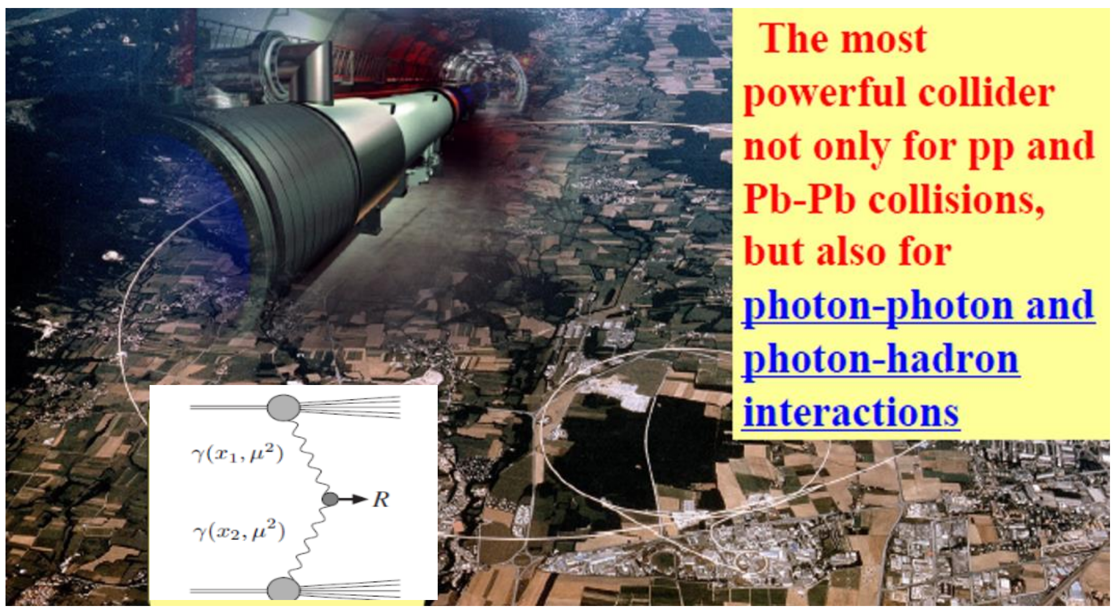
EDS Blois 2017

17th International Conference on Elastic and Diffractive Scattering
Prague, Czech Republic, 26-30 June 2017

PHOTON-PHOTON COLLISIONS AT THE LHC
(very selected topics)

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

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



Outline

- Introduction and Motivation.
- SuperChic- MC and Survival Guide
- The photon PDF and photon-photon Luminosities
- Photon-initiated processes with rapidity gaps
- Summary and Outlook.

INTRODUCTION & MOTIVATION

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

(FNAL/RHIC-experience)

Motivation: why study $\gamma\gamma$ collisions at the LHC?

- Exclusive production:
  - How do we model it?
  - Example processes: lepton pairs, anomalous couplings, light-by-light scattering, axion-like particles and massive resonances, charginos, invisibles...
  - Outlook - tagged protons at the LHC.

"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.

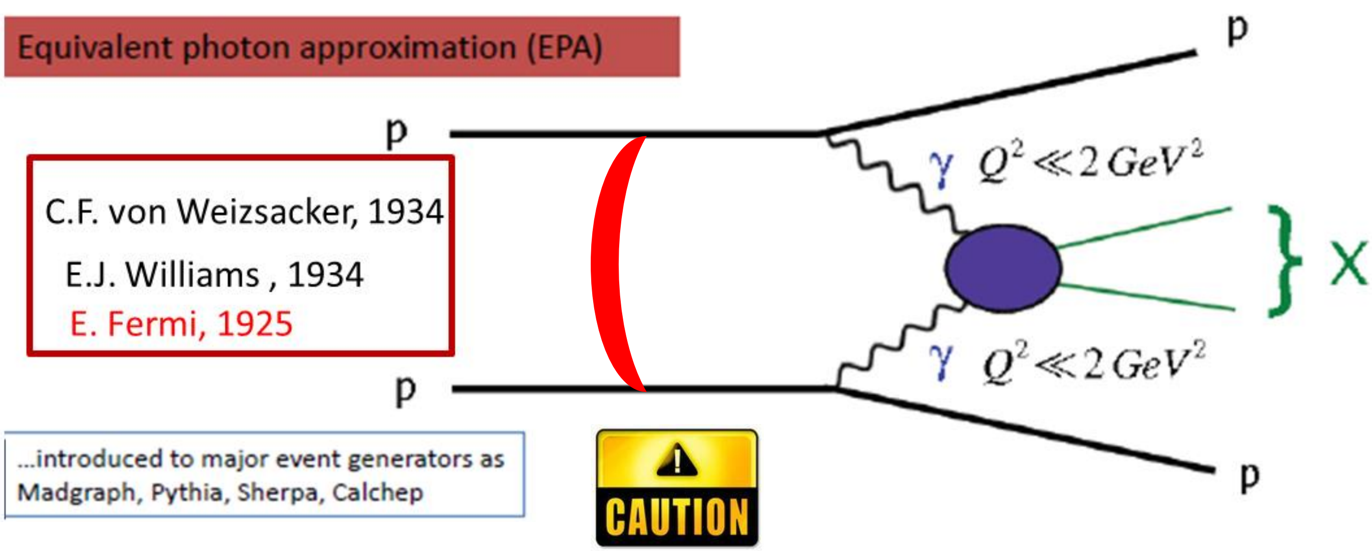
(More than 600 papers)

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.

Modelling Exclusive Photon-Photon 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.



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':

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

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

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

$$\frac{\mathrm{d}\sigma^{pp\to pXp}}{\mathrm{d}M_X^2\mathrm{d}y_X} = \langle S_{\mathrm{eik}}^2\rangle\,\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2}\mathrm{d}y_X\;\hat{\sigma}(\gamma\gamma \to X)$$

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

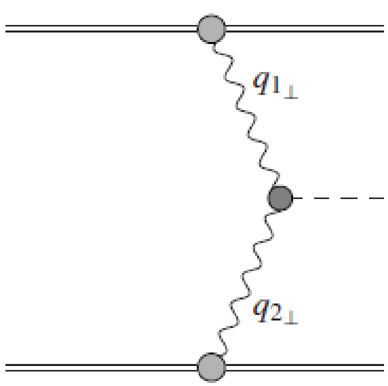
In fact, the situation is more complicated due to the effects caused by the polarization structure of the production amplitude.

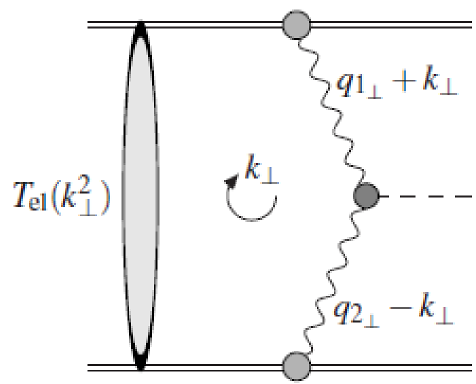
Soft survival factor

- 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'.

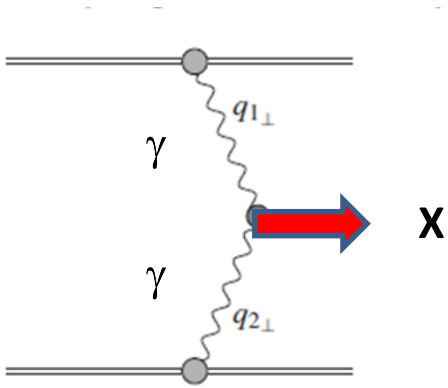
(Giulia, Sergey)



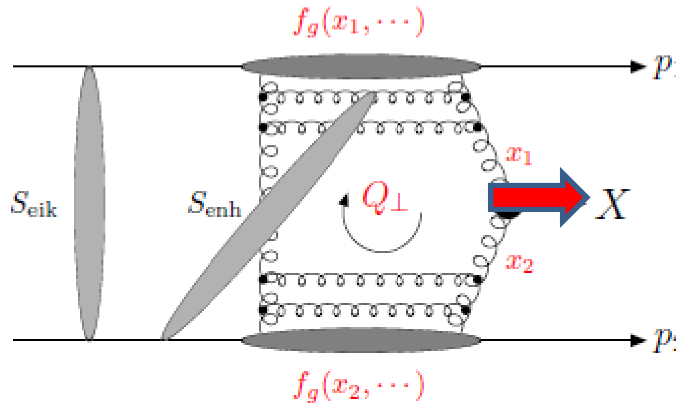


Durham Group-KMR
Tel-Aviv Group- GLM

S. Ostapchenko…
Lonnblad & Zlebcik



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:

'Large' Pomeron size in the production of the small size objects.

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

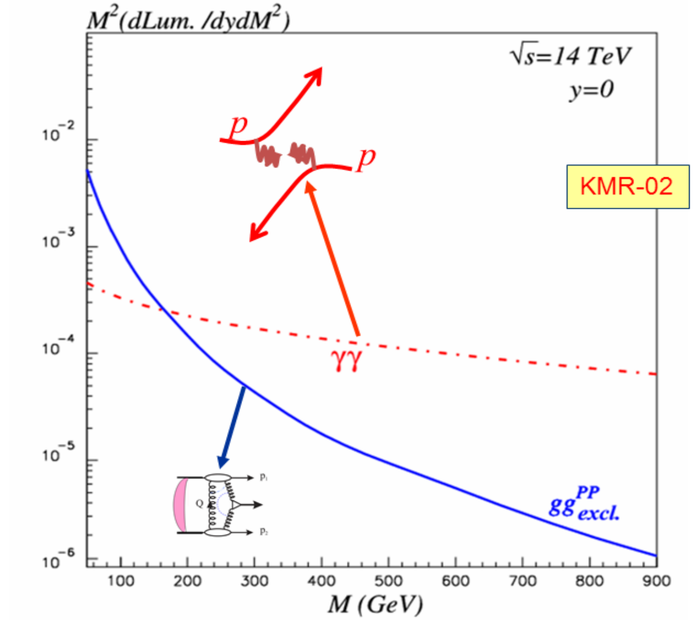
- Increasing M_X $\Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

+ absorptive/rescattering effects- survival factor $S^2_{\rm soft}$

KMR-2001

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

QCD 'radiation damage' in action

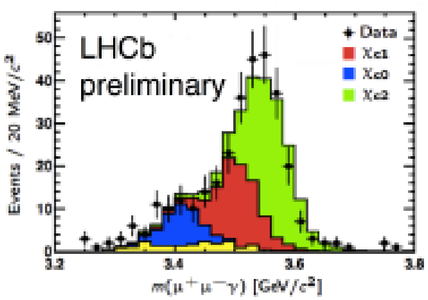


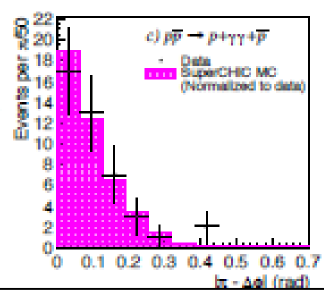
• Situation summarised in 'effective' exclusive gg and $\gamma\gamma$. luminosities. This Sudakov suppression in QCD cross section leads to enhancement in $\gamma\gamma$ already* for $M_X \gtrsim 200\,\mathrm{GeV}$ - well before CT-PPS/AFP mass acceptance region.

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

SuperChic

- A MC event generator for CEP processes. Common platform for:
  - QCD-induced CEP.
  - Photoproduction.
  - **Photon-photon** induced CEP.
- With fully differential treatment of survival effects.
- Photon-induced collisions currently for e/p beams. Work towards heavy ions ongoing
- Fortran-based. Generates histograms and unweighted (LHE/HEPEVT) events with arbitrary user-defined cuts.





arXiv:1508.02718

Exclusive physics at the LHC with SuperChic 2

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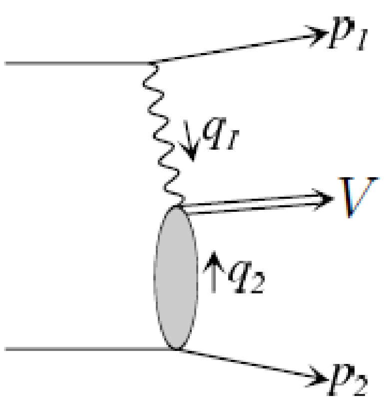
Abstract

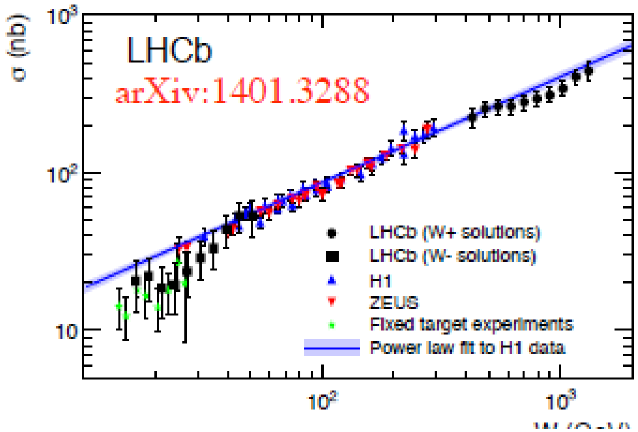
We present a range of physics results for central exclusive production processes at the LHC, using the new SuperChic 2 Monte Carlo event generator. This includes

Generated Processes - photoproduction

- $\rho(\to \pi^+\pi^-)$
- $\phi(\to K^+K^-)$
- $J/\psi(\to \mu^+\mu^-)$
- $\Upsilon(\to \mu^+\mu^-)$
  $\psi(2S)(\to \mu^+\mu^-, J/\psi\pi^+\pi^-)$



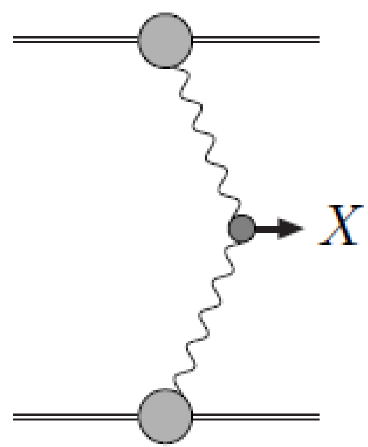
- Takes simple power-law fit to HERA/LHC data.



Generated Processes - photon-photon

- SM Higgs to $b\bar{b}$
- $W^+W^- \to ll\nu\nu$, including spin correlations.
- l^+l^-
- $\gamma\gamma$ (light-by-light).
- Monopolium, Monopole pairs*.

• In official release, both proton and electron beams included. Work ongoing on including heavy ions.



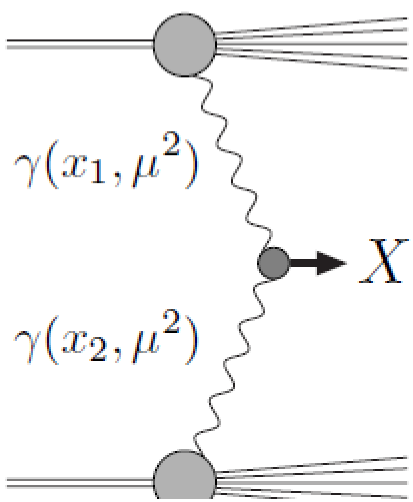
*To appear in next version.

Photon-photon Luminosities

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



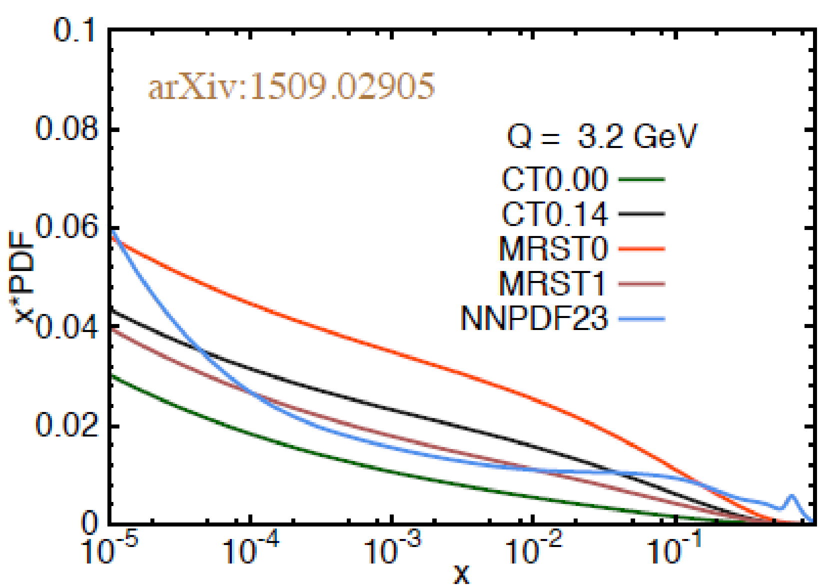
- Earlier photon PDF sets either:

Not so long ago

  - '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.

worrisome range

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



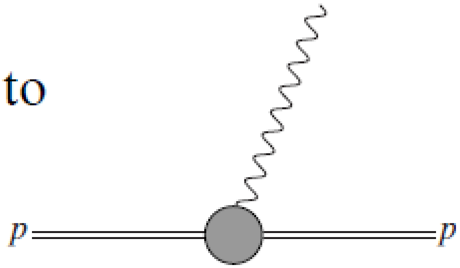
- Comparing these different sets reveals apparently large uncertainties.

  ➤ Model-independent uncertainty (NNPDF) was 50–100%

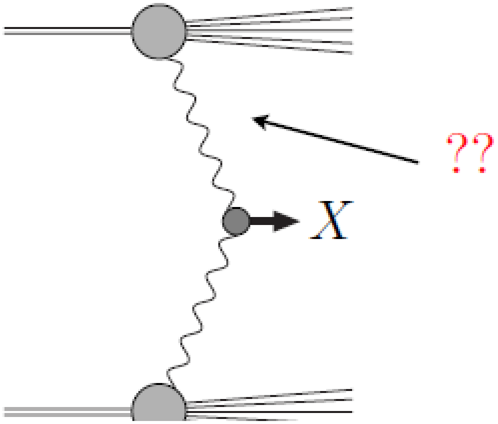
PDFs and QED

- 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:



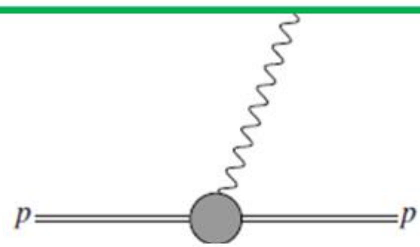
HKR arXiv:1601.03372, 1601.07187, 1607.4635

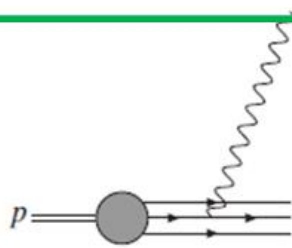
Photon distribution inside the proton (photon PDF)

- 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.



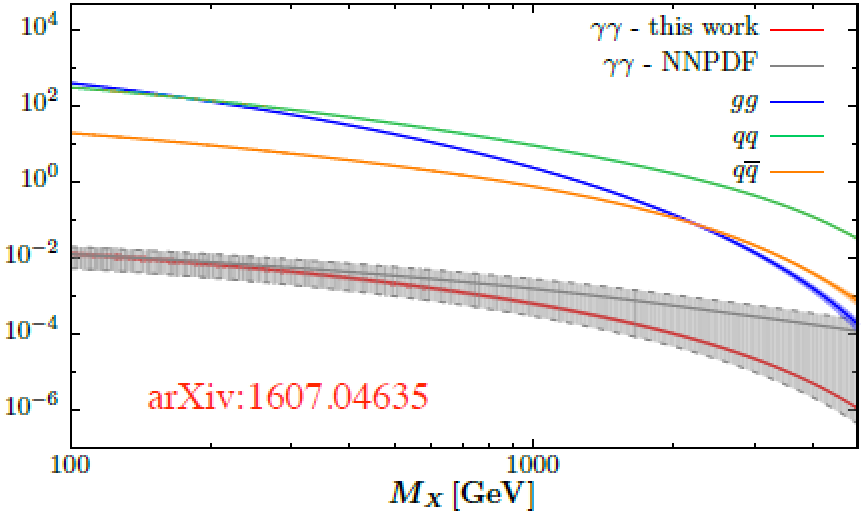


• Previous result translates to large uncertainty and potentially large luminosity at high mass. q, g fall much more steeply than central γ NNPDF prediction.

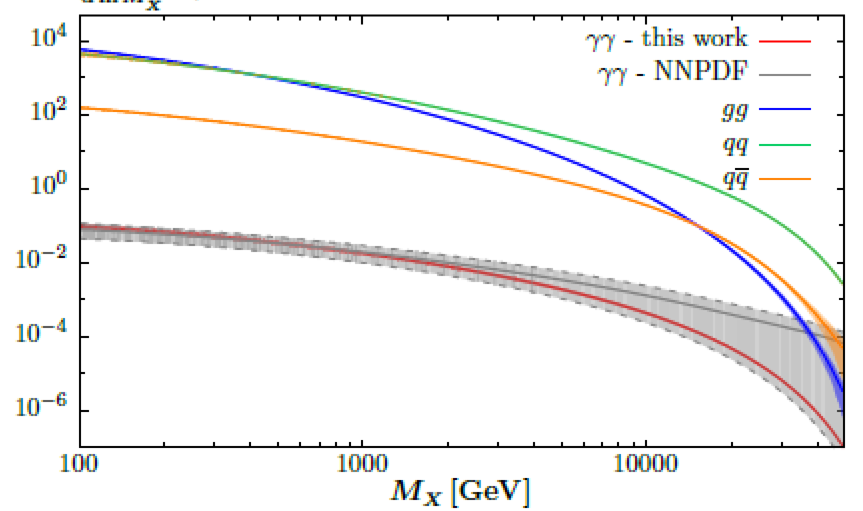
(pre '750-explosion')

• 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.

- **HKR-16** = 13 TeV



$\frac{d\mathcal{L}}{d\ln M_X^2}$, $\sqrt{s} = 100$ TeV



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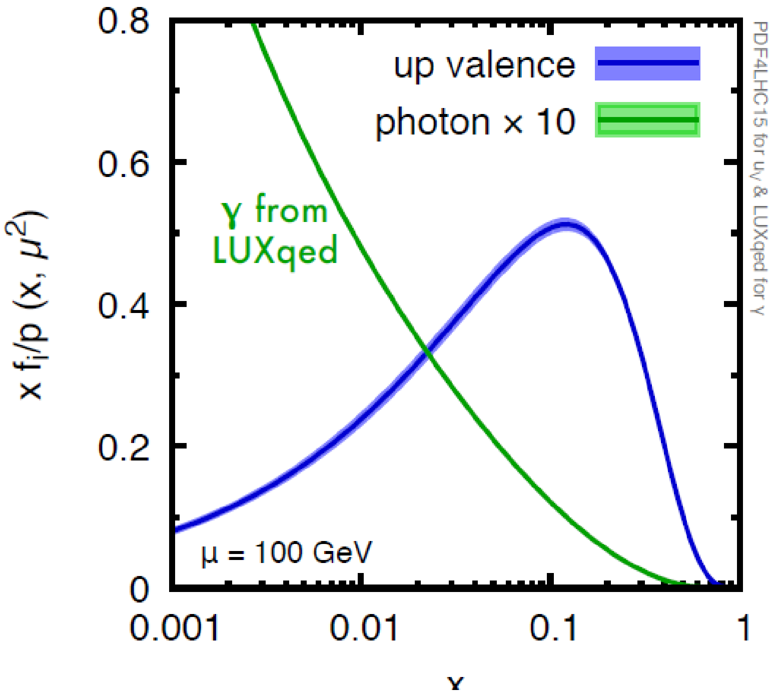
HKR,

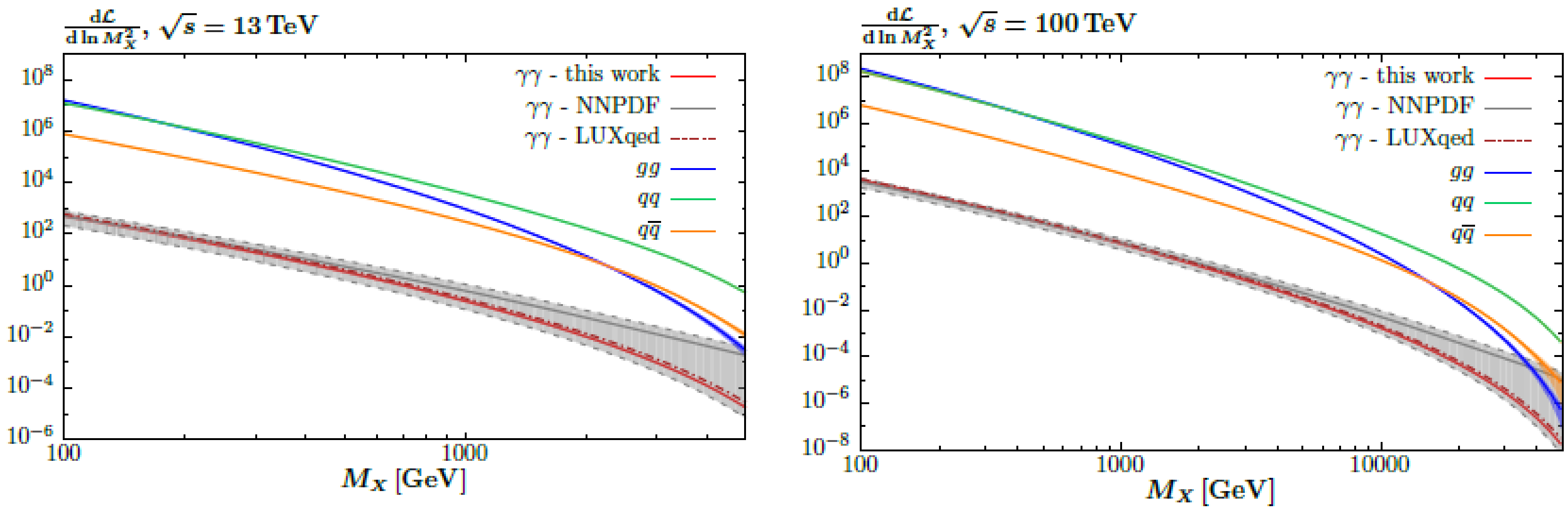
MNSZ, PRL 117,242002 (2016)
LUXqed-use DIS data to directly constraint photon PDF.

photon PDF results

- Model-independent uncertainty (NNPDF) was 50–100%
- Goes down to O(1%) with LUXqed determination



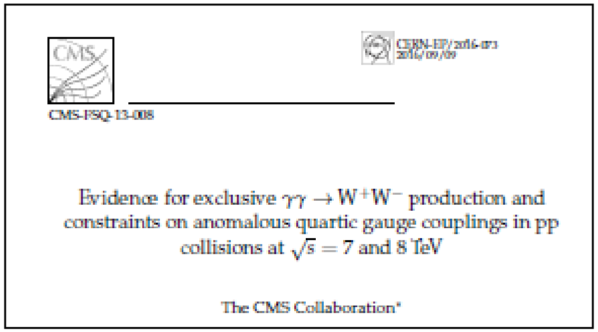
Comparison with LUXqed



- 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.

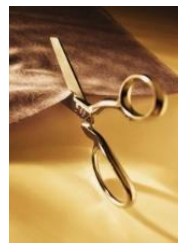
Photon-initiated processes with rapidity gaps

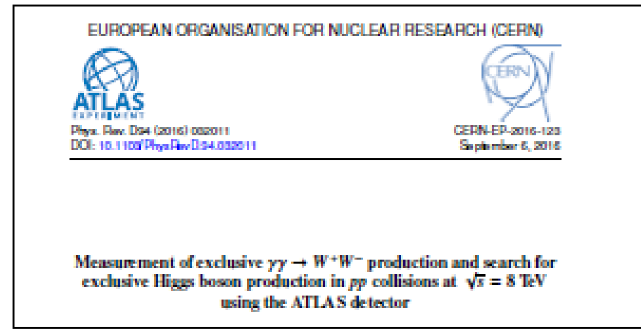
Caveat: in the real life, when studying photon-photon processes we as a rule need to go beyond the inclusive photon PDF (event selection: rapidity gaps, isolation cuts..)


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

The CMS Collaboration*




EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

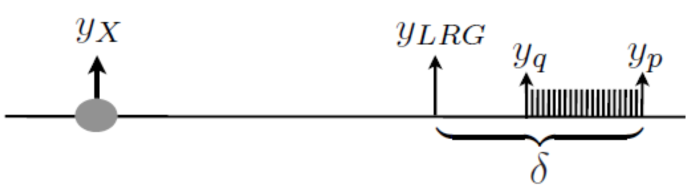
Phys. Rev. D94 (2016) 032011
DOI: 10.1103/PhysRevD.94.032011

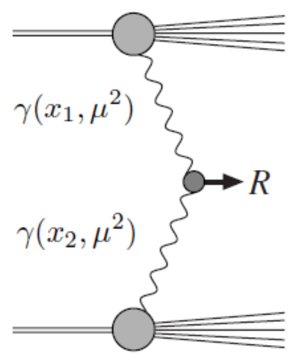
CERN-EP-2016-123
September 6, 2016

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

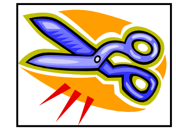
- Semi-exclusive processes with rapidity gaps: how do we include a rapidity veto within the standard inclusive approach?
- Comparison to CMS 7 and 8 TeV $\mu^+\mu^-$ data.

HKR arXiv:1601.03772





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



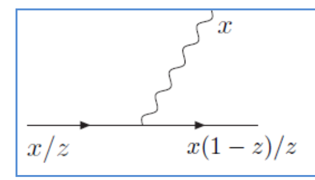
$$\gamma(x,\mu^2) \equiv \gamma^{\rm in}(x,\mu^2) + \gamma^{\rm evol}(x,\mu^2)$$

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

(satisfies veto)

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

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



- And photon PDF becomes simply:

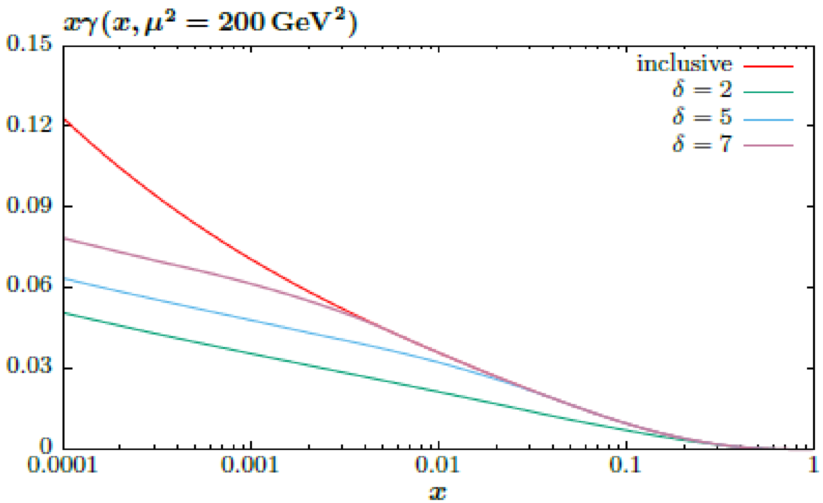
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\, S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{{\rm d}Q^2}{Q^2}\int_x^1 \frac{dz}{z}\bigg(\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2$$

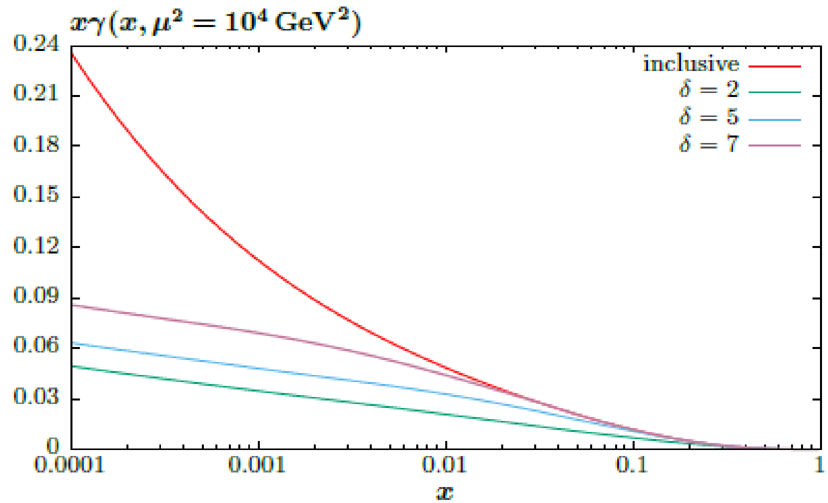
$$+ P_{\gamma g}(z) g(\frac{x}{z},Q^2)\bigg)\, S_\gamma(Q^2,\mu^2)\Theta\left[e^\delta - \frac{q_t}{m_p}\frac{z}{x(1-z)}\right]\ ,$$

(RG veto in DGLAP equation)

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

Modified photon PDF



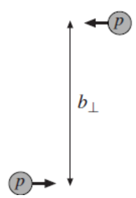


Suppression due to LRG veto.

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

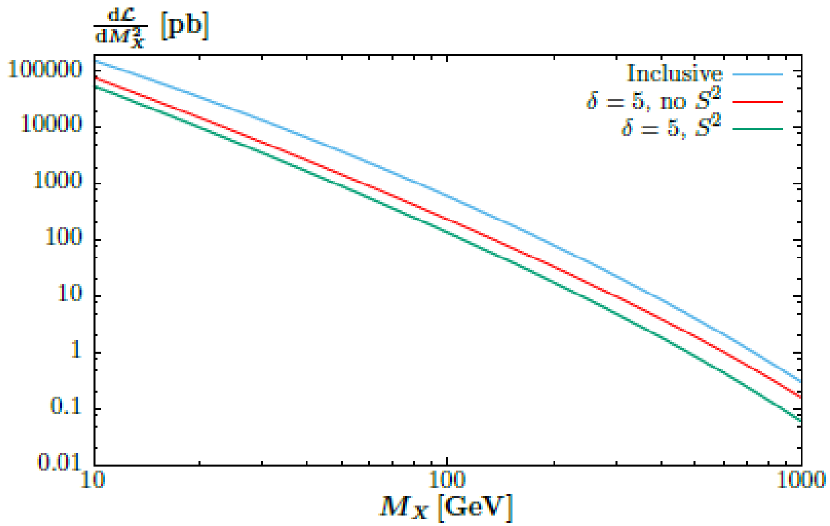
phenomenological objects only-factorization explicitly violated by rescattering effects

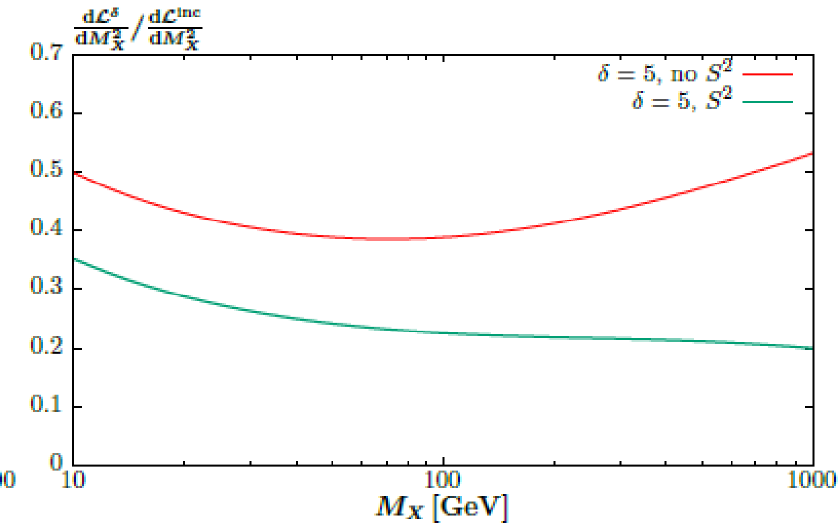
- Not the end of the story. Protons may interact additionally- underlying event. Include probability that this does not happen: the survival factor.



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

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

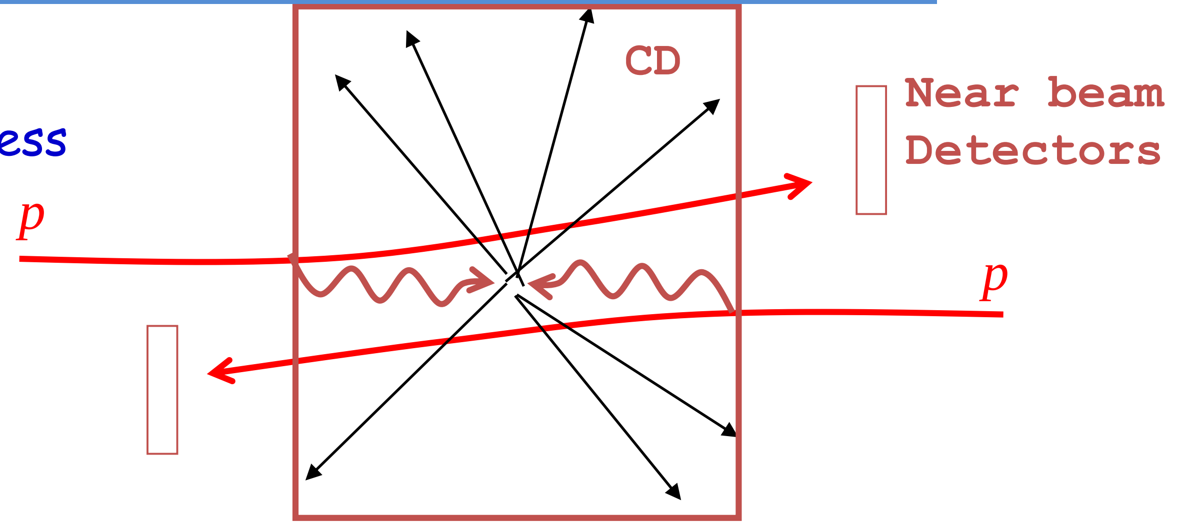




$\tau = M_X^2/s$ and we take $\mu^2 = M_X^2$ as the scale of the PDFs

γγ collisions- applications

Process



Installed (AFP)
Installed (CT-PPS)
projects

Extensive Program

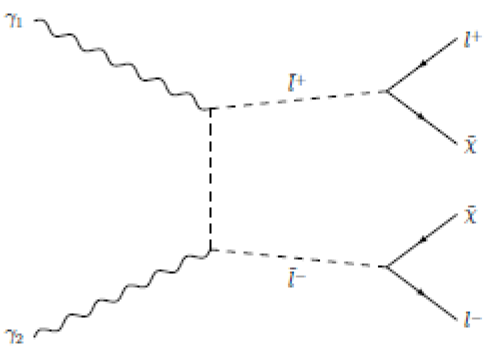
- γ γ→ μμ, ee QED processes
- γ γ→ QCD (jets..)
- γ γ→ WW anomalous couplings
- γ γ→ squark, top… pairs
- γ γ→ Charginos (natural SUSY)
- New BSM objects

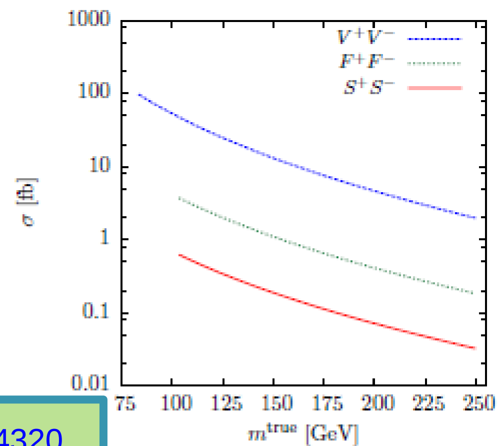
$$pp \to p + \gamma\gamma + p\,,$$
$$\gamma\gamma \to X^+X^-\,,$$

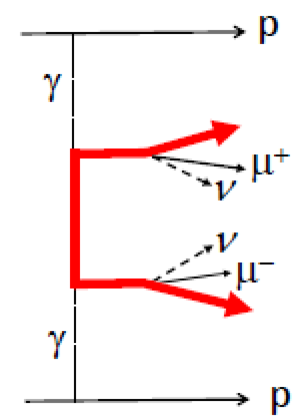
Diphoton X-Pair Production

where $X =$ W–boson, lepton, slepton, chargino...

- If particle decays semi–invisibly, then additional information from tagged proton momenta can be used to measure masses and discriminate BG.







HKSS, arXiv:1110.4320

- Consider exclusive production of chargino pair $\tilde{\chi}_1^+\tilde{\chi}_1^-$, decaying via

$$\tilde{\chi}_1^+(\tilde{\chi}_1^-) \to l^+(l^-) + \nu(\overline{\nu}) + \tilde{\chi}_1^0\,,$$

electroweakinos

where the $\tilde{\chi}_1^0$ is an LSP neutralino.

- For cases that $\Delta M = M(\tilde{\chi}_1^0) - M(\tilde{\chi}_1^\pm)$ is relatively small, can be difficult to observe inclusively. **(compressed mass BSM scenarios)**

Summary & Outlook

- 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. (Patricia)
-
  - **SuperChic** - a MC event generator for CEP processes.
  - Unified platform for QCD-induced, photoproduction and photon-photon collisions.
  - Fully differential treatment of survival factor.
- A formalism (**HKR-16**) 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

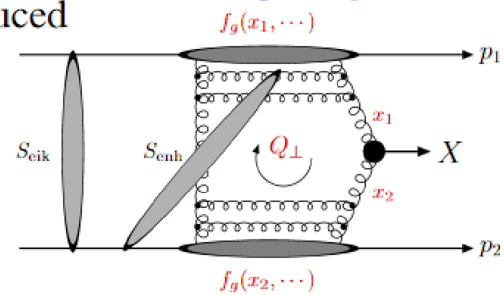
Photon-photon collisions in Superchic

Production mechanisms

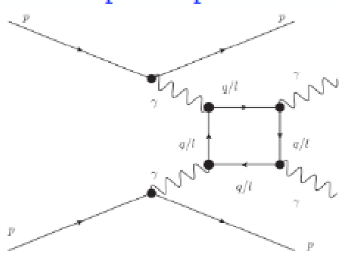
Exclusive final state can be produced via three different mechanisms, depending on kinematics and quantum numbers of state:

Gluon-induced

C-even, couples to gluons

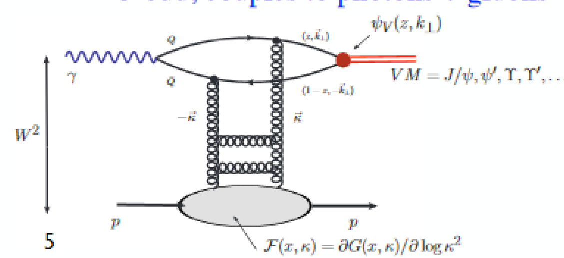


Couples to photons



Photon-induced

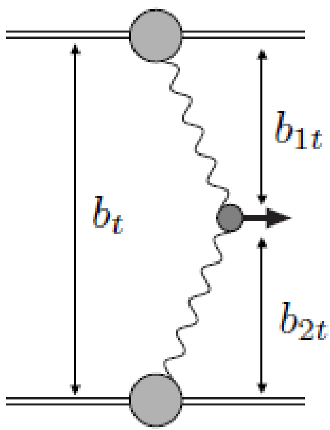
C-odd, couples to photons + gluons



Photoproduction

Soft survival factor

- How do we calculate the survival factor? Work in impact parameter space and apply 'eikonal' approach:



$$\langle S^2 \rangle = \frac{\int d^2 b_{1t}\, d^2 b_{2t}\, |T(s, b_{1t}, b_{2t})|^2 \exp(-\Omega(s, b_t))}{\int d^2\, b_{1t} d^2 b_{2t}\, |T(s, b_{1t}, b_{2t})|^2}\,,$$

$\exp(-\Omega(s, b_t))$: Poissonian probability of no inelastic scattering at impact parameter b_t .

↑ proton opacity

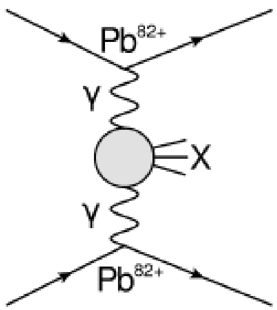
- Underlying event generated by soft QCD. Cannot use pQCD $\Rightarrow$ take phenomenological approach to this non-pert. observable.

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

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

UPC

- 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.



[Fermi, Nuovo Cim. 2 (1925) 143]
[Weizsacker, Z. Phys. 88 (1934) 612]
[Williams, Phys. Rev. 45 (10 1934) 729]

$$Q^2 < \frac{1}{R^2} \quad \text{and} \quad \omega_{\max} \approx \frac{\gamma}{R}$$

- 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.

Ongoing work

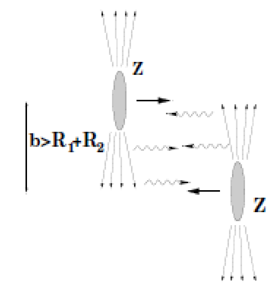
- So far the current processes are included:
  - SM Higgs to $b\bar{b}$
  - $W^+W^- \to ll\nu\nu$, including spin correlations.
  - l^+l^-
  - $\gamma\gamma$ (light-by-light).
- In all cases with e/p beams.
- Recalling form of cross section for pp collisions:

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

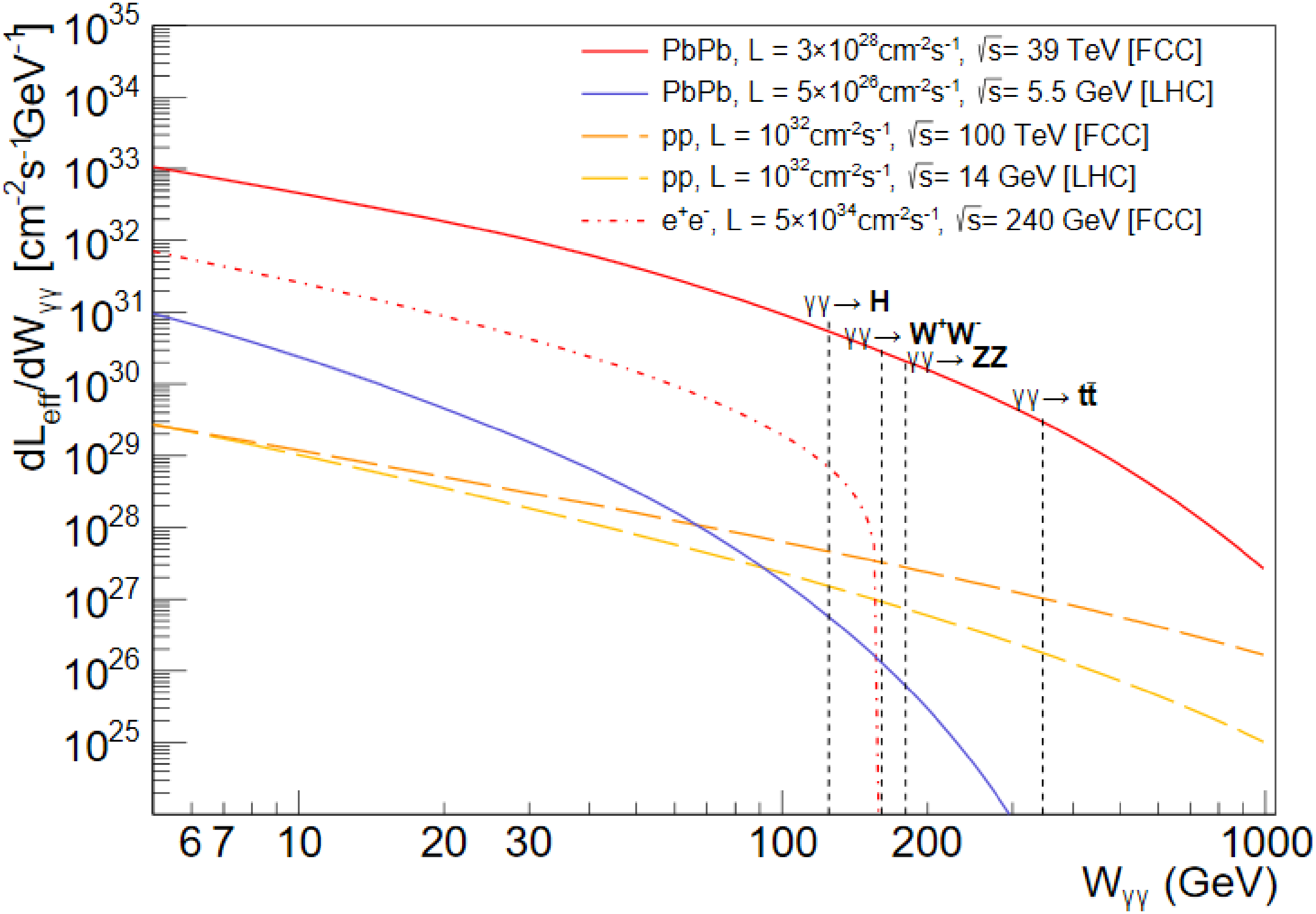
$\longrightarrow$ Two clear ways to extend:
  - New beam types.
  - New processes.

- Work ongoing in both directions.

- Work ongoing on extending to heavy ions



ArXiv:1605.01389



Effective photon–photon luminosities as a function of $\gamma\gamma$ c.m. energy ($W_{\gamma\gamma}$) for five colliding systems at FCC and LHC energies: Pb–Pb at $\sqrt{s}$ = 39, 5.5 TeV (at their corresponding nominal beam luminosities); pp at $\sqrt{s}$ = 100, 14 TeV (corresponding to 1 fb^{-1} integrated luminosities); and e^+e^- at $\sqrt{s}$ = 240 GeV (FCC-ee nominal luminosity per IP). The vertical dashed lines indicate the energy thresholds for Higgs, W^+W^-, ZZ, and $t\bar{t}$ production.

$$d\mathcal{L}_{\rm eff}/dW_{\gamma\gamma} \equiv \mathcal{L}_{AB}\, d\mathcal{L}_{\gamma\gamma}/dW_{\gamma\gamma},$$

Cross sections

$$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)[m_{\tilde{\chi}_1^\pm} \simeq 200\,\text{GeV}] \simeq 0.6\,\text{fb},$$
$$\sigma(W^+W^-) = 108.5\,\text{fb},$$

For $\mathcal{L}_{\text{int}} = 300\,\text{fb}^{-1}$, the number of expected events are

$$N(\tilde{\chi}_1^+\tilde{\chi}_1^-) \simeq 180,$$
$$N(W^+W^-) = 32550,$$