QCD and electroweak radiative corrections in two-photon processes

Hua-Sheng Shao

Progress in algorithms and numerical tools for QCD
Orsay
10 June 2026

Introduction

- **The studies of two-photon processes**

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  - e+e- colliders (PETRA, PEP, TRISTAN, LEP, SLC, …, CEPC/FCC-ee)

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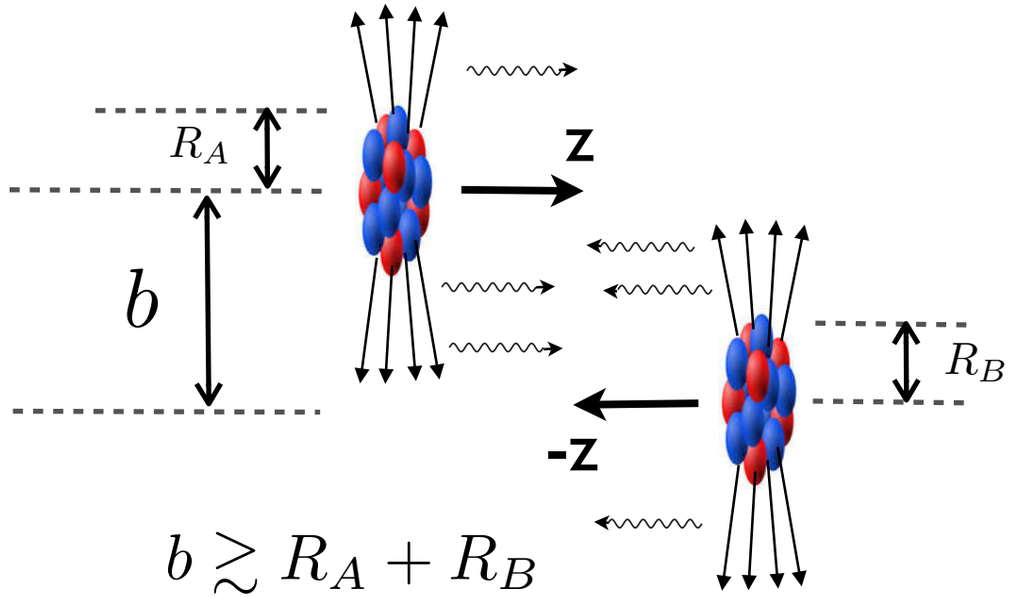
  - Ultra-Peripheral Collisions (UPCs)
  - Large photon flux $\propto Z^2$
  - Cross section in AA enhanced by Z^4



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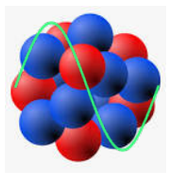
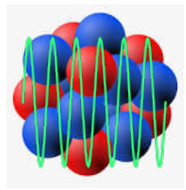
  - Coherent vs incoherent photons



$\lambda \gtrsim R_A$

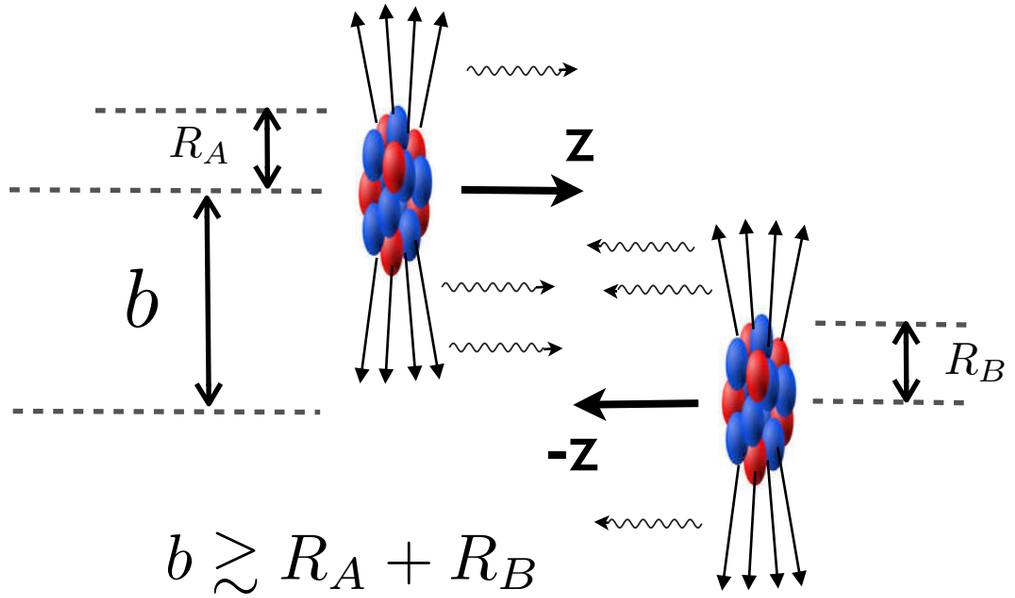
Coherent

vs



$\lambda < R_A$

Incoherent



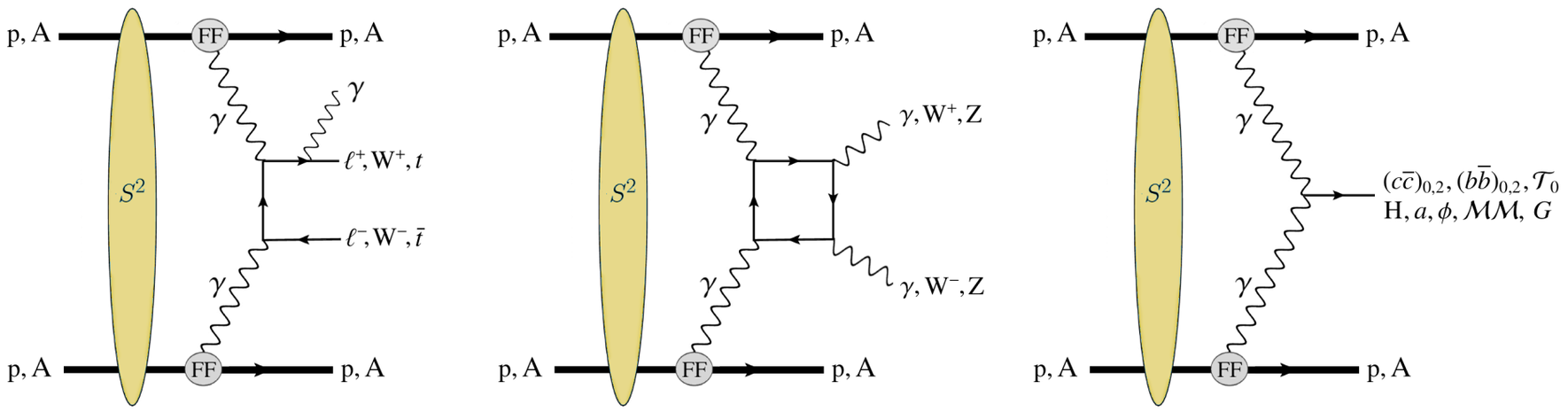
$b \gtrsim R_A + R_B$

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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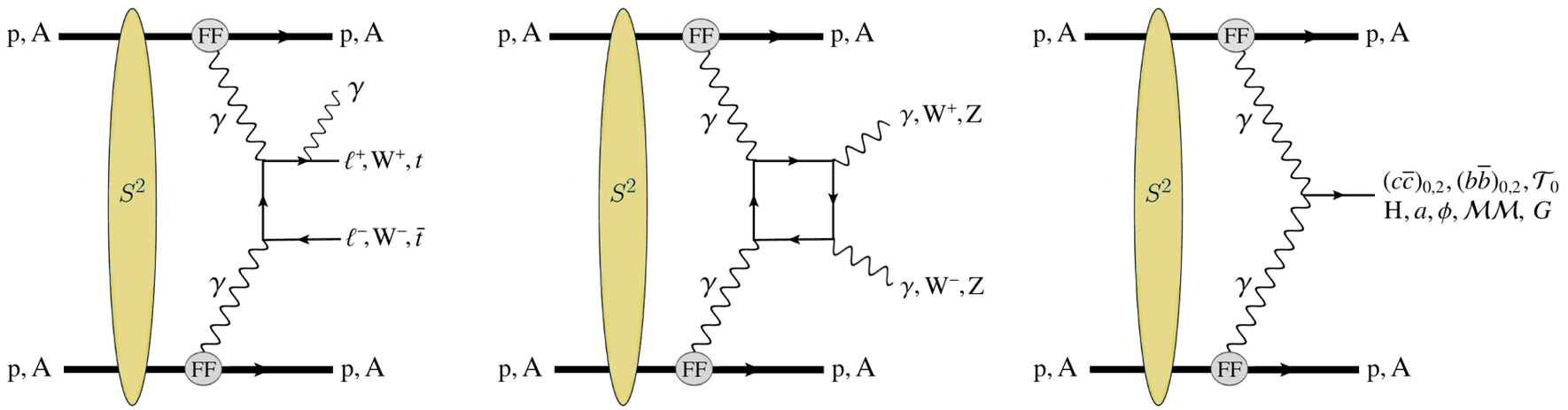

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- **Cross section:**

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

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gamma-UPC

HSS, d'Enterria (JHEP'22)

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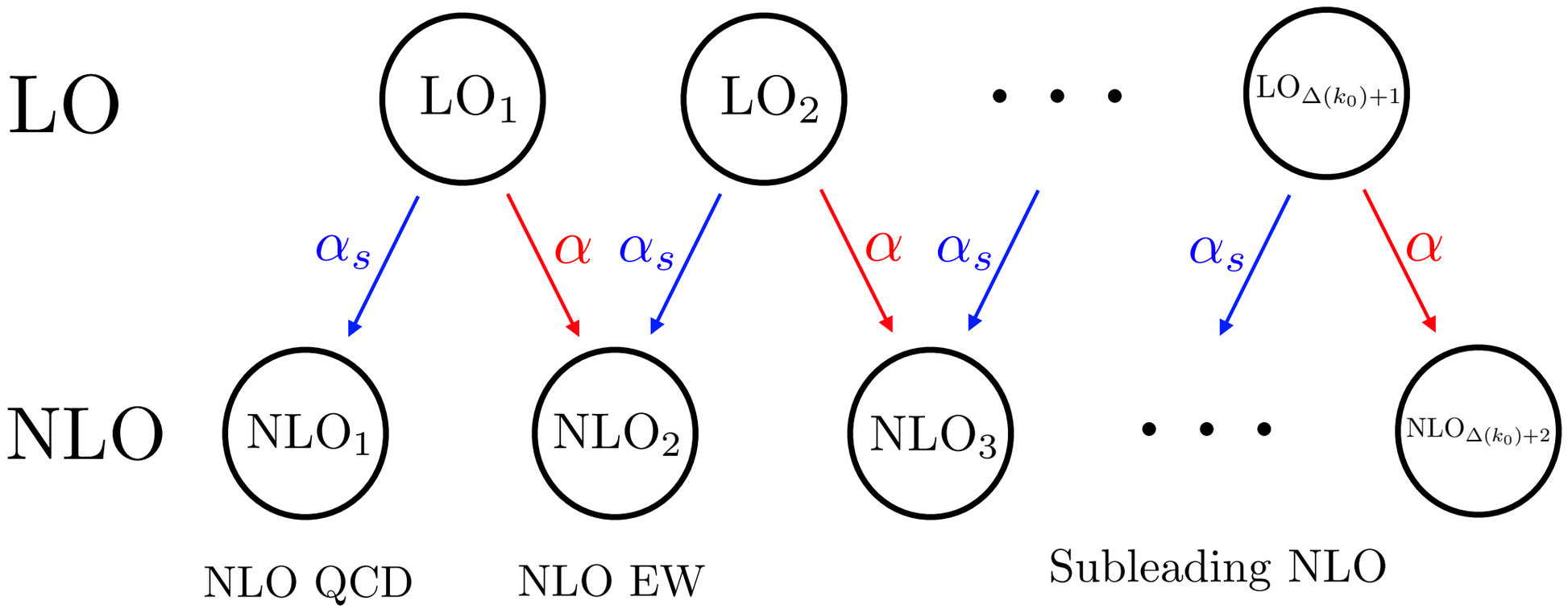

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- **Summary of existing high-order calculations**
  - In customized ways:

$\gamma\gamma \to t\bar{t}$	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, spin-density matrix elements	Jiang, Lu, Si, Zhang[2] (2410.21963, 2511.18935)
$\gamma\gamma \to \tau^+\tau^- \to e^+\mu^-\bar{\nu}_\tau\nu_\tau\bar{\nu}_\mu\nu_e$	bare leptons, NLO EW NWA, spin correlations	Dittmaier, Engel, Hernando Ariza, Pellen (2504.11391)
$\gamma\gamma \to \gamma\gamma$	two-loop, massive, NLO QCD+QED	Ajjath, Chaubey, Fraaije, Hirschi, HSS (2312.16956, 2312.16966, 2604.00099)
	three-loop, massless NNLO QCD+QED	Bargiela, Chakraborty, Gambuti, Ozcelik (2603.22423)
$\gamma\gamma \to Q\bar{Q}$	NNLO QCD+NLO EW+Coulomb res	Capatti, Fraaije, Hirschi, Huber, Ruijl, HSS (2509.13439)

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

NLO QCD & EW Automation

MadGraph5_aMC@NLO since version 3.7.0

NLO Automation

- **MadGraph5_aMC@NLO (in 3.7.0+)** HSS, Simon (JHEP'25)

```
./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 (JHEP'25)

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

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

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

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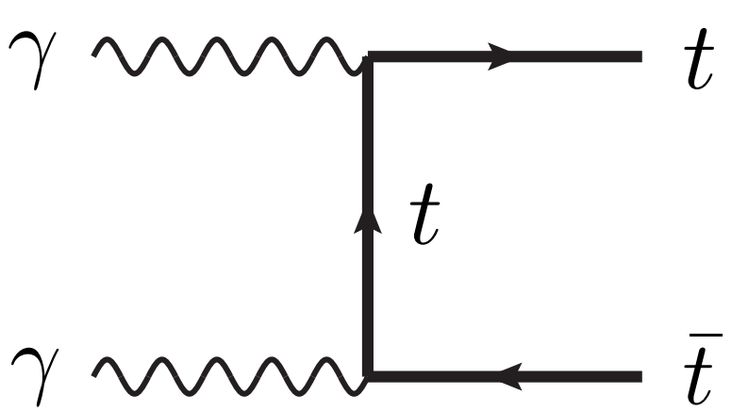

Process: $\gamma\gamma \to t\bar{t}$	gamma-UPC+MG5_aMC		
Colliding system, c.m. energy	$\sigma_{\rm LO}$	$\sigma_{\rm NLO\ QCD}$	$\sigma_{\rm NLO\ QCD+EW}$
p-p at 13 TeV	212.40(6) ab	$256.43(9)^{+4.5}_{-3.7}$ ab	$244.8(1)^{+4.5}_{-3.7}$ ab
p-p at 13.6 TeV	228.53(6) ab	$275.5(1)^{+4.8}_{-4.0}$ ab	$263.1(1)^{+4.8}_{-4.0}$ 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
p-Pb at 62.8 TeV		1.194	1.140
Pb-Pb at 39.4 TeV		1.259	1.205

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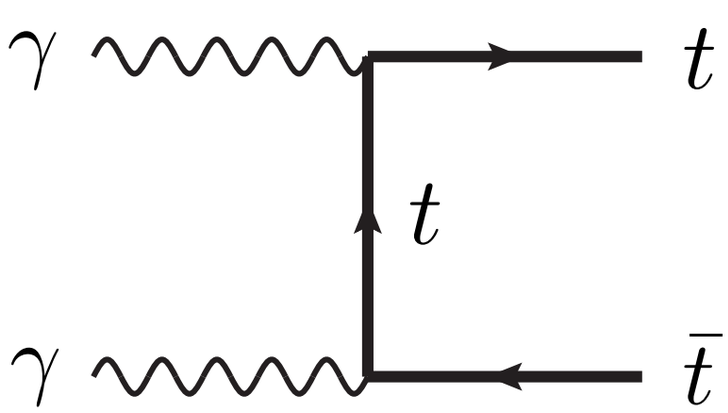

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p-p at 13.6 TeV	228.53(6) ab	$275.5(1)^{+4.8}_{-4.0}$ ab	$263.1(1)^{+4.8}_{-4.0}$ ab
p-p at 14 TeV	239.58(7) ab	$288.7(1)^{+5.0}_{-4.2}$ ab	$275.5(1)^{+5.0}_{-4.2}$ ab
p-Pb at 8.8 TeV	46.89(1) fb	$59.87(2)^{+1.3}$ fb	$57.32(2)^{+1.3}_{-1.1}$ fb
Pb-Pb 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
Pb-Pb at 39			$5(2)^{+0.026}_{-0.021}$ nb

- Sizable NLO QCD:

+20%

K factor			$\sigma_{\rm QCD+EW}/\sigma_{\rm LO}$
p-p at 13 Te			1.153
p-p at 13.6			1.151
p-p at 14 Te			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
p-Pb at 62.8 TeV		1.194	1.140
Pb-Pb at 39.4 TeV		1.259	1.205

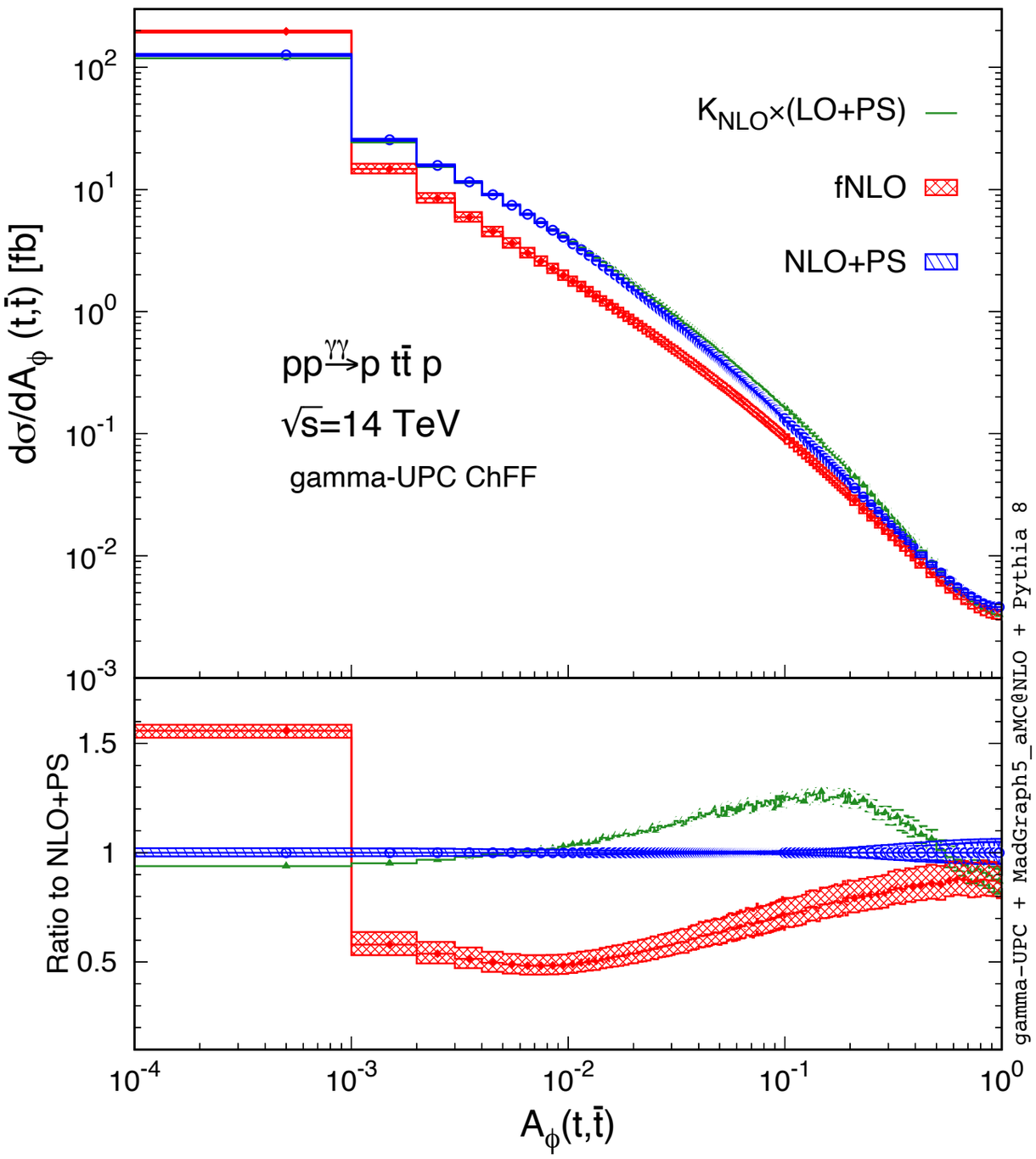
- Non-negligible NLO EW:

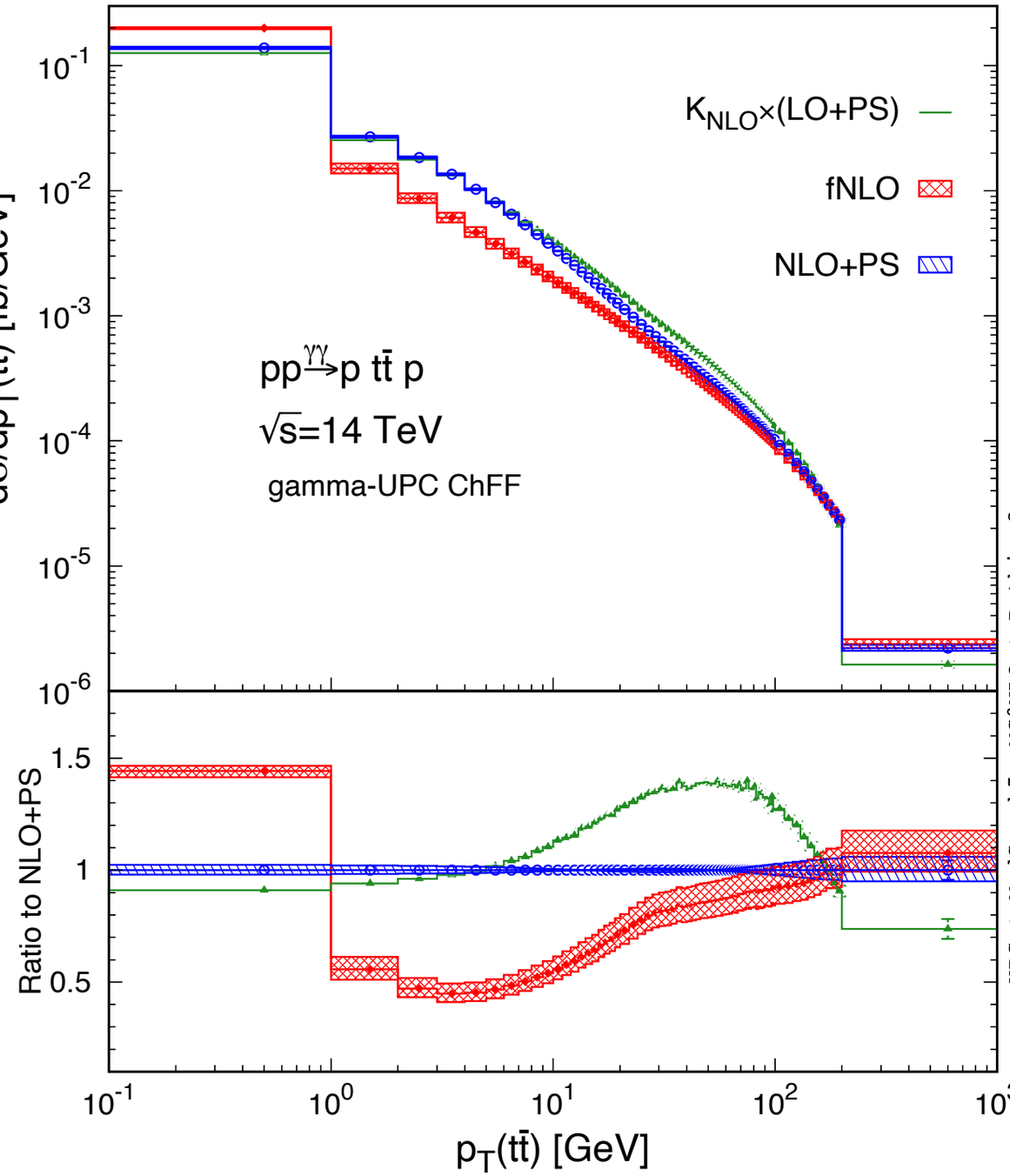
-5%

NLO Automation: an example

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

HSS, Simon (JHEP'25)





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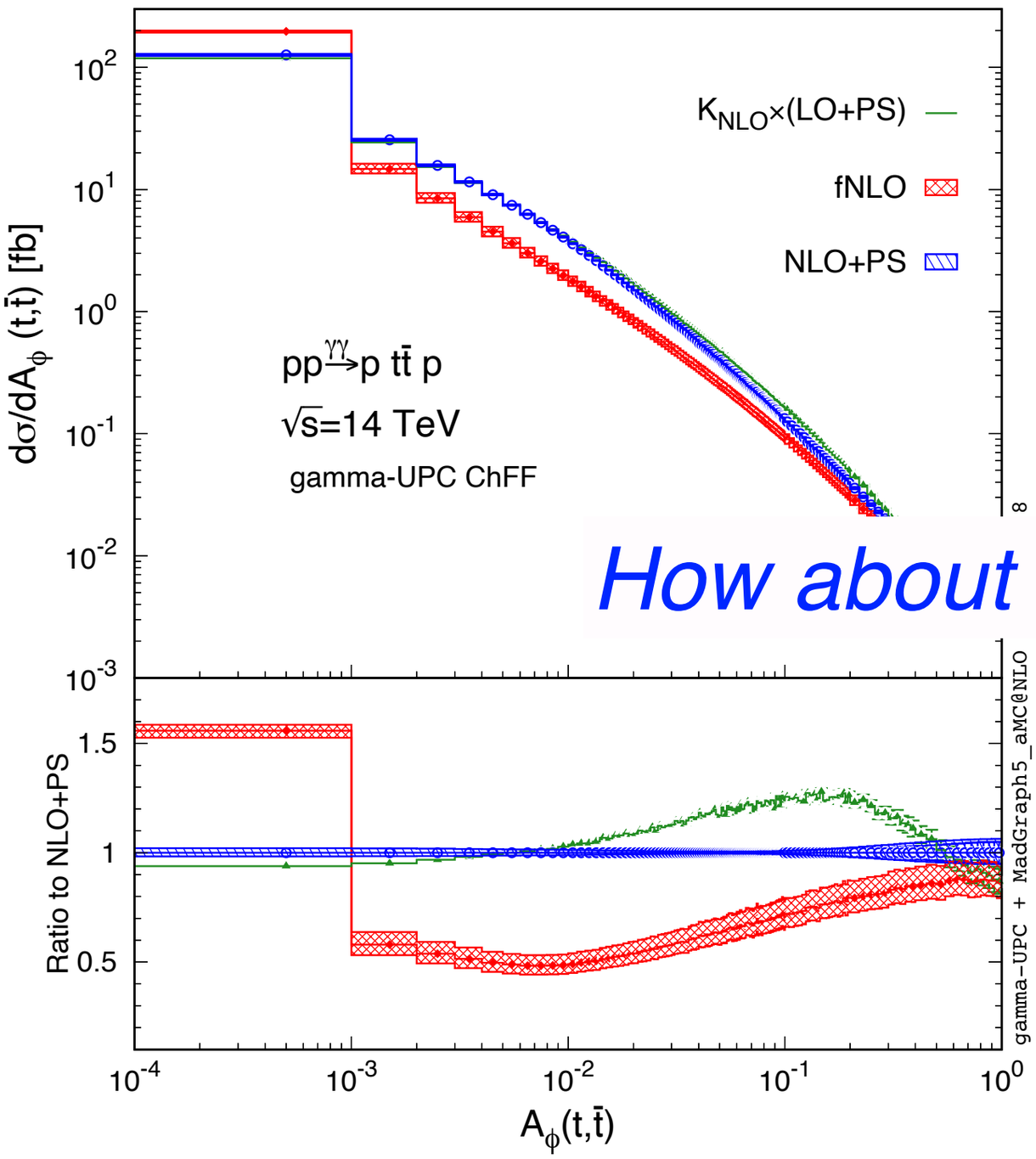

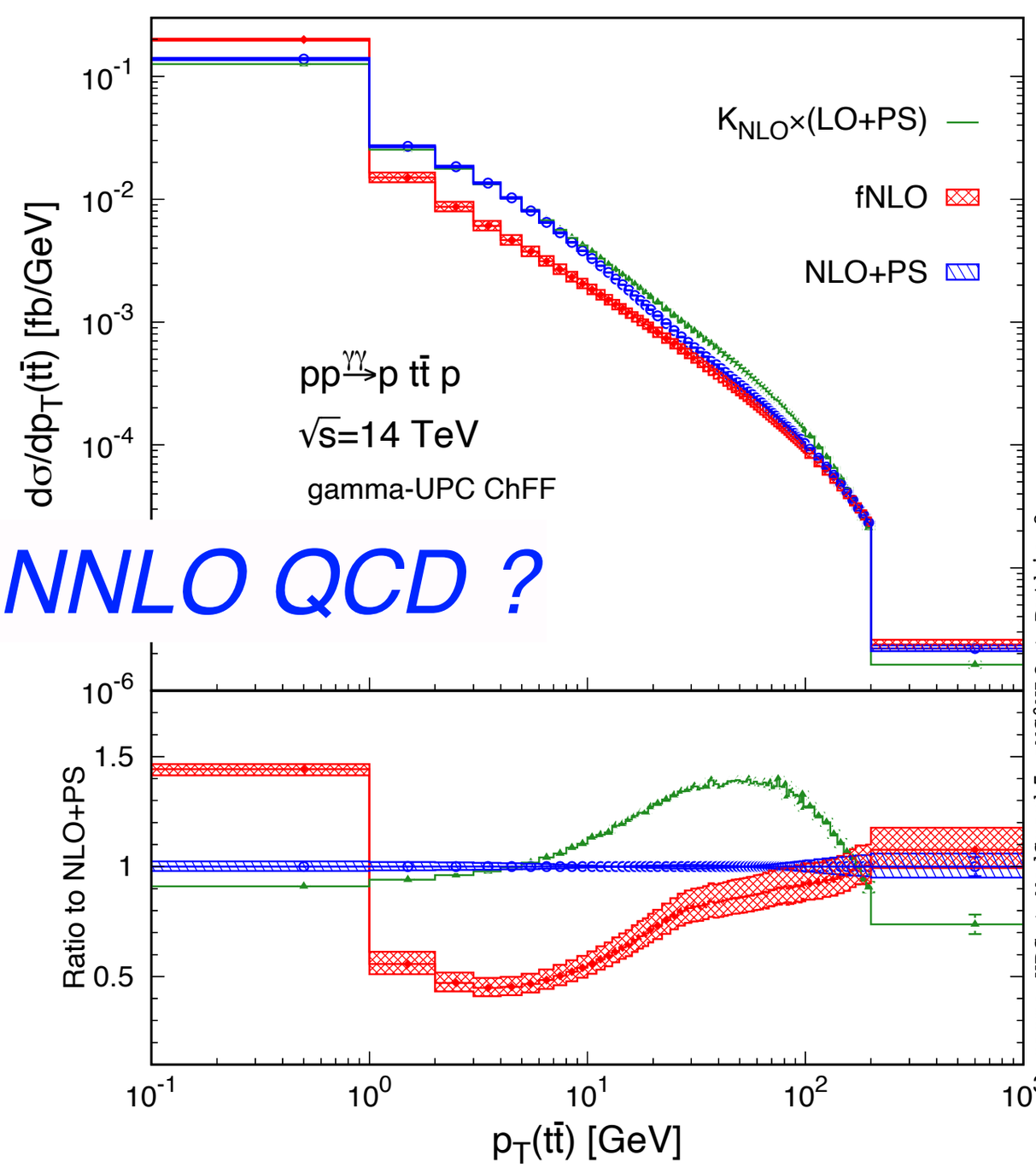

How about NNLO QCD ?

NNLO QCD for $\sigma(\gamma\gamma \to Q\bar{Q} + X)$

PHIQUE

PHIQUE: PHoton-Induced heavy QUark pair procEss

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NNLO QCD & Coulomb Resummation

- NNLO QCD with Local Unitarity construction (αLoop, by Bern Group)

Talks by Valentin Hirschi and Lucien Huber

https://github.com/alphal00p/alphaloop/

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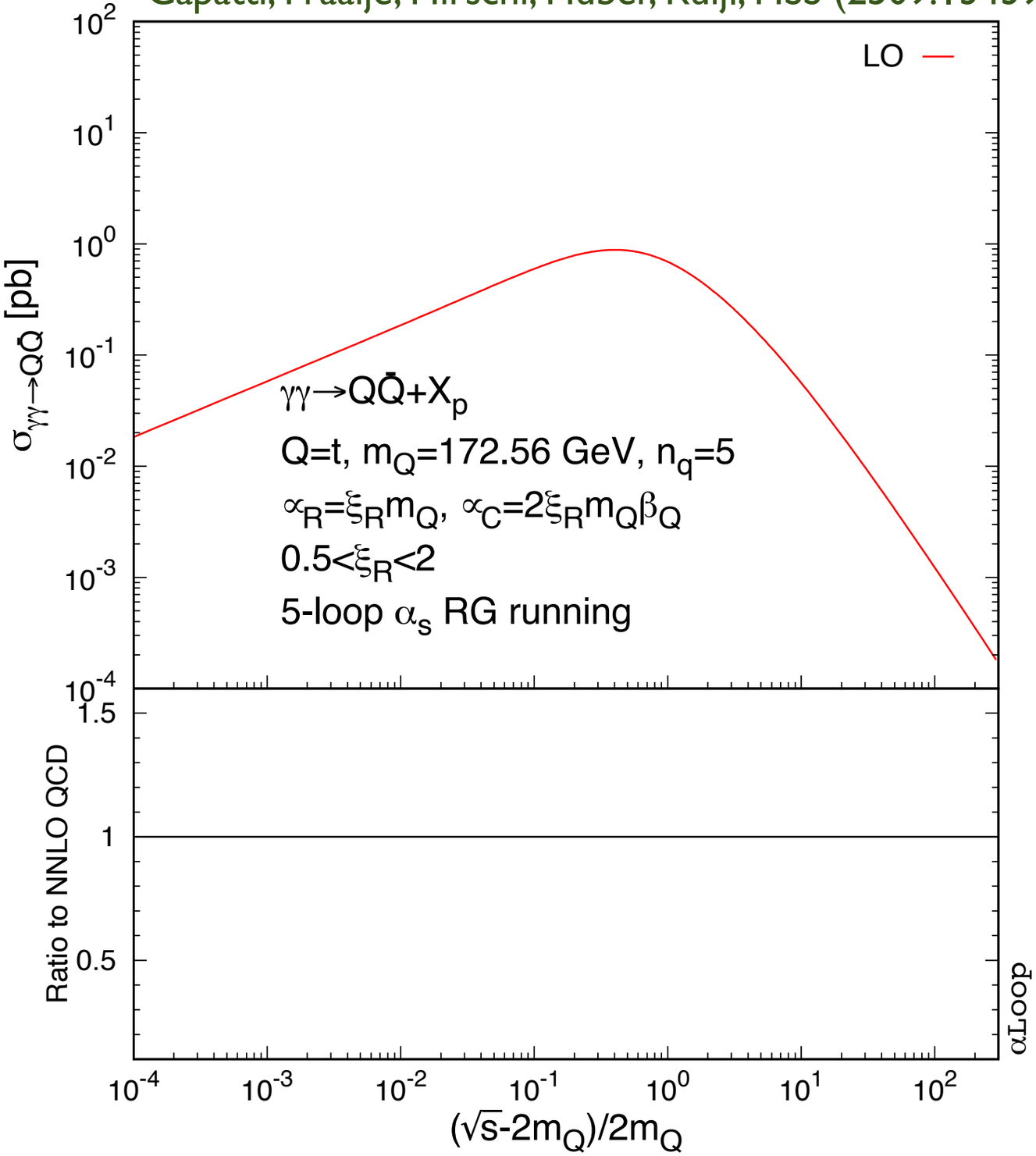

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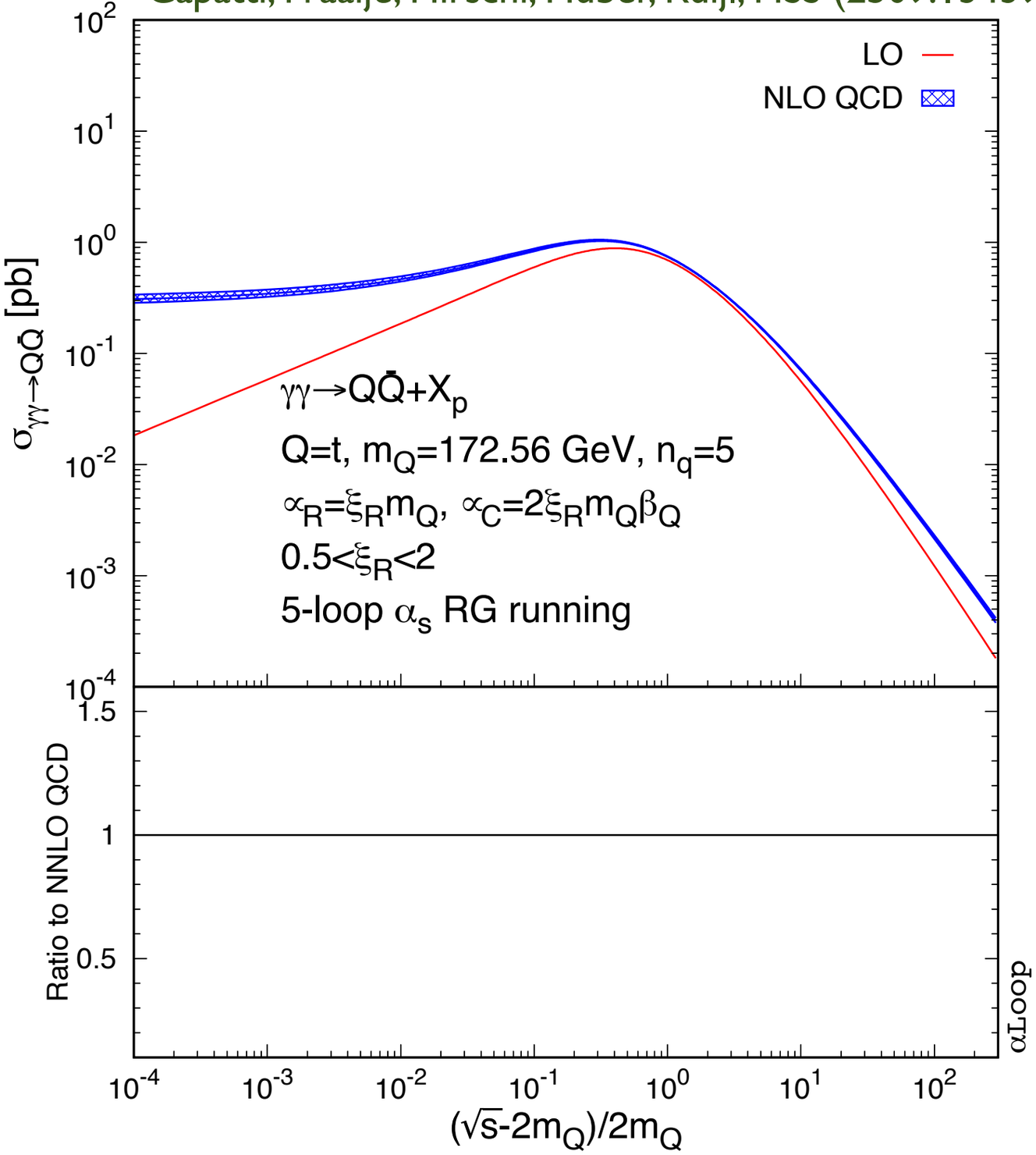

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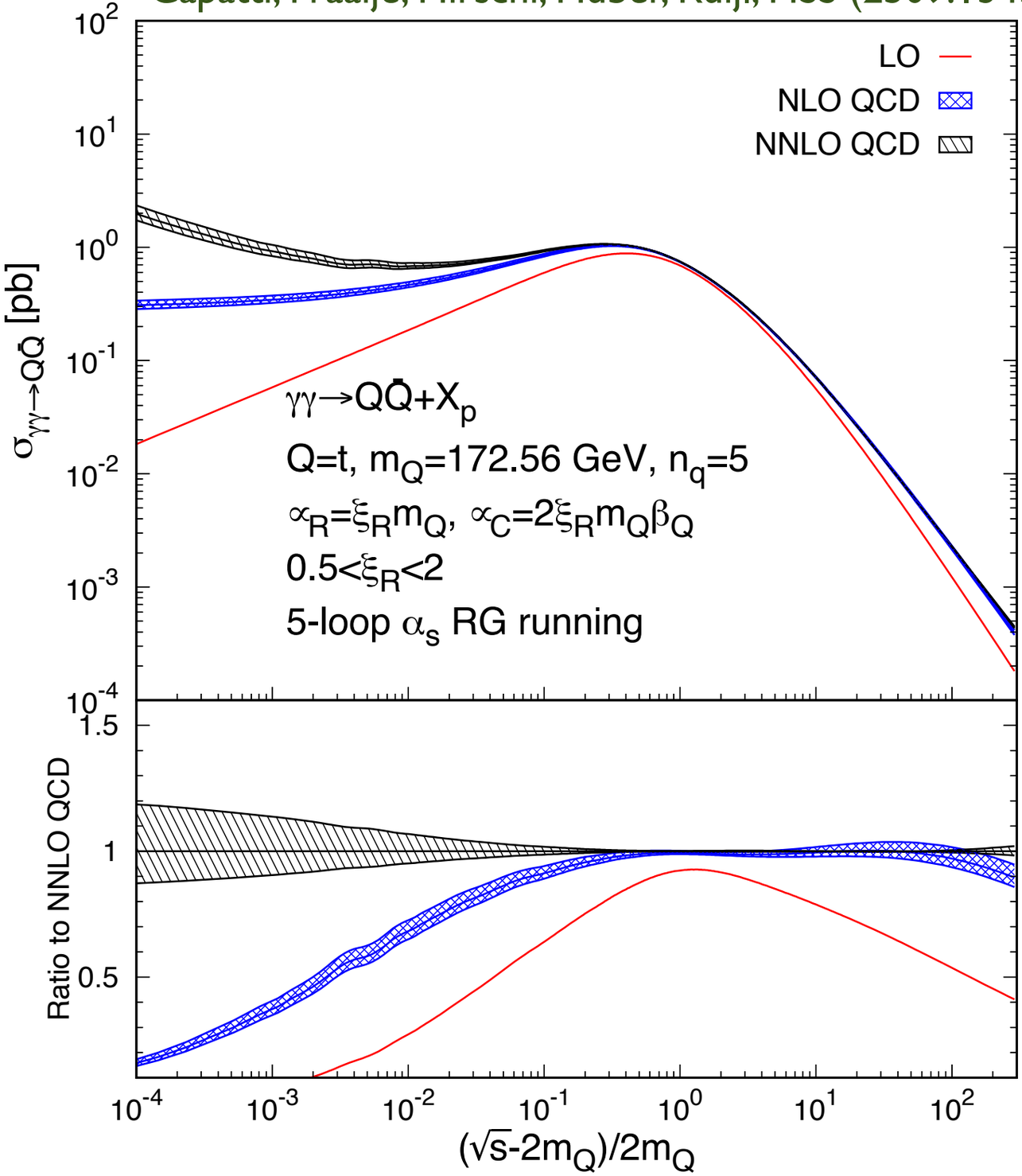

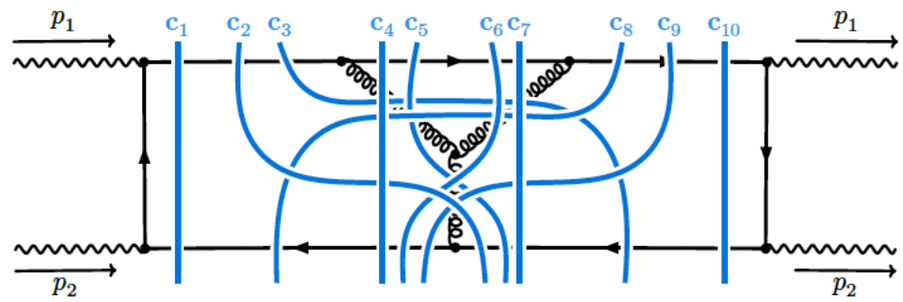

+ 137 other FS graphs

NNLO QCD & Coulomb Resummation

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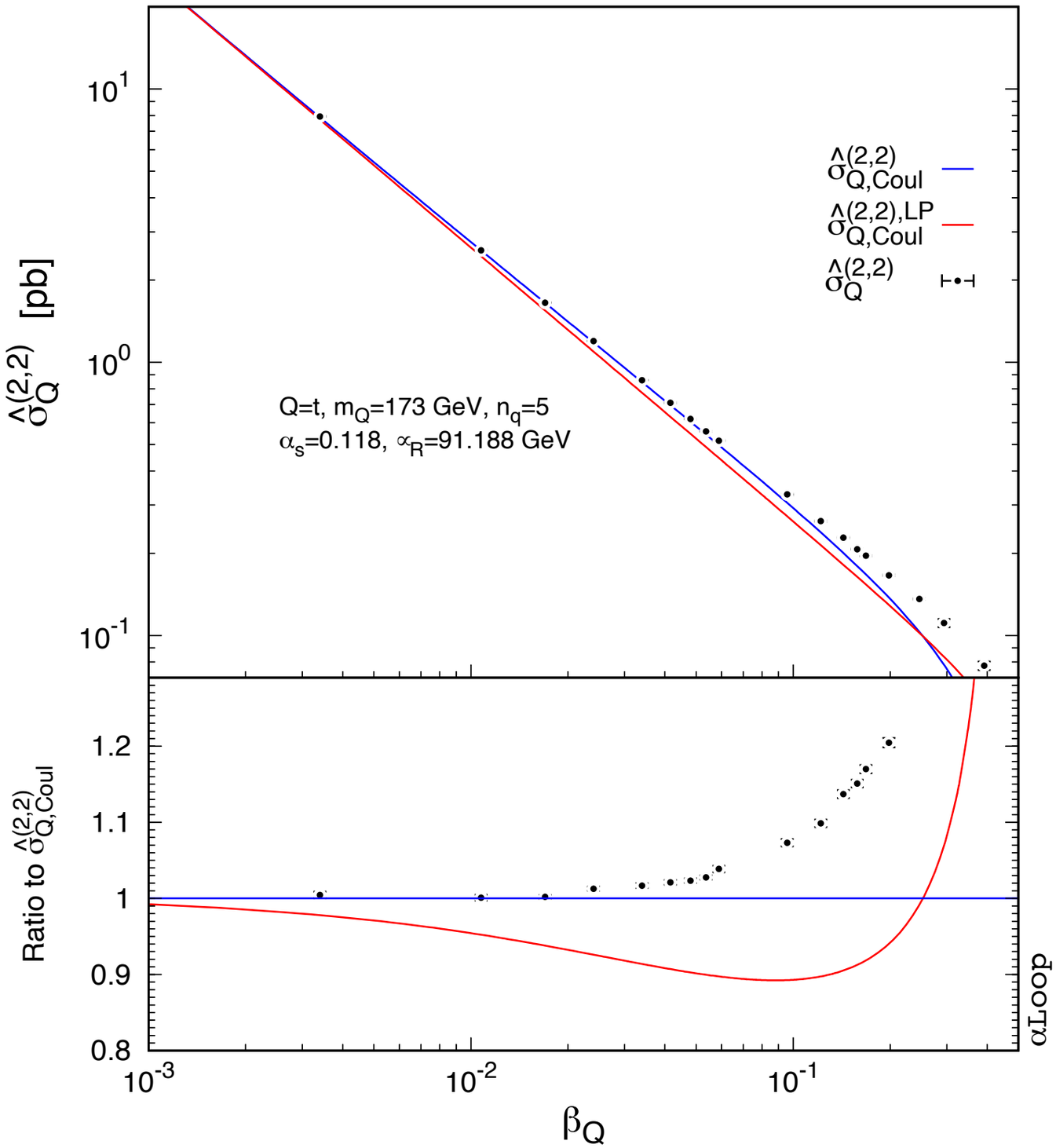

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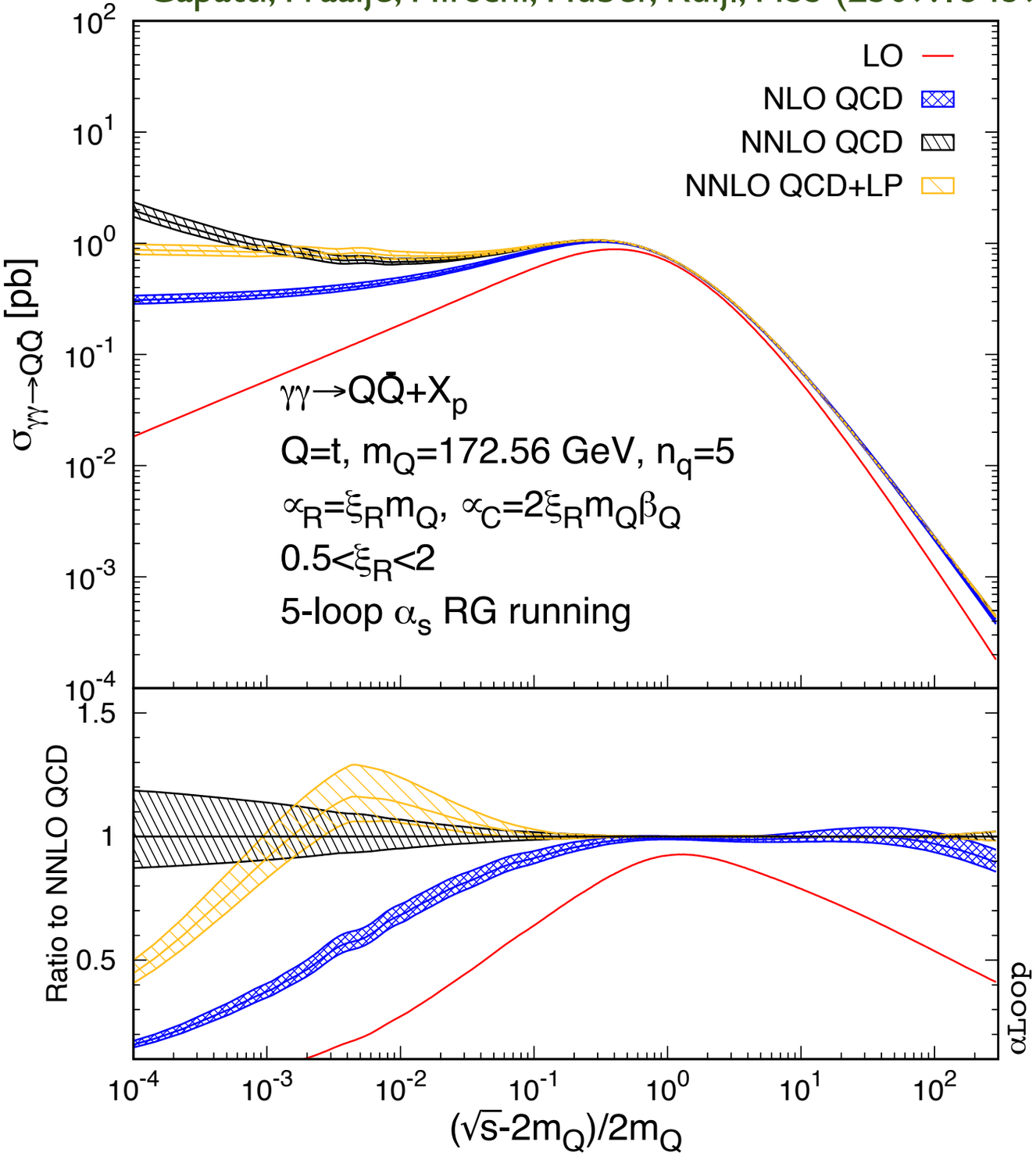

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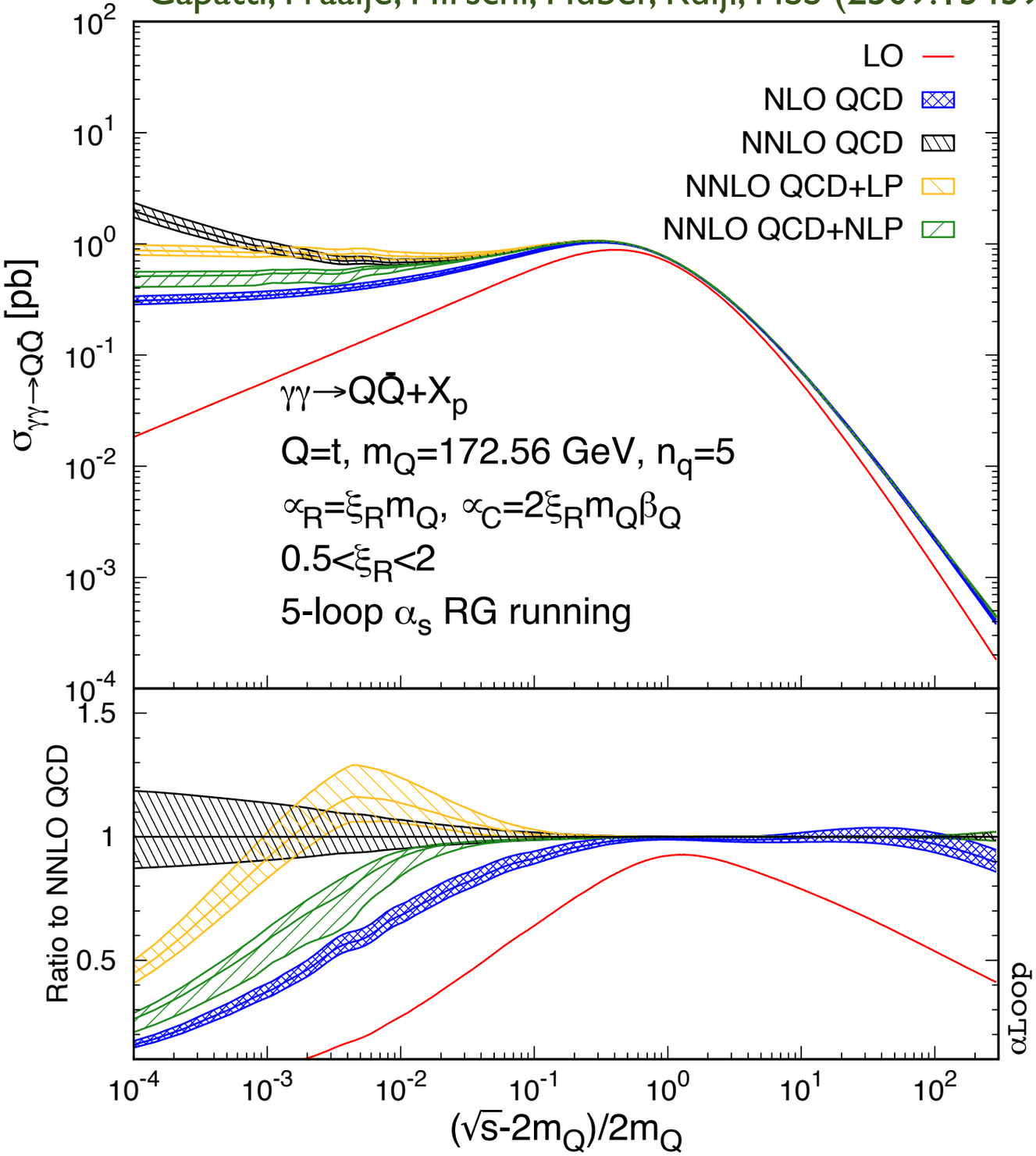

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Process: $\gamma\gamma \to t\bar{t}$	gamma-UPC+αLoop			
Colliding system	σ_{LO}	$\sigma_{\text{NLO QCD}}$	$\sigma_{\text{NNLO QCD}}$	$\sigma_{\text{NNLO QCD+NLP}}$
p-p at 13 TeV	212.3 ab	$257.3^{+4.7}_{-3.5}$ ab	$270.2^{+2.6}_{-2.0}$ ab	$267.5^{+0.0}_{-1.0}$ 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		$\sigma_{\text{NLO QCD}}/\sigma_{\text{LO}}$	$\sigma_{\text{NNLO QCD}}/\sigma_{\text{LO}}$	$\sigma_{\text{NNLO QCD+NLP}}/\sigma_{\text{LO}}$
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

NNLO QCD & Coulomb Resummation

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Process: $\gamma\gamma \to t\bar{t}$	gamma-UPC+αLoop			
Colliding syste				D+NLP
p-p at 13 TeV				$^{0}_{0}$ ab
p-p at 13.6 TeV				$^{0}_{1}$ ab
p-p at 14 TeV				$^{0}_{1}$ ab
K factor				$\sigma_{\rm NLP}/\sigma_{\rm LO}$
p-p at 13 TeV				0
p-p at 13.6 TeV				8
p-p at 14 TeV		1.210	1.270	1.257

- Non-negligible NNLO QCD:

+6%

- Small Coulomb resummation effect:

-1%

NNLO QCD & Coulomb Resummation

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- Non-negligible NNLO QCD:

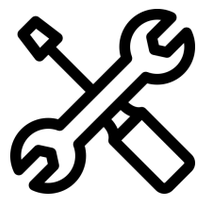
+6%

- Small Coulomb resummation effect:

-1%

1. Top-quark pair in other collision systems (heavy ions, e+e- etc)
2. Bottom-quark pair and charm-quark pair
3. git repository: https://github.com/alphal00p/phique

NLO QCD+QED for $\gamma\gamma \to \gamma\gamma$



LbLatNLO

LbLatNLO

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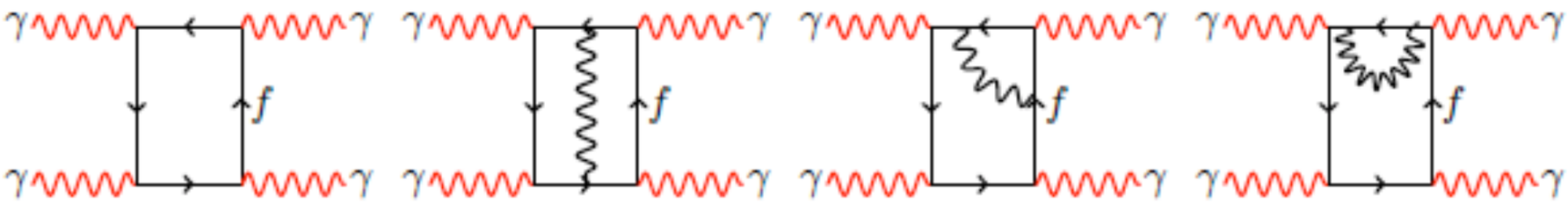
Theoretical Predictions

- **Going beyond one-loop (for fermions)**
  - Low-energy (LE) approx. : NLO from Euler-Heisenberg Lagrangian

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

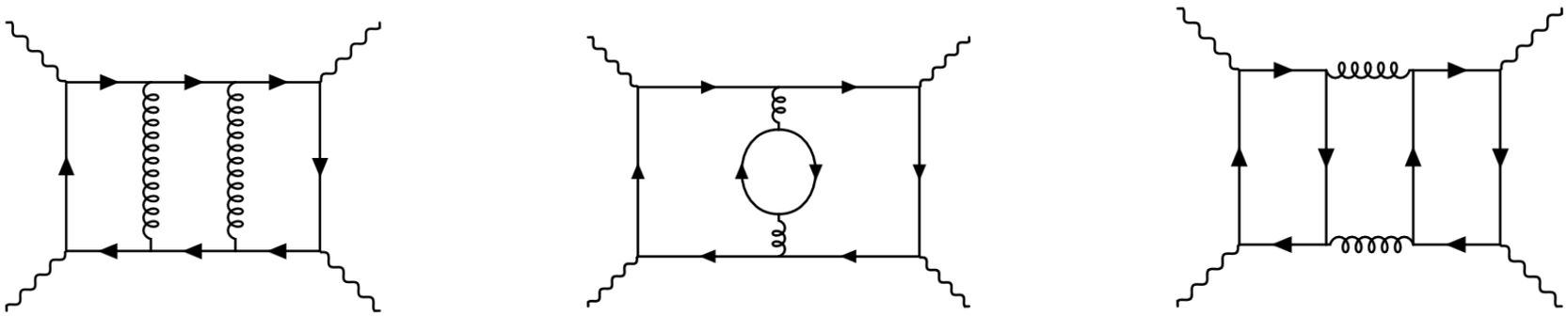
    Bern, De Freitas, Dixon, Ghinculov & Wong JHEP'01
  - Full NLO without approx.

    Ajjath, Chaubey, HSS (JHEP'24, 2604.00099); Ajjath, Chaubey, Fraaije, Hirschi, HSS (PLB'24)



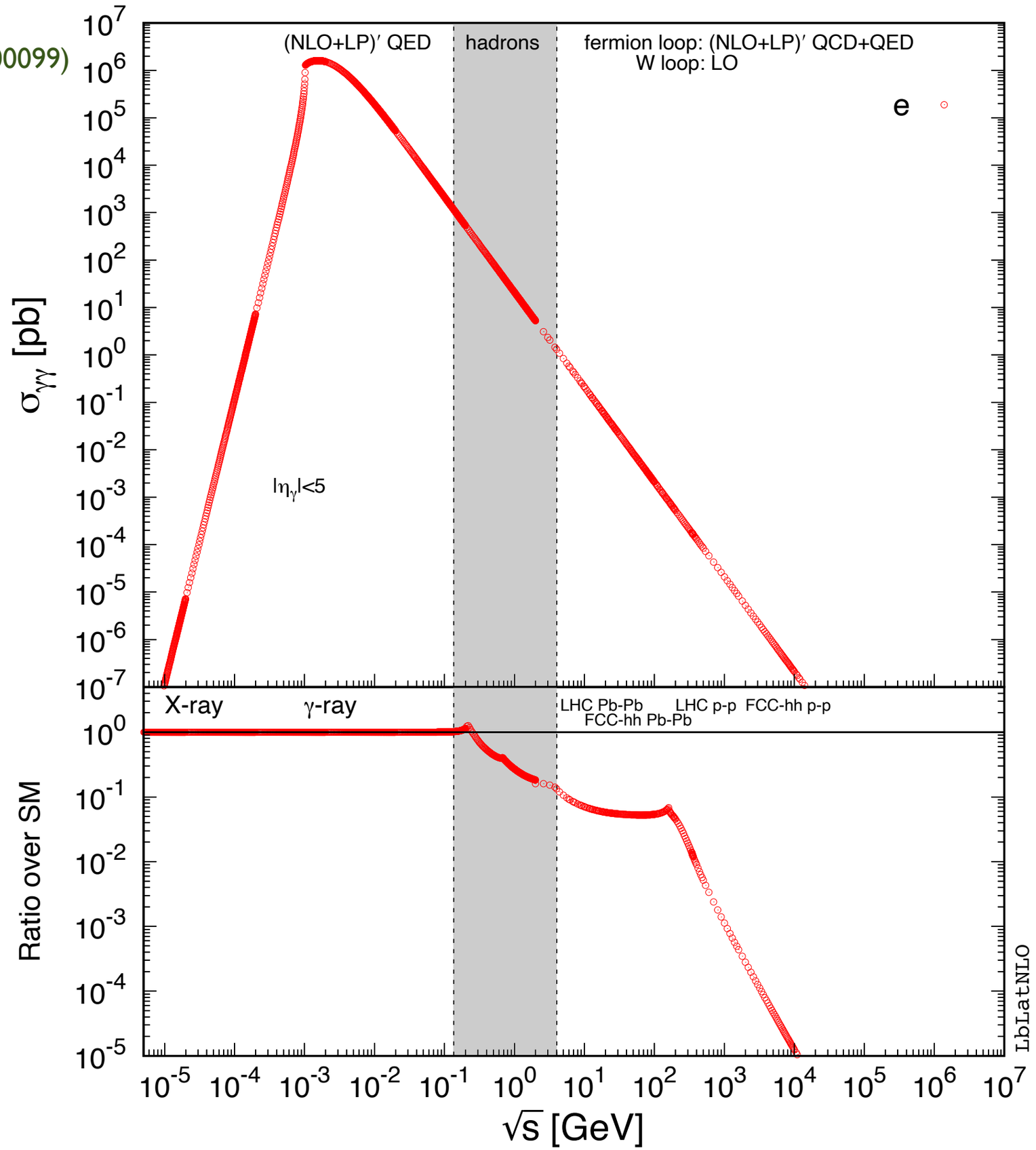
- NNLO in HE approx.

  Bargiela, Chakraborty, Gambuti, Ozcelik (2603.22423)



LbL Cross Section

Ajjath, Chaubey, HSS (2604.00099)



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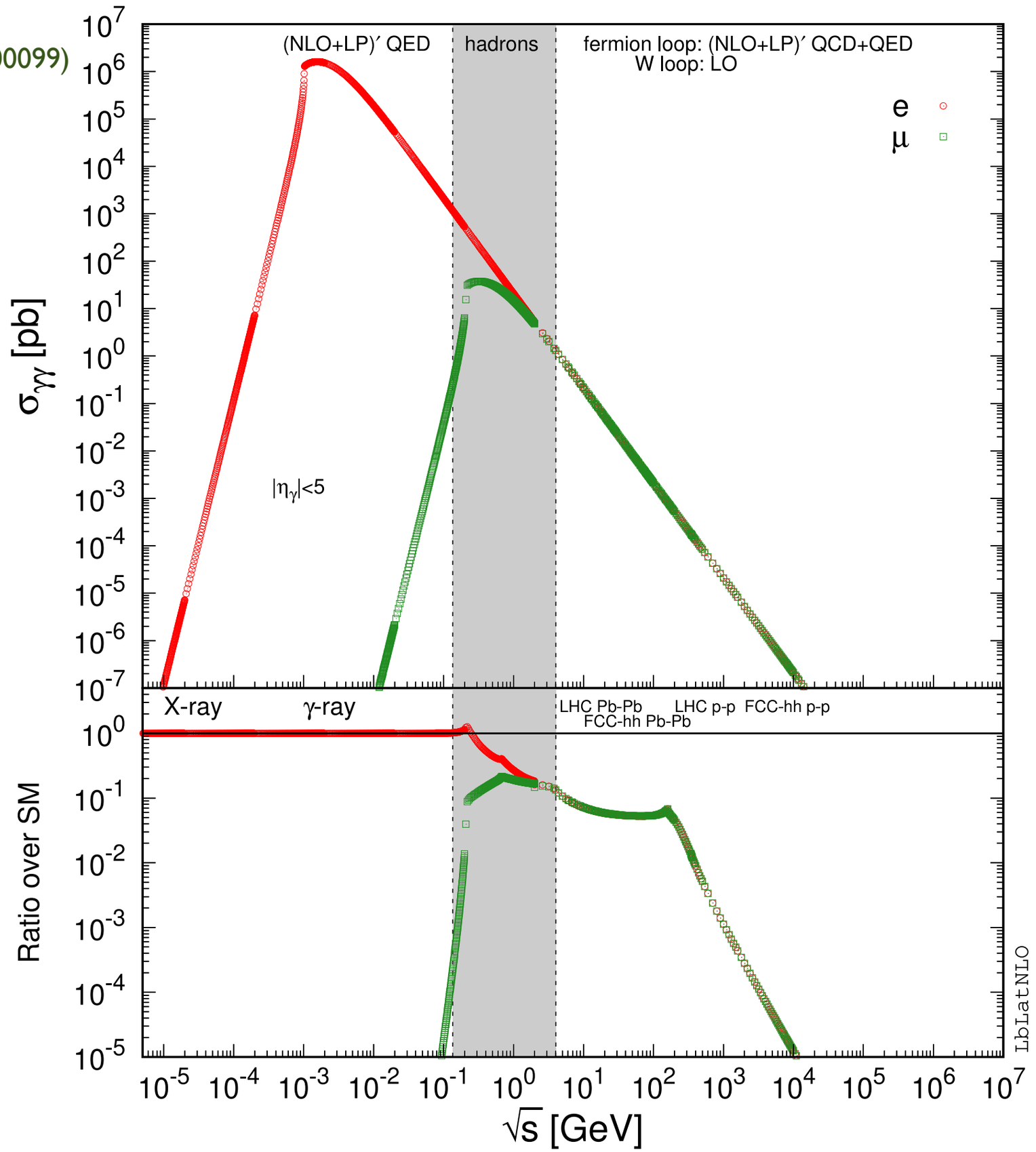

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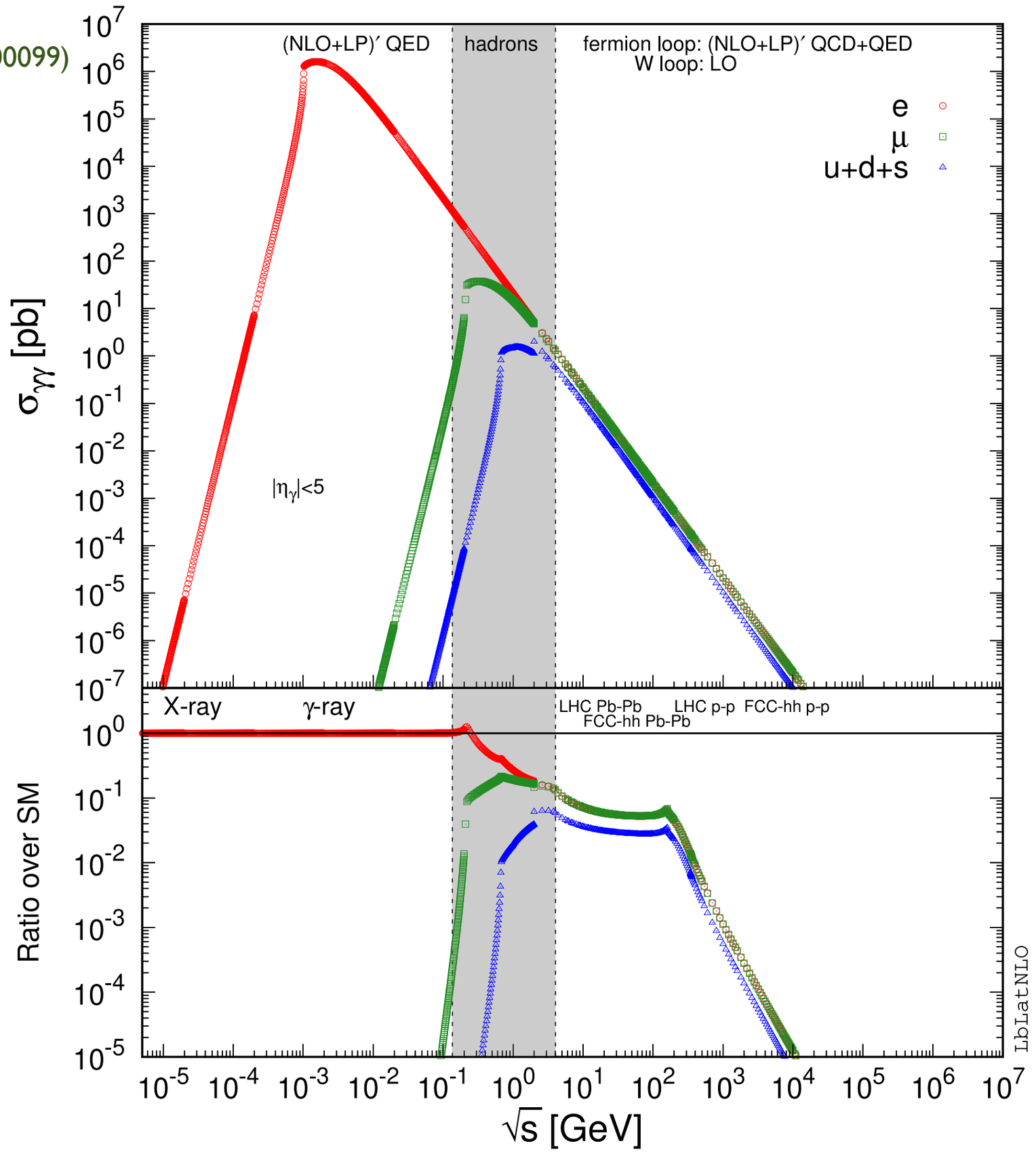

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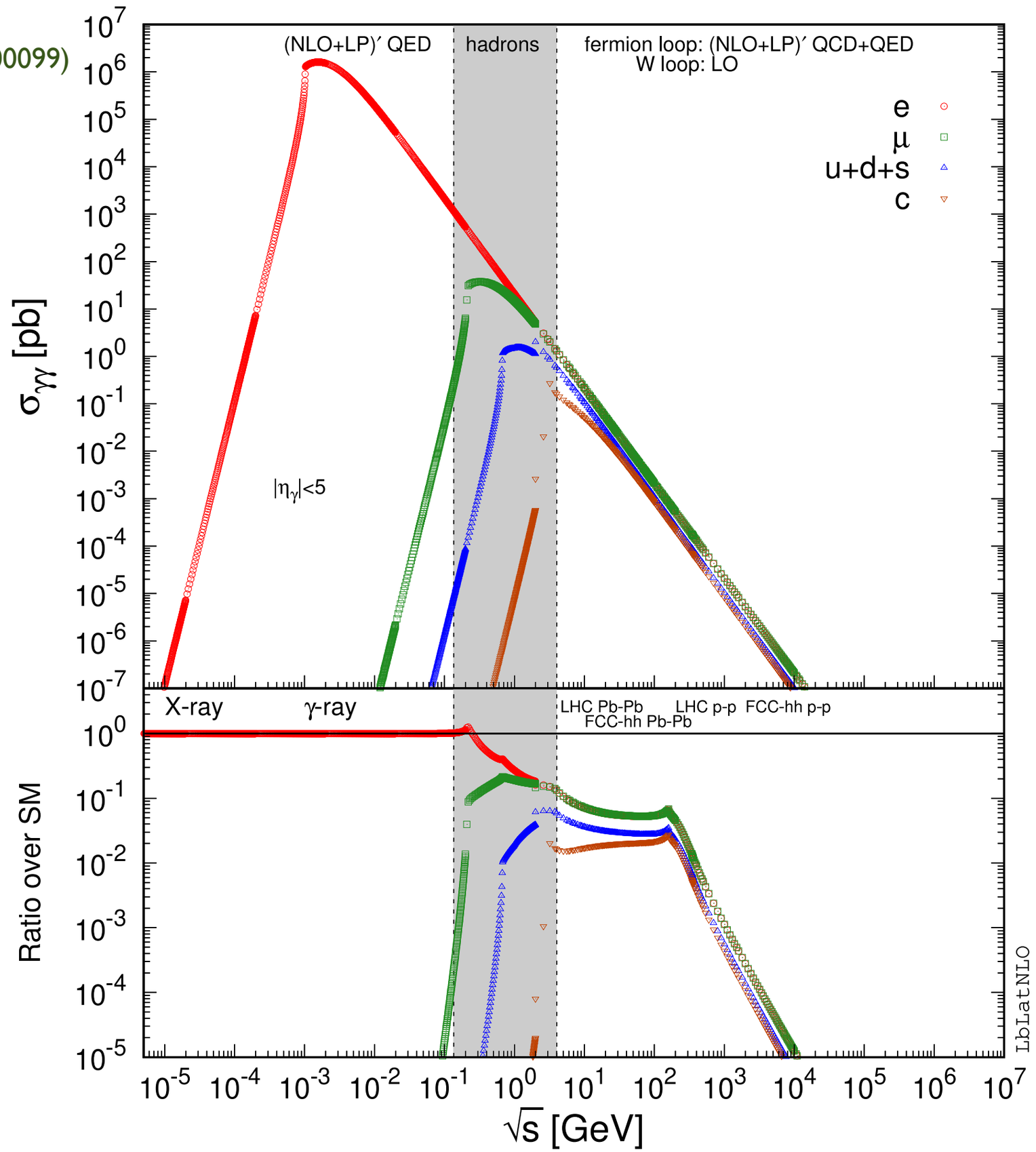

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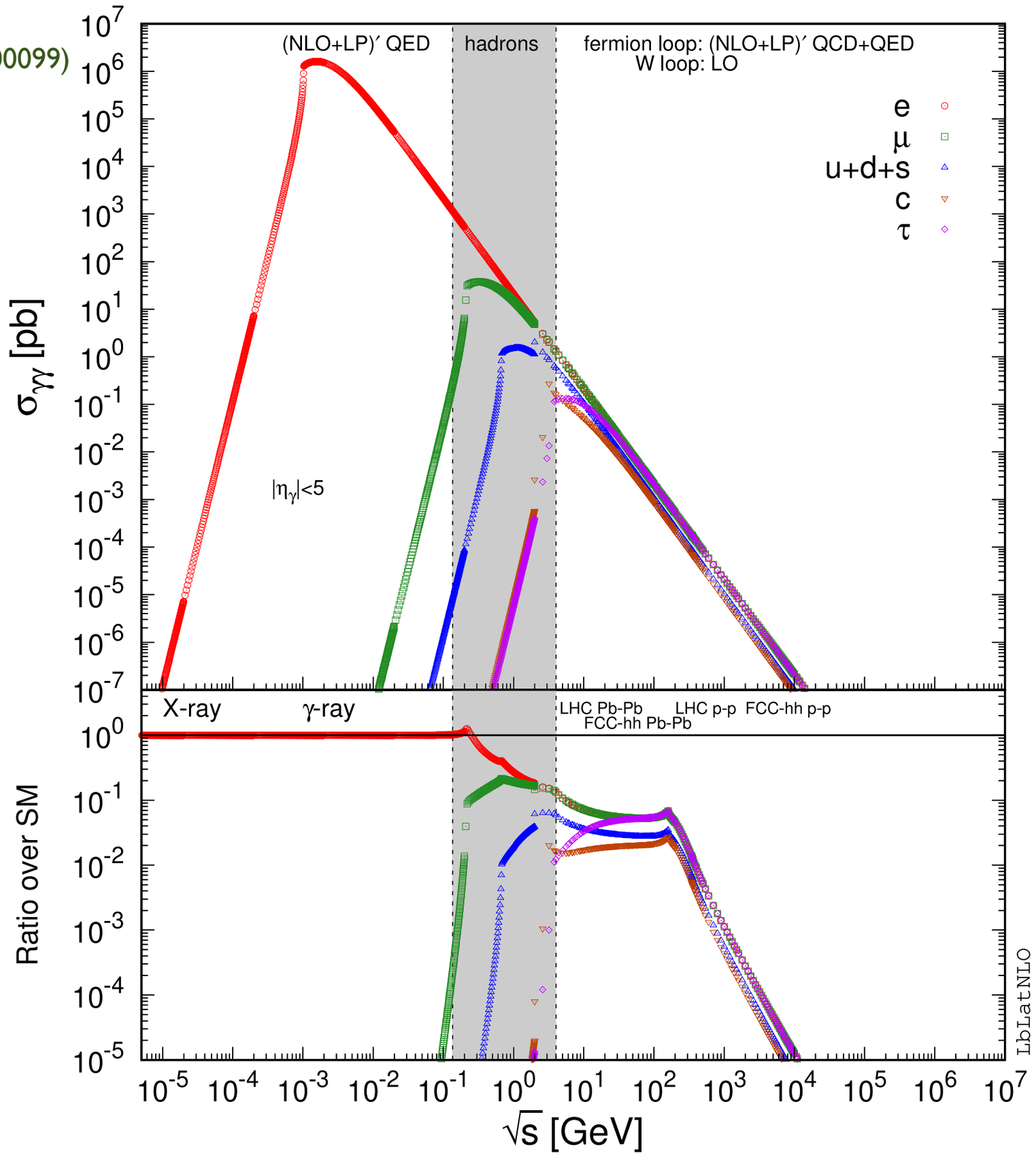

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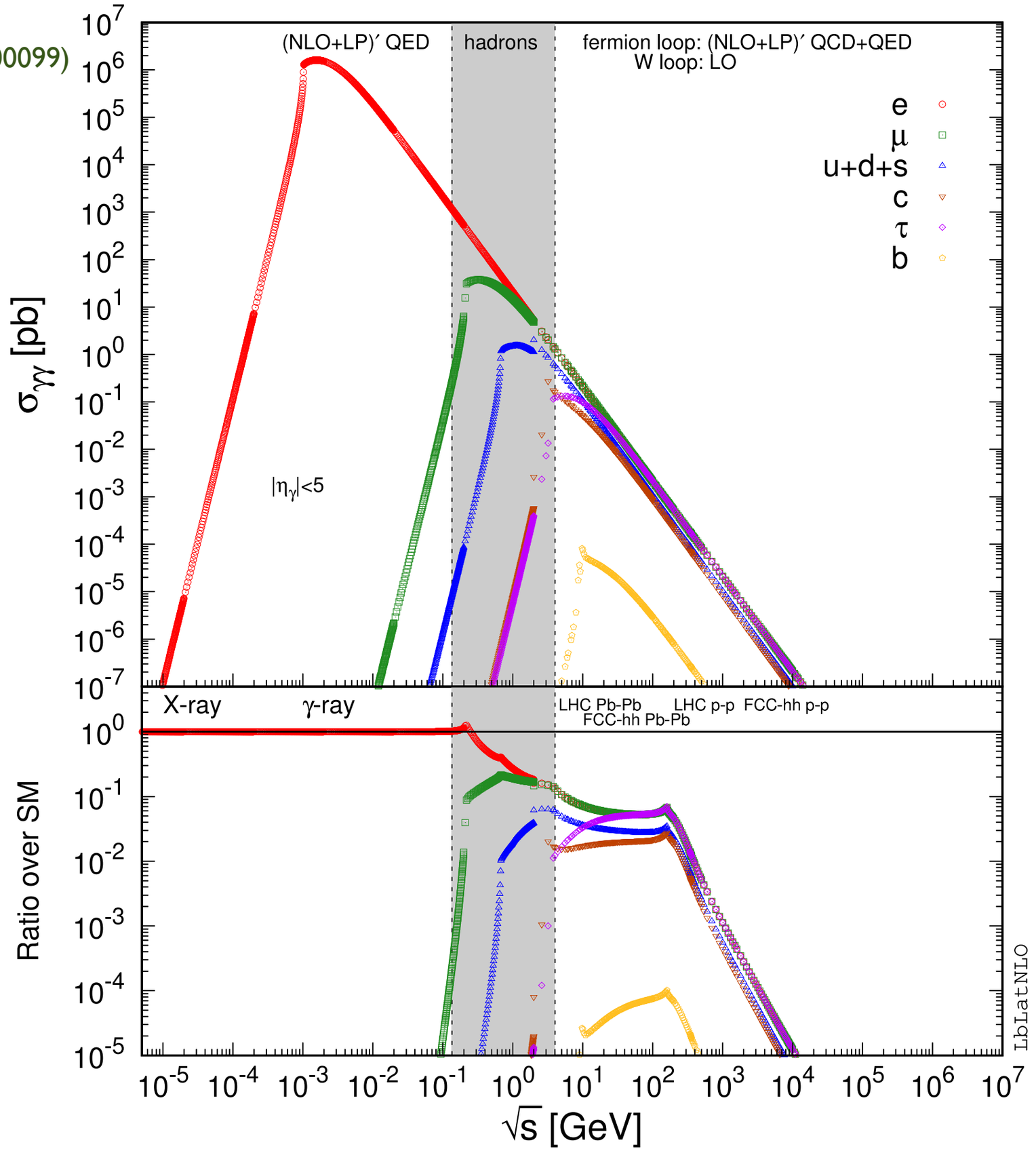

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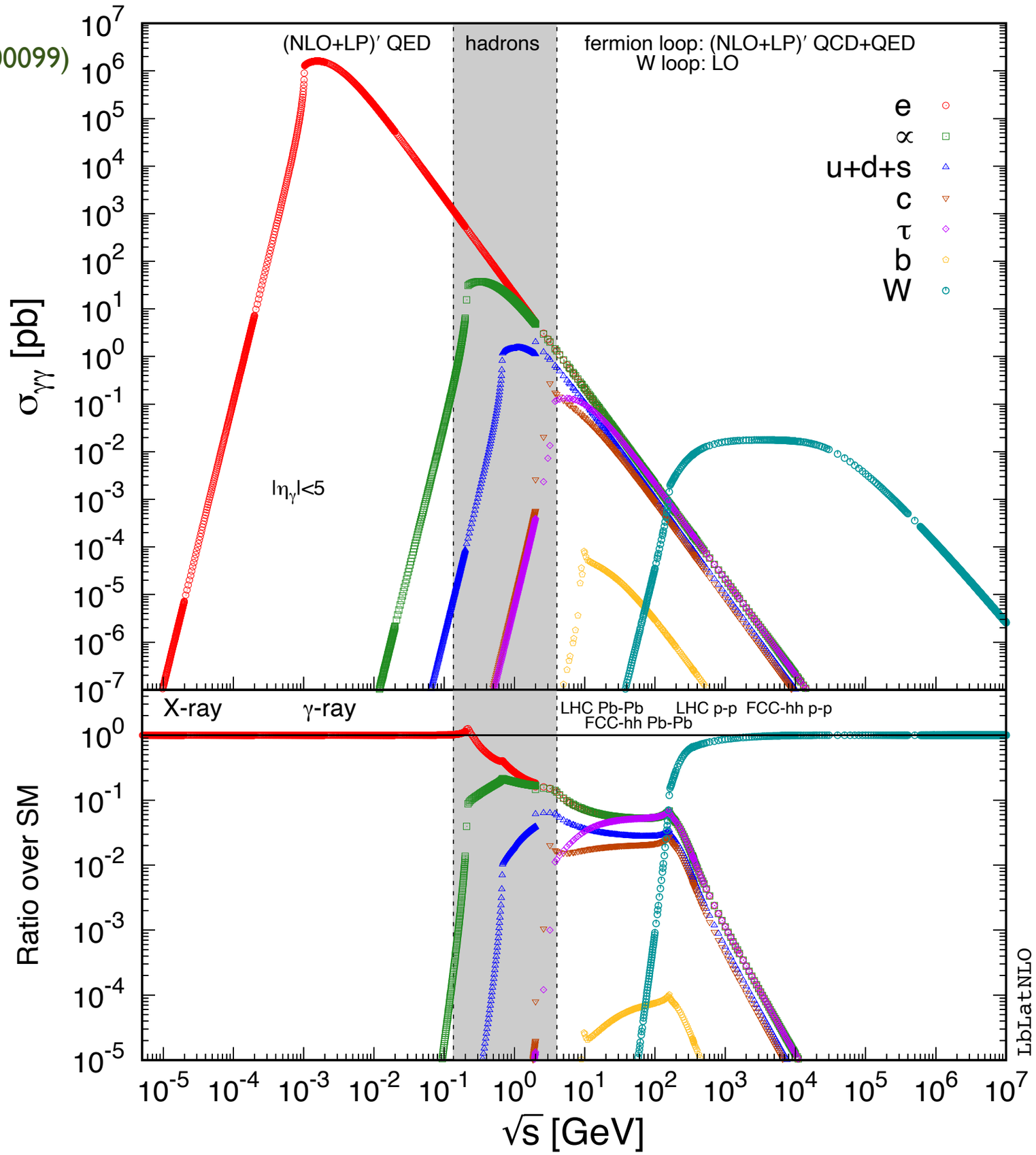

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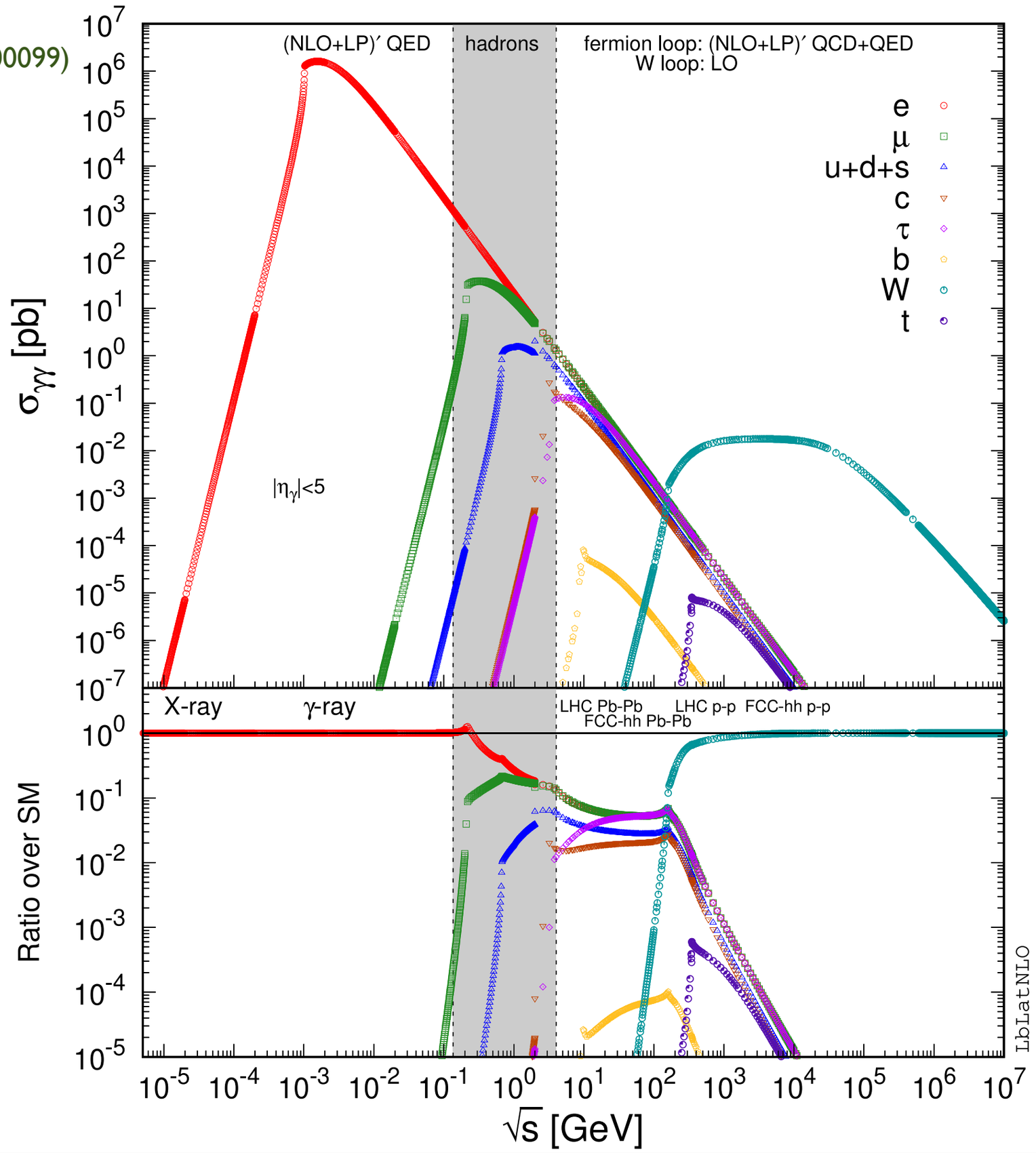

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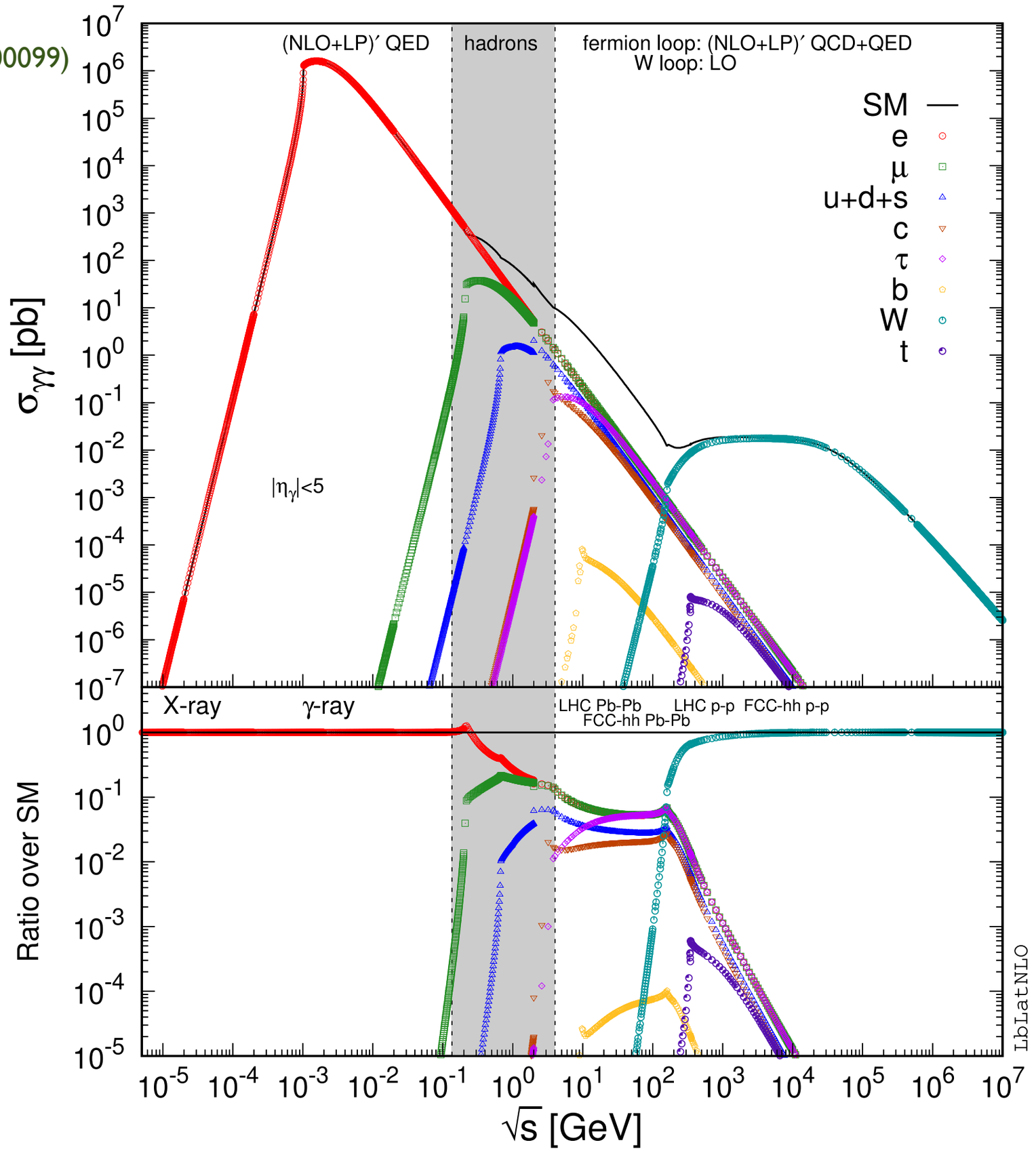
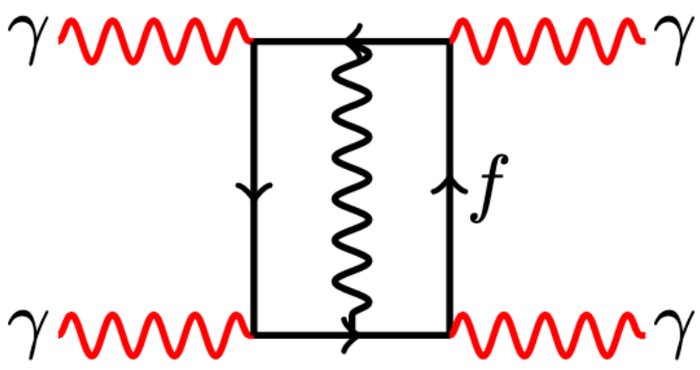


LbL Cross Sections

- **A process with many things to learn/understand**
  - For simplicity, consider a single fermion (top quark) contribution only



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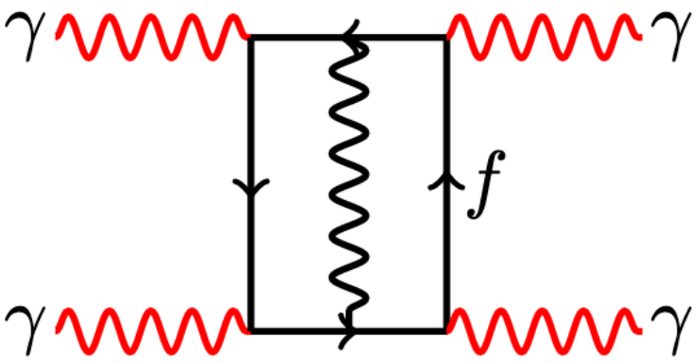

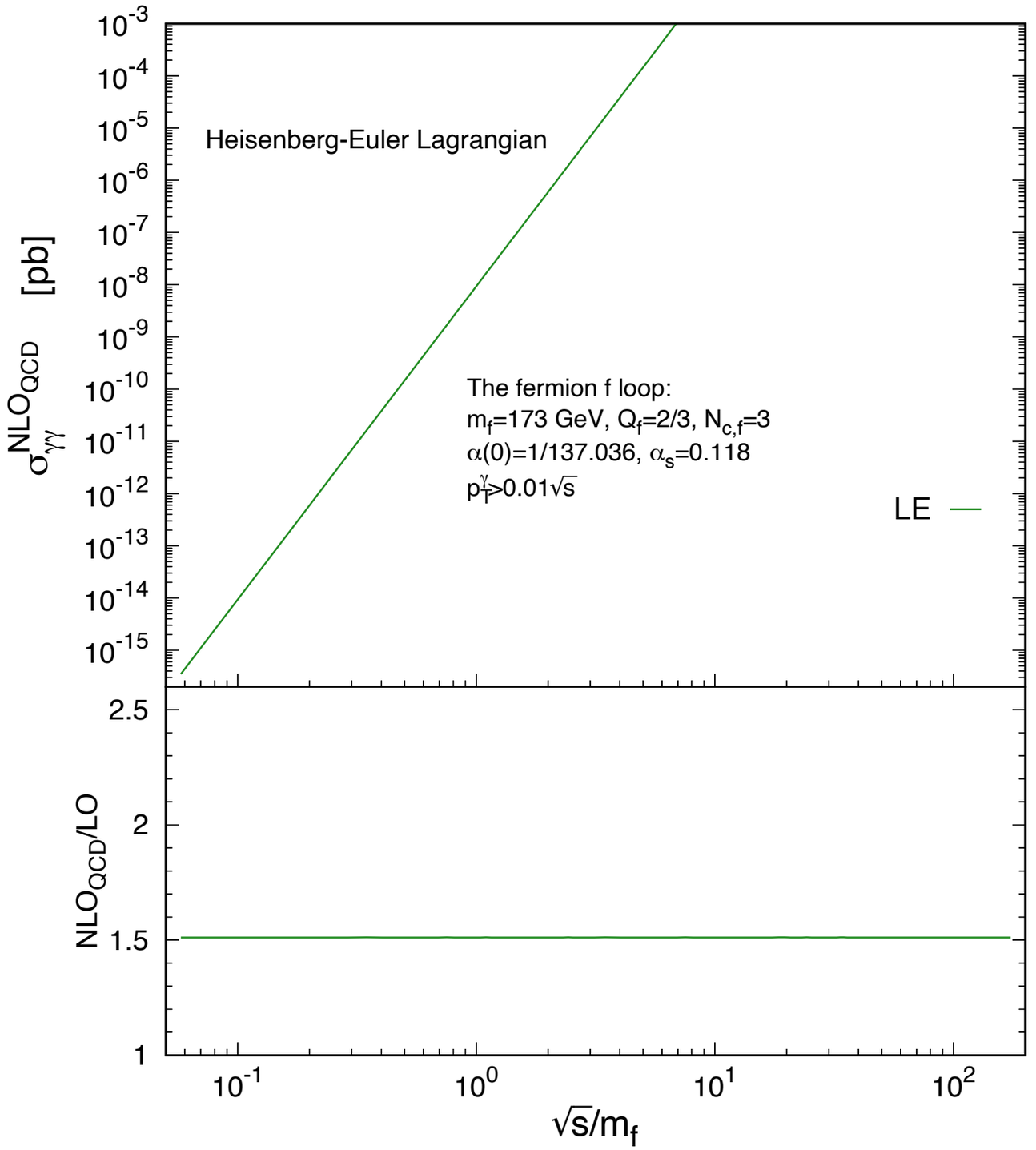

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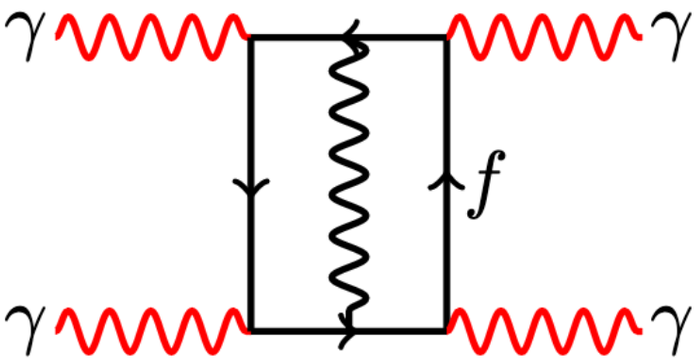

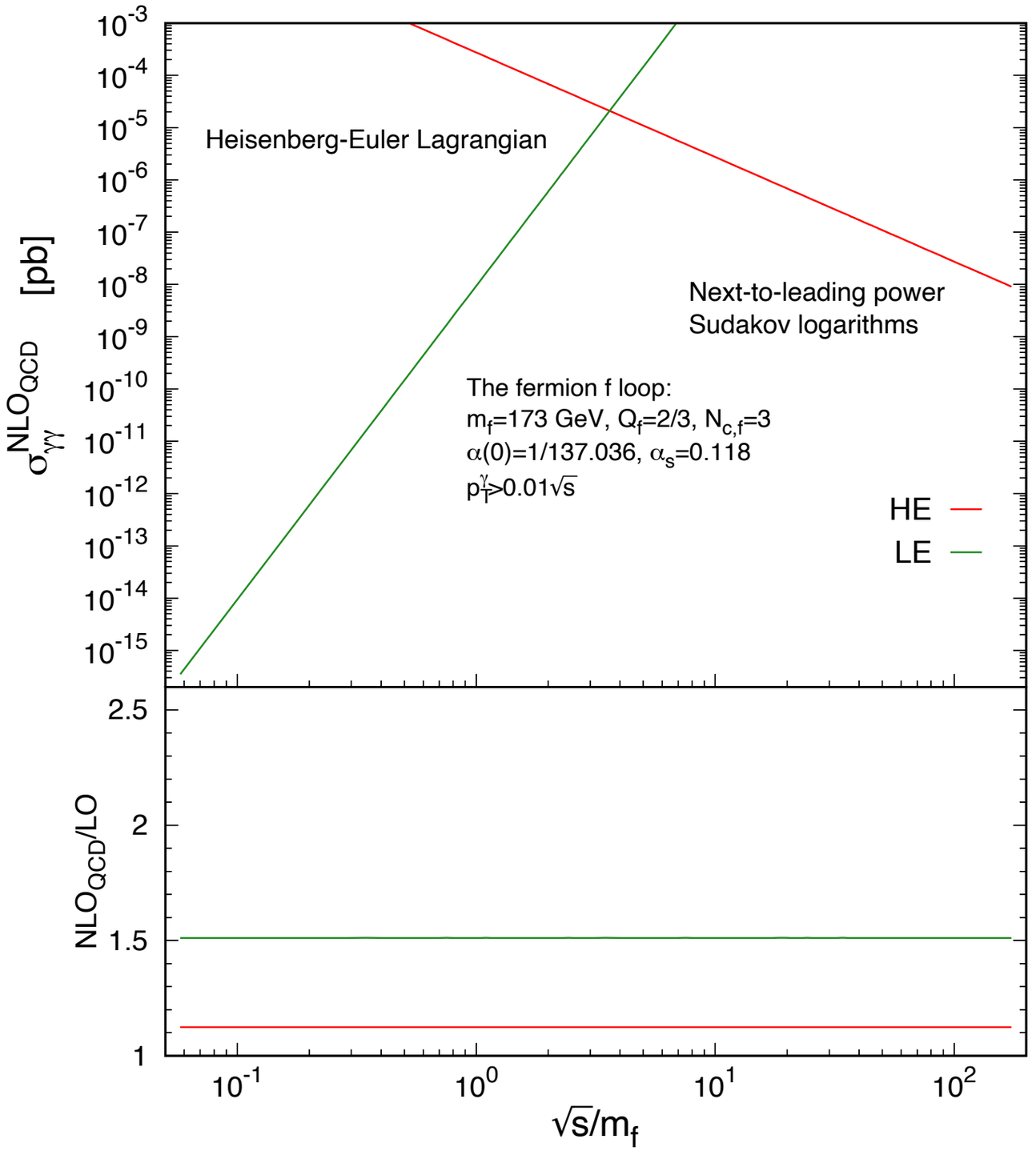

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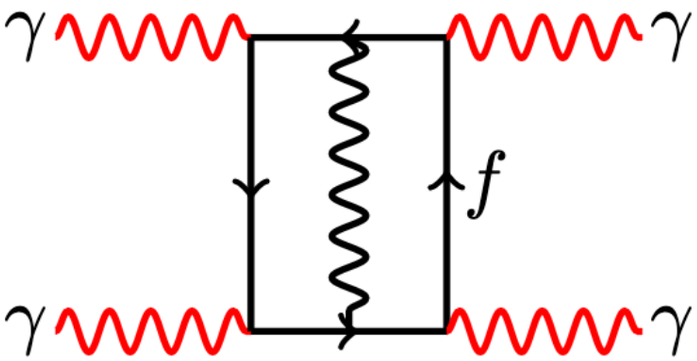

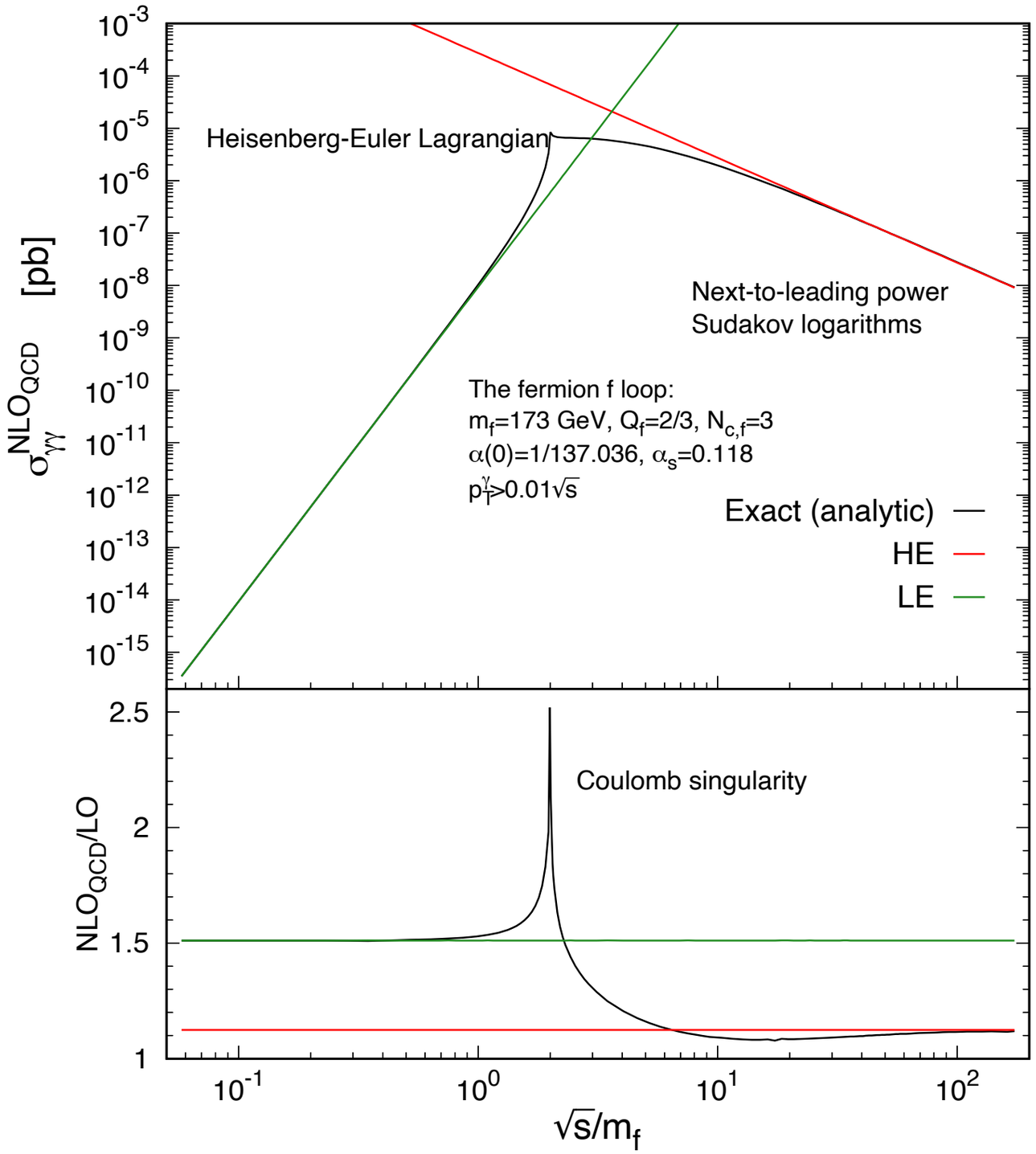

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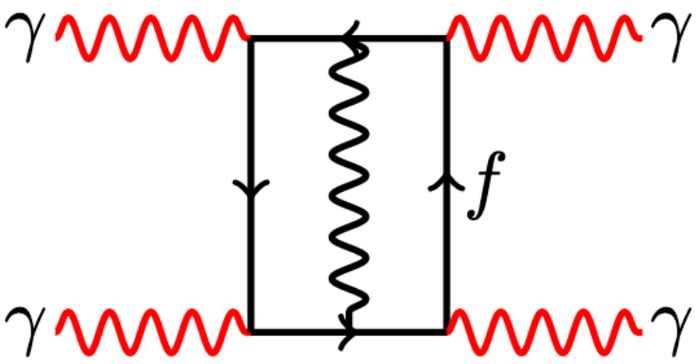
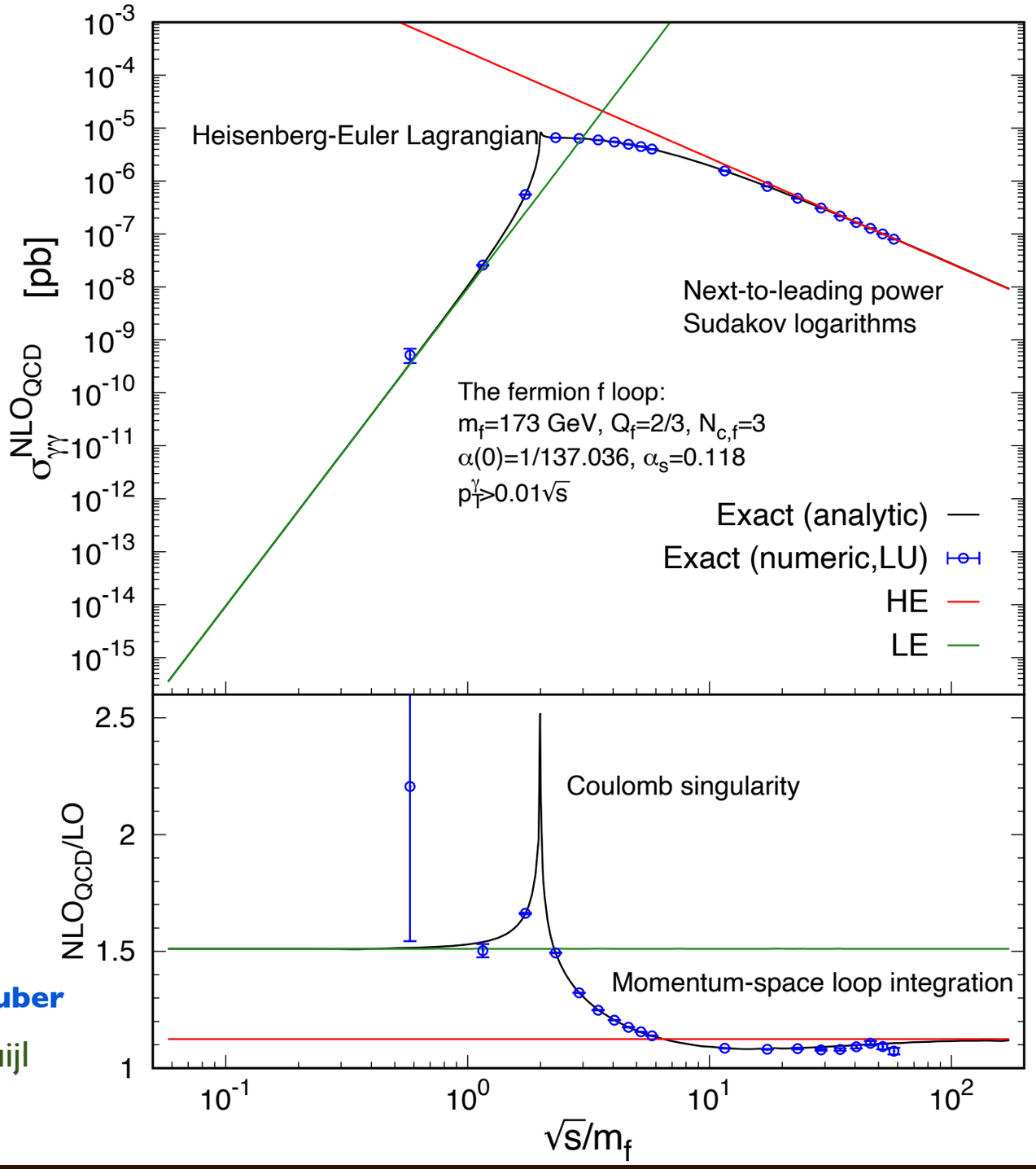




αLoop

Talks by Valentin Hirschi and Lucien Huber

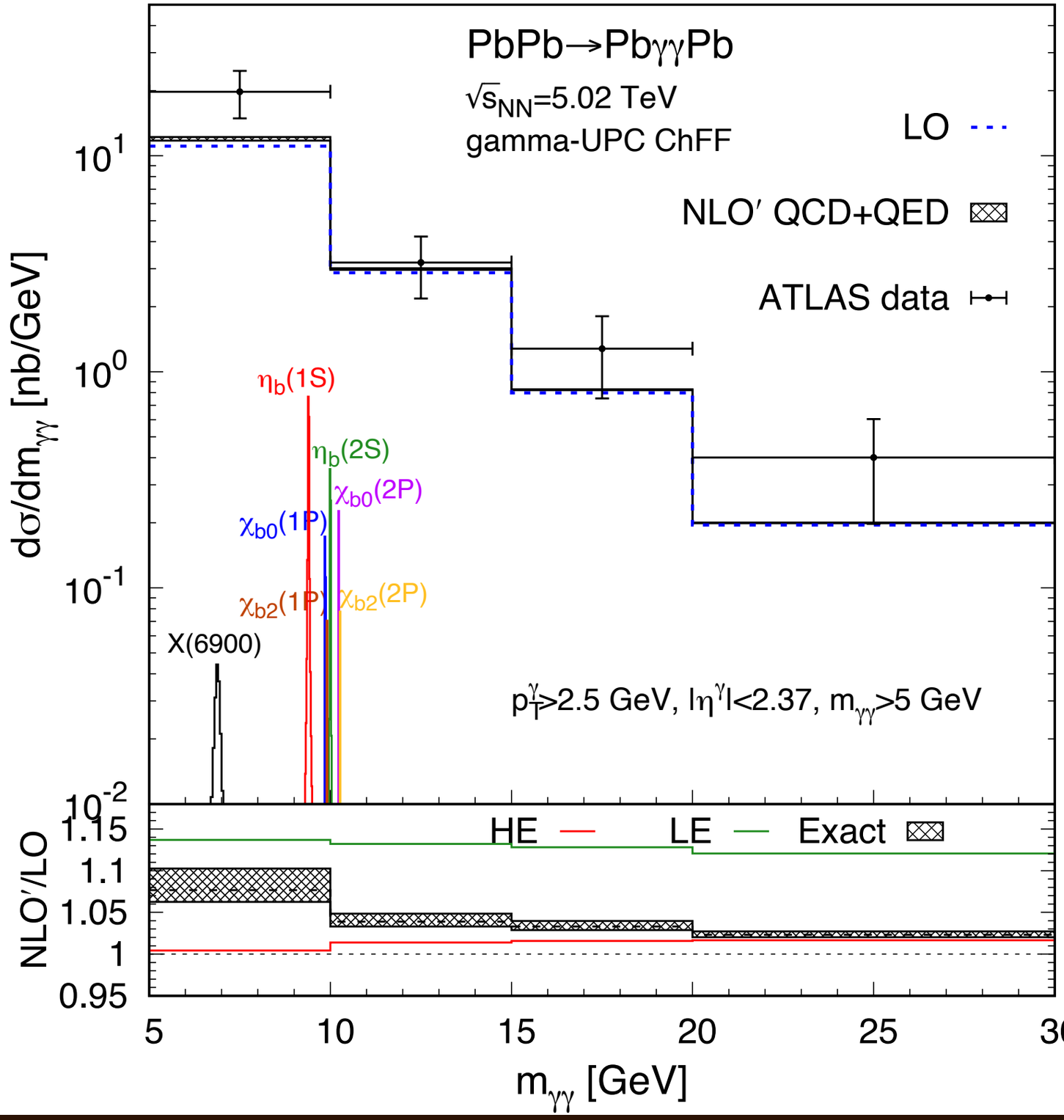
Capatti, Hirschi, Kermanschah, Pelloni, Ruijl

https://github.com/alphal00p/alphaloop/

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

- **Theory-data comparison**

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



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

- 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.) !

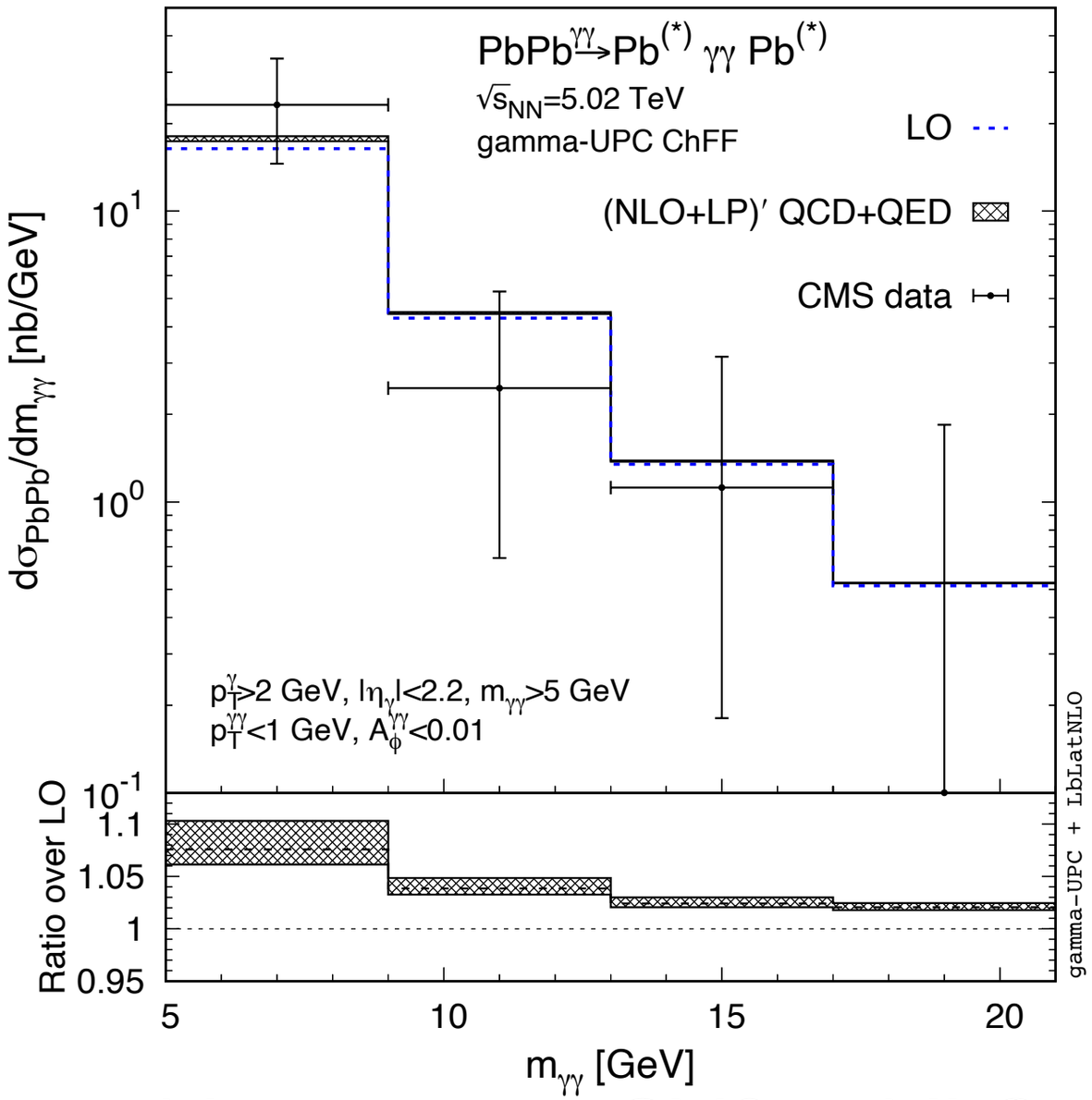
- <2% from massless NNLO

Bargiela, Chakraborty, Gambuti, Ozcelik (2603.22423)

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

- **Theory-data comparison** Ajjath, Chaubey, Fraaije, Hirschi, HSS (PLB'24, 2604.00099)

$$\sigma_{\rm CMS} = 107 \pm 33_{\rm stat} \pm 20_{\rm syst}\ {\rm nb} \quad \text{vs}$$
$$\sigma_{\rm NLO'} = 97.8\,{}^{(+2.0)}_{(-1.0)}{}_{\rm scale}\,{}^{(+1.0)}_{(-1.5)}{}_{\rm param}\ {\rm nb}$$



- No excess in CMS vs NLO

Conclusion

- For two-photon processes in UPC, NLO QCD+EW calculations have been automated in MadGraph5_aMC@NLO (since 3.7.0)
  - Restricted to: SM+elementary particles+elastic/coherent+not loop-induced
  - NLO QCD+PS for processes without jets is automated too

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- Dedicated higher order calculations and public tools available:
  - $\sigma(\gamma\gamma \to Q\bar{Q} + X)$ at NNLO QCD : PHIQUE
  - Event generation at NLO QCD+QED for LbL : LbLatNLO

Conclusion

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- Dedicated higher order calculations and public tools available:
  - $\sigma(\gamma\gamma \to Q\bar{Q} + X)$ at NNLO QCD : PHIQUE
  - Event generation at NLO QCD+QED for LbL : LbLatNLO

Thank you for your attention !