DIFFERENTIAL γ^* PRODUCTION WITH N3LO QCD CORRECTIONS

RADCOR & LOOPFEST 2021

Karlsruhe Institute of Technology

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ITP, IAP, Karlsruhe Institute of Technology
Online, May 18, 2021

??? IN THE DETAILS

- Precision phenomenology examples
- g-2 exam with 4.2 σ significance

$$a_\mu = \frac{g-2}{2}$$

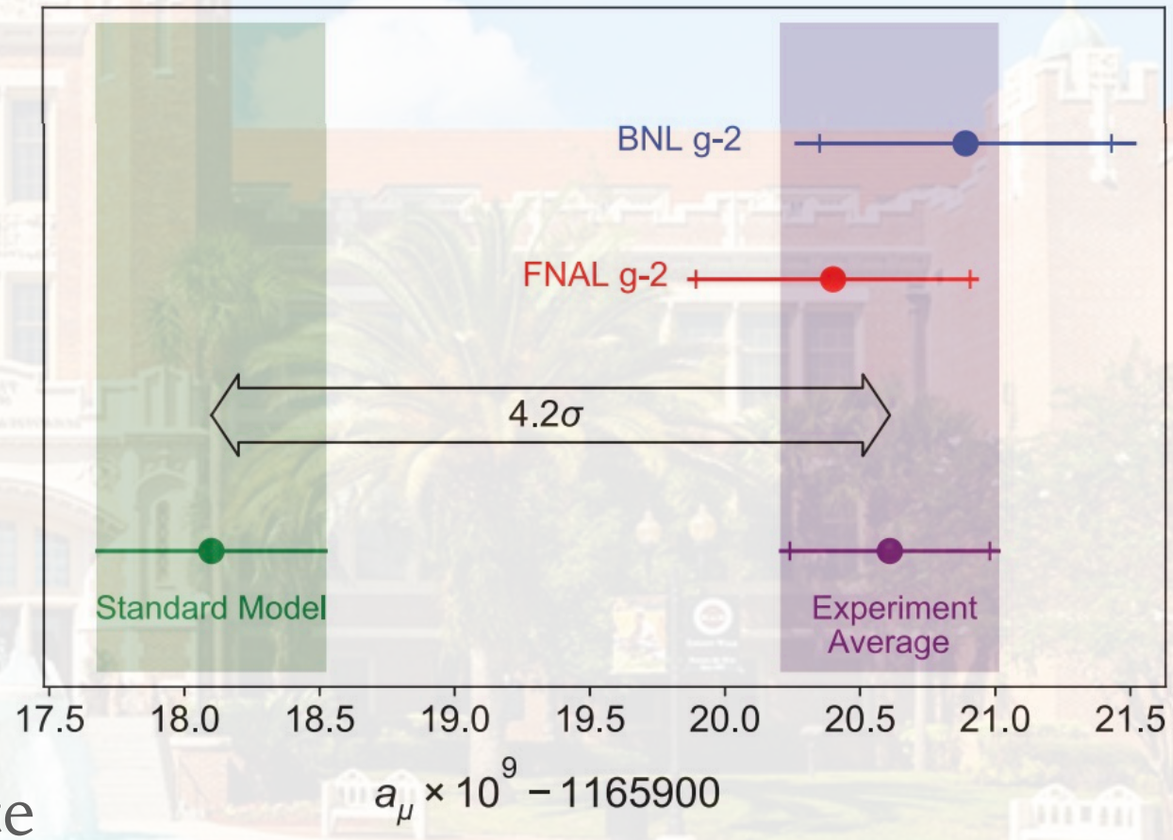
$$a_\mu^{EXP} = 116592061(41) \times 10^{-11}$$

Phys.Rev.Lett. 126, 141801 (2021)

$$a_\mu^{SM} = 116591810(43) \times 10^{-11}$$

Phy. Reports 887 (2020) 1-116

More in Massimo's talk



Phys.Rev.Lett. 126, 141801 (2021)

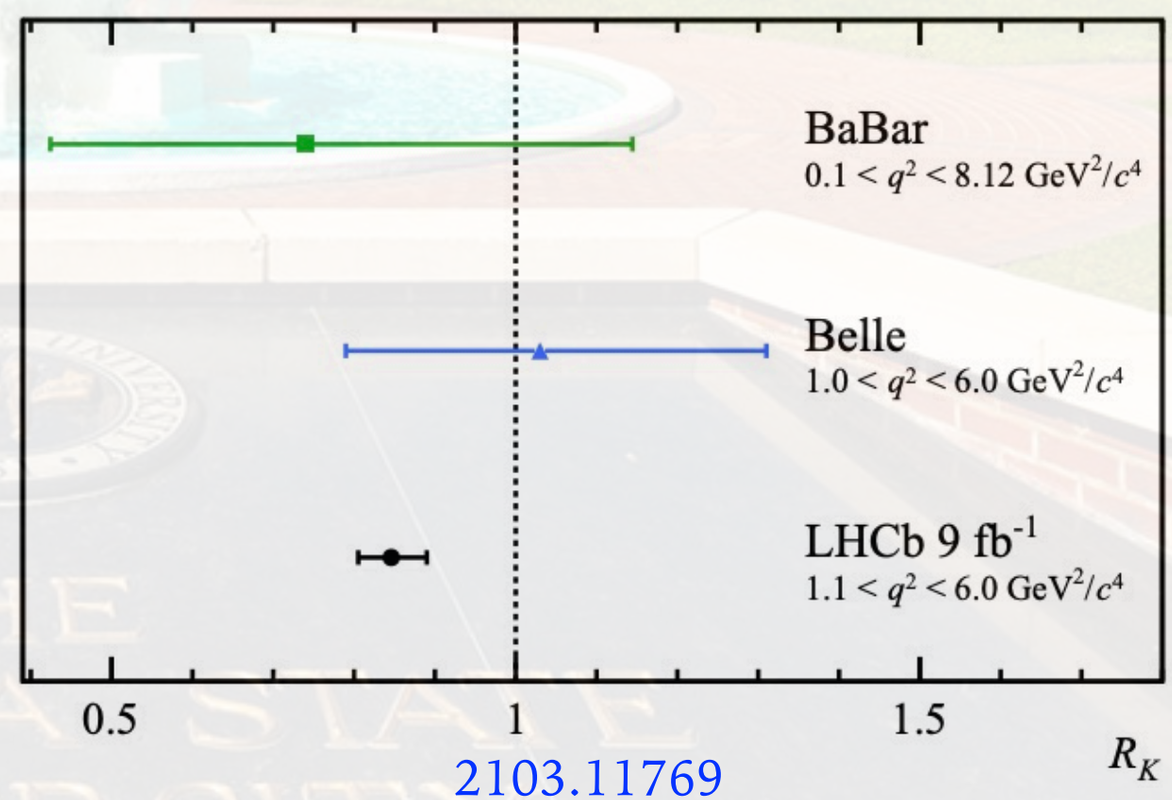
- Beauty-quark decays with 3.1 σ difference

$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2} dq^2}$$

$$R_K = 0.846^{+0.044}_{-0.041}$$

2103.11769

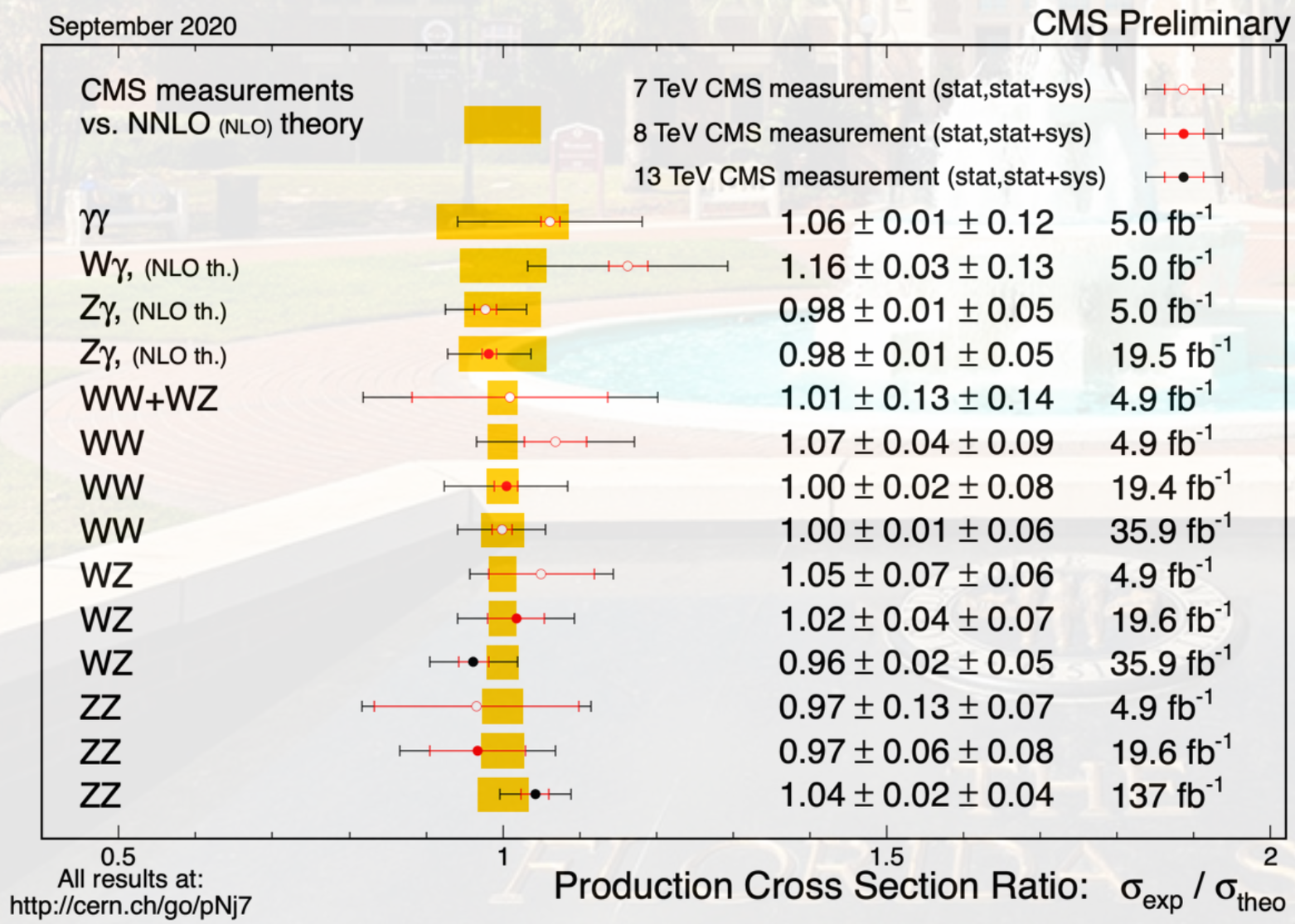
- Anomaly in fundamental parameters
  - Discovery needs more precision
  - Accurate interpretation of SM
  - Manifest in other observables



2103.11769

PRECISION MEASUREMENT AT THE LHC

- Flip every stone searching for new physics: (More in Harrison's talk)
  - Measured total cross section at 10% accuracy for di-boson productions
  - Gauge boson production in associate with jets (from 1 to 7 jets)
  - HL-LHC projected Higgs cross section measurements at 2-4% precision



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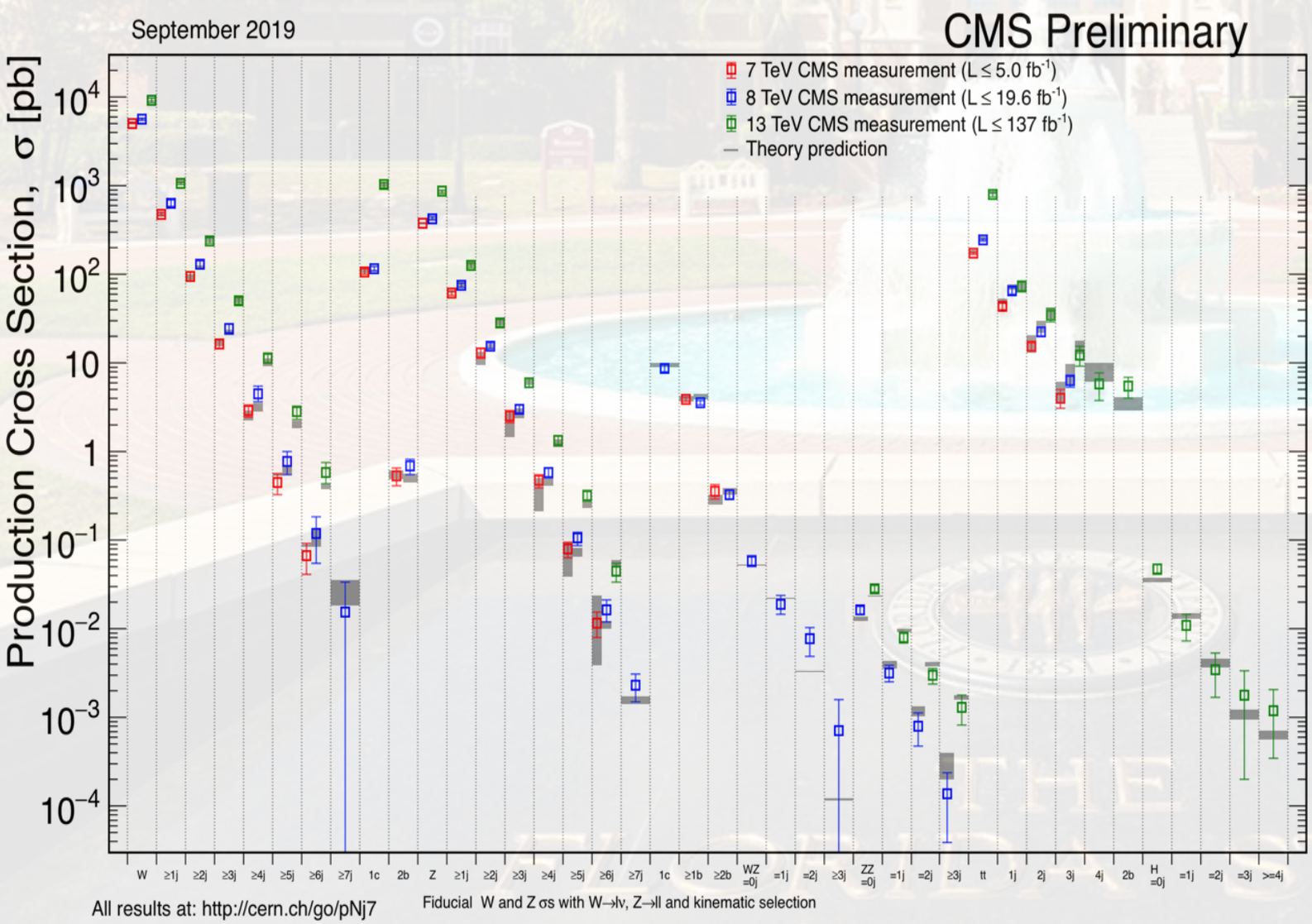

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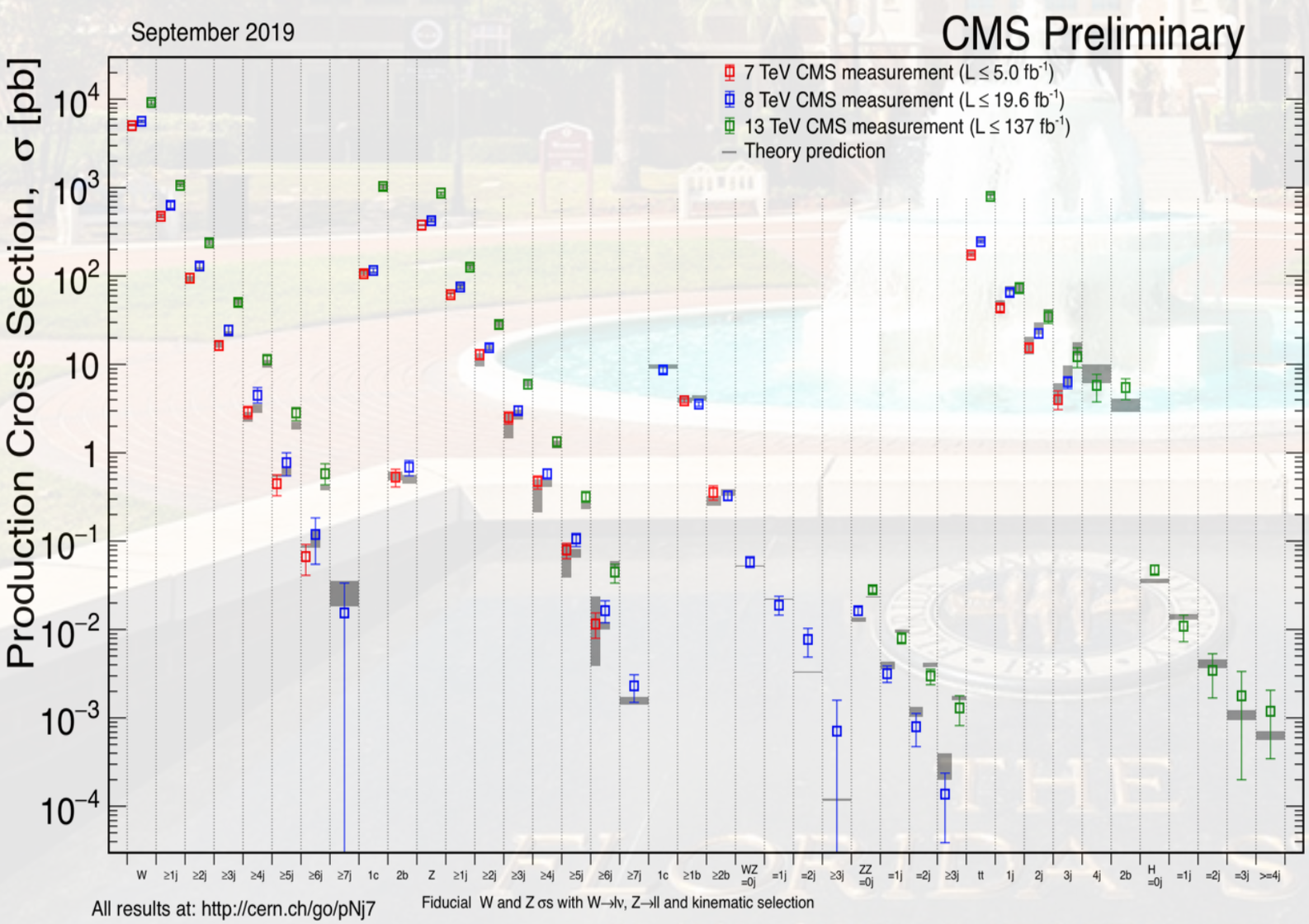

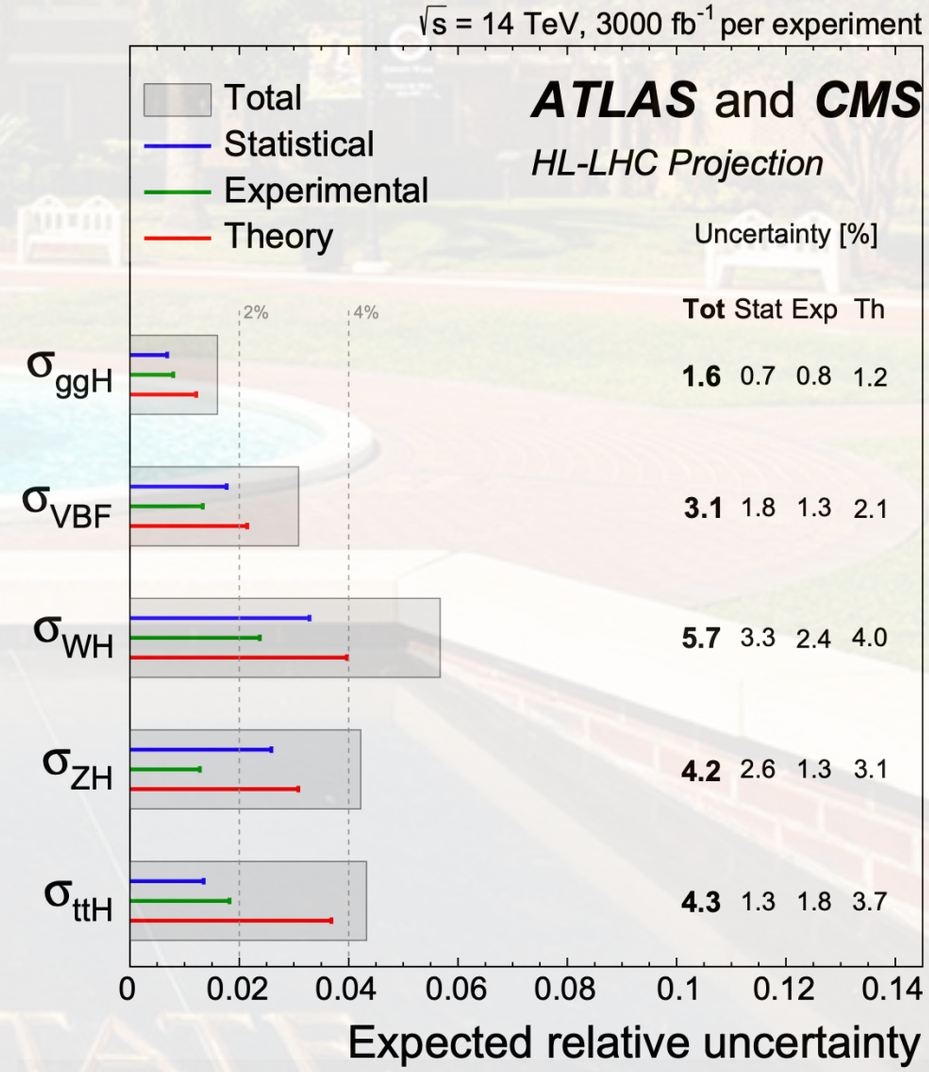

WG2 report on HL-LHC 1902.00134

THE PRECISION THEORY FRONTIER AT THE LHC

- Parton model

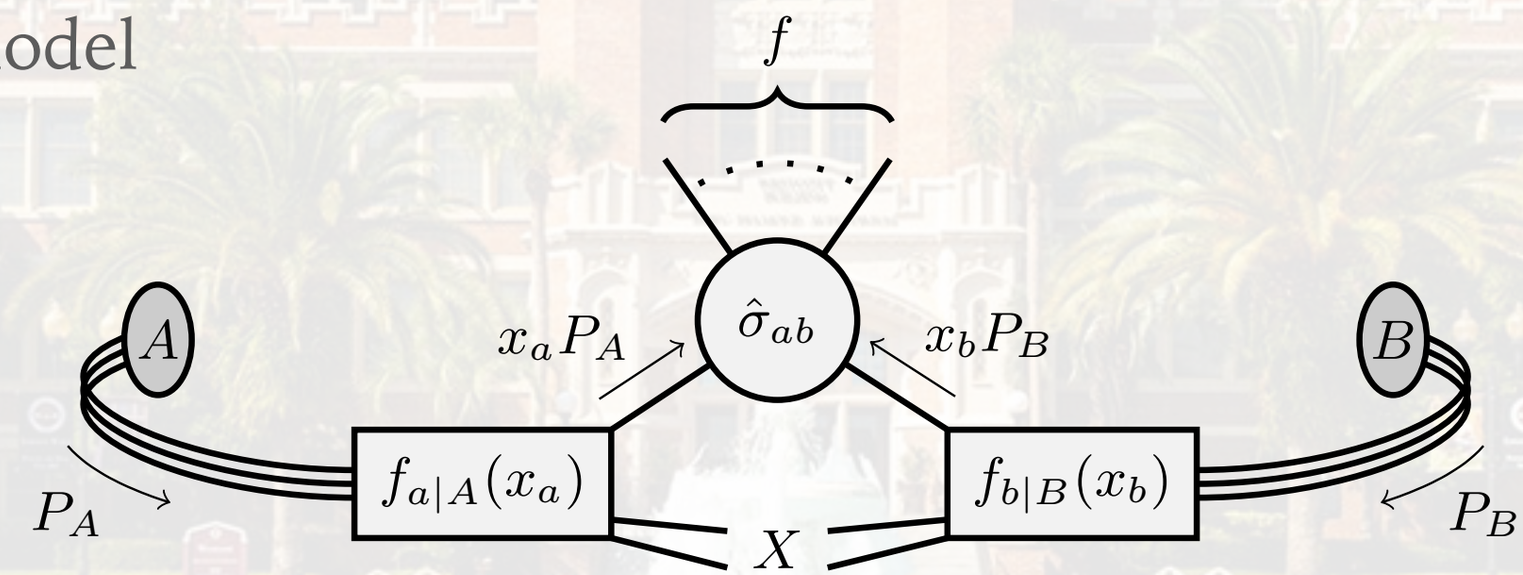

Figure by A. Huss

$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_{a|A}(x_a) \; f_{b|B}(x_b) \; \hat{\sigma}_{ab}(x_a, x_b) \; \left(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\right)$$

THE PRECISION THEORY FRONTIER AT THE LHC

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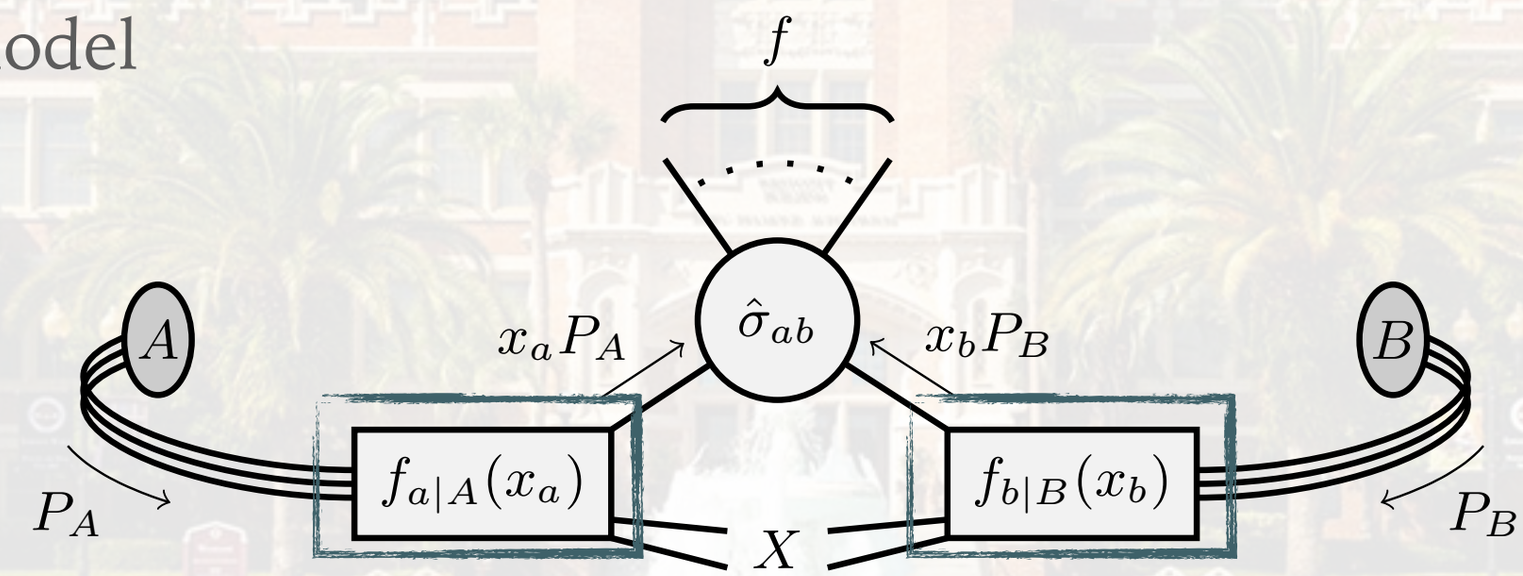

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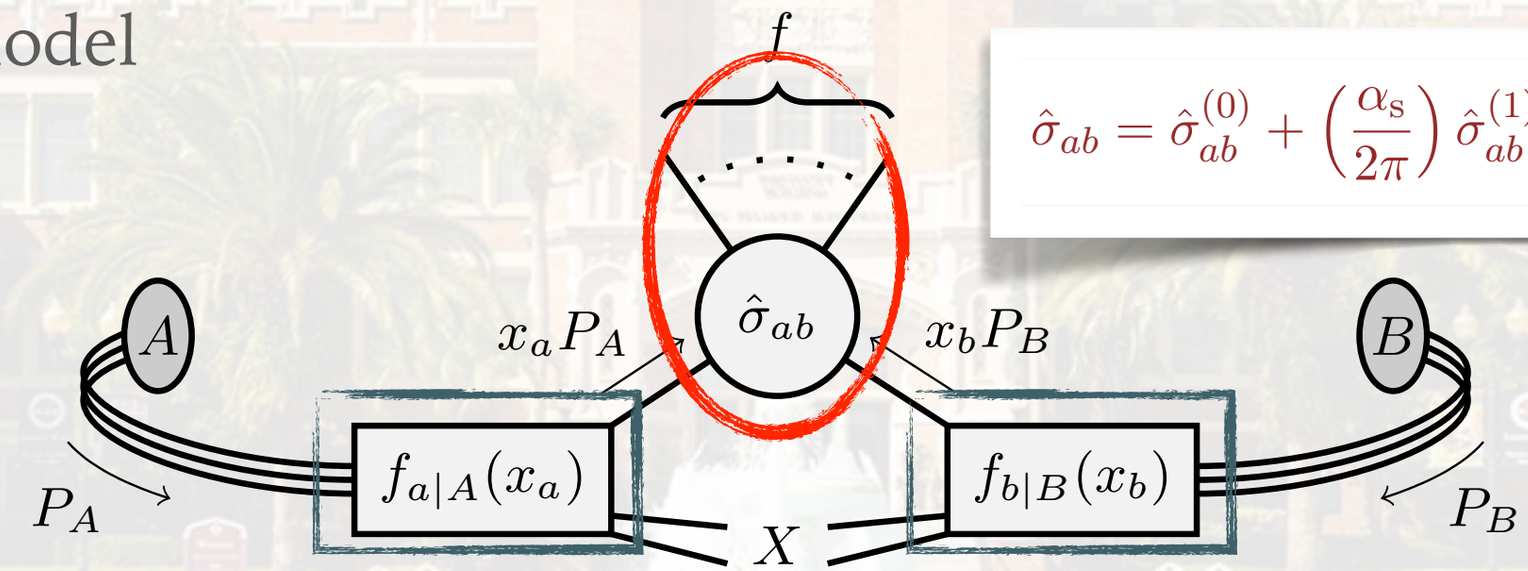
parton distribution functions
(systematically, improvable)
few % at LHC

THE PRECISION THEORY FRONTIER AT THE LHC

- Parton model

$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0)} + \left(\frac{\alpha_s}{2\pi}\right)\hat{\sigma}_{ab}^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}_{ab}^{(2)} + \ldots$$



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hard scattering
(systematically improvable)
aim for few % level!

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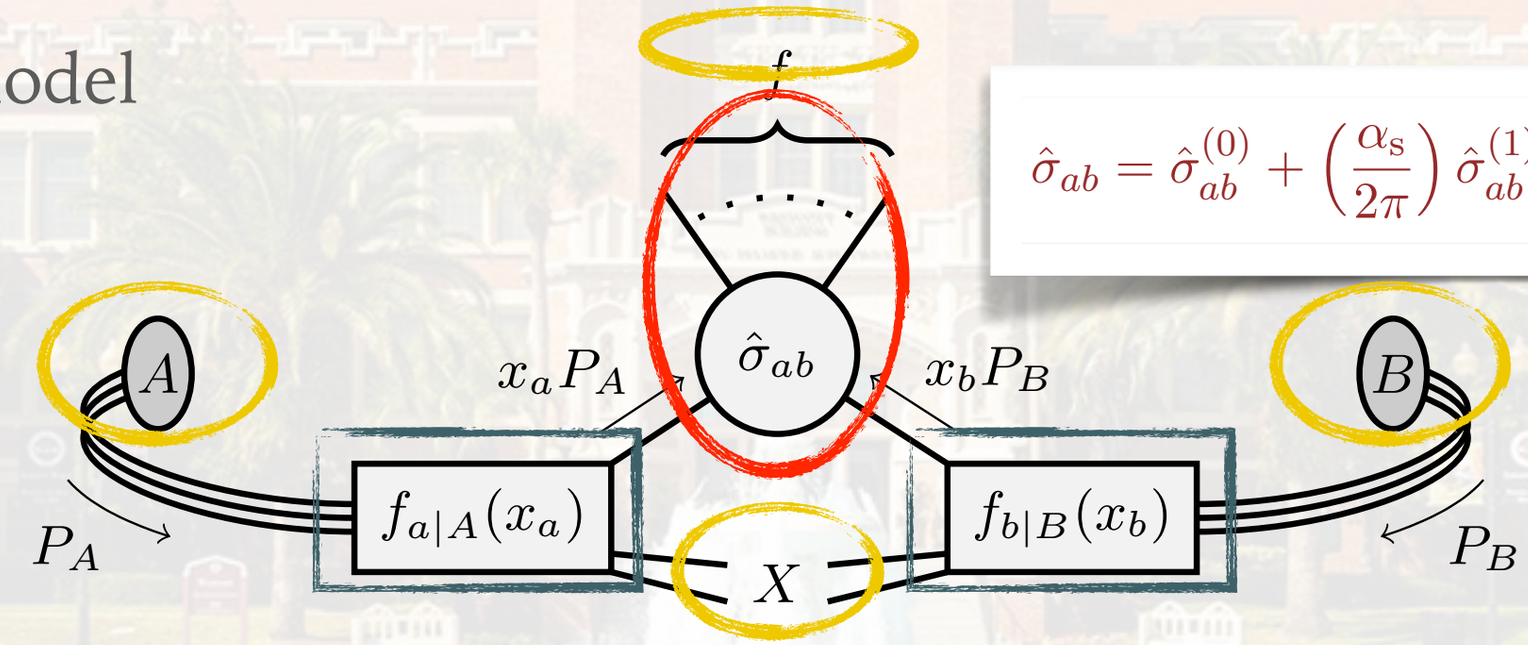

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(systematically, improvable)
few % at LHC

hard scattering
(systematically improvable)
aim for few % level!

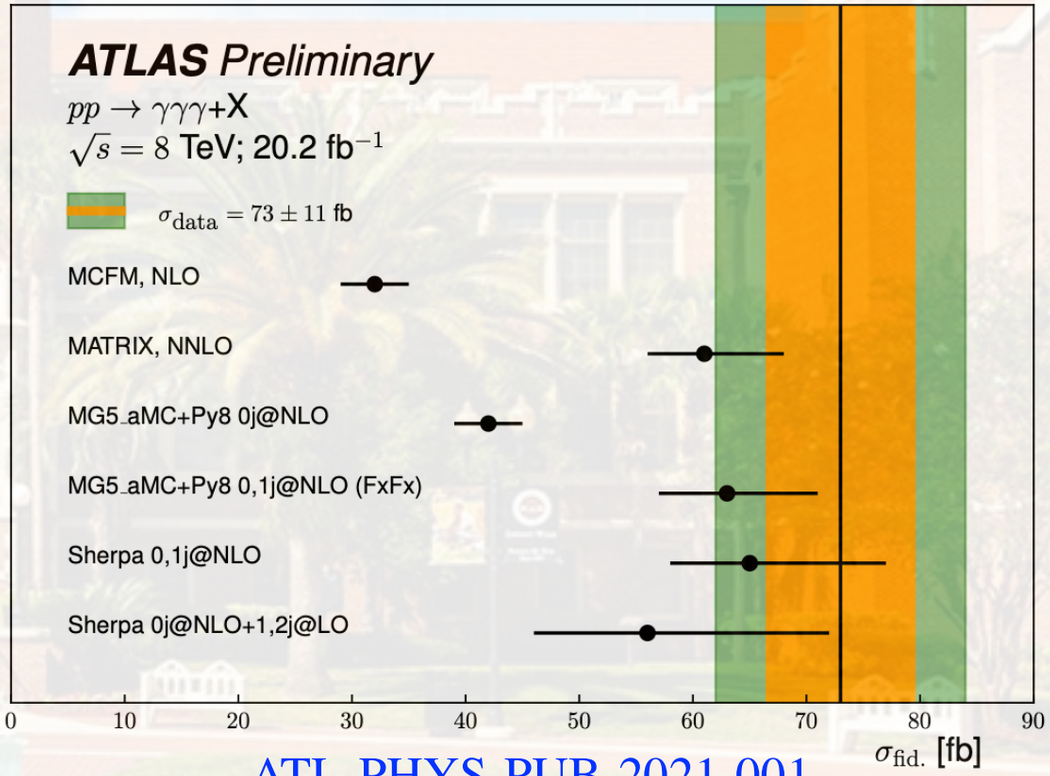
non-perturbative effects
(no good understanding)
~ few %?

THE PRECISION THEORY FRONTIER AT THE LHC

- Remarkable progress at differential NNLO

THE PRECISION THEORY FRONTIER AT THE LHC

- Remarkable progress at differential NNLO
  - Complexity at 2 to 3 scattering
    Tri-photon: *JHEP* 02 (2020) 057
    Phys.Lett.B 812 (2021) 136013
    Di-photon+Jet: 2105.06940
    WH+Jet: *Phys.Lett.B* 817 (2021) 136335
  - Di-jet triple differential predictions



ATL-PHYS-PUB-2021-001

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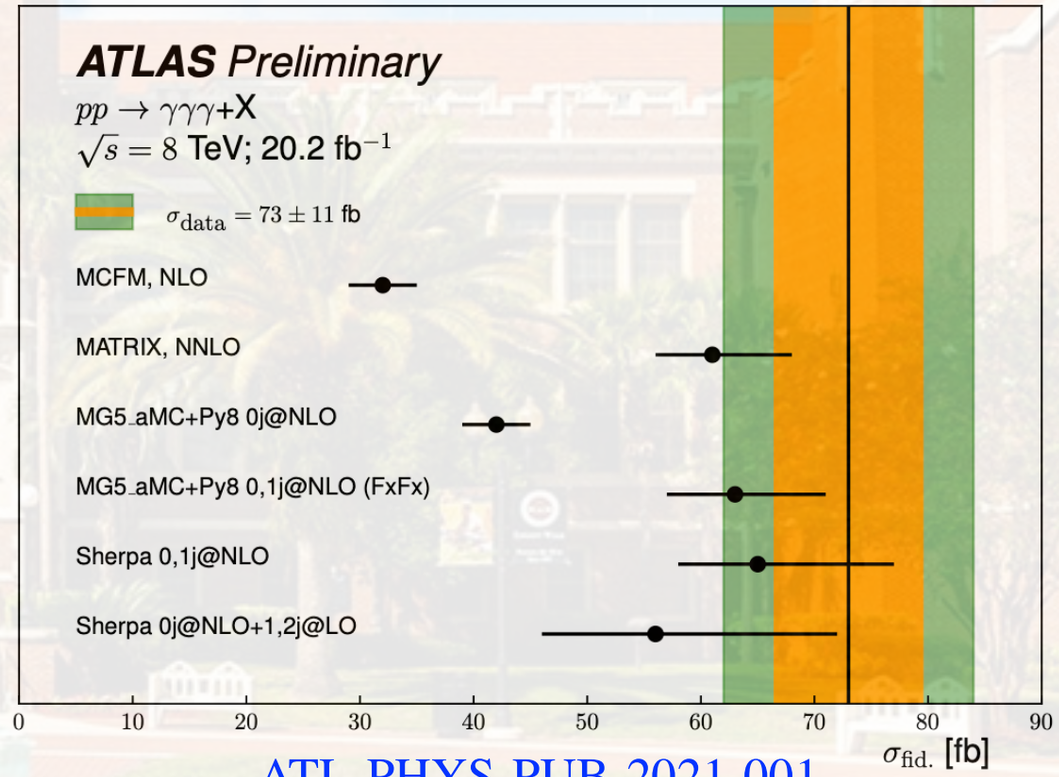

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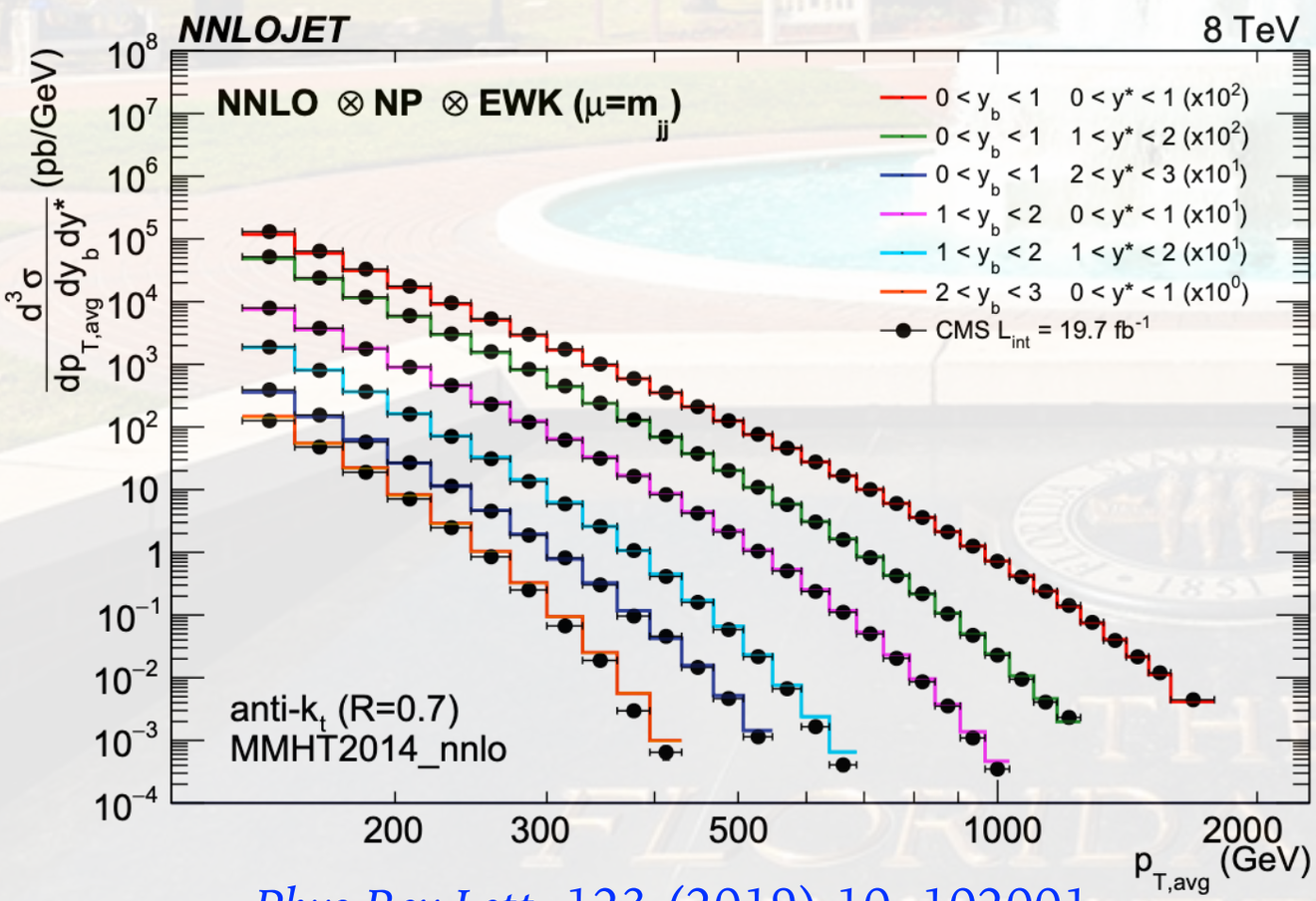

Phys.Rev.Lett. 123 (2019) 10, 102001

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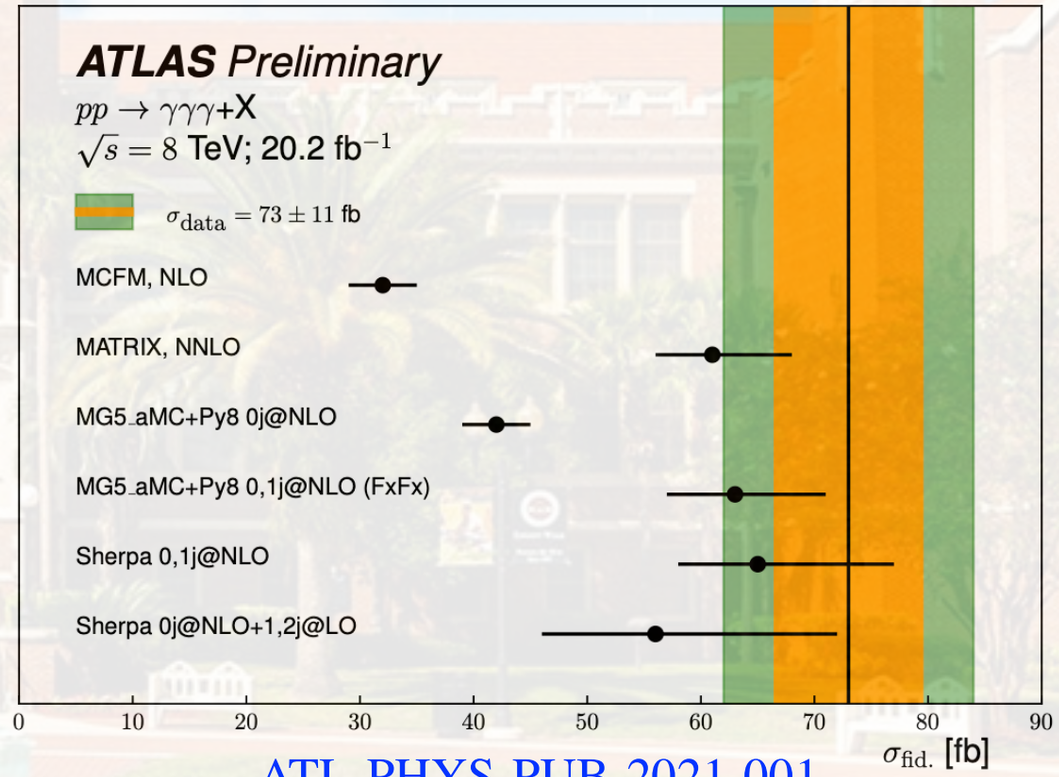

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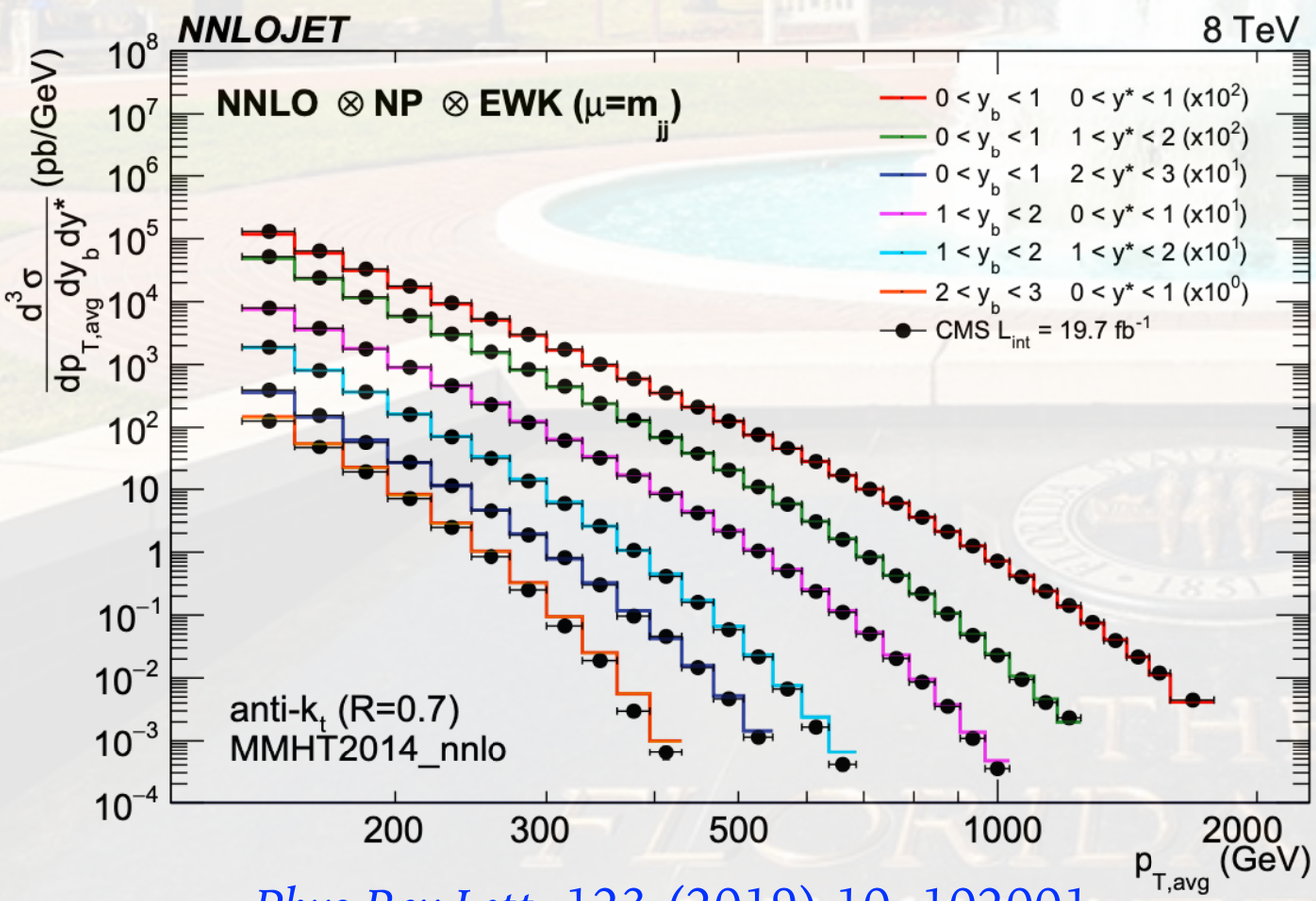


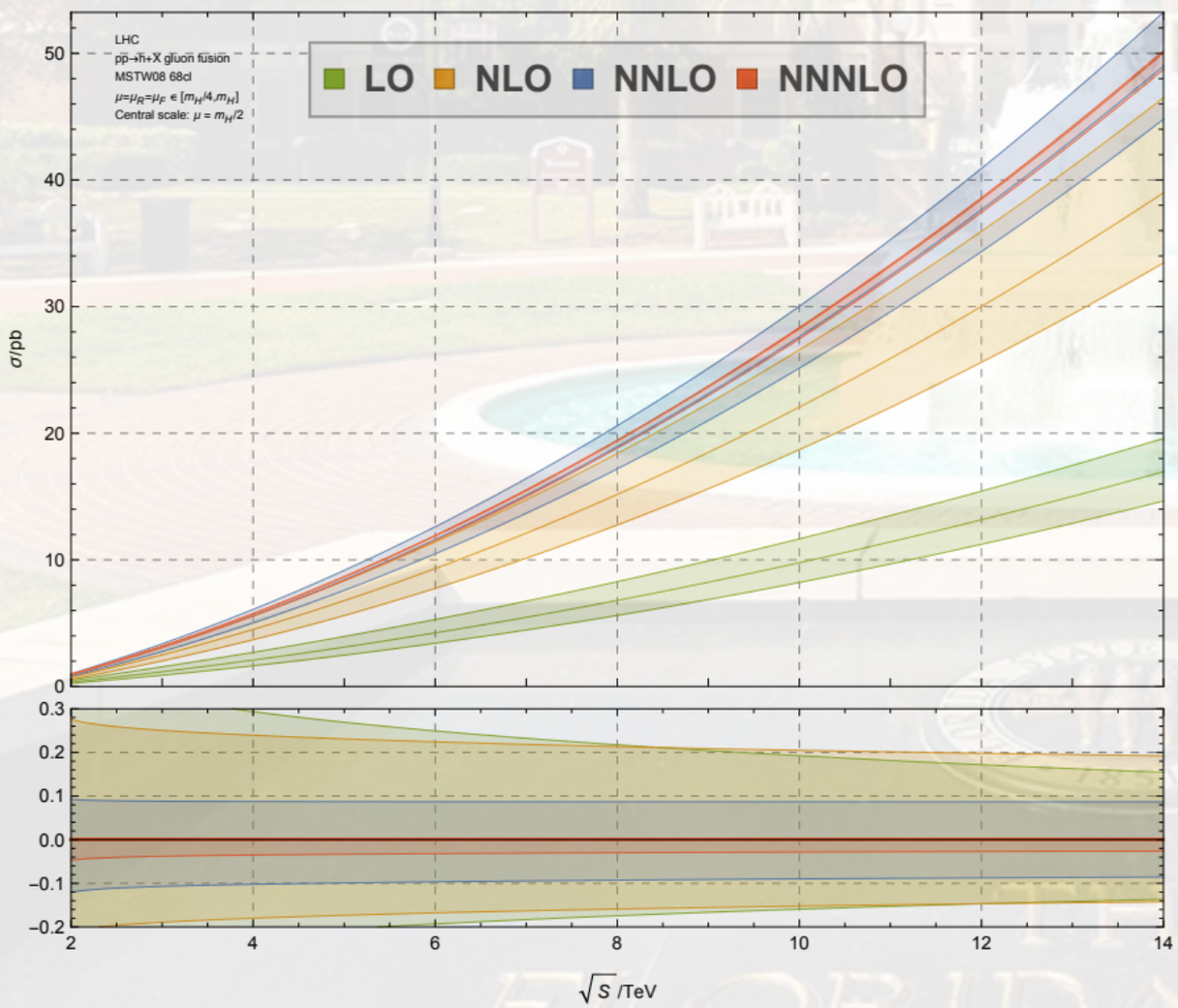
Phys.Rev.Lett. 123 (2019) 10, 102001

- RADCOR 2019 talks
  - 6 on NNLO pheno
  - 8 on 2-loop amplitudes
  - 2 on N3LO pheno+amplitude
- RADCOR+LoopFest 2021 talks
  - 12 on NNLO pheno
  - 14 on 2-loop amplitudes
  - 5 on N3LO pheno+amplitude

THE PRECISION THEORY FRONTIER AT THE LHC

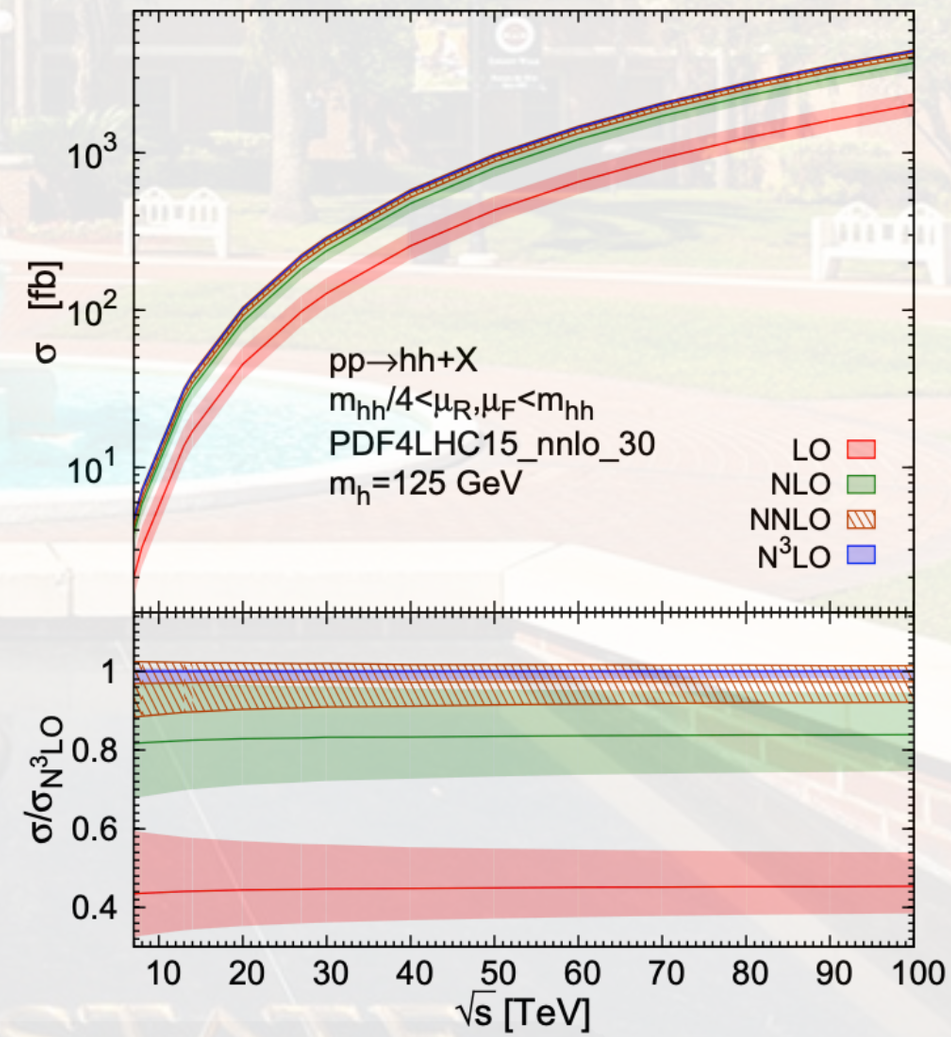
- N3LO QCD corrections available for LHC observables
  - Total and differential predictions of Higgs production and decay
  - Gluon fusion channel (ggF) in heavy top quark limit (HTL): H and HH

σ_H



Phys.Rev.Lett. 114 (2015) 212001

σ_{HH}



Phys.Lett.B 803 (2020) 135292

THE PRECISION THEORY FRONTIER AT THE LHC

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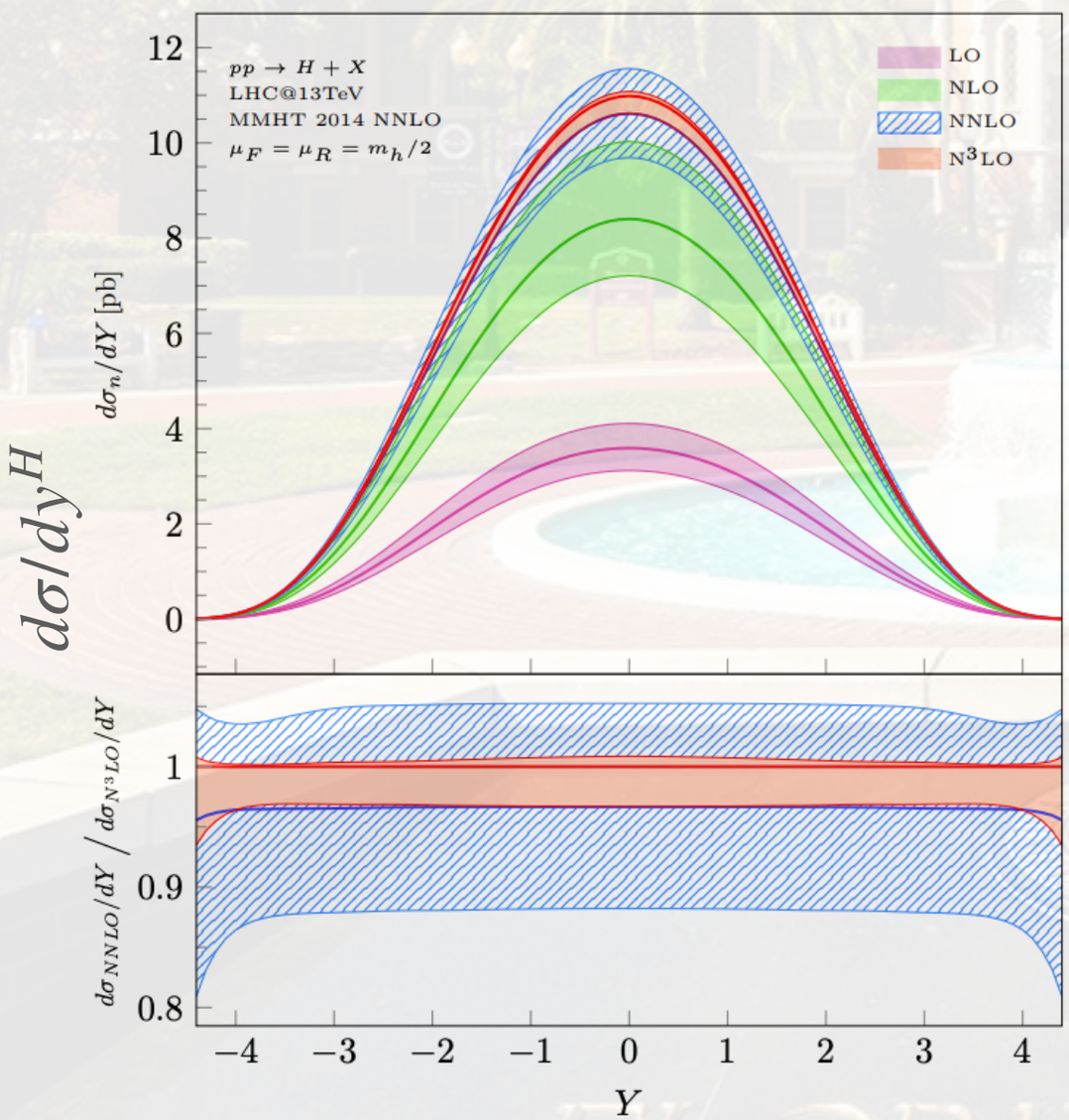
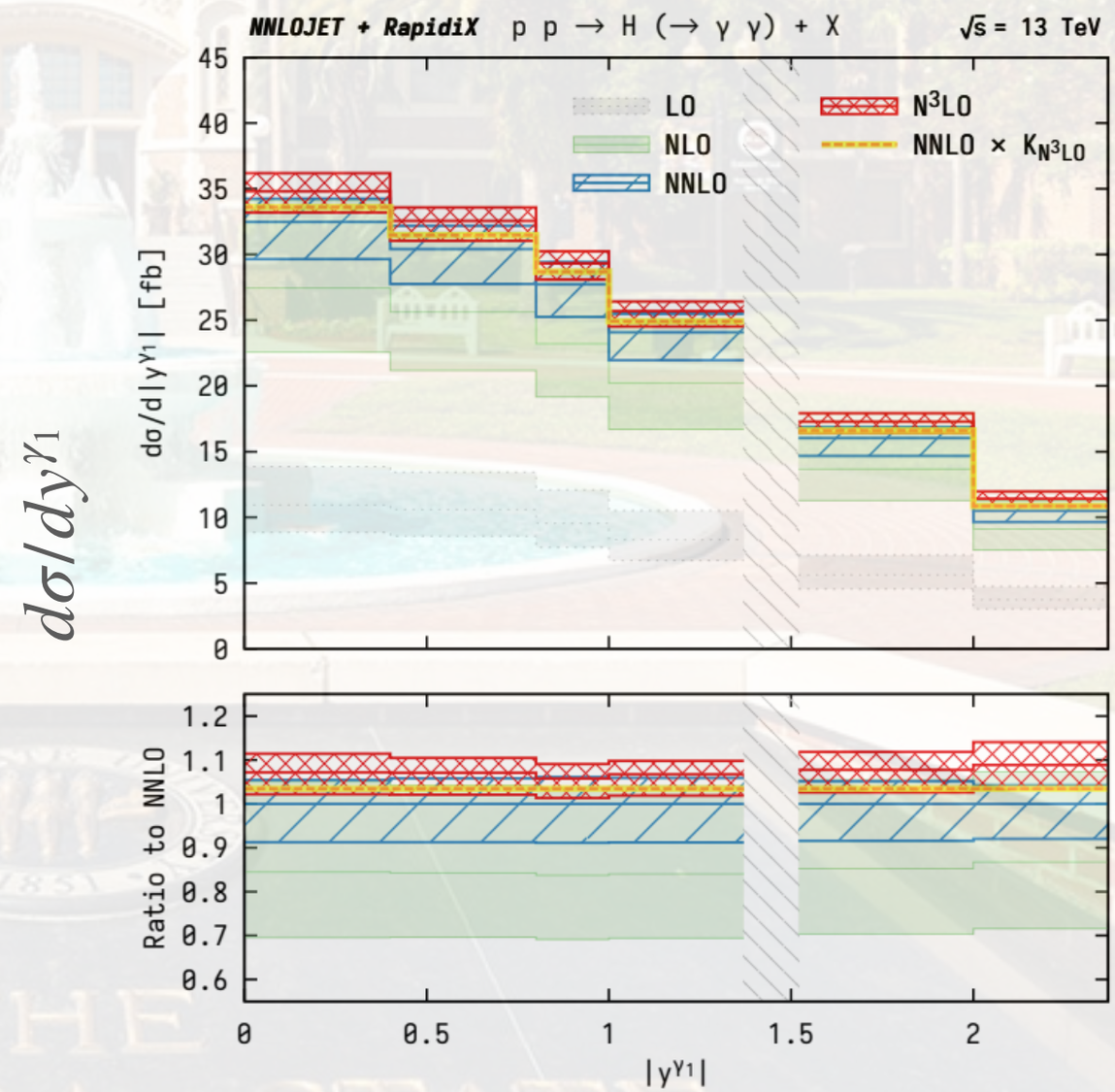
  - Total and differential predictions of Higgs production and decay
  - Differential distributions from ggF channel in HTL



Phys.Rev.D 99 (2019) 3, 034004
See also JHEP 02 (2019) 096



2102.07607

THE PRECISION THEORY FRONTIER AT THE LHC

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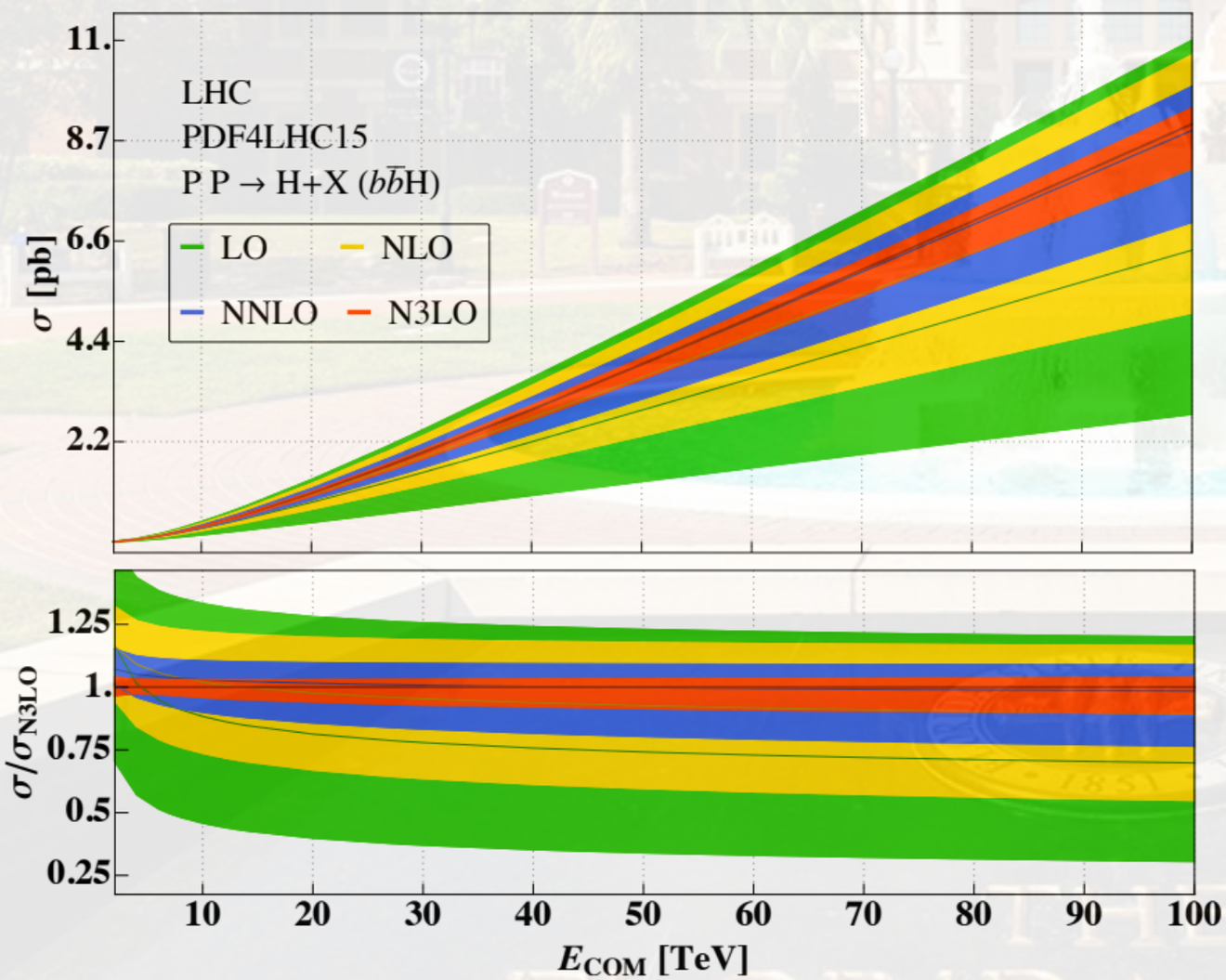
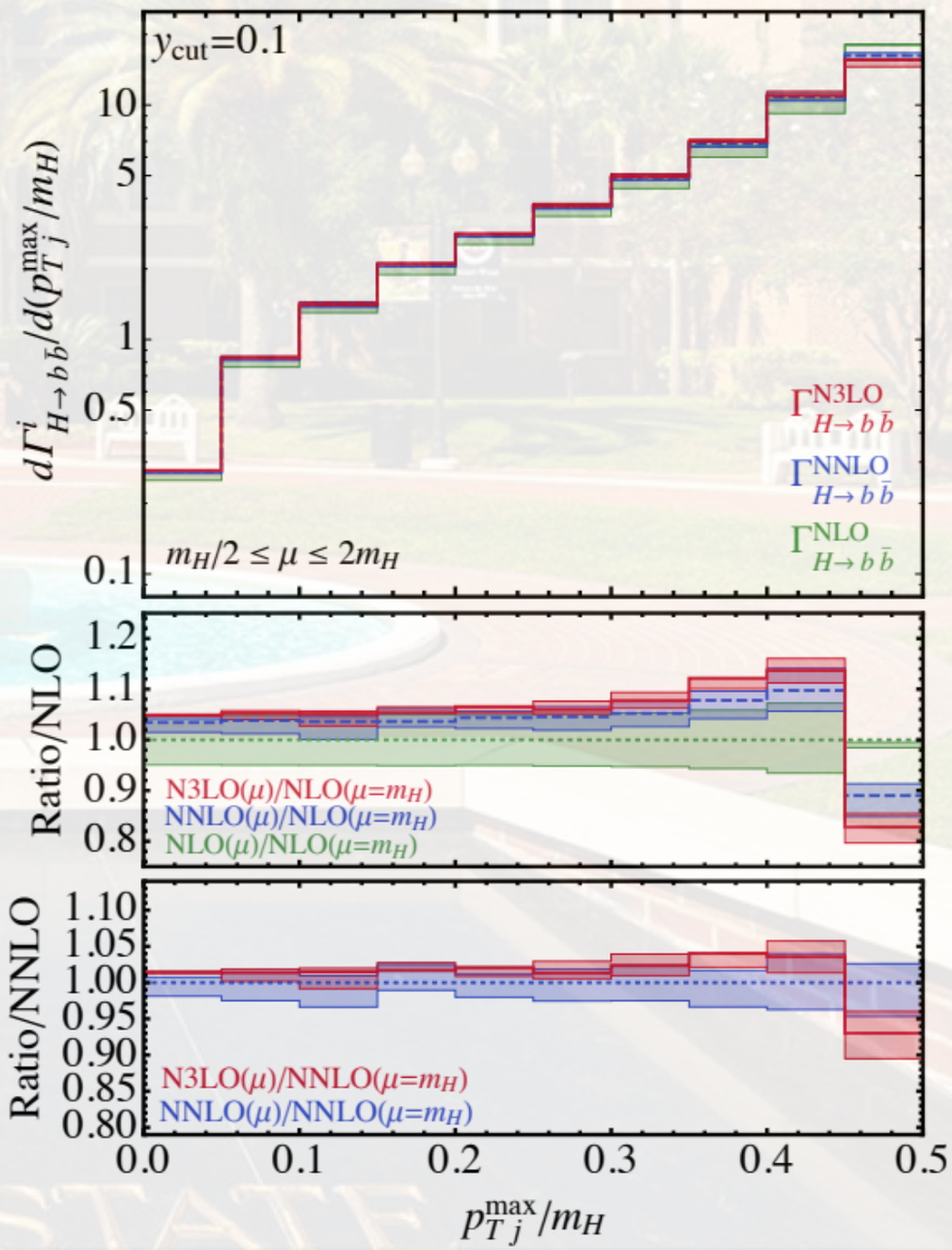
  - Total and differential predictions of Higgs production and decay
  - $b\bar{b}H$ production and decay predictions

$b\bar{b} \to H$



$H \to b\bar{b}$

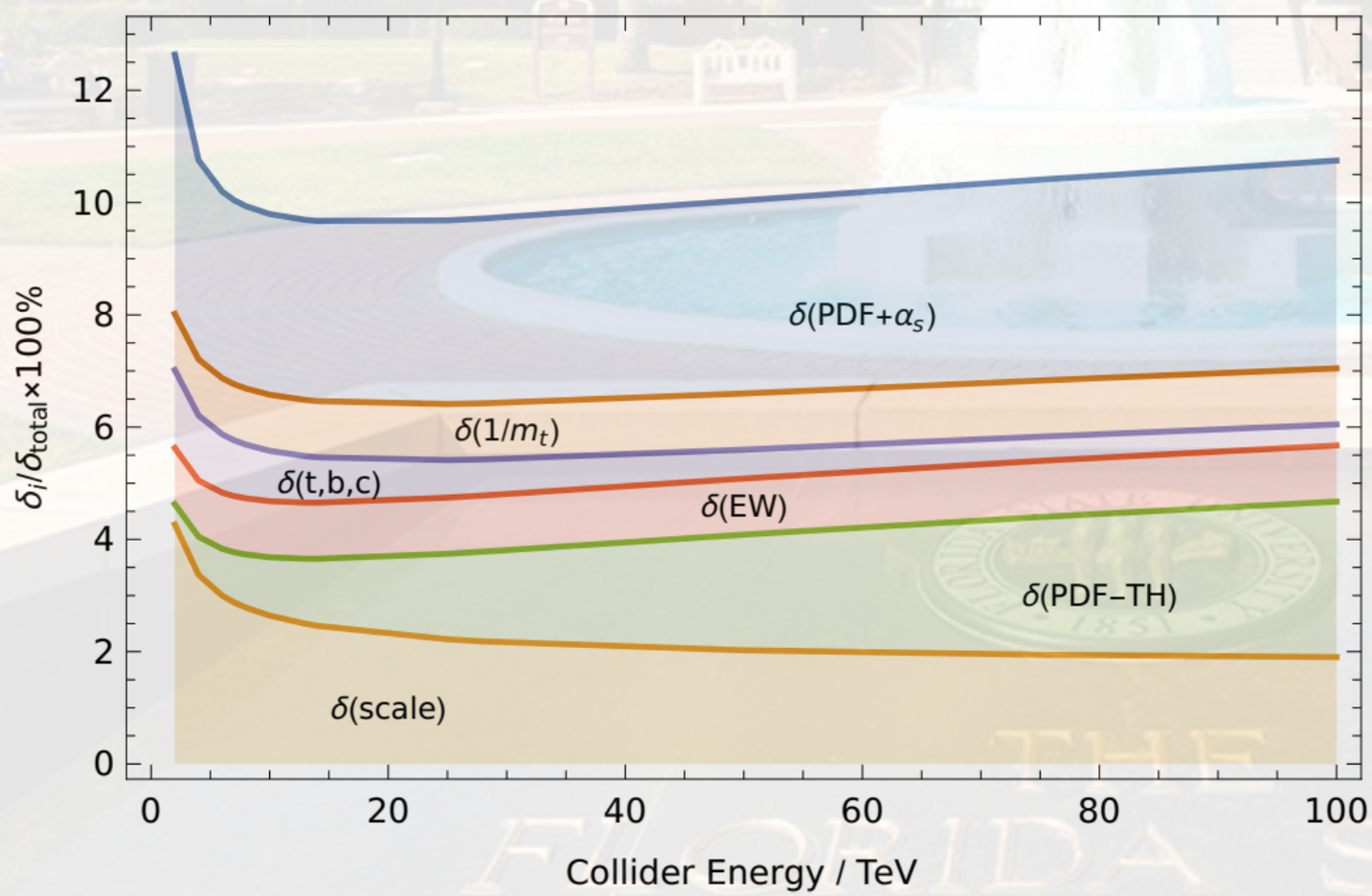


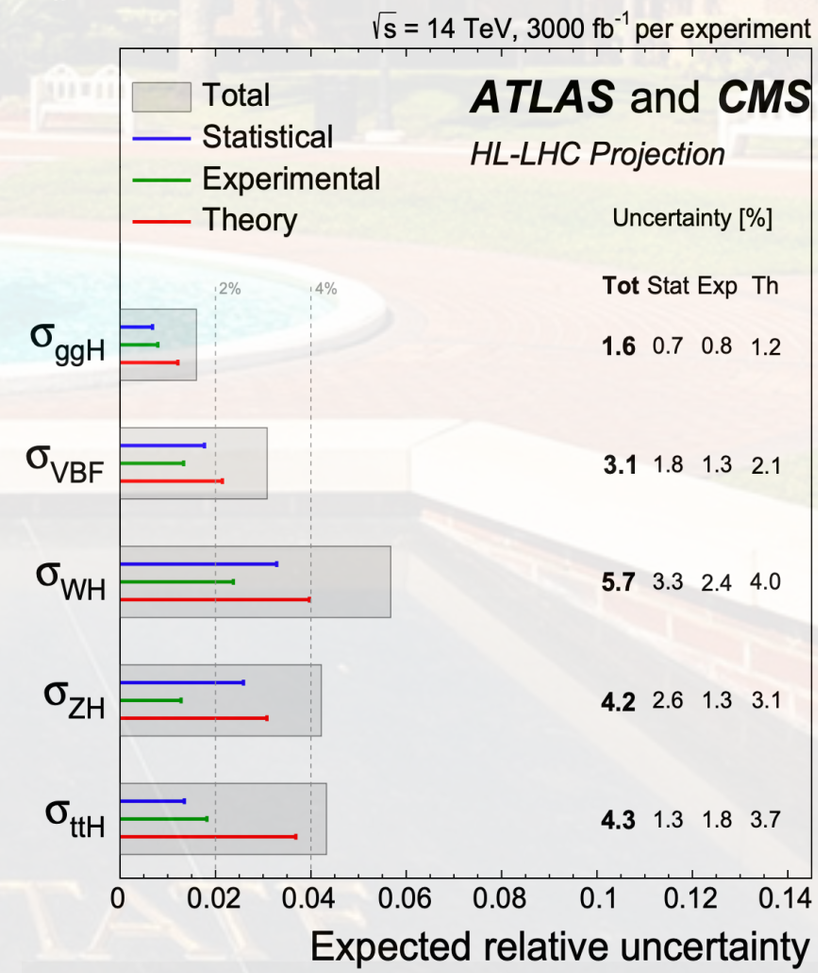
Phys.Rev.Lett. 125 (2020) 5, 051804

JHEP 06 (2019) 079

THE PRECISION THEORY FRONTIER AT THE LHC

- N3LO QCD corrections available for LHC observables
  - Excellent convergence of perturbative series for Higgs related obs.
  - To answer the precision challenge from HL-LHC
  - Critical thinking needed for the new "shortest board of a bucket"
    - Uncertainties from PDF, α_s, fixed couplings, mass effect etc.





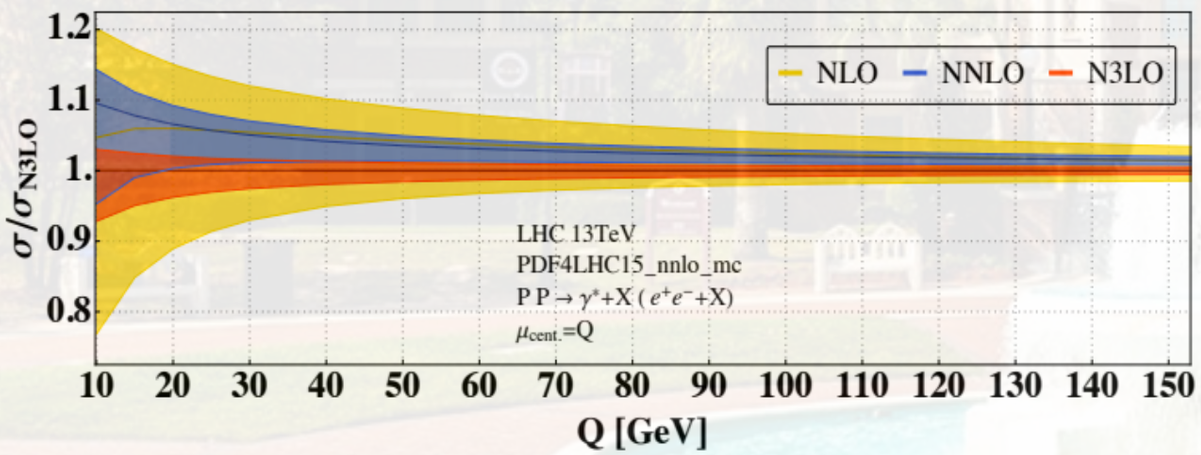
Comput.Phys.Commun. 233 (2018) 243-260

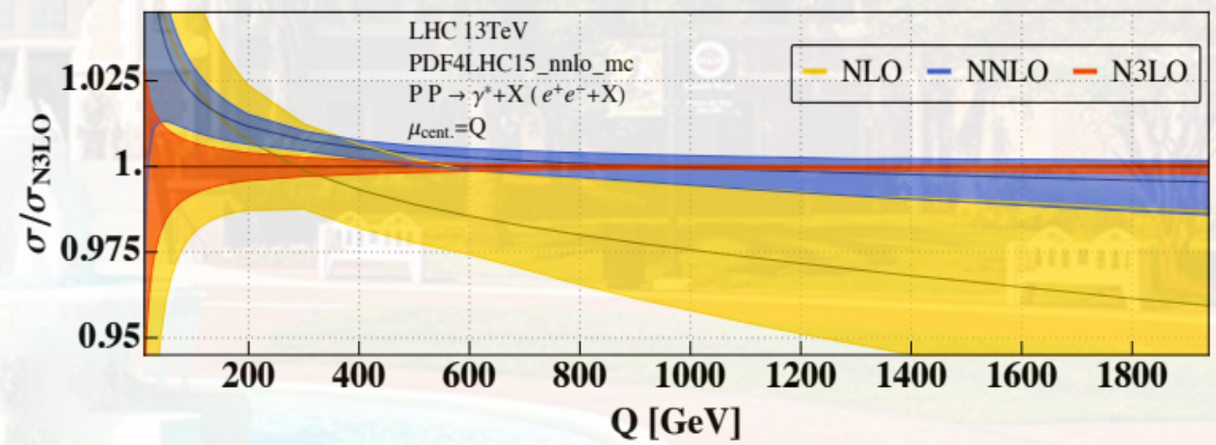
WG2 report on HL-LHC 1902.00134

THE PRECISION THEORY FRONTIER AT THE LHC

- N3LO QCD corrections available for LHC observables
  - Neutral and charged current total cross section (CFB collaboration)
    - Tension for perturbative convergence of fixed order corrections

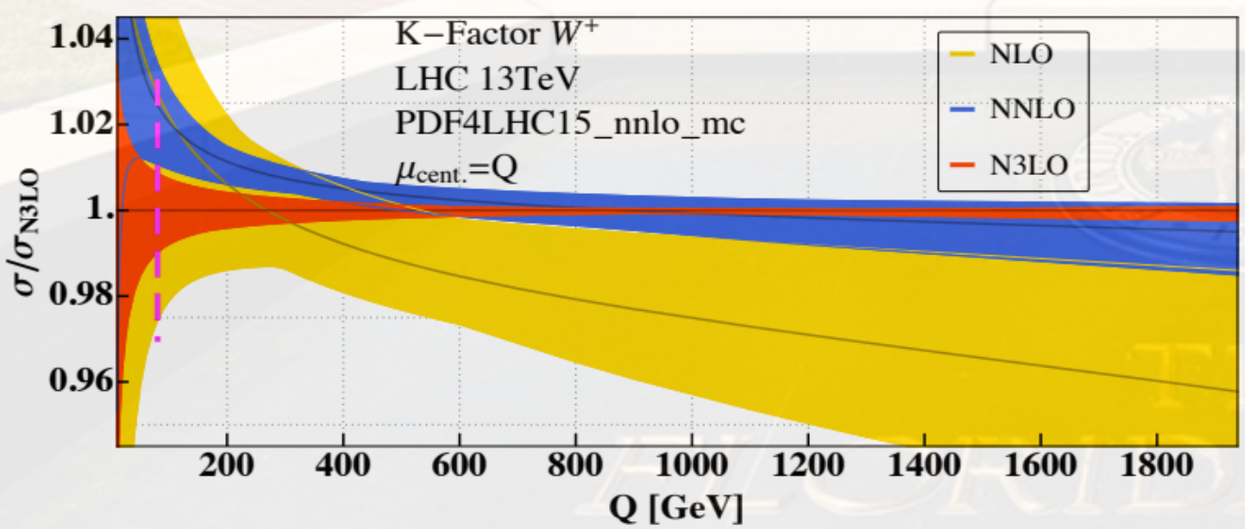
$pp \to \gamma^*$

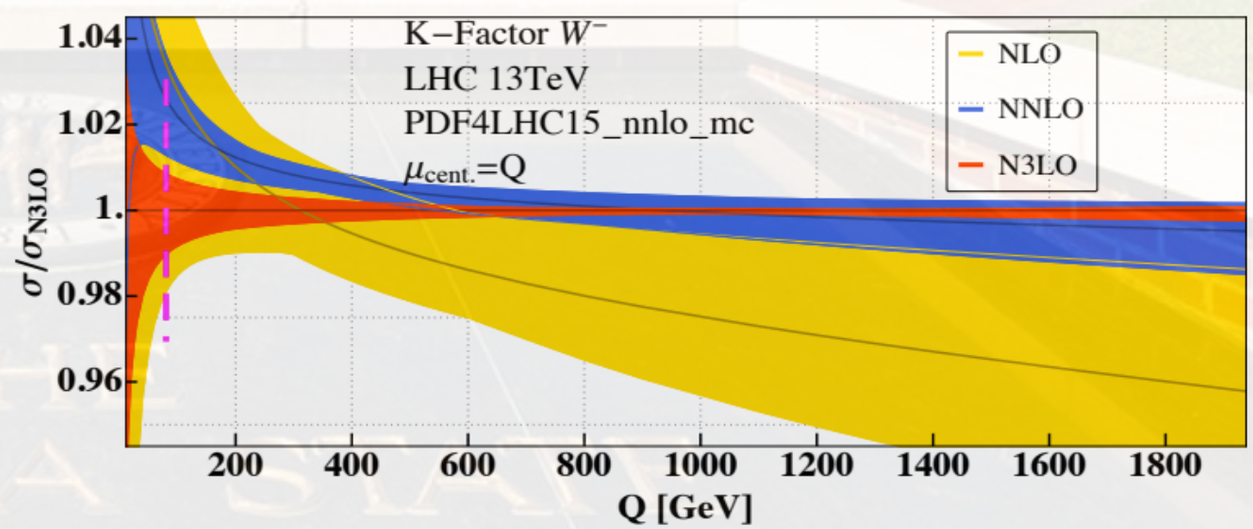




C. Duhr, F. Dulat and B. Mistlberger *Phys.Rev.Lett.* 125 (2020) 17, 172001

$pp \to W^{\pm}$





C. Duhr, F. Dulat and B. Mistlberger *JHEP* 11 (2020) 143

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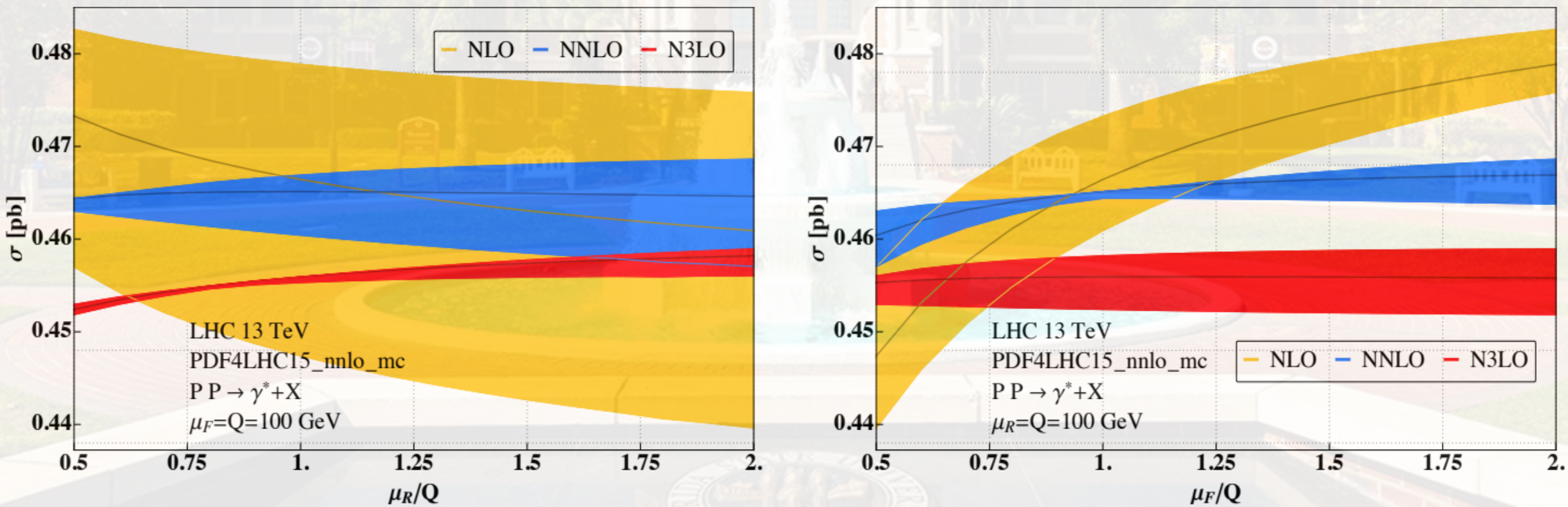
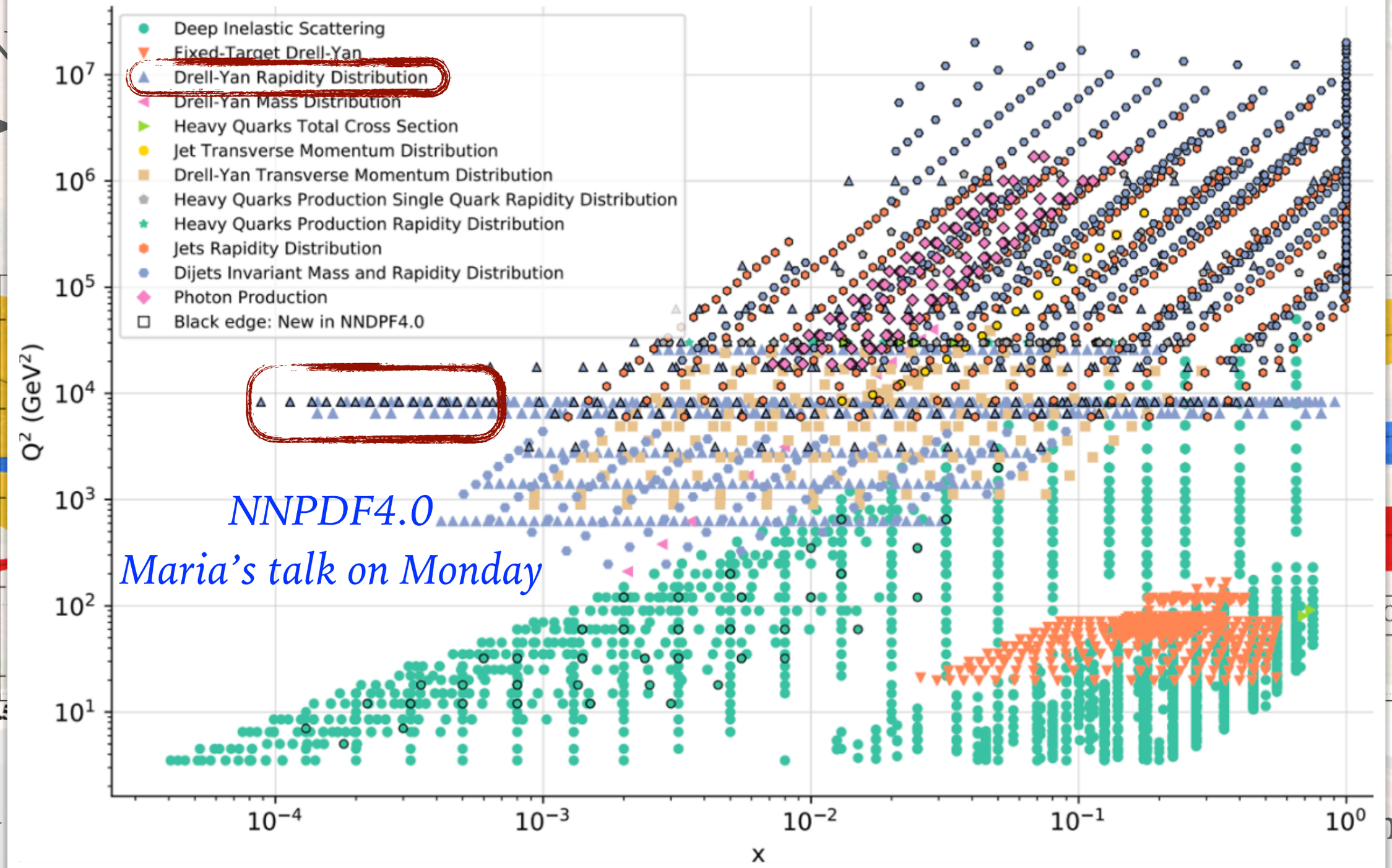


C. Duhr, F. Dulat and B. Mistlberger *Phys.Rev.Lett.* 125 (2020) 17, 172001

- Require 2nd calculation to check the -2% correction & scale variation
- Need to study differential observables with wide dynamic range
  - To feed coherent predictions for PDF and α_s fittings

THE PRECISION THEORY FRONTIER AT THE LHC



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XC, T. Gehrmann, N. Glover, A. Huss, T. Z. Yang, H. X. Zhu

- Apply qt-subtraction at N3LO with SCET factorisation and expand to N3LO:

$$\frac{d^3\sigma}{dQ^2 d^2\vec{q}_T dy} = \int \frac{d^2 b_\perp}{(2\pi)^2} e^{-iq_\perp \cdot b_\perp} \sum_q \sigma_{\rm LO}^{\gamma^*} H_{q\bar{q}} \Big[\sum_k \int_{x_1}^1 \frac{dz_1}{z_1} \mathcal{I}_{qk}\left(z_1, b_T^2, \mu\right) f_{k/h_1}(x_1/z_1, \mu)$$
$$\times \sum_j \int_{x_2}^1 \frac{dz_2}{x_2} \mathcal{I}_{\bar{q}j}\left(z_2, b_T^2, \mu\right) f_{j/h_2}(x_2/z_2, \mu) \mathcal{S}\left(b_\perp, \mu\right) + (q \leftrightarrow \bar{q}) \Big] + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

- All factorised functions are recently known up to N3LO:
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  2) TMD soft function $S(b_\perp, \mu)$ at α_s^3 from *Phys.Rev.Lett.* 118 (2017) 022004
  3) Matching kernel of TMD beam function I_{qk} at α_s^3 from:
     Phys.Rev.Lett. 124 (2020) 092001 and *JHEP* 09 (2020) 146

- Apply qt cut to factorise N3LO contribution into two parts:

$$\mathrm{d}\sigma_{N^3LO}^{\gamma^*} = [\mathscr{H}^{\gamma^*} \otimes \mathrm{d}\sigma^{\gamma^*}]_{N^3LO}\Big|_{\delta(p_{T,\gamma^*})} + \left[\mathrm{d}\sigma_{NNLO}^{\gamma^*+jet} - \mathrm{d}\sigma_{N^3LO}^{\gamma^*\,CT}\right]_{p_{T,\gamma^*}>qt}$$

- $\mathrm{d}\sigma_{NNLO}^{\gamma^*+jet}$ from NNLOJET with excellent numerical stability at small p_{T,γ^*}

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     Phys.Rev.Lett. 124 (2020) 092001 and *JHEP* 09 (2020) 146

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$$\mathrm{d}\sigma_{N^3LO}^{\gamma^*} = [\mathscr{H}^{\gamma^*} \otimes \mathrm{d}\sigma^{\gamma^*}]_{N^3LO}\Big|_{\delta(p_{T,\gamma^*})} + \left[\mathrm{d}\sigma_{NNLO}^{\gamma^*+jet} - \mathrm{d}\sigma_{N^3LO}^{\gamma^*\,CT}\right]_{p_{T,\gamma^*}>qt}$$

- $\mathrm{d}\sigma_{NNLO}^{\gamma^*+jet}$ from NNLOJET with excellent numerical stability at small p_{T,γ^*}

DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

XC, T. Gehrmann, N. Glover, A. Huss, T. Z. Yang, H. X. Zhu

- Apply qt-subtraction at N3LO with SCET factorisation and expand to N3LO:

$$\frac{d^3\sigma}{dQ^2 d^2\vec{q}_T dy} = \int \frac{d^2 b_\perp}{(2\pi)^2} e^{-iq_\perp\cdot b_\perp} \sum_q \sigma_{\rm LO}^{\gamma^*} H_{q\bar{q}} \Big[\sum_k \int_{x_1}^1 \frac{dz_1}{z_1} \mathcal{I}_{qk}\left(z_1, b_T^2, \mu\right) f_{k/h_1}(x_1/z_1,\mu)$$
$$\times \sum_j \int_{x_2}^1 \frac{dz_2}{x_2} \mathcal{I}_{\bar{q}j}\left(z_2, b_T^2, \mu\right) f_{j/h_2}(x_2/z_2,\mu) \mathcal{S}\left(b_\perp,\mu\right) + (q \leftrightarrow \bar{q}) \Big] + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

- All factorised functions are recently known up to N3LO:
  1) 3-loop hard function $H_{q\bar{q}}^{(3)}$ from *JHEP* 06 (2010) 094
  2) TMD soft function $S(b_\perp,\mu)$ at α_s^3 from *Phys.Rev.Lett.* 118 (2017) 022004
  3) Matching kernel of TMD beam function I_{qk} at α_s^3 from:
     Phys.Rev.Lett. 124 (2020) 092001 and *JHEP* 09 (2020) 146

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  JHEP 12 (2018) 132 and *Eur.Phys.J.C* 79 (2019) 10

DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- Computational setup for $pp \to \gamma^*$
  (identical to CFB paper *Phys.Rev.Lett.* 125 (2020) 17, 172001)
  - Fix Q value for γ^* at 100 GeV (NNLO and N3LO scale variations deviate)
  - Use central value of PDF4LHC15_nnlo_mc as benchmark input
  - $\alpha_s(m_Z) = 0.118$ with scale variation values calculated from LHAPDF
  - G_μ EW-scheme with fixed α value
  - $\mu_R = \mu_F = 100$ GeV for central QCD scale and use 7-point variations for uncertainty estimation
- Apply $p_{T,\gamma^*} > 0.25$ GeV constrain for NNLO $\gamma^* + Jet$ without jet definition
- Use SCET factorisation to integrate contributions below qt cut.
- Dedicated MC adaption to four sub-channels:
  gg, qqb = (qqb+qbq), qg = (qg+gq+qbg+gqb), qq = (qq+qbqb)

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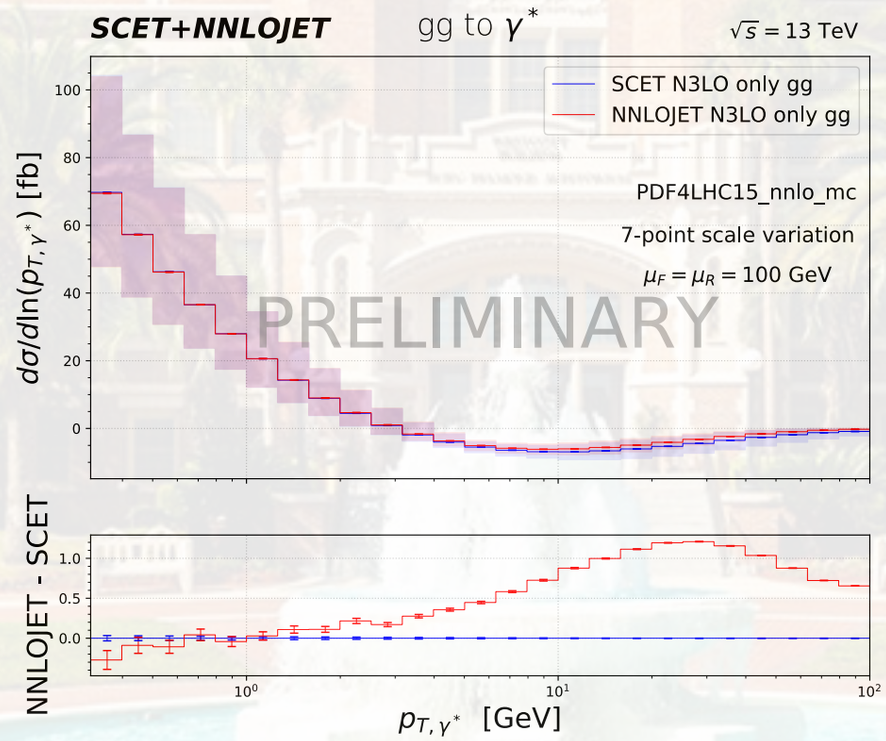
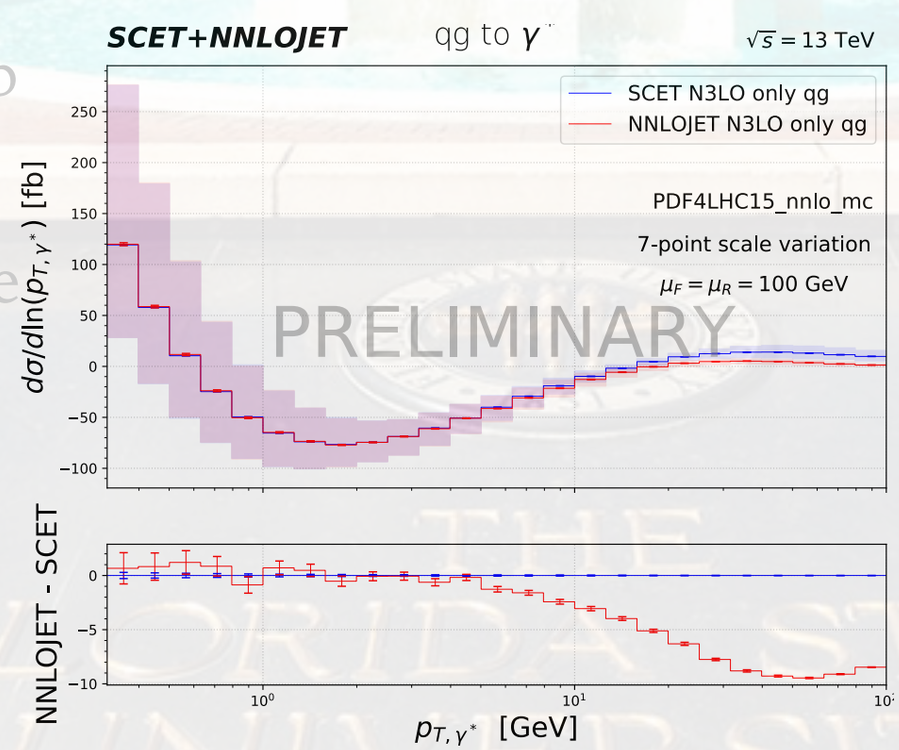
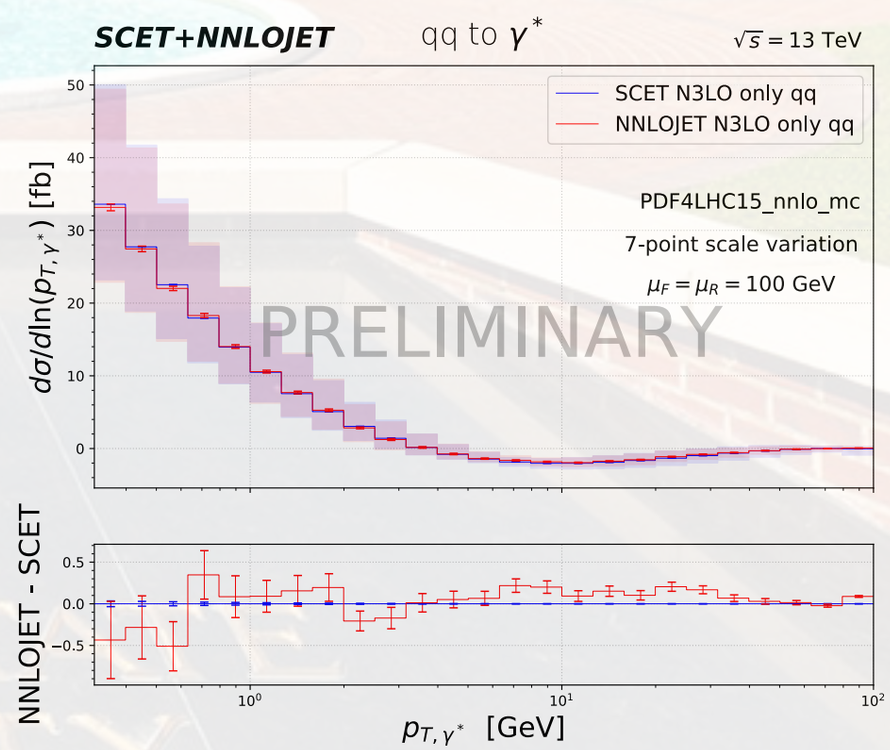
DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- $d\sigma^{\gamma^*+jet}_{NNLO}$ vs. $d\sigma^{\gamma^*\ CT}_{N^3LO}$ at small p_{T,γ^*}

- Check each channel for N3LO only
- Convergence between SCET and NNLOJET: gg below ~1 GeV qg below ~4 GeV qq below ~6 GeV
- Deviations seen in qqb obvious below 4 GeV
- Surface only with large statistics at small p_{T,γ^*}
- Large cancellation between qg and qqb







DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

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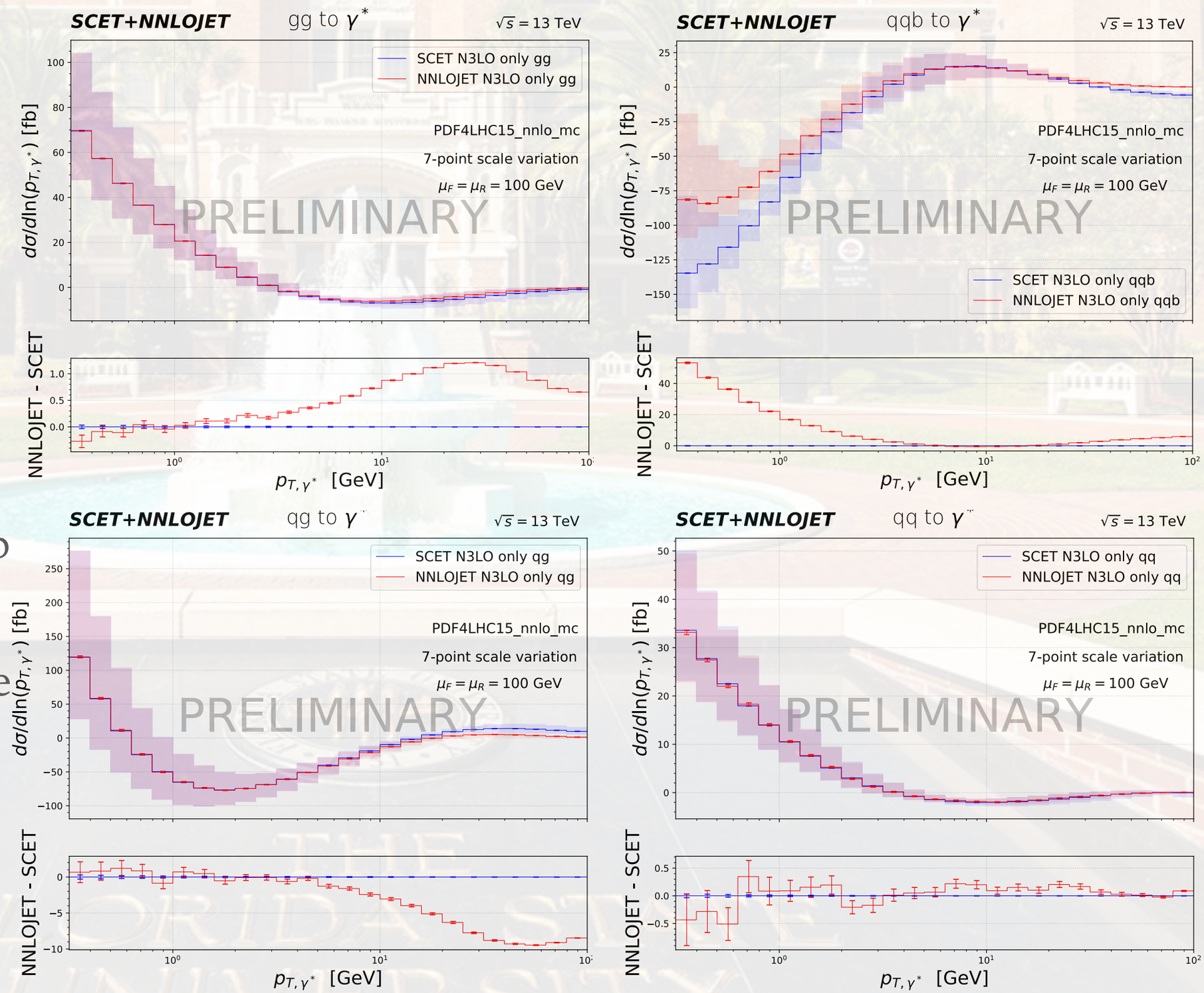

DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- $d\sigma^{\gamma^*+jet}_{NNLO}$ vs. $d\sigma^{\gamma^*\ CT}_{N^3LO}$ at small p_{T,γ^*}
  - Dive into each colour level of qqb channel: $\sigma^{\gamma^*}_{q\bar{q}}|_{N3LO\ only} = (N^2-1)\times$
    $$\left[N^0 + N_f N^{-1} + N^{-1} + N_f N^{-2} + N^{-2} + N_f N^{-3} + N^{-3} + N^{-4}\right]$$

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Nc0 *Ncm1* *Ncm2* *Ncm3* *Ncm4*

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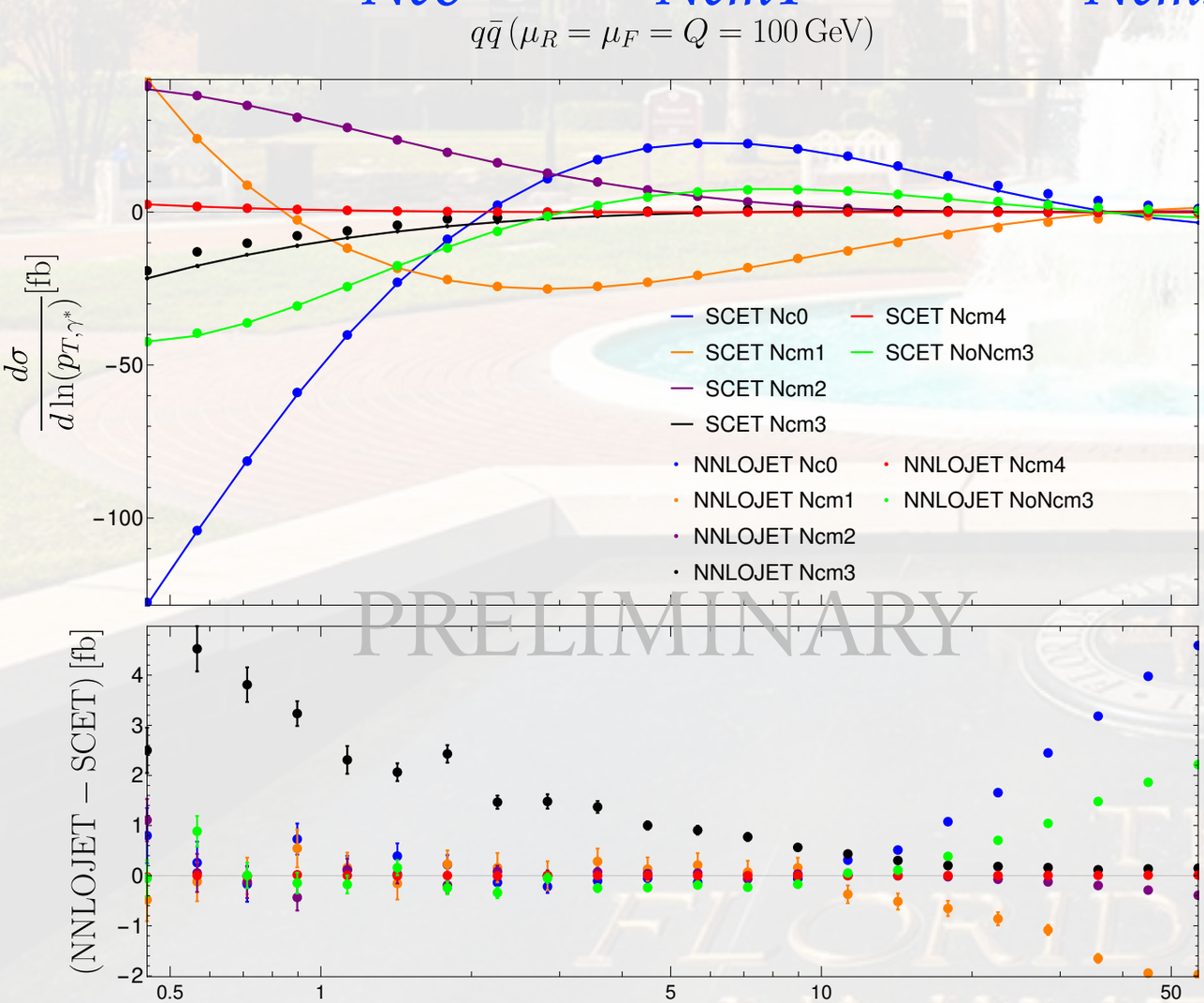

- Excellent agreement in leading colour
- Problematic part in Ncm3
- More specifically in $N_f N^{-3}$ SLC
- Dangerous for recent application in N3LO+N3LL' matching: 2102.08039, 2103.04974
- Still under investigation
- Proceed without Ncm3 (temporary)

DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- $d\sigma^{\gamma^*+jet}_{NNLO}$ vs. $d\sigma^{\gamma^*\ CT}_{N^3LO}$ at small p_{T,γ^*}
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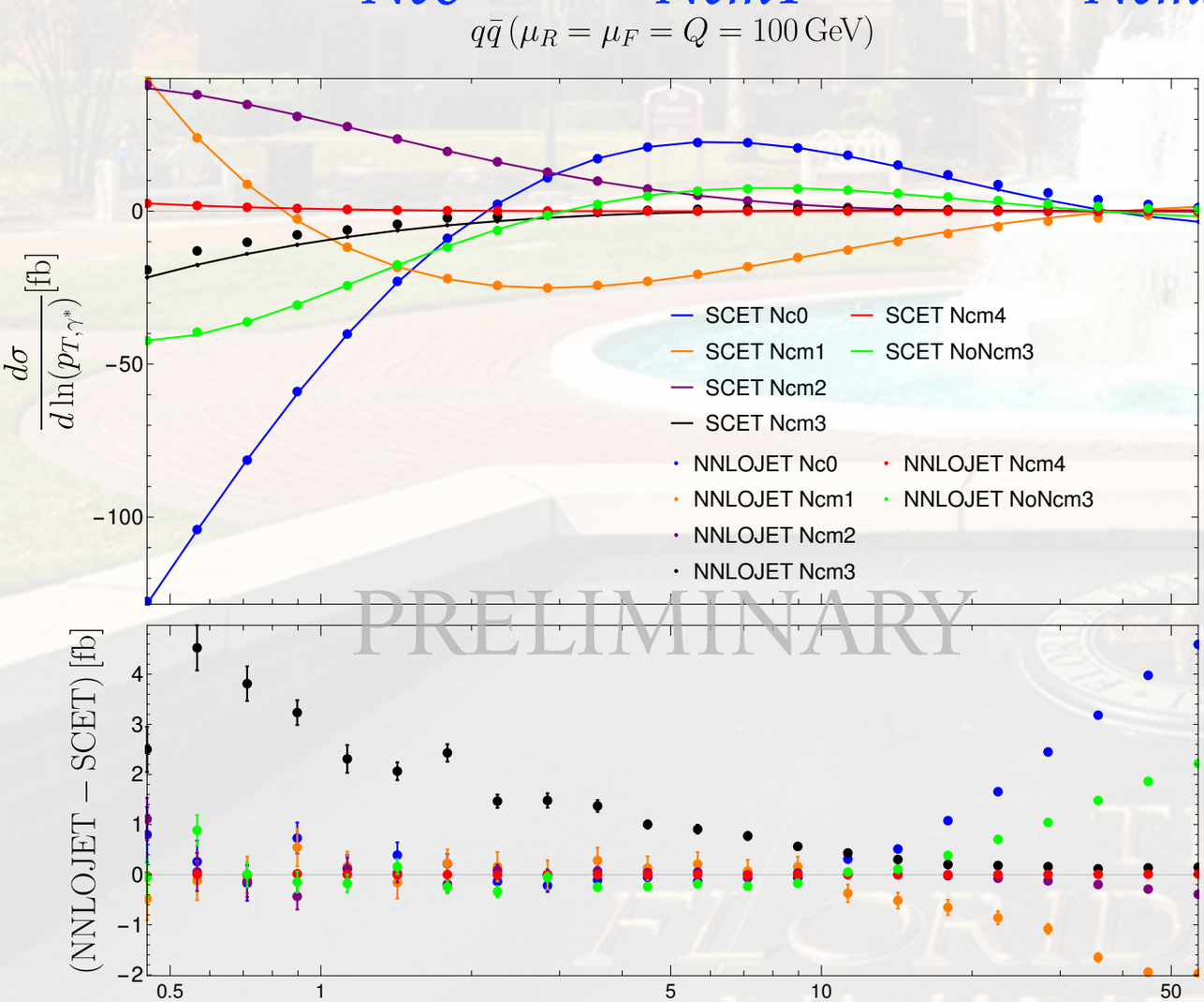
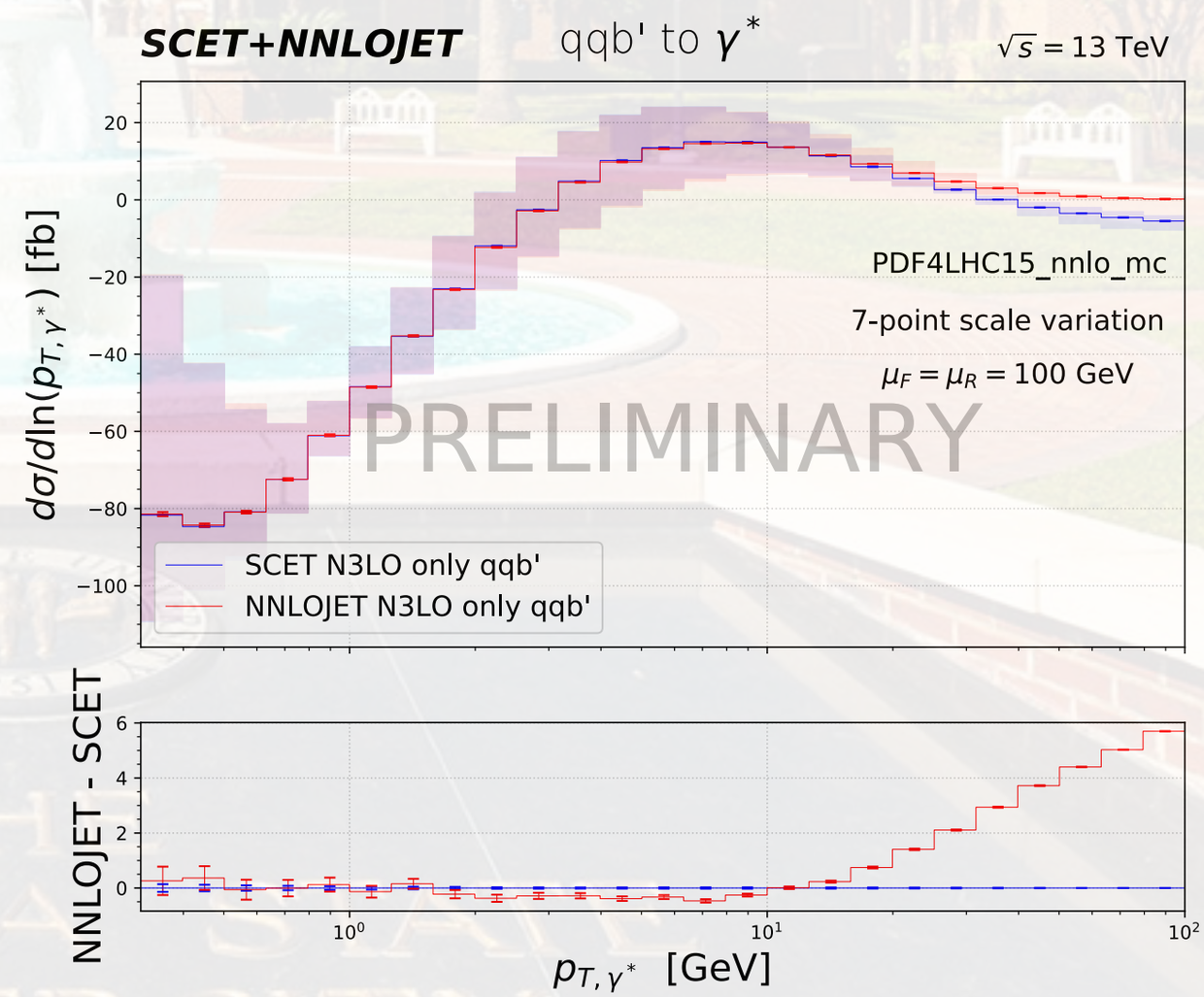
$$[N^0 + N_f N^{-1} + N^{-1} + N_f N^{-2} + N^{-2} + N_f N^{-3} + N^{-3} + N^{-4}] \rightarrow \sigma^{\gamma^*}_{q\bar{q}'}$$

Nc0 Ncm1 Ncm2 Ncm3 Ncm4



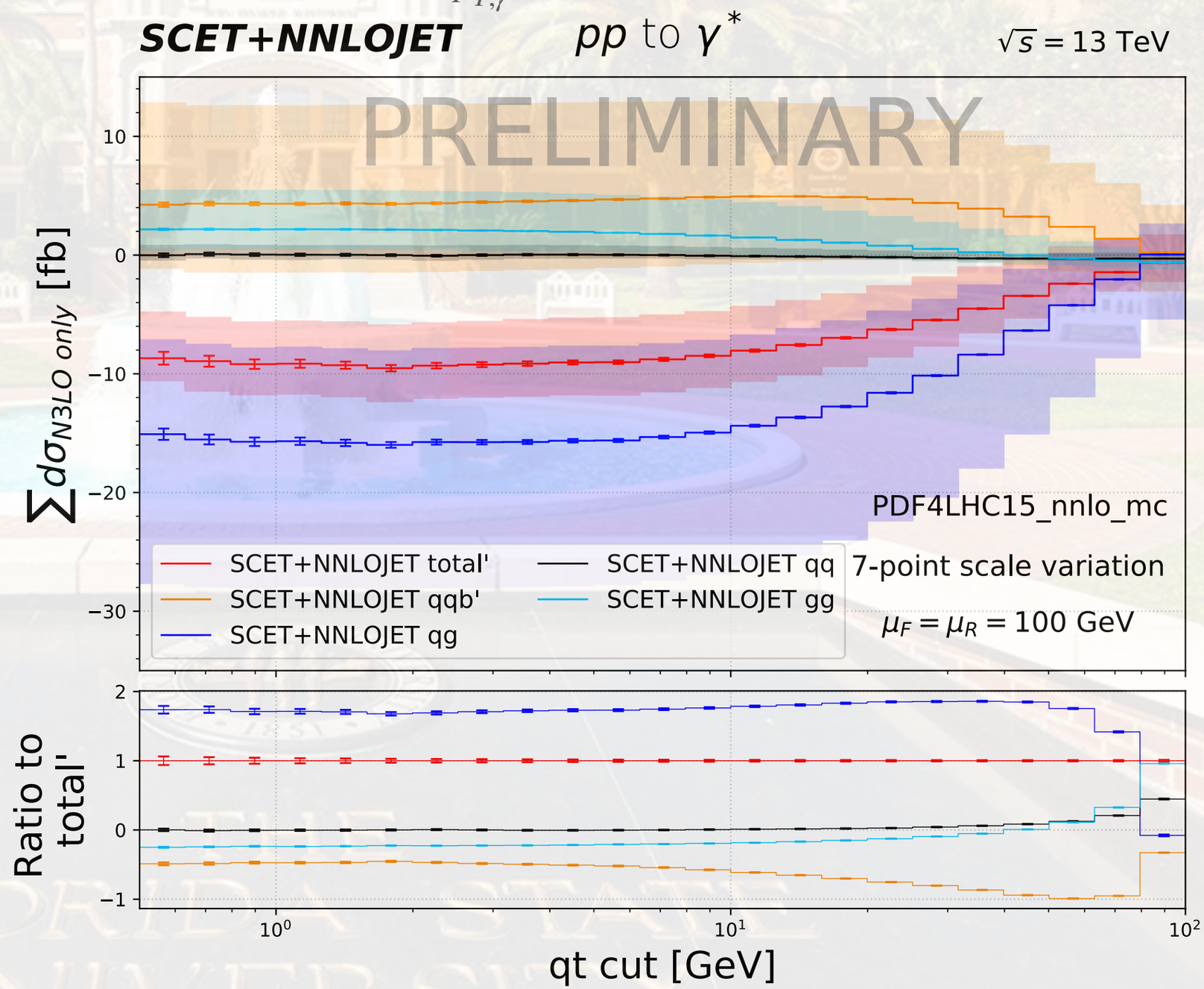


DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- N3LO ccumulated cross section from p_{T,γ^*} (N3LO' coefficient)

$$\sum d\sigma^{\gamma^*}_{N3LO} \equiv \sum_{dp_{T,\gamma^*}} d\sigma^{\gamma^*+jet}_{NNLO}/dp_{T,\gamma^*}\,|_{p_{T,\gamma^*}>qt} + \sum_{dp_{T,\gamma^*}} d\sigma^{\gamma^*\ SCET}_{N^3LO}/dp_{T,\gamma^*}\,|_{p_{T,\gamma^*}\in[0,qt]}$$

- More challenging than p_{T,γ^*}
- Large scale cancellation among channels



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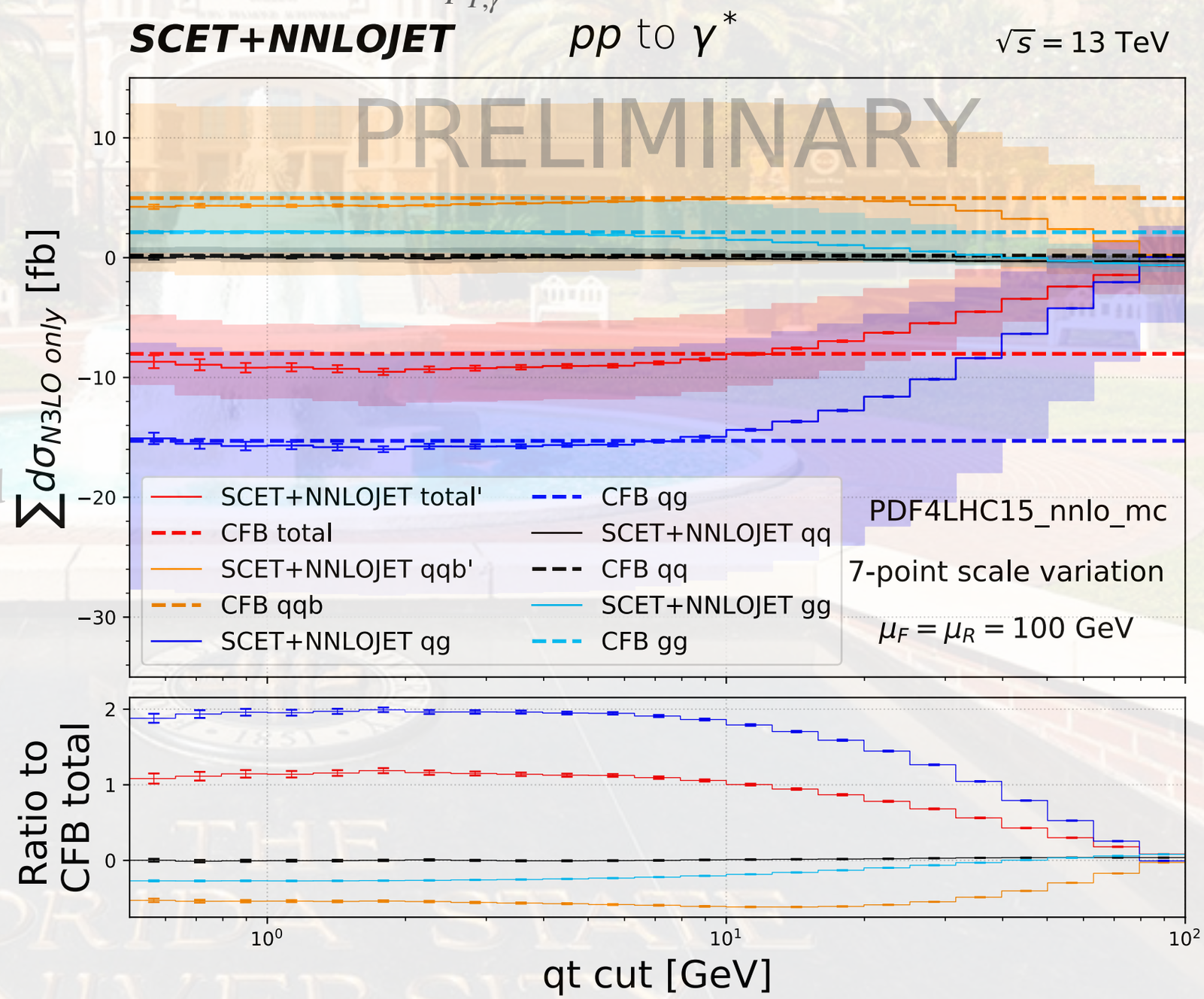
- More challenging than p_{T,γ^*}
- Large scale cancellation among channels
- Compare to CFB total cross section results
- First validation for gg, qq and qg channels (below 1 GeV)
- Missing Ncm3 contribution in qqb channel at ~13% (8% with respect to N3LO)
- Within MC error of full channel N3LO coefficient



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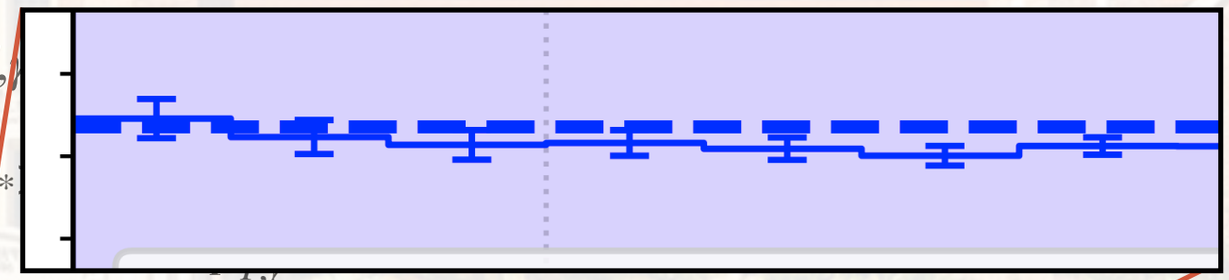

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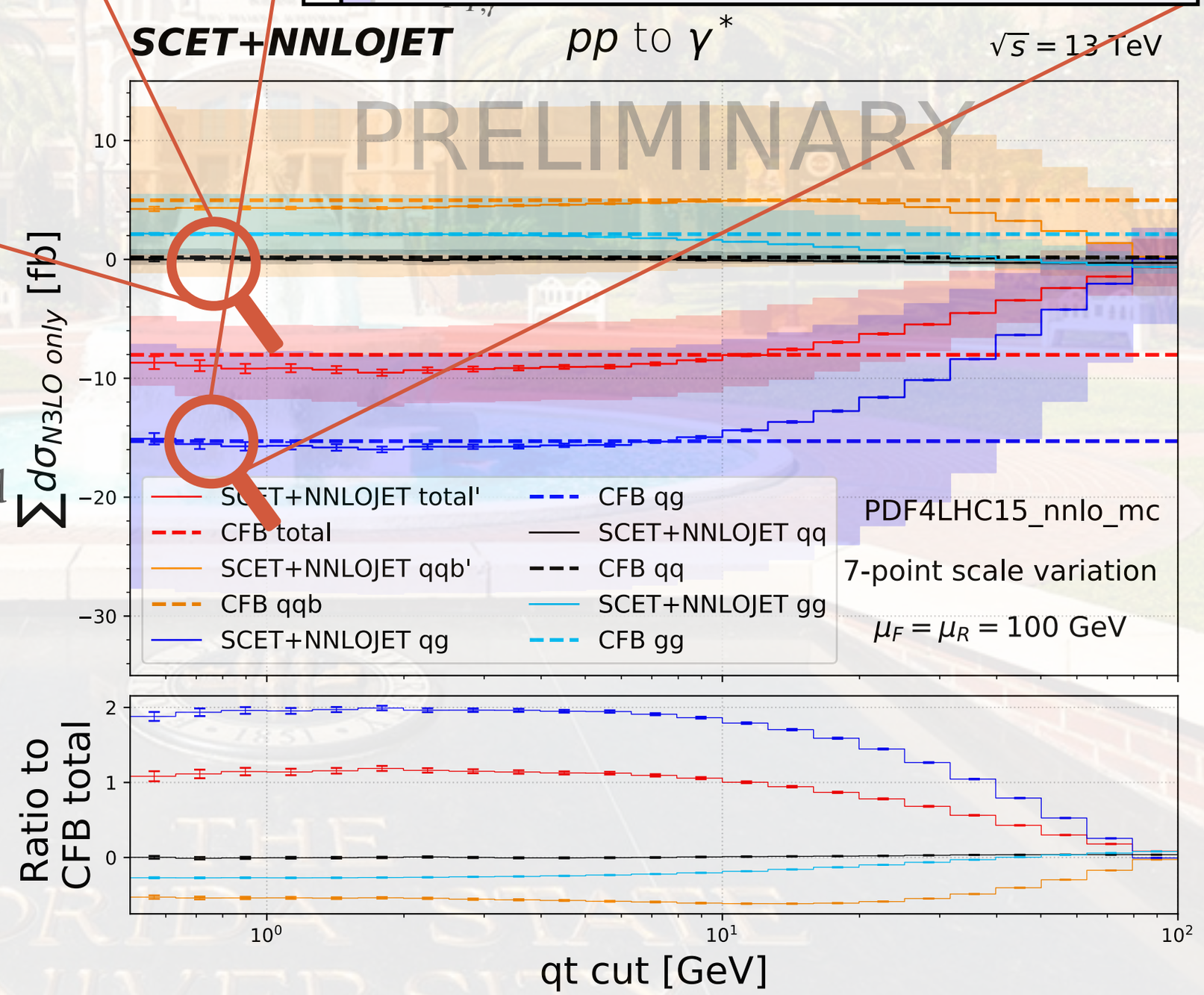

DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- N3LO ccumulated cross section from p_{T,γ^*} (N3

$$\sum d\sigma^{\gamma^*}_{N3LO} \equiv \sum_{dp_{T,\gamma^*}} d\sigma^{\gamma^*+jet}_{NNLO}/dp_{T,\gamma^*}\,|_{p_{T,\gamma^*}>qt} +$$

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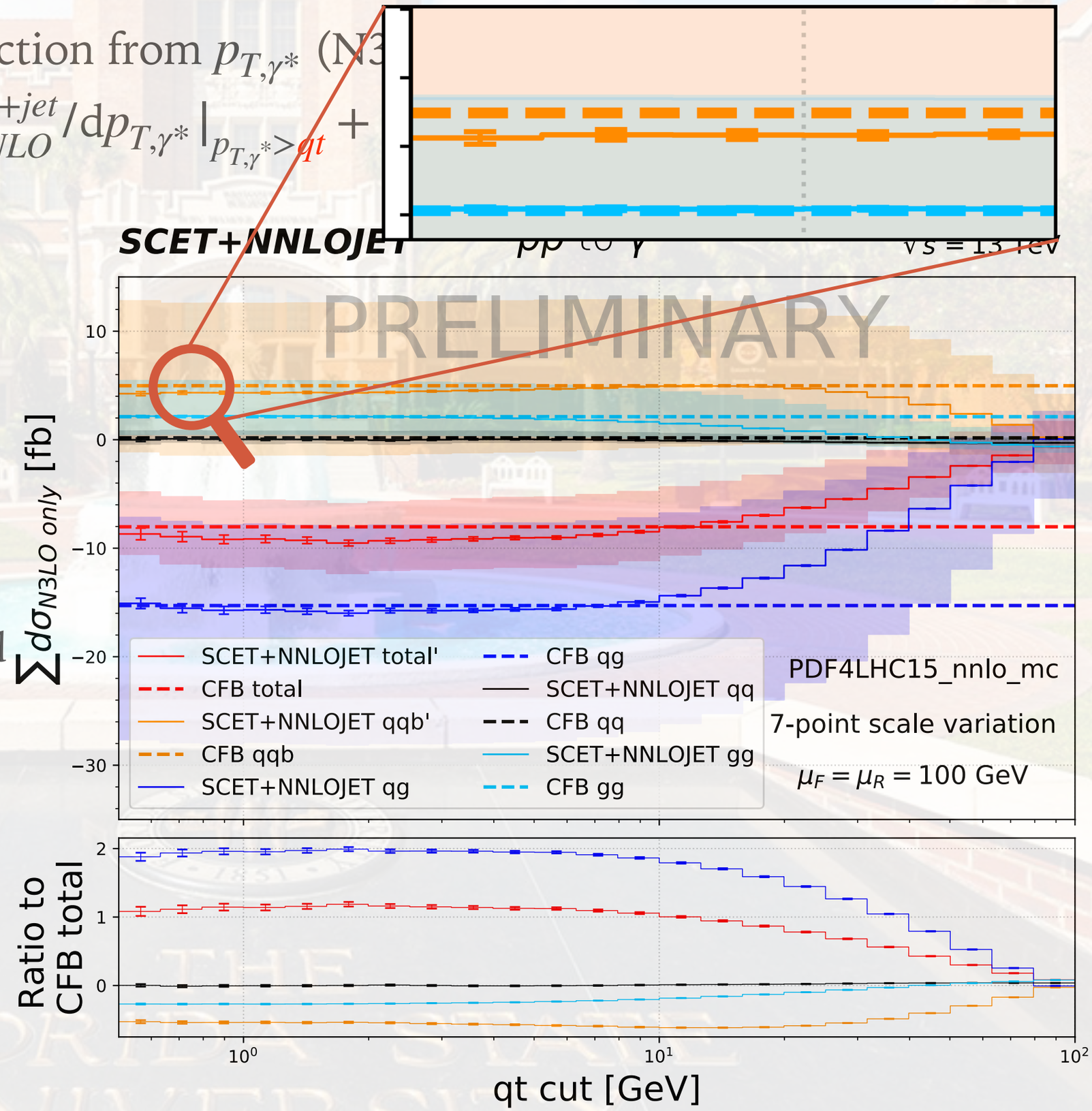

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$$\sum d\sigma^{\gamma^*}_{N3LO} \equiv \sum_{dp_{T,\gamma^*}} d\sigma^{\gamma^*+jet}_{NNLO}/dp_{T,\gamma^*}\,|_{p_{T,\gamma^*}>qt} + \sum_{dp_{T,\gamma}}$$

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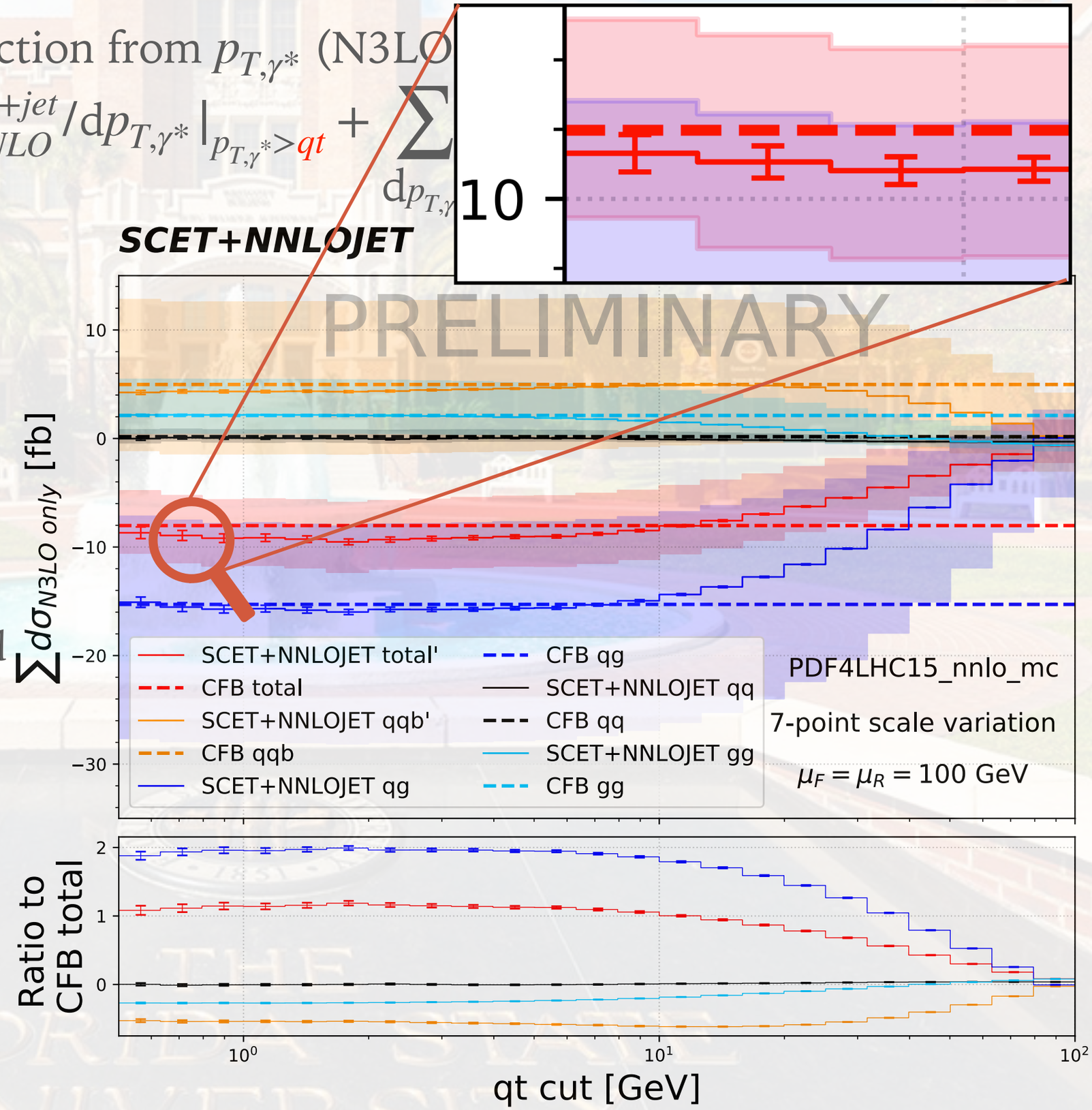
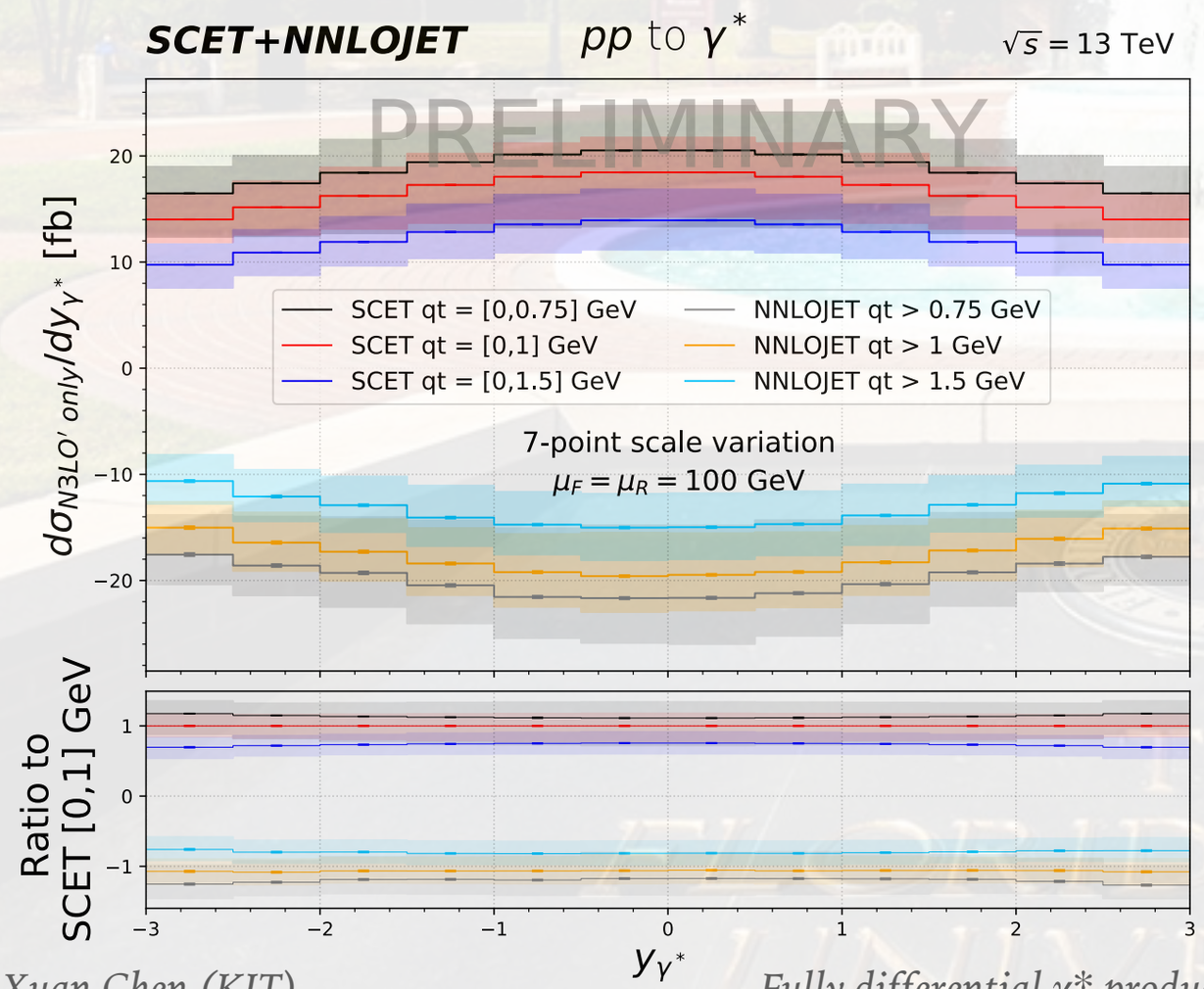
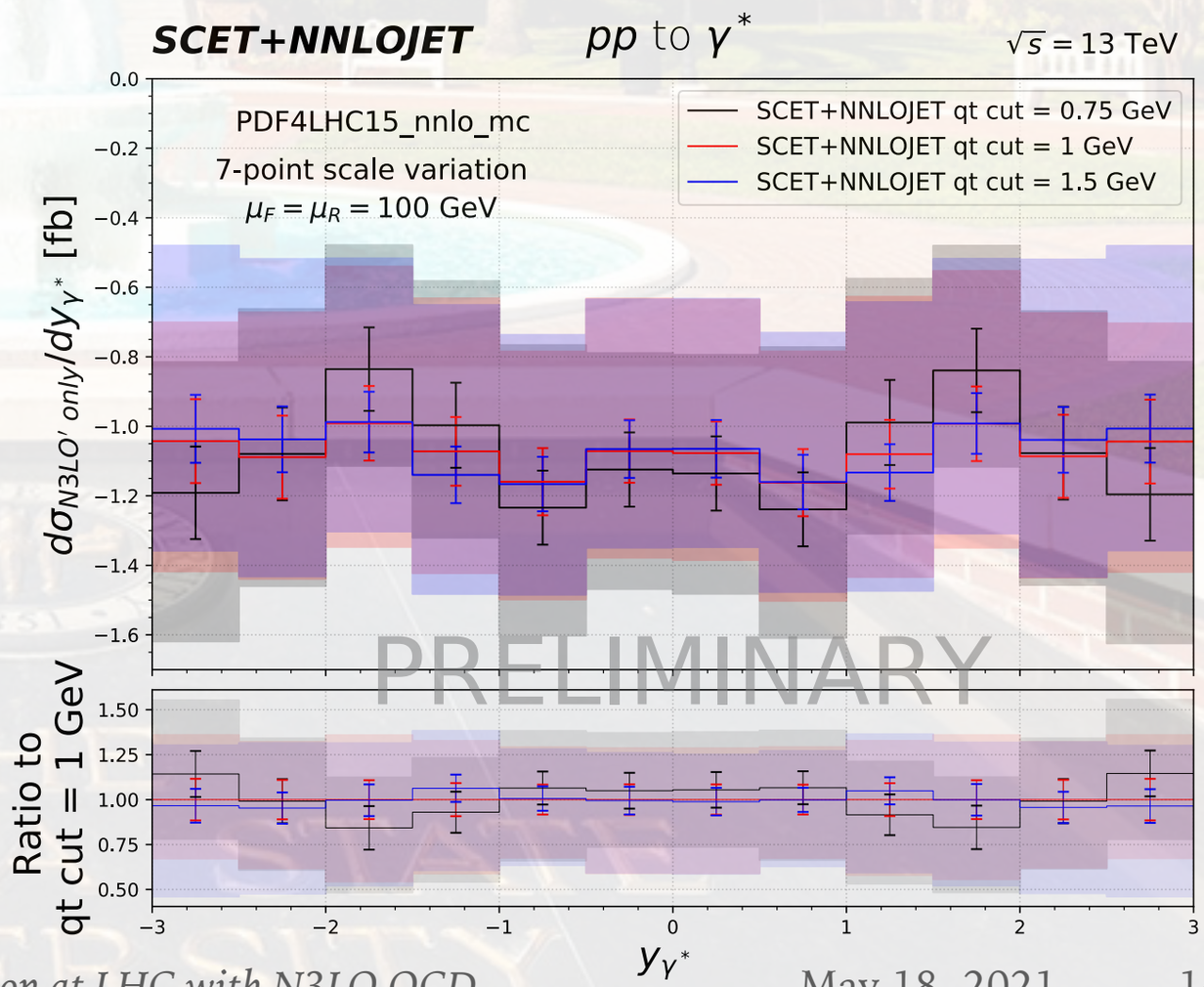


DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- N3LO differential cross sections (N3LO' coefficient)
  - Apply SCET+NNLOJET calculations for y_{γ^*} distribution
  - Large cancellation in each histogram bin with $\times$ 20 multiplier

    $\pm$ 0.5% accuracy $\rightarrow$ $\pm$ 10% fluctuation
  - Stable predictions with qt cut variation at 1 GeV

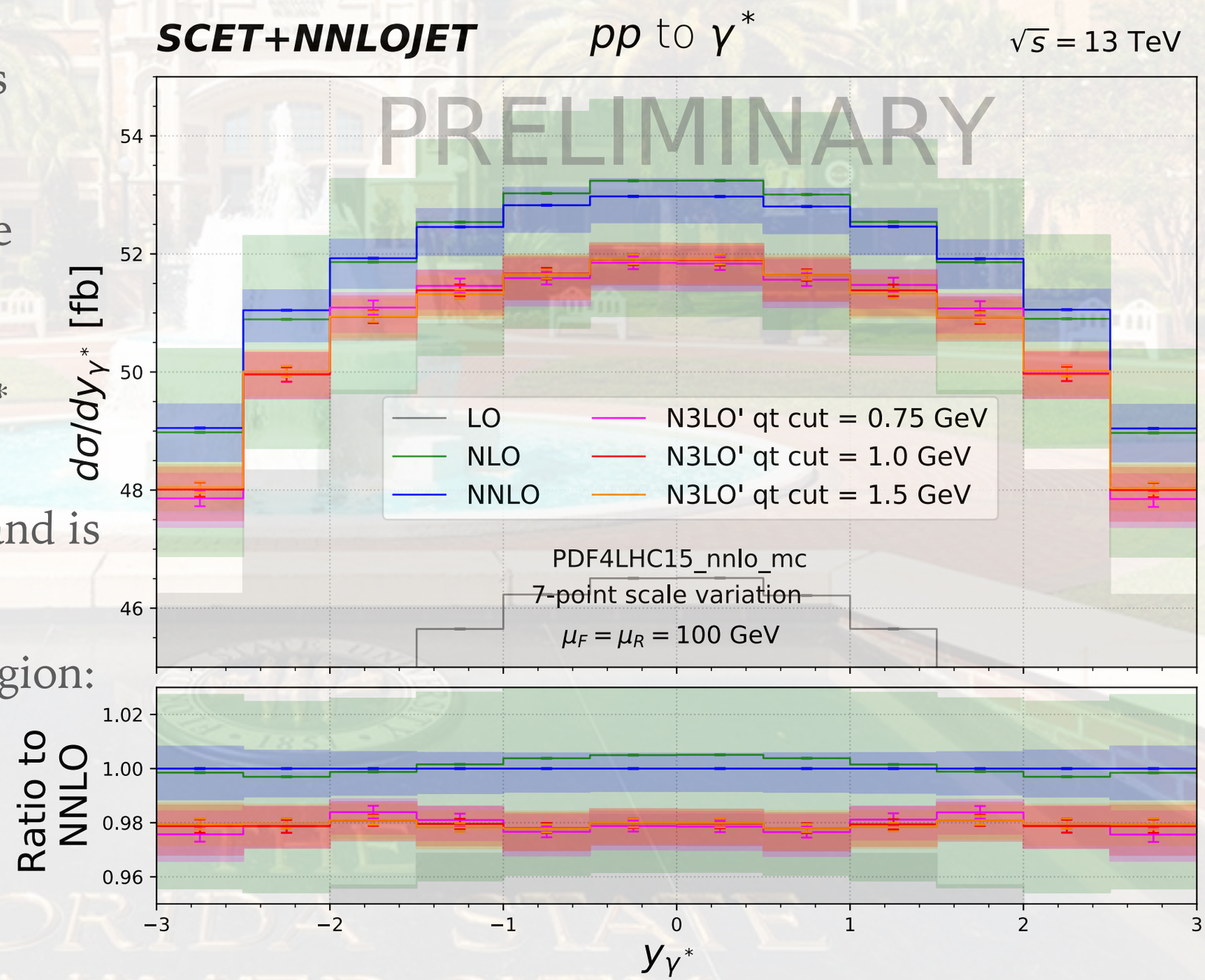




DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- N3LO differential cross sections
  - Apply SCET+NNLOJET calculations for y_{γ^*} distribution

- First N3LO differential cross section for γ^* production
- N3LO corrections contribute -2% with respect to NNLO
- Uniformly distributed for y_{γ^*} cross central rapidity region
- The N3LO scale variation band is outside the NNLO ones
- Scale variations at central region: NNLO: $^{+0.26\%}_{-0.4\%}$ N3LO: $^{+0.26\%}_{-0.33\%}$
- Scale variation range mildly increase towards large y_{γ^*}



SUMMARY

- Precision phenomenology could be the key to reveal new physics principles.
- Comprehensive understanding requires comparable precision between theory and experiment to achieve accurate interpretation/reveal disagreement.
- For theory predictions of LHC observables, there has been rapid progress in perturbative QCD calculations towards to NNLO and N3LO.
- Our standard methodology to estimate theoretical uncertainties via scale variation is challenged by N3LO calculations of charge and neutral current.
- We preform an independent calculation of the N3LO QCD correction to γ^* production and confirm the N3LO scale uncertainty disagree with NNLO for Q = 100 GeV.
- We use qt slicing method to further calculate N3LO differential y_{γ^*} distribution and find disagreement of scale uncertainties at differential level.

SUMMARY

- During the N3LO calculation, we find mismatch between FO and SCET expansion for contributions from sub-leading colour qqb channel.
- The mismatch is very likely due to numerical instability issues from FO and more investigation is needed. (We have to fix this)
- Luckily, by omitting this sub-leading colour contribution, we only miss 0.16% of the N3LO total cross section of γ^* production.
- The performance of qt slicing is stable with qt cut around 1 GeV. This estimation will get worse when applying fiducial cuts on decay products of γ^*.
- With all factorisation functions at N3LO available, N3LO+N3LL' precision is expected but require careful validation of matching for inclusive production and could be very challenging with fiducial cuts upon decay products.
- Progress on qt cut power correction of LL at NNLO would help in the future.
- Differential N3LO DY and W production in the future, hopefully we could better estimate uncertainties due to missing higher order contributions.

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Thank You for Your Attention

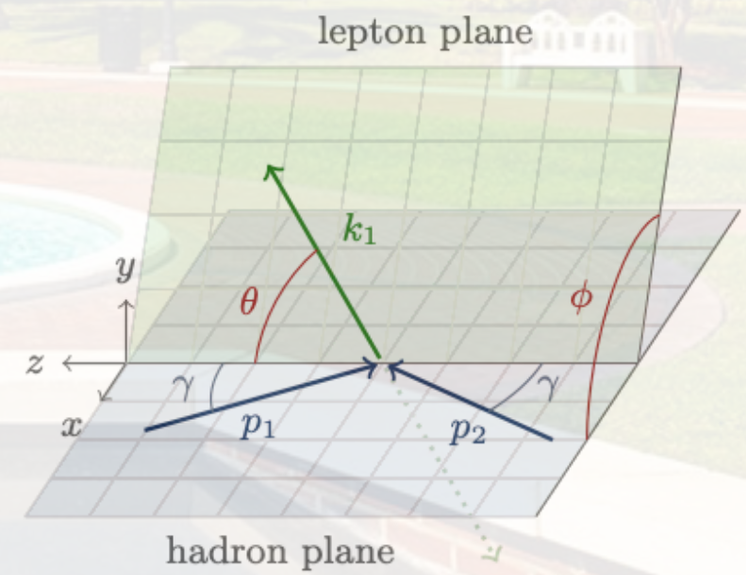
Triple-differential Drell-Yan cross section

- Lepton pair production: EW precision observable

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{ll}\mathrm{d}y_{ll}\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{ll}s}\sum_q P_q(\cos\theta^*)\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2) + (q \leftrightarrow \bar{q})\right]$$

- ATLAS 8 TeV measurement [1710.05167]

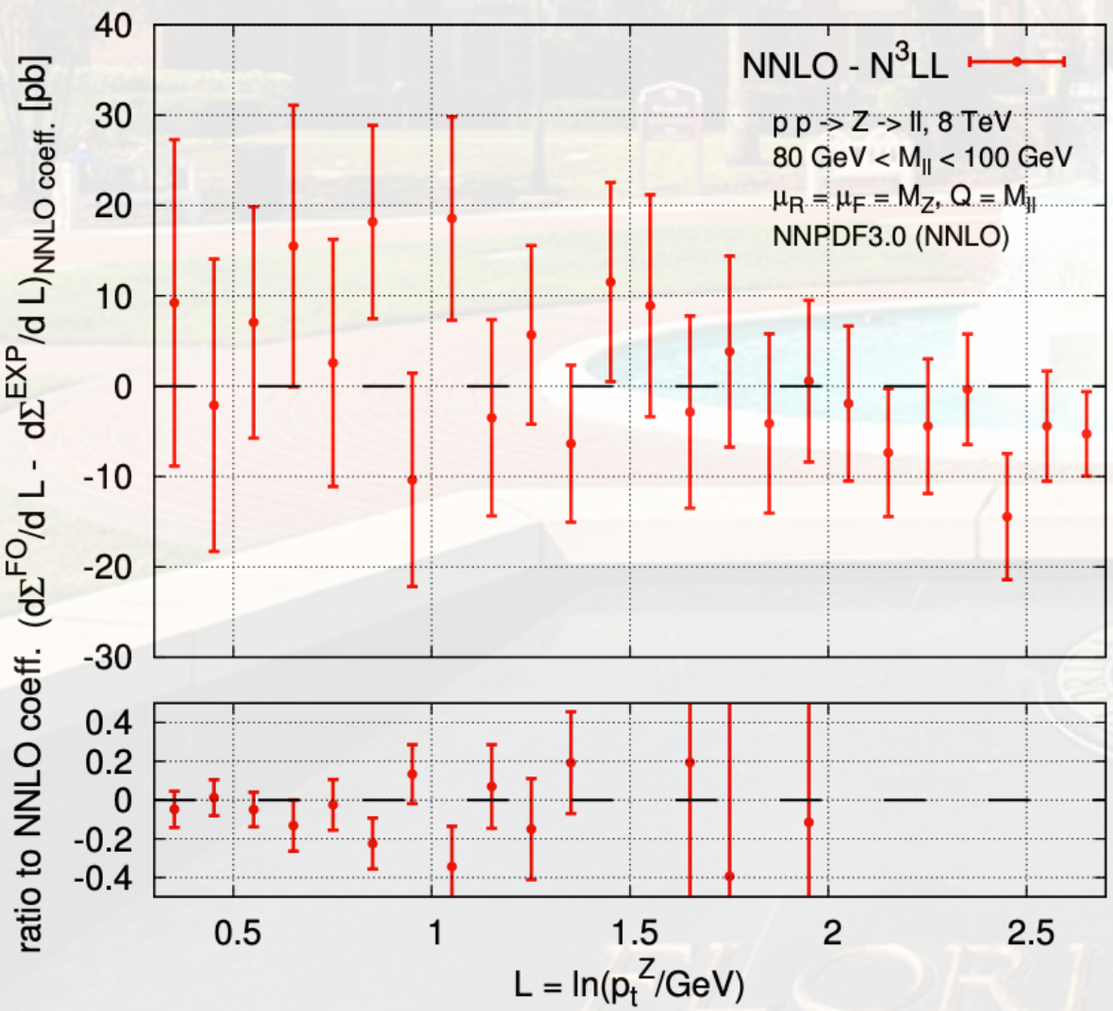
Observable	Central-Central	Central-Forward
m_{ll} [GeV]	[46,66,80,91,102,116,150,200]	[66,80,91,102,116,150]
$\lvert y_{ll}\rvert$	[0,0.2,0.4,0.6,0.8,1,1.2, 1.4,1.6,1.8,2,2.2,2.4]	[1.2,1.6,2,2.4,2.8,3.6]
$\cos\theta^*$	[-1,-0.7,-0.4,0,0.4,0.7,1]	[-1,-0.7,-0.4,0,0.4,0.7,1]
Total Bin Count:	504	150

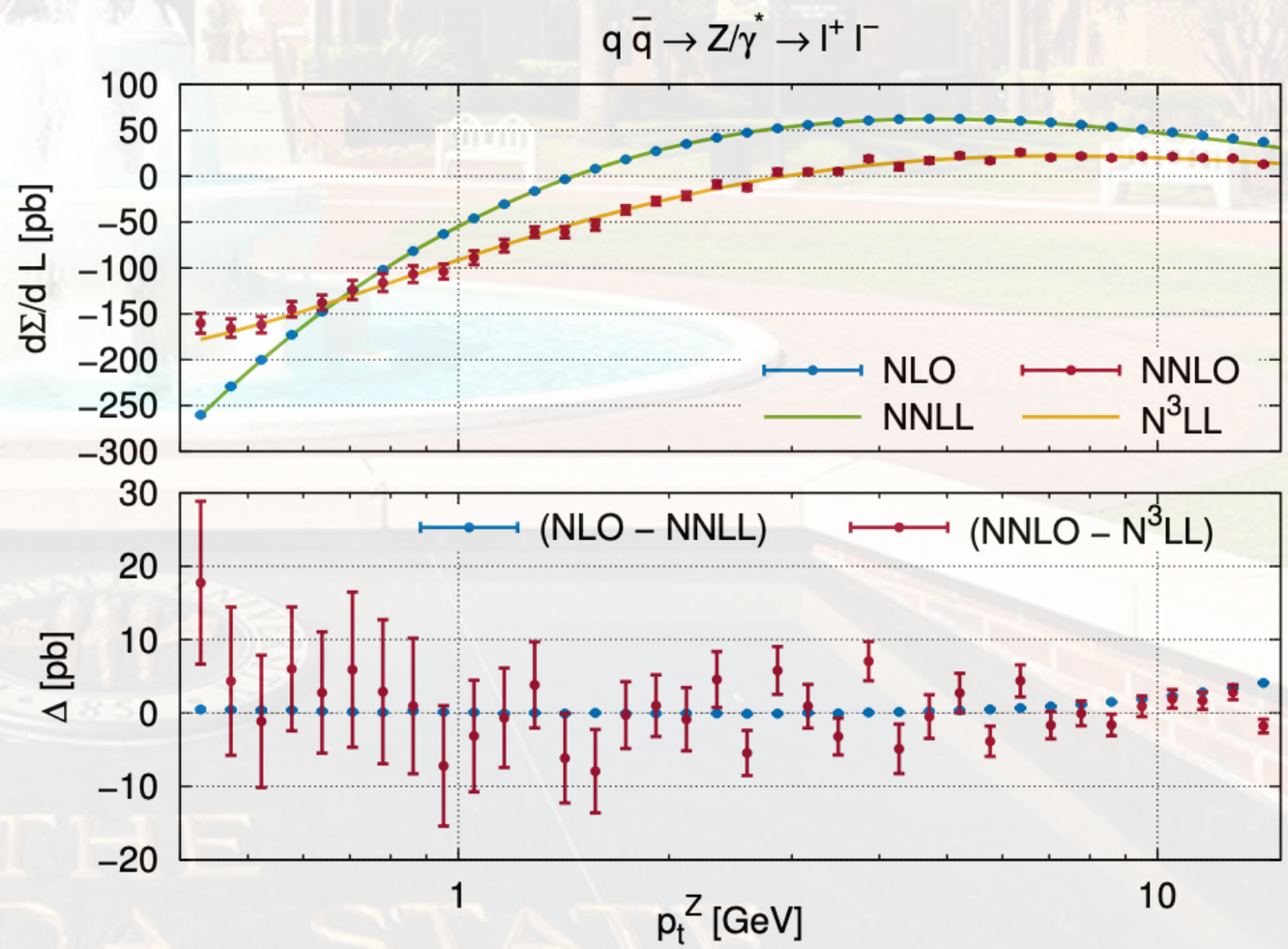


Slide from T. Gehrmann at LHCP 2020

DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- $p_{T,Z}$ validation with single MC adaption for full channel
- General good agreement between FO and RadISH for qqb channel
- Large numerical error with fluctuated plateau
- Matching $p_{T,Z}$ distribution at NNLO+N3LL accuracy with transition region at medium $p_{T,Z}$ is fine but may not be accurate





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DIFFERENTIAL γ^* PRODUCTION AT LHC WITH N3LO CORRECTIONS

- N3LO differential cross sections
  - Apply SCET+NNLOJET calculations for y_{γ^*} distribution
  - Left: with mirror statistics. Right: without mirror statistics