HIGHER ORDER THEORETICAL TOOLS FOR PROCESSES WITH PHOTONS

Leandro Cieri
INFN Milano Bicocca

Workshop on Photon Physics and Simulation at Hadron Colliders
Photon 19
Frascati, Italy

06.06.2019

OUTLINE

- Introduction and motivation: why to go higher?
- The theoretical toolkit
- News from theory
- EW effects and qT resummation
- Higgs boson signal/background interference
- Theoretical uncertainties
- Outlook

INTRODUCTION

- No striking manifestation of New Physics (NP) beyond the Standard Model (SM) at the LHC
- "Precision Physics" represents *the key instrument* to find NP
- In this framework QCD perturbative corrections play a crucial role
- Until a few years ago, the standard for such calculations was next-to-leading order (NLO) accuracy
- In the past recent years a number of growing next-to-next-to-leading order (NNLO) results were computed

INTRODUCTION

- No striking manifestation of New Physics (NP) beyond the Standard Model (SM) at the LHC

David Marzocca's Talk

- "Precision Physics" represents *the key instrument* to find NP
- In this framework QCD perturbative corrections play a crucial role
- Until a few years ago, the standard for such calculations was next-to-leading order (NLO) accuracy
- In the past recent years a number of growing next-to-next-to-leading order (NNLO) results were computed

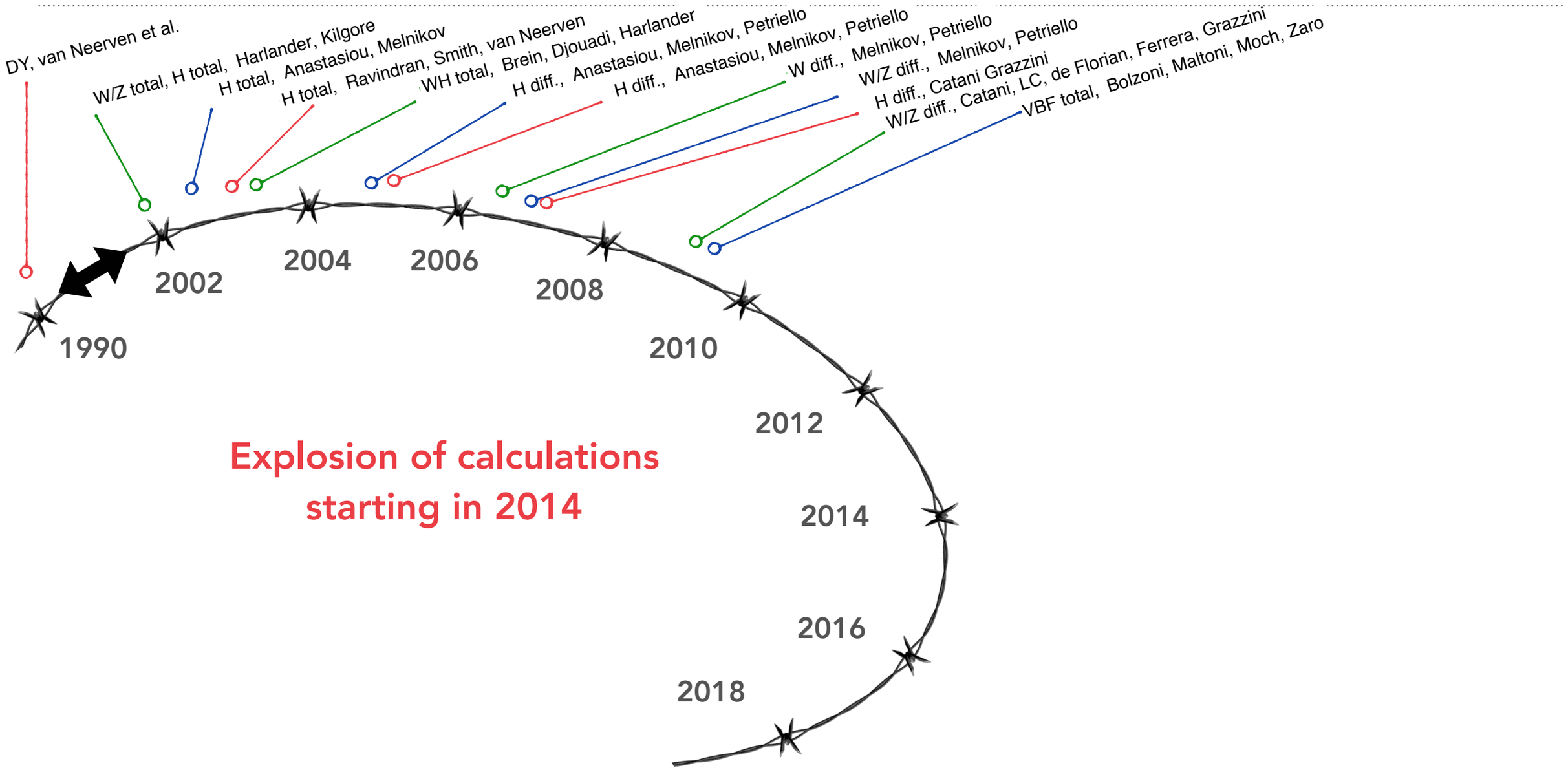
INTRODUCTION

- No striking manifestation of New Physics (NP) beyond the Standard Model (SM) at the LHC
- "Precision Physics" represents *the key instrument* to find NP
- In this framework QCD perturbative corrections play a crucial role
- Until a few years ago, the standard for such calculations was next-to-leading order (NLO) accuracy
- In the past recent years a number of growing next-to-next-to-leading order (NNLO) results were computed

"The NNLO revolution"

THE NNLO STANDARD

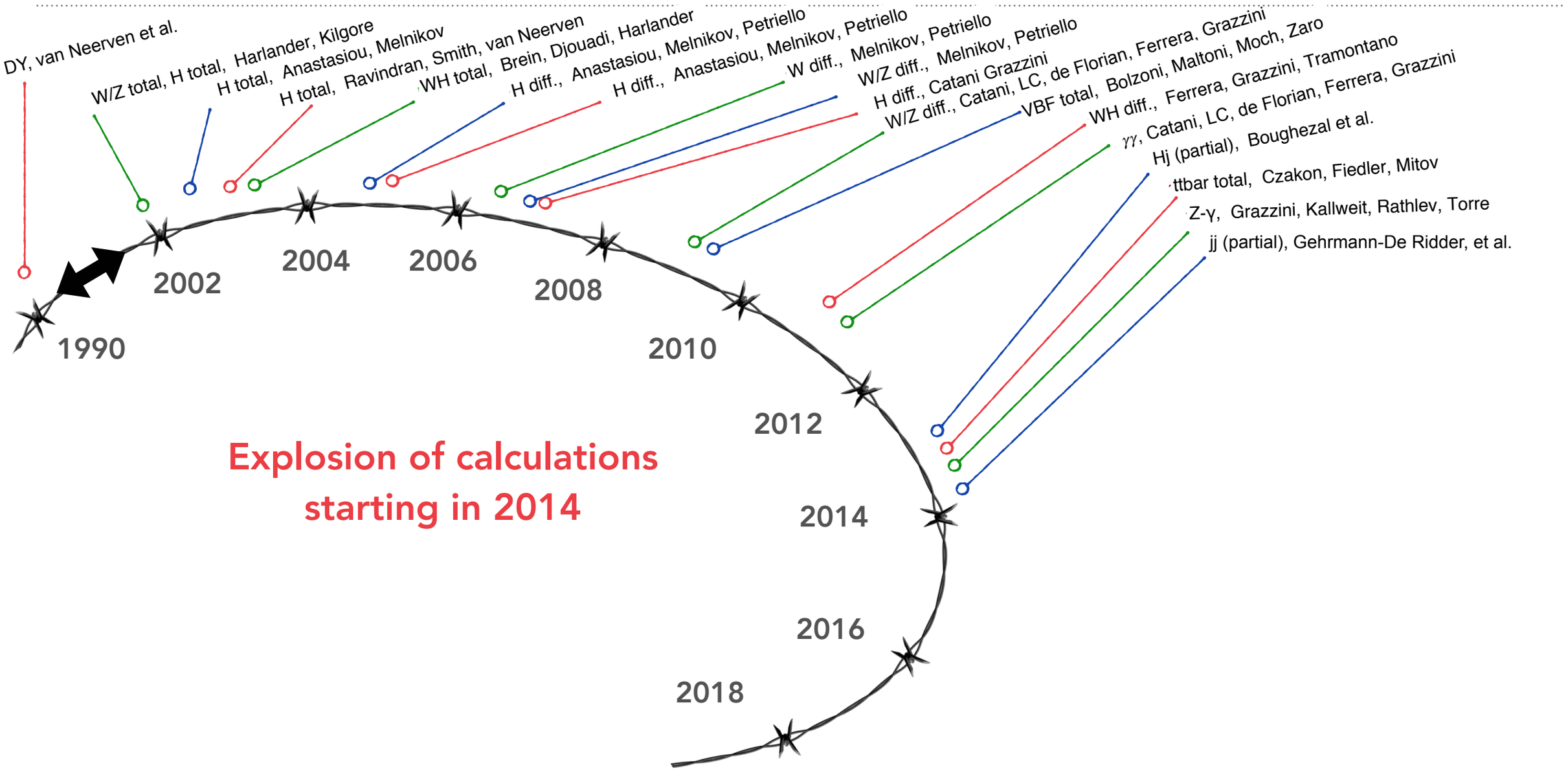
NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



Explosion of calculations starting in 2014

THE NNLO STANDARD

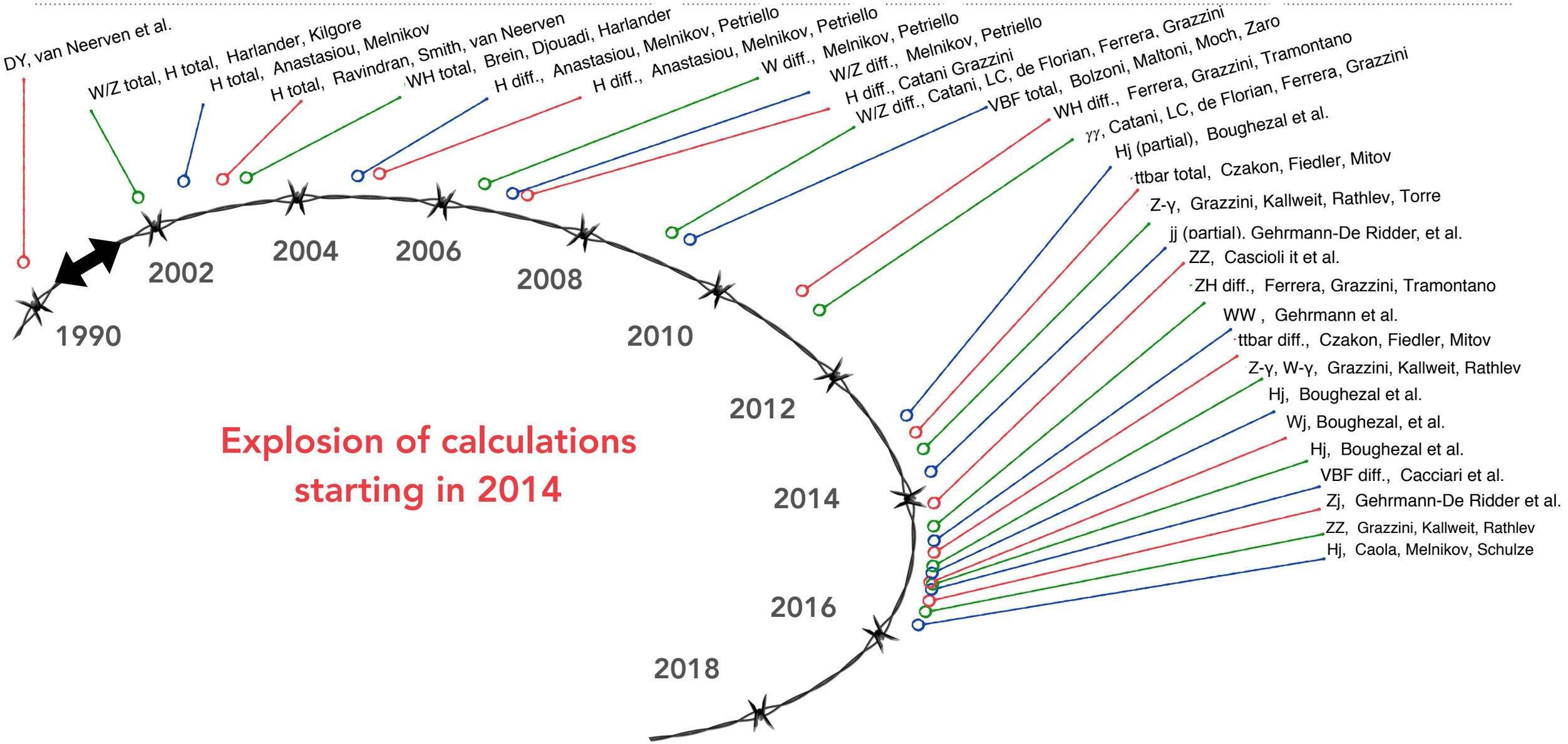
NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



Explosion of calculations starting in 2014

THE NNLO STANDARD

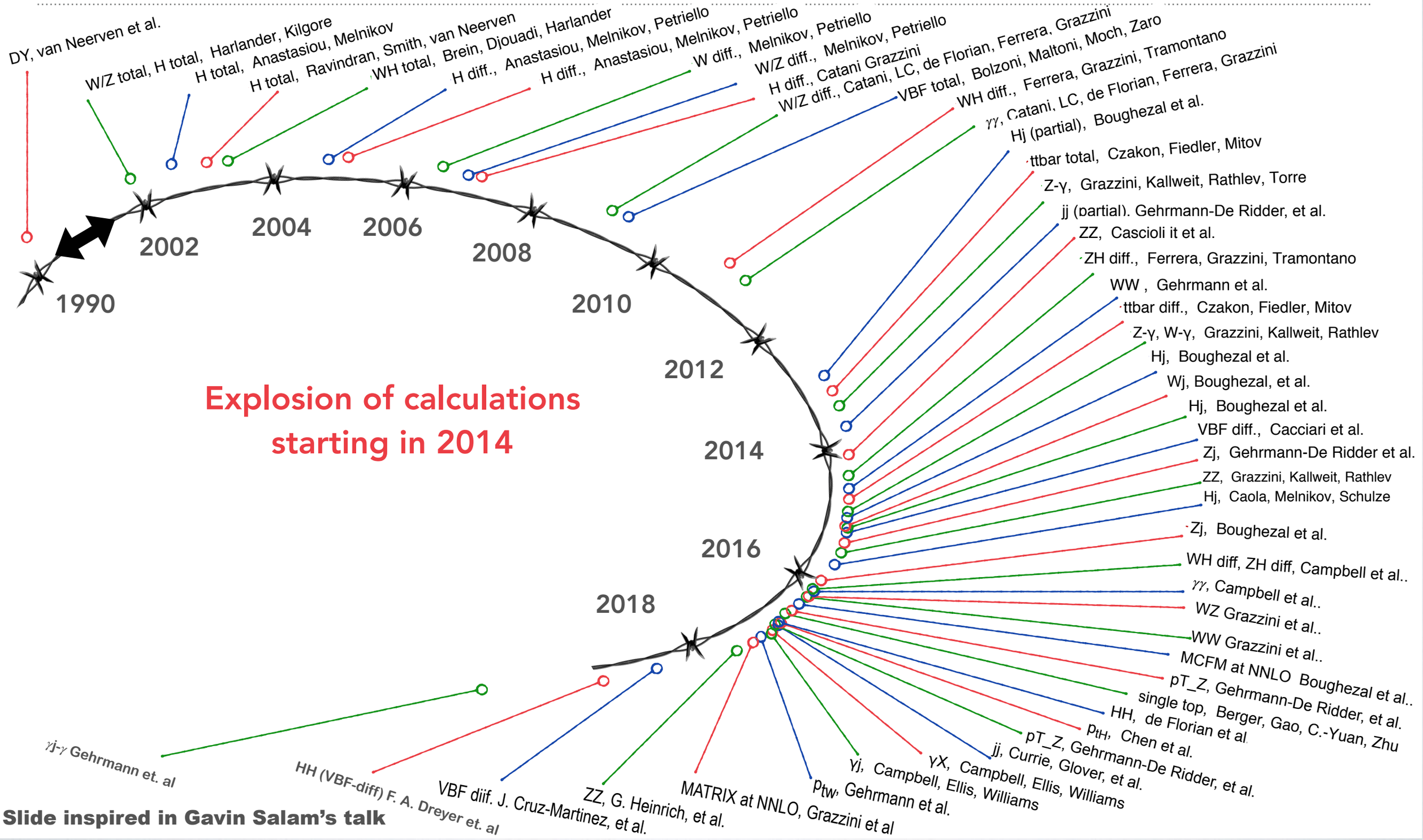
NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



Explosion of calculations starting in 2014

THE NNLO STANDARD

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME

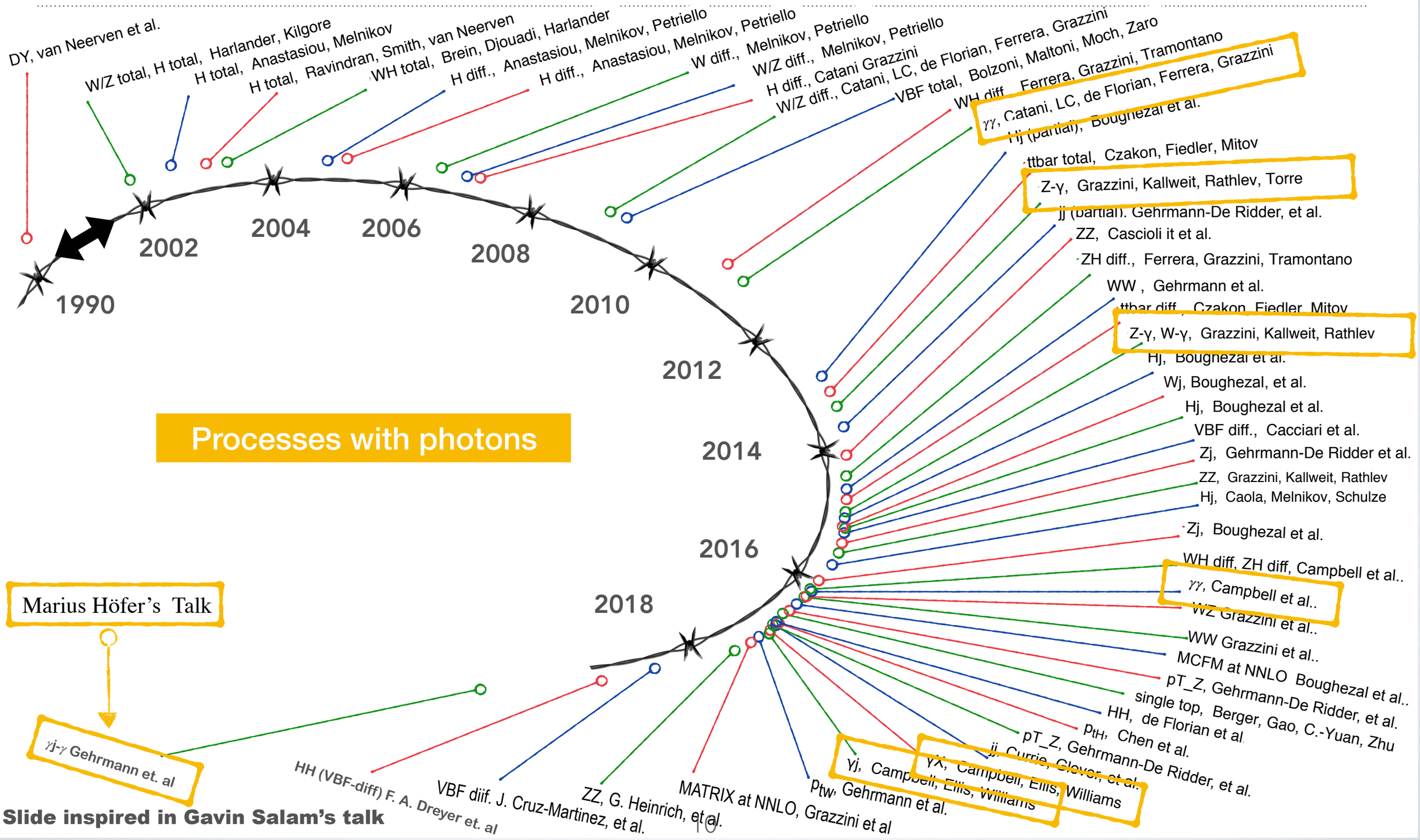


Explosion of calculations starting in 2014

Slide inspired in Gavin Salam's talk

THE NNLO STANDARD

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



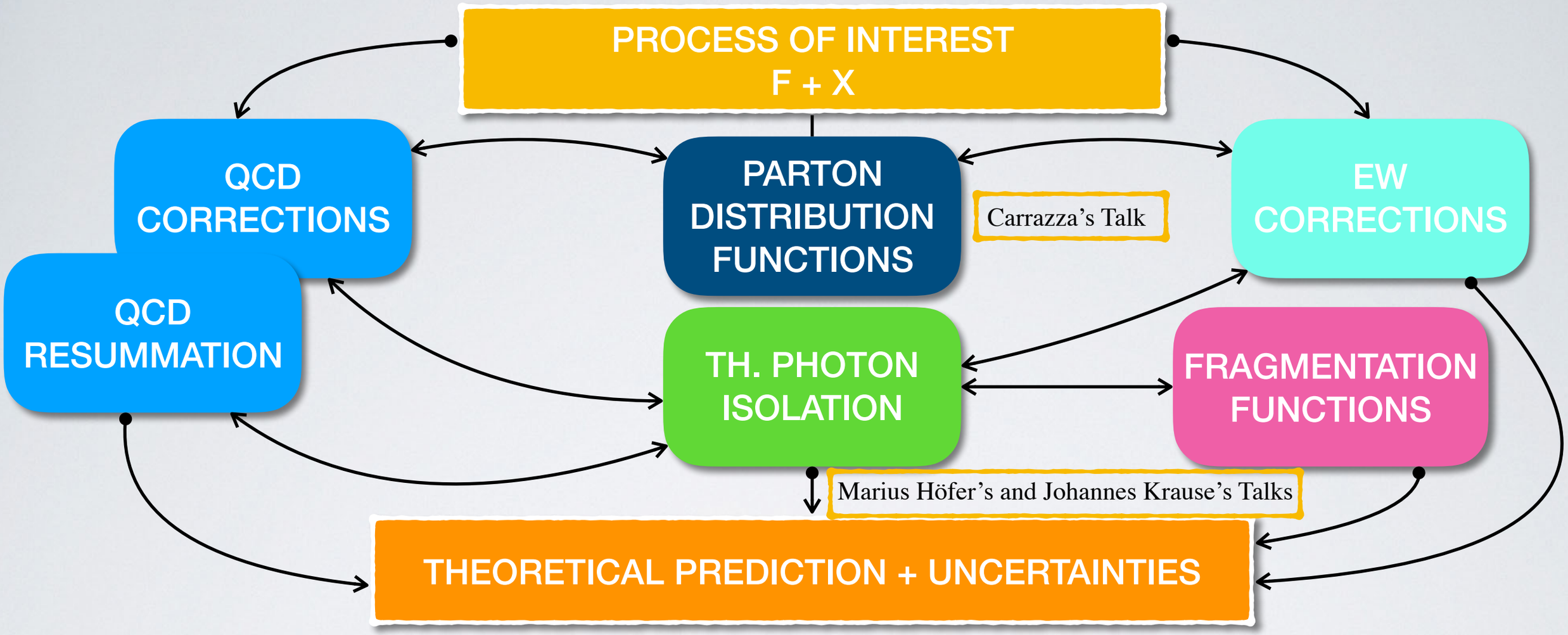
Slide inspired in Gavin Salam's talk

FIXED ORDER CALCULATIONS TOOLKIT

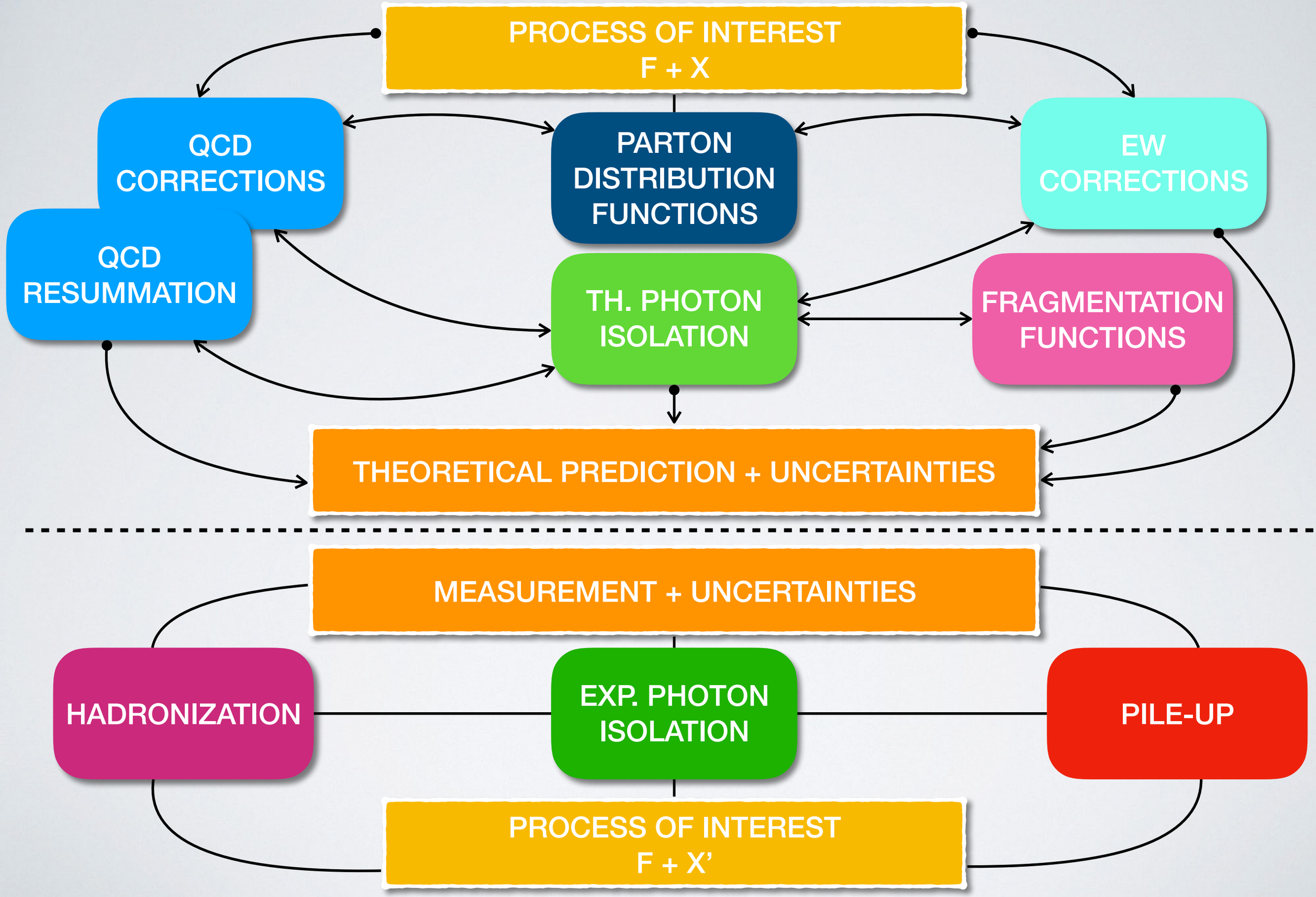
FIXED ORDER TOOLS + RESUMMATION (I.E NOT PARTON SHOWER GENERATORS)

Frank Siegert's Talk

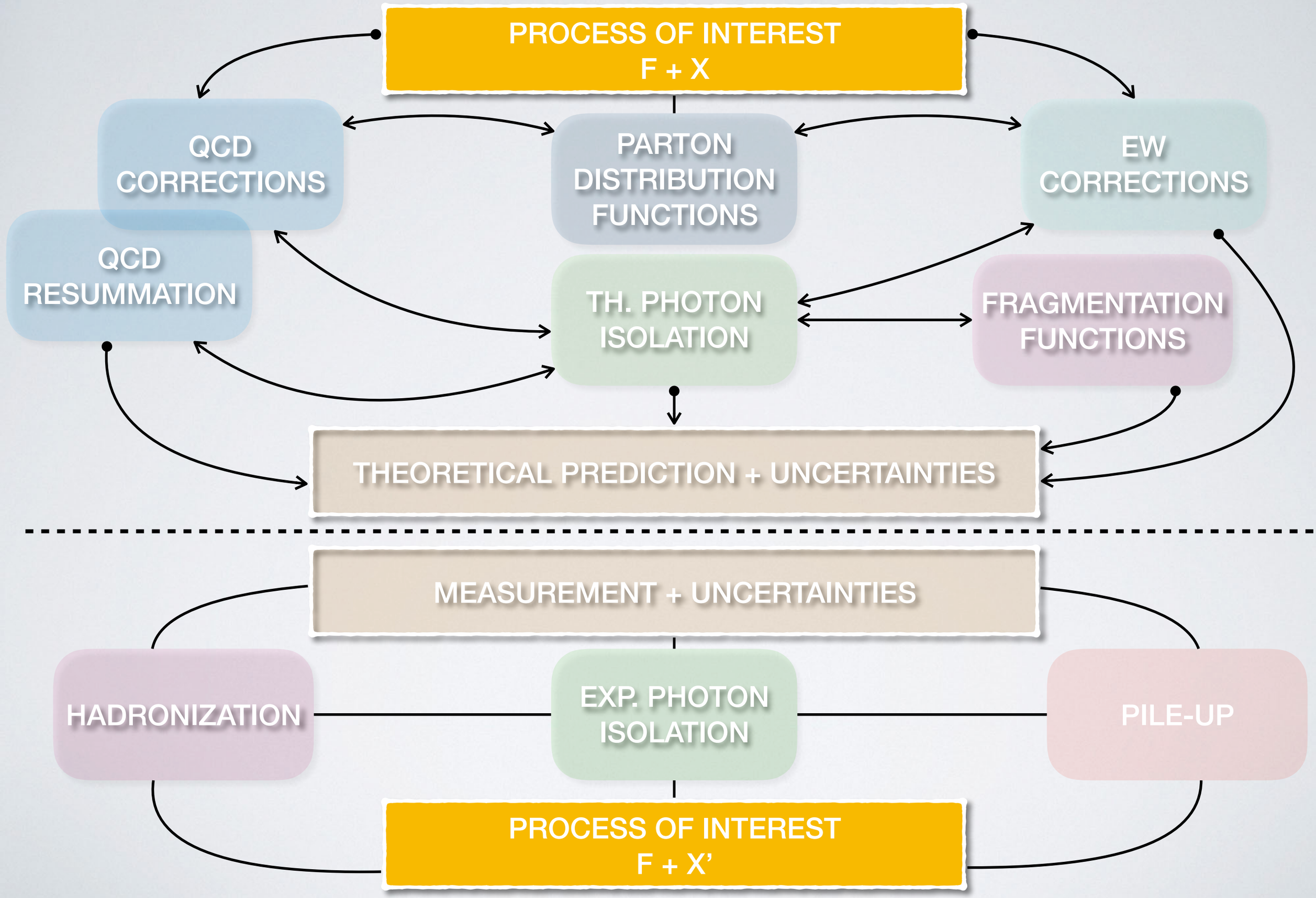
FIXED ORDER CALCULATIONS TOOLKIT



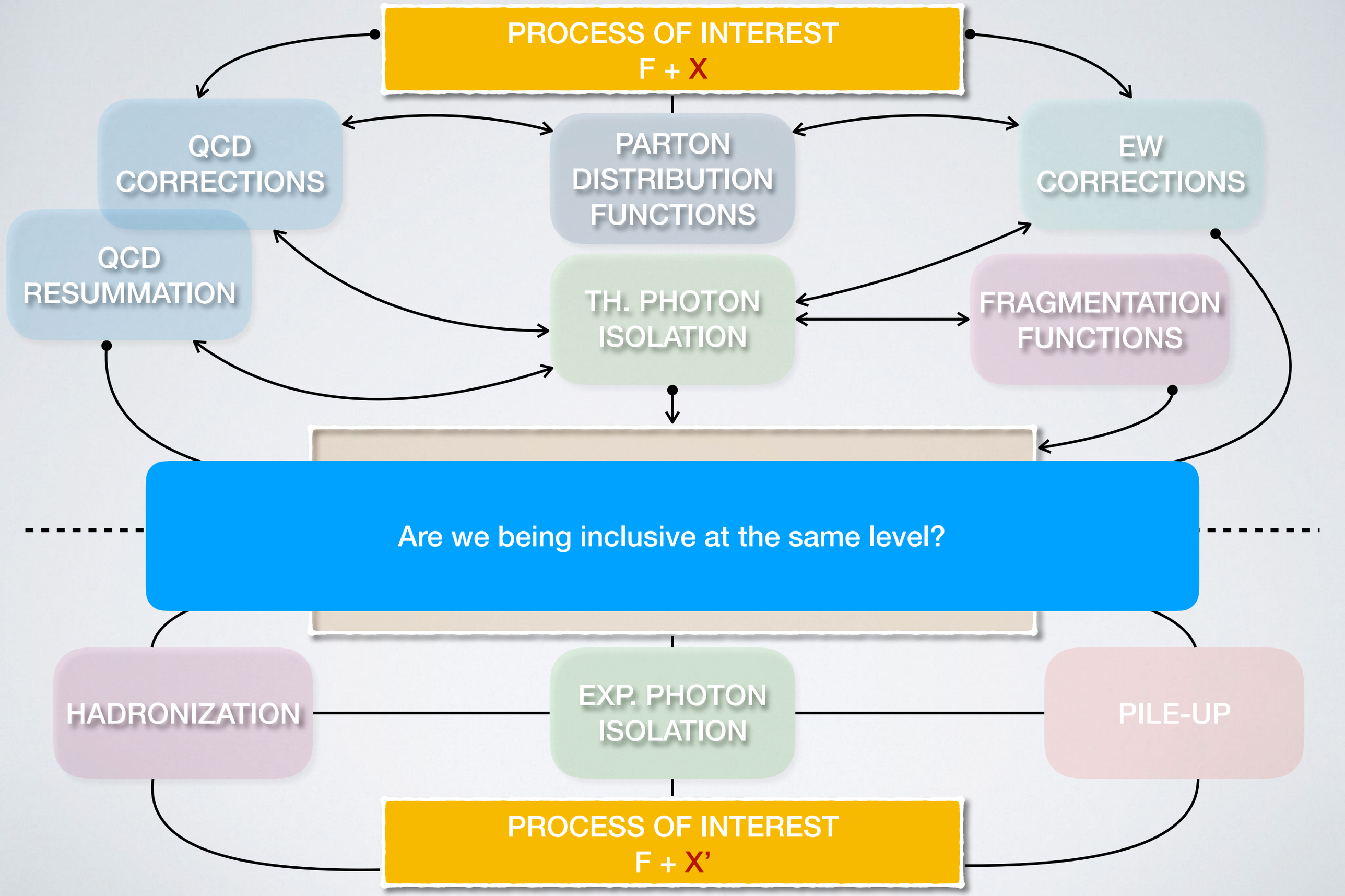
FIXED ORDER CALCULATIONS TOOLKIT



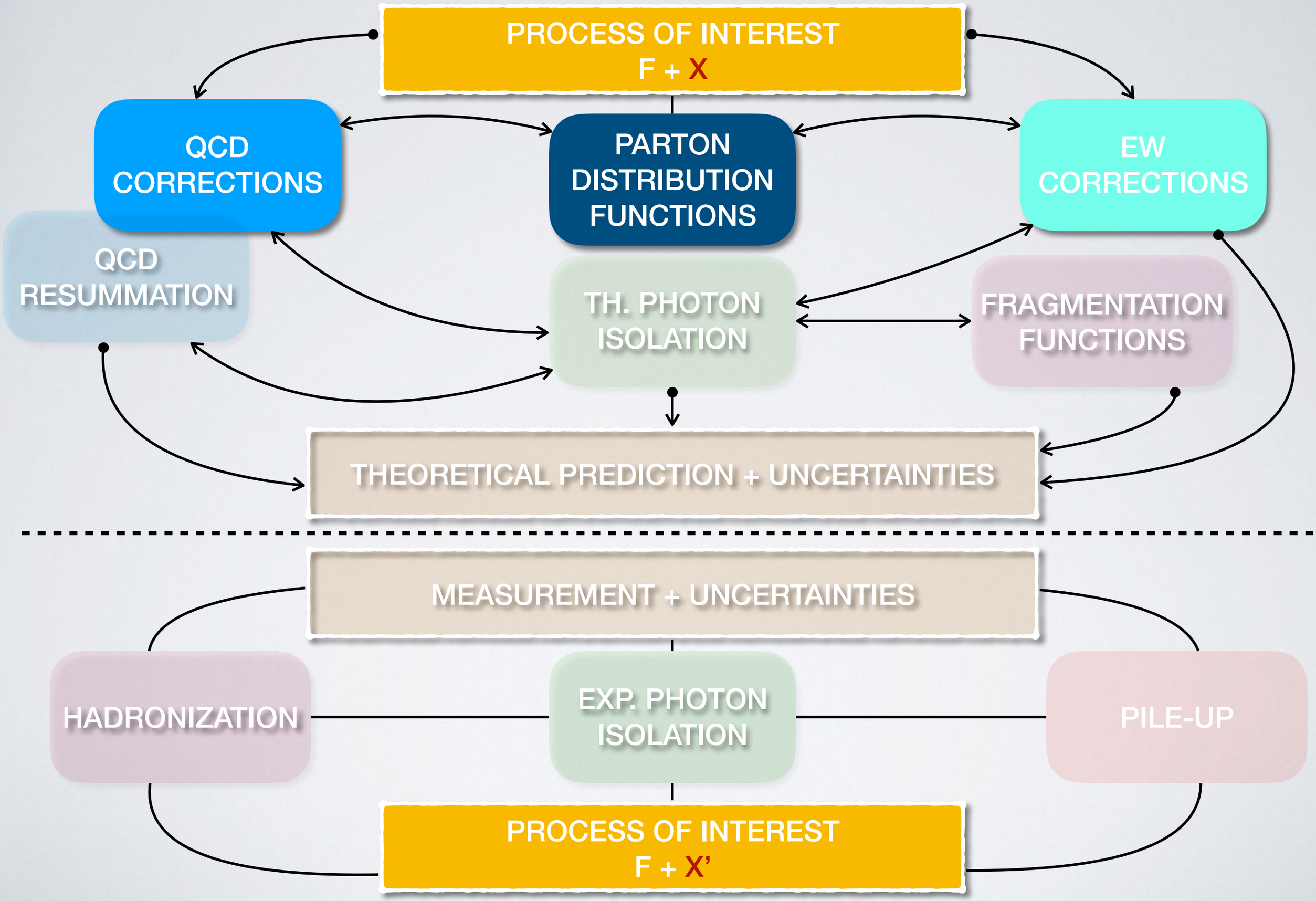
FIXED ORDER CALCULATIONS TOOLKIT



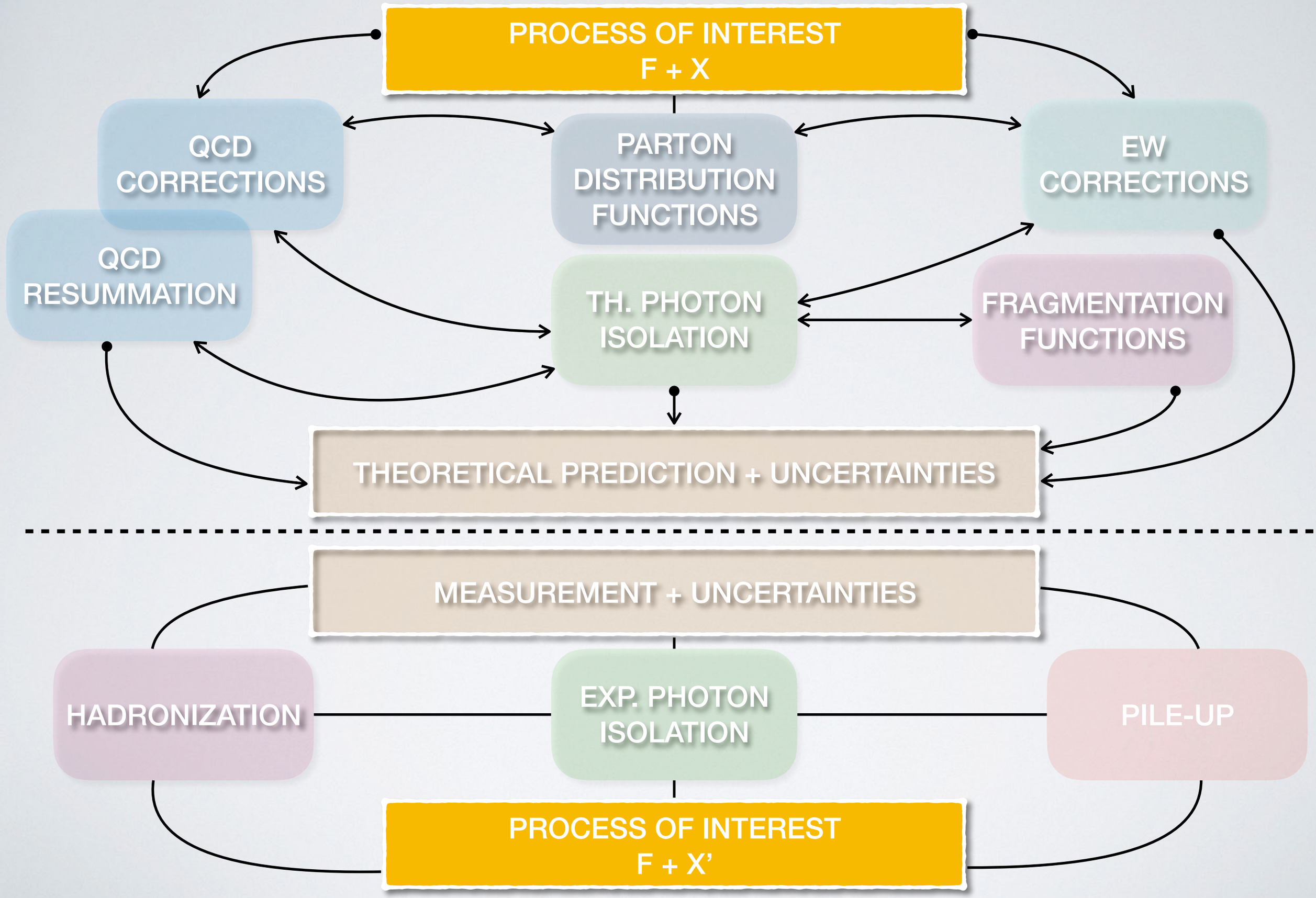
FIXED ORDER CALCULATIONS TOOLKIT



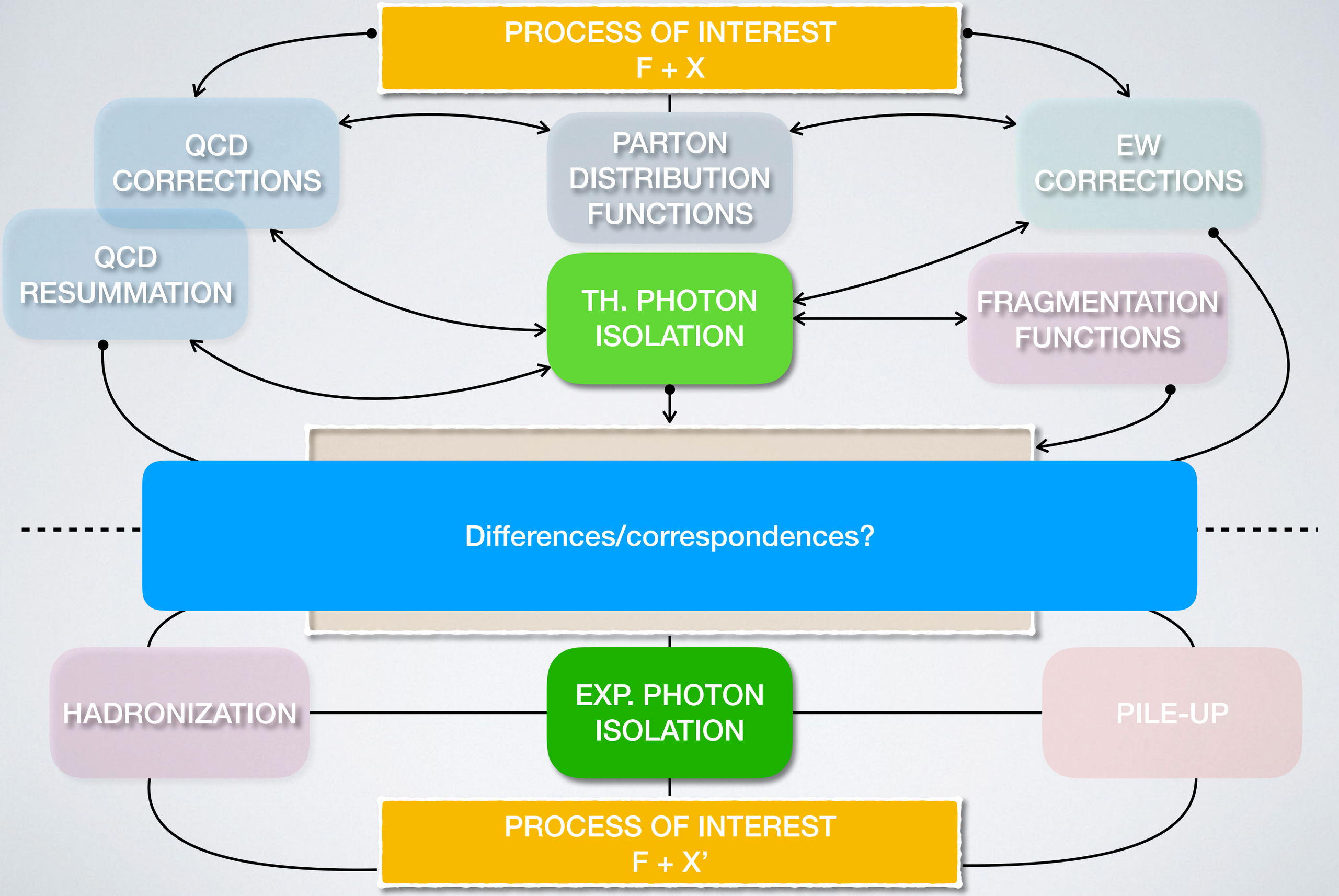
FIXED ORDER CALCULATIONS TOOLKIT



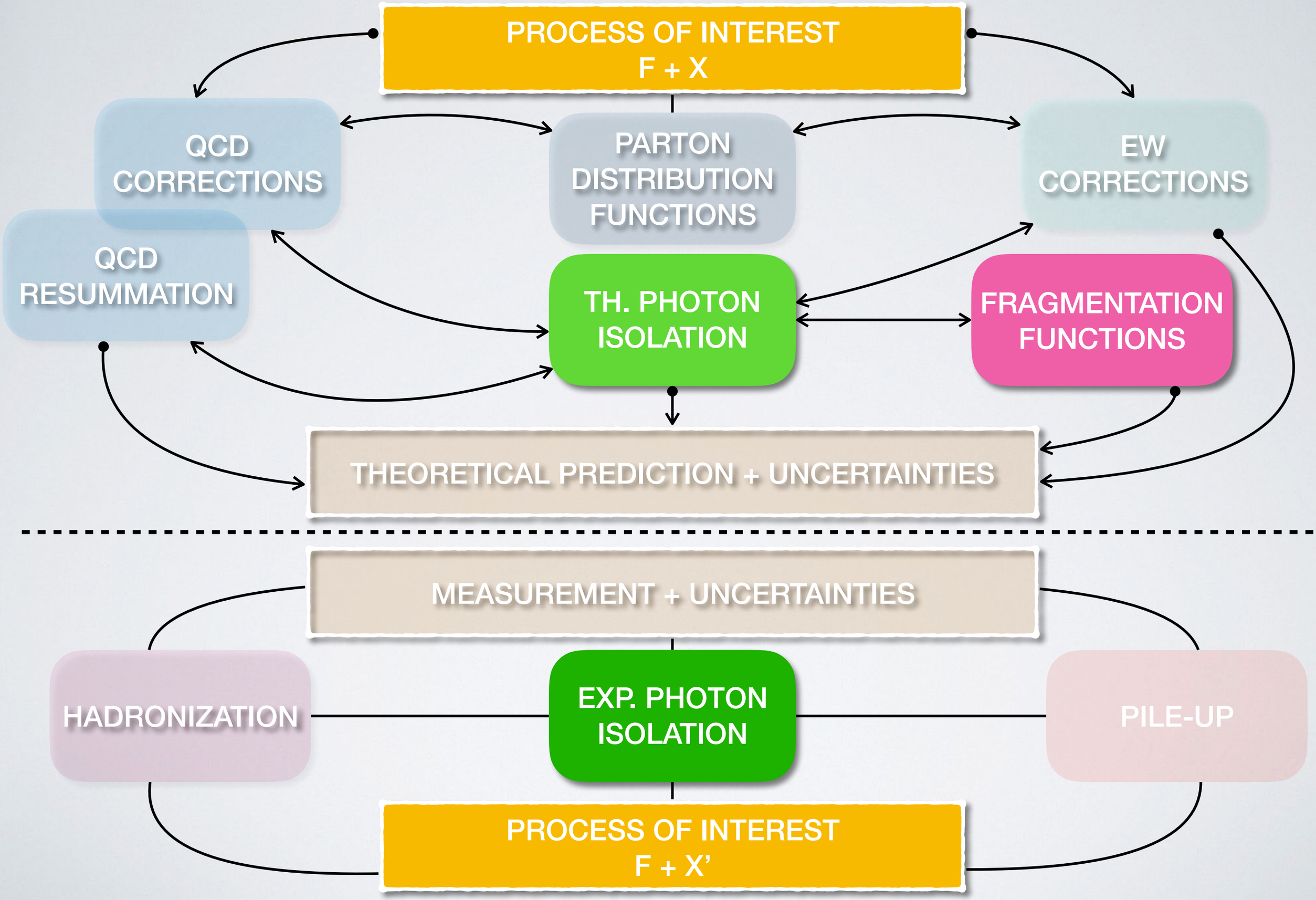
FIXED ORDER CALCULATIONS TOOLKIT



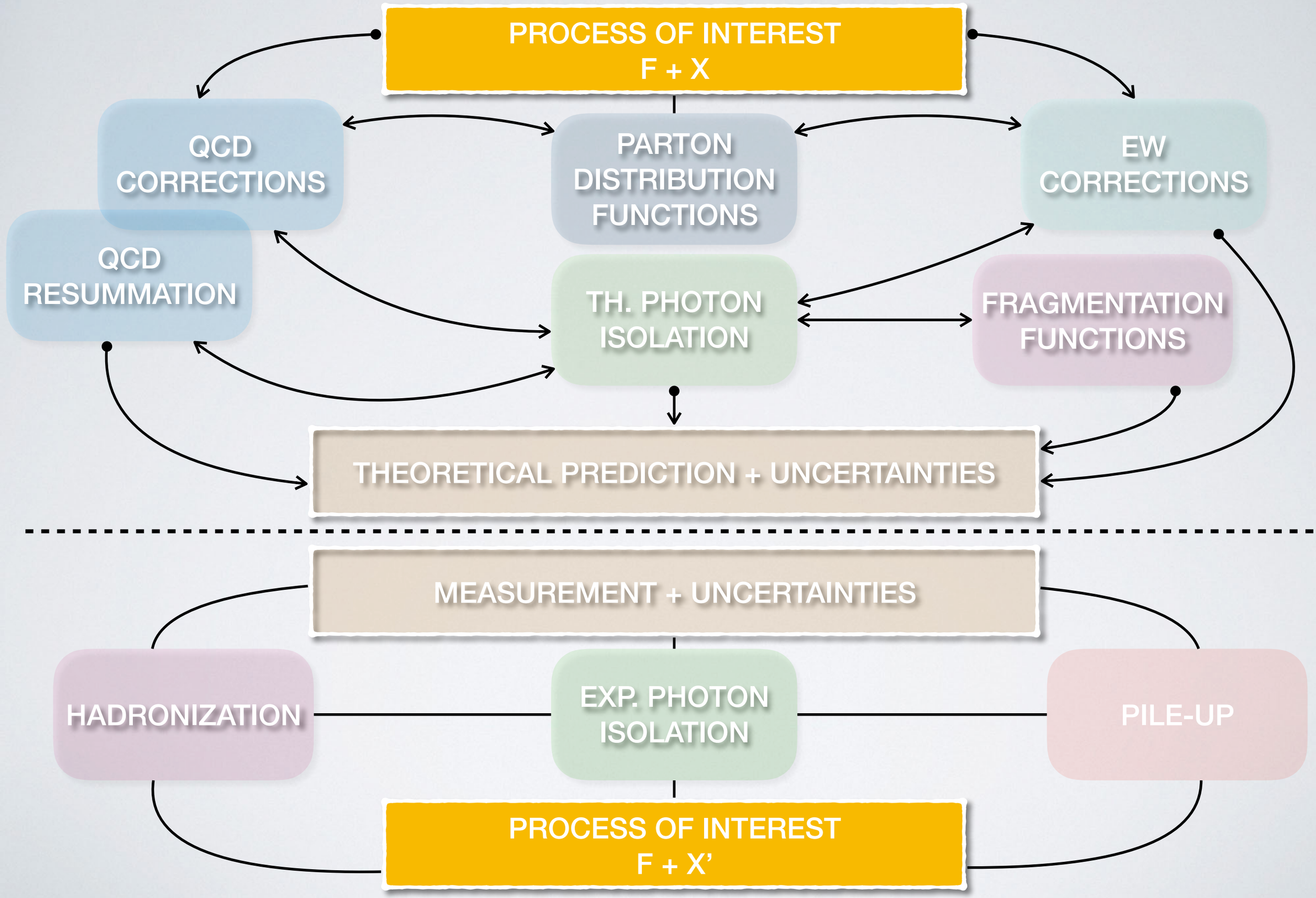
FIXED ORDER CALCULATIONS TOOLKIT



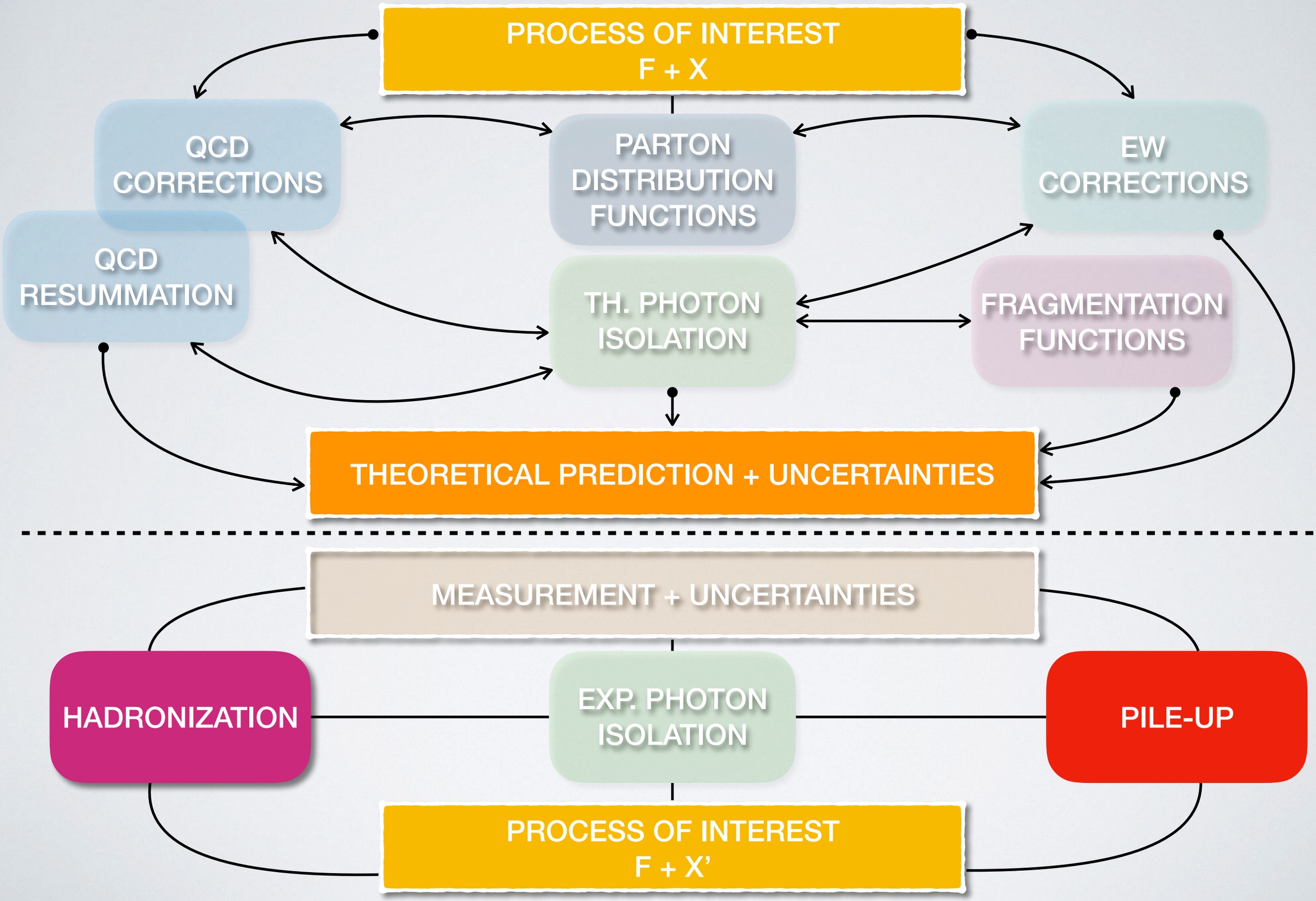
FIXED ORDER CALCULATIONS TOOLKIT



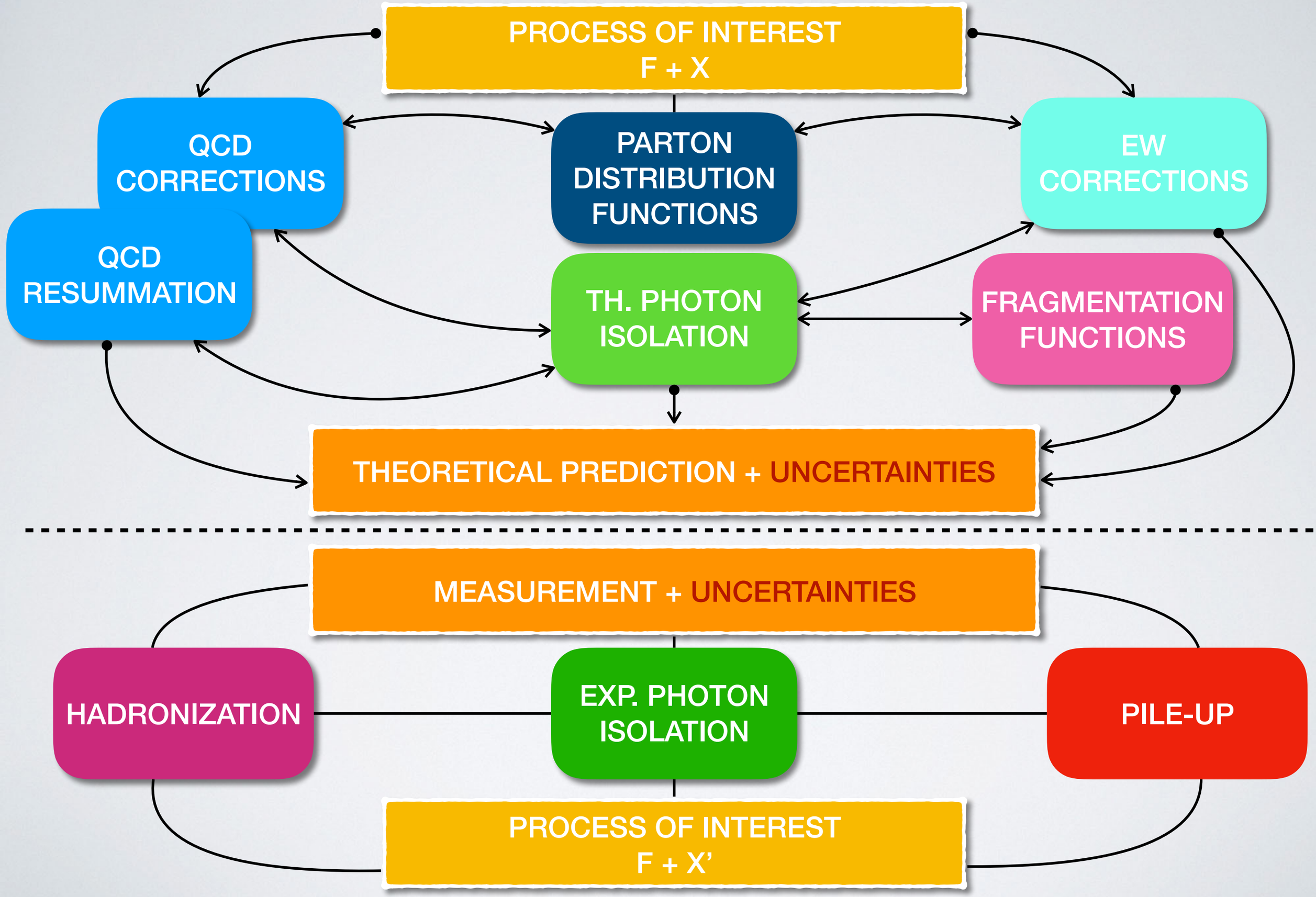
FIXED ORDER CALCULATIONS TOOLKIT



FIXED ORDER CALCULATIONS TOOLKIT



FIXED ORDER CALCULATIONS TOOLKIT



BRIEF LIST OF CODES

Process	Codes QCD	EW corrections (NLO)	Resummation
$pp \to \gamma + \text{Jet}$	`JetPhox`: NLO(QCD)+NLO(Frag) [99'] `MCFM`: NNLO(QCD) [2016/2017] `NNLOJET`: NNLO(QCD) [2019]	Kuhn, Kulesza, Pozzorini, Schulze [2005] Becher, Garcia i Tormo [2013] Schwartz [2016]	`Peter`: N^3LL Threshold Resummation arXiv:1206.6115
$pp \to \gamma\gamma$	`DiPhox`: NLO(QCD)+NLO(Frag) [99'] `2yNNLO`: NNLO(QCD) [2011] `MCFM`: NNLO(QCD) [2016] `MATRIX`: NNLO(QCD) [2016]	Bierweiler, Kasprzik, Kuhn. [2013] Chiesa,Greiner, Schoenherr, Tramontano [2017]	`2yRes`: [2015] qT Resummation NNLL+NNLO(QCD) `Resbos`: [1997] qT Resummation NNLL+NLO(QCD)
$pp \to \gamma\gamma + \text{Jets}$	`NLOJet++`: NLO(QCD). [2003] `2yNNLO`: NLO(QCD) [2011] Gehrmann, Greiner, Heinrich: NLO(QCD)+LO(Frag) [2013] Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Lo Presti, Maitre [2013] Badger, Guffanti, Yundin [2013] Greiner, Fäh [2017]	Chiesa,Greiner, Schoenherr, Tramontano [2017]	
$pp \to Z\gamma$ $pp \to W\gamma$	`MATRIX`: NNLO(QCD) [2015] `MCFM`: NNLO(QCD) (Zy) [2017]	Denner, Dittmaier, Hecht, Pasold [2015] Denner, Dittmaier, Hecht, Pasold [2014]	

BRIEF LIST OF CODES

(Fixed order + Resummation) tools that use smooth cone isolation (in red)

Process	Codes QCD	EW corrections (NLO)	Resummation
$pp \to \gamma + \text{Jet}$	`JetPhox`: NLO(QCD)+NLO(Frag) [99'] `MCFM`: NNLO(QCD) [2016/2017] `NNLOJET`: NNLO(QCD) [2019]	Kuhn, Kulesza, Pozzorini, Schulze [2005] Becher, Garcia i Tormo [2013] Schwartz [2016]	`Peter`: N^3LL Threshold Resummation arXiv:1206.6115
$pp \to \gamma\gamma$	`DiPhox`: NLO(QCD)+NLO(Frag) [99'] `2yNNLO`: NNLO(QCD) [2011] `MCFM`: NNLO(QCD) [2016] `MATRIX`: NNLO(QCD) [2016]	Bierweiler, Kasprzik, Kuhn. [2013] Chiesa,Greiner, Schoenherr, Tramontano [2017]	`2yRes`: [2015] qT Resummation NNLL+NNLO(QCD) `Resbos`: [1997] qT Resummation NNLL+NLO(QCD)
$pp \to \gamma\gamma + \text{Jets}$	`NLOJet++`: NLO(QCD). [2003] `2yNNLO`: NLO(QCD) [2011] Gehrmann, Greiner, Heinrich: NLO(QCD)+LO(Frag) [2013] Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Lo Presti, Maitre [2013] Badger, Guffanti, Yundin [2013] Greiner, Fäh [2017]	Chiesa,Greiner, Schoenherr, Tramontano [2017]	
$pp \to Z\gamma$ $pp \to W\gamma$	`MATRIX`: NNLO(QCD) [2015] `MCFM`: NNLO(QCD) (Zy) [2017]	Denner, Dittmaier, Hecht, Pasold [2015] Denner, Dittmaier, Hecht, Pasold [2014]	

BRIEF LIST OF PROCESSES

Process	Known	Desired LH 2017	Some LHC recent measurements
$pp \to \gamma + \text{Jet}$	• NNLO_{QCD} • NLO_{EW} • $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{Frag}}$		• ATLAS: 1801.00112 • ATLAS: 1701.06882 • ATLAS: 1611.06586 • ATLAS-CONF-2017-059 • ATLAS:1605.03495 • CMS-SMP-16-003 • CMS-TOP-17-016 • CMS: 1311.6141
$pp \to \gamma\gamma$	• NNLO_{QCD} • NLO_{EW} • $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{Frag}}$		• ATLAS: 1707.04147 • ATLAS:1704.03839 • ATLAS:1606.03833 • CMS:1405.7225 • CMS:1108.2044 • CMS: 1609.02507 • CMS:1606.04093 • CMS-PAS-EXO-16-027
$pp \to \gamma\gamma + \text{Jets}$	• NLO_{QCD} • NLO_{EW} • $\text{NLO}_{\text{QCD}} + \text{LO}_{\text{Frag}}$	• NNLO_{QCD} • $\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	• CMS PAS-SMP-14-021
$pp \to \gamma\gamma\gamma$	• NLO_{QCD} • $\text{NLO}_{\text{QCD}} + \text{LO}_{\text{Frag}}$	• $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	• ATLAS:1712.07291

BRIEF LIST OF PROCESSES

Process	Known	Desired LH 2017	Some LHC recent measurements
$pp \to \gamma\gamma\gamma$	• $\mathrm{NLO_{QCD}}$		
$pp \to Z\gamma$	• $\mathrm{NNLO_{QCD}}$ • $\mathrm{NLO_{EW}}$	• $\mathrm{NNLO_{QCD} + NLO_{EW}}$	• CMS PAS EXO-17-005 • CMS: 1612.09516 • CMS-SMP-14-018 • ATLAS: 1810.04995 • ATLAS: 1705.01966 • ATLAS: 1604.05232 • ATLAS: 1407.8150
$pp \to W\gamma$	• $\mathrm{NNLO_{QCD}}$ • $\mathrm{NLO_{EW}}$	• $\mathrm{NNLO_{QCD} + NLO_{EW}}$	• CMS: 1612.09256 • ATLAS: 1407.8150
$pp \to W\gamma\gamma$	• $\mathrm{NLO_{QCD}}$	• $\mathrm{NLO_{QCD} + NLO_{EW}}$	• CMS-SMP-15-008 • ATLAS: 1503.03243

NEWS FROM THEORY

TOP QUARK EFFECTS IN DIPHOTON PRODUCTION

Eur. Phys. J. C (2017) 77:323
DOI 10.1140/epjc/s10052-017-4884-8

THE EUROPEAN PHYSICAL JOURNAL C

Letter

Top-quark mass from the diphoton mass spectrum

Sayaka Kawabata[1,a], **Hiroshi Yokoya**[2,b]

[1] Institute of Convergence Fundamental Studies, Seoul National University of Science and Technology, Seoul 01811, Korea
[2] Quantum Universe Center, KIAS, Seoul 02455, Korea

Received: 9 March 2017 / Accepted: 5 May 2017 / Published online: 18 May 2017

Eur. Phys. J. C (2018) 78:715
https://doi.org/10.1140/epjc/s10052-018-6188-z

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

The top threshold effect in the $\gamma\gamma$ production at the LHC

Shashikant R. Dugad[1,a], **Pankaj Jain**[2,b], **Subhadip Mitra**[3,c], **Prasenjit Sanyal**[2,d], **Ravindra K. Verma**[1,2,e]

[1] Department of High Energy Physics, Tata Institute of Fundamental Research, 1 Homi Bhabha Road, Mumbai 400 005, India
[2] Department of Physics, Indian Institute of Technology Kanpur, Kanpur 208 016, India
[3] Center for Computational Natural Sciences and Bioinformatics, International Institute of Information Technology, Hyderabad 500 032, India

Received: 8 March 2018 / Accepted: 23 August 2018 / Published online: 5 September 2018

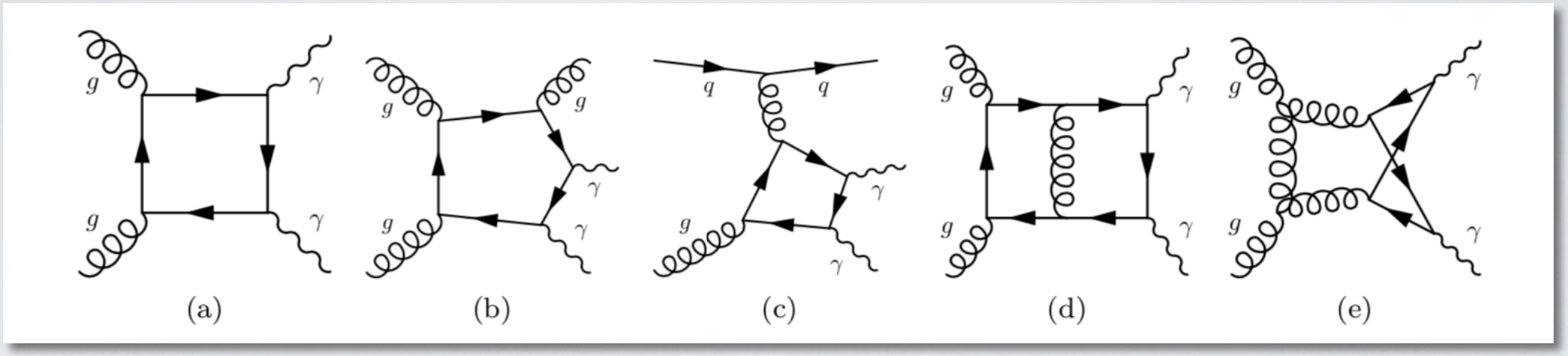
Top-quark effects in diphoton production through gluon fusion at NLO in QCD

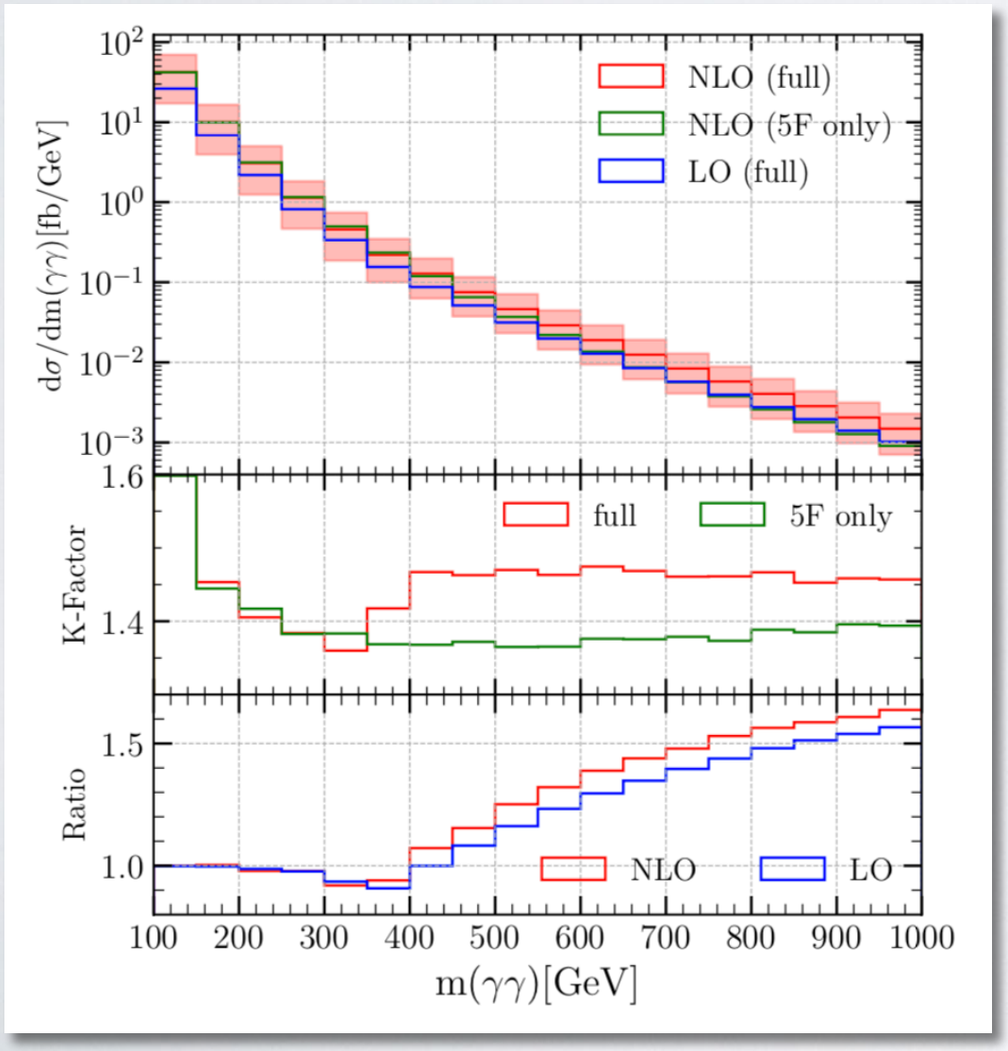
Fabio Maltoni,[1,2,*] Manoj K. Mandal,[3,†] and Xiaoran Zhao[1,‡]

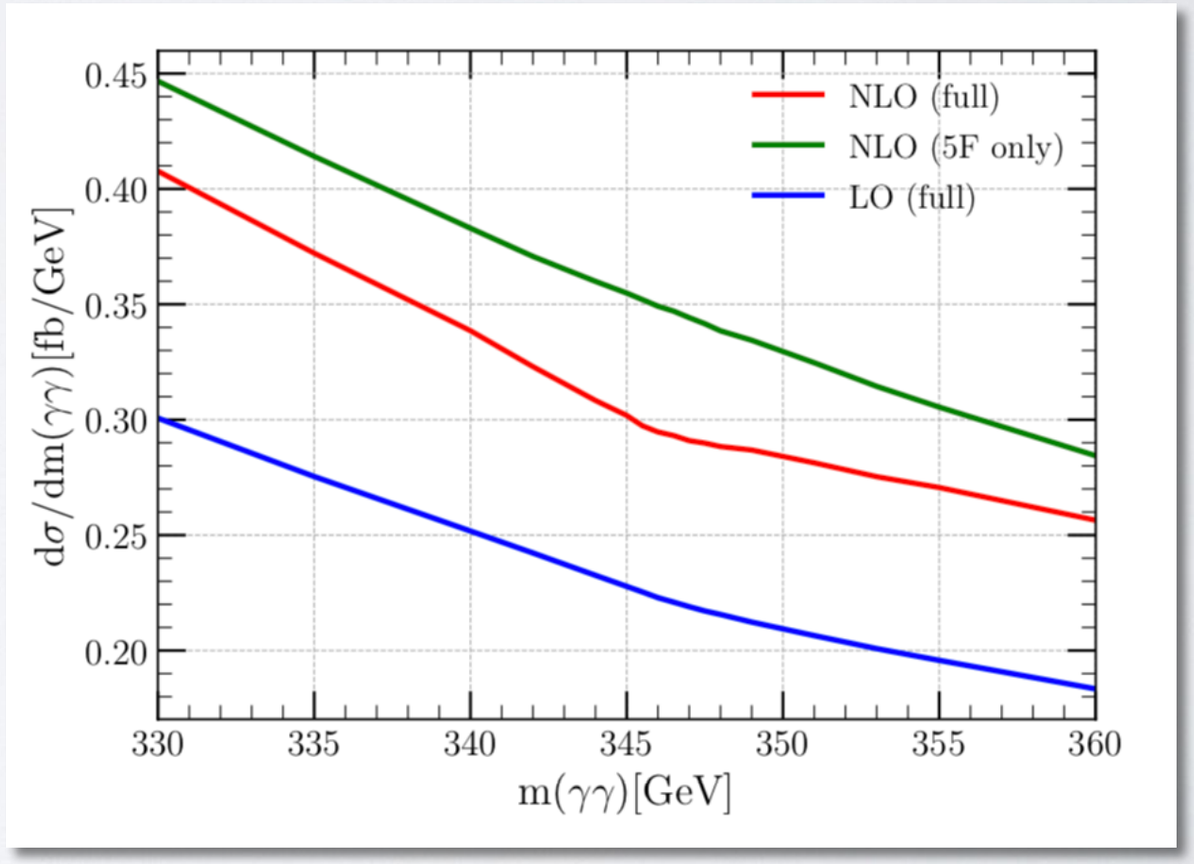
[1] *Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium*
[2] *Dipartimento di Fisica e Astronomia, Università di Bologna and INFN, Sezione di Bologna, via Irnerio 46, 40126 Bologna, Italy*
[3] *Dipartimento di Fisica e Astronomia, Università di Padova and INFN, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

NEWS FROM THEORY

TOP QUARK EFFECTS IN DIPHOTON PRODUCTION



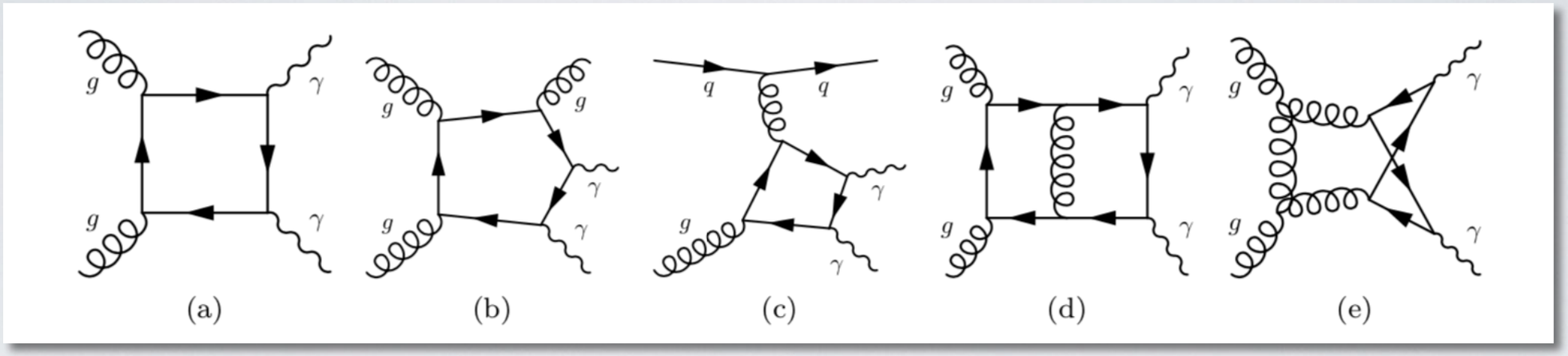


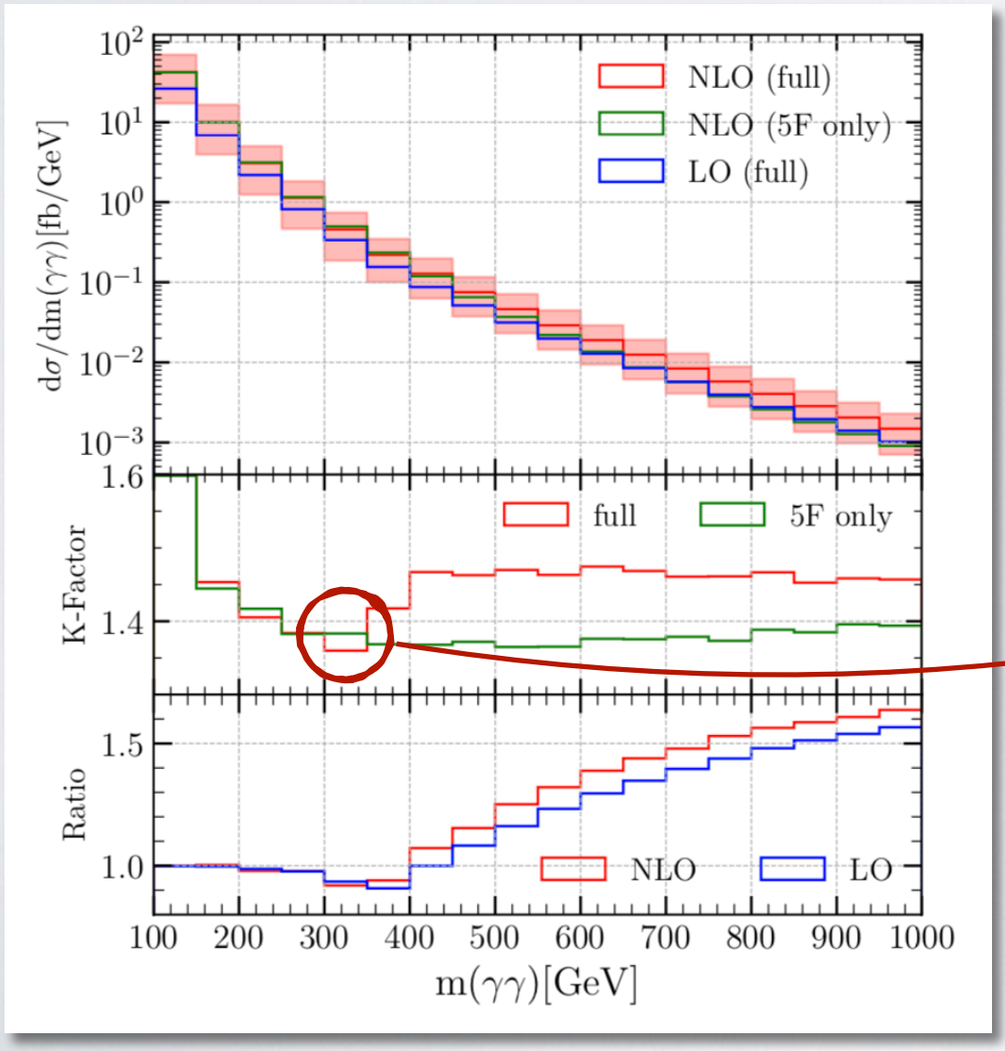


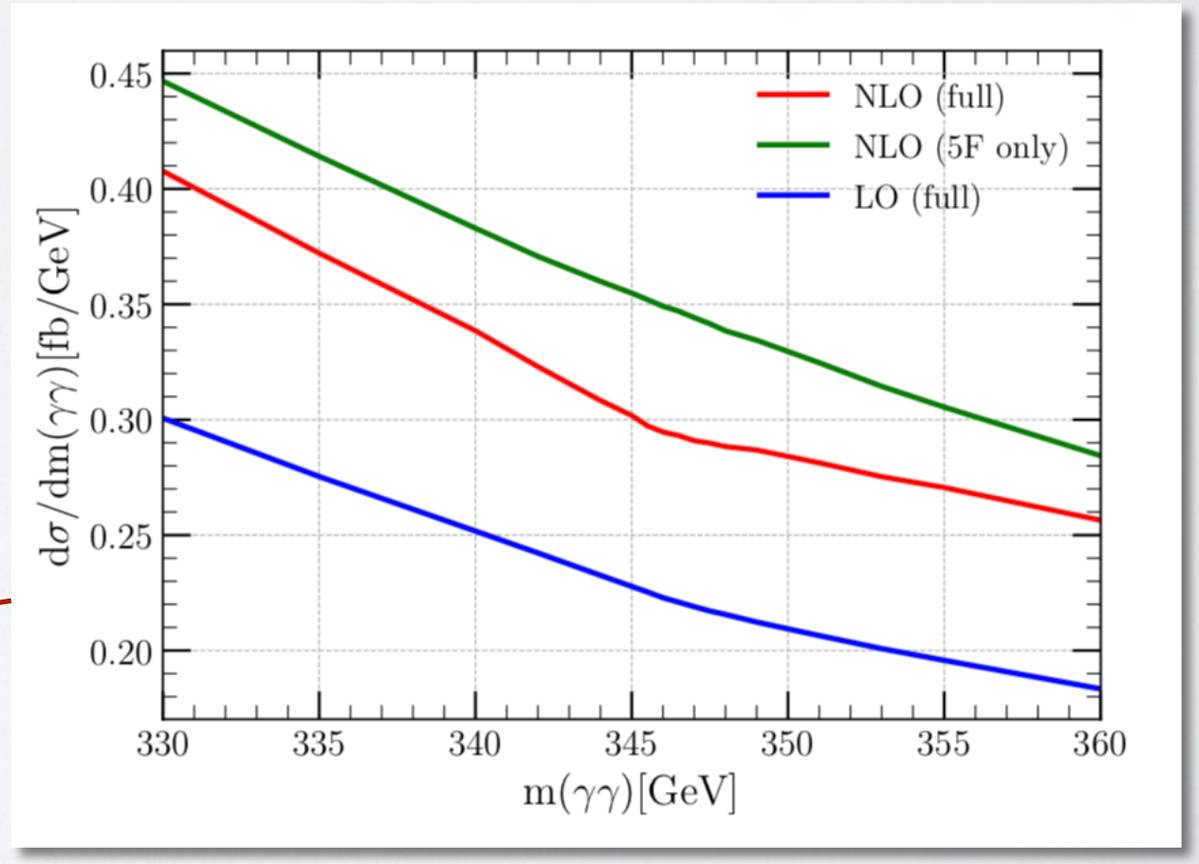
Maltoni, Mandal, Zhao [2018]

NEWS FROM THEORY

TOP QUARK EFFECTS IN DIPHOTON PRODUCTION



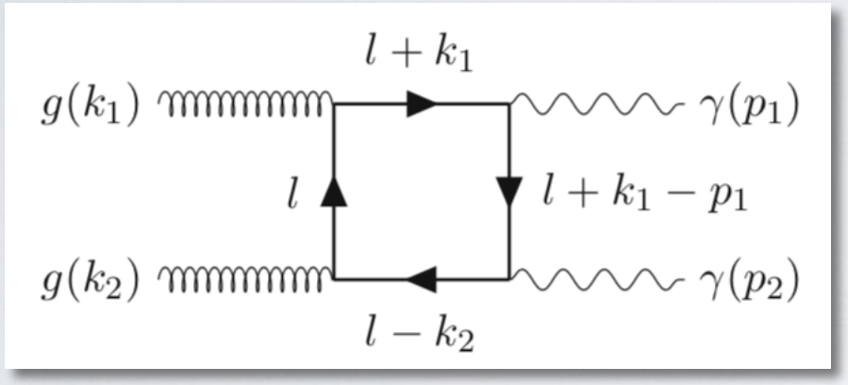


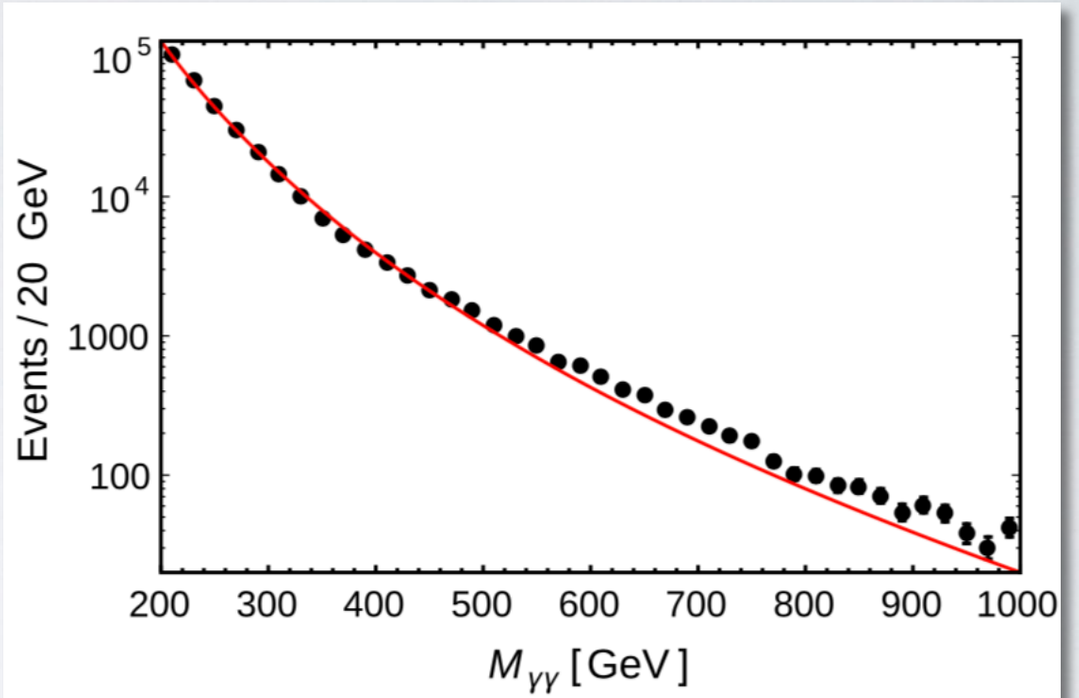


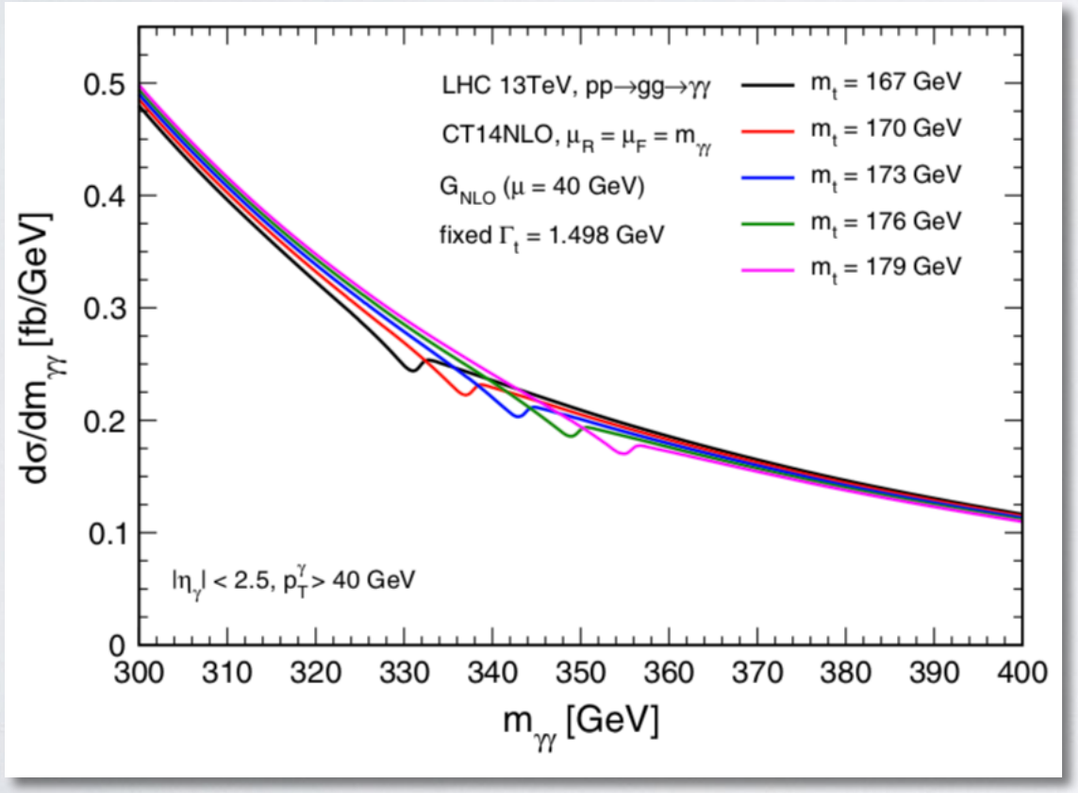
Maltoni, Mandal, Zhao [2018]

NEWS FROM THEORY

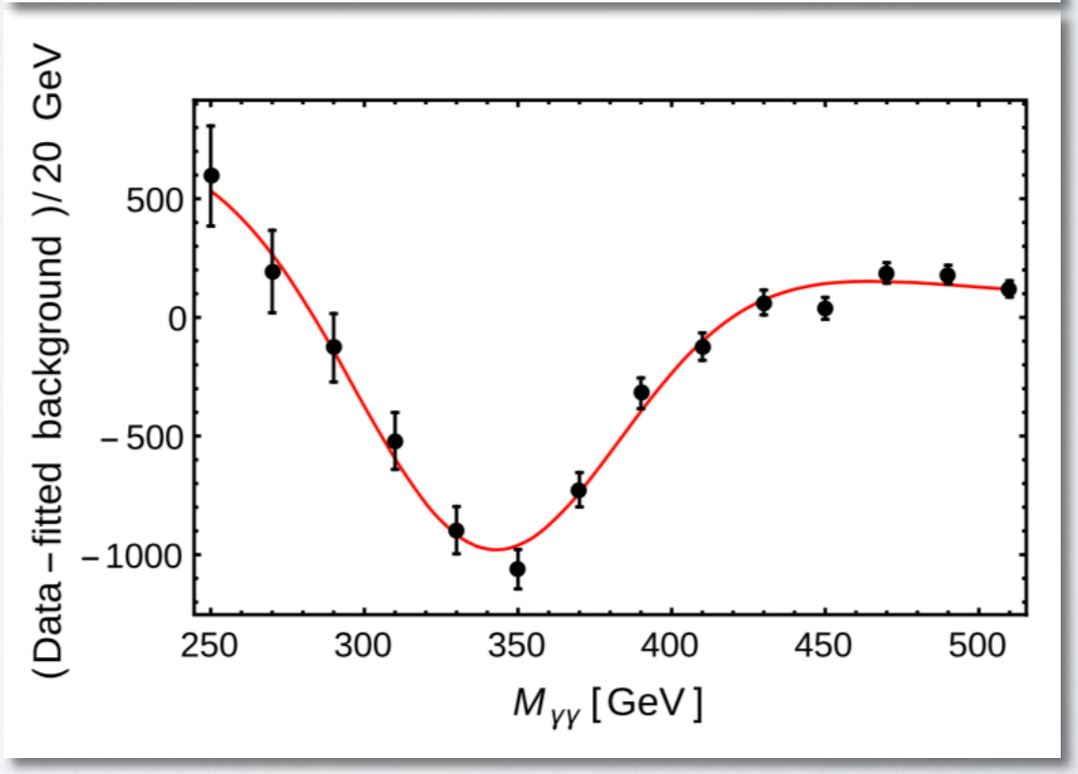
TOP QUARK EFFECTS IN DIPHOTON PRODUCTION







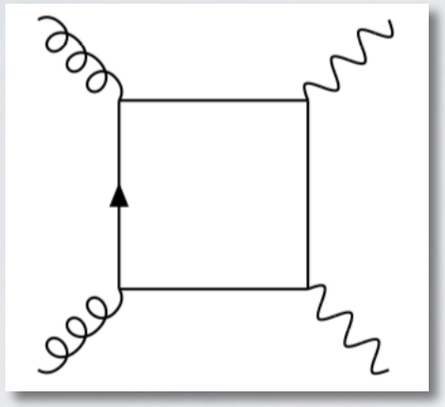
Kawabata, Yokoya [2017]



Dugad, Jain, Mitra, Sanyal, Verma [2018]

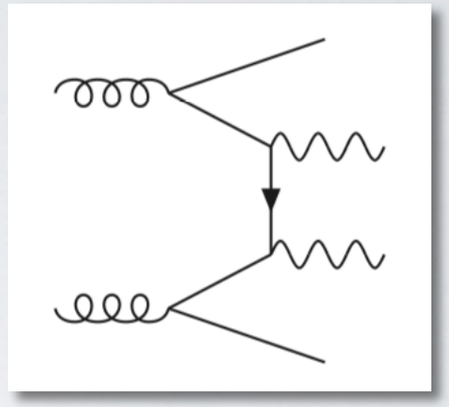
NEWS FROM THEORY

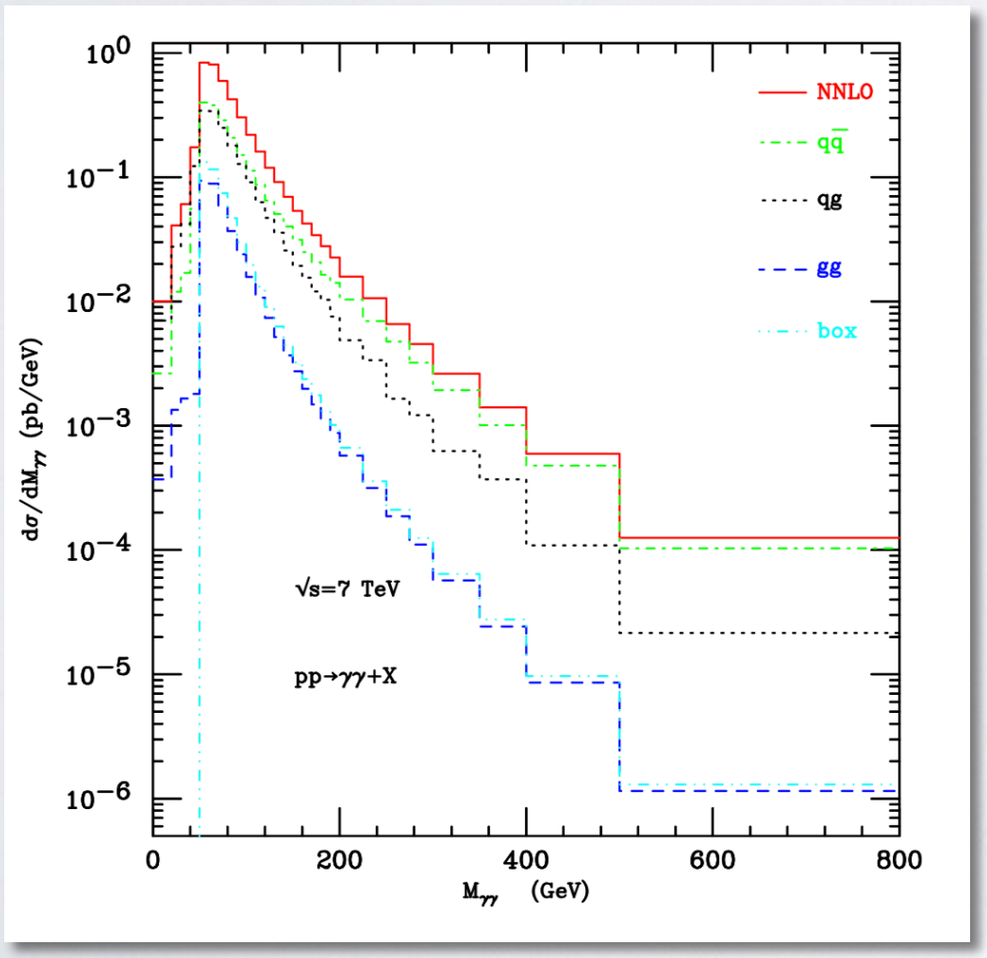
TOP QUARK EFFECTS IN DIPHOTON PRODUCTION

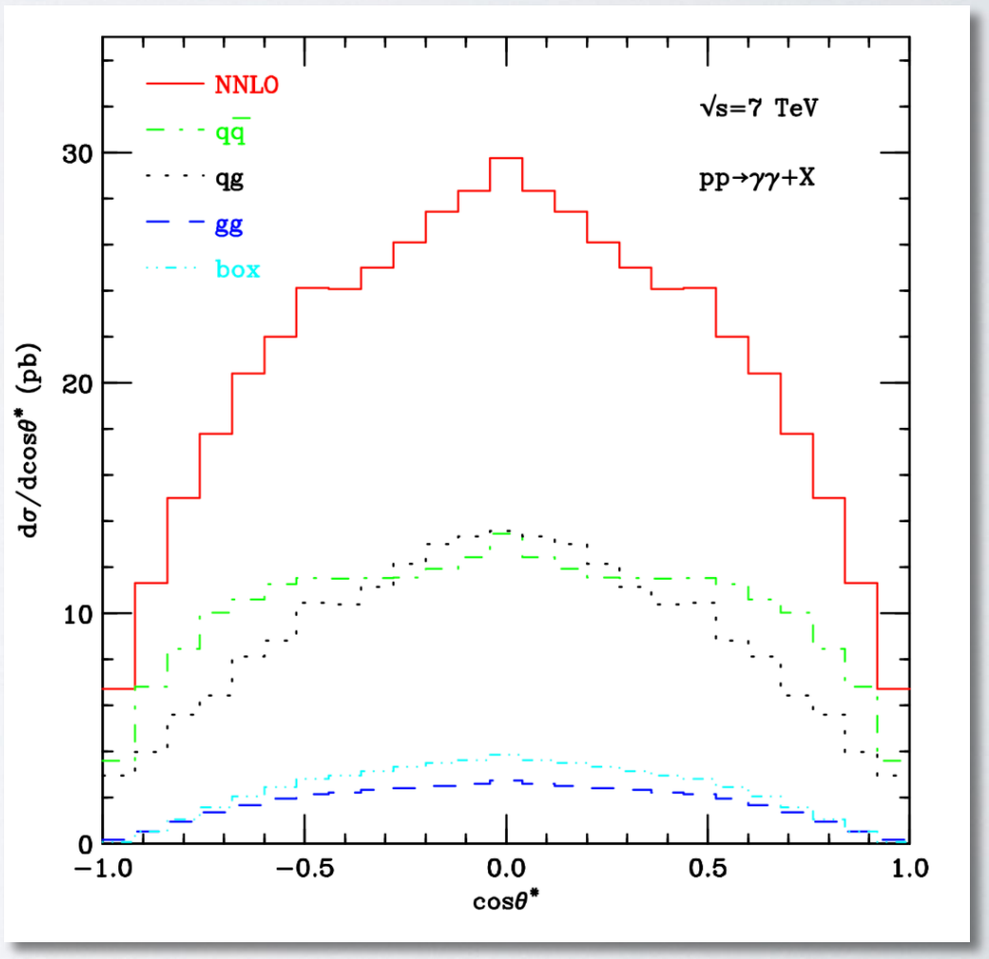


NNLO example

In some phase-space regions they differ in sign



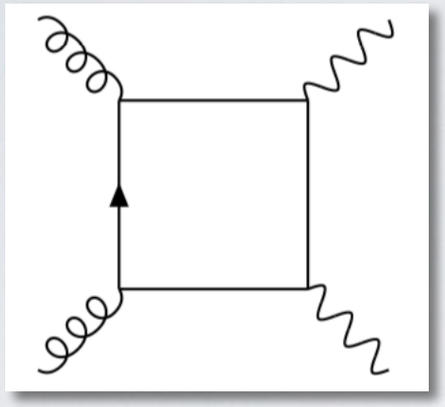




Catani, LC, de Florian, Ferrera, Grazzini, [2018]

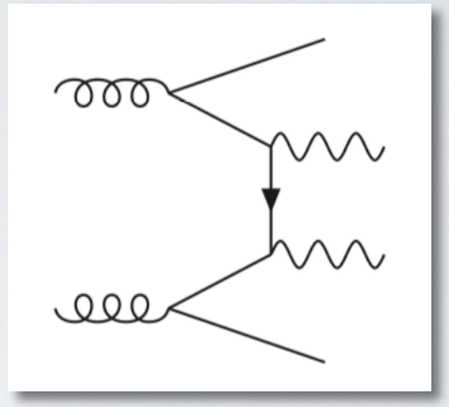
NEWS FROM THEORY

TOP QUARK EFFECTS IN DIPHOTON PRODUCTION



NNLO example

In some phase-space regions they differ in sign

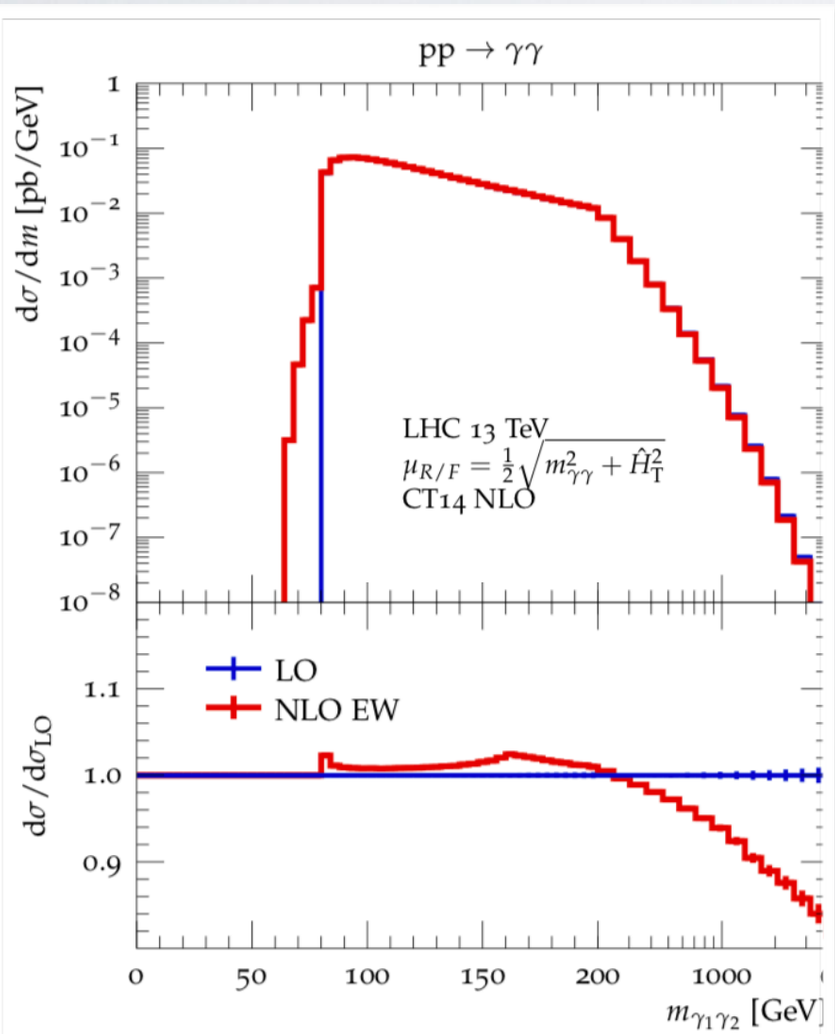


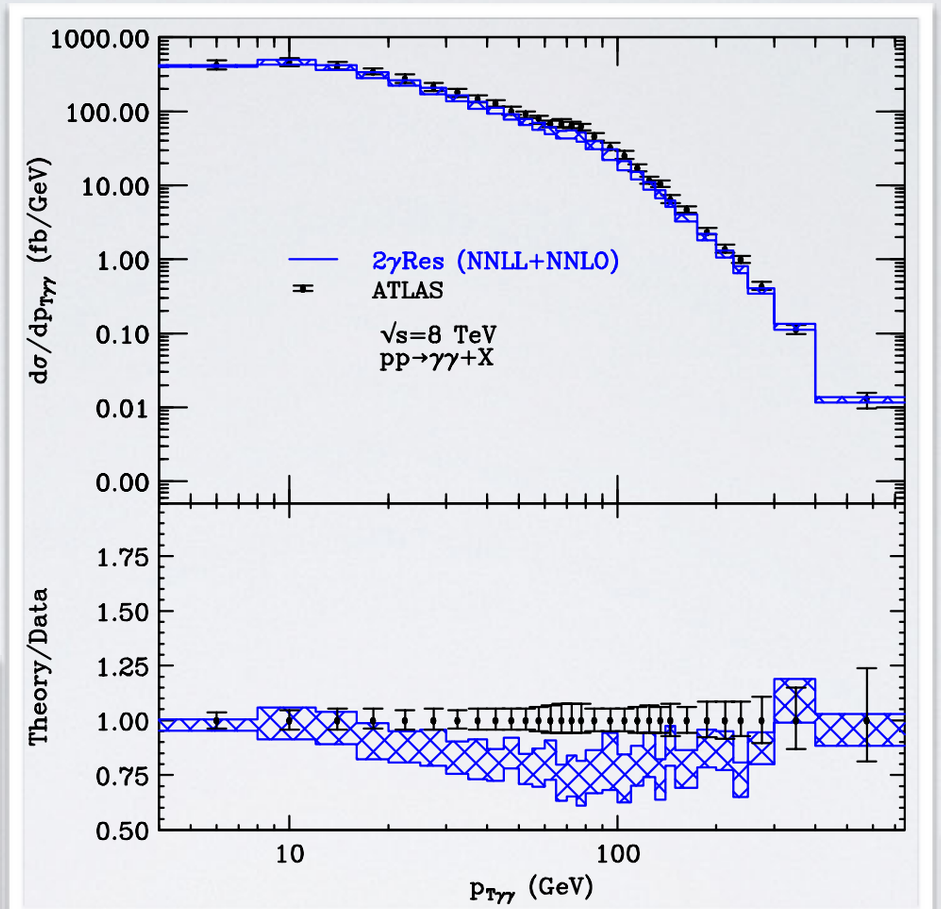
- We have to be aware that the final and complete answer could be different
- This consideration is valid for any computation which uses a gauge invariant subset of scattering amplitudes at N3LO/NNLO

EW EFFECTS IN DIPHOTON + JETS PRODUCTION AND TRANSVERSE-MOMENTUM RESUMMATION

Chiesa,Greiner, Schoenherr, Tramontano [2017]

No photon initiated processes



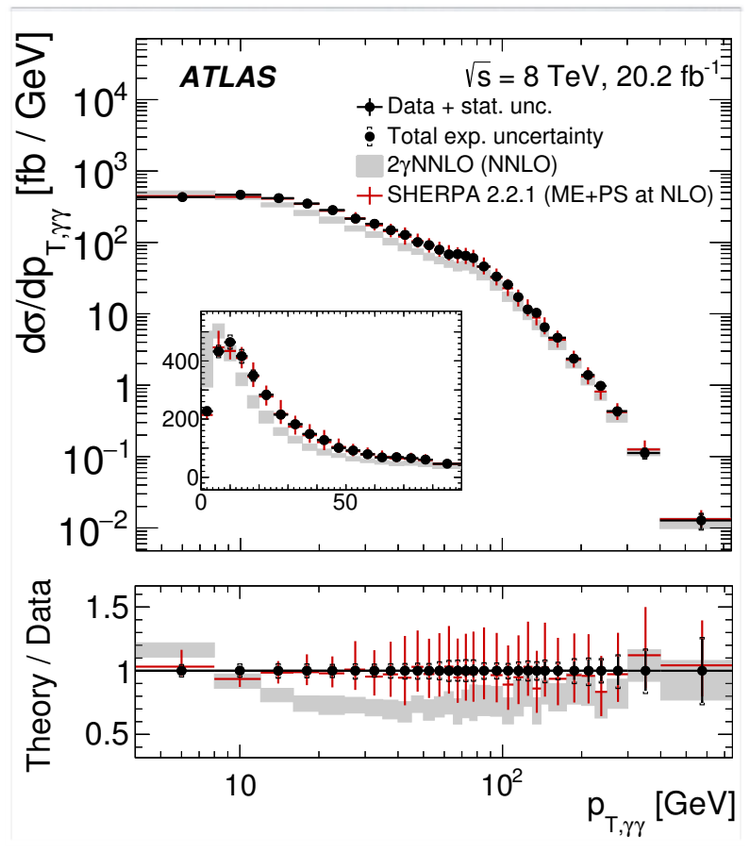


2yRes: LC, Coradeschi, de Florian [2015]

PDFs uncertainties only included in the ATLAS analysis (2%).

Thanks to Juan Terron Cuadrado, Matthias Saimpert and Bruno Lenzi, For share their 2yRes runs

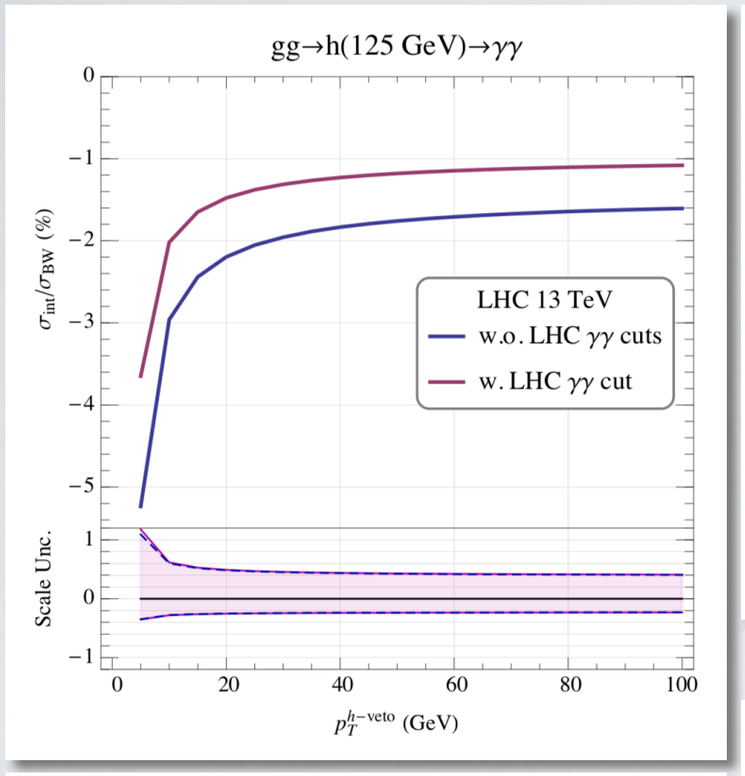
ATLAS:1704.03839

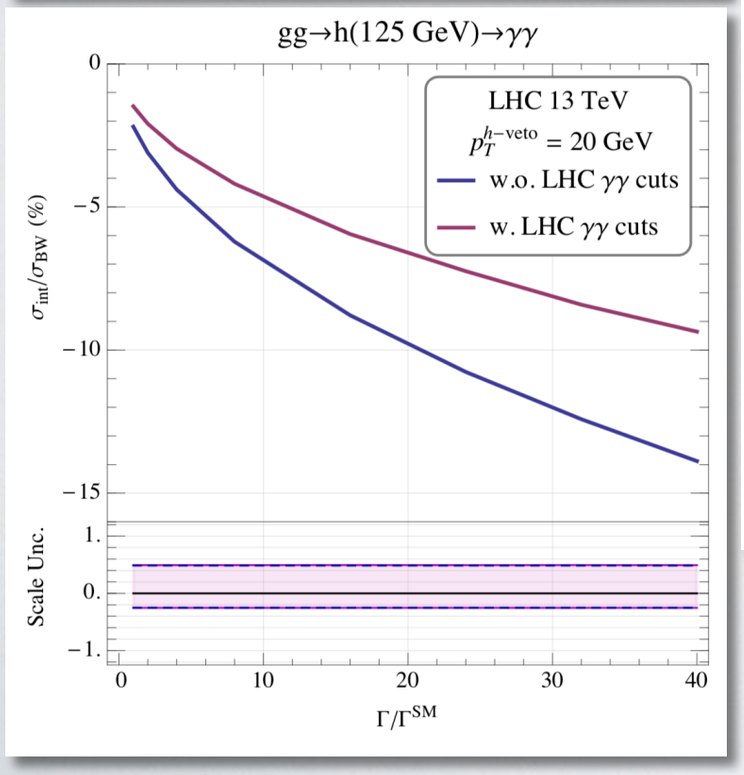


HIGGS BOSON SIGNAL-BACKGROUND INTERFERENCE

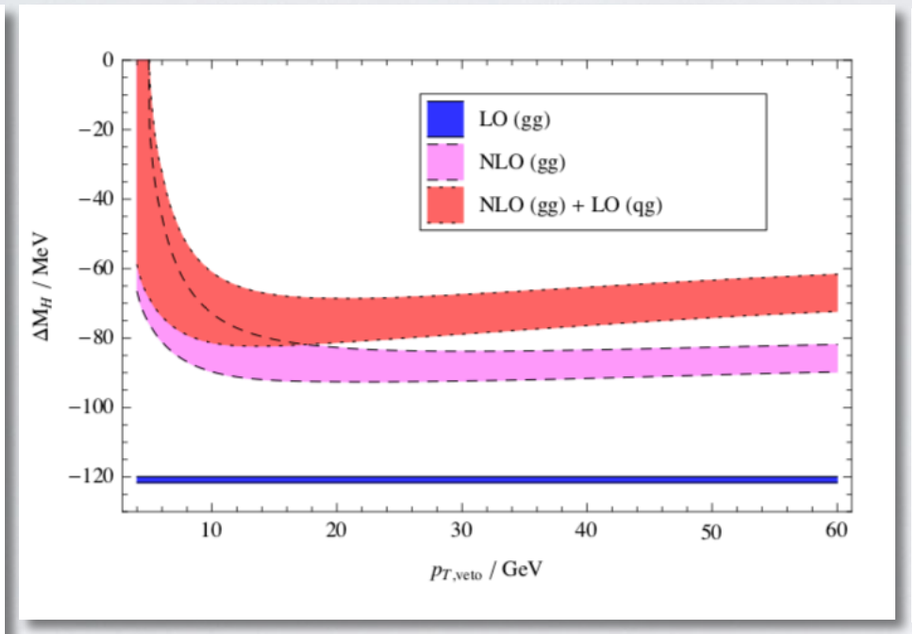
Campbell, Carena, Harnika, Liua [2017]

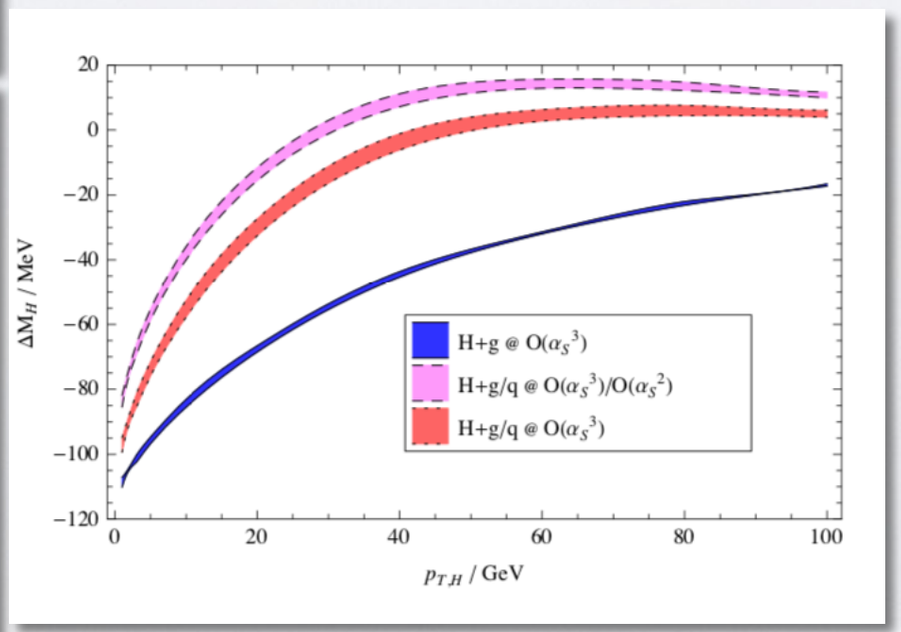
Fixed order





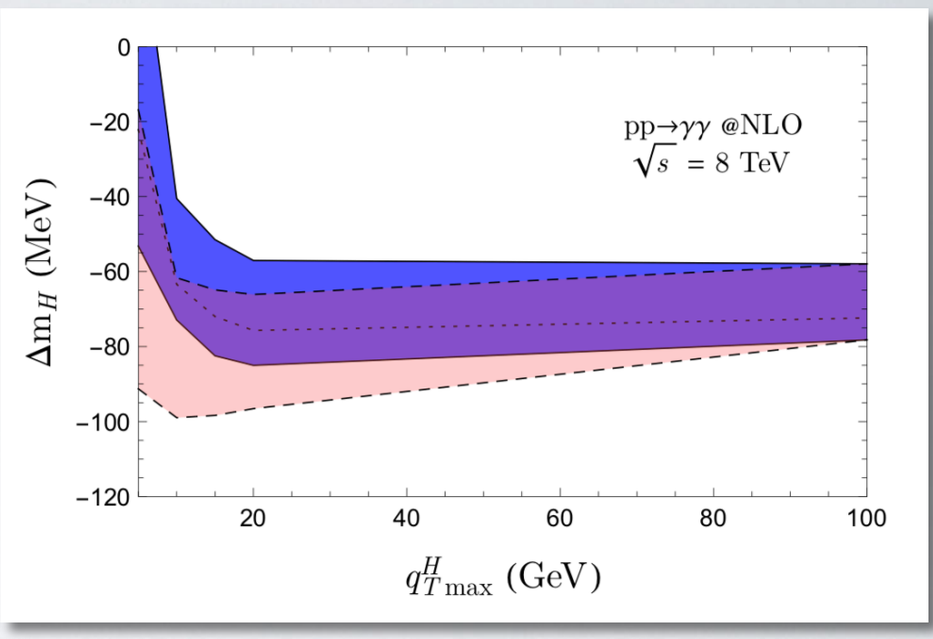
Fixed order

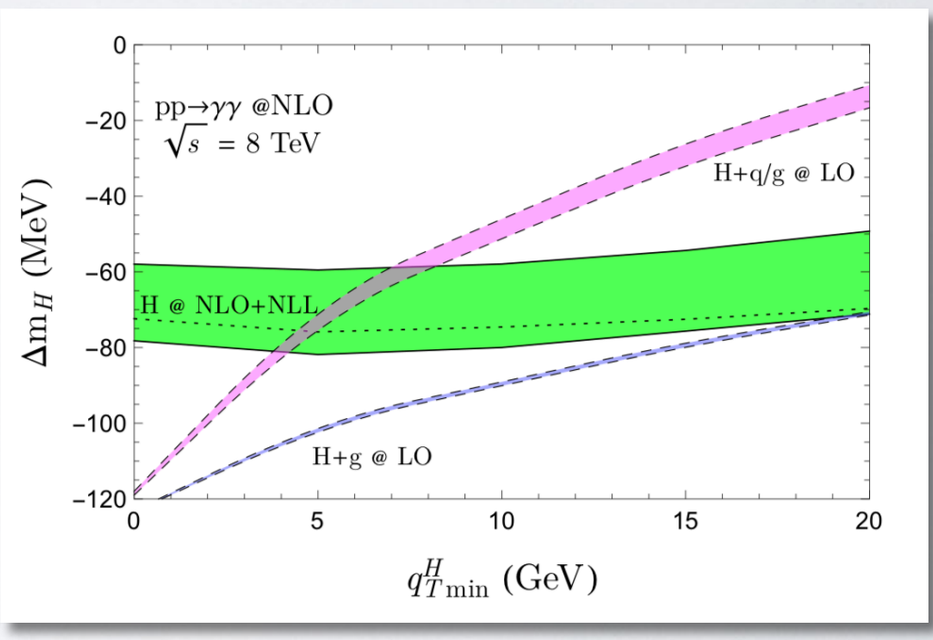




Dixon, Li [2013]

Fixed order + qT resummation





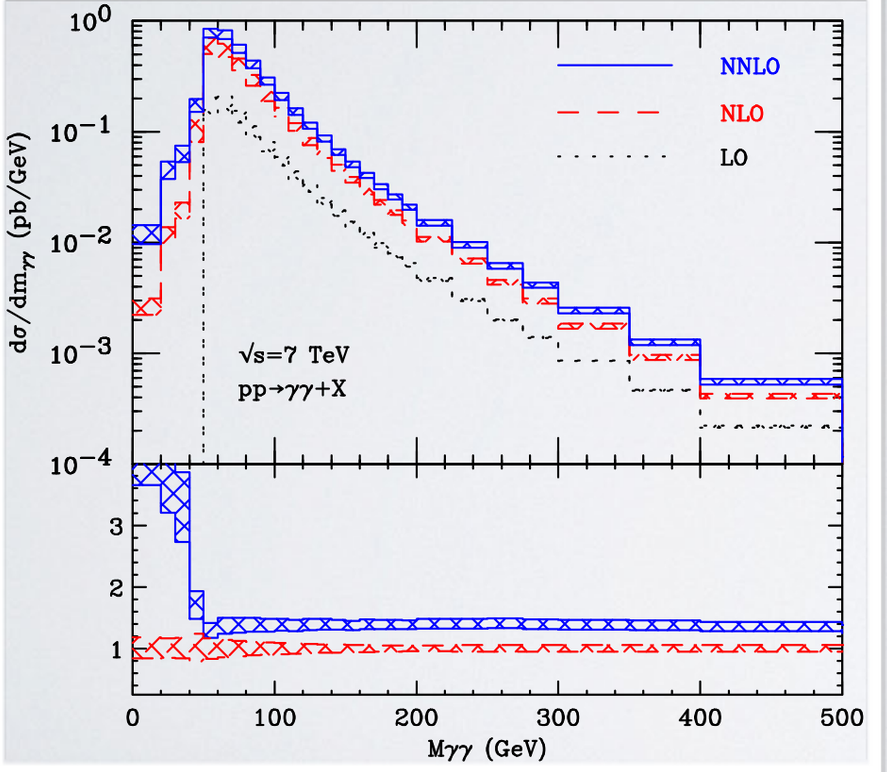
LC, Coradeschi, de Florian, Fidanza [2017]

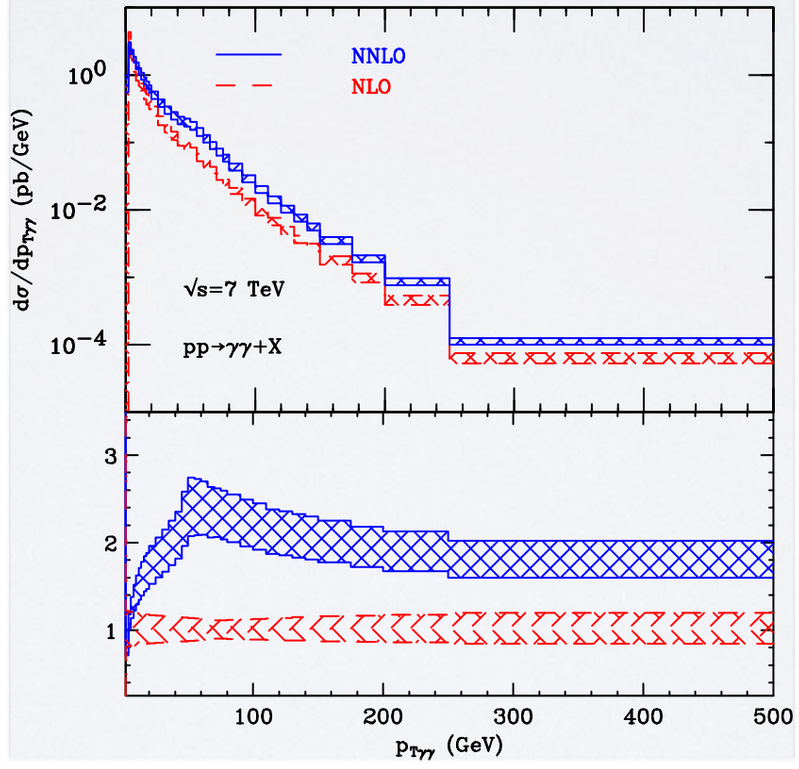
THEORETICAL UNCERTAINTIES

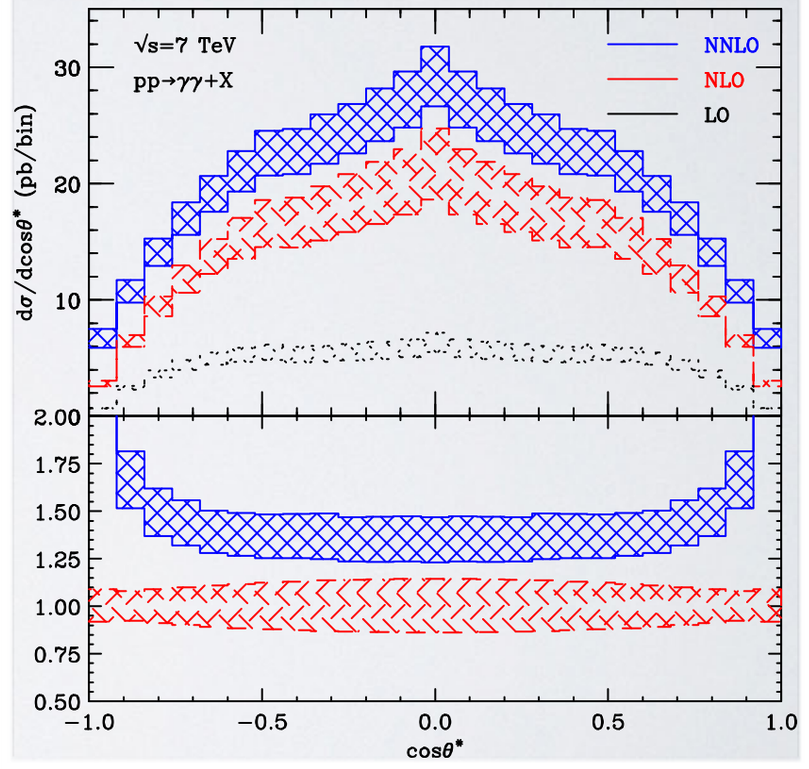
$$\sqrt{s} = 7 \text{ TeV}$$
$$p_{T\gamma}^{\text{hard}} \geq 25 \text{ GeV}, \; p_{T\gamma}^{\text{soft}} \geq 22 \text{ GeV}$$
$$|y_\gamma| < 1.37 \text{ and } 1.52 < |y_\gamma| \leq 2.37, \; R_{\gamma\gamma}^{\min} = 0.4,$$
$$R = 0.4 \text{ and } E_{T\ max} = 4 \text{ GeV}.$$

Results obtained with 2yNNLO and cross checked with MATRIX

Selection cuts of:
ATLAS (1211.1913)



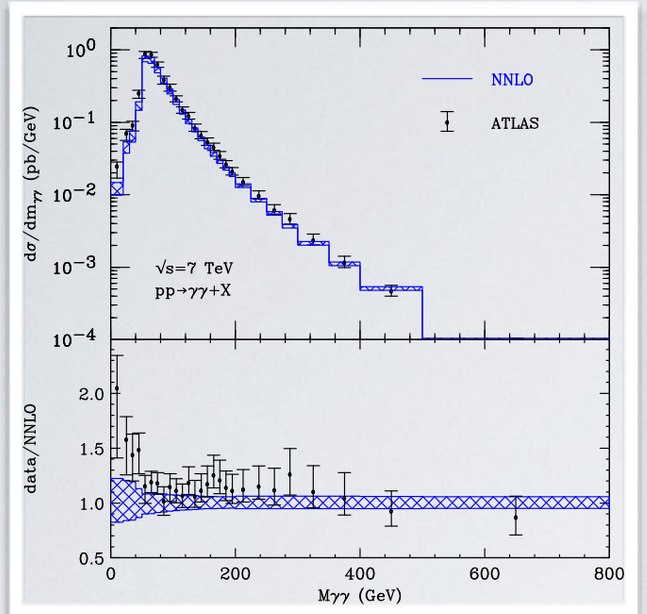


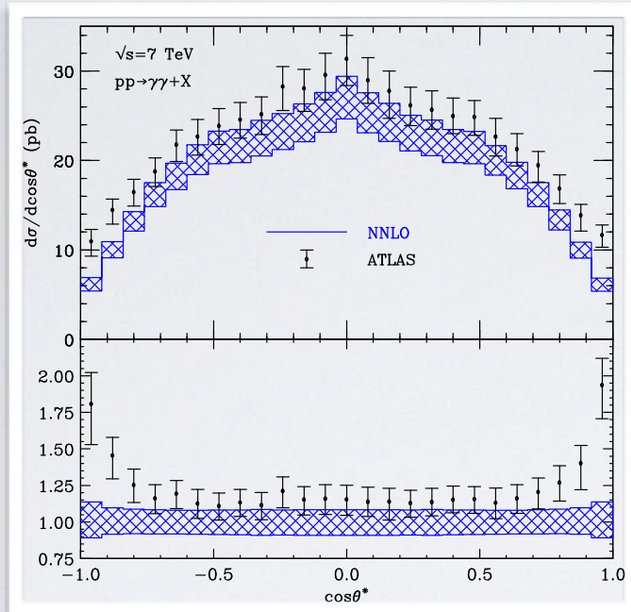


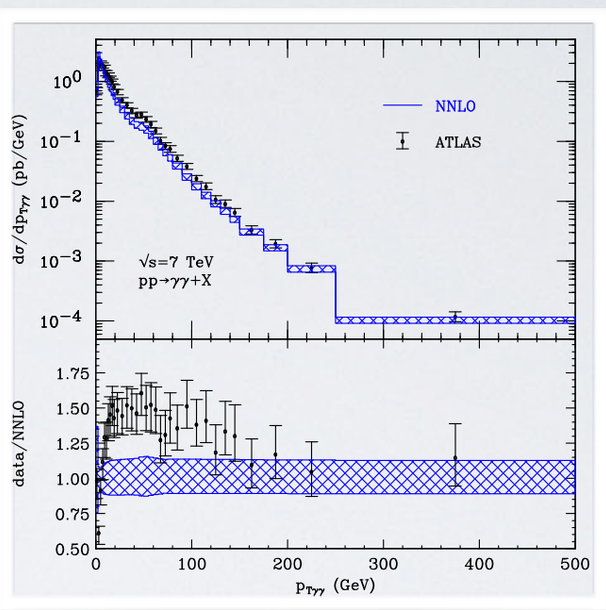
Catani, LC, de Florian, Ferrera, Grazzini, [2018]

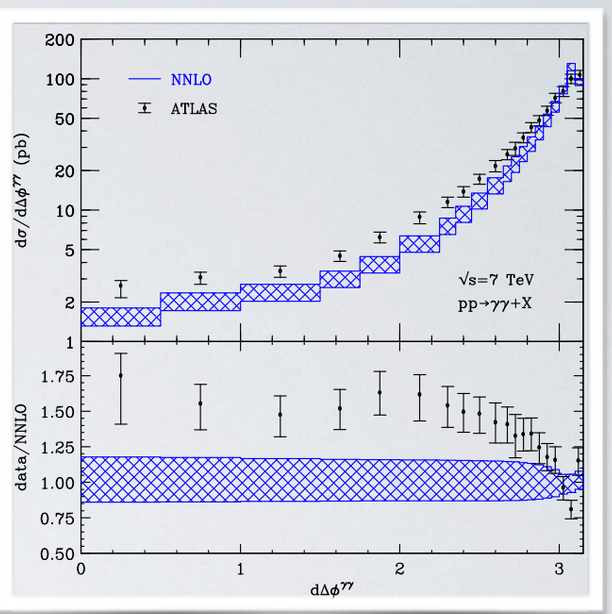
THEORETICAL UNCERTAINTIES

Uncertainties estimated as 9 point scale variation at NNLO

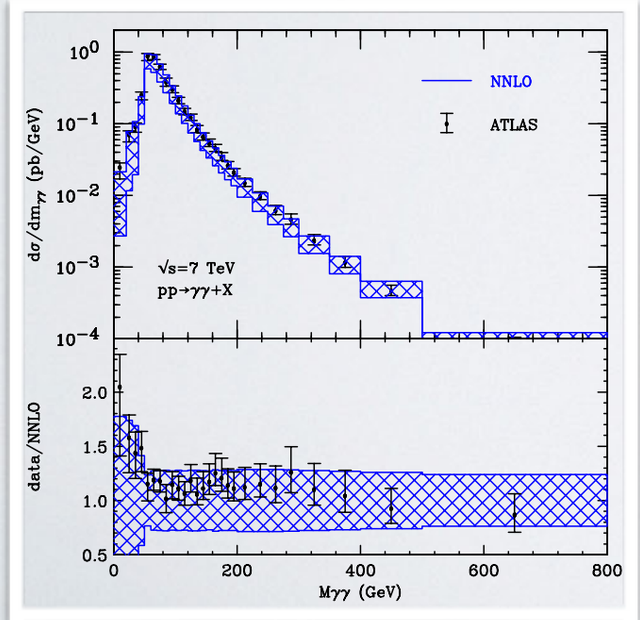


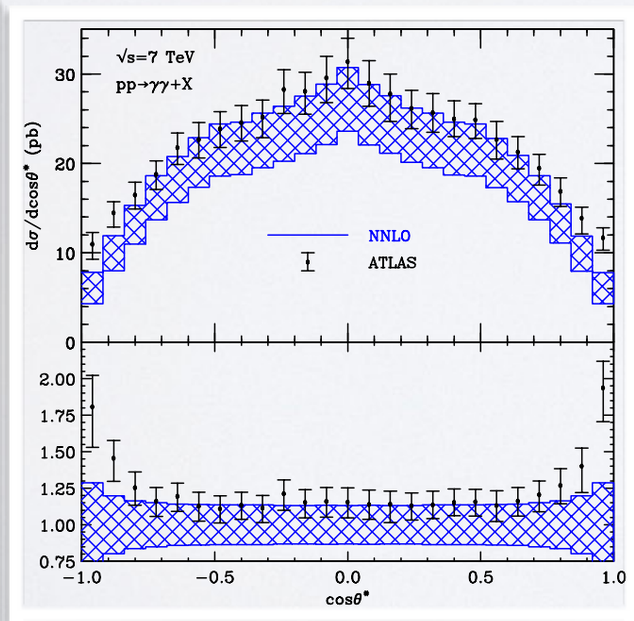


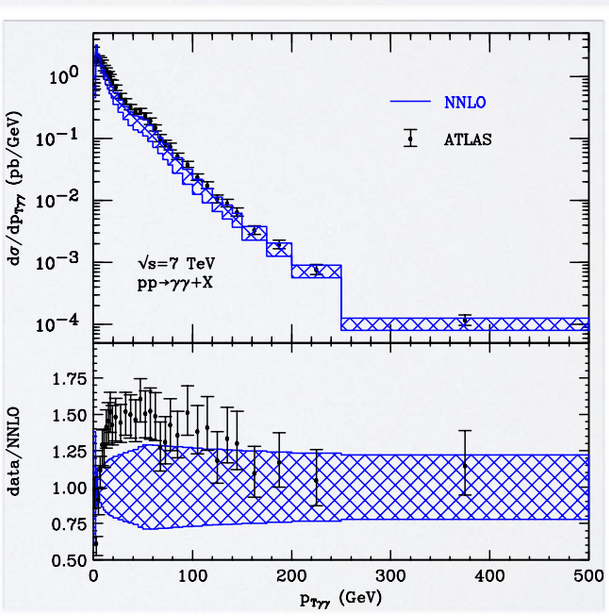


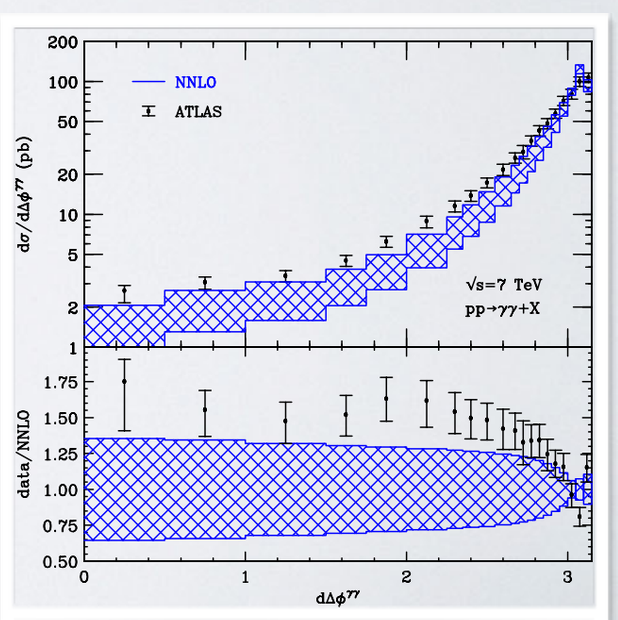


Uncertainties estimated as the half distance between NNLO and NLO central scale









Catani, LC, de Florian, Ferrera, Grazzini, [2018]

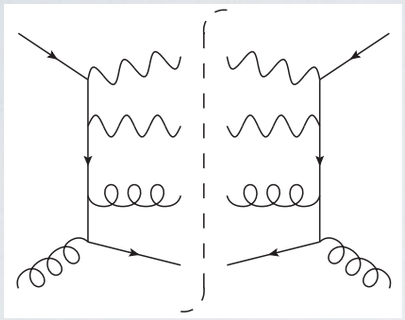
CONCLUSIONS AND OUTLOOK

- A lot of TH codes (the number is growing) describing photon processes are using smooth isolation
- If we are interested in the process F + X, TH and EXP have to be inclusive in the same way (important for a consistent treatment of EW corrections)
- Proposals for the LH 2019 wishlist?
- In some pathological cases, the customary variation of the factorization and renormalization scales constitutes a poor estimation of the TH uncertainties
- The use of transverse-momentum resummation in analysis of the interference between the signal and the background in Higgs production is well justified

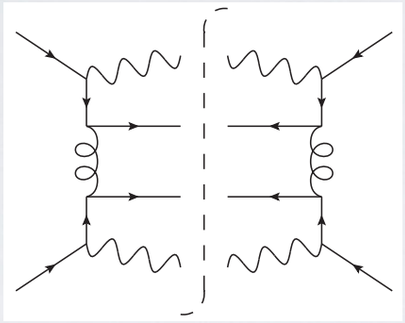
THANK YOU!

BACKUP SLIDES

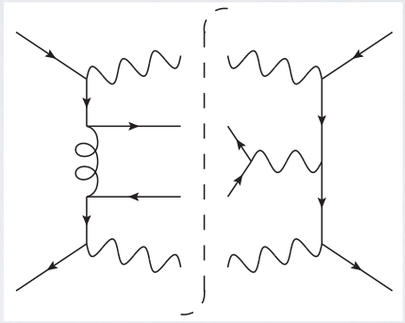
EW CORRECTIONS FOR $\gamma\gamma$(+JETS)



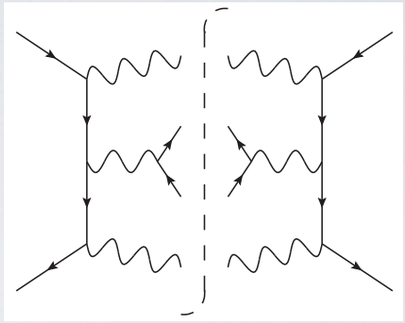
$\mathcal{O}(\alpha_s^2\alpha^2)$



$\mathcal{O}(\alpha_s^2\alpha^2)$

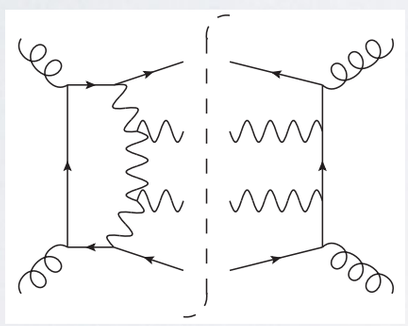


$\mathcal{O}(\alpha_s\alpha^3)$

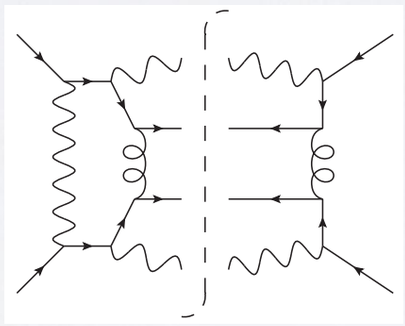


$\mathcal{O}(\alpha^4)$

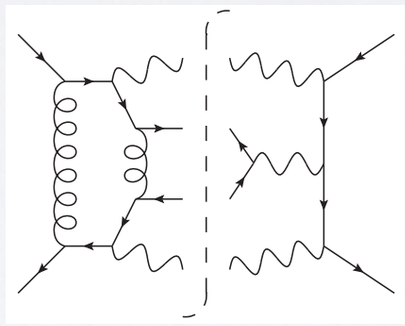
Figure 1: Illustrative leading and sub-leading tree-level diagrams for $\gamma\gamma + jj$ production.



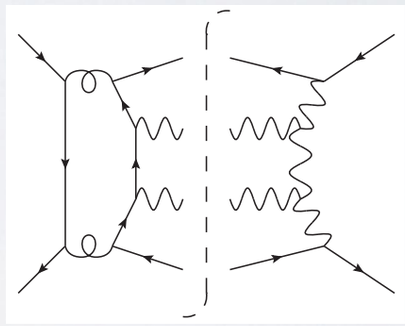
$\mathcal{O}(g_s^2e^4) \times \mathcal{O}(g_s^2e^2)$



$\mathcal{O}(g_s^2e^4) \times \mathcal{O}(g_s^2e^2)$



$\mathcal{O}(g_s^4e^2) \times \mathcal{O}(e^4)$



$\mathcal{O}(g_s^4e^2) \times \mathcal{O}(e^4)$

Figure 2: Representative virtual corrections at $\mathcal{O}(\alpha_s^2\alpha^3)$ for $\gamma\gamma + jj$ production.

'NLO EW$*$' includes also O($\alpha s\alpha^3$) contributions
'NLO EW$**$' includes both the O($\alpha s\alpha^3$) and O(α^4) terms

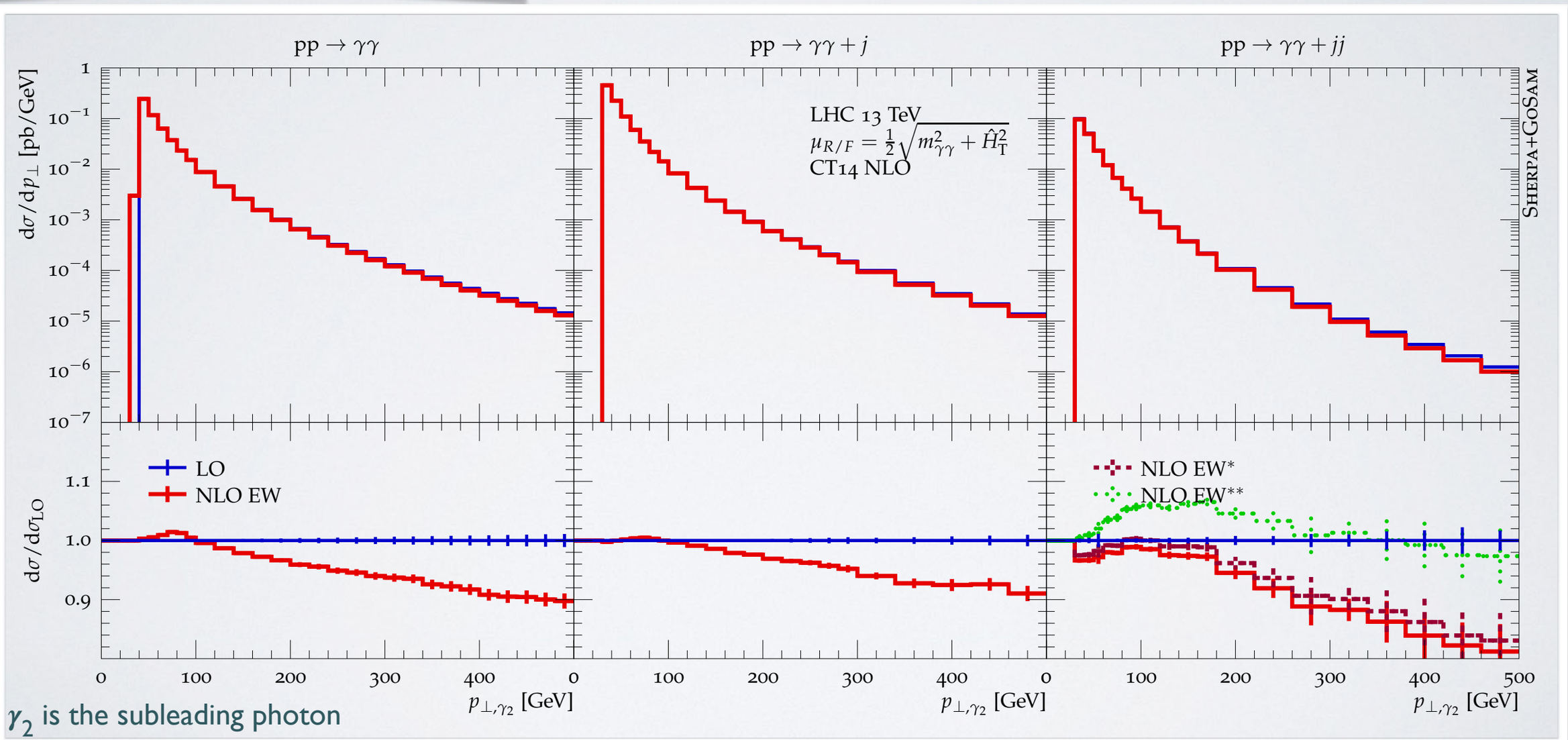
Chiesa, Greiner, Schoenherr, Tramontano [2017]

EW CORRECTIONS FOR $\gamma\gamma$(+JETS)

$$\sqrt{s} = 13 \text{ TeV}$$
$$p_{T\gamma}^{\text{hard}} \geq 40 \text{ GeV}, \; p_{T\gamma}^{\text{soft}} \geq 30 \text{ GeV}$$
$$|y_\gamma| < 1.37, \; \text{n=1}, \Delta R_{\gamma\gamma} > 0.4$$
$$R = 0.4, \; E_{T\ max} = 0.05\ p_T^\gamma.$$

Comparing transverse momentum vs. invariant mass distributions, we note that in this observable the EW corrections easily reach 10% deviation from the LO at a few hundreds of GeV.
This fact is similar (grosso modo) to what we can find for the EW corrections for ZZ and WW production.

Biedermann, Denner, Dittmaier,Hofer,Jäger [2016]
Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder [2016]



γ_2 is the subleading photon

No photon initiated processes

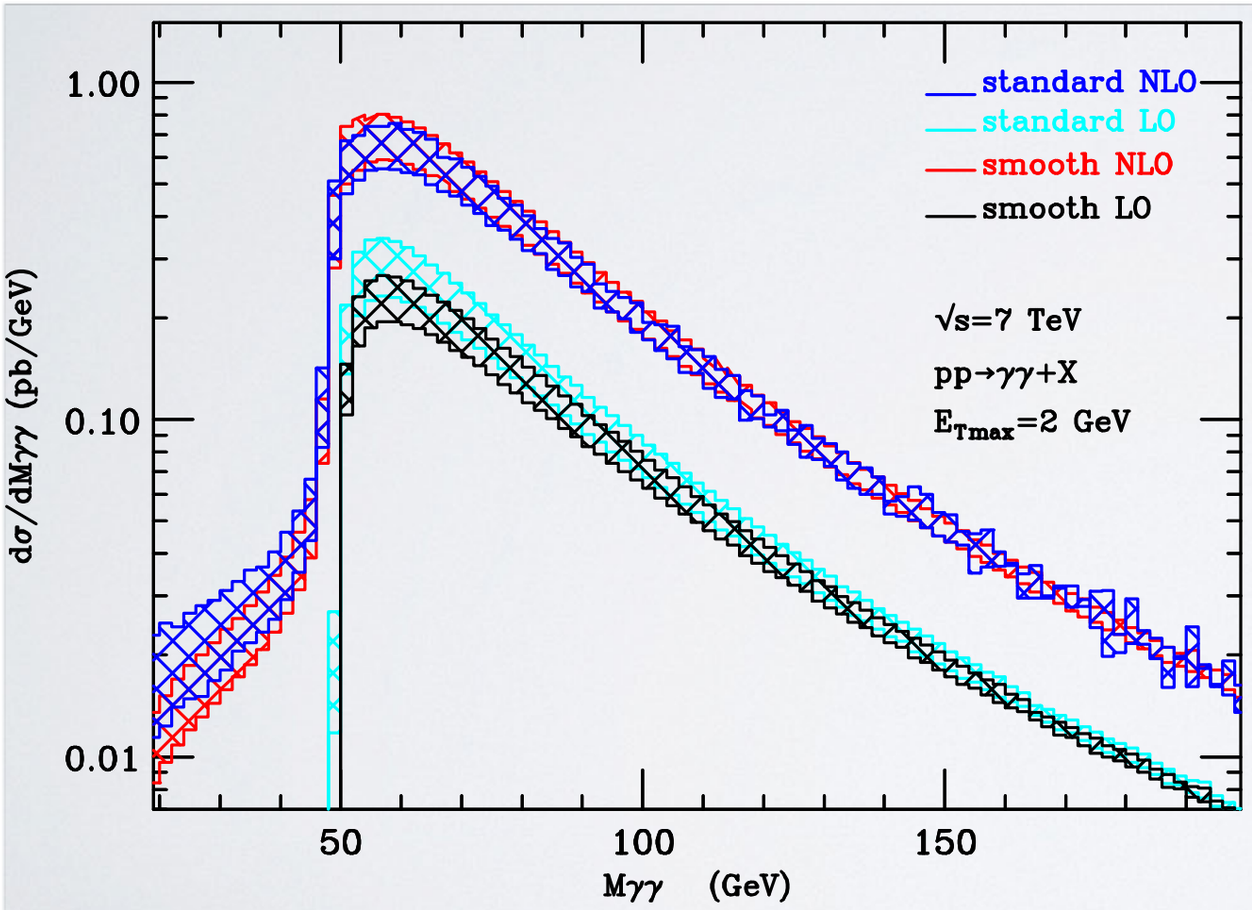
Chiesa,Greiner, Schoenherr,Tramontano [2017]

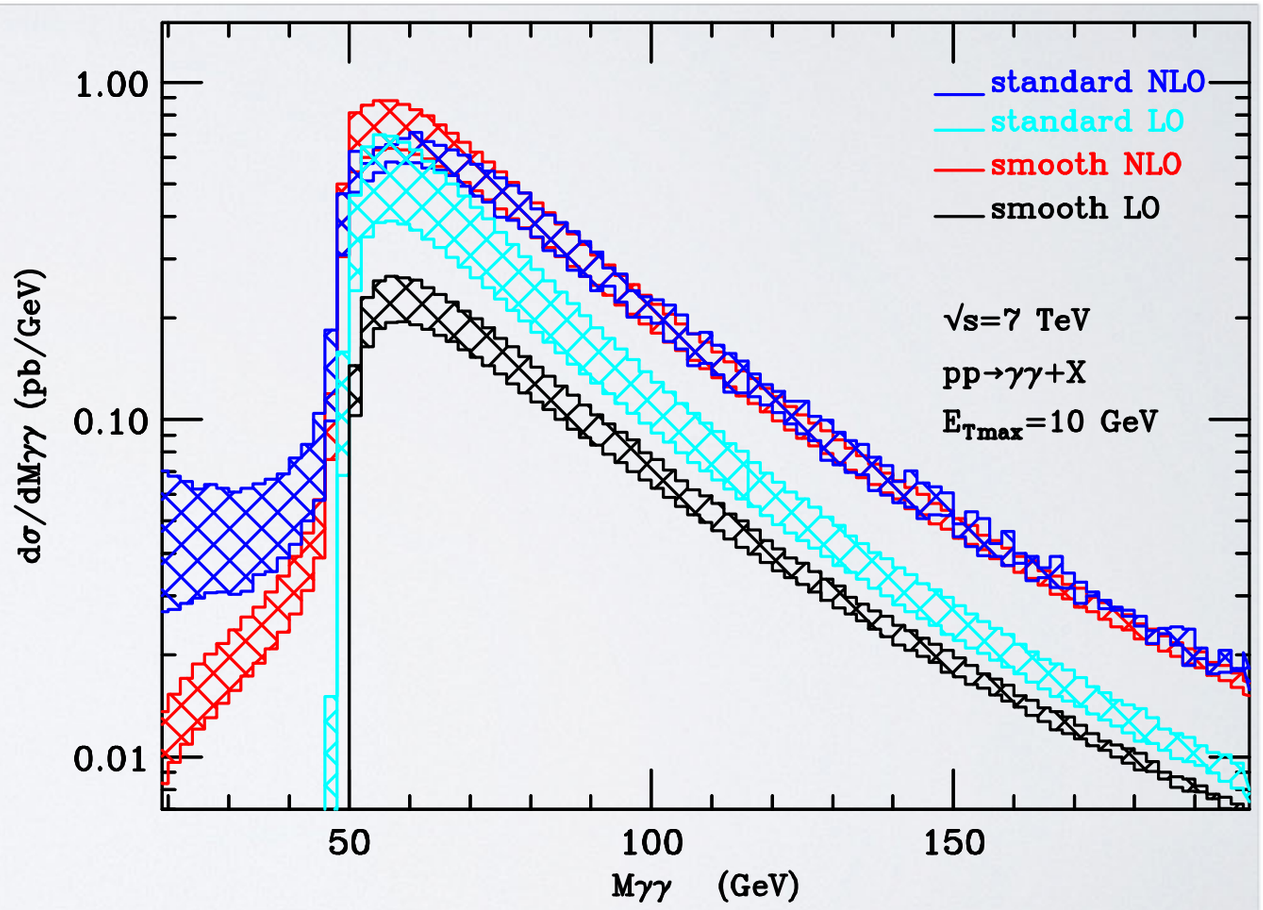
'NLO EW$*$' includes also $O(\alpha_s\alpha^3)$ contributions
'NLO EW$**$' includes both the $O(\alpha_s\alpha^3)$ and $O(\alpha^4)$ terms

PHOTON ISOLATION

$$\sqrt{s} = 7 \text{ TeV}$$
$$p_{T\gamma}^{\text{hard}} \geq 25 \text{ GeV}, \; p_{T\gamma}^{\text{soft}} \geq 22 \text{ GeV}$$
$$|y_\gamma| < 2.37, \; R_{\gamma\gamma}^{\min} = 0.4$$

Neglecting the rapidity crack these are the cuts implemented in the following measurement of the diphoton cross section: ATLAS (1211.1913)





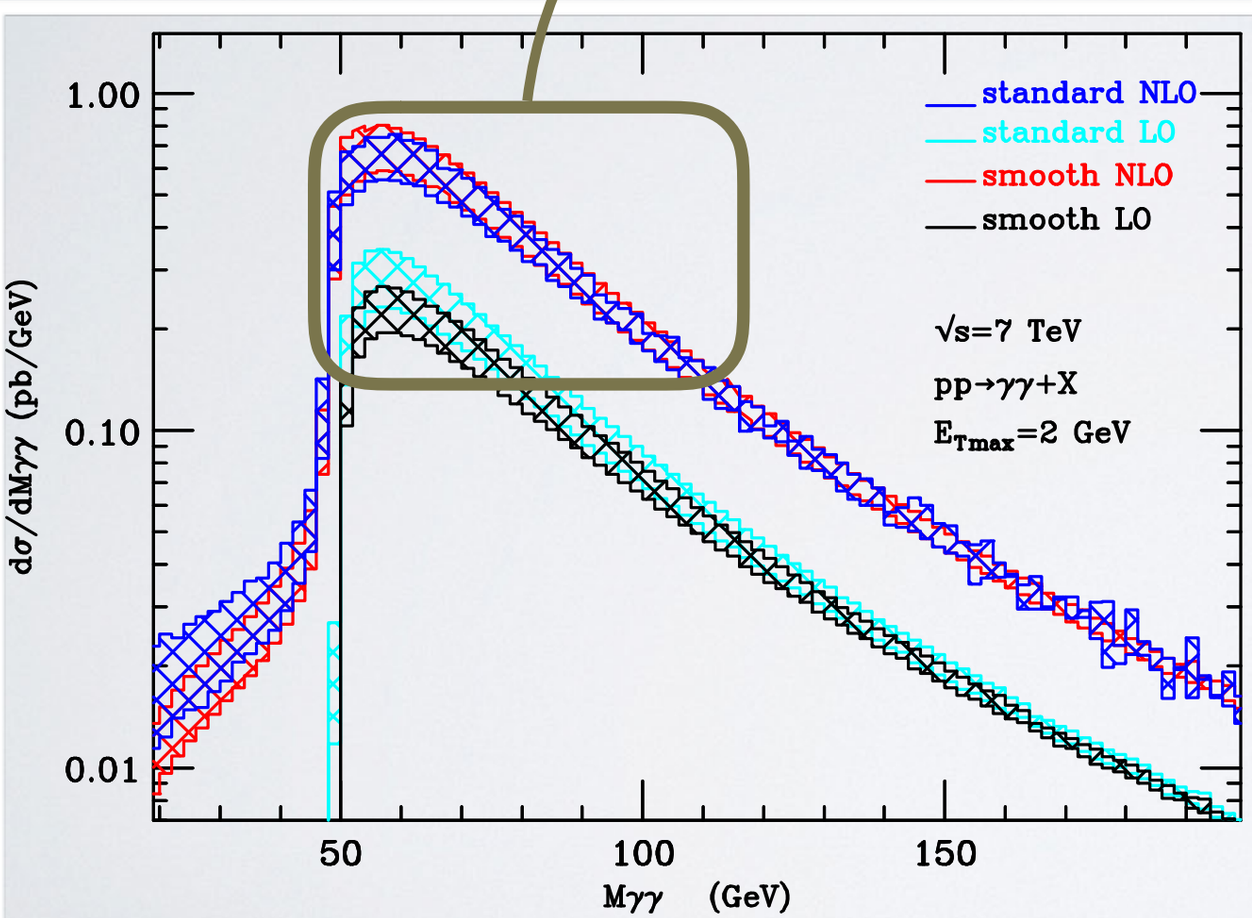
Standard results obtained with DIPHOX
Smooth cone results obtained with 2yNNLO

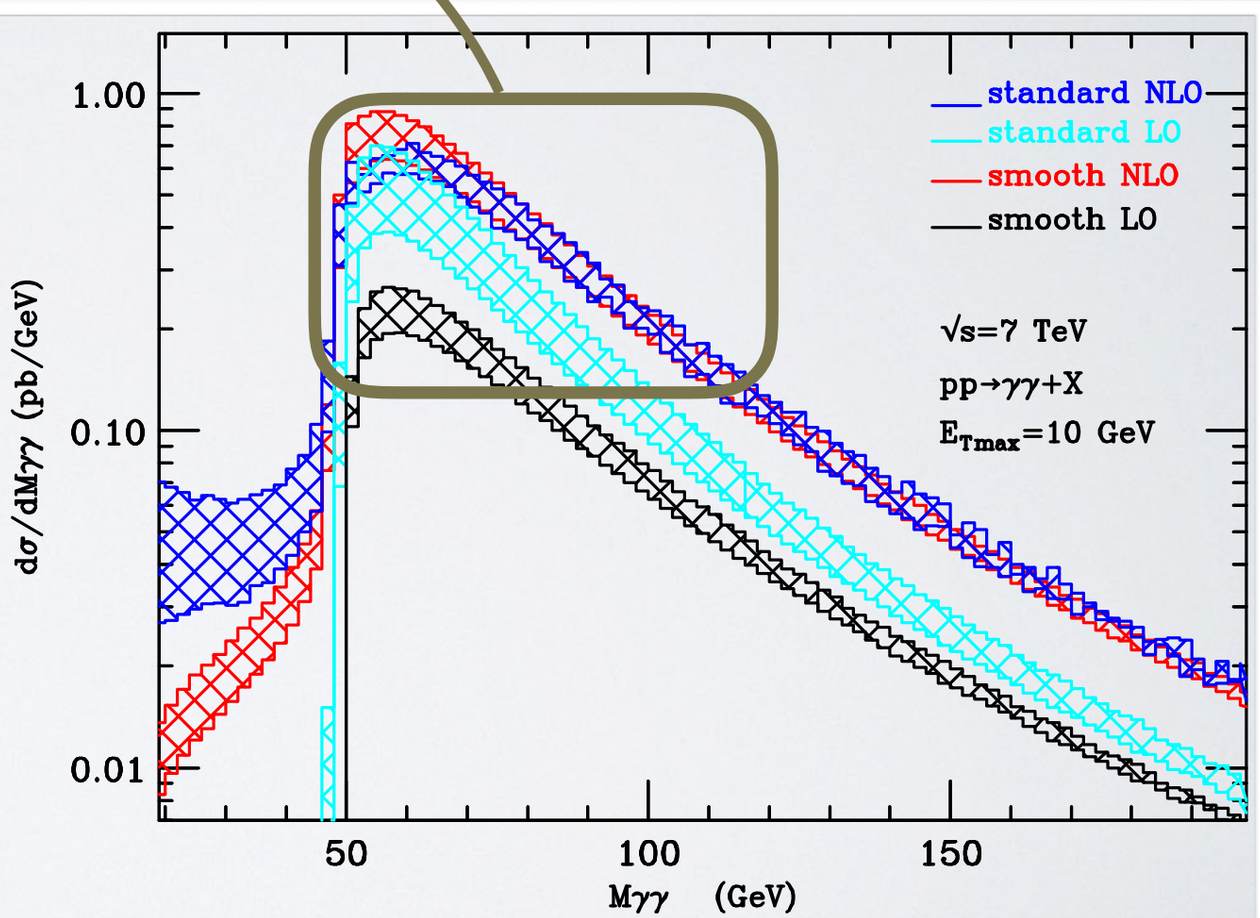
Catani, LC, de Florian, Ferrera, Grazzini, in preparation [2017]

PHOTON ISOLATION

Quantitative results

Bulk of the cross section





Standard results obtained with DIPHOX

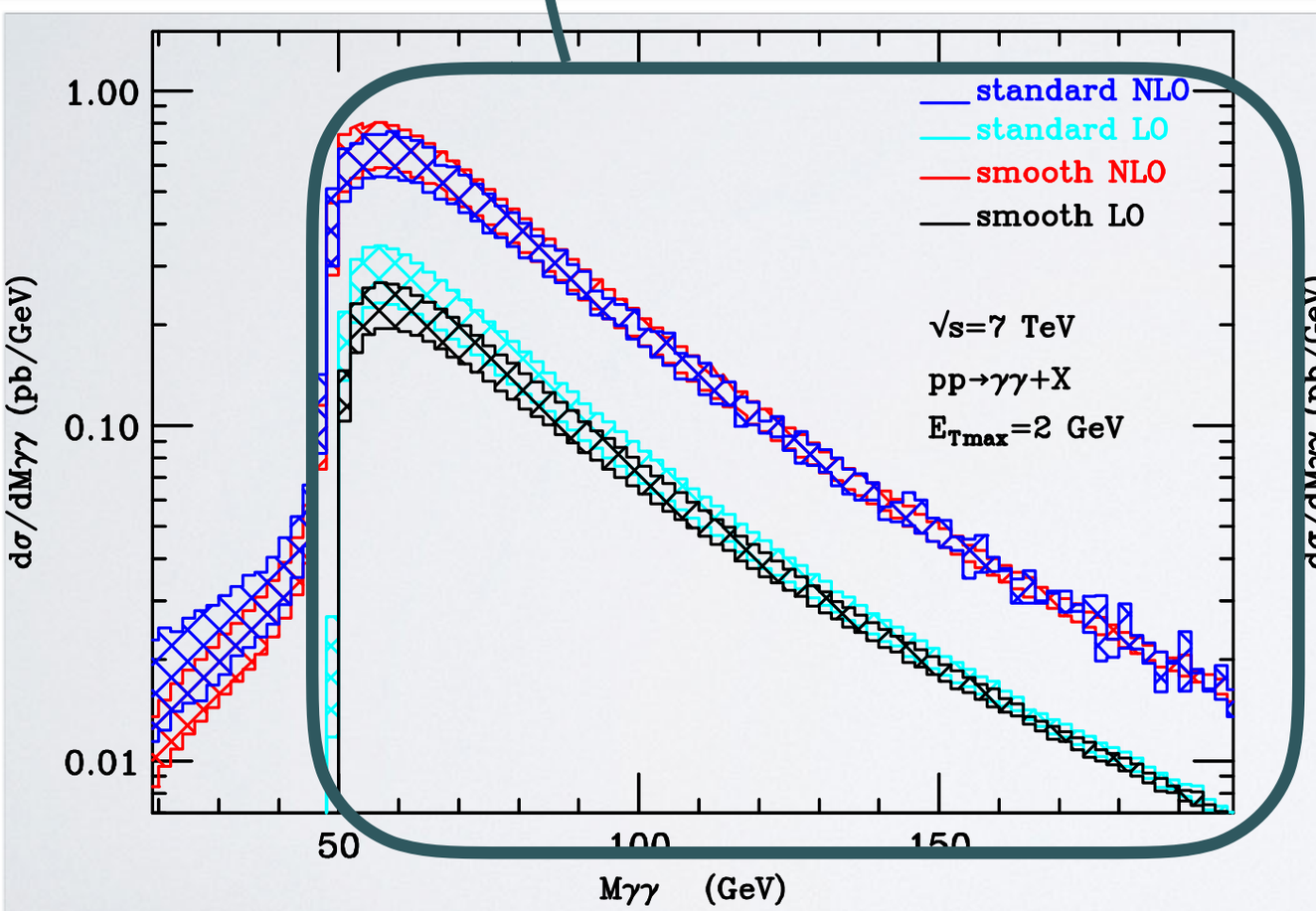
Smooth cone results obtained with 2yNNLO

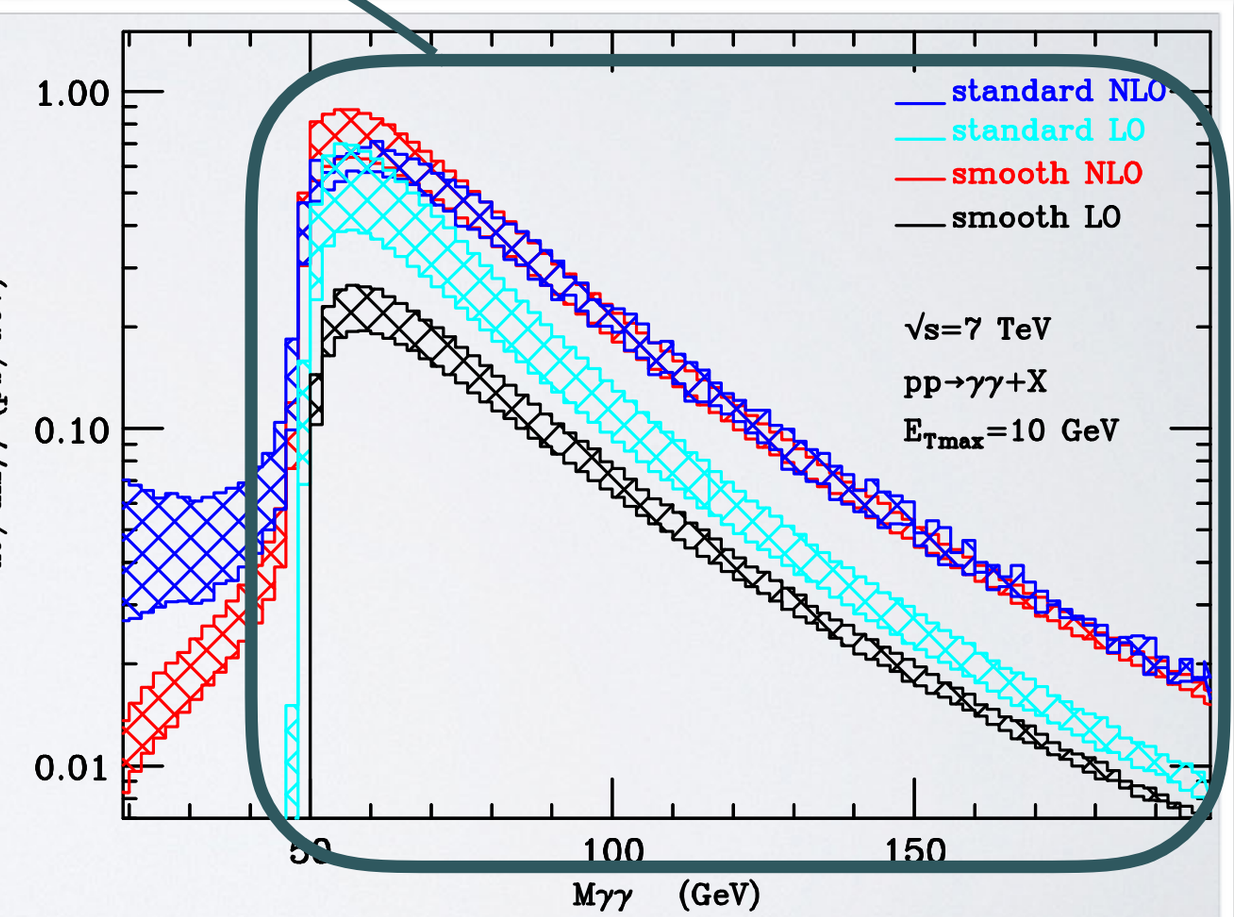
Catani, LC, de Florian, Ferrera, Grazzini, in preparation [2017]

PHOTON ISOLATION

Quantitative results

The LO and NLO bands do not overlap





Standard results obtained with DIPHOX
Smooth cone results obtained with 2γNNLO

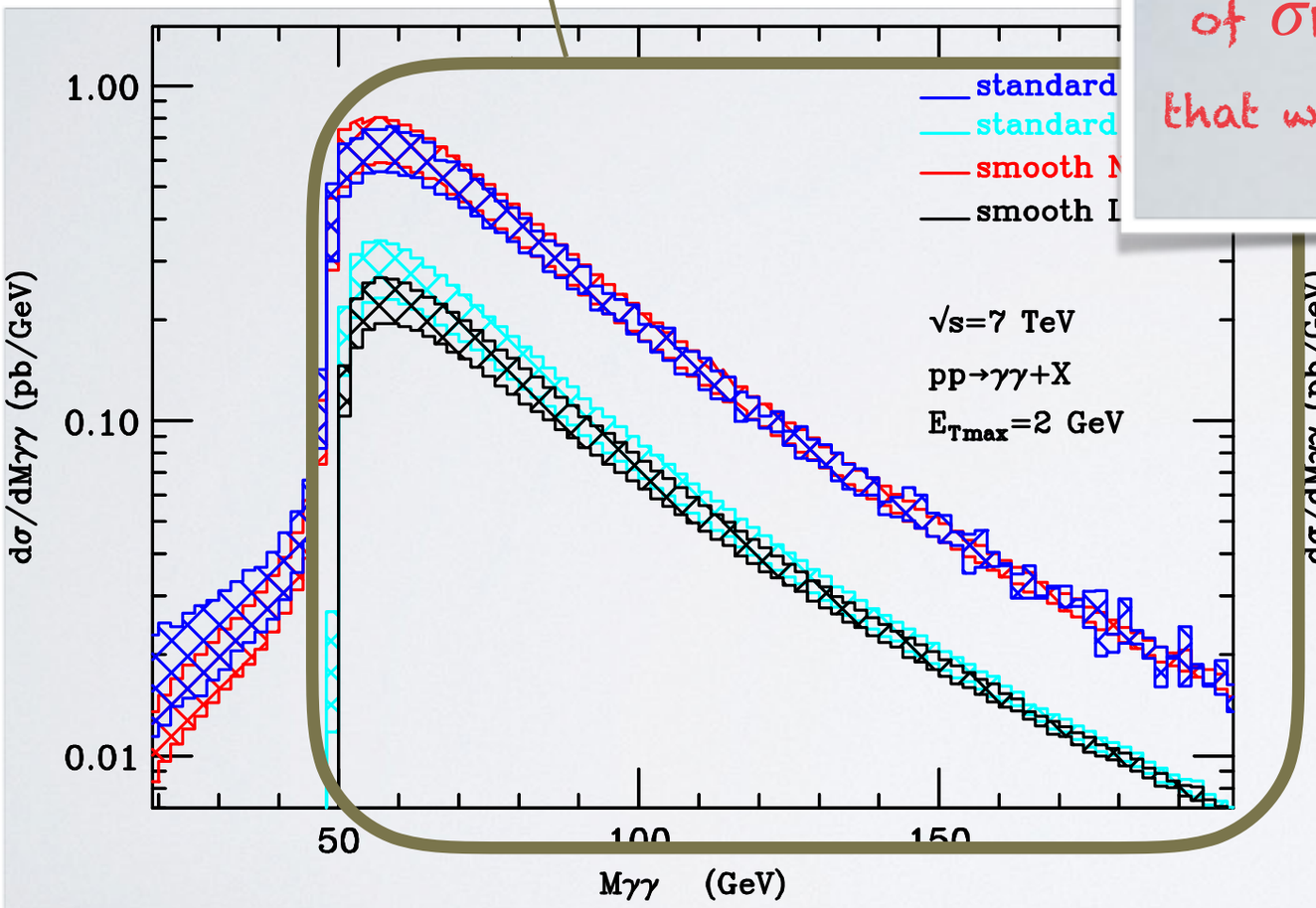
Catani, LC, de Florian, Ferrera, Grazzini, in preparation [2017]

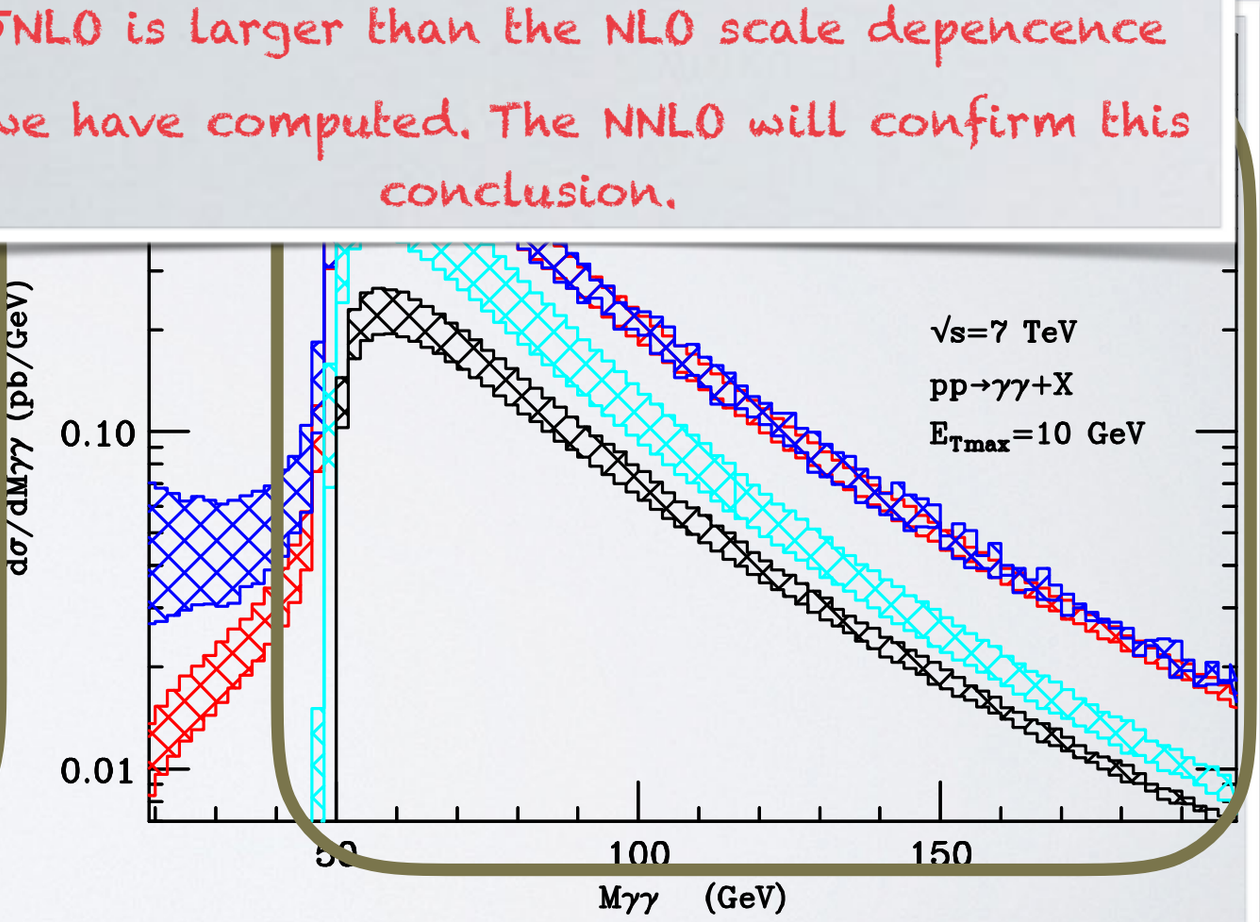
PHOTON ISOLATION

Quantitative results

The LO and NLO bands do not overlap

This implies that the scale dependence of σNLO cannot be consistently regarded as a reliable estimate of uncalculated higher-order radiative corrections to σ: the 'true' theoretical uncertainty of σNLO is larger than the NLO scale depencence that we have computed. The NNLO will confirm this conclusion.





Standard results obtained with DIPHOX
Smooth cone results obtained with 2γNNLO

Catani, LC, de Florian, Ferrera, Grazzini, in preparation [2017]

FIXED ORDER CALCULATIONS TOOLKIT

PROCESS OF INTEREST
F + X

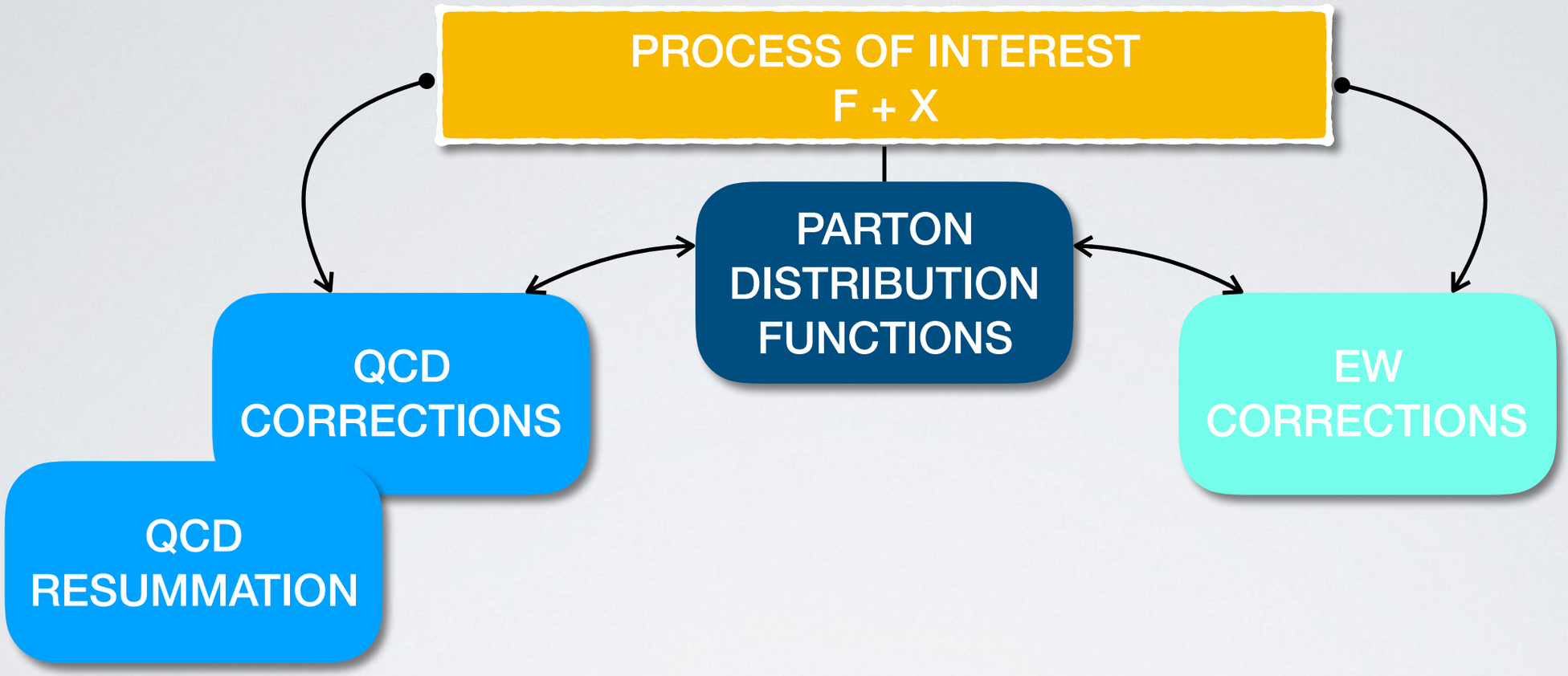
FIXED ORDER CALCULATIONS TOOLKIT

PROCESS OF INTEREST
F + X

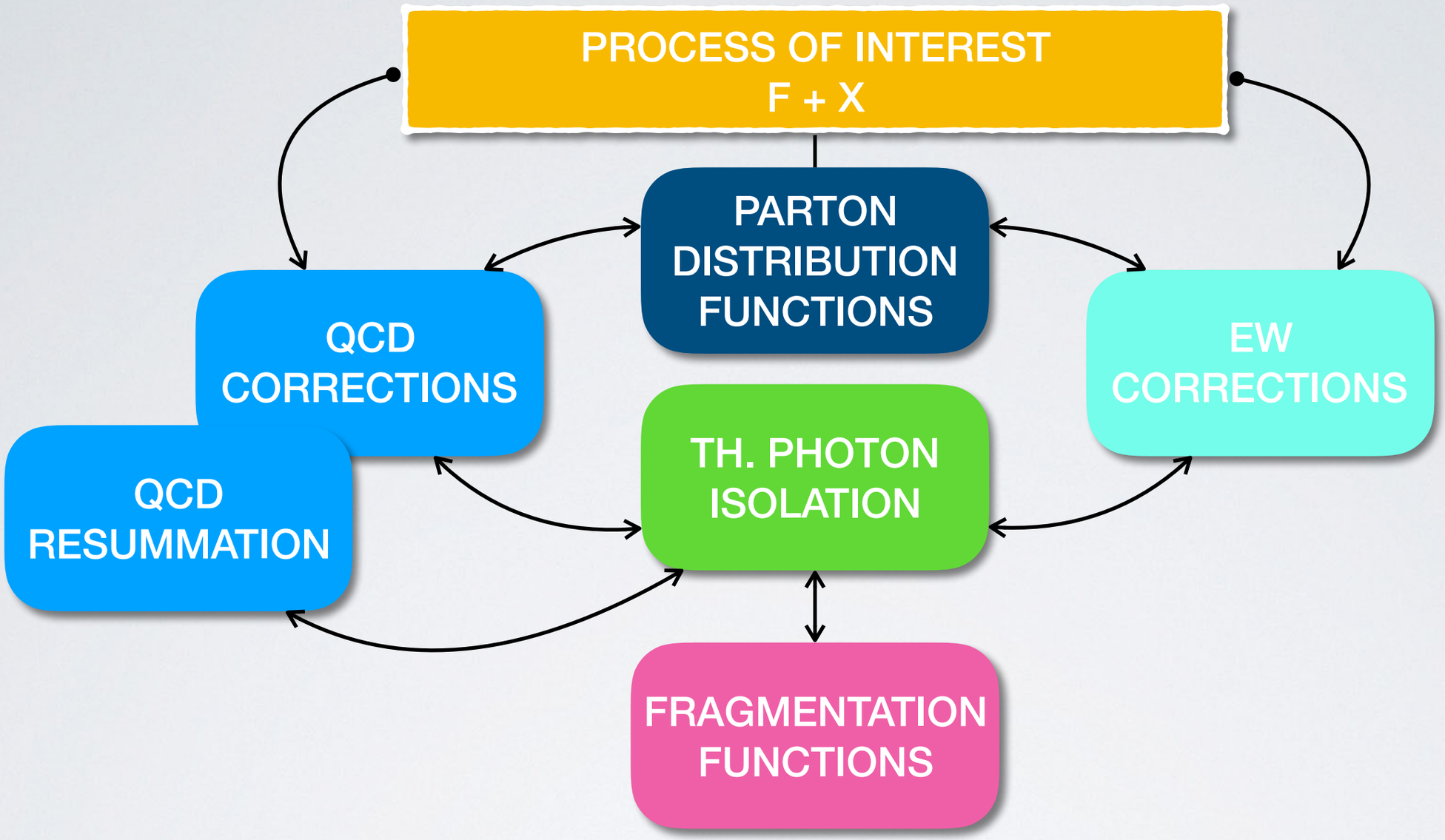
F = MISURED γ FINAL STATE

X = UNDETECTED ACOMPANYING RADIATION

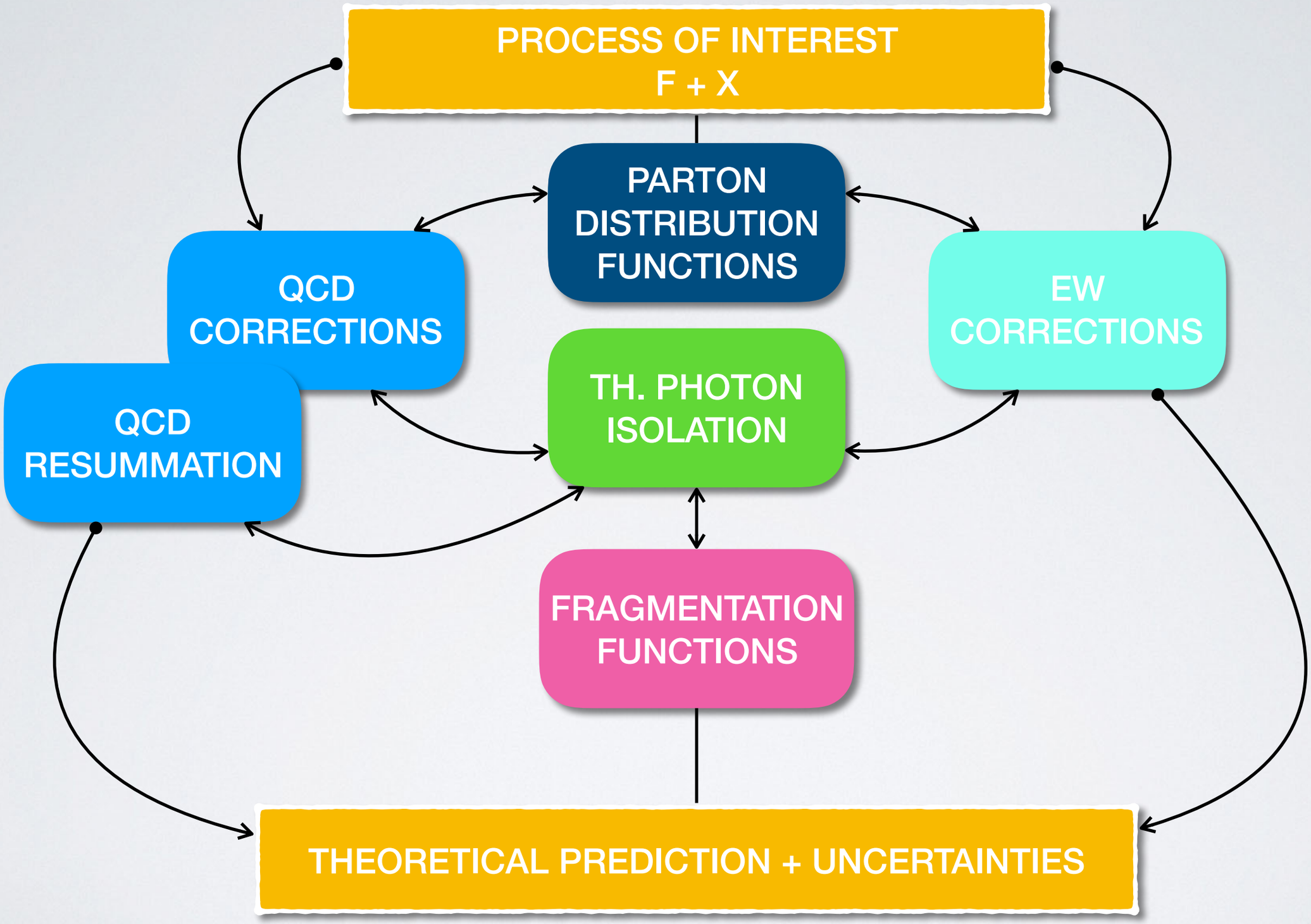
FIXED ORDER CALCULATIONS TOOLKIT



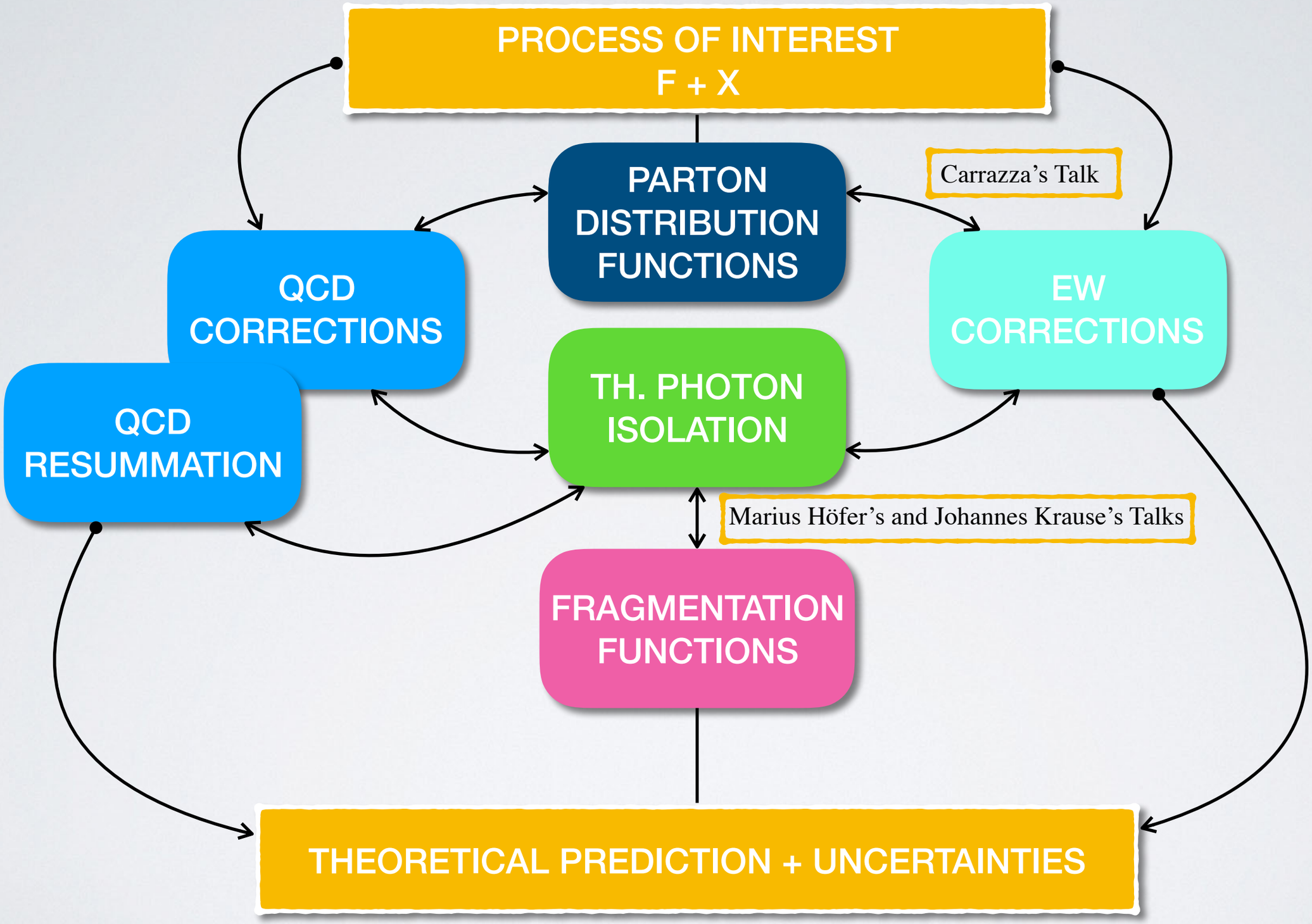
FIXED ORDER CALCULATIONS TOOLKIT



FIXED ORDER CALCULATIONS TOOLKIT



FIXED ORDER CALCULATIONS TOOLKIT



FIXED ORDER CALCULATIONS TOOLKIT

FIXED ORDER CALCULATIONS TOOLKIT

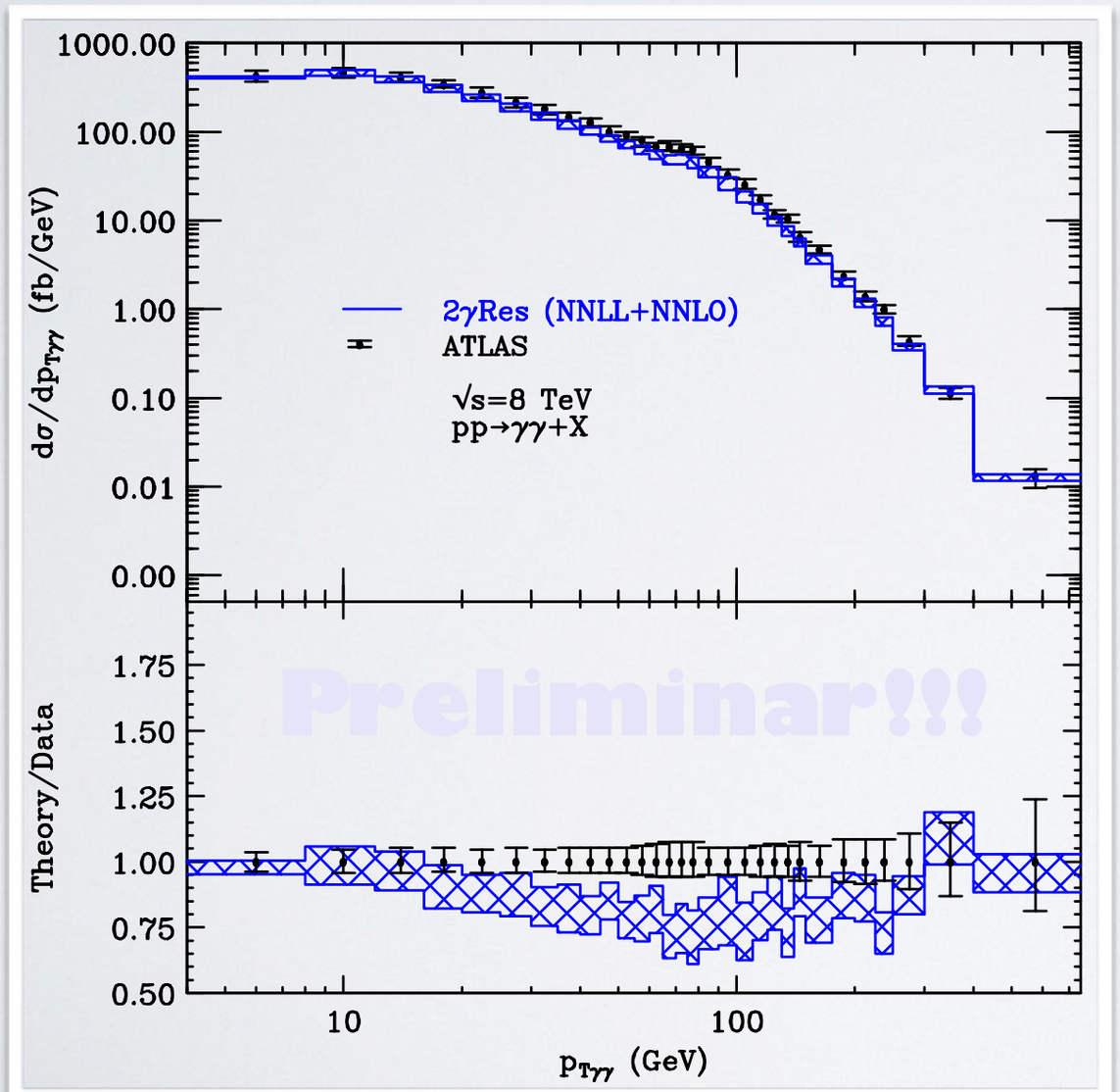
FIXED ORDER TOOLS + RESUMMATION (I.E NOT PARTON SHOWER GENERATORS)

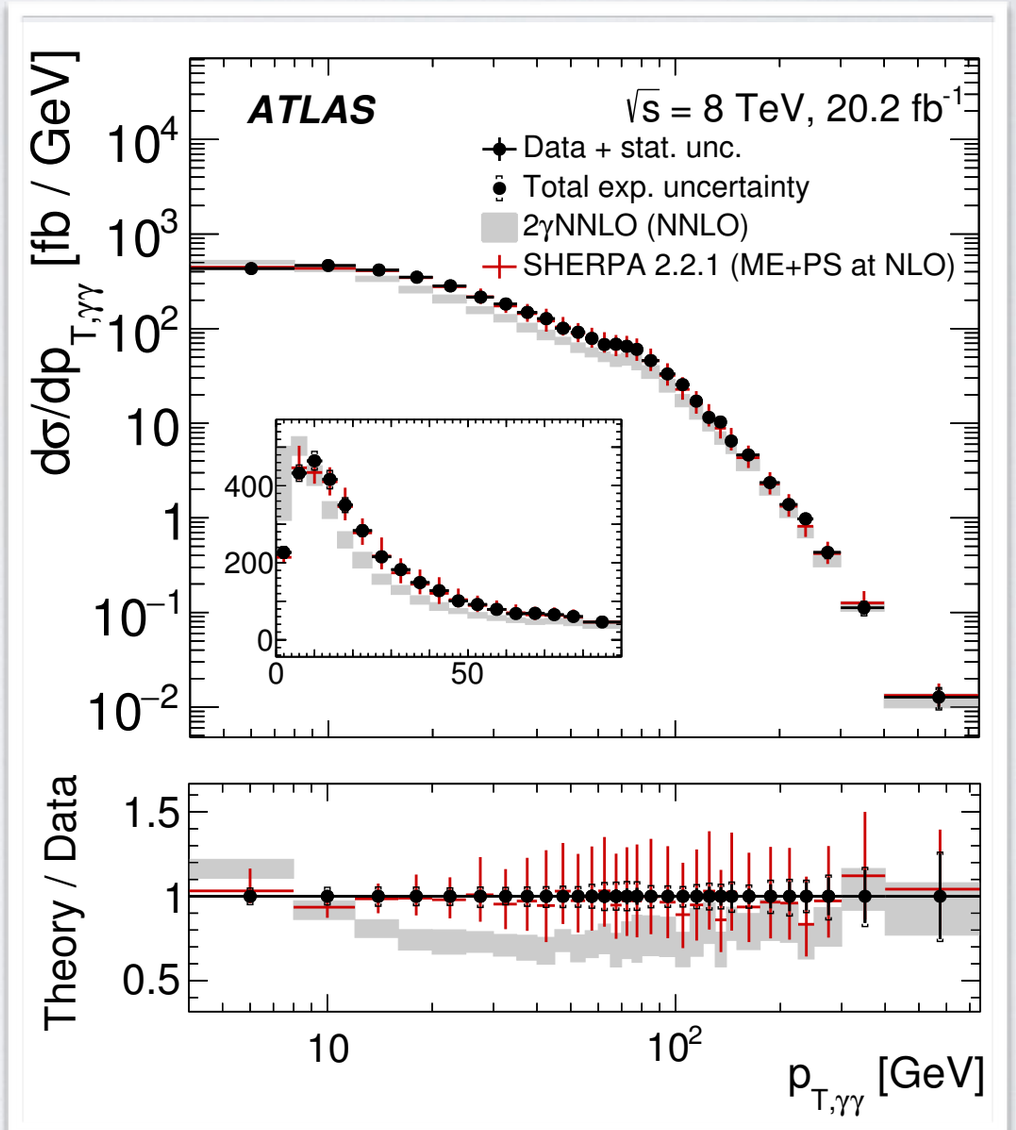
TRANSVERSE-MOMENTUM RESUMMATION

$$\sqrt{s} = 8 \text{ TeV}$$
$$p_{T\gamma}^{\text{hard}} \geq 40 \text{ GeV}, \; p_{T\gamma}^{\text{soft}} \geq 30 \text{ GeV}$$
$$|y_\gamma| < 1.37 \text{ and } 1.56 < |y_\gamma| \leq 2.37, \; R_{\gamma\gamma}^{\min} = 0.4,$$
$$R = 0.4 \text{ and } E_{T\ max} = 11 \text{ GeV}.$$

ATLAS:1704.03839

PDFs uncertainties only included in the ATLAS analysis (2%).





2yRes: LC, Coradeschi, de Florian [2015]

Thanks to Juan Terron Cuadrado, Matthias Saimpert and Bruno Lenzi, For share their 2yRes runs

EW EFFECTS IN DIPHOTON + JETS PRODUCTION

$\sqrt{s} = 13$ TeV

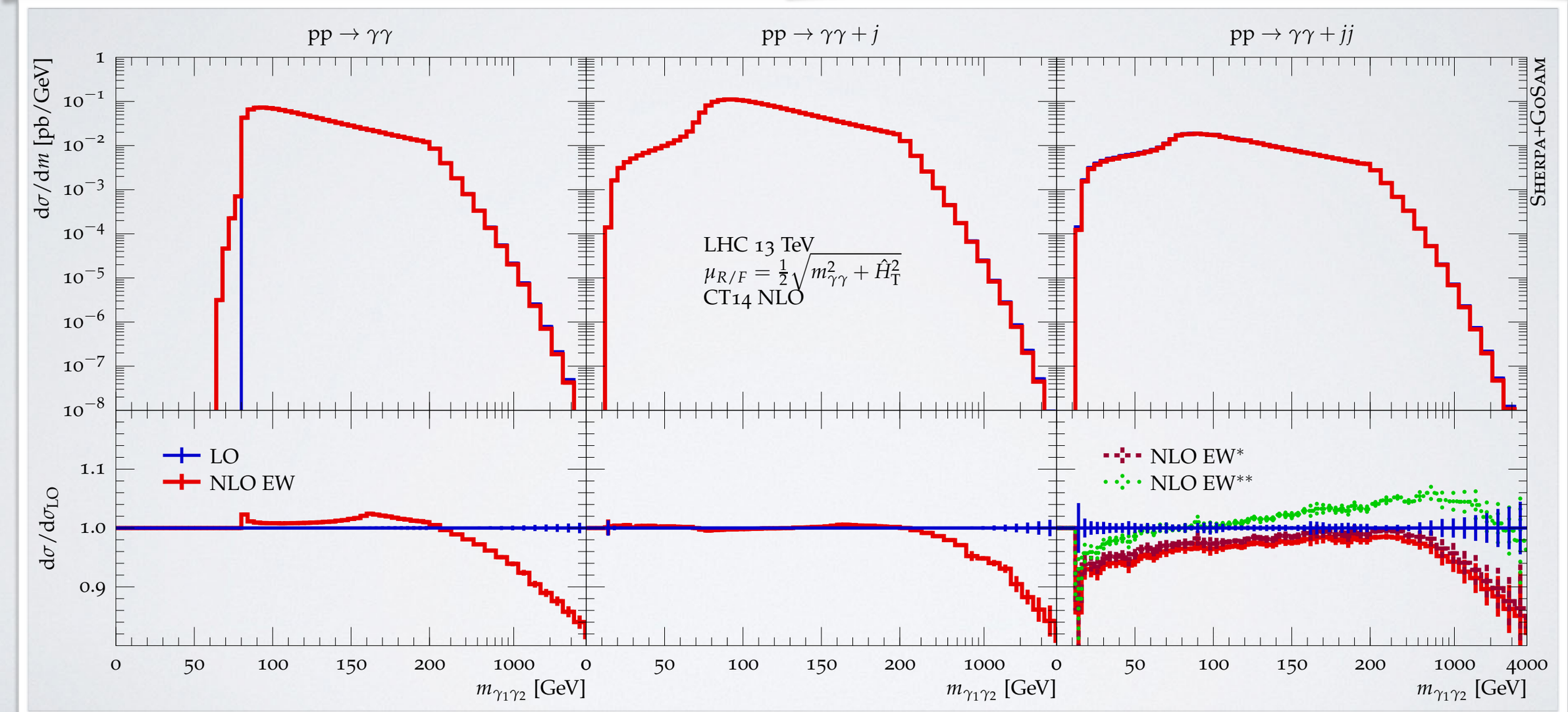
$p_{T\gamma}^{\text{hard}} \geq 40$ GeV, $p_{T\gamma}^{\text{soft}} \geq 30$ GeV

$|y_\gamma| < 1.37$, n=1, $\Delta R_{\gamma\gamma} > 0.4$

$R = 0.4$, $E_{T\ max} = 0.05\ p_T^\gamma$.

	$pp \to \gamma\gamma$	$pp \to \gamma\gamma + j$	$pp \to \gamma\gamma + jj$
σ_{LO} [pb]	5.398	9.597	2.073
$\sigma_{\text{NLO EW}}$ [pb]	5.449	9.587	2.009
δ_{EW} [%]	0.9	−0.1	−3.1

Table 1: Total cross sections at LO and NLO for $\gamma\gamma + 0, 1, 2$ jets production at 13 TeV at the LHC.



No photon initiated processes

'NLO EW$*$' includes also $O(\alpha_s\alpha^3)$ contributions

'NLO EW$**$' includes both the $O(\alpha_s\alpha^3)$ and $O(\alpha^4)$ terms

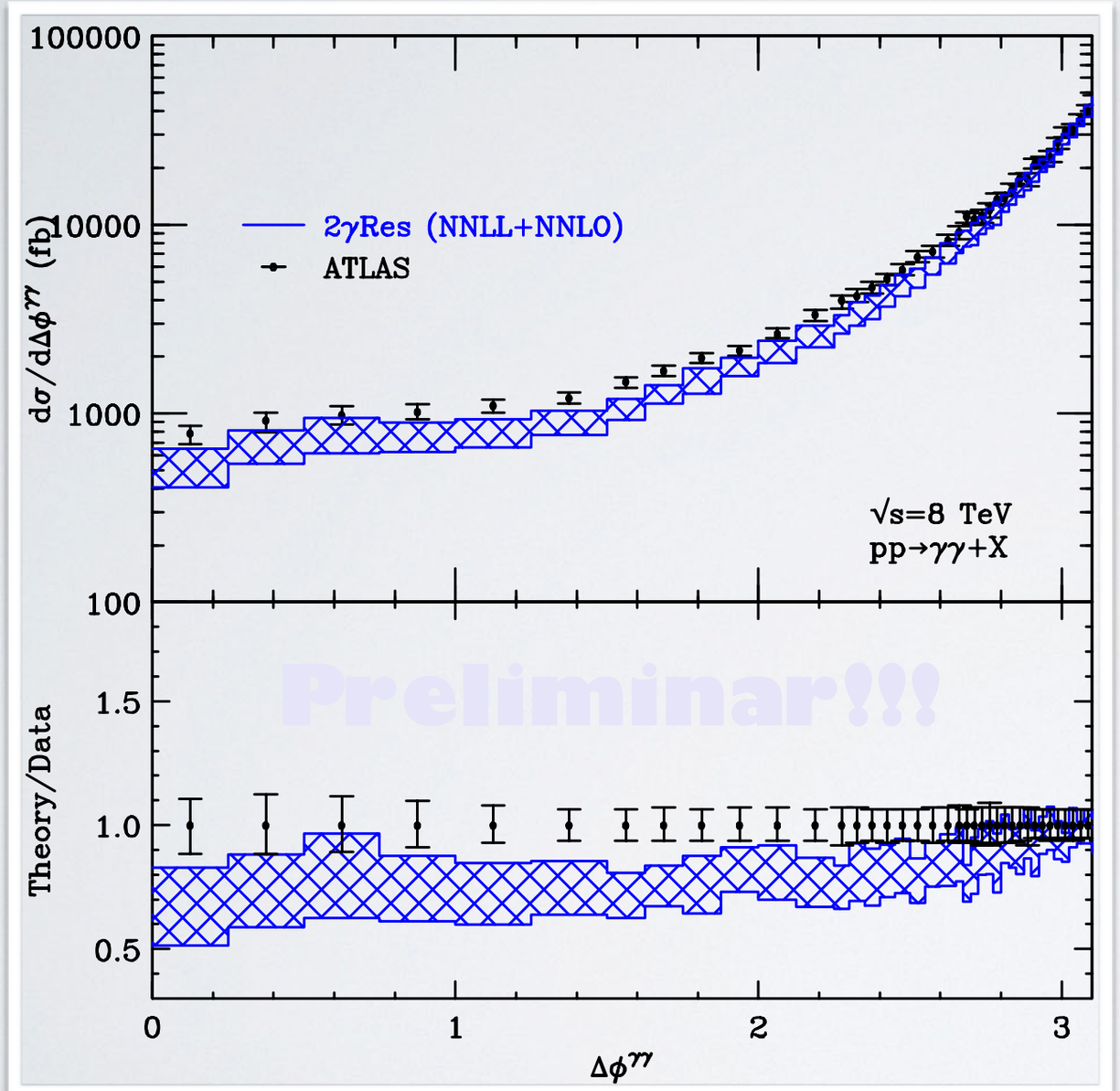
Chiesa,Greiner, Schoenherr, Tramontano [2017]

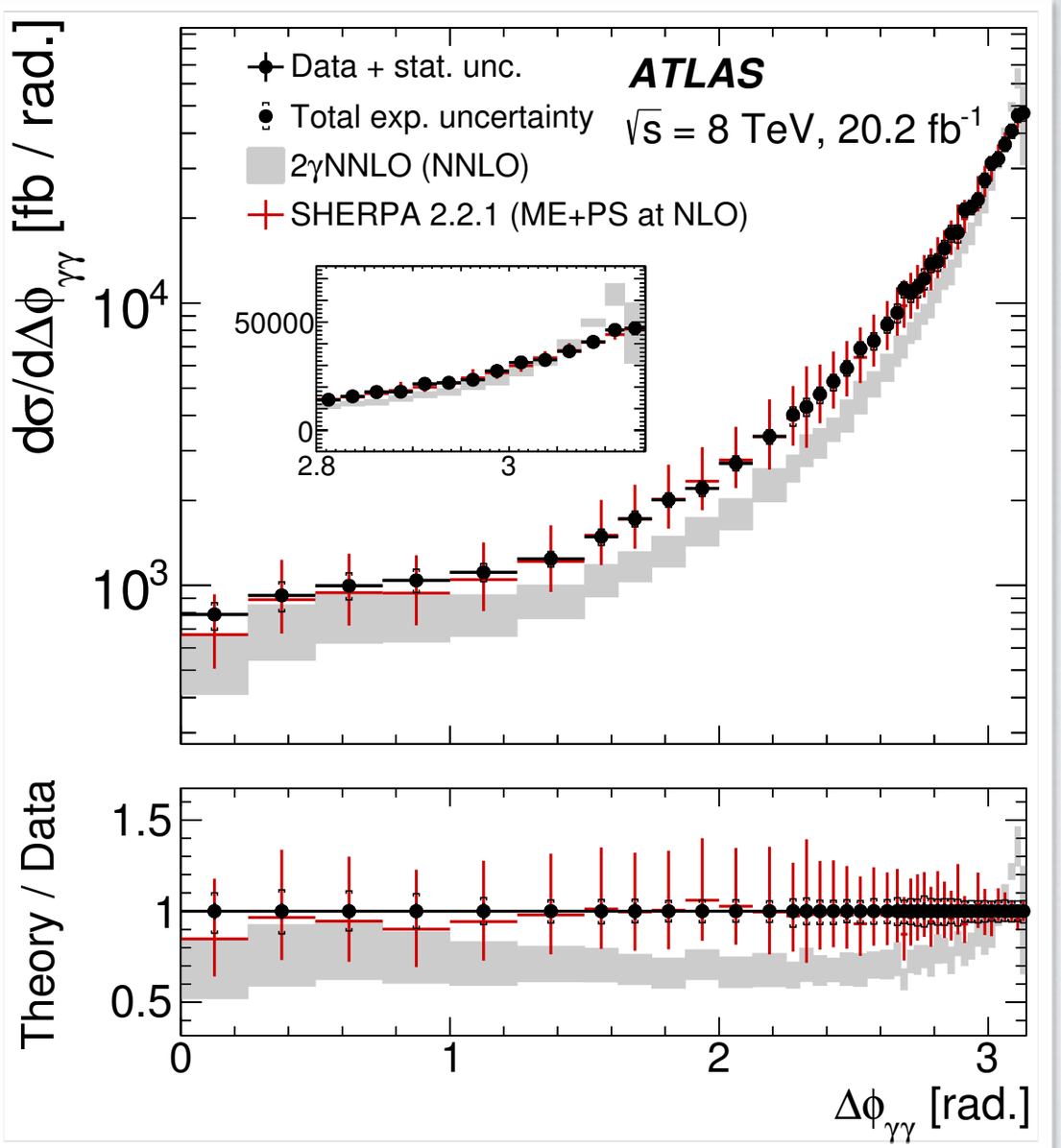
NEWS FROM THEORY

TRANSVERSE-MOMENTUM RESUMMATION

ATLAS:1704.03839

PDFs uncertainties only included in the ATLAS analysis (2%).





2yRes: LC, Coradeschi, de Florian [2015]

Thanks to Juan Terron Cuadrado, Matthias Saimpert and Bruno Lenzi, For share their 2yRes runs