Theory predictions for $pp \rightarrow \gamma\gamma + \text{jets}$

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Photon physics at the LHC, Paris

Di-photon plus jets

$pp \to \gamma\gamma$	NNLO	Catani, Cieri, de Florian, Ferrera, Grazzini [1110.2375]
		NLO available with DIPHOX [Binoth et al hep-ph/9911340]
$pp \to \gamma\gamma + 1j$	NLO	Gehrmann, Greiner, Heinrich [1303.0824] Del Duca, Maltoni, Nagy, Trocsanyi [hep-ph/0303012]
$pp \to \gamma\gamma + 2j$	NLO	Gehrmann, Greiner, Heinrich [1308.3660] Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Lo Presti, Maitre [1312.0592, 1402.4127]
$pp \to \gamma\gamma + 3j$	NLO	SB, Guffanti, Yundin [1312.5927]

Available tools

- GoSam (+ Sherpa)

  [Cullen, van Deurzen, Greiner, Heinrich, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Schlenk, Soden-Fraunhofen, Tramontano]

  gosam.hepforge.org

- NJet (+ Sherpa)

  [SB, Yundin, Biedermann, Uwer]

  bitbucket.org/njet/njet

- BlackHat (+ Sherpa)

  [Bern, Dixon, Forde, Febres Cordero, Hoeche, Ita, Kosower, Lo Presti, Maitre]

- aMC@NLO_MadGraph5

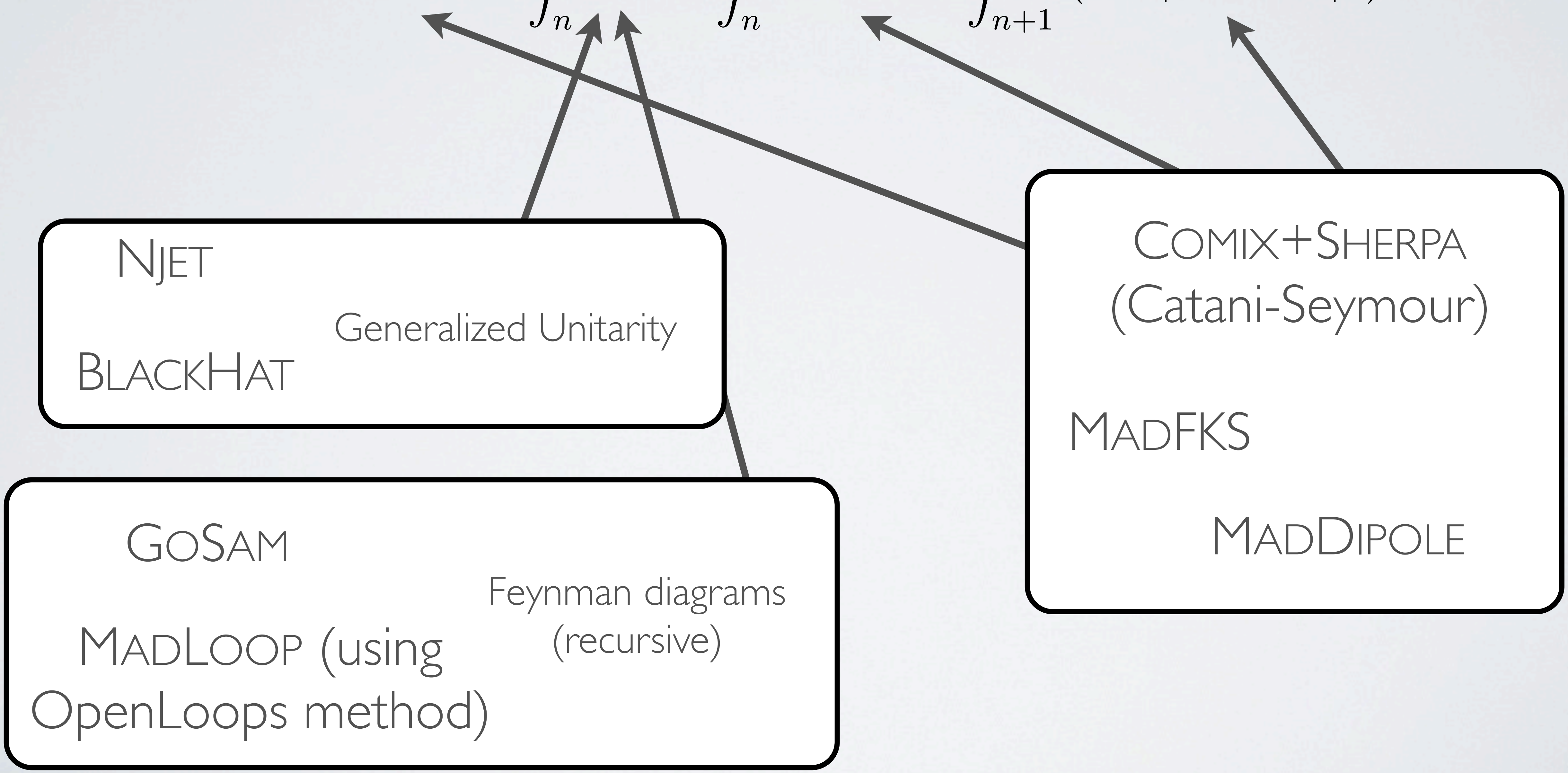
  [Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro]

  amcatnlo.cern.ch

Root Ntuples available: BlackHat (via PPGrid), NJet (via EOS@CERN)

Efficient NLO calculations

$$\sigma_n^{\mathrm{NLO}} = \sigma^{\mathrm{LO}} + \int_n d\sigma_n^{\mathrm{V}} + \int_n d\sigma_n^{\mathrm{I+fac.}} + \int_{n+1} \left(d\sigma_{n+1}^{R} - d\sigma_{n+1}^{S}\right)$$



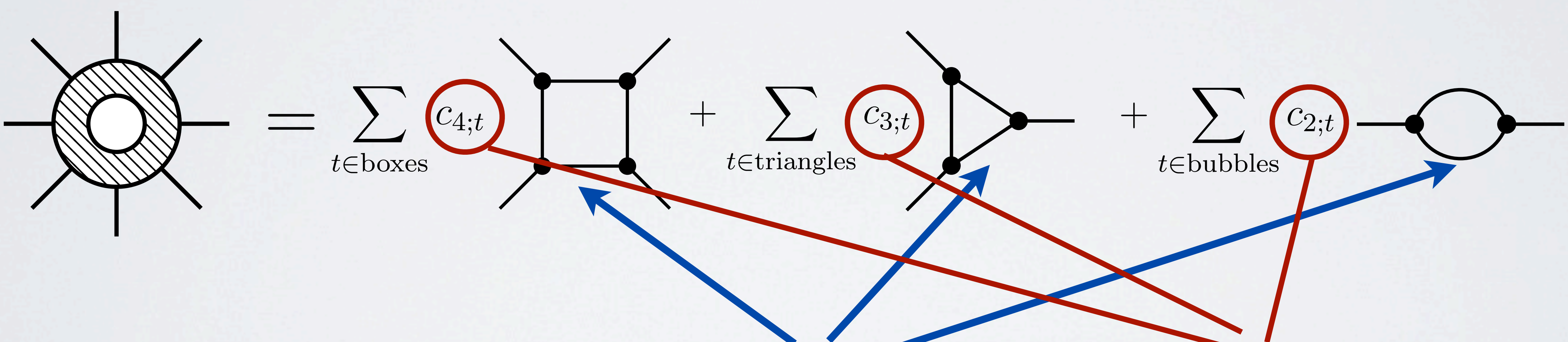
Loop amplitudes

Efficient tree level generators well established

e.g. MadGraph, Alpgen, Comix, Helac,...

Tree Methods

Feynman diagrams
off-shell recursion
on-shell recursion (BCFW)



integral basis separates **analytic** and **algebraic** parts

known functions at one-loop
process independent

e.g. QCDLoop, OneLoop

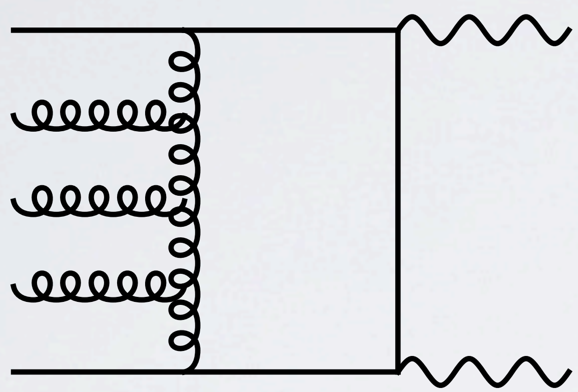
tree-like

complex momenta

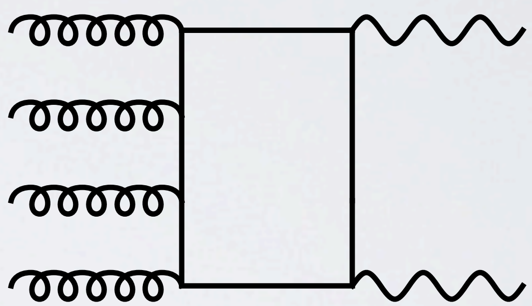
calculate numerically

$pp \to \gamma\gamma + \text{jets}$

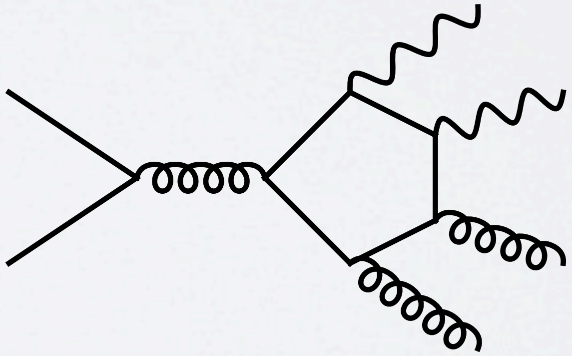
dominant channels - split into leading and sub-leading colour



gluon only channels ~ 2.5% for 2 jets [Bern et al 1402.4127]



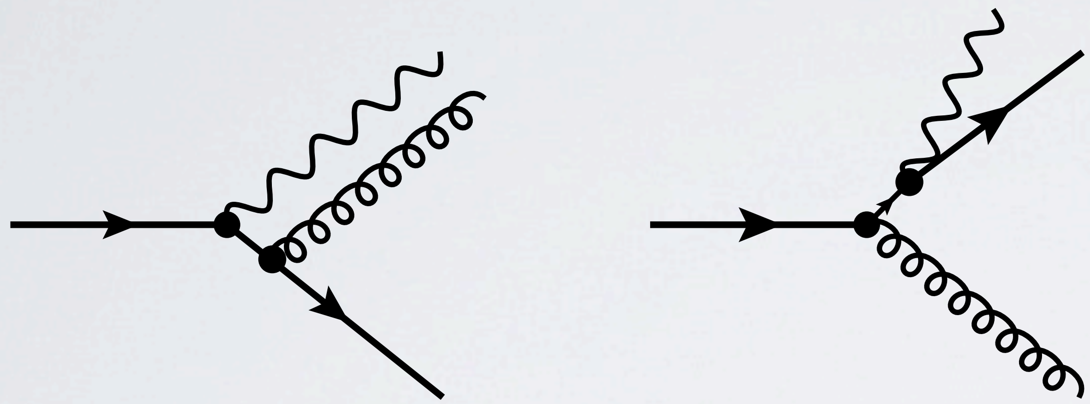
vector loops ~ 0.5% for 2 jets



cut dependent!

Isolating hard photons

[Frixione (1998)]



Infra-red safe definition of a hard photon must include QCD partons

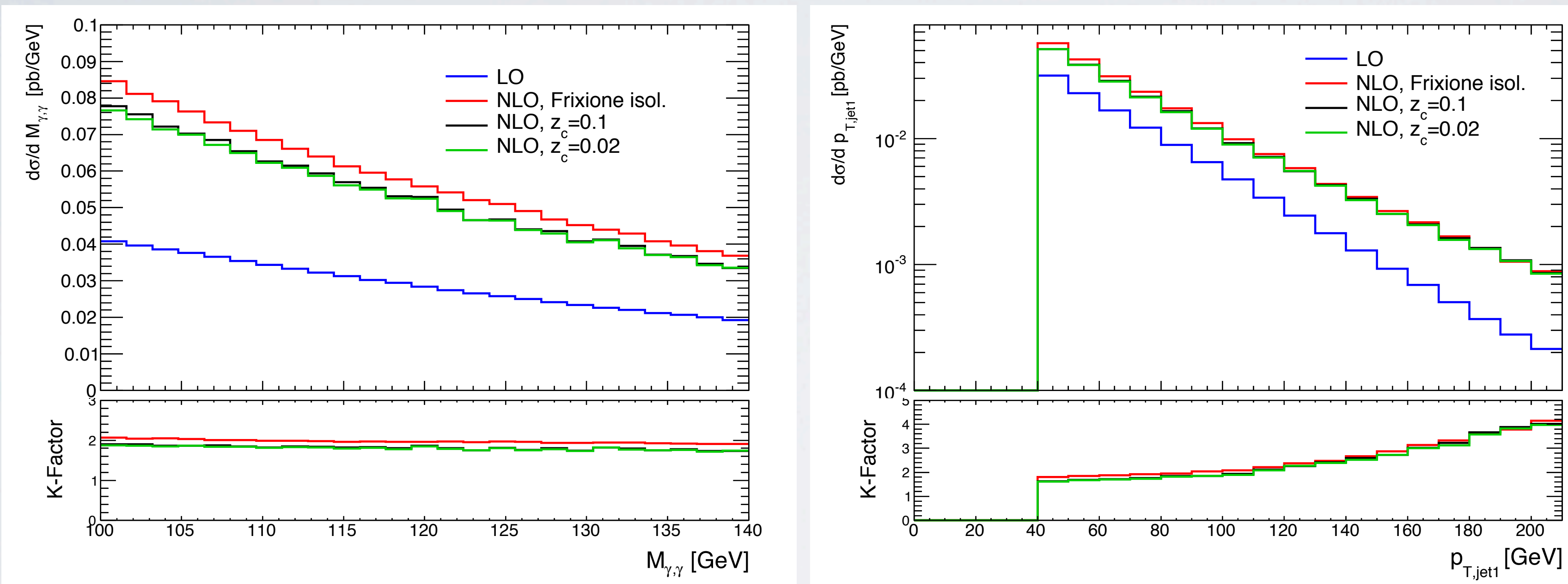
Smooth cone isolation

- keep soft gluons
- discard partons collinear to photon

$$E_{\text{hadronic}}(r_\gamma) \leq \epsilon\, p_{T,\gamma} \left(\frac{1-\cos r_\gamma}{1-\cos R} \right)^n$$

no need for fragmentation functions

Fragmentation vs. Smooth Cone



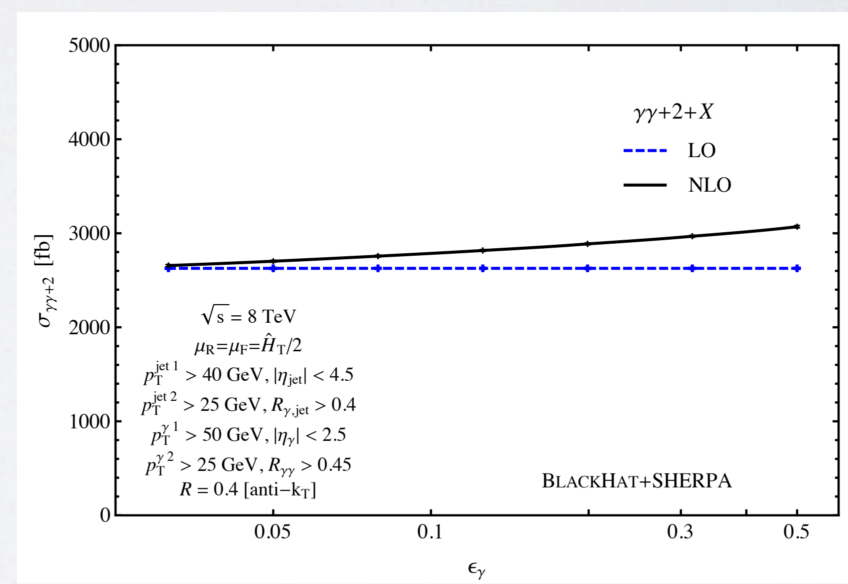
[Gehrmann, Greiner, Heinrich (2013)]

Pragmatic approach:
Tight isolation accord

$$E_T^{max} \leq 5 \text{ GeV} \quad (\text{or } \epsilon < 0.1)$$

$$R \sim 0.4 \qquad R_{\gamma\gamma} \sim 0.4$$

[Cieri, de Florian (Les Houches 2013)]



[Bern at al. (2014)]

$pp \to \gamma\gamma + \text{jets}$ at NLO

SB, Guffanti, Yundin [1312.5927]

$p_{T,j} > 30\,\text{GeV}$ $\qquad |\eta_j| \leq 4.7$

$p_{T,\gamma_1} > 40\,\text{GeV}$ $\qquad p_{T,\gamma_2} > 25\,\text{GeV}$ $\qquad |\eta_\gamma| \leq 2.5$

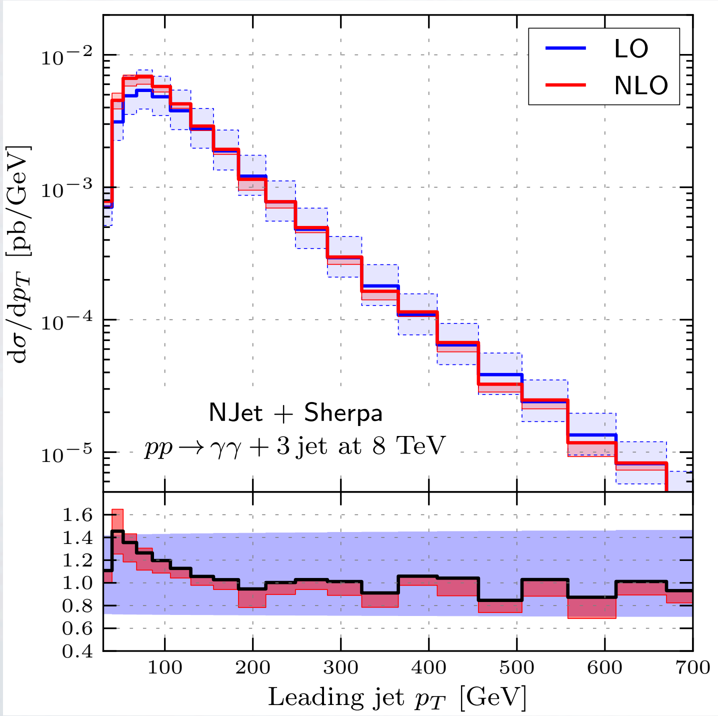
$R_{\gamma,j} = 0.5$ $\qquad R_{\gamma,\gamma} = 0.45$

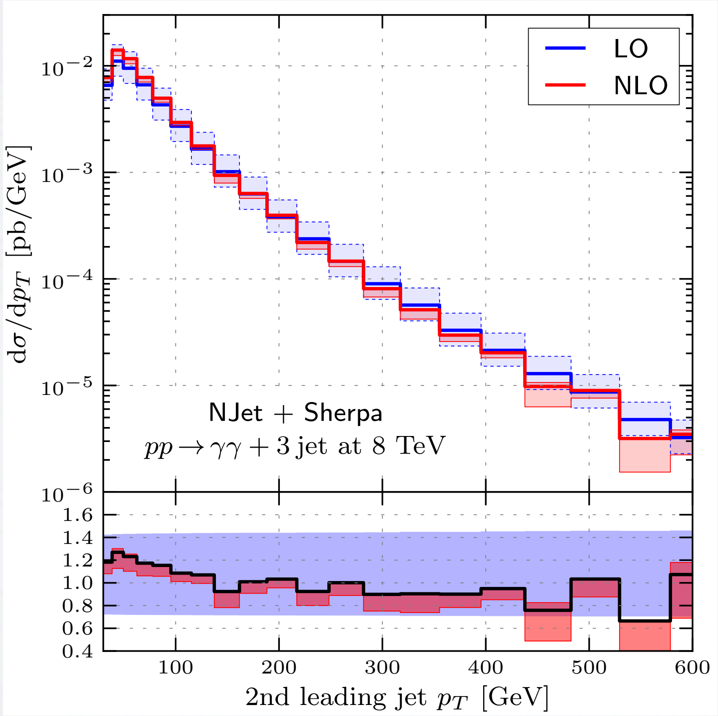
anti-kT $R = 0.5$ (FastJet)

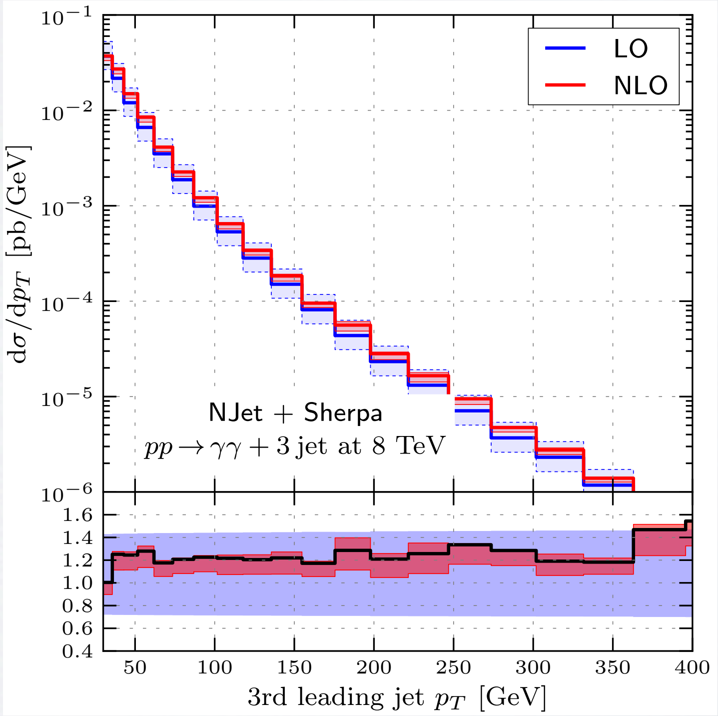
Frixione smooth cone photon isolation $\quad \epsilon = 0.05,\ R = 0.4 \text{ and } n = 1$

CT10 NLO PDF set

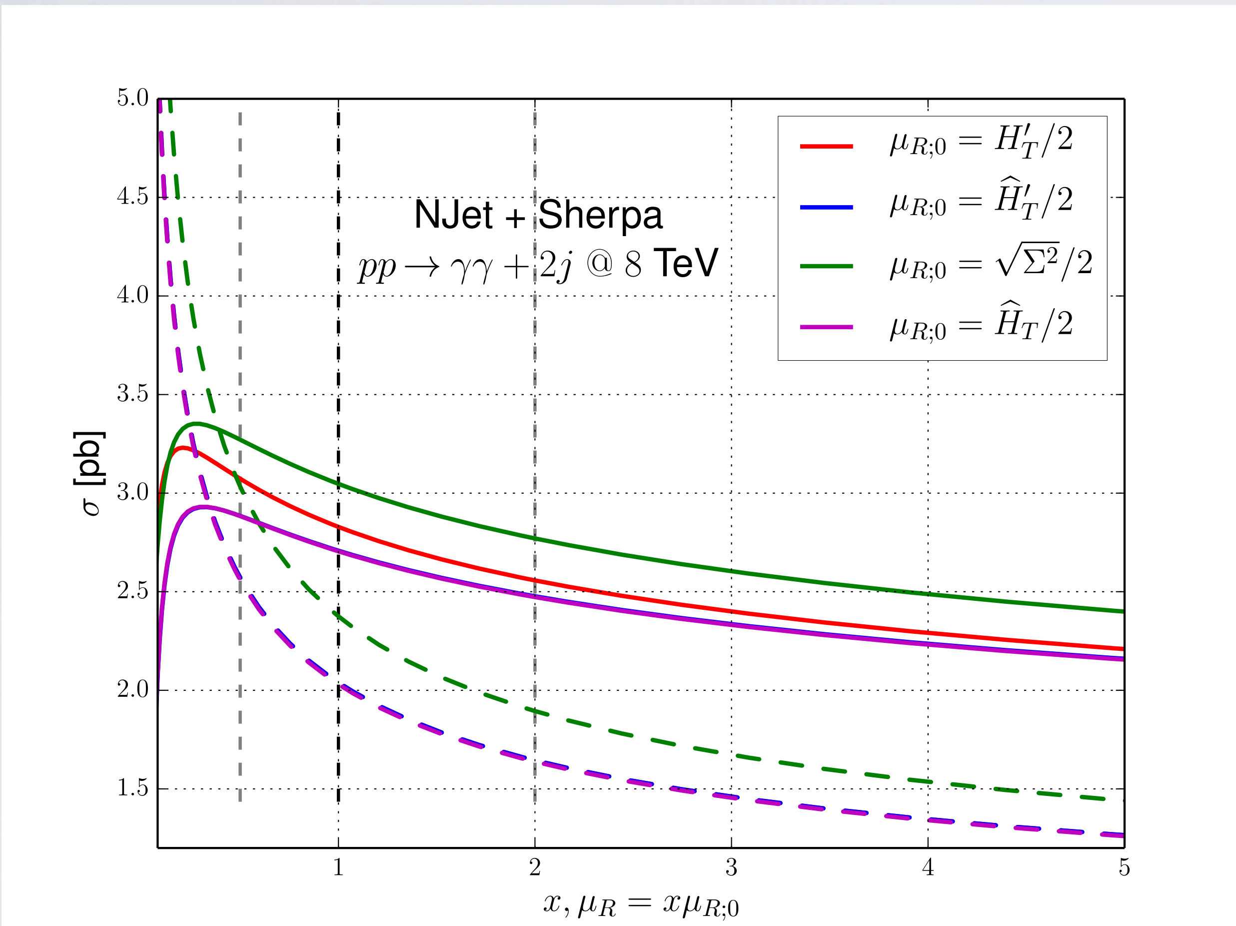
$$\sigma^{LO}_{\gamma\gamma+3j}(\widehat{H}'_T/2) = 0.643(0.003)^{+0.278}_{-0.180}\,\text{pb} \qquad \sigma^{NLO}_{\gamma\gamma+3j}(\widehat{H}'_T/2) = 0.785(0.010)^{+0.027}_{-0.085}\,\text{pb}$$

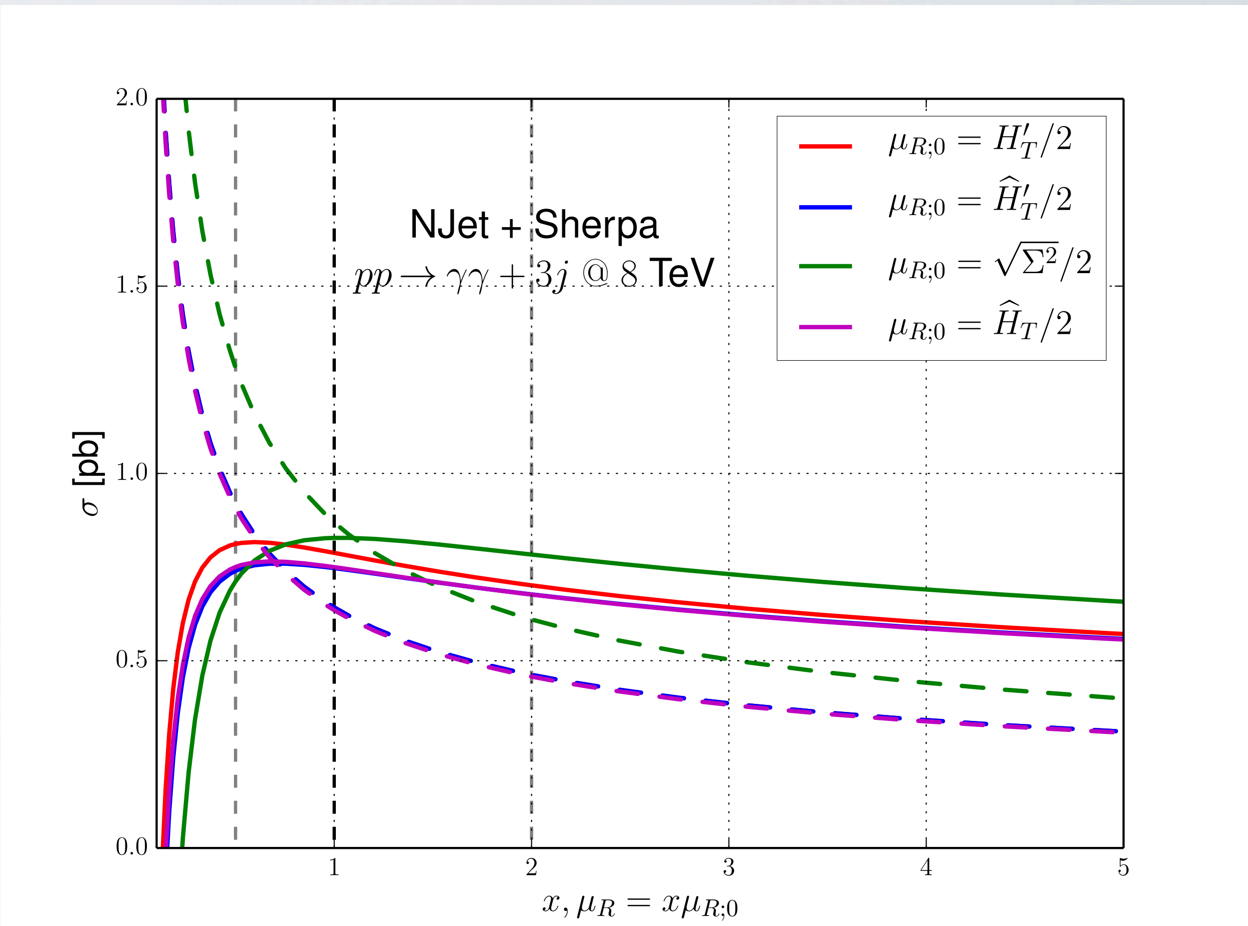






Scale dependence

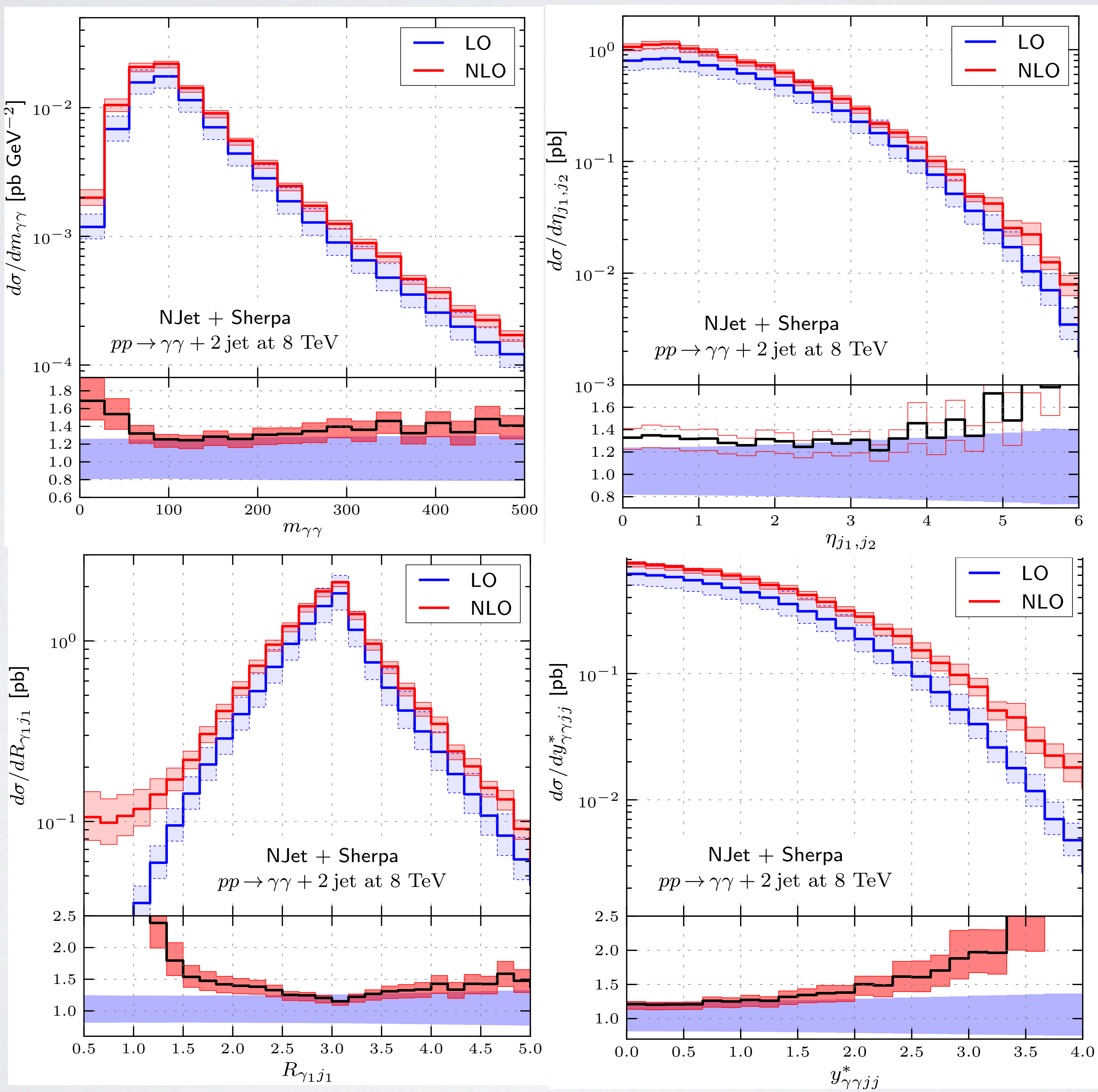




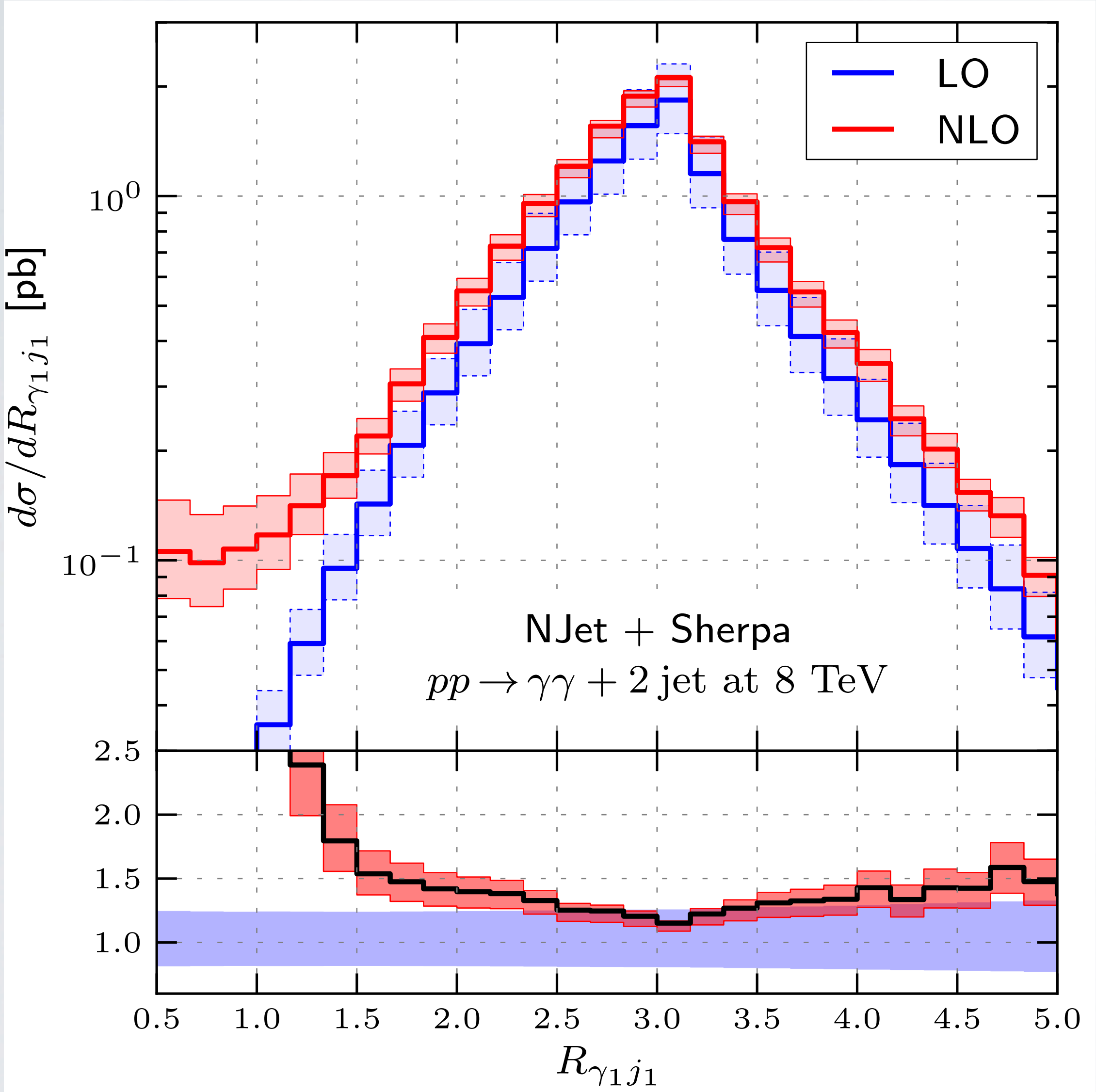
NLO predictions reduce uncertainty from 50% to ~15%

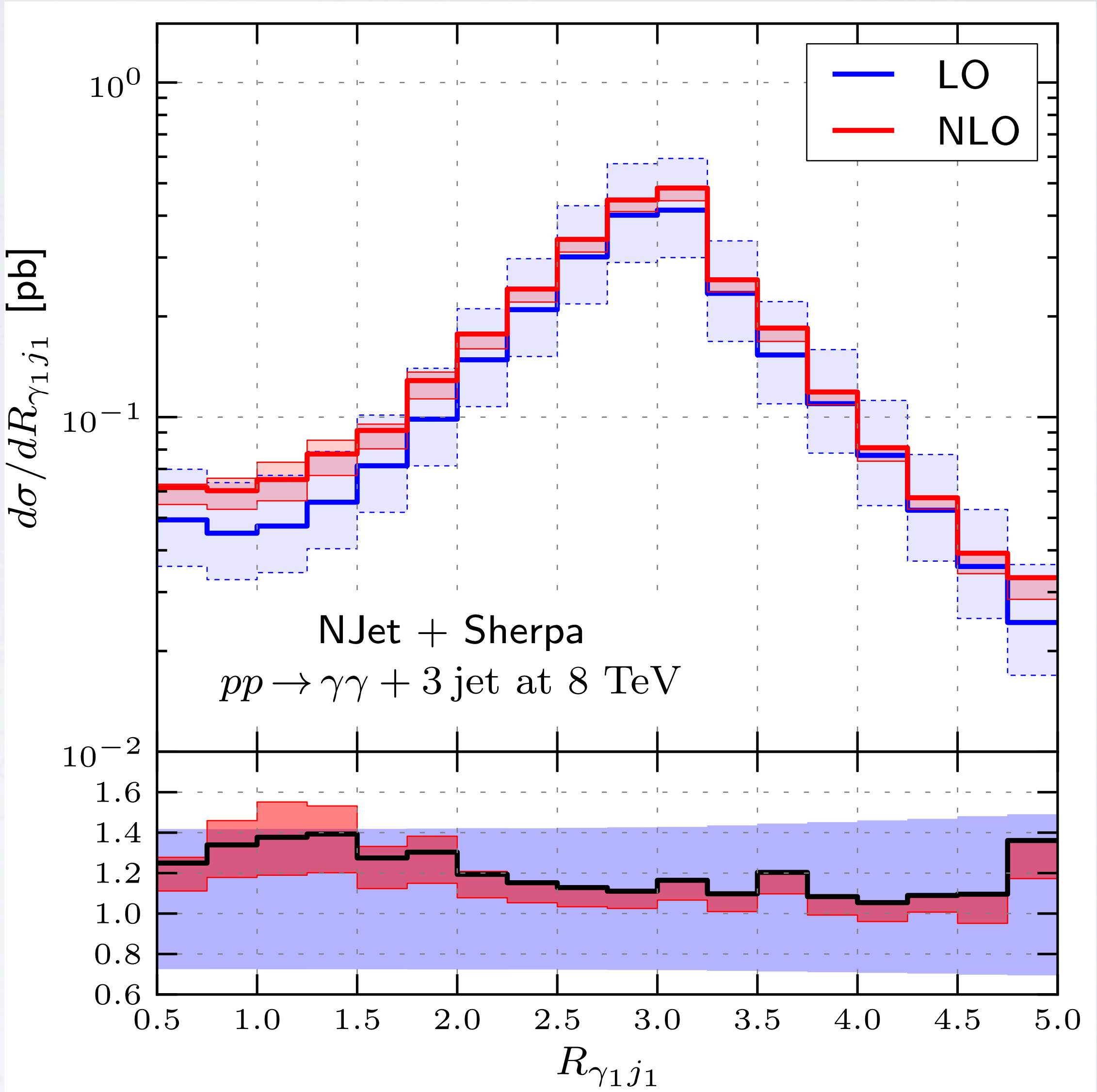
Fairly wide range of predictions with different dynamical scales

NLO distributions

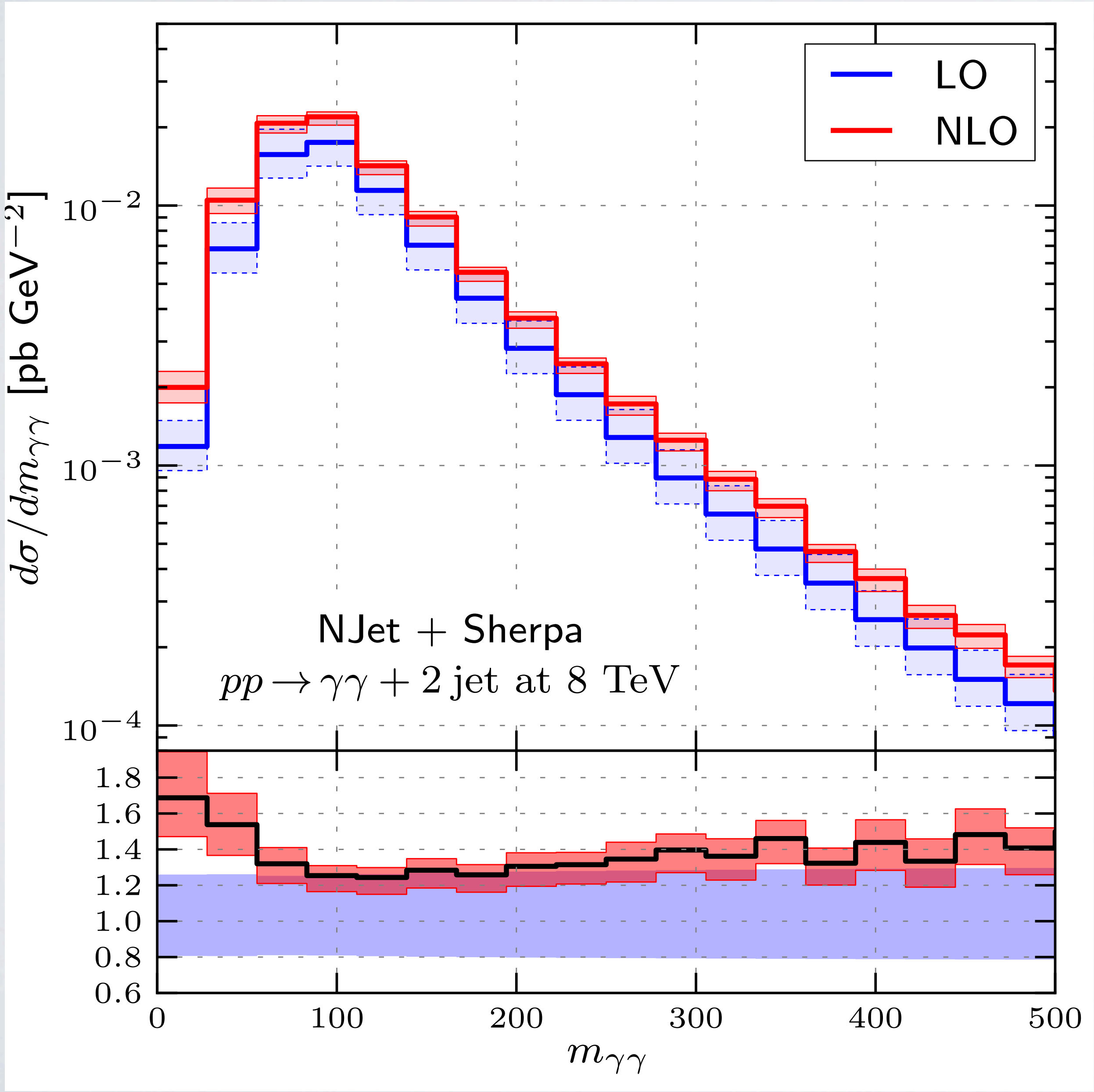


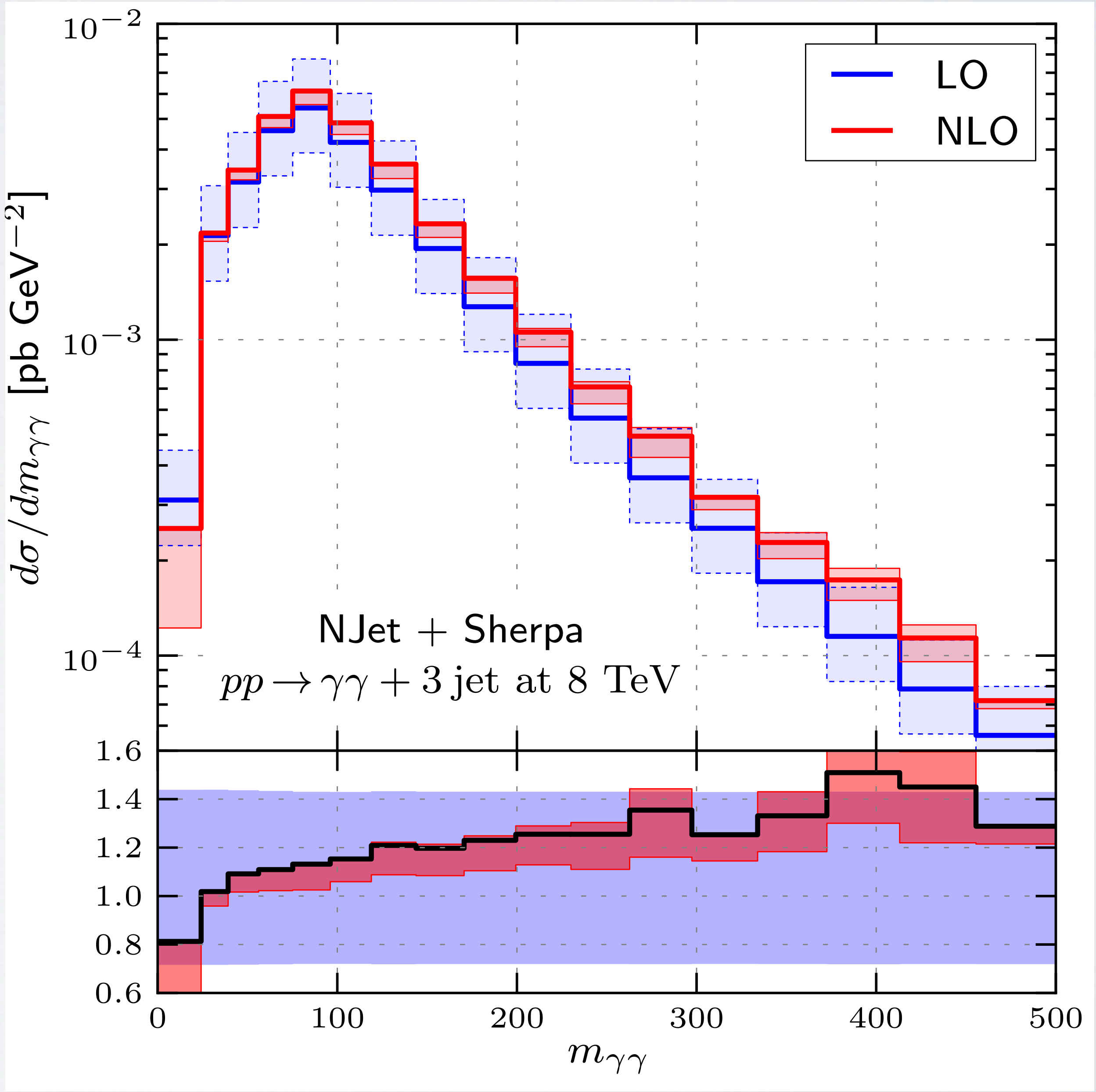
NLO distributions



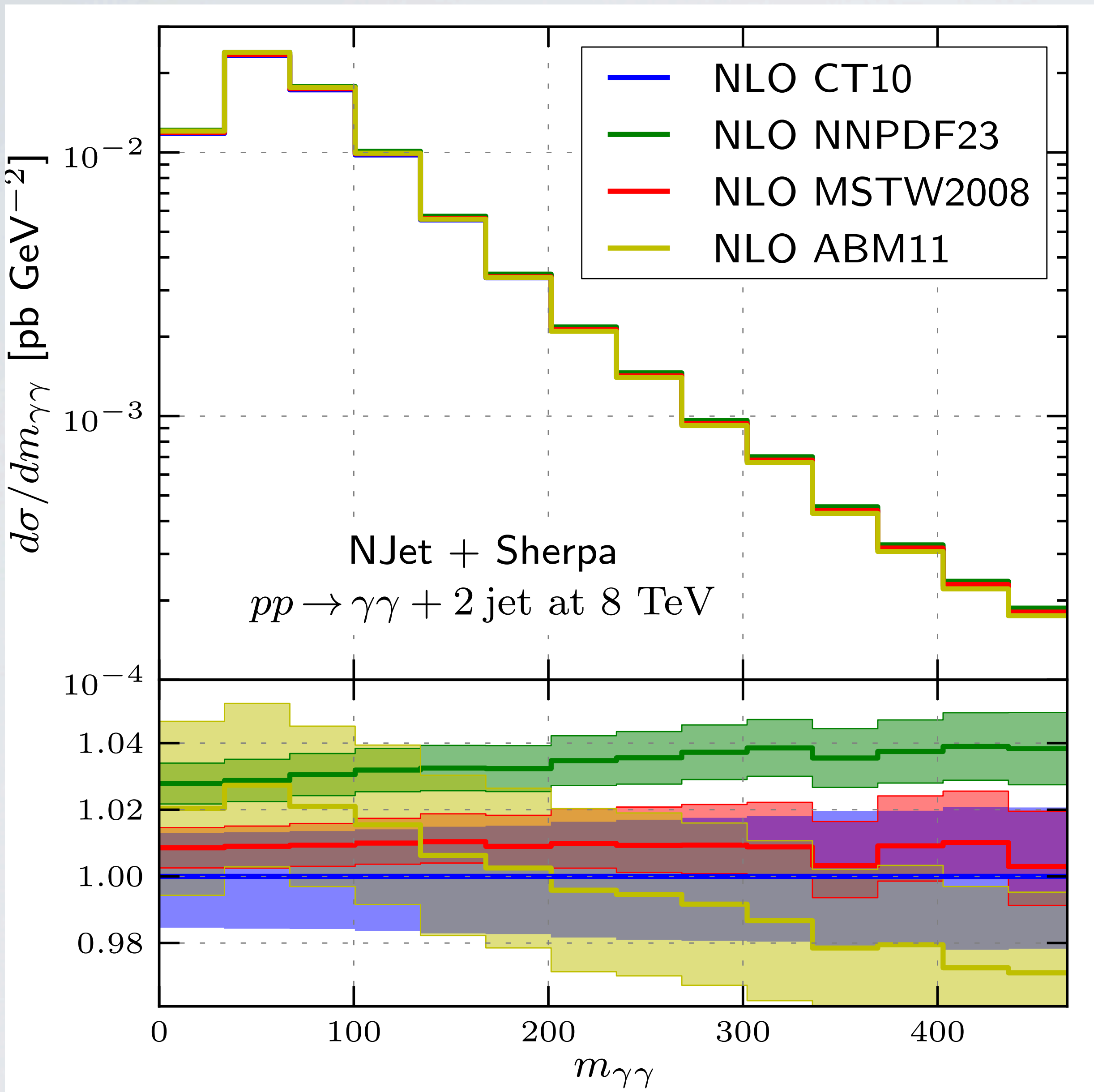


$pp \to \gamma\gamma + \text{jets}$ at NLO



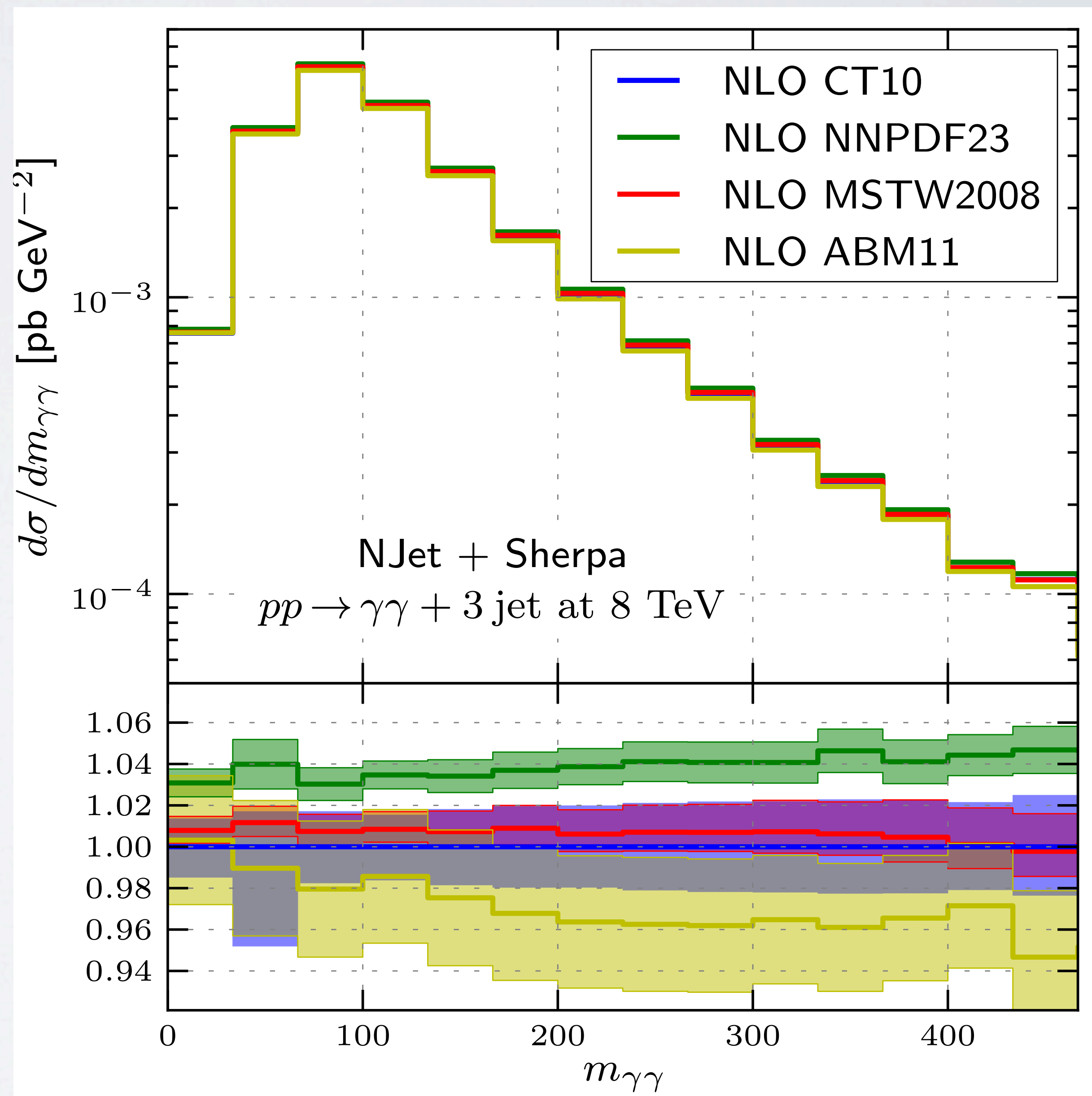


PDF dependence



comparison using all sets with

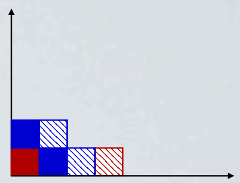
$$\alpha_s(M_Z) = 0.118$$



APPLgrids produced from ROOT Ntuples

(APPLgrid framework Carli et al. [0911.2985])

Beyond fixed order

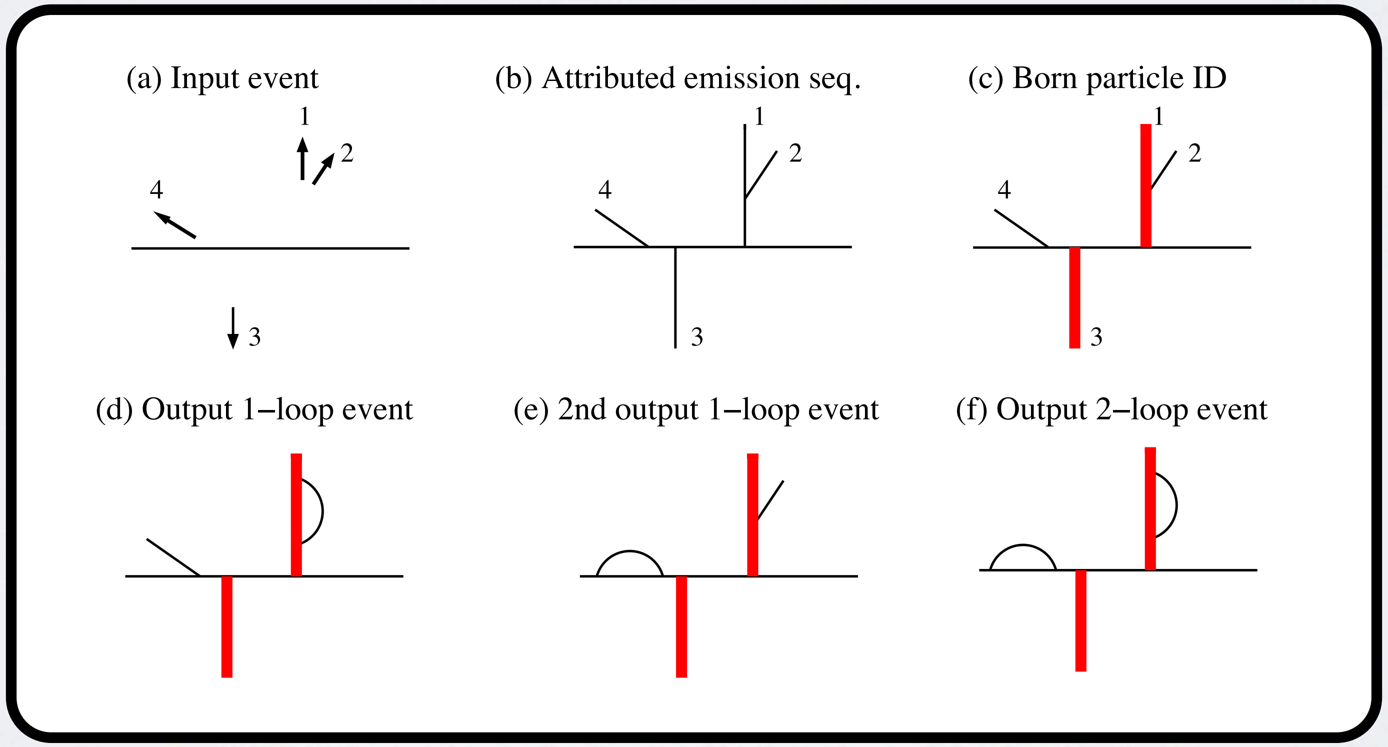


- LoopSim offers a fixed order alternative to NLO merging but without shower matching

  [Rubin, Sapeta, Salam (2010)]

- predictions at nNLO include some NNLO ingredients - double real and real-virtual

- fixed order Root Ntuples can be merged using a modified analysis

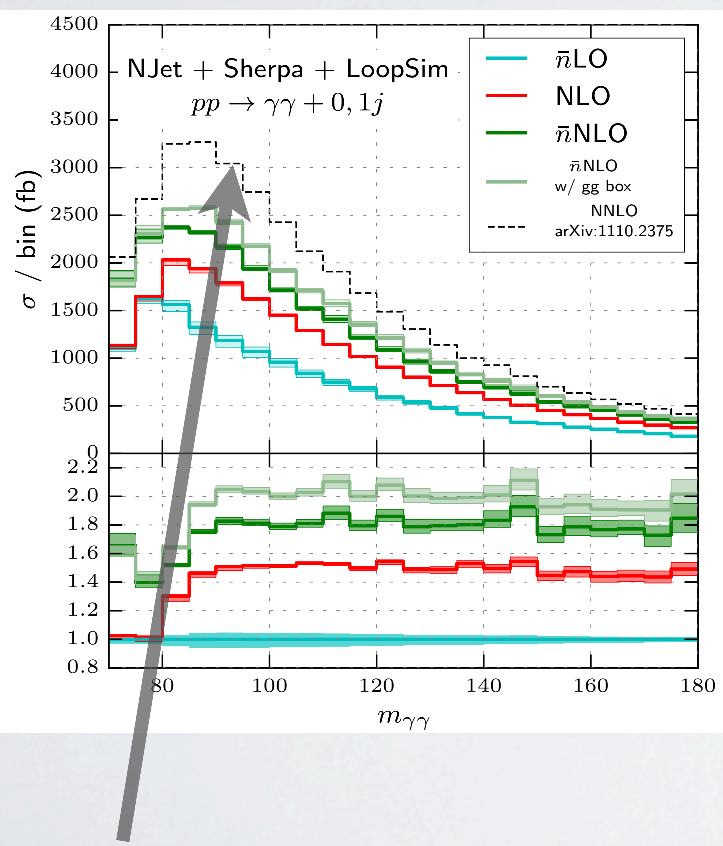


$pp \to \gamma\gamma + \text{jets}$ beyond NLO

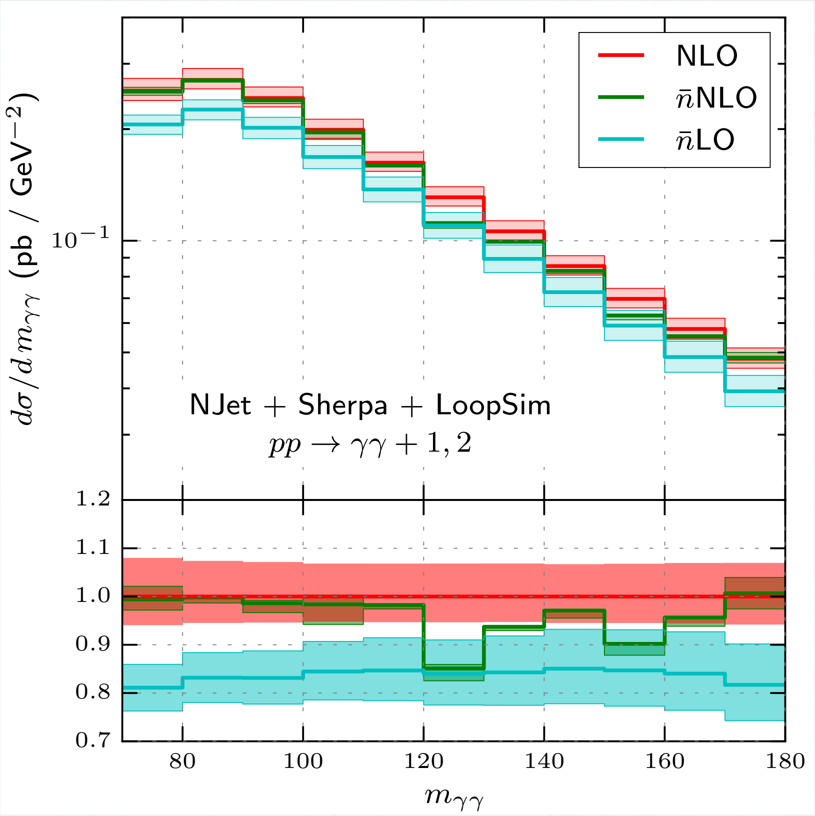
very preliminary!

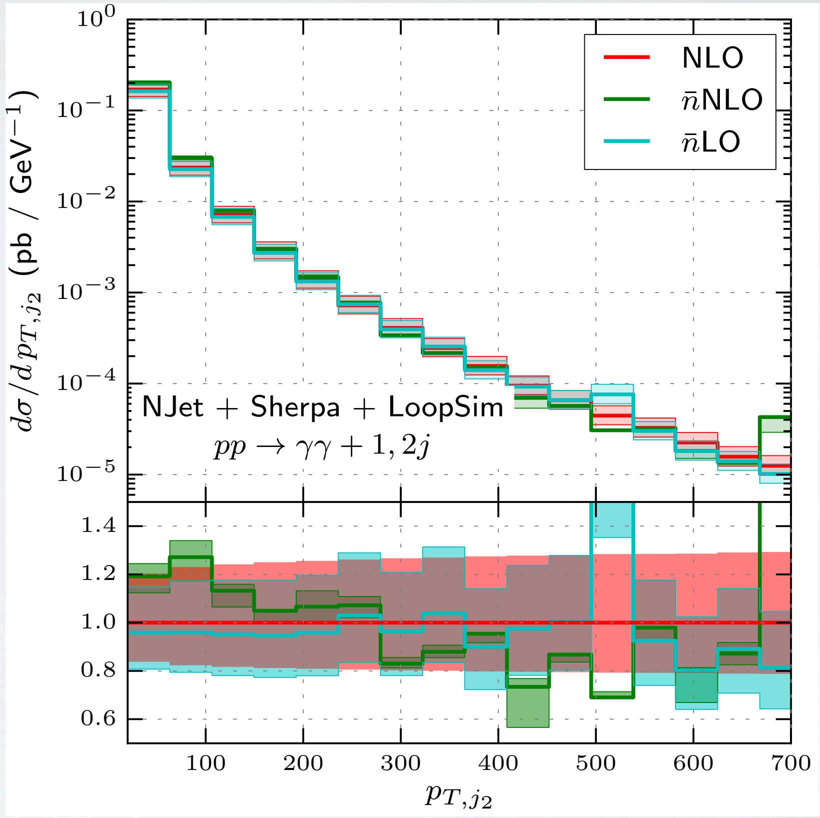
[SB, Sapeta]

$pp \to \gamma\gamma$



[full NNLO Catani et al.]





$pp \to \gamma\gamma + 1j$

$\sqrt{s} = 14$ TeV $\quad p_{T,j} > 20$ GeV

$p_{T,\gamma_1} > 40$ GeV $\quad p_{T,\gamma_2} > 25$ GeV $\quad 20 \text{ GeV} < m_{\gamma\gamma} < 250$ GeV

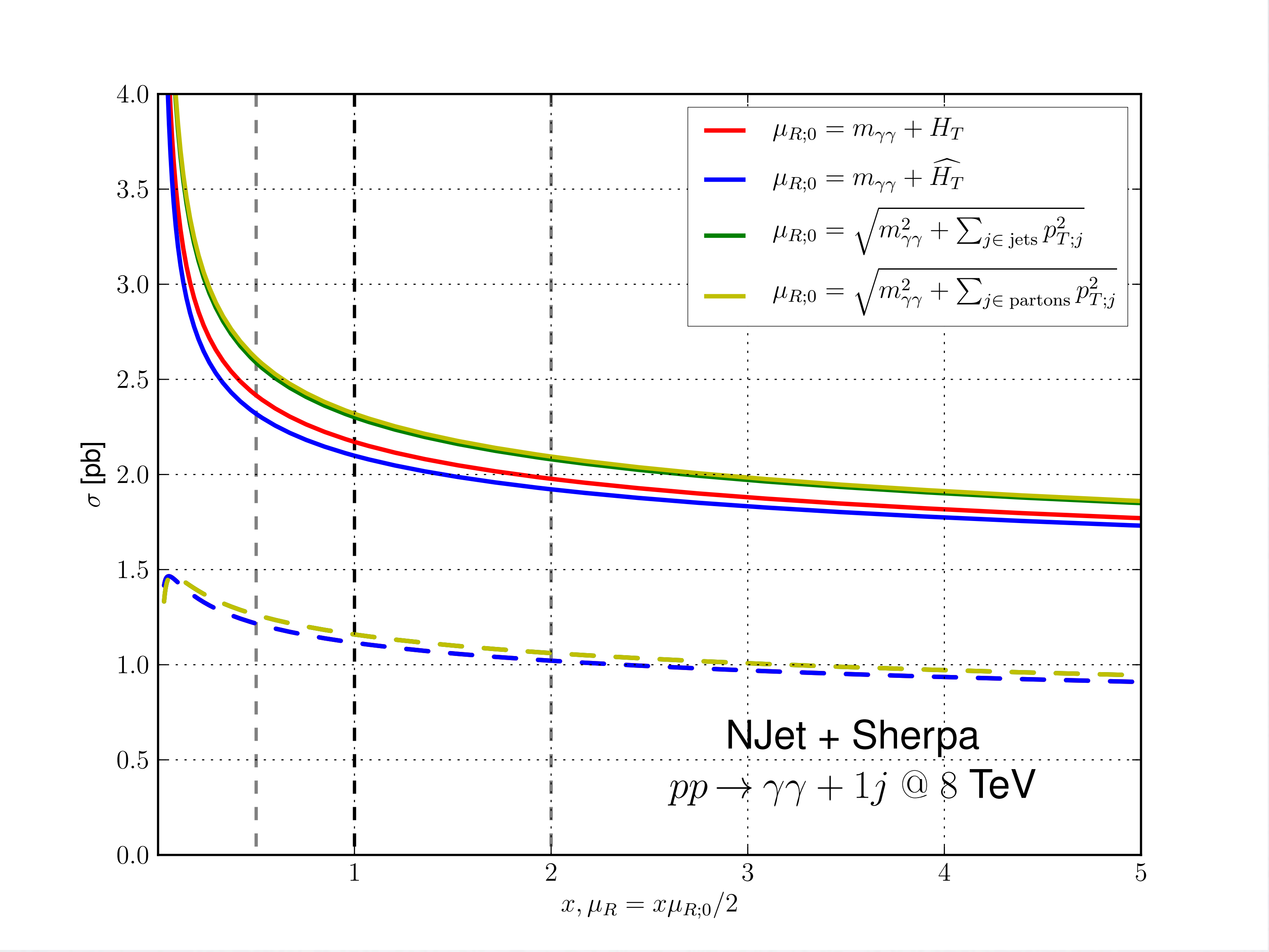
Conclusions

- Di-photon production with up to 3 jets now available at NLO
- Good agreement between different theory predictions
  - scale variations ~ 10(15)% uncertainty at NLO $pp \to \gamma\gamma + 2(3)j$
- Smooth cone vs. fragmentation
  - mild dependence on Frixione isolation parameters
- nNLO predictions for $pp \to \gamma\gamma + 1j$ with LoopSim

Backup slides

Scale variations for

$pp \to \gamma\gamma + 1j$



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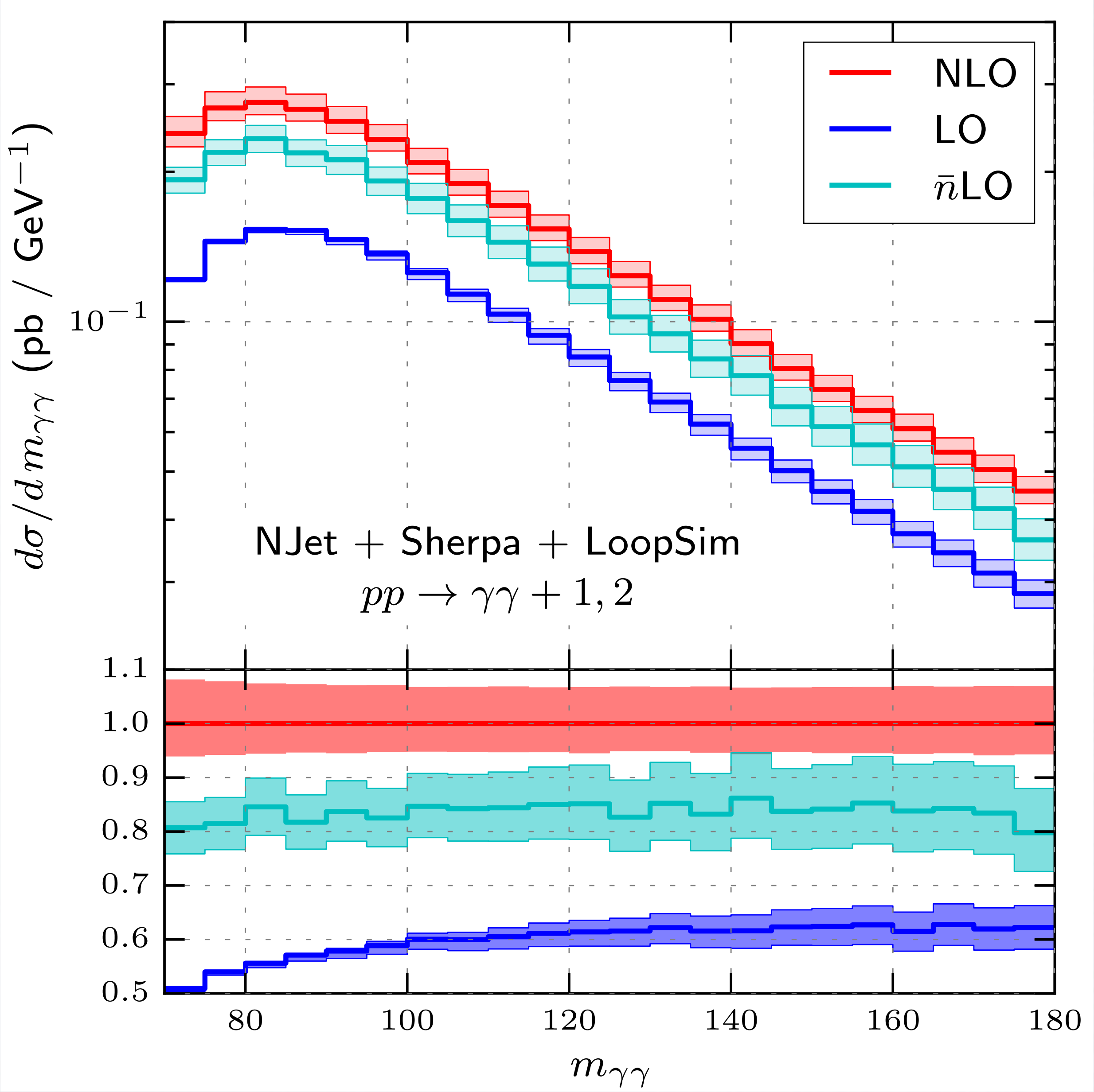

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