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

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in collaboration with Jun Gao, Meisen Gao, T.J. Hobbs, DianYu Liu (arXiv:2211.01094 (JHEP))

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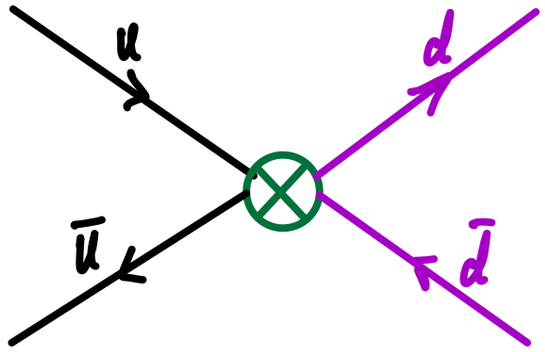
Indirect BSM effects in framework of SMEFT

- Ingredients of SM Effective Field Theory (SMEFT)
  - field (particle) content: same as SM
  - symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$ (+ flavor symmetry + L/B conservation)
  - expanded in $\Lambda_{\rm NP}$ ($\gg \Lambda_{\rm EW}$)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$



- Parameterize indirect BSM effects by SMEFT
  - model-independent
  - dim-6 operators suffice if $\Lambda_{\rm NP}$ is very large

Motivation for joint SMEFT-PDF fits

- SMEFT analyses may be biased using SM PDFs

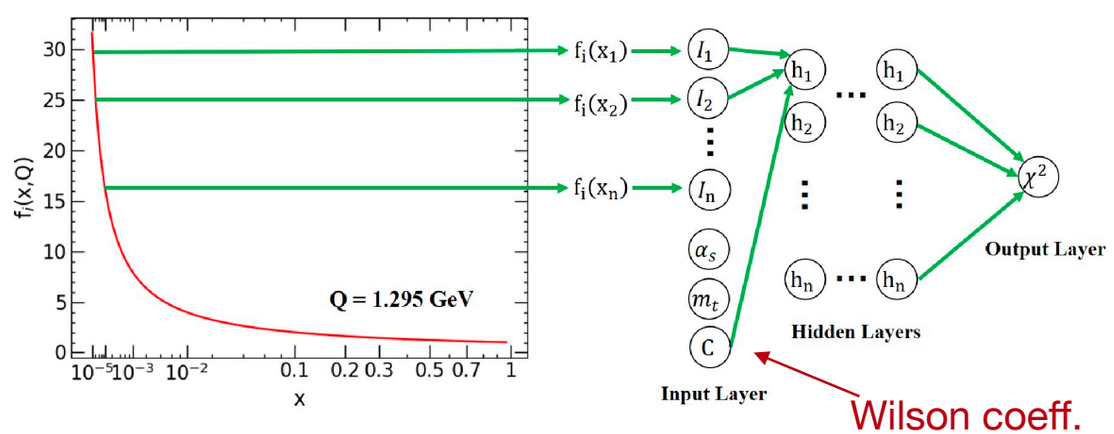
  → joint SMEFT-PDF fits

- Recent interest in this direction

  1902.03048, 1905.05215, 2104.02723, 2111.10431, 2201.07240, 2211.01094, 2303.06159, 2307.10370,…
  talks from Maeve Madigan, Katerina Lipka, James Moore

- In this work:

  - demonstration study of **joint SMEFT-PDF** fits
    - CT18 framework + more jet, $t\bar{t}$ data
  - explore possible correlations between SMEFT and QCD (PDF,α_s, m_t)
    - uncertainties estimation by Lagrange Multiplier scans
    - boosted by ML skills



The data sets

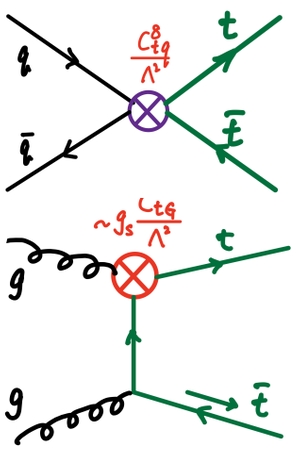
- default CT18 fitted experiments + additional $t\bar{t}$, jet data
- 112 (67) $\mathrm{fb}^{-1}$of $t\bar{t}$ (jet) production data for nominal fit

Experiments	$\sqrt{s}$(TeV)	$\mathcal{L}(\mathrm{fb}^{-1})$	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)

Setup of theoretical predictions

- selected dim-6 operators relavant for top/jet production



$t\bar{t}$ production: SMEFT@NLO

$$O_{tu}^1 = \sum_{i=1}^{2} (\bar{t}\,\gamma_\mu\, t_R)\,(\bar{u}_{Ri}\,\gamma^\mu\, u_i)$$

$$O_{td}^1 = \sum_{i=1}^{3} (\bar{t}\,\gamma^\mu\, t)\,(\bar{d}_{Ri}\,\gamma_\mu\, d_i)$$

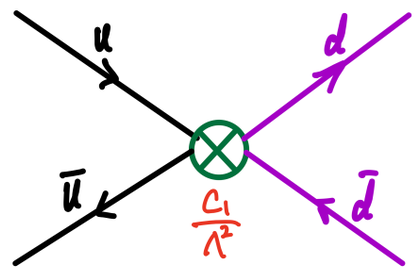
$$O_{tq}^8 = \sum_{i=1}^{2} (\bar{q}_i\,\gamma^\mu\, T^A\, q_i)\,(\bar{t}\,\gamma_\mu\, T^A\, t)$$

$$O_{tG} = i\, g_s\, (\bar{Q}\,\tau^{\mu\nu}\, T_A\, t)\,\tilde{\varphi}\, G_{\mu\nu}^A + \text{h.c.}$$

jet production: CIJet

contact interaction

$$O_1 = 2\pi \left(\sum_{i=1}^{3} \bar{q}_i\,\gamma_\mu\, q_i \right) \left(\sum_{j=1}^{3} \bar{q}_j\,\gamma^\mu\, q_j \right)$$



32 DIS & DY data sets not affected

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

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

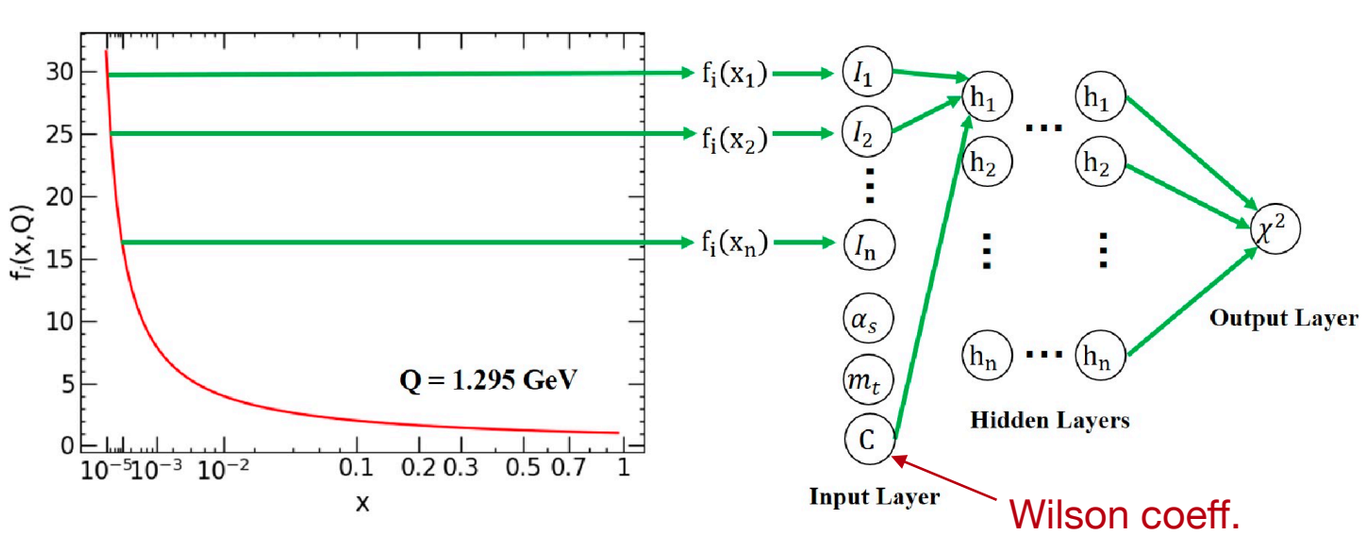
Log-likelihood function learned by neural network

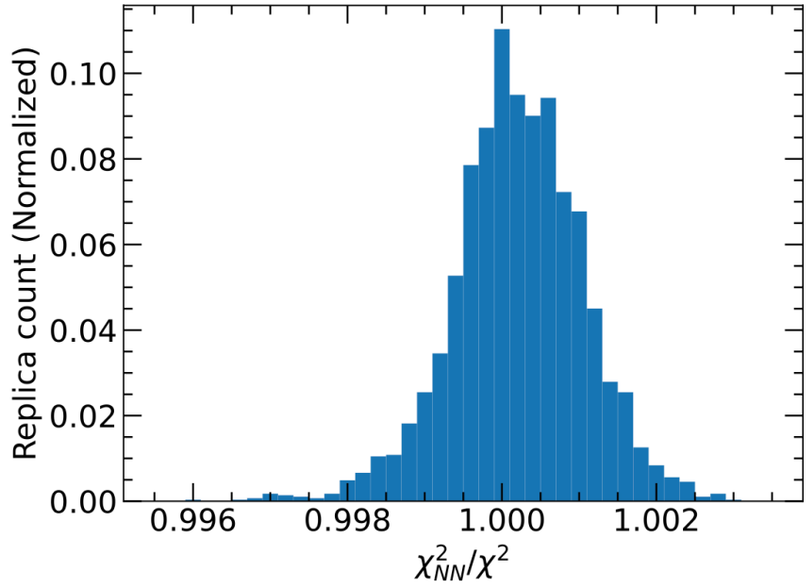
- quality of agreement quantified by profiled log-likelihood function

$$\chi^2(\mathrm{PDF},\mathrm{SMEFT}) = \sum_{i,j=1}^{N_{\mathrm{pt}}} (T_i - D_i)(\mathrm{cov}^{-1})_{ij} (T_j - D_j)$$

- uncertainties evaluated by **Lagrange Multiplier (LM) scans** **[Pumplin et al, hep-ph/0008191]**

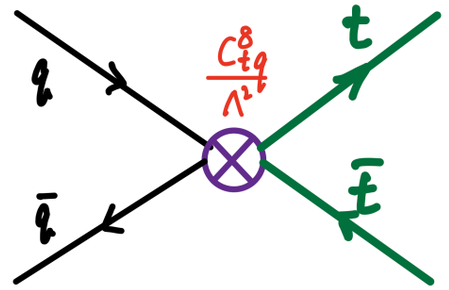
- χ^2 functions are then modelled by NNs. **[D. Liu et al., 2201.06586]**



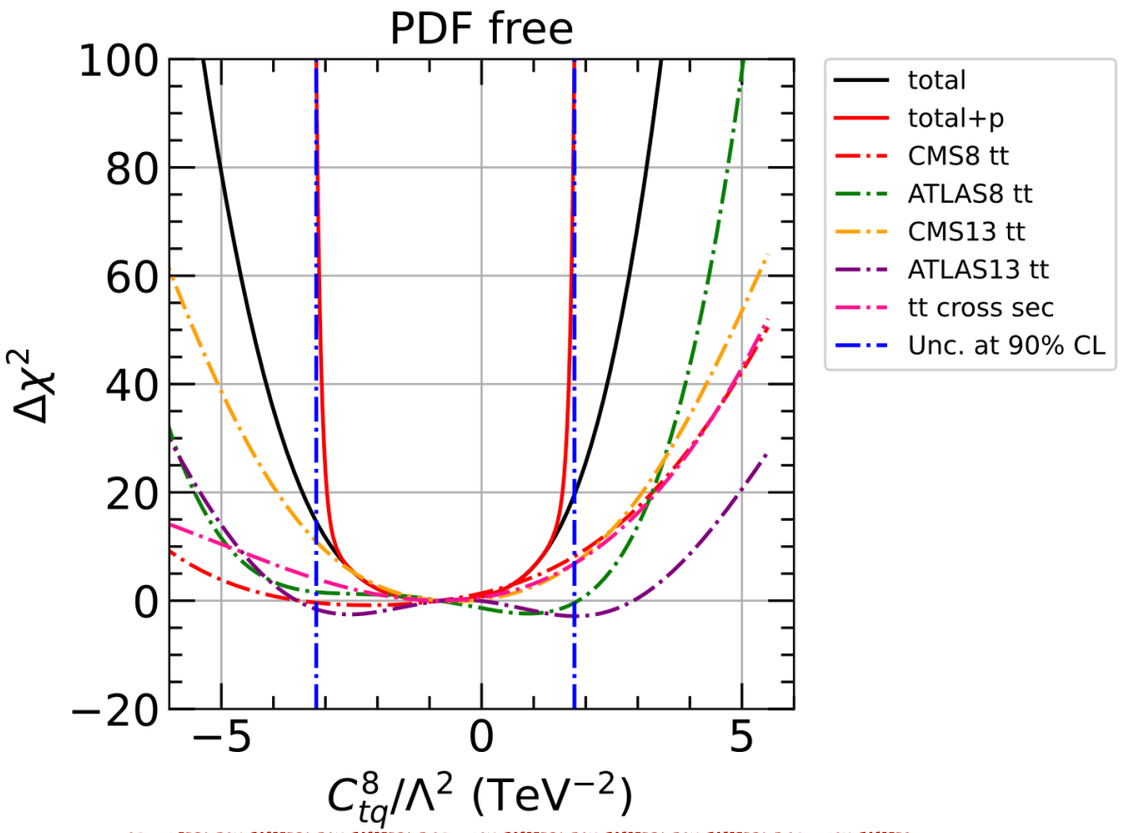


- training: 12000 PDF replicas with different α_s, m_t and Wilson coefficients
- validation: using another 4000 replicas
- allow **efficient** scan of the PDF-SMEFT parameter space

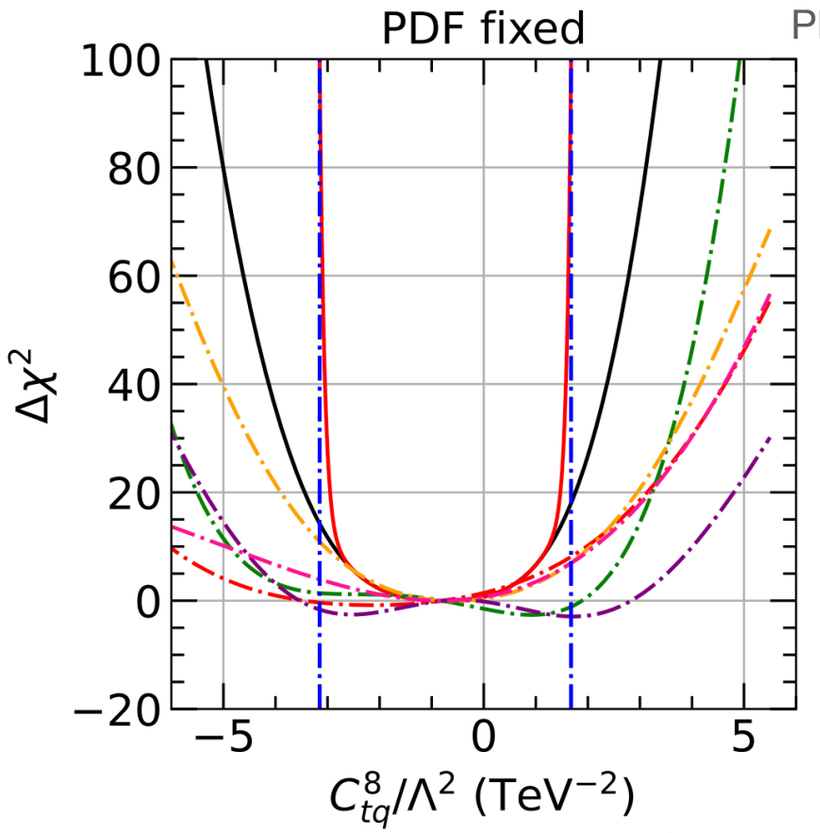
Joint fits of PDFs and C_{tq}^8



- explore SMEFT uncertainties with Lagrange Multiplier (LM) scans
  - fixing $\alpha_s(m_Z) = 0.118,\ m_t = 172.5\ \text{GeV}$
  - 90% C.L. uncertainties given by CT18 tolerance criterion $\Delta\chi^2 + P \leq 100$



$$C_{tq}^8/\Lambda^2 = -0.80^{+2.58}_{-2.38}\ \text{TeV}^{-2}$$



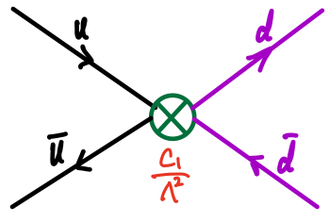
PDF parameters fixed to global minimum of joint SMEFT-PDF fit

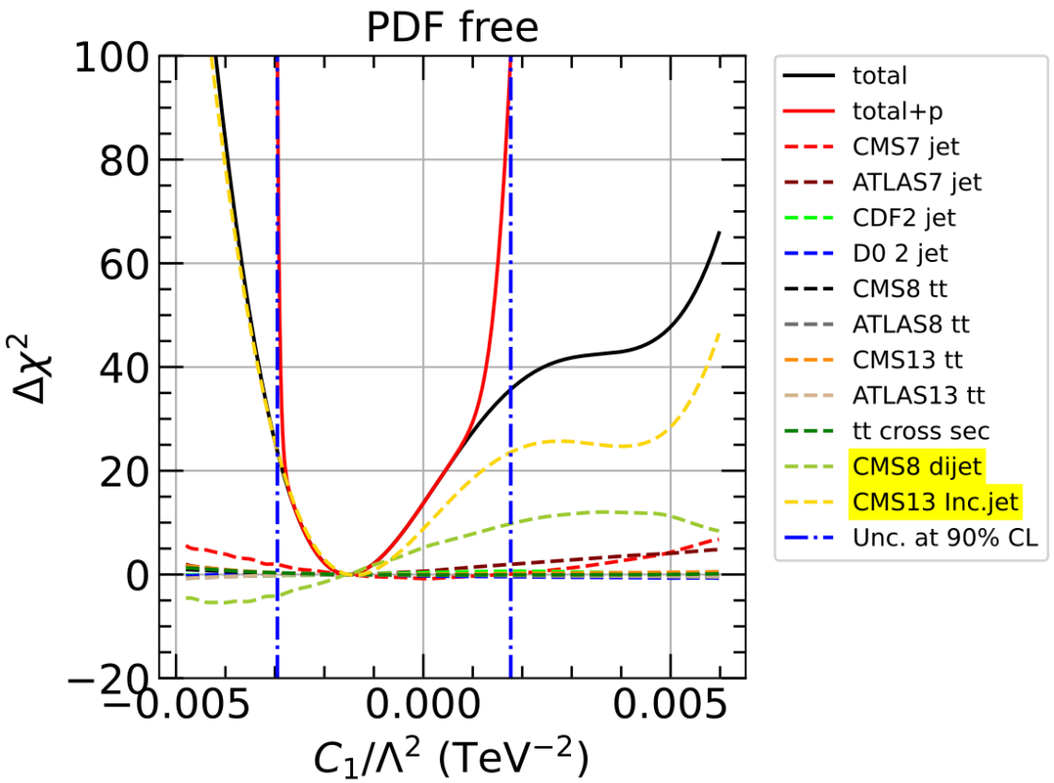
$$C_{tq}^8/\Lambda^2 = -0.80^{+2.48}_{-2.35}\ \text{TeV}^{-2}$$

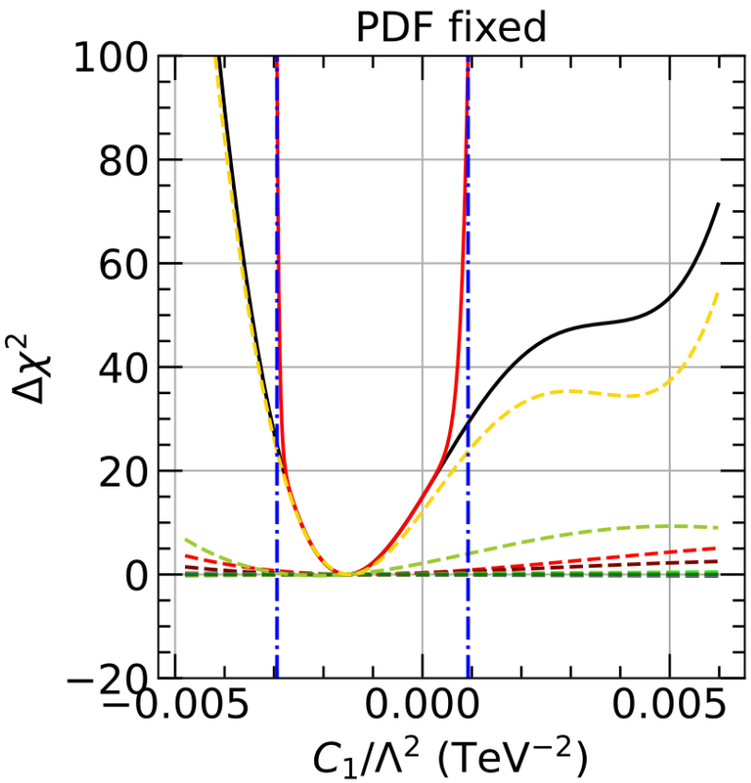
- approx. quartic shape for $\Delta\chi^2$ reflects quadratic SMEFT corrections $\sim \left(C_{tq}^8/\Lambda^2\right)^2$

Joint fits of PDFs and contact interaction

- LM scans for quark contact interaction $\frac{C_1}{\Lambda^2} o_1$
  - fixing $\alpha_s(m_Z) = 0.118$, $m_t = 172.5$ GeV





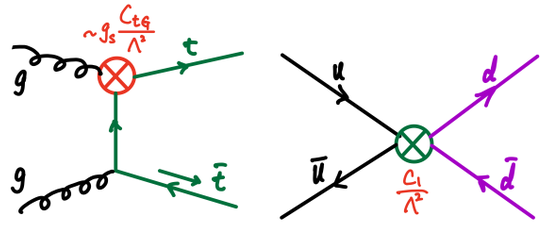


similar analysis:
[CMS,2111.10431]
see Katerina Lipka's talk

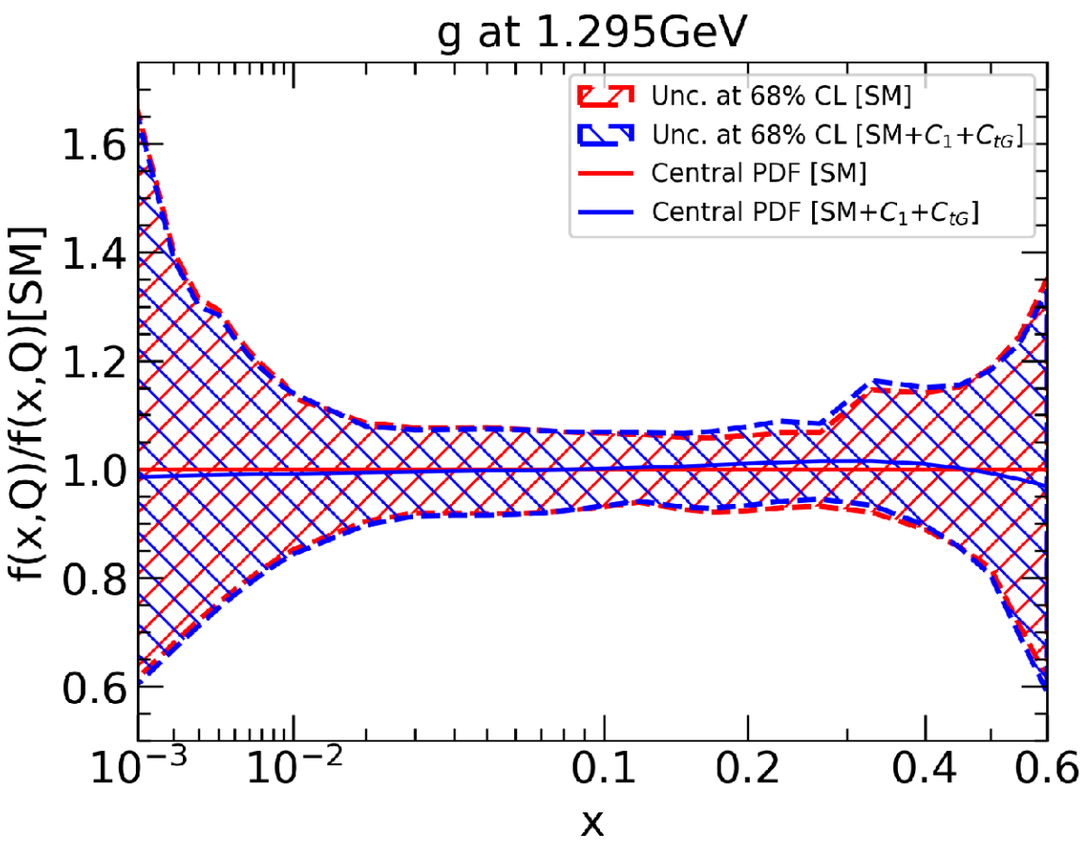
- mainly constrained by CMS 13 TeV inclusive jet data and CMS 8 TeV dijet data
- uncertainties underestimated for fixed PDF

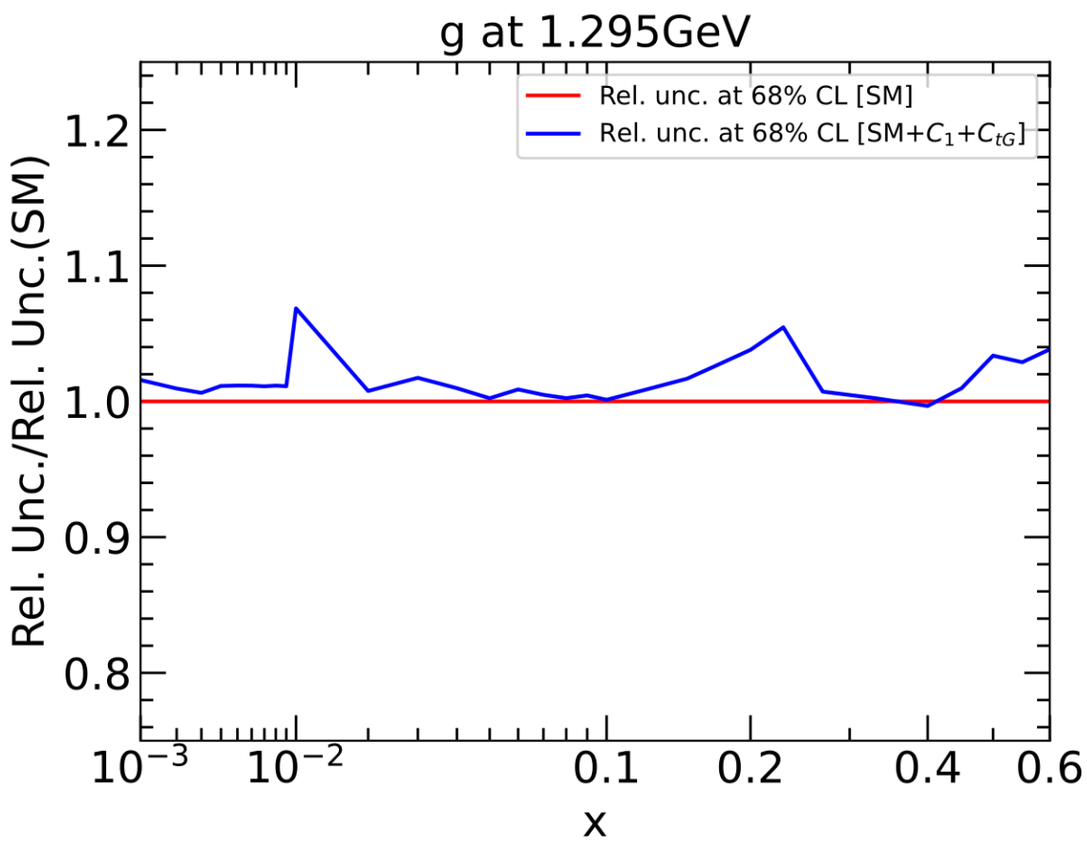
TeV^{-2}	nominal	CMS 8 dijet	CMS 8 jet	CMS 13 jet
PDF free	$-0.0015^{+0.0033}_{-0.0014}$	$-0.0022^{+0.0187}_{-0.0054}$	$-0.0009^{+0.0138}_{-0.0045}$	$-0.0013^{+0.0059}_{-0.0016}$
PDF fixed	$-0.0015^{+0.0024}_{-0.0014}$	$-0.0022^{+0.0180}_{-0.0051}$	$-0.0009^{+0.0131}_{-0.0049}$	$-0.0013^{+0.0026}_{-0.0015}$

Gluon PDF with/without SMEFT



- compare gluon PDF with/without SMEFT contributions from O_{tG} and O_1

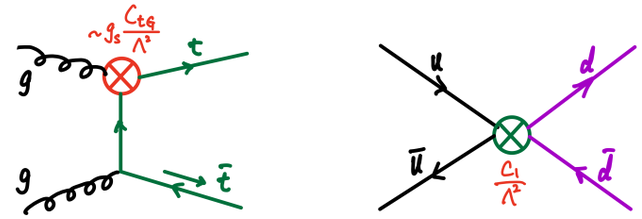


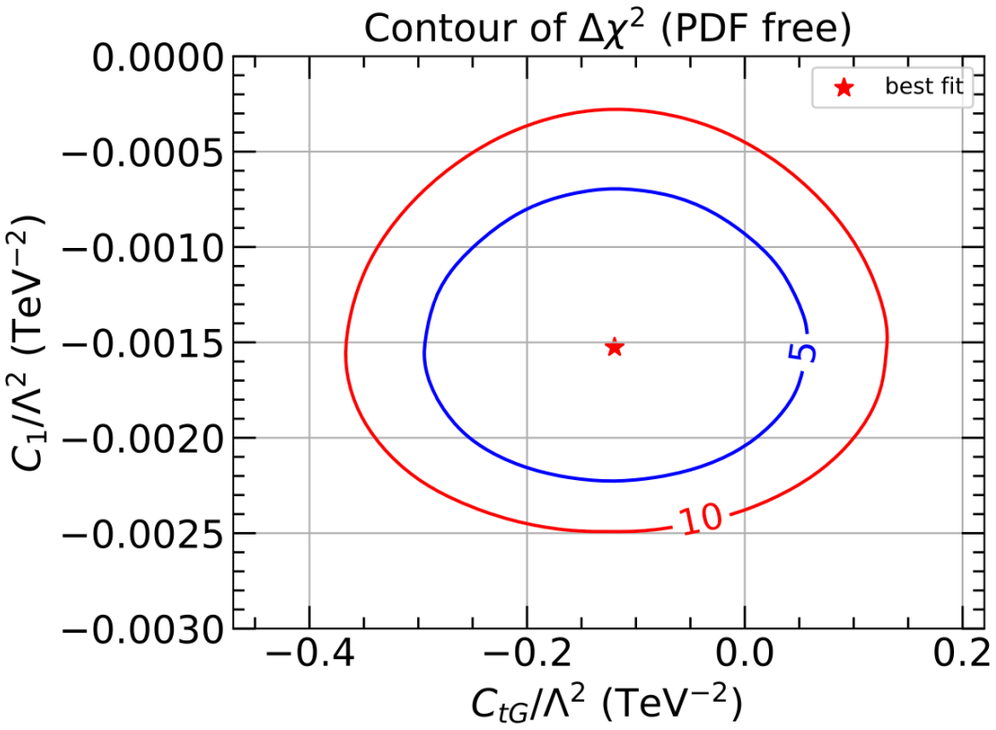


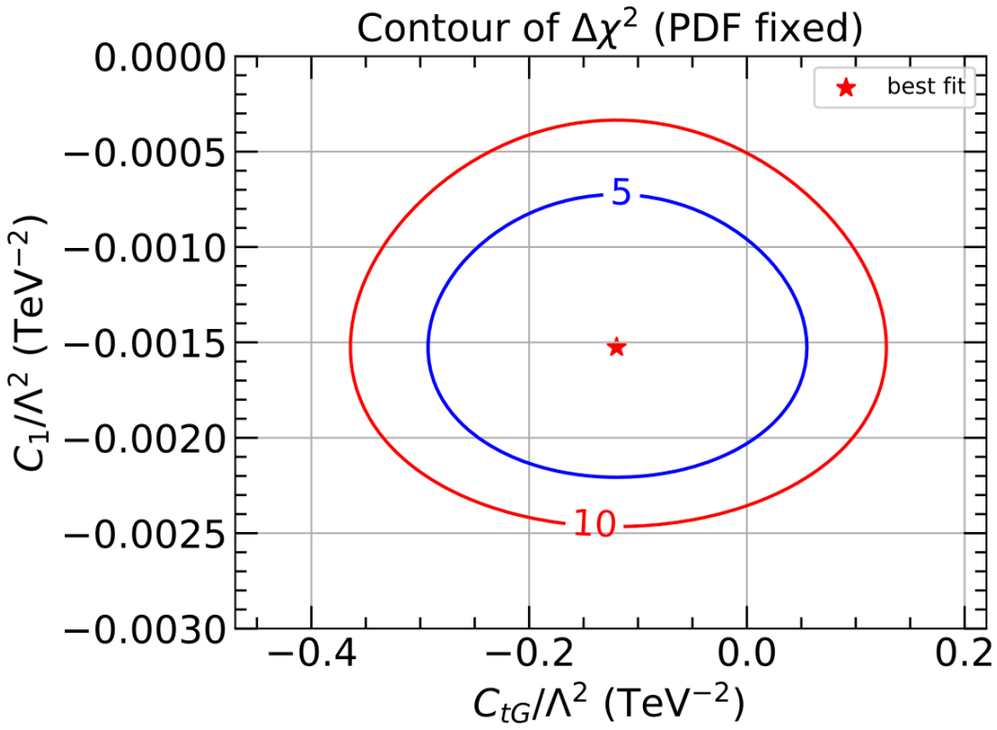
- small ($< 5\,\%$) deviation in the $x > 0.2$ region
- PDF uncertainties slightly enlarged by including O_1, O_{tG} in the fit

Correlations between top/jet Wilson coefficients

- Simultaneous fits of PDFs, O_{tG} and O_1





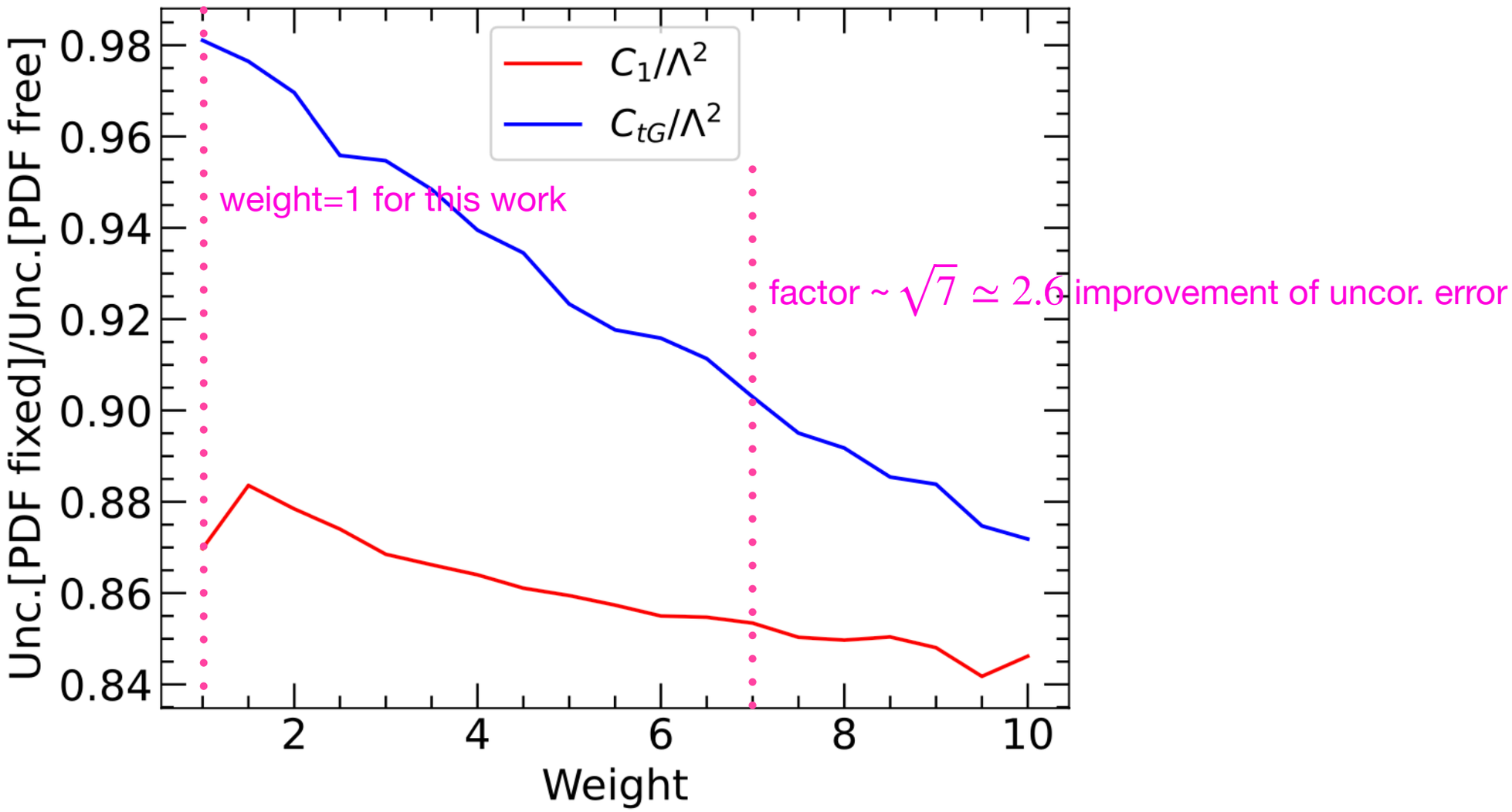


- very weak correlations between C_1 and C_{tG}

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 for future experiments

- mimicking future improvements in theory/exp. precision: $\chi^2_{\text{top(jet)}} \rightarrow \text{weight} \times \chi^2_{\text{top(jet)}}$



- ~10% underestimation in the uncertainty of C_{tG}/Λ^2 at the HL-LHC if PDF is fixed

Summary

- simultaneous SMEFT-PDF fit within CTEQ-TEA framework
  - SMEFT corrections with full PDF dependence calculated at NLO QCD
  - ML-based; allows rapid fit and Lagrange Multiplier scans
  - can be generalized to include more SMEFT parameters
- explore correlations between SMEFT and PDF
  - uncertainties of Wilson coefficients slightly underestimated with fixed PDF
  - find mild correlations between SMEFT and gluon PDF at large x
  - the correlations may increase with growing precision

Summary

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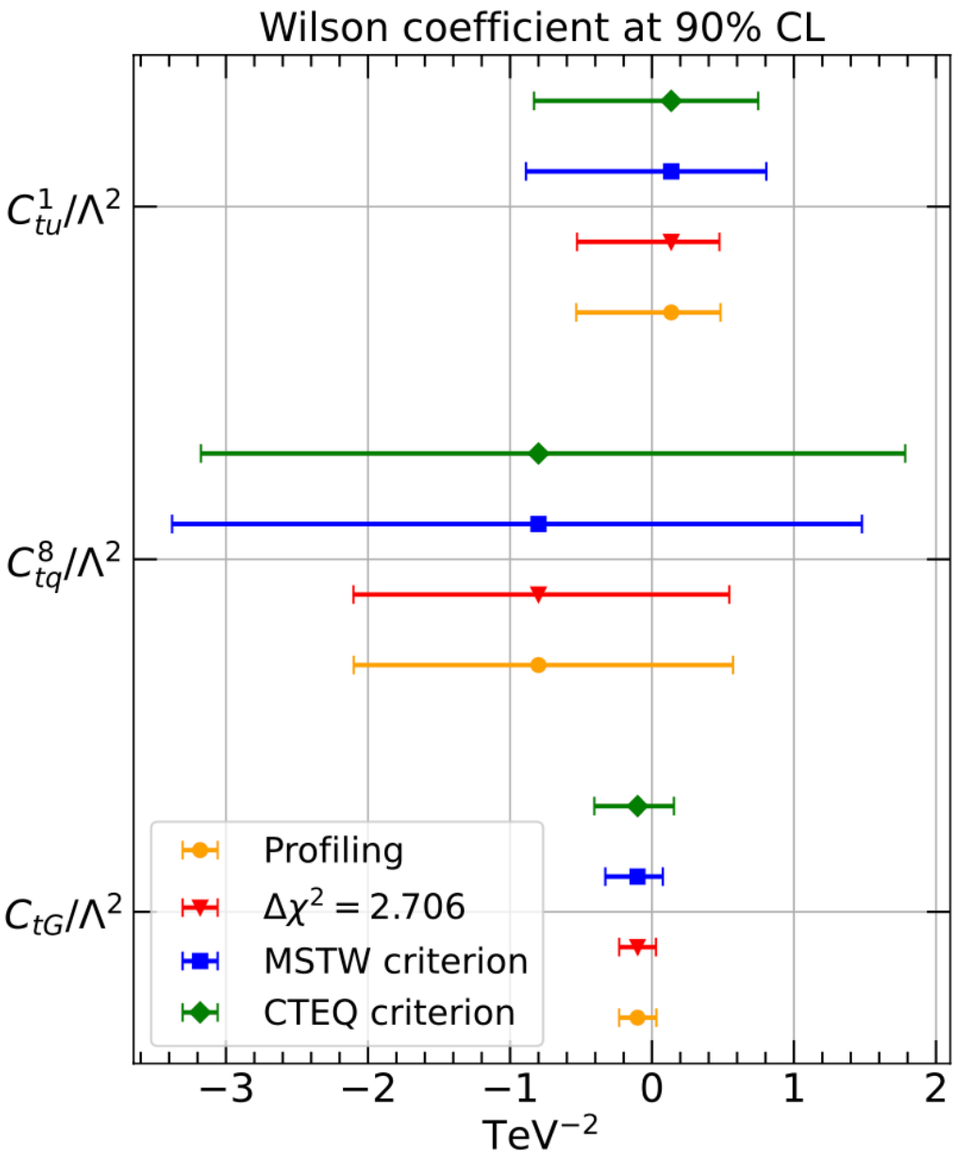
I am also working toward simultaneous SMEFT-PDF extraction within **xFitter**, a powerful open-source QCD fit framework.

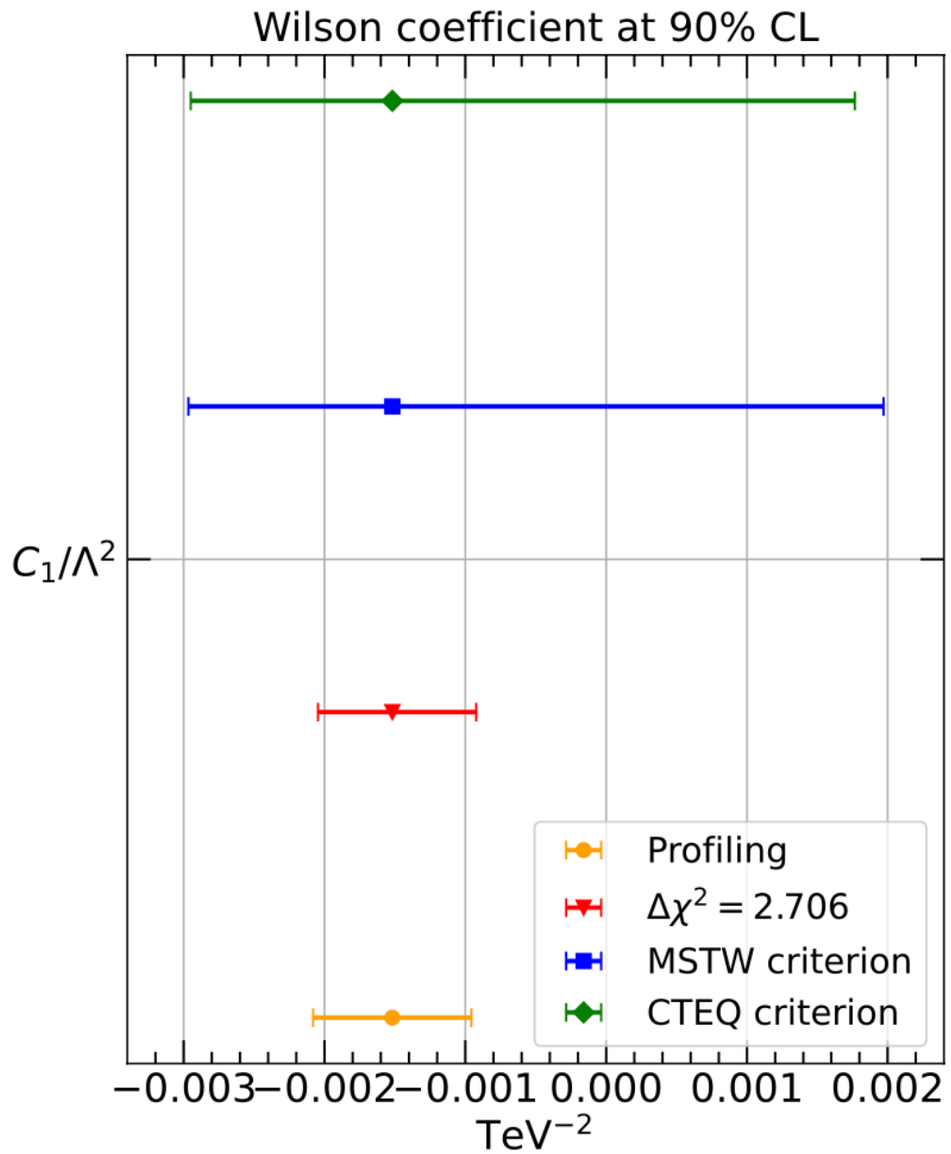
Thank you!

backup slides

Impact of different tolerance criteria

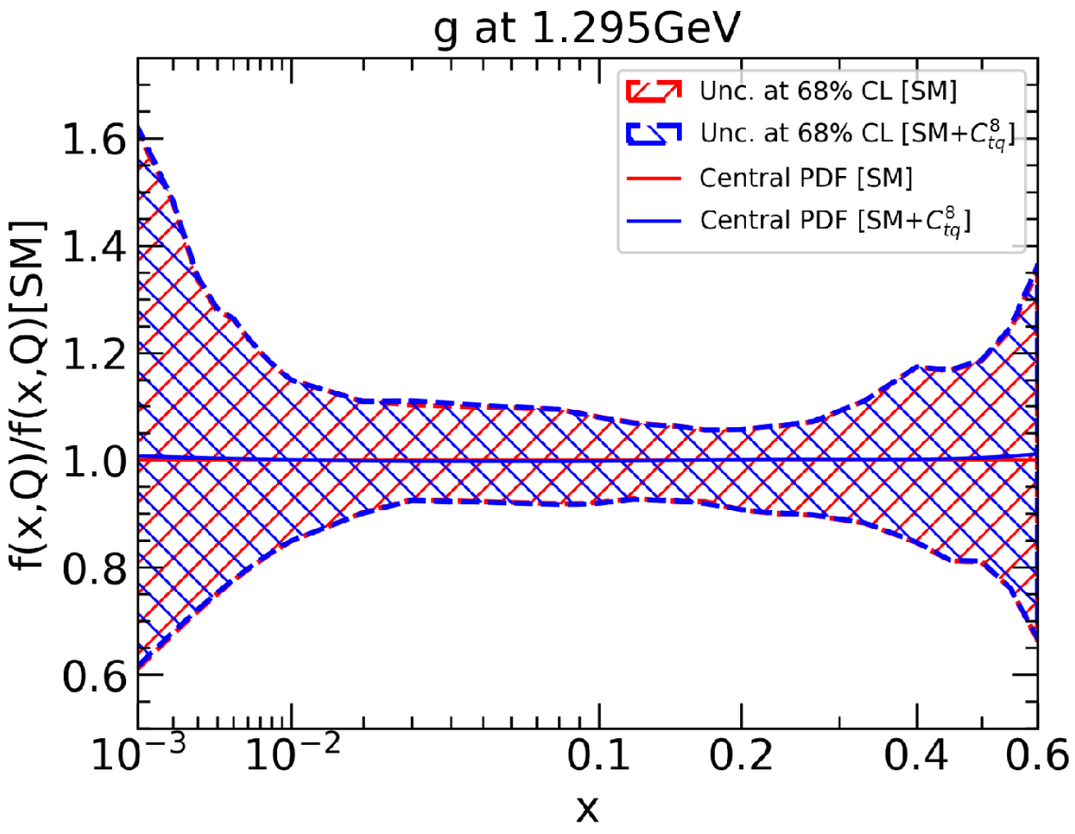
- CTEQ criterion of $\Delta\chi^2 + P = 100$ is used in this work

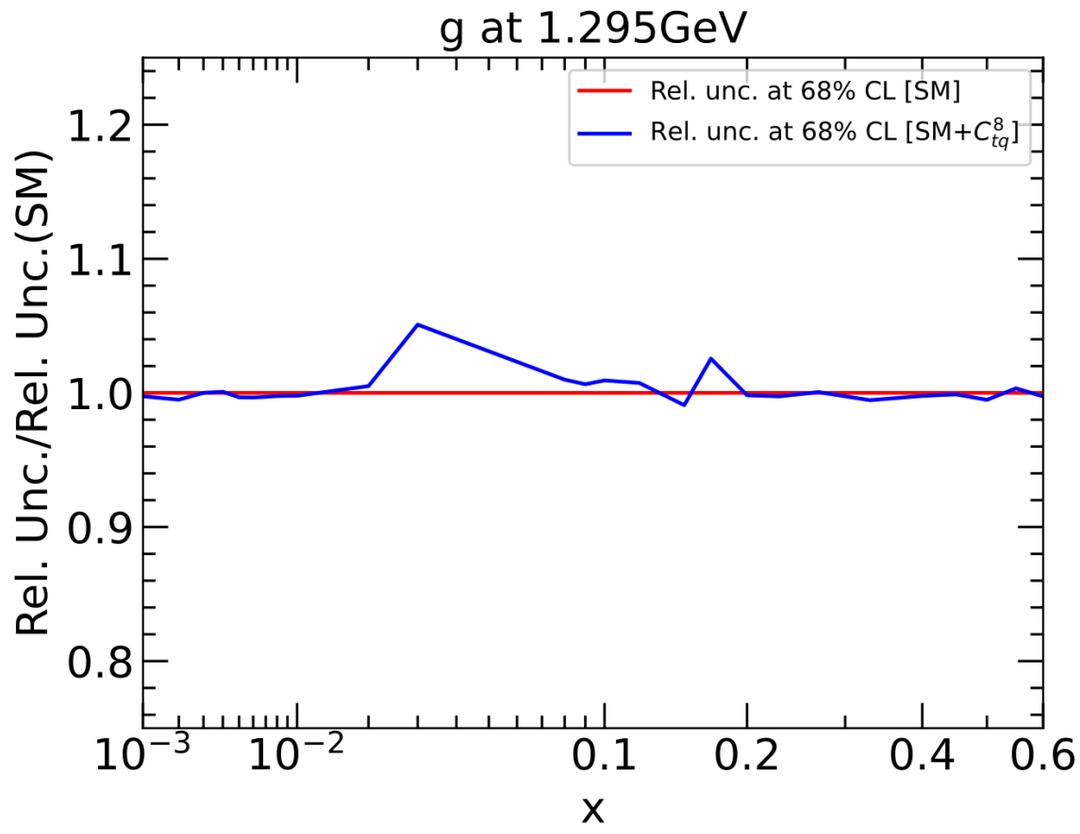




Gluon PDF with/without SMEFT

- compare gluon PDF with/without SMEFT contributions from O_{tq}^{8}

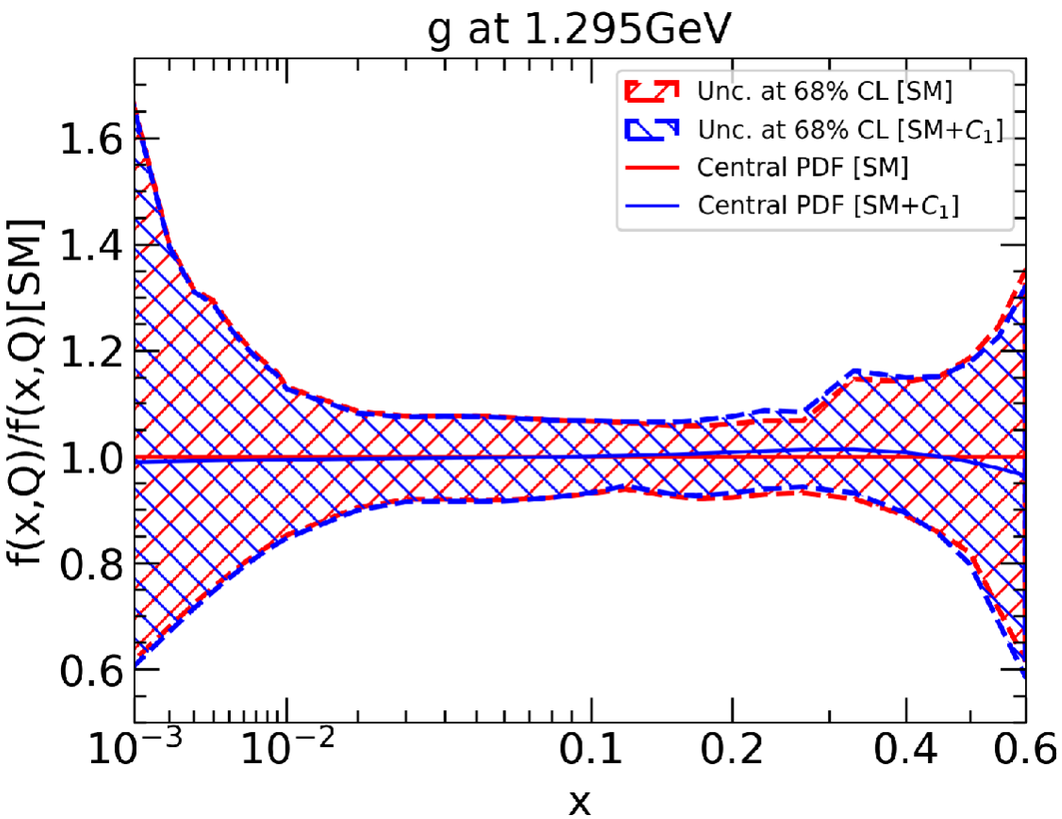


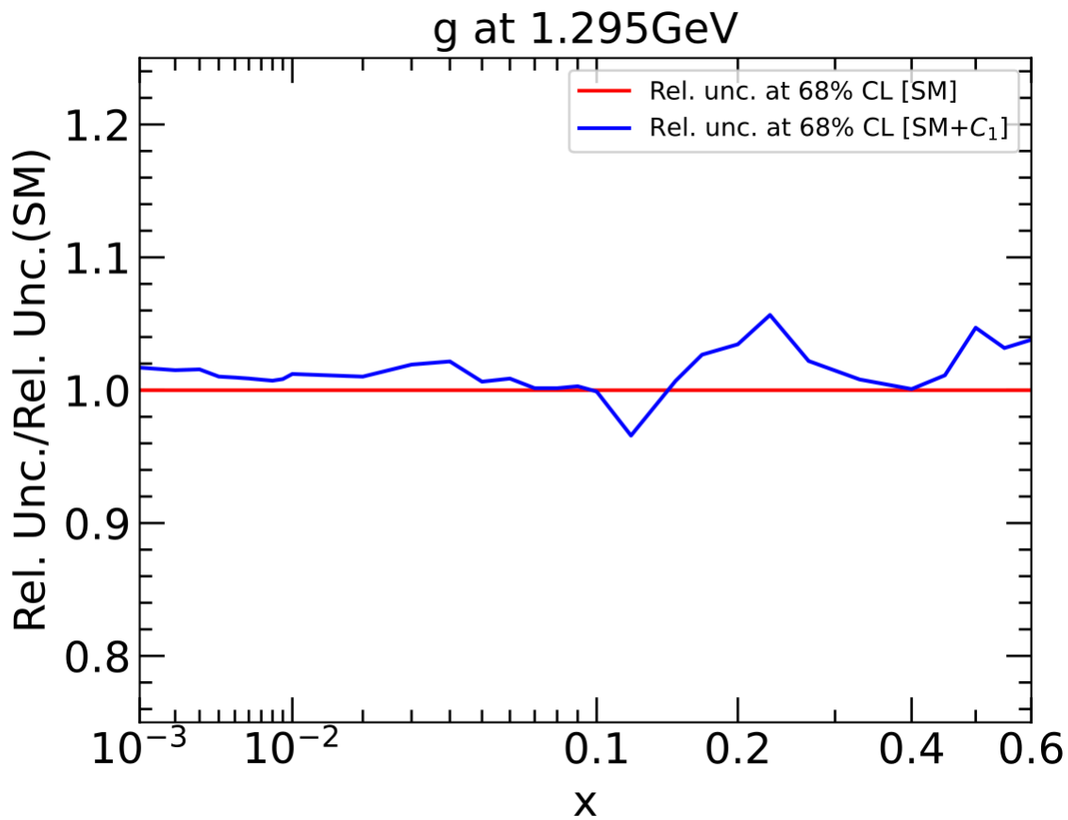


- almost indistinguishable
- negligible upward shift smaller than 1% in the endpoint x regions
- PDF uncertainties enlarged by 5% around x=0.03 by including O_{tq}^{8} in the fit

Gluon PDF with/without SMEFT

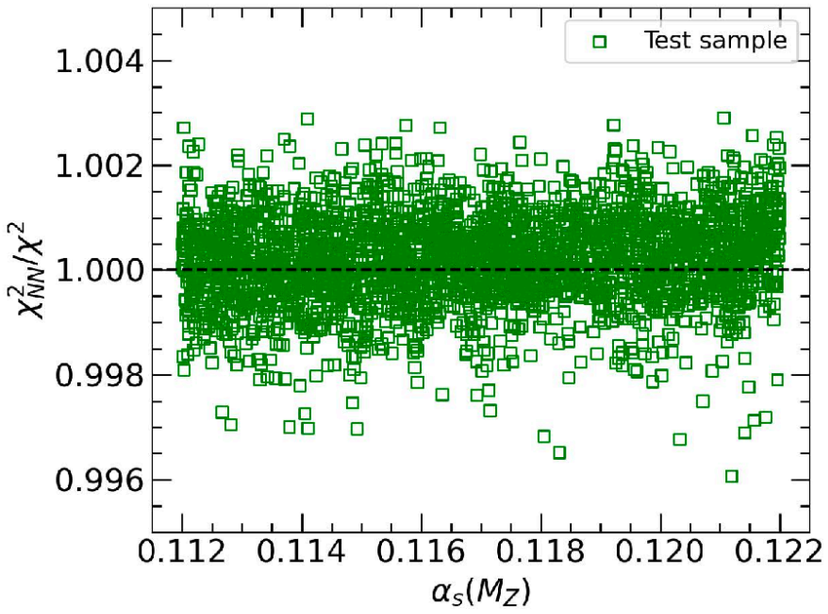
- compare gluon PDF with/without quark contact interaction C_1



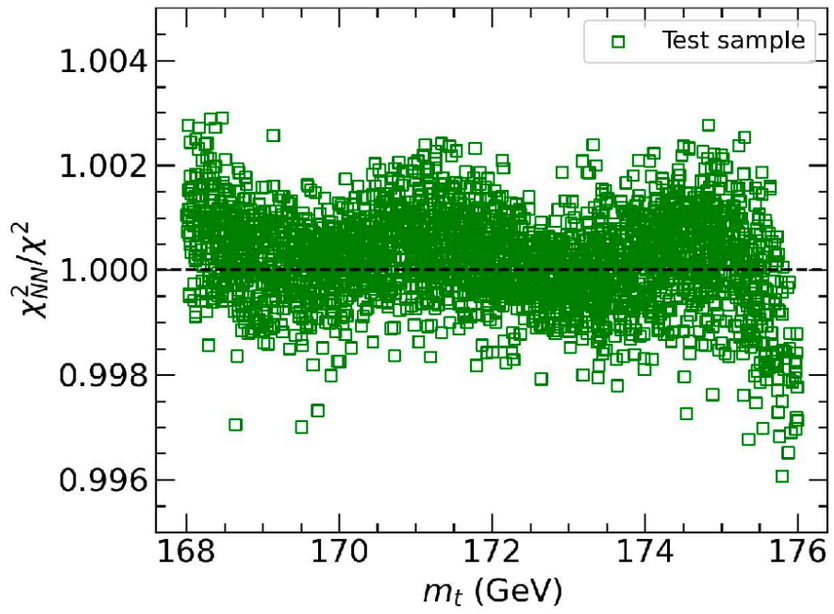


- C_1 is moderately correlated to the gluon PDF at $x > 0.1$

Validating the NNs



(a)



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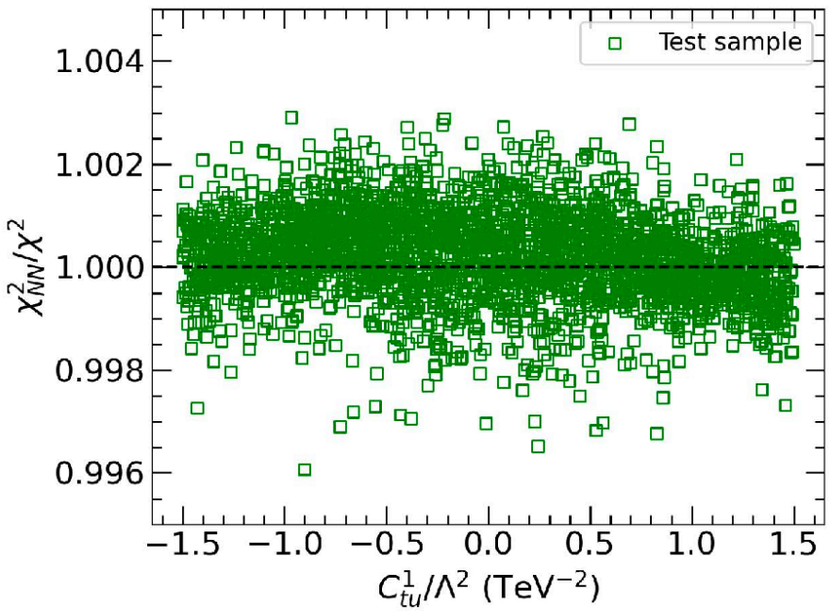

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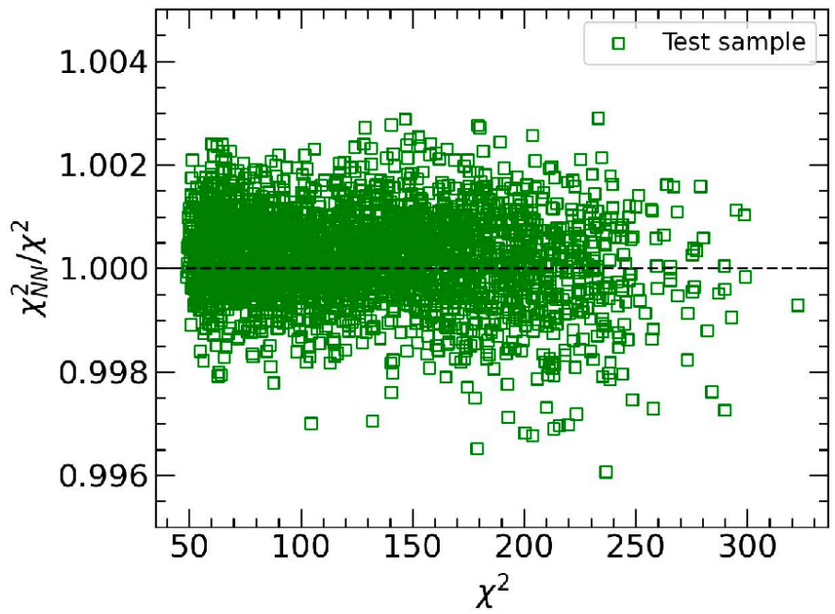

(d)