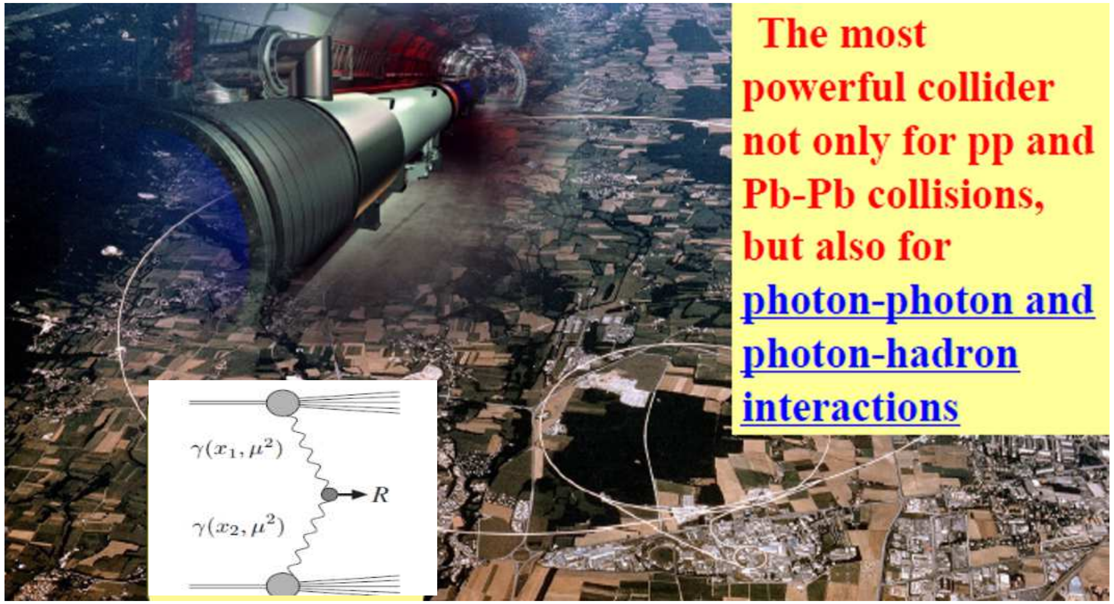
EDS Blois 2017

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.

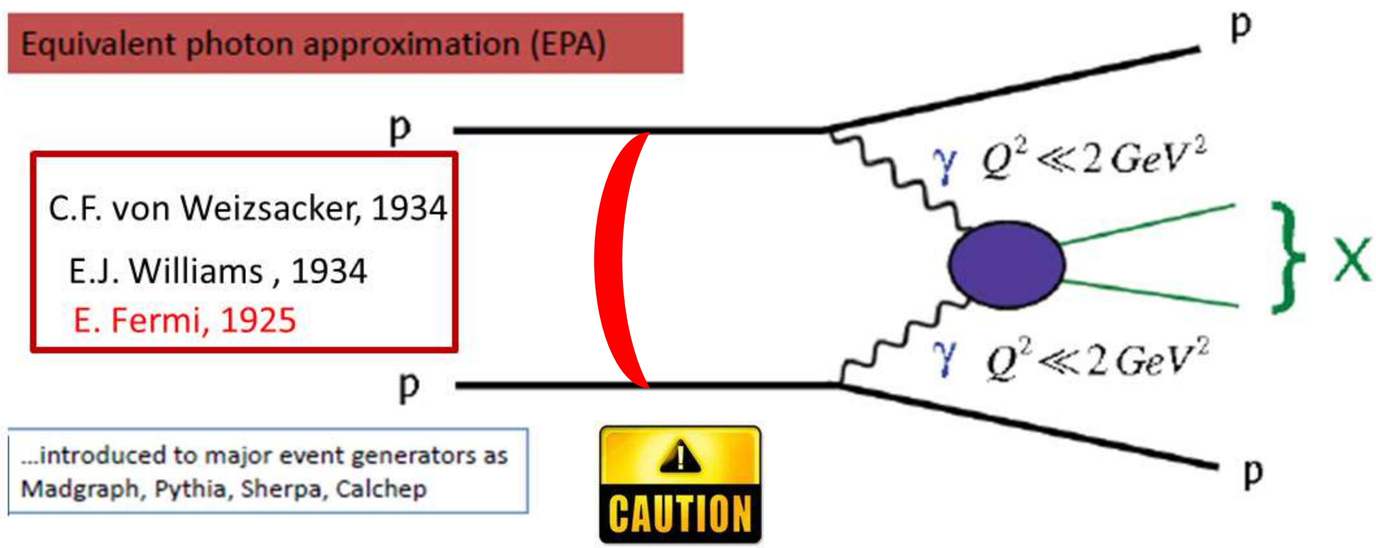
(More than 600 papers)

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':

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

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.

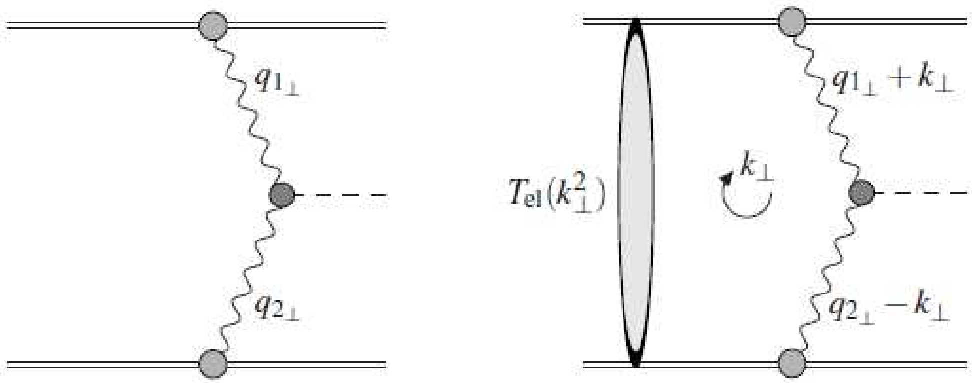
SURVIVAL GUIDE

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).

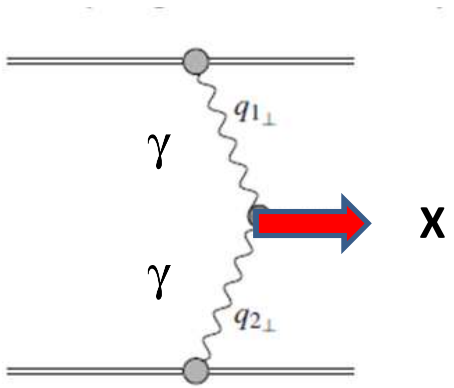
$\rightarrow$ Must multiply our cross section by probability of no underlying event activity, known as the soft 'survival factor'.

(Giulia, Sergey)

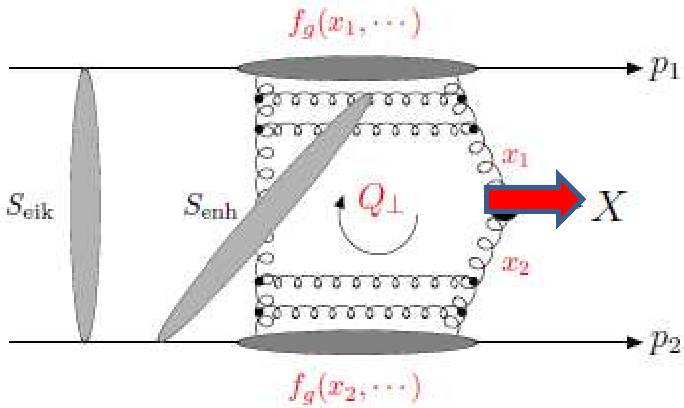


Durham Group-KMR
Tel-Aviv Group- GLM

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.

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

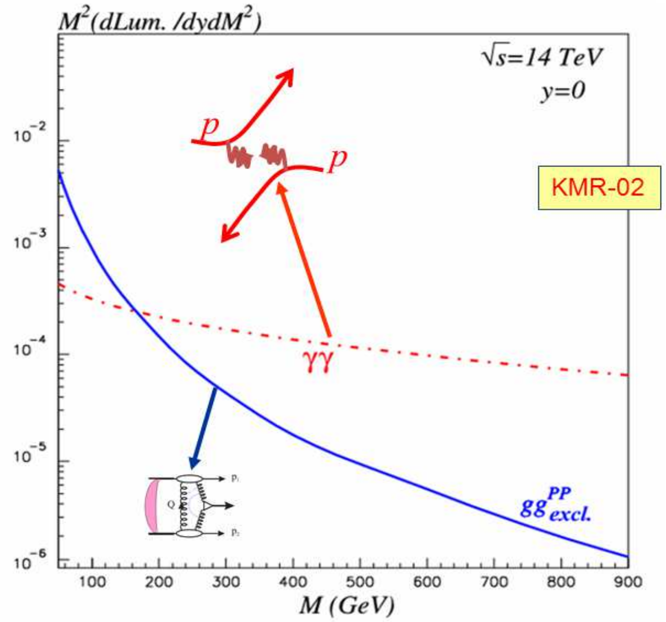
- Increasing $M_X \Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

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

KMR-2001

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

QCD ‘radiation damage’ in action



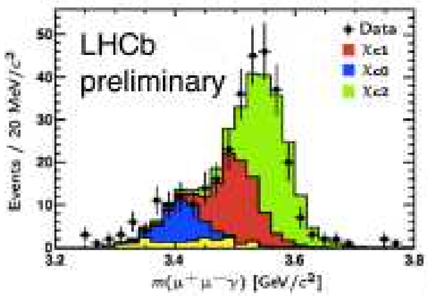
- Situation summarised in ‘effective’ exclusive gg and $\gamma\gamma$. luminosities. This Sudakov suppression in QCD cross section leads to enhancement in $\gamma\gamma$ already* for $M_X \gtrsim 200\,\mathrm{GeV}$ - well before CT-PPS/AFP mass acceptance region.

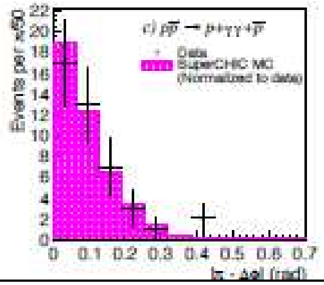
$\longrightarrow$ Can study $\gamma\gamma$ collisions at the LHC with unprecedented $s_{\gamma\gamma}$.

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

L.A. Harland-Lang[1], V.A. Khoze[2,3], M.G. Ryskin[3]

[1]Department of Physics and Astronomy, University College London, WC1E 6BT, UK
[2]Institute for Particle Physics Phenomenology, University of Durham, Durham, DH1 3LE
[3]Petersburg Nuclear Physics Institute, NRC Kurchatov Institute, Gatchina, St. Petersburg, 188300, Russia

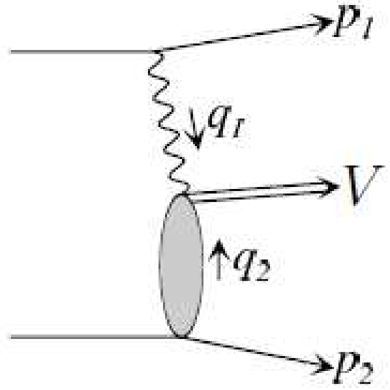
Abstract

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

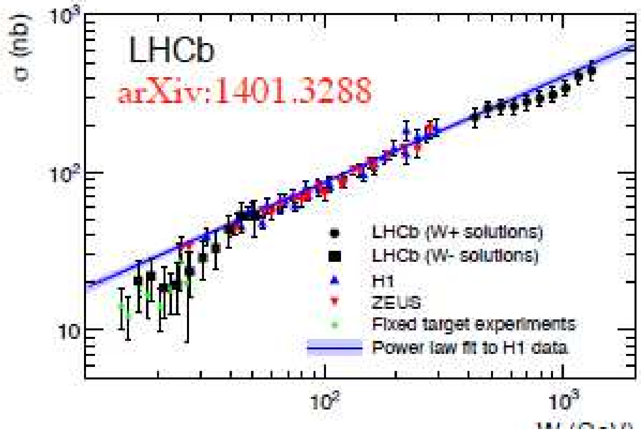
Generated Processes - photoproduction

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

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



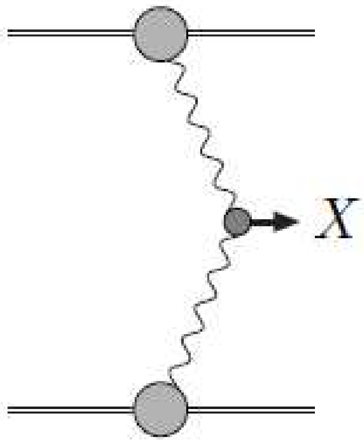
- Takes simple power-law fit to HERA/LHC data.



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.



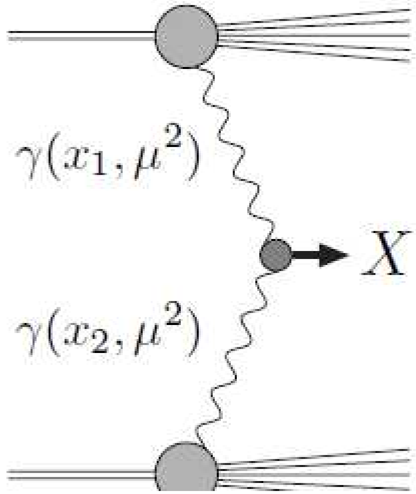
*To appear in next version.

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



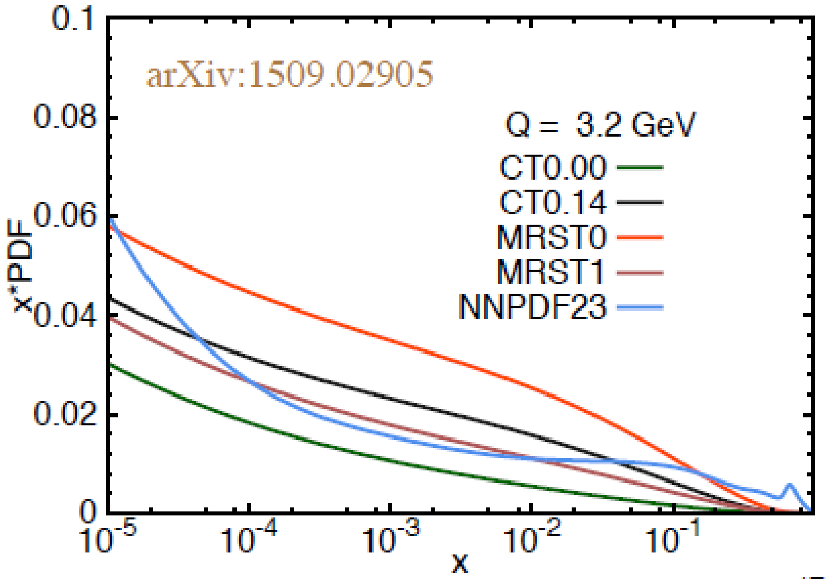
- Earlier photon PDF sets either:

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.



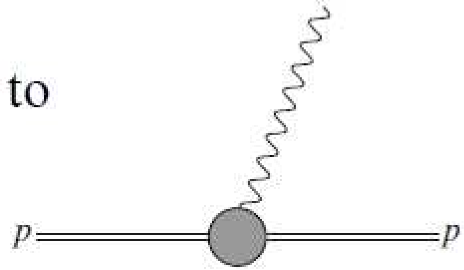
- Comparing these different sets reveals apparently large uncertainties.

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

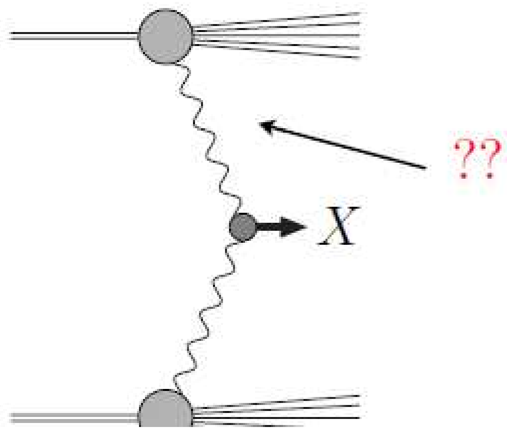
PDFs and QED

• 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:



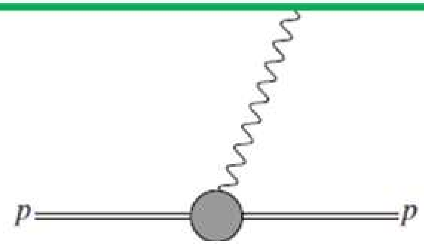
HKR arXiv:1601.03372, 1601.07187, 1607.4635

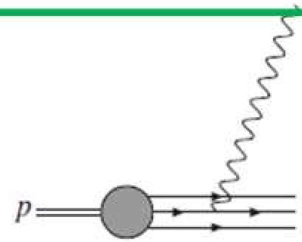
Photon distribution inside the proton (photon PDF)

- 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.



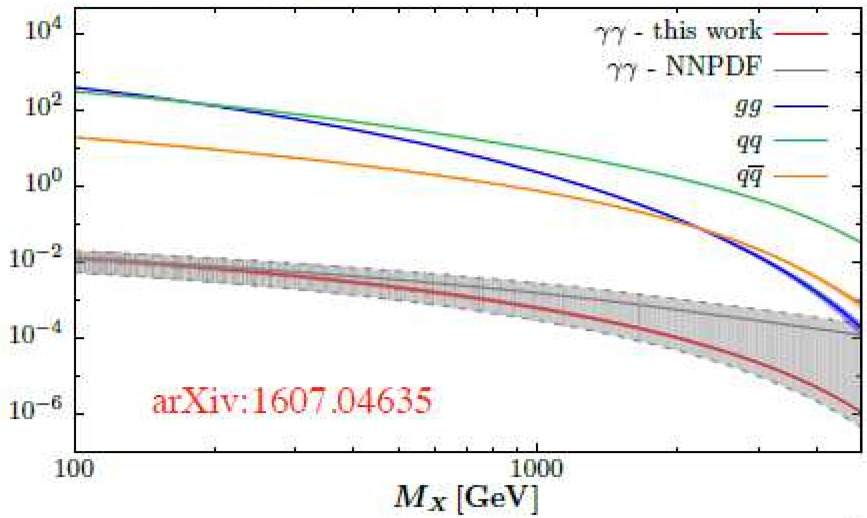


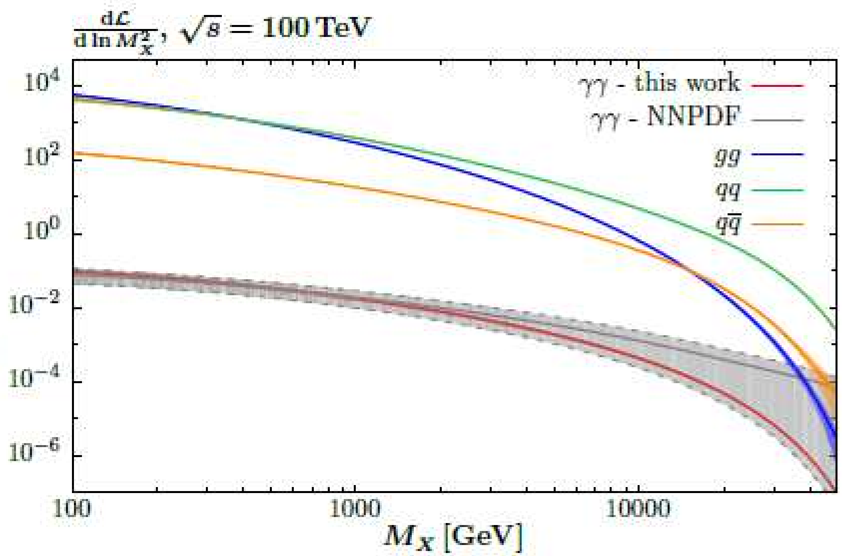
• Previous result translates to large uncertainty and potentially large luminosity at high mass. q, g fall much more steeply than central γ NNPDF prediction.

(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





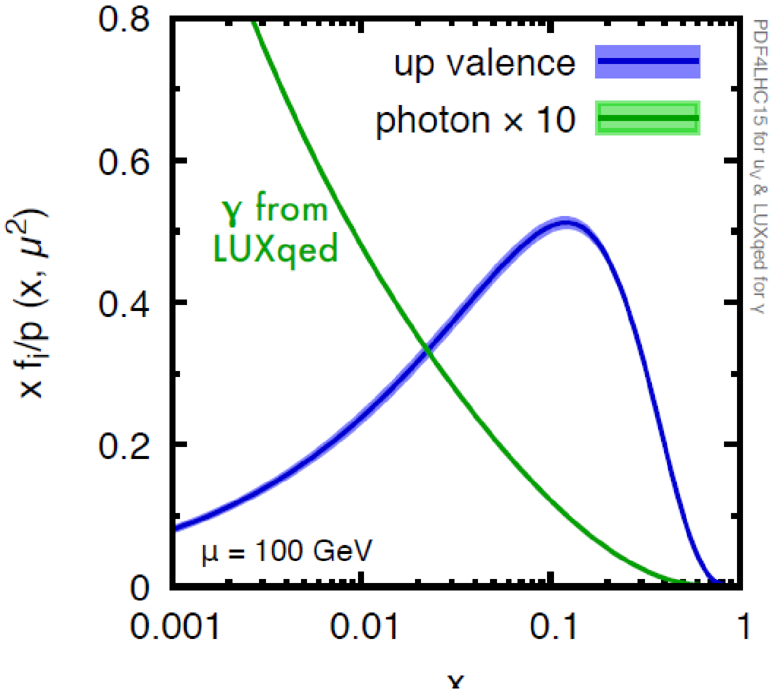
HKR,

52

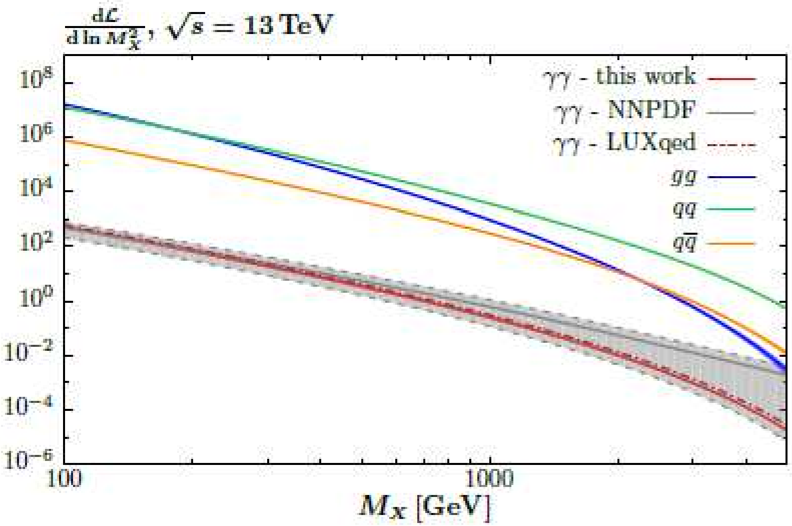
MNSZ, PRL 117,242002 (2016)
LUXqed-use DIS data to directly constraint photon PDF.

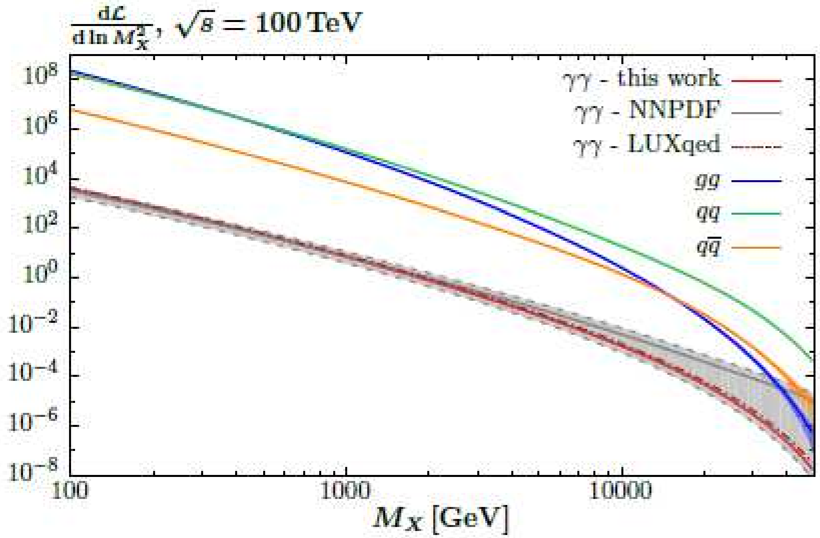
photon PDF results

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



Comparison with LUXqed

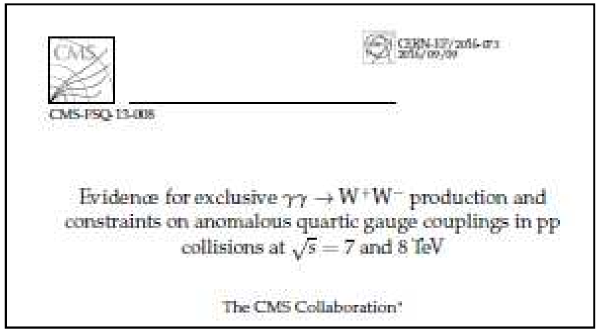




- Comparing our and LUXqed $\gamma\gamma$ luminosities can see these are quite similar ($\longrightarrow$ importance of coherent component).
- Devil is in detail - some enhancement seen in LUXqed at higher M_X, appears to be due to low Q^2 resonant contribution.
- However, clear we have moved beyond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

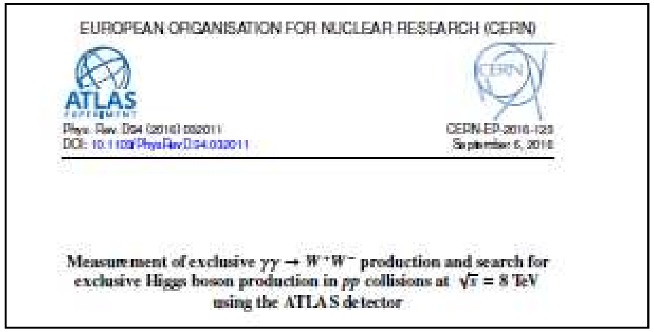
Photon-initiated processes with rapidity gaps

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

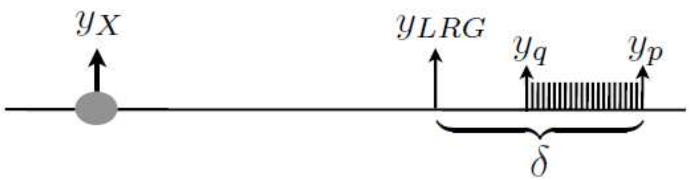
The CMS Collaboration*

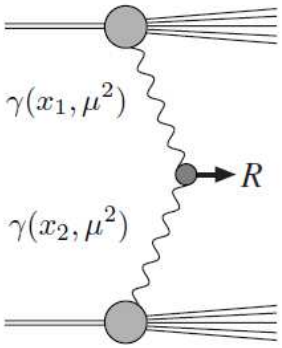

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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

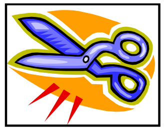
- Semi-exclusive processes with rapidity gaps: how do we include a rapidity veto within the standard inclusive approach?
- Comparison to CMS 7 and 8 TeV $\mu^+\mu^-$ data.

HKR arXiv:1601.03772





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



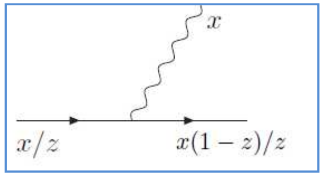
$$\gamma(x,\mu^2) \equiv \gamma^{\mathrm{in}}(x,\mu^2) + \gamma^{\mathrm{evol}}(x,\mu^2)$$

- $\gamma^{\mathrm{in}}(x,\mu^2)$: 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:

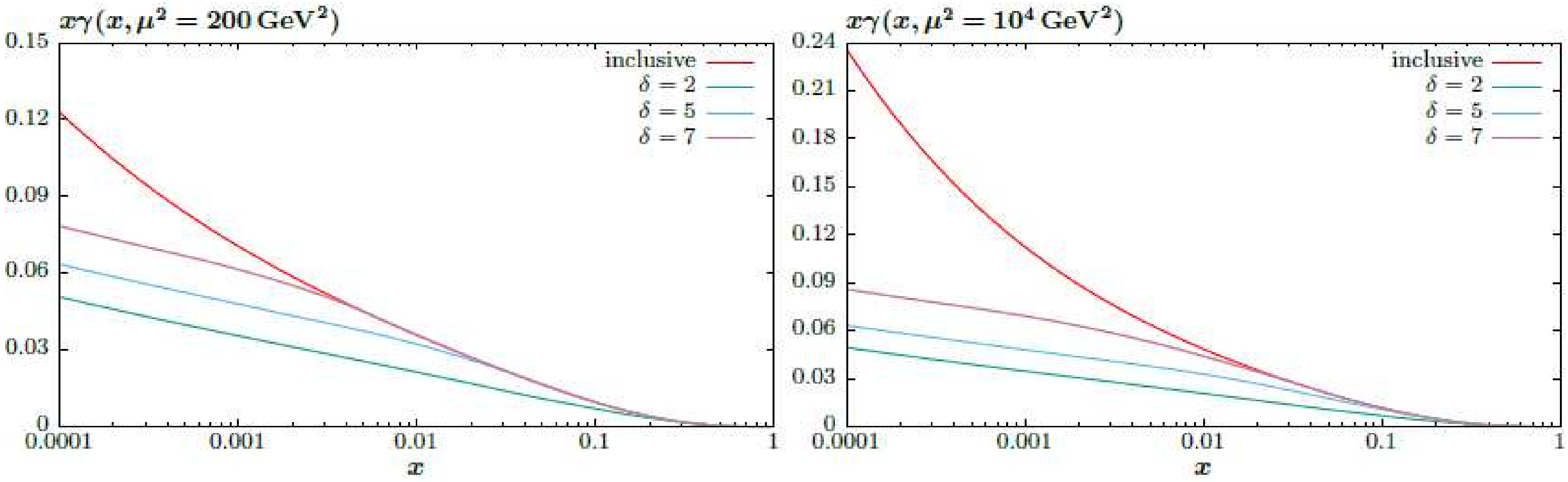
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\, S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{\mathrm{d}Q^2}{Q^2}\int_x^1 \frac{dz}{z}\Big(\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z}, Q^2$$

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

(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

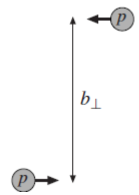


Suppression due to LRG veto.

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

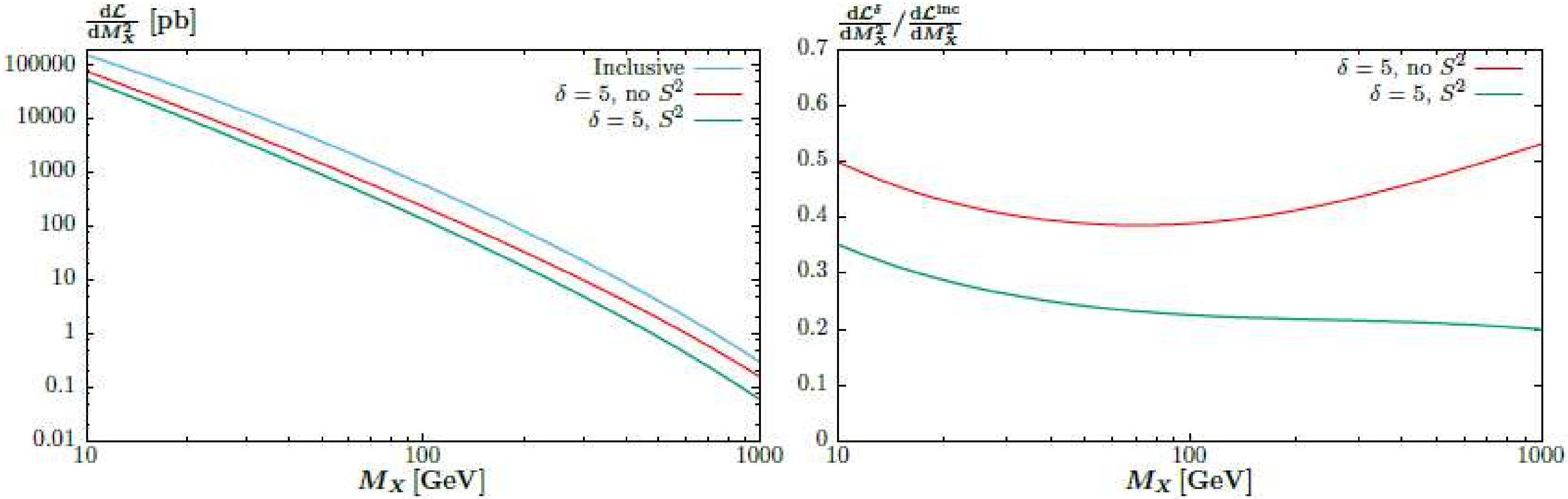
phenomenological objects only-factorization explicitly violated by rescattering effects

- 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 $\gamma^{\rm veto}(x,\mu^2)$.

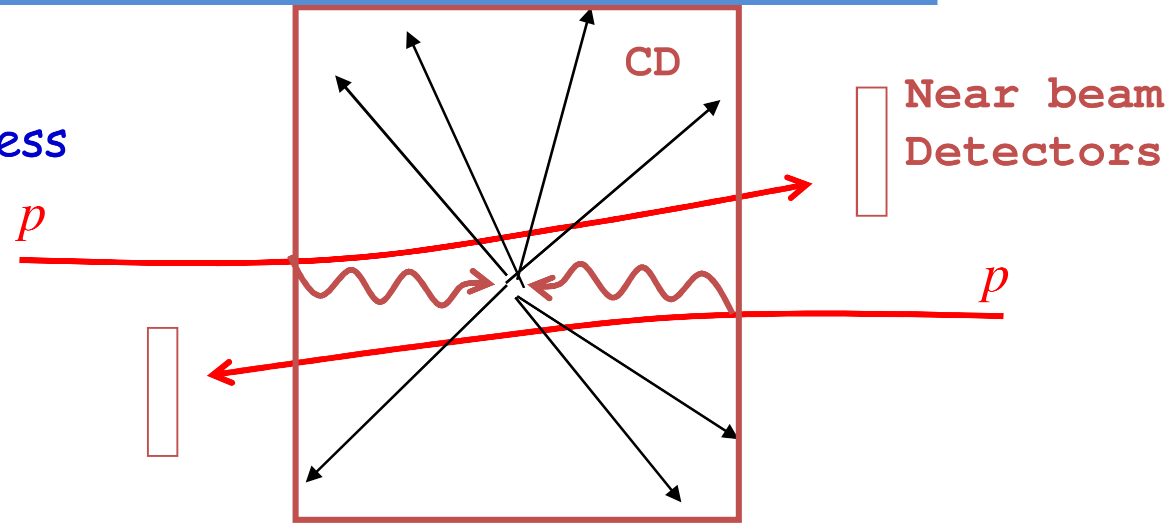
- Instead have effective $\gamma\gamma$ luminosity: $\dfrac{{\rm d}\mathcal{L}}{{\rm d}M_X^2} = \dfrac{1}{s}\displaystyle\int_\tau^1 \dfrac{{\rm d}x_1}{x_1}\gamma(x_1, M_X^2)\gamma(\tau/x_1, M_X^2)$



$\tau = M_X^2/s$ 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

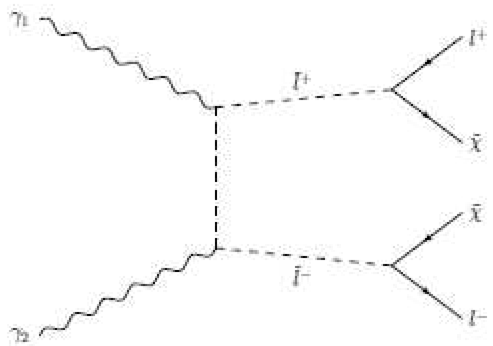
- $\gamma\gamma \rightarrow \mu\mu$, ee QED processes
- $\gamma\gamma \rightarrow$ QCD (jets..)
- $\gamma\gamma \rightarrow$ WW anomalous couplings
- $\gamma\gamma \rightarrow$ squark, top… pairs
- $\gamma\gamma \rightarrow$ Charginos (natural SUSY)
- New BSM objects

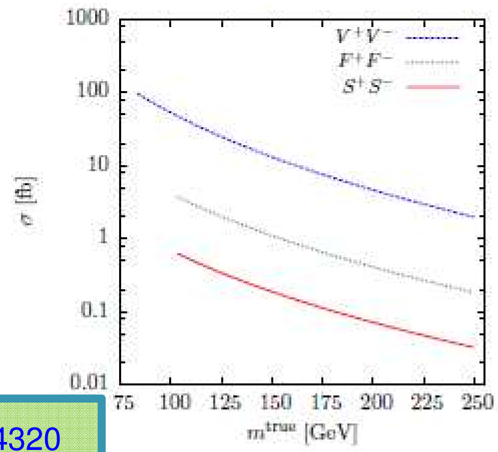
$$pp \to p + \gamma\gamma + p\,,$$
$$\gamma\gamma \to X^+X^-\,,$$

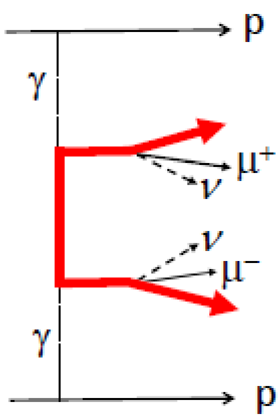
Diphoton X-Pair Production

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

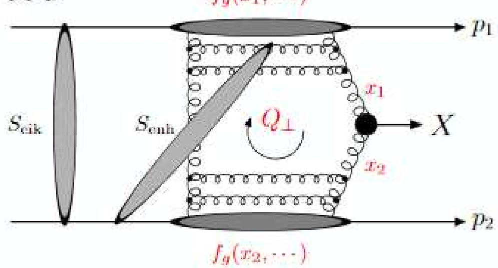
Photon-photon collisions in Superchic

Production mechanisms

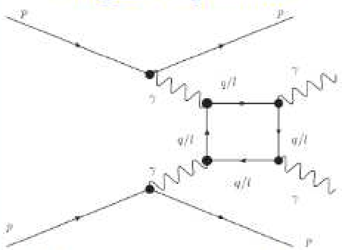
Exclusive final state can be produced via three different mechanisms, depending on kinematics and quantum numbers of state:

Gluon-induced

C-even, couples to gluons

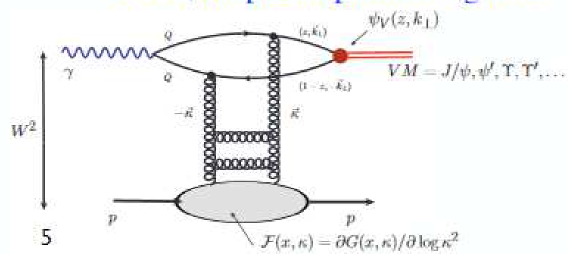


Couples to photons



Photon-induced

C-odd, couples to photons + gluons

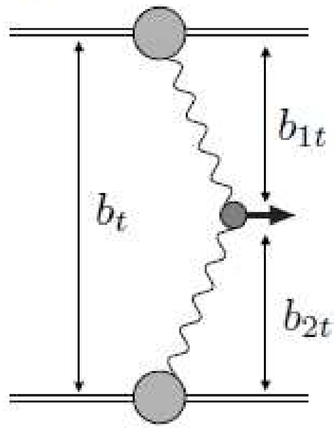


Photoproduction

5

Soft survival factor

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



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

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

$\uparrow$

proton opacity

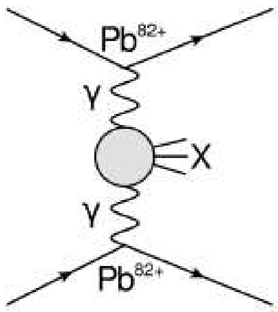
• Underlying event generated by soft QCD. Cannot use pQCD $\Rightarrow$ take phenomenological approach to this non-pert. observable.

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

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]

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

- 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

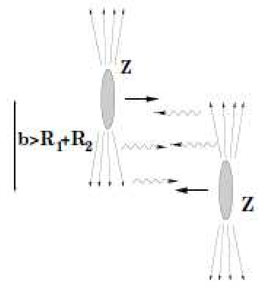
- So far the current processes are included:
  - SM Higgs to $b\bar{b}$
  - $W^+W^- \to ll\nu\nu$, including spin correlations.
  - l^+l^-
  - $\gamma\gamma$ (light-by-light).
- In all cases with e/p beams.
- Recalling form of cross section for pp collisions:

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

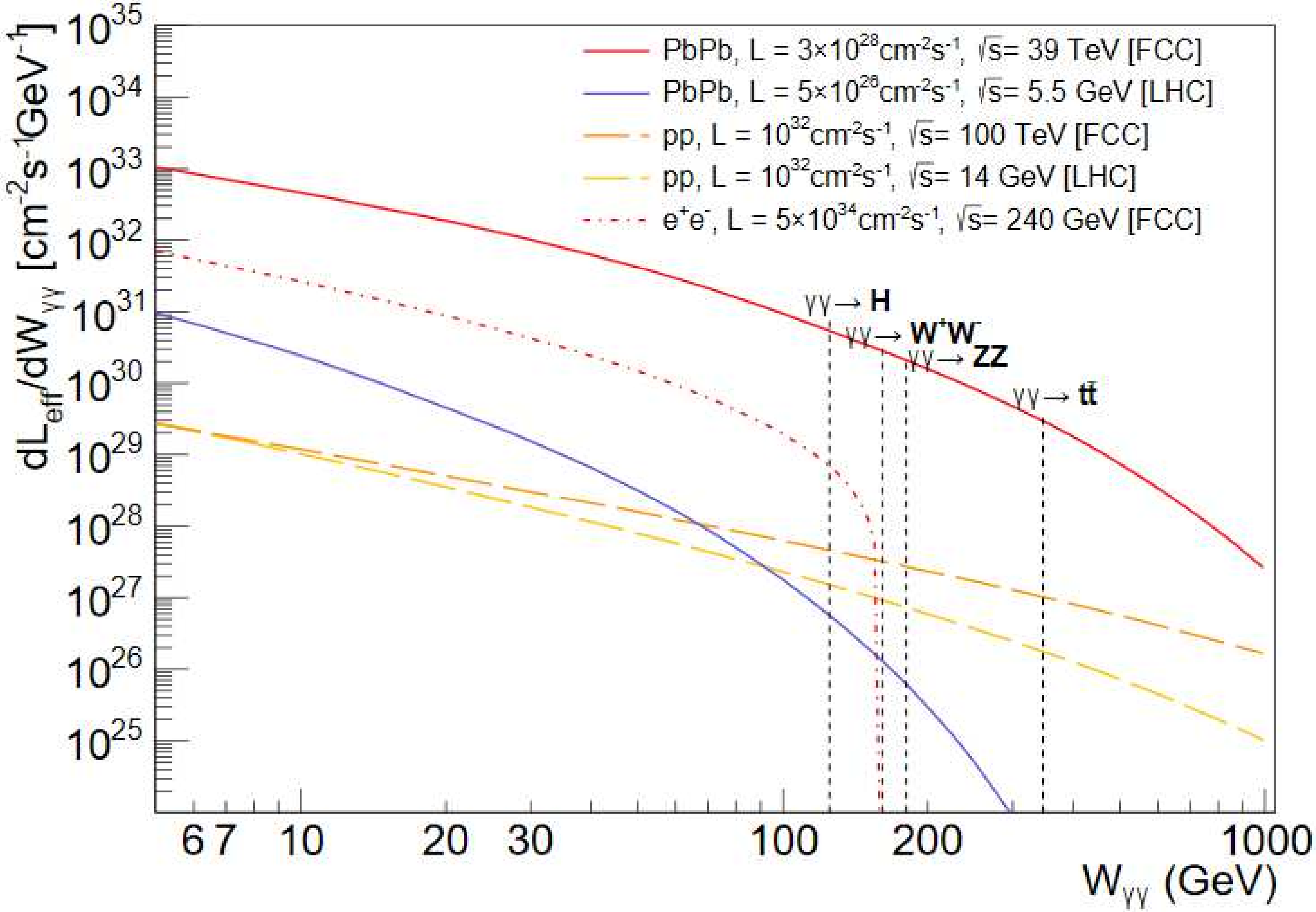
$\longrightarrow$ Two clear ways to extend:
  - New beam types.
  - New processes.

- 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.

$$\mathrm{d}\mathcal{L}_{\mathrm{eff}}/\mathrm{d}W_{\gamma\gamma} \equiv \mathcal{L}_{AB}\,\mathrm{d}\mathcal{L}_{\gamma\gamma}/\mathrm{d}W_{\gamma\gamma}.$$

Cross sections

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

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

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