Photon-photon collisions at the LHC

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IPPP seminar, Durham, 6 Oct 2016

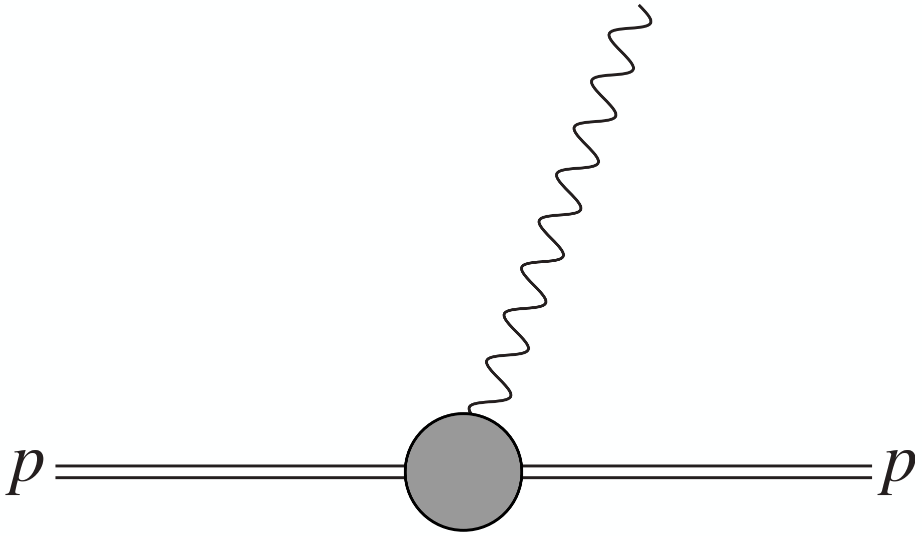
In collaboration with Valery Khoze and Misha Ryskin

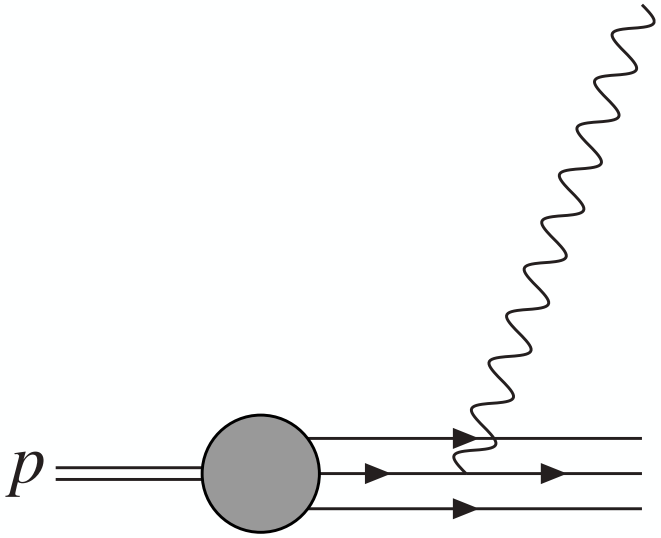
Outline

- Motivation: why study $\gamma\gamma$ collisions at the LHC?
- Exclusive production:
    - How do we model it?
    - Example processes: lepton pairs, anomalous couplings, light-by-light scattering, axion-like particles.
    - Outlook.
- Inclusive production:
    - How well do we understand it?
    - Connection to exclusive case- precise determination.
    - Predictions for LHC/FCC.
    - Comparison to LUXqed.

The proton and the photon

- The proton is an electrically charged object- it can radiate photons.





→ As well as talking about quarks/gluons in the initial state, we should consider the photon.

- How large an effect is this? Where is it significant? Can it be a background to other processes? How can we exploit this QED production mode?

Why bother?

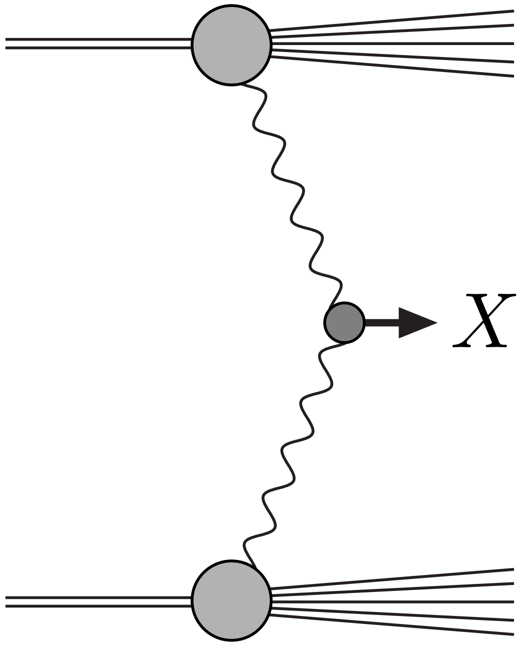
- In era of high precision phenomenology at the LHC: NNLO calculations rapidly becoming the ‘standard’. However:

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

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

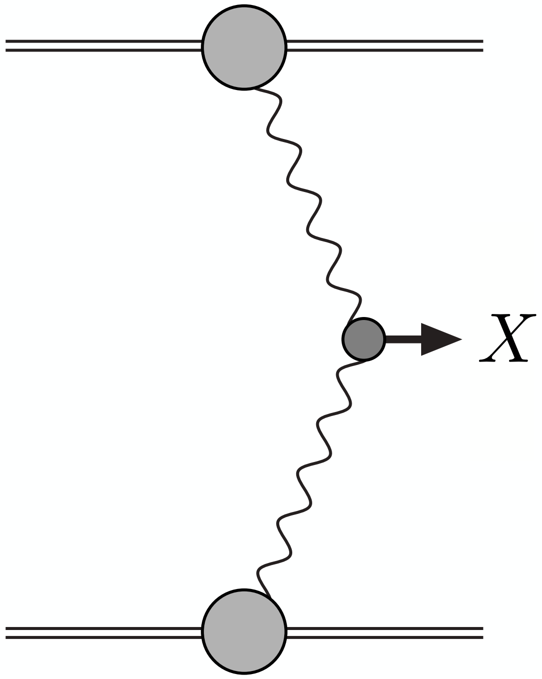
- Thus at this level of accuracy, must consider a proper account of EW corrections. At LHC these can be relevant for a range of processes (W, Z, WH, ZH, WW, $t\bar{t}$, jets...).

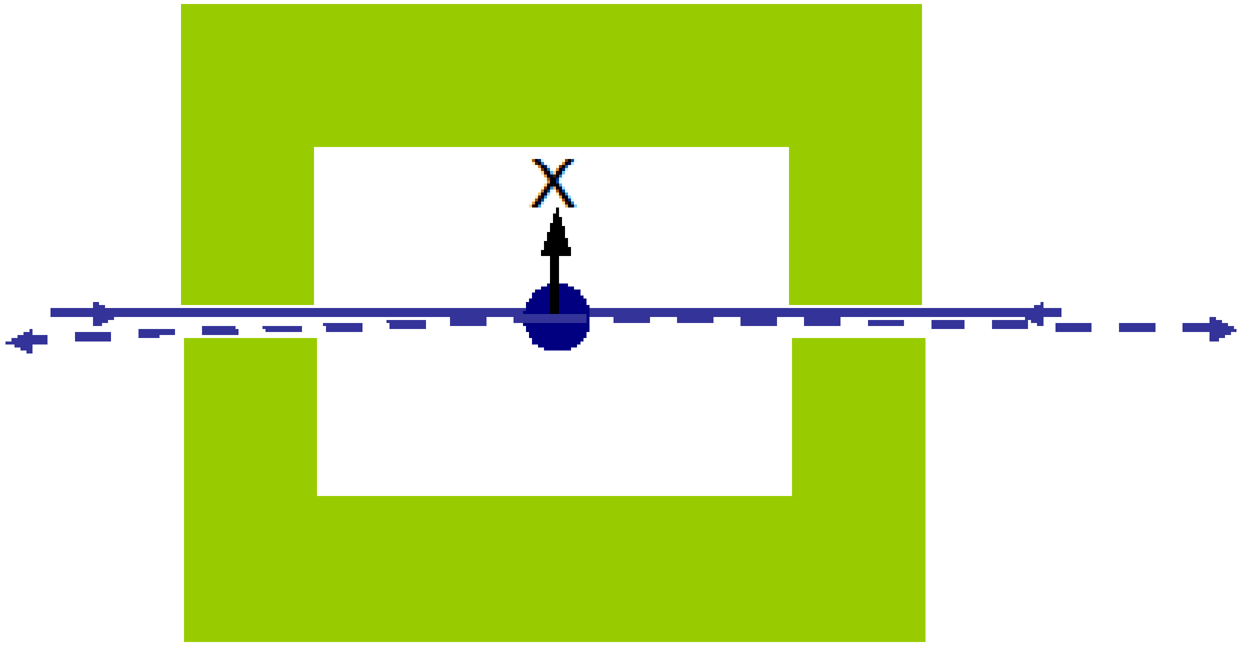
  - For consistent treatment of these, must incorporate QED in initial state: photon-initiated production.



Why bother?

- Unlike the quarks/gluons, photon is colour-singlet object: can naturally lead to exclusive final state, with intact outgoing protons.
- Exclusive photon-initiated processes of great interest. Potential for clean, almost purely QED environment to test electroweak sector and probe possible BSM signals.
- Protons can be measured by tagging detectors installed at ATLAS/CMS. Handle to select events and provides additional information.





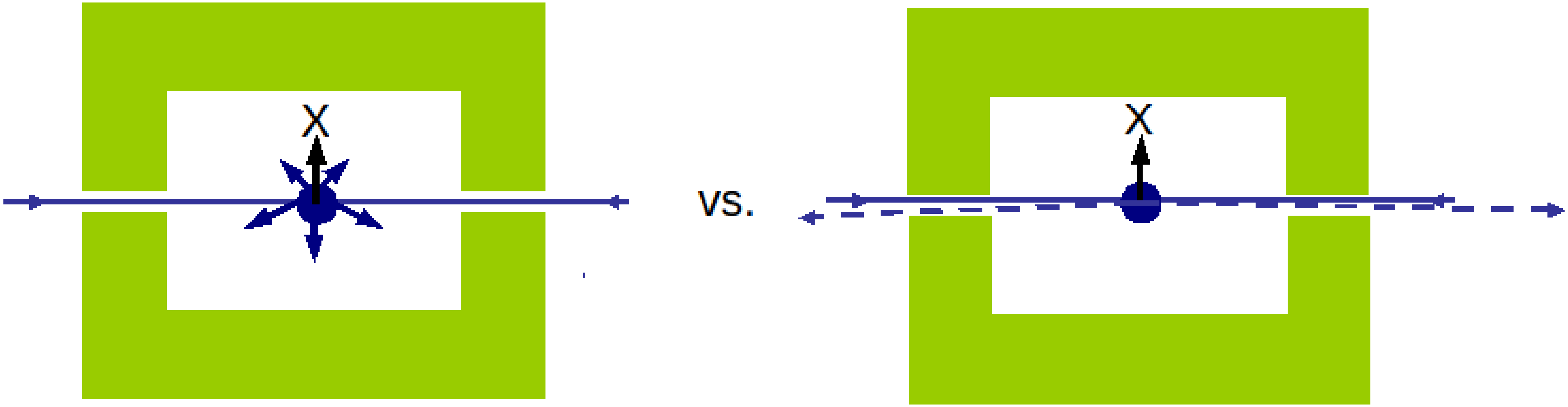
Exclusive production

Central Exclusive Production

Central Exclusive Production (CEP) is the interaction:

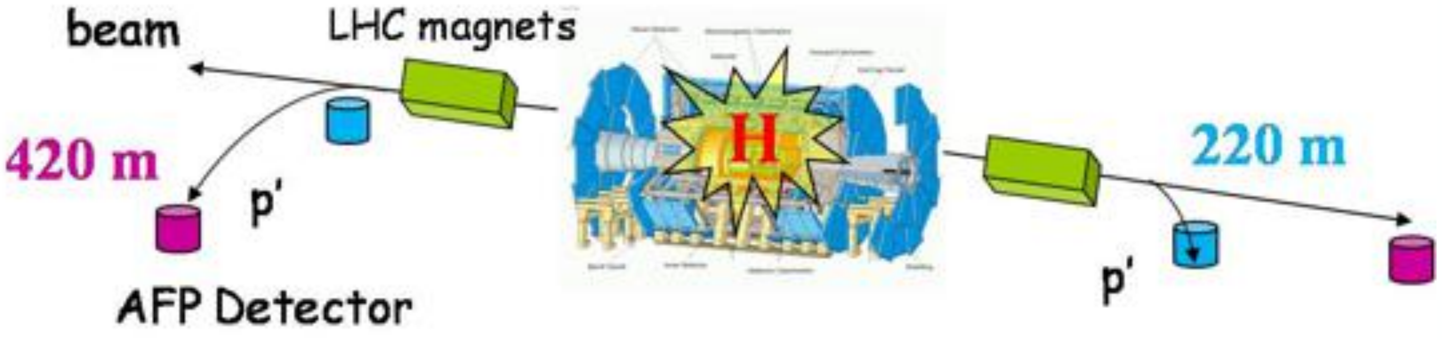
$$pp \rightarrow p + X + p$$

- Diffractive: colour singlet exchange between colliding protons, with large rapidity gaps ('+') in the final state.
- Exclusive: hadron lose energy, but remain intact after the collision.
- Central: a system of mass M_X is produced at the collision point and only its decay products are present in the central detector.



Selecting exclusive events

- Exclusive final states can be selected in two ways:
  - Measuring intact protons with purpose-built detectors $\Rightarrow$ purely exclusive signal.
  - Demanding no additional hadronic activity in large enough rapidity region. Some BG from events where proton breakup occurs outside veto region, but generally under control and can subtract.
- Latter possible at all LHC experiments. Common method - charged final state ($l^+l^-, W^+W^-...$) and veto on extra tracks.
- Former also possible at LHC - proton tagging detectors installed at $O(100\,\mathrm{m})$ from ATLAS/CMS interaction points (AFP, CT-PPS).

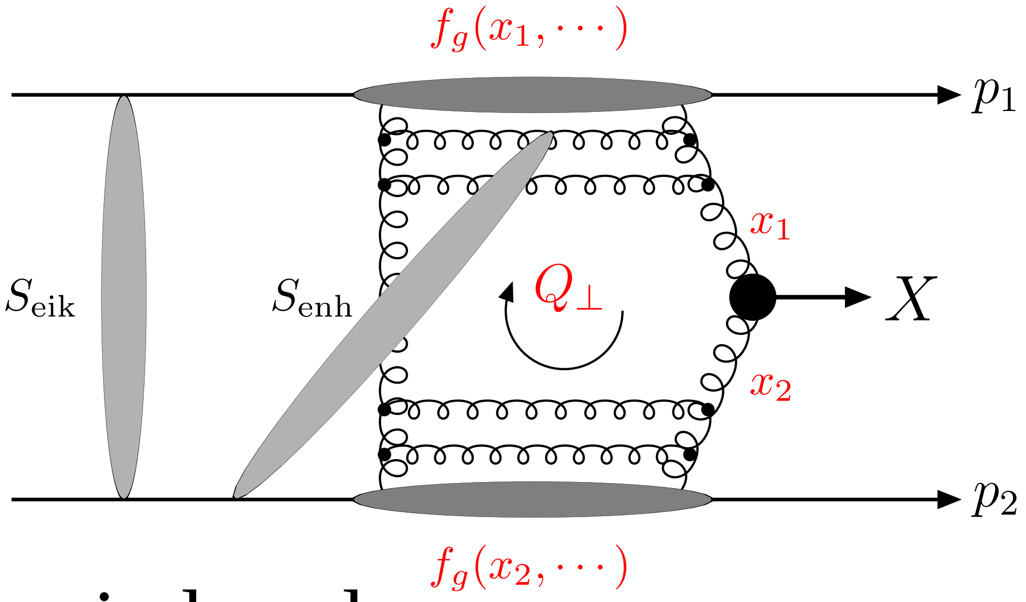


Production mechanisms

Exclusive final state can be produced via three different mechanisms, depending on quantum numbers of state:

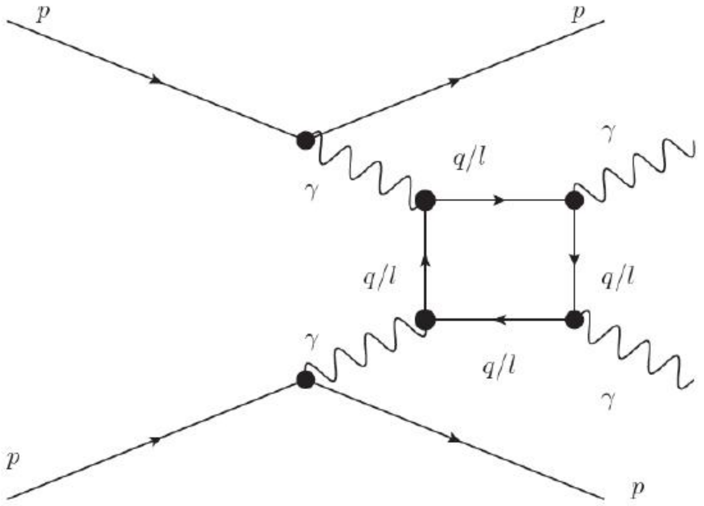
Gluon-induced
(double pomeron exchange):

C-even, couples to gluons



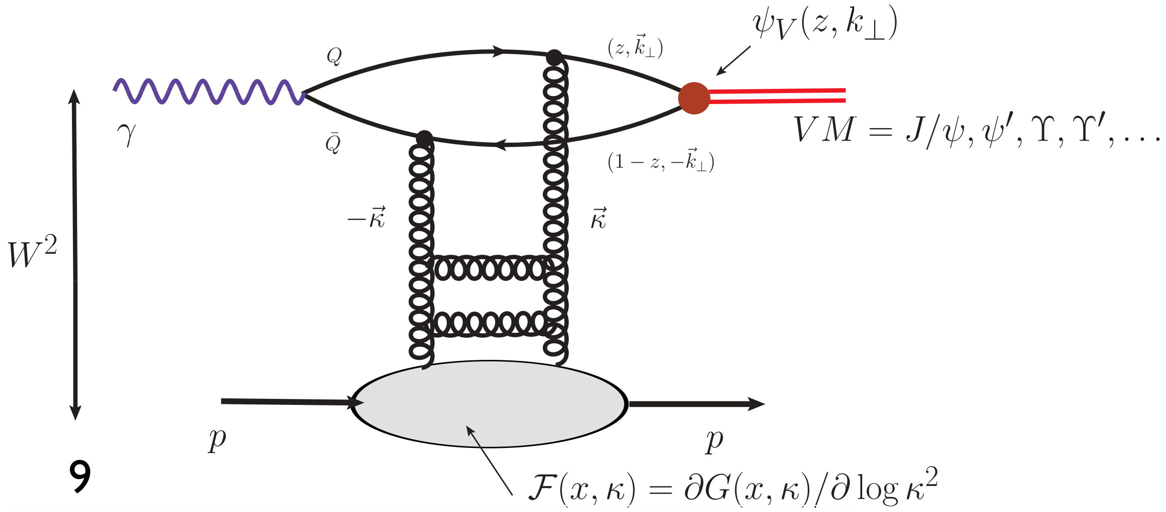
Photon-induced

Couples to photons



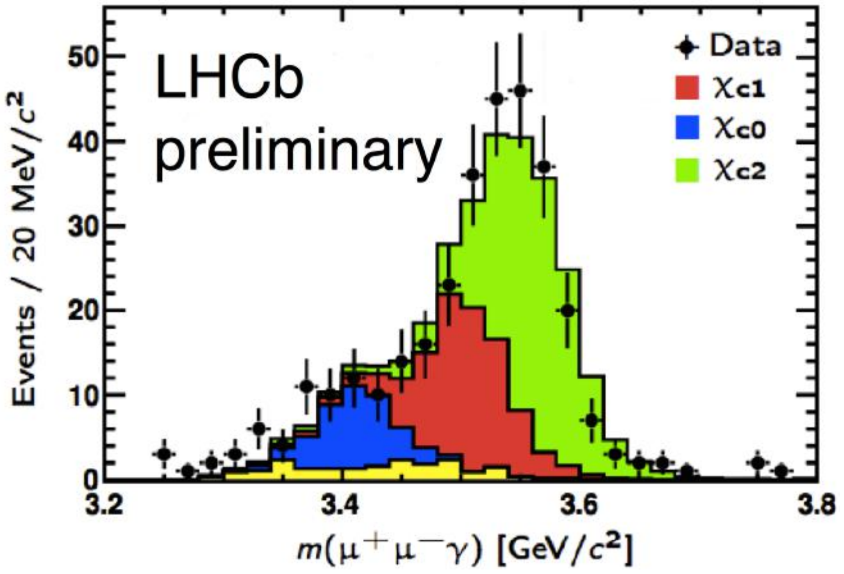
Photoproduction

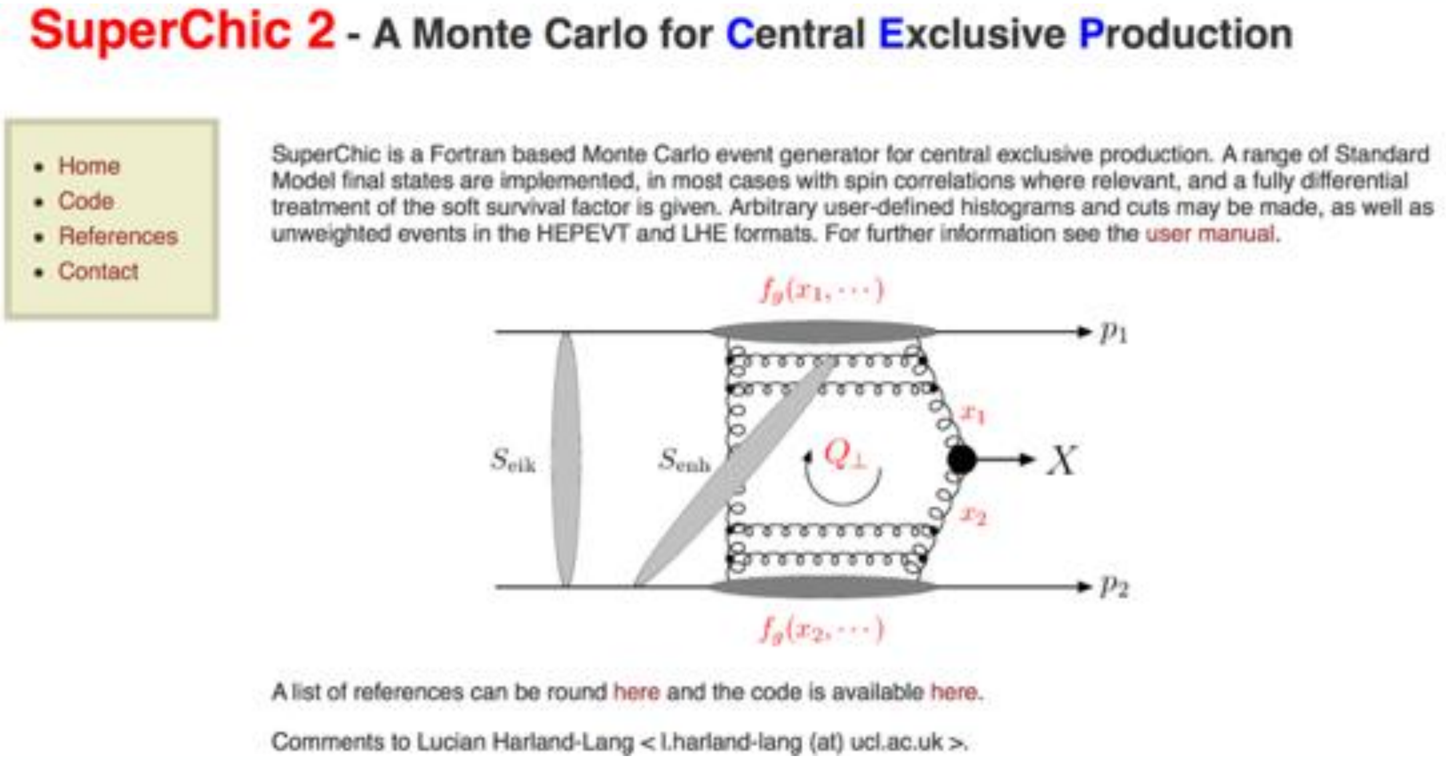
C-odd, couples to photons + gluons



SuperChic

- Have developed a MC for a range of CEP processes, widely used for LHC analyses. Available on Hepforge:





SuperChic 2 - A Monte Carlo for Central Exclusive Production

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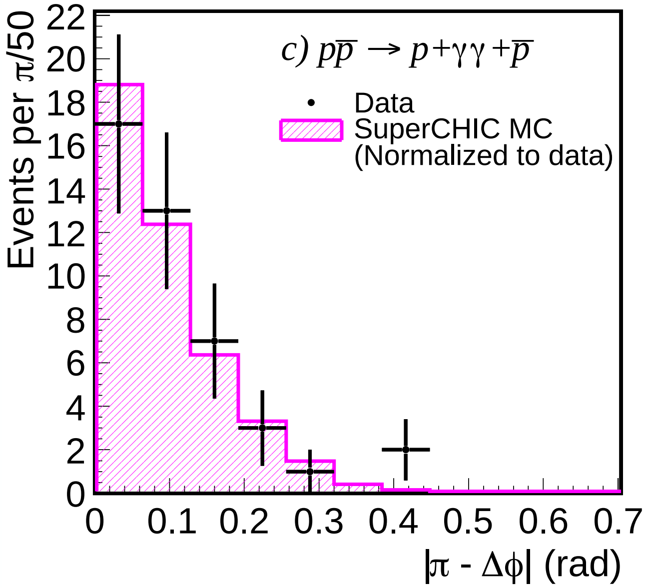
SuperChic is a Fortran based Monte Carlo event generator for central exclusive production. A range of Standard Model final states are implemented, in most cases with spin correlations where relevant, and a fully differential treatment of the soft survival factor is given. Arbitrary user-defined histograms and cuts may be made, as well as unweighted events in the HEPEVT and LHE formats. For further information see the user manual.

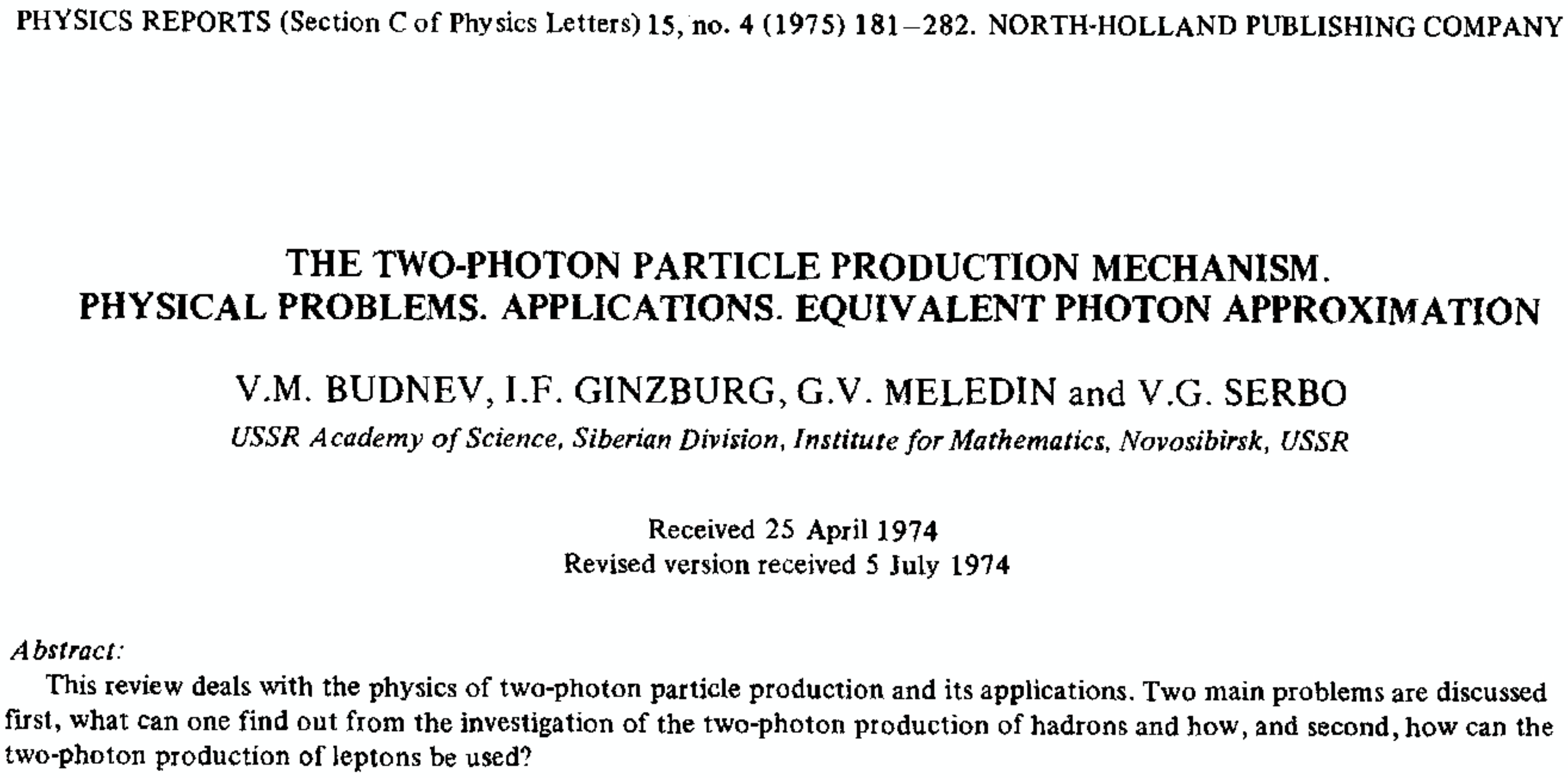
A list of references can be round here and the code is available here.

Comments to Lucian Harland-Lang < l.harland-lang (at) ucl.ac.uk >.



Modelling exclusive $\gamma\gamma$ collisions

- In exclusive photon-mediated interactions, the colliding protons must both coherently emit a photon, and remain intact after the interaction. How do we model this?
- Answer is well known- the ‘equivalent photon approximation’ (EPA): cross section described in terms of a flux of quasi-real photons radiated from the proton, and the $\gamma\gamma \to X$ subprocess cross section.



PHYSICS REPORTS (Section C of Physics Letters) 15, no. 4 (1975) 181–282. NORTH-HOLLAND PUBLISHING COMPANY

THE TWO-PHOTON PARTICLE PRODUCTION MECHANISM.
PHYSICAL PROBLEMS. APPLICATIONS. EQUIVALENT PHOTON APPROXIMATION

V.M. BUDNEV, I.F. GINZBURG, G.V. MELEDIN and V.G. SERBO
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Received 25 April 1974
Revised version received 5 July 1974

Abstract:
This review deals with the physics of two-photon particle production and its applications. Two main problems are discussed first, what can one find out from the investigation of the two-photon production of hadrons and how, and second, how can the two-photon production of leptons be used?

Equivalent photon approximation

- Initial-state $p \to p\gamma$ emission can be to very good approximation factorized from the $\gamma\gamma \to X$ process in terms of a flux:

$$n(x_i) = \frac{1}{x_i}\frac{\alpha}{\pi^2}\int \frac{\mathrm{d}^2 q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_p^2}\left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_p^2}(1-x_i)F_E(Q_i^2) + \frac{x_i^2}{2}F_M(Q_i^2)\right)$$

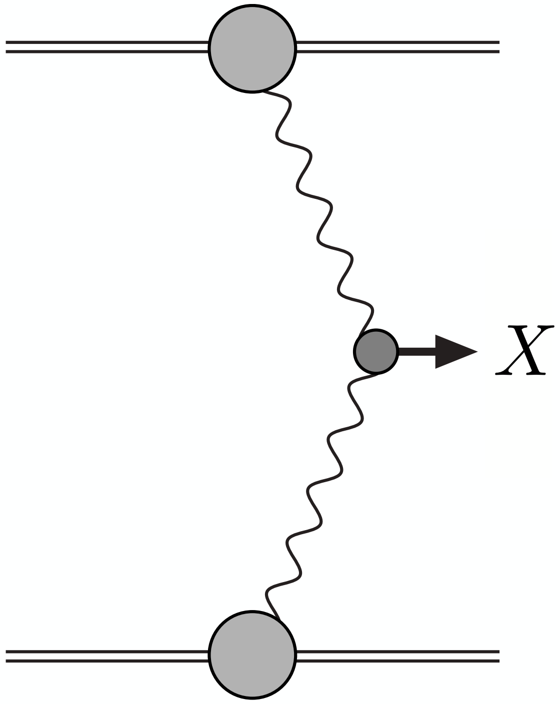
- Cross section then given in terms of $\gamma\gamma$ `luminosity':

$$\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2\,\mathrm{d}y_X} = \frac{1}{s}\,n(x_1)\,n(x_2)$$

with

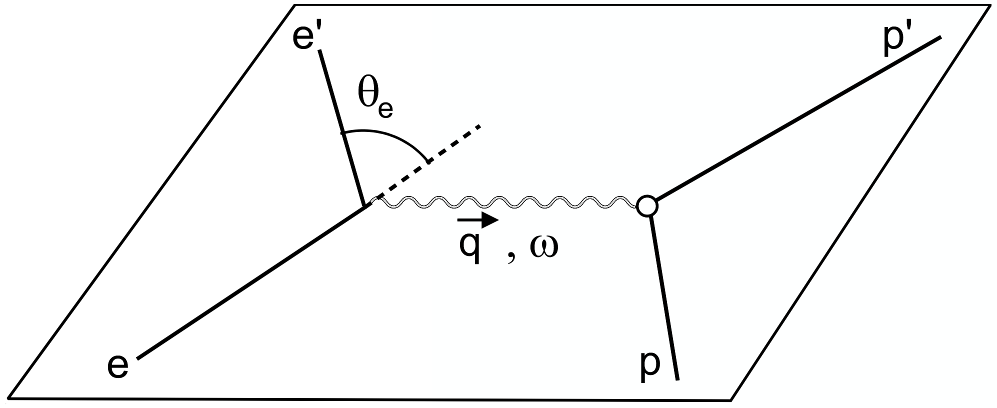
$$\frac{\mathrm{d}\sigma^{pp\to pXp}}{\mathrm{d}M_X^2\mathrm{d}y_X} \underset{\uparrow}{\sim} \frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2\mathrm{d}y_X}\hat{\sigma}(\gamma\gamma \to X)$$

Not exact equality: see later



Proton form factors

- Where does photon flux come from? Consider e.g. elastic ep scattering:



$\mathcal{M} \sim l_\mu H^\mu$

proton rest frame

- Most general form for hadronic current is

$$H^\mu = e\overline{P}(p')\left[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m_p}F_2(Q^2)\right]P(p)$$

$F_1(Q^2)$: 'Dirac' form factor, proton spin preserved

$F_2(Q^2)$: 'Pauli' form factor, proton spin flipped

Proton form factors

- Defining: $G_E = F_1 - \frac{Q^2}{4m_p} F_2 \qquad G_M = F_1 + F_2$

get well known 'Rosenbluth' formula:

$$\frac{\mathrm{d}\sigma^{ep\to ep}}{\mathrm{d}\cos\theta} \propto \left(F_E(Q^2)\cos^2\frac{\theta}{2} + \frac{Q^2}{2m_p^2} F_M(Q^2)\sin^2\frac{\theta}{2} \right)$$

where $F_M(Q^2) = G_M^2(Q^2) \quad F_E(Q^2) = \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2}$

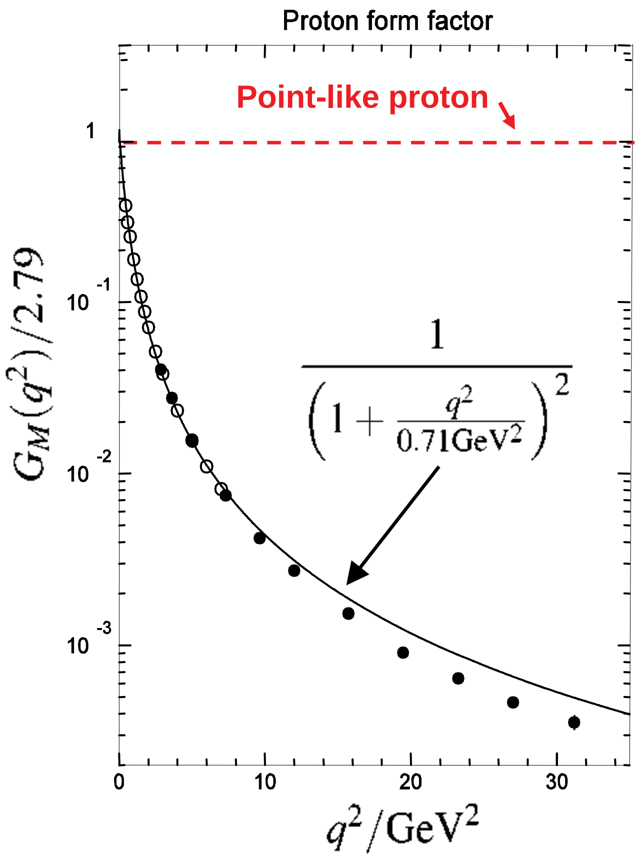
- Here G_E/G_M are the proton electric/magnetic form factors $\sim$ the Fourier transform of the charge/magnetic moment distribution within proton.

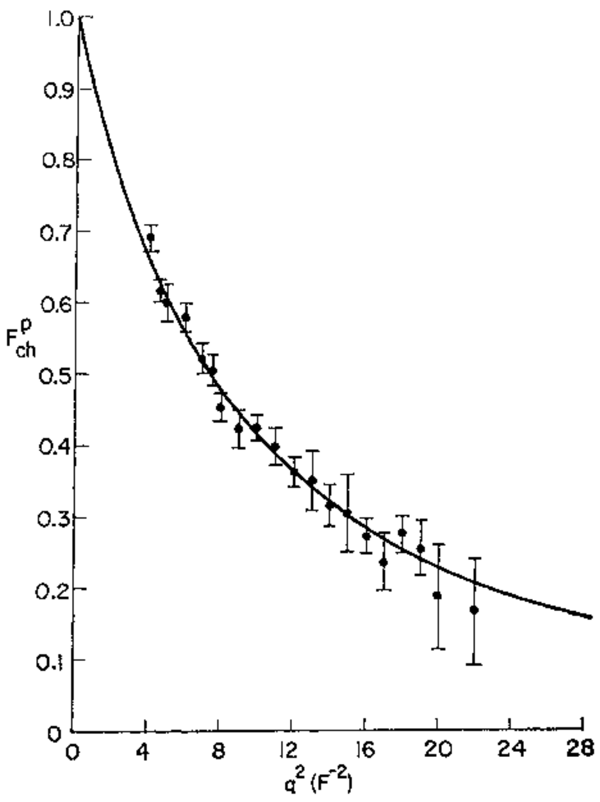
Proton form factors

- Through extensive measurements of angular distribution of elastic ep scattering, the form factors are *very* well determined. Have characteristic 'dipole' form:

$$G_E^2(Q^2) = \frac{G_M^2(Q^2)}{7.78} = \frac{1}{(1+Q^2/0.71\,\mathrm{GeV}^2)^4}$$

Coherent emission $\Rightarrow$ steeply falling with Q^2





Equivalent photon approximation (again)

- How does the previous discussion connect with our $\gamma\gamma$-initiated process in pp collisions? Mediated by exactly the same coherent emission. After changing to appropriate kinematic variables/frame:

$$\frac{\mathrm{d}\sigma^{ep\to ep}}{\mathrm{d}\cos\theta} \propto \left(F_E(Q^2)\cos^2\frac{\theta}{2} + \frac{Q^2}{2m_p^2}F_M(Q^2)\sin^2\frac{\theta}{2}\right)$$

$$\downarrow$$

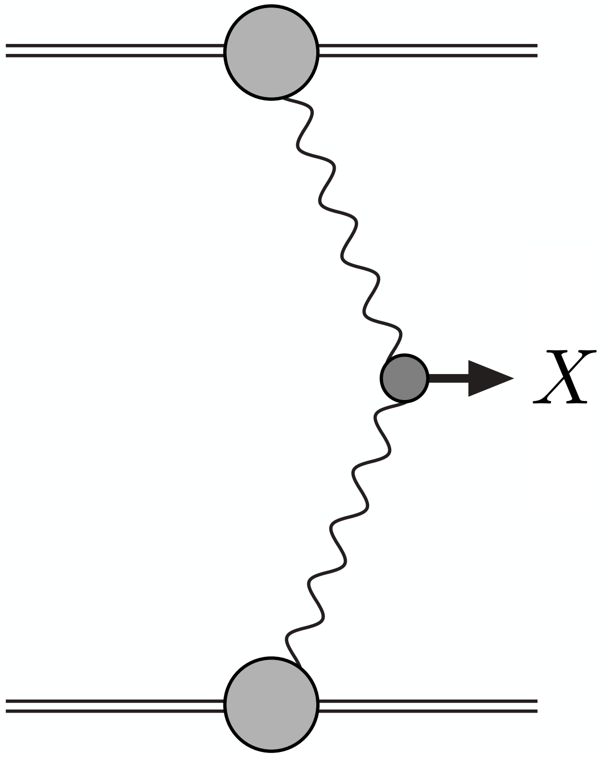
$$n(x_i) = \frac{1}{x_i}\frac{\alpha}{\pi^2}\int \frac{\mathrm{d}^2 q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_p^2}\left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_p^2}(1-x_i)F_E(Q_i^2) + \frac{x_i^2}{2}F_M(Q_i^2)\right)$$

$\longrightarrow$ Photon flux from colliding protons well constrained by elastic ep scattering data.

Exclusive production: theory

- Recall formula for exclusive $\gamma\gamma$-initiated production in terms of EPA photon flux

$$\frac{\mathrm{d}\sigma^{pp\to pXp}}{\mathrm{d}M_X^2\mathrm{d}y_X} \sim \frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2\mathrm{d}y_X}\hat{\sigma}(\gamma\gamma\to X)$$

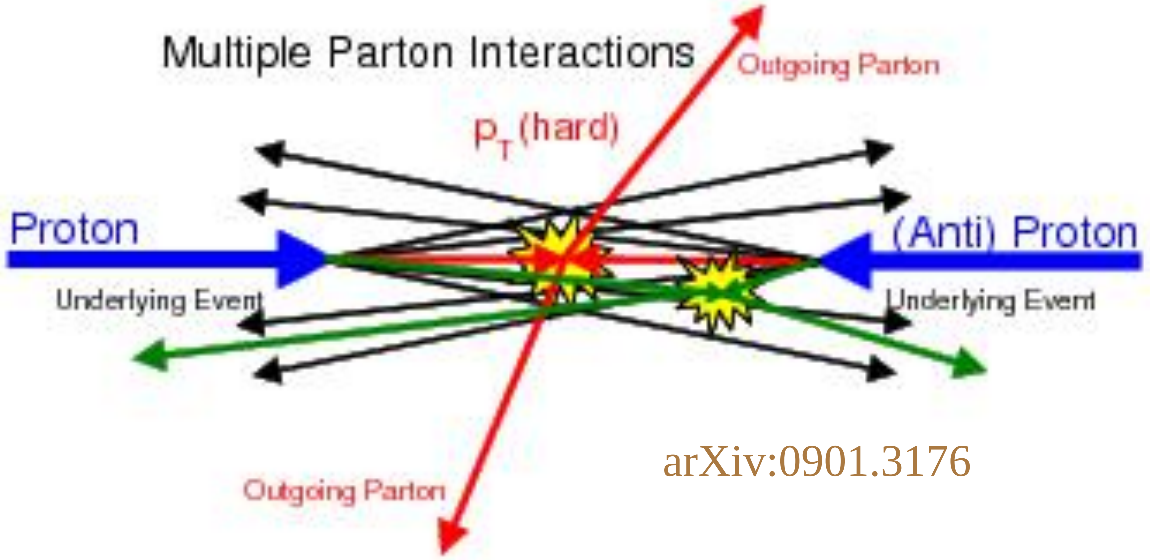


- Why is this not an exact equality? Because we are asking for final state with intact protons, object X and *nothing* else- colliding protons may interact independently: ‘Survival factor’.

Soft survival factor

- In any pp collision event, there will in general be ‘underlying event’ activity, i.e. additional particle production due to pp interactions secondary to the hard process (a.k.a. ‘multiparticle interactions’, MPI).
- Our $\gamma\gamma$-initiated interaction is no different, but we are now requiring final state with no additional particle production (X + nothing else).

$\rightarrow$ Must multiply our cross section by probability of no underlying event activity, known as the soft ‘survival factor’.



arXiv:0901.3176

Soft survival factor

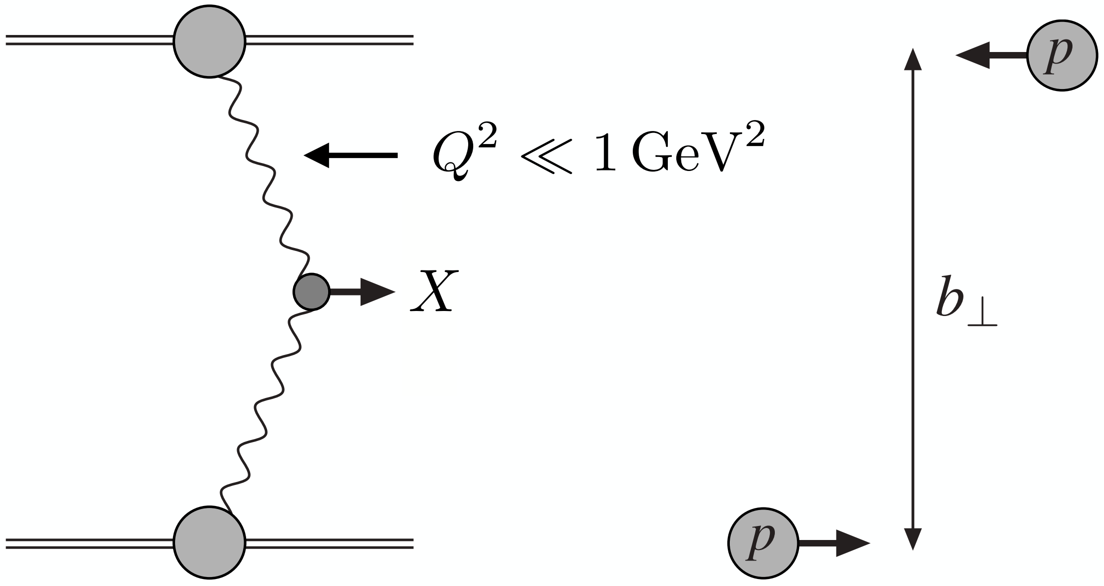
- Underlying event generated by soft QCD. Cannot use pQCD $\Rightarrow$ take phenomenological approach to this non-pert. observable.

V.A. Khoze, A.D. Martin, M.G. Ryskin, arXiv:1306.2149

- Naively: might expect probability to produce extra particles from underlying event to be high, and indeed generally it is.
- Not true for $\gamma\gamma$-initiated processes - interaction via quasi-real photon exchange $\Rightarrow$ large proton separation $b_\perp$, and prob. of UE low.

$b_\perp \sim 1/p_\perp$

$\longrightarrow$ Impact of non-QED physics is low.



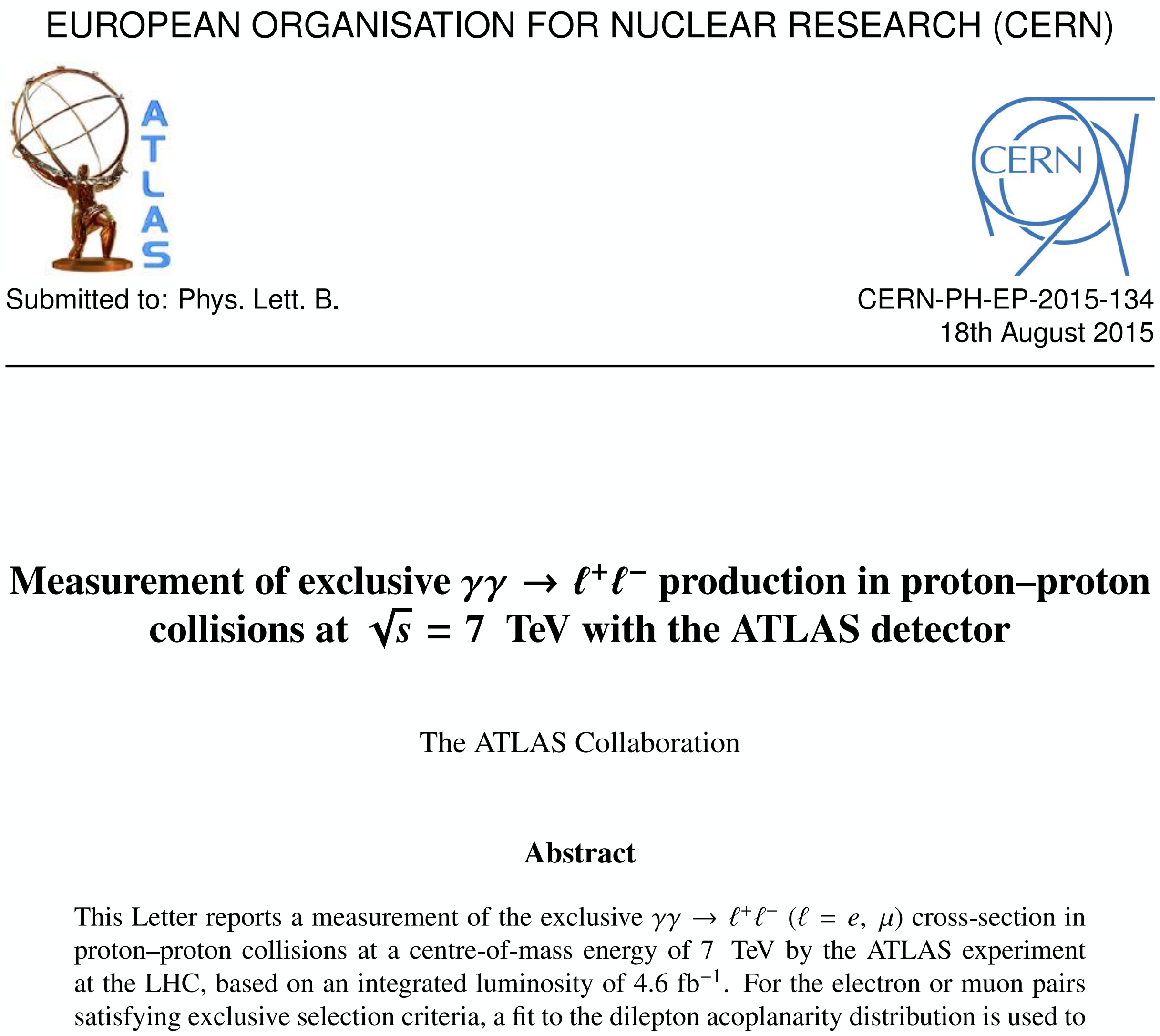
$S^2_{\rm soft} \sim 0.7 - 0.9$

small model dep.

Protons far apart $\Rightarrow$ less interaction $\Rightarrow$ survival factor, $S^2_{\rm soft} \sim 1$

Simple test: lepton pairs

- ATLAS (arXiv:1506.07098) have measured exclusive e and μ pair production ⇒ use `SuperChic` to compare to this.



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Lett. B.

CERN-PH-EP-2015-134
18th August 2015

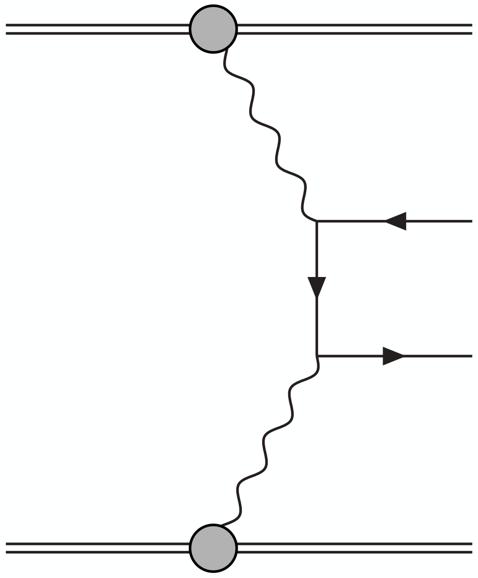
Measurement of exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ production in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This Letter reports a measurement of the exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) cross-section in proton–proton collisions at a centre-of-mass energy of 7 TeV by the ATLAS experiment at the LHC, based on an integrated luminosity of 4.6 fb^{-1}. For the electron or muon pairs satisfying exclusive selection criteria, a fit to the dilepton acoplanarity distribution is used to

Variable	Electron channel	Muon channel
p_{T}^{ℓ}	> 12 GeV	> 10 GeV
$\lvert\eta^{\ell}\rvert$	< 2.4	< 2.4
$m_{\ell^+\ell^-}$	> 24 GeV	> 20 GeV



Comparison to ATLAS

- Using results from above:

Variable	Electron channel	Muon channel
p_{T}^{ℓ}	> 12 GeV	> 10 GeV
$\lvert\eta^{\ell}\rvert$	< 2.4	< 2.4
$m_{\ell^+\ell^-}$	> 24 GeV	> 20 GeV

	$\mu^+\mu^-$	e^+e^-
$\sigma_{\rm EPA}$	0.768	0.479
$\sigma_{\rm EPA} \cdot \langle S^2 \rangle$	0.714	0.441
$\langle S^2 \rangle$	0.93	0.92
ATLAS data	$0.628 \pm 0.032 \pm 0.021$	$0.428 \pm 0.035 \pm 0.018$

→ Excellent agreement for e^+e^- and reasonable for $\mu^+\mu^-$. Role of coherent photon emission seen experimentally at the LHC and small and under control impact of (non-pert) QCD effects confirmed experimentally.

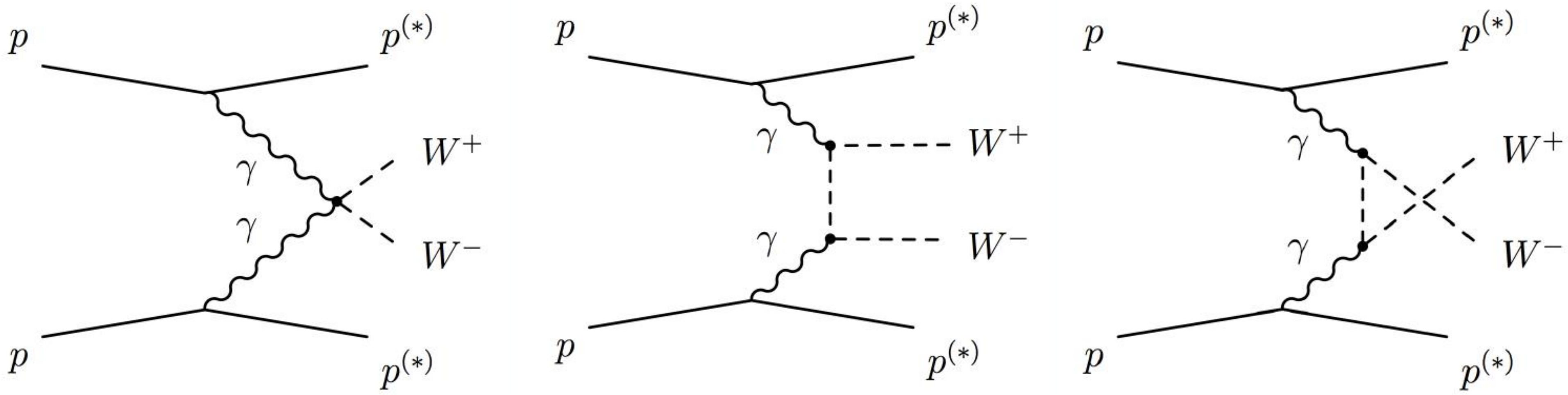
- Have confidence in framework $\Rightarrow$ consider implications for BSM…

Anomalous couplings

- Exclusive W^+W^- production: no contribution from $q\bar{q} \to W^+W^- \Rightarrow$ sensitive to $\gamma\gamma \to W^+W^-$ process alone.

$\rightarrow$ Directly sensitive to any deviations from the SM gauge couplings. Predicted in various BSM scenarios.

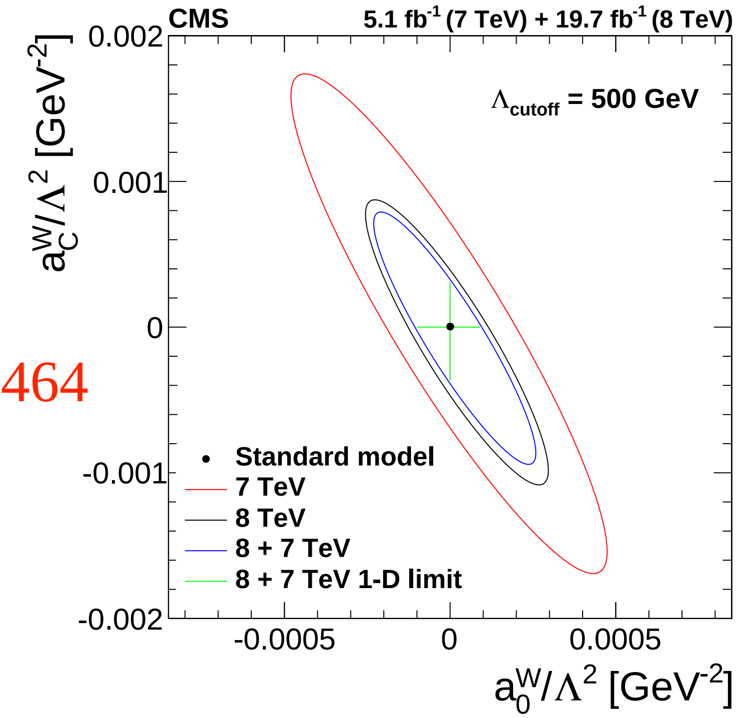
Composite Higgs, warped extra dimensions….



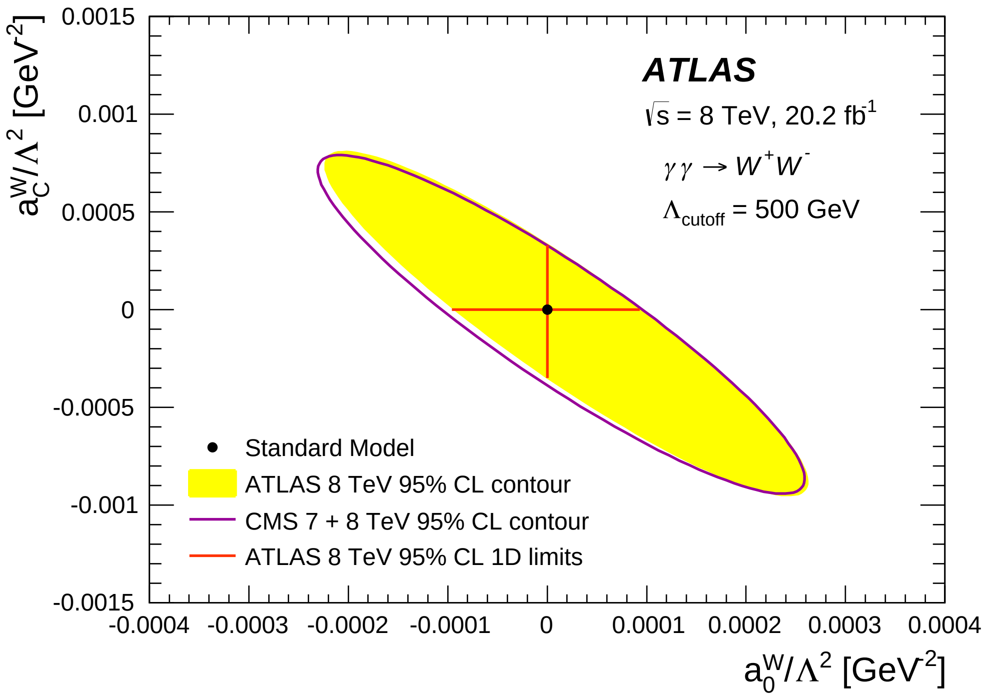
- Limits have been set at LEP, and in inclusive final-states at the Tevatron and LHC. How does the exclusive case compare?

Anomalous couplings - data

- ATLAS + CMS data: $W \to l\nu$ pair production with no associated charged tracks $\Rightarrow$ use this veto to extract quasi-exclusive signal. Use data-driven method to subtract non-exclusive BG ($p \to p^*$).



arXiv:1604.04464

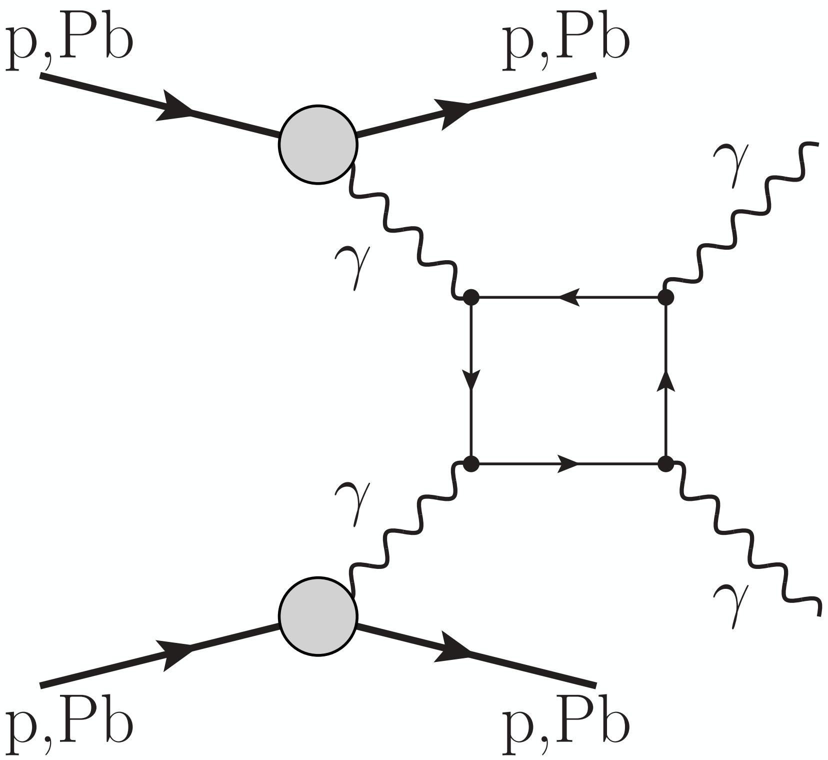


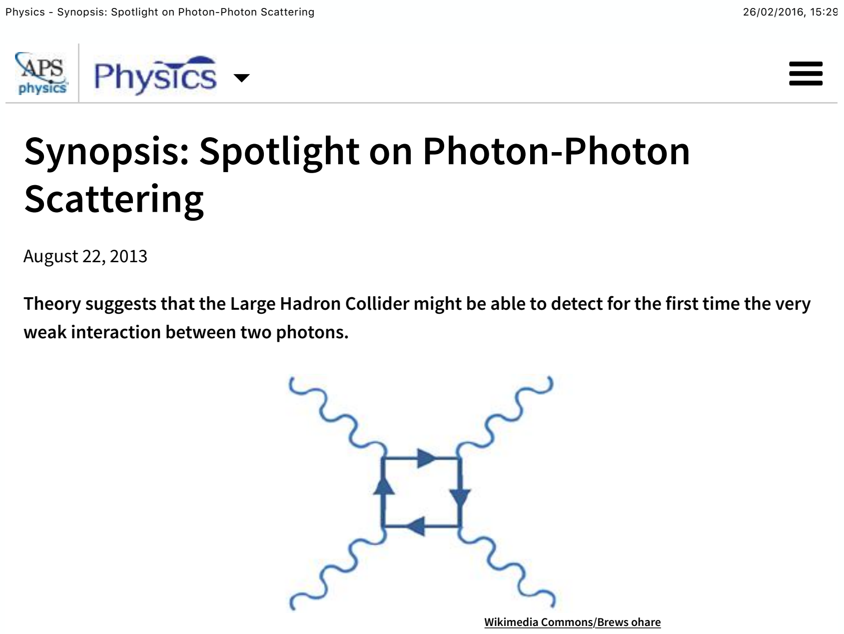
arXiv:1607.03745

- These data place the most stringent constraints to date on AGCs: two orders of mag. better than LEP, and tighter than inclusive LHC.
- Direct consequence of exclusive selection $\Rightarrow$ precisely understood $\gamma\gamma$ collisions, but at a hadron collider.

Light-by-light scattering

- Possibility for first observation of light-by-light scattering: until very recently not seen experimentally, sensitive to new physics in the loop. Same final state sensitive to axion-like particle production.





Synopsis: Spotlight on Photon-Photon Scattering

August 22, 2013

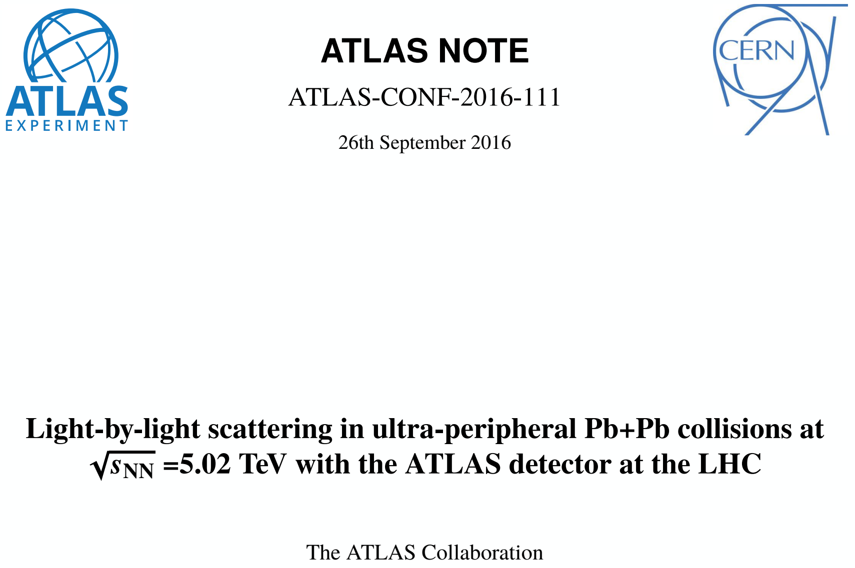
Theory suggests that the Large Hadron Collider might be able to detect for the first time the very weak interaction between two photons.

Wikimedia Commons/Brews ohare

- Analysis of d’Enterria and Silveira (arXiv:1305.7142,1602.08088): realistic possibility, in particular in $PbPb$ collisions.

Light-by-light scattering

- Not just theoretical idea. Very recent ATLAS prelim. data: first evidence for light-by-light scattering in Pb-Pb collisions taken with $\mathcal{L} = 480\,\mu\text{b}^{-1}$.

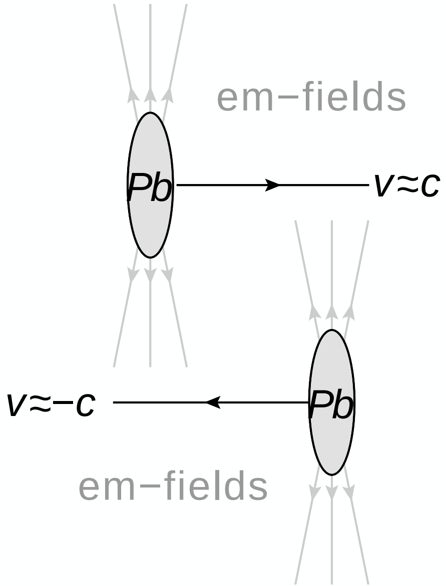


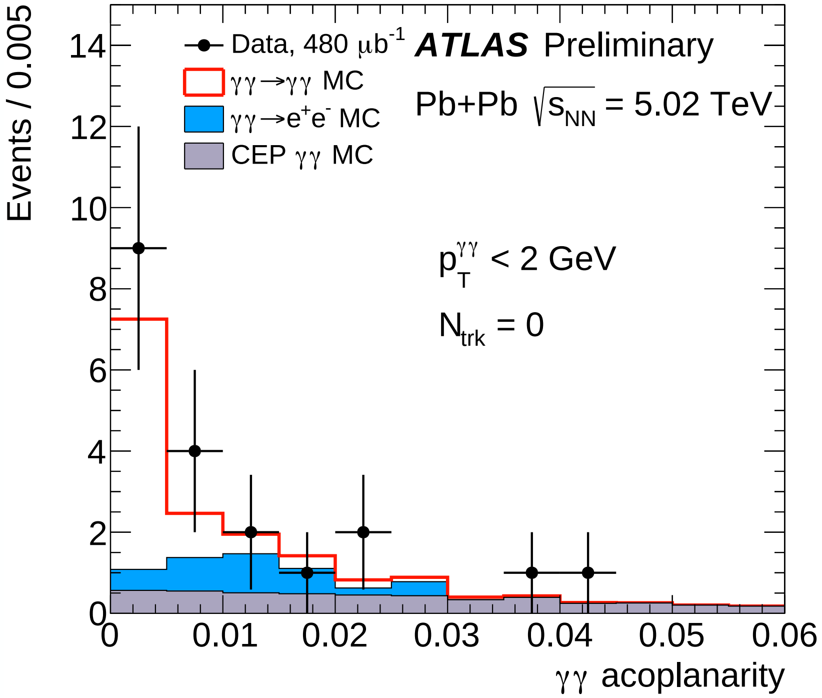
ATLAS NOTE
ATLAS-CONF-2016-111
26th September 2016

Light-by-light scattering in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{\text{NN}}}$ =5.02 TeV with the ATLAS detector at the LHC

The ATLAS Collaboration

- Data: 70 ± 20 (stat.) ± 17 (syst.) nb SM pred. : 49 ± 10 nb.



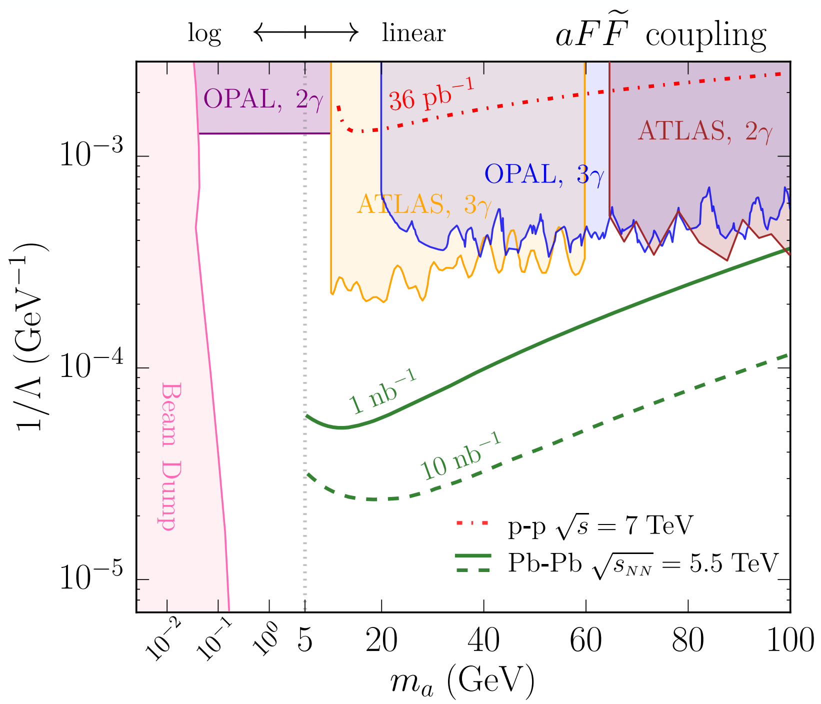


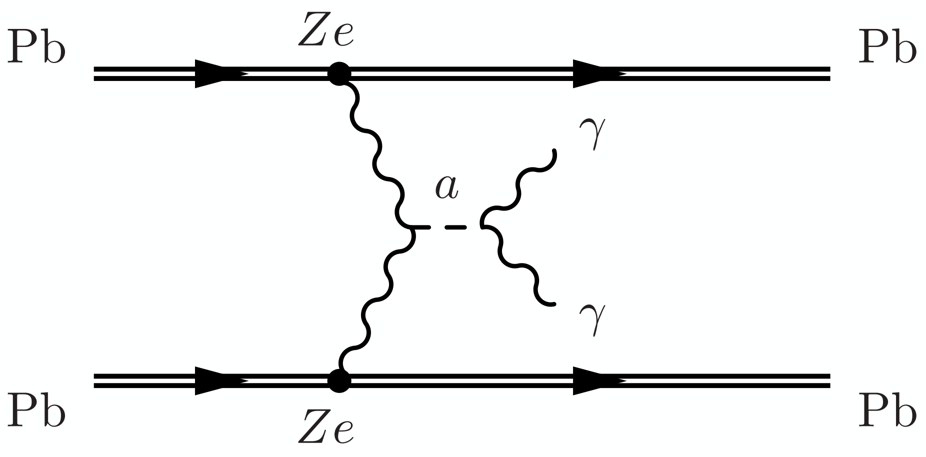
Axion-like particles

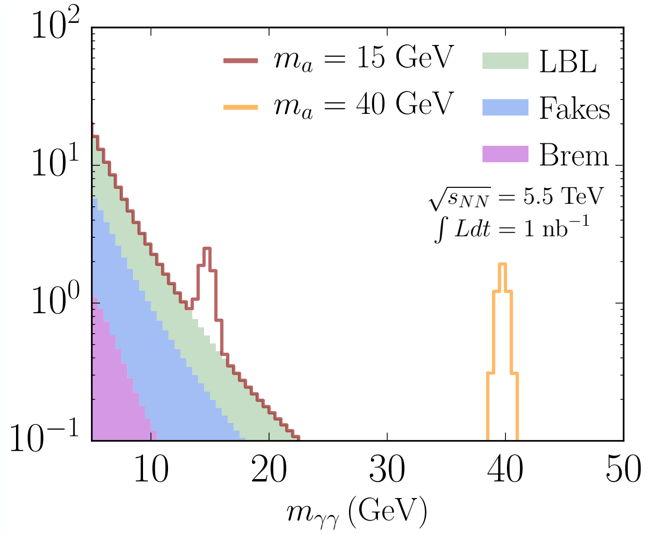
- Consider same $\gamma\gamma \to \gamma\gamma$ transition: sensitive to coupling of light axion-like particle to photons.

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\widetilde{F}\,,$$

- Discussed in Kapen et al. (1607.06083) - find that in heavy ion collisions can set the strongest limits yet on these couplings.







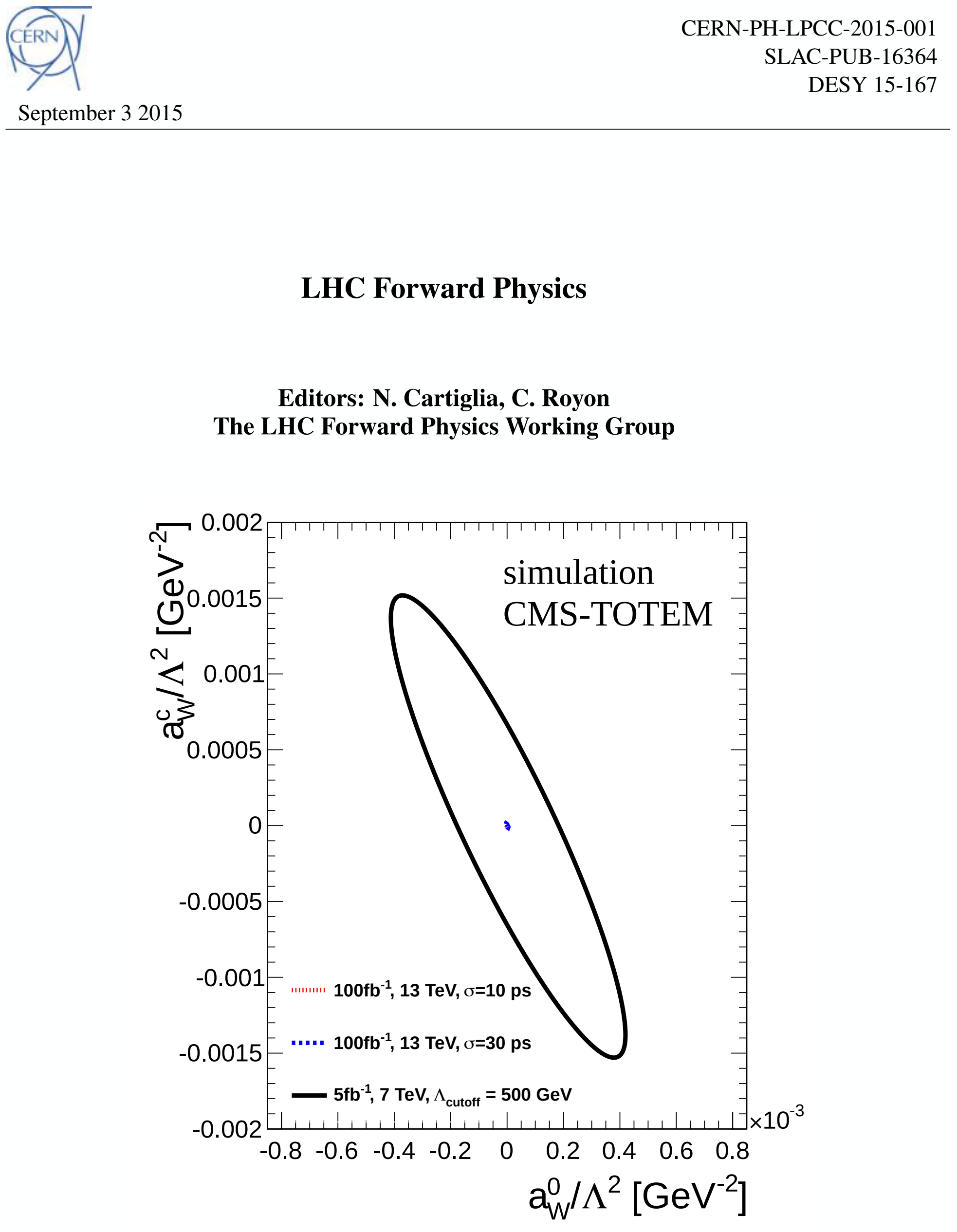
Outlook

- Still at early stage- in the future data with the outgoing protons detected by that ATLAS AFP and CMS CT-PPS proton taggers will be taken: allows even purer sample of exclusive events to be selected.

- Expect the most stringent constrains on anomalous couplings in $WW, ZZ, \gamma\gamma$ final states - $\sim$ 4 orders of mag. beyond LEP limits for $\mathcal{L} = 300\,\text{fb}^{-1}$!

$\longrightarrow$ Will use LHC as high precision photon-photon collider.

- Anomalous couplings one example- in general any process with significant EW couplings can be probed (monopoles…). More possibilities to explore.



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DESY 15-167

September 3 2015

LHC Forward Physics

Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

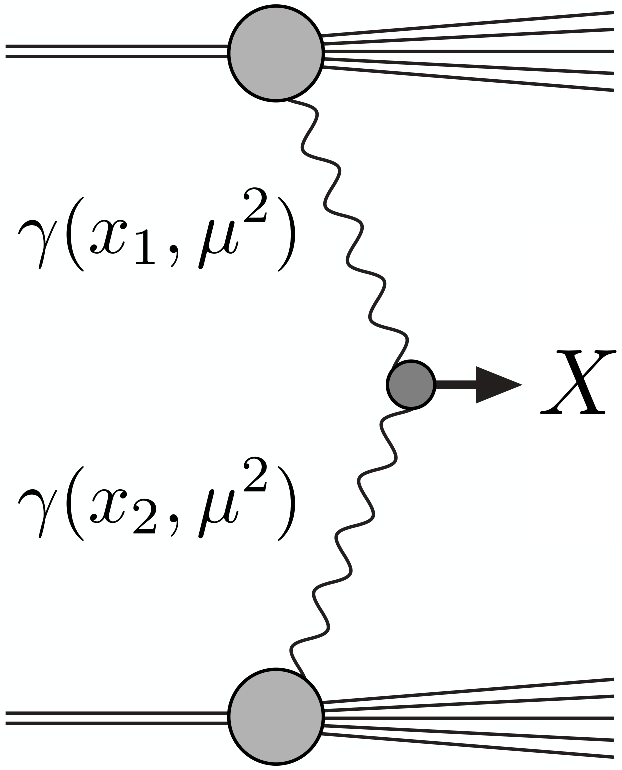
Inclusive production - the photon PDF

Modelling $\gamma\gamma$ fusion

- Inclusive production of X + anything else.
- Can write LO cross section for the $\gamma\gamma$ initiated production of a state in the usual factorized form:

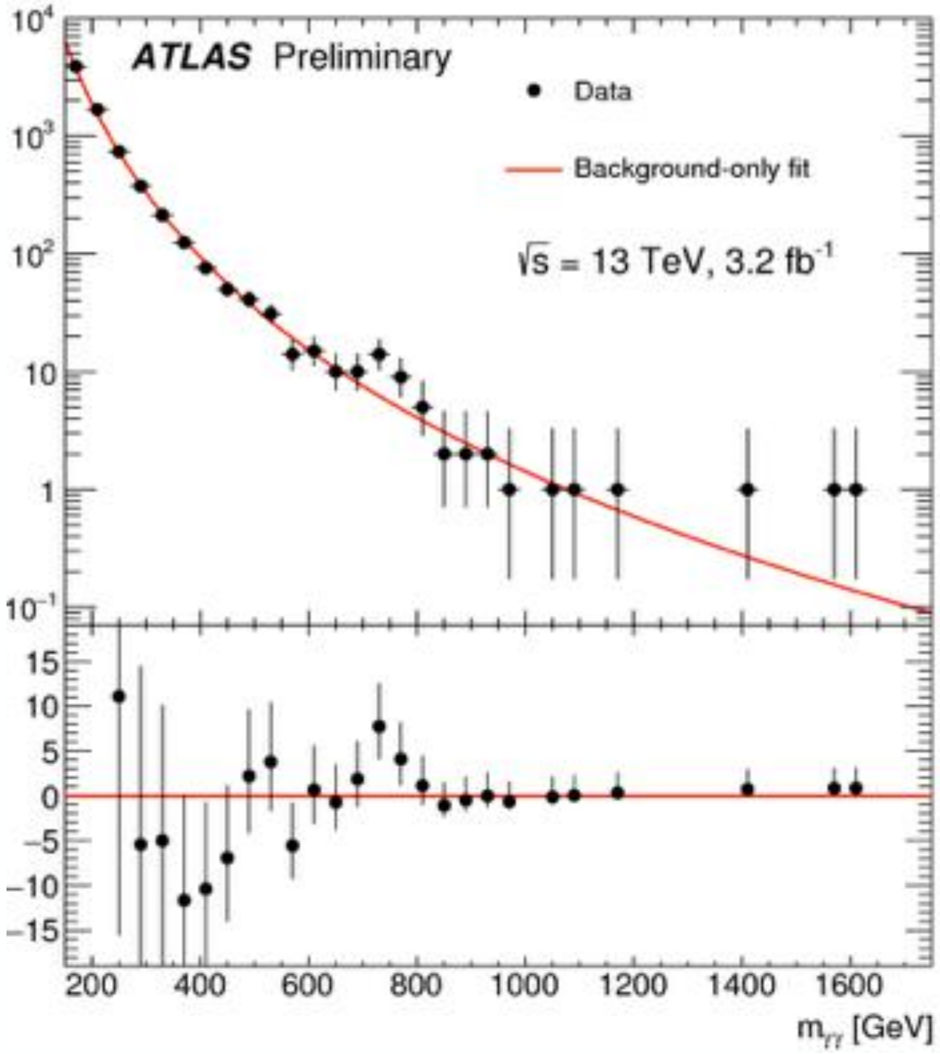
$$\sigma(X) = \int \mathrm{d}x_1 \mathrm{d}x_2\, \gamma(x_1,\mu^2)\gamma(x_2,\mu^2)\,\hat{\sigma}(\gamma\gamma \to X)$$

but in terms of *photon* parton distribution function (PDF), $\gamma(x,\mu^2)$.



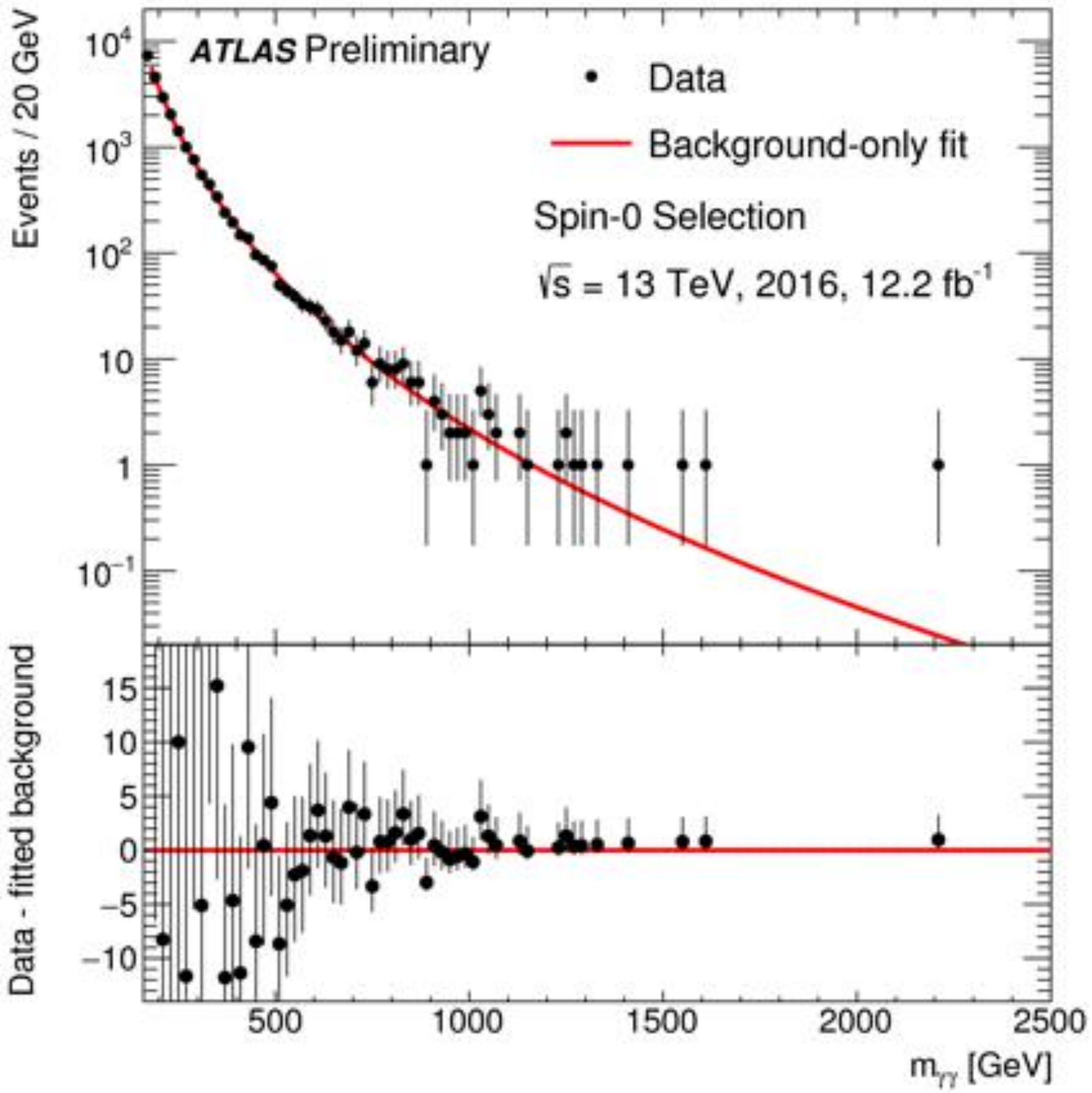
Photon PDF - ‘revival’

- Resonance in $\gamma\gamma$ collisions? Lots of interest at time in BSM resonance not just decaying to $\gamma\gamma$ but dominantly produced in $\gamma\gamma$ collisions.
- However also lots of misinformation about how well such an initial state is understood $\longrightarrow$ important to get this right!



Photon PDF - ‘revival’

- Diphoton resonance - RIP. But the motivation still remains to understand the $\gamma\gamma$ initial state: other SM (and BSM?) processes with potentially important $\gamma\gamma$ production channels.



Recent Studies

- Resurgence of interest in photon-initiated contribution to Drell-Yan (1606.00523, 1606.06646, 1607.01831), WW (1607.01831) and $t\bar{t}$ (1606.01915) at LHC and FCC.
- E.g. 1606.06646 considers photon-initiated BG to Z' production. Using NNPDF2.3QED set, find this is potentially large, with huge uncertainties. E. Accomando, J. Fiaschi, F. Hautmann, S. Moretti, C.H. Sheperd-Themistocleous

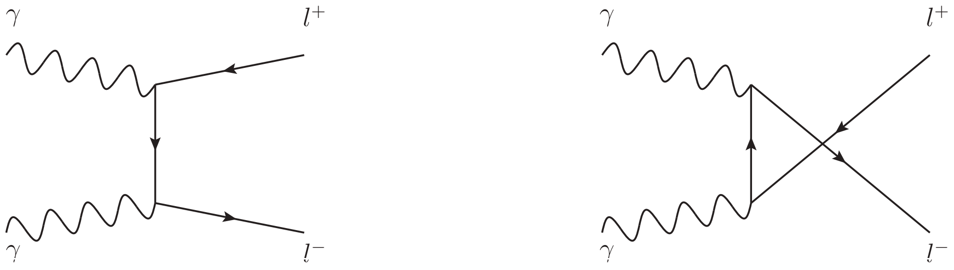
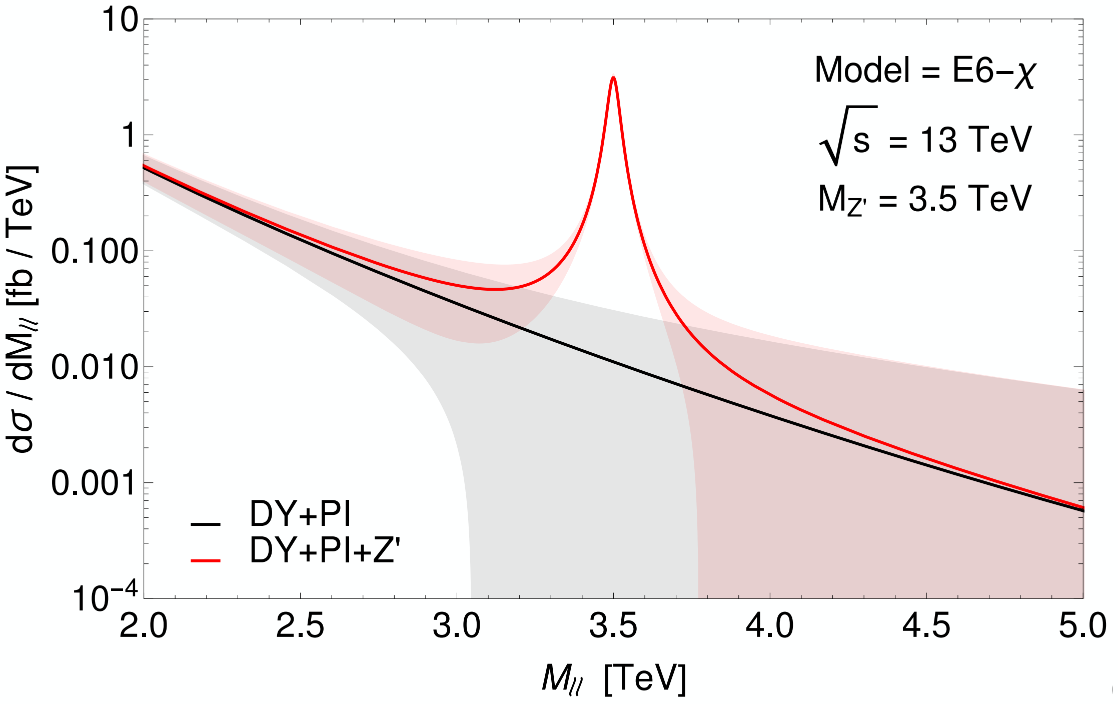


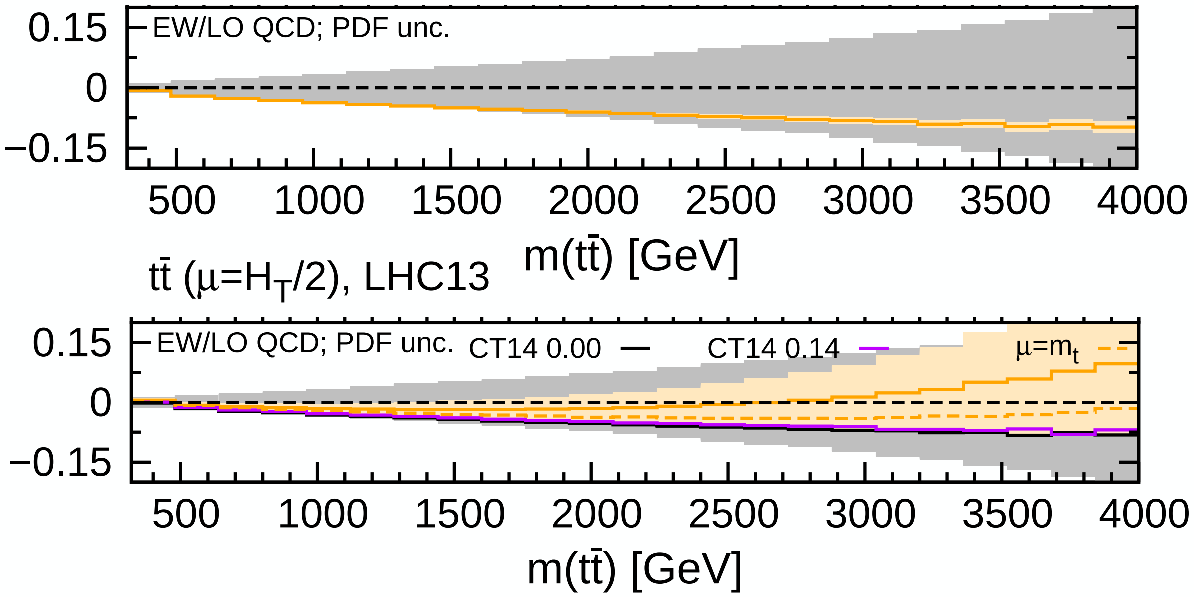
FIG. 1. Photon Induced process contributing to the dilepton final state.

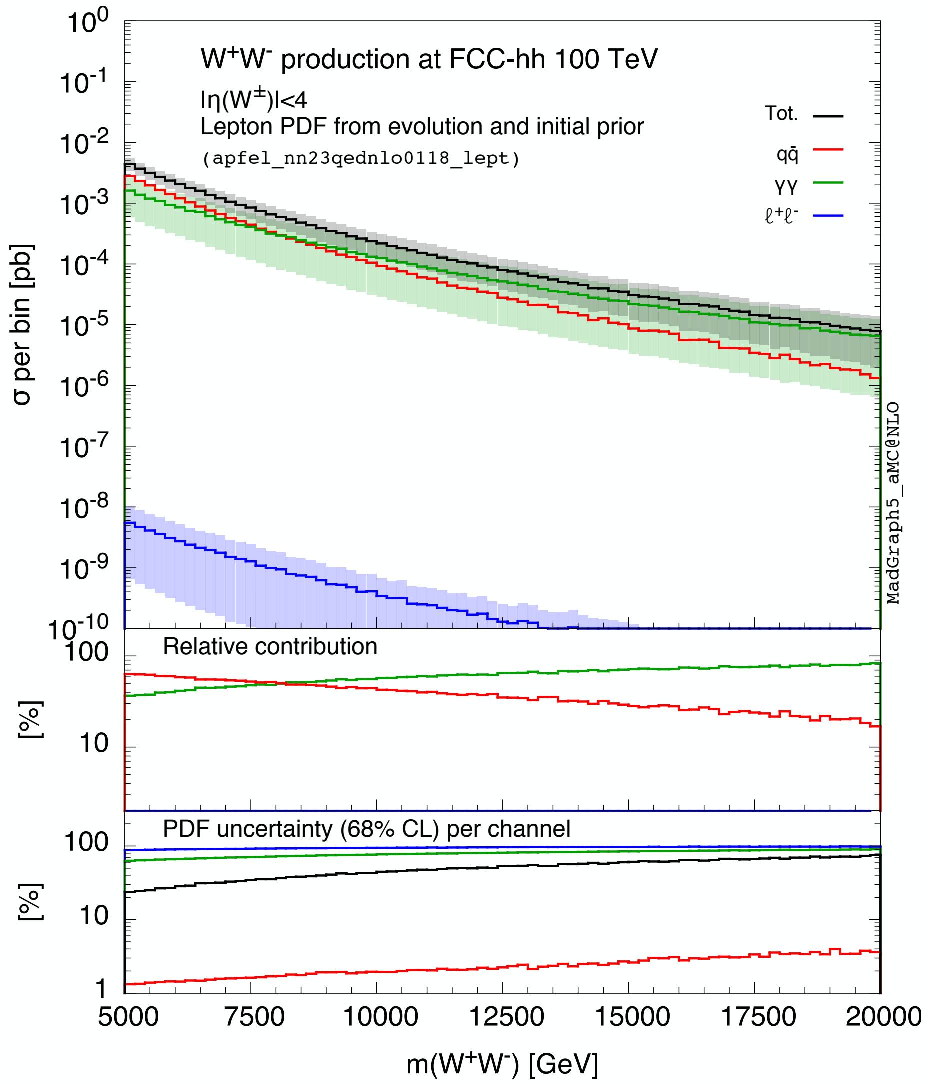


Recent Studies

M.L. Mangano et al.

- 1607.01831 : $\gamma\gamma$ contribution to W^+W^- production at high mass could be large (although under control after cuts).





D. Pagani, I. Tsinikos, M. Zaro

- 1606.01915 : $\gamma\gamma$ contribution to $t\bar{t}$ could be large, cancelling other EW corrections.

$\longrightarrow$ Potentially large photon-initiated contributions predicted using NNPDF photon PDF. Is this correct?

The photon PDF

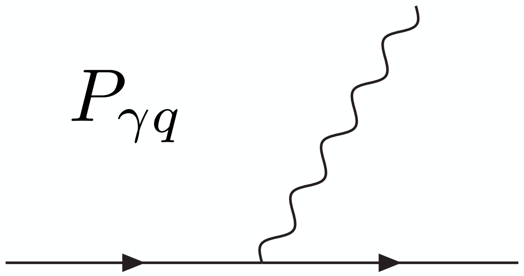
- As with other partons, the photon obeys a DGLAP evolution equation:

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

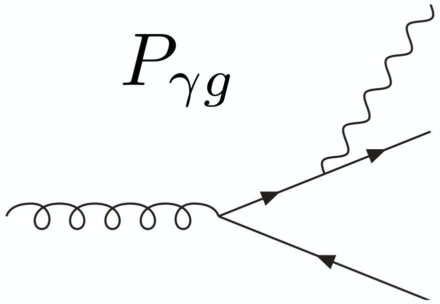
NLO in QCD

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

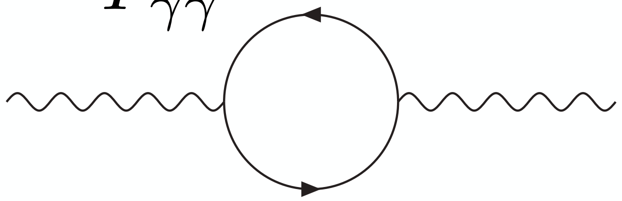
$P_{\gamma q}$



$P_{\gamma g}$



$P_{\gamma\gamma}$



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

Previous Approaches

‘Model’ approaches: MRST/CT

hep-ph/0411040

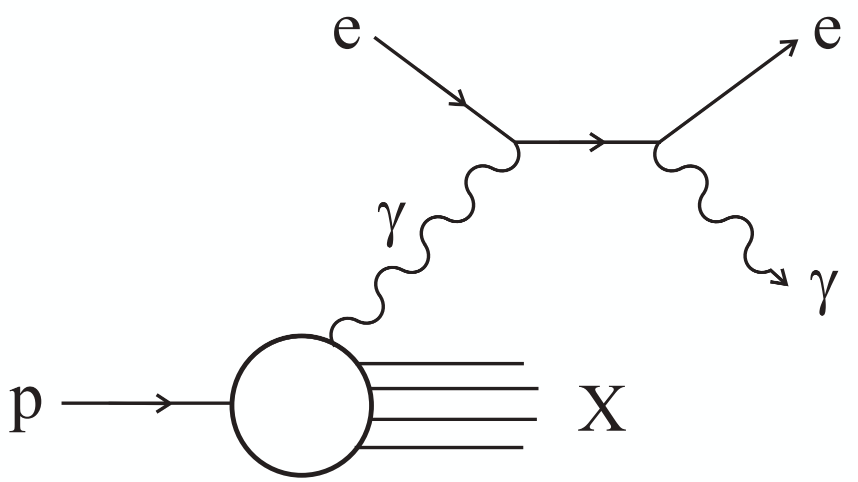
- MRST2004QED: first set to include QED contributions. Model assumed, with $\gamma(x, Q_0^2)$ generated by one-photon emission off valence quarks at LL:

‘valence-type’

$\sim P_{\gamma q}$

$$\begin{aligned}
\gamma^p(x, Q_0^2) &= \frac{\alpha}{2\pi}\left[\frac{4}{9}\log\left(\frac{Q_0^2}{m_u^2}\right) u_0(x) + \frac{1}{9}\log\left(\frac{Q_0^2}{m_d^2}\right) d_0(x)\right] \otimes \frac{1+(1-x)^2}{x} \\
\gamma^n(x, Q_0^2) &= \frac{\alpha}{2\pi}\left[\frac{4}{9}\log\left(\frac{Q_0^2}{m_u^2}\right) d_0(x) + \frac{1}{9}\log\left(\frac{Q_0^2}{m_d^2}\right) u_0(x)\right] \otimes \frac{1+(1-x)^2}{x}
\end{aligned}$$

- CT14QED: ‘Radiative ansatz’, similar to MRST2004QED model, but with additional freedom to set normalization. Fitted to ZEUS isolated photon data.

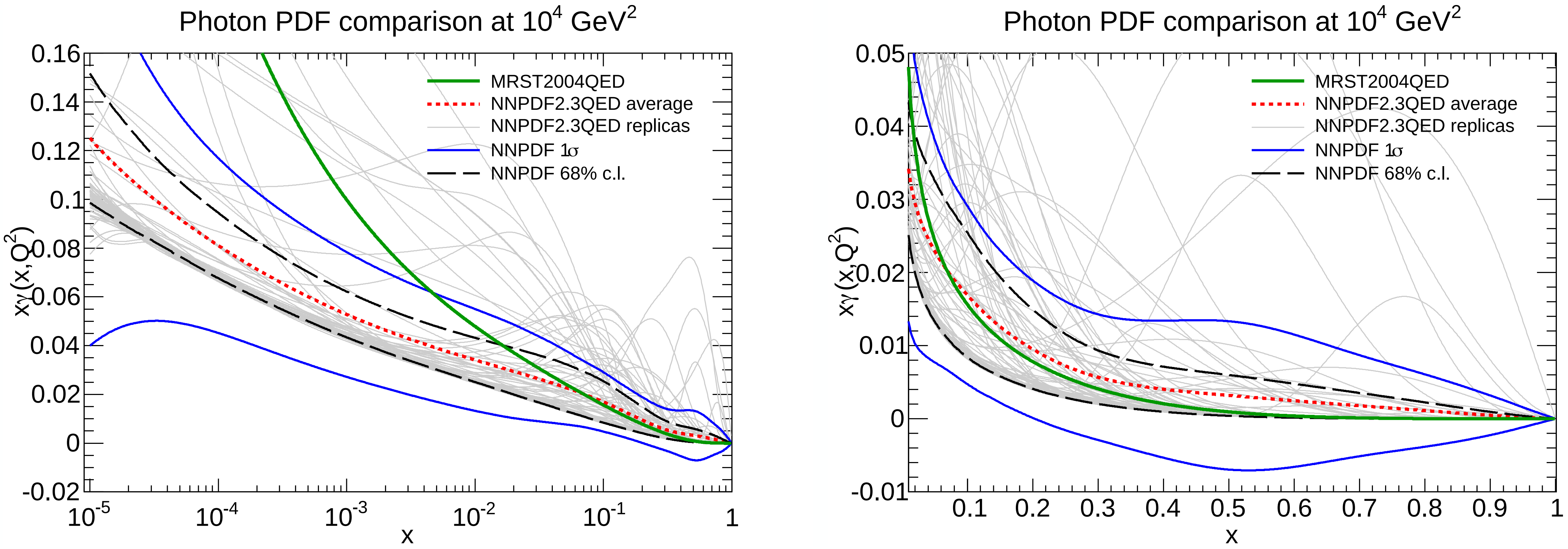


‘Agnostic’ approach: NNPDF

arXiv:1308.0598

- NNPDF2.3QED: treat photon as we would quark and gluons. Freely parametrise $\gamma(x, Q_0)$ in usual way.

- Fitting to DIS and some LHC W, Z data places some constraint:

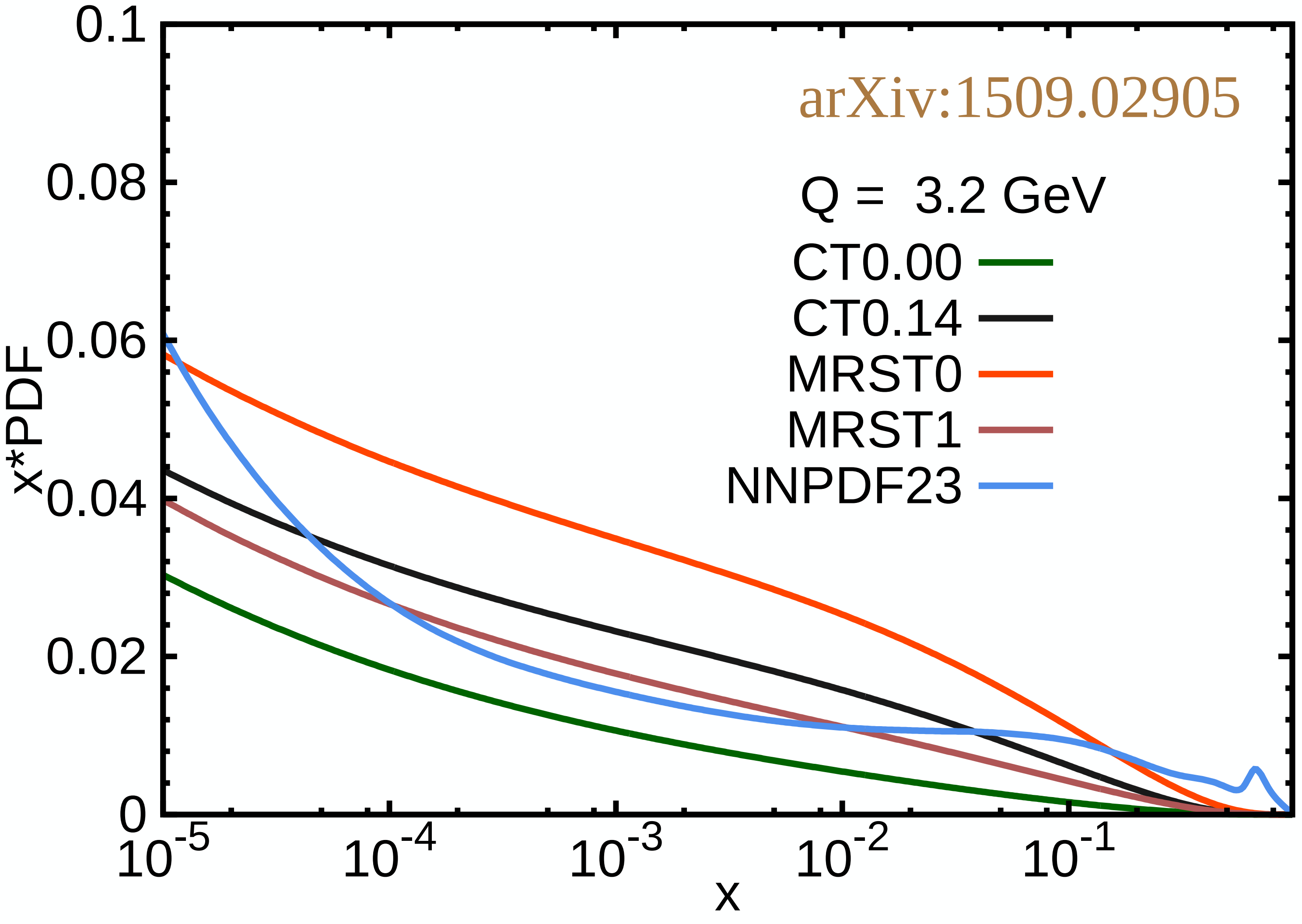


…but uncertainties (so far) remain large. Still widely used.

Photon PDF sets: comparison

- Comparing these different sets reveals a large spread in predictions
  $\Rightarrow$ apparently large uncertainties.

- However: have we included all of the available information?

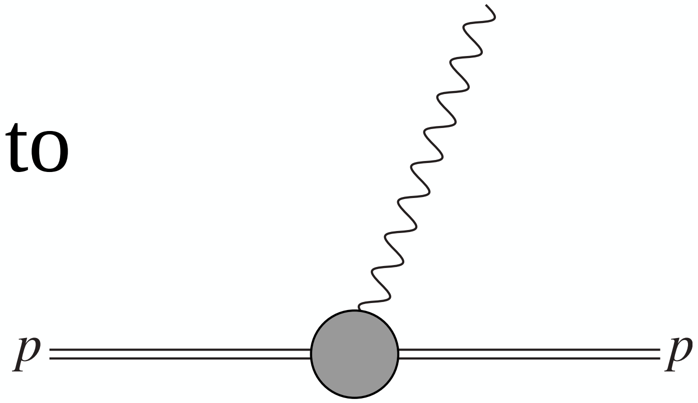


Recent Studies

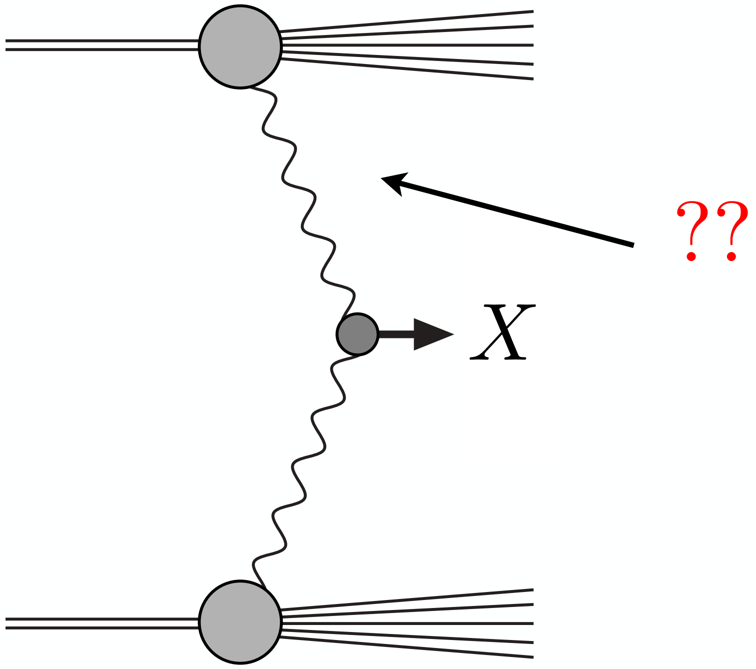
PDFs and QED

- Previous approaches missing crucial physics ingredient - the contribution from elastic photon emission.

$\longrightarrow$ Use what we know about exclusive production to constrain the (inclusive) photon PDF.

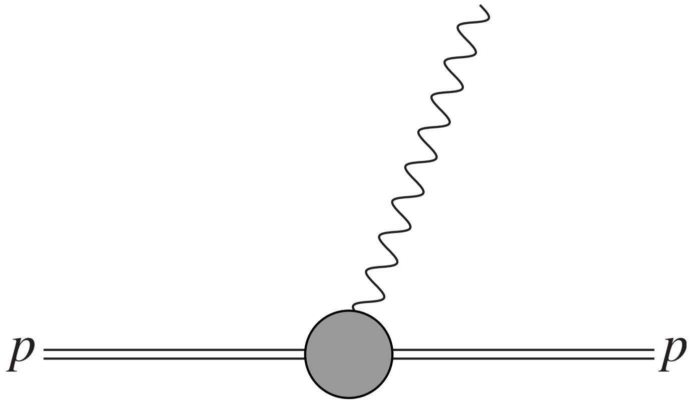


- How do we do this? Consider what can generate initial state photon in $\gamma\gamma \to X$ production process:



PDFs and QED

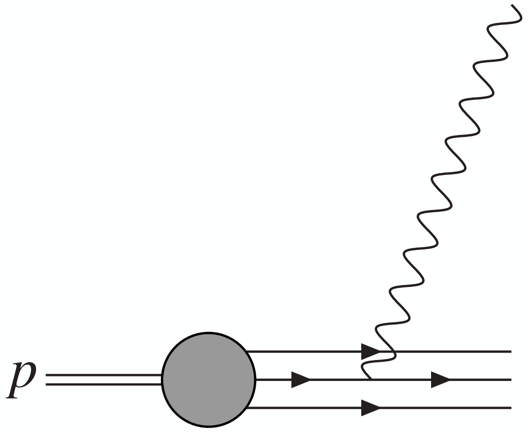
- Inclusive $\equiv$ system X + anything else $\Rightarrow$ exclusive production by definition should be included, i.e. elastic emission.



Elastic emission

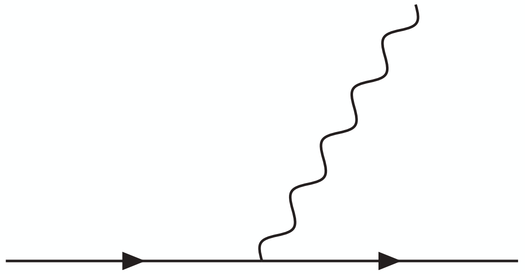
- However clearly not end of story:

‣ For $Q^2 \lesssim 1\,\mathrm{GeV}^2$ also have emission where proton breaks up.



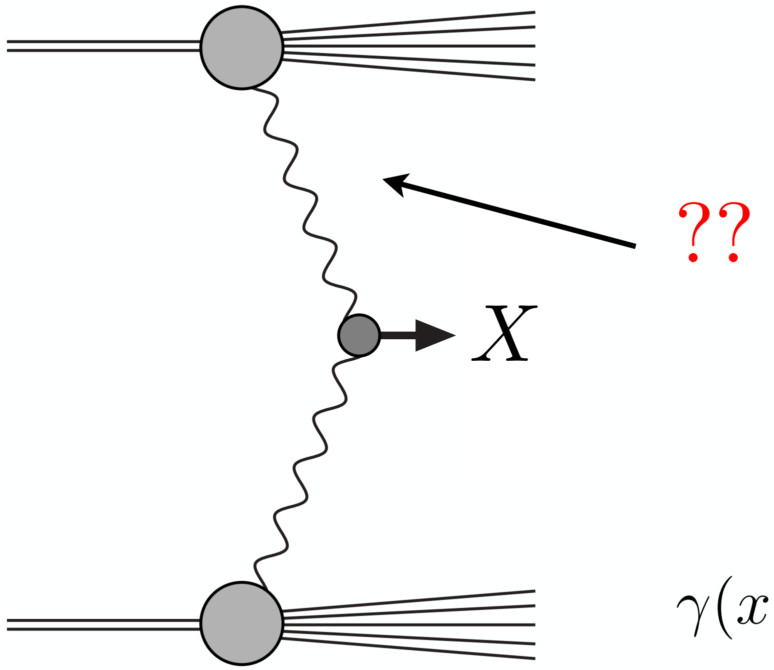
(Low scale) ‘incoherent’ emission.

‣ In addition, a photon may be emitted by a quark at a higher scale $Q^2 \gg 1\,\mathrm{GeV}^2$ i.e. in last step of DGLAP evolution.



DGLAP evolution

PDFs and QED



- Schematically:

$$\gamma \sim \gamma^{\rm coh.} + \gamma^{\rm incoh.} + \gamma^{\rm evol}$$

- More precisely, recall DGLAP equation:

$$\begin{aligned} \gamma(x,\mu^2) &= \gamma(x,Q_0^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\Bigg(P_{\gamma\gamma}(z)\gamma(\frac{x}{z},Q^2) \\ \gamma^{\rm evol} \longrightarrow \quad & + \sum_q e_q^2 P_{\gamma q}(z)q(\frac{x}{z},Q^2) + P_{\gamma g}(z)g(\frac{x}{z},Q^2)\Bigg)\ , \end{aligned}$$

$\longrightarrow$ Input photon at $Q_0 \sim 1\,{\rm GeV}$ generated by elastic emissions + incoherent:

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

A.D. Martin, M.G. Ryskin, arXiv:1406.2118

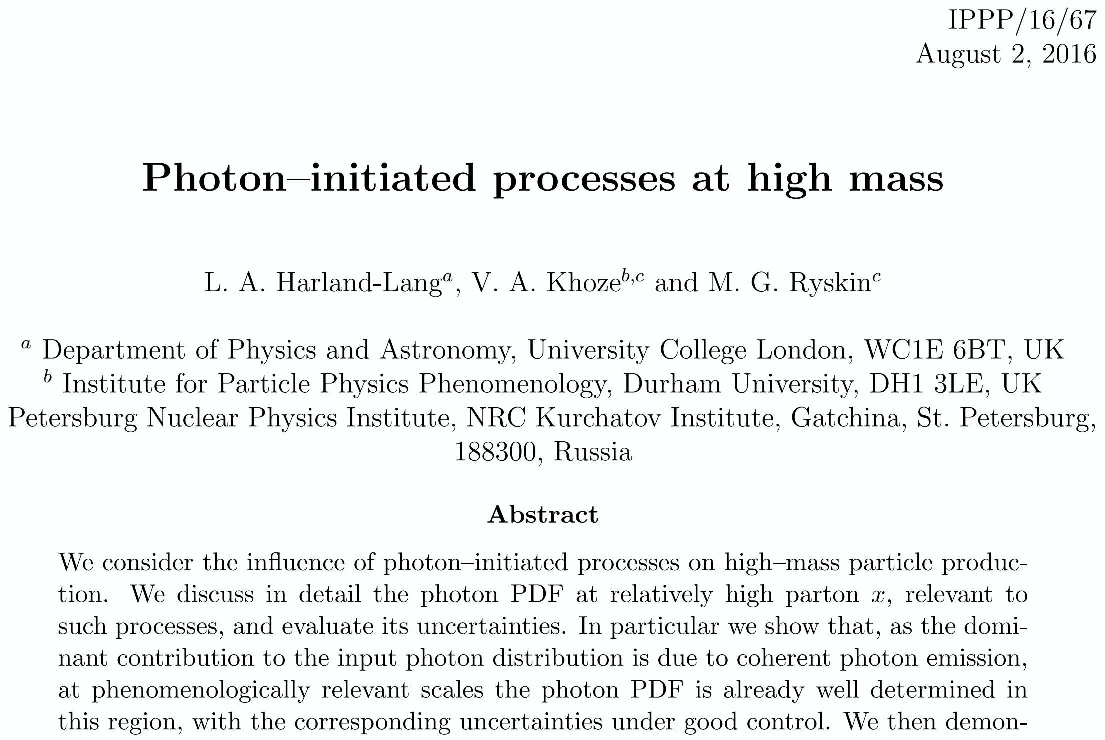
M. Gluck, C. Pisano, E. Reya, hep-ph/0206126

PDFs and QED

- We have recently applied this approach to photon-initiated processes at high mass, semi-exclusive processes, and diphoton resonance production.

RIP

LHL, V.A. Khoze, M.G. Ryskin, arXiv:1601.03372, 1601.07187, 1607.4635



IPPP/16/67
August 2, 2016

Photon–initiated processes at high mass

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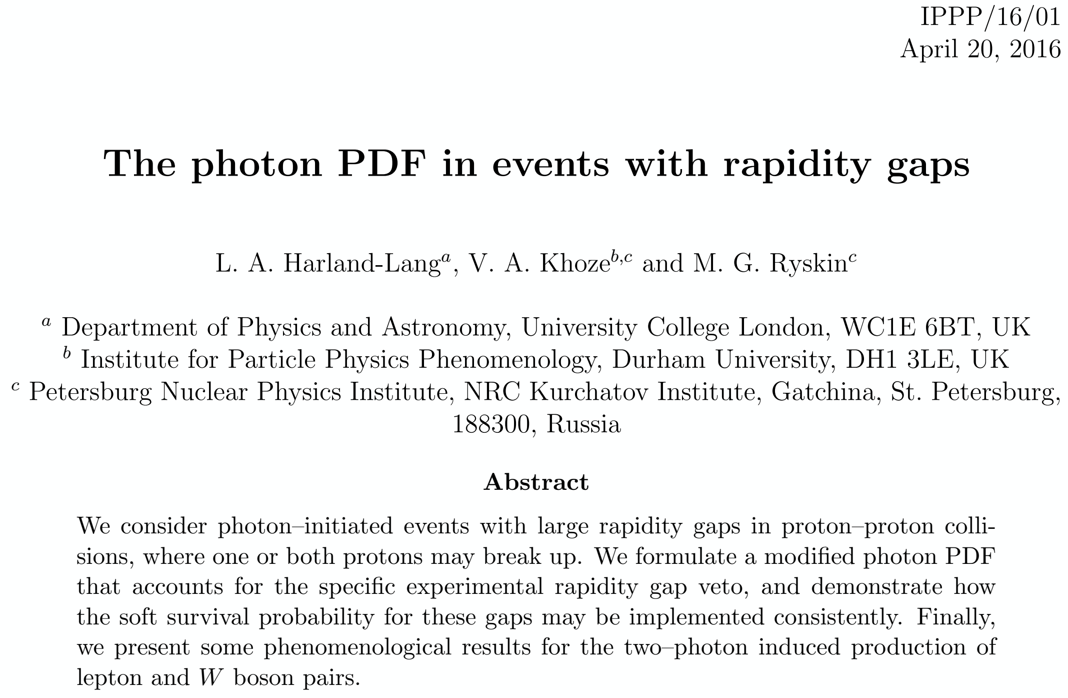
Petersburg Nuclear Physics Institute, NRC Kurchatov Institute, Gatchina, St. Petersburg, 188300, Russia

Abstract

We consider the influence of photon–initiated processes on high–mass particle production. We discuss in detail the photon PDF at relatively high parton x, relevant to such processes, and evaluate its uncertainties. In particular we show that, as the dominant contribution to the input photon distribution is due to coherent photon emission, at phenomenologically relevant scales the photon PDF is already well determined in this region, with the corresponding uncertainties under good control. We then demon-



IPPP/16/01
April 20, 2016

The photon PDF in events with rapidity gaps

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Abstract

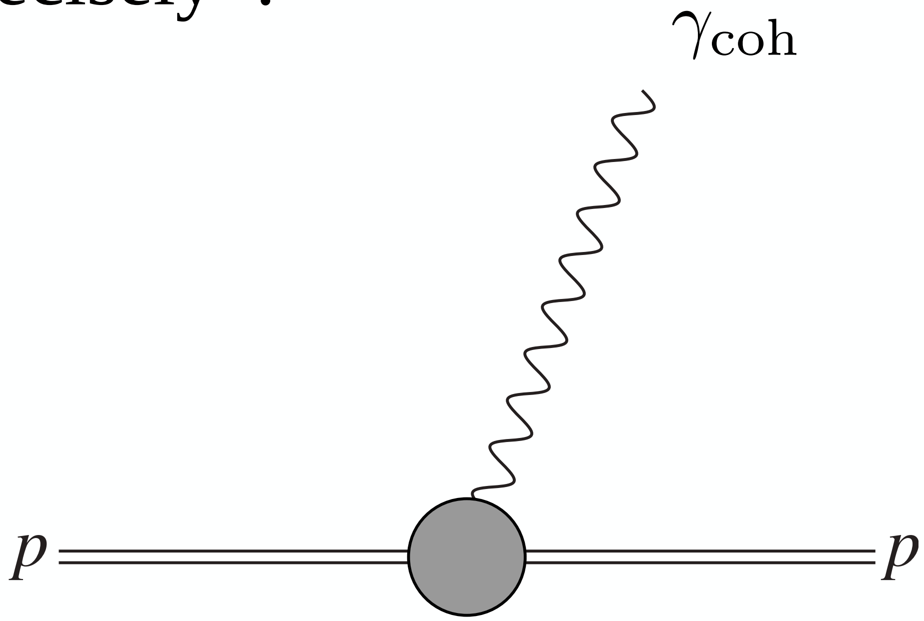
We consider photon–initiated events with large rapidity gaps in proton–proton collisions, where one or both protons may break up. We formulate a modified photon PDF that accounts for the specific experimental rapidity gap veto, and demonstrate how the soft survival probability for these gaps may be implemented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

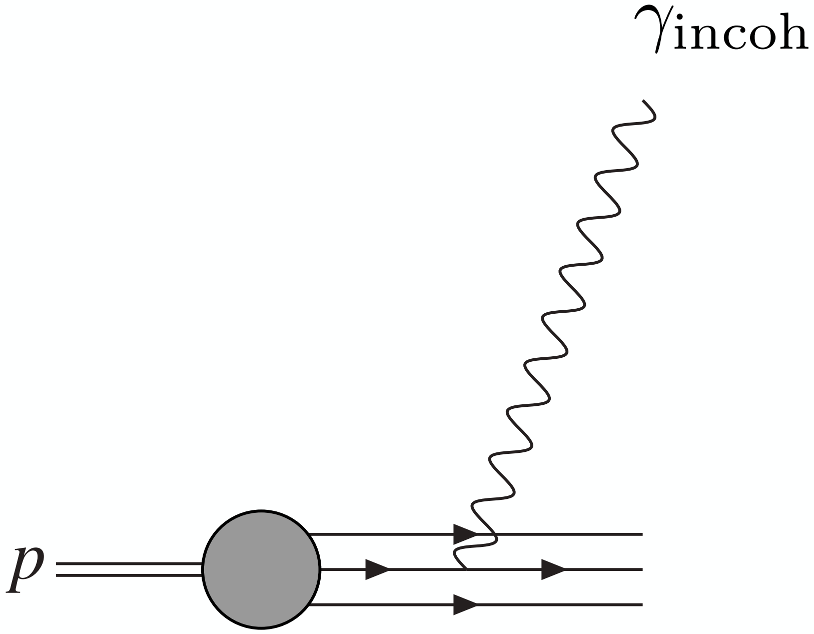
The starting distribution

- Photon at $Q_0 \sim 1\,\mathrm{GeV}$ given as sum of ‘coherent’ and ‘incoherent’ terms:

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

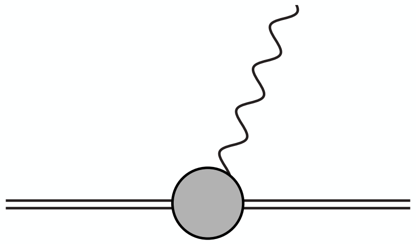
  - Coherent: due to elastic $p \to p\gamma$ emission $\Rightarrow$ exactly as in exclusive production, very well understood.
  - Incoherent: emission from individual quarks. Known potentially less precisely*.





*in fact can constrain well from data- see later.

Coherent photon emission



- The part of $\gamma(x,Q_0^2)$ due to coherent photon emission is given by

$\gamma(x,Q_0^2)\sim n(x)$

γ transverse mom.

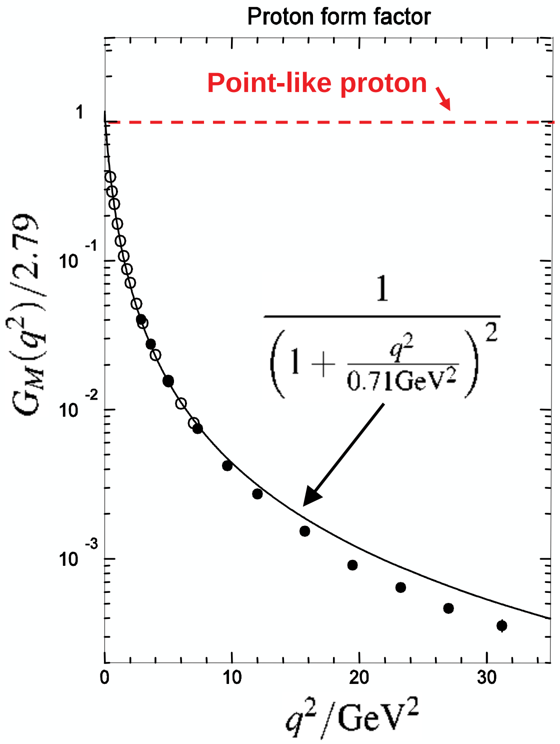
Equivalent photon

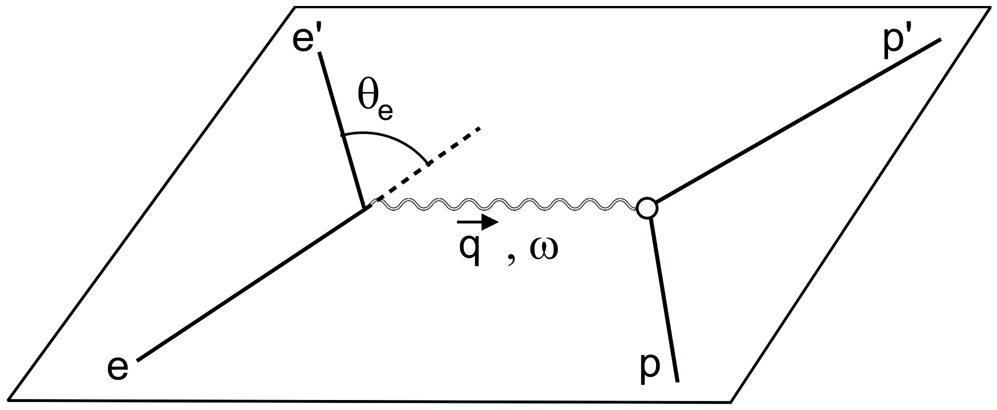
$$\gamma_{\rm coh}(x,Q_0^2)=\frac{1}{x}\frac{\alpha}{\pi}\int_0^{Q^2<Q_0^2}\frac{{\rm d}q_t^2}{q_t^2+x^2m_p^2}\left(\frac{q_t^2}{q_t^2+x^2m_p^2}(1-x)F_E(Q^2)+\frac{x^2}{2}F_M(Q^2)\right)$$

where F_E/F_M are the proton electric/magnetic form factors. These are *very* precisely measured from elastic *ep* scattering. Given in terms of `dipole' form factors*:

$$G_E^2(Q_i^2)=\frac{G_M^2(Q_i^2)}{7.78}=\frac{1}{\left(1+Q_i^2/0.71{\rm GeV}^2\right)^4}$$

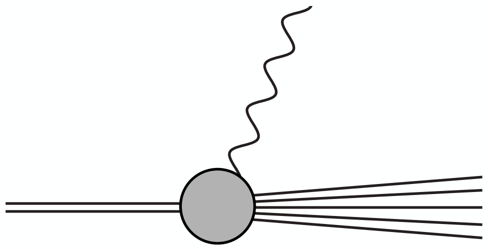
Elastic $\Rightarrow$ steeply falling





*for sub-% precision more general forms extracted from data should be taken

Incoherent photon emission



- In addition, there will be some contribution to $\gamma(x, Q_0^2)$ due to emission from the individual quarks, as in CT/MRST.

- For now take simple phenomenological approach: freeze the quark PDFs for $Q < Q_0$, but must include form factor for incoherent emission to avoid double counting with coherent piece:

$$\gamma_{\rm incoh}(x, Q_0^2) = \frac{\alpha}{2\pi} \int_x^1 \frac{{\rm d}z}{z} \left[\frac{4}{9} \overset{\color{red}{u+\overline{u}}\ \swarrow}{u_0} \left(\frac{x}{z}\right) + \frac{1}{9} d_0 \left(\frac{x}{z}\right) \right] \frac{1+(1-z)^2}{z} \int_{Q^2_{\rm min}}^{Q_0^2} \frac{{\rm d}Q^2}{Q^2 + m_q^2} \overset{\color{blue}{\text{form factor}}\ \downarrow}{\left(1 - G_E^2(Q^2)\right)} \ ,$$

$\nwarrow \quad \nearrow$ quarks frozon at Q_0 (include strange as well)

- $u, d \downarrow$ as $Q^2 \downarrow$ for relevant x, $\Rightarrow$ freezing corresponds to upper limit.

- Consider simple model here, but in a more complete treatment, it is this object - $\gamma_{\rm incoh}(x, Q_0^2)$ - that should be fit.

Input photon PDF

- Photon PDF at Q_0 given as sum of coherent and incoherent terms:

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

- Consider momentum fraction of proton at Q_0 due to two contributions:

$$p_\gamma = \int {\rm d}x \, x\gamma(x, Q_0^2)$$

- Find: $p_\gamma^{\rm coh} = 0.15\%$ $\quad p_\gamma^{\rm incoh.} = 0.05\%$

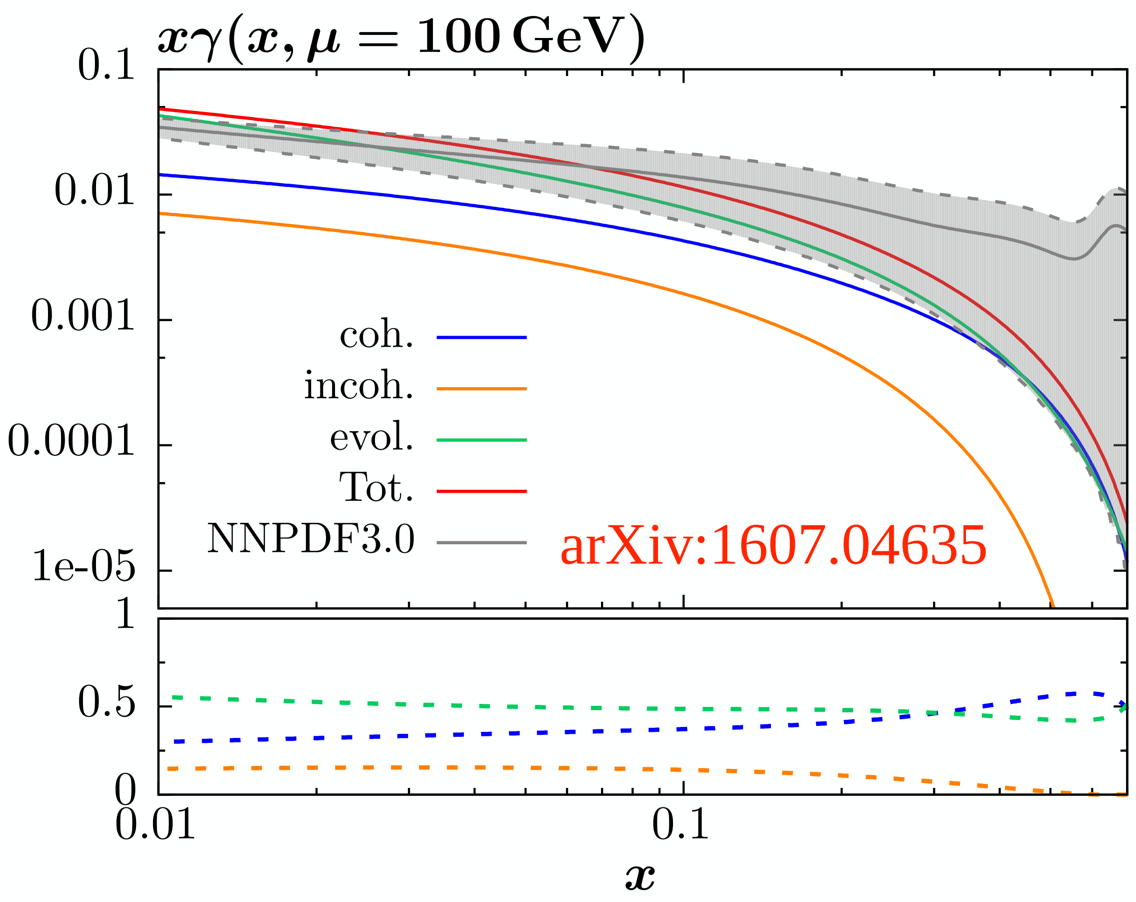
NNPDF3.0QED: $p_\gamma = (1.26 \pm 1.26)\%$

- Recall our incoherent term is upper limit $\Rightarrow$ at least $\sim 75\%$ of photon PDF is known very precisely. Entirely expected: at low Q^2 the dominant mechanism for γ emission from a proton is coherent.

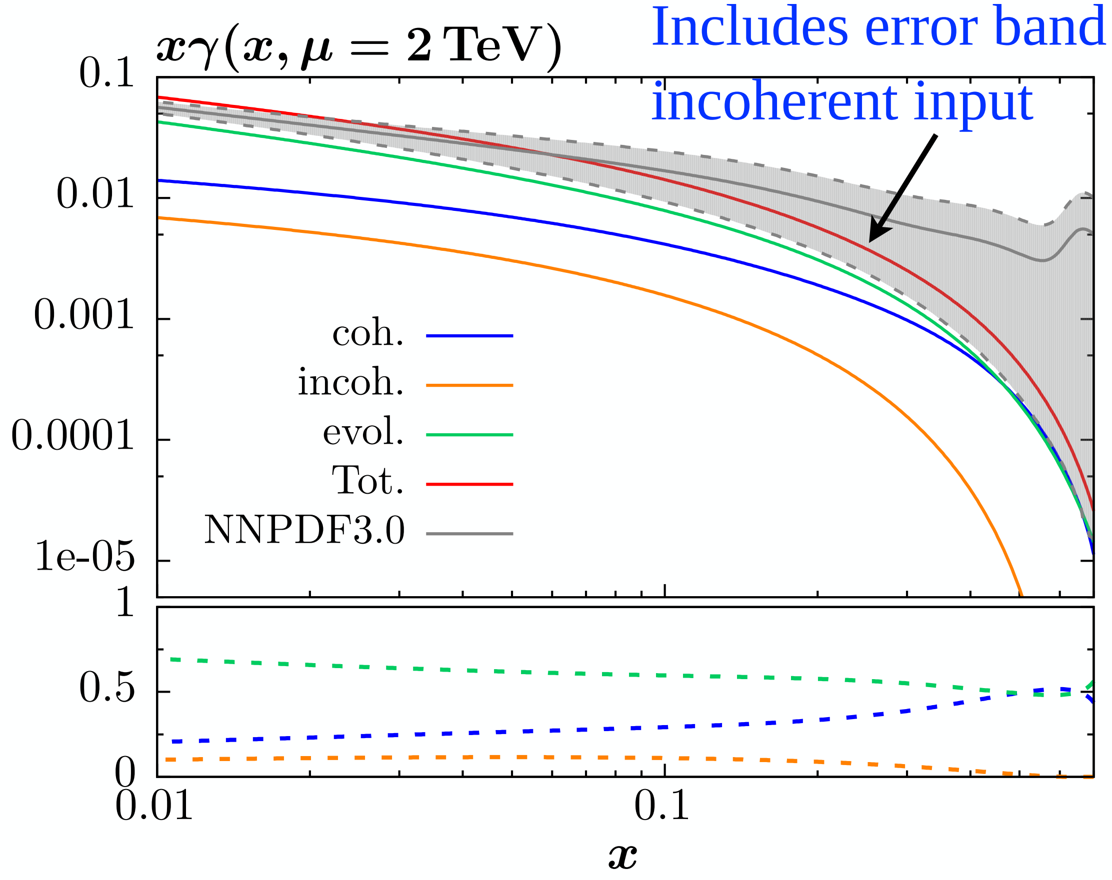
Predictions

PDF comparison

- Consider photon PDF at high scale μ :
  - $x \downarrow$: dominated by evolution. Uncertainty under good control.
  - $x \uparrow$: input component more important.
- NNPDF has huge uncertainties at higher x .
- But in our physical approach this is not the case. Prediction lies on lower end of NNPDF uncertainty band.



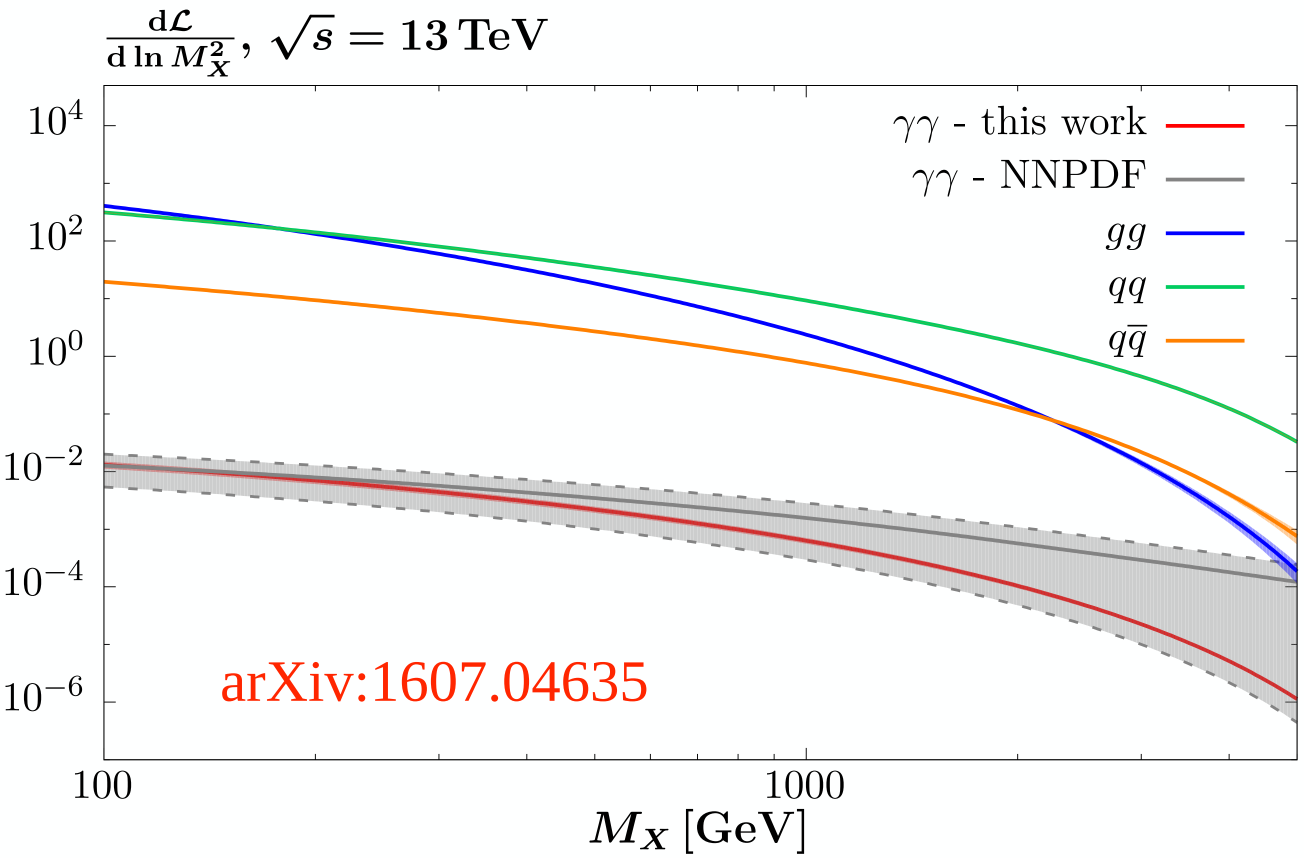
arXiv:1607.04635



Includes error band due to incoherent input

PDF luminosities

- Consider parton-parton luminosities at LHC and FCC.
- Previous result translates to large uncertainty and potentially large luminosity at high mass. q, g fall much more steeply than central γ NNPDF prediction.
- Our approach: scaling very similar to $qq/q\overline{q}$, with gg only slightly stepper. Uncertainties fairly small, again a lower end of NNPDF band.



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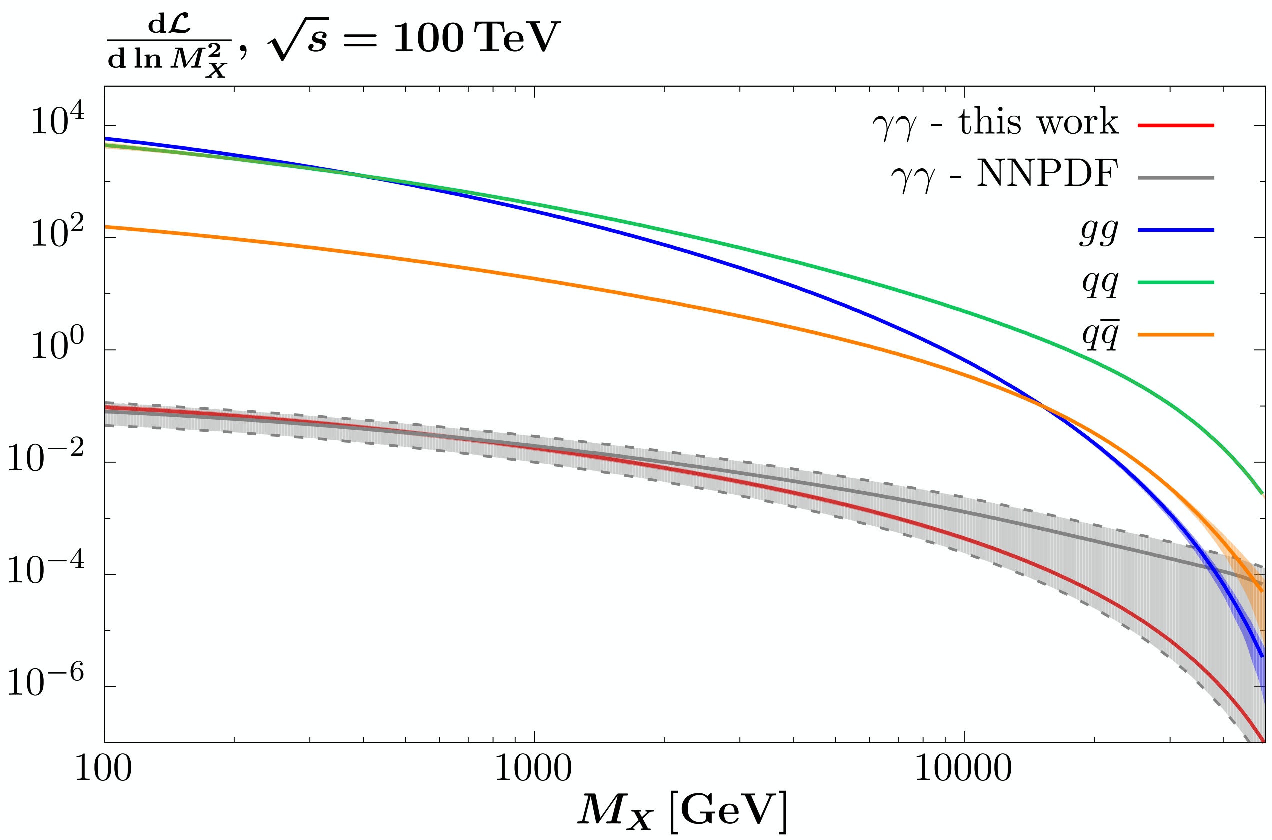
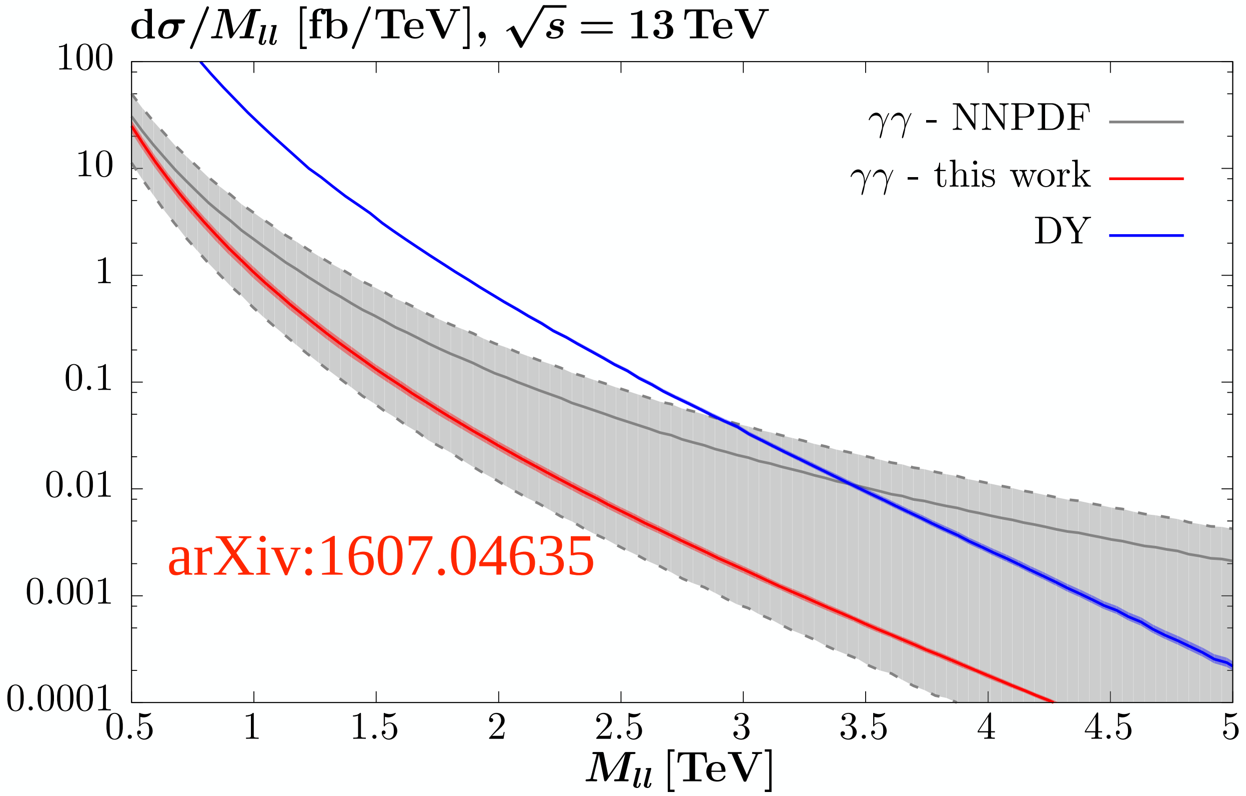


Drell-Yan production

- Consider lepton pair production at LHC/FCC. As M_{ll} increases find central NNPDF $\gamma\gamma$ prediction becomes sizeable/dominant. Discussed in detail in 1606.00523, 1606.06646, 1607.01831.
- Follows directly from previous slide: relatively gentle decrease of NNPDF $\gamma\gamma$ luminosity at higher mass.
- We find this is not expected. Photon-initiated contribution $\lesssim 10\%$.
- BG to Z' production - small and well constrained.



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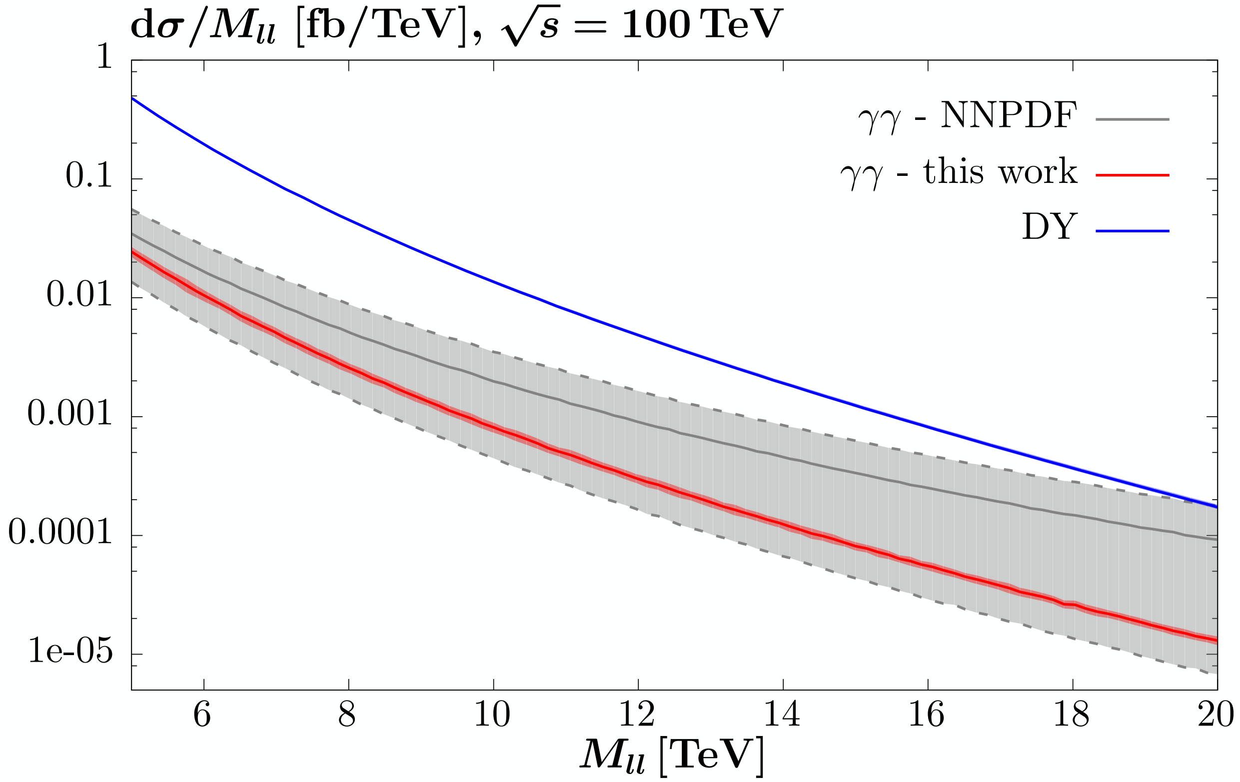
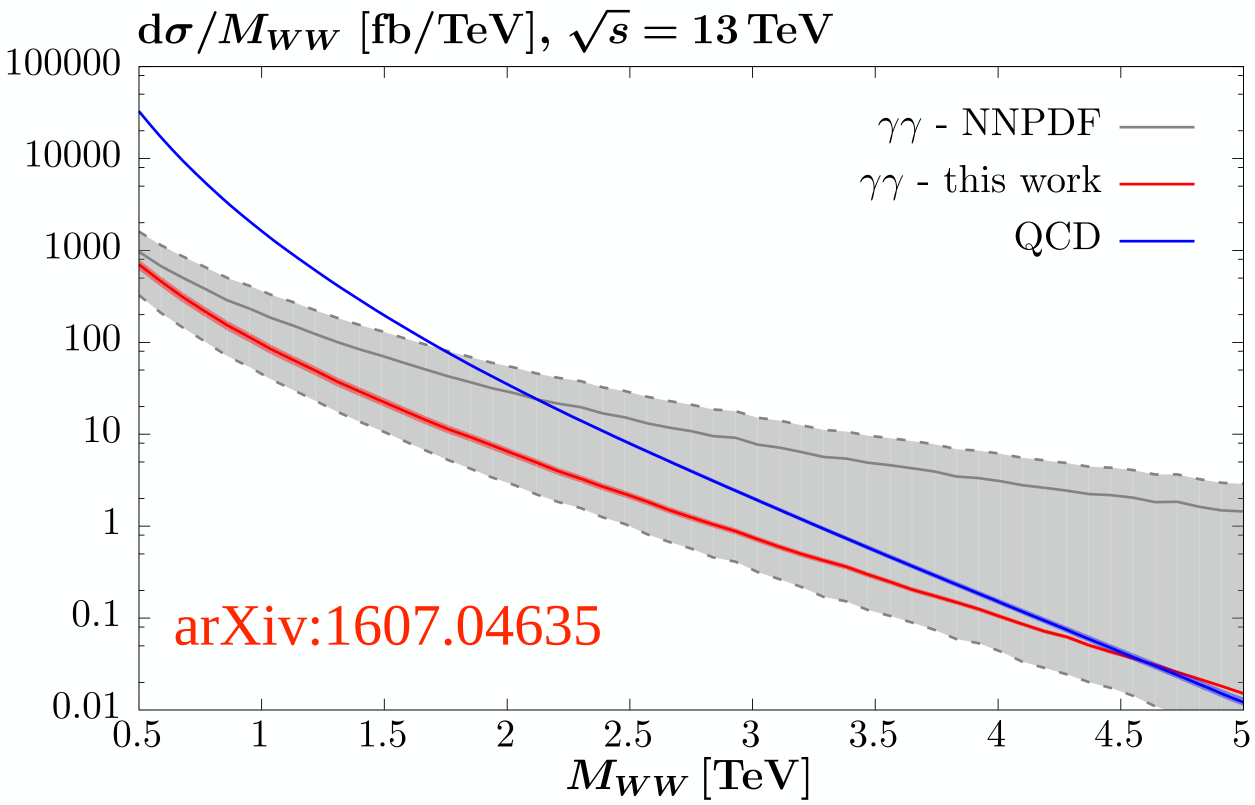
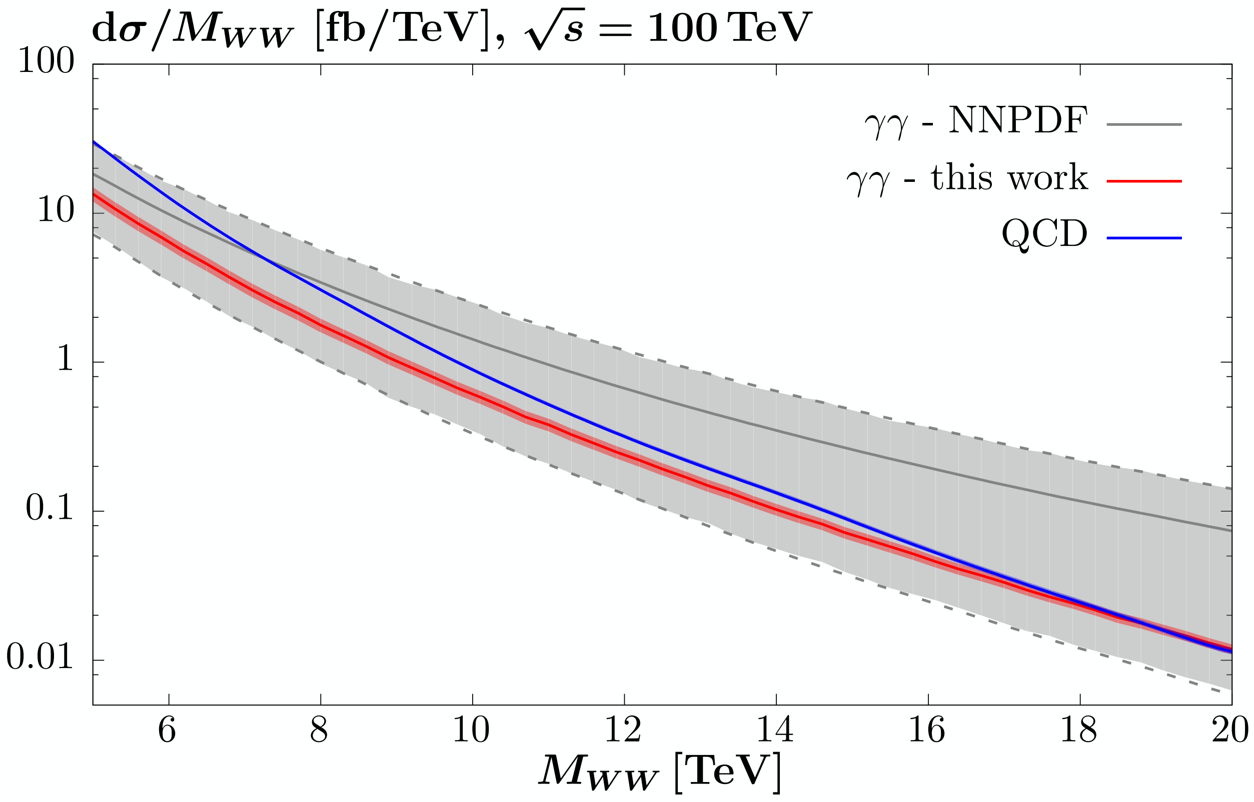


W^+W^- production

- Similar story for W^+W^- production: our results at lower end of NNPDF uncertainty band.
- However here the photon-initiated contribution is still quite large (caveat: depends somewhat on cuts).



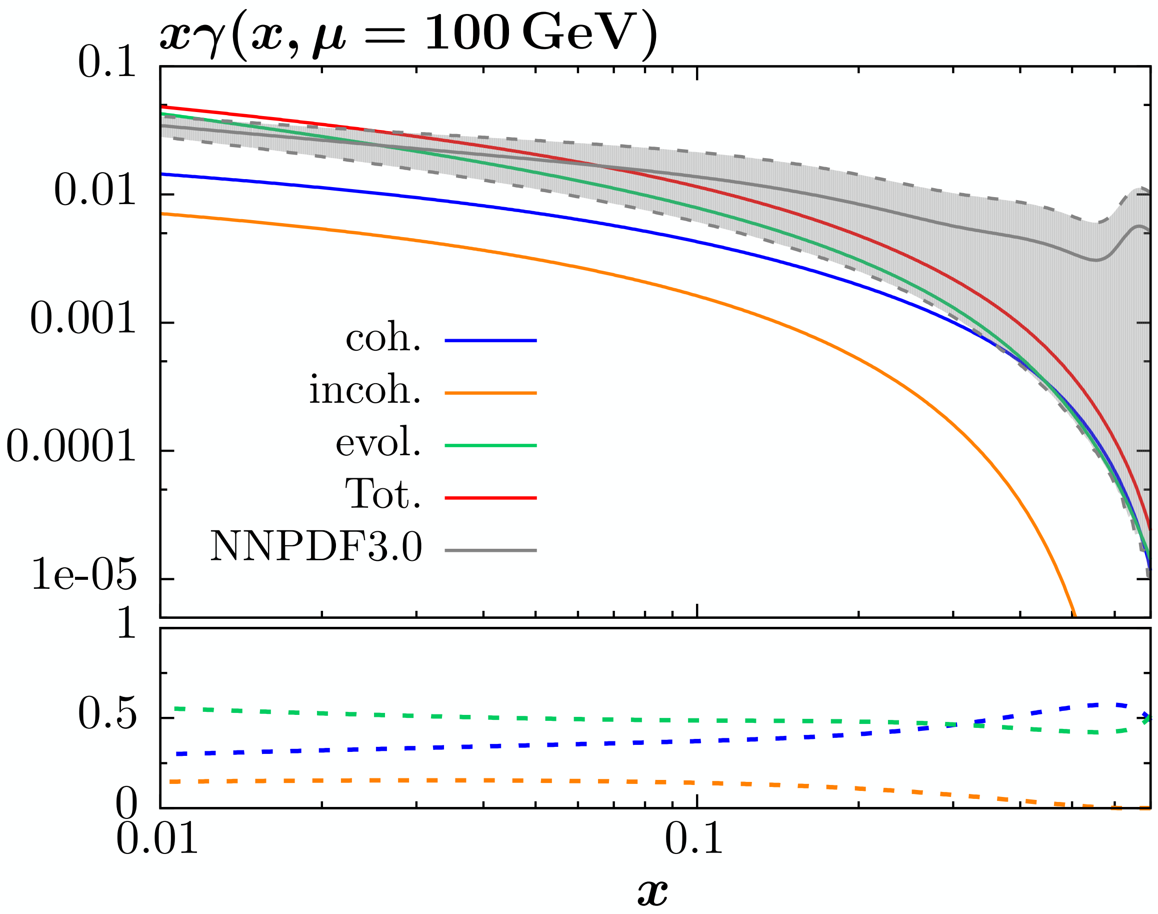
arXiv:1607.04635



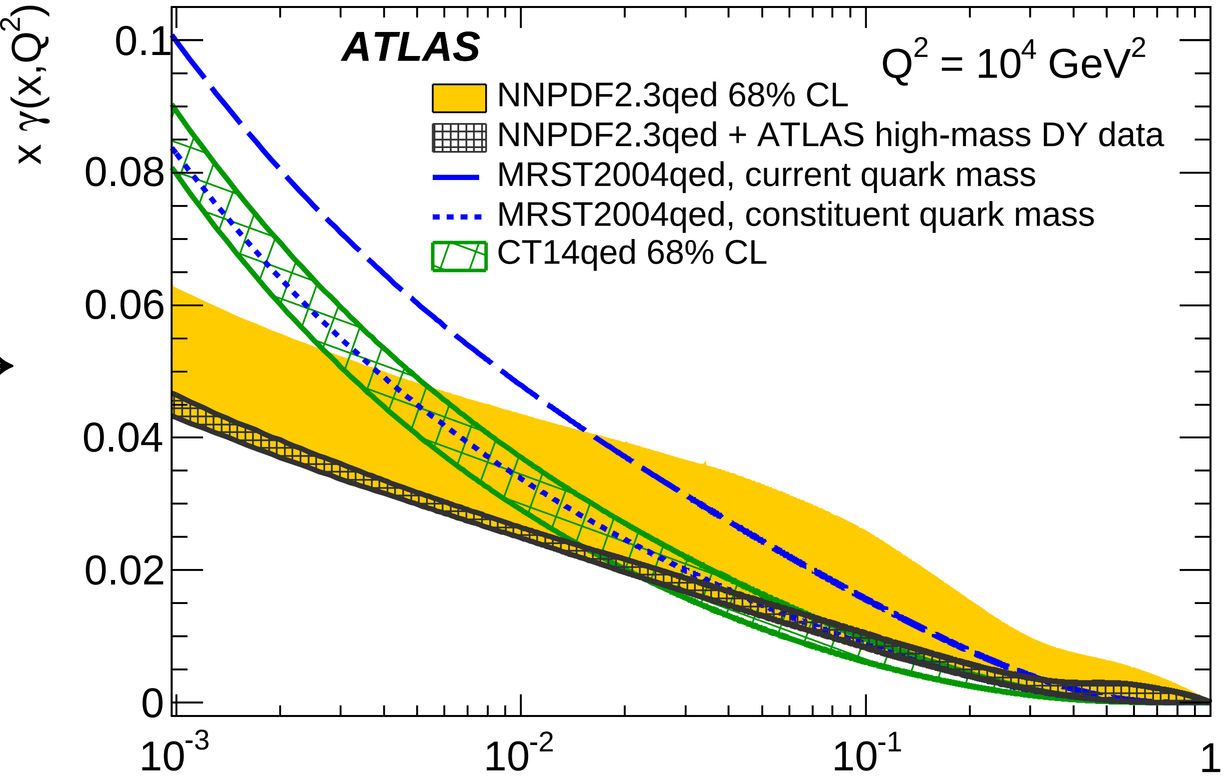
Constraint from ATLAS data

- Recent ATLAS measurement of double-differential DY, extending to high mass $M_{ll} < 1500\,\mathrm{GeV}$. Sensitive to photon PDF.
- Bayesian reweighting exercise clearly disfavours larger NNPDF2.3 predictions $\Rightarrow$ consistent with our results.

- ATLAS data only sensitive to higher x, constraint as $x \downarrow$ largely artefact of reweighting. Would be interesting to include this in fit.



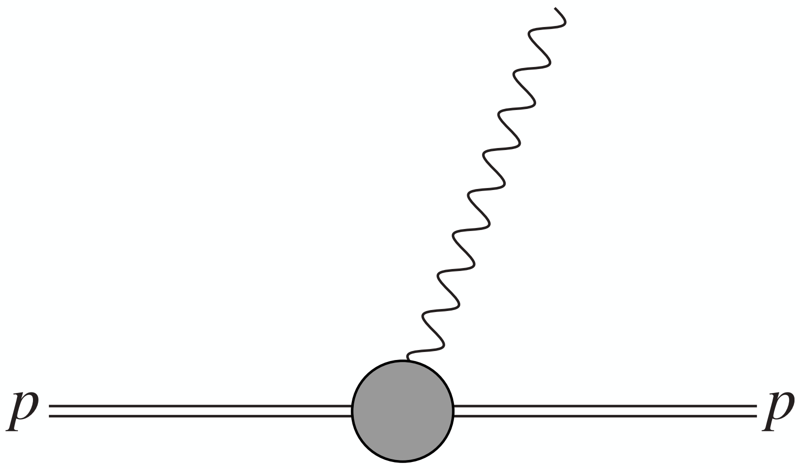
$\leftrightarrow$

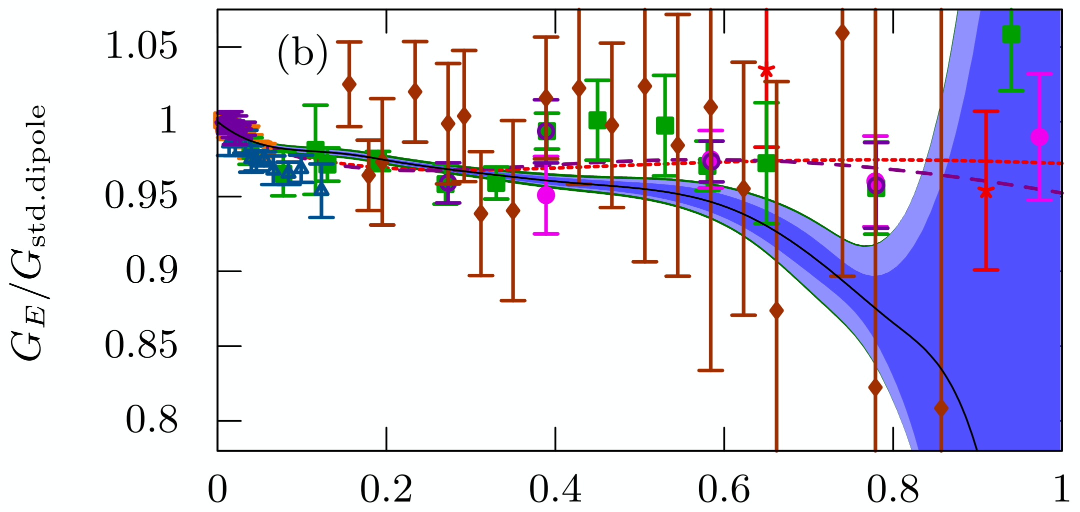


Further progress - LUXqed

LUXqed (1)

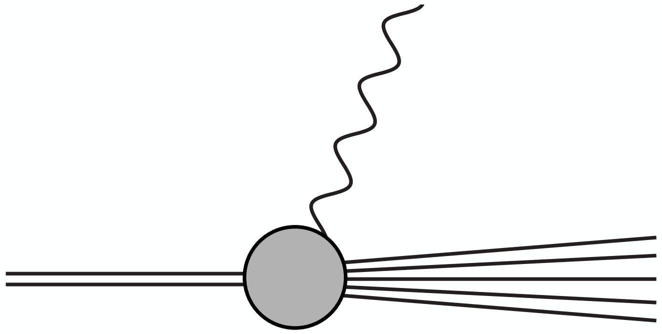
- Have discussed how dominant coherent $p \to p\gamma$ emission process is well constrained from elastic *ep* scattering.




A1 Collaboration, arXiv:1307.6227

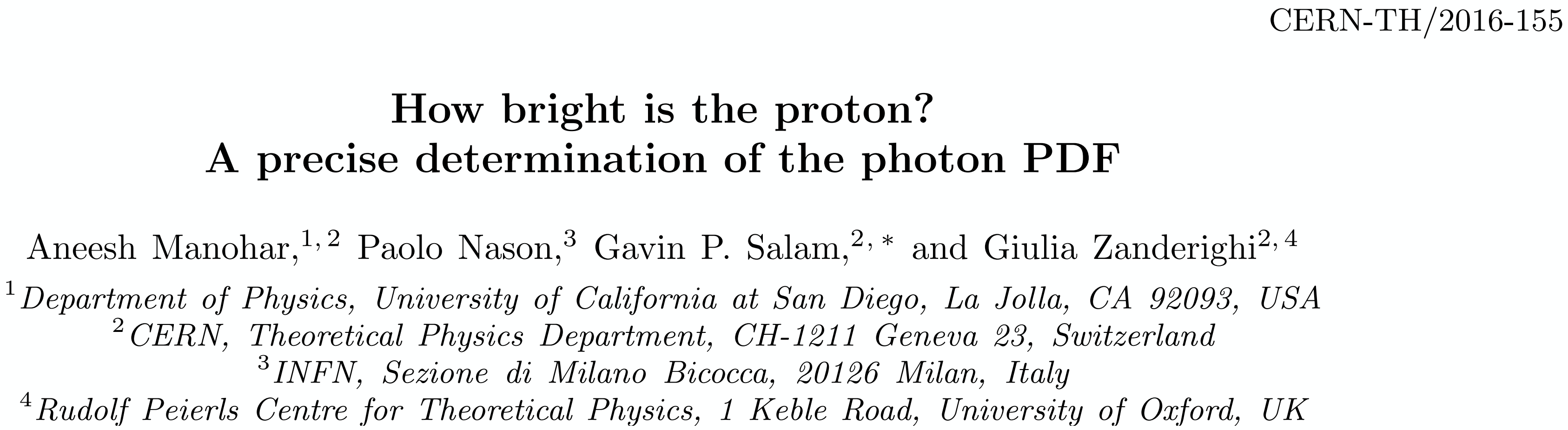
- What about incoherent component? Can we not also constrain this from well measured inelastic *ep* scattering?

- Yes! $\longrightarrow$ Recent LUXqed study show precisely how this can be done.



LUXqed (2)

- Recent study of arXiv:1607.04266:



CERN-TH/2016-155

How bright is the proton?
A precise determination of the photon PDF

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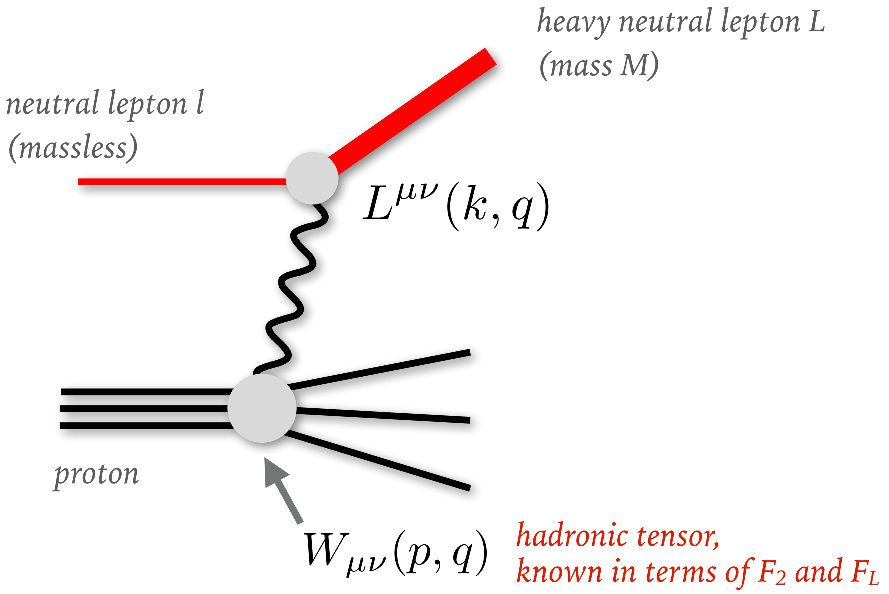
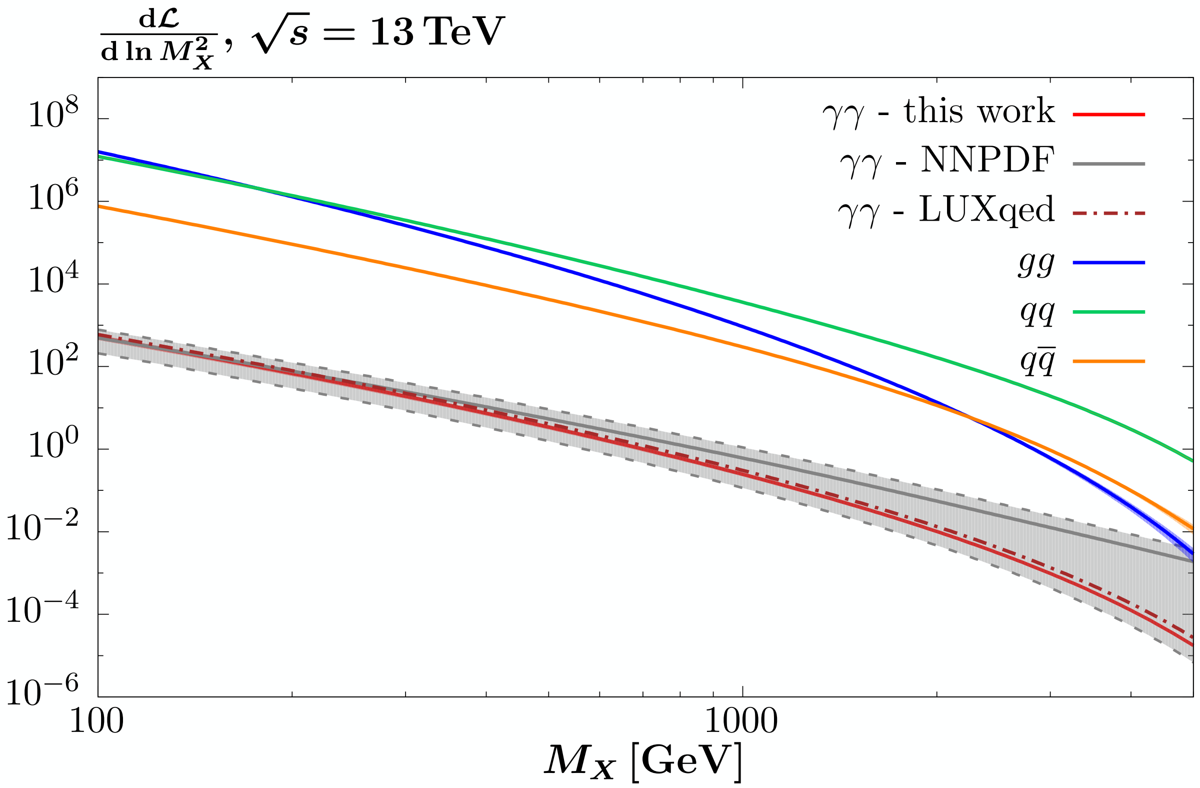
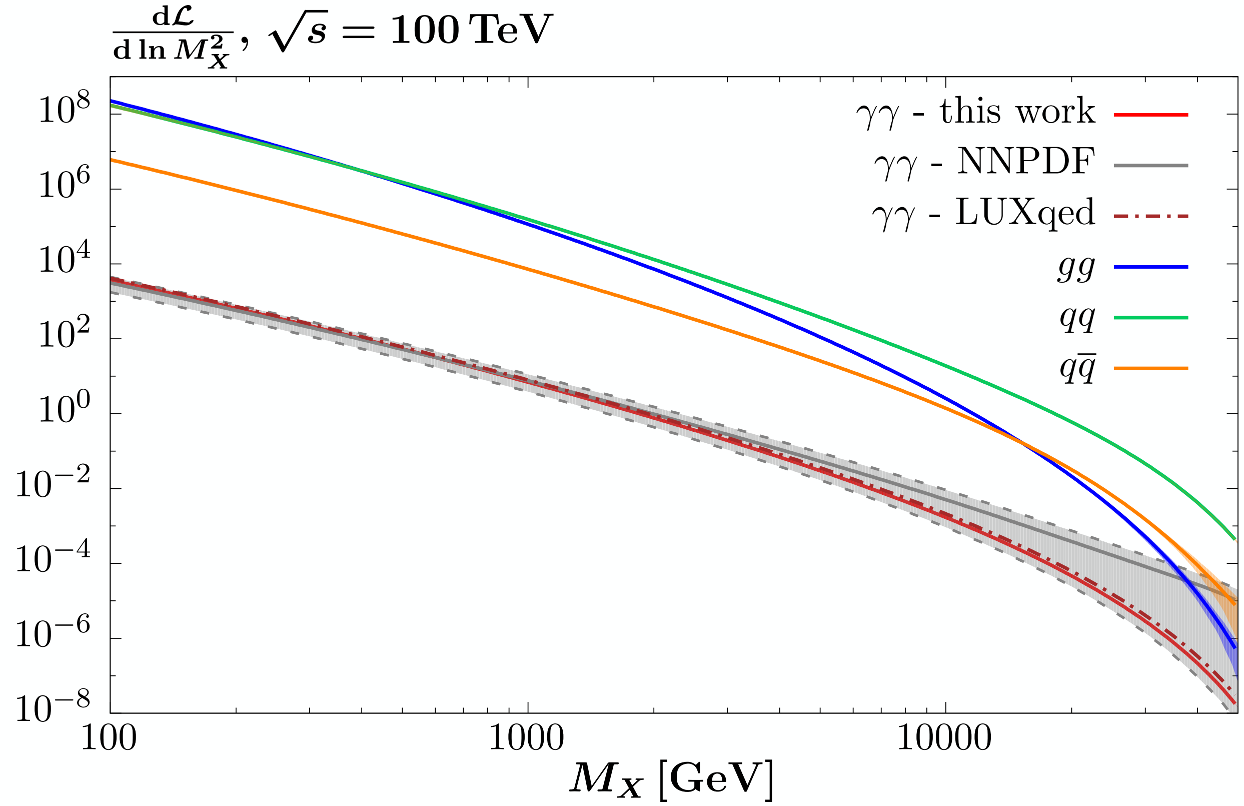
- Show how photon PDF can be expressed in terms of F_2 and F_L. Use measurements of these to provide well constrained `LUXqed` photon PDF.

$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z,Q^2) - z^2 F_L\left(\frac{x}{z},Q^2\right) \right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z},\mu^2\right) \right\}, \qquad (6)$$



LUXqed - comparison





- Comparing our and LUXqed $\gamma\gamma$ luminosities can see these are quite similar ($\longrightarrow$ importance of coherent component).
- Devil is in detail - some enhancement seen in LUXqed at higher M_X, appears to be due to low Q^2 resonant contribution.
- However, clear we have moved beyond the era of large photon PDF uncertainties. Now interested in precision determinations.

See backup for more details

LUXqed - connecting approaches

See backup for more details

- While the formalism may appear different, in fact connection to our results can be quite simply made. Divide Q^2 integral into $Q^2 < Q_0^2 \sim 1\,\mathrm{GeV}^2$ and $Q^2 > Q_0^2$ regions:

Caveat: omits influence of γ on quarks/gluons

- $Q^2 > Q_0^2$ - standard DGLAP ($= \gamma^{\rm evol}$).
- $Q^2 < Q_0^2$ - separates into:
  - ‘Elastic’ = coherent component. Treatment very similar.
  - ‘Inelastic’ = incoherent component. Treatment different.

$$F_2^{\rm el}(x,Q^2) = \frac{[G_E(Q^2)]^2 + [G_M(Q^2)]^2\tau}{1+\tau}\delta(1-x)\,,$$

$$F_L^{\rm el}(x,Q^2) = \frac{[G_E(Q^2)]^2}{\tau}\delta(1-x)\,,$$

$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(zp_{\gamma q}(z) + \frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right] - \alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}, \quad (6)$$

LUXqed

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

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

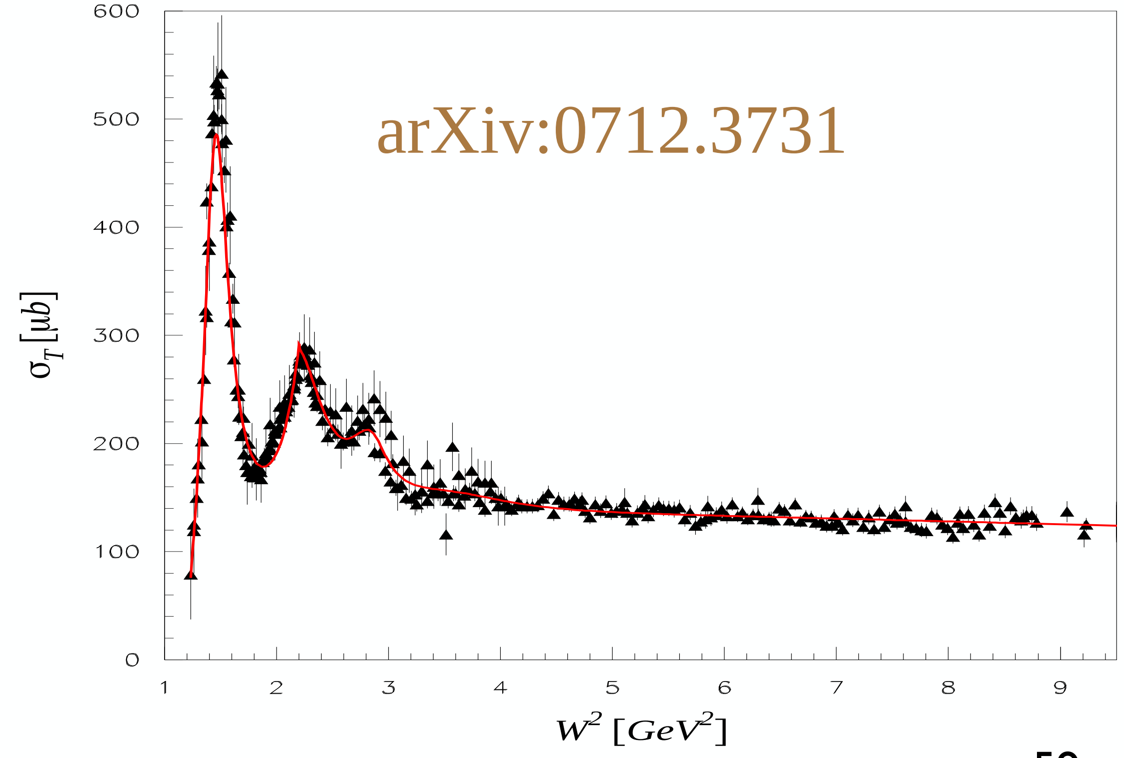
HKR

LUXqed - incoherent component

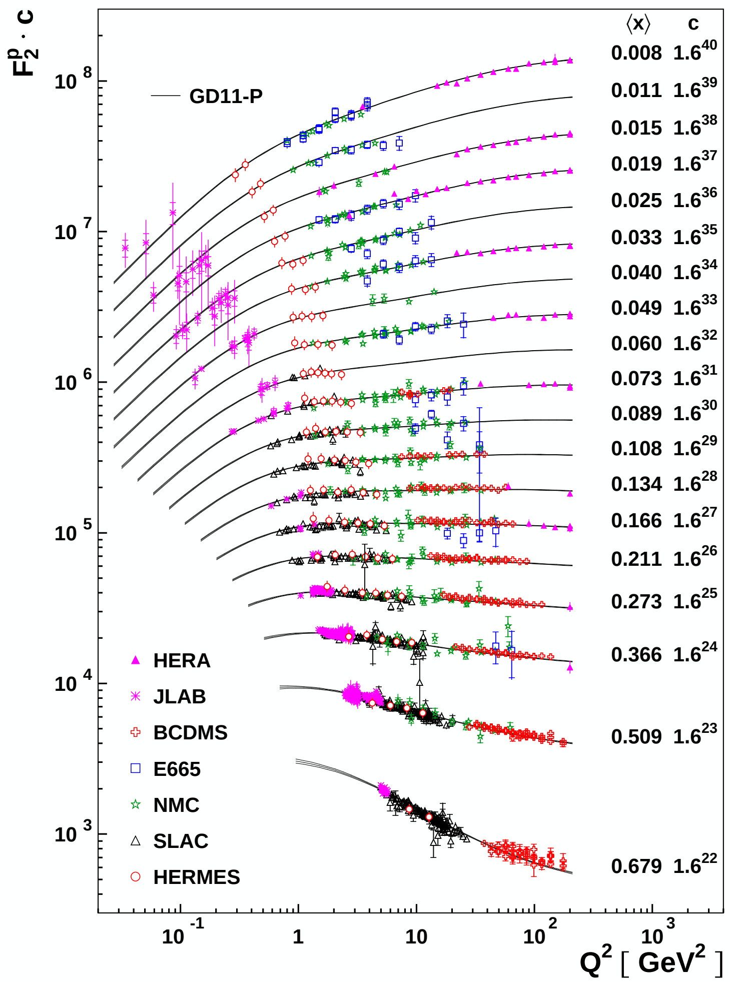
- The incoherent component is divided into two pieces:
  - Continuum ($W^2 \gtrsim 3.5\,\mathrm{GeV}^2$) : take HERMES fit to structure function data from various experiments, extending to $Q^2 = 0$ (photoproduction).
  - Resonance region ($W^2 \lesssim 3.5\,\mathrm{GeV}^2$): consider two different fits to world data.

$\longrightarrow$ Places important constraints. $p \to \gamma X$

arXiv:1103.5704



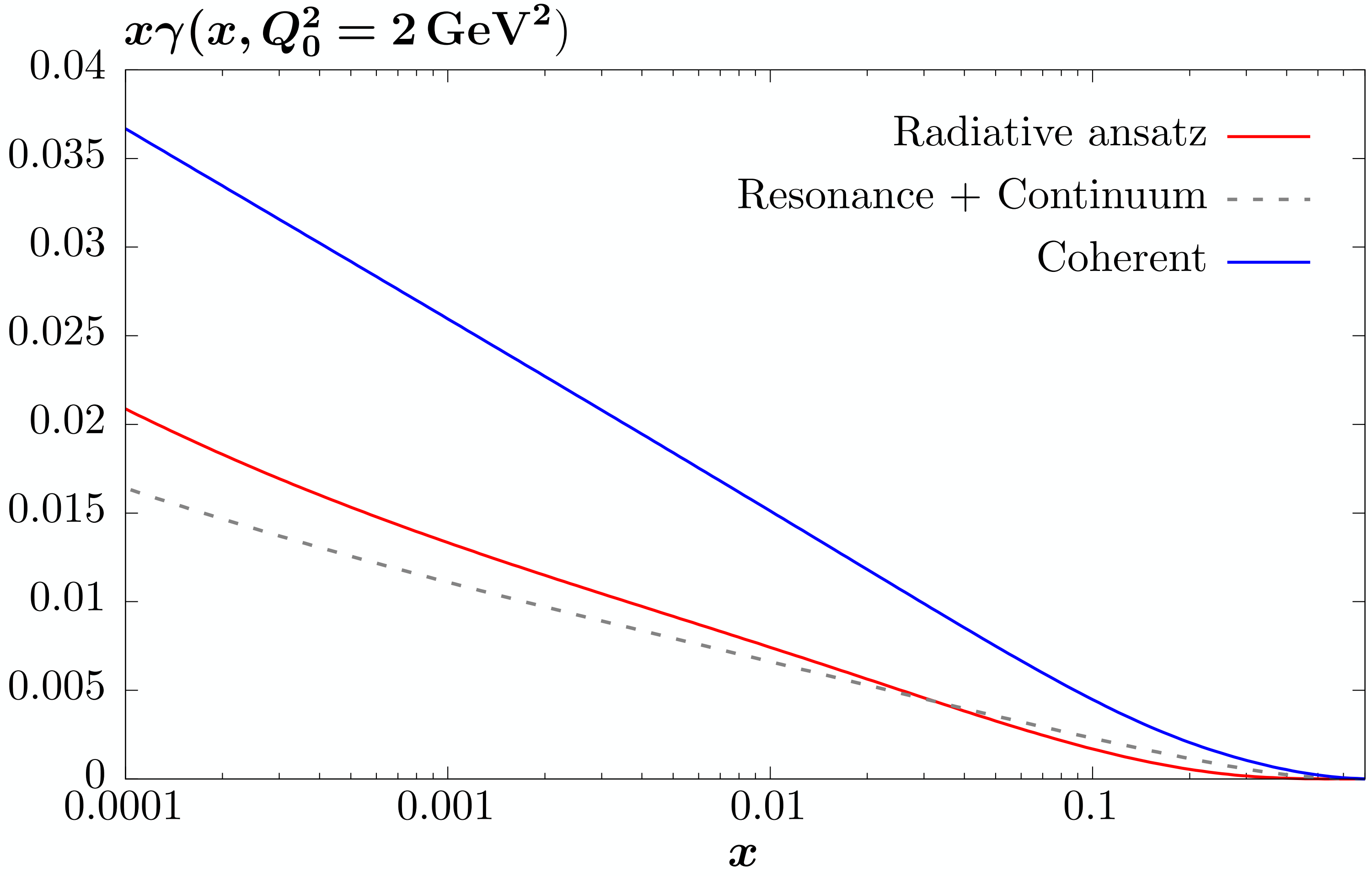
arXiv:0712.3731



LUXqed - incoherent component

- Outlook: unify approaches. Consider constraints from both LHC and low Q^2 structure function data. Full treatment of uncertainties and coupled DGLAP evolution.

- In particular: with ‘standard’ PDF approach, taking same data input for $\gamma^{\rm incoh.}(x,Q_0^2)$, we find sub-percent level agreement with LUXqed.



Conclusions

- The LHC is a photon-photon collider!
- The $\gamma\gamma$ initial state naturally leads to exclusive events, with intact outgoing protons.
- Theory well understood, and use as highly competitive and clean probe of EW sector and BSM physics already demonstrated at LHC. Much further data with tagged protons to come.
- Inclusive production- the $\gamma\gamma$ initial state thought in the past to be potentially very important at high system mass, with large uncertainties.
- Precise determination, including $p \to p\gamma$ emission shows this is not the case. Nonetheless for precision LHC physics, need to include.
- MMHT work to include photon PDF in global fit framework ongoing.

Backup

Solving the DGLAP equation

- Returning to photon DGLAP evolution equation:

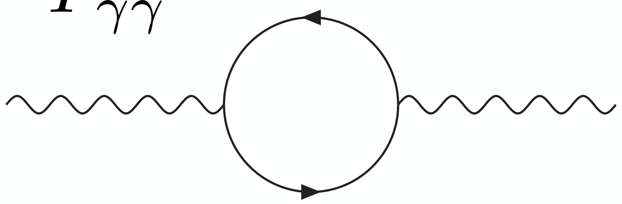
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\Bigg(P_{\gamma\gamma}(z)\gamma(\frac{x}{z},Q^2)$$
$$+ \sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2) + P_{\gamma g}(z) g(\frac{x}{z},Q^2)\Bigg) \,,$$

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 at scale μ 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.

- Sudakov factor $S_\gamma(Q_0^2,\mu^2)$ is prob. for no emission between Q_0^2 and μ^2 :

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

LUXqed - making connection (1)

- While the formalism may appear different, in fact connection to our results can be quite simply made. Divide Q^2 integral into $Q^2 < Q_0^2 \sim 1\,\mathrm{GeV}^2$ and $Q^2 > Q_0^2$ regions.
- $Q^2 > Q_0^2$: keep on leading $\ln \mu^2/Q_0^2$ term and $Q^2 \gg m_p^2$

$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \cancel{\frac{2x^2 m_p^2}{Q^2}} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \cancel{\alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right)} \right\}, \quad (6)$$

- Take LO in α_S for simplicity, then:

LL

$$x f_{\gamma/p}(x,\mu^2) \to x \int_x^1 \frac{\mathrm{d}z}{z} \int_{Q_0^2}^{\mu^2} \frac{\mathrm{d}Q^2}{Q^2} \frac{\alpha(Q^2)}{2\pi} \frac{\alpha(Q^2)}{\alpha(\mu^2)} p_{\gamma q}(z) \sum e_q^2\, q\left(\frac{x}{z}, Q^2\right) ,$$

Cutoff

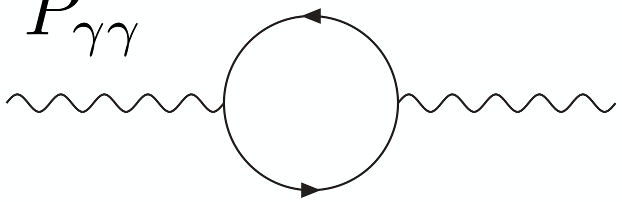
LUXqed - making connection (2)

$$xf_{\gamma/p}(x,\mu^2) = x\int_x^1 \frac{\mathrm{d}z}{z}\int_{Q_0^2}^{\mu^2}\frac{\mathrm{d}Q^2}{Q^2}\frac{\alpha(Q^2)}{2\pi}\frac{\alpha(Q^2)}{\alpha(\mu^2)}\,P_{\gamma q}(z)\sum e_q^2\, q\left(\frac{x}{z},Q^2\right)\ ,$$

- What about $\alpha(Q^2)/\alpha(\mu^2)$ term? Recall Sudakov factor:

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

$P_{\gamma\gamma}$



comes from resumming self-energy contribution to DGLAP.

- Connection to running of α. Find: $S_\gamma(Q^2,\mu^2) = \dfrac{\alpha(Q^2)}{\alpha(\mu^2)} + O(\alpha)$

$\longrightarrow$ Recover precisely the LO $Q^2 > Q_0^2$ term in DGLAP evolution:

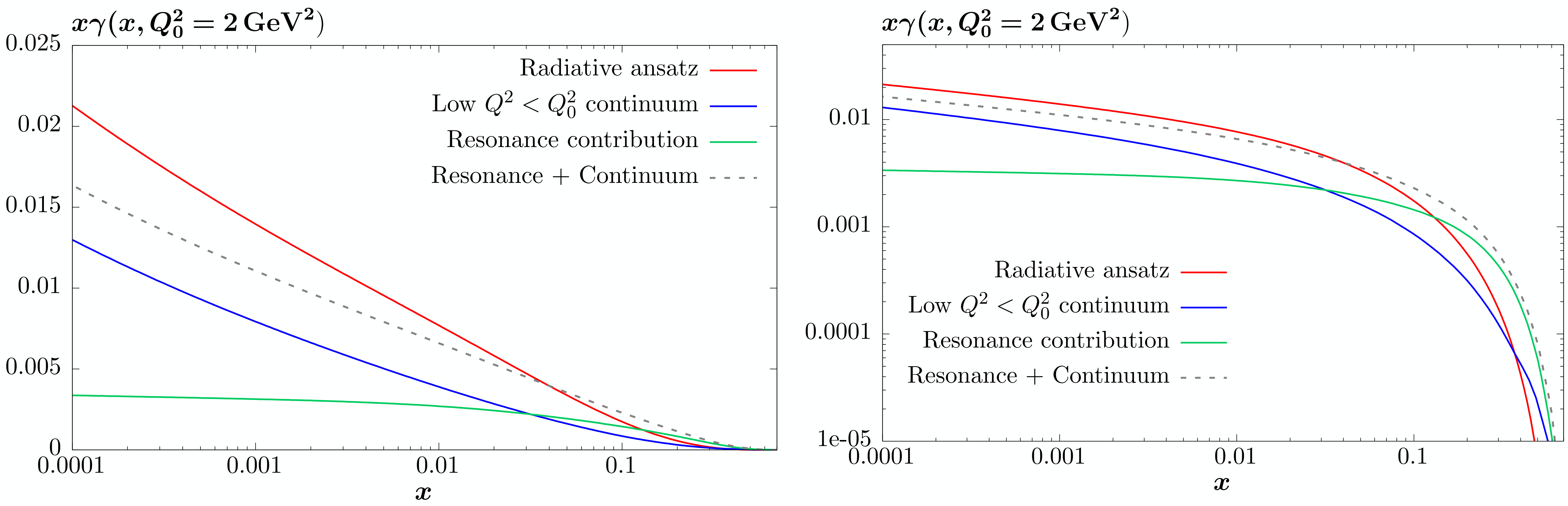
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\,S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2}\frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1\frac{dz}{z}\Big(\sum_q \underline{e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2)} + P_{\gamma g}(z) g(\frac{x}{z},Q^2)\Big)\,\underline{S_\gamma(Q^2,\mu^2)}\ ,$$

Caveat: omits influence of γ on quarks/gluons.

LUXqed - comparison (1)

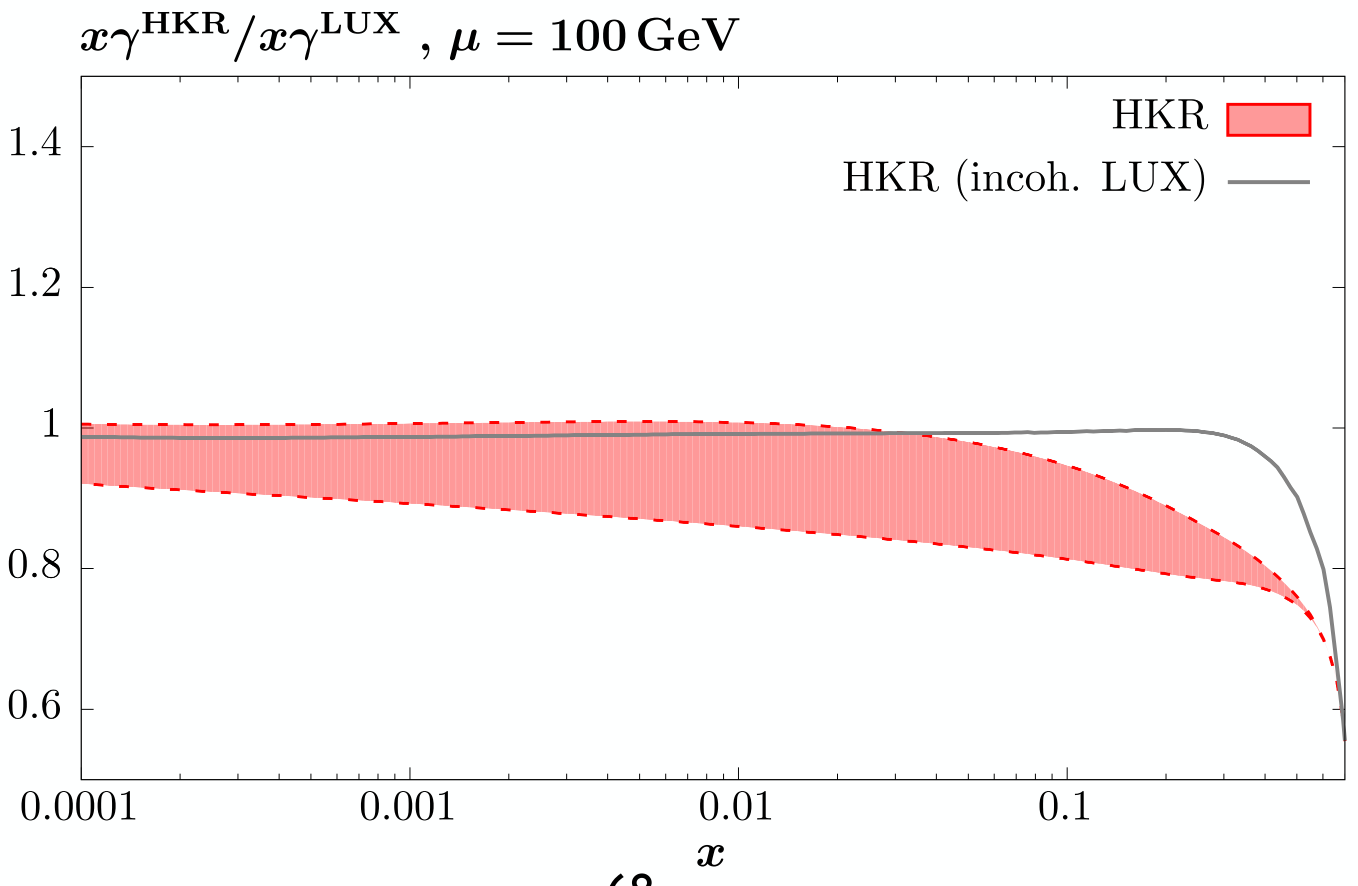
- Compare photon at Q_0 in our approach (‘radiative ansatz’) and using low Q^2 structure function data:
  - Continuum contribution less than the $\sim$ upper bound set by our model, and similar in shape.
  - But resonance contribution flatter ($W^2 \sim Q^2/x$) and exceeds our result at higher x .

‘Christy-Bosted’ fit



LUXqed - comparison (2)

- Consider ratio of PDFs at $\mu = 100\,\mathrm{GeV}$. Lower end of HKR band given by setting $\gamma_{\rm incoh} = 0$ (for illustration).
- Complete consistency found at lower x, but deviation as $x \uparrow$ (resonance contribution).
- Check: result of our approach + incoherent calculated using structure function data within $O(\%)$ of LUXqed over all relevant x.



LUXqed - comparison (3)

- Have demonstrated that standard PDF approach very close to LUXqed when taking same data input for $\gamma(x, Q_0^2)$.

$\longrightarrow$ Possible to unify approaches. Consider constraints from both LHC and low Q^2 structure function data. Full treatment of uncertainties and coupled DGLAP evolution.