Quantum Corrections in Two-Photon Processes

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International Workshop on New Opportunities for Particles Physics
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- **The studies of two-photon processes**

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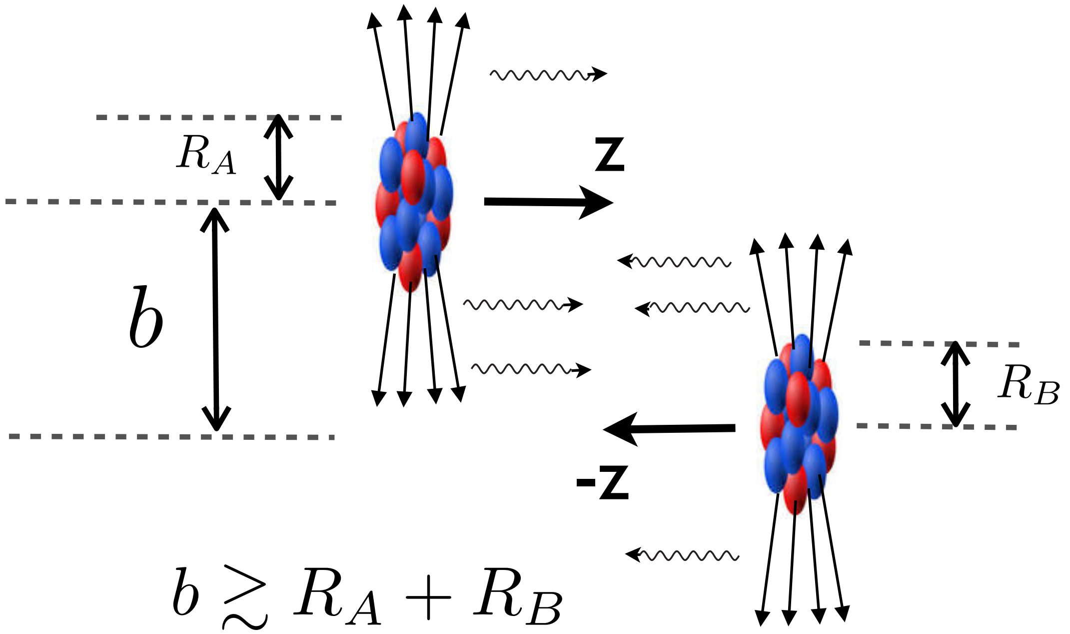
  - Ultra-Peripheral Collisions (UPCs)
  - Large photon flux $\propto Z^2$
  - Cross section in AA enhanced by Z^4



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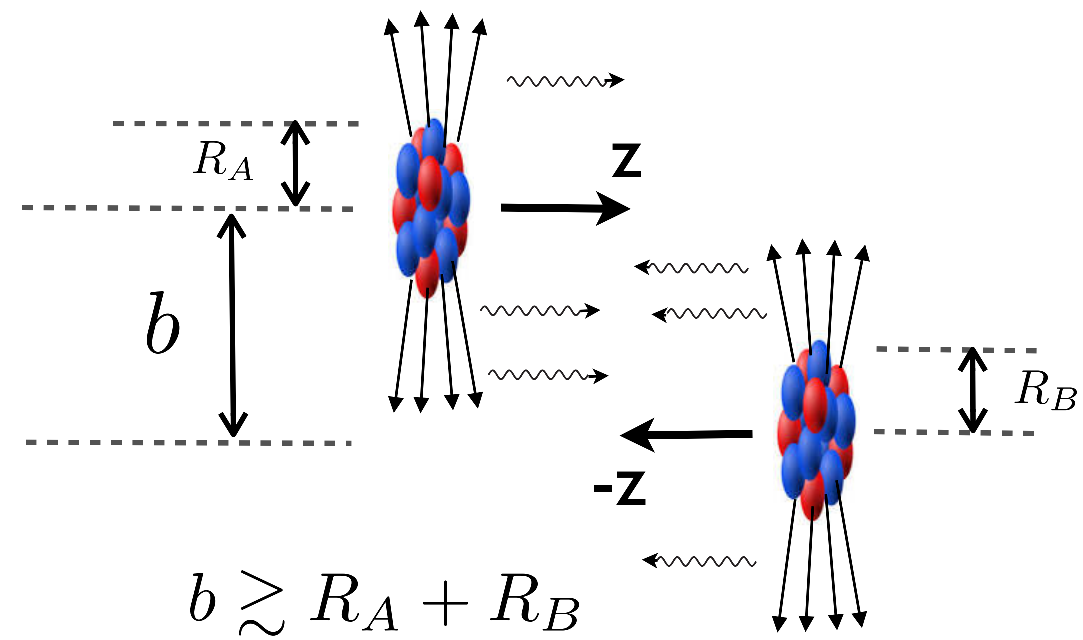
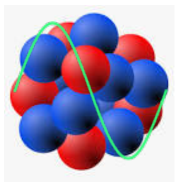
  - Coherent vs incoherent photons

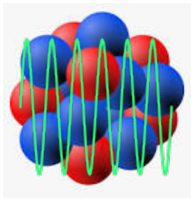




$\lambda \gtrsim R_A$

Coherent

vs



$\lambda < R_A$

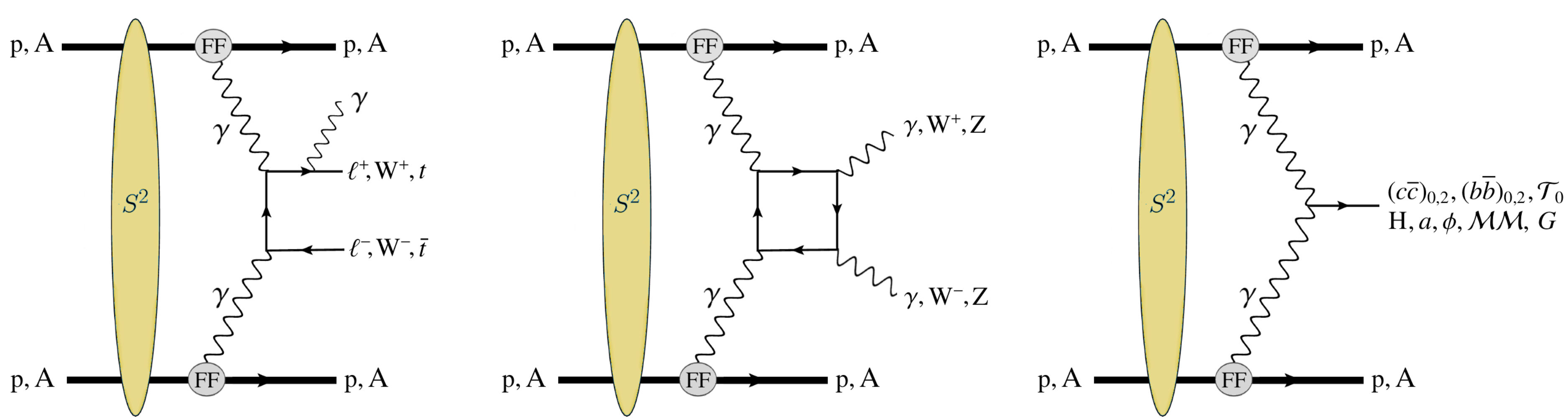
Incoherent

Introduction

- **Gold-plated SM and BSM processes**

Process	Physics motivation
$\gamma\gamma \to e^+e^-, \mu^+\mu^-$	"Standard candles" for proton/nucleus γ fluxes, EPA calculations, and higher-order QED corrections
$\gamma\gamma \to \tau^+\tau^-$	Anomalous τ lepton e.m. moments [29–32]
$\gamma\gamma \to \gamma\gamma$	aQGC [25], ALPs [27], BI QED [28], noncommut. interactions [36], extra dims. [37],...
$\gamma\gamma \to \mathcal{T}_0$	Ditauonium properties (heaviest QED bound state) [38, 39]
$\gamma\gamma \to (c\bar{c})_{0,2}, (b\bar{b})_{0,2}$	Properties of scalar and tensor charmonia and bottomonia [40, 41]
$\gamma\gamma \to$ XYZ	Properties of spin-even XYZ heavy-quark exotic states [42]
$\gamma\gamma \to$ VM VM	(with VM = ρ, ω, ϕ, J/ψ, Υ): BFKL-Pomeron dynamics [43–46]
$\gamma\gamma \to W^+W^-, ZZ, Z\gamma, \cdots$	anomalous quartic gauge couplings [11, 26, 47, 48]
$\gamma\gamma \to$ H	Higgs-γ coupling, total H width [49, 50]
$\gamma\gamma \to$ HH	Higgs potential [51], quartic $\gamma\gamma$HH coupling
$\gamma\gamma \to t\bar{t}$	anomalous top-quark e.m. couplings [11, 49]
$\gamma\gamma \to \tilde{\ell}\tilde{\ell}, \tilde{\chi}^+\tilde{\chi}^-, H^{++}H^{--}$	SUSY pairs: slepton [11, 52, 53], chargino [11, 54], doubly-charged Higgs bosons [11, 55].
$\gamma\gamma \to a, \phi, \mathcal{MM}, G$	ALPs [27, 56], radions [57], monopoles [58–61], gravitons [62–64],...

HSS d'Enterria (JHEP'22)



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Loop-induced in the SM !

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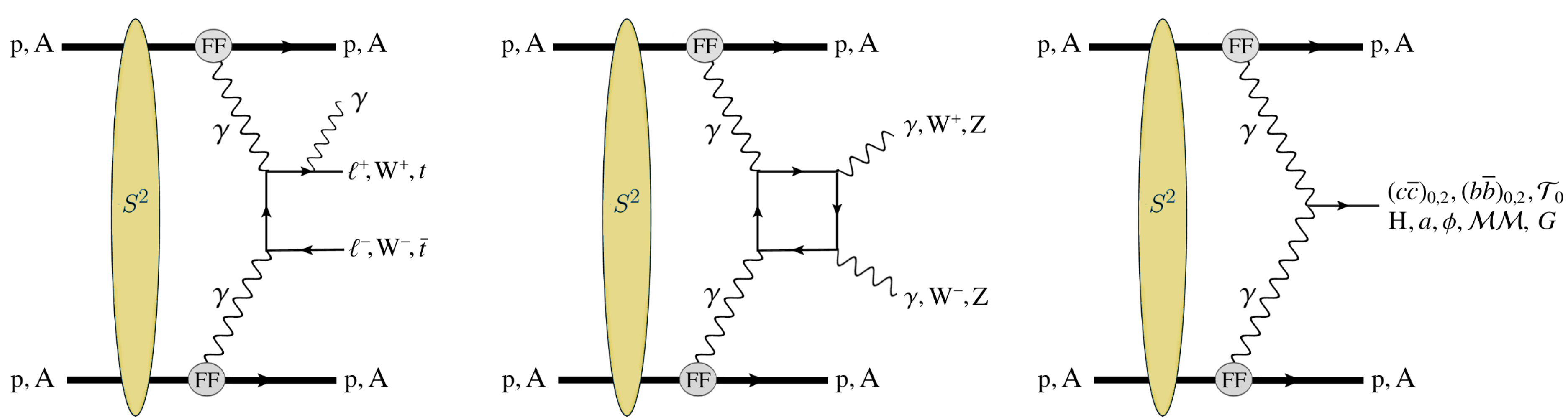

- **Cross section:**

$$\sigma(\mathrm{A\ B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$$

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gamma-UPC

HSS, d'Enterria (JHEP'22)

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$$= \sigma^{(\mathrm{LO})}(W_{\gamma\gamma}) + \sigma^{(\mathrm{NLO})}(W_{\gamma\gamma}) + \ldots$$

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&= \sigma^{(\mathrm{LO})}(W_{\gamma\gamma}) + \sigma^{(\mathrm{NLO})}(W_{\gamma\gamma}) + \ldots \\
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&= \Sigma_{\mathrm{LO}_1} + \ldots + \Sigma_{\mathrm{LO}_{\Delta(k_0)+1}} \\
\sigma^{(\mathrm{NLO})}(W_{\gamma\gamma}) &= \alpha_s^{c_s(k_0)}\alpha^{c(k_0)} \sum_{q=0}^{\Delta(k_0)+1} \Sigma_{k_0+1,q}\alpha_s^{\Delta(k_0)+1-q}\alpha^q \\
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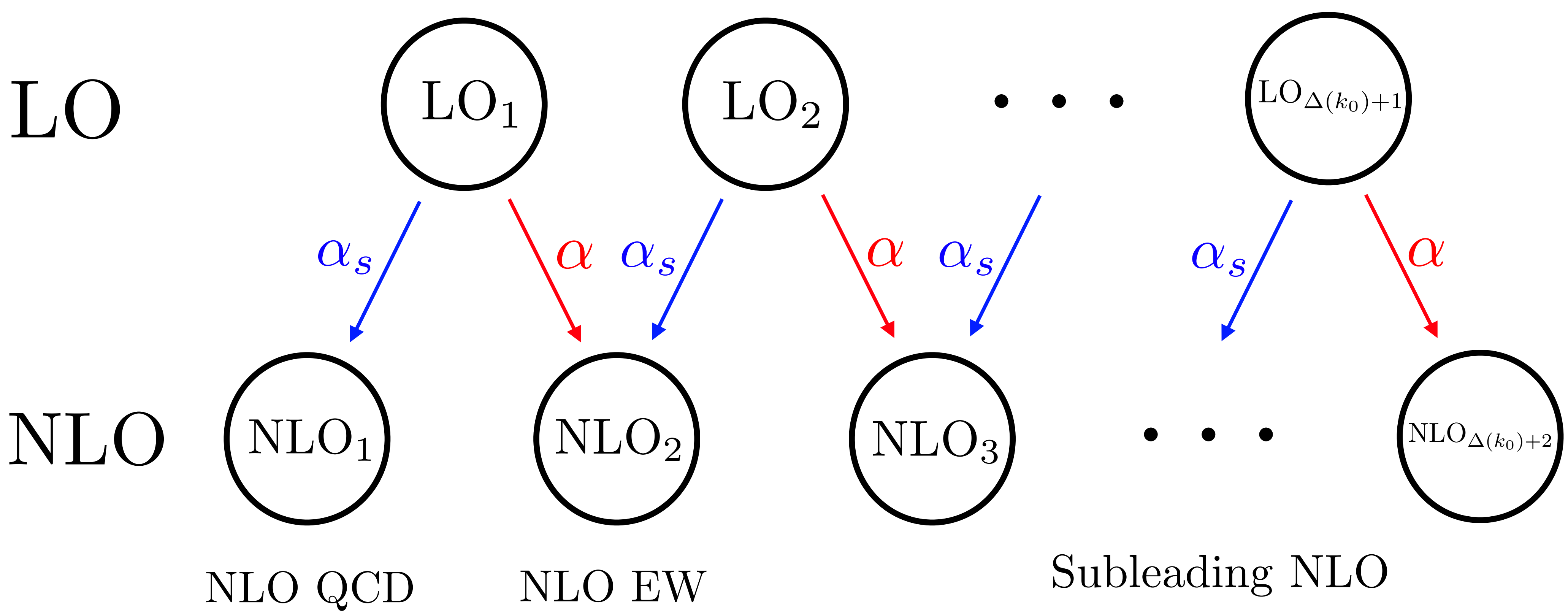

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- **Summary of existing NLO calculations**
  - In customized ways:

$\gamma\gamma \to t\bar{t}$	NLO QCD	HSS, d'Enterria (2207.03012)
$\gamma\gamma \to \mu^+\mu^-, \tau^+\tau^-$	bare leptons, NLO QED	HSS, d'Enterria (2407.13610)
$\gamma\gamma \to \tau^+\tau^-$	bare leptons, NLO EW	Jiang, Lu, Si, Zhang[2] (2410.21963)
$\gamma\gamma \to \tau^+\tau^- \to e^+\mu^-\bar{\nu}_\tau\nu_\tau\bar{\nu}_\mu\nu_e$	bare leptons, NLO EW NWA, spin correlations	Dittmaier, Engel, Hernando Ariza, Pellen (2504.11391)
$\gamma\gamma \to \gamma\gamma$	two-loop, NLO QCD+QED	Ajjath, Chaubey, Fraaije, Hirschi, HSS (2312.16956, 2312.16966)

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  - NLO automation in MadGraph5_aMC@NLO — HSS, Simon (2504.10104)

$\gamma\gamma \to \mu^+\mu^-$

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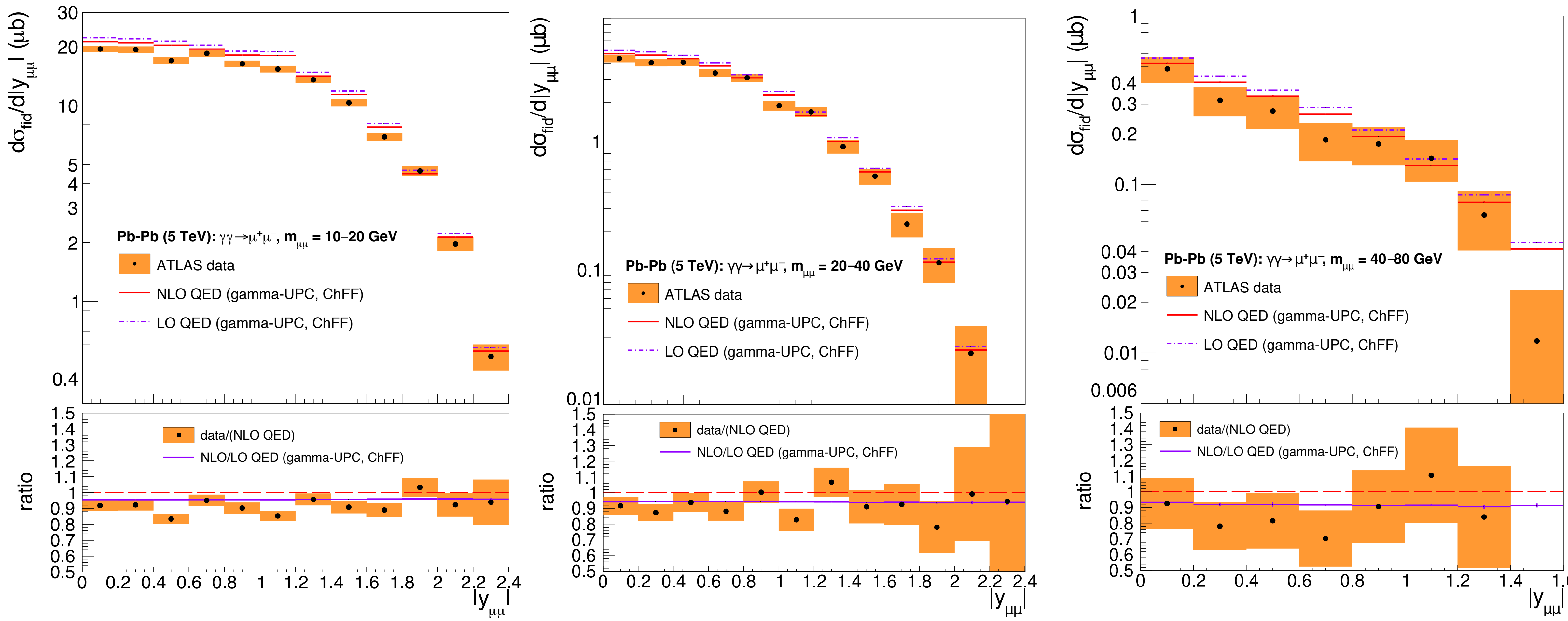
- **NLO QED in the $\alpha(0)$ scheme:**

HSS, d'Enterria (2407.13610)

$\gamma\gamma \to \mu^+\mu^-$ System, experiment	measured σ^{data}	gamma-UPC σ^{LO} ChFF (EDFF)	gamma-UPC σ^{NLO} ChFF (EDFF)	ratio $\sigma^{\text{data}}/\sigma^{\text{NLO}}$ ChFF (EDFF)
p-p at 7 TeV, CMS [54]	$3.38^{+0.62}_{-0.59}$ pb	3.62 (3.20) pb	3.50 (3.10) pb	$0.97^{+0.18}_{-0.17}$ ($1.09^{+0.20}_{-0.19}$)
p-p at 7 TeV, ATLAS [37]	0.628 ± 0.038 pb	0.687 (0.59) pb	0.653 (0.56) pb	0.96 ± 0.06 (1.12 ± 0.07)
p-p at 13 TeV, ATLAS [55]	3.12 ± 0.16 pb	3.23 (2.88) pb	3.09 (2.76) pb	1.00 ± 0.05 (1.13 ± 0.06)
Pb-Pb at 5.02 TeV, ATLAS [58]	34.1 ± 0.8 μb	39.4 (31.5) μb	37.5 (30.0) μb	0.91 ± 0.02 (1.14 ± 0.03)



Importance of NLO and photon flux modeling (ChFF) !

$$\gamma\gamma \to \tau^+\tau^-$$

- **NLO QED in the $\alpha(0)$ scheme:**

HSS, d'Enterria (2407.13610)

$\gamma\gamma \to \tau^+\tau^-$ Colliding system (kinematic cuts)	Measured $\sigma^{\rm data}$ (extrapolated)	gamma-UPC $\sigma^{\rm LO}$ ChFF (EDFF)	gamma-UPC $\sigma^{\rm NLO}$ ChFF (EDFF)	K factor $\sigma^{\rm NLO}/\sigma^{\rm LO}$
Pb-Pb at 5.02 TeV (inclusive)	580–850 μb	1060 (860) μb	1070 (870) μb	1.01
p-p at 13 TeV ($m_{\tau\tau} > 50$ GeV)	855^{+260}_{-215} fb	900 (730) fb	895 (725) fb	0.995
p-p at 13.6 TeV ($m_{\tau\tau} > 300$ GeV, $\|y^\tau\| < 2.5$)	–	1.35 (1.02) fb	1.31 (0.98) fb	0.965

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- **NLO EW in the same scheme:** HSS, Simon (2504.10104)

Process: $\gamma\gamma \to \tau^+\tau^-$	gamma-UPC+MG5_aMC		
Colliding system, c.m. energy	σ_{LO}	$\sigma_{NLO\ EW}$	$\sigma_{NLO\ EW}/\sigma_{LO}$
p-p at 13 TeV	190.57(6) pb	192.30(6) pb	1.009
p-p at 13.6 TeV	194.93(7) pb	196.68(7) pb	1.009
p-p at 14 TeV	197.67(6) pb	199.45(7) pb	1.009
p-Pb at 8.8 TeV	564.3(2) nb	569.6(2) nb	1.009
Pb-Pb at 5.52 TeV	1.1628(4) mb	1.1742(4) mb	1.010
p-p at 100 TeV	459.5(2) pb	463.6(2) pb	1.009
p-Pb at 62.8 TeV	1.6578(6) μb	1.6727(6) μb	1.009
Pb-Pb at 39.4 TeV	5.117(2) mb	5.164(2) mb	1.009

$$\gamma\gamma \to \tau^+\tau^-$$

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- **NLO EW in the G_μ scheme:** Jiang, Lu, Si, Zhang[2] (2410.21963)

$\sqrt{s_{NN}}$ [TeV]	σ_{LO}[mb]	$\delta\sigma_{\text{QED}}$[mb]	$\delta\sigma_{\text{weak}}$[mb]	σ_{NLO}[mb]	$\frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}}$
5.02	1.02	1.00×10^{-2}	-4.18×10^{-2}	0.99	0.97
5.36	1.08	1.06×10^{-2}	-4.44×10^{-2}	1.05	0.97
5.52	1.11	1.09×10^{-2}	-4.57×10^{-2}	1.08	0.97
6.00	1.20	1.17×10^{-2}	-4.92×10^{-2}	1.16	0.97

$$|\delta\sigma_{\text{weak}}| > |\delta\sigma_{\text{QED}}|$$

at a scale $\ll M_W$?

$\gamma\gamma \to \tau^+\tau^-$

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HSS, d'Enterria (2407.13610)

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- **Comparison of two EW schemes:**

Dittmaier, Engel, Hernando Ariza, Pellen (2504.11391)

$\gamma\gamma \to \tau^+\tau^-$	$\alpha(0)$-scheme		G_μ-scheme	
	σ or $\Delta\sigma$ [mb]	δ [%]	σ or $\Delta\sigma$ [mb]	δ [%]
σ^{LO}	1.063(2)	-	1.136(3)	-
$\Delta\sigma^{\text{NLO}}_{\text{QED}}$	0.010(3)	0.94(3)	0.012(1)	1.08(6)
$\Delta\sigma^{\text{NLO}}_{\text{weak}}$	$9.1(7) \times 10^{-8}$	$8.5(6) \times 10^{-6}$	$-0.009(3)$	$-0.84(1)$
$\Delta\sigma^{\text{NLO}}_{\text{ferm}}$	$6.6(1) \times 10^{-7}$	$6.2(6) \times 10^{-5}$	$-0.058(1)$	$-5.10(2)$
σ^{NLO}	1.073(2)	0.94(3)	1.081(3)	$-4.86(6)$

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$\gamma\gamma \to \tau^+\tau^-$ Colliding system (kinematic cuts)	Measured $\sigma^{\rm data}$ (extrapolated)	gamma-UPC $\sigma^{\rm LO}$ ChFF (EDFF)	gamma-UPC $\sigma^{\rm NLO}$ ChFF (EDFF)	K factor $\sigma^{\rm NLO}/\sigma^{\rm LO}$
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p-p at 13 TeV ($m_{\tau\tau} > 50$ GeV)	855^{+260}_{-215} fb	900 (730) fb	895 (725) fb	0.995
p-p at 13.6 TeV ($m_{\tau\tau} > 300$ GeV, $\|y^\tau\| < 2.5$)	–	1.35 (1.02) fb	1.31 (0.98) fb	0.965

- **Comparison of two EW schemes:**

Dittmaier, Engel, Hernando Ariza, Pellen (2504.11391)

$\gamma\gamma \to \tau^+\tau^-$	$\alpha(0)$-scheme		G_μ-scheme	
	σ or $\Delta\sigma$ [mb]	δ [%]	σ or $\Delta\sigma$ [mb]	δ [%]
$\sigma^{\rm LO}$	1.063(2)	-	1.136(3)	-
$\Delta\sigma^{\rm NLO}_{\rm QED}$	0.010(3)	0.94(3)	0.012(1)	1.08(6)
$\Delta\sigma^{\rm NLO}_{\rm weak}$	$9.1(7) \times 10^{-8}$	$8.5(6) \times 10^{-6}$	$-0.009(3)$	$-0.84(1)$
$\Delta\sigma^{\rm NLO}_{\rm ferm}$	$6.6(1) \times 10^{-7}$	$6.2(6) \times 10^{-5}$	$-0.058(1)$	$-5.10(2)$
$\sigma^{\rm NLO}$	1.073(2)	0.94(3)	1.081(3)	$-4.86(6)$

Two LO are quite different !

$$\gamma\gamma \to \tau^+\tau^-$$

- **NLO QED in the $\alpha(0)$ scheme:**

HSS, d'Enterria (2407.13610)

$\gamma\gamma \to \tau^+\tau^-$ Colliding system (kinematic cuts)	Measured σ^{data} (extrapolated)	gamma-UPC σ^{LO} ChFF (EDFF)	gamma-UPC σ^{NLO} ChFF (EDFF)	K factor σ^{NLO}/σ^{LO}
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Large correction from misplaced corrections from the definition of α

Importance of choosing an appropriate EW scheme !

$\gamma\gamma \to \tau^+\tau^-$

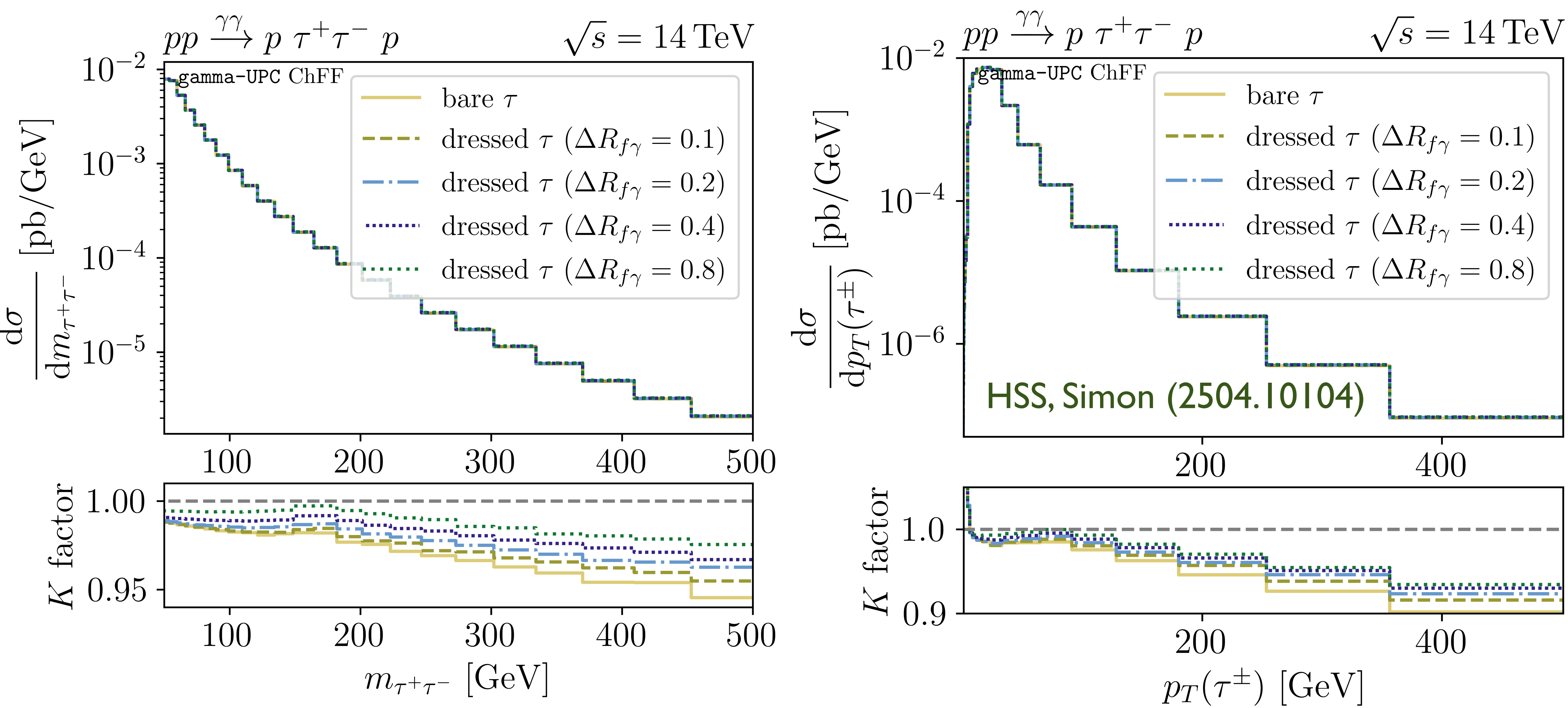
- **Dressed or bare leptons ?**

$$\gamma\gamma \to \tau^+\tau^-$$

- **Dressed or bare leptons ?**
  - At high scales, EW corrections can be enhanced by quasi-collinear logs

$\gamma\gamma \to \tau^+\tau^-$

- **Dressed or bare leptons ?**
  - At high scales, EW corrections can be enhanced by quasi-collinear logs
  - Log enhancements can be mitigated by using more inclusive lepton definitions

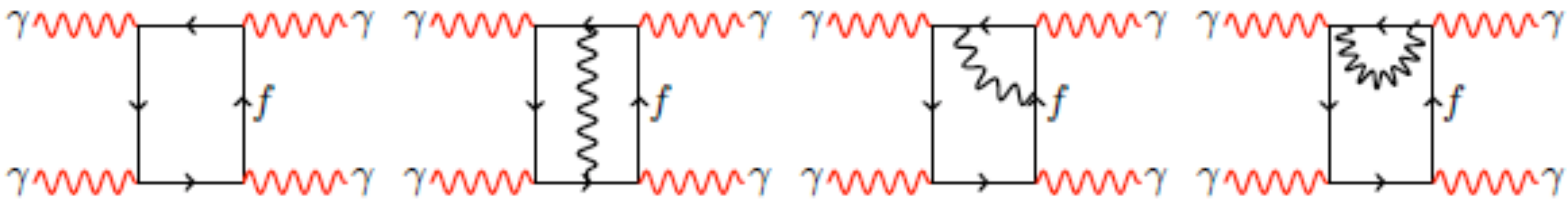


- **NLO for fermion loops**
  - Low-energy (LE) approx. : NLO from Euler-Heisenberg Lagrangian

    Martin, Schubert & Villaneuva Sandoval (NPB'03)
  - High-energy (HE) approx. : NLO from unitarity-based technique

    Bern, De Freitas, Dixon, Ghinculov & Wong (JHEP'01)
  - NLO with full fermion-mass dependence

    Ajjath, Chaubey, Fraaije, Hirschi, HSS (PLB'24)

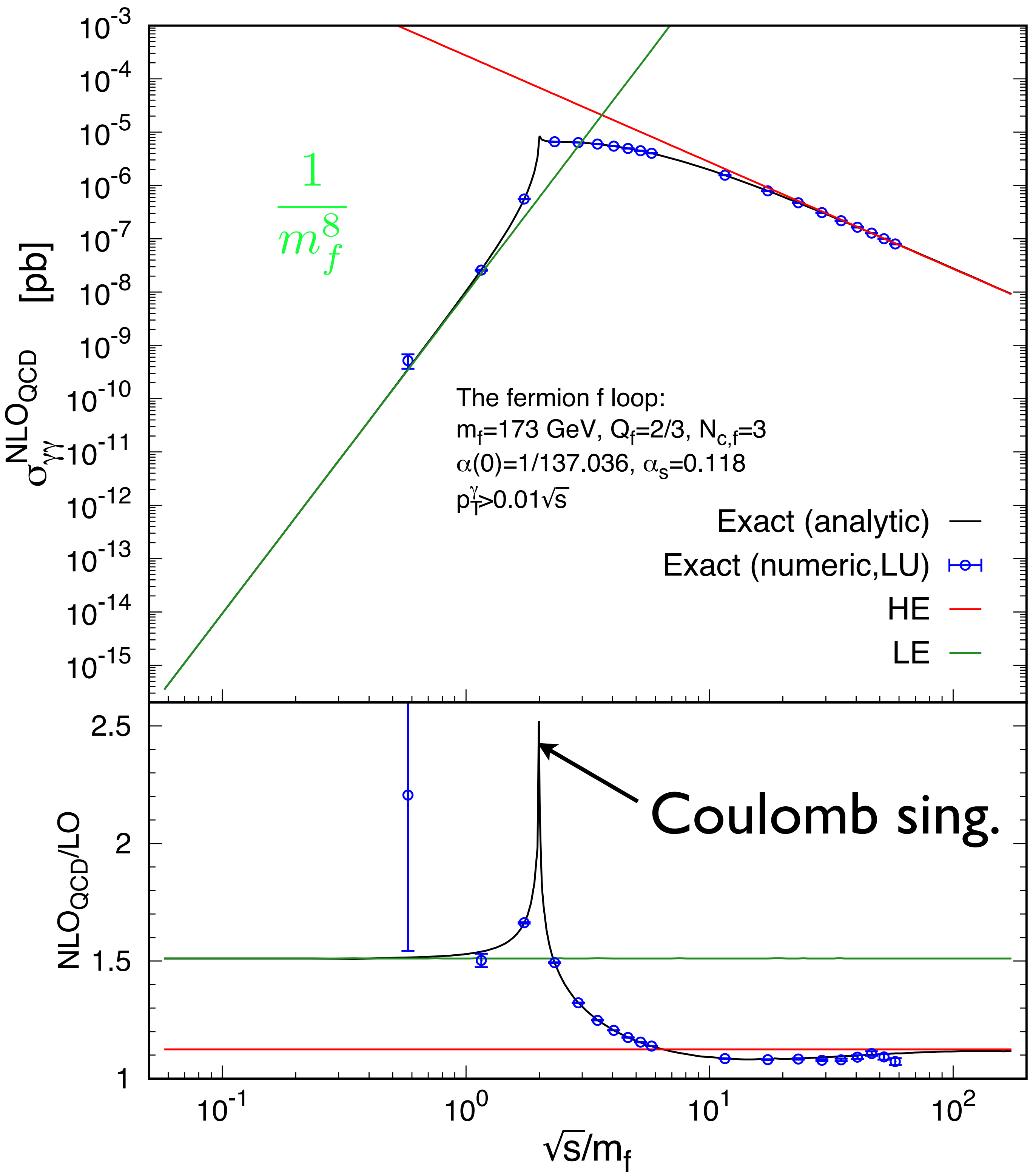


    - Two radically different computational approaches
      - A traditional approach with a full analytic control — Ajjath, Chaubey, HSS (JHEP'24)
      - A numerical approach with local unitarity construction — Capatti et al. (JHEP'20, JHEP'22)

$\gamma\gamma \to \gamma\gamma$

- **One fermion species**

Ajjath, Chaubey, Fraaije, Hirschi, HSS (PLB'24)

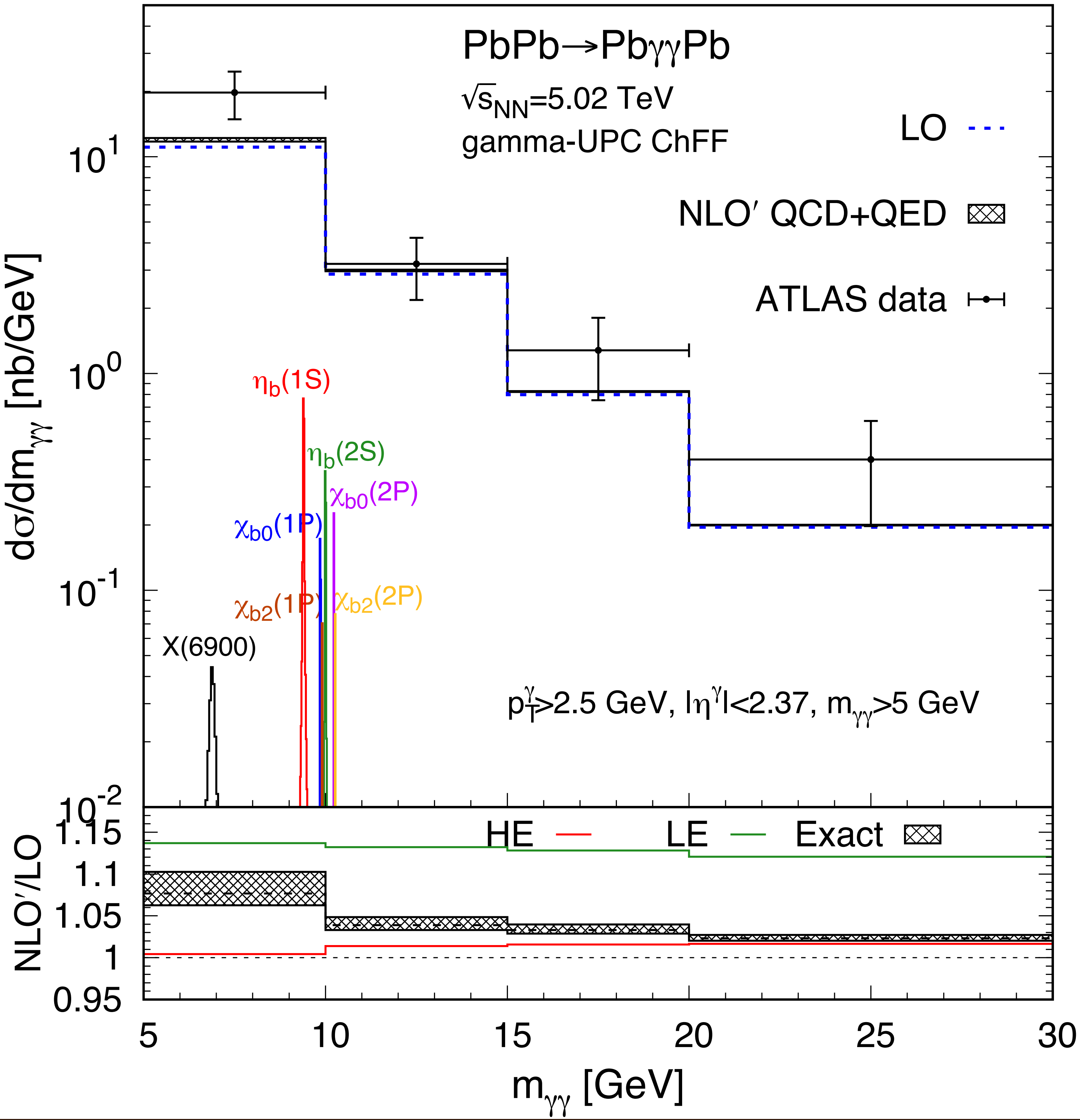


- Exact result agrees with the approximations in their applicable regimes
- Analytical exact result agrees with the numerical exact one.
- The structure of the exact K factor is more rich than the approximations
- The exact K factor approaches the HE K factor rather slowly

$\gamma\gamma \to \gamma\gamma$

- **Theory-data comparison**

Ajjath, Chaubey, Fraaije, Hirschi, HSS (PLB'24)



$$\sigma_{\rm ATLAS} = 120 \pm 22 \text{ nb}$$
vs $\sigma_{\rm LO} = 76$ nb
vs $\sigma_{\rm NLO'} = 81.2^{+1.6}_{-0.9}$ nb

- Tension persists though is reduced a bit
- H(L)E under(over)estimates the size of quantum corr.
- 6 C-even bottomonia and X(6900) seems cannot explain the discrepancy neither

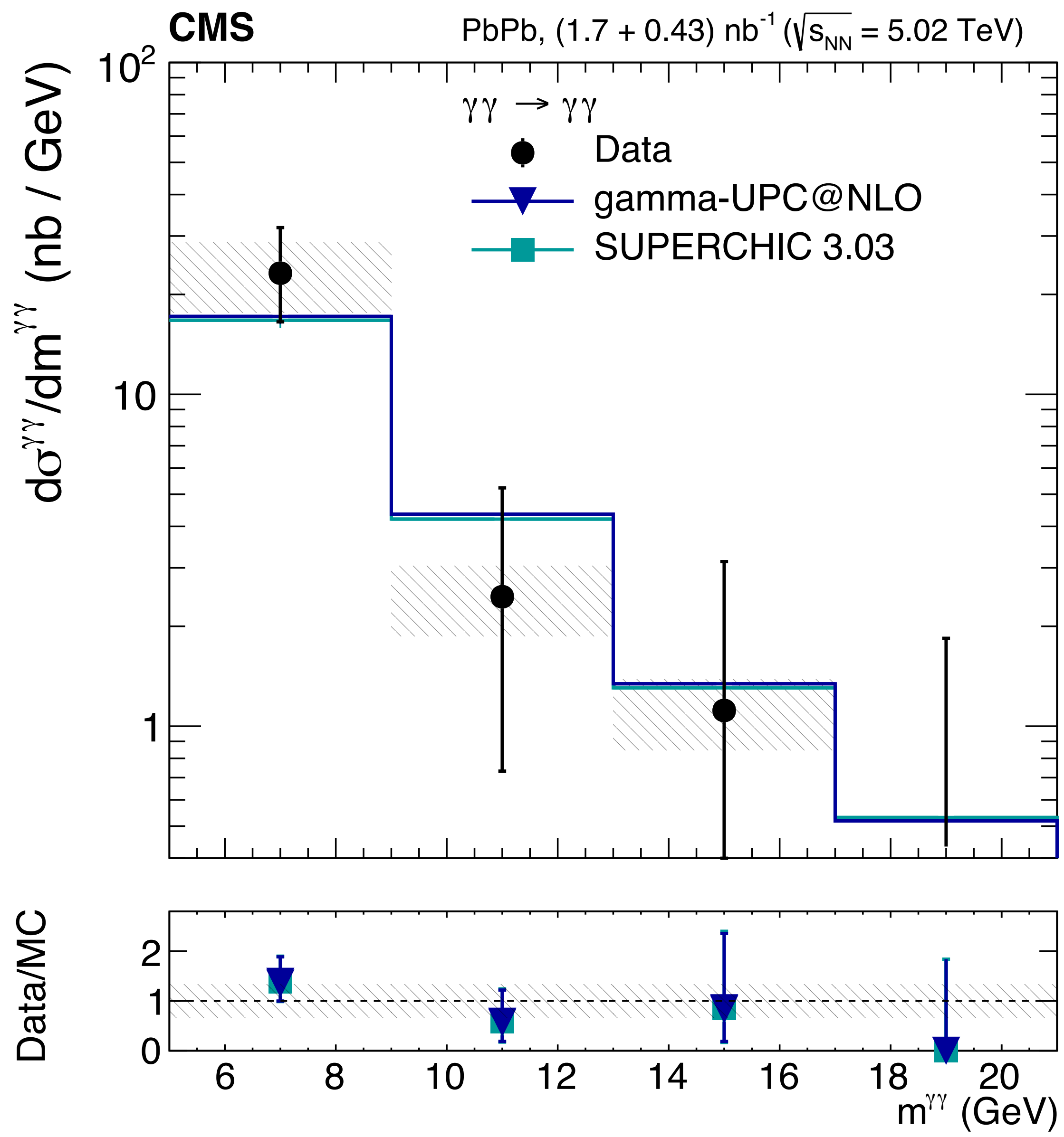
Caveat: some di-photon widths are not well constrained (only theory calc.) !

$$\gamma\gamma \to \gamma\gamma$$

- **Theory-data comparison**

Ajjath, Chaubey, Fraaije, Hirschi, HSS (PLB'24)

$$\sigma_{\rm CMS} = 107 \pm 33_{\rm stat} \pm 20_{\rm syst}\ \text{nb} \qquad \text{vs}$$
$$\sigma_{\rm NLO'} = 95.4 \left({}^{+2.0}_{-1.0}\right)_{\rm scale} \left({}^{+1.0}_{-1.5}\right)_{\rm param}\ \text{nb}$$



- No excess in CMS vs NLO

NLO Automation

- **MadGraph5_aMC@NLO (to be released)**

HSS, Simon (2504.10104)

```
./bin/mg5_aMC
MG5_aMC> import model myNLOmodel_w_qcd_qed
MG5_aMC> generate !a! !a! > p1 p2 p3 p4 [QCD QED]
MG5_aMC> output; launch
```

	gamma-UPC+MG5_aMC			
	Processes without jets		Processes with jets	
	QCD ($i = 1$)	EW ($i \geq 2$)	QCD ($i = 1$)	EW ($i \geq 2$)
fLO	✓	✓	✓	✓
LO+PS	✓	✓	✓	✓
fNLO	✓	✓	✓	✓
NLO+PS	✓	✗	✗	✗

NLO Automation

- **Coherent photon generation syntax: !a!**
  - Same as the tagged final-state photons at NLO Pagani, HSS, Tsinikos, Zaro (2106.02059)
  - Generally, a long-distance photon at NLO
- **A hybrid EW renormalisation scheme:**
  - Interactions with long-distance photons are in the $\alpha(0)$ scheme
  - Other interactions are in the G_μ scheme
- **Treatment of IR divergences**
  - Amendments of FKS subtraction in order to accommodate
    - Initial-state particles can only be photons
    - Initial-state collinear singularities in jet processes

NLO Automation: an example

HSS, Simon (2504.10104)

4.2 $\gamma\gamma \to \mu^+\mu^-$

4.3 $\gamma\gamma \to \tau^+\tau^-$

4.4 $\gamma\gamma \to W^+W^-$

4.5 $\gamma\gamma \to t\bar{t}$

4.6 $\gamma\gamma \to t\bar{t}\gamma_{\mathrm{iso}}$

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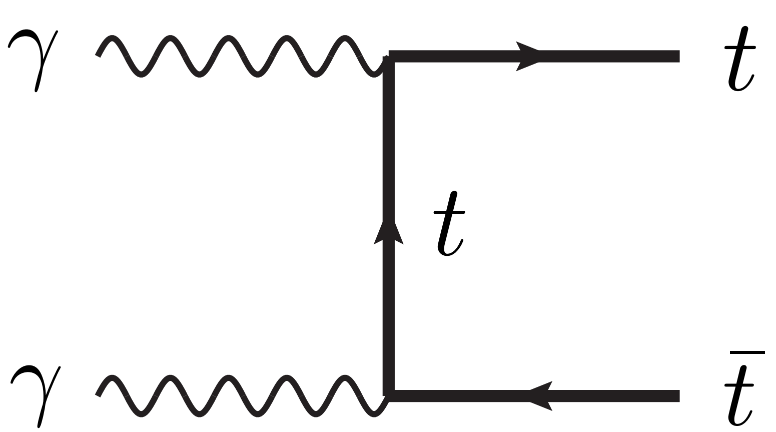

Process: $\gamma\gamma \to t\bar{t}$	gamma-UPC+MG5_aMC		
Colliding system, c.m. energy	$\sigma_{\rm LO}$	$\sigma_{\rm NLO\ QCD}$	$\sigma_{\rm NLO\ QCD+EW}$
p-p at 13 TeV	212.40(6) ab	$256.43(9)^{+4.5}_{-3.7}$ ab	$244.8(1)^{+4.5}_{-3.7}$ ab
p-p at 13.6 TeV	228.53(6) ab	$275.5(1)^{+4.8}_{-4.0}$ ab	$263.1(1)^{+4.8}_{-4.0}$ ab
p-p at 14 TeV	239.58(7) ab	$288.7(1)^{+5.0}_{-4.2}$ ab	$275.5(1)^{+5.0}_{-4.2}$ ab
p-Pb at 8.8 TeV	46.89(1) fb	$59.87(2)^{+1.3}_{-1.1}$ fb	$57.32(2)^{+1.3}_{-1.1}$ fb
Pb-Pb at 5.52 TeV	30.64(1) fb	$39.08(1)^{+0.87}_{-0.72}$ fb	$37.43(1)^{+0.87}_{-0.72}$ fb
p-p at 100 TeV	2.3080(2) fb	$2.7111(2)^{+0.041}_{-0.034}$ fb	$2.5816(2)^{+0.041}_{-0.034}$ fb
p-Pb at 62.8 TeV	3.0742(2) pb	$3.6721(3)^{+0.061}_{-0.050}$ pb	$3.5045(3)^{+0.061}_{-0.050}$ pb
Pb-Pb at 39.4 TeV	0.9583(1) nb	$1.2062(2)^{+0.026}_{-0.021}$ nb	$1.1545(2)^{+0.026}_{-0.021}$ nb
K factor		$\sigma_{\rm NLO\ QCD}/\sigma_{\rm LO}$	$\sigma_{\rm NLO\ QCD+EW}/\sigma_{\rm LO}$
p-p at 13 TeV		1.207	1.153
p-p at 13.6 TeV		1.205	1.151
p-p at 14 TeV		1.205	1.151
p-Pb at 8.8 TeV		1.277	1.222
Pb-Pb at 5.52 TeV		1.276	1.222
p-p at 100 TeV		1.175	1.119
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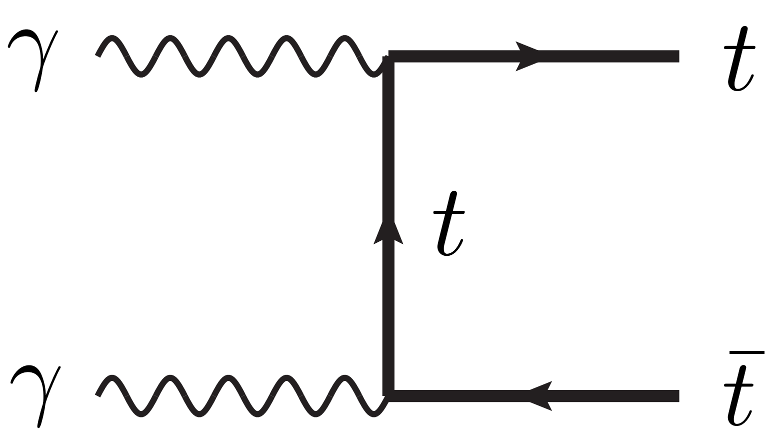

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Pb-Pb at 5.:			$3(1)^{+0.87}_{-0.72}$ fb
p-p at 100			$6(2)^{+0.041}_{-0.034}$ fb
p-Pb at 62.8			$5(3)^{+0.061}_{-0.050}$ pb
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- Sizable NLO QCD:

  +20%

- Non-negligible NLO EW:

  -5%

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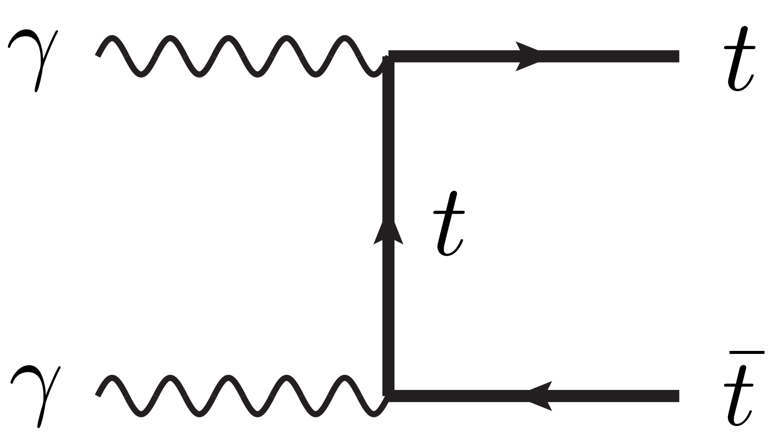

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  +20%
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How about NNLO QCD ?

NNLO QCD & Coulomb Resummation

Capatti et al. (JHEP'20, JHEP'22)

- NNLO QCD with Local Unitarity construction ($\alpha\mathrm{Loop}$)

NNLO QCD & Coulomb Resummation

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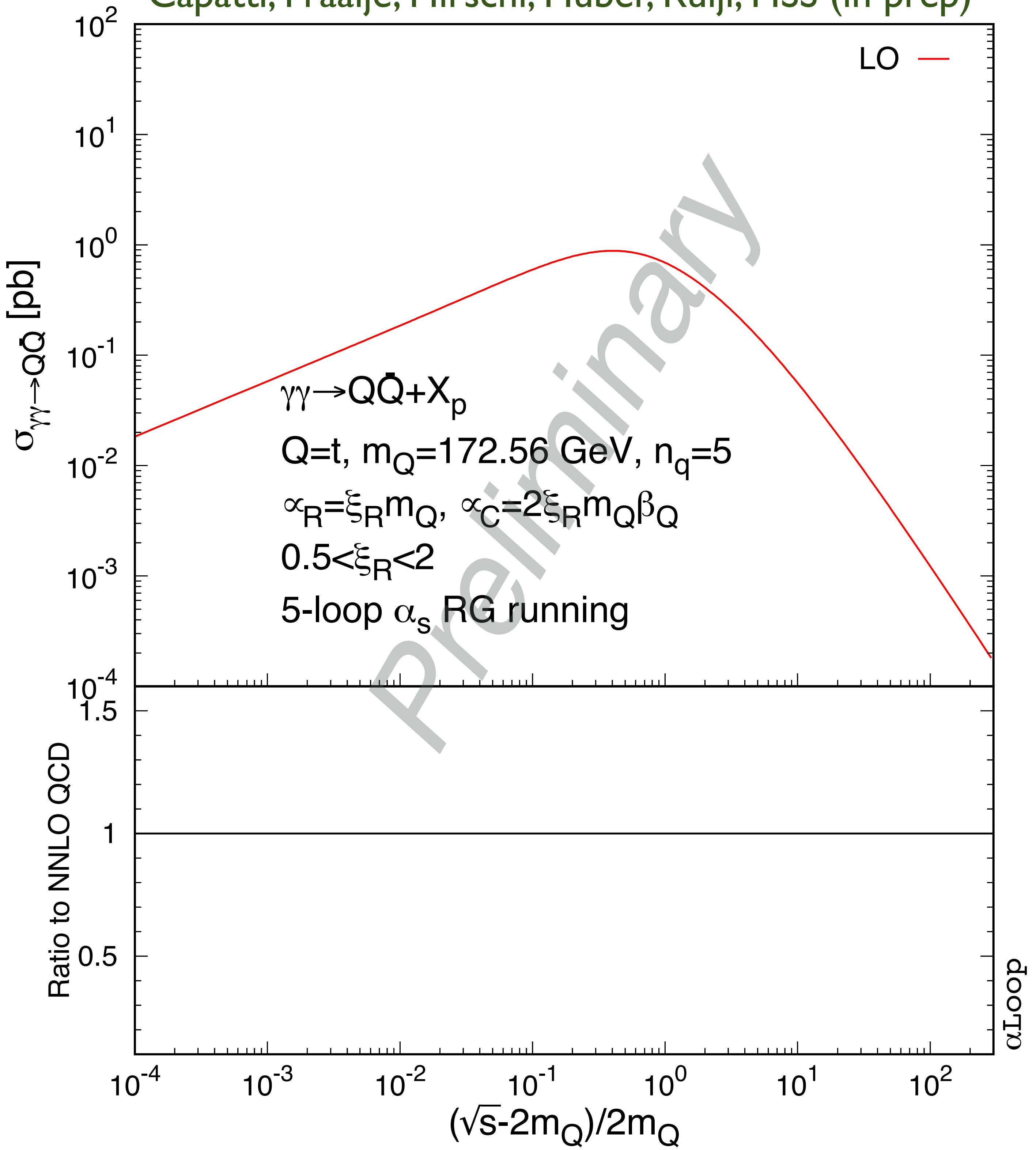

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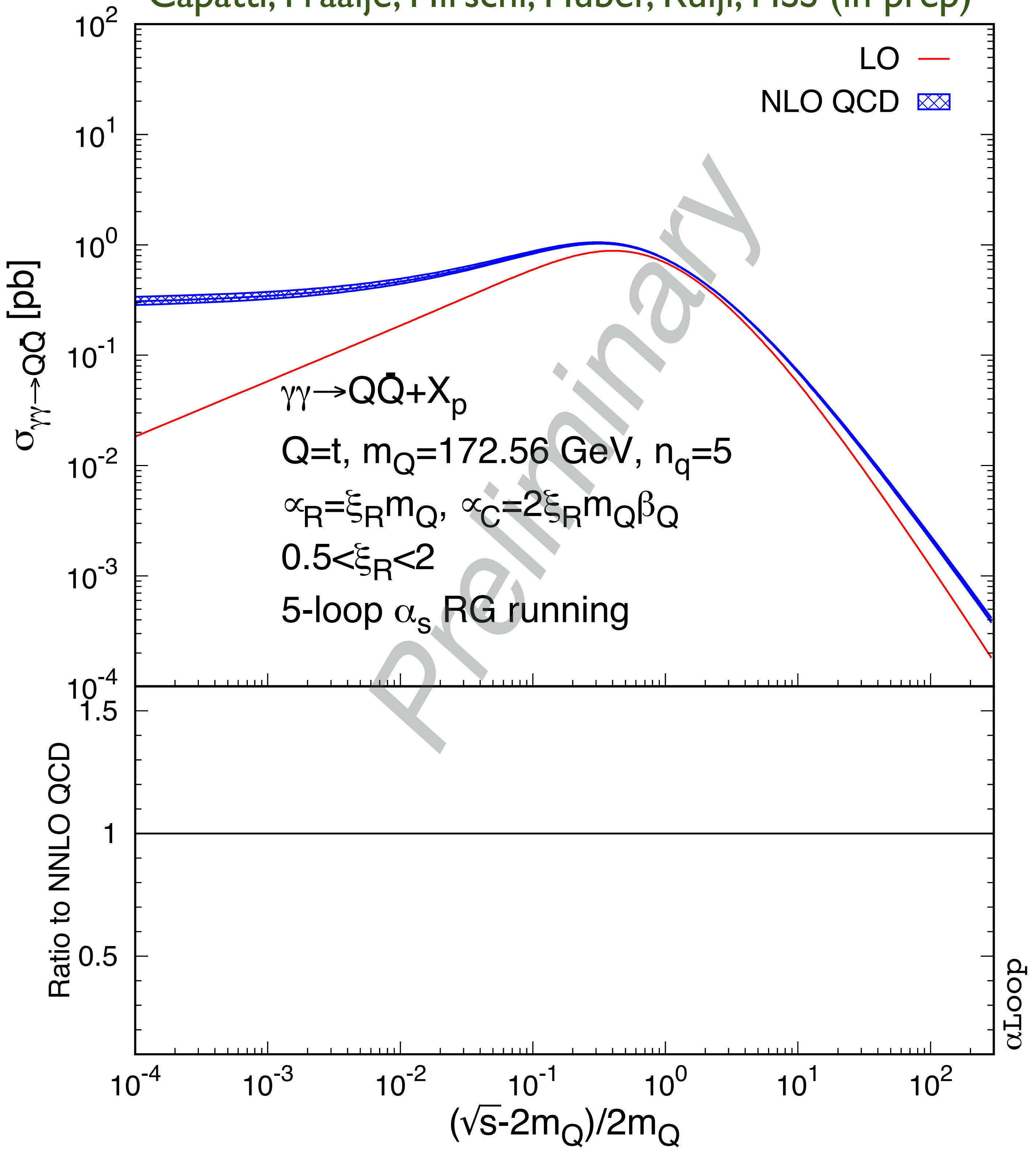

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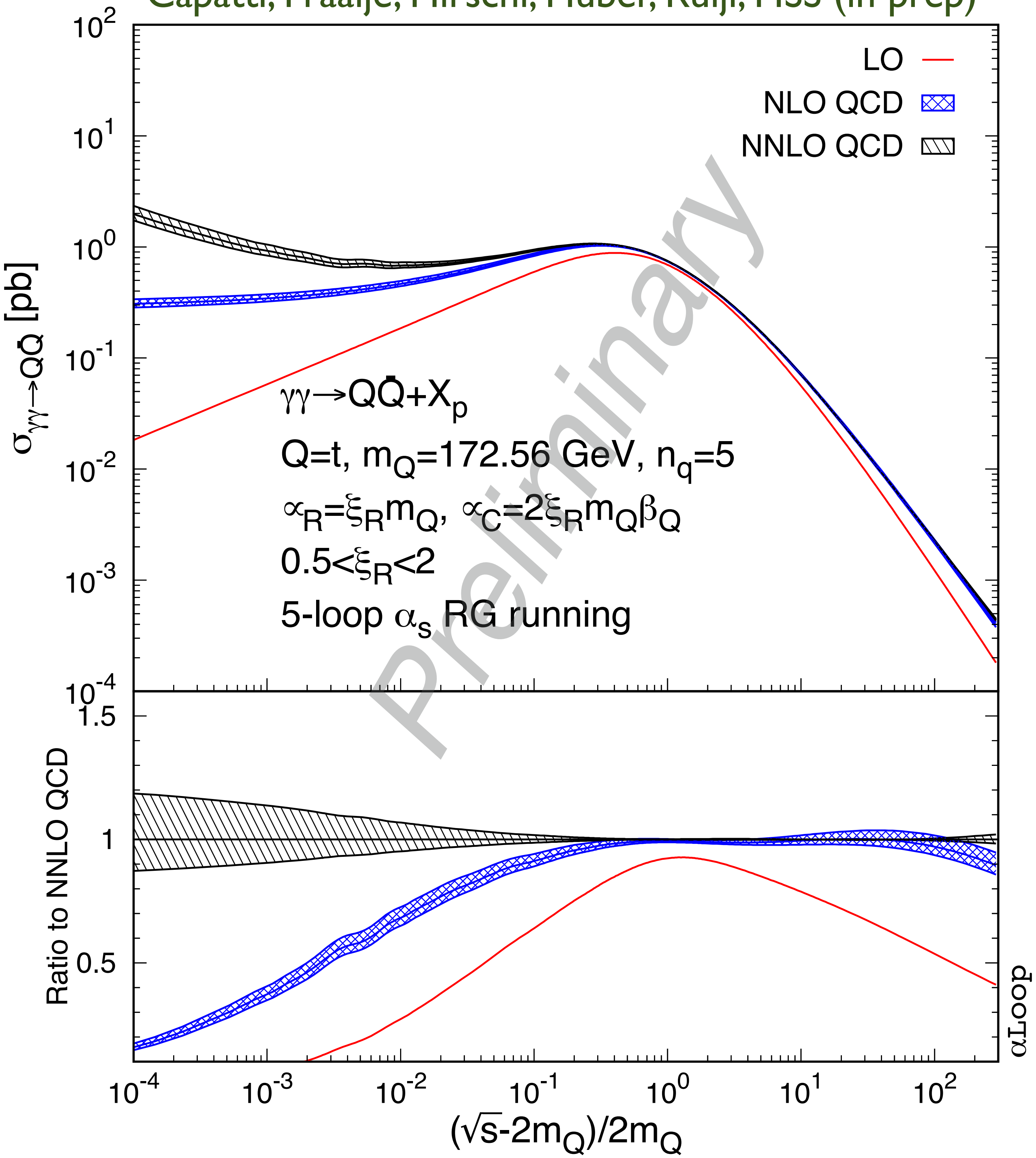

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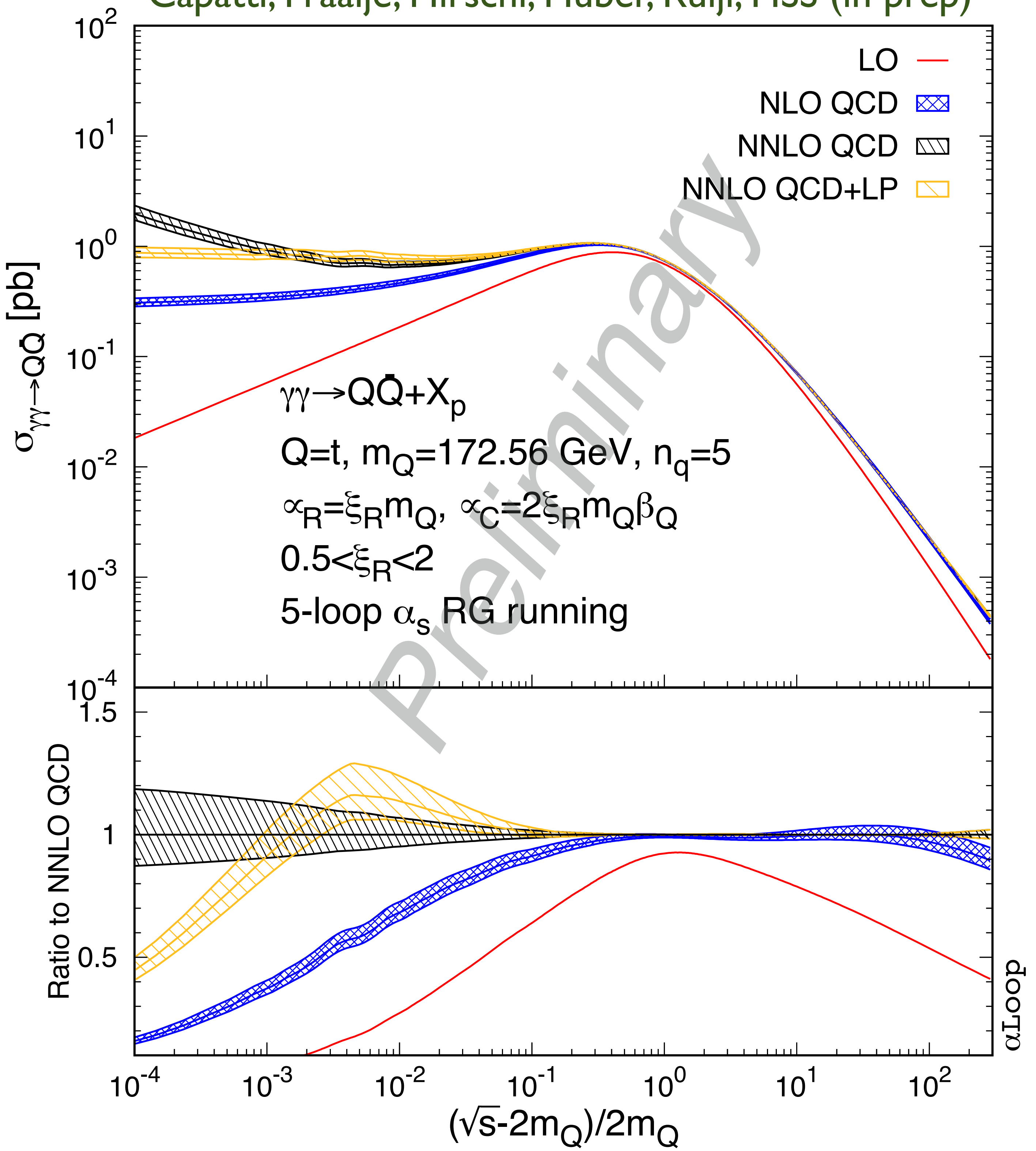

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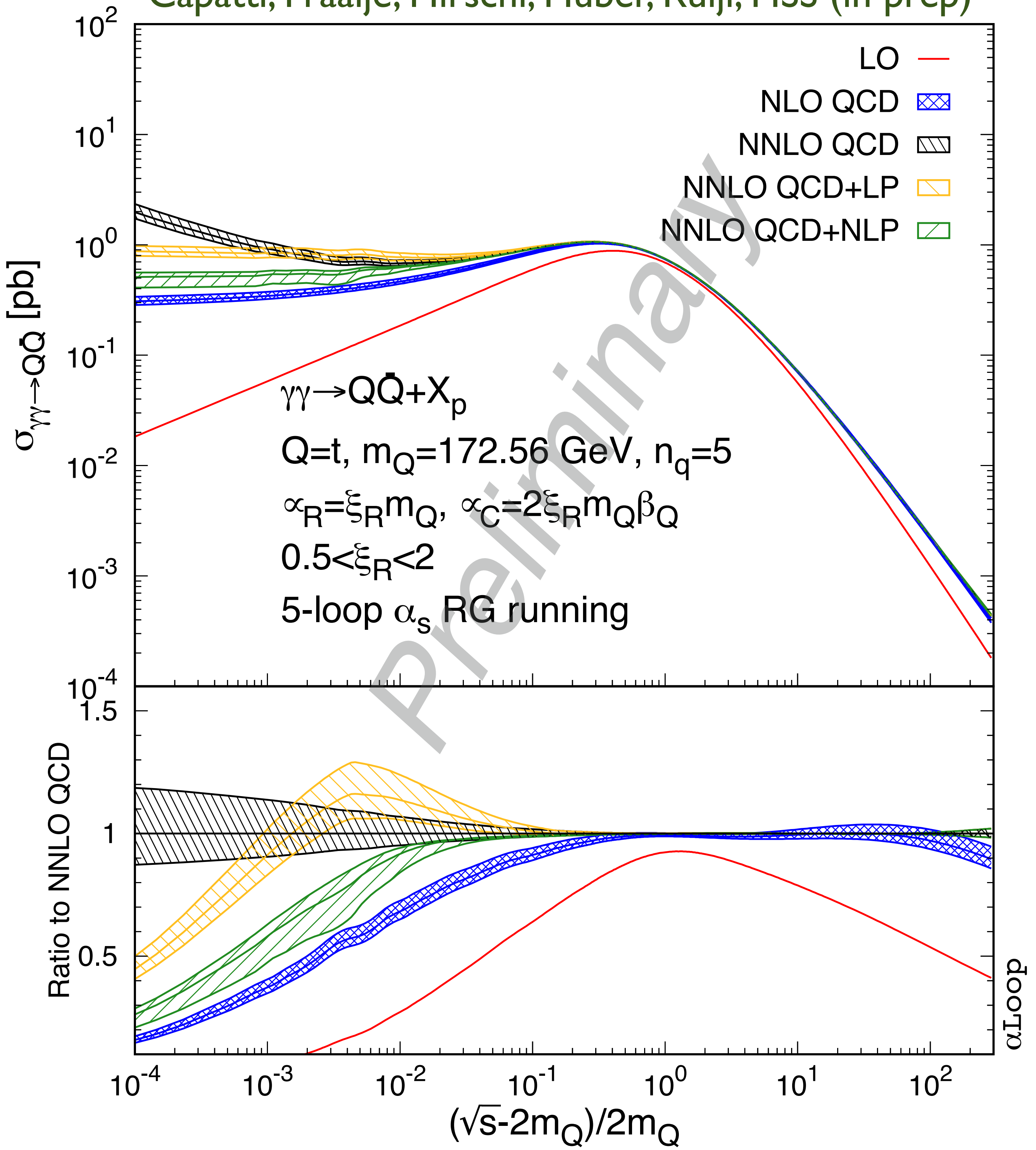

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Process: $\gamma\gamma \to t\bar{t}$	gamma-UPC+αLoop			
Colliding system	σ_{LO}	$\sigma_{\mathrm{NLO\ QCD}}$	$\sigma_{\mathrm{NNLO\ QCD}}$	$\sigma_{\mathrm{NNLO\ QCD+NLP}}$
p-p at 13 TeV	212.3 ab	$257.3^{+4.7}_{-3.5}$ ab	$270.2^{+2.6}_{-2.0}$ ab	$267.5^{+0.0}_{-1.0}$ ab
p-p at 13.6 TeV	228.5 ab	$276.7^{+5.1}_{-3.8}$ ab	$290.5^{+2.8}_{-2.1}$ ab	$287.6^{+0.0}_{-1.1}$ ab
p-p at 14 TeV	239.5 ab	$289.8^{+5.3}_{-3.9}$ ab	$304.1^{+2.9}_{-2.2}$ ab	$301.1^{+0.0}_{-1.1}$ ab
K factor		$\sigma_{\mathrm{NLO\ QCD}}/\sigma_{\mathrm{LO}}$	$\sigma_{\mathrm{NNLO\ QCD}}/\sigma_{\mathrm{LO}}$	$\sigma_{\mathrm{NNLO\ QCD+NLP}}/\sigma_{\mathrm{LO}}$
p-p at 13 TeV		1.212	1.273	1.260
p-p at 13.6 TeV		1.211	1.271	1.258
p-p at 14 TeV		1.210	1.270	1.257

Preliminary

NNLO QCD & Coulomb Resummation

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Colliding syste				D+NLP
p-p at 13 TeV				.0 .0 ab
p-p at 13.6 Te\				.0 .1 ab
p-p at 14 TeV				.0 .1 ab
K factor				NLP$/\sigma_{\mathrm{LO}}$
p-p at 13 TeV				0
p-p at 13.6 Te\				8
p-p at 14 TeV		1.210	1.270	1.257

- Non-negligible NNLO QCD:

+6%

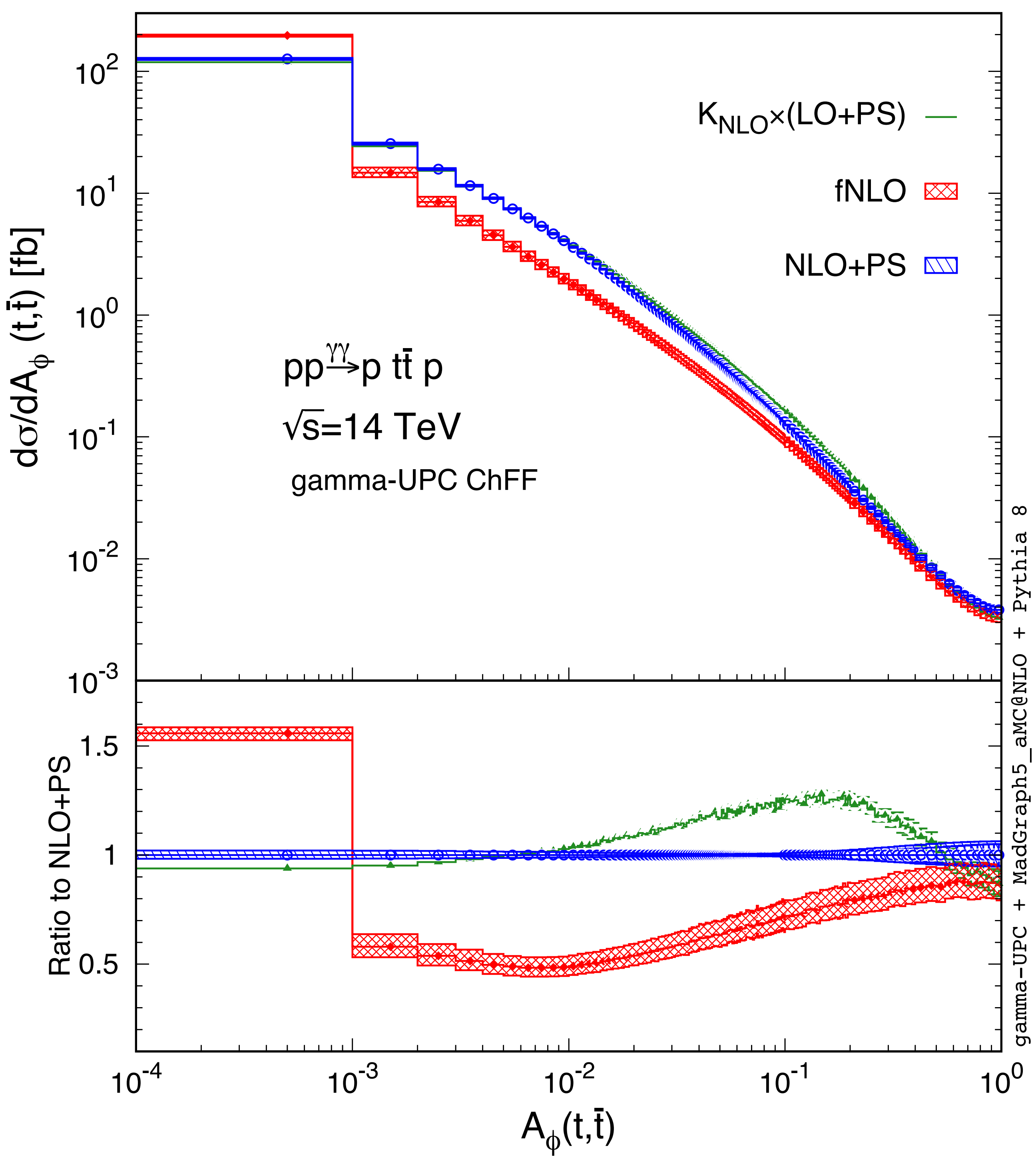
- Small Coulomb resummation effect:

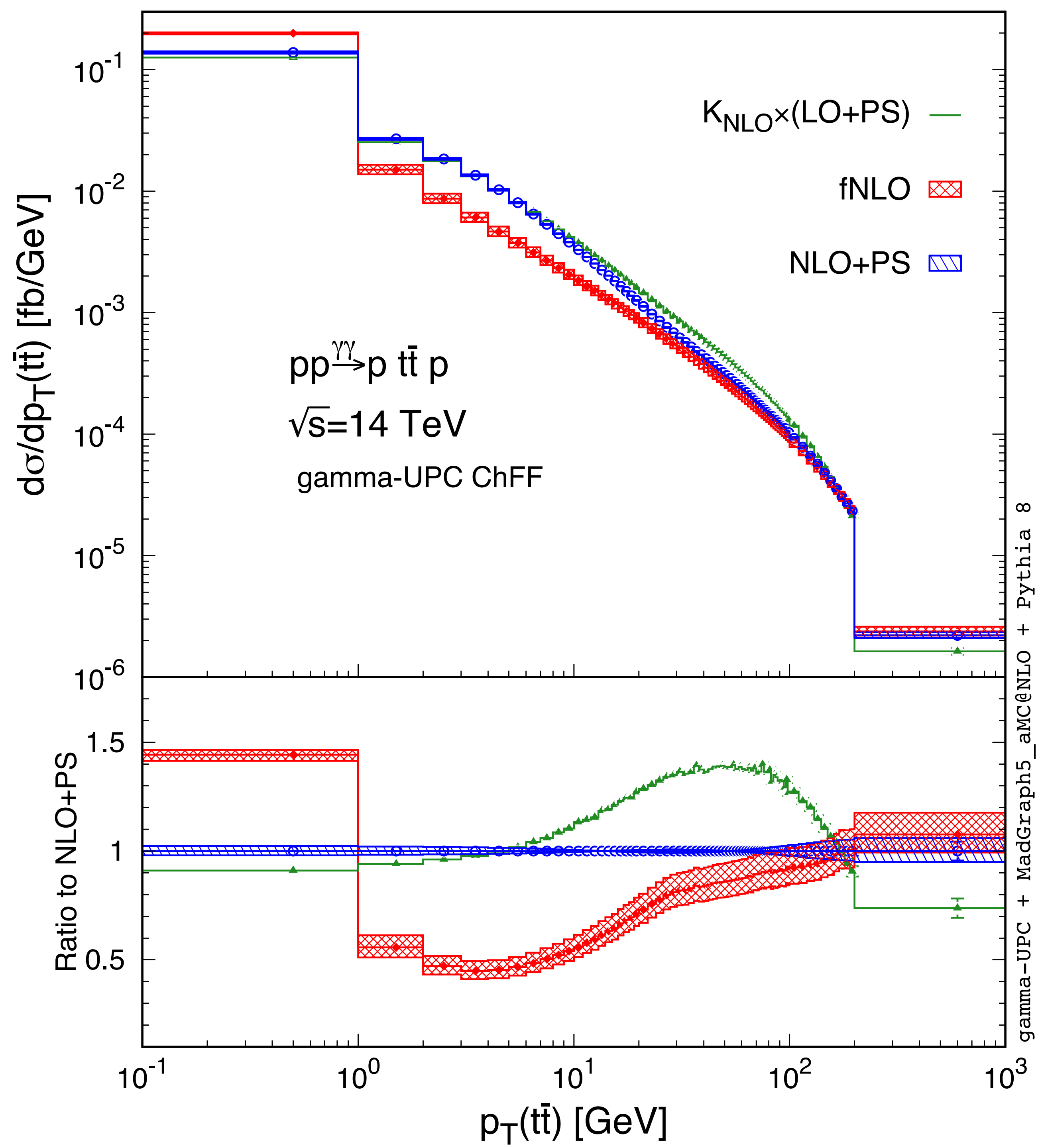
-1%

NLO Automation: an example

- At NLO QCD (w/o NLO EW), we can have NLO+PS simulations

HSS, Simon (2504.10104)





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Thank you for your attention !