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**

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VBS

- **Vector Boson Scattering (VBS)**: broad class of process with sensitivity to the EW sector of the SM and BSM extensions of it. $WW, ZZ, WZ, W\gamma, Z\gamma ...$
- Rich programme of theory + experimental studies at LHC.
- Focus on selecting such events via VBS cuts: require two well separated jets in addition to diboson final state (suppress s-channel $q\bar{q} \to VV$).
- However not the only way to look for this!

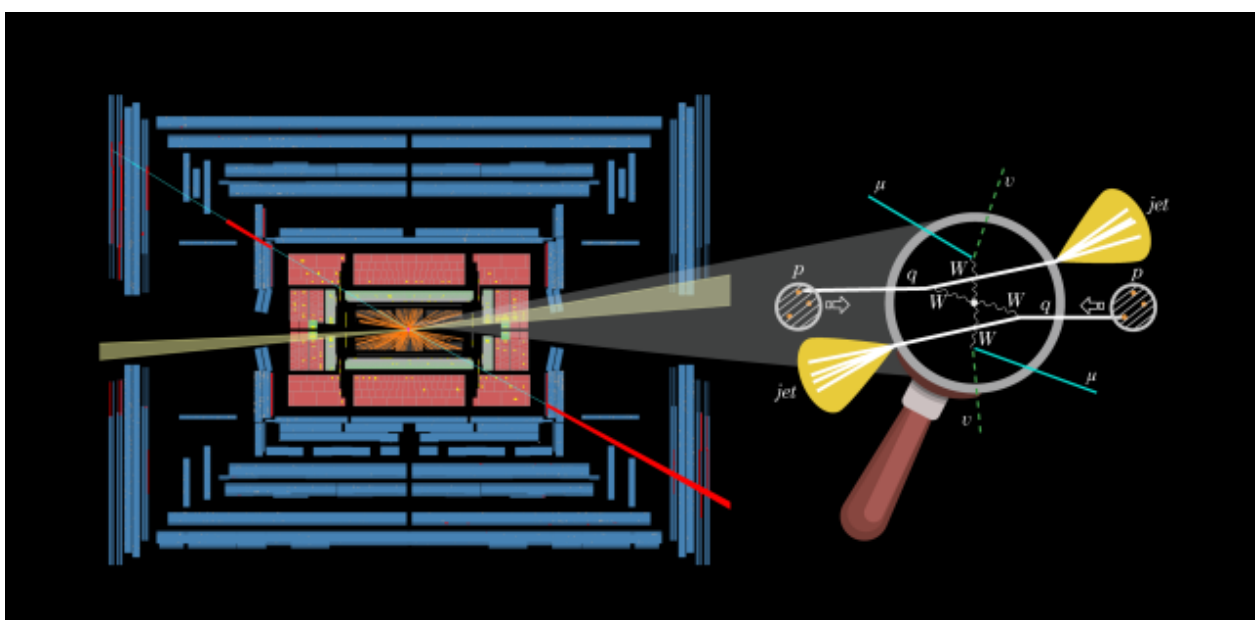
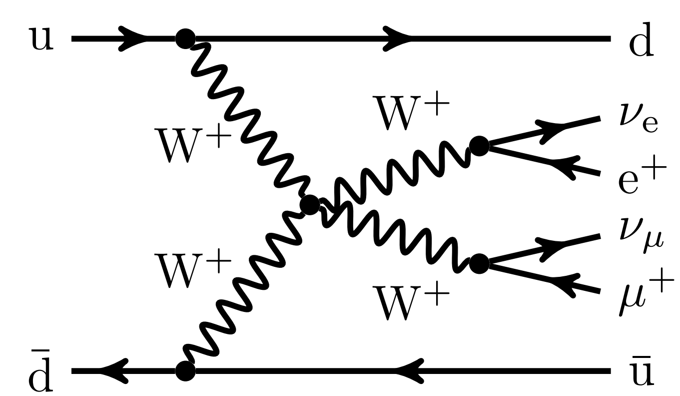
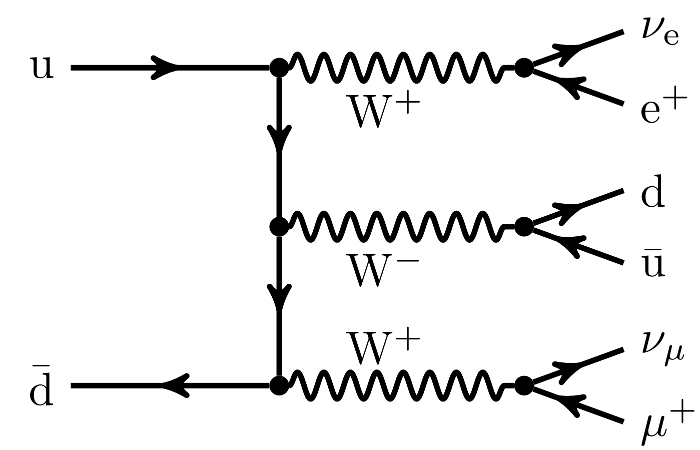


Image credit: Lucia Di Ciaccio, Simone Pagan Griso



t-channel

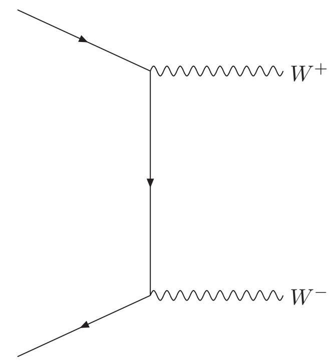


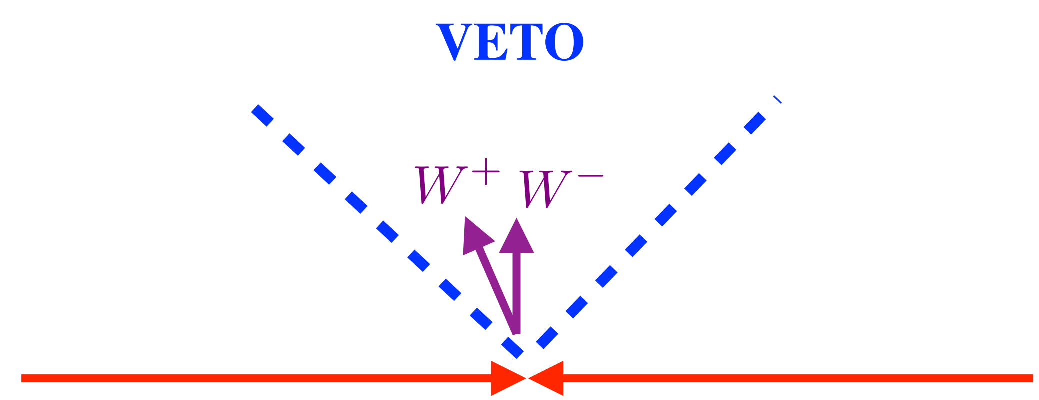
s-channel

A. Ballestrero et al., *Eur.Phys.J.C* 78 (2018) 8, 671

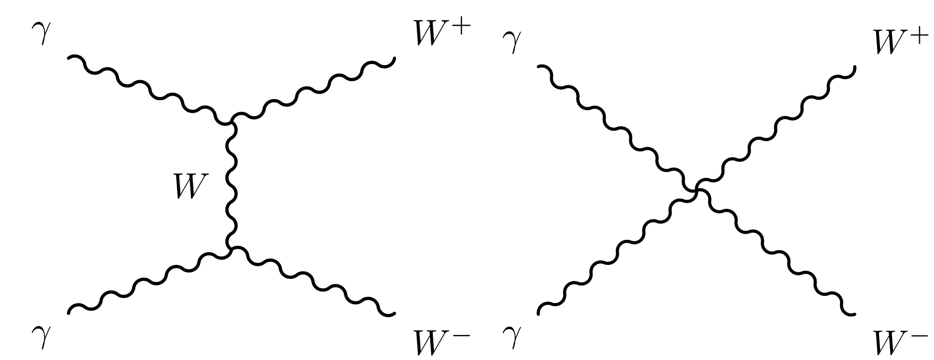
VBS with rapidity gaps

- **Alternative**: select diboson final state + no addition track activity in central detector ⇒ VV + rapidity gaps.

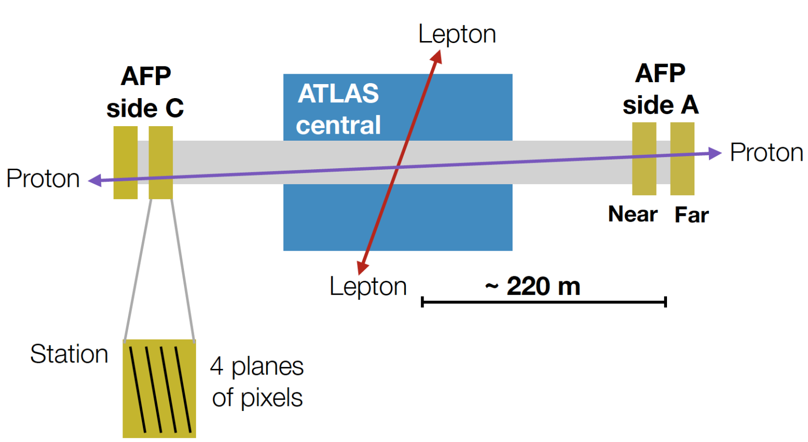


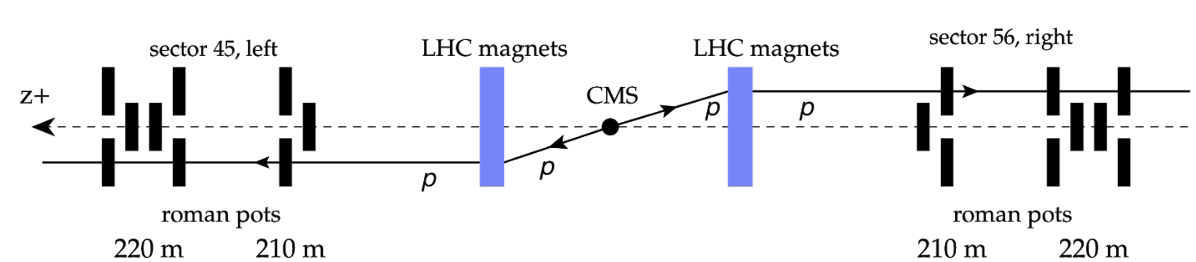


  - s-channel: colour flow between proton ⇒ activity!
  - Key example, opposite sign W^+W^-:
  - Aim: by imposing veto can dominantly isolate the pure **P**hoton-**I**nitiated (**PI**) process*.
  - Clean probe of γW (anomalous?) couplings.



- Can do even better: by **tagging** intact outgoing **protons** the PI mechanism is isolated even further! Dedicated detectors installed at ATLAS + CMS.





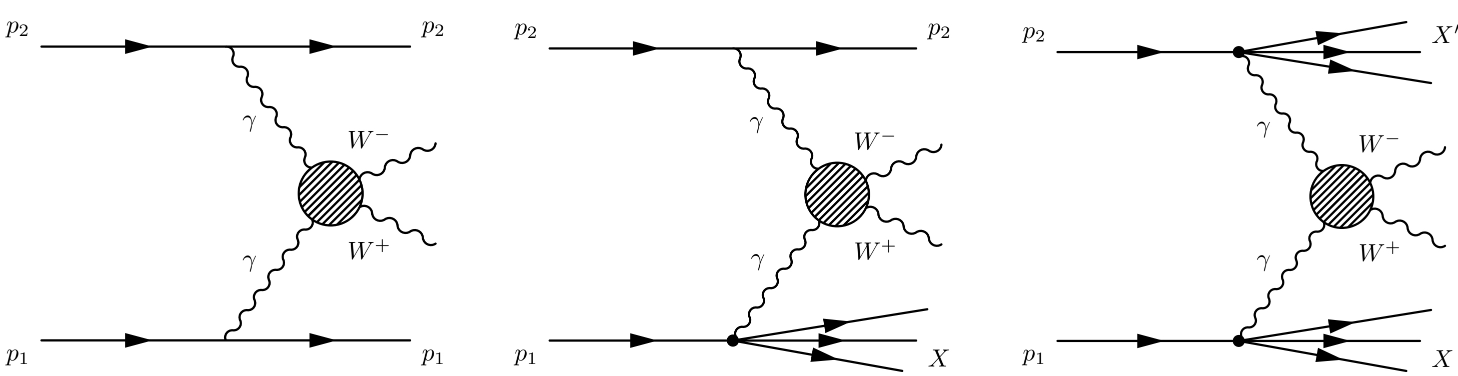
***s-channel: colour flow between beams and no gap.**

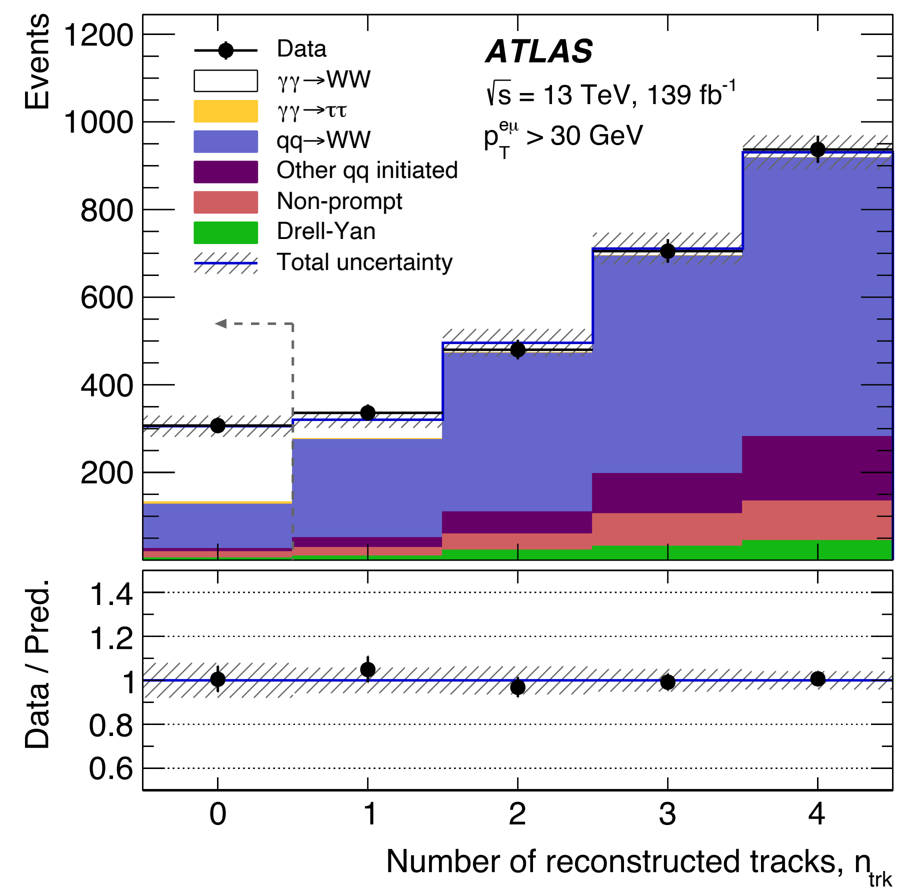
Recent data

- 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**





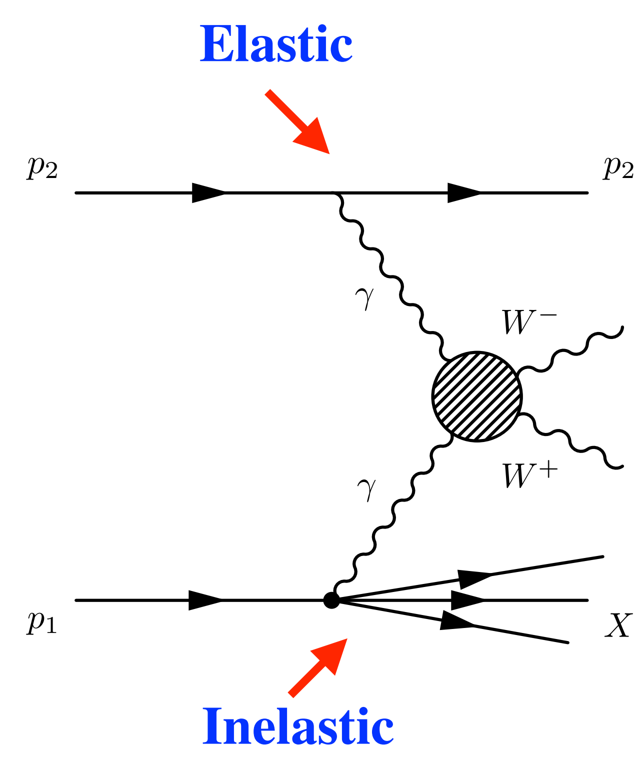
- No colour flow between beams ⇒ pass veto.

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**.

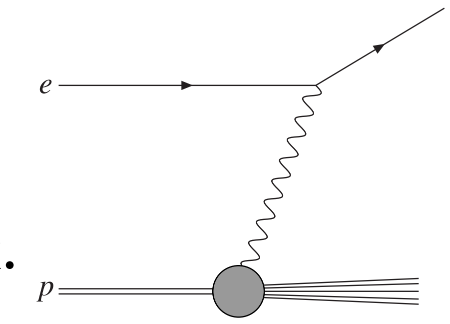
- I will report here the first such full theoretical treatment, including a MC implementation.

For more details see S. Bailey and LHL, arXiv:2201.08403

LHL, *JHEP* 03 (2020) 128

Structure Function Calculation

- Basic idea: apply '**structure function**' calculation.
- Structure functions parameterise the $\gamma p \to X$ vertex.



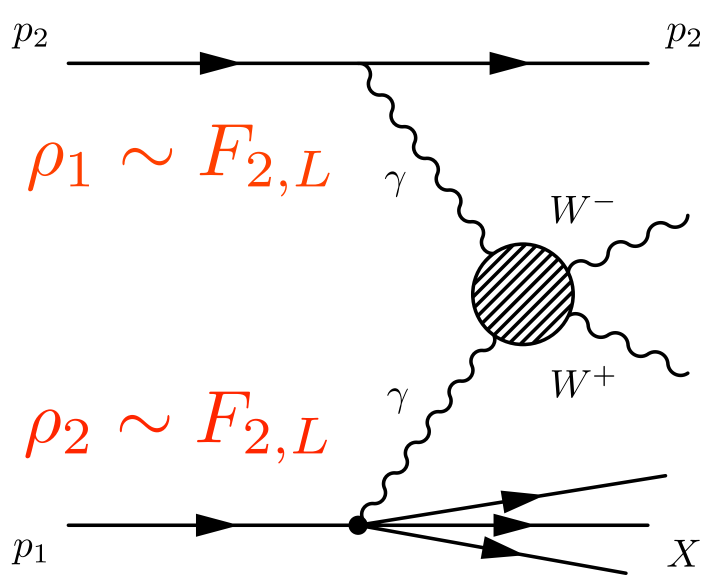
$$\frac{d^2\sigma}{dx\,dy} \propto L_{\alpha\beta}\, W^{\alpha\beta}$$

- Use same idea as for DIS to write:

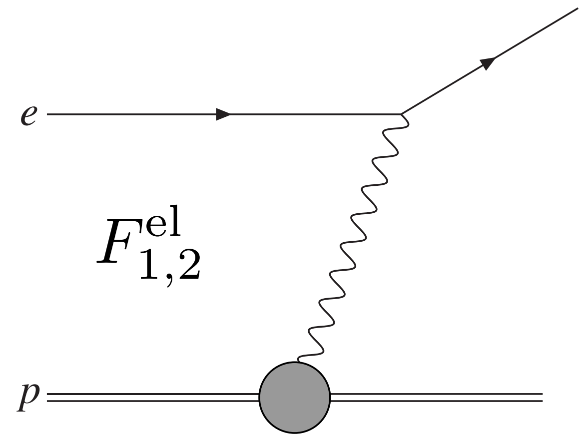
$$W^{\alpha\beta}(p,q) = \left(g^{\alpha\beta} - \frac{q^\alpha q^\beta}{q^2}\right) W_1(x,Q^2) + \left(p^\alpha + \frac{1}{2x}q^\alpha\right)\left(p^\beta + \frac{1}{2x}q^\beta\right) W_2(x,Q^2)$$

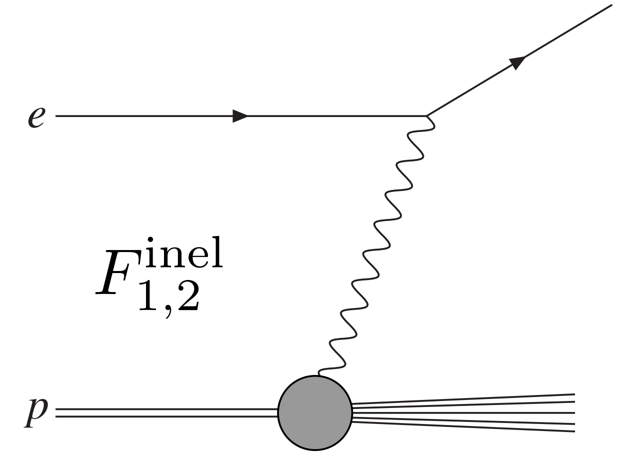
$$\sigma_{pp} = \frac{1}{2s}\int \underbrace{\mathrm{d}x_1 \mathrm{d}x_2\, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp}}_{\text{Photon } x,\, Q^2} \mathrm{d}\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\underbrace{\rho_1^{\mu\mu'}\rho_2^{\nu\nu'}}_{\gamma^* p \to X}\, \underbrace{M^*_{\mu'\nu'} M_{\mu\nu}}_{\sim \sigma(\gamma^*\gamma^* \to W^+W^-)}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X)\,,$$

- Cross section given in terms of photon density matrices ρ_i :



- Both elastic and inelastic SFs accounted for:

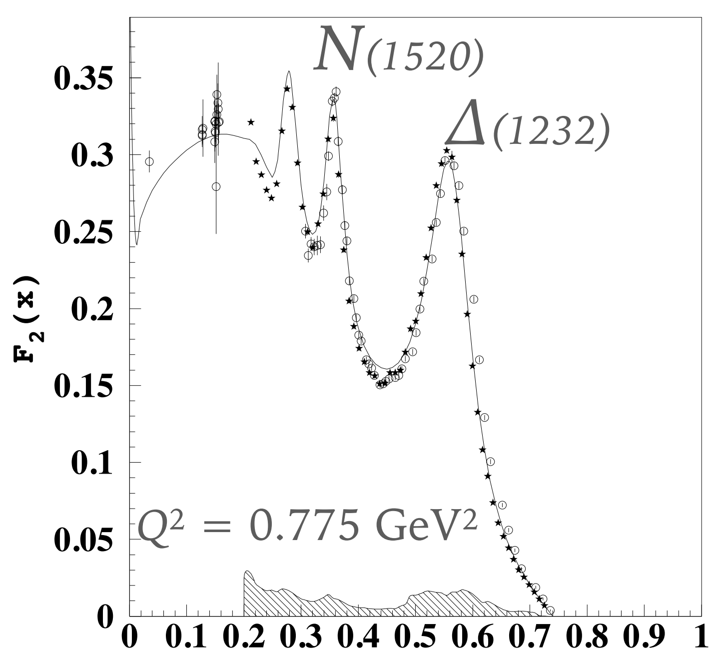


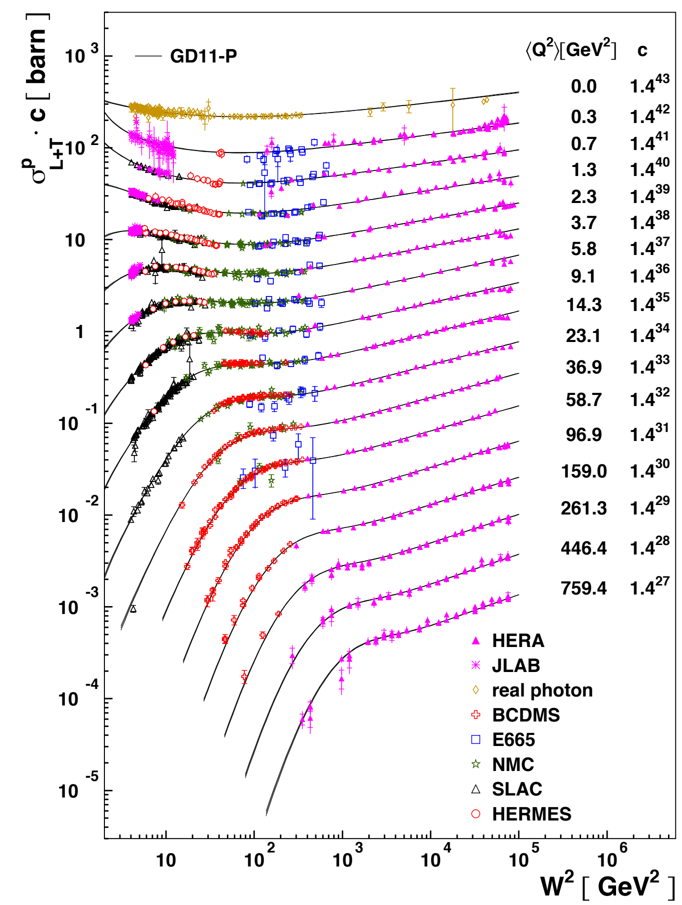


★ **Elastic**: precisely measured proton EM form factor.

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

- Low (non-perturbative) Q^2 and/or W^2 region, take direct experimental determinations.

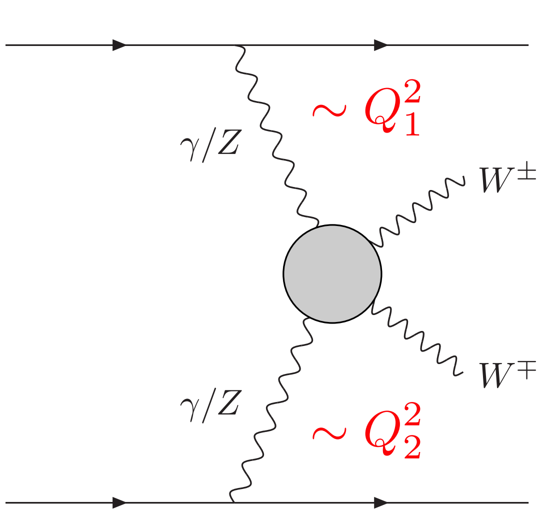




- High Q^2 region, simplest to calculate using (NNLO) pQCD + global PDFs.

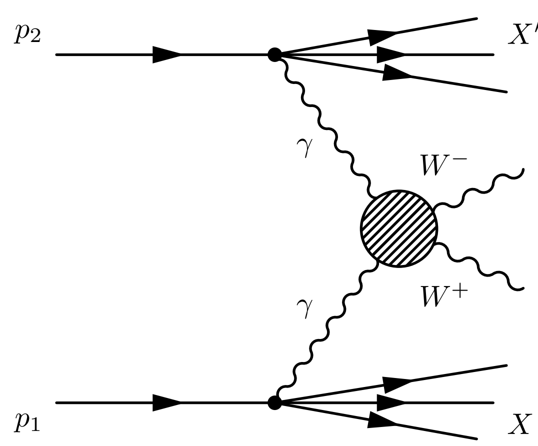
Beyond PI production

LO parton-level:



- SF calculation only accounts for pure PI (+ Z-initiated) production.

  - Considering e.g. **double dissociative** (**DD**) case, this is not the only contribution:



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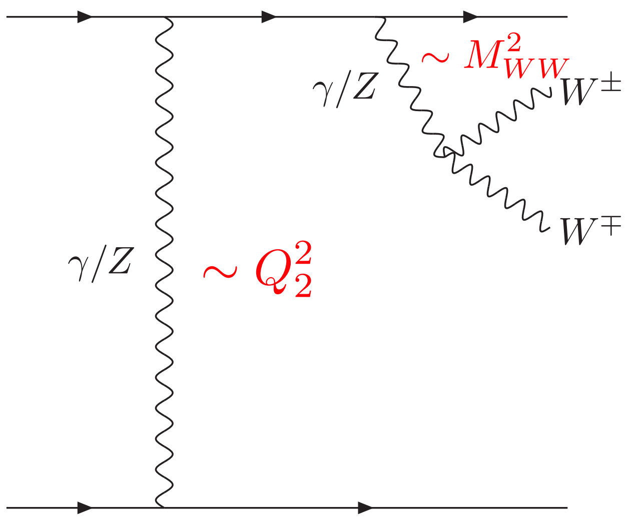
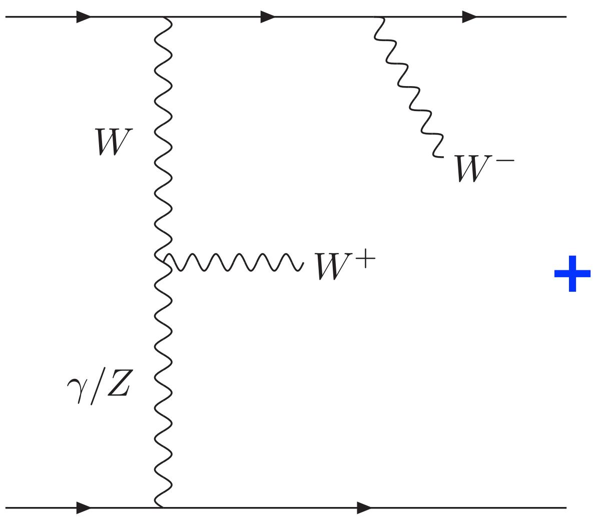




+ ...

$$\int \frac{\mathrm{d}Q^2}{Q^2}$$

$$Q^2 = (p_q^{\rm in} - p_q^{\rm out})^2$$

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

  ⋆ The contribution is not necessarily negligible - to be determined.

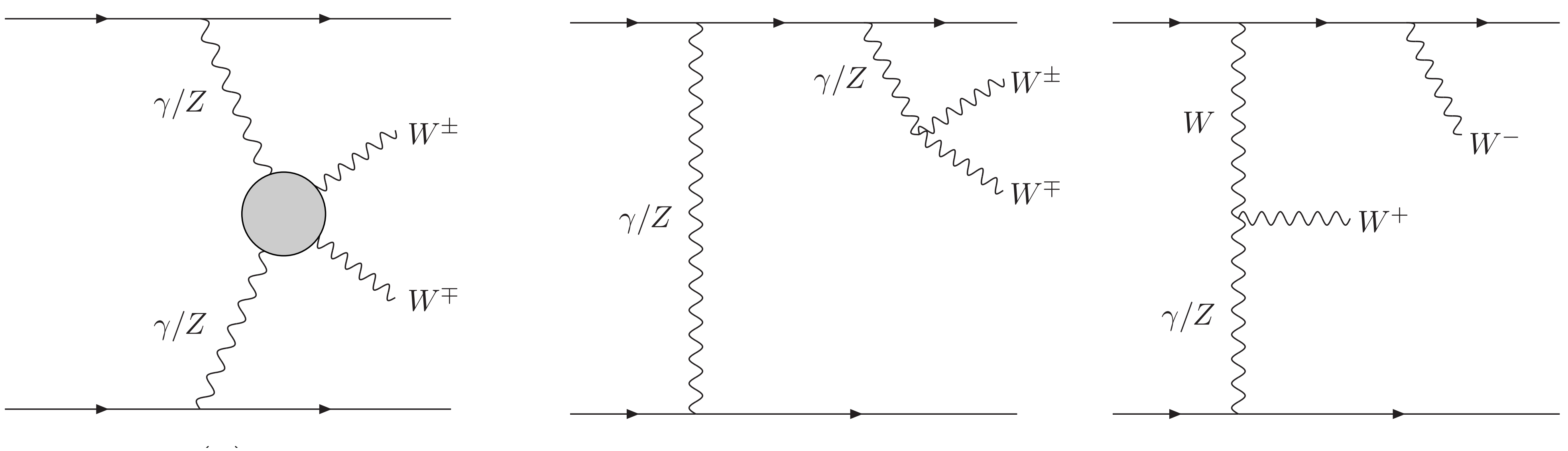
  ⋆ More importantly, the pure PI (+Z) contribution is **not individually gauge invariant**. For W^+W^-production power counting in $Q^2/M_{W,Z}^2$ can completely break down!

- Breakdown in power counting evident when working in e.g. **unitary gauge**. Compare 13 TeV DD cross section with on-shell approximation for $\gamma\gamma \to W^+W^-$

σ [fb]

Unitary			On–shell		
EL	SD	DD	EL	SD	DD
0.704	5.01	222	0.696	3.31	3.81

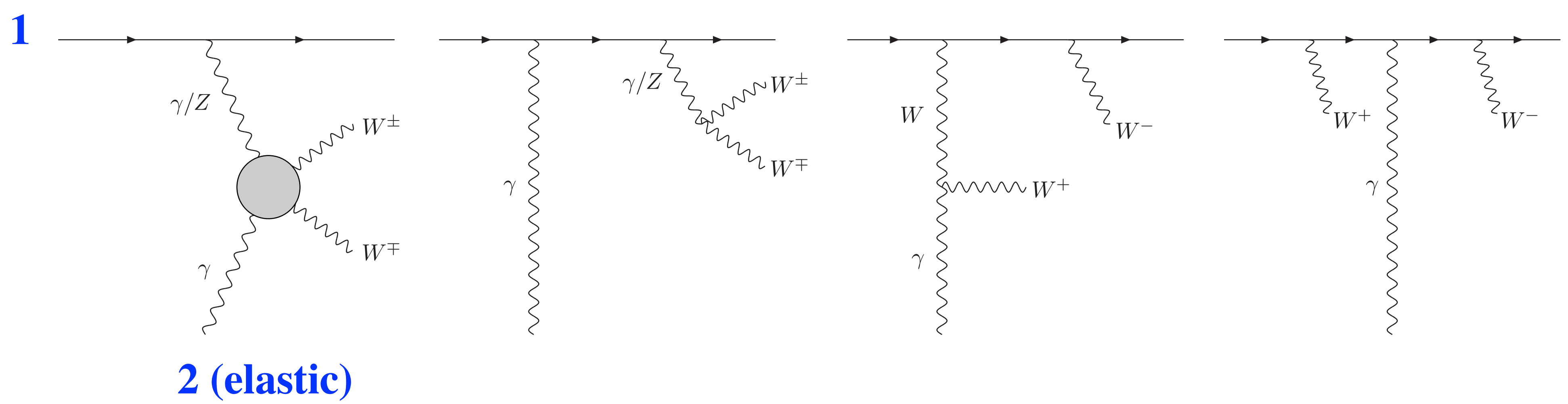
- **Huge difference**! Well known effect, due to longitudinal W polarizations when all diagrams not included.
  - Can rescue appropriate power counting by working in EW **axial gauge**: longitudinal W polarizations do not $\sim E_W/M_W$ (**Backup**).
  - But appropriate solution has to be to include **all relevant diagrams**.



'Hybrid' Calculation

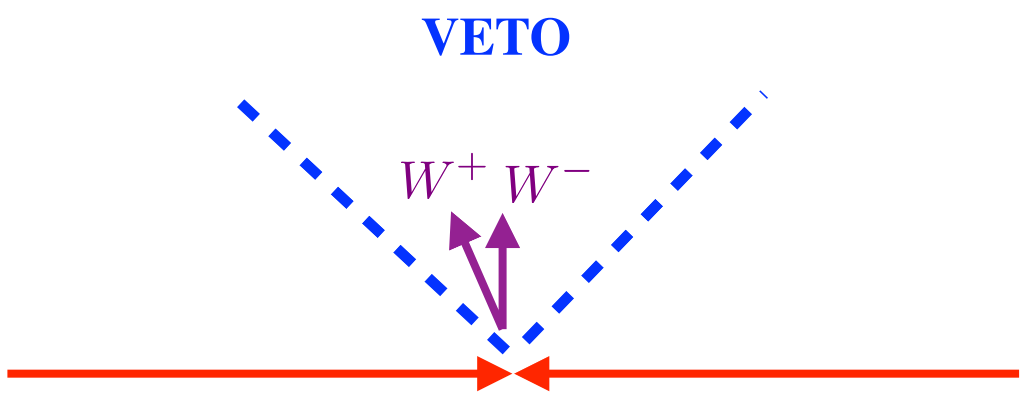
- Apply cutoff above which we include all relevant diagrams. For e.g. **SD**:

$$Q_1^2 > Q_{\rm cut}^2$$
$$W_1^2 > W_{\rm cut}^2$$
$$W_{\rm cut}^2 = 3.5\,{\rm GeV}^2$$
$$Q_{\rm cut}^2 = 1\,{\rm GeV}^2$$



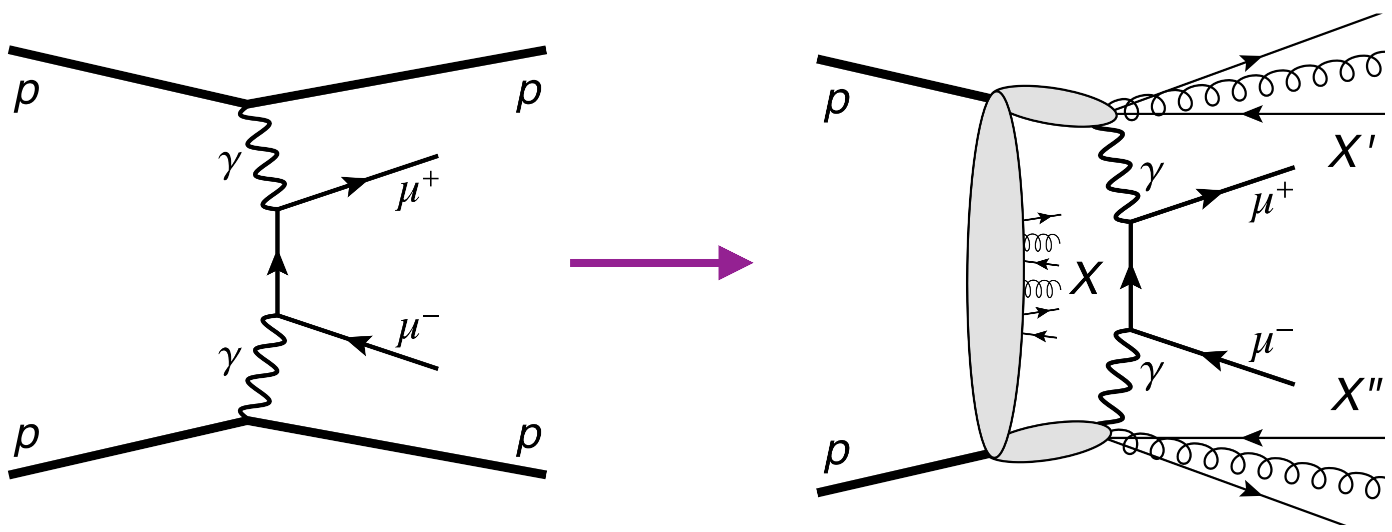
- **Below cutoff** (or even higher $W_{\rm cut}^2, Q_{\rm cut}^2$) contribution from **non-PI** diagrams **tiny** ($<$ 0.1%) in any gauge $\Rightarrow$ safely consider PI production as per SF approach.
- **Above cutoff** include full gauge invariant set of diagrams in parton model.
  - ★ As we will see, having control over this low Q^2 region crucial for evaluating **no-MPI** probability.
  - ★ This automatically regulates the $Q^2 \to 0$ region of **collinear** $q \to q\gamma$ emission. Only collinear singularity for such t-channel diagrams.
- A similar approach applied for the **DD** case (**backup**).
- **Theory uncertainty** on the result at the **1%** level (**backup**) - prior to considering S^2 .

The Survival Factor



- Possibility of proton-proton **MPI** to consider.

$p_\perp > 500\,\text{MeV}, \; |\eta| < 2.5$

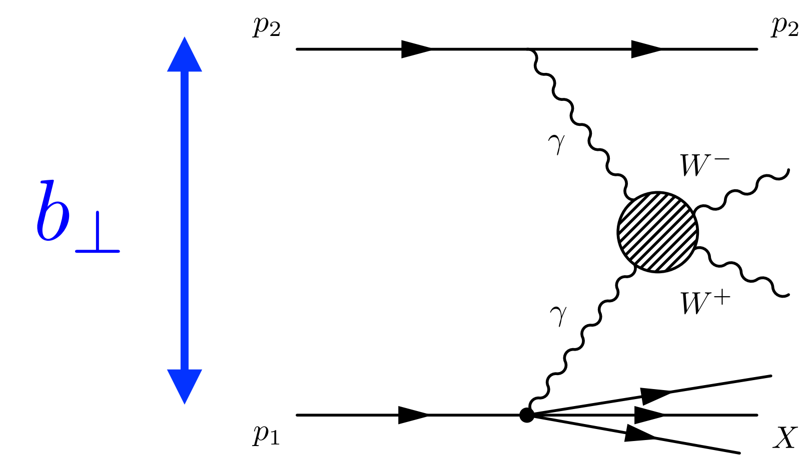


- '**Survival factor**' = probability of no additional inelastic hadron-hadron interactions (MPI), which will fill veto region*.

***if there is colour flow between colliding beams, then probability of gap v. small. We assume for now to be zero.**

- Will not go into details here, but roughly speaking, **survival factor** expressed ~ as a cut on the **hadron-hadron** impact parameter:

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



with departure from sharp cutoff coming from details of inelastic pp scattering.

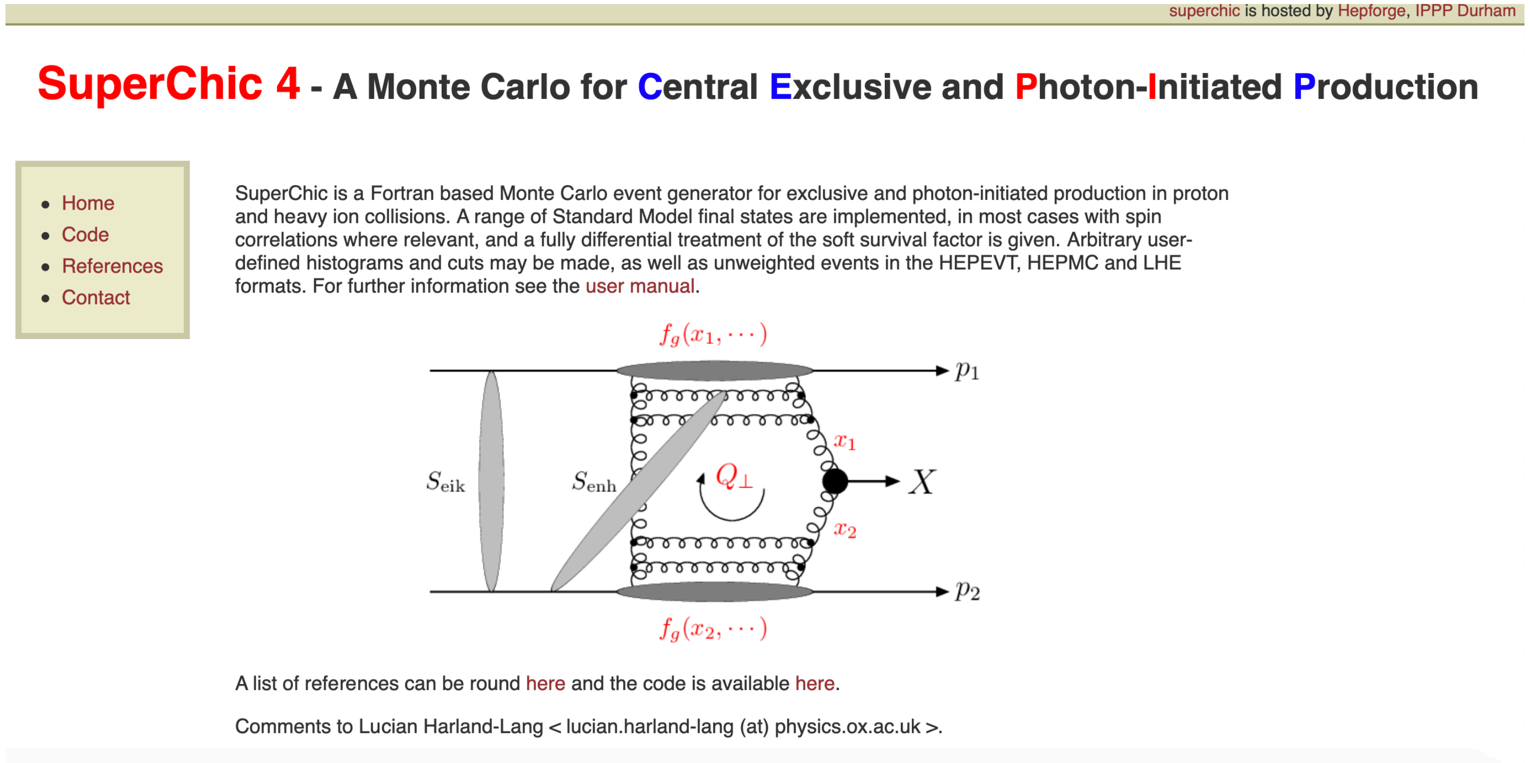
- Impact parameter $b_\perp^2$ is ~ Fourier conjugate to momentum transfer Q^2 and so survival factor depends on this.
  - ★ **Elastic** production: strongly peaked at low Q^2(~ high $b_\perp^2$). Generally outside range of QCD pp interactions.
  - ★ **Inelastic** γp vertex: extends to largerQ^2 (~ lower $b_\perp^2$), i.e. lower S^2 . Find:

$$S^2_{\rm EL} \sim 0.85 \pm 0.01 > S^2_{\rm SD} \sim 0.6 \pm 0.05 > S^2_{\rm DD} \sim 0.15 \pm 0.07$$

- Thus MPI will tend to **suppress DD** production, as well as higher Q^2 region (i.e. non-PI). Though as we will see not entirely.
- Cannot simply run with MPI on general purpose MC - misses crucial Q^2 & elastic vs. inelastic dependence. The application of the hybrid approach is key to this.

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.

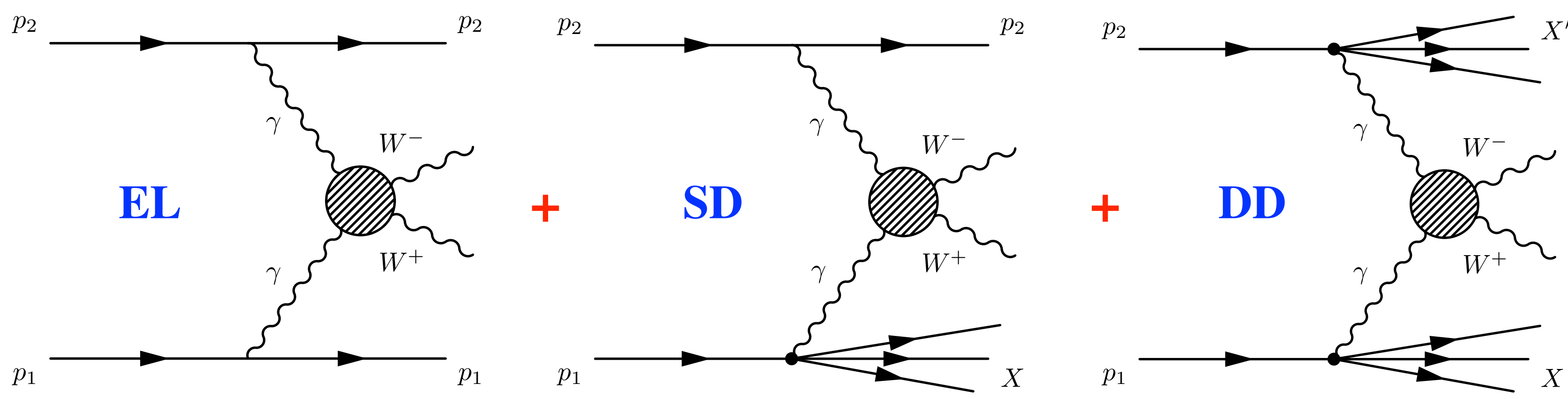


https://superchic.hepforge.org

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....

σ [fb] ($\sigma_i/\sigma_{\rm tot}$), W^+W^-	EL	SD	DD	Total
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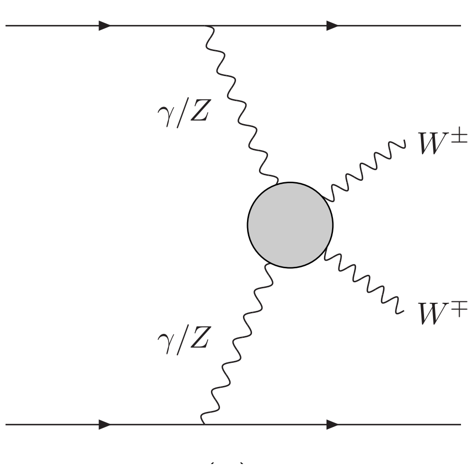
3.0 ± 0.5

- 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**?



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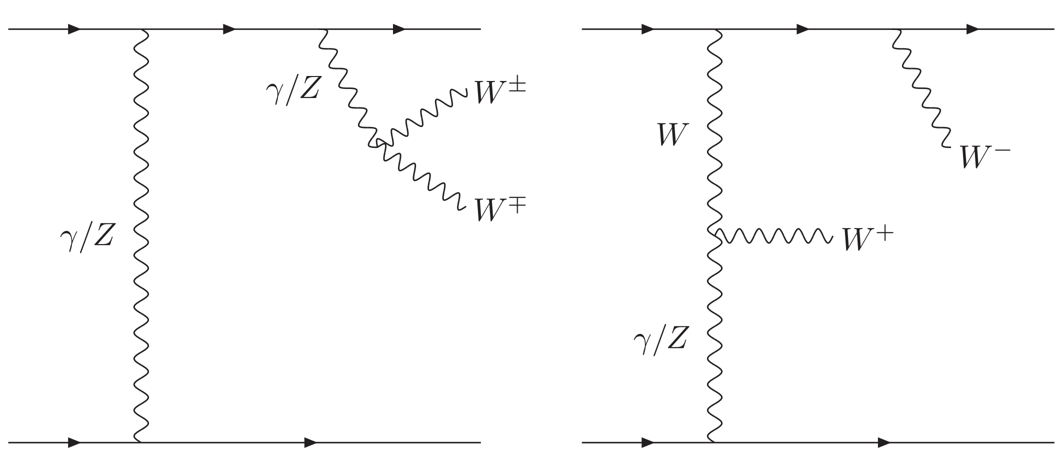

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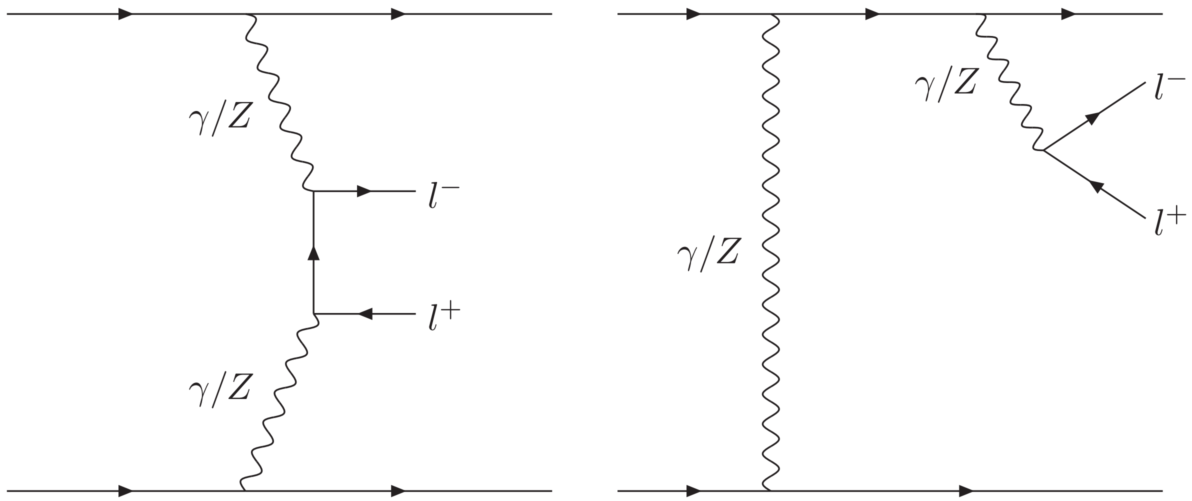
- Impact of **non-PI**: can only sensibly address by working in **axial gauge**, where power counting present.
- Alternative: compare with **lepton pair** production in similar kinematic region.

- 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

Final Remarks

- **Alternative procedure**: 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.

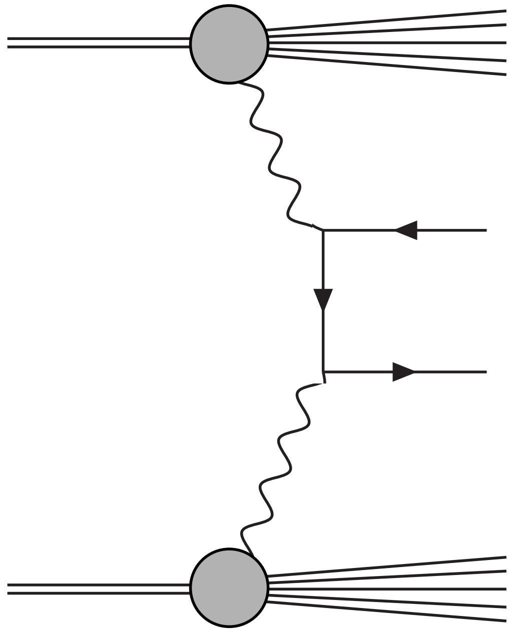
Summary

- ⋆ 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!

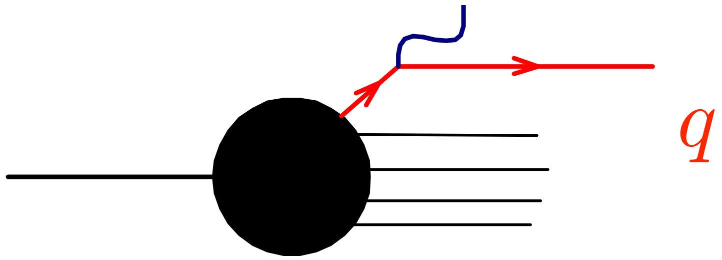
Backup

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).

Axial gauge

- Gauge fixing term in SM Lagrangian has the form:

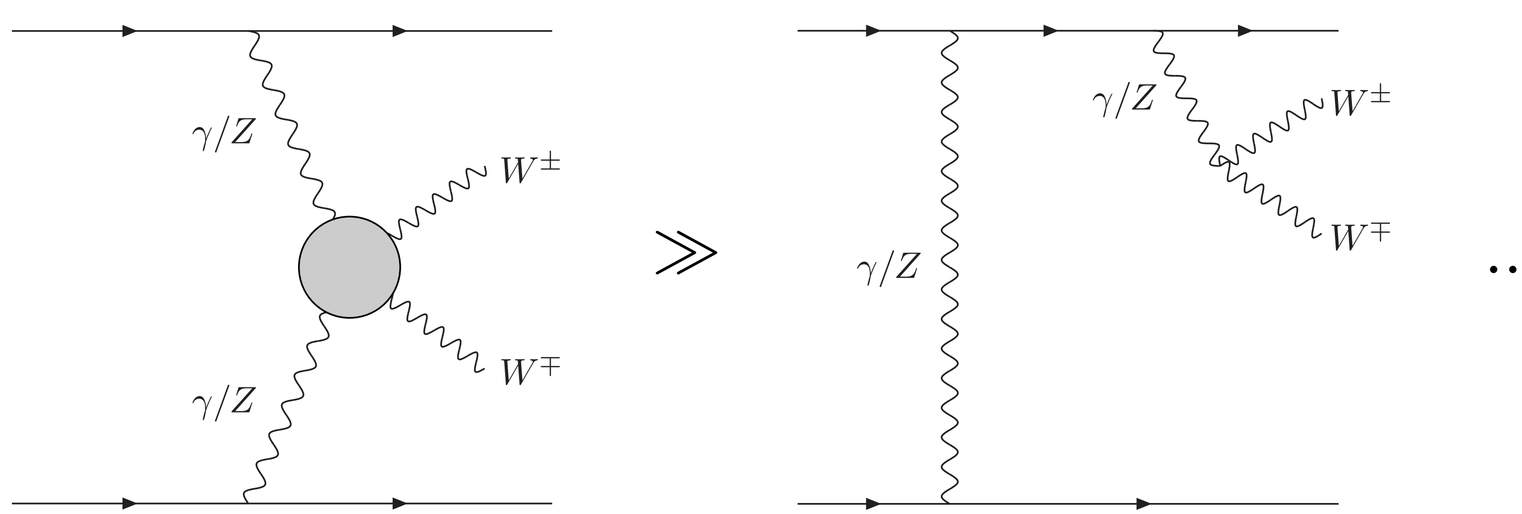
$$\mathcal{L}_{gf} = -\frac{1}{2}\lambda n^\mu A^a_\mu A^b_\nu n^\nu - \frac{1}{2}\lambda (n\cdot B)^2 \ ,$$

  where n^μ is arbitrary 4-vector.

- This leads to W, Z longitudinal polarizations that no longer grow with energy. For $n^2 = 0$ have:

$$\epsilon^\mu_L(k) = i\frac{M_W}{k\cdot n}n^\mu$$

- In such a case power counting reintroduced:



Axial gauge

- Cross sections well behaved (even without veto), and rather close to full result.

σ [fb]	On–shell	Collinear	Axial	Axial (inc. Z)	Full
EL	0.696	0.713	0.701	0.701	0.701
SD	3.31	$3.73^{+0.40}_{-0.41}$	3.25	6.11	6.00
DD	3.81	$4.71^{+1.07}_{-0.95}$	3.64	11.9	13.1
Total	7.82	$9.15^{+1.47}_{-1.36}$	7.59	18.7	19.8

vs

σ [fb]	Unitary		
	EL	SD	DD
No veto	0.704	5.01	222

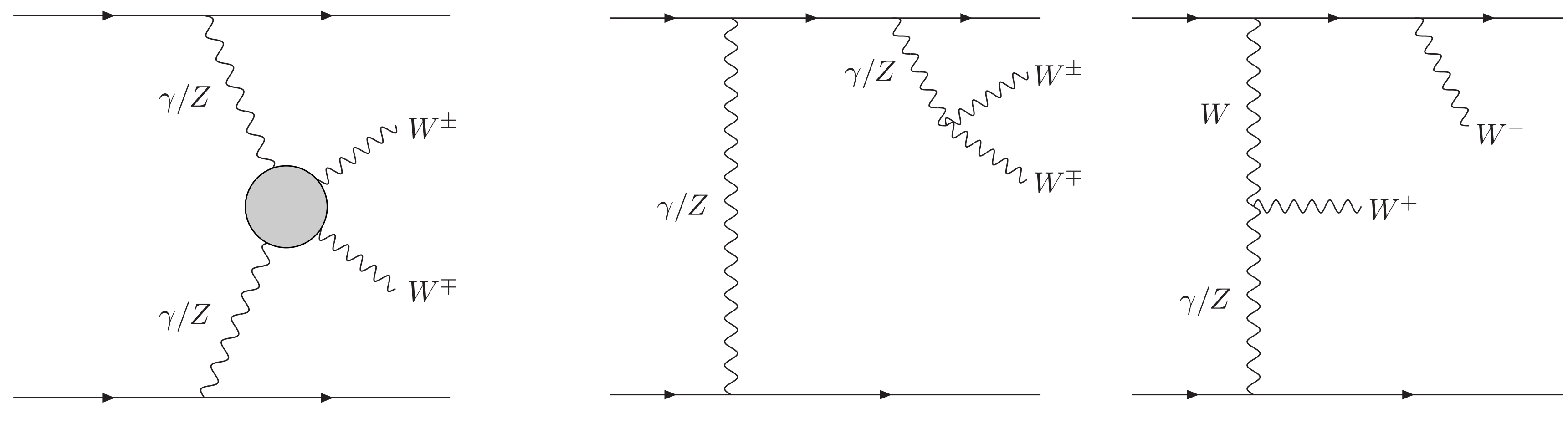
- Interestingly this is particularly true once we include Z-initiated production.

‘Hybrid’ Calculation: DD

- If satisfy: $Q_i^2 > Q^2_{\rm cut}$ $W_i^2 > W^2_{\rm cut}$

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

then include all diagrams:



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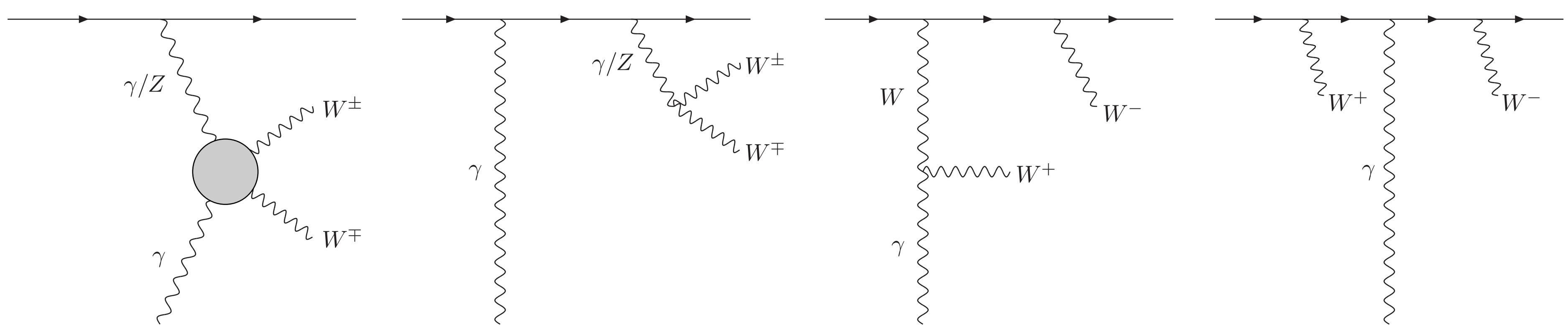
- If only satisfied by one beam then include:

1



2 (inelastic)

- If neither, then apply SF calculation.

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.

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

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

- Above result has significant bearing on **common practice**. That is, to measure: 3.5 ± 0.5

$$\sigma^{\rm EL} + \sigma^{\rm SD} + \sigma^{\rm DD}$$

in **dilepton** sample with $m_{ll} > 2M_W$ and evaluate (EL better known theory):

$$f_\gamma^{ll} \approx \frac{\sigma^{\rm EL} + \sigma^{\rm SD} + \sigma^{\rm DD}}{\sigma^{\rm EL,theor}}$$

- This is then used to give a predicted W^+W^- cross section assuming $f_\gamma^{ll} = f_\gamma^{WW}$

$$\sigma^{WW} = \sigma^{WW}_{\rm EL,theor} \cdot f_\gamma^{ll}$$

- But we do not expect this to be true! **ATLAS** measure: $f_\gamma^{ll} = 3.59 \pm 0.15$
- Agrees well with our theory ✓. But follow above procedure get:

$$\sigma^{WW}_{f_\gamma} = 3.5 \times 0.701\,{\rm fb} = 2.45\,{\rm fb}$$

i.e. rather low wrt data. Exactly as we would expect - effectively **omits non-PI**. Not sufficient for precision physics! **Essential** to follow approach as per this talk.