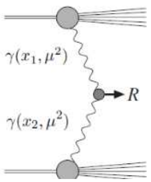
PHOTON COLLISIONS AT THE LHC (selected topics)

Valery Khoze (IPPP, Durham & PNPI, St.Pb.)

(in collaboration with Lucian Harland-Lang and Misha Ryskin)



Outline

- **Introduction and motivation**
- **Modelling exclusive photon-photon collisions.**
- **$\gamma\gamma$ · collisions- applications.**
- **Inclusive production-the photon PDF.**
- **Photon-initiated processes with rapidity gaps.**
- **Conclusion**

INTRODUCTION & MOTIVATION

- No immediate plans for a future $\gamma\gamma$ collider, but the LHC is already a photon-photon collider!

- 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 $\gamma\gamma$- Resonance that Stole Christmas 2015"

ATLAS &CMS seminar on 15 Dec. 2015

The ATLAS announcement of a 3.6 σ local excess in diphotons with invariant mass ~750 GeV in first batch of LHC Run –II data, combined with CMS announcing 2.6 σ local excess.

EW Moriond, 17.03.2016

Theoretical community –frenzy of model building: >150 papers within a month.

Unprecedented explosion in the number of exploratory papers.

(More than 400 papers currently)

If it were not a statistical fluctuation,
a natural minimal interpretation:
scalar/pseudoscalar resonance coupling dominantly to photons.

As an outcome -great improvement in our understanding of photon PDF and development of the effective tools for analysing potential diphoton resonances.

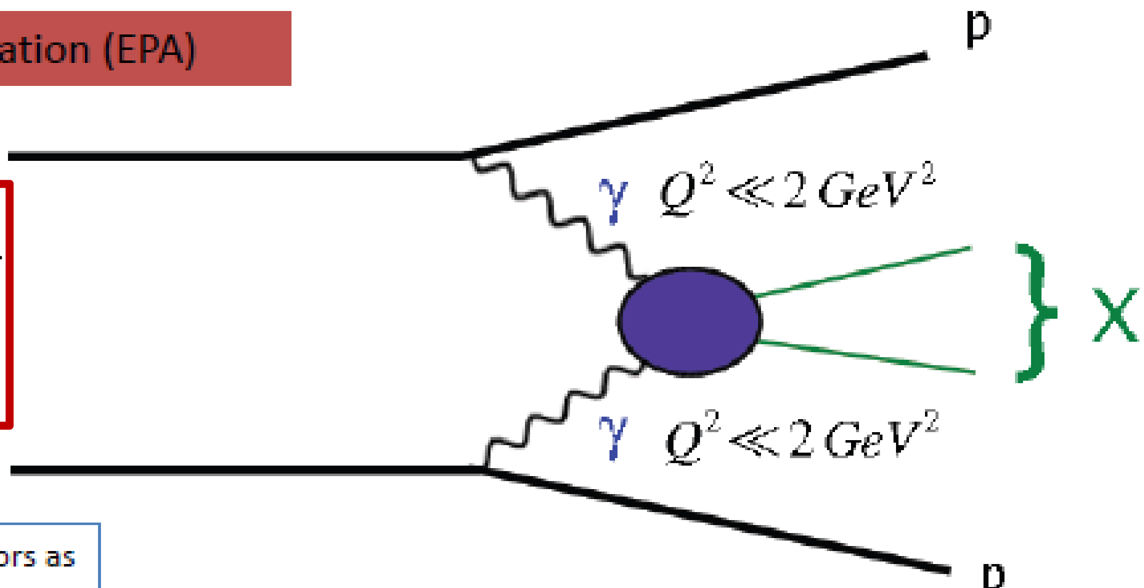
LHC as a $\gamma\gamma$ collider

Equivalent photon approximation (EPA)

C.F. von Weizsacker, 1934

E.J. Williams , 1934

E. Fermi, 1925



...introduced to major event generators as Madgraph, Pythia, Sherpa, Calchep

(FPMC)

$$\sigma(\,pp \to (\gamma\gamma \to X)\,pp\,)$$

low γ virtuality 

(SuperChic 2 HKR-1508.02718)

- factorization to
  - long distance photon exchange
  - short distance $\gamma\gamma \to X$ interaction

Equivalent photon approximation

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

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

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

$$\frac{d\mathcal{L}_{\gamma\gamma}^{\rm EPA}}{dM_X^2\, dy_X} = \frac{1}{s}\, n(x_1)\, n(x_2)$$

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

$$\frac{d\sigma^{pp\to pXp}}{dM_X^2 dy_X} = \langle S_{\rm eik}^2\rangle \frac{d\mathcal{L}_{\gamma\gamma}^{\rm EPA}}{dM_X^2} dy_X\, \hat{\sigma}(\gamma\gamma \to X)$$

$$\langle S_{\rm eik}^2\rangle = 0.72 \quad : \quad J_P = 0^+$$
$$\langle S_{\rm eik}^2\rangle = 0.77 \quad : \quad J_P = 0^-$$

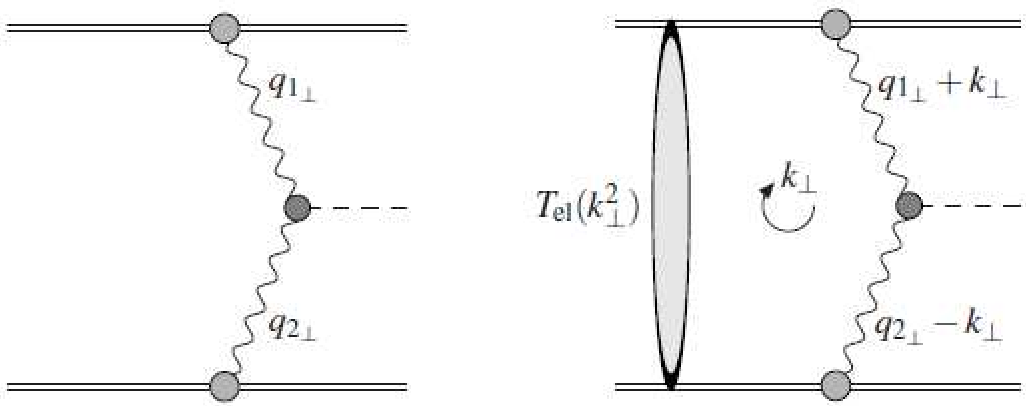
In fact, the situation is more complicated due to the effects caused by the polarization structure of the production amplitude.

SURVIVAL GUIDE

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).
- $\gamma\gamma$-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'.

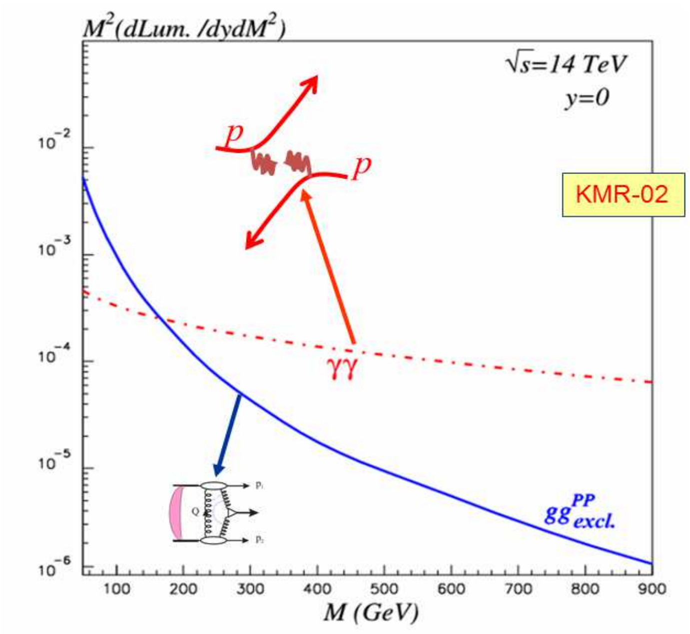


Durham Group-KMR
Tel-Aviv Group- GLM

(Radek, this meeting)

$\alpha_s^2/8 \to \alpha^2$

QCD ‘radiation damage’ in action



- 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 $M_X \gtrsim 200\,\mathrm{GeV}$ - 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.

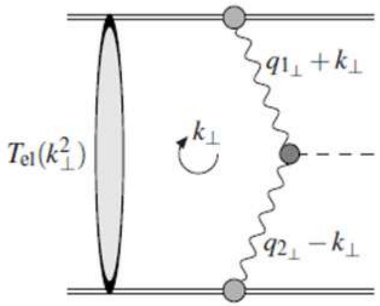
The only MC generator which consistently incorporates the calculation of survival factors and Sudakov effects (HKR arXiv:1508.02718)

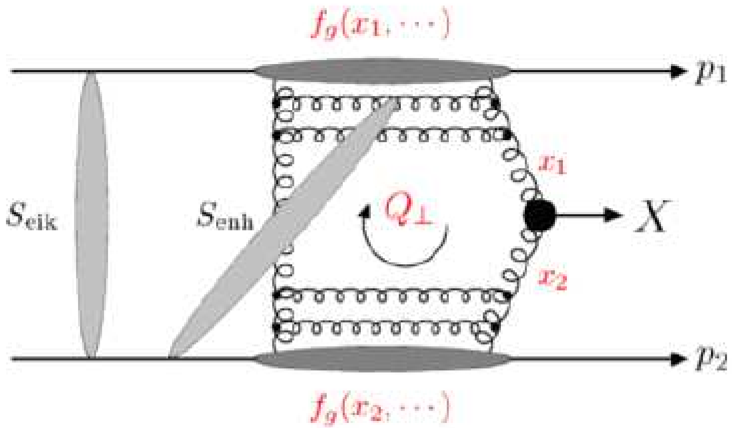
- Have developed a MC for a range of CEP processes, widely used for LHC analyses. Available on Hepforge:

SuperChic 2 - A Monte Carlo for Central Exclusive Production

- Home
- Code
- References
- Contact

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 >.

$\gamma\gamma$ 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

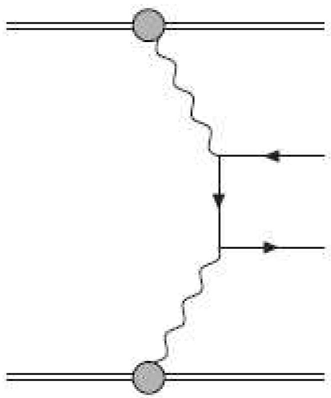
Measurement of exclusive $\gamma\gamma \to \ell^+\ell^-$ production in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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
$\lvert\eta^{\ell}\rvert$	< 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	$0.628 \pm 0.032 \pm 0.021$	$0.428 \pm 0.035 \pm 0.018$

HKR,arXiv:1508.02718

$\rightarrow$ 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.

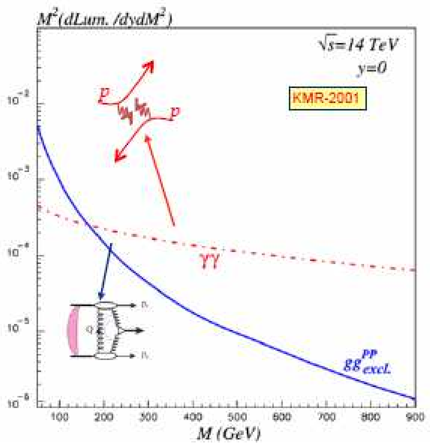
- Have confidence in framework $\Rightarrow$ consider implications for BSM…

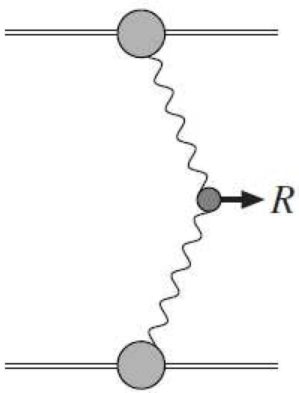
The diphoton (ex)-resonance

- 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.

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

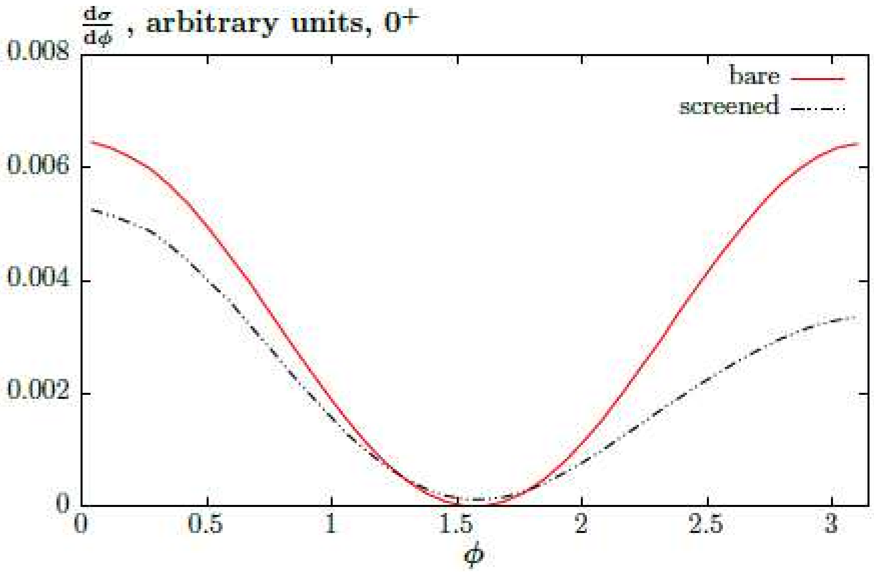
$\longrightarrow$ Observation of just a few events in exclusive mode would give strong evidence for $\gamma\gamma$ production mode.

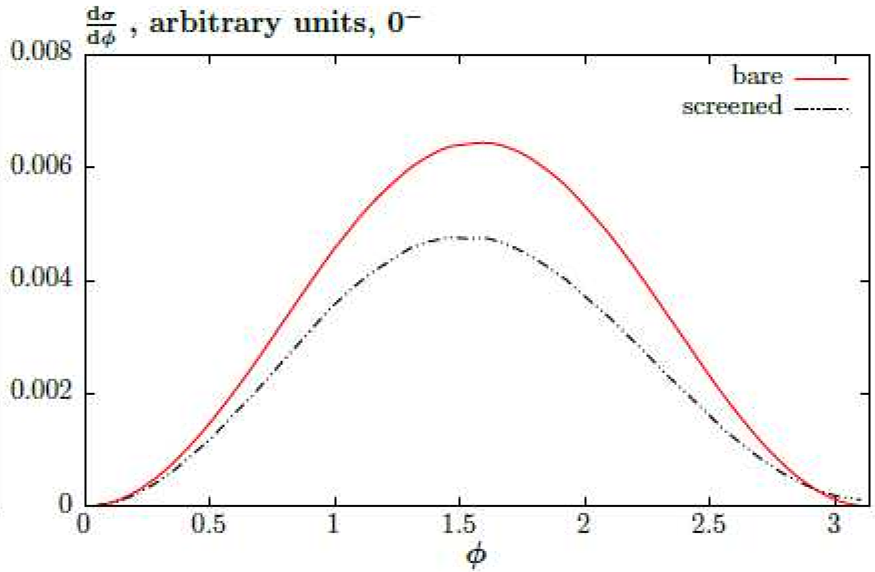




Proton correlations

- 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.

KMR-2004

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.

September 3 2015

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

Finally published in J. Phys. G.

LHC Forward Physics

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

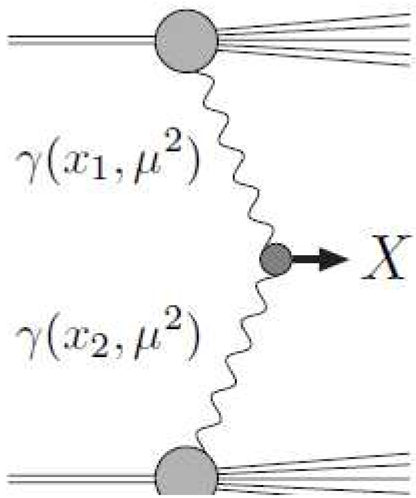
• Rich $\gamma\gamma$ physics at LHC: see E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003; S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys.Rev. D89 (2014) 114004 ; S.Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP 1502 (2015) 165

Inclusive Production-the Photon PDF

- 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), $\gamma(x, \mu^2)$.

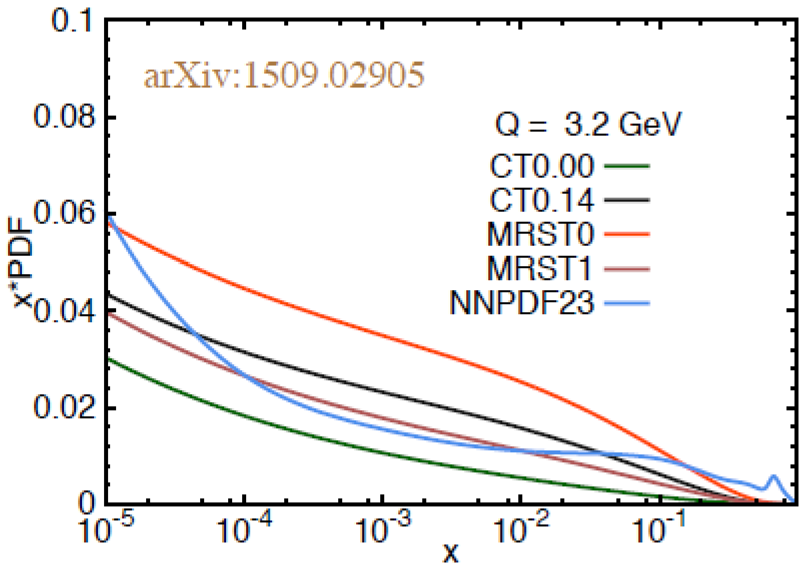


NOT SO LONG AGO

- 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.

    worrisome range

  - 'Model' approach. MRST2004QED/CT14QED: take simple ansatz for photon emission from quarks. Compare/fit to ZEUS isolated photon DIS.



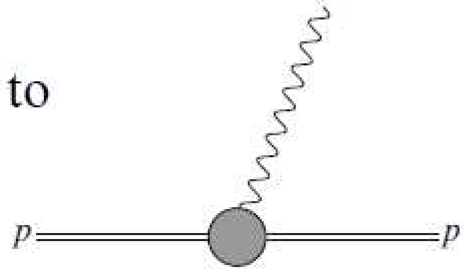
- Comparing these different sets reveals apparently large uncertainties.

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

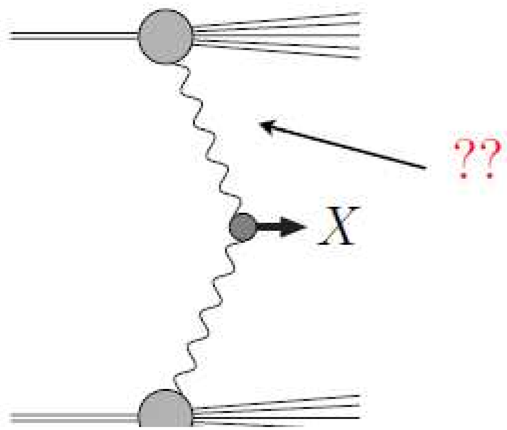
PDFs and QED

• 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.

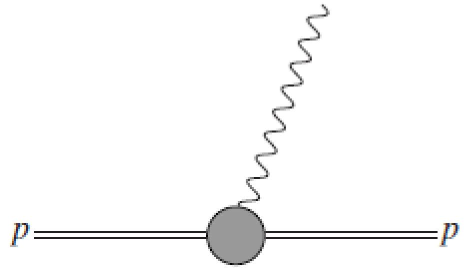


• How do we do this? Consider what can generate initial state photon in $\gamma\gamma \to X$ production process:



PDFs and QED

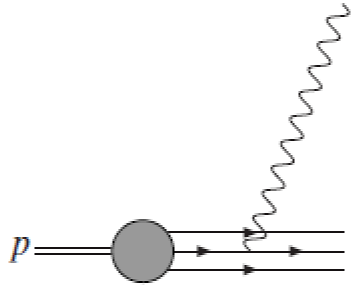
- Inclusive $\equiv$ system X + anything else $\Rightarrow$ exclusive production by definition should be included, i.e. elastic emission.



Elastic emission

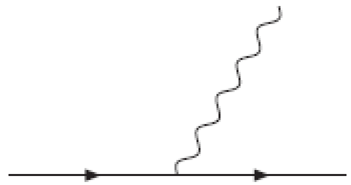
- However clearly not end of story:

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

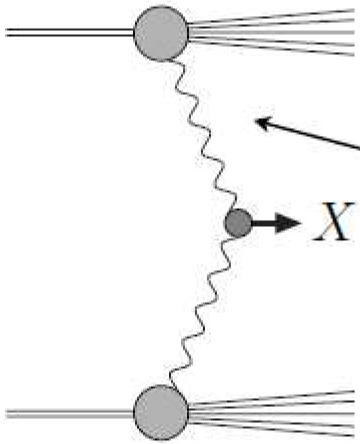


(Low scale) 'incoherent' emission.

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



DGLAP evolution



- Schematically:

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

- More precisely, from DGLAP equation:

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

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

$\longrightarrow$ 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).

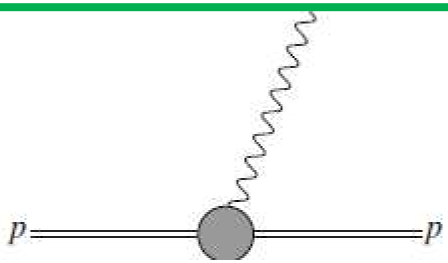
LHL, V.A. Khoze, M.G. Ryskin, arXiv:1601.03372, 1601.07187, 1607.4635

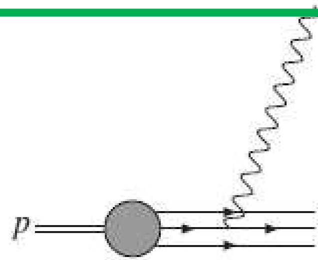
PDFs and QED

- 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.

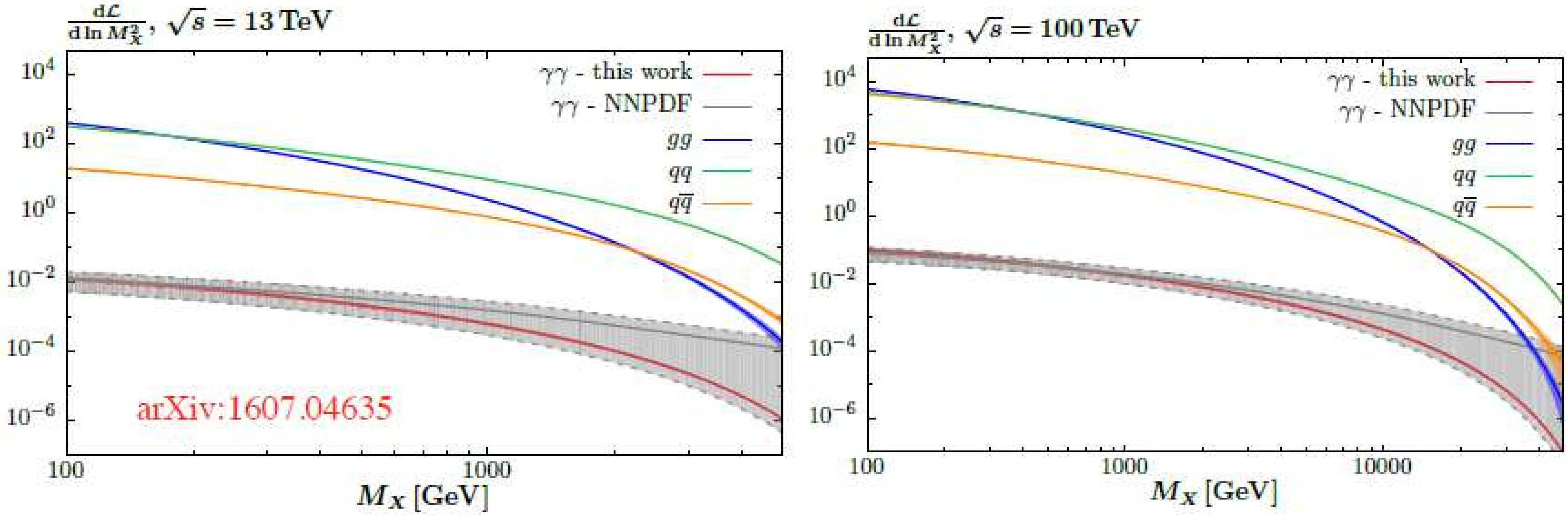
- We treat the coherent emission process exactly as in exclusive production, while taking simple model for (low scale) incoherent. Sufficient to give some fairly dramatic results w.r.t. previous studies.





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 $qq/q\overline{q}$, with gg only slightly stepper. Uncertainties fairly small, again a lower end of NNPDF band.



LUXqed (1)

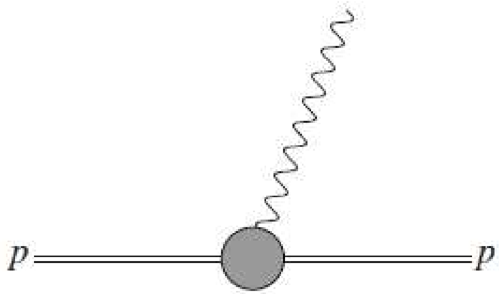
The LUX photon PDF determination

arXiv:1607.04266

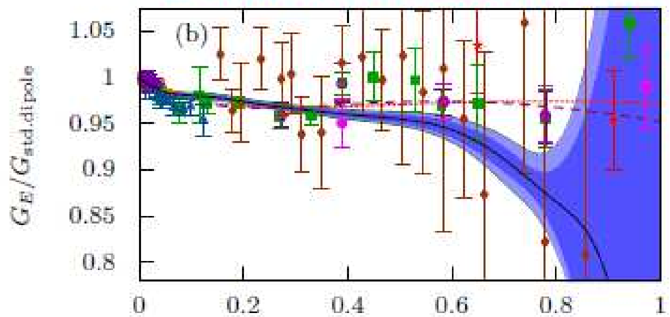
How bright is the proton?
A precise determination of the photon PDF

Aneesh Manohar,[1,2] Paolo Nason,[3] Gavin P. Salam,[2,*] and Giulia Zanderighi[2,4]

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

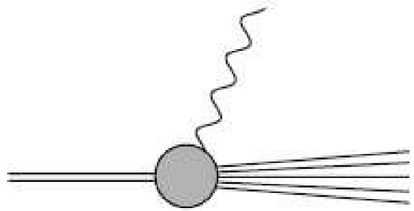


A1 Collaboration, arXiv:1307.6227



• 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.



▸ Compute the photon PDF at $\mu = 100\,\mathrm{GeV}$, with the low Q^2 component determined from A1, CLAS and Hermes GD11-P

LUXqed (2)

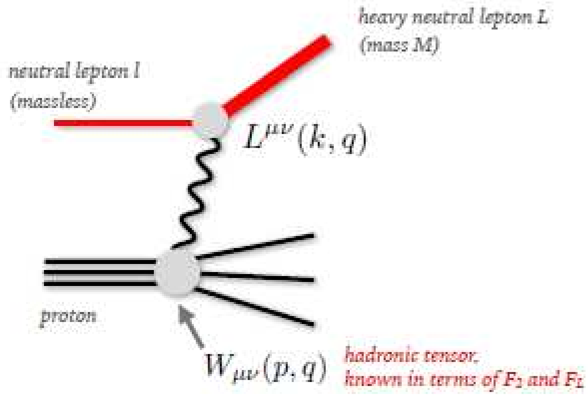
Take a hypothetical (BSM) flavour-changing heavy-neutral lepton production process, and calculate the cross section in two ways

- using proton structure functions (F_2 and F_L)
- using photon parton distribution function

Imposing an equality between the two expression gives a model-independent, data driven determination on the photon PDF

- 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.

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

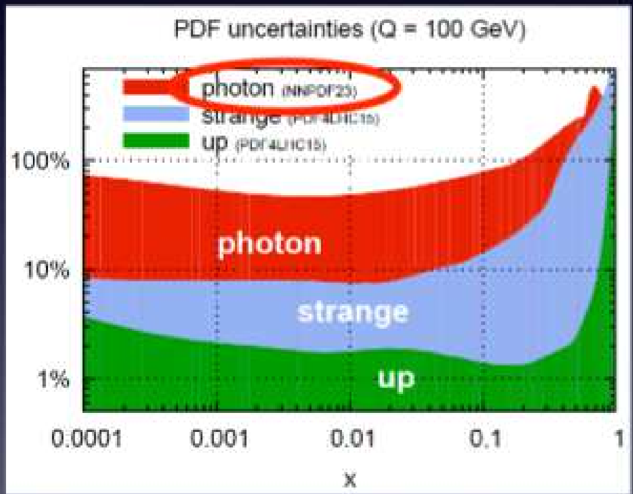


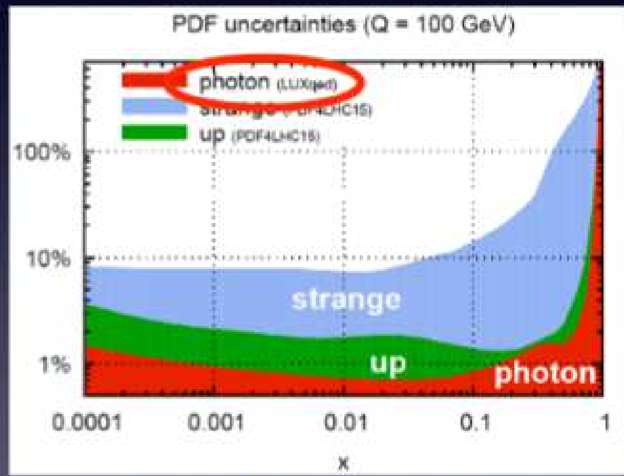
LUX Photon PDF determination relies on high precision DIS data

(also A. Szczurek et al, 2015)

The photon PDF

Interest in photon PDF spurred by 750 GeV di-photon resonance, but also important for precision physics in general (electro-weak corrections, Higgs, Drell Yan, di-bosons …)

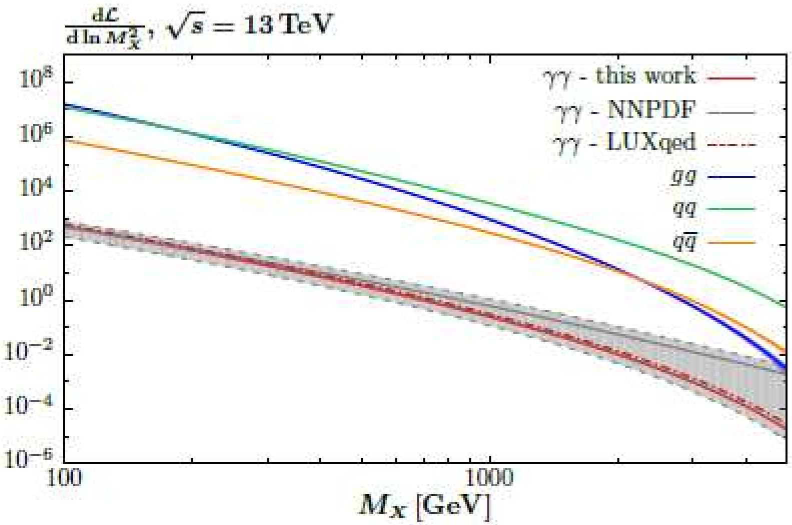


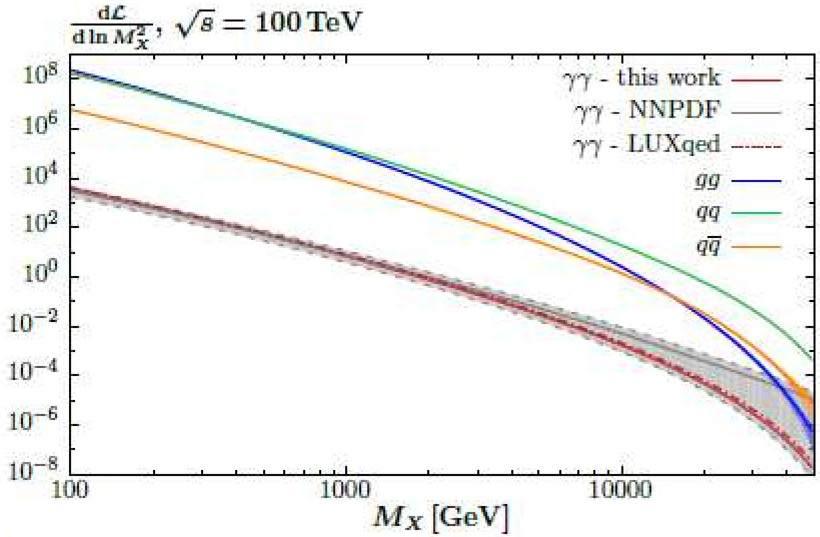


A. Manohar, P. Nason, G. Salam, GZ 1607.04266

- valence quarks known to few percent
- others quarks to 10% over a large x-range
- data driven photon PDFs have O(100%) uncertainty (model dependent PDFs have much small uncertainties, vast literature)

LUXqed - comparison

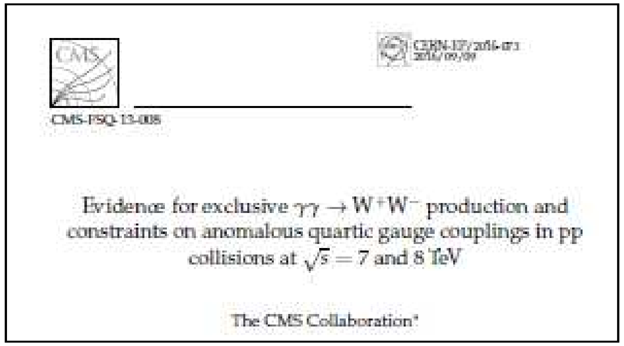




- Comparing our and LUXqed $\gamma\gamma$ luminosities can see these are quite similar ($\longrightarrow$ importance of coherent component).
- Devil is in detail - some enhancement seen in LUXqed at higher M_X, appears to be due to low Q^2 resonant contribution.
- However, clear we have moved beyond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

- MMHT work to include photon PDF in global fit framework ongoing.

Photon-initiated processes with rapidity gaps

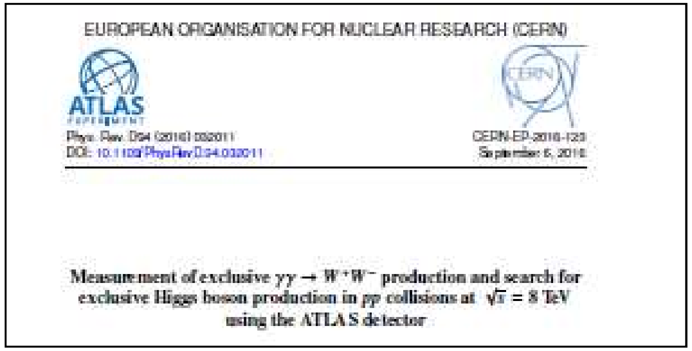


CMS-FSQ-13-008

CERN-EP/2016-071
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)

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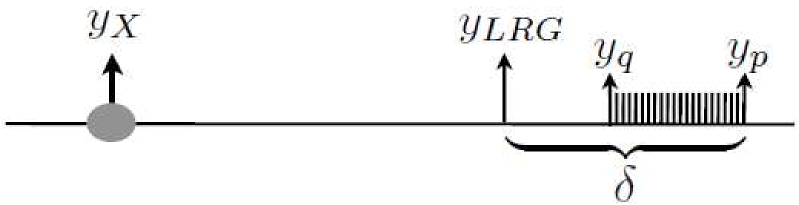
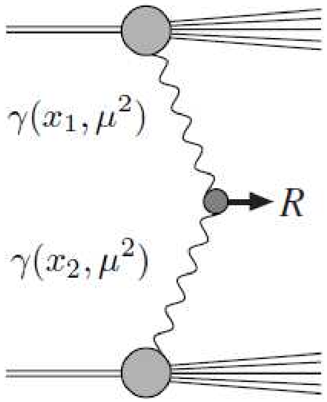
CERN-EP-2016-123
September 6, 2016

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

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

HKR arXiv:1601.03772



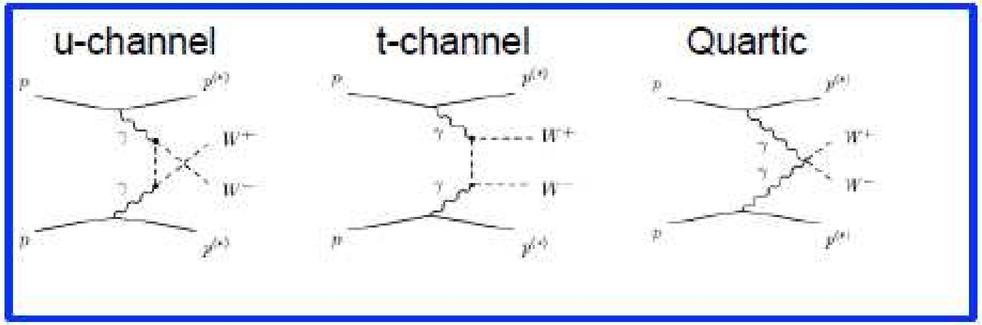


Exclusive $\gamma\gamma \rightarrow W^+W^-$, exclusive Higgs production

Search for $pp \rightarrow p^{(*)} W^+W^- p^{(*)}$

- Measure Standard Model Cross section
- Search for anomalous quartic gauge couplings (aQGC)

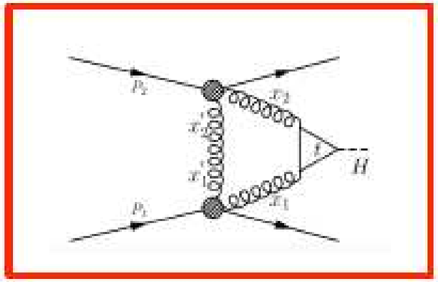
ATLAS & CMS



Search for exclusive Higgs production via $H \rightarrow WW$

- Production mechanism via gluon fusion
- opportunity to study Higgs properties in clean environment

ATLAS



Both cases: Similar characteristics

- Opposite sign μe pair (final state) originating from common primary vertex (same sign not used due to high Drell Yan and elastic production)
- Vertex must be isolated from other objects
- $p_T(e\mu) > 30$ GeV (SM), $p_T(e\mu) > 100$ GeV (aQCG)

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

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 colour-singlet photon initial state can lead naturally to large rapidity gaps in the final state.

• In such cases can no longer apply usual inclusive PDFs, but with suitable modifications accounting for:

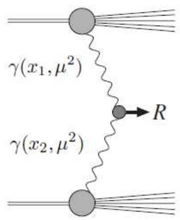
- Rapidity veto in DGLAP equation.
- Soft survival effects.

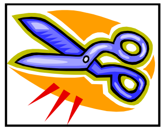
can make robust predictions for such semi-exclusive processes.

• Consider photon-initiated production of a system X:

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

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





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

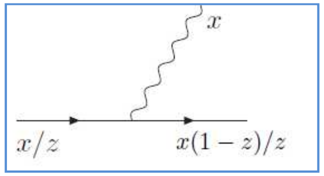
$$\gamma(x,\mu^2) \equiv \gamma^{\mathrm{in}}(x,\mu^2) + \gamma^{\mathrm{evol}}(x,\mu^2)$$

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

(satisfies veto)

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

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



- And photon PDF becomes simply:

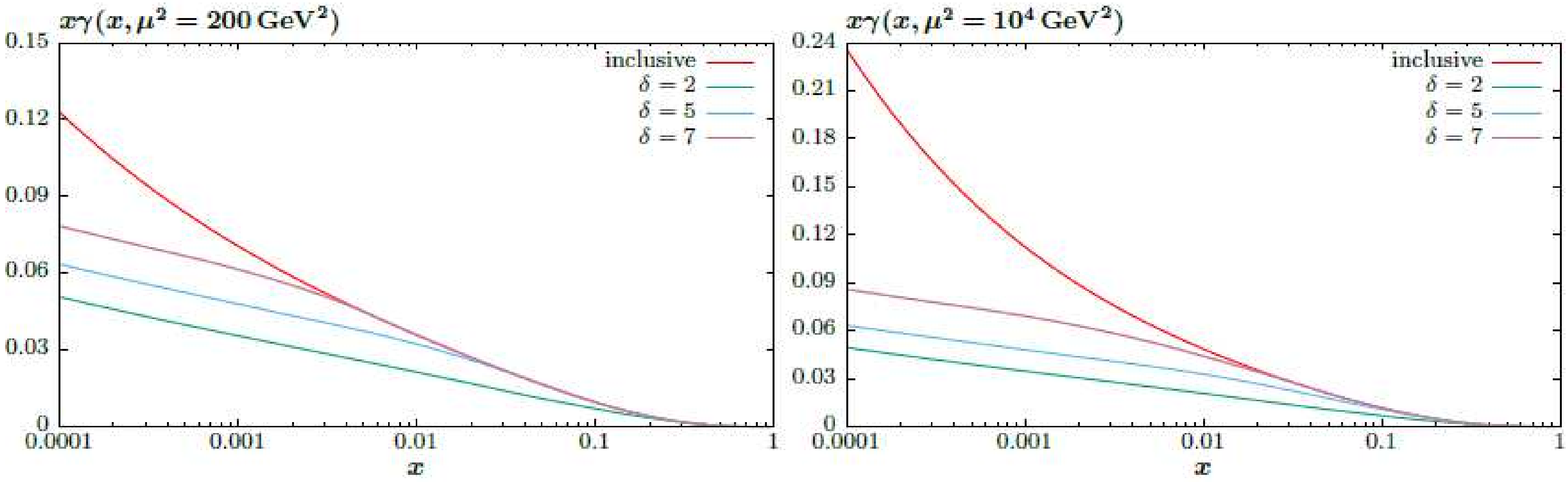
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\, S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{\mathrm{d}Q^2}{Q^2}\int_x^1 \frac{dz}{z}\Bigg(\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2$$

$$+ P_{\gamma g}(z) g(\frac{x}{z},Q^2)\Bigg) S_\gamma(Q^2,\mu^2)\Theta\left[e^\delta - \frac{q_t}{m_p}\frac{z}{x(1-z)}\right]\ ,$$

(RG veto in DGLAP equation)

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

Modified photon PDF

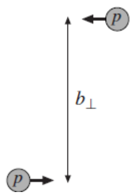


Suppression due to LRG veto.

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

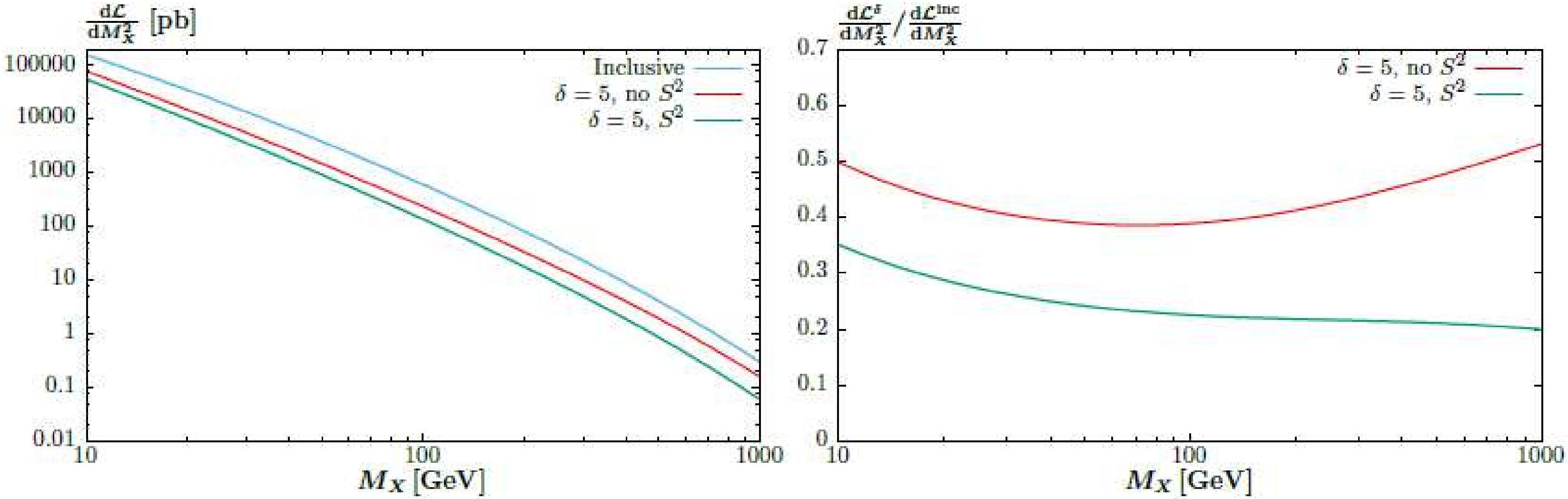
phenomenological objects only-factorization explicitly violated by rescatteringl effects

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



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

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



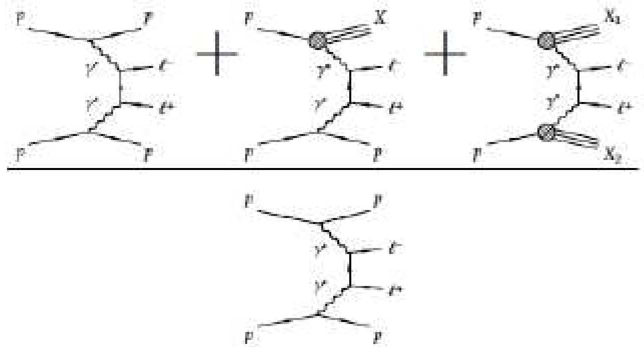
$\tau = M_X^2/s$ and we take $\mu^2 = M_X^2$ as the scale of the PDFs

Exclusive $\gamma\gamma \rightarrow W^+W^-$: Proton Dissociation Backgrounds

$$\sigma_{\gamma\gamma}^{\text{total}} = F \times \sigma_{\gamma\gamma}^{\text{elastic}}$$

- F measures the single and double proton dissociation contribution to signal
- It is extracted using a data driven method

$F =$

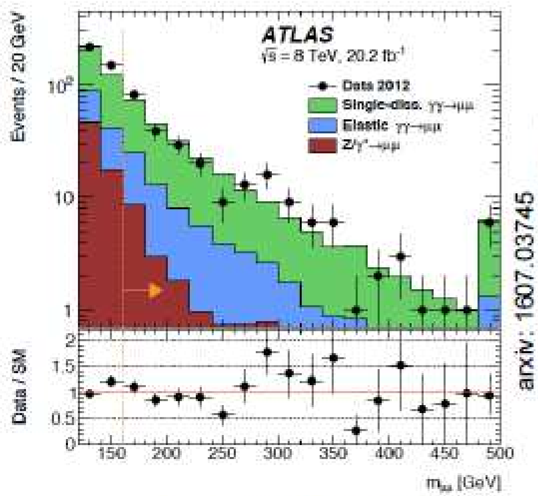


signal kinemati region

Pure elastic $\gamma\gamma \rightarrow l^+l^-$ selection at > twice W mass

$$F = \frac{N_{\text{Data}} - N_{\text{MC Background}}}{N_{\text{MC Elastic}}}$$

.Resulting correction factor ~ 3.3 (ATLAS) / 4.1 (CMS)
Uncertainties of ~7% dominated by statistical uncertainty



arxiv: 1607.03745
Submitted to Phys.Rev.D

ATLAS: control sample including correction factor F

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

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

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

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

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

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

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

CMS 8 TeV data

CMS

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

CMS-FSQ-13-008

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

- measurement: $F = 4.10 \pm 0.43,$
- Our central prediction: $F = 3.7$

Good agreement.

Also a good agreement with ATLAS 8 TeV result: $3.30 \pm 0.22(\text{stat}) \pm 0.06(\text{sys}).$

PHYSICAL REVIEW D **94**, 032011 (2016)

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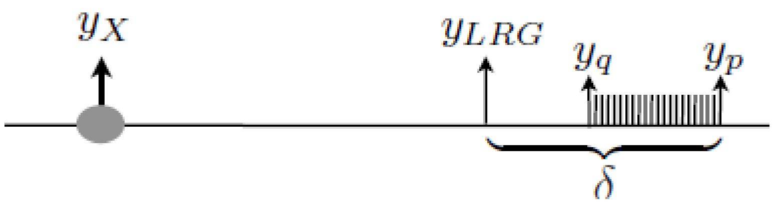
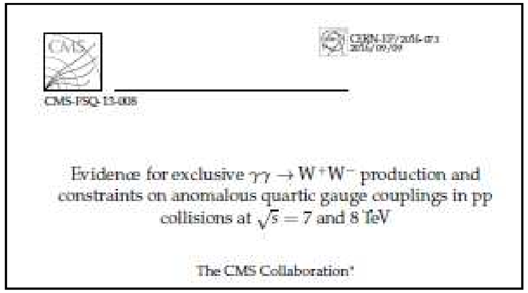
Semi-exclusive production

- 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.

In principle allows to evaluate the photon flux using the DIS-based LUXqed results for input incoherent photon distribution to describe the events with Rapidity Gaps (or other experimental cuts).

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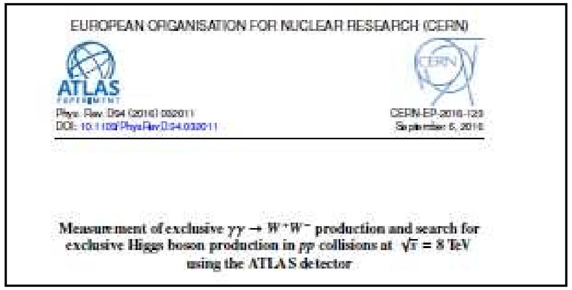
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CONCLUSION

- 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.

- 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.
- A formalism is developed allowing to describe photon-induced events with LRG in terms of modified photon PDF with consistent implementation of the soft survival effects


THANK YOU


QUESTIONS?

BACKUP

"On the Theory of Collisions between Atoms and Electrically Charged Particles"
Note by: Enrico Fermi, 1924
Appeared in Nuovo Cimento 2, pp. 143-158 (1925)
(translated from Italian by Michele Gallinaro and Sebastian White, New York 2001)

Enrico FERMI

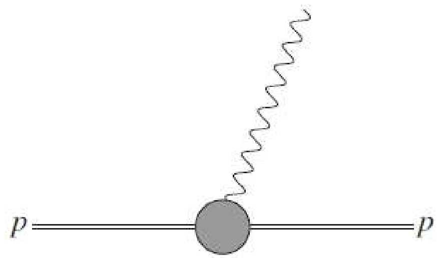
arXiv:hep-th/0205086v1 9 May 2002

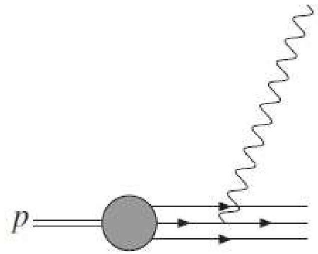
Translators' Note:

In the fall of 1924, Enrico Fermi visited Paul Ehrenfest at Leyden on a 3-month fellowship from the International Education Board (IEB). Fermi was 23 years old. In his trip report to the IEB, Fermi says he learned a lot about cryogenics and worked on two scientific papers, including the following one. It was submitted in German to Zeitschrift für Physik. The German version was known to Weizsäcker and Williams and cited in the papers (10 years) later in which they extended Fermi's method to the Ultra-Relativistic case. The German version was subsequently translated into a Russian version and perhaps other languages. Fermi's Italian version (printed in *Nuovo Cimento*) is less widely known and does not appear in the "Collected Works". Nevertheless, Persico remarks that this was one of Fermi's favorite ideas and that he often used it in later life. So, we would like to think of this as a late 100^{th} birthday present to the Italian Navigator.
We would like to thank Professor T.D. Lee for his encouragement of this project and for interesting discussions about Fermi. Also Tom Rosenblum at the Rockefeller Archives for bringing Fermi's correspondence to our attention and Bonnie Sherwood for typing the original manuscript.

Why is it important ?

• 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.

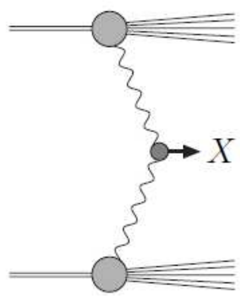
• In era of high precision phenomenology at the LHC: NNLO calculations rapidly becoming the 'standard'. However:

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

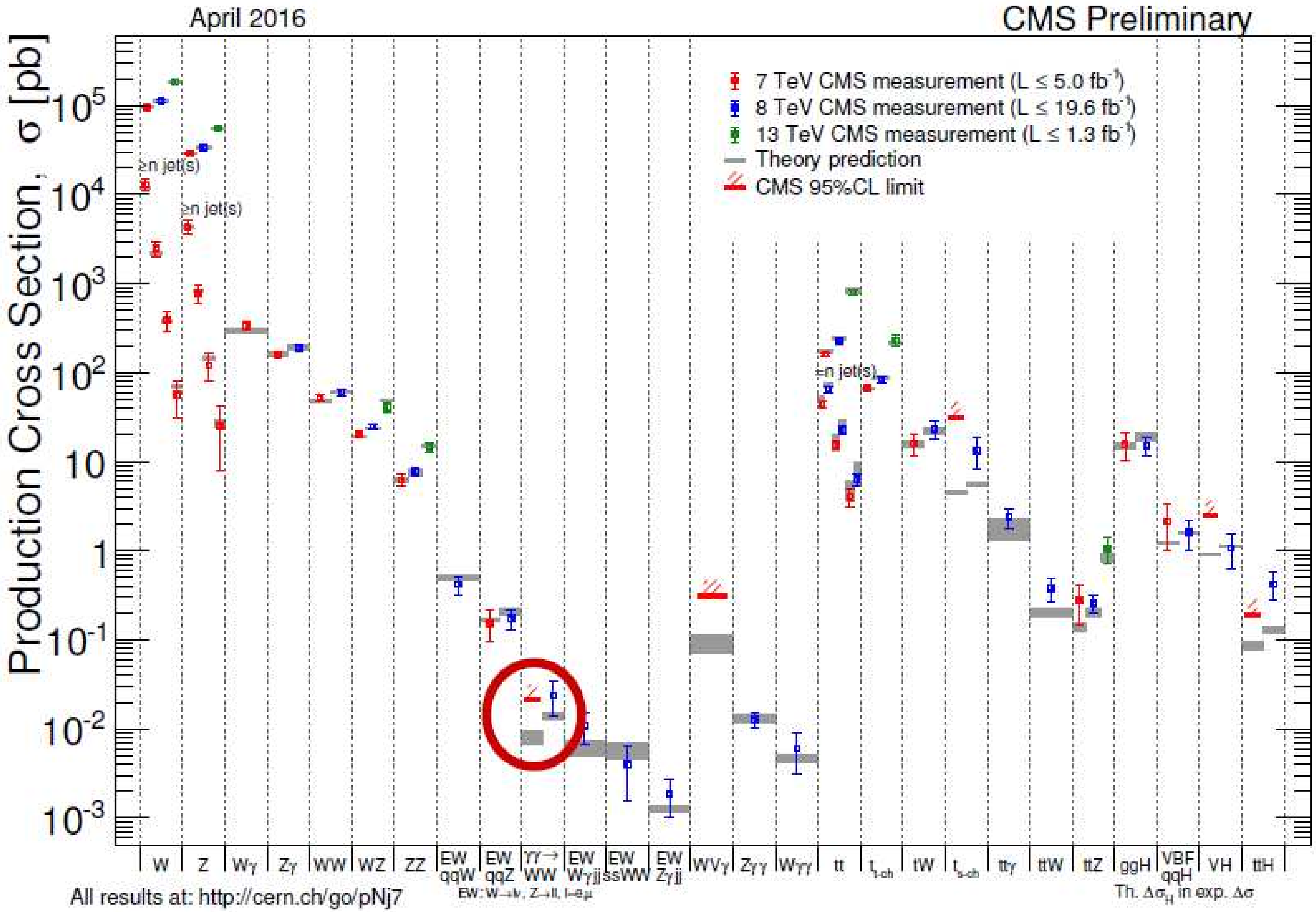
→ EW and NNLO QCD corrections can be comparable in size.

• 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.

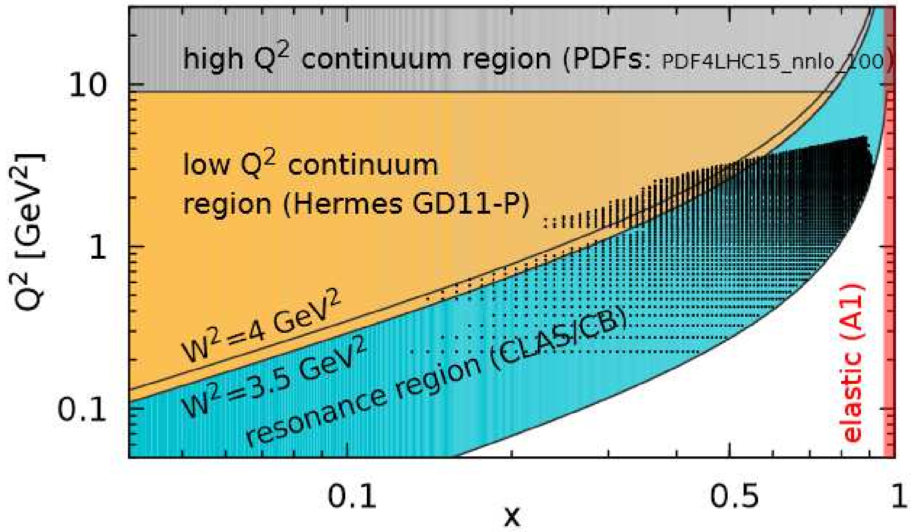


Still among the lowest cross sections reachable at the LHC



Inelastic Data coverage

- Low Q^2 continuum essentially covered by data.
- F_2 and F_L must vanish as Q^2 and Q^4 at constant W (by analiticity of $W^{\mu\nu}$).



Also:

$$F_2(x,Q^2) = \frac{1}{4\pi^2\alpha}\frac{Q^2(1-x)}{1+\frac{4x^2m_p^2}{Q^2}}(\sigma_T(x,Q^2)+\sigma_L(x,Q^2)) \underset{Q^2\to 0}{\Longrightarrow} \frac{Q^2\sigma_{\gamma p}(W)}{4\pi^2\alpha^2}.$$

At small Q^2, $\sigma_T \Longrightarrow \sigma_{\gamma p}(W)$, becoming a function of W only (the *CM* energy in photoproduction), and σ_L vanishes.
Photoproduction data included in Hermes and Christy-Bosted parametrizations.

There is a vast literature touching this topic.

- Elastic component: Budnev etal, 1975; Gluck, Pisano and Reya, 2002; Martin and Ryskin, 2014; Harland-Lang, Khoze and Ryskin, 2016; `CTEQ14qed_inc`
- *ep* scattering connection: Mukherjee and Pisano, 2003; Łuszczak, Schäfer, and Szczurek, 2015. (PRD 93(2016)074018)

In the work of Mukherjee and Pisano, a formula similar to our master equation appears, except for the inclusion of the $\overline{\mathrm{MS}}$ correction, and for different integration limits.
A similar formula appears also in Łuszczak, Schäfer, and Szczurek, except that, due to their small x approximation, their result does not obey the correct evolution equations. They also make use of data driven parametrizations of structure functions.