Photon-initiated processes with rapidity gaps at the LHC

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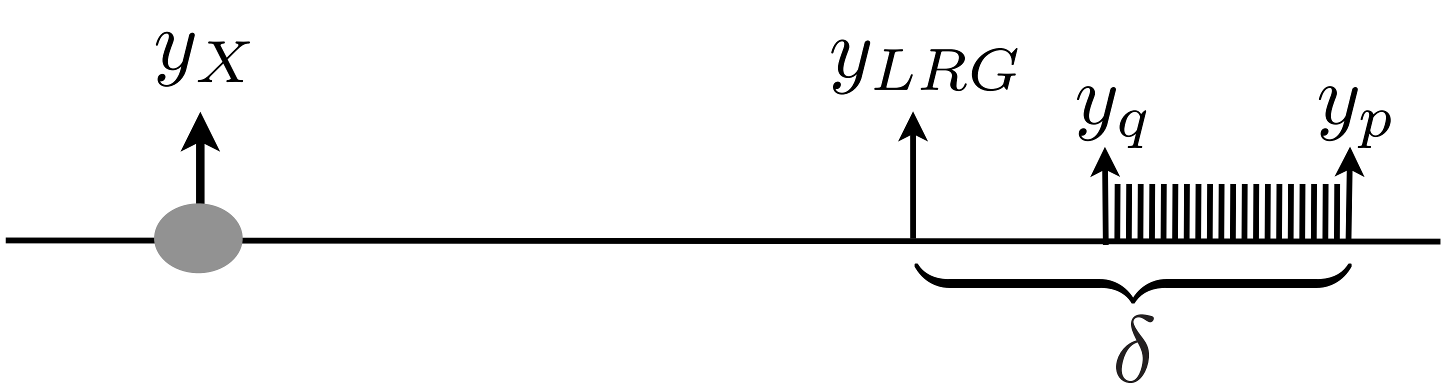
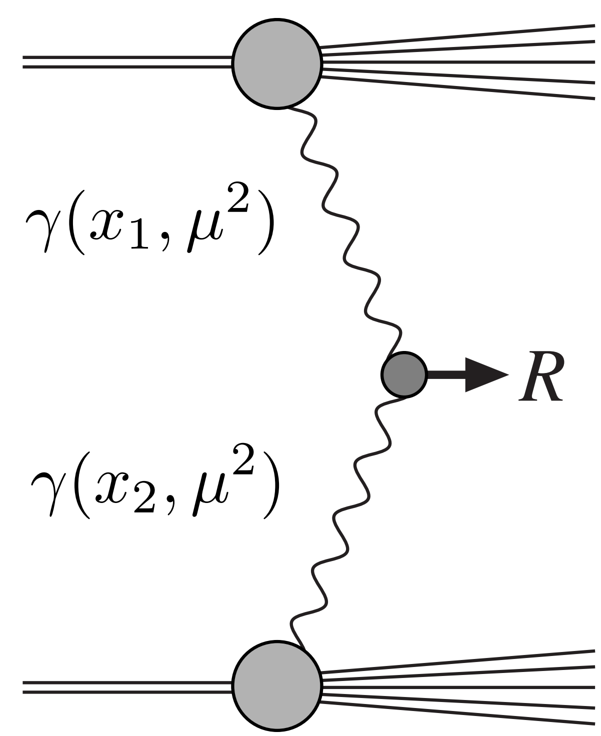
Low-x 2016, 7 June, Gyöngyös, Hungary

In collaboration with Valery Khoze and Misha Ryskin

Outline

- Motivation: why study photon-initiated processes at the LHC?
- Semi-exclusive processes with rapidity gaps: how do we include a rapidity veto within the standard inclusive approach?
- Comparison to CMS 7 and 8 TeV $\mu^+\mu^-$ data.





Why study photon-initiated processes? (1)

- In era of high precision phenomenology at the LHC: NNLO calculations rapidly becoming the 'standard'. However:

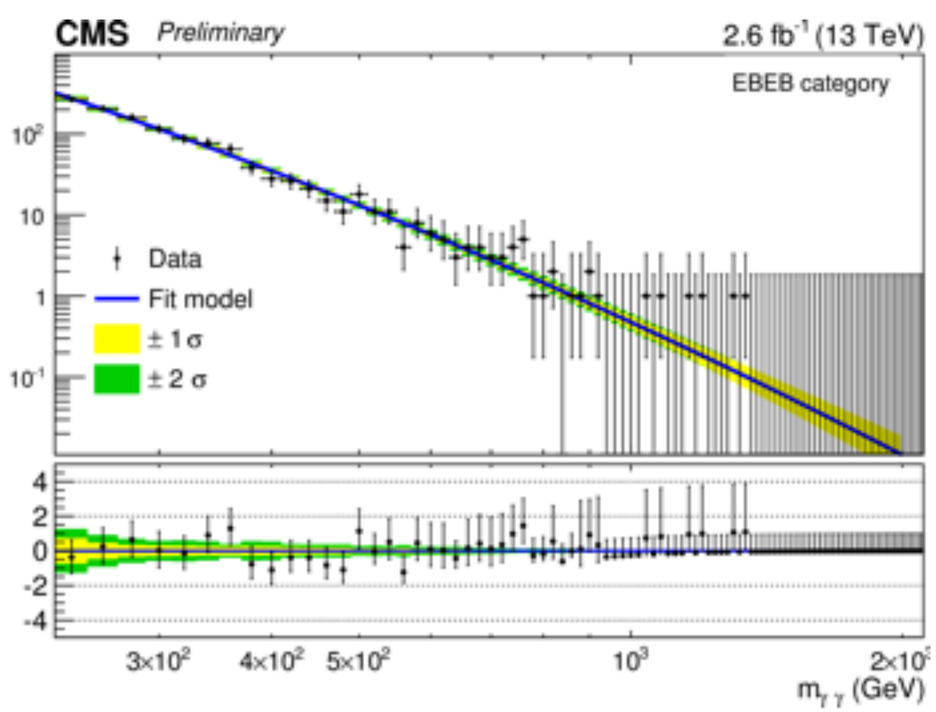
$$\alpha_S^2(M_Z) \sim 0.118^2 \sim \frac{1}{70} \qquad \alpha_{\rm QED}(M_Z) \sim \frac{1}{130}$$

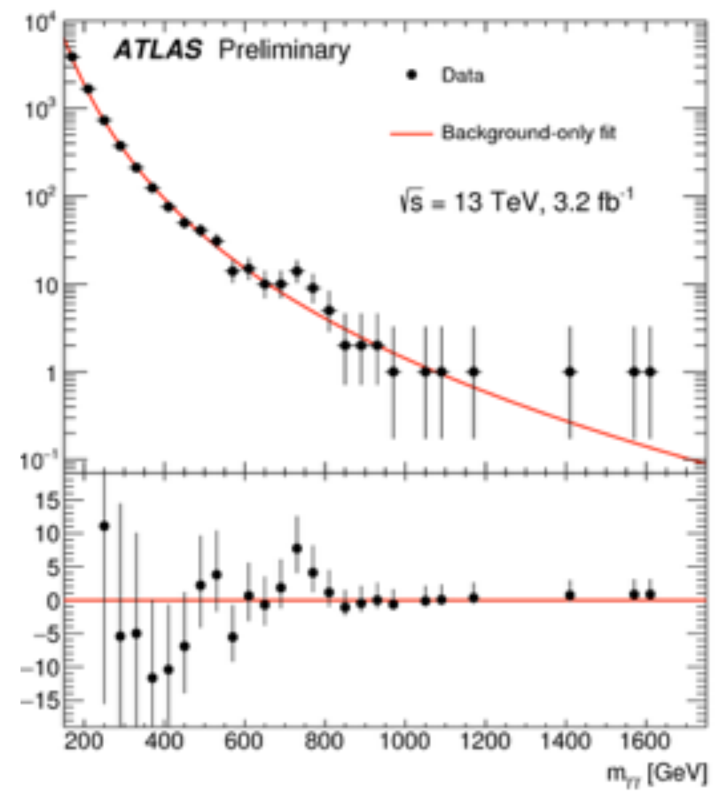
$\longrightarrow$ NLO EW and NNLO QCD corrections can be comparable in size.

- Thus at this level of accuracy, must consider a proper account of EW corrections. At LHC these can be relevant for a range of processes (W, Z, WH, ZH, WW, $t\bar{t}$, jets...).
- For consistent treatment of these, must incorporate QED in initial state: QED corrections to DGLAP evolution and a photon PDF.

Why study photon-initiated processes? (2)

- Excess of events at $750\,\mathrm{GeV}$ seen so far only in $\gamma\gamma$ final-state, and not e.g. in dijet mass spectrum. What if this is due to a new state R which couple dominantly to photons?
- Subject of a range of studies: arXiv:1512.05751, 1512.05776, 1512.08502,1512.04933,1601.00624,1601.00386,1601.01144,1601.01571,1601.00638,1601.01712,1601.07167,1602.00475,1601.07564…
- If this is the case, essential to have the most precise possible calculation of the $\gamma\gamma$ initial-state $\longrightarrow$ important to understand photon PDF.

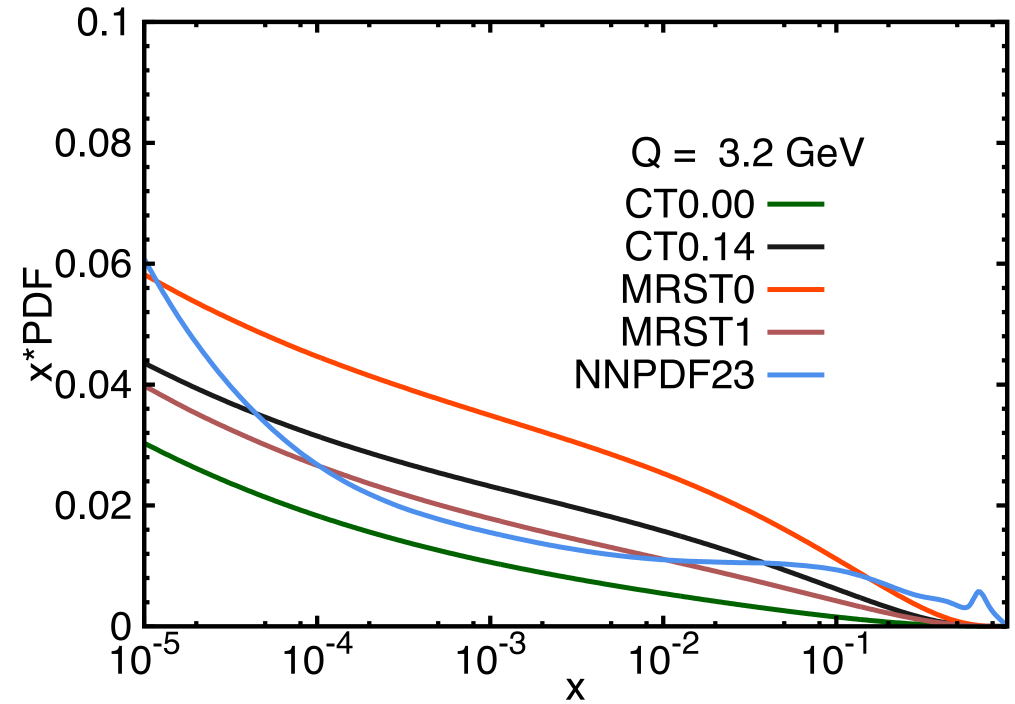




Why study photon-initiated processes? (3)

- Unlike the quark/gluons, photon is colour-singlet object: can lead naturally to large rapidity gaps (LRGs) in the final state:
  - ‘Exclusive’ production: LRGs between centrally produced object and outgoing intact protons.
  - ‘Semi-exclusive’: protons may break up, but LRGs still present between X and dissociation products.

- We will consider the latter processes: test of gap survival, and potentially most direct probe available at LHC for $\gamma(x, Q^2)$ - large variations between different sets (limited constraints).



arXiv:1509.02905

The photon and rapidity gaps

- arXiv:1601.03772: aim to give systematic treatment of the effect of LRG vetoes on the photon PDF.

IPPP/16/01
April 20, 2016

The photon PDF in events with rapidity gaps

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Abstract

We consider photon–initiated events with large rapidity gaps in proton–proton collisions, where one or both protons may break up. We formulate a modified photon PDF that accounts for the specific experimental rapidity gap veto, and demonstrate how the soft survival probability for these gaps may be implemented consistently. Finally, we present some phenomenological results for the two–photon induced production of lepton and W boson pairs.

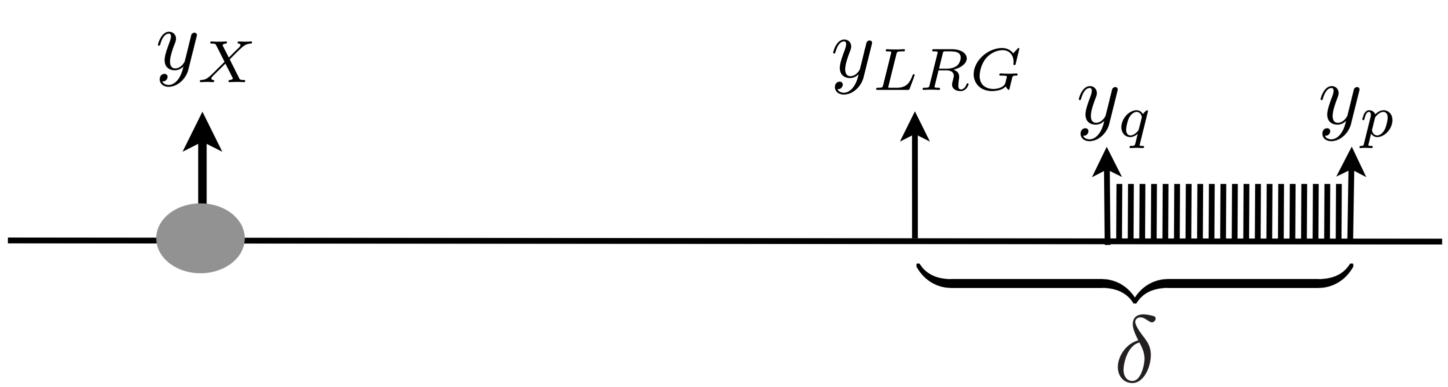
The photon and rapidity gaps: setup

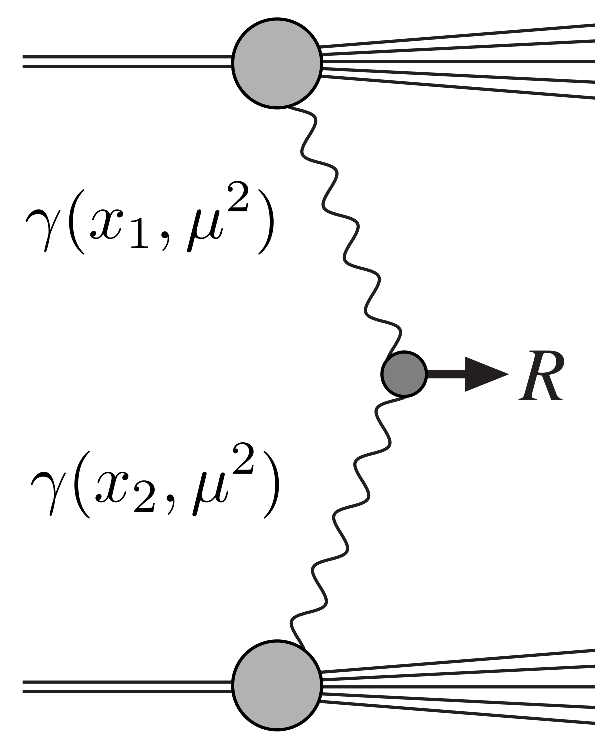
- Consider photon-initiated production of a system X:

$$\sigma(R) = \int \mathrm{d}x_1 \mathrm{d}x_2 \, \gamma(x_1,\mu^2)\gamma(x_2,\mu^2)\, \hat{\sigma}(\gamma\gamma \to R)$$

but require no additional particles out to rapidity y_{LRG}.

- Question: how does this modify the photon PDF $\gamma(x, Q^2)$?





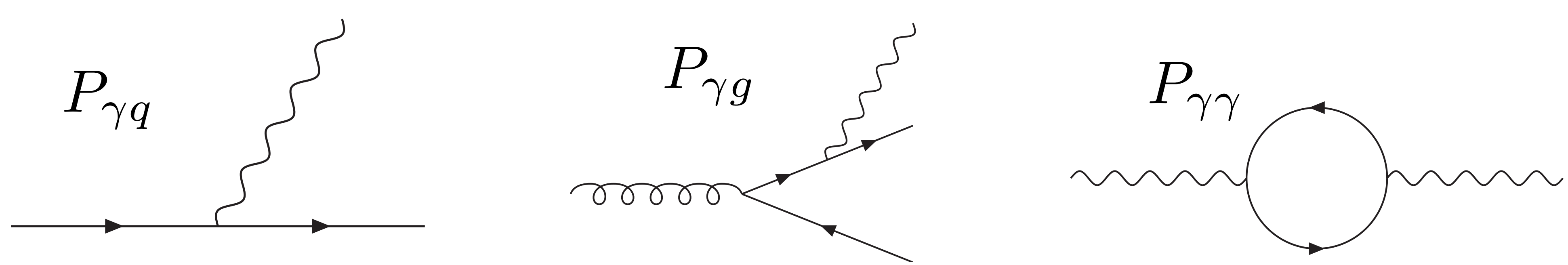
The photon PDF

- As with other partons, the photon obeys a DGLAP evolution equation:

$$\gamma(x,\mu^2) = \gamma(x,Q_0^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\Bigg(P_{\gamma\gamma}(z)\gamma(\frac{x}{z},Q^2) + \sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2) + P_{\gamma g}(z) g(\frac{x}{z},Q^2)\Bigg)\,,$$

NLO in QCD

- Thus PDF at scale μ given in terms of:
  - PDF at starting scale $Q_0 \sim 1\,\mathrm{GeV}$.
  - Evolution term from, due to emission from quarks up to scale μ.



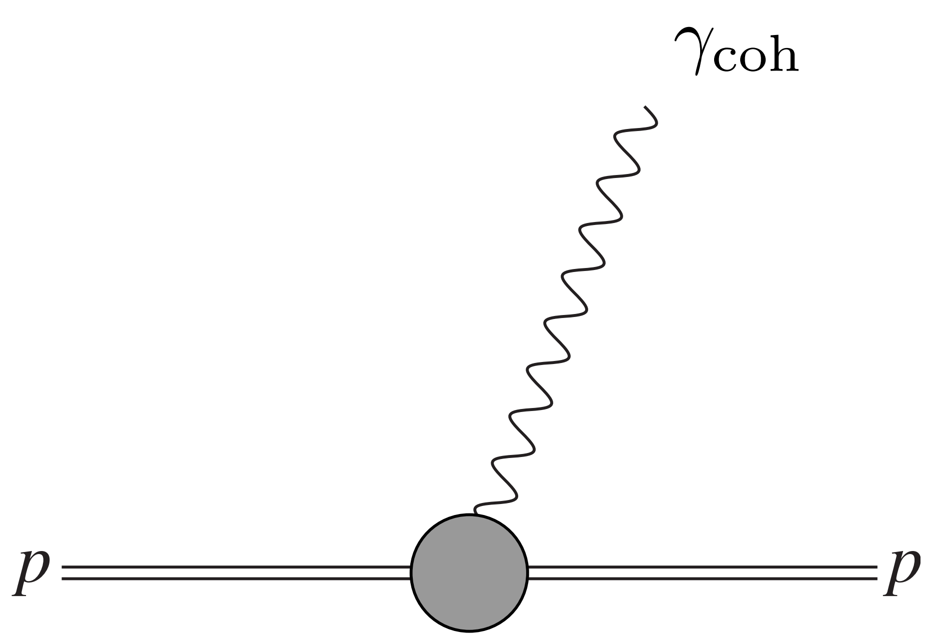
- Question: how do we model the starting distribution $\gamma(x,Q_0^2)$?

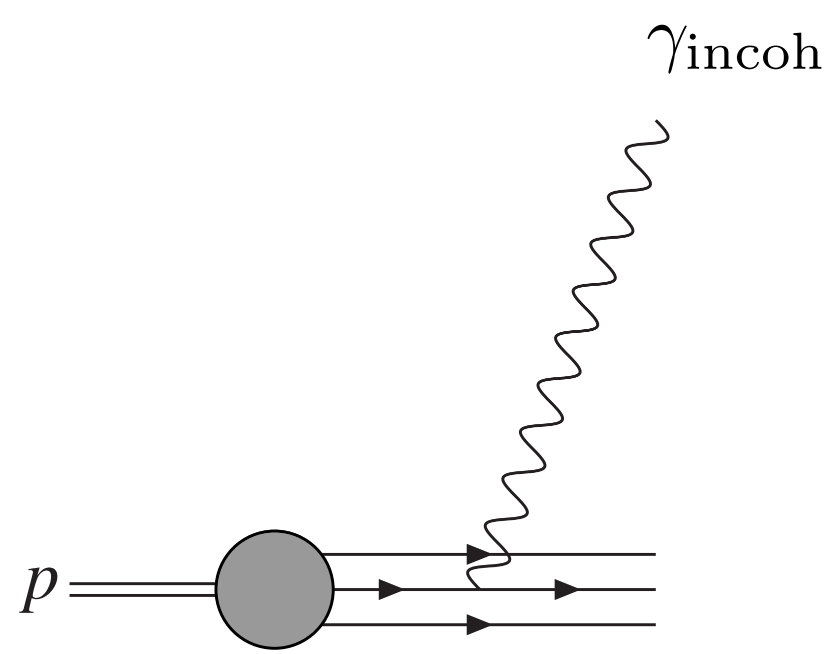
The starting distribution

- Take approach of A.D. Martin and M.G. Ryskin, arXiv:1406.2118. Photon at $Q_0 \sim 1\,\text{GeV}$ given as sum of coherent and incoherent terms:

$$\gamma(x, Q_0^2) = \gamma_{\text{coh}}(x, Q_0^2) + \gamma_{\text{incoh}}(x, Q_0^2)$$

  - Coherent: due to elastic $p \to p\gamma$ emission $\Rightarrow$ connection to purely exclusive production.
  - Incoherent: emission from individual quarks. Some theoretical guidance, but known less precisely.





Solving the DGLAP equation

- Returning to photon DGLAP evolution equation:

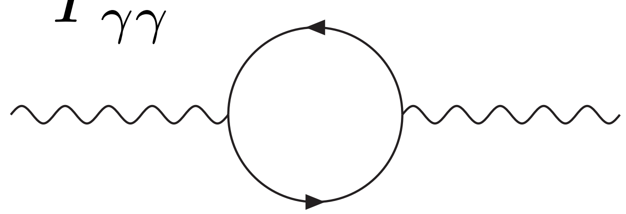
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\bigg(P_{\gamma\gamma}(z)\gamma(\frac{x}{z},Q^2) + \sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2) + P_{\gamma g}(z) g(\frac{x}{z},Q^2)\bigg)\,,$$

NLO in QCD

- As $\alpha \ll 1$ we can simplify to very good approx: take q and g as independent of γ .

- The self-energy contribution $P_{\gamma\gamma}(z) \sim \delta(1-z)$ and therefore this term on RHS of DGLAP $\sim \gamma(x,Q^2)$ i.e. at same x as LHS.

$P_{\gamma\gamma}$



$\longrightarrow$ Can solve the photon DGLAP equation!

Solving the DGLAP equation

- We find:

$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\, S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\bigg(\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2)$$
$$+ P_{\gamma g}(z) g(\frac{x}{z},Q^2)\bigg)\, S_\gamma(Q^2,\mu^2)\;,$$

i.e. we have

$$\gamma(x,\mu^2) \;\equiv \gamma^{\rm in}(x,\mu^2) + \gamma^{\rm evol}(x,\mu^2)$$

$\longrightarrow$ Photon PDF given separately in terms of:

- $\gamma^{\rm in}(x,\mu^2)$: component due to low scale $Q^2 < Q_0^2 \sim 1\,{\rm GeV}^2$ emission.
- $\gamma^{\rm evol}(x,\mu^2)$: component due to high scale DGLAP emission from quarks.

- What is $S_\gamma(Q^2,\mu^2)$?

The Sudakov factor

- Solution to DGLAP equation:

$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\, S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\Big(\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2)$$

$$+ P_{\gamma g}(z) g(\frac{x}{z},Q^2)\Big)\, S_\gamma(Q^2,\mu^2)\ ,$$

$$\mathcal{P}(\text{no branching}) = e^{-\lambda_\gamma}$$

given in terms of Sudakov factor:

$$\lambda_\gamma = \mathcal{P}(\gamma \to q\bar{q}(l\bar{l}))$$

$$S_\gamma(Q_0^2,\mu^2) = \exp\left(-\frac{1}{2}\int_{Q_0^2}^{\mu^2} \frac{\mathrm{d}Q^2}{Q^2}\frac{\alpha(Q^2)}{2\pi}\int_0^1 \mathrm{d}z \sum_{a=q,\,l} P_{a\gamma}(z)\right)$$

where $P_{q(l)\gamma}(z)$ is the $\gamma \to q\bar{q}(l\bar{l})$ splitting function $\Rightarrow$ Poissonian probability for no extra emission between scales Q_0 and μ.

$\longrightarrow$ Allows seperation: $\gamma(x,\mu^2) \equiv \gamma^{\text{in}}(x,\mu^2) + \gamma^{\text{evol}}(x,\mu^2)$

to be readily applied to case of rapidity gap veto.

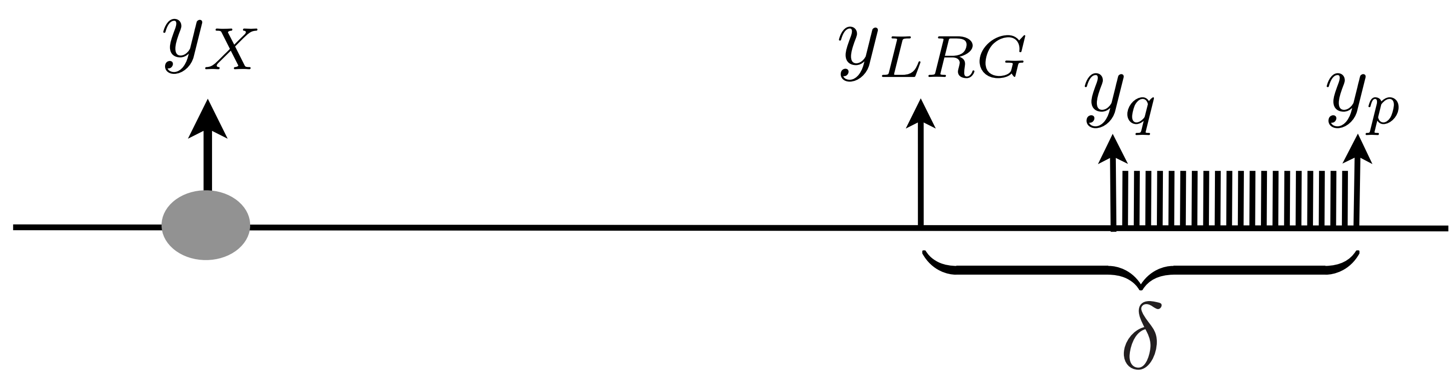
The photon and rapidity gaps: again

- Require no additional particles out to rapidity $y_{\rm LRG}$.
- How does this effect photon?

$$\gamma(x,\mu^2) \equiv \gamma^{\rm in}(x,\mu^2) + \gamma^{\rm evol}(x,\mu^2)$$

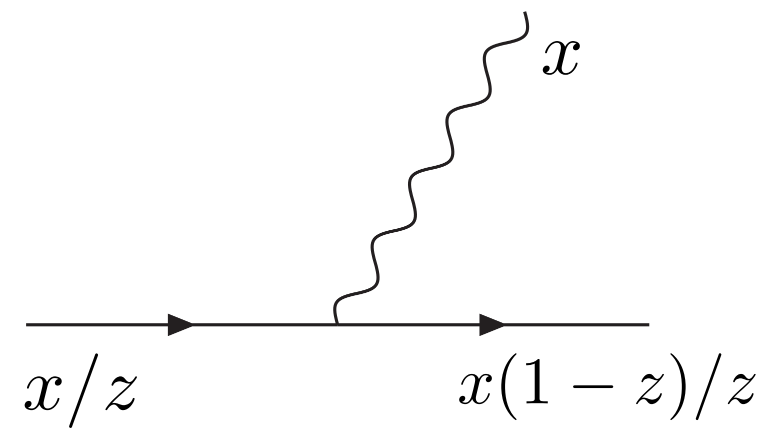
- $\gamma^{\rm in}(x,\mu^2)$: input component due to low scale elastic and inelastic photon emission. Transverse momenta q_t of produced secondaries $q_t < Q_0$

$\longrightarrow$ Input component automatically satisfies veto. What about evolution component?



Effect of veto on evolution

$$\int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\Big(\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z}, Q^2)$$



- Working in terms of interval $\delta = y_p - y_{LRG}$ between proton and gap, requirement that rapidity of final-state quark $y_q > y_{\rm LRG}$ translates to

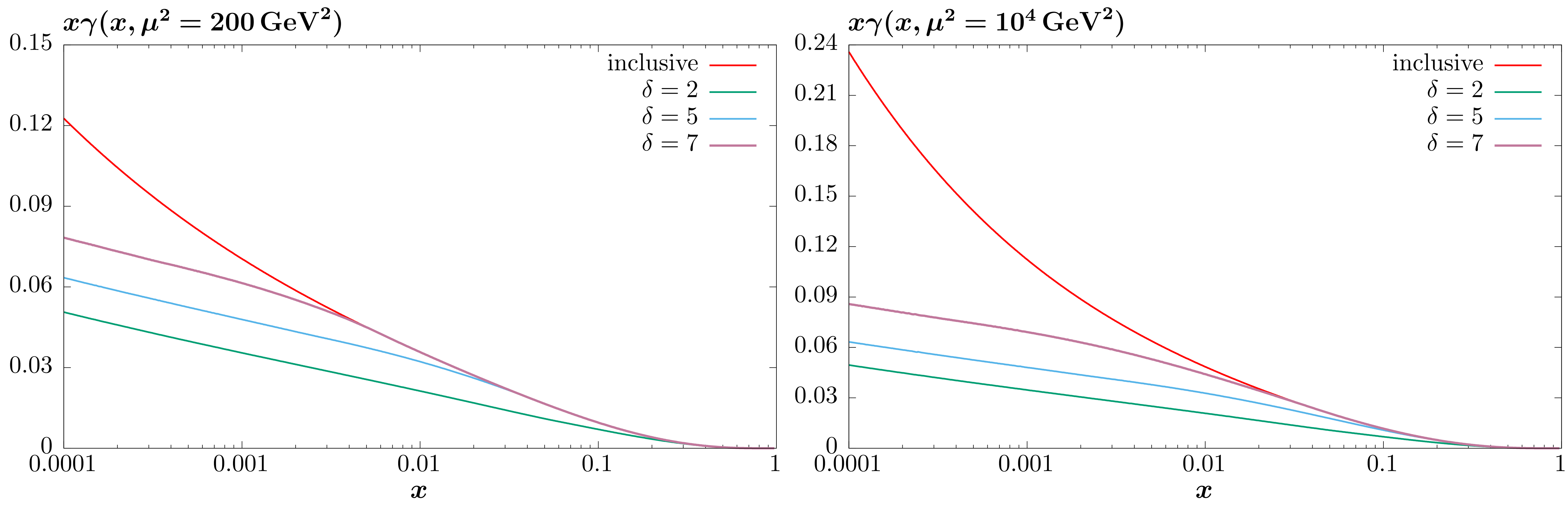
$$y_p - y_q = \ln\left(\frac{q_t}{m_p}\frac{z}{x(1-z)}\right) < \delta \ ,$$

- And photon PDF becomes simply:

$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\, S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{{\rm d}Q^2}{Q^2}\int_x^1 \frac{dz}{z}\Big(\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z}, Q^2)$$
$$+ P_{\gamma g}(z) g(\frac{x}{z}, Q^2)\Big) S_\gamma(Q^2,\mu^2)\Theta\left[e^\delta - \frac{q_t}{m_p}\frac{z}{x(1-z)}\right] \ ,$$

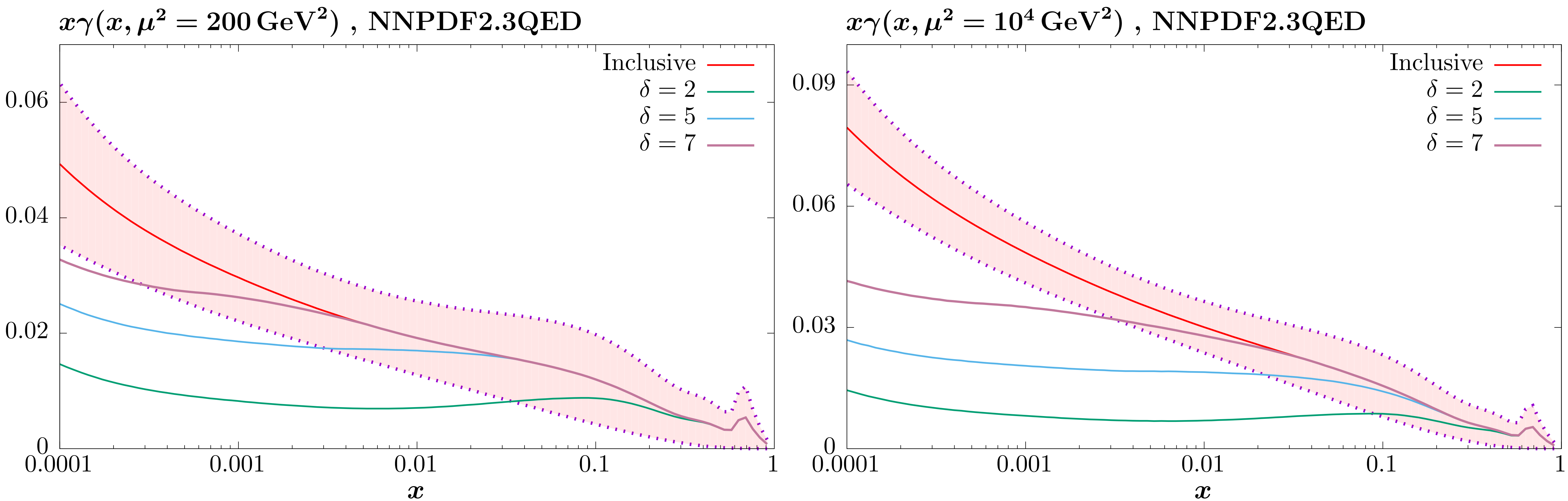
- Due to strong q_t ordering, all previous emissions will have $y > y_q > y_{\rm LRG}$

Modified photon PDF



- Suppression due to LRG veto clear, in particular at:
  - Lower x : outgoing quark has on average lower long. momentum (lower y_q)
  - Higher Q^2 : outgoing quark has on average higher q_t .

Modified photon PDF



- Similar picture with e.g. NNPDF set: suppression outside of (large) PDF uncertainty.

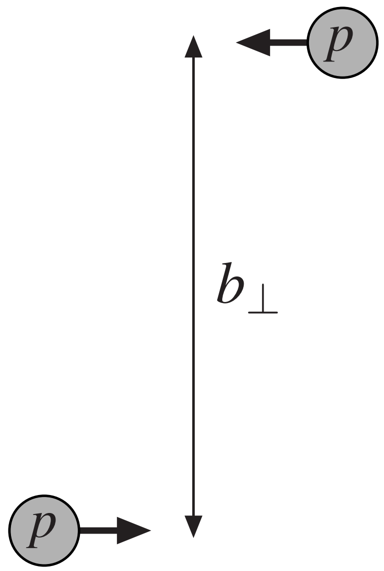
Survival effects

• Not the end of the story. Protons may interact additionally- underlying event. Include probability that this does not happen: the survival factor.

• However this probability depends on the separation in impact parameter of the colliding protons:

- Low scale $\gamma(x, Q_0^2)$: $b_t \uparrow$ and $S^2 \uparrow$
- High scale $\gamma^{\rm evol}(x, Q^2)$: $b_t \downarrow$ and $S^2 \downarrow$

$\langle S^2 \rangle$	$M_X^2 = 200\,\mathrm{GeV}^2$	$M_X^2 = 10^4\,\mathrm{GeV}^2$
(coh., coh.)	0.95	0.89
(coh., incoh.)	0.84	0.76
(incoh., incoh.)	0.18	0.18
(evol., coh.)	0.83	0.74
(evol., incoh.)	0.16	0.16
(evol., evol.)	0.097	0.097

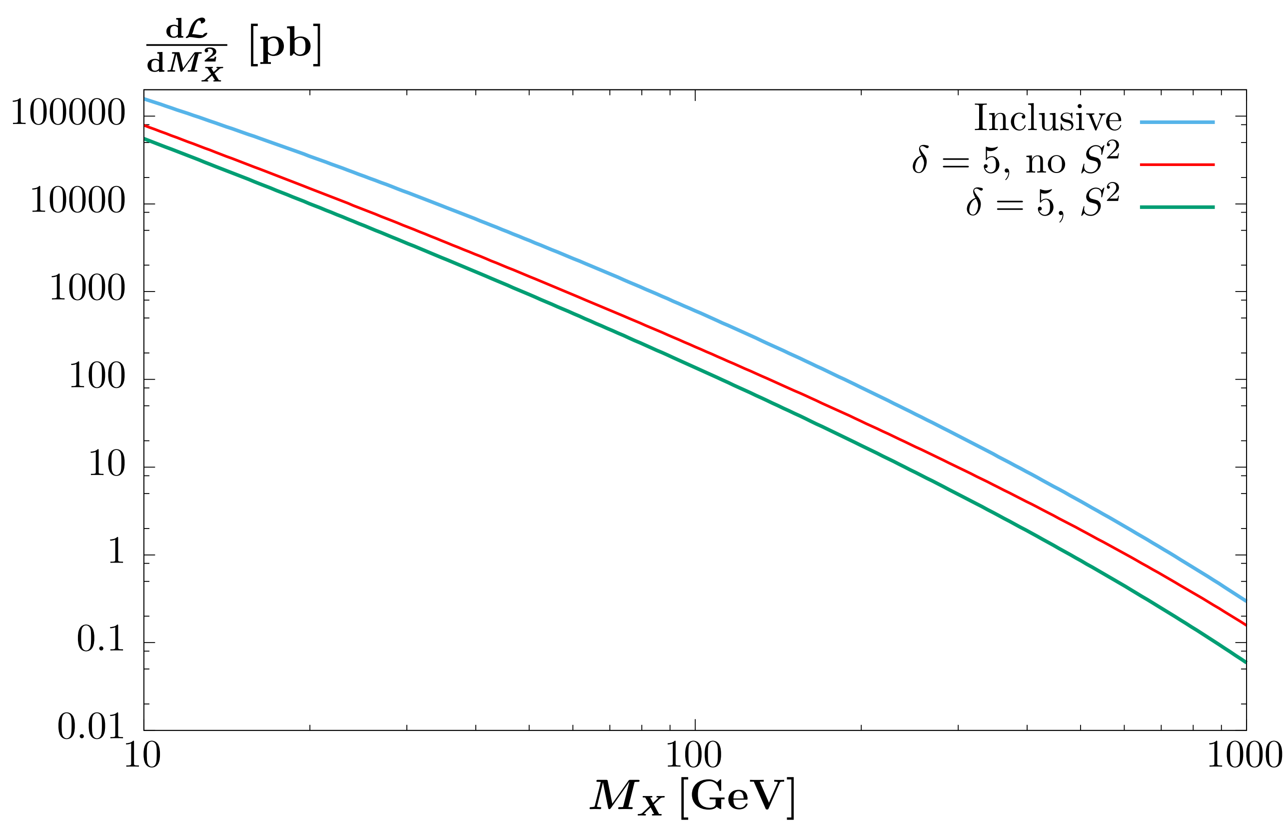


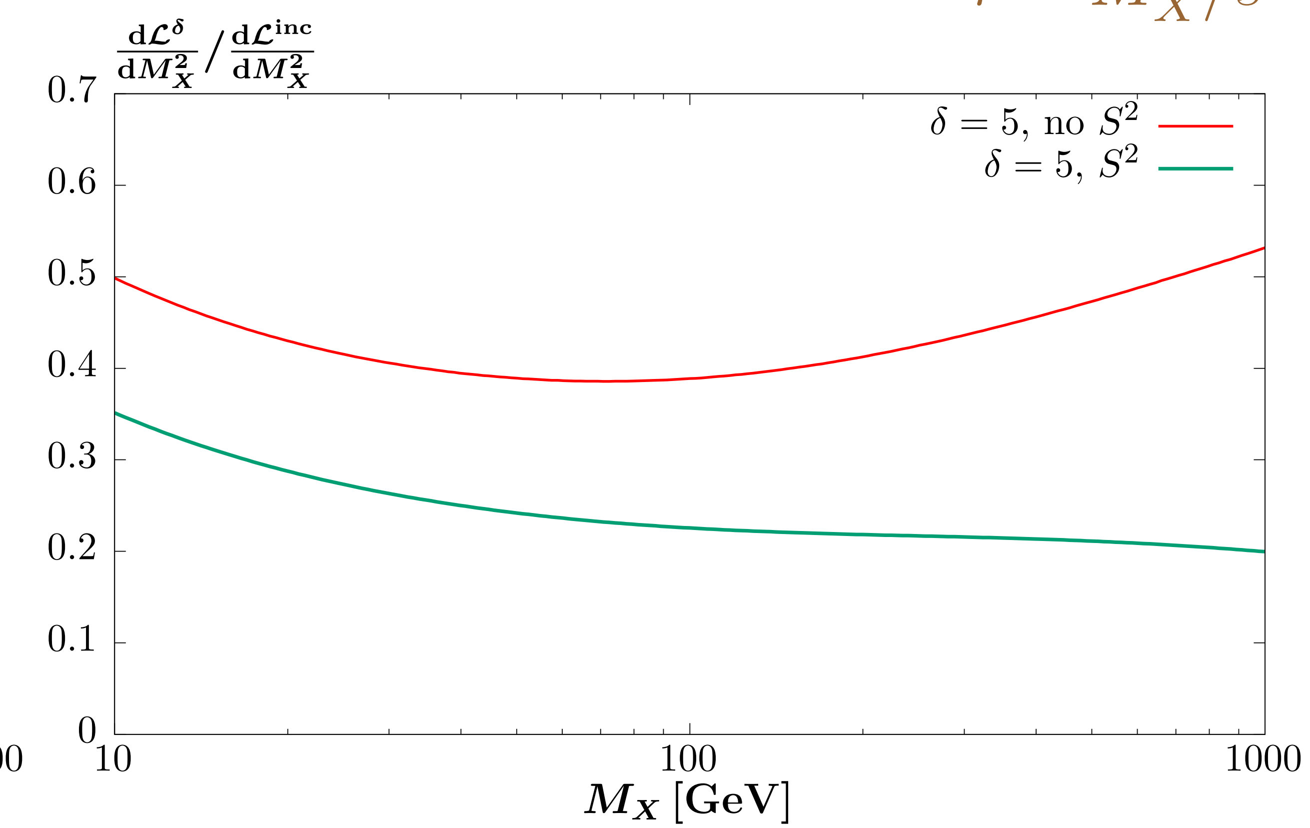
Survival effects

- As S^2 depends on proton b_t, it is sensitive to emission process for both protons $\Rightarrow$ can no longer define independent $\gamma^{\text{veto}}(x,\mu^2)$.

- Instead have effective $\gamma\gamma$ luminosity: $$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}M_X^2} = \frac{1}{s}\int_\tau^1 \frac{\mathrm{d}x_1}{x_1}\gamma(x_1, M_X^2)\gamma(\tau/x_1, M_X^2)$$

$\tau = M_X^2/s$





CMS semi-exclusive $\mu^+\mu^-$: 7 TeV

CMS

CERN-PH-EP/2013-084
2013/08/22

CMS-FSQ-12-010

Study of exclusive two-photon production of W^+W^- in pp collisions at $\sqrt{s} = 7$ TeV and constraints on anomalous quartic gauge couplings

The CMS Collaboration*

- CMS select sample of $W^+W^- \to l\nu l\nu$ events with enhanced exclusive component: veto on extra tracks with $|\eta| < 2.4$.
- To give exclusive cross section, they derive correction factor from larger sample of $\mu^+\mu^-$ events in same region. Present ratio

$$F = \left.\frac{N_{\mu\mu\ \mathrm{data}} - N_{\mathrm{DY}}}{N_{\mathrm{elastic}}}\right|_{m(\mu^+\mu^-)>160\,\mathrm{GeV}} .$$

of measured $\mu^+\mu^-$events to exclusive LPAIR prediction.

$\longrightarrow$ $\mu^+\mu^-$ rapidity veto cross section with $y_{\mathrm{LRG}} = 2.4$!

Comparison to CMS data

- Consider prediction before/after veto, find excellent agreement:

	F
Inclusive	10.9
$\delta = 6.5$	3.6
$\delta = 6.5,\ \gamma_{\rm incoh} = 0$	3.0
CMS [22]	3.23 ± 0.53

- Can also compare to other photon PDF predictions:

	F
CT14	$3.1 - 5.1$
NNPDF2.3	4.0 ± 3.7
MRST2004	$1.2 - 5.3$
CMS [22]	3.23 ± 0.53

- All in agreement within very large uncertainties.

$\rightarrow$ Even taking conservative estimate of our model uncertainties (e.g. S^2), can dramatically improve constraints on $\gamma(x, \mu^2)$!

CMS 8 TeV data

CMS-FSQ-13-008

CERN-EP/2016-073
2016/04/18

Evidence for exclusive $\gamma\gamma \to \mathrm{W^+W^-}$ production and constraints on anomalous quartic gauge couplings in pp collisions at $\sqrt{s} = 7$ and 8 TeV

The CMS Collaboration*

- 8 TeV measurement: $\mathrm{F} = 4.10 \pm 0.43$,
- Our central prediction: $\mathrm{F} = 3.7$

$\to$ Good agreement. More precise future data (mass dependence…) will further probe photon PDF and this approach.

Conclusions

- Photon PDF has range of phenomenological applications at the LHC, and a more precise knowledge of it is a higher priority.
- The colour-singlet photon initial state can lead naturally to large rapidity gaps in the final state.
- Can no longer apply inclusive PDFs, but with modifications for:
    - Rapidity veto in DGLAP equation.
    - Soft survival effects.

  can make robust predictions for such semi-exclusive processes.

- Comparing to CMS data on semi-exclusive $\mu^+\mu^-$production: agreement very encouraging, demonstrates how such processes can give (the most) competitive constrains on the photon PDF.