Robust estimates of theoretical uncertainties at fixed-order in perturbation theory

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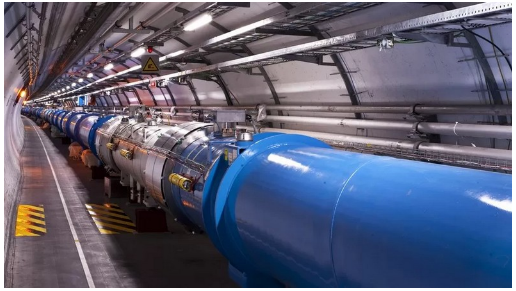
Outline

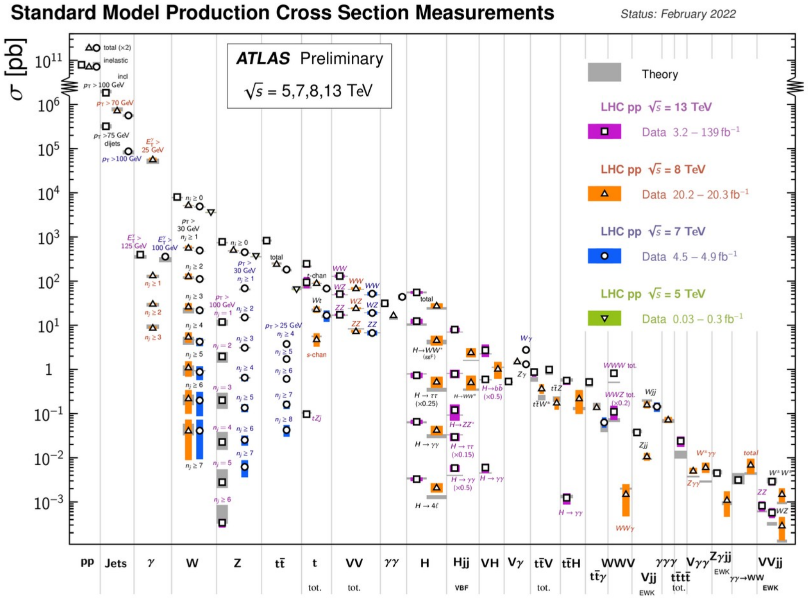
- Precision predictions at the LHC
- Missing Higher Order Uncertainties (MHOU)
  How to estimate the uncertainty of (truncated) perturbative expansions?
  - Scale variations for fixed-order and resummed cross sections
  - Bayesian methods
  - Theory Nuisance Parameters (TNPs)
- Application of TNPs to fixed-order perturbation theory
- Discussion/Summary/Outlook

Standard Model phenomenology at the LHC

Scattering experiments

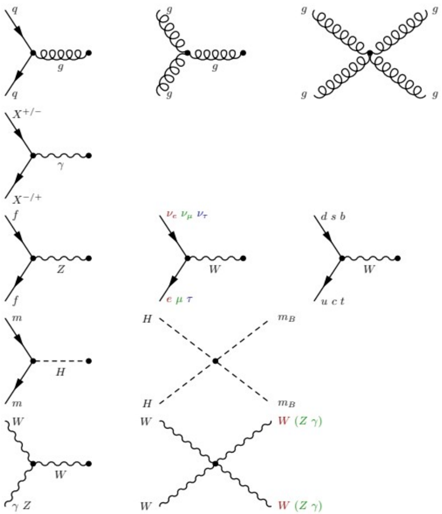


Credit: CERN



Credit: ATLAS

Theory/Model

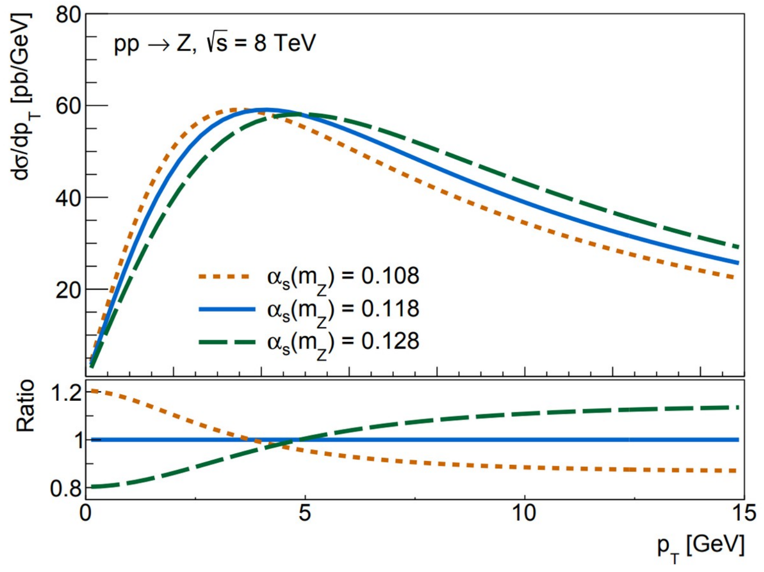


Credit: Jack Lindon, CERN

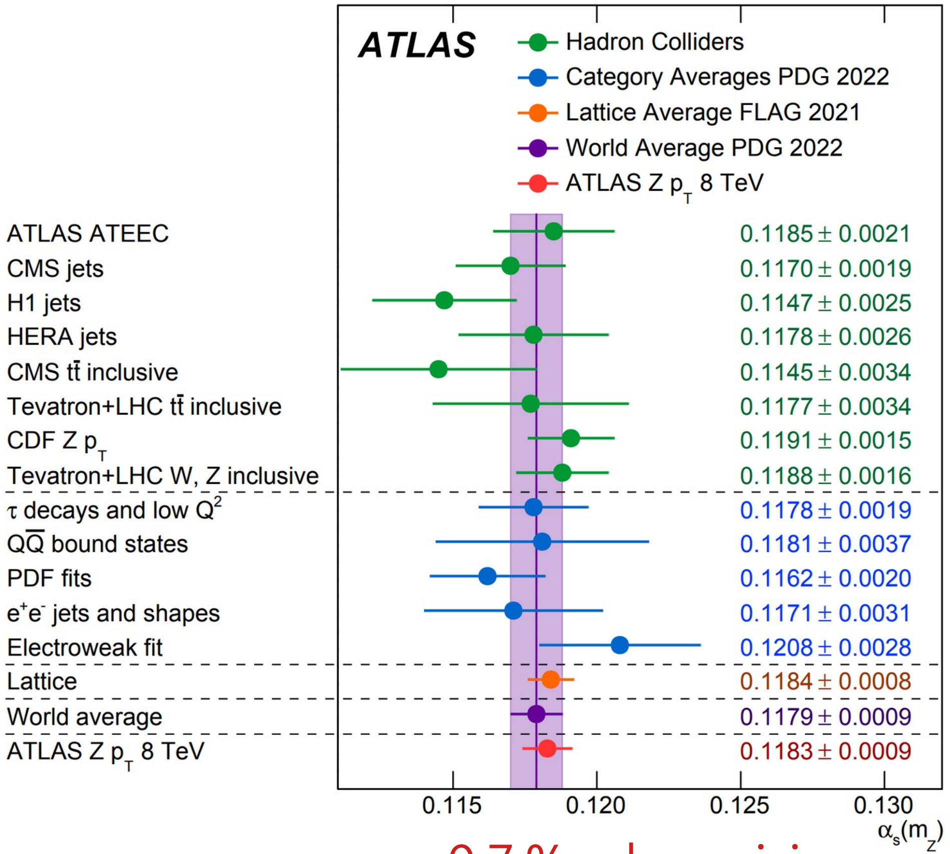
Precision example: strong coupling from pT(Z)

[ATLAS 2309.12986]

Sensitivity of Z-boson's recoil to the strong coupling constant:



→ at low pT resummation regime!
→ theory uncertainty?

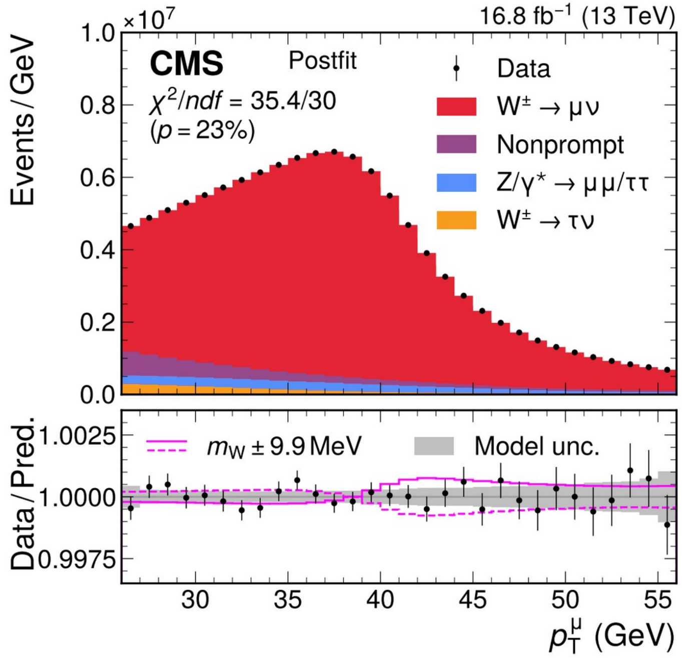


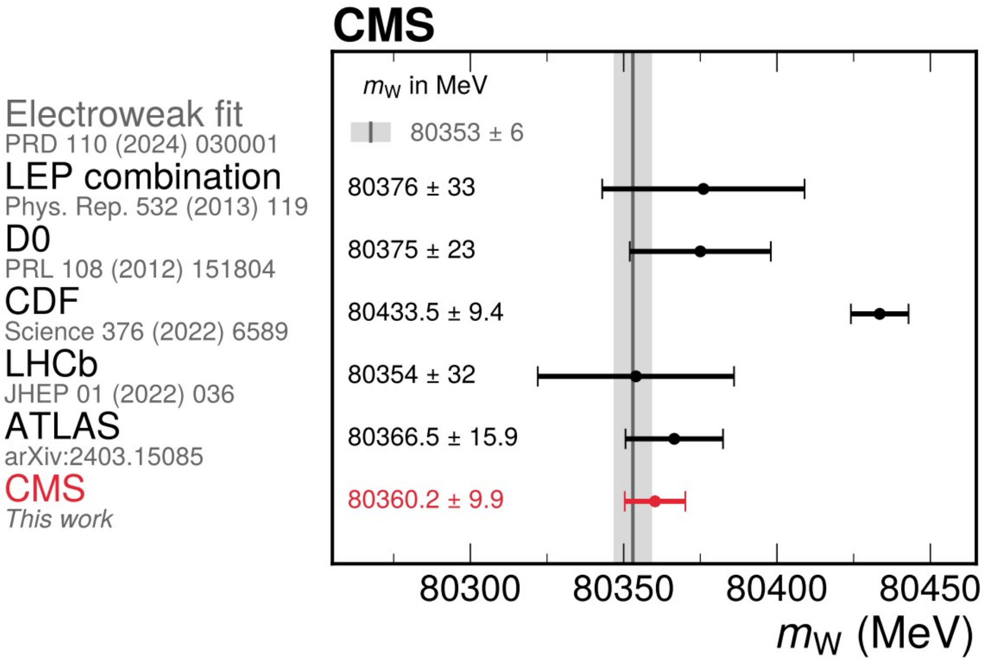
~0.7 % rel. precision

Precision example: W-mass measurement by CMS

[CMS 2412.13872]

Mass dependence of pT(l):



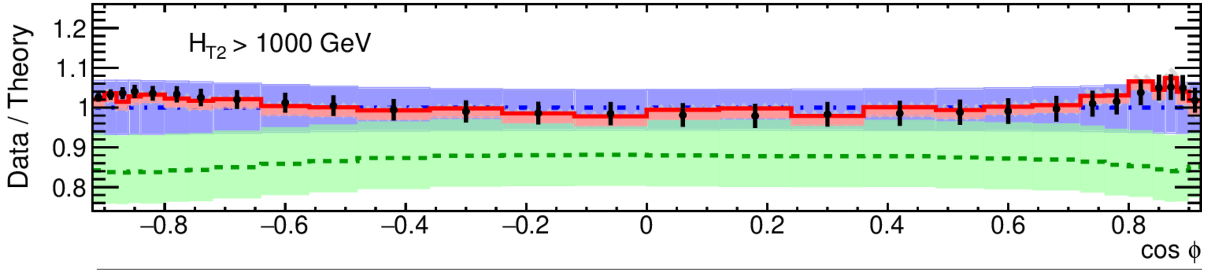


Jacobian peak position ~m(W)/2 → resummation sensitive → theory uncertainty?

Precision example: strong-coupling from TEEC

Next-to-Next-to-Leading Order Study of Three-Jet Production at the LHC
Czakon, Mitov, **Poncelet** Phys.Rev.Lett. 127 (2021) 15, 152001

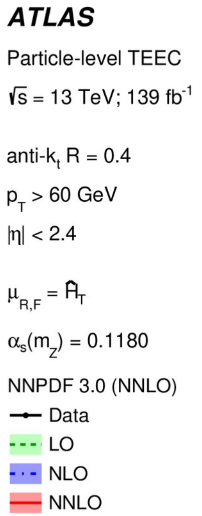
[ATLAS 2301.09351]

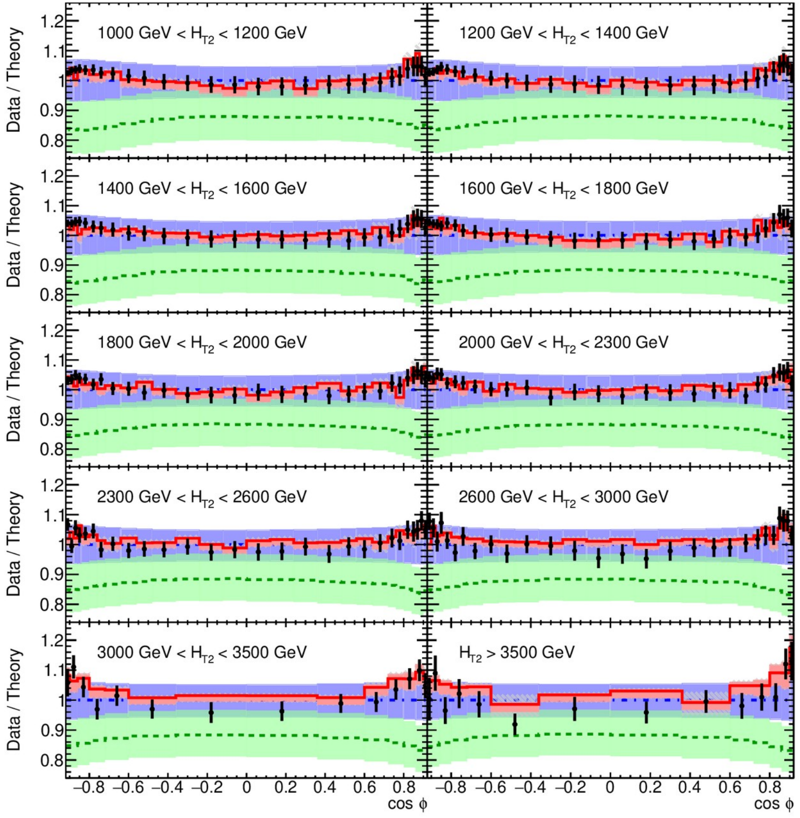


Multi-jet angular correlations

Uncertainties driven by
fixed-order precision through ratio:

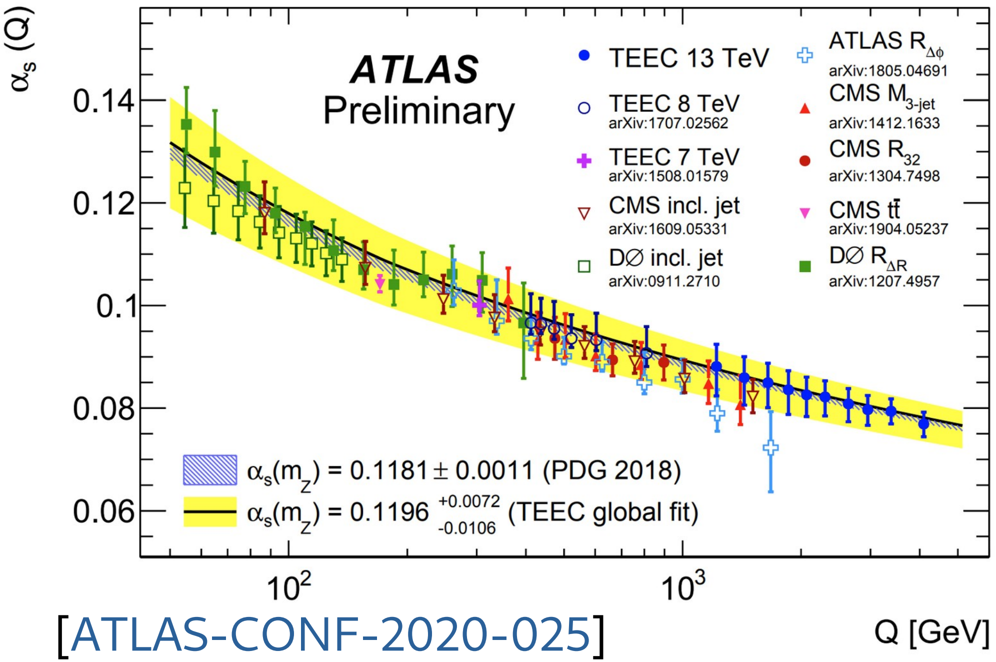
$$R^i(\mu_R,\mu_F,\mathrm{PDF},\alpha_{S,0}) = \frac{\mathrm{d}\sigma_3^i(\mu_R,\mu_F,\mathrm{PDF},\alpha_{S,0})}{\mathrm{d}\sigma_2^i(\mu_R,\mu_F,\mathrm{PDF},\alpha_{S,0})}$$





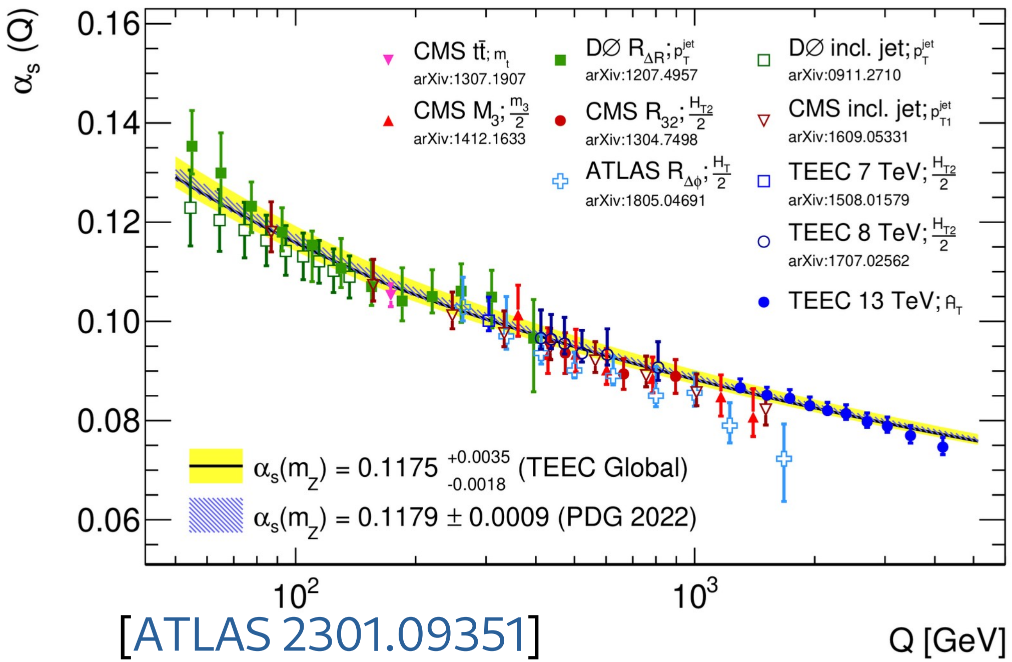
Precision example: strong-coupling from TEEC

NLO QCD



[ATLAS-CONF-2020-025]

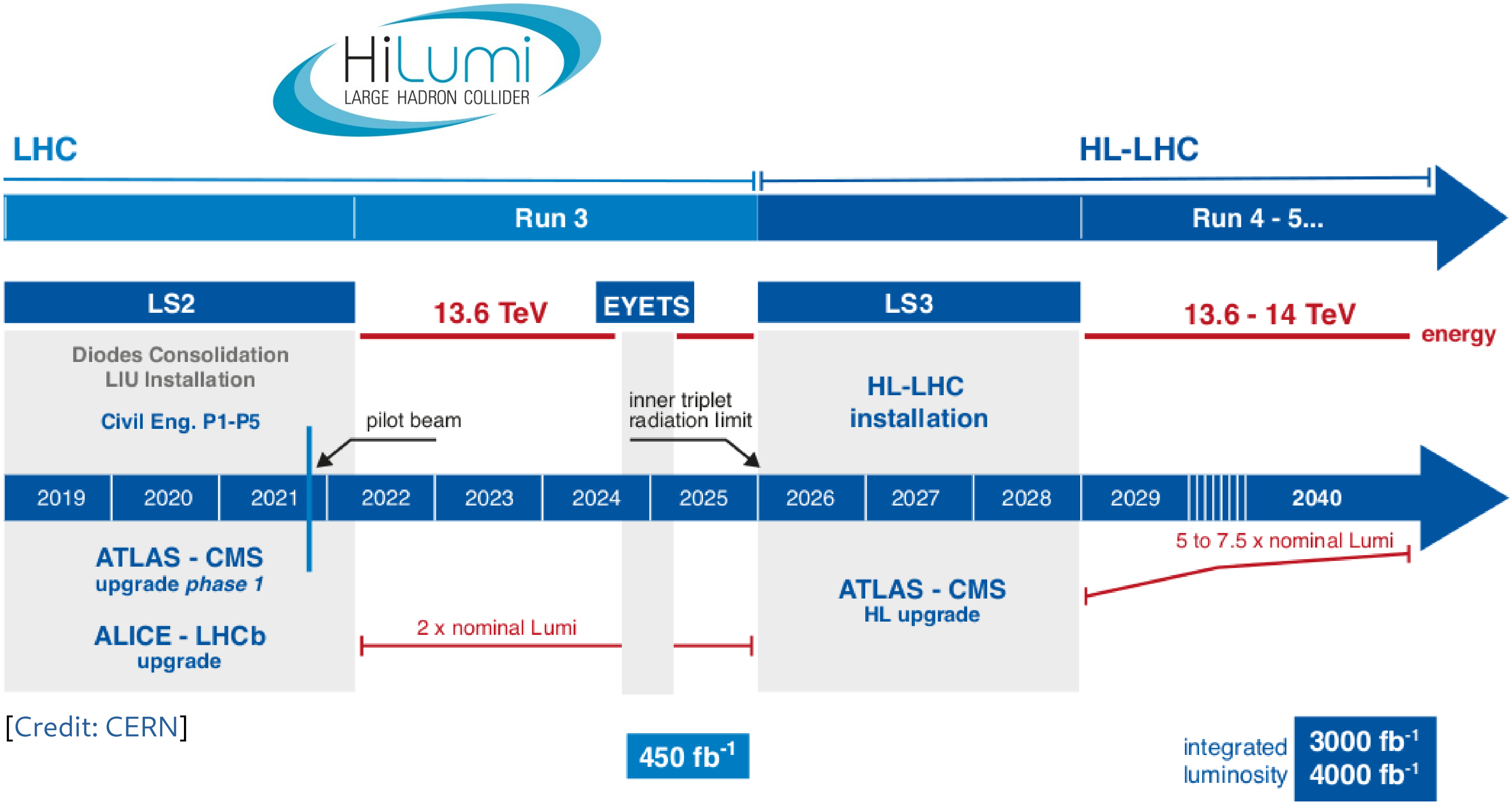
NNLO QCD



[ATLAS 2301.09351]

Theory uncertainty dominant effect!

LHC Precision era and future experiments



[Credit: CERN]

Uncertainties in precision phenomenology

Experiments are getting more precise → theory uncertainties matter!

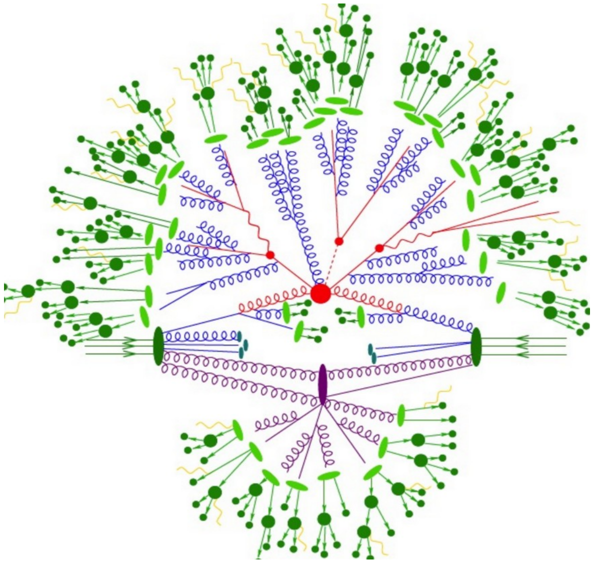
Sources of theory uncertainties:

- parametric (values of coupling parameters etc.)
→ variation of parameters within their uncertainties

- parton distribution functions (PDFs)
→ different error propagation methods (fit parameter, replicas,...)

- non-perturbative parameters in Monte Carlo simulations.
→ needs data constraints by definition. Problematic if dominant effect...

- missing higher orders in fixed-order and resummed predictions (MHOU)
→ tricky because we are trying to estimate the unknown….



[Credit: SHERPA]

Theory uncertainties from scale variations

Lets focus on QCD as an example:

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{(0)} + \alpha_s \mathrm{d}\sigma^{(1)} + \alpha_s^2 \mathrm{d}\sigma^{(2)} + \ldots \quad \xrightarrow{\text{RGE}} \quad \mu \frac{\mathrm{d}\sigma^{(n)}}{\mathrm{d}\mu} = \mathcal{O}\left(\alpha_s^{(n_0+n+1)}\right)$$

Of same order as the next dominant term → exploiting this to estimate size of $\mathrm{d}\sigma^{(n+1)}$

Scale variation prescription

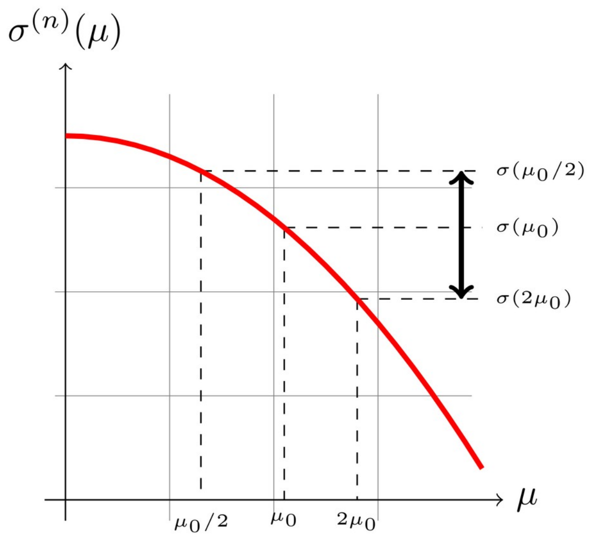
- choose 'sensible' μ_0

$\sigma^{(n)}(\mu_{\mathrm{FAC}}) = 0$ → principle of fasted apparent convergence

$\mu \frac{\mathrm{d}\sigma(\mu)}{\mathrm{d}\mu}\Big|_{\mu=\mu_{\mathrm{PMC}}} = 0$ → principle of minimal sensitivity

→ ...

- vary with a factor (typically 2)
- take envelope as uncertainty
- ad-hoc and heuristic choice



Missing higher orders

Notation from:
Beyond Scale Variations: Perturbative Theory Uncertainties from Nuisance Parameters, Frank Tackmann [2411.18606]

Generic perturbative expansion:

$$f(\alpha) = f_0 + f_1\alpha + f_2\alpha^2 + f_3\alpha^3 + \ldots$$

For QCD: $\alpha = \alpha_s(\mu_0)$

f_i : the coefficient of the series, potentially unknown

We can compute the truncated series:

$$f^{\mathrm{LO}}(\alpha) = \hat{f}_0 \qquad f^{\mathrm{NLO}}(\alpha) = \hat{f}_0 + \hat{f}_1\alpha \qquad f^{\mathrm{NNLO}}(\alpha) = \hat{f}_0 + \hat{f}_1\alpha + \hat{f}_2\alpha^2$$

$\hat{f}_i$: the true value, i.e. a value we actually computed

The missing terms are the source of uncertainty.
(assume convergence → the first missing is the dominant one)

$$f^{\mathrm{LO+1}}(\alpha) = \hat{f}_0 + f_1\alpha \qquad f^{\mathrm{NLO+1}}(\alpha) = \hat{f}_0 + \hat{f}_1\alpha + f_2\alpha^2 \qquad f^{\mathrm{NNLO+1}}(\alpha) = \hat{f}_0 + \hat{f}_1\alpha + \hat{f}_2\alpha^2 + f_3\alpha^3$$

Scale variation approach

Change of scale = change of renormalisation scheme: $\tilde{\alpha}(\alpha) = \alpha(1 + b_0\alpha + b_1\alpha^2 + b_2\alpha^3 + \dots)$

For QCD: $\alpha = \alpha_s(\mu_0)$ $\tilde{\alpha} = \alpha_s(\mu)$

$$b_0 = \frac{\beta_0}{2\pi}L \qquad b_1 = \frac{\beta_0^2}{4\pi^2}L^2 + \frac{\beta_1}{8\pi^2}L \qquad b_2 = \frac{\beta_0^3}{8\pi^3}L^3 + \frac{5\beta_0\beta_1}{32\pi^2}L^2 + \frac{\beta_2}{32\pi^3}L \qquad L = \ln\frac{\mu_0}{\mu}$$

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

$$\tilde{f}^{\text{NLO}}(\tilde{\alpha}) = \hat{\tilde{f}}_0 + \hat{\tilde{f}}_1\tilde{\alpha} = \hat{f}_0 + \alpha\hat{f}_1 + \boxed{\alpha^2 b_0\hat{f}_1} + \mathcal{O}(\alpha^3)$$

$$\tilde{f}^{\text{NNLO}}(\tilde{\alpha}) = \hat{\tilde{f}}_0 + \hat{\tilde{f}}_1\tilde{\alpha} + \hat{\tilde{f}}_2\tilde{\alpha}^2 = \hat{f}_0 + \alpha\hat{f}_1 + \alpha^2\hat{f}_2 + \boxed{\alpha^3(2b_0(\hat{f}_2 - b_0\hat{f}_1) + b_1\hat{f}_1)} + \mathcal{O}(\alpha^4)$$

Scale variation approach

Change of scale = change of renormalisation scheme: $\tilde{\alpha}(\alpha) = \alpha(1 + b_0\alpha + b_1\alpha^2 + b_2\alpha^3 + \dots)$

For QCD: $\alpha = \alpha_s(\mu_0)$ $\tilde{\alpha} = \alpha_s(\mu)$

$$b_0 = \frac{\beta_0}{2\pi}L \qquad b_1 = \frac{\beta_0^2}{4\pi^2}L^2 + \frac{\beta_1}{8\pi^2}L \qquad b_2 = \frac{\beta_0^3}{8\pi^3}L^3 + \frac{5\beta_0\beta_1}{32\pi^2}L^2 + \frac{\beta_2}{32\pi^3}L \qquad L = \ln\frac{\mu_0}{\mu}$$

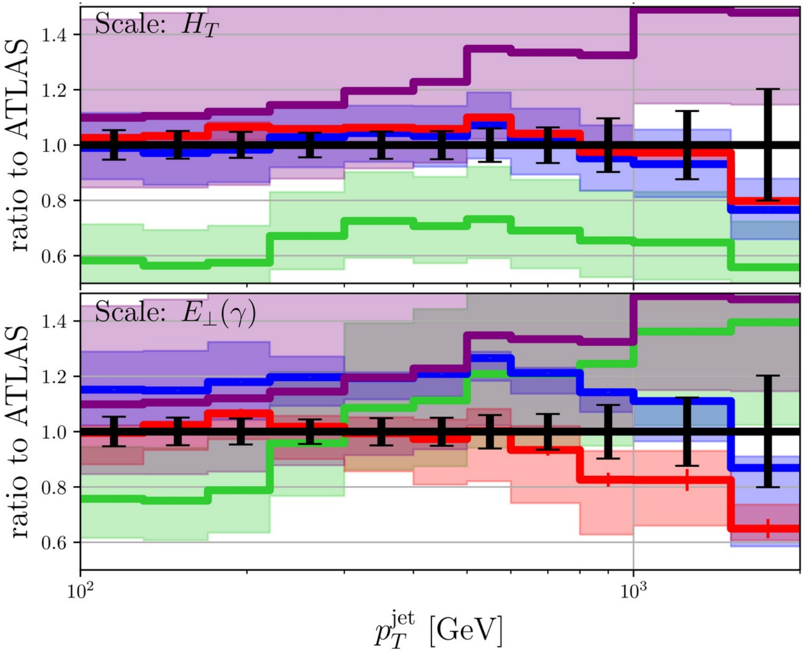
$$\Delta f^{\mathrm{NLO}} = f^{\mathrm{NLO}} - \tilde{f}^{\mathrm{NLO}}(\tilde{\alpha}) = -\alpha^2 b_0 \hat{f}_1 + \mathcal{O}\big(\alpha^3\big)$$

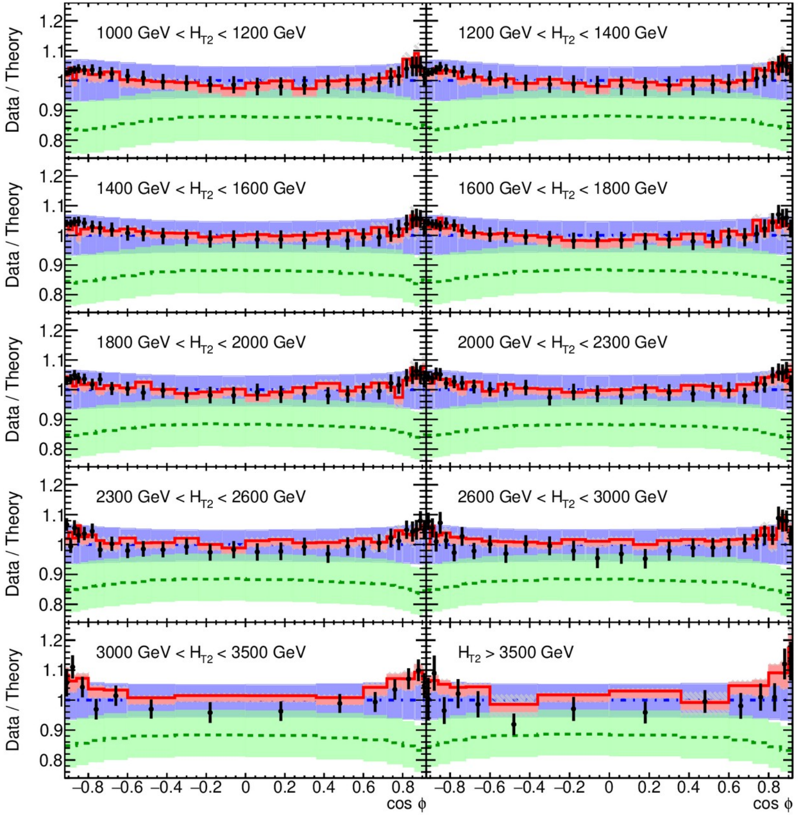
$$\Delta f^{\mathrm{NNLO}} = f^{\mathrm{NNLO}} - \tilde{f}^{\mathrm{NNLO}}(\tilde{\alpha}) = \alpha^3(2b_0(\hat{f}_2 - b_0\hat{f}_1) + b_1\hat{f}_1) + \mathcal{O}\big(\alpha^4\big)$$

Issues:

1) There is no reason to believe that there is a value L (i.e. scale choice) that describes all $\hat{f}_i$
2) If f is not a scalar, correlations are unclear

Still, scale variation works ...

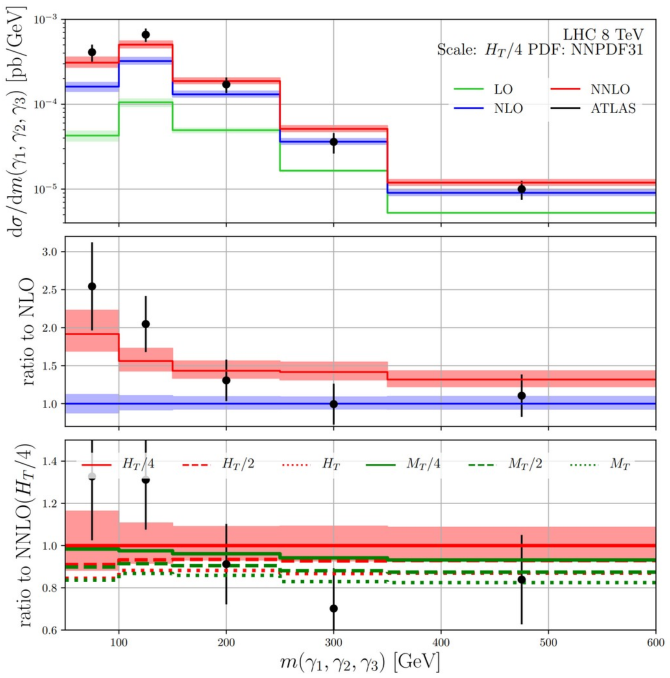




Badger, Czakon, Hartanto, Moodie, Peraro, **Poncelet**, Zoia [2304.06682]

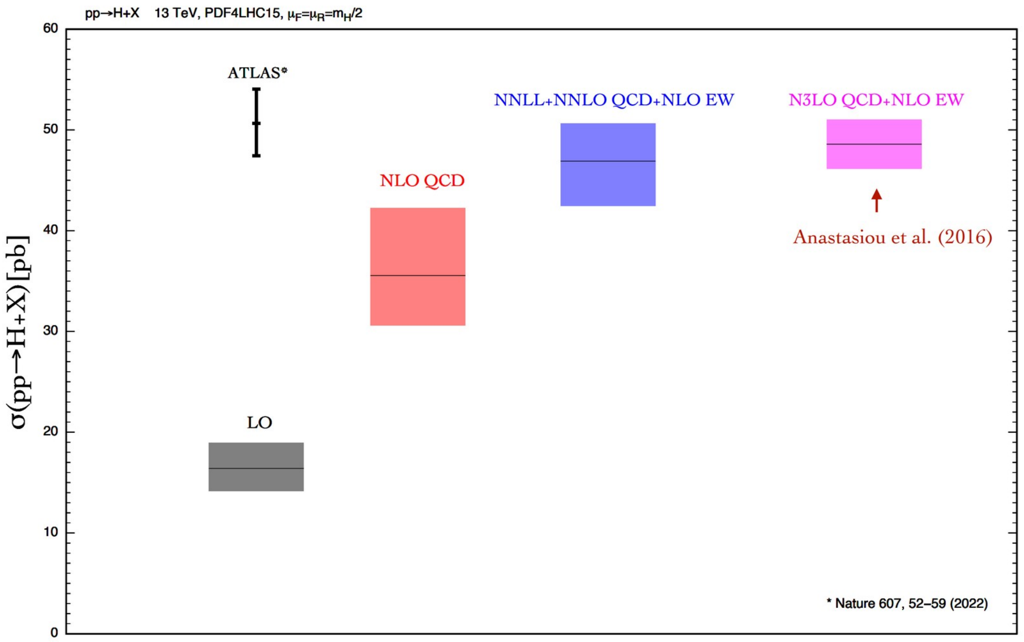
...sometimes :/

Three photon production



NNLO QCD corrections to three-photon production at the LHC, Chawdhry, Czakon, Mitov, **Poncelet** [JHEP 02 (2020) 057]

Higgs production



[talk by Grazzini]

Short comings of scale variations

- not always reliable

- ...but in most cases issues are understood/expected:
  new channels, phase space constraints, etc.
  → workarounds

- however, some issues are more fundamental:

  → how to choose the central scale? → not a physical parameter, no ‘true’ value
  (Principle of fasted apparent convergence, principle of minimal sensitivity,...)

  → how to propagate the estimated uncertainty, no statistical interpretation!

  → what about correlations? Based on ‘fixed form’ of the lower orders and RGE.

(At the moment) two alternative approaches under investigation:
“Bayesian” and “Theory Nuisance Parameter”

Bayesian approach I

→ Instead of ad-hoc fixed variation try to give some probabilistic interpretation

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{(0)}(1 + \delta^{(1)} + \delta^{(2)} + \dots)$$

Probability to find coefficient $\delta^{(n+1)}$ given $\delta^{(n)}$: [Cacciari,Houdeau 1105.5152]

$$P(\delta^{(n+1)}|\delta^{(n)}) = \frac{P(\delta^{(n+1)})}{P(\delta^{(n)})} = \frac{\int \mathrm{d}a P(\delta^{(n+1)}|a) P_0(a)}{\int \mathrm{d}a P(\delta^{(n)}|a) P_0(a)}$$

Need to provide model and prior

Bayes: $P(A|B) = P(B|A)P(A)/P(B)$ with: $P(\delta^{(n)}|\delta^{(n+1)}) = 1$

CH model: $\delta_k = c_k \alpha_s^k$ c_k come from geometric series: $|c_k| \leq \bar{c} \quad \forall k$

Geometric model: $|\delta_k| \leq c a^k \quad \forall k$ [Bonvini 2006.16293]

abc model: $b - c \leq \frac{\delta_k}{a^k} \leq b + c \quad \forall k$ [Duhr, Huss, Mazeliauskas, Szafron 2106.04585]

Bayesian approach II

Inclusion of scale dependence: $$P(\delta_{n+1}|\delta_n) = \int \mathrm{d}\mu P(\delta_{n+1}|\delta_n;\mu)P(\mu|\delta_n)$$

Scale marginalisation (the scale becomes a model parameter)

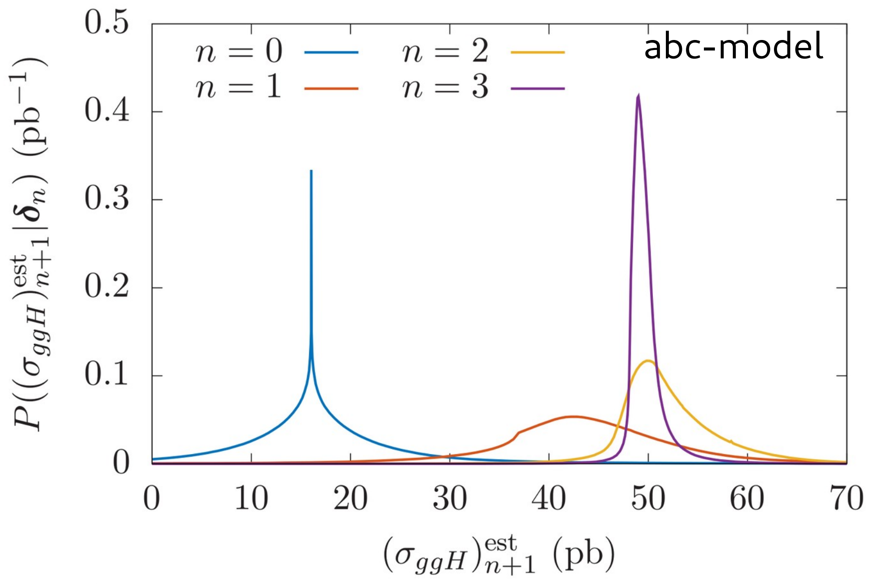
$$\mathcal{P}_{\rm sm}(\Sigma|\boldsymbol{\Sigma}_n) \approx \frac{\int d\mu\, P(\Sigma - \Sigma_n(\mu)|\boldsymbol{\Sigma}_n(\mu))\, P(\boldsymbol{\Sigma}_n(\mu))\, P_0(\mu)}{\int d\mu'\, P(\boldsymbol{\Sigma}_n(\mu'))\, P_0(\mu')}\,. \qquad \mu_{\rm FAC}$$

Scale average (the results are averaged with weight function)

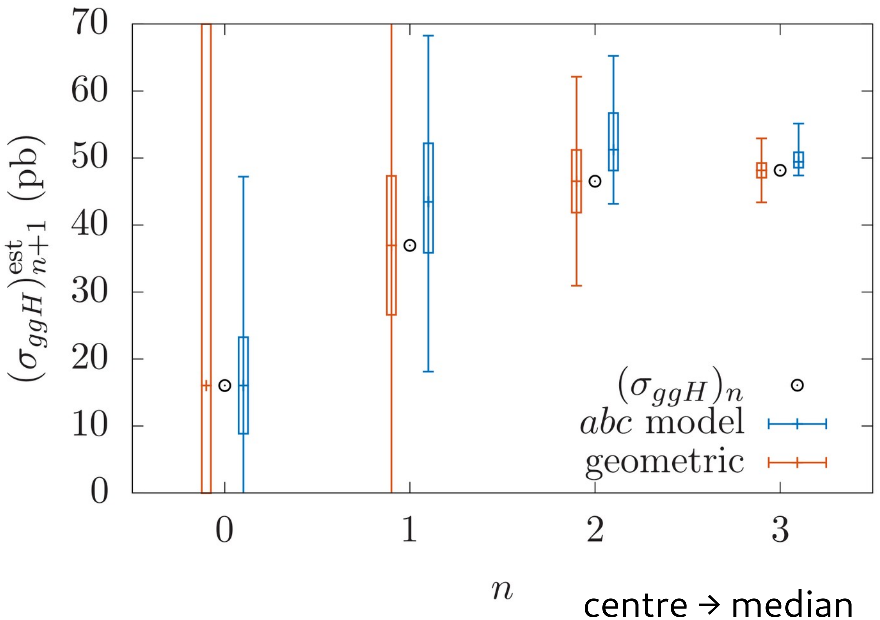
$$\mathcal{P}_{\rm sa}(\Sigma|\boldsymbol{\Sigma}_n) \approx \int d\mu\, w(\mu)\, P(\Sigma - \Sigma_n(\mu)|\boldsymbol{\Sigma}_n(\mu)) \qquad \mu_{\rm PMS}$$

Bayesian approach III

Example: Higgs production in gluon - fusion



Comparison of different unc. estimates:



centre → median
error box → 68% CI
error bar → 95% CI

Introducing theory nuisance parameters (TNPs)

Generic perturbative expansion:

$$f(\alpha) = f_0 + f_1\alpha + f_2\alpha^2 + f_3\alpha^3 + \ldots$$

Beyond Scale Variations: Perturbative Theory Uncertainties from Nuisance Parameters, Frank Tackmann [2411.18606]

$$f^{\mathrm{LO+1}}(\alpha) = \hat{f}_0 + f_1(\theta)\alpha$$

$$f^{\mathrm{NLO+1}}(\alpha) = \hat{f}_0 + \hat{f}_1\alpha + f_2(\theta)\alpha^2$$

$$f^{\mathrm{NNLO+1}}(\alpha) = \hat{f}_0 + \hat{f}_1\alpha + \hat{f}_2\alpha^2 + f_3(\theta)\alpha^3$$

Introduce a parametrisation of unknown coefficients in terms of

"Theory nuisance parameters" θ

- The parametrization such that there is a true value: $f_i(\hat{\theta}) = \hat{f}_i$
- Distributions of θ "known" (for example from already existing computations)

→ Expert knowledge to construct such a parametrisation

Example: TNPs in resummed cross sections

Transverse momentum resummation:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} = \underbrace{[H \times B_a \times B_b \times S]}(\alpha_s, \ln\left(\frac{p_T}{Q}\right)) + \mathcal{O}\left(\frac{p_T}{Q}\right)$$

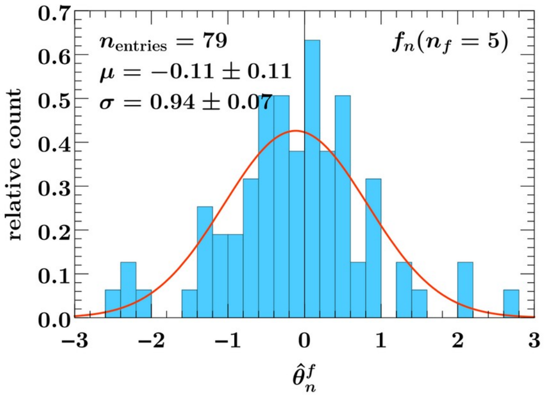
$$X(\alpha_s, L) = X(\alpha_s) \exp \int_0^L \mathrm{d}L' \{\Gamma(\alpha_s(L'))L' + \gamma_X(\alpha_s(L'))\}$$

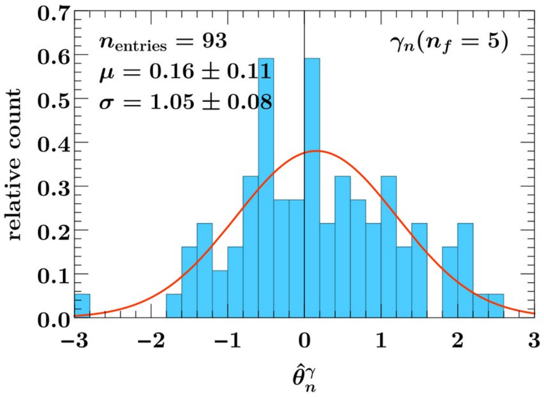
Perturbative expansion of resummation ingredients:

$$X(\alpha_s) = X_0 + \alpha_s X_1 + \alpha_s^2 X_2 + \ldots$$

$$\Gamma(\alpha_s) = \alpha_s[\Gamma_0 + \alpha_s\Gamma_1 + \alpha_s^2\Gamma_2 + \ldots]$$

$$\gamma(\alpha_s) = \alpha_s[\gamma_0 + \alpha_s\gamma_1 + \alpha_s^2\gamma_2 + \ldots]$$





Normalisation:

$$f_n(\theta_n^f) = N_n^f\, \theta_n^f \quad \text{with} \quad N_n^f = 4^n C_r C_A^{n-1}(n-1)!$$

$$\gamma_n(\theta_n^\gamma) = N_n^\gamma\, \theta_n^\gamma \quad \text{with} \quad N_n^\gamma = 4^{n+1} C_r C_A^n$$

Higgs pT spectrum

[Cal,Lim, Scott,Tackmann Waalewijn 2408.13301]

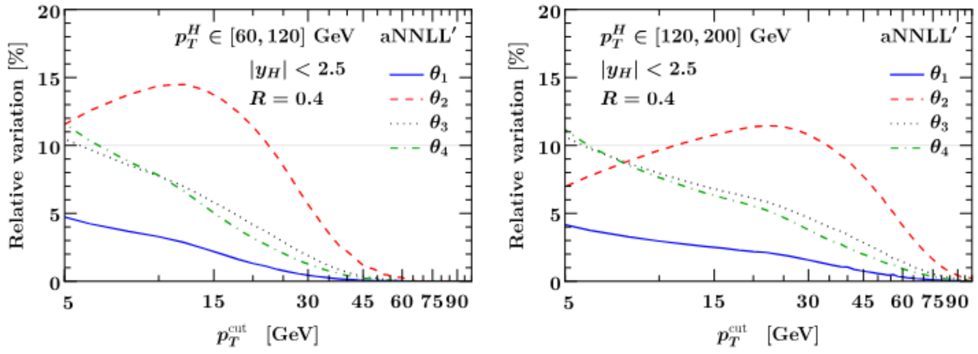
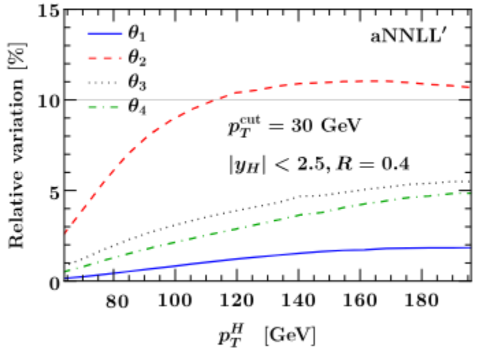


Figure 6: Relative uncertainty from varying each theory nuisance parameter as a function of $p_T^{\rm cut}$ for two different STXS bins.



Example: incomplete knowledge of NNLL resummation

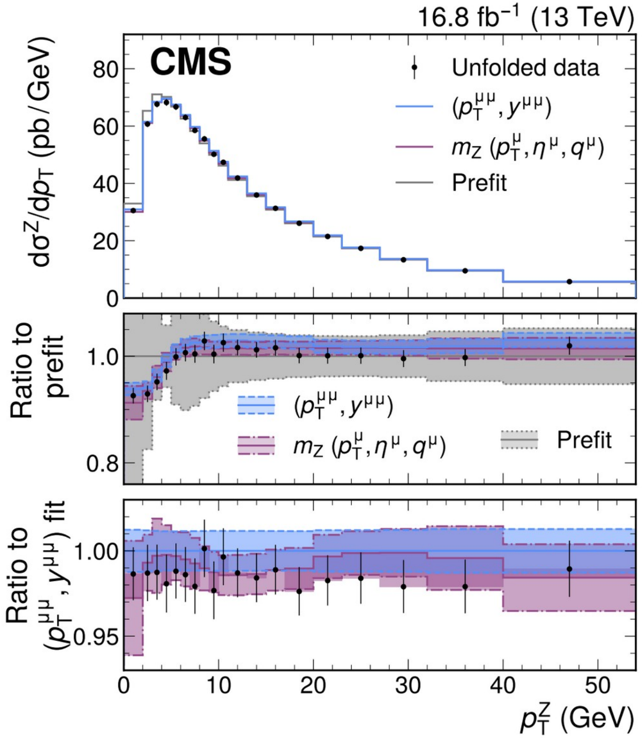
→ some two-loop ingredients unknown
→ parametrise by TNPs

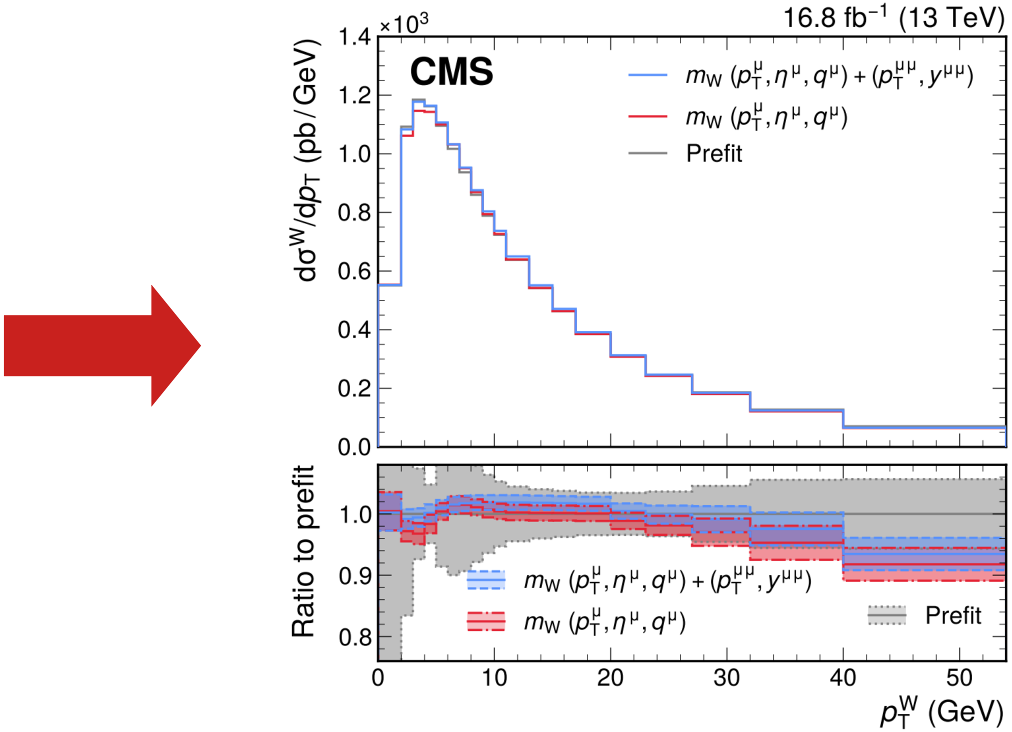
→ Make predictions and vary TNPs:

- correlated uncertainty for different bins!
- See impact of different missing ingredients

Constraint of TNPs from data → W-mass extraction

Resummation ingredients the same for W or Z production
→ constraint from precisely measured pT(Z) → use for pT(W)
→ massive reduction of unc. with correct correlations!





Some remarks on TNPs in resummation

Picture: simple ingredients that enter different computations/processes etc.

→ ideal situation

But actually not that simple:

- Scheme dependence of ingredients? E.g. scales, IR subtraction, …
  → might need modified parametrisations
- Some TNPs represent directly numbers: $\Gamma,\ \gamma,\ H$ for simple processes
  but others are functions → Beam functions, hard functions for more complicated processes
- Parametrisation works for the resummed spectrum. What about other observables?
- "Easy to implement" for use-cases so far
  → might be really expensive if each variation needs a full computations (Monte Carlos,…)

TNP approach for fixed-order computations

[Lim, Poncelet, 2412.14910]

$$\mathrm{d}\sigma = \alpha_s^n N_c^m \,\mathrm{d}\bar{\sigma}^{(0)} + \alpha_s^{n+1} N_c^{m+1}\,\mathrm{d}\bar{\sigma}^{(1)} + \alpha_s^{n+2} N_c^{m+2}\,\mathrm{d}\bar{\sigma}^{(2)} + \dots$$

$$= \alpha_s^n N_c^m \,\mathrm{d}\bar{\sigma}^{(0)} \left[1 + \alpha_s N_c \left(\frac{\mathrm{d}\bar{\sigma}^{(1)}}{\mathrm{d}\bar{\sigma}^{(0)}}\right) + \alpha_s^2 N_c^2 \left(\frac{\mathrm{d}\bar{\sigma}^{(2)}}{\mathrm{d}\bar{\sigma}^{(0)}}\right) + \dots\right]$$

Observation, i.e. "expert knowledge": $\frac{\mathrm{d}\bar{\sigma}^{(i)}}{\mathrm{d}\bar{\sigma}^{(0)}} \sim \mathcal{O}(1)$

Use some knowledge about lower orders but introduce parametric dependence:

$$\frac{\mathrm{d}\bar{\sigma}^{(N+1)}_{\mathrm{TNP}}}{\mathrm{d}\bar{\sigma}^{(0)}} = \sum_{j=1}^{N} f_k^{(j)}\left(\vec{\theta}, x\right)\left(\frac{\mathrm{d}\bar{\sigma}^{(j)}}{\mathrm{d}\bar{\sigma}^{(0)}}\right)$$

x → mapped kinematic variable

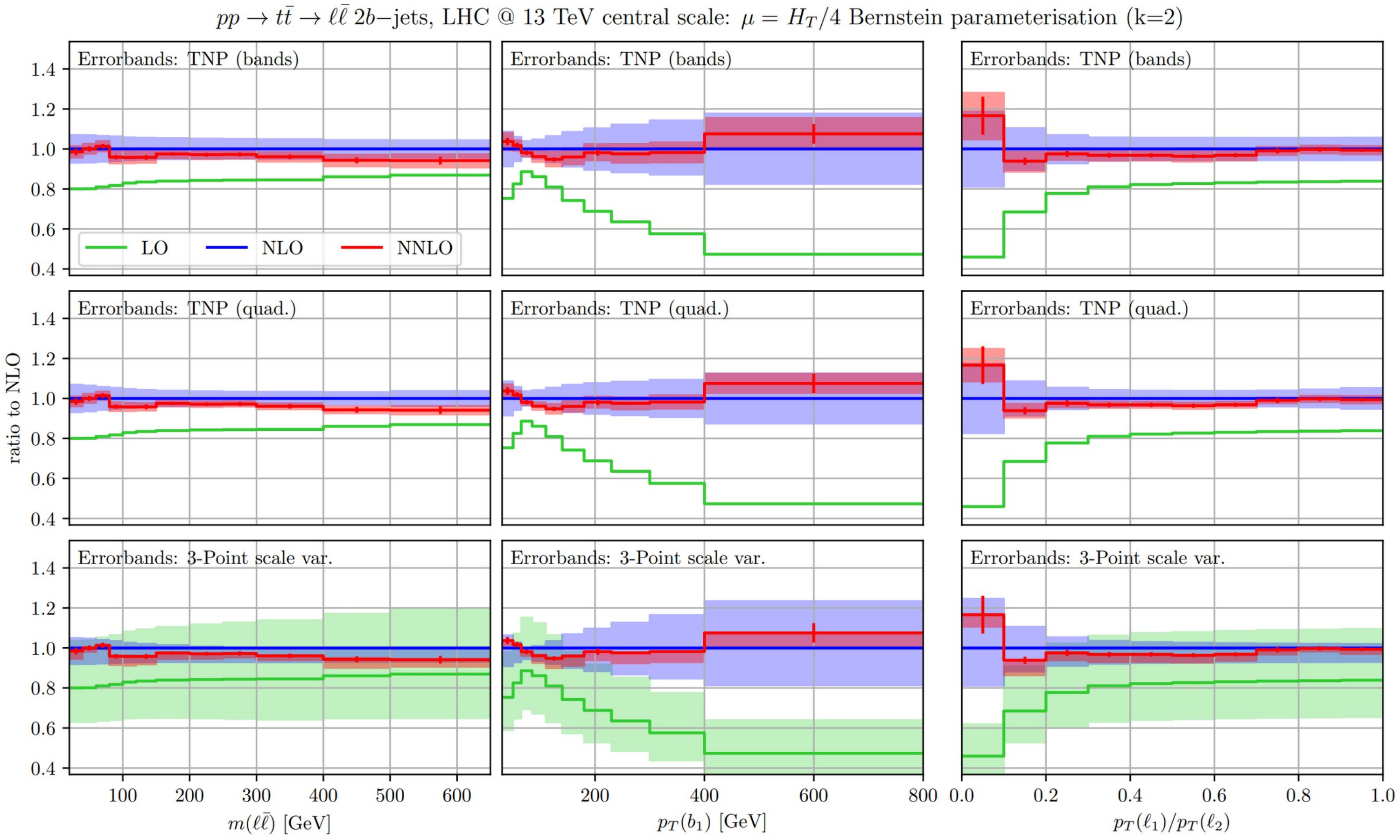
Approximation of original TNP philosophy

→ there is only $f_i(\hat{\theta}) \approx \hat{f}_i$

Bernstein: $f_k^B\left(\vec{\theta}, x\right) = \sum_{i=0}^{k} \theta_i \binom{k}{i} x^{k-i}(1-x)^i$, $x \in [0,1]$

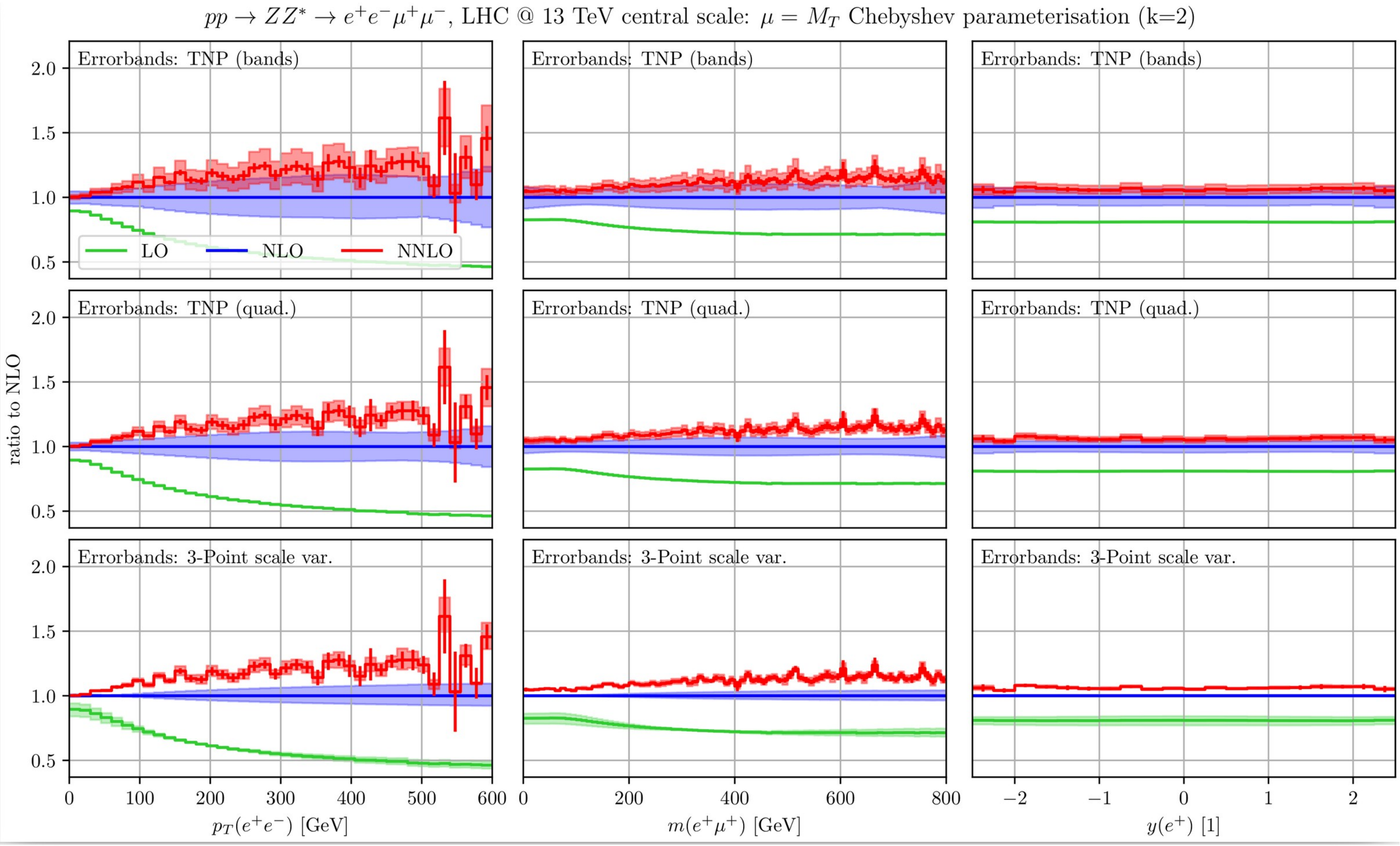
Chebyshev: $f_k^C\left(\vec{\theta}, x\right) = \frac{1}{2}\sum_{i=0}^{k} \theta_i T_i(x)$, $x \in [-1,1]$

Uncertainties from TNPs - ttbar+decays



Band: sample
$\theta \in [-1, 1]$
Quad: add individual
$\theta = \pm 1$
in quadrature

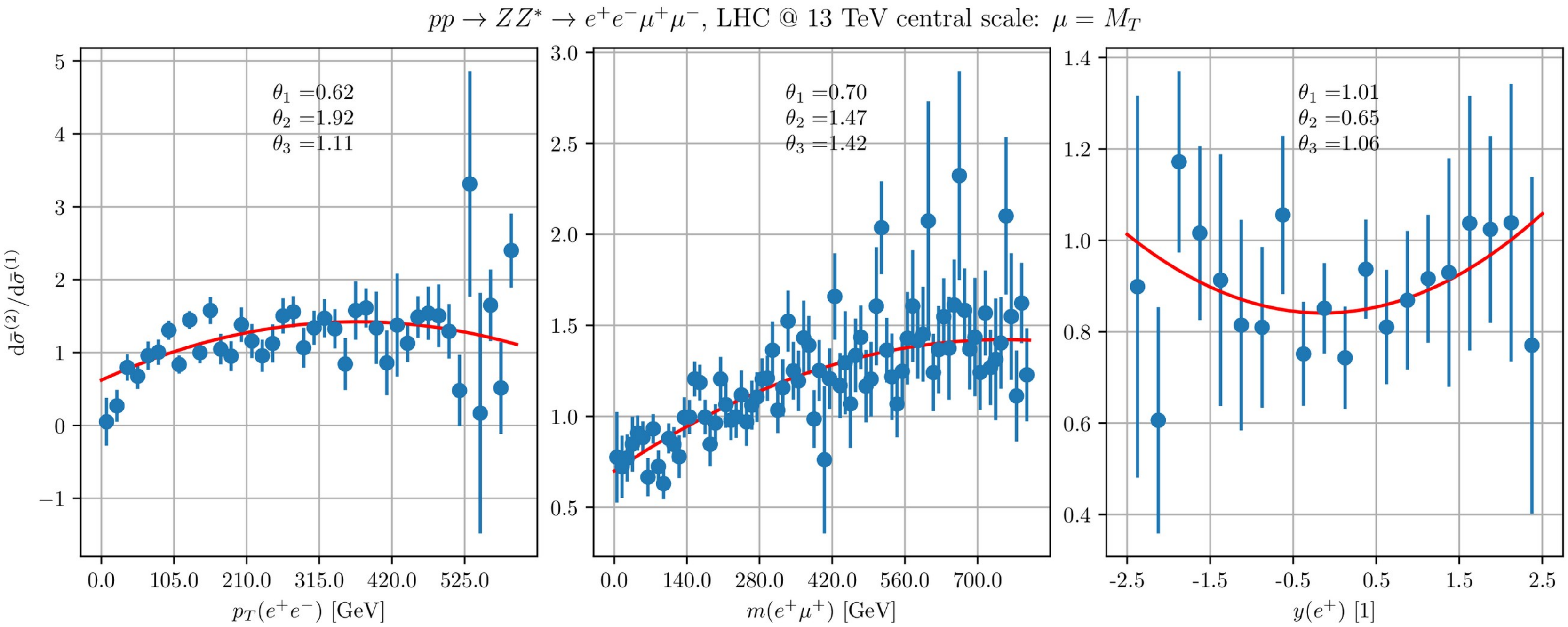
Uncertainties from TNPs - ZZ



Example of TNP fit: pp → ZZ

$$\frac{\mathrm{d}\bar{\sigma}^{(N+1)}_{\mathrm{TNP}}}{\mathrm{d}\bar{\sigma}^{(0)}} = \sum_{j=1}^{N} f_k^{(j)}\left(\vec{\theta}, x\right)\left(\frac{\mathrm{d}\bar{\sigma}^{(j)}}{\mathrm{d}\bar{\sigma}^{(0)}}\right)$$

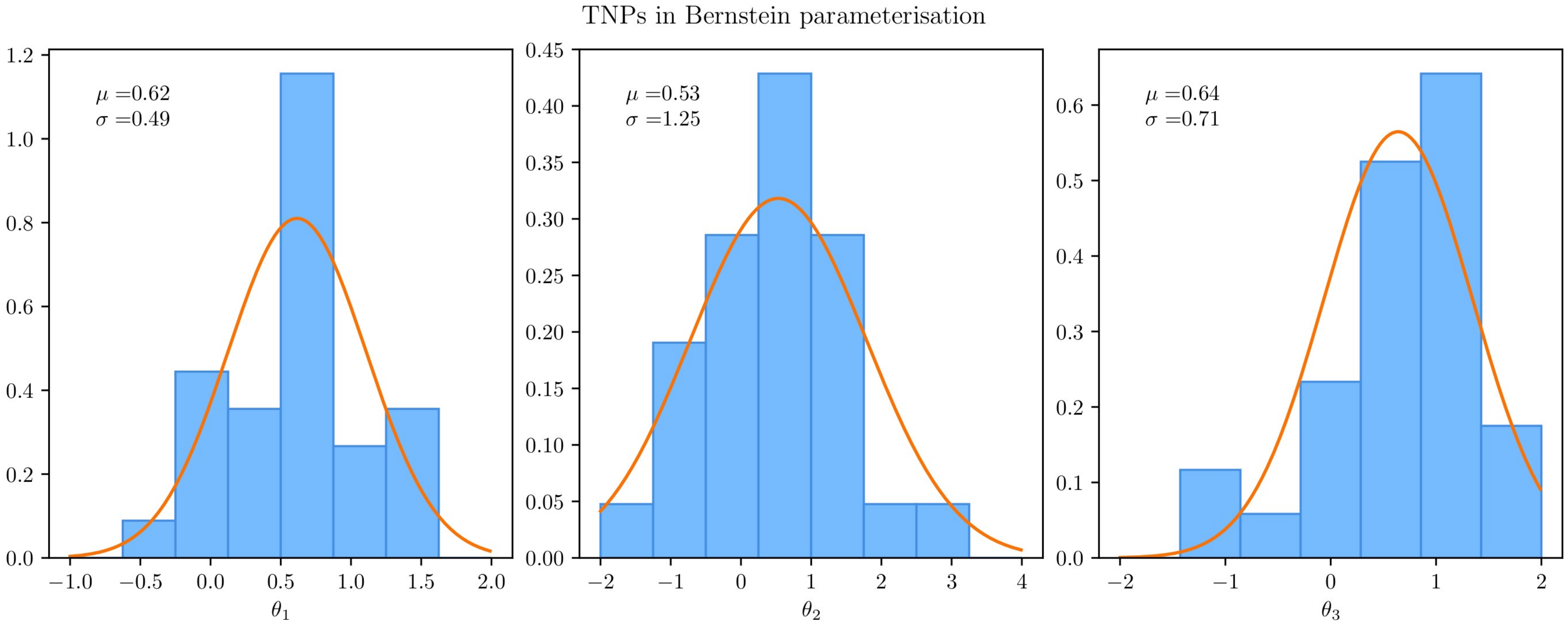
$$f_k^B\left(\vec{\theta}, x\right) = \sum_{i=0}^{k} \theta_i \binom{k}{i} x^{k-i}(1-x)^i$$



Process meta study

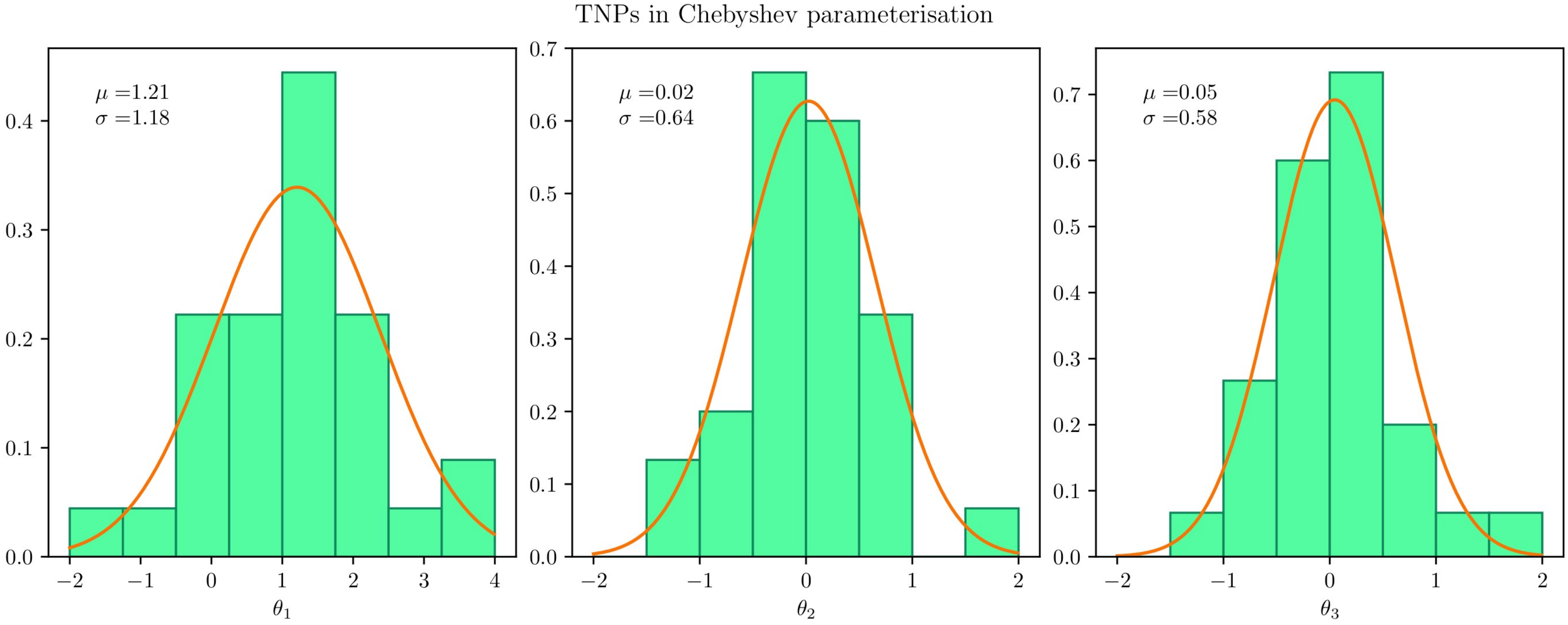
Process	$\sqrt{s}$/TeV	Scale	PDF	Distributions
$pp \to H$ (full theory)	13	$m_H/2$	`NNPDF3.1`	y_H
$pp \to ZZ^* \to e^+e^-\mu^+\mu^-$	13	M_T	`NNPDF3.1`	$M_{e^+\mu^+}$, $p_T^{e^+e^-}$, y_{e^+}
$pp \to WW^* \to e\nu_e\mu\nu_\mu$	13	m_W	`NNPDF3.1`	M_{WW}, $p_T^{\mu^-}$, y_{W^-}
$pp \to (W \to \ell\nu) + c$	13	$E_T + p_T^c$	`NNPDF3.1`	p_T^ℓ ,$\lvert y_\ell \rvert$,
$pp \to t\bar{t}$	13	$H_T/4$	`NNPDF3.1`	$M_{t\bar{t}}$, p_T^t, y_t
$pp \to t\bar{t} \to b\bar{b}\ell\bar{\ell}$	13	$H_T/4$	`NNPDF3.1`	$M_{\ell\bar{\ell}}$, $p_T^{b_1}$, $p_{T,\ell_1}/p_{T,\ell_2}$
$pp \to \gamma\gamma$	8	$M_{\gamma\gamma}$	`NNPDF3.1`	$M_{\gamma\gamma}$, $p_T^{\gamma_1}$, $y_{\gamma\gamma}$
$pp \to \gamma\gamma j$	13	$H_T/2$	`NNPDF3.1`	$M_{\gamma\gamma}$, $p_T^{\gamma\gamma}$, $\cos\phi_{\mathrm{CS}}$, $\lvert y_{\gamma_1}\rvert$, $\Delta\phi_{\gamma\gamma}$
$pp \to jjj$	13	$\hat{H}_T$	`MMHT2014`	TEEC with $H_{T,2} \in [1000, 1500), [1500, 2000), [3500, \infty)$ GeV
$pp \to \gamma jj$	13	H_T	`NNPDF3.1`	$M_{\gamma jj}$, p_T^j, $\lvert y_{\gamma-\mathrm{jet}}\rvert$, $E_{T,\gamma}$

Fits - Bernstein parametrisation



$$f_k^B\left(\vec{\theta}, x\right) = \sum_{i=0}^{k} \theta_i \begin{pmatrix} k \\ i \end{pmatrix} x^{k-i}(1-x)^i$$

Fits - Chebyshev parametrisation

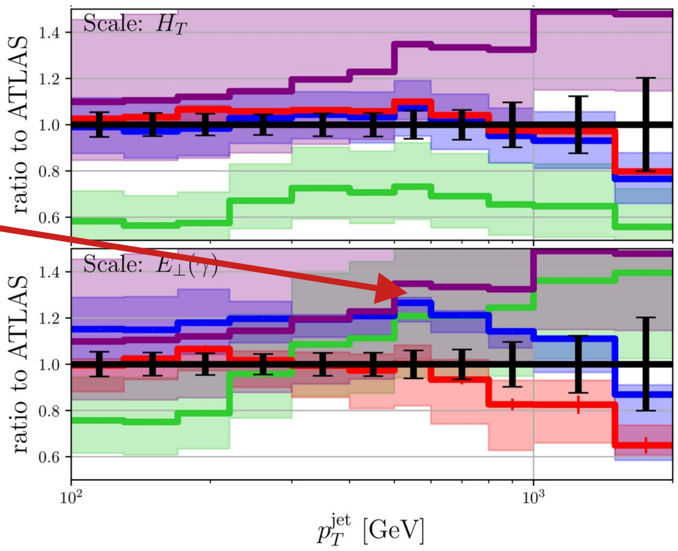


$$f_k^C\left(\vec{\theta}, x\right) = \frac{1}{2}\sum_{i=0}^{k} \theta_i T_i(x)$$

Caveats and open questions

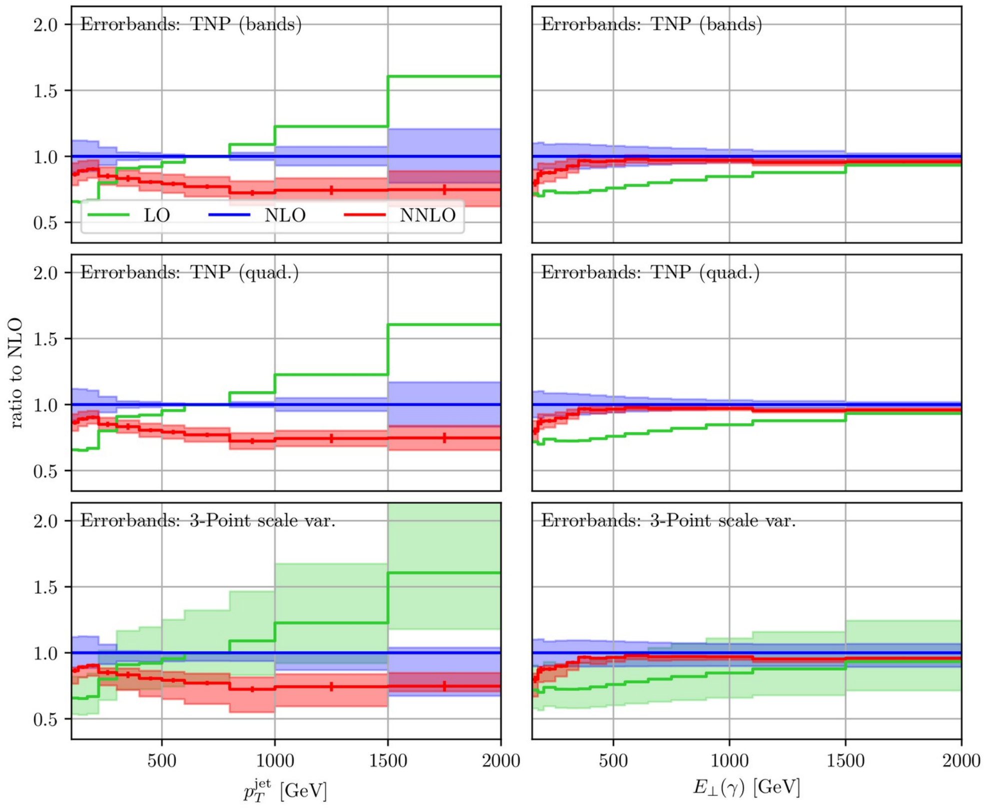
Some arising questions regarding fixed-order model: $\frac{d\bar{\sigma}^{(N+1)}_{\mathrm{TNP}}}{d\bar{\sigma}^{(0)}} = \sum_{j=1}^{N} f_k^{(j)}\left(\vec{\theta}, x\right)\left(\frac{d\bar{\sigma}^{(j)}}{d\bar{\sigma}^{(0)}}\right)$

- How does the uncertainty estimate depend on the central scale choice?
  → **bad scale choices lead to large uncertainties by construction due to large corrections.**
- What about NLO uncertainty if $d\bar{\sigma}^{(1)} = 0$ for given scale?
  → **amend parametrisation by j = 0 term.**
- How sensitive are we to the parametrisation? How many terms?
  → **two quite general parametrisations tested, increase degree by demand.**

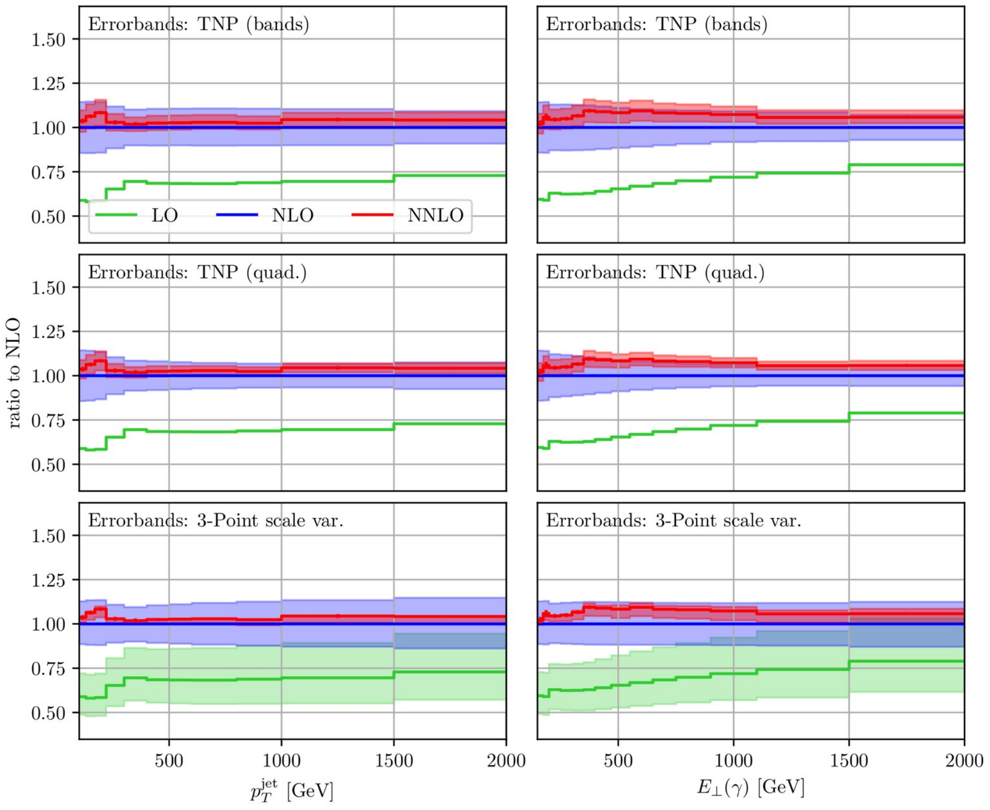


Challenging case

“Bad” scale choice $\mu = E_T$ no j=0 term

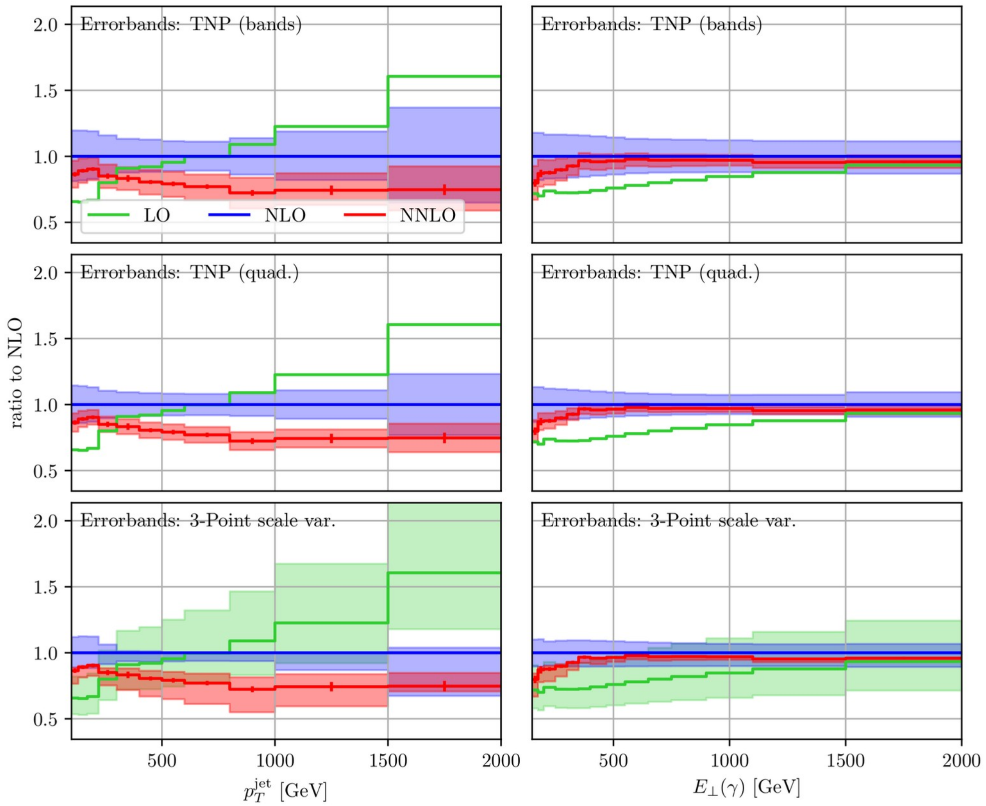


“Good” choice $\mu = H_T$ no j=0 term

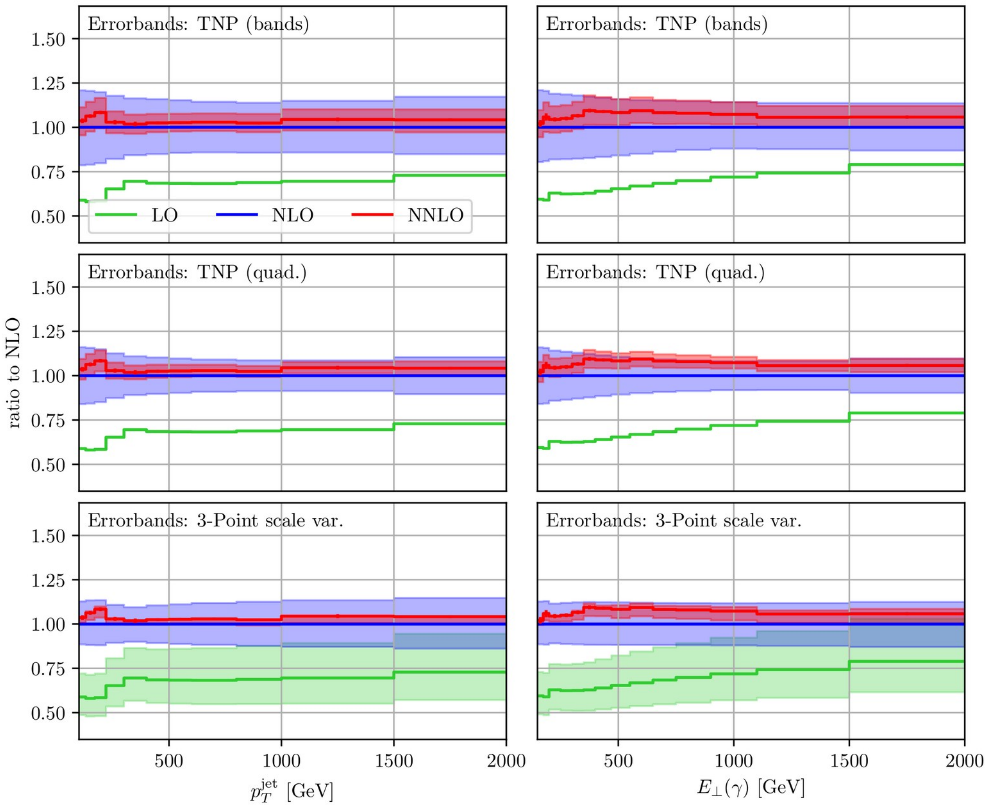


Challenging case → extended parametrisations

"Bad" scale choice $\mu = E_T$ with j=0 term

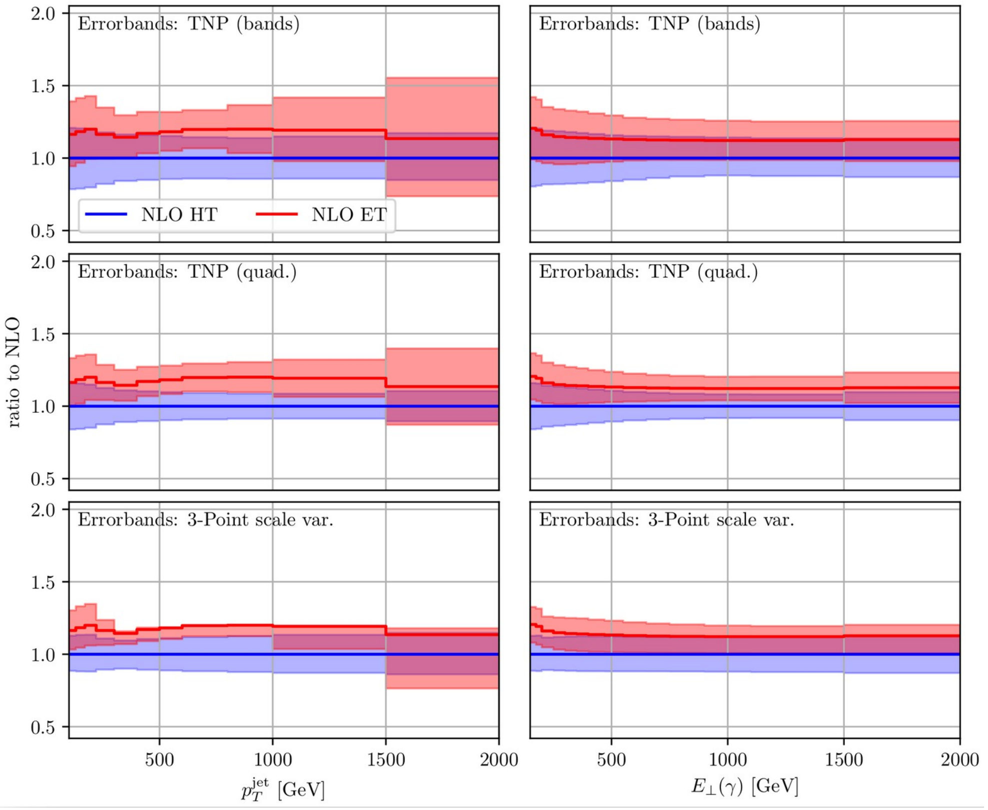


"Good" choice $\mu = H_T$ with j=0 term

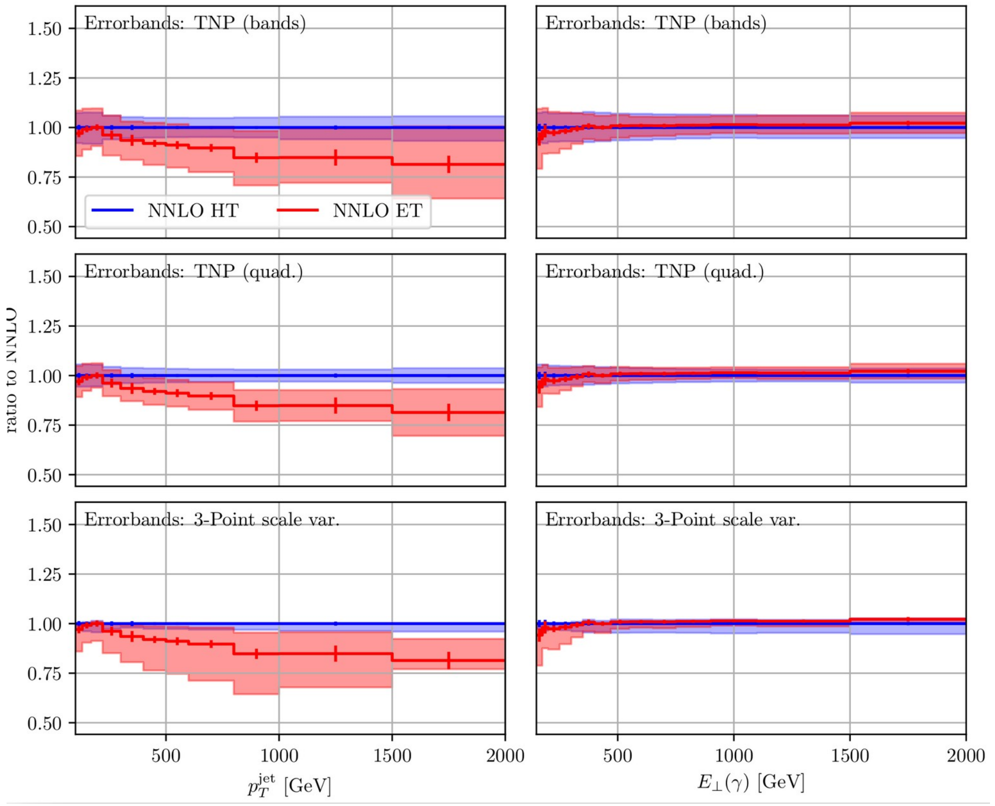


Challenging case → comparisons

NLO QCD



NNLO QCD



More caveats and open questions

Some arising questions regarding fixed-order model:

$$\frac{\mathrm{d}\bar{\sigma}^{(N+1)}_{\mathrm{TNP}}}{\mathrm{d}\bar{\sigma}^{(0)}} = \sum_{j=1}^{N} f_k^{(j)}\left(\vec{\theta}, x\right)\left(\frac{\mathrm{d}\bar{\sigma}^{(j)}}{\mathrm{d}\bar{\sigma}^{(0)}}\right)$$

- Each parametrisation is for one observable at a time
  - How to deal with higher dimensional distributions?
  - Consistency upon integration?

→ **work in progress**

- What about EW corrections?
  → **here the approach should work well for Sudakov logs!**
  → **Radiation from resonances more difficult.**
- How to correlate different processes?
  → **that’s tricky…**

$$\mathrm{d}\bar{\sigma}^{(n)}(\theta) = \mathrm{d}\Phi \left\langle M^0 \middle| \mathcal{P}(\theta) \middle| M^0 \right\rangle$$

$\mathcal{P}(\theta)$ → process-independent “operator”

Discussion/Summary/Outlook

- Theory precision is more and more relevant → needs accurate uncertainty estimates
- De-facto standard: scale variations
  → various short-comings: robustness, no statistical interpretation, correlations,…
- Alternative approaches to scale variations: Bayesian and TNP approach
- Theory Nuisance Parameters
  - In principle less biased →does not depend on any “known” orders
  - Statistical interpretation
  - Needs “expert knowledge”
  - Resummed computations are well-suited scenario
  - Fixed-order more difficult: not much knowledge about higher-order terms
    Proposed TNP parametrisation shows promising results
    → applications to fits