SuperChic 4: Latest Developments for Heavy Ions

Lucian Harland-Lang, University of Oxford

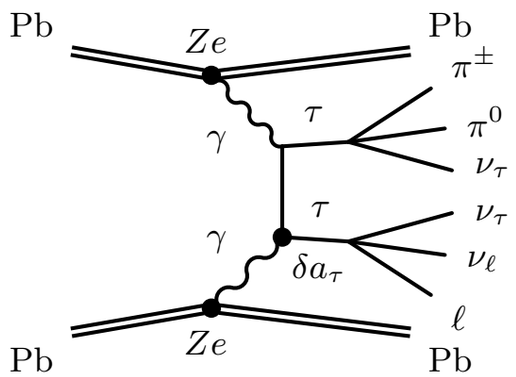
Heavy Ions and New Physics, May 20 2021

LHL, V.A Khoze, M.G. Ryskin, *Eur.Phys.J.C* 79 (2019) 1, 39
LHL, V.A Khoze, M.G. Ryskin, arXiv:2104.13392

Motivation

- **Ultraperipheral** photon-initiated production: colour singlet photon naturally leads to events with intact ions/low multiplicity in final state.
- **Clean** production mechanism and BSM probe.

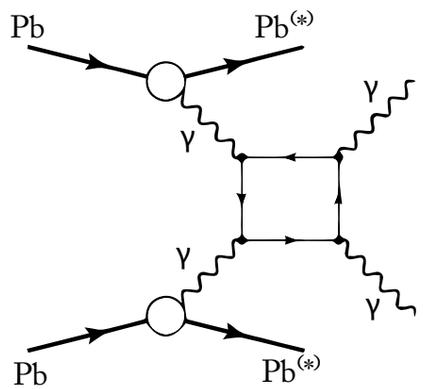
tau g-2



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

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

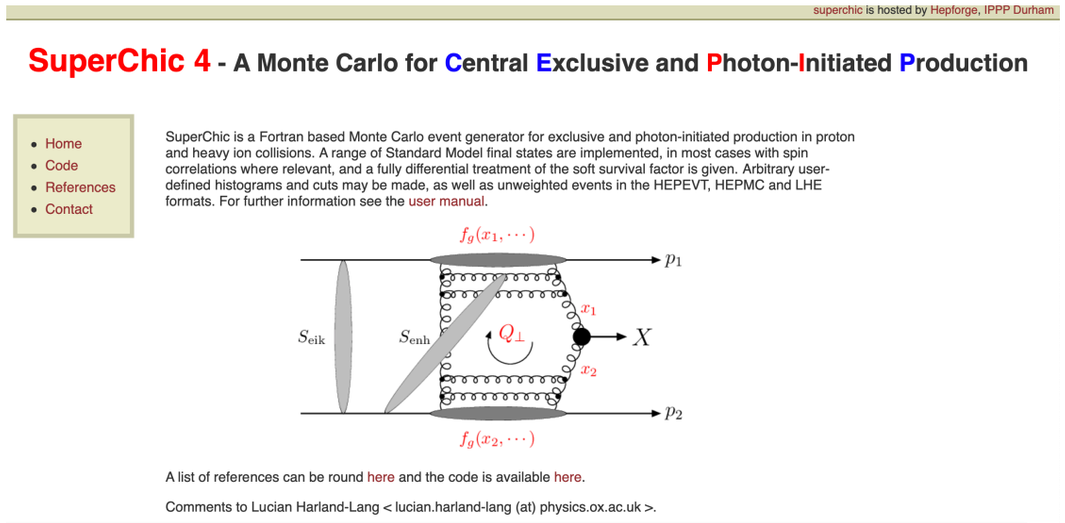
SuperChic 4

- 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.

- In heavy ions, currently implemented of most relevance:
  - Lepton pairs.
  - LbyL scattering.
  - ALPs.
  - Monopoles

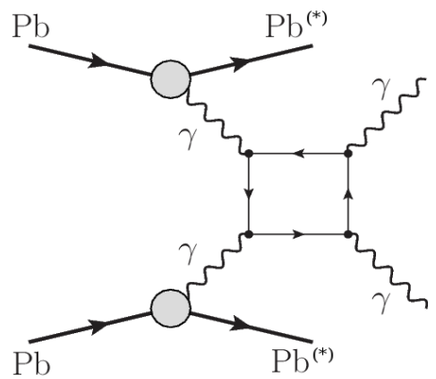
- But open to collaboration/discussion for including other channels!



https://superchic.hepforge.org

SuperChic 4: Heavy Ions

- Basic idea: apply equivalent photon approximation.
- Cross section given in terms of:



$$\sigma_{N_1 N_2 \to N_1 X N_2} = \int \mathrm{d}x_1 \mathrm{d}x_2 \, n(x_1) n(x_2) \hat{\sigma}_{\gamma\gamma \to X}$$

Photon flux from ion

Subprocess cross section

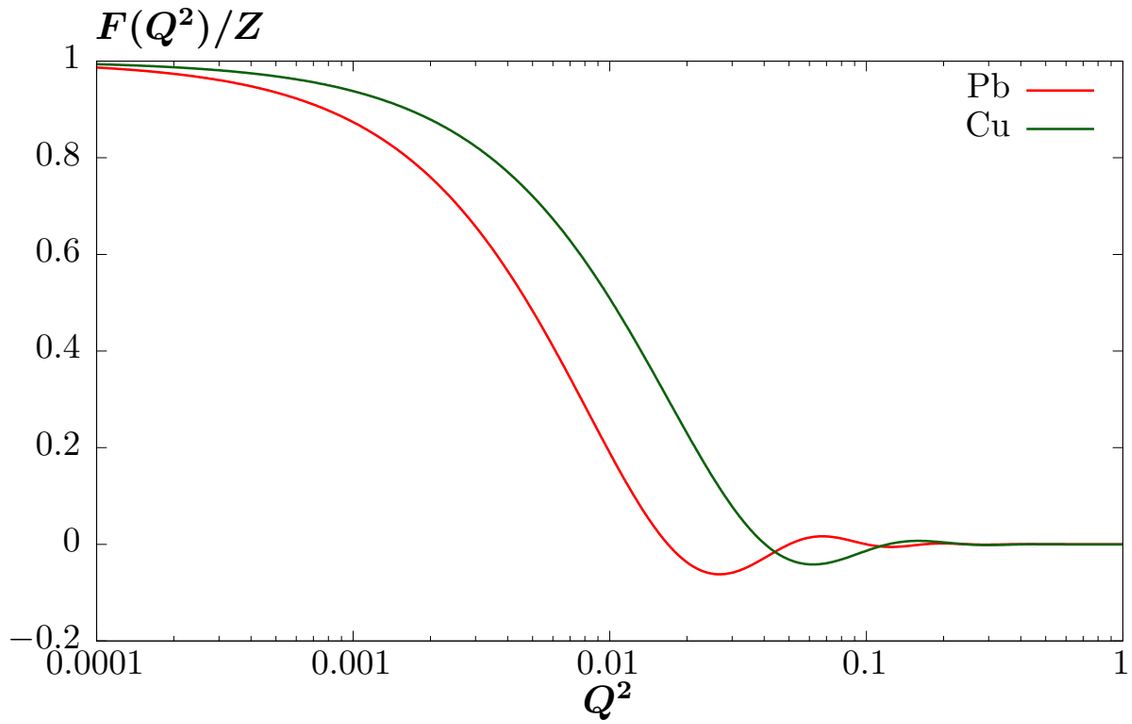
- The flux $n(x)$ well-known, given in terms of ion EM form factor $F_p(Q^2)$, related to proton distribution within ion

$$F_p(|\vec{q}|) = \int \mathrm{d}^3 r \, e^{i\vec{q}\cdot\vec{r}} \rho_p(r) \qquad \rho_p(r) = \frac{\rho_0}{1 + \exp\left(r - R\right)/d} \, ,$$

- Form factor rapidly falling with photon Q^2.
- Input parameters for e.g. Pb have very small uncertainties

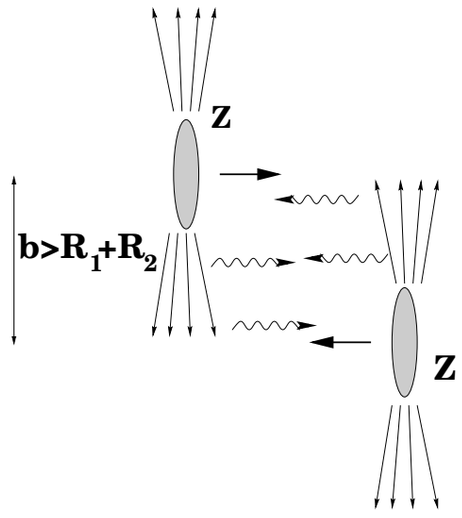
$$\rho_p(r) = \frac{\rho_0}{1 + \exp\left(r - R\right)/d} \,,$$

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



- Final element of calculation: what about possibility for additional soft particle production from ion-ion interactions $\Rightarrow$ the survival factor?

$\gamma\gamma$ collisions - survival factor



- Basic approach - consider collision in impact parameter space. If ions overlap, will generally have additional particle production. So require:

$$|b_{1\perp} - b_{2\perp}| > R_1 + R_2$$

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

$$\sigma = \int \mathrm{d}^2 b_{1\perp} \mathrm{d}^2 b_{2\perp}\, \mathrm{d}\sigma(\vec{b}_{1\perp}, \vec{b}_{2\perp})\, e^{-\Omega_{A_1 A_2}(\vec{b}_{1\perp} - \vec{b}_{2\perp})}$$

$e^{-\Omega_{A_1 A_2}(\vec{b}_{1\perp} - \vec{b}_{2\perp})}$: survival factor - probability for no additional particle production at impact parameter $b_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$. Roughly:

$$e^{-\Omega_{A_1 A_2}(\vec{b}_{1\perp} - \vec{b}_{2\perp})} \approx \theta(b_\perp - R_1 - R_2)$$

but not exact!

Ion-ion survival factor

- In more detail, we have:

$$\Omega_{A_1A_2}(b_\perp) = \int \mathrm{d}^2 b_{1\perp} \mathrm{d}^2 b_{2\perp} T_{A_1}(b_{1\perp}) T_{A_2}(b_{2\perp}) A_{nn}(b_\perp - b_{1\perp} + b_{2\perp})$$

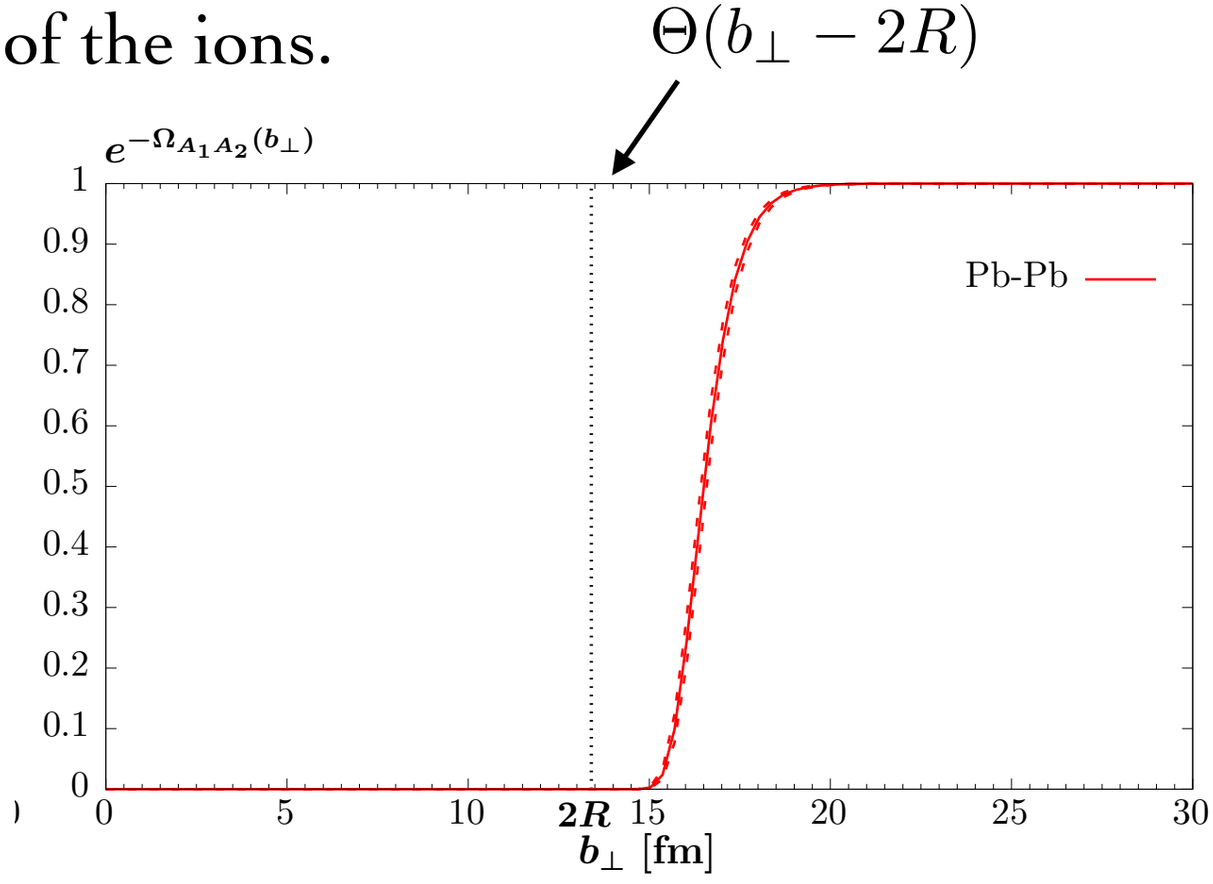
where: $T_A(b_\perp) = \int \mathrm{d}z\, \rho_A(r) = \int \mathrm{d}z\, (\rho_n(r) + \rho_p(r))$, is transverse nucleon density.

$A_{nn}(b_\perp) = 2(1 - e^{-\Omega(b_\perp)/2})$: nucleon-nucleon scattering amplitude.

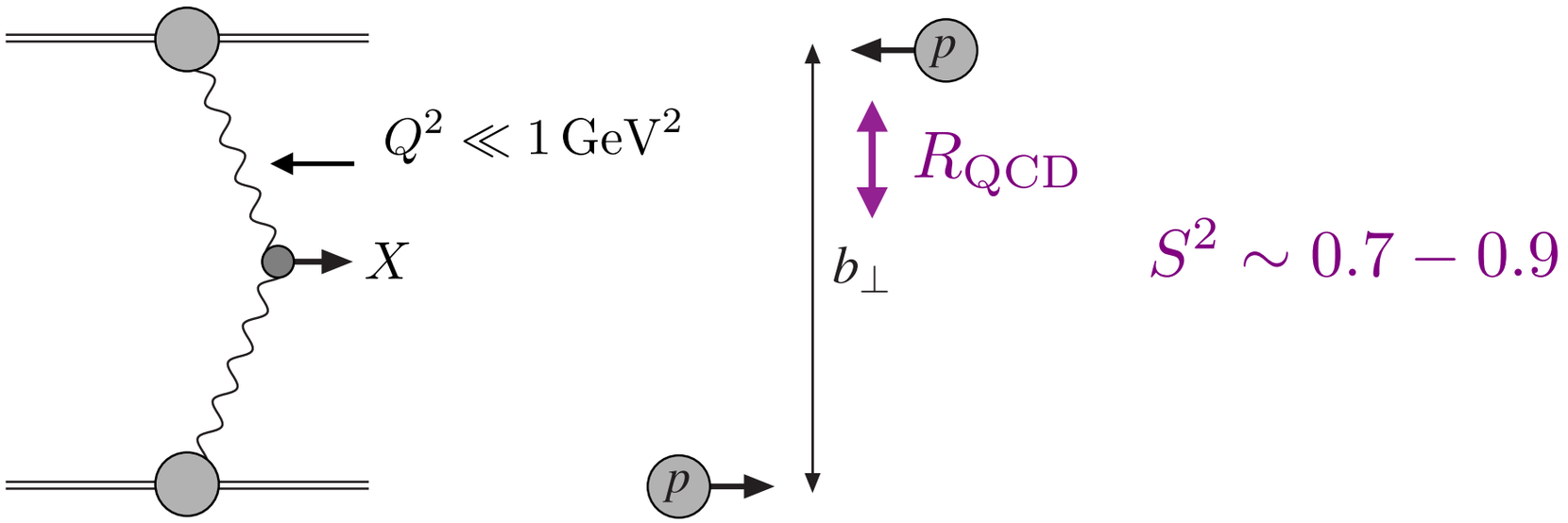
i.e. schematically given in terms of integrating individual nucleon-nucleon scatterings over the overlap area of the ions.

- Result for Pb-Pb*:

$\Rightarrow$ expect larger suppression vs. simple $b_\perp > 2R$ cut.

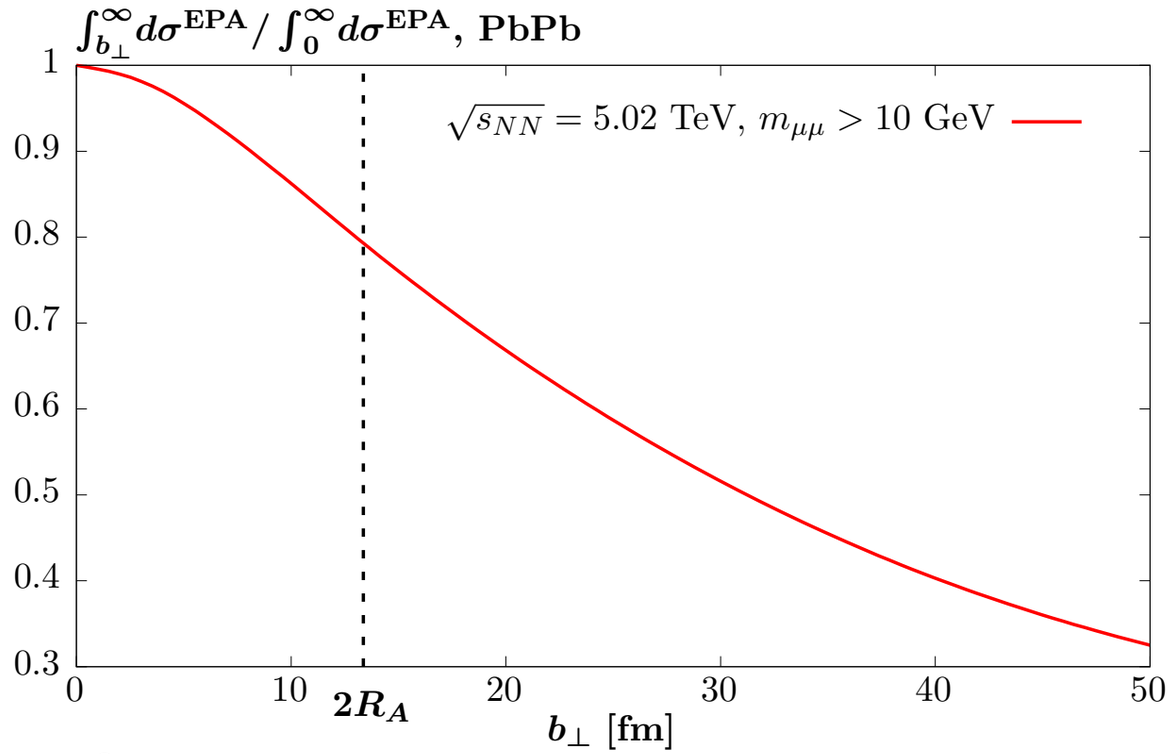


- Ions like to interact: naively expect $S^2 \ll 1$.
- However elastic PI production a **special case**: quasi-real photon $Q^2 \sim 0 \Rightarrow$ large average pp impact parameter $b_\perp \gg R_{\rm QCD}$, and $S^2 \sim 1$.



$S^2 \sim 0.7 - 0.9$

- Impact parameter dependence of cross section:



In more detail…

- Survival factor not exactly unity, and depends on process/kinematics.

$$\langle S^2 \rangle = \frac{\int \mathrm{d}^2 b_{1\perp}\, \mathrm{d}^2 b_{2\perp}\, |\tilde{T}(s, b_{1\perp}, b_{2\perp})|^2 \exp(-\Omega_{N_1 N_2}(s, b_\perp))}{\int \mathrm{d}^2\, b_{1\perp} \mathrm{d}^2 b_{2\perp}\, |\tilde{T}(s, b_{1\perp}, b_{2\perp})|^2}$$

$$b_\perp \leftrightarrow q_\perp$$

$$\langle S^2 \rangle = \frac{\int \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp} |T^{b+sc.}(q_{1_\perp}, q_{2_\perp})|^2}{\int \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp} |T(q_{1_\perp}, q_{2_\perp})|^2}$$

Kinematics

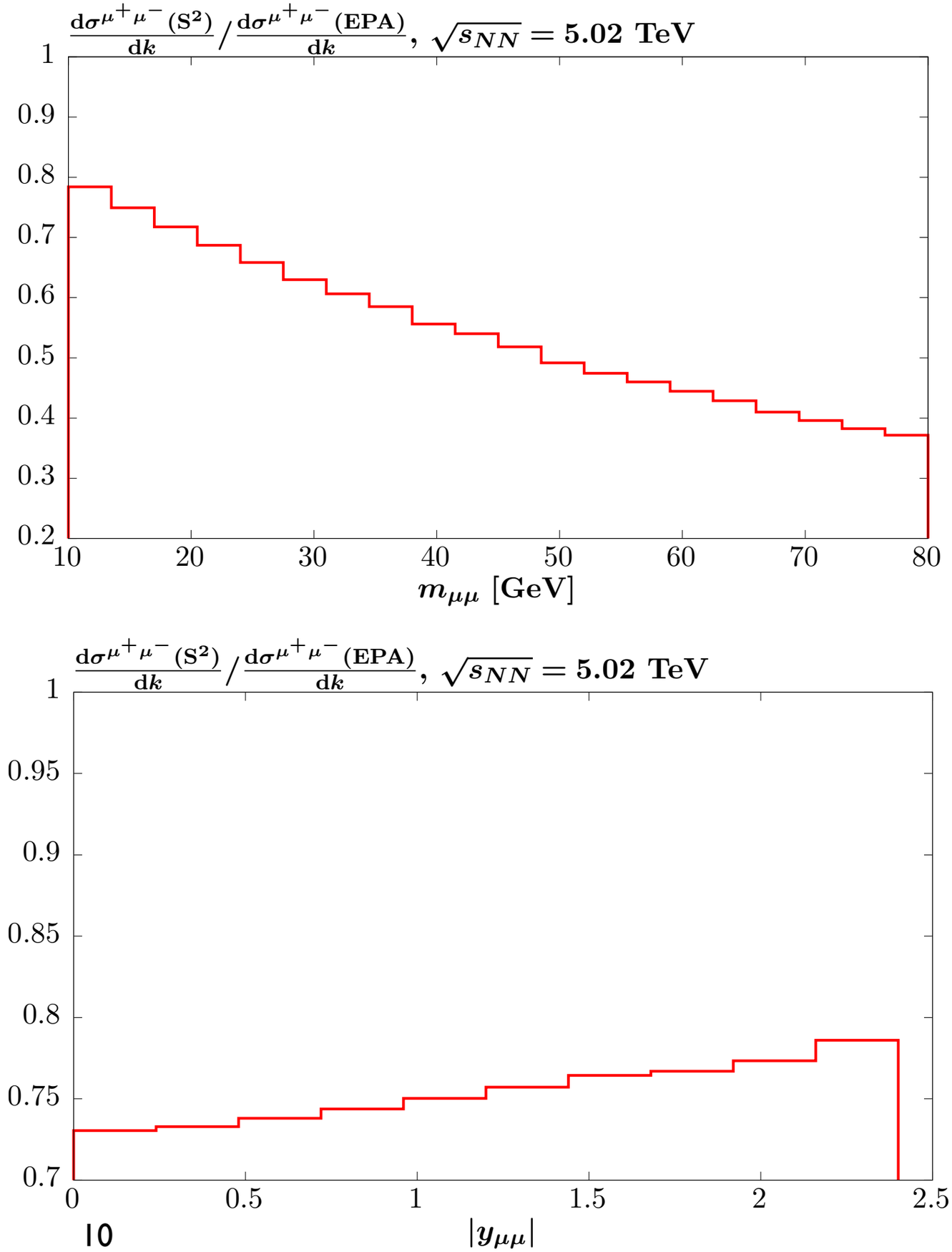
Process

$T \sim n(x_1) n(x_2) V(\gamma\gamma \to X)$

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

$T \sim n(x_1) n(x_2)$ ✗

- Consider **dimuon** production in PbPb.
- Survival factor ~ 0.7-0.8 at low mass, but lower at high mass.



- Some (mild) dependence on rapidity.

Comparison to data

ATLAS, arXiv:2011.12211

- Recent ATLAS data on ultraperipheral dimuon production at 5.02 TeV.
- Differential data not publicly available (yet), but can compare to total rate.

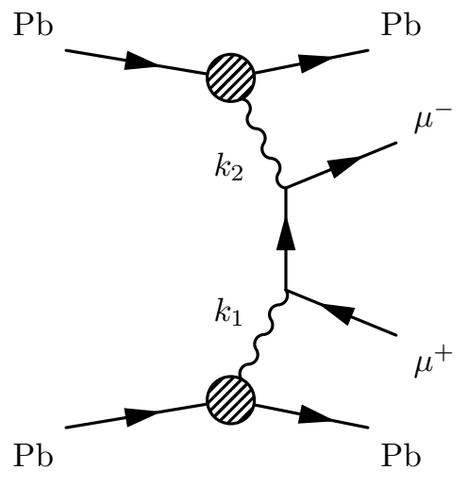
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. C

CERN-EP-2020-138
November 25, 2020

Exclusive dimuon production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV with ATLAS

The ATLAS Collaboration

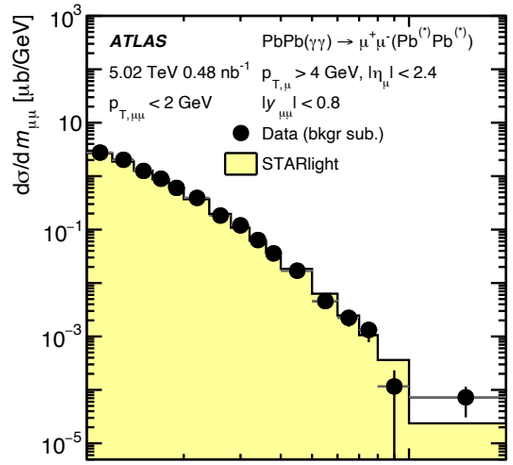


	ATLAS data [23]	Pure EPA	inc. S^2	inc. S^2 + FSR
σ [μb]	34.1 ± 0.8	52.2	38.9	37.3

- Overshoot by $\sim 4\sigma$!
- Data also compared to Starlight MC, for which

$$\sigma(S^2 + FSR) = 30.8\,\mu\mathrm{b}$$

i.e. undershooting by $\sim 4\sigma$! What is going on?

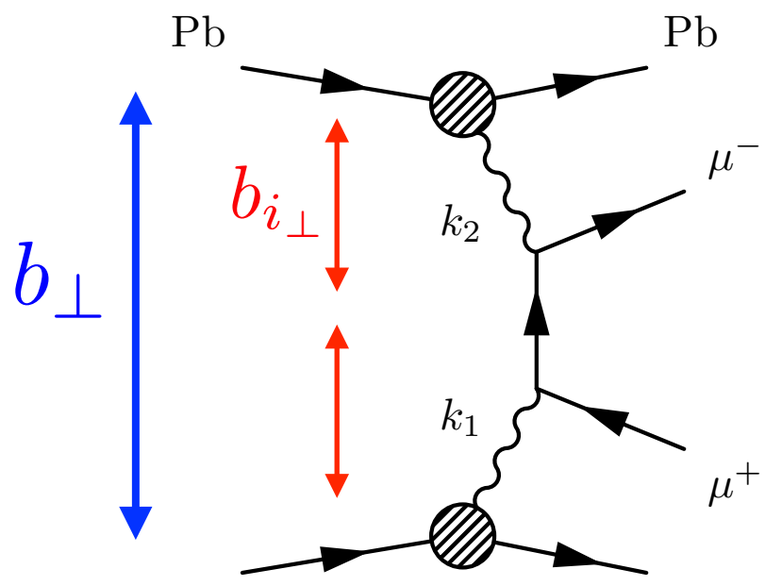


Impact of the $b_{1,2\perp} > R_A$ cut

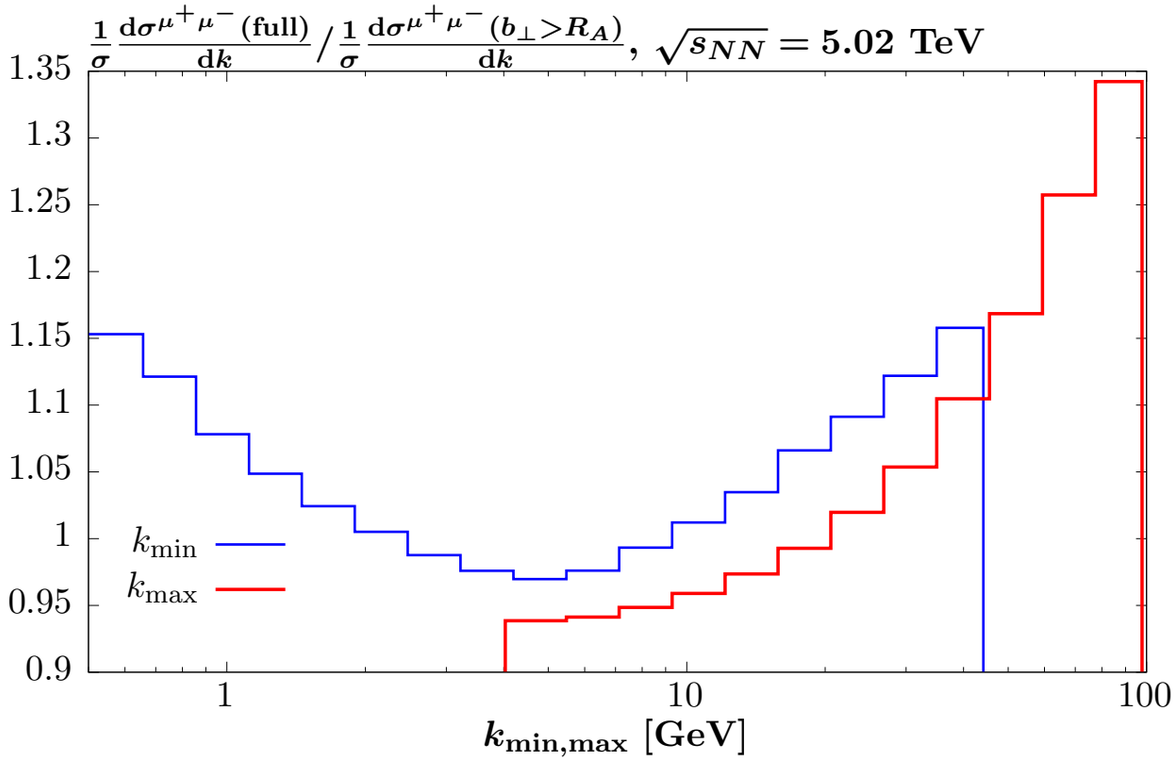
- This issue discussed in detail in recent paper: **arXiv:2104.13392**.

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

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

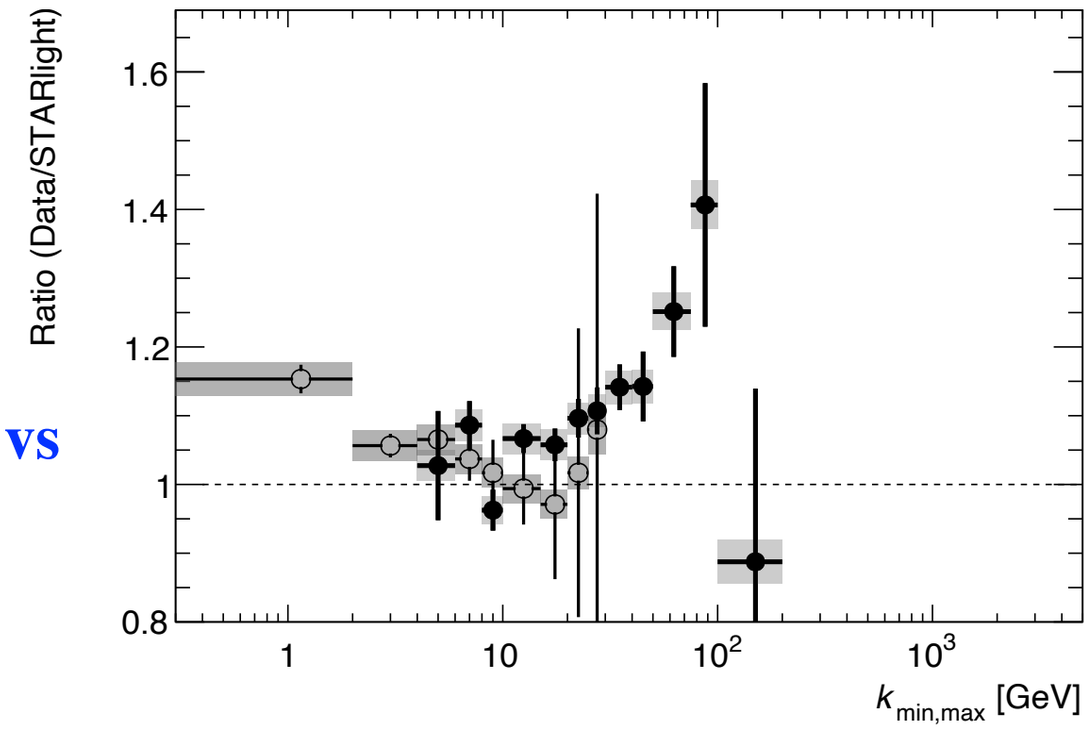


- However, in some of the Starlight an additional cut on the dilepton-hadron impact parameter is imposed: $b_{1,2\perp} > R_A$
- This is unphysical: no lepton-hadron QCD interaction. HO QED interactions small and not to be included in this way.
- And we show is disfavoured by differential ATLAS data in PbPb…



LHL, V.A Khoze, M.G. Ryskin, arXiv:2104.13392

vs



ATLAS, arXiv:2011.12211

- Effect of removing $b_{1,2\perp} > R_A$ cut will improve data/STARlight theory comparison significantly.
- Removing this cut leads to much better agreement with SuperChic.

	ATLAS data [23]	Pure EPA	$b_{i\perp} > R_A$	$b_{i\perp} > R_A$, inc. S^2
σ [μb]	34.1 ± 0.8	52.2	37.1	29.9

- STARlight $b_{1,2\perp} > R_A$, inc S^2: 32.1 pb.

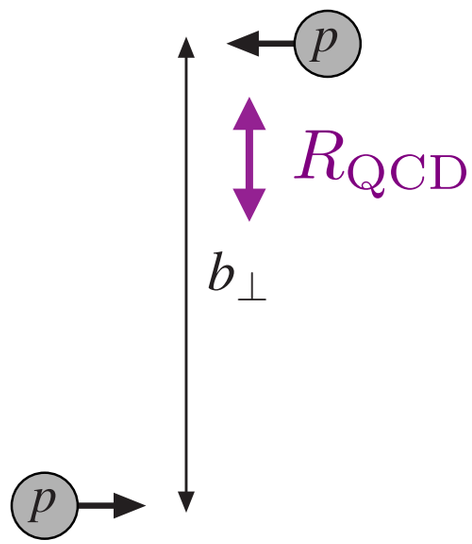
Theory vs. Data?

- Thus difference wrt Starlight broadly understood, but still we overshoot data:

	ATLAS data [23]	Pure EPA	inc. S^2	inc. S^2 + FSR
σ [μb]	34.1 ± 0.8	52.2	38.9	37.3

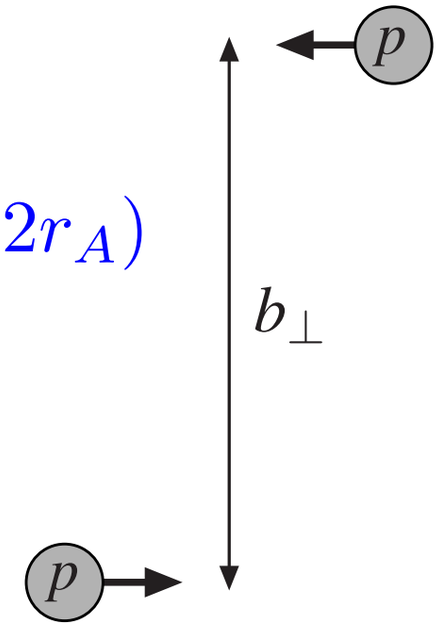
- What are theory uncertainties here?
- Naively one might assume the survival factor could easily introduce a ~ 10% level theoretical uncertainty and explain the data/theory discrepancy. However not the case.

- Reason due to unique nature of PI production: hadron-hadron impact parameter generally **outside** the **range** of QCD.



- 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 the ATLAS data, instead need to take: $S^2(b_\perp) \approx \theta(b_\perp - 3r_A)$

  i.e. ~ 100% inelastic interaction probability out to ~ r_A (~ 6.7 fm) beyond hadron edge.

	ATLAS data [23]	$\theta(b_\perp - 2R_A)$	$\theta(b_\perp - 3R_A)$
σ [μb]	34.1 ± 0.8	41.4	34.7

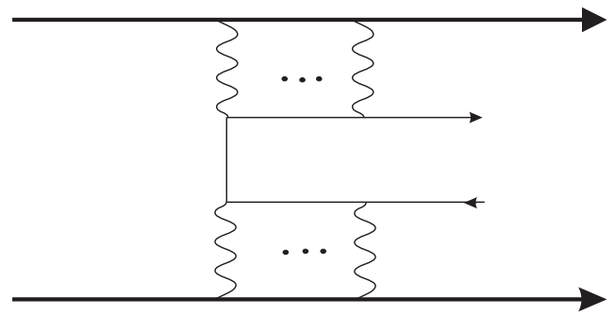
$\longrightarrow$ Very unphysical behaviour would be required. Hard to imagine that this can be the solution.

- Other possibilities?

Other effects?

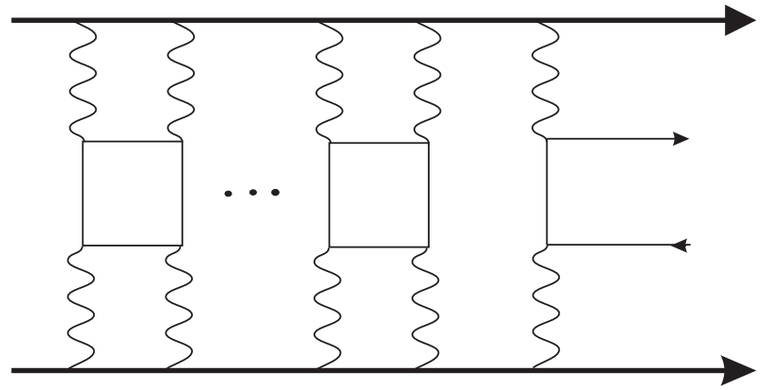
W. Zha and Z. Tang, (2021), 2103.04605.

- **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 $\sim Q^2/m^2_{\mu\mu}$



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.

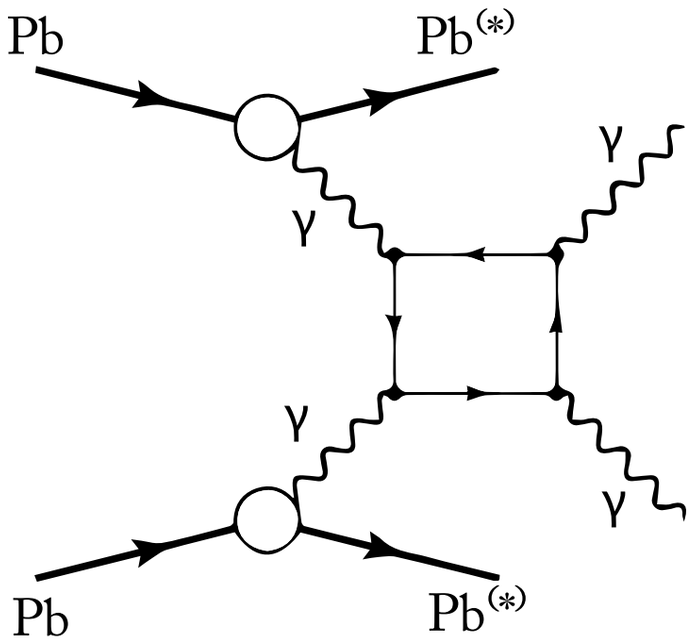
$\longrightarrow$ Relevance of these effects clearly not limited to (SM) dimuon production!

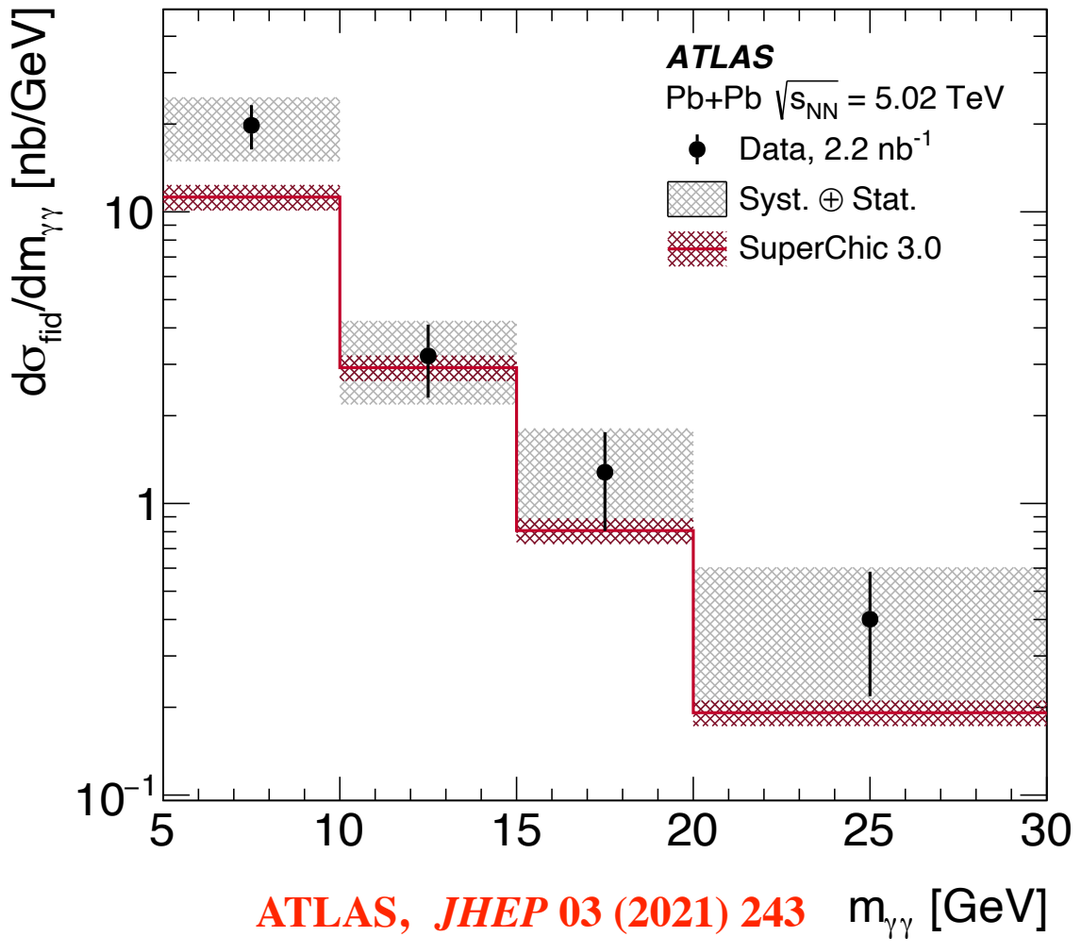
Light-by-Light Scattering

- MC prediction compared with ATLAS data on LbyL scattering:

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

- **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.

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.

- In heavy ions, currently implemented of most relevance:
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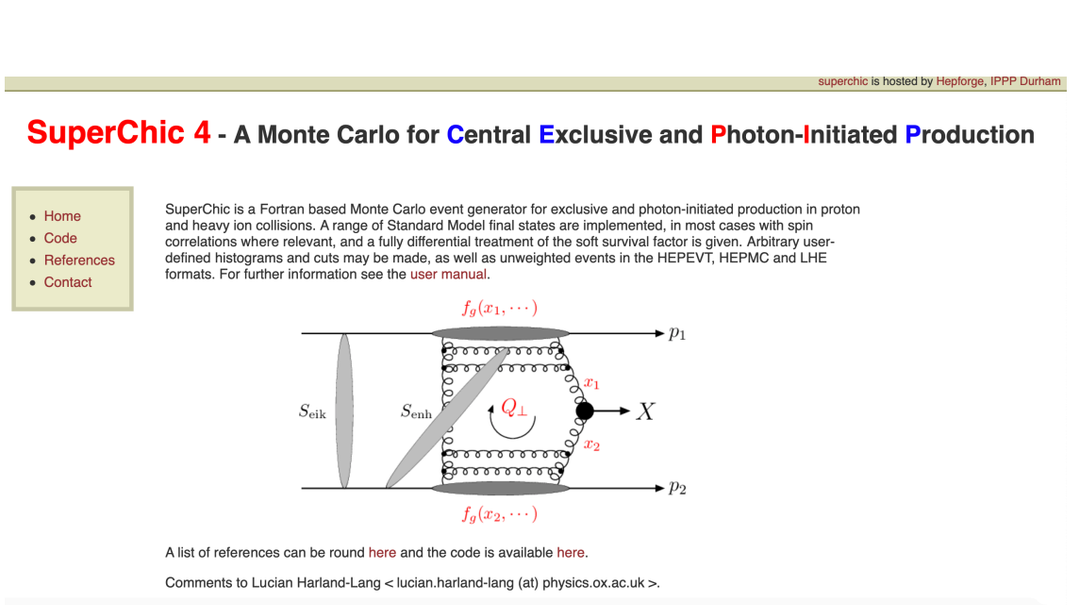
Talks by M. Rangel, K. Schmieden…

- But open to collaboration/discussion for including other channels!



https://superchic.hepforge.org

Summary/Outlook

- ★ Ultraperipheral heavy ion collisions a key mode for BSM (and SM) production.
- ★ SuperChic *4* MC: fully differential generation of this channel, including complete treatment of survival factor.
- ★ Further work: including ion dissociation, understanding theory/data difference, HO QED effects, new channels…
- ★ Much to do - stay tuned!

Thank you for listening