Photon-Initiated Production: Theory Overview

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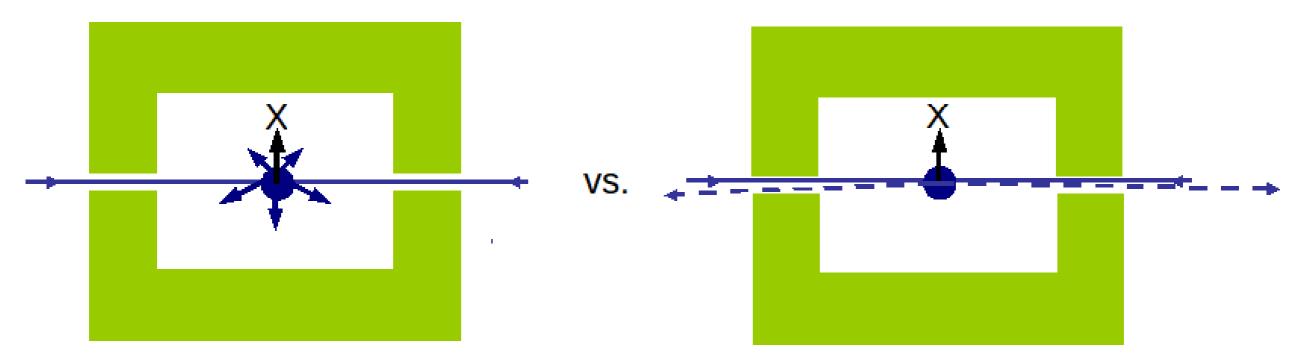
Workshop on Photon-Induced Processes, IPPP Durham, Nov 3 2022

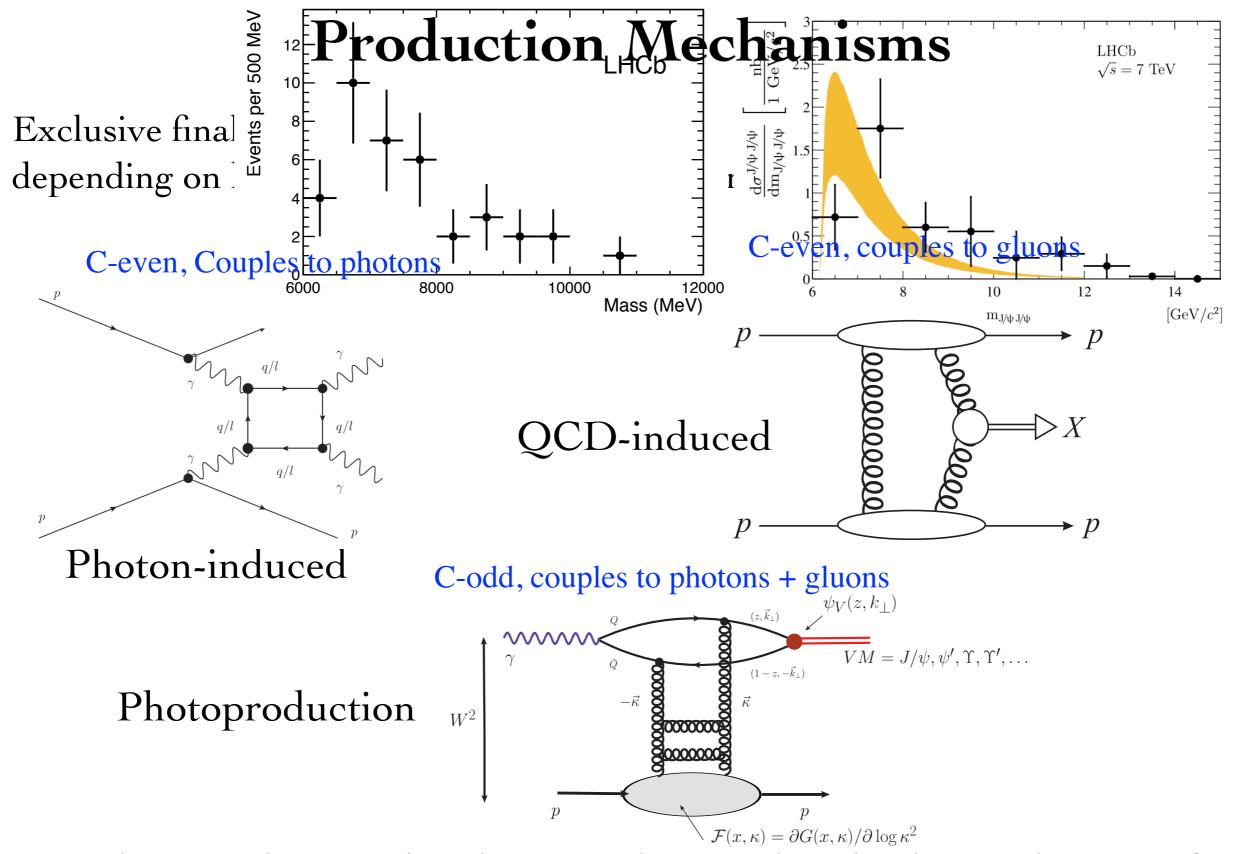
Central Exclusive Production

Central Exclusive Production (CEP) is the interaction:

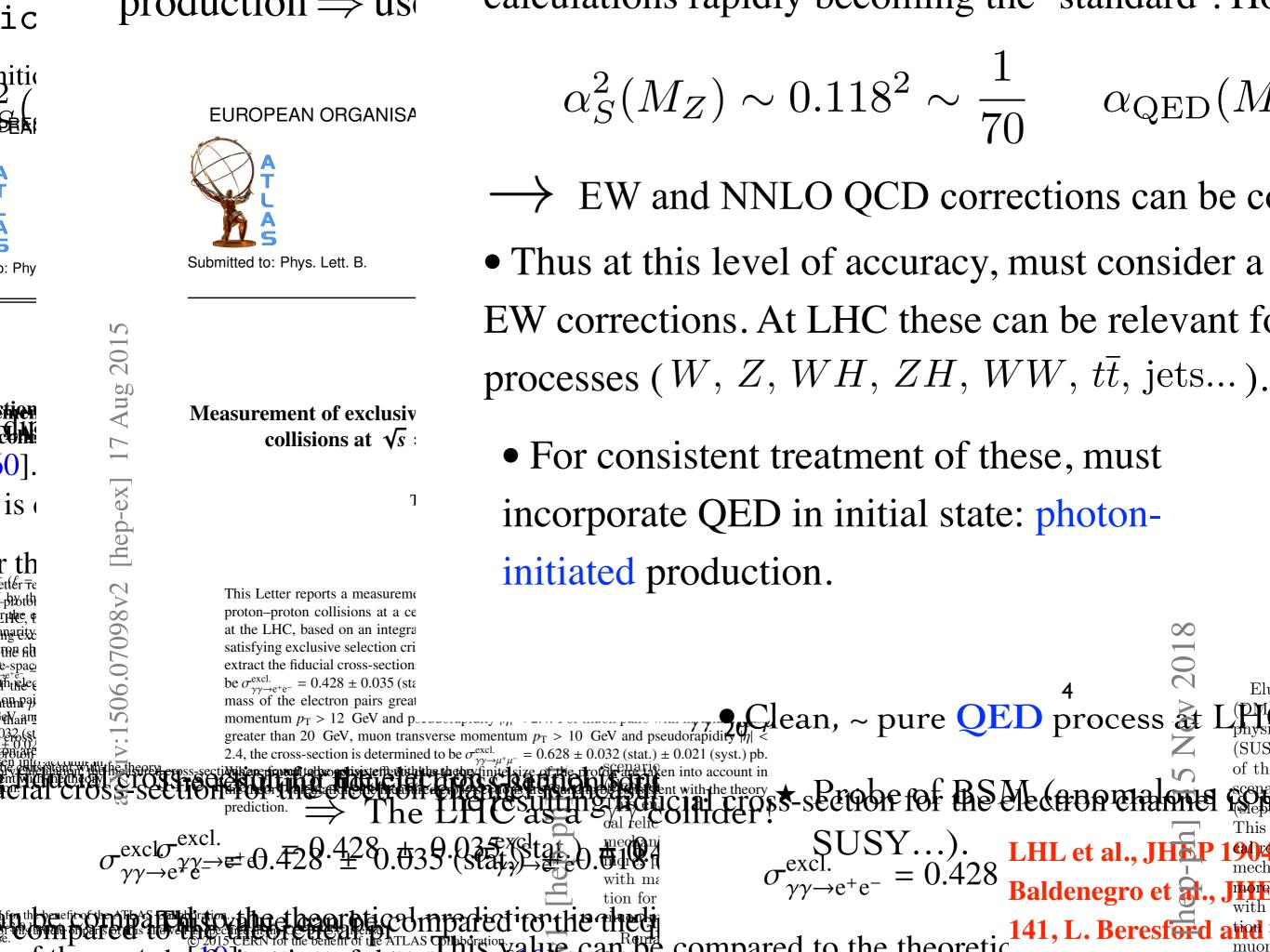
$$hh \rightarrow h + X + h$$

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





Focus here on photon-induced (PI) production, though other mechanisms of course of broader interested in CEP programme.

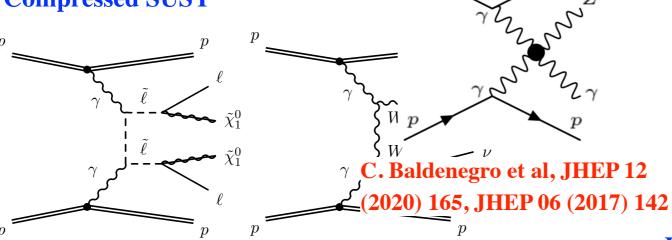


★ Probe of BSM:

Anomalous couplings

tau g-2





L. Beresford and J. Liu, PRD 102 (2020) 11, 113008 M. Dyndal et al., PLB 809 (2020) 135682

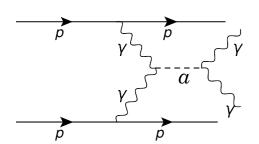
LbyL scattering/ALPS

LHL et al., JHEP 1904 (2019) 010 $_W$ boson pairs via photon–photon fusion in the $\ell\nu\ell\nu$ final

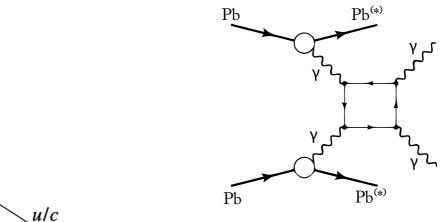
L. Beresford and J. Liu, PRL 123 (2019) no.14

Axion-like Particles

LHL and M. Tasevsky, arXiv:2208.10526 C. Baldenegro et al., *JHEP* 06 (2018) 131



★ Probe of the top sector.



er 3, 2018 — 13

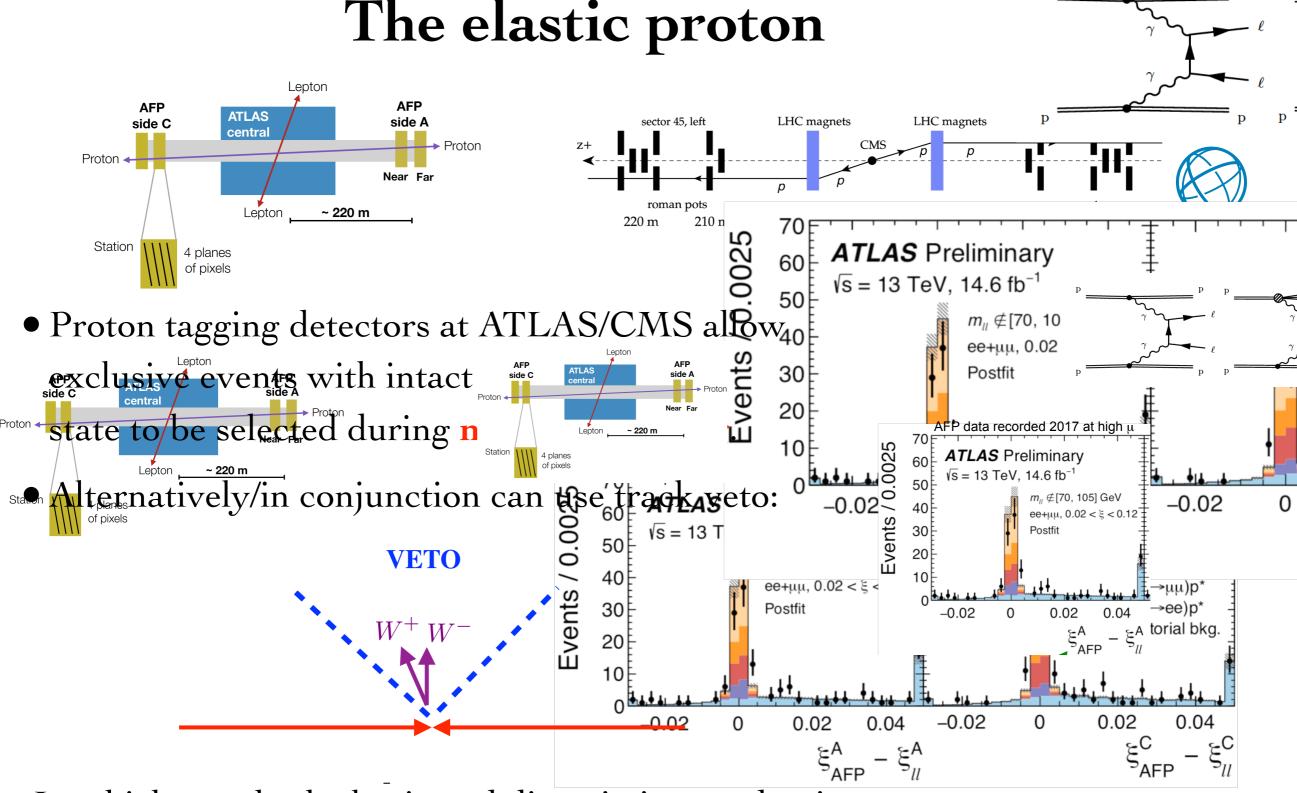
C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

V. Goncalves et al., *Phys.Rev.D* 102 (2020) 7, 074014 J. Howarth, arXiv:2008.04249

★ Laboratory to test our models of proton dissociation + proton-

min

proton MPI effects. LHL et al., EPJC 76 (2016) no. 5, 255, LHL et al., Eur.Phys.J.C 80 (2020) 10, 925 L. Forthomme et al., PLB 789 (2019) 300-307



- In which case both elastic and dissociative production can enter.
- How do we model this process theoretically? And how well can we model it?

SuperChic 4 - MC Implementation

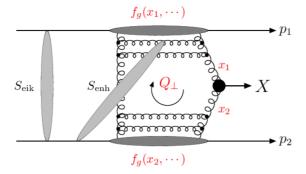
- A MC event generator for CEP processes. Common platform for:
- QCD-induced CEP.
- Photoproduction.
- Photon-photon induced CEP.
- For pp, pA and AA collisions. Weighted/unweighted events (LHE, HEPMC) available- can interface to Pythia/HERWIG etc as required.

SuperChic 4 - A Monte Carlo for Central Exclusive and Photon-Initiated Production

Home • Code References

Contact

SuperChic is a Fortran based Monte Carlo event generator for exclusive and photon-initiated 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 userdefined 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



A list of references can be round here and the code is available here

Comments to Lucian Harland-Lang < lucian.harland-lang (at) physics.ox.ac.uk >.

https://superchic.hepforge.org

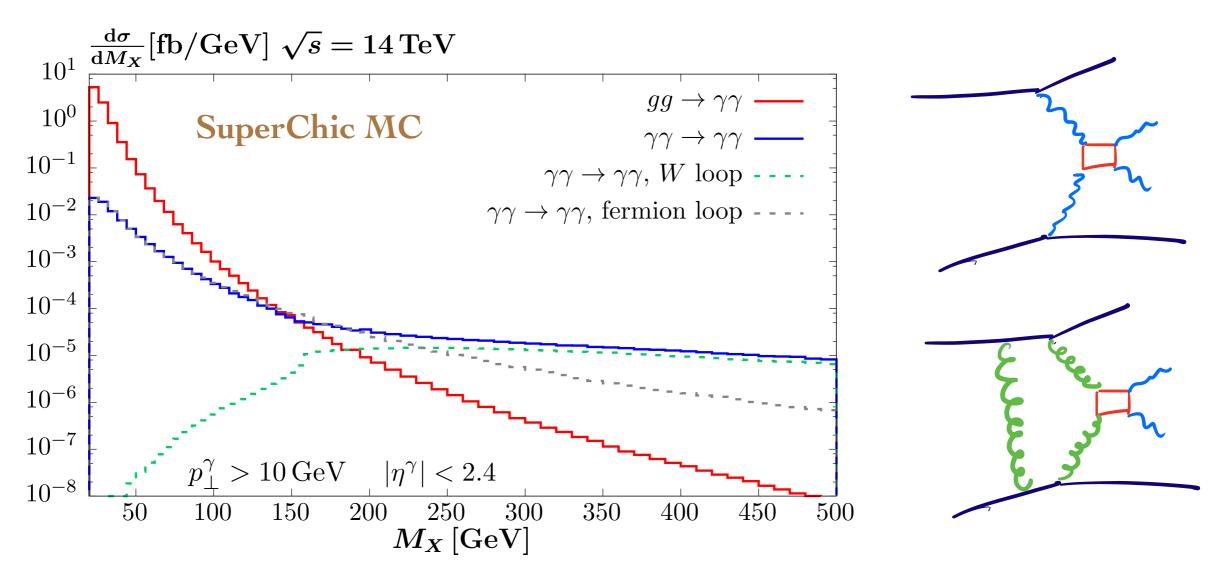
• N.B.: discussion here will follow the theory implementation of the SC4 MC.

LHL et al., Eur. Phys. J.C 80 (2020) 10, 925

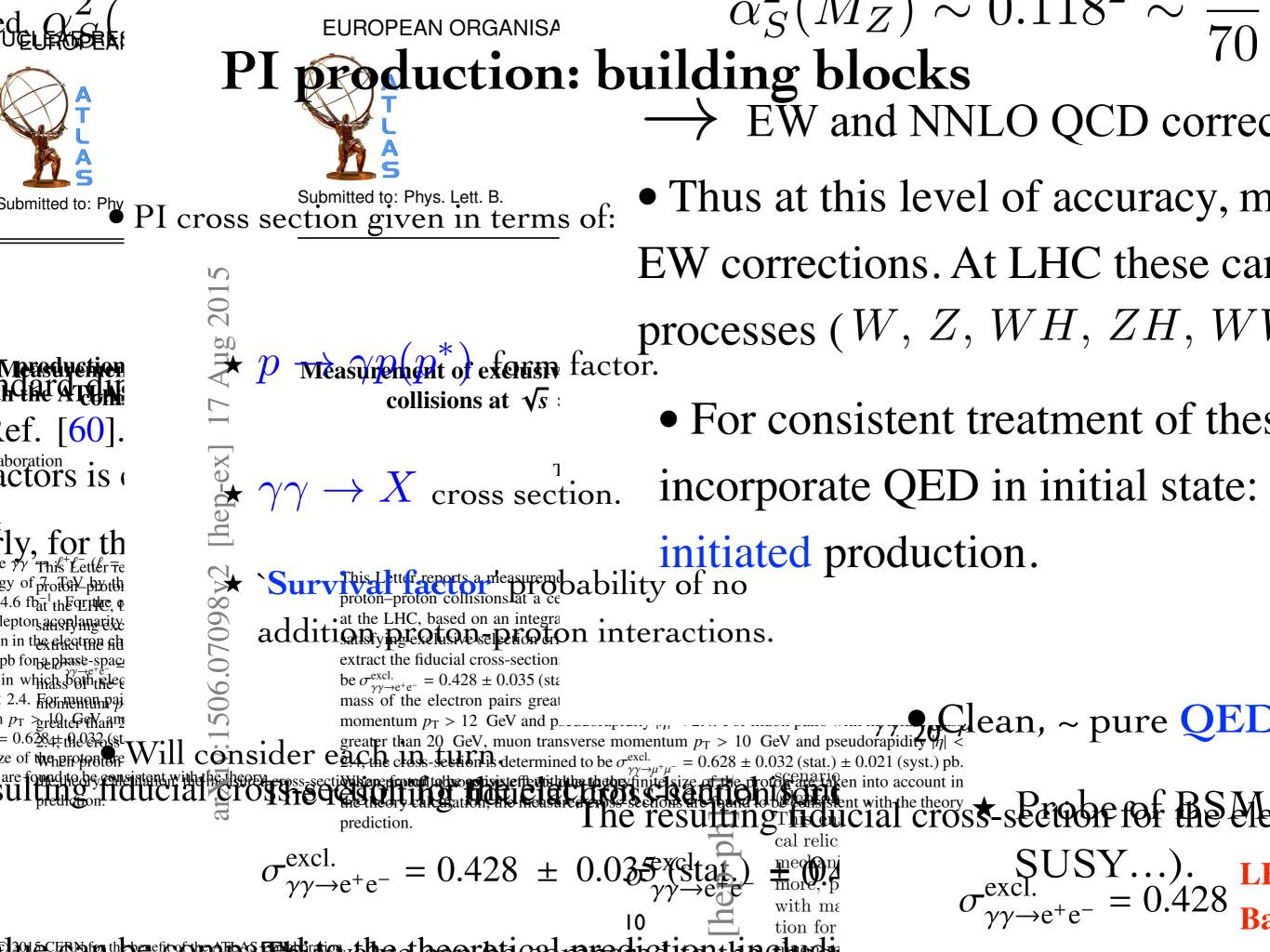
gg vs. $\gamma\gamma$

- For some processes both QCD and photon initiated production can contribute.
- However, for higher masses QCD production strongly suppressed by no radiation probability from initial-state gluons.

→ At higher mass PI production starts to dominate.

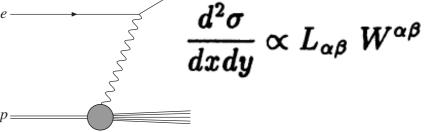


Modelling PI Production (pp collisions)



Structure Function Calculation

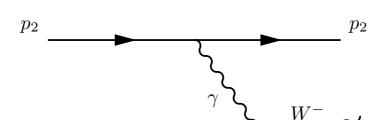
- Both elastic and dissociative PI production can be modelled in `Structure function' approach:
- ullet Structure functions parameterise the $\gamma p o X$ vertex.



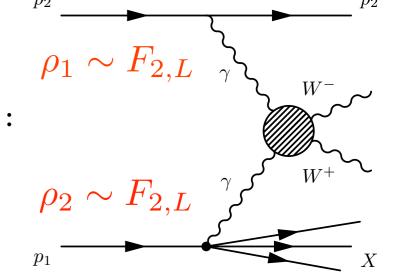
• Use same idea as for DIS to write:

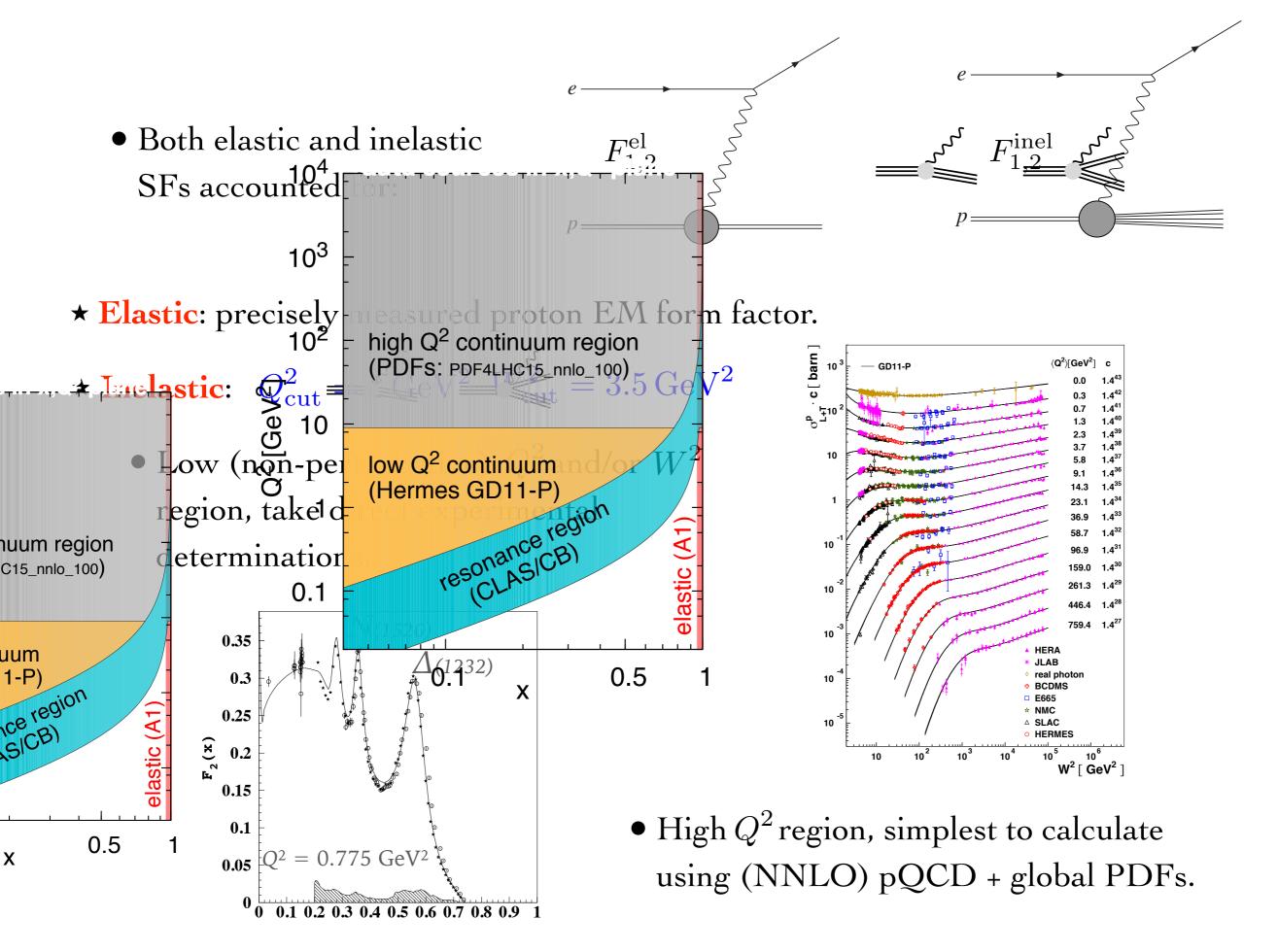
$$W^{lphaeta}(p,q) = \Big(g^{lphaeta} - rac{q^lpha q^eta}{q^2}\Big)W_1(x,Q^2) + \Big(p^lpha + rac{1}{2x}q^lpha\Big)\Big(p^eta + rac{1}{2x}q^eta\Big)W_2(x,Q^2)$$

$$\sigma_{pp} = \frac{1}{2s} \int dx_1 dx_2 d^2 q_{1_{\perp}} d^2 q_{2_{\perp}} d\Gamma \alpha(Q_1^2) \alpha(Q_2^2) \frac{\rho_1^{\mu\mu'} \rho_2^{\nu\nu'} M_{\mu'\nu'}^* M_{\mu\nu}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X) ,$$



• Cross section given in terms of photon density magnetic ρ_i





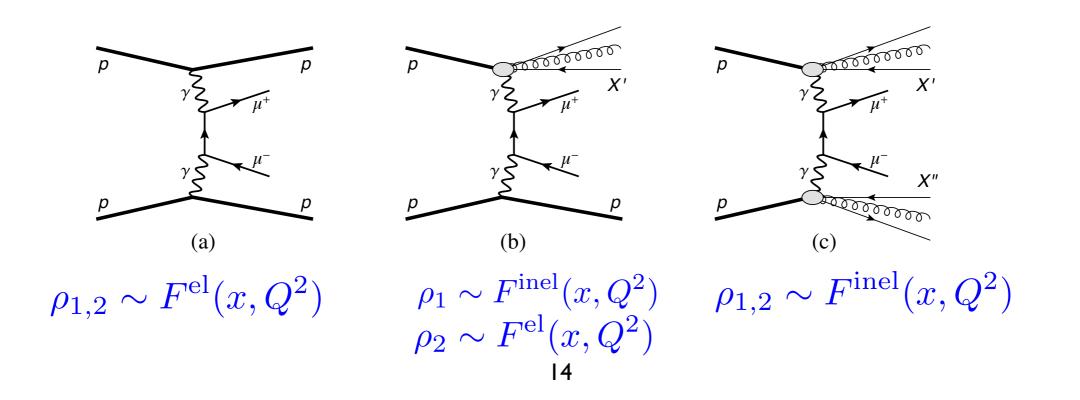
EW corrections. At LHC thes processes (W, Z, WH, ZH) $z
ightarrow \ell^+ \ell$ Nexadvetion **Measurement of exclusiv** pestandara and collisions at \sqrt{s} : • For consistent treatment of om Ref. [60]. A. Manohar et al., JHEP 1712 (2017) 046 incorporate QED in initial st Abstract initiated production. This Letter reports a measureme of-mass energy of Trotter photh proton-proton collisions at a ce minosity of 4.6 fbat the orthog e afit to the dilepton agoplanarity at the LHC, based on an integra satisfying exclusive selection cri cross-section in the electron sh 0.018 (syst.) pb foரு phase-spac extract the fiducial cross-section be $\sigma_{\gamma\gamma\to e^+e^-}^{\rm excl.} = 0.428 \pm 0.035$ (sta 24 GeV, in which both the ec rapidity $|\eta| < 2.4$. From Panagan pai mass of the electron pairs great greater than 20 GeV, muon transverse momentum $p_T > 10$ GeV and pseudorapidity 2.4, the cross-section is determined to be $\sigma_{av}^{\text{excl.}}$ $_{+\mu^{-}} = 0.628 \pm 0.032 \text{ (stat.)} \pm 0.021 \text{ (syst.) pb.}$ 0.01 **PDF** $\sigma_{\gamma\gamma\to e^+e^-}^{\text{excl.}} = 0.4$ The ration of the first the control of the control ne finite size of the proton desprise the benefit of the ATLAS Compared to the theore Uncertainty in inputs ~ to equivalent photon HDE upper plainty. That is % ton PPS Lifter proton in the p level or less (in particular Por elastic 0.39) $\gamma\gamma = 0$ Strategies for invisible DM states and 0diators [18-29]: the kinematics of Clicking Applied or the muon channel, the fidule is haros elso then the hards end delighted the second of the second is measurable. Without the

Los the second by DM can only be determined in the plane trade

- SF approach can provide high precision predictions for inclusive PI production.
- But also uniquely suited to deal with situation where we ask for limited hadronic activity/intact protons in PI process:

$$\sigma_{pp} = \frac{1}{2s} \int dx_1 dx_2 d^2 q_{1\perp} d^2 q_{2\perp} d\Gamma \alpha(Q_1^2) \alpha(Q_2^2) \frac{\rho_1^{\mu\mu'} \rho_2^{\nu\nu'} M_{\mu'\nu'}^* M_{\mu\nu}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X) ,$$

- ★ Can isolate elastic component of $F_{1,2}$ to give exclusive prediction.
- * Fully differential in photon $x, Q^2 \Rightarrow$ invariant mass of proton dissociation system (higher $W^2 \Rightarrow$ more hadronic activity).



→ EW and NNLO QCD corrections can be comparable in size.

Having generated exclusive/semi-exclusive events, pass to general
 Thus at this level of accuracy, must consider a proper account of purpose MC for showering/hadronisation of dissociation system.

EW corrections. At LHC these can be relevant for a range of

Backup processes $(W, Z, WH, ZH_QWW) t\bar{t}$ to pose Photon collider search strategy

• For consistent treatment of these, must incorporate QED in initial state: photoninitiated production.

 $Q^2, M^2 \to \text{General Purpose } \underline{MC}_{\text{INTRODUCTIO}}$

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detect

We propose a search strategy using th

masses of up to 200 GeV 101 10 2

Elucidating the elementary properties of dark m

for these key targets have no sensitivity when mas ferences are $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \lesssim 60 \text{ GeV } [11\text{-}\text{Figure}]$.

We encourage the LHC collaborations to

lepton (slepton ℓ) $\tilde{\chi}_1^0$. This region is

searches are hind

measuring initial peripheral collision

Then-simply imposed than t particle developments process at Lippes among the most urgent problems in fundaments werse momentum $p_T > 10$ GeV and pseudorapidity $p_T < 10$ GeV and $p_T < 10$ G (SUSY) extensions of the Standard Model (SM) is to be $\sigma_{\gamma\gamma\to\mu^+\mu^-}^{\rm excl.} = 0.628 \pm 0.032 \, ({\rm stat.}) \pm 0.021 \, ({\rm syst.}) \, {\rm photographic control of PL products on the Standard Model (SM) is the product of the standard Model (SM) is the product of the product of the standard Model (SM) is the product of the product of the product of the standard Model (SM) is the product of t$

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th masses near the weak scale are a leading exp 141. L. Beresferd ation of July devisions to ween the aspendented or the ATLAS Combination and the compared to the theoretic 11 Remarkably, Large Hadron Collider (LHC) sea

the finite size of the proton [10]:

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 $\mathbf{B}_{-}^{\text{tr.}} = 0.398 \mathbf{B}_{\perp} \mathbf{t0}$

Large Electron Positron (LEP) collider limits remai it stringent, evaluding melő) (± 97-GeV-15-TT). ICO IOM GO PAR SAMASTICIA A SEPERTE EVAN Y search strategies for invisible DM states Pand Quit metegi diators [18–29]: the kinematics of colliding and the

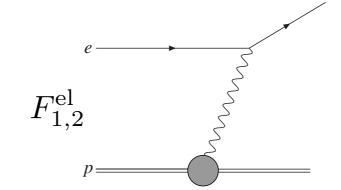
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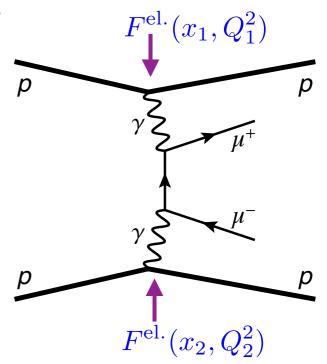
The Survival Factor

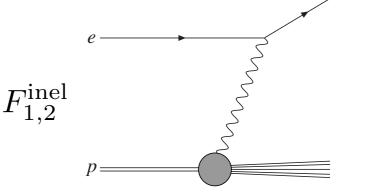
• Consider e.g. the exclusive process. So far we have (very) schematically:

$$\sigma \sim F^{\text{el.}}(x_1, Q_1^2) F^{\text{el.}}(x_2, Q_2^2)$$

- Similarly for SD + DD, with $F^{\text{el.}} \to F^{\text{inel.}}$
- These inputs are measured in lepton-hadron scattering.



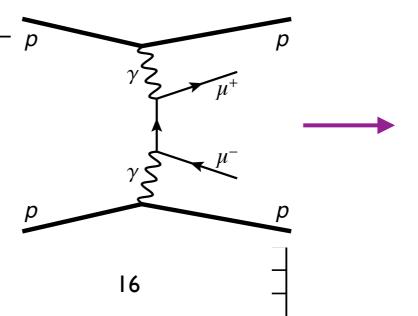


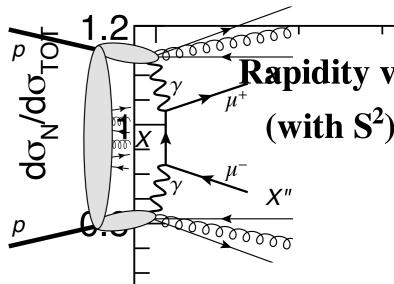


But we are interested in

Inclusivedron-hadron scatter hgy.8.2

need to account for additional hadron-hadron interactions.



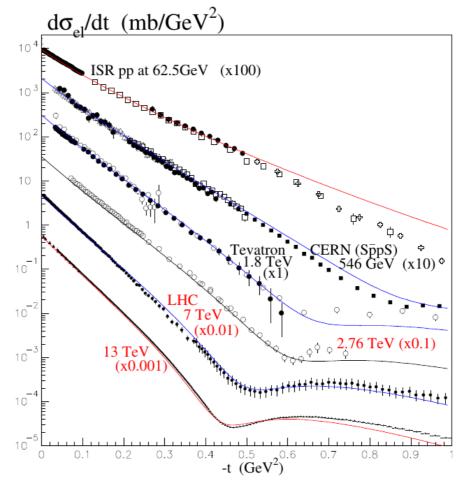


• 'Survival factor' = probability of no additional inelastic hadron-hadron interactions. Schematically:

$$\sigma \sim S^2 \cdot \sigma^{\gamma \gamma}$$

- How to model this? Depends on e.g. $\sigma^{\rm inel}$ in soft regime \Rightarrow requires understanding of proton + strong interaction in non-perturbative regime.
- Build phenomenological models, and tune to wealth of data on elastic + inelastic proton scattering at LHC (and elsewhere).

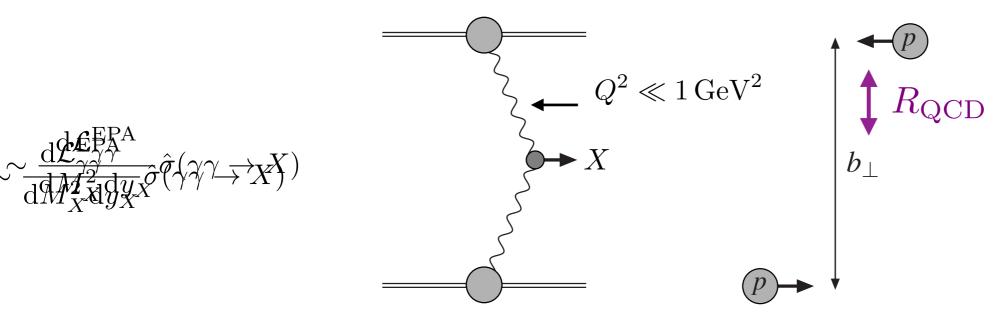
 In general source of uncertainty. Is this the case for PI production?



V. A. Khoze et al., *Eur.Phys.J.C* 81 (2021) 2, 175

The Survival Factor in PI processes

- Protons like to interact: naively expect $S^2 \ll 1$.
- However elastic PI production a special case: quasi-real photon $Q^2 \sim 0 \Rightarrow$ large average pp impact parameter $b_{\perp} \gg R_{\rm QCD}$, and $S^2 \sim 1$.



- XRelatively clean $\gamma \gamma$ initial state, with QCD playing small role in elastic case. LHC as a $\gamma \gamma$ collider!
 - In more detail...

- How do we calculate survival factor for PI production? Simplest if we consider collision in terms of proton-proton impact parameter.
- Writing schematically:

$$\sigma = \int d^2 q_{1_{\perp}} d^2 q_{2_{\perp}} |M(\vec{q}_{1_{\perp}}, \vec{q}_{2_{\perp}}, ...)|^2$$

• We can write this as integral over ion impact parameters:

$$\sigma = \int d^2b_{1_{\perp}} d^2b_{2_{\perp}} |\tilde{M}(\vec{b}_{1_{\perp}}, \vec{b}_{2_{\perp}}, ...)|^2$$

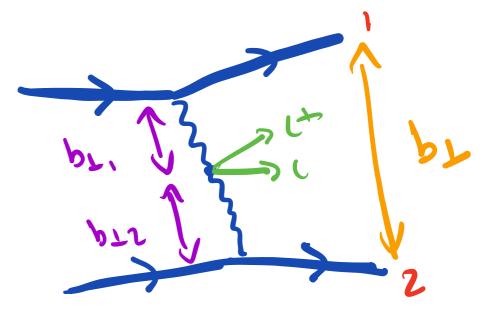
• Where:

$$M(\vec{b}_{11},\vec{b}_{12},...) = FT(M(\vec{z}_{11},\vec{z}_{21},...))$$

$$M(\vec{b}_{11},\vec{b}_{12},...) \sim \int d^{2}z_{11} d^{2}z_{11} e^{-i\vec{z}_{11}\cdot\vec{b}_{11}} e^{-i\vec{z}_{11}\cdot\vec{b}_{21}}$$

$$M(\vec{z}_{11},\vec{z}_{11},...) \sim \int d^{2}z_{11} d^{2}z_{11} e^{-i\vec{z}_{11}\cdot\vec{b}_{21}}$$

$$M(\vec{z}_{11},\vec{z}_{11},...) = 0$$



• To first approximation, we then simply require:

$$\sigma = \int d^{2}b_{1_{\perp}} d^{2}b_{2_{\perp}} |\tilde{M}(\vec{b}_{1_{\perp}}, \vec{b}_{2_{\perp}}, ...)|^{2}$$

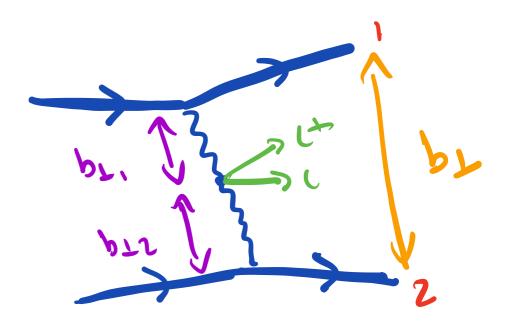
$$\sigma = \int d^{2}b_{1_{\perp}} d^{2}b_{2_{\perp}} |\tilde{M}(\vec{b}_{1_{\perp}}, \vec{b}_{2_{\perp}}, ...)|^{2} \Theta(b_{\perp} - 2r_{p})$$

$$b_{\perp} = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$$

• That is, only integrate over impact region where:

$$b_{\perp} > 2r_p$$

holds!



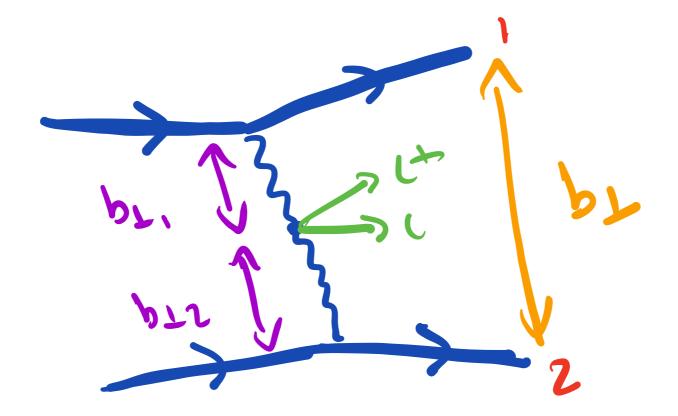
• In more detail, condition is not discrete - some overlap can occur. Schematically:

$$\sigma = \int d^2b_{1_{\perp}} d^2b_{2_{\perp}} |\tilde{M}(\vec{b}_{1_{\perp}}, \vec{b}_{2_{\perp}}, ...)|^2 e^{-\Omega(\vec{b}_{1_{\perp}} - \vec{b}_{2_{\perp}})}$$

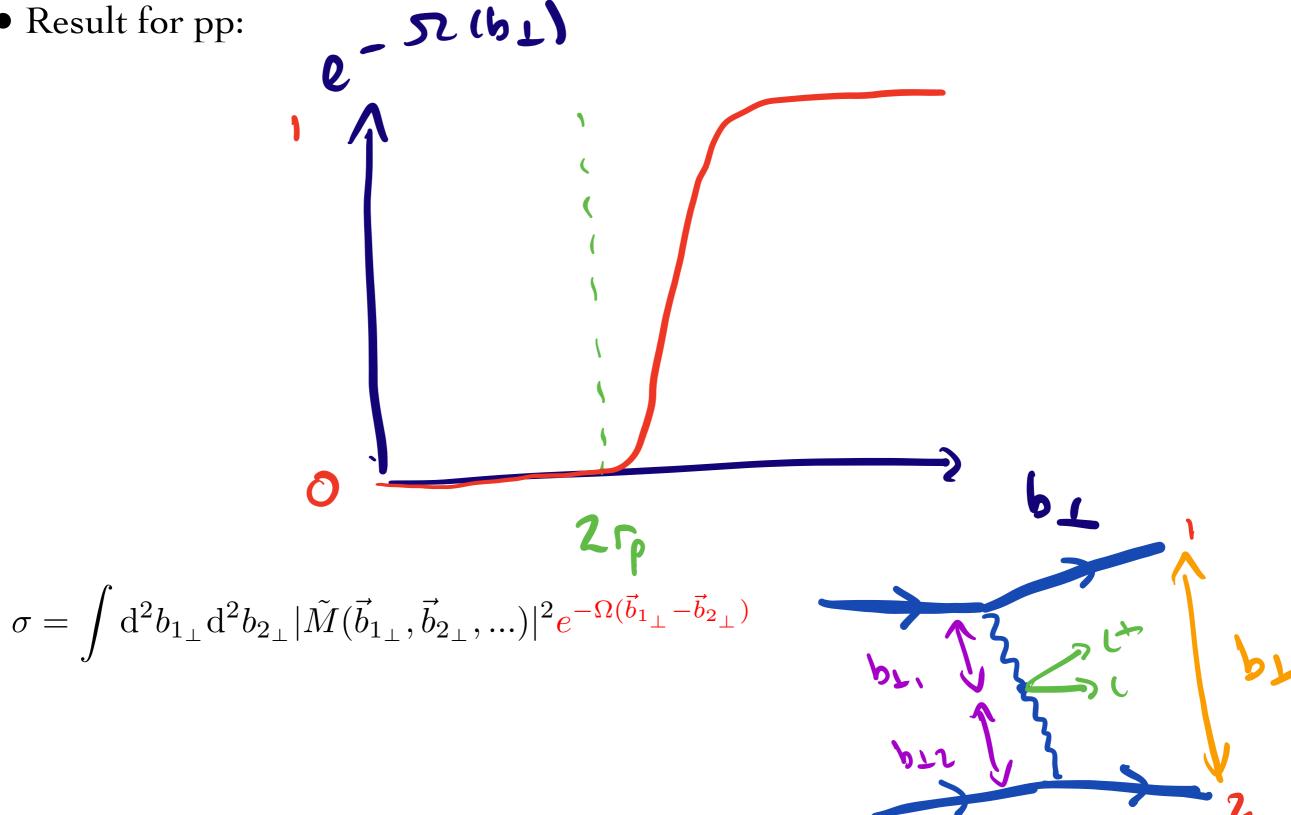
 $e^{-\Omega(\vec{b}_{1}_{\perp} - \vec{b}_{2}_{\perp})}$: survival factor - probability for no additional particle production at impact parameter $b_{\perp} = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$. Roughly:

$$e^{-\Omega(b_{\perp})} \approx \Theta(b_{\perp} - 2r_p)$$

but not exact!



• Result for pp:



• What does this tell us about survival factor for purely elastic production?

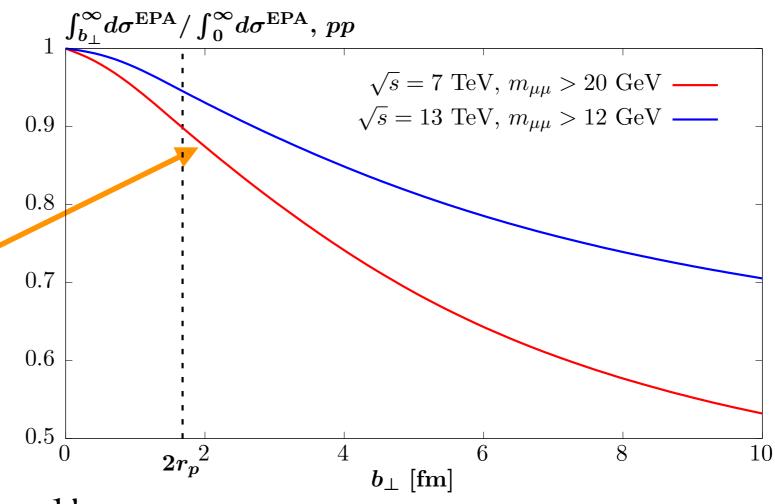
• Have a look at ratio:

$$\frac{\sigma(b_{\perp} > b_{\perp}^{\text{cut}})}{\sigma(b_{\perp} > 0)}$$

~ 90% of cross section lies outside

$$b_{\perp} > 2r_p$$

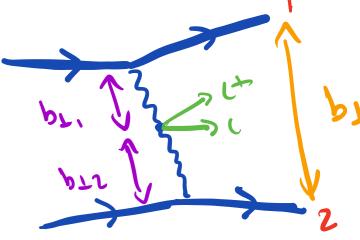
where $e^{-\Omega(\vec{b}_{1\perp} - \vec{b}_{2\perp})}$ is ~ 1!



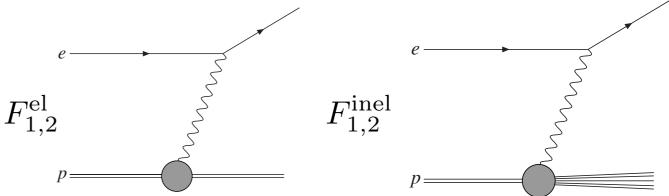
- Elastic PI production: quasi-real photon Q^2 corresponds to large average pp impact parameter \Rightarrow outside range of QCD interactions.
- Depending on precise process/
 kinematics have:

$$S^2 \sim 0.7 - 0.9$$

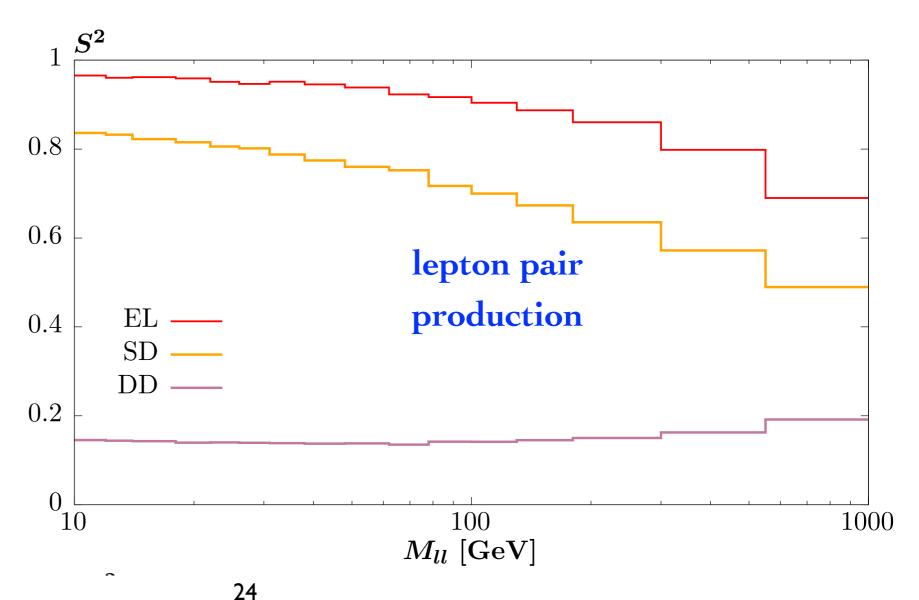
• What about dissociative production?



- Dissociation \Rightarrow larger photon $Q^2 \Rightarrow$ smaller pp $b_{\perp} \Rightarrow S^2 \downarrow$
- ullet For SD production elastic proton side results in \sim peripheral interaction and S^2 still rather high.



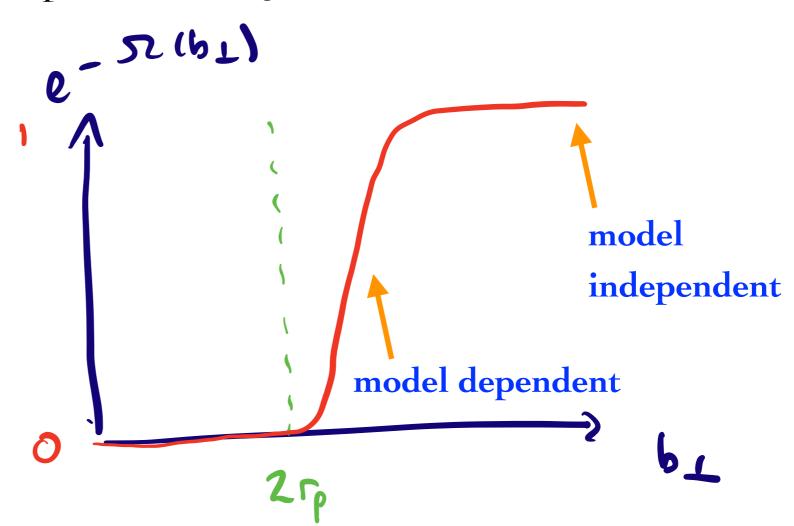
ullet For DD no longer case and $S^2 \sim 0.1$.



- What about uncertainties?
- Naively might assume inelastic ion-ion interactions has large uncertainties requires knowledge of non-perturbative QCD.
- However, not the case: majority of EL/SD interaction occurs for

$$b_{\perp} > 2r_p$$

where $S^2 \sim 1$ independent of QCD modelling.



- \longrightarrow Uncertainty on S^2 small, at % level.
- However no longer true for DD production \Rightarrow uncertainty O(50%) (though S^2 itself smaller).

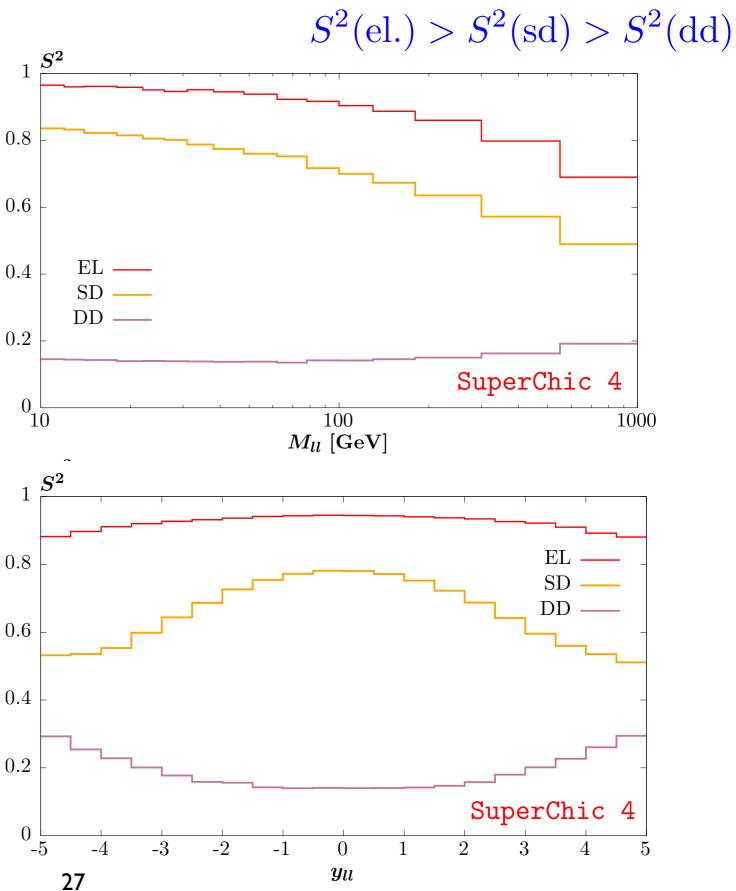
- Other effects?
- Survival factor not constant: depends on process/kinematics.

• NB: this process dependence is often (incorrectly) omitted in literature

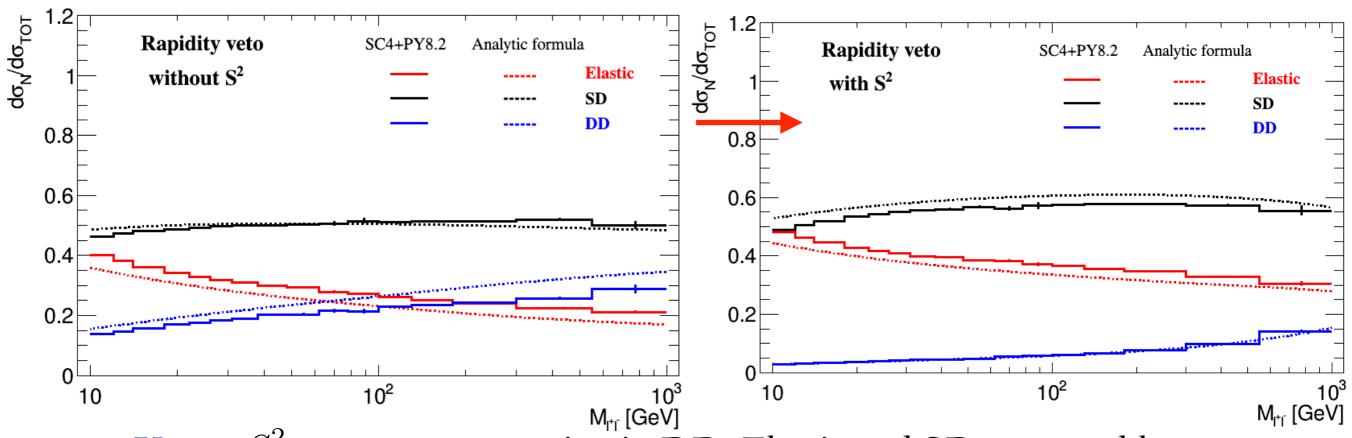
Results

- (Again) scaling with elastic vs. dissociative clear.
- For SD case, $S^2 \sim 1$ still generally true as one proton elastic.

• Dependence on kinematics (e.g. y_{ll} , m_{ll}) also evident.



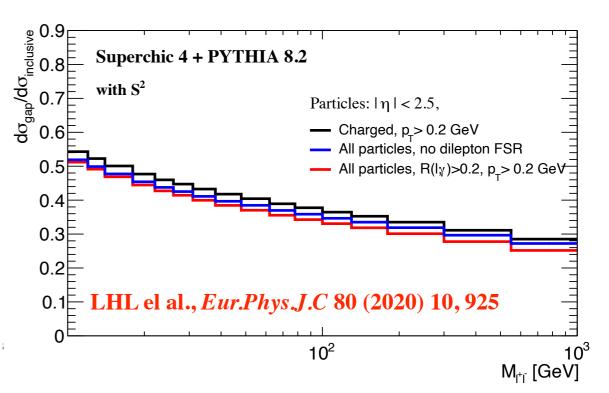
Veto Impact



★ Veto + S^2 : strong suppression in DD. Elastic and SD comparable at lower m_{ll} , SD dominant as m_{ll} increases.

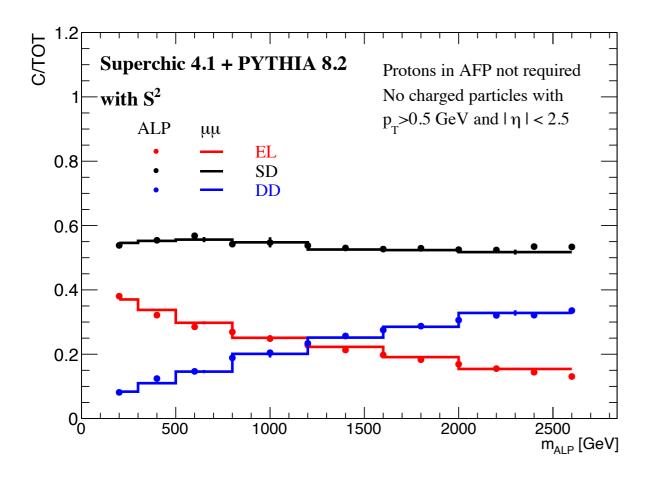
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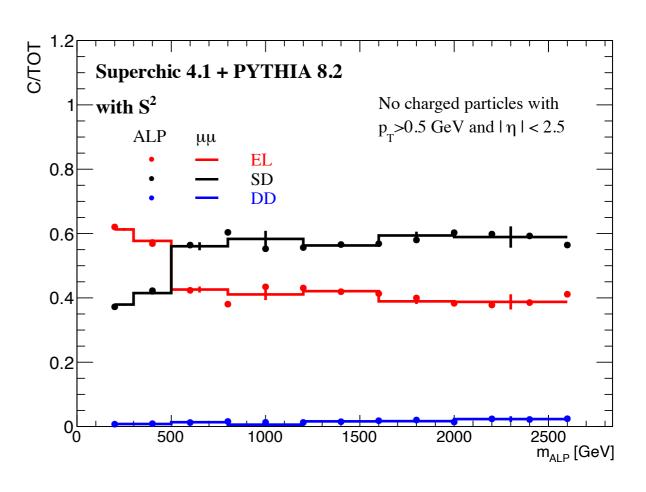
- Above result ~ close to analytic expectation (LO kinematics).
- Vetoing on charged particles only + realistic threshold gives similar results.



Proton Tag Impact

- Proton tag can be included at MC level (here for ALP production).
- As expected dissociation suppressed by even single tag.





LHL and M. Tasevsky, arXiv:2208.10526

Other Considerations





Submitted to: Phys. Lett. B.

- \rightarrow EW and NNLO QCD co
- Thus at this level of accurac
- Also possible relatively common to calculate Wordsrection is collined to thes factorization Given in terms of photon PDF processes (W, Z, WH, ZH)

Measurement of exclusiv collisions at \sqrt{s} :

• For consistent treatment of incorporate QED in initial stimitiated production.

This Letter reports a measurement proton—proton collisions at a ce

satisfying exclusive selection for extract the fiducial cross-section: be $\sigma_{\gamma\gamma\to e^+e^-}^{\rm excl.} = 0.428 \pm 0.035$ (statemass of the electron pairs greated momentum $p_{\rm T} > 12$ GeV and property and the electron pairs greated momentum $p_{\rm T} > 12$ GeV, muon transverse momentum $p_{\rm T} > 10$ GeV and pseudorapidity $|\eta| < 2.4$, the pross-section is determined to be $\sigma_{\gamma\gamma\to\mu^+\mu^-}^{\rm excl.} > 0.628 \pm 0.032$ (stat.) ± 0.021 (syst.) pb. the pross-section is determined to be a finite property of the pross-section in the property of the pross-section in the property of the pross-section in the property of the pr

The resulting of the state of t

 $\sigma_{\gamma\gamma\to e^+e^-}^{\text{excl.}} = 0.2$

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Destandaration (CLAS Collaboration is (Carter)

Abstract
Milarly, for the exclusive $\gamma\gamma$ This Letter Te

f-mass energy of protosy protth minosity of 4.6 fb_t¹th Forthe, ¢ a fit to the dileptor applying ity

cross-section in the electron fit 0.018 (syst.) pb for phase-space 24 GeV, in which so the lectron apidity $|\eta| < 2.4$. From the pair momentum p_T graduations

be $\sigma_{\gamma\gamma\to\mu^+\mu^-}^{\rm excl.} = 0.6284 \pm 10.0320$ st the finite size of the proposition

nss-sections are found to be consistent with the resulting on Iducial

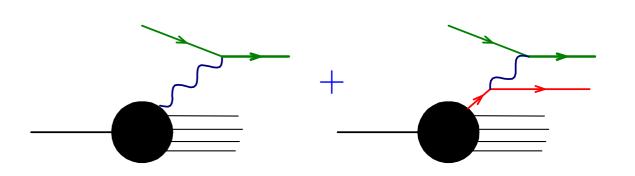
• Can show that collinear calculation is (approximately) equivalent to full structure function calculation for pure PI production:

$$\sigma_{pp} = \frac{1}{2s} \int dx_1 dx_2 d^2 q_{1_{\perp}} d^2 q_{2_{\perp}} d\Gamma \alpha(Q_1^2) \alpha(Q_2^2) \frac{\rho_1^{\mu\mu'} \rho_2^{\nu\nu'} M_{\mu'\nu'}^* M_{\mu\nu}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X) ,$$

$$\gamma^* p \to X \sim \sigma(\gamma^* \gamma^* \to l^+ l^-)$$

$$\rho_1^{\mu\mu'} \rho_2^{\nu\nu'} M_{\mu'\nu'}^* M_{\mu\nu} \sim \gamma(x_1, \mu_F) \gamma(x_2, \mu_F^2) \sigma(\gamma\gamma \to l^+ l^-) + O\left(\frac{Q^2}{m_{ll}^2}\right)$$

- Approximate equivalence manifests itself in μ_F dependence of collinear result (absent in SF result).
- For LO collinear, this dependence is large (i.e. approximation relatively poor). Can improve agreement with SF by including higher order diagrams:

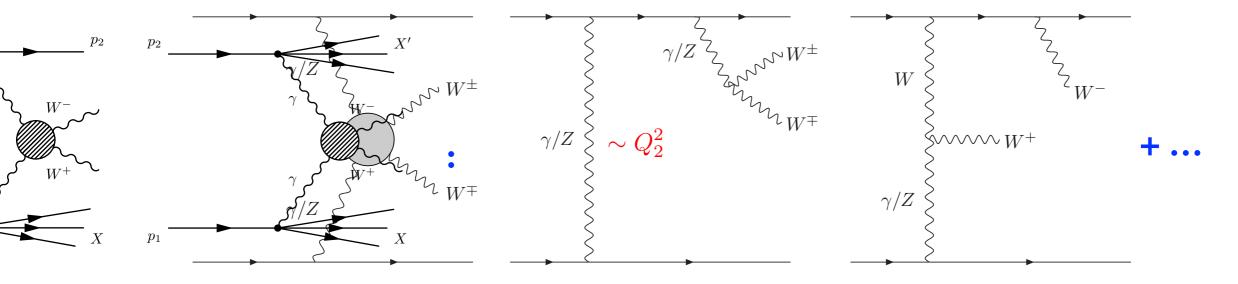


- But fore pure PI this is automatically accounted for in SF calculation.
- Moreover SF calculation (unintegrated in photon k_{\perp}) fundamental to calculation of survival factor.

However...

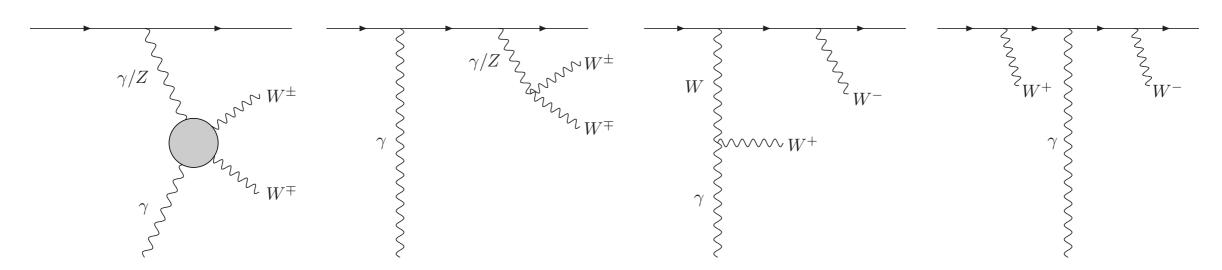
- SF calculation only accounts for pure PI (+ Z-initiated) production.
- For dissociative production this is not the only contribution. Discussed in detail for the case of WW production in arXiv:2201.08403.
- For e.g. the DD case also have:

LHL, Phys.Rev.D 105 (2022) 9, 093010



- These non-PI diagrams are suppressed by at least $\sim Q^2/M_{W,Z}^2$ and so on principle subleading. But:
 - * The contribution is not necessarily negligible to be determined.
 - * More importantly, the pure PI (+Z) contribution is not individually gauge invariant away from collinear limit. $\begin{cases} & \\ & \\ & \\ & \end{cases}$

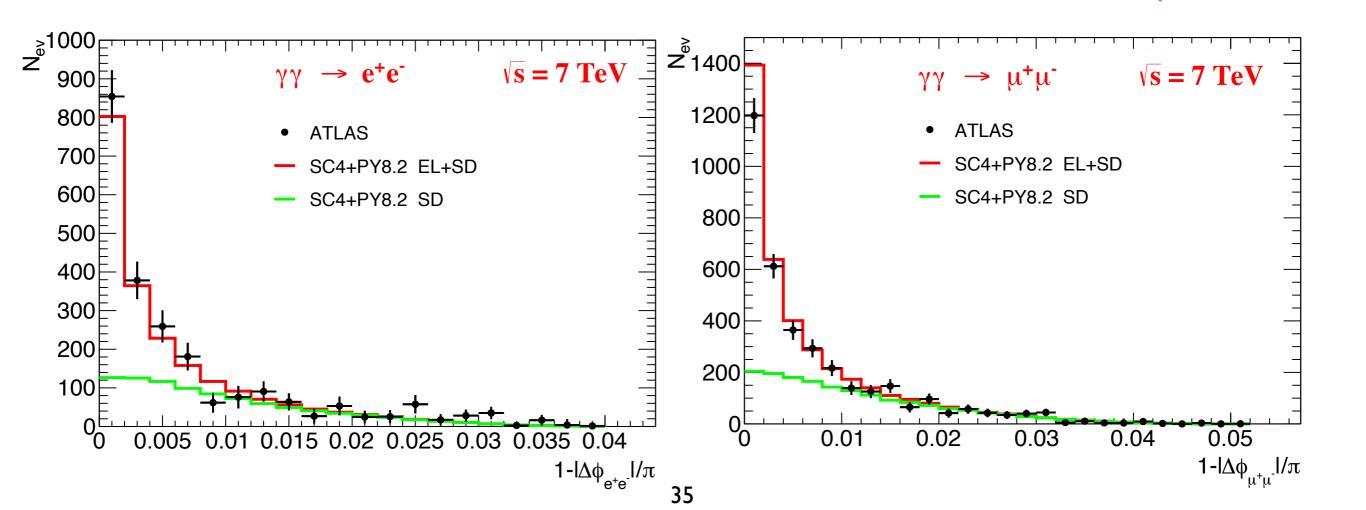
• In general necessary to include both PI and non-PI diagrams when considering data without tagged protons.



- Accounted for in arXiv:2201.08403 via so-called 'hybrid' approach:
 - * SF calculation used in low photon Q^2 region. LHL, Phys.Rev.D 105 (2022) 9, 093010
 - \star Full set of non-PI diagrams included in higher photon Q^2 region.
- Could also use (NLO...) collinear factorization although this comes with complications.
- Impact of non-PI production depends on experimental selection and process:
 - ★ W pair production: O(10%) correction.
 - ★ Lepton pair production: O(1%) correction.

Higher order QED?

- Final consideration: $\gamma\gamma \to X$ subprocess.
- In general QED corrections should be 1% level under good control.
- Only remark: if experimental cuts placed on acoplanarity \Rightarrow sensitivity to system p_{\perp} . May enhance this.
- E.g. FSR in case of dilepton production, though can account after passing to general purpose MC.



Measurement of exclusive $\gamma_s \rightarrow \ell^+ \ell_1$ measurement collisions at $\sqrt{s} = 10^{\circ} e^{s}$ with the argument of exclusive $\gamma_s \rightarrow \ell^+ \ell_1$ measurement of exclusive $\gamma_s \rightarrow \ell^+ \ell_2$ measurement of exclusiv from Ref. [60]. The ATLAS Collaboration form-factors is (This Letter reports a measurement of the exclusive $\gamma \gamma$ This Letter Te

proton-proton collisions at a centre-of-mass energy of proton-proton at the LHC, based on an integrated impinosity of 4.6 fbat the equation satisfying exclusive selection criteria afit to the dilepton acoplanatity extract the fiducial cross-sections. The cross-section in the electron file be $\sigma_{\gamma\gamma\to e^+e^-}^{\rm excl.} = 0.428 \pm 0.035 \, ({\rm stat.}) \pm 0.018 \, ({\rm syst.})$ pb for phase-space mass of the electron pairs greater than 24 GeV, in which both the electron momentum $p_T > 12$ GeV and pseudorapidity $|\eta| < 2.4$. From the majoration of the contraction of the contr greater than 20 GeV, muon transverse momentum $p_T > \text{greater fill and } 2$.4, the cross-section is determined to be $\sigma_{\gamma\gamma\to\mu^+\mu^-}^{\text{excl.}} = 0.628 + 10.032 \text{ sst}$ When proton absorptive effects due to the finite size of the peroperater

Measurement of exclusiv

collisions at \sqrt{s} :

This Letter reports a measureme proton-proton collisions at a ce at the LHC, based on an integra satisfying exclusive selection cri extract the fiducial cross-section be $\sigma_{\gamma\gamma \to e^+e^-}^{\text{excl.}} = 0.428 \pm 0.035$ (sta mass of the electron pairs great momentum $p_T > 12$ GeV and p...

Clean, ~ pure 🔾 greater than 20 GeV, muon transverse momentum $p_T > 10$ GeV and pseudorapid $= 0.628 \pm 0.032$ (stat.) ± 0.021 (syst.) pb.

initiated production.

2.4, the cross-section is determined to be $\sigma_{\gamma\gamma\to i}^{\text{excl.}}$ the theory calculation, the measured cross-sections are found to be consistent with the theory prediction. tivis and formula to the existing the theory in the light of the protection into account in the control of the protection with the theory prediction.

The resulting flique at Cross-section for the protection of the prediction.

* Survival factor' probability of pr

v:1506.07098v2 [hep-ex] 17 Aug 2015

© 2015 CRN for the benefit of the ATLAS Theoretion, planes to provide or parts of its answer as pectification of this article of parts of its answer as pectification of the ATLAS Unborration, a large configuration of the ATLAS Unborration of the ATLAS Unbo

the finite size of the proton expressive of the proton of the finite size of the proton [10]:

large reduction for DD $\rho_{\gamma\gamma\to e^+e^-} = 0.398 \pm 0.39$

larger uncertainties
For the muon channel, the fiduciah gross else stieln tisenfelse in the muon channel, the fiduciah gross else stieln tisenfelse in the muon channel. For the muon channel bthe fiducial persons

 $\star \gamma \gamma \to X$ cross section.

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to be compared with [10] the Estation with these are lider [30]. In a beam crossing, protons can linede [30]

Theory under good control ready for applications to Bost of the very clean final state of the control of the co proton absorptive corrections of tab symptoted by evaluated by evaluat according to Ref. [64]. Figure disbowres retips of the property of the propert

 For consistent treatment of t incorporate QED in initial star

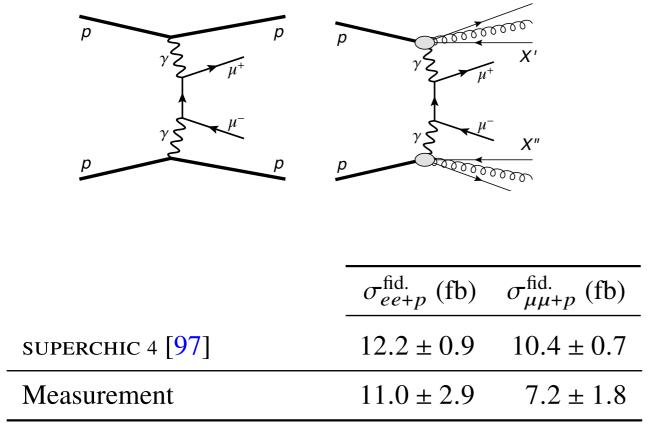
EW corrections. At LHC these

processes (W, Z, WH, ZH,

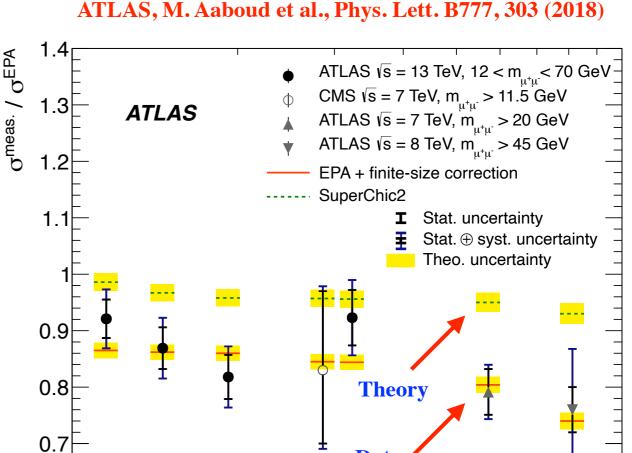
Where do we stand? Comparison to Data

What does the data say?

• Many BSM/SM scenarios to explore. First step: consider simplest 'standard candle' of lepton pair production.



ATLAS, Phys. Rev. Lett. 125 (2020) 261801



2×10⁻³

Data

3×10⁻³

5×10⁻³

<m $_{\mu^{+}\mu}$ >/ \sqrt{s}

- Multiple measurements of lepton pair production by ATLAS/CMS, selected via rapidity veto and/or single proton tag.
- Broad agreement, but SC predictions overshoot by O(10%) 2-3 sigma.

10⁻³

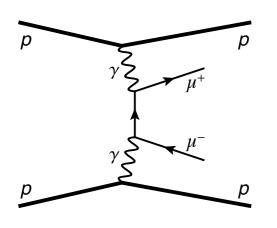
Theory vs. Data?

LHL, V.A Khoze, M.G. Ryskin, SciPost Phys. 11 (2021) 064

• This issue discussed in detail in recent paper: arXiv:2104.13392.

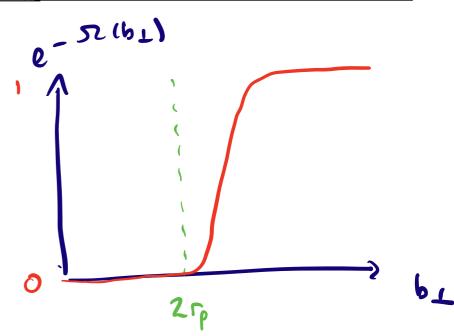
ATLAS, Phys. Lett. B 749, 242 (2015), Phys. Lett. B 777, 303 (2018)

	ATLAS data [14,16]	Baseline	FF uncertainty	Dipole FF
σ [pb], 7 TeV	0.628 ± 0.038	0.742	$+0.003 \\ -0.005$	0.755
σ [pb], 13 TeV	3.12 ± 0.16	3.43	± 0.01	3.48



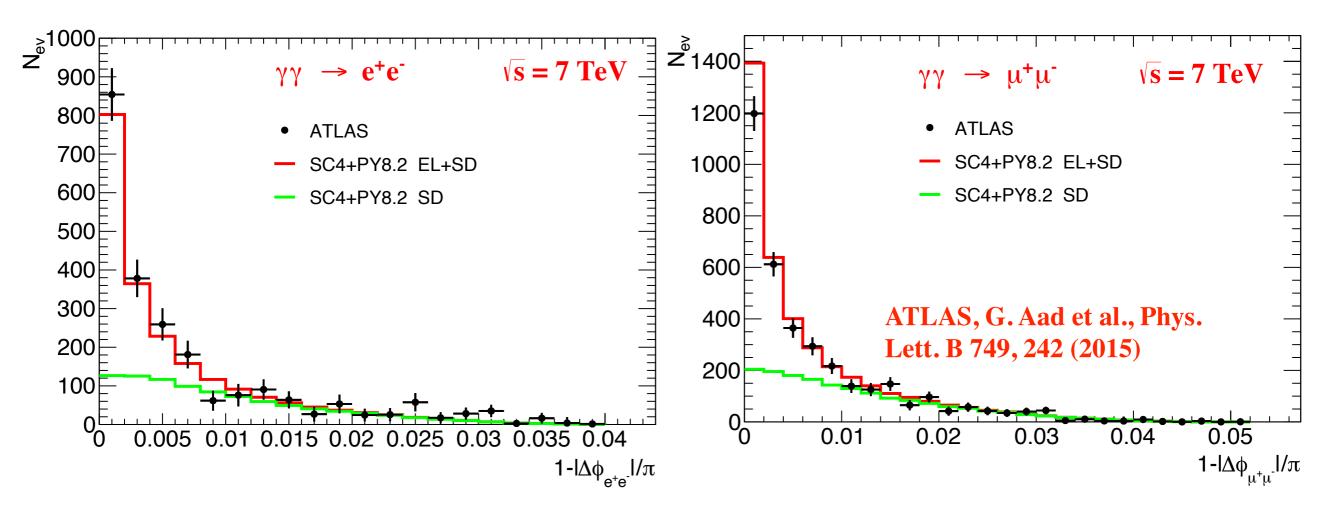
	ATLAS data [14, 16]	$\theta(b_{\perp}-2r_p)$	$\theta(b_{\perp} - 3r_p)$
σ [pb], 7 TeV	0.628 ± 0.038	0.719	0.668
σ [pb], 13 TeV	3.12 ± 0.16	3.34	3.25

- Reasons for difference?
 - ★ Uncertainty from form factor: sub % level.
 - \star Uncertainty from S^2 : even extreme (unrealistic) changes not sufficient.
- Source of ~ 10% effect remains open question.



pp: other effects?

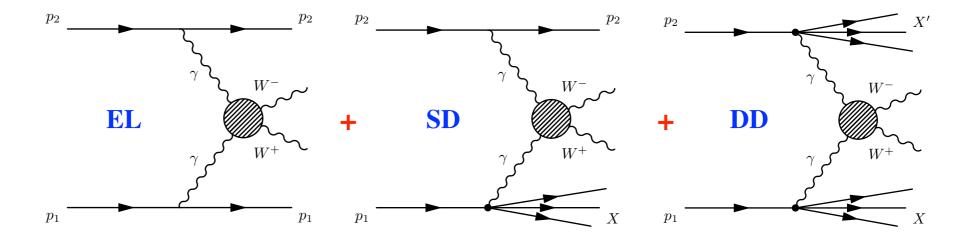
- ATLAS 7 TeV data suggests peaked at low dimuon acoplanarity.
- More differential data, including with proton tags will guide the way.
- Treatment of dissociative production (subtracted when quoting `El' result, sometimes with old MCs)? Higher order QED? No clear issue to point to.
- Electron data appear to be described better, but larger experimental errors.



• ATLAS 13 TeV data, with lepton cuts + veto on associated tracks in:

$$p_{\perp} > 500 \,\mathrm{MeV}, \, |\eta| < 2.5$$

i.e. aftersubtractingBGs includes:



• We therefore need to evaluate all three contributions in SC:

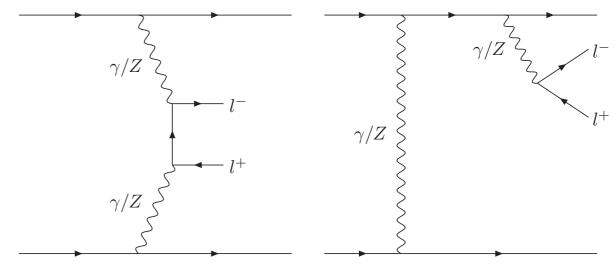
σ [fb] $(\sigma_i/\sigma_{\rm tot}), W^+W^-$	EL	SD	DD	Total
No veto, no S^2	0.701 (3.5%)	6.00 (30.3%)	13.1 (66.2%)	19.8
Veto, no S^2	0.701 (9.2%)	3.21 (42.3%)	3.68 (48.5%)	7.59
Veto, S^2	0.565 (18.6%)	1.87 (61.6%)	0.599 (19.8%)	3.03

• To compare with data: $\sigma_{\text{meas}} = 3.13 \pm 0.31 \text{ (stat.)} \pm 0.28 \text{ (syst.) fb}$

⇒ Very good agreement! In more detail....

• Impact of non-PI: compare with lepton pair production in similar kinematic region.

 Here impact of non-PI is found to be 1% level at most, and no issue with gauge invariance.



$\sigma \; [\mathrm{fb}] \; (\sigma_i/\sigma_{\mathrm{tot}}) \;\;\; bracket$	EL	SD	DD	Total	f_{γ}^{X}
W^+W^-	0.565 (18.6%)	1.87 (61.6%)	0.599 (19.8%)	3.03	4.3
l^+l^-	9.61 (24.0%)	24.9 (62.5%)	5.42 (13.5%)	39.9	3.5

i.e. relative contribution from SD + DD is ~ 20% larger wrt pure EL in W^+W^- case. Dominantly due to non-PI.

$$f_{\gamma}^{X} pprox rac{\sigma^{\mathrm{EL}} + \sigma^{\mathrm{SD}} + \sigma^{\mathrm{DD}}}{\sigma^{\mathrm{EL}}}$$

• Also leads to rather different breakdown between various channels. Crucial to account for - common previously to assume these are equal in extracting an 'exclusive' W^+W^- signal. In more detail...

$\sigma \text{ [fb] } (\sigma_i/\sigma_{ ext{tot}})$	EL	SD	DD	Total	f_{γ}^{X}
W^+W^-	0.565 (18.6%)	1.87 (61.6%)	0.599 (19.8%)	3.03	4.3
l^+l^-	9.61 (24.0%)	24.9~(62.5%)	5.42 (13.5%)	39.9	3.5

ullet Above result has significant bearing on common practice. That is, to measure: 3.5 ± 0.5

$$\sigma^{\rm EL} + \sigma^{\rm SD} + \sigma^{\rm DD}$$

in dilepton sample with $m_{ll} > 2M_W$ and evaluate (EL better known theory):

$$f_{\gamma}^{ll} pprox rac{\sigma^{\mathrm{EL}} + \sigma^{\mathrm{SD}} + \sigma^{\mathrm{DD}}}{\sigma^{\mathrm{EL,theor}}}$$

• This is then used to give a predicted W^+W^- cross section assuming $f_{\gamma}^{ll}=f_{\gamma}^{WW}$

$$\sigma^{WW} = \sigma^{WW}_{\text{EL,theor}} \cdot f^{ll}_{\gamma}$$

- ullet But we do not expect this to be true! ATLAS measure: $f_{\gamma}^{ll}=3.59\pm0.15$
- Agrees well with our theory 🗸 . But follow above procedure get:

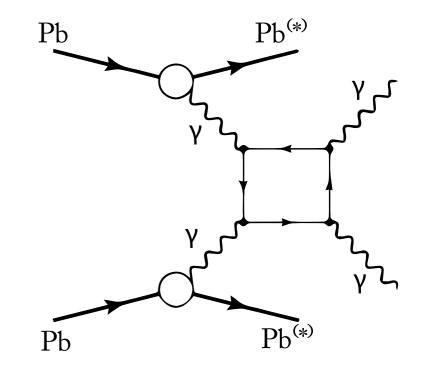
$$\sigma_{f_{\gamma}}^{WW} = 3.5 \times 0.701 \,\text{fb} = 2.45 \,\text{fb}$$

i.e. rather low wrt data. Exactly as we would expect - effectively omits non-PI. Not sufficient for precision physics! Essential to follow approach as per this talk.

Heavy Ion Collisions

PI production and Heavy Ion Collisions

- PI production also key channel in heavy ion collisions.
- Theoretical framework broadly similar to pp case:
 - ★ Elastic form factor.
 - $\star \gamma \gamma \to X$ cross section.
 - **★ `Survival factor**' probability of no addition ion-ion interactions.



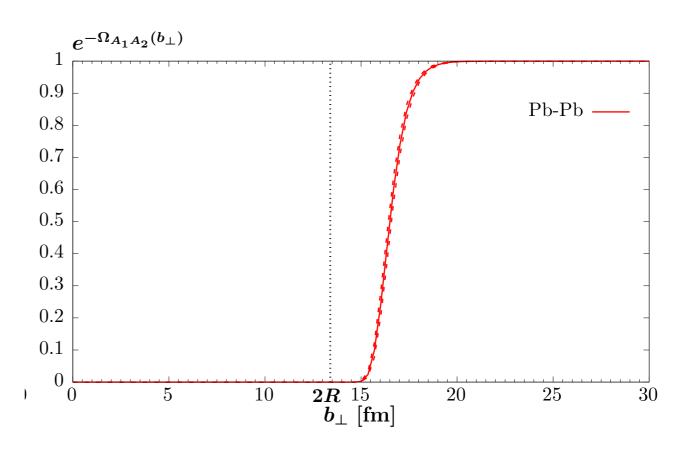
• Elastic form factor ~ ion charge density.

$$F_p(|\vec{q}|) = \int d^3r \, e^{i\vec{q}\cdot\vec{r}} \rho_p(r)$$

 $F_p \propto Z \Rightarrow \text{cross section} \propto F_p^4 \sim Z^4$: strong enhancement

★ Survival factor: similar situation to pp, i.e. cross section dominantly occurs outside range of QCD.

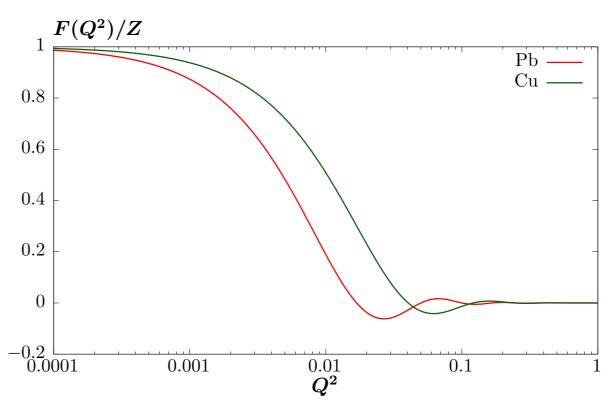
$$\Rightarrow S^2 \sim 1$$
, with small uncertainty



★ Input for elastic form factors very well determined.

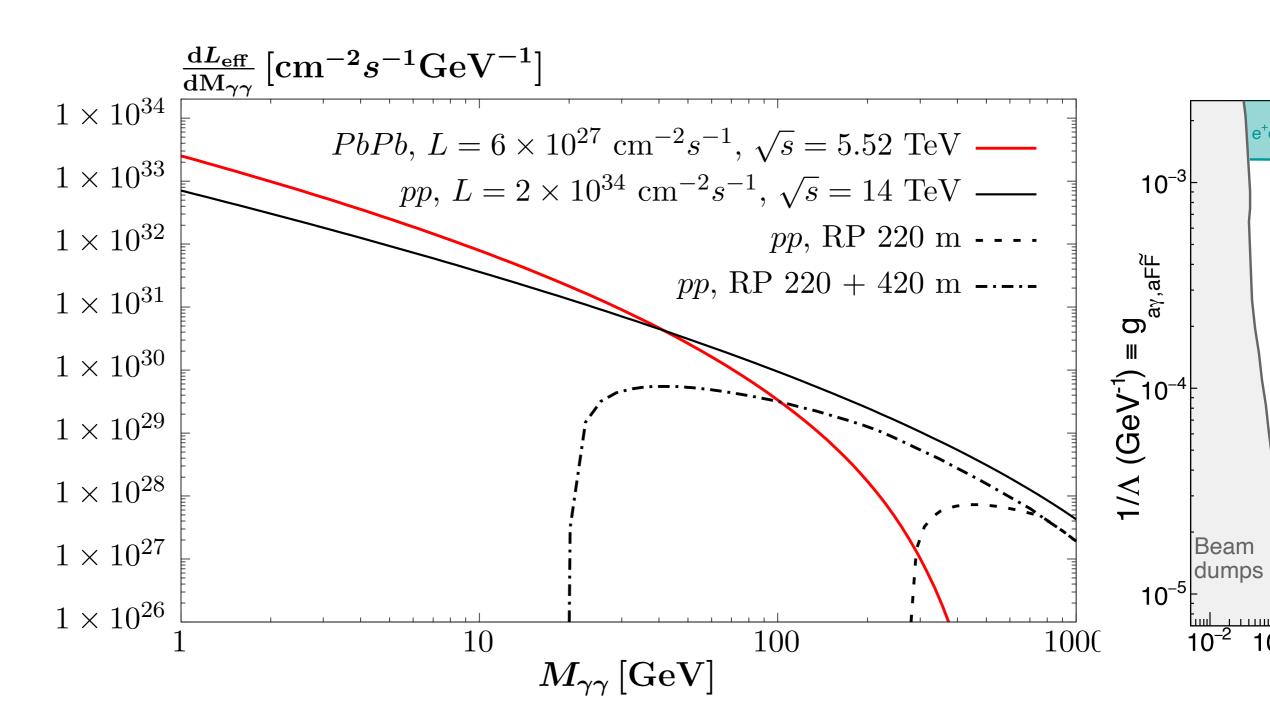
$$\rho_p(r) = \frac{\rho_0}{1 + \exp(r - R)/d} ,$$

$$R_p = 6.680 \,\text{fm} \;, \qquad d_p = 0.447 \,\text{fm} \;,$$



* Form factor peaked at very low photon Q^2 limits photon energy fraction x and hence $M_{\gamma\gamma}$ to be rather low...

- Lower $M_{\gamma\gamma}$: heavy ions dominate.
- Higher $M_{\gamma\gamma}$: pp dominates.



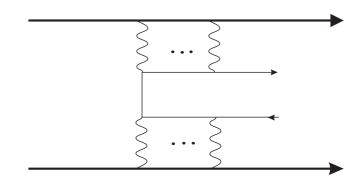
• In addition, range of theoretical effects enter that play less of a role in pp case...

$P_2 \longrightarrow$

PbPb: other effects

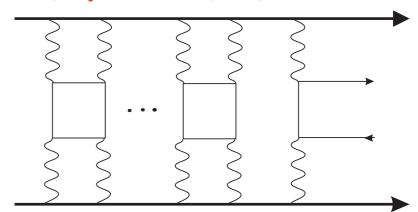
W. Zha and Z. Tang, (2021), 2103.04605.

- HO QED effects? Recent paper suggests could act in this direction/with this size.
- But controversial. Previous studies predict much smaller effect, expect to be suppressed by $\sim Q^2/m_{\mu\mu}^2$



K. Hencken, E.A. Kuraev, V. Serbo, *Phys.Rev.C* 75 (2007) 034903...

- Unitary corrections? Studies suggest ~ 50% events accompanied by additional e^+e^- pairs.
- Might these be vetoed on? Strongly peaked at low m_{ee} so perhaps not. But requires study.



- Ion dissociation? Not in SC (but in Starlight). Dominantly driven by additional ion-ion QED exchanges, i.e. unitary. Other inelastic emission subtracted from data.
- QED FSR? Included via Pythia in predictions, but worth recalling that production of such back-to-back leptons particularly sensitive to this.
- → Relevance of these effects clearly not limited to (SM) dimuon production!

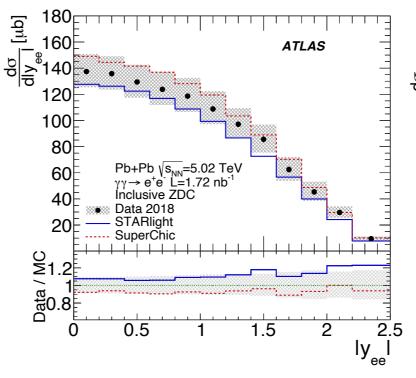
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• All of the above relevant to feet tendency to overshoot data:

E 10 B 10 T	Pb+Pb $\sqrt{s_{NN}}$ =5.02 TeV $\gamma\gamma \rightarrow e^+e^-$ L=1.72 nb ⁻¹ Inclusive ZDC Data 2018 STARlight SuperChic	ATLAS	10 ² 10 10 10 10 10 10 10 10 10 10 10 10 10	Pb+Pb √s _{NN} =5.02 TeV γγ→ e ⁺ e L=1.72 nb ⁻¹ Inclusive ZDC Data 2018 STARlight SuperChic
Data / WC 8.0 8.0		0 40 m _{ee} [GeV]	Data / MC	10

	ATLAS data [23]	Pure
$\sigma [\mu b]$	34.1 ± 0.8	5

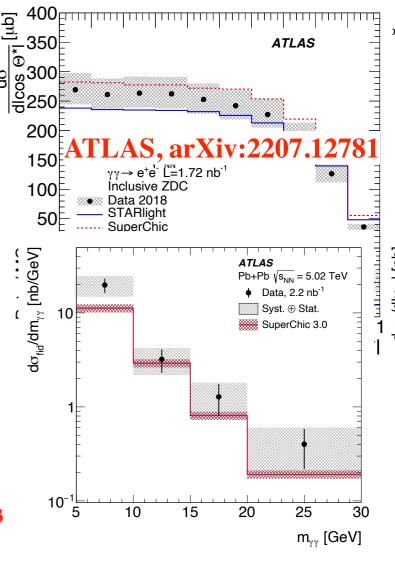
• Though distributions ~ well described.



• For LbyL scattering on the other hand tendency to undershoot data!

ATLAS, *JHEP* 03 (2021) 243

49



ATLAS

20 30 <p₊> [GeV]

Summary/Outlook

- ★ Robust theoretical framework + MC implementation for (semi -) exclusive photon-initiated production available.
- ★ Basic physics is well understood, impact of non-QED survival factor effects small but not negligible for EL and SD.
- ★ For DD strong suppression from survival factor, uncertainties larger.
 - → Provides firm theoretical basis for BSM/EFT studies etc. Many promising channels with both double and proton single tags.
- On the other hand theoretical work not over:
 - **★** Small differences in data/theory?
 - **★** Higher-order QED?
 - ★ Going beyond 100% survival?
 - ★ Heavy ions: dissociation, higher order QED.
 - ***** ...

Thank you for listening!

Backup

processes (W, Z, WH, ZH, ent of exclusive $\chi \overline{\chi} o \ell^+ \ell$ Mprodyction **Measurement of exclusiv** llisions at $\sqrt{s} = \sqrt{10} \text{ eV}$ collisions at \sqrt{s} : For consistent treatment of from Ref. [60]. The ATLAS Collaboration 10 TOTM-TACTORS 1S (incorporate QED in initial st r reports a measurement of the exclusive $\gamma\gamma$ This Letter Te initiated production. This Letter reports a measureme oton collisions at a centre-of-mass energy of proton platth proton-proton collisions at a ce C, based on an integrated luminosity of 4.6 fb_{at th}Eqritice & at the LHC, based on an integra exclusive selection criteria afit to the dilepton acoplanatity satisfying exclusive selection cri fiducial cross-sections. The cross-section in the electron sh $_{-}$ = 0.428 ± 0.035 (stat.) ± 0.018 (syst.) pb for a phase-space extract the fiducial cross-section ne electron pairs greater than 34 GeV, in which pair lee be $\sigma_{\nu\nu\to e^+}^{\text{excl.}}$ = 0.428 ± 0.035 (sta shelf way to do this spospirtake simplified approach: $p_T > 12$ Ge and New of the Arr 1. The state of the sta momentum p_T \Rightarrow_{T} \Rightarrow_{T} The resulting fluctal cross-sections for the * Generate outgoing γ quark according to $\gamma\gamma \rightarrow e^{-\frac{1}{2}}$ $\sigma_{\gamma\gamma\to e^+e^-}^{\text{SUSY...}} = 0.47$ r the benefit of the ATLAS The biration. The property of the benefit of the ATLAS The biration of the parts of the article or parts of it is allowed as specification of this larger of parts of it is allowed as specification of this larger of parts of it is allowed as specification of the parts of the parts of it is allowed as specification of the parts o the finithsizerofthaproton of the proton of the ATLAS philipration, a life cap the compared to the theoretical proton of the compared to the theoretical proton of the pro the finite size of the proton [10]: • ISR/FSR will then modify photon 4-momentum to the but for purpose of Visearch strategies for invisible DM states and diators [18–29]: the kinematics of Ciliding Approximation current study sufficient.

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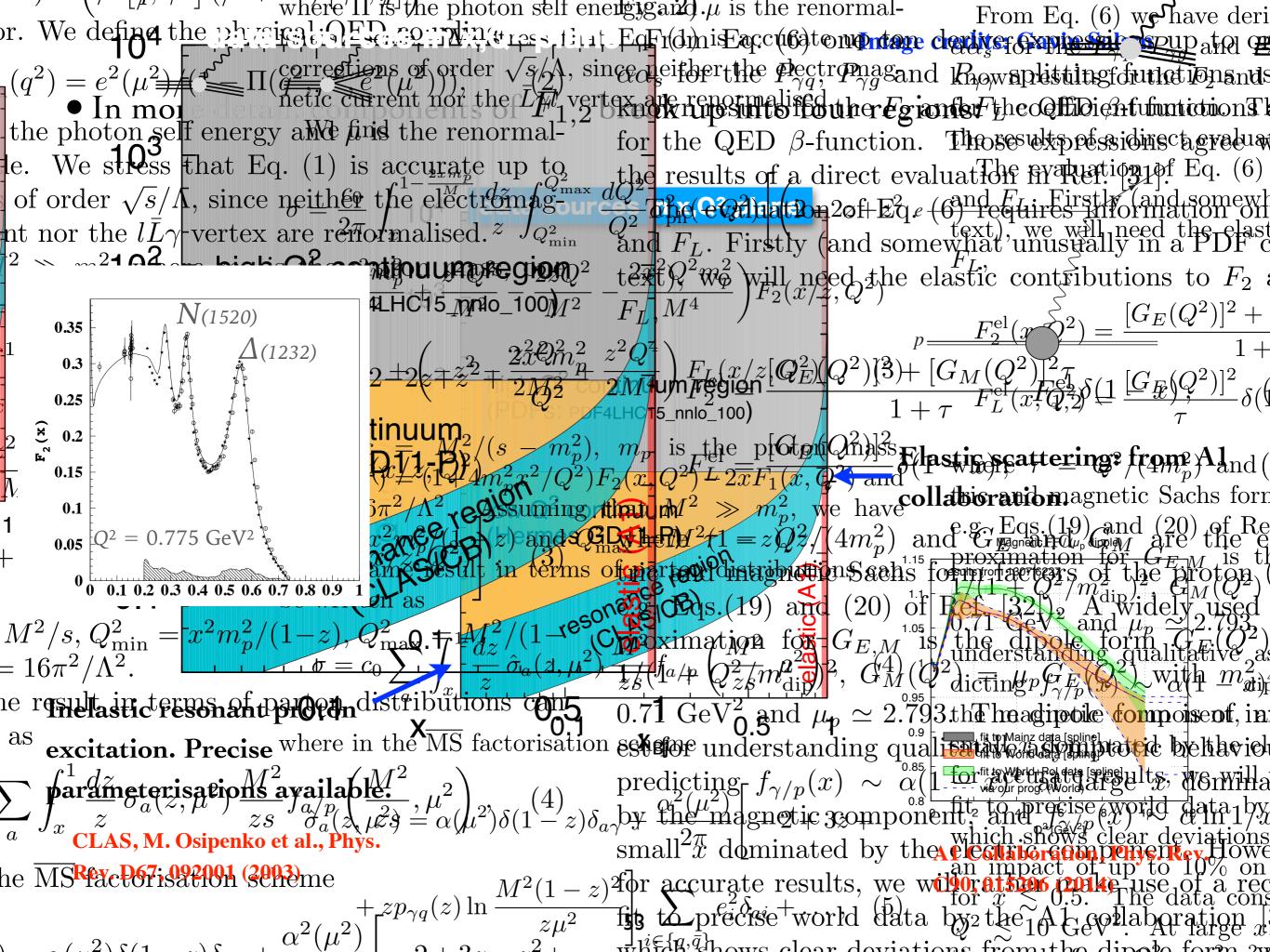
to be compared with [10] be compared with [10]:

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This Letter proposes a search strategy to respin

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ullet In more detail, components of $F_{1,2}$ break up into four regions:

