Central Exclusive Production: Summary and Recent Progress

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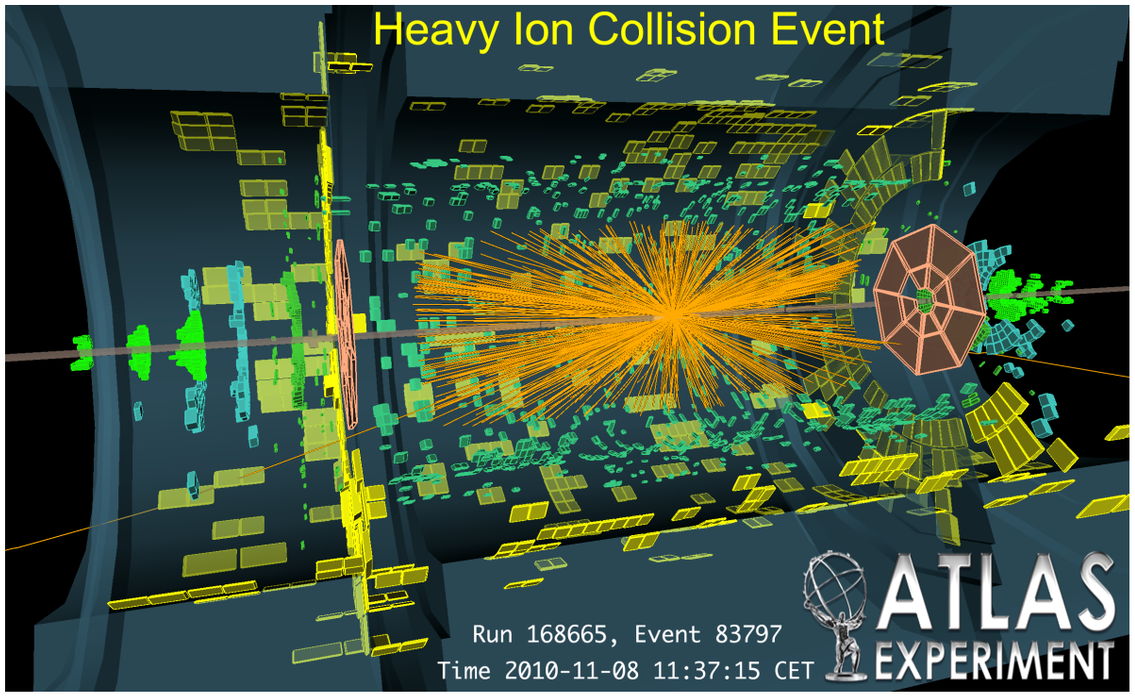
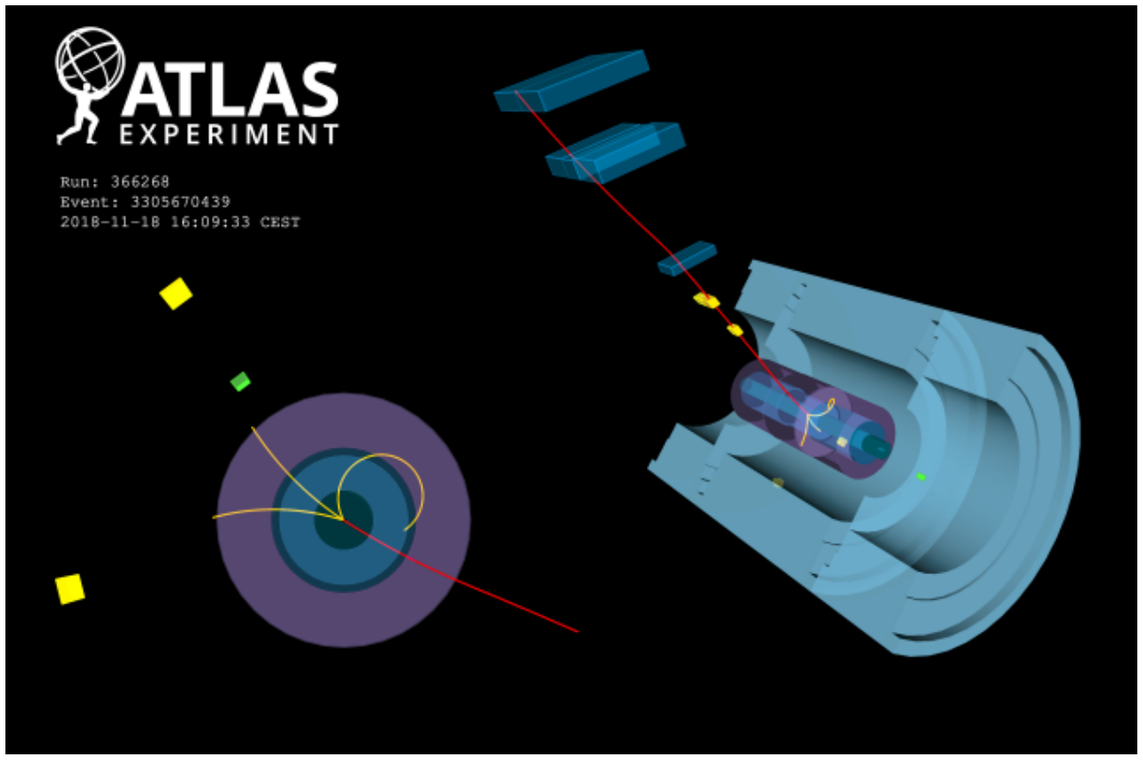
QCD@LHC, Durham, September 8 2023

Central Exclusive Production

Central Exclusive Production (CEP) - what is it?

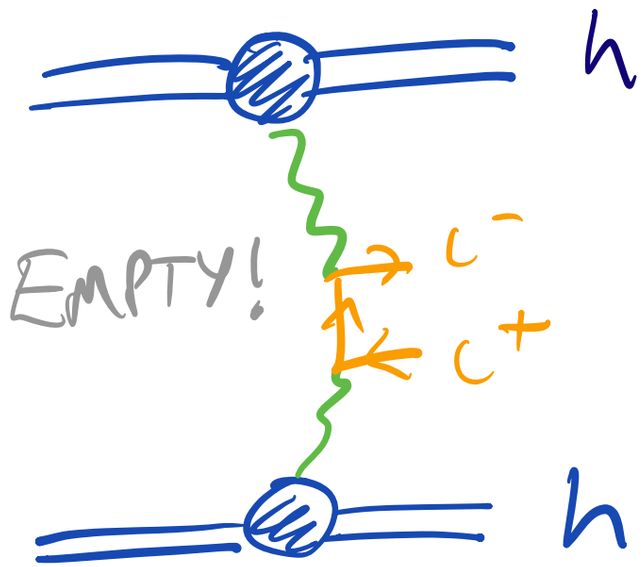


vs.



- Strict definition ('exclusive'):

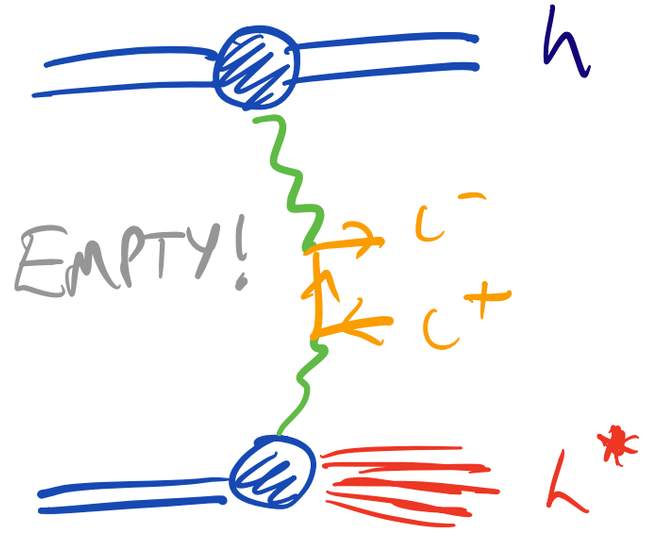
$$hh \to h + X + h$$



interaction where only X is produced and outgoing hadrons remain intact.

- Less strict definition (semi-exclusive):

$$hh \to h(h^*) + X + h(h^*)$$



interaction where only X is produced centrally, with no colour flow between outgoing hadron systems and X - intact hadrons and/or rapidity gaps.

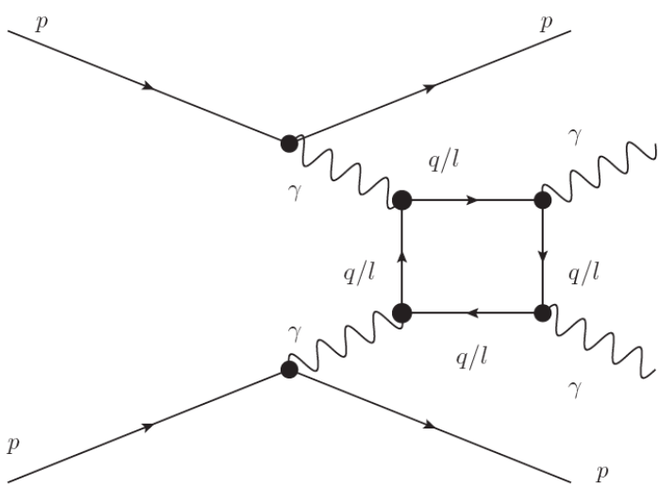
- Both rather unique topologies, and of phenomenological interest.

What can generate CEP?

• Generated by t-channel exchange with no colour flow - can occur in pure QED and QCD interaction:

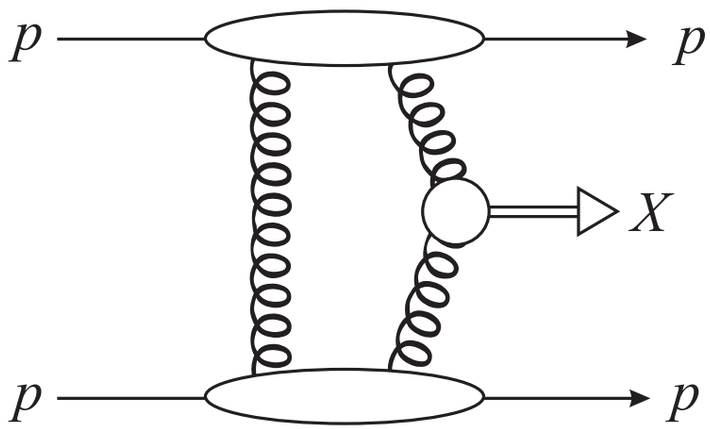
• Combination of these leads to three principle classes of process:

C-even, Couples to photons



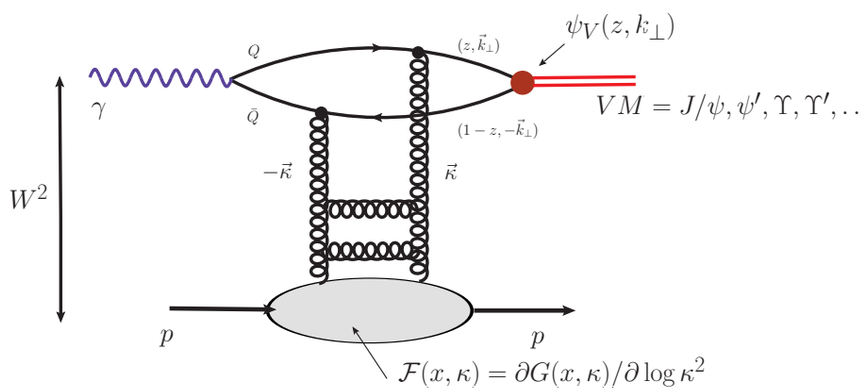
Photon-induced

C-even, couples to gluons



QCD-induced

C-odd, couples to photons + gluons

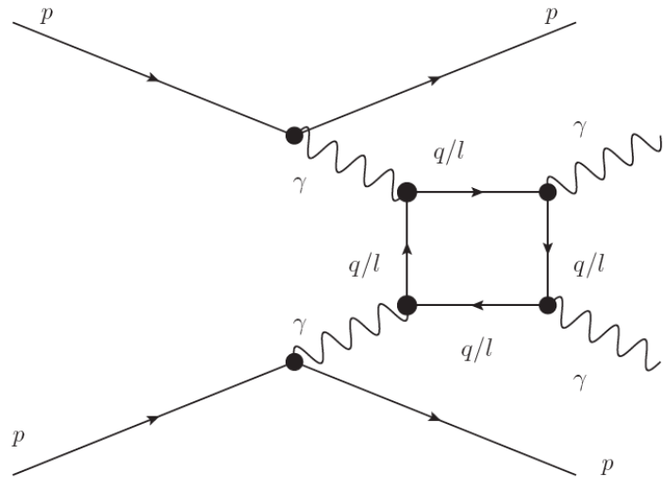


Photoproduction

Why is it interesting?

• In a nutshell, the 'clean' signature places useful constraints on production mechanism and backgrounds.

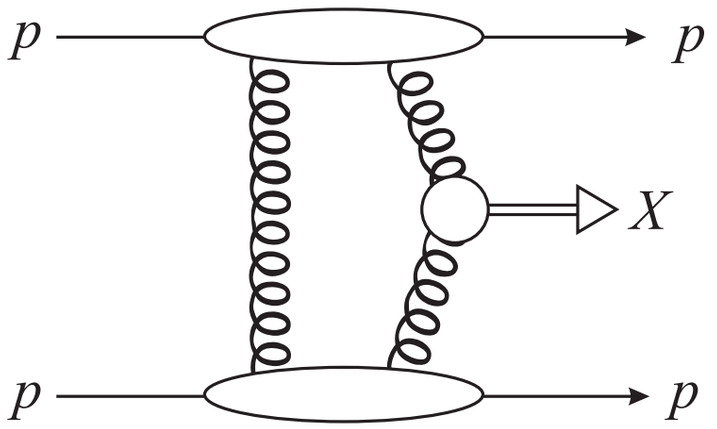
⋆ Photon-induced. QCD interactions between hadrons can be largely ignored, i.e. ~ pure QED production



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

gives increased sensitivity to EW couplings of SM particles and BSM in both pp and heavy ions.

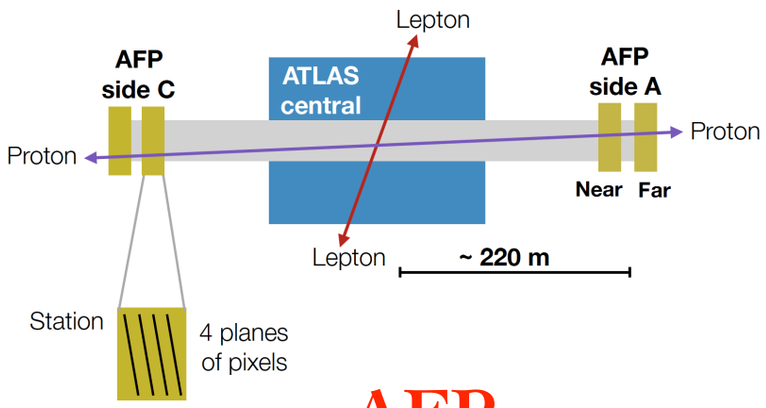
⋆ QCD-induced. Event topology leads to quantum number ($J_z^P = 0^+$) selection rule for produced state. Tests QCD in distinct regime.



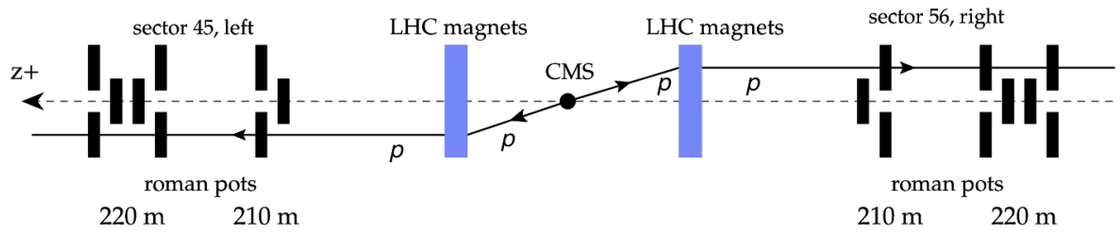
• In this talk will mainly focus on QCD-related elements, but not to forget significant results and potential for BSM searches.

Proton Tagging

- Outgoing intact protons can be detected in forward proton taggers. Situation ~200m from ATLAS and CMS IPs. Slide in (and out) close to the beam line.

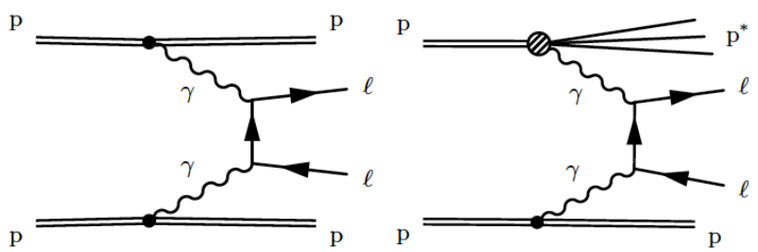


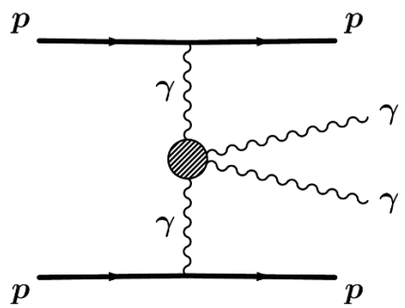
AFP



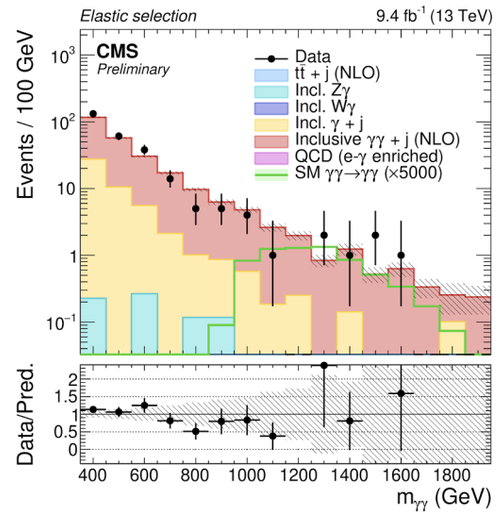
CT-PPS

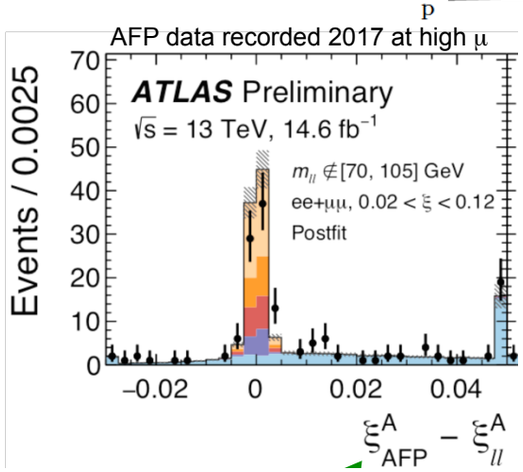
- Allows CEP to be selected. Reconstructed proton momenta - key event info.





ATLAS + CMS Highlights, ICHEP 2020



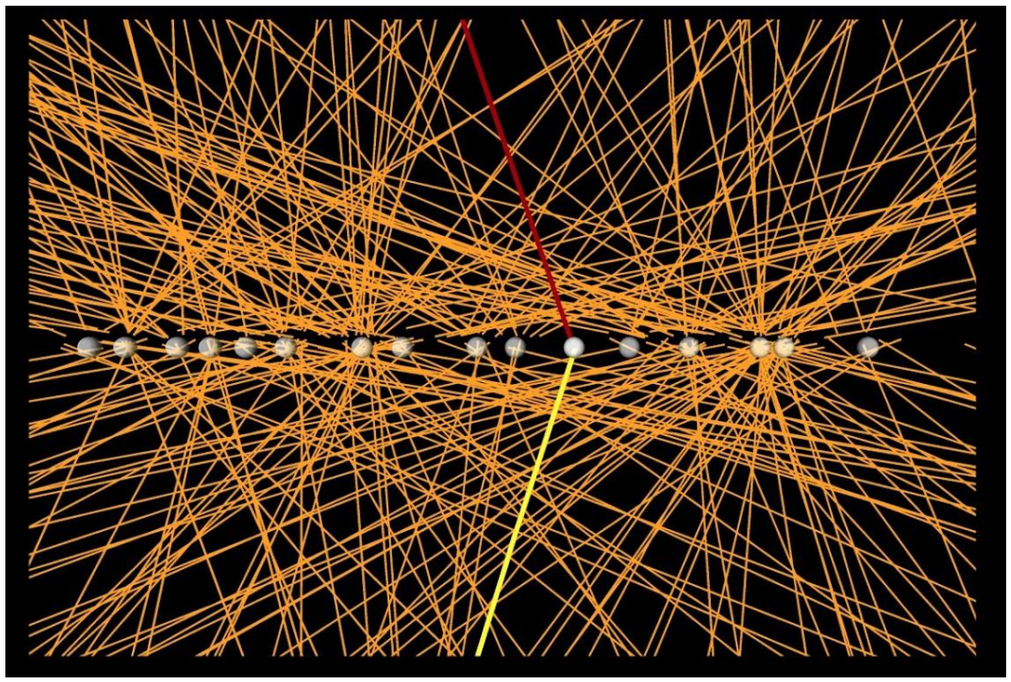


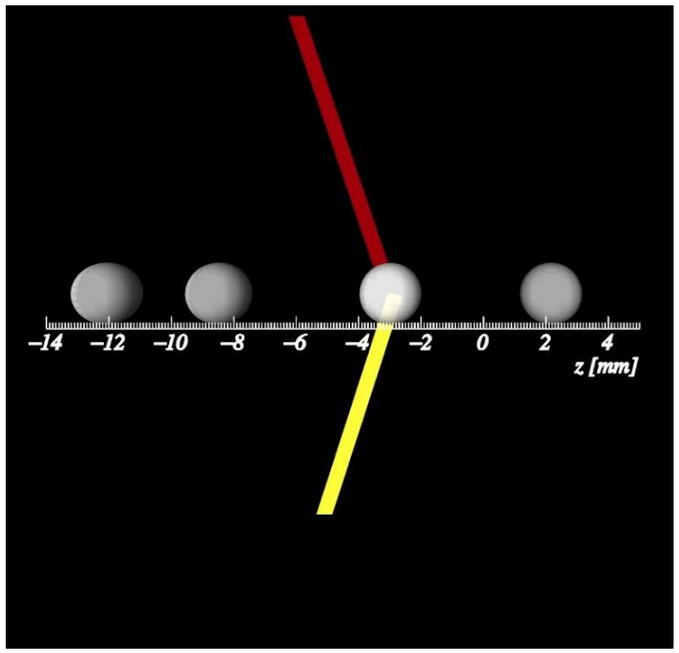
- Many analyses published and data being collected.

• During nominal LHC running can have multiple proton hits due to unassociated pile-up interactions.

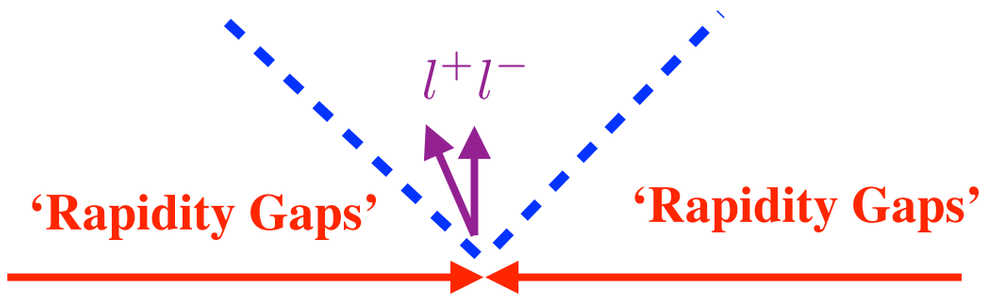
• Not a show-stopper. Proton arrival time can be measured and matched to central vertex position.

• Allows proton tagger to operate in high pile-up conditions.



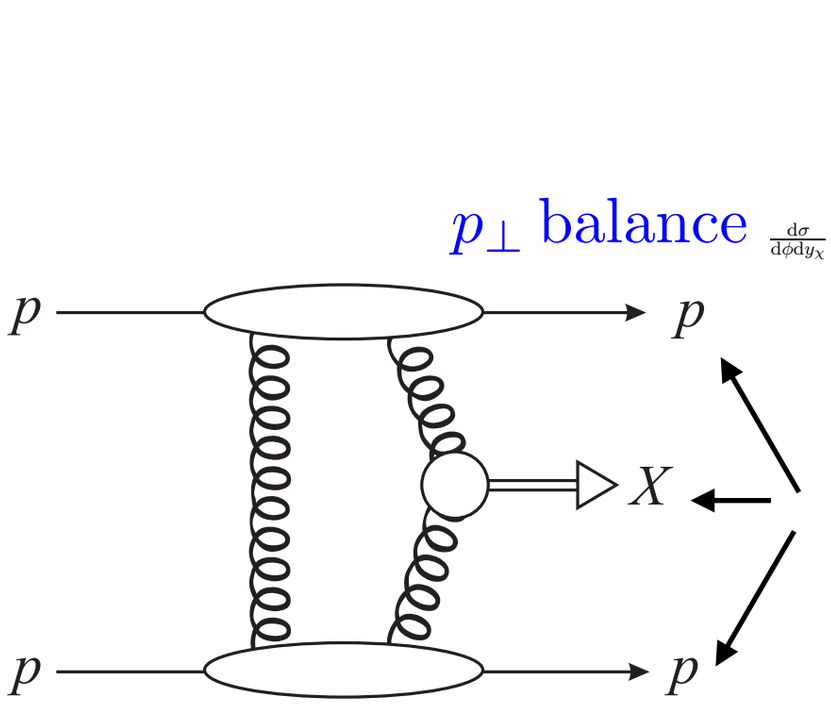


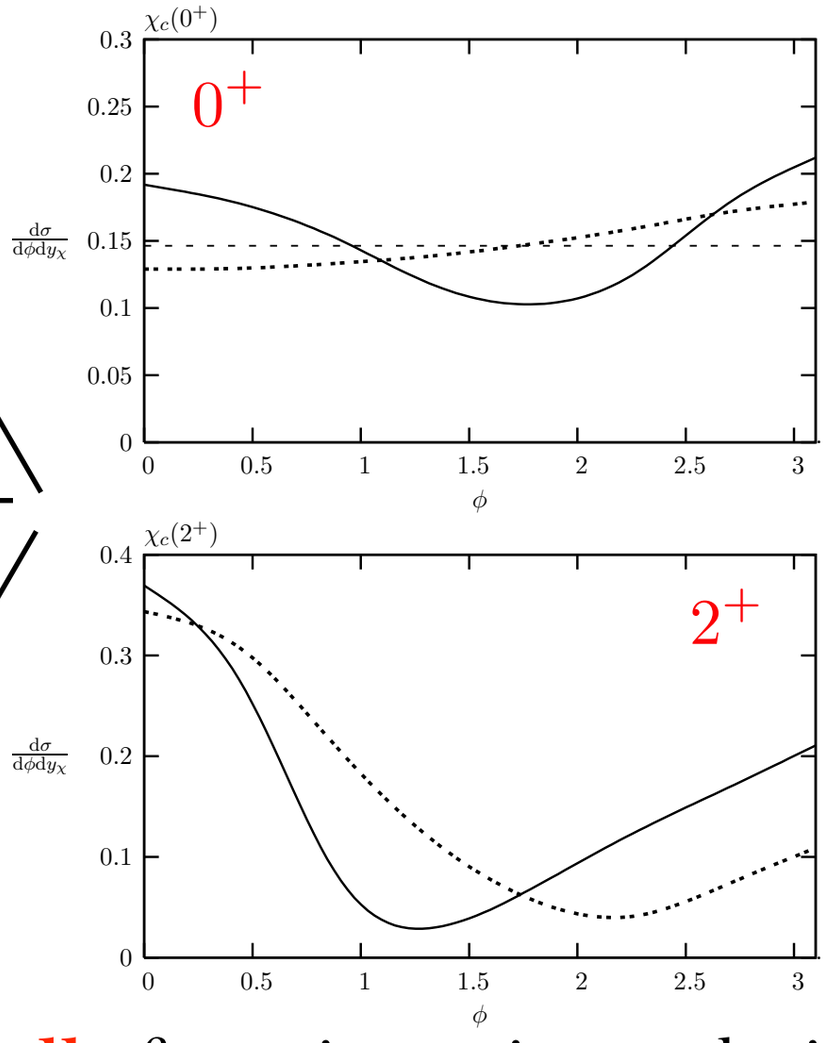
• Proton taggers not essential for selecting dominantly exclusive production: requiring vertices to be isolated kills inclusive production.

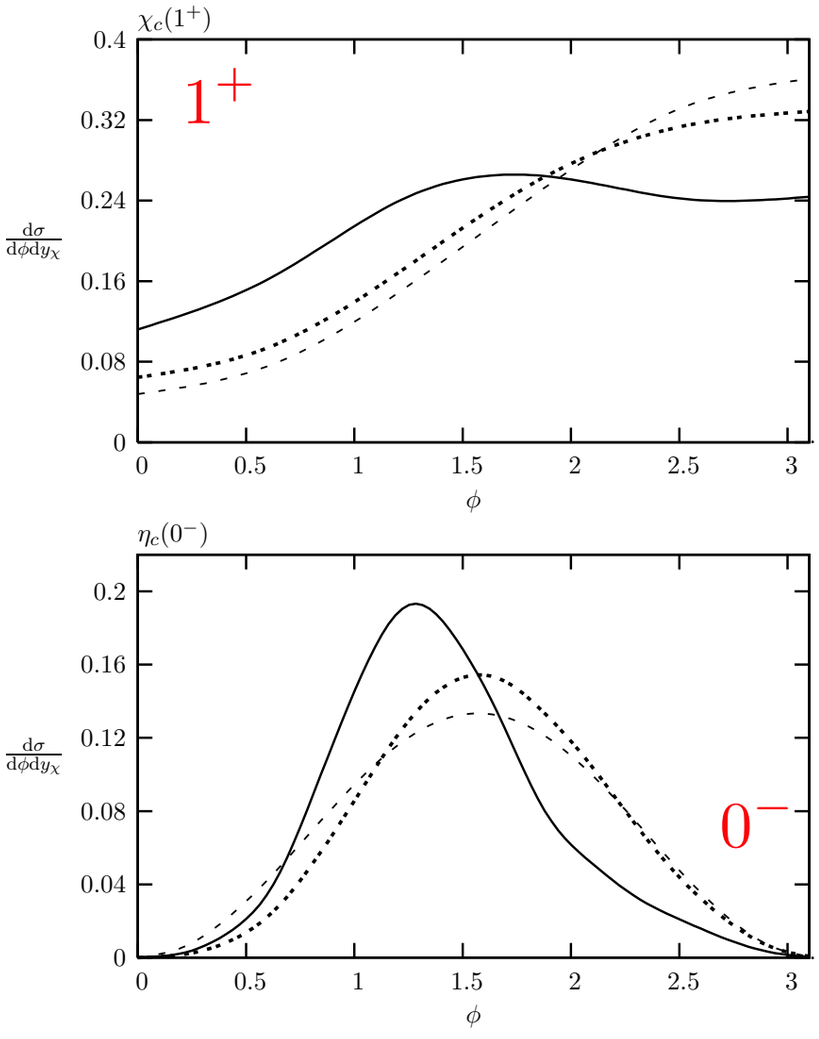


CEP and Tagged Protons

- For different object spin-parities, expect **distinct distributions** in the azimuthal angle ϕ between the outgoing proton $p_\perp$ vectors.







→ **Additional handle** for spin-parity analysis.

LHL, V.A. Khoze, M.G. Ryskin, Eur. Phys. J C69 (2010) 179-199

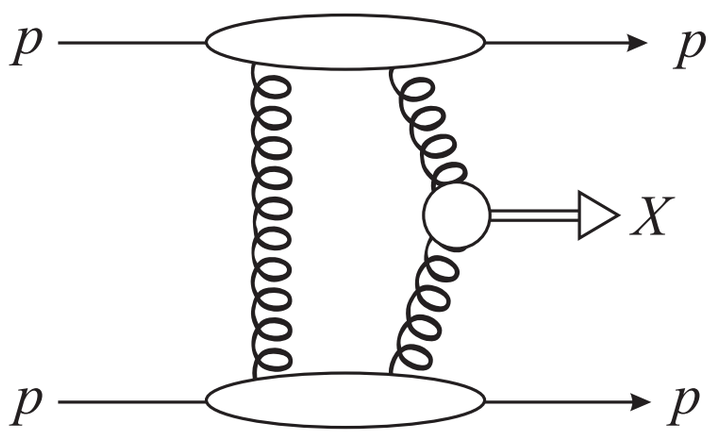
- In addition 'missing mass' of system M_X can be reconstructed from protons.

QCD-induced production

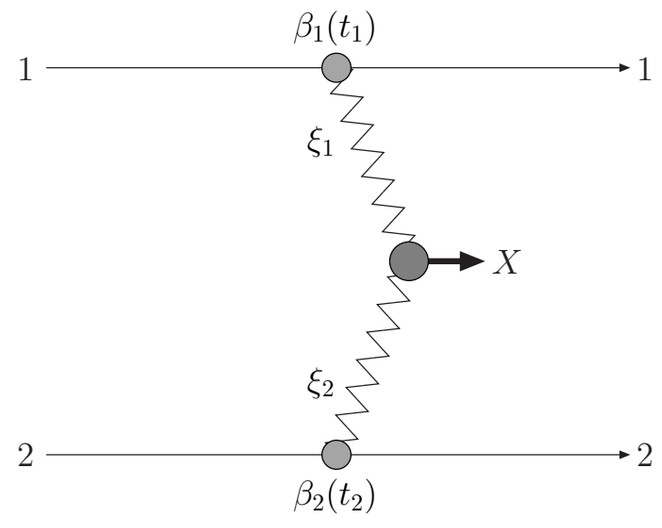
QCD-induced CEP

- Dominant mechanism for states that couple via strong interaction. How do we model it? Answer depends on scale of production:

  - For sufficiently large scale (~ object mass M_X), apply **perturbative** '**Durham**' model.
  - Mediated via colour-singlet gg exchange.



  - At lower scales (~ object mass M_X) pQCD description will break down.
  - Diffractive, so can apply well established tools of Regge theory **Double Pomeron Exchange** (**DPE**).



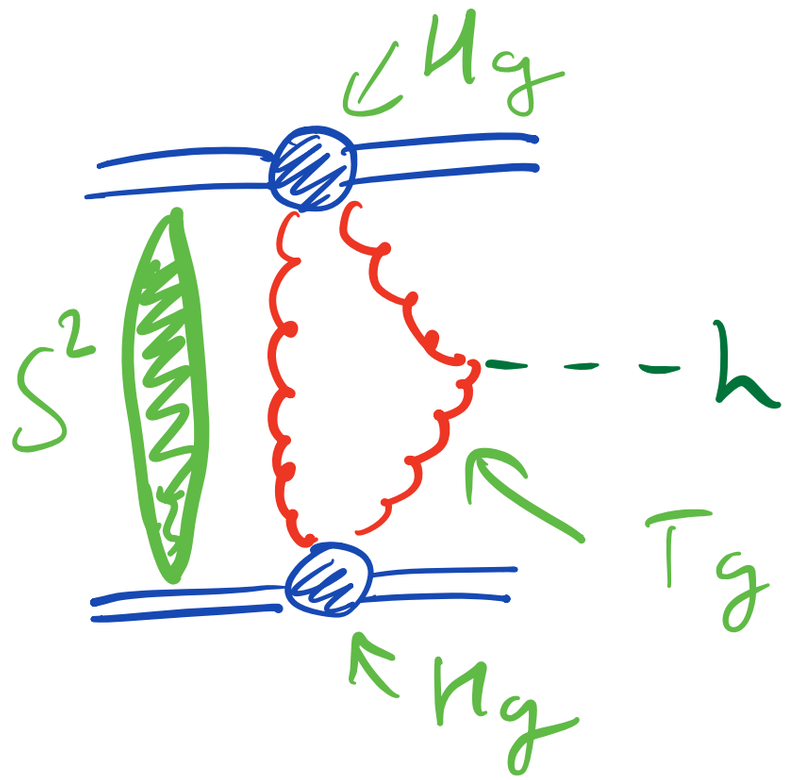
- Nature of the DPE to pQCD transition is open question.

Durham Model

• Long established, remains 'the' model of high scale QCD-induced CEP. In brief, cross section given in terms of:

★ Generalised gluon PDFs H_g - relatable to collinear gluon for CEP kinematics.

★ Sudakov factors $T_g(Q_\perp, \mu_F^2)$ - probability of no gluon emission.



★ `Survival factor' probability of no soft proton-proton interactions (no MPI).

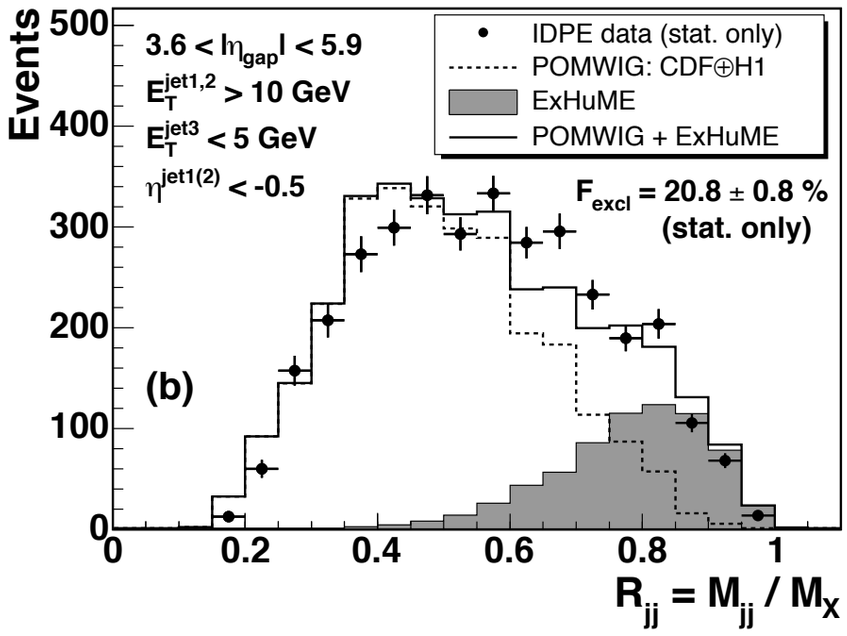
★ $gg \to X$ amplitudes, but dominantly only for $g(\pm)g(\pm) \to X$.

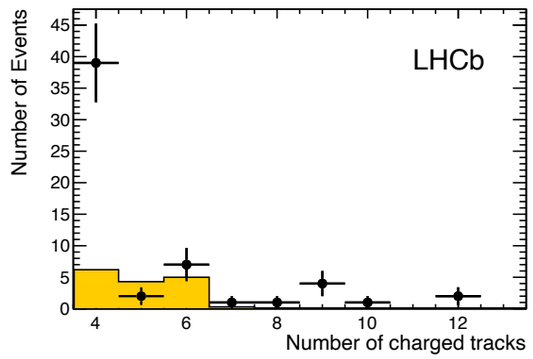
$$T = \pi^2 \int \frac{d^2\mathbf{Q}_\perp \, \overline{\mathcal{M}}}{\mathbf{Q}_\perp^2 (\mathbf{Q}_\perp - \mathbf{p}_{1_\perp})^2 (\mathbf{Q}_\perp + \mathbf{p}_{2_\perp})^2} \, f_g(x_1, x_1', Q_1^2, \mu_F^2; t_1) f_g(x_2, x_2', Q_2^2, \mu_F^2; t_2) \; ,$$

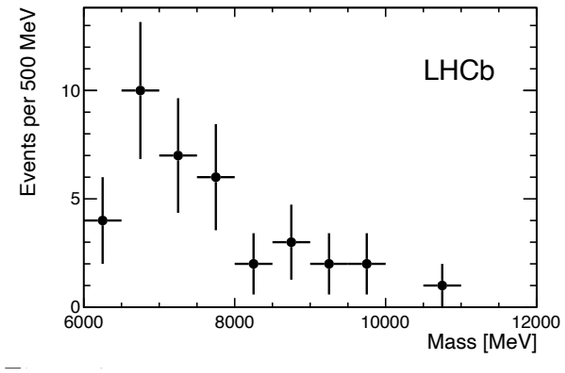
Where do we stand?

- Involves production of strongly interacting particles - experimentally more challenging. But range of data taken at LHC and Tevatron before it.

CDF, *Phys.Rev.D* 77 (2008) 052004



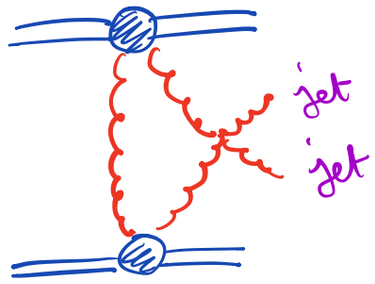




LHCb, *J.Phys.G* 41 (2014) 11, 115002

- Broadly consistent with Durham model approach.
- At LHC so far experimental results have focussed on lower mass objects, but high mass region also has great potential…

Exclusive Jets



- **Precisely defined** CEP mechanism $\longrightarrow$ colour singlet gg initial-state with certain $(++/--)$ helicity configurations ($J_z = 0$). In CEP:

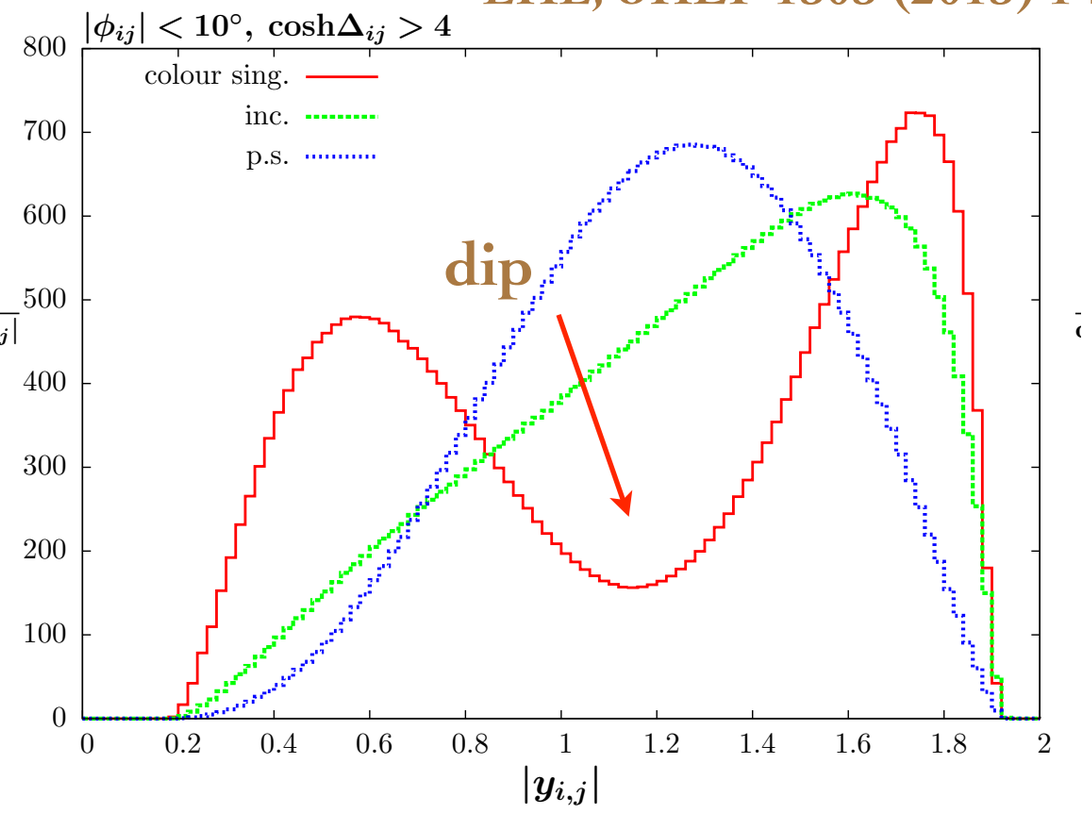
$gg \to q\overline{q}$: **Vanishes** for massless quarks - suppressed as $\sim m_q^2/M_{jj}^2$

$gg \to gg$: **Unsuppressed** $\longrightarrow$ gluon dominated jets.

- Possibility to study dominantly **isolated** gg jet production at LHC.

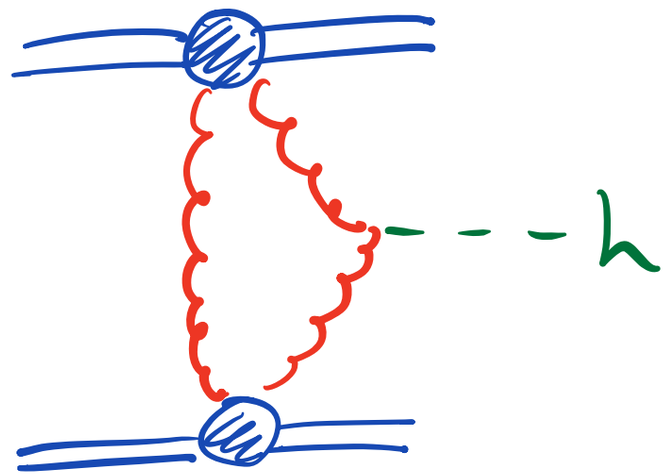
- For 3 jet production - '**radiation zeros**' appear. Only possible for colour-singlet gg initial-state. Seen in e.g. $W\gamma$ production, but never in pure QCD (yet).

LHL, JHEP 1505 (2015) 146



Exclusive Higgs

- Signal with a long history - first motivation of Durham model and initial experimental efforts.
- Original motivation:



  - ⋆ $h \to b\bar{b}$ favourable as QCD BG suppressed.
  - ⋆ Measure CP properties via proton correlations.

- Now already established, but nonetheless represents a unique Higgs production channel - worth pursuing in its own right.

T. Biekotter et al., arXiv:2303.12018…

- Not to forget: other hints of BSM resonances in mass region.

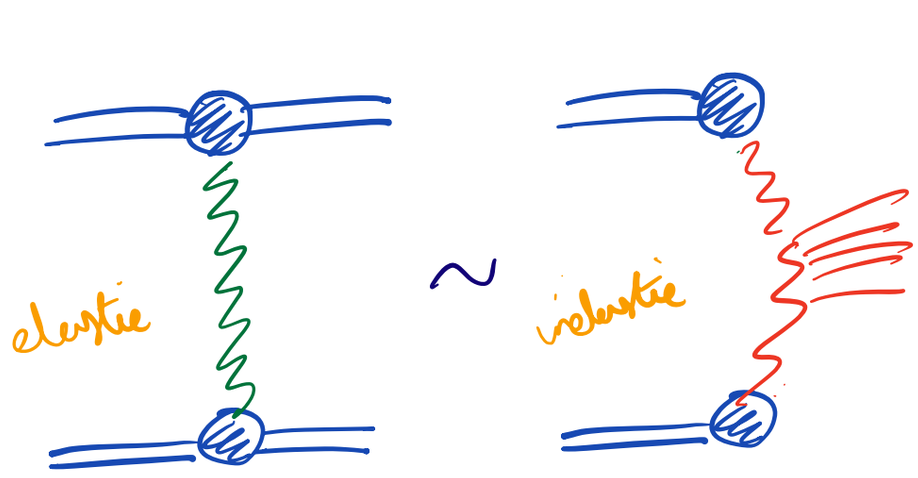
- LHC proton taggers do not have acceptance for SM Higgs with two tagged protons, but possibility for new detectors (~ 400m) under examination during HL-LHC.

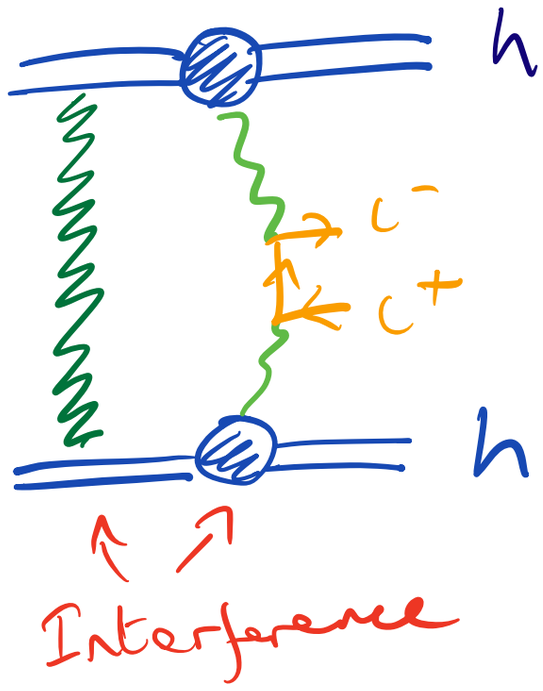
Low Scale Processes - soft QCD

- Key element of CEP cross section is the survival factor probability of no additional particle production.

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

- Fundamentally soft QCD object - requires tuned phenomenological model.
- Not simply a multiplicative constant. Impacts on central kinematics but also azimuthal correlations between outgoing protons.



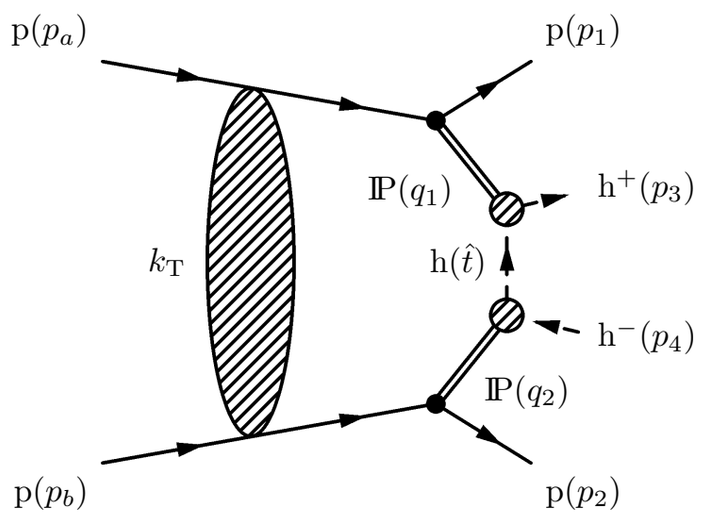


induces dips in proton ϕ distributions.

$\longrightarrow$ Direct and differential sensitivity to modelling of soft proton interactions

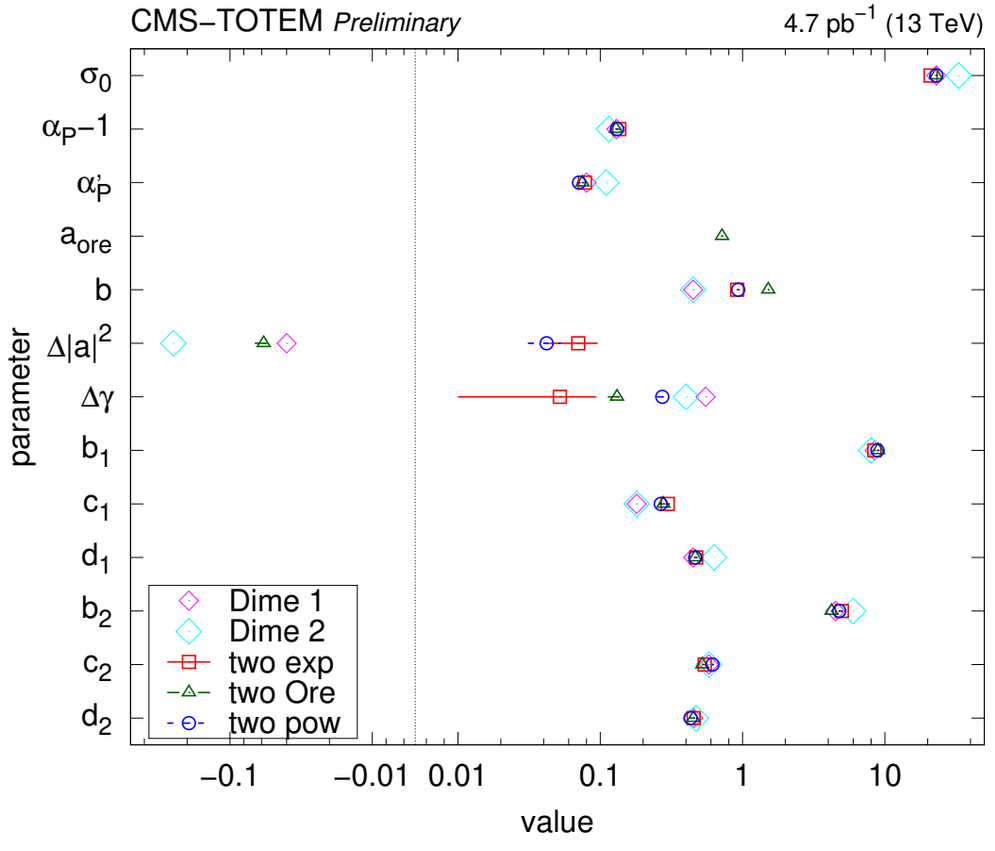
CMS PAS SMP-21-004, TOTEM NOTE 2023-001

- Effect predicted for long time, and measured for first time very recently by CMS-TOTEM in CEP of charged hadron ($\pi^+\pi^-, K^+K^-, p\bar{p}$) pairs in association with tagged outgoing protons.



- Detailed multi-differential data taken: full kinematics of the $2 \to 4$ process measured!
- Soft proton-proton interactions and internal proton structure affect this differentially.

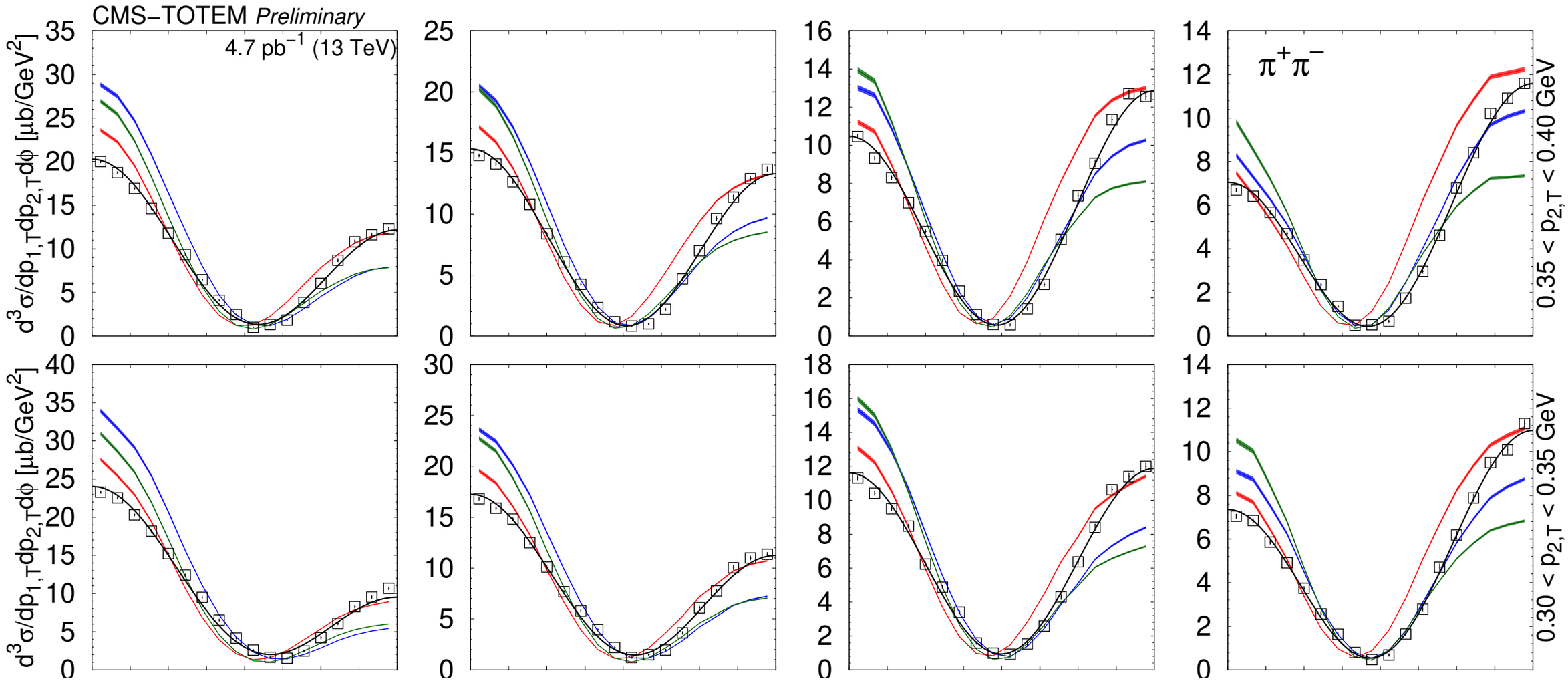
- Allows multi-dimensional fit to parameters describing low energy proton structure and interactions.



LHL, V.A. Khoze, M.G. Ryskin
***Eur.Phys.J.C* 74 (2014) 2848**

See also: CDF *Phys. Rev. D* 91 (2015) 091101, STAR JHEP 07 (2020) ATLAS EPJC 83 (2023) 627, CMS Eur. Phys. J. C 80 (2020) 718

- Proton azimuthal correlations mapped out - complex dip structure observed for first time. Direct result of soft QCD!



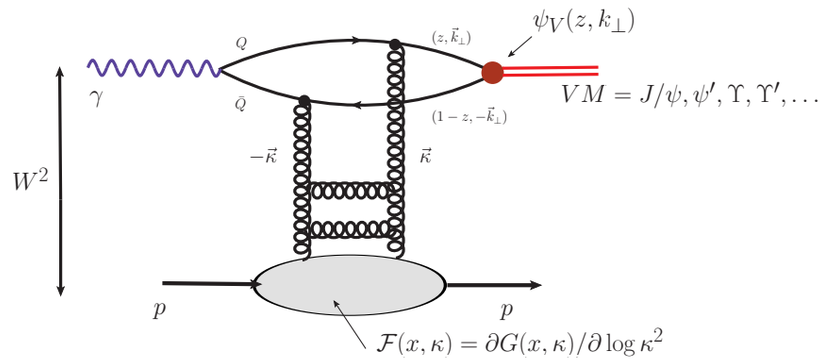
- Not the only relevant low energy QCD phenomena: can look for **glueballs** and **instanton** production in CEP.

Backup

Photoproduction

Quarkonia

- Large cross sections for the production of C-odd quarkonia ($J/\psi, \psi', \Upsilon...$) in photoproduction:



- Well motivated theoretically:

★ Mass scale ($\sim m_{VM}$) such that pQCD approach may be tried.

★ Test of different approaches to QCD factorization - collinear vs. high-energy

★ Sensitive to gluon $x \sim 10^{-6}$ - probe of gluon PDF in unconstrained region and/or saturation?

★ Can measured in pp, pA, AA - proton and nuclear structure probed.

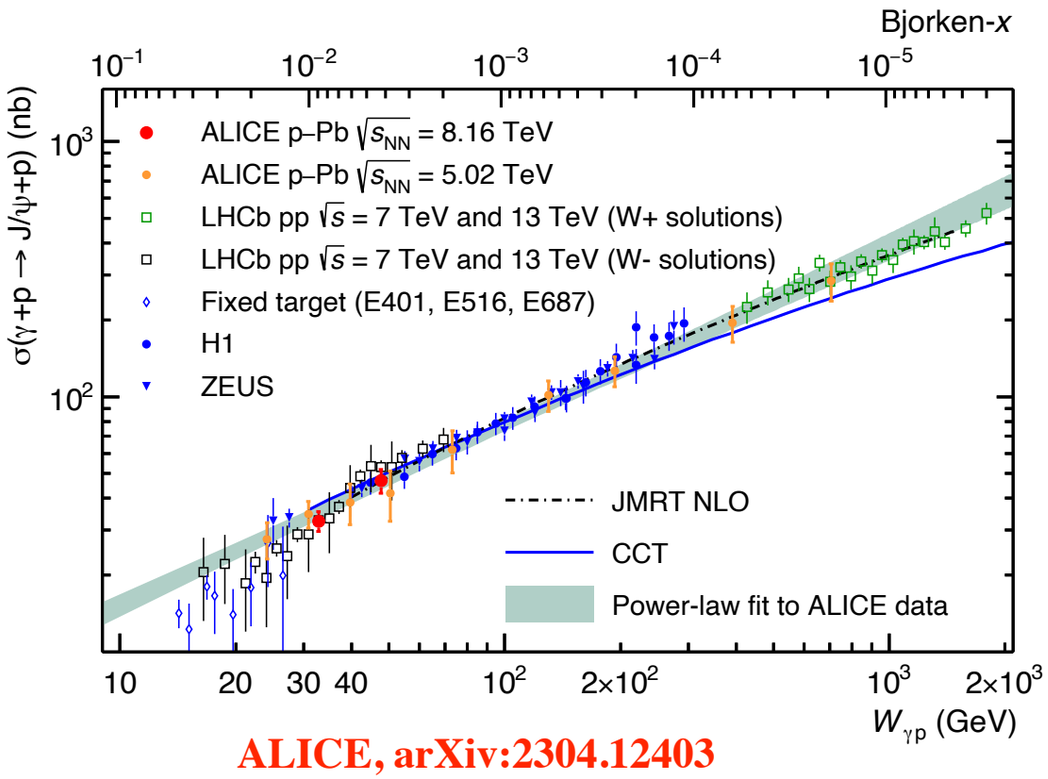
- Much recent theoretical progress:

  ⋆ Investigations for stabilising the NLO collinear prediction and applications to pp, pA and AA. **K. Eskola et al., arXiv:2303.03007, *Phys.Rev.C* 107 (2023) 4, 044912, C. Flett et al., *Phys.Rev.D* 106 (2022) 7, 074021…**

  ⋆ Full NLO calculation in high-energy factorization. **H. Mantysaari and J. Pentalla, *JHEP* 08 (2022) 247…**

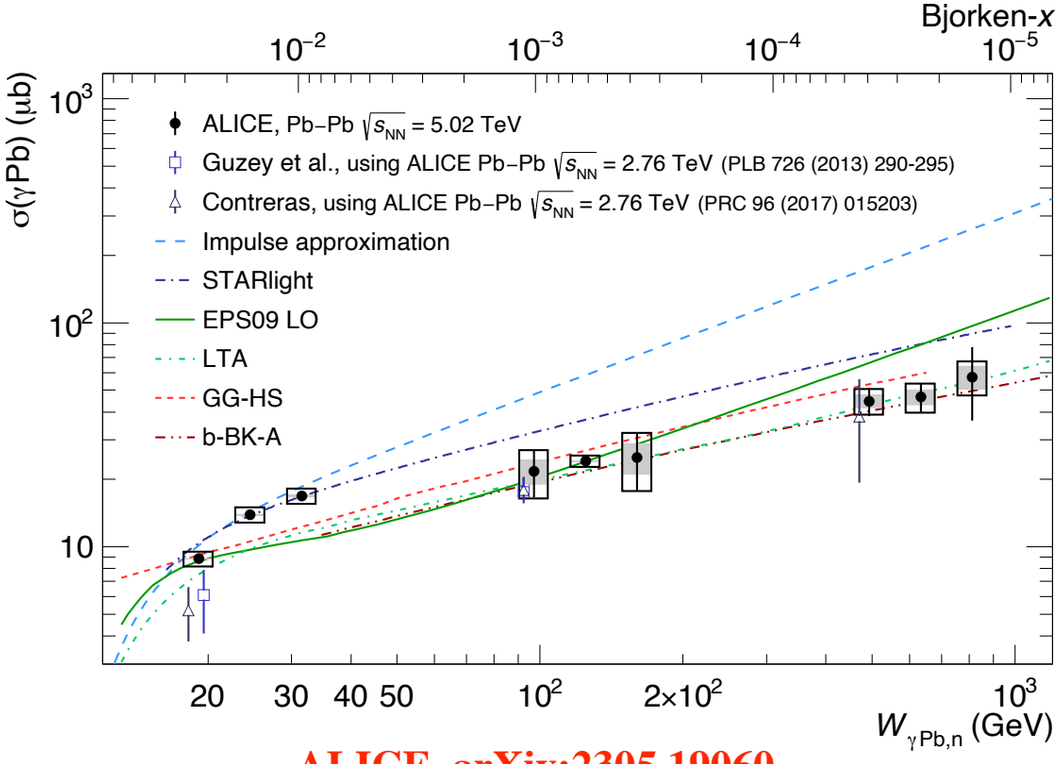
- As well as large dataset collected in pp, pA and AA. **CMS, arXiv:2303.1694, ALICE arXiv:2305.19060, LHCb JHEP, 10:167, 2018…**

⋆ Data in pp, pA so far well described by collinear QCD:



ALICE, arXiv:2304.12403

⋆ Data in AA may hint at gluon saturation, but model dependence large!



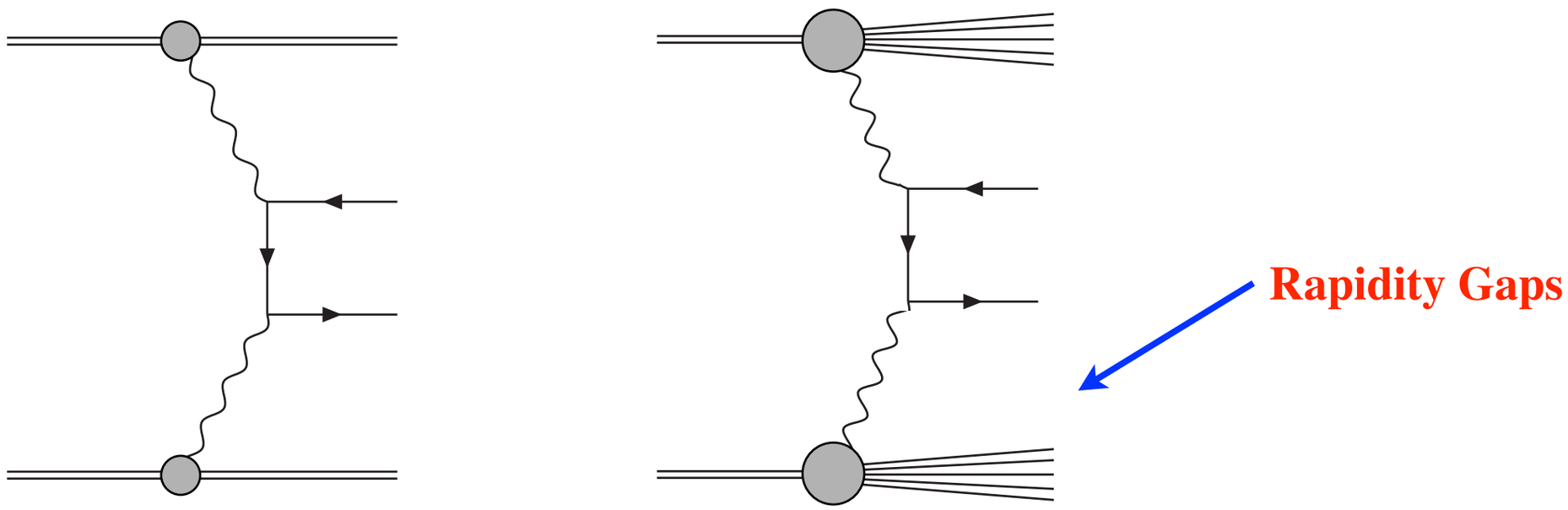
ALICE, arXiv:2305.19060

- Fast developing field where data will have significant input.

Photon-Initiated CEP

Photon-Initiated CEP

- Photon-initiated (PI) production most natural candidate CEP: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state.



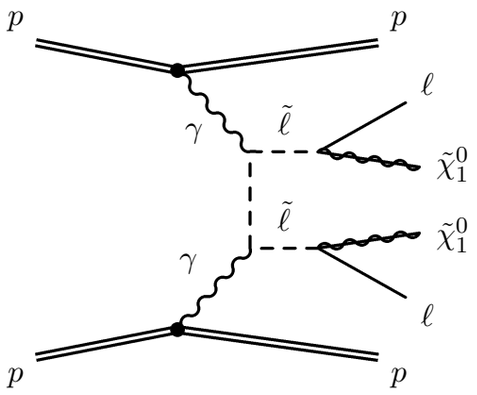
- Clean, ~ pure **QED** process:

$$\Rightarrow \text{ The LHC as a } \gamma\gamma \text{ collider!}$$

- Well understood initial-state $\Rightarrow$ clean probe of BSM and SM EW couplings…

★ Probe of BSM:

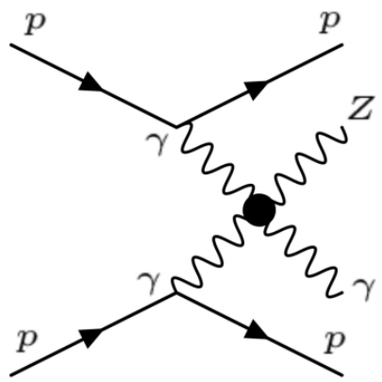
Compressed SUSY



LHL et al., JHEP 1904 (2019) 010

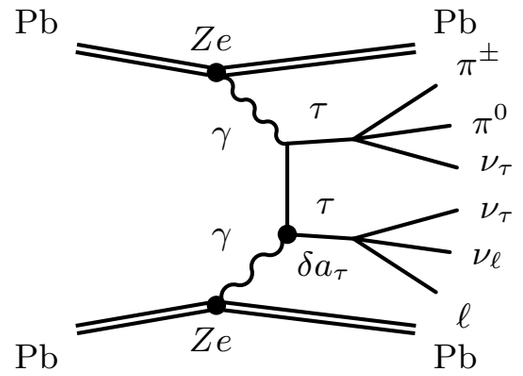
L. Beresford and J. Liu, PRL 123 (2019) no.14

Anomalous couplings



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

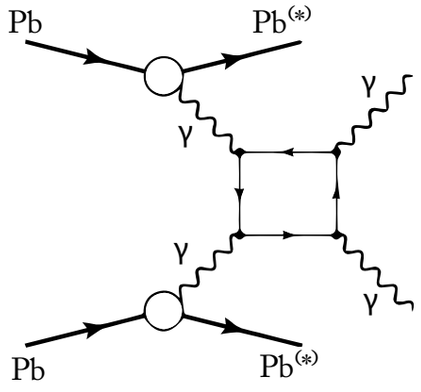
tau g-2



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

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

LbyL scattering/ALPS

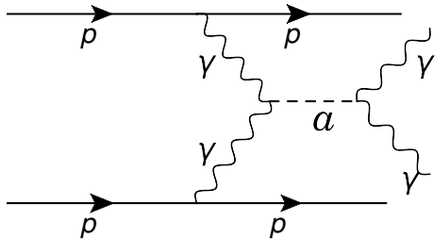


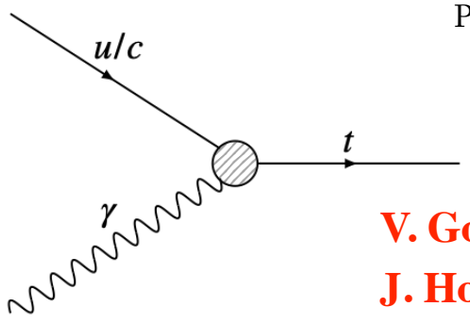
C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

Axion-like Particles

LHL and M. Tasevsky, arXiv:2208.10526

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





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

J. Howarth, arXiv:2008.04249

★ **Probe** of the top sector.

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

LHL et al., EPJC 76 (2016) no. 5, 255, LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925

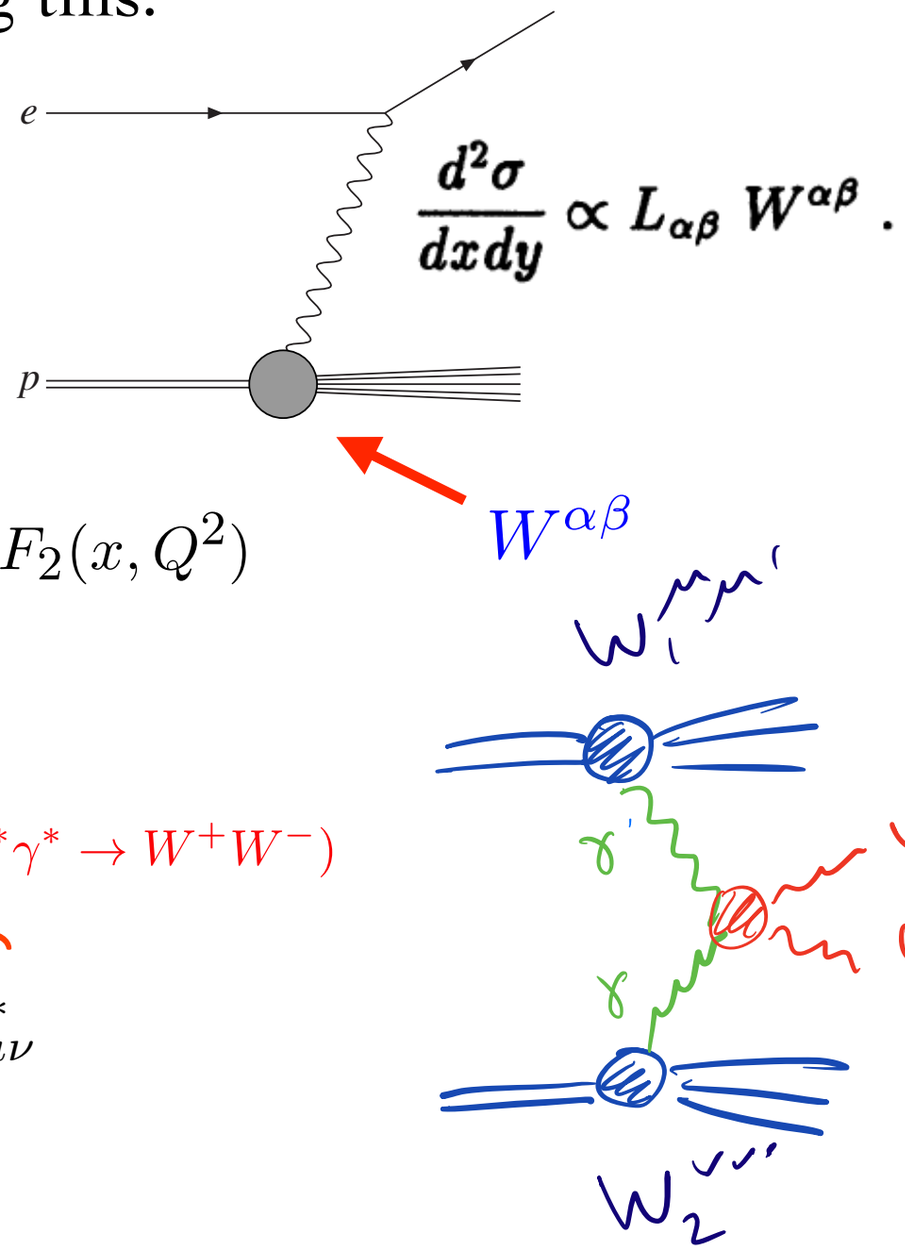
L. Forthomme et al., PLB 789 (2019) 300-307

LHC as a $\gamma\gamma$ collider?

- How true is this? How well can we model PI production? Do we not need to worry about the (strongly interacting) initial-state protons.

- Quite some progress in past few years to clarifying this.

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



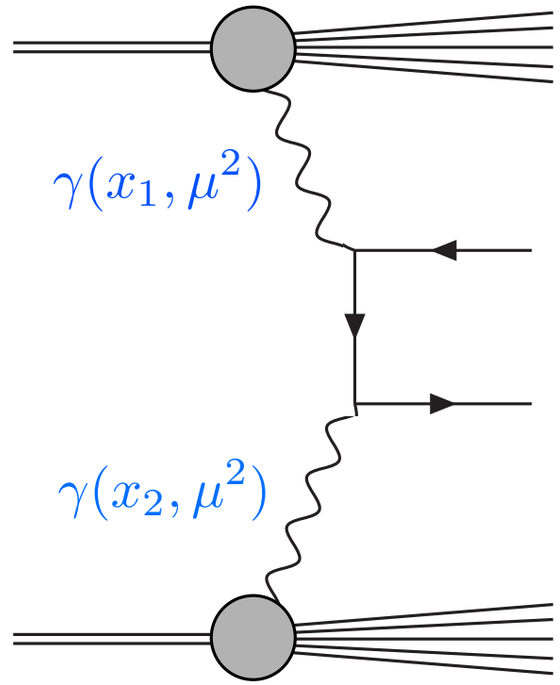
- Structure functions parameterise the $\gamma p \to X$ vertex:

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x, Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P \cdot q} F_2(x, Q^2)$$

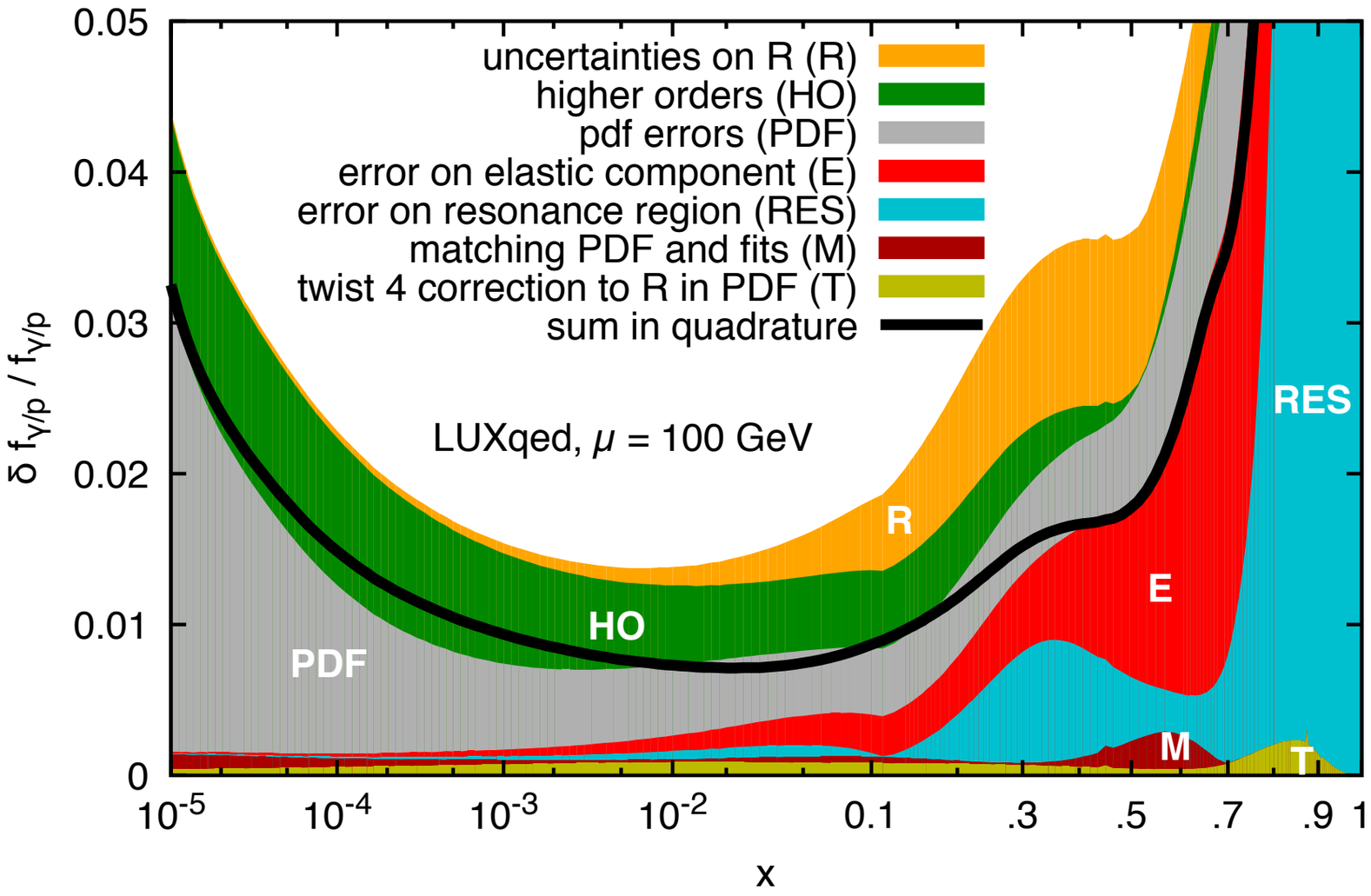
- Use same idea as for DIS to write:

$$\sigma \sim \int \overbrace{\mathrm{d}x_1 \mathrm{d}x_2 \, \mathrm{d}^2 q_{1\perp} \, \mathrm{d}^2 q_{2\perp}}^{\textbf{Photon } x, Q^2} \; \overbrace{W_1^{\mu\mu'}}^{\gamma^* p \to X} \; \overbrace{W_2^{\nu\nu'}}^{\sim \sigma(\gamma^*\gamma^* \to W^+W^-)} M_{\mu'\nu'} M^*_{\mu\nu}$$

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



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



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

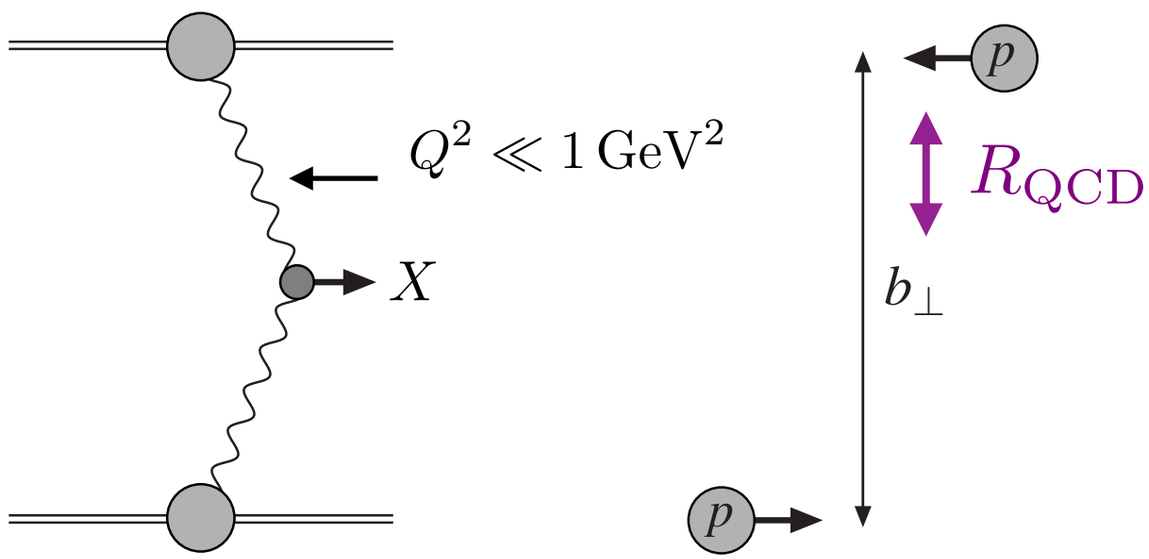
Survival Factor

- '**Survival factor**' = probability of no additional inelastic hadron-hadron interactions.
- In general requires understanding of proton + strong interaction in **non-perturbative** regime, i.e. sizeable uncertainty.

LHL el al., *SciPost Phys.* 11 (2021) 064

- Not the case for PI production - studied in detail recently.
- Basic idea: elastic PI production a **special case**: quasi-real photon large average pp impact parameter $b_\perp \gg R_{\rm QCD}$, and $S^2 \sim 1$.

$Q^2 \sim 0 \Rightarrow$



- In more detail…

LHL el al., *SciPost Phys.* 11 (2021) 064

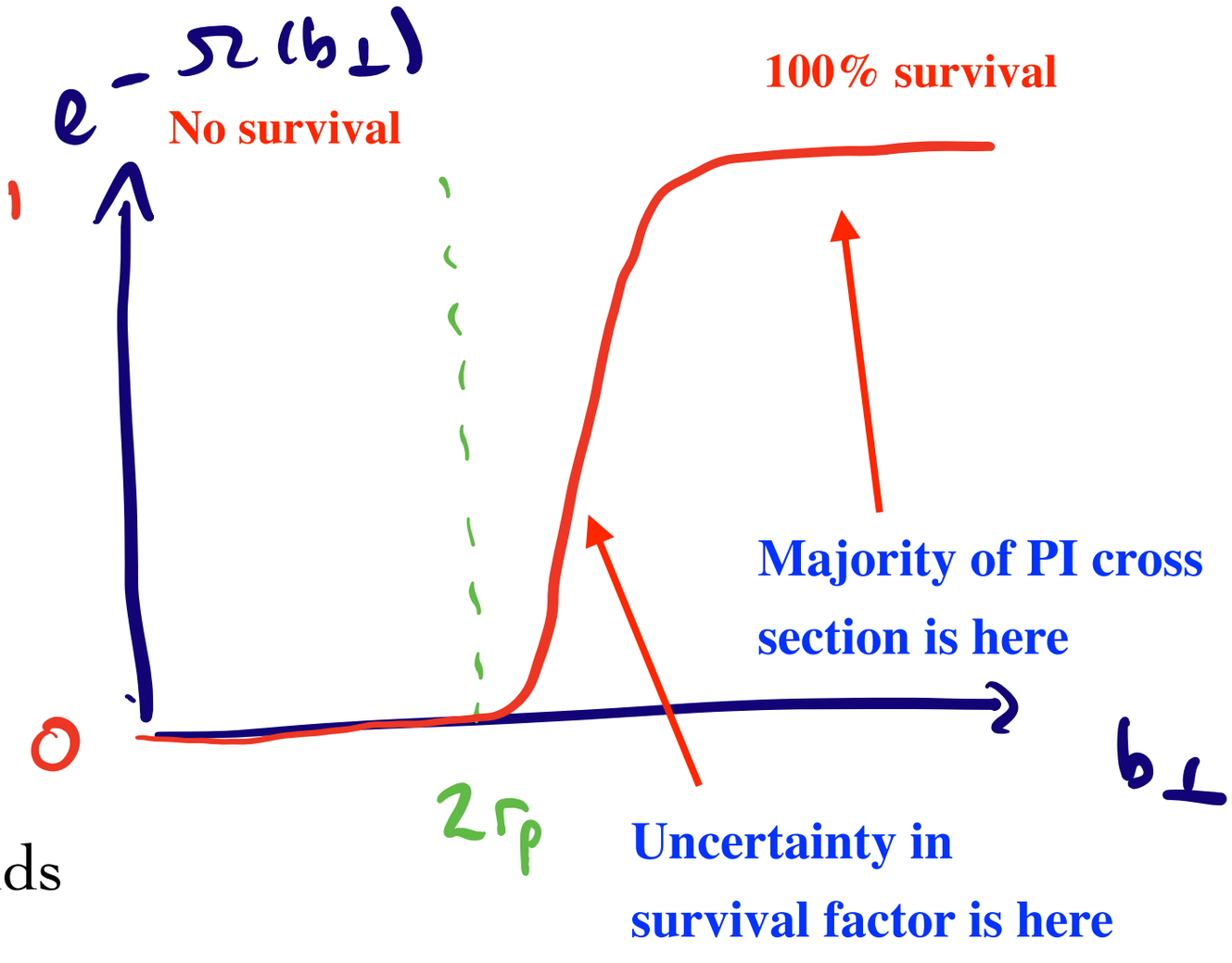
- Impact parameter picture can be formulated mathematically:

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

PI amplitude **Survival Factor**

- Schematically:

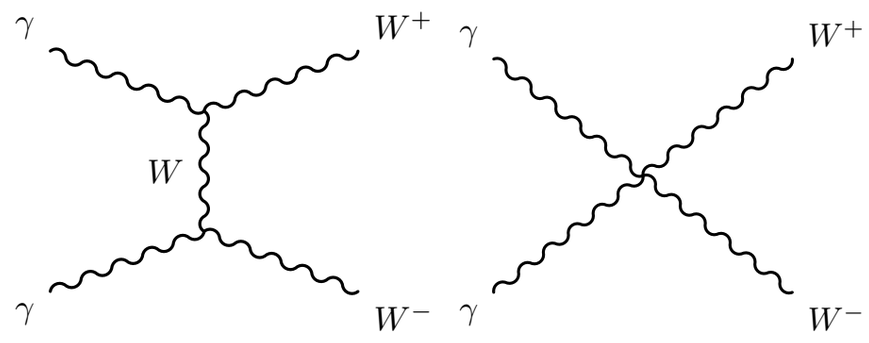
→ Survival factor is ~ 1 and with small uncertainty!



- On further analysis, still ~ holds for single dissociation but not double dissociation;

WW production

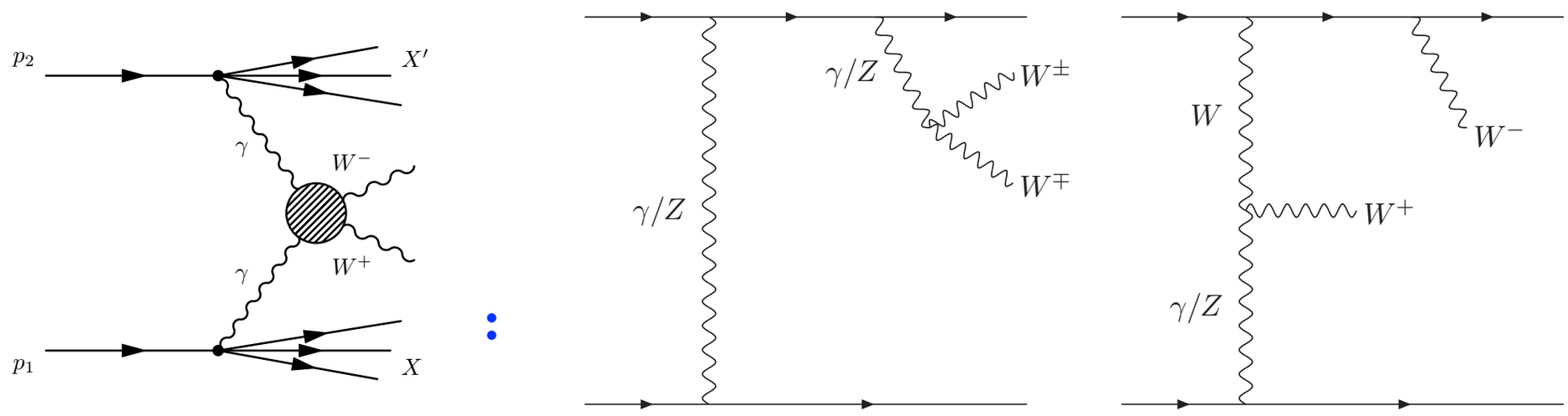
- Recent topical example. Effectively 'inverse VBS': instead of tagging jets ask for no activity to isolate:



and probe (anomalous?) EW couplings of W.

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

- Only recently been fully understood. Subtleties related to non-PI diagrams:



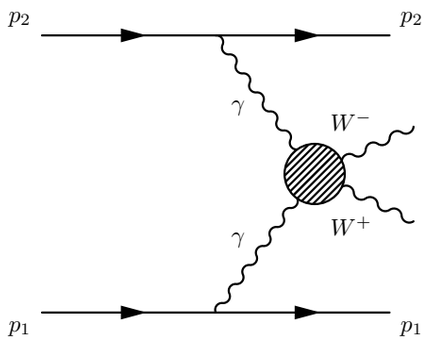
require some care, but can be accounted for, maintaining precision in predictions.

Recent data

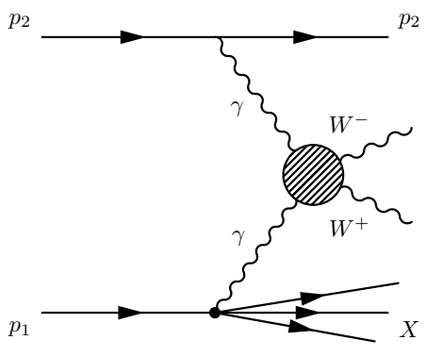
- Evidence for such '**semi-exclusive**' W^+W^- production in leptonic channel seen by ATLAS + CMS previously.
- Recently: first observation by **ATLAS**, at 13 TeV, via rapidity veto.

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

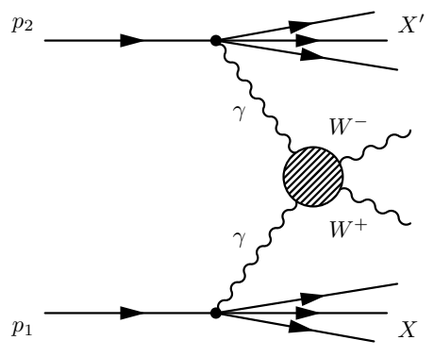
Elastic

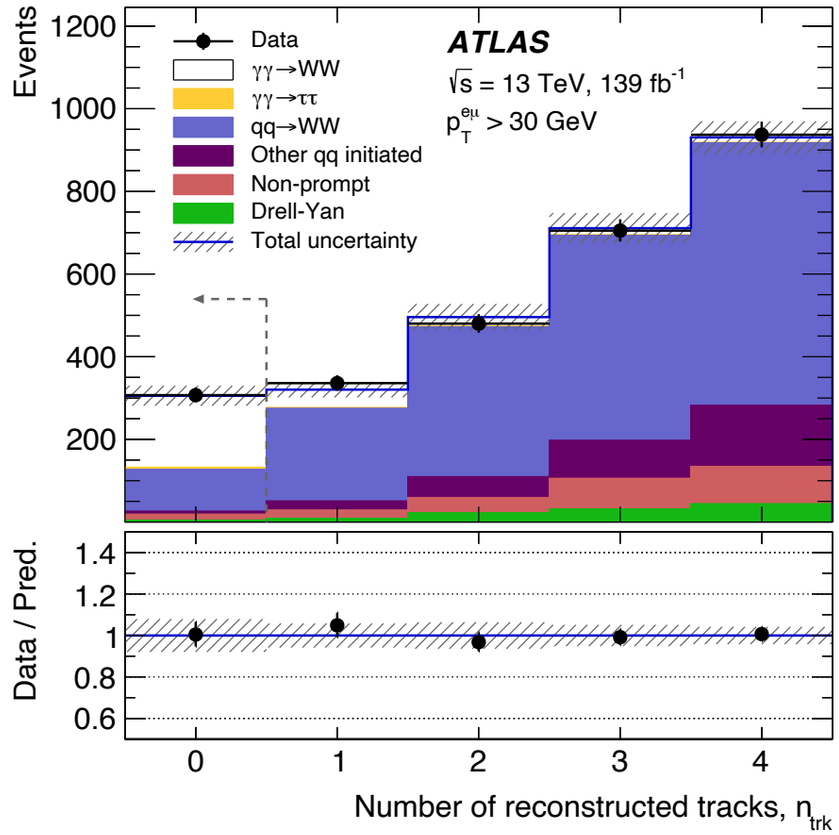


Single Dissociative



Double Dissociative



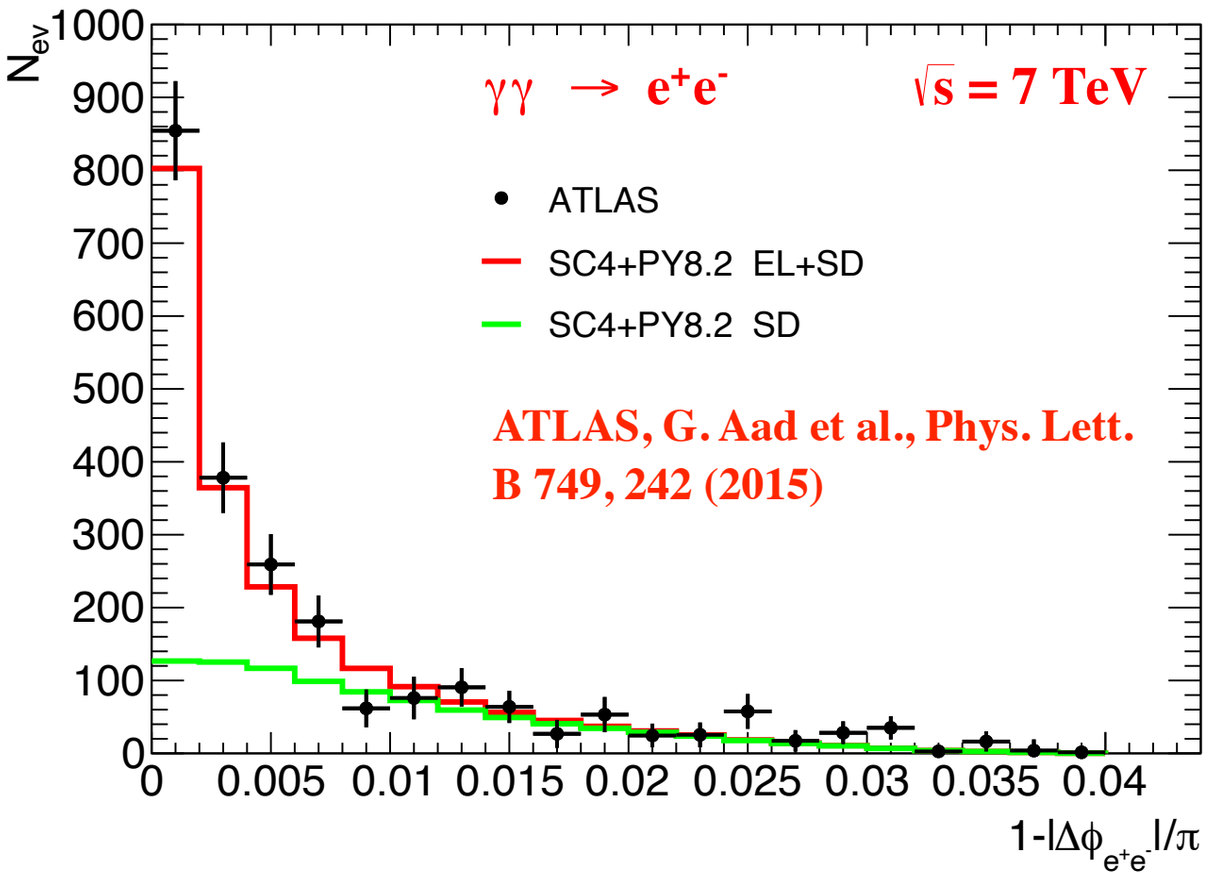


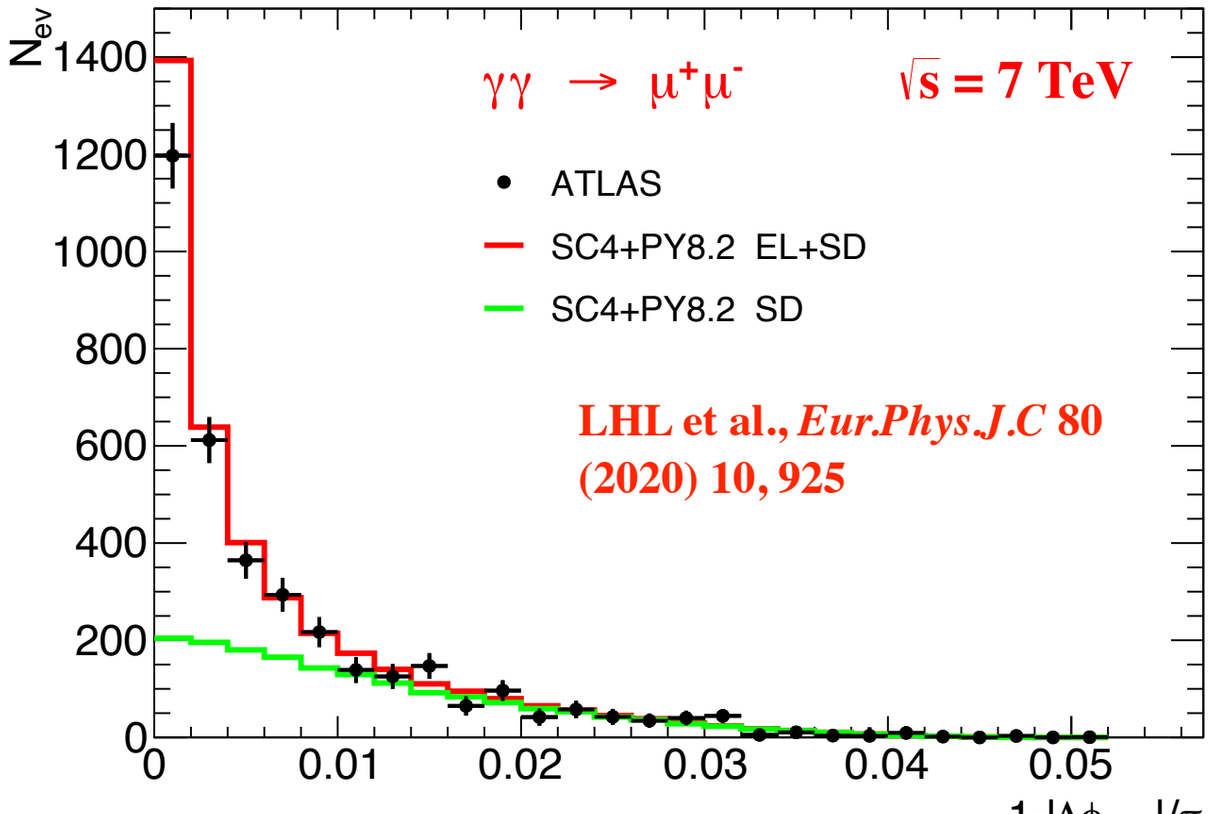
ATLAS, Phys. Lett. B 816, 136190 (2021)

- Agrees well with theory, after including all diagrams.
- So far just a single number. Next steps: (multi)-differential, EFT analysis…

Lepton pair production

- Semi-exclusive lepton pair production extensively measured by ATLAS and CMS, with and without proton tag. Agreement rather good…





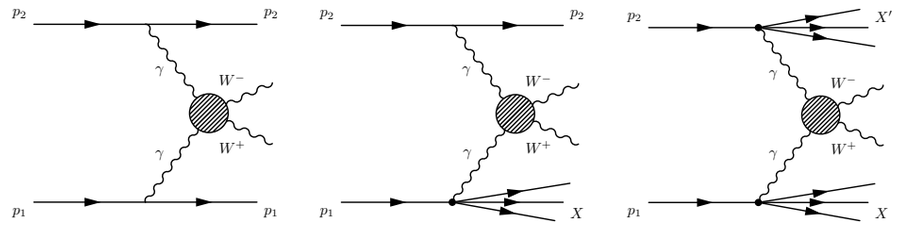
- But not perfect!
- Various theory refinements to consider, but of relevance here…

Backup

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

Role of QCD/MC modelling?



- For purely elastic production modelling straightforward.

- For dissociative production precise data comparison requires particle-level treatment of dissociation system $\longrightarrow$ interface to general-purpose MC.

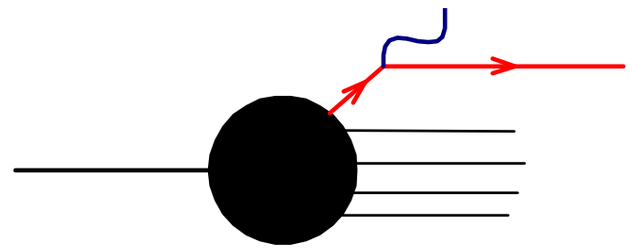
- First consistent attempt in SuperChic 4, with encouraging results, but:

  ★ Interface to MC (Pythia) requires approximations- map back to LO kinematics.

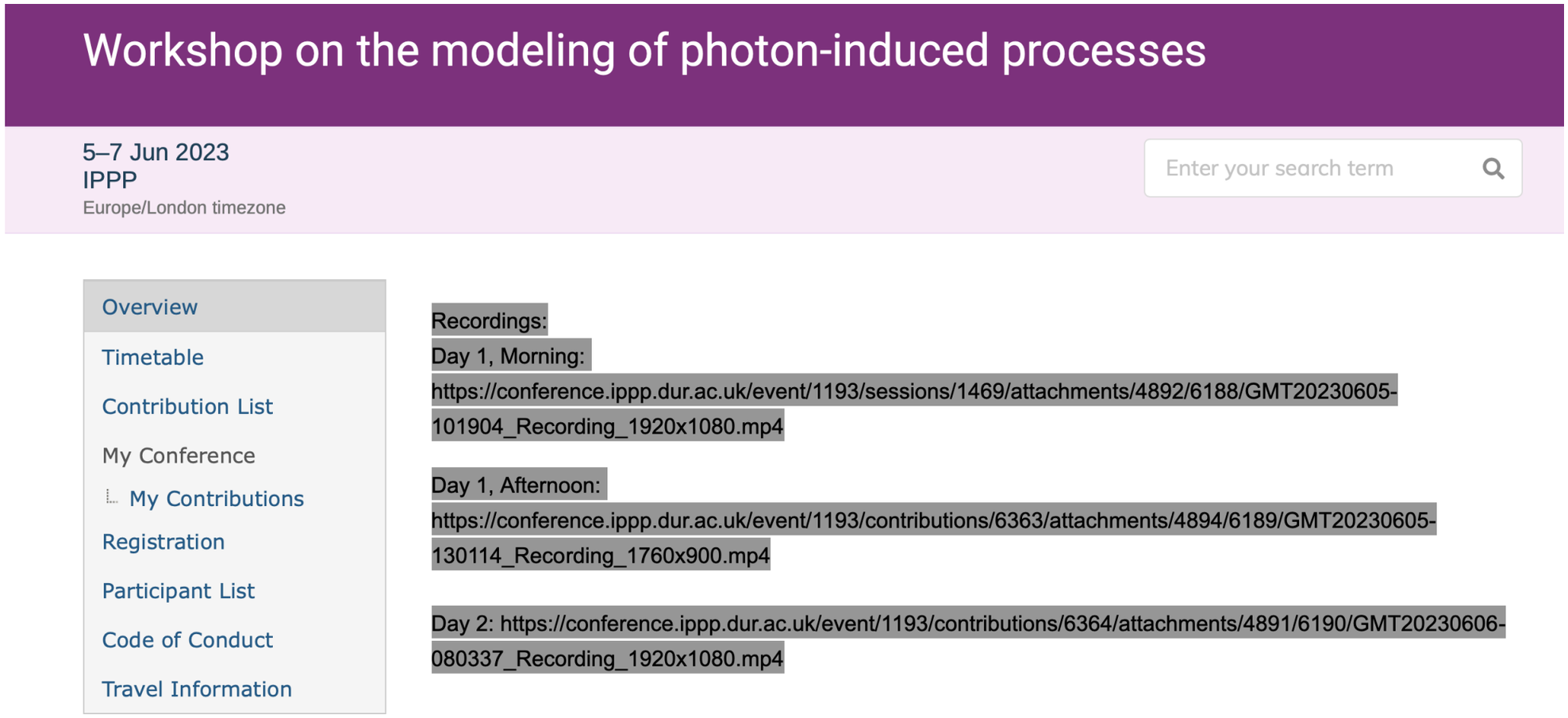
  ★ How much model dependence is there? Requires further work/interfacing to other MCs/showers.

  ★ Survival factor? Modelled theoretically, but what if we do allow MPI for a PI process? Collision impact parameter different from standard event - dedicated work needed.

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



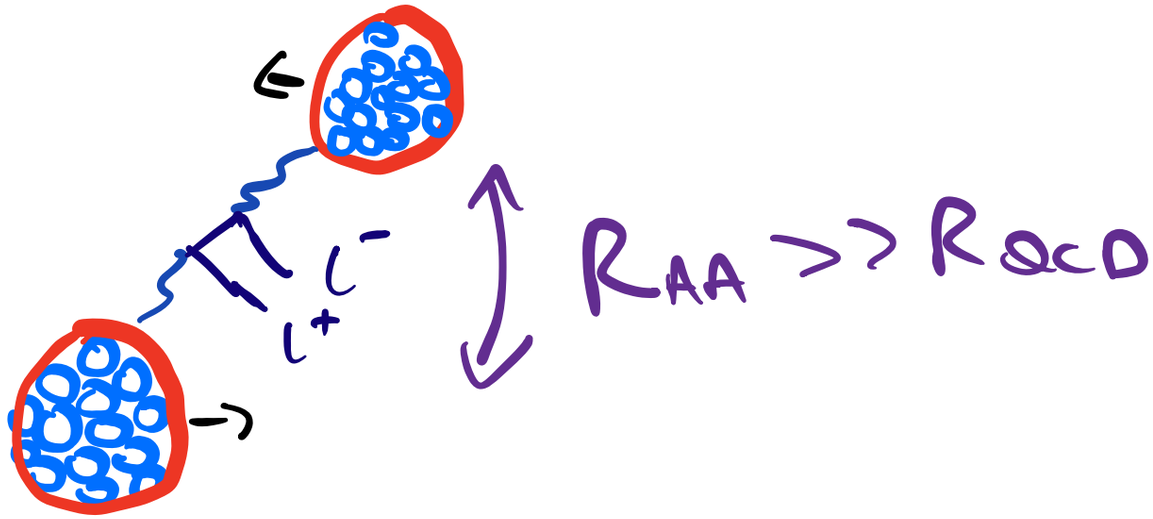
- Quite a bit of work to do yet to fully exploit semi-exclusive data - focus of ongoing collaborative efforts.

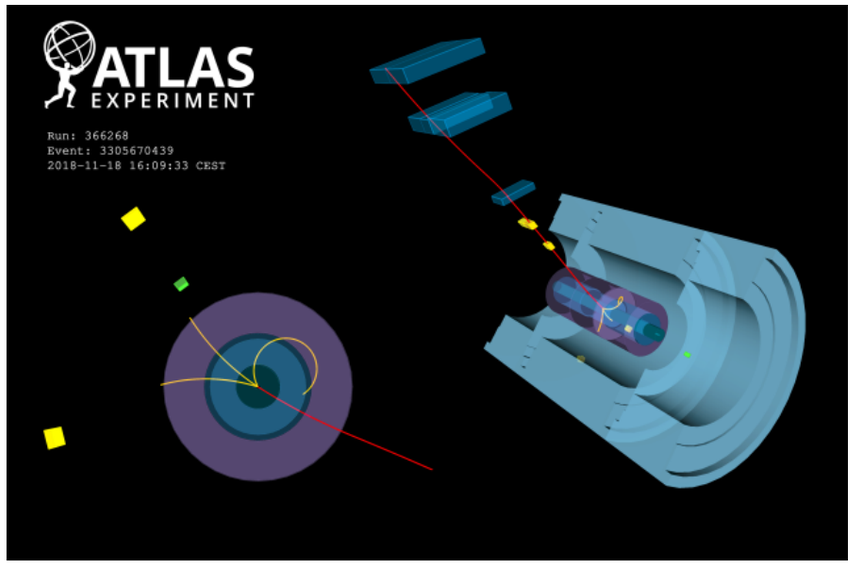


- More broadly the area of photon-boson scattering, with and without tagged protons a promising area for future study.

Heavy Ions

- Heavy ion collisions in fact natural arena for photon-initiated production.
- If photons emitted coherently from ions their virtuality Q^2 is very low and ion-ion impact parameter $b_\perp \gg R_{\mathrm{QCD}} \Rightarrow$clean, low multiplicity event. Known as ultraperipheral collisions (UPCs).



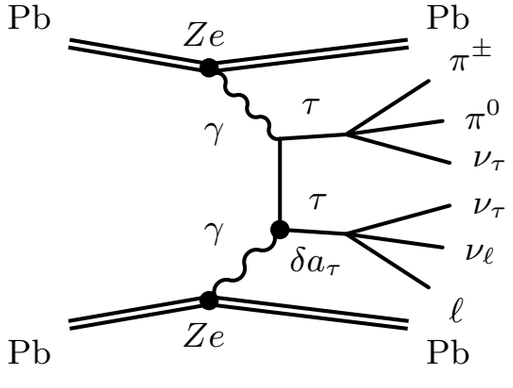


- Photon flux from ions falls v. quickly with central object mass $M_X \Rightarrow$ limited to $M_X \lesssim 50\,\mathrm{GeV}$, but here great deal has been achieved…

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

- Two flagship analyses - anomalous magnetic moment of the tau lepton and light-by-light scattering:

tau g-2

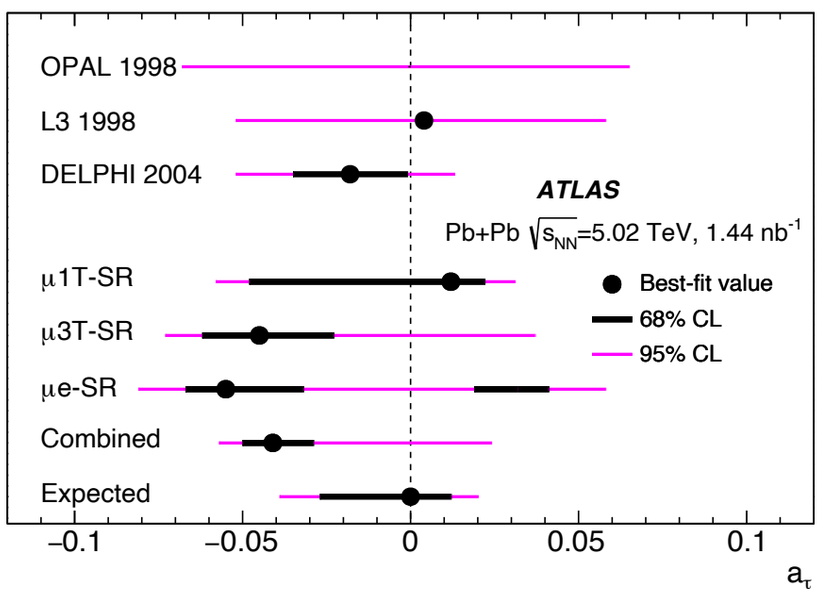


L. Beresford and J. Liu, PRD 102 (2020) 11, 113008

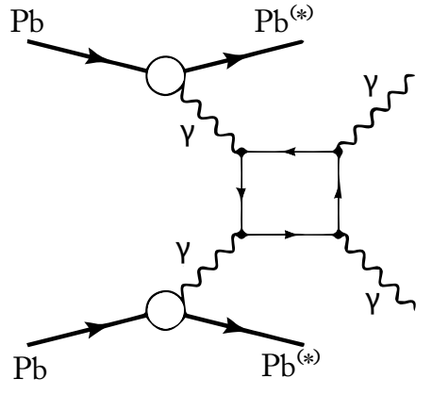
M. Dyndal et al., PLB 809 (2020) 135682

★ Tightest yet constraints on tau g-2.

ATLAS, arXiv: 2204.13478 (accepted PRL)



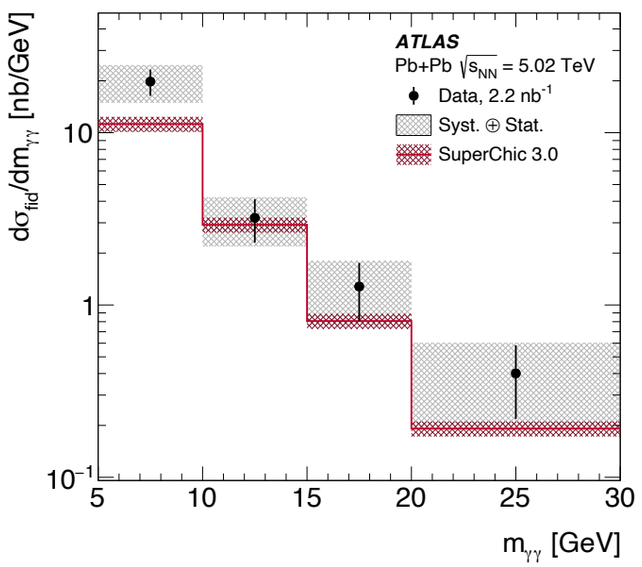
LbyL scattering



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

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

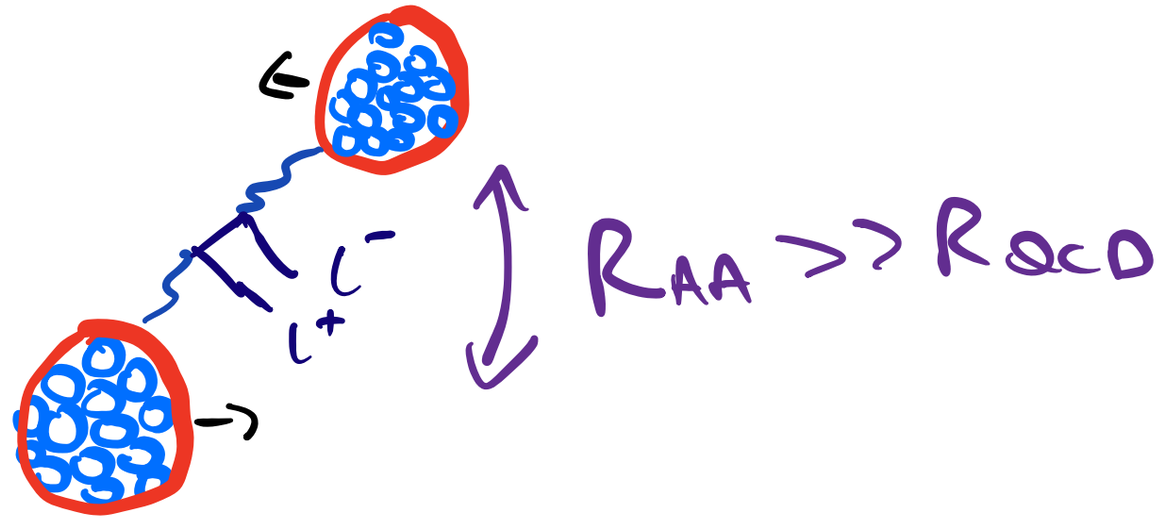
★ First ever observation of this!

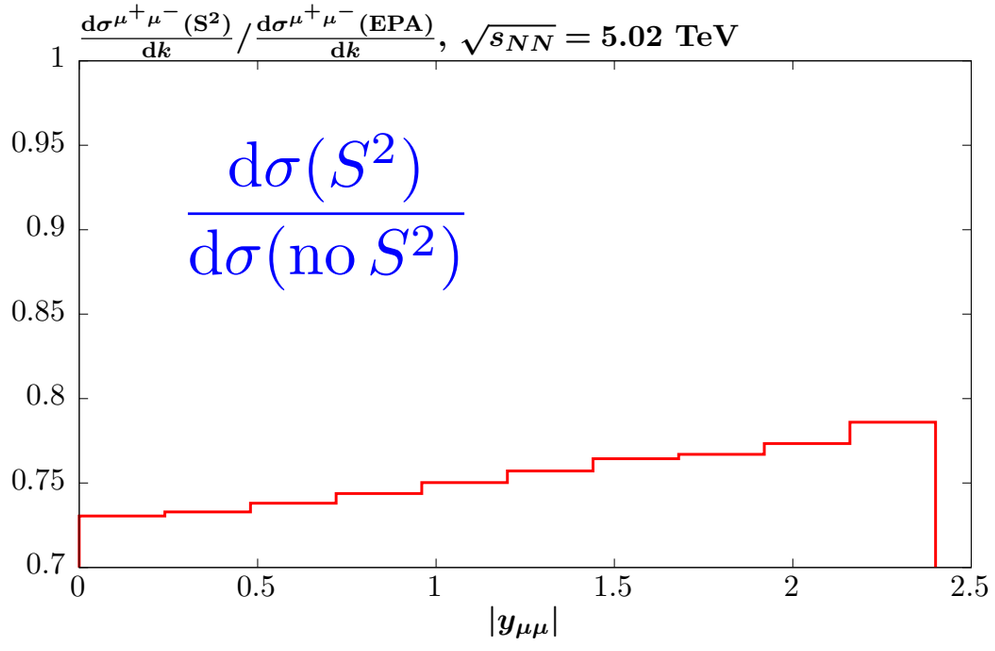


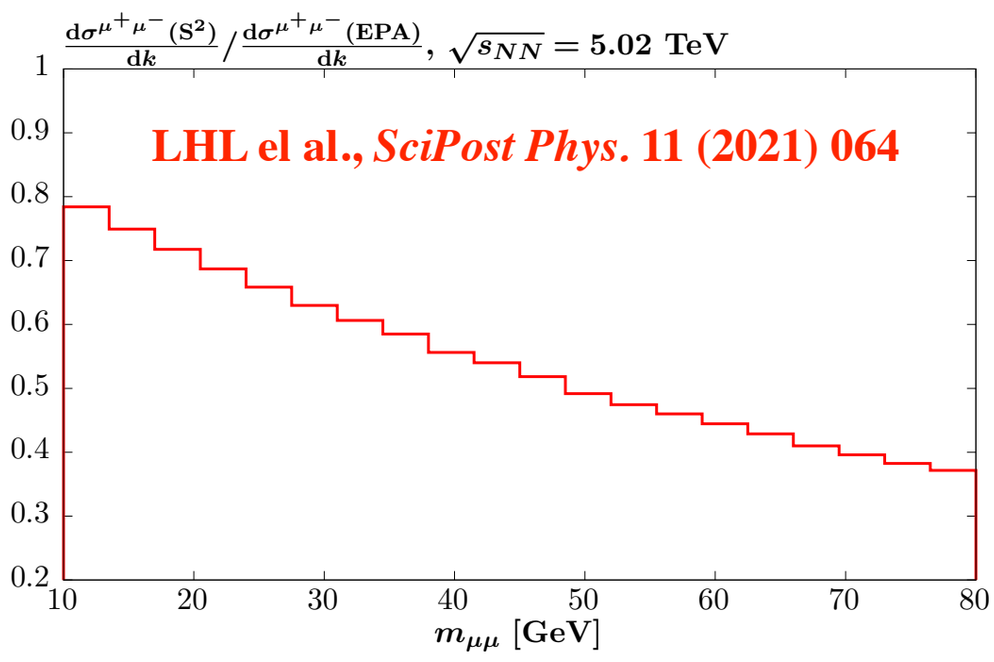
ATLAS, *JHEP* 03 (2021) 243

Role of QCD?

- A priori very minimal, however devil in detail, in particular as aim is for precision tests…



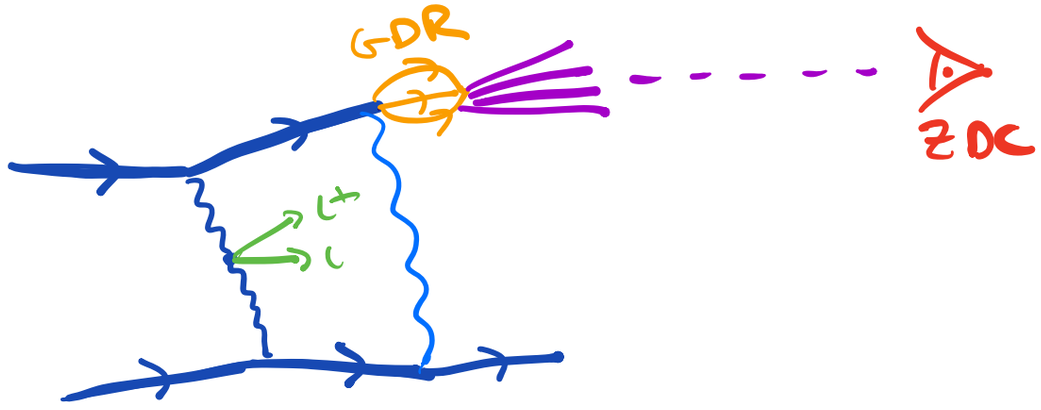




- Even for UPCs impact of QCD interactions between ions is small but far from negligible, and impacts on distributions. Focus of much recent theoretical progress.

- As with pp purely elastic collisions not the only case of interest.

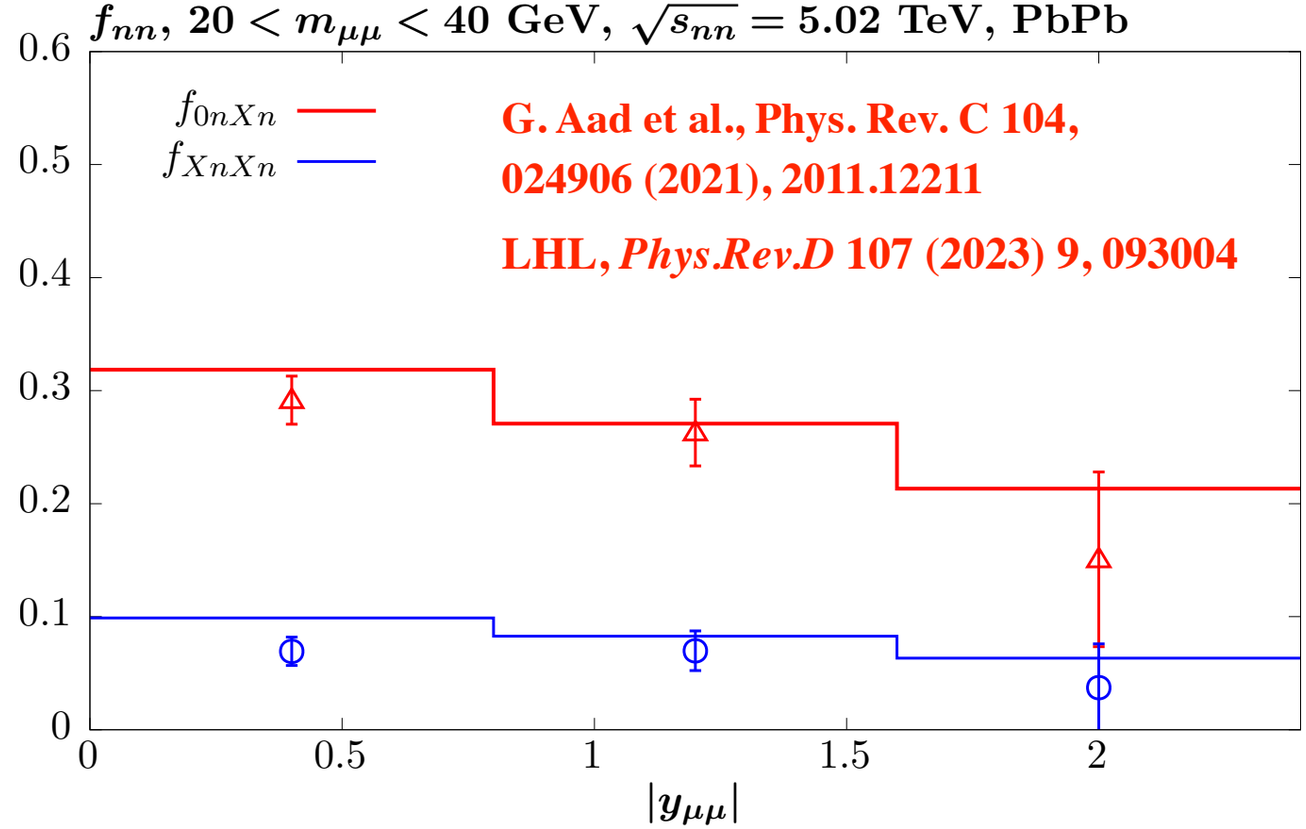
★ Ions can dissociate: additional boosted neutron production measured by ATLAS/ CMS Zero Degree Calorimeters detectors.



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

★ Recent study: predicted rather well in e, μ production.

★ Possibilities BSM? Different handle for e.g. EFT analyses…



Looking to the future

- Already many LHC CEP measurements, 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.
- Work towards HL-LHC running at **CMS** (and **ATLAS**) underway, with new taggers being proposed.
- Similarly in AA collisions, much new data to come, with **ALICE** and **LHCb** entering the game.
- However many of these searches rely on precise **theoretical understanding** of underlying production process.
- Much progress has been made here, but much more still to do…
- And of course **new channels** out there to explore! Much **physics** to come.

Thank you for listening!

Backup

SuperChic 4 - MC Implementation

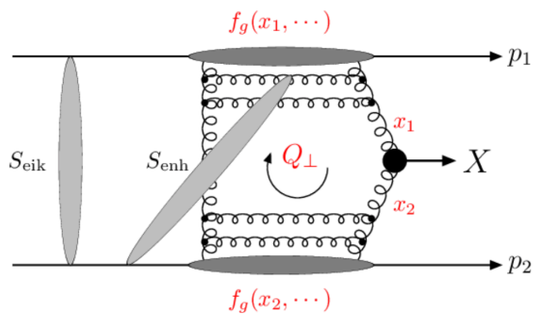
- A MC event generator for CEP processes. **Common platform** for:
  - QCD-induced CEP.
  - Photoproduction.
  - Photon-photon induced CEP.

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

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

- Home
- Code
- References
- Contact

SuperChic is a Fortran based Monte Carlo event generator for exclusive and photon-initiated production in proton and heavy ion collisions. A range of Standard Model final states are implemented, in most cases with spin correlations where relevant, and a fully differential treatment of the soft survival factor is given. Arbitrary user-defined histograms and cuts may be made, as well as unweighted events in the HEPEVT, HEPMC and LHE formats. For further information see the user manual.



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

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

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

https://superchic.hepforge.org

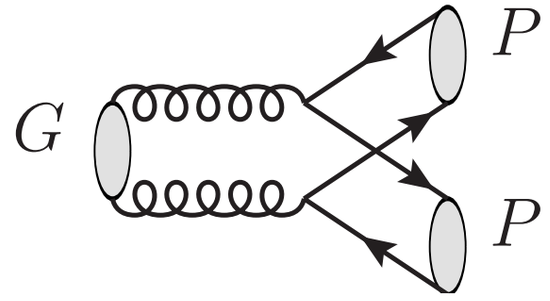
LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925

Glueballs

- A well-known feature of **QCD** - it is non-abelian $\Rightarrow$ gluon self-interactions.

As a direct consequence of this, in addition to $q\overline{q}$ mesons, expect gg bound states $\rightarrow$ '**glueballs**'.

- Range of states predicted on lattice, but experimentally elusive.
- CEP in principle very promising channel to investigate this:
  - **Production** enhanced in **glue-rich** environment.
  - **Decays** to u, d, s (i.e. $\pi\pi, KK, \rho\rho \ldots$) with equal amplitudes. Can map out decays in low pile up CEP runs.



- CEP can greatly resolve this unsolved issue. Possibility of glueball observation among existing theoretical candidates.

CEP Instanton production

• Instantons: tunnelling between different QCD vacuum configurations. Predicted from non-trivial vacuum structure of (non-Abelian) QCD.

• Violate (B+L) and chirality in QCD.

• Typical signature at LHC: gluon-initiated production of multi-parton final state, produced uniformly at an undetermined scale M_{inst}:

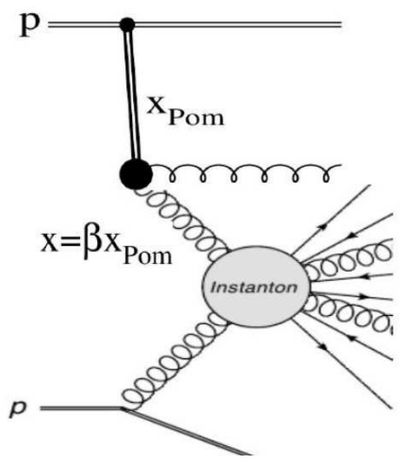
$$g + g \;\to\; n_g \times g \;+\; \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf})\,.$$

• Inclusively very hard to distinguish from MPI and other BGs.

• CEP a natural channel to look for this (no MPI!). Focus of ongoing study.

• In CEP BGs and pile-up still a significant issue here. But promising results at low luminosity in single tag case.

• Double tag more challenging - requires higher pile-up runs where BGs large.



V. V. Khoze et al., *JHEP* 04 (2020) 201, *Phys.Rev.D* 103 (2021) 1, 014017

V. A. Khoze et al., *Phys.Rev.D* 104 (2021) 5, 054013

M. Tasevsky et al., *Eur.Phys.J.C* 83 (2023) 1, 35