Modelling W boson pair production with rapidity gaps at the LHC

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DIS 2022, 4 May 2022

S. Bailey and LHL, arXiv:2201.08403
LHL, M. Tasevsky, V. A. Khoze, M.G. Ryskin
***Eur.Phys.J.C* 80 (2020) 10, 925**

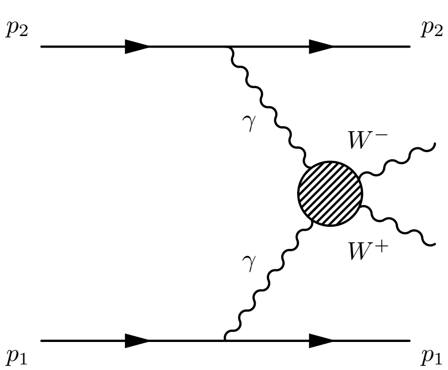
UNIVERSITY OF OXFORD

Recent data

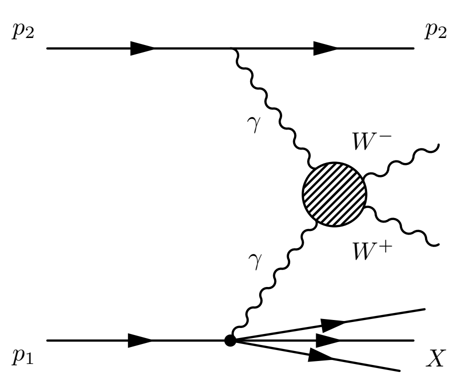
- Evidence for such '**semi-exclusive**' W^+W^-production in leptonic channel seen by ATLAS + CMS previously.
- Recently: first observation by **ATLAS**, at 13 TeV, via rapidity veto.

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

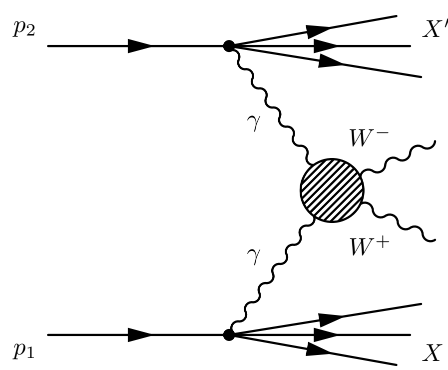
Elastic

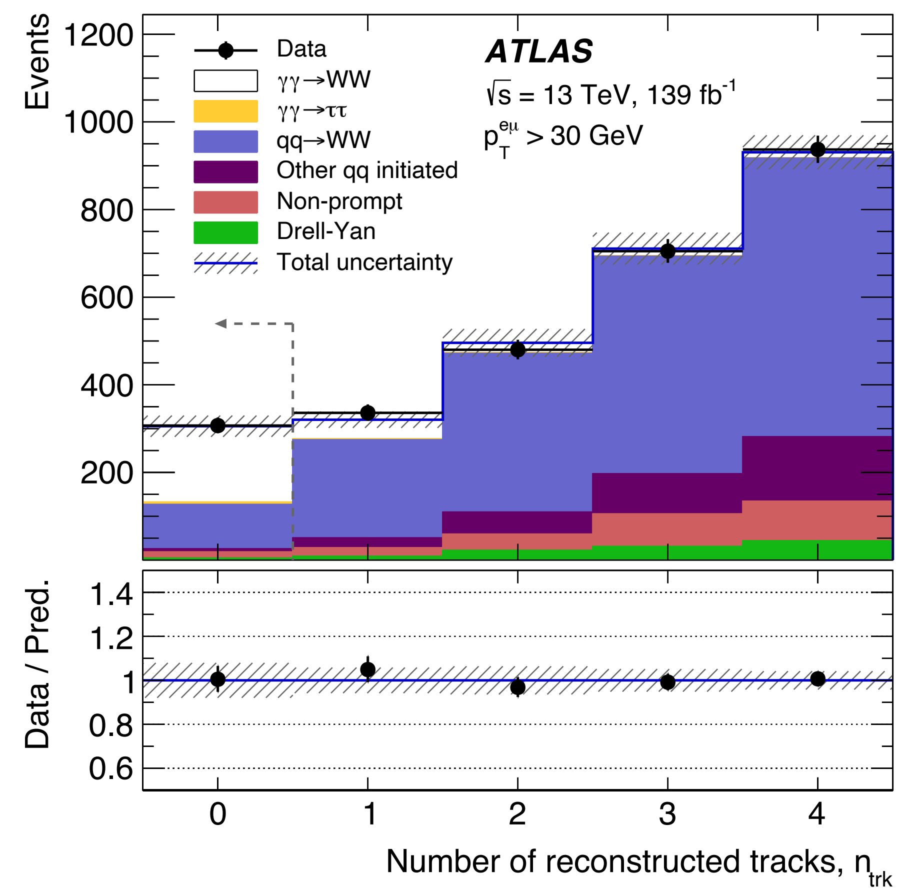


Single Dissociative



Double Dissociative





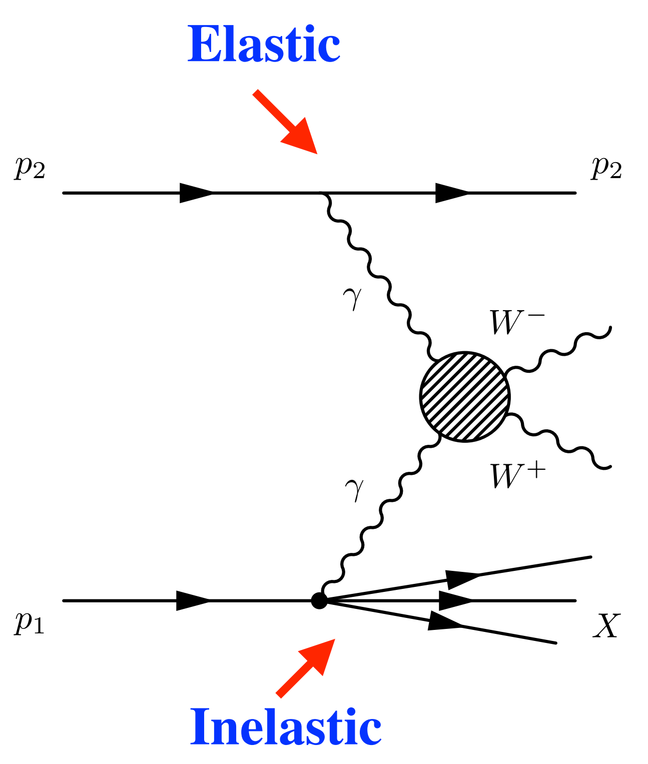
- No colour flow between beams ⇒ pass veto.

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

- **Question**: how do we model this process?

Modelling WW production

- Any theoretical calculation should:



  - ⋆ Account for both **elastic** and **inelastic** production.
  - ⋆ Fully account for all contributing diagrams, **beyond PI** production.
  - ⋆ Systematically account for probability of no additional particle production, due to **MPI**.

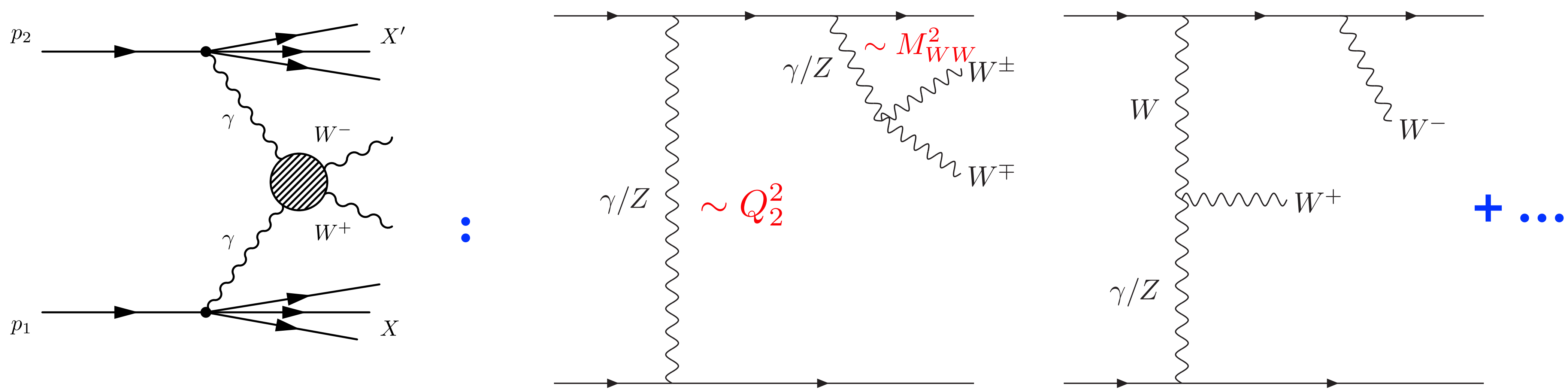
- I will report here the first such full theoretical treatment, including a MC implementation.

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

LHL, *JHEP* 03 (2020) 128

Structure Function Calculation

- Basic idea: apply '**structure function**' calculation.
- Structure functions parameterise the $\gamma p \to X$ vertex. Very precisely determined!
- Then systematically include non-PI diagrams in so-called 'hybrid' approach:



- These non-VBS 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**. For W^+W^- production power counting in $Q^2/M^2_{W,Z}$ can completely break down!

SuperChic 4.1 - MC Implementation

- Results of above calculation implemented in SuperChic 4.1 MC:
  - ★ Hybrid (**SF + parton-level**) calculation of production process.
  - ★ Fully differential treatment of no-MPI probability (**survival factor**).

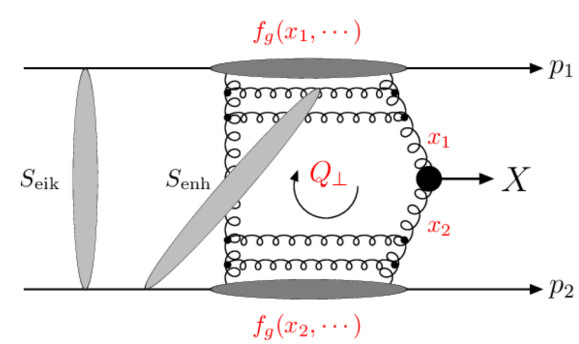
- Unweighted events can then be passed to Pythia for showering/hadronization of proton dissociation products.

superchic is hosted by Hepforge, IPPP Durham

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.

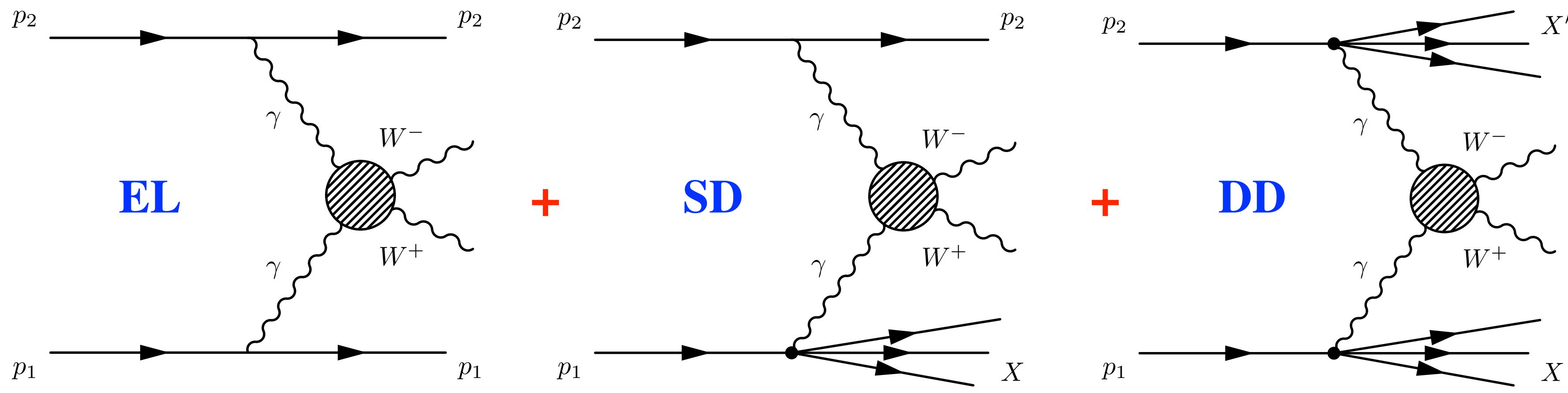
Comments to Lucian Harland-Lang < lucian.harland-lang (at) physics.ox.ac.uk >.

`https://superchic.hepforge.org`

ATLAS data: comparison

- **ATLAS 13 TeV** data, with lepton cuts + veto on associated tracks in: $p_\perp > 500\,\text{MeV},\ |\eta| < 2.5$

i.e. after subtracting BGs includes:



- We therefore need to evaluate all three contributions in SC:

σ [fb] $(\sigma_i/\sigma_{\rm tot})$, 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: $\sigma_{\rm meas} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\,\text{fb}$

$\Rightarrow$ **Very good agreement**! In more detail….

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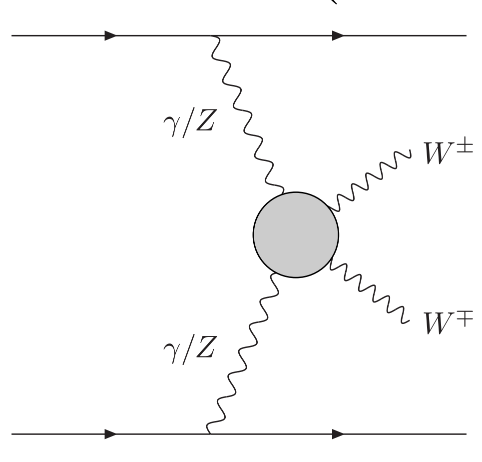
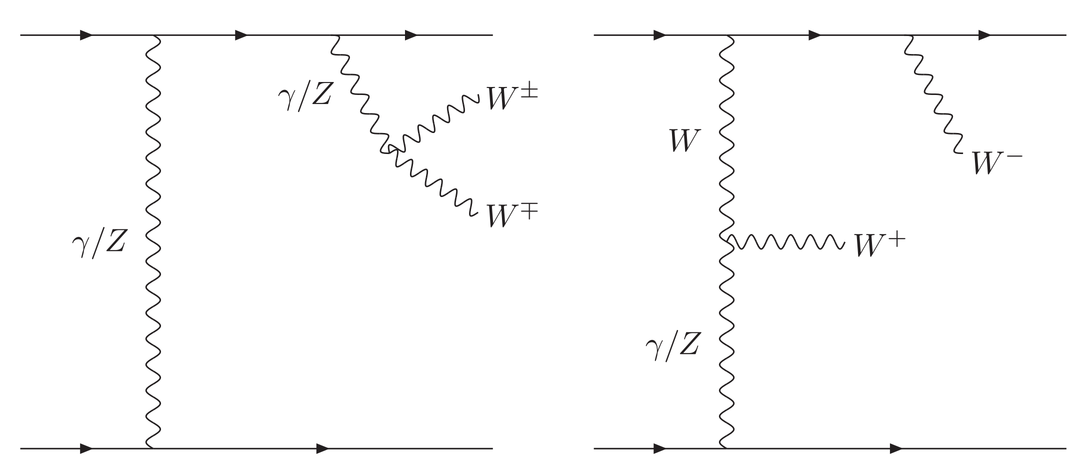
3.0 ± 0.5

- Break down to show impact of veto and survival factor for demonstration:
    - ★ **Veto** (imposed at particle level on SC + Pythia) reduces cross section by a factor of over ~ 2.
    - ★ **Survival factor** reduces cross section by further factor of over ~ 2.
    - ★ In both cases impact on DD largest, EL smallest.
- Proper account of both effects clearly key to matching data.
- What about impact of **non-PI**? rContribution from SD + DD is ~ 20% larger wrt pure PI case (Backup).



vs.



+...

Summary

- ⋆ Have described first complete approach to modelling W^+W^- production with rapidity gaps at the LHC. Process with promising sensitivity to the EW sector of the SM and beyond.
- ⋆ Delicate interplay of photon-initiated + non-photon-initiated diagrams + MPI effects. Need to account for these if we are to do precision physics, at least without tagged protons.
- ⋆ Much work to do, and interesting studies to perform!

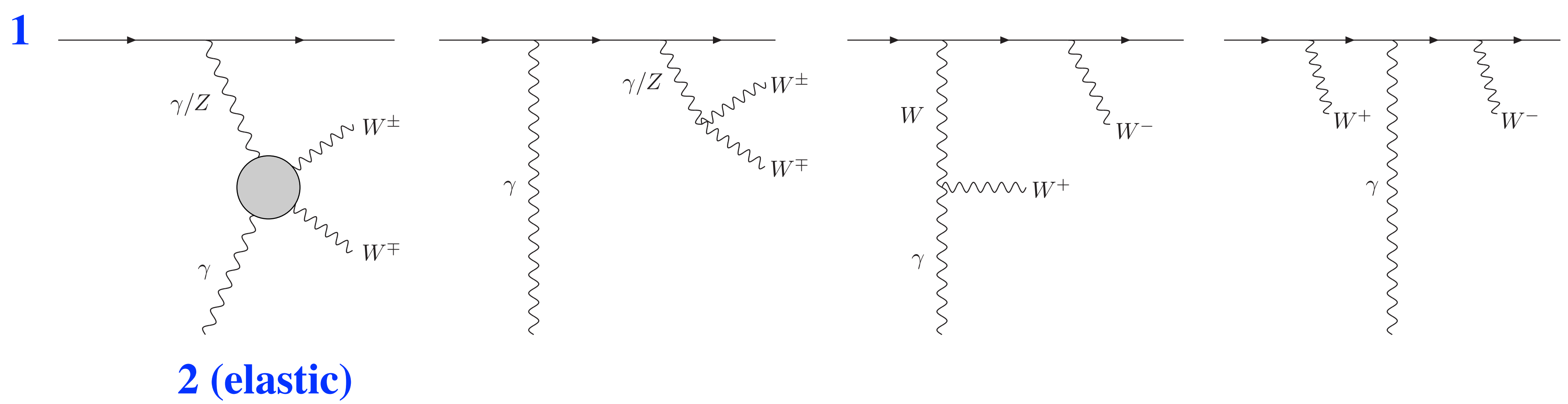
Thank you for listening!

Backup

'Hybrid' Calculation

- Apply cutoff above which we include all relevant diagrams. For e.g. **SD**:

$$Q_1^2 > Q^2_{\rm cut}$$
$$W_1^2 > W^2_{\rm cut}$$
$$W^2_{\rm cut} = 3.5\,{\rm GeV}^2$$
$$Q^2_{\rm cut} = 1\,{\rm GeV}^2$$

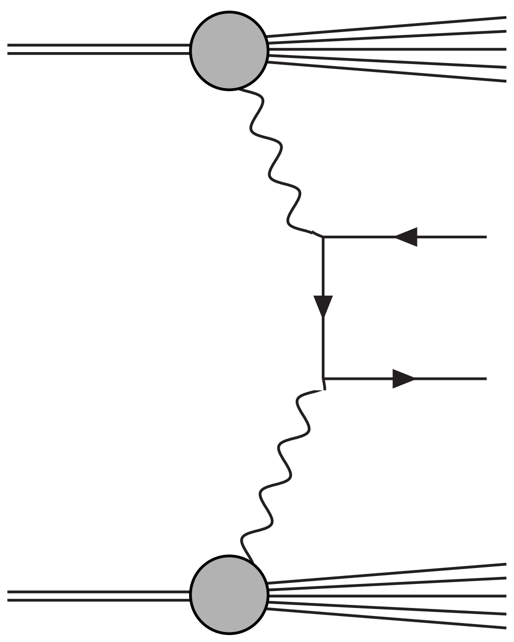


- **Below cutoff** (or even higher $W^2_{\rm cut}, Q^2_{\rm cut}$) contribution from **non-PI** diagrams **tiny** (< 0.1%) in any gauge $\Rightarrow$ safely consider PI production as per SF approach.
- **Above cutoff** include full gauge invariant set of diagrams in parton model.

Final Remarks

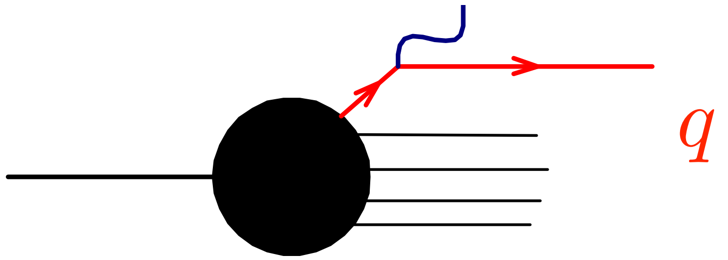
- **Alternative procedur**e: work in collinear factorization. However the DD component then requires a NNLO EW calculation + μ_F dependence that is absent in our approach. Also not currently possible to evaluate S^2.
- Theory uncertainty dominantly due to survival factor, but largely correlated with l^+l^-: possibility to calibrate. Another possibility: select **same sign** $W^\pm W^\pm$ with gap (only DD present).
- A way to further test this approach + provide more information is clearly to **tag** the **protons** (ideally both). Then EL more effectively isolated.
- In the meantime a full account of all effects (non-PI, survival factor…) **key** for precision studies, EFT analyses etc.

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).

Theoretical uncertainties

- Experimental uncertainty on SFs:
  - ★ Elastic form factors - A1 collaboration, experimental uncertainty.
  - ★ 50% varation in $R_{L/T}$.
  - ★ Variation of W^2 transition between CLAS/HERMES fits.
  - ★ Difference between CLAS and CB fits to resonant region.
  - ★ PDF uncertainty on NNLO QCD prediction for $Q^2 > 1\text{GeV}^2$ continuum.

✦ Gives ~ 1-1.5% uncertainty. Largest for DD.

- Higher order corrections in parton-level result:
  - ★ Varying $\mu_F = \sqrt{Q_i^2}$ by factor of 2 gives 2(3)% variation in SD(DD).
  - ★ Taking $\mu_F = M_W$ gives result consistent with this variation.
  - ★ Removing reweighting to have fixed α as per Madgraph - 1% level.
  - ★ To give better description of low region where PI dominates we reweight by NNLO K-factor for F_2 . Removing this leads to ~ 2(5)% change in SD, DD. Conservative as default choice is more accurate.

✦ Gives ~ 2(5)% uncertainty for SD (DD). None for EL.

Theoretical uncertainties

- Increasing values of $Q^2_{\rm cut}, W^2_{\rm cut}$ to $10\,{\rm GeV}^2$ results in ~ 1% reduction in cross section. Even this is conservative.

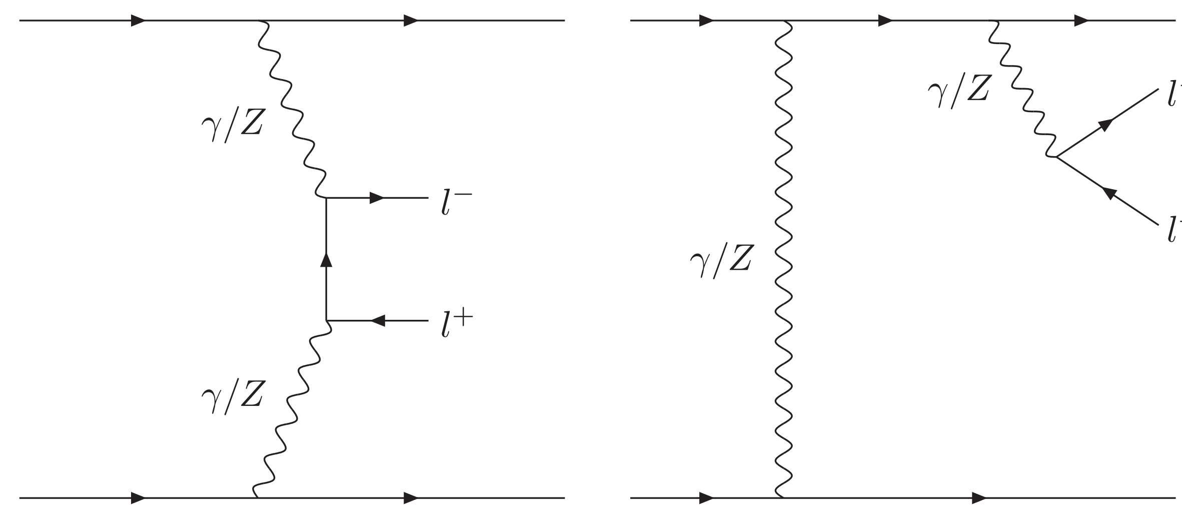
- Survival factor:

  ⋆ EL: ~1% level, due to peripheral nature of interaction.

  ⋆ SD, DD: calculation assume 'two-channel' model of proton, where incoming beam superposition of two diffractive eigenstates. Freedom in modelling how production process couples to these. Reasonable variation gives ~ 10(50)% in SD (DD) case.

✦ For DD in particular this is an estimate. Survival factor modelling constrained by existing soft hadronic data, but certainly model dependent. Constraining with similar (lepton, same sign W) data useful.

- Impact of **non-PI**: can only sensibly address by working in **axial gauge**, where power counting present.
- Alternative: compare with **lepton pair** production in similar kinematic region.



- Here impact of non-PI is found to be 1% level at most, and no issue with gauge invariance.

σ [fb] $(\sigma_i/\sigma_{\rm tot})$	EL	SD	DD	Total	f_γ^X
W^+W^-	0.565 (18.6%)	1.87 (61.6%)	0.599 (19.8%)	3.03	4.3
l^+l^-	9.61 (24.0%)	24.9 (62.5%)	5.42 (13.5%)	39.9	3.5

i.e. relative contribution from SD + DD is ~ 20% larger wrt pure EL in W^+W^- case. Dominantly due to **non-PI**.

$$f_\gamma^X \approx \frac{\sigma^{\rm EL}+\sigma^{\rm SD}+\sigma^{\rm DD}}{\sigma^{\rm EL}}$$

- Also leads to rather different breakdown between various channels. Crucial to account for - common previously to assume these are equal in extracting an 'exclusive' W^+W^- signal.

Backup