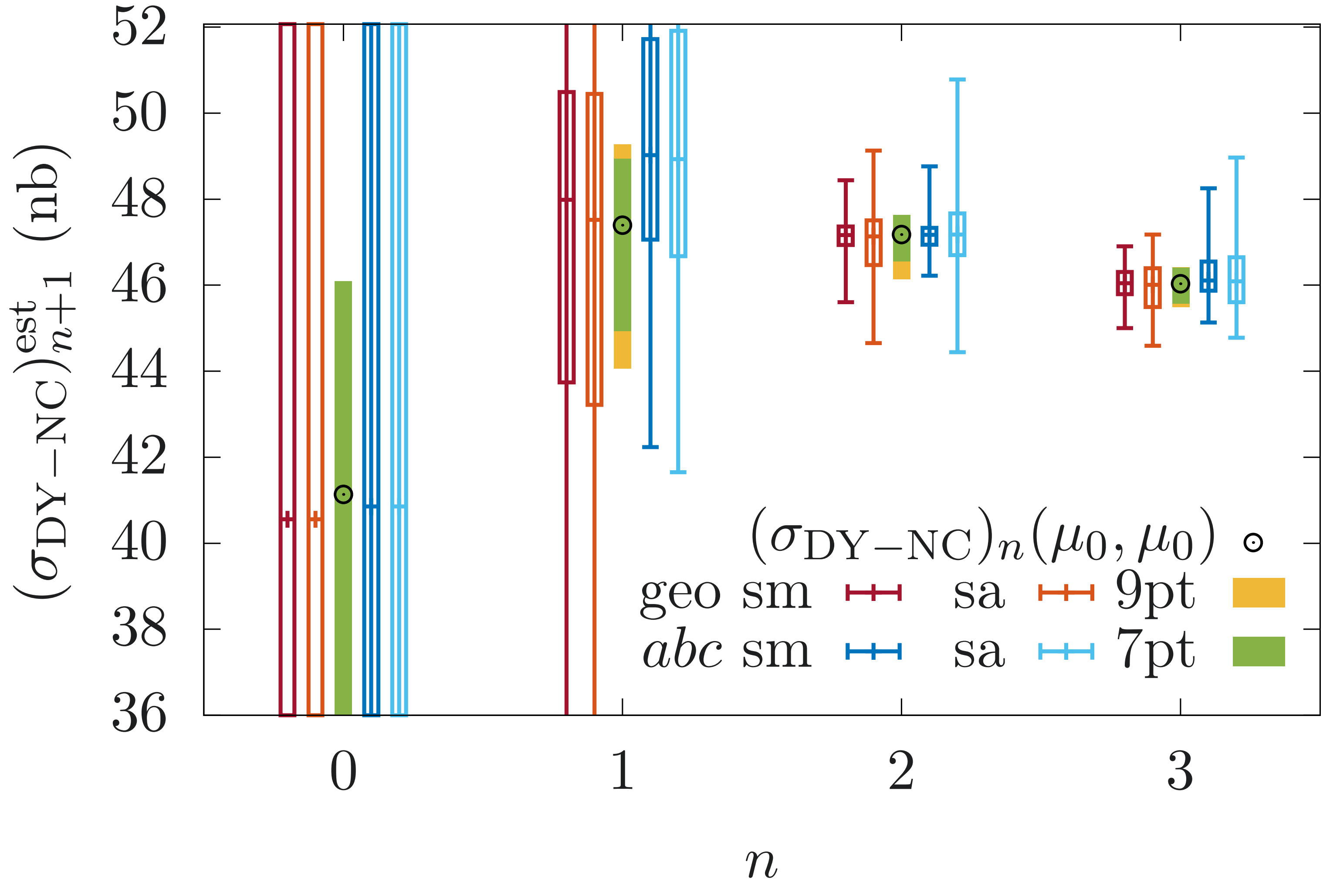


[Duhr, Huss, Mazeliauskas, Szafron '21]

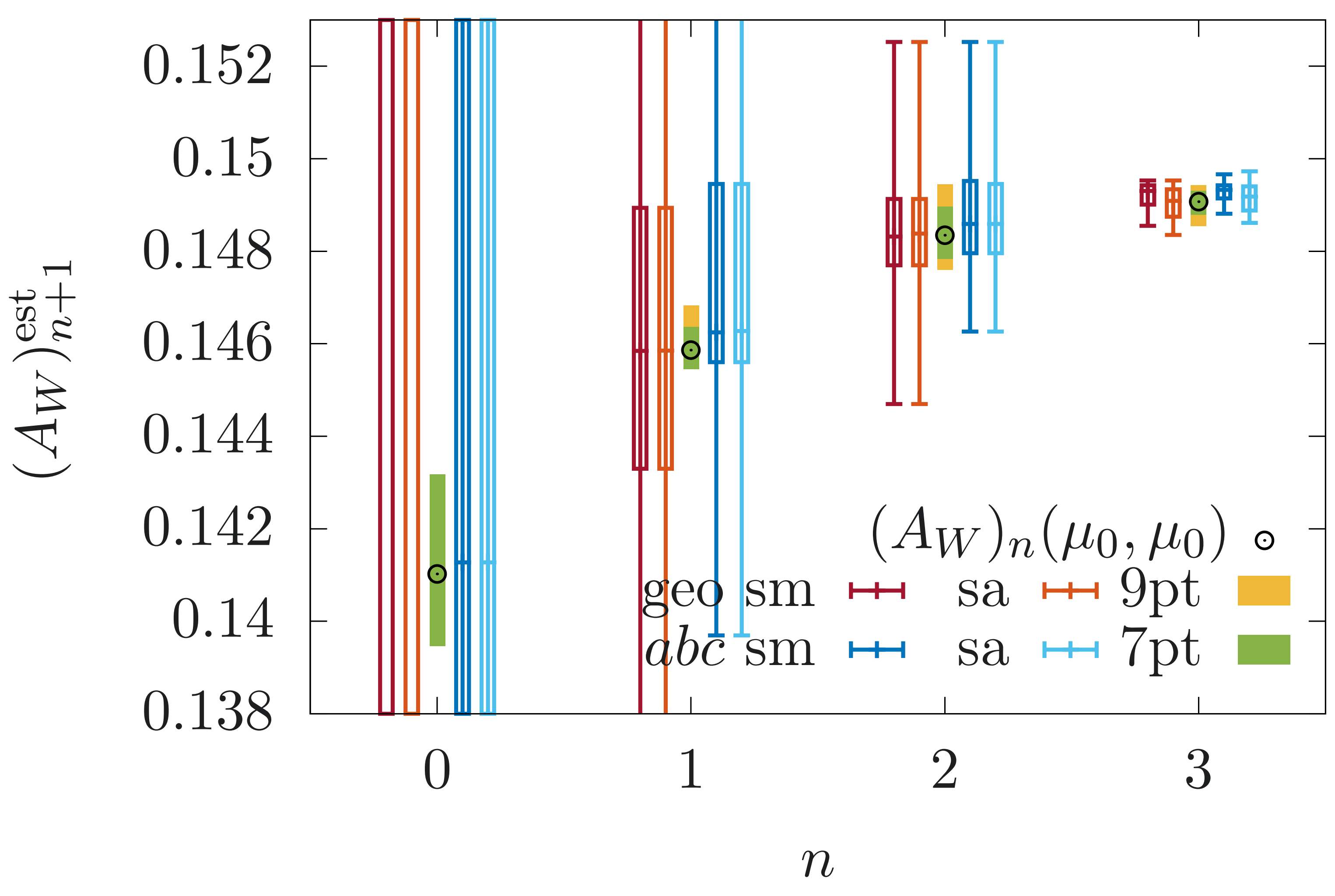
VBF–H



DY–NC



$A_W = \frac{W^+ - W^-}{W^+ + W^-}$



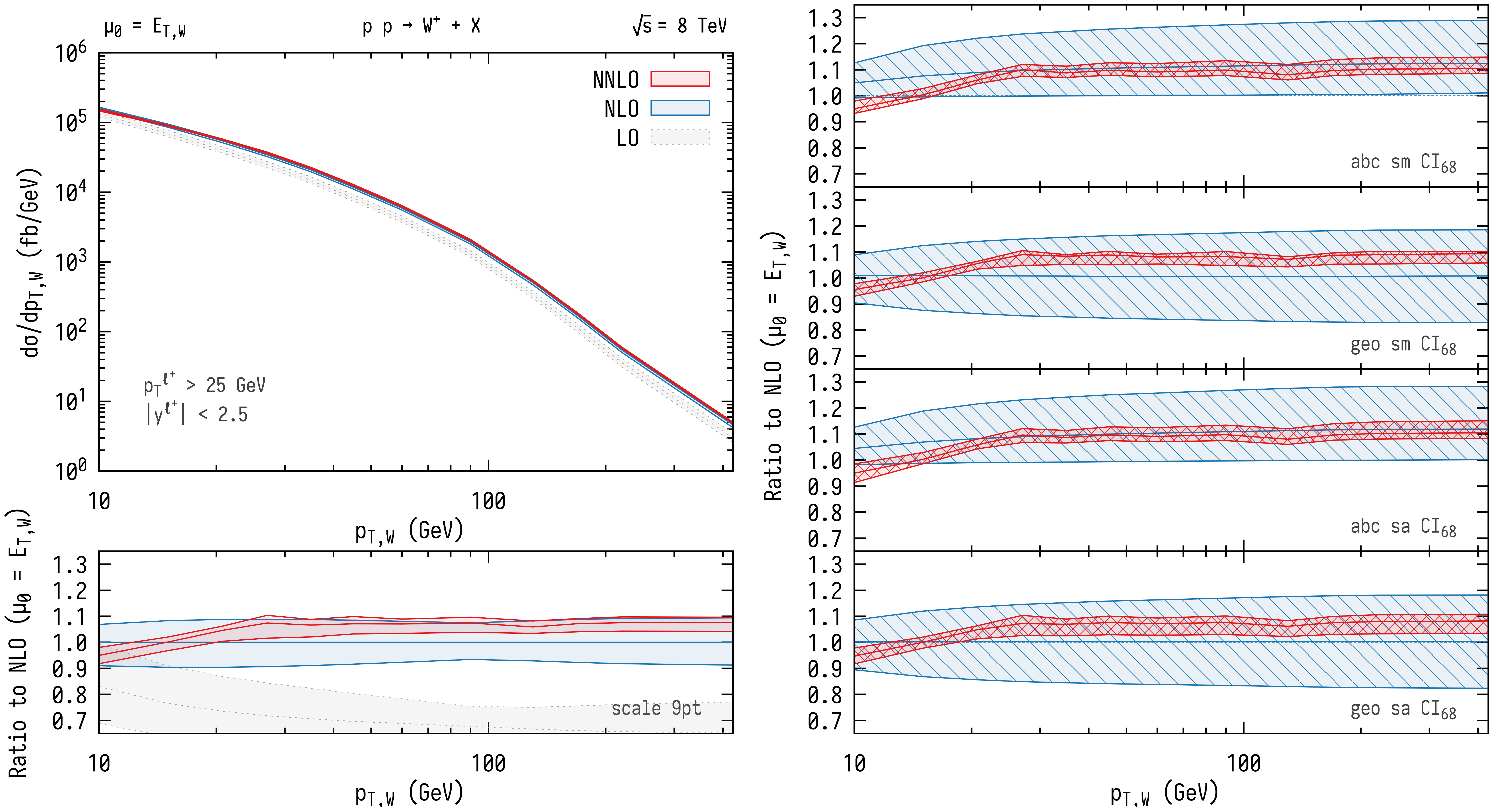
- $n < 2$: CI_{68} bigger than 9pt
- $\delta_1 < 0$ ⇝ *abc* alternating
- $n > 2$: all prescriptions similar

- δ_3 is large and outside of 9pt!
- similar unc.: sa $\simeq$ 9pt
- $n = 2$: sm $\ll$ others (μ_{FAC})
- $n = 3$: all prescriptions similar

- large cancellations in the ratio
- $n < 2$: 9pt performs poorly
- $(A_W)_n \nearrow$ (anticipated by *abc*)
- size: *abc* $\lesssim$ others

overall: not radically different estimates for $\Delta_{\text{pert.}}$ $(n \geq 2)$

Differentail Distributions



- $n < 2$:
  - CI_{68} bigger than 9pt
  - *abc* captures pos. shift
- $n = 2$:
  - almost identical bands
  - Δ_{MHO} very robust
- sm vs. sa
  - almost identical CI

3 Theory Nuisance Parameters

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

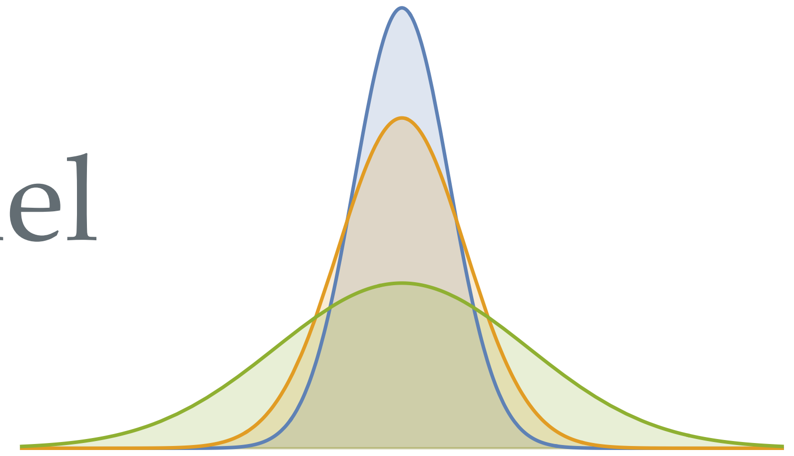
General Idea & Steps

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

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

$\to \mathcal{N}\,\theta$ (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

RESUMMED PREDICTION

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

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

RGE

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

- boundary conditions:

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

- anomalous dimensions:

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

[Tackmann '24]

RESUMMED PREDICTION

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

- boundary conditions: $\mathcal{X} \in \{H, B_a, B_b, S\}$

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

  → actually functions: $B_i(x_i)$

- 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

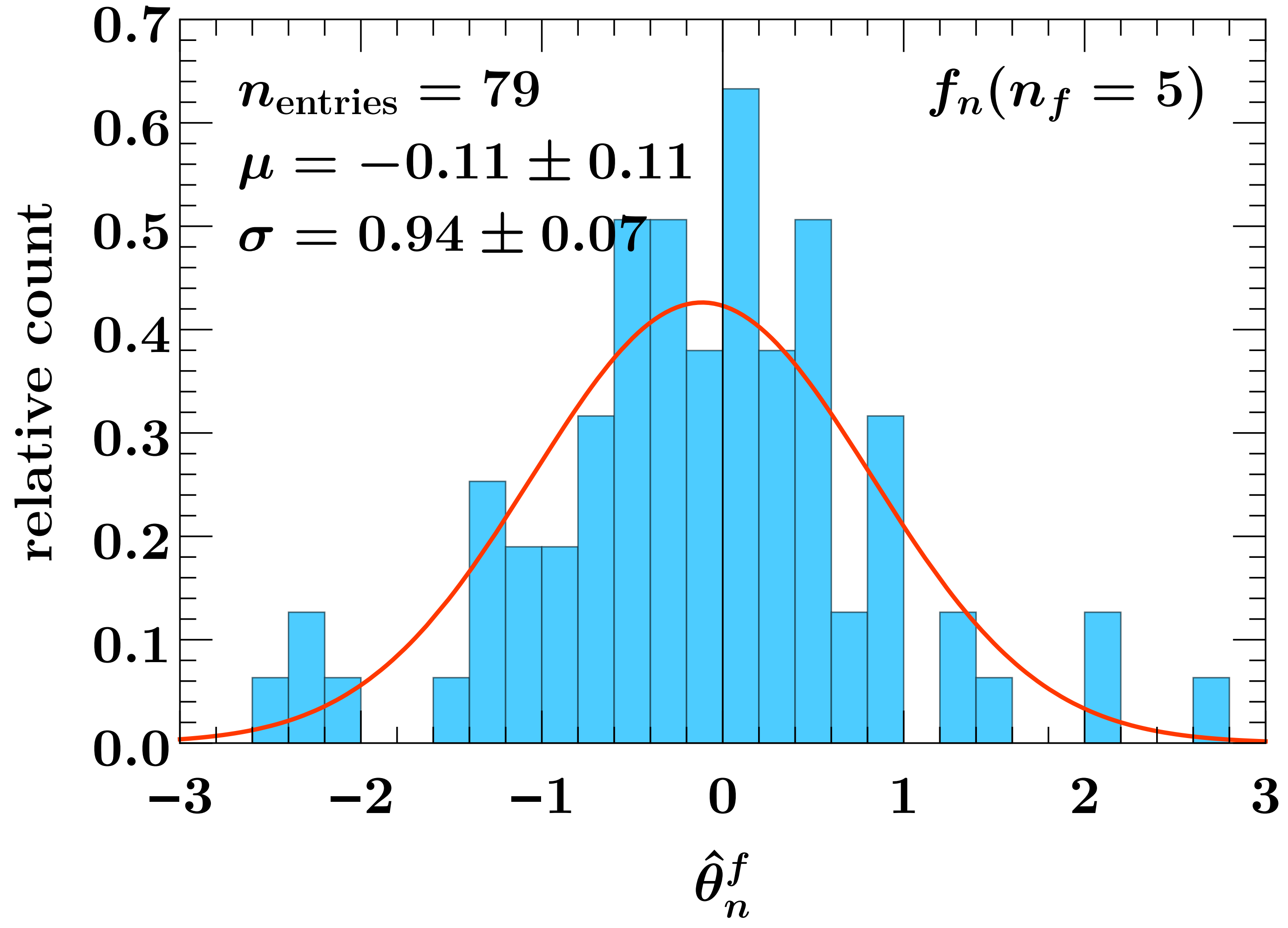
[Tackmann '24]

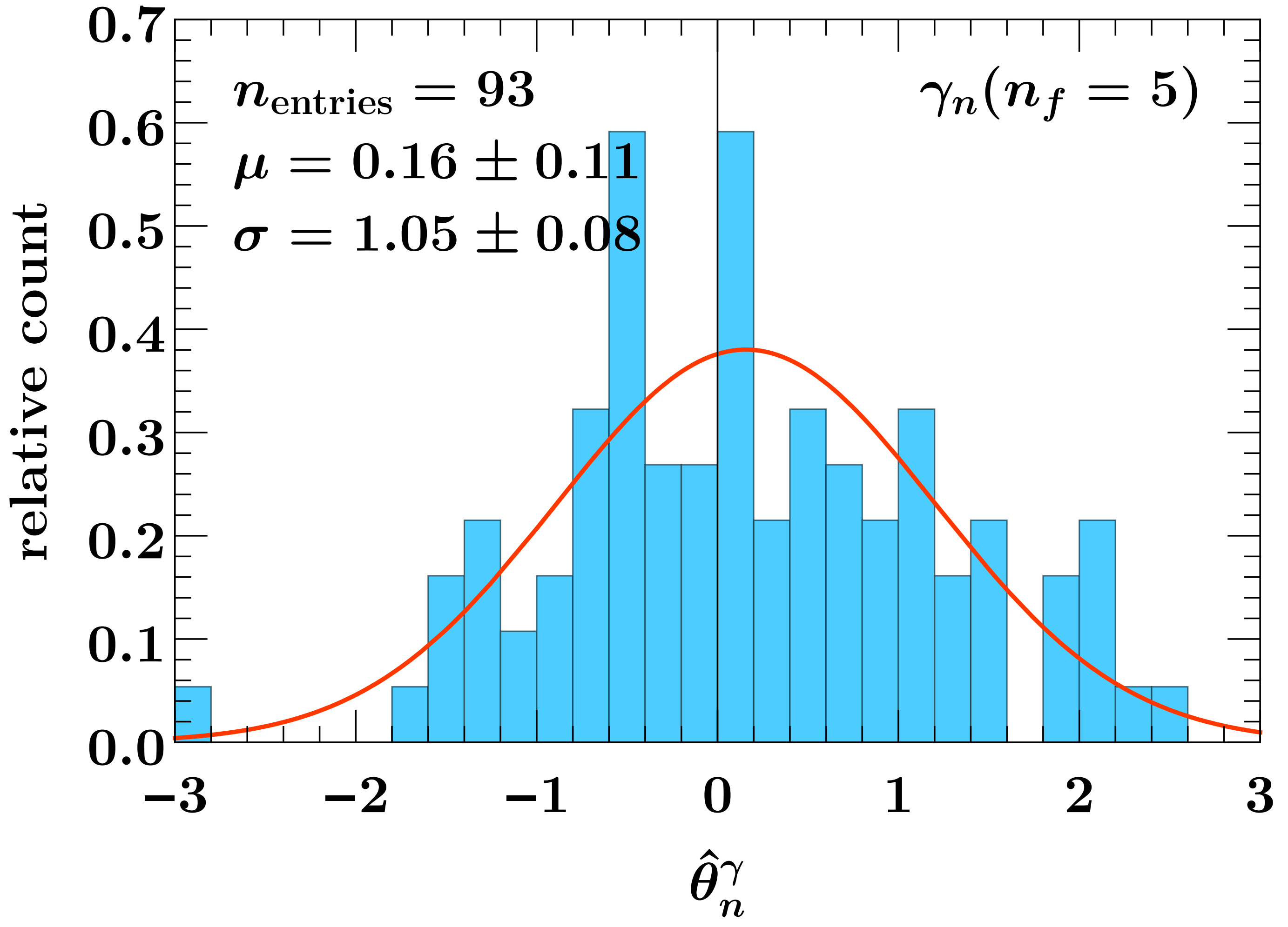
RESUMMED PREDICTION

selection bias?

2. assign a probability distribution (statistics over ∃ calculations)
   ⇝ assume universality in order n as well as processes / ingredients

valid?





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

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

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

"massaging"

CHOICES (⇝ ambiguities)

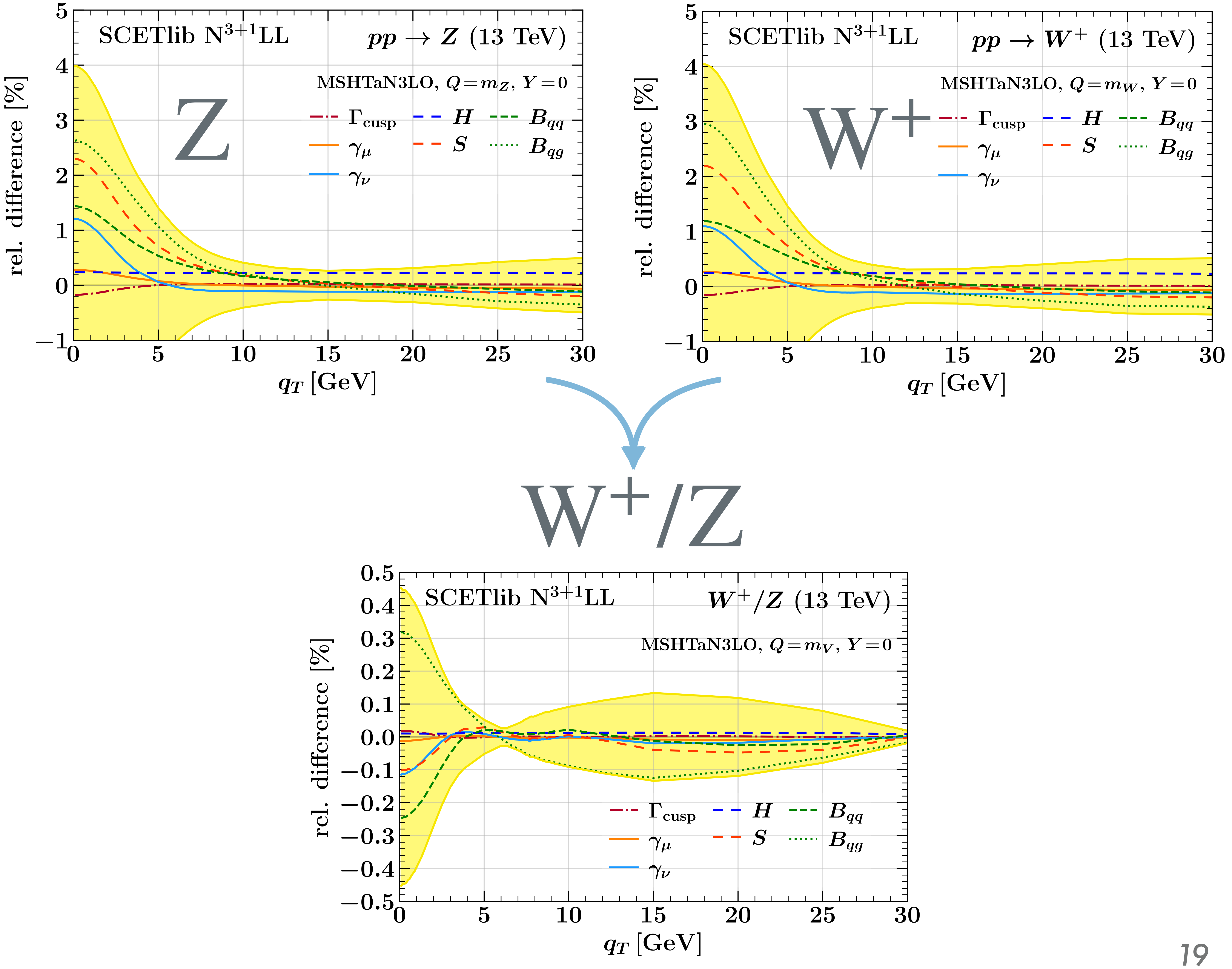
- scheme dependence (scale, ren. scheme, IR subtr., …)
- parametrisation freedom ($\vec{\theta} \to \vec{\theta}'$: changes what is uncorrelated / independent)

3 Theory Nuisance Parameters

[Tackmann '24]

Resummed Prediction

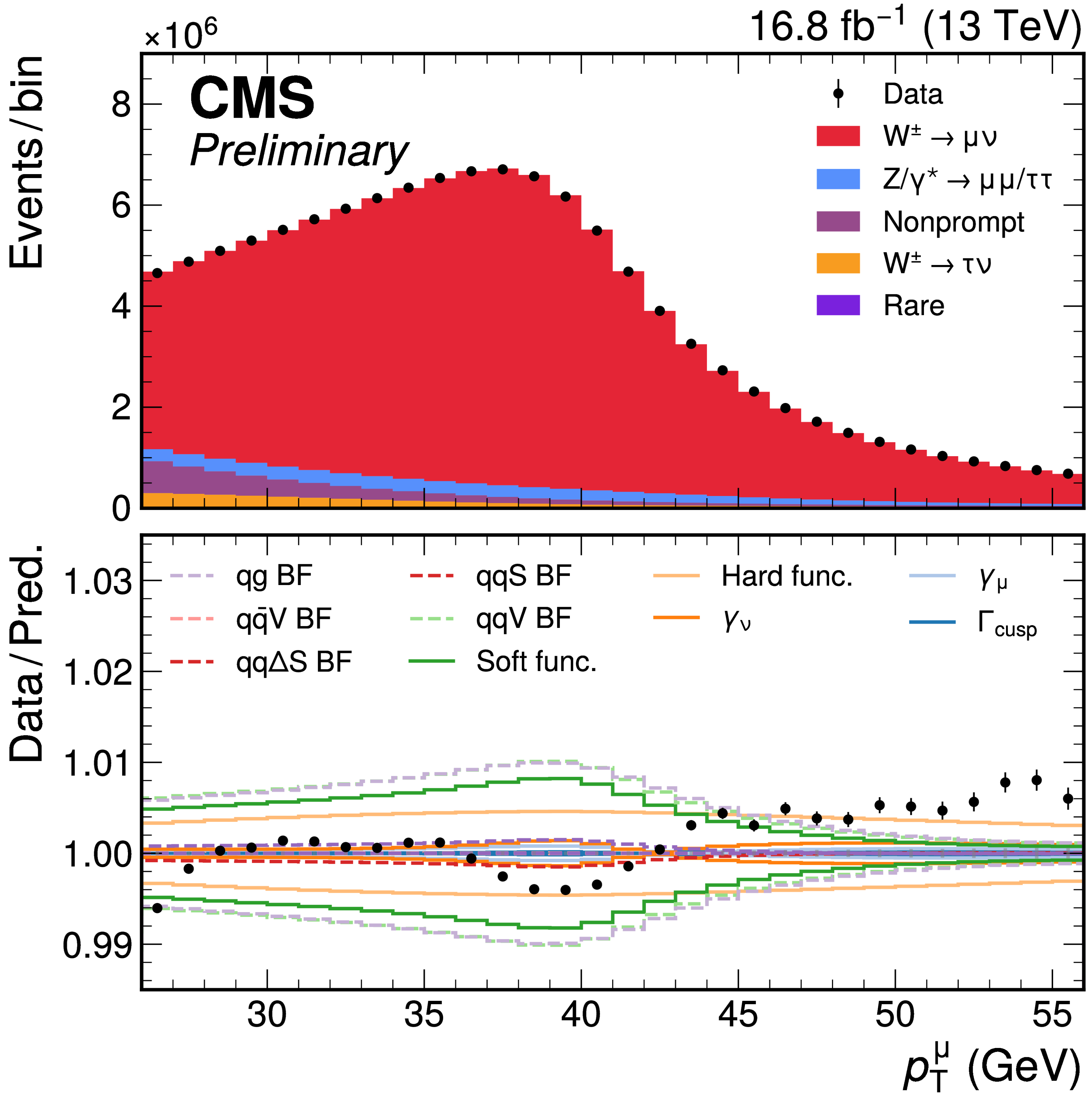
- 2′ 100% correlation of $\vec{\theta}$
  - large cancellation in W^+/Z
  - dominant residual uncertainties from B_{ab}
- similar absolute errors to Δ_{scl}
- valid at low p_T
  ↪ requires matching @ high p_T (μ_R, μ_F)
- missing: non-pert. modelling



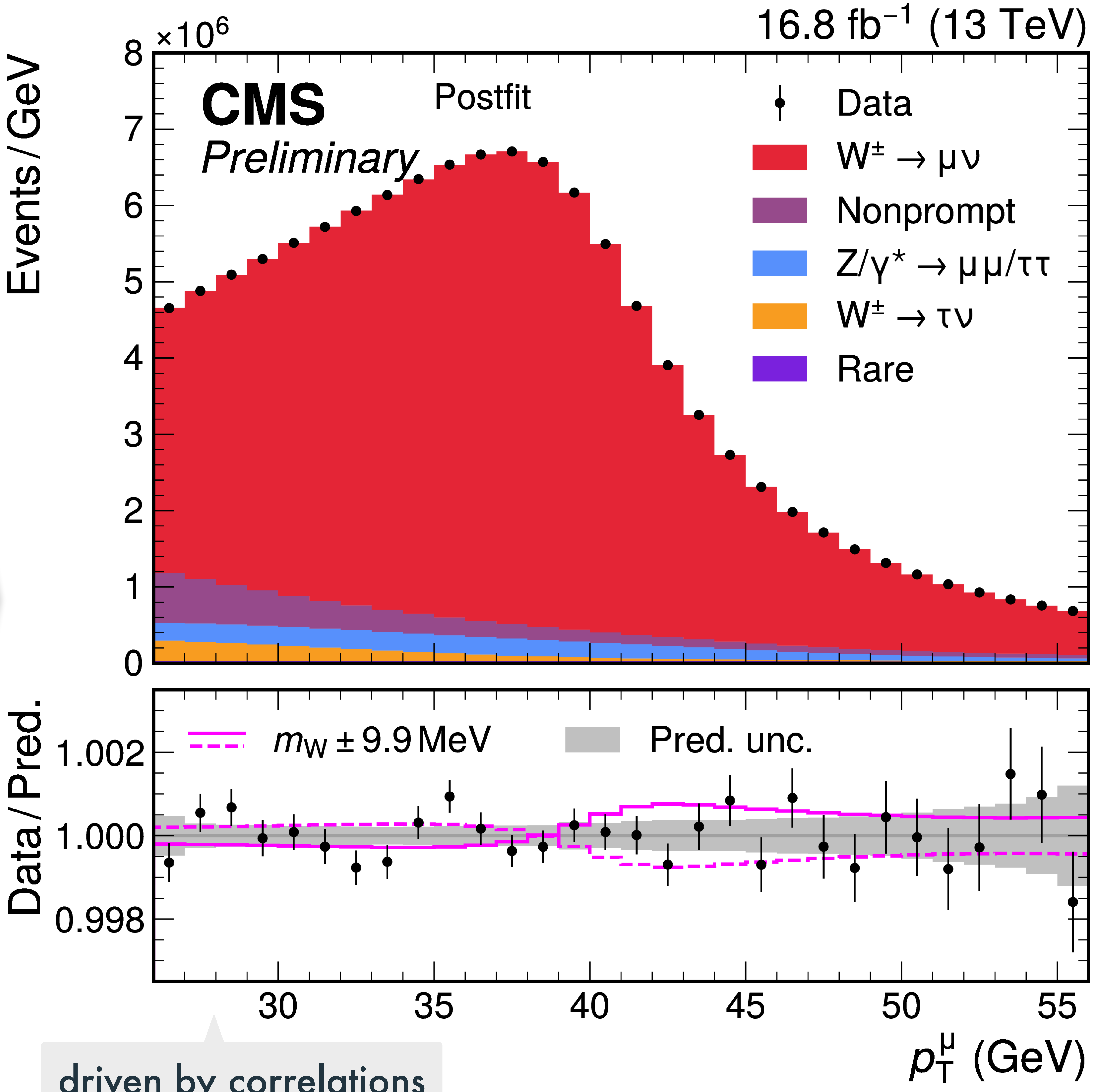
Theory Nuisance Parameters

CMS M_W Measurement

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



FIT



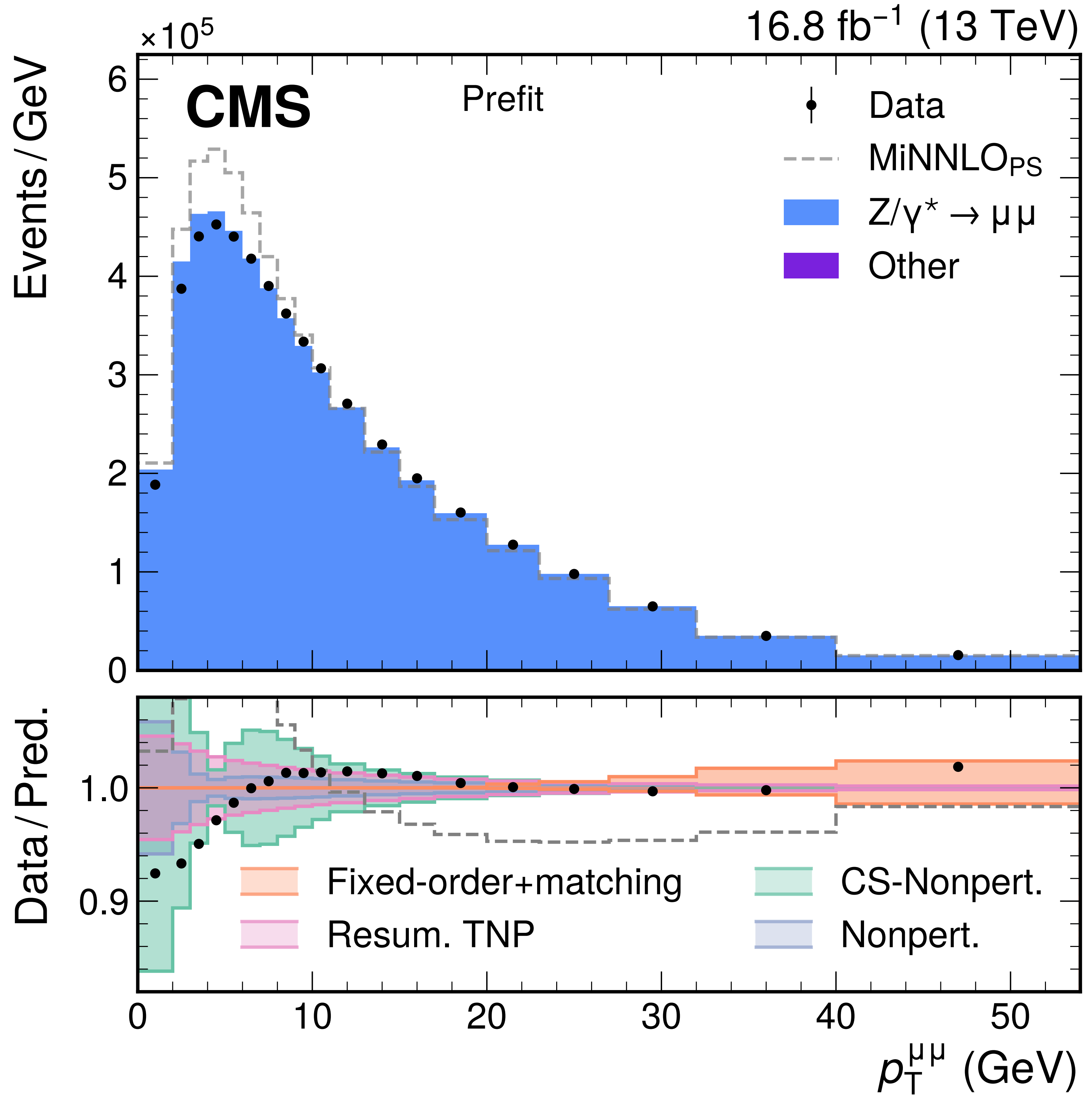
driven by correlations

[CMS arXiv:2412.13872 [hep-ex]]

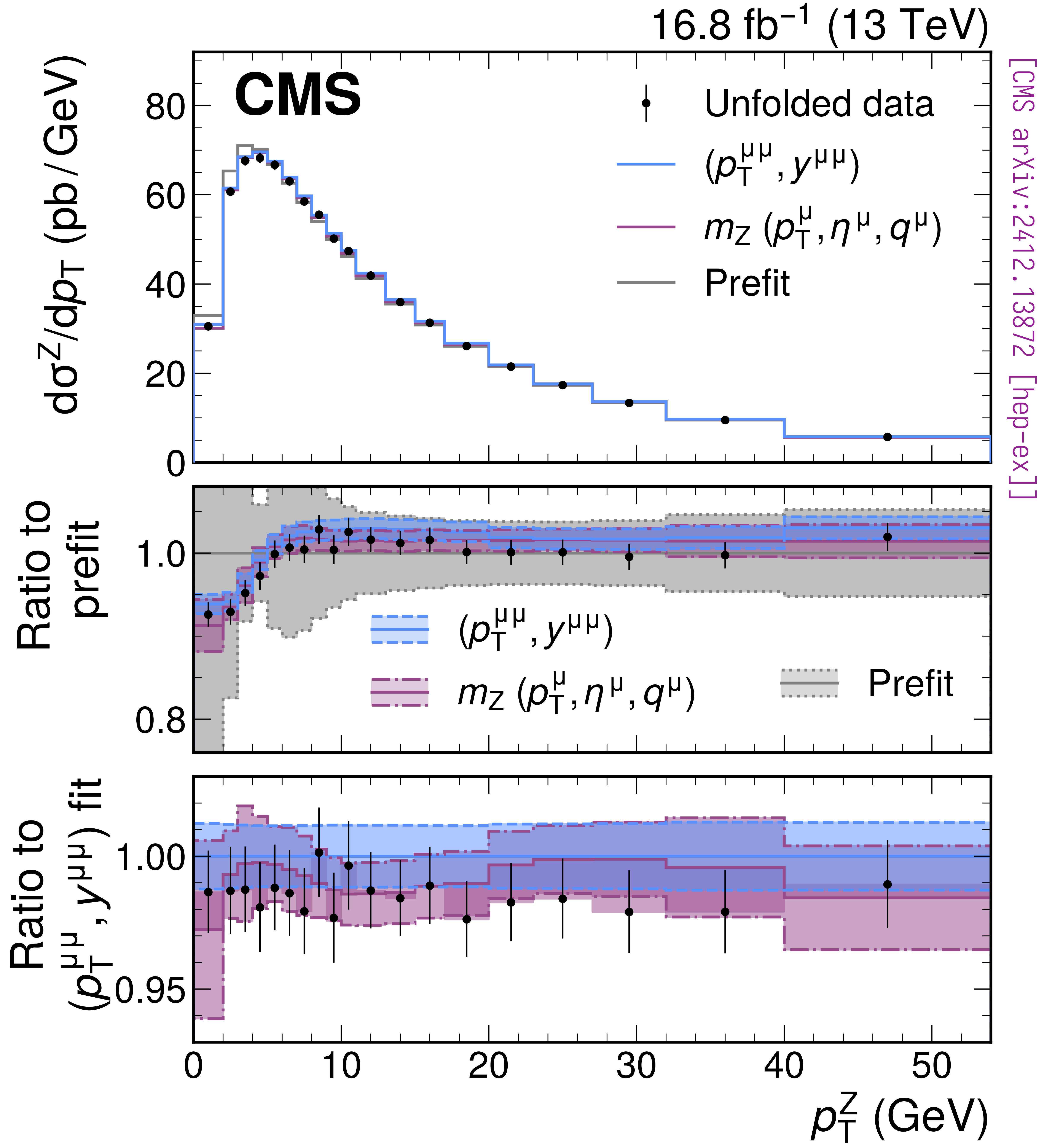
3 Theory Nuisance Parameters

CMS M_W Measurement

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



FIT



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

BEYOND RESUMMED SPECTRA

- pull out the Born prediction and split off leading-colour factor at each order n

$$\frac{d\sigma}{dx} = \frac{d\sigma^{(0)}}{dx}\left[1 + \alpha_s N_c \overline{K}^{(1)}(x) + \alpha_s^2 N_c^2 \overline{K}^{(2)}(x) + \ldots\right] \qquad \overline{K}^{(n)}(x) \equiv \frac{1}{N_c^n}\frac{d\sigma^{(n)}/dx}{d\sigma^{(0)}/dx}$$

- parametrise first unknown order as superposition of lower-order $\overline{K}^{(n)}$

$$\overline{K}^{(n+1)}_{\text{TNP}}(\vec{\theta};\, x) = \sum_{j=1}^{n} \underbrace{f_k^{(j)}(\vec{\theta};\, x)}_{\text{polyn. modulation}} \overline{K}^{(j)}(x)$$

$$f_k^{(j)}(\vec{\theta};\, x) = \sum_{i=0}^{k} \theta_i^{(j)} \binom{k}{i} x^{k-i}(1-x)^i \qquad \text{(Bernstein)}$$

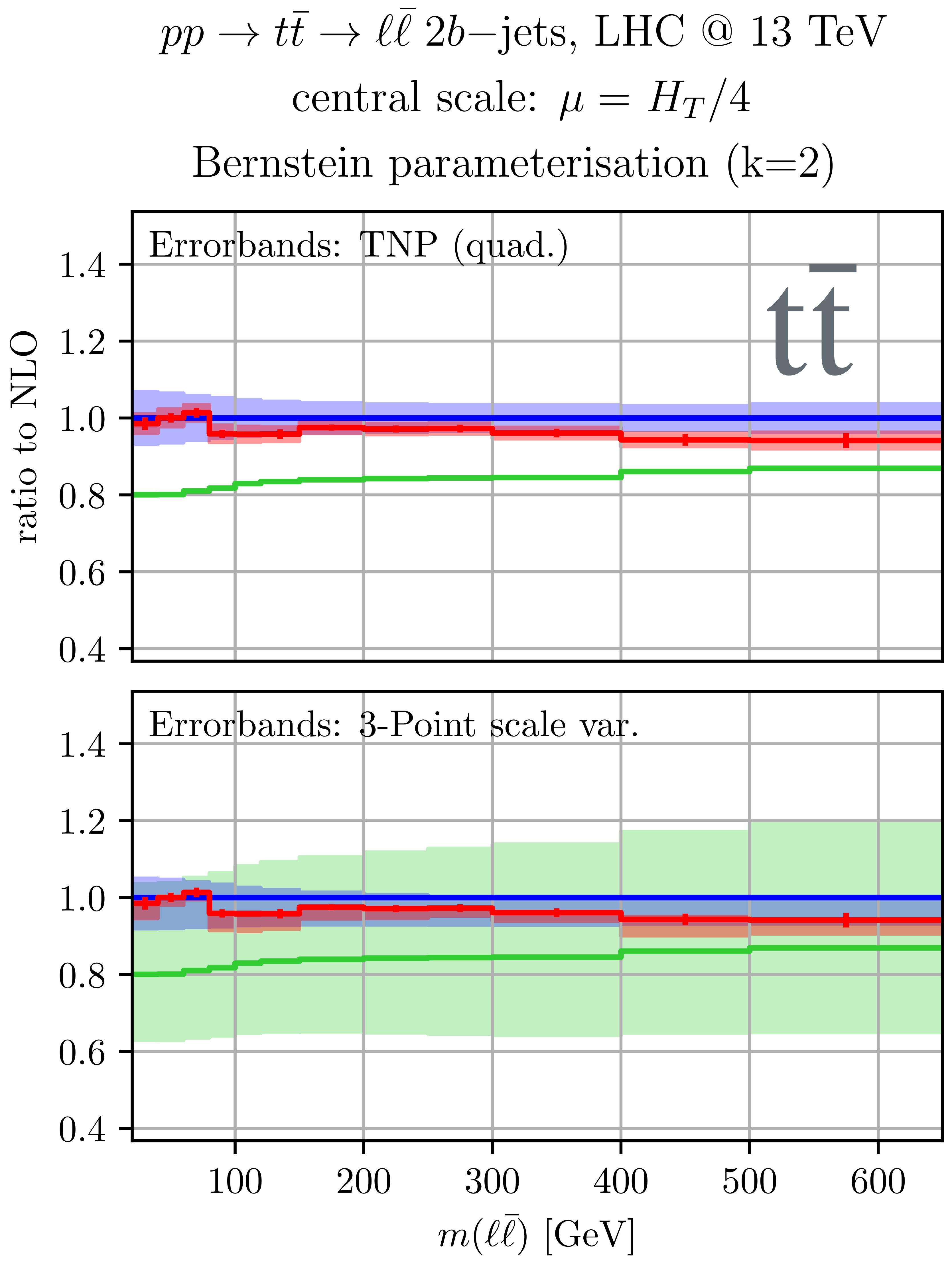
$$f_k^{(j)}(\vec{\theta};\, x) = \frac{1}{2}\sum_{i=0}^{k} \theta_i^{(j)} T_i(x) \qquad \text{(Chebyshev)}$$

$P\left(\theta_i^{(j)}\right)$: uniform in $[-1, +1]$, normal with $\sigma = 1$

- $k = 0 \Rightarrow f_0^{(j)}(\vec{\theta};\, x) \to \theta_0^{(j)}$ ⇜⇝ approach to approx. N³LO in MSHT PDF fit

[Lim, Poncelet '24]

TNP's:
symmetric by construction



scale variation:
3-point, *not* 7-point

can be asymmetric

Beyond Resummed Spectra

- LO: no uncertainty estimate
- NLO: effectively a $\sim \alpha_s N_c \mathcal{O}(1)$ modulation of NLO correction
- NNLO: first time an interplay between two independent $\overline{K}^{(1,2)}$

Theory Nuisance Parameters

[Lim, Poncelet '24]

TNP's:
symmetric by construction

- how to map x?
- multi-dim?
- …

scale variation:
3-point, *not* 7-point

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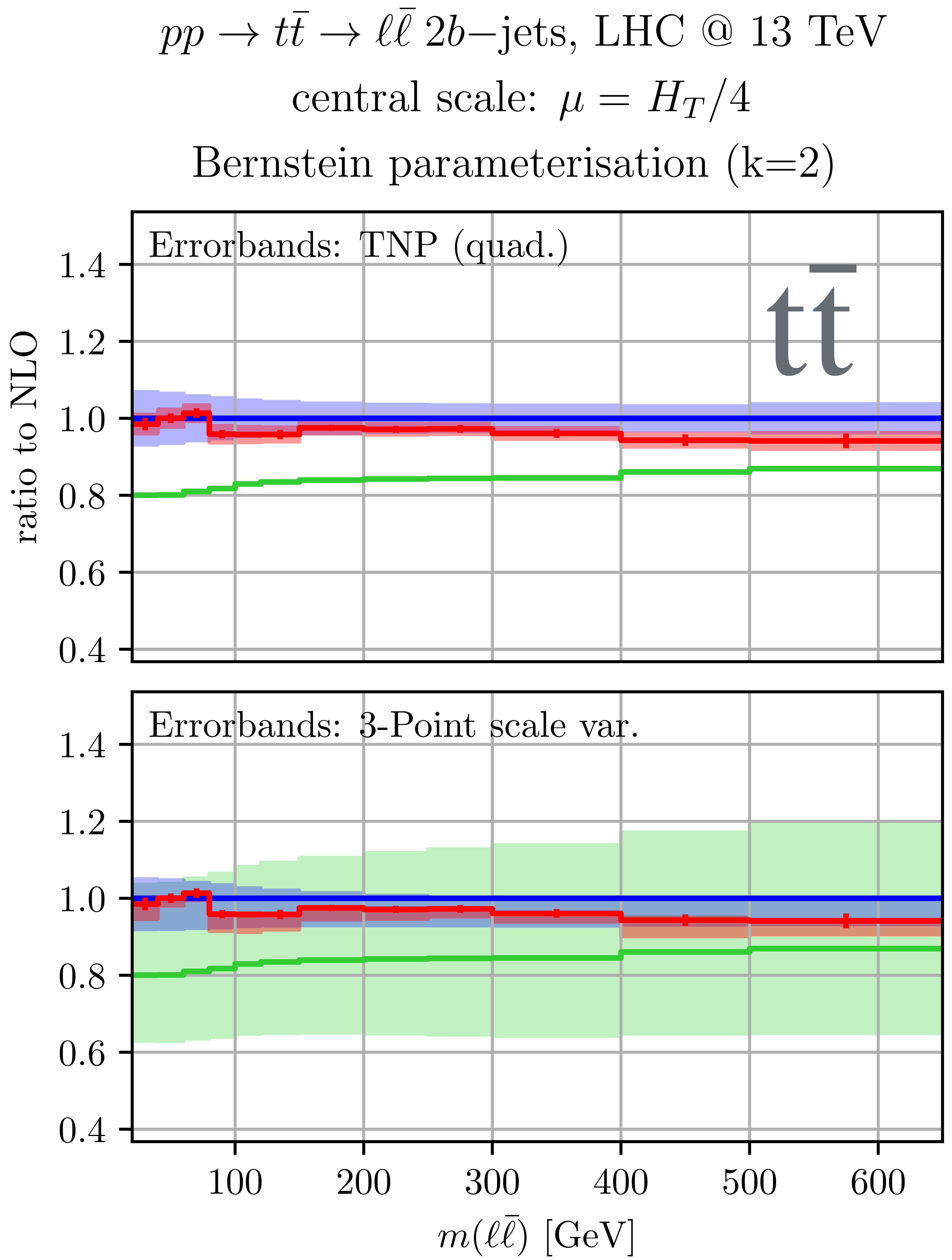

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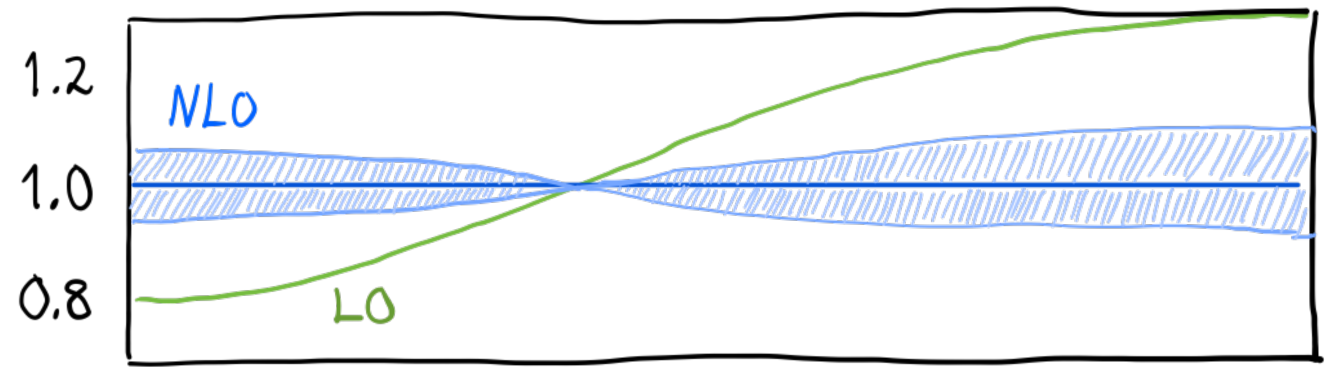
- NLO can have artefacts?



LO–NLO cross
$\Rightarrow \Delta_{\mathrm{NLO}} = 0$?!

- similar errors @ NNLO

Theory Nuisance Parameters

[Lim, Poncelet '24]

TNP's:
symmetric by construction

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- …

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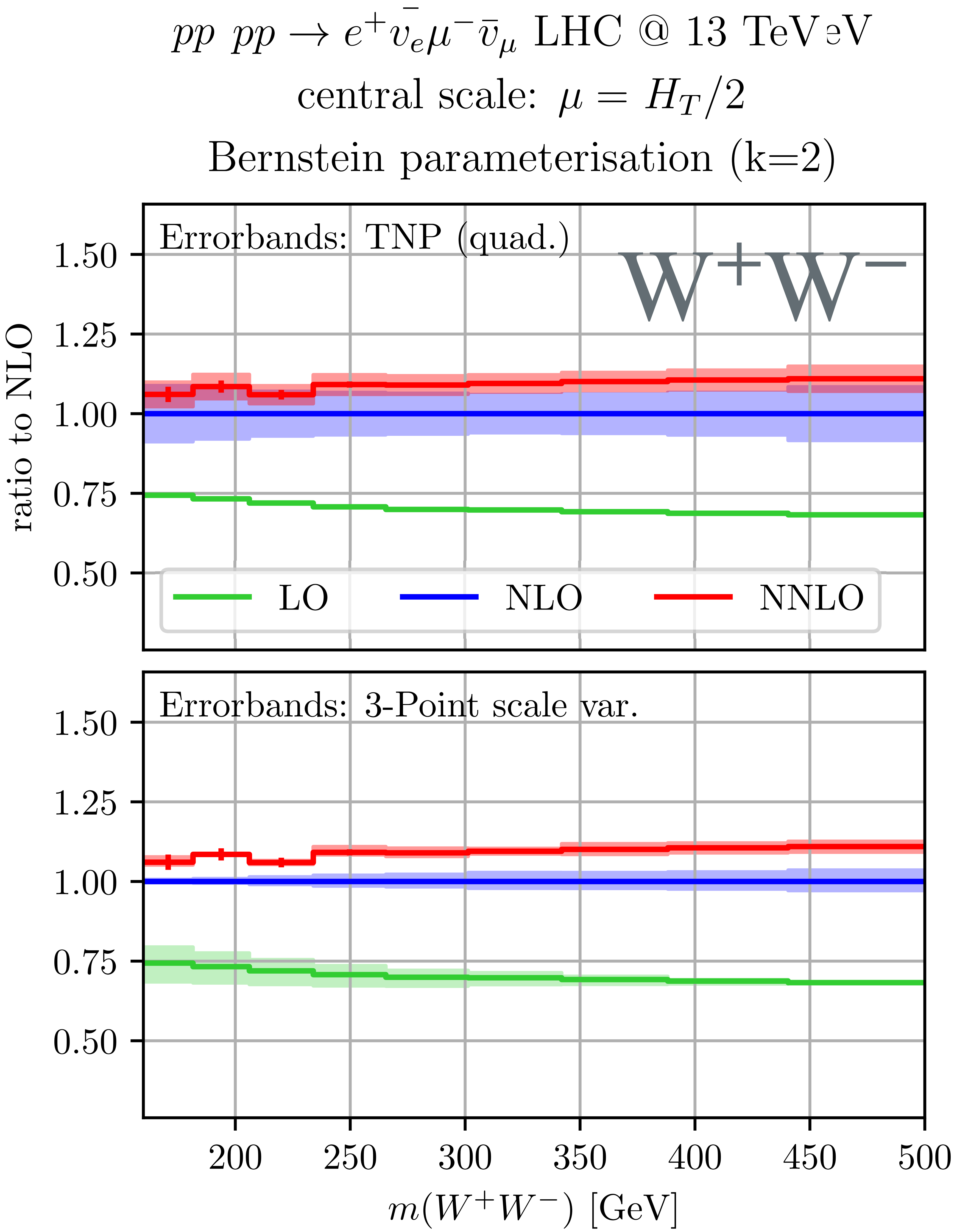

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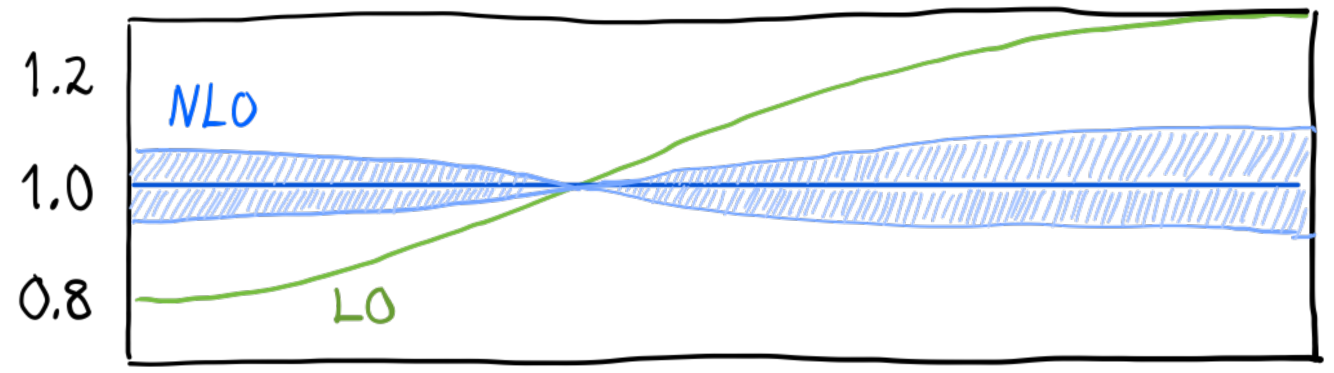


LO–NLO cross $\Rightarrow\ \Delta_{\text{NLO}} = 0$?!

- more robust?

gg channel?

Parton Distribution Functions

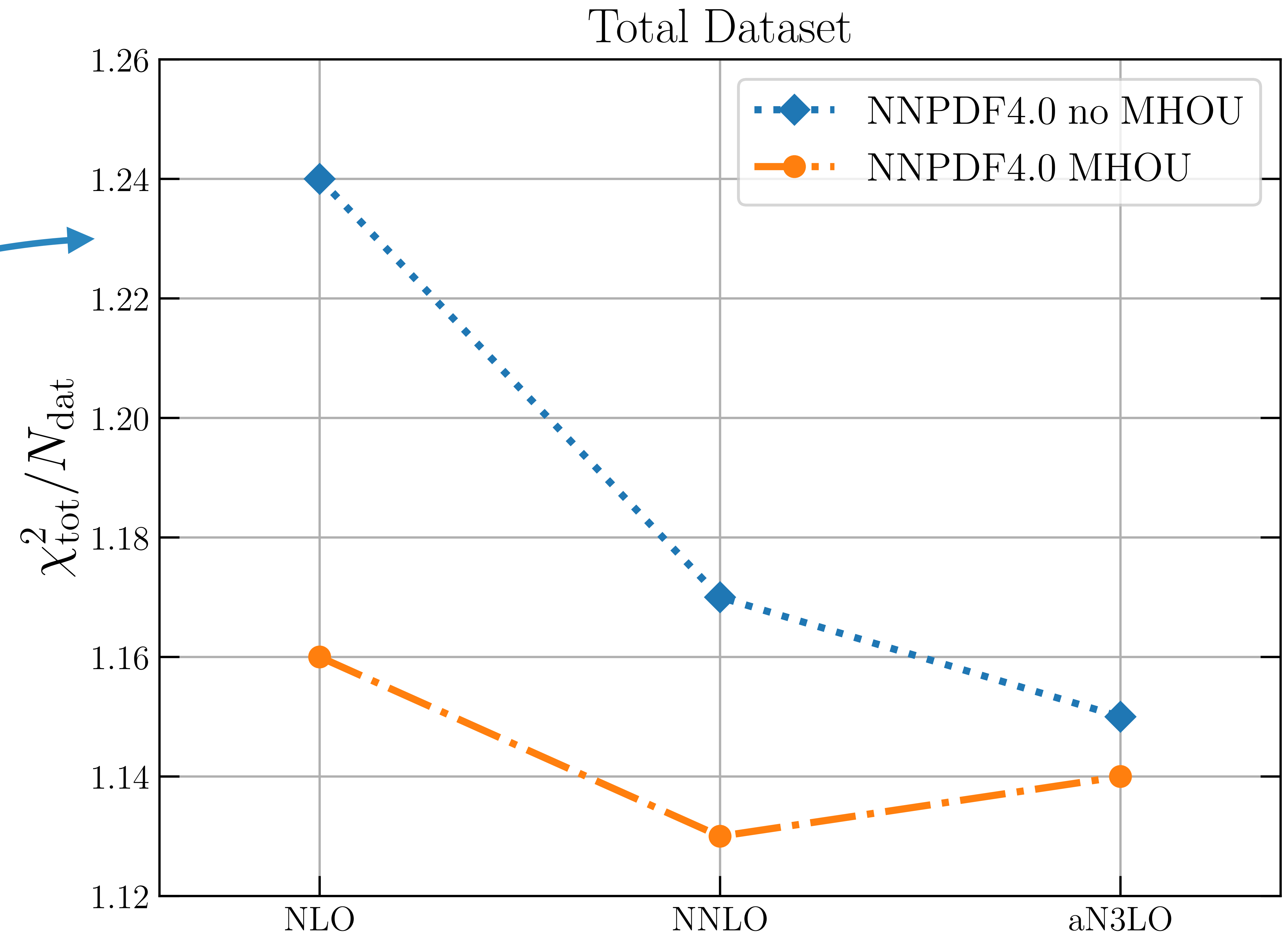
Dataset & Tolerances

- $\mathcal{O}(4000)$ 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 aN^{3}LO (nuisance parameter)
- mandatory in aN^{3}LO as (almost) no predictions available at this order

more stable χ^2 in the progression of the orders



[NNPDF 2402.18635]

ggH @ N³LO

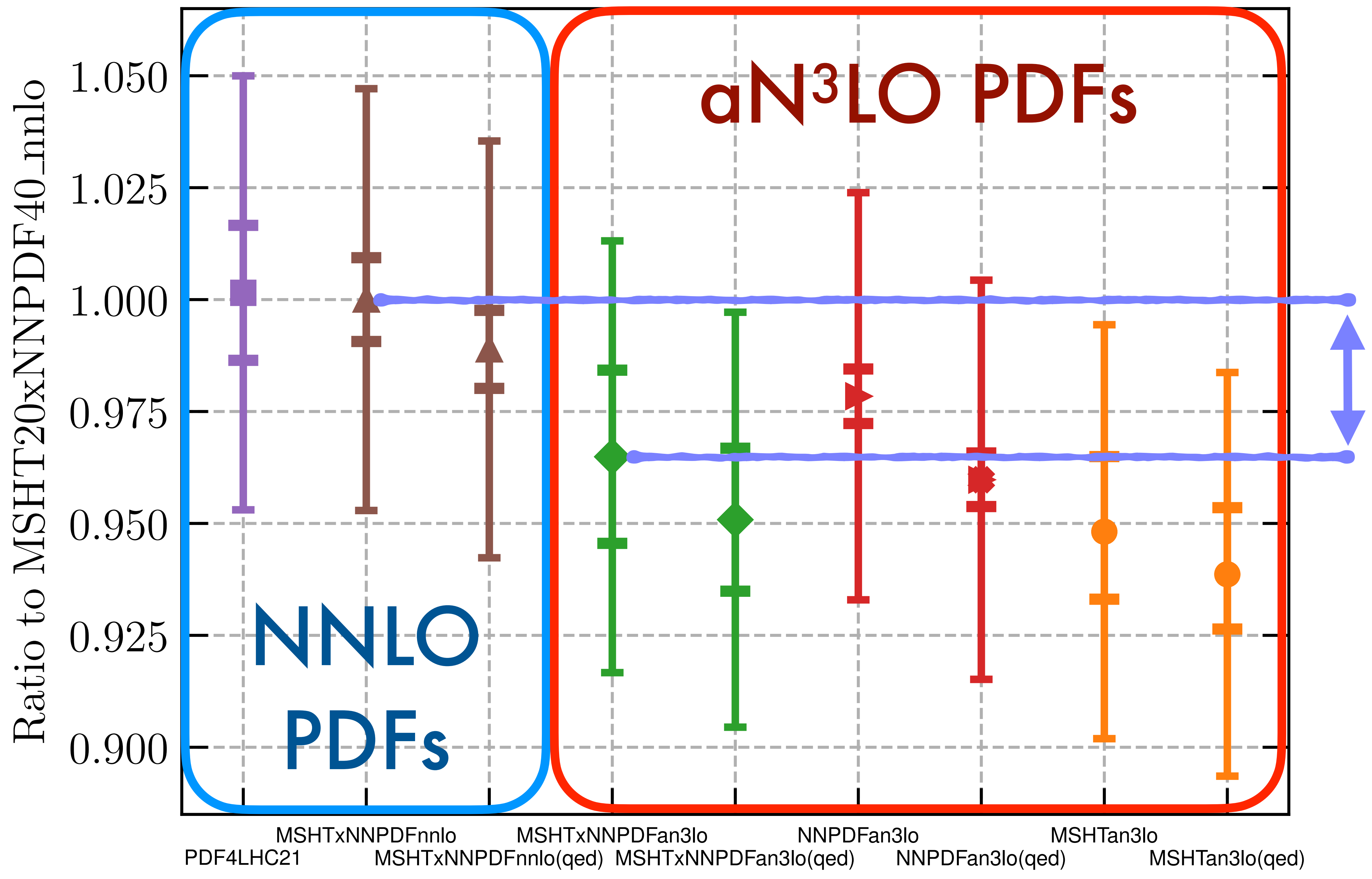
- estimate $\sim 1\,\%$ error $\left(\Delta^{\text{app}}_{\text{NNLO}} \equiv \frac{1}{2}\left|\frac{\sigma^{\text{NNLO}}_{\text{NNLO-PDF}} - \sigma^{\text{NNLO}}_{\text{NLO-PDF}}}{\sigma^{\text{NNLO}}_{\text{NNLO-PDF}}}\right| \right)$
  ↪ actual shift much larger:

$\sigma^{\text{N}^3\text{LO}}_{\text{ggH}}(\text{NNLO PDF})$
$= 48.3\,\text{pb}$

3.8%

$\sigma^{\text{N}^3\text{LO}}_{\text{ggH}}(\text{aN}^3\text{LO PDF})$
$= 46.5\,\text{pb}$

[MSHT, NNPDF 2411.05373]



Parton Distribution Functions

ggH @ N³LO

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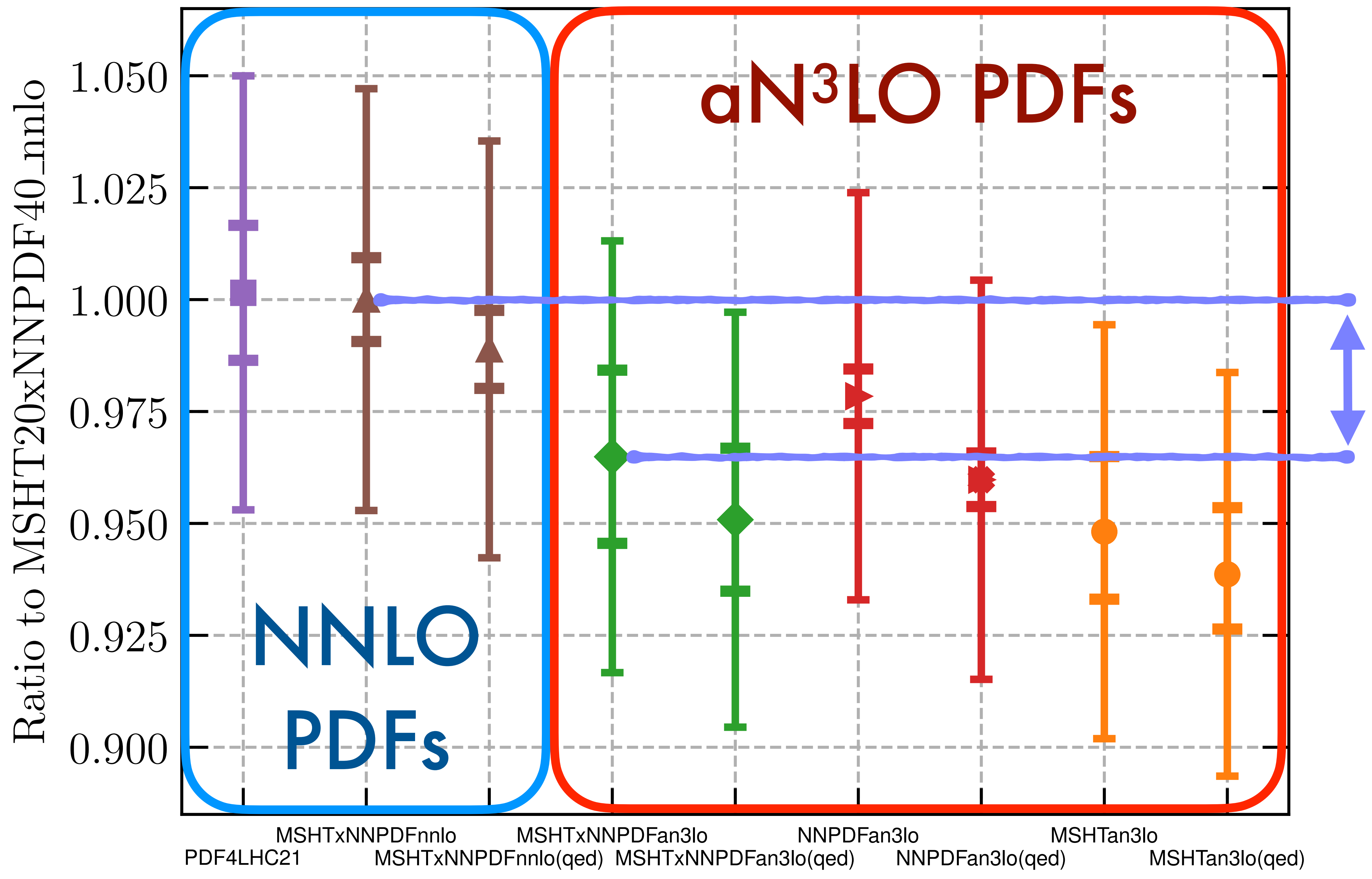
[MSHT, NNPDF 2411.05373]



$\sigma^{\rm N^3LO}_{\rm ggH}$(NNLO PDF) $= 48.3\,\text{pb}$

3.8%

$\sigma^{\rm NNLO}_{\rm ggH}$(NNLO PDF) $= 46.7\,\text{pb}$

$\sigma^{\rm N^3LO}_{\rm ggH}$(aN³LO PDF) $= 46.5\,\text{pb}$

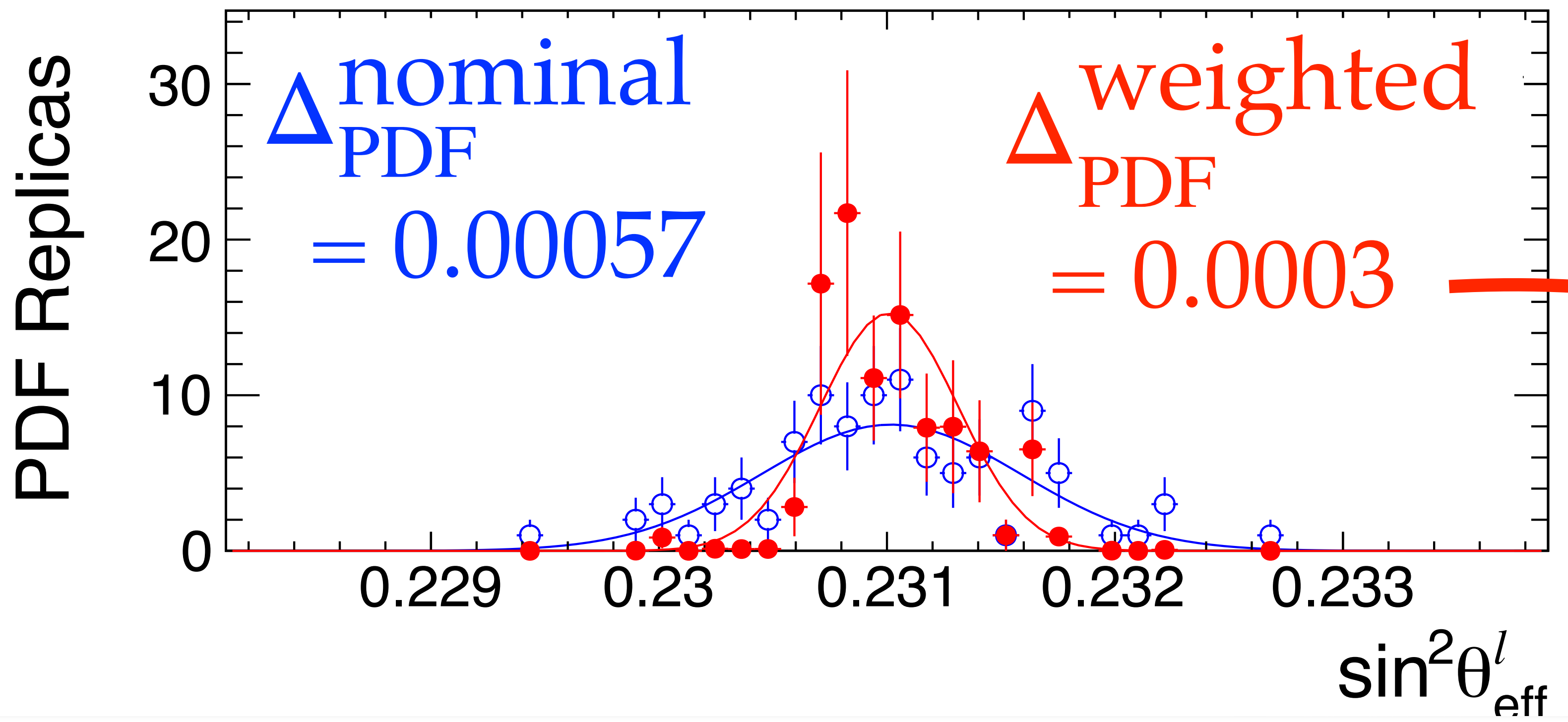
0.4%

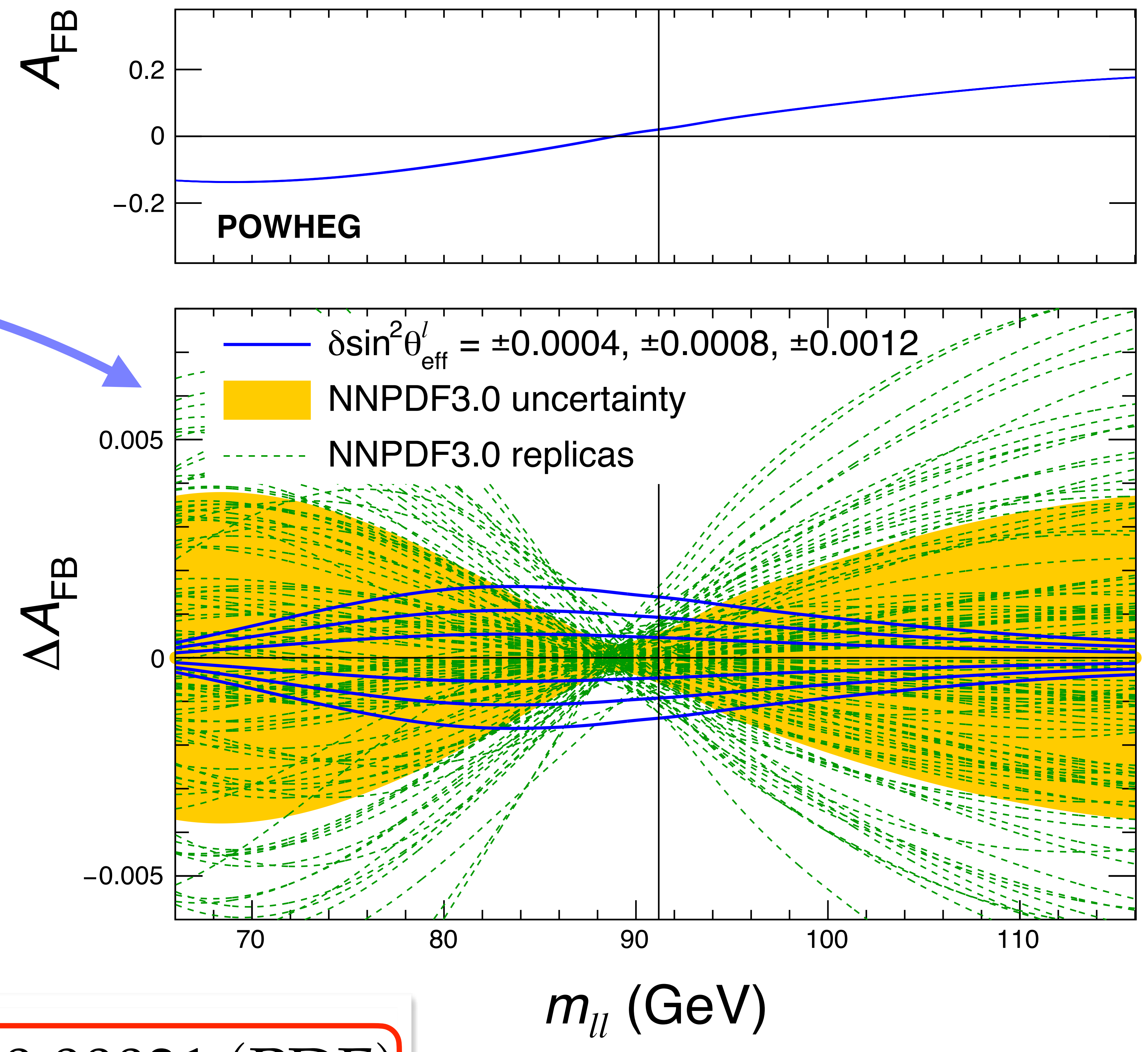
did we just see some artefacts from the mismatch between $\hat{\sigma}$ & PDFs? (uncompensated logs, ...)

[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}!





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

still almost 50% of Δ_{tot}

how sensible is that $\mathcal{O}(100)$ extra datapoints have such a big impact?
⇜ this data effectively carries a very high weight!

Parton Distribution Functions

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

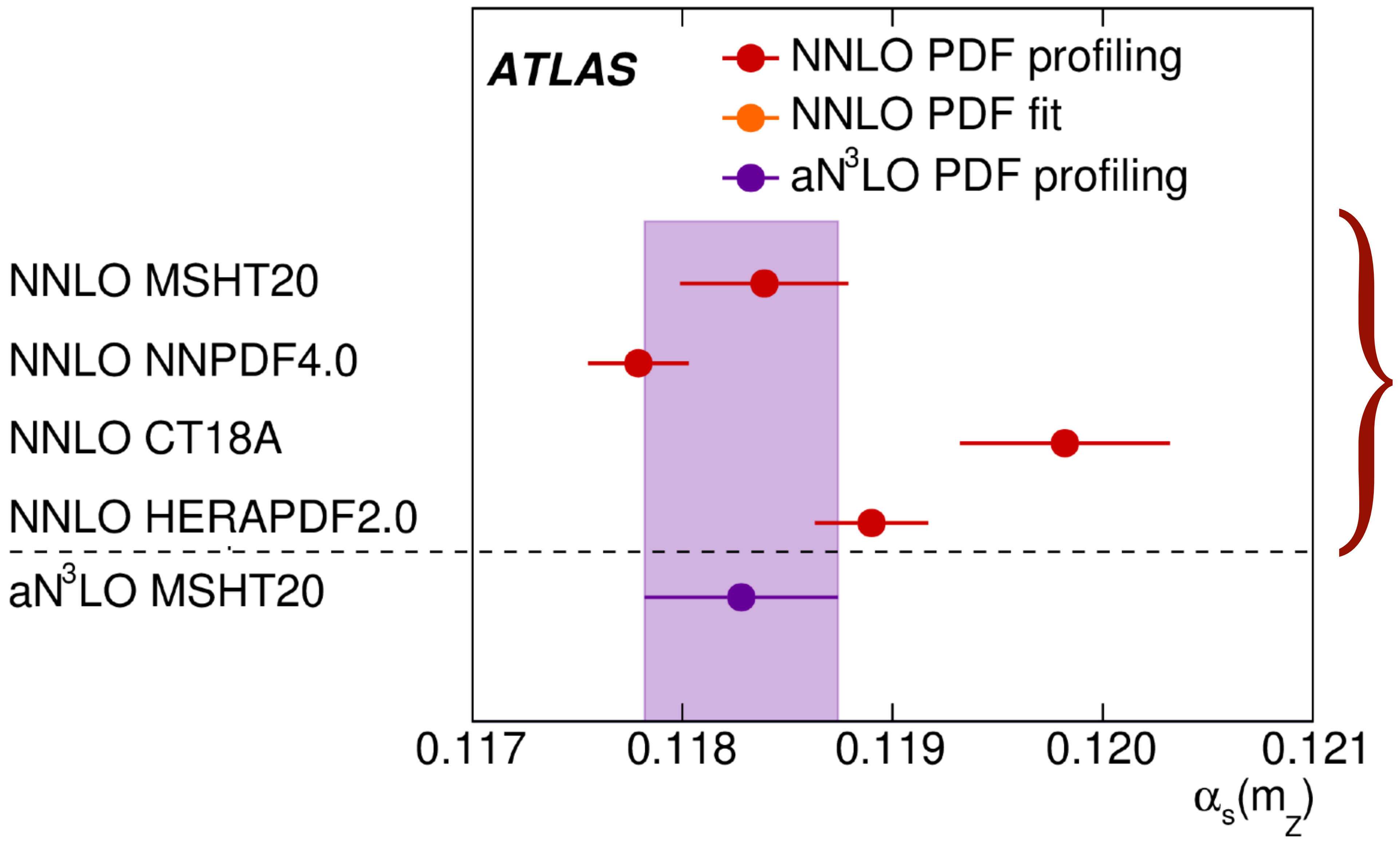
[ATLAS 2309.12986]

Profiling / Reweighting for α_s

profiling may bias probing direction of factorised approx.

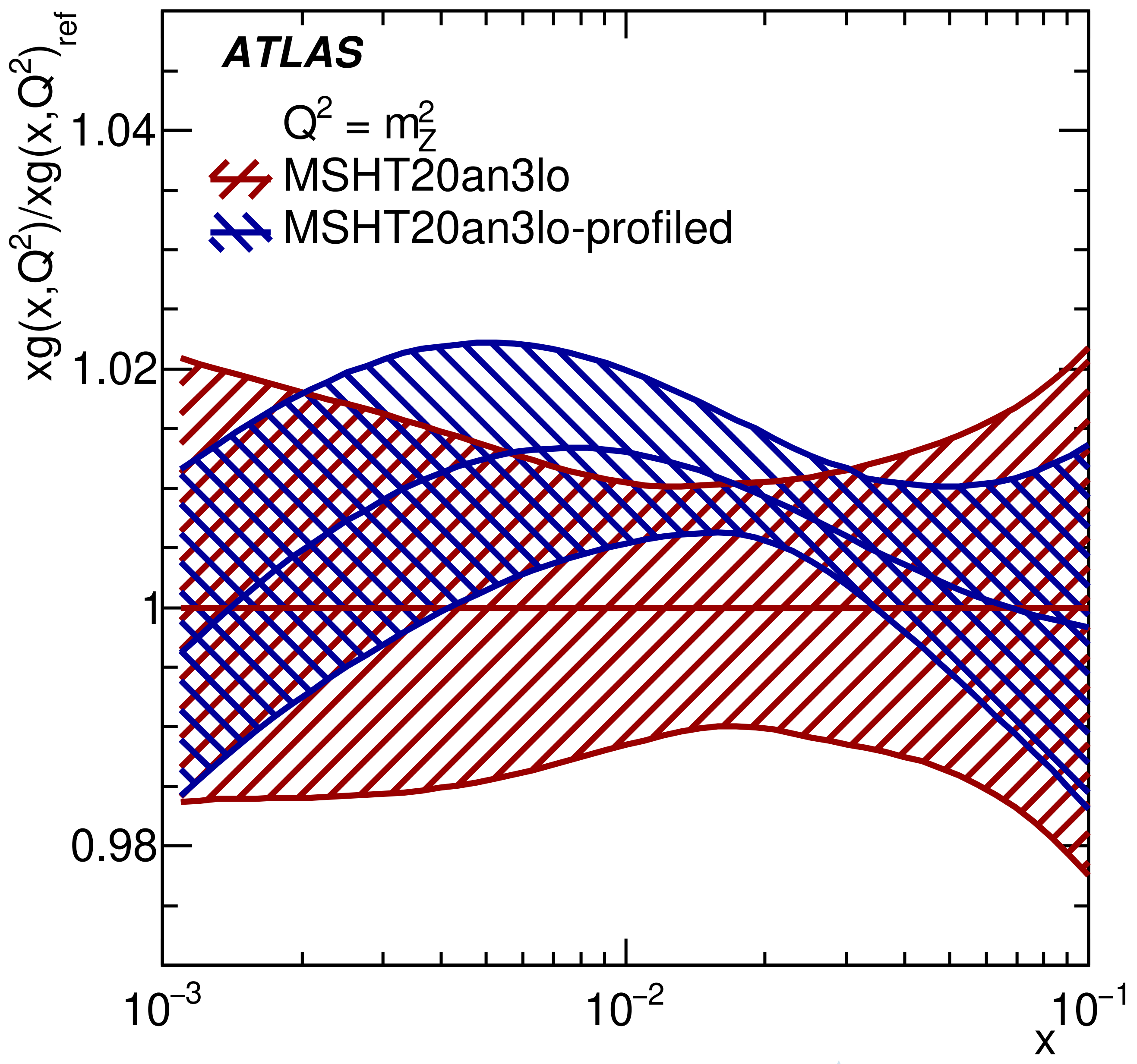
- situation is even more delicate for α_s
  $\leftrightsquigarrow$ strong correlations between α_s & PDFs (g)
- quoted $\Delta_{\rm PDF} = \pm 0.00051$

$4\times$



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

underestimated unc. / unaccounted $\Delta_{\rm model}$



back-reaction to other measurements in the fit?

Conclusions & Outlook

- Covered two dominant TH systematics in precision measurements
  ⇝ QCD modelling & PDF uncertainties.
  - no time to cover: EW corrections, PS, non-pert. uncertainties, …
- Situation: $\Delta_{\mathrm{EXP}} \ll \Delta_{\mathrm{TH}}$ puts analyses in the position to constrain Δ_{TH} from data
  ↪ prob. interpretation & correlation model crucial in this endeavour
  - **Bayesian estimates:** prob. interpretation (can also implement correlations)
  - **Theory nuisance parameters:** "physical" correlation model $\oplus\ P(\theta)$
- ∄ a "correct" $\Delta_{\mathrm{pert.}}$ model (each approach relies on set of assumptions)

relying on a single prescription is potentially dangerous!

- PDF reweighting / profiling by now standard practice
  - can reduce nominal Δ_{PDF} by factors of 2–4
  - impact on global PDF fit picture needs to be better understood & potential missing model / methodology uncertainties?

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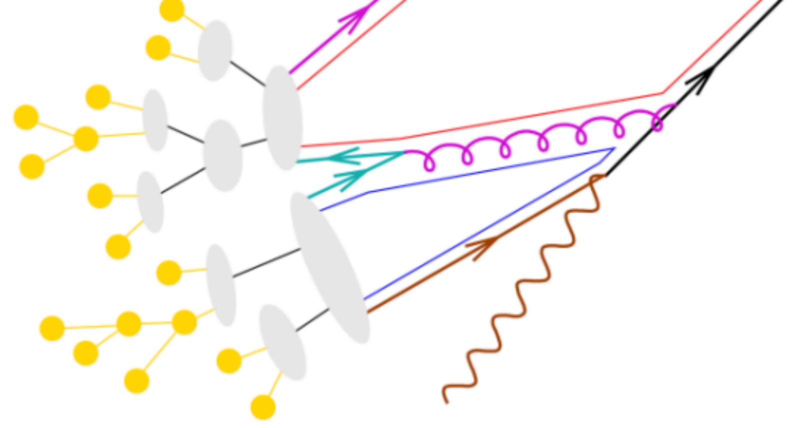
Thank you!

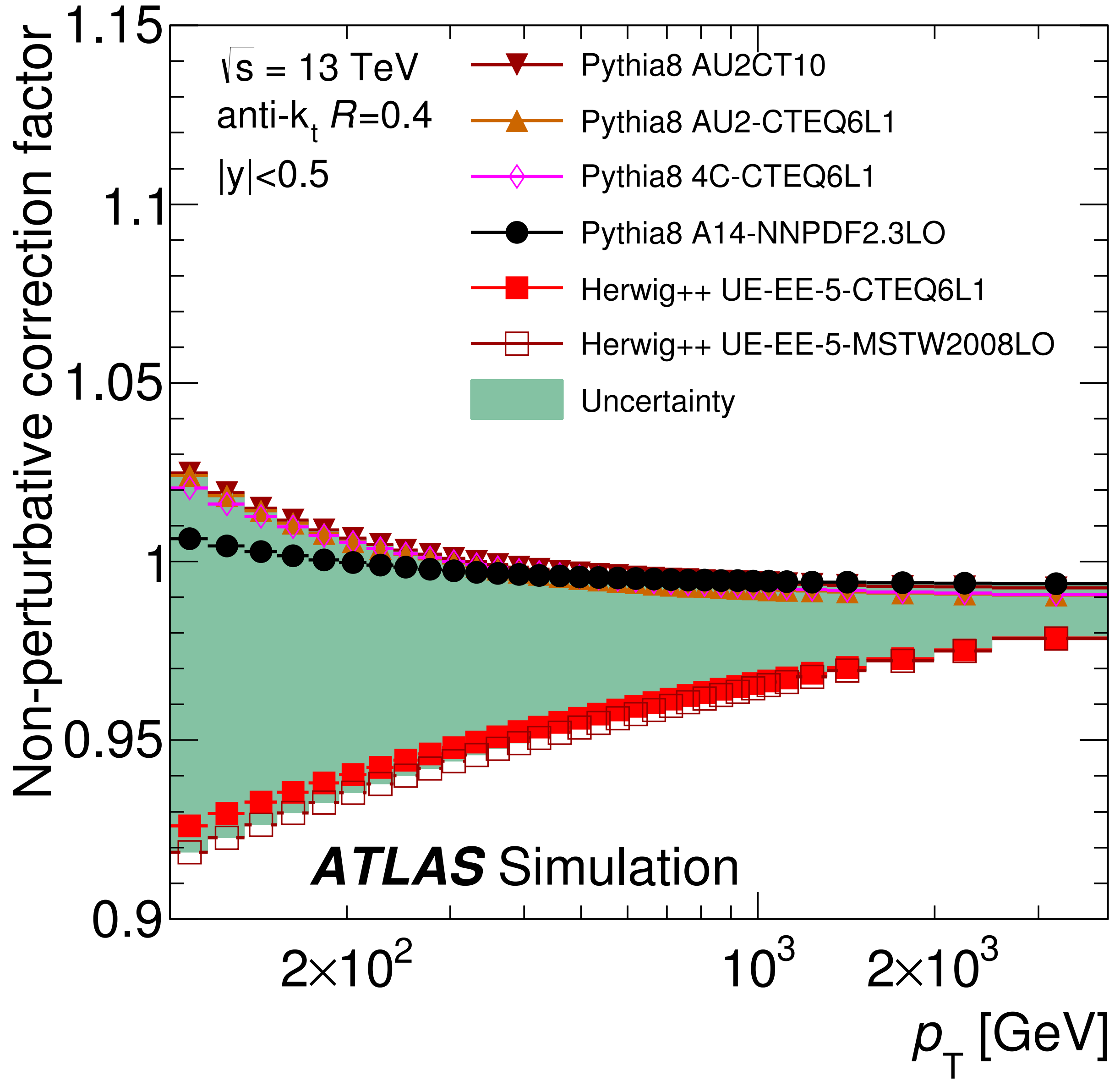
BACKUP



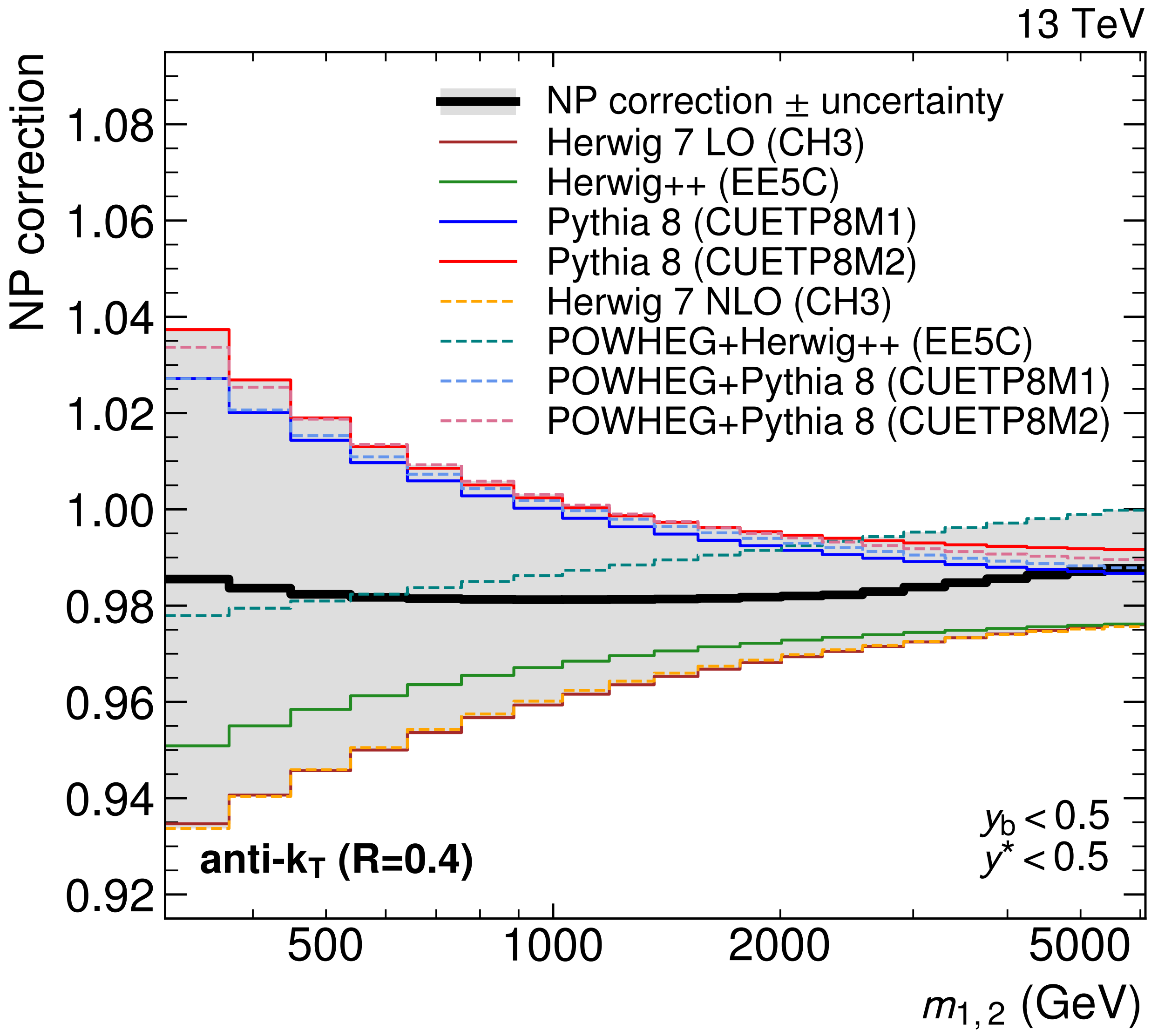
χ Parton Showers

Perturbative ⇜⇝ Non-Perturbative

- Parton showers (PS) model all-order QCD emissions through the evolution from hard to soft scales
- no systematic approach (afaik) to assess *perturbative* uncertainties in PS
- tuning of PS further entangles the pert. part with the non-pert. (NP) model
  - ↪ latter very sizeable
  - ↪ difficult to assess due to the notorious
    "Herwig vs. Pythia"
    effective two-point systematics



[ATLAS 1711.02692]

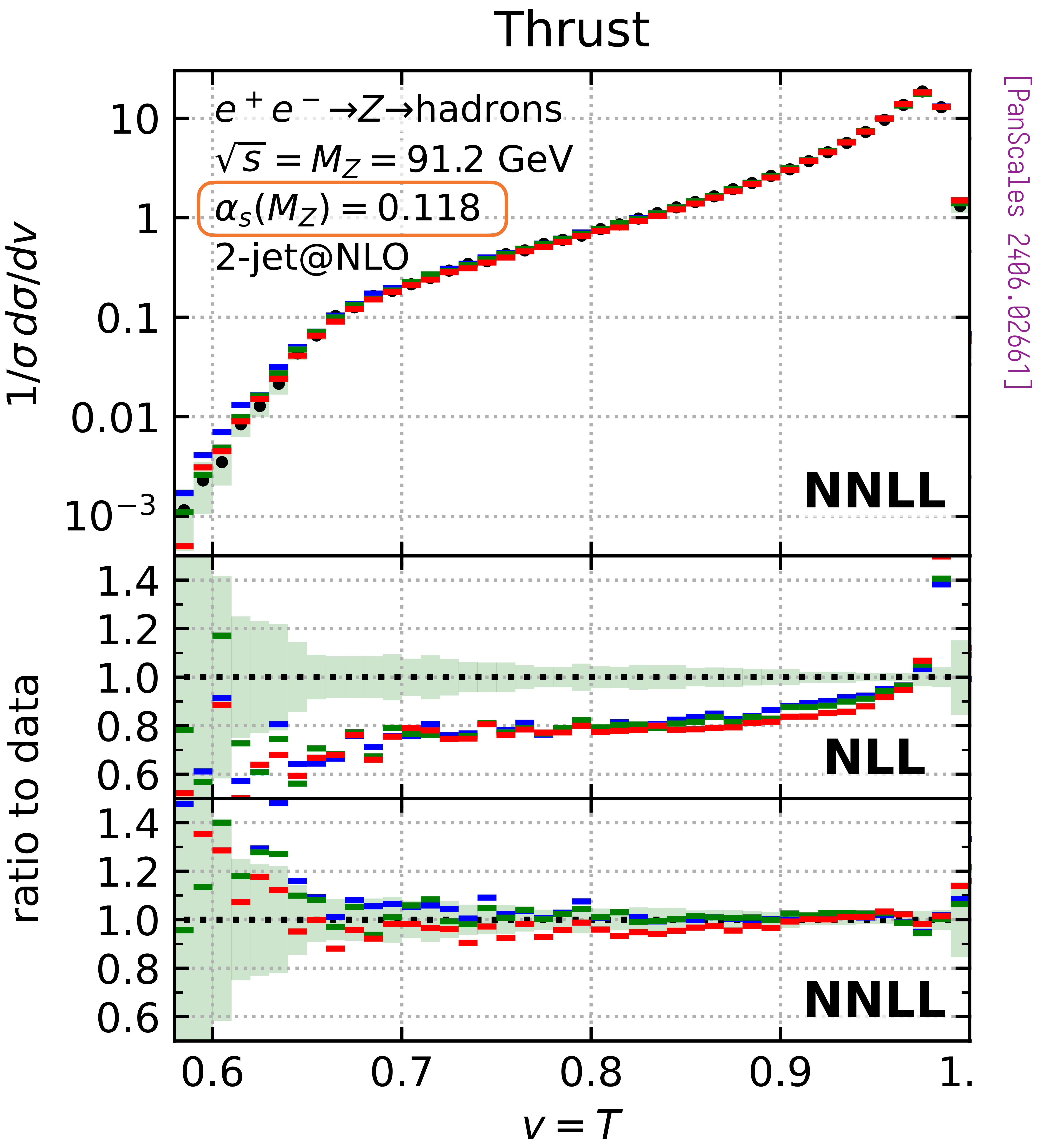


[CMS 2312.16669]

χ Parton Showers

Formal Accuracy

- tremendous progress in improving the formal accuracy of PS to
  - ↪ NLL [Alaric, Deductor, Herwig, Apollo, FHP, Panscales]
  - ↪ NNLL [PanScales 2406.02661]
- addresses long-standing issue with dipole showers that required an anomalously large $\alpha_s(M_Z) \gtrsim 0.130$
- NP effectively absorbing pert. effects?
  - ⇒ can formally accurate PS lead to better alignment in NP modelling?



Work in Progress — Correlations

[AH, Mazeliauskas w.i.p]

- idea: if two bins show similar (opposite) perturbative behaviour
  ↪ two bins should be partially (anti-)correlated.
- we want: joint probability distribution $P(x, y)$ for two bins x & y
  ↪ preserve projections for compatibility:

$$P(x) = \int \mathrm{d}y\, P(x, y) = \int \mathrm{d}z\, P(x, z)$$

  ↪ hidden parameter $-1 < c < +1$ to smoothly implement the correlation
- possibilities: algorithmic "earth movers distance"; map $P(x)$ onto $P(y)$, …
  ↪ can be done much simpler

Work in Progress – Correlation Model

[AH, Mazeliauskas w.i.p]

- projections of multi-dim. Gaussians (+ correlation matrix) are again Gaussian
  ↪ map P_i onto Gaussians, implement correlations, map back

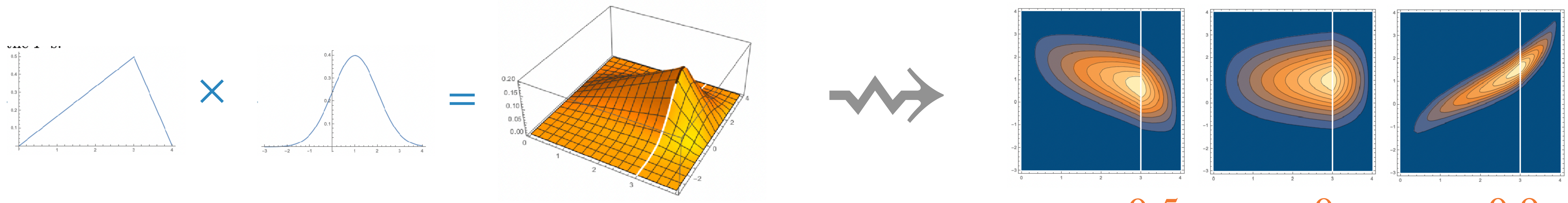
$$P(x,y) = P_1(x)P_2(y) \times \left.\frac{d\Phi^{-1}(\alpha)}{d\alpha}\right|_{\alpha=\Sigma_1(x)} \left.\frac{d\Phi^{-1}(\beta)}{d\beta}\right|_{\beta=\Sigma_2(y)} \times \frac{1}{2\pi\sqrt{1-c^2}} \exp\left(-\frac{1}{2(1-c^2)}\left[\xi(x)^2+\eta(y)^2-c2\xi(x)\eta(y)\right]\right)$$

$$\Sigma_i(x) = \int_{-\infty}^{x} dx' P_i(x')$$

$$\Phi^{-1}(p) = \sqrt{2}\mathrm{Erf}^{-1}(-1+2p)$$

$$\xi(x) = \Phi^{-1}(\Sigma_1(x))$$

$$\eta(y) = \Phi^{-1}(\Sigma_2(y))$$

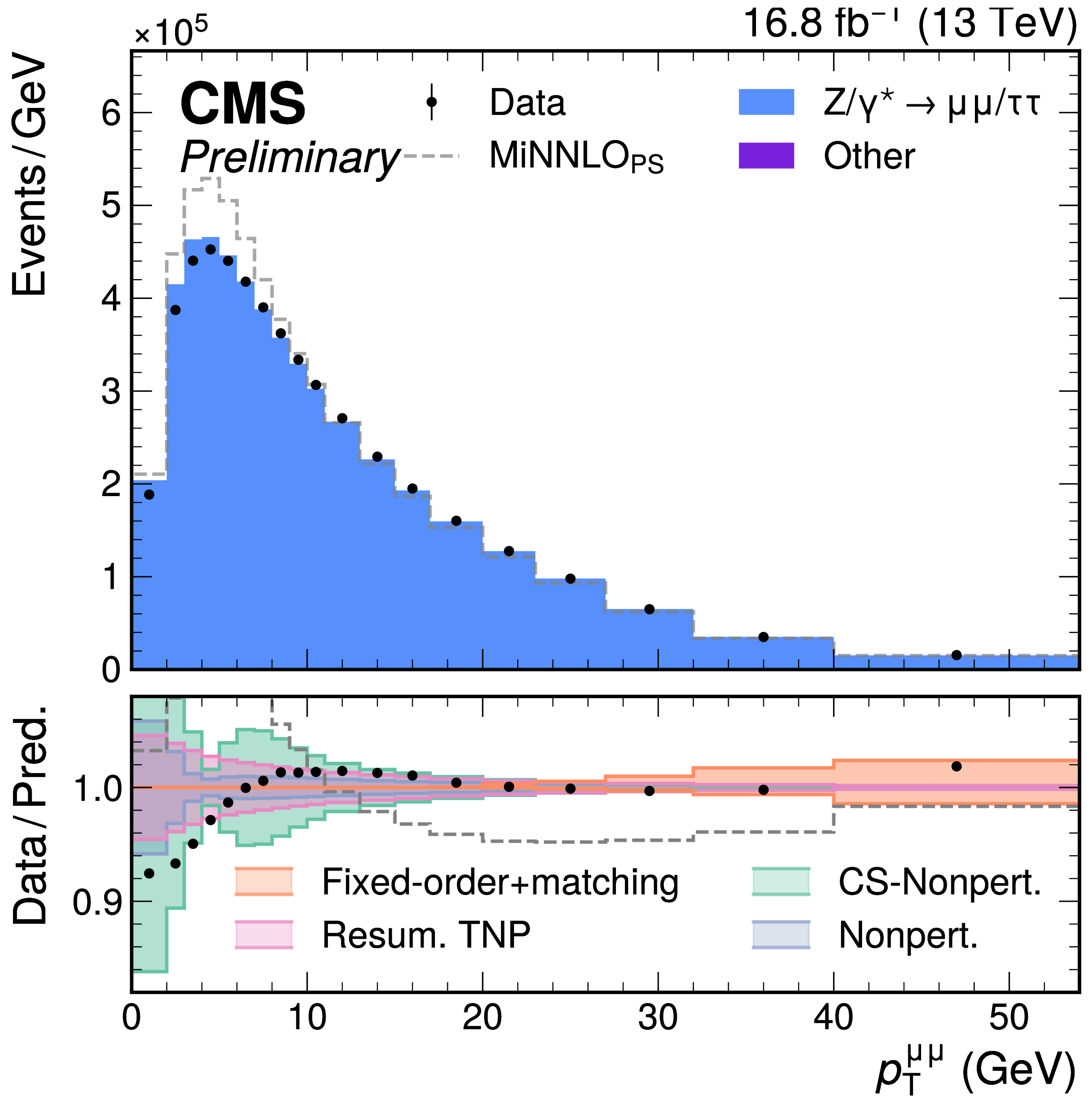


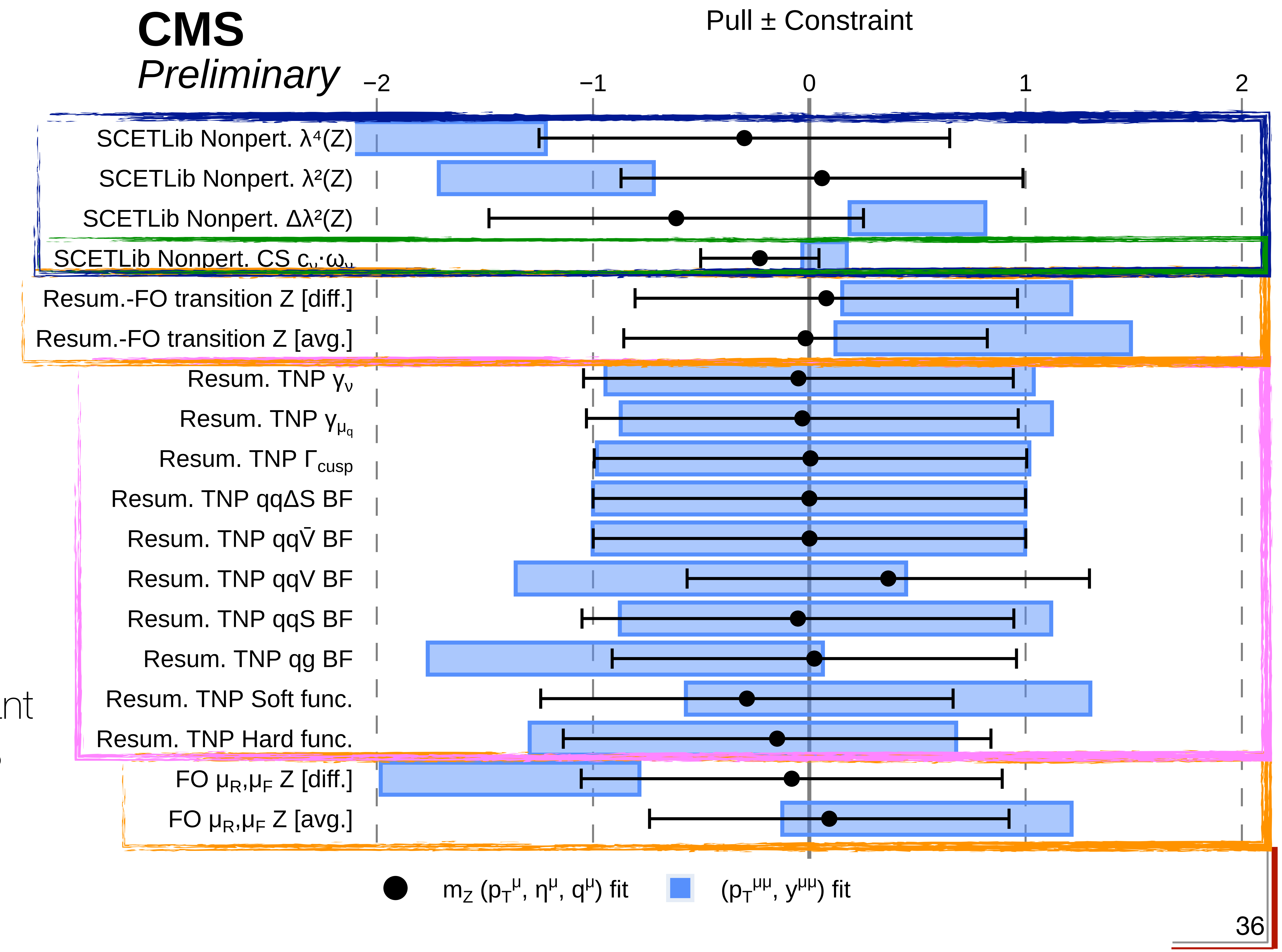
$c = -0.5$ $c = 0$ $c = 0.9$

use inference to constrain c

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**