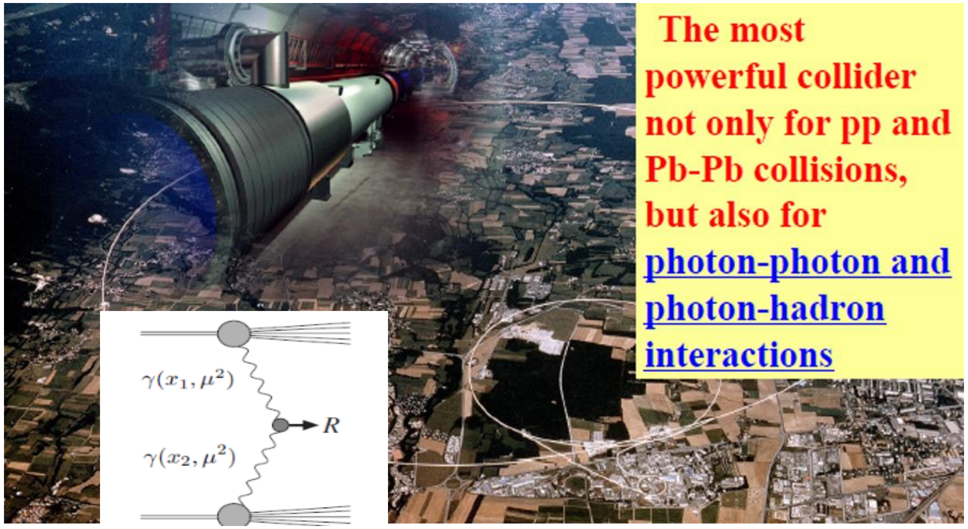
TOTEM COLLABORATION MEETING:

MALAUCENE, FRANCE
June 5-10 2017

PHOTON-PHOTON COLLISIONS AT THE LHC
(selected topics)

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

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



Daniel Tapia Takaki Diffraction – *Catania, Sicily* 7 September 2016

Outline

- Introduction and Motivation.
- Selecting Photon-Photon Exclusive Events.
- SuperChic- MC and Survival Guide
- The photon PDF and photon-photon Luminosities
- Photon-initiated processes with rapidity gaps
- $\gamma\gamma$ - collisions at the LHC- Applications (with an emphasis on BSM physics).
- Summary and Outlook.

INTRODUCTION & MOTIVATION

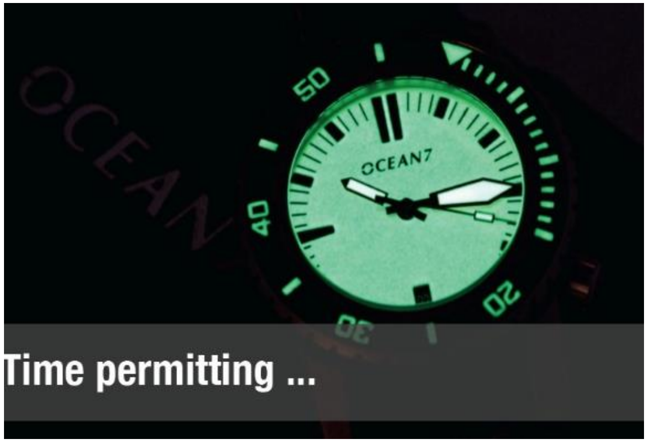
- No immediate plans for a future $\gamma\gamma$ collider, but the LHC is already a photon-photon collider!

(FNAL/RHIC-experience)

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

- Exclusive production:
  - How do we measure it ?
  - 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.



CENTRAL EXCLUSIVE PRODUCTION PROCESSES

What is it?

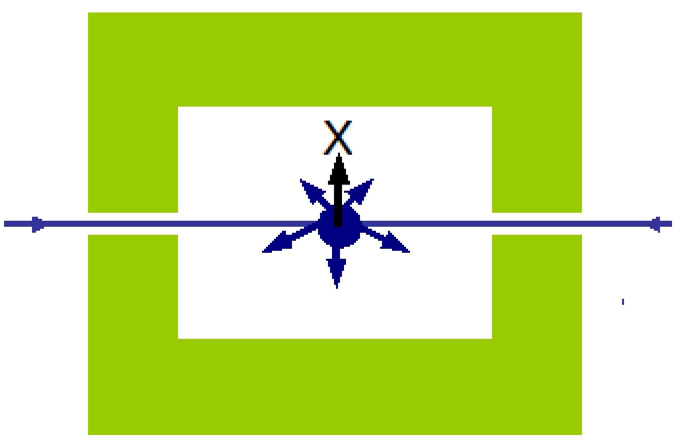
Central Exclusive Production (CEP) is the interaction:

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

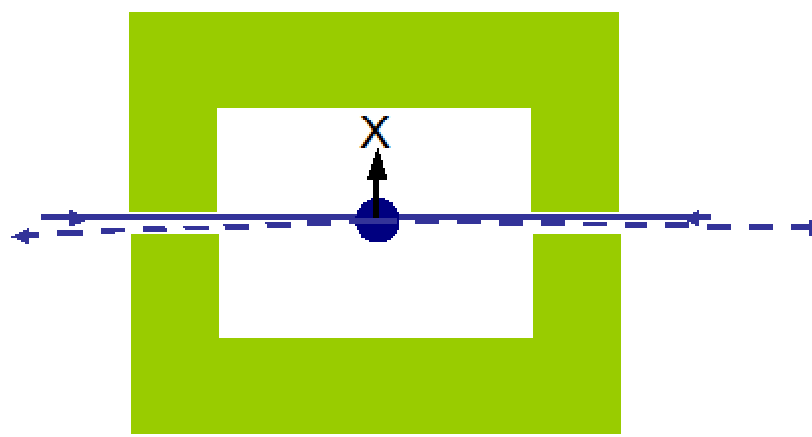
- **CEP** colour singlet exchange between colliding protons, with large rapidity gaps ('+') in the final state.

Photons, Pomerons..

- 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.



vs.



SELECTING EXCLUSIVE PHOTON-PHOTON EVENTS AT THE LHC

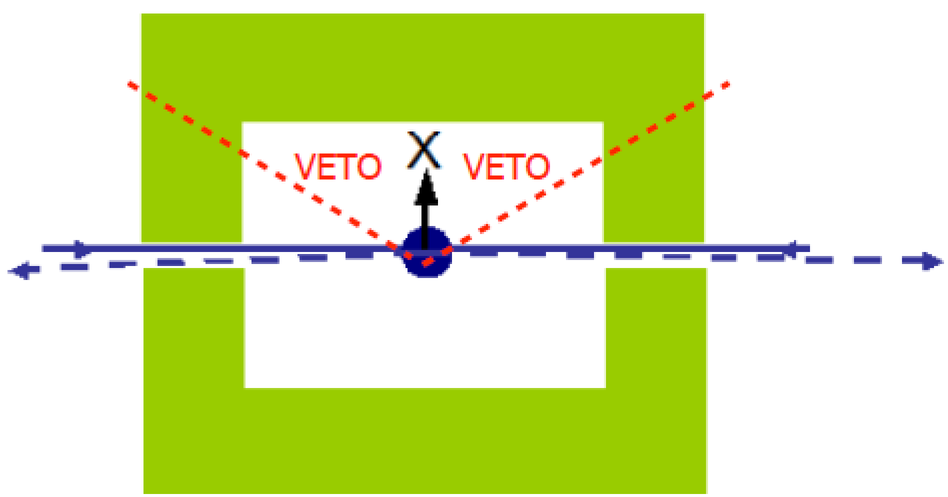
MIND THE GAP

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

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

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

(CT- PPS first measurements with the one arm proton)



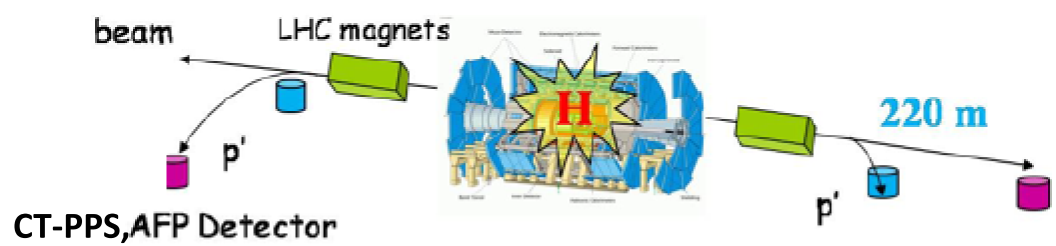
2) Proton tagging: $pp \rightarrow p + X + p$

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

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

- Basic principle: use LHC beam magnet as a spectrometer. After interaction protons have $E < \sqrt{s}/2$ and will gradually bend out of beam line.

- Insert 'roman pot' detectors at $O(\mathrm{mm})$ from beam line and $O(100\,\mathrm{m})$ from IP. Reconstruct momenta and measure arrival time of protons.



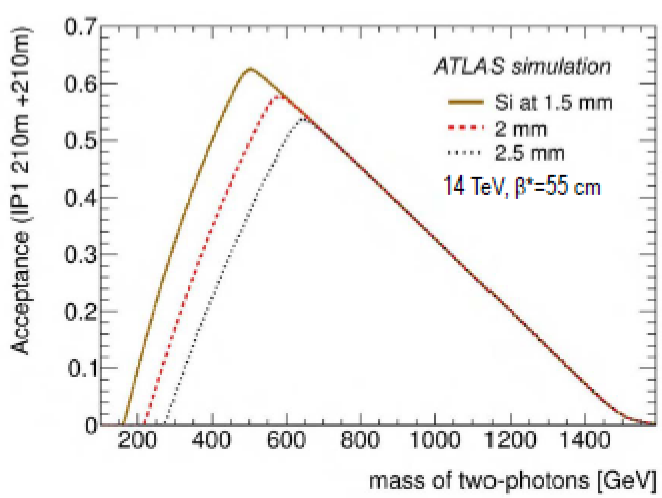
Mass acceptance

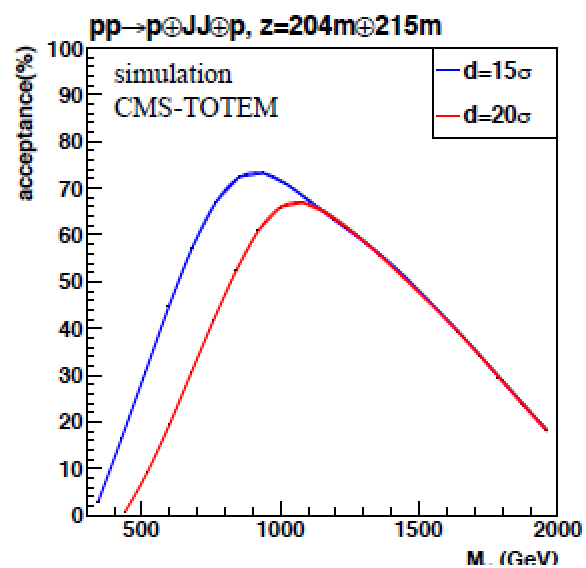
- Momentum loss ξ of protons related to mass of central system:

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

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

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





how close the RPs can safely approach the beam ?

“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 500 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.

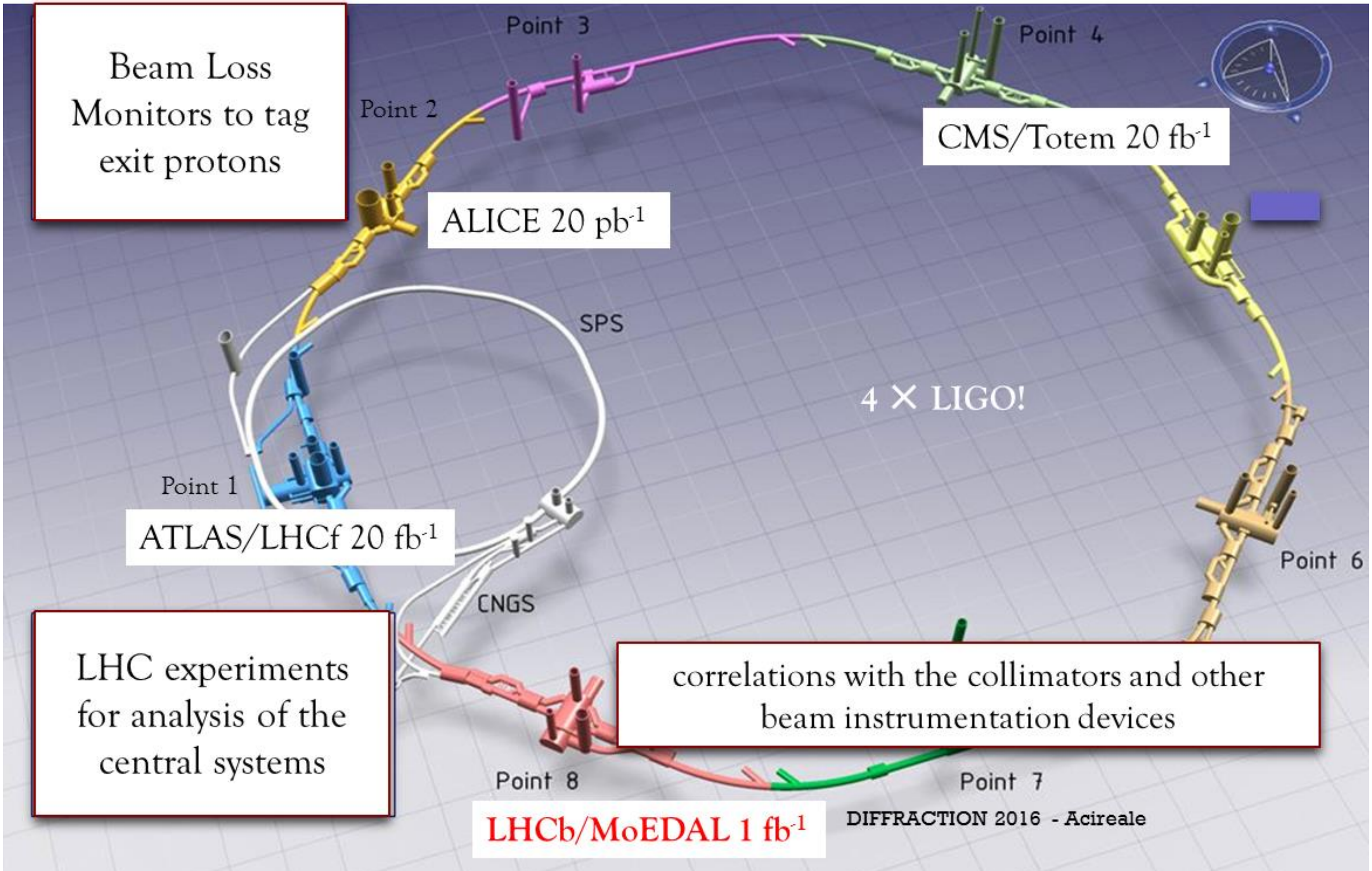
3) Turning the LHC Ring into a New Physics Search Machine

(Risto's talk)

LHC Ring –proto collaboration

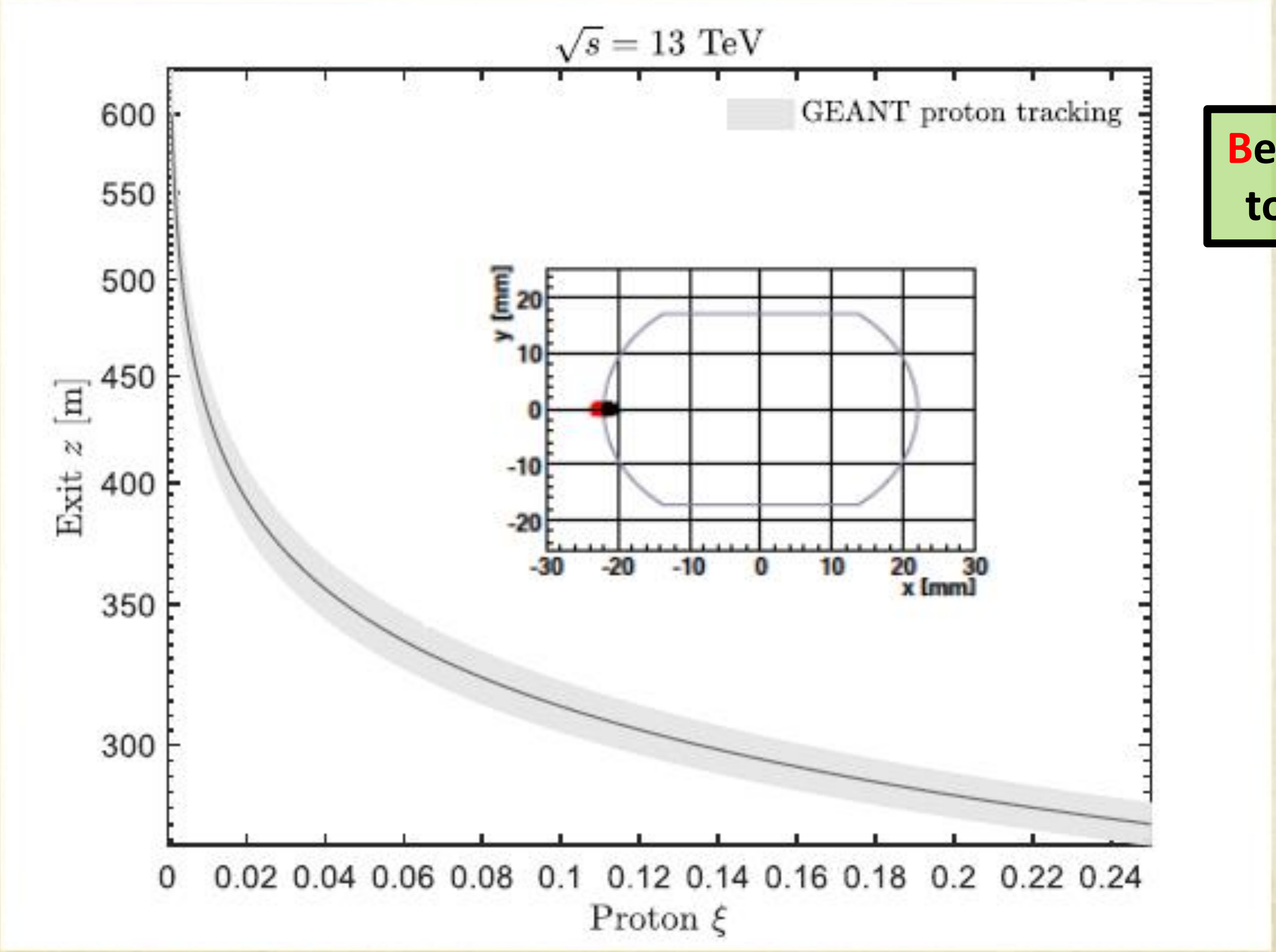
(S. Redaelli et al., CERN Beams Division), accelerator theory (Werner Herr, CERN Beams Division), theoretical high energy physics (Lucian Harland-Lang, University College, London, K. Huitu, Division of Particle Physics and Astrophysics, University of Helsinki; Valery Khoze, University of Durham University; M.G. Ryskin Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg; V. Vento, University of Valencia and CSIC) and experimental high energy physics (A. De Roeck, CERN EP; M. Kalliokoski, CERN Beams Division; Beomkyu Kim, University of Jyväskylä; Jerry W. Lämsä, Iowa State University, Ames; C. Mesropian, Rockefeller University; Matti Mikael Mieskolainen, University of Helsinki; Toni Mäkelä, Aalto University, Espoo; Risto Orava, University of Helsinki, Helsinki Institute of Physics and CERN; J. Pinfold, FRSC, Centre for Particle Physics Research, Physics Department, University of Alberta; Sampo Saarinen, University of Helsinki; M. Tasevsky, Institute of Physics of Academy of Sciences, Czech Republic) and seismology (Pekka Heikkinen, Institute of Seismology, University of Helsinki).

LHC RING AS A NEW PHYSICS SEARCH MACHINE



the LHC Ring represents a continuous "Roman Pot" !

PROTON EXIT POINTS vs. $\xi = \Delta p / p$



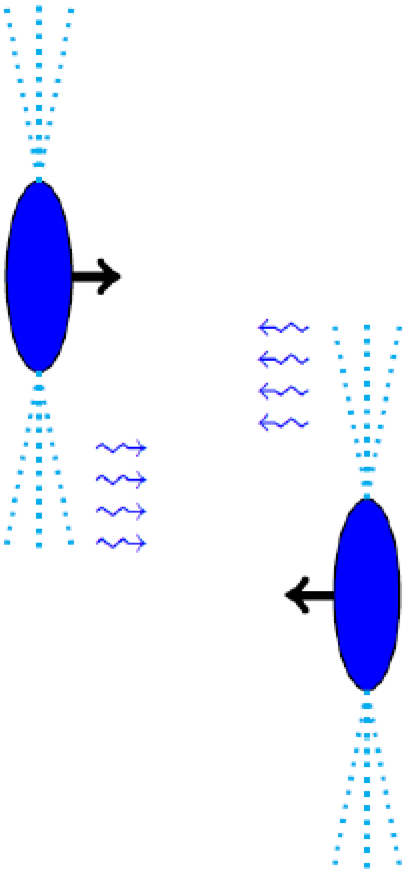
Beam Loss Monitors to tag exit protons

Matti K. Kalliokoski, RO et al., arXiv:1604.5778; Diffraction 2016

J. Aaron. *Hacking the LHC to shift trash could help find a mystery particle* – 2016.New Scientist Daily News, 25th April.

4)

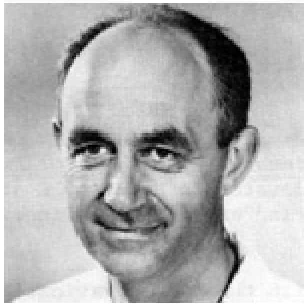
Ultra Peripheral HI Collisions



Nuovo Cim.,2:143-158,1925

http://arxiv.org/abs/hep-th/0205086

Therefore, we consider that when a charged particle passes near a point, it produces, at that point, a variable electric field. If we decompose this field, via a Fourier transform, into its harmonic components we find that it is equivalent to the electric field at the same point if it were struck by light with an appropriate continuous distribution of frequencies.



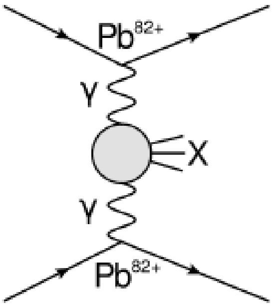
Enrico FERMI

The electromagnetic field surrounding these protons/ions can be treated as a beam of quasi real photons

Two ions (or protons) pass by each other with impact parameters b > 2R. **Hadronic interactions are strongly suppressed**

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]

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

- 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.

LHC as a photon-photon collider

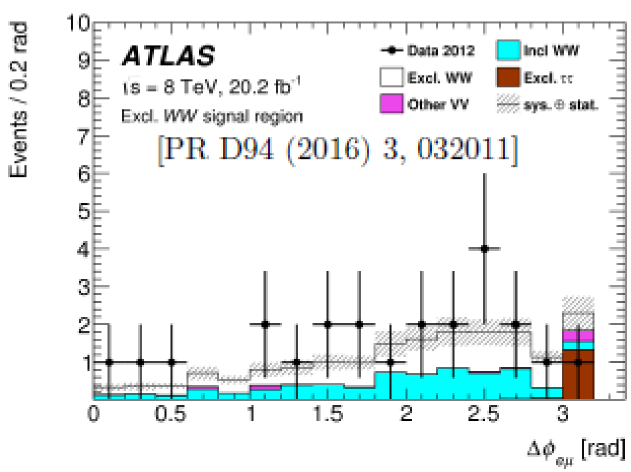
pp collisions

Pros

- harder EPA γ spectrum ($\omega_{\max} \sim$ TeV)
- more data available ($\sim 35\,\mathrm{fb}^{-1}$)

Cons

- large pile-up (multiple interactions per bunch crossing)
- problems with triggering on low p_T objects



Pb+Pb collisions

Pros

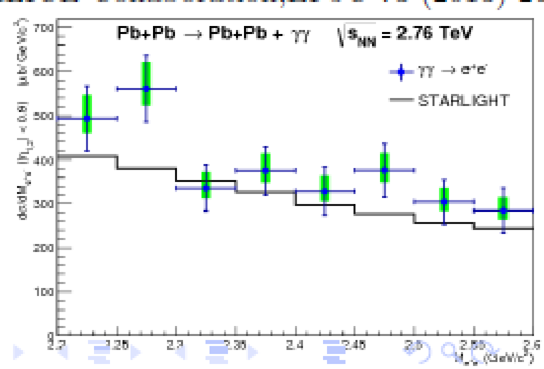
- AA ($\gamma\gamma$) x-sec $\propto Z^4$
- gluonic x-sec $\propto A^2$ $\Rightarrow$ lower QCD bkg.
- low pile-up ($< 1\%$)

$A^{2/3}$

Cons

- softer EPA γ spectrum ($\omega_{\max} \sim 0.1$TeV)
- relatively small data sample

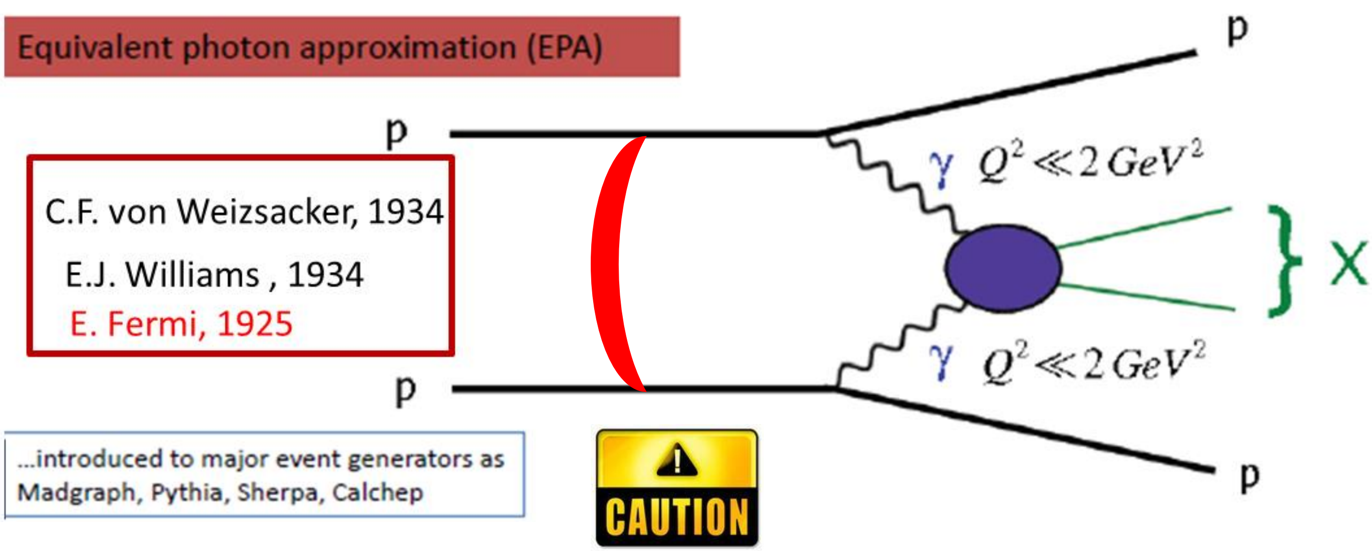
[ALICE Collaboration,EPJC 73 (2013) 2617]



ATLAS 2016

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

Received 25 April 1974
Revised version received 5 July 1974

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

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

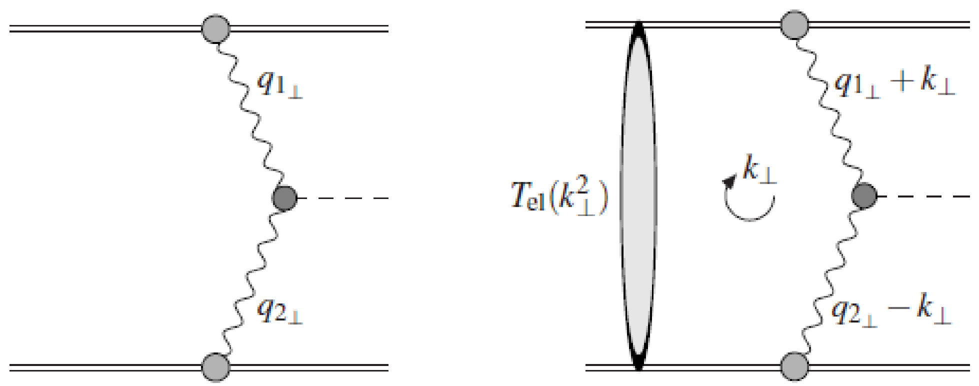
$\langle S_{\mathrm{eik}}^2\rangle = 0.77 \quad : \quad J_P = 0^-$

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'.



Durham Group-KMR
Tel-Aviv Group- GLM

S. Ostapchenko...
Lonnblad&Zlebcik

- Photon virtuality has kinematic minimum $Q^2_{1,\mathrm{min}} = \frac{\xi_1^2 m_p^2}{1-\xi_1}$

where $\xi_1 \approx \frac{M_\psi}{\sqrt{s}} e^{y_\psi}$ assuming photon emitted from proton 1 positive z-direction

$\longrightarrow$ Forward production $\Rightarrow$ higher photon Q^2 and less peripheral interaction

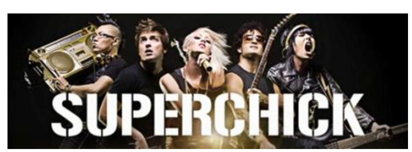
$\Rightarrow$ Smaller S^2_{eik}

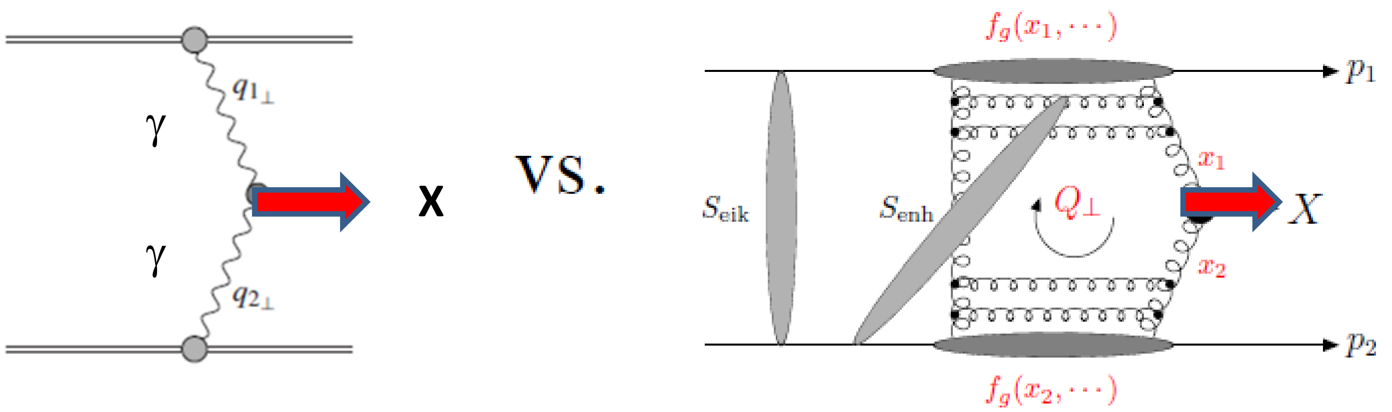
- Not a constant: depends sensitively on the outgoing proton $\mathbf{p}_\perp$ vectors. Physically- survival probability will depend on impact parameter of colliding protons. Further apart $\longrightarrow$ less interaction, and $S^2_{\mathrm{eik}} \to 1$. b_t and $p_\perp$: Fourier conjugates.

Process dependence

$\longrightarrow$ Need to include survival factor differentially in MC.

First fully differential implementation of soft survival factor – **SuperChic 2** MC event generator- HKR, ArHiv:1508.02718





- 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.

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

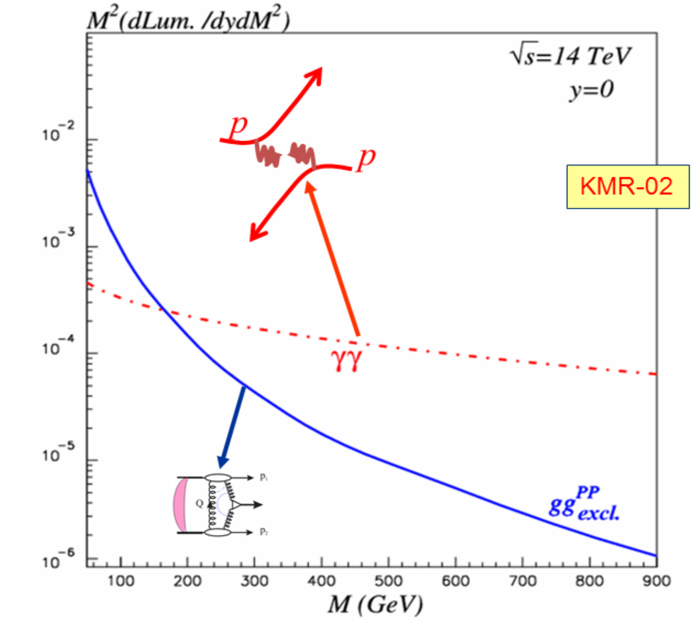
- Increasing $M_X \Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

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

KMR-2001

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

QCD 'radiation damage' in action



Superchic vs FPMC

Devil is in the details

• 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 $s_{\gamma\gamma}$.

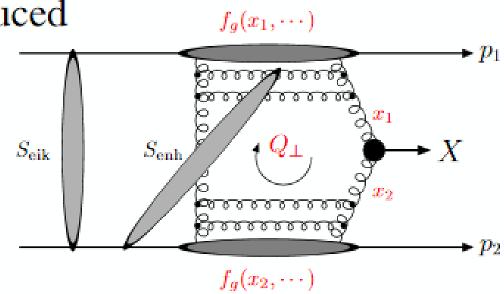
Photon-photon collisions in Superchic

Production mechanisms

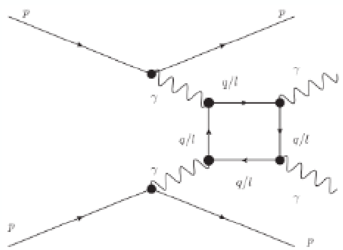
Exclusive final state can be produced via three different mechanisms, depending on kinematics and quantum numbers of state:

Gluon-induced

C-even, couples to gluons

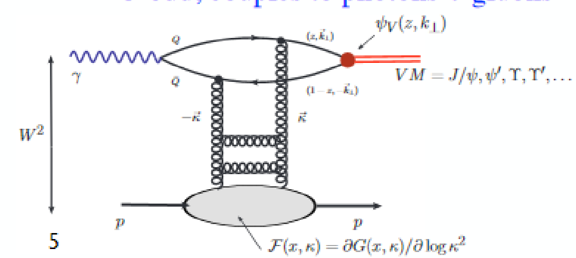


Couples to photons



Photon-induced

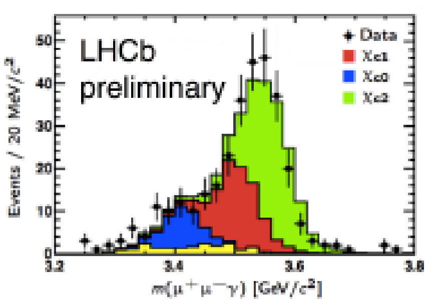
C-odd, couples to photons + gluons

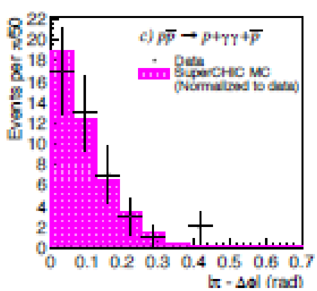


Photoproduction

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

Availability

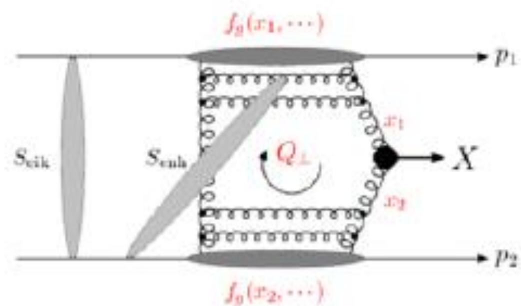
- Code and user manual available on Hepforge:

`https://superchic.hepforge.org`

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>.

SuperChic v2.04

A Monte Carlo for Central Exclusive Production

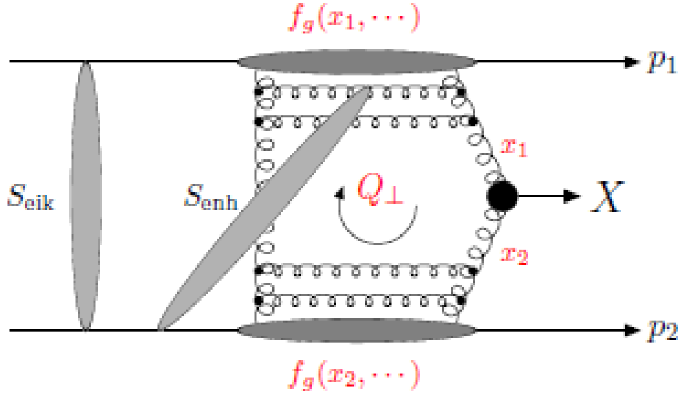
Users guide

Lucian Harland-Lang (l.harland-lang@ucl.ac.uk)

7

Generated Processes - QCD

- 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 - $\pi\pi, \eta(')\eta('), KK, \phi\phi$
- Quarkonium pairs - $J/\psi, \psi(2S)$
- $\chi_{c,b}$ quarkonia, via 2/3 body decays
- $\eta_{c,b}$.
- $\gamma\gamma$.



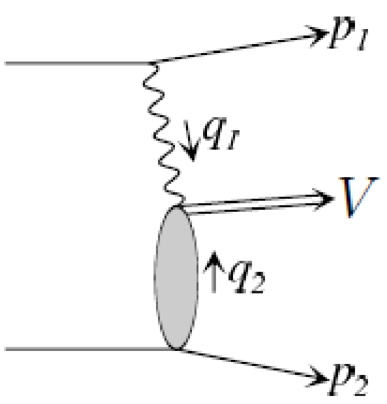
- Applies 'Durham' pQCD-based model.

LKR Int.J.Mod.Phys. A29 (2014) 1430031

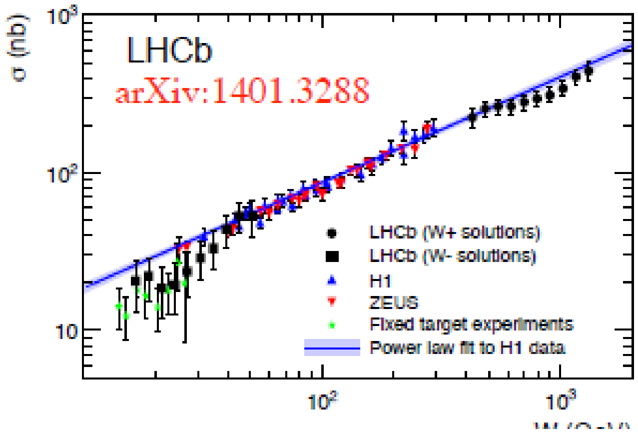
Generated Processes - photoproduction

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

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



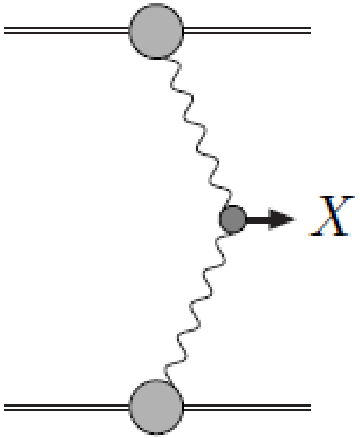
- Takes simple power-law fit to HERA/LHC data.



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.

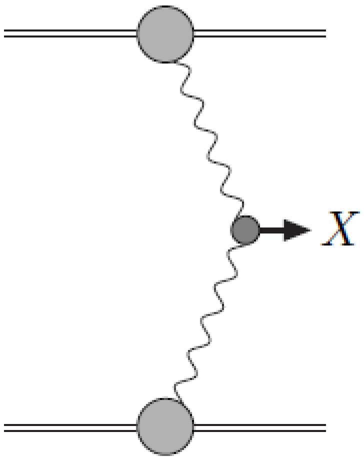


*To appear in next version.

Soft survival factor

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

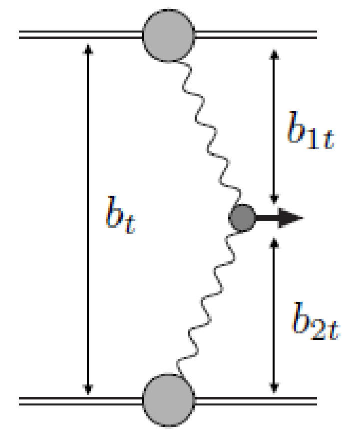
$$\frac{\mathrm{d}\sigma^{pp\to pXp}}{\mathrm{d}M_X^2\,\mathrm{d}y_X} \sim \frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2\,\mathrm{d}y_X}\hat{\sigma}(\gamma\gamma\to X)$$



- Why is this not an exact equality? Because we are asking for final state with intact protons, object X and *nothing* else- colliding protons may interact independently: 'Survival factor' = prob. of no MPI.

Soft survival factor

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



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

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

↑ proton opacity

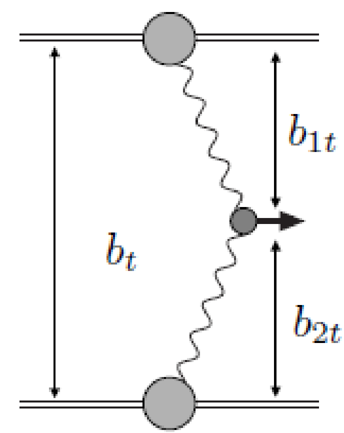
- Underlying event generated by soft QCD. Cannot use pQCD $\Rightarrow$ take phenomenological approach to this non-pert. observable.

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

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

- Naively - expect significant MPI. But S^2 not a constant: larger $b_t \Rightarrow$ less interaction, and $S^2 \sim 1$.
- For $\gamma\gamma$ -initiated processes interaction via quasi-real photon exchange - large proton separation b_t , and prob. of MPI low.

$b_\perp \sim 1/p_\perp$



$\longrightarrow$ Impact of non-QED physics is low.

$$S^2_{\rm soft} \sim 0.7 - 0.9$$

small model dep.

Protons far apart $\Rightarrow$ less interaction $\Rightarrow$ survival factor, $S^2_{\rm soft} \sim 1$

- But survival factor not negligible, and depends on process/kinematics:

$$\frac{d\sigma}{dy_X} = \int d^2p_{1\perp} d^2p_{2\perp} \frac{|T(s, p_{1\perp}, p_{2\perp}))|^2}{16^2\pi^5} S^2_{\rm eik}(s, p_{1\perp}, p_{2\perp}) \; .$$

$\longrightarrow$ Precise treatment needed for precise $\gamma\gamma$ physics. Implemented in SuperChic.

Kinematic dependence

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

- Factor of $x^2 m_p^2$ in photon propagator $\Rightarrow$ for $x\uparrow$, average $q_\perp \uparrow$, hence higher proton $p_\perp$.

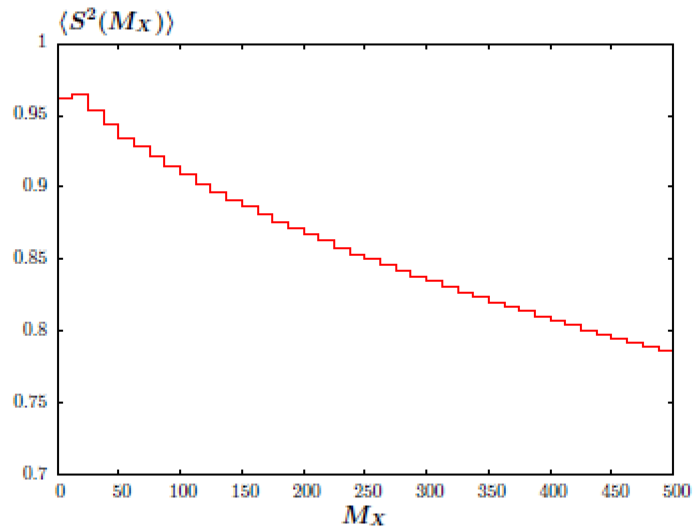
- Higher $p_\perp \Rightarrow$ lower $b_\perp \Rightarrow$ smaller S^2.

- Result from SuperChic:

Muon pair production

$M_X = M_{ll}$

$p_{\mu\perp} > 2.5\,\mathrm{GeV}$

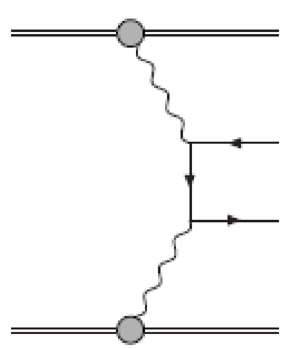


Kinematic dependence

- More generally S^2 depends on process and cuts:

	$\mu^+\mu^-$	$\mu^+\mu^-,\ M_{\mu\mu} > 2M_W$	$\mu^+\mu^-,\ p_\perp^{\rm prot.} < 0.1$ GeV	W^+W^-
$\sigma_{\rm bare}$	6240	11.2	3170	87.5
$\sigma_{\rm sc.}$	5990	9.58	3150	71.9
$\langle S^2_{\rm eik}\rangle$	0.96	0.86	0.994	0.82

$\longrightarrow$ SuperChic is only generator to correctly include this.



Lepton pair production

- 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

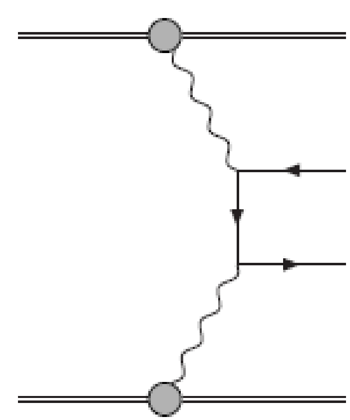
Measurement of exclusive $\gamma\gamma \to \ell^+\ell^-$ production in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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

- Find:

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

	$\mu^+\mu^-$	e^+e^-
$\sigma_{\rm EPA}$	0.768	0.479
$\sigma_{\rm EPA} \cdot \langle S^2 \rangle$	0.714	0.441
$\langle S^2 \rangle$	0.93	0.92
ATLAS data	$0.628 \pm 0.032 \pm 0.021$	$0.428 \pm 0.035 \pm 0.018$

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

- Have confidence in framework $\Rightarrow$ tool for BSM.

Looking forward to seeing **blessed** CT-PPS results

Ongoing work

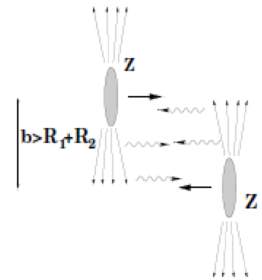
- So far the current processes are included:
  - SM Higgs to $b\bar{b}$
  - $W^+W^- \to ll\nu\nu$, including spin correlations.
  - l^+l^-
  - $\gamma\gamma$ (light-by-light).
- In all cases with e/p beams.
- Recalling form of cross section for pp collisions:

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

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

- Work ongoing in both directions.

- Work ongoing on extending to heavy ions



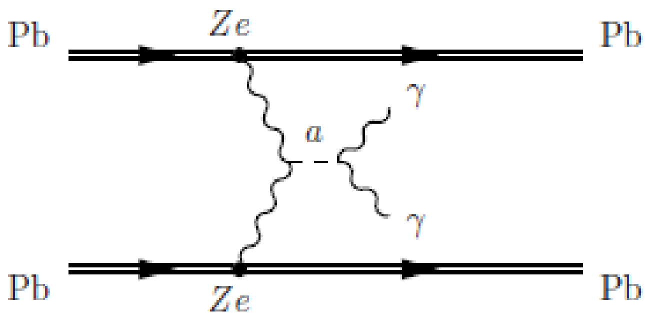
New processes

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

- SuperChic has the capability to simulate any arbitrary process given the $\gamma\gamma \to X$ amplitudes.

$\rightarrow$ Simple to implement new processes within framework. Suggestions/collaboration welcome!

- One example currently working on: axion-like particles.

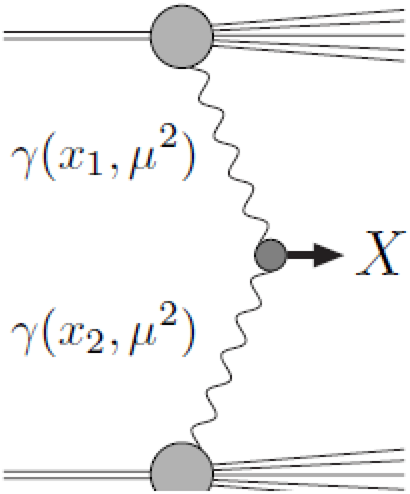


Photon-photon Luminosities

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



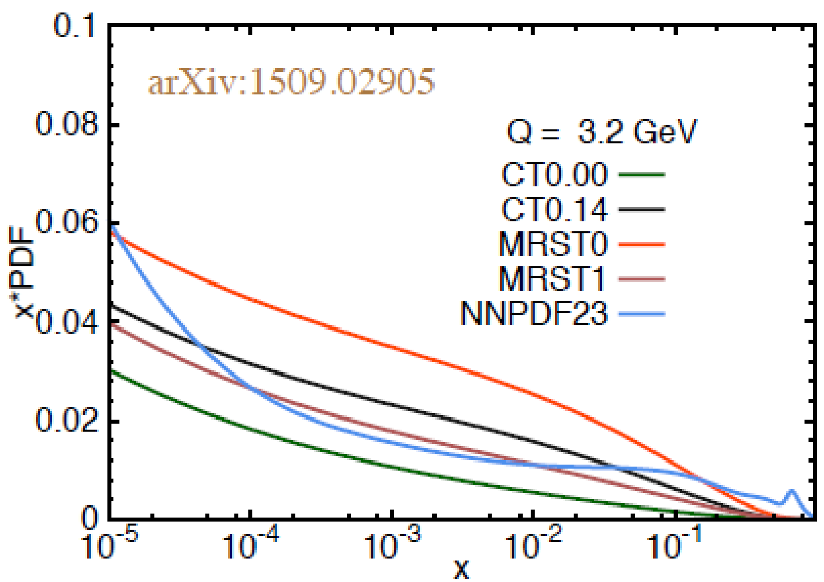
- Earlier photon PDF sets either:

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.



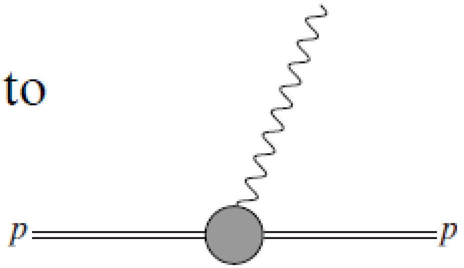
- Comparing these different sets reveals apparently large uncertainties.

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

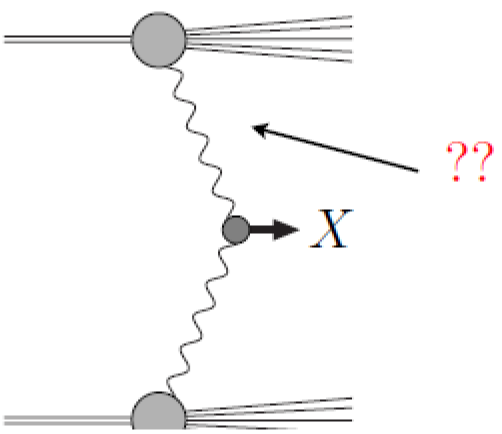
PDFs and QED

• 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:



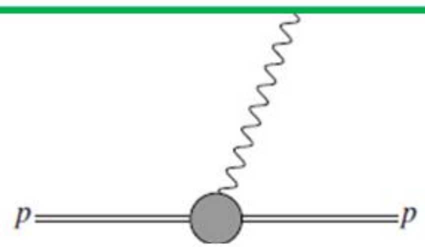
HKR arXiv:1601.03372, 1601.07187, 1607.4635

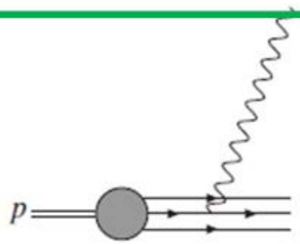
Photon distribution inside the proton (photon PDF)

- 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.



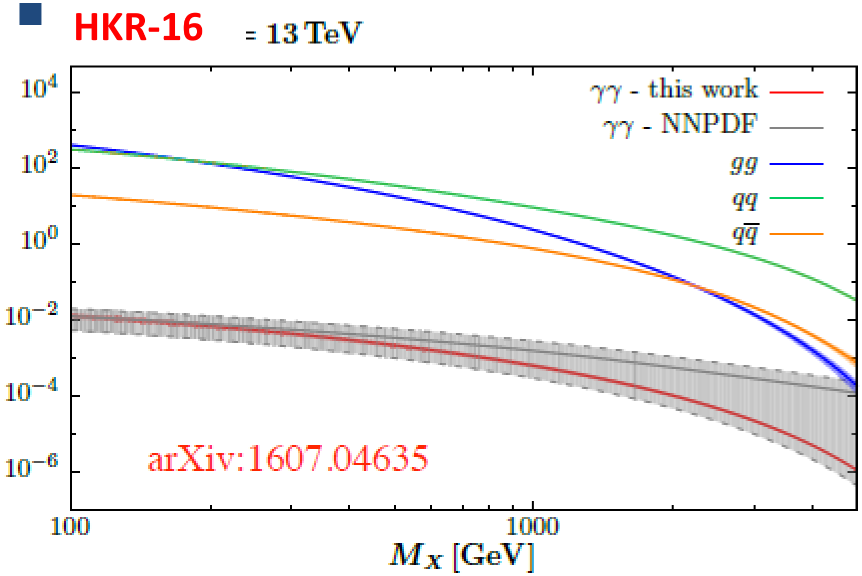


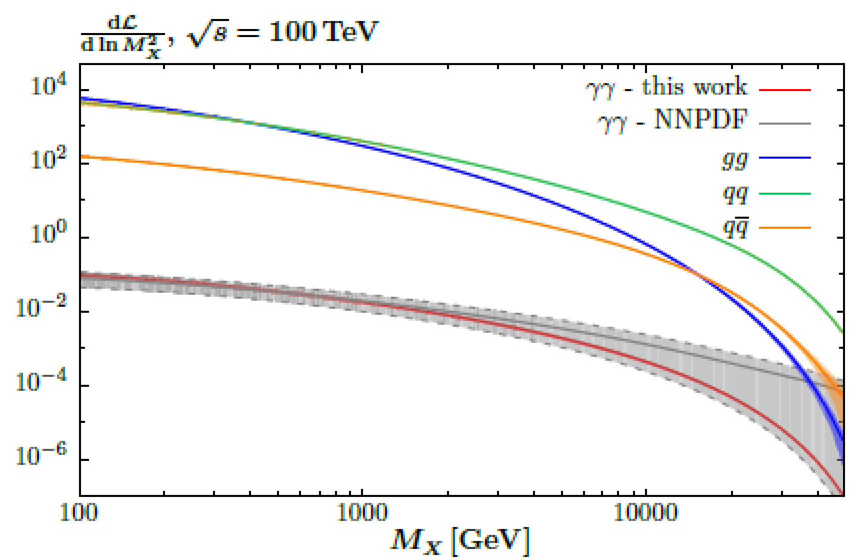
• Previous result translates to large uncertainty and potentially large luminosity at high mass. q, g fall much more steeply than central γ NNPDF prediction.

(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**





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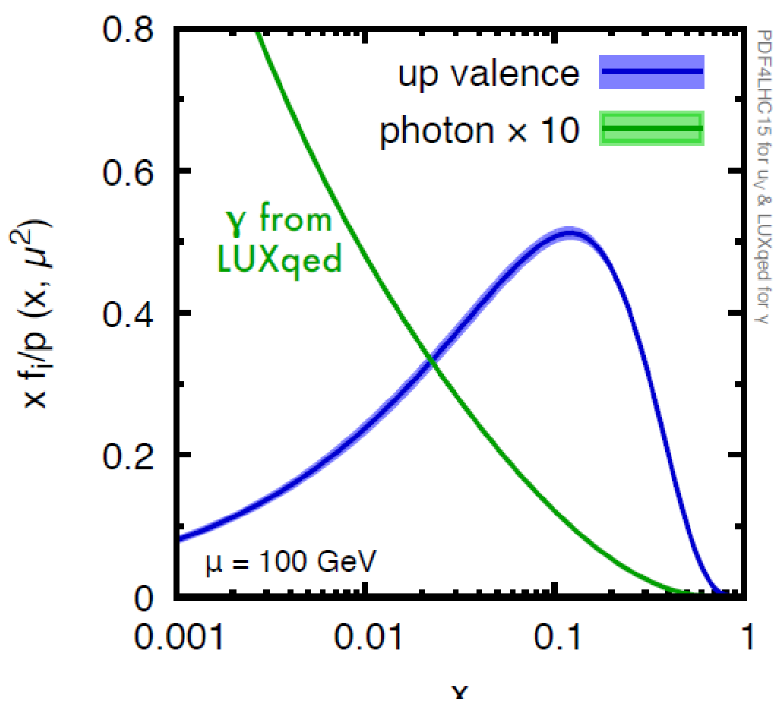
HKR,

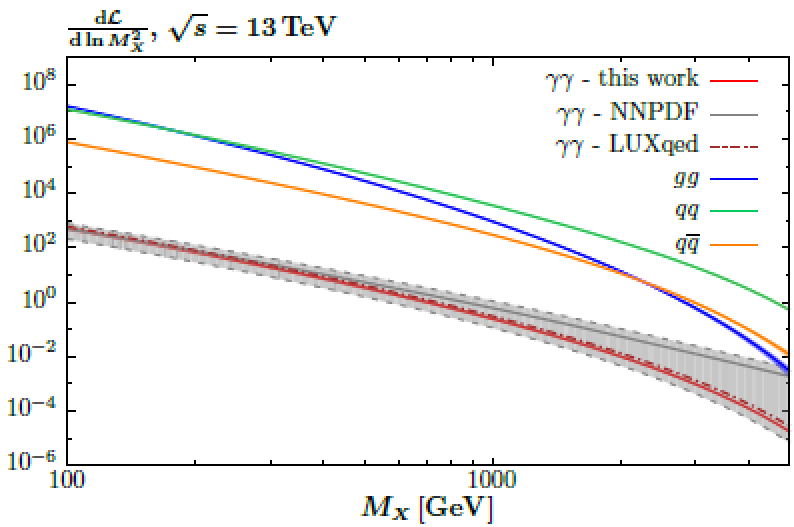
MNSZ, PRL 117,242002 (2016)
LUXqed-use DIS data to directly constraint photon PDF.

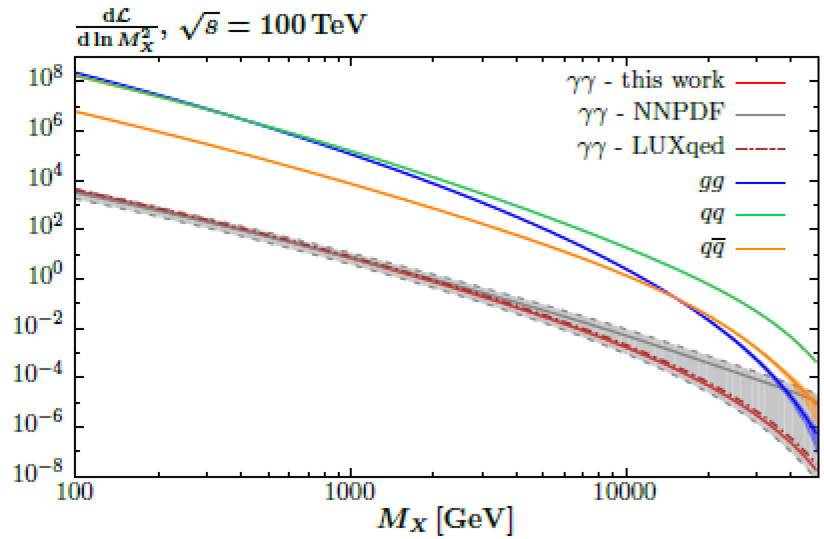
photon PDF results

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



Comparison with LUXqed

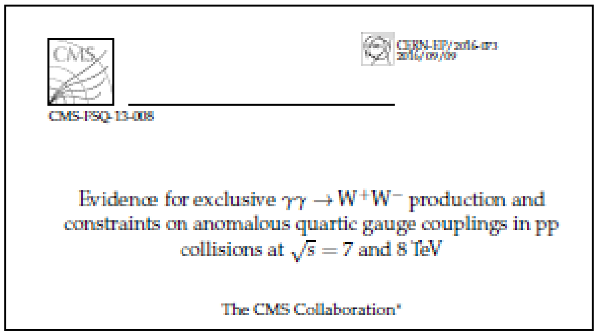




- Comparing our and LUXqed $\gamma\gamma$ luminosities can see these are quite similar ($\longrightarrow$ importance of coherent component).
- Devil is in detail - some enhancement seen in LUXqed at higher M_X, appears to be due to low Q^2 resonant contribution.
- However, clear we have moved beyond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

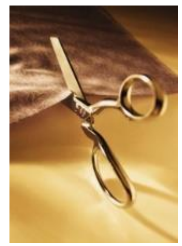


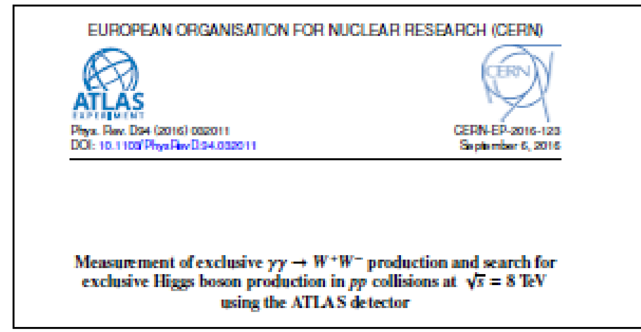
CMS-FSQ-13-008

CERN-EP/2016-073
2016/09/09

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

The CMS Collaboration*





EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

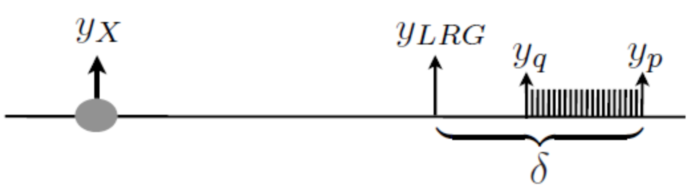
Phys. Rev. D94 (2016) 032011
DOI: 10.1103/PhysRevD.94.032011

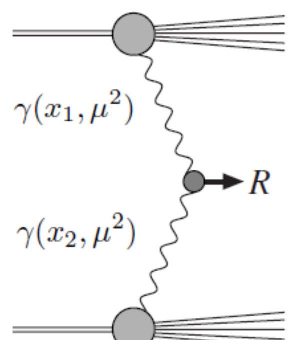
CERN-EP-2016-123
September 6, 2016

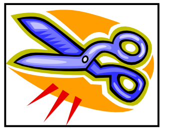
Measurement of exclusive $\gamma\gamma \to W^+W^-$ production and search for exclusive Higgs boson production in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector

- 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?

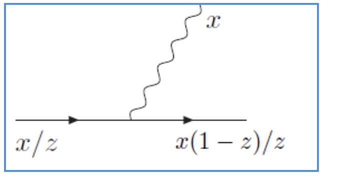
$$\gamma(x,\mu^2) \equiv \gamma^{\rm in}(x,\mu^2) + \gamma^{\rm evol}(x,\mu^2)$$

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

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



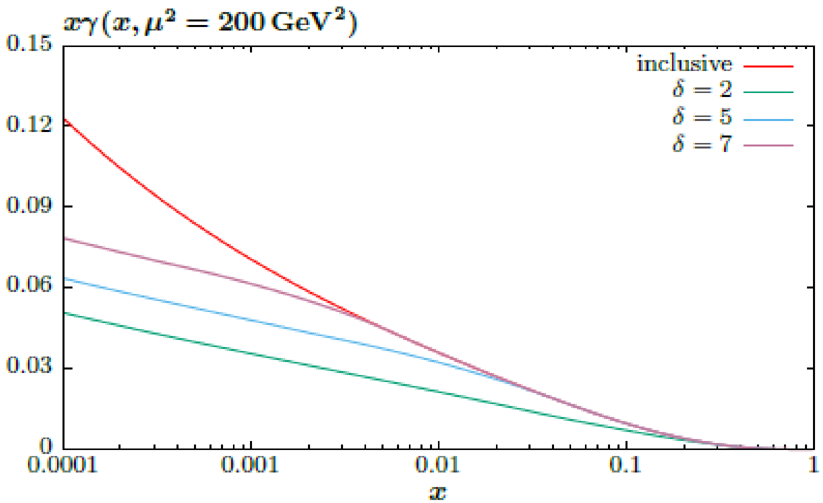
- And photon PDF becomes simply:

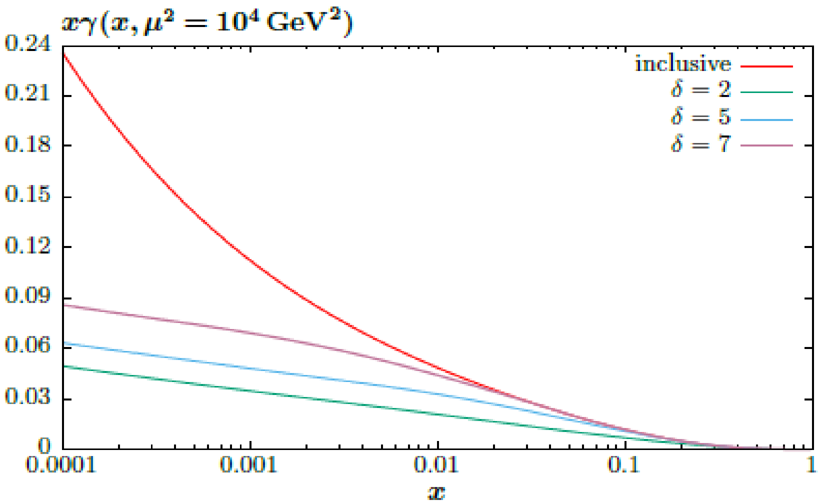
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\,S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2}\frac{\alpha(Q^2)}{2\pi}\frac{{\rm d}Q^2}{Q^2}\int_x^1\frac{dz}{z}\Bigg(\sum_q e_q^2 P_{\gamma q}(z)q(\frac{x}{z},Q^2$$
$$+P_{\gamma g}(z)g(\frac{x}{z},Q^2)\Bigg)\,S_\gamma(Q^2,\mu^2)\Theta\left[e^\delta - \frac{q_t}{m_p}\frac{z}{x(1-z)}\right]\ ,$$

(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



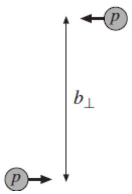


Suppression due to LRG veto.

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

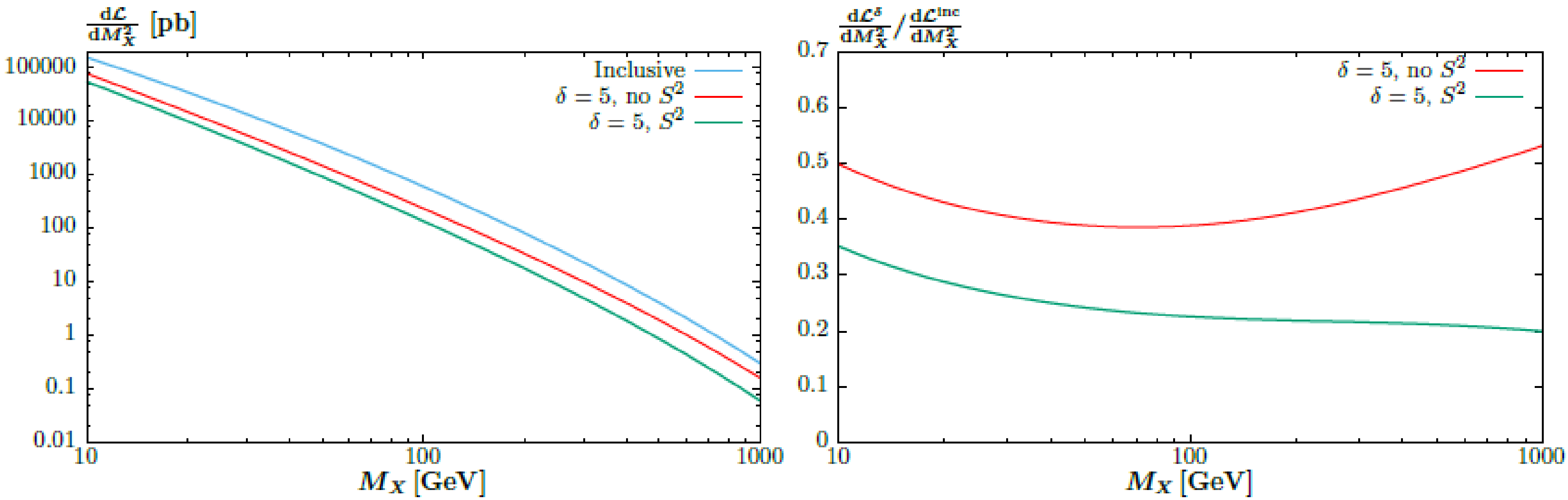
phenomenological objects only-factorization explicitly violated by rescattering effects

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

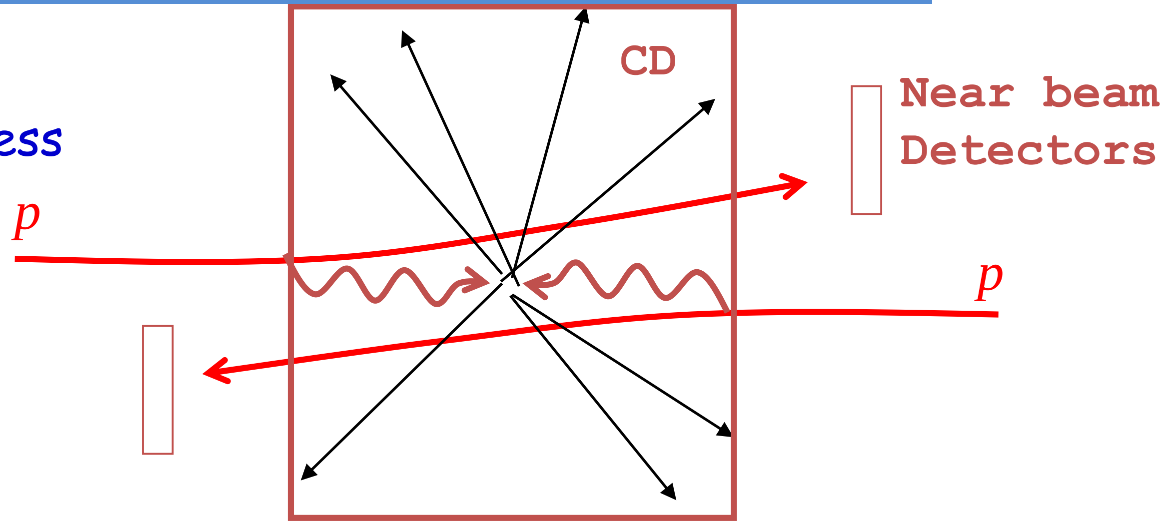
- Instead have effective $\gamma\gamma$ luminosity: $\dfrac{\mathrm{d}\mathcal{L}}{\mathrm{d}M_X^2} = \dfrac{1}{s}\displaystyle\int_\tau^1 \dfrac{\mathrm{d}x_1}{x_1}\gamma(x_1, M_X^2)\gamma(\tau/x_1, M_X^2)$



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

$\gamma\gamma$ collisions- applications

Process



Installed (AFP)
Installed (CT-PPS)
projects

Extensive Program

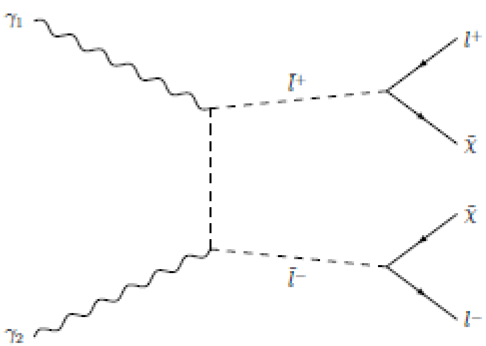
- $\gamma\,\gamma \rightarrow \mu\mu$, ee QED processes
- $\gamma\,\gamma \rightarrow$ QCD (jets..)
- $\gamma\,\gamma \rightarrow$ WW anomalous couplings
- $\gamma\,\gamma \rightarrow$ squark, top… pairs
- $\gamma\,\gamma \rightarrow$ Charginos (natural SUSY)
- New BSM objects

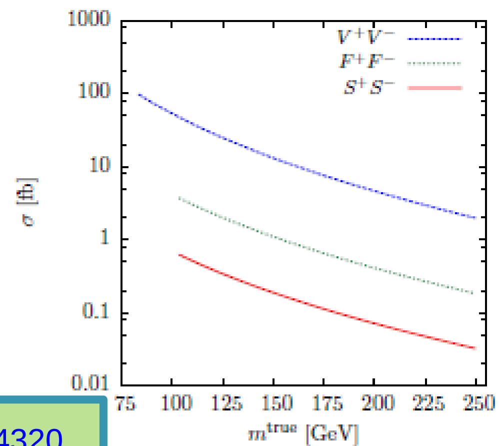
$$pp \to p + \gamma\gamma + p\ ,$$
$$\gamma\gamma \to X^+X^-\ ,$$

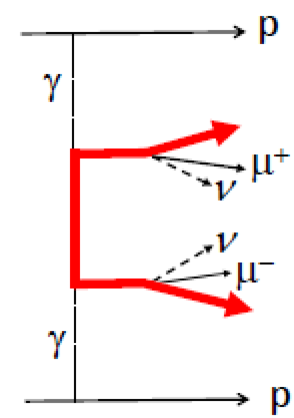
Diphoton X-Pair Production

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

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

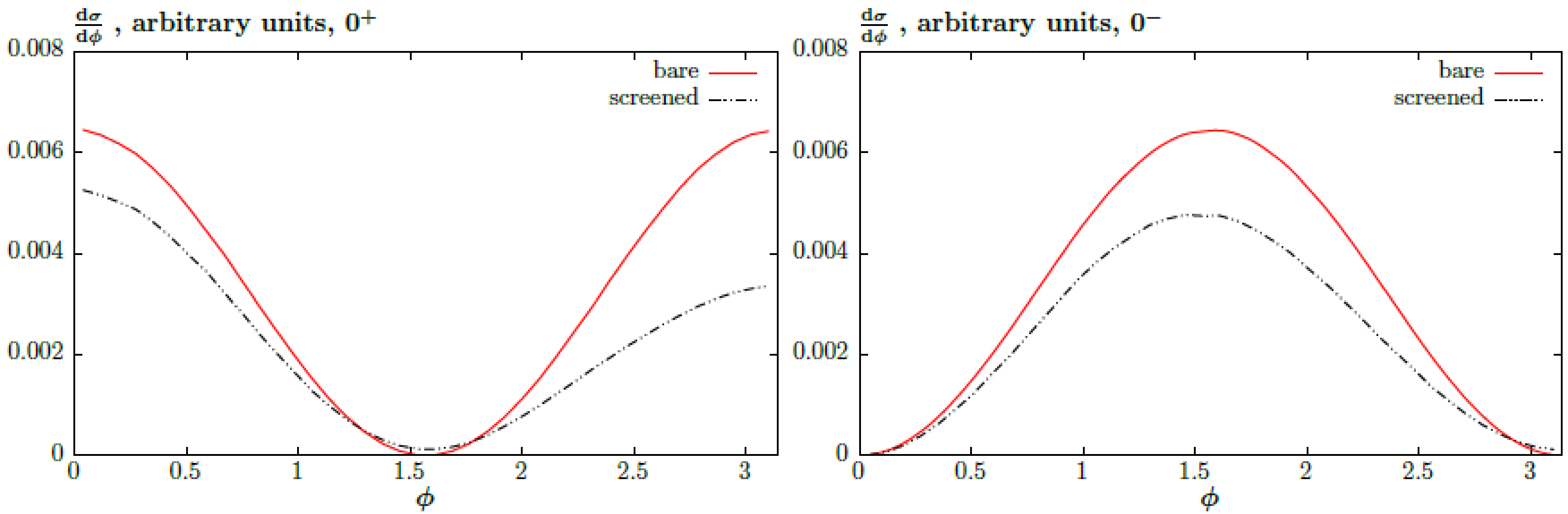
electroweakinos

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**)

High-mass resonances- tagged proton correlations

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



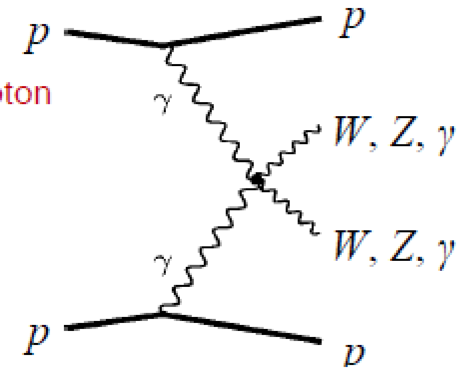
$\longrightarrow$ With just a handful of events, scalar/pseudoscalar hypotheses distinguishable.

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

KMR-2004

Anomalous Gauge Quartic Couplings

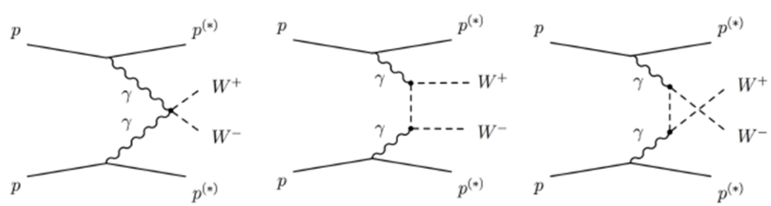
- Low Cross sections: ~few fb
  - AFP has a Missing-Mass resolution (from the proton measurements) of 2-4 %
- Match with invariant central object mass is efficient: ($Z \to ee$, $\gamma\gamma$)
  - powerful rejection of non-exclusive backgrounds
- Much interest in this from theory side
  - e.g. "LHC Forward Physics" CERN-PH-LPCC-2015-001)



"Probing anomalous quartic gauge couplings using proton tagging at the Large Hadron Collider", M. Saimpert, E. Chapon, S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon; 23/05/2014

- Exclusive W^+W^- production: no contribution from $q\bar{q} \to W^+W^- \Rightarrow$ sensitive to $\gamma\gamma \to W^+W^-$ process alone.

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



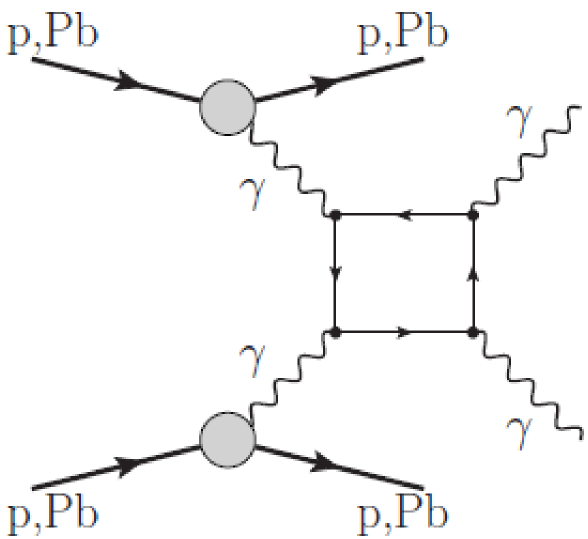
- Limits have been set at LEP, and in inclusive final-states at the Tevatron and LHC. How does the exclusive case compare?

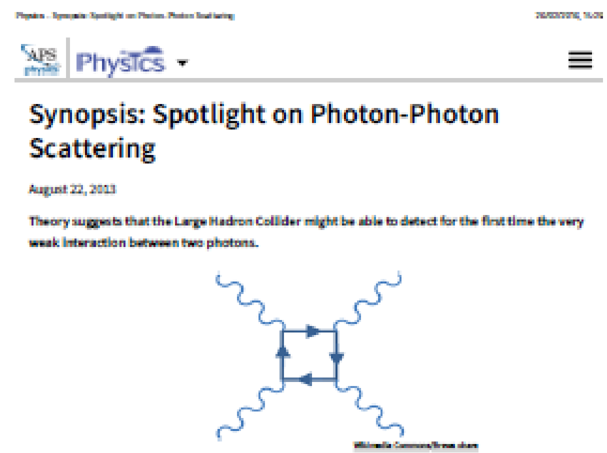
Currently very encouraging ATLAS & CMS data

(Christophe)

LIGHT-by-light Scattering

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

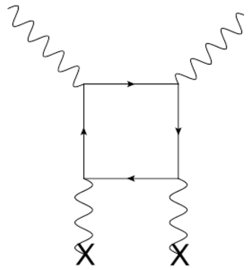




- Analysis of d'Enterria and Silveira (arXiv:1305.7142,1602.08088): realistic possibility, in particular in $PbPb$ collisions.

Long and chequered history

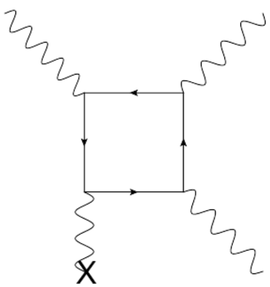
(nonlinear effects of QED)



Delbrück **1933**

Scattering of gamma-rays by a Coulomb field of heavy nuclei.
First observed-1953 for 1.33 MeV on lead nuclei.
Most accurate high-energy results- Novosibirsk,VEPP-4M 1998.

Delbrück scattering



First claims of observation- DESY, PRD 8(1973) 3813.
Criticised by V.A.Khoze et al, ZhETF Pis.Red.19 (1974) 47.
First observation- Novosibirsk, VEPP-4M 2002.

Photon splitting in atomic Coulomb field

first direct observation of $\gamma\gamma \to \gamma\gamma$ scattering

(ArXiv:1702.01625)

Search for light-by-light scattering
[arXiv:1702.01625]

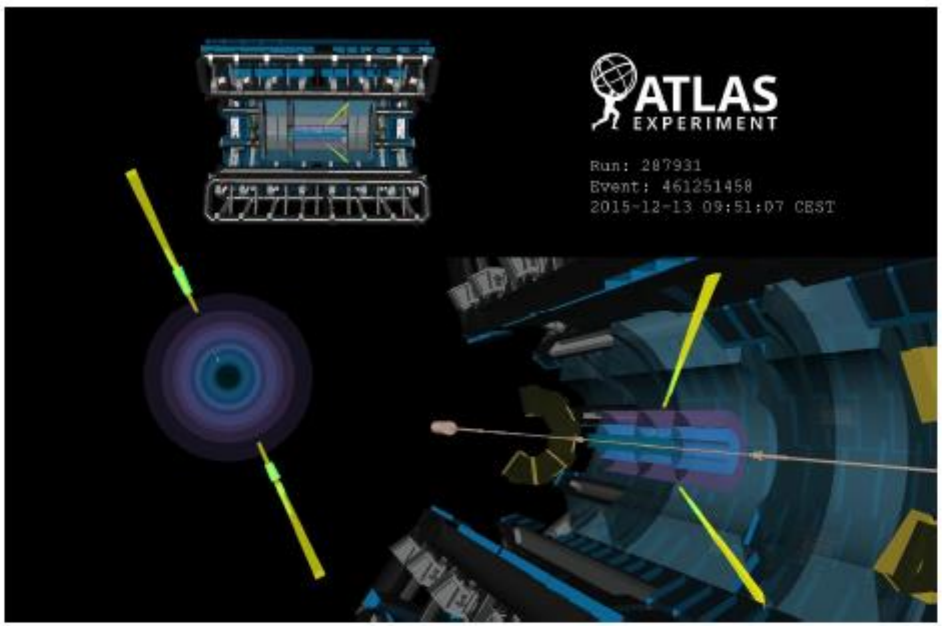
ATLAS @ $\sqrt{s_{NN}}$ = 5.02 TeV:

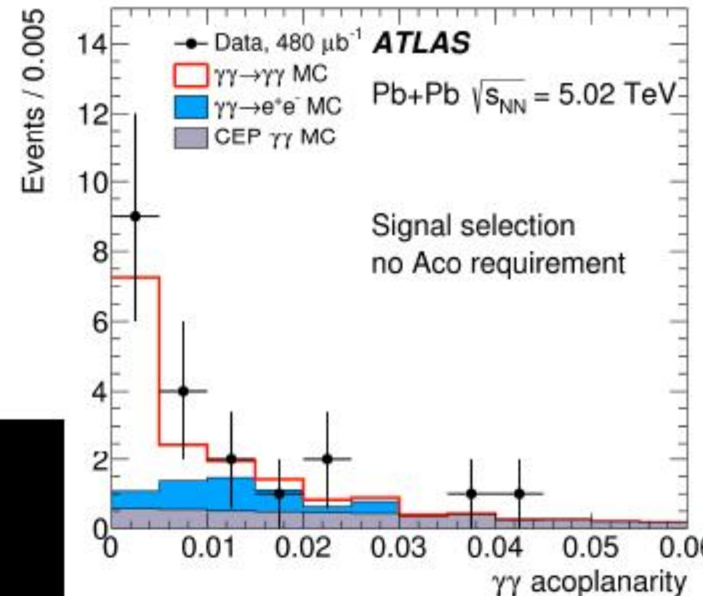
13 events (bkgd 2.6) $\Rightarrow$ 4.4σ evidence

σ = 70 ± 20 (stat) ± 17 (syst) nb

($p_{T,\gamma}$ > 3 GeV, $|\eta_\gamma|$ < 2.4, $M_{\mu+\mu-}$ > 6 GeV, $p_T(\gamma\gamma)$ < 2 GeV, Aco < 0.01)

ATLAS coll., ArXiv:1702.01625(2017)





SM predictions:

- 45 ± 9 nb

D. d'Enterria et al., PRL 111 (2013) 080405

- 49 ± 10 nb

A. Szczurek et al., PRC 93 (2016) 044907

Need ZDC in order to separate purely UPC events

Constraint on Born-Infeld Theory from Light-by-Light Scattering at the LHC

ATLAS measurement of light-by-light scattering provides

first significant constraint on nonlinear extension of QED (suggested by string theory)

JE, Mavromatos & You, arXiv:1703.08450

John Ellis

KING'S College LONDON

LbyL Scattering Constraint on Born-Infeld Theory

[arXiv:1703.08450]

$$L_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \rightarrow L_{BI} = \beta^2\left(1 - \sqrt{1 + \frac{1}{2\beta^2}F_{\mu\nu}F^{\mu\nu} - \frac{1}{6\beta^4}F_{\mu\nu}\tilde{F}^{\mu\nu}}\right)$$

Interest from the string-theoretic point of view
ArXiv: 1701.07375

Light-by-Light Scattering Constraint on Born-Infeld Theory

John Ellis[1,2], Nick E. Mavromatos[1] and Tevong You[3]

[1] *Theoretical Particle Physics and Cosmology Group, Physics Department, King's College London, London WC2R 2LS, UK*

[2] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

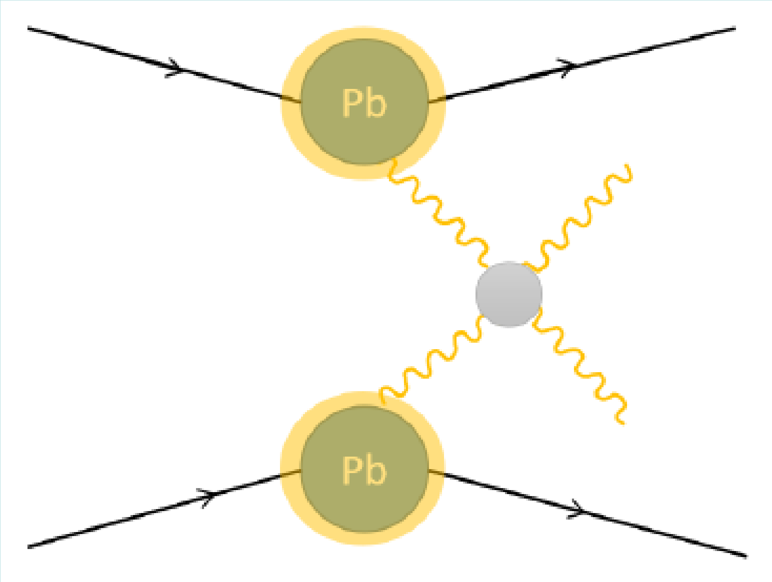
[3] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK; Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge, CB3 0HE, UK*

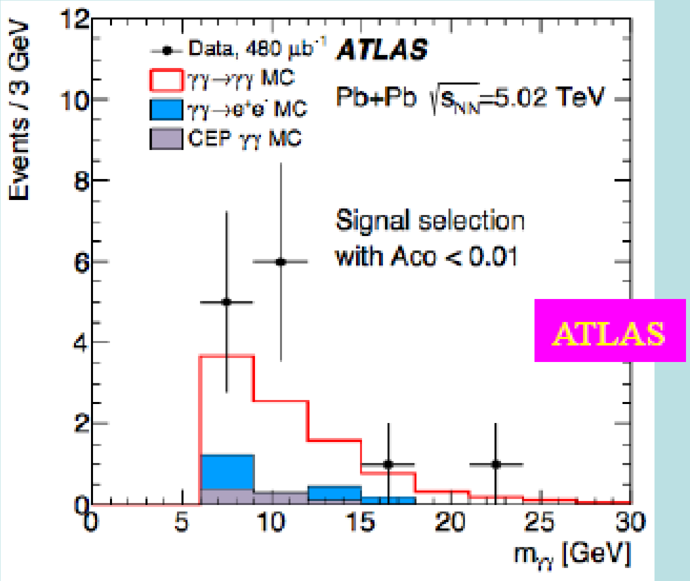
Abstract

The recent measurement by ATLAS of light-by-light scattering in LHC Pb-Pb collisions is the first direct evidence for this basic process. We find that it requires the mass scale of a nonlinear Born-Infeld extension of QED to be $\gtrsim$ 100 GeV, a much stronger constraint than those derived previously. In the case of a Born-Infeld extension of the Standard Model in which the $U(1)_Y$ hypercharge gauge symmetry is realized nonlinearly, the limit on the corresponding mass scale is $\gtrsim$ 90 GeV, which in turn imposes a lower limit of $\gtrsim$ 11 TeV on the magnetic monopole mass in such a $U(1)_Y$ Born-Infeld theory.

First Measurement of Light-by-Light Scattering

- Peripheral heavy-ion collisions at the LHC: $\gamma\gamma \rightarrow \gamma\gamma$





- Expected in ordinary QED from fermion loops
- ATLAS measurement agrees with QED

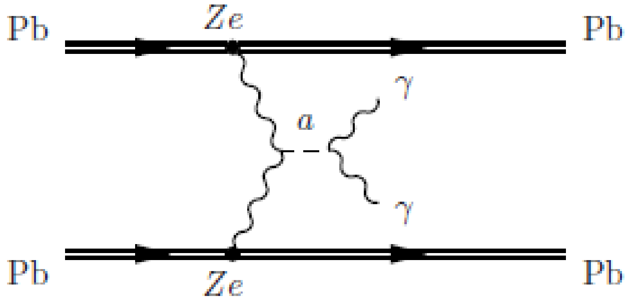
Heisenberg & Euler 1936

- Can be used to constrain nonlinearities in Born-Infeld

JE, Mavromatos & You: arXiv:1703.08450

Axion-like particles

- The $\gamma\gamma \to \gamma\gamma$ transition in CEP can be sensitive to Axion like particles.
- Discussed in Kapen et al. (1607.06083) - find that in heavy ion collisions can set the strongest limits yet on these couplings.

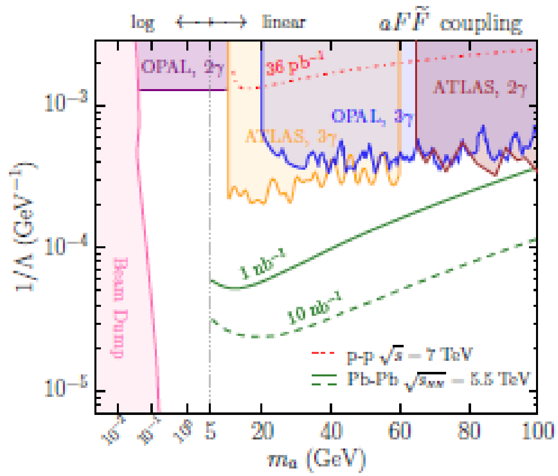


- Lagrangian:

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

gives simple production amplitudes:

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



- Implementation, including full $\gamma\gamma$ decay kinematics, will be included in next SuperChic release.

Summary & Outlook

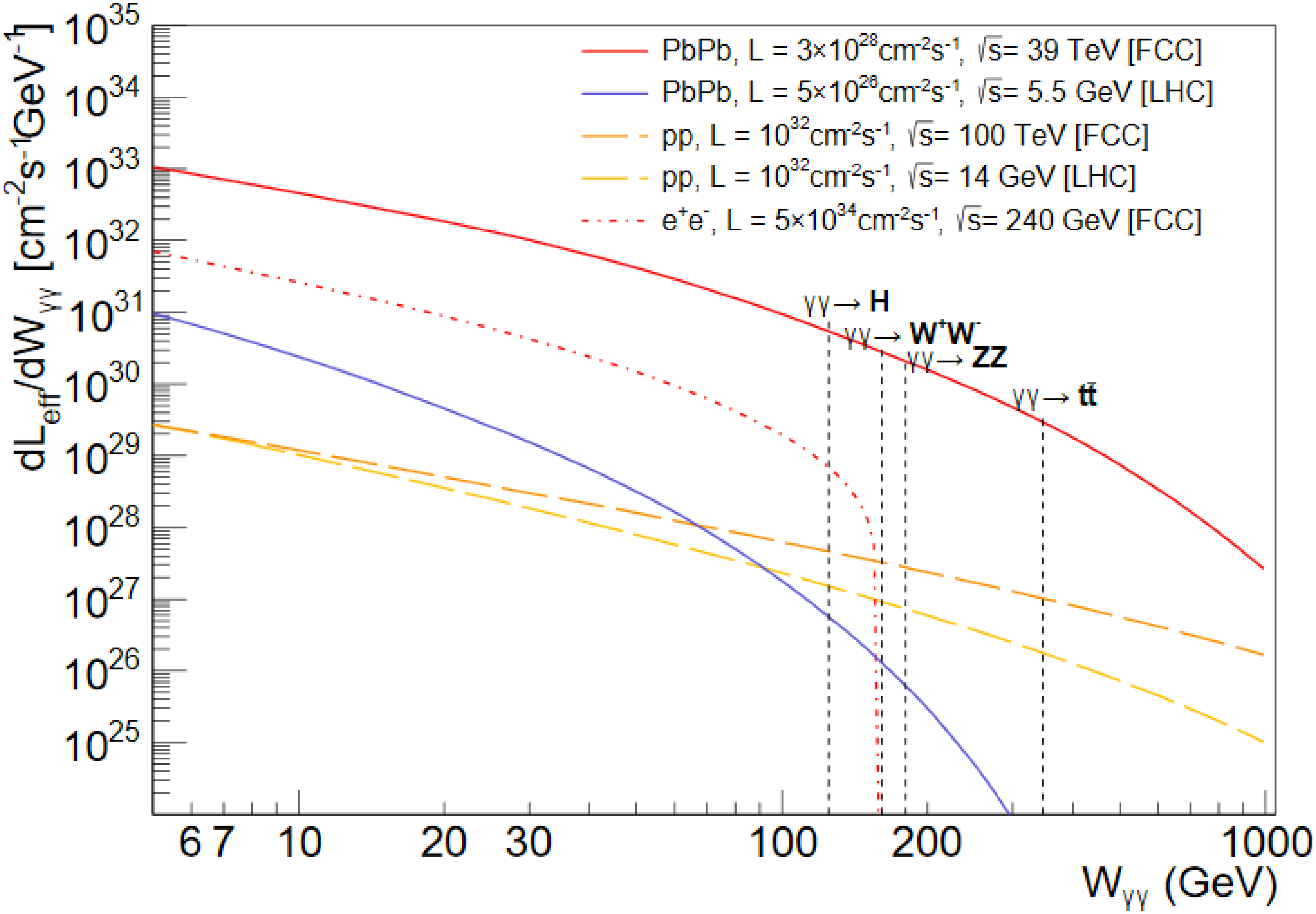
- No immediate plans for a future $\gamma\gamma$ collider, but the LHC is already a photon-photon collider!
- The $\gamma\gamma$ initial state naturally leads to exclusive events, with intact outgoing protons.
- Theory well understood, and use as highly competitive and clean probe of EW sector and BSM physics already demonstrated at LHC. Much further data with tagged protons to come.
- Such studies equally possible (with higher $s_{\gamma\gamma}$) at FCC.
-
    - **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

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^-, $Z\,Z$, and $t\bar{t}$ production.

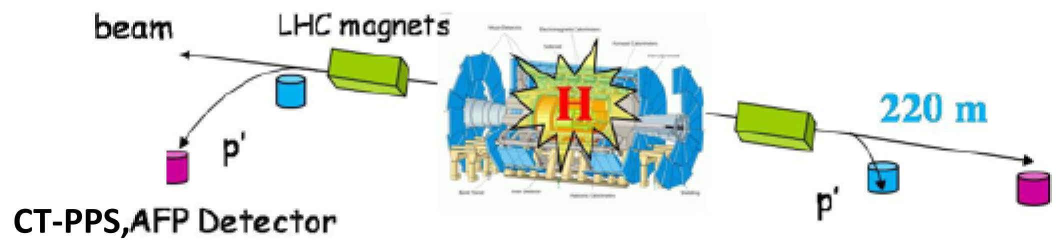
$$d\mathcal{L}_{\rm eff}/dW_{\gamma\gamma} \equiv \mathcal{L}_{AB}\, d\mathcal{L}_{\gamma\gamma}/dW_{\gamma\gamma}.$$

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

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

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

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



Anomalous couplings - outlook

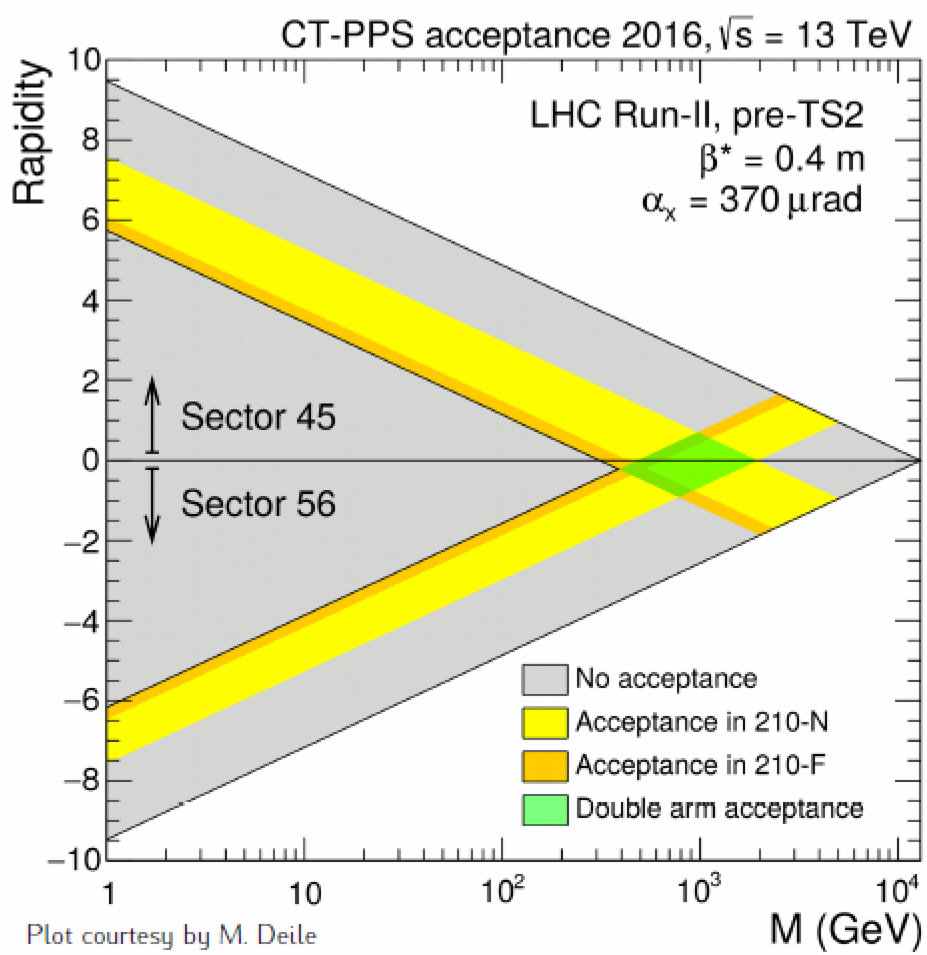
- What are the prospects for e.g. anomalous $\gamma\gamma WW$ coupling measurements with tagged protons at the LHC?
- Detailed studies, including full detector sim., given in LHC Forward Physics WG Yellow Report.
- This is just one example- in general any process with significant EW couplings can be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

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

Promising prospects of the studies at the FCC.

CT-PPS mass and rapidity acceptance

- Two-dimensional **missing mass-rapidity acceptance** determined by the ξ acceptance for each station:
  - Detectors' distance of approach (lower limit)
  - Upper limit: determined by the position of forward collimators (TCL4) and spatial extension of the detectors
- $m_{miss} = \sqrt{s\,\xi_1 \xi_2}, \quad y_{pp} = \frac{1}{2} \log \frac{\xi_2}{\xi_1}$
- Overall sensitivity with double tags to missing mass range **between 385 and 1950 GeV** (for low-rapidity of the central system)
  - **Lower masses** can be reached in **proton dissociative events**

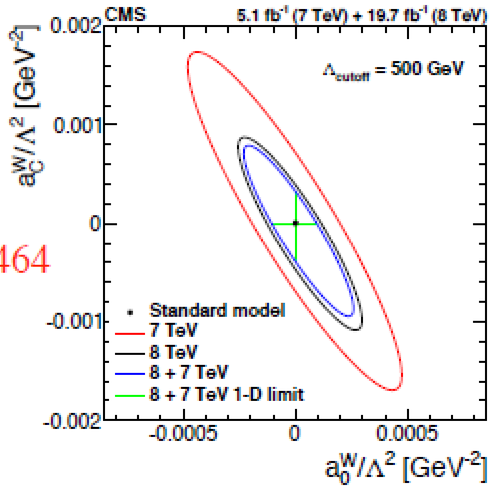


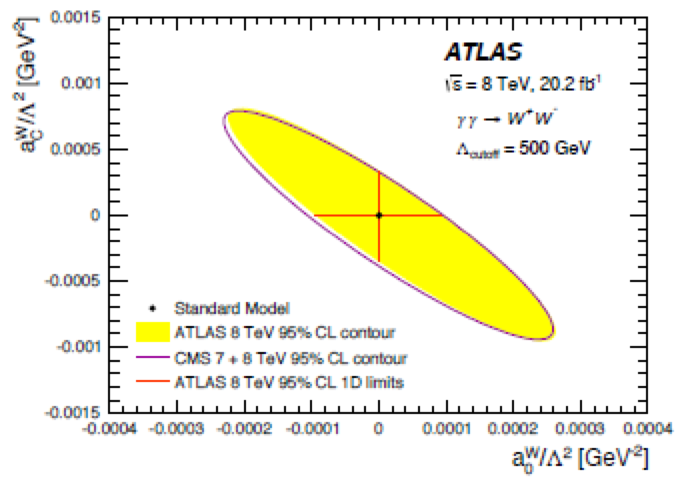
Plot courtesy by M. Deile

Anomalous couplings - data

• ATLAS + CMS data: $W \to l\nu$ pair production with no associated charged tracks $\Rightarrow$ use this veto to extract quasi-exclusive signal. Use data-driven method to subtract non-exclusive BG ($p \to p^*$).

arXiv:1604.04464





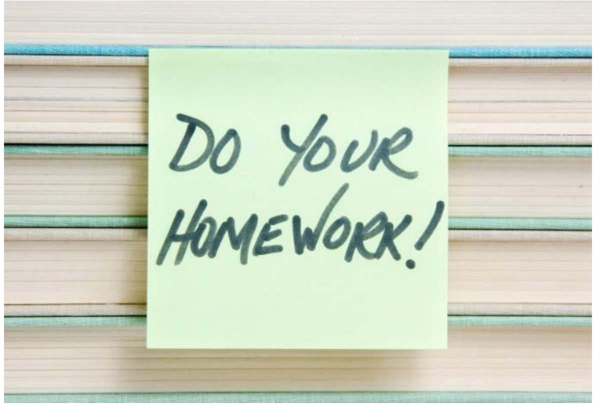
arXiv:1607.03745

• These data place the most stringent constraints to date on AGCs: two orders of mag. better than LEP, and ~ order of mag. tighter than equivalent inclusive LHC.

• Direct consequence of exclusive selection $\Rightarrow$ precisely understood $\gamma\gamma$ collisions, but at a hadron collider.

Exclusive QED lepton pair production has a potential for precise luminosity calibration but no practical proposal has been put forward by any LHC experiment.

V.M.Budnev et al, PL B39 (1972) 526
A.G. Shamov & V.I.Telnov-ATLAS note,1998
KMRO-2001
M.W. Krasny et al, **hep-ex/0610052**



Motivation: Exclusive electroweak boson pairs

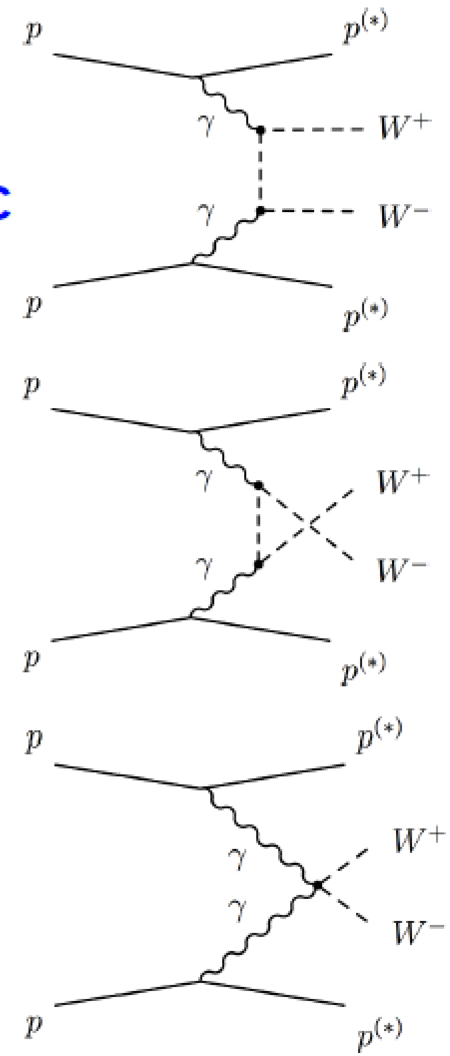
- The exclusive production of W pairs is sensitive to anomalous quartic gauge couplings (aQGC)
- **The electroweak sector of Standard Model predicts QGC**
- **Any deviation from SM expectations can reveal a sign of new physics**
- Objective: Measure SM cross section and look for aQGC.
- aQGC are introduced via effective Lagrangian

$$\mathcal{L}_6^0 = \frac{-e^2}{8} \boxed{\frac{a_0^W}{\Lambda^2}} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_\alpha^-$$

$$\mathcal{L}_6^C = \frac{-e^2}{16} \boxed{\frac{a_C^W}{\Lambda^2}} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_\beta^- - W^{-\alpha} W_\beta^+)$$

Anomalous coupling constant for quartic vertex

Λ : Scale for New Physics



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

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