

# SuperChic MC: Updates

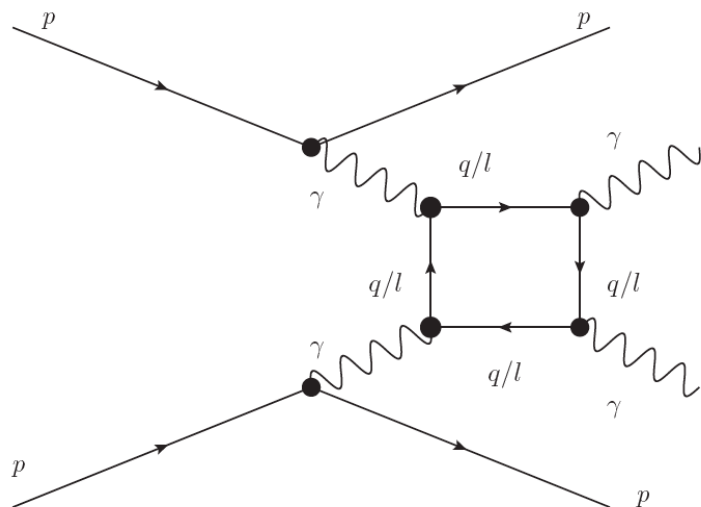
Lucian Harland-Lang, University of Oxford

LHC WG on Forward Physics and Diffraction, 7  
December, 2017, CERN

*In collaboration with Valery Khoze and Misha  
Ryskin*

# Outline

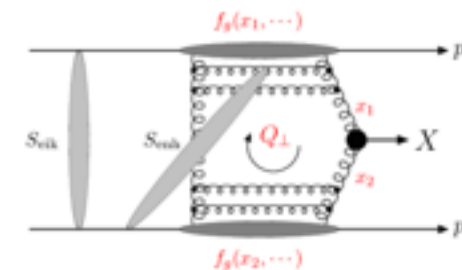
- ▶ CEP - brief introduction
- ▶ SuperChic - what is it? Processes generated.
- ▶ Updates - new processes.
- ▶ Ongoing work - heavy ions.



## SuperChic 2 - A Monte Carlo for Central Exclusive Production

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



A list of references can be found [here](#) and the code is available [here](#).

Comments to Lucian Harland-Lang <[l.harland-lang@ucl.ac.uk](mailto:l.harland-lang@ucl.ac.uk)>.

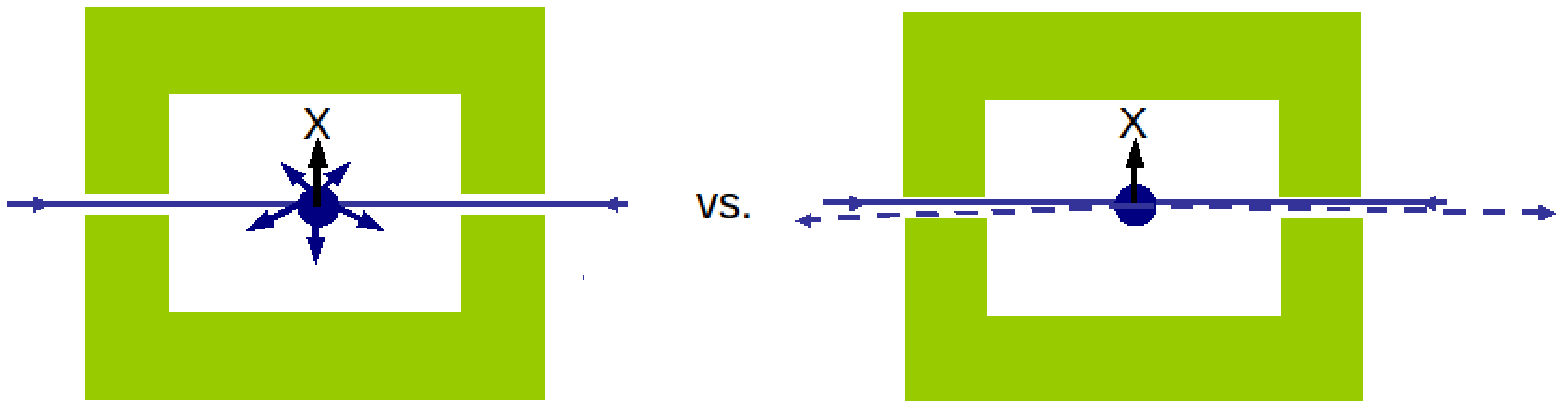
# SuperChic - overview

# Central Exclusive Production

Central Exclusive Production (CEP) is the interaction:

$$hh \rightarrow h + X + h$$

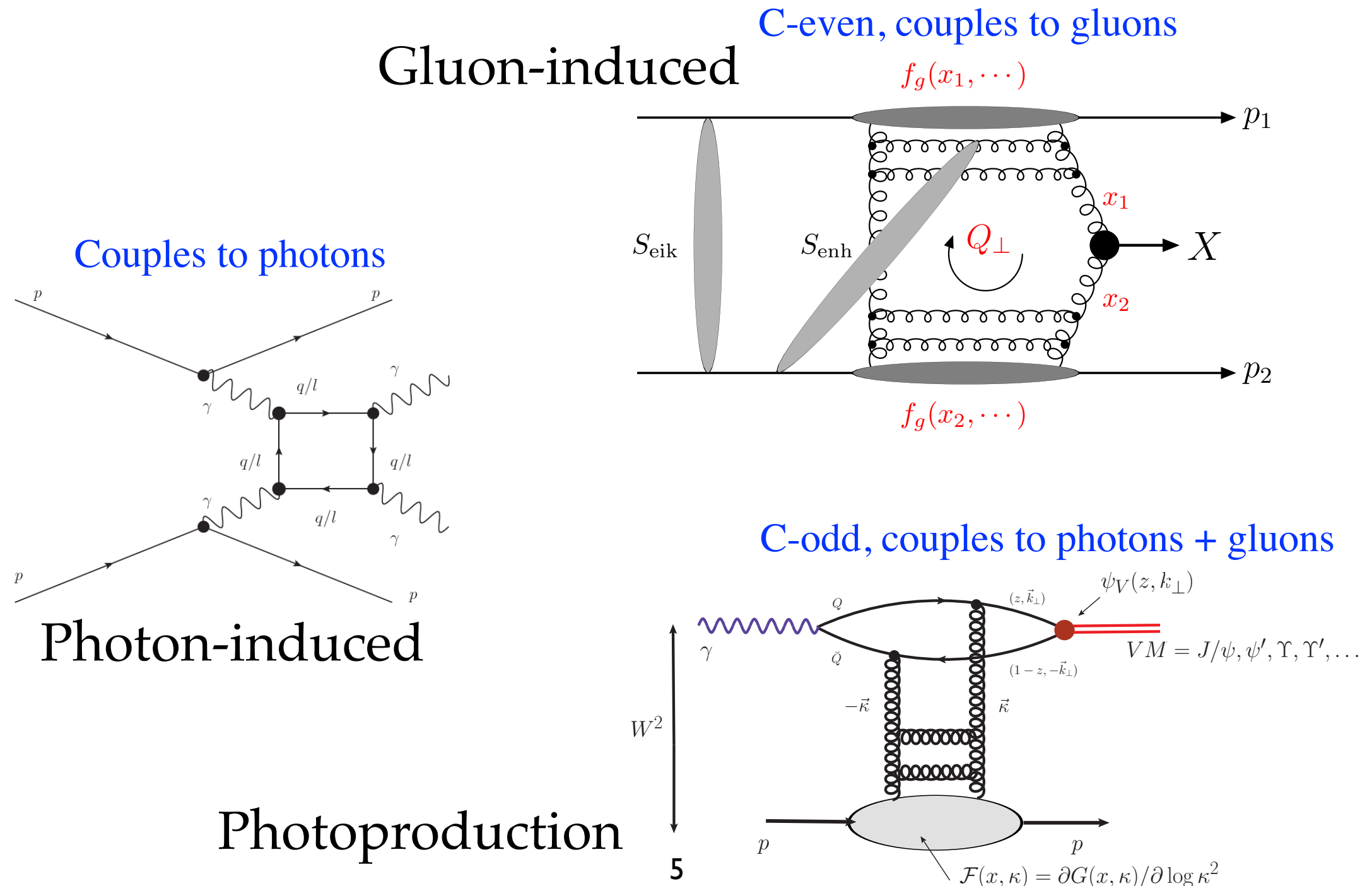
- **Diffractive**: colour singlet exchange between colliding protons, with large rapidity gaps (‘+’) in the final state.
- **Exclusive**: hadron lose energy, but remain intact after the collision.
- **Central**: a system of mass  $M_X$  is produced at the collision point and only its decay products are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



# 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.
- 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<sup>1</sup>, V.A. Khoze<sup>2,3</sup>, M.G. Ryskin<sup>3</sup>

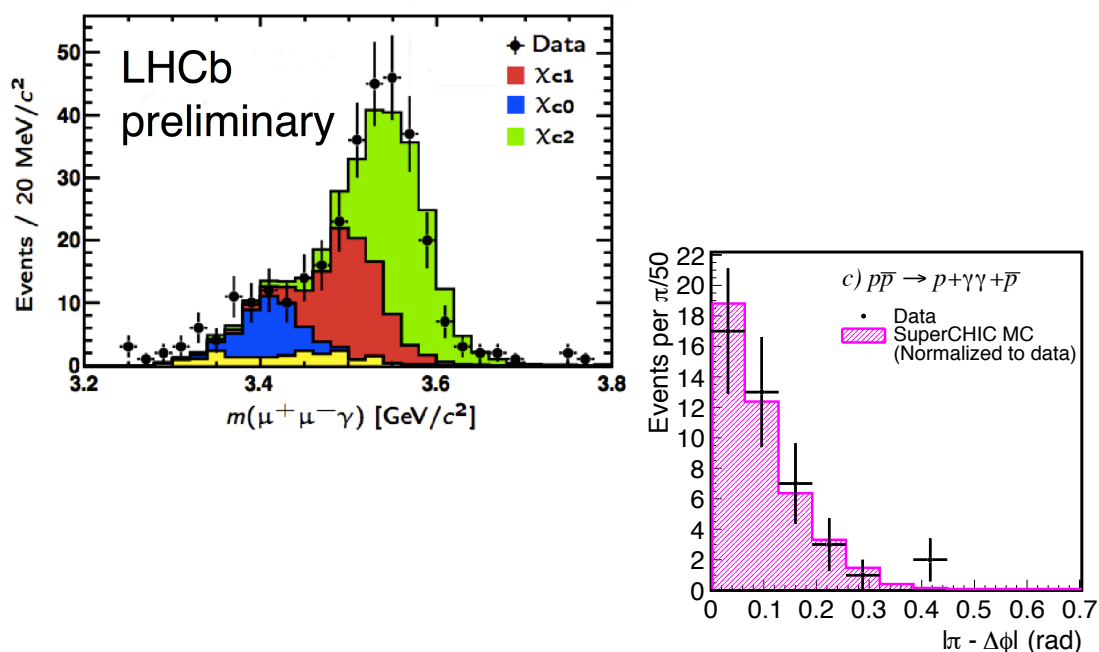
<sup>1</sup>Department of Physics and Astronomy, University College London, WC1E 6BT, UK

<sup>2</sup>Institute for Particle Physics Phenomenology, University of Durham, Durham, DH1 3LE

<sup>3</sup>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



# Availability

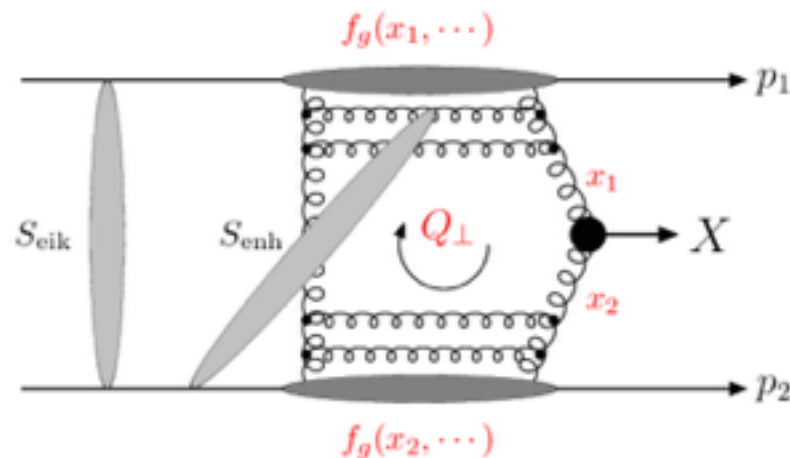
- Code and user manual available on Hepforge:

<https://superchic.hepforge.org>

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SuperChic v2.04

A Monte Carlo for Central Exclusive Production

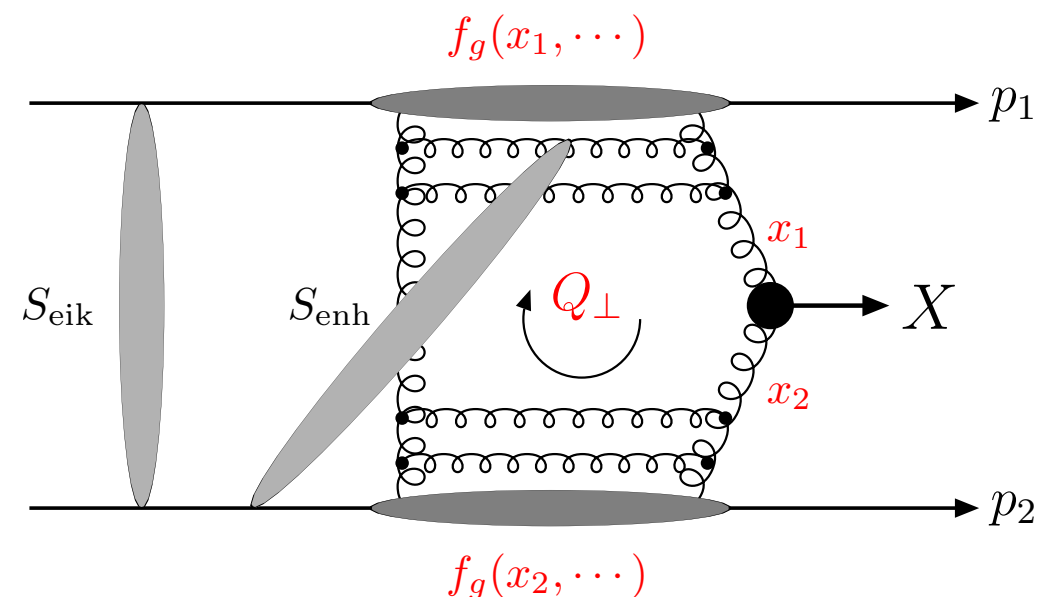
Users guide

Lucian Harland-Lang ([l.harland-lang@ucl.ac.uk](mailto:l.harland-lang@ucl.ac.uk))

# QCD-mediated production

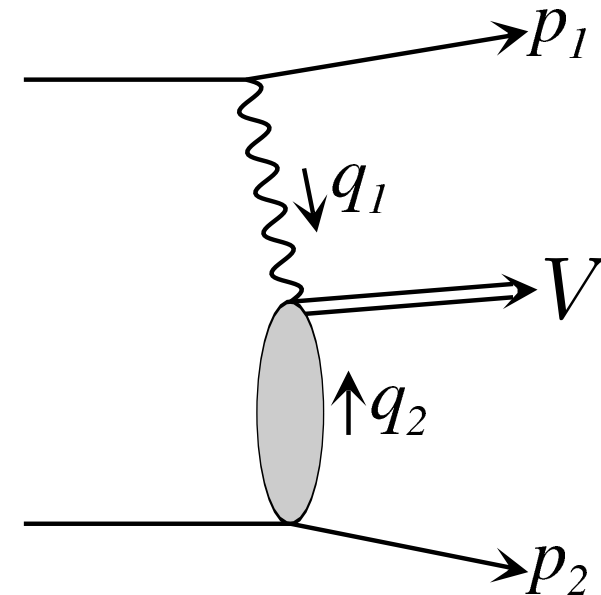
- ▶ SM Higgs to  $b\bar{b}$ .
  - ▶ Dijets -  $q\bar{q}$ ,  $gg$ ,  $b\bar{b}(c\bar{c})$
  - ▶ Trijets -  $q\bar{q}g$ ,  $ggg$
  - ▶ Light meson pairs -  $\pi\pi$ ,  $\eta(\prime)\eta(\prime)$ ,  $KK$ ,  $\phi\phi$
  - ▶ Quarkonium pairs -  $J/\psi$ ,  $\psi(2S)$
  - ▶  $\chi_{c,b}$  quarkonia, via 2/3 body decays
  - ▶  $\eta_{c,b}$ .
  - ▶  $\gamma\gamma$ .
- Applies 'Durham' pQCD-based model.

LHL, V.A. Khoze, M. G. Ryskin.  
Int.J.Mod.Phys. A29 (2014) 1430031

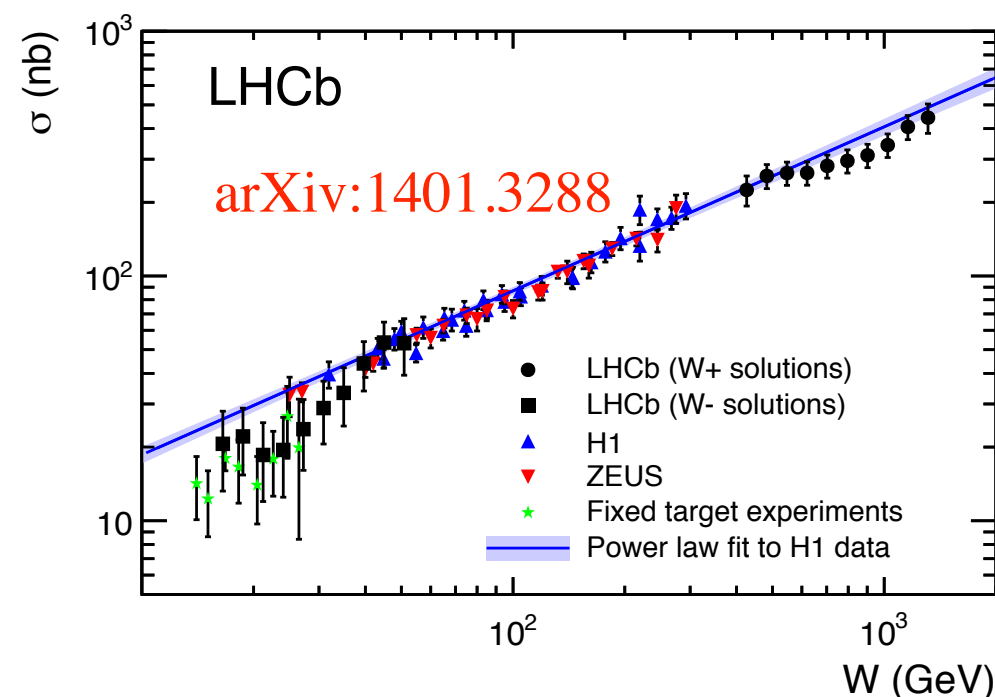


# Photoproduction

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

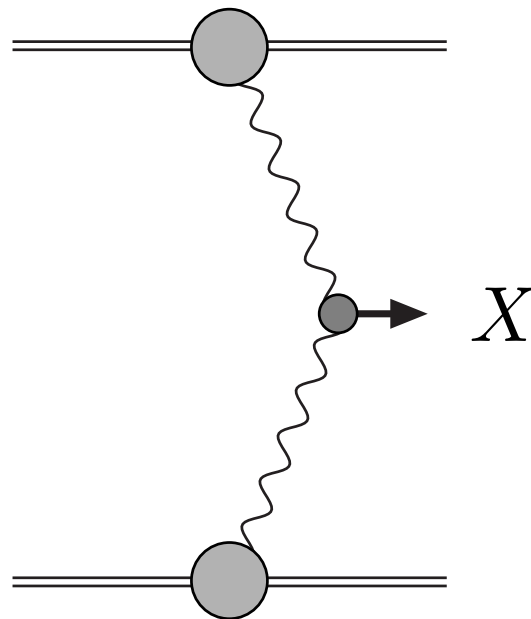


- Takes simple power-law fit to HERA / LHC data.



# Photon-induced production

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



# Updates

# Updates

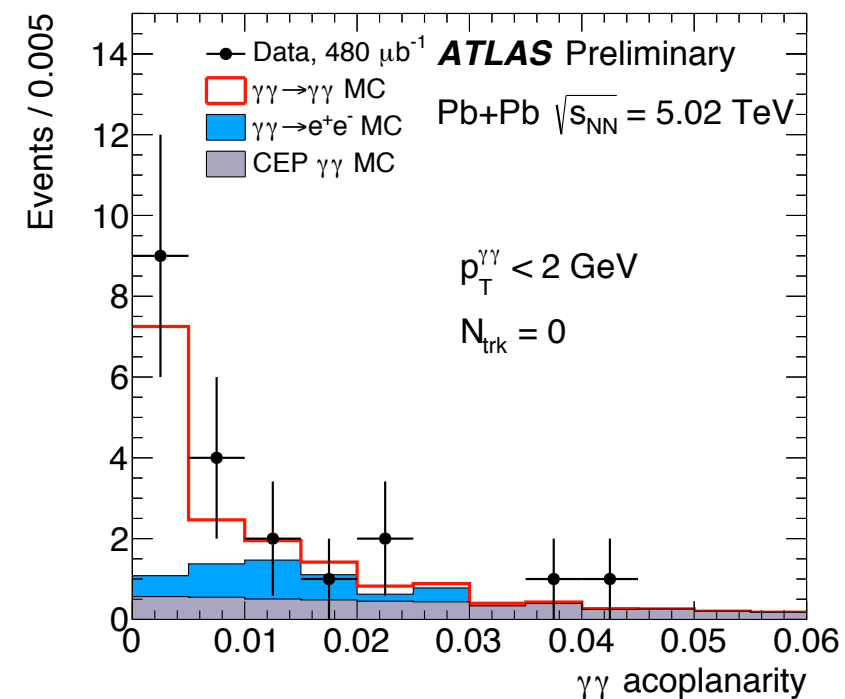
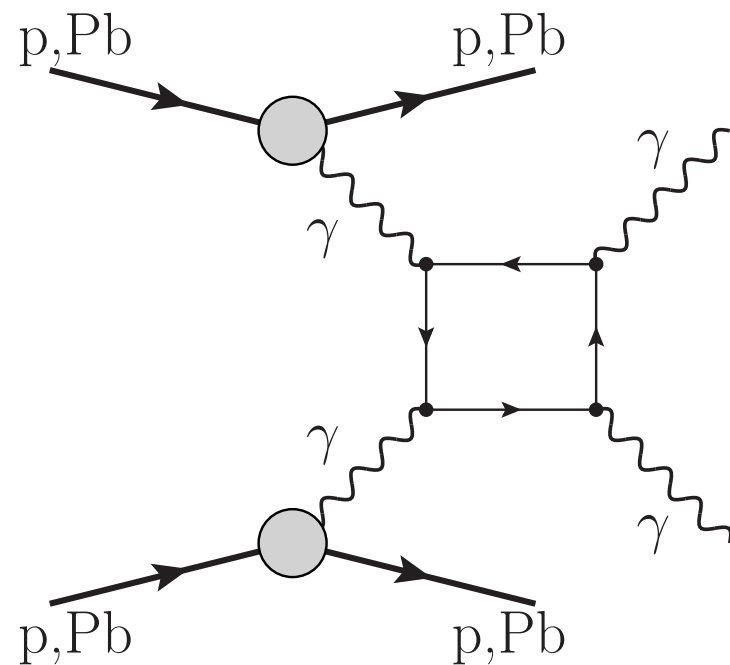
- Various updates to photon-induced CEP:
  - Light-by-light  $W$  loop contribution ( $\gamma\gamma \rightarrow W^*W^* \rightarrow \gamma\gamma$ ).
  - Axion-like particle
  - Monopole / monopolium

all implemented and available on request.
- Work ongoing to include ultra-peripheral heavy ions.



# Light-by-light scattering

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



- Analysis of d'Enterria and Silveira ([arXiv:1305.7142](https://arxiv.org/abs/1305.7142), [1602.08088](https://arxiv.org/abs/1602.08088)): realistic possibility, in particular in  $PbPb$  collisions.
- Subsequently, first evidence presented by ATLAS ([arXiv:1702.01625](https://arxiv.org/abs/1702.01625))

# LbyL - $W$ loops

- Light-by-light scattering mediated in the SM by virtual lepton, quark and  $W$  boson loops. Latter not relevant until  $M_{\gamma\gamma} \sim 2M_W$ .
- Earlier versions omitted  $W$  loop contribution. Fine for  $M_{\gamma\gamma} \lesssim 2M_W$  but not above.

→ Must include to get high mass region right.

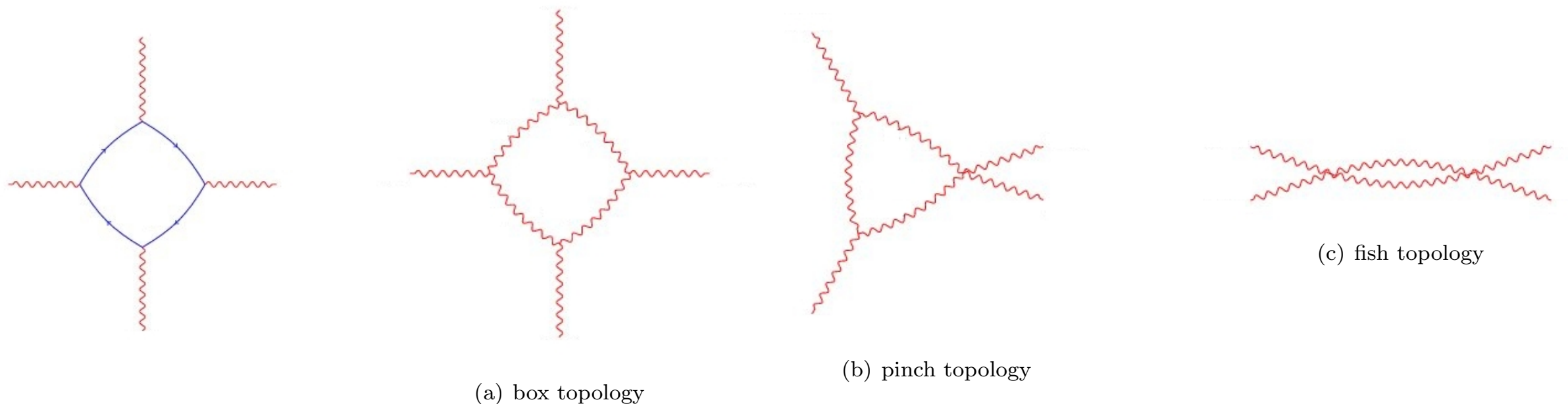


Figure 2:  $\gamma\gamma \rightarrow \gamma\gamma$  process EW diagrams

- Earlier version used explicit implementation of fermion loop amplitudes, with no  $W$  loops.
- Now, instead interface SANC implementation directly to MC:
  - $W$  loops included.
  - More precise treatment of  $s_{\gamma\gamma} \sim m_f^2$  transition.

Standard Model light-by-light scattering in SANC:  
analytic and numeric evaluation.

D. Bardin, L. Kalinovskaya, E. Uglov

*Dzhelepov Laboratory for Nuclear Problems, JINR,  
ul. Joliot-Curie 6, RU-141980 Dubna, Russia*

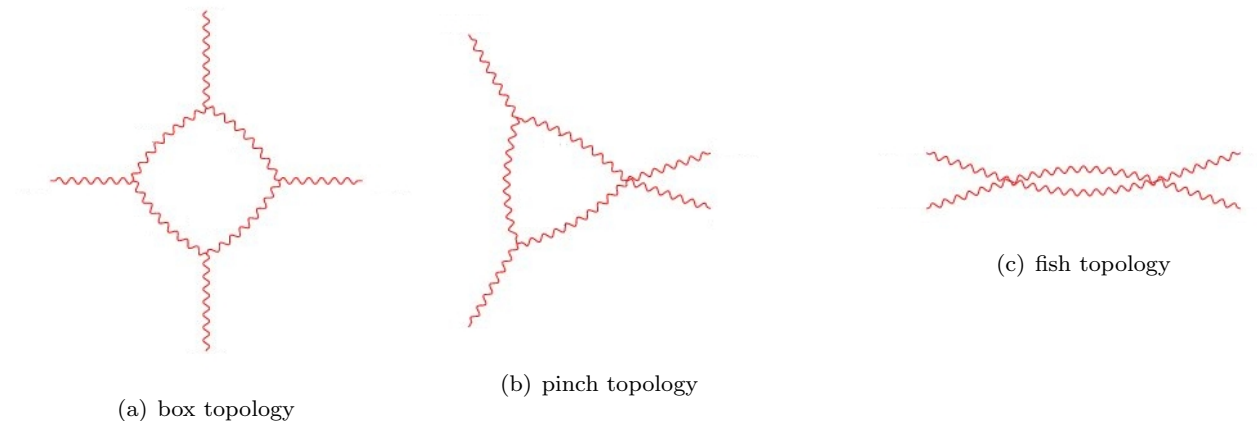
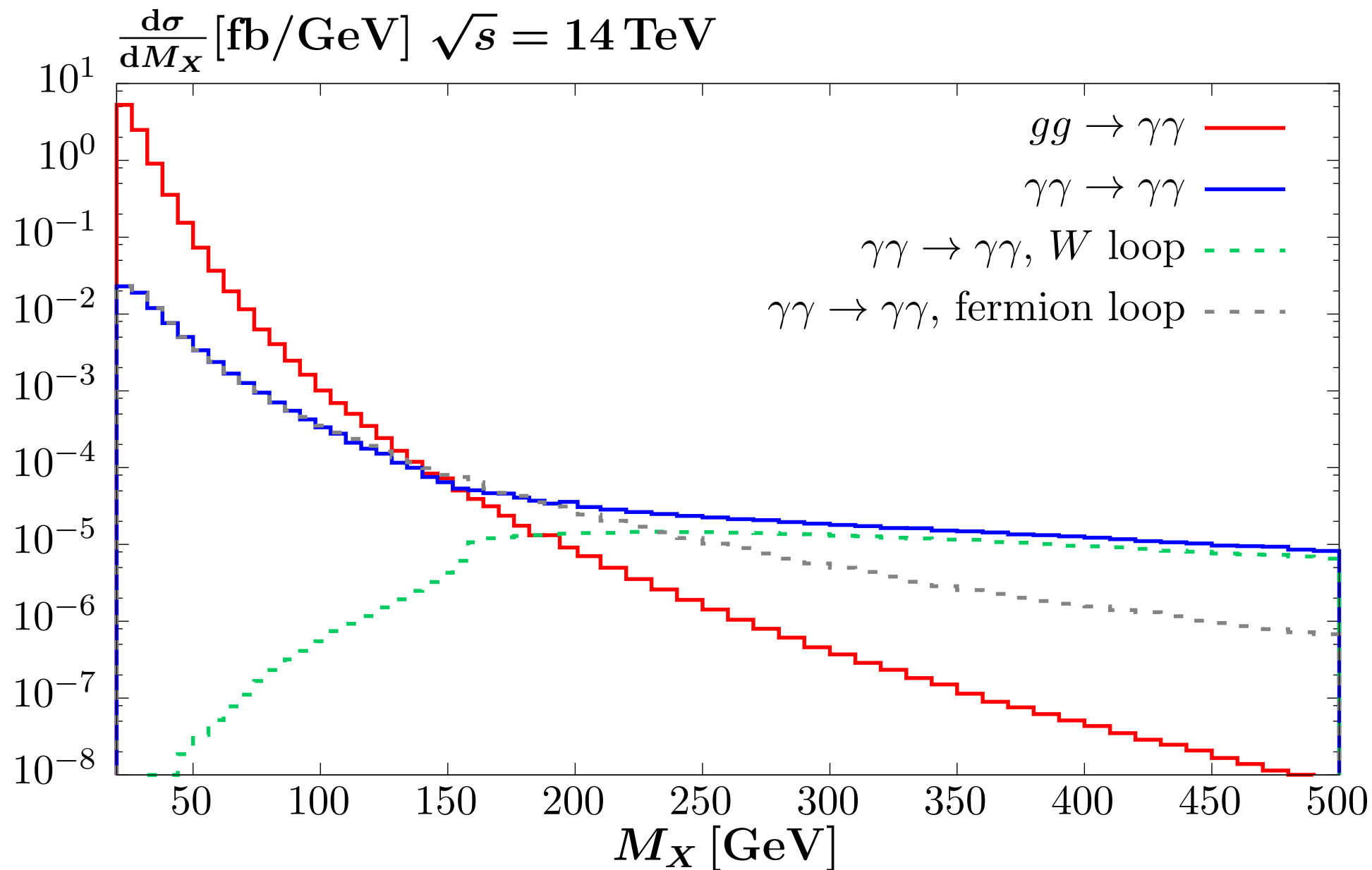


Figure 2:  $\gamma\gamma \rightarrow \gamma\gamma$  process EW diagrams

D. Bardin et al, Phys. Atom. Nucl. 73 (2010) 1878-1888



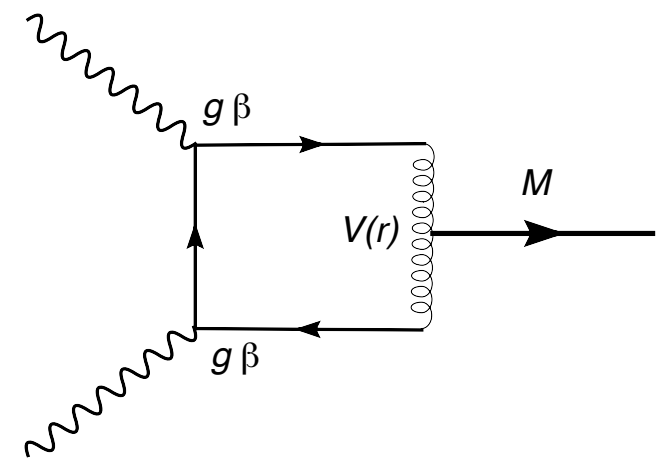
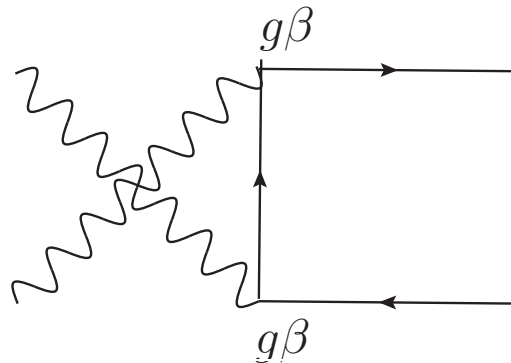
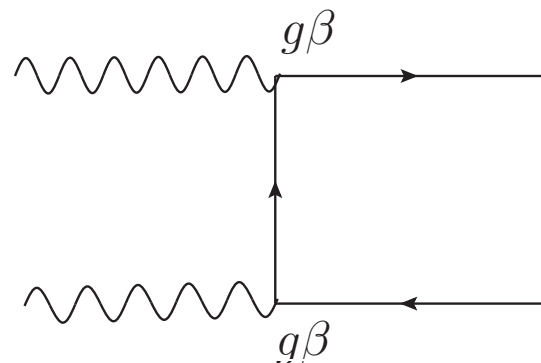
- Impact of  $W$  loops at high mass clear. For  $s_{\gamma\gamma} \gg M_W^2$  completely dominates!
- Also shown is QCD-mediated contribution (' $gg$ '). In the mass region the  $\gamma\gamma$  mediated contribution dominates (  $\rightarrow$  Sudakov suppression of  $gg$  ).

# Monopoles / monopolium

- Monopoles - add symmetry to Maxwell's equations and explain charge quantisation. As Dirac said:

*"...one would be surprised if Nature had made no use of it [the monopole]."*

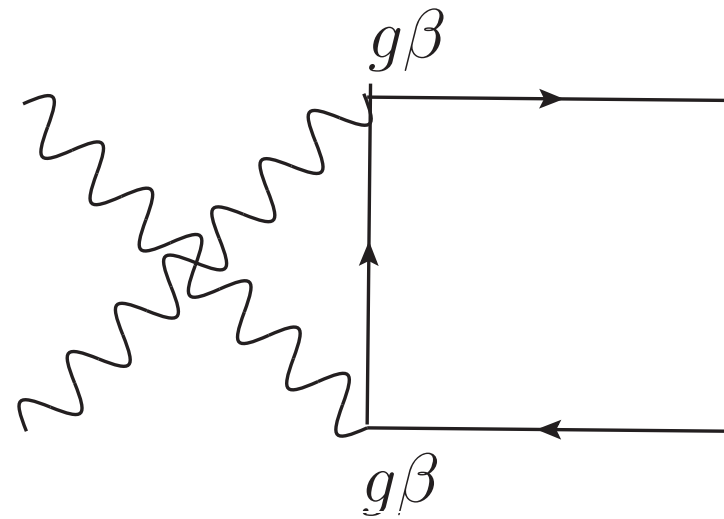
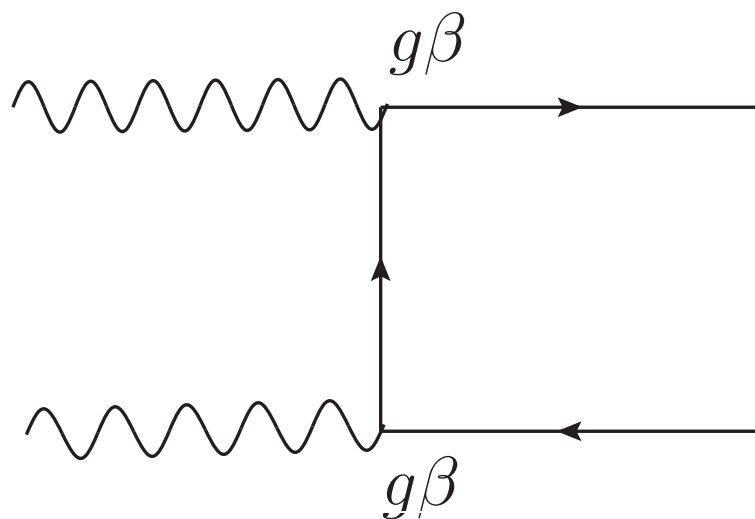
- Dirac quantization leads to monopole coupling,  $g^2 = N^2 \pi / \alpha$ .
- Photon-initiated production ideal channel to search for these object, with large QED couplings.
- As well as monopole pair production, can produce a  $M\bar{M}$  bound state - monopolium.



T. Dougall and S. D. Wick, Eur.Phys.J. A39 (2009) 213-217

L. N. Epele et al., Eur.Phys.J C62 (2009) 587-592

- Dirac quantization leads to monopole coupling  $g^2 = N\pi/\alpha$   
 → Monopole production non-perturbative process.
- Different approaches to deal with this are available, correspond to different choices of coupling. We implement two:
  - Basic Dirac monopole coupling  $g_D = (\pi/\alpha)^{1/2}$
  - The beta-coupling  $\beta g_D$ , where  $\beta$  is monopole velocity.



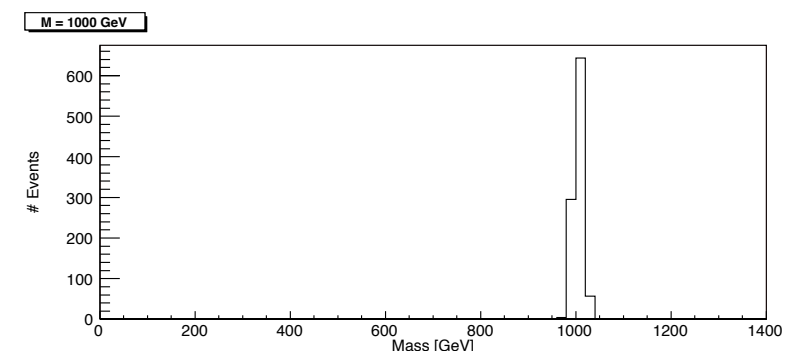
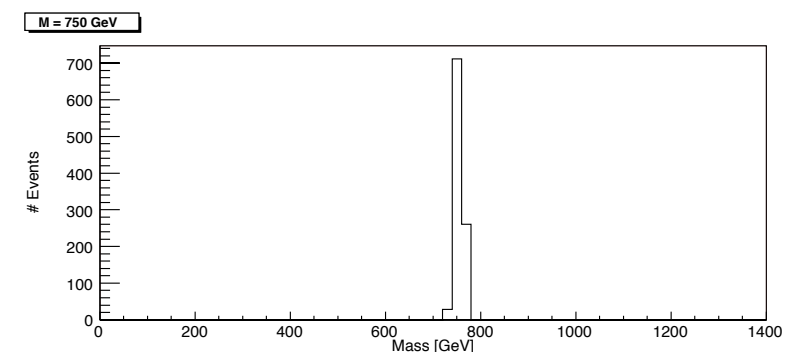
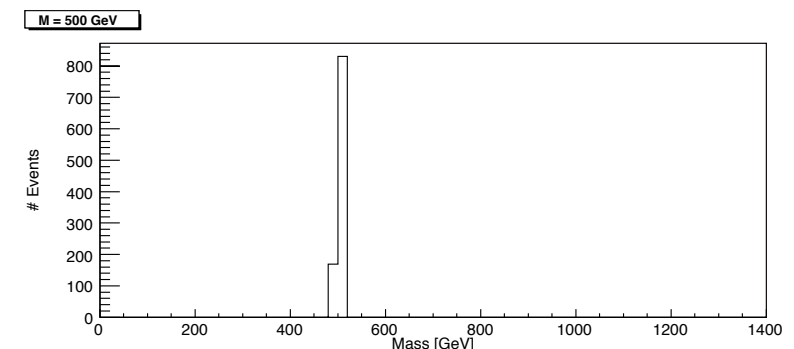
- ‘LHC ring proto-collaboration’ - searching for CEP physics with the LHC BLMs.
- Monopolium production (SuperChic implementation) a case study to demonstrate possibilities.
- Ongoing study - paper in preparation.

## Turning the LHC Ring into a New Physics Search Machine

Risto Orava<sup>1, a)</sup>

For the LHC Ring proto-collaboration

R. Orava, AIP Conf. Proc. 1819 (2017) no .1, 04022



# Axion-like particles

- The  $\gamma\gamma \rightarrow \gamma\gamma$  transition in CEP can be sensitive to Axion like particles.  
S. Knapen et al., Phys. Rev. Lett. 118 (2017) no.17, 171801
- Discussed in Knapen et al. (1607.06083) - find that in heavy ion collisions can set the strongest limits yet on these couplings.

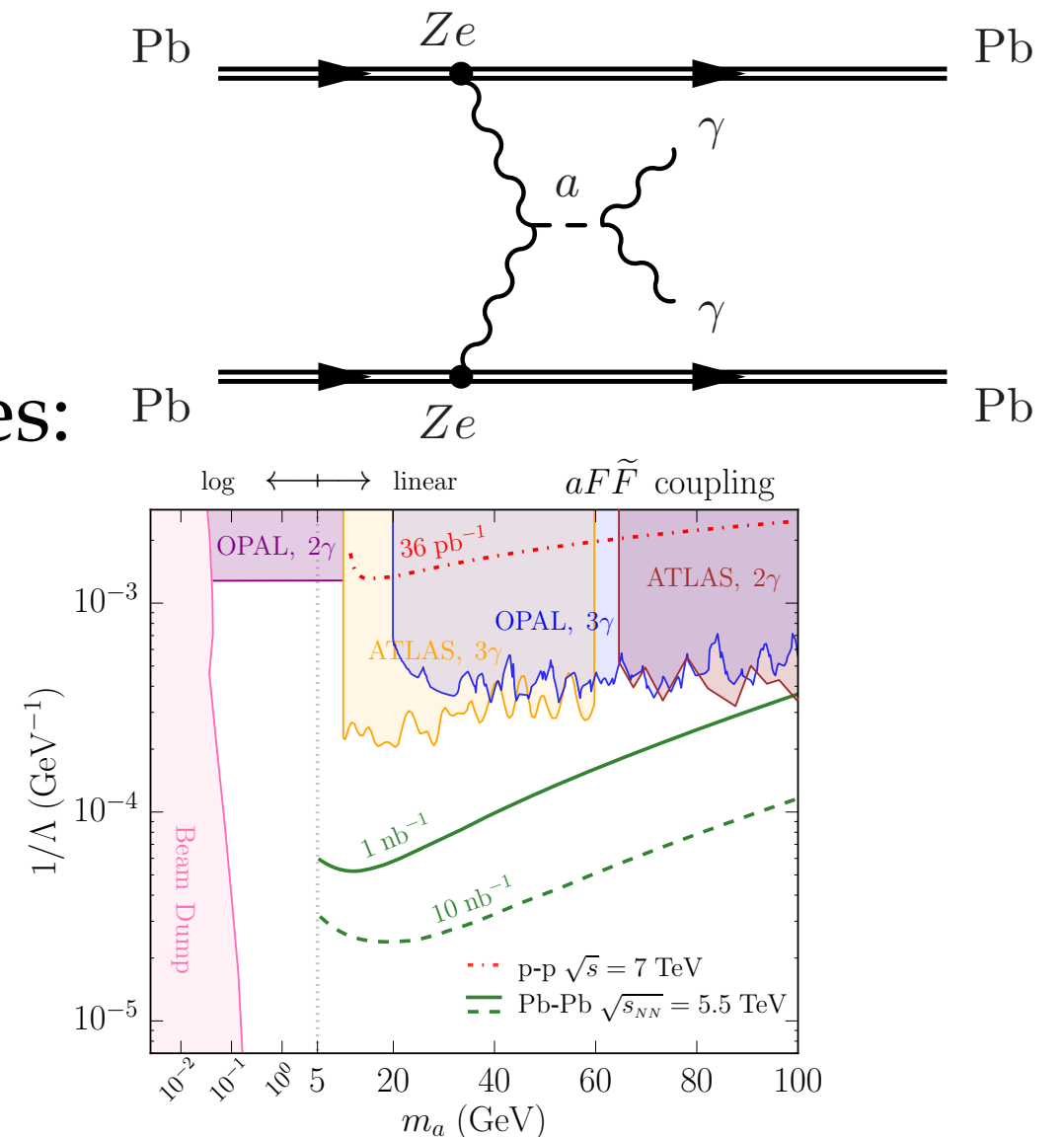
- Lagrangian:

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

gives simple production amplitudes:

$$\mathcal{M}_{\pm\pm} = \frac{1}{2} \frac{m_a^2}{\Lambda} \quad \mathcal{M}_{\pm\mp} = 0$$

- Implementation, including full decay kinematics, will be included in next release.





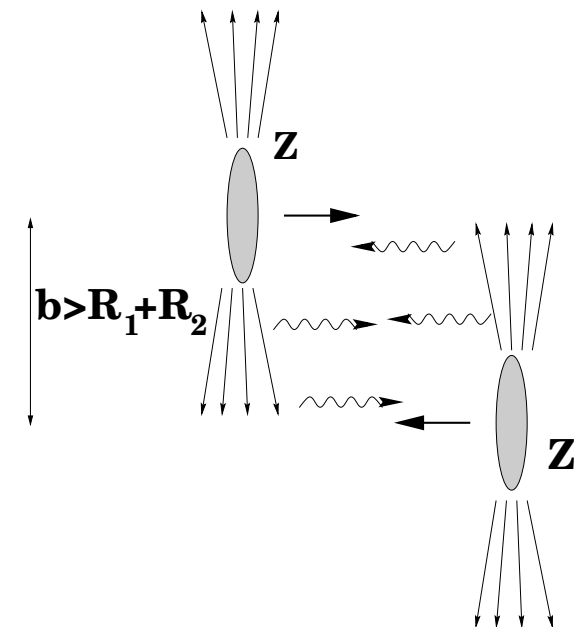
# Ultra-peripheral heavy ion collisions

# Heavy ions

- Work ongoing on extending to heavy ions. Typically work in impact parameter space. Flux often given by:

$$N(\omega, b) = \frac{Z^2 \alpha \omega^2}{\pi^2 \gamma^2 \hbar^2 \beta^2 c^2} \left( K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right). \quad x = \omega b / \gamma \beta \hbar c$$

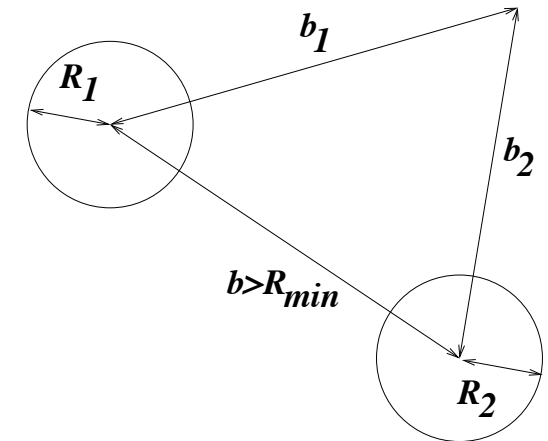
- Then integrate over  $b_{1\perp}, b_{2\perp}$ , requiring  $|b_{1\perp} - b_{2\perp}| > R_1 + R_2$ .
- Implemented in unofficial\* SuperChic release, provided by authors of [arXiv:1305.7142](#)
- However this approach is simplified. We now wish to be more exact:
  - Exact kinematics ( $Q^2 \neq 0$ ).
  - Nuclear overlap/Form factors.
  - Survival effects.
  - Dissociation?



\*Available on request!

- As starting point, we write

$$\sigma = \int d^2b_1 d^2b_2 \sigma_{\text{CEP}}(\vec{b}_1, \vec{b}_2) e^{-\Omega(b)}$$



where  $e^{-\Omega}$  is the survival factor, i.e. direct analogue of  $pp$  case. To first approx we have  $e^{-\Omega(b)} \approx \Theta(b - R_1 - R_2)$  but not exact!

- More precisely:

$$\Omega(b) = \sigma_{\text{inel.}} \int d^2b'_1 d^2b'_2 T(b'_1) T(b'_2) \delta(\vec{b} - \vec{b}') , \quad S^2 \leftrightarrow e^{-\Omega} \quad \text{: survival factor}$$

$$\vec{b}' = \vec{b}'_1 - \vec{b}'_2$$

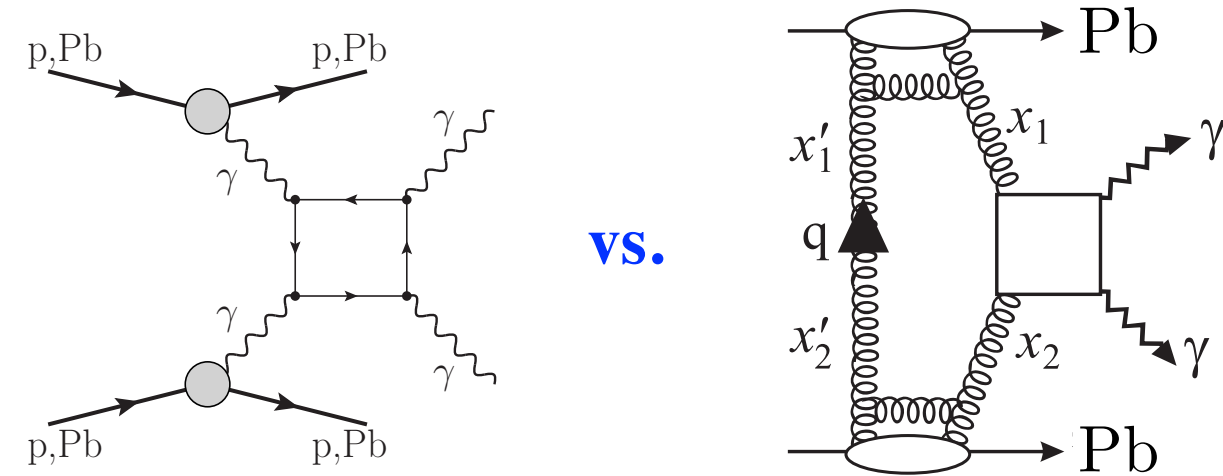
$$T(b) = \int dz \rho(r) , \text{ with e.g. } \rho(r) = \frac{\rho_0}{1 + \exp((r - R)/D)} \quad \text{: nucleon density}$$

- Some simple consequences follow from this:

- **Consequence 1:**  $A^{1/3}$  scaling for QCD-mediated production.
- **Consequence 2:** departure from simple  $b > R_{\text{min}}$  for QED-mediated production.

# Consequence 1 - QCD-mediated production

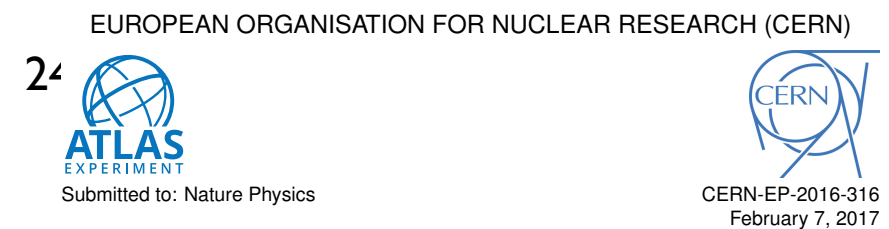
- Question: do we need to worry about QCD-induced CEP background in heavy ion collisions?



- Considered in (first!) ATLAS evidence for light-by-light scattering.

- Argued that SuperChic prediction for  $pp \rightarrow p\gamma\gamma p$  via  $gg$  should be scaled by  $A^2$ . Found to be quite small (also  $p_{\perp}^{\gamma\gamma}$  distribution broader).

Is this right?



Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

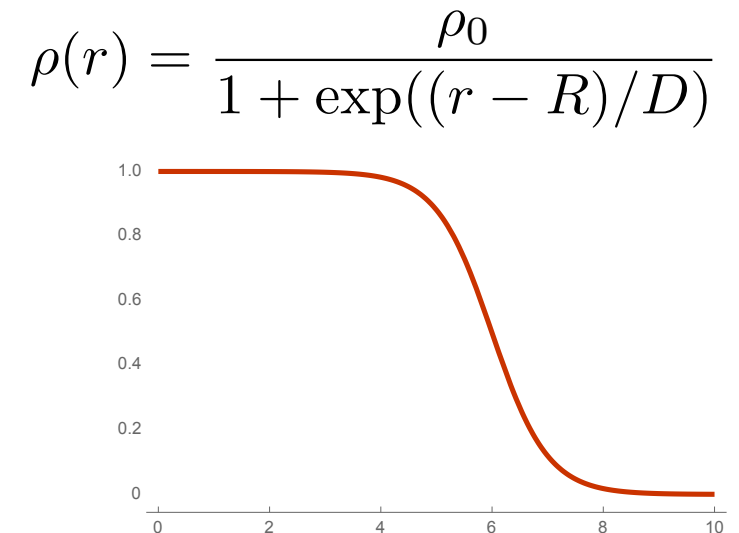
The ATLAS Collaboration

arXiv:1702.01625

- Cross section:  $\sigma = \int d^2b_1 d^2b_2 \sigma_{\text{CEP}}(\vec{b}_1, \vec{b}_2) e^{-\Omega(b)}$

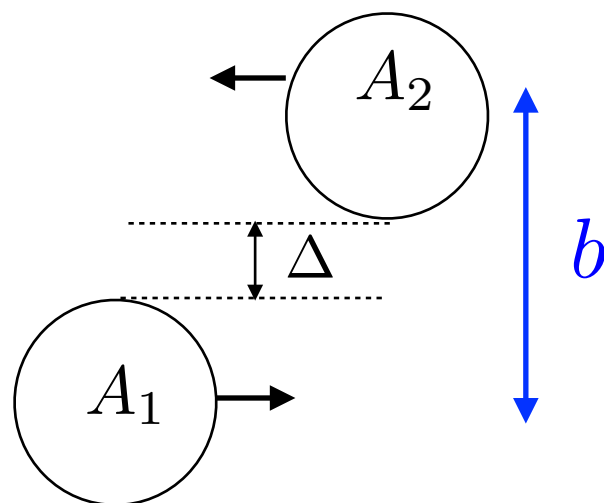
- The exponent in the  $e^{-\Omega}$  suppression factor:

$$\Omega(b) = \sigma_{\text{inel.}} \int d^2b'_1 d^2b'_2 T(b'_1) T(b'_2) \delta(\vec{b} - \vec{b}') ,$$



is generally very large  $\rightarrow$  need  $b \gtrsim R_1 + R_2$  for non-negligible contribution, where nuclear density not too large.

- On the other hand, QCD is short-range -  $R_{\text{QCD}} \ll R_A$
- $\rightarrow$  all interactions must happen on ion periphery, with some small separation  $\Delta$  along impact parameter direction.

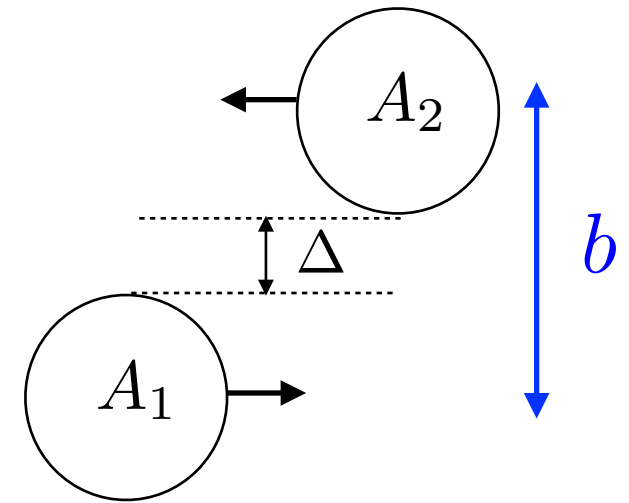


- QCD is short-range -  $R_{\text{QCD}} \ll R_A$  - so simplify

$$\sigma = \int d^2b_1 d^2b_2 \sigma_{\text{CEP}}(\vec{b}_1, \vec{b}_2) e^{-\Omega(b)}$$

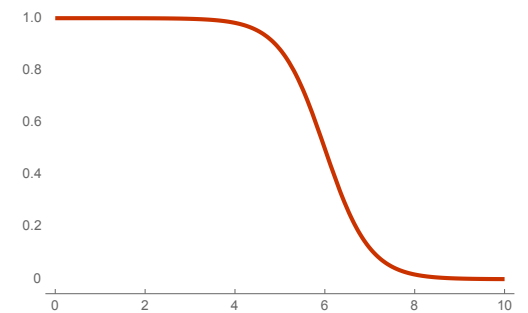
with:

$$\sigma \approx \int d^2b_1 d^2b_2 T(b_1) T(b_2) \sigma_{\text{CEP}}^{gg} e^{-\Omega(b)}, \quad \rho(r) = \frac{\rho_0}{1 + \exp((r - R)/D)}$$



- Performing the integral, with  $d^2b \rightarrow 2\pi(R_1 + R_2)d\Delta$ , we end up with:

$$\sigma \sim (R_1 + R_2)D \sim (A_1 + A_2)^{1/3}$$



→ QCD-mediated CEP occurs in ring of radius  $R_1 + R_2$  and width  $D$ . This surface-like interactions has a  $\sim A^{1/3}$ , and not  $\sim A^2$  scaling, i.e. much lower cross section than ATLAS expectations.

Numerical calculation in prep.

## Consequence 2 - photon-induced production

- What about photon-initiated CEP? No longer dealing with short range interaction  $\Rightarrow$  must keep full  $b$ -dependent form:

$$\sigma = \int d^2b_1 d^2b_2 \sigma_{\text{CEP}}^{\gamma\gamma}(\vec{b}_1, \vec{b}_2) e^{-\Omega(b)} ,$$

now  $\sigma_{\text{CEP}}^{\gamma\gamma}$  in general extends far beyond  $b \sim R_A$ , where  $e^{-\Omega} \sim 1$  .

$\longrightarrow$  As we know well,  $S^2$  not dramatic for ultra-peripheral collisions.

- However cannot ignore completely:
  - Contribution for  $b \lesssim R_A$  not negligible, in particular for larger  $M_X$  , where  $t_{\text{min}} \uparrow$  and  $b \downarrow$  .
  - For  $b \gtrsim R_A$  will have some suppression as well.

$$\sigma = \int d^2b_1 d^2b_2 \sigma_{\text{CEP}}^{\gamma\gamma}(\vec{b}_1, \vec{b}_2) e^{-\Omega(b)} ,$$

- Often  $S^2$  effects included via simple  $b > R_1 + R_2$  cut.

However this approximates:

$$e^{-\Omega(b)} \approx \Theta(b - R_1 - R_2)$$

which is clearly not exactly true  $\Rightarrow$  misses physics in  $b \sim R$  region.

- In addition, as in  $pp$  collisions  $\sigma_{\text{CEP}}^{\gamma\gamma}$  has non-trivial vector  $\vec{b}_1, \vec{b}_2$  dependence, due to the polarization structure of the  $\gamma\gamma \rightarrow X$  process. Will impact final result and should be included.
- Finally, transforming back to  $q_\perp$  space at the end we can calculate the impact of this on the ion  $q_\perp$  distribution (typically assume  $\delta(\vec{q}_\perp)$ ).

$\longrightarrow$  Work actively ongoing to do this. Watch this space!



# Conclusion and outlook

- **SuperChic** - a MC event generator for CEP processes.
- Unified platform for QCD-induced, photoproduction and photon-photon collisions. Differential treatment of survival factor.
- Recent updates:
  - Light-by-light scattering -  $W$  loops.
  - Monopole pair / monopolium production.
  - Axion-like particle production.
- Ongoing work: complete treatment of ultra-peripheral heavy ion collisions following extension of SuperChic approach.
- A new public release with these updates to come soon.
- Open to suggestions- collaborations / requests welcome.

Thank you for listening!