INSTITUTE FOR THEORETICAL PHYSICS

THEORETICAL PHYSICS

ITP

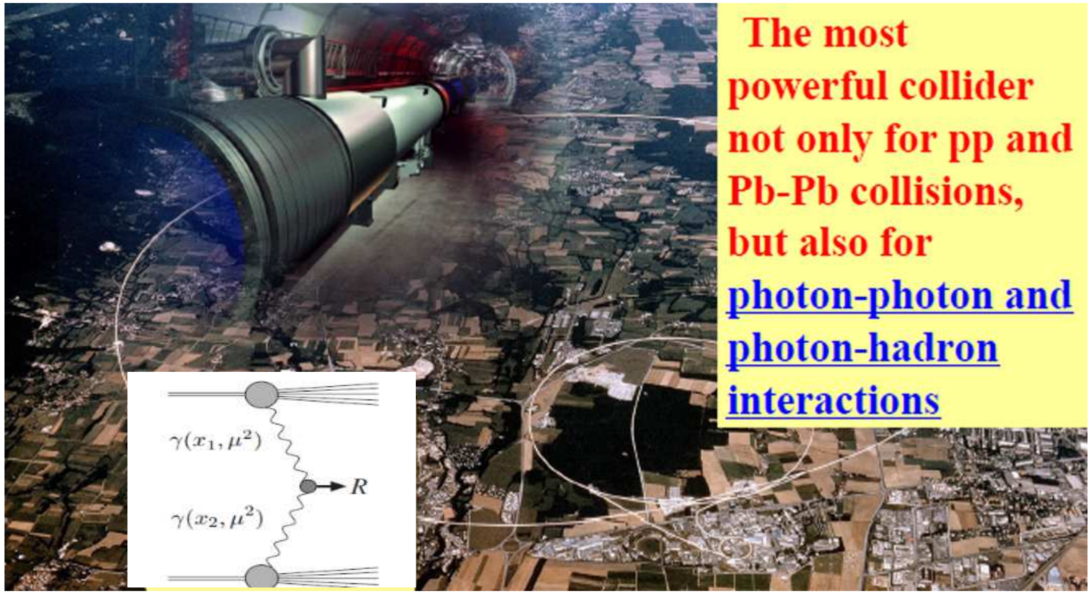
Teilchentee WS 2017/18

THE LHC AS A PHOTON-PHOTON COLLIDER
(selected topics)

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

The Royal Society of Edinburgh
KNOWLEDGE MADE USEFUL

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



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?

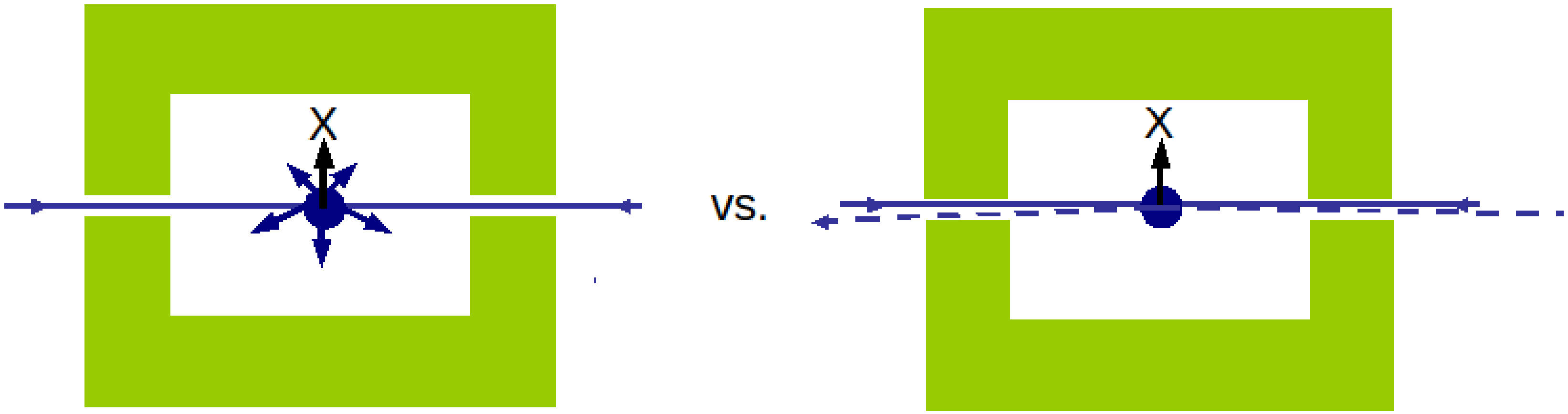
Central Exclusive Production (CEP) is the interaction:

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

- **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.



SELECTING EXCLUSIVE PHOTON-PHOTON EVENTS AT THE LHC

MIND THE GAP

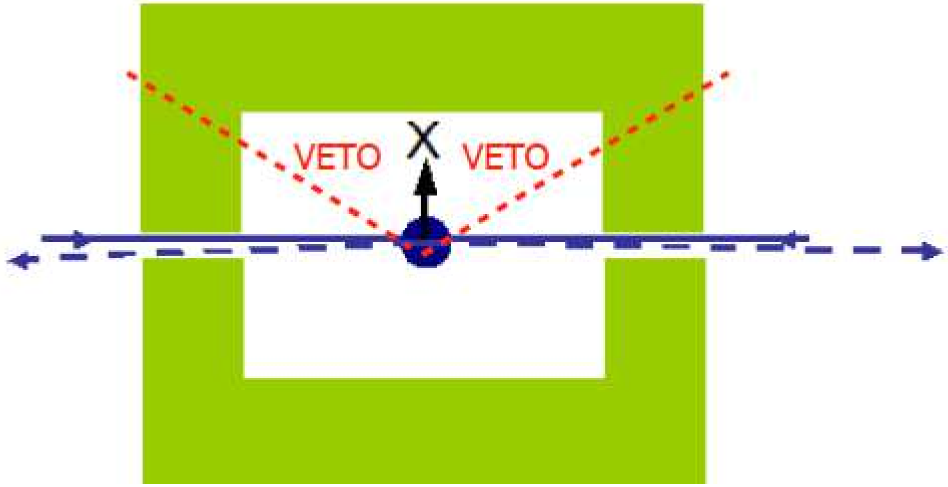
1) Gap-based selection: no extra activity in large enough rapidity region.

- 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).

NEW

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



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

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

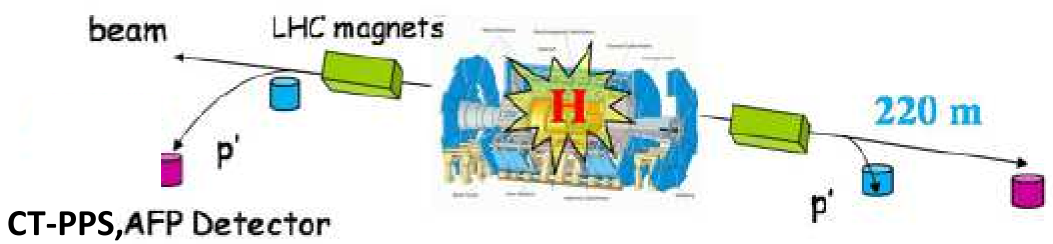
  $\longrightarrow$ If we can measure the outgoing protons, po...

  purely exclusive event sa...

- Basic principle: us... ...After interaction pr... ...bend out of beam li...

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

The LHC is best mass spectrometer



Physics motivations

Central Exclusive Production

$$pp \rightarrow p \oplus X \oplus p$$

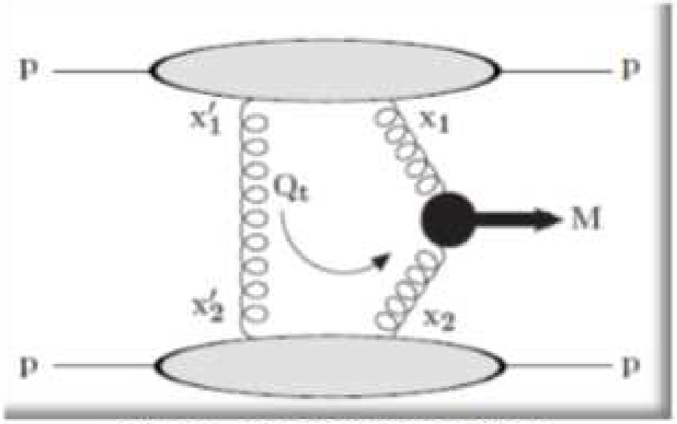
photon or Pomeron exchanges

$\oplus$ rapidity gap

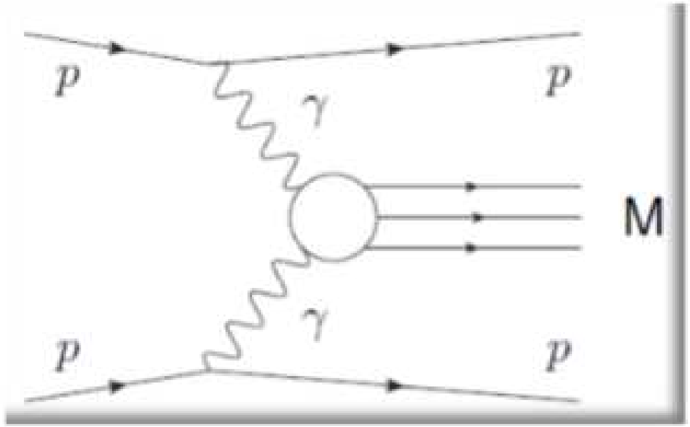
X = high-E_T jets, WW, ZZ, $\gamma\gamma$, … measured in the central detector

Measurement of two scattered protons fully determines the kinematics of the central system X :

- ξ: fractional momentum lost by the proton
- t: 4-momentum transfer squared



Gluon-gluon interaction. Additional gluon(s) exchange needed to conserve the colour



Photon-photon interaction.

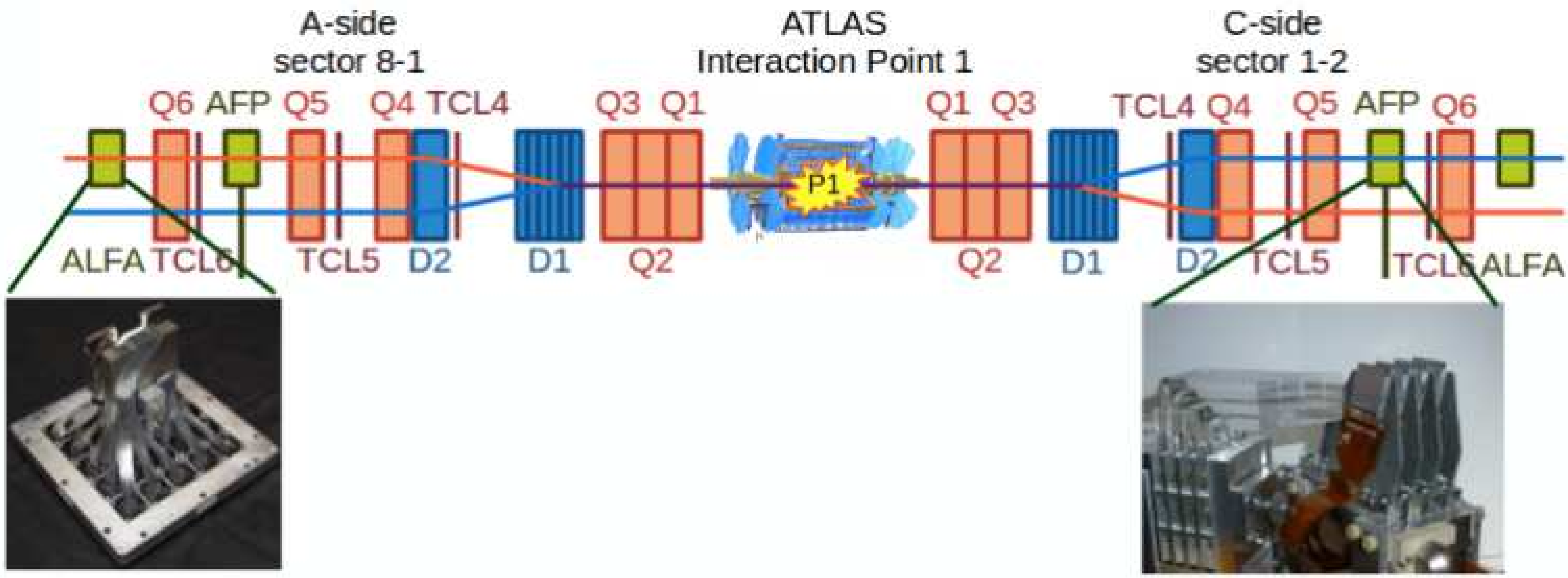
ATLAS Forward Detectors for Diffraction

In ATLAS it is possible to **identify diffractive events** by, e.g. large rapidity gaps

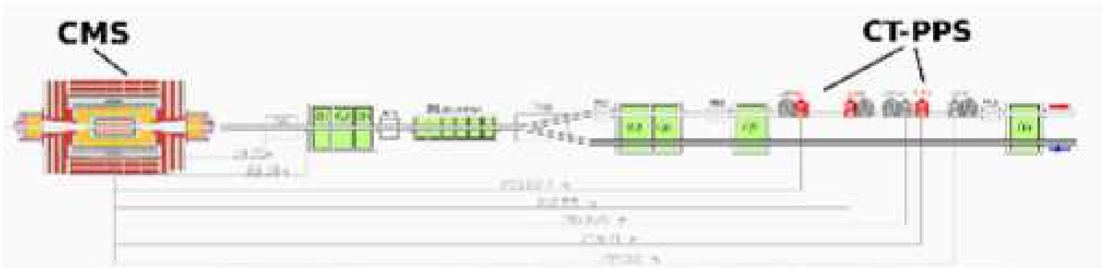
However, ATLAS is equipped with two forward detectors for **proton tagging**

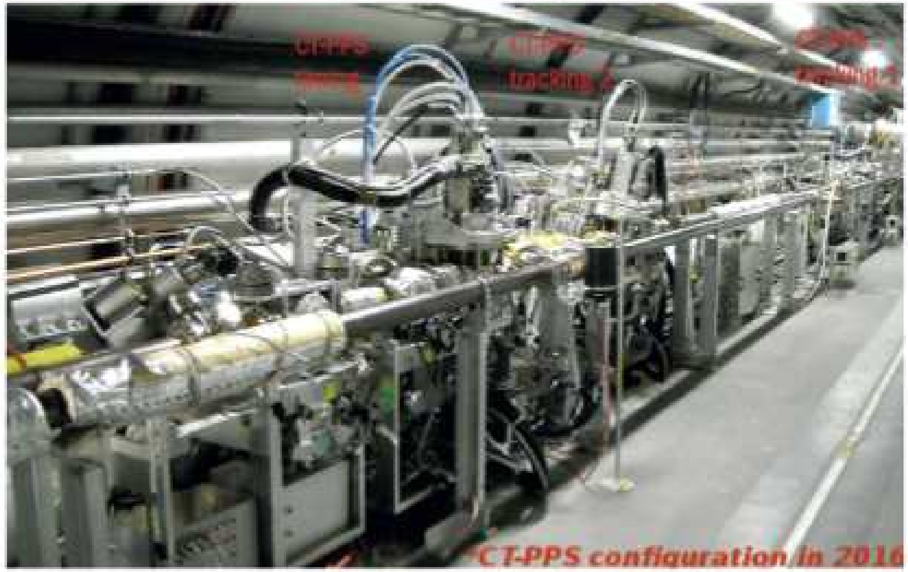
- ALFA (Absolute Luminosity For ATLAS) vertical Roman Pots
  at $z = \pm 237$ and $z = \pm 245$ m for *elastic* and *diffractive* scattering measurements
- AFP (ATLAS Forward Proton) horizontal Roman Pots
  at $z = \pm 205$ and $z = \pm 217$ m for *diffractive* scattering measurements "NEW"

➡ Tag protons leaving intact the interaction point to **identify diffractive processes**



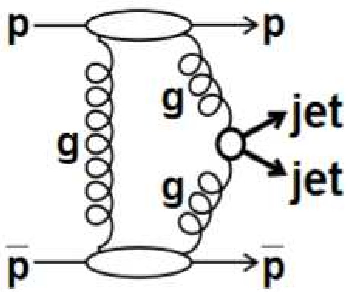
What is CT-PPS?

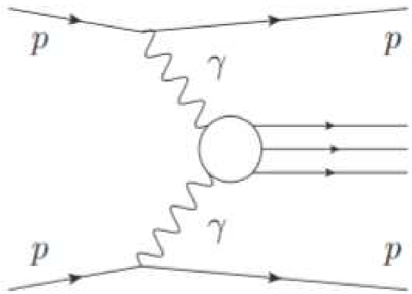


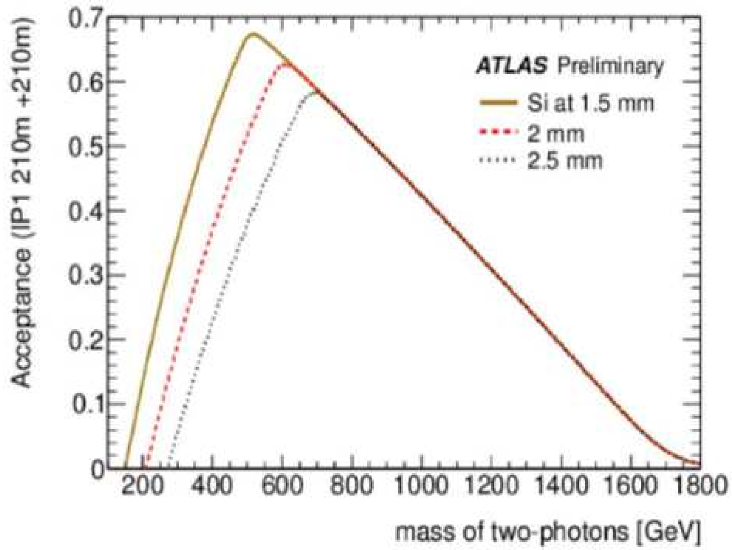


- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795,
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few mm from the beam (both sides of CMS
- First data taking in 2016: $\sim$ 15 fb^{-1}

What is AFP/CT-PPS?



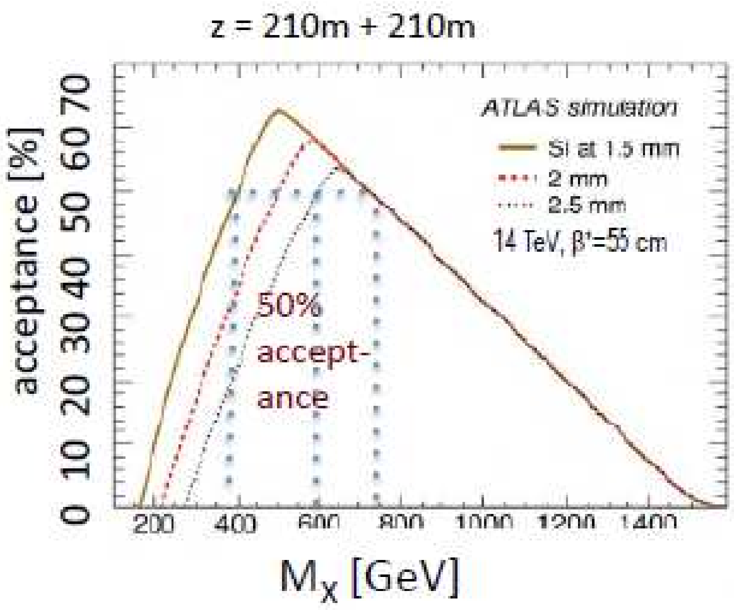


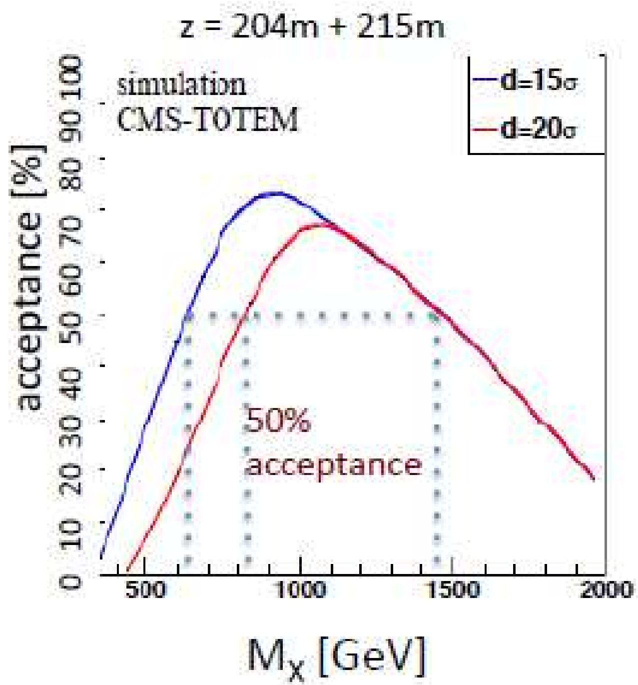


- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)

- Sensitivity to high mass central system, X, as determined using AFP/CT-PPS: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements

ATLAS & TOTEM ROMAN POTS HAVE LIMITED ACCEPTANCES





ATLAS: *M_X≈400/600 – 750 GeV* **CMS/TOTEM: *M_X≈650/820 – 1450 GeV***

- **allowed distances to the beam?**
- **acceptance in φ & t?**
- **options via correction dipoles...**

"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.

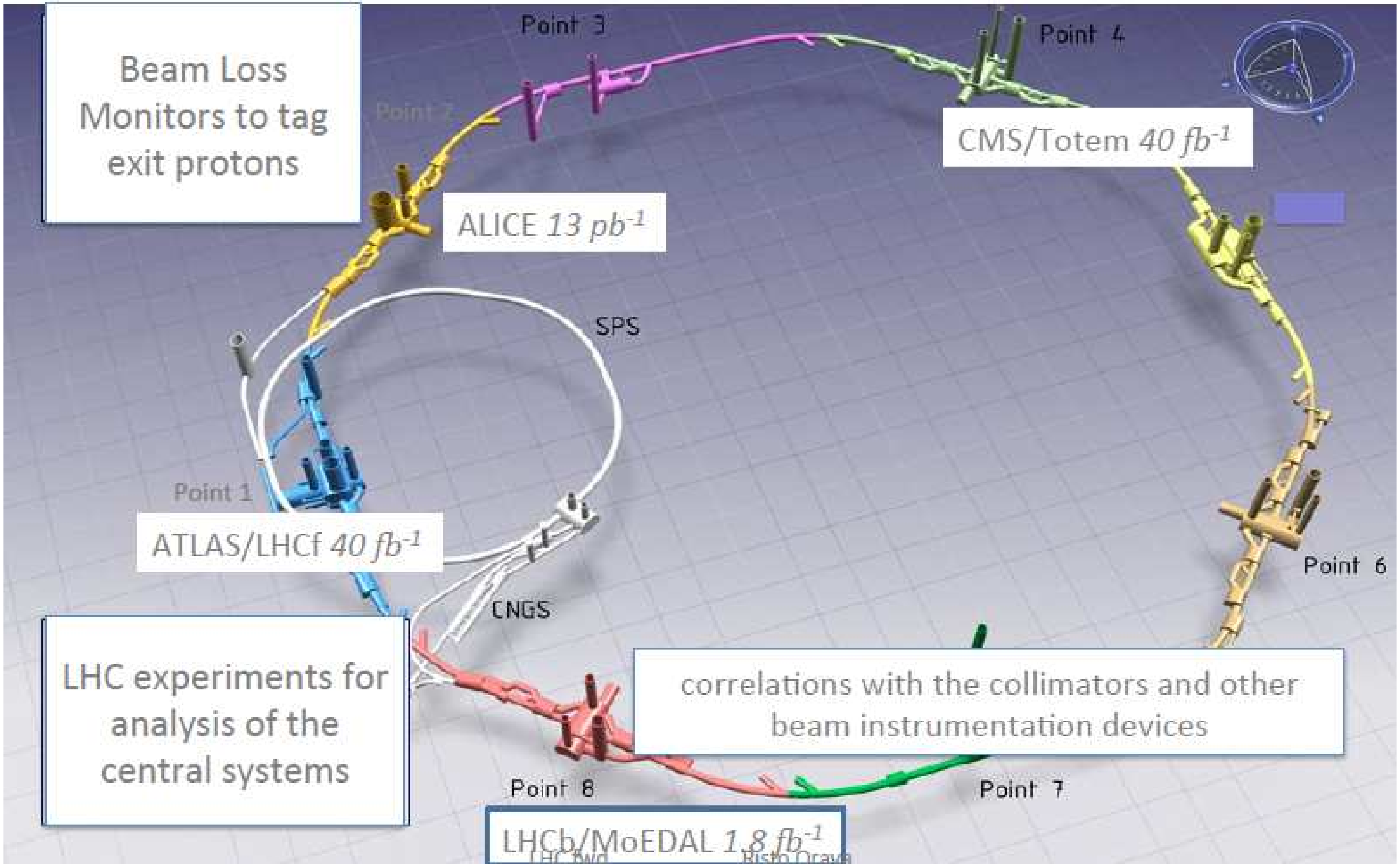
As an outcome -great improvement in our understanding of photon PDF and development of the effective tools for analysing potential diphoton resonances.

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

LHC Ring –proto collaboration

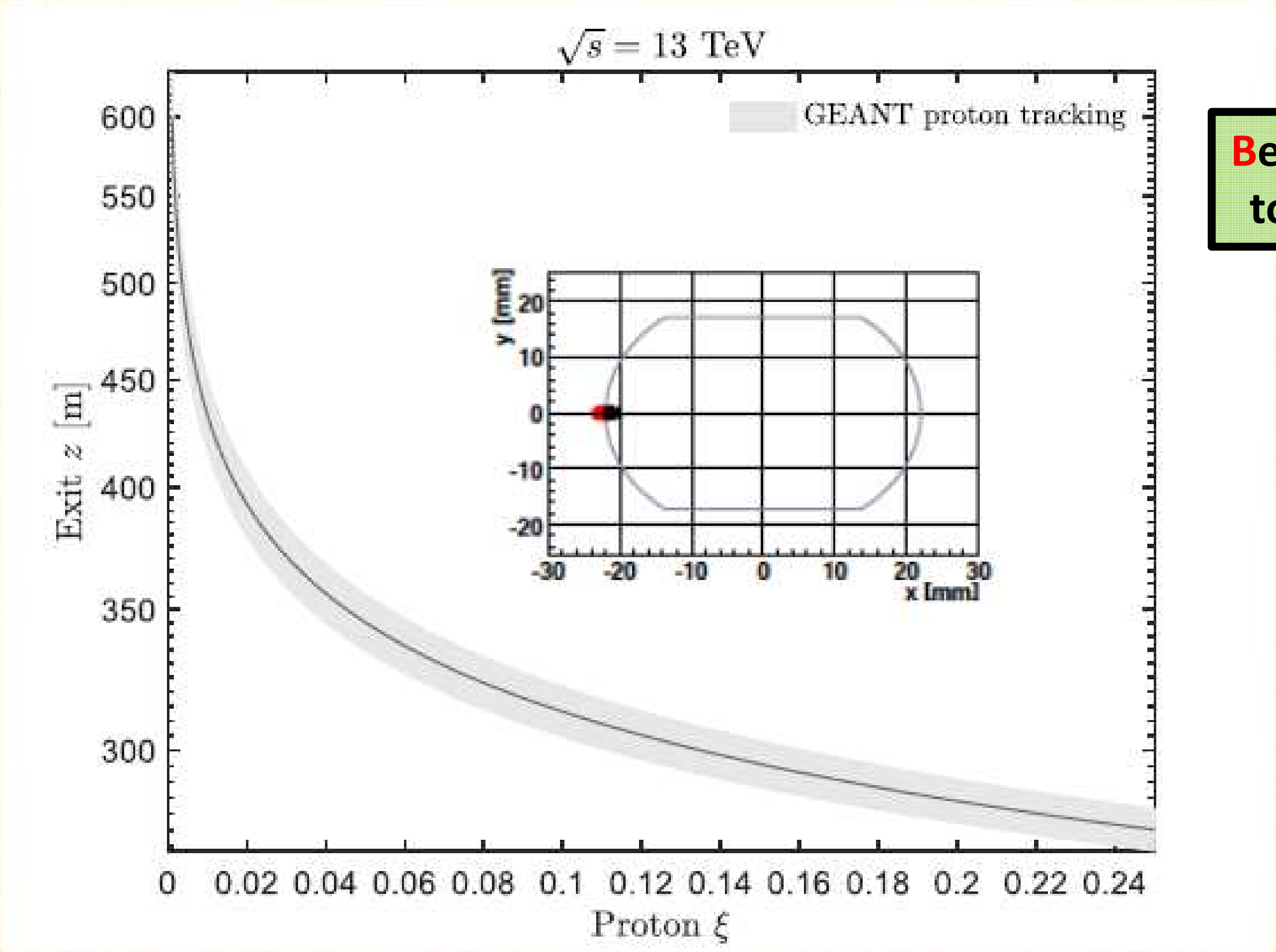
(S. Redaelli et al., CERN Beams Division), accelerator theory (Werner Herr, CERN Beams Division), theoretical high energy physics (Lucian Harland-Lang, University College, London, K. Huitu, Division of Particle Physics and Astrophysics, University of Helsinki; Valery Khoze, University of Durham University; 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. $\xi = \Delta p / p$

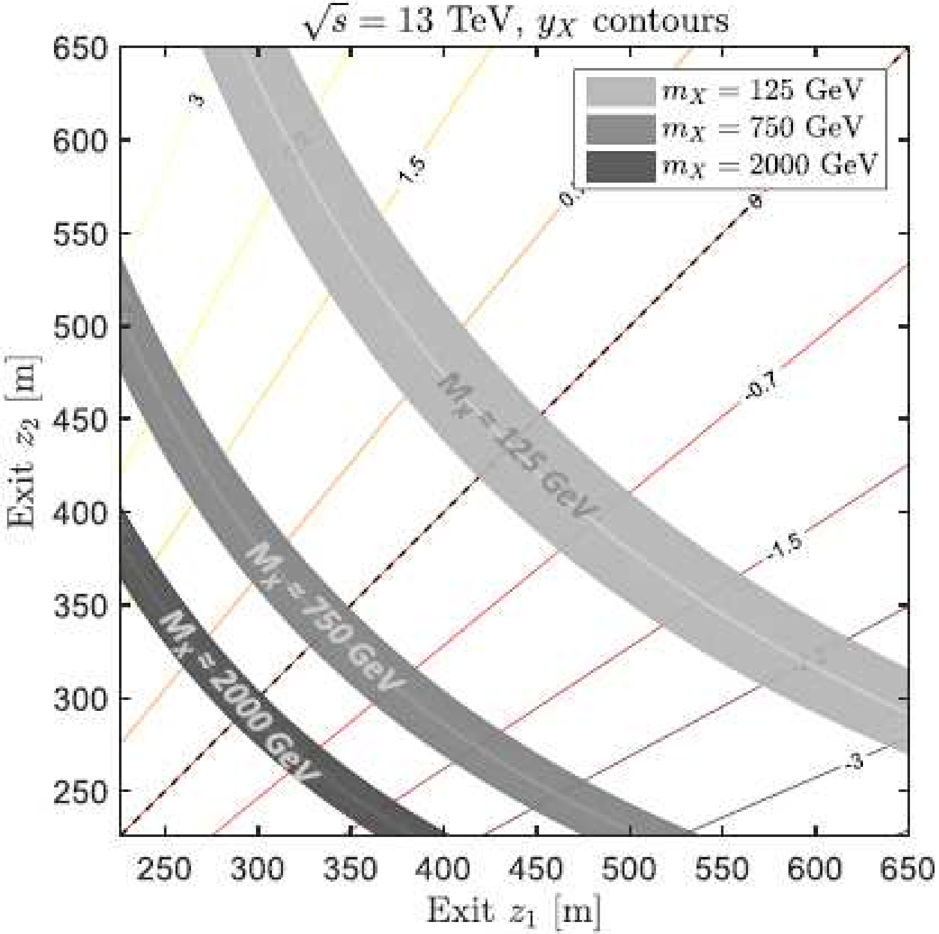


Beam Loss Monitors to tag exit protons

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

PAIRS OF PROTON EXIT POINTS MAP OUT THE CENTRAL MASSES



$\xi = 1 - \Delta p_z / p_{beam}$

$z_{1,2} \rightarrow \xi_{1,2}$

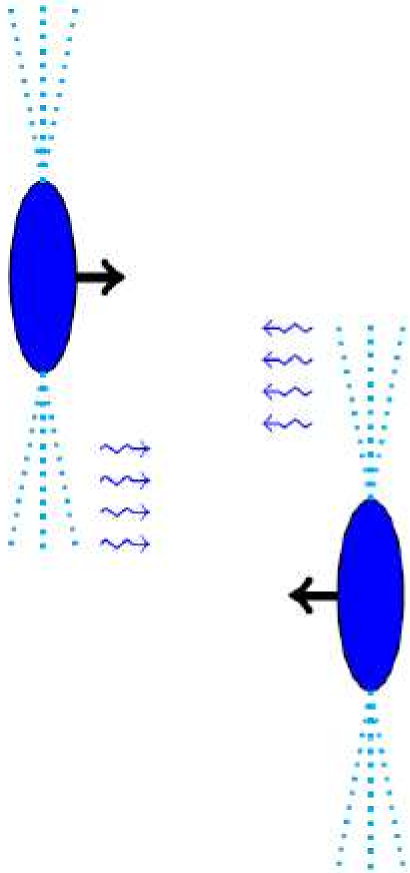
$M_X \approx sqrt(\xi_1 \times \xi_2 \times s)$

3

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.

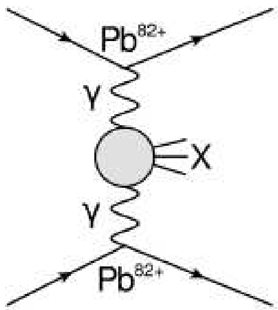
Enrico FERMI

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]

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

• 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.

LHC as a photon-photon collider

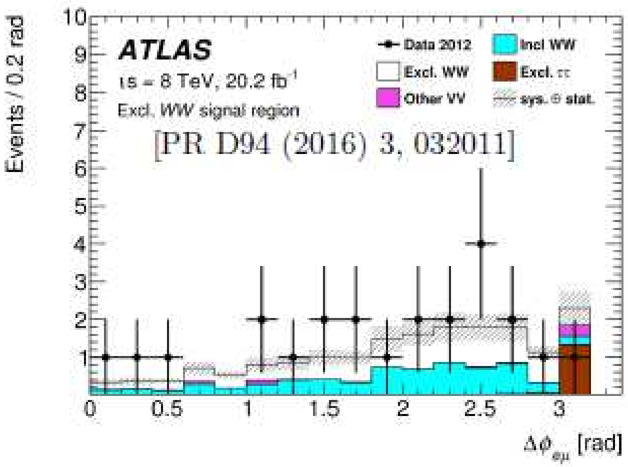
pp collisions

Pros

- harder EPA γ spectrum ($\omega_{\mathrm{max}} \sim \mathrm{TeV}$)
- 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

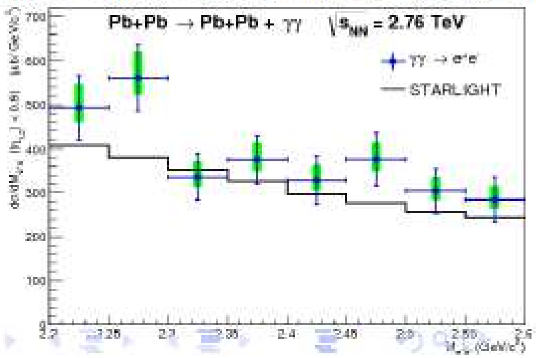
- AA ($\gamma\gamma$) x-sec $\propto Z^4$
- gluonic x-sec $\propto A^2$ $\Rightarrow$ lower QCD bkg.
- low pile-up ($< 1\%$)

$A^{1/3}$

Cons

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

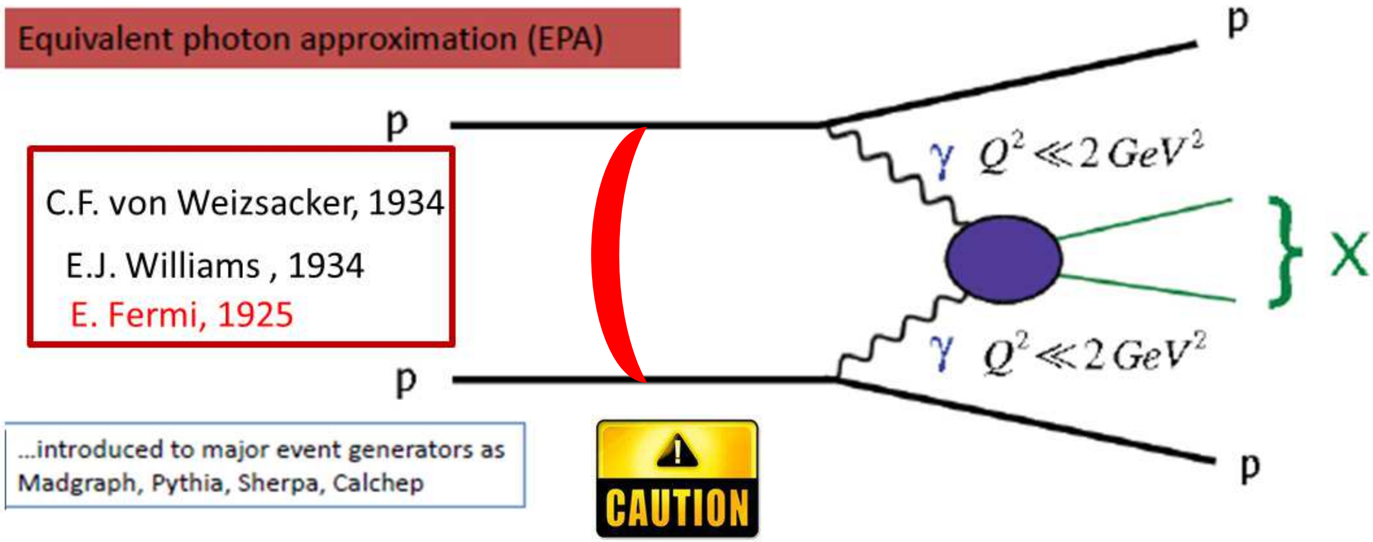
[ALICE Collaboration,EPJC 73 (2013) 2617]



ATLAS/CMS 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:

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

- 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

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

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

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

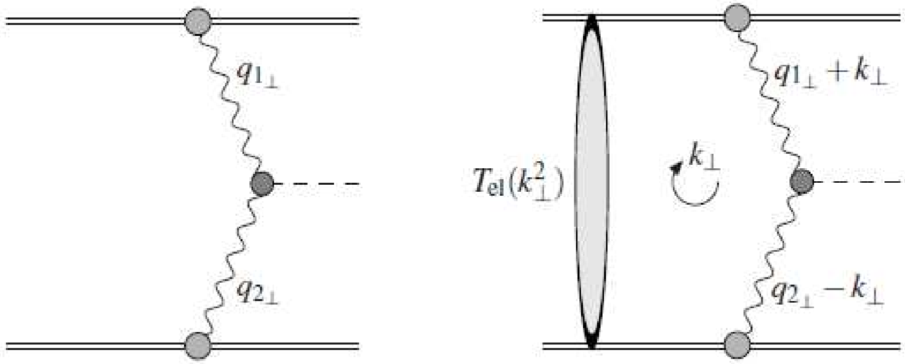
In fact, the situation is more complicated due to the effects caused by the polarization structure of the production amplitude.

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).

- Our $\gamma\gamma$-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

MC

S. Ostapchenko…
Lonnblad&Zlebcik

- 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}

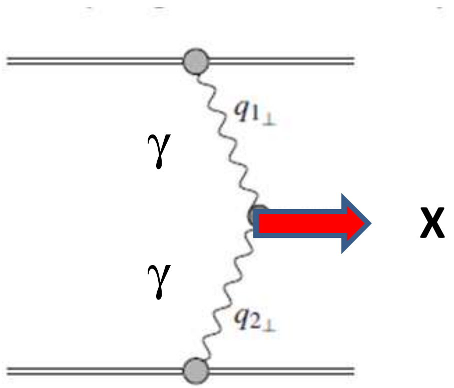
- Not a constant: depends sensitively on the outgoing proton $\mathbf{p}_\perp$ vectors. Physically- survival probability will depend on impact parameter of colliding protons. Further apart $\longrightarrow$ less interaction, and $S^2_{\text{eik}} \to 1$.

b_t and $p_\perp$: Fourier conjugates.

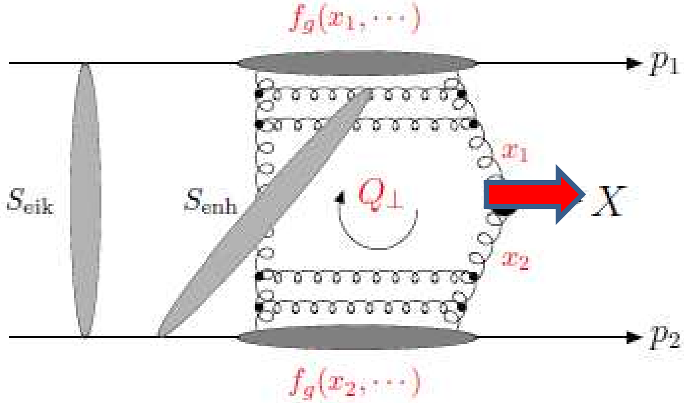
Process dependence

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

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



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.

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

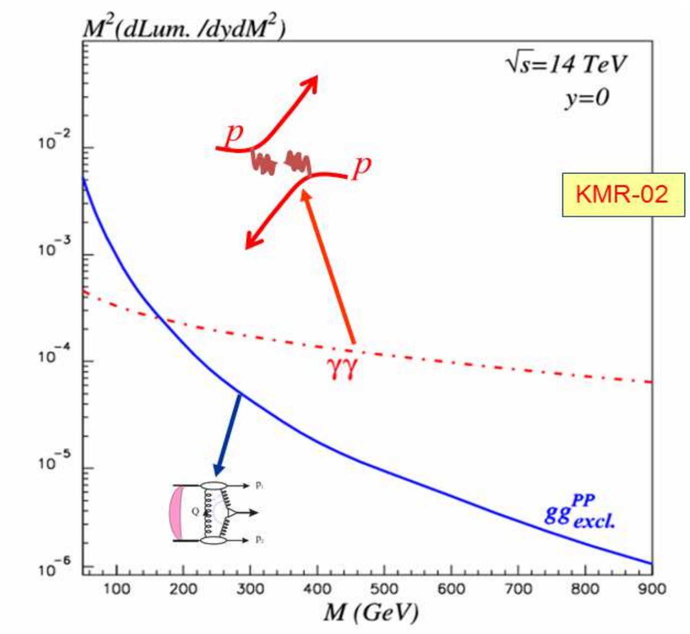
- Increasing M_X $\Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

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

KMR-2001

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

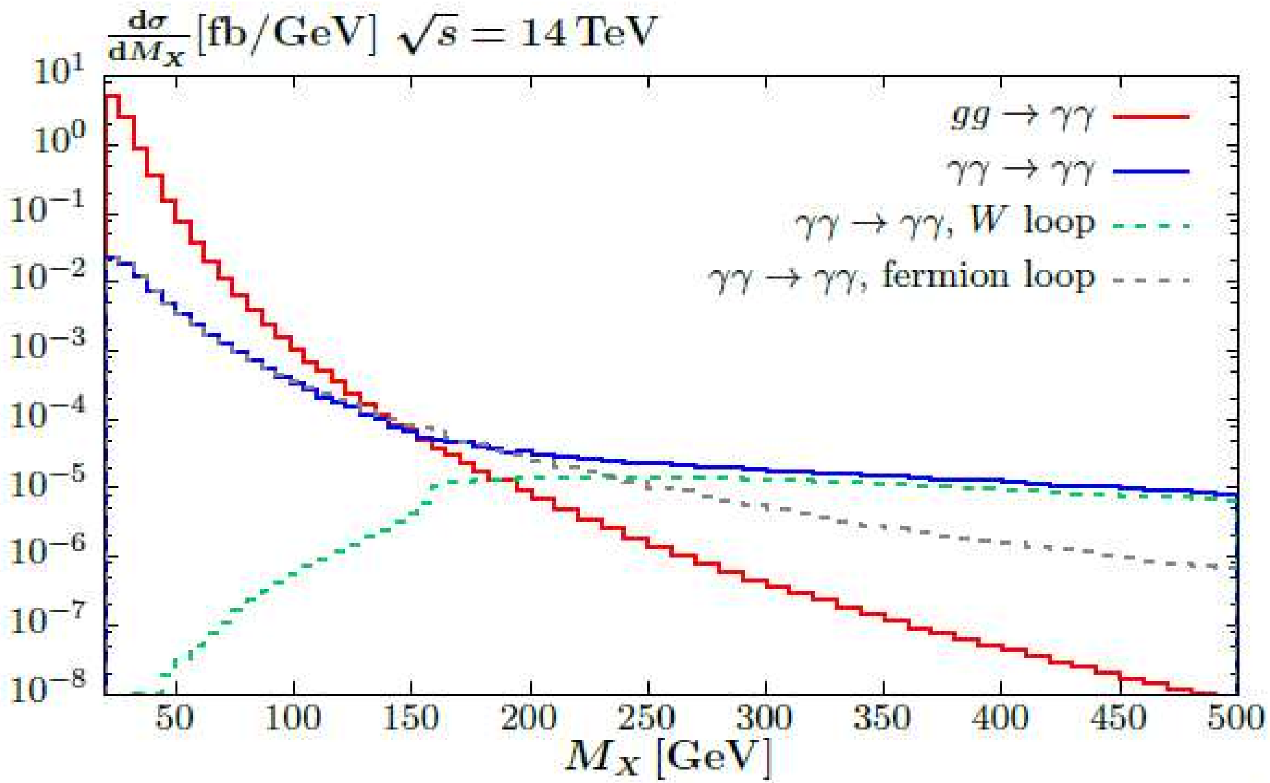
QCD ‘radiation damage’ in action



• 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 $s_{\gamma\gamma}$.

Light-by-light scattering



SuperChic

$p_\perp^\gamma > 10$ GeV

$|\eta^\gamma| < 2.4$

- 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 ($\longrightarrow$ Sudakov suppression of gg).

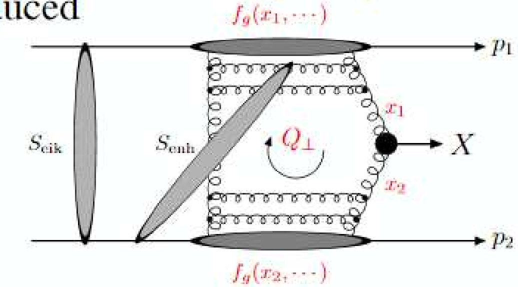
Photon-photon collisions in Superchic

Production mechanisms

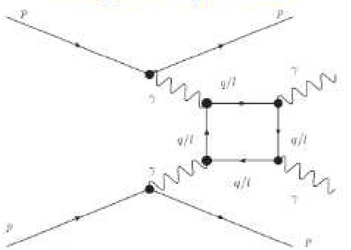
Exclusive final state can be produced via three different mechanisms, depending on kinematics and quantum numbers of state:

Gluon-induced

C-even, couples to gluons

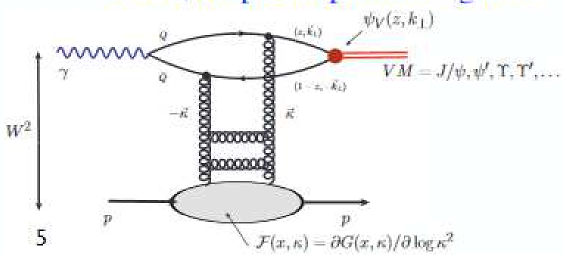


Couples to photons



Photon-induced

C-odd, couples to photons + gluons



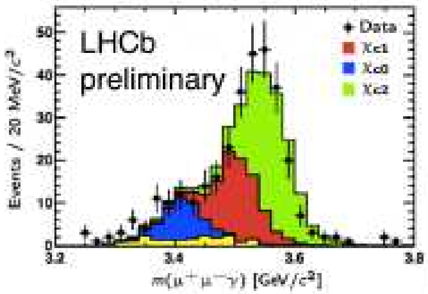
Photoproduction

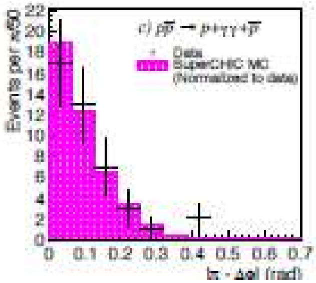
5

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

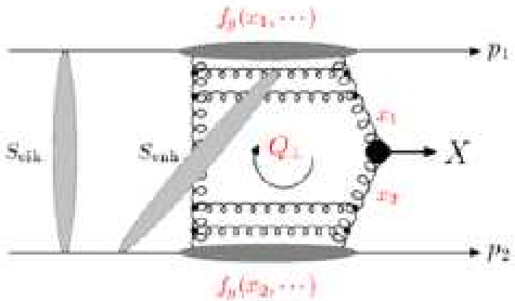
- Code and user manual available on Hepforge:

`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 found 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

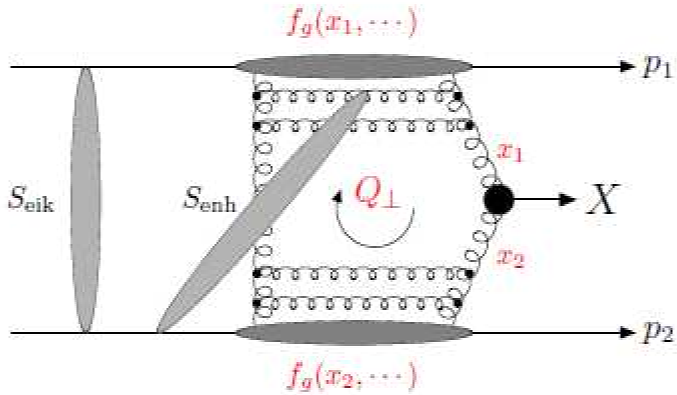
Lucian Harland-Lang (l.harland-lang@ucl.ac.uk)

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 - $\pi\pi, \eta(')\eta('), KK, \phi\phi$
- 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.

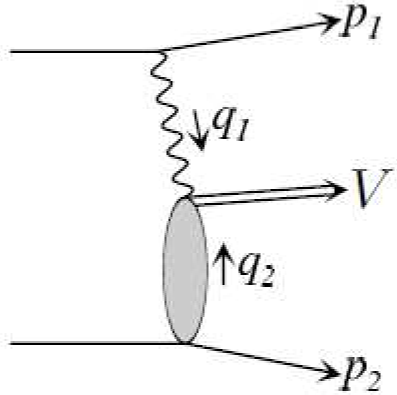
LHL, V.A. Khoze, M. G. Ryskin.
Int.J.Mod.Phys. A29 (2014) 1430031



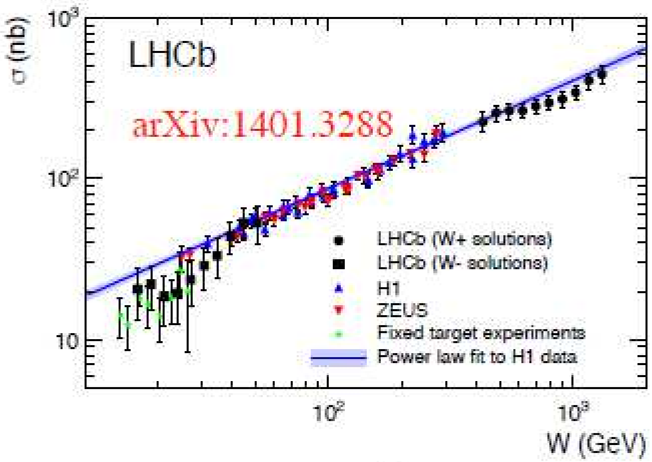
Photoproduction

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

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

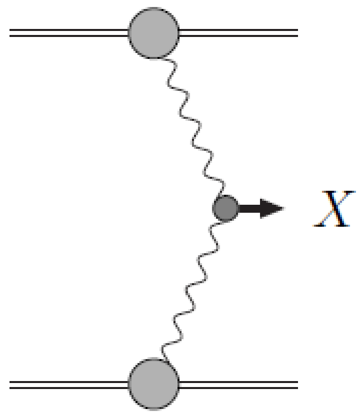


- Takes simple power-law fit to HERA/LHC data.



Photon-induced production

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



Updates

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

  all implemented and available on request.

- Work ongoing to include ultra-peripheral heavy ions.

- 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

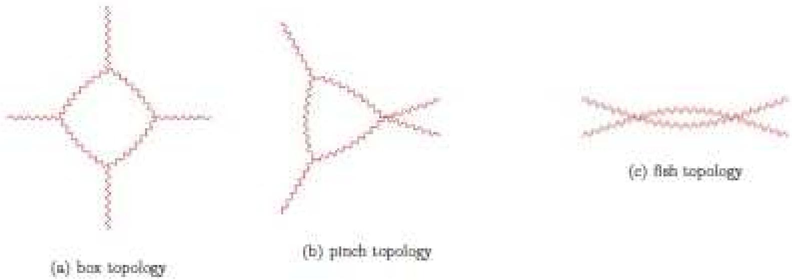


Figure 2: $\gamma\gamma \to \gamma\gamma$ process EW diagrams

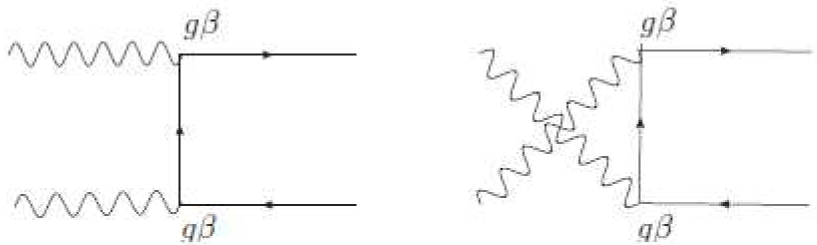
D. Bardin et al, Phys. Atom. Nucl. 73 (2010) 1878-1888

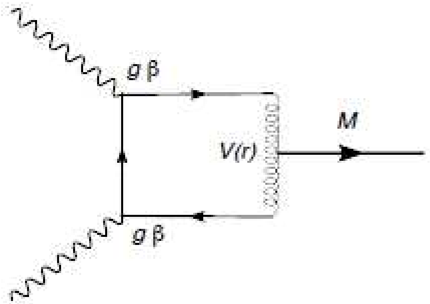
Monopoles/monopolium

- 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 $M\overline{M}$ bound state - monopolium.



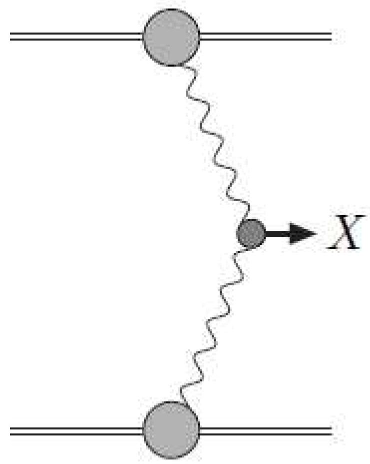


T. Dougall and S. D. Wick, Eur.Phys.J. A39 (2009) 213-217
L. N. Epele et al., Eur.Phys.J C62 (2009) 587-592

Soft survival factor

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

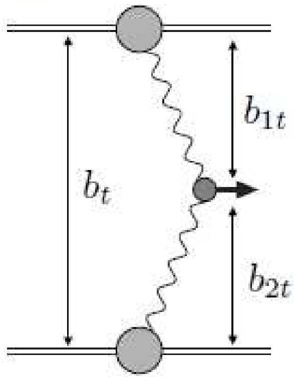
$$\frac{\mathrm{d}\sigma^{pp\to pXp}}{\mathrm{d}M_X^2\,\mathrm{d}y_X} \sim \frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2\,\mathrm{d}y_X}\hat{\sigma}(\gamma\gamma\to X)$$



• 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:



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

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

↑ proton opacity

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

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

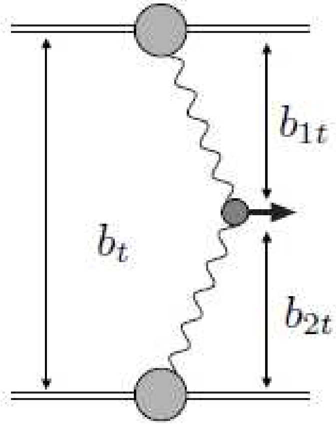
V.A. Khoze, A.D. Martin, M.G. Ryskin, arXiv:1306.2149

Well established in the QCD-mediated processes, e.g. CDF-diffractive dijets (2000), CMS/ATLAS- dijets in events with LRG (2013/2015),H1 –diffractive dijet photoproduction (2011).

• 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:

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

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

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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 $p_\perp$.

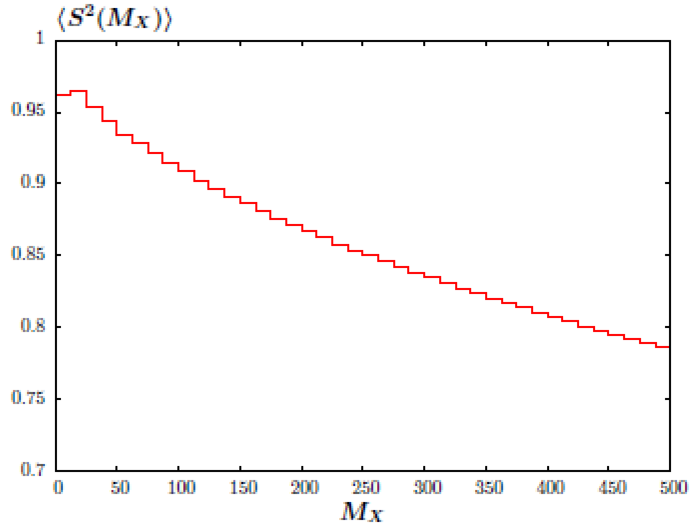
- Higher $p_\perp \Rightarrow$ lower $b_\perp \Rightarrow$ smaller S^2.

- Result from SuperChic:

Muon pair production

$M_X = M_{ll}$

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

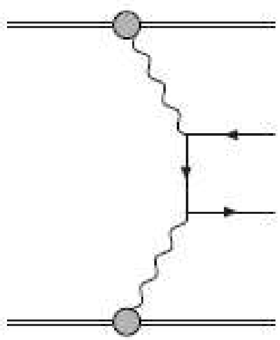


Kinematic dependence

- 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)

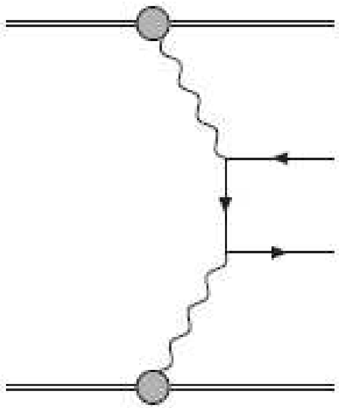
Submitted to: Phys. Lett. B.

CERN-PH-EP-2015-134
18th August 2015

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

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

Comparison to ATLAS

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

- Find:

	$\mu^+\mu^-$	e^+e^-
σ_{EPA}	0.768	0.479
$\sigma_{\text{EPA}} \cdot \langle S^2 \rangle$	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.

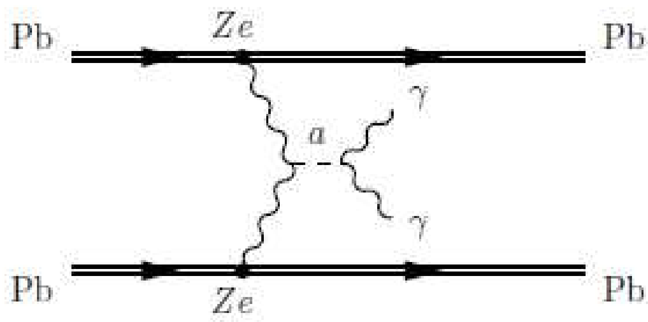
New processes

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

- 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!

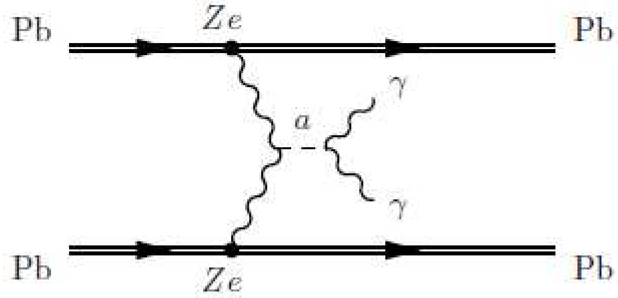
- One example currently working on: axion-like particles.



Axion-like particles

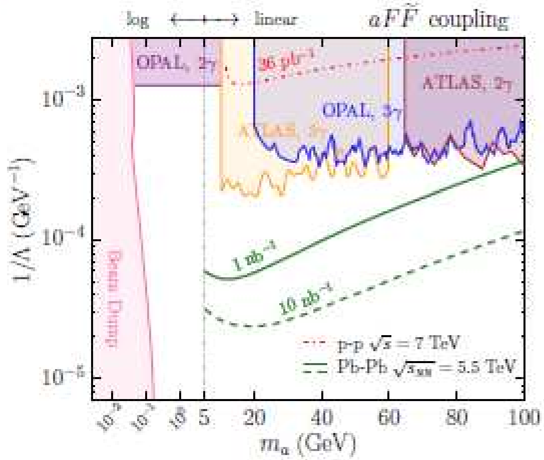
- The $\gamma\gamma \to \gamma\gamma$ transition in CEP can be sensitive to Axion like particles. S. Knapen et al., Phys. Rev. Lett. 118 (2017) no.17, 171801
- Discussed in Kapen et al. (1607.06083) - find that in heavy ion collisions can set the strongest limits yet on these couplings.
- Lagrangian:

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



gives simple production amplitudes:

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



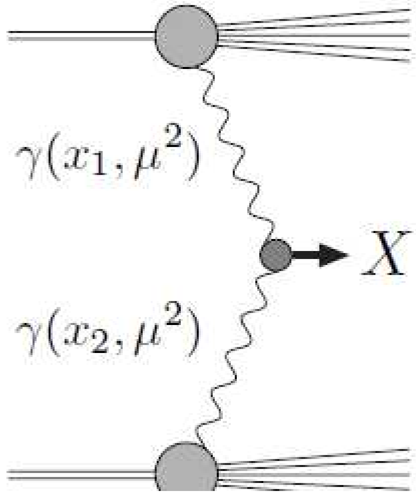
- Implementation, including full decay kinematics, will be included in next release.

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



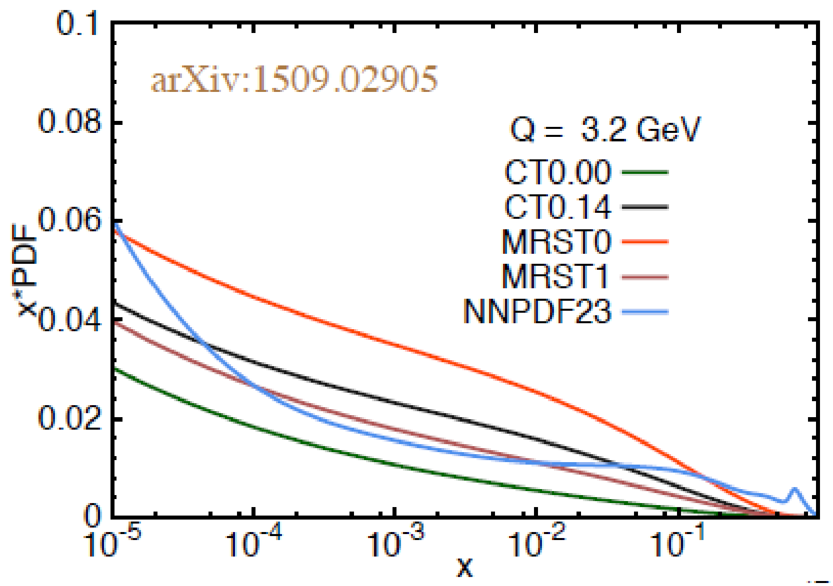
- Earlier photon PDF sets either:

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.



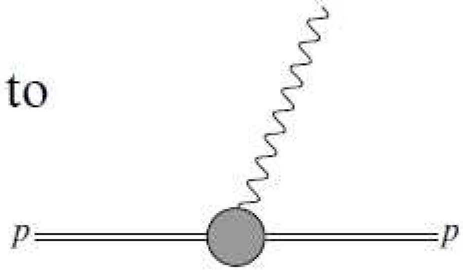
- Comparing these different sets reveals apparently large uncertainties.

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

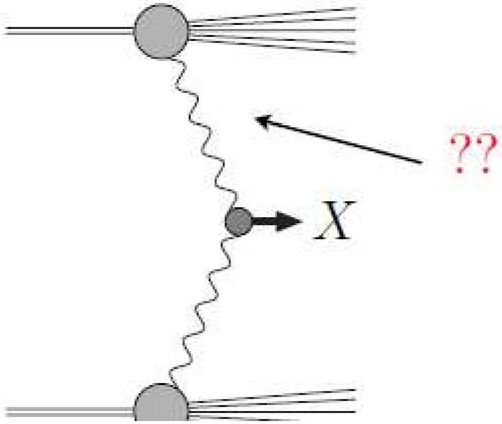
PDFs and QED

• 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:



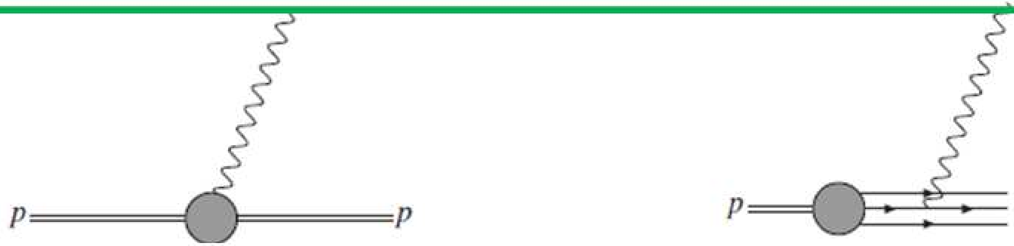
Photon distribution inside the proton (photon PDF)

HKR arXiv:1601.03372, 1601.07187, 1607.4635

- Crucial point:
  - At low $Q^2 \lesssim 1\,\text{GeV}^2$: photon is dominantly generated by well understood coherent emission ($p \to p\gamma$).
  - At high $Q^2 \gtrsim 1\,\text{GeV}^2$: 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.



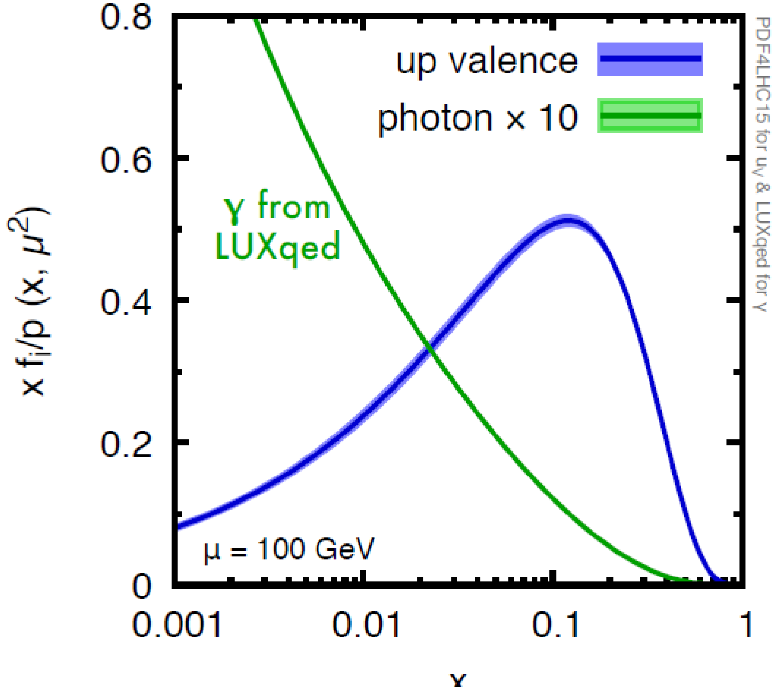
Including dominant elastic component strongly reduces the PDF uncertainty- almost sufficient for the LHC pheno purposes

MNSZ, PRL 117,242002 (2016), 1708.01256.
LUXqed-photon PDF determined in terms of **measured** EM proton structure functions F2 and FL.

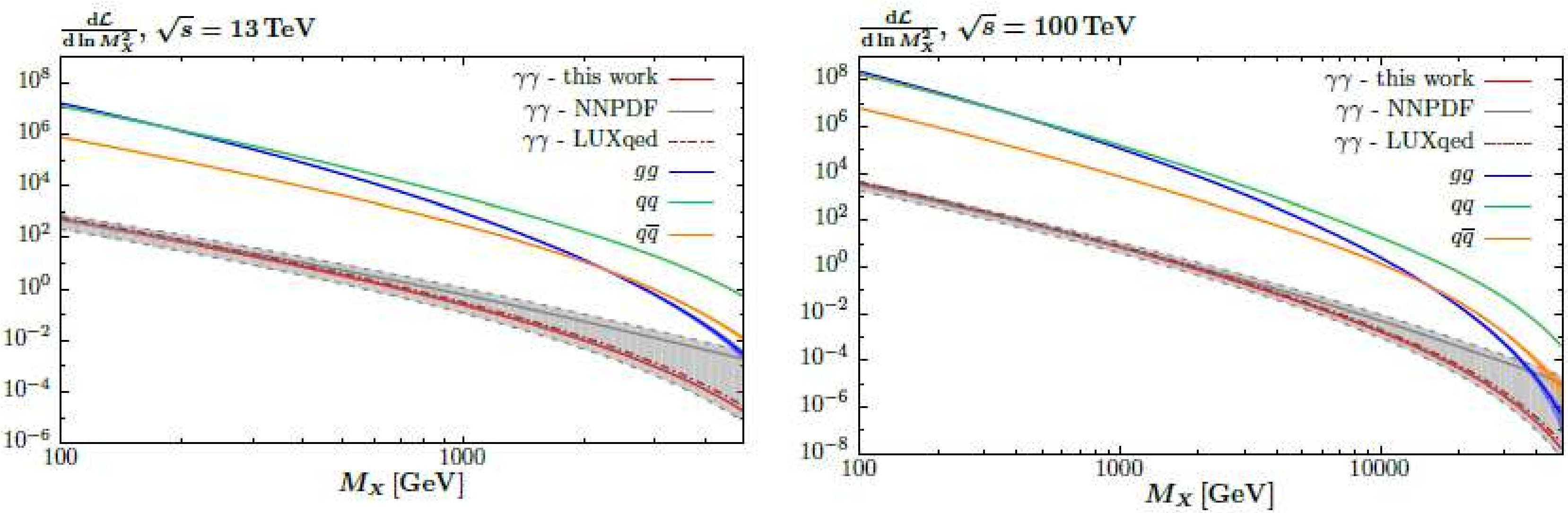
photon PDF results

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

Currently the most precise calculation when considering **inclusive** production processes



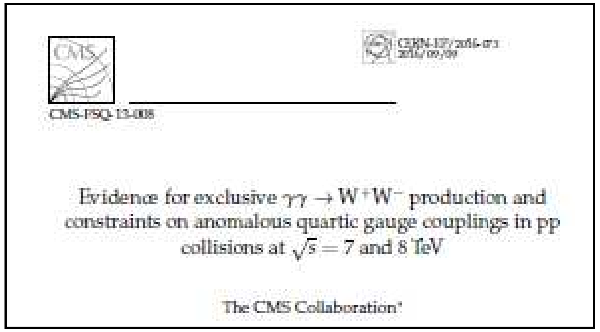
Comparison with LUXqed



- 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..)

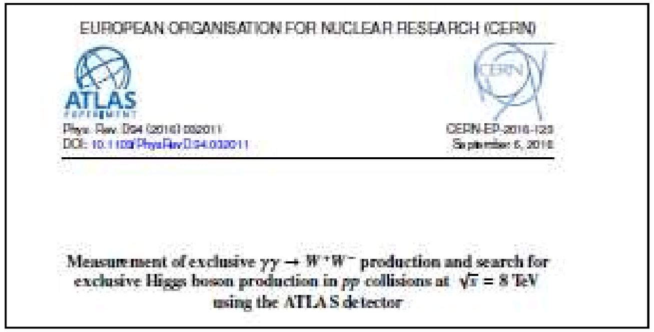


CERN-EP/2016-073
2016/09/09

CMS-FSQ-13-008

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

The CMS Collaboration*



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

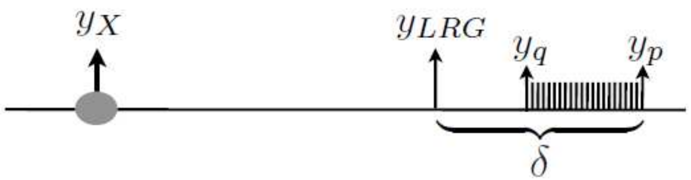
Phys. Rev. D94 (2016) 032011
DOI: 10.1103/PhysRevD.94.032011

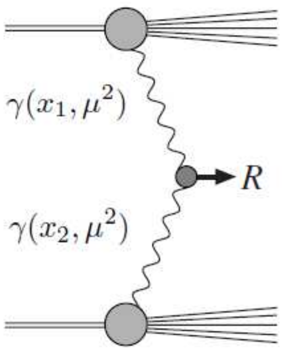
CERN-EP-2016-123
September 6, 2016

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

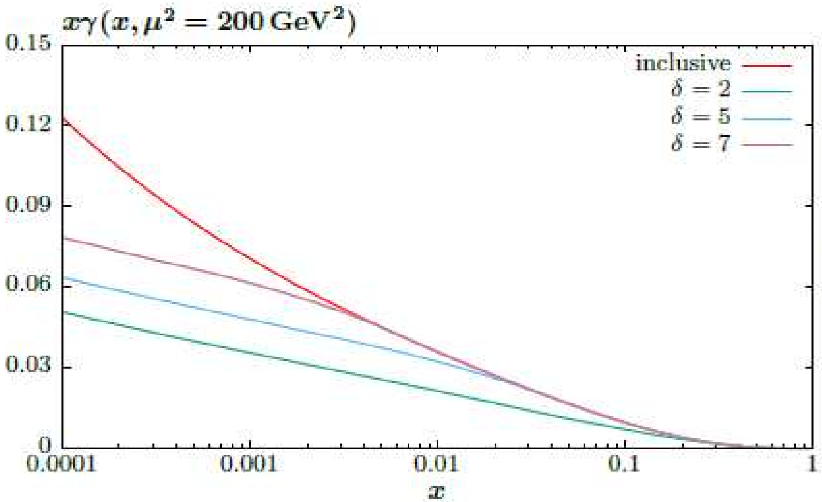
- Semi-exclusive processes with rapidity gaps: how do we include a rapidity veto within the standard inclusive approach?
- Comparison to CMS 7 and 8 TeV $\mu^+\mu^-$ data.

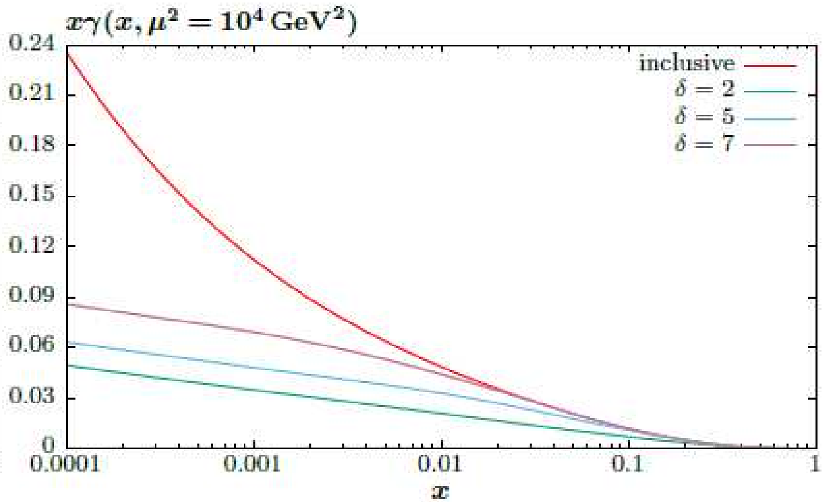
HKR arXiv:1601.03772





Modified photon PDF



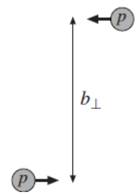


Suppression due to LRG veto.

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

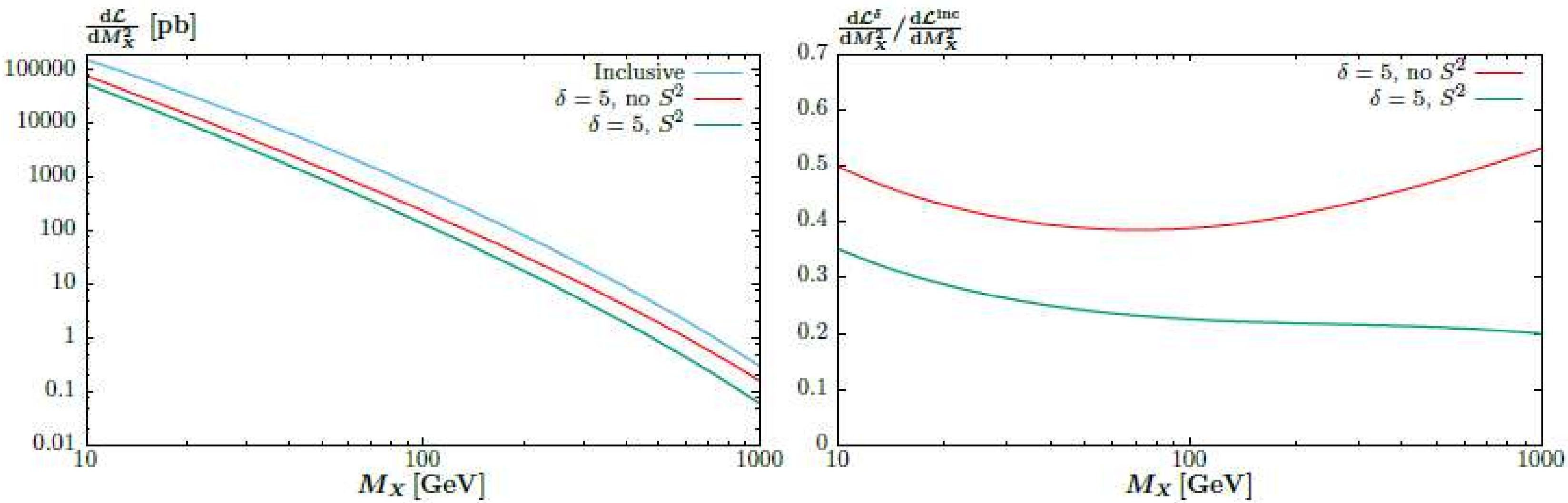
phenomenological objects only-factorization explicitly violated by rescattering effects

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



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

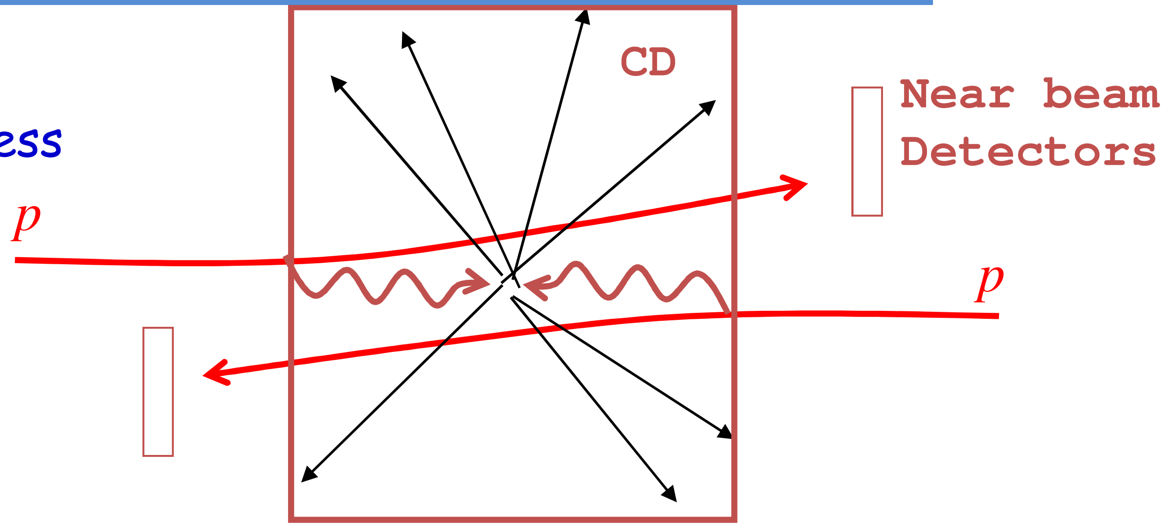
• Instead have effective $\gamma\gamma$ luminosity: $\dfrac{{\rm d}\mathcal{L}}{{\rm d}M_X^2} = \dfrac{1}{s}\displaystyle\int_\tau^1 \dfrac{{\rm d}x_1}{x_1}\gamma(x_1,M_X^2)\gamma(\tau/x_1,M_X^2)$



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

γγ collisions- applications

Process



Installed (AFP)
Installed (CT-PPS)
projects

Extensive Program

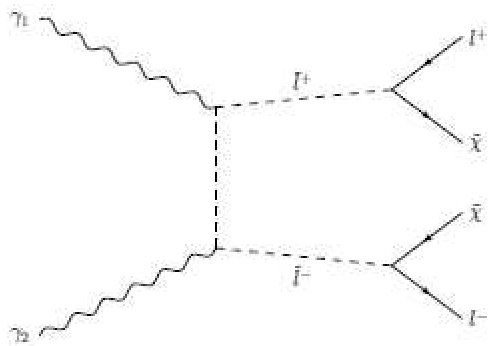
- γ γ→ μμ, ee QED processes
- γ γ→ QCD (jets..)
- γ γ→ WW anomalous couplings
- γ γ→ squark, top… pairs
- γ γ→ Charginos (natural SUSY)
- New BSM objects

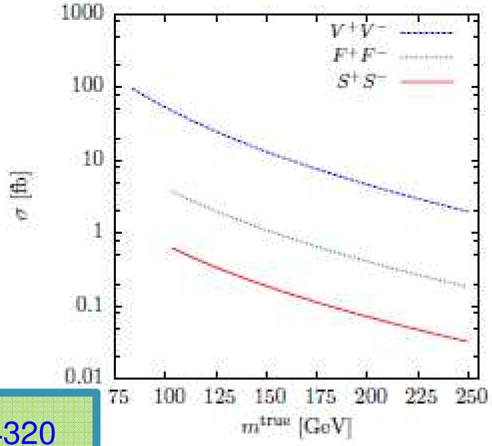
$$pp \to p + \gamma\gamma + p\,,$$
$$\gamma\gamma \to X^+X^-\,,$$

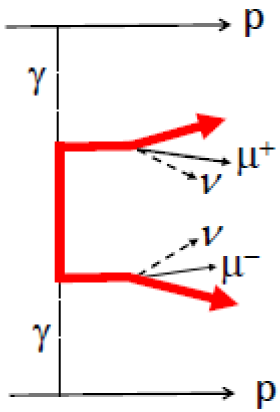
Diphoton X-Pair Production

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**) arXiv:1710.02406

Radiatively –driven natural SUSY existence of light nearly mass-degenerate Higgsinos
Mass~ 100-200GeV,
mass splitting ~ 4-20 GeV

Naturalness and light Higgsinos: why ILC is the right machine for SUSY discovery

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Keisuke Fujii, Ja
KEK, T

Tokyo, Japan E-mail:

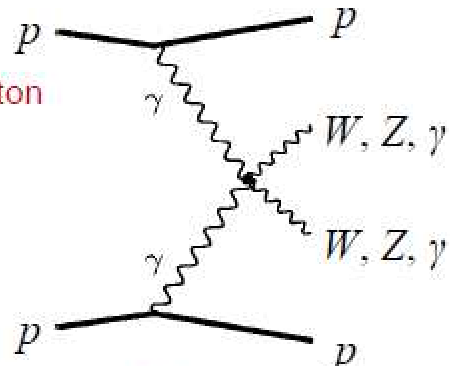
We can try to do this at the LHC during our lifetime

...oretically and experimentally well-motivated ...ed existence of four light, nearly mass-degenerate Hig-... 00 GeV (not too far above m_Z). The small mass splittings amongst ..., typically 4-20 GeV, results in very little visible energy arising from decays of the heavier higgsinos. Given that other SUSY particles are considerably heavy, this makes detection challenging at hadron colliders. On the other hand, the clean environment of an electron-positron collider with $\sqrt{s} > 2m_{higgsino}$ would enable a decisive search of these required higgsinos, and thus either the discovery or exclusion of natural SUSY. We present a detailed simulation study of precision measurements of higgsino masses and production cross sections at $\sqrt{s}$ = 500 GeV of the proposed International Linear Collider currently under consideration for construction in Japan.

$$e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^- \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0 q\bar{q}' e\nu_e(\mu\nu_\mu).$$

Anomalous Gauge Quartic Couplings

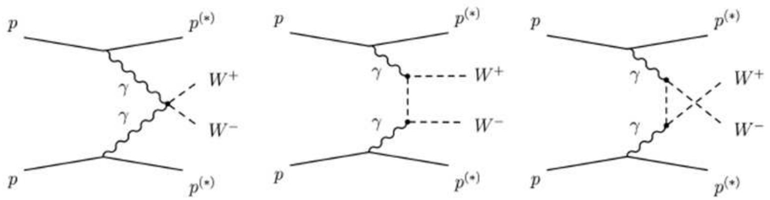
- Low Cross sections: ~few fb
  - AFP has a Missing-Mass resolution (from the proton measurements) of 2-4 %
- Match with invariant central object mass is efficient: ($Z \to ee$, $\gamma\gamma$)
  - powerful rejection of non-exclusive backgrounds
- Much interest in this from theory side
  - e.g. "LHC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

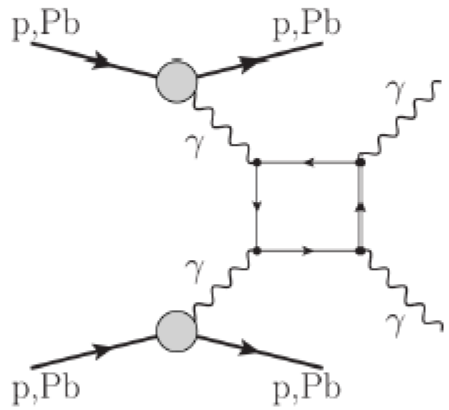
Currently very encouraging ATLAS & CMS data

Light-by-light scattering in Pb+Pb

- **Motivation**

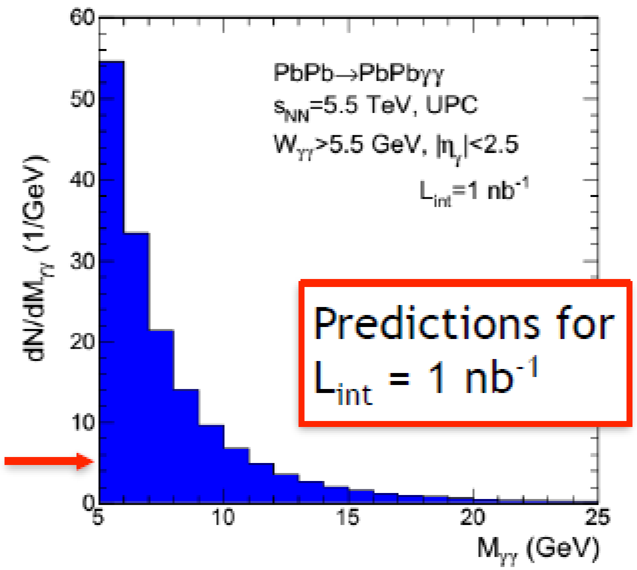
[Nature Physics (2017)]

- Light-by-light ($\gamma\gamma \to \gamma\gamma$) scattering
  - Tested indirectly in measurements of the anomalous magnetic moment of the electron and muon
  - Previous LbyL measurements involve Delbruck scattering and photon splitting process at low-energies



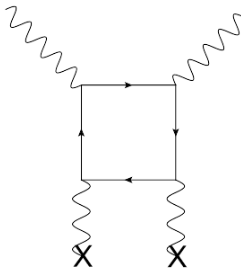
- Proposed as a possible channel to study
  - Anomalous gauge couplings
  - Contributions from BSM particles

- Recent studies/predictions for SM rates
  - [**D. d'Enterria et al.** PRL 111 (2013) 080405]
  - [**A. Szczurek et al.** PRC 93 (2016) 4, 044907]



Long and chequered history

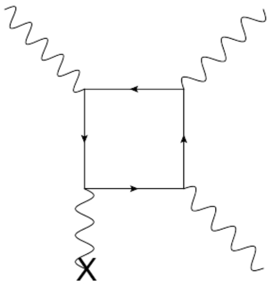
(nonlinear effects of QED)



Delbrück **1933**

Delbrück scattering

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.



Photon splitting in atomic Coulomb field

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.

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

(ArXiv:1702.01625)

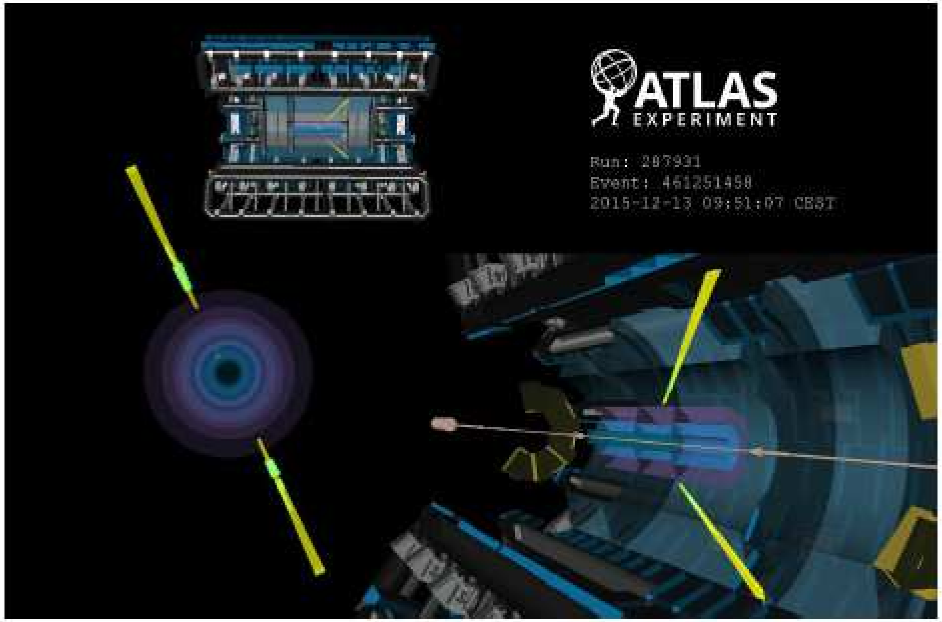
Search for light-by-light scattering
[arXiv:1702.01625]

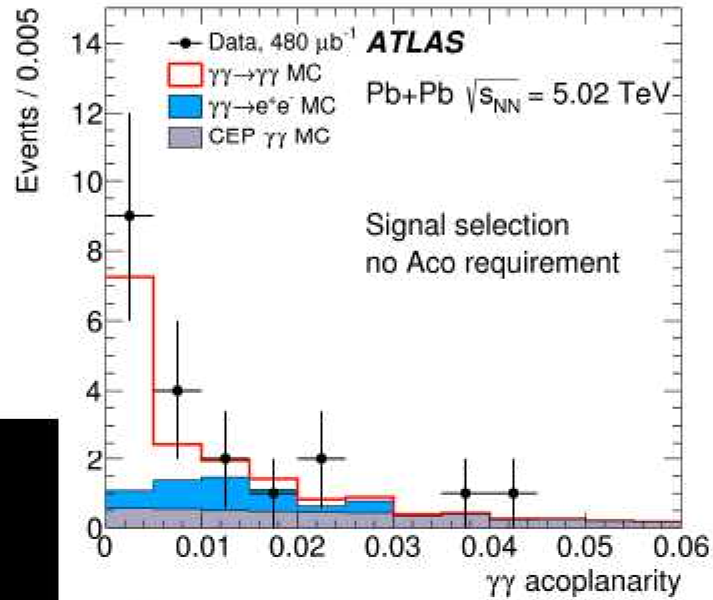
ATLAS @ $\sqrt{s_{NN}}$ = 5.02 TeV:

13 events (bkgd 2.6) ⇒ 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

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

arXiv:1703.08450v1 [hep-ph] 24 Mar 2017

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

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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.

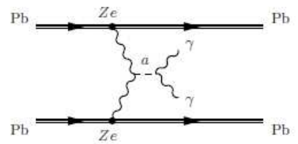
LHC limits on axion-like particles from heavy-ion collisions

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

ArXiv:1709.07110

J. Jaeckel and M. Spannowsky, "Probing MeV to 90 GeV axion-like particles with LEP and LHC," *Phys. Lett.* **B753** (2016) 482–487, arXiv:1509.00476 [hep-ph].

J. Jaeckel, M. Jankowiak, and M. Spannowsky, "LHC probes the hidden sector," *Phys. Dark Univ.* **2** (2013) 111–117, arXiv:1212.3620 [hep-ph].



l: Exclusive ALP production in ultra-peripheral Pb-Pb co

$$7\,\mathrm{GeV} < m_a < 100\,\mathrm{GeV},$$

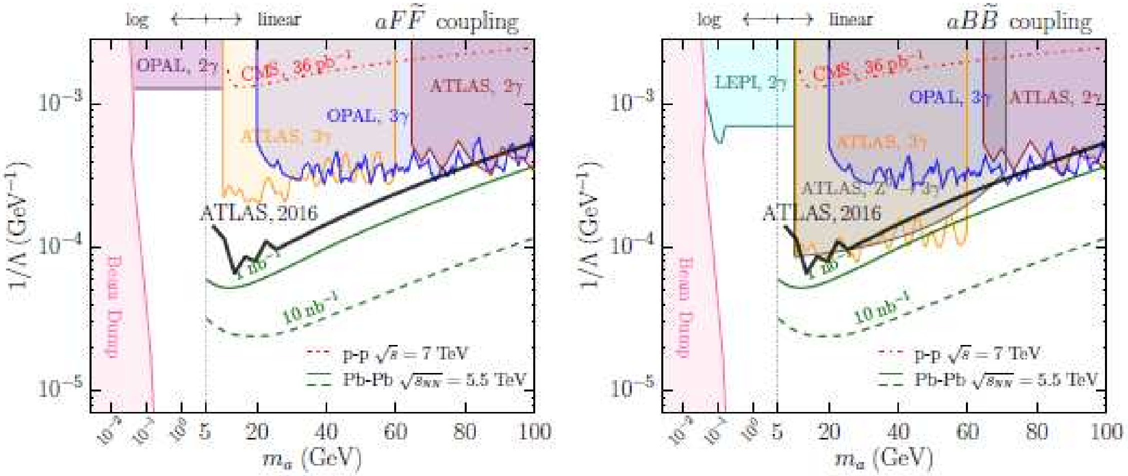


Fig. 2: *Left:* We show 95% exclusion limits on the operator $\frac{1}{4}\frac{1}{\Lambda}aF\tilde{F}$ using recent ATLAS results on heavy-ion UPCs [2] (solid black line). The expected sensitivity assuming a luminosity of 1 nb^{-1} (10 nb^{-1}) is shown in solid (dashed) green. For comparison, we also give the analogous limit from 36 pb^{-1} of exclusive p-p collisions [17] (red dot-dash). Remaining exclusion limits are recast from LEP II (OPAL 2γ, 3γ) [22] and from the LHC (ATLAS 2γ, 3γ) [23, 24] (see [1] for details). *Right*: The corresponding results for the operator $\frac{1}{4\cos^2\theta_W}\frac{1}{\Lambda}aB\tilde{B}$. The LEP I, 2γ (teal shaded) limit was obtained from [14].

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

Cross sections

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

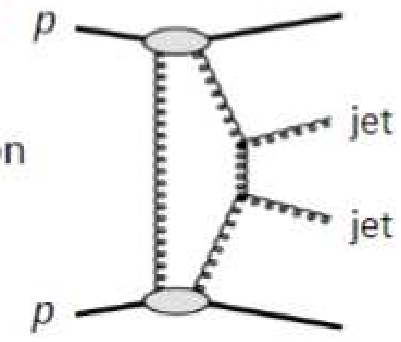
For $\mathcal{L}_{\rm int} = 300\,\mathrm{fb}^{-1}$, the number of expected events are

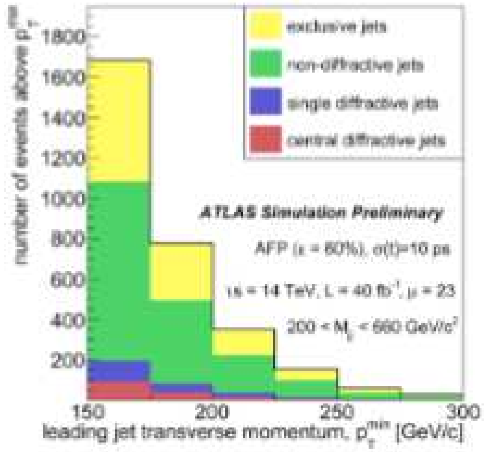
$$N(\tilde{\chi}_1^+\tilde{\chi}_1^-) \simeq 180,$$
$$N(W^+W^-) = 32550,$$

Physics with AFP 2+2 (high μ)

Central Exclusive Jet Production

First observed by CFD@Tevatron
Low σ → high pile-up run
→ double tag
→ ToF to control bkg

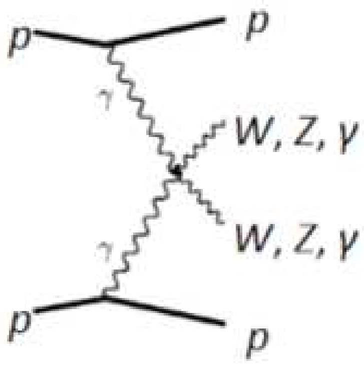


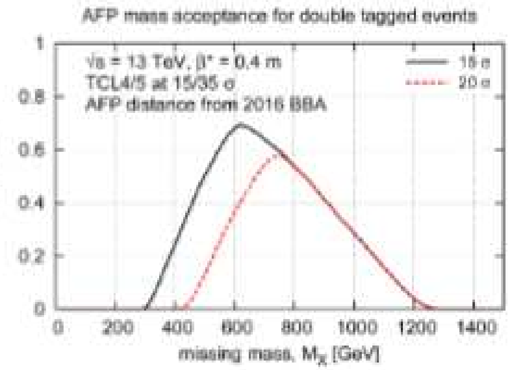


Photon-induced WW/ZZ/γγ Production

Best sensitivity to aQGC (few % missing mass resolution): factor 100 better than "standard" LHC analyses (sensitivity to higgless models, extra dimensions)

Compare mass and rapidity of central and pp systems





New Particles?

Dileptons good for calibration

The (foreseeable) future

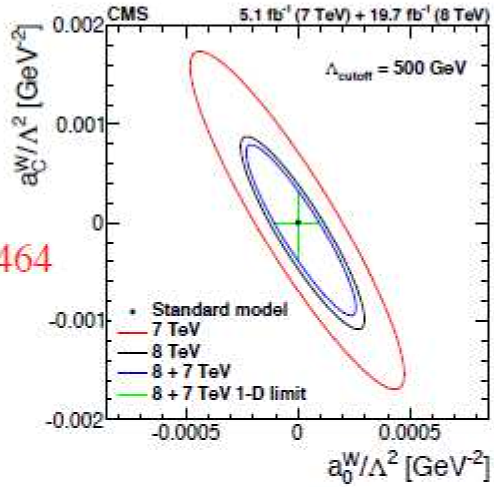
- **Run III** (2020-2022)
  - Run with possibly improved detector (luminosity in standard runs increased mostly by leveling)
- **HL-LHC** (2025 and beyond)
  - Available space/optics?
  - Detector at 420 m for exclusive Higgs (defined spin-parity state) and H→bb (couplings)?
  - $\gamma\gamma \rightarrow WW/ZZ/\gamma\gamma$ and new high-mass resonances
  - ...

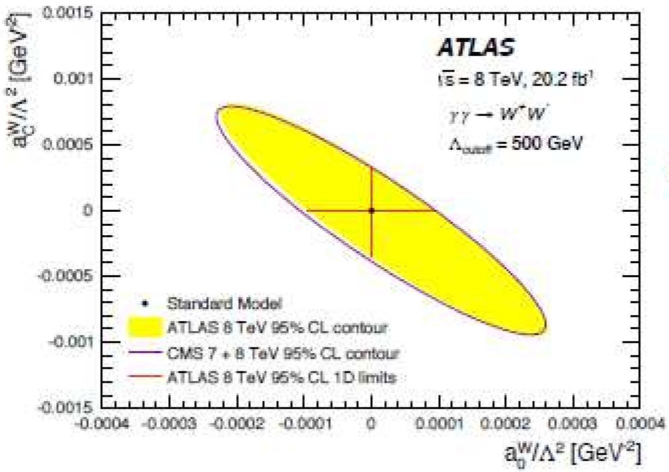
Research Program will depend on LHC strategy and Previous Results

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.