Photon-Induced Prodution in SuperChic

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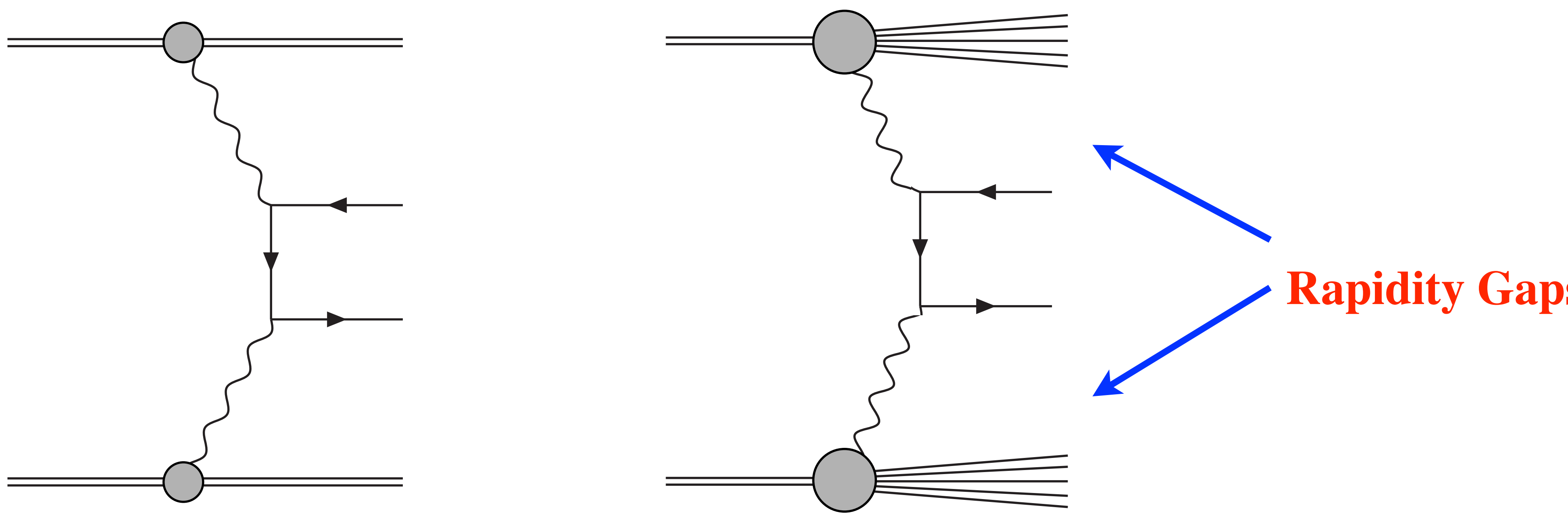
Workshop on the Modelling of Photon-Induced Processes, IPPP Durham, June 6 2023

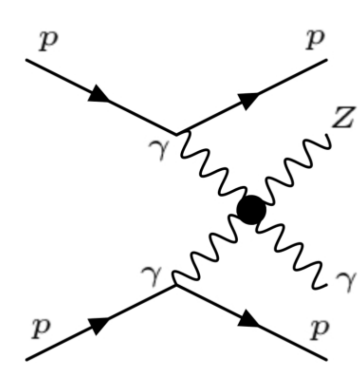
PI Production @ LHC

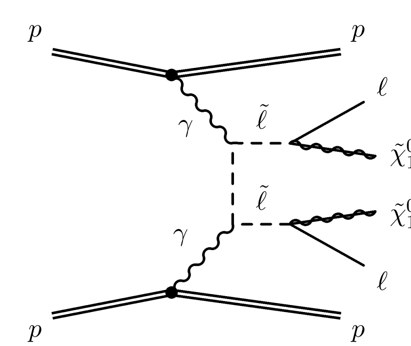
- **Exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state.
- Can be selected either with proton tagging or via rapidity gap vetos (i.e. elastic + inelastic = semi-exclusive production).



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

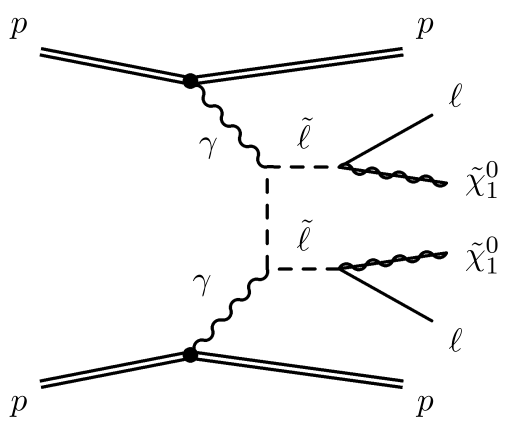
$\Rightarrow$ The LHC as a $\gamma\gamma$ collider!





★ Probe of BSM:

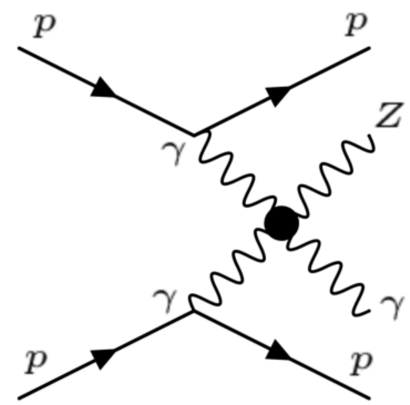
Compressed SUSY



M. Tasevsky et al., JHEP 1904 (2019) 010

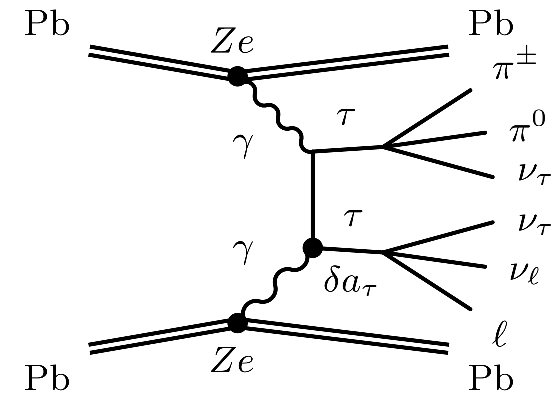
L. Beresford and J. Liu, PRL 123 (2019) no.14

Anomalous couplings



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

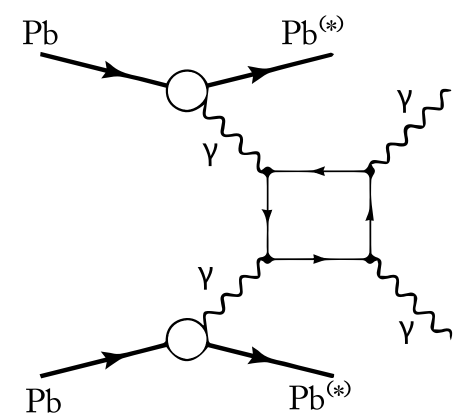
tau g-2



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

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

LbyL scattering/ALPS

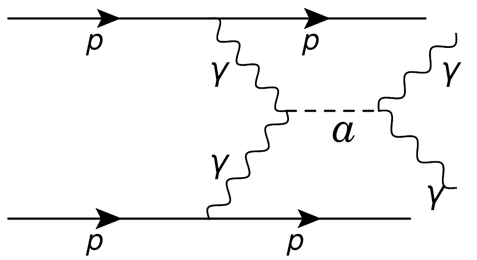


C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

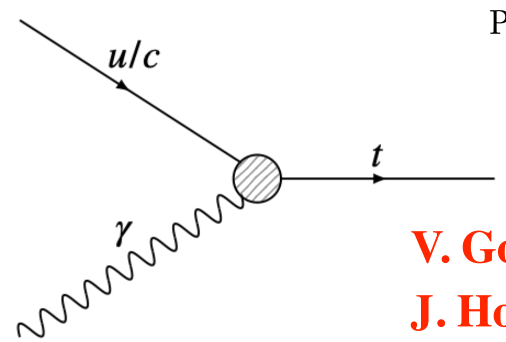
Axion-like Particles

LHL and M. Tasevsky, arXiv:2208.10526

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



★ **Probe** of the top sector.



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

J. Howarth, arXiv:2008.04249

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

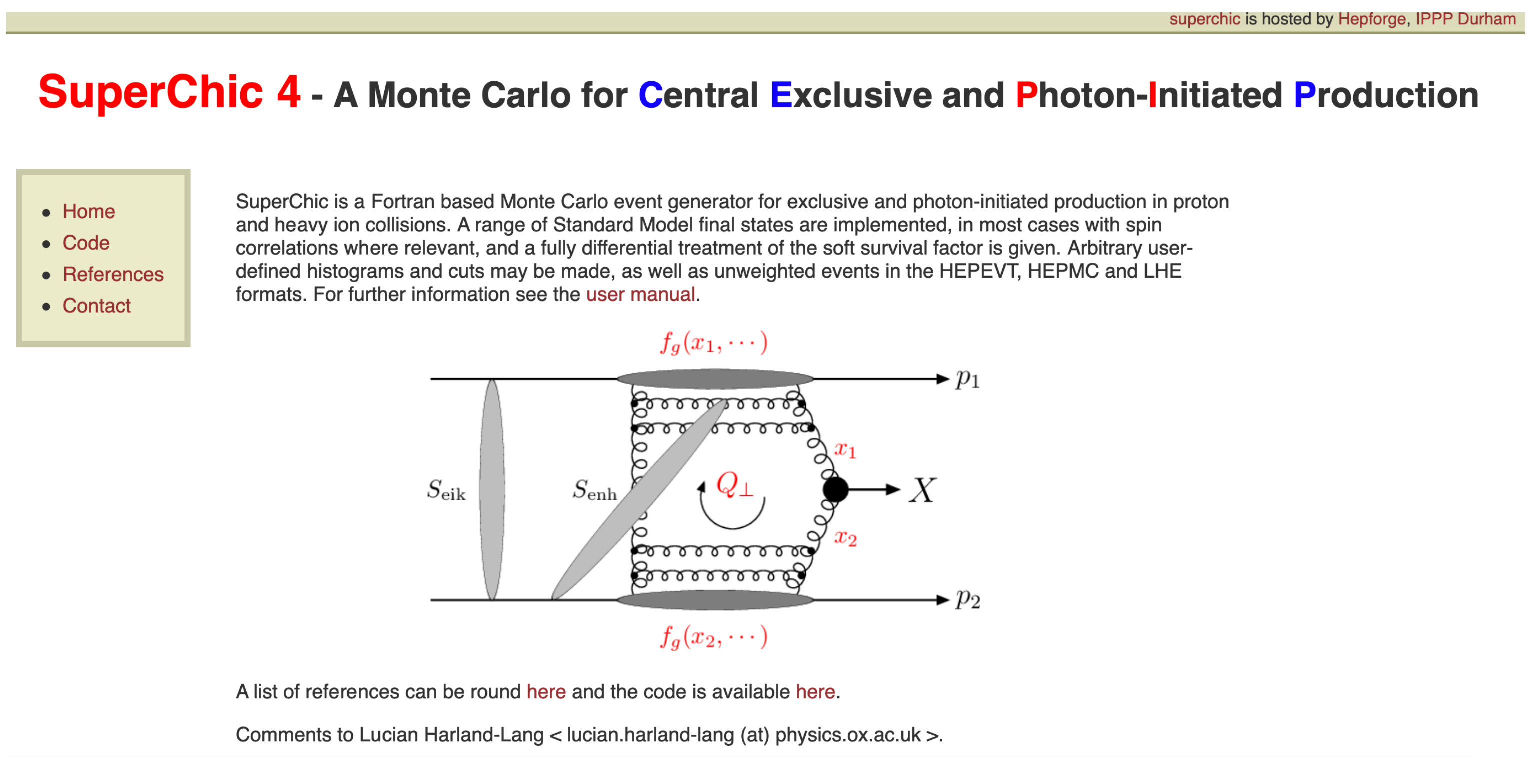
LHL et al., EPJC 76 (2016) no. 5, 255, LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925

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

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.



`https://superchic.hepforge.org`

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

Modelling PI Production in SC

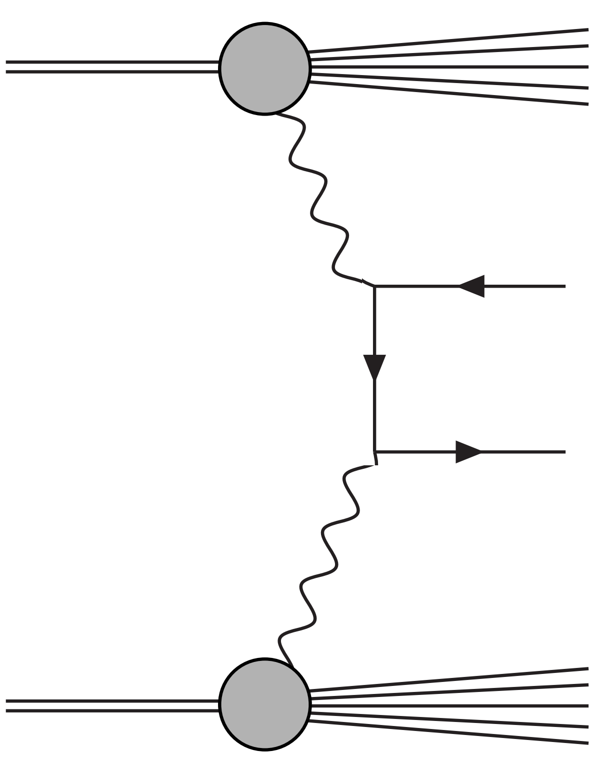
Questions

- Two questions of relevance here asked by organizers for me to address:

    ★ **Tuning:** How can one improve modelling of the dissociative part? What measurements could be done to improve the modelling and integration?

    ★ **Parton Shower Interface:** What is the best way to propagate the information about which proton dissociates and which stays intact?

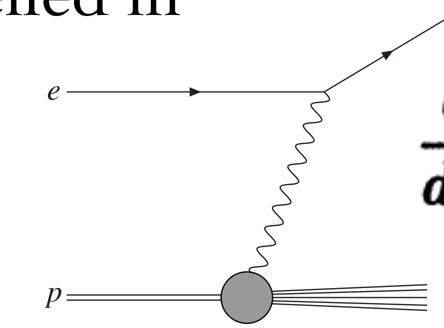
- To (try and) answer these, first briefly recap how dissociative PI production is modelled in SC.



LHL, *JHEP* 03 (2020) 128

Structure Function Calculation

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



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

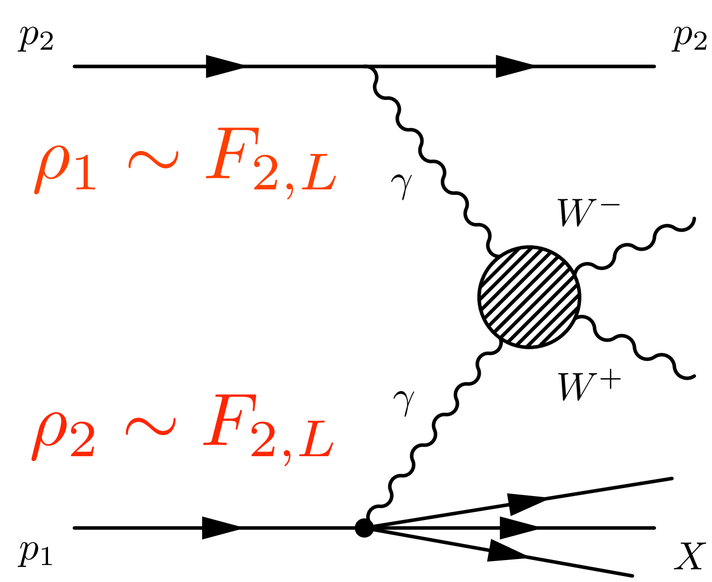
- Structure functions parameterise the $\gamma p \to X$ vertex.

- Use same idea as for DIS to write:

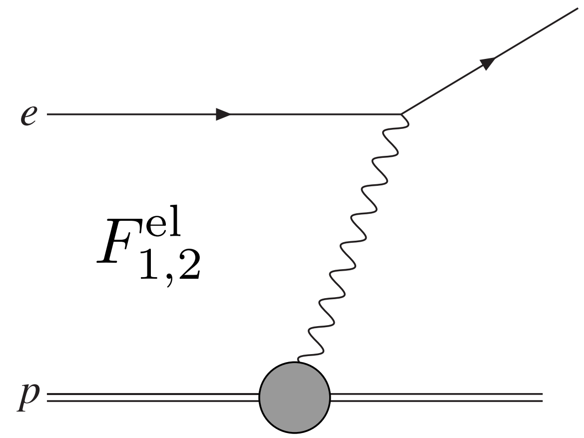
$$W^{\alpha\beta}(p,q) = \left(g^{\alpha\beta} - \frac{q^\alpha q^\beta}{q^2}\right) W_1(x,Q^2) + \left(p^\alpha + \frac{1}{2x}q^\alpha\right)\left(p^\beta + \frac{1}{2x}q^\beta\right) W_2(x,Q^2)$$

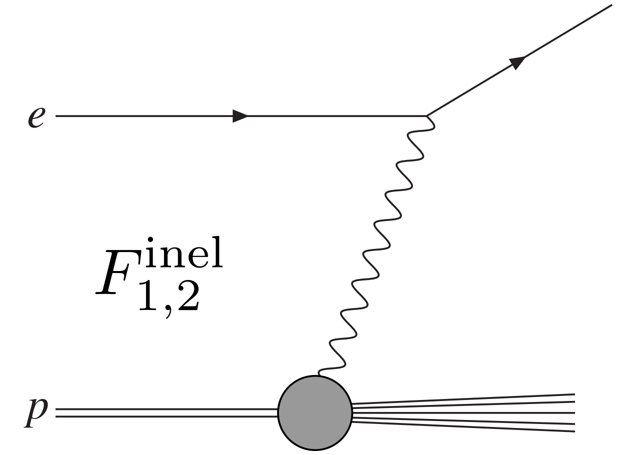
$$\sigma_{pp} = \frac{1}{2s}\int \overbrace{\mathrm{d}x_1 \mathrm{d}x_2\, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp}}^{\textbf{Photon }x,\,Q^2} \mathrm{d}\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\overbrace{\rho_1^{\mu\mu'}\,\rho_2^{\nu\nu'}}^{\gamma^* p \to X}\, \overbrace{M^*_{\mu'\nu'} M_{\mu\nu}}^{\sim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

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



- Both elastic and inelastic SFs accounted for:

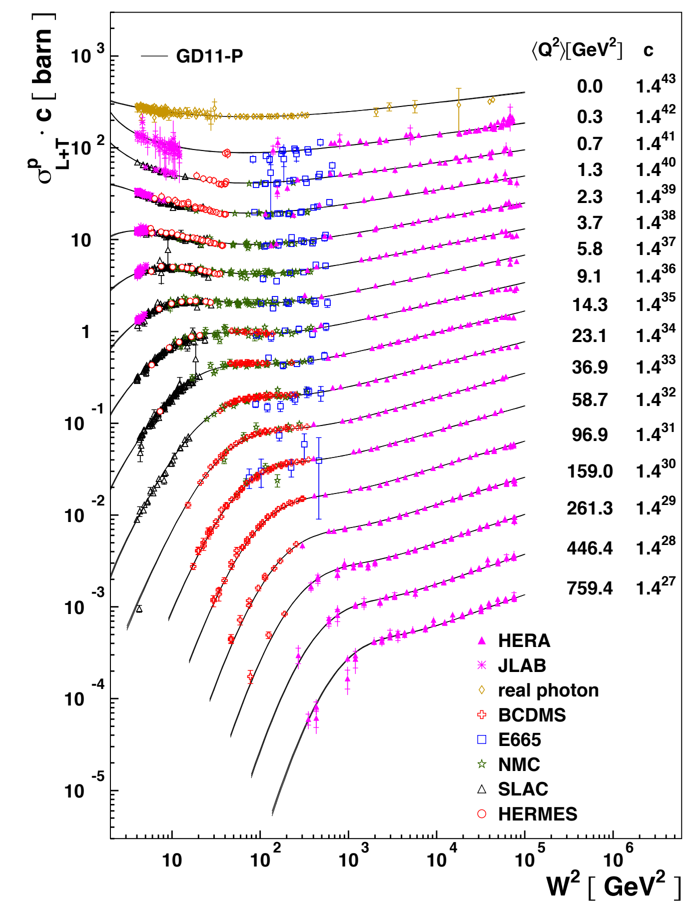


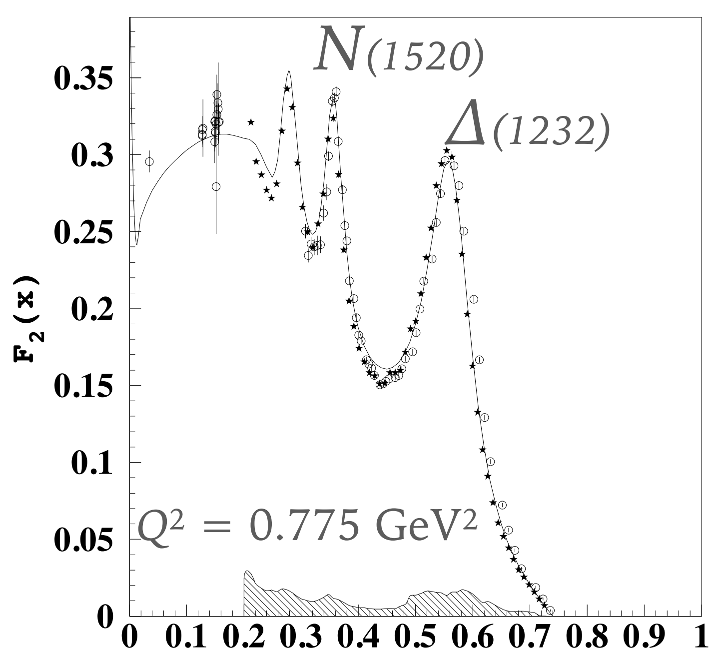


★ **Elastic**: precisely measured proton EM form factor.

★ **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.

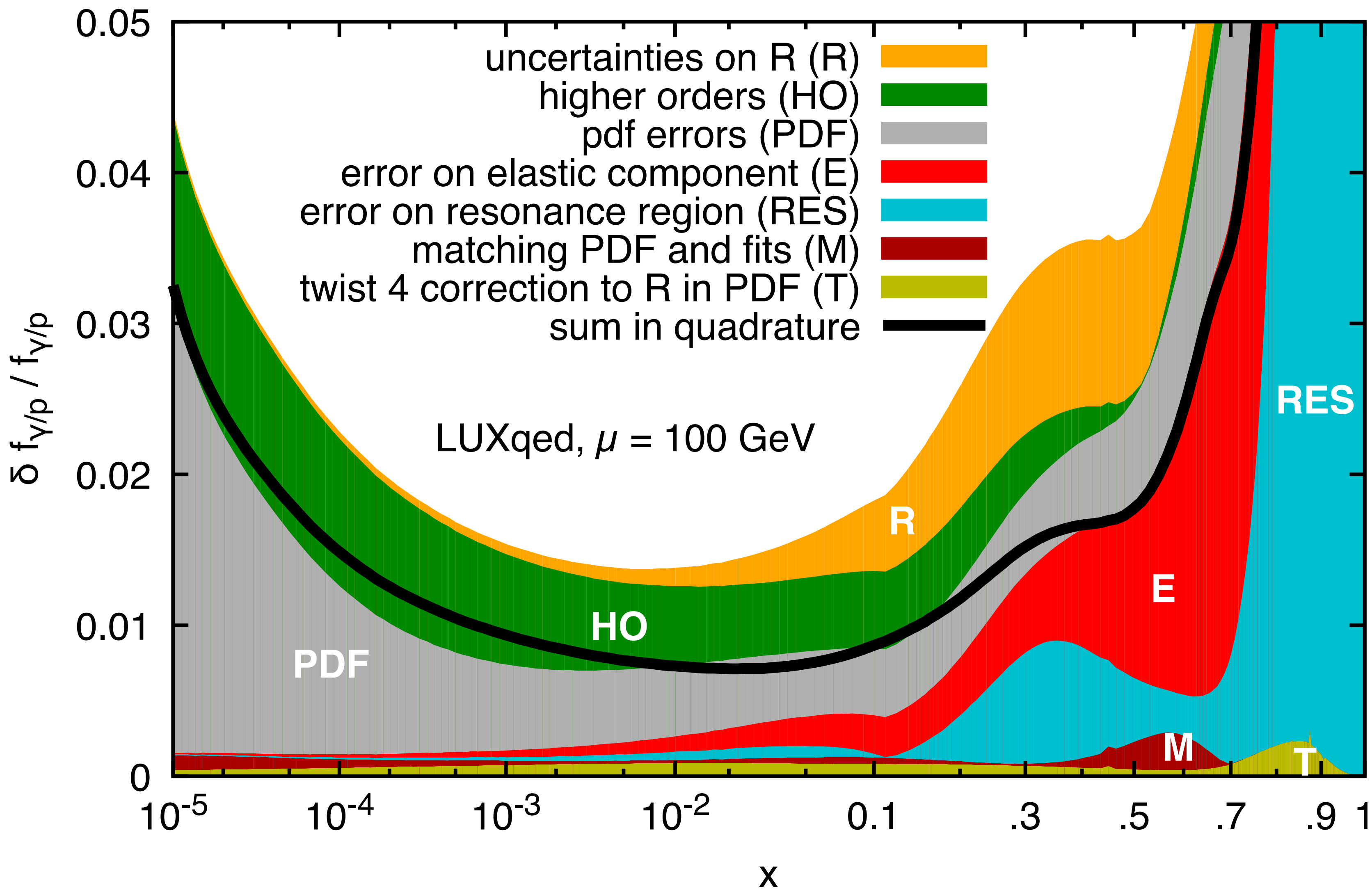


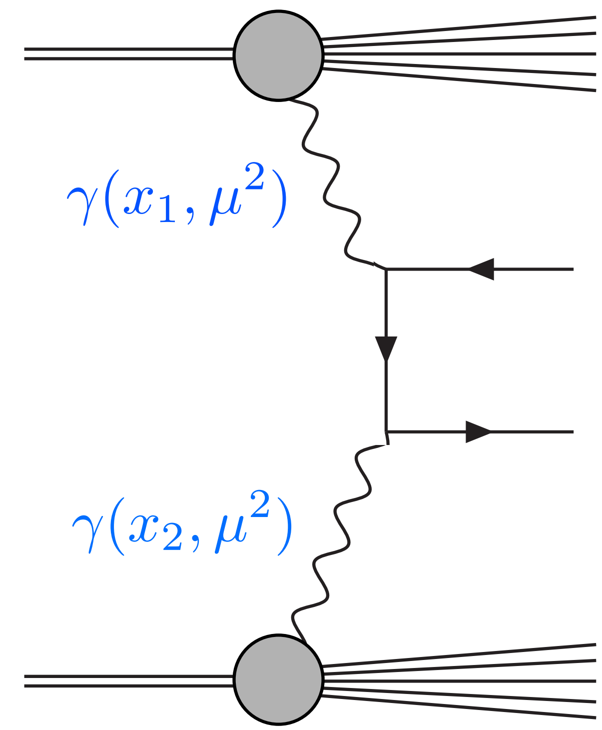


- High Q^2 region, simplest to calculate using (NNLO) pQCD + global PDFs.

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

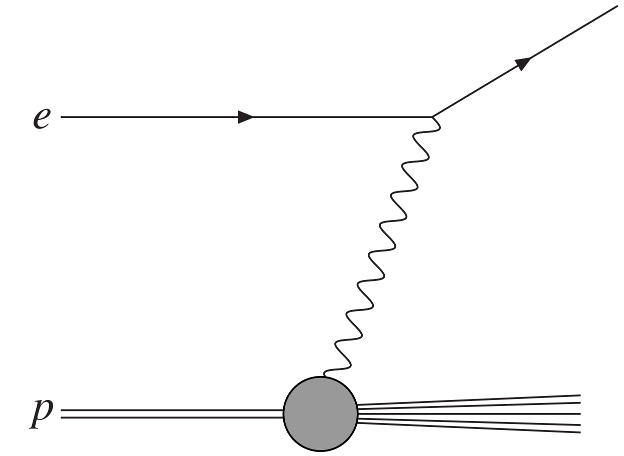
A. Manohar et al., JHEP 1712 (2017) 046



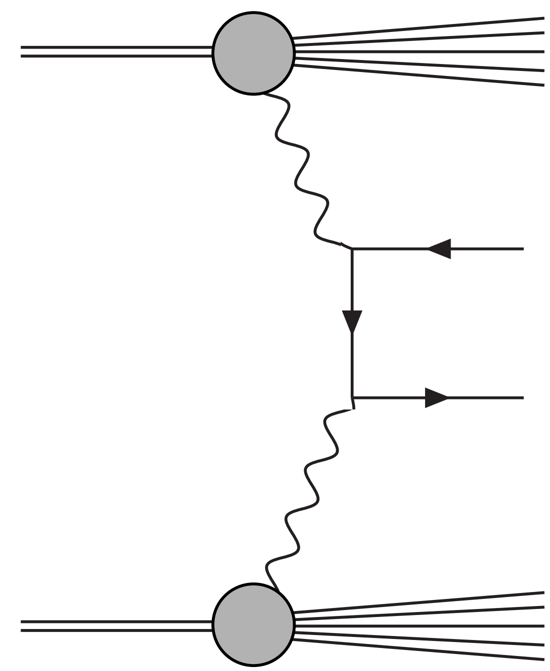


- Uncertainty in inputs ~ to equivalent photon PDF uncertainty. That is % level or less (in particular for elastic case). **No tuning required??**

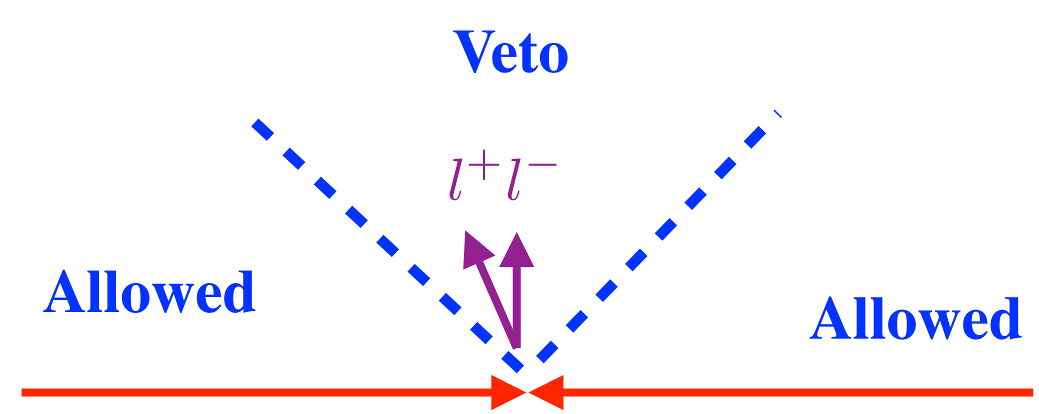
- SF approach can provide high precision predictions for kinematics of $\gamma p \to X$ vertex:



  - Gives cross section fully differential in both photon 4-momenta $q_{1,2} \Rightarrow$ central system $p = q_1 + q_2$



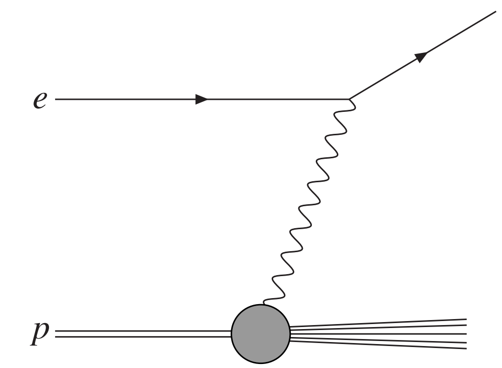
  - 'Inclusively' this is modelled with high precision*. However in presence of veto, particle level modelling required.



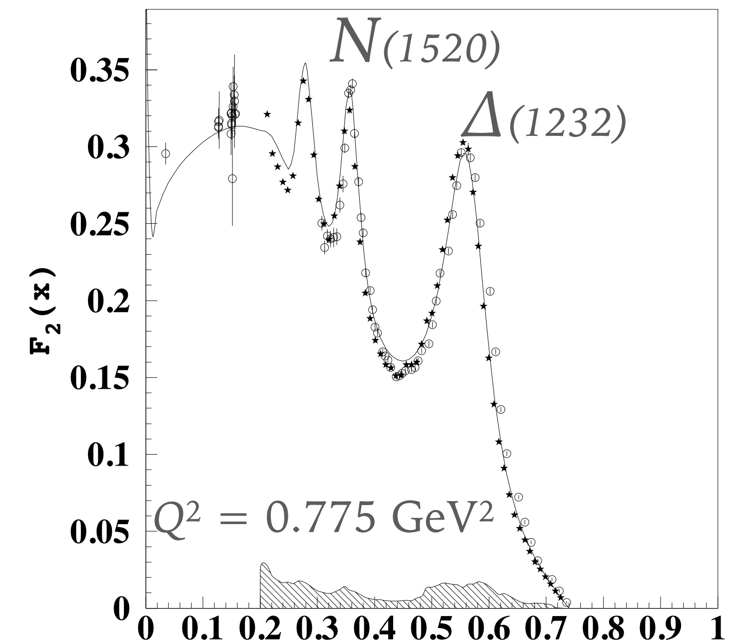
*Up to survival factor - more later

Dissociation Modelling

- What does particle distribution look like?

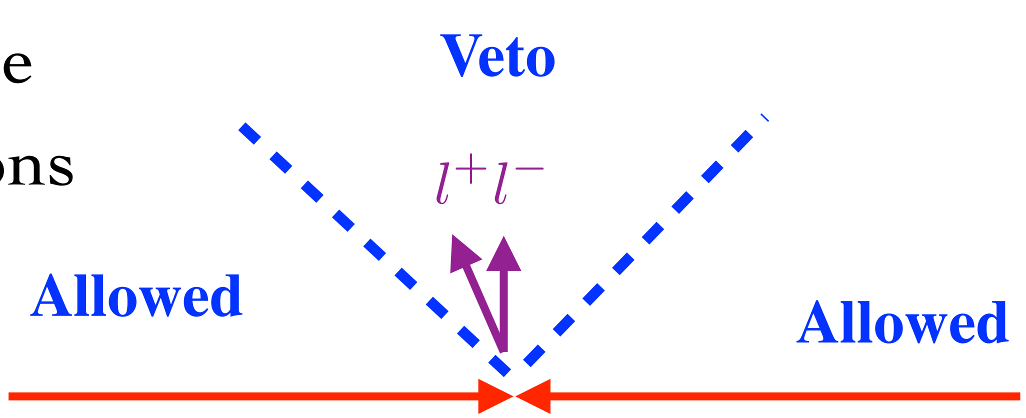


★ Low system $W^2 (> Q^2)$: non-perturbative region. In principle should account for various resonances, decay modes etc

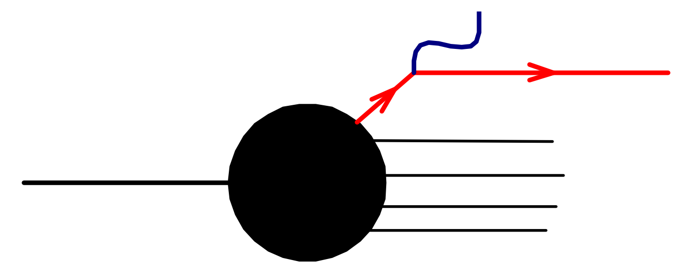


- However particle $p_\perp^2 \sim Q^2$ is low $\Rightarrow$ should be unaffected by veto ('elastic-like').

- Sensitivity to modelling in this region should be limited $\longrightarrow$ remain 'inclusive' with SF predictions providing central particle distributions.



★ Higher system W^2, Q^2 : perturbative region.
LO parton-level process is $\gamma q \to q$



- Generate outgoing quark according to momentum conservation, preserving photon 4-momentum.
- Take this and dress with parton-shower + hadronisation in usual way.

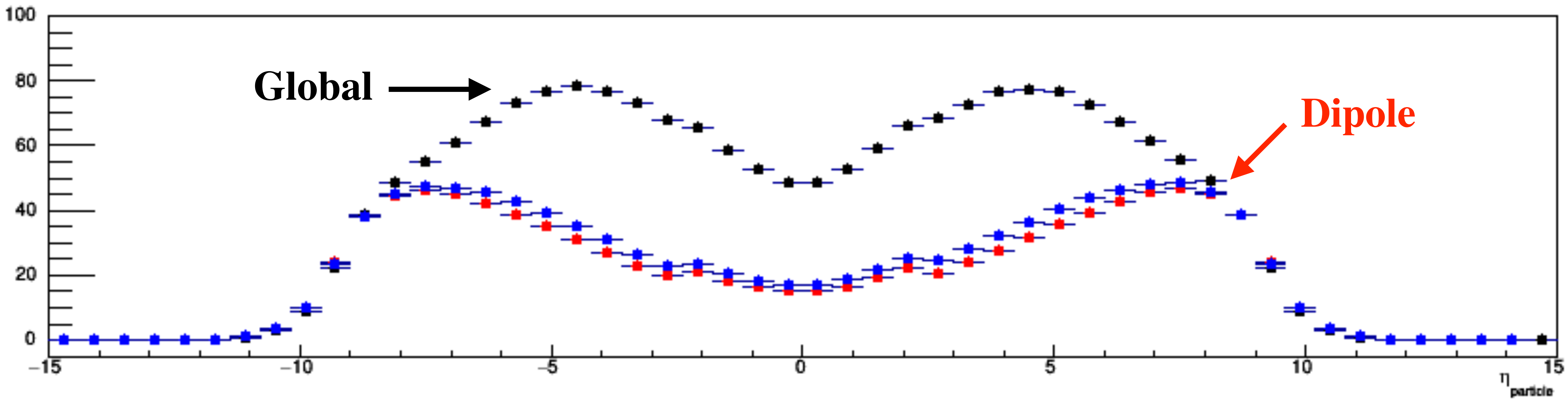
✤ Caveats, comments:

- Parton showering will modifying photon ($\Rightarrow$ central system) 4-momentum. Not necessarily what we want - for dileptons predicted by SF approach, so should not change after.

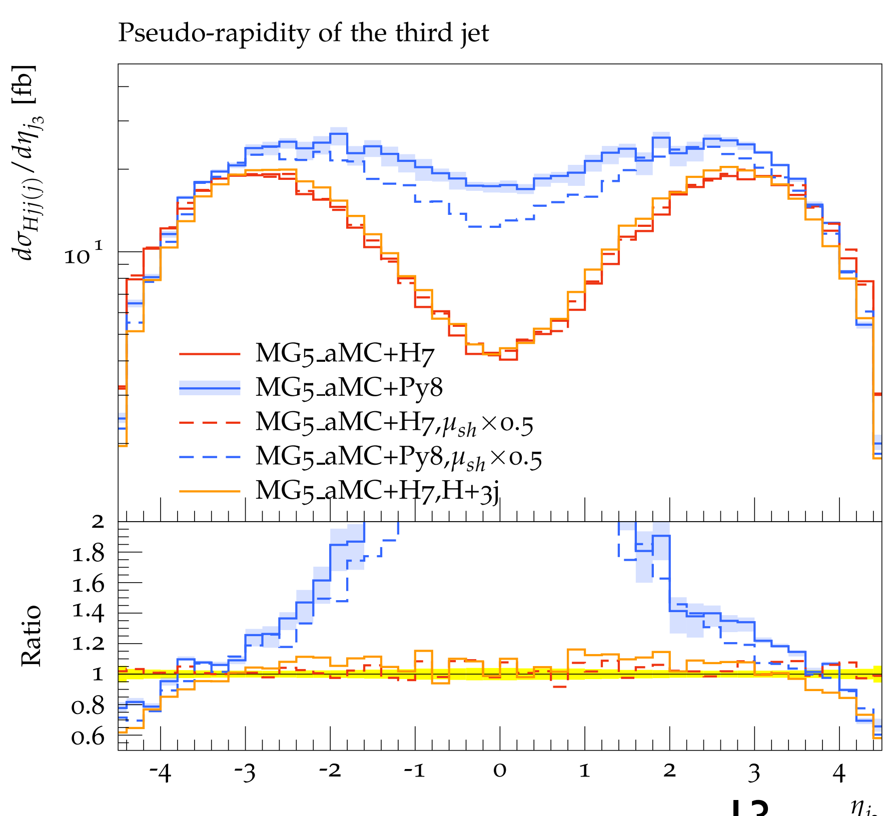
$$\sigma_{pp} = \frac{1}{2s} \int \mathrm{d}x_1 \mathrm{d}x_2 \, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp} \mathrm{d}\Gamma \, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\rho_1^{\mu\mu'} \rho_2^{\nu\nu'} M^*_{\mu'\nu'} M_{\mu\nu}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X) \,,$$

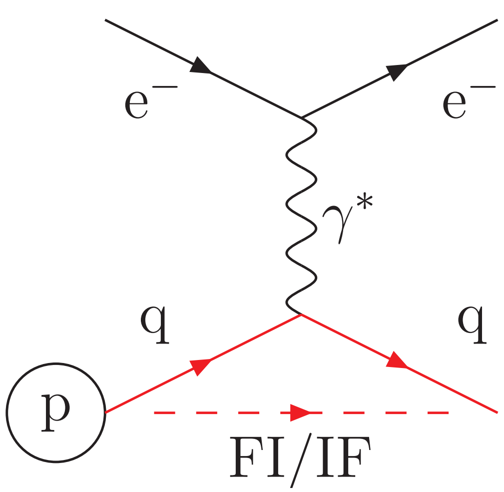
- Impact should be mild, and less clear for other processes (WW...), but may warrant further study?
- Assume up quark for simplicity. Dependence on this should be v. mild.

- In addition, must turn off global recoil in Pythia to get realistic result (no colour connection between beams). If not $\Rightarrow$ too much central production.



- Similar point emphasised in e.g. VBF Higgs studies.

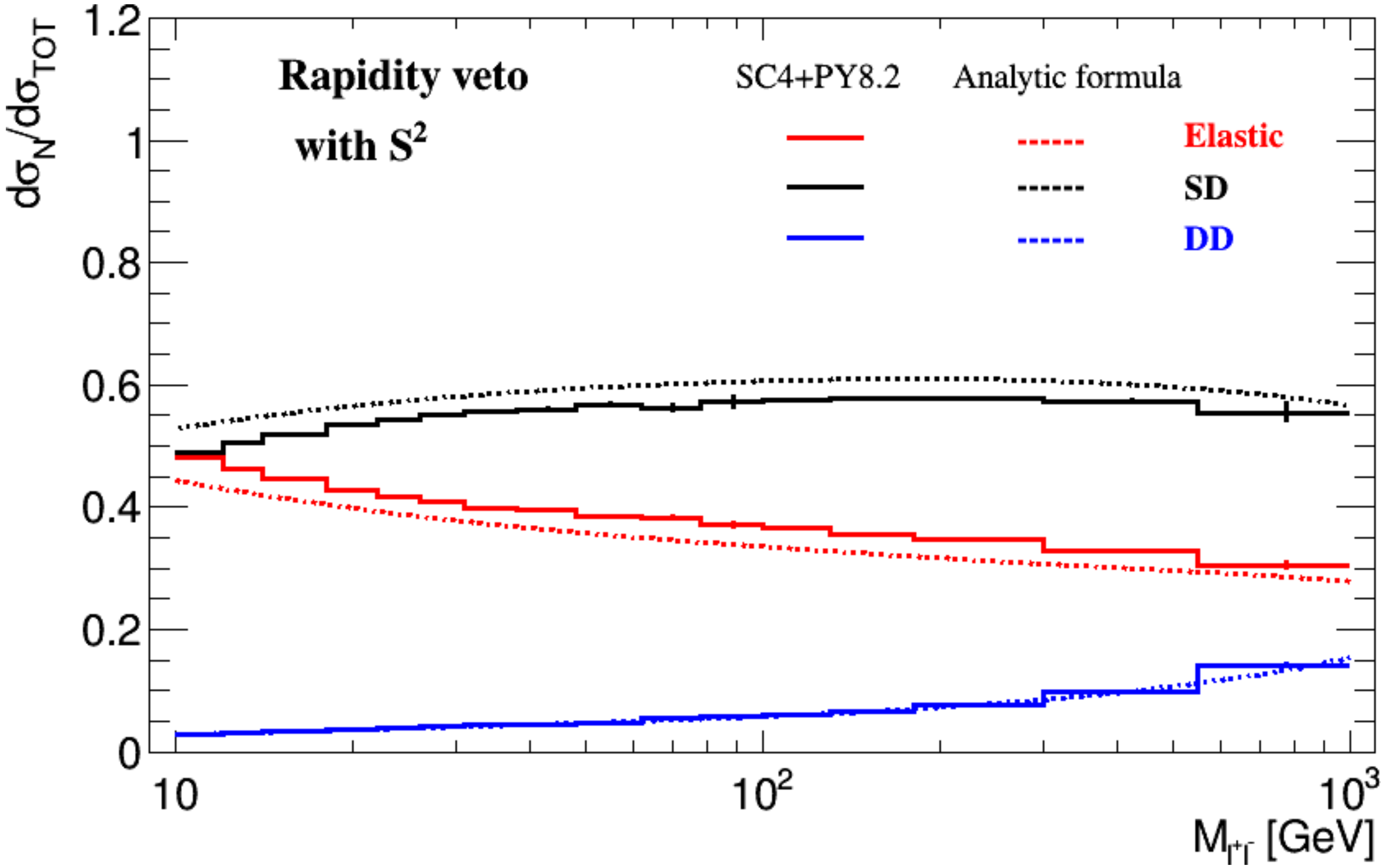




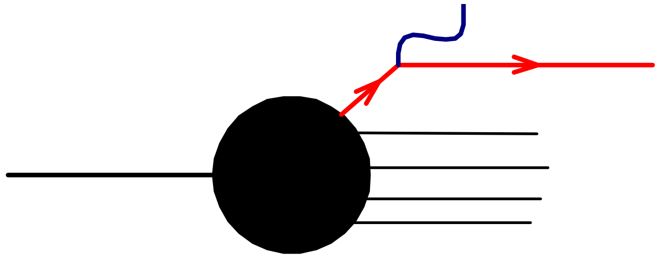
B. Cabouat and T. Sjostrand, arXiv:1710.00391

B. Jager et al., *Eur.Phys.J.C* 80 (2020) 8, 756

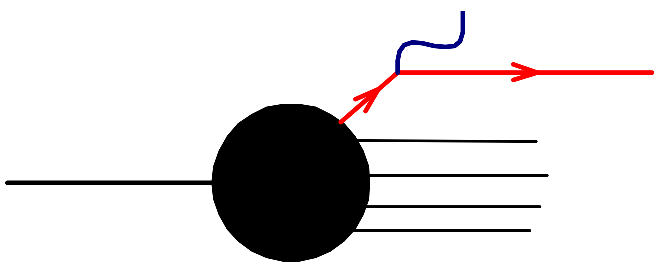
- Look at EL,SD,DD event fractions in dilepton production, after veto.



- Dashed lines: result of imposing veto on final-state quark in LO $\gamma q \to q$, i.e. without showering/hadronisation. Difference relatively small.

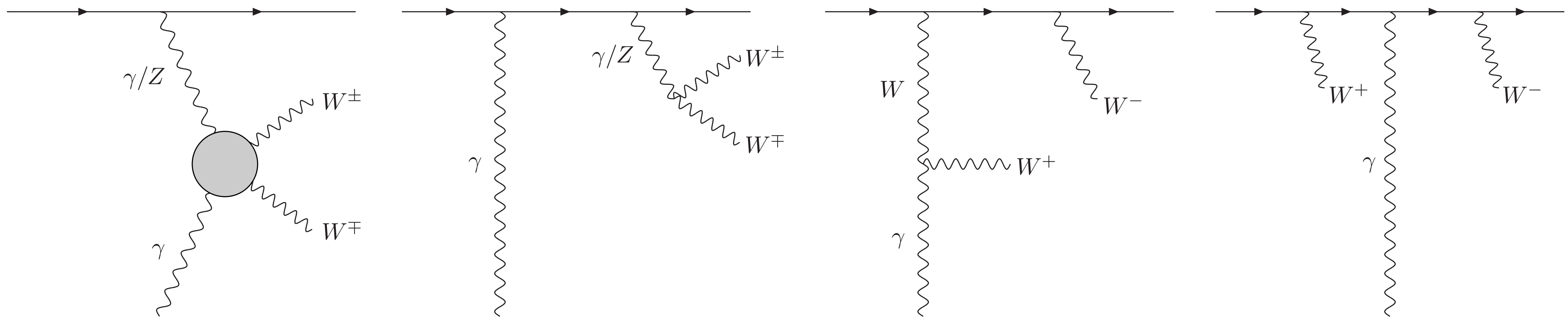


★ **Aside (clarification):** LHE filled with initial + final-state quarks. So no assumption about photon initiator.



```
<event>
6    0   1.     0.775434673E+00     0.729740000E-02     0.582009373E+00
               2        -1     0     0  501     0  0.000000000E+00  0.000000000E+00  0.497315333E+02  0.497326282E+02  0.330000000E+00 0. 9.
               2        -1     0     0  502     0  0.000000000E+00  0.000000000E+00 -0.483160434E+02  0.483171703E+02  0.330000000E+00 0. 9.
               2         1     1     2  501     0 -0.474389763E-01  0.472902801E+00  0.215668401E+02  0.215746004E+02  0.330000000E+00 0. 9.
               2         1     1     2  502     0 -0.277136784E+00 -0.255432013E+00 -0.415155360E+02  0.415185583E+02  0.330000000E+00 0. 9.
              11         1     1     2    0     0 -0.255154515E+00 -0.695964925E+01  0.258934809E+02  0.268136938E+02  0.511007393E-03 0. 9.
             -11         1     1     2    0     0  0.579730275E+00  0.674217847E+01 -0.452929501E+01  0.814294610E+01  0.511002089E-03 0. 9.
</event>
```

- Relevant as at higher Q^2, W^2 other topologies can play significant role.



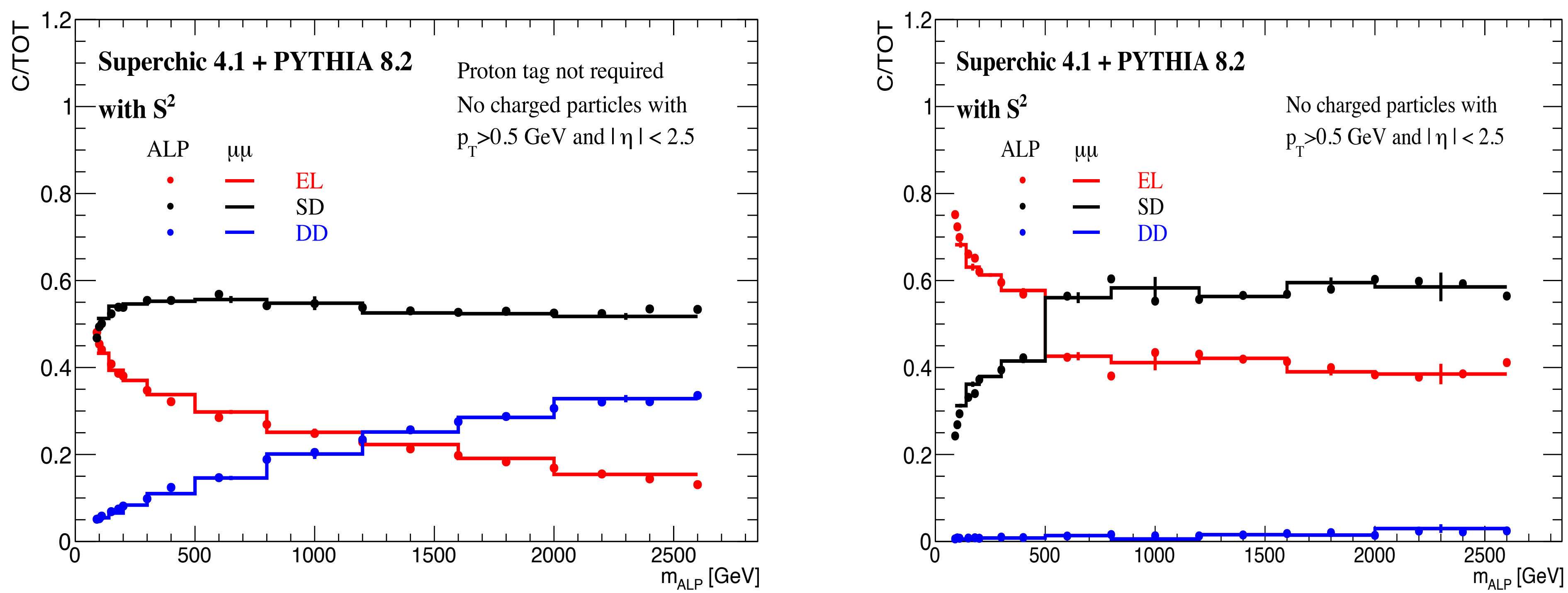
S. Bailey and LHL, *Phys.Rev.D* 105 (2022) 9, 093010

- Away from pure $\gamma^* p \to X$ the Q^2 dependence predicted at LO only - modifications from parton shower acceptable.

★ **Caveat:** impact of rapidity veto not only case where dissociation modelling important.

- For cases with proton tag, can be interested in probability of getting proton hit from dissociation system.

PLOT



LHL and M. Tasevsky, *Phys.Rev.D* 107 (2023) 3, 3

- Probability clearly low, but in some low signal cases (e.g. dark matter searches) can be a BG. **LHL et al., *JHEP* 04 (2019) 010**
- Model dependence larger, and observable to be tuned ($P(p \to X \to p)$) rather different to rapidity veto probability.

★ **Parton Shower Interface:** What is the best way to propagate the information about which proton dissociates and which stays intact?

- Returning to this question. How it is done in SC:
  - On elastic side(s) fill LHE with initial-state **photon** and set `BeamRemnants:unresolvedHadron` appropriately.

$p_\perp^\gamma = 0$

SD

```
<event>
5    0   1.     0.763319477E+00     0.729740000E-02     0.589921396E+00
               2        -1     0     0  501     0  0.000000000E+00  0.000000000E+00  0.231049300E+03  0.231049536E+03  0.330000000E+00 0. 9.
              22        -1     0     0    0     0  0.000000000E+00  0.000000000E+00 -0.412400091E+01  0.412400062E+01  0.000000000E+00 0. 9.
               2         1     1     2  501     0 -0.166098282E+00 -0.723086591E+00  0.218403803E+03  0.218405312E+03  0.329999840E+00 0. 9.
              11         1     1     2    0     0  0.122458429E+01  0.550156647E+01  0.101501806E+02  0.116100391E+02  0.511010557E-03 0. 9.
             -11         1     1     2    0     0 -0.105848600E+01 -0.477847988E+01 -0.162868408E+01  0.515818521E+01  0.511004570E-03 0. 9.
</event>
```

EL

```
<event>
4    0   1.     0.923496688E+01     0.729740000E-02     0.181525494E+00
              22        -1     0     0    0     0  0.277350185E-02 -0.534734409E-02  0.870790633E+00  0.870790565E+00  0.000000000E+00 0. 9.
              22        -1     0     0    0     0 -0.207937295E-01 -0.380647535E-03 -0.244849517E+02  0.244849499E+02  0.000000000E+00 0. 9.
              11         1     1     2    0     0  0.345953538E+01 -0.159583196E+01 -0.189271203E+02  0.193067591E+02  0.511013919E-03 0. 9.
             -11         1     1     2    0     0 -0.347755561E+01  0.159010397E+01 -0.468704074E+01  0.604898130E+01  0.511002715E-03 0. 9.
</event>
```

  - For SD to be passed through Pythia without errors requires further '**fix**': EL photon must be collinear + on-shell.
  - Set $p_\perp^\gamma = 0$ in LHE record to achieve this. Not ideal, but central system dominated by inelastic side, so impact should be small.

- Other choices:

```
BeamRemnants:primordialKT = off
```

- Want to keep initiating partons collinear to match SF calculation.

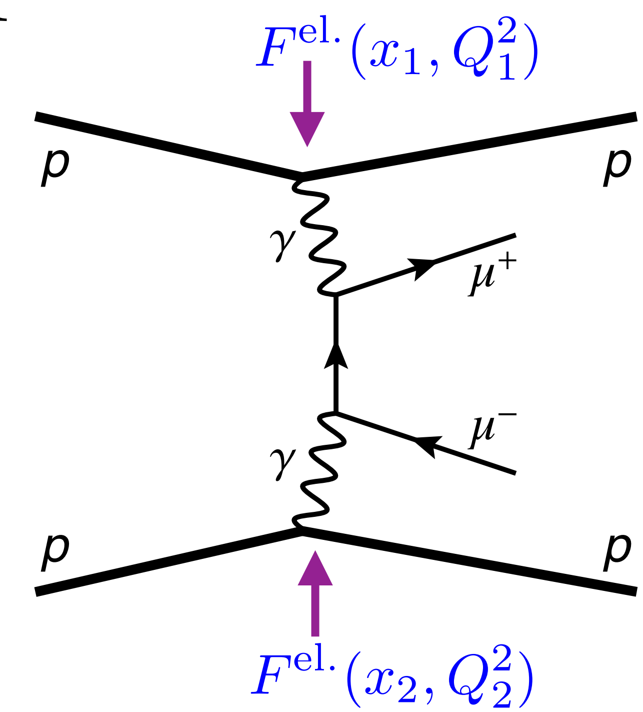
```
SpaceShower:pTmaxMatch = 2
SpaceShower:pTdampMatch=1
```

- As recommended by Pythia manual. First option fills whole phase space with shower. Second damps above $\text{SCALUP} = \max\left(\sqrt{Q_i^2}\right)$
- Impact of this is small.

```
SpaceShower:QEDshowerByQ = off
```

- No backward evolution of elastic photon - would make it inelastic!

The Survival Factor



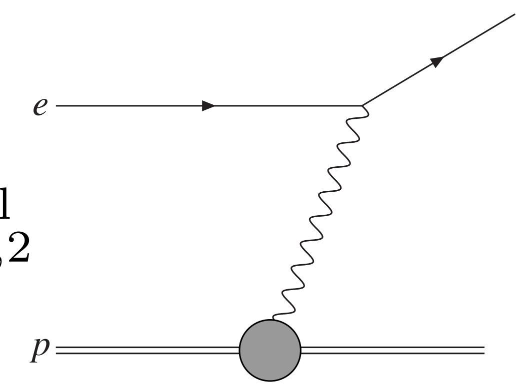
- Consider e.g. the exclusive process. So far we have (very) schematically:

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

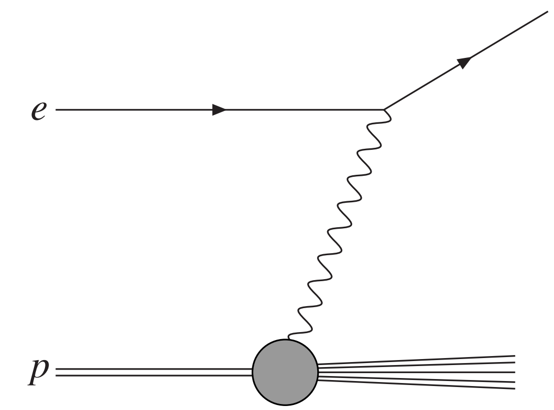
- Similarly for SD + DD, with $F^{\rm el.} \to F^{\rm inel.}$

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

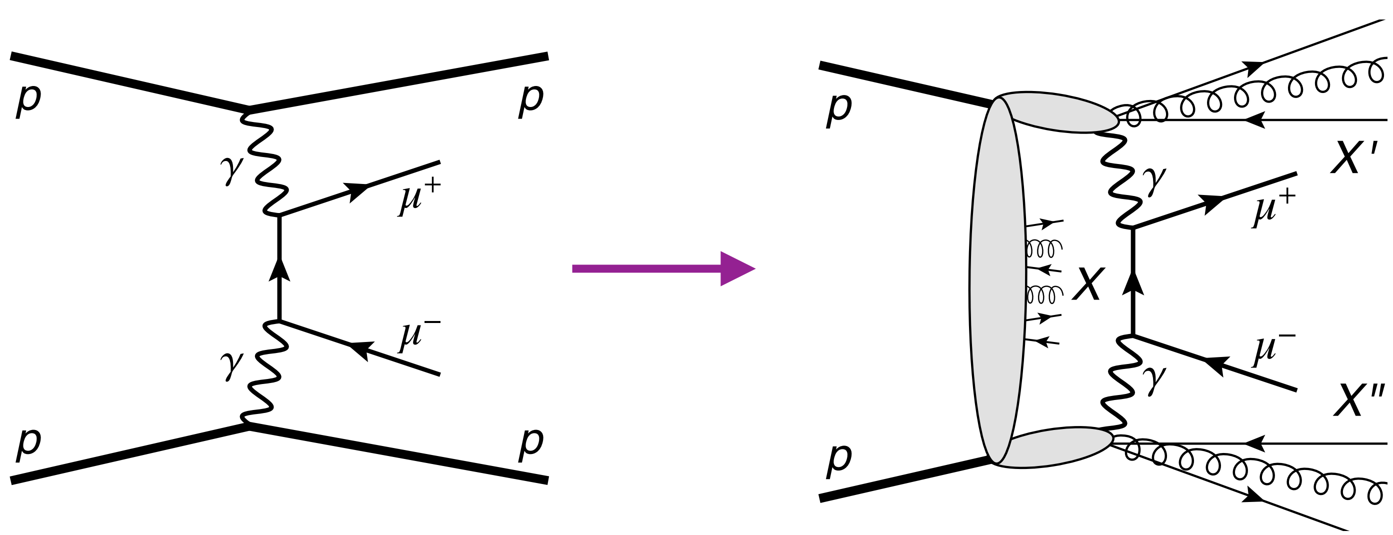
$F_{1,2}^{\rm el}$



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



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

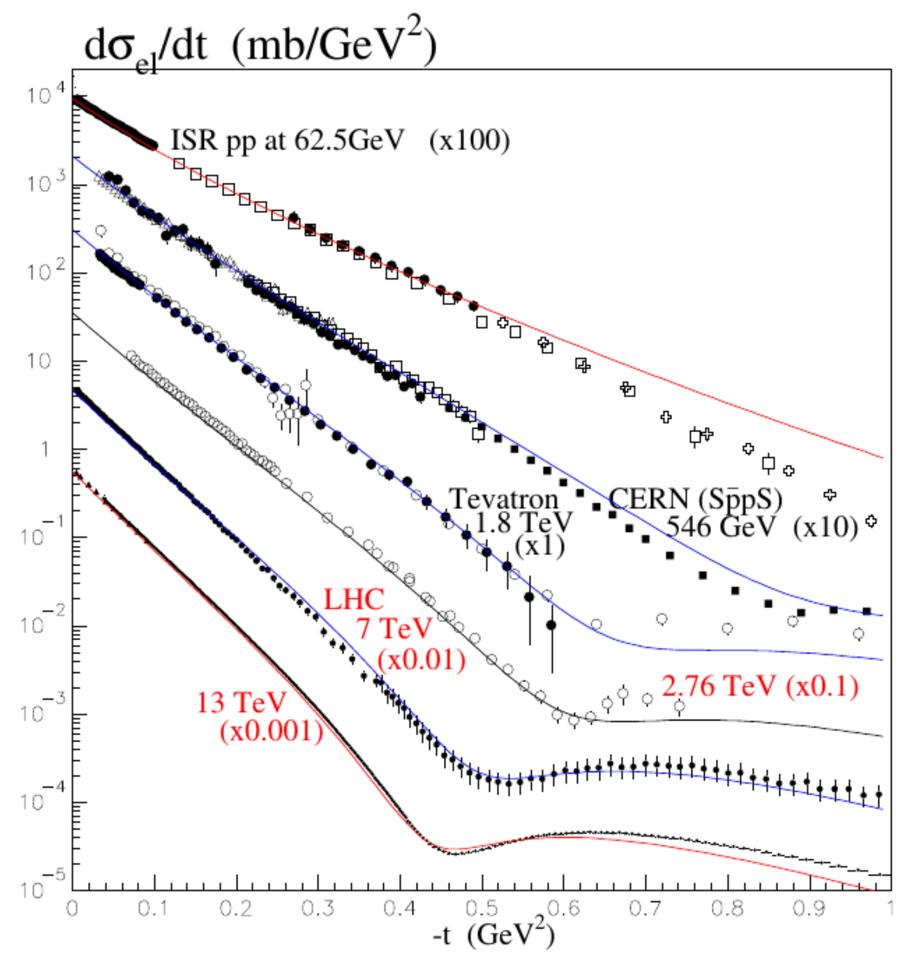


- ‘**Survival factor**’ = probability of no additional inelastic hadron-hadron interactions. Schematically:

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

- How to model this? Depends on e.g. $\sigma^{\rm inel}$ 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).

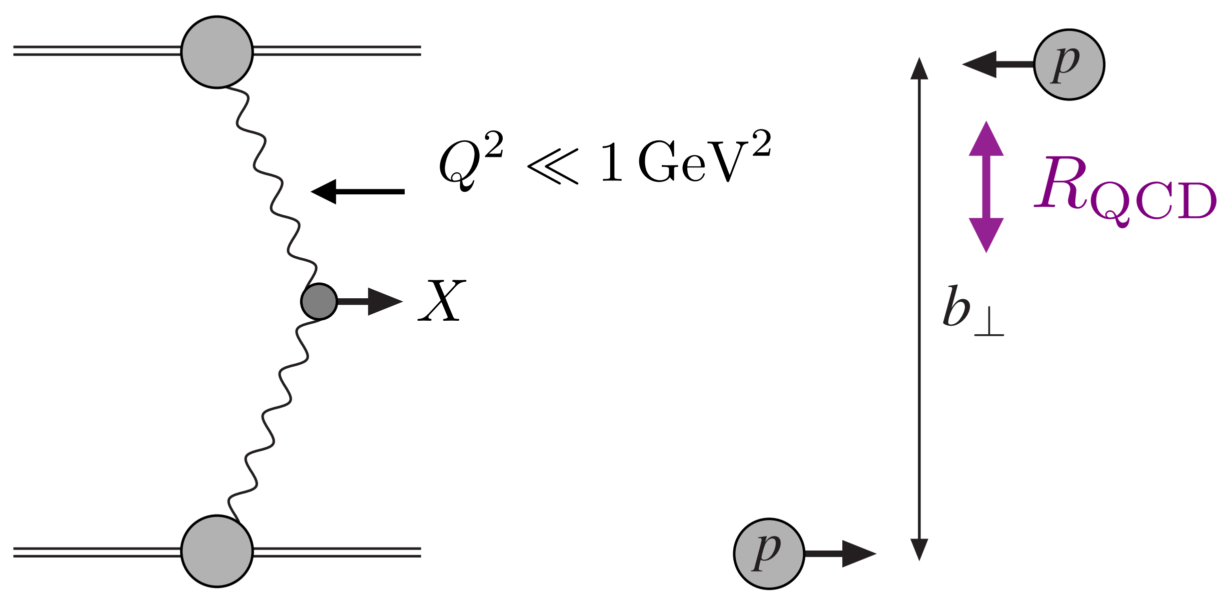
- In general source of **uncertainty**. Is this the case for PI production?



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

The Survival Factor in PI processes

- 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 $S^2 \sim 1$.

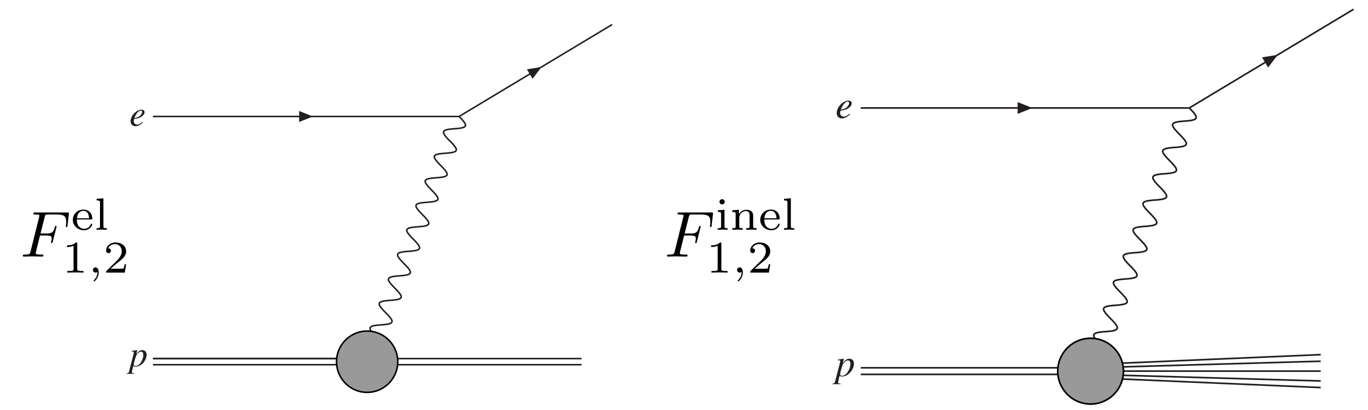


$\longrightarrow$ Relatively **clean** $\gamma\gamma$ initial state, with **QCD playing small role** in elastic case. LHC as a $\gamma\gamma$ collider!

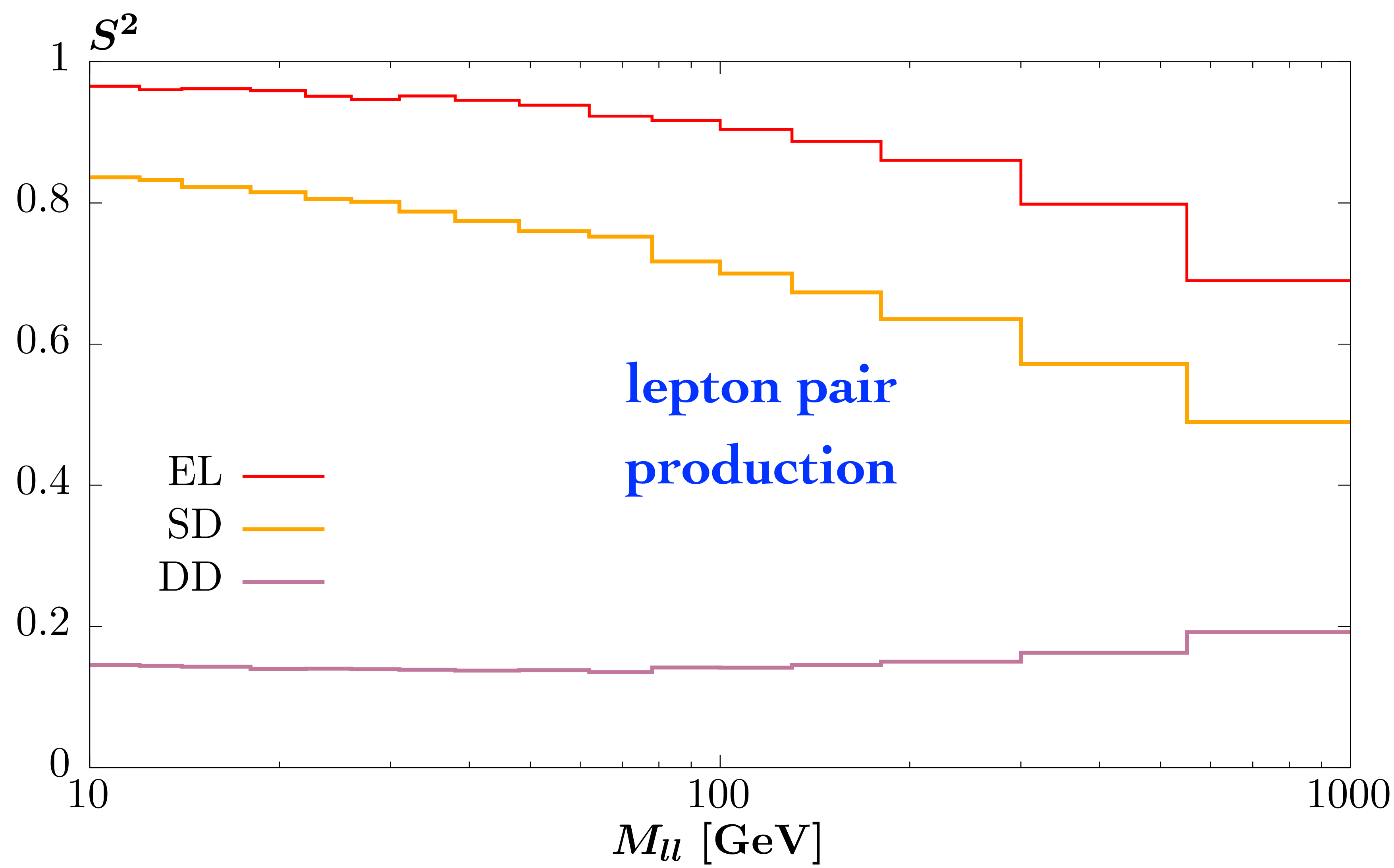
- What about dissociation?

- 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^2still rather high.



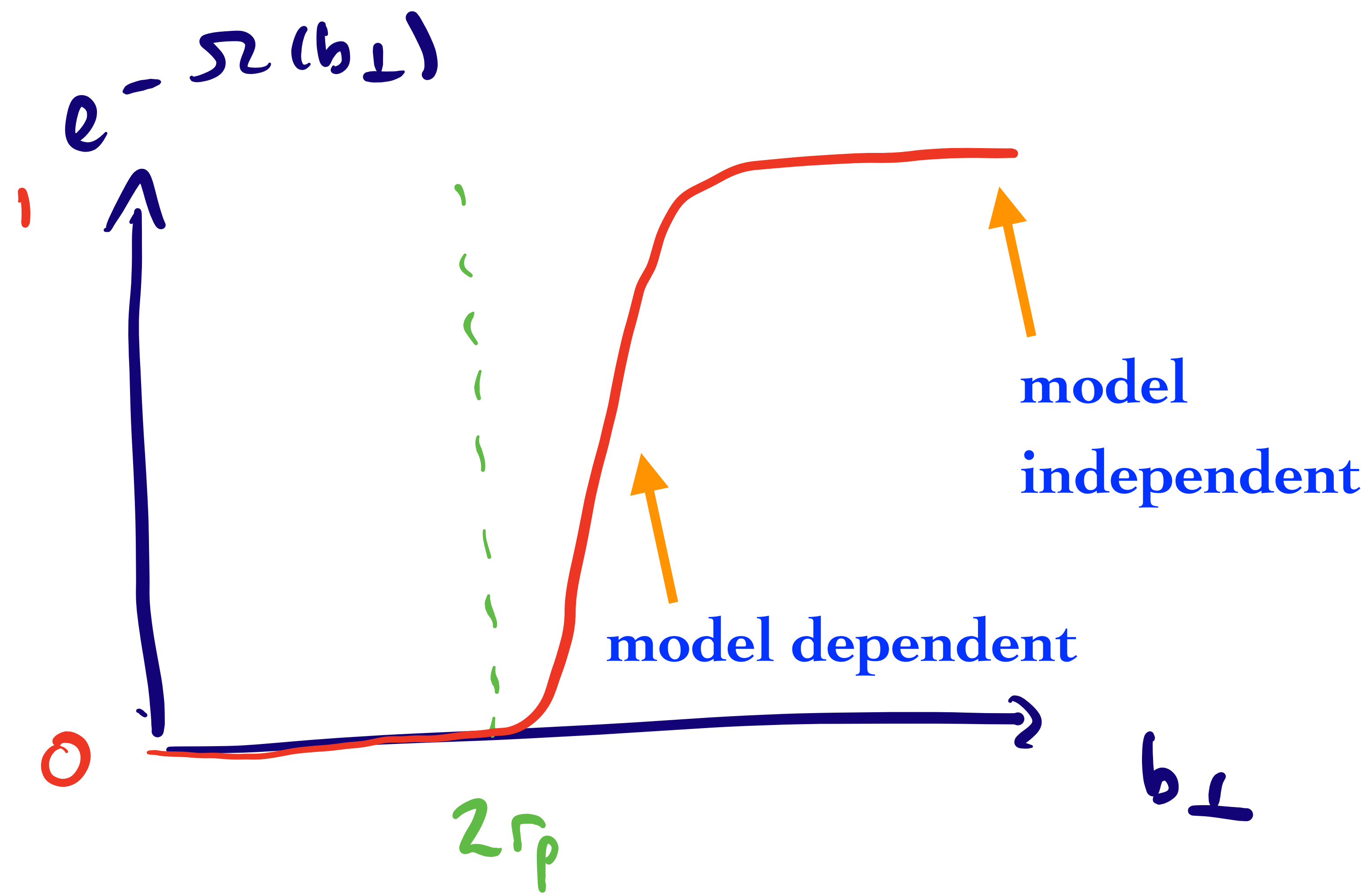
- For DD no longer case and $S^2 \sim 0.1$.



- What about uncertainties?
- Naively might assume inelastic ion-ion interactions has large uncertainties - requires knowledge of non-perturbative QCD.
- However, not the case: majority of EL/SD interaction occurs for

$$b_\perp > 2r_p$$

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



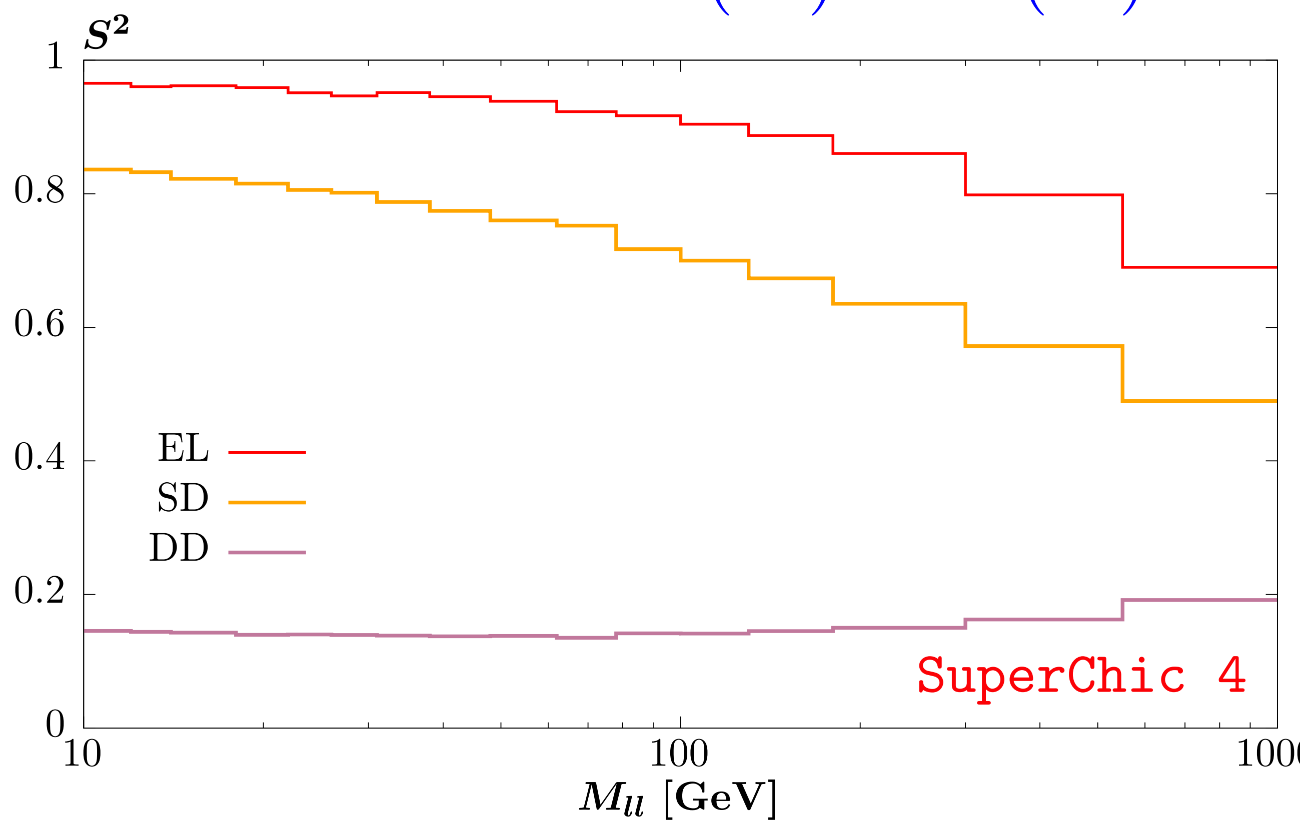
$\longrightarrow$ Uncertainty on S^2 small, at % level.

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

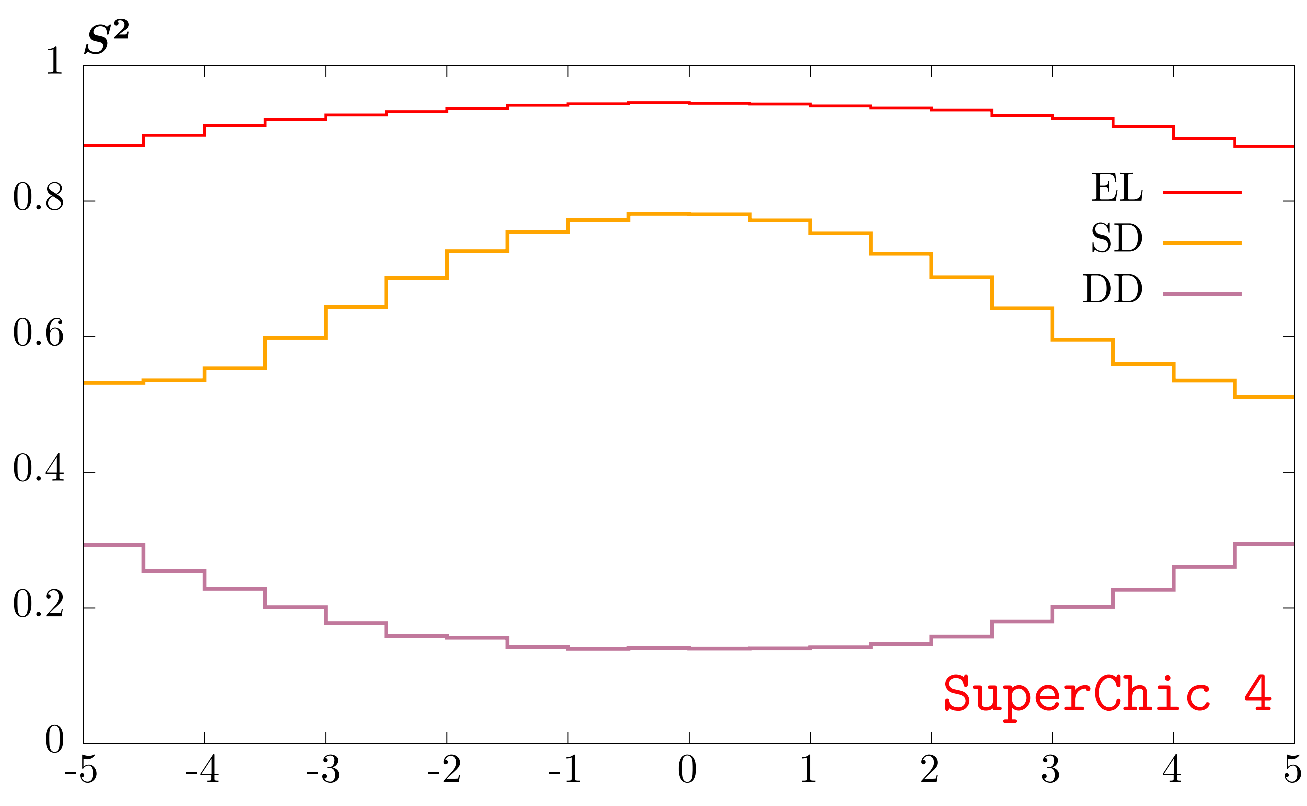
Results

$S^2(\text{el.}) > S^2(\text{sd}) > S^2(\text{dd})$

- (Again) scaling with elastic vs. dissociative clear.
- For SD case, $S^2 \sim 1$ still generally true as one proton elastic.



- Dependence on kinematics (e.g. y_{ll}, m_{ll}) also evident.



- What about the questions:

  ★ **Tuning:** How can one improve modelling of the dissociative part? What measurements could be done to improve the modelling and integration?

  ★ **Parton Shower Interface:** What is the best way to propagate the information about which proton dissociates and which stays intact?

- Must set `PartonLevel:MPI = off` otherwise double counts survival factor.

- Moreover this does not account for specific impact parameter dependence of EL, SD and DD. Gives uniformly $S^2 \sim 0.1$ and no kinematic dependence.

$\longrightarrow$ Have to use SC implementation.

- However, gives probability of no addition hadronic activity. Might it be of interest to allow some?
- Underlying event topology should e.g. be different for these PI events (less of it). Future study?

Other Questions

★ **Generator:** What is the maintainability of the code? Personpower? Are there specific libraries/tools behind the choice of fortran? How do you see the code developing in the future?

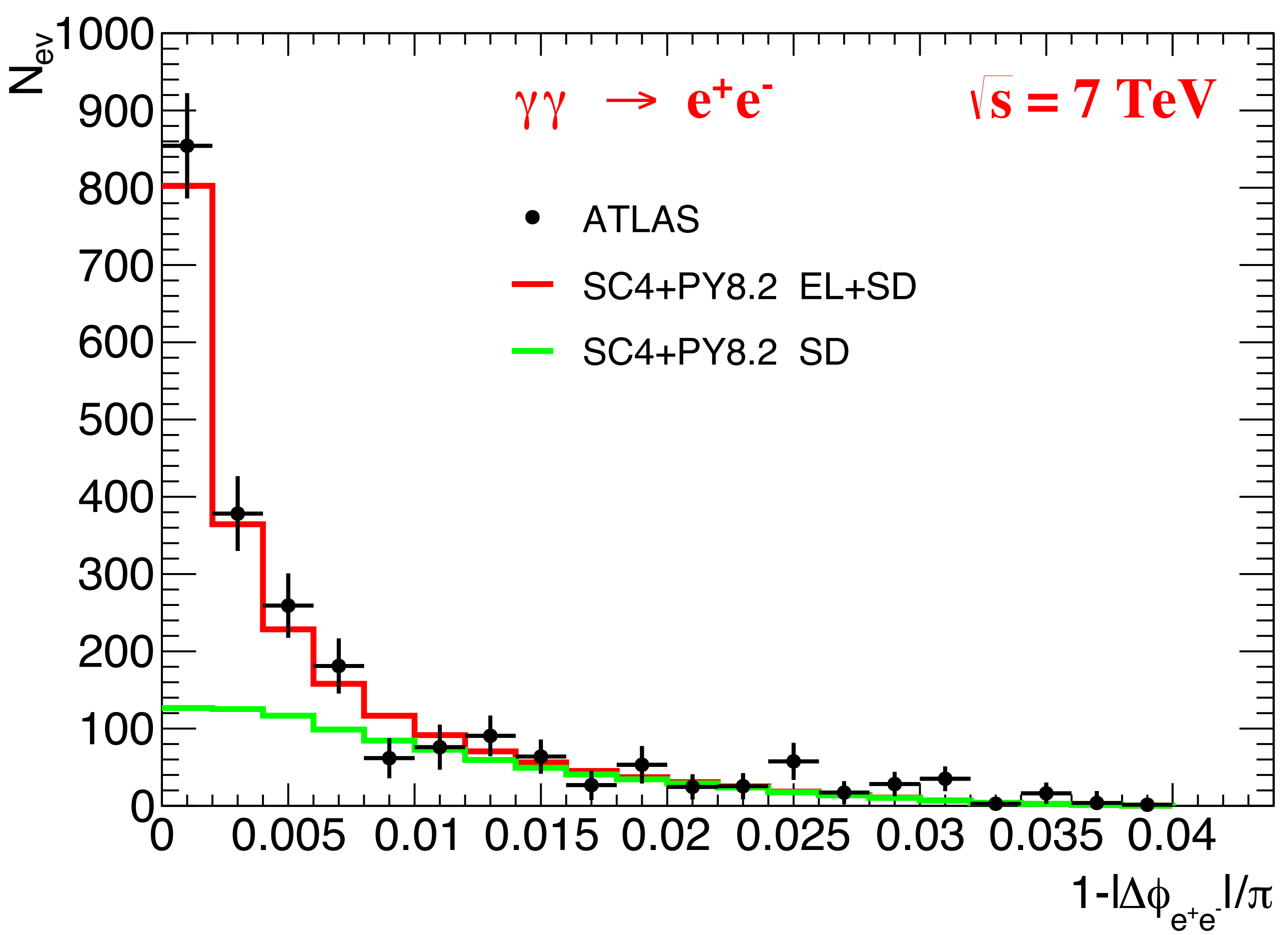
- **Personpower/maintainability.** Currently just me as a code developer, with assistance from experimental colleagues (in particular M. Tasevksy) in interfacing to Pythia.
- **Fortran?** Choice largely historical. Libraries: LHAPDF + APFEL, so no requirement from that point of view.
- **Future?** Personpower is currently limited, but certainly open to collaborations in developing code. My role dependent on future career steps.

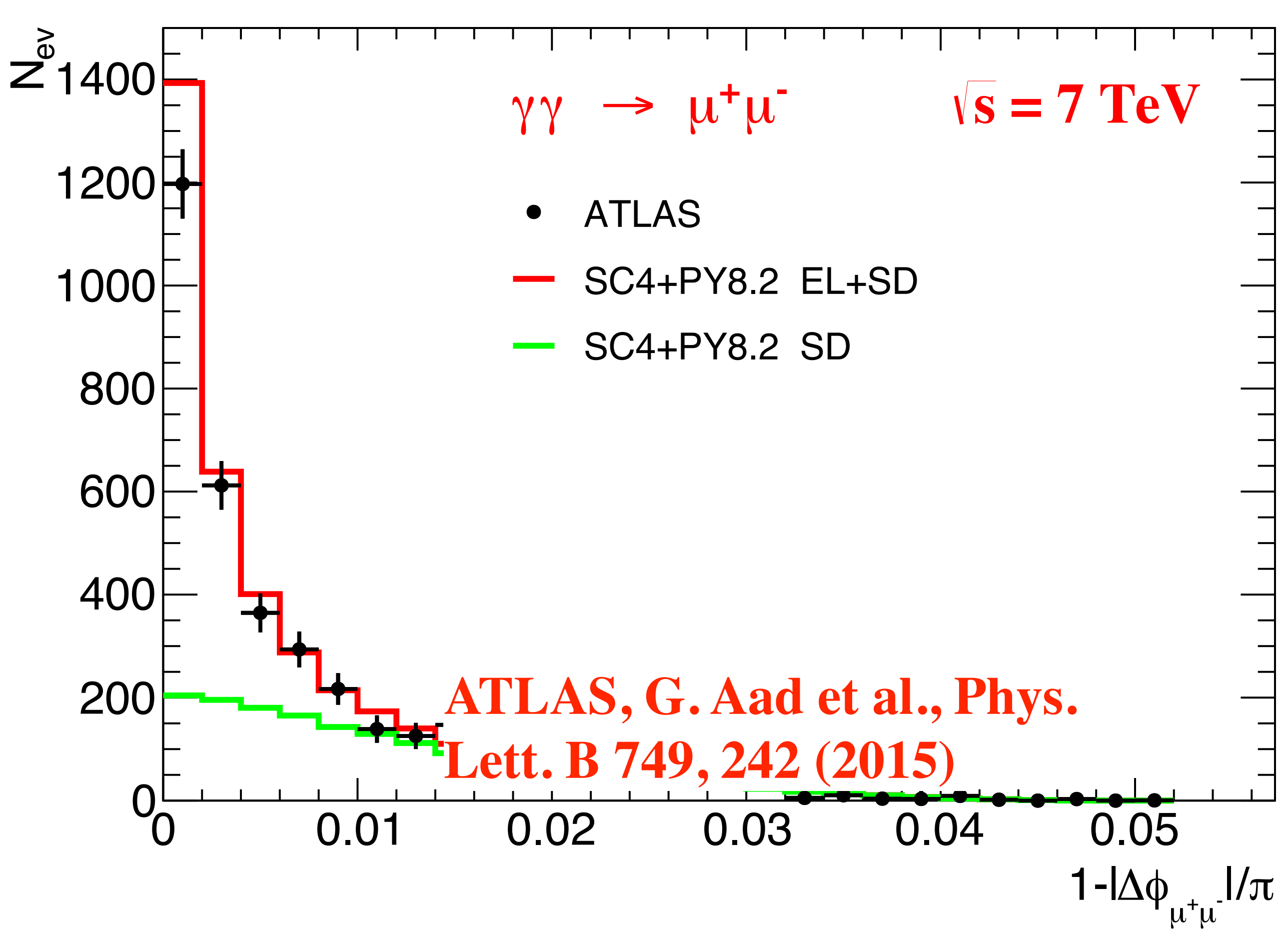
★ We (ATLAS) always have to implement a custom patch before installation in the ATLAS Software (modify the file src/diss/Elastic.f to add the content of the file src/diss/SplinesWithVariableKnots.dat) can we make this configurable?

- For sure yes. General comment: I am always happy to receive requests/ suggestions of this sort.

Experimental input

- Specifically to this question:
  - ★ **Tuning:** How can one improve modelling of the dissociative part? What measurements could be done to improve the modelling and integration?
- For centrally system, dissociation dominates at higher system $p_\perp, \Delta\phi$:

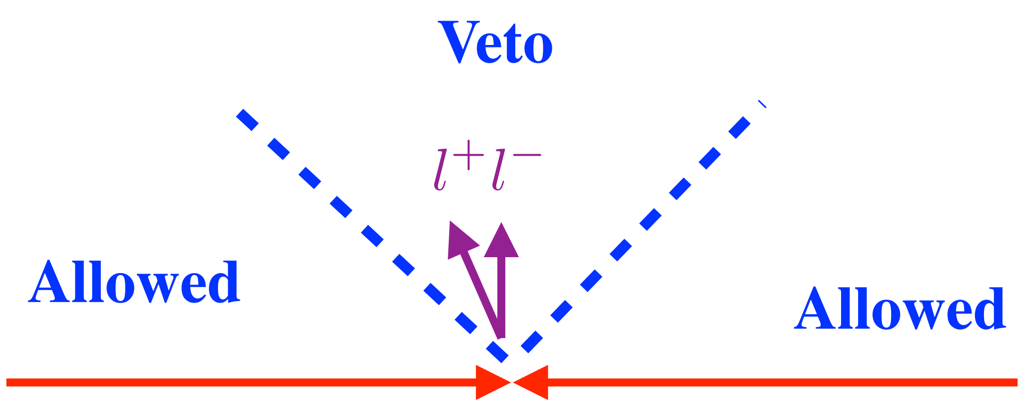




- However rather broad handle, delicate interplay with survival factor, FSR…

- Other options:

  - Variation in veto region?



  - Single tag data: cleaner handle (although DD generally low).

  - Events where edge of dissociation system observed? Challenging (!).

Summary/Open Questions

- ★ Underlying calculation of semi-exclusive PI production is generally well understood, with some exceptions, e.g. survival factor in DD.
- ★ However, impact of rapidity veto requires interface to showering/hadronization, and here there are some subtleties:
  - Assumption about $\gamma^* p \to X$ vertex necessary. We take LO $\gamma^* q \to q$ - well motivated as veto populated by higher Q^2, W^2 perturbative region.
  - For dilepton production photon 4-momentum ideally would not be touched by showering, but not (I believe) currently achievable.
  - Ability to leave elastic initial-state photon momentum untouched (i.e. off-shell) would be preferable.

- ★ Basis for interface to any general purpose MC:
  - **Dissociative side(s):** safe to take "$\gamma^* q \to q$" parton level vertex as underlying input. Should I believe then work well with any general purpose MC to shower + hadronize?
  - **Elastic side(s):** in principle 'easy' - just have initial and final state intact protons! In practice Pythia at least appears to struggle with this.
  - Work arounds focussed on this - for SC initial-state elastic photon, but requires approximations (setting to be collinear for SD) to be imposed. Best solution to me seems to be to get the general purpose MC to allow (elastic) protons in the event record?
  - **Survival factor/MPI:** currently has to be handled offline from general purpose MCs. Would be nice to treat differentially, but long term project.

Thank you for listening!

Backup