ФЕДЕРАЛЬНОЕ ГОСУДАРСТВЕННОЕ БЮДЖЕТНОЕ УЧРЕЖДЕНИЕ
«ПЕТЕРБУРГСКИЙ ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ ИМ. Б.П. КОНСТАНТИНОВА
НАЦИОНАЛЬНОГО ИССЛЕДОВАТЕЛЬСКОГО ЦЕНТРА «КУРЧАТОВСКИЙ ИНСТИТУТ»

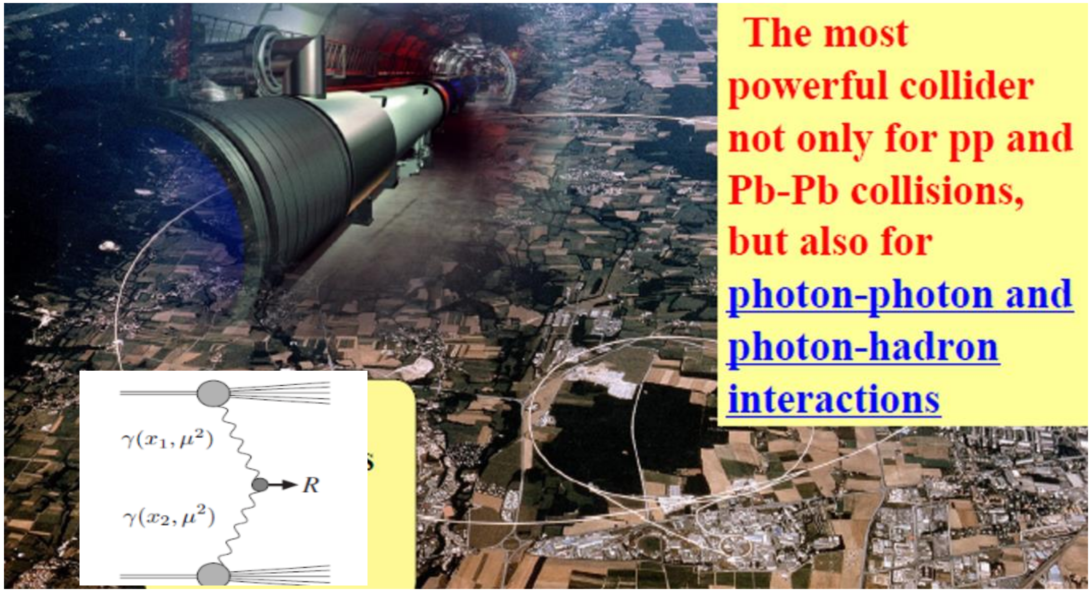
Семинары ОФВЭ

ОТДЕЛЕНИЕ ФИЗИКИ ВЫСОКИХ ЭНЕРГИЙ (СЕМИНАРЫ ОФВЭ - переход на английскую версию)

PHOTON-PHOTON COLLISIONS AT THE LHC
(selected topics)

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

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



The most powerful collider not only for pp and Pb-Pb collisions, but also for photon-photon and photon-hadron interactions

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).
- Topical Examples, 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?

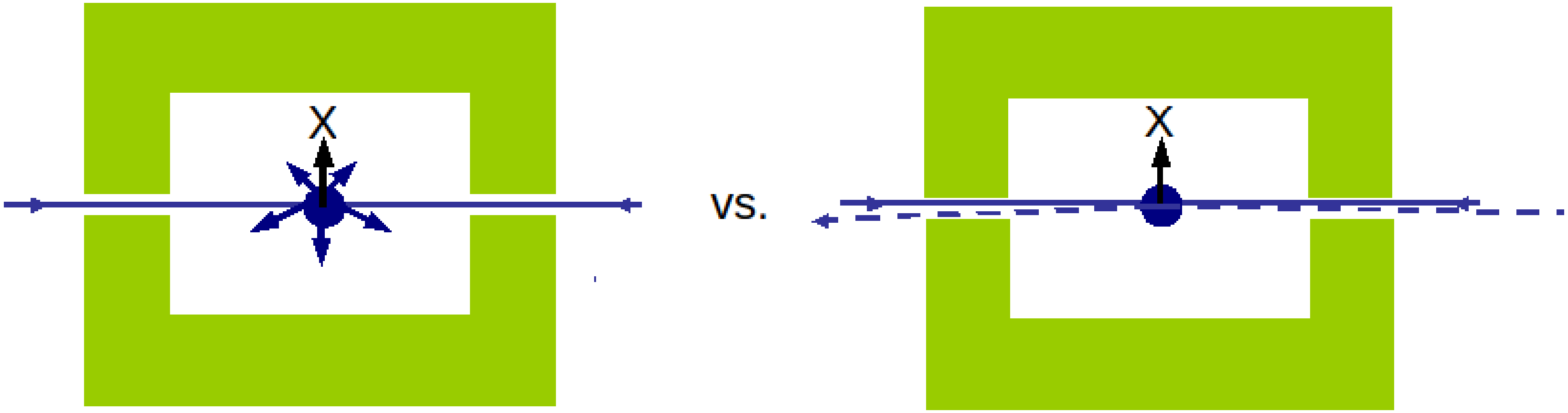
Central Exclusive Production (CEP) is the interaction:

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

- **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

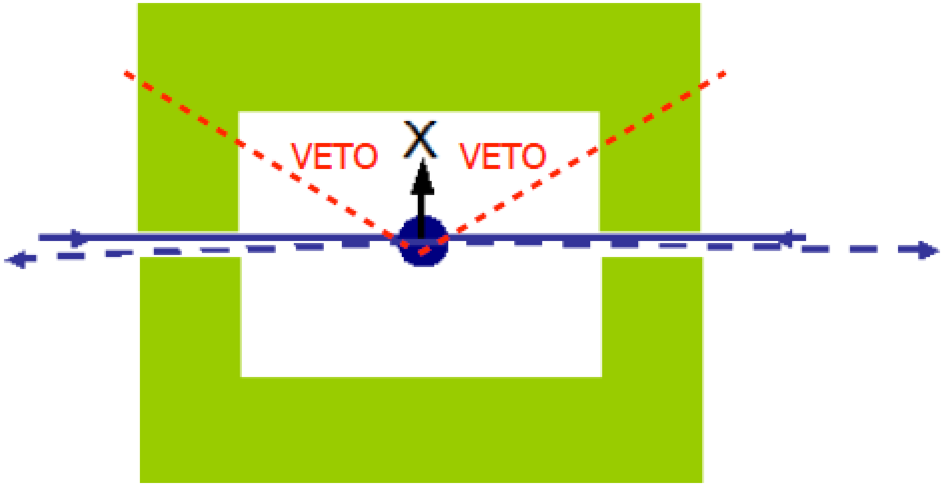
1) Gap-based selection: no extra activity in large enough rapidity region.

- 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)



PAY THE PRICE!

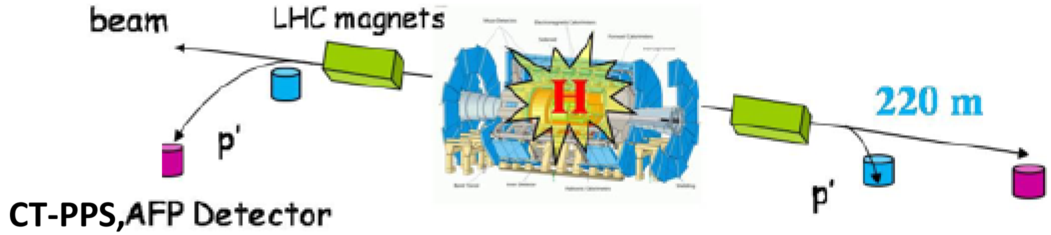
2) Proton tagging: $pp \to p + X + p$

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

  $\longrightarrow$ If we can measure the outgoing protons [illegible] purely exclusive event sa[illegible]

The LHC is best mass spectrometer

- Basic principle: us[illegible] After interaction pr[illegible] bend out of beam li[illegible]
- Ins[illegible] $O(\mathrm{mm})$ from beam line and $O(100\,\mathrm{m})$ from IP. Reconstruct momenta and measure arrival time of protons.



Physics motivations

Central Exclusive Production

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

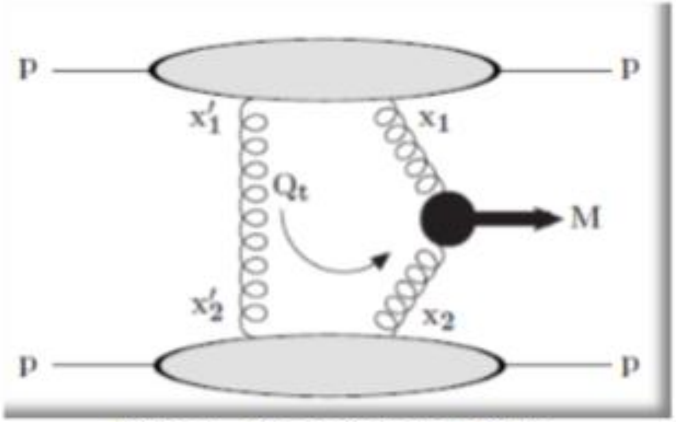
photon or Pomeron exchanges

$\oplus$ rapidity gap

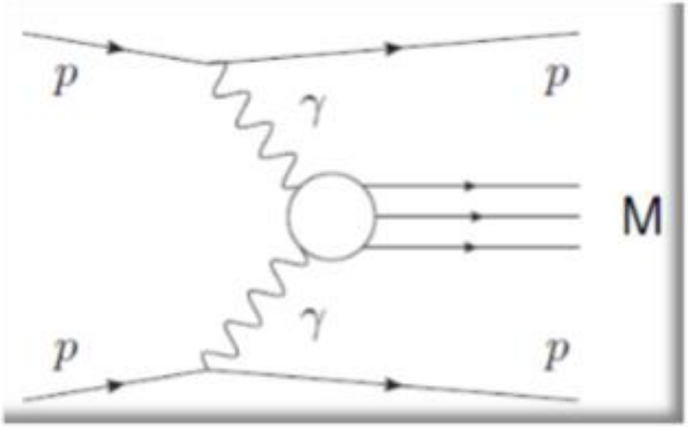
X = high-E_T jets, WW, ZZ, $\gamma\gamma$, … measured in the central detector

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.

F. Ravera - HESZ 2017

ATLAS Forward Detectors for Diffraction

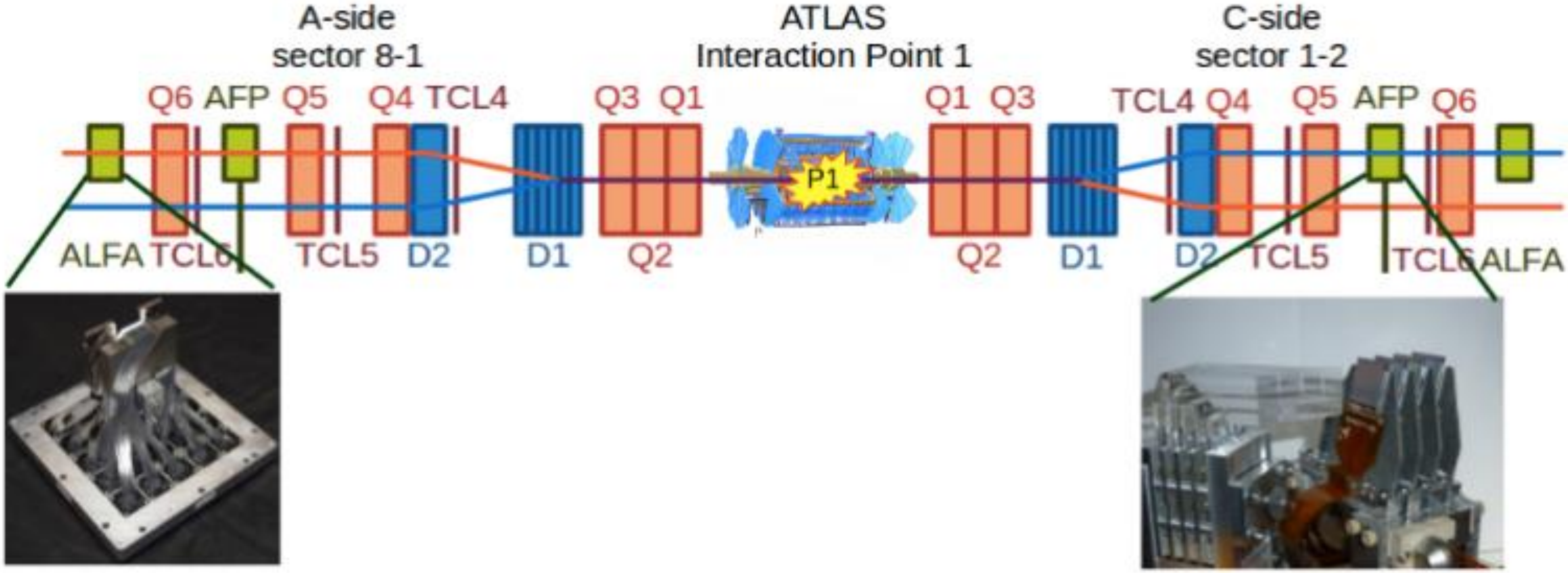
In ATLAS it is possible to **identify diffractive events** by, e.g. large rapidity gaps

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

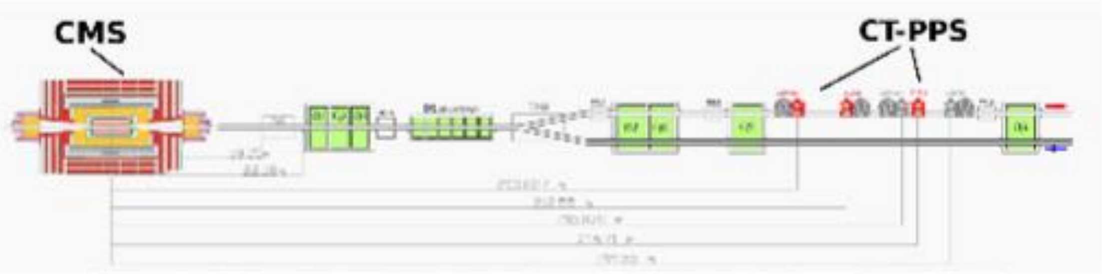
- ALFA (Absolute Luminosity For ATLAS) vertical Roman Pots
  at $z = \pm 237$ and $z = \pm 245$ m for *elastic* and *diffractive* scattering measurements
- AFP (ATLAS Forward Proton) horizontal Roman Pots
  at $z = \pm 205$ and $z = \pm 217$ m for *diffractive* scattering measurements

“NEW”

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



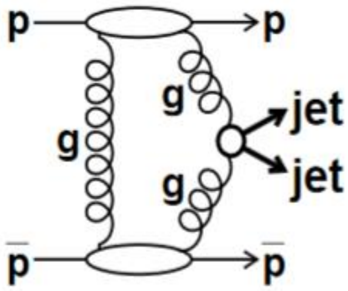
What is CT-PPS?

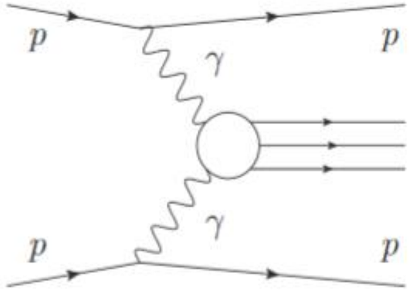


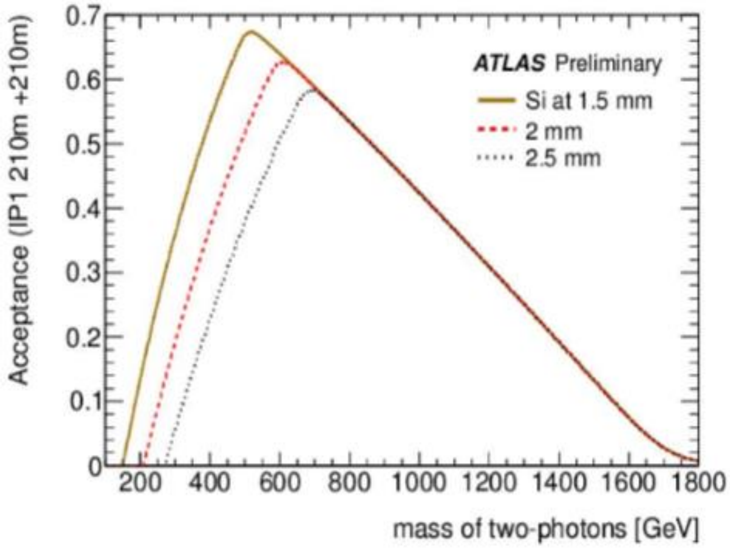
CT-PPS configuration in 2016

- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795, see Fabio's talk
- 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

“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.

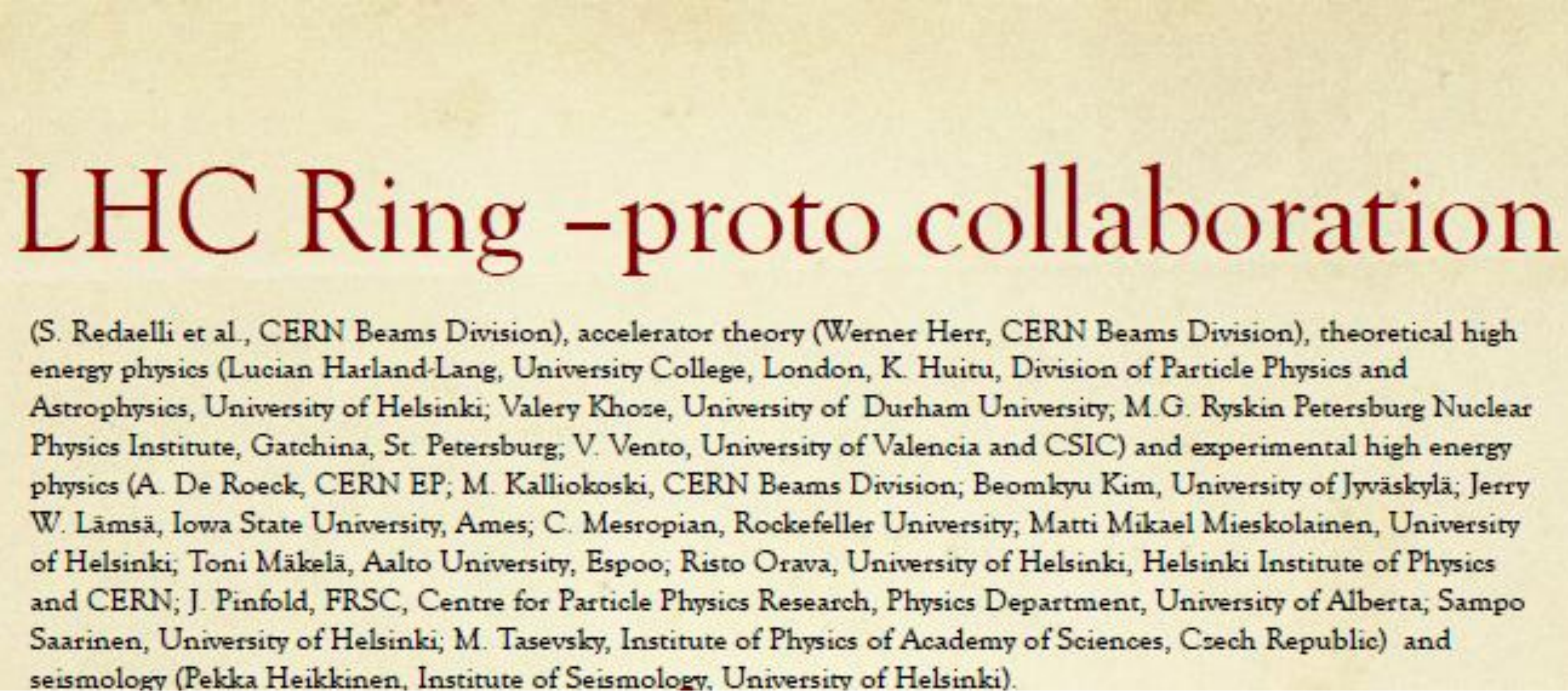
Unprecedented explosion in the number of exploratory papers.

(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.

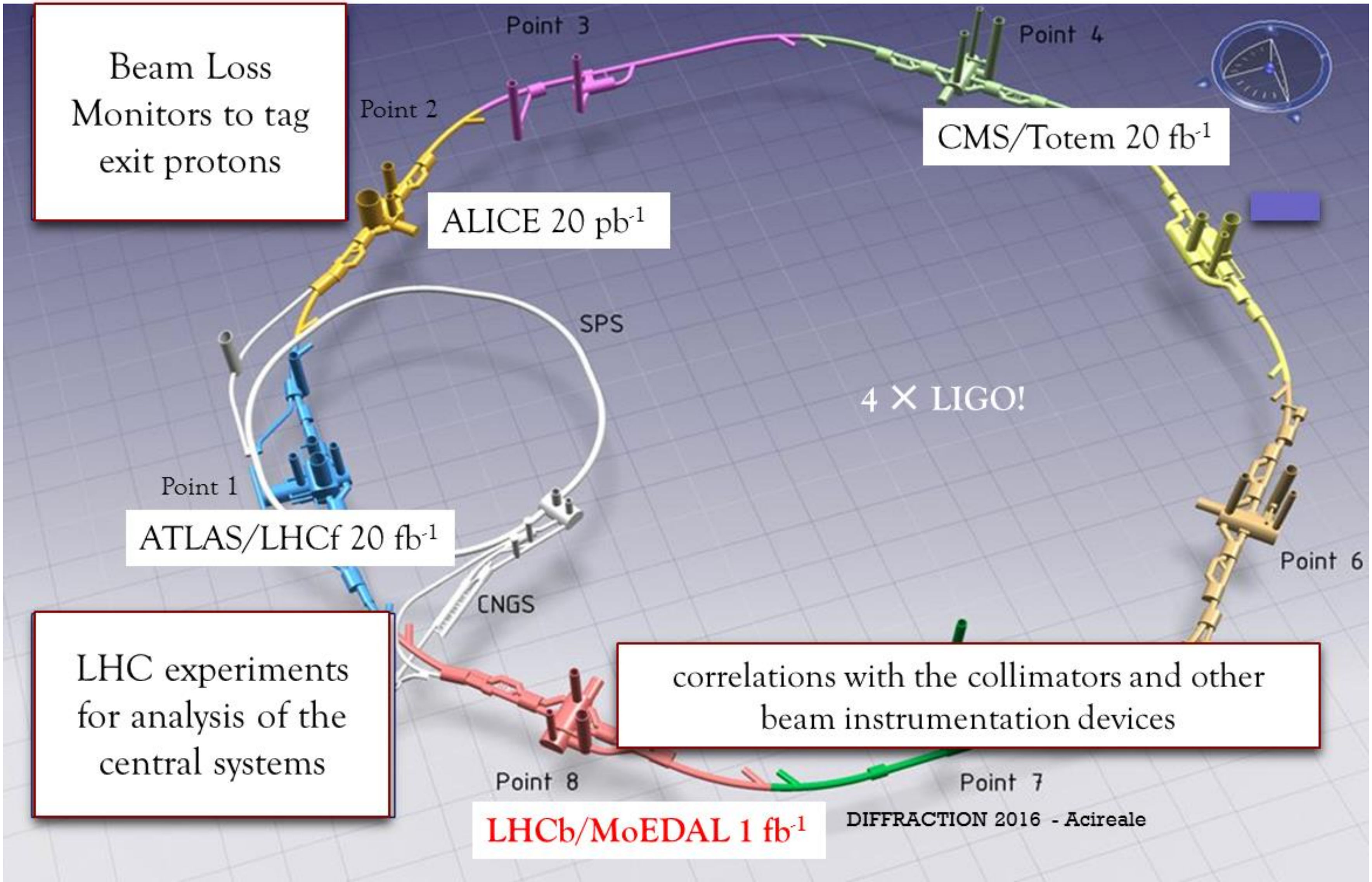
3) Turning the LHC Ring into a New Physics Search Machine



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



Beam Loss Monitors to tag exit protons

ALICE 20 pb^{-1}

CMS/Totem 20 fb^{-1}

4 × LIGO!

ATLAS/LHCf 20 fb^{-1}

LHC experiments for analysis of the central systems

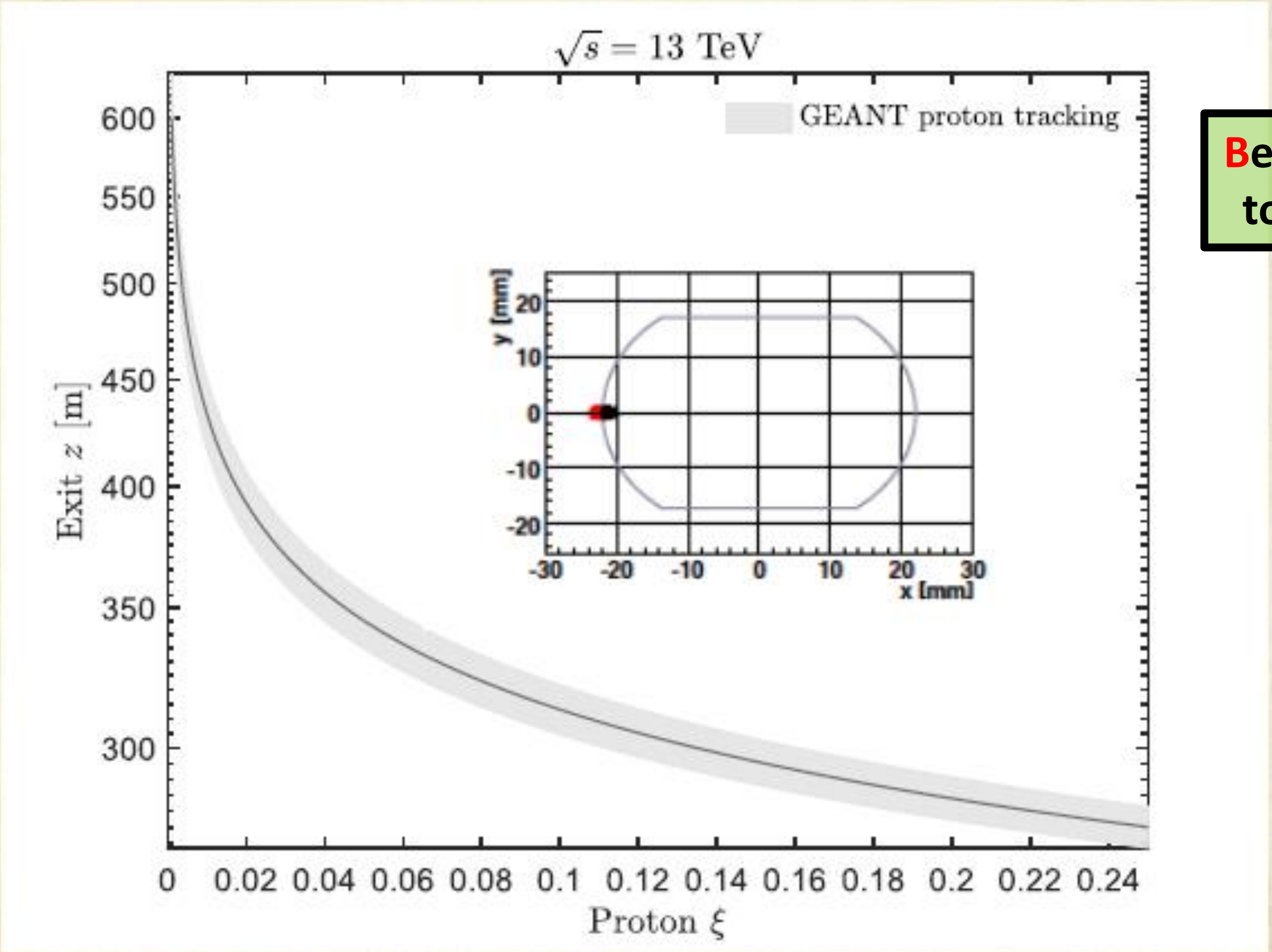
correlations with the collimators and other beam instrumentation devices

LHCb/MoEDAL 1 fb^{-1}

DIFFRACTION 2016 - Acireale

the LHC Ring represents a continuous “Roman Pot” !

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



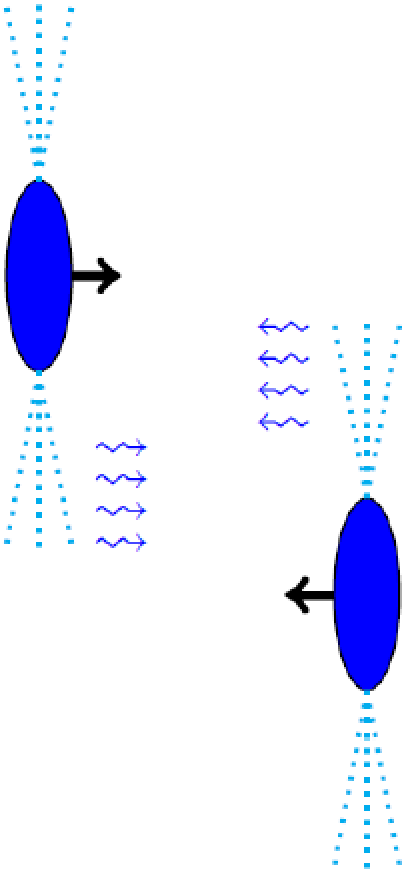
Beam Loss Monitors to tag exit protons

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)

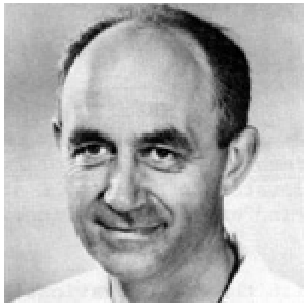
Ultra Peripheral HI Collisions



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.



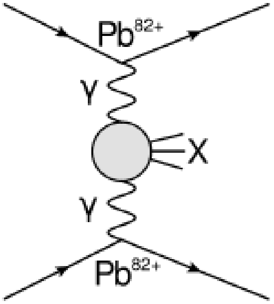
Enrico FERMI

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]

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

- 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

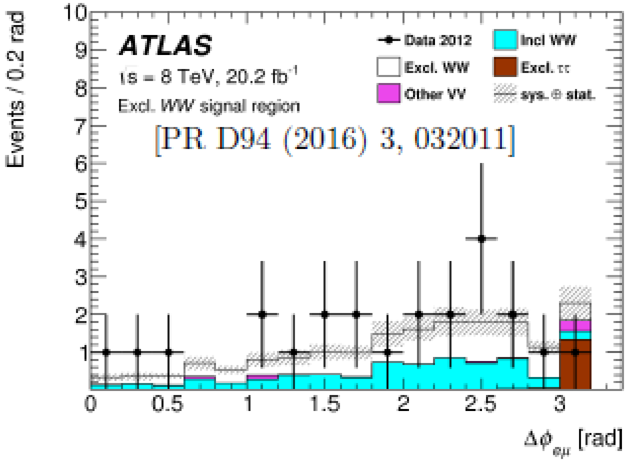
pp collisions

Pros

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



[PR D94 (2016) 3, 032011]

Pb+Pb collisions

Pros

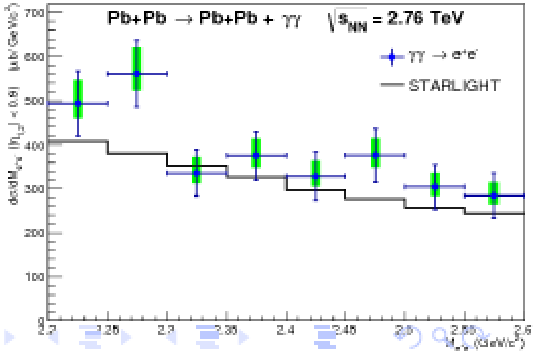
- AA ($\gamma\gamma$) x-sec $\propto Z^4$
- gluonic x-sec $\propto A^2$ $\Rightarrow$ lower QCD bkg.
- low pile-up ($< 1\%$)

$A^{1/3}$

Cons

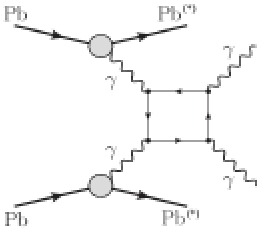
- softer EPA γ spectrum ($\omega_{\max} \sim 0.1$TeV)
- relatively small data sample

[ALICE Collaboration,EPJC 73 (2013) 2617]

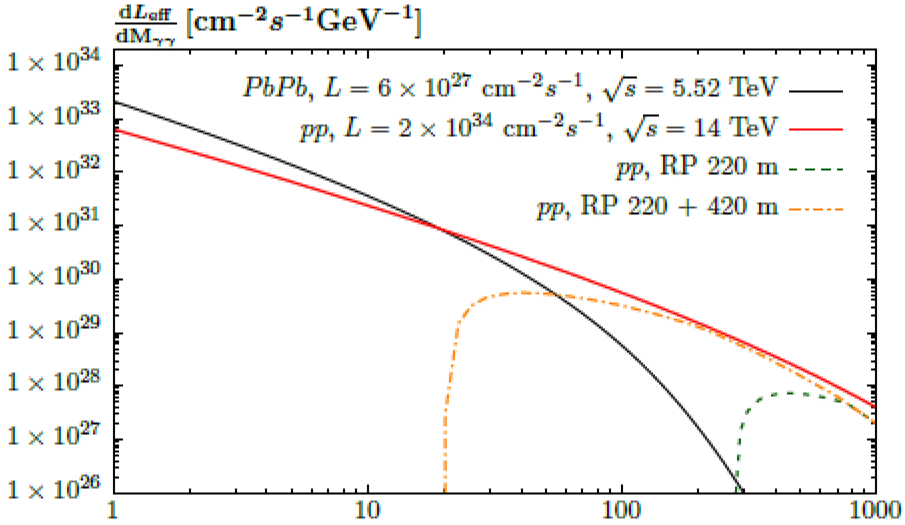


ATLAS/CMS 2016

Heavy Ion Collisions

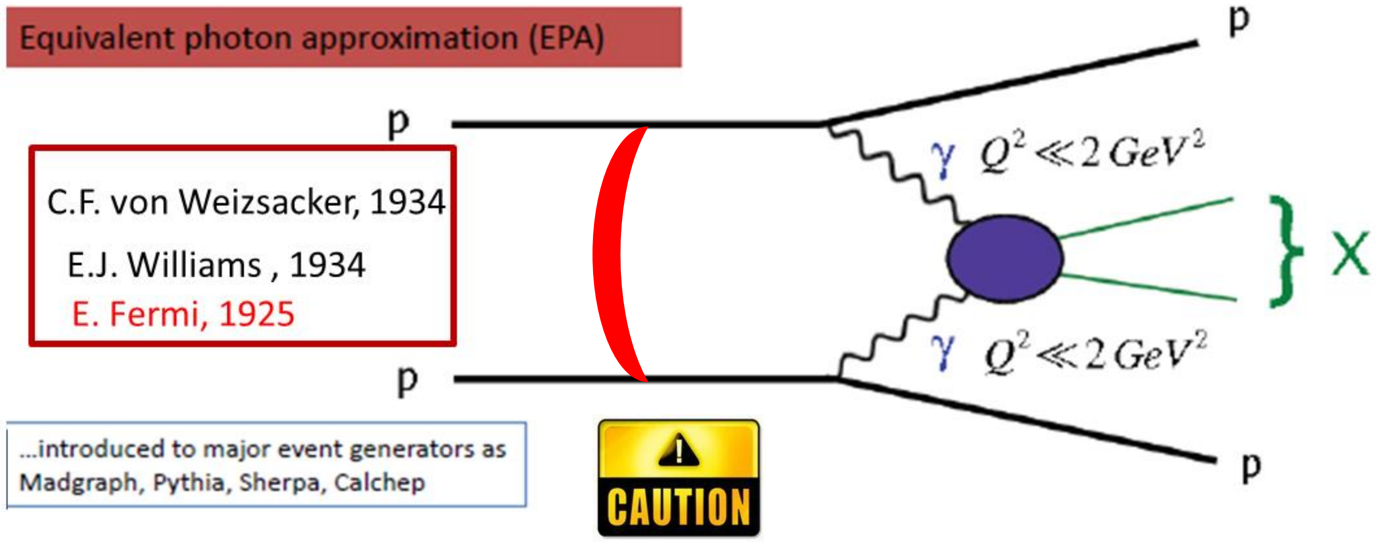


- **Photon-initiated** CEP equally possible in heavy ion collisions. Indeed in some cases has significant **advantages**:
  - Significant $\sim Z^4$ enhancement in rate. After accounting for differing luminosities, still ~ 2 relative to pp , but with no pile-up.
  - QCD-initiated production essentially absent - clear interpretation.
  - Low pile-up - can go to low $M_{\gamma\gamma}$.
  - Conversely, steep fall off at high mass - pp essential here ⇒ **complementary**.



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

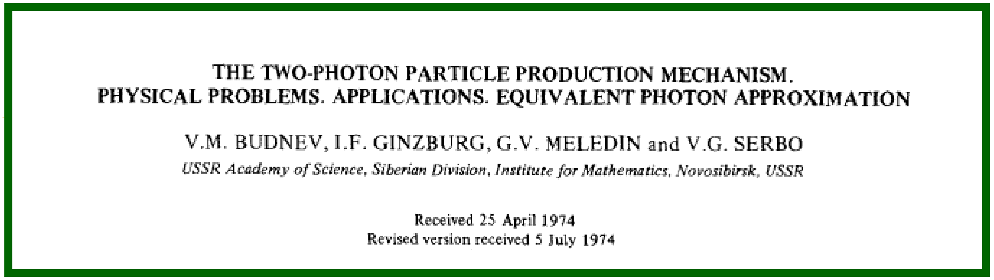
Equivalent photon approximation

- 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

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

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

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

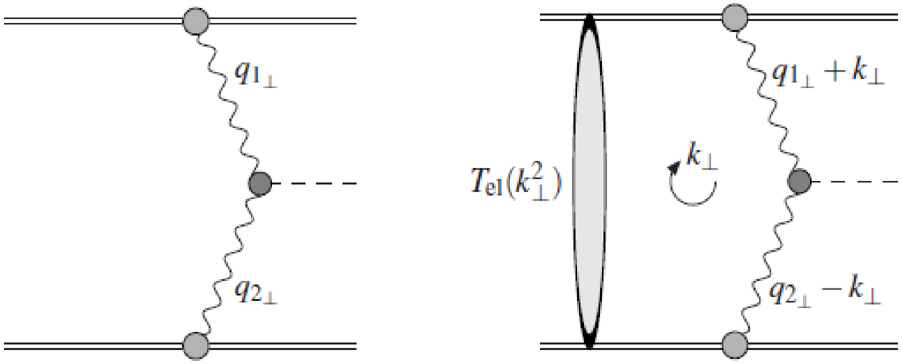
In fact, the situation is more complicated due to the effects caused by the polarization structure of the production amplitude.

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).

→ 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 $Q^2_{1,\mathrm{min}} = \dfrac{\xi_1^2 m_p^2}{1-\xi_1}$

where $\xi_1 \approx \dfrac{M_\psi}{\sqrt{s}} e^{y_\psi}$ 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}

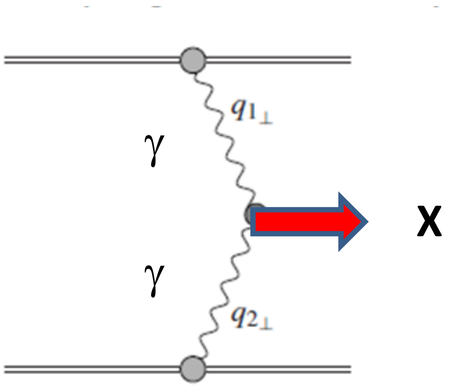
- Not a constant: depends sensitively on the outgoing proton $\mathbf{p}_\perp$vectors. Physically- survival probability will depend on impact parameter of colliding protons. Further apart $\longrightarrow$ less interaction, and $S^2_{\mathrm{eik}} \to 1$.

b_t and $p_\perp$: Fourier conjugates.

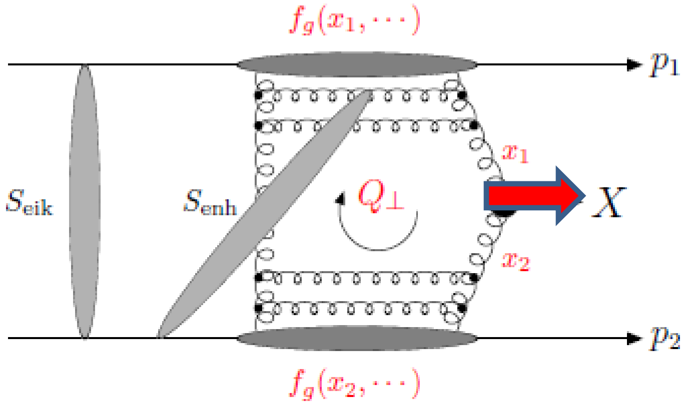
Process dependence

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

First fully differential implementation of soft survival factor – **SuperChic 2,3** MC event generator- HKR, ArHiv:1508.02718;1810.06567



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.

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

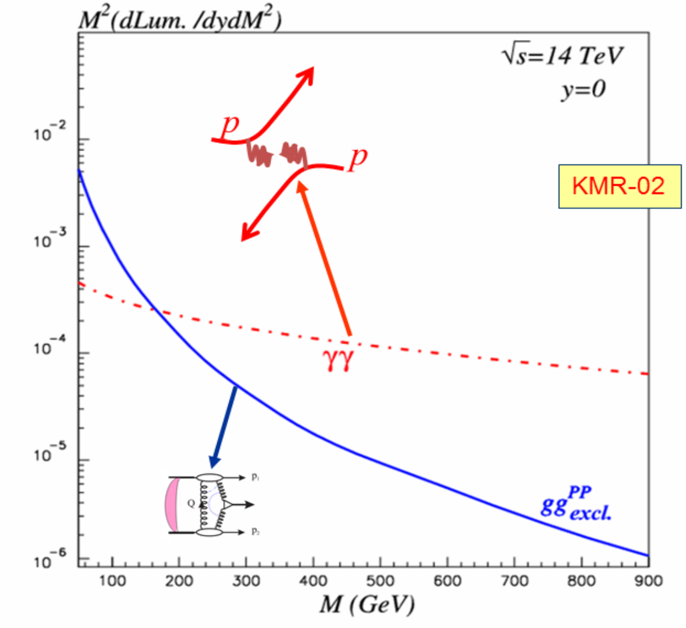
- Increasing M_X $\Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

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

KMR-2001

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

QCD ‘radiation damage’ in action

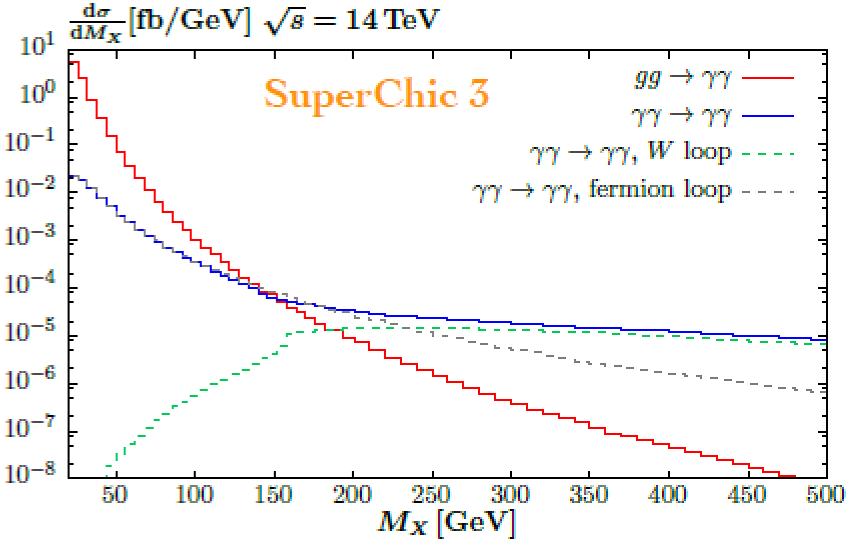


- Situation summarised in ‘effective’ exclusive gg and $\gamma\gamma$. luminosities. This Sudakov suppression in QCD cross section leads to enhancement in $\gamma\gamma$ already* for $M_X \gtrsim 200\,\mathrm{GeV}$ - well before CT-PPS/AFP mass acceptance region.

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

★ As mass of central system M_X increases, QCD-initiated production cross section suppressed by no radiation probability $\Rightarrow$ BG often low*.

- Example of $\gamma\gamma$ production:



- CEP: unique possibility to observe photon-initiated production of states with EM coupling in clean/well understood environment.
- However typically considering high mass region (RPs) and relatively low cross sections (EM couplings). **Statistics limited**.

⟶ Increased statistics from HL-LHC running offer **clear advantage** here, in particular in terms of pushing to higher mass.

*Precise level depends on particular process.

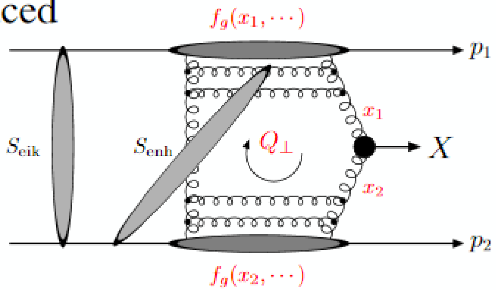
Photon-photon collisions in Superchic

Production mechanisms

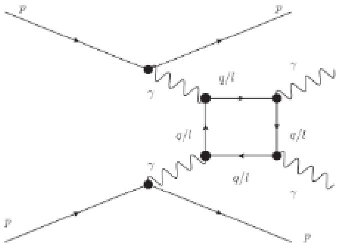
Exclusive final state can be produced via three different mechanisms, depending on kinematics and quantum numbers of state:

Gluon-induced

C-even, couples to gluons

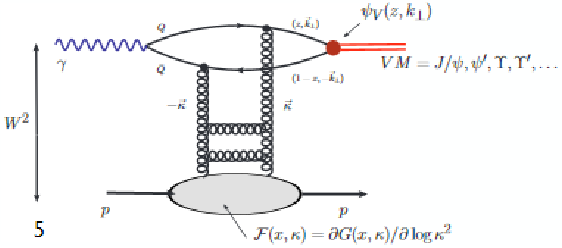


Couples to photons



Photon-induced

C-odd, couples to photons + gluons



Photoproduction

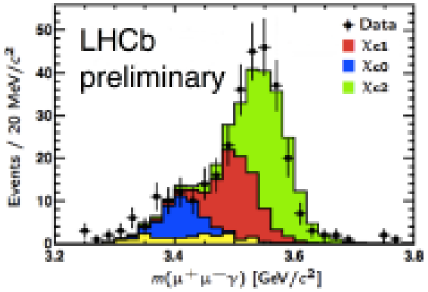
SuperChic

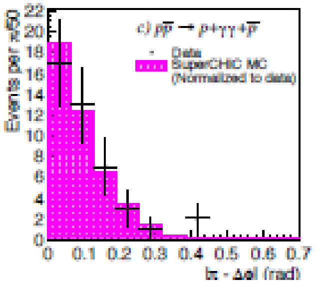
- A MC event generator for CEP processes. Common platform for:
  - QCD-induced CEP.
  - Photoproduction.
  - **Photon-photon** induced CEP.

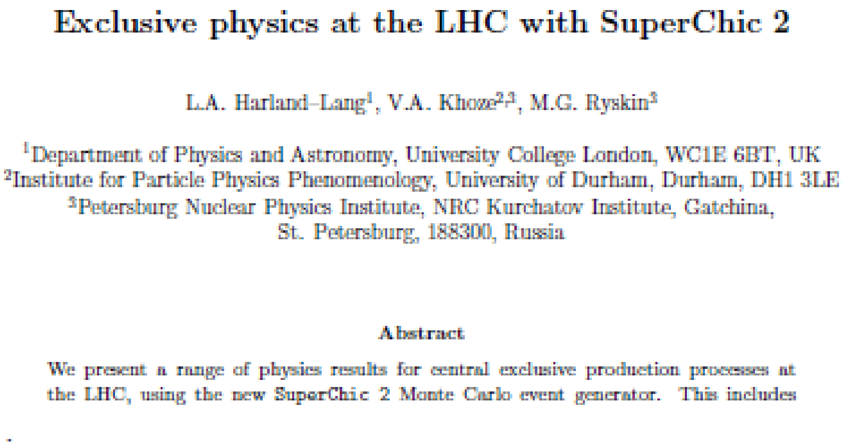
- With fully differential treatment of survival effects.
- Photon-induced collisions currently for e/p beams.

- 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]

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[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

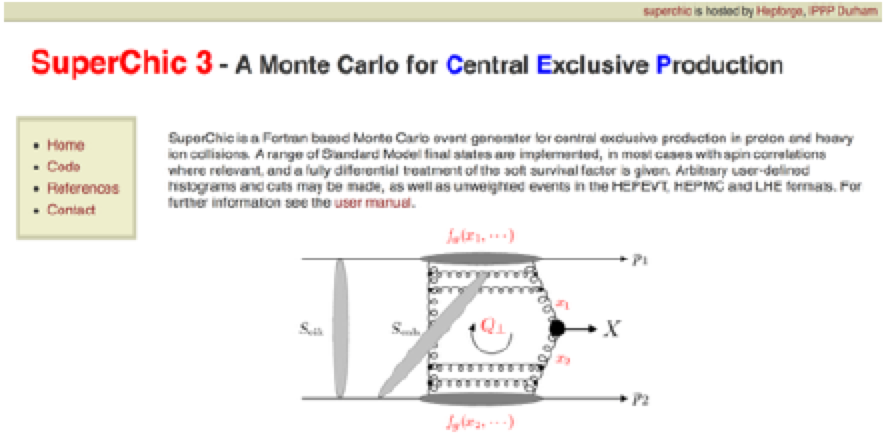
We present a range of physics results for central exclusive production processes at the LHC, using the new SuperChic 2 Monte Carlo event generator. This includes

Tools for future studies - SuperChic MC

- A MC event generator for CEP processes. **Common platform** for:
  - QCD-initiated CEP.
  - Photoproduction.
  - Photon-initiated CEP.

- Previously generated pp collisions only, but recently updated to include pA and AA collisions.

LHL, V. A. Khoze, M. G. Ryskin, arXiv:1810.06567

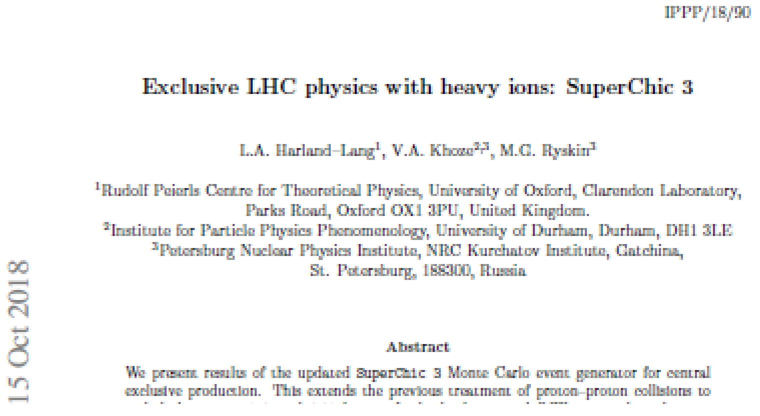


superchic is hosted by Hepforge, IPPP Durham

SuperChic 3 - A Monte Carlo for **C**entral **E**xclusive **P**roduction

- Home
- Code
- References
- Contact

SuperChic is a Fortran based Monte Carlo event generator for central exclusive production in proton and heavy ion collisions. 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, HEPMC and LHE formats. For further information see the user manual.



IPPP/18/90

15 Oct 2018

Exclusive LHC physics with heavy ions: SuperChic 3

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

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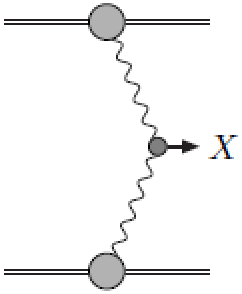
St. Petersburg, 188300, Russia

Abstract

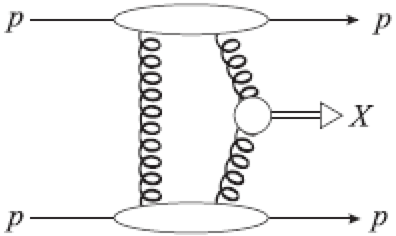
We present results of the updated SuperChic 3 Monte Carlo event generator for central exclusive production. This extends the previous treatment of proton–proton collisions to

https://superchic.hepforge.org

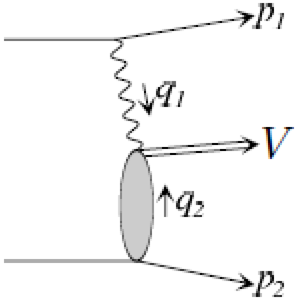
SuperChic MC - processes generated



★ W^+W^-, l^+l^-, LbyL, SM Higgs, ALPs, monopoles, monopolium.



★ SM Higgs, dijets, trijets, light meson pairs, heavy quarkonia (single and double), $\gamma\gamma$.



★ Light to heavy vector meson production.

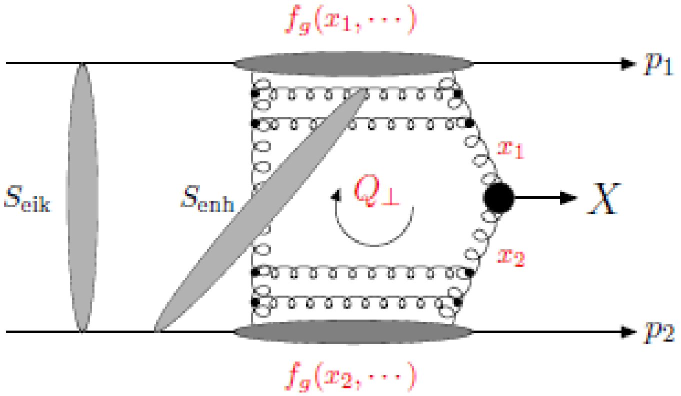
- In all cases in pp , pA and AA collisions.

Generated Processes - QCD

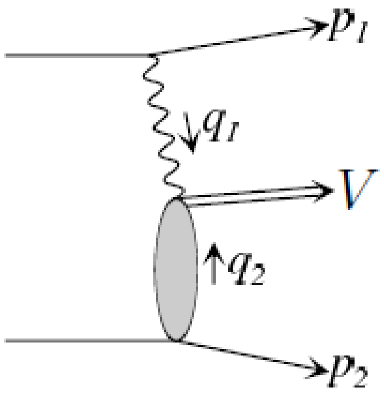
- SM Higgs to $b\bar{b}$.
- Dijets - $q\bar{q}, gg, b\bar{b}(c\bar{c})$
- Trijets - $q\bar{q}g, ggg$
- Light meson pairs - $\pi\pi, \eta(')\eta('), KK, \phi\phi$
- Quarkonium pairs - $J/\psi, \psi(2S)$
- $\chi_{c,b}$ quarkonia, via 2/3 body decays
- $\eta_{c,b}$.
- $\gamma\gamma$.

- Applies 'Durham' pQCD-based model.

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



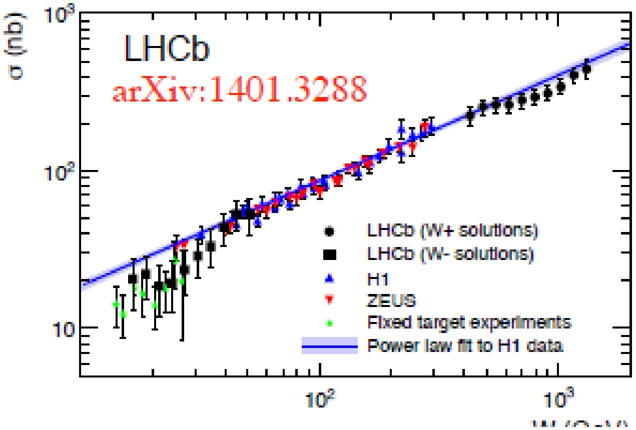
Generated Processes - photoproduction



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

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

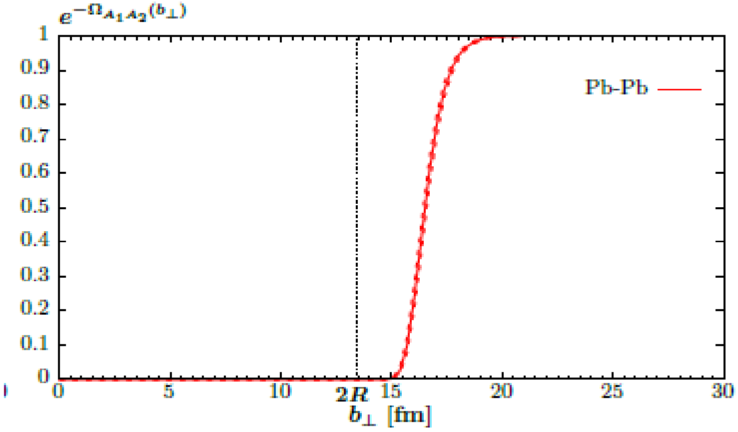
- Takes simple power-law fit to HERA/LHC data.



SuperChic MC - Recent Developments

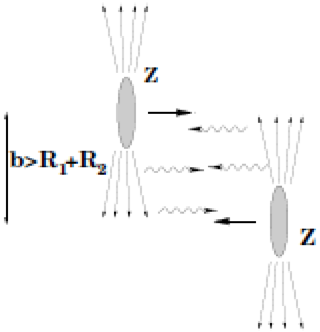
LHL, V. A. Khoze, M. G. Ryskin, arXiv:1810.06567

- Extension to heavy ion collisions- first ever treatment of QCD-initiated production.
- Requires detailed treatment of survival factor of no additional particle production in ion-ion QCD interactions.
- Relatively staightforward in photon-initiated case (~ no overlap), but great care needed in QCD-initiated case.



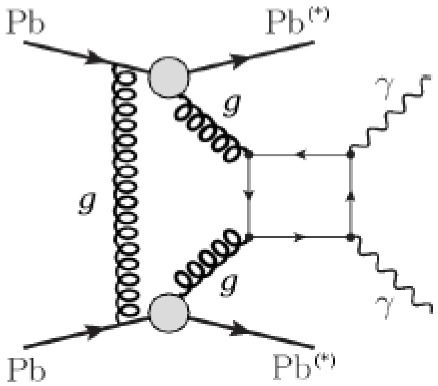
QCD

QED →

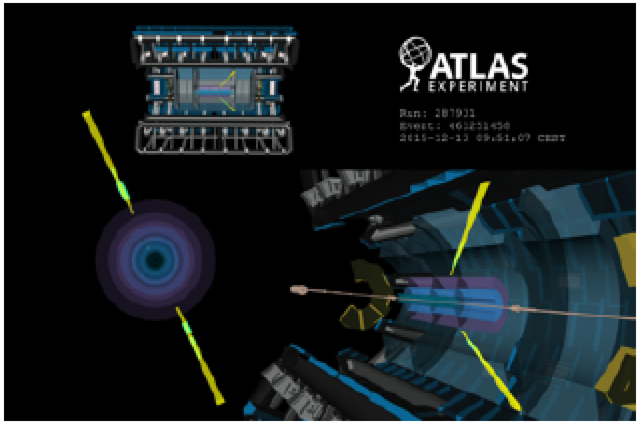


- Application of this - possible QCD-initiated BG to LbyL scattering.
- Previously no MC available for this - in ATLAS/CMS analyses scale superchic prediction for pp by:

$$\sigma^{PbPb} = \sigma^{pp} \cdot \underset{\substack{\nearrow \\ \text{Scale by} \\ \text{nucleon pairs}}}{A^2} \cdot \underset{\substack{\nwarrow \\ \text{Nuclear} \\ \text{shadowing} \sim (0.7)^4}}{R^4}$$



ATLAS Collab., Nature Phys. 13 (2017) no.9, 852-858



- Full calculation - not the case. Not all nucleons can participate in short-range QCD interaction while leaving ions intact. Find:

$$\sigma^{PbPb} \sim \sigma^{pp} \cdot A^{1/3}$$

$\longrightarrow$ Find that QCD-initiated BG expected to be negligible.

SuperChic MC - Recent Developments

- - prospects for compressed SUSY searches in photon-initiated CEP.
- Signal for this study:

$$\gamma\gamma \to \tilde{l}^+\tilde{l}^- \to l^+l^-\tilde{\chi}_0\tilde{\chi}_0$$

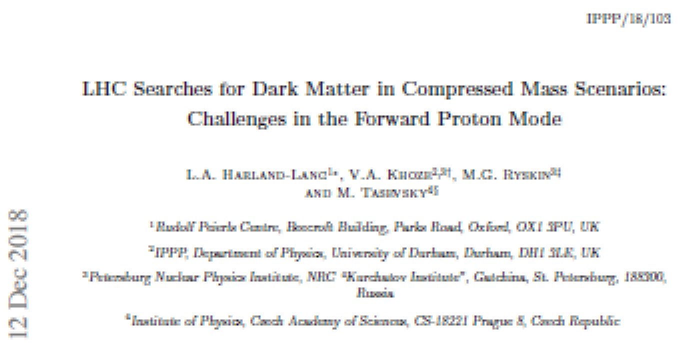
implemented in SuperChic, as well as more challenging case:

$$\gamma\gamma \to \tilde{\chi}^+\tilde{\chi}^- \qquad \text{(hadron/leptonic decays)}$$

- To be included in official version early in new year.

LHL et al., arXiv:1812.04886

- In addition, contribution from proton dissociation included in effective way, interfaced to SuperChic.
- Future work: include (more) complete treatment of dissociation. Stay tuned!



IPPP/18/103

LHC Searches for Dark Matter in Compressed Mass Scenarios:
Challenges in the Forward Proton Mode

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AND M. TASEVSKY[4]

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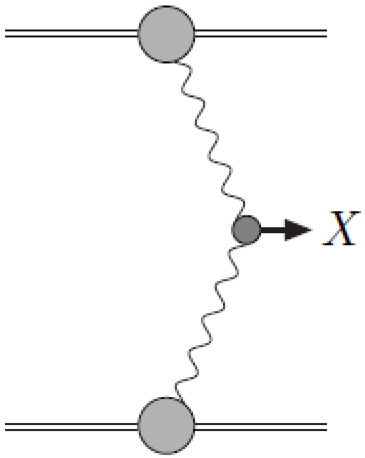
12 Dec 2018

Soft survival factor

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

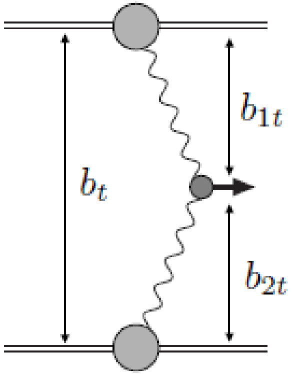
$$\frac{\mathrm{d}\sigma^{pp\to pXp}}{\mathrm{d}M_X^2\mathrm{d}y_X} \sim \frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2\mathrm{d}y_X}\hat{\sigma}(\gamma\gamma \to X)$$



- 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:



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

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

↑

proton opacity

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

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

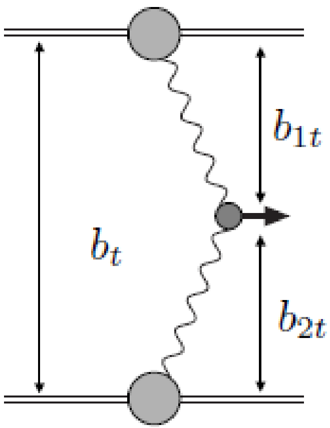
V.A. Khoze, A.D. Martin, M.G. Ryskin, arXiv:1306.2149

Well established in the QCD-mediated processes, e.g. CDF-diffractive dijets (2000), CMS/ATLAS- dijets in events with LRG (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.

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

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



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

small model dep.

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

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

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

$\longrightarrow$ 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 $p_\perp$.

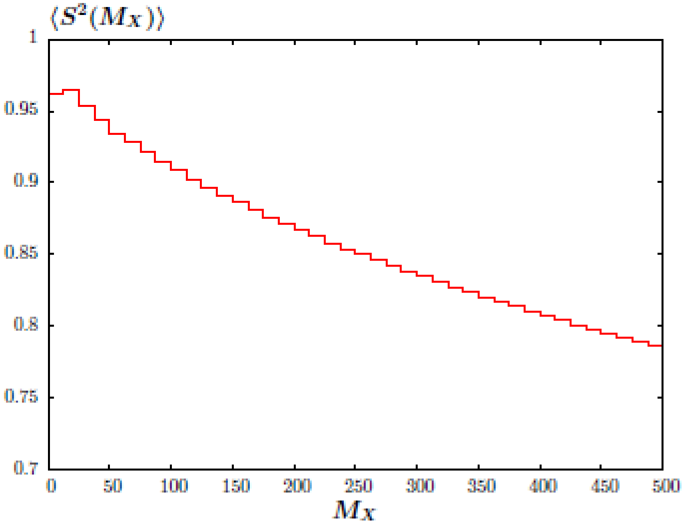
- Higher $p_\perp \Rightarrow$ lower $b_\perp \Rightarrow$ smaller S^2.

- Result from SuperChic:

Muon pair production

$M_X = M_{ll}$

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

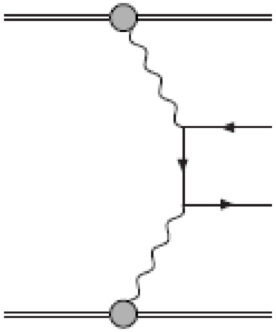


Kinematic dependence

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

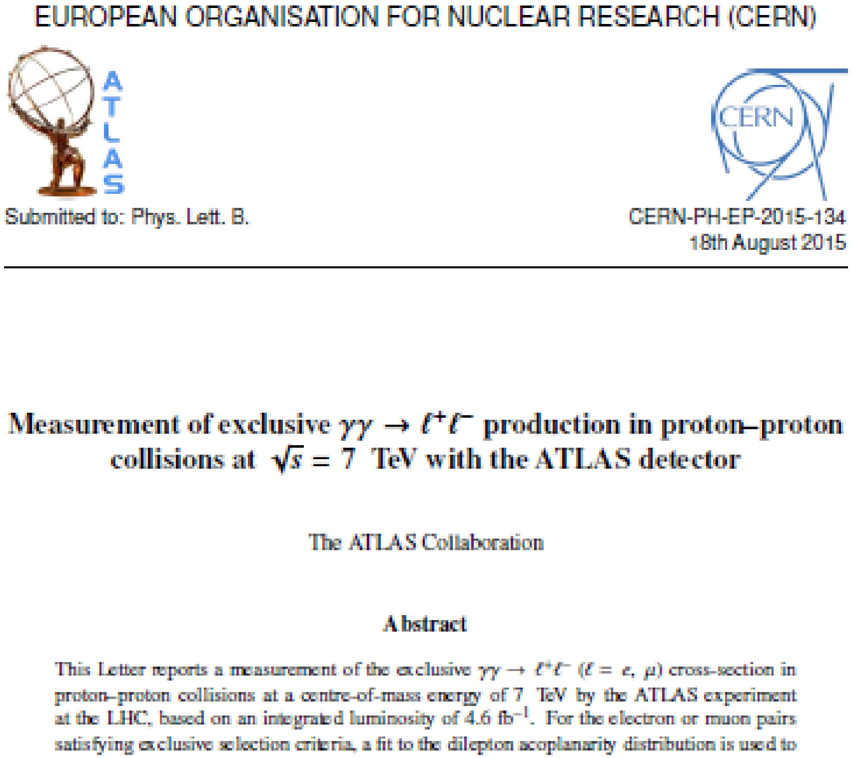
	$\mu^+\mu^-$	$\mu^+\mu^-$, $M_{\mu\mu} > 2M_W$	$\mu^+\mu^-$, $p_\perp^{\text{prot.}} < 0.1$ GeV	W^+W^-
σ_{bare}	6240	11.2	3170	87.5
$\sigma_{\text{sc.}}$	5990	9.58	3150	71.9
$\langle S^2_{\text{eik}} \rangle$	0.96	0.86	0.994	0.82

$\longrightarrow$ 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.

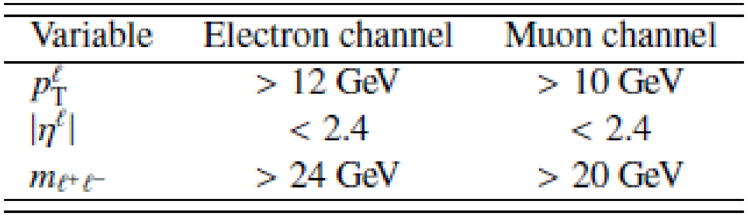
CERN-PH-EP-2015-134
18th August 2015

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

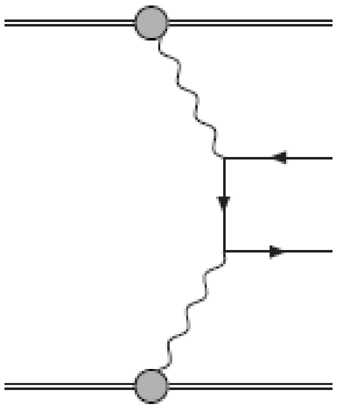
The ATLAS Collaboration

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

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.

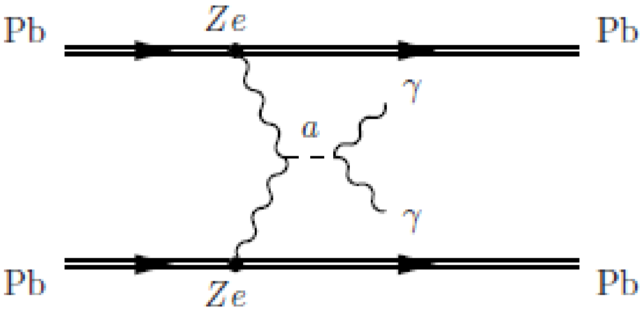
New processes

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

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

→ Simple to implement new processes within framework. Suggestions/collaboration welcome!

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

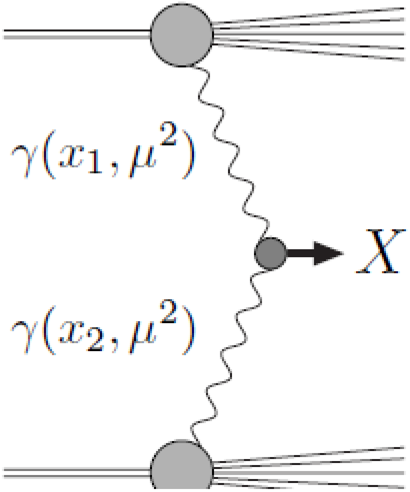


Photon-photon Luminosities

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



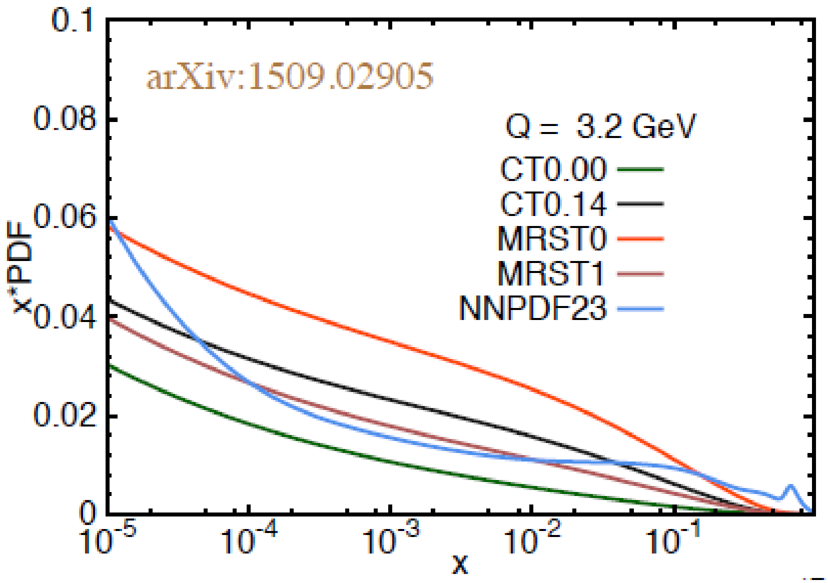
- Earlier photon PDF sets either:

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.

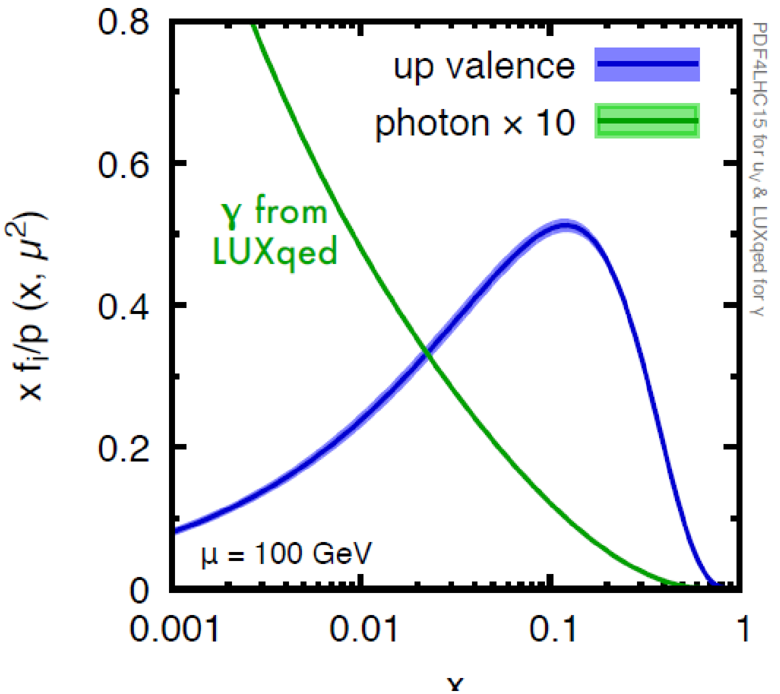
  - Model-independent uncertainty (NNPDF) was 50–100%

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

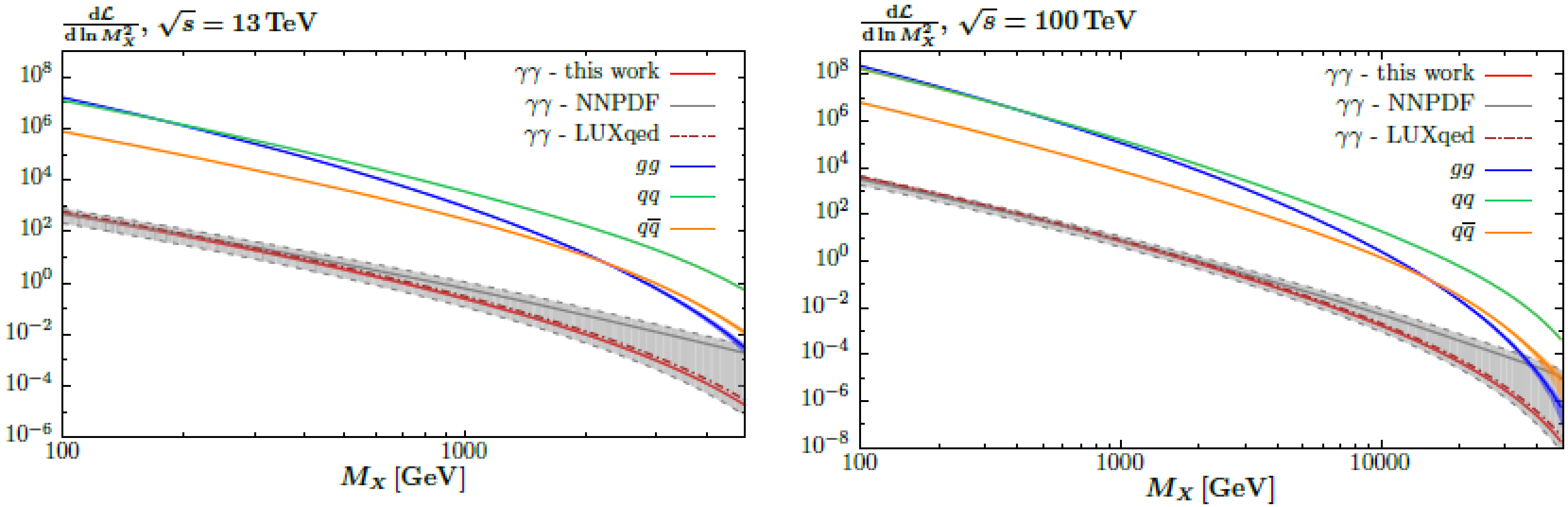
photon PDF results

- 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



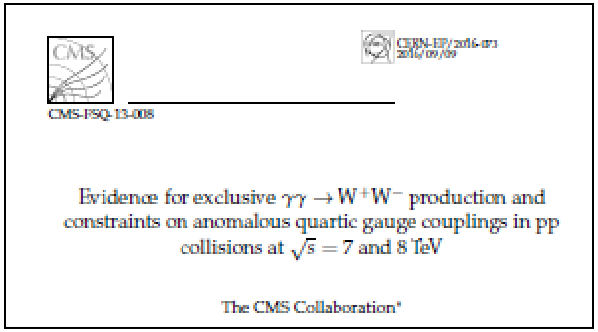
Comparison with LUXqed



- 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..)

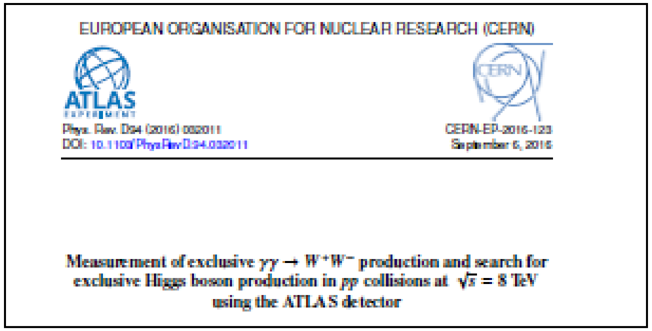


CMS-FSQ-13-008

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

Evidence for exclusive $\gamma\gamma \rightarrow W^+W^-$ 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)

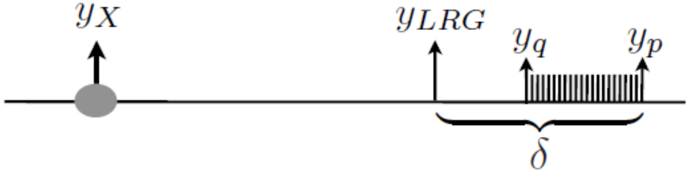
Phys. Rev. D94 (2016) 032011
DOI: 10.1103/PhysRevD.94.032011

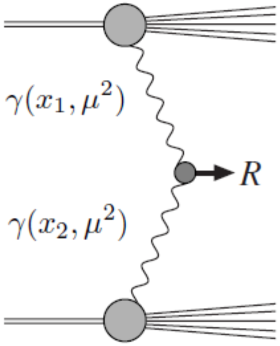
CERN-EP-2016-123
September 6, 2016

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

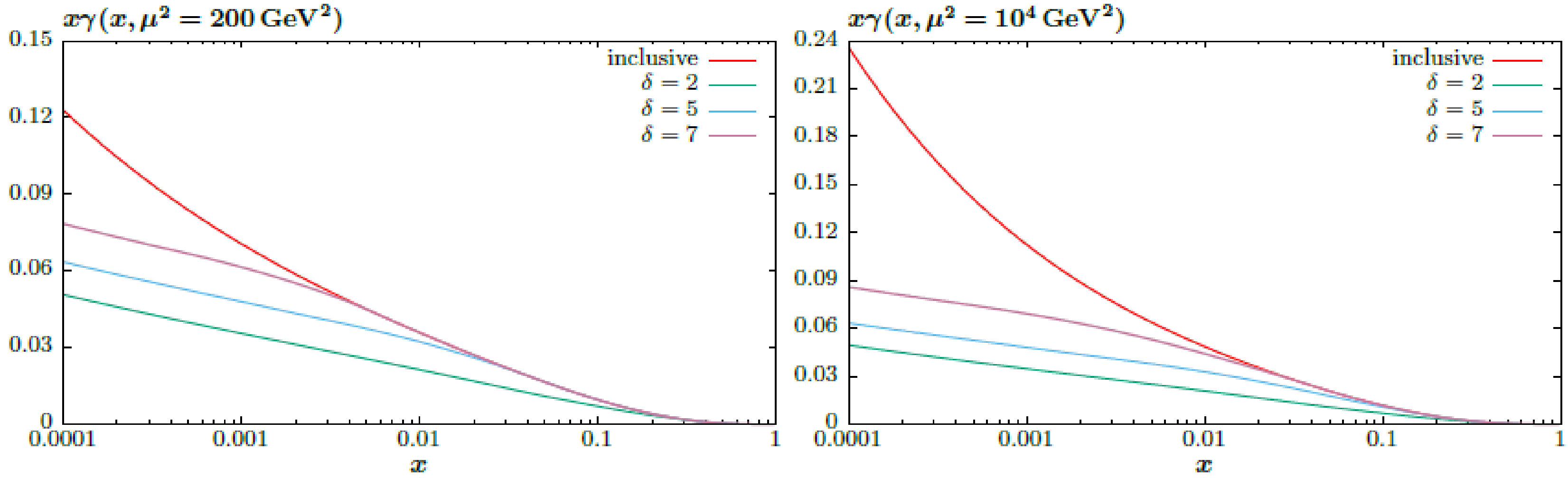
- Semi-exclusive processes with rapidity gaps: how do we include a rapidity veto within the standard inclusive approach?
- Comparison to CMS 7 and 8 TeV $\mu^+\mu^-$ data.

HKR arXiv:1601.03772





Modified photon PDF

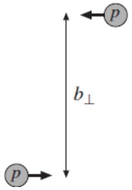


Suppression due to LRG veto.

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

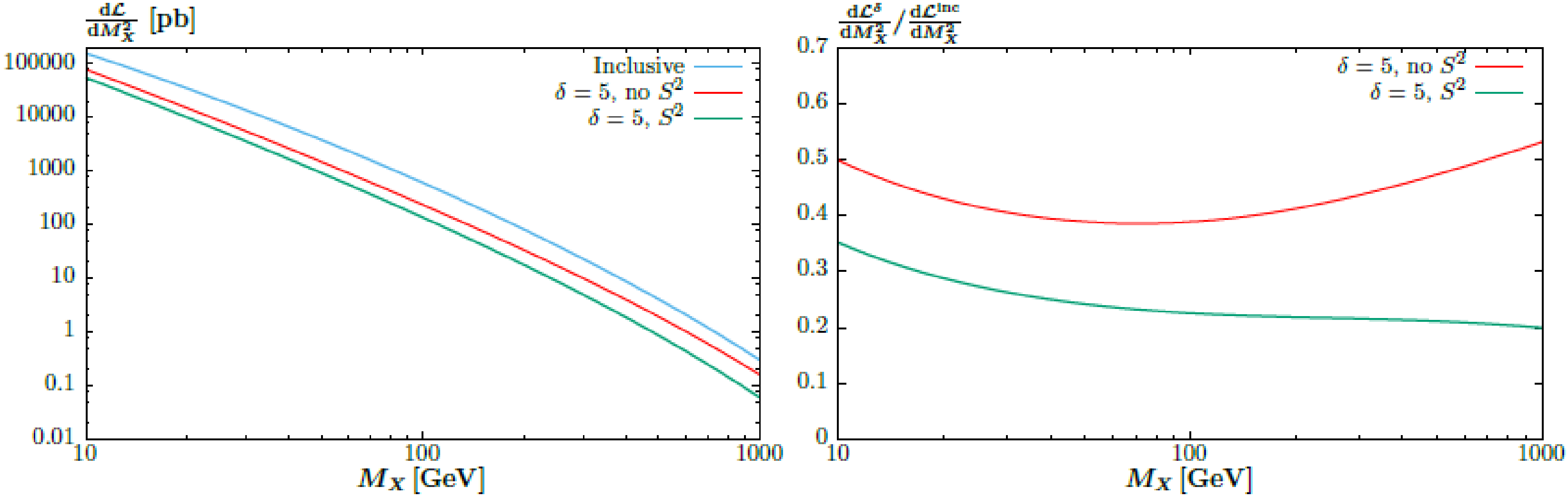
phenomenological objects only-factorization explicitly violated by rescattering effects

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



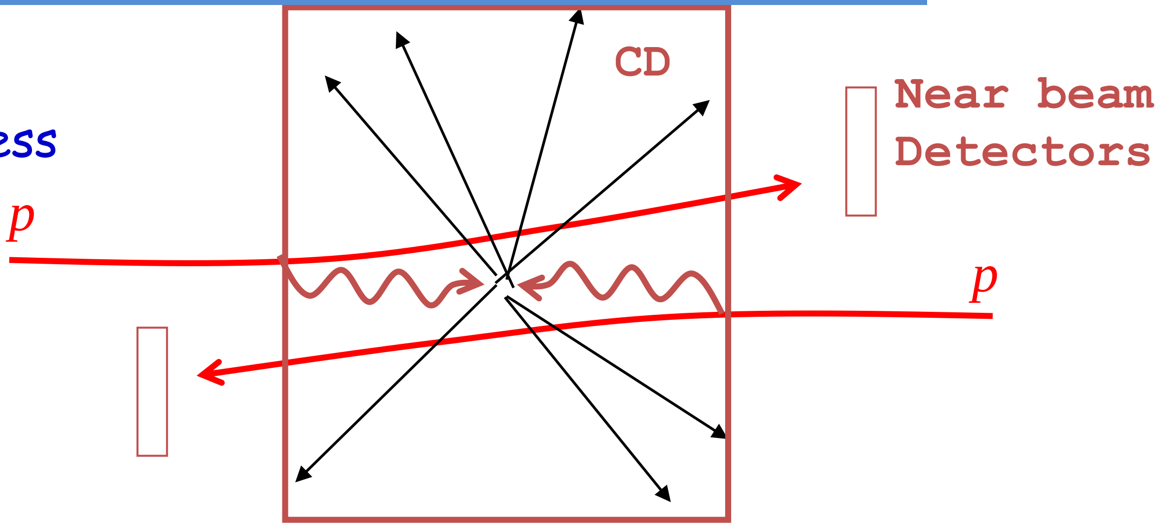
- As S^2 depends on proton b_t, it is sensitive to emission process for both protons $\Rightarrow$ can no longer define independent $\gamma^{\rm veto}(x,\mu^2)$.

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



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

γγ collisions- applications



Process

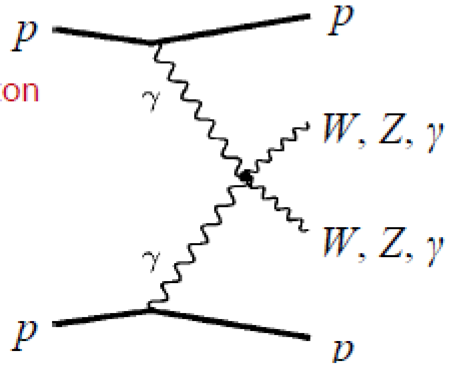
Installed (AFP)
Installed (CT-PPS)
projects

Extensive Program

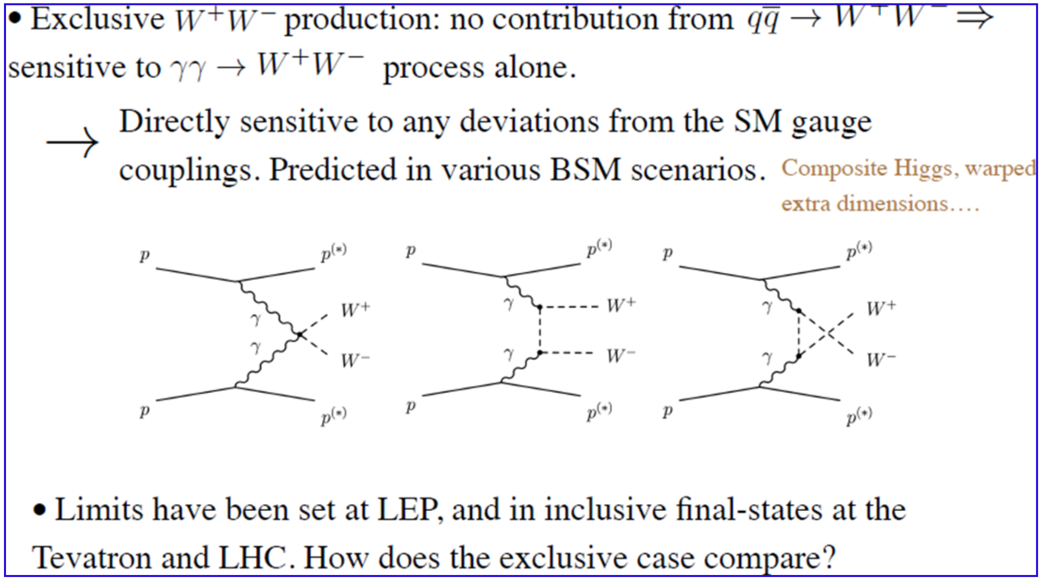
- γ γ→ μμ, ee QED processes
- γ γ→ QCD (jets..)
- γ γ→ WW anomalous couplings
- γ γ→ squark, top… pairs
- γ γ→ Charginos (natural SUSY)
- New BSM objects

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: ($Z \rightarrow ee$, $\gamma\gamma$)
  - 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



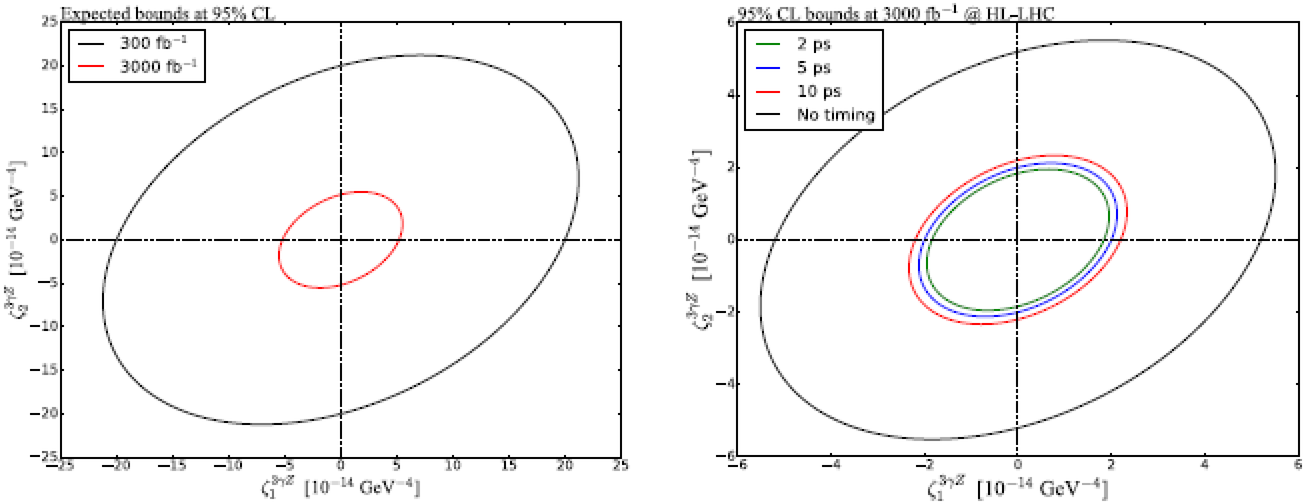
- Exclusive W^+W^- production: no contribution from $q\bar{q} \rightarrow W^+W^- \Rightarrow$ sensitive to $\gamma\gamma \rightarrow W^+W^-$ process alone.

$\rightarrow$ 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@ HL-LHC



Left: Comparison between 300 fb^{-1} and 3000 fb^{-1}. **Right:** (Zoomed-in; change of scale in X-Y axis) comparison between the use of timing $\delta t = 2, 5, 10$ ps. $Z\gamma \to \text{hadrons} + \gamma$ benefits the most from the use of timing.

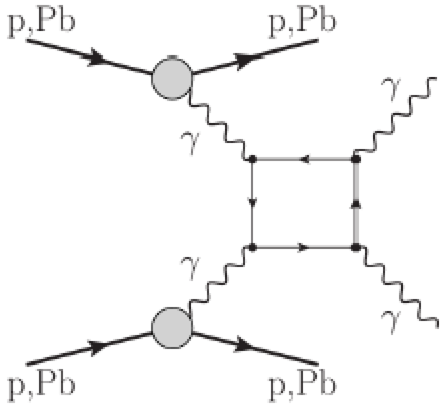
- Expected improvements from HL-LHC impressive ~ an order of magnitude (~ 5 orders of magnitude better than current best inclusive limits).

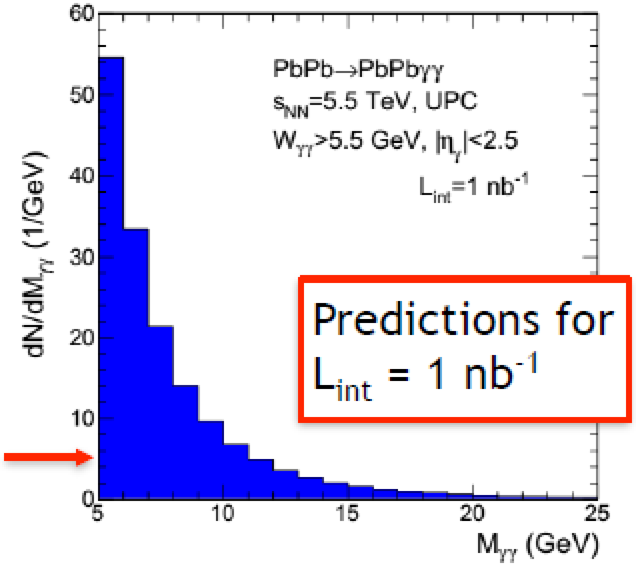
Light-by-light scattering in Pb+Pb

- **Motivation**

[Nature Physics (2017)]

- Light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) 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]

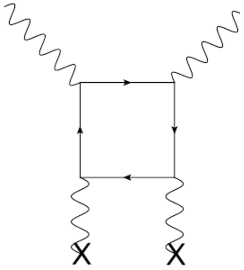




Predictions for L_{int} = 1 nb^{-1}

Long and chequered history

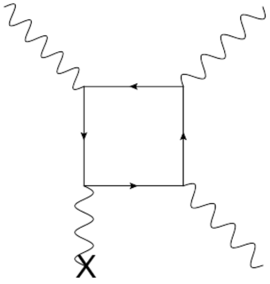
(nonlinear effects of QED)



Delbrück **1933**

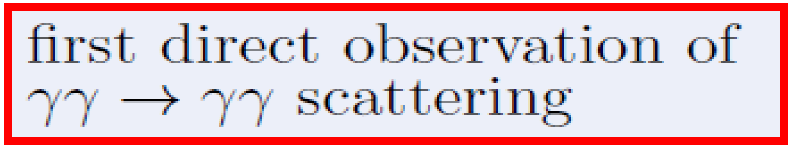
Scattering of gamma-rays by a Coulomb field of heavy nuclei.
First observed-1953 for 1.33 MeV on lead nuclei.
Most accurate high-energy results- Novosibirsk,VEPP-4M 1998.

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
$\gamma\gamma \rightarrow \gamma\gamma$ scattering

(ArXiv:1702.01625)

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

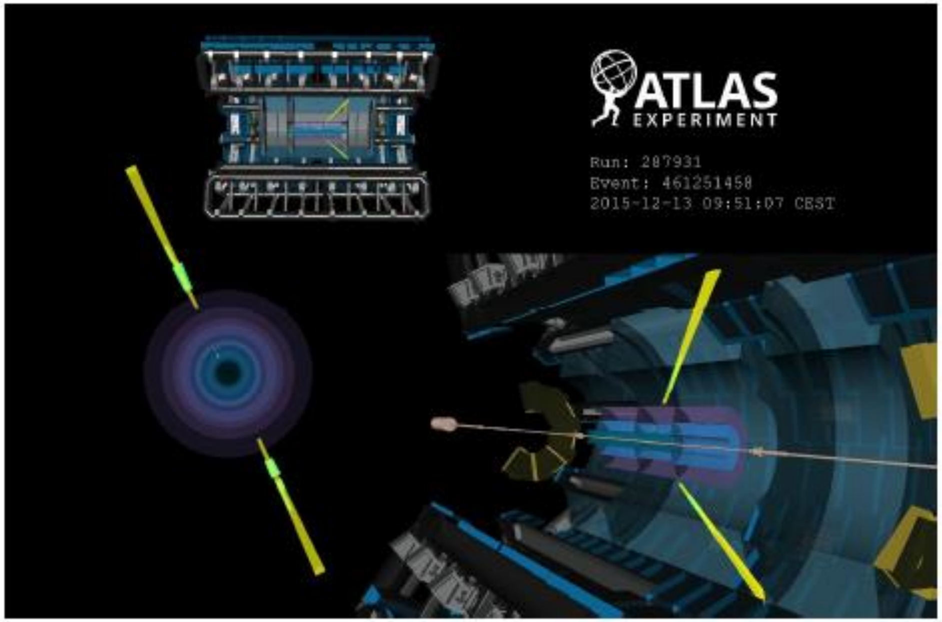
ATLAS @ $\sqrt{s_{NN}}$ = 5.02 TeV:

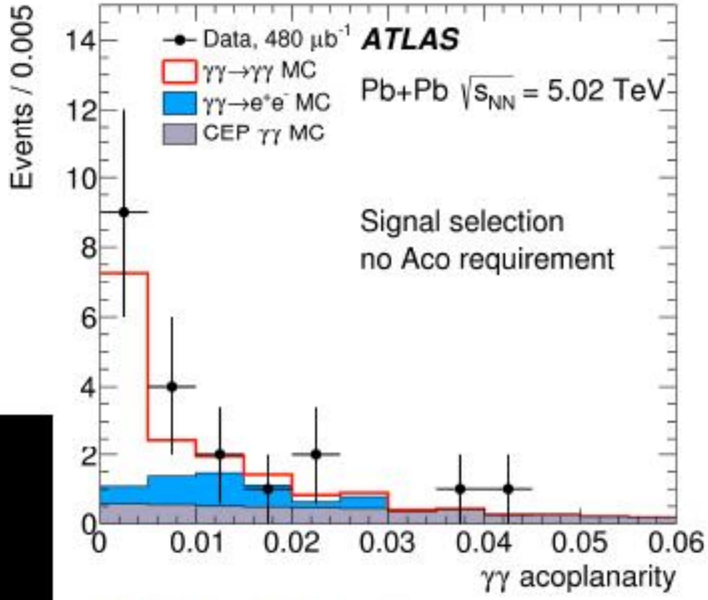
13 events (bkgd 2.6) ⇒ 4.4σ evidence

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

Needed ZDC in order to separate purely UPC events

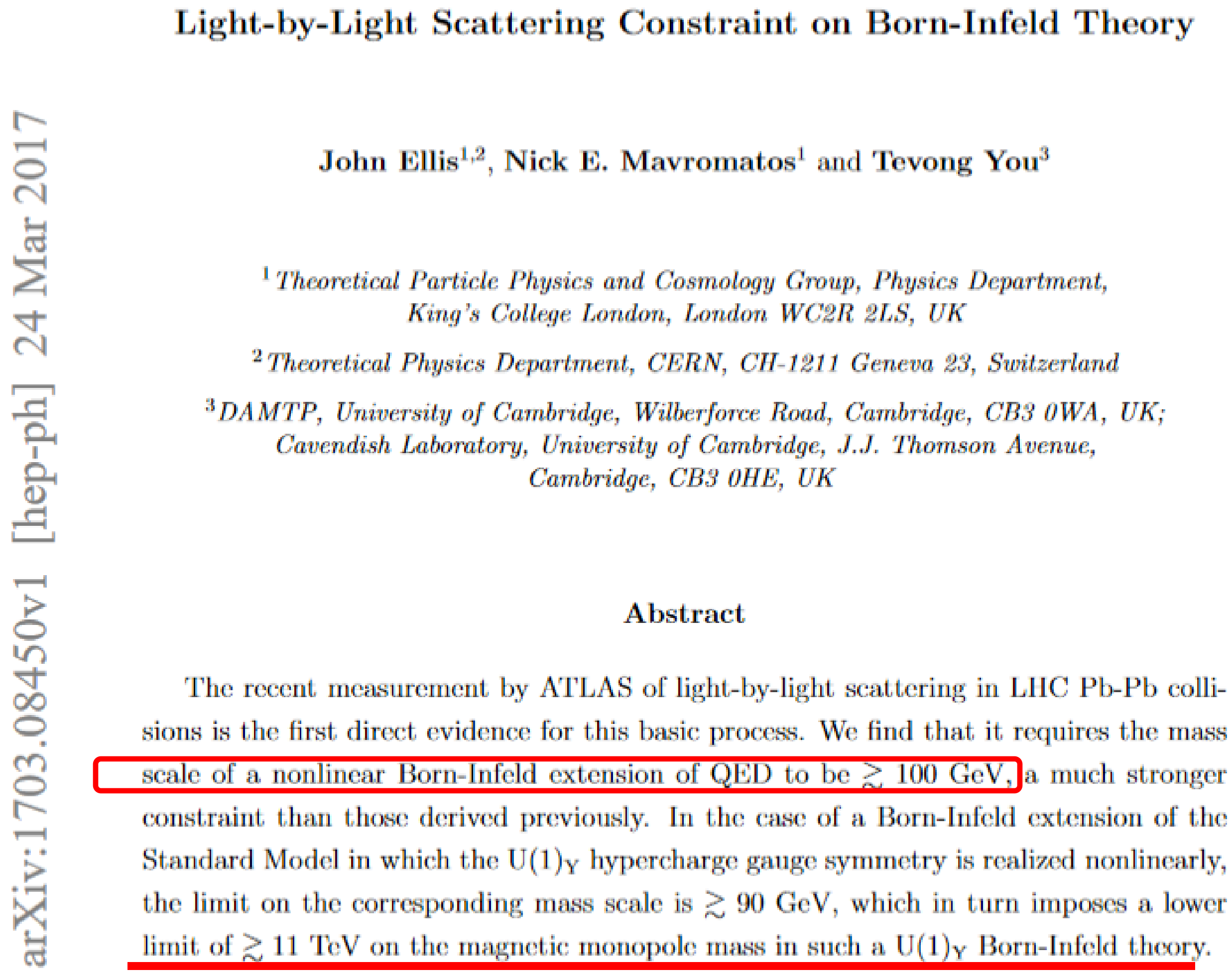
Processes of interest

- Many processes of interest in the lower mass region. Main channel of interest - $\gamma\gamma$ final-state.
  - ★ Light-by-light SM signal, but also e.g. Born-Infeld extensions.
  - ★ Axion-like particle production.
  - ★ Magnetic monopoles.
  - ★ Other possibilities? Gravitons, radions, unparticles, SUSY?
- A principle drawback of heavy ions for these studies is the low luminosity $\Rightarrow$ benefit from increased datasets can be significant.

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

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

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



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

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

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

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

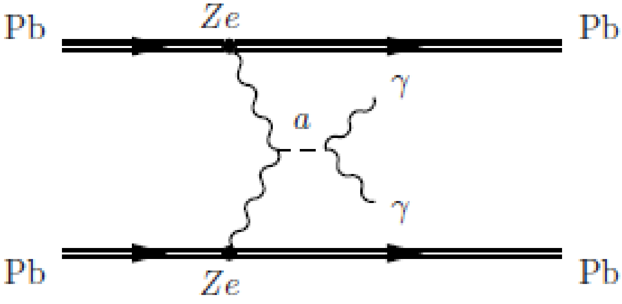
[3] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK;*
Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue,
Cambridge, CB3 0HE, UK

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.

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.



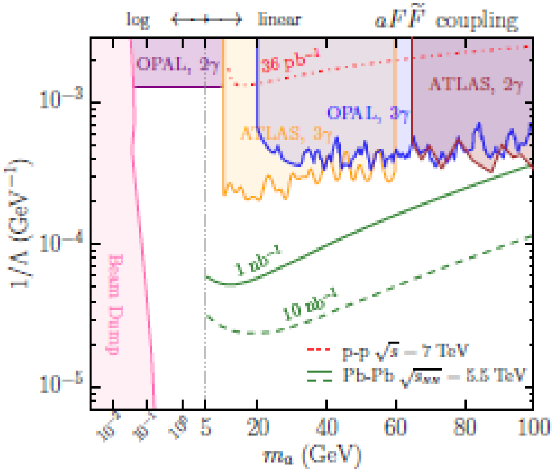
- Lagrangian:

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

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.



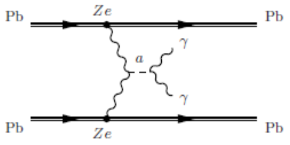
LHC limits on axion-like particles from heavy-ion collisions

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

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]`.



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

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

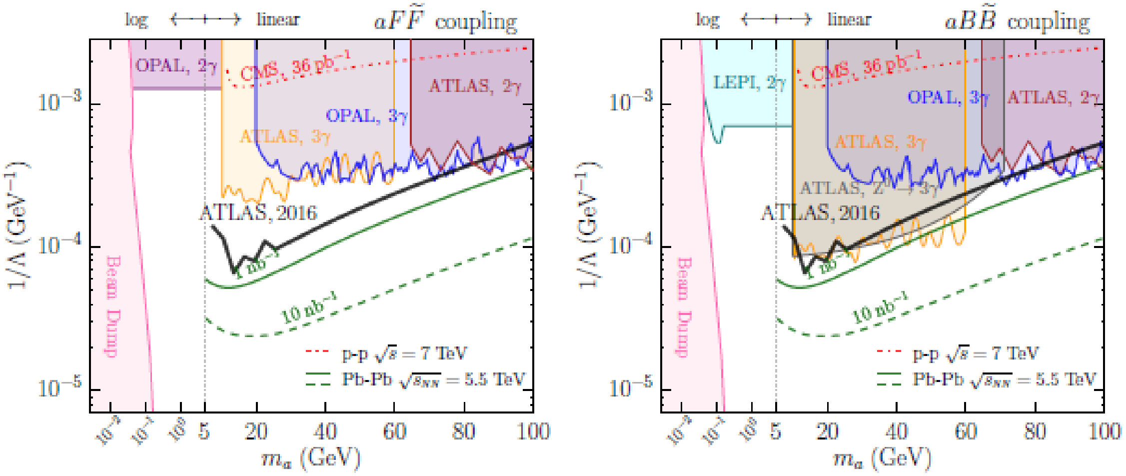
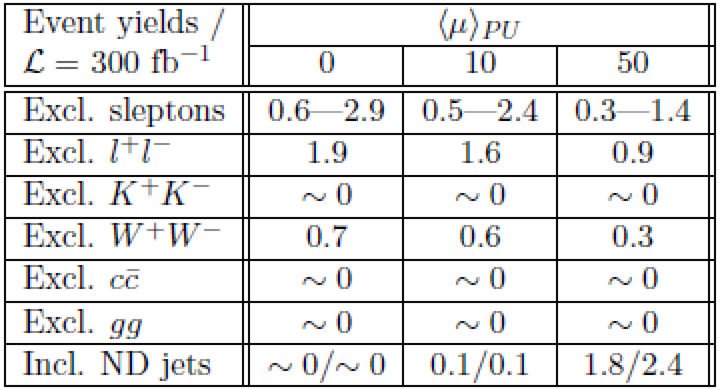


Fig. 2: *Left:* We show 95% exclusion limits on the operator $\frac{1}{4}\frac{1}{\Lambda}aF\tilde{F}$ using recent ATLAS results on heavy-ion UPCs [2] (solid black line). The expected sensitivity assuming a luminosity of 1 nb^{-1} (10 nb^{-1}) is shown in solid (dashed) green. For comparison, we also 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].

Example - Compressed SUSY

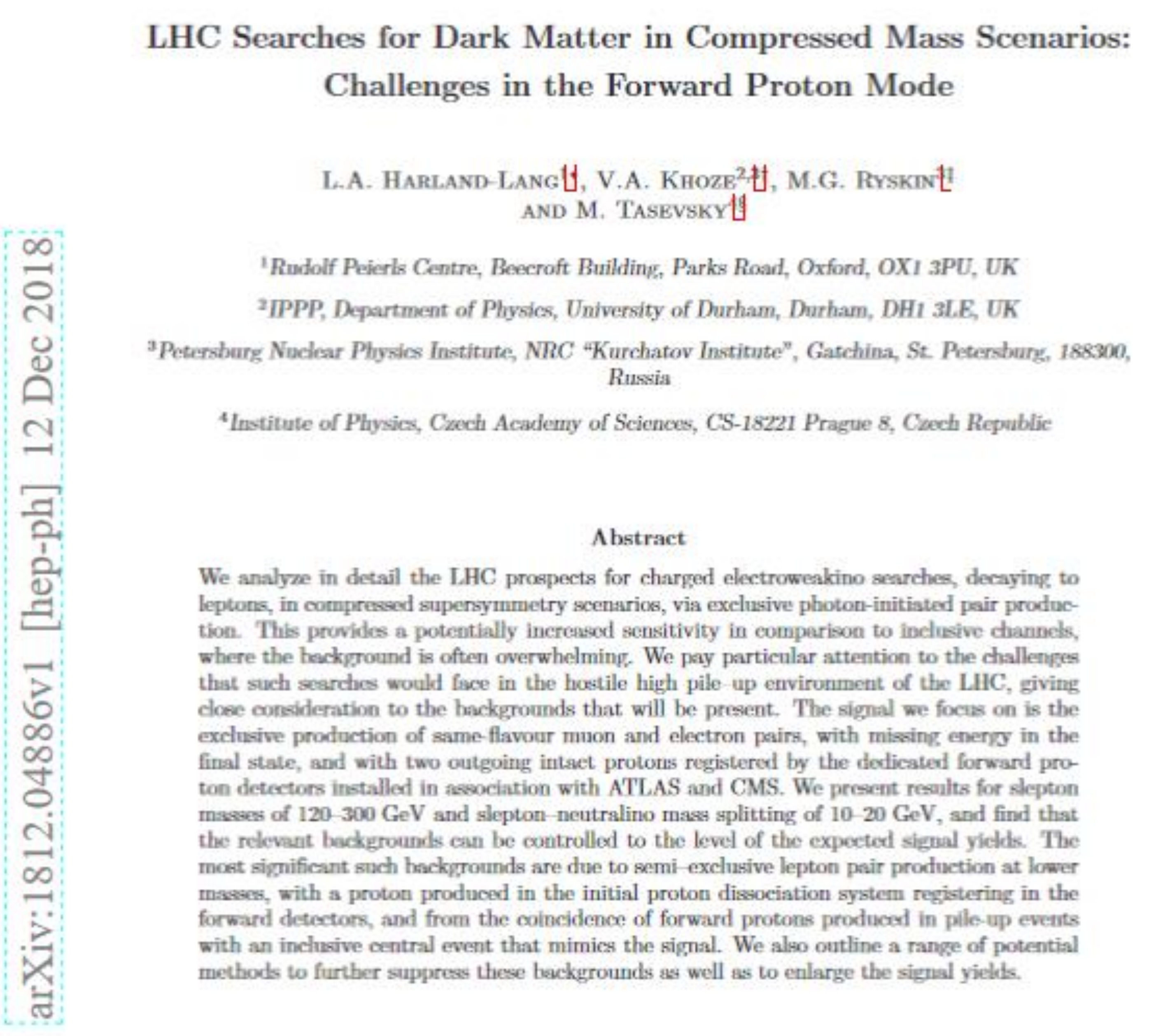
- Searches for compressed SUSY scenarios - potential to increase reach in regions of parameter space (EW couplings, low mass difference) where inclusive searches struggle.
- Signal cross section low - **gain** from HL-LHC.
- In addition - detector upgrades can help **reduce BGs**:
  - Increased tracker coverage.
  - Timing in forward detectors at IP.
  - Radiation-hard ZDC with timing?
- However higher pile will clearly lead to more challenging environment - **further studies needed**.



Event yields / $\mathcal{L} = 300\ \text{fb}^{-1}$	$\langle\mu\rangle_{PU}$		
	0	10	50
Excl. sleptons	0.6—2.9	0.5—2.4	0.3—1.4
Excl. l^+l^-	1.9	1.6	0.9
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.7	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0/\sim 0$	0.1/0.1	1.8/2.4

- Note: here and elsewhere **~420m RPs** could also greatly improve things, increasing acceptance towards lower mass region.

arXiv:1812.04886



LHC Searches for Dark Matter in Compressed Mass Scenarios: Challenges in the Forward Proton Mode

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AND M. TASEVSKY[4]

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Abstract

We analyze in detail the LHC prospects for charged electroweakino searches, decaying to leptons, in compressed supersymmetry scenarios, via exclusive photon-initiated pair production. This provides a potentially increased sensitivity in comparison to inclusive channels, where the background is often overwhelming. We pay particular attention to the challenges that such searches would face in the hostile high pile-up environment of the LHC, giving close consideration to the backgrounds that will be present. The signal we focus on is the exclusive production of same-flavour muon and electron pairs, with missing energy in the final state, and with two outgoing intact protons registered by the dedicated forward proton detectors installed in association with ATLAS and CMS. We present results for slepton masses of 120–300 GeV and slepton–neutralino mass splitting of 10–20 GeV, and find that the relevant backgrounds can be controlled to the level of the expected signal yields. The most significant such backgrounds are due to semi-exclusive lepton pair production at lower masses, with a proton produced in the initial proton dissociation system registering in the forward detectors, and from the coincidence of forward protons produced in pile-up events with an inclusive central event that mimics the signal. We also outline a range of potential methods to further suppress these backgrounds as well as to enlarge the signal yields.

Aim:

- to report current status of our ongoing long-term studies on prospects of searches at the LHC for ELECTROWEAKINO pair production via photon fusion with forward proton detectors (AFP, CT-PPS)

- exemplified within the framework of the compressed mass **MSSM**

First discussed: KMR, J.Phys. G44 (2017) no.5, 055002 , **VAK**- talks at a number of conferences; Marek, FWG meeting Dec. 2017-experimental aspects.

Recently: Lydia Beresford, Jesse Liu, 1811.0646**5** (Jesses's talk)
(focused mainly on the WW background)

SUSY – solution to various shortcomings of SM (as an example only)

If (it looks like) squarks and gluinos are too heavy,
sleptons, charginos, neutralinos- the main target. **(null search result so far)**

MSSM : charginos $\tilde{\chi}^{\pm}_{1,2}$ four neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$

$\tilde{\chi}^{0}_{1}$, natural candidate for cold Dark Matter –**LSP** arXiv:1710.02406

(and quite a few other papers)

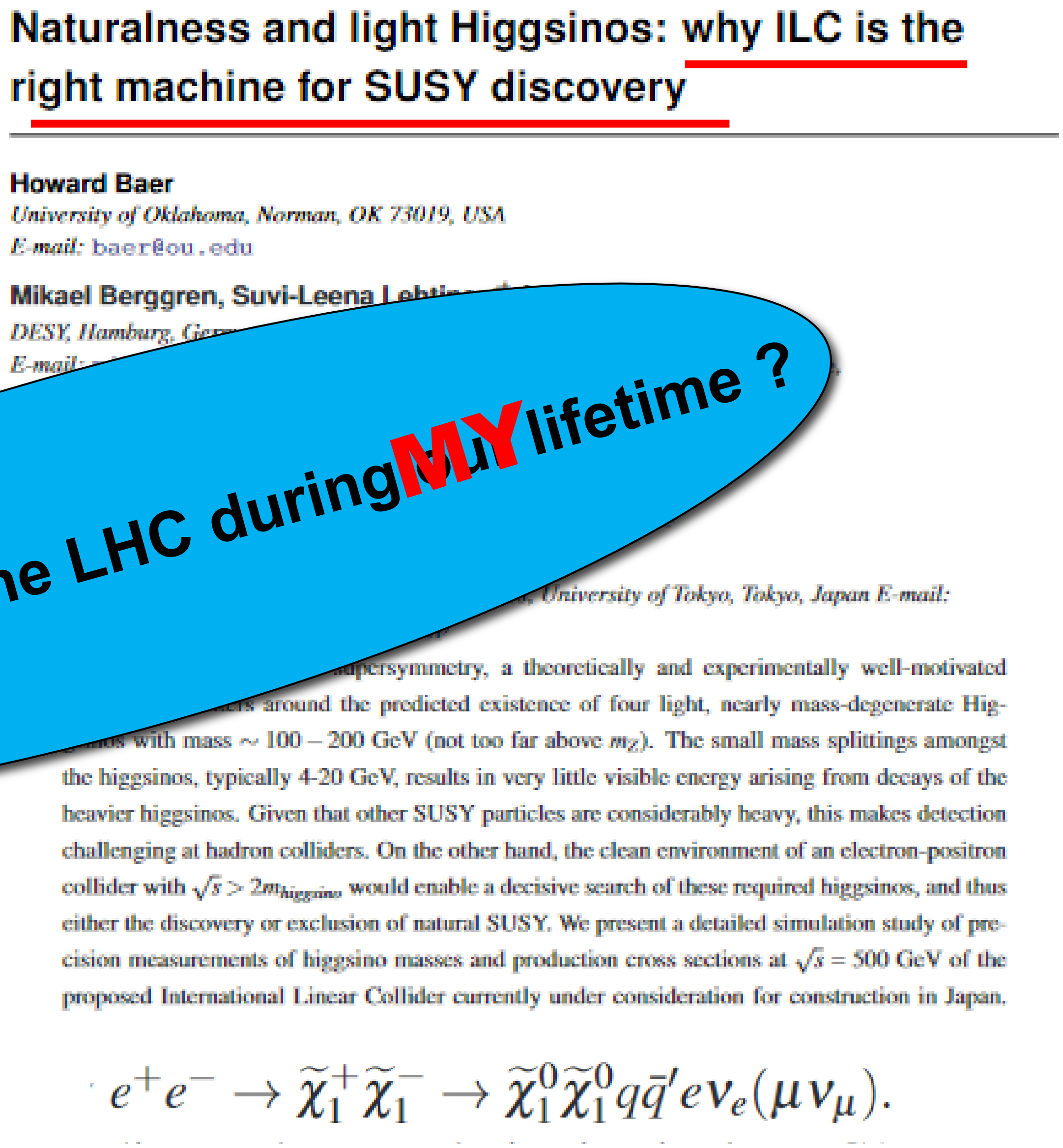
natural SUSY:
existence of light nearly
mass-degenerate Higgsinos/chargin
Mass~ 100-200GeV
mass splitting ~

Most challe
scenario
between

What about the LHC during MY lifetime ?

Motivated by naturalness, cosmological observations and (g-2) phenomenology.

(Introduction-Jessse)



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

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University of Tokyo, Tokyo, Japan E-mail:

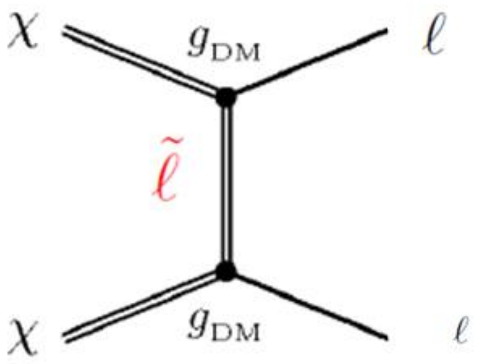
upersymmetry, a theoretically and experimentally well-motivated ers around the predicted existence of four light, nearly mass-degenerate Higgsinos with mass ~ 100 – 200 GeV (not too far above m_Z). The small mass splittings amongst the higgsinos, typically 4-20 GeV, results in very little visible energy 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.

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

Co-annihilation

(1702.00750, model-1a)

Dark matter annihilation

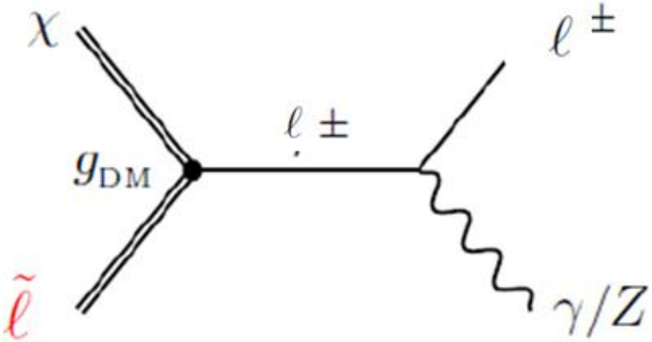


to bring DM abundance down to the observed value

Initially DM in thermal equilibrium with SM, later it freezes out

- Overproduces dark matter (Unless large couplings)
- We need a mechanism to reduce the DM relic density

Co-annihilation:

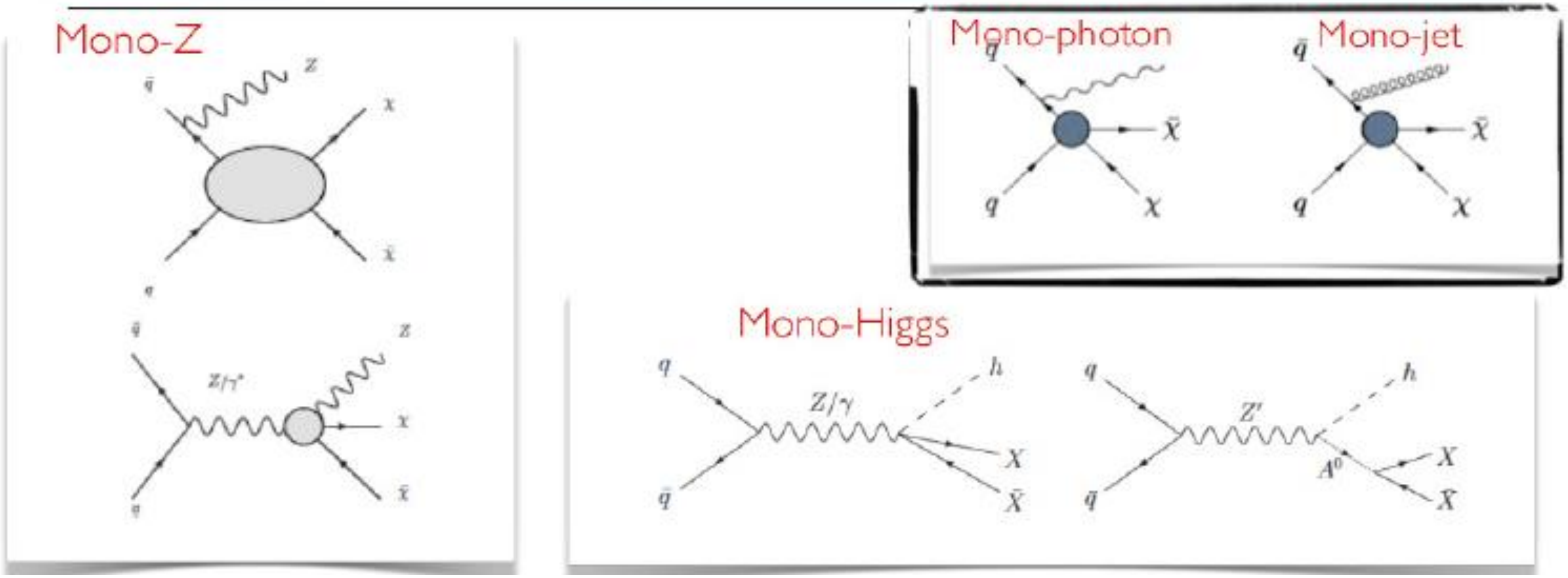


Freeze-out temperature $T_F \sim m_{DM}/25$

Boltzmann factor $\exp\left(-\frac{\Delta M}{T}\right)$ → $\Delta M \lesssim m_{DM}/25$

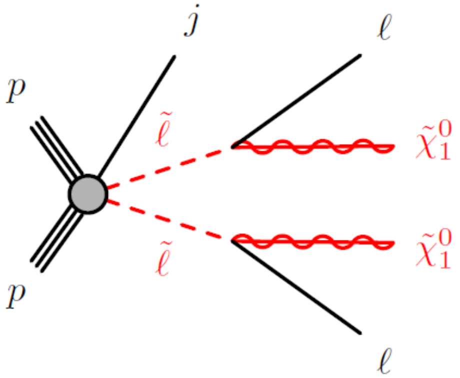
We need **mass splitting of 4% of m_{DM}** (very conservatively <10%)

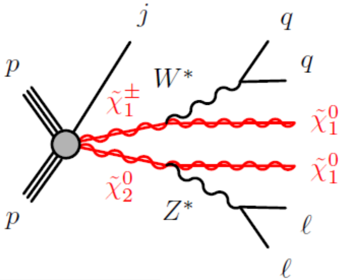
Mono-Mania (at the LHC)



DM Searches @ LHC O. Buchmüller

Searches for Electroweakinos at the LHC





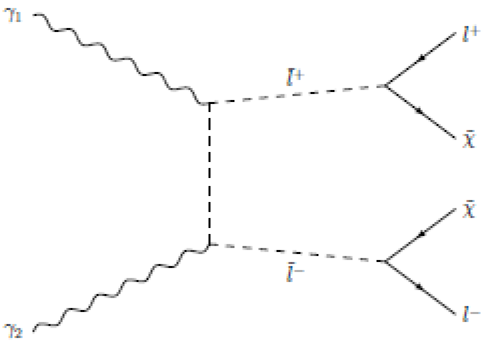
Model dependence

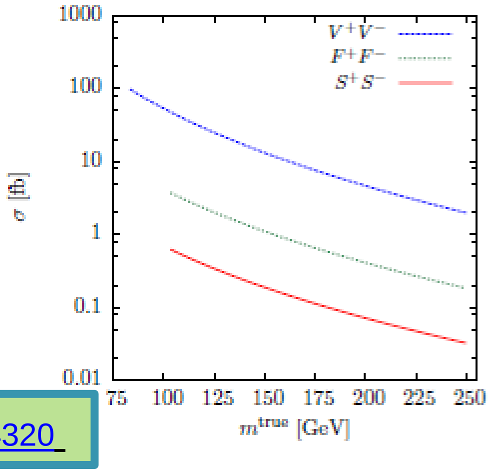
$$pp \to p + \gamma\gamma + p\ ,$$
$$\gamma\gamma \to X^+X^-\ ,$$

Diphoton X-Pair Production

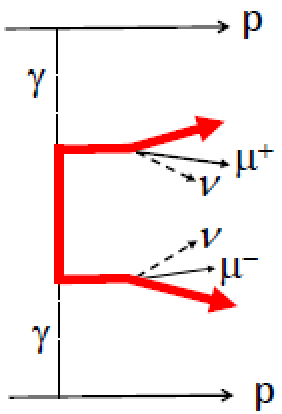
where $X =$ W–boson, lepton, slepton, chargino...

- 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)**

$M_{\tilde{l}}$ =120-300GeV, $\Delta M = M_{\tilde{l}} - M_{\tilde{\chi}_1^0} = 10-20$ GeV

Major backgrounds

- $\gamma\gamma \to W^+W^- \to l^+\nu + l^-\bar{\nu}$
- Low mass $\gamma\gamma \to l^+l^-$ production
  Semi-exclusive process with proton from (SD,DD) dissociation detected in the FPD.
- Semi-exclusive QCD-initiated BGs due to low-pt (mainly c-quark) jets, with SD and DD followed by proton hits in the FPD.
- Coincidence of inelastic lepton pair production with two independent SD/DD events from the PU interactions that mimics the signal.
  (danger for other New Physics searches with σ≤1 fb)
- ττ, dimeson, vector resonances etc…

Event Selection

$\geq$ 100 GeV from the LEP constraints

Compressed mass scenario → difference between slepton and DM candidate mass, ΔM, is small <m_{ll}> ~ ΔM → aim is to keep <m_{ll}> low → 2 < m_{ll} < 40 GeV

- $|\eta(l)| < 2{,}5$, cuts on $\eta(l_1) - \eta(l_2)$ (to supress BG)
- $p_T(l)$ >5 GeV (trigger conditions)

$p_T(l)$ <30 GeV (in order to supress the WW BG)

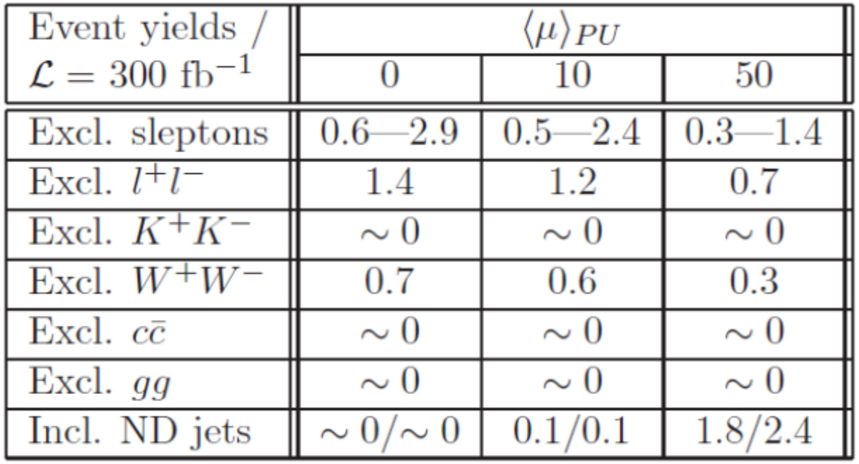
$\gamma\gamma \rightarrow W^+W^-$ with $W \rightarrow l\nu$

- requirement of no additional tracks with pt > 0.4 GeV at $|\eta| < 2{,}5$)
- both protons detected by the proton taggers (with FT)
- sleptons-quite small cross sections (0.01 -0.3 fb), +hostile PU environment
- chargino pair production- extra factor of ~25 suppression

Calculations: **SuperChic**, analytical, **PYTHIA 8.2, HERWIG 7.1** (quite reasonable agreement)

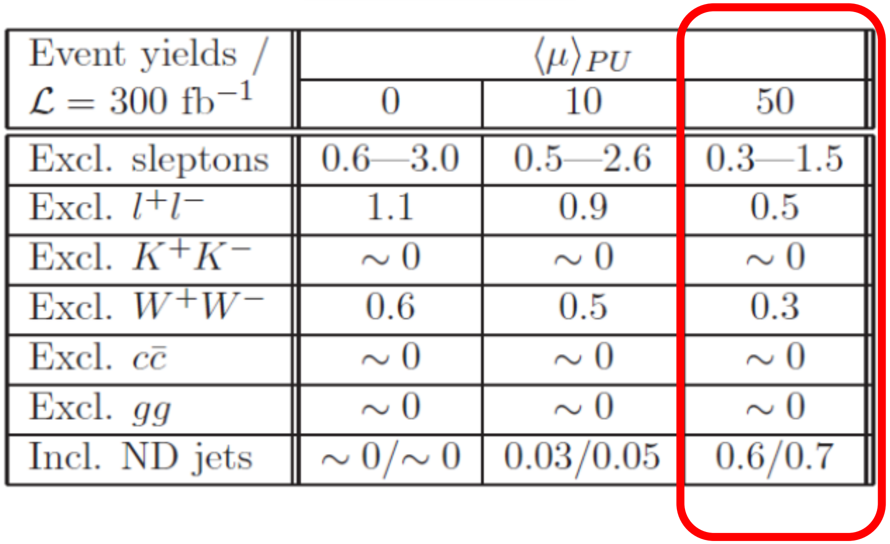
Integrated event yields for L=300fb^{-1}

|η| < 2.5



Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$		
	0	10	50
Excl. sleptons	0.6—2.9	0.5—2.4	0.3—1.4
Excl. l^+l^-	1.4	1.2	0.7
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.7	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0/\sim 0$	0.1/0.1	1.8/2.4

|η| < 4.0



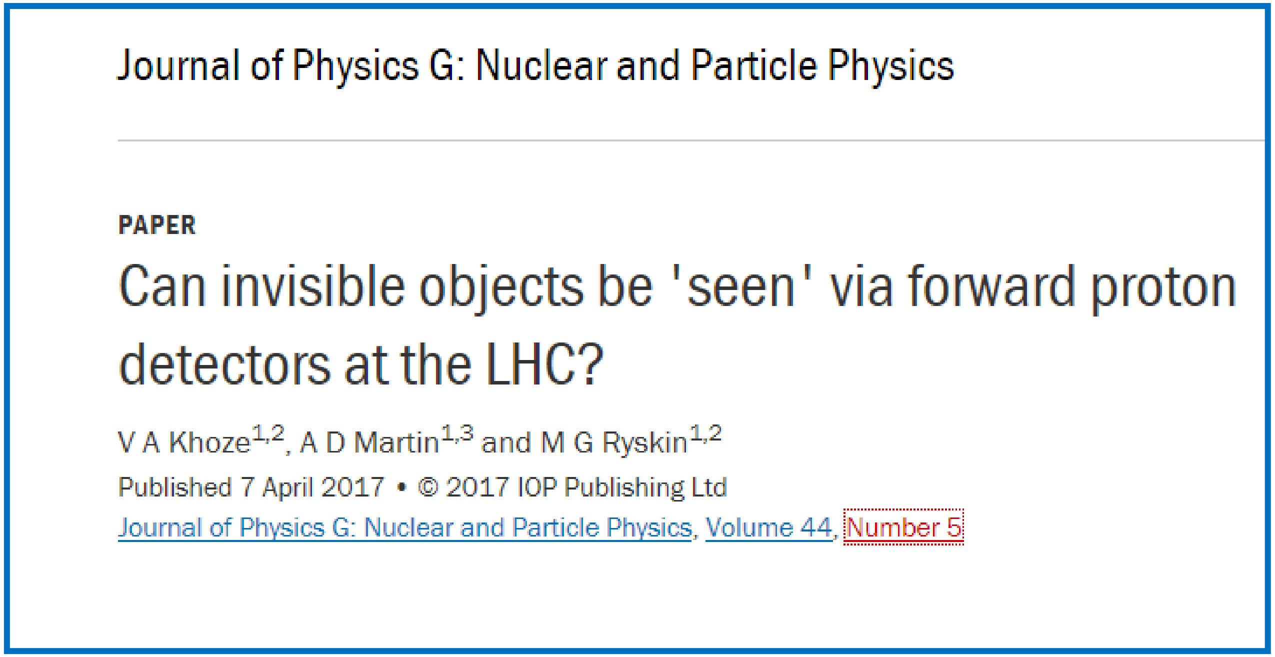
Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$		
	0	10	50
Excl. sleptons	0.6—3.0	0.5—2.6	0.3—1.5
Excl. l^+l^-	1.1	0.9	0.5
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.6	0.5	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0/\sim 0$	0.03/0.05	0.6/0.7

The yield range for signal corresponds to the slepton mass range studied: X(300 GeV) – Y(120 GeV)

Possible ways to suppress backgrounds:

- Cut on the distance of the secondary vertex from the primary vertex or on the pseudo-proper lifetime (many leptons from inclusive jets come from decays of heavy particles)
- Improve ToF resolution (ToF rejection improves with σ_t decreasing)
- ATLAS and CMS tracker upgrade: extend coverage up to |η|=4 and provide time info for tracks in 2.5<|η|<4.0.
- Timing detector in |η|<2.5??? (envisaged in CMS)

Courtesy of Marek Tasevsky



Journal of Physics G: Nuclear and Particle Physics

PAPER

Can invisible objects be 'seen' via forward proton detectors at the LHC?

V A Khoze[1,2], A D Martin[1,3] and M G Ryskin[1,2]

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$$pp \to p + \text{invisible} + p,$$

An attractive idea, but huge backgrounds caused by soft proton dissociation, photon bremsstrahlung and PU (at high lumi)

$p \to p + \gamma,\ N^* \to p + \gamma$ and $N^* \to p + \pi^o.$ $p \to p\pi^+\pi^-$

Measurements at low lumi ($\mu \sim 1$)with ‘veto’ detectors (like ZDC and FSC/ADA/ADC)

LHCb, ALICE, BLM-approach

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

Searches for Odderon- current status (personal view)

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

(in collaboration with Alan Martin and Misha Ryskin)

First measurement of proton-proton σ_{tot} at $\sqrt{s} = 13$ TeV ...

CERN-EP-2017-321, http://cds.cern.ch/record/2296409

First measurement of the ρ parameter at $\sqrt{s} = 13$ TeV ...

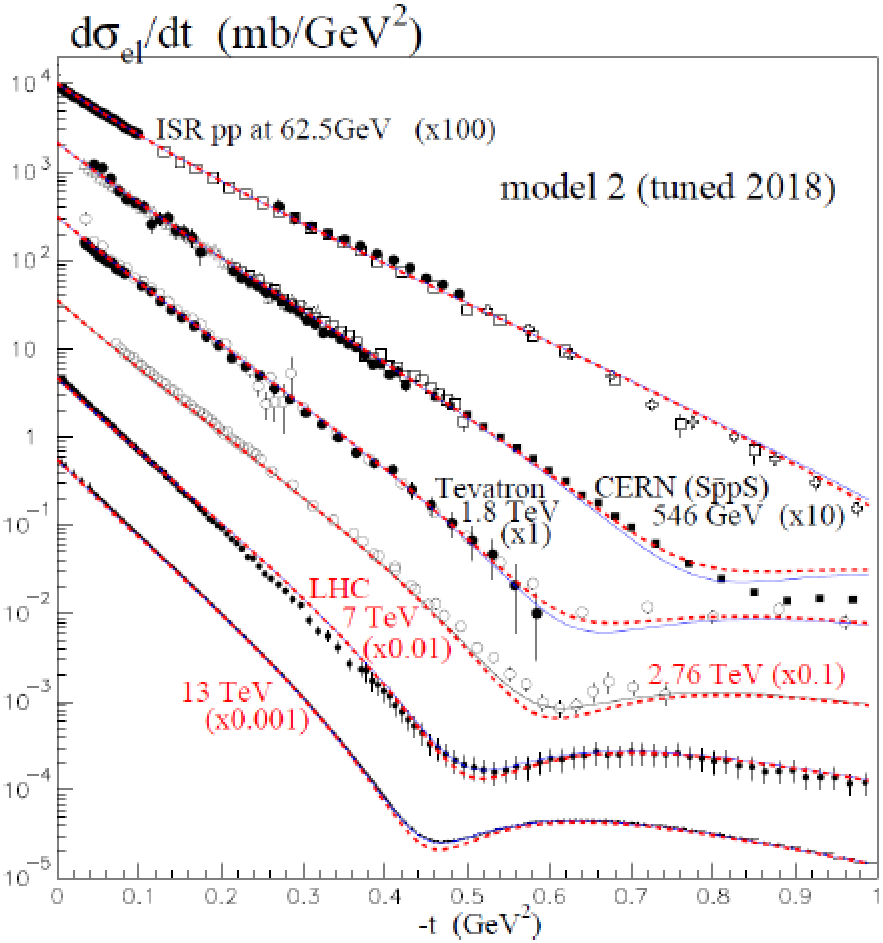
CERN-EP-2017-335 https://cds.cern.ch/record/2298154

$$\rho = \left.\frac{\Re \mathcal{A}_{\rm el}}{\Im \mathcal{A}_{\rm el}}\right|_{t=0}, \qquad (t = \text{four-momentum transfer squared})$$

- σ_{tot} and ρ: bound together by dispersion relations
  → measurement of both has greater discriminative power
- exploratory work
  - first measurements at the highest LHC energy
  - first ρ measurement in proton-proton collisions after decades
- follow up articles: CERN Courier, Finnish Physics Society, INFN press release, Kansas media communication, ...

- No consensus among the (theory) experts.

- ALFA is still silent.



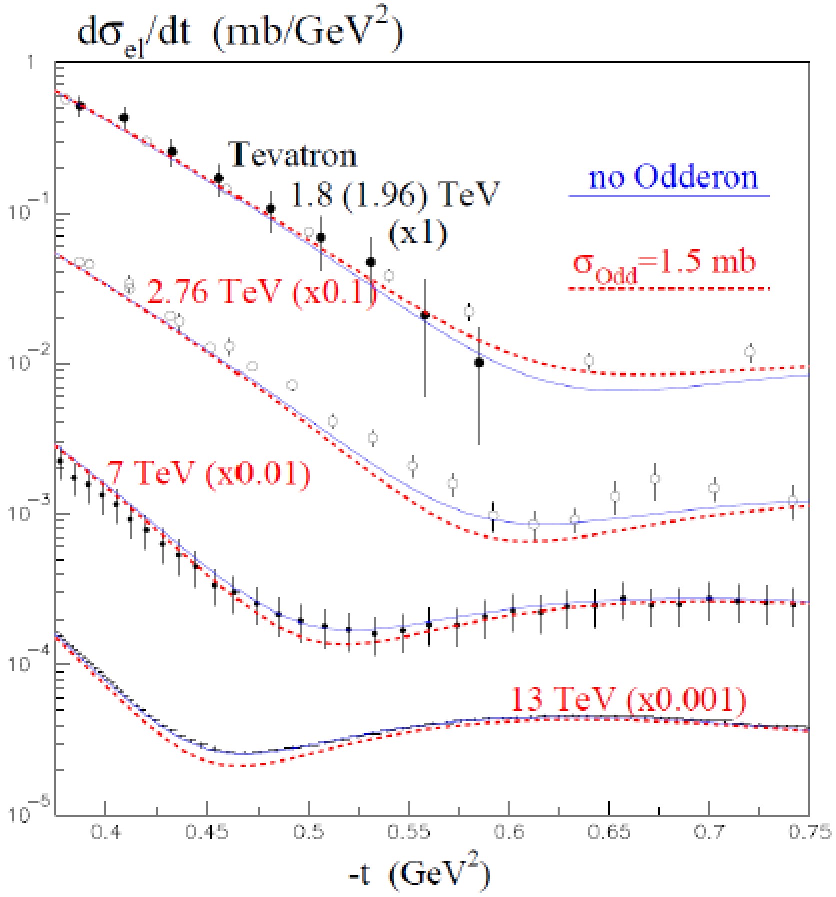
Previous fit, but now red-dotted curves show the effect of the Odderon fixed to agree with $\rho=\mathrm{Re}A/\mathrm{Im}A$

Note Odderon increases pp(bar)
decreases pp
Main effect in dip region

New TOTEM data at 2.76 TeV

Dip region

No conclusive evidence for a larger Odderon



pp(bar)

pp

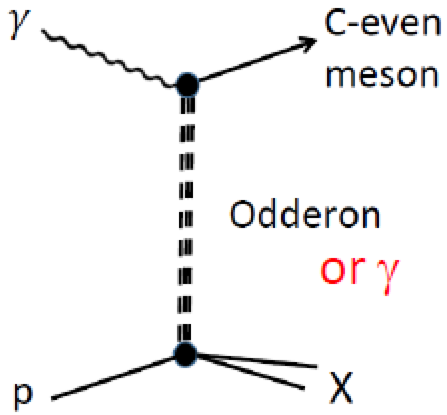
pp

pp

Other ideas ?

Odderon signals

- pp scatt Odderon exch. is a small correction to even-signature term $(g_{pO})^2$
- photoproduction of C even mesons π^0, f_2, η …



g_{pO}

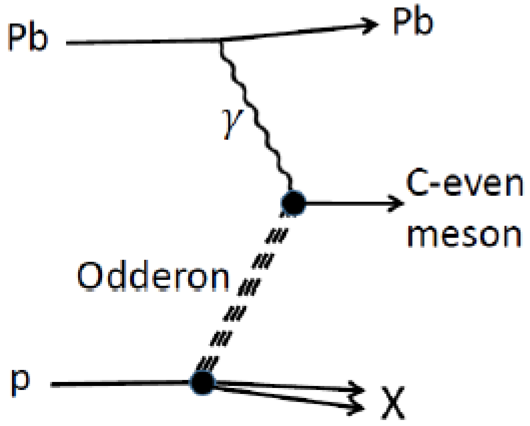
No evidence in HERA data

upper limits $\sigma(\pi^0)$=39nb, $\sigma(f_2)$=16nb

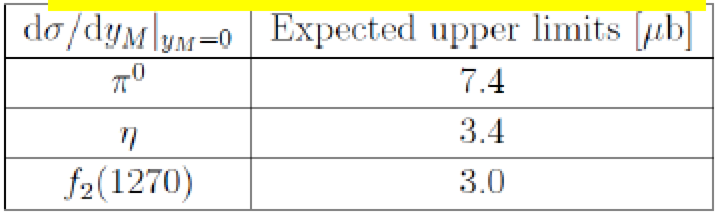
Need to suppress back^{gd} due to γ exchange

- ultraperipheral production in p-Pb collisions

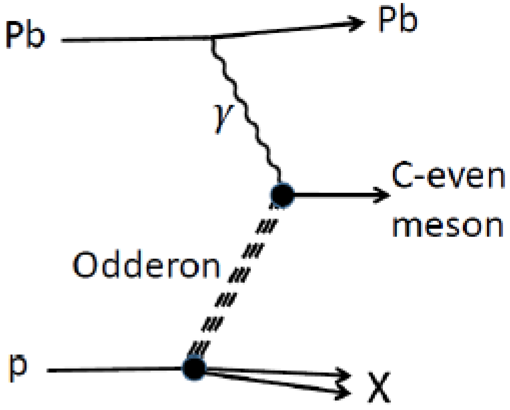
Z^2 in photon flux



Odderon signal in p-Pb collisions?



$d\sigma/dy_M\|_{y_M=0}$	Expected upper limits [μb]
π^0	7.4
η	3.4
$f_2(1270)$	3.0

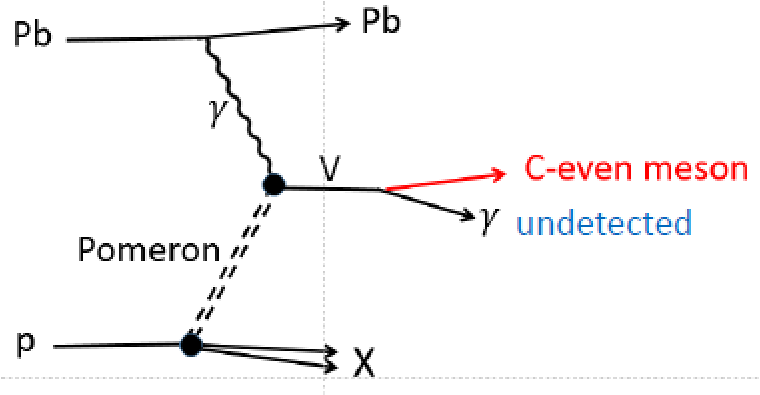


Healthy signal,
but backgrounds
are due to

production of C-even meson by

1. $\gamma\gamma$ fusion
2. Pomeron-Pomeron fusion
3. Via vector meson

   V → C-even meson + undetected γ

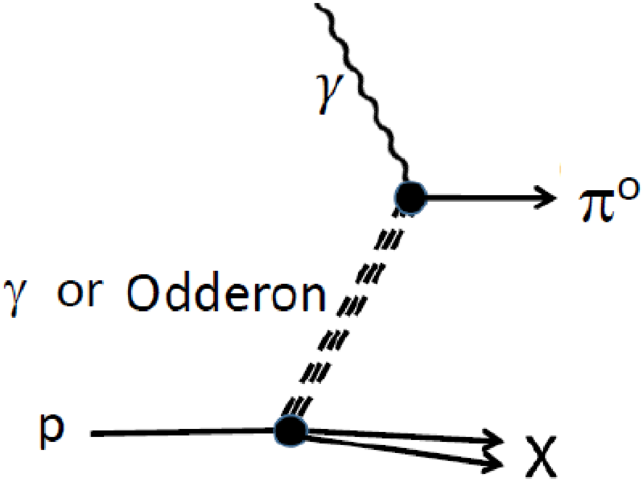


π^0

$\sigma(\pi^0)$ from $\gamma\gamma$ fusion is well known.
Estimwating the cross section due to Odderon exchange, allowing for the colour factors etc. and integrating over $|t| > 1$ GeV^2 we find

$$\sigma_{Odd}(\gamma p \rightarrow \pi^0 + X) \sim 5(1) \text{ nb}$$

for the cutoff $\mu = 0.3(0.5)$ GeV.
The t cut adequately suppresses the $\gamma\gamma$ fusion background.

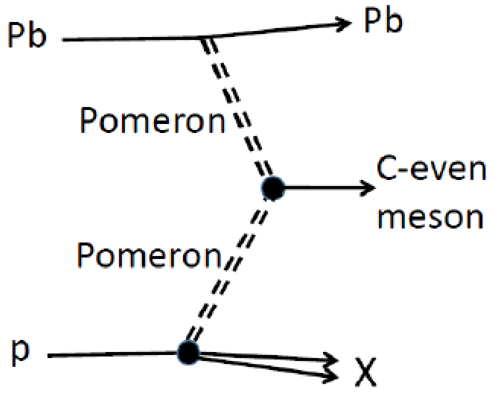


Pomeron-Pomeron background entirely absent by SU(3) flavour

However the reducible background from radiative ω decay is very large

$\omega \rightarrow \pi^0 + \gamma$ (undetected)

f_2



There is a very low backround due to radiative V decay. However the problem here is the v.large Pomeron-Pomeron background. The signal-to-bkgd may be suppressed by observing central (semi)exclusive production (CEP*) of C-even mesons in which the proton may break up but the Pb-ion remains intact. For such events we expect a larger possibility of break-up for Odderon exchange --- exptally challenging.

In any nucleon-proton interaction creating the C-even meson there is a large probability of inelastic nucleon-proton interactions which will populate the rapidity gaps. Only in very peripheral ion-proton collisions is there a chance to observe a CEP* event.

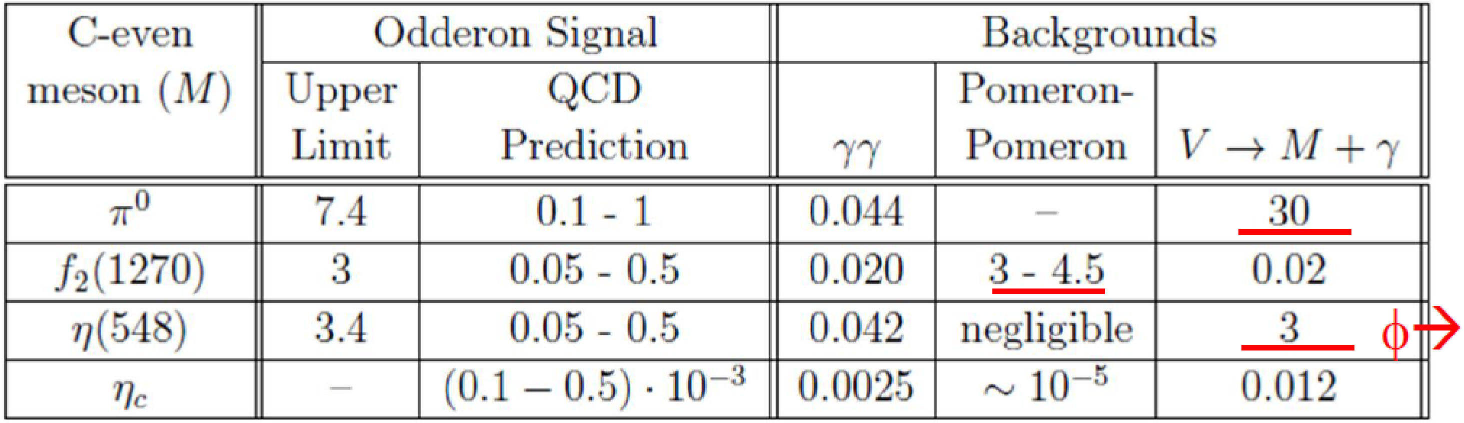
Can show the A dependence of CEP* events scales as $A^{1/3}$. Recall the photoprod^n cross section (the signal) scales as Z^2, so the expected $A^{1/3}$ back^{gd} scaling is much milder.

η

Pom-Pom background is small as η has small SU(3) singlet compt.
However again the reducible backgrounds coming from
$\phi \rightarrow \eta\gamma$ and $\eta' \rightarrow \eta\pi^0\pi^0$ are rather large

η_c

In principle, viable channel but has a much smaller production rate.



C-even meson (M)	Odderon Signal		Backgrounds		
	Upper Limit	QCD Prediction	$\gamma\gamma$	Pomeron-Pomeron	$V \rightarrow M + \gamma$
π^0	7.4	0.1 - 1	0.044	–	30
$f_2(1270)$	3	0.05 - 0.5	0.020	3 - 4.5	0.02
$\eta(548)$	3.4	0.05 - 0.5	0.042	negligible	3
η_c	–	$(0.1 - 0.5) \cdot 10^{-3}$	0.0025	$\sim 10^{-5}$	0.012

$\phi \rightarrow \eta\gamma$

signal and background for dσ(Pb p → Pb + *M* +X)/dY at Y=0

$d\sigma/dY_M$ at $Y_M = 0$ in μb

C-even meson (M)	Odderon Signal		Backgrounds			
	Upper Limit	QCD Prediction	$\gamma\gamma$	Pomeron-Pomeron	$V \to M + \gamma$	γ unobserved
π^0	7.4	0.1 - 1	0.044	–	30	($\omega \to \pi^0\gamma$)
$f_2(1270)$	3	0.05 - 0.5	0.020	3 - 4.5	0.02	($J/\psi \to f_2\gamma$)
$\eta(548)$	3.4	0.05 - 0.5	0.042	negligible	3	($\phi \to \eta\gamma$)
η_c	–	$(0.1 - 0.5) \cdot 10^{-3}$	0.0025	$\sim 10^{-5}$	0.012	($J/\psi \to \eta_c\gamma$)

η_c x 0.05 for observable BR

p p → p + *M* + X Pom – Pom background overwhelming

Pb Pb → Pb + *M* + Pb γγ background overwhelming

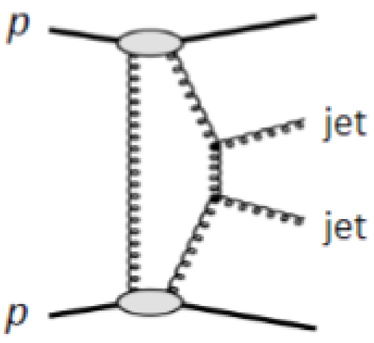
Ronan McNulty: Pb-Pb data could check model for Pom-Pom bk^{gd} for f_2; BR($f_2 \to \gamma\gamma$)~10^{-5}

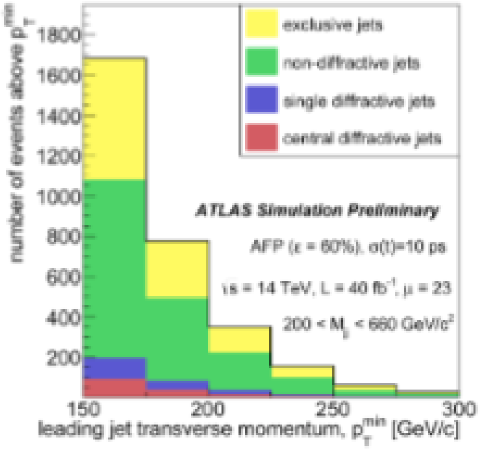
Physics with AFP 2+2 (high μ)

Central Exclusive Jet Production

First observed by CFD@Tevatron

Low σ → high pile-up run
- → double tag
- → ToF to control bkg



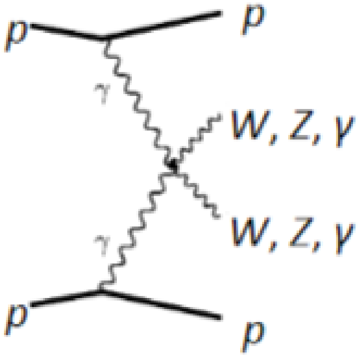


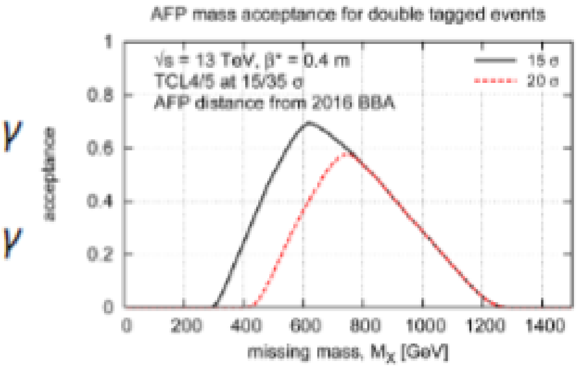
Photon-induced WW/ZZ/γγ Production

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

New Particles?

Compare mass and rapidity of central and pp systems





Dileptons good for calibration

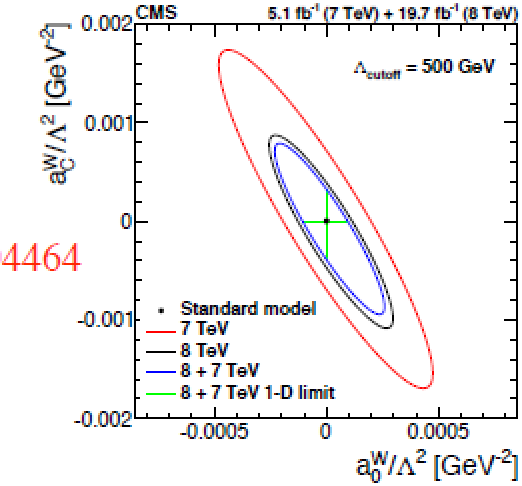
The (foreseeable) future

- **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)?
  - γγ→WW/ZZ/γγ and new high-mass resonances
  - …

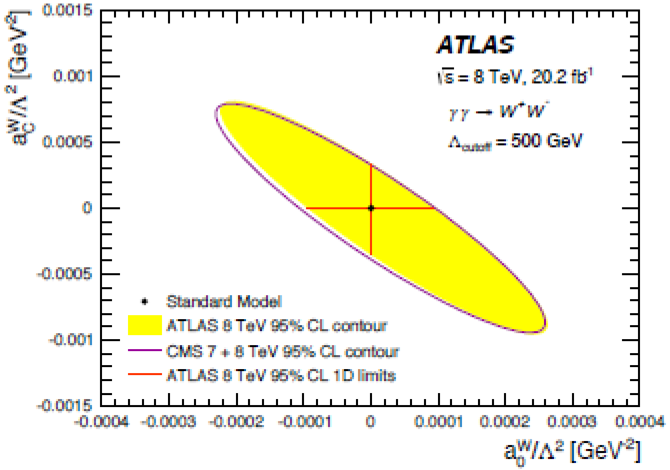
Research Program will depend on LHC strategy and Previous Results

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.