

Simultaneous CTEQ-TEA extraction of PDFs and SMEFT parameters from jet and $t\bar{t}$ data

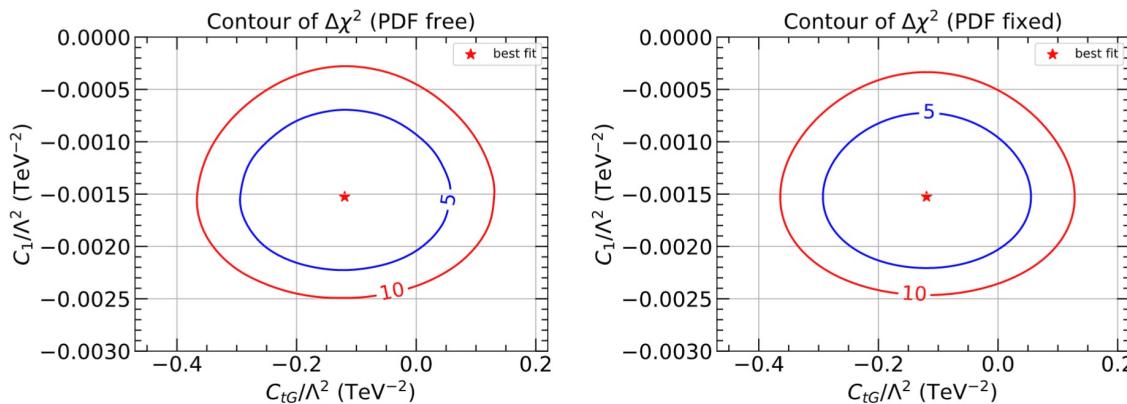
arXiv:2211.01094

Jun Gao^{1,2}, MeiSen Gao^{1,2}, T. J. Hobbs³, DianYu Liu^{1,2}, and XiaoMin Shen^{1,2}

¹Shanghai Jiao-Tong University

²Key Laboratory for Particle Astrophysics and Cosmology (MOE), Shanghai

³HEP Division, Argonne National Laboratory



presented by Tim Hobbs

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motivation

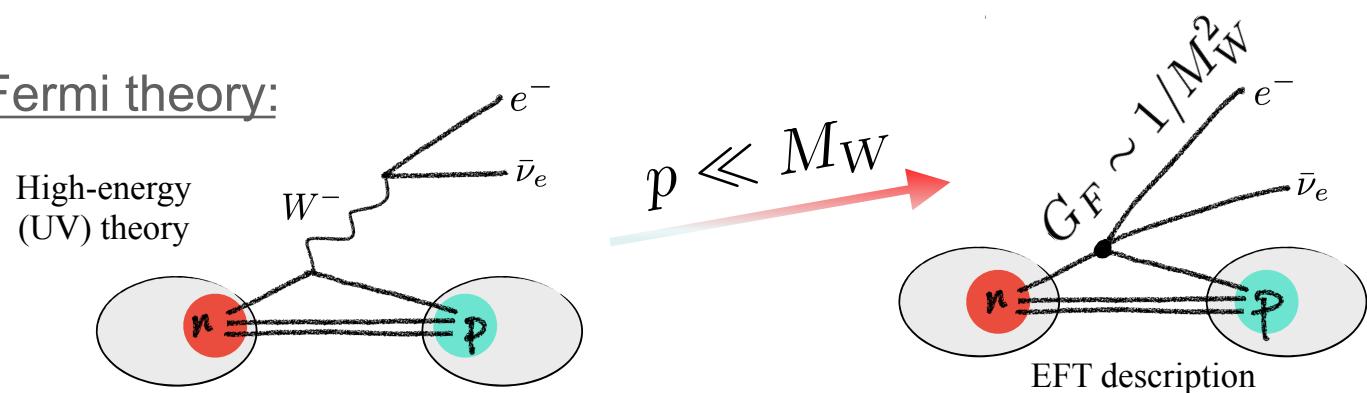
- strong recent interest: model-independent BSM analyses
 - EFT-based parametrizations: *e.g.*, SM effective field theory (SMEFT)
- EFT global analyses often assumed *fixed* SM calculations
 - PDFs not actively fitted alongside **SMEFT parameters**
 - could potentially bias resulting SMEFT analysis
- some recent studies: preliminary attempts at joint SMEFT/PDF fits
 - this work: explore in context of CTEQ-TEA (CT) framework
 - demonstration study focusing on select data: jet, $t\bar{t}$ production
 - examine possible PDF-SMEFT correlations

basics of SMEFT

- presume BSM scale above the electroweak, $\Lambda \gg M_{W,Z}$
 - explicit non-standard degrees-of-freedom may be integrated away
 - leaves behind basis of higher-dimensional operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i O_i^{(6)}}{\Lambda^2} + \dots \quad \text{built from SM field content!}$$

analogous EFT – Fermi theory:



- BSM quantified via nonzero Wilson coefficients, $C_i \neq 0$
 - extract from global fit alongside PDFs

selecting dominant SMEFT operators

- this study: dim-6 operators only
 - dim-8 contributions small (may be relevant for future precision)
 - consider several SMEFT operators associated with jet, $t\bar{t}$

jet production: contact interaction

$$O_1 = 2\pi \left(\sum_{i=1}^3 \bar{q}_{Li} \gamma_\mu q_{Li} \right) \left(\sum_{j=1}^3 \bar{q}_{Lj} \gamma^\mu q_{Lj} \right)$$

Warsaw operator basis

top production

$$\begin{aligned} O_{tu}^1 &= \sum_{i=1}^2 (\bar{t} \gamma_\mu t) (\bar{u}_i \gamma^\mu u_i) , \\ O_{td}^1 &= \sum_{i=1}^3 (\bar{t} \gamma^\mu t) (\bar{d}_i \gamma_\mu d_i) , \\ O_{tG} &= ig_s (\bar{Q}_{L,3} \tau^{\mu\nu} T^A t) \tilde{\varphi} G_{\mu\nu}^A + \text{h.c.} , \\ O_{tq}^8 &= \sum_{i=1}^2 (\bar{Q}_i \gamma_\mu T^A Q_i) (\bar{t} \gamma^\mu T^A t) , \end{aligned}$$

- have imposed multiple symmetries on SMEFT space

theory calculation setup

- nonzero Wilson coeffs.: finite SMEFT contributions to X-sections
 - pure SM, pure dim-6 SMEFT, and *interference* pieces:

$$\frac{d\sigma}{d\hat{O}} = \frac{d\sigma_{\text{SM}}}{d\hat{O}} + \sum_i \frac{d\tilde{\sigma}_i}{d\hat{O}} \frac{C_i}{\Lambda^2} + \sum_{i,j} \frac{d\tilde{\sigma}_{ij}}{d\hat{O}} \frac{C_i C_j}{\Lambda^4}$$

- relevant for interference term, SMEFT-QCD computed to NLO
- constrain Wilson coefficients, $C(\mu_c)/\Lambda^2$, for $\mu_c = 1 \text{ TeV}$

- status of theory calculations, uncertainties for all processes:

observable	μ_0	SM QCD	SM EW	SMEFT QCD	th. unc.
$t\bar{t}$ total	m_t	NNLO+NNLL	no	NLO	$\mu_{F,R}$ var.
$t\bar{t}$ p_T dist.	$m_T/2$	NNLO	NLO	NLO	$\mu_{F,R}$ var.
$t\bar{t}$ $m_{t\bar{t}}$ dist.	$H_T/4$	NNLO(+NLP)	NLO	NLO	$\mu_{F,R}$ var.
$t\bar{t}$ 2D dist.	$H_T/4$	NNLO	no	NLO	no
inc. jet	$p_{T,j}$	NNLO	NLO	NLO	0.5% uncor.
dijet	m_{jj}	NNLO	NLO	NLO	0.5% uncor

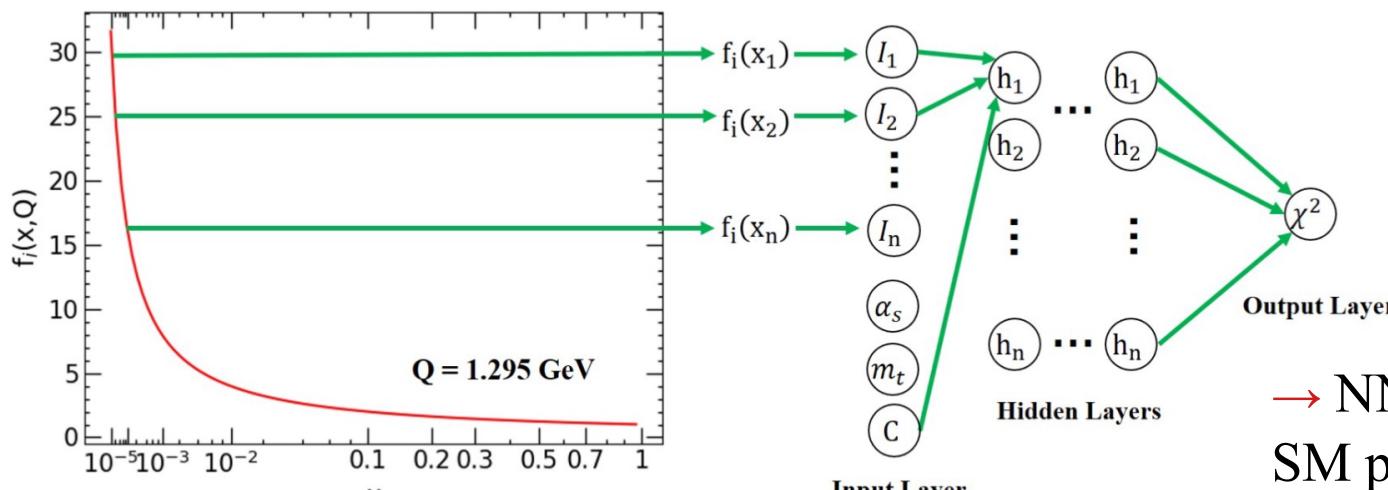
learning log-likelihoods through neural net training

- quantify agreement of theory/data through χ^2 :

$$\chi^2(\{a_\ell\}, \{\lambda\}) = \sum_{k=1}^{N_{\text{pt}}} \frac{1}{s_k^2} \left(D_k - T_k(\{a_\ell\}) - \sum_{\alpha=1}^{N_\lambda} \beta_{k,\alpha} \lambda_\alpha \right)^2 + \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha^2$$

→ train a feed-forward neural network (NN) on PDF replicas

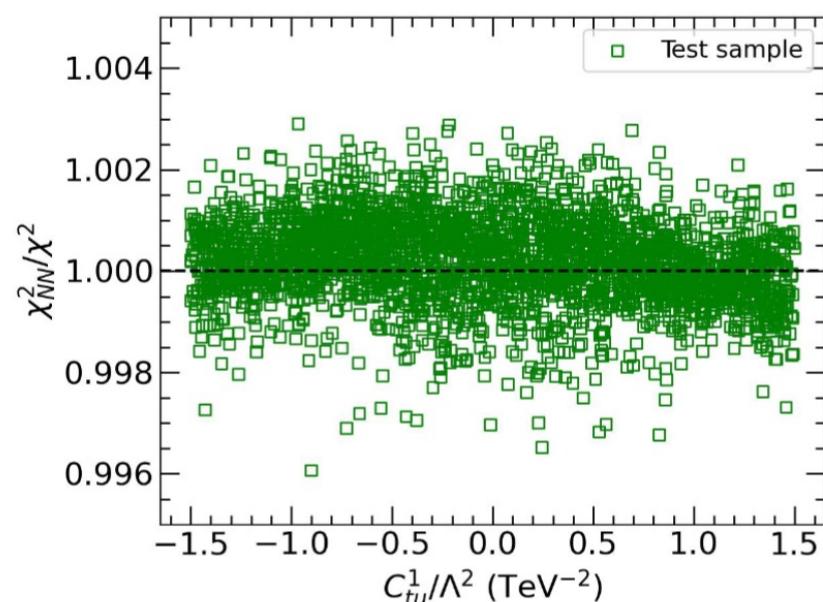
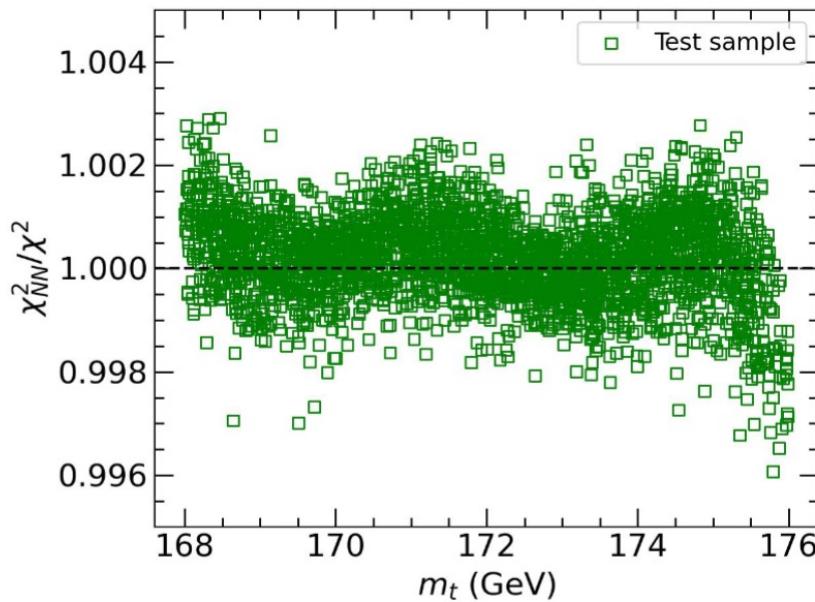
Liu, Sun, and Gao; arXiv: [2201.06586](https://arxiv.org/abs/2201.06586)



→ NN associates PDFs, SM parameters, SMEFT coefficients with χ^2

NNs effectively learn (PDF-SMEFT) likelihood function

- generate 1.2×10^4 replicas over PDFs, SM parameters, SMEFT coeffs.
 - validate performance on 4×10^3 test set



→ strong, permille-level agreement achieved!

(NB: perfect agreement corresponds to $\chi_{\text{NN}}^2/\chi^2 = 1$)

- allows *rapid* exploration of combined PDF-SMEFT uncertainties

explore SMEFT constraints from range of LHC expts

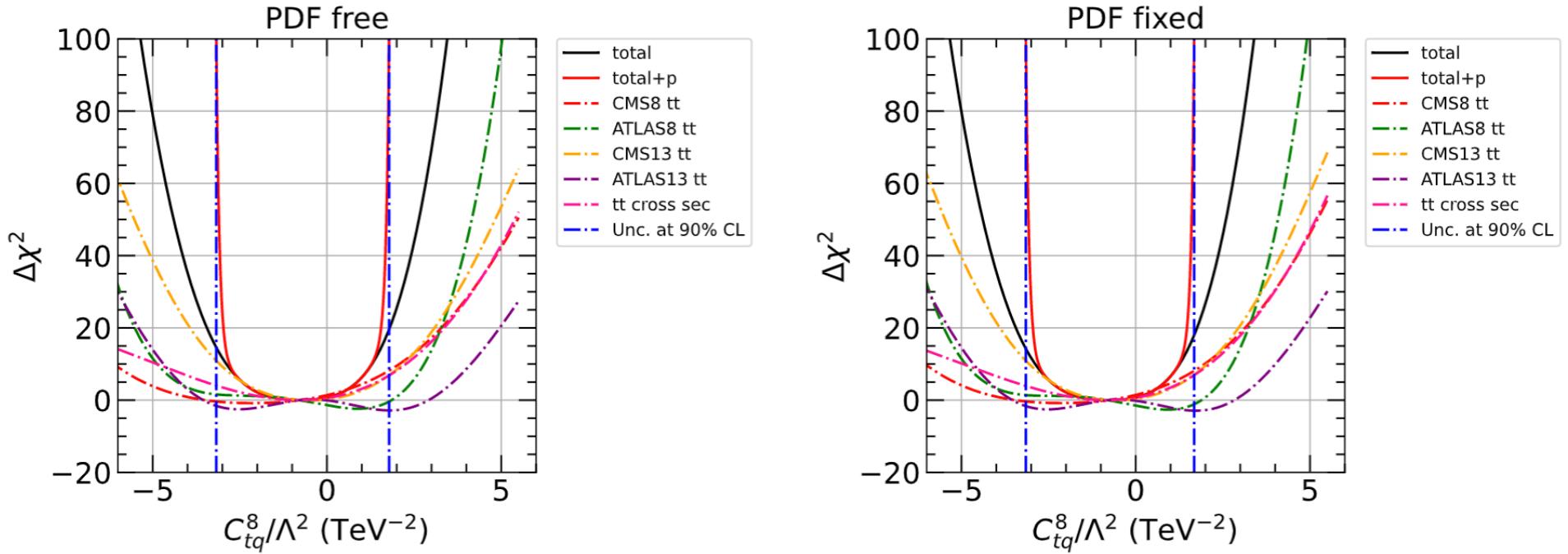
- included on top of default CT18 fitted experiments
 - nominally fit $\sim 112 \text{ fb}^{-1}$ of top data; $\sim 67 \text{ fb}^{-1}$ for jet production

Experiments	$\sqrt{s}(\text{TeV})$	$\mathcal{L}(\text{fb}^{-1})$	observable	N_{pt}
*† LHC(Tevatron)	7/8/13(1.96)	—	$t\bar{t}$ total cross section	8
*† ATLAS $t\bar{t}$	8	20.3	1D dis. in $p_{T,t}$ or $m_{t\bar{t}}$	15
*† CMS $t\bar{t}$	8	19.7	2D dis. in $p_{T,t}$ and y_t	16
CMS $t\bar{t}$	8	19.7	1D dis. in $m_{t\bar{t}}$	7
*† ATLAS $t\bar{t}$	13	36	1D dis. in $m_{t\bar{t}}$	7
*† CMS $t\bar{t}$	13	35.9	1D dis. in $m_{t\bar{t}}$	7
*† CDF II inc. jet	1.96	1.13	2D dis. in p_T and y	72
*† D0 II inc. jet	1.96	0.7	2D dis. in p_T and y	110
*† ATLAS inc. jet	7	4.5	2D dis. in p_T and y	140
*† CMS inc. jet	7	5	2D dis. in p_T and y	158
* CMS inc. jet	8	19.7	2D dis. in p_T and y	185
† CMS dijet	8	19.7	3D dis. in $p_T^{ave.}$, y_b and y^*	122
† CMS inc. jet	13	36.3	2D dis. in p_T and y	78

*(in nominal top fits); †(in nominal jet fits)

examine SMEFT uncertainties in joint PDF fit

- quantify SMEFT uncert. through Lagrange Multiplier (LM) scans:



→ constraints to top-associated Wilson coefficient, C_{tq}^8/Λ^2

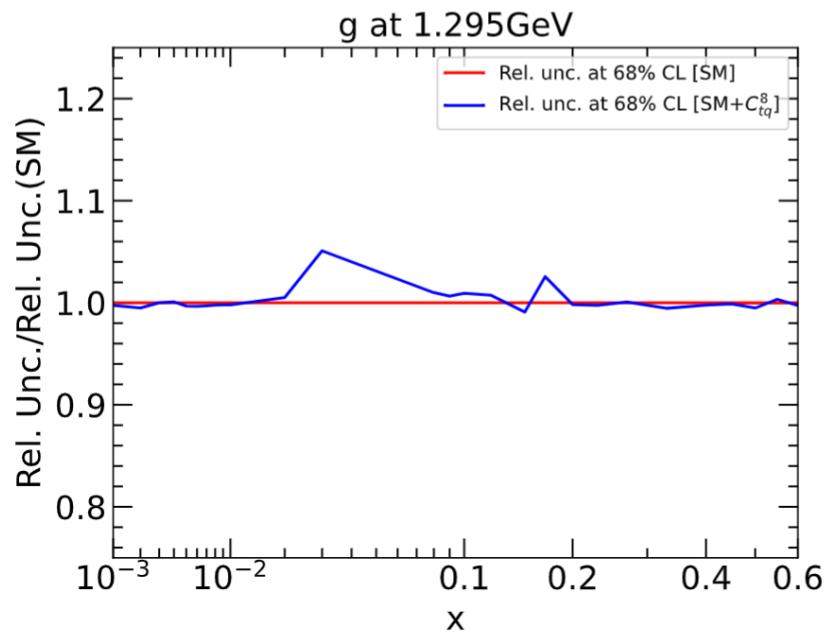
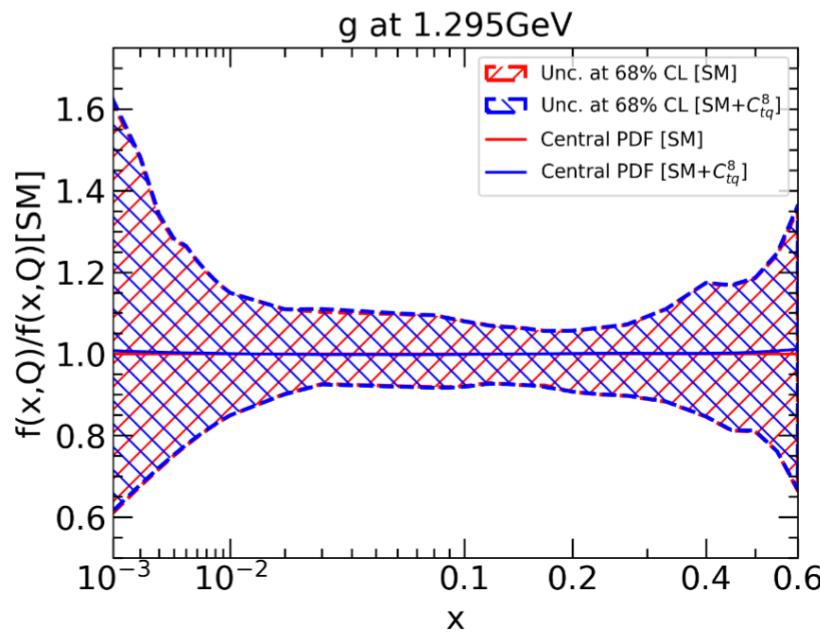
- modest increase in uncertainty when co-fitted with PDFs
- predominantly *quartic* shapes for $\Delta\chi^2$ reflect pure SMEFT contributions $\sim \frac{1}{\Lambda^4}$

joint fits: very weak correlations with PDFs' x dependence

- SMEFT coefficient uncertainties depend on active fitting of PDFs:

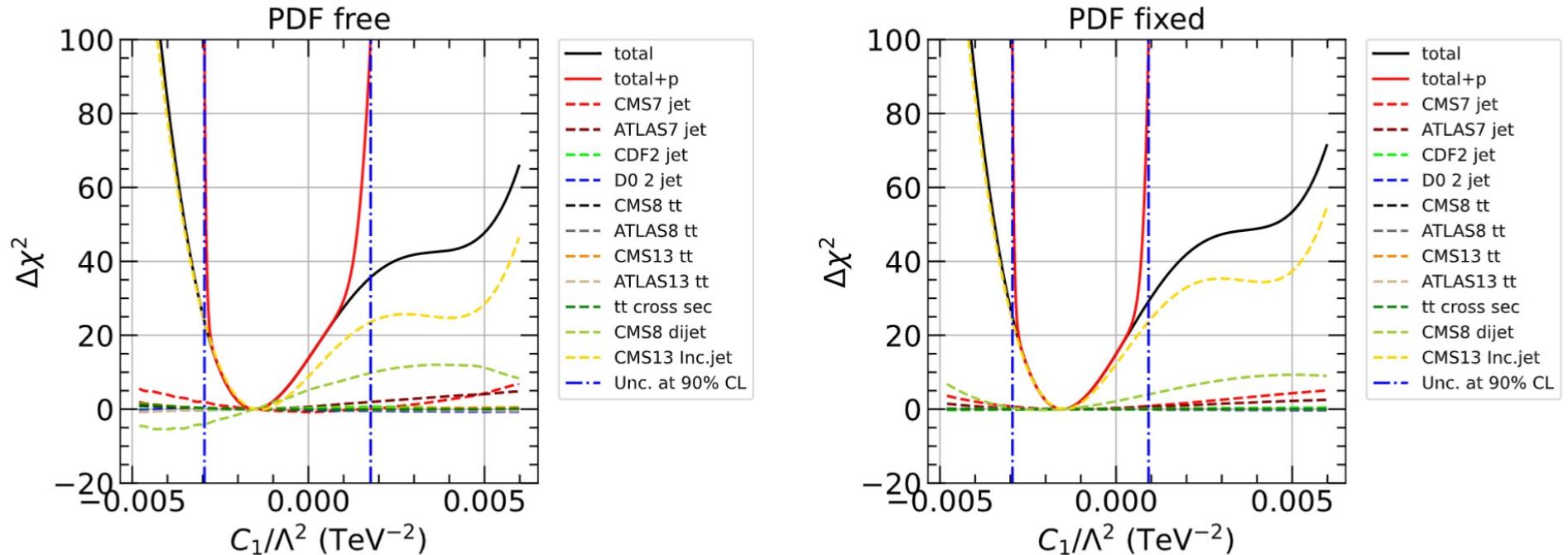
TeV^{-2}	nominal	PDF fixed	no the. unc.
C_{tu}^1/Λ^2	$0.14^{+0.61}_{-0.97}$	$0.14^{+0.60}_{-0.95}$	$0.14^{+0.57}_{-0.92}$
C_{tq}^8/Λ^2	$-0.80^{+2.58}_{-2.38}$	$-0.80^{+2.48}_{-2.35}$	-
C_{tG}/Λ^2	$-0.10^{+0.26}_{-0.30}$	$-0.10^{+0.25}_{-0.30}$	-

- small variations in gluon PDF, unc. from co-fitting SMEFT:



analogous joint fits: jet data and contact interaction

- fitted jet data modestly sensitive to C_1 :

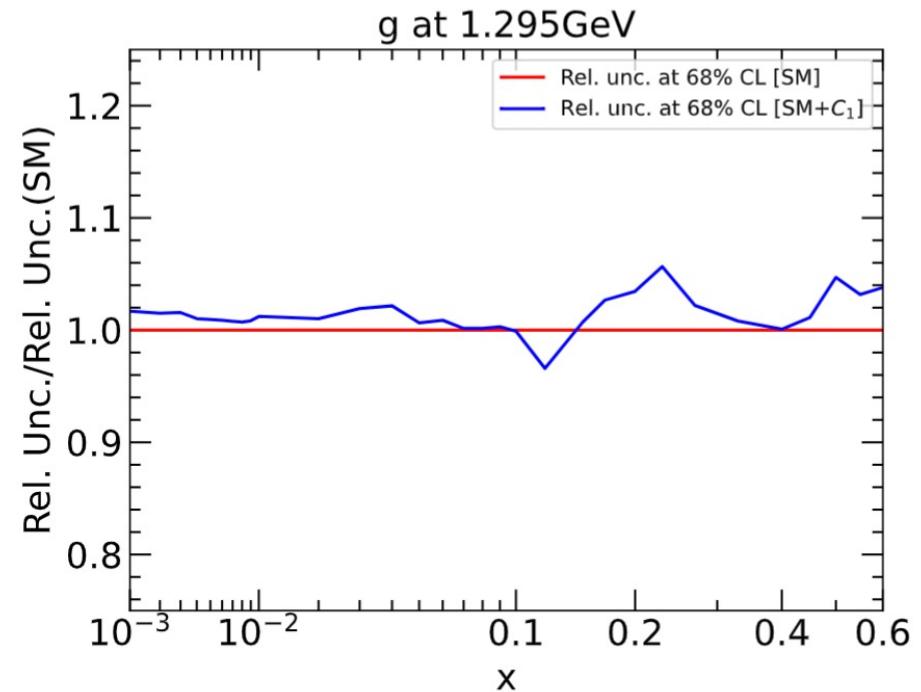
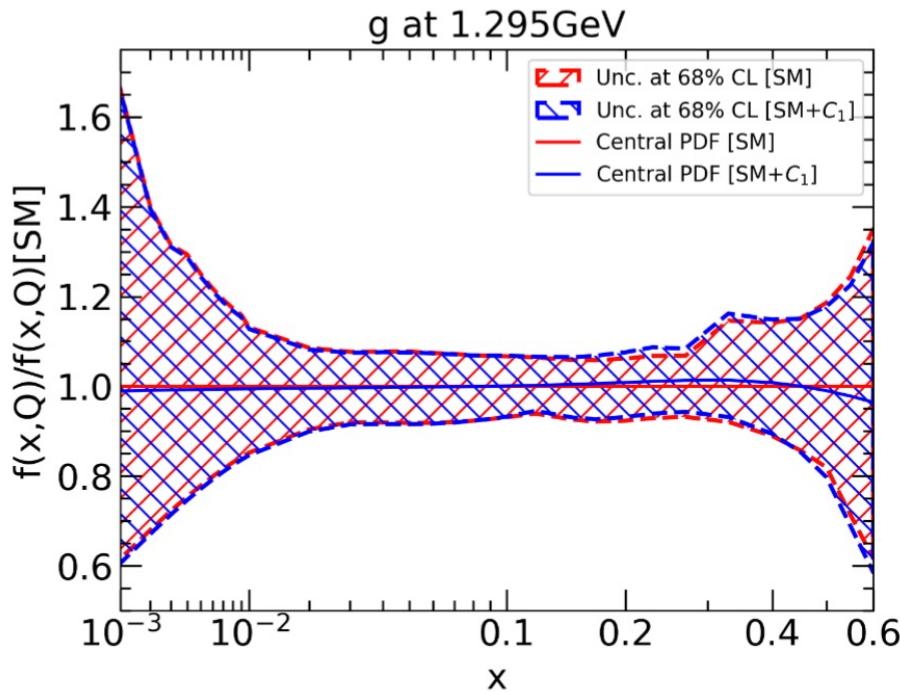


- leading SMEFT sensitivity from CMS: 13 TeV incl. jet, 8 TeV dijet data
- fixing PDFs: (slightly) larger uncertainty underestimate

TeV^{-2}	nominal	CMS 8 dijet	CMS 8 jet	CMS 13 jet
PDF free	$-0.0015^{+0.0033}_{-0.0014}$	$-0.0022^{+0.0187}_{-0.0054}$	$-0.0009^{+0.0138}_{-0.0045}$	$-0.0013^{+0.0059}_{-0.0016}$
PDF fixed	$-0.0015^{+0.0024}_{-0.0014}$	$-0.0022^{+0.0180}_{-0.0051}$	$-0.0009^{+0.0131}_{-0.0049}$	$-0.0013^{+0.0026}_{-0.0015}$

more pronounced PDF correlation for jet data

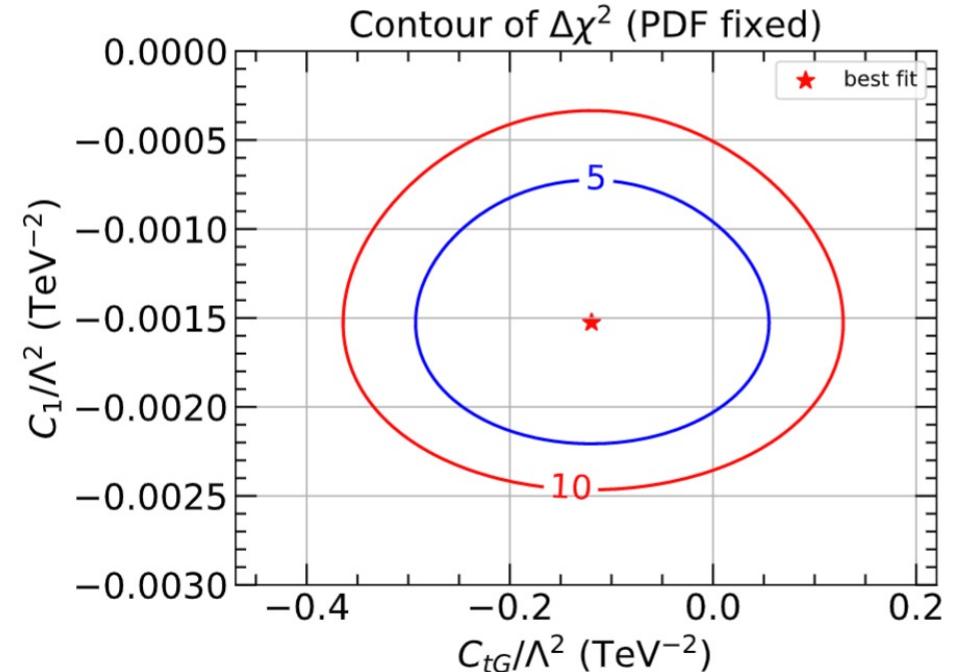
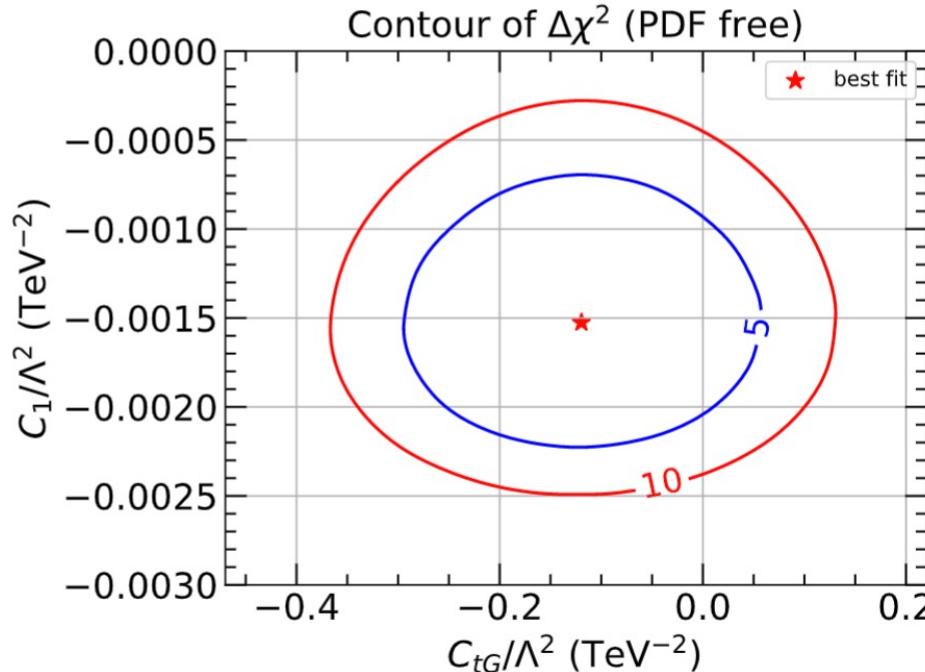
- jointly fitting contact interaction to jet prod. shifts gluon PDF



- effect somewhat greater at large $x > 0.1$
- suggests slightly stronger correlation of gluon PDF with C_1

correlations between SMEFT coefficients are mild

- co-varying top-, jet-associated coeffs. minimally effects uncertainties

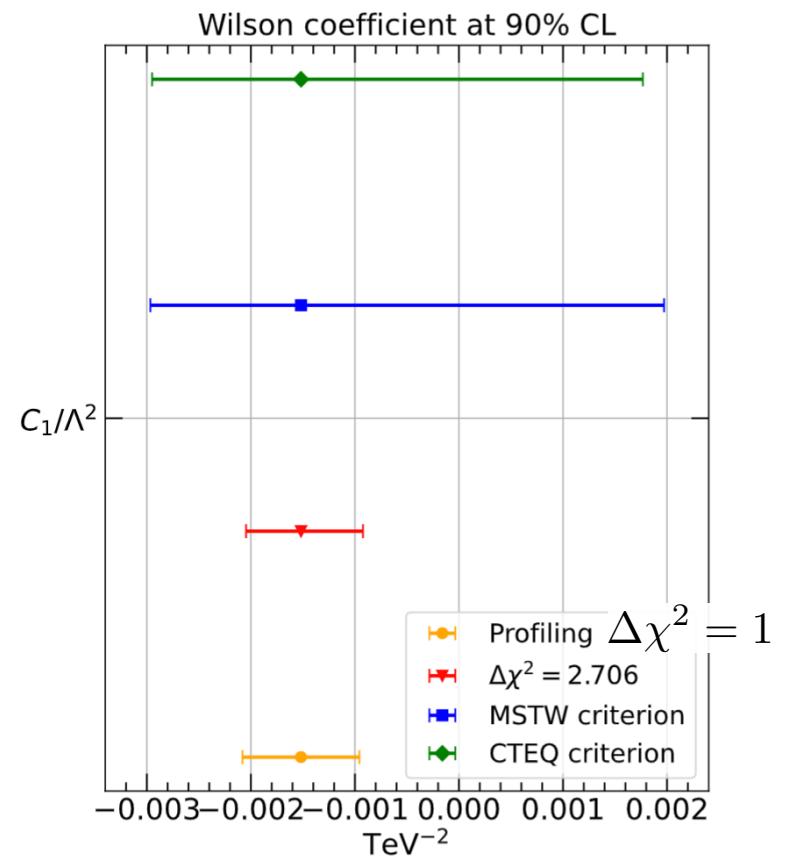
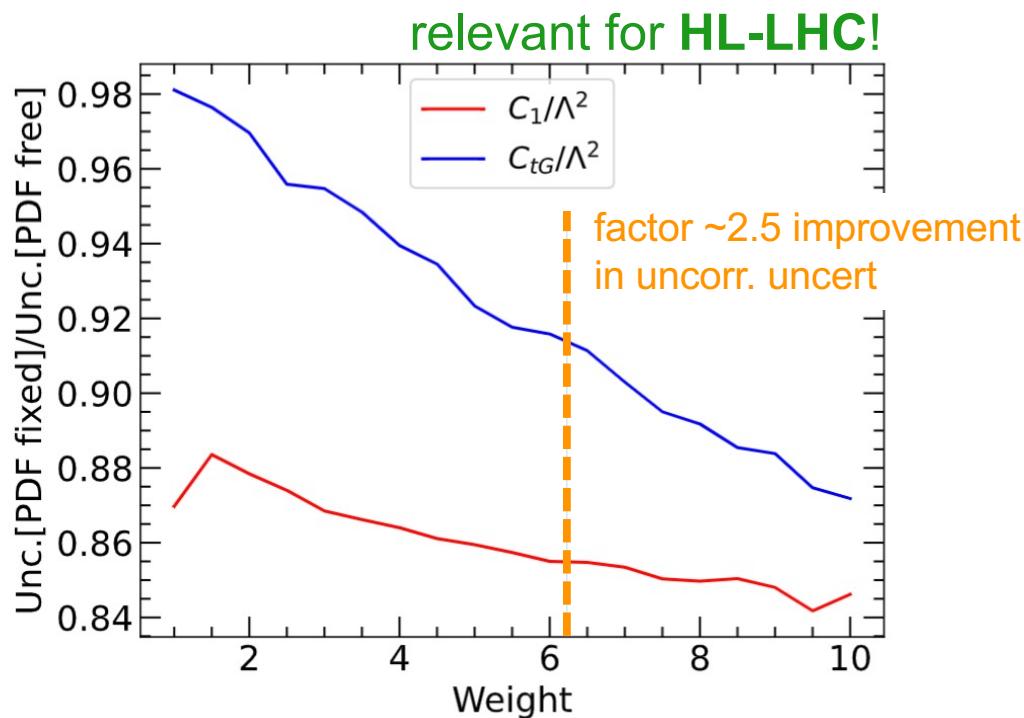


→ strongly rotationally-symmetric $\Delta\chi^2$ contours imply very weak correlations

TeV^{-2}	C_1, C_{tG} free	fix C_1	fix C_{tG}
C_1/Λ^2	$-0.0015^{+0.0033}_{-0.0014}$	0	$-0.0015^{+0.0033}_{-0.0014}$
C_{tG}/Λ^2	$-0.120^{+0.248}_{-0.309}$	$-0.117^{+0.247}_{-0.309}$	0

correlations may strengthen with future expts

- increasing Weight (expt. precision) enhances SMEFT coeff. uncertainty dependence on co-fitted PDFs



- in addition, extracted SMEFT unc. depends on PDF error (tolerance) conventions
 - both points suggest a **growing need for further investigation**

conclusions

- growing interest in EFT global fits, joint analyses with PDFs
 - completed first simultaneous PDF-SMEFT fit within CT framework
 - explore jet and $t\bar{t}$ data as a demonstration study; examine correlations
 - relatively weak PDF-SMEFT correlations
 - evidence of correlation between high-x gluon, contact interaction
 - these will increase with growing expt precision; e.g., at HL-LHC
 - need further theory development; more operator combinations, ...
 - ML-based framework; scalable to larger SMEFT parameter space
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