Physics from Photons at the LHC

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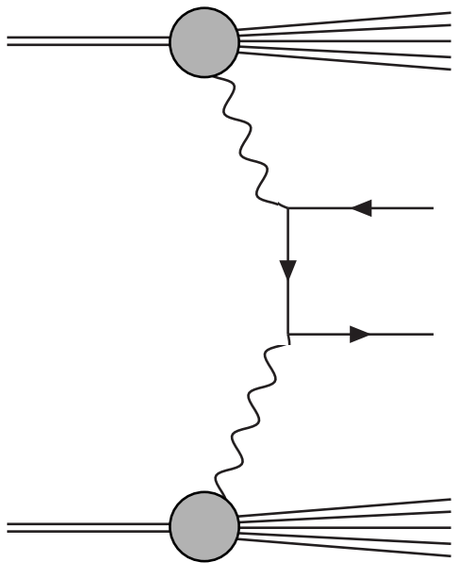
DIS2021, April 14 2021

LHL, *JHEP* 03 (2020) 128
LHL, M. Tasevsky, V. A. Khoze, M.G. Ryskin
***Eur.Phys.J.C* 80 (2020) 10, 925**
LHL, arXiv:2101.04127

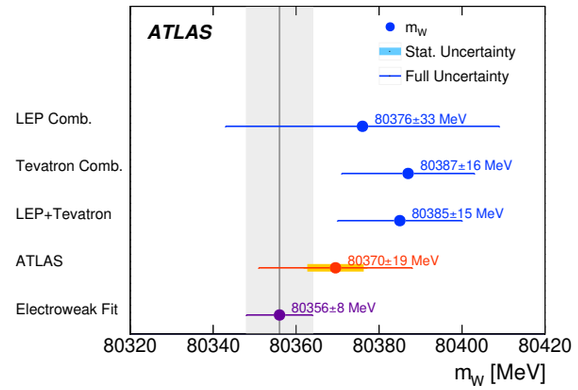
Motivation(s)

- LHC officially in the **precision EW race.**
- Dilepton final state key element of this: photon-initiated (PI) production a key channel.

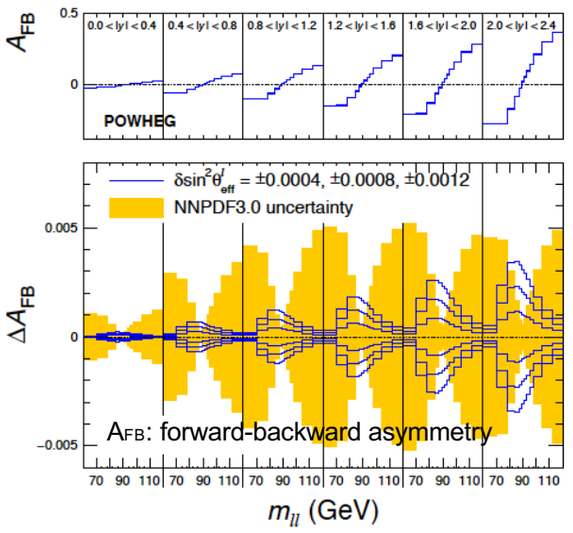


- Precise handle on this production mechanism is essential for LHC precision programme.

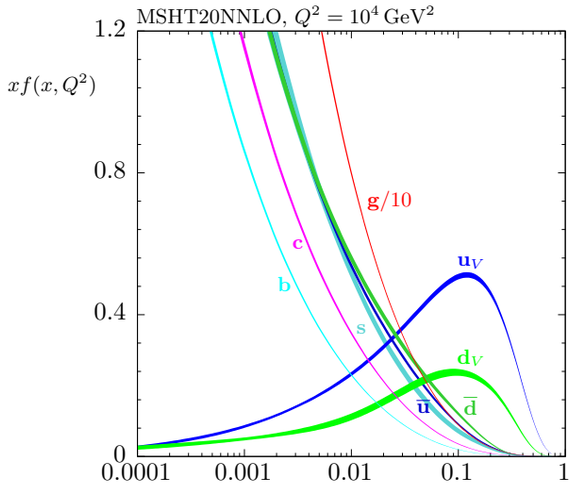
$$\alpha_{\mathrm{QED}}(M_Z) \sim \alpha_S^2(M_Z)$$



M_W



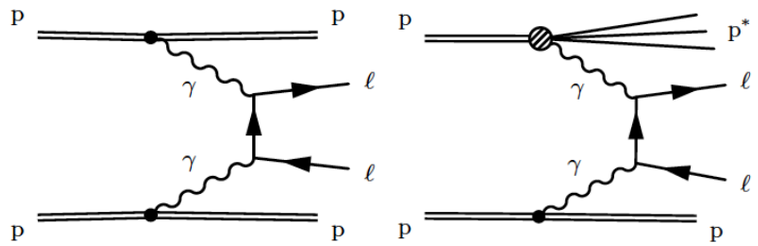
$\sin^2\theta_W$

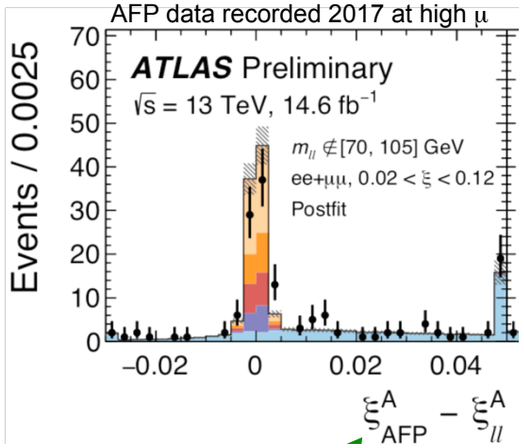


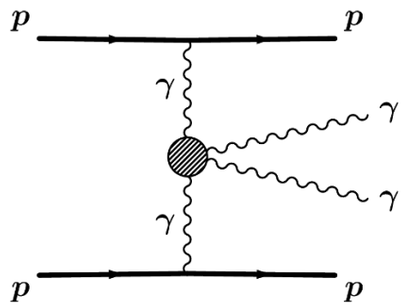
PDFs

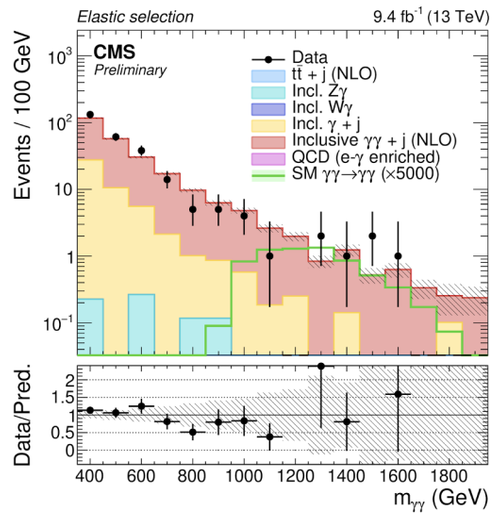
Motivation(s)

- Inclusive production not the only lever arm! Proton tagging detectors at ATLAS/CMS: events with intact protons in final state selected during **nominal running***.



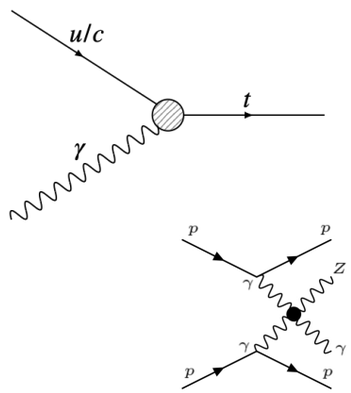






ATLAS + CMS Highlights, ICHEP 2020

- Colour singlet photon: events with intact protons/rapidity gaps in final state.
  - Clean, ~ pure **QED** process $\Rightarrow$ the LHC as a $\gamma\gamma$ collider!



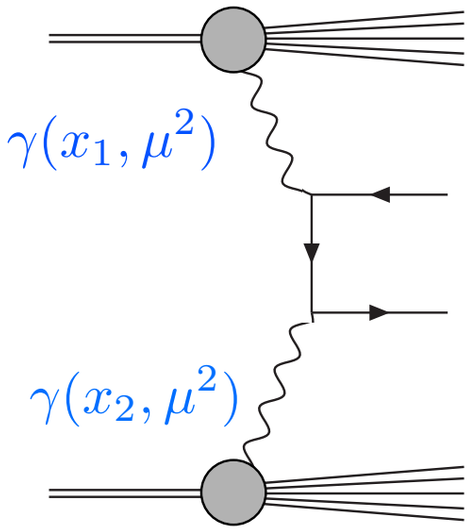
★ Probe of BSM (anomalous couplings, ALPs, SUSY…), top sector and our models of soft proton interactions.

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

PI Production and the Photon PDF

- Inclusive cross section given in terms of (collinear) **photon PDF** within proton.

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

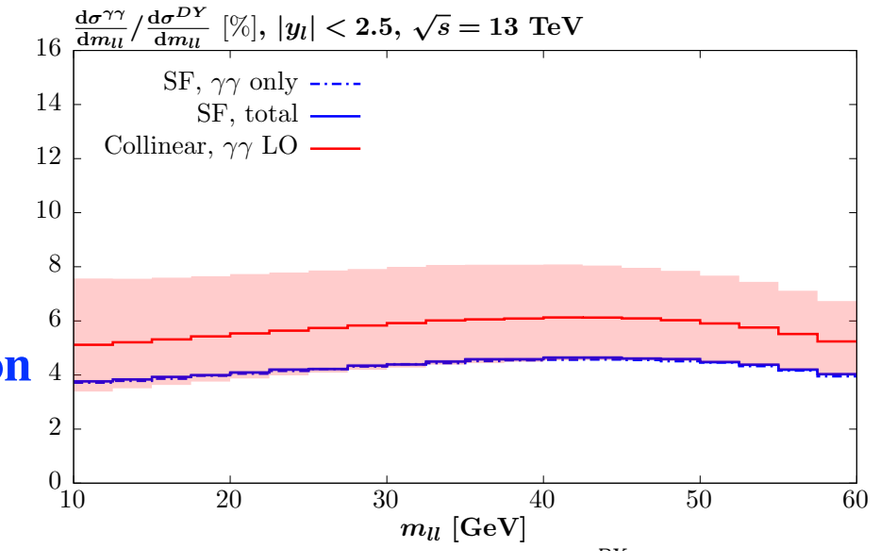


- LUXqed: PDF given in terms of elastic/inelastic proton Structure Functions: ~1% PDF uncertainty!

- However, high precision determination of photon **PDF** does not automatically translate to high precision predictions for **observables**:

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

No μ_F dependence $\Longrightarrow$ no compensation



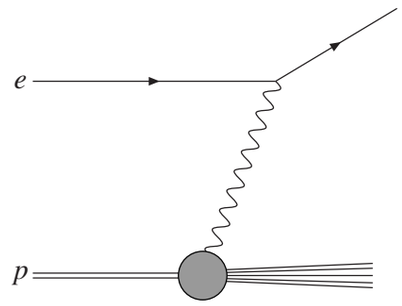
★ LO (in α) $\sigma^{\gamma\gamma}$ have v. large μ_F **uncertainty**.

- So what? We should simply calculate to NLO (…) in α then! Yes we could do, but is there an alternative way?

Structure Function Calculation

- Alternative approach: apply 'structure function' calculation directly.

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

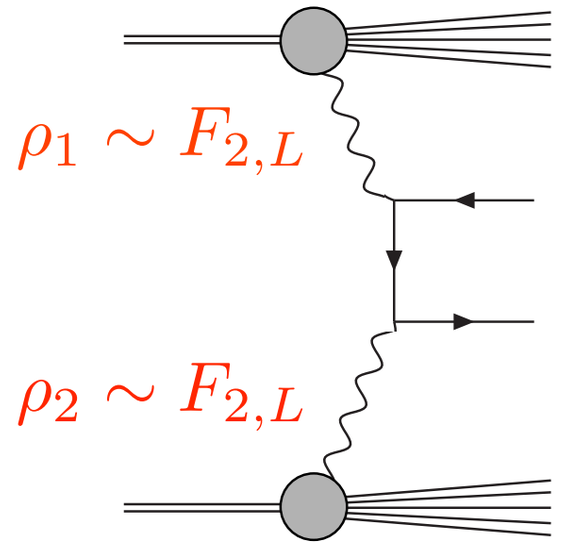


$$\frac{d^2\sigma}{dxdy} \propto L_{\alpha\beta}\, W^{\alpha\beta} \,.$$

- Use precisely same argument as for DIS to write:

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

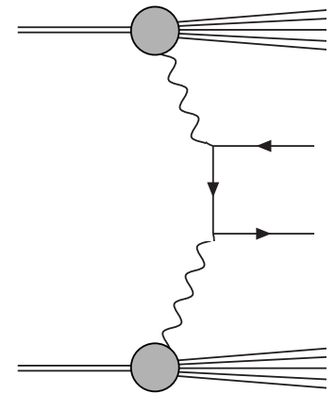
- Cross section given in terms of photon density matrices ρ_i :



Uncertainties/relation to photon PDF

- Uncertainties on SF predicted l^+l^- cross section:

  ⋆ Experimental uncertainty on $F_i^{\text{el,inel.}}$, HO corrections to $\gamma\gamma \to l^-l^+$, non-factorizable NLO EW/NNLO QCD corrections connecting beams.



- All enter at ~ 1% level or less, and no μ_F dependence

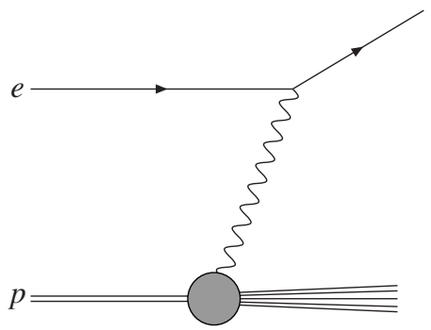
  $\longrightarrow$ **Percent level precision** in predicted cross section.

- Relationship to collinear PDF? Based on expanding SF result in $\sim Q^2/M^2$.

$$\rho_1^{\mu\mu'}\,\rho_2^{\nu\nu'}\,M^*_{\mu'\nu'}M_{\mu\nu} \quad \sim \quad \gamma(x_1,\mu_F)\gamma(x_2,\mu_F^2)\sigma(\gamma\gamma\to l^+l^-) + O\left(\frac{Q^2}{m_{ll}^2}\right)$$

- At LO $Q^2 = 0$ and no control over non-zero Q^2 behaviour.

  - Improves at NLO (+ …) but key point: these corrections are known before they are calculated. Already contained in the SF calculation.

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

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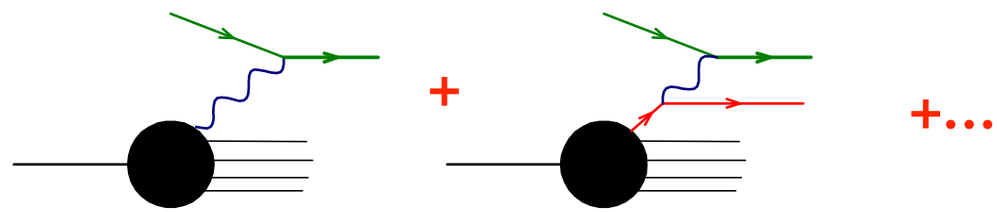
+…

SFGen

Physics with Leptons and Photons at the LHC

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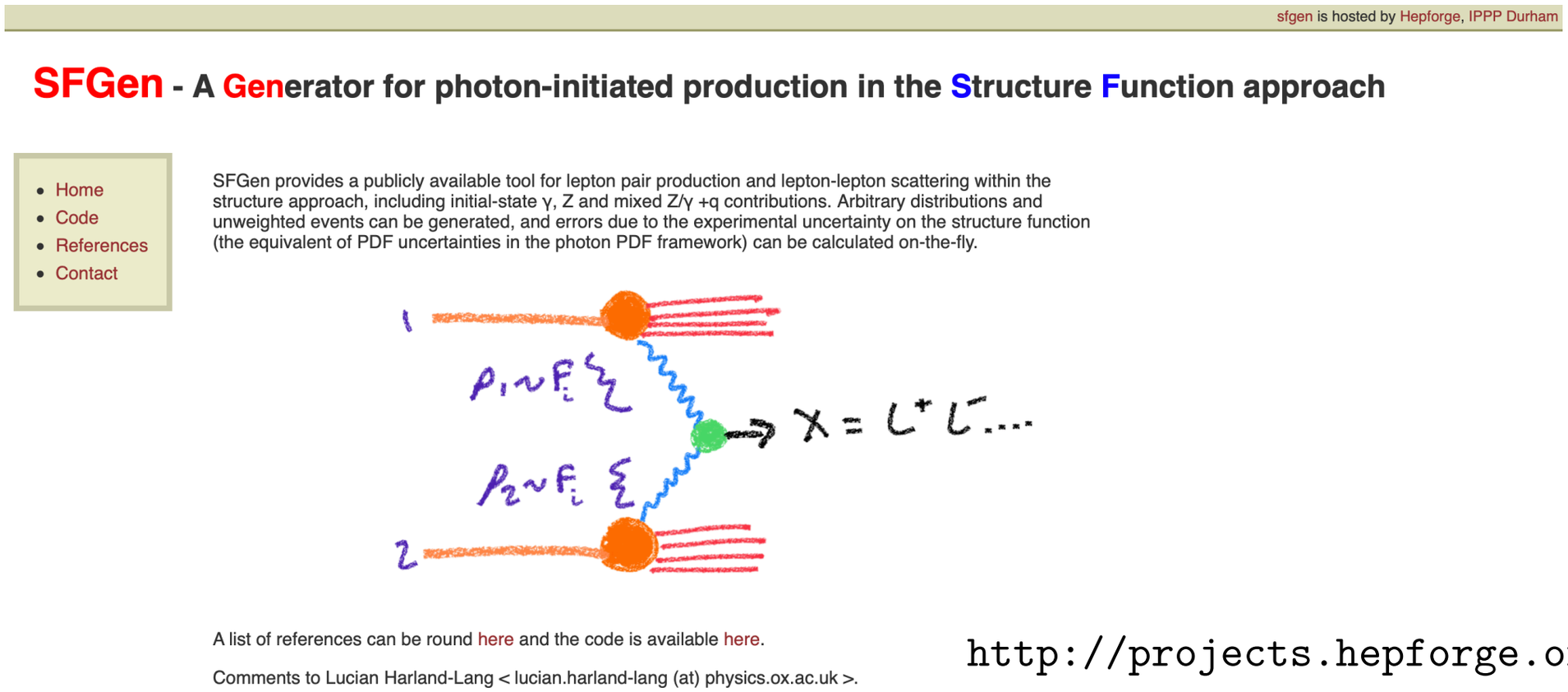
Abstract

We present a phenomenological study of photon–initiated (PI) lepton production at the LHC, as implemented in the structure function (SF) approach. We provide detailed predictions for multi–differential lepton pair production, and show that the impact on observables sensitive

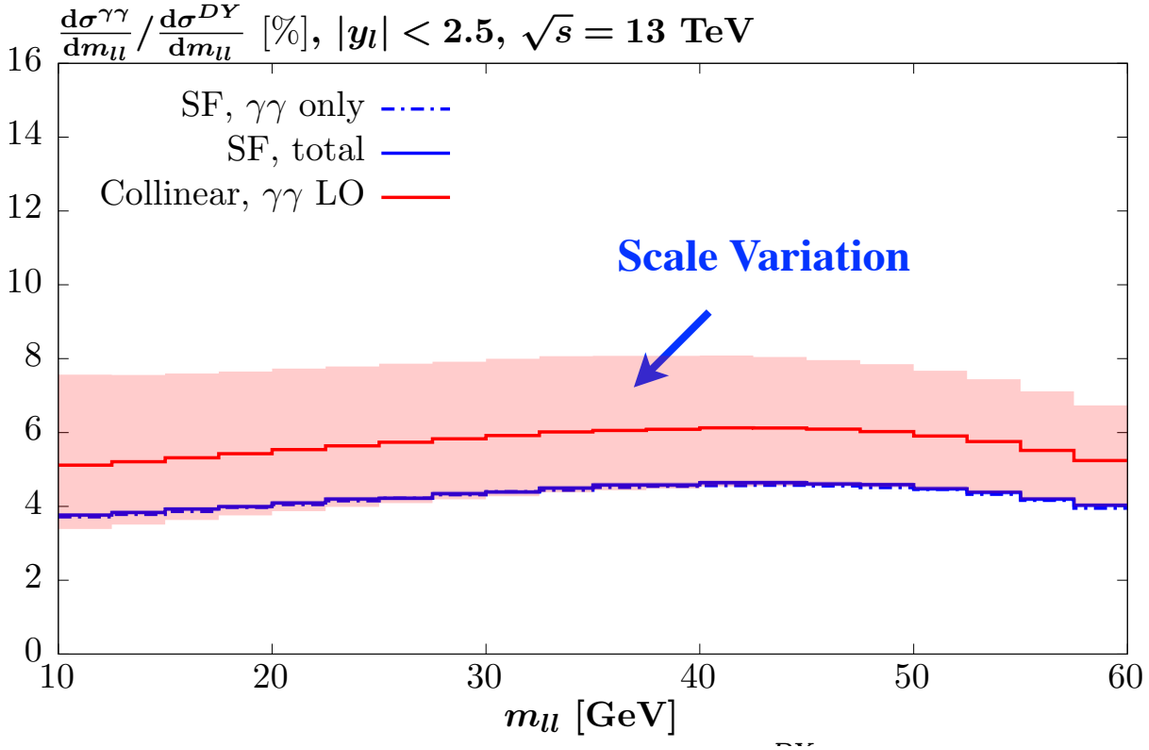
- New paper - **arXiv:2101.04127**.
- Updated results in SF framework + publicly available SFGen MC implementation
- Arbitrary distributions, unweighted events, interfaceable to Pythia, SF errors on-the-fly…Available on **Hepforge**.

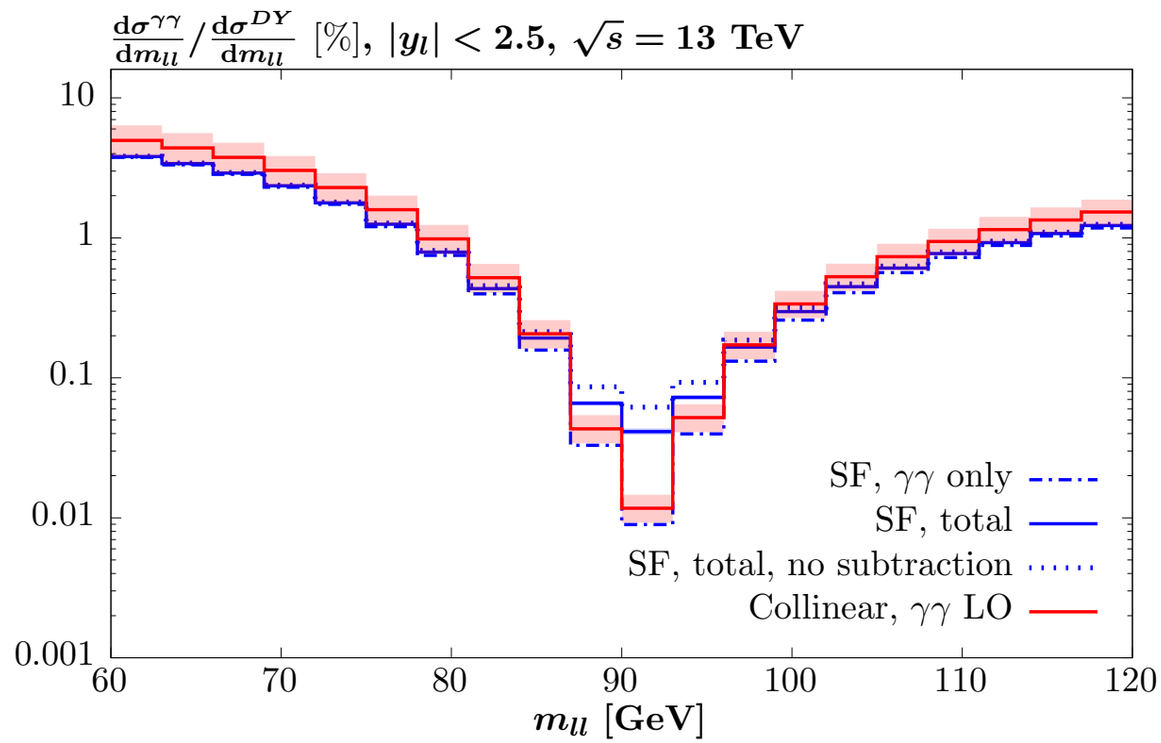


http://projects.hepforge.org/SFGen

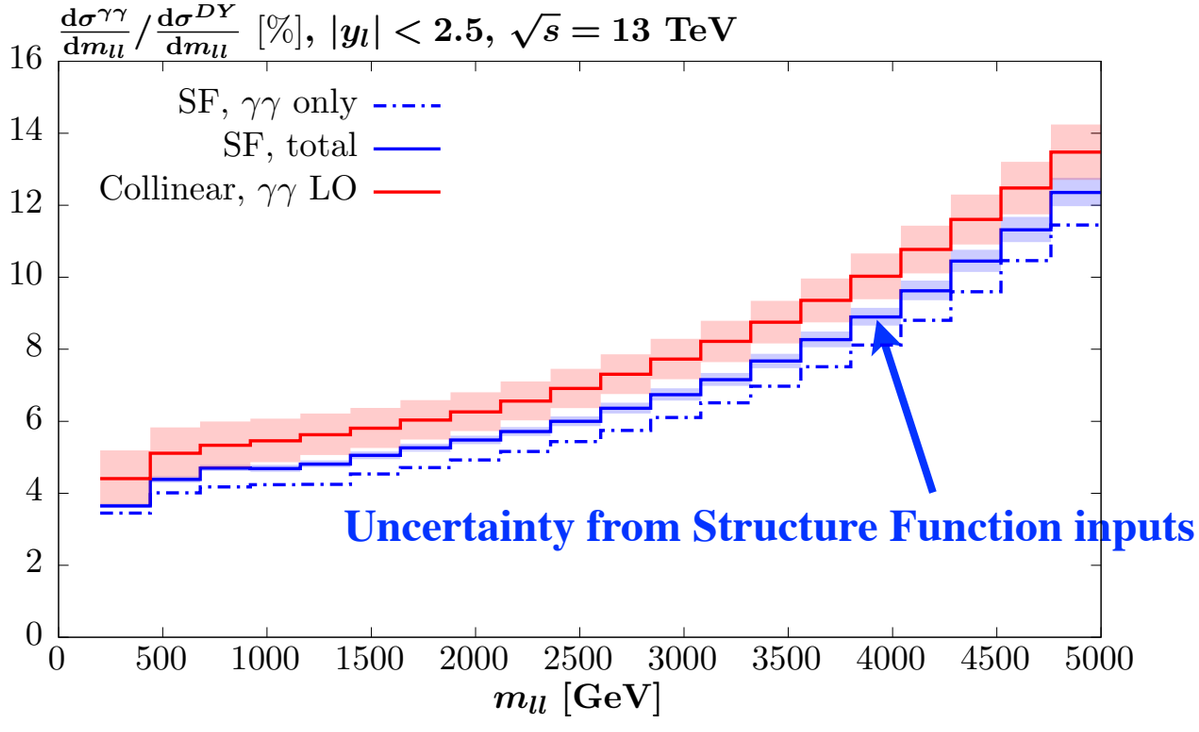
- Includes initial state Z bosons + mixed $\gamma/Z + q$ initial states (not discussed here). Some brief selected results follow…

DY: overview





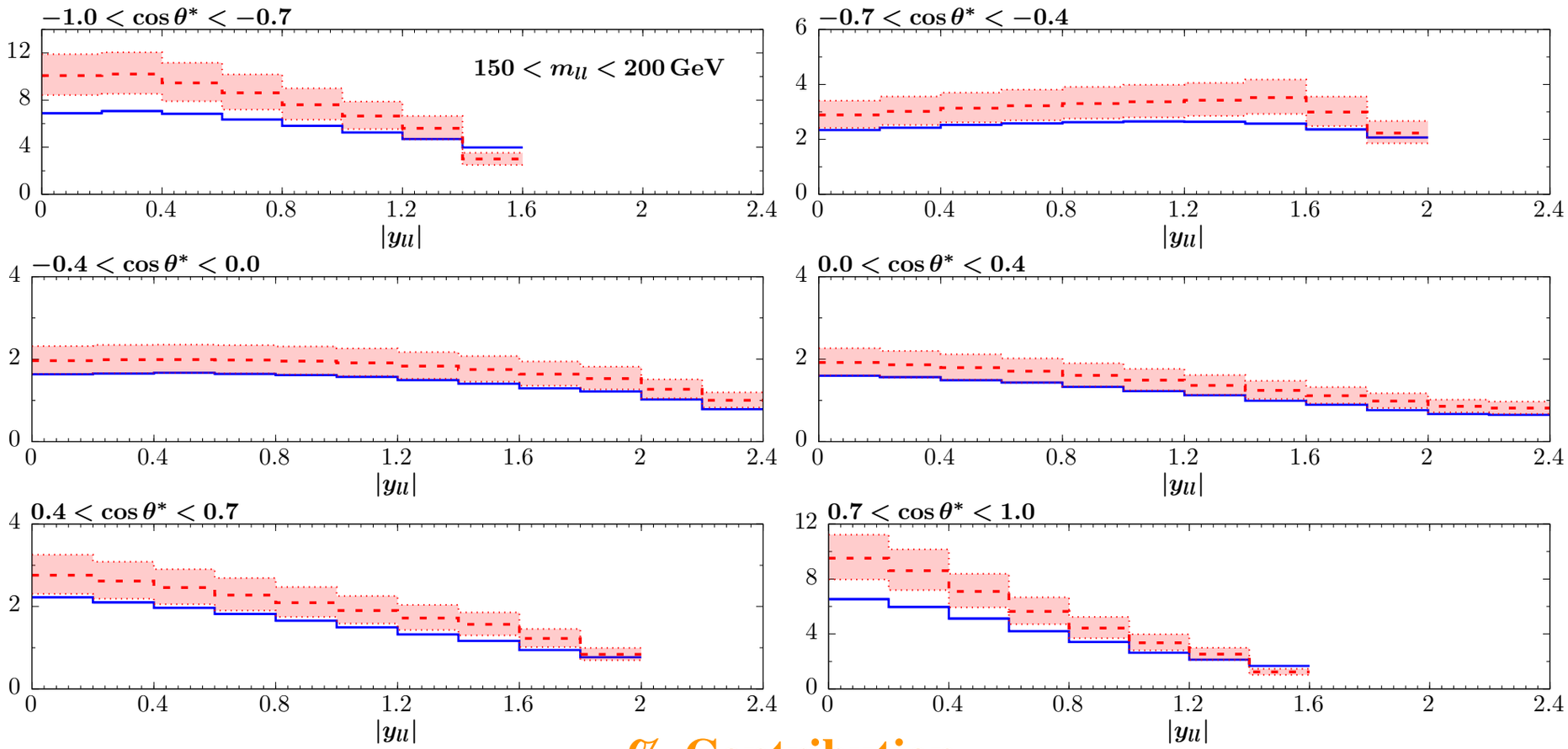
- Compare SF calculation of lepton pair production at LHC to LO collinear.
- **Large scale variation uncertainties** in LO clear, with significant deviations at higher mass.
- At least NLO in collinear case needed here, but get for free in SF.



DY: triple differential

- DY presented differentially in $(m_{ll}, y_{ll}, \cos\theta^*)$: sensitivity to PDFs and $\sin^2\theta_W$.
- Consider ratio of PI to NNLO QCD within **ATLAS 8 TeV** event selection:

e.g.



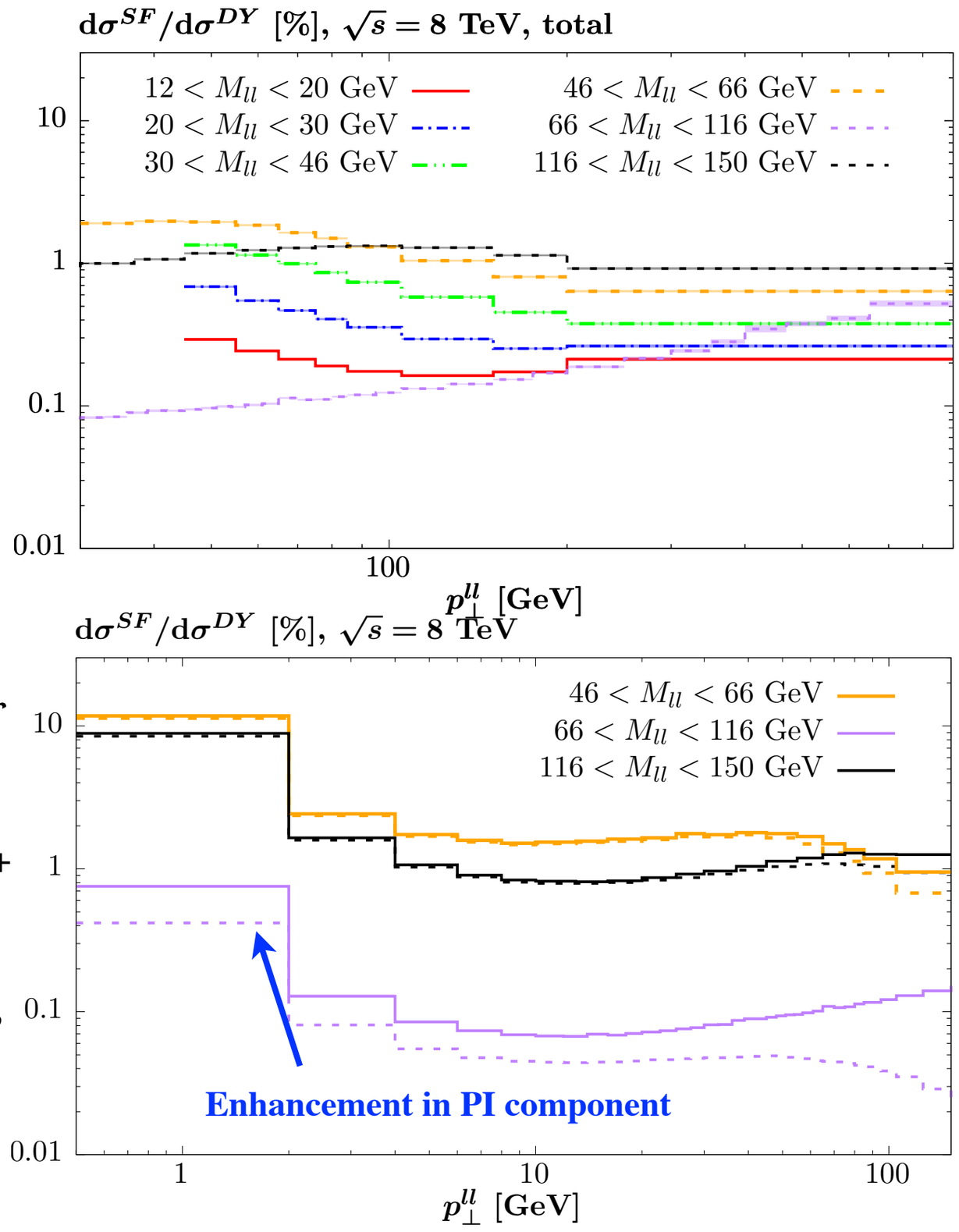
% Contribution

- **PI contribution ~ 1-6 %**. Sizeable uncertainties in LO collinear predictions.
- PI less relevant on Z peak, but recall CMS already using on + off peak to derive insitu PDF constraints and improve precision on $\sin^2\theta_W$ measurement.

$\longrightarrow$ Proper account of PI contribution crucial to EW precision.

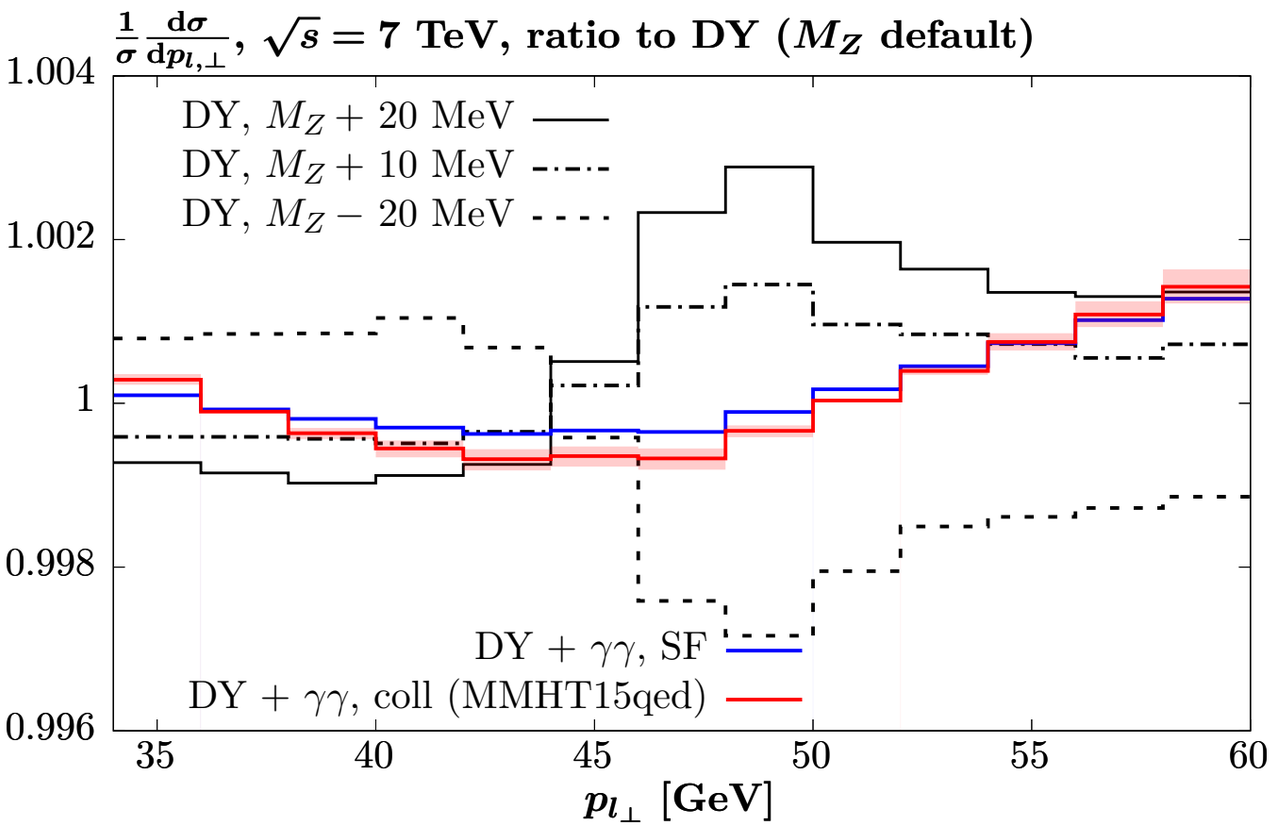
DY: $p_\perp^{ll}$ distribution

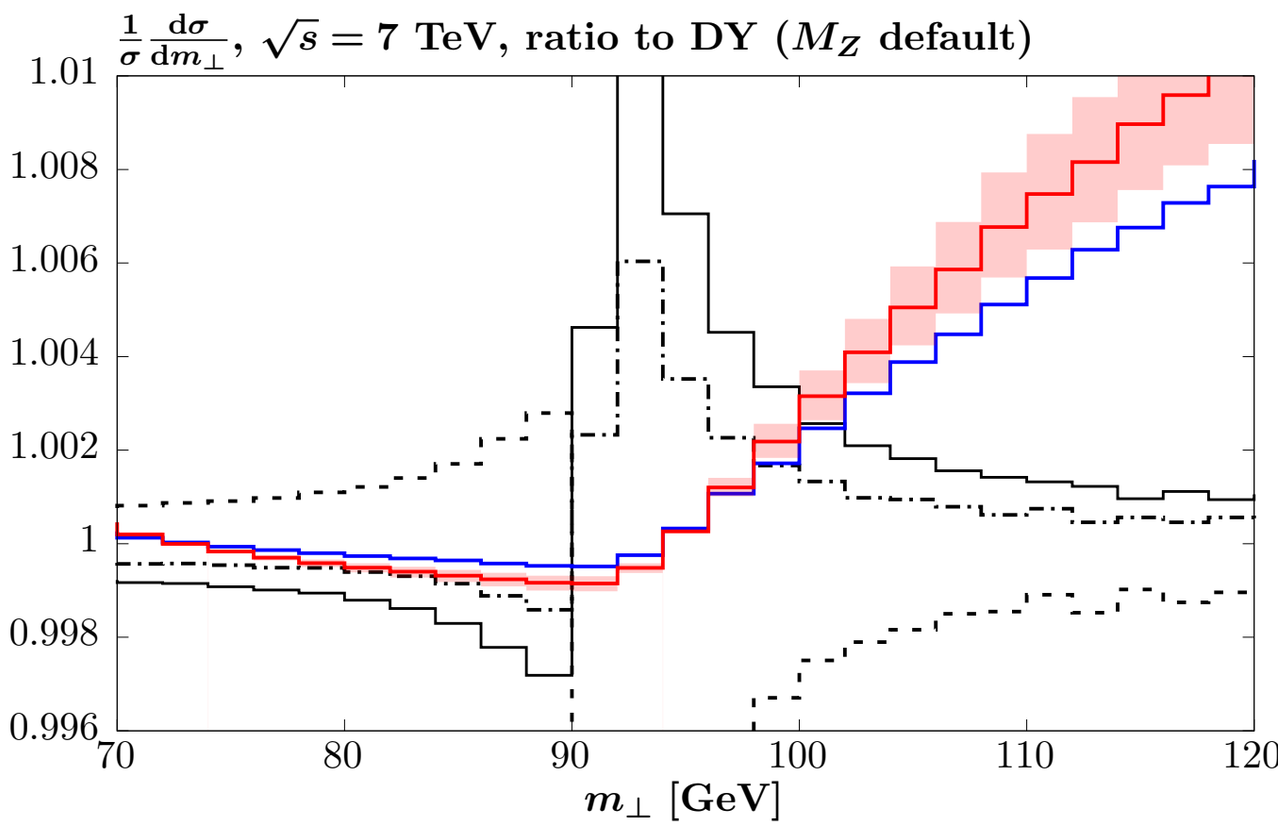
- Can also straightforwardly predict the PI component of the dilepton $p_\perp^{ll}$ distribution.
- In ATLAS 8 TeV selection enters at ~ 1% level. Relevant for e.g. **precision PDF determination.**



- In addition gives precision modelling of low $p_\perp^{ll}$ region. Can never be accounted for in pure collinear result.
- Large elastic $p \to p + \gamma$ component here + suppression in QCD DY.
- Possible relevance to M_W **determination**, via tuning performed to $p_\perp^{ll}$ data?

W mass determination





- Inclusion of PI contribution in lepton pair production comparable to (though smaller than) shift of Z mass by ~ 10 MeV.
- Difference between SF result and LO collinear small but not negligible. Only former can fully describe the correct shift (inclusion of elastic production differentially).
- The $p_\perp^{ll}$ measurement is tuned to to determine corresponding distribution in $l\nu$.

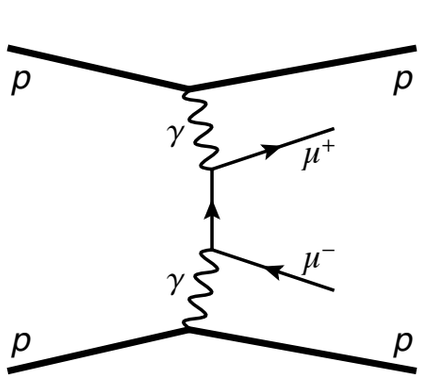
PI in exclusive mode: basic idea

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

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

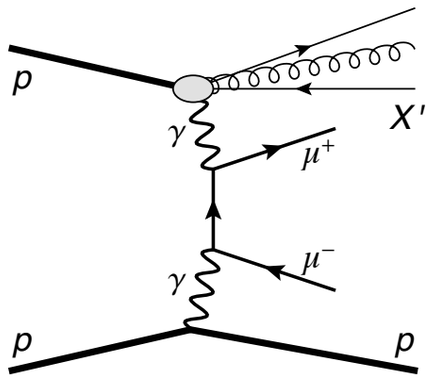
  ⋆ Can isolate elastic component of $F_{1,2}$ to give exclusive prediction.

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



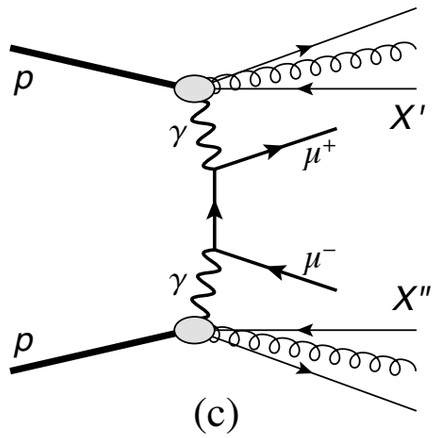
(a)

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



(b)

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



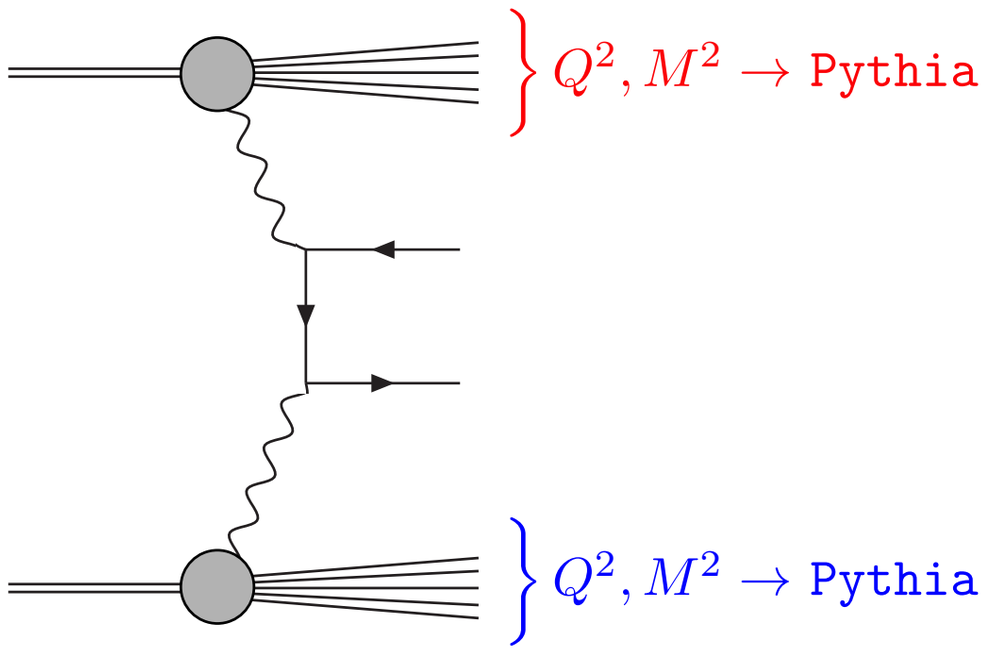
(c)

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

$\} Q^2, M^2$

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

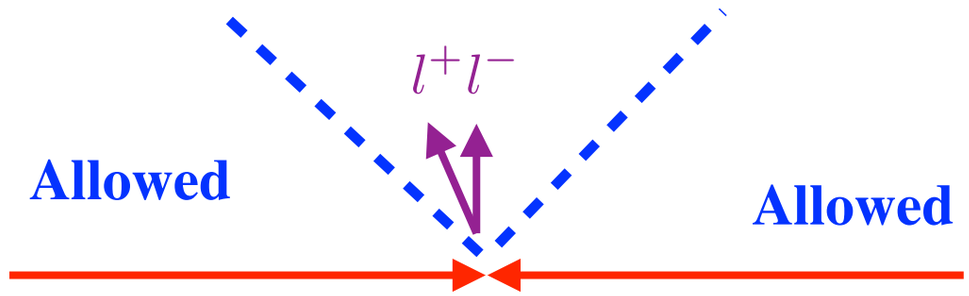
Backup



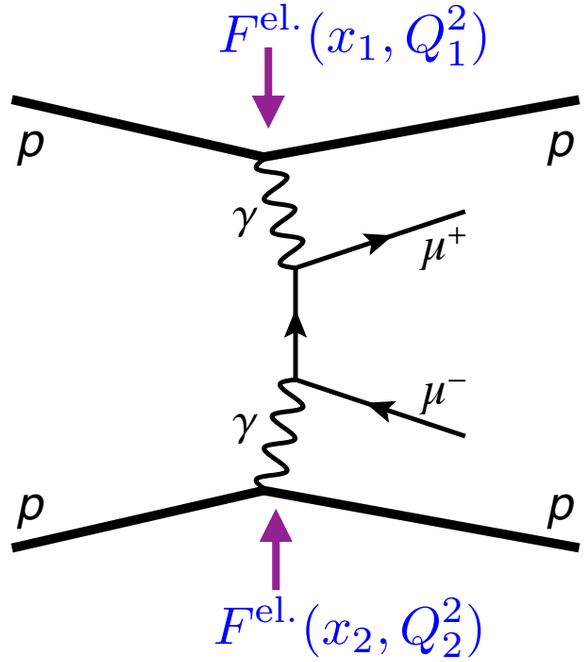
- This gives us full particle-level treatment of exclusive/semi-exclusive events:

★ Can impose e.g. rapidity gap veto…

★ …and/or proton tag!



The Survival Factor

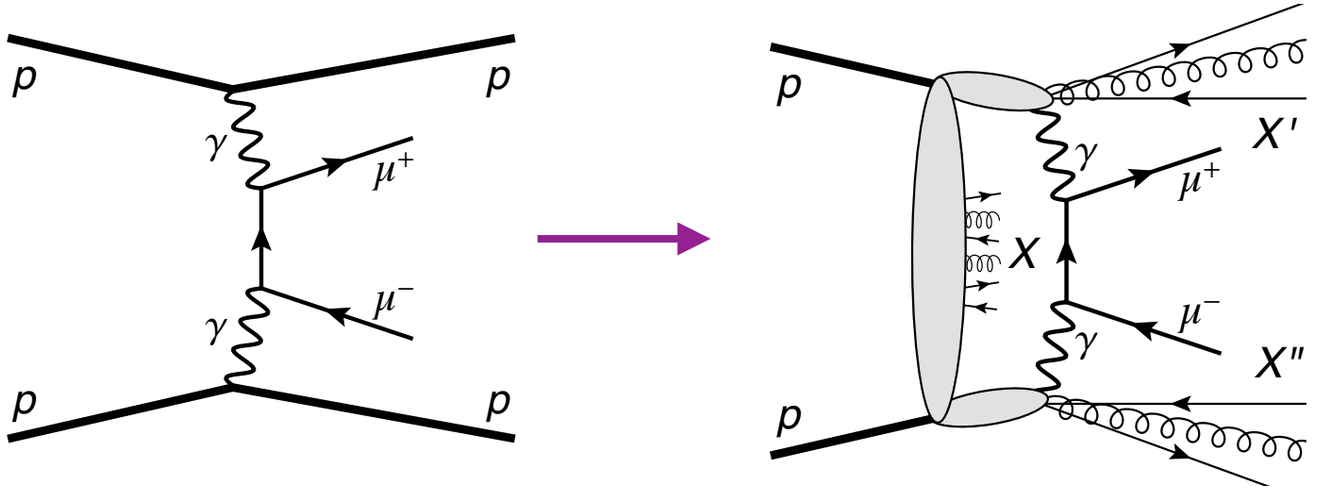


- Consider e.g. the exclusive process. So far we have (very) schematically:

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

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

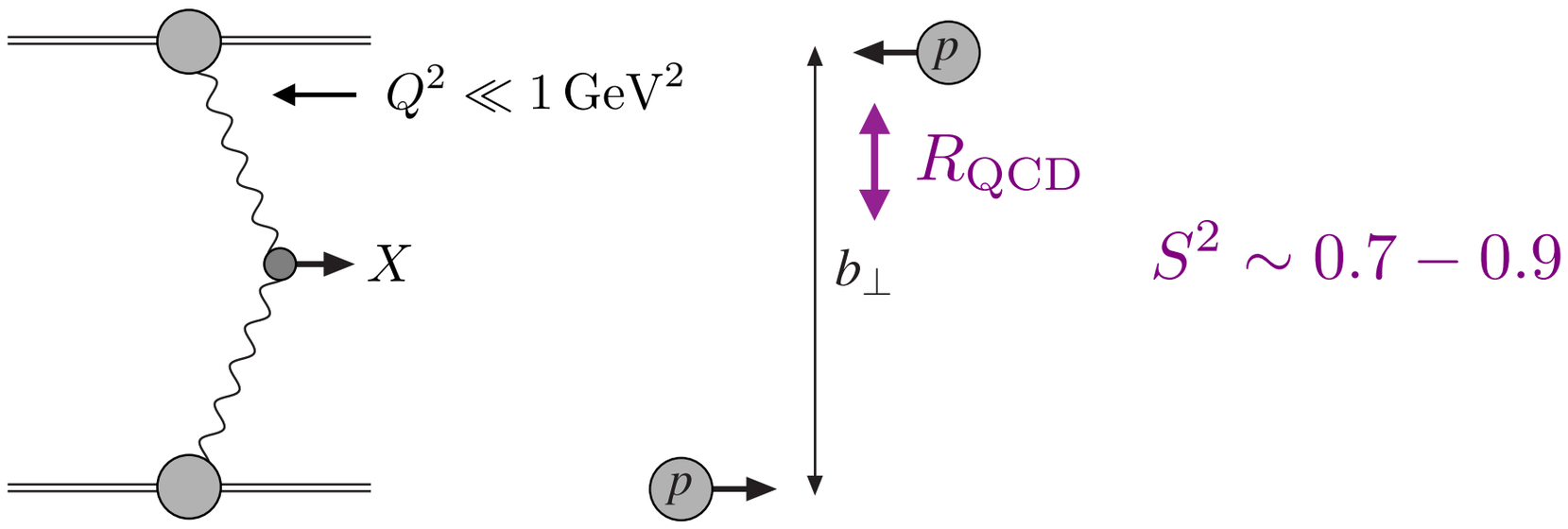
- But we are interested in **hadron-hadron** scattering: need to account for additional hadron-hadron interactions.



- Need to include **Survival Factor**: probability of no additional inelastic hadron-hadron interactions (= no MPI probability).

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.

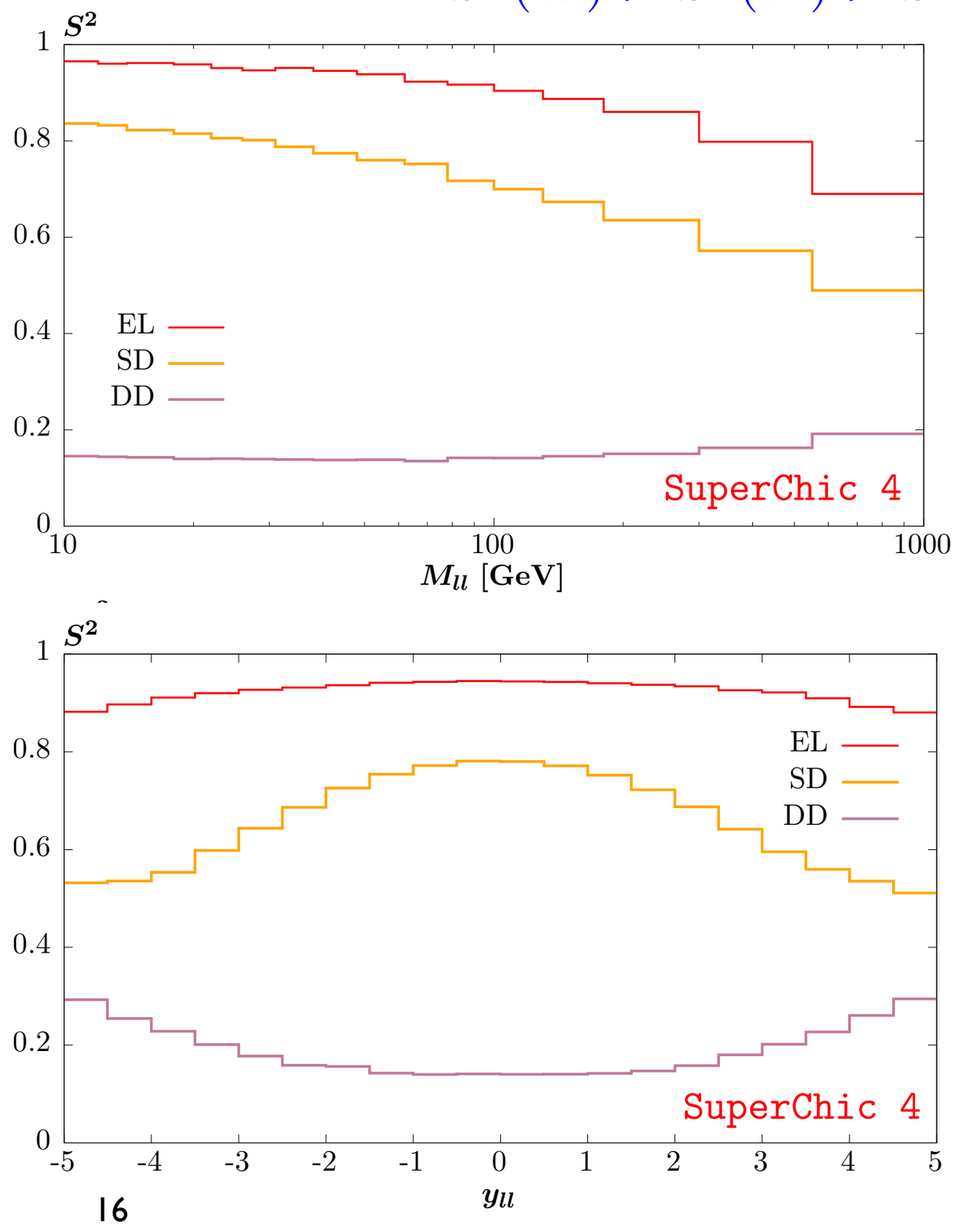
$S^2(\text{el.}) > S^2(\text{sd}) > S^2(\text{dd})$

- All accounted for in SuperChic 4.

Results

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

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

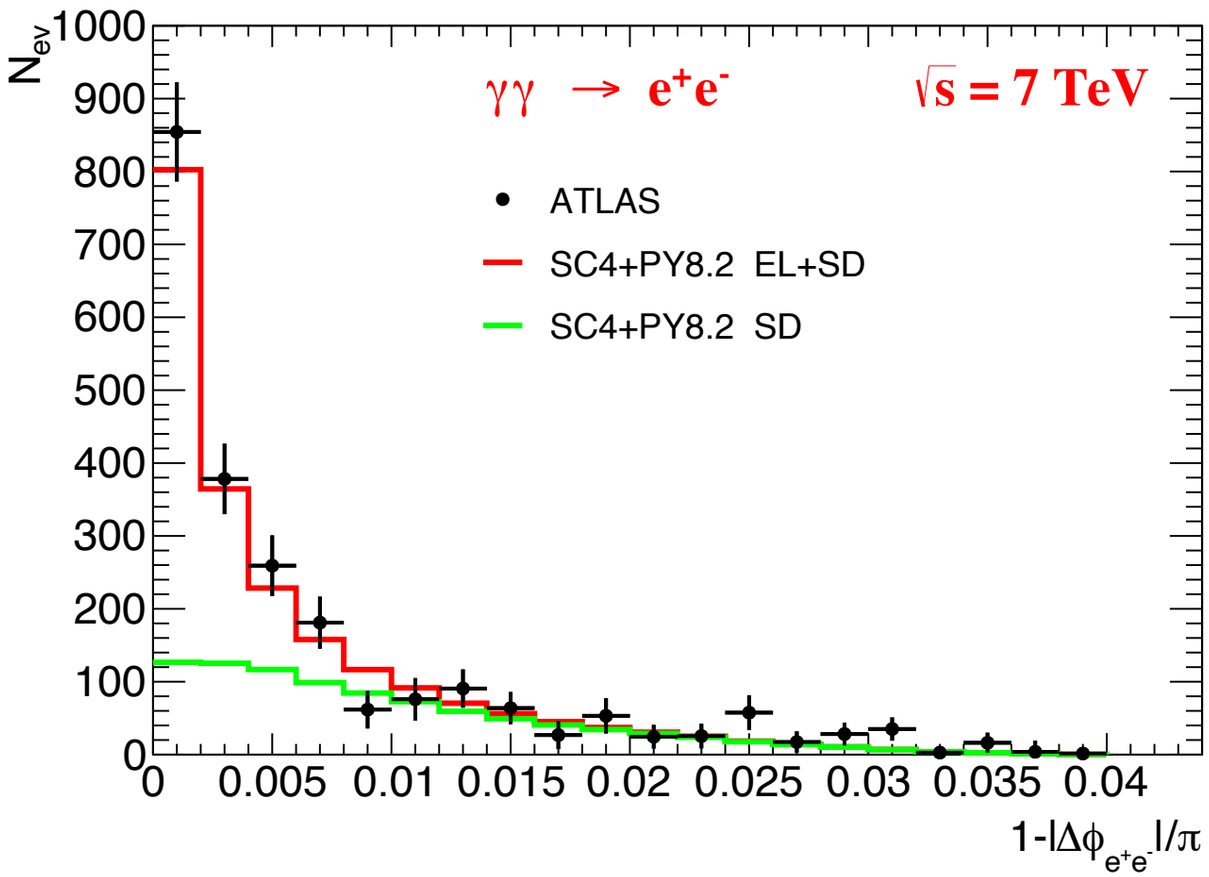


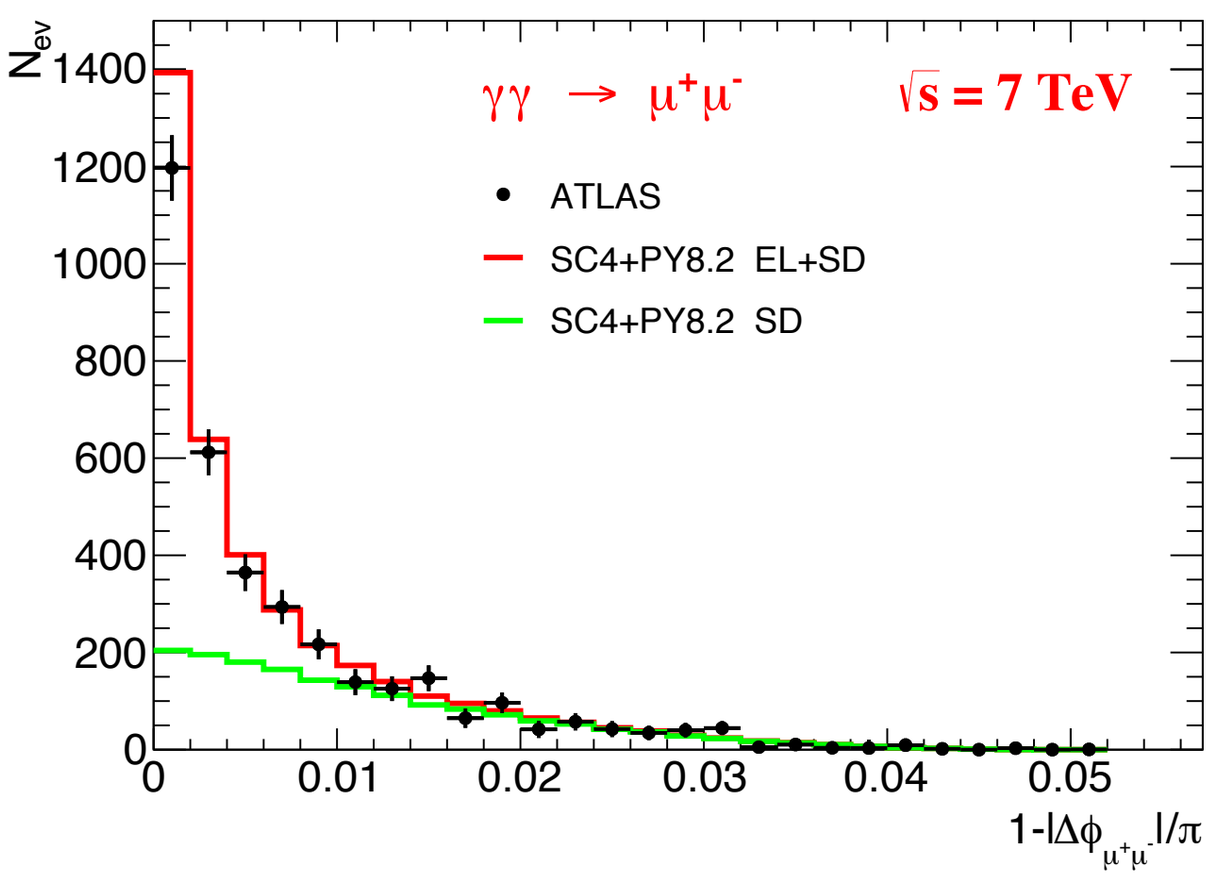
- Dependence on kinematics (e.g. y_{ll}, m_{ll}) also evident.

Comparison to Data

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 $\mu^+\mu^-$ and in more recent data: under investigation!





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.

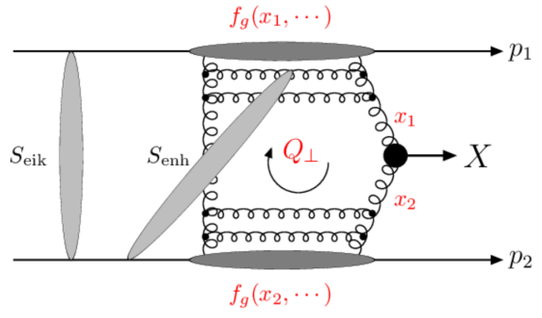
- Full treatment of proton dissociation for photon-initiated production in pp collisions currently available for lepton pair production.

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

Summary/Outlook

★ Photon-initiated production of great phenomenological interest/ relevance in both inclusive and exclusive channels.

★ Structure Function calculation can provide the most precise calculation for inclusive $\gamma\gamma \to l^+l^-, W^+W^- \cdots$ production (**SFGen 1.00**). Also true for lepton-initiated production (not covered here).

★ Caveat: true for $\gamma\gamma \to l^+l^-$, but in e.g. mixed γq channels less clear. Photon PDF indispensable for e.g. QED DGLAP $\Rightarrow$ **complementary**.

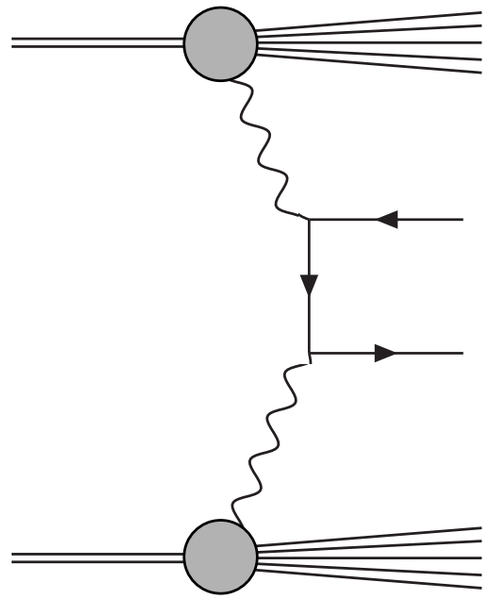
★ Also provides solid (only possible) foundation for exclusive/semi-exclusive photon-initiated production (**SuperChic 4**). Tool with which to explore the rich field of exclusive photon-initiated production.

★ Much work to do - understanding comparison to data, including more processes (WW underway). Applications to BSM (e.g. ALPs). Not to forget Pb-Pb as well!

Thank you for listening!

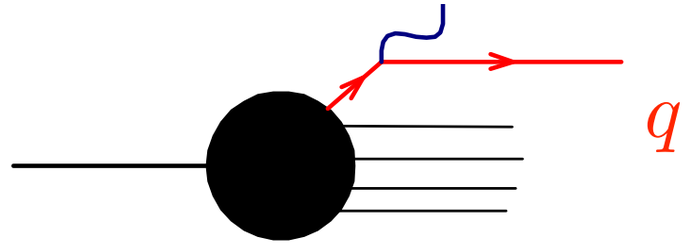
Backup

PI + ISR Showering



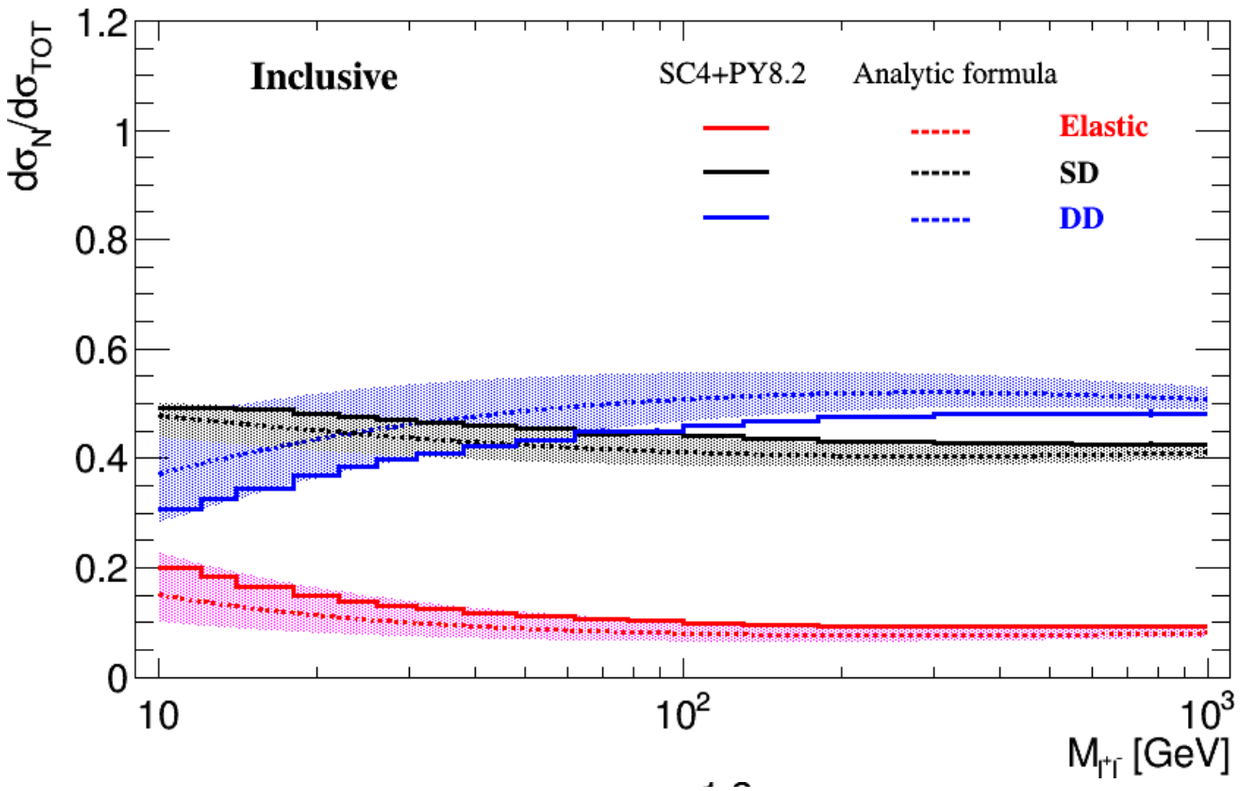
- SF calculation give precision prediction for photon x, Q^2 and we would like showering/hadronisation of dissociation system to respect this.

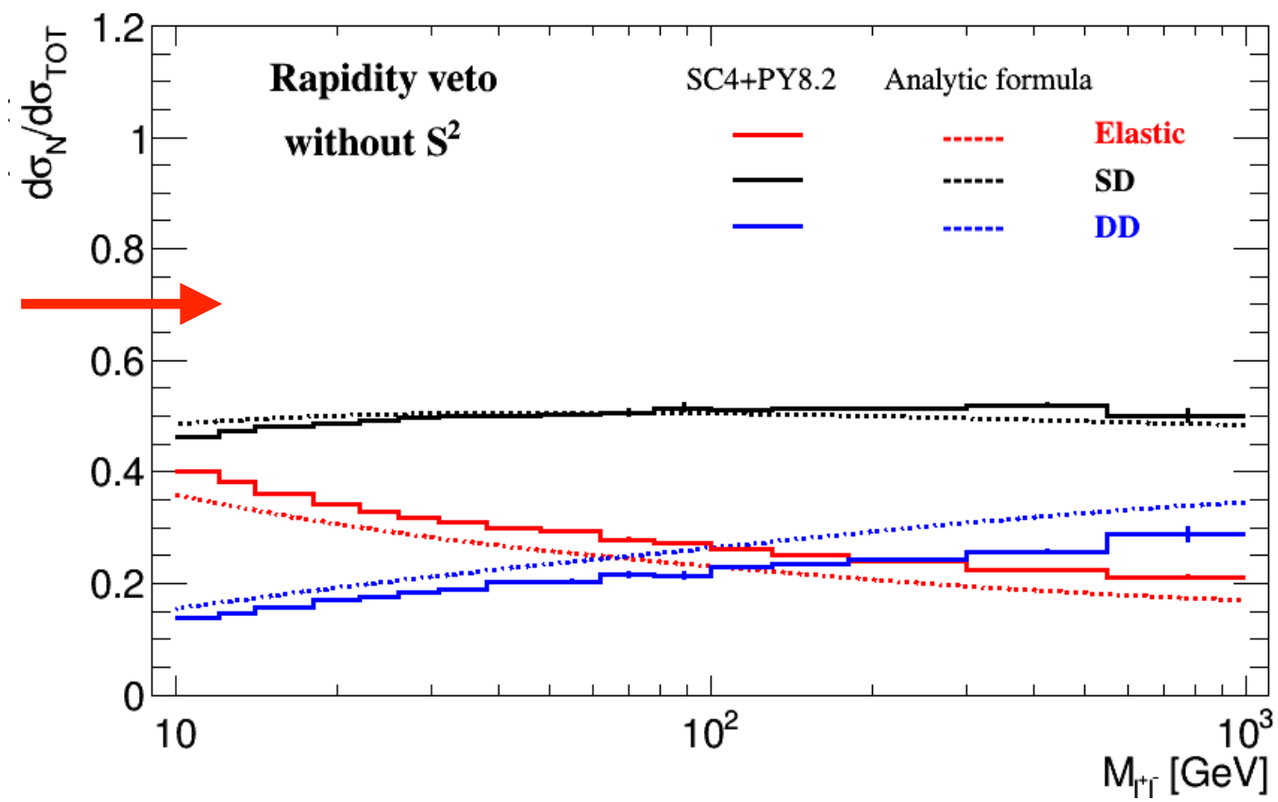
- No clear off-the-shelf way to do this, so take simplified approach:
  - ★ For purposes of LHE record, for inelastic emission take LO $q \to q\gamma$ vertex
  - ★ Generate outgoing quark according to momentum conservation, preserving photon 4-momentum.



- 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).

Gap veto - impact



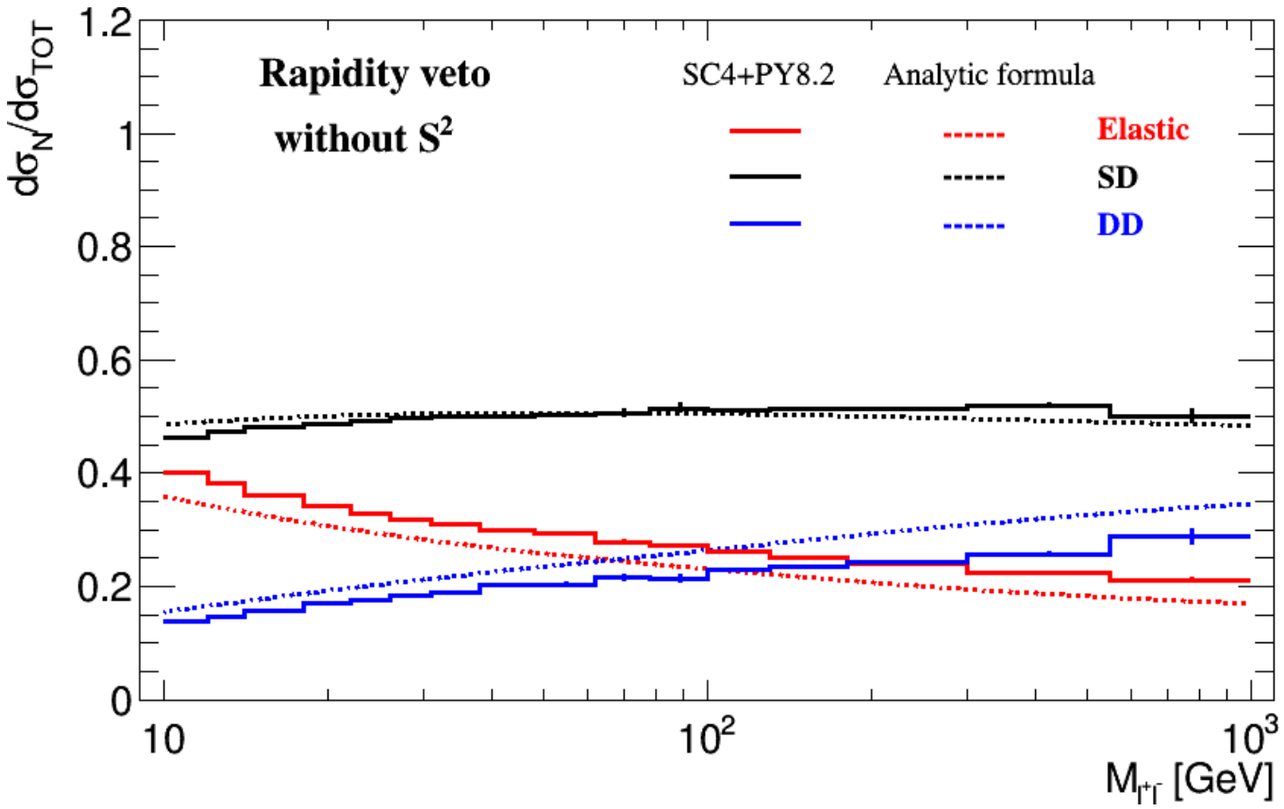


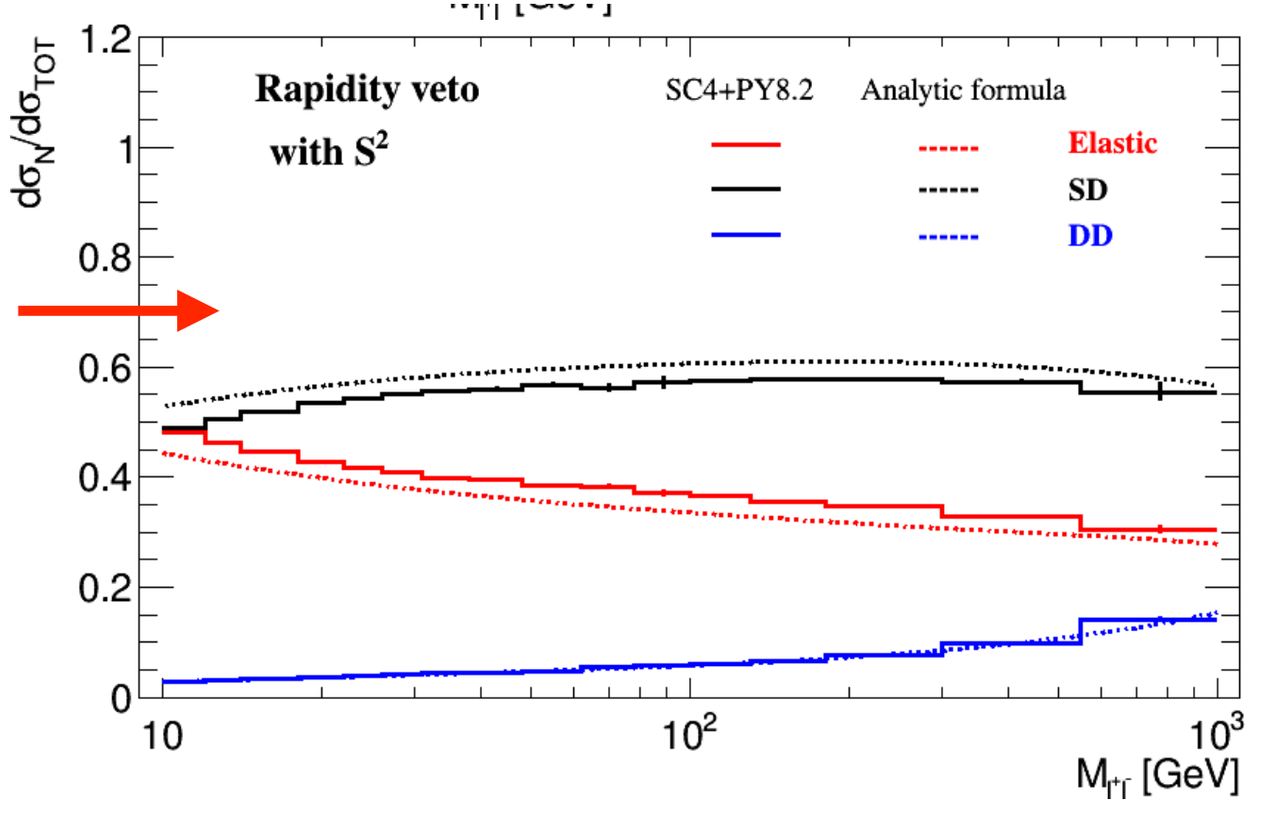
- Consider veto in 13 TeV muon pair production. Compare with analytic approach of arXiv:1601.03772. Take $|\eta| < 4.4$ for comparison with this, but trends similar for realistic veto regions.

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

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

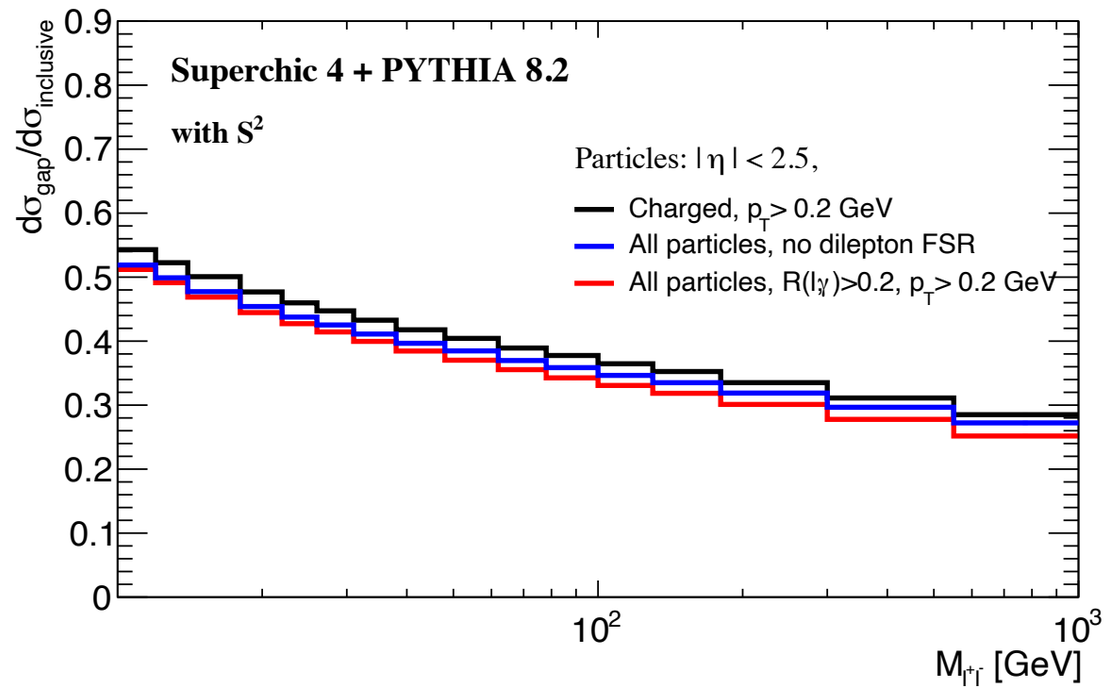
*nb. scale variations only shown for inclusive case





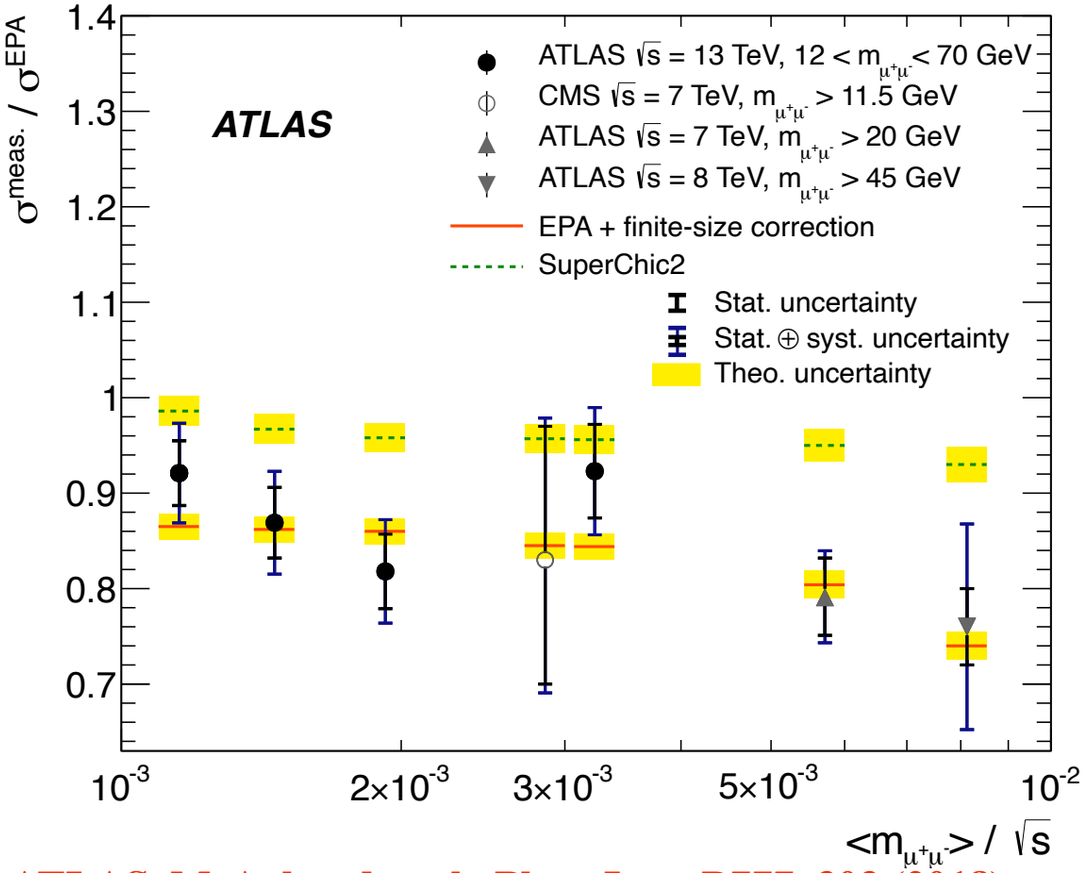
★ **Veto** + S^2 : strong suppression in DD. Elastic and SD comparable at lower m_{ll}, SD dominant as m_{ll} increases.

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



- 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 $F^{\text{el.}}$ at ~ 1% level.
- 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.

$b_\perp \gg R_{\text{QCD}}$

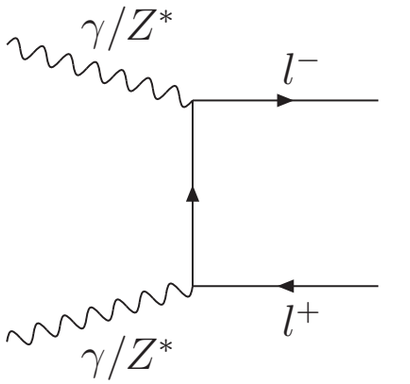


ATLAS, M. Aaboud et al., Phys. Lett. B777, 303 (2018)

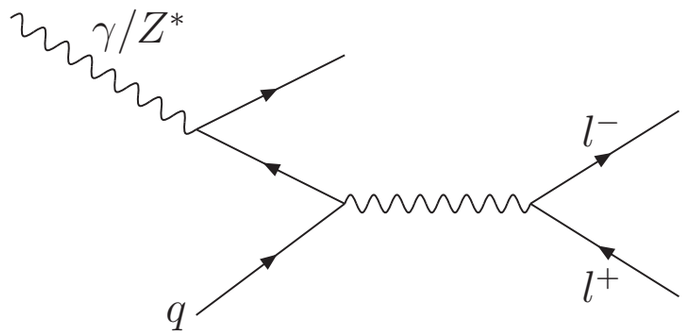
	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
SUPERCHIC 4 [97]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

ATLAS, Phys. Rev. Lett. 125 (2020) 261801

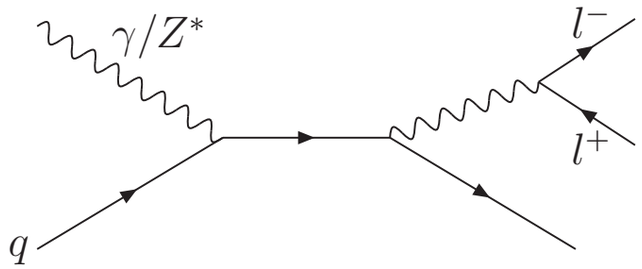
Mixed Contributions



(a)



(b)



(c)