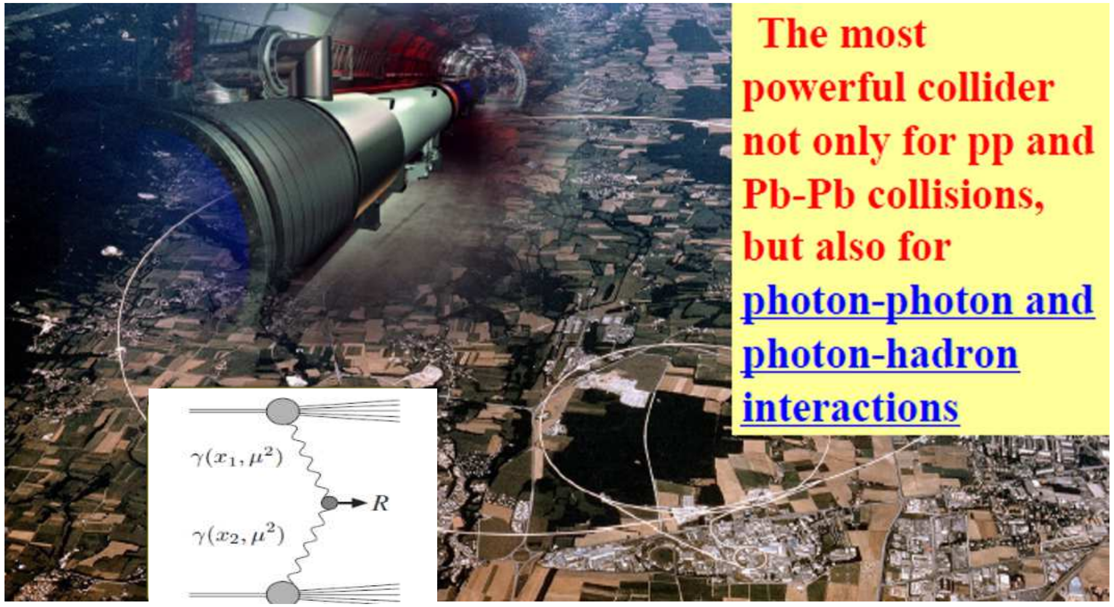
Photon 2017: International Conference on the Structure and the Interactions of the Photon | International Workshop on Photon-Photon Collisions | International Workshop on High Energy Photon Colliders

PHOTON-PHOTON COLLISIONS AT THE LHC
(selected topics)

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



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

Outline

- Introduction and Motivation.
- Selecting Photon-Photon Exclusive Events.
- The Photon-Photon Luminosities .
- $\gamma\gamma$ - 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?

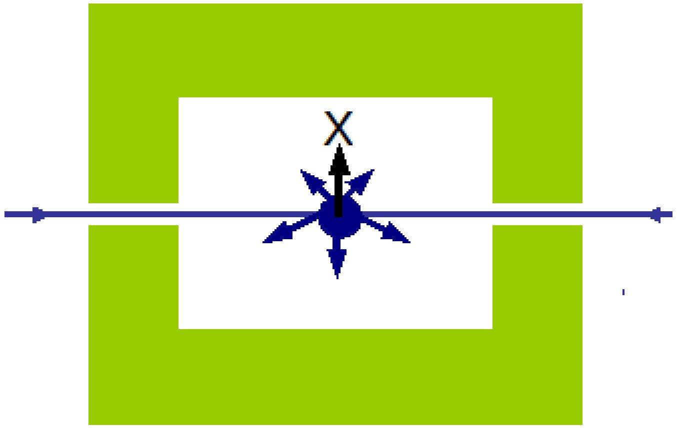
Central Exclusive Production (CEP) is the interaction:

$$pp \rightarrow p + X + p$$

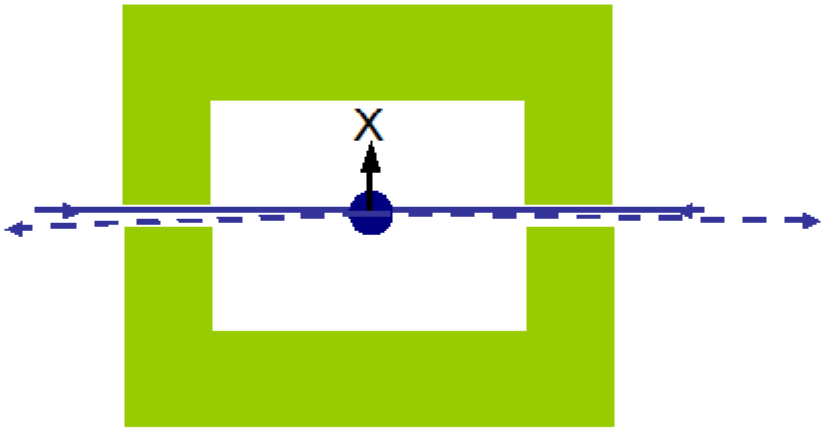
- **CEP** colour singlet exchange between colliding protons, with large rapidity gaps ('+') in the final state.

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.

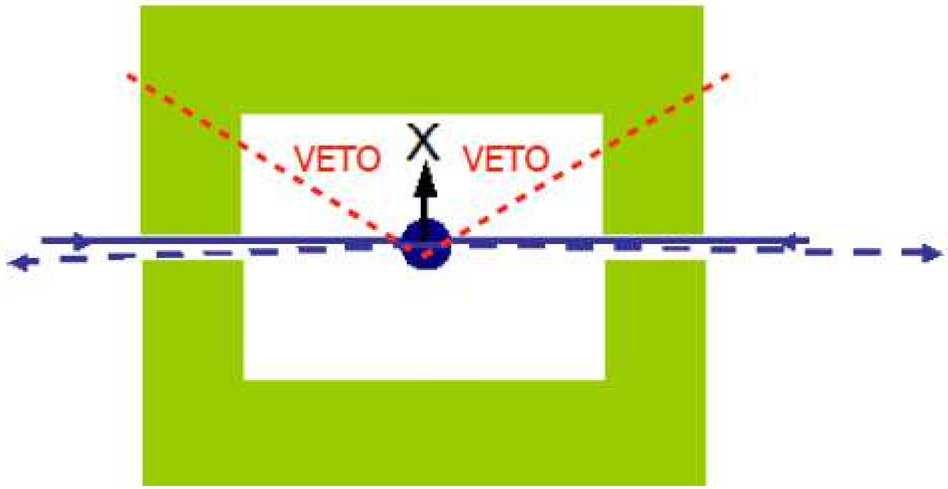


SELECTING EXCLUSIVE PHOTON-PHOTON EVENTS AT THE LHC

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).

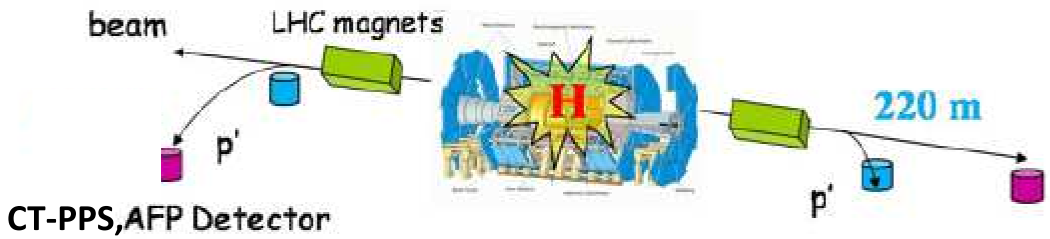


2) Proton tagging: $pp \to p + X + p$

- 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 $O(\text{mm})$ from beam line and $O(100\,\text{m})$ from IP. Reconstruct momenta and measure arrival time of protons.



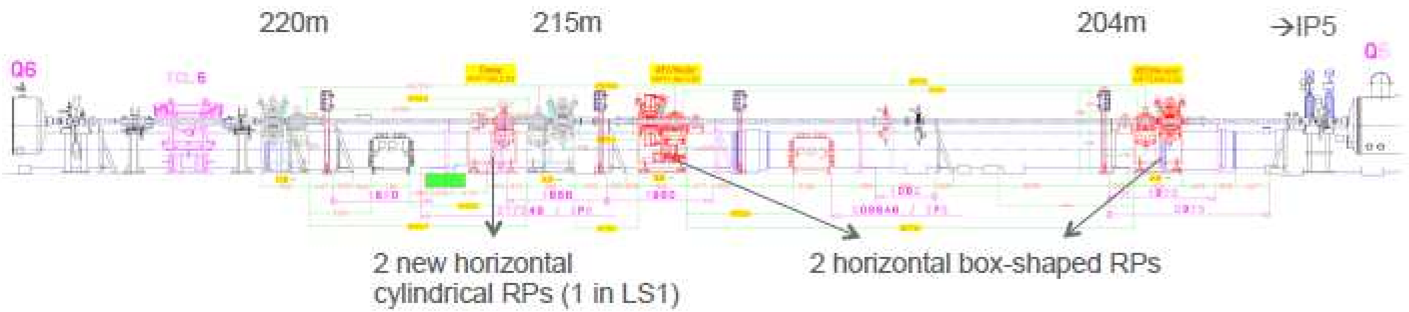
Proton tagging at the LHC

- These detectors are installed:
  - CMS-TOTEM Precision Proton Spectrometer - CT-PPS.
  - ATLAS Forward Proton - AFP. **(Maciej's talk)**

(Jonathan's talk)

- In both cases 'roman pot' detectors installed at $\sim 200\,\mathrm{m}$ from IPs.

Measure position ($\sim$ proton momentum loss) and arrival time ($\longrightarrow$ pile-up rejection) of protons.



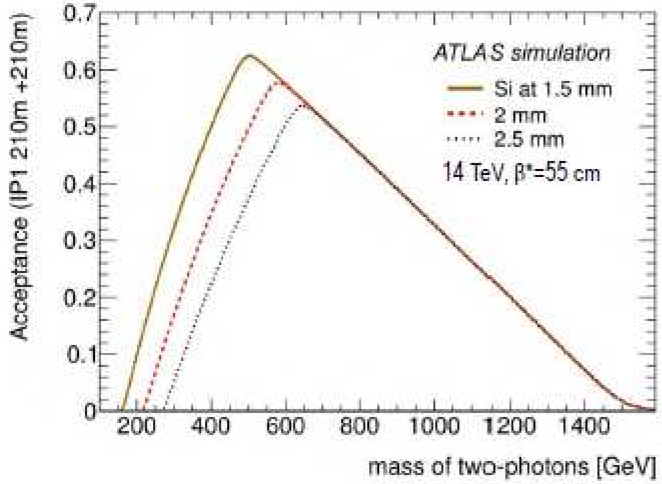
Mass acceptance

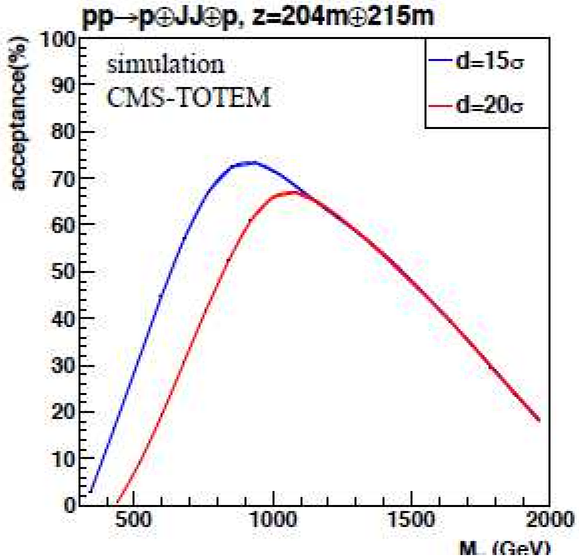
- Momentum loss ξ of protons related to mass of central system:

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

- 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

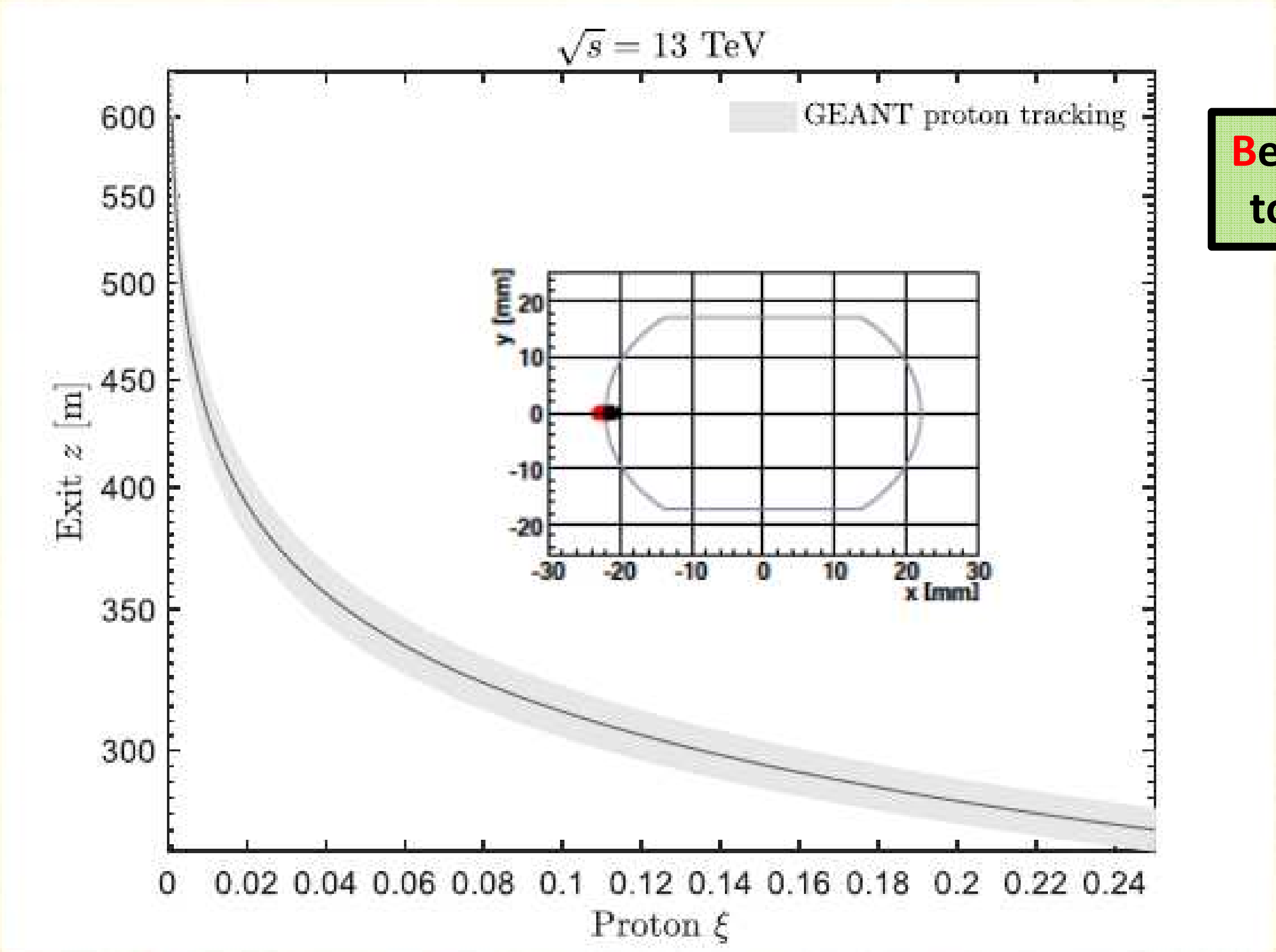
(Risto's talk)

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).

the LHC Ring represents a continuous "Roman Pot" !

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

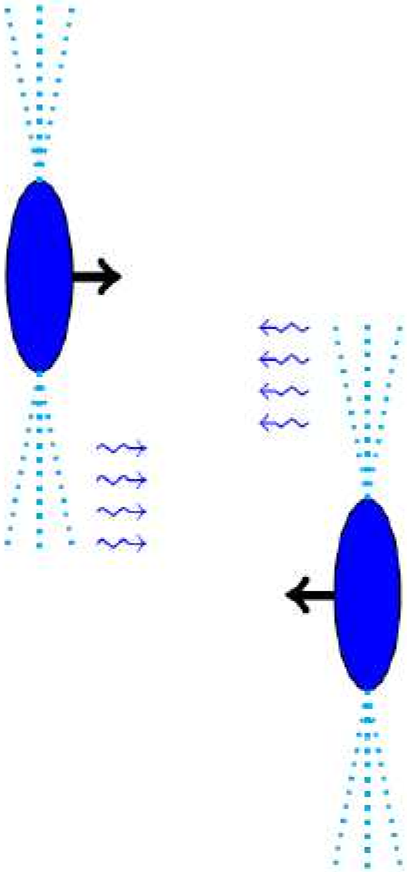


Beam Loss Monitors to tag exit protons

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

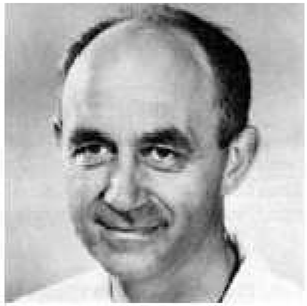
4) **Ultra Peripheral HI Collisions**



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

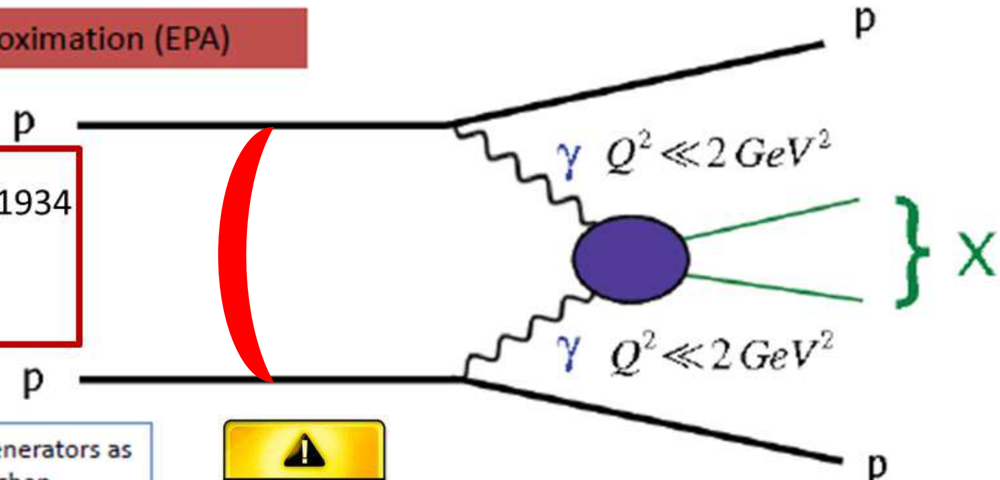
Two ions (or protons) pass by each other with impact parameters b > 2R. **Hadronic interactions are strongly suppressed**

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 (EPA)

C.F. von Weizsacker, 1934
E.J. Williams , 1934
E. Fermi, 1925

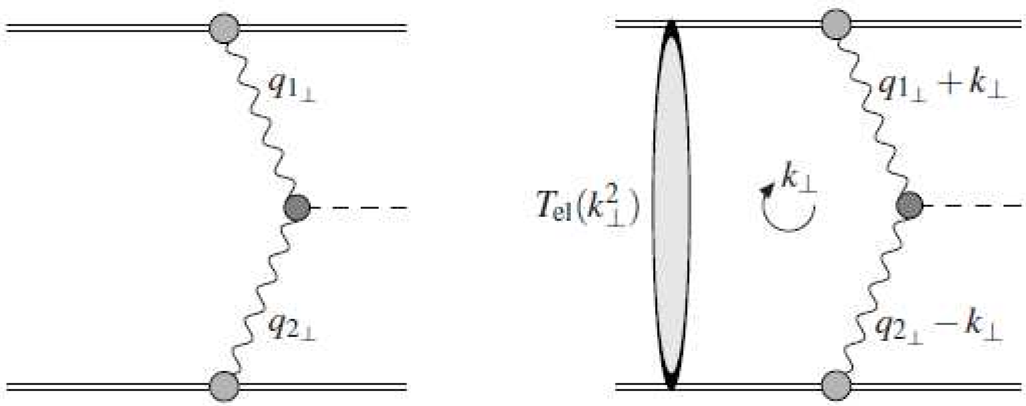


...introduced to major event generators as Madgraph, Pythia, Sherpa, Calchep

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).

→ 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…

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:

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

- 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

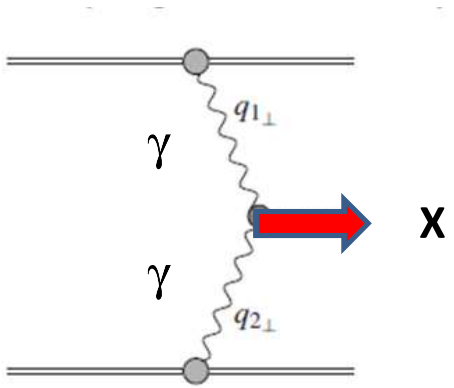
Received 25 April 1974
Revised version received 5 July 1974

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

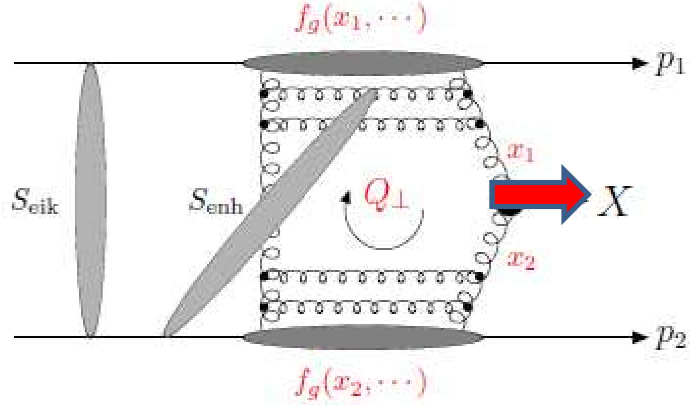
$\langle S_{\mathrm{eik}}^2\rangle = 0.72 \quad : \quad J_P = 0^+$

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

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



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.

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

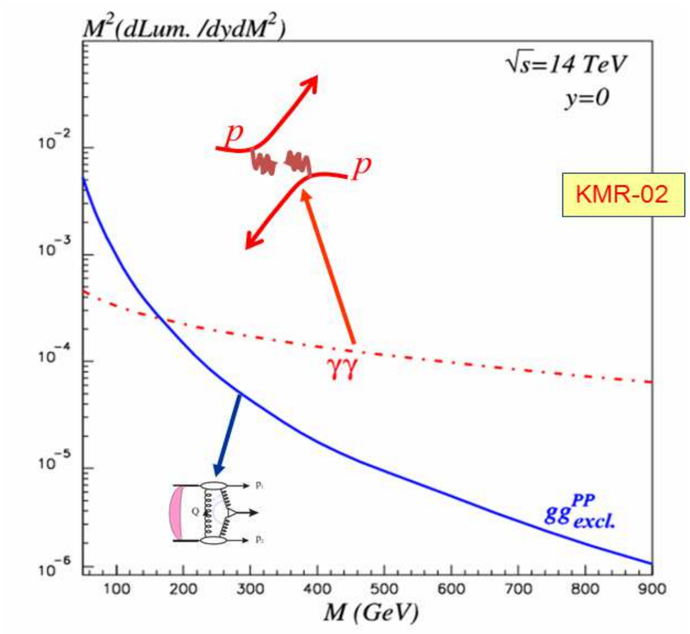
- Increasing $M_X \Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

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

KMR-2001

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

QCD 'radiation damage' in action



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

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

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

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 $S^2_{\text{eik}} \to 1$.

b_t and $p_\perp$: Fourier conjugates.

Process dependence

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

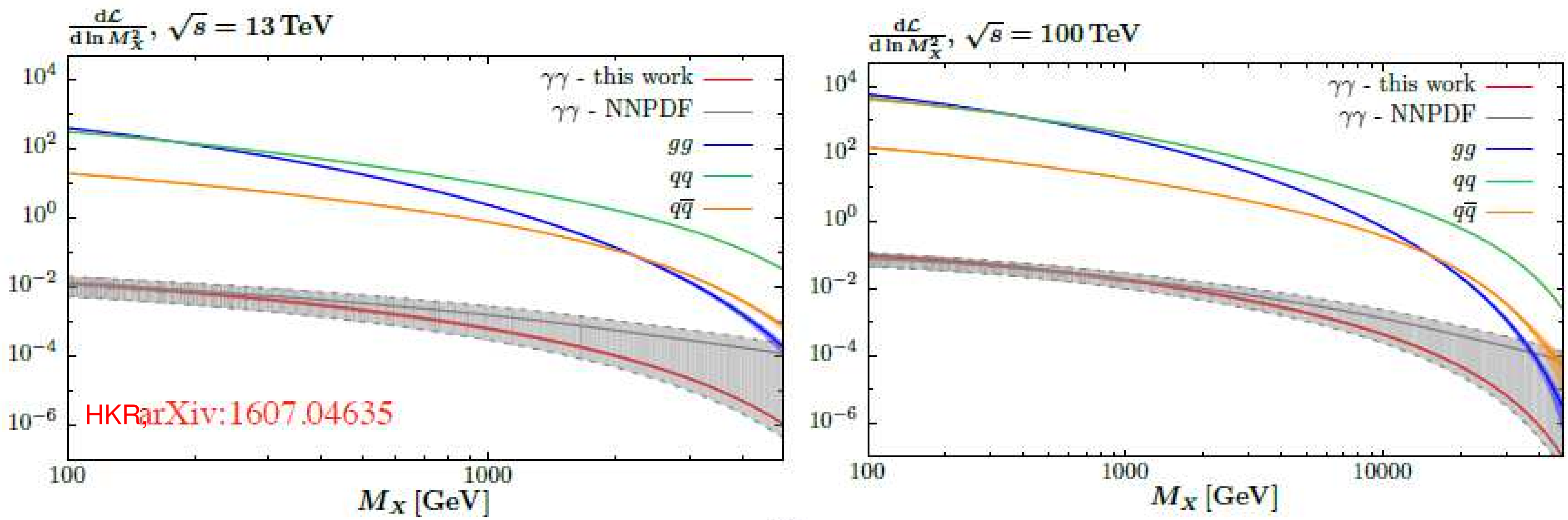
First fully differential implementation of soft survival factor – **SuperChic 2** MC event generator- HKR, ArXiv:1508.02718 (Lucian's talk)

Photon-photon Luminosities

(LUXqed-Giulia's talk, Lucian's talk)

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

- **HKR-16** approach: scaling very similar to $qq/q\overline{q}$, with gg only slightly stepper. Uncertainties fairly small, again a lower end of NNPDF band.



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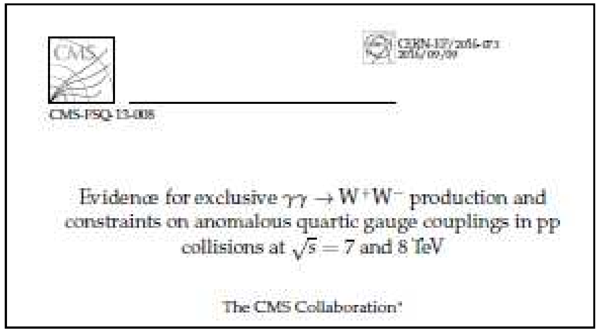
Photon-initiated processes with rapidity gaps

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

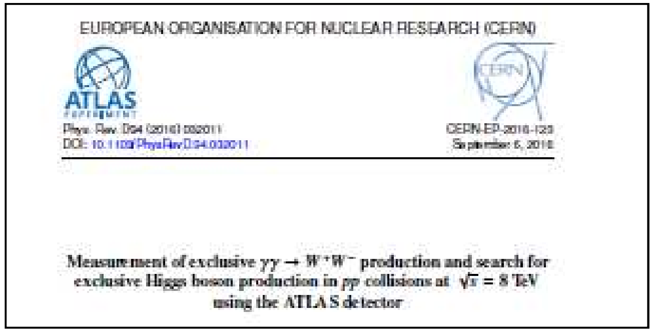


CMS-FSQ-13-008

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

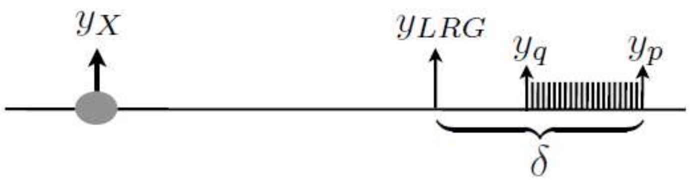
CERN-EP-2016-123
September 6, 2016

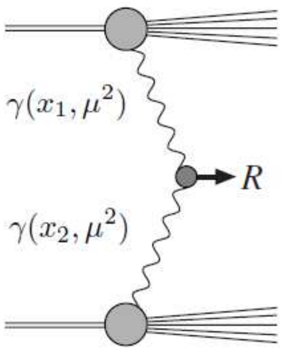
Measurement of exclusive $\gamma\gamma \to W^+W^-$ production and search for exclusive Higgs boson production in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector

- 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.

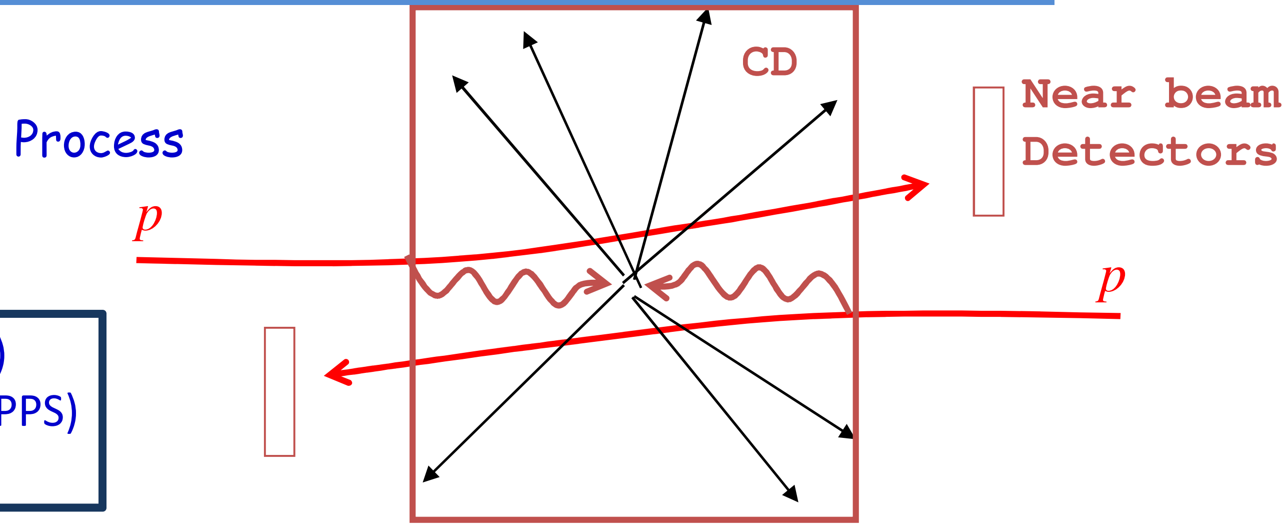
HKR arXiv:1601.03772

(Lucian's talk)





γγ collisions- applications



Installed (AFP)
Installed (CT-PPS)
projects

Extensive Program

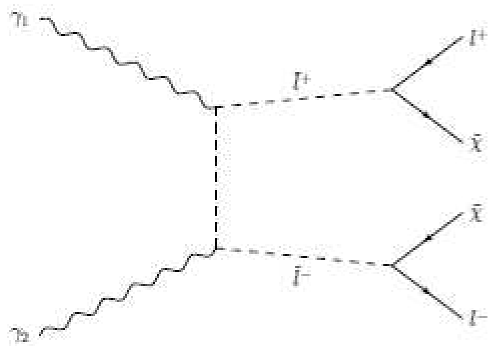
- γ γ→ μμ, ee QED processes
- γ γ→ QCD (jets..)
- γ γ→ WW anomalous couplings
- γ γ→ squark, top… pairs
- γ γ→ Charginos (natural SUSY)
- New BSM objects

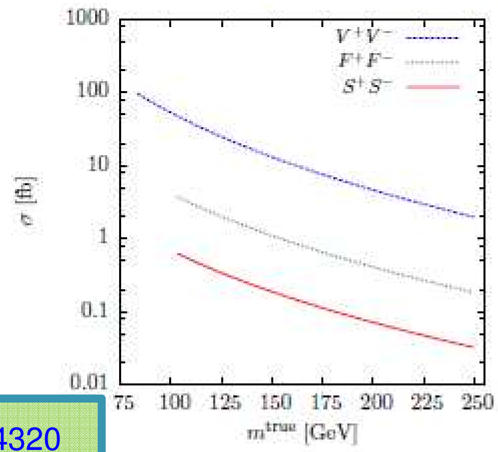
$$pp \to p + \gamma\gamma + p\,,$$
$$\gamma\gamma \to X^+X^-\,,$$

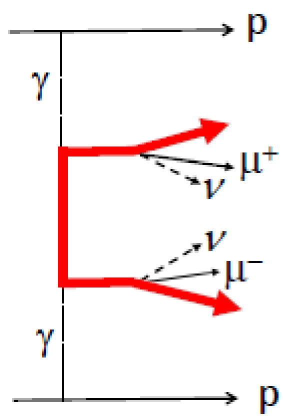
Diphoton X-Pair Production

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

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







HKSS, arXiv:1110.4320

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

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

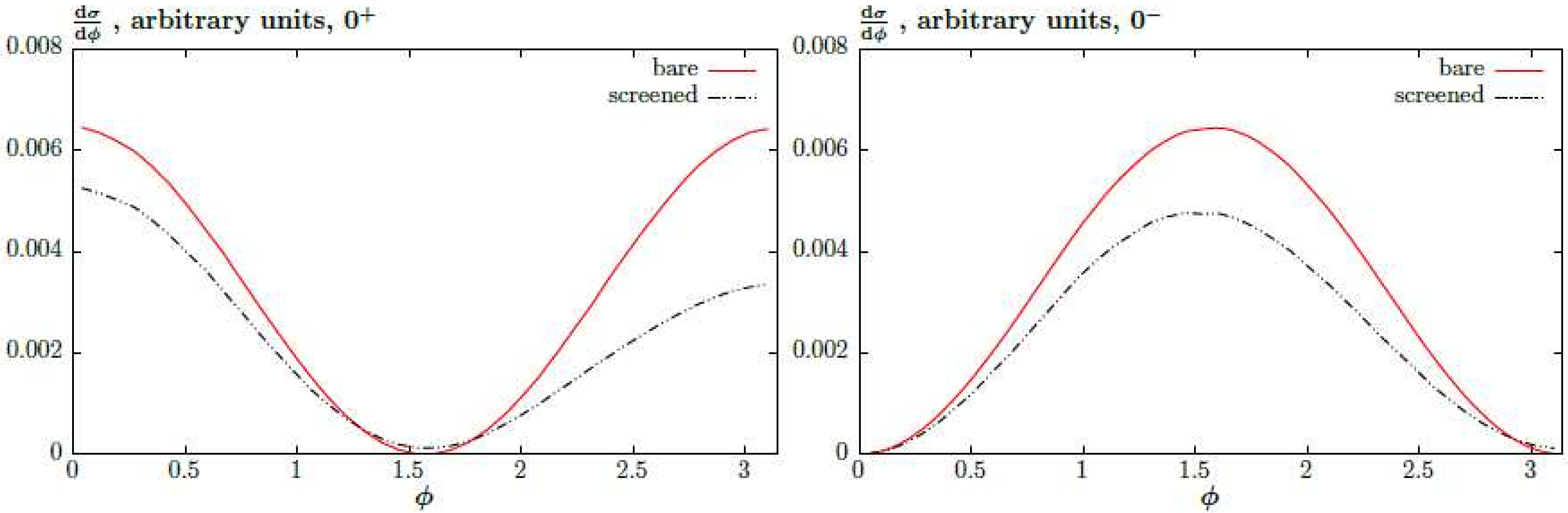
electroweakinos

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

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

High-mass resonances- tagged proton correlations

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



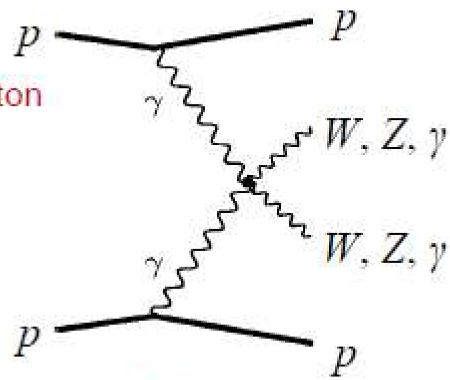
$\longrightarrow$ With just a handful of events, scalar/pseudoscalar hypotheses distinguishable.

- 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
  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)

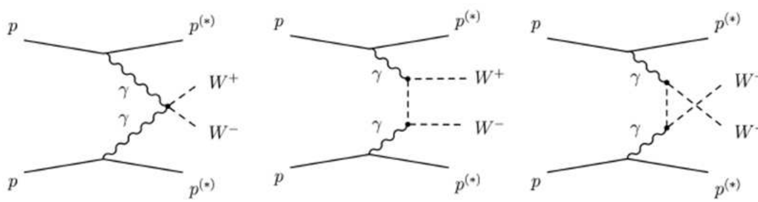


"Probing anomalous quartic gauge couplings using proton tagging at the Large Hadron Collider", M. Saimpert, E. Chapon, S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon; 23/05/2014

(Sylvain's talk)

• 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

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.

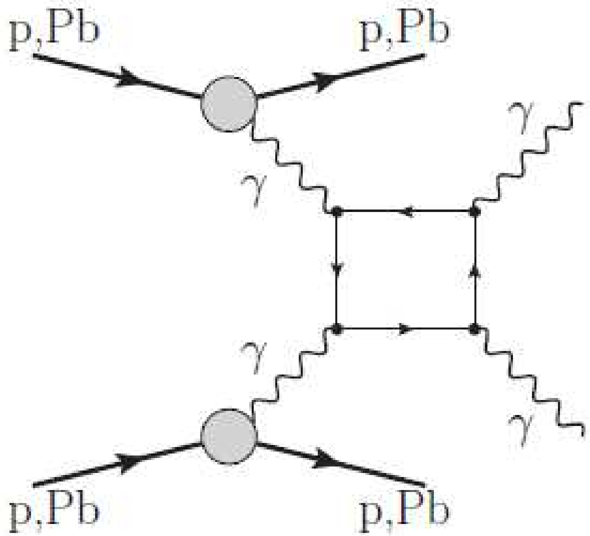
• Studies done for $\sim 100\,\mathrm{fb}^{-1}$ of lumi, i.e. including significant pile-up, for both AFP and CT-PPS (results similar).

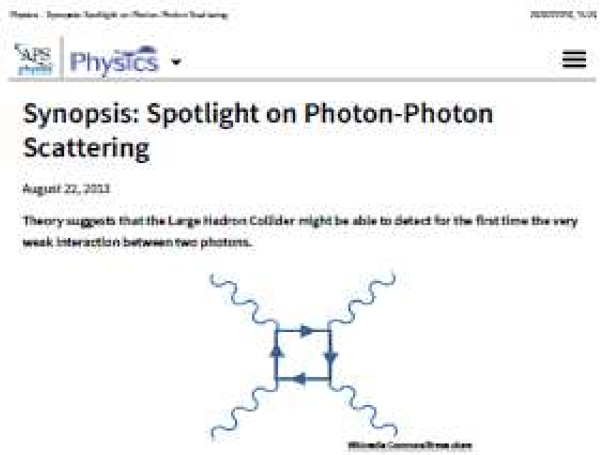
• How to suppress BG? As before, limiting number of tracks in PV (+ other cuts) helps.

• **But**, huge gain from proton tagging requirement. Fast timing (+ correlating proton/system kinematics) dramatically reduces pile-up BG and selects very pure exclusive signal.

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.



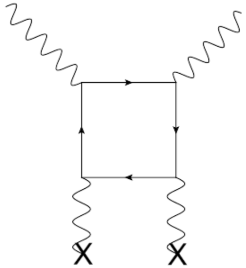


- Analysis of d'Enterria and Silveira (arXiv:1305.7142,1602.08088): realistic possibility, in particular in $PbPb$ collisions.

(Gustavo's talk)

Long and chequered history

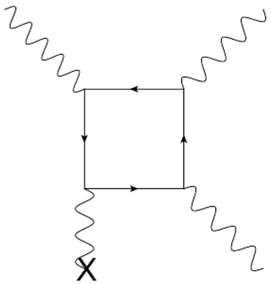
(nonlinear effects of QED)



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

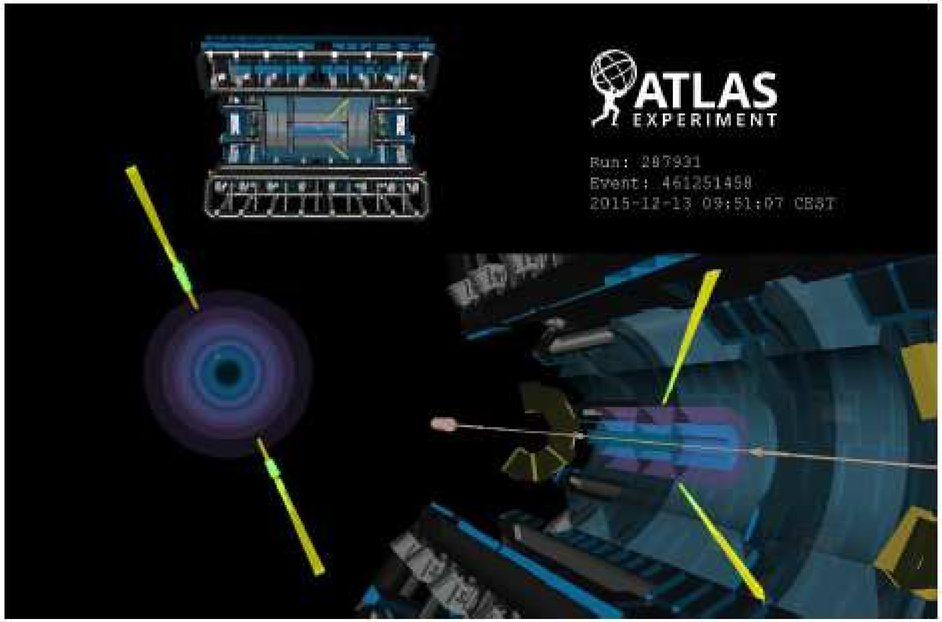
ATLAS @ $\sqrt{s_{NN}}$ = 5.02 TeV:

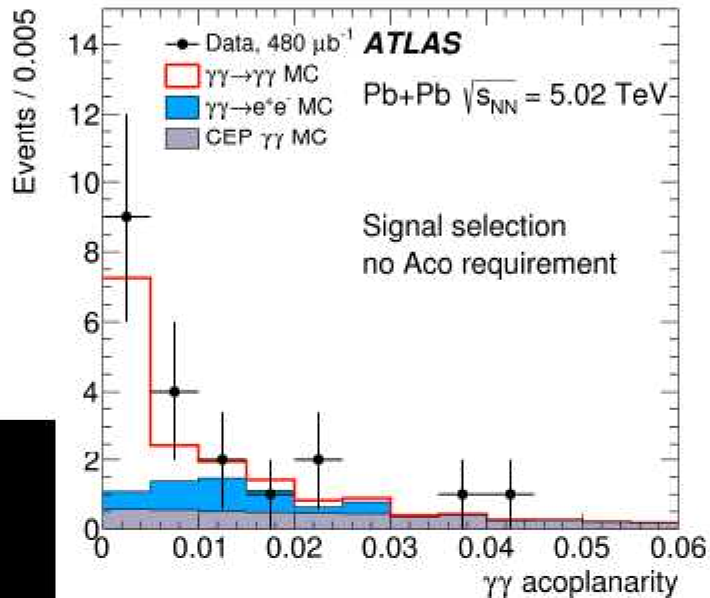
13 events (bkgd 2.6) ⇒ 4.4σ evidence

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

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LbyL Scattering Constraint on Born-Infeld Theory
[arXiv:1703.08450]

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

Interest from 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

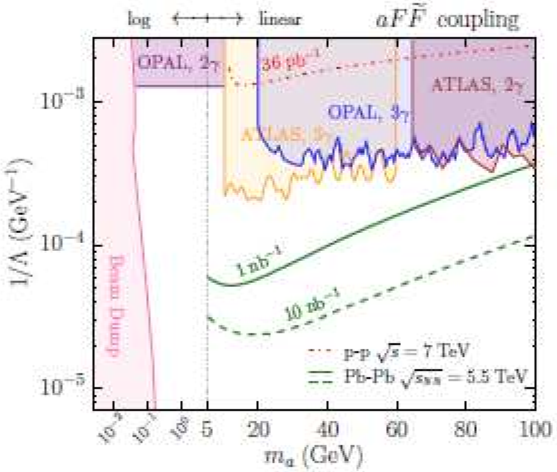
The recent measurement by ATLAS of light-by-light scattering in LHC Pb-Pb collisions is the first direct evidence for this basic process. We find that it requires the mass scale of a nonlinear Born-Infeld extension of QED to be $\gtrsim 100$ GeV, a much stronger constraint than those derived previously. In the case of a Born-Infeld extension of the Standard Model in which the $\mathrm{U(1)_Y}$ 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 $\mathrm{U(1)_Y}$ Born-Infeld theory.

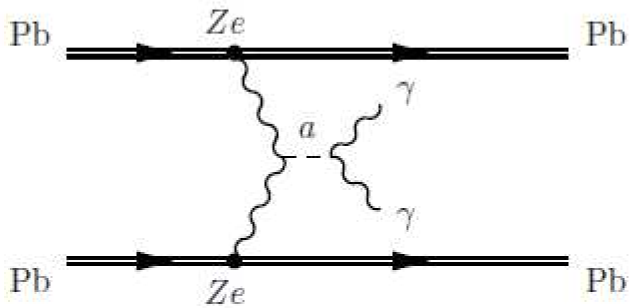
Axion-like particles

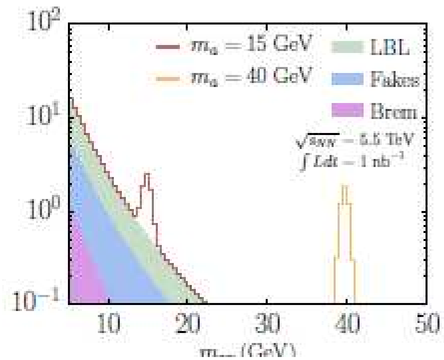
• Consider same $\gamma\gamma \to \gamma\gamma$ transition: sensitive to coupling of light axion-like particle to photons.

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

• Discussed in Kapen et al. (1607.06083) - find that in heavy ion collisions can set the strongest limits yet on these couplings.







(Lou's talk)

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.
- 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

LHC as a photon-photon collider

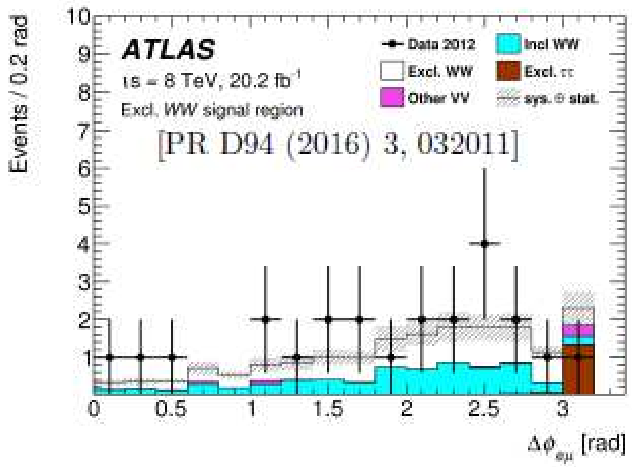
pp collisions

Pros

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

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 ($< 1\%$)

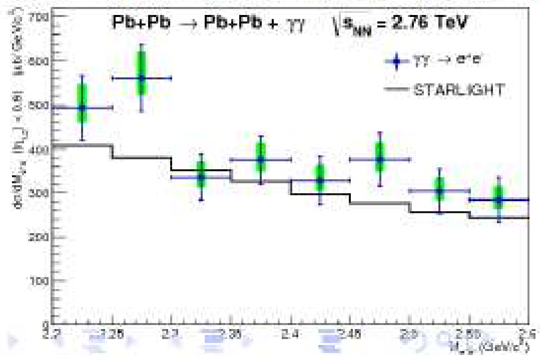
$A^{2/3}$

(Lucian'stalk)

Cons

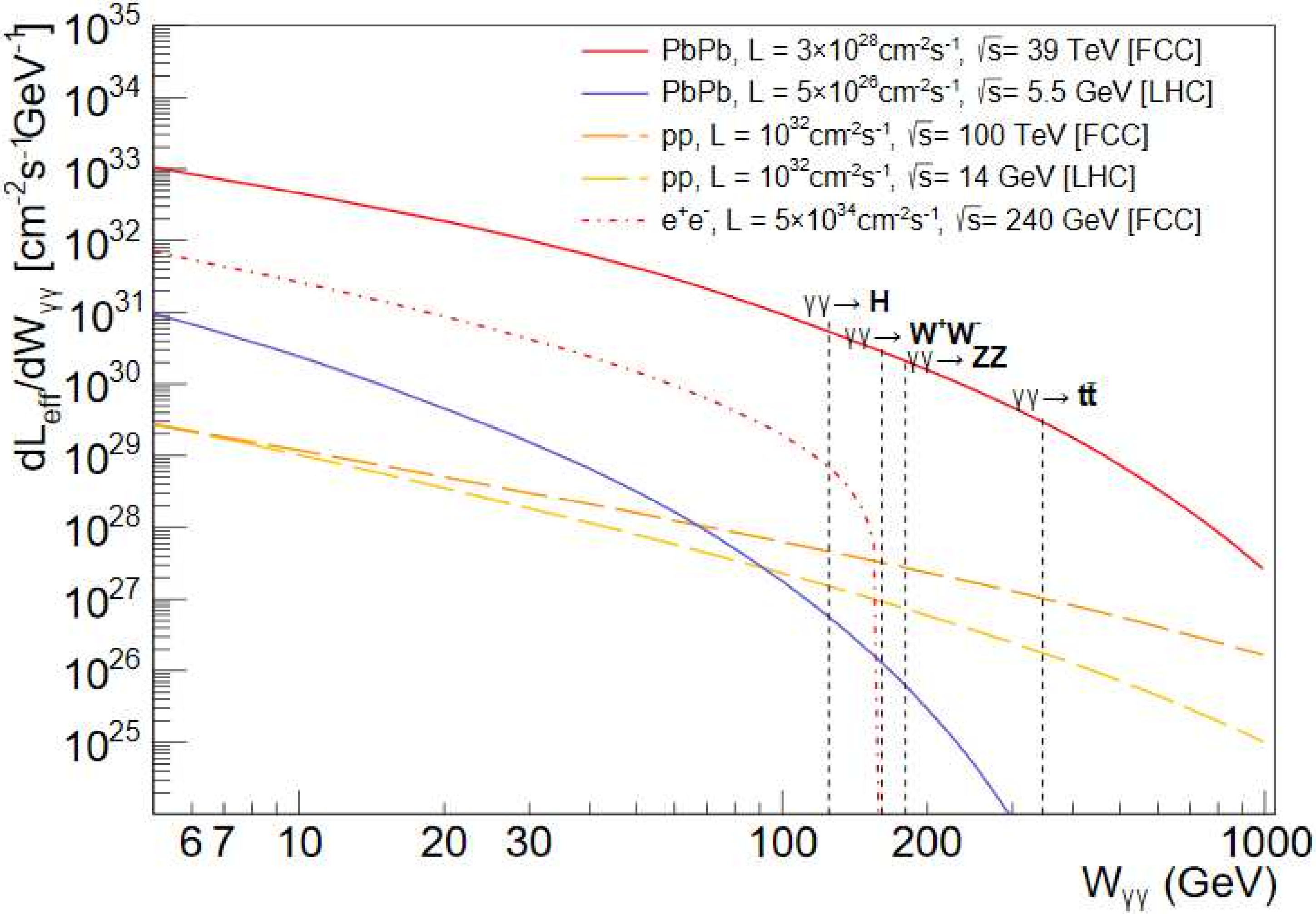
- softer EPA γ spectrum ($\omega_{\max} \sim 0.1$ TeV)
- relatively small data sample

[ALICE Collaboration,EPJC 73 (2013) 2617]



ATLAS 2016

ArXiv:1605.01389

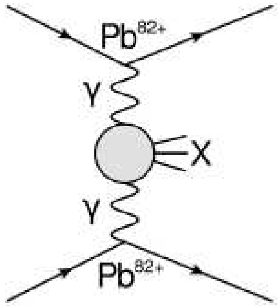


Effective photon–photon luminosities as a function of $\gamma\gamma$ c.m. energy ($W_{\gamma\gamma}$) for five colliding systems at FCC and LHC energies: Pb–Pb at $\sqrt{s}$ = 39, 5.5 TeV (at their corresponding nominal beam luminosities); pp at $\sqrt{s}$ = 100, 14 TeV (corresponding to 1 fb^{-1} integrated 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.

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

UPC

• Ions do not necessarily collide 'head-on' - for 'ultra-peripheral' collisions, with $b > R_1 + R_2$ the ions can interact purely via EM and remain intact $\Rightarrow$ exclusive $\gamma\gamma$-initiated production.



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

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

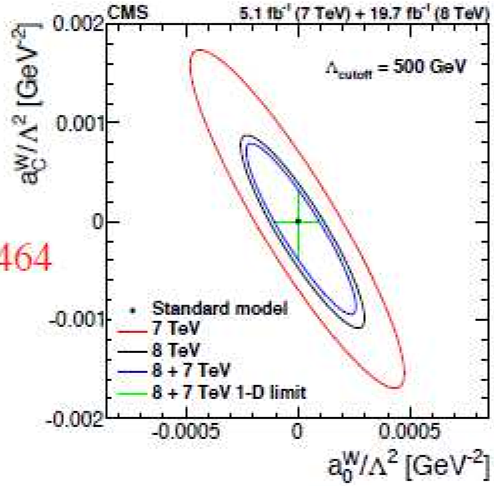
• Ions interact via coherent photon exchange- feels whole charge of ion $\Rightarrow$ cross section $\propto Z^4$. For e.g. Pb-Pb have $Z^4 \sim 5 \times 10^7$ enhancement!

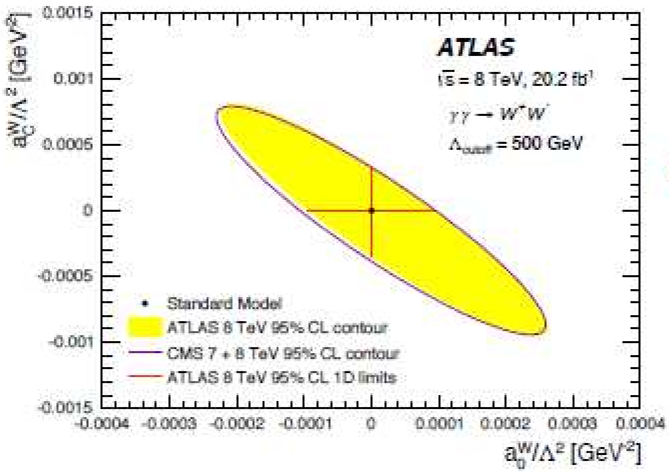
• Photon flux in ion tends to be cutoff at high M_X, but potentially very sensitive to lower mass objects with EW quantum numbers.

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.

LbyL Scattering Constraint on Born-Infeld Theory

[arXiv:1703.08450]

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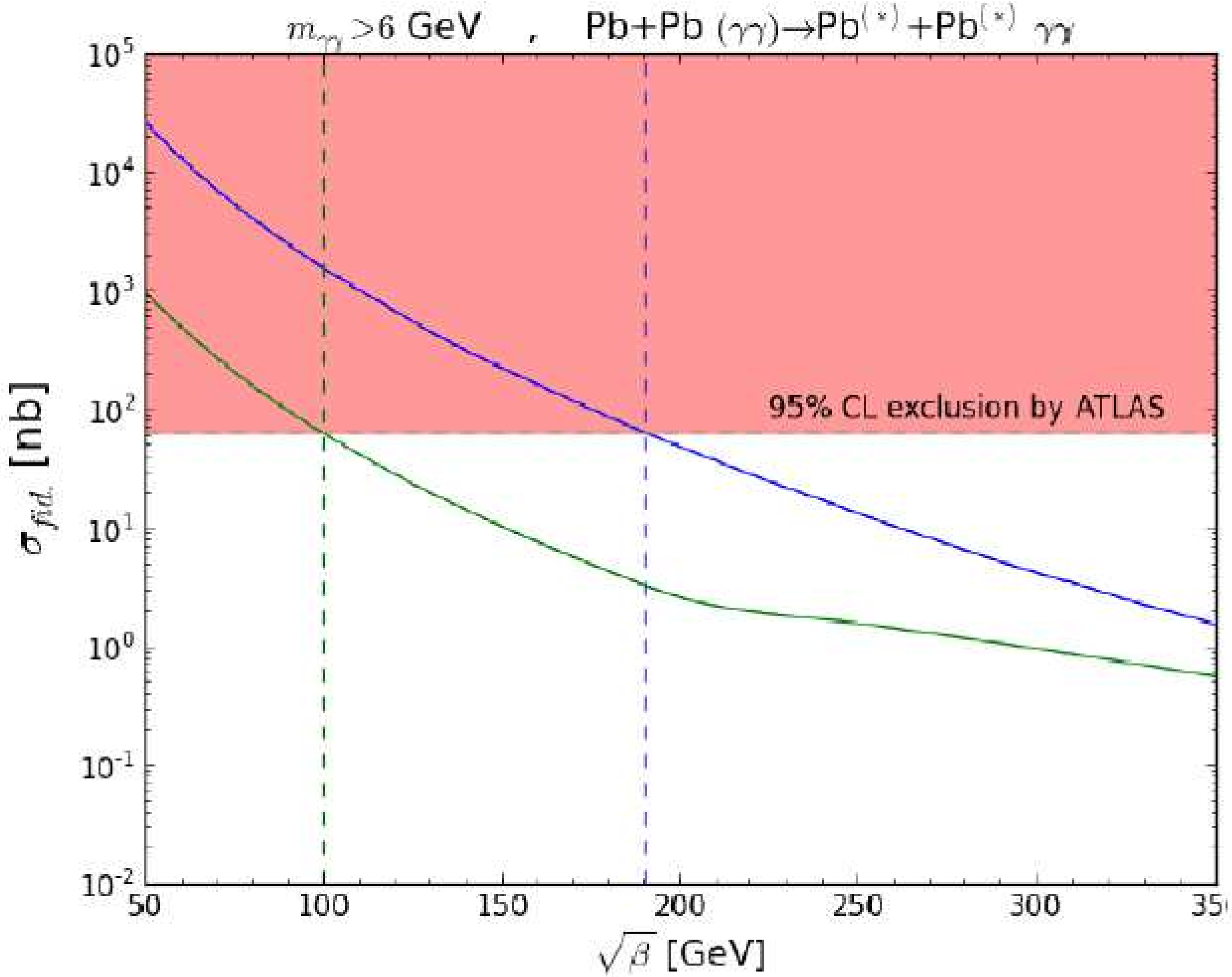

Cross sections

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

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

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

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**