Elastic photon-initiated production at the LHC: the role of hadron-hadron interactions

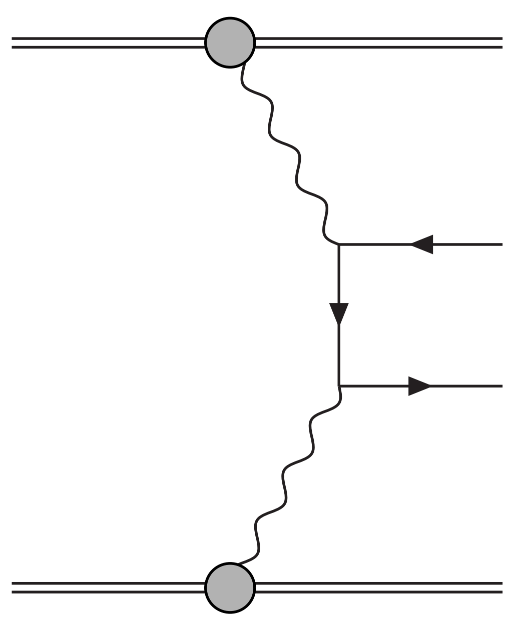
Lucian Harland-Lang, University of Oxford

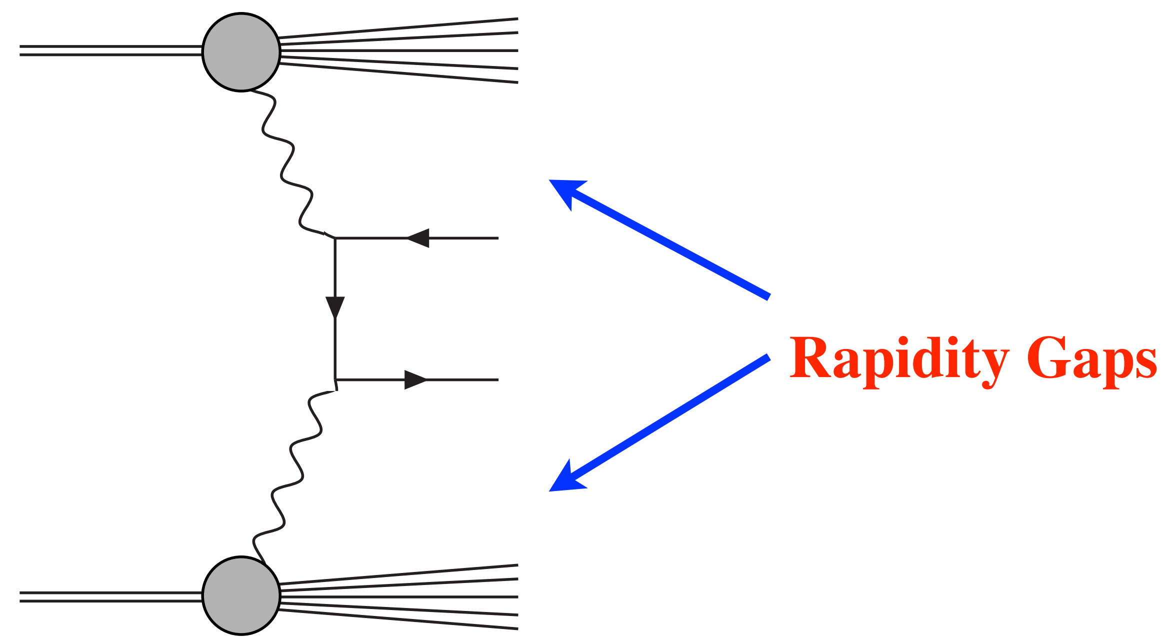
MPI 2021, Lisbon, October 13 2021

LHL, V.A Khoze, M.G. Ryskin,
***SciPost Phys*. 11 (2021) 064, arXiv:2104.13392**

PI Production: Relevance @ LHC

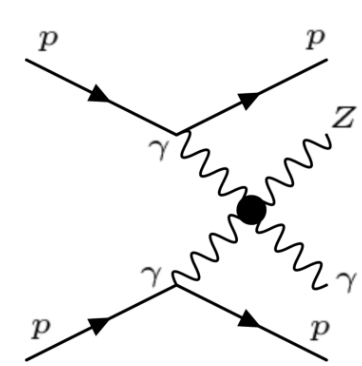
- **Exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state.
- Can be selected either with proton tagging or via rapidity gap vetos (i.e. elastic + inelastic = semi-exclusive production).

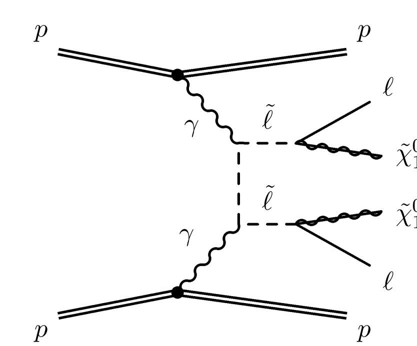




- Clean, ~ pure **QED** process:

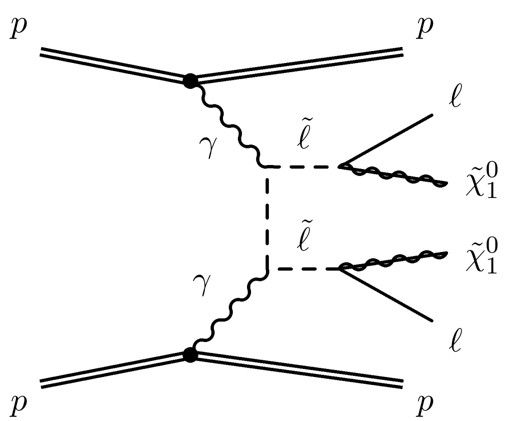
$\Rightarrow$ The LHC as a $\gamma\gamma$ collider!





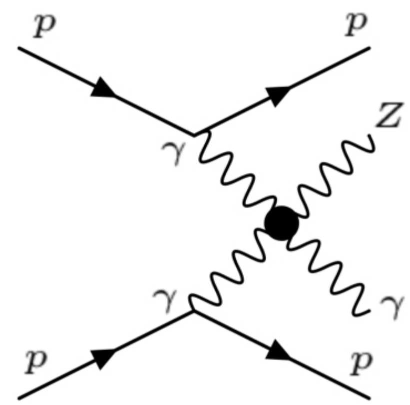
★ Probe of BSM:

Compressed SUSY



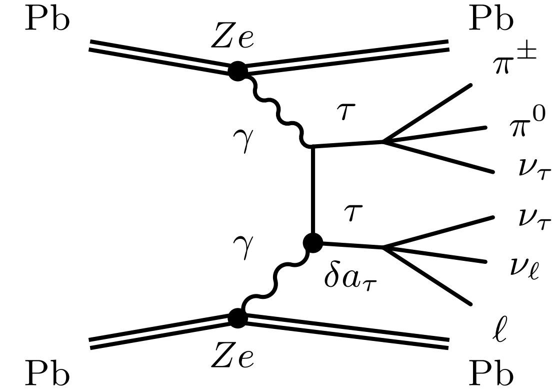
LHL et al., JHEP 1904 (2019) 010
L. Beresford and J. Liu, PRL 123 (2019) no.14

Anomalous couplings



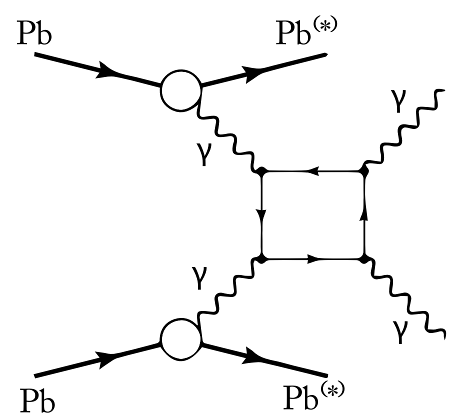
C. Baldenegro et al, JHEP 12 (2020) 165, JHEP 06 (2017) 142

tau g-2



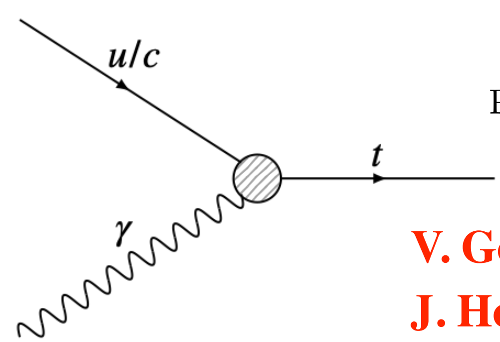
L. Beresford and J. Liu, PRD 102 (2020) 11, 113008
M. Dyndal et al., PLB 809 (2020) 135682

LbyL scattering/ALPS



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

★ **Probe** of the top sector.

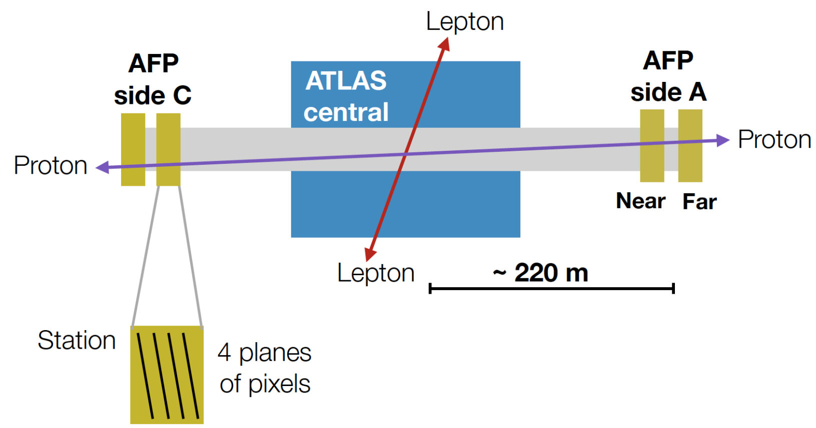


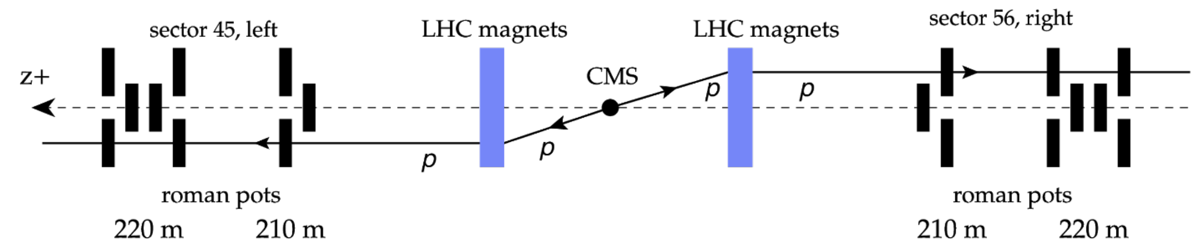
V. Goncalves et al., *Phys.Rev.D* 102 (2020) 7, 074014
J. Howarth, arXiv:2008.04249

★ **Laboratory** to test our models of proton dissociation + proton-proton MPI effects.

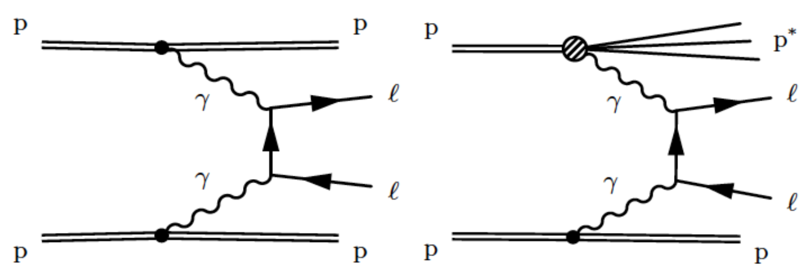
LHL et al., EPJC 76 (2016) no. 5, 255, LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925
L. Forthomme et al., PLB 789 (2019) 300-307

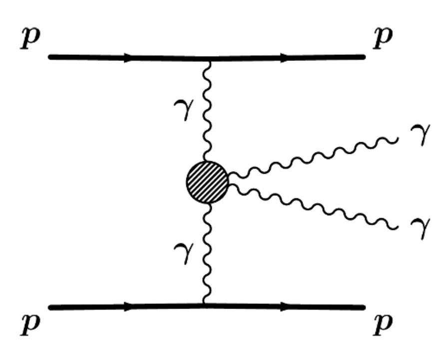
The elastic proton

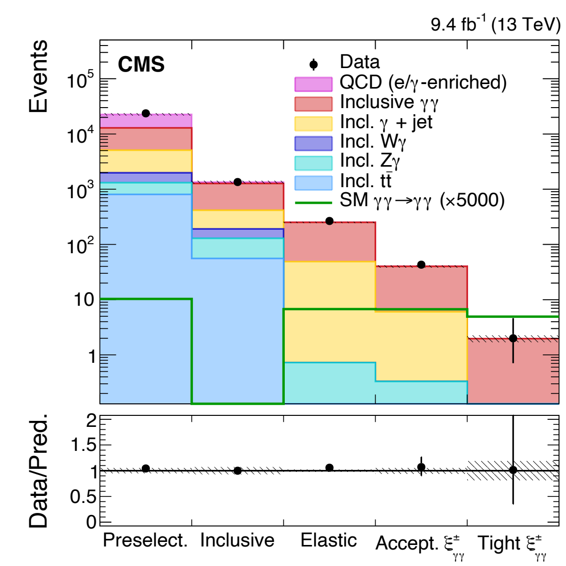


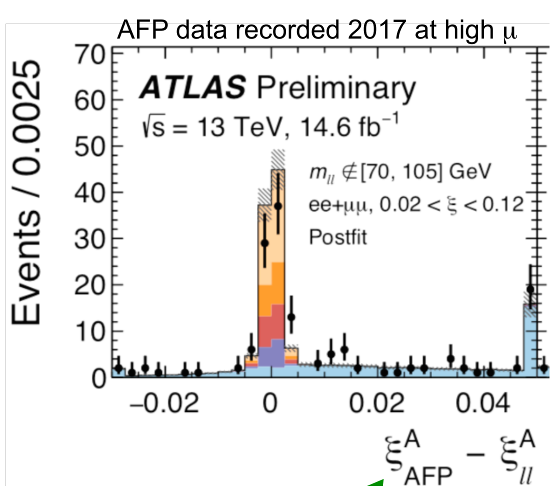


- Dedicated proton tagging detectors at ATLAS/CMS allow exclusive events with intact protons in final state to be selected during **nominal running**.









ATLAS + CMS Highlights, ICHEP 2020

CMS + TOTEM - arXiv:2110.05916

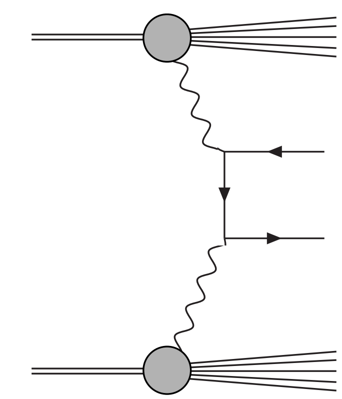
- Unique & complementary probe of SM/BSM at LHC. Data already public!
- Possibilities for HL-LHC running actively being explored.

CT-PPS, arXiv:2103.02752

Modelling (semi)-exclusive PI production

LHL, *JHEP* 03 (2020) 128
LHL, arXiv:2101.04127

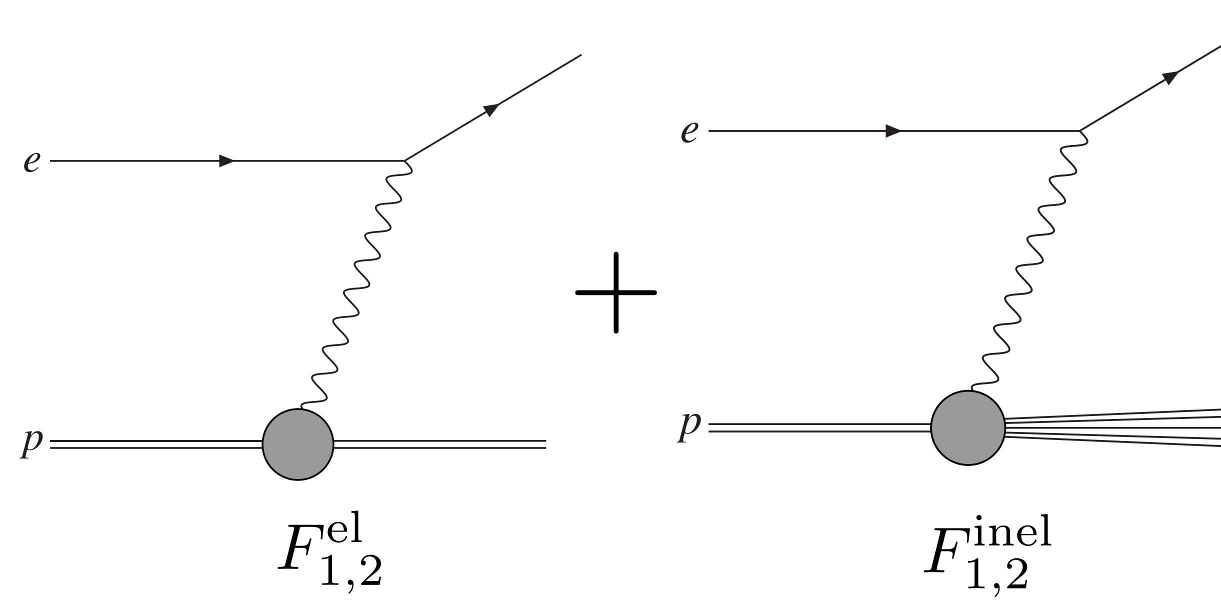
- Basic idea applies the `Structure function' approach.



$$\sigma_{pp} = \frac{1}{2s}\int \overbrace{\mathrm{d}x_1 \mathrm{d}x_2\, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp}}^{\text{Photon } x,\, Q^2} \mathrm{d}\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\overbrace{\rho_1^{\mu\mu'}\rho_2^{\nu\nu'}}^{\gamma^* p \to X} \overbrace{M^*_{\mu'\nu'} M_{\mu\nu}}^{\sim \sigma(\gamma^*\gamma^* \to l^+ l^-)}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X)\;,$$

- With: $$\rho_i^{\alpha\beta} = 2\int \frac{\mathrm{d}M_i^2}{Q_i^2}\left[-\left(g^{\alpha\beta} + \frac{q_i^\alpha q_i^\beta}{Q_i^2}\right) F_1(x_{B,i}, Q_i^2) + \frac{(2p_i^\alpha - \frac{q_i^\alpha}{x_{B,i}})(2p_i^\beta - \frac{q_i^\beta}{x_{B,i}})}{Q_i^2}\frac{x_{B,i}}{2} F_2(x_{B,i}, Q_i^2)\right]$$

- Cross section given in terms of proton EM form factors and inelastic **structure functions**.



Exclusive **Dissociative**

- SF approach can provide high precision predictions for inclusive PI production.

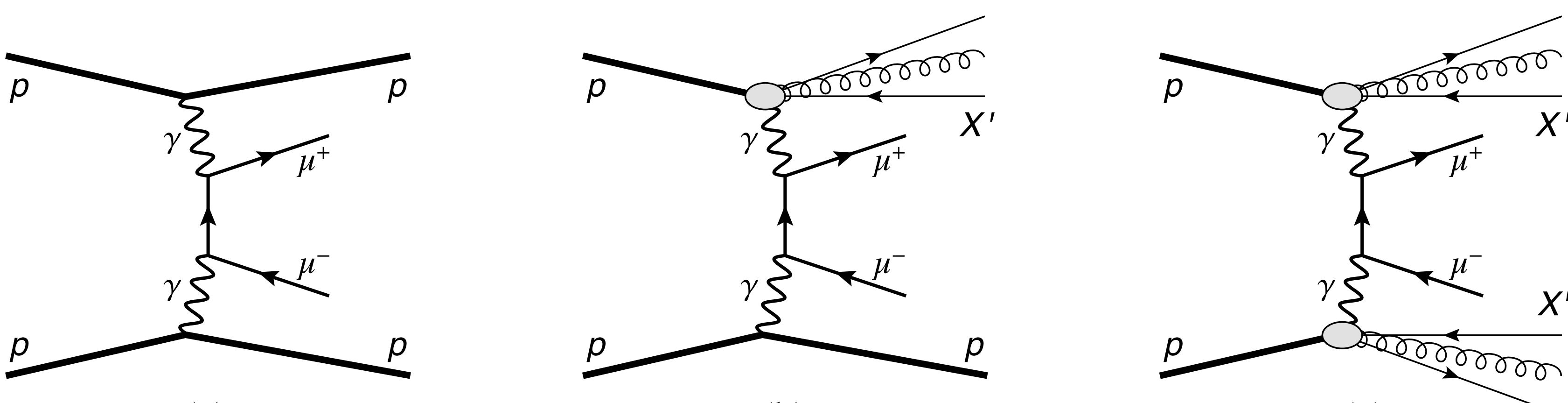
LHL, *JHEP* 03 (2020) 128
LHL, arXiv:2101.04127

- But also uniquely suited to deal with situation where we ask for limited hadronic activity/intact protons in PI process:

$$\sigma_{pp} = \frac{1}{2s} \int \mathrm{d}x_1 \mathrm{d}x_2\, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp} \mathrm{d}\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\rho_1^{\mu\mu'} \rho_2^{\nu\nu'} M^*_{\mu'\nu'} M_{\mu\nu}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X)\ ,$$

  ★ Can isolate elastic component of $F_{1,2}$ to give exclusive prediction (for both proton and ion beams).

  ★ Fully differential in photon $x, Q^2 \Rightarrow$ invariant mass of proton dissociation system (higher $W^2 \Rightarrow$ more hadronic activity).



(a) (b) (c)

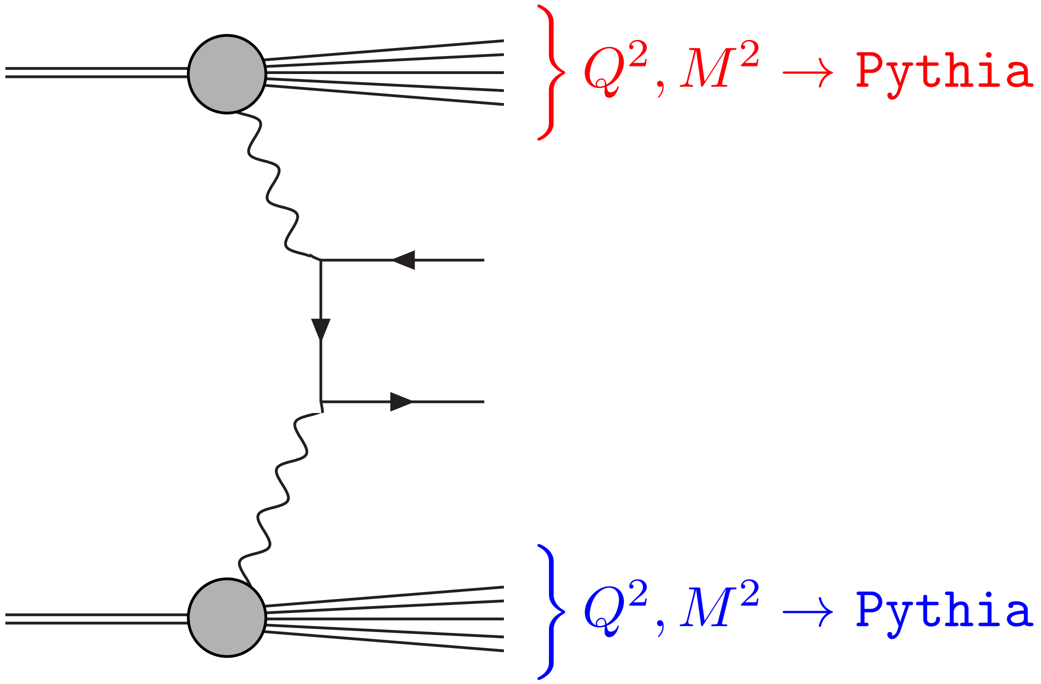
$\rho_{1,2} \sim F^{\mathrm{el}}(x, Q^2)$

$\rho_1 \sim F^{\mathrm{inel}}(x, Q^2)$
$\rho_2 \sim F^{\mathrm{el}}(x, Q^2)$

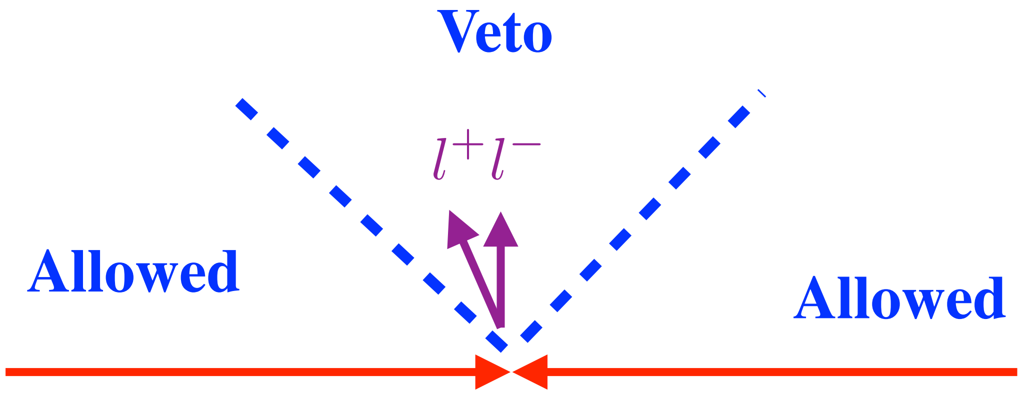
$\rho_{1,2} \sim F^{\mathrm{inel}}(x, Q^2)$

- Having generated exclusive/semi-exclusive lepton pair production events, interface to **Pythia** for showering/hadronisation of dissociation system.

Backup

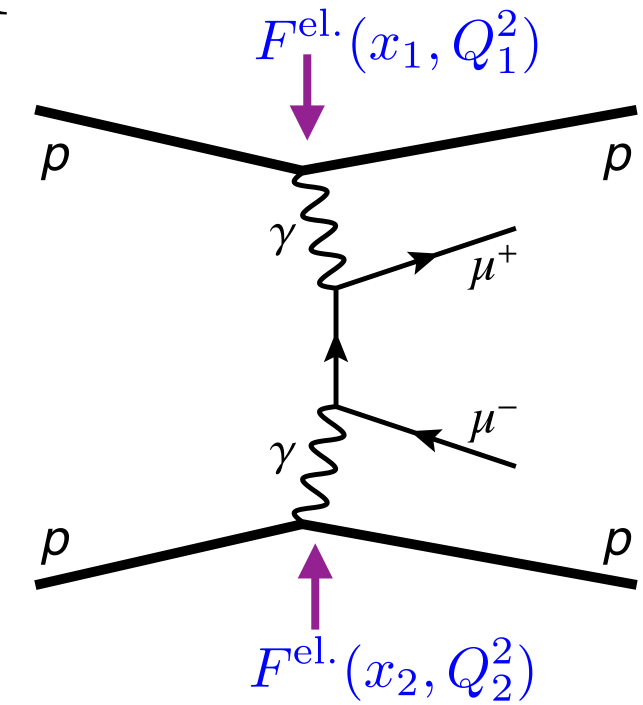


- For semi-exclusive case can impose veto at particle level after passing to Pythia.



- But not the end of the story.

The Survival Factor



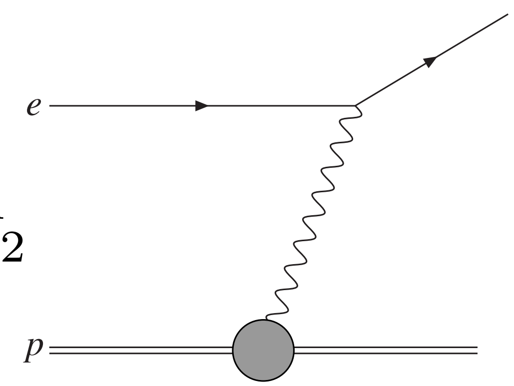
- Consider e.g. the exclusive process. So far we have (very) schematically:

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

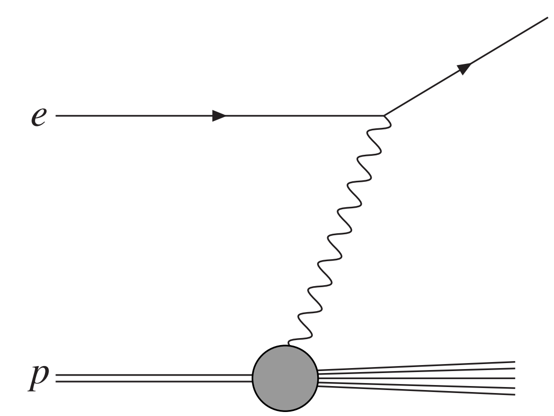
- Similarly for SD + DD, with $F^{\text{el.}} \to F^{\text{inel.}}$

- These inputs are measured in **lepton-hadron** scattering.

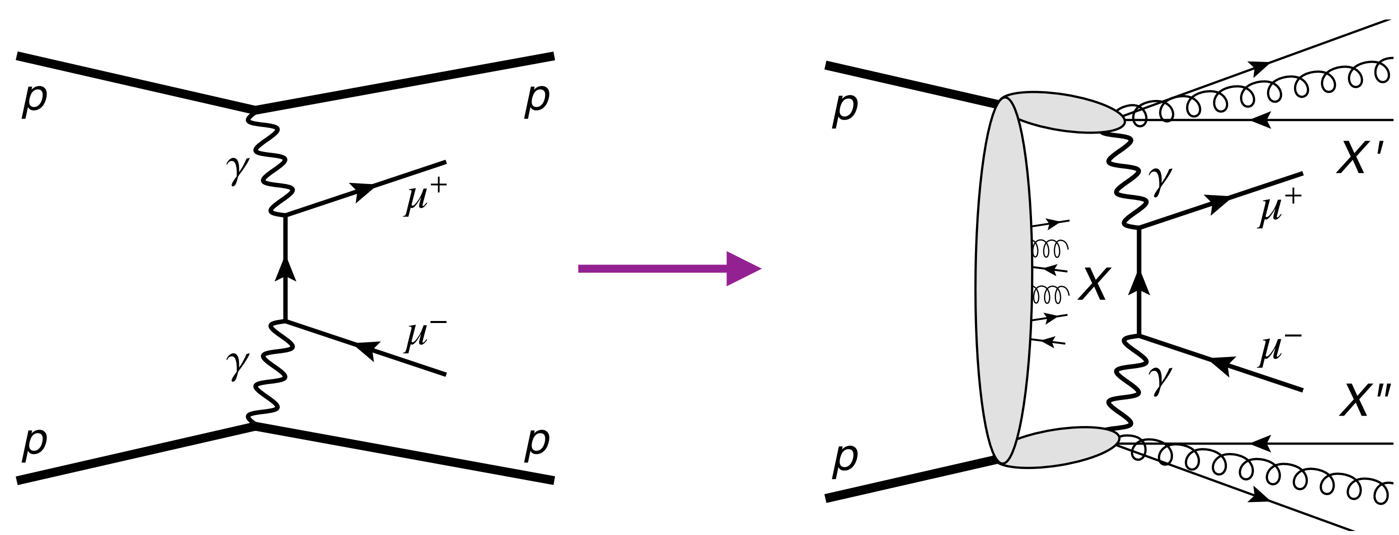
$F_{1,2}^{\text{el}}$



$F_{1,2}^{\text{inel}}$



- But we are interested in **hadron-hadron** scattering: need to account for additional hadron-hadron interactions.



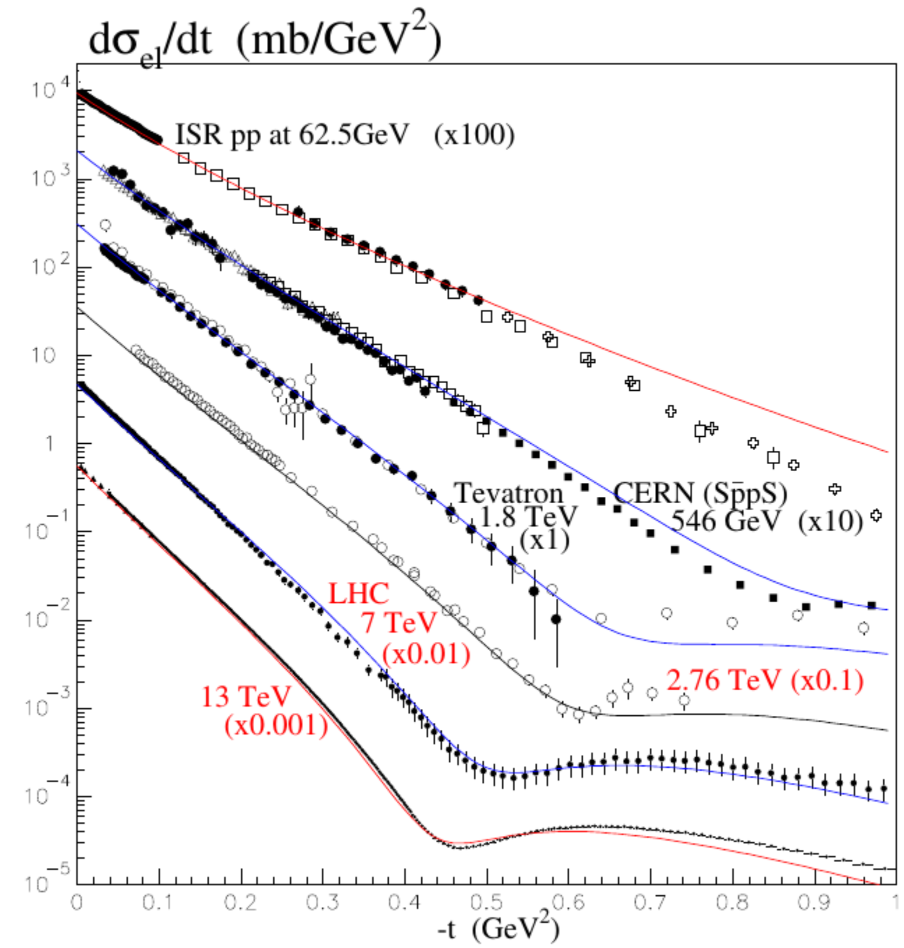
• '**Survival factor**' = probability of no additional inelastic hadron-hadron interactions. Schematically:

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

• How to model this? Depends on e.g. σ^{inel} in soft regime $\Rightarrow$ requires understanding of proton + strong interaction in **non-perturbative** regime.

V. A. Khoze, A. D. Martin & M. G. Ryskin, arXiv:2012.07967

- Build phenomenological models, and tune to wealth of data on elastic + inelastic proton scattering at LHC (and elsewhere). But in general source of **uncertainty**.
- However much less true in PI case (more later).

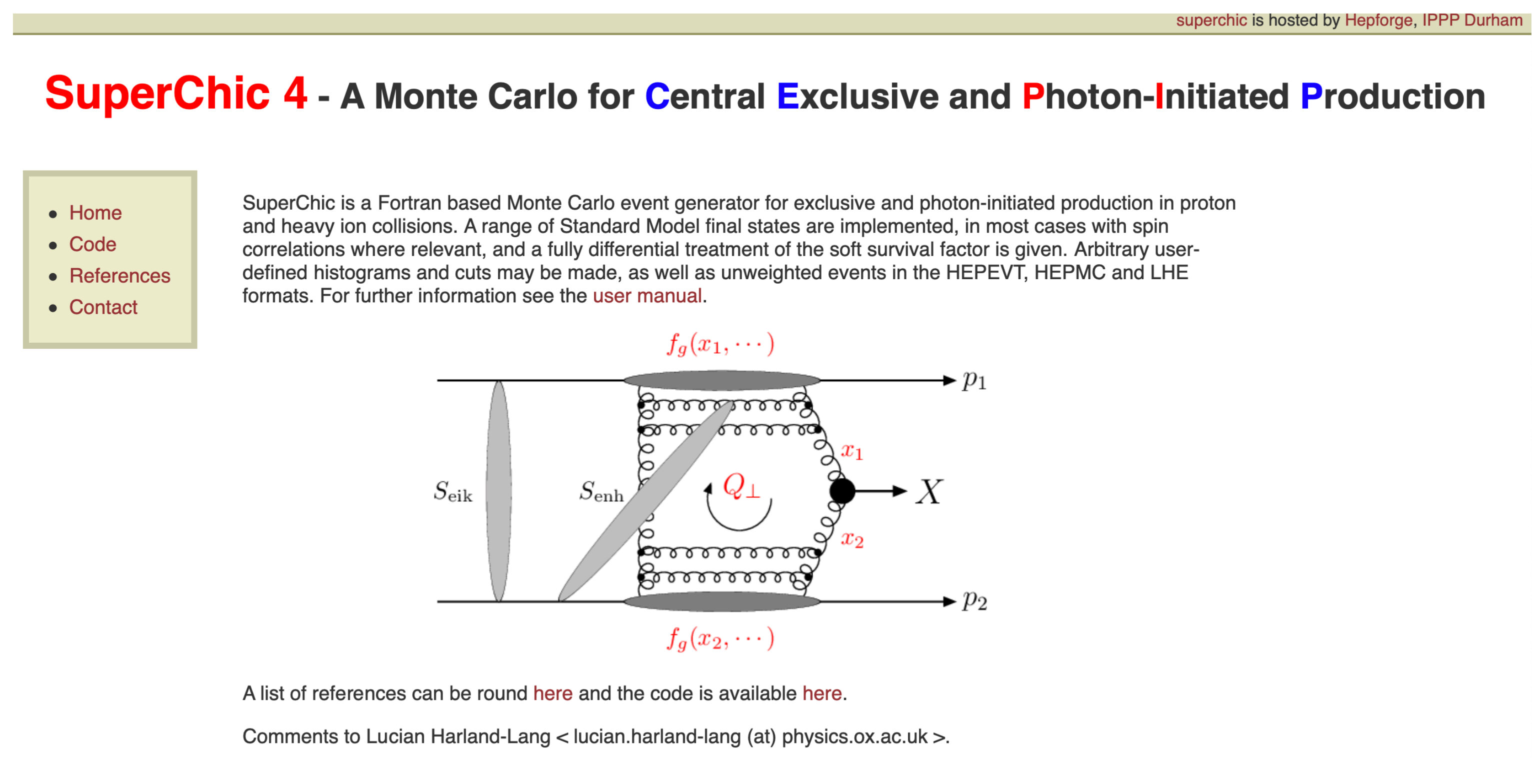


SuperChic 4 - MC Implementation

- 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.

- Full treatment of proton dissociation for photon-initiated production in pp collisions currently available for lepton pair production.

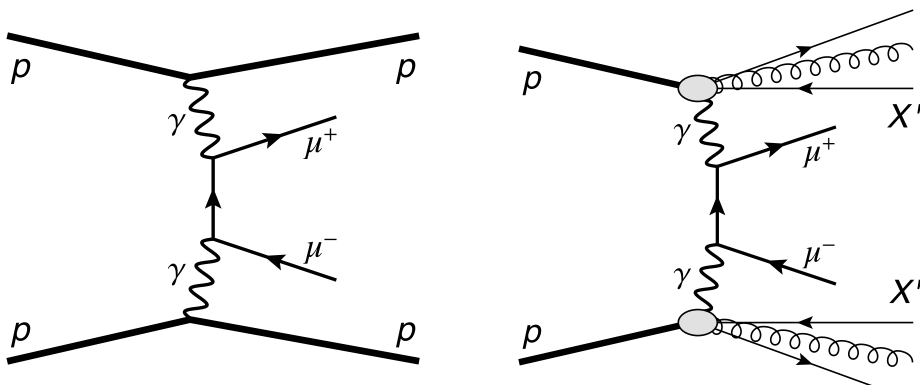


https://superchic.hepforge.org

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

What does the data say?

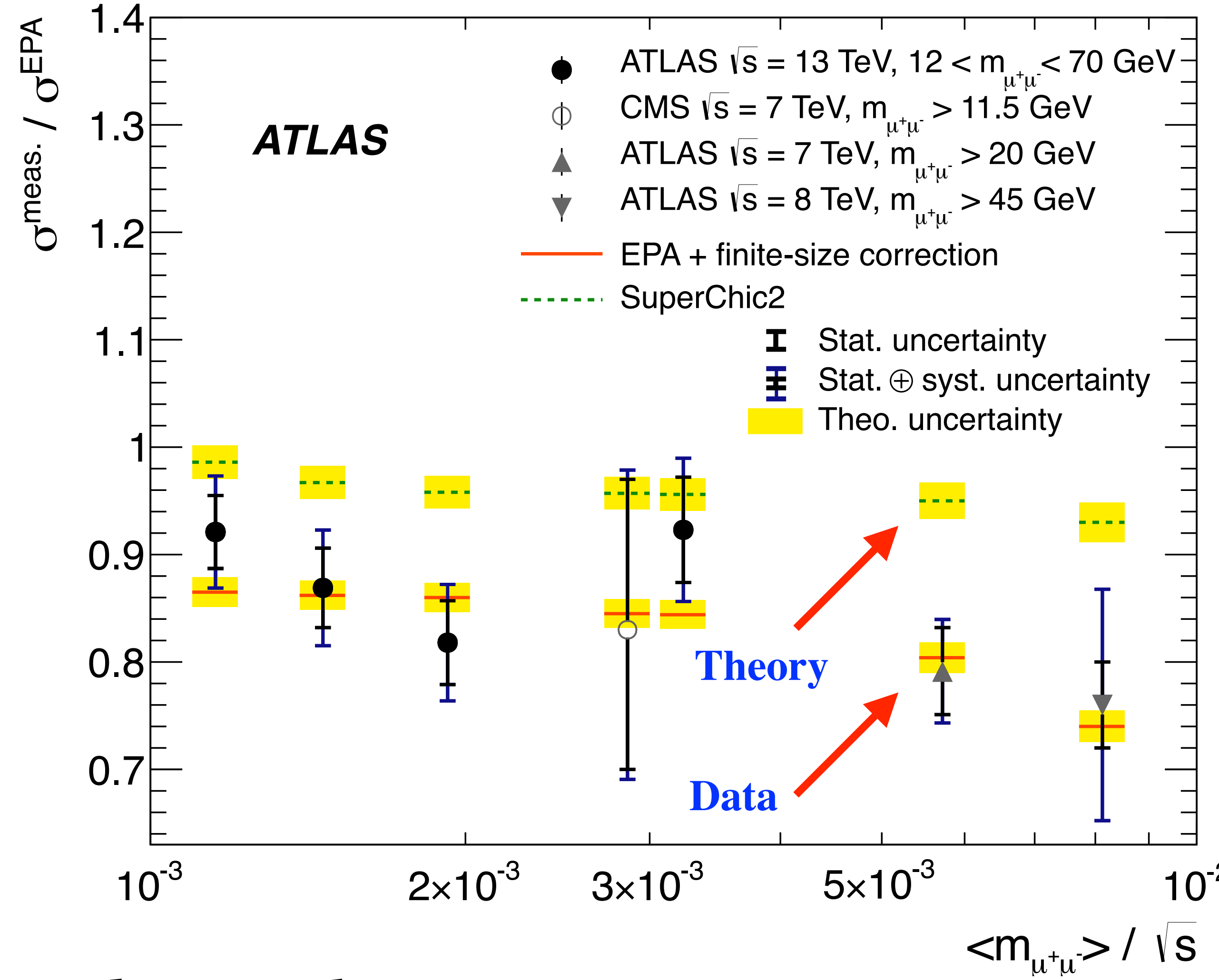
- Many BSM/SM scenarios to explore. First step: consider simplest 'standard candle' of **lepton pair** production.



	$\sigma^{\rm fid.}_{ee+p}$ (fb)	$\sigma^{\rm fid.}_{\mu\mu+p}$ (fb)
SUPERCHIC 4 [97]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

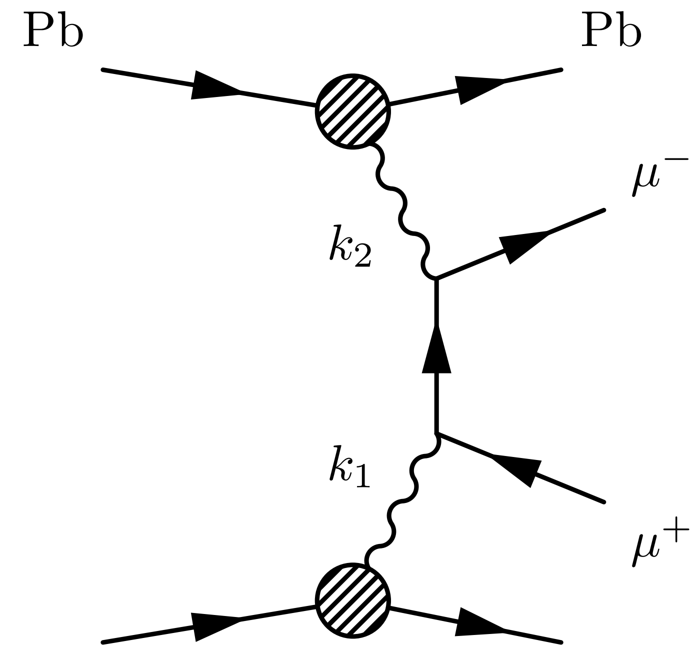
ATLAS, Phys. Rev. Lett. 125 (2020) 261801

ATLAS, M. Aaboud et al., Phys. Lett. B777, 303 (2018)



- 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.

- Recent ATLAS data on elastic* muon pair production in **PbPb** collisions provides another testing ground.



ATLAS, *Phys.Rev.C* 104 (2021) 024906

LHL, V.A Khoze, M.G. Ryskin, *SciPost Phys.* 11 (2021) 064, arXiv:2104.13392

	ATLAS data [24]	inc. S^2 + FSR
σ [μb]	34.1 ± 0.8	37.3

- Again SC predictions overshooting by O(10%), 4 sigma!
- What is going on?

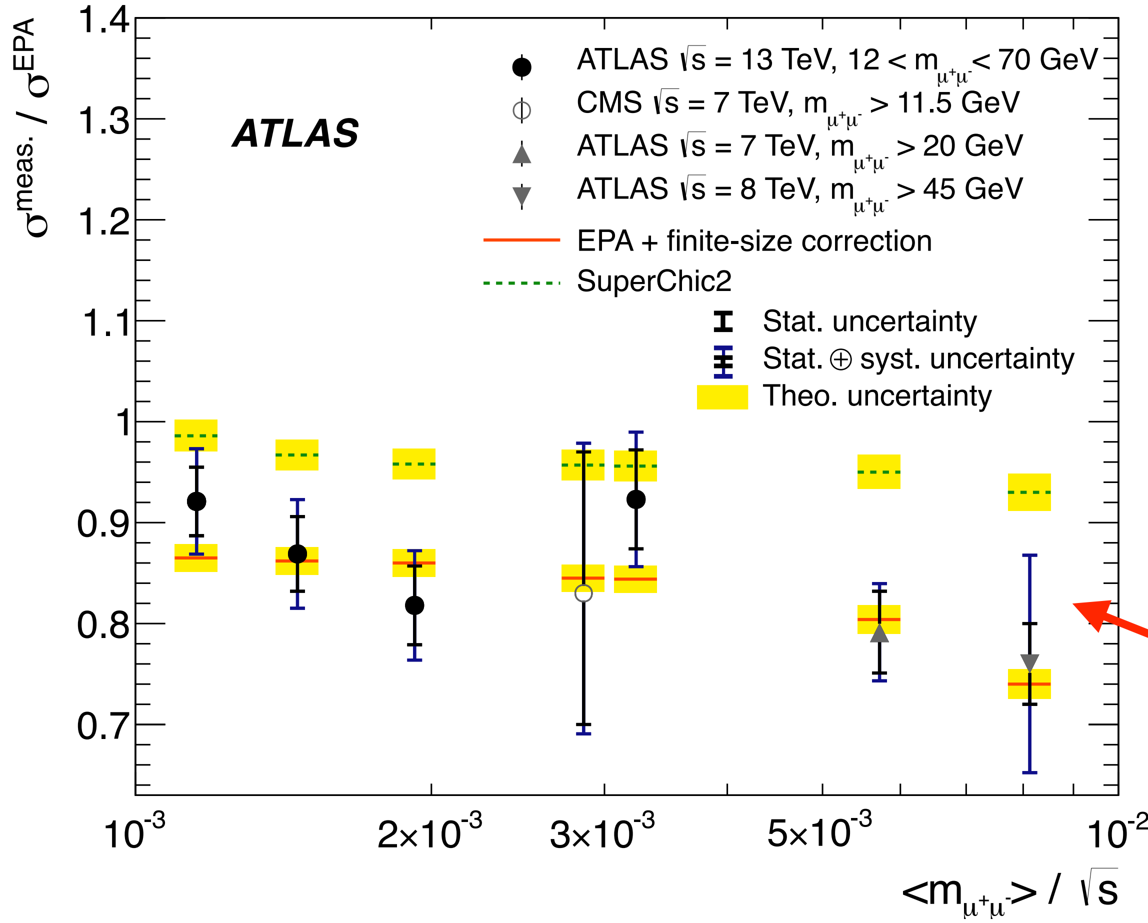
*In fact data includes ion dissociation, but unitary wrt elastic theory

Theory vs. Data?

LHL, V.A Khoze, M.G. Ryskin, *SciPost Phys.* 11 (2021) 064, arXiv:2104.13392

- This issue discussed in detail in recent paper: arXiv:2104.13392.
- Discrepancy seen in case of **elastic** production: will consider only this.
- First question: appears that other approaches describe data better/differently

ATLAS, M. Aaboud et al., Phys. Lett. B777, 303 (2018)



A. J. Baltz et al. Phys. Rev. C 80, 044902 (2009)

	ATLAS data [24]
σ $[\mu\text{b}]$	34.1 ± 0.8

Starlight MC

$30.8\ \mu$b

(SC: 37.3)

"Finite size" correction

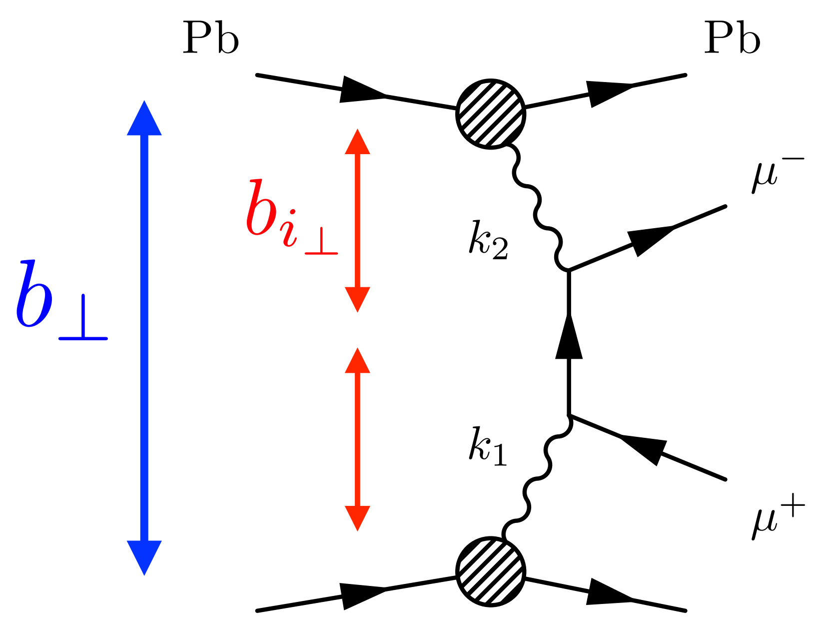
M. Dyndal and L. Schoeffel, Phys. Lett. B 741, 66 (2015), 1410.2983

- Why is this? Differing approach to e.g. survival factor? Genuine model dependence?

Impact of the $b_{1,2\perp} > R_A$ cut

- Survival factor due to hadron-hadron interactions - expressed ~ as a cut on the **hadron-hadron** impact parameter:

$$S^2(b_\perp) \approx \theta(b_\perp - 2r_A)$$



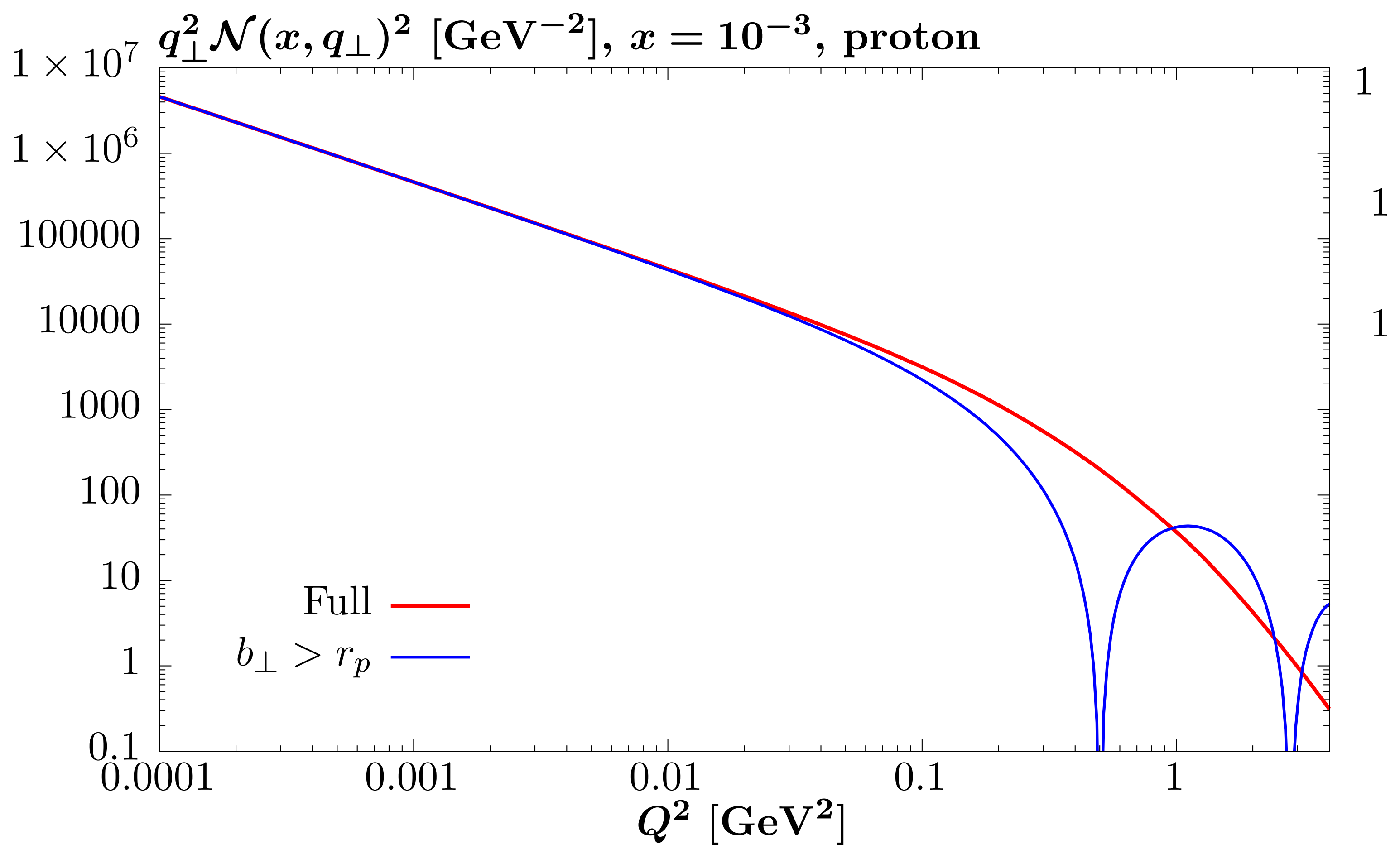
- However, in these calculations an additional cut on the **dilepton-hadron** impact parameter is imposed: $b_{1,2\perp} > R_A$
- This is **unphysical**: no lepton-hadron QCD interaction. HO QED interactions small and not to be included in this way.
- And we will show is disfavoured by differential ATLAS data in PbPb.
- **First step**: verify this leads to difference wrt SC predictions.

Impact of the $b_{1,2\perp} > R_A$ cut

- The $b_{1,2\perp} > R_A$ cut can straightforwardly be applied as a modification to the ($q_\perp$ space) elastic hadron form factor:

$$\mathcal{N}_i^{b_{i\perp}<R_A}(x_i, q_{i_\perp}) = \frac{1}{|\vec{q}_{i_\perp}|^2}\int \mathrm{d}^2 b_{i_\perp}\, \vec{q}_{i_\perp}\cdot \vec{b}_{i_\perp} \tilde{\mathcal{N}}_i(x_i, b_{i_\perp})\, e^{-i\vec{b}_{i_\perp}\cdot\vec{q}_{i_\perp}}\theta(R_A - b_{i_\perp}) \,,$$

Form factor ~ $\quad \mathcal{N}_i(x_i, q_{i_\perp}) \to \mathcal{N}_i^{b_{i\perp}>R_A}(x_i, q_{i_\perp}) \equiv \mathcal{N}_i(x_i, q_{i_\perp}) - \mathcal{N}_i^{b_{i\perp}<R_A}(x_i, q_{i_\perp})\,.$



- Applying this cut leads to much better agreement with **SuperChic**.

PbPb

	ATLAS data [24]
σ [μb]	34.1 ± 0.8

inc. S^2
38.9

$\leftrightarrow$

$b_{i\perp} > R_A$, inc. S^2
29.9

- STARlight : 32.1 pb.

pp

	ATLAS data [14, 16]
σ [pb], 7 TeV	0.628 ± 0.038
σ [pb], 13 TeV	3.12 ± 0.16

inc. S^2
0.742
3.43

$\leftrightarrow$

$b_{i\perp} > r_p$, inc. S^2
0.626
3.02

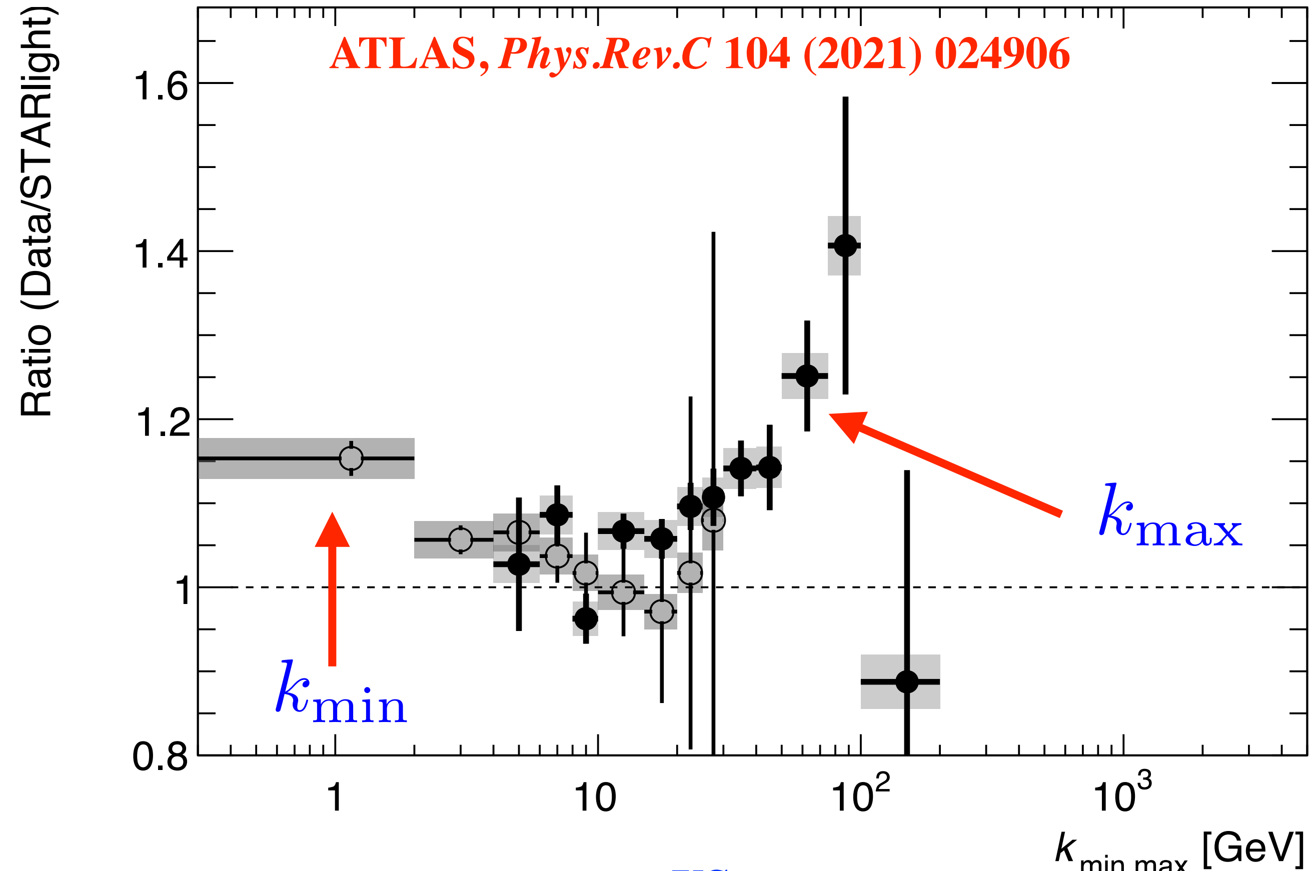
- Finite-size (13 TeV) : 3.06 pb.

- Note we argued on general grounds that the $b_{1,2\perp} > R_A$ cut is unphysical.
- Do data have anything to say. Yes!

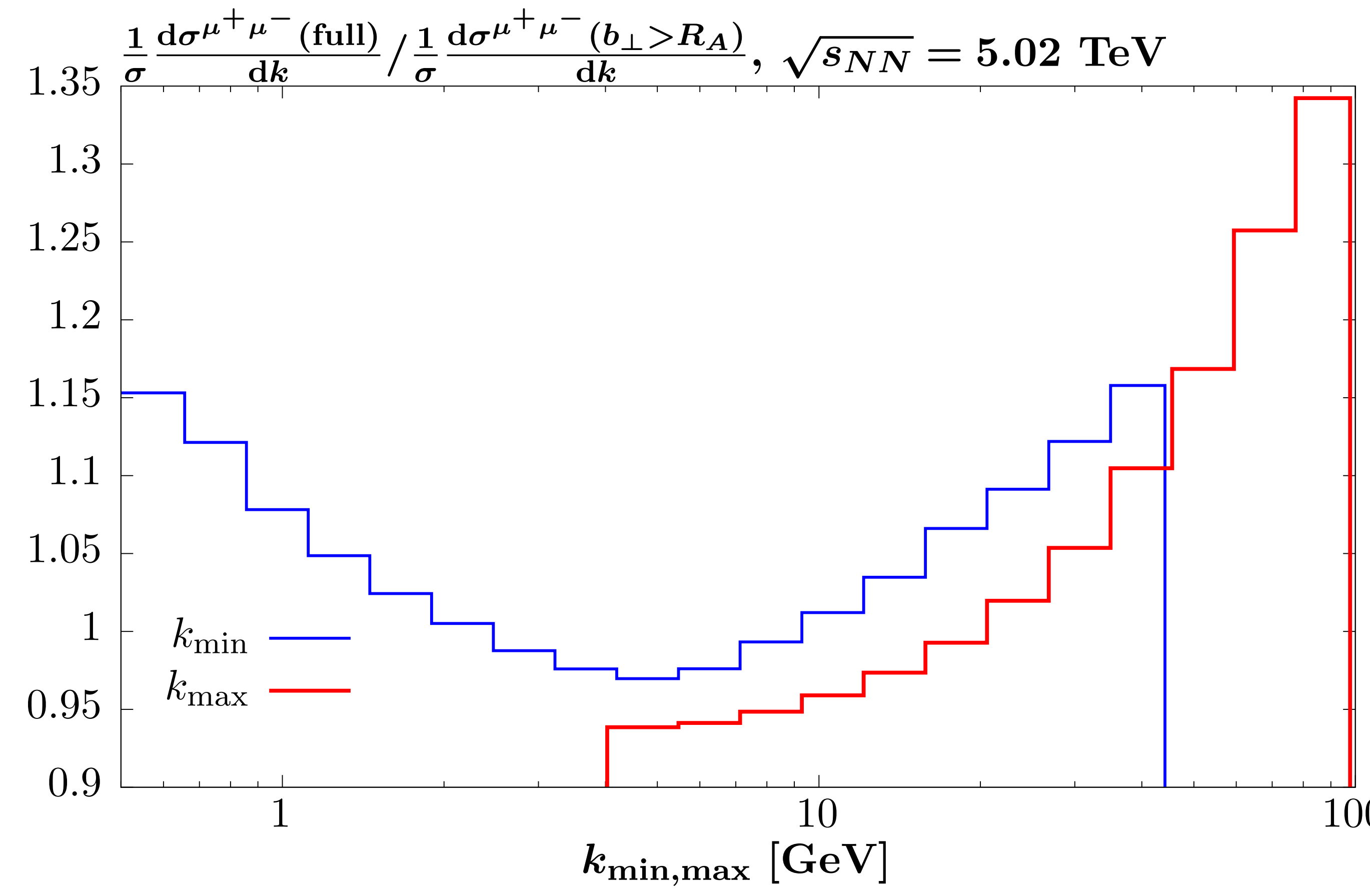
- Clear discrepancies seen in Starlight vs. data differential distributions in PbPb case

- We find that effect of removing $b_{1,2\perp} > R_A$ cut will improves data/STARlight theory comparison significantly.

$$k_{1,2} = \frac{\sqrt{s}}{2} x_{1,2}$$



vs



Theory vs. Data?

- Once we remove unphysical $b_{1,2\perp} > R_A$ cut we are still left with a data vs. theory discrepancy.

PbPb:

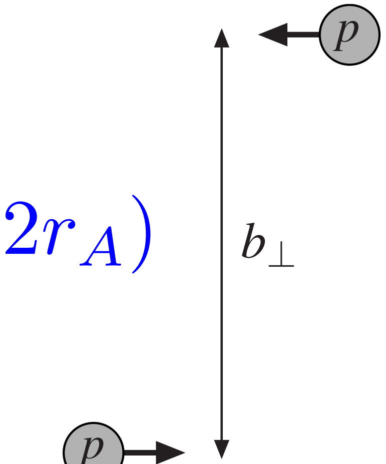
	ATLAS data [24]	inc. S^2 + FSR
σ [μb]	34.1 ± 0.8	37.3

	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
SUPERCHIC 4 [97]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

: pp

- Naively obvious source of this: the **survival factor** could introduce a ~ 10% level theoretical uncertainty and explain the data/theory discrepancy.
- Is this possible?

- Forget about details of soft QCD modelling. First (pretty good) approximation: $S^2(b_\perp) \approx \theta(b_\perp - 2r_A)$

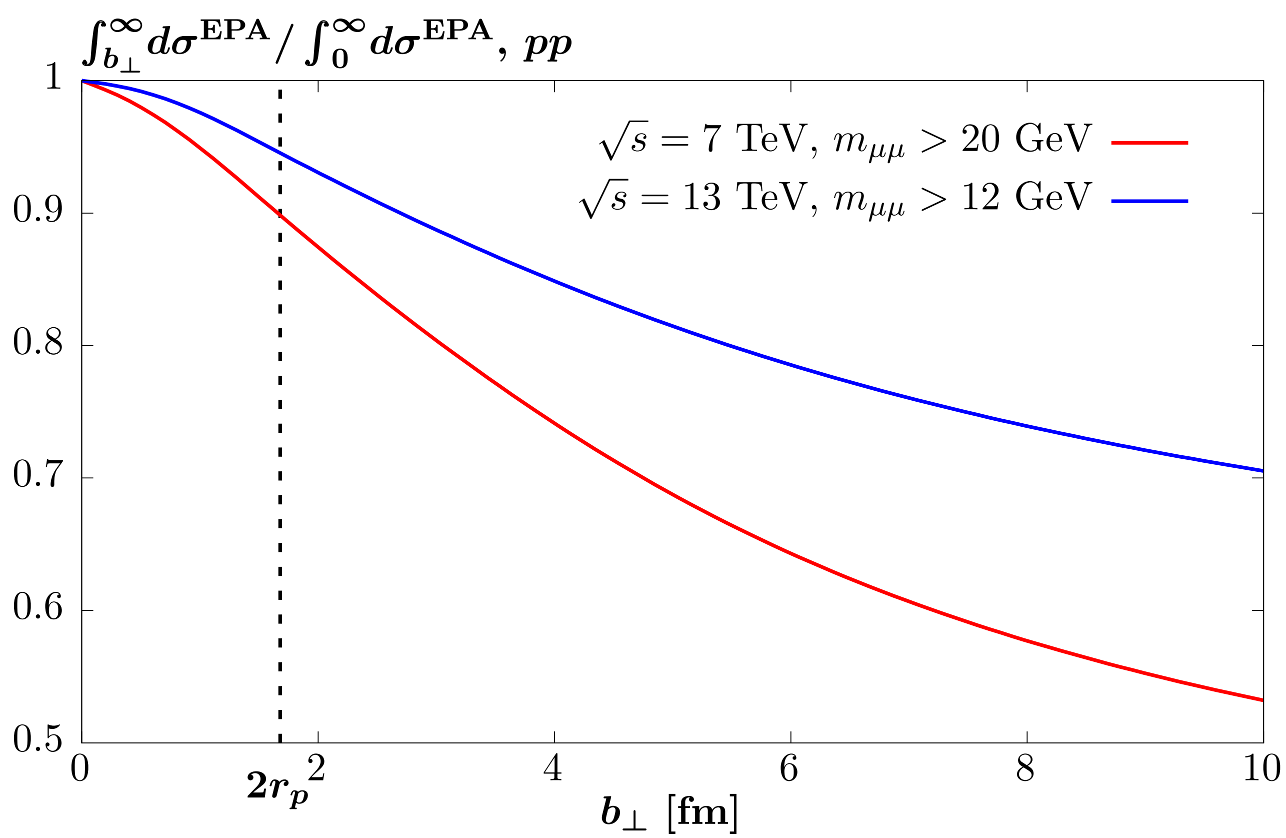


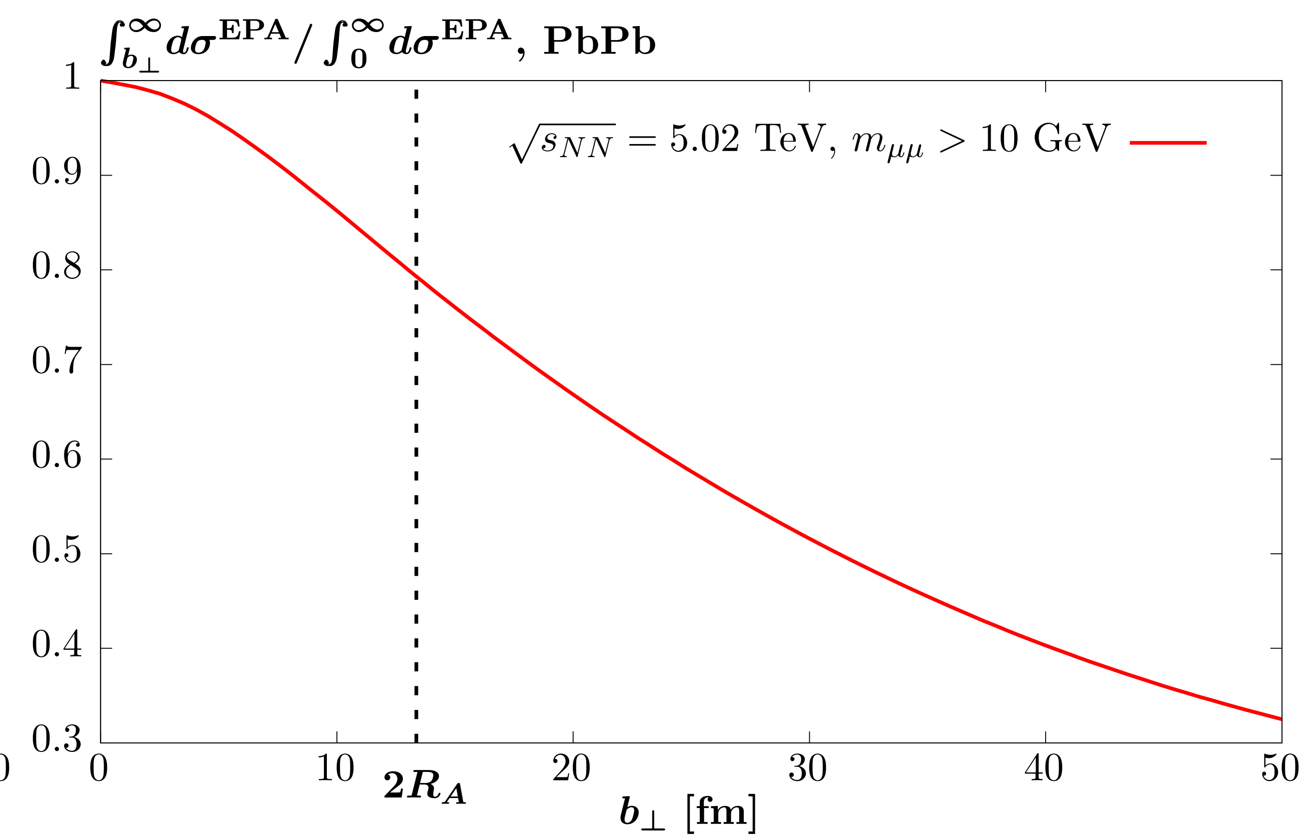
i.e. if hadrons overlap, they will interact inelastically.

- To match e.g. ATLAS **PbPb** data, instead need: $S^2(b_\perp) \approx \theta(b_\perp - 3r_A)$

i.e. ~ 100% inelastic interaction probability out to ~ r_A (~ 0.8, 6.7 fm for p, Pb) beyond hadron edge.

$\longrightarrow$ Very unphysical behaviour would be required. Hard to imagine that this can be the solution. Peripheral PI interaction ~ outside **range of QCD**!





- In more detail:

PbPb:

	ATLAS data [24]	$\theta(b_\perp - 2R_A)$	$\theta(b_\perp - 3R_A)$
σ [μb]	34.1 ± 0.8	41.4	34.7

pp:

	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

- In pp case a very similar picture emerges if one takes e.g. a simplified one-channel model:

$$A_{pp}(s, k_\perp^2) = isC^* \sigma_{\rm pp}^{\rm tot}(s) \exp\left(-Bk_\perp^2/2\right) .$$

- Extreme variations in parameter C^* (can think of this as varying $\sigma^{\rm tot}$):

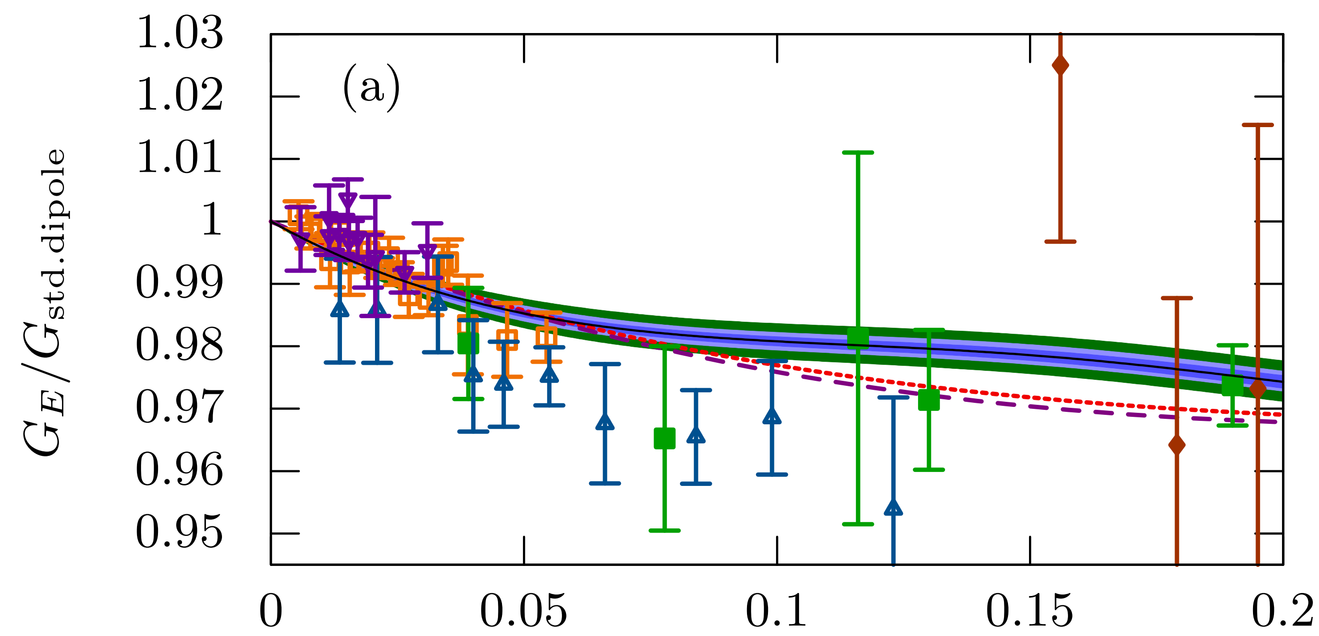
	ATLAS data [14, 16]	1 ch. ($C^* = 1 - 2$)
σ [pb], 7 TeV	0.628 ± 0.038	0.748 - 0.727
σ [pb], 13 TeV	3.12 ± 0.16	3.45 - 3.40

- Note the above explains why other approaches give similar cross sections: they model survival factor in different ways, but result insensitive to this.

Form factor

A1 collab., J. C. Bernauer et al., Phys. Rev. C 90, 015206 (2014), 1307.6227.

- Elastic proton form factor take from fit by A1 Collaboration:
  - This fit comes with precisely determined experimental uncertainties.
  - Standard dipole form is strongly disfavoured:



$$G_{\rm standard\ dipole}(Q^2) = \left(1 + \frac{Q^2}{0.71{\rm GeV}^2}\right)^{-2}$$

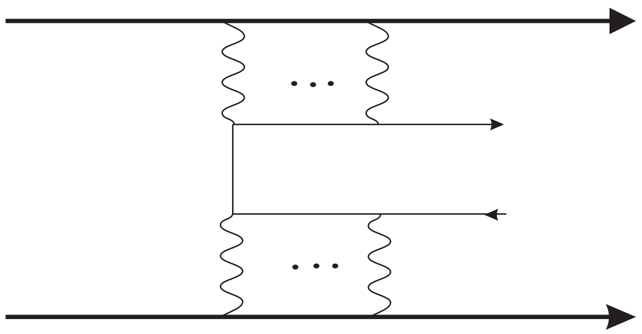
	ATLAS data [14, 16]	Baseline	FF uncertainty	Dipole FF
σ [pb], 7 TeV	0.628 ± 0.038	0.742	$^{+0.003}_{-0.005}$	0.755
σ [pb], 13 TeV	3.12 ± 0.16	3.43	± 0.01	3.48

- Varying in allowed uncertainties gives ~ 1% level differences.
- A very similar picture in PbPb case.

PbPb: Other effects?

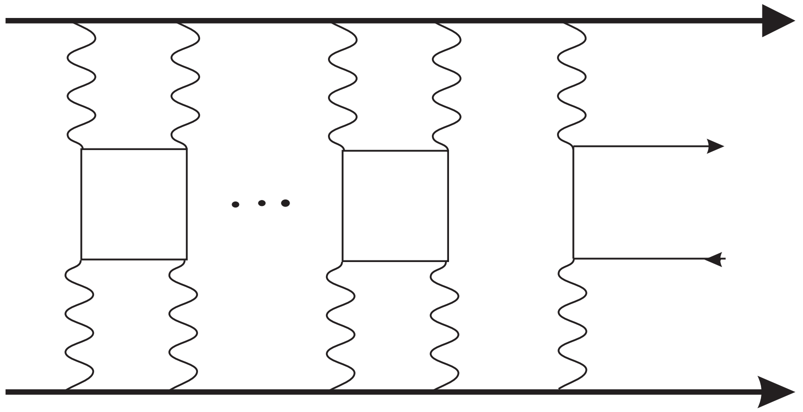
W. Zha and Z. Tang, (2021), 2103.04605.

- **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.

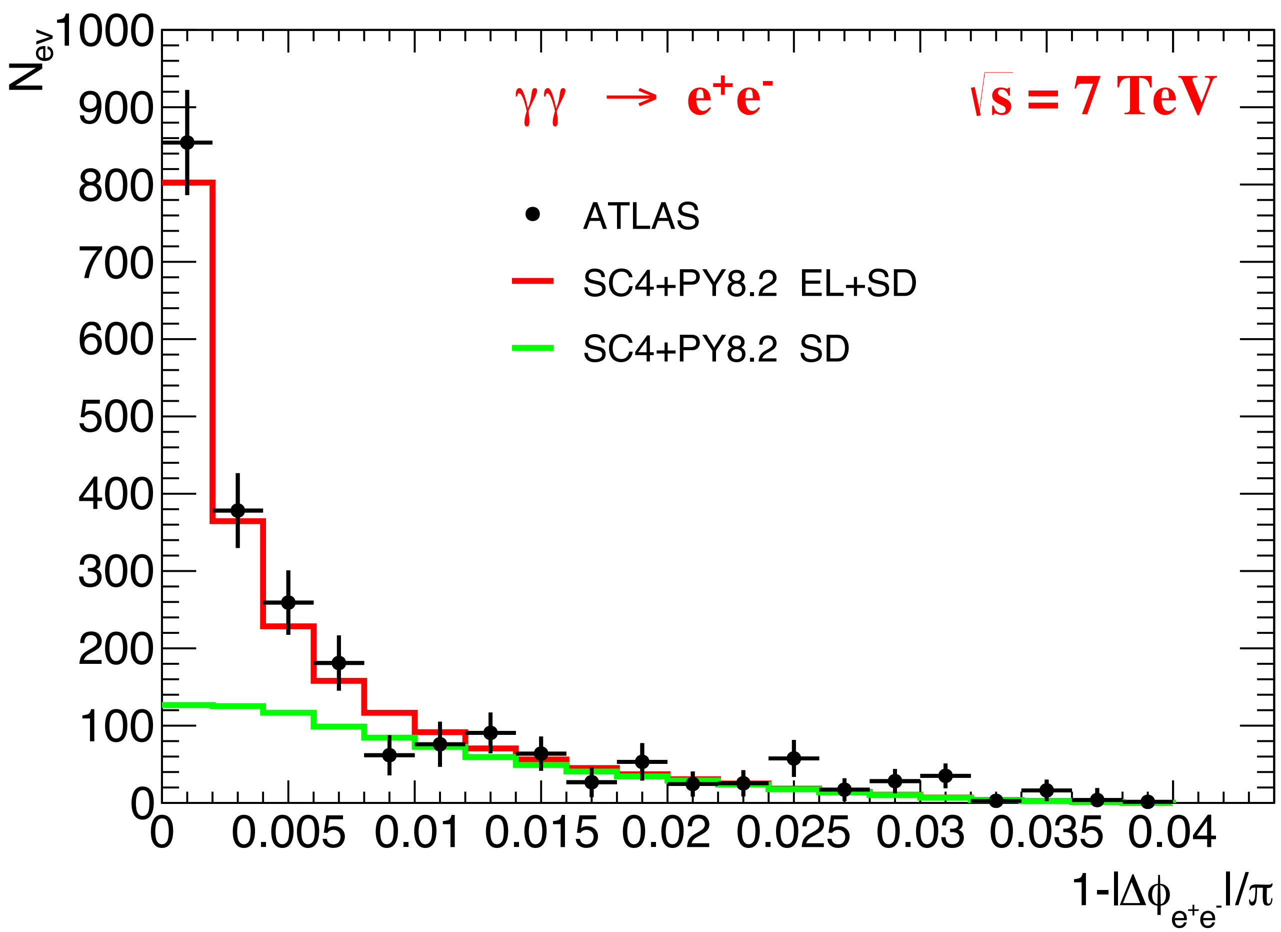


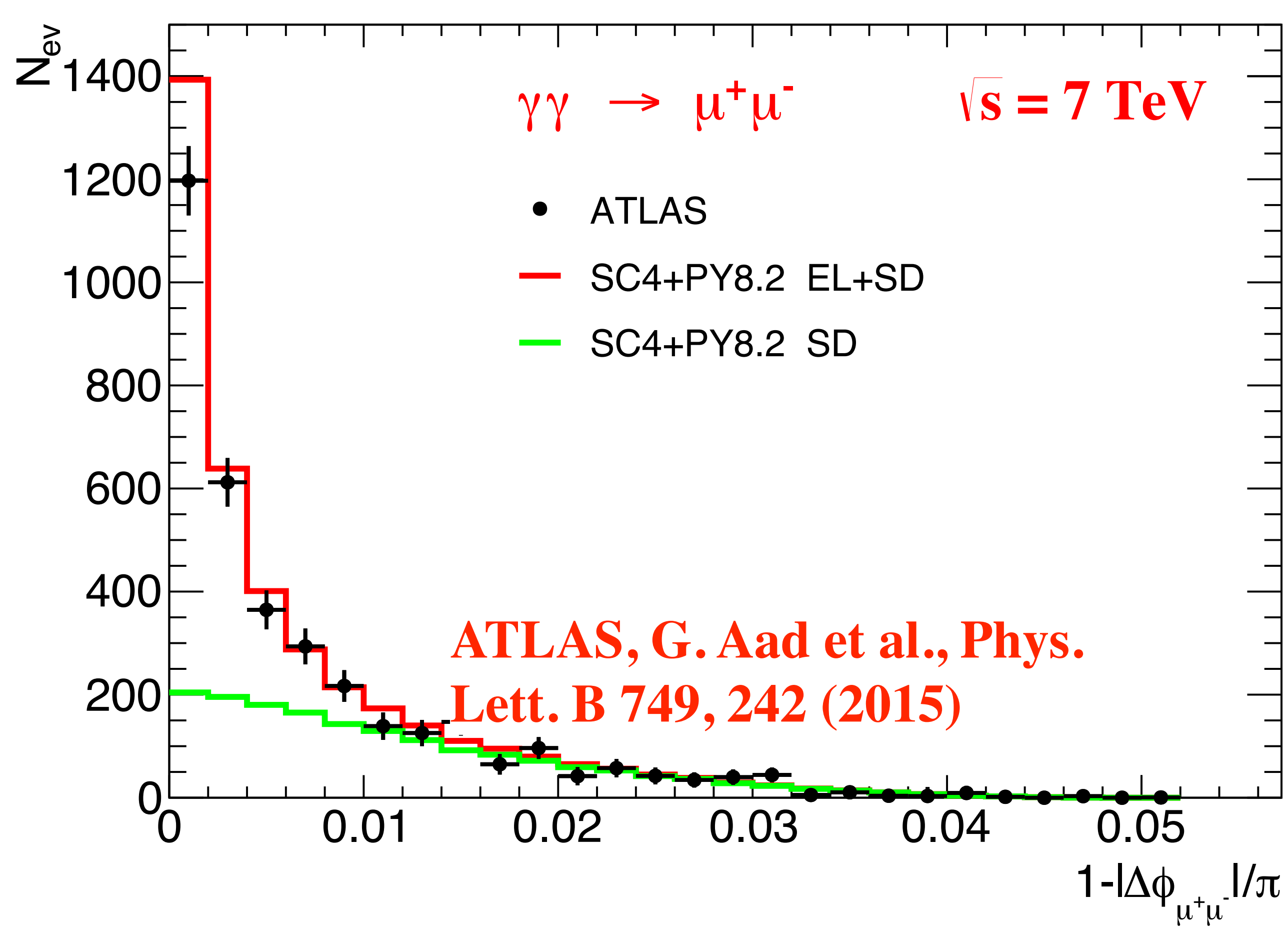
- **Ion dissociation**? Not in SC (but in Starlight). Dominantly driven by additional ion-ion QED exchanges, i.e. unitary. Other inelastic emission subtracted from data.
- **QED FSR**? Included via Pythia in predictions, but worth recalling that production of such back-to-back leptons particularly sensitive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

$\longrightarrow$ Relevance of these effects clearly not limited to (SM) dimuon production!

pp: Other effects?

- Most of the above points not relevant for pp case: less room for manoeuvre!
- ATLAS 7 TeV data suggests peaked at low dimuon acoplanarity.
- More differential data, including with proton tags will guide the way.
- Most natural culprit: treatment of dissociative production, though no clear issue to point to.



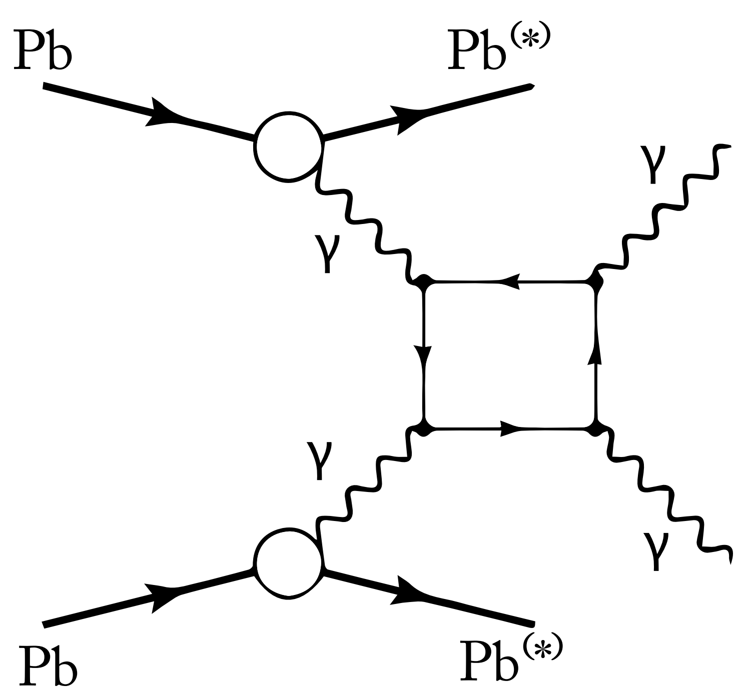


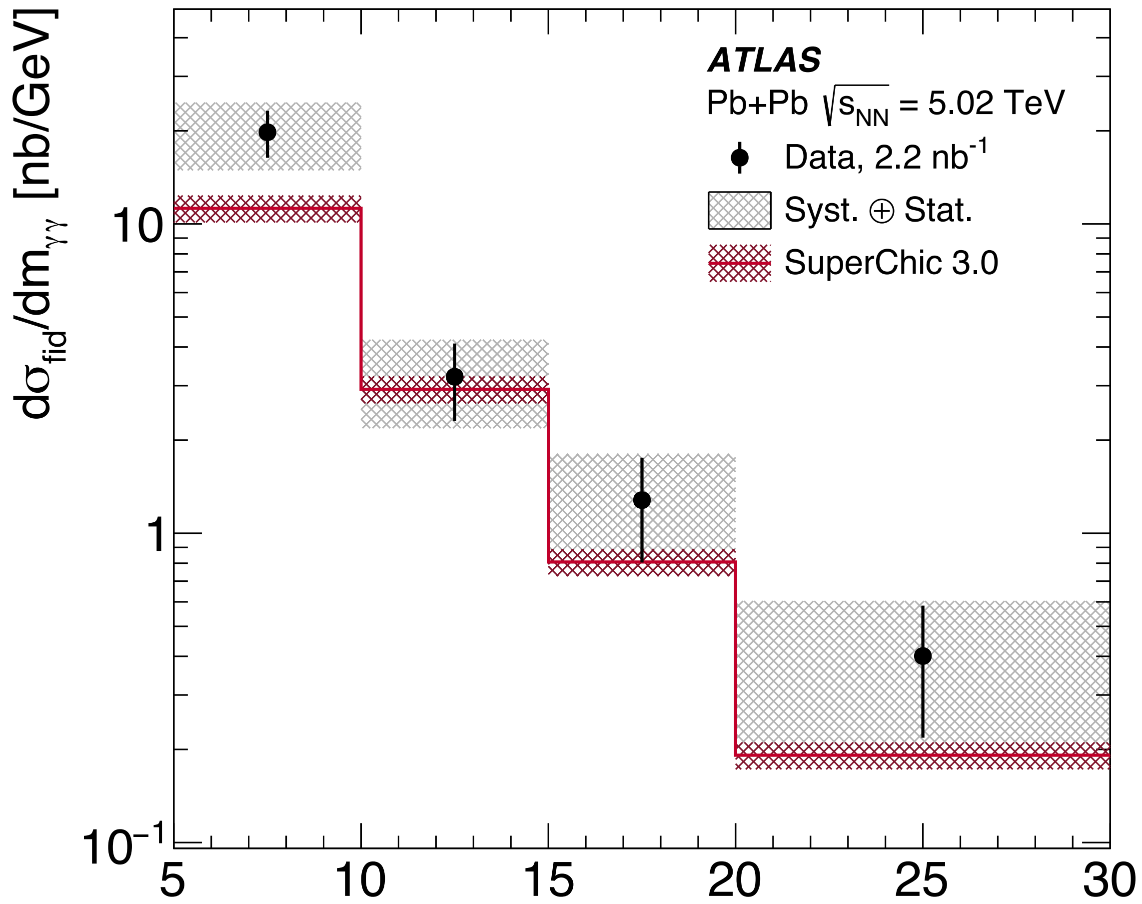
Light-by-Light Scattering

- MC prediction compared with ATLAS data on LbyL scattering:

$$\sigma_{\mathrm{fid}} = 120 \pm 17\ (\mathrm{stat.}) \pm 13\ (\mathrm{syst.}) \pm 4\ (\mathrm{lumi.})\ \mathrm{nb}.$$

- **SuperChic** central prediction: 78 nb, i.e. now **below** the data. Differentially:





ATLAS, *JHEP* 03 (2021) 243

- Enhancement dominantly in lower mass region. In general comparison to/calibration w.r.t. process such as dimuon production have key role here.

Summary/Outlook

- ★ Photon-initiated production a key mode for BSM (and SM) production.
- ★ SuperChic 4 MC: fully differential generation of this channel, including complete treatment of survival factor.
- ★ Intriguing data/theory discrepancy in dilepton channel (pp & PbPb).
- ★ New study: variation between some predictions due to inconsistencies in some approaches and not genuine model dependence
- ★ Dependence on details of survival factor calculation v. small due to peripheral nature of PI interaction.
- ★ Reason for apparent data/theory discrepancy tbd. Some possibilities described here, but difficult to see that survival factor is solution.
- ★ Much to do - stay tuned!

Thank you for listening