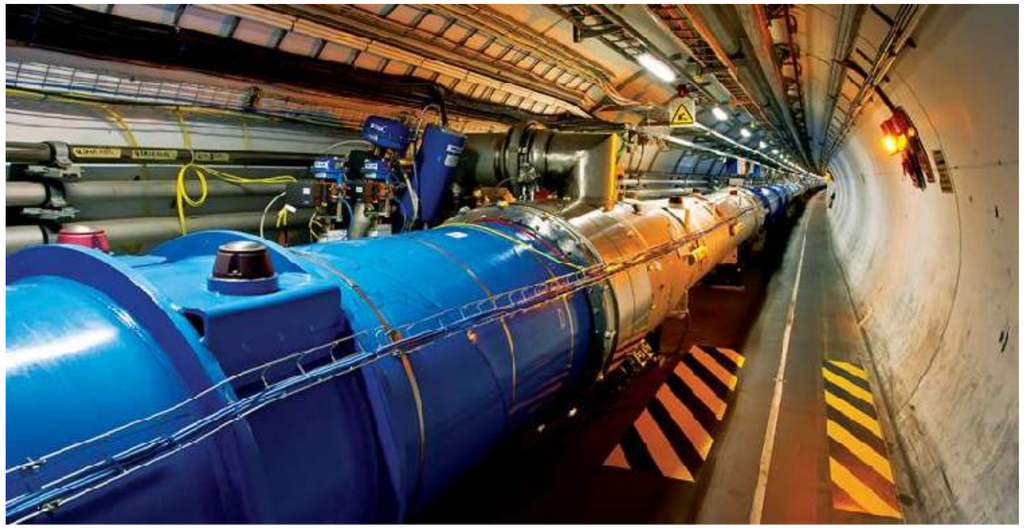
The LHC as a photon-photon collider

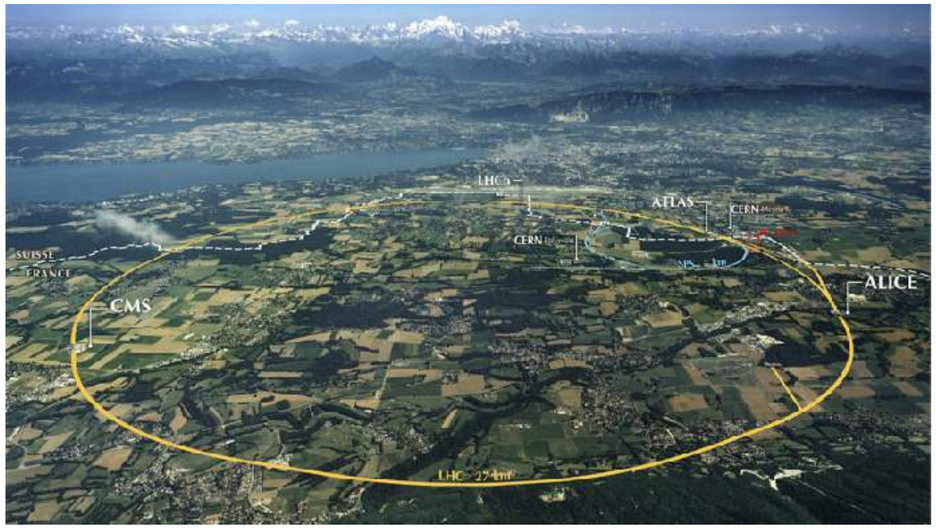
Lucian Harland-Lang, University College London

Bohr Seminar, Manchester, April 18 2026

The LHC: a hadron-hadron collider

- The **LHC** works by colliding hadron beams head on at high energy.
- We examine the debris of these interactions in order to probe the Higgs sector, look for physics beyond the Standard Model and to understand the SM better.
- It is both a **discovery** and a **precision** measurement machine.
- Before doing any of that that we need to understand what we are colliding: the **proton.**

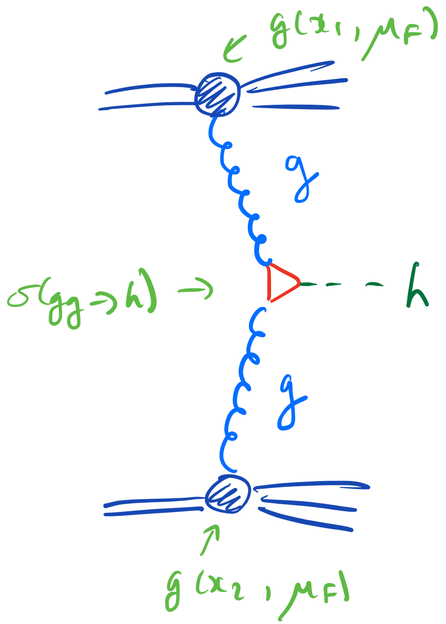


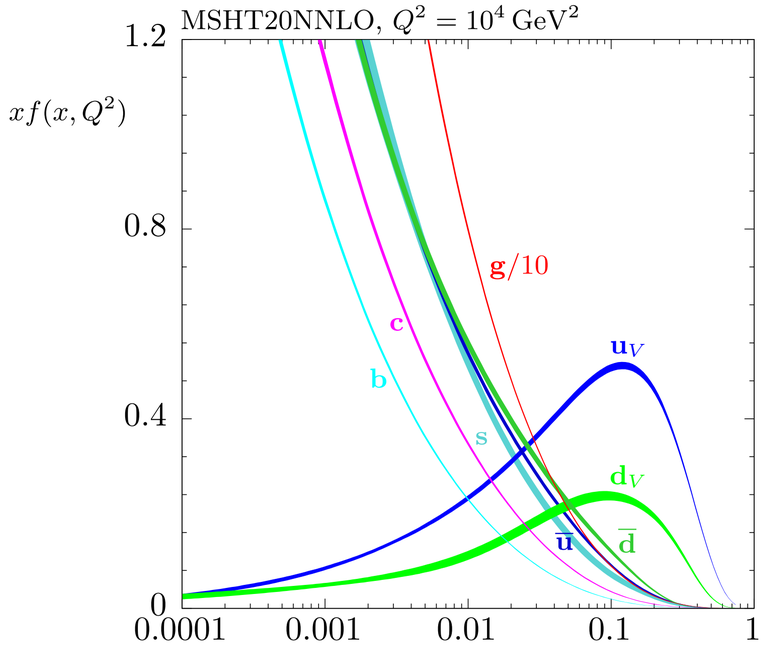


The LHC: a parton-parton collider

- Proton-proton collision modelled in terms of interactions of fundamental QCD degrees of freedom: quark + gluon '**partons**' in proton.

$$\sigma(pp \to X) \sim \hat{\sigma}(ij \to X) \otimes f_i(x_1, \mu^2) \otimes f_j(x_2, \mu^2)$$

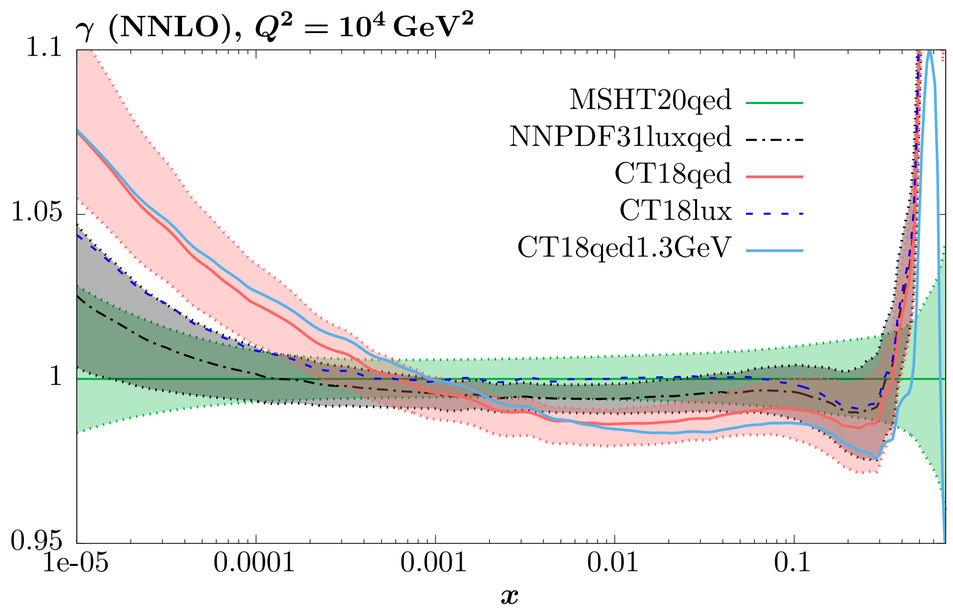


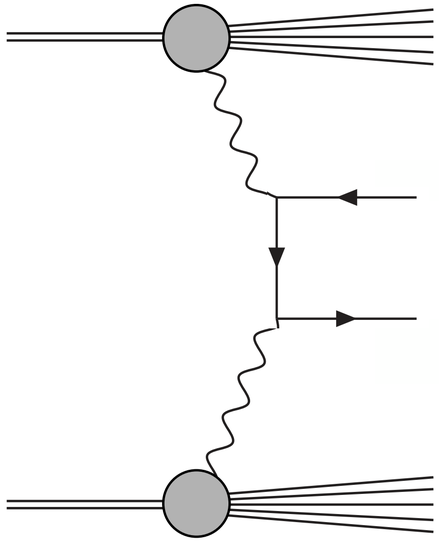


- Density of partons encoded in `parton distribution functions' (PDFs).
- Story for another seminar. Question: are quark/gluons all there is?

The LHC: a photon-photon collider

- **No!** Protons and their quark constituents also have QED charge: photons are a proton constituent. **Photon-initiated** production possible.

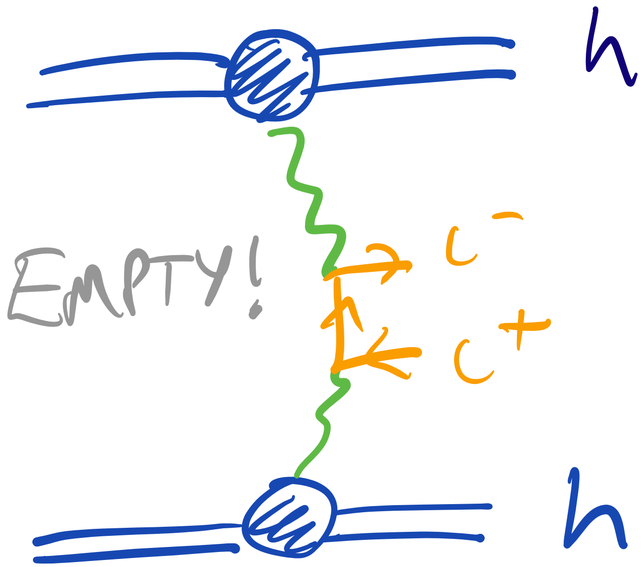




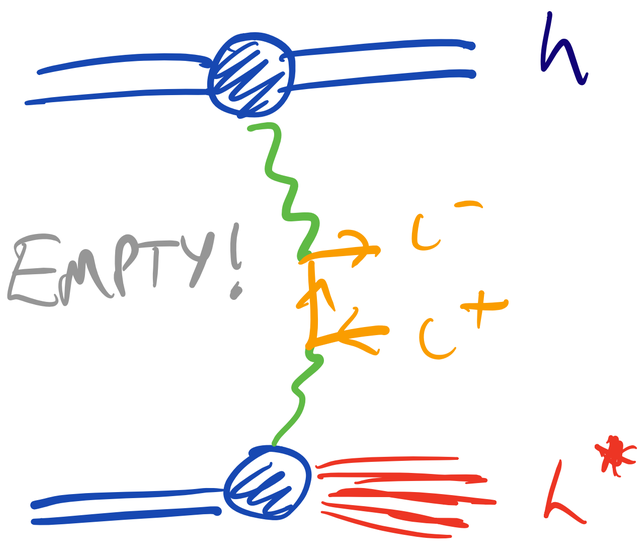
- Initial-state photons can be accounted for in proton PDFs. Generally ~ % level contributions to inclusive LHC cross sections.
- Essential component of high precision theoretical calculations - % level corrections. **End of story?**

The (semi) exclusive photon

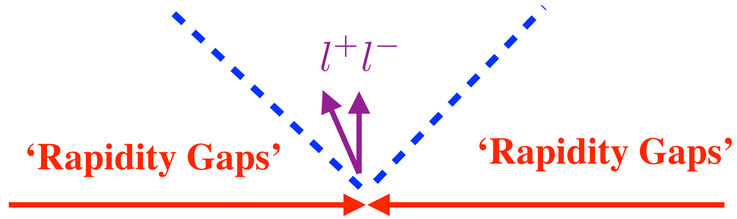
- **Exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state:



Exclusive



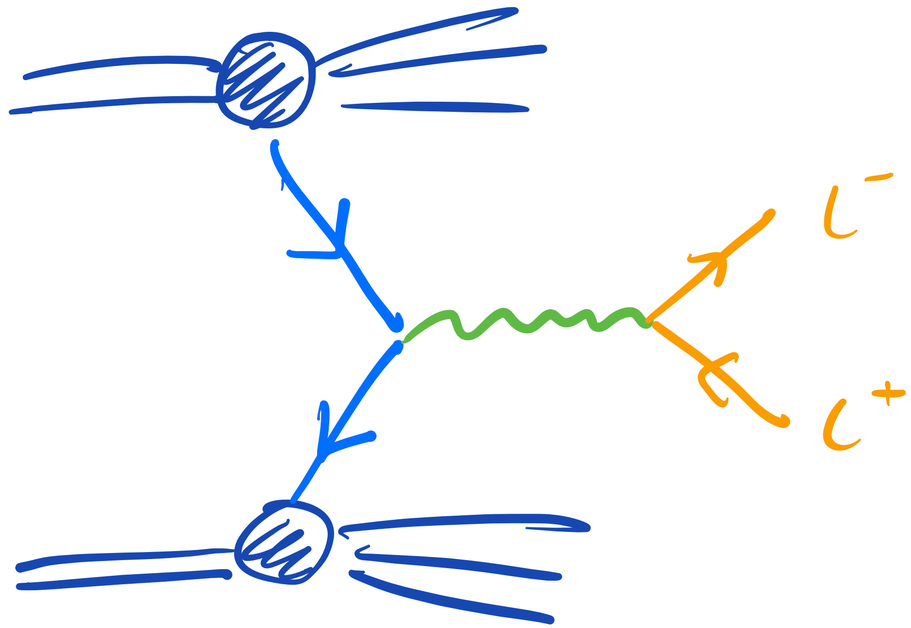
Semi-exclusive



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

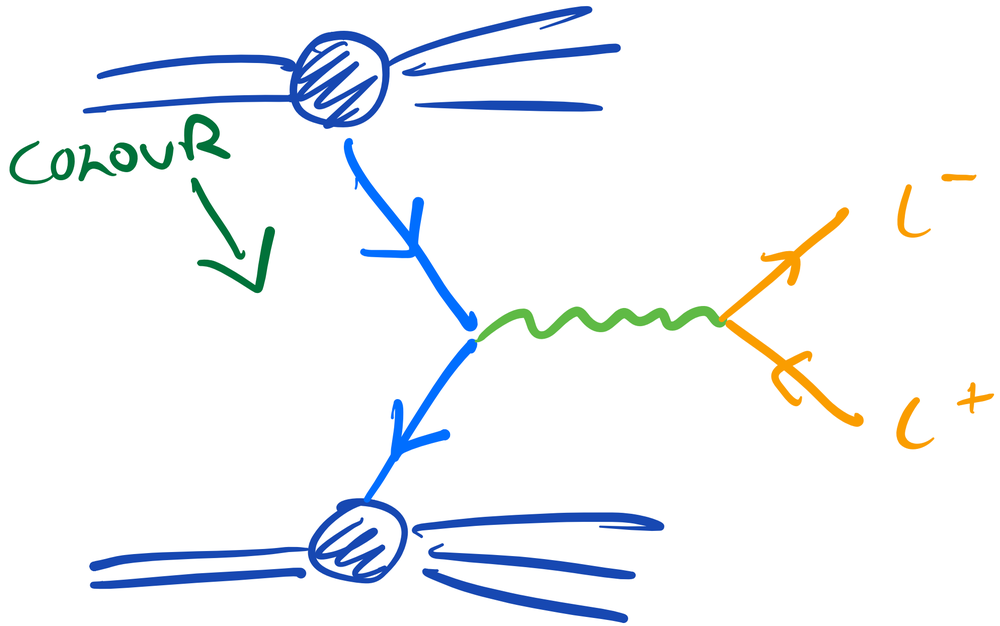
Inclusive Production

- **Key point:** quark/gluon-initiated production leads to colour flow between protons $\Rightarrow$ these break up + significant amount of additional particles present in detector.



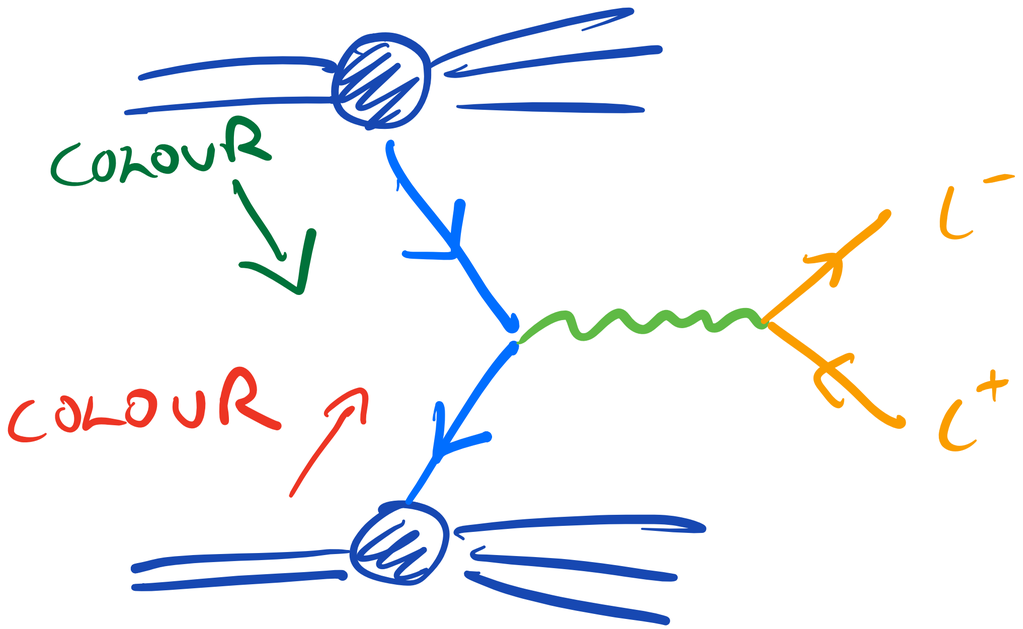
Inclusive Production

- **Key point:** quark/gluon-initiated production leads to colour flow between protons $\Rightarrow$ these break up + significant amount of additional particles present in detector.



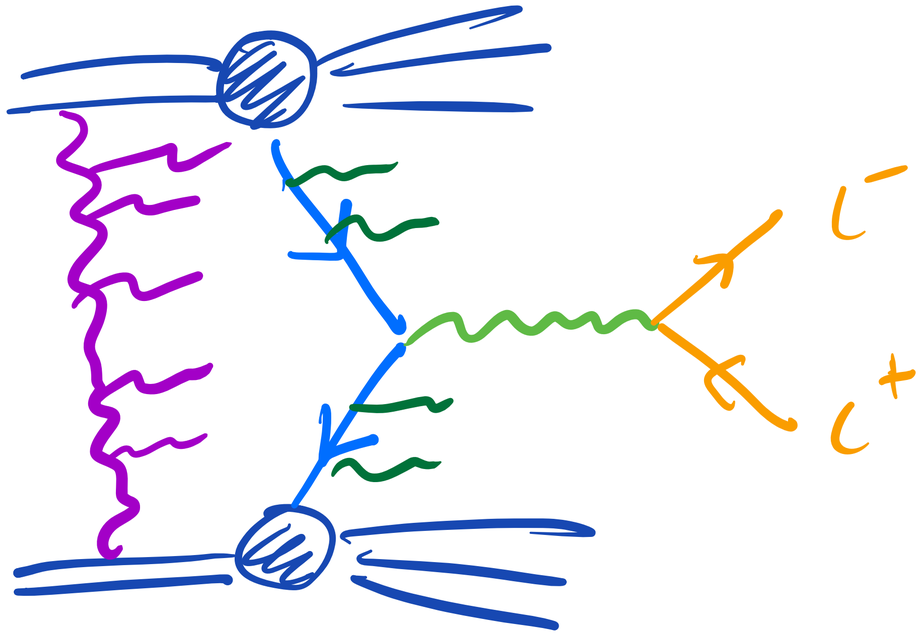
Inclusive Production

- **Key point:** quark/gluon-initiated production leads to colour flow between protons $\Rightarrow$ these break up + significant amount of additional particles present in detector.



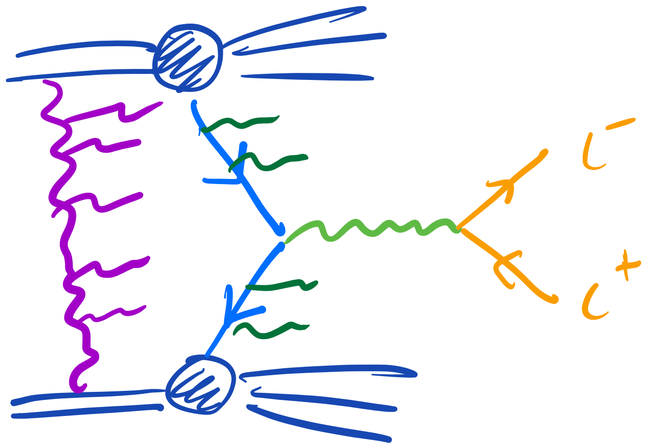
Inclusive Production

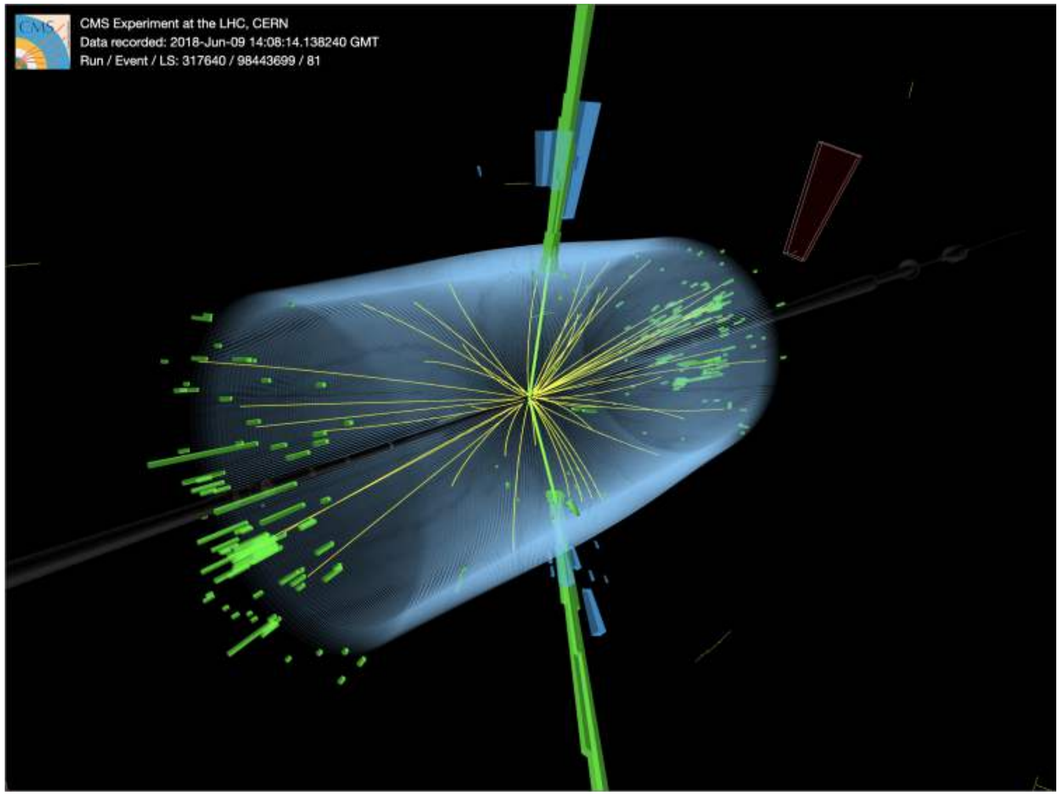
- **Key point:** quark/gluon-initiated production leads to colour flow between protons $\Rightarrow$ these break up + significant amount of additional particles present in detector.



Inclusive Production

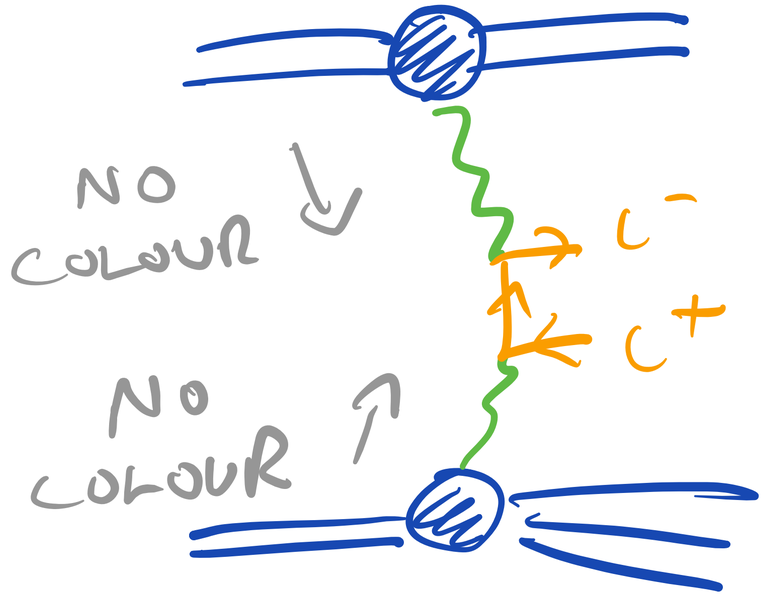
- **Key point:** quark/gluon-initiated production leads to colour flow between protons $\Rightarrow$ these break up + significant amount of additional particles present in detector.





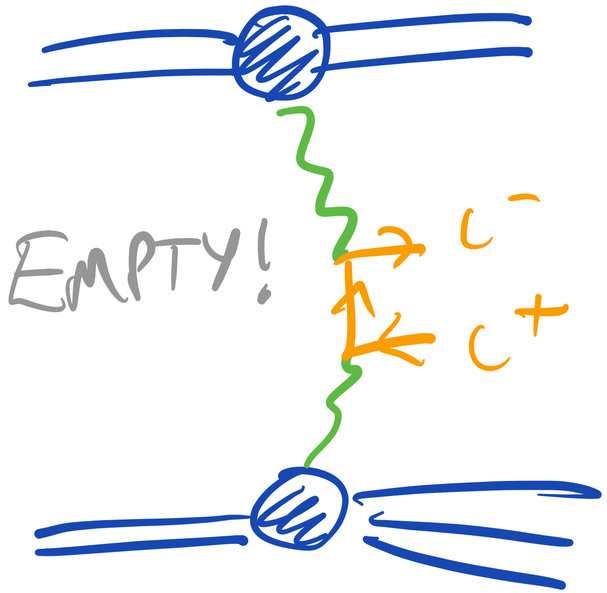
Semi-exclusive production

- For photon-initiated production no longer the case: colour flow not necessary.



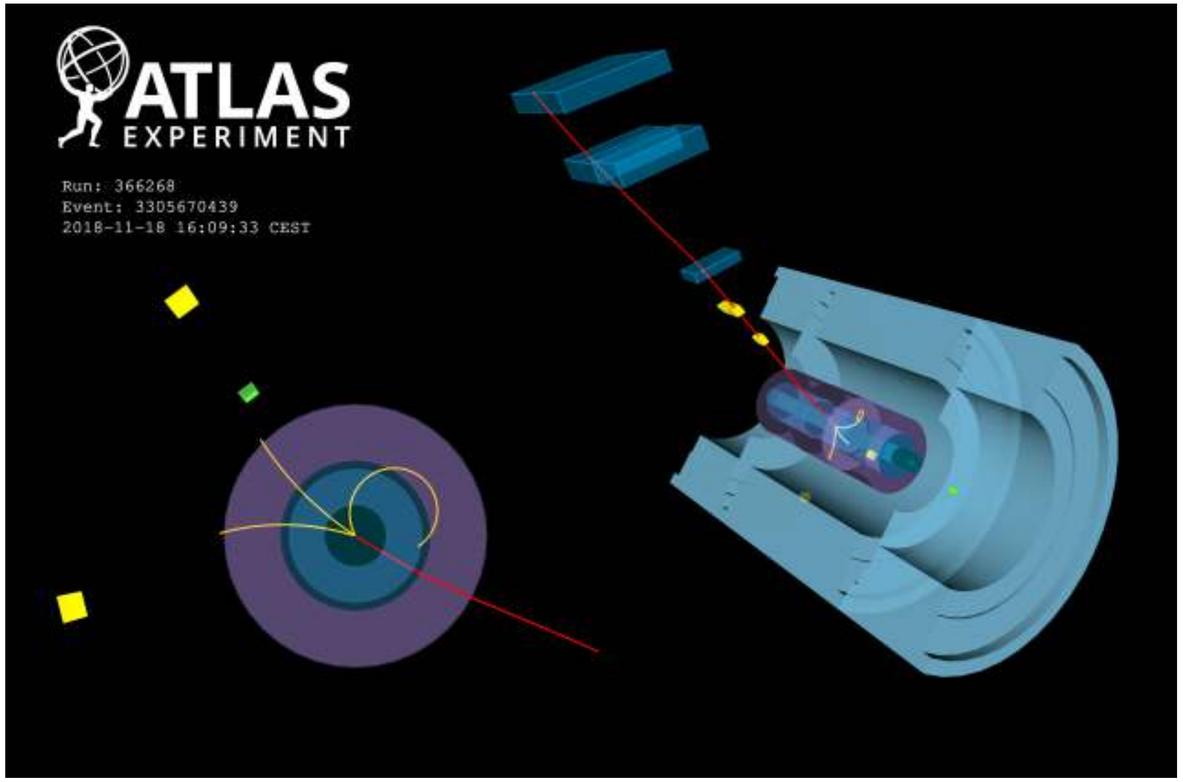
Semi-exclusive production

- For photon-initiated production no longer the case: colour flow not necessary.



Semi-exclusive production

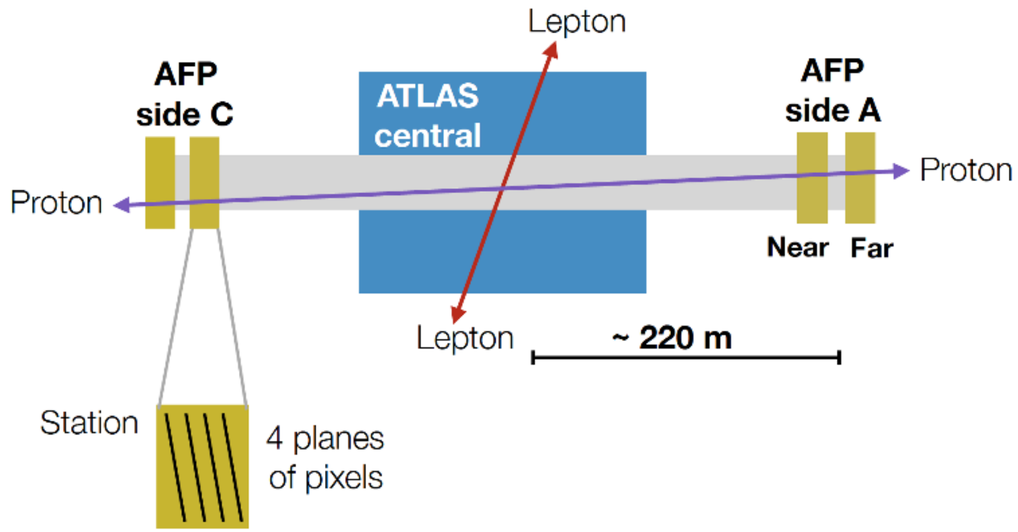
- For photon-initiated production no longer the case: colour flow not necessary.

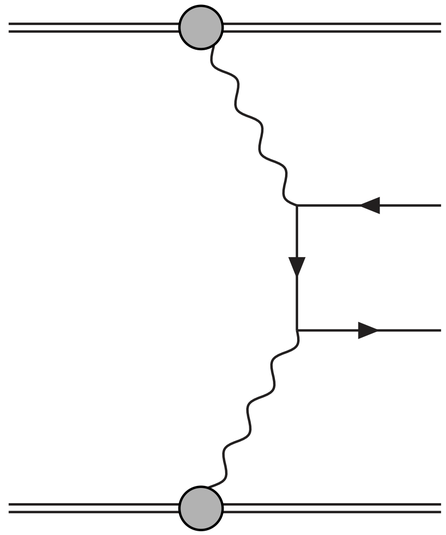


N.B. for experts - this is not a pp event…

The elastic proton

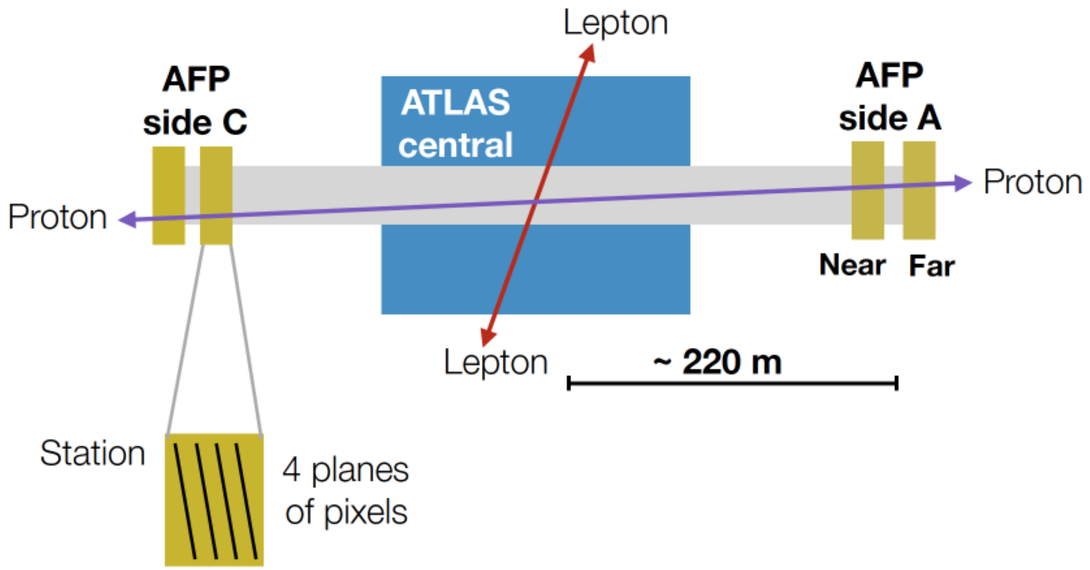
- If proton remains intact will continue down the beam line but with lower energy $E < \sqrt{s}/2$: will be bent out of beamline by LHC magnets.
- Can measure with dedicated detectors ~ 200m (+): proton taggers.



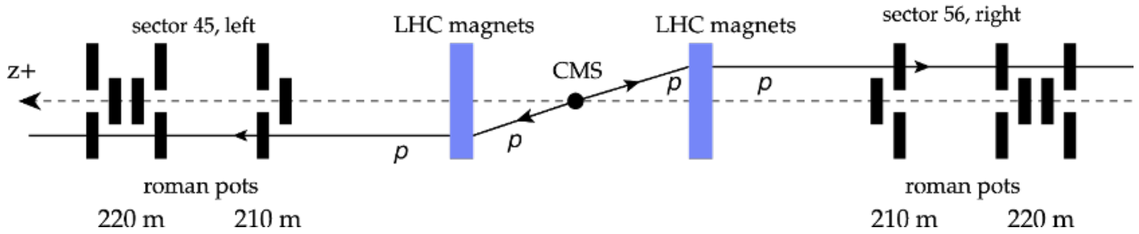


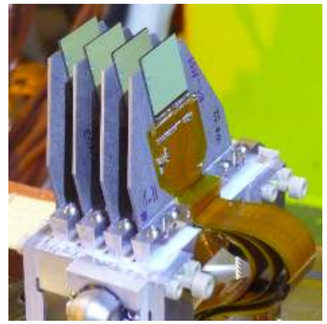
- Allows exclusive events to be selected, and momentum of proton to be reconstructed.
- These are installed and running in association with ATLAS and CMS…

AFP



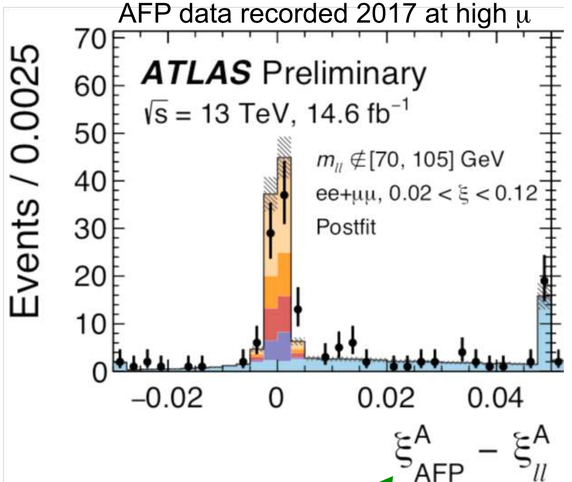
CT-PPS

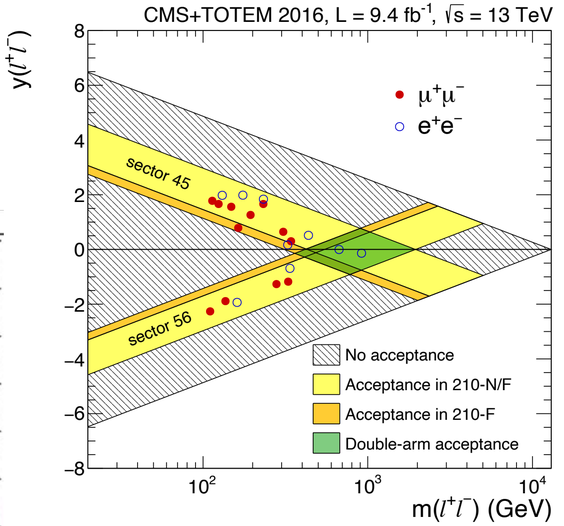




- Proton taggers ~ 200m from ATLAS (AFP) and CMS (CT-PPS)
- Measurements/searches data performed/ongoing…
- …with many to come, including during HL-LHC with CMS.

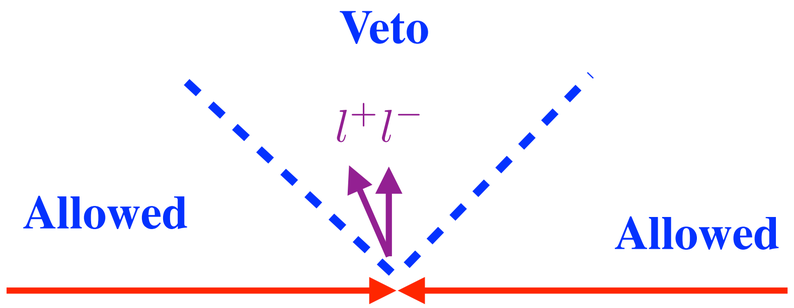
CT-PPS, arXiv:2103.02752

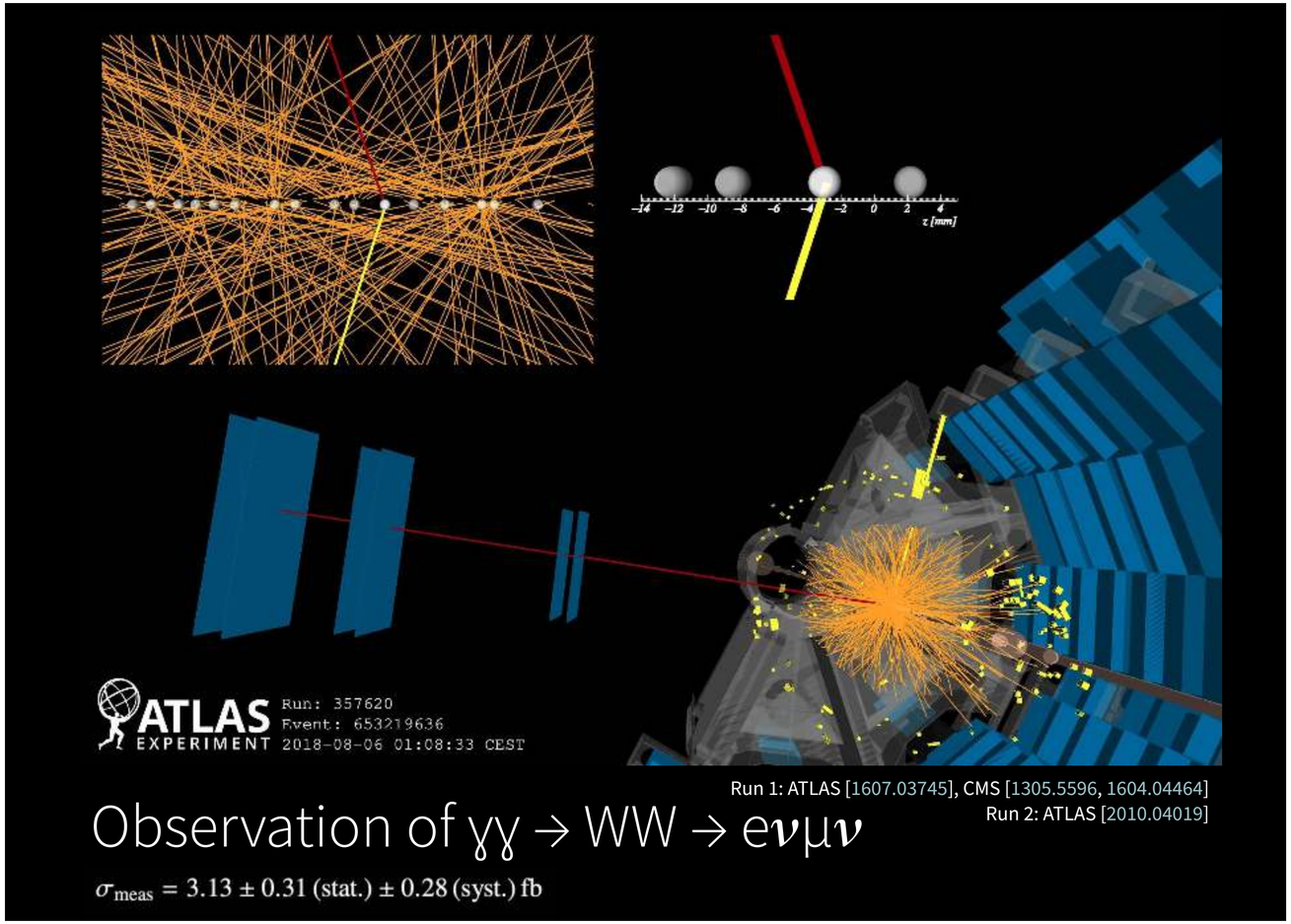




Selecting semi-exclusive production

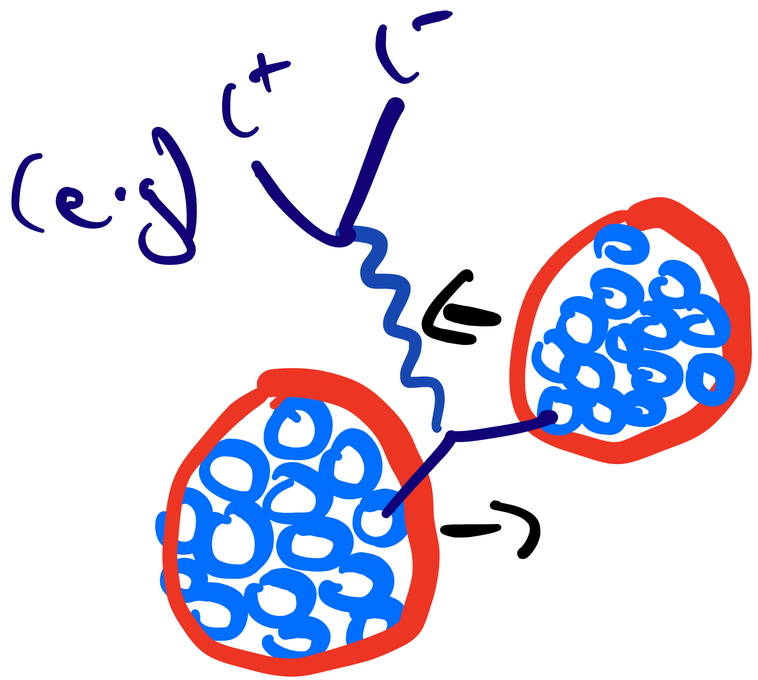
- Proton tagging useful but not essential.
- During normal LHC pp running multiple (10s) of collision events during the same bunch crossing.
- Events can be selected by requiring no addition associated tracks in the (very) high multiplicity environment of the high pile-up LHC.



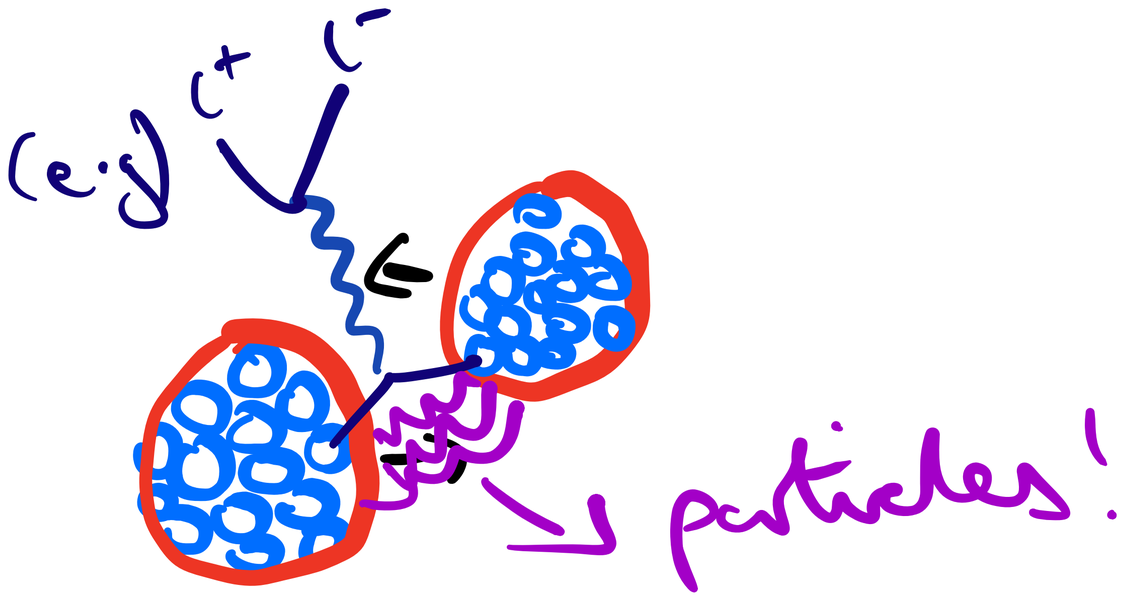


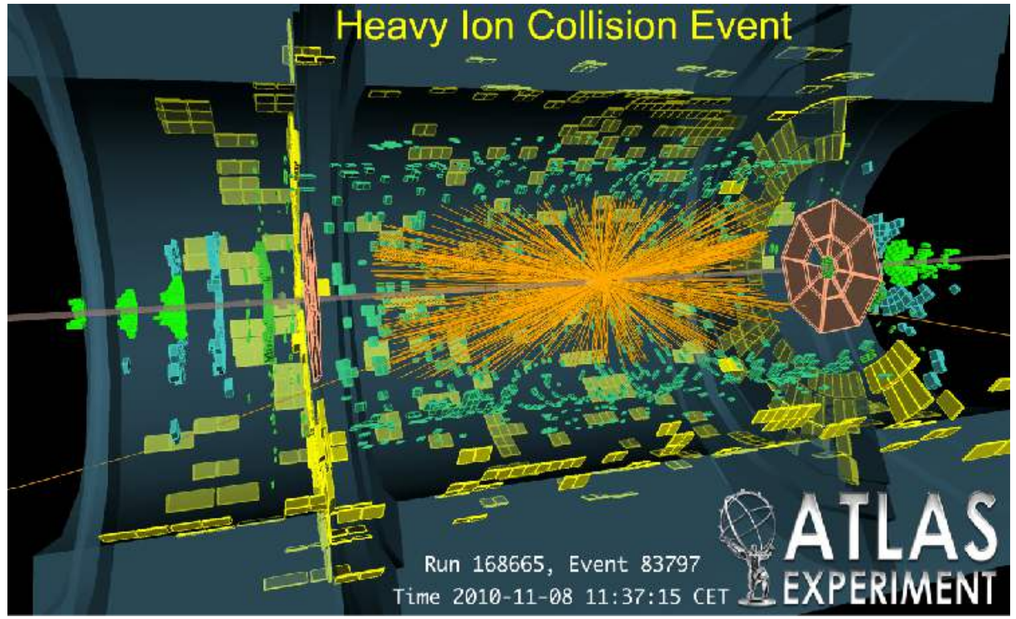
Heavy Ions

- Possibilities not limited to pp collisions. LHC also a **heavy ion collider**.
- In 'standard' heavy collision, large number of nucleons in initial state $\Rightarrow$ QCD particle production enhanced and multiplicity can be very high.

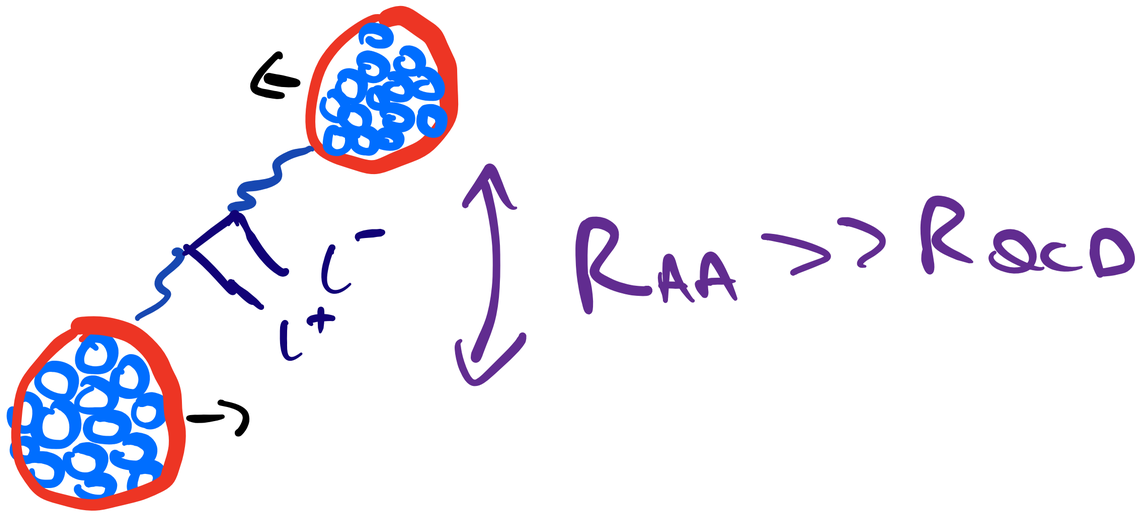


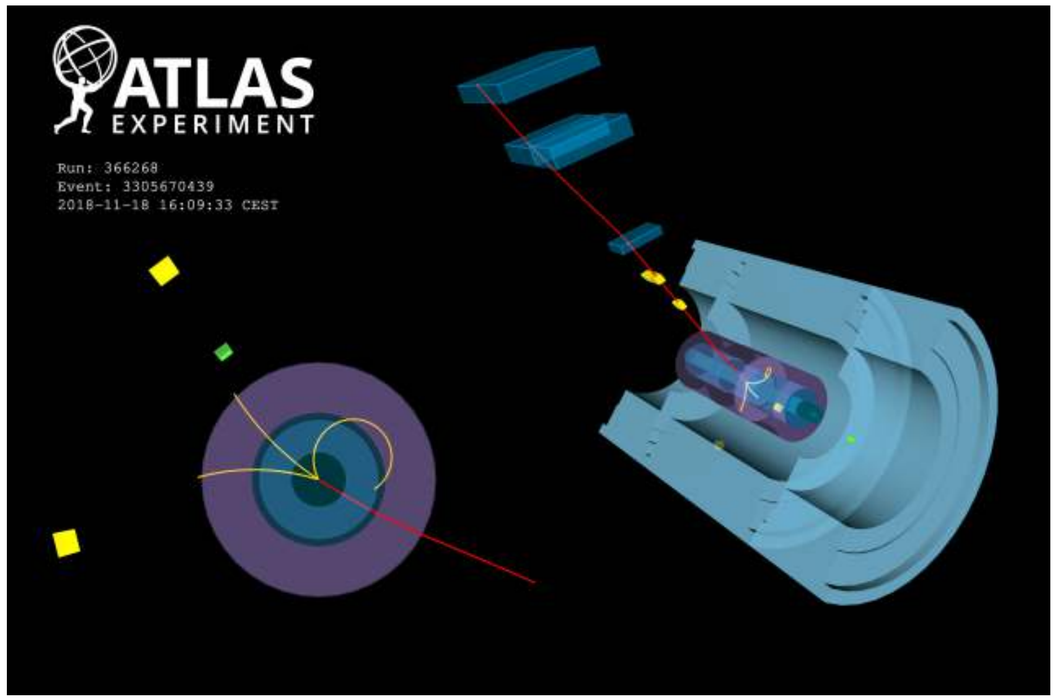
- Possibilities not limited to pp collisions. LHC also a **heavy ion collider**.
- In 'standard' heavy collision, large number of nucleons in initial state $\Rightarrow$ QCD particle production enhanced and multiplicity can be very high.





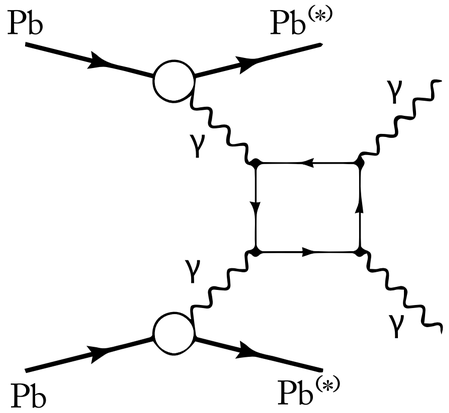
- Possibilities not limited to pp collisions. LHC also a **heavy ion collider**.
- However if colliding ions sufficiently separated in impact parameter ('ultraperipheral') does have to be the case:

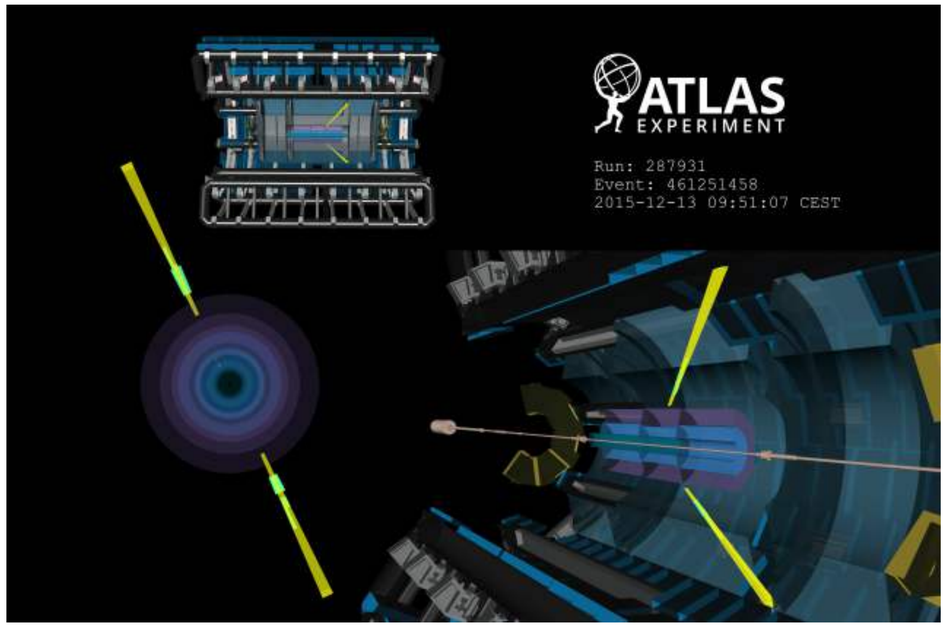




- QED interaction is **long-range**: photon-initiated production can (and does) lead to this.

- **Key point:** heavy ions have significant electric charge $Z_{\rm Pb} = 82$





nature physics
ARTICLES
PUBLISHED ONLINE: 14 AUGUST 2017 | DOI: 10.1038/NPHYS4208
OPEN

Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration†

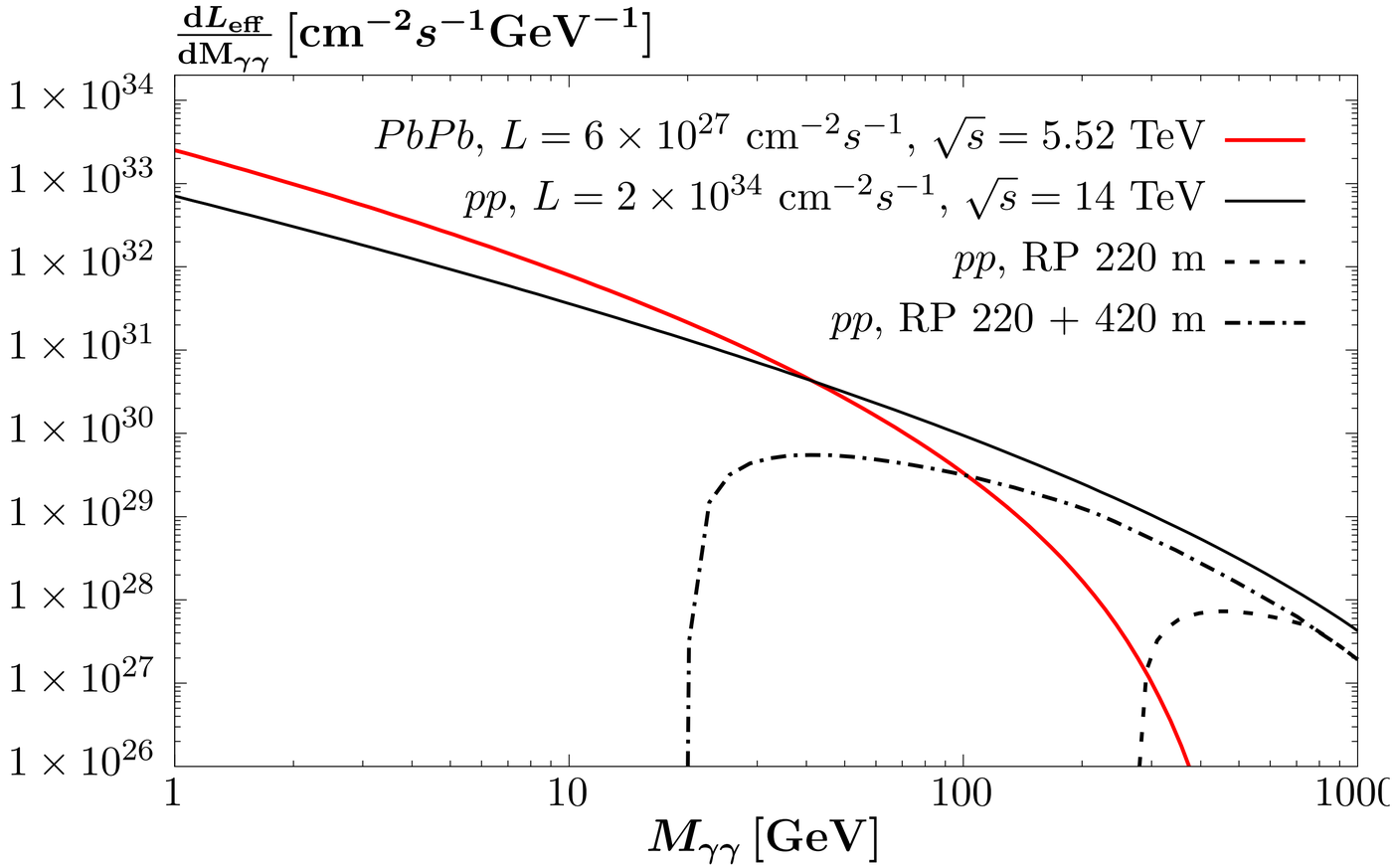
ATLAS, *Nature Phys.* 13 (2017) 9, 852-858

- Photons emitted coherently from colliding ions $\Rightarrow$ cross section enhanced by $Z^4 \gg 1$.
- For in particular light objects, this allows previously untested production to be probed, and with unprecedented precision.

- Photon flux from ions falls v. quickly with central object mass but here great deal has been achieved…

$$F_p \propto Z \Rightarrow \text{cross section} \propto F_p^4 \sim Z^4\text{: strong enhancement} \qquad F_p(|\vec{q}|) = \int \mathrm{d}^3 r \, e^{i\vec{q}\cdot\vec{r}} \rho_p(r)$$

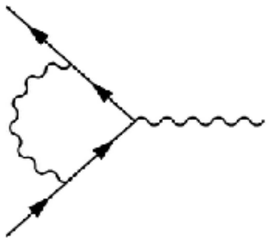
- Lower $M_{\gamma\gamma}$: heavy ions dominate.
- Higher $M_{\gamma\gamma}$: pp dominates.



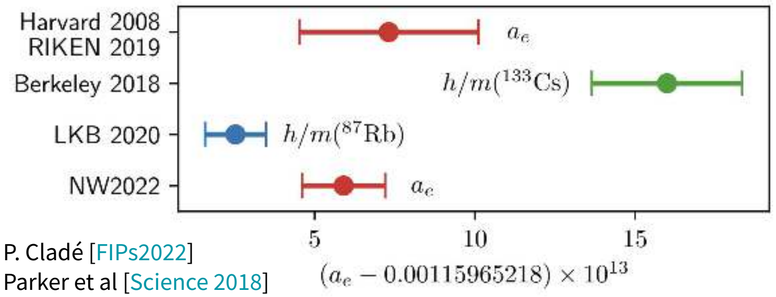
Physics Cases: Some Examples

⋆ Probing the tau g-2:

- While experimental situation for lighter leptons well developed…



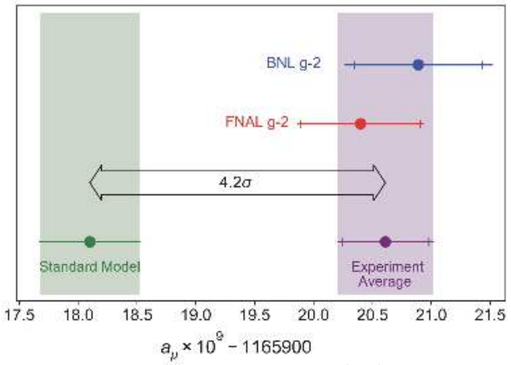
Electron $g-2$ (–2.5σ?)



P. Cladé [FIPs2022]
Parker et al [Science 2018]
Morel et al [Nature 2022], Fan et al [2209.13084]

0.2 parts per billion

Muon $g-2$ (+4.2σ?)



0.5 parts per million

- For the tau lepton surprisingly little is known!

$$a_\tau^{\mathrm{exp}} = -0.018\,(17)$$

DELPHI [hep-ex/0406010]

(Pre - LHC)

$$a_{\tau,\,\mathrm{SM}}^{\mathrm{pred}} = 0.001\,177\,21\,(5)$$

Eidelman, Passera [hep-ph/0701260]

- Does not even probe 1-loop QED:

$$\alpha/2\pi = 0.001162$$

Schwinger [1948]

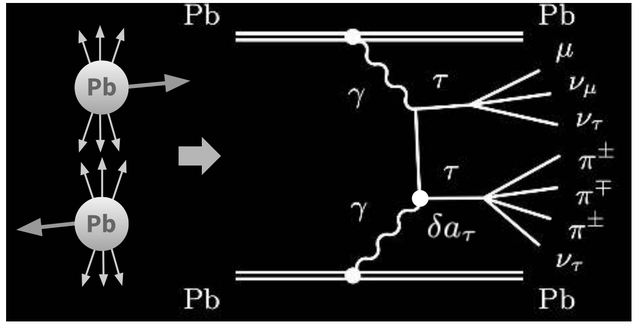
- Sensitivity to BSM unprobed:

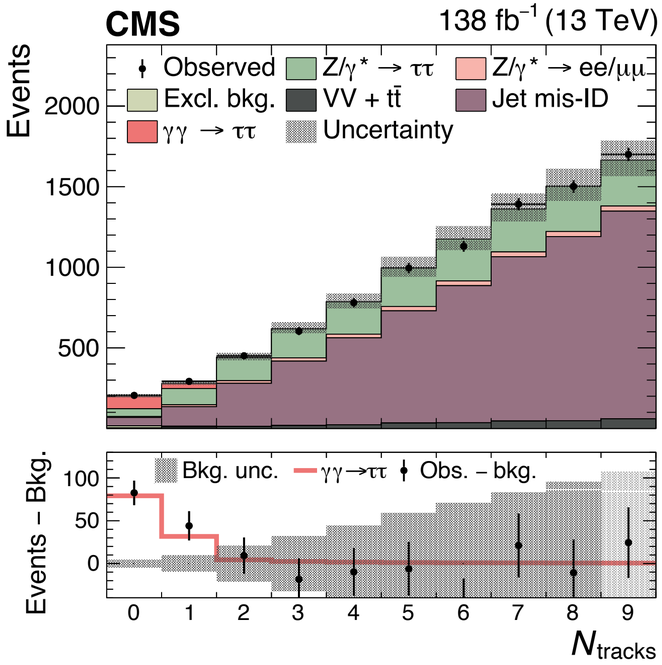
$$\delta a_\ell \sim m_\ell^2/M_{\mathrm{SUSY}}^2 \qquad m_\tau^2/m_\mu^2 \sim 280$$

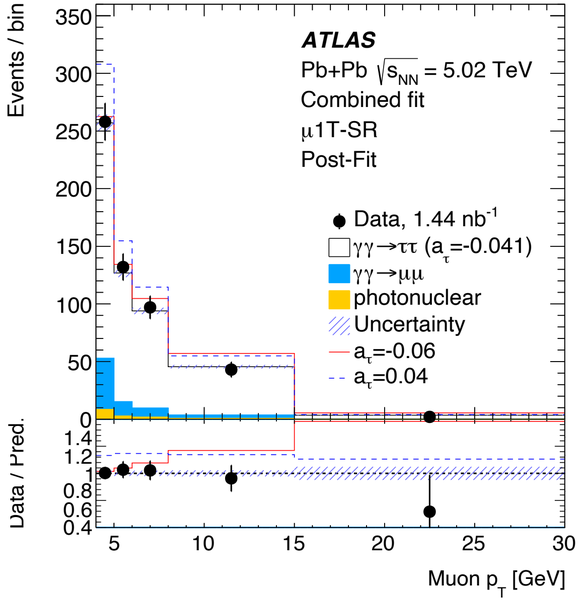
Martin, Wells [hep-ph/0103067]

Figures curtesy of J. Liu

- Measured in both PbPb collisions ($Z^4 \gg 1$), and recently in pp - $\gamma - \tau$ coupling $\Rightarrow$ τ g-2

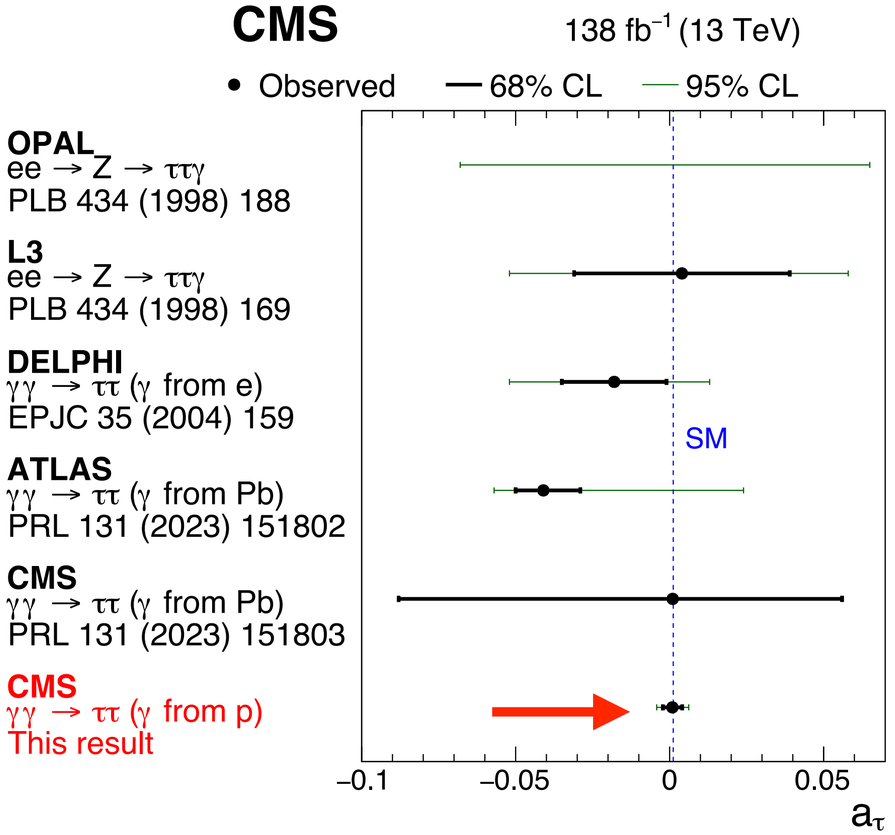






ATLAS, *Phys.Rev.Lett.* 131 (2023) 15, 151802

- Sensitivity via differential cross section has already set new limits.



CMS, *Rept.Prog.Phys.* 87 (2024) 10, 107801

⋆ Vector boson production in pp collisions.

- **V**ector **B**oson **S**cattering (**VBS**): broad class of process with sensitivity to the EW sector of the SM and BSM extensions of it.
- Often select events via VBS cuts: require two well separated jets (suppress s-channel $q\bar{q} \to VV$). However not the only way!

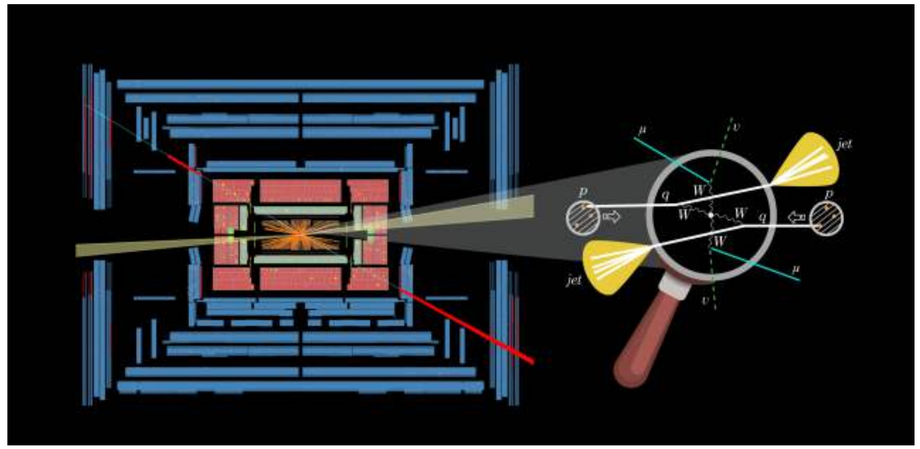
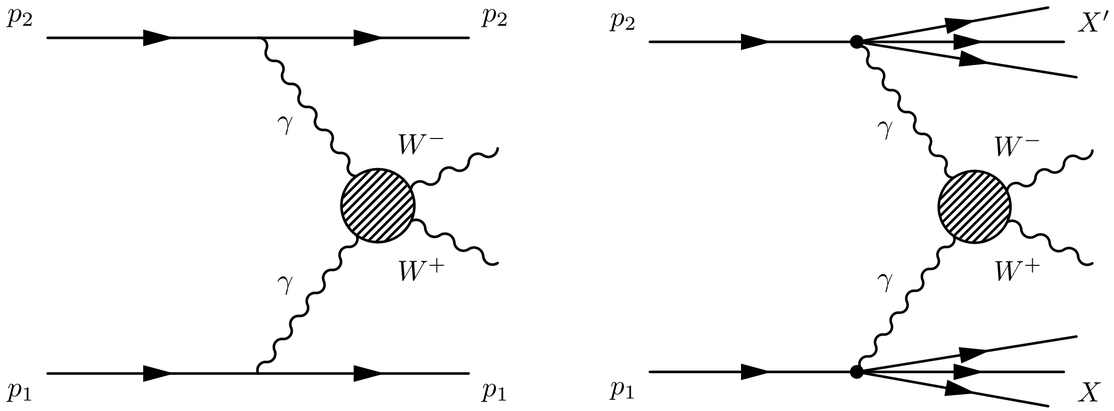


Image credit: Lucia Di Ciaccio, Simone Pagan Griso

- By selecting semi-exclusive VV events, focus in on underlying $\gamma\gamma \to VV$ process, e.g. W^+W^- :

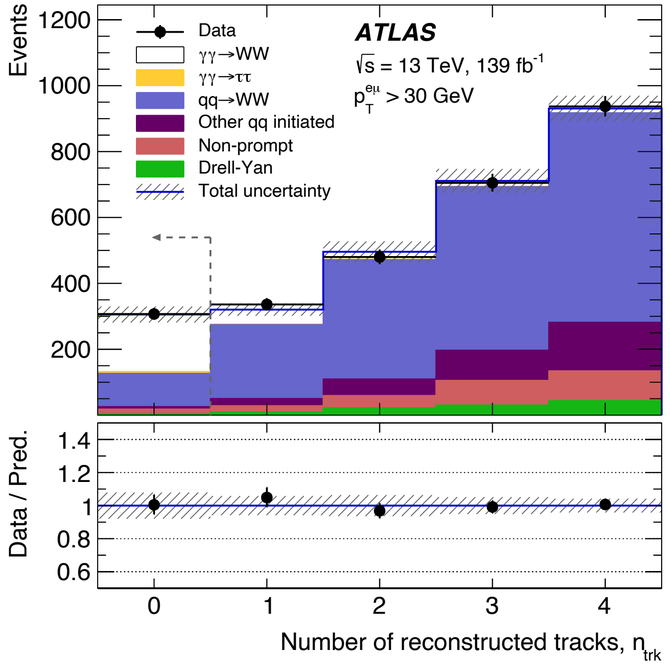


- 'Empty' event + VV final state $\Rightarrow \gamma\gamma \to VV$

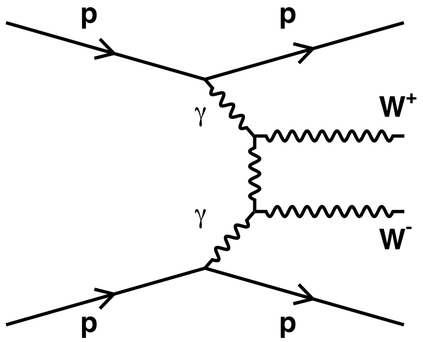
- First observation by ATLAS, by vetoing on additional associated tracks. Cross section agrees well with SM (within uncertainties).

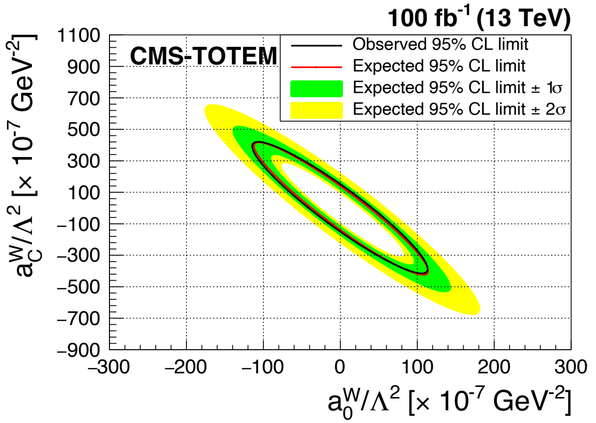
$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

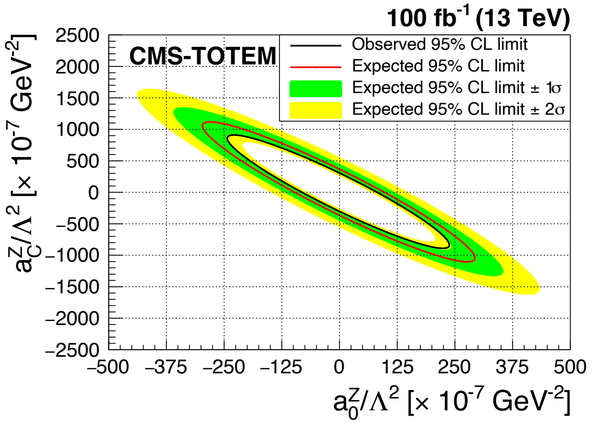
- Searches have also been performed with tagged protons (hadronic decays).



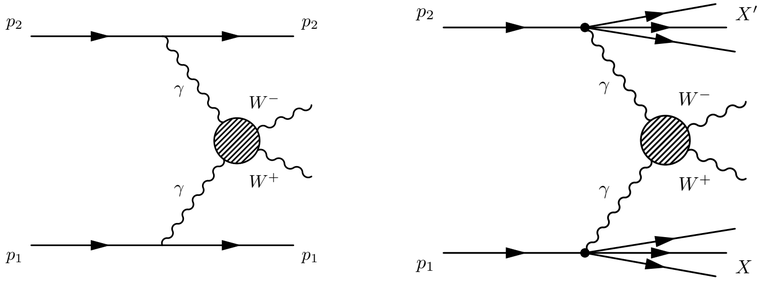
ATLAS, Phys. Lett. B 816, 136190 (2021)



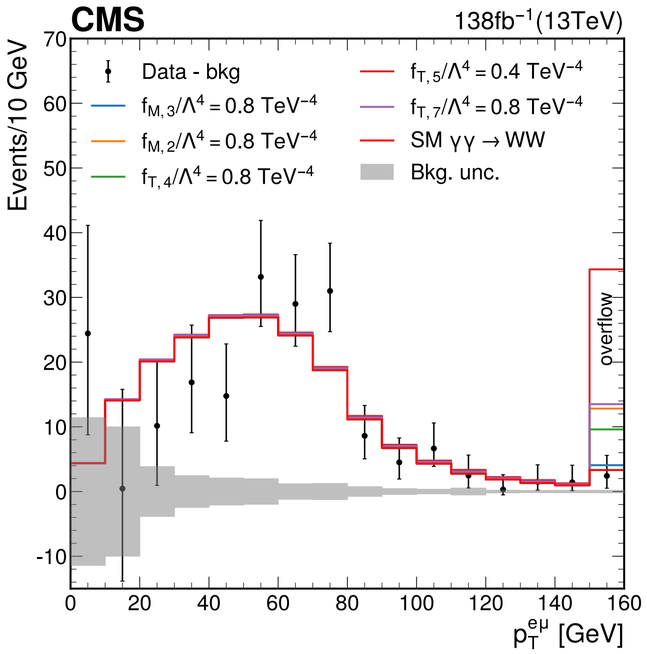


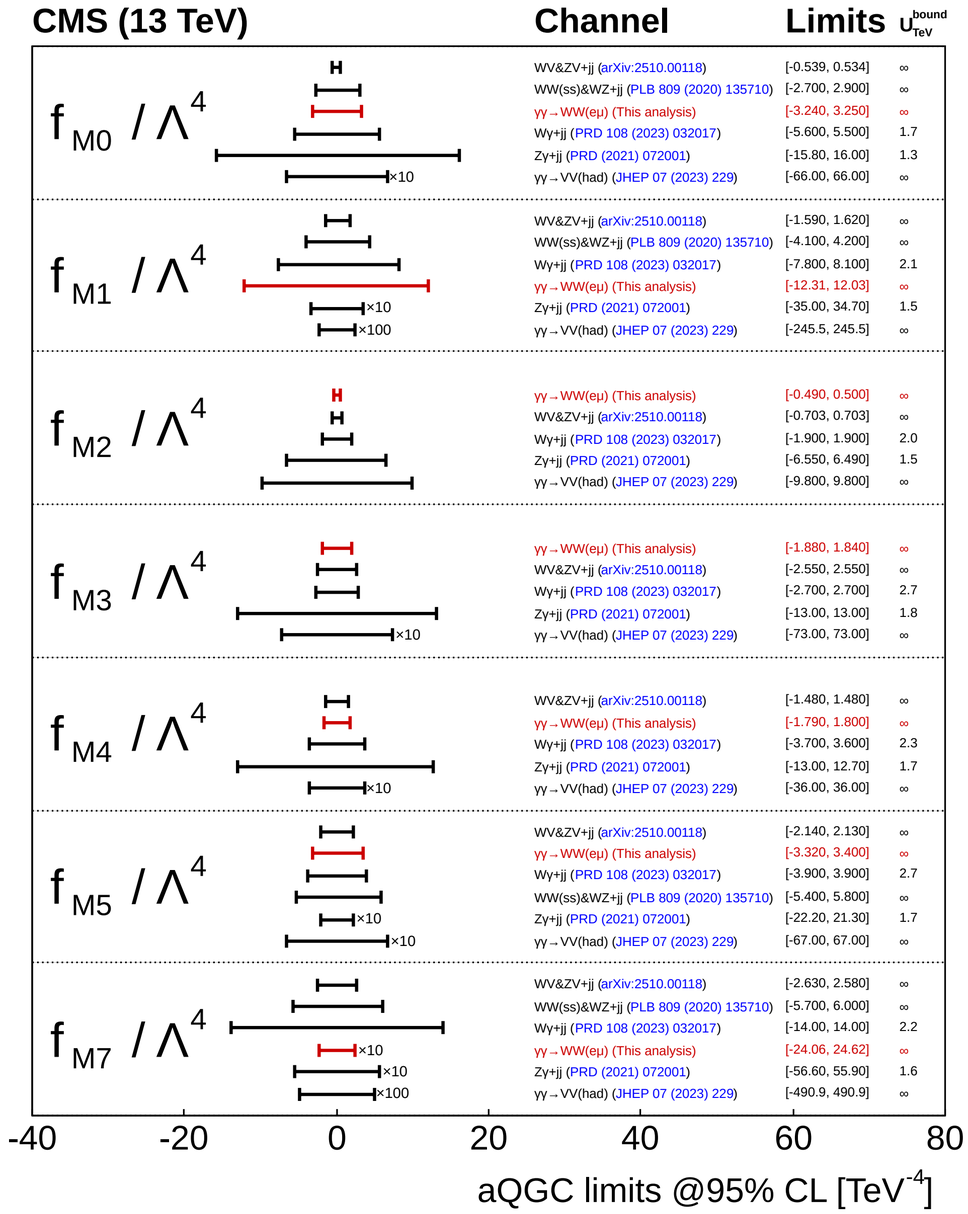


- Limits already competitive with other vector boson scattering results. Promising hunting ground for BSM.



- More recently, semi-exclusive WW production (dilepton channel) observed by CMS at 13 TeV.
- Good agreement with SM predictions, and extensive EFT limits set.

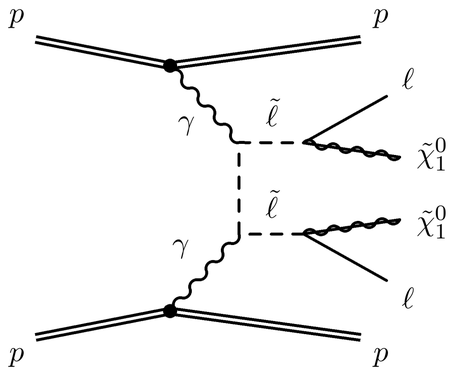




CMS, arXiv: 2601.21574

★ Many physics cases of interest…can't mention them all.

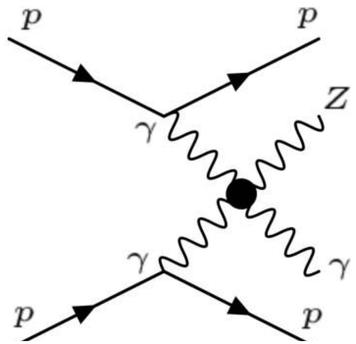
Compressed SUSY



LHL et al., JHEP 1904 (2019) 010

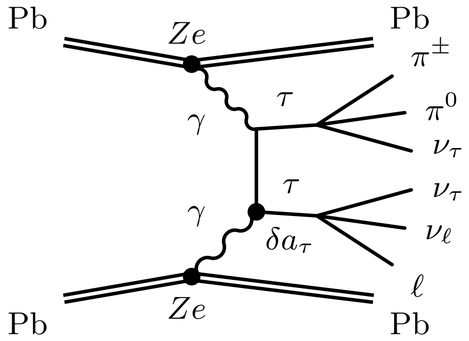
L. Beresford and J. Liu, PRL 123 (2019) no.14

Anomalous couplings



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

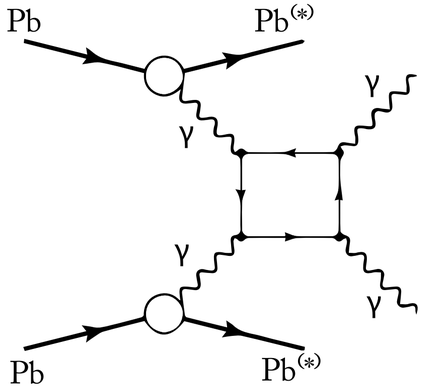
tau g-2



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

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

LbyL scattering/ALPS

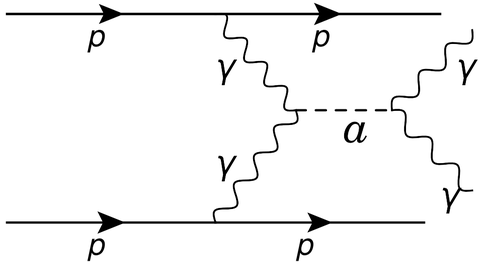


C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

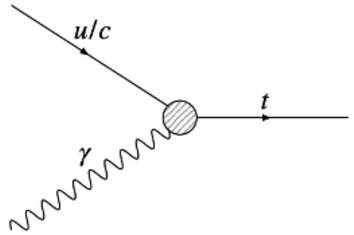
Axion-like Particles

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

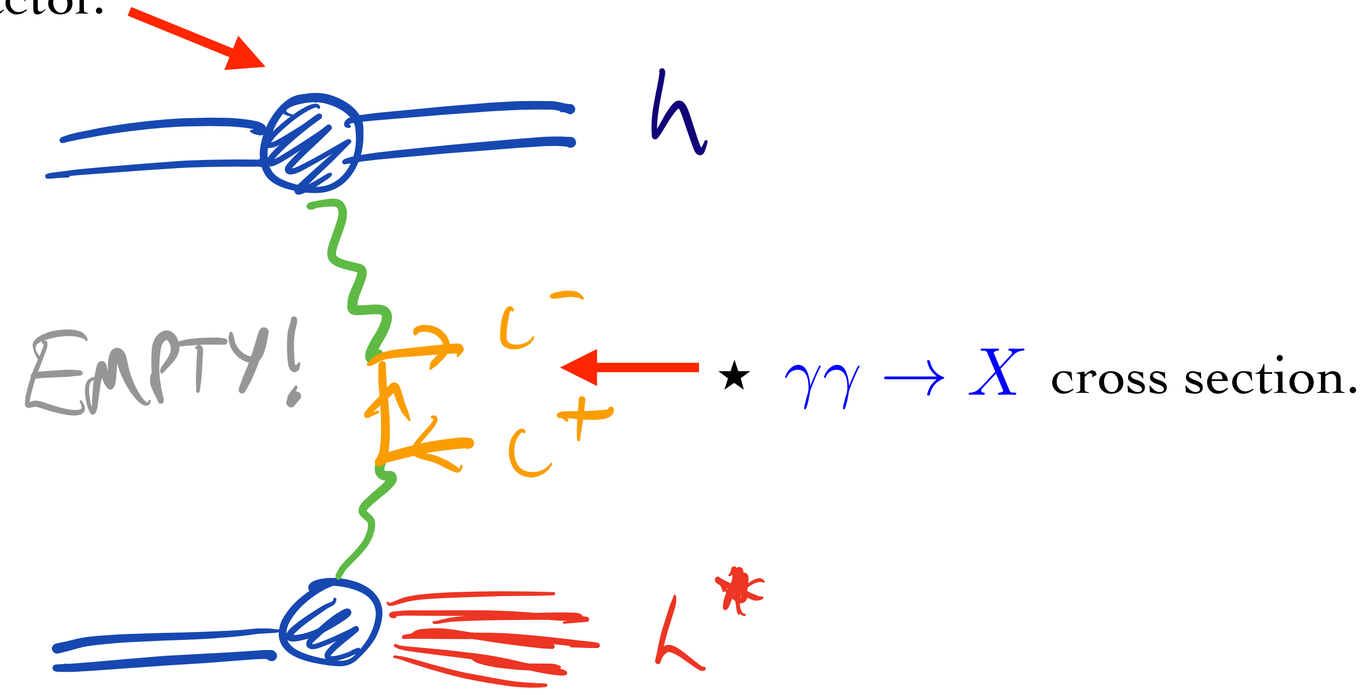
Modelling PI Production (pp collisions)

PI production: building blocks

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

★ $p \to \gamma p(p^*)$ form factor.

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

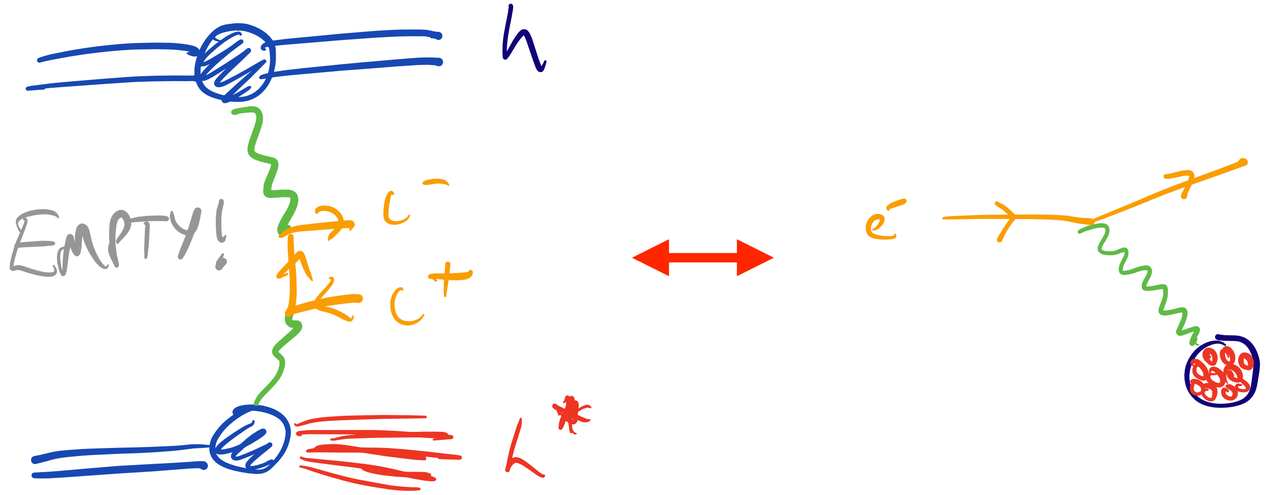


★ $\gamma\gamma \to X$ cross section.

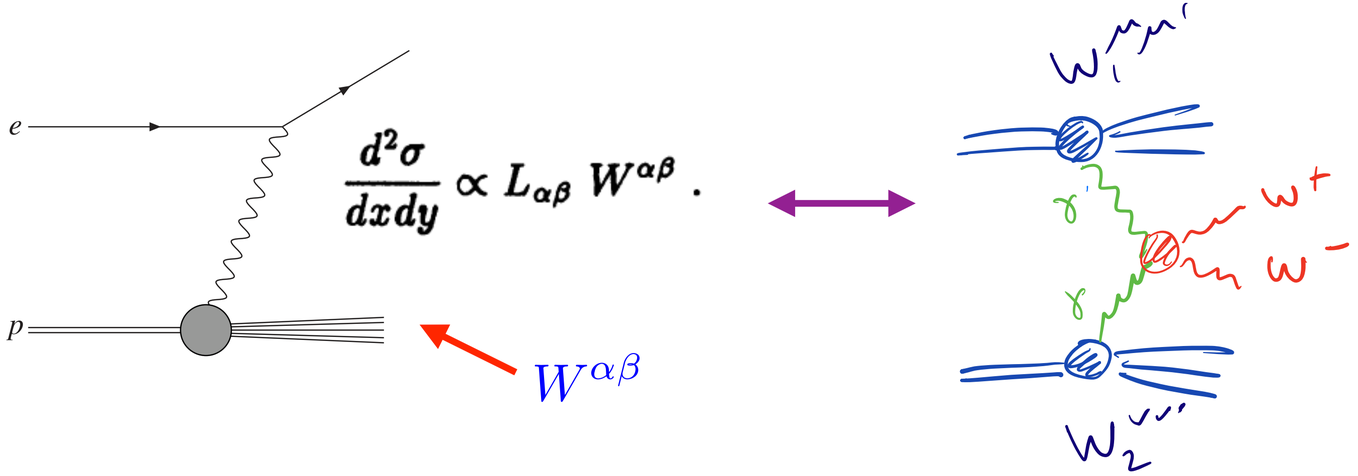
- Start with $p \to \gamma p(p^*)$ form factor…

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

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

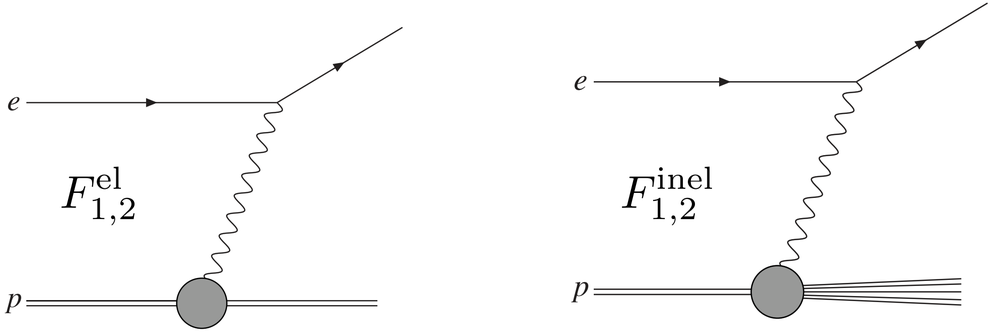


★ Protons - both elastic and dissociative PI production can be modelled in `Structure function' approach:



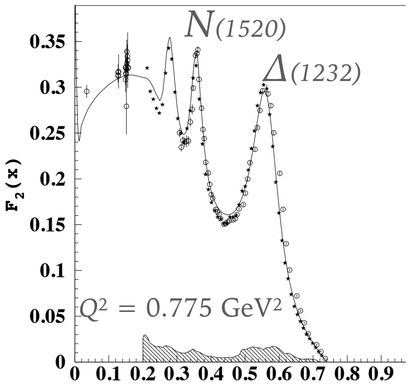
- Structure functions parameterise the $\gamma p \to X$ vertex: $W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x, Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P \cdot q} F_2(x, Q^2)$

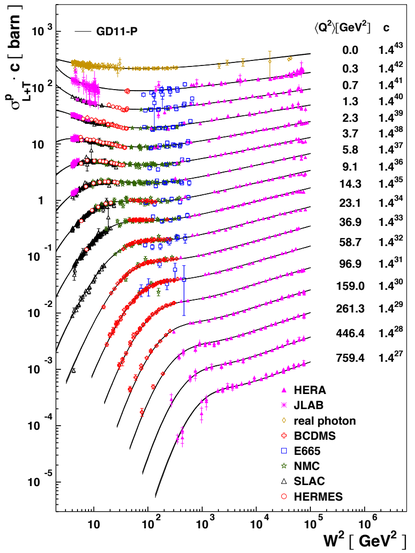
- Both elastic and inelastic SFs accounted for:



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

★ **Inelastic**: wealth of data on inelastic lepton-proton collisions. At higher photon this is just DIS - take from pQCD + global PDFs!





- Aside: all of this is exactly as goes into the 'LUXqed' photon PDF approach - now standard for including photon in proton PDFs.

A. Manohar et al., JHEP 1712 (2017) 046

LHL, *JHEP* 03 (2020) 128,
Phys.Rev.D 104 (2021) 7, 073002

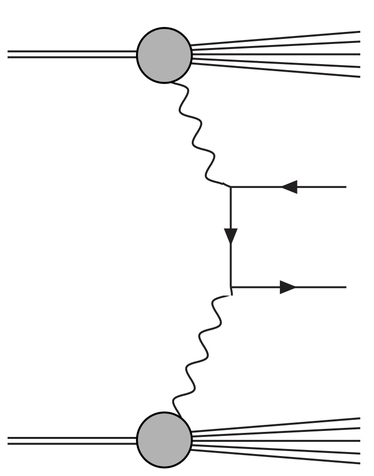
- Calculation readily amenable to MC treatment:

  ★ 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).

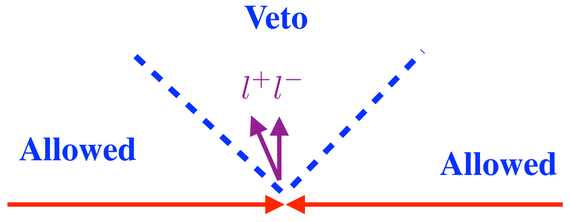
$$\sigma_{pp} = \frac{1}{2s}\int \mathrm{d}x_1 \mathrm{d}x_2\, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp}\, \mathrm{d}\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2)\frac{\rho_1^{\mu\mu'}\rho_2^{\nu\nu'}M^*_{\mu'\nu'}M_{\mu\nu}}{q_1^2 q_2^2}\delta^{(4)}(q_1+q_2-p_X)\,,$$

- Pass to general purpose MC for showering/hadronisation of dissociation system.
- Can evaluate impact of e.g. rapidity veto (proton tag) with this.



Backup

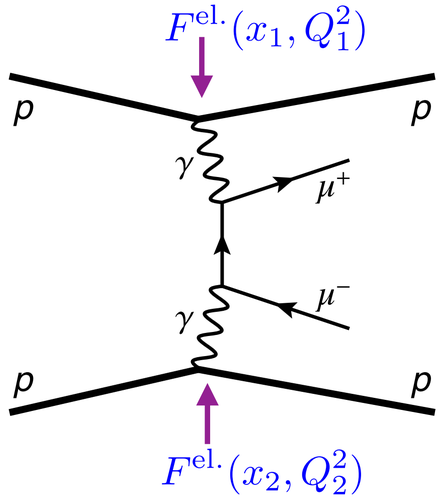
- **But not the end of the story!**



The Survival Factor

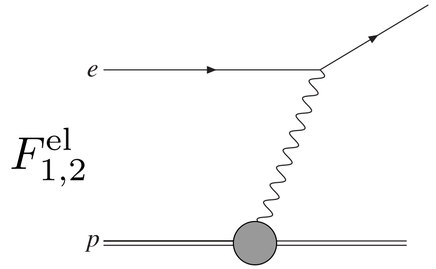
- Consider e.g. the exclusive process. So far we have (very) schematically:

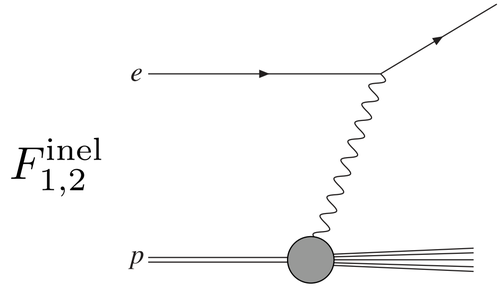
$$\sigma \sim F^{\text{el.}}(x_1, Q_1^2) F^{\text{el.}}(x_2, Q_2^2)$$



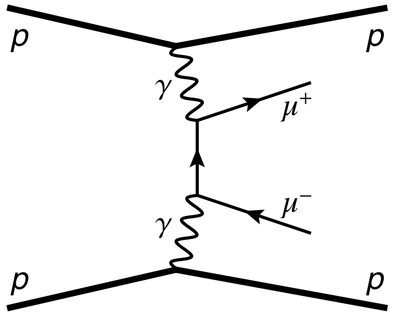
- Similarly for SD + DD, with $F^{\text{el.}} \to F^{\text{inel.}}$

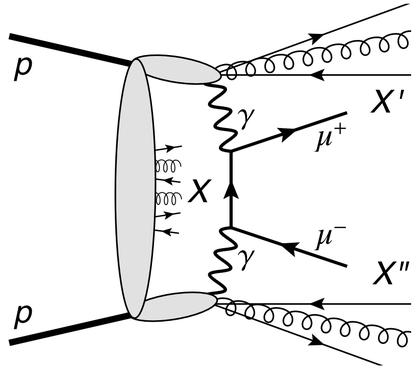
- These inputs are measured in **lepton-hadron** scattering.





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



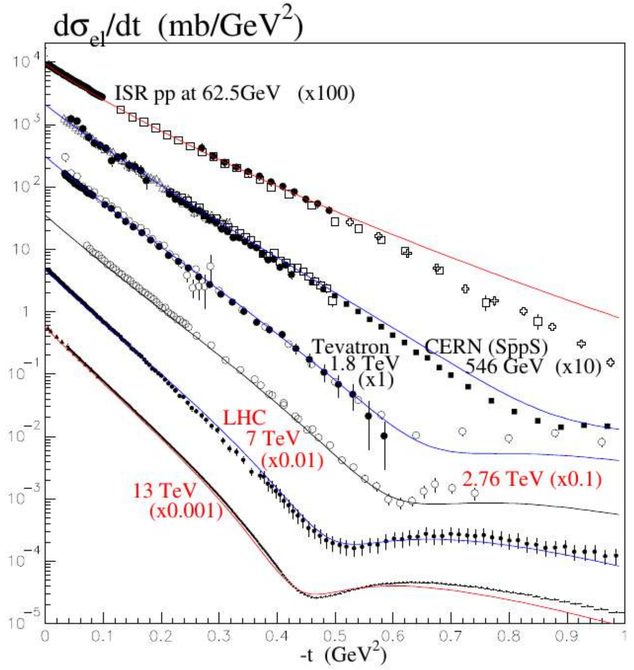


- '**Survival factor**' = probability of no additional inelastic hadron-hadron interactions. Schematically:

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

- How to model this? Depends on e.g. σ^{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).

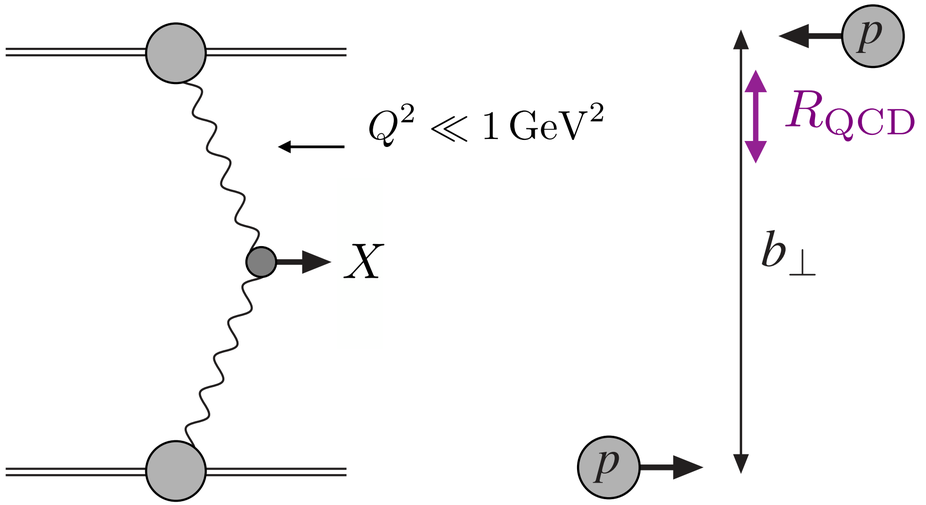
  - In general source of **uncertainty**. Is this the case for photon-initiated production?



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

The Survival Factor in PI processes

- Consider purely elastic case for simplicity.
- 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 $S^2 \sim 1$.



$\longrightarrow$ Relatively **clean** $\gamma\gamma$ initial state, with **QCD playing small role** in elastic case. Why we can say the LHC is 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:

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

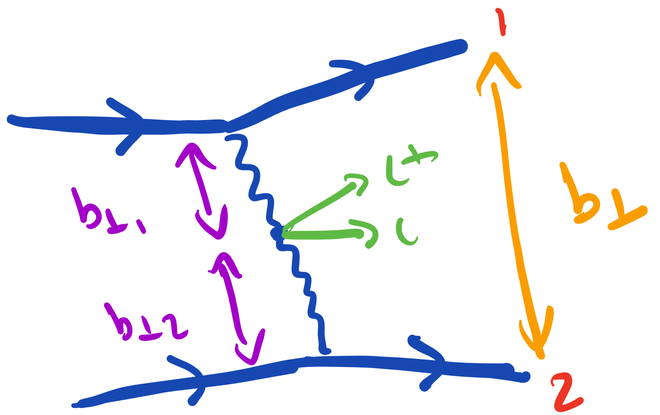
- We can write this as integral over proton impact parameters:

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

- Where:

$$\tilde{M}(\vec{b}_{1\perp}, \vec{b}_{2\perp}..) = FT(M(\vec{\xi}_{1\perp}, \vec{\xi}_{2\perp}..))$$

$$\tilde{M}(\vec{b}_{1\perp}, \vec{b}_{2\perp}..) \sim \int d^2\xi_{1\perp}\, d^2\xi_{2\perp}\, e^{-i\vec{\xi}_{1\perp}\cdot\vec{b}_{1\perp}}\, e^{i\vec{\xi}_{2\perp}\cdot\vec{b}_{2\perp}} \cdot M(\vec{\xi}_{1\perp}, \vec{\xi}_{2\perp}, ...)$$



- To first approximation, we then simply require:

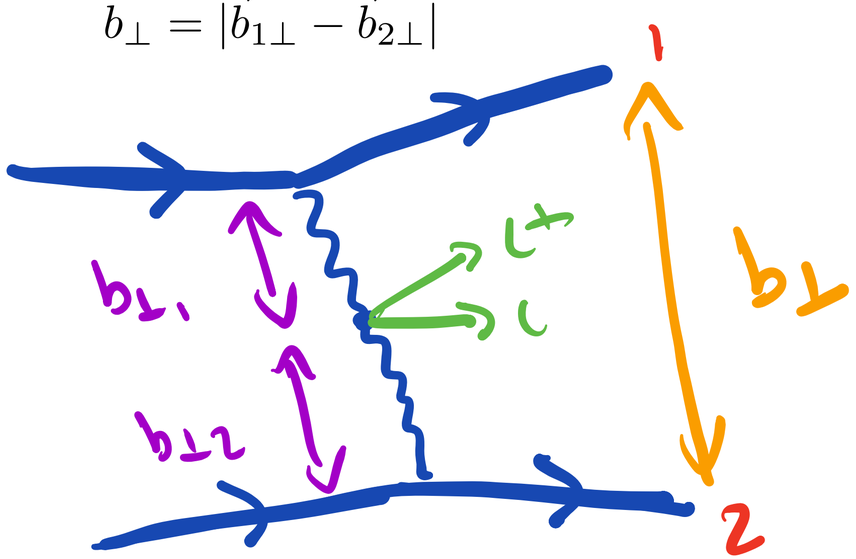
$$\sigma = \int \mathrm{d}^2 b_{1\perp}\, \mathrm{d}^2 b_{2\perp}\, |\tilde{M}(\vec{b}_{1\perp}, \vec{b}_{2\perp}, ...)|^2$$

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

- That is, only integrate over impact region where:

$$b_\perp > 2r_p$$

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



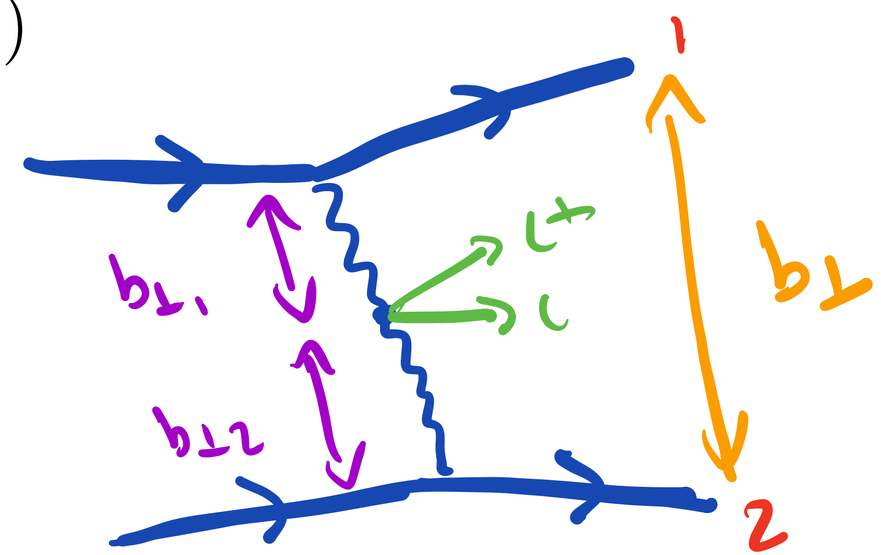
- In more detail, condition is not discrete - some overlap can occur. Schematically:

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

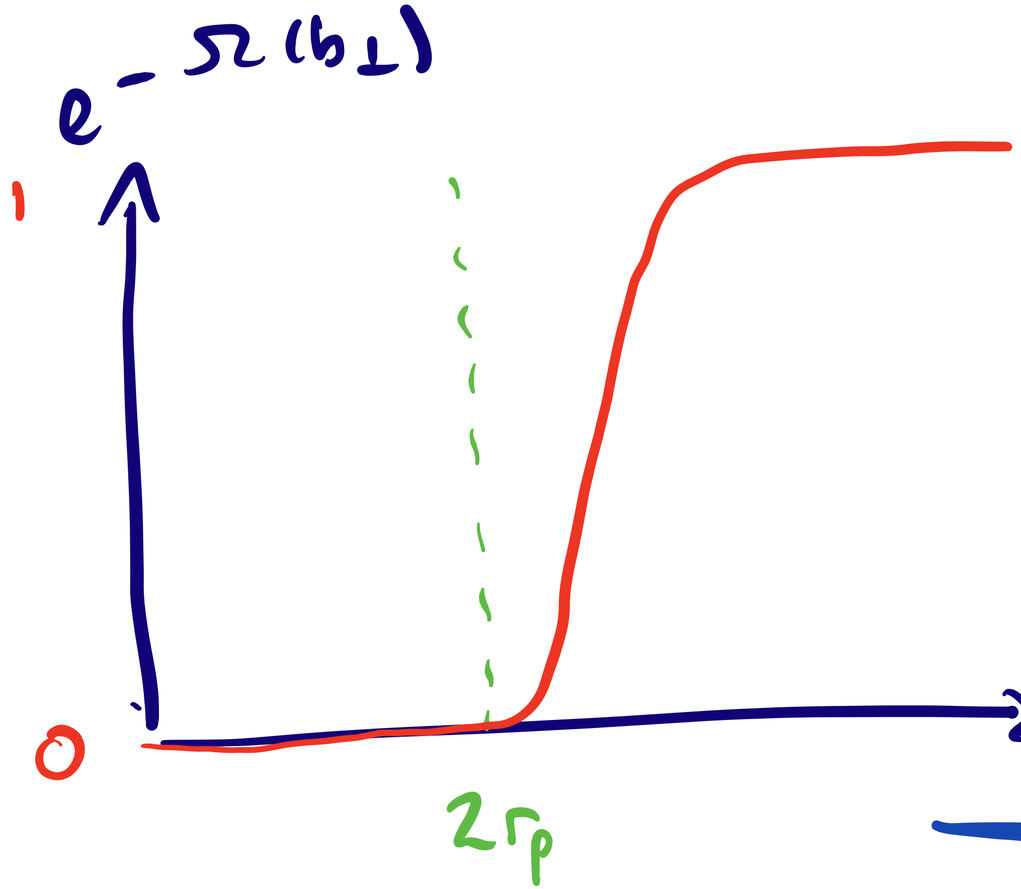
$e^{-\Omega(\vec{b}_{1\perp} - \vec{b}_{2\perp})}$: **survival factor** - probability for no additional particle production at impact parameter $b_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$. Roughly:

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

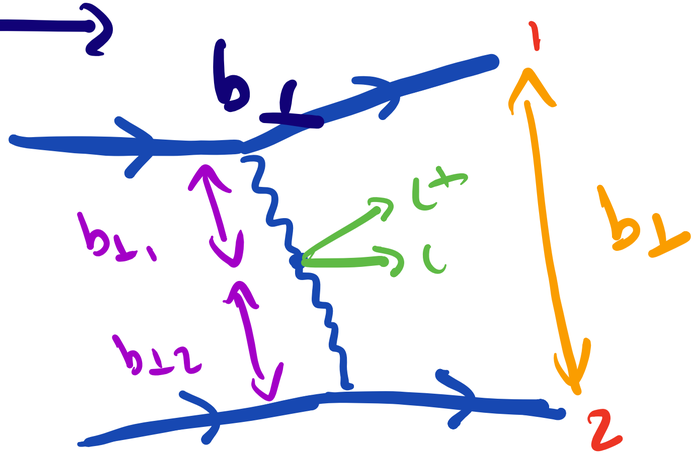
but not exact!



- Result for pp:



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



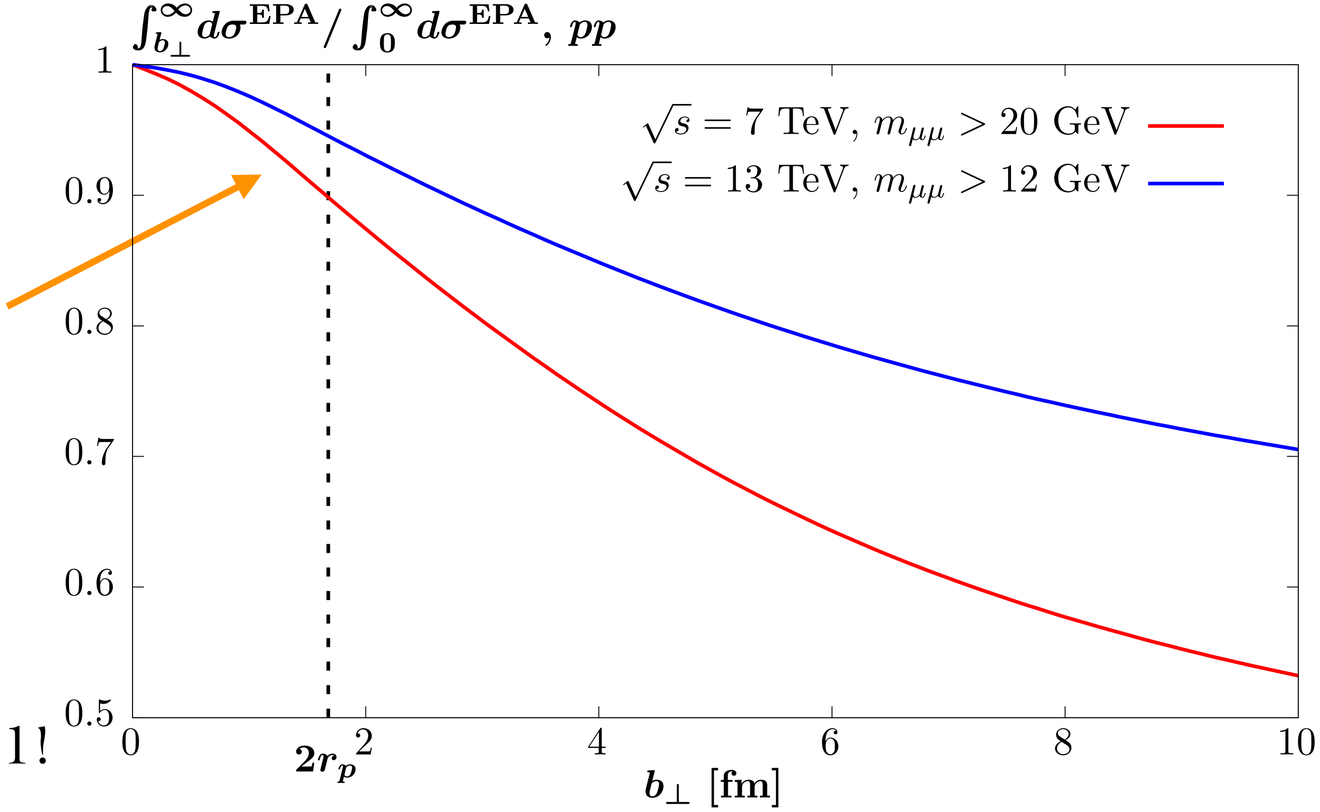
- What does this tell us about survival factor for purely elastic production?

- Have a look at ratio:

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

~ 90% of cross section lies outside

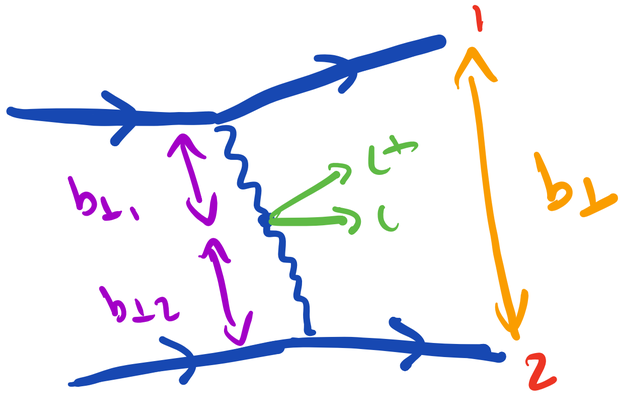
$$b_\perp > 2r_p$$



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

- Depending on precise process/ kinematics have:

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

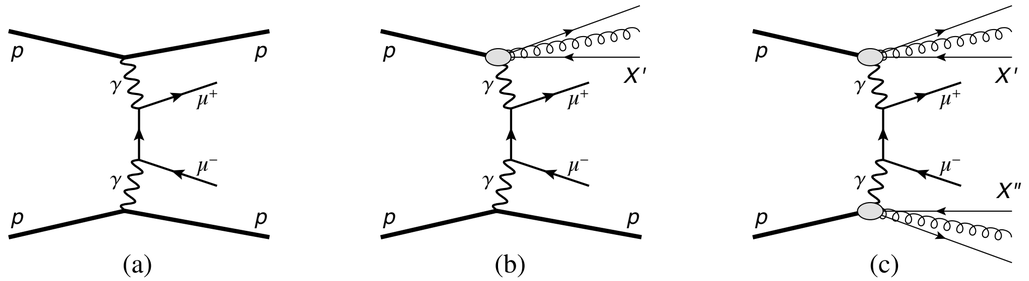


Backup

- True for elastic production. What about dissociation?

- Dissociation $\Rightarrow$ larger photon $Q^2 \Rightarrow$ smaller pp $b_\perp \Rightarrow S^2 \downarrow$

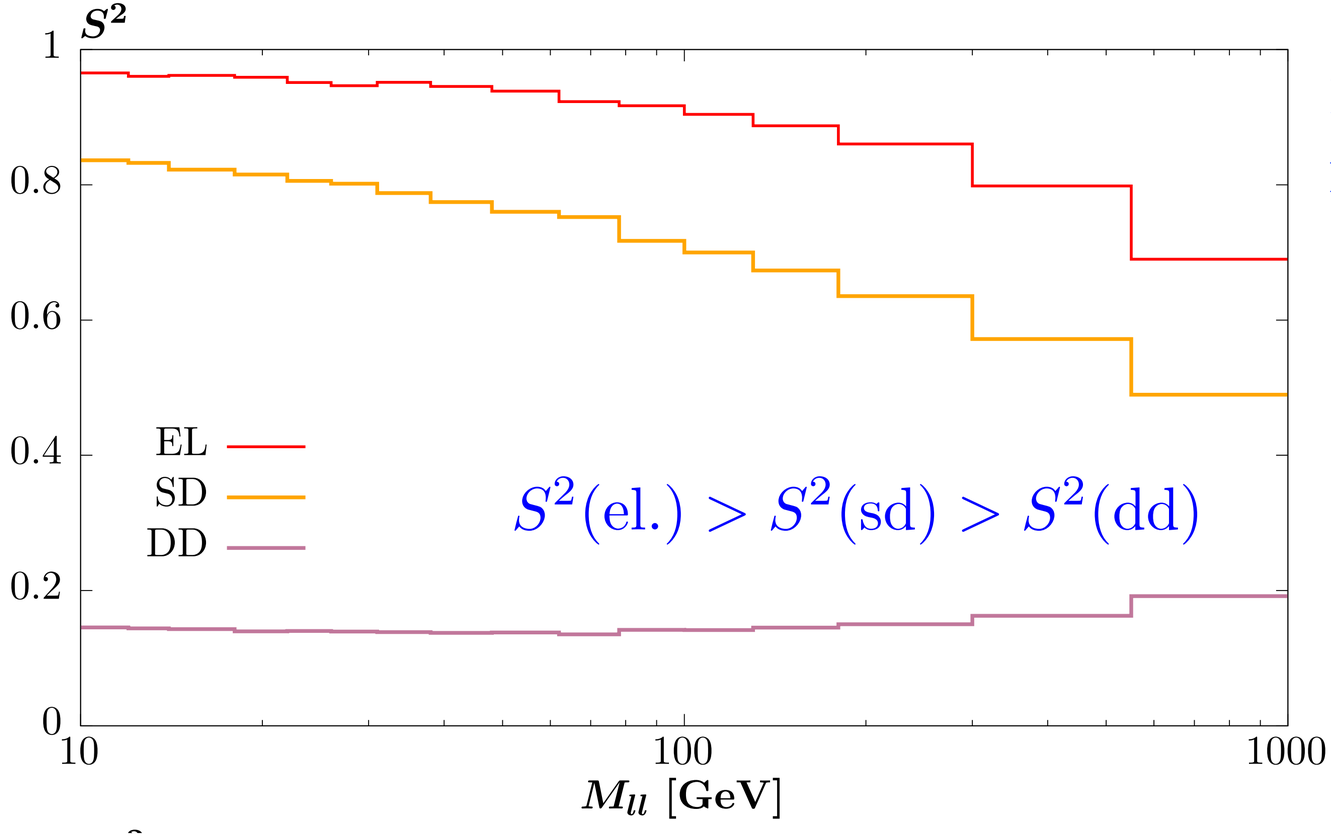
  - For SD production elastic proton side results in ~ peripheral interaction and S^2 still rather high.



  - For DD no longer case and

$$S^2 \sim 0.1$$

  - Also not kinematic dependence - not a flat factor (MC treatment mandatory).



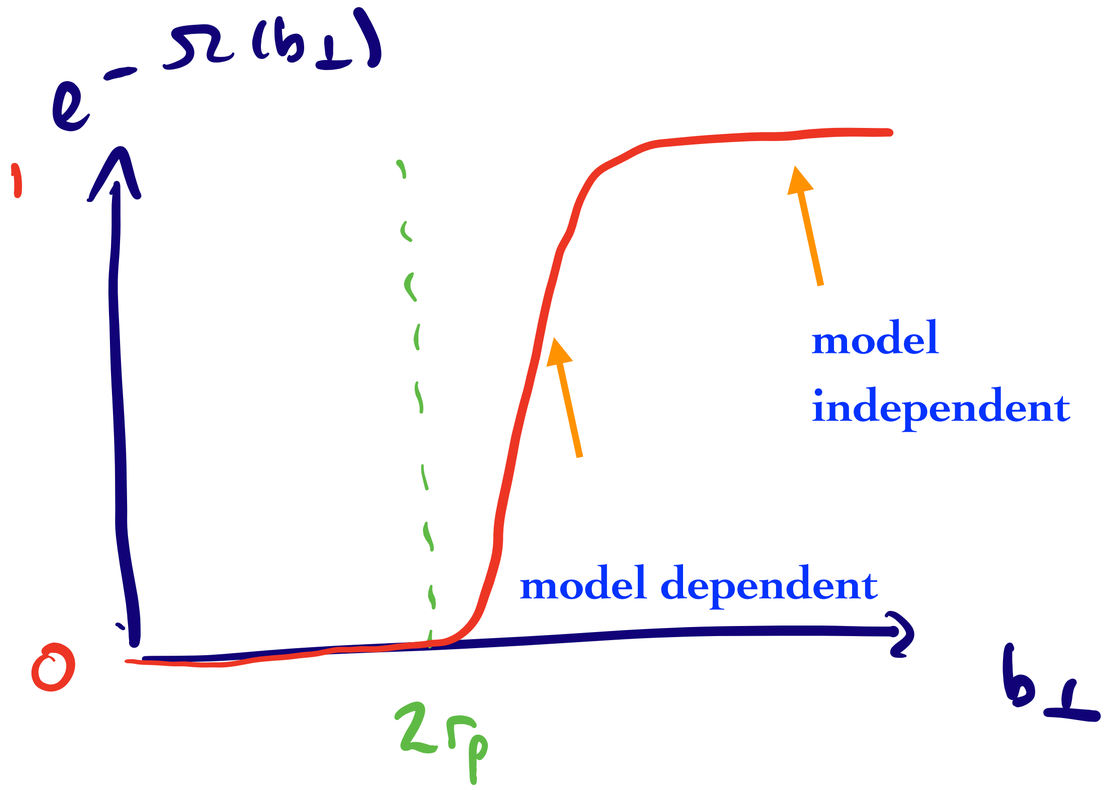
lepton pair production

- What about **uncertainties**?

- Majority of elastic (SD) interaction occurs for

$$b_\perp > 2r_p$$

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



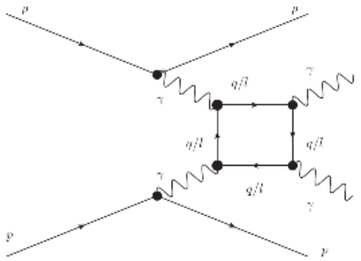
$\longrightarrow$ Uncertainty on S^2 small, at % level.

- This justifies talking about the LHC as a **photon-photon collider**: for purely elastic production at least impact of QCD interactions is very small!

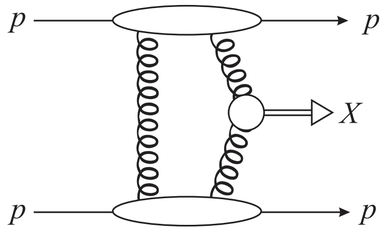
N.b. no longer true for DD production - uncertainty $O(50\%)$ (though S^2 itself much smaller).

SuperChic MC Implementation

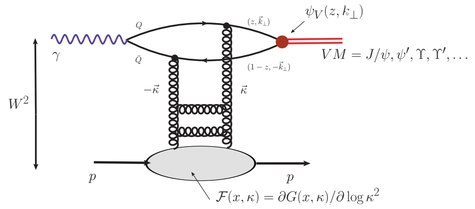
- A MC event generator for CEP processes.
Common platform for:
  - QCD-induced CEP.
  - Photoproduction.
  - Photon-photon induced CEP.



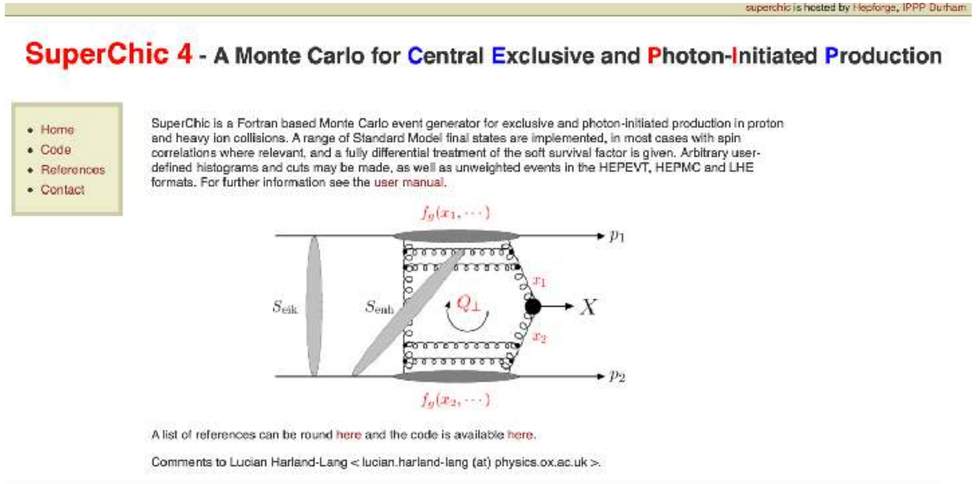
Photon-induced



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

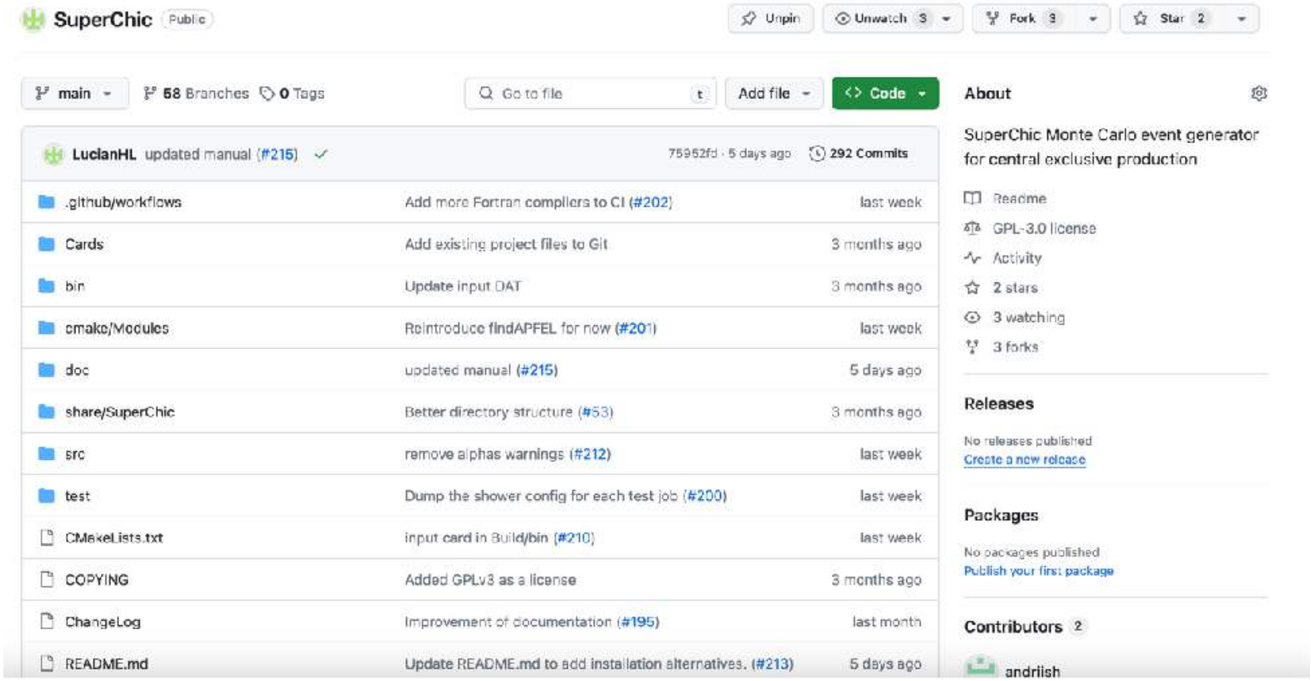
- Version 5 now released. Significant updates to code:

★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!

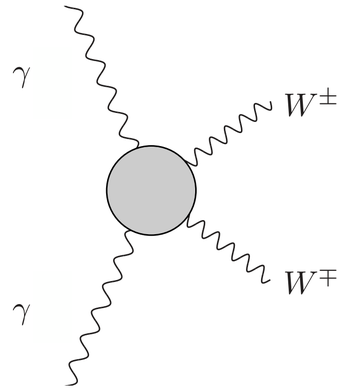


`https://github.com/LucianHL/SuperChic`

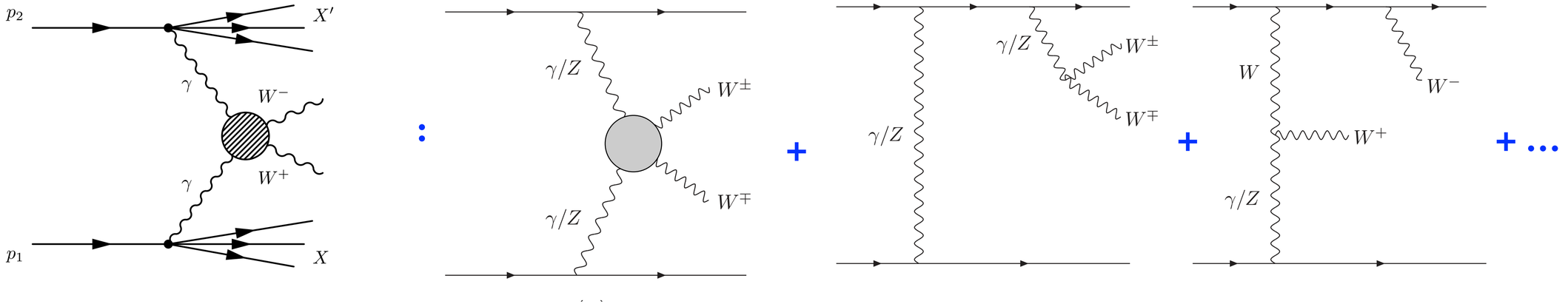
WW production: case study

S. Bailey and LHL, *Phys.Rev.D* 105 (2022) 9, 093010

WW production

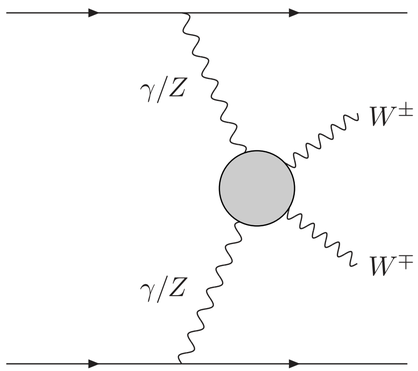


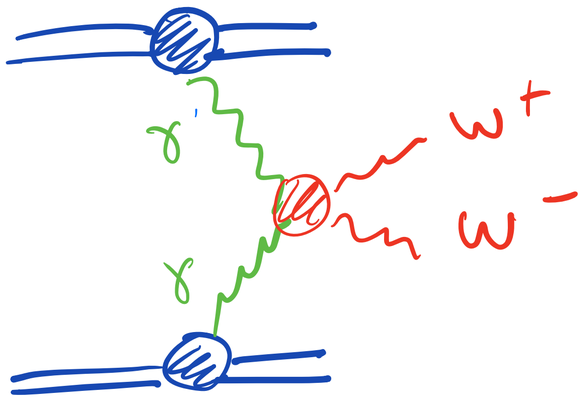
- **Basic idea:** ask for no activity to isolate semi-exclusive $\gamma\gamma \to WW$ signal.
- If both protons tagged we would isolate this alone. But otherwise other diagrams will enter.
- For e.g. double dissociation we have:



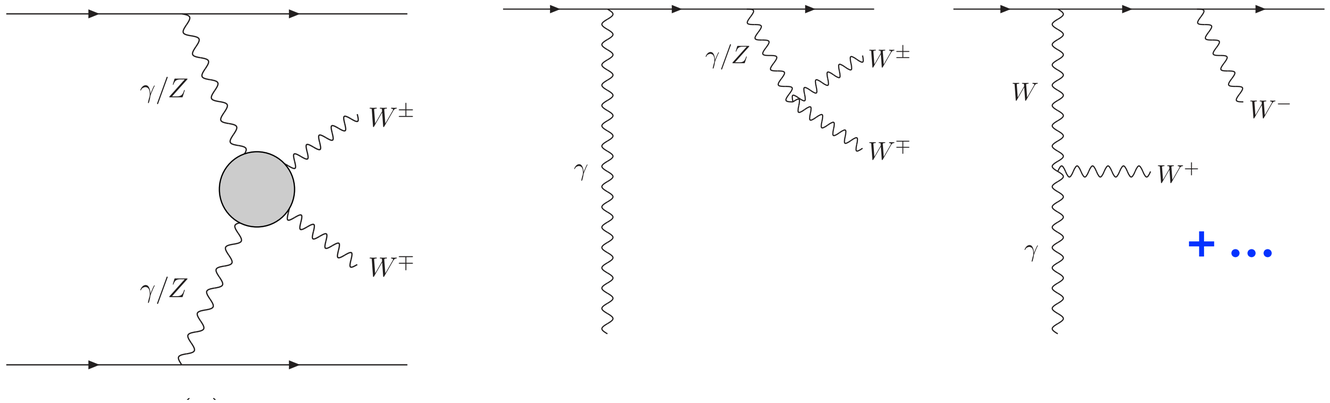
- Needed not just for precision but also gauge invariance!
- To get cross section right, need to include…

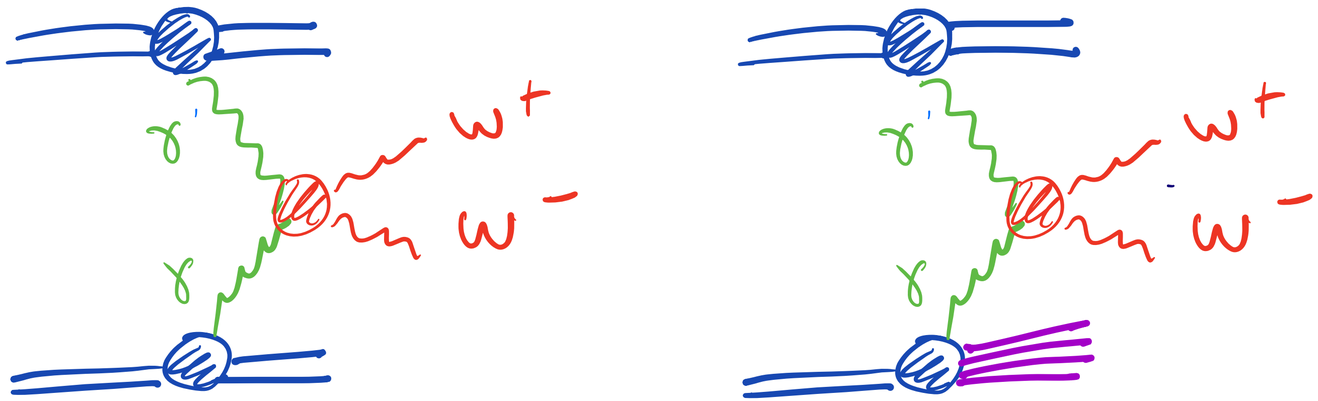
★ All contributing diagrams:



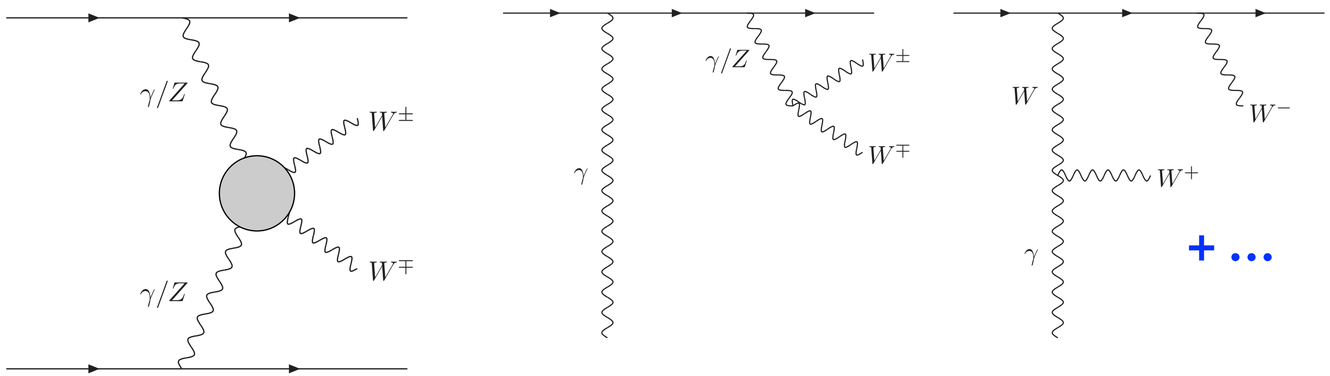


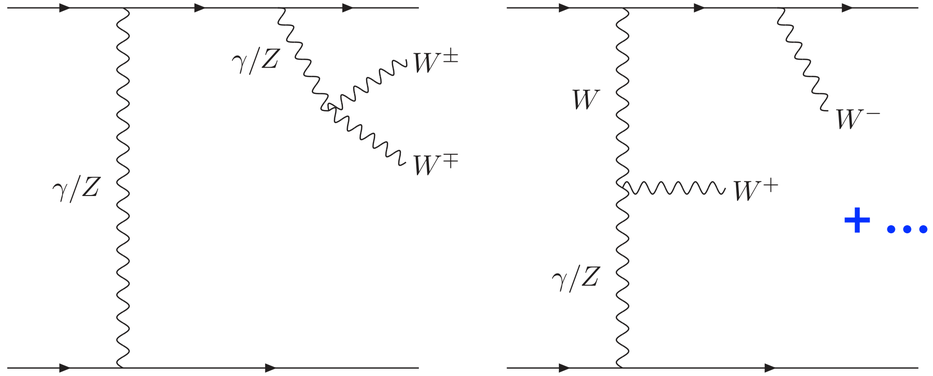
★ All contributing diagrams:

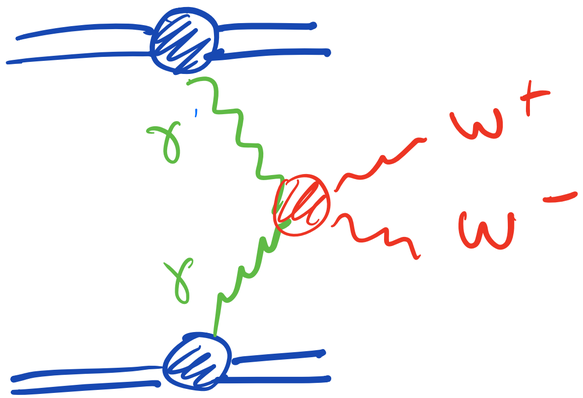


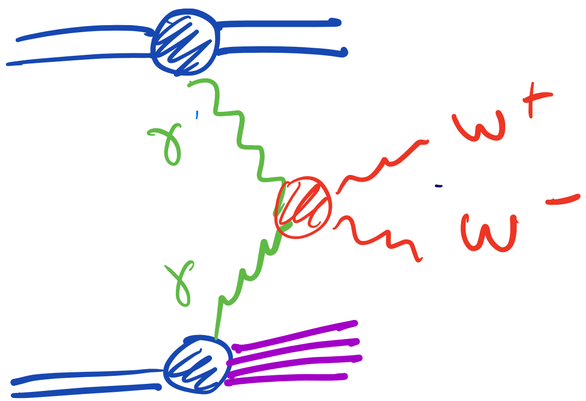


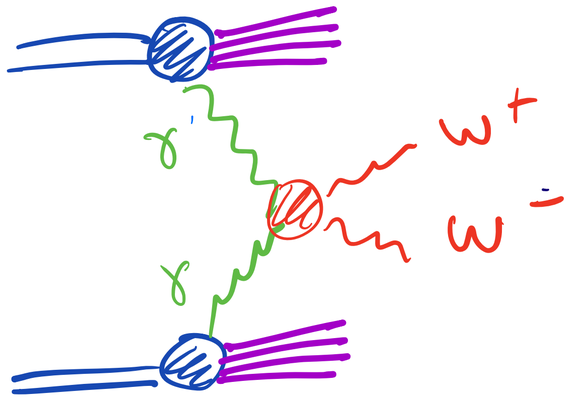
★ All contributing diagrams:



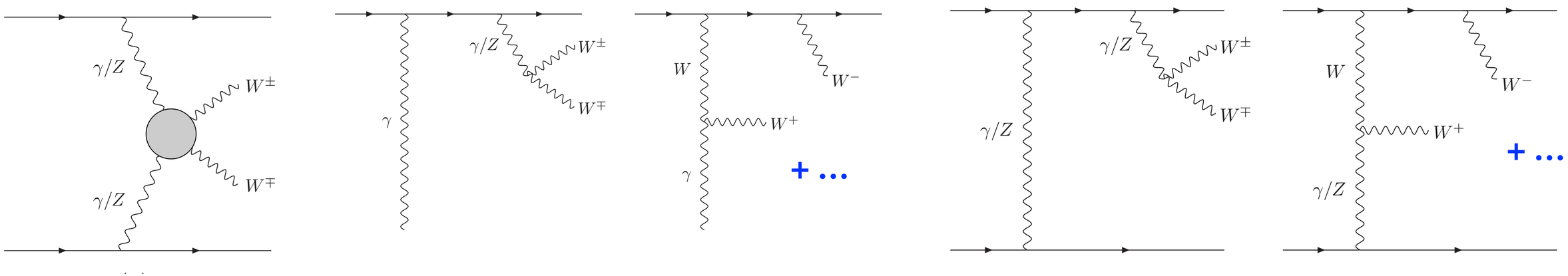






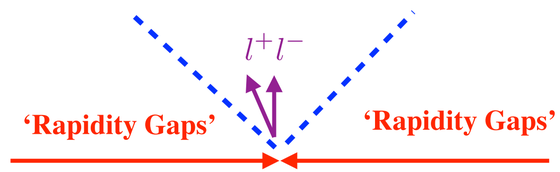


★ **All contributing diagrams:**



★ **Survival factor**, and its non-trivial kinematic dependence. $S^2(\text{el.}) > S^2(\text{sd}) > S^2(\text{dd})$

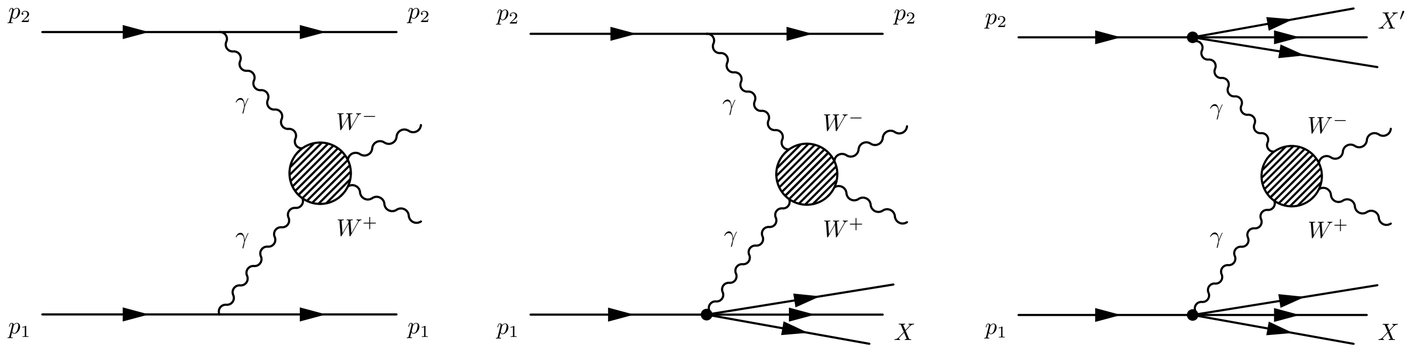
★ And combine this in MC treatment that can then be passed to general purpose MC to account for exclusivity veto.

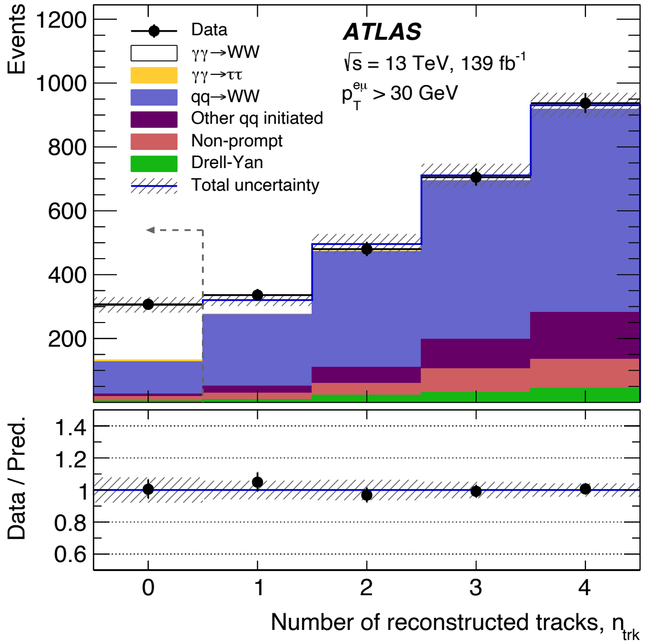


- Can be done, after overcoming various subtleties, gauge dependencies etc…

S. Bailey and LHL,*Phys.Rev.D* 105 (2022) 9, 093010

- First observation of semi-exclusive WW production by **ATLAS**, at 13 TeV, via rapidity veto.





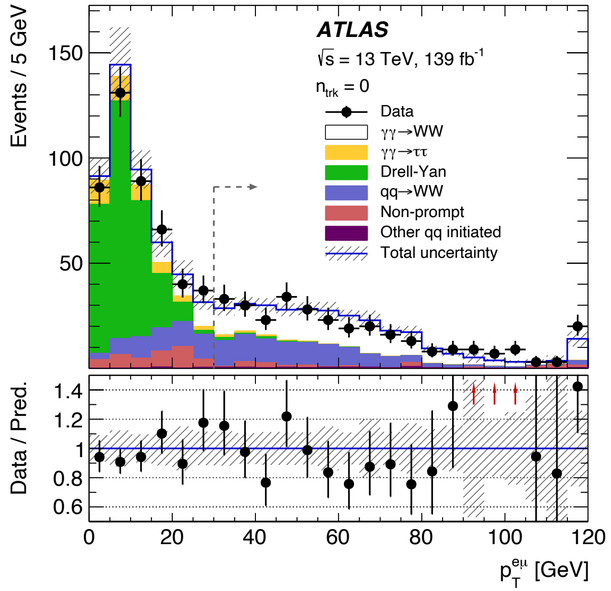
ATLAS, Phys. Lett. B 816, 136190 (2021)

- All channels enter, and full treatment as above needed to match data!

- Find:

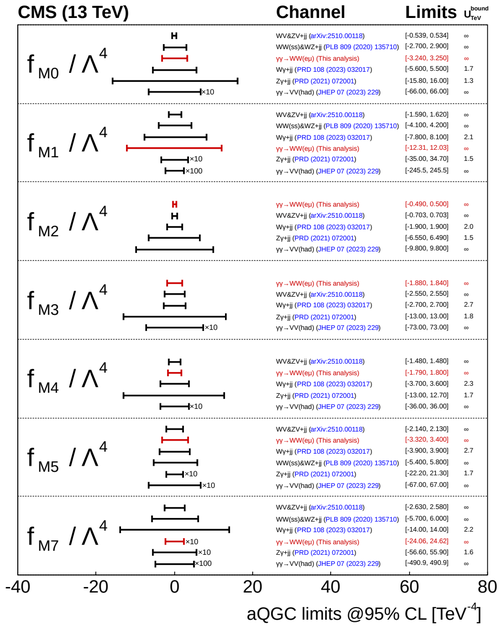
σ [fb] $(\sigma_i/\sigma_{\text{tot}})$, W^+W^-	EL	SD	DD	Total
No veto, no S^2	0.701 (3.5%)	6.00 (30.3%)	13.1 (66.2%)	19.8
Veto, no S^2	0.701 (9.2%)	3.21 (42.3%)	3.68 (48.5%)	7.59
Veto, S^2	0.565 (18.6%)	1.87 (61.6%)	0.599 (19.8%)	3.03

- To compare with data: $\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\,\text{fb}$ $\Rightarrow$ **Very good agreement**!
- Assuming relative SD + DD to EL components are as in e.g. dilepton production would miss contribution from non-PI diagrams - undershoot data by ~ 20%.
- Looking to the future. Go beyond one number and look at distributions - EFT analyses…

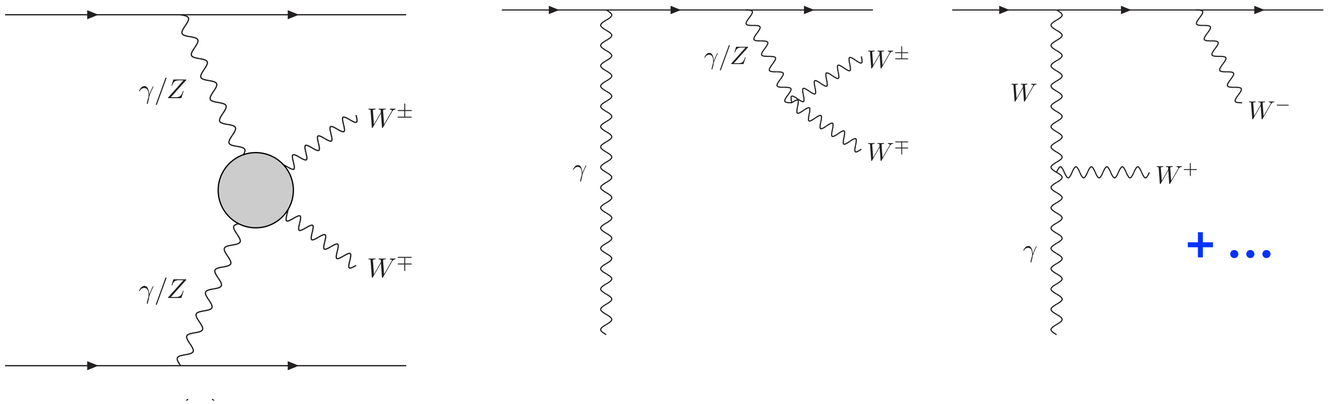


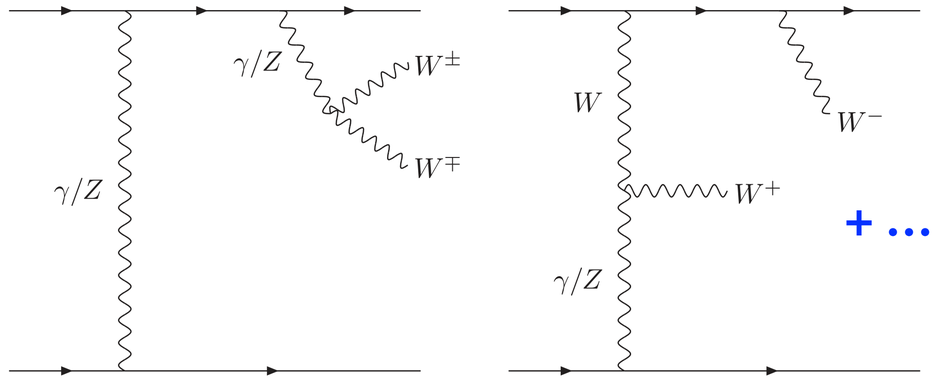
EFT analysis?

- For pure SM cross section have to include all contributing diagrams, not just photon-initiated.
- This is equally true for EFT analyses (currently assume pure photon-initiated).
- Dedicated study required here, including survival factor etc…



CMS, arXiv: 2601.21574



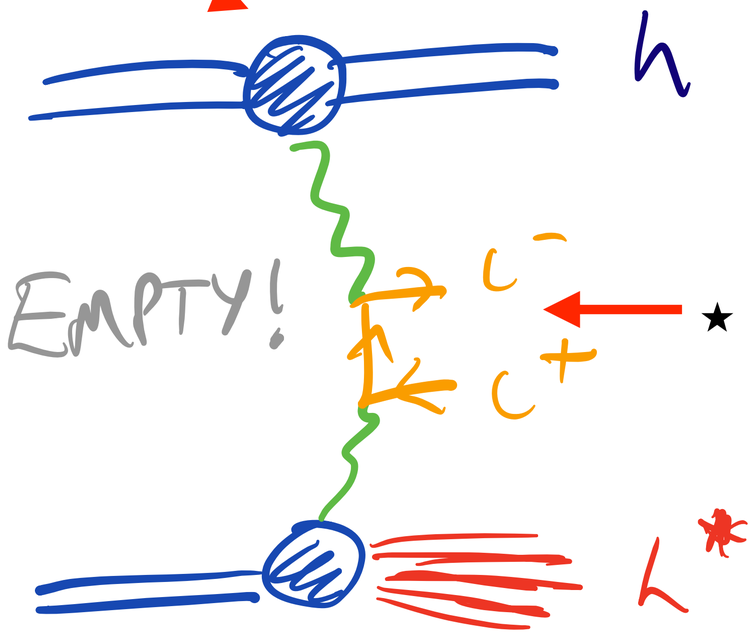


Heavy Ion Collisions

PI production: building blocks

- PI production also key channel in heavy ion collisions.
- Theoretical framework broadly similar to pp case:

★ $h \to \gamma h(h^*)$ form factor.

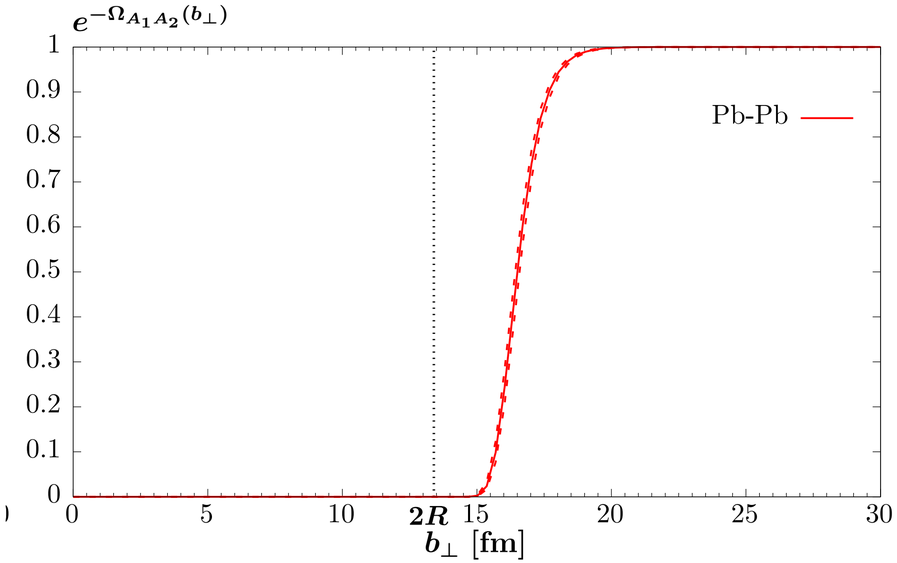


★ $\gamma\gamma \to X$ cross section.

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

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

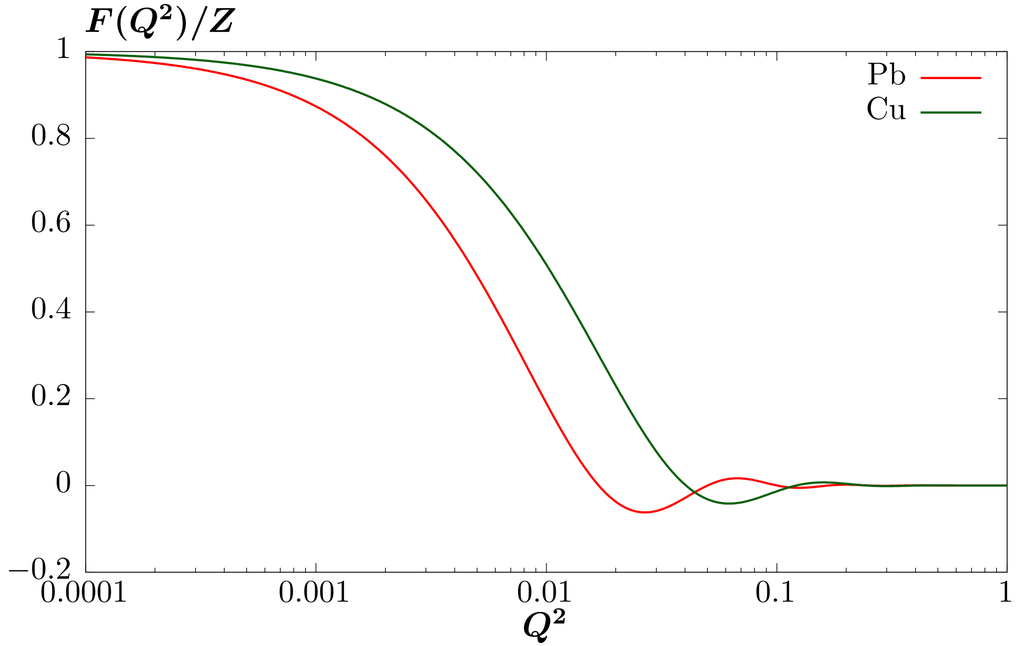
$\Rightarrow S^2 \sim 1$, with small uncertainty



★ Input for elastic form factors very well determined.

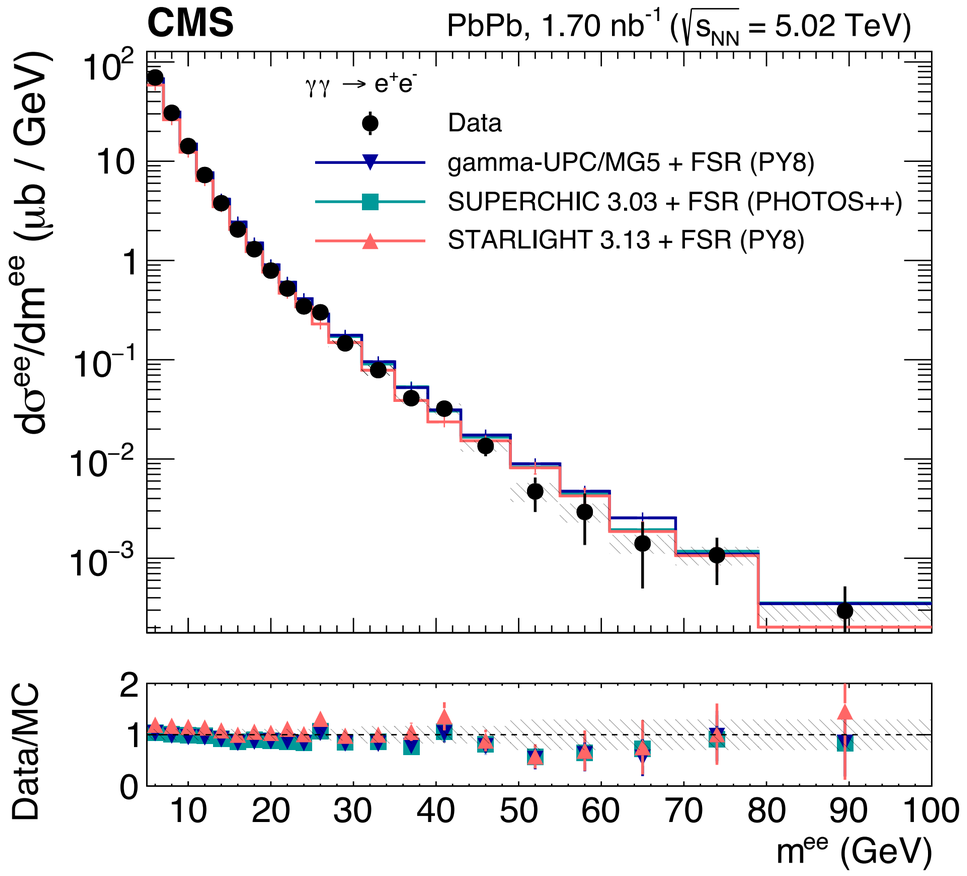
$$\rho_p(r) = \frac{\rho_0}{1 + \exp\,(r - R)/d} \,,$$

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

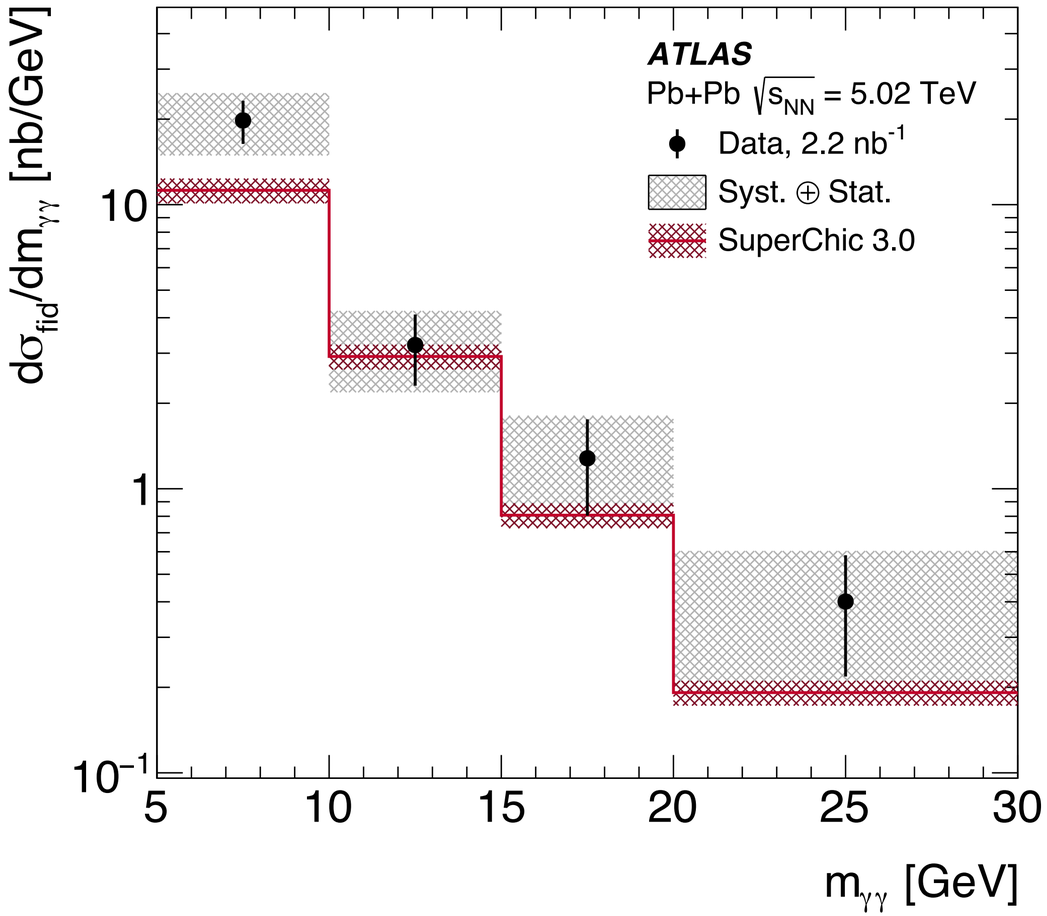


→ Theory **well understood** - supported by generally good data/theory agreement.

CMS, *JHEP* 08 (2025) 006

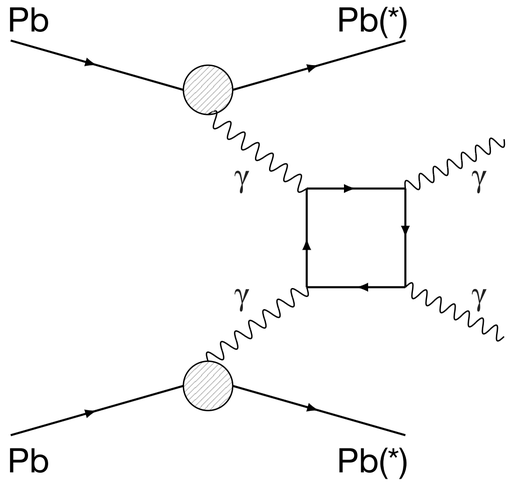


ATLAS, *JHEP* 03 (2021) 243

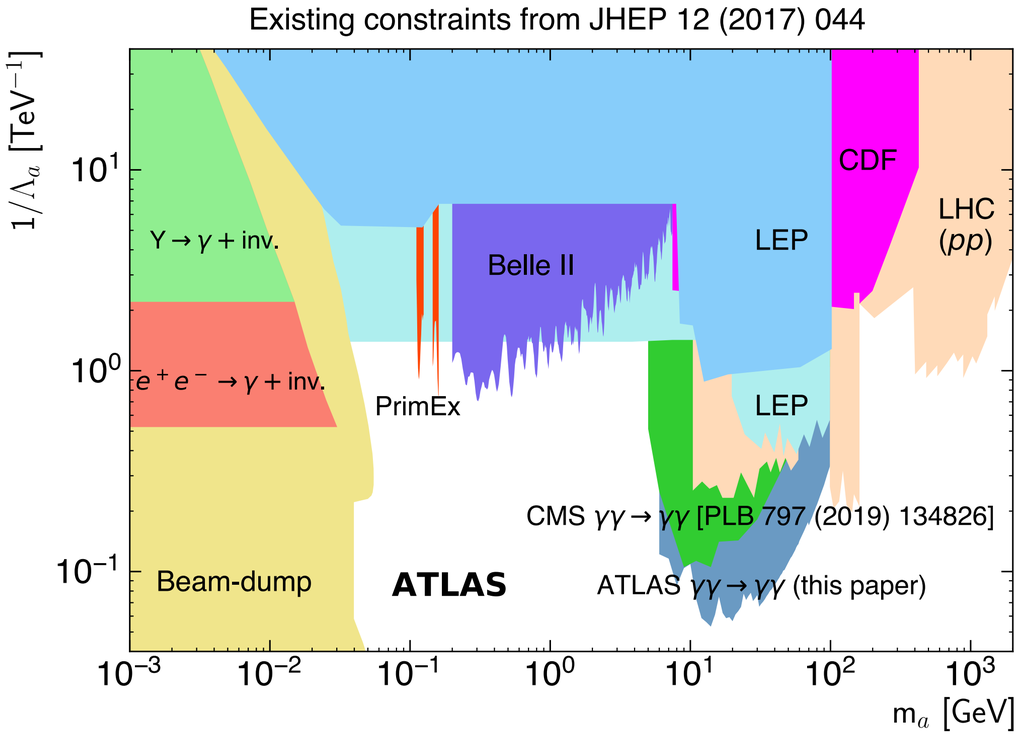


- But here will focus on two open challenges, and (some!) resolutions.

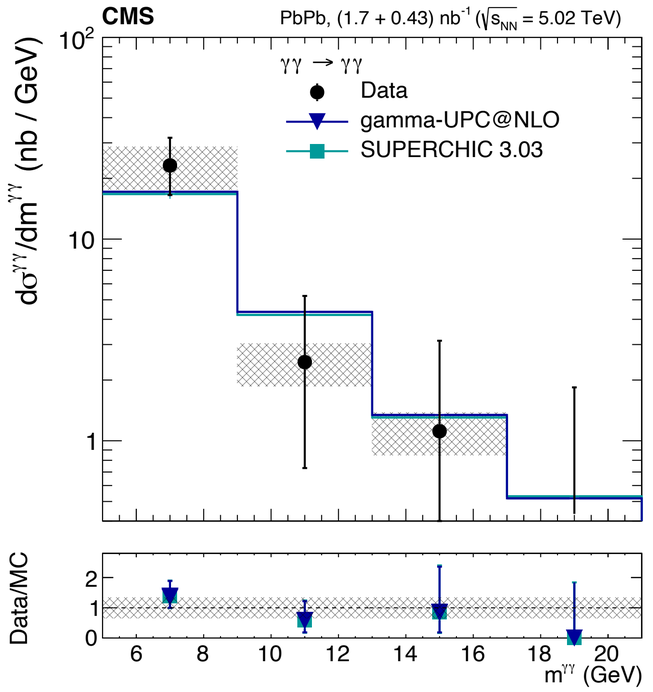
Recent Studies (1)



- **Light-by-light scattering**: flagship UPC measurement. Loop suppressed process with sensitivity to e.g. ALPs.



ATLAS, *JHEP* 03 (2021) 243

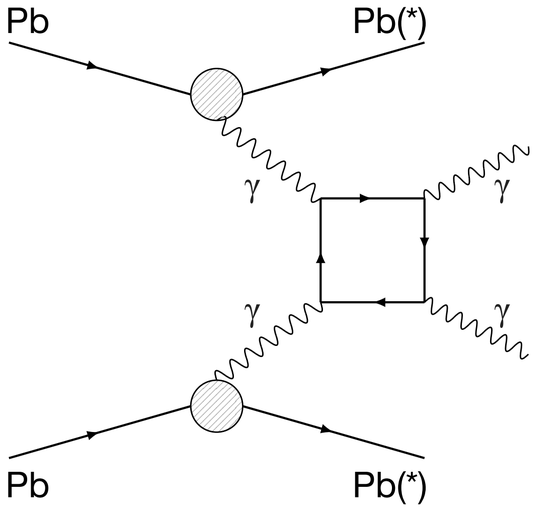


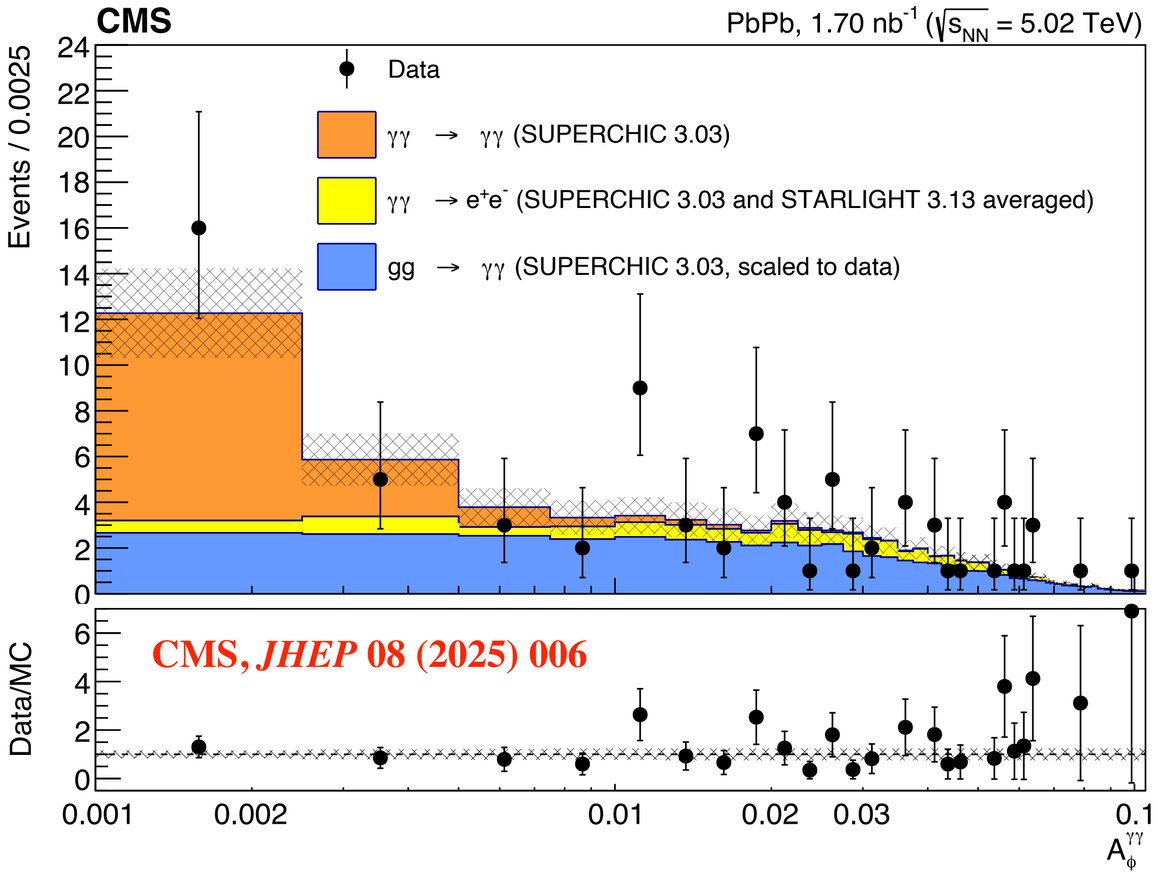
CMS, *JHEP* 08 (2025) 006

- Encouraging agreement with theory, but devil is in the detail…

$$A_\phi = (1 - |\Delta\phi_{\gamma\gamma}|/\pi)$$

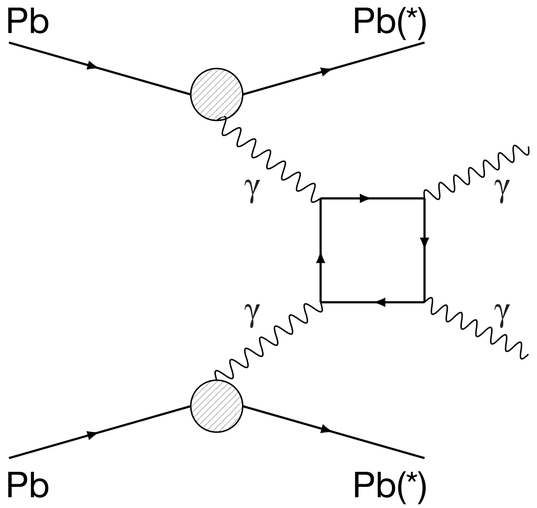
- Key observable is '**acoplanarity**' - measure of how back-to back photons are.
- For exclusive UPC production these should very back to back…

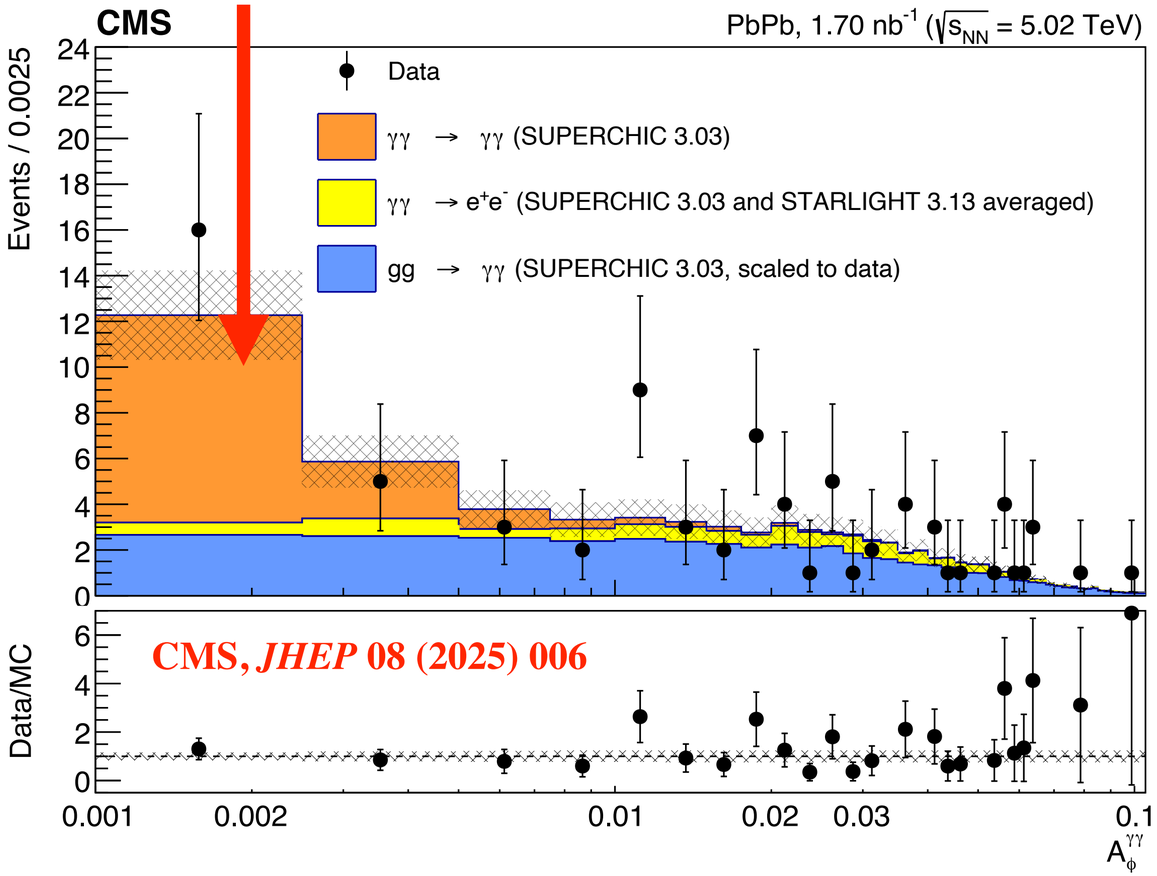




$$A_\phi = (1 - |\Delta\phi_{\gamma\gamma}|/\pi)$$

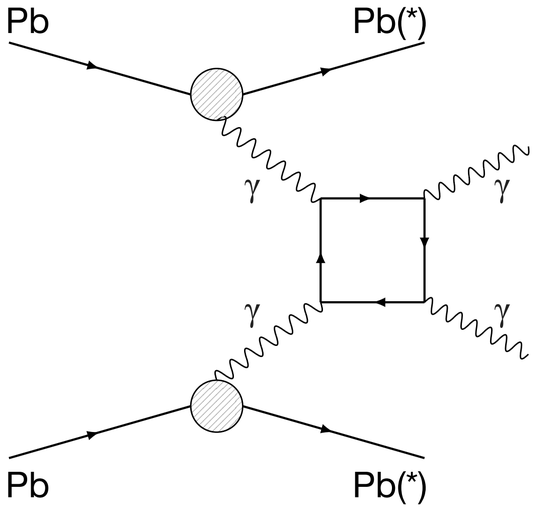
- Key observable is '**acoplanarity**' - measure of how back-to back photons are.
- For exclusive UPC production these should very back to back… and this is seen!

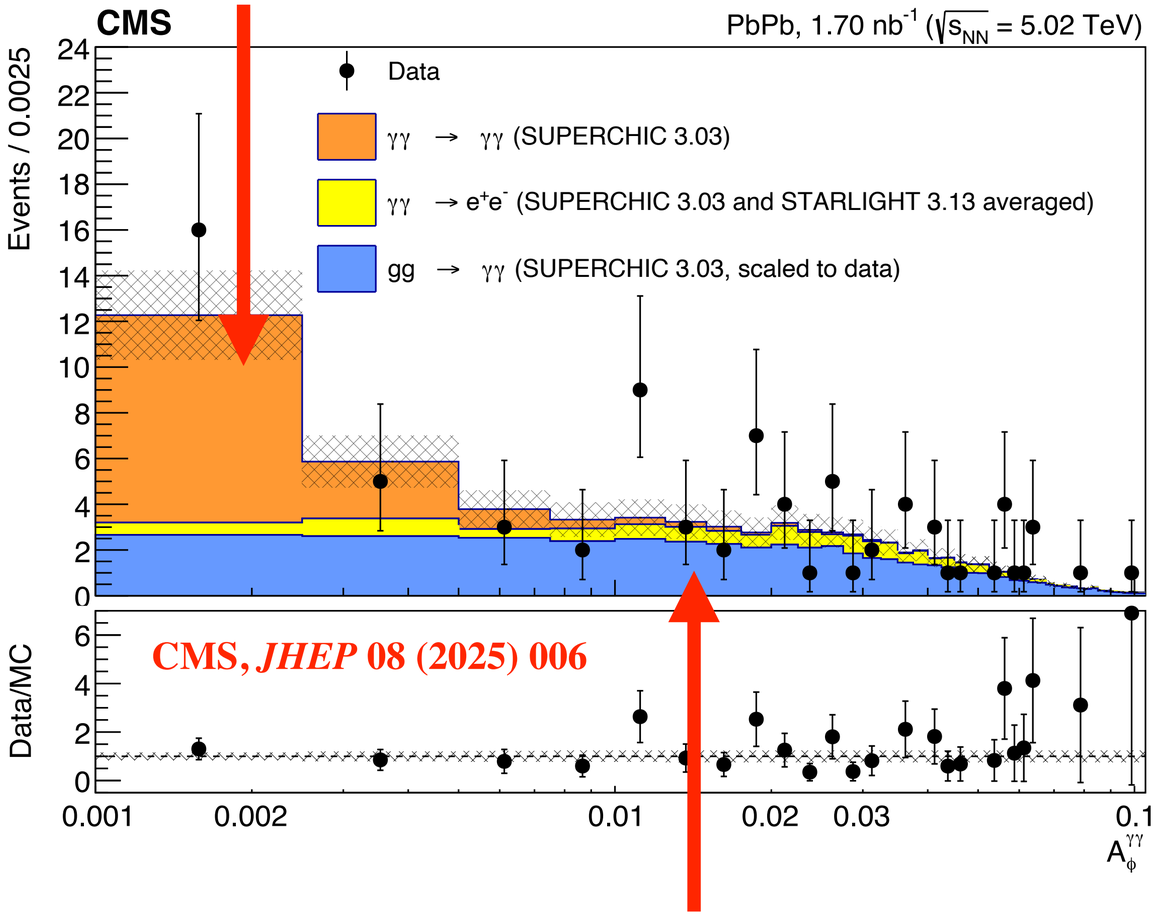




$$A_\phi = (1 - |\Delta\phi_{\gamma\gamma}|/\pi)$$

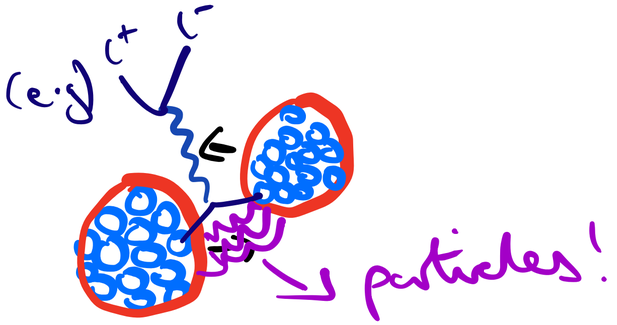
- Key observable is '**acoplanarity**' - measure of how back-to back photons are.
- For exclusive UPC production these should very back to back… and this is seen!

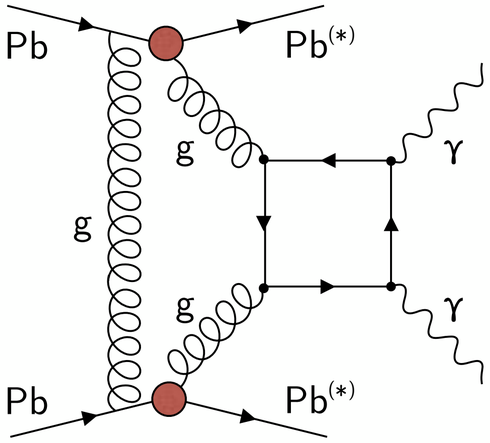


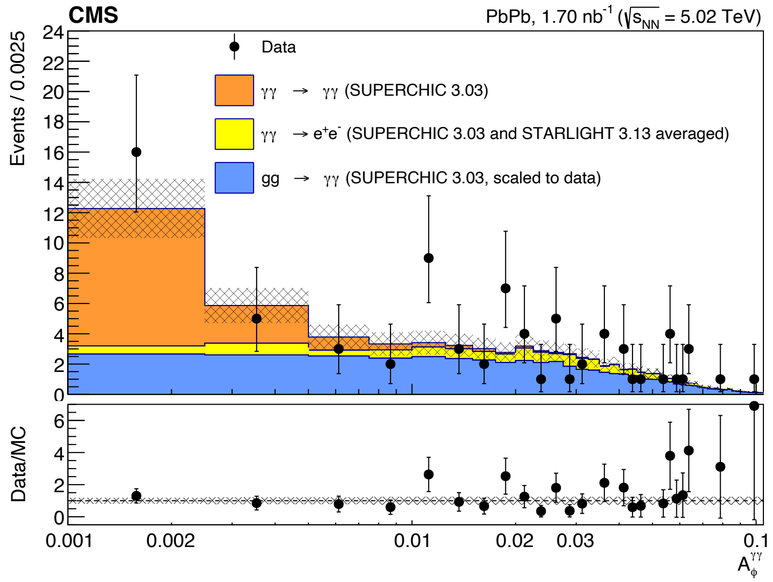


- But a sizeable tail at larger acoplanarities is also seen that cannot be explained…

- Currently assumed to be due to QCD production, but observed S/B ~ 50% much larger than theory predicts.
- Key point: QCD is short ranged so exclusive production strongly suppressed.

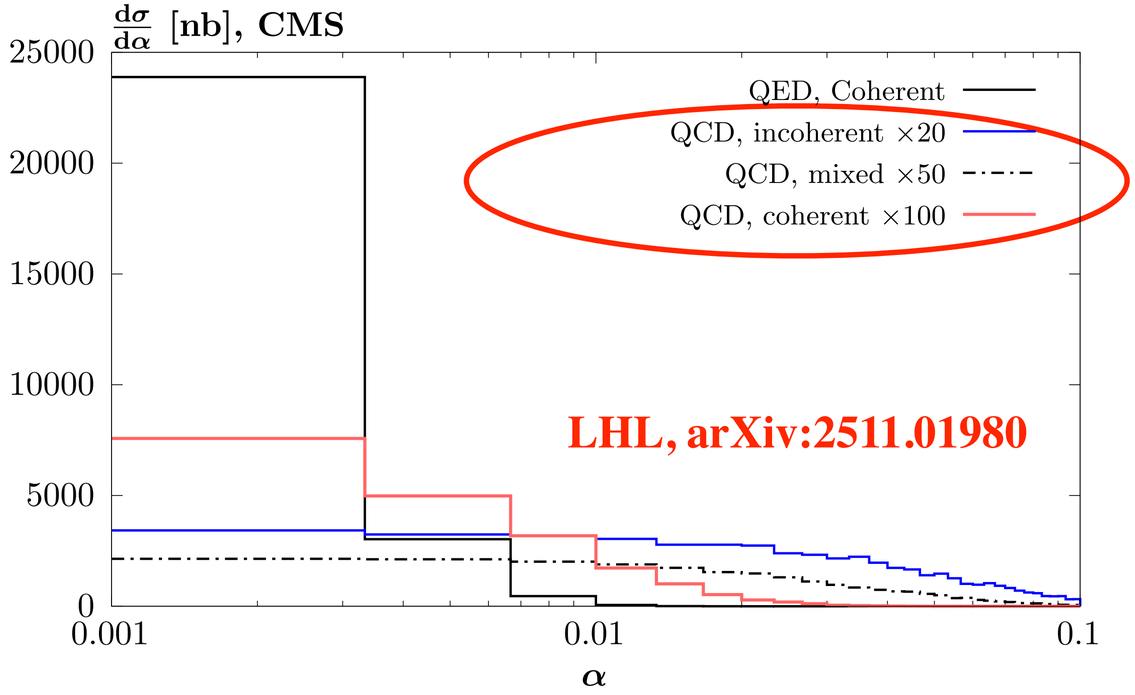






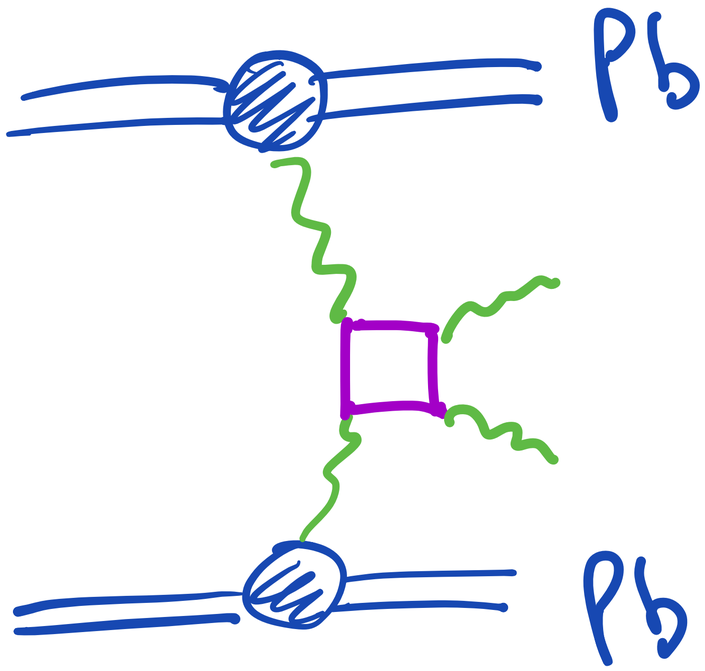
- At the moment QCD-initiated predictions are floated to match size of BG data, but this requires significant normalization increase.

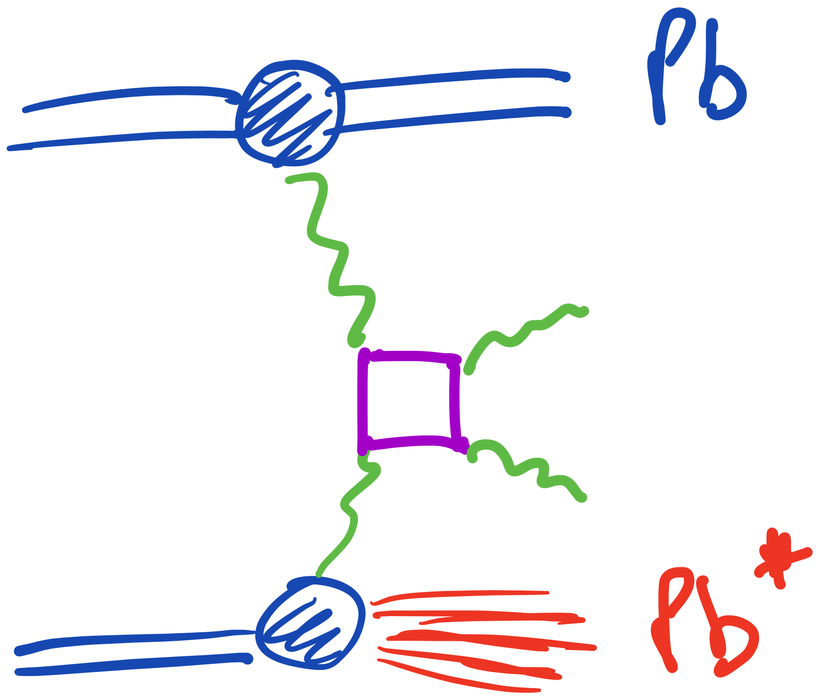
- What is going on?



- Above LbyL results only consider exclusive production in ion-ion UPCs.
- But what about semi-exclusive production?

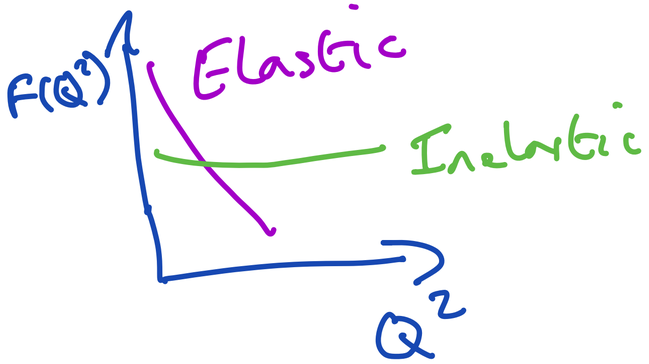
Exclusive





Semi-exclusive

- Key point: inelastic vertex has higher photon $Q^2 \Rightarrow$ less back-to-back diphotons.



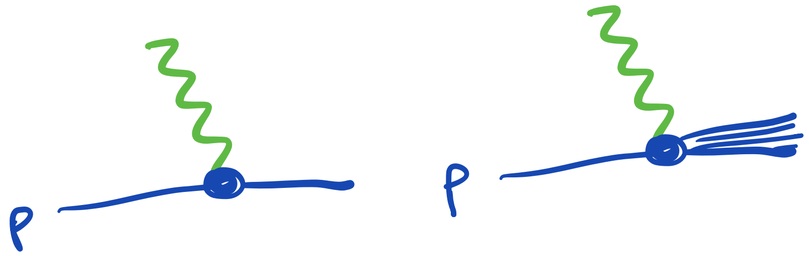
New Study (in very brief)

- **Basic idea:** semi-exclusive ('incoherent') production due to photon emission from individual nucleons in ion:

$$f^{inel}_{\gamma/Pb}(x,\mu^2) = Z \times f_{\gamma/p}(x,\mu^2) + (A-Z) \times f_{\gamma/n}(x,\mu^2)\ .$$

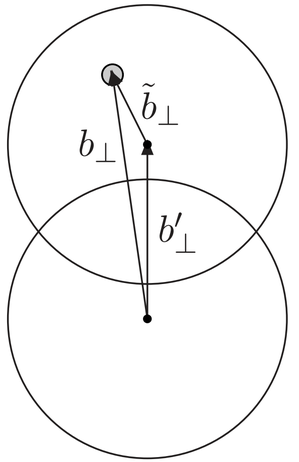
- Both elastic and inelastic emission from nucleons present:

$$f_{\gamma/n}(x,\mu^2) = f^{el}_{\gamma/n}(x) + f^{inel}_{\gamma/n}(x,\mu^2)\ ,$$



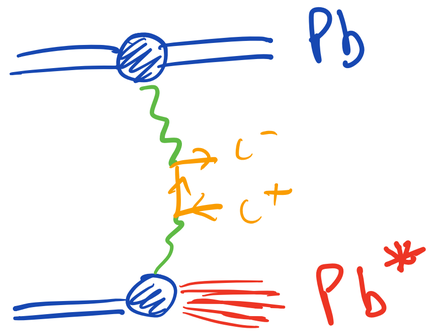
- Using these basic building blocks use established theory input for pp collisions and suitably generalise.

- Note above results suggest a ~ **1/Z (% level)** suppression w.r.t exclusive (not good for LbyL BG) but needs to be confirmed…



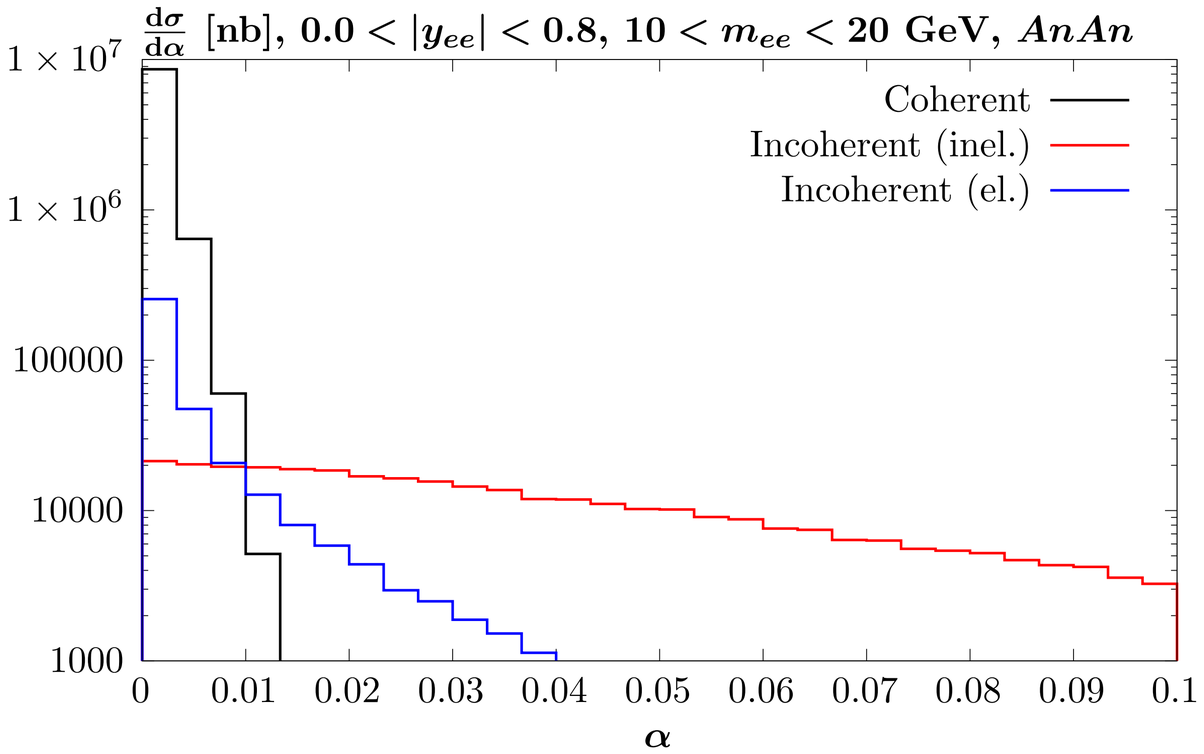
LHL, arXiv:2511.01980

Comparison to data

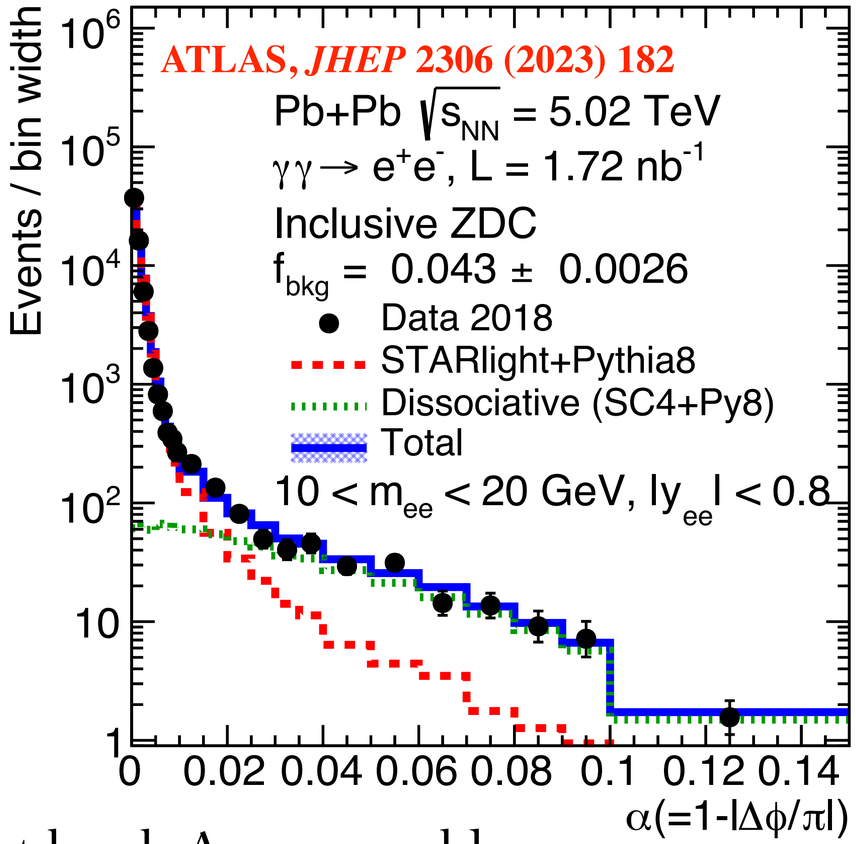


- Put these ingredients together in full SuperChic implementation.

Compare to ATLAS data on **dielectron** production:



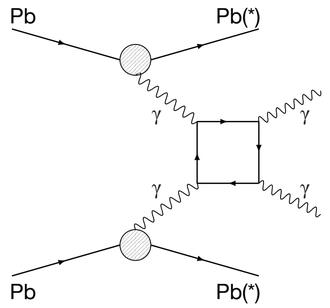
vs.



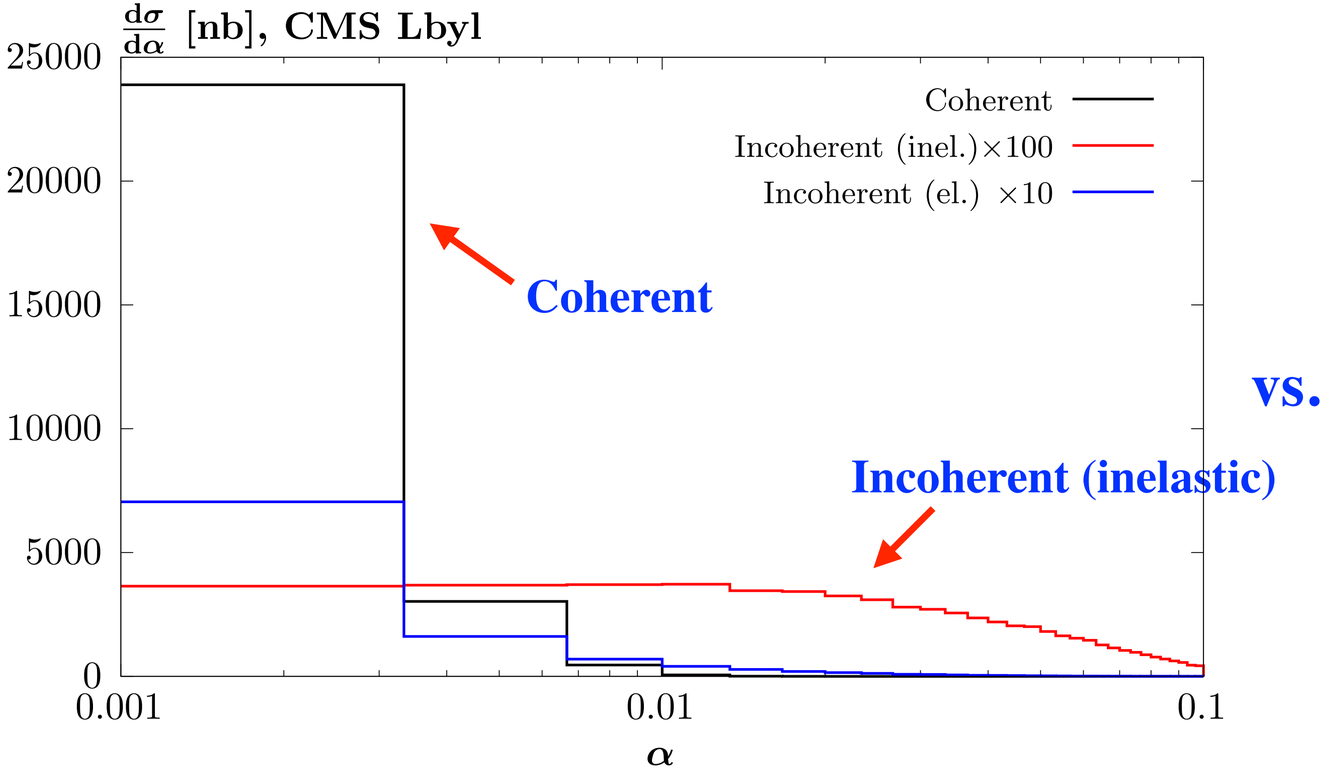
- **Looks ~ good**! Note size of inelastic contribution is percent level. As we would expect from ~ 1/Z suppression. Precise data/theory comparisons match well.

Backup

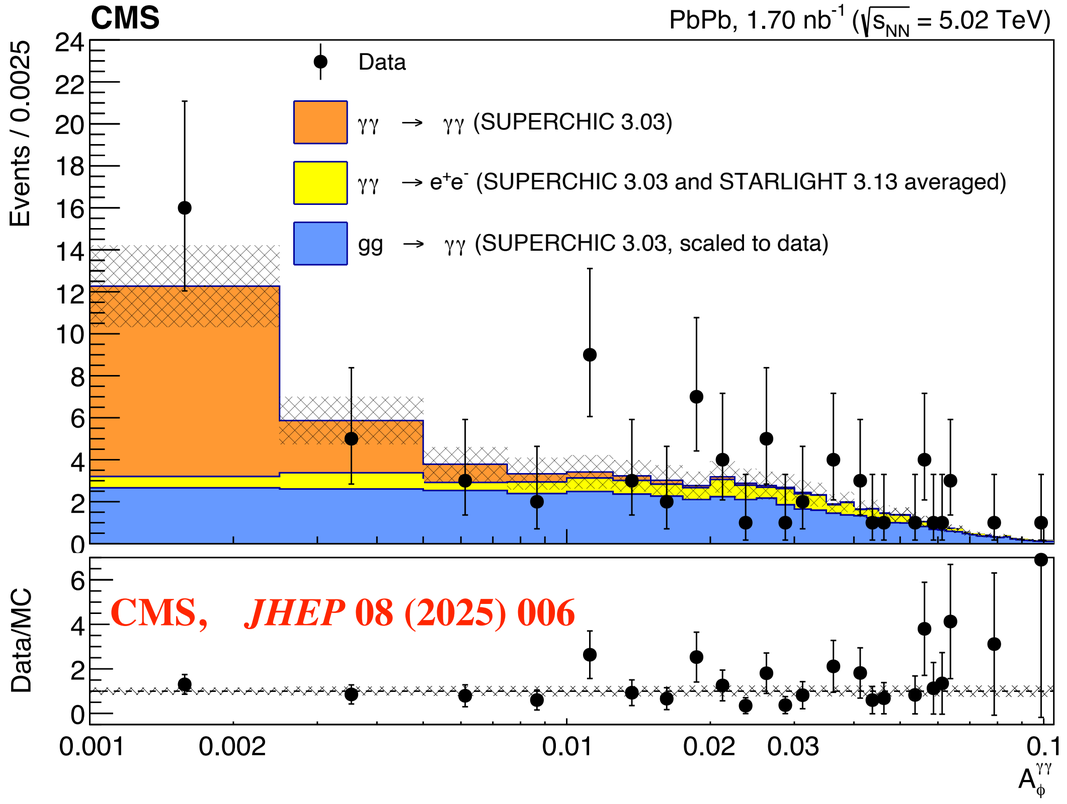
Light by Light Scattering



- Using same approach can predict incoherent component of LbyL, in particular acoplanarity distribution.

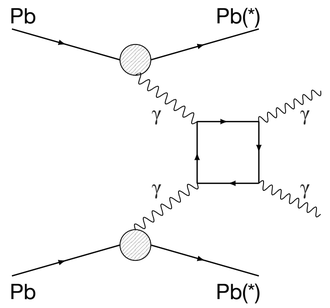


vs.

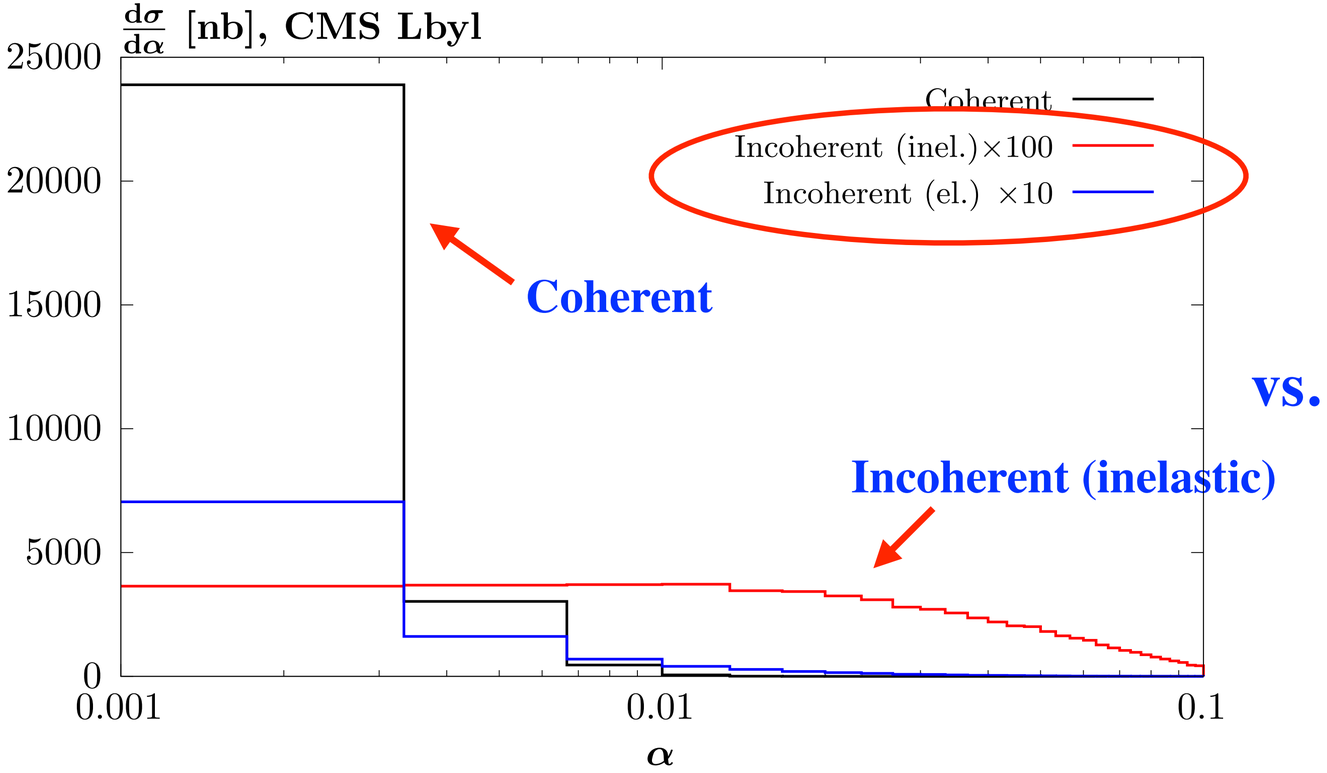


- Incoherent (inelastic) has broader tail, with **shape** matching data…

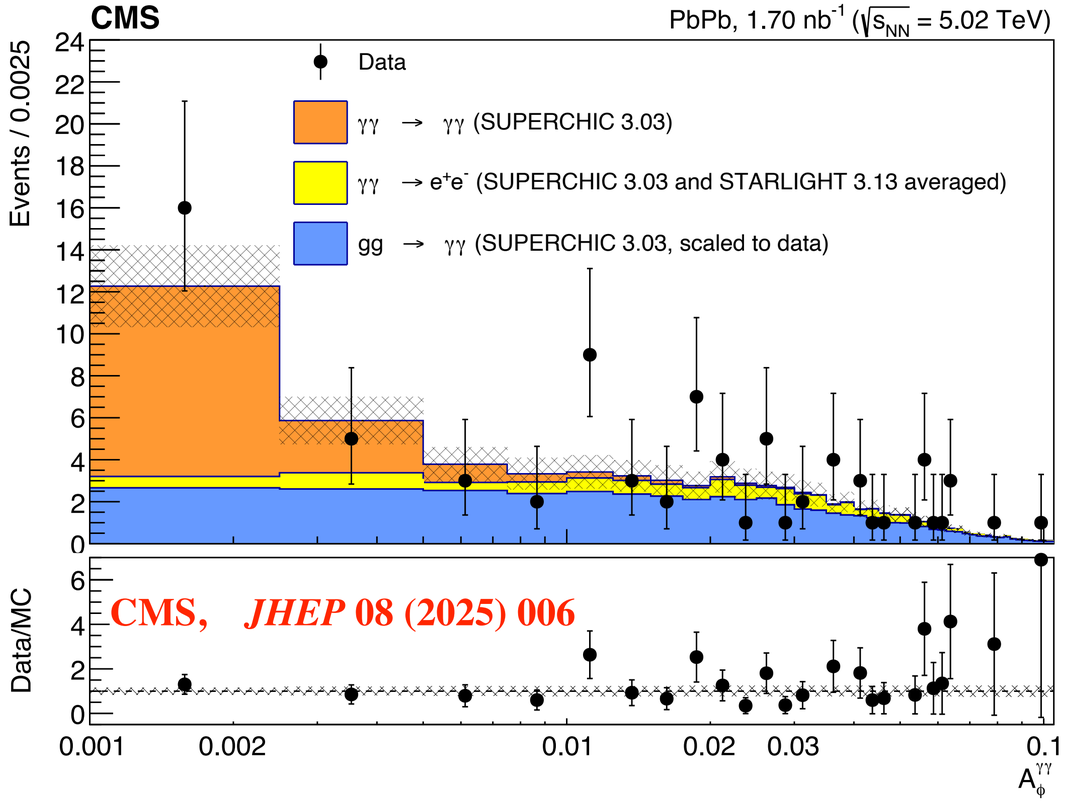
Light by Light Scattering



- Using same approach can predict incoherent component of LbyL, in particular acoplanarity distribution.

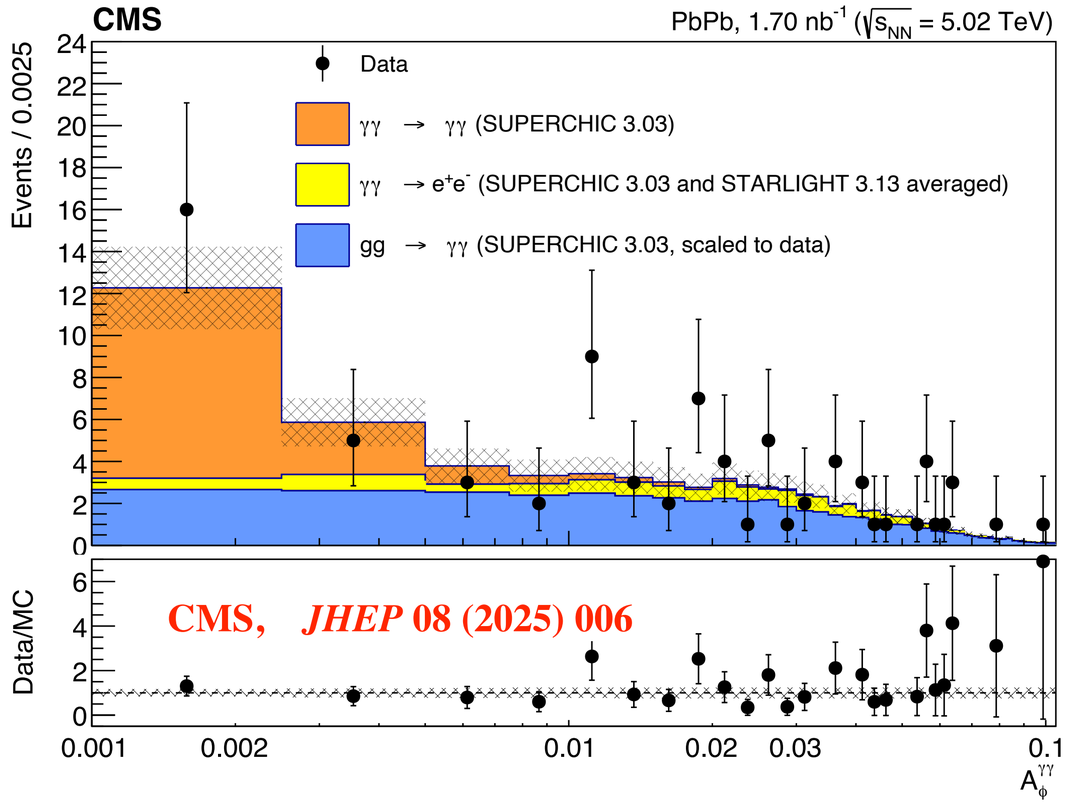


vs.



- Incoherent (inelastic) has broader tail, with **shape** matching data…but **not normalization!**

- Therefore semi-exclusive production **cannot explain** the sizeable higher acoplanarity tail observed in LbyL scattering.
- Source of this background remains **unexplained**!



- Note this might seem "obvious" from expected 1/Z suppression but there were other reasons to expect some enhancement beyond this…
- …but in the final analysis (and after accounting for all cuts) this is not the case.

Backup

Other background sources?

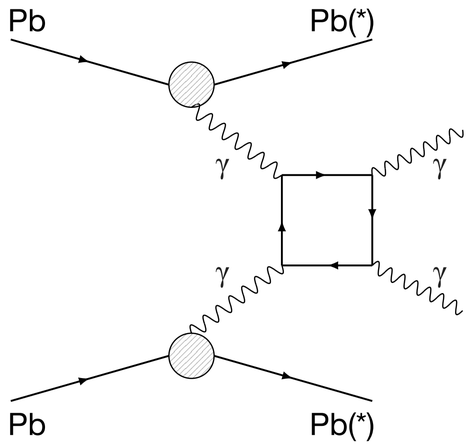
- In theory '**photoproduction**-like' mechanisms could play significant role - lower order in α !

- However in final analysis not the case:

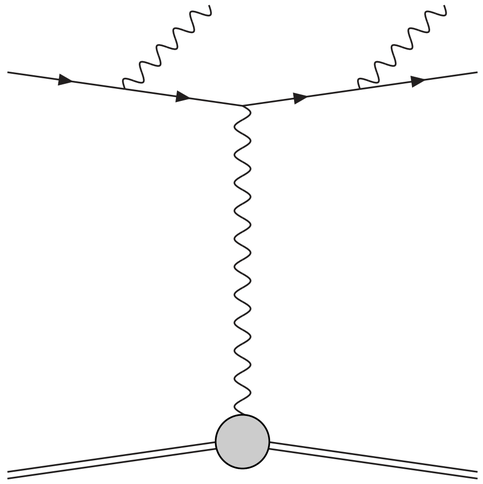
  ⋆ Quark emission: no t-channel enhancement + amplitude suppression.

  ⋆ Photoproduction: C-odd amplitude leads to valence quark GPDs - huge supression!

Quark emission:

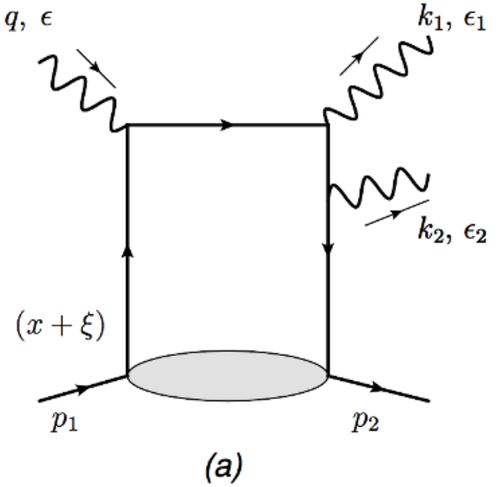


vs.



A. Pedrak et al., *Phys.Rev.D* 96 (2017) 7, 074008

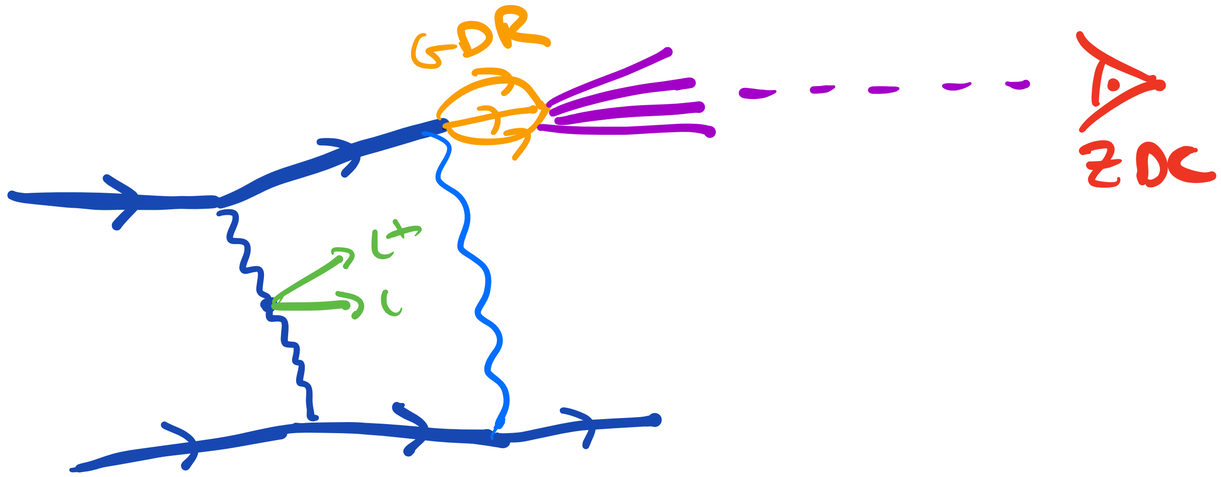
Photoproduction:



Recent Studies (2)

$Z_{\mathrm{Pb}} = 82$

- Sizeable ($\sim Z^2$) photon flux does not only enhance UPC cross section - can have multiple excitations



- Additional photon exchanges can excite ion - leads to forward neutron production that can be detected by Zero Degree Calorimeters (ZDCs)

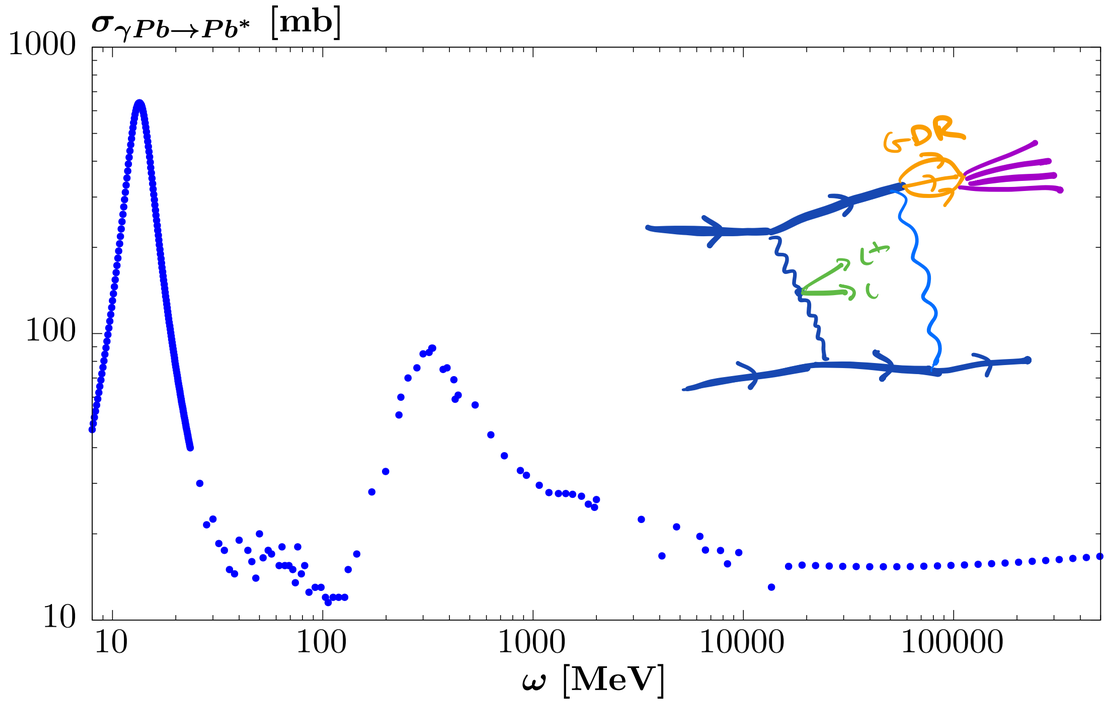
- Cross section given in terms of:

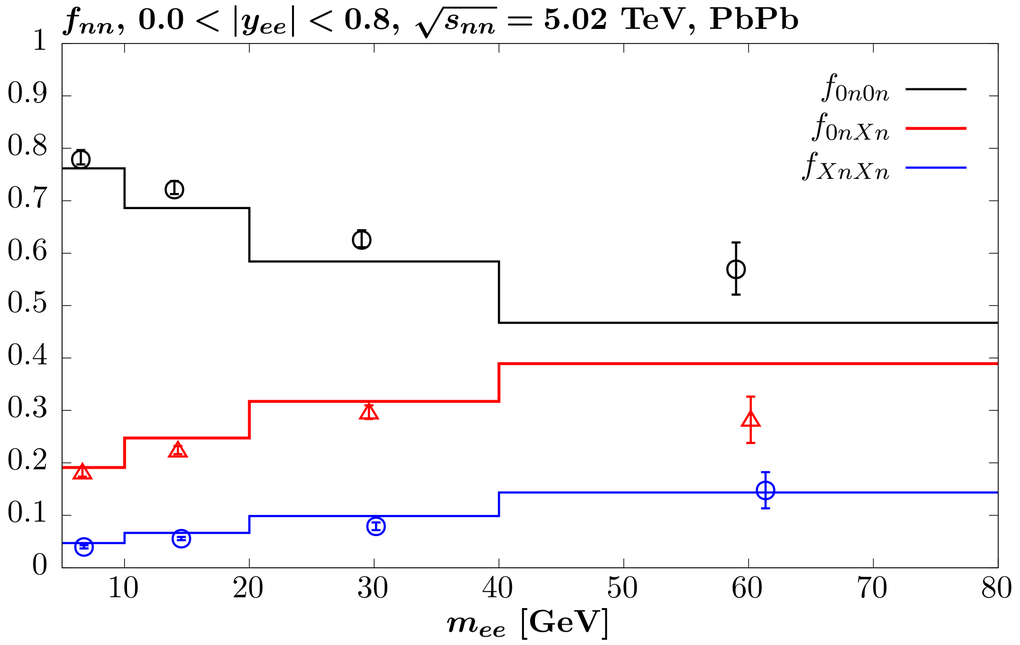
$$P^1_{Xn}(b_\perp) = \int \frac{\mathrm{d}\omega}{\omega} |\tilde{\mathbf{N}}(x, b_\perp)|^2 \sigma_{\gamma A \to A^*}(\omega)$$

Photon flux

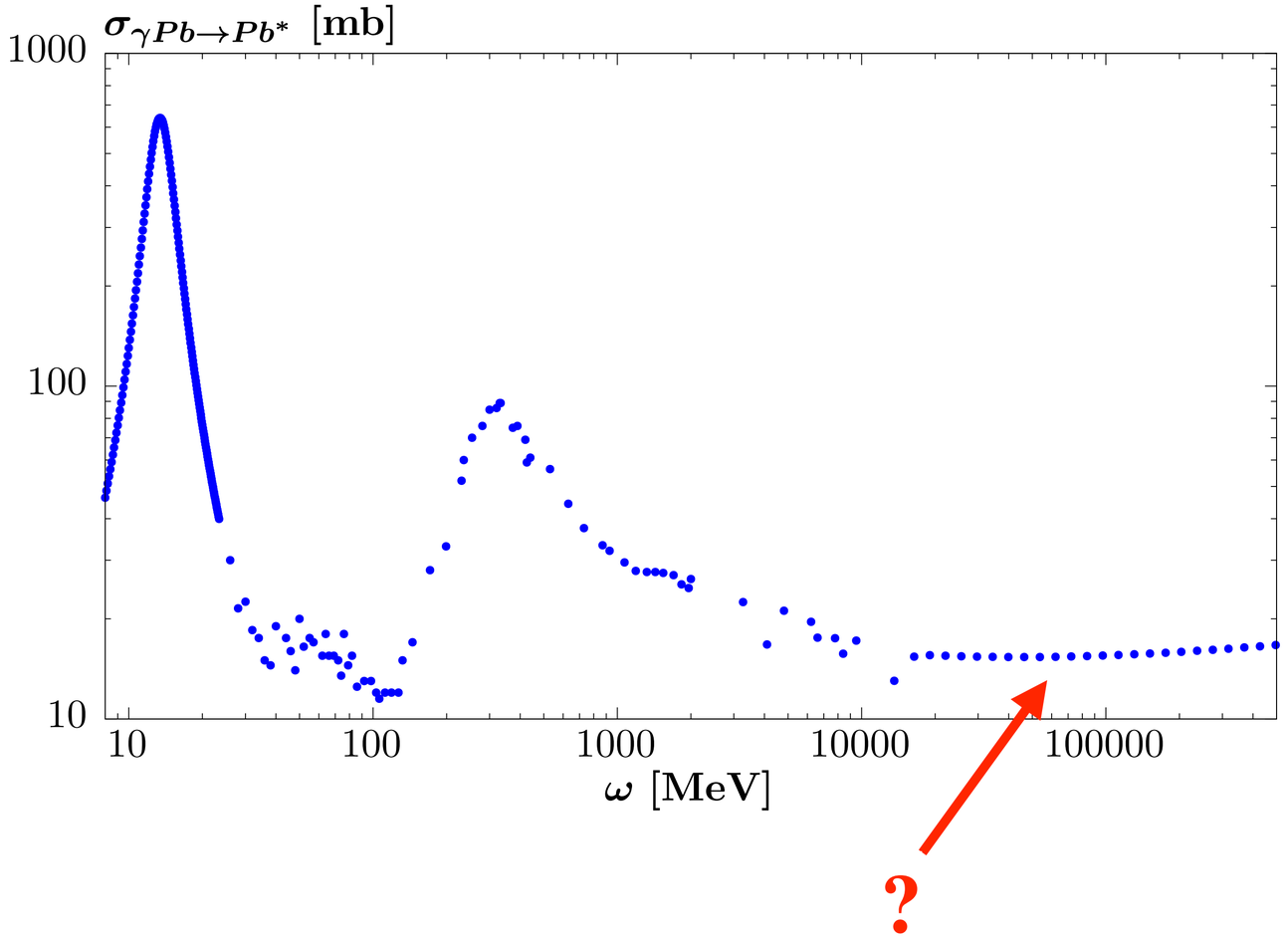
- Most ingredients rather well determined from lepton-ion scattering data.

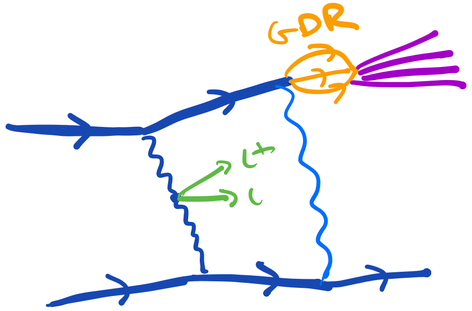
- And predictions for 'ZDC event fractions' match data rather nicely!





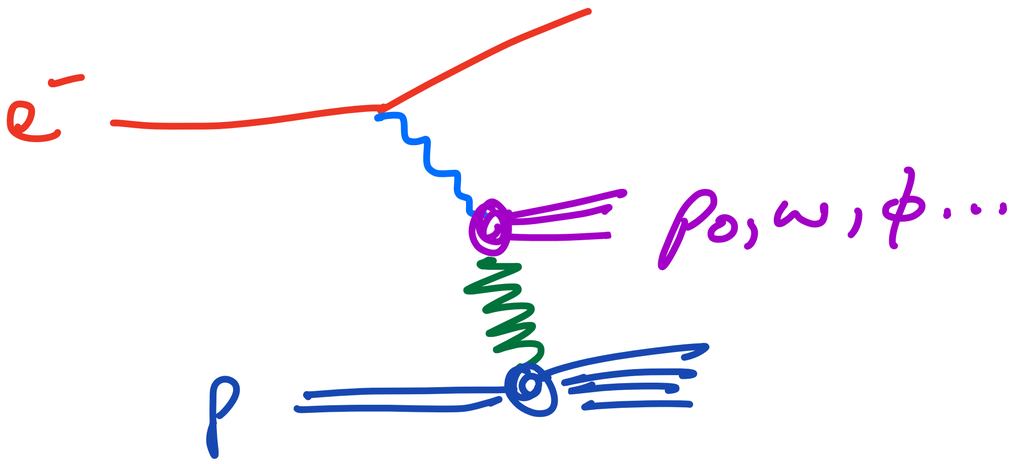
- **Question**: what about this high energy tail?

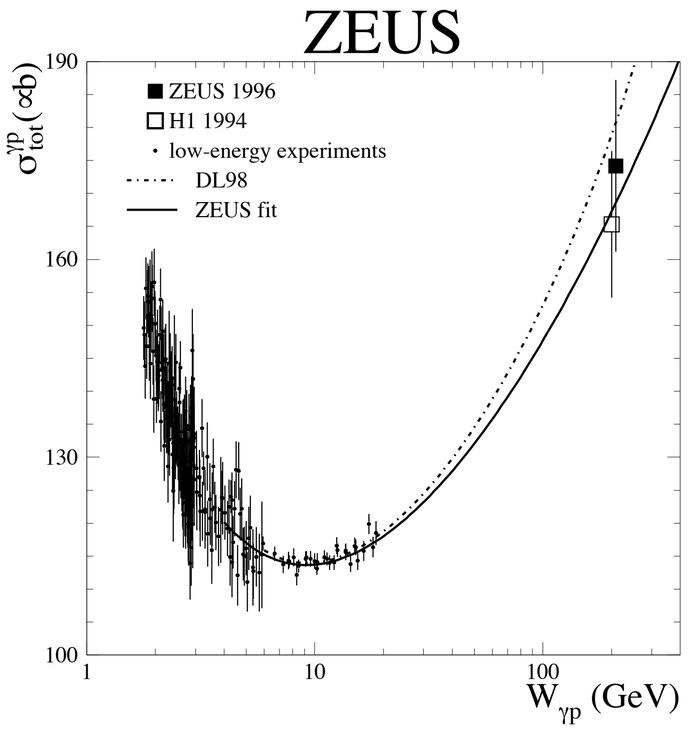




★ **Theoretically**: not well determined.

- High energy γn cross section observed to follow 'Regge-scaling'. $\sigma_{\text{tot}} = A \cdot s^{\epsilon} + B \cdot s^{-\eta}$,
- Handful of HERA datapoints in energy region ~ an order of magnitude below LHC energies - extrapolate from there in energy and from nucleon to ion.

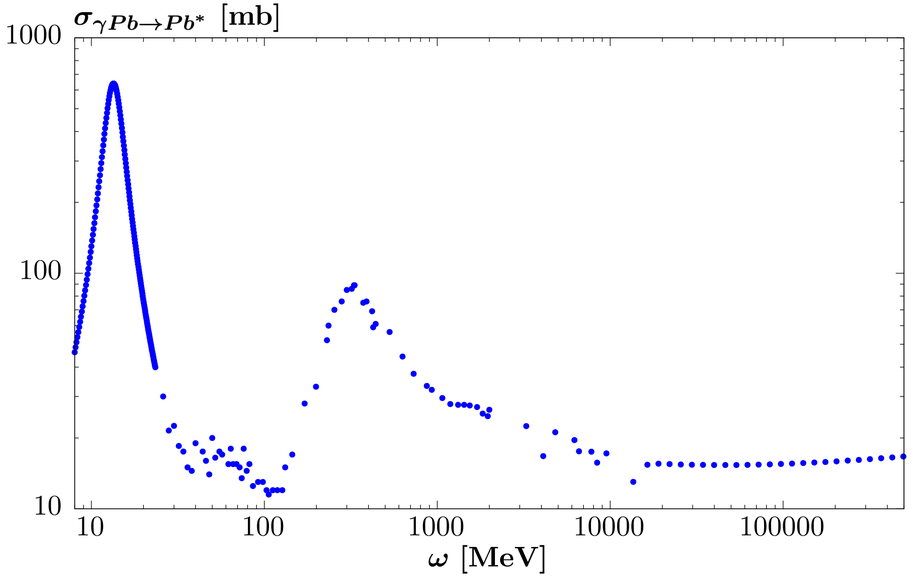




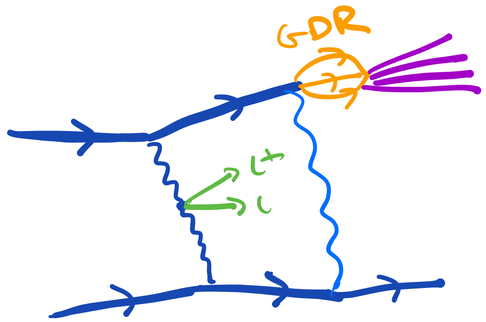
ZEUS, Nucl.Phys.B 627 (2002)

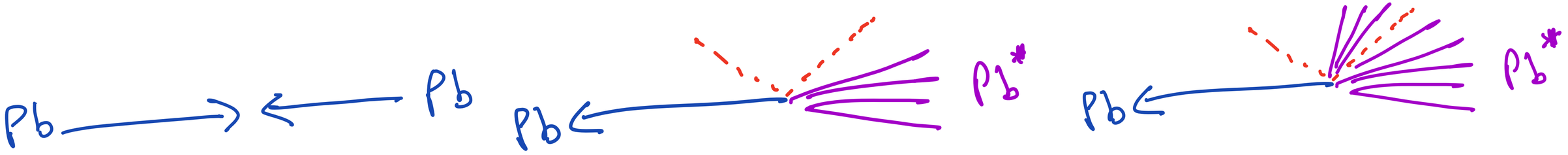
★ **Experimentally**: might this be polluting our data samples??

$$P^1_{Xn}(b_\perp) = \int \frac{\mathrm{d}\omega}{\omega} |\tilde{\mathbf{N}}(x, b_\perp)|^2 \sigma_{\gamma A \to A^*}(\omega)$$



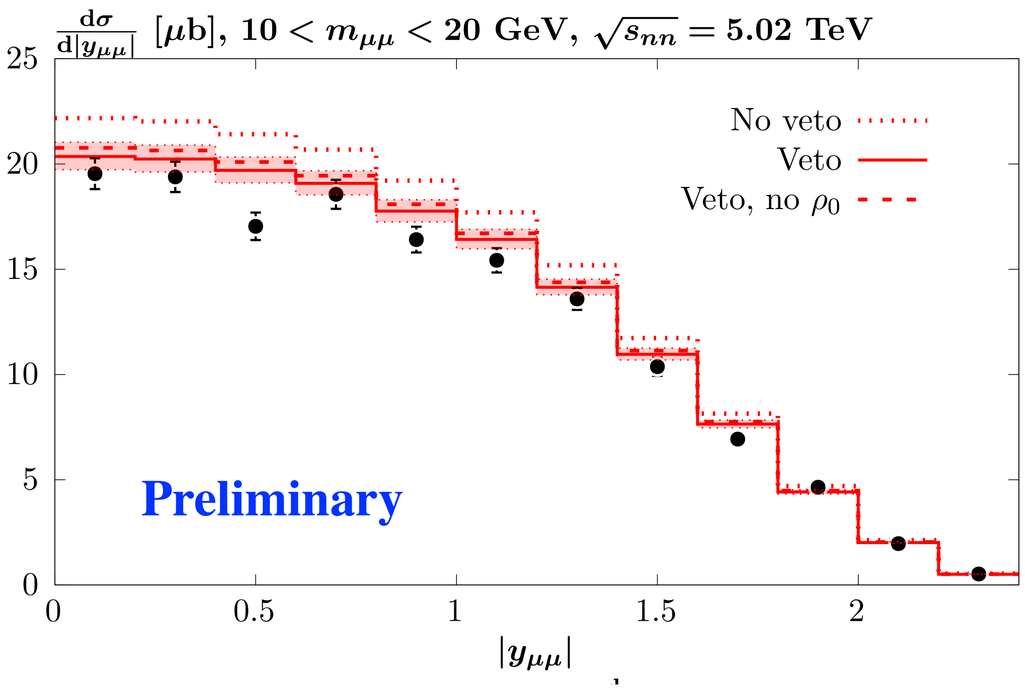
- Key point: contribution from high energy tail is not negligible, and would lead to particle production in the detector.

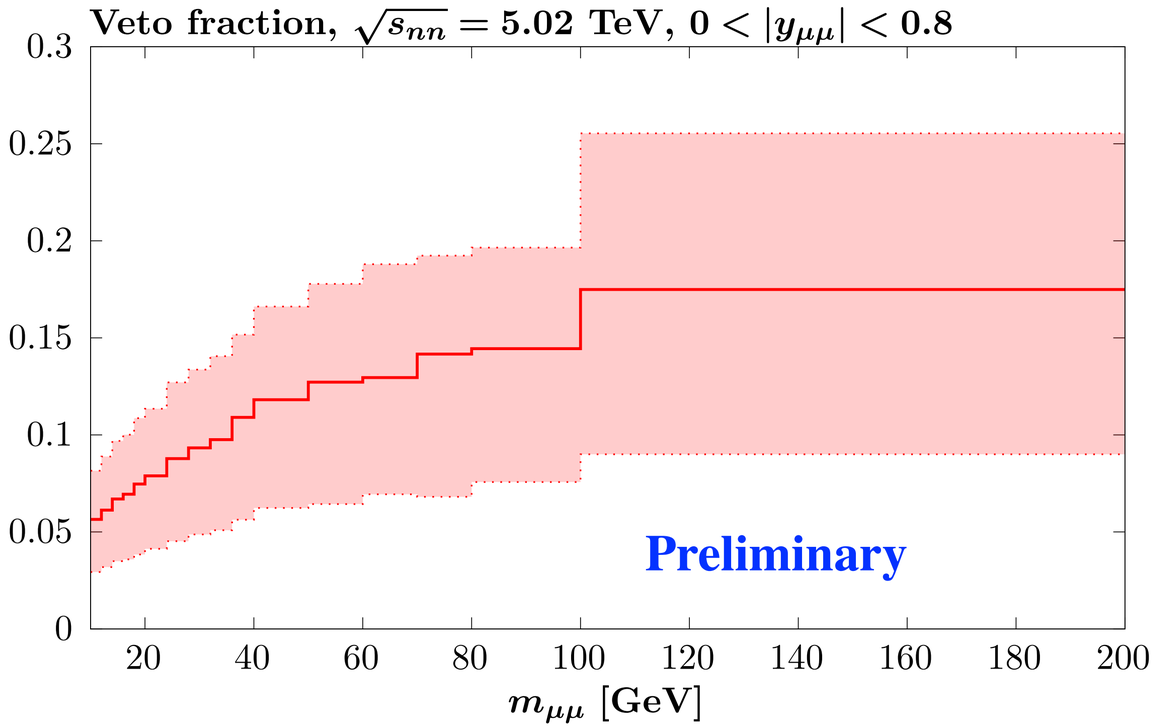




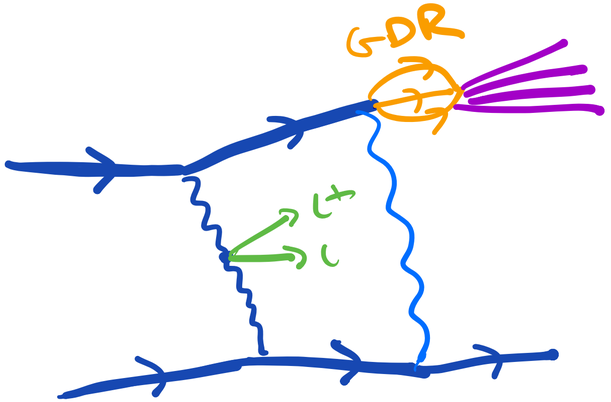
- But we impose exclusivity vetos in measurements, just as in pp. Might this be missed?

M. Dyndal and LHL, in preparation.





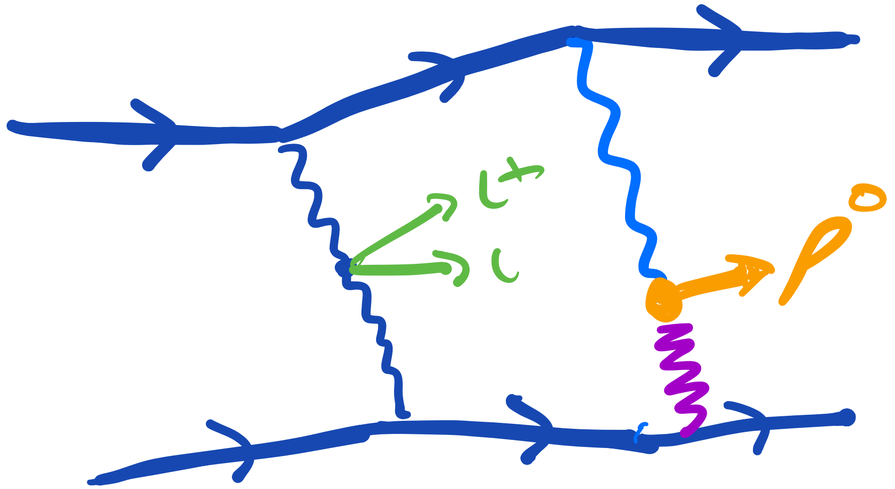
- Study in final stages: we find fraction of events that fail representative ATLAS veto due to ion excitation can be sizeable.
- Acts to bring predictions into much agreement with data (long-standing puzzle).
- Need to account for! Can also affect ZDC fractions, other results (photoproduction etc) - **stay tuned**.

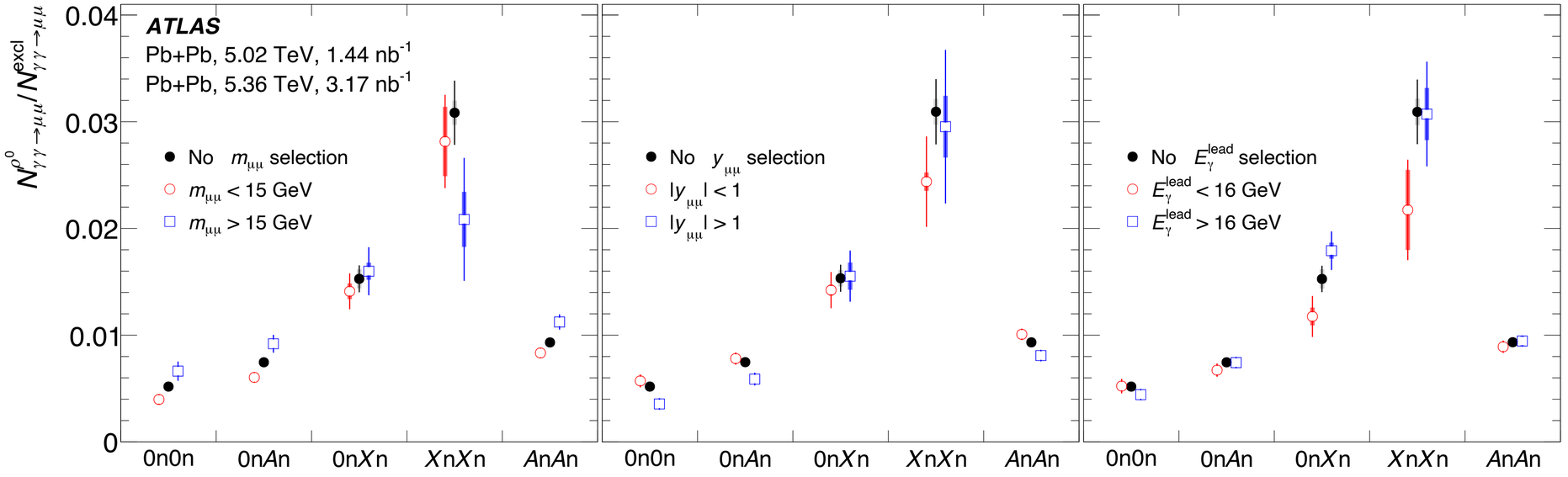


ATLAS, arXiv:2504.07795

Recent Studies (3)

- Recent ATLAS measurement of coincident ρ^0 and $\mu^+\mu^-$ production!
- First time this DPS-like observable has been measured.
- But **no theoretical predictions**…



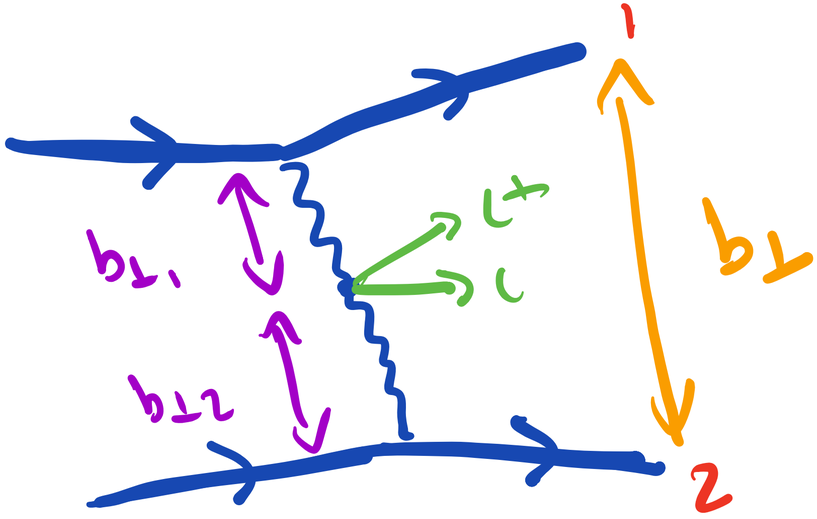


- Until recent study - first detailed theoretical work. **LHL, arXiv:2506.03264**

- To account for coincident production, simply take standard formula:

$$\sigma \sim \int \mathrm{d}^2 b_{1\perp} \mathrm{d}^2 b_{2\perp} P^{\mathrm{surv}}(b_\perp) N(x_1, b_{1\perp}) N(x_2, b_{2\perp}) \cdot \sigma_{\gamma\gamma \to X}$$

Survival factor — Photon flux



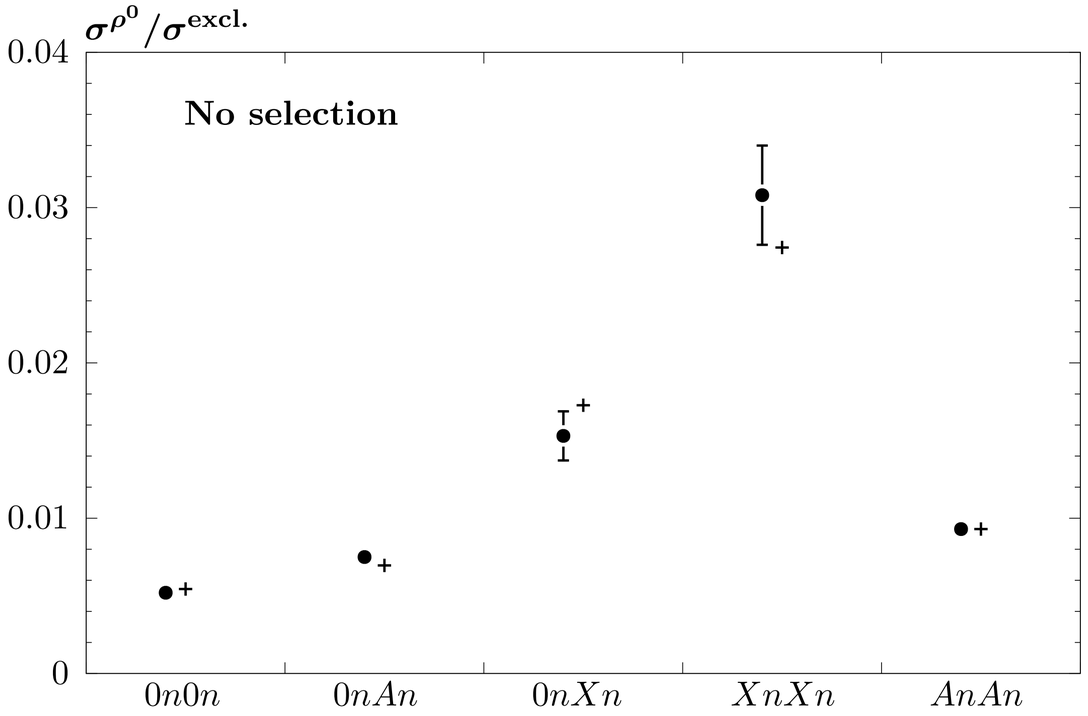
- And multiply by probability for coincident $\gamma A \to \rho^0 A$

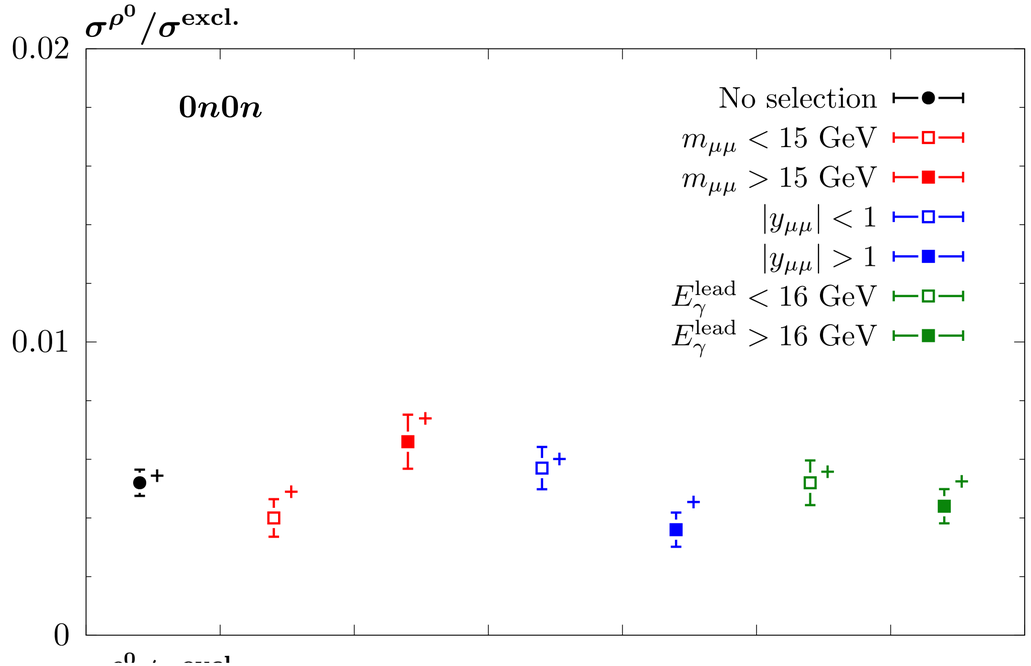
$$\mathrm{d}\sigma_{X_1 X_2} = \int \mathrm{d}^2 b_{1\perp} \mathrm{d}^2 b_{2\perp} \mathrm{d}\sigma_{S^2} \quad \longrightarrow \quad \mathrm{d}\sigma_{X_1 X_2} = \int \mathrm{d}^2 b_{1\perp} \mathrm{d}^2 b_{2\perp} \mathrm{d}\sigma_{S^2} P_{X_1 X_2}(s, b_\perp) P_V(b_\perp)$$

- With: $\sigma(\gamma P b \to \rho^0 P b) : O(\mathrm{mb})$ $\qquad P_V(b_\perp) = 2 \int \dfrac{\mathrm{d}\omega}{\omega} |\tilde{\mathbf{N}}(x, b_\perp)|^2 \sigma_{\gamma A \to V A}(\omega)$,

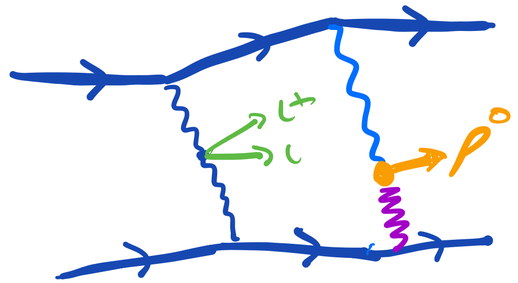
taken from LHC data on ρ^0 photoproduction.

- Both ZDC class and kinematic dependence nicely **in line with expectations**.





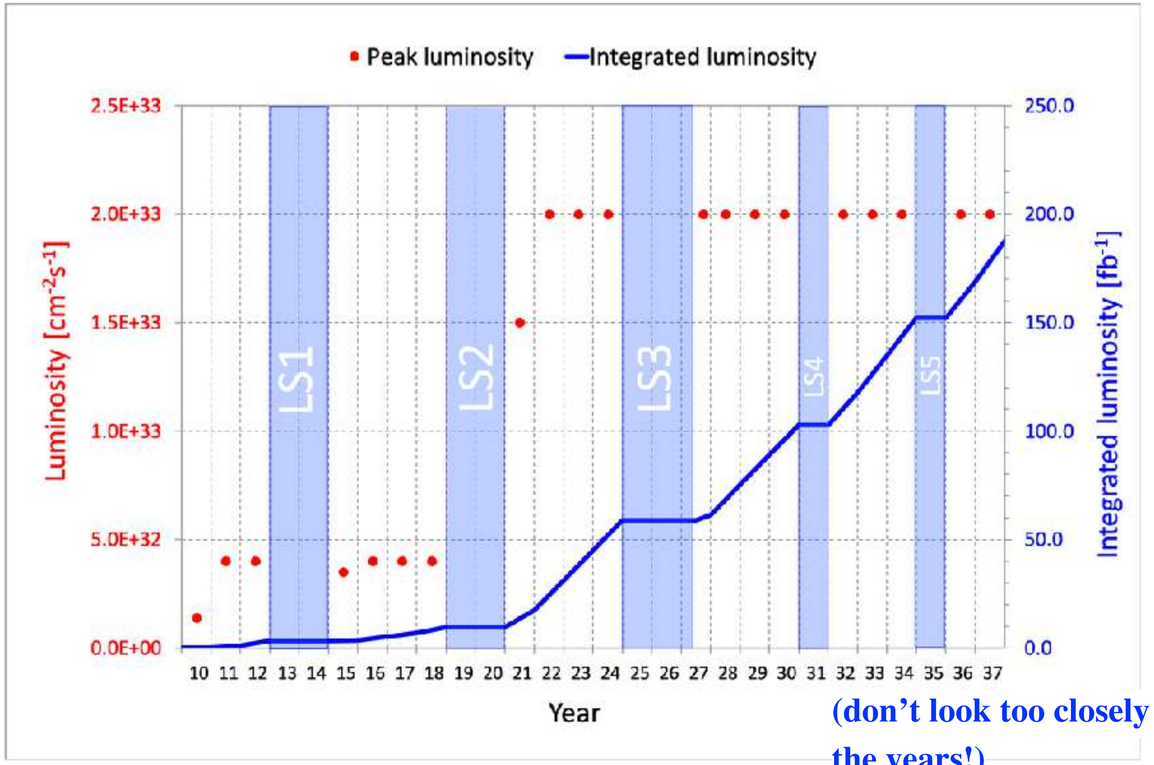
- First study of its kind - opens up new type of observable. Other coincident processes? Correlations between them…?



Summary and Outlook

- Already many new LHC measurements in the photon-initiated channel.
- But still in foothills of data taking.

- During Run 3 both **ATLAS** and **CMS** continuing to take semi-exclusive pp data with and without tagged protons.

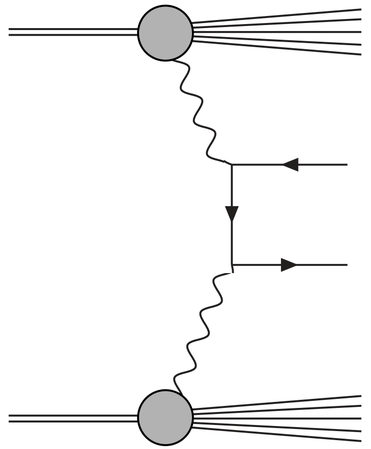


(don't look too closely at the years!)

- Work towards HL-LHC running at **CMS** underway, with new taggers being proposed.
- Similarly in AA collisions, much new data to come, with **ALICE** and **LHCb** entering the game.
- An exciting programme of measurements ongoing and to come, and much theory work to do.

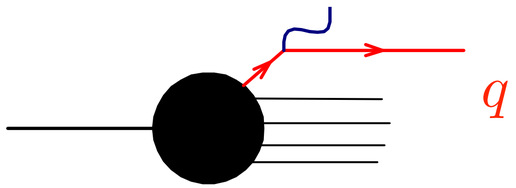
Backup

PI + ISR Showering



- SF calculation give precision prediction for photon x, Q^2 and we would like showering/hadronisation of dissociation system to respect this.

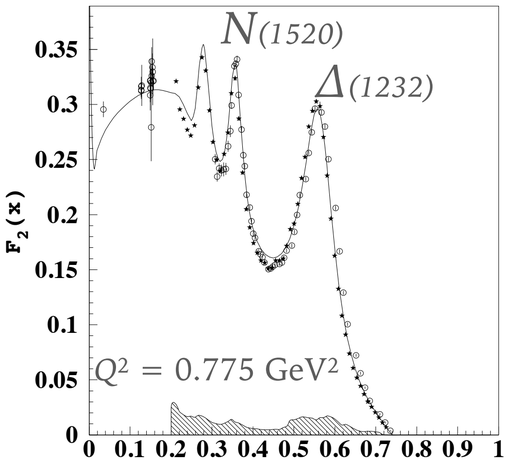
- No clear off-the-shelf way to do this, so take simplified approach:
  - ★ For purposes of LHE record, for inelastic emission take LO $q \to q\gamma$vertex
  - ★ Generate outgoing quark according to momentum conservation, preserving photon 4-momentum.

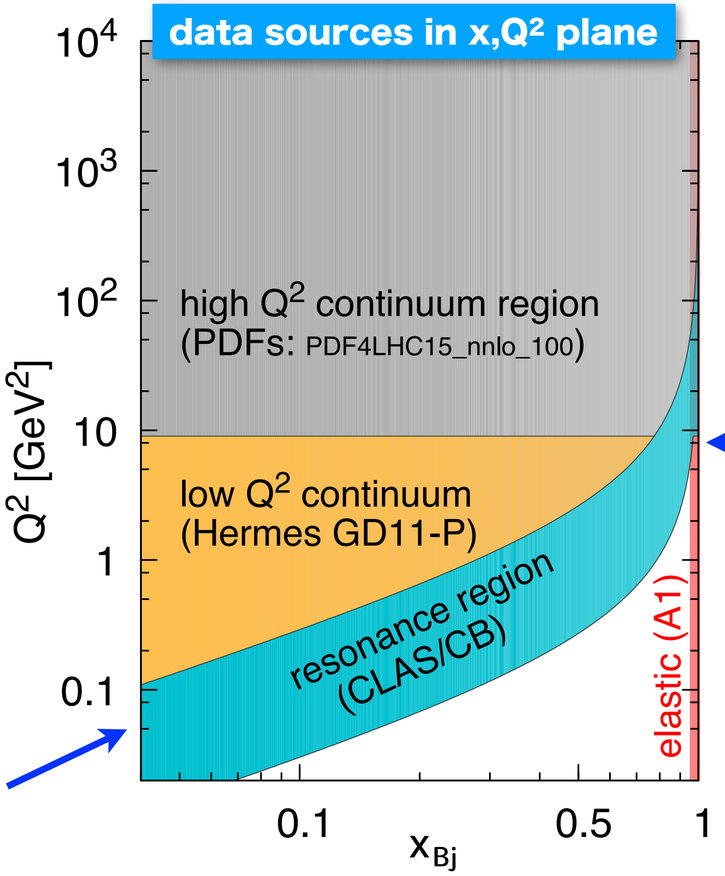


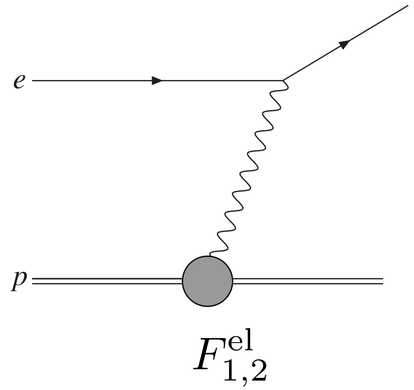
- ISR/FSR will then modify photon 4-momentum. Not ideal, but for purpose of current study sufficient.
- In addition, must turn off global recoil in Pythia to get realistic result (no colour connection between beams).

Image credits: Gavin Salam

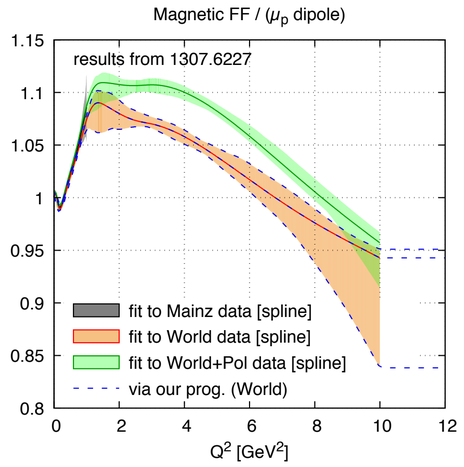
- In more detail, components of $F_{1,2}$ break up into four regions:







Elastic scattering: from A1 collaboration.



Inelastic resonant proton excitation. Precise parameterisations available.

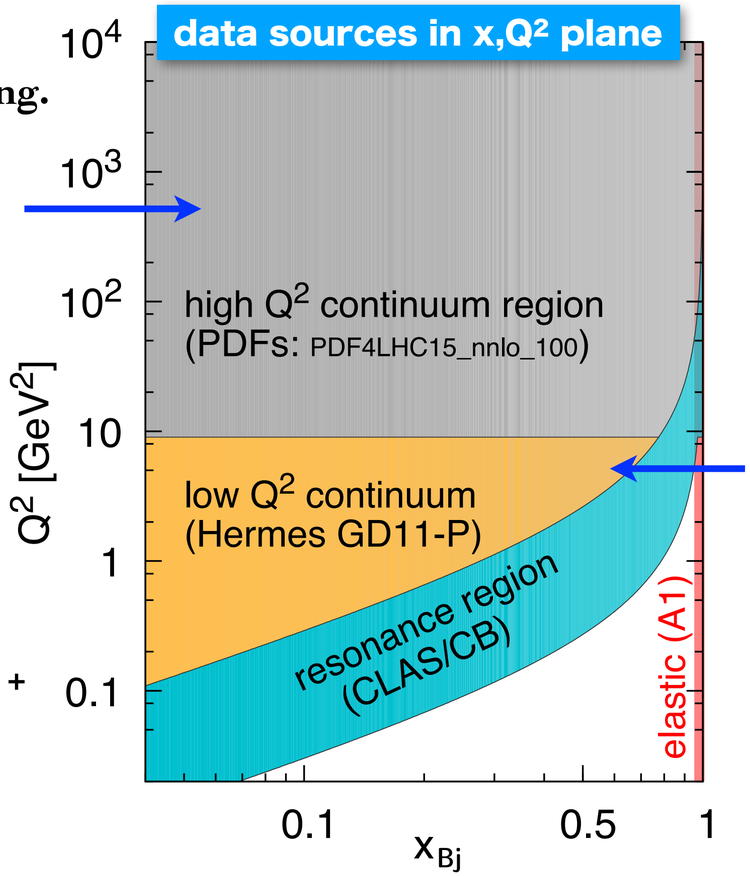
CLAS, M. Osipenko et al., Phys. Rev. D67, 092001 (2003)

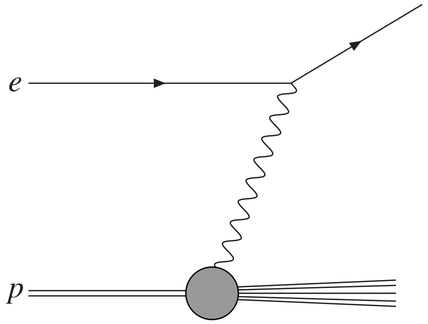
A1 Collaboration, Phys. Rev. C90, 015206 (2014)

Image credits: Gavin Salam

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

Inelastic high Q^2 scattering. Could in principle use direct experimental determination (e.g. from HERA).



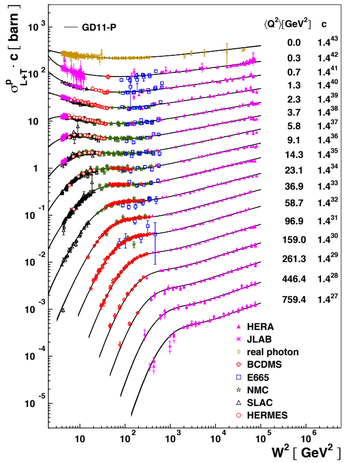


$F_{1,2}^{\text{inel}}$

Inelastic low Q^2 scattering. Precise parameterisation available.

HERMES, A. Airapetian et al., JHEP 05, 126 (2011)

But better precision achieved by combining pQCD NNLO prediction + quark/gluon PDFs from global fit.



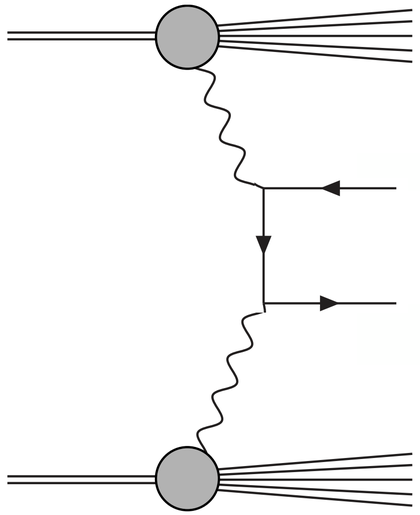
- Closely follow LUXqed inputs here.

NB: plot just for display purposes. I take direct pQCD determination above $Q^2 > 1\text{GeV}^2$

Other Considerations

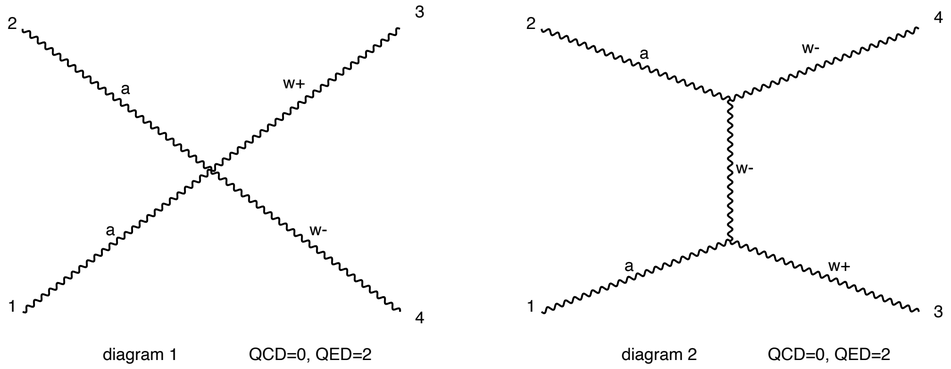
Collinear Calculation

- Also possible/relatively common to calculate PI cross section in collinear factorization. Given in terms of photon PDF



$$\sigma_{\gamma\gamma}^{LO} = \int \mathrm{d}x_1 \mathrm{d}x_2 \, \hat{\sigma}^{\gamma\gamma \to l^+ l^-}(\mu_R; \cdots) \gamma(x_1, \mu_F) \gamma(x_2, \mu_F)$$

- This is what comes out of e.g. MG5 generator.



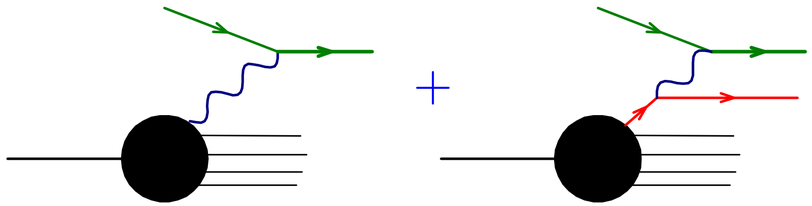
- Can show that collinear calculation is (approximately) equivalent to full structure function calculation for pure PI production:

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

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

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

- 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:

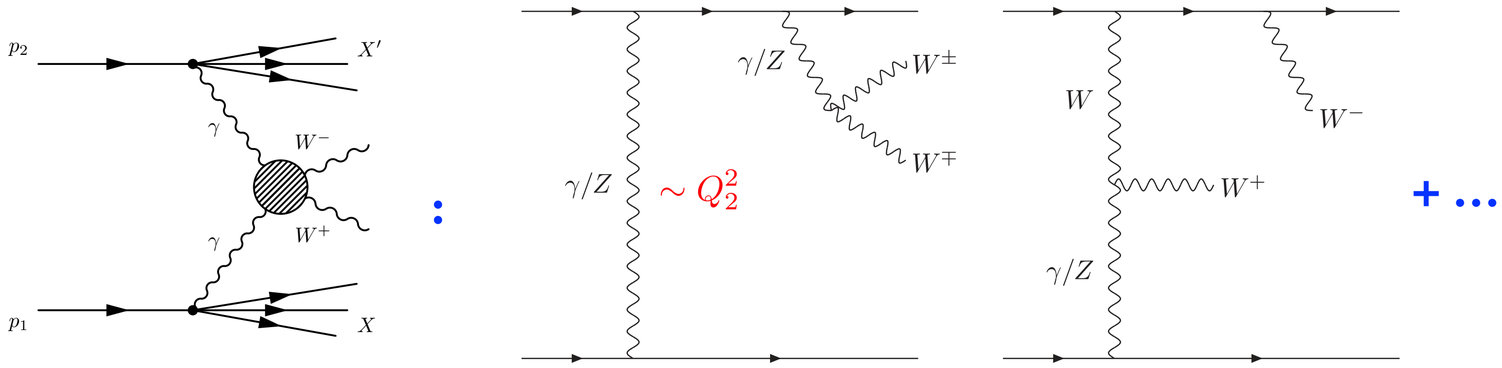


- But fore pure PI this is automatically accounted for in SF calculation.
- Moreover SF calculation (unintegrated in photon $k_\perp$) fundamental to calculation of survival factor.

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

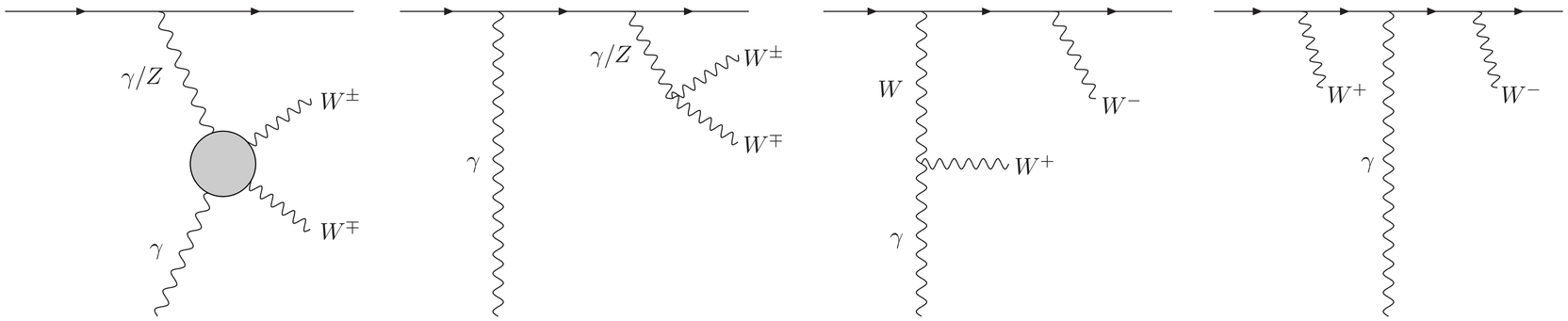


- These non-PI diagrams are suppressed by at least $\sim Q^2/M^2_{W,Z}$ and so on principle **subleading**. But:

  ⋆ 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.

- 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**

  ⋆ 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:

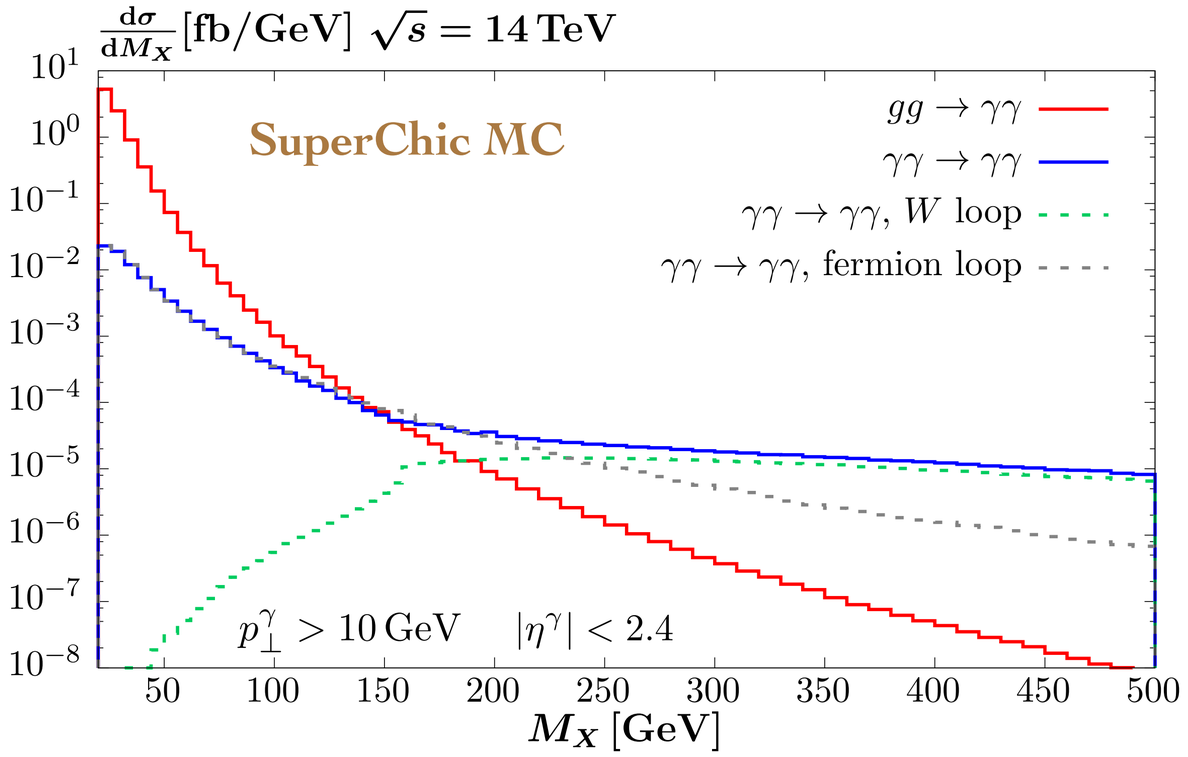
  ⋆ W pair production: O(10%) correction.

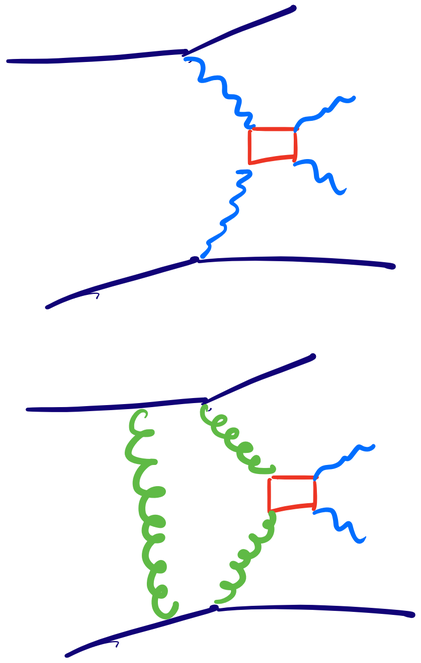
  ⋆ Lepton pair production: O(1%) correction.

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.

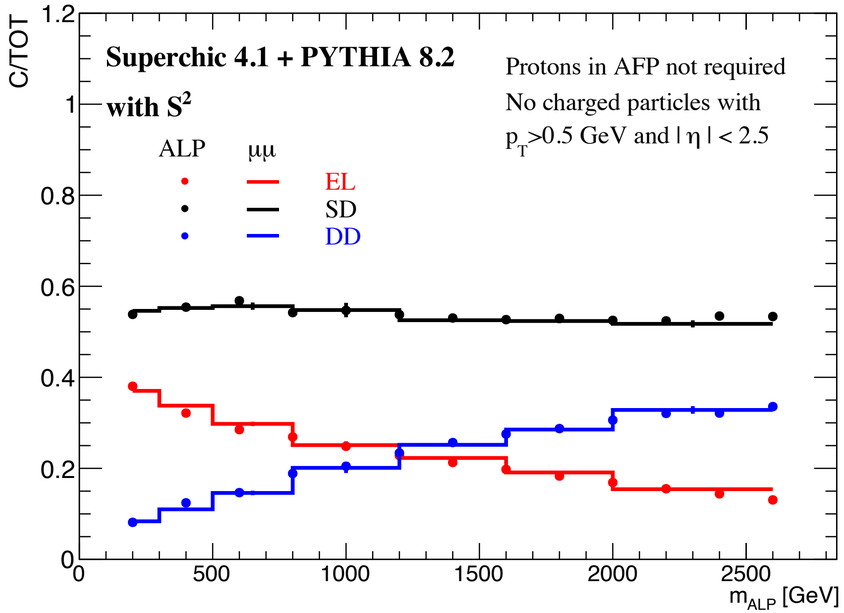
$\longrightarrow$ At higher mass PI production starts to dominate.

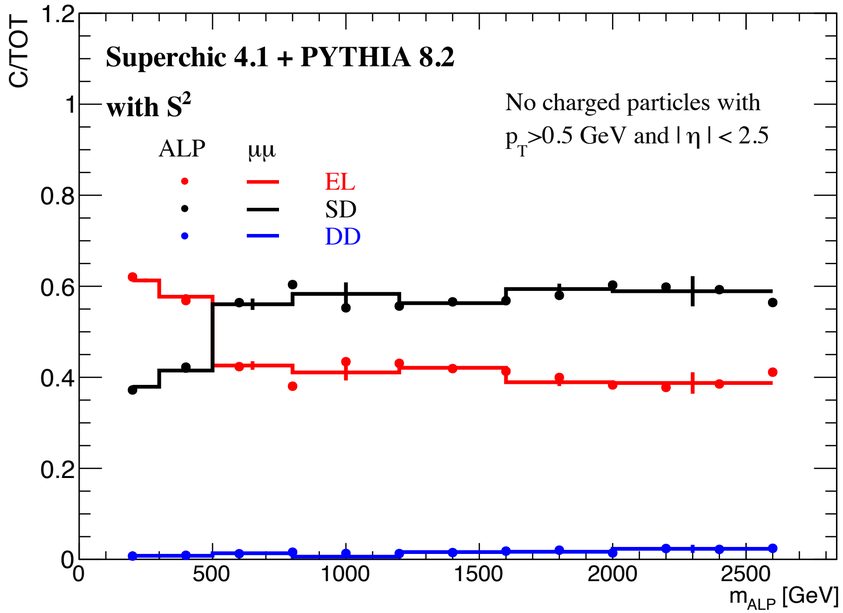




Proton Tag Impact

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

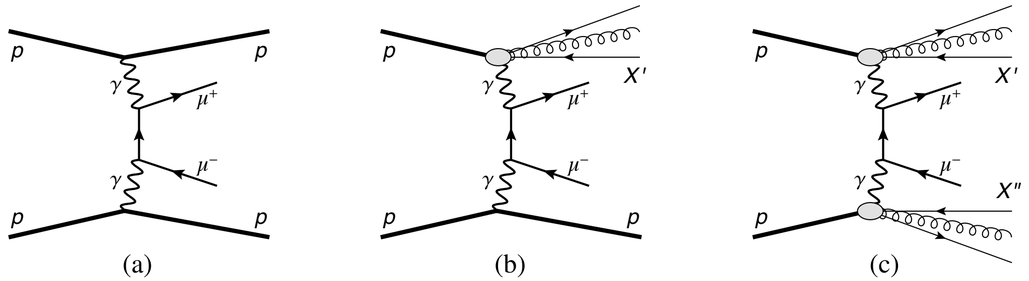




LHL and M. Tasevsky, arXiv:2208.10526

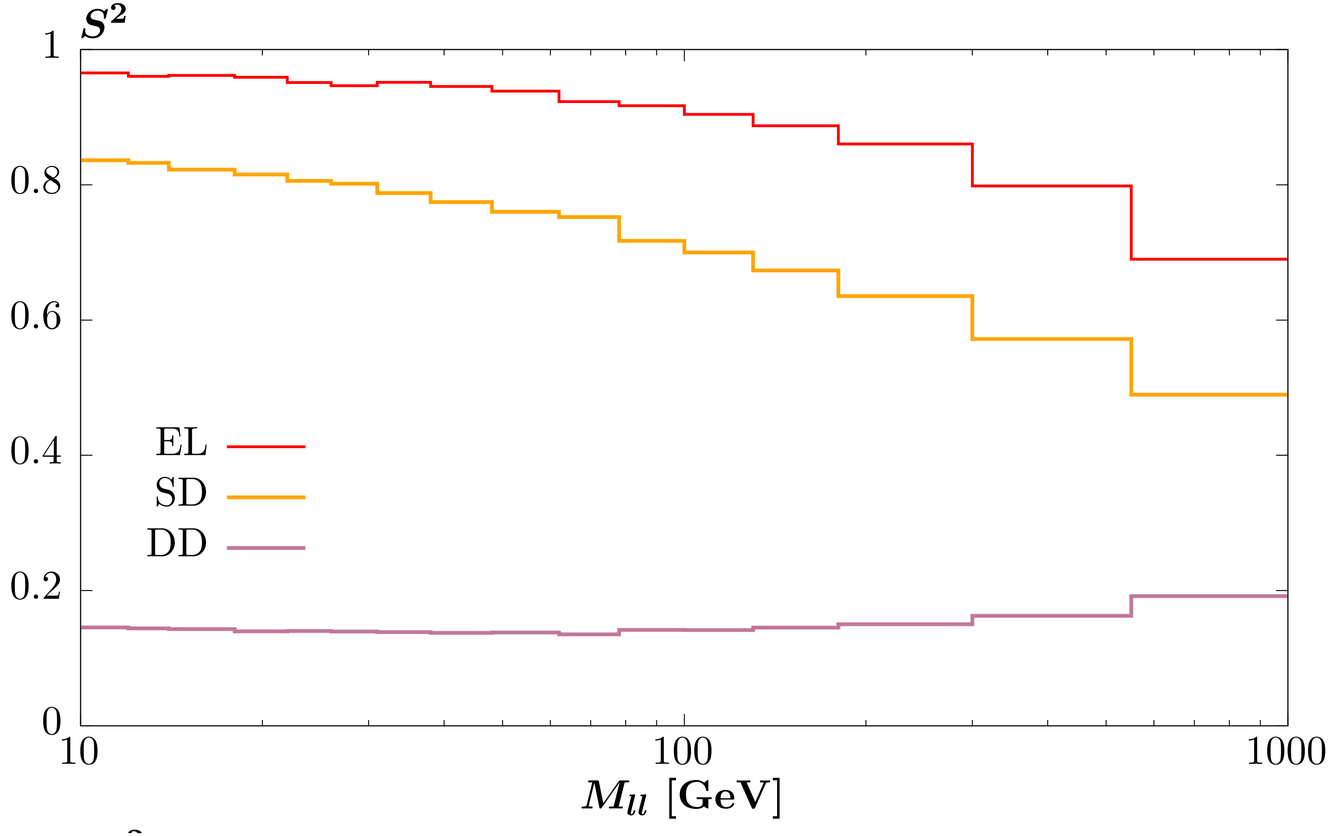
- Dissociation $\Rightarrow$ larger photon $Q^2 \Rightarrow$ smaller pp $b_\perp \Rightarrow S^2 \downarrow$

  - For SD production elastic proton side results in ~ peripheral interaction and S^2 still rather high.



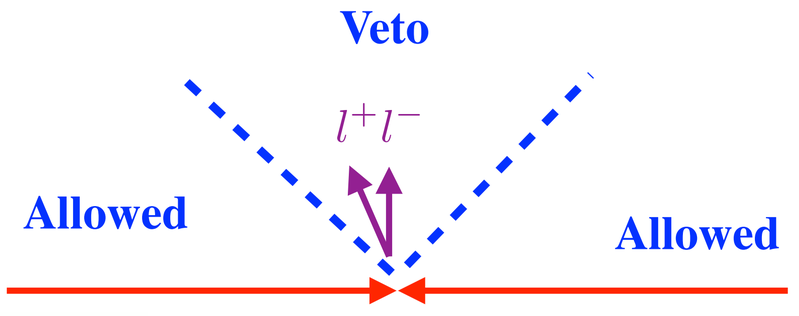
  - For DD no longer case and

$$S^2 \sim 0.1$$

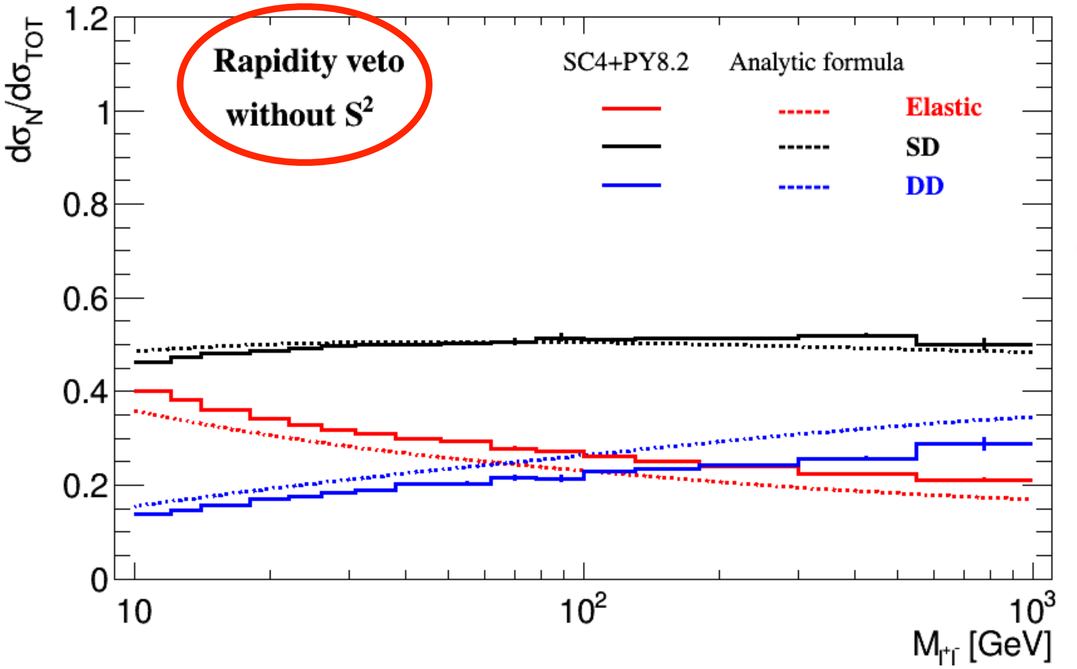


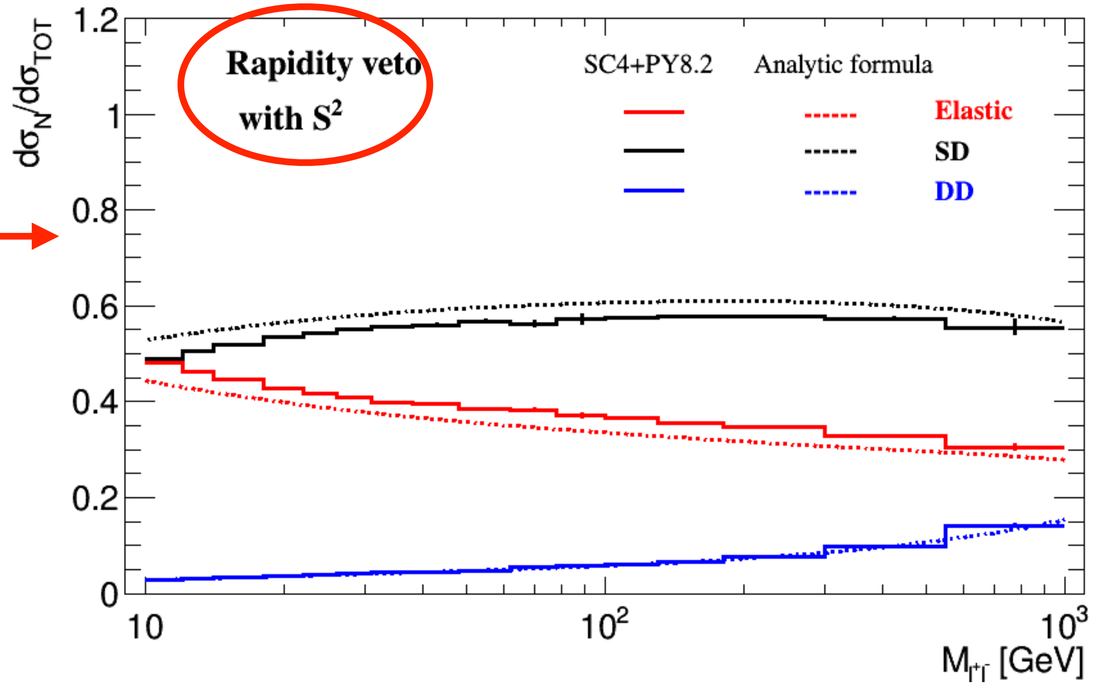
lepton pair production

Veto Impact



- MC generation allows us to assess impact of rapidity veto on cross section and different (EL, SD, DD) components.





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

★ **Proton tagging** : single tag removes DD and double tag gives pure EL.

Impact of Photon Kinematics

- Estimate by working in collinear approach:

$$\sigma_{pA} \approx \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_{\gamma/p}(x_1, \mu^2) \, f_{\gamma/A}(x_2, \mu^2) \hat{\sigma}(\gamma\gamma \to X) \, ,$$

- But with modified PDFs:

- Limit upper limit $\mu \to$ cut on photon $p_\perp$

$$x f_{\gamma/p,A}(x, \mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \int_{\frac{x^2 m_i^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2)$$
$$\cdot \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_i^2}{Q^2} \right) F_2^{p,A}(x/z, Q^2) - z^2 F_L^{p,A}\left(\frac{x}{z}, Q^2\right) \right] ,$$

- Can also use this to ~ cut on final-state quark η i.e. exclusivity veto.

- Look at impact on $\gamma\gamma$ luminosity. $$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}m^2_{\gamma\gamma}} = \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_{\gamma/p}(x_1,\mu^2)\, f_{\gamma/A}(x_2,\mu^2)\delta(s x_1 x_2 - m^2_{\gamma\gamma}) \,,$$

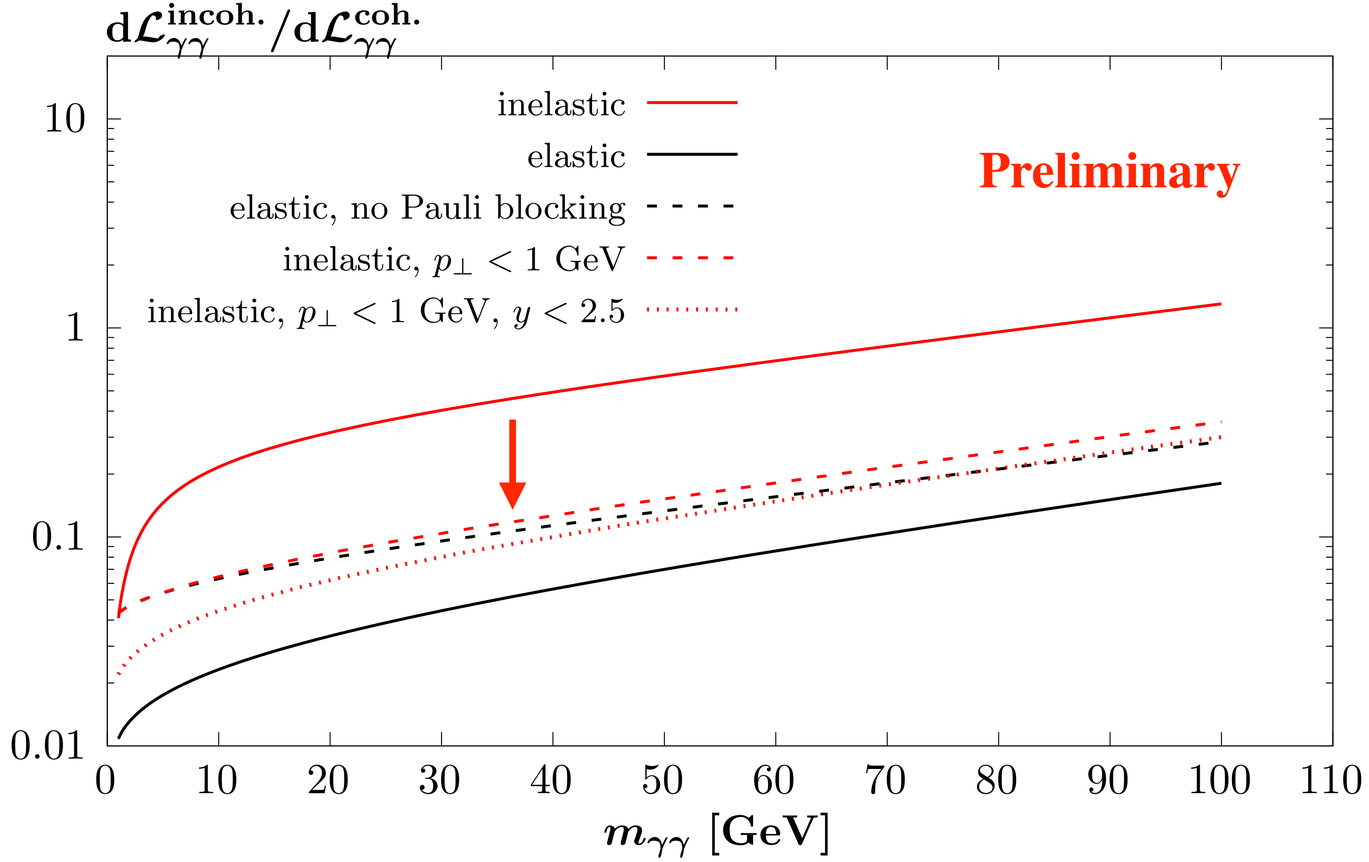
- Plot ratio to purely coherent (i.e. exclusive) case:

★ Experimental analyses restrict system $p_\perp^{\gamma\gamma}$ to be $< 1-2$ GeV

★ Impact significant - reduces incoherent inelastic by ~ 10.

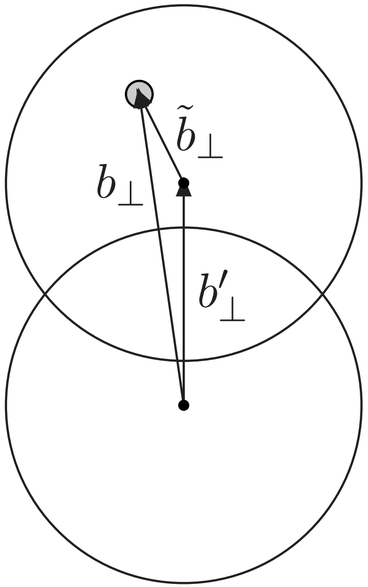
★ Exclusivity veto ($|\eta_q| > 2.5$) has some further impact.

★ 'Pauli blocking' required for incoherent elastic - reduced cross section by ~ 3-5.



- Accounting for these effects expect ~ **percent level incoherent contributions**.

Survival Factor



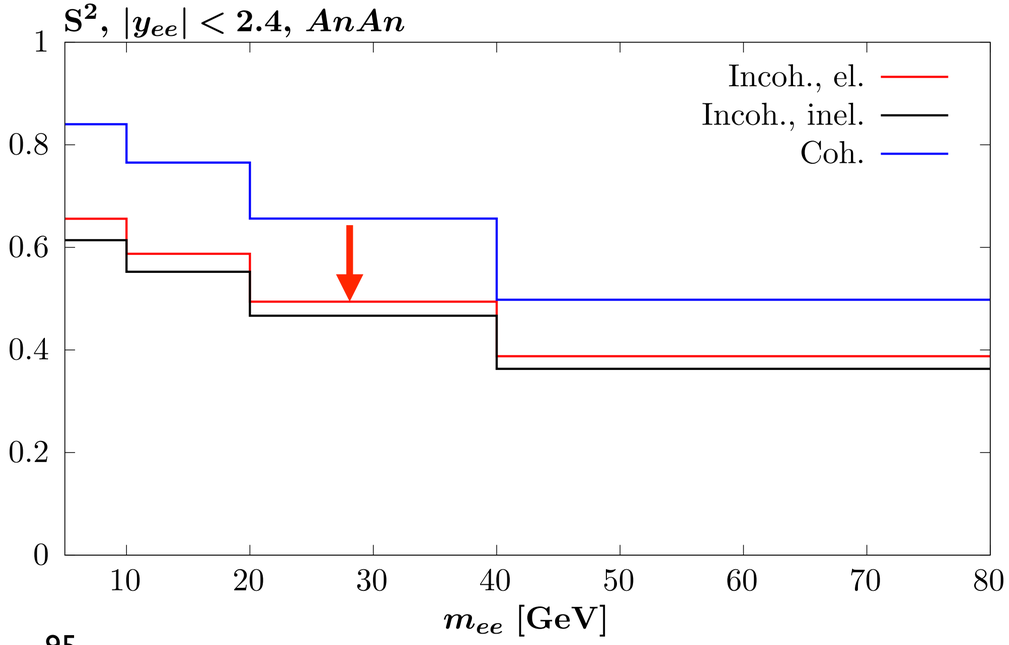
- Not all nucleons in ion always active:

$$\sigma^{\text{inel,el}}_{AA\to pAX} = \int \mathrm{d}^2 b_{1\perp} \mathrm{d}^2 b_{2\perp} \int \mathrm{d}^2 \tilde{b}_\perp T_{A,p}(\tilde{b}_\perp) \Gamma_{AA}(s, b'_\perp) \frac{\mathrm{d}^2 \sigma_{pA\to pAX}}{\mathrm{d}^2 b_{1\perp} \mathrm{d}^2 b_{2\perp}} \ ,$$

Nucleon density **Survival Factor**

- Yes: $\int \mathrm{d}^2 b_\perp T_{A,p}(b_\perp) = Z \ ,$ but if ion - ion $b_\perp \lesssim 2R_A$ then does not contribution!

- Can account for in full calculation of ion-ion survival factor.
- Gives some **further relative suppression**.



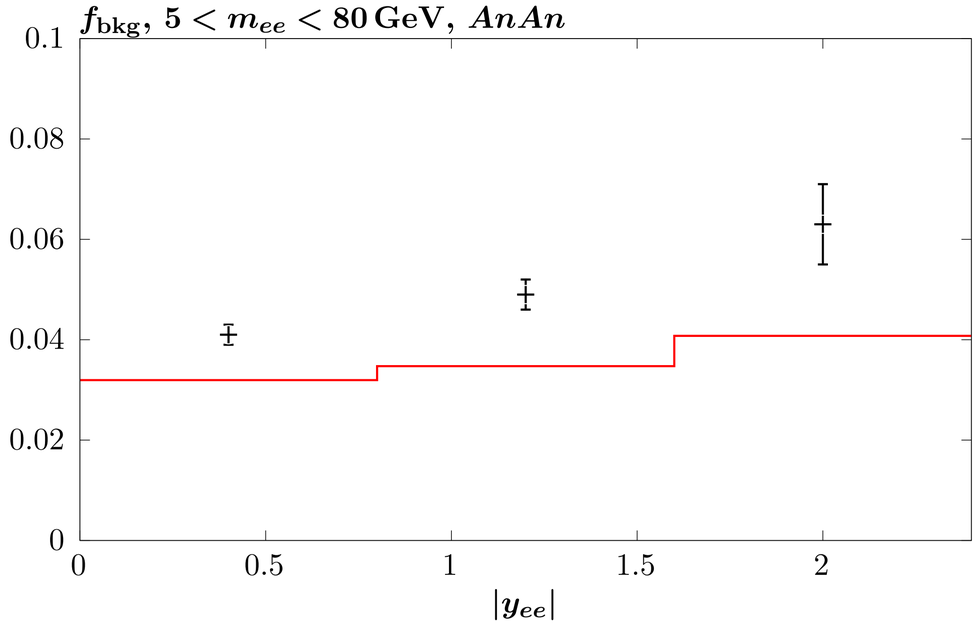
- Compare to published numbers - looks good! **Confirm ~ percent level predictions**.

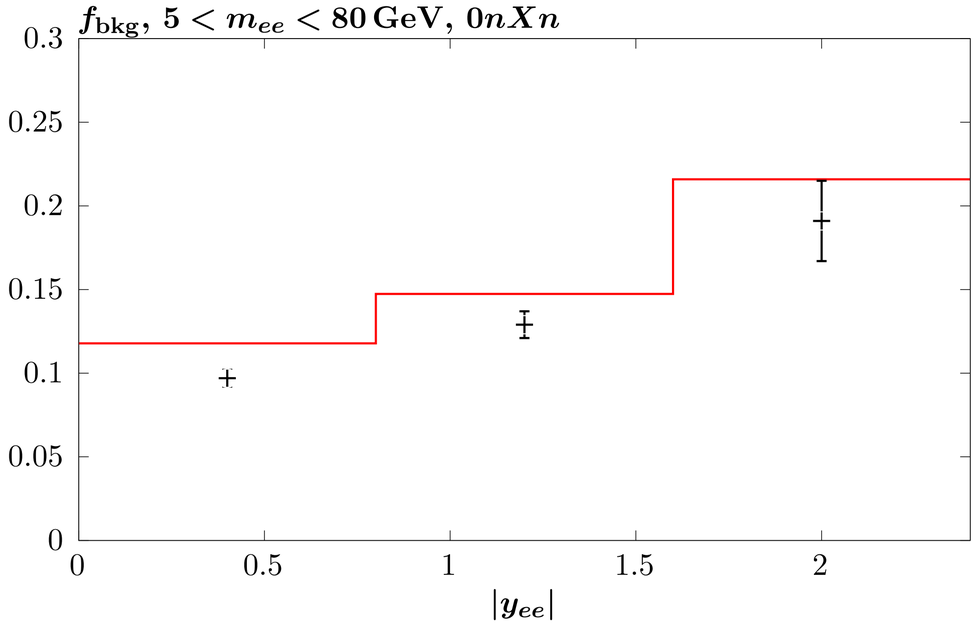
	AnAn	0nXn	XnXn
ATLAS [3],$\lvert y_{ee}\rvert < 0.8$, $10 < m_{ee} < 20$ GeV	0.043 ± 0.0026	0.099 ± 0.006	0.13 ± 0.01
Central prediction	0.039	0.12	0.17

- Can also predict other ZDC classes. Incoherent automatically gives Xn on inelastic side - incoherent fractions enhanced for 0nXn and XnXn.

A. Ogrodnik, *Measurement of photon-induced processes in heavy-ion collisions with the ATLAS detector*, PhD thesis, AGH-UST, Cracow, 2022.

- Larger range of comparisons from corresponding thesis:





- Encouraging agreement. Theory uncertainty ~ 20-30% level.