NLO predictions for a Z boson + photons final states at the LHC

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(with John Campbell and Ciaran Williams, arXiv:1208.0566)

Florida State University/Fermilab

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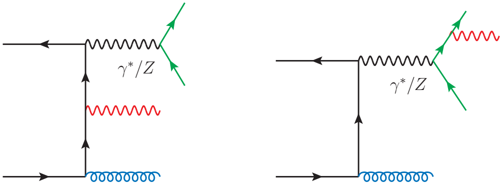
NLO QCD predictions for:

$$p + p \to \ell\bar{\ell} + \gamma + \text{jet} \qquad \text{“}Z\gamma j\text{”}$$

$$p + p \to \ell\bar{\ell} + \gamma + \gamma \qquad \text{“}Z\gamma\gamma\text{”}$$

where $\ell = e, \nu$.

For electron case, the final state radiation of photons from electrons are included.



$Z\gamma\gamma$ production $\Rightarrow$ by-product of $Z\gamma j$ production.

The calculations are implemented in MCFM.

Outline:

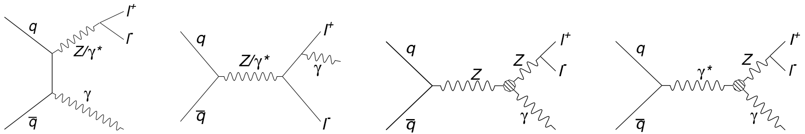
- Introduction
- Some Basic Tools
- $Z\gamma j$ production: Calculation and Results
- $Z\gamma\gamma$ production: Calculation and Results
- Conclusions

Introduction

Introduction

Diboson processes: study of the anomalous Three Gauge Couplings (aTGCs). For example:

- $W\gamma$ process $\Rightarrow$ $WW\gamma$ coupling
- WZ process $\Rightarrow$ WWZ coupling
- WW process $\Rightarrow$ $WW\gamma$ and WWZ couplings
- $Z\gamma$ process $\Rightarrow$ $Z\gamma\gamma$ and $Z\gamma Z$ couplings



$Z\gamma\gamma$: background new physics search involving MET+diphotons final states

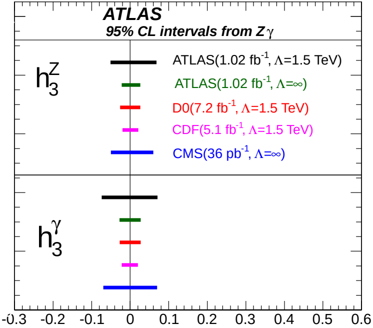
$Z\gamma Z$ and $Z\gamma\gamma$ non-standard couplings

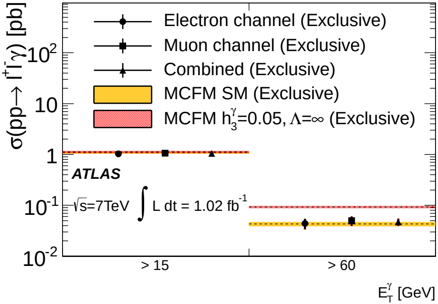
Non-standard $Z\gamma Z$ vertex: [Hagiwara,Peccei,Zeppenfeld,Hikasa (1987)]

$$\Gamma^{\alpha,\beta,\mu}_{Z\gamma Z}(q_1,q_2,p) = i\frac{p^2-q_1^2}{M_Z^2}\Big[h_1^Z\left(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}\right)+\frac{h_2^Z}{M_Z^2}p^\alpha\left(p\cdot q_2 g^{\mu\beta}-q_2^\mu p^\beta\right) - h_3^Z\epsilon^{\mu\alpha\beta\nu}q_{2\nu}-\frac{h_4^Z}{M_Z^2}\epsilon^{\mu\beta\nu\sigma}p^\alpha p_\nu q_{2\sigma}\Big]$$

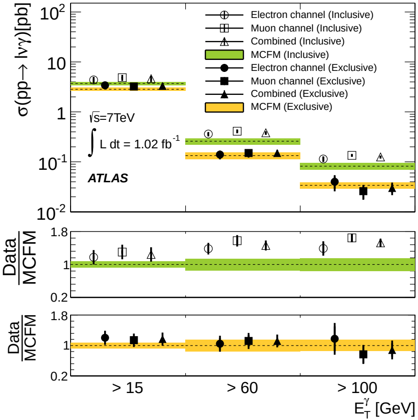
For $Z\gamma\gamma$ vertex, $q_1^2\to 0$, $h_i^Z\to h_i^\gamma$.

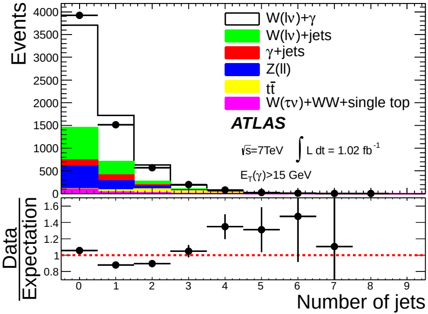
$$h_i^{Z/\gamma}\to\frac{h_i^{Z/\gamma}}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^n}$$





$W\gamma$ measurement (ATLAS 1.02 fb^{-1}, arXiv:1205.2531[hep-ex])





- The measurements are categorized according to p_T^{γ}: low, intermediate and high-p_T regions.
- Searches divided based on the number of reconstructed jets

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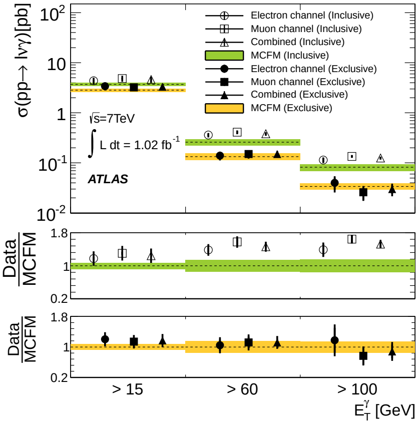

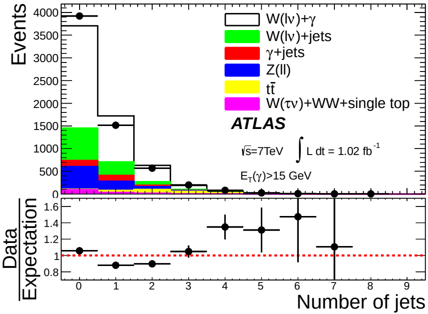

- good agreement between measured cross sections and theoretical predictions for exclusive cross sections
- Inclusive measurements are somewhat higher compare to theoretical predictions

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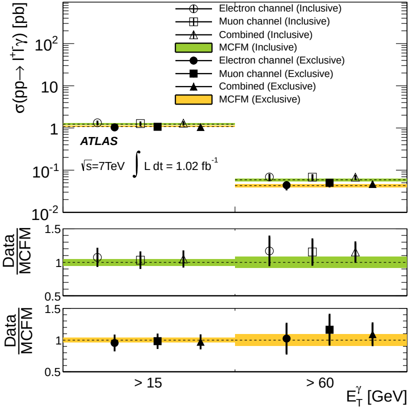

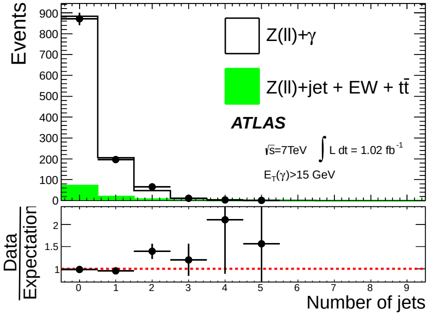

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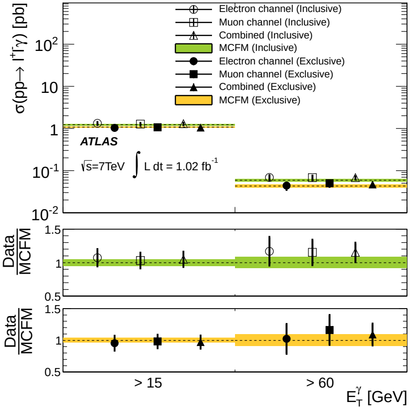

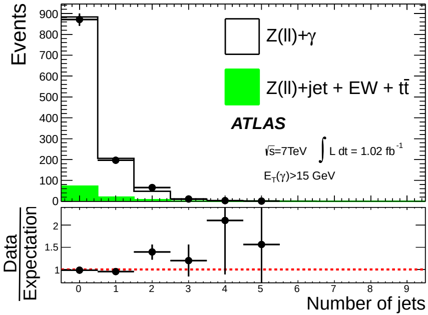

- good agreement between measured cross sections and theoretical predictions
- Note that: uncertainties in exclusive predictions smaller or comparable to that on the inclusive predictions

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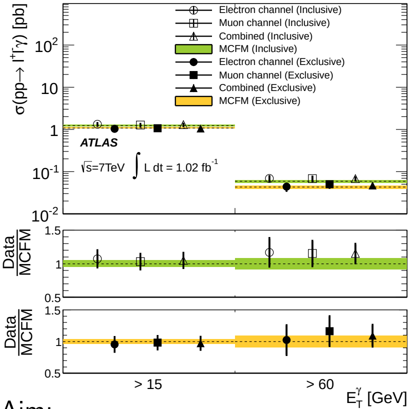
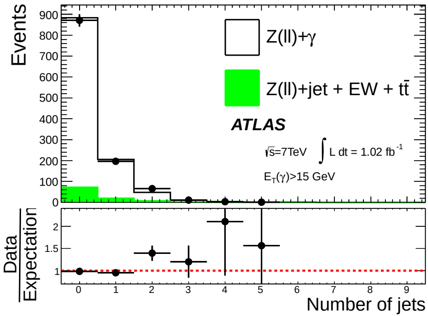


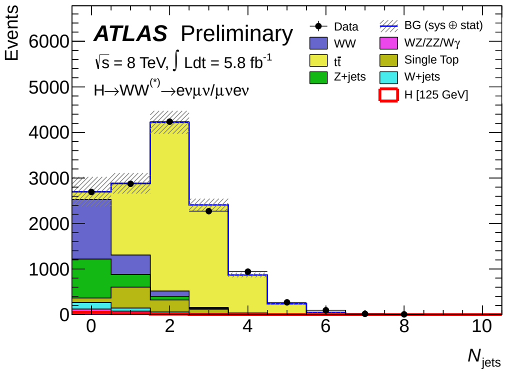


Aim:

- Reasses the uncertainties for exclusive predictions
- Provide the prediction for 1-jet bin at NLO accuracy (have the $Z\gamma j$, working on $W\gamma j$)

Searches using Jet Bin

Example: Higgs search in WW channel [ATLAS-CONF-2012-098]



- background composition depend on the number of jets in the final state
- the overall sensitivity can be increased
- How do we estimate theory uncertainties in the presence of jet veto?

Exclusive Cross Section: perturbative uncertainties

Evaluating uncertainties: [Stewart, Tackmann: arXiv:1107.2117]

- Directly varying the μ_r and μ_f for each σ_N

  Potentially underestimate the uncertainties in individual jet bin due to numerical cancellation.

$$\sigma_{\rm total} \simeq \sigma_B \left[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\right], \qquad L = \ln(p_T^{\rm cut}/Q)$$

$$\sigma_{\geq 1}(p_T^{\rm cut}) \simeq \sigma_B \left[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\right]$$

$$\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p_T^{\rm cut})$$

Exclusive Cross Section: perturbative uncertainties

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$$\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total}-\sigma_{\geq 1}(p_T^{\rm cut})$$

- Combine uncertainties in inclusive N-jet cross section

$$\Delta_0^2=\Delta_{\rm total}^2+\Delta_{\geq 1}^2$$

$\rightarrow$ $\Delta_{\rm total}$ and $\Delta_{\geq 1}$ are treated as independent

$\rightarrow$ takes into account large logarithmic corrections

$\rightarrow$ Applied to H + 0,1 jets, WW + 0 jets, W + 0,1,2 jets

Existing calculations:

- NLO prediction for $W\gamma$ and $Z\gamma$

  Ohnemus (1993); Baur, Han, Ohnemus (1998); de Florian, Signer (2000)

  Hollik, Meier (2004); Accomando, Denner, C. Meier (2005)

  Ametller, Gava, Paver, Treleani (1985); van der Bij, Glover (1988)

  Adamson, de Florian, Signer (2003); Campbell, Ellis, Williams (2010)

  (EW corrections, $gg \to Z\gamma$)
- NLO prediction for $W\gamma j$

  Campanario,Englert,Spannowsky,Zeppenfeld (2009)
- NLO prediction for $Z\gamma\gamma$

  Bozzi, Campanario, Rauch, Zeppenfeld (2011)
- Two-loop QCD helicity amplitudes for $q\bar{q}' \to W^{\pm}\gamma$ and $q\bar{q} \to Z\gamma$

  Gehrmann, Tancredi (2012)

Some Basic Tools

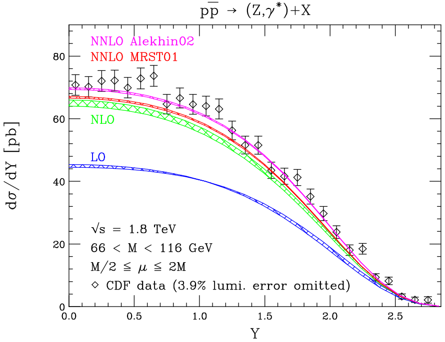
Going Beyond Leading Order

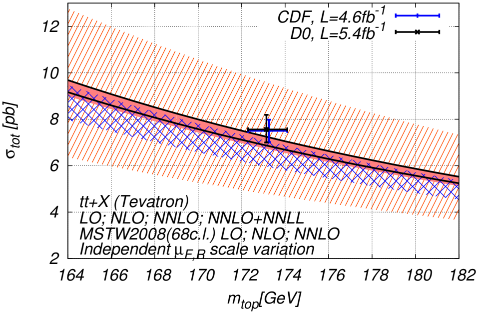
What do we gain?

- reliable prediction for total rates and shape of the distributions
- reduced scale dependence
- test the convergence of the perturbative series

[Anastasiou,Dixon,Melnikov,Petriello: hep-ph/0312266]

[Baernreuther,Czakon,Mitov: arXiv:1204.5201]





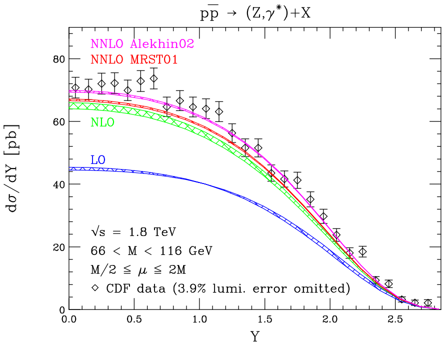
Going Beyond Leading Order

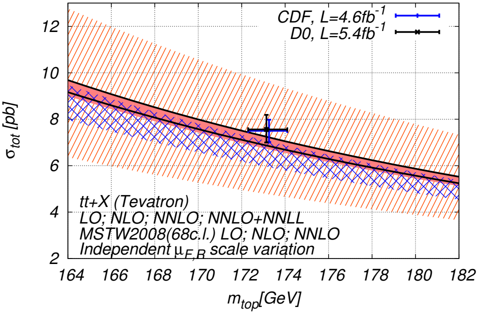
In fixed order calculations, there are some regions of phase space that dont match the data/not well behaved

- Resummation
- Shower MC: NLO+PS

[Anastasiou,Dixon,Melnikov,Petriello: hep-ph/0312266]

[Baernreuther,Czakon,Mitov: arXiv:1204.5201]

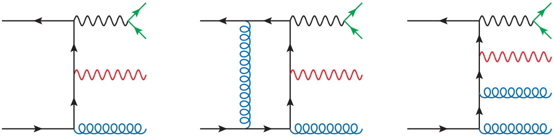




NLO calculation (1)

NLO cross section:

$$\sigma^{NLO} = \int_n d\sigma^B + \int_n d\sigma^V + \int_{n+1} d\sigma^R$$



- Virtual corrections contain UV and IR singularities
  Extract the singularities: dimensional regularization, compute loop diagrams in $d = 4 - 2\epsilon$ dimensions.
  Singularities manifest in the $1/\epsilon^2$ and $1/\epsilon$ poles.
  UV singularities are removed by renormalization
- Real corrections suffer from IR singularities when massless partons become soft or collinear

NLO calculation (2)

Subtraction Method

$$\sigma^{NLO} = \int_n d\sigma^B + \int_n \left[d\sigma^V + \int_1 d\sigma^A \right]_{\epsilon=0} + \int_{n+1} \left[d\sigma^R_{\epsilon=0} - d\sigma^A_{\epsilon=0} \right] + \int_n d\sigma^C$$

[Catani,Seymour]

- $d\sigma^A$ composed from the underlying Born process $d\sigma^B$ and the dipoles dV_{dipole} by summing over all possible dipole contributions

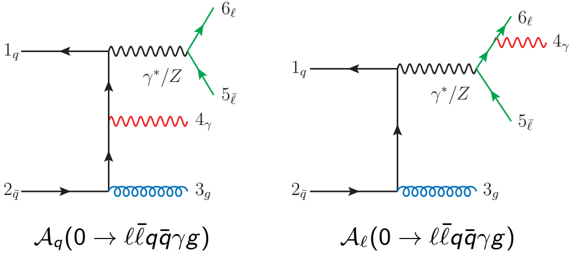
$$d\sigma^A = \sum_{\mathrm{dipole}} d\sigma^B \otimes dV_{\mathrm{dipole}}$$

  $\rightarrow$ Each dipole cancels the singularity at a particular kinematic region
  $\rightarrow$ $d\sigma^A$ has the same singular behavior as $d\sigma^R$ at each PS point

- $d\sigma^A$ exactly integrable analytically over one-parton PS in d-dim
  $\Rightarrow$ has to be simple functions
  After analytically integrated over 1-parton PS in $d = 4 - 2\epsilon$ dimensions, the IR singularities manifest in $1/\epsilon^2$ and $1/\epsilon$ poles.

$Z\gamma$+jet: Calculation

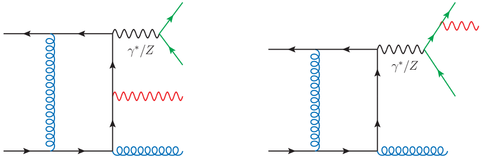
$Z\gamma j$ production at LO



- Two separately gauge invariant classes of diagrams:
  $\to$ γ from quark line ("q-type")
  $\to$ γ from lepton line ("ℓ-type")
- only q-type diagrams for neutrino final state
- Matrix elements are computed using spinor helicity formalism
- Checked against `MadGraph`/`MadEvent`

$Z\gamma j$ production: $\mathcal{O}(\alpha_s)$ virtual correction

$\rightarrow$ self energy, vertex, box and pentagon one-loop corrections



$\mathcal{A}_q(0 \to \ell\bar{\ell}q\bar{q}\gamma g)$ $\mathcal{A}_\ell(0 \to \ell\bar{\ell}q\bar{q}\gamma g)$

Decomposition of one-loop amplitude:

$$
\begin{aligned}
A^{(1)}(1_q,2_{\bar{q}},3_g,4_\gamma,5_{\bar{\ell}},6_\ell) \;=\;& 2\sqrt{2}e^3 g_s^3 c_\Gamma T^{a_3}_{i_1 i_2} \times \Big\{ \quad Q_q\left(-Q_q + v^q_{L,R} v^\ell_{L,R} \mathcal{P}_Z(s_{56})\right) \mathcal{A}^{(1)}_{q;1}(1_q,2_{\bar{q}},3_g,4_\gamma,5_{\bar{\ell}},6_\ell) \\
& + Q_q \sum_{i=1}^{n_\mathrm{f}} \left(-Q_i + \frac{1}{2} v^\ell_{L,R}(v^i_L + v^i_R)\mathcal{P}_Z(s_{56})\right) \mathcal{A}^{(1)}_{q;2}(1_q,2_{\bar{q}},3_g,4_\gamma,5_{\bar{\ell}},6_\ell) \\
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& + Q_\ell \left(-Q_q + v^q_{L,R} v^\ell_{L,R} \mathcal{P}_Z(t_{456})\right) \mathcal{A}^{(1)}_{\ell;1}(1_q,2_{\bar{q}},3_g,4_\gamma,5_{\bar{\ell}},6_\ell) \\
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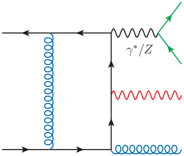
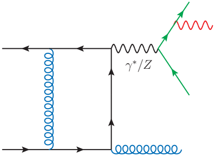
$Z\gamma j$ production: $\mathcal{O}(\alpha_s)$ virtual correction

$\rightarrow$ self energy, vertex, box and pentagon one-loop corrections



$\mathcal{A}_q(0 \rightarrow \ell\bar{\ell}q\bar{q}\gamma g)$



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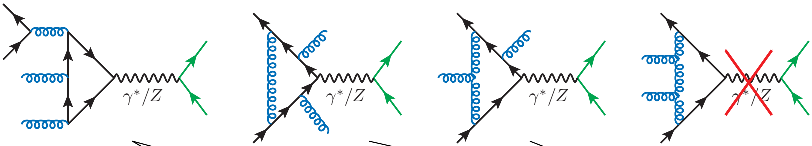
REUSE
REDUCE
RECYCLE
SAVE the PLANET
SAVE THE PLANET

$Z\gamma j$ production: $\mathcal{O}(\alpha_s)$ virtual correction

$\mathcal{A}_q(0 \to \ell\bar{\ell}q\bar{q}\gamma g)$ are obtained from $e^+e^- \to q\bar{q}gg$ one-loop amplitudes

[Bern,Dixon,Kosower:hep-ph/9708239]



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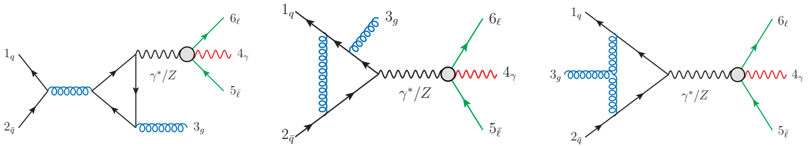
$Z\gamma j$ production: $\mathcal{O}(\alpha_s)$ virtual correction

Need to compute $\mathcal{A}_\ell(0 \to \ell\bar{\ell}q\bar{q}\gamma g)$



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\end{aligned}
$$

Interlude: Spinor Helicity Formalism

For massless four-vector p_i, define spinor products:

$$\langle ij\rangle = \bar{u}_-(p_i)u_+(p_j), \quad [ij] = \bar{u}_+(p_i)u_-(p_j), \quad \langle ij\rangle\,[ji] = 2p_i\cdot p_j.$$

where

$$u_+(p) = P_R u(p) \qquad u_-(p) = P_L u(p)$$

Spinor sandwiches

$$\begin{aligned}
\langle i|m\cdots n|j] &= \bar{u}_-(p_i)\,\not{p}_m\cdots\not{p}_n\,u_-(p_j) && (\text{odd}\ \#\ \text{of}\ p)\\
\langle i|m\cdots n|j\rangle &= \bar{u}_-(p_i)\,\not{p}_m\cdots\not{p}_n\,u_+(p_j) && (\text{even}\ \#\ \text{of}\ p)\\
[i|m\cdots n|j] &= \bar{u}_+(p_i)\,\not{p}_m\cdots\not{p}_n\,u_-(p_j) && (\text{even}\ \#\ \text{of}\ p)
\end{aligned}$$

Polarization vectors

$$\epsilon_+^\mu(k,q) = \frac{\langle q|\gamma^\mu|k]}{\sqrt{2}\,\langle qk\rangle}, \quad \epsilon_-^\mu(k,q) = \frac{[q|\gamma^\mu|k\rangle}{\sqrt{2}\,[qk]}.$$

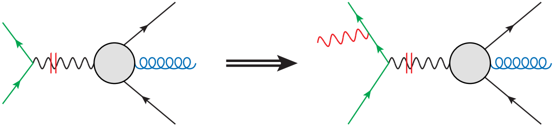
Useful relations

$$\begin{aligned}
&\langle ij\rangle = -\langle ji\rangle, \quad [ij] = -[ji], \quad \langle ii\rangle = 0, \quad [ii] = 0\\
&\not{p}_i = |i]\langle i| + |i\rangle[i|\\
&\langle i|\gamma_\mu|j]\langle k|\gamma^\mu|l] = 2\,\langle ik\rangle\,[lj] && (\text{Fierz id.})\\
&\langle ij\rangle\,\langle kl\rangle + \langle ik\rangle\,\langle lj\rangle + \langle il\rangle\,\langle jk\rangle = 0 && (\text{Schouten id.})
\end{aligned}$$

Work with $\mathcal{A}(\langle ij\rangle, [ij])$ instead of $|\mathcal{A}|^2(p_i\cdot p_j)$.

$\mathcal{A}_\ell(0 \to \ell\bar{\ell}q\bar{q}\gamma g)$:

Replace lepton current in $e^+e^- \to q\bar{q}g$ 1-loop amplitudes by $\ell\bar{\ell}\gamma$ current.



$$\mathcal{M} = \quad L_\mu^{e^+e^-} V^\mu \quad \to \quad L_\mu^{\gamma e^+e^-} V^\mu$$

$\to$ applies to tree and virtual amplitudes

Example at tree level:

$$J^\mu_{\ell\bar{\ell}}(5^-_{\bar{\ell}}, 6^+_\ell) = -\frac{\langle 5|\gamma^\mu|6]}{s_{56}}$$

$$\mathcal{A}^{(0)}_q(1^+_q, 2^-_{\bar{q}}, 3^+_g, 5^-_{\bar{\ell}}, 6^+_\ell) = -i\frac{\langle 25\rangle^2}{\langle 13\rangle\,\langle 23\rangle\,\langle 56\rangle}$$

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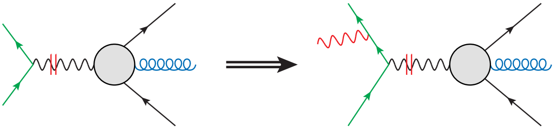

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then use

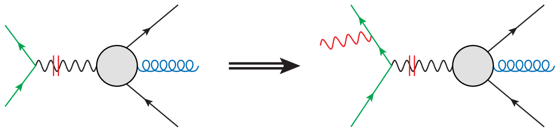
$$\langle 56\rangle[65] = s_{56}$$

$$\langle 25\rangle[56] = \langle 2|5|6] \quad \text{from} \quad |5]\langle 5| + |5\rangle[5| = \not{p}_5$$

$$= -\langle 2|(1+3)|6] \quad \text{mom.conservation}$$

$\mathcal{A}_\ell(0 \to \ell\bar{\ell}q\bar{q}\gamma g)$:

Replace lepton current in $e^+e^- \to q\bar{q}g$ 1-loop amplitudes by $\ell\bar{\ell}\gamma$ current.



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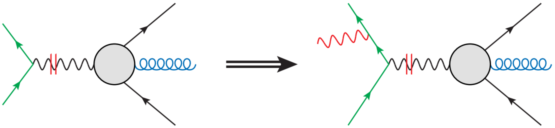

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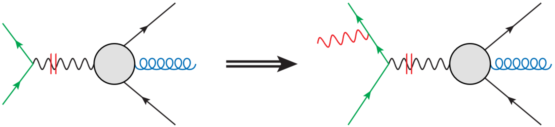
$$= -i\frac{\langle 2|(1+3)|6]\langle 25\rangle}{\langle 13\rangle\langle 23\rangle s_{56}}$$

undo the Fierz identity

$$\langle ik\rangle[lj] = \frac{1}{2}\langle i|\gamma_\mu|j]\langle k|\gamma^\mu|l]$$

$\mathcal{A}_\ell(0 \to \ell\bar{\ell}q\bar{q}\gamma g)$:

Replace lepton current in $e^+e^- \to q\bar{q}g$ 1-loop amplitudes by $\ell\bar{\ell}\gamma$ current.



$$\mathcal{M} = \quad L_\mu^{e^+e^-} V^\mu \quad \to \quad L_\mu^{\gamma e^+e^-} V^\mu$$

$\to$ applies to tree and virtual amplitudes

Example at tree level:

$$\begin{aligned}
\mathcal{A}_q^{(0)}(1_q^+, 2_{\bar{q}}^-, 3_g^+, 5_{\bar{\ell}}^-, 6_\ell^+) &= -i\frac{\langle 25\rangle^2}{\langle 13\rangle\langle 23\rangle\langle 56\rangle} \\
&= -i\frac{\langle 2|(1+3)|6]\langle 25\rangle}{\langle 13\rangle\langle 23\rangle s_{56}} \\
&= i\frac{\langle 2|(1+3)|\gamma_\mu|2\rangle}{2\langle 13\rangle\langle 23\rangle} \times \left(-\frac{\langle 5|\gamma^\mu|6]}{s_{56}}\right) \\
&= \tilde{A}_\mu(1_q^+, 2_{\bar{q}}^-, 3_g^+) \times J^\mu_{\ell\bar{\ell}}(5_{\bar{\ell}}^-, 6_\ell^+)
\end{aligned}$$

Currents with photon radiation from leptons

$$J^{\mu}_{\ell\bar{\ell}\gamma}(4^{+}_{\gamma}, 5^{-}_{\bar{\ell}}, 6^{+}_{\ell}) = \frac{\langle 5|\gamma^{\mu}|(4+6)|5\rangle}{t_{456}\,\langle 45\rangle\,\langle 46\rangle}$$

$$J^{\mu}_{\ell\bar{\ell}\gamma}(4^{-}_{\gamma}, 5^{-}_{\bar{\ell}}, 6^{+}_{\ell}) = \frac{[6|\gamma^{\mu}|(4+5)|6]}{t_{456}\,[45]\,[46]}$$

Currents with photon radiation from leptons

$$J^{\mu}_{\ell\bar{\ell}\gamma}(4^+_\gamma, 5^-_{\bar{\ell}}, 6^+_\ell) = \frac{\langle 5|\gamma^\mu|(4+6)|5\rangle}{t_{456}\,\langle 45\rangle\,\langle 46\rangle}$$

$$J^{\mu}_{\ell\bar{\ell}\gamma}(4^-_\gamma, 5^-_{\bar{\ell}}, 6^+_\ell) = \frac{[6|\gamma^\mu|(4+5)|6]}{t_{456}\,[45]\,[46]}$$

Compute $\mathcal{A}^{(0)}_\ell(1_q, 2_{\bar{q}}, 3_g, 4_\gamma, 5_{\bar{\ell}}, 6_\ell)$

$$\begin{aligned}\mathcal{A}^{(0)}_\ell(1^+_q, 2^-_{\bar{q}}, 3^+_g, 4^+_\gamma, 5^-_{\bar{\ell}}, 6^+_\ell) &= \tilde{A}_\mu(1^+_q, 2^-_{\bar{q}}, 3^+_g) \times J^{\mu}_{\ell\bar{\ell}\gamma}(4^+_\gamma, 5^-_{\bar{\ell}}, 6^+_\ell) \\ &= i\,\frac{\langle 2|(1+3)|\gamma_\mu|2\rangle}{2\,\langle 13\rangle\,\langle 23\rangle}\,\frac{\langle 5|\gamma^\mu|(4+6)|5\rangle}{t_{456}\,\langle 45\rangle\,\langle 46\rangle} \\ &= i\,\frac{\langle 25\rangle^2}{\langle 13\rangle\,\langle 23\rangle\,\langle 45\rangle\,\langle 46\rangle}\end{aligned}$$

$\rightarrow$ analytic expression for $\mathcal{A}_\ell(0 \rightarrow \ell\bar{\ell}q\bar{q}\gamma g)$.

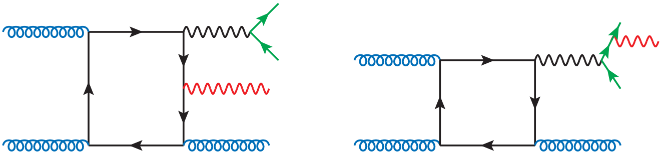
$$\mathcal{A}^{(1)}_\ell(1^+_q, 2^-_{\bar{q}}, 3^+_g, 4^+_\gamma, 5^-_{\bar{\ell}}, 6^+_\ell)$$
$$\mathcal{A}^{(1)}_\ell(1^+_q, 2^-_{\bar{q}}, 3^+_g, 4^-_\gamma, 5^-_{\bar{\ell}}, 6^+_\ell)$$

→ Renormalization to cancel UV singularities.

→ IR singularities cancelled by corresponding singularities from the real part.

→ Pole cancellations are checked numerically.

What we don't include: virtual $gg \to Z\gamma g$

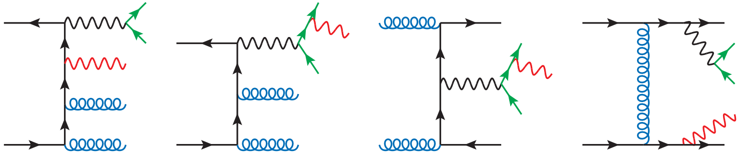


Formally NNLO correction $\mathcal{O}(\alpha^3 \alpha_s^3)$

[Agarwal,Shivaji: arXiv:1207.2927]

- On-shell Z-boson, no decay to leptons
- Contribute ~ 2 %

$Z\gamma j$ production: $\mathcal{O}(\alpha_s)$ real correction



$\mathcal{A}_q(0 \to \ell\bar{\ell}q\bar{q}\gamma gg)$ $\mathcal{A}_\ell(0 \to \ell\bar{\ell}q\bar{q}\gamma gg)$ $\mathcal{A}_\ell(0 \to \ell\bar{\ell}q\bar{q}\gamma gg)$ $\mathcal{A}_q(0 \to \ell\bar{\ell}q\bar{q}Q\bar{Q}\gamma)$

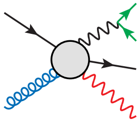
- Tree level contributions open up at $\mathcal{O}(\alpha^3\alpha_s^2)$:
  $\to$ gg initial state
  $\to$ $qq, \bar{q}\bar{q}$ initial state from 4 quarks amplitude
- $\mathcal{A}_q$ helicity amplitudes from $e^+e^- \to q\bar{q}ggg$ and $e^+e^- \to q\bar{q}Q\bar{Q}g$
  [Nagy, Trocsanyi:hep-ph/9806317]
- Need to compute $\mathcal{A}_\ell$
- Cross checked against MadGraph/MadEvent
- Dipole subtraction to cancel soft and collinear singularities

Photon isolation and fragmentation

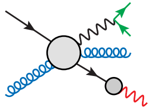
Production of photons:

- Prompt photons:

  ⇒ photons directly produced from hard scattering:



  ⇒ photons from fragmentation of QCD partons:



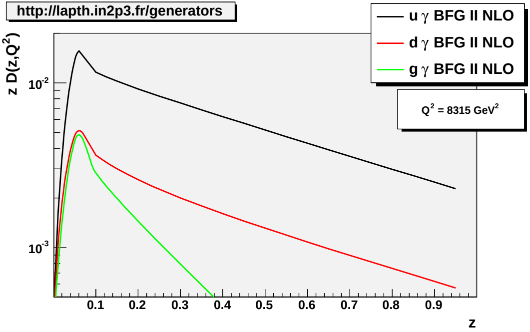
  Probability for a parton i to fragment into a photon: $D_{i\to\gamma}(z, M_F)$
  Photon FFs must be extracted from data due to their non-perturbative nature

- Secondary photon: hadronic activities (e.g. $\pi^0 \to \gamma\gamma$)
  Removed by isolation cuts

$$\sum_{\in R_0} E_T(\mathrm{had}) < E_T^{\max} \text{ with } R_0 = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

Photon Fragmentation Functions

- BFG (set I and II) [Bourhis,Fontannaz,Guillet:hep-ph/9704447]
- GdRG [Gehrmann-De Ridder,Glover:hep-ph/9806316]



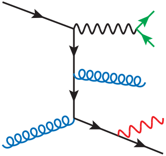
$z \rightarrow$ fraction of parton momentum that is carried by the photon

FFs dominant in the low z region

After isolation cut, z is typically large

$\rightarrow$ Isolation drops the fragmentation contribution substantially

Quark-photon FS collinear singularities

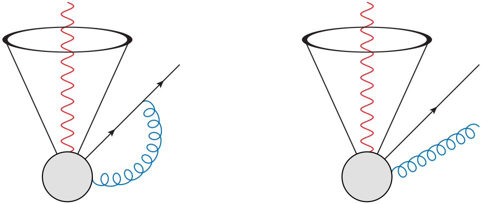


Impose photon-jet separation cut to remove singularities

$$R(\gamma, j) > R_{\rm min}$$

→ OK at LO

→ What about NLO?



Naive separation cut between photon and jet restrict the gluon phase space, thus spoils IR cancellations.

- Absorb the singularities into photon FFs.

  $\rightarrow$ Using variant of CS dipole subtraction method

  [Catani,Fontannaz,Guillet,Pilon:hep-ph/0204023]

  $\rightarrow$ Integral of subtraction terms has the form

$$D_q^\gamma = -\frac{1}{\epsilon}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu^2}{M_F^2}\right)^\epsilon \frac{\alpha}{2\pi} Q_q^2 P_{\gamma q}(z)$$

  $\rightarrow$ Perform isolation in an IR-safe way

  The NLO cross section:

$$\sigma_{NLO}^\gamma = \sigma_{NLO,\mathrm{direct}}^\gamma(M_F) + \int_0^1 dz \sum_a \sigma_f^a D_{a\rightarrow\gamma}(z, M_F)$$

  $M_F \Rightarrow$ Fragmentation Scale

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  $M_F \Rightarrow$ Fragmentation Scale

- Frixione's smooth cone isolation [Frixione:hep-ph/9801442]

$$\sum_{\mathrm{had}} E_T^{\mathrm{had}}\,\theta(R - R_{\mathrm{had},\gamma}) < \epsilon_h E_T^\gamma \left(\frac{1-\cos R}{1-\cos R_0}\right)^n \qquad \text{for all } R \le R_0$$

  → Soft radiation is allowed inside the cone but collinear singularities are removed

  → Remove fragmentation contributions

  → Useful for theoretical calculation, difficult to implement experimentally

MCFM (http://mcfm.fnal.gov)

- MCFM = Monte Carlo for FeMtobarn processes
- parton level Monte Carlo program (with NLO accuracy) written in `Fortran`

  ⇒ "one-stop shopping" for many NLO predictions.

  ⇒ Latest version: v6.3, August 2012

  Authors: J. Campbell, R. K. Ellis, C. Williams
- Includes SM processes involving γ, W, Z + jets, top quarks, Higgs.
- Decays of unstable particles are included, maintaining spin correlations and (sometimes) including NLO effects.
- Anomalous couplings for $W\gamma$ and $Z\gamma$ processes.
- Photon fragmentation and realistic isolation included.
- Cross sections and differential distributions, flexible cuts.
- Analytic helicity amplitudes calculated from scratch or taken from literature.
- Slightly-modified implementation of Catani-Seymour dipole subtraction

$Z\gamma$+jet: Results

Setup

Standard Cuts:

$$\begin{aligned}
\text{Photon} \quad &: \quad |\eta_\gamma| < 2.37,\ R_{\ell\gamma} > 0.7\ , \\
& \quad p_T^\gamma > 15 \text{ GeV} \quad (\text{low}-p_T), \\
& \quad p_T^\gamma > 60 \text{ GeV} \quad (\text{intermediate}-p_T), \\
& \quad p_T^\gamma > 100 \text{ GeV} \quad (\text{high}-p_T). \\
& \quad R_0 = 0.3 \text{ and } E_T^{\max} = 6 \text{ GeV} \ (\text{isolation})\ .
\end{aligned}$$

$$\begin{aligned}
\text{Leptons} \quad &: \quad m_{\ell^+\ell^-} > 40 \text{ GeV},\ p_T^\ell > 25 \text{ GeV},\ |\eta_\ell| < 2.47,\ R_{\ell j} > 0.6, \\
& \quad E_T^{\text{miss}} > 25 \text{ GeV}\ .
\end{aligned}$$

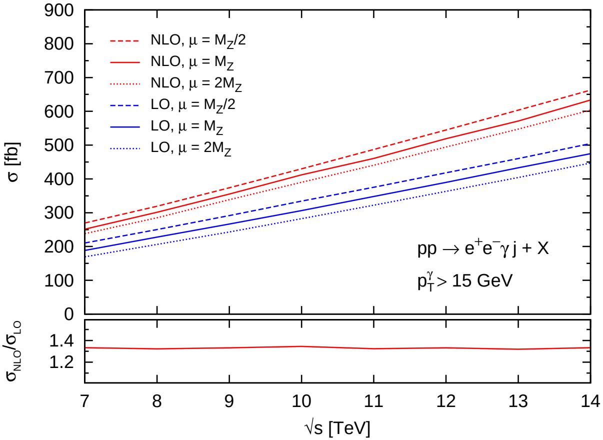
$$\text{Jets} \quad : \quad p_T^j > 30 \text{ GeV},\ |y_j| < 4.4,\ \ k_T \text{ algorithm with } R = 0.4\ .$$

Scale: $\mu_r = \mu_f = M_F = M_Z$

PDFs: CTEQ6L1 for LO, CT10 for NLO

Photon FFs: BFG set II

$Z\gamma j$ inclusive cross section vs LHC operating energy.



Exclusive cross section: $pp \to e^+e^-\gamma + (0,1)$ jet

Evaluating uncertainties: [Stewart,Tackmann: arXiv:1107.2117]

- Directly varying the μ_r and μ_f for each σ_N

  Potentially underestimate the uncertainties in individual jet bin

  due to numerical cancellation.

$$\sigma_{\text{total}} \simeq \sigma_B \left[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\right], \qquad L = \ln(p_T^{\text{cut}}/Q)$$

$$\sigma_{\geq 1}(p_T^{\text{cut}}) \simeq \sigma_B \left[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\right]$$

$$\sigma_0(p_T^{\text{cut}}) = \sigma_{\text{total}} - \sigma_{\geq 1}(p_T^{\text{cut}})$$

- Combine uncertainties in inclusive N-jet cross section

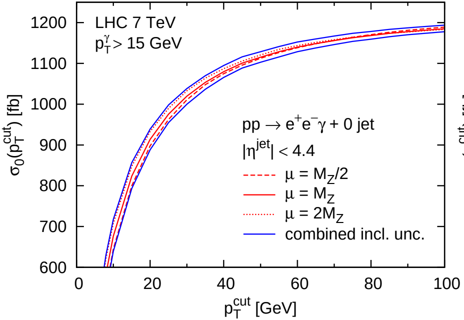
$$\Delta_0^2 = \Delta_{\text{total}}^2 + \Delta_{\geq 1}^2, \qquad \Delta_1^2 = \Delta_{\geq 1}^2 + \Delta_{\geq 2}^2$$

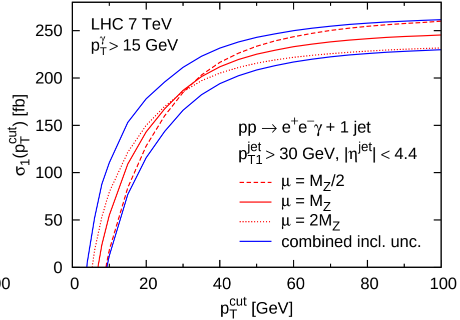
$\rightarrow$ Δ_{total} and $\Delta_{\geq 1}$ are treated as independent

$\rightarrow$ takes into account large logarithmic corrections

$\rightarrow$ Applied to H + 0,1 jets, WW + 0 jets, W + 0,1,2 jets

Exclusive cross section: $pp \to e^+e^-\gamma + (0,1)$ jet





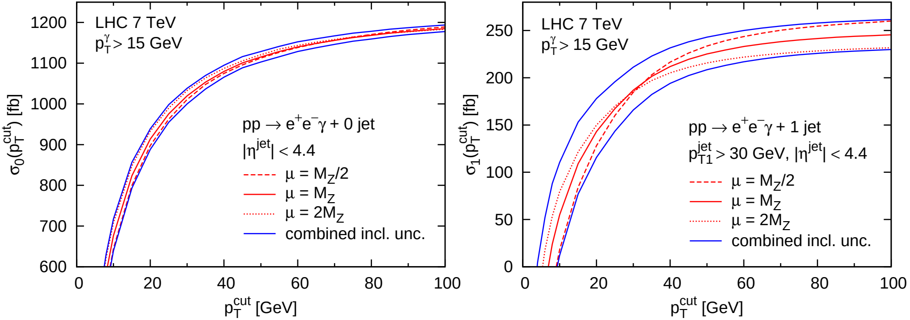
$e^+e^-\gamma + (0,1)$ jets: $(p_T^{\rm jet} \geq 30$ GeV$)$

$$\delta(\sigma_{\rm tot}) = {}^{+0.7\%}_{-0.5\%}, \; \delta(\sigma_{\geq 1}) = {}^{+7.4\%}_{-5.2\%}, \; \delta(\sigma_{\geq 2}) = {}^{+28.0\%}_{-21.6\%}$$

$\delta(\sigma_0) = {}^{+1.8\%}_{-1.9\%}, \; \delta(\sigma_1) = {}^{+13.0\%}_{-11.2\%}$ (combined incl. uncertainties)

$\delta(\sigma_0) = {}^{+1.3\%}_{-0.9\%}, \; \delta(\sigma_1) = {}^{-0.8\%}_{-1.2\%}$ (direct scale variation)

Exclusive cross section: $pp \to e^+e^-\gamma + (0,1)$ jet



$e^+e^-\gamma + 1$ jet: $(\mu = M_Z)$

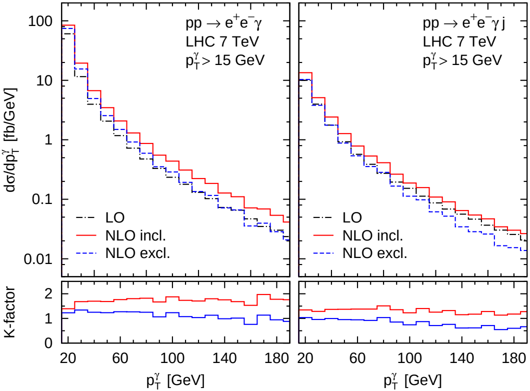
$$\sigma_{\geq 1}(p_{T1}^{\text{jet}} \geq 30\ \text{GeV}) = (188\ \text{fb})[1 + 2.89\alpha_s + \mathcal{O}(\alpha_s^2)]$$

$$\sigma_{\geq 2}(p_{T1,2}^{\text{jet}} \geq 30\ \text{GeV}) = (188\ \text{fb})[2.93\alpha_s + \mathcal{O}(\alpha_s^2)]$$

$$\sigma_1(p_{T1,2}^{\text{jet}} \geq 30\ \text{GeV}) = \sigma_{\geq 1}(p_{T1}^{\text{jet}} \geq 30\ \text{GeV}) - \sigma_{\geq 2}(p_{T1,2}^{\text{jet}} \geq 30\ \text{GeV})$$

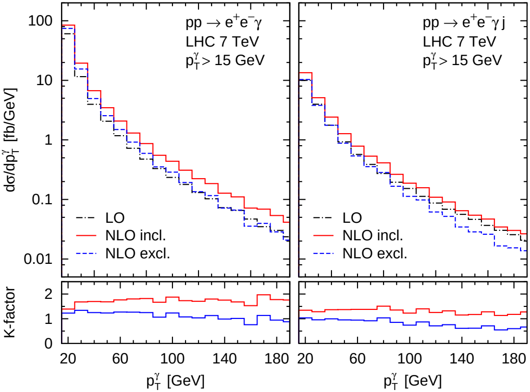
$\to$ sizeable numerical cancellation for α_s term

Photon p_T distributions



- deviation from the SM prediction may indicate the presence of anomalous couplings
- searches in MET+photon channel use photon as a probe (e.g. DM production at colliders)

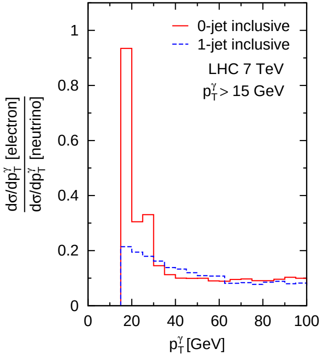
Photon p_T distributions



- Increased K factor for 0-jet inclusive but smaller and flatter for 0-jet exclusive, 1-jet inclusive and exclusive.

Photon p_T distributions

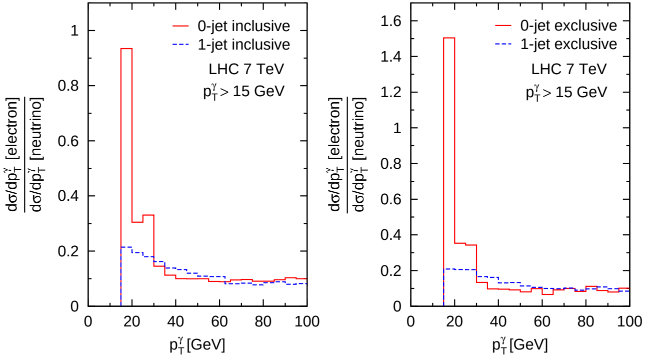
Ratio of p_T distributions between electron and neutrino final state



- In SM the ratio is sensitive to photon radiated from leptons
- Expect cancellation of some systematic errors in experiment
- Sensitive to models that modify the spectrum in one of the channels
  $\Rightarrow$ DM scenarios $\rightarrow$ only MET+photon channel is modified
  $\Rightarrow$ Anomalous couplings $\rightarrow$ both channel are modified

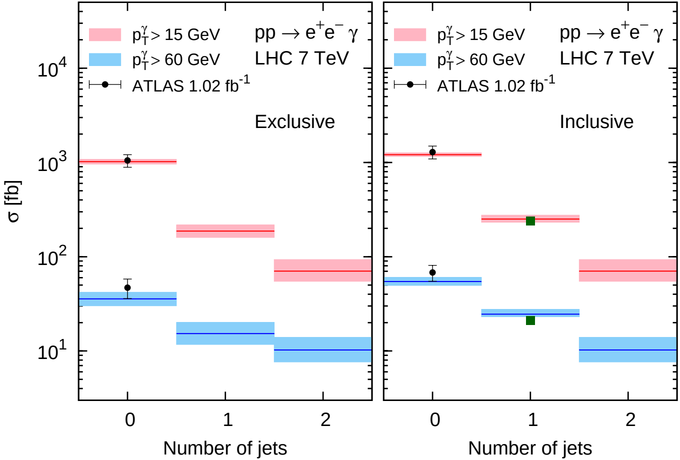
Photon p_T distributions

Ratio of p_T distributions between electron and neutrino final state



- Strong peak in the 0-jet ratio $\rightarrow$ soft photon from FS leptons
- This peak is diminished in 1-jet ratio: hard jet that balances the Z-boson
- The tail of the ratio tends to a constant.
  Smaller than $\mathrm{BR}(Z \rightarrow e^+e^-)/\mathrm{BR}(Z \rightarrow 3\nu\bar{\nu}) \sim 1/6$ due to selection cuts

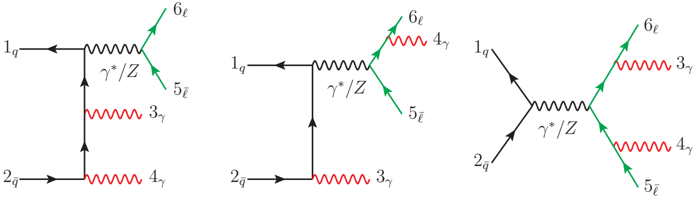
MCFM at Work



Theoretical uncertainties include: scale variation, PDFs and photon fragmentation.

$Z\gamma\gamma$: Calculation

$Z\gamma\gamma$ production at LO

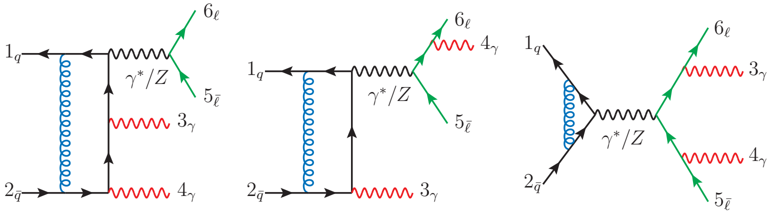


$\mathcal{A}_{qq}(0 \to \ell\bar{\ell}q\bar{q}\gamma\gamma)$ $\mathcal{A}_{q\ell}(0 \to \ell\bar{\ell}q\bar{q}\gamma\gamma)$ $\mathcal{A}_{\ell\ell}(0 \to \ell\bar{\ell}q\bar{q}\gamma\gamma)$

- Three separately gauge invariant classes of diagrams:
  $\to$ both photons from quark line ("qq-type")
  $\to$ 1 photon from each line ("$q\ell$-type")
  $\to$ both photons from lepton line ("$\ell\ell$-type")
- only qq-type diagrams for neutrino final state
- LO amplitudes:

$$
\begin{aligned}
\mathcal{A}^{(0)}_{qq}(1_q, 2_{\bar{q}}, 3_\gamma, 4_\gamma, 5_{\bar{\ell}}, 6_\ell) &= \mathcal{A}^{(0)}_{q}(1_q, 2_{\bar{q}}, 3_g, 4_\gamma, 5_{\bar{\ell}}, 6_\ell) \\
\mathcal{A}^{(0)}_{q\ell}(1_q, 2_{\bar{q}}, 3_\gamma, 4_\gamma, 5_{\bar{\ell}}, 6_\ell) &= \mathcal{A}^{(0)}_{\ell}(1_q, 2_{\bar{q}}, 3_g, 4_\gamma, 5_{\bar{\ell}}, 6_\ell) \\
\mathcal{A}^{(0)}_{\ell\ell}(1_q, 2_{\bar{q}}, 3_\gamma, 4_\gamma, 5_{\bar{\ell}}, 6_\ell) &= \mathcal{A}^{(0)}_{qq}(6_\ell, 5_{\bar{\ell}}, 3_\gamma, 4_\gamma, 2_{\bar{q}}, 1_q)
\end{aligned}
$$

$Z\gamma\gamma$ production: $\mathcal{O}(\alpha_s)$ virtual correction



$\mathcal{A}^{(1)}_{qq}(0 \to \ell\bar{\ell}q\bar{q}\gamma\gamma)$ $\mathcal{A}^{(1)}_{q\ell}(0 \to \ell\bar{\ell}q\bar{q}\gamma\gamma)$ $\mathcal{A}^{(1)}_{\ell\ell}(0 \to \ell\bar{\ell}q\bar{q}\gamma\gamma)$

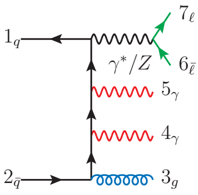
- Virtual amplitudes:

$$\begin{aligned}\mathcal{A}^{(1)}_{qq}(1_q, 2_{\bar{q}}, 3_\gamma, 4_\gamma, 5_{\bar{\ell}}, 6_\ell) &= A_6(1_q, 2_{\bar{q}}, 3, 4) + A_6(1_q, 2_{\bar{q}}, 4, 3)\\ \mathcal{A}^{(1)}_{q\ell}(1,_q 2_{\bar{q}}, 3_\gamma, 4_\gamma, 5_{\bar{\ell}}, 6_\ell) &= -A^{\rm sl}_\ell(1_q, 2_{\bar{q}}, 3_g, 4_\gamma, 5_{\bar{\ell}}, 6_\ell)\end{aligned}$$

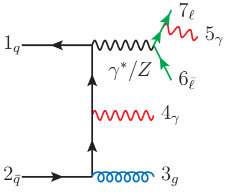
- Only need to compute $\mathcal{A}_{\ell\ell}(0 \to \ell\bar{\ell}q\bar{q}\gamma\gamma)$

$$\mathcal{A}^{(1)}_{\ell\ell}(1_q, 2_{\bar{q}}, 3_\gamma, 4_\gamma, 5_{\bar{\ell}}, 6_\ell) = \left(\frac{\mu^2}{-s_{12}}\right)^\epsilon \left[-\frac{1}{\epsilon^2} - \frac{3}{2\epsilon} - 4\right] \mathcal{A}^{(0)}_{\ell\ell}(1_q, 2_{\bar{q}}, 3_\gamma, 4_\gamma, 5_{\bar{\ell}}, 6_\ell).$$

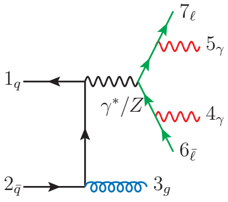
$Z\gamma\gamma$ production: $\mathcal{O}(\alpha_s)$ real correction



$\mathcal{A}^{(0)}_{qq}(0 \to \ell\bar{\ell}q\bar{q}g\gamma\gamma)$



$\mathcal{A}^{(0)}_{q\ell}(0 \to \ell\bar{\ell}q\bar{q}g\gamma\gamma)$



$\mathcal{A}^{(0)}_{\ell\ell}(0 \to \ell\bar{\ell}q\bar{q}g\gamma\gamma)$

- Real emission amplitudes:

$$\mathcal{A}^{(0)}_{qq}(1_q, 2_{\bar{q}}, 3_g, 4_\gamma, 5_\gamma, 6_{\bar{\ell}}, 7_\ell) = \mathcal{A}^{(0)}_{q}(1_q, 2_{\bar{q}}, 3_g, 4_g, 5_\gamma, 6_{\bar{\ell}}, 7_\ell) + \mathcal{A}^{(0)}_{q}(1_q, 2_{\bar{q}}, 3_g, 5_\gamma, 4_g, 6_{\bar{\ell}}, 7_\ell)$$

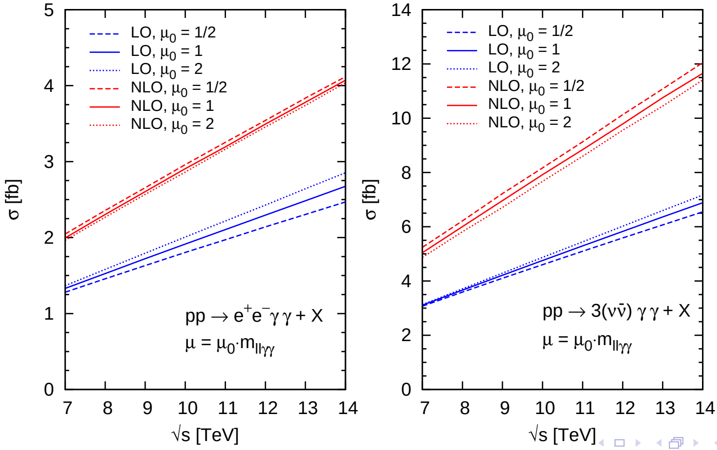
$$\mathcal{A}^{(0)}_{q\ell}(1_q, 2_{\bar{q}}, 3_g, 4_\gamma, 5_\gamma, 6_{\bar{\ell}}, 7_\ell) = \mathcal{A}^{(0)}_{\ell}(1_q, 2_{\bar{q}}, 3_g, 4_g, 5_\gamma, 6_{\bar{\ell}}, 7_\ell) + \mathcal{A}^{(0)}_{\ell}(1_q, 2_{\bar{q}}, 4_g, 3_g, 5_\gamma, 6_{\bar{\ell}}, 7_\ell)$$

$$\mathcal{A}^{(0)}_{\ell\ell}(1_q, 2_{\bar{q}}, 3_g, 4_\gamma, 5_\gamma, 6_{\bar{\ell}}, 7_\ell) = \mathcal{A}^{(0)}_{q\ell}(7_\ell, 6_{\bar{\ell}}, 5_g, 3_\gamma, 4_\gamma, 2_{\bar{q}}, 1_q)$$

$Z\gamma\gamma$: Results

$Z\gamma\gamma$ inclusive cross section

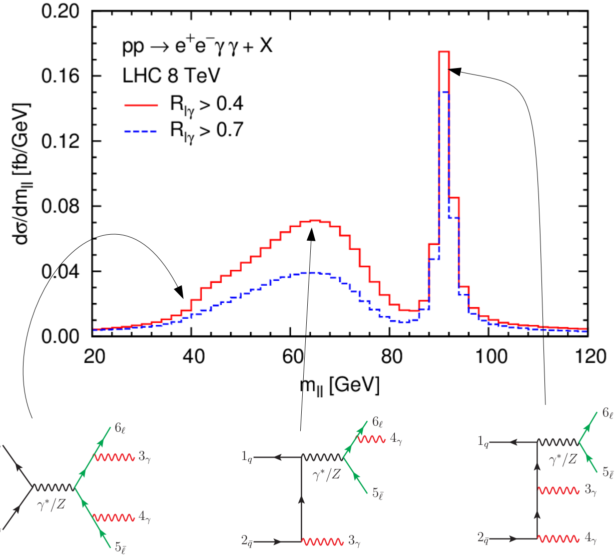
$$p_T^{\gamma} > 20\,\mathrm{GeV}\ , \quad |\eta_\gamma| < 2.5\ , \quad R_{\gamma\gamma} > 0.4\ ,$$
$$p_T^{\ell_h} > 25\,\mathrm{GeV}\ , \quad p_T^{\ell_s} > 15\,\mathrm{GeV}\ , \quad |\eta_\ell| < 2.5\ ,$$
$$m_{\ell\ell} > 12\,\mathrm{GeV}\ , \quad R_{\ell\gamma} > 0.7\ , \quad E_T^{\mathrm{miss}} > 25\,\mathrm{GeV}\ .$$



$K \sim 1.5$
for $\nu\bar{\nu}\gamma\gamma$

$K \sim 1.6$
for $e^+e^-\gamma\gamma$

$m_{\ell\bar{\ell}}$ distribution



Conclusions

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- We computed NLO QCD corrections to $Z\gamma j$ and $Z\gamma\gamma$ productions at hadron colliders
- We present the phenomenology for the $Z\gamma$,$Z\gamma$+jet and $Z\gamma\gamma$ processes at NLO
- Include the fragmentation contributions
- We studied the perturbative uncertainty of the exclusive cross section following Stewart/Tackmann's method
- $Z\gamma j$ and $Z\gamma\gamma$ processes are available in `MCFMv6.3`

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THANK YOU

BACKUPs

Predictions for $Z\gamma$ and $Z\gamma$+jet.

	Inclusive NLO ($e^+e^-\gamma + X$) [pb]
$p_T^\gamma > 15$ GeV	$1.21^{+0.7\%}_{-0.5\%}$(scale)$\pm$3.5%(PDF)$\pm$0.4%(frag)
$p_T^\gamma > 60$ GeV	$0.0545^{+5.7\%}_{-4.1\%}$(scale)$\pm$3.7%(PDF)$\pm$1.2%(frag)
	Exclusive NLO ($e^+e^-\gamma$ + no jets) [pb]
$p_T^\gamma > 15$ GeV	$1.02^{+1.8\%}_{-1.9\%}$(scale)$\pm$3.8%(PDF)$\pm$0.5%(frag)
$p_T^\gamma > 60$ GeV	$0.0357^{+11.6\%}_{-9.4\%}$(scale)$\pm$4.4%(PDF)$\pm$1.8%(frag)

	Inclusive 1-jet NLO ($e^+e^-\gamma$ + jet + X) [fb]
$p_T^\gamma > 15$ GeV	$252^{+7.4\%}_{-5.2\%}$(scale)$\pm$2.0%(PDF)$\pm$0.6%(frag)
$p_T^\gamma > 60$ GeV	$24.6^{+8.1\%}_{-6.8\%}$(scale)$\pm$2.5%(PDF)$\pm$1.9%(frag)
	Exclusive 1-jet NLO ($e^+e^-\gamma$ + jet) [fb]
$p_T^\gamma > 15$ GeV	$188^{+13.0\%}_{-11.2\%}$(scale)$\pm$2.4%(PDF)$\pm$0.8%(frag)
$p_T^\gamma > 60$ GeV	$15.3^{+25.3\%}_{-17.4\%}$(scale)$\pm$2.9%(PDF)$\pm$3.1%(frag)