Photon-photon collisions at the LHC

Lucian Harland-Lang, University College London

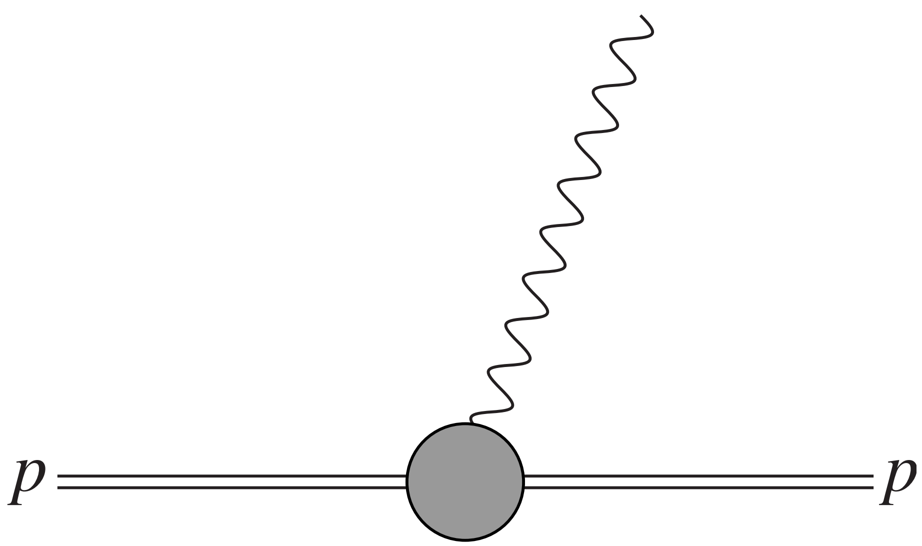
UK HEP forum, Cosener’s House, 3 Nov 2016

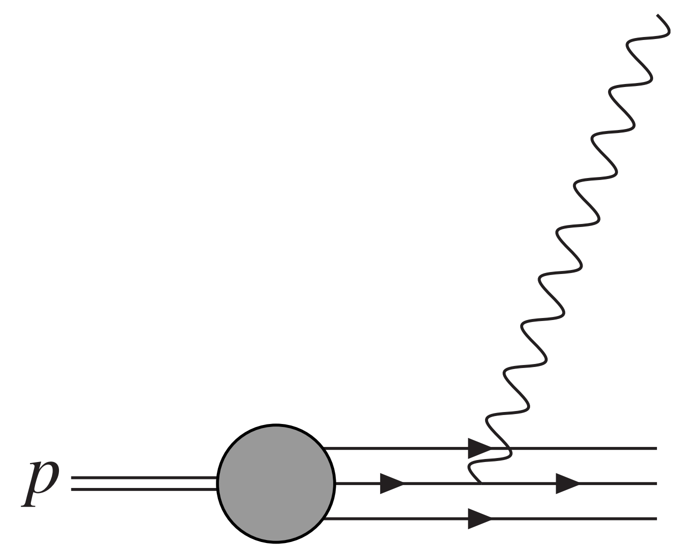
Outline

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

The proton and the photon

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





$\longrightarrow$ 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 is it interesting?

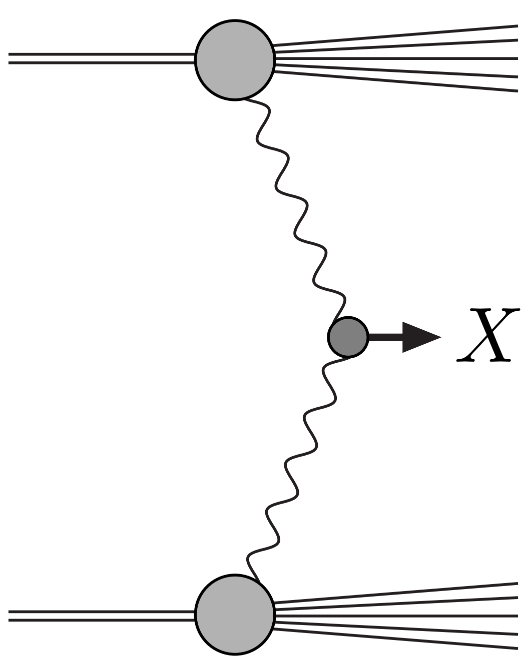
- In era of high precision phenomenology at the LHC: NNLO calculations rapidly becoming the 'standard'. However:

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

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

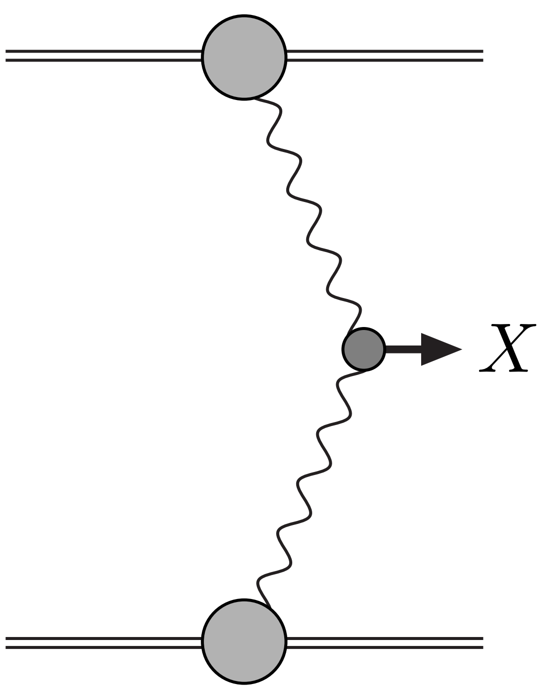
- Thus at this level of accuracy, must consider a proper account of EW corrections. At LHC these can be relevant for a range of processes (W, Z, WH, ZH, WW, $t\bar{t}$, jets...).

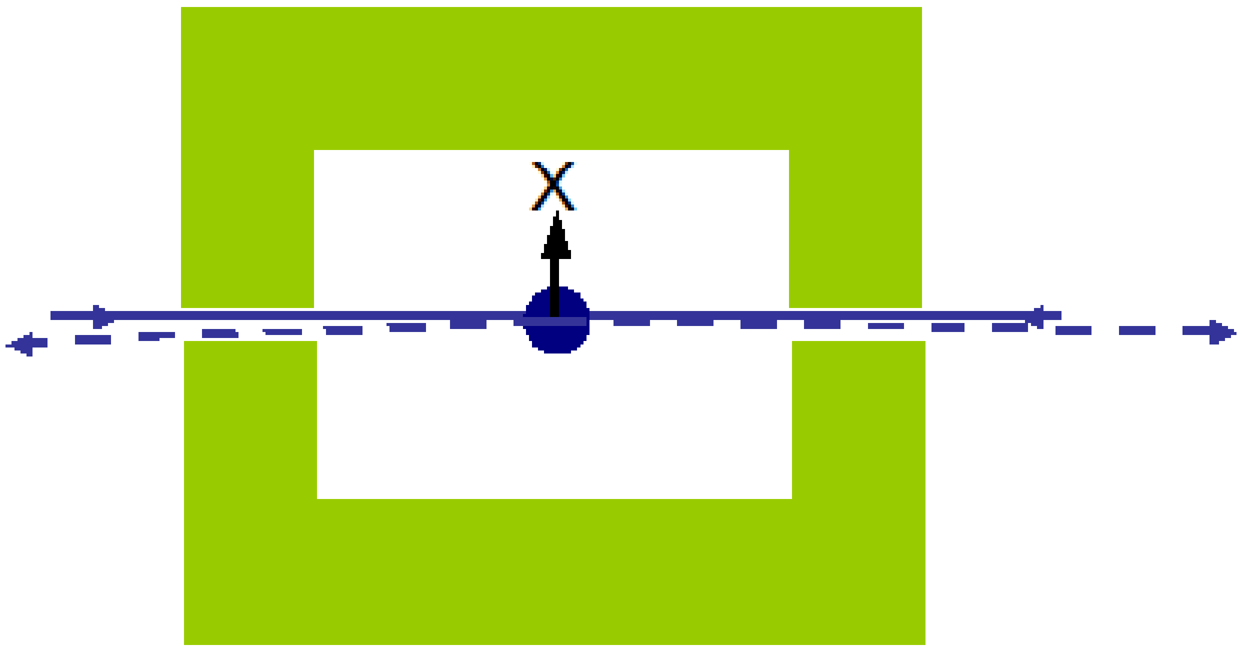
  - For consistent treatment of these, must incorporate QED in initial state: photon-initiated production.



Why is interesting?

- 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.





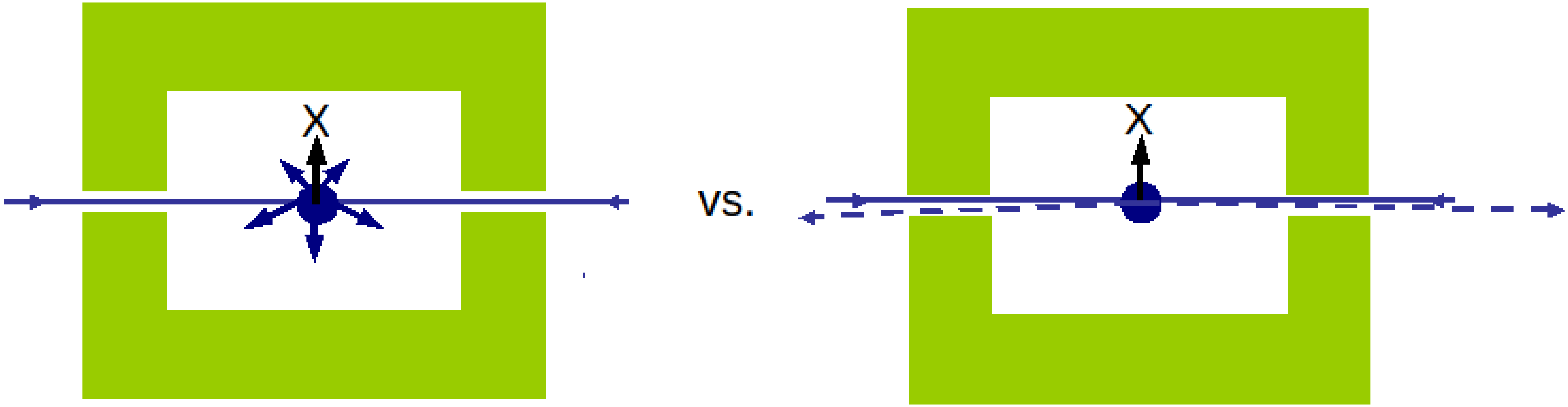
Exclusive production

Central Exclusive Production

Central Exclusive Production (CEP) is the interaction:

$$pp \to p + X + p$$

- 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.

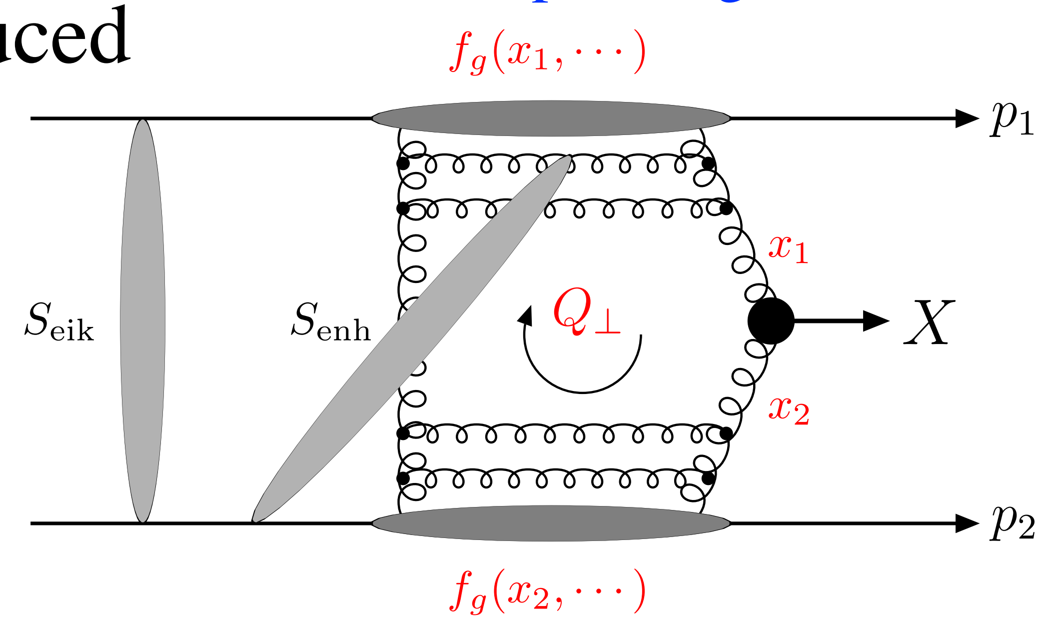


Production mechanisms

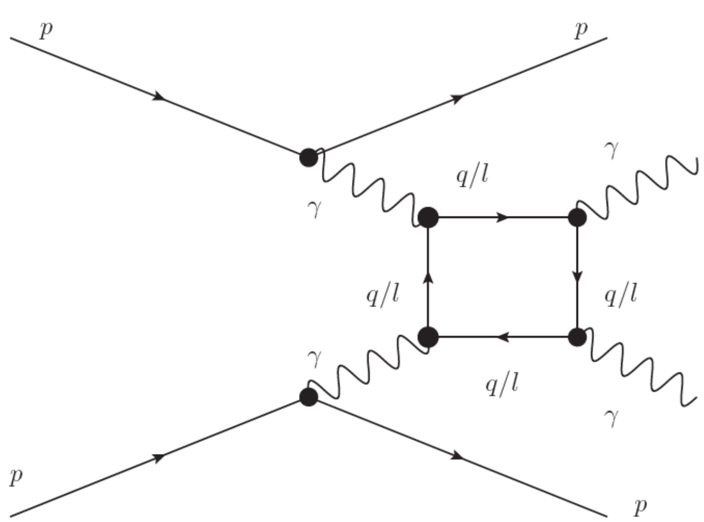
Exclusive final state can be produced via three different mechanisms, depending on kinematics and quantum numbers of state:

Gluon-induced

C-even, couples to gluons

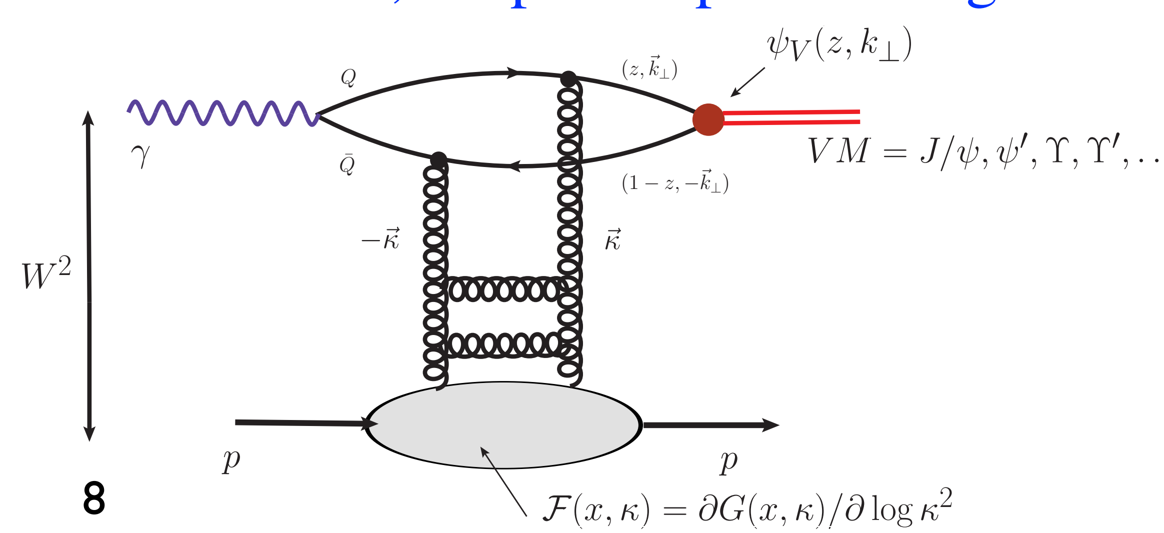


Couples to photons



Photon-induced

C-odd, couples to photons + gluons



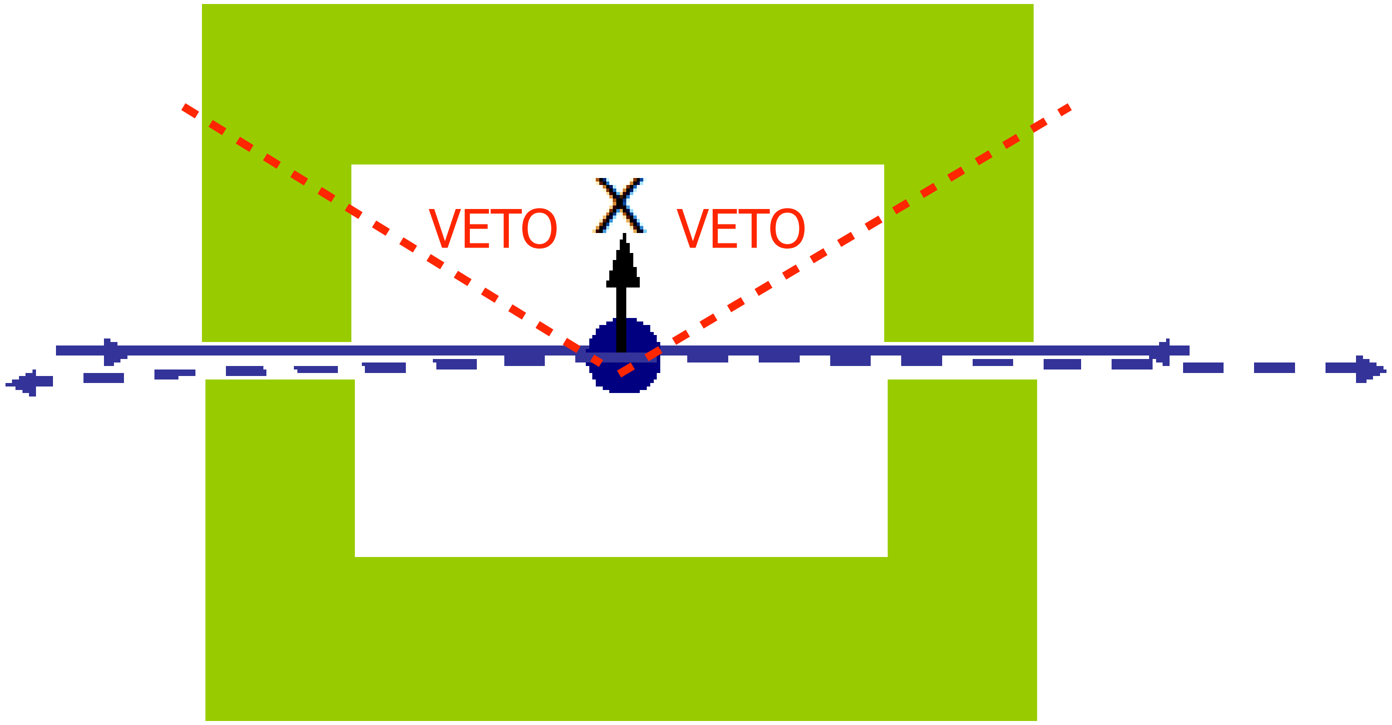
Photoproduction

Selecting exclusive events

1) Gap-based selection: no extra activity in large enough rapidity region.

- No guarantee of pure exclusivity - BG with proton breakup outside veto region. Large enough gap $\Rightarrow$ BG small and can be subtracted.

- Pile-up contaminating gap? Either: low pile-up running (dedicated runs/ LHCb defocussed beams) or can veto on additional charged tracks only (already used to select charged - l^+l^-, W^+W^--by ATLAS/CMS/LHCb).



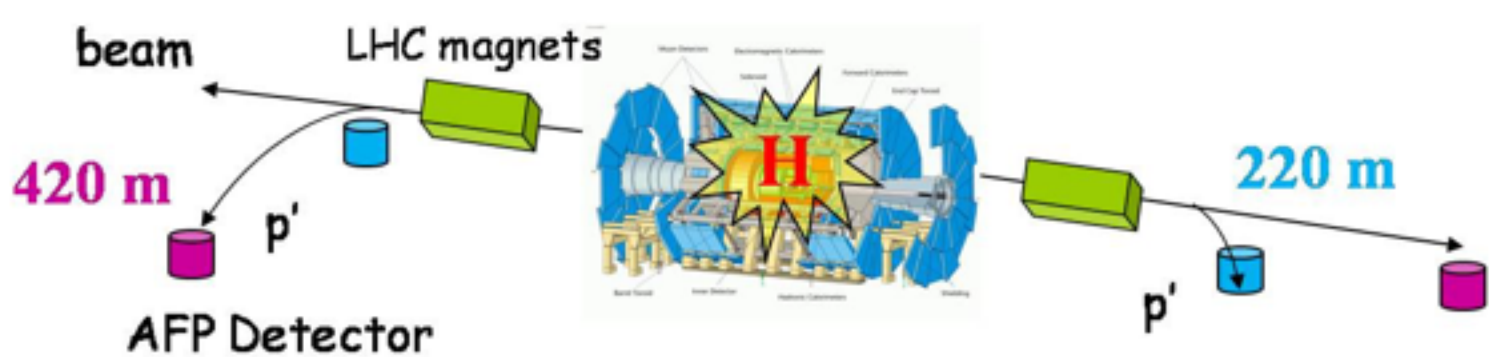
Selecting exclusive events

2) Proton tagging: $pp \to p + X + p$

- Defining feature of exclusive events: protons intact after collision,

  $\longrightarrow$ If we can measure the outgoing protons, possible to select purely exclusive event sample.

- Basic principle: use LHC beam magnet as a spectrometer. After interaction protons have $E < \sqrt{s}/2$ and will gradually bend out of beam line.
- Insert 'roman pot' detectors at $O(\text{mm})$ from beam line and $O(100\,\text{m})$ from IP. Reconstruct momenta and measure arrival time of protons.

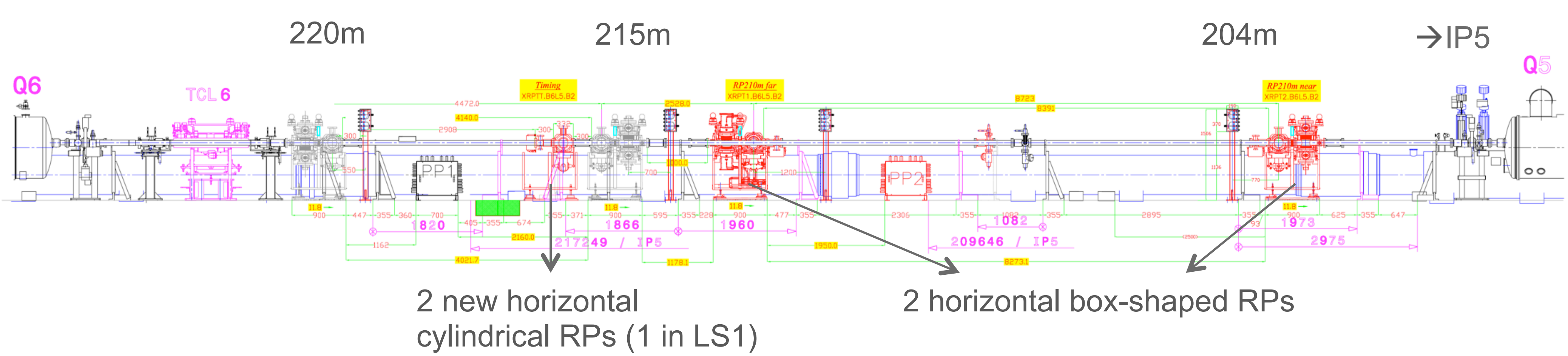


Proton tagging at the LHC

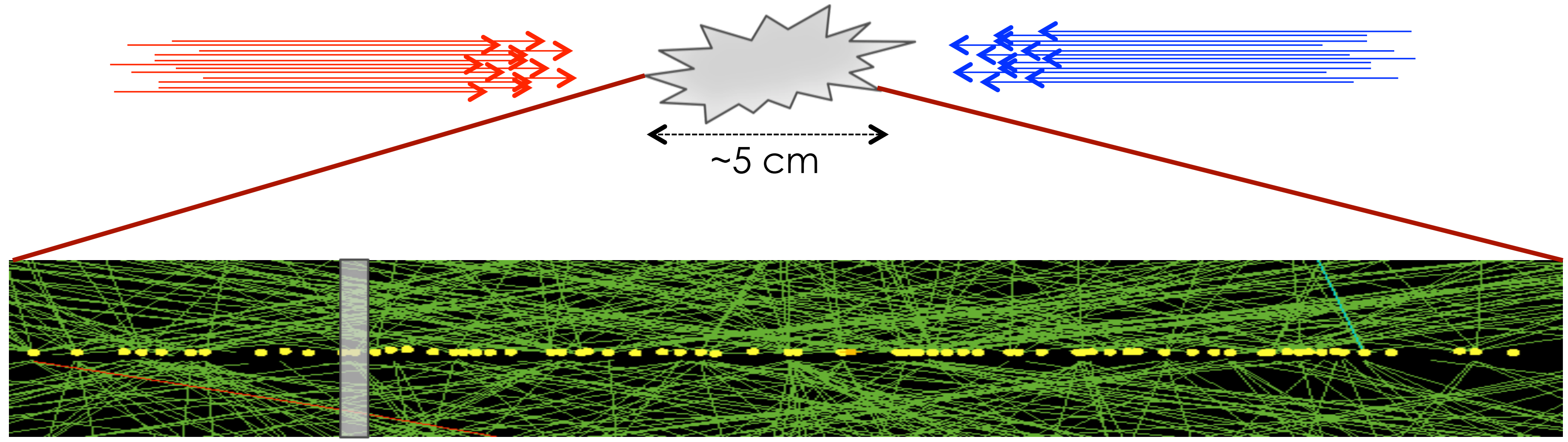
- These detectors are installed:
  - CMS-TOTEM Precision Proton Spectrometer - CT-PPS.
  - ATLAS Forward Proton - AFP.

- In both cases ‘roman pot’ detectors installed at $\sim 200\,\mathrm{m}$ from IPs. Measure position ($\sim$ proton momentum loss) and arrival time ($\longrightarrow$ pile-up rejection) of protons.

- In early stages of data taking. In 2017 will both be fully ready to take data during normal LHC running.



Timing and pile-up rejection



N. Cartaglia, INFN, April 2015

- Pile-up! At LHC expect ~ 50 interactions per bunch crossing:
  - If we measure two intact protons, which of these central interactions is the right one??
  - Probability for two protons from independent single-diffractive interactions ($pp \to p + X$) is high. What about this BG?
- Solution: fast timing detectors measure arrival time of protons $\to$ convert to expected z position of central vertex. For $\sim 10\,\mathrm{ps}$ precision can control pile-up BG. Achieved in current detectors with further improvements foreseen.

Mass acceptance

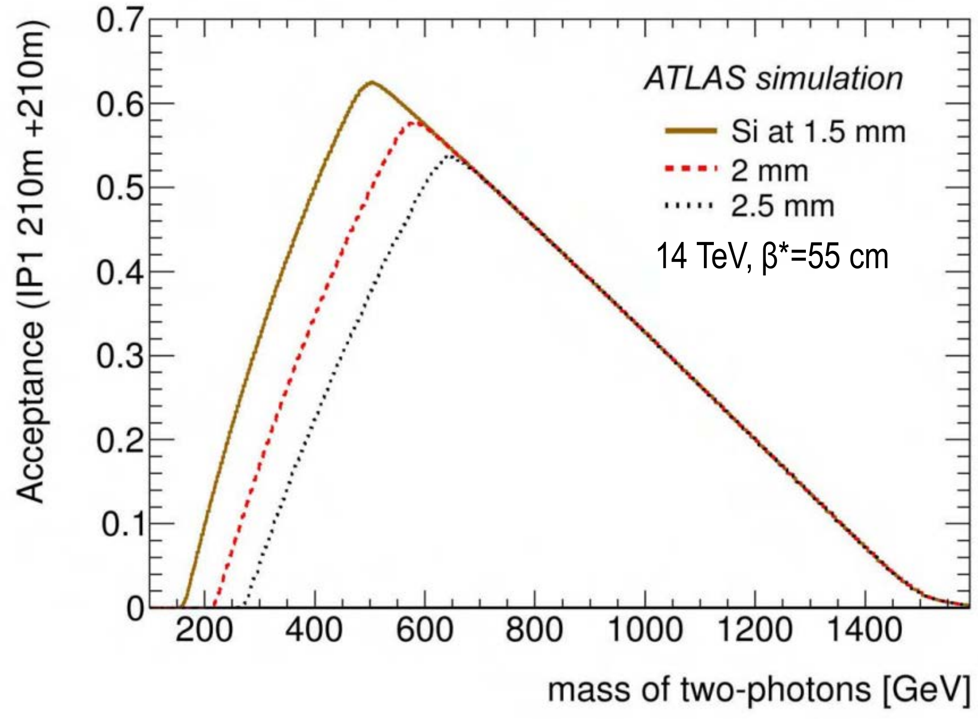
- Momentum loss ξ of protons related to mass of central system:

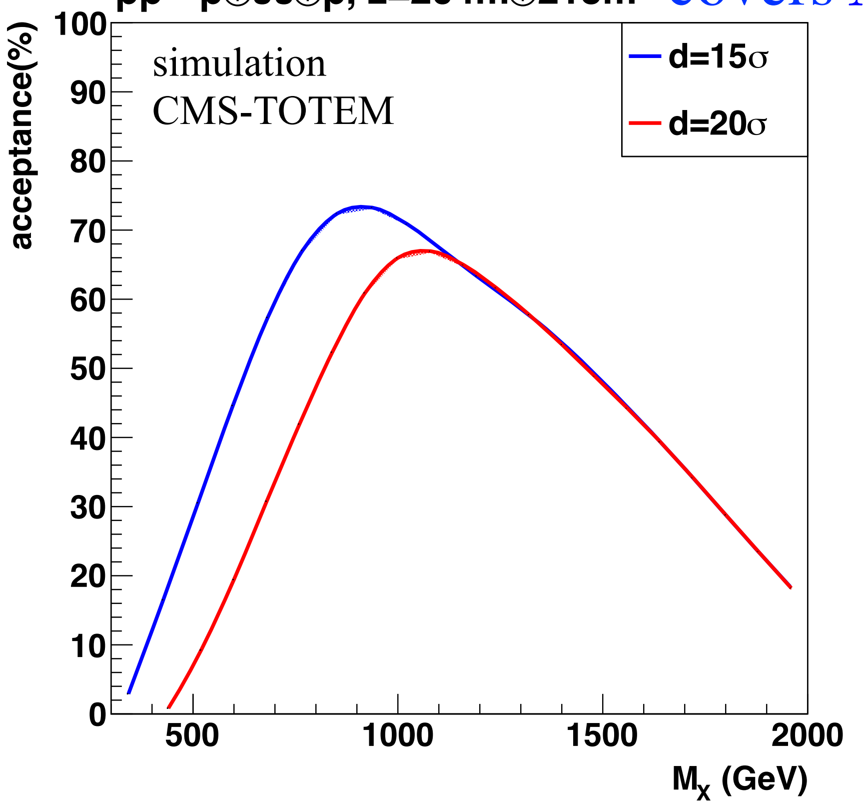
$$M_X^2 = \xi_1 \xi_2 s$$

- The ξ acceptance is directly related to distance d of the RPs from the IP: for $d\uparrow$ have $\xi\downarrow$.

$\longrightarrow$ Decreasing d leads to acceptance at larger M_X . Turns out that for $d \sim 200\,\mathrm{m}$ this gives $M_X \gtrsim 500\,\mathrm{GeV}$.

Detectors at $d \sim 400\,\mathrm{m}$ under discussion $\Rightarrow$ covers $M_X \sim M_h$.



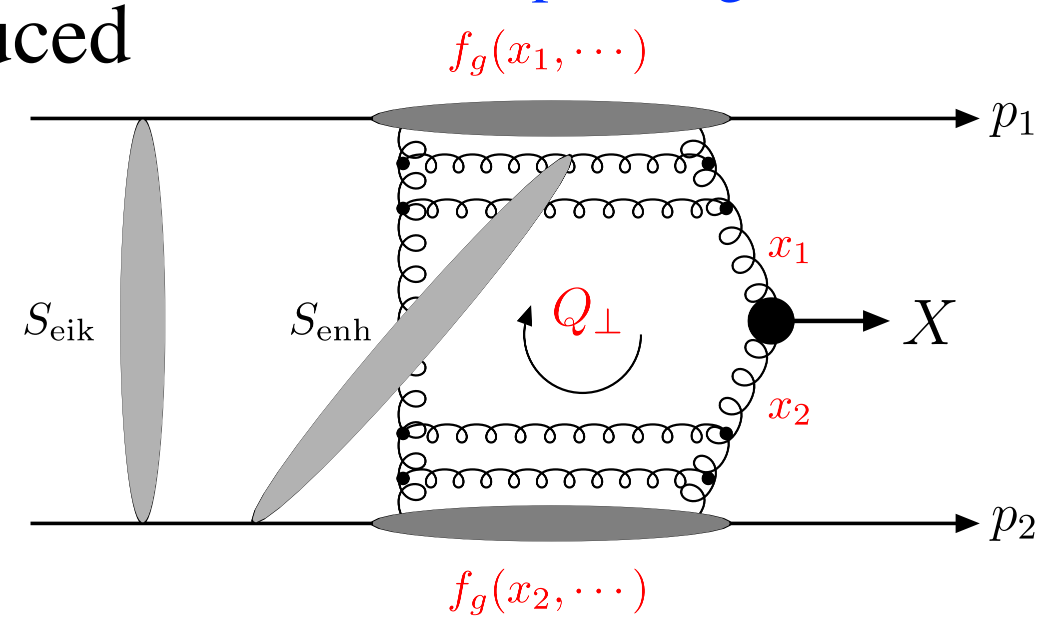


Production mechanisms

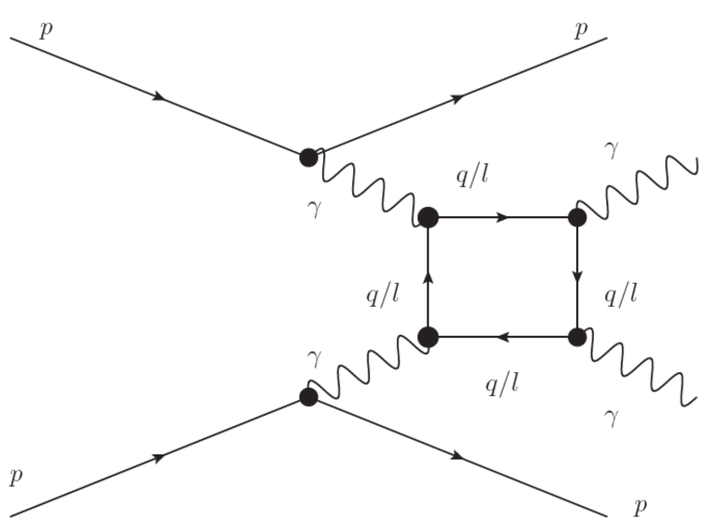
Recall three production mechanisms:

Gluon-induced

C-even, couples to gluons

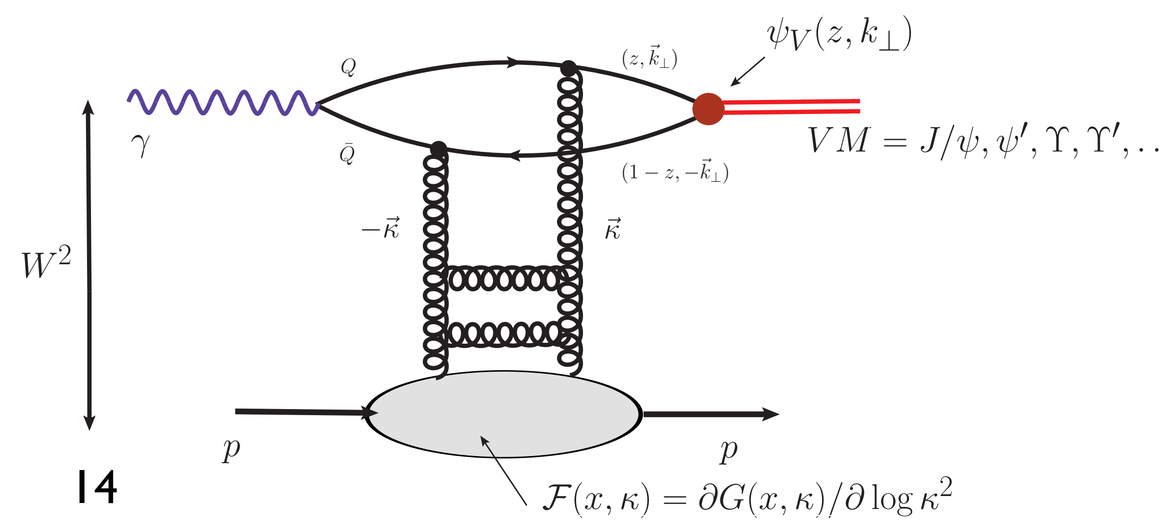


Couples to photons

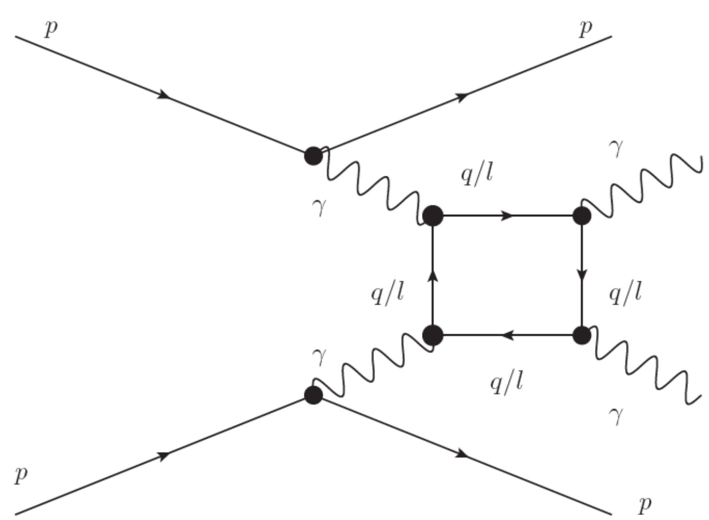


Photon-induced

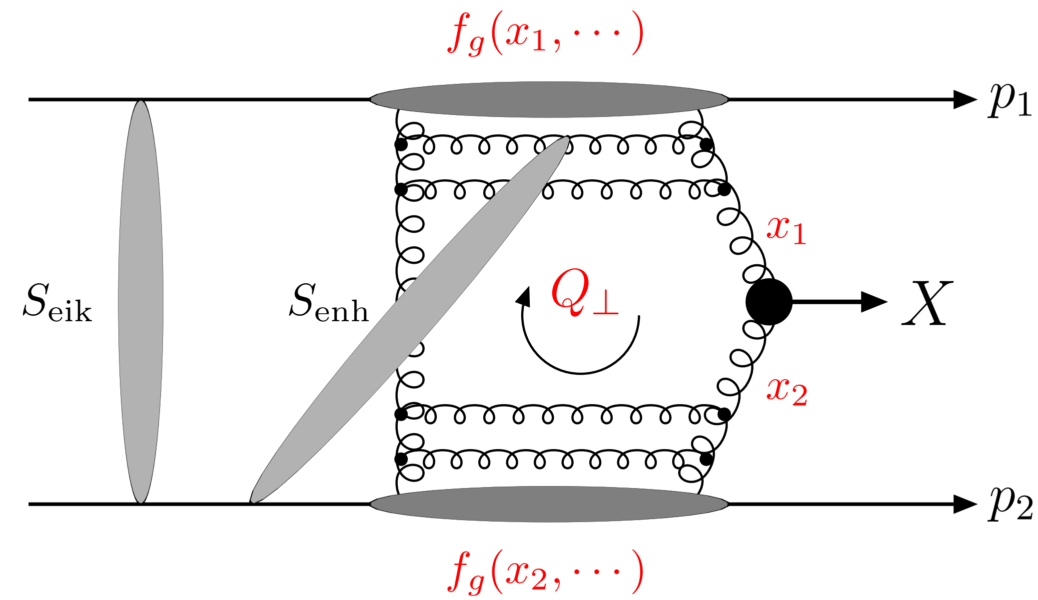
C-odd, couples to photons + gluons



Photoproduction



vs.



- Naively expect strong interaction to dominate- $\alpha_S \gg \alpha$.
- However QCD enhancement can also be a weakness: exclusive event requires no extra gluon radiation into final state. Requires introduction of Sudakov suppressing factor:

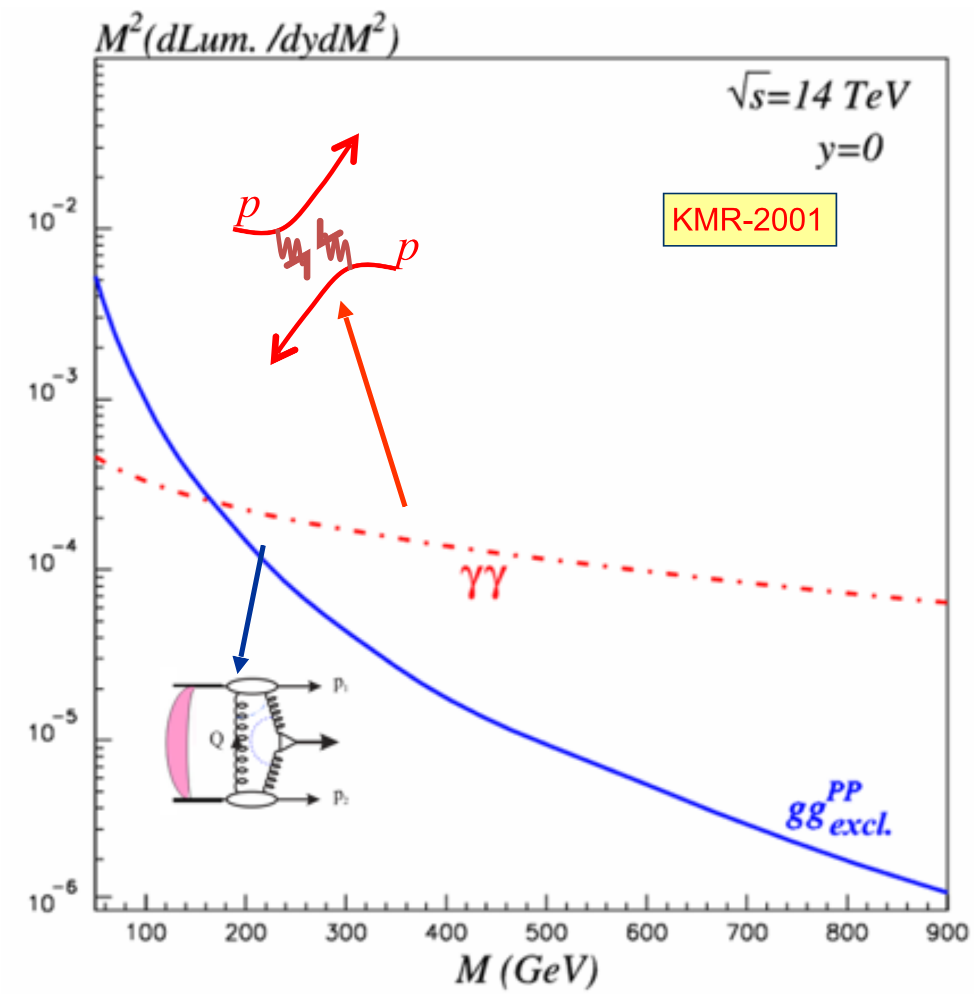
$$T_g(Q_\perp^2, \mu^2) = \exp\left(-\int_{Q_\perp^2}^{\mu^2} \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2} \frac{\alpha_s(k_\perp^2)}{2\pi} \int_0^{1-\Delta} \left[zP_{gg}(z) + \sum_q P_{qg}(z) \right] dz \right)$$

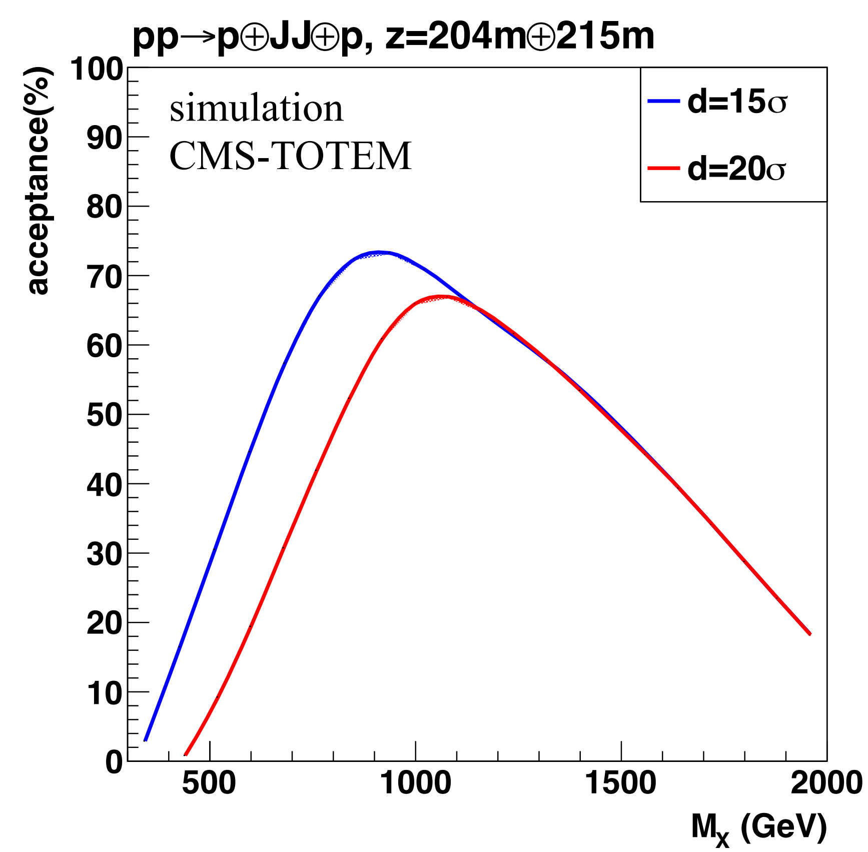
- Increasing $M_X \Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

gg vs. $\gamma\gamma$

• Situation summarised in 'effective' exclusive gg and $\gamma\gamma$. luminosities. This Sudakov suppression in QCD cross section leads to enhancement in $\gamma\gamma$ already* for $M_X \gtrsim 200\,\text{GeV}$ - well before CT-PPS/AFP mass acceptance region.

$\longrightarrow$ Can study $\gamma\gamma$ collisions at the LHC with unprecedented $s_{\gamma\gamma}$.

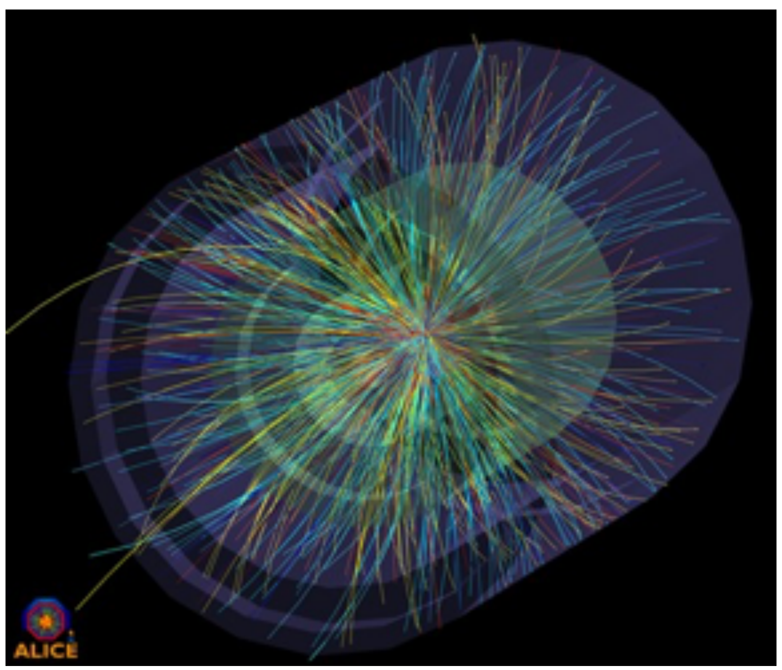


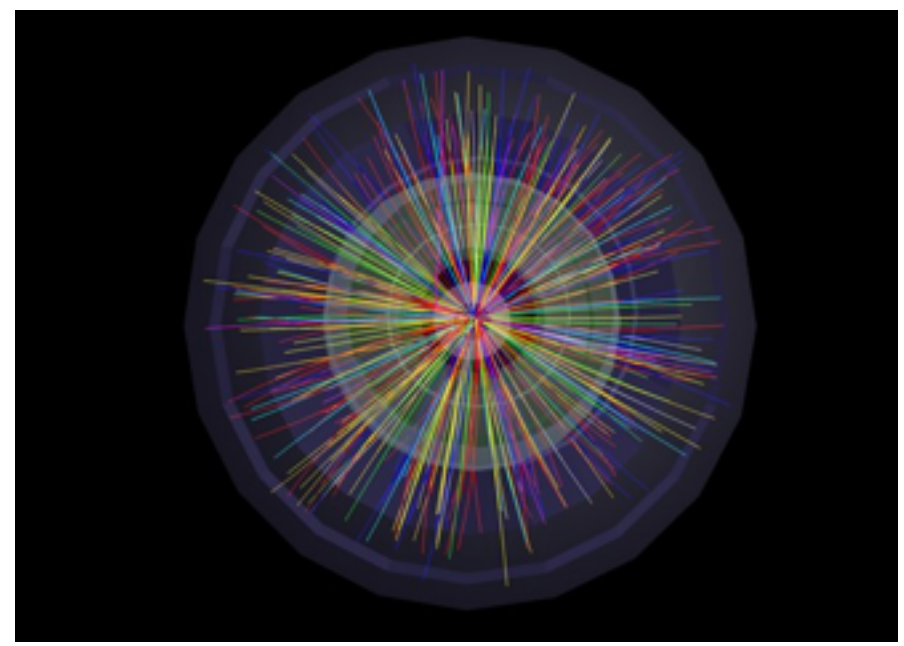


*Caveat - this is enhancement in initial state only. Of course depends on coupling to produced state.

Heavy ions

- LHC is not just a proton-proton collider- in addition have heavy ions (AA, Ap) collisions.
- On the face of it strange thing to consider for exclusive production…

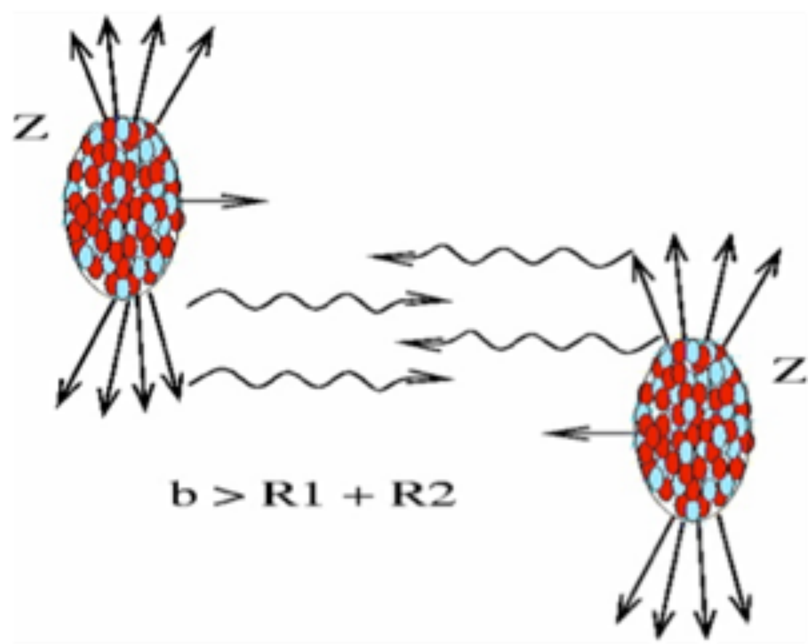




- However for heavy ion physics it is quite natural…

Heavy ions - ultra-peripheral collisions

• Ions do not necessarily collide 'head-on' - for 'ultra-peripheral' collisions, with $b > R_1 + R_2$ the ions can interact purely via EM and remain intact $\Rightarrow$ exclusive $\gamma\gamma$-initiated production.

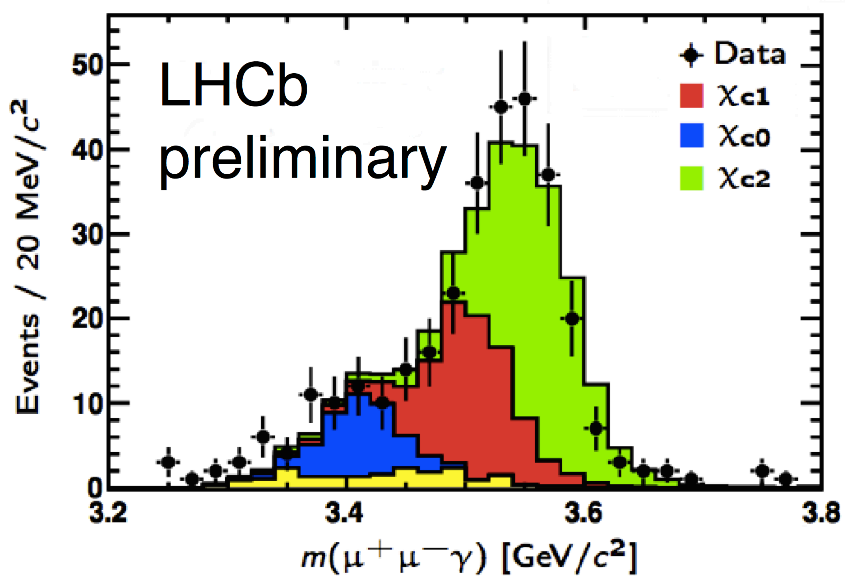


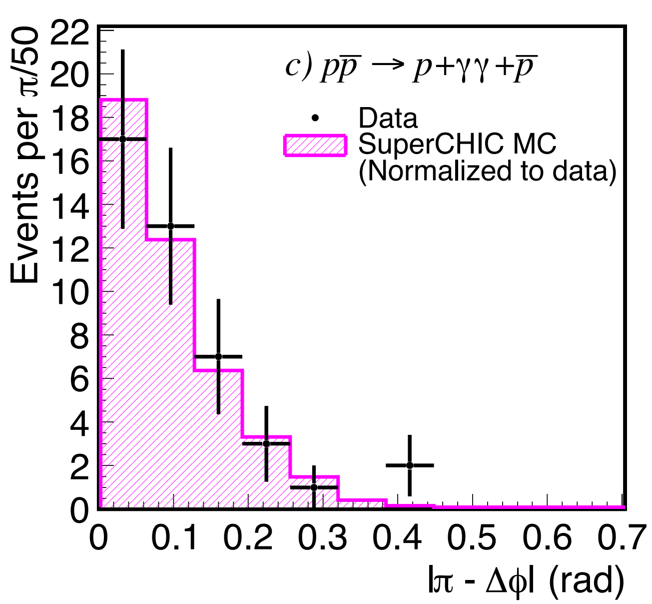
• Ions interact via coherent photon exchange- feels whole charge of ion $\Rightarrow$ cross section $\propto Z^4$. For e.g. Pb-Pb have $Z^4 \sim 5 \times 10^7$ enhancement!

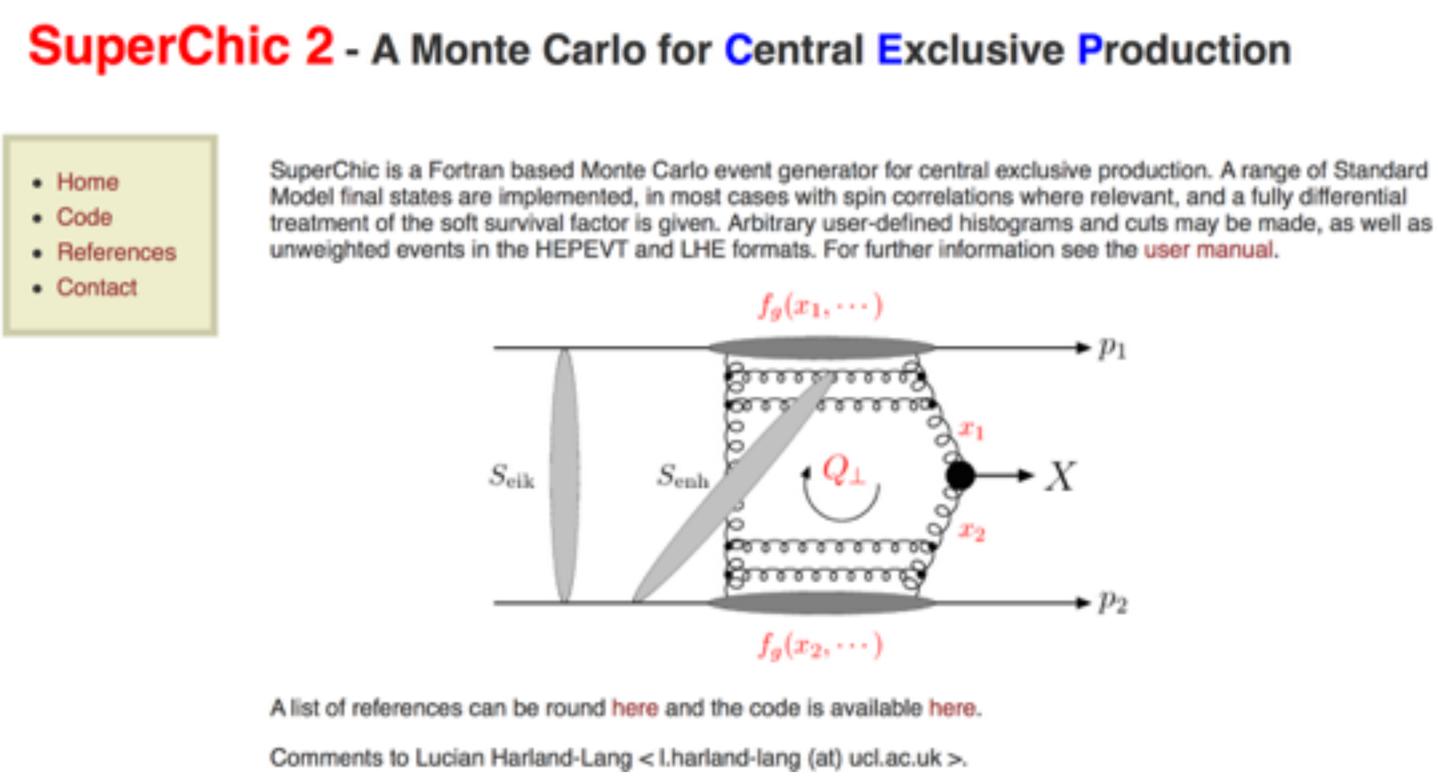
• Photon flux in ion tends to be cutoff at high M_X, but potentially very sensitive to lower mass objects with EW quantum numbers.

SuperChic

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







$\gamma\gamma$ collisions - theory

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
USSR Academy of Science, Siberian Division, Institute for Mathematics, Novosibirsk, USSR

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?

E. Fermi (1925), Weizsacker and Williams (1935)

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:

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

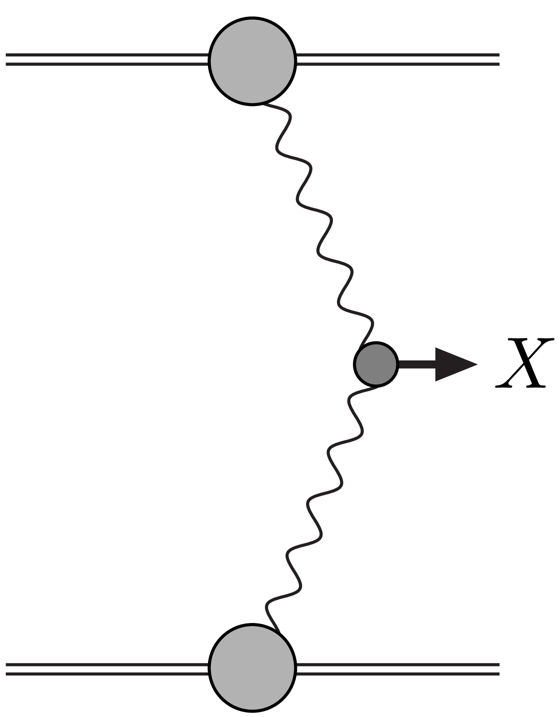
- Cross section then given in terms of $\gamma\gamma$ `luminosity':

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

with

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

Not exact equality: see later



Proton form factors

- The photon flux:

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

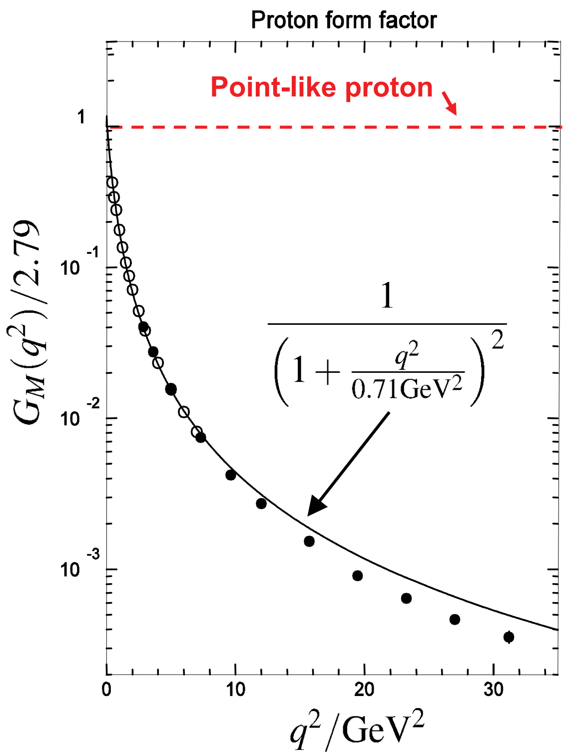
is given in terms of the proton electric/magnetic form factors F_E/F_M:

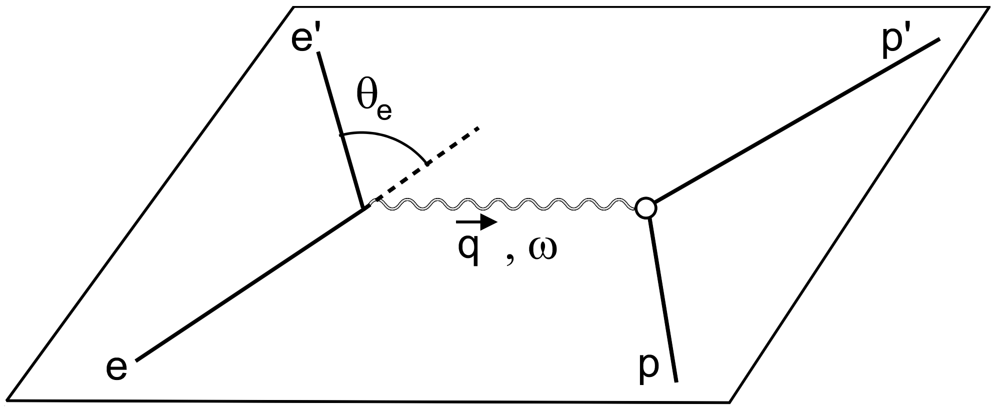
- Related to charge/magnetic moment distribution of protons.
- *Very* precisely measured from elastic *ep* scattering.

- To first approx. given in term so 'dipole' form factors:

Elastic $\Rightarrow$ steeply falling

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

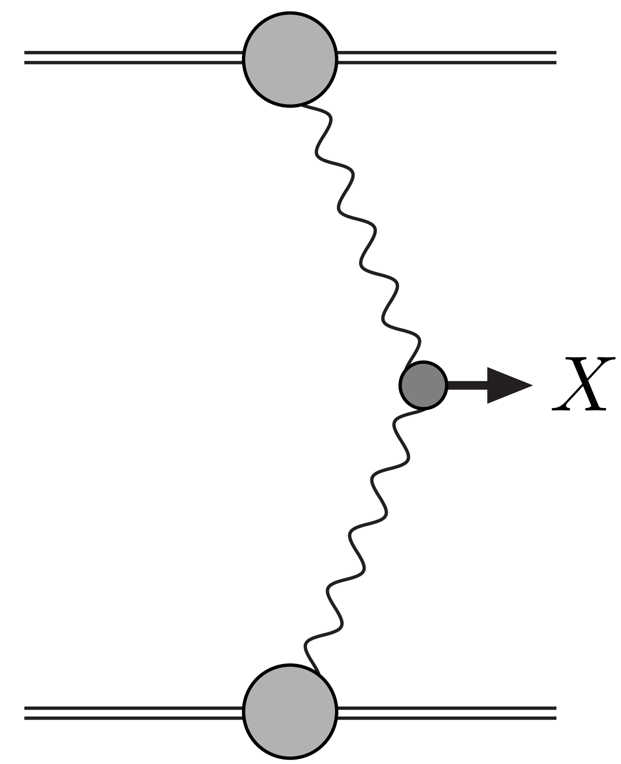




Soft survival factor

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

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



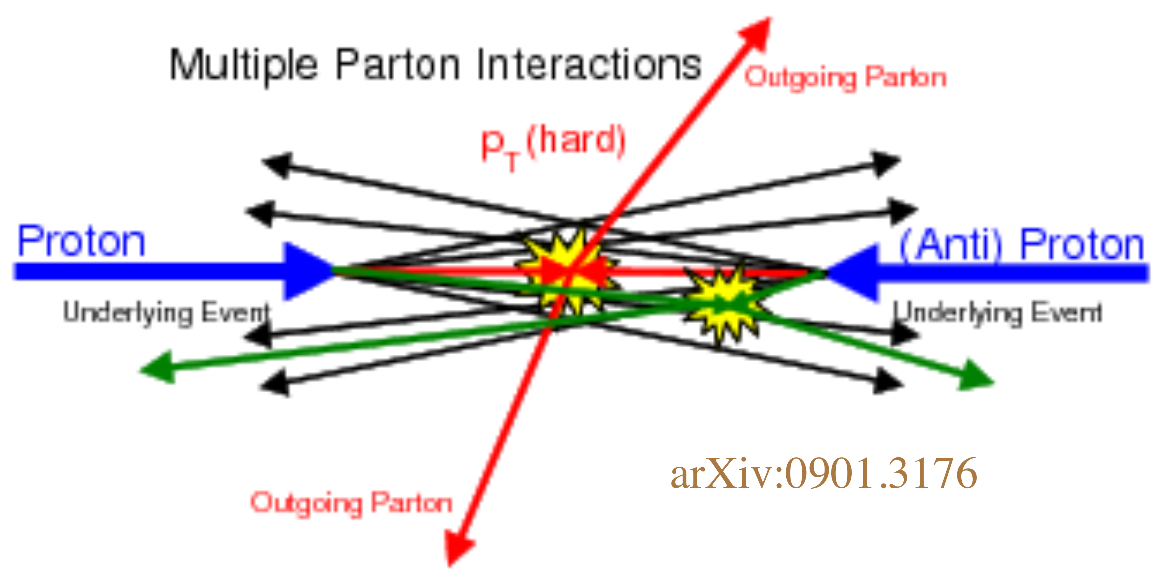
- Why is this not an exact equality? Because we are asking for final state with intact protons, object X and *nothing* else- colliding protons may interact independently: 'Survival factor'.

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'.



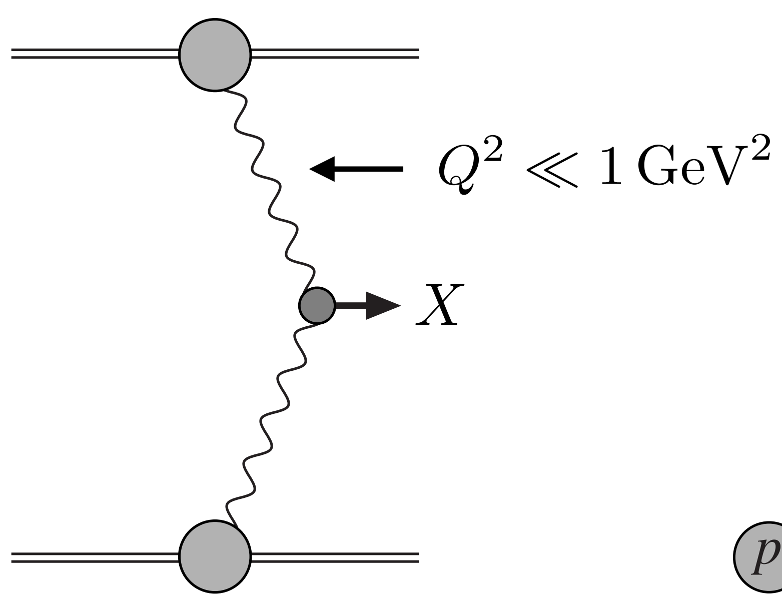
arXiv:0901.3176

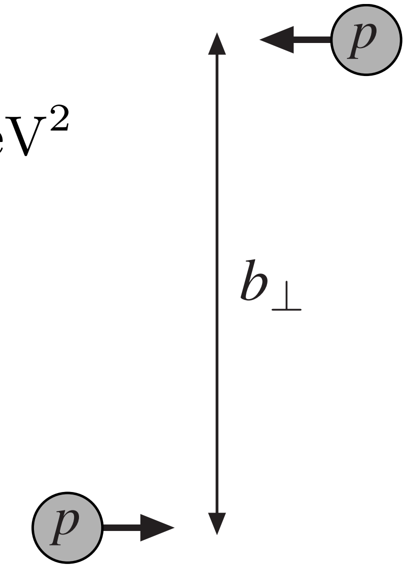
Soft survival factor

- 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, $S^2_{\rm soft} \sim 1$

$\gamma\gamma$ collisions - applications

Simple test: lepton pairs

- ATLAS (arXiv:1506.07098) have measured exclusive e and μ pair production $\Rightarrow$ 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

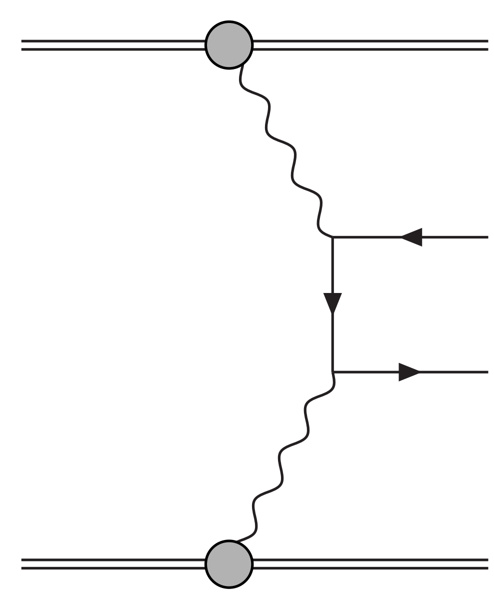
Measurement of exclusive $\gamma\gamma \to \ell^+\ell^-$ production in proton–proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This Letter reports a measurement of the exclusive $\gamma\gamma \to \ell^+\ell^-$ ($\ell = e, \mu$) 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

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

- Using results from above:

	$\mu^+\mu^-$	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	$0.628 \pm 0.032 \pm 0.021$	$0.428 \pm 0.035 \pm 0.018$

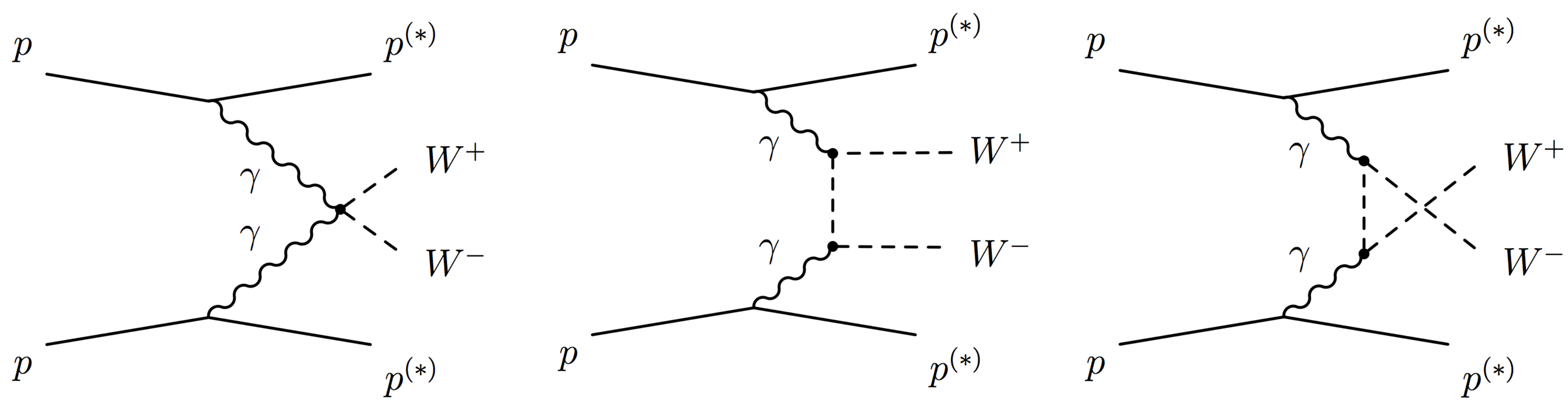
$\rightarrow$ Excellent agreement for e^+e^- and reasonable for $\mu^+\mu^-$. Role of coherent photon emission seen experimentally at the LHC and small and under control impact of (non-pert) QCD effects confirmed experimentally.

- 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.

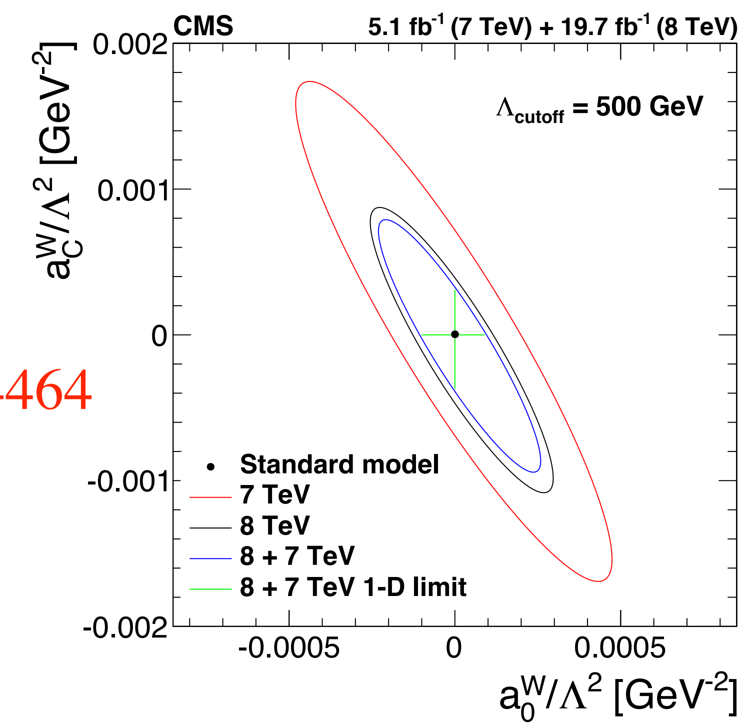
$\to$ Directly sensitive to any deviations from the SM gauge couplings. Predicted in various BSM scenarios. Composite Higgs, warped extra dimensions….



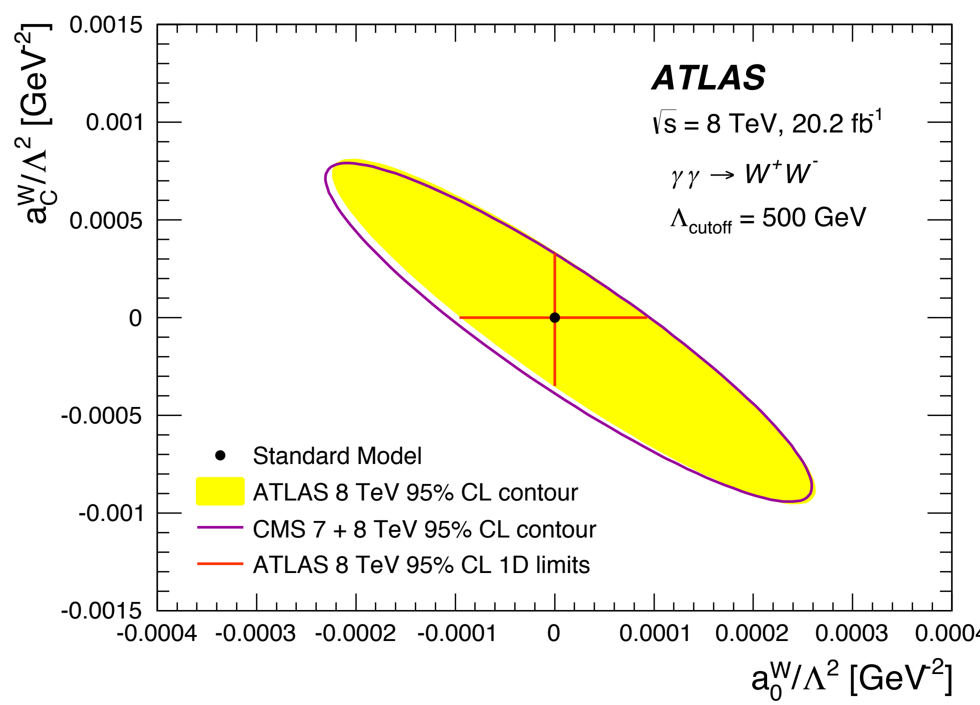
- Limits have been set at LEP, and in inclusive final-states at the Tevatron and LHC. How does the exclusive case compare?

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 ~ order of mag. tighter than equivalent inclusive LHC.
- Direct consequence of exclusive selection $\Rightarrow$ precisely understood $\gamma\gamma$ collisions, but at a hadron collider.

about same time...

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
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LHC PHYSICS

CMS sees first direct evidence for $\gamma\gamma \rightarrow WW$

In a small fraction of proton collisions at the LHC, the two colliding protons interact only electromagnetically, radiating high-energy photons that subsequently interact or "fuse" to produce a pair of heavy charged particles. Fully exclusive production of such pairs takes place when quasi-real photons are emitted coherently by the protons rather than by their quarks, which survive the interaction. The ability to select such events opens up the exciting possibility of transforming the LHC into a high-energy photon–photon collider and of performing complementary or unique studies of the Standard Model and its possible extensions.

The CMS collaboration has made use of this opportunity by employing a novel method to select "exclusive" events based only on tracking information. The selection is made by requesting that two – and only two – tracks originate from a candidate vertex for the exclusive two-photon production. The power of this method, which was first developed for the pioneering measurement of exclusive production of muon and electron pairs, lies in its effectiveness even in difficult high-luminosity conditions with large event pile-up at the LHC.

The collaboration has recently used this approach to analyse the full data sample collected at $\sqrt{s}$=7 TeV and to obtain the first direct evidence of the $\gamma\gamma \rightarrow WW$ process. Fully leptonic W-boson decays have been measured in final states characterized by opposite-sign and opposite-flavour lepton pairs where one W decays into an electron and a neutrino, the other into a muon and a

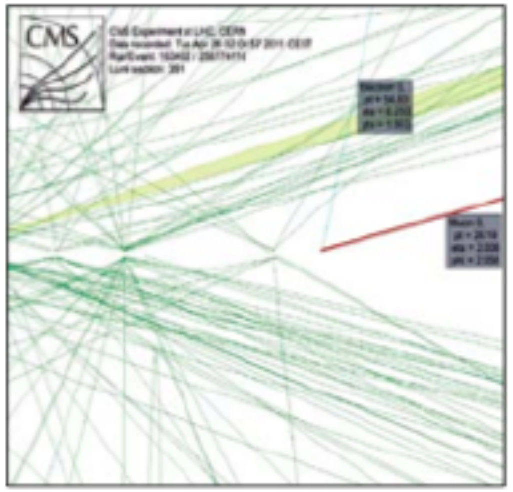


Fig. 1. Above: Proton–proton collisions recorded by CMS at $\sqrt{s}$=7 TeV, featuring candidates for the exclusive two-photon production of a W^+W^- pair, where one W boson has decayed into an electron and a neutrino, the other into a muon and a neutrino.

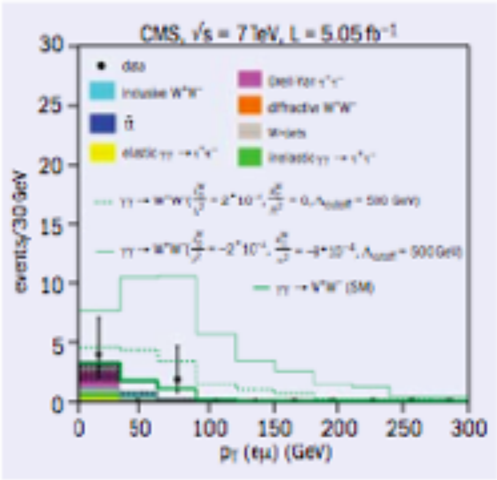


Fig. 2. Top right: The p_T distribution of $e\mu$ pairs in events with no extra tracks compared with the Standard Model expectation (thick green line) and predictions for anomalous quartic gauge couplings (dashed green histograms).

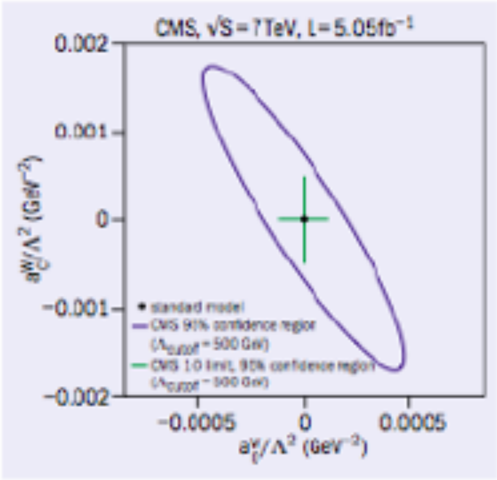


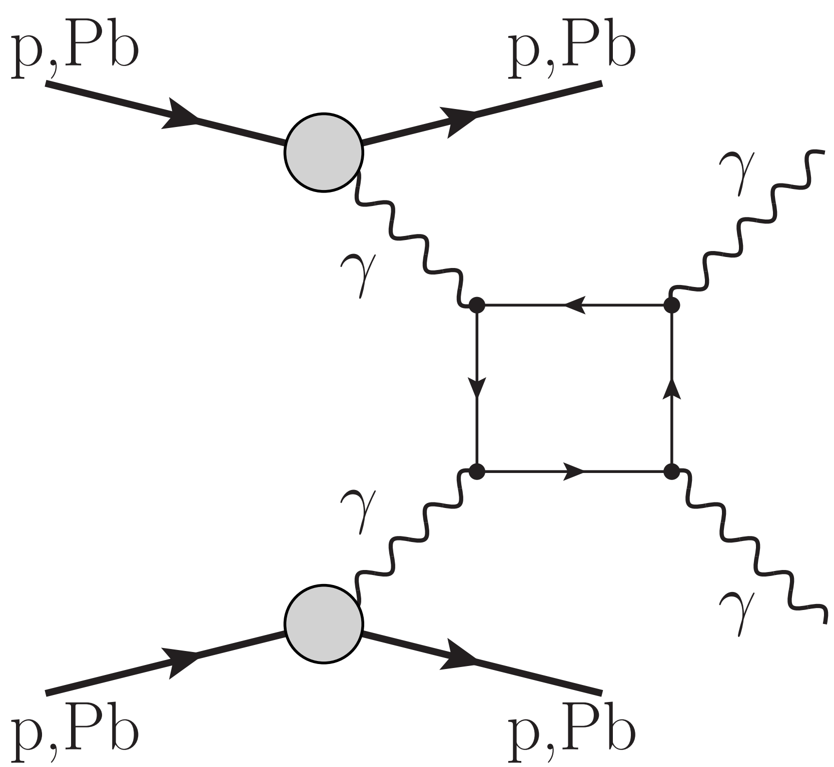
Fig. 3. Right: Limits on anomalous quartic $\gamma\gamma WW$ couplings.

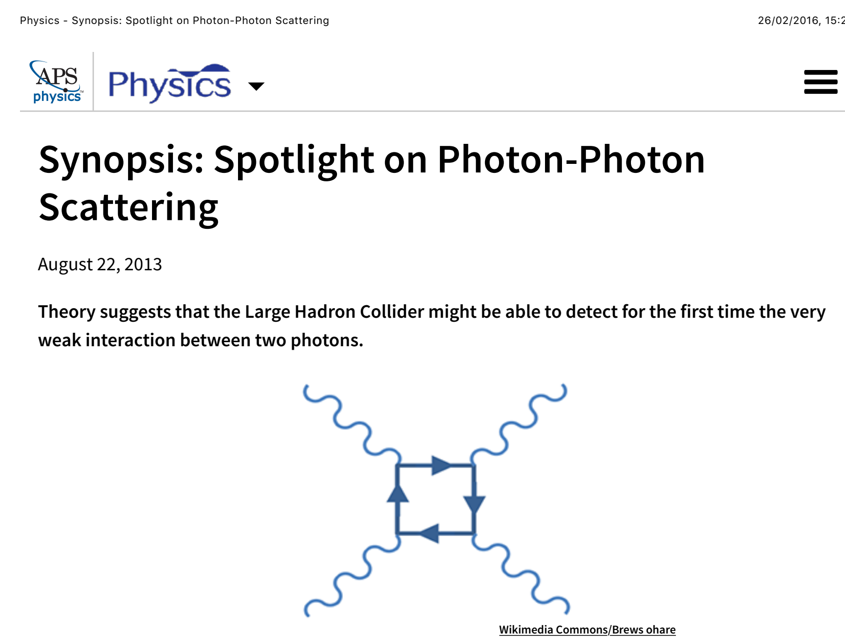
$|\eta|<2.1$; no extra track associated with their vertex; and for the pair, a total $p_T>30$ GeV/c. After applying all selection criteria, only two events remained – compared with an expectation of 3.2 events: 2.2 from $\gamma\gamma \rightarrow WW$ and 1 from background (figure 2).

Model, allows stringent limits on anomalous quartic $\gamma\gamma WW$ couplings to be derived. These surpass the previous best limits, set at the Large Electron–Positron collider and at the Tevatron, by up to two orders of magnitude (figure 3).

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.




Physics - Synopsis: Spotlight on Photon-Photon Scattering 26/02/2016, 15:29

APS physics | Physics

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 $\mathcal{L} = 480\,\mu\mathrm{b}^{-1}$.

ATLAS NOTE

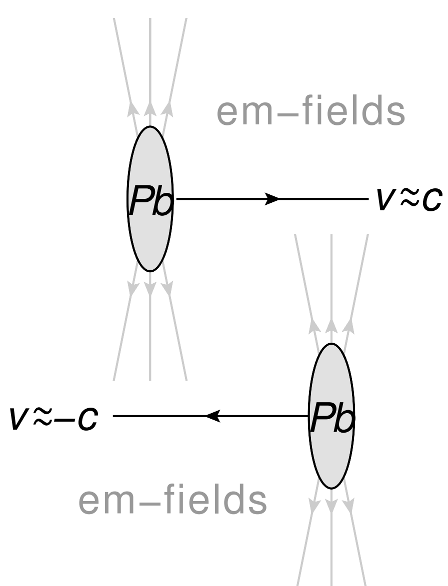
ATLAS-CONF-2016-111

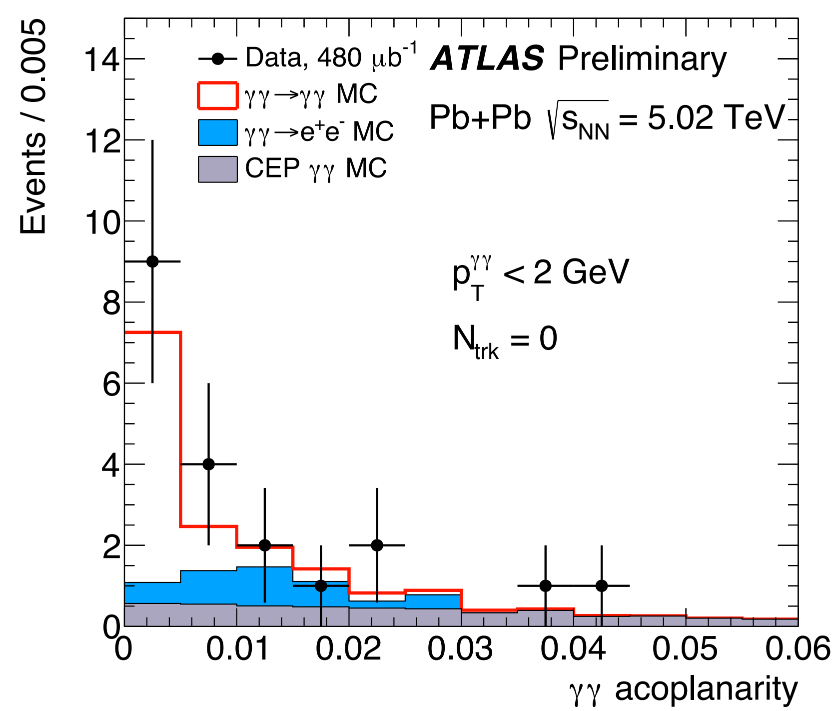
26th September 2016

Light-by-light scattering in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{NN}}$ =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.



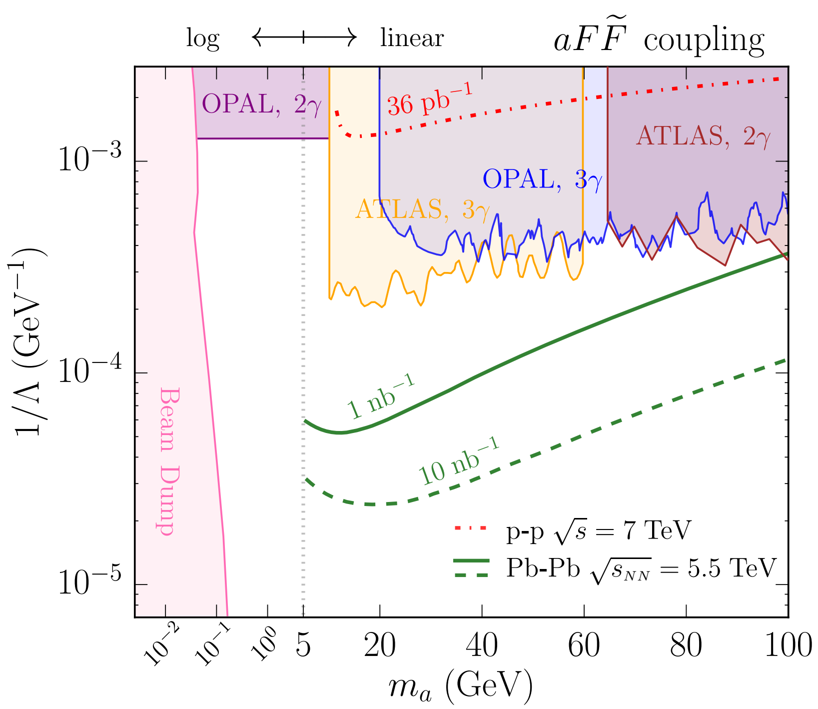


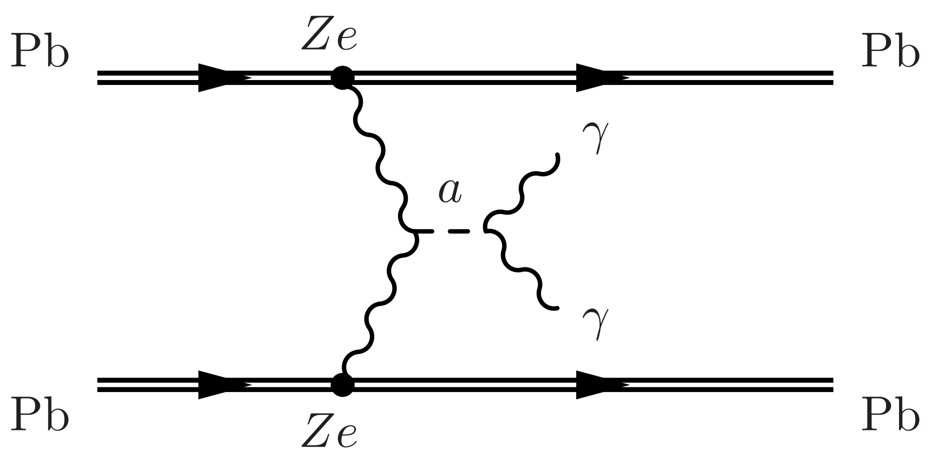
Axion-like particles

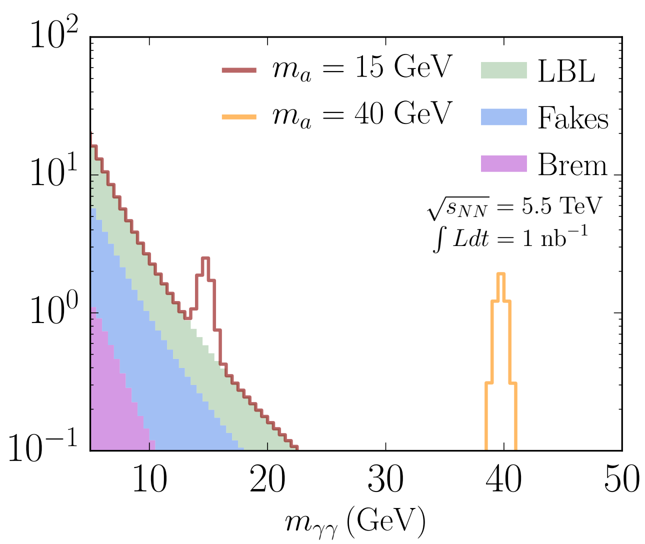
- Consider same $\gamma\gamma \to \gamma\gamma$ transition: sensitive to coupling of light axion-like particle to photons.

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

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

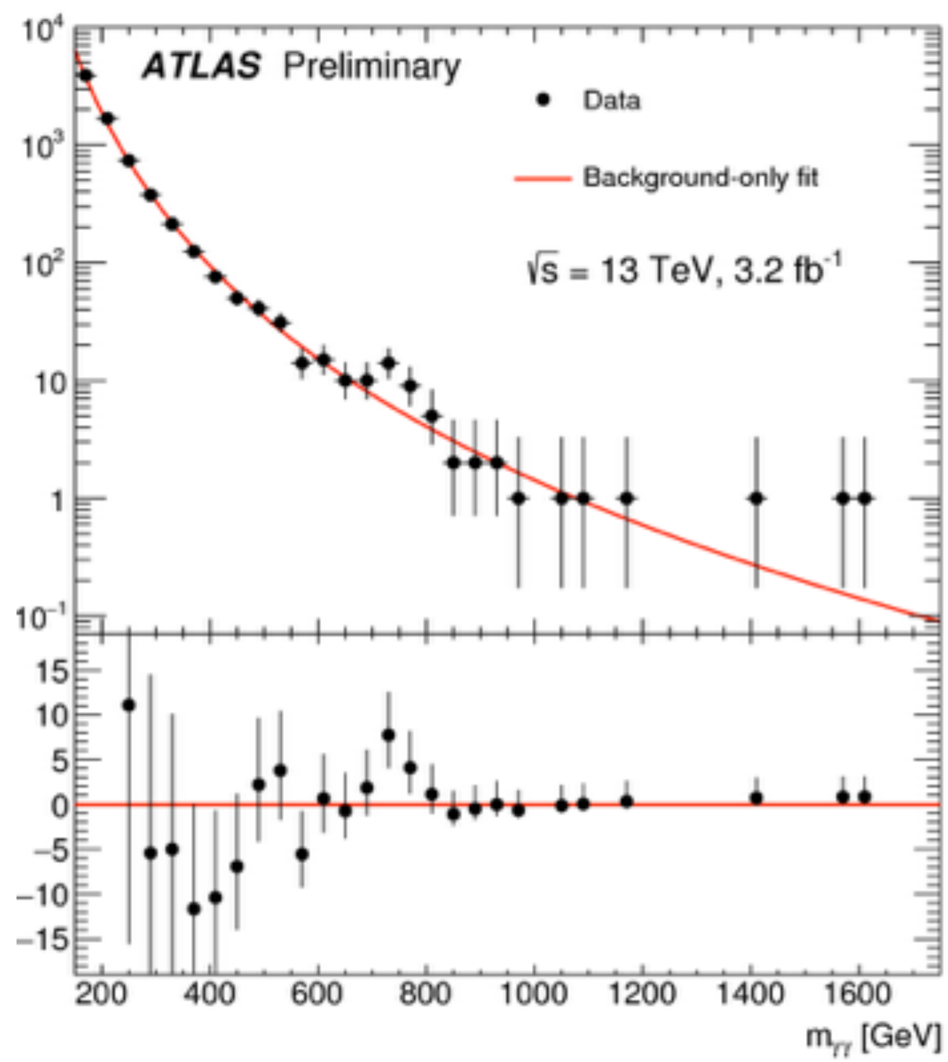


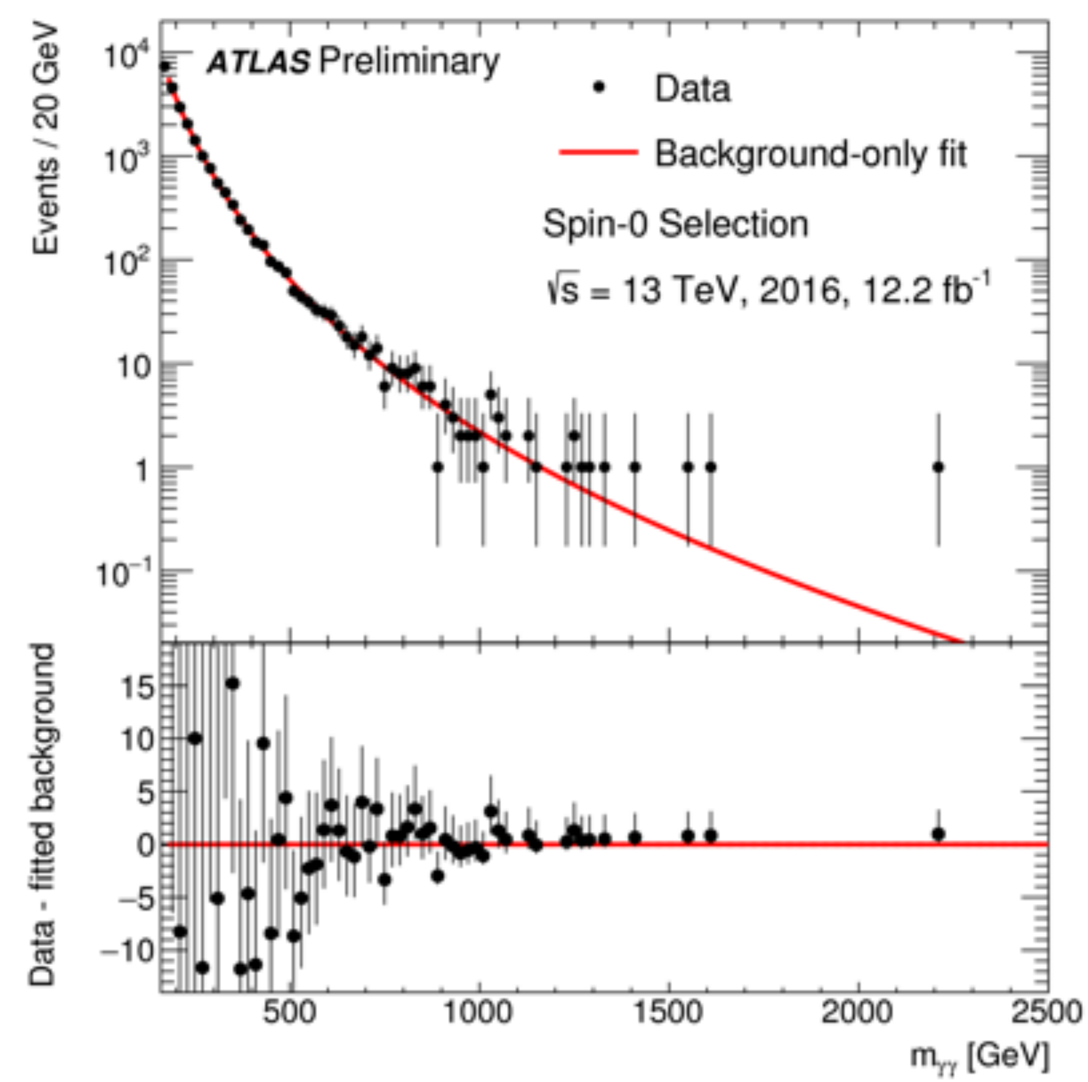




The diphoton (ex)-resonance

- 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.
- Diphoton resonance - RIP. But worth recapping what can be done exclusively for some new resonance with large/dominant $\gamma\gamma$ coupling.

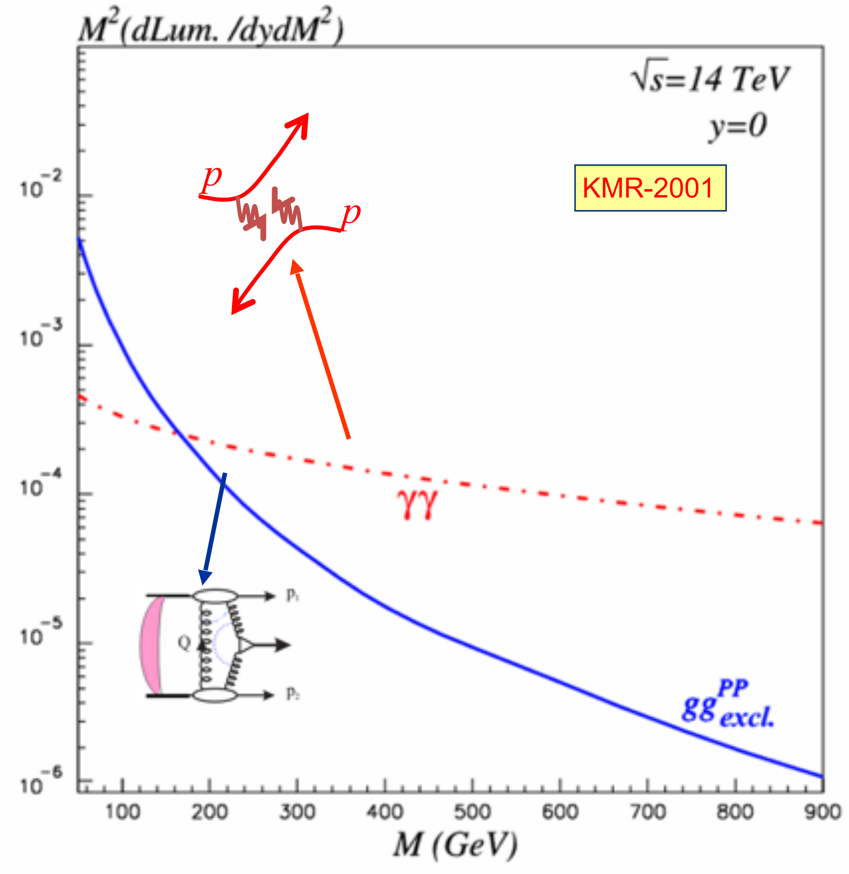


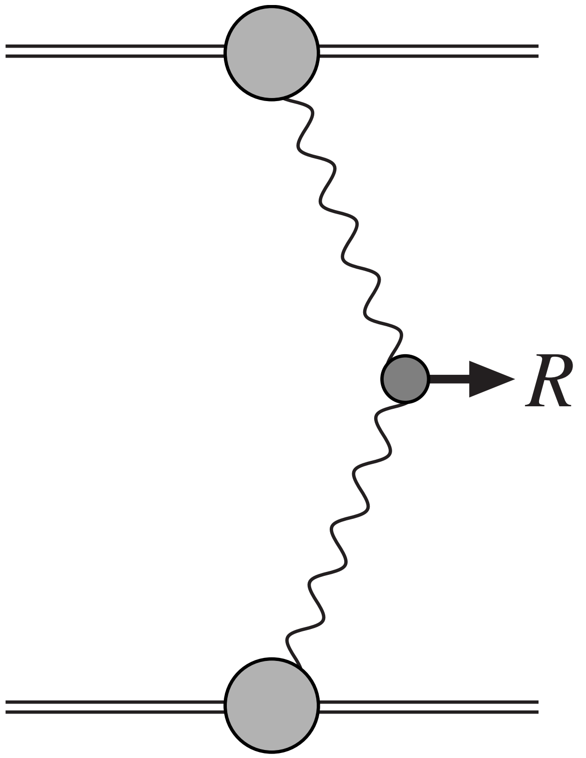


High mass resonances

- Crucial point: dominance of $\gamma\gamma$ initial-state for high mass exclusive production $\Rightarrow$ contribution from gg couplings suppressed - $q\bar{q}\,(WW...)$ induced will not give intact protons.

$\rightarrow$ Observation of just a few events in exclusive mode would give strong evidence for $\gamma\gamma$ production mode.





High mass resonances - tagged protons

- As well as selecting exclusive events, proton taggers reconstruct the full 4-momenta of the outgoing proton $\Rightarrow$ use as handle to analyse structure of production process.

- In particular, can show that the distribution of the proton $p_\perp$ vectors is strongly correlated with the spin-parity of the produced state.

- E.g. in terms of the proton $p_\perp$, exclusive cross sections depends on

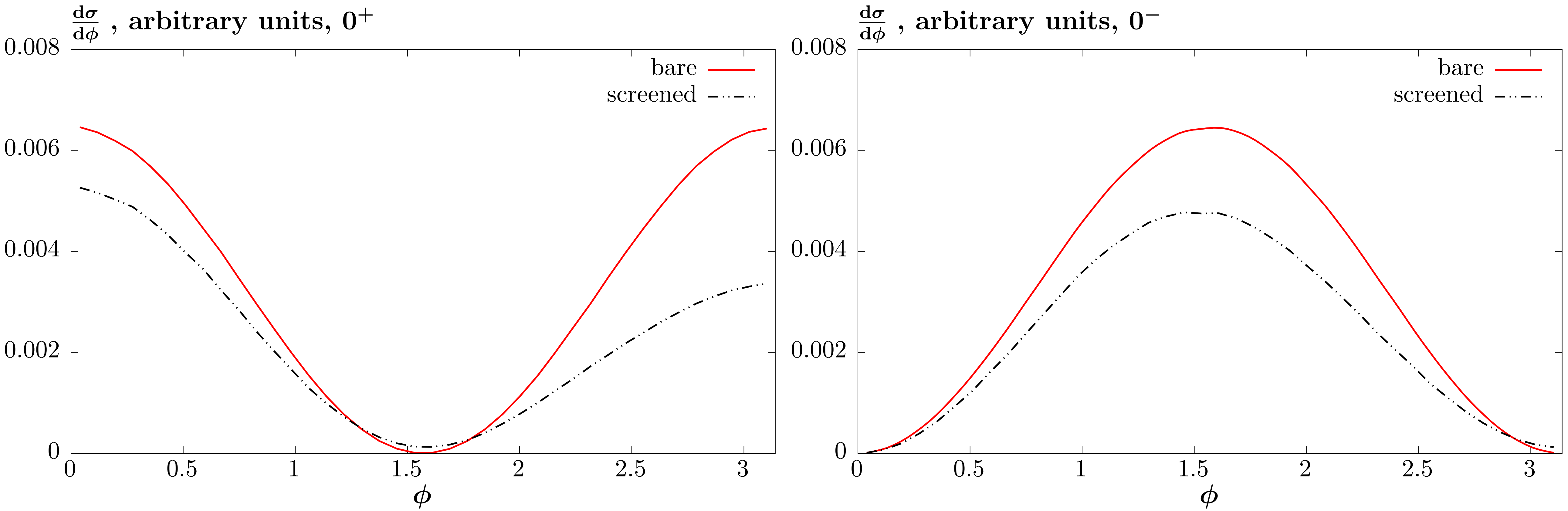
$$|A^+|^2 \sim |p_{1_\perp} \cdot p_{2_\perp}|^2 \sim \cos^2\phi \,,$$
$$|A^-|^2 \sim |\epsilon_{\alpha\beta\mu\nu}\, p_1^\alpha p_2^\beta p_{1_\perp}^\mu p_{2_\perp}^\nu|^2 \sim \sin^2\phi$$

for scalar/pseudoscalar $(+/-)$ state, where ϕ is azimuthal angle between vectors of outgoing protons (measurable!).

$\longrightarrow$ Dramatically different behaviour expected.

Proton correlations

- Consider $d\sigma/d\phi$:



$\longrightarrow$ With just a handful of events, scalar/pseudoscalar hypotheses distinguishable.

- In addition (not discussed here) these distributions also sensitive to CP-violating effects in production mechanism.

Outlook - tagged protons

- These measurements, while promising, are still at early stage.
- So far events selected using gap vetoes only. However, outgoing protons can be detected by the AFP and CT-PPS proton taggers.

  - AFP - detectors currently installed on one side only, to be completed in winter shut down $\longrightarrow$ fully operational from 2017.
  - CT-PPS - detectors installed and $\sim 11\,\mathrm{fb}^{-1}$ of 2016 data taken.

$\longrightarrow$ Now entering era of exclusive physics with tagged protons at the LHC.

Anomalous couplings - outlook

- What are the prospects for e.g. anomalous $\gamma\gamma WW$ coupling measurements with tagged protons at the LHC?
- Detailed studies, including full detector sim., given in LHC Forward Physics WG Yellow Report.
- This is just one example- in general any process with significant EW couplings can be probed (monopoles, ALPS, BSM charged pair production…). Other possibilities to explore.

CERN

CERN-PH-LPCC-2015-001
SLAC-PUB-16364
DESY 15-167

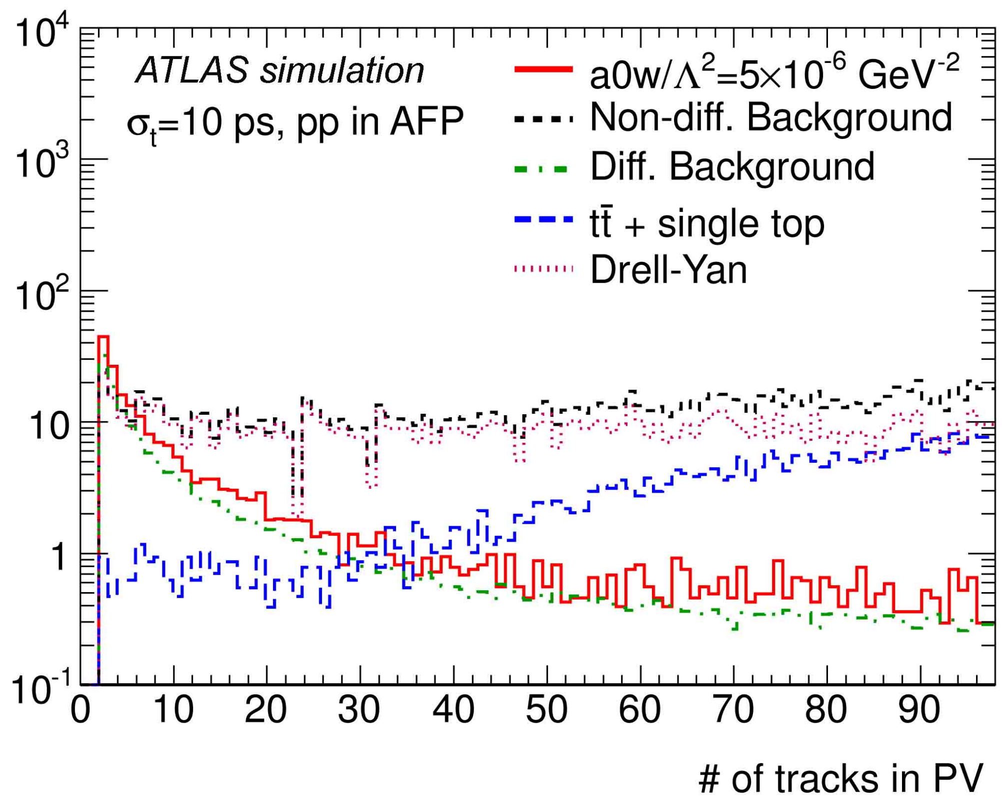
September 3 2015

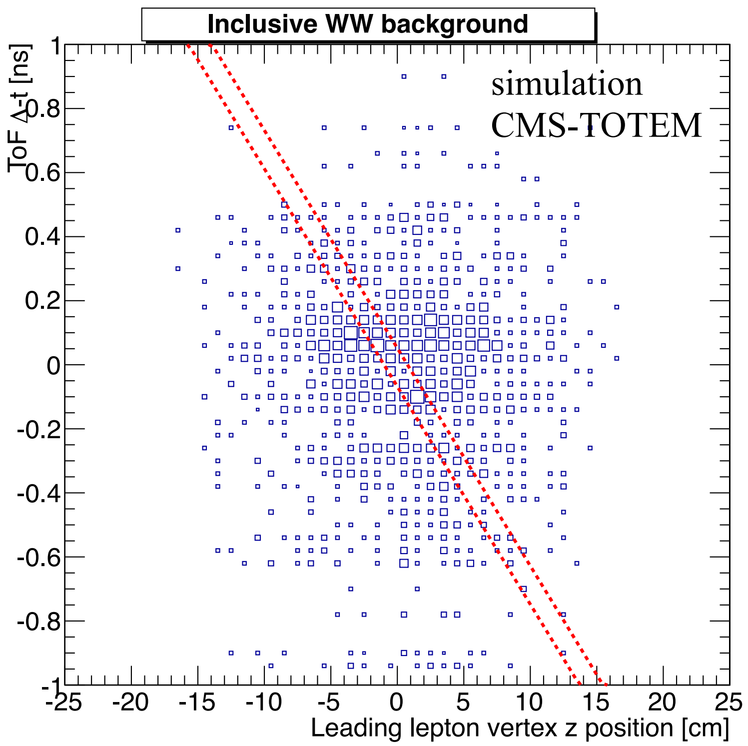
LHC Forward Physics

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

Anomalous couplings - outlook

- Studies done for $\sim 100\,\mathrm{fb}^{-1}$ of lumi, i.e. including significant pile-up, for both AFP and CT-PPS (results similar).
- How to suppress BG? As before, limiting number of tracks in PV (+ other cuts) helps.
- **But**, huge gain from proton tagging requirement. Fast timing (+ correlating proton/system kinematics) dramatically reduces pile-up BG and selects very pure exclusive signal.

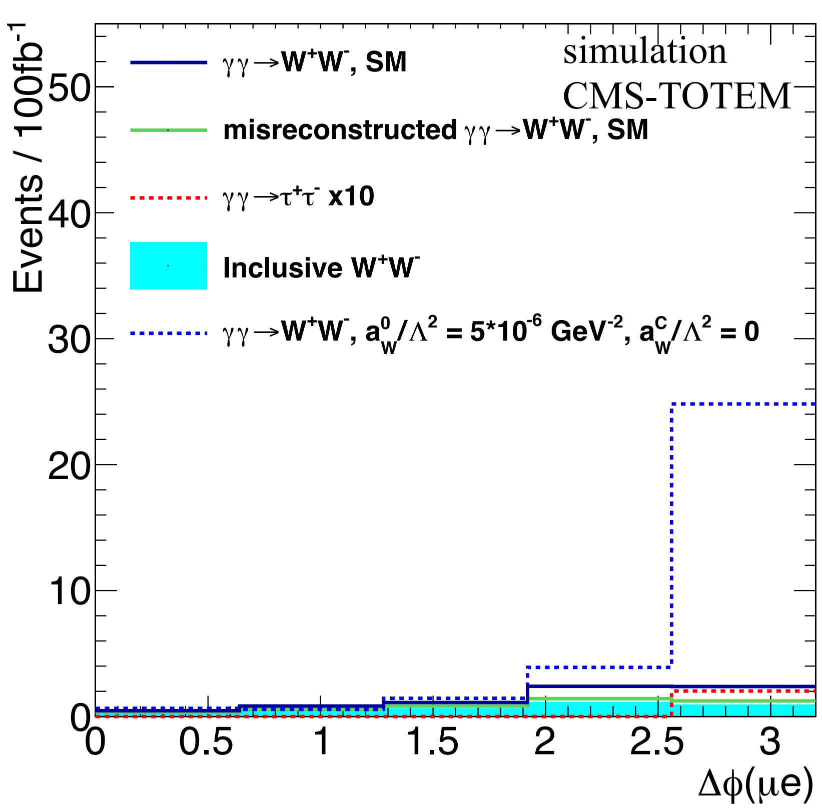


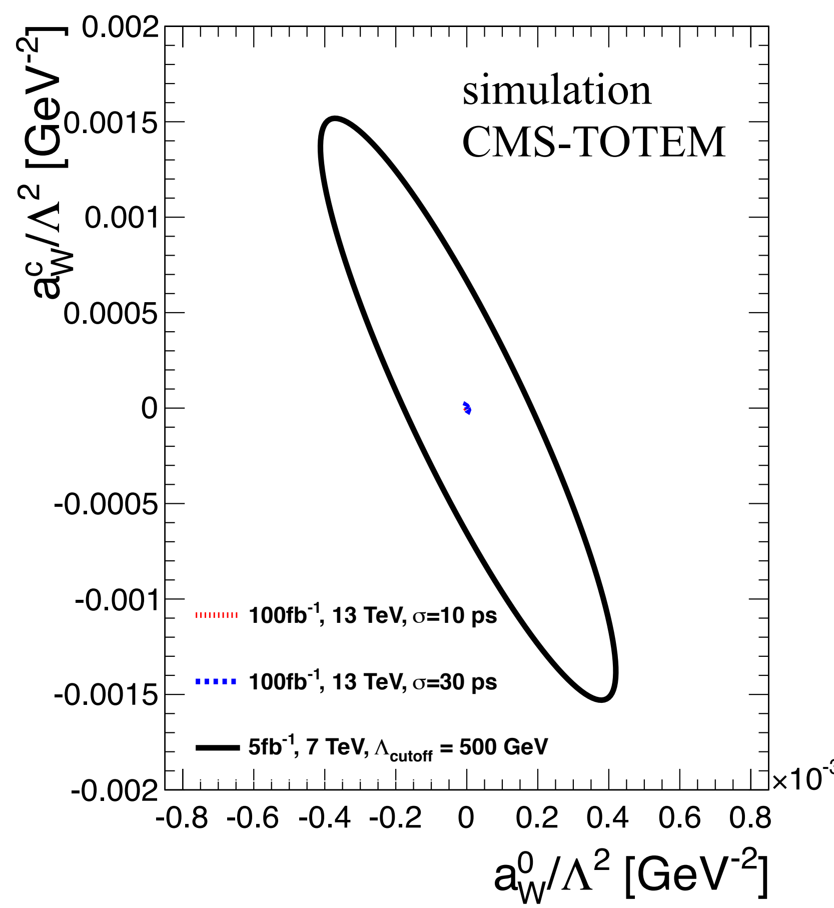


Anomalous couplings - outlook

- For $100\,\mathrm{fb}^{-1}$, expect ~ 3 pure SM exclusive events, and ~3 BG events.
- However with $a_0^W/\Lambda^2 = 2\times10^{-6}$, i.e. ~ *two orders of magnitude* below current best limits, expect ~ 30 events.

$\longrightarrow$ Striking signal, and absence allows extremely stringent limits to be set, ~ 4 orders of mag. below LEP and the tightest bounds possible at the LHC.





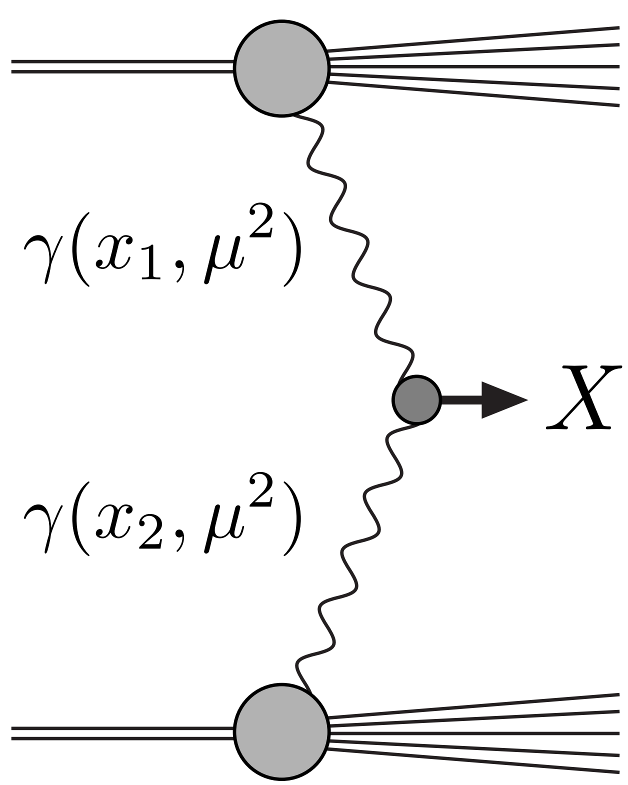
Inclusive production - the photon PDF

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:

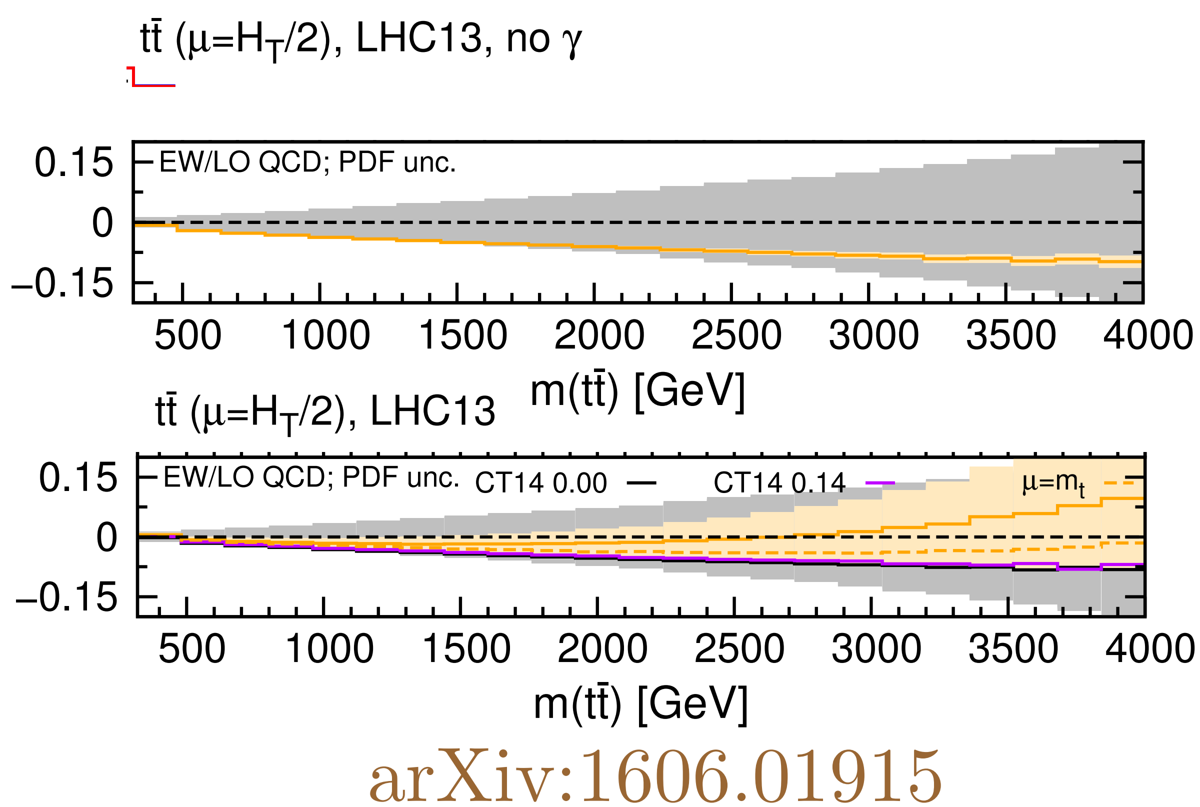
$$\sigma(X) = \int \mathrm{d}x_1 \mathrm{d}x_2\, \gamma(x_1,\mu^2)\gamma(x_2,\mu^2)\,\hat{\sigma}(\gamma\gamma \to X)$$

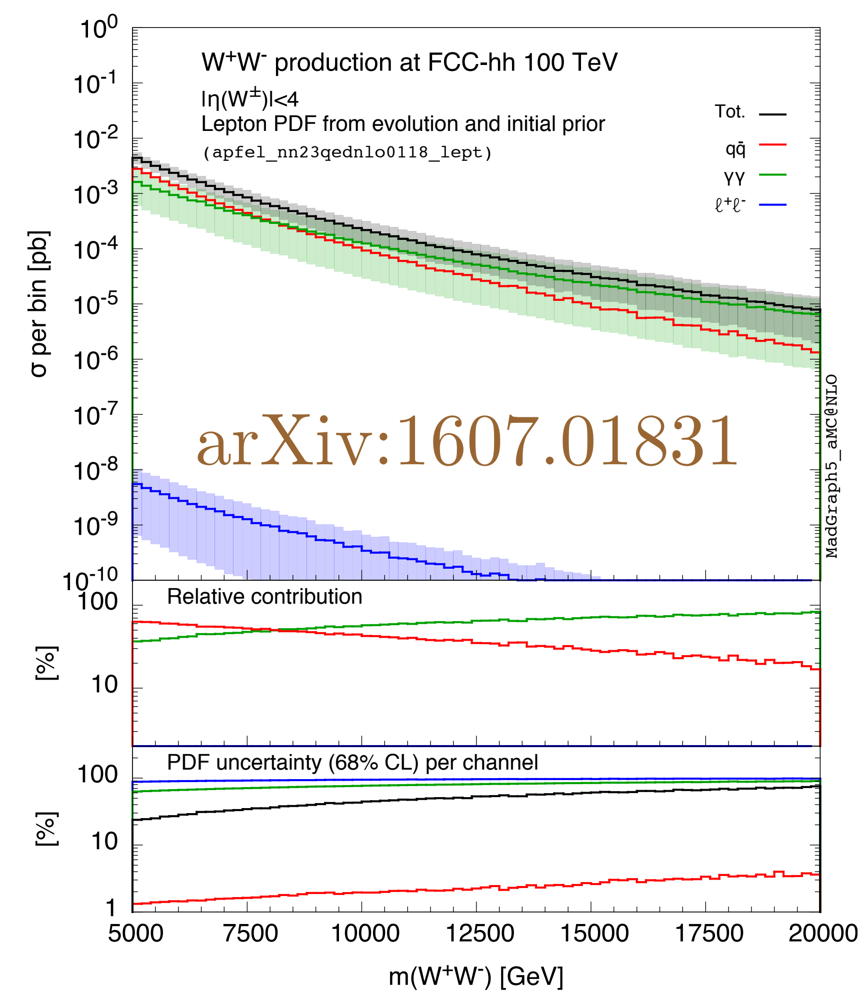
but in terms of *photon* parton distribution function (PDF), $\gamma(x,\mu^2)$.



Recent Studies

- Diphoton resonance in $\gamma\gamma$ collisions? RIP, but important to get initial-state right!
- 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.

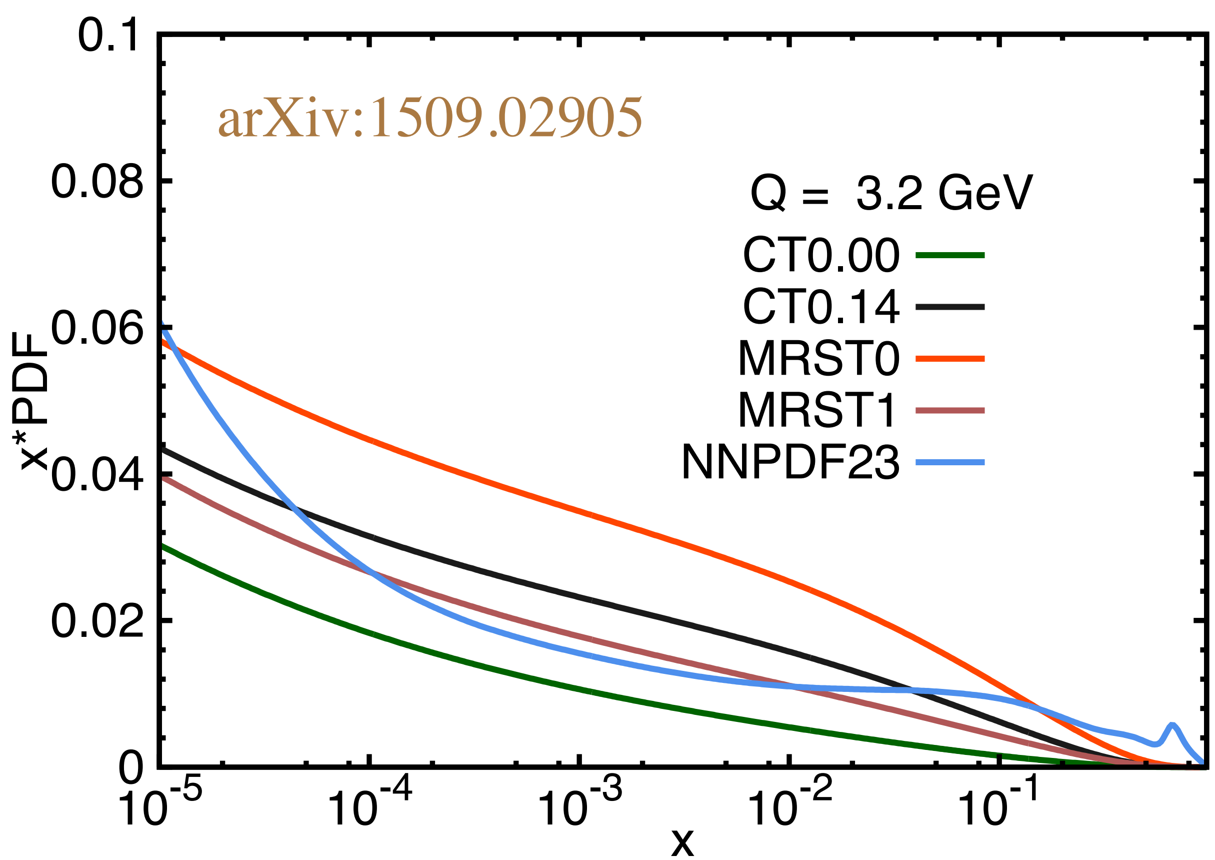




- Contribution from photon initial state potentially quite large, within quoted uncertainties. Is this the case?

Previous approaches

- Earlier photon PDF sets either:
  - ‘Agnostic’ approach. NNPDF2.3QED: treat photon as we would quark and gluons. Freely parametrise $\gamma(x, Q_0)$ and fit to DIS and some LHC W, Z data. Uncertainties (so far) remain large.
  - ‘Model’ approach. MRST2004QED/CT14QED: take simple ansatz for photon emission from quarks. Compare/fit to ZEUS isolated photon DIS.



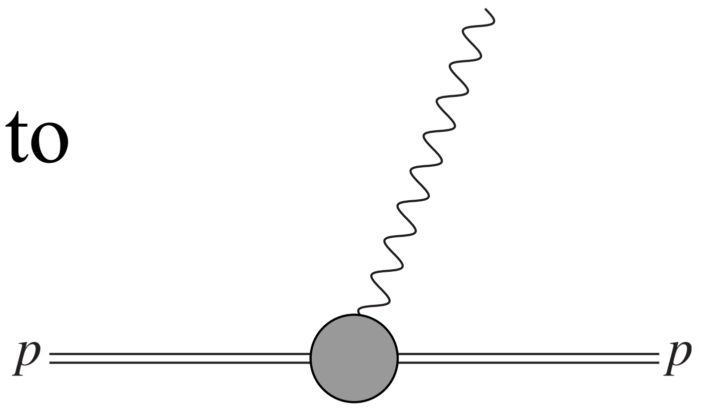
- Comparing these different sets reveals apparently large uncertainties.

$\longrightarrow$ However: have we included all of the available information?

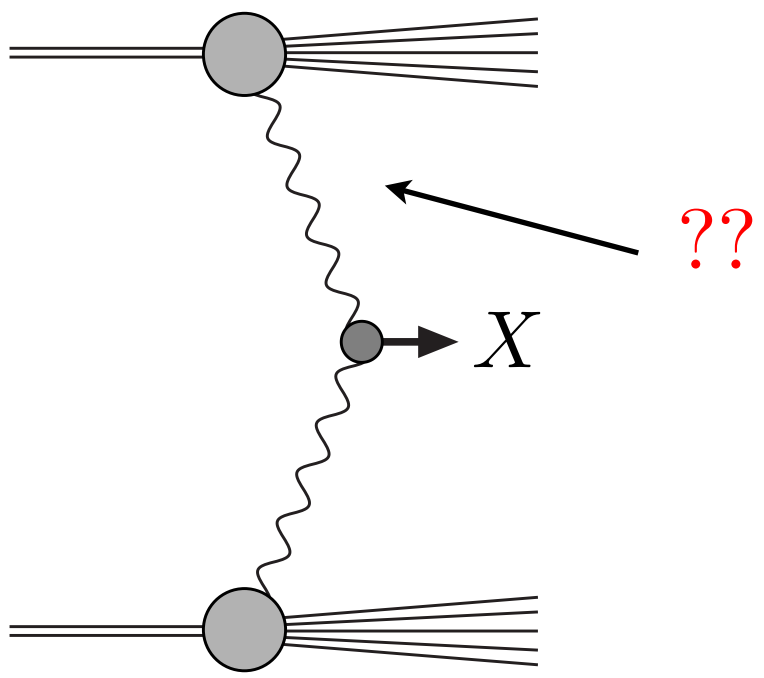
PDFs and QED

• Previous approaches missing crucial physics ingredient - the contribution from elastic photon emission. QED is a long range force!

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

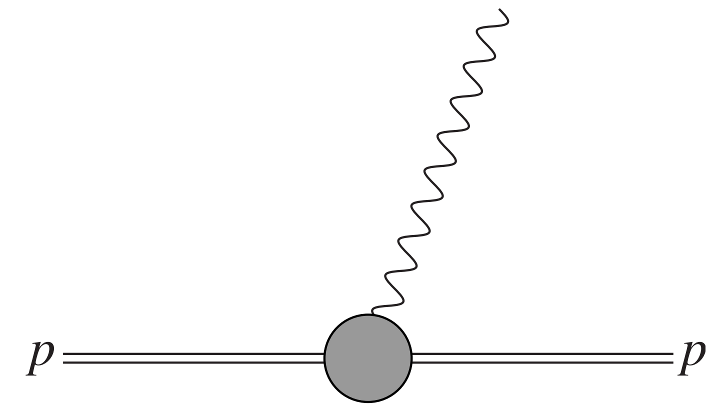


• How do we do this? Consider what can generate initial state photon in $\gamma\gamma \to X$ production process:



PDFs and QED

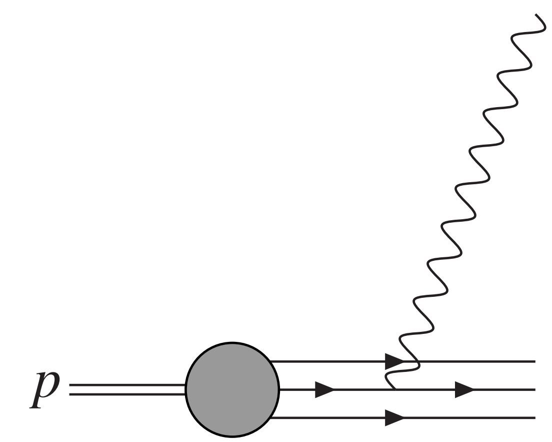
- Inclusive $\equiv$ system X + anything else $\Rightarrow$ exclusive production by definition should be included, i.e. elastic emission.



Elastic emission

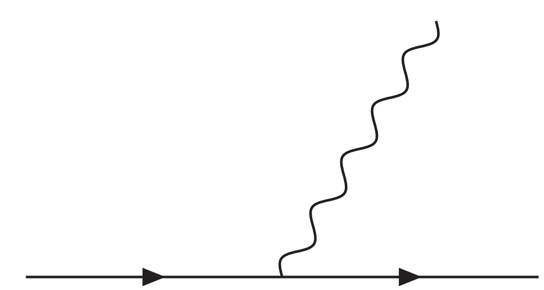
- However clearly not end of story:

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

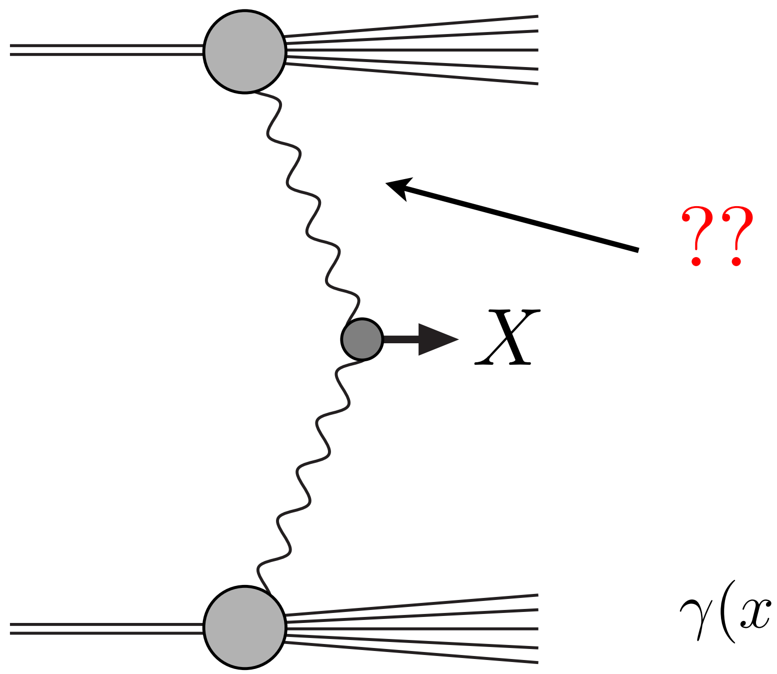


(Low scale) ‘incoherent’ emission.

‣ 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:

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

- More precisely, from DGLAP equation:

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

$\gamma^{\text{evol}} \longrightarrow$

$$+\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2) + P_{\gamma g}(z) g(\frac{x}{z},Q^2)\Bigg)\,,$$

$\longrightarrow$ Input photon at $Q_0 \sim 1\,\text{GeV}$ generated by elastic emissions + incoherent: $\gamma(x,Q_0^2) = \gamma_{\text{coh}}(x,Q_0^2) + \gamma_{\text{incoh}}(x,Q_0^2)$

A.D. Martin, M.G. Ryskin, arXiv:1406.2118 M. Gluck, C. Pisano, E. Reya, hep-ph/0206126

- But dominant process here is coherent - long wavelength photon feels EM charge of entire proton - and hence well understood (n.b. no equivalent process for QCD partons).

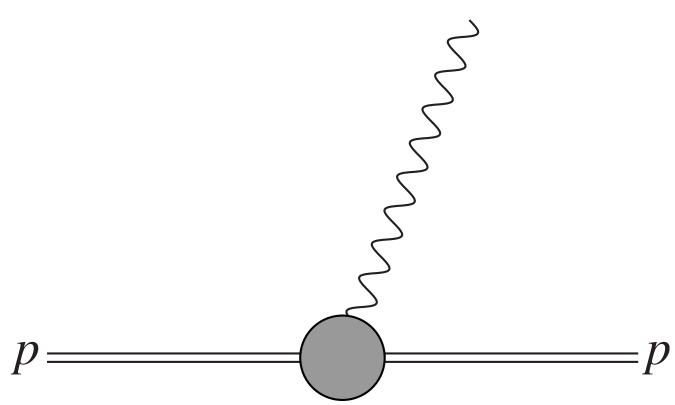
LHL, V.A. Khoze, M.G. Ryskin, arXiv:1601.03372, 1601.07187, 1607.4635

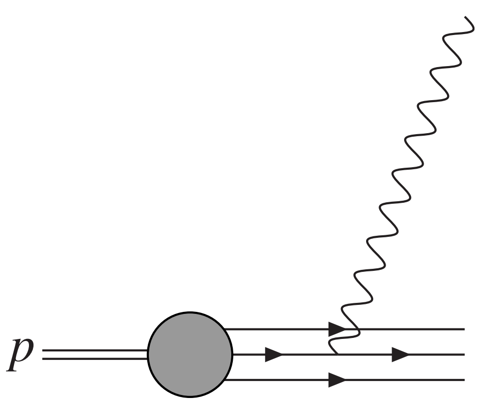
PDFs and QED

- We have recently applied this approach to photon-initiated processes at high mass, semi-exclusive processes, and diphoton resonance production. RIP
- Crucial point:
  - At low $Q^2 \lesssim 1\,\mathrm{GeV}^2$: photon is dominantly generated by well understood coherent emission ($p \to p\gamma$).
  - At high $Q^2 \gtrsim 1\,\mathrm{GeV}^2$: photon generated by DGLAP emission off quarks (with well constrained PDFs).

$\longrightarrow$ Photon PDF is in fact under very good control.

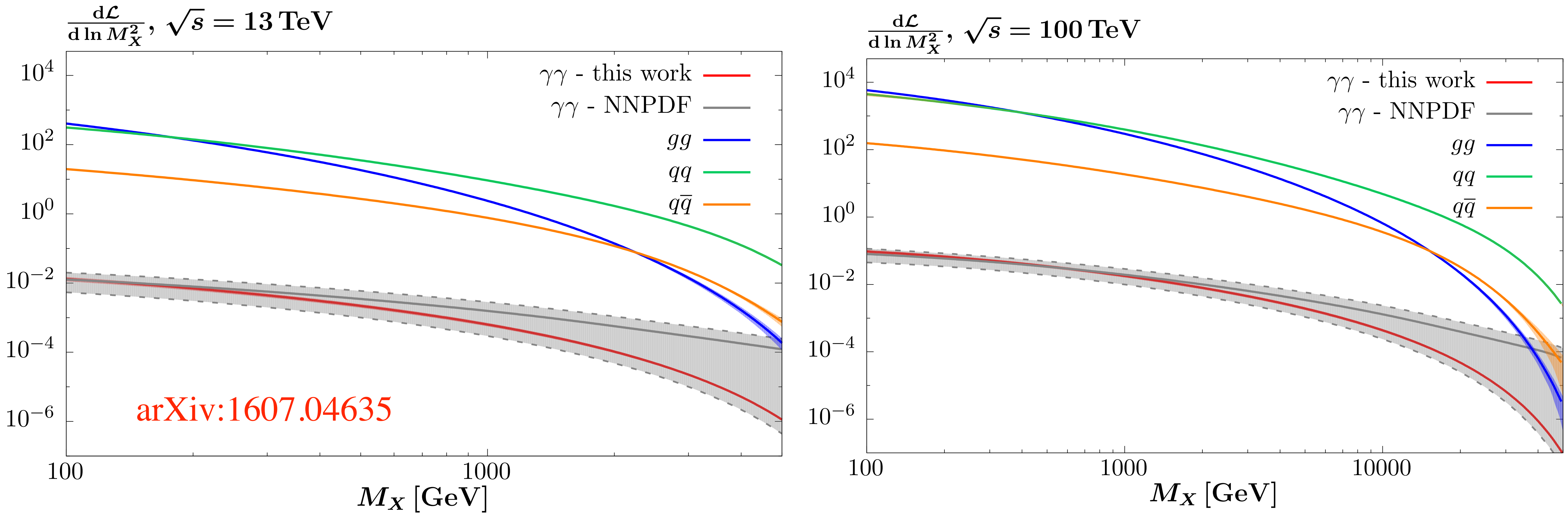
- We treat the coherent emission process exactly as in exclusive production, while taking simple model for (low scale) incoherent. Sufficient to give some fairly dramatic results w.r.t. previous studies.





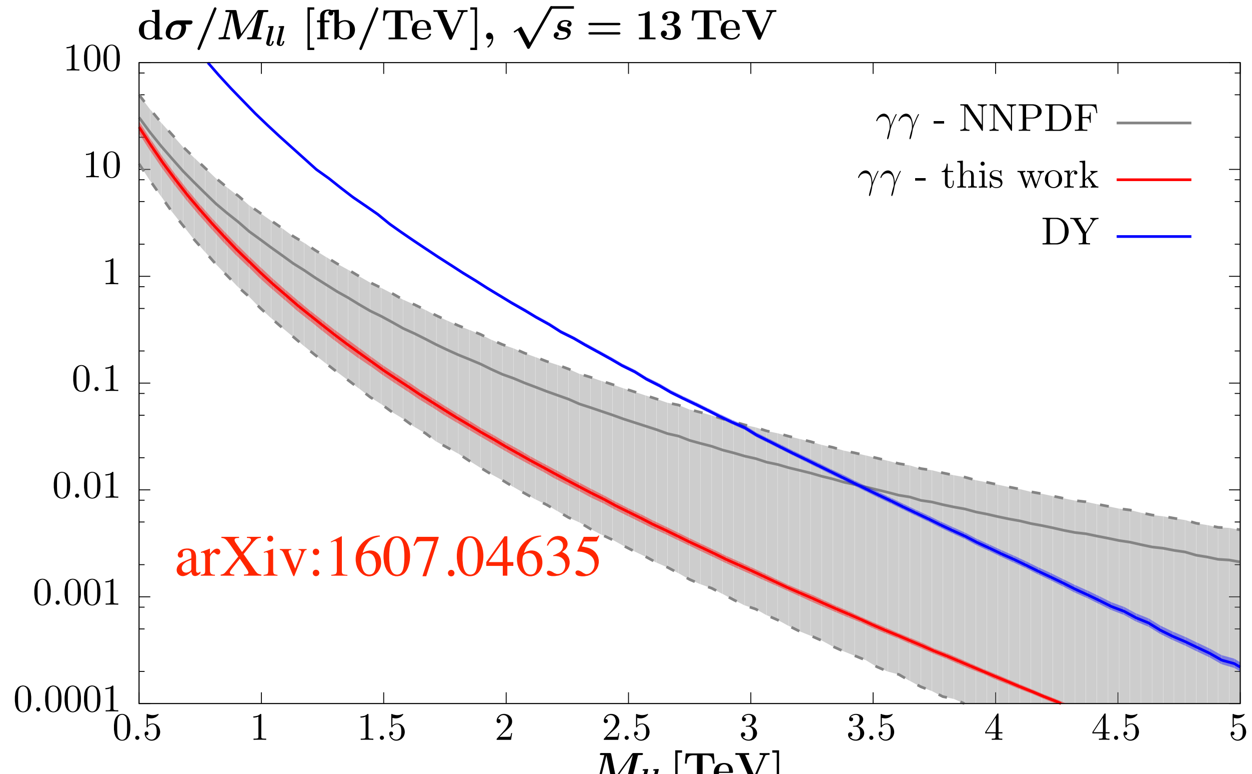
PDF luminosities

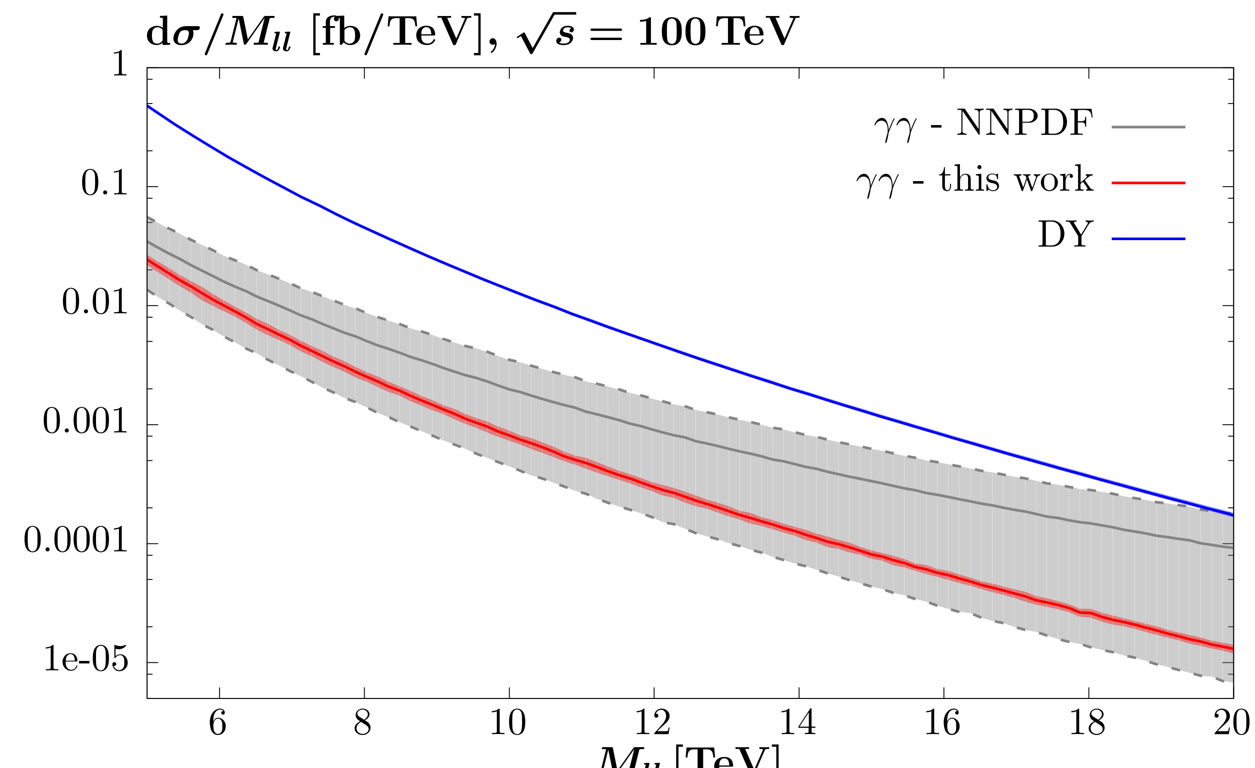
- Consider parton-parton luminosities at LHC and FCC.
- Previous result translates to large uncertainty and potentially large luminosity at high mass. q, g fall much more steeply than central γ NNPDF prediction.
- Our approach: scaling very similar to $qq/q\bar{q}$, with gg only slightly stepper. Uncertainties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



Drell-Yan production

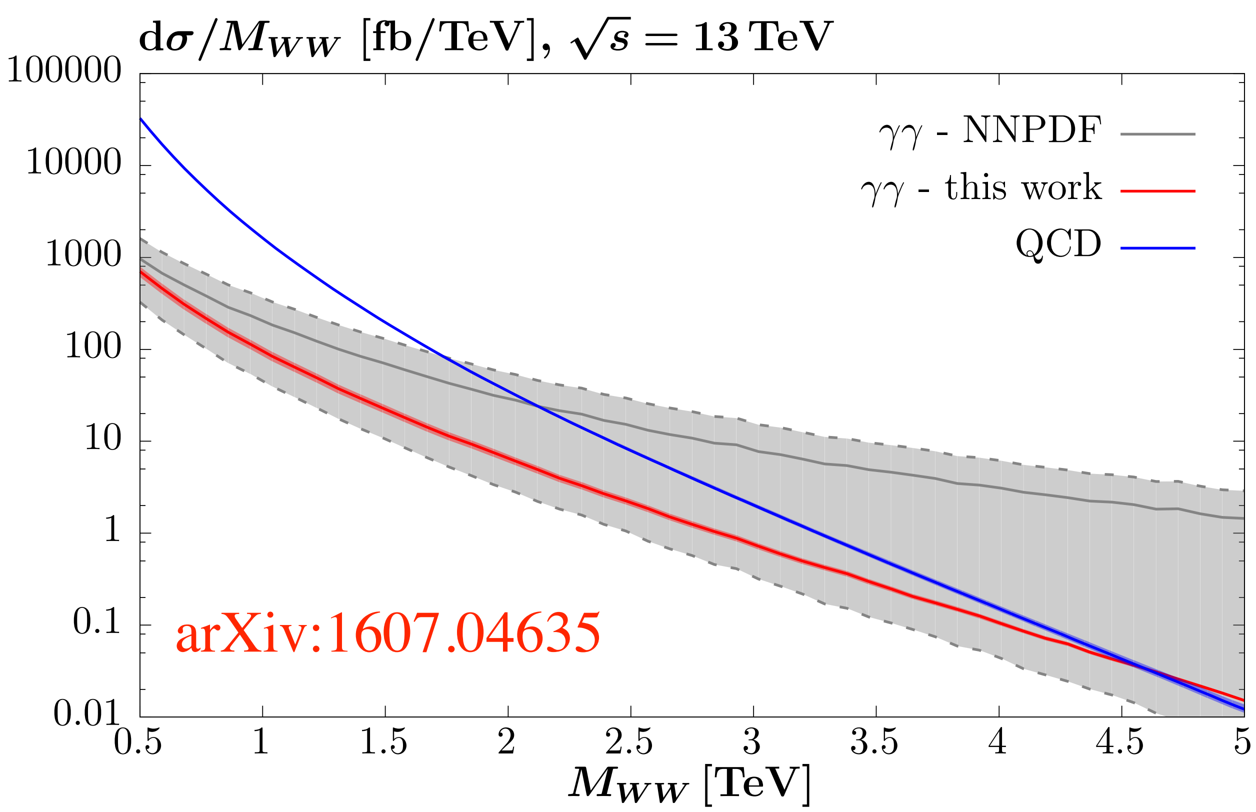
- Consider lepton pair production at LHC/FCC. As M_{ll} increases find central NNPDF $\gamma\gamma$ prediction becomes sizeable/dominant. Discussed in detail in 1606.00523, 1606.06646, 1607.01831.
- Follows directly from previous slide: relatively gentle decrease of NNPDF $\gamma\gamma$ luminosity at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

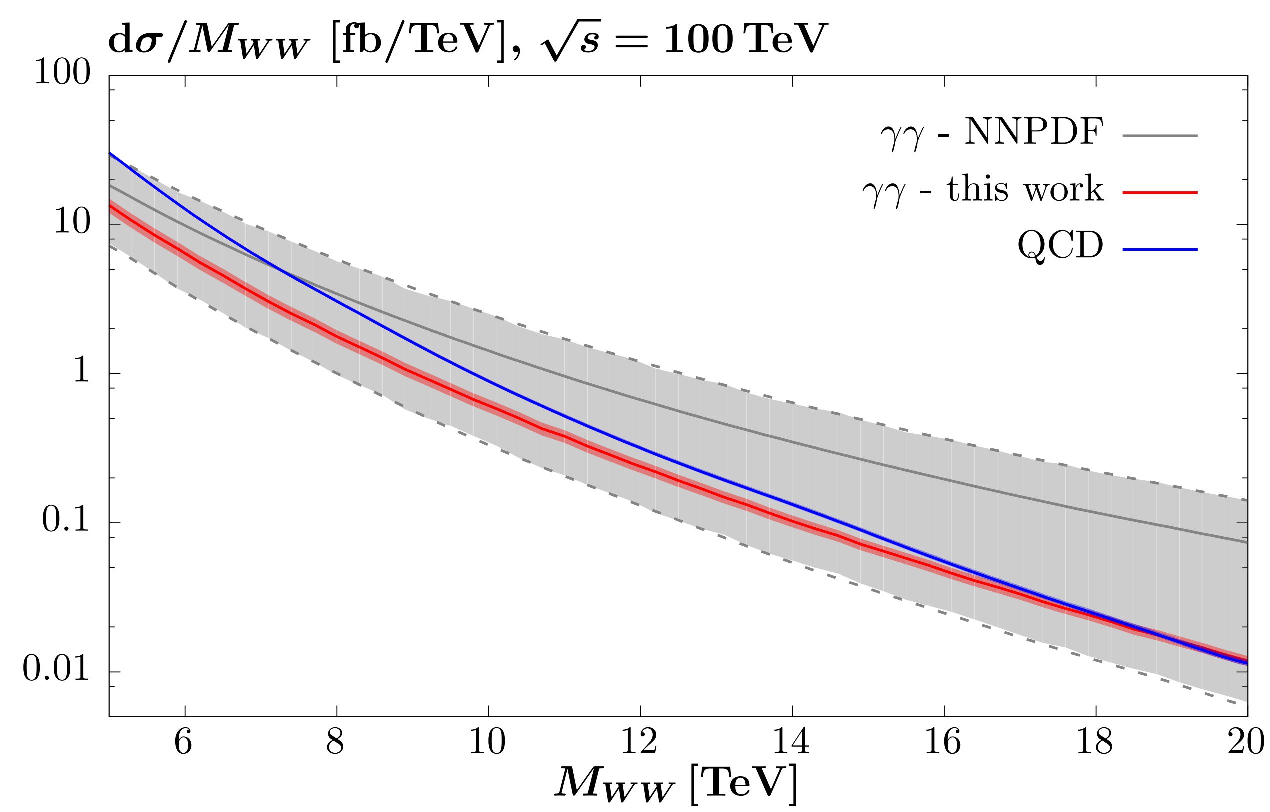




W^+W^- production

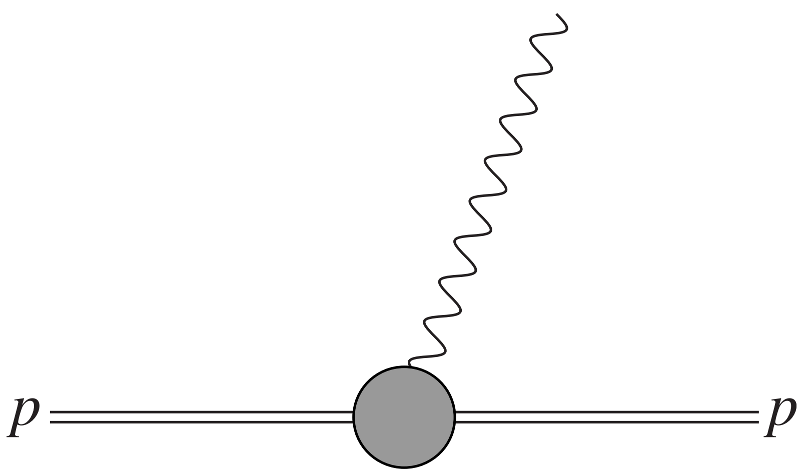
- Similar story for W^+W^- production: our results at lower end of NNPDF uncertainty band.
- However here the photon-initiated contribution is still quite large (caveat: depends somewhat on cuts).



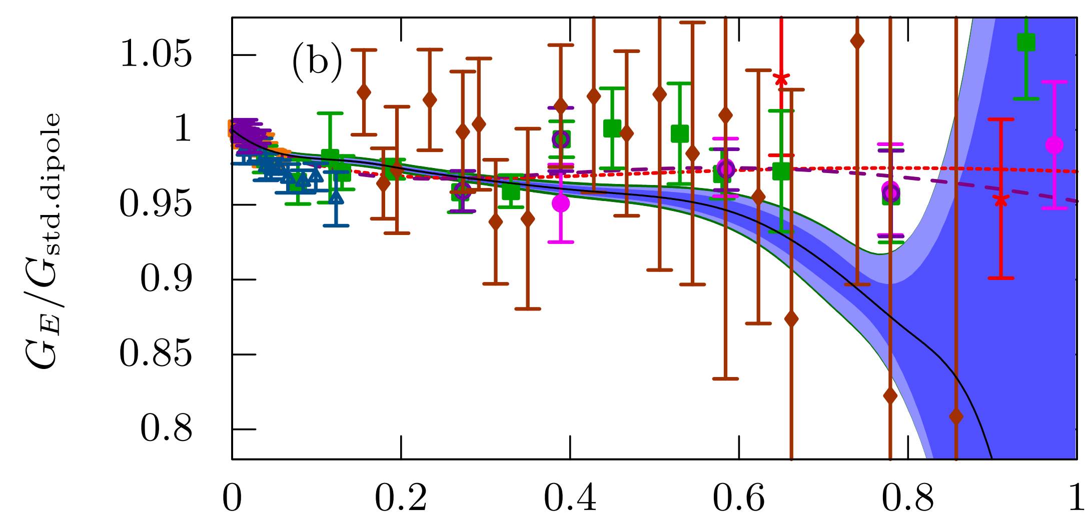


LUXqed (1)

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

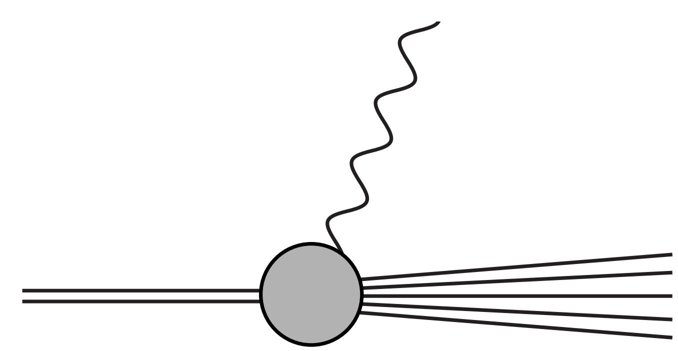


A1 Collaboration, arXiv:1307.6227



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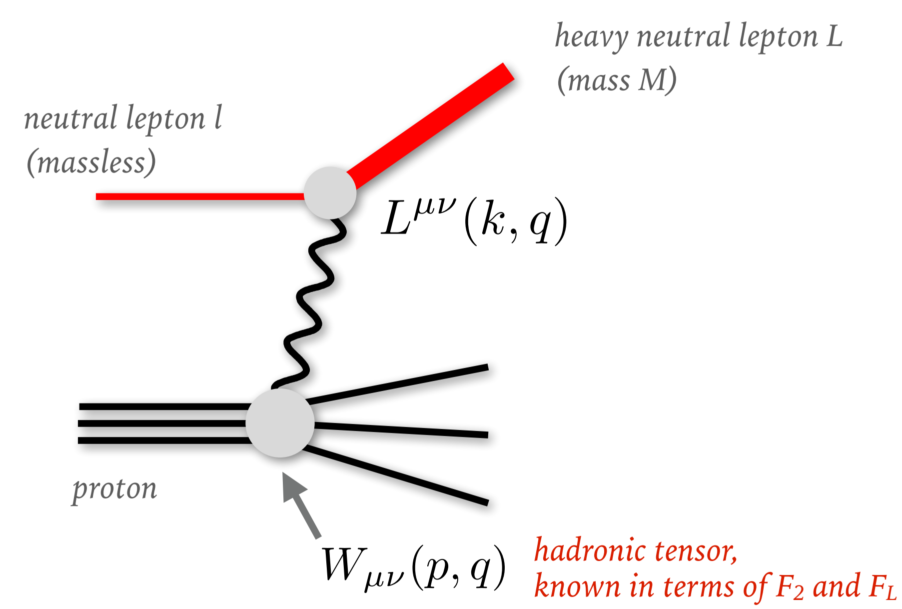
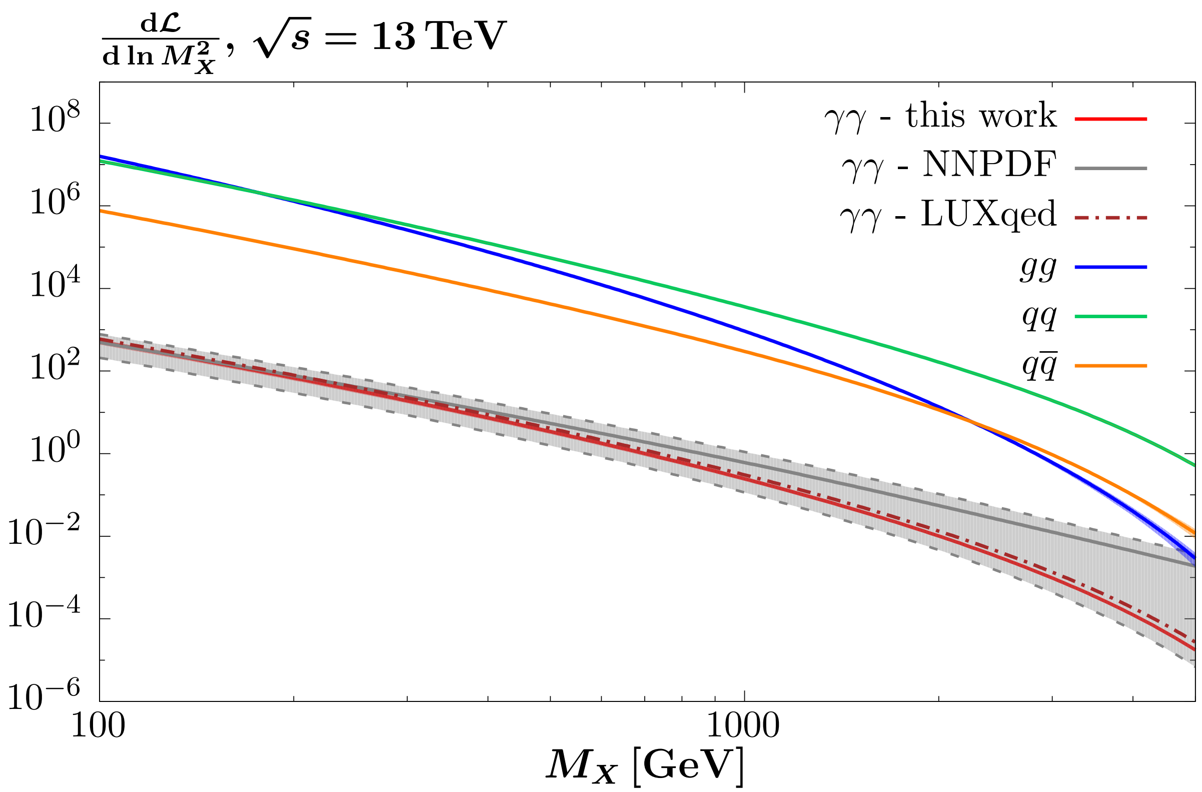
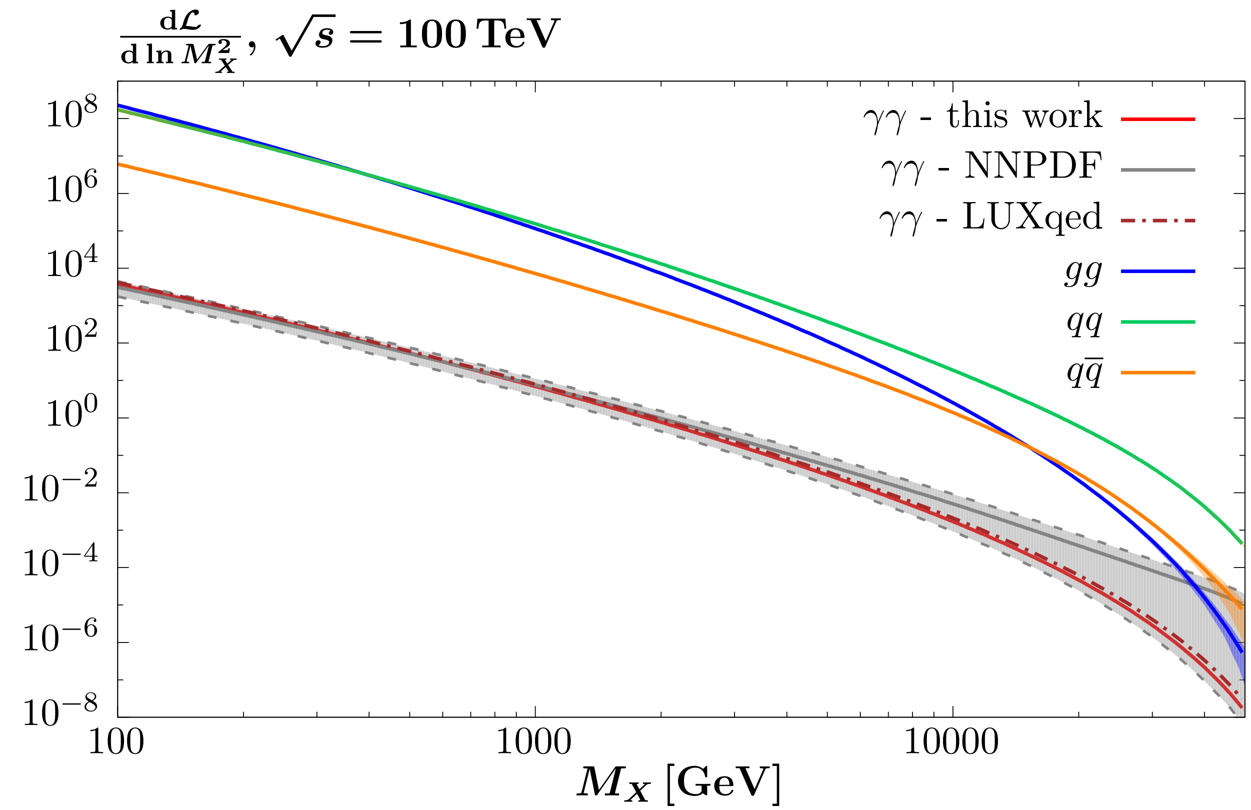
- Show how photon PDF can be expressed in terms of F_2 and F_L. Use measurements of these to provide well constrained `LUXqed` photon PDF.

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



LUXqed - comparison



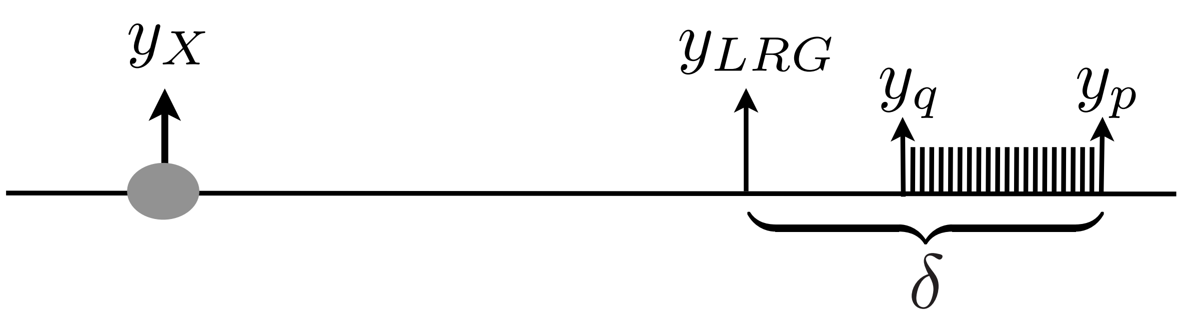


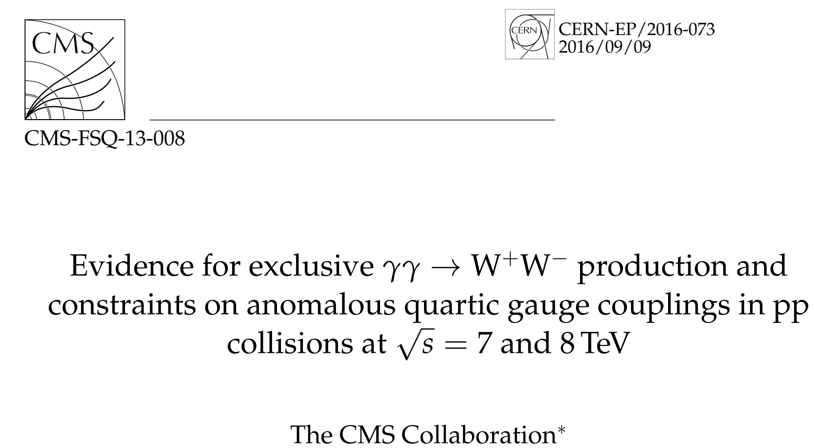
- Comparing our and LUXqed $\gamma\gamma$ luminosities can see these are quite similar ($\longrightarrow$ importance of coherent component).
- Devil is in detail - some enhancement seen in LUXqed at higher M_X, appears to be due to low Q^2 resonant contribution.
- However, clear we have moved beyond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

See backup for more details

Semi-exclusive production

- Nice connection between inclusive and exclusive cases: 'semi-exclusive' production, with rapidity gaps but proton break-up allowed.
- arXiv:1601.03772: by combining ingredients of inclusive (photon PDF) and exclusive (gap survival) production, and accounting for experimental gap can probe photon + QCD in unconstrained regions.

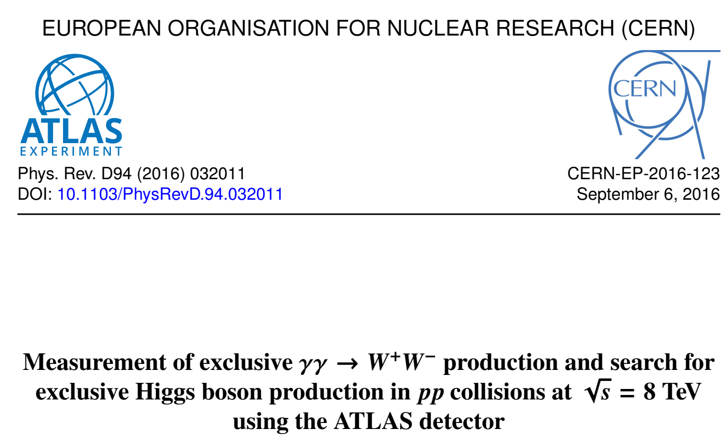




CMS-FSQ-13-008
CERN-EP/2016-073
2016/09/09

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

The CMS Collaboration*



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)
Phys. Rev. D94 (2016) 032011
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CERN-EP-2016-123
September 6, 2016

Measurement of exclusive $\gamma\gamma \to W^+W^-$ production and search for exclusive Higgs boson production in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector

Conclusions

- No immediate plans for a future $\gamma\gamma$ collider, but the LHC is already 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.
- Such studies equally possible (with higher $s_{\gamma\gamma}$) at FCC.
- 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

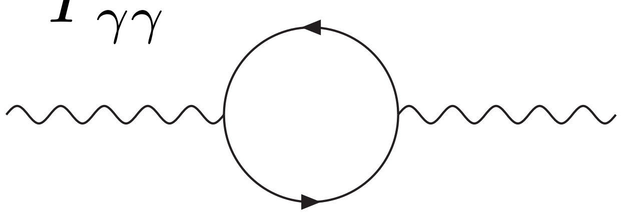
- Returning to photon DGLAP evolution equation:

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

- 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:

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

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.

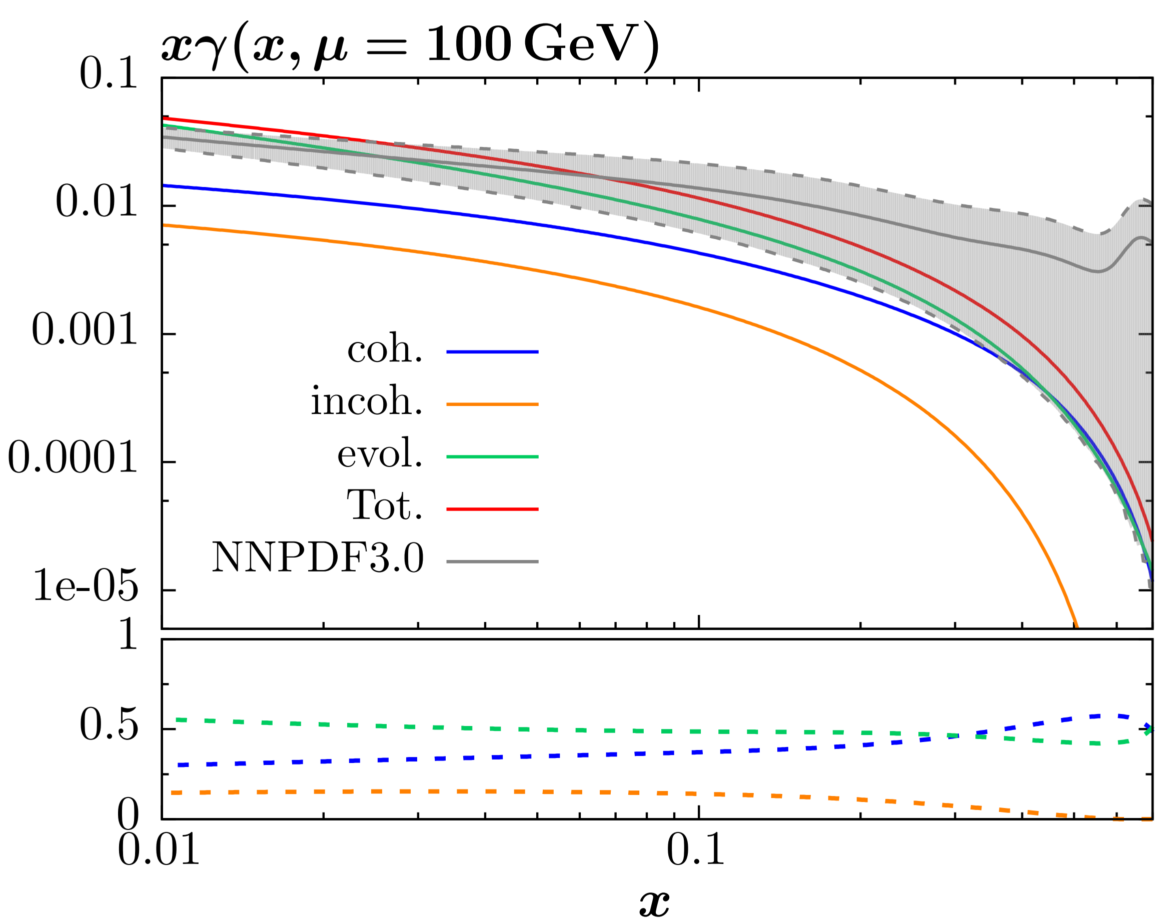
- Sudakov factor $S_\gamma(Q_0^2,\mu^2)$ is prob. for no emission between Q_0^2 and μ^2 :

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

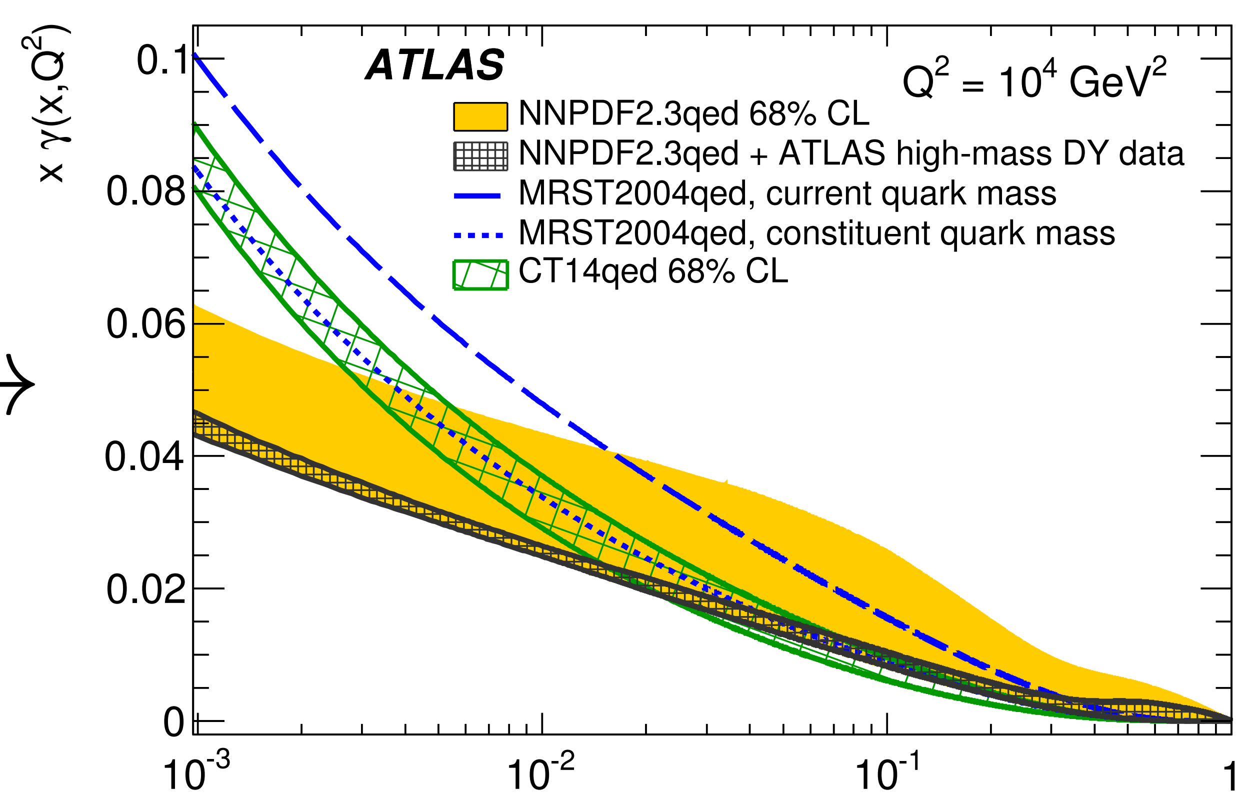
Constraint from ATLAS data

- 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.



$\leftrightarrow$



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 $Q^2 \gg m_p^2$

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

- Take LO in α_S for simplicity, then:

LL

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

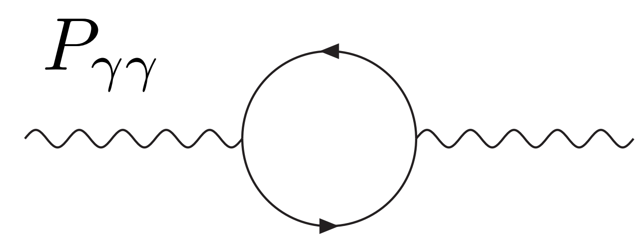
Cutoff

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:

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



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:

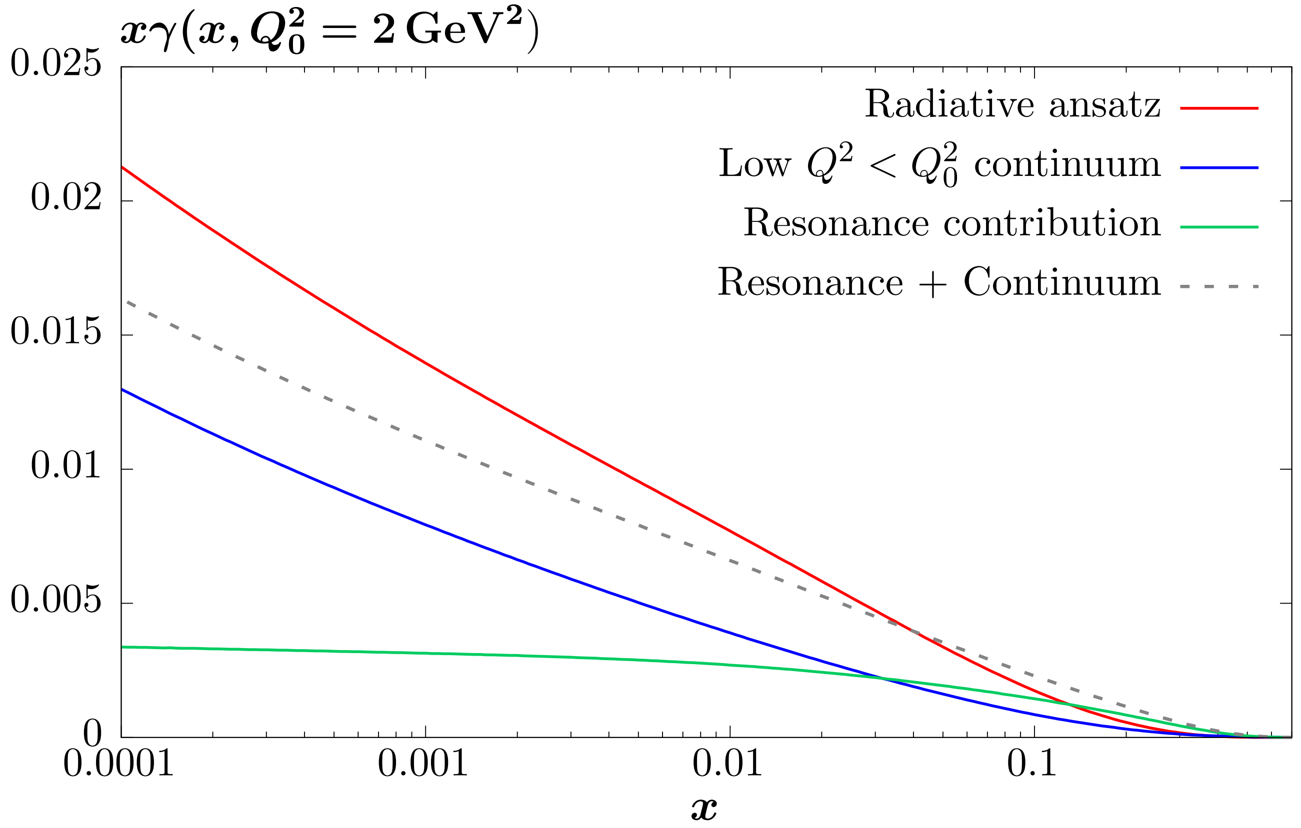
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\,S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2}\frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1\frac{dz}{z}\Big(\sum_q \underline{e_q^2 P_{\gamma q}(z)q(\frac{x}{z},Q^2)}$$
$$+ P_{\gamma g}(z)g(\frac{x}{z},Q^2)\Big)\,\underline{S_\gamma(Q^2,\mu^2)}\ ,$$

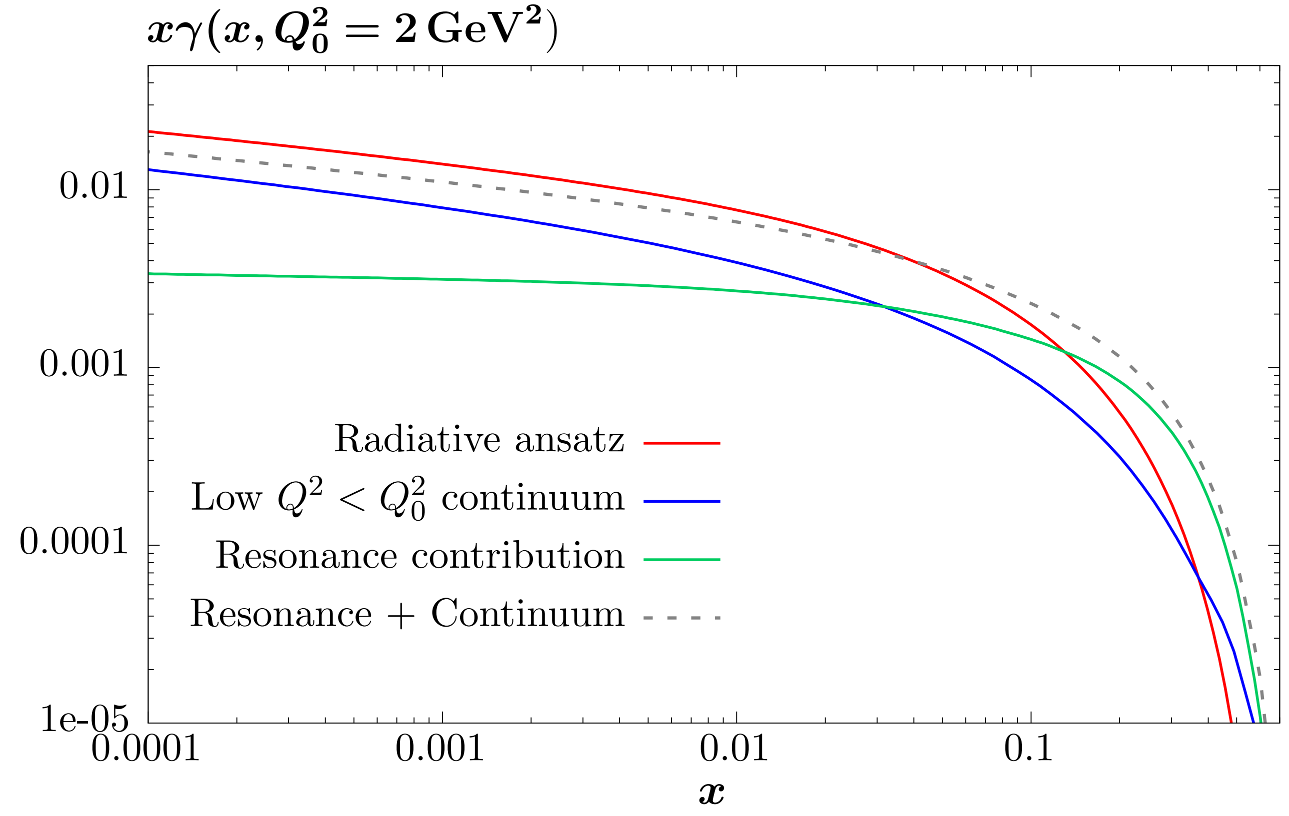
Caveat: omits influence of γ on quarks/gluons.

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 .

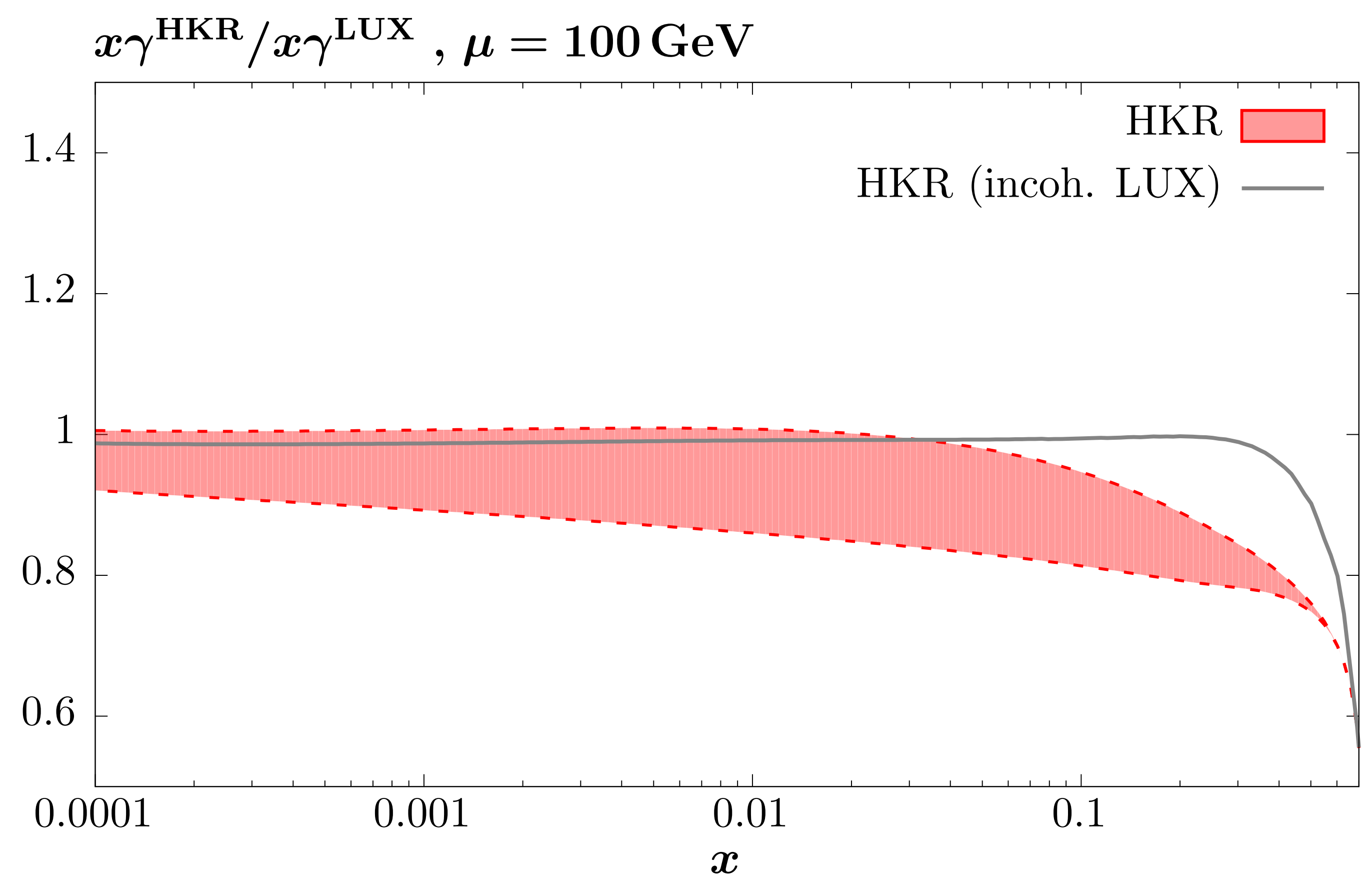
'Christy-Bosted' fit





LUXqed - comparison (2)

- Consider ratio of PDFs at $\mu = 100\,\mathrm{GeV}$. Lower end of HKR band given by setting $\gamma_{\mathrm{incoh}} = 0$ (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.