A new approach to modelling elastic and inelastic photon-initiated production at the LHC: SuperChic 4

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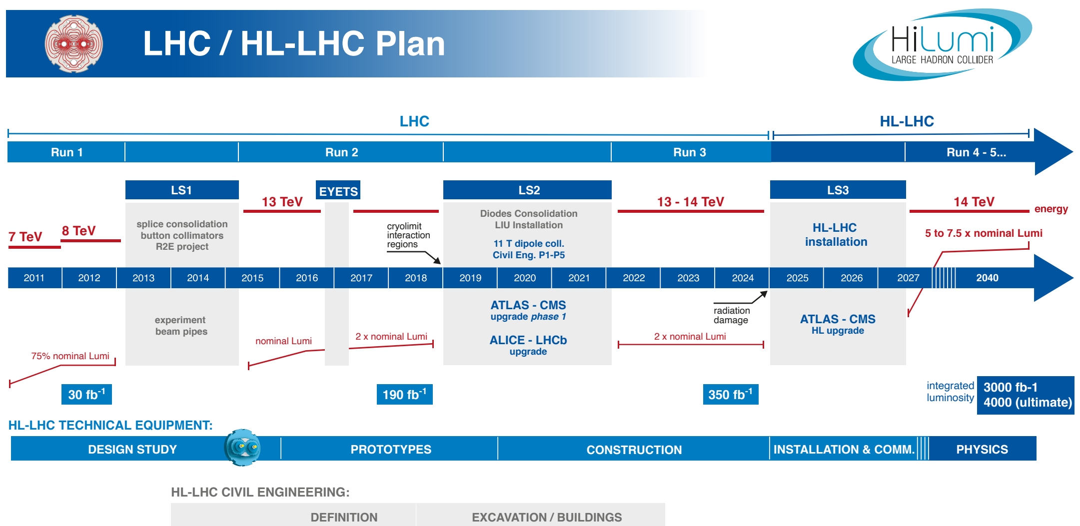
LHC Forward Physics Meeting, 5 March 2021

In collaboration with Valery Khoze, Misha Ryskin and Marek Tasevsky

LHL, *JHEP* 03 (2020) 128
LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925
LHL, arXiv:2101.04127

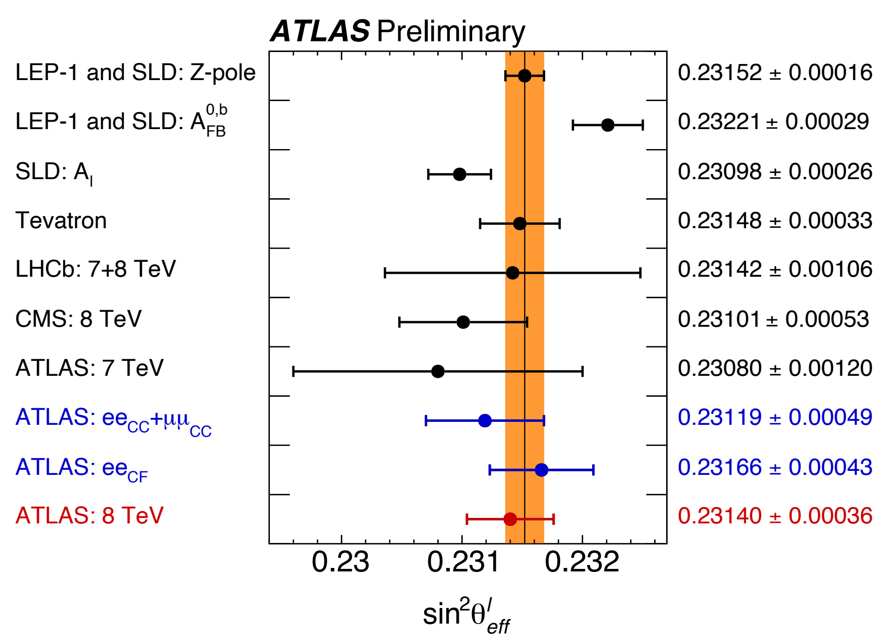
UNIVERSITY OF OXFORD

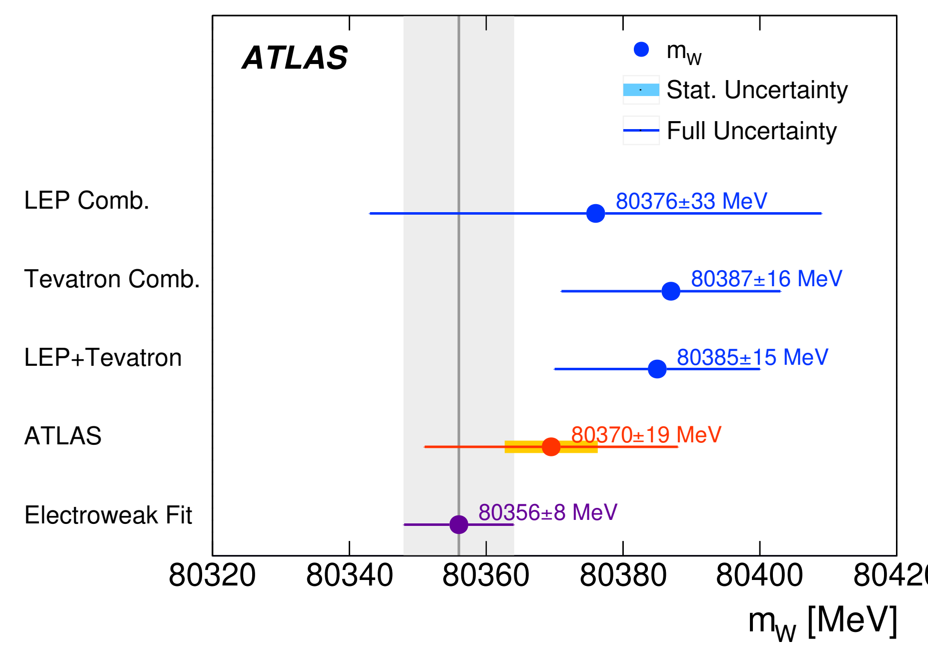
Motivation: Data



- Heading into high precision LHC era.

- LHC officially in the **precision EW race**:

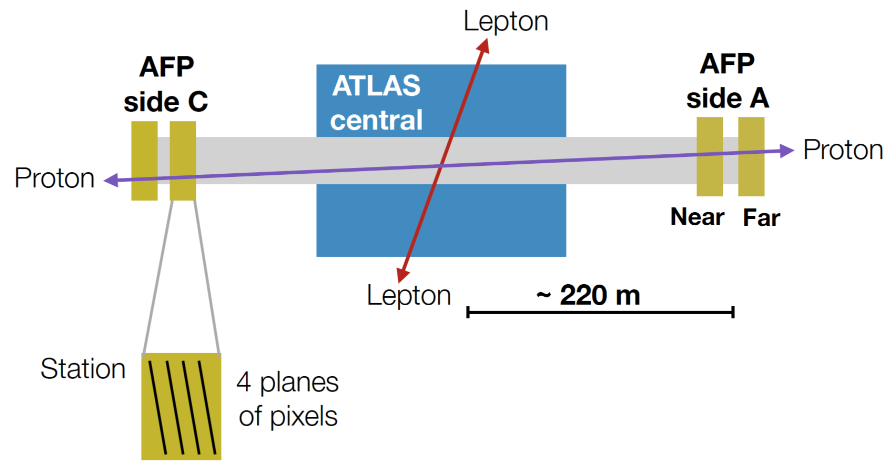


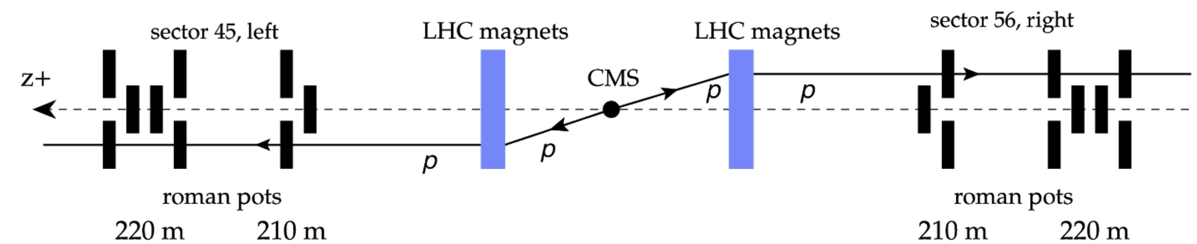


★ ATLAS/CMS measurements of $\sin^2\theta_W$ starting to bear down on LEP precision.

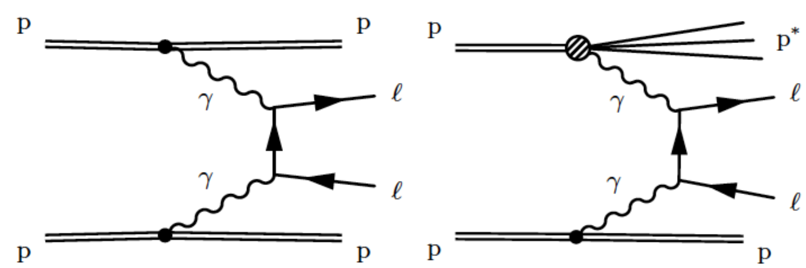
★ ATLAS measurement of M_W from Run-I data comparable to Tevatron/LEP determination.

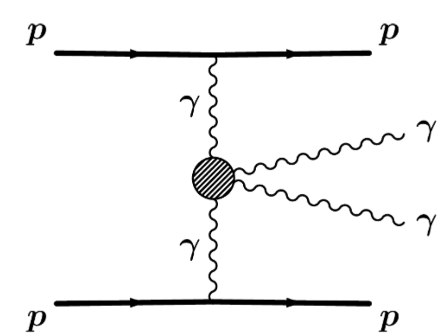
- But standard inclusive production not the only lever arm available…

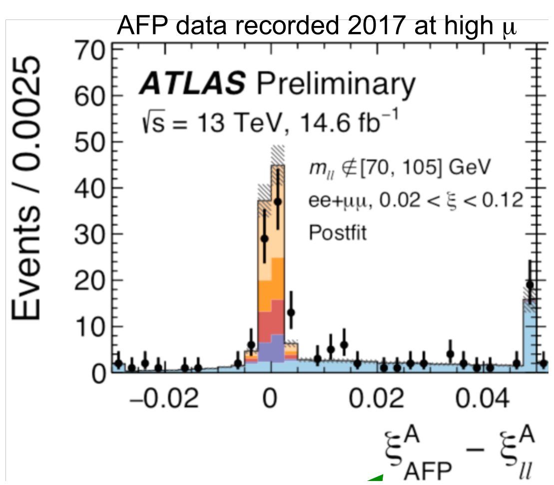




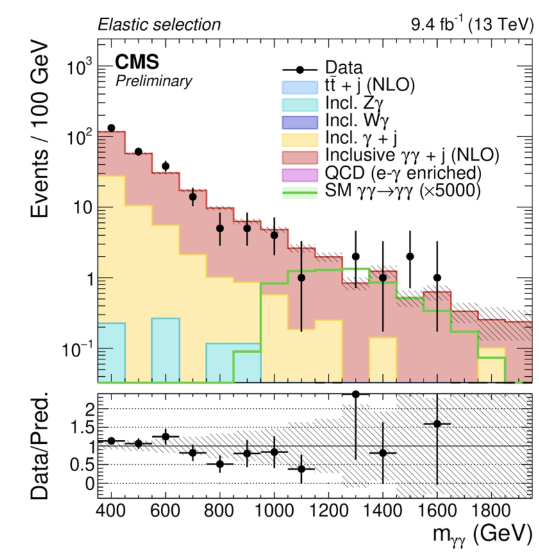
- Dedicated proton tagging detectors at ATLAS/CMS allow exclusive events with intact protons in final state to be selected during **nominal running***.







ATLAS + CMS Highlights, ICHEP 2020



- Unique & complementary probe of SM/BSM at LHC. Data already public!

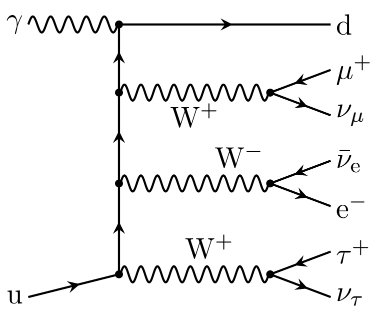
***see e.g. K. Cerny et al., arXiv:2010.00237 for a recent study on the use of ToF detectors at high lumi.**

The role of the photon

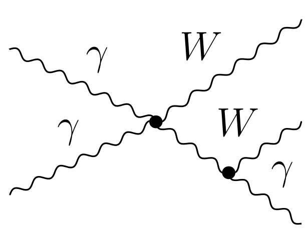
- In both of these cases photon-initiated production plays a key role.
  - ★ NNLO QCD the standard for inclusive processes, but:

$$\alpha_{\rm QED}(M_Z) \sim \alpha_S^2(M_Z)$$

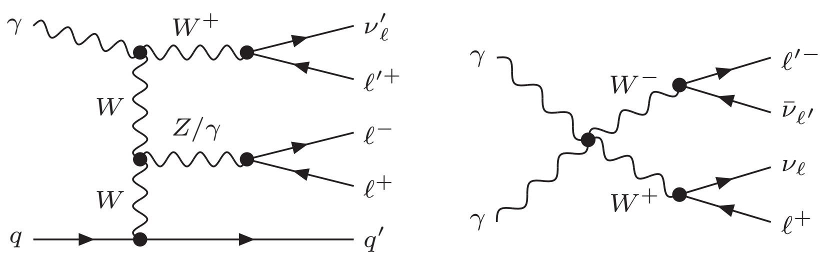
$\Rightarrow$ crucial to include EW corrections. **Photon-initiated** (PI) production important element of **inclusive** cross sections at this level of precision.



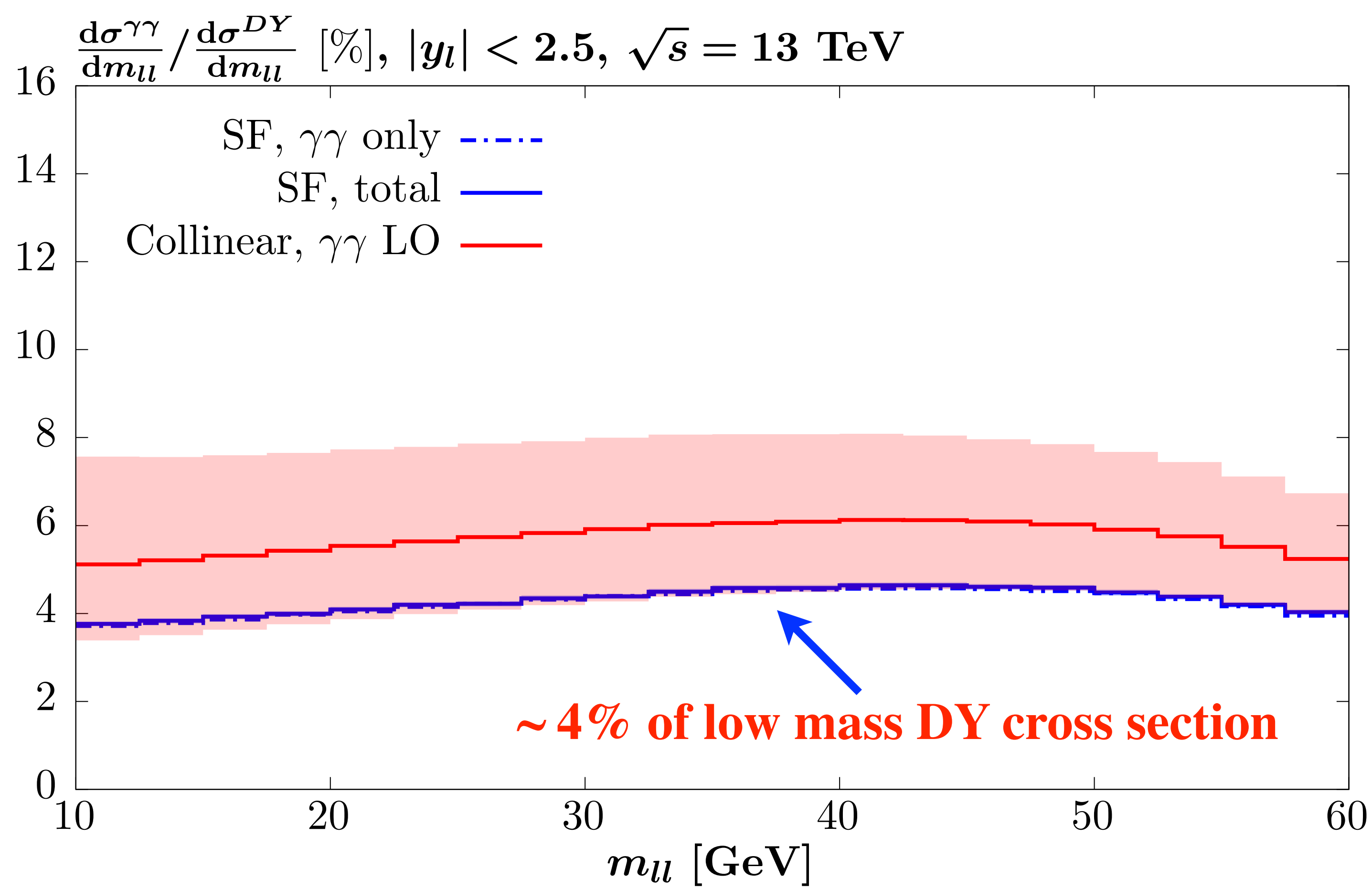
S. Dittmaier, G Knippen, C. Schwan, *JHEP* 02 (2020) 003



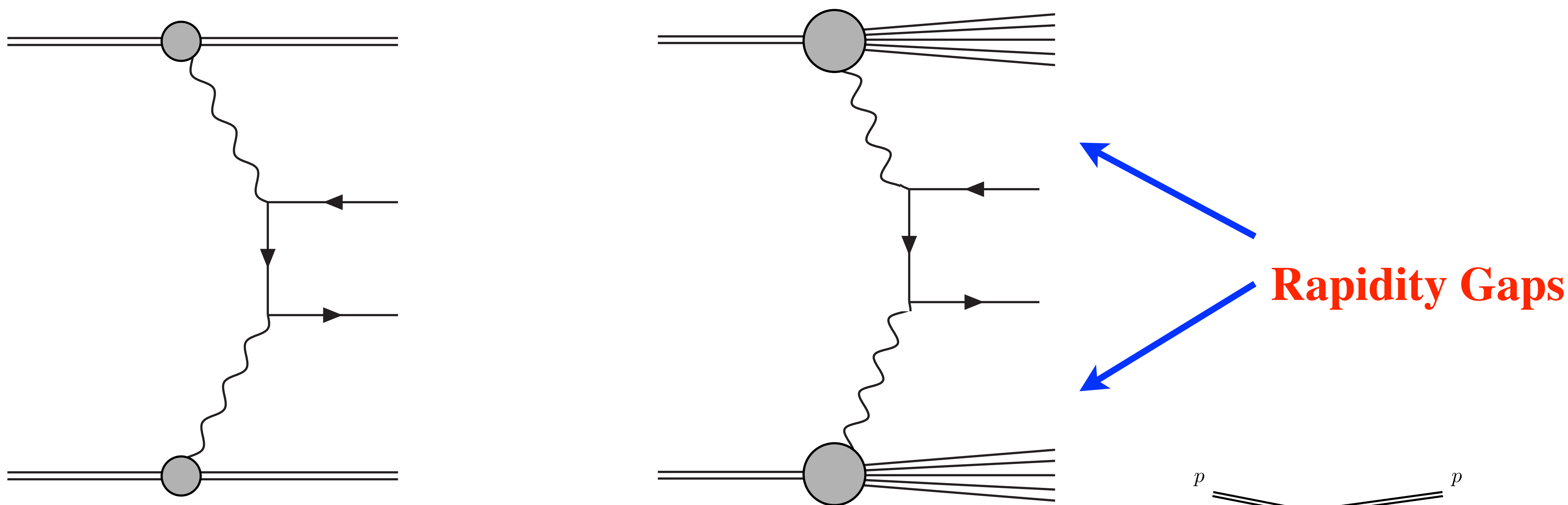
J-W Zhu et al., arXiv:2005.10707



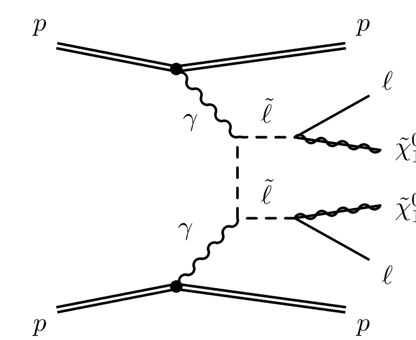
M. Grazzini et al., *JHEP* 02 (2020) 087

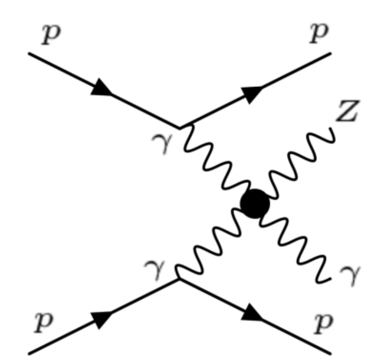


★ **Exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state.



- Clean, ~ pure **QED** process at LHC:
  - ★ Probe of BSM (anomalous couplings, ALPs, DM, SUSY…).

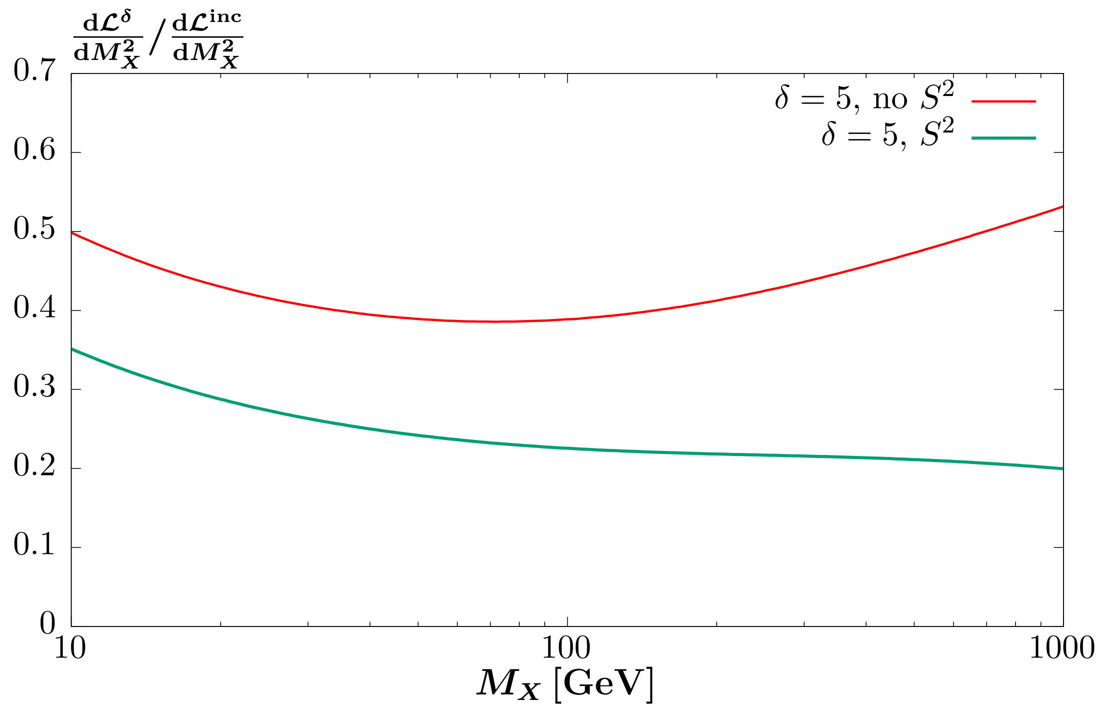


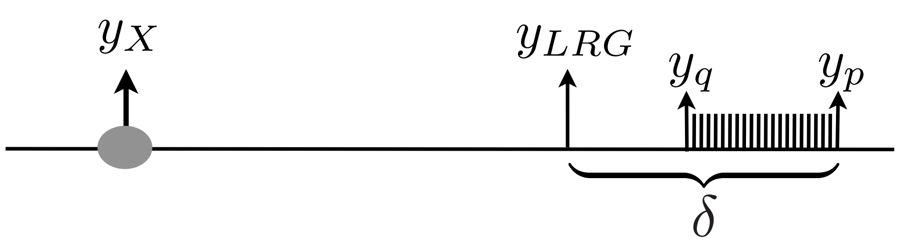


LHL, V. A. Khoze, M.G. Ryskin and M. Tasevsky, JHEP 1904 (2019) 010, EPJC 72 (2012) 1969, C. Baldenegro et al., JHEP 1806 (2018) 131, JHEP 1706 (2017) 141, L. Beresford and J. Liu, arXiv:1908.05180, PRL 123 (2019) no.14, 141801…

- Clean, ~ pure QED process at LHC:

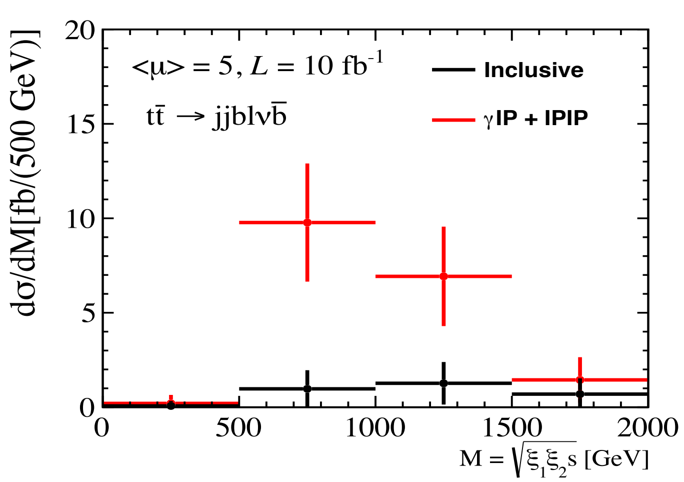
  ★ **Laboratory** to test our models of proton dissociation + proton-proton MPI effects.

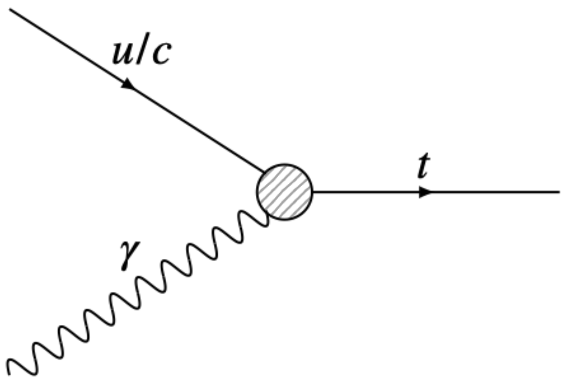




LHL et al., EPJC 76 (2016) no. 5, 255,
LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925
L. Forthomme et al., PLB 789 (2019) 300-307

  ★ **Probe** of the top sector.



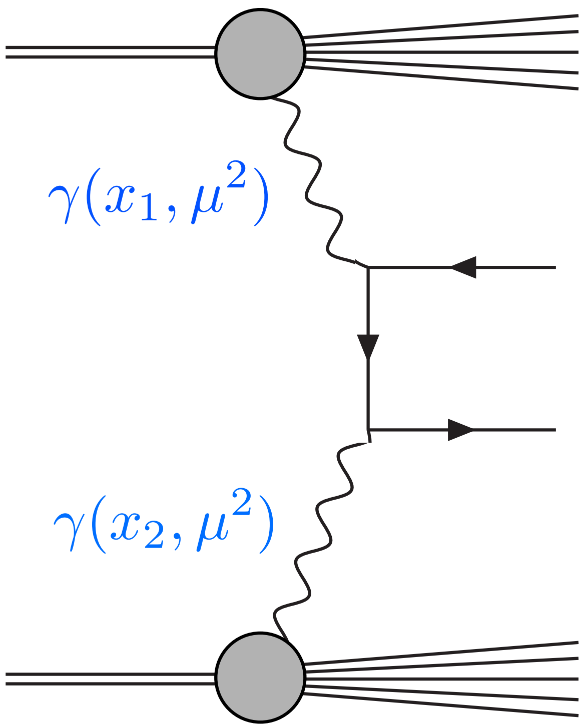


V. Goncalves et al., *Phys.Rev.D* 102 (2020) 7, 074014
J. Howarth, arXiv:2008.04249

Photon-initiated production: how well do we understand it?

PI Production and the Photon PDF

- Start with the inclusive case.
- Basic idea for calculating PI contribution to inclusive cross section: given in terms of (collinear) **photon PDF** within proton.



$$\sigma^{pp\to l^+l^-+\cdots} = \sigma^{\gamma\gamma\to l^+l^-} \otimes \gamma(x_1, \mu^2) \otimes \gamma(x_2, \mu^2)$$

- What does this photon PDF look like, and how can we predict it?

- Historically photon PDF was given in terms of:

  - Simple **model** of $q \to q\gamma$ emission: model dependent/sensitive to low scales.

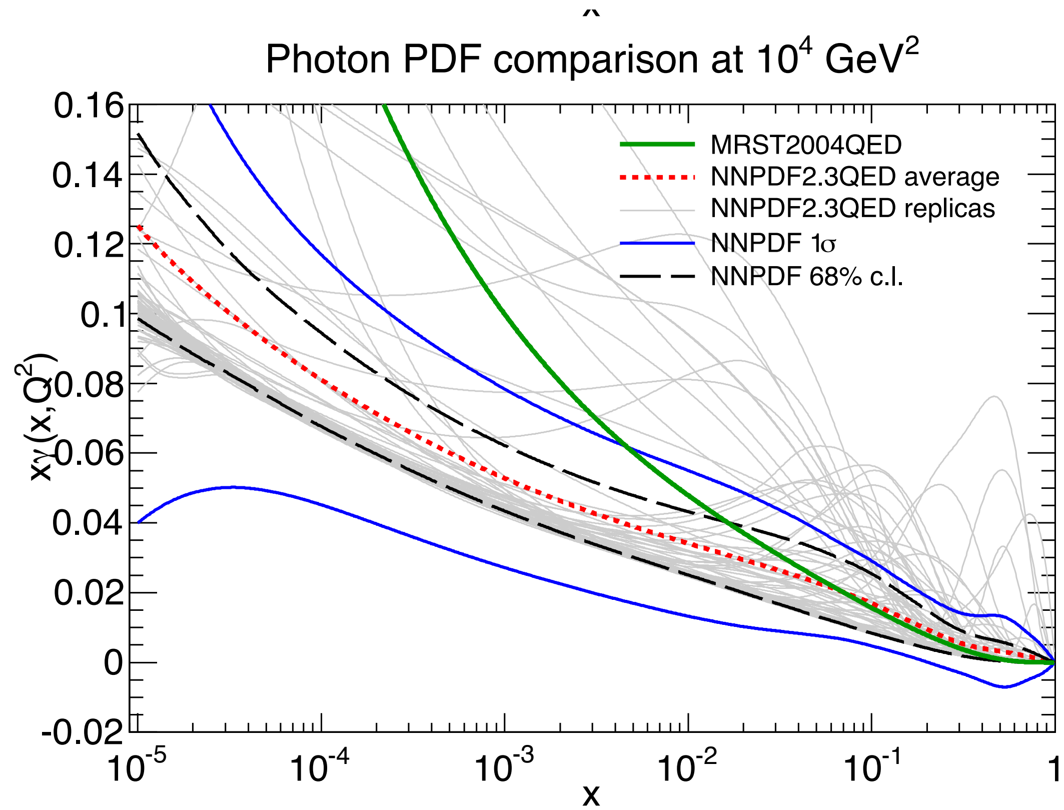
A.D. Martin et al., EPJC 39, 155 (2005), C. Schmidt et al., PRD 93 114015 (2016)…

$$\gamma(x, Q_0^2) = \frac{\alpha}{2\pi}\left[\frac{4}{9}\ln\left(\frac{Q_0^2}{m_u^2}\right)u_0(x) + \frac{1}{9}\ln\left(\frac{Q_0^2}{m_d^2}\right)d_0(x)\right] \otimes p_{\gamma q}(x)$$

  - Completely **agnostic** fit to LHC W, Z data + DIS: huge PDF uncertainties.

NNPDF2.3QED, NNPDF3.0QED….

R.D. Ball et al., NPB 877, 290 (2013)



The Photon PDF and the EPA

THE TWO-PHOTON PARTICLE PRODUCTION MECHANISM. PHYSICAL PROBLEMS. APPLICATIONS. EQUIVALENT PHOTON APPROXIMATION

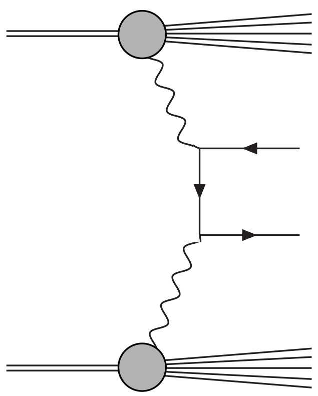
V.M. BUDNEV, I.F. GINZBURG, G.V. MELEDIN and V.G. SERBO
USSR Academy of Science, Siberian Division, Institute for Mathematics, Novosibirsk, USSR

Received 25 April 1974
Revised version received 5 July 1974

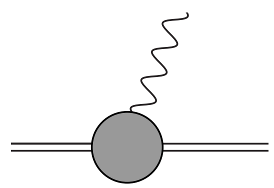
- A more precise evaluation of photon PDF given by well known **equivalent photon approximation** (EPA).
  - Cross section given in terms of:

$$\langle d\sigma\rangle_\varphi = \sigma_{\gamma\gamma}\, dn_1 dn_2 .$$

$\gamma\gamma$ cross section **Photon flux**



$$dn_i = \frac{\alpha}{\pi}\frac{d\omega_i}{\omega_i}\frac{d(-q_i^2)}{|q_i^2|}\left[\left|\frac{q_{i\perp}^2}{q_i^2}\right| D_i + \frac{\omega_i^2}{2E^2} C_i\right].$$



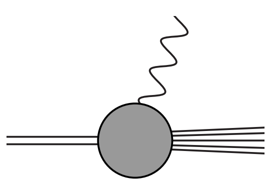
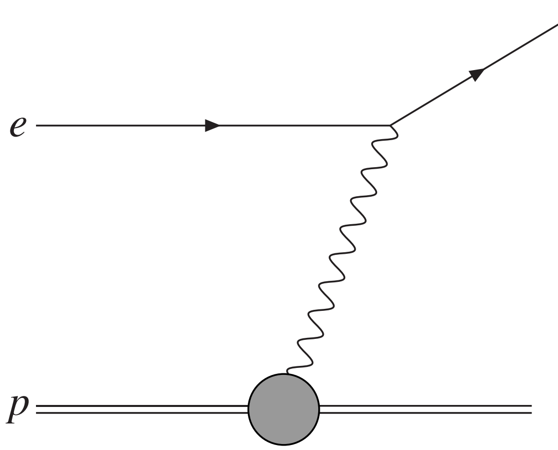


Table 8

Elastic →	p	$G_M^2(q^2)$	$\dfrac{4m_p^2 G_E^2 - q^2 G_M^2}{4m_p^2 - q^2}$
Dissociation →	hadron → jet	$-\dfrac{2m}{q^2}\int W_1(M_1^2 q^2)\, dM^2$	$\dfrac{1}{2m}\int W_2(M^2, q^2)\, dM^2$

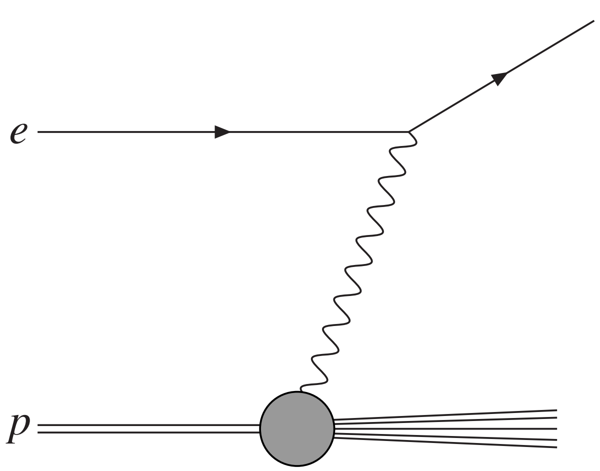
- Photon flux given in terms of proton EM form factors and inelastic **structure functions**.

$$\gamma(x, Q^2) \sim$$



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

$+$



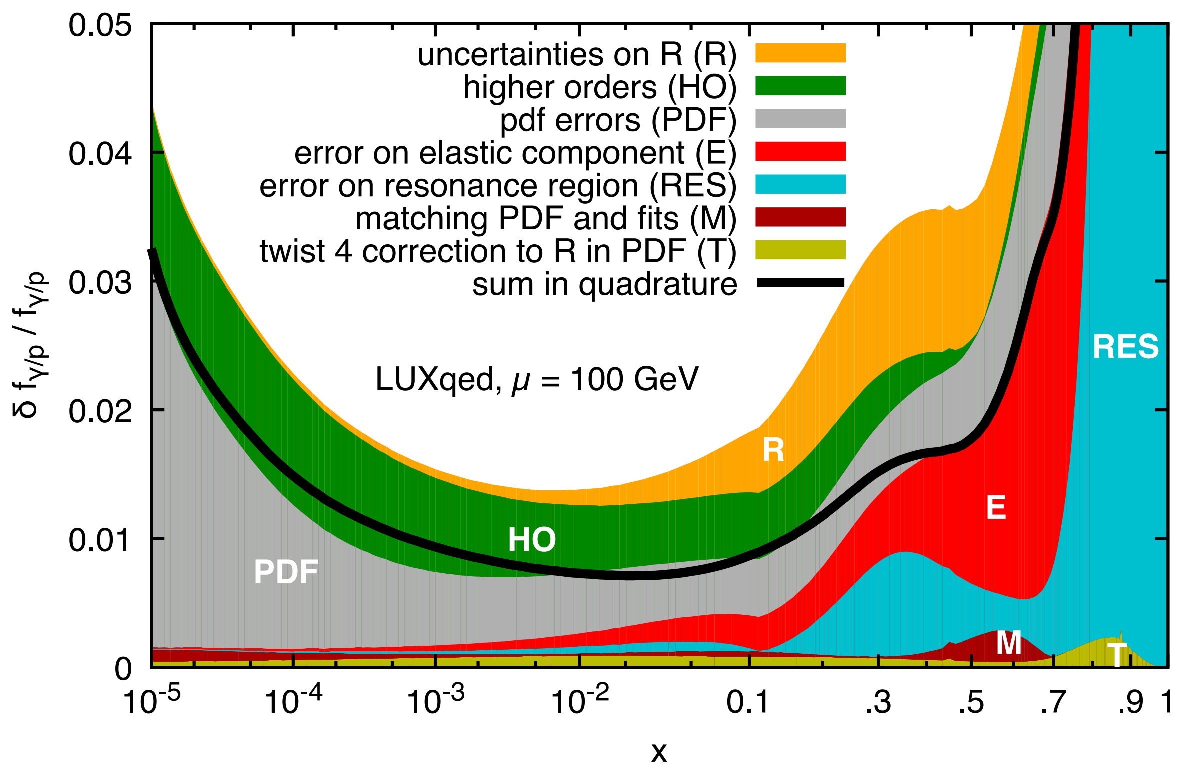
$F_{1,2}^{\rm inel}$

LUXqed

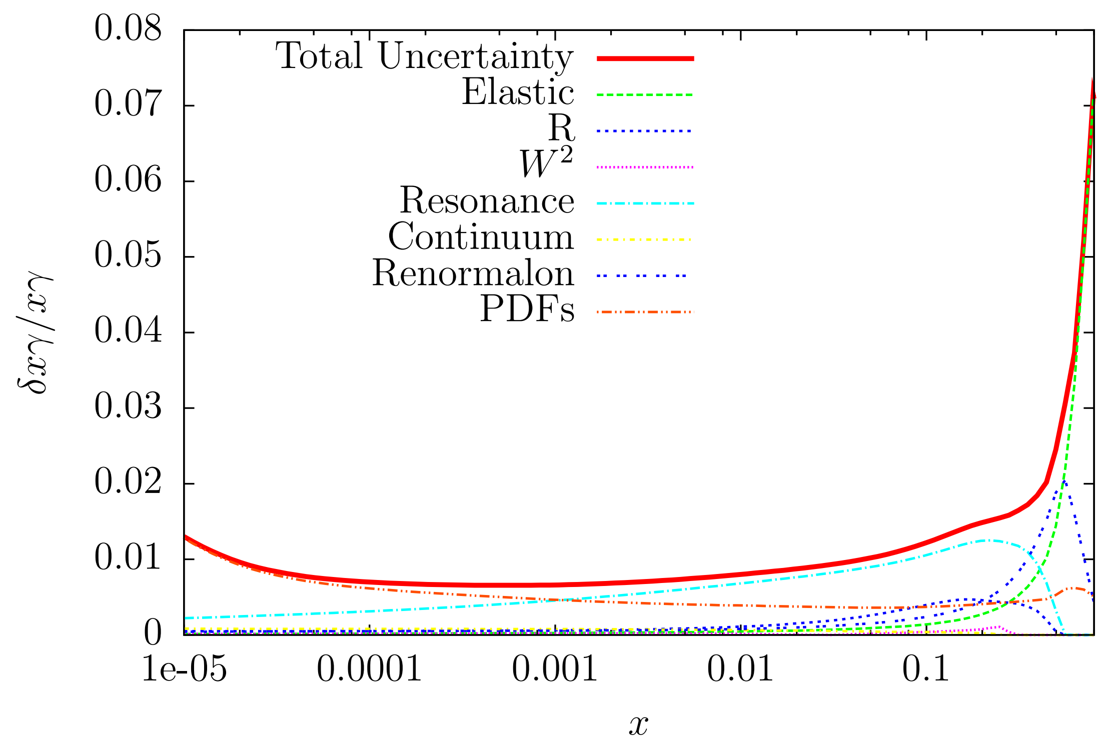
- This idea was placed on rigorous/precision footing by **LUXqed** group:
  - ★ Extended beyond LO in α .
  - ★ Precise inputs for structure functions and hence photon PDF at high precision.

$\Rightarrow$ % -level **precision determination** of photon PDF!

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



Photon PDF Uncertainty contributions, $Q^2 = 10$ GeV^2

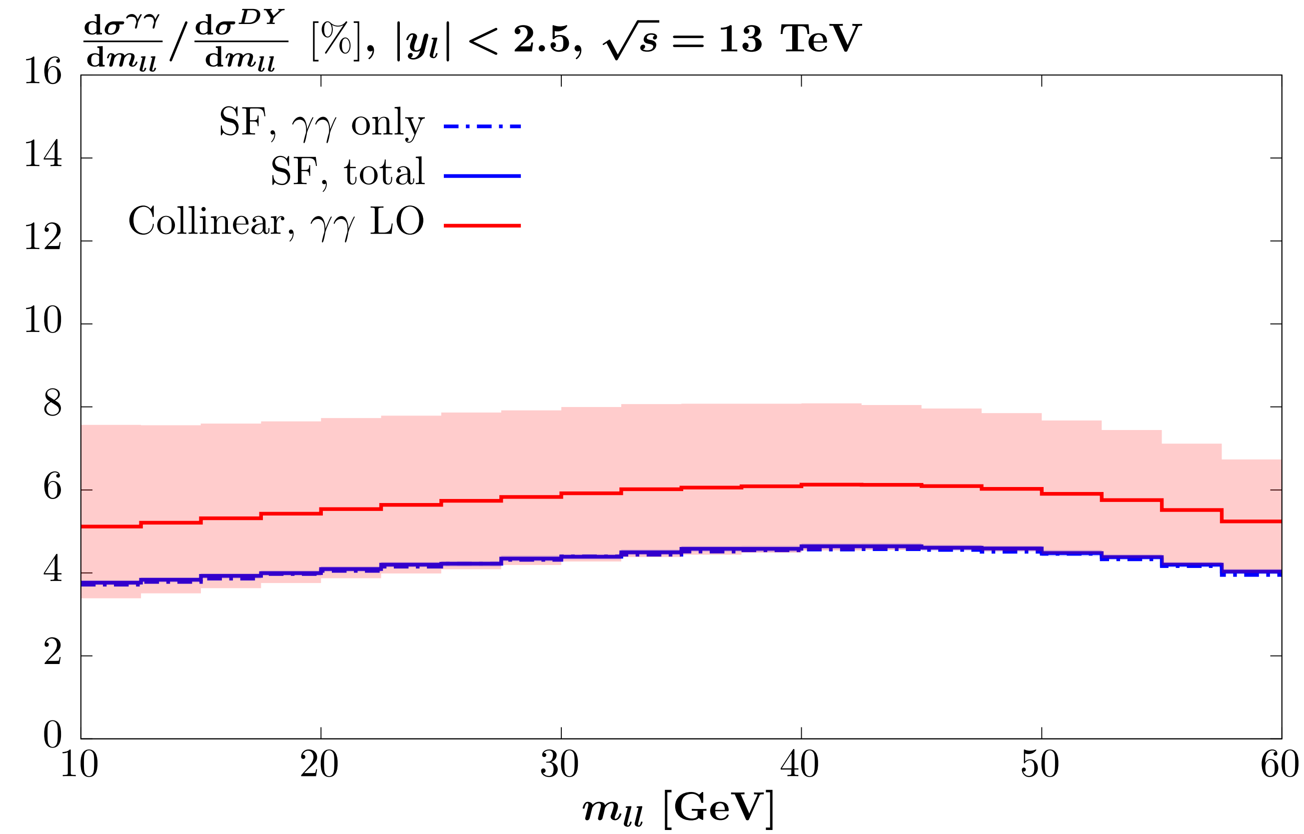


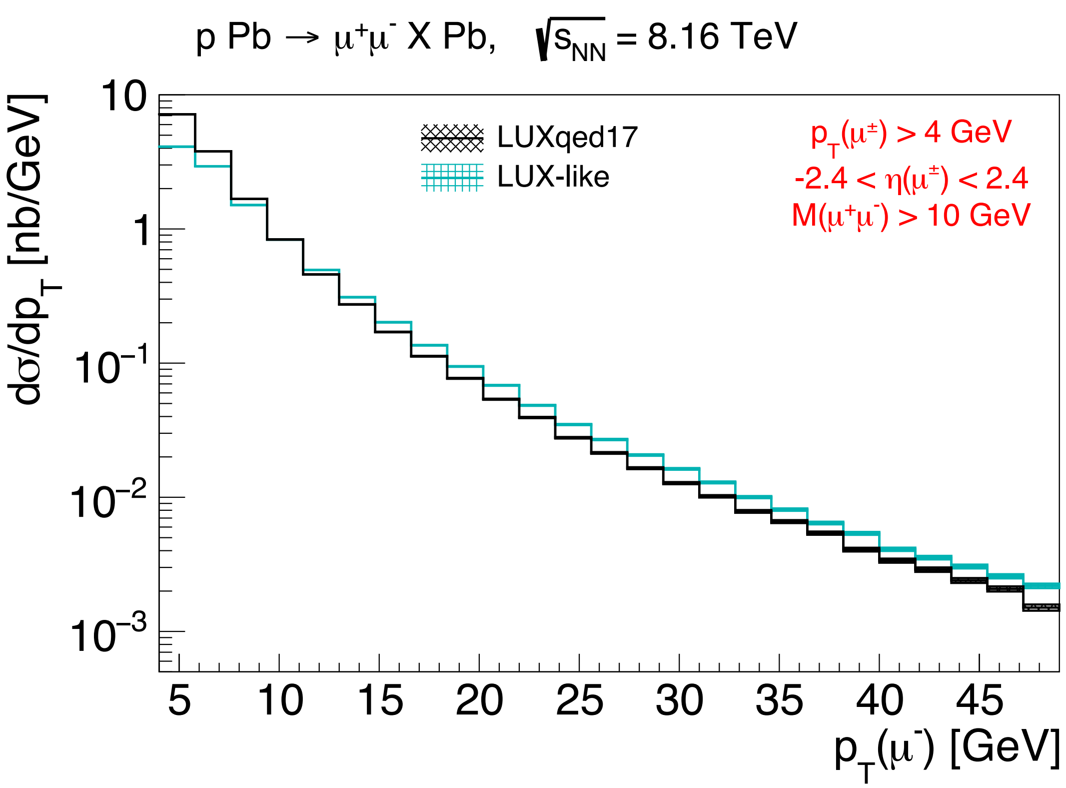
LHL et al., Eur.Phys.J.C 79 (2019) 10, 811

- **However** not the end of the story…

- High precision determination of photon **PDF** achieved, but does not necessarily translate to high precision predictions for **observables**:

  ★ LO (in α) $\sigma^{\gamma\gamma}$ have v. large μ_F **uncertainty**.





M. Dyndal et al., PRD 99 (2019) no.11, 114008

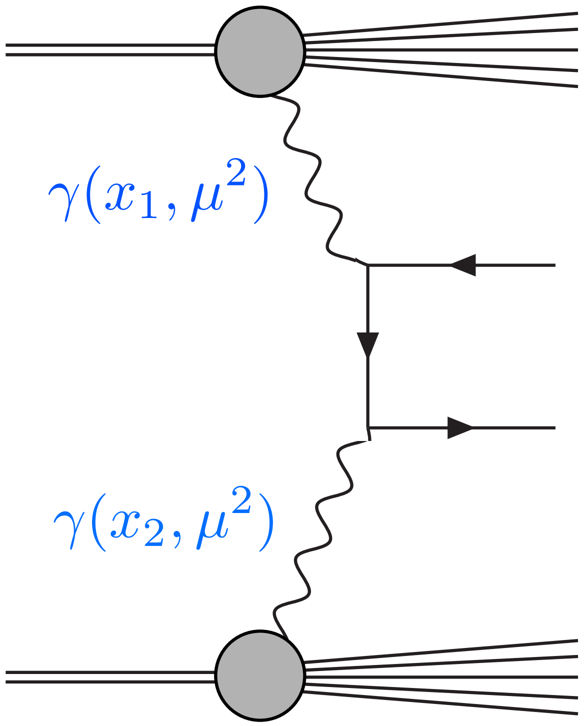
★ Sizeable **discrepancies** seen between -factorization approach ($k_\perp$dependent photon PDF) and collinear.

Collinear Factorization at LO

- Large uncertainty in cross section, despite small PDF uncertainty, completely standard: we are calculating so far only at LO in α. E.g.:

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

No μ_F dependence $\Longrightarrow$ no compensation



- So what? We should simply calculate to NLO (...) in α then!

- Yes we could do*, but is there a better way?

***Indeed LUXqed PDF uncertainty assumes we have calculated to NLO.**

- Better way: apply 'structure function' calculation directly:

LHL, *JHEP* 03 (2020) 128

The Proton in High Definition: Revisiting Photon–Initiated Production in High Energy Collisions

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Abstract

We re–examine the current state of the art for the calculation of photon–initiated processes at the LHC, as formulated in terms of a photon PDF in the proton that may be determined rather precisely from the known proton structure functions. We in particular demonstrate that a by construction more precise calculation is provided by a direct application of the

- What do we mean by this and how does it relate to photon PDF?

(With thanks to the pink book)

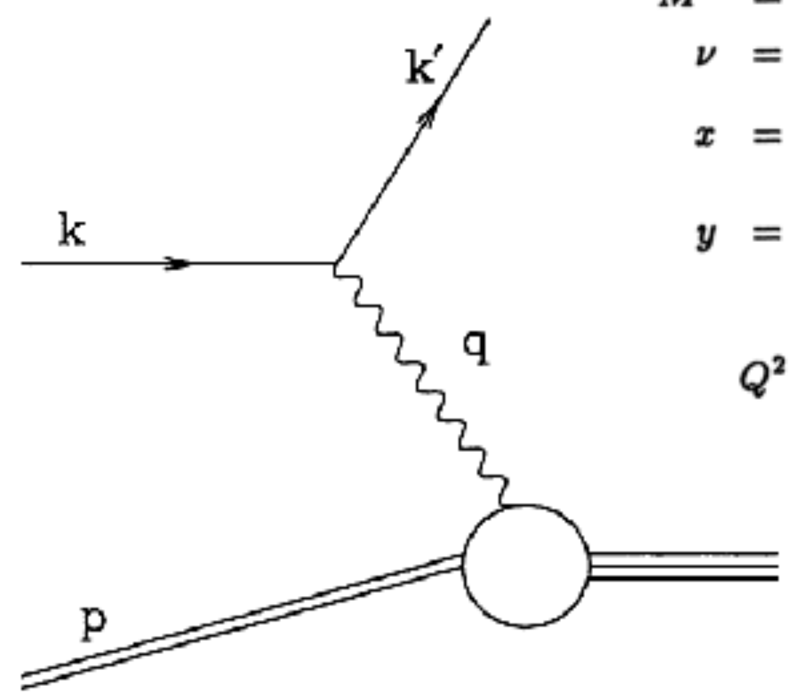
Structure Function Calculation

- To understand this and its relation to photon PDF, worth going (way) back to textbook analysis of Deep Inelastic Scattering (DIS).

- Cross section has form:

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

Leptonic tensor ($L_{\alpha\beta}$) **Hadronic tensor** ($W^{\alpha\beta}$)



$$\begin{aligned} M^2 &= p^2 \\ \nu &= p\cdot q = M(E'-E) \\ x &= \frac{Q^2}{2\nu} = \frac{Q^2}{2M(E-E')} \\ y &= \frac{q\cdot p}{k\cdot p} = 1 - E'/E\,, \\ Q^2 &= -q^2 \end{aligned}$$

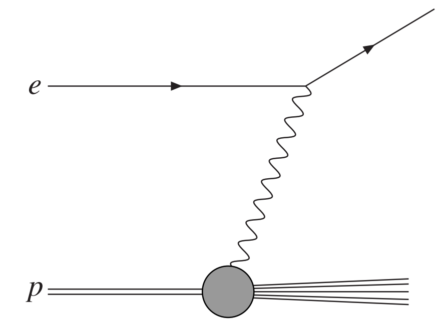
- Using basic requirements of gauge/Lorentz invariance but knowing **nothing else** about the physics of the $\gamma p \to X$ vertex we can write:

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

- In terms of **structure functions**:

$$\begin{aligned} F_1(x,Q^2) &= W_1(x,Q^2) \\ F_2(x,Q^2) &= \nu W_2(x,Q^2). \end{aligned}$$

- Structure function parameterise all physics that goes on in $\gamma p \to X$ vertex.



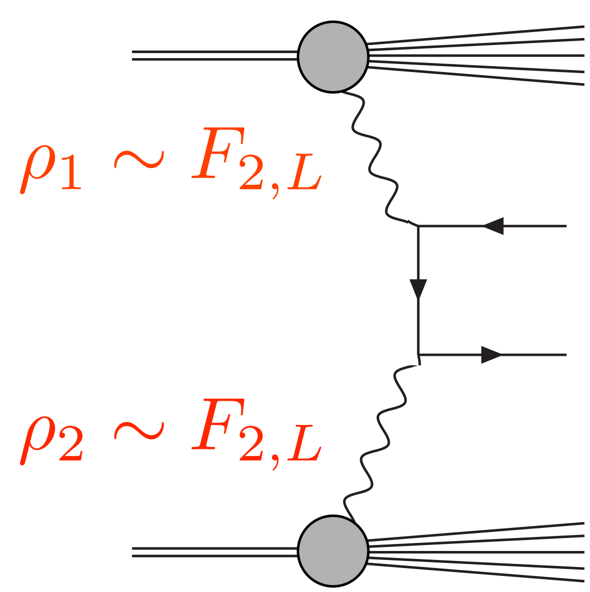
- Data interpreted in terms of these, and in parton model calculated in terms of quark/gluon PDFs.

$$
\begin{aligned}
F_2(x,Q^2) &= x\sum_{q,\bar{q}} e_q^2 \int_x^1 \frac{d\xi}{\xi}\, q(\xi,Q^2)\left\{\delta\left(1-\frac{x}{\xi}\right)+\frac{\alpha_S}{2\pi}C_q^{\overline{MS}}\left(\frac{x}{\xi}\right)+\ldots\right\} \\
&+x\sum_{q,\bar{q}} e_q^2 \int_x^1 \frac{d\xi}{\xi}\, g(\xi,Q^2)\left\{\frac{\alpha_S}{2\pi}C_g^{\overline{MS}}\left(\frac{x}{\xi}\right)+\ldots\right\}. \qquad (4.84)
\end{aligned}
$$

- But also answers our question of how to evaluate/ parameterise PI production at LHC $\Rightarrow$ use precisely same argument as for DIS to write:

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

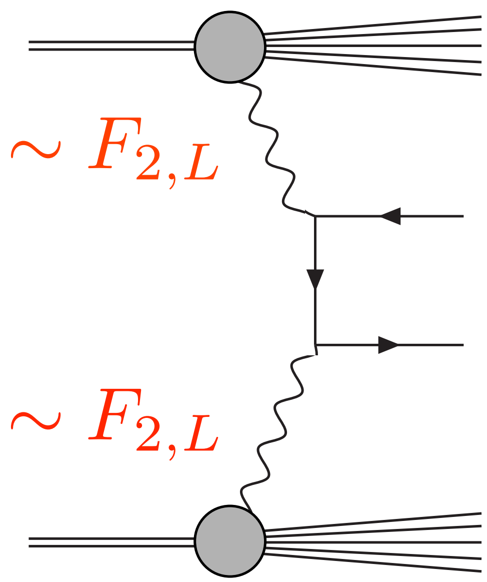
σ_{pp} :



- Cross section given in terms of photon density matrix:

$$\rho_i^{\alpha\beta} = 2\int \frac{\mathrm{d}x_{B,i}}{x_{B,i}^2}\left[-\left(g^{\alpha\beta}+\frac{q_i^\alpha q_i^\beta}{Q_i^2}\right)F_1(x_{B,i},Q_i^2)+\frac{(2p_i^\alpha-\frac{q_i^\alpha}{x_{B,i}})(2p_i^\beta-\frac{q_i^\beta}{x_{B,i}})}{Q_i^2}\frac{x_{B,i}}{2}F_2(x_{B,i},Q_i^2)\right],$$

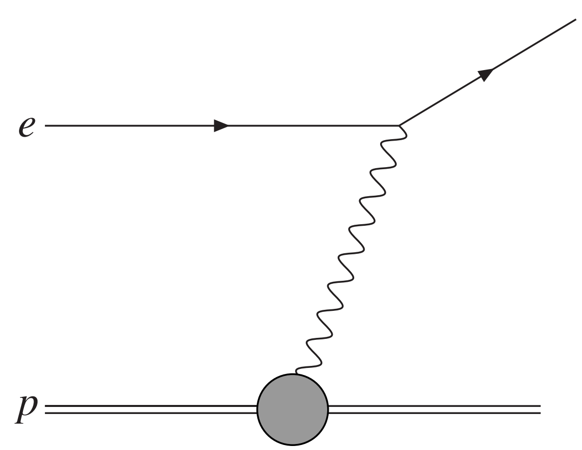
which relates to same structure functions as before.



- The only ingredient we need is therefore a precise input for $F_{1,2}$. Comes from lp scattering data.

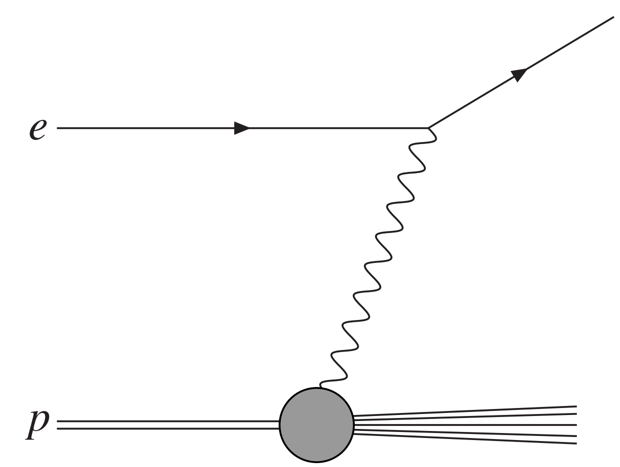
- (Briefly) contributions to $F_{1,2}$ broken down into:

Elastic scattering:



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

Inelastic scattering:



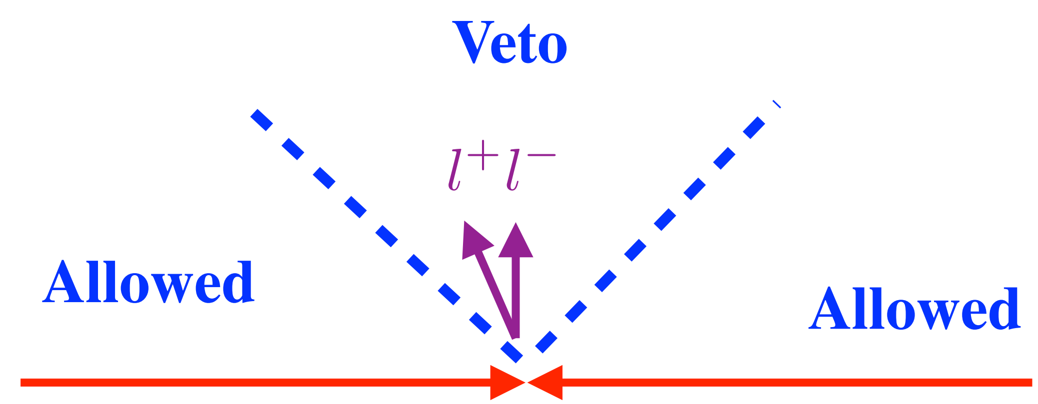
$F_{1,2}^{\mathrm{inel}}$

- And there is a wealth of precise experimental inputs for these. **Backup**

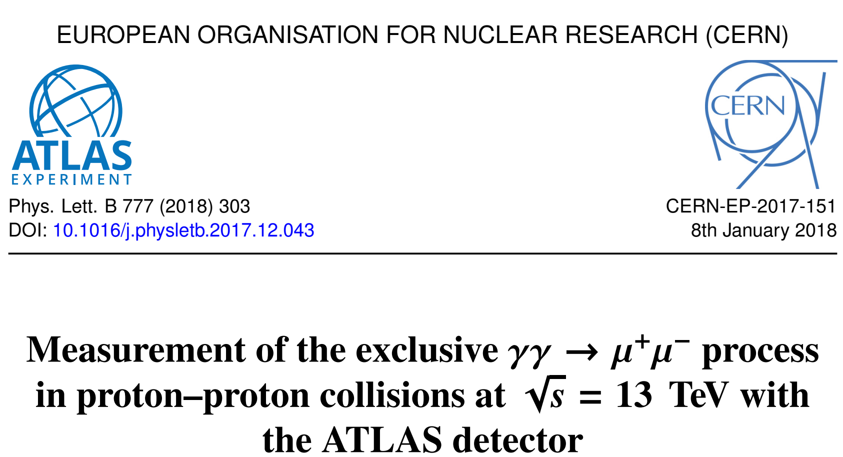
(Semi-)Exclusive Photon-initiated production

Observables

- Consider **lepton pair** production.
- **Basic observable**: fraction of events that pass veto on additional particle production in certain region*.



- Very relevant experimentally: e.g. in selection of ‘exclusive’ events without proton tagging, veto on extra charged tracks within tracker.
- But events with dissociation outside veto region pass this:

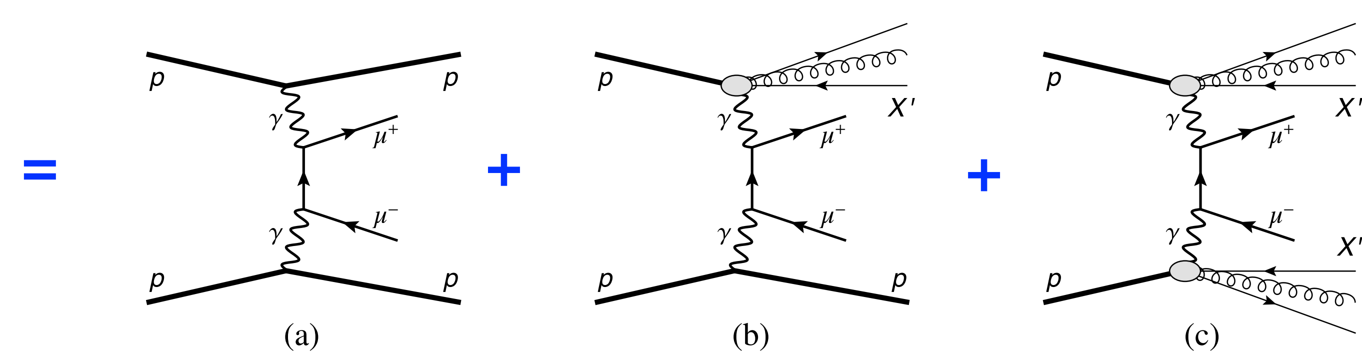

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Phys. Lett. B 777 (2018) 303
DOI: 10.1016/j.physletb.2017.12.043

CERN-EP-2017-151
8th January 2018

Measurement of the exclusive $\gamma\gamma \to \mu^+\mu^-$ process in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector



- Data-driven techniques applied to remove this BG, but current results based on rather outdated simulations.
- How to model this?

*Once we have accounted for this, straightforward to include proton tag requirements as well

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

IPPP/20/33

A new approach to modelling elastic and inelastic photon-initiated production at the LHC: SuperChic 4

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Abstract

We present the results of the new `SuperChic 4` Monte Carlo implementation of photon–initiated production in proton–proton collisions, considering as a first example the case of

- Considered in detail in recent paper.
- Implemented in **SuperChic 4** MC.

superchic is hosted by Hepforge, IPPP Durham

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

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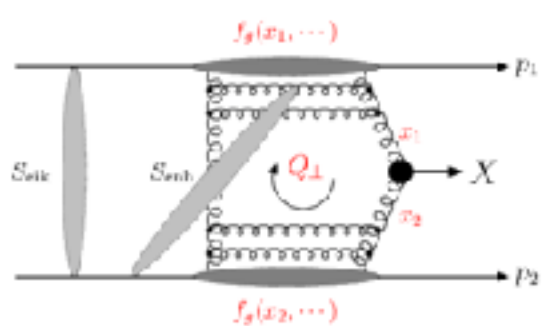
SuperChic is a Fortran based Monte Carlo event generator for exclusive and photon-initiated production in proton and heavy ion collisions. A range of Standard Model final states are implemented, in most cases with spin correlations where relevant, and a fully differential treatment of the soft survival 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 found here and the code is available here.

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

- SF calculation applied to exclusive/semi-exclusive final states.

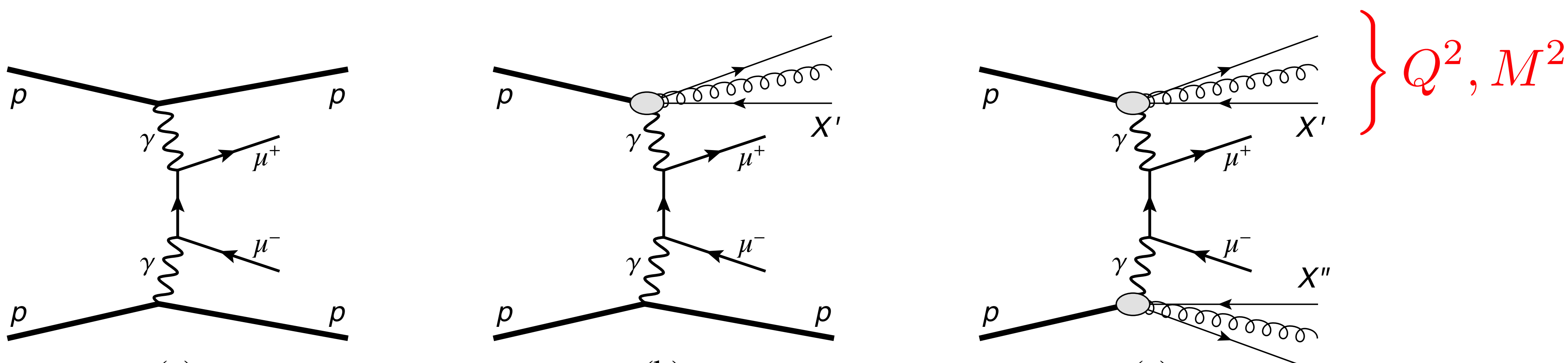
Basic Idea

- SF calculation uniquely suited to deal with situation where we ask for limited hadronic activity/intact protons in PI process:

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

⋆ Can isolate elastic component of $F_{1,2}$ to give exclusive prediction.

⋆ Fully differential in photon $x, Q^2 \Rightarrow$ invariant mass of proton dissociation system (higher $W^2 \Rightarrow$ more hadronic activity).



(a) (b) (c)

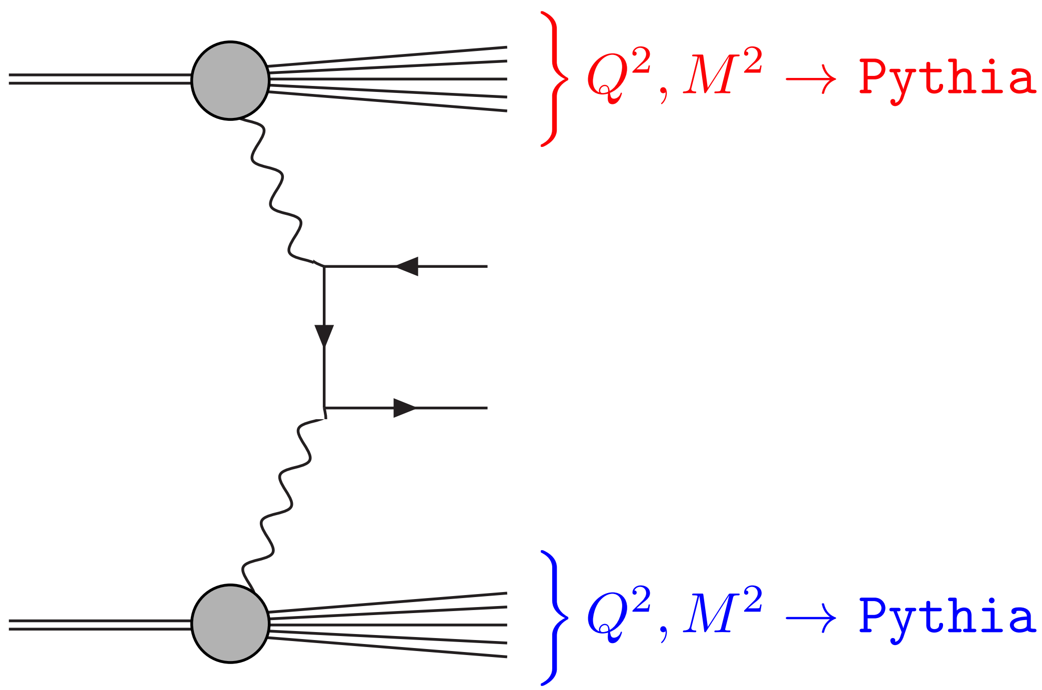
$\rho_{1,2} \sim F^{\mathrm{el}}(x, Q^2)$

$\rho_1 \sim F^{\mathrm{inel}}(x, Q^2)$
$\rho_2 \sim F^{\mathrm{el}}(x, Q^2)$

$\rho_{1,2} \sim F^{\mathrm{inel}}(x, Q^2)$

- Having generated exclusive/semi-exclusive lepton pair production events, interface to **Pythia** for showering/hadronisation of dissociation system.

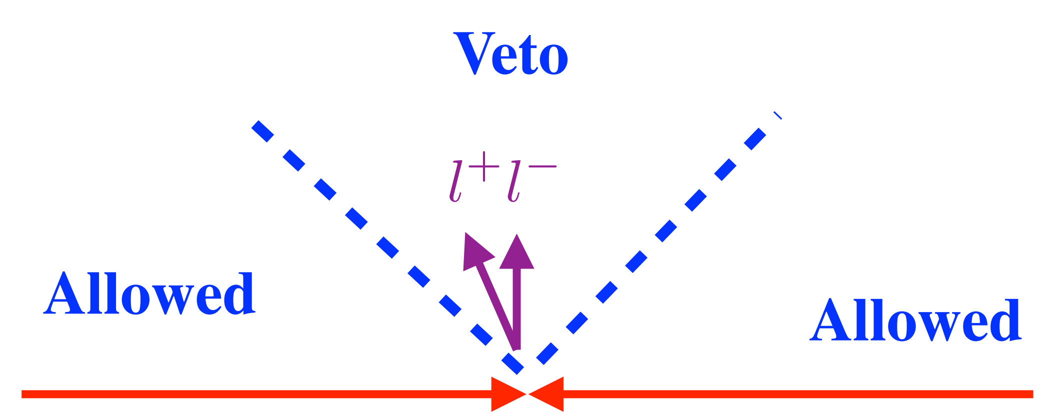
Backup



- Then simply impose veto at particle level after passing to Pythia.
- Expectation (so far) for different components of PI production:

  ★ All elastic events pass veto. $A^{\rm el} = 1$

  ★ Fraction of events with proton dissociation fail veto. $A^{\rm dd} < A^{\rm sd} < 1$

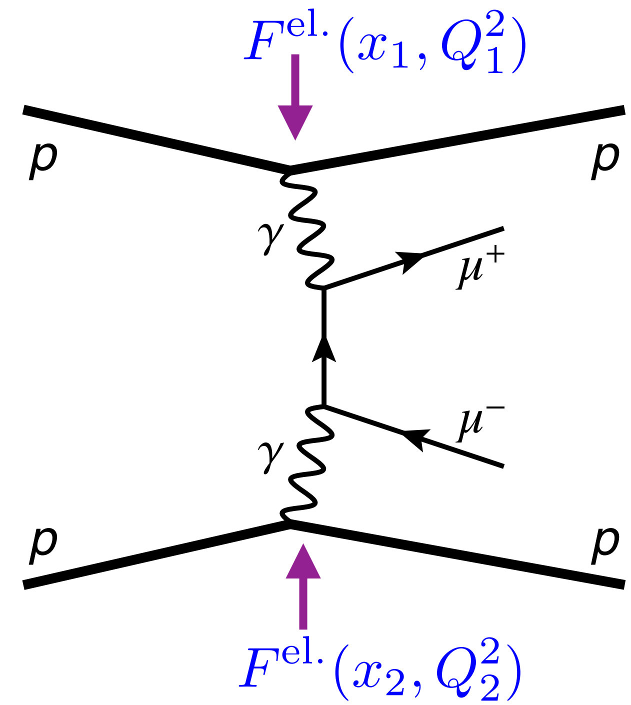


- **But not the end of the story**!

The Survival Factor

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

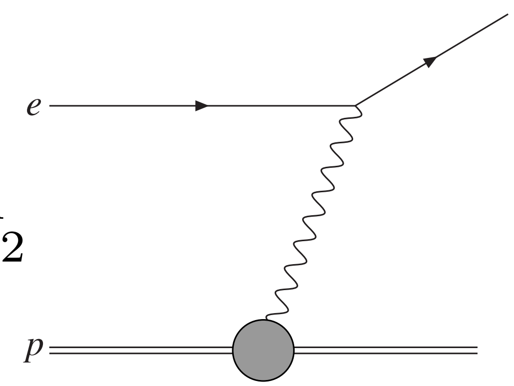
$$\sigma \sim F^{\text{el.}}(x_1, Q_1^2) F^{\text{el.}}(x_2, Q_2^2)$$



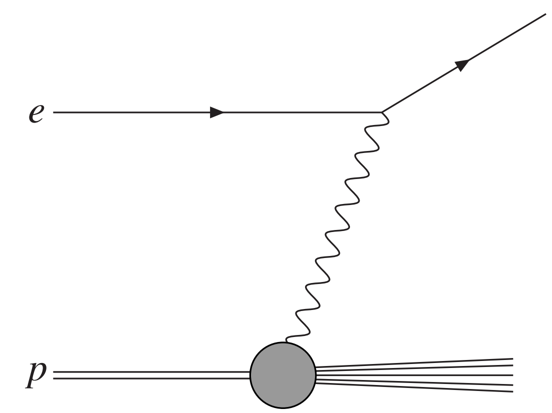
- Similarly for SD + DD, with $F^{\text{el.}} \to F^{\text{inel.}}$

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

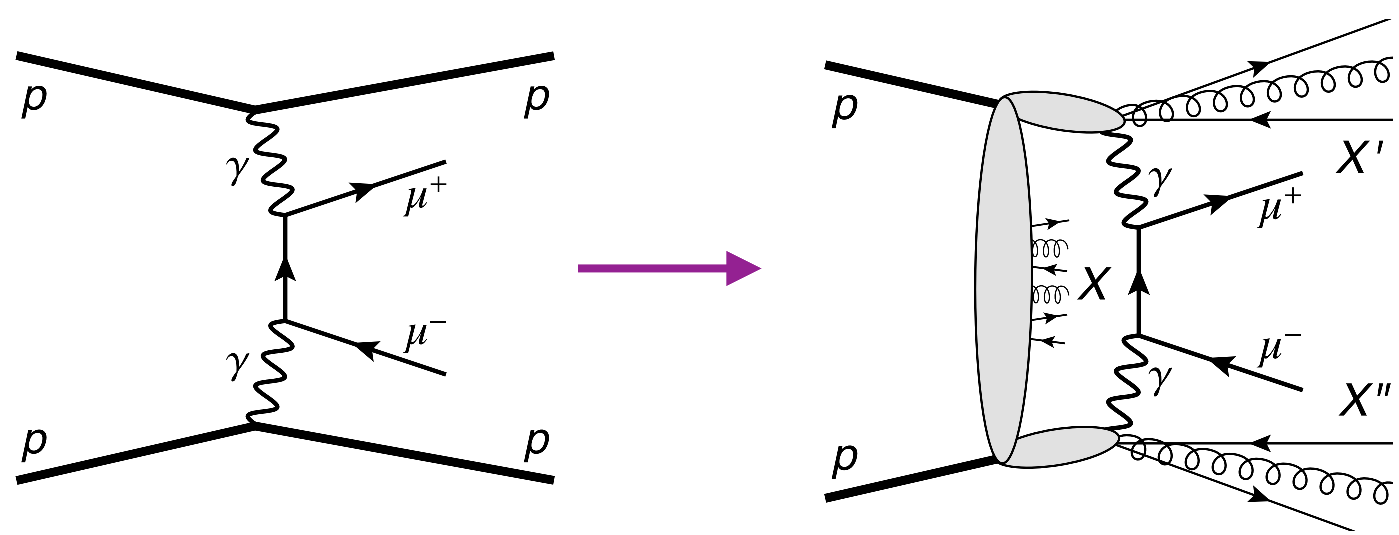
$F_{1,2}^{\text{el}}$



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



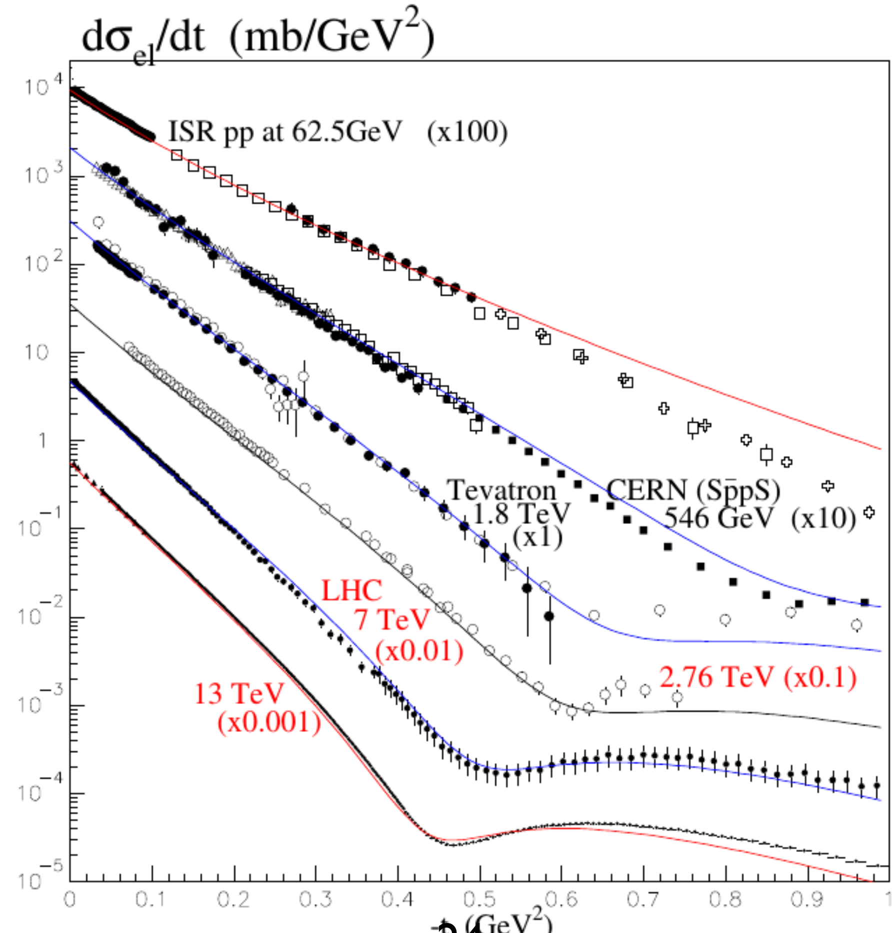
- But we are interested in **hadron-hadron** scattering: need to account for additional hadron-hadron interactions.



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

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

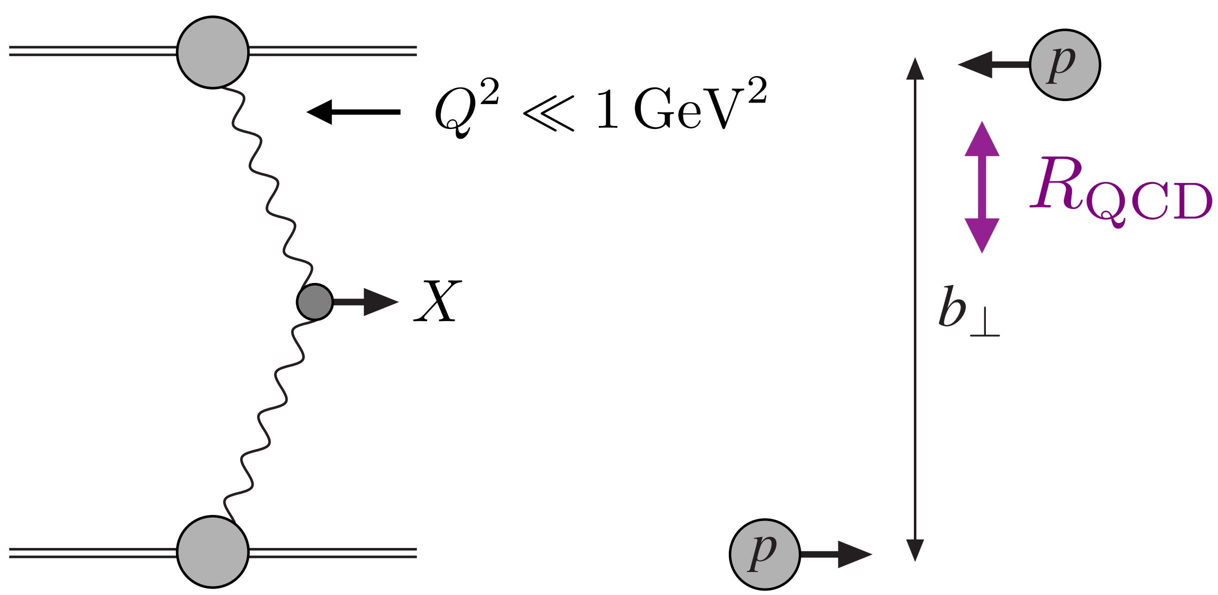
- How to model this? Depends on e.g. σ^{inel} in soft regime $\Rightarrow$ requires understanding of proton + strong interaction in **non-perturbative** regime.
- Build phenomenological models, and tune to wealth of data on elastic + inelastic proton scattering at LHC (and elsewhere). But in general source of **uncertainty**.



V. A. Khoze, A. D. Martin & M. G. Ryskin, arXiv:2012.07967

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 $S^2 \sim 1$.



$S^2 \sim 0.7 - 0.9$

- In more detail, **survival factor** depends on:
  - ⋆ Whether underlying PI process is elastic or SD/DD. In latter case average $b_\perp$ is smaller, and hence $S^2 \downarrow$.
  - ⋆ Precise process kinematics.

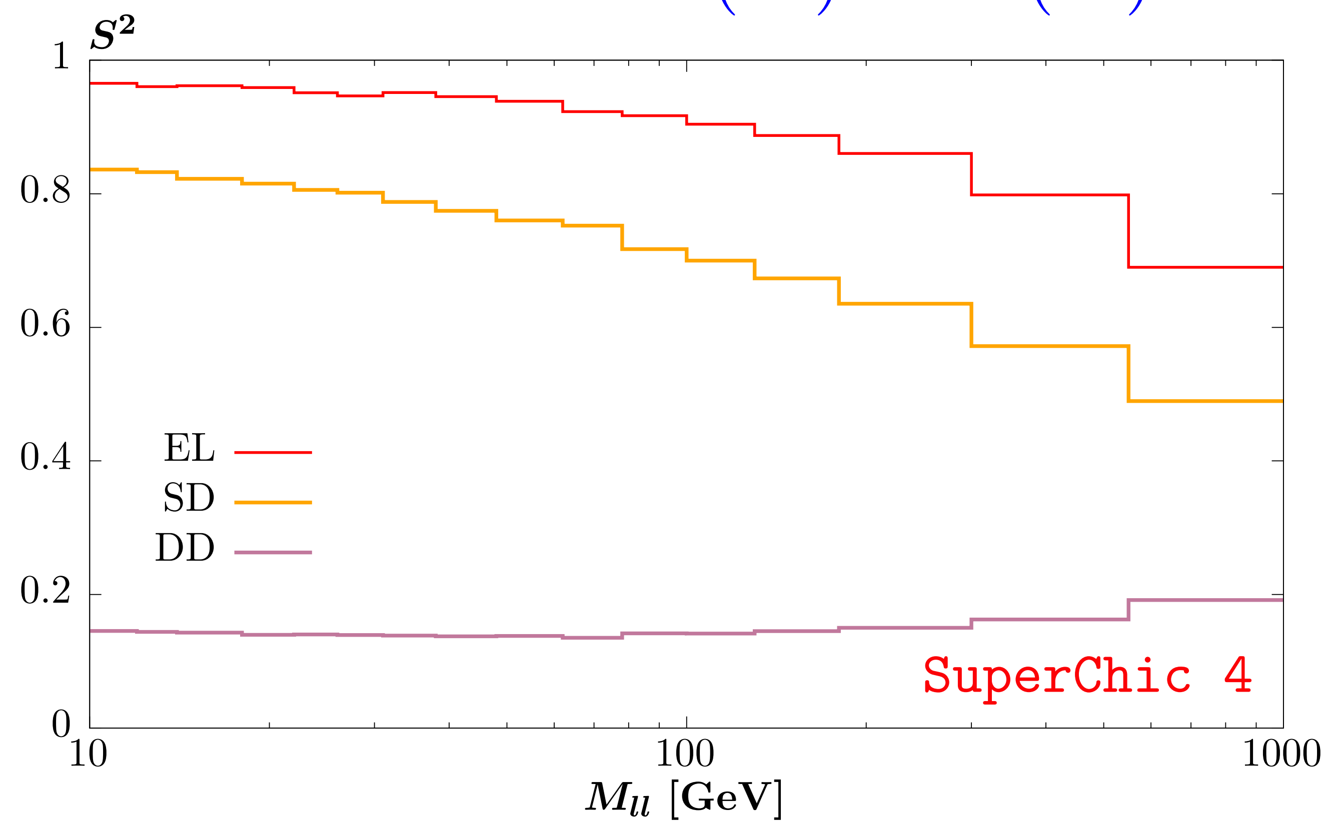
$S^2({\rm el.}) > S^2({\rm sd}) > S^2({\rm dd})$

- All accounted for in SuperChic 4.

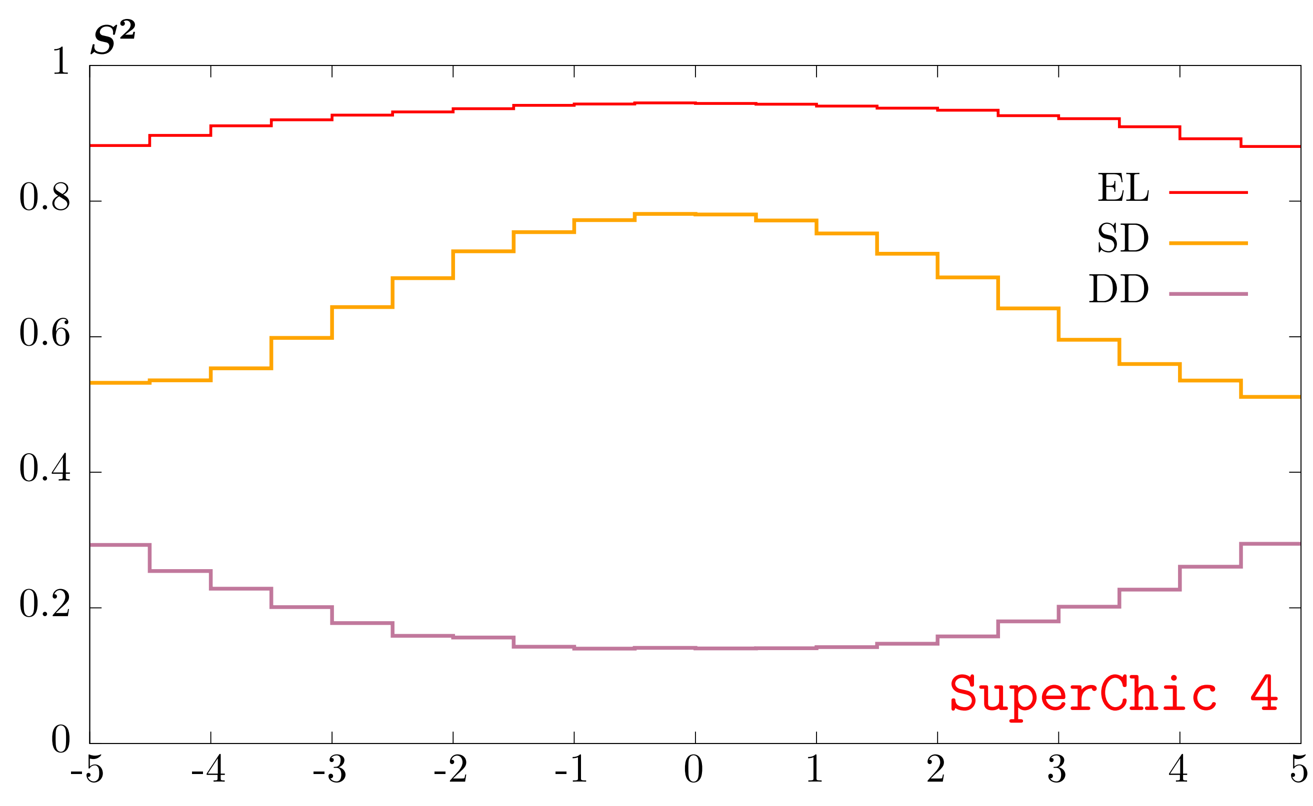
Results

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

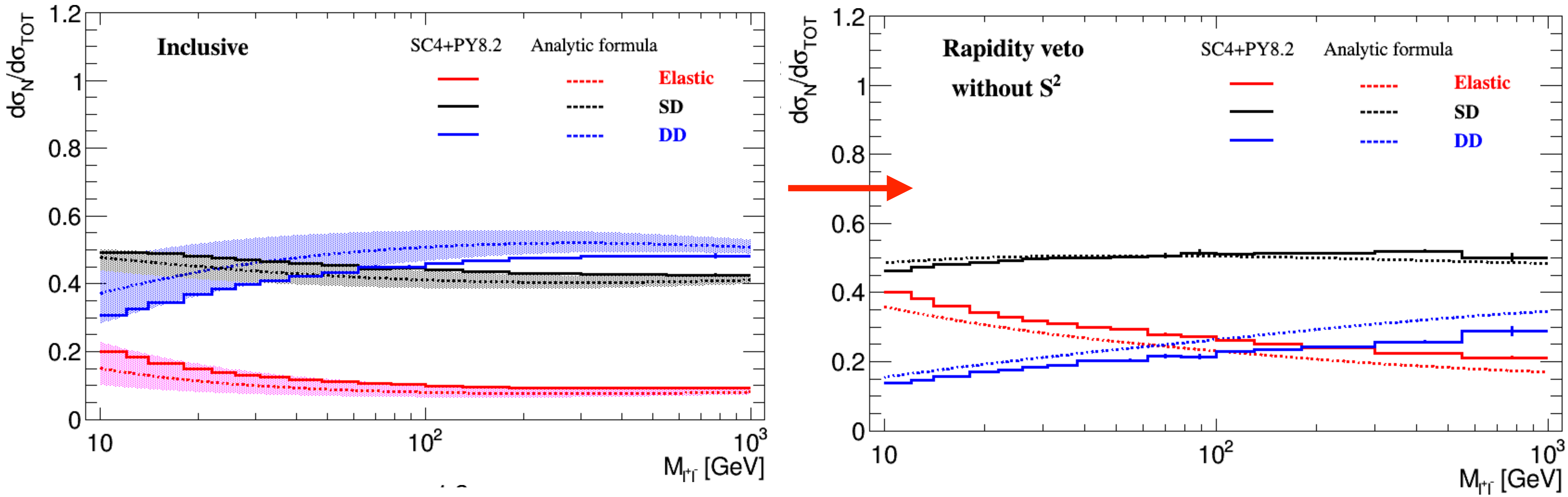
- Scaling with elastic vs. dissociative clear.
- For SD case, $S^2 \sim 1$ still generally true as one proton elastic.



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



Gap veto - impact

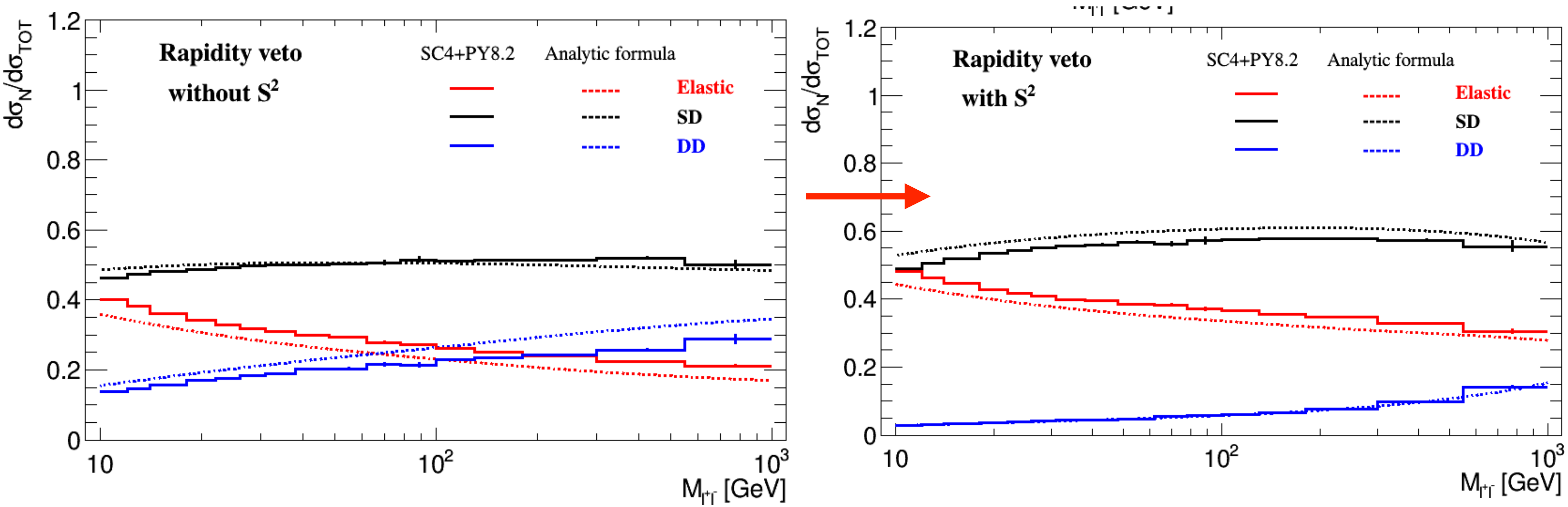


- Consider veto in 13 TeV muon pair production. Compare with analytic approach of arXiv:1601.03772. Take $|\eta| < 4.4$ for comparison with this, but trends similar for realistic veto regions.

  ⋆ **Inclusive**: dominance of DD at larger m_{ll}, elastic generally small. Large scale uncertainties in analytic* $\longrightarrow$ based on collinear LO approach.

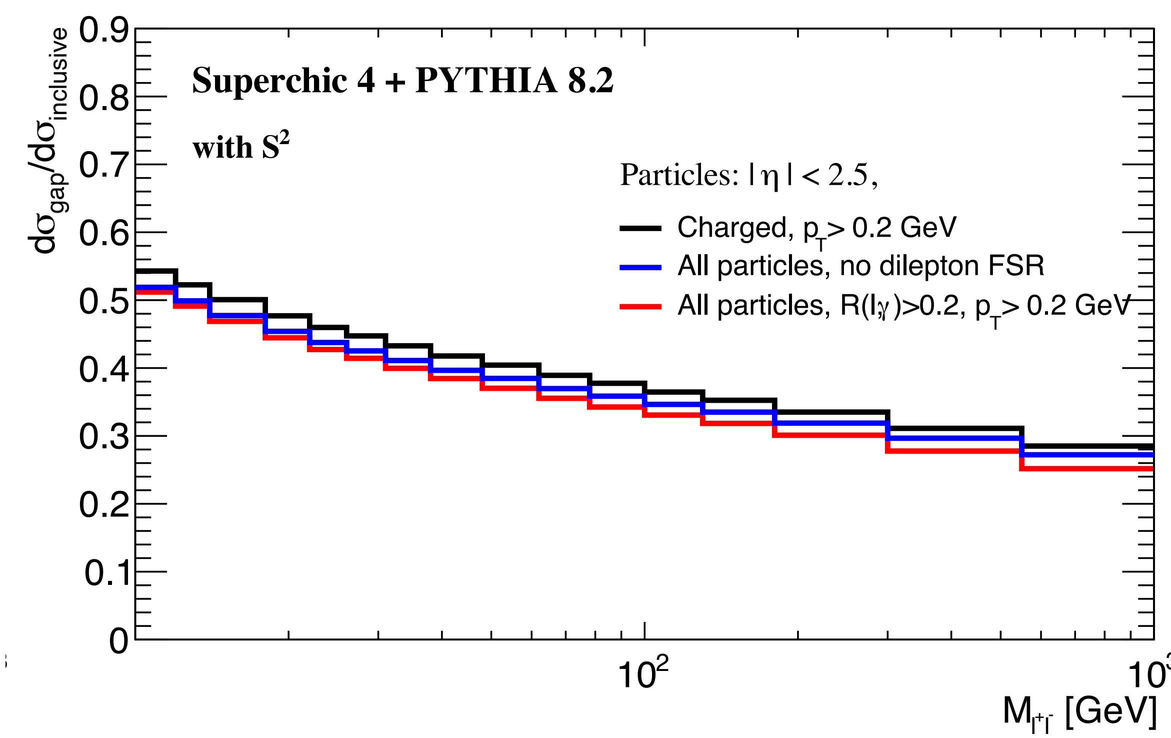
  ⋆ **Include veto** (no S^2): suppression in SD + DD, as expected.

***nb. scale variations only shown for inclusive case**



★ **Veto** + S^2 : strong suppression in DD. Elastic and SD comparable at lower m_{ll}, SD dominant as m_{ll} increases.

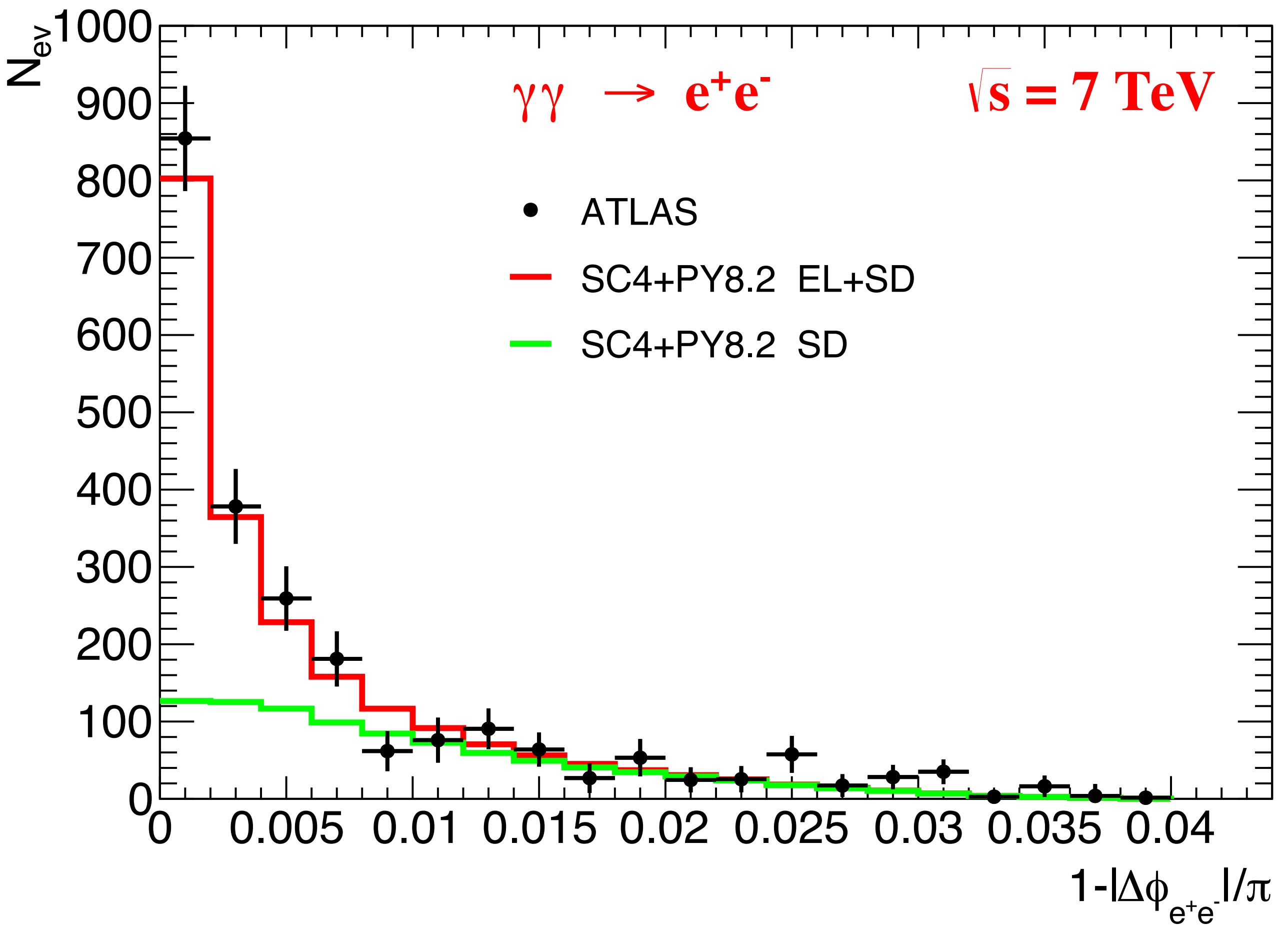
- Above veto imposed on all particles. Vetoing on charged particles only + realistic threshold gives **similar results**.

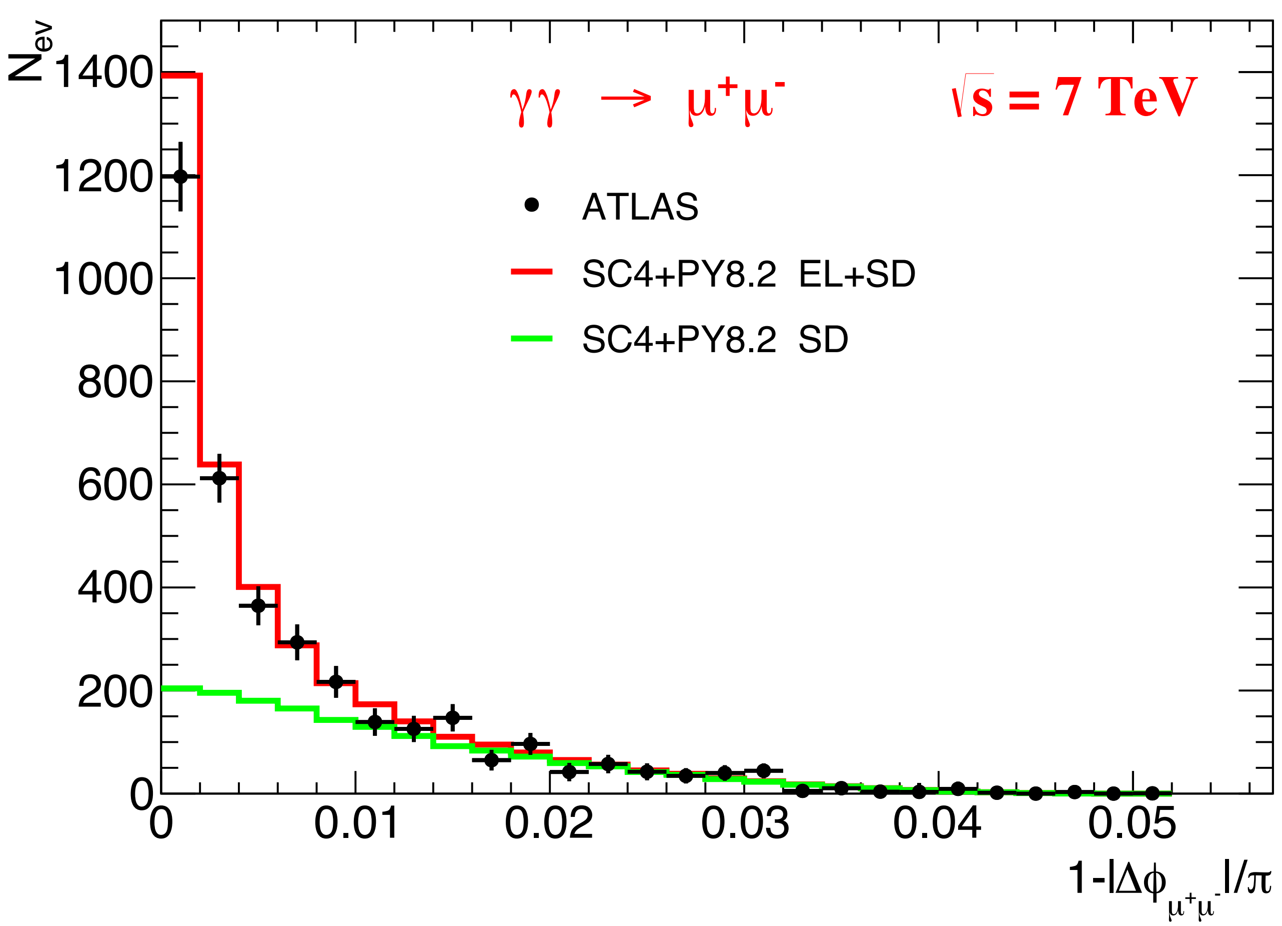


Comparison to Data (1)

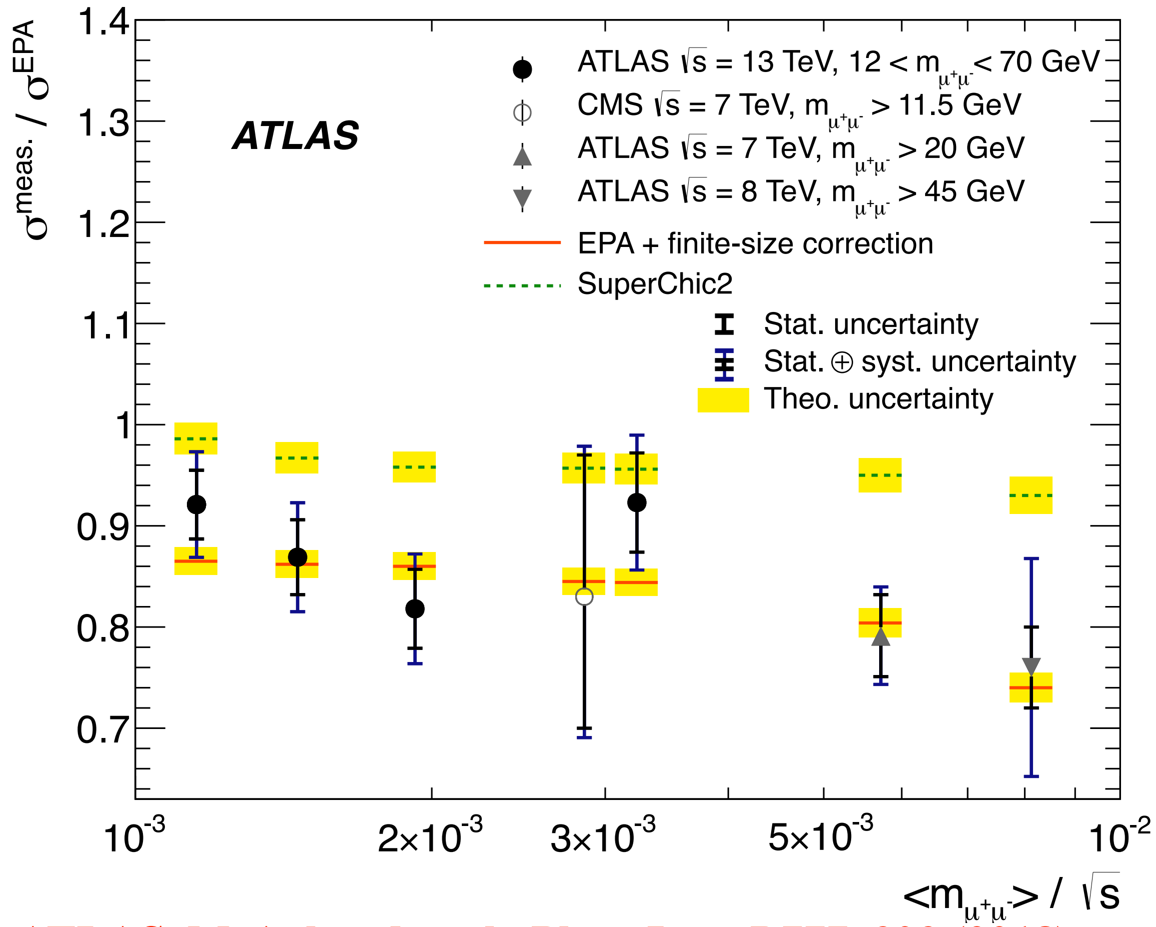
ATLAS, G. Aad et al., Phys. Lett. B 749, 242 (2015)

- Compare to **ATLAS** 7 TeV data on (semi)-exclusive lepton pair production, selected via veto on charged tracks.
- DD subtracted from data via NNPDF2.3QED + LO collinear model. Out of date, but contribution very small after veto in any case.
- Find **SuperChic 4** predictions for SD and elastic acoplanarity distributions describes data in general very well (some overshoot in $\mu^+\mu^-$ in lowest bin).





- However comparing to 8 and 13 TeV data, trend for **SuperChic 4** predictions to overshoot data by up to ~ 10%.
- Assuming theoretical issue: uncertainties on $F^{\rm el.}$ at ~ 1% level. $b_\perp \gg R_{\rm QCD}$
- Could S^2 be the culprit? $S^2 \sim 1$ in elastic/SD case a general expectation, so uncertainties should also be ~ 1% (less sensitivity to details of model).
- **Homework** for us theorists to look at. Having unsubtracted data as differentially as possible to compare to will guide things. E.g. is issue in elastic region or SD (DD?), or both?



ATLAS, M. Aaboud et al., Phys. Lett. B777, 303 (2018)

	$\sigma^{\rm fid.}_{ee+p}$ (fb)	$\sigma^{\rm fid.}_{\mu\mu+p}$ (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

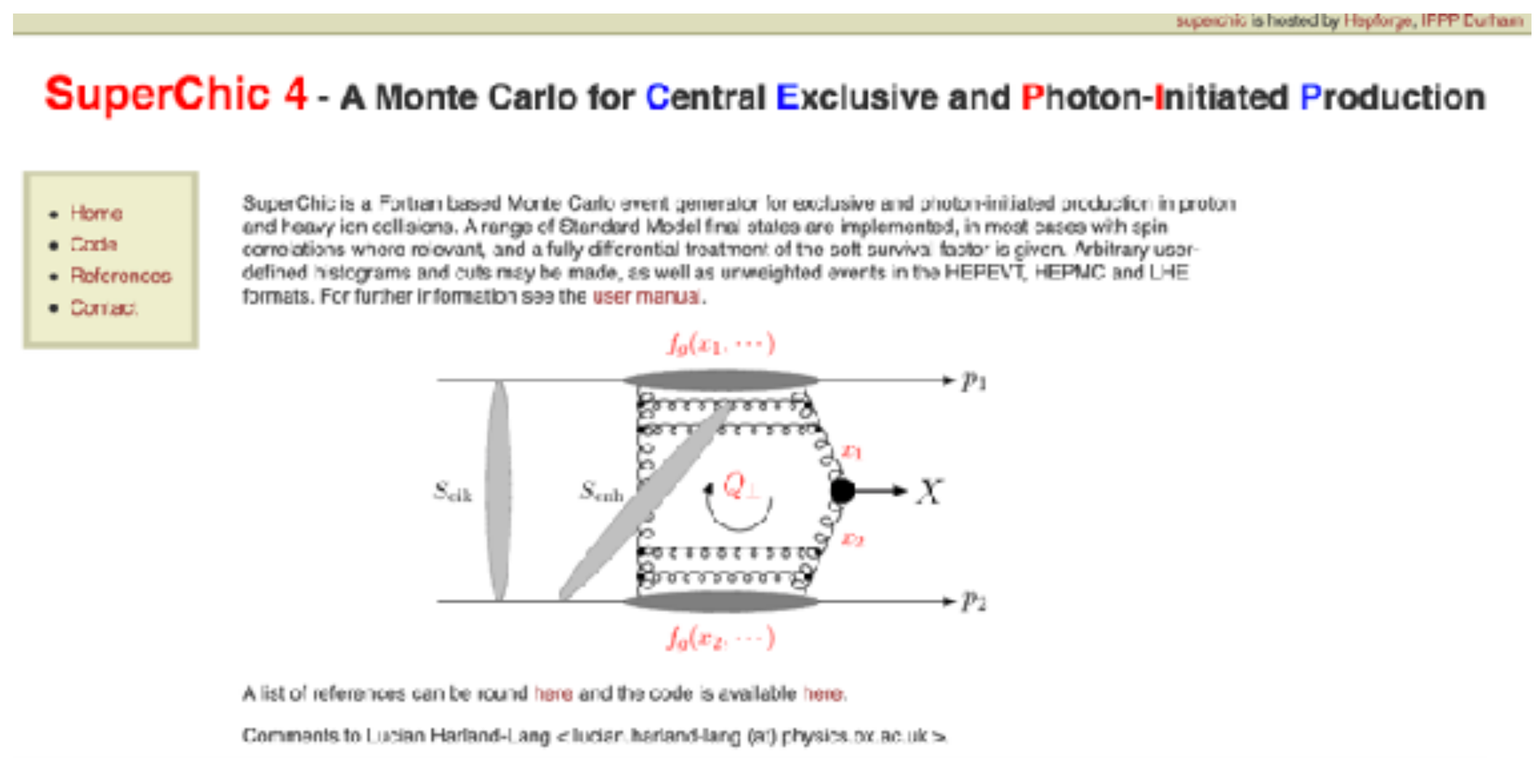
Note there are issues in ‘finite size’ predictions compared to - Backup.

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.

- Full treatment of proton dissociation for photon-initiated production in pp collisions currently available for lepton pair production.



https://superchic.hepforge.org

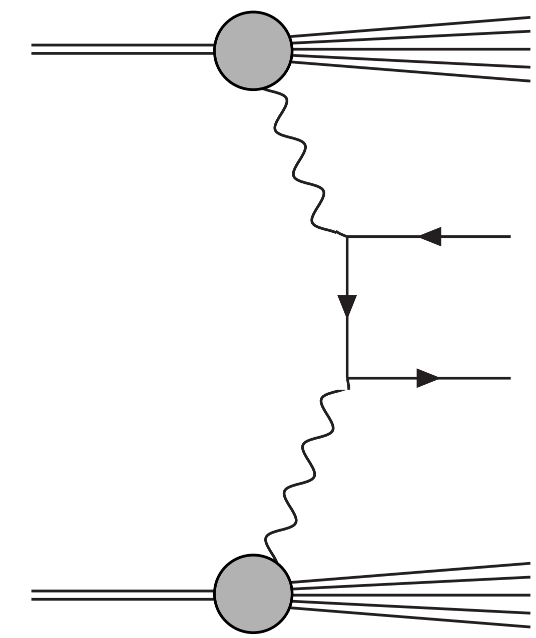
Summary/Outlook

- ★ We are entering the high precision LHC era.
- ★ Exciting programme of exclusive/semi-exclusive photon-initiated production measurements with tagged protons underway at LHC.
- ★ Photon-initiated production of great phenomenological interest/ relevance in both inclusive and exclusive channels.
- ★ Solid foundation for modelling of exclusive/semi-exclusive photon-initiated production (SuperChic 4).
- ★ Much work to do - understanding comparison to data, including more processes (WW underway). Not to forget Pb-Pb as well!

Thank you for listening!

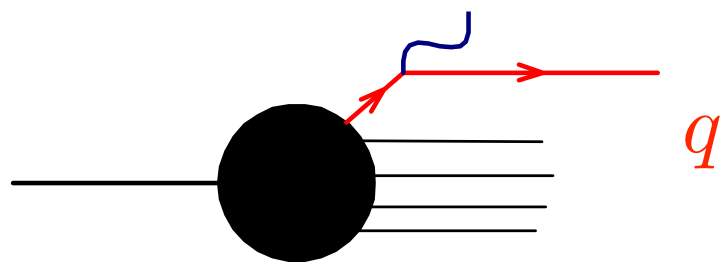
Backup

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).

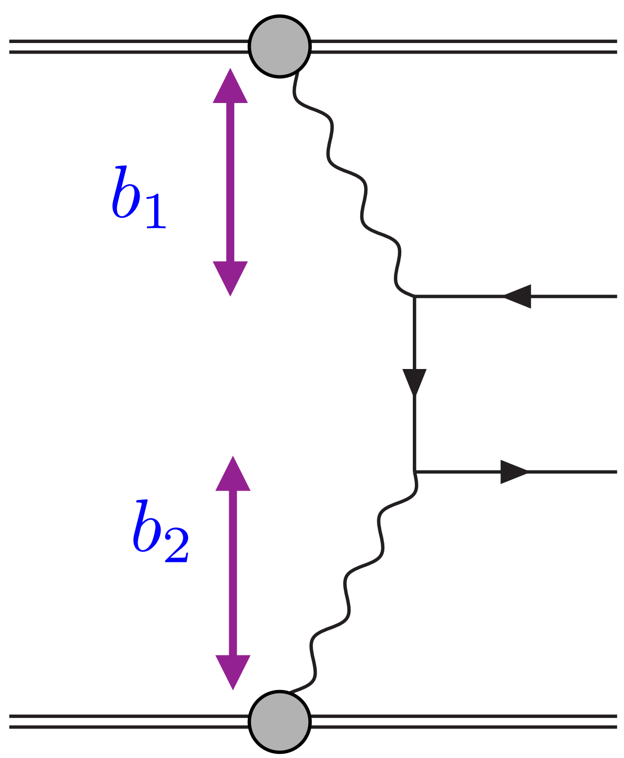
‘Finite-size’ calculation

M. Dyndal and L. Schoeffel, Phys.Lett. B741, 66 (2015)

- ATLAS data compare to ‘finite size’ prediction, which gives lower values of S^2, in better agreement with data.
- Is this preferred? This includes requirement that lepton-proton impact parameter is constrained to be:

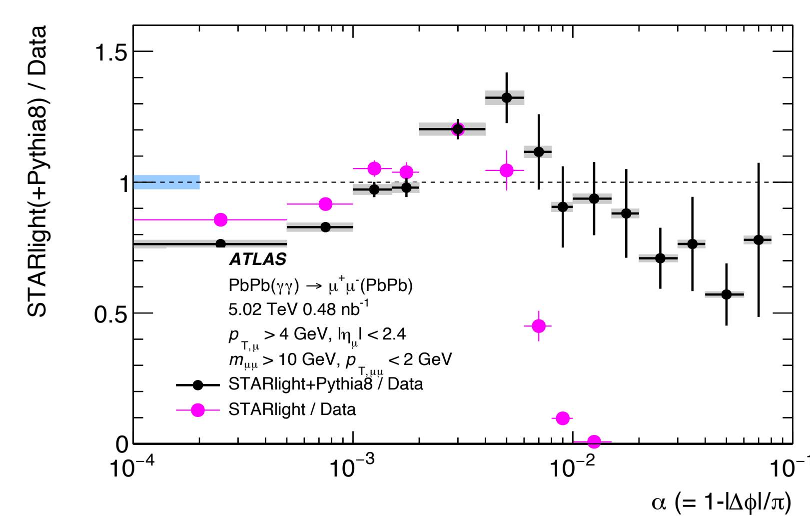
$$b_i > r_p$$

i.e. effectively assumes lepton and proton can interact strongly*.



$$S^2_{\gamma\gamma} = \frac{\underline{\int_{b_1>r_p}\int_{b_2>r_p}} n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)P_{non-inel}(|\vec{b}_1-\vec{b}_2|)d^2\vec{b}_1 d^2\vec{b}_2}{\int_{b_1>0}\int_{b_2>0} n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)d^2\vec{b}_1 d^2\vec{b}_2},$$

- This reduces S^2, but is certainly an unphysical requirement. If this is removed, the predicted S^2 will be close to SuperChic.
- Note this choice is also disfavoured by recent ATLAS data of $\mu^+\mu^-$ production in PbPb.

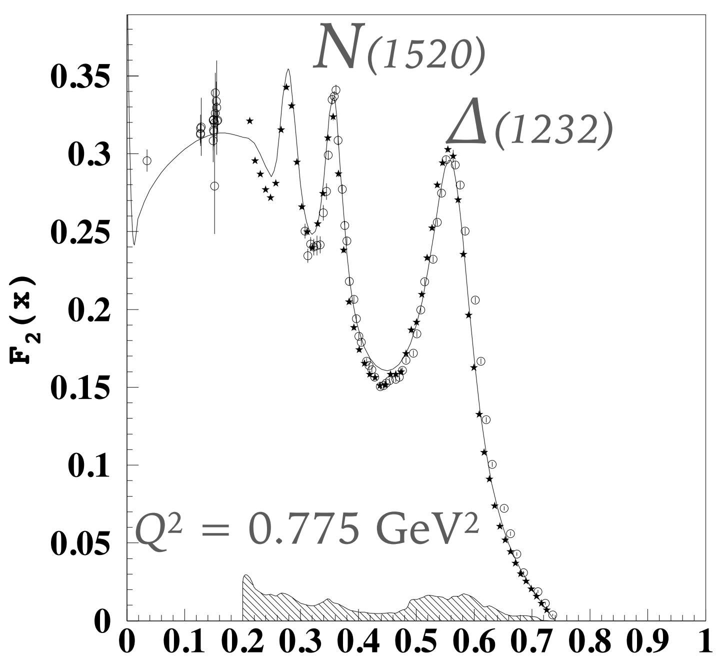


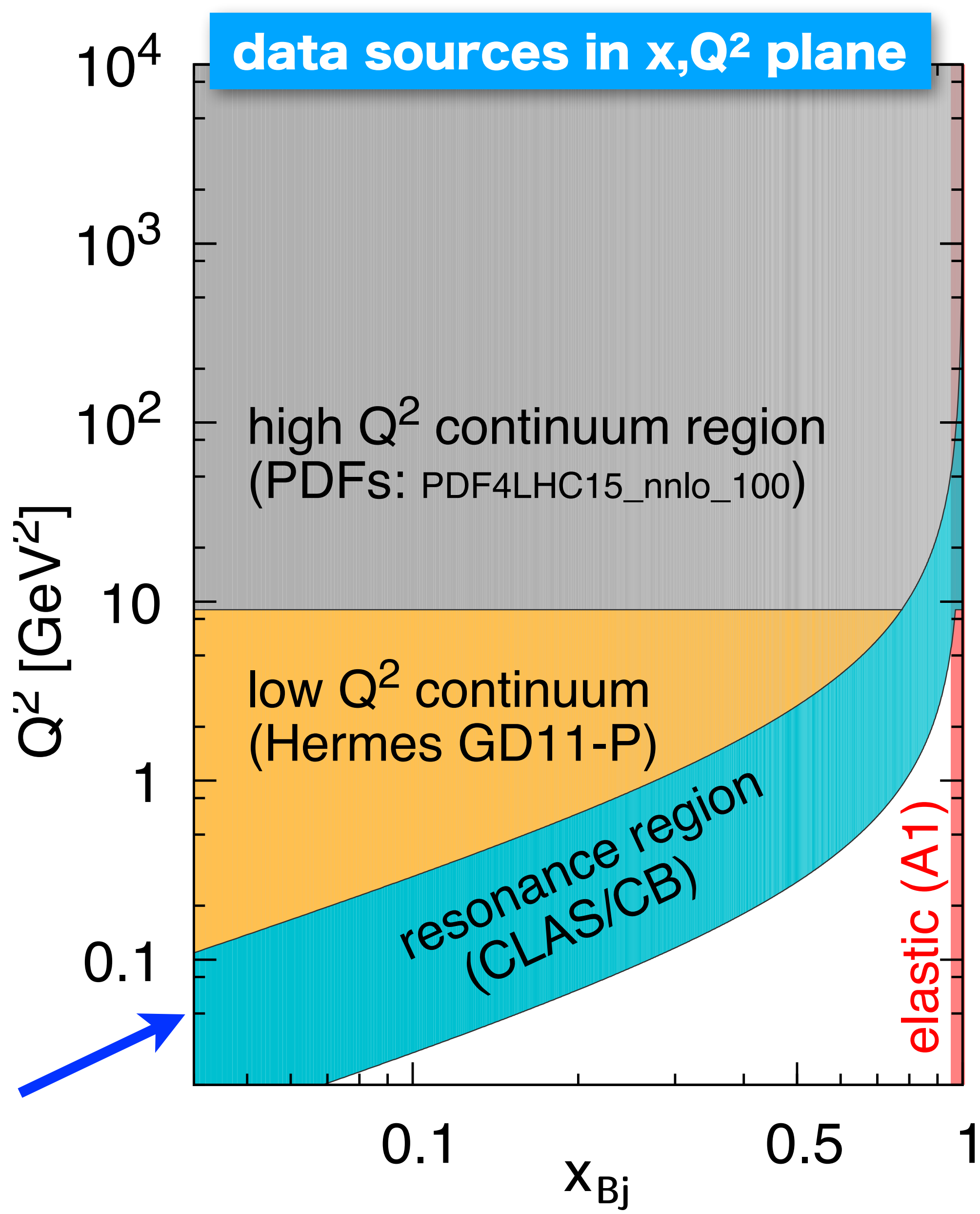
ATLAS, arXiv:2011.12211

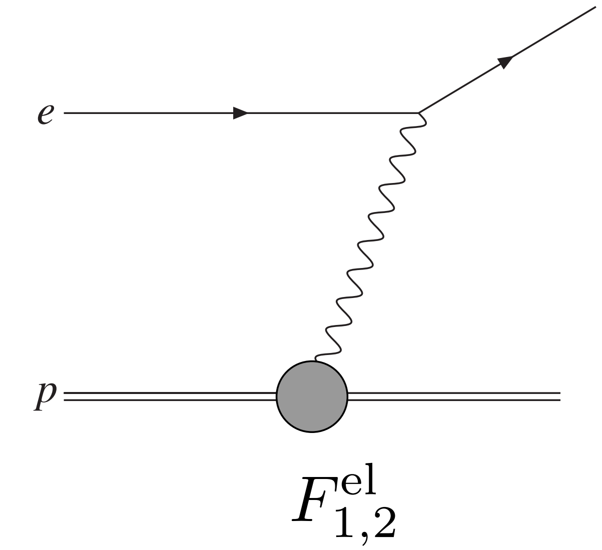
*n.b. effect of any QED proton-lepton interactions v. small and already included in $F_{1,2}$.

Image credits: Gavin Salam

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



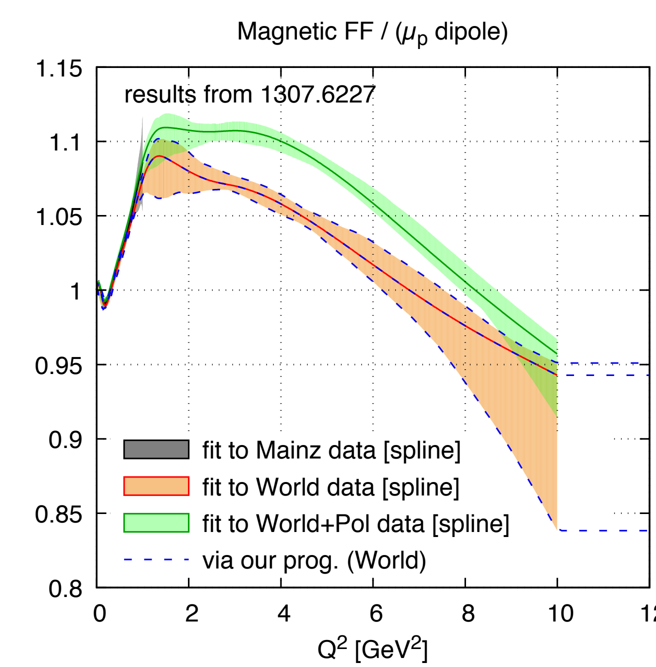




Inelastic resonant proton excitation. Precise parameterisations available.

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

Elastic scattering: from A1 collaboration.

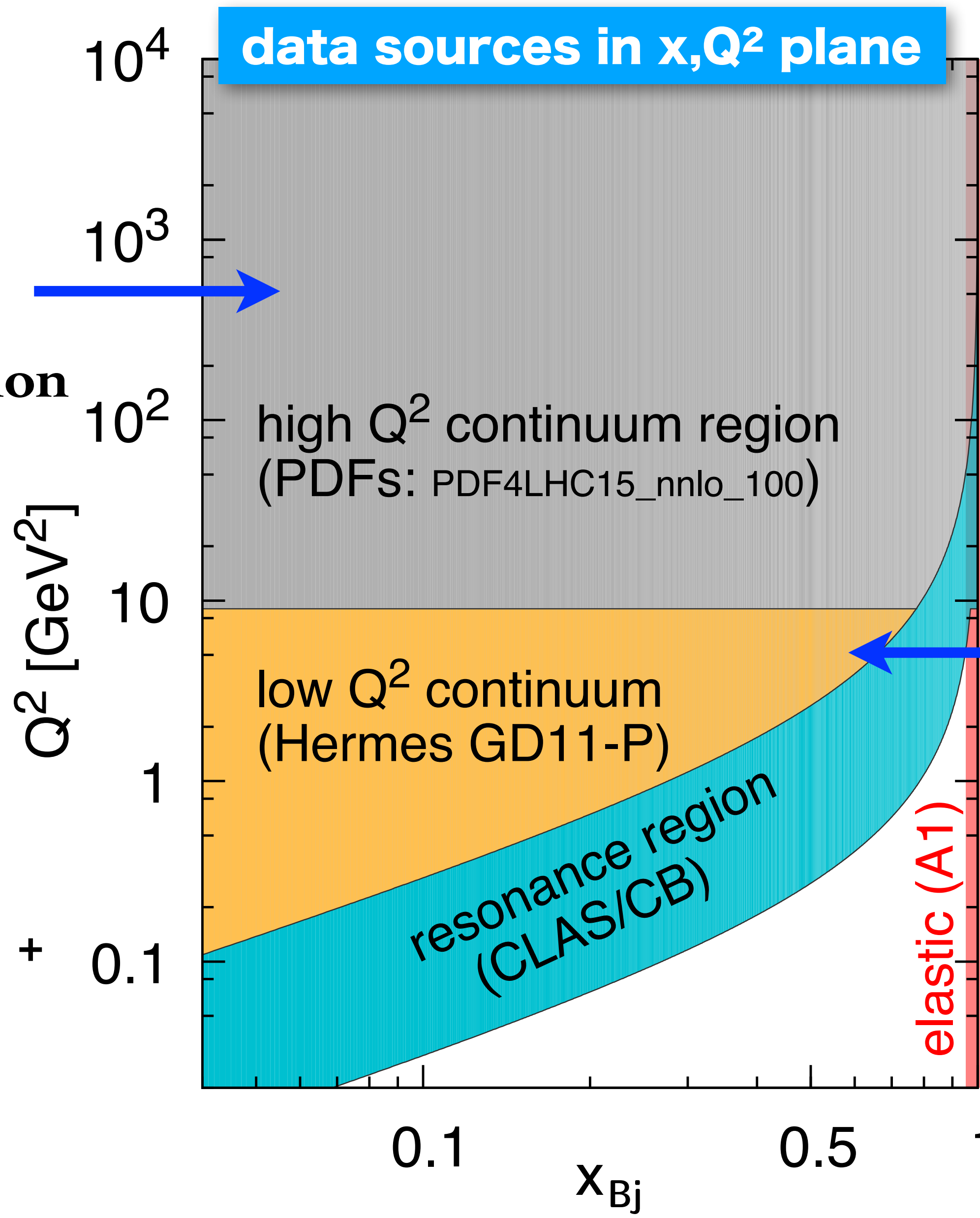


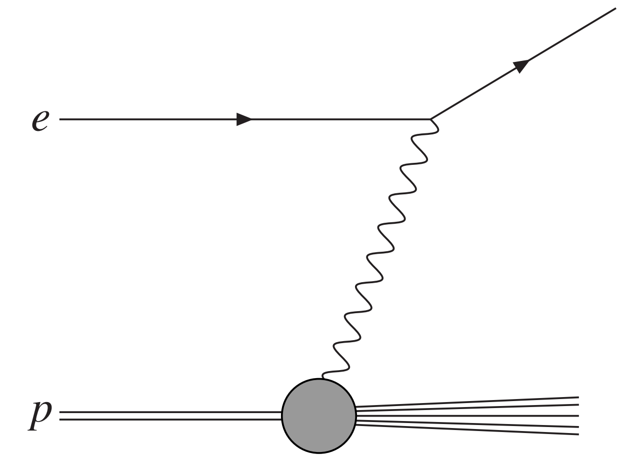
A1 Collaboration, Phys. Rev. C90, 015206 (2014)

Image credits: Gavin Salam

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

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



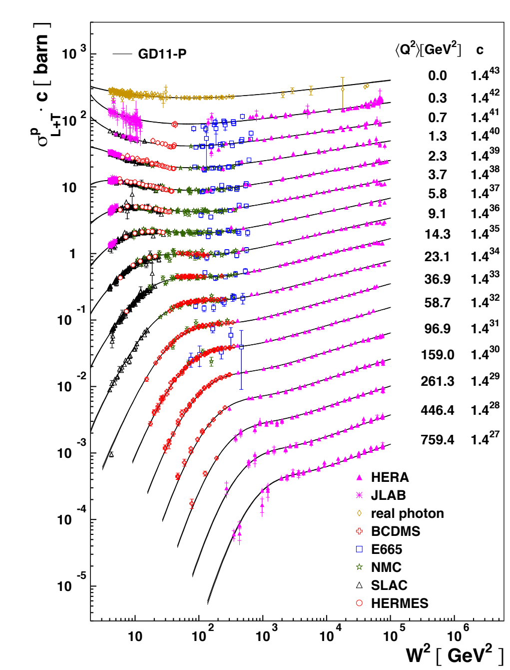


$F_{1,2}^{\rm inel}$

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

Inelastic low Q^2 scattering. Precise parameterisation available.

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



- Closely follow LUXqed inputs here.

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