Photon-photon physics in pA collisions

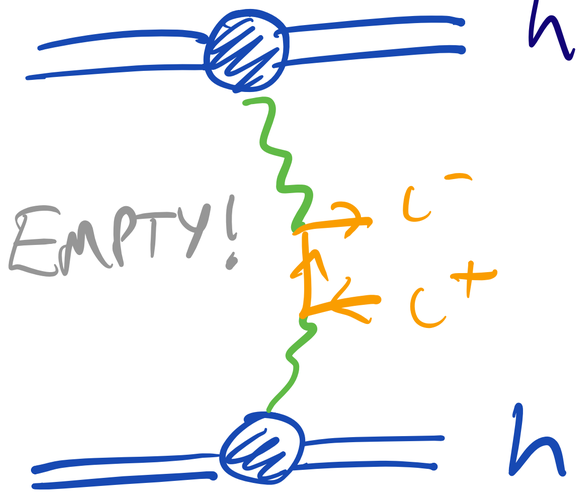
Lucian Harland-Lang, University College London

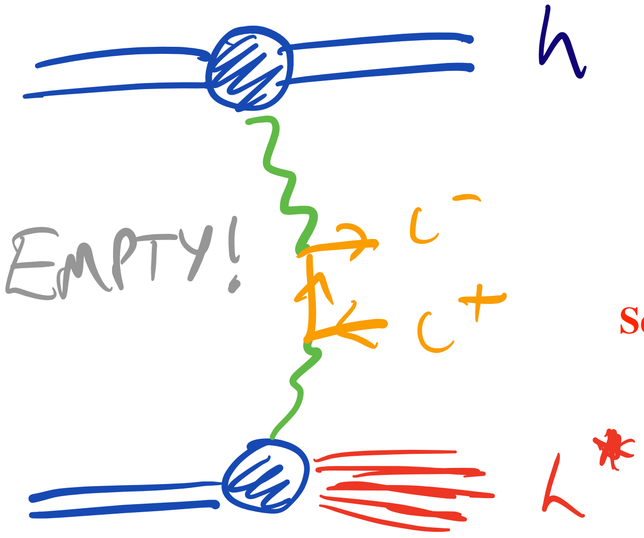
Physics with high luminosity proton-nucleus collisions, CERN, Jul 4 2024

Photon-Photon Physics

- Both protons and heavy ions can act as source of initial-state photons $\Rightarrow$ purely photon-initiated production possible.
- This allows for **exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state:

Exclusive



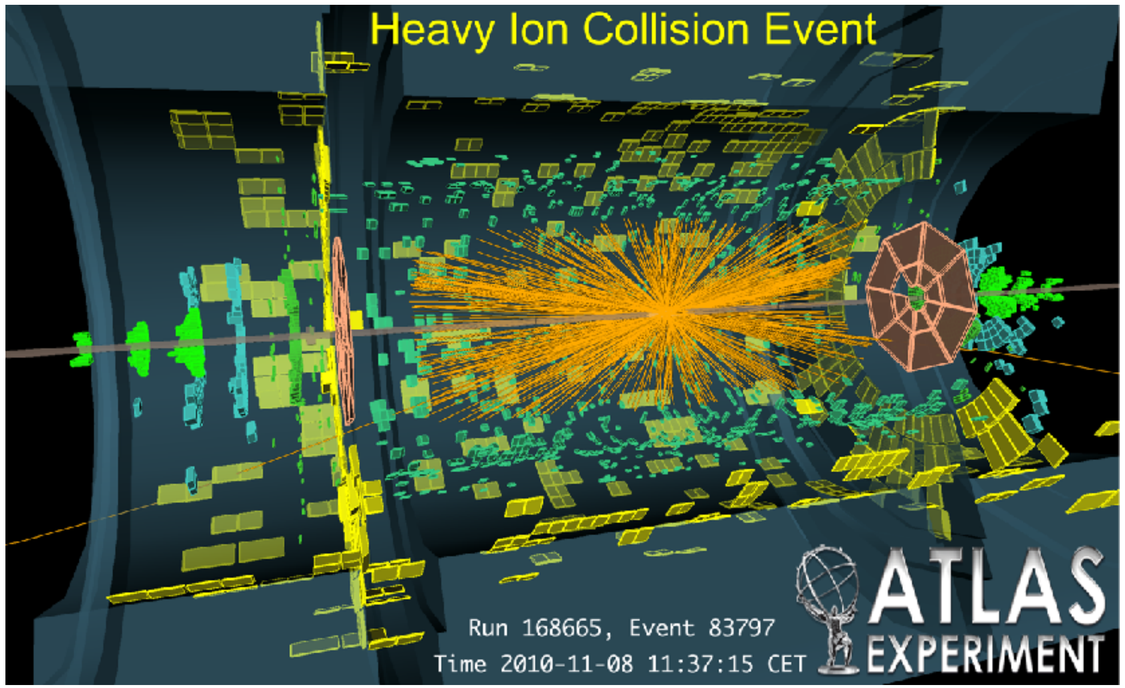


Semi-exclusive

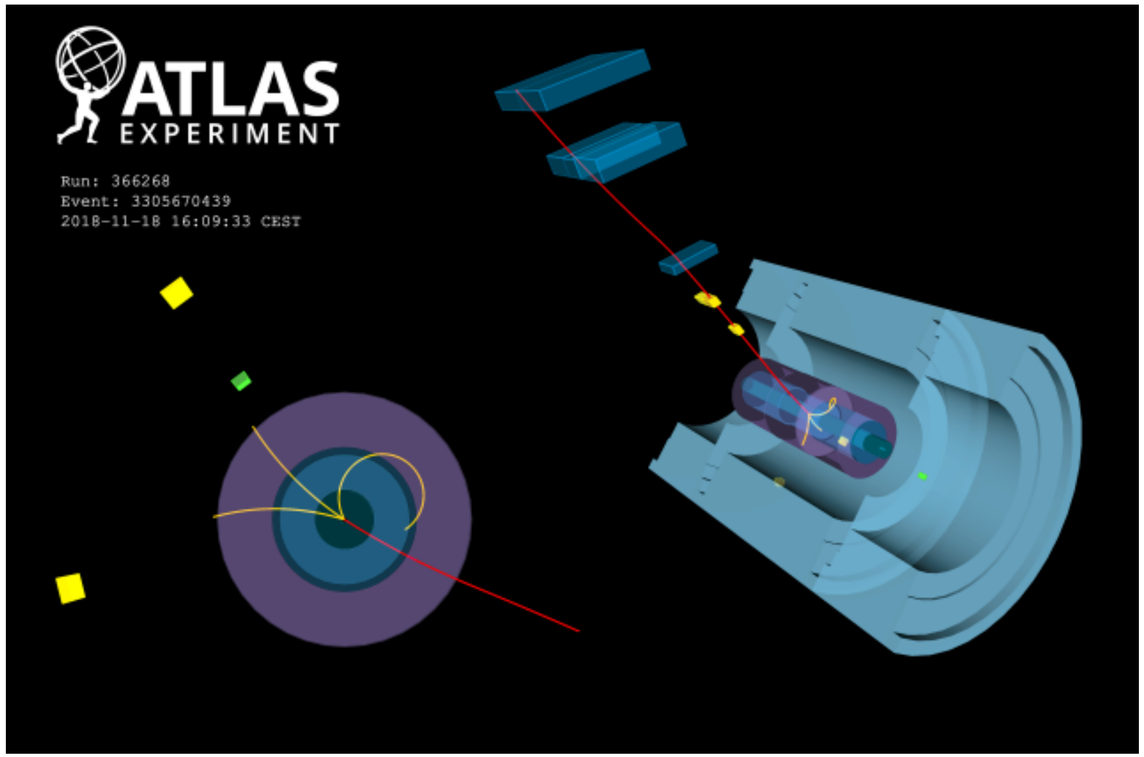
⋆ QCD interactions between hadrons can be largely ignored, i.e. ~ pure QED production

$\Rightarrow$ The LHC as a $\gamma\gamma$ collider! How does this differ from `standard' LHC collisions?

What does is it look like?

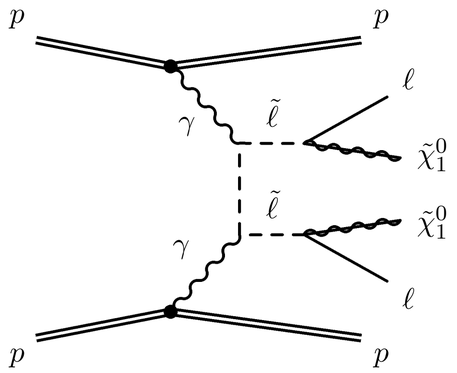


vs.



★ By dealing with ~ pure QED initial state, many studies of the EW sector and BSM modifications to it open up…

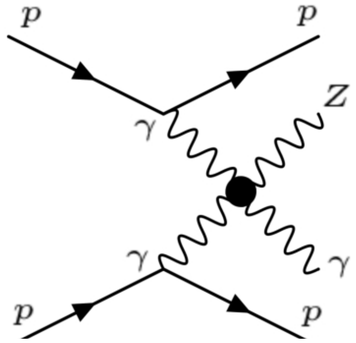
Compressed SUSY



LHL et al., JHEP 1904 (2019) 010

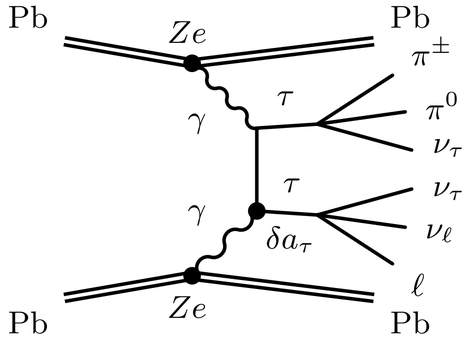
L. Beresford and J. Liu, PRL 123 (2019) no.14

Anomalous couplings



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

tau g-2



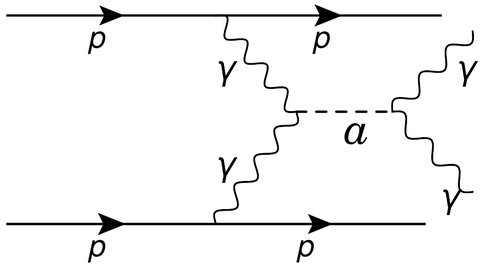
L. Beresford and J. Liu, PRD 102 (2020) 11, 113008

M. Dyndal et al., PLB 809 (2020) 135682

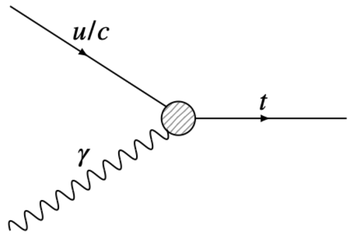
Axion-like Particles

LHL and M. Tasevsky, arXiv:2208.10526

C. Baldenegro et al., *JHEP* 06 (2018) 131



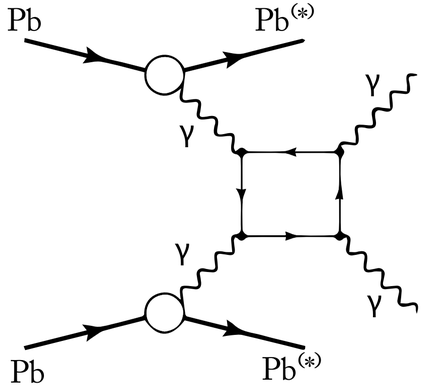
Top quarks



V. Goncalves et al., *Phys.Rev.D* 102 (2020) 7, 074014

J. Howarth, arXiv:2008.04249

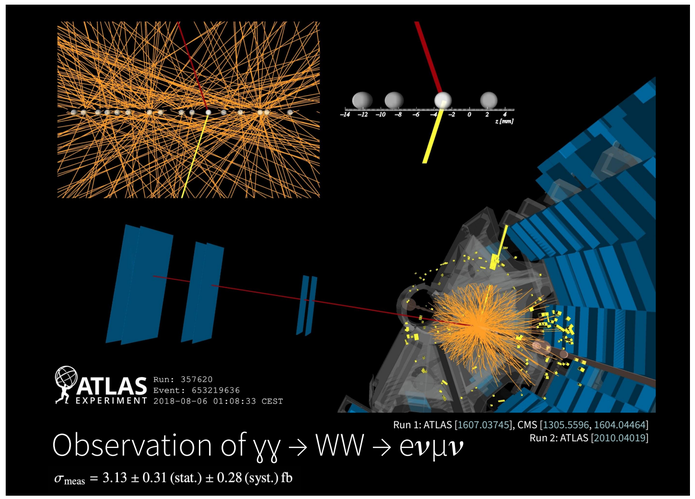
LbyL scattering/ALPS



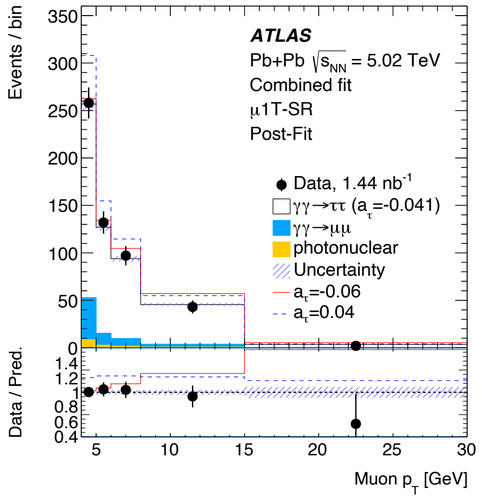
C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

★ And there has been significant experimental progress…

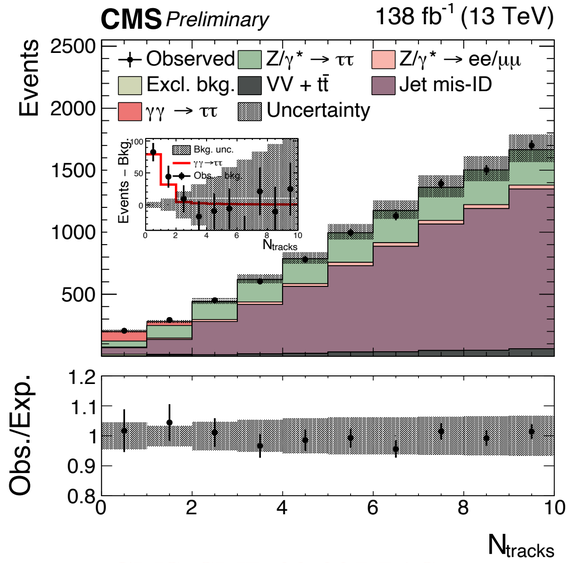
W^+W^- **ATLAS, Phys. Lett. B 816, 136190 (2021)**



$\tau^+\tau^-$



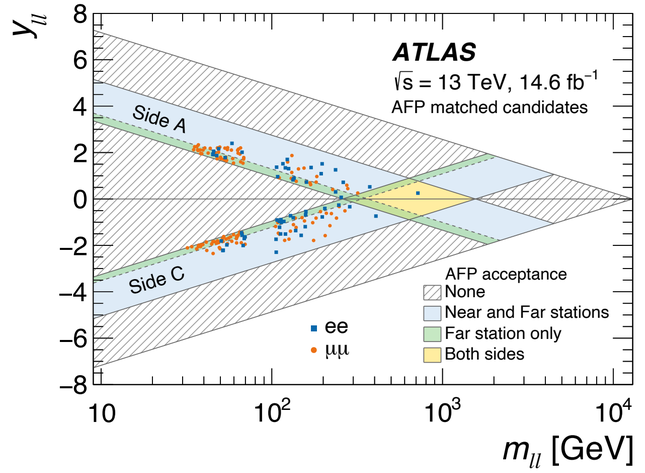
ATLAS, *Phys.Rev.Lett.* 131 (2023) 15, 151802



$\tau^+\tau^-$

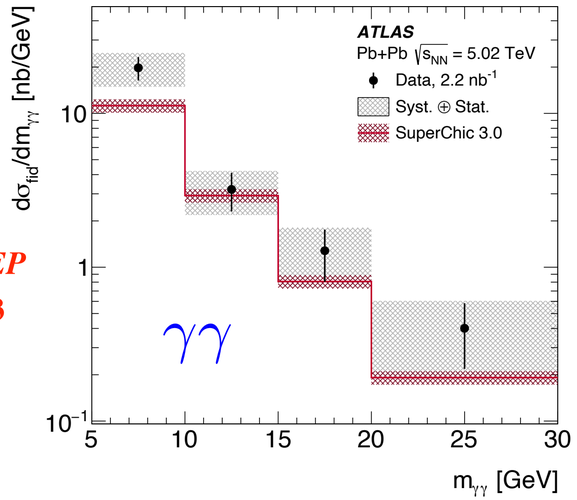
CMS, SMP-23-005-PAS

l^+l^-



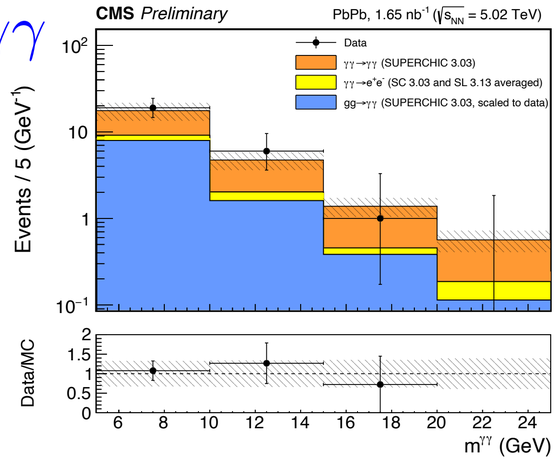
ATLAS, Phys. Rev. Lett. 125 (2020) 261801

ATLAS, *JHEP* 03 (2021) 243



$\gamma\gamma$

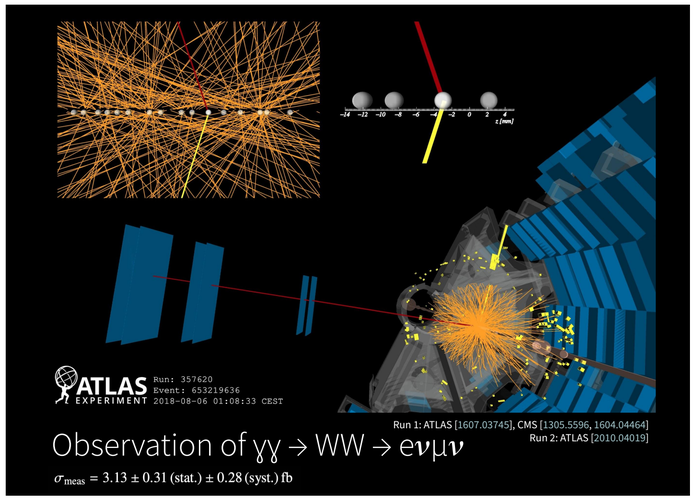
CMS, CMS PAS HIN-21-015



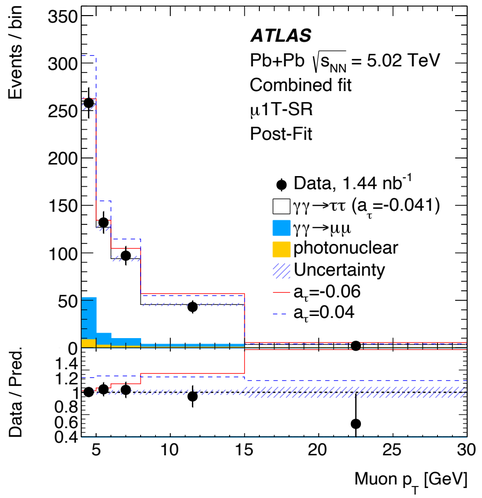
★ And there has been significant experimental progress…**but** with focus on pp and PbPb.

W^+W^- **ATLAS, Phys. Lett. B 816, 136190 (2021)**

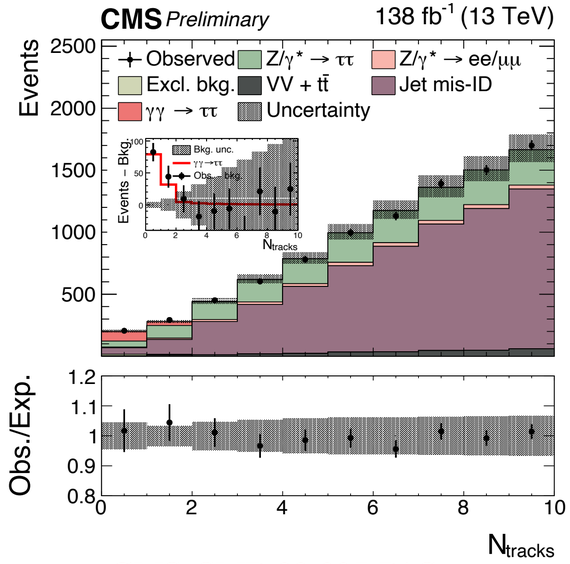
pp



$\tau^+\tau^-$



PbPb

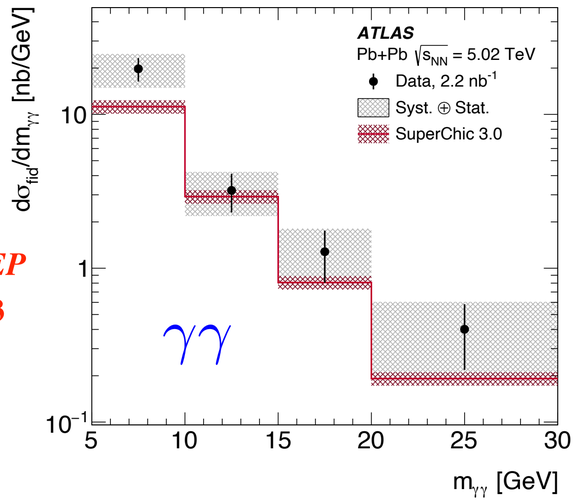


$\tau^+\tau^-$

pp

CMS, SMP-23-005-PAS

ATLAS, *Phys.Rev.Lett.* 131 (2023) 15, 151802



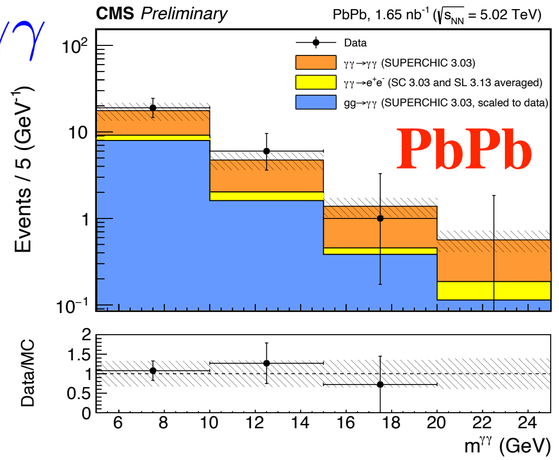
ATLAS, *JHEP* 03 (2021) 243

$\gamma\gamma$

PbPb

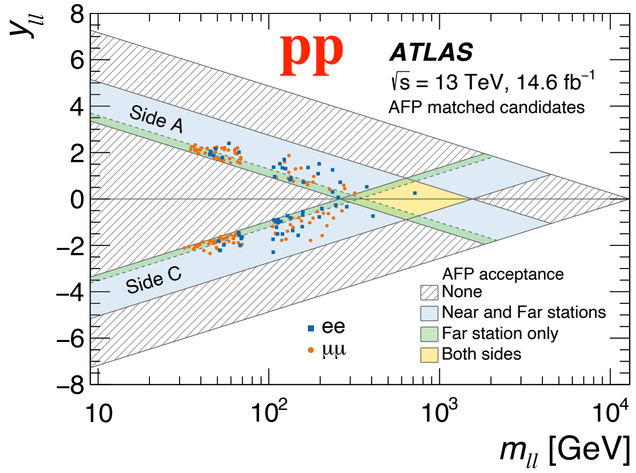
CMS, CMS PAS HIN-21-015

$\gamma\gamma$



PbPb

l^+l^-



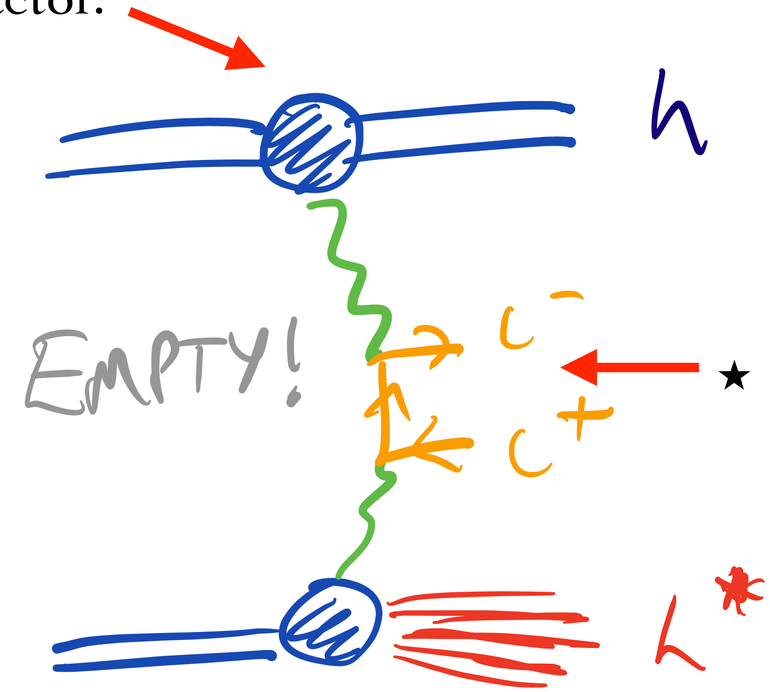
ATLAS, Phys. Rev. Lett. 125 (2020) 261801

★ Why is this? First, quick recap of how we model photon-initiated production.

PI production: building blocks

- (Semi)-Exclusive PI cross section given in terms of:

★ $h \to \gamma h(h^*)$ form factor.



★ $\gamma\gamma \to X$ cross section.

★ `**Survival factor**' probability of no addition hadron-hadron interactions.

- Start with $h \to \gamma h(h^*)$ form factor…

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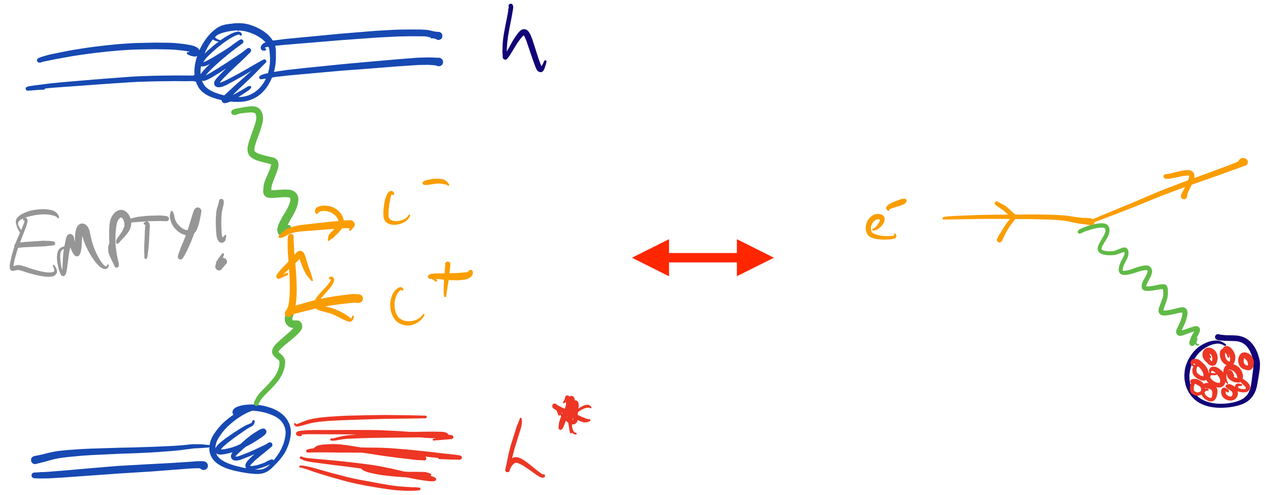
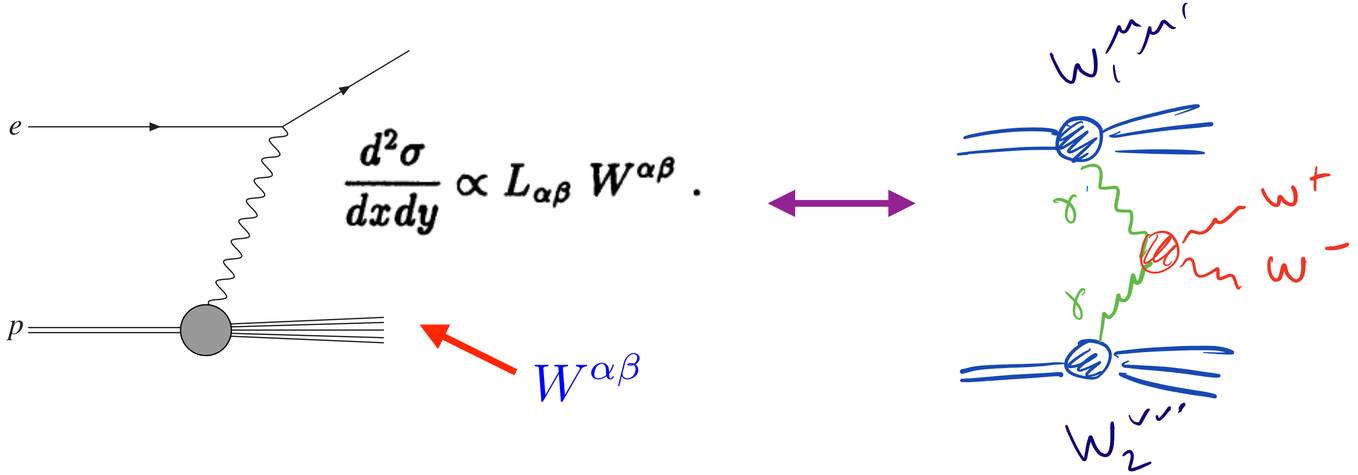
- Key point: form factors determined with **percent level precision** from wealth of lepton-hadron scattering data:

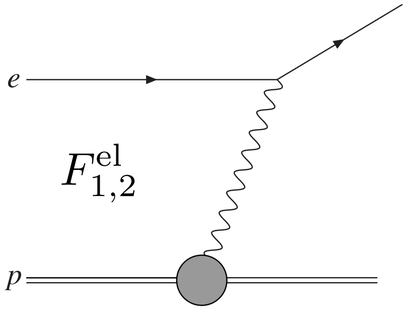


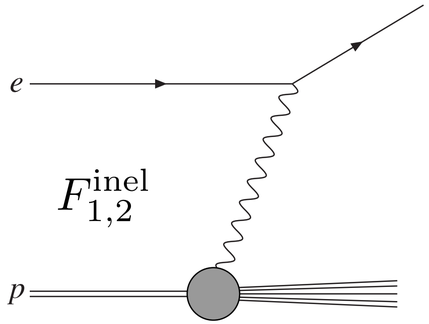
★ Protons - both elastic and dissociative PI production can be modelled in `Structure function' approach:



- Structure functions parameterise the $\gamma p \to X$ vertex: $W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P \cdot q} F_2(x,Q^2)$

- Both elastic and inelastic SFs accounted for:



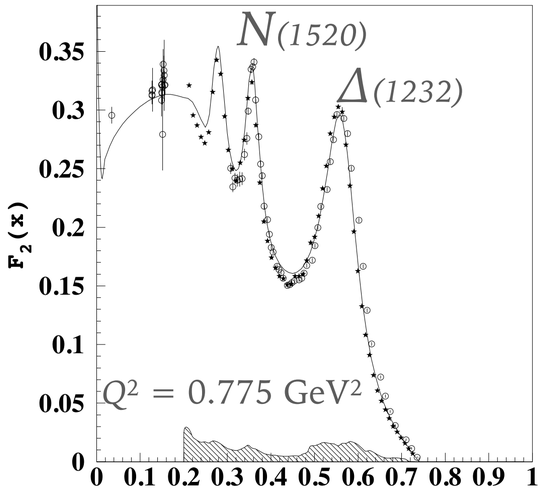


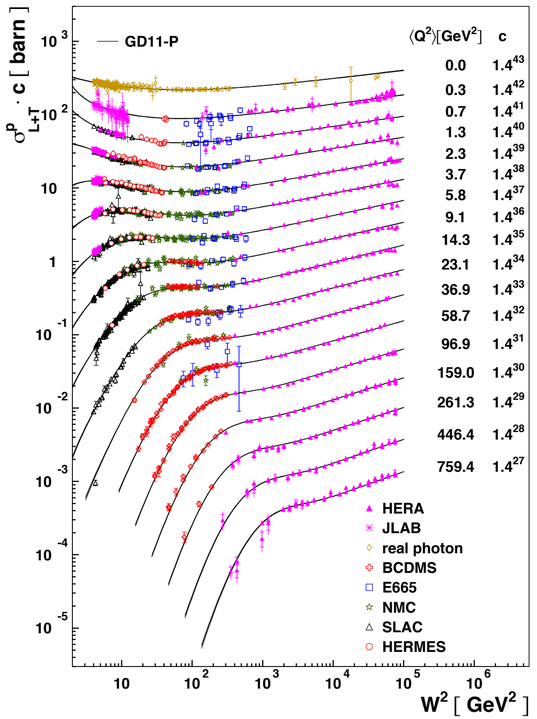
★ **Elastic**: precisely measured proton EM form factor.

★ **Inelastic**: $Q^2_{\mathrm{cut}} = 1\,\mathrm{GeV}^2 \;\; W^2_{\mathrm{cut}} = 3.5\,\mathrm{GeV}^2$

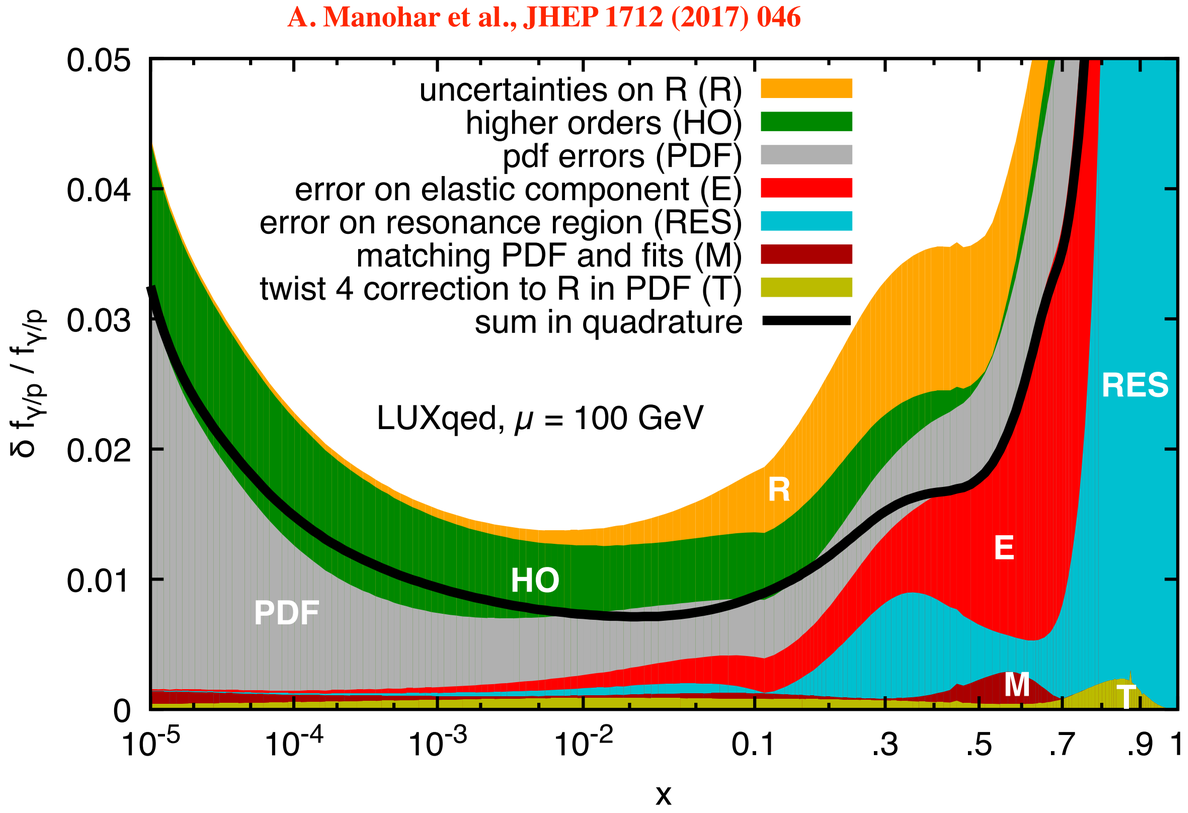
- High Q^2 region, simplest to calculate using (NNLO) pQCD + global PDFs.

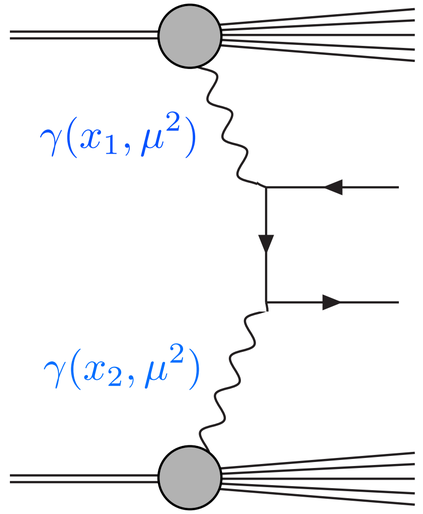
- Low Q^2 and/or W^2 region: take direct experimental determinations.





- These inputs are exactly as in the original `LUXqed' decomposition of the photon PDF.





- Uncertainty in inputs ~ to equivalent photon PDF uncertainty. That is % level or less (in particular for elastic case).

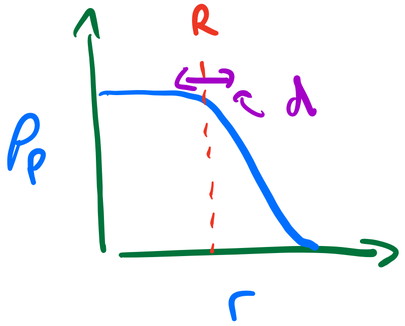
★ Heavy ions - form factor similarly v. well determined.

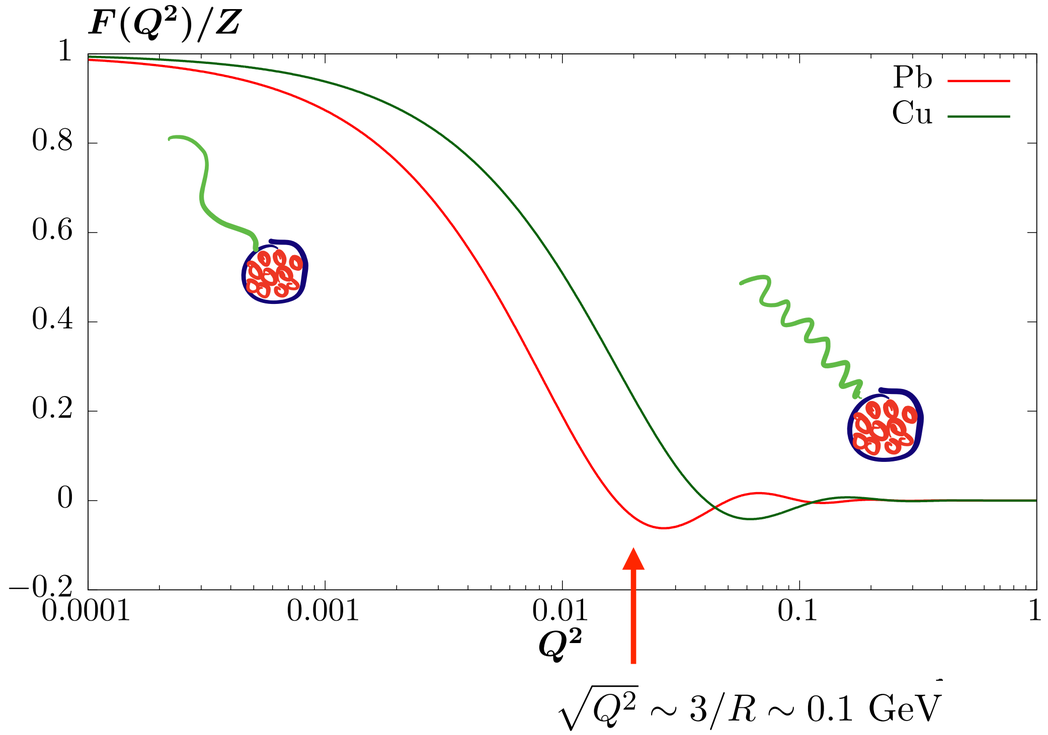
- Low Q^2 : constant (~ Z)
- Higher Q^2 : falls off as substructure probed.

$$F(Q^2) = \int d^3\vec{r}\, e^{i\vec{q}\cdot\vec{r}}\, \rho_p(\vec{r})$$

Ion charge density

$\rho_p(\vec{r})$:





- Form factor uncertainty explicitly studied, and is small.

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

$\mu^+\mu^-$ $(PbPb)$ ATLAS, Phys. Lett. B 749, 242 (2015), Phys. Lett. B 777, 303 (2018)

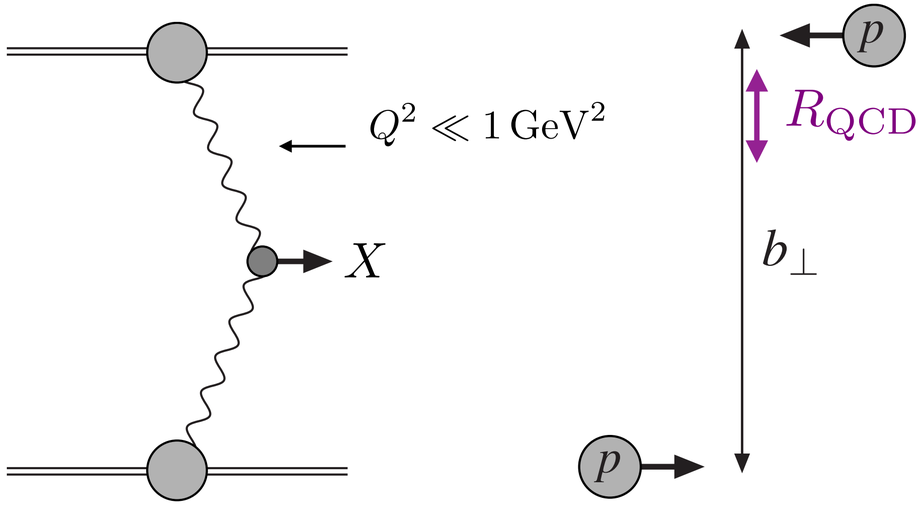
	ATLAS data [14, 16]	Baseline	FF uncertainty	Dipole FF
σ [pb], 7 TeV	0.628 ± 0.038	0.742	$^{+0.003}_{-0.005}$	0.755
σ [pb], 13 TeV	3.12 ± 0.16	3.43	± 0.01	3.48

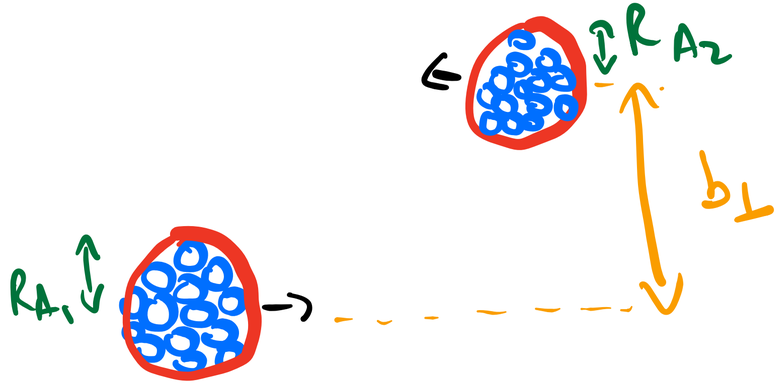
- **Key point**: ~ Z^2 enhancement for each ion.

N.B $F(Q^2=0) = \int d^3\vec{r}\, \rho_p(\vec{r}) \equiv Z$

Survival Factor

- Probability of no additional inelastic hadron-hadron interactions. In general requires understanding of **non-perturbative** QCD - sizeable uncertainty.
- Hadrons like to interact: naively expect $S^2 \ll 1$.
- Exclusive PI production a **special case**: quasi-real photon $Q^2 \sim 0 \Rightarrow$ large average hh impact parameter $b_\perp \gg R_{\rm QCD}$, and $S^2 \sim 1$.





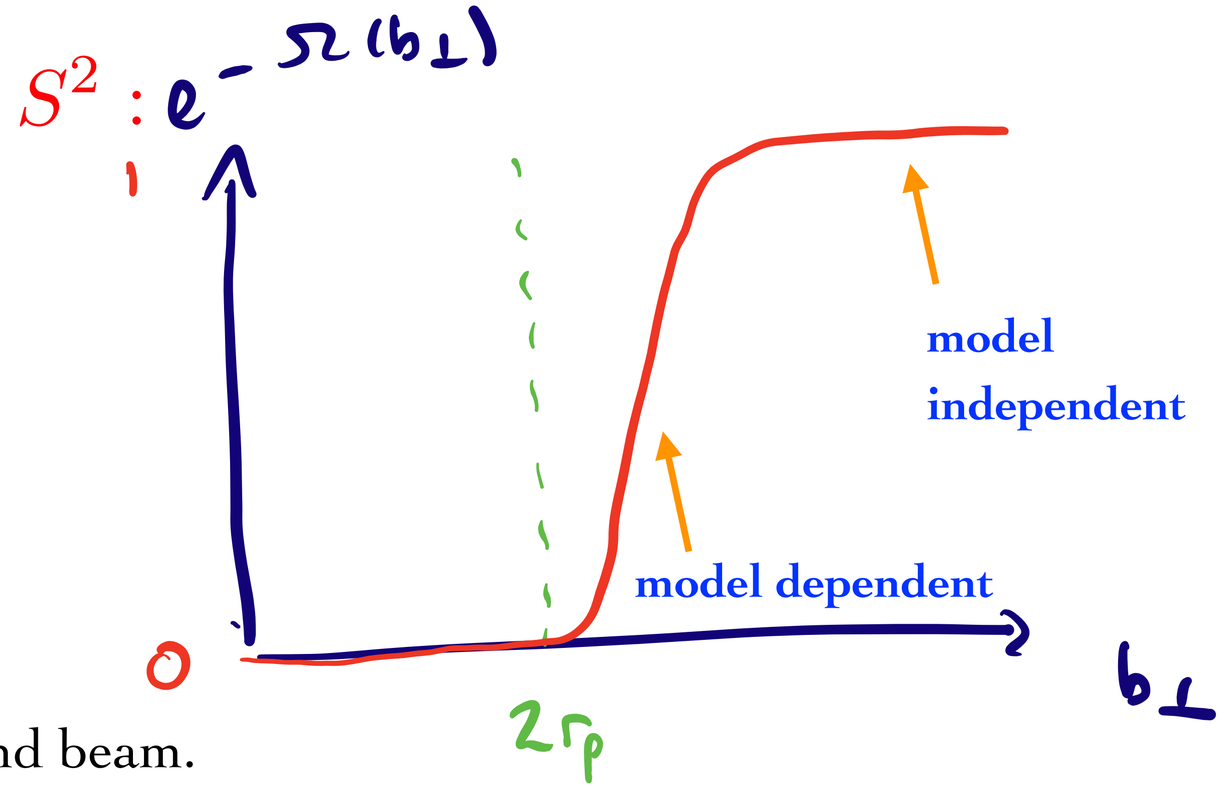
$\longrightarrow$ Relatively **clean** $\gamma\gamma$ initial state, with **QCD playing small role**.
Why we can say the LHC is a $\gamma\gamma$ collider.

- In a little more detail: can show that cross section dominated by region of impact parameter where $S^2 \sim 1$.

- Full account gives:

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

Depending on precise process, kinematics and beam.



- Uncertainty on S^2 small, at % level.

- Above plot is for pp case, but story is very similar for PbPb and pPb:

$$2r_p \to 2R_A \text{ and } (R_A + r_p) \text{ for } AA \text{ and pA}$$

- With steeper Q^2 fall off of ion form factors (i.e. larger ion size) ensuring dominant cross section contribution again outside these overlaps. Mild trend for lower S^2 in pA, AA.

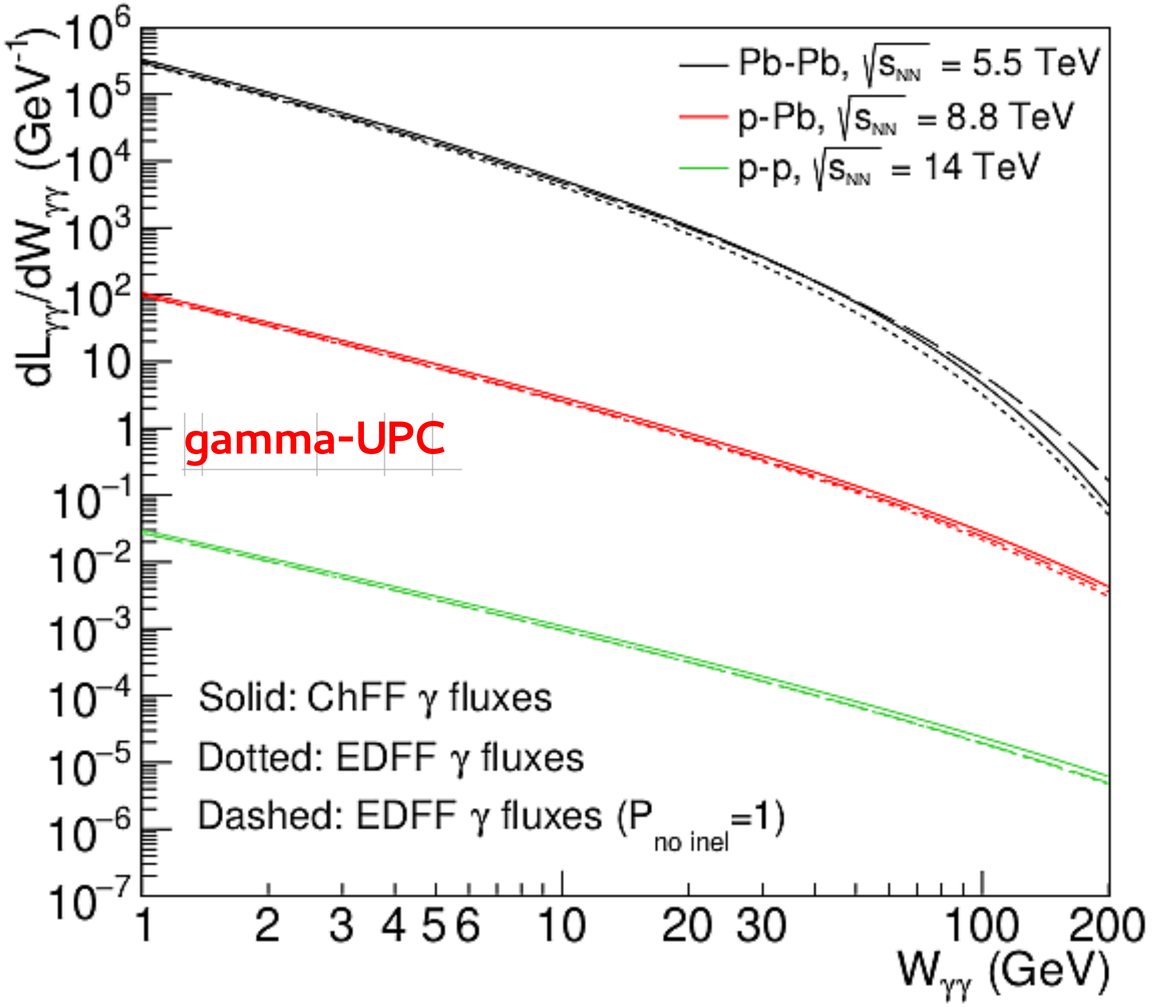
Effective Luminosities

David d'Enterria, ECT* workshop, May 23

- Look at effective luminosities ~ cross sections for different beam configurations.
- Key points:
  - ★ Clear enhancement with Pb beams due to Z^2 in form factor.
  - ★ Steeper fall off in PbPb due to lower maximum photon energy

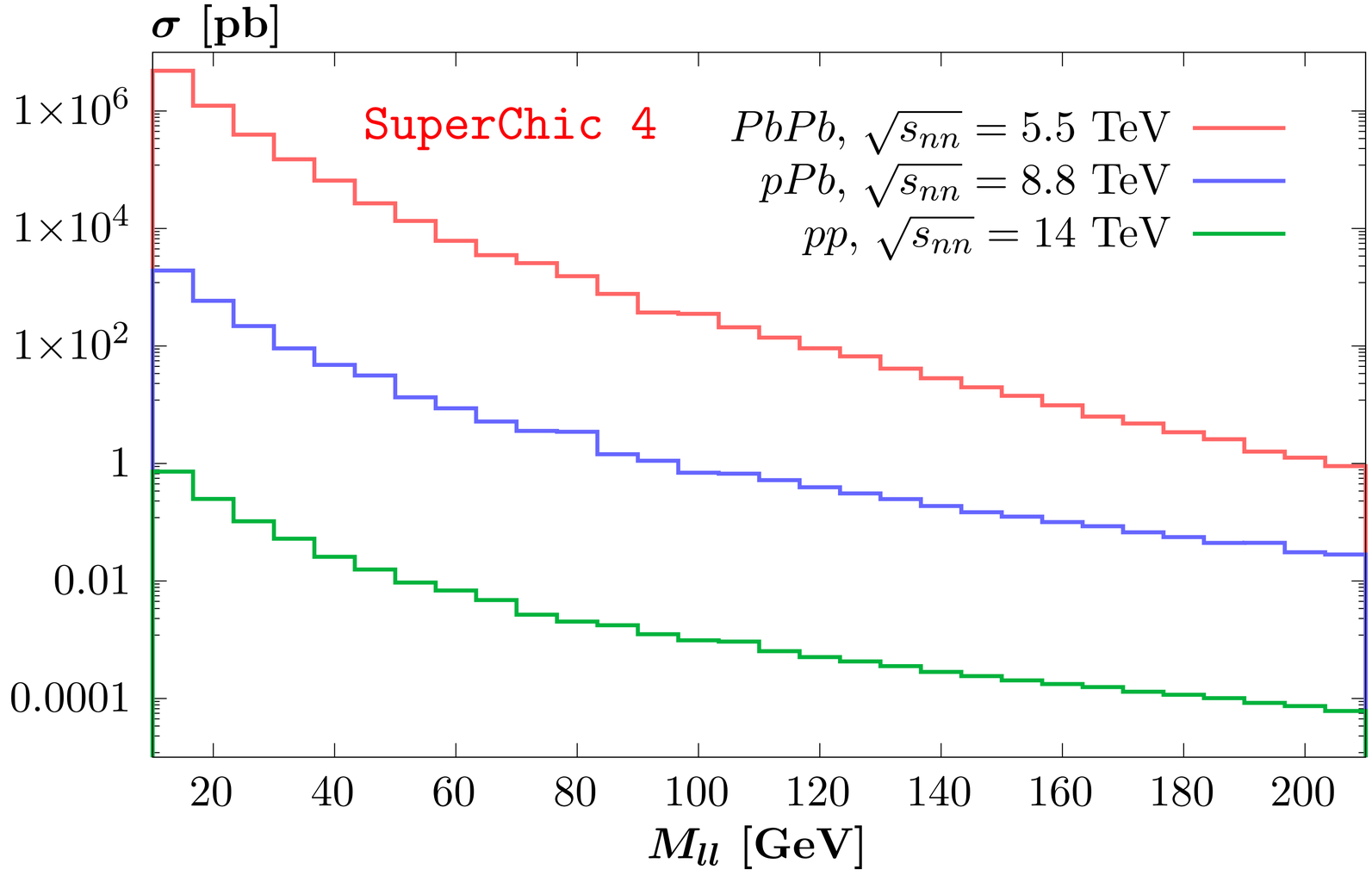
$$\omega < \omega_{max} \approx \frac{\gamma}{R}$$ ~ 80 GeV (Pb), ~ 2.5 TeV (p)

- But need to scale by machine luminosities…

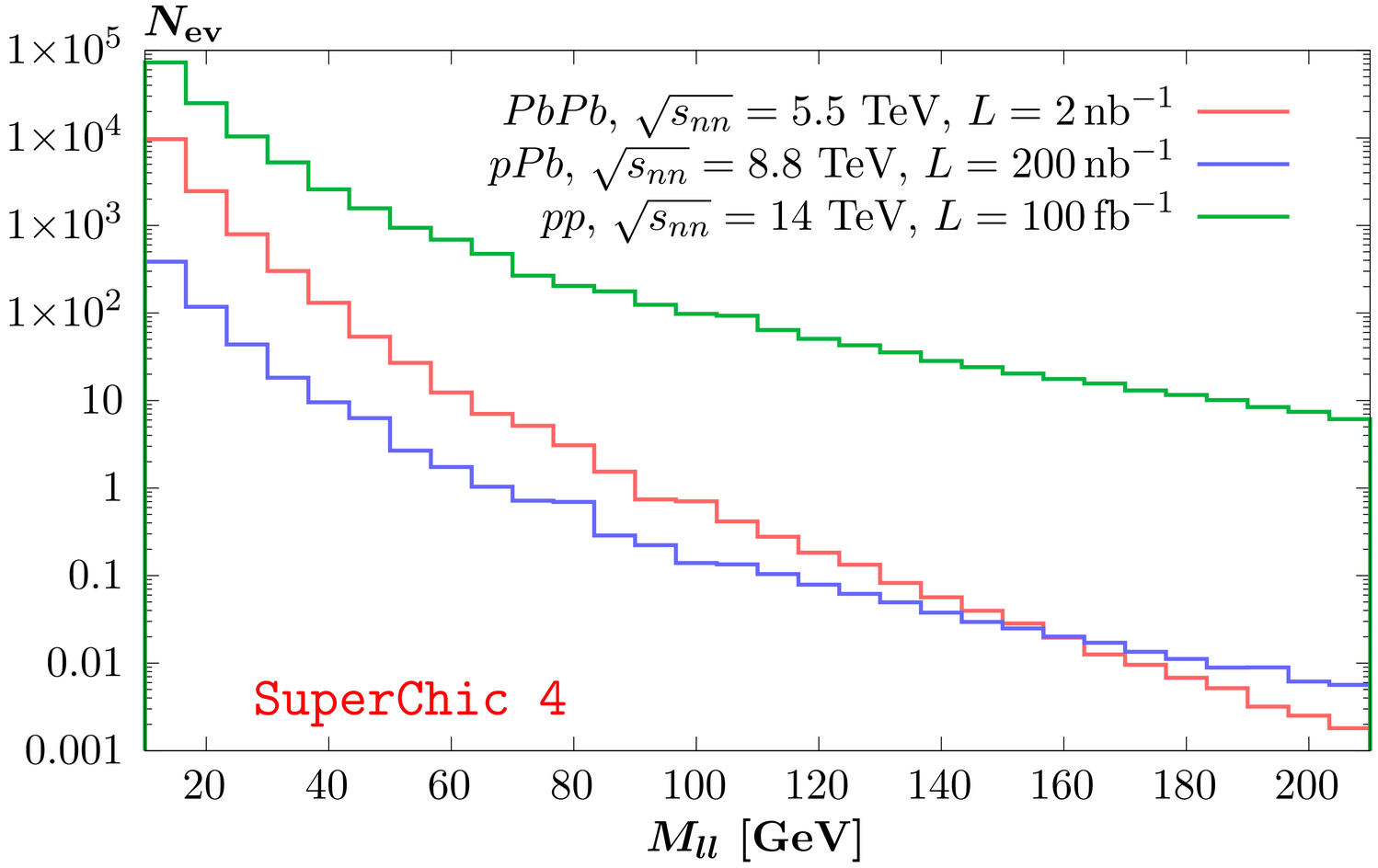


Dilepton Cross Sections

- Consider dimuon production with some representative cuts. Similar scaling to before.



- Scaling by roughly representative luminosities, pPb lowest in terms of rate. Remain true even with $1\ \mathrm{pb}^{-1}$.
- Challenging, though note in terms of raw number of events in lower m_{ll} region still viable.
- Well known fall off in PbPb rates not seen in pPb.



What can pA add?

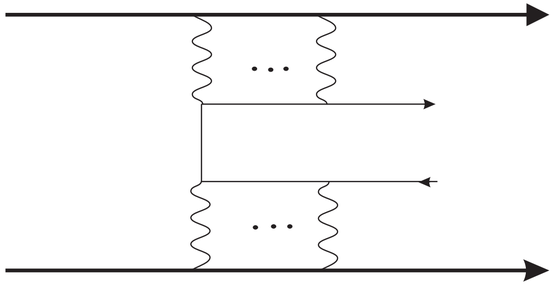
- Seems clear that in terms of cross sections, pA not particularly competitive with pp and AA.
- Initial state is (in theory) well understood for both proton and ion beams - see earlier slides.
- So what can pA add? One possible avenue:

★ There are differences between the pp and AA cases. In AA (but not pp/pA) we have:

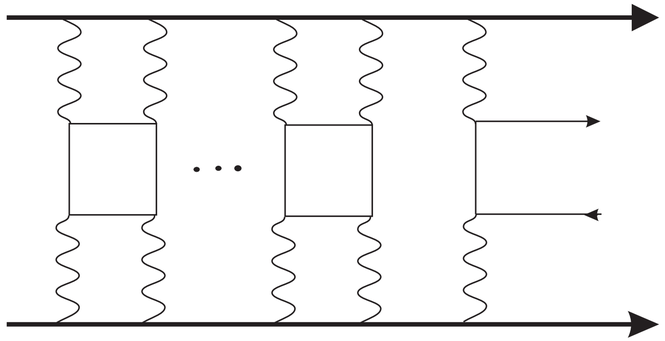
W. Zha and Z. Tang, (2021), *JHEP* 08 (2021) 083

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

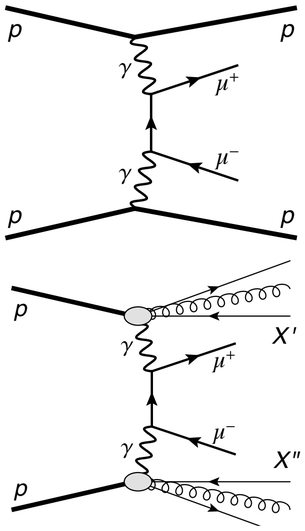
K. Hencken, E.A. Kuraev, V. Serbo, *Phys.Rev.C* 75 (2007) 034903…



- **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.

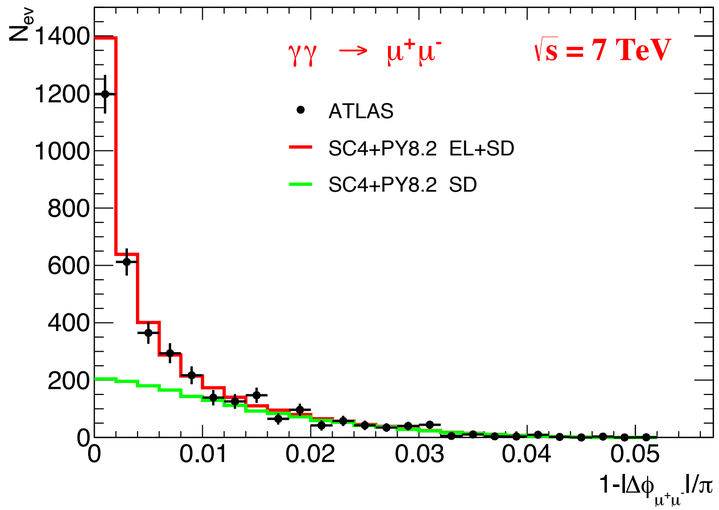


- Moreover, agreement between data and theory not perfect for standard candle case of dilepton production. Tendency to overshoot data by ~ 10% in pp…



	$\sigma^{\text{fid.}}_{ee+p}$ (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

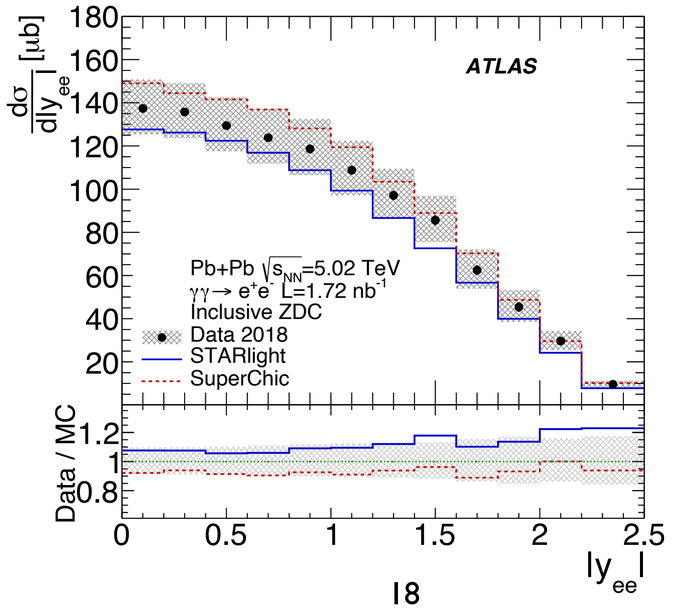
ATLAS, Phys. Rev. Lett. 125 (2020) 261801

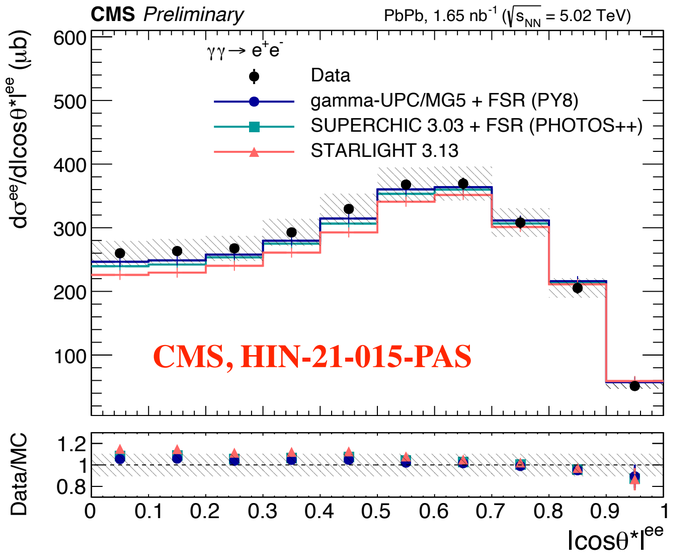


LHL, V. A. Khoze, M. G. Ryskin, M. Tasevsky, *Eur.Phys.J.C* 80 (2020) 10, 925

- In PbPb latest picture is mixed. Similar tendency wrt ATLAS data, but recent CMS data.

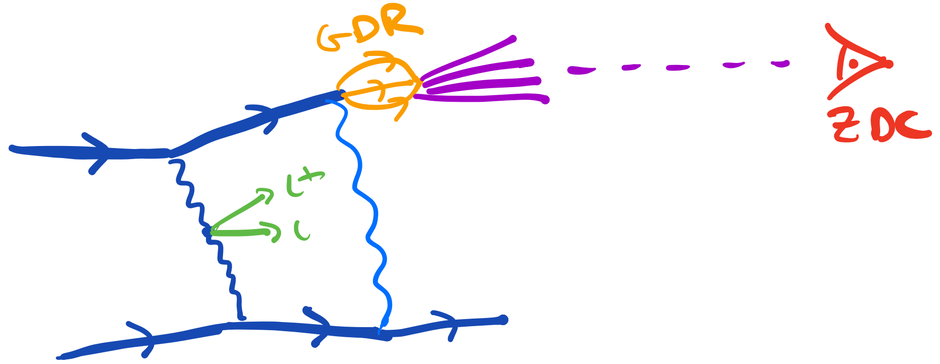
ATLAS, *JHEP* 2306 (2023) 182





- Even for the standard candle case, picture in pp and PbPb in detail mixed, even if broadly agreement is good!
- Looking in pA collisions could provide useful additional handle here, completing the picture. Generally true for other processes beyond dilepton production.

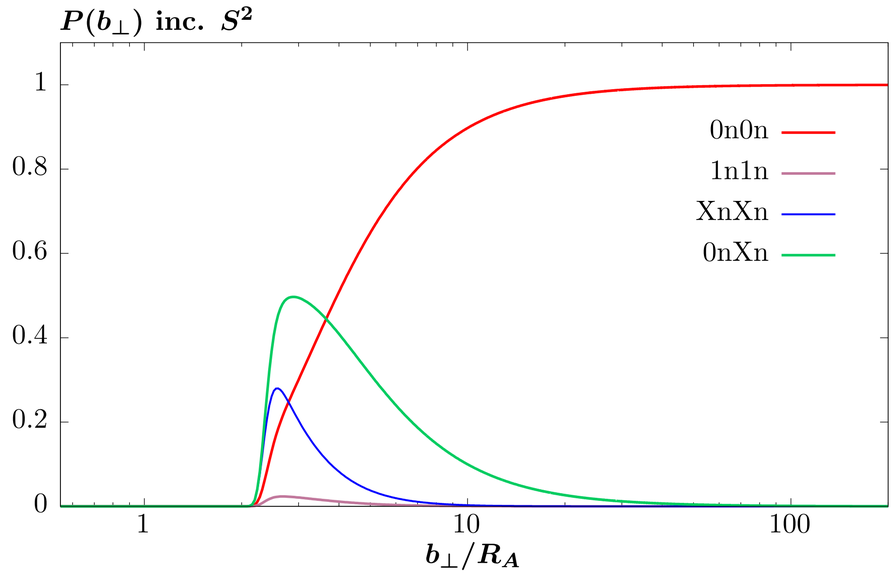
★ Further possibility: ion dissociation.

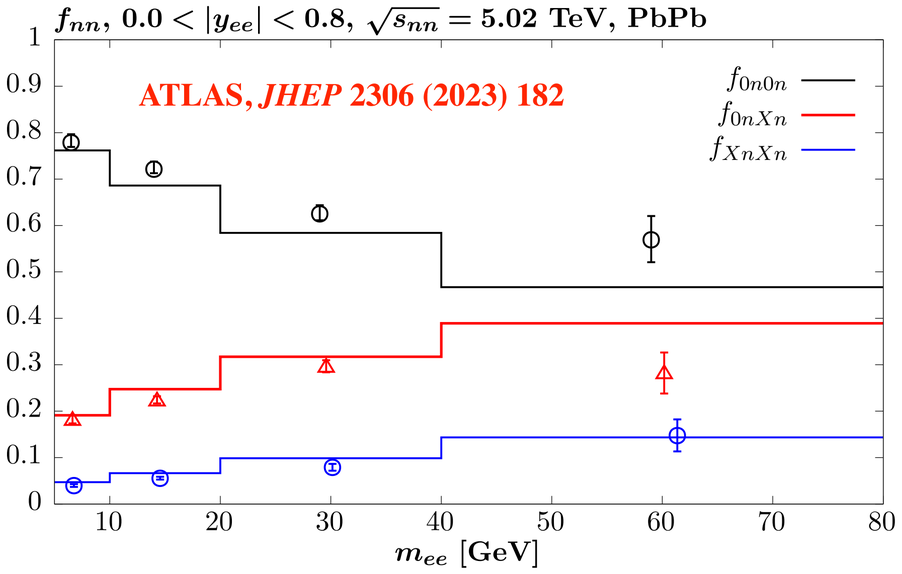


LHL, *Phys.Rev.D* 107 (2023) 9, 093004

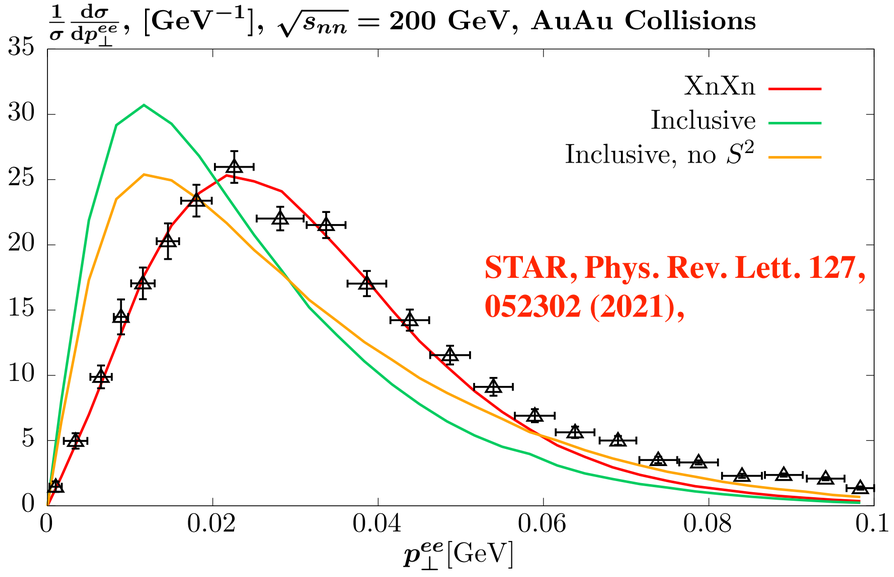
✦ Additional boosted neutron production measured by ATLAS/CMS Zero Degree Calorimeters detectors.

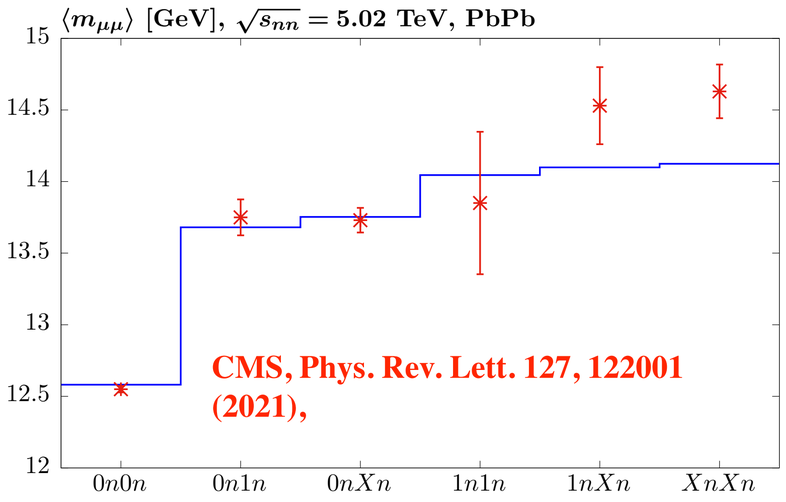
✦ Different neutron multiplicities have different impact parameter profiles → modifies central kinematics.

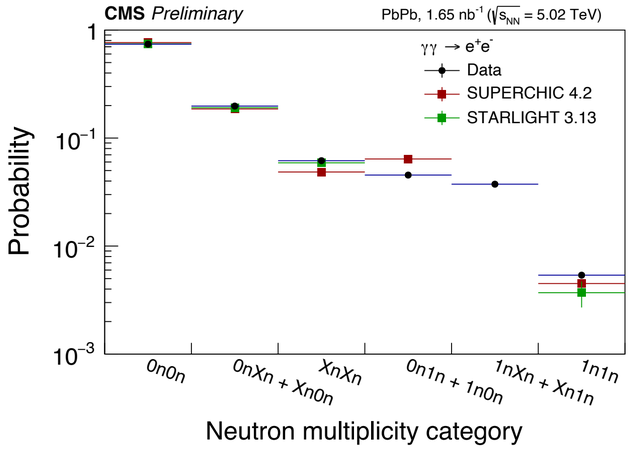




- Neutron dissociation categories and their kinematic dependence opens up wealth of new information from data.
- Broad agreement with range of LHC/RHIC data, but devil in detail!
- Additional handle in measurements/searches.
  - ⋆ All so far for PbPb. What about pA? Just one ion dissociating - somewhat simpler?





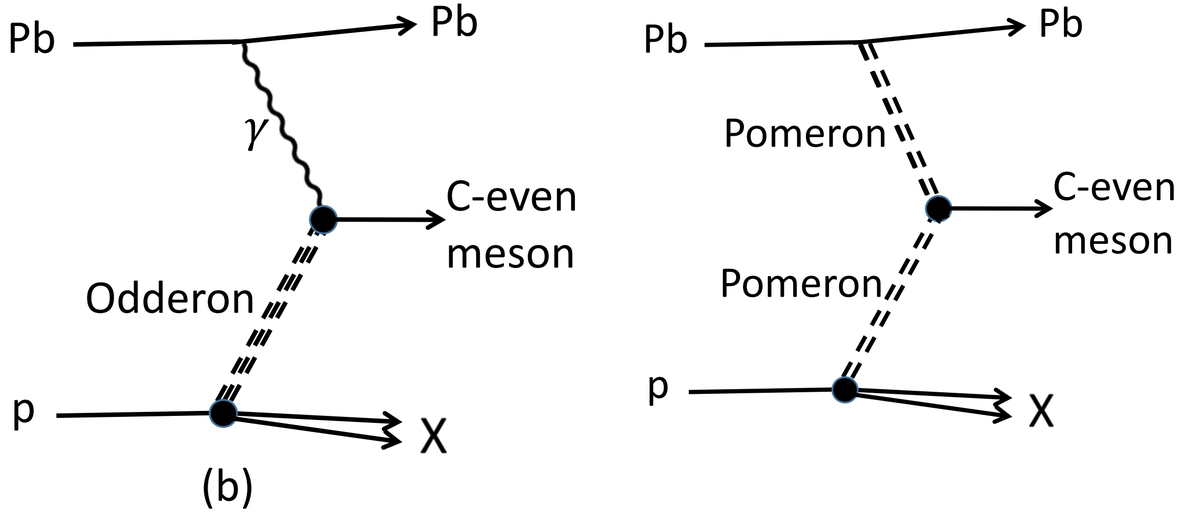


CMS, HIN-21-015-PAS

Aside: the Odderon

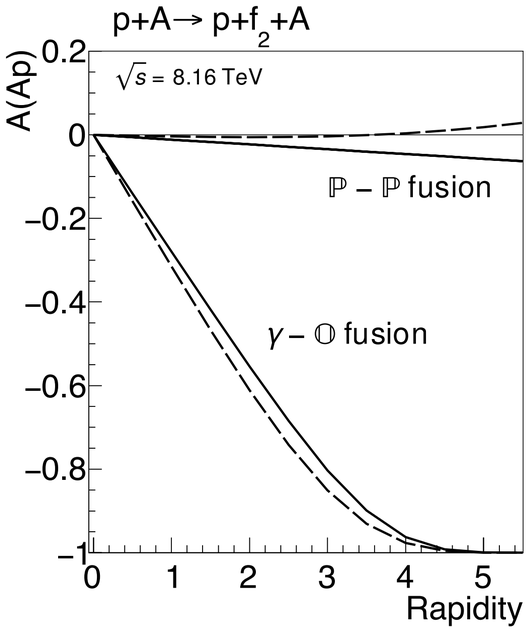
- Not strictly photon-photon, but pA collisions can serve as possible environment to search for odderon contribution to light meson production.

LHL et al., *Phys.Rev.D* 99 (2019) 3, 034011



- Background from pomeron-pomeron suppressed by UPC requirement, from photon-photon by pA instead of AA.

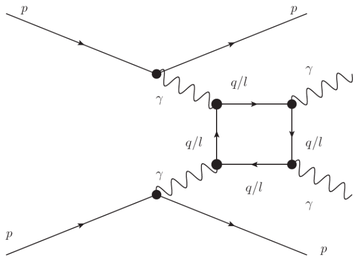
- Nonetheless backgrounds can be challenging. Looking at rapidity distributions may help.



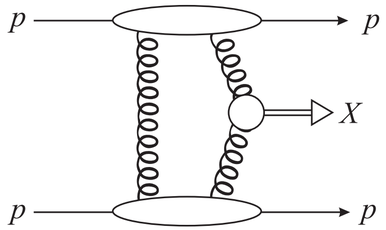
R. McNulty et al., *Eur.Phys.J.C* 80 (2020) 3, 288

SuperChic MC Implementation

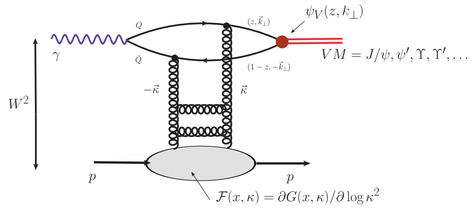
- A MC event generator for CEP processes.
Common platform for:
  - QCD-induced CEP.
  - Photoproduction.
  - Photon-photon induced CEP.



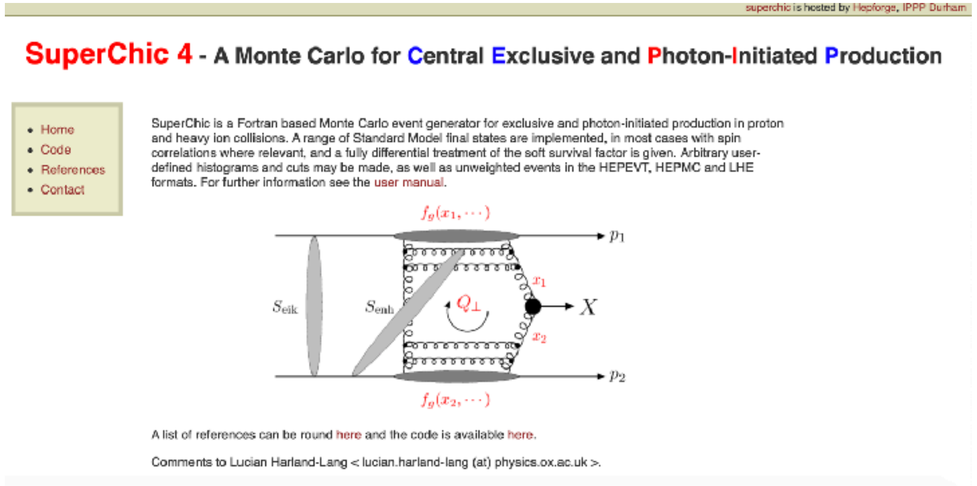
Photon-induced



QCD-induced



Photoproduction



- For **pp**, **pA** and **AA** collisions. Weighted/unweighted events (LHE, HEPMC) available- can interface to Pythia/HERWIG etc as required.

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

SuperChic 5 - MC Implementation

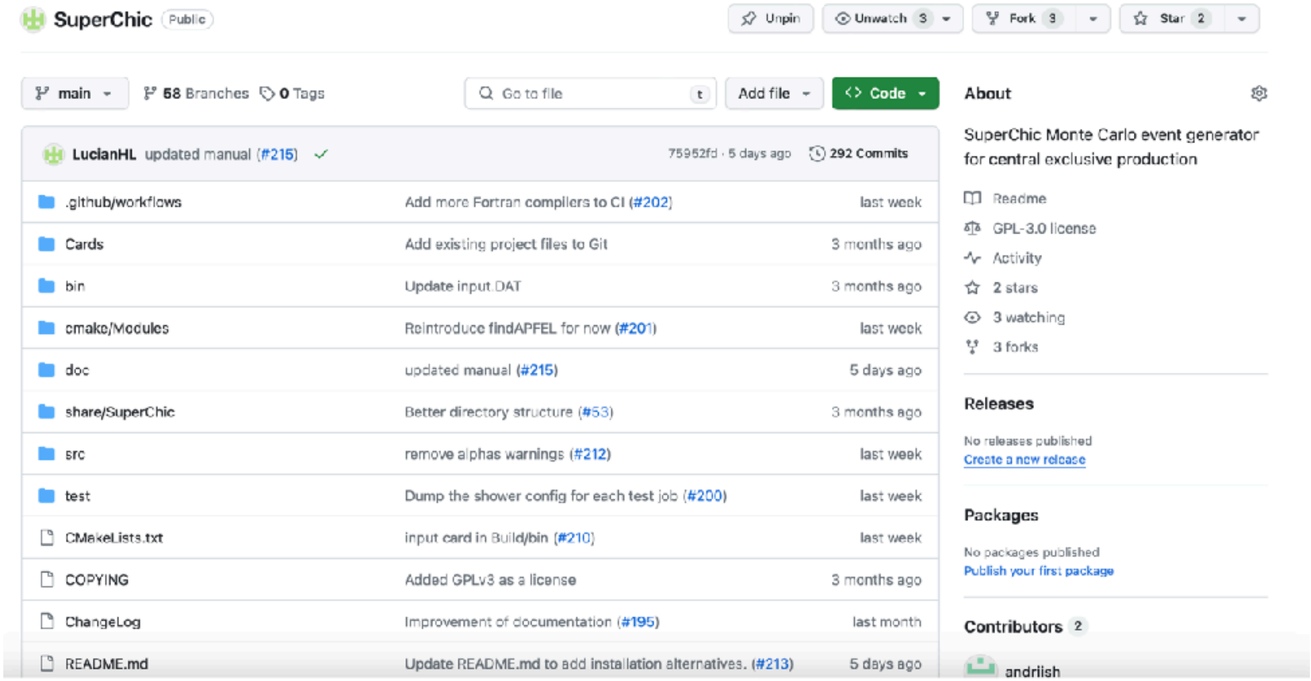
- Version 5 now released. Significant updates to code:

★HepMC output now properly supported.

★Full testing suite added + cmake build system.

★Various bug fixes + code improvements.

★ Future releases will be via github. Collaboration/PRs welcome!



https://github.com/LucianHL/SuperChic

Summary/Outlook

- ★ Photon-photon initiated production provides a relatively clean environment with which to probe the EW sector of the SM and extensions of it.
- ★ Initial-state rather well understood, and impact of QCD interactions between hadrons small but not negligible. No qualitative changes between p and A cases.
- ★ In terms of expected rates, pA does not appear to be competitive with pp/AA. However expected cross sections measurable in low to intermediate mass region!
- ★ Many physics effects still being disentangled in e.g. case of dilepton production. Having additional handle of pA measurement could be key here. Similarly for ion dissociation.
- ★ Have set the scene here, and presented some first thoughts in this direction, but not intended to be exhaustive - other motivations may be there to discuss.