A Complete Picture of Photon-Initiated Production at the LHC

Lucian Harland-Lang, University of Oxford

MPI 2019, Prague, 19th November 2019

LHL, arXiv:1910.10178

LHL, V.A. Khoze, M.G. Ryskin, M. Tasevsky, in preparation.

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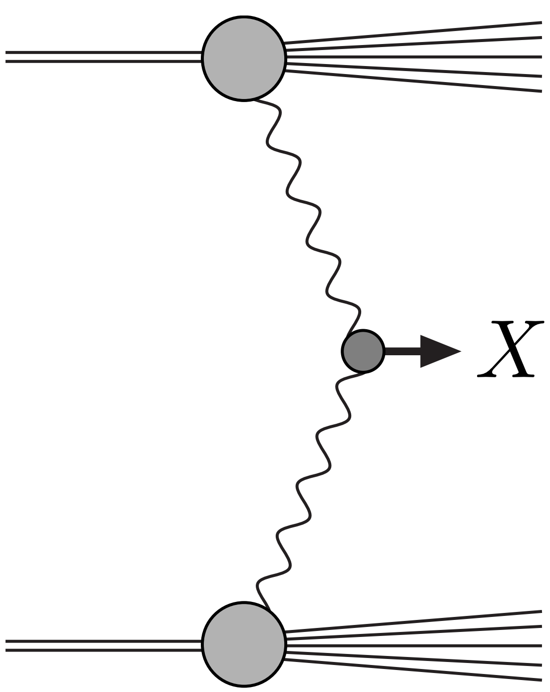
PI Production: Relevance @ LHC

- In high precision LHC era, 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.



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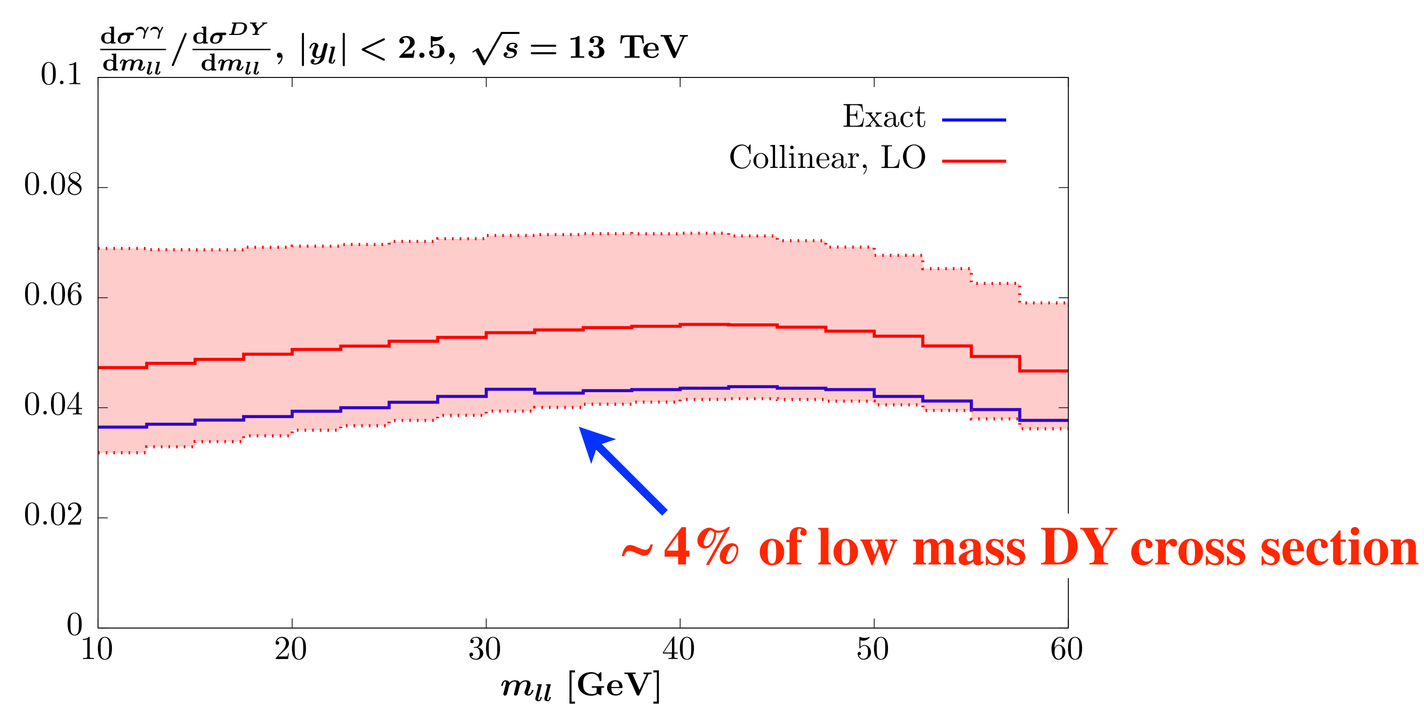
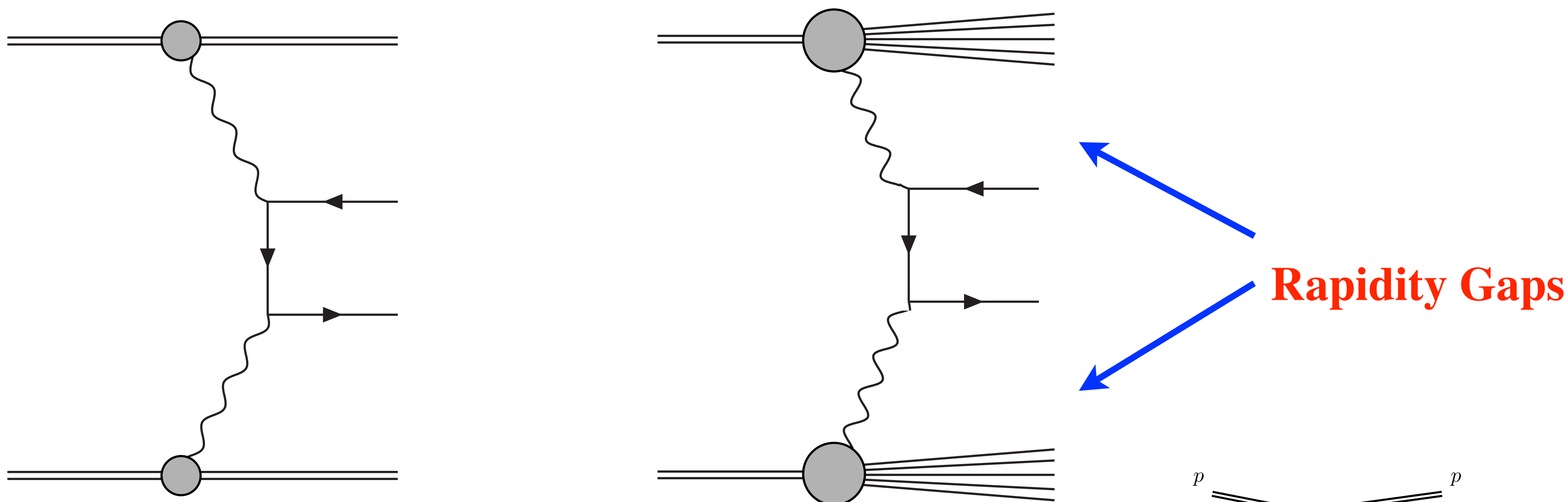
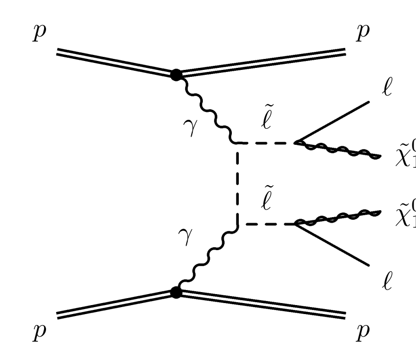


PI Production: Relevance @ LHC

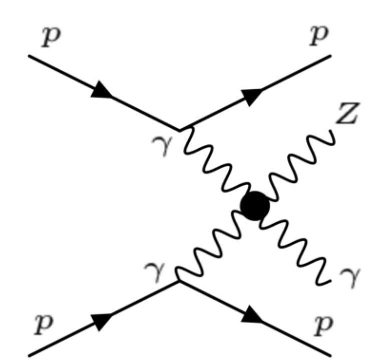
- **Exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state.





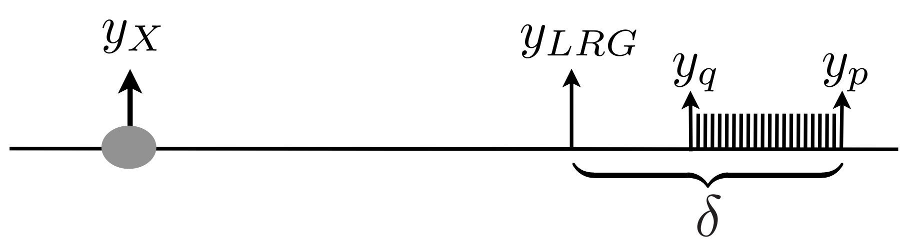
- Clean, ~ pure **QED** process at LHC:
  - ★ Probe of BSM (anomalous couplings, ALPs, SUSY…).

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…

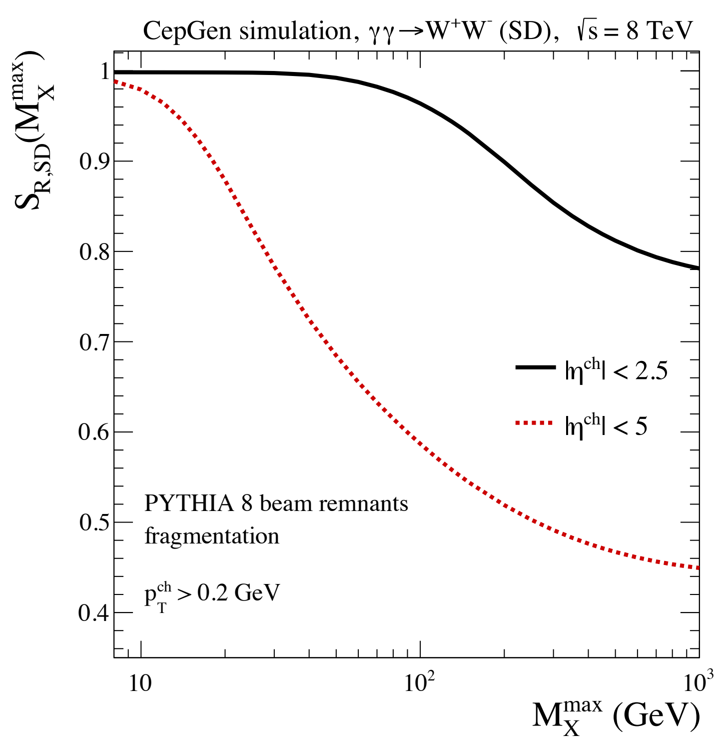


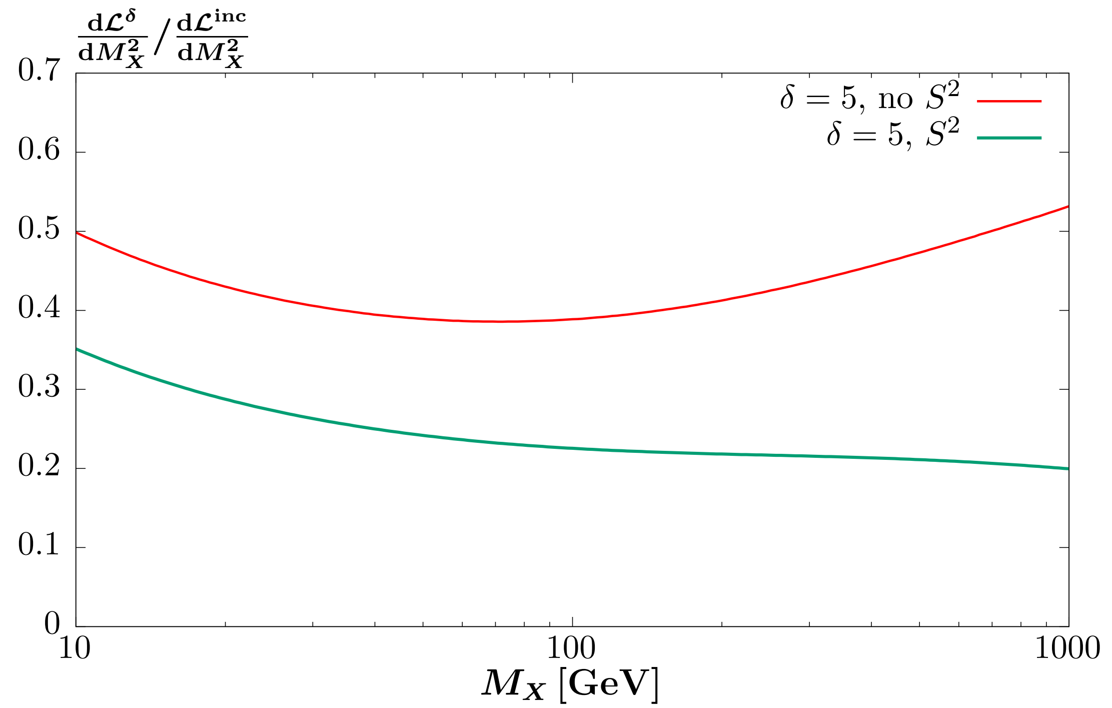
PI Production: Relevance @ LHC

- Clean, ~ pure QED process at LHC:
  - ★ **Laboratory** to test our models of proton dissociation + proton-proton rescattering effects.



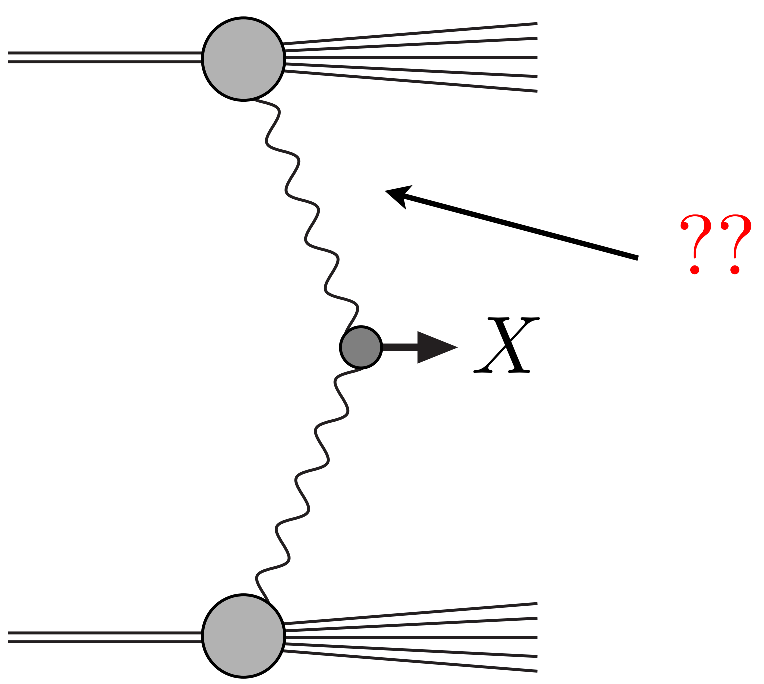
LHL et al., EPJC 76 (2016) no. 5, 255, L. Forthomme et al., PLB 789 (2019) 300-307





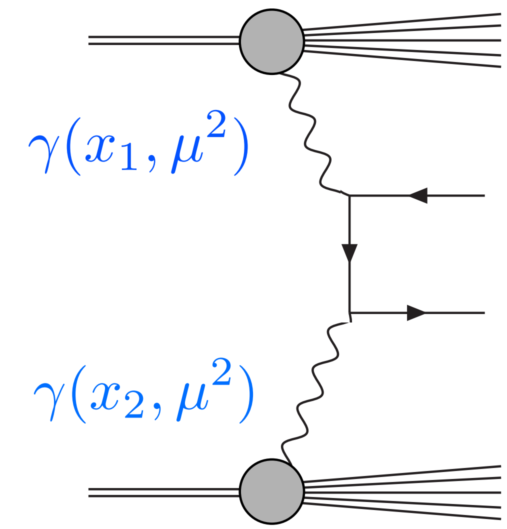
PI processes with Dissociation

- Focus of today's talk: work towards a unified treatment of PI production, relevant to both:
  - ⋆ **Inclusive** production ($\Rightarrow$ high precision predictions).
  - ⋆ **Exclusive/semi-exclusive** production, including rapidity gap survival.
- The latter case in particular requires a full **MC** treatment.
- Will first consider inclusive case, before moving on to exclusive.
- **Basic question**: how well do we understand PI production at the LHC?



PI Production and the Photon PDF

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



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

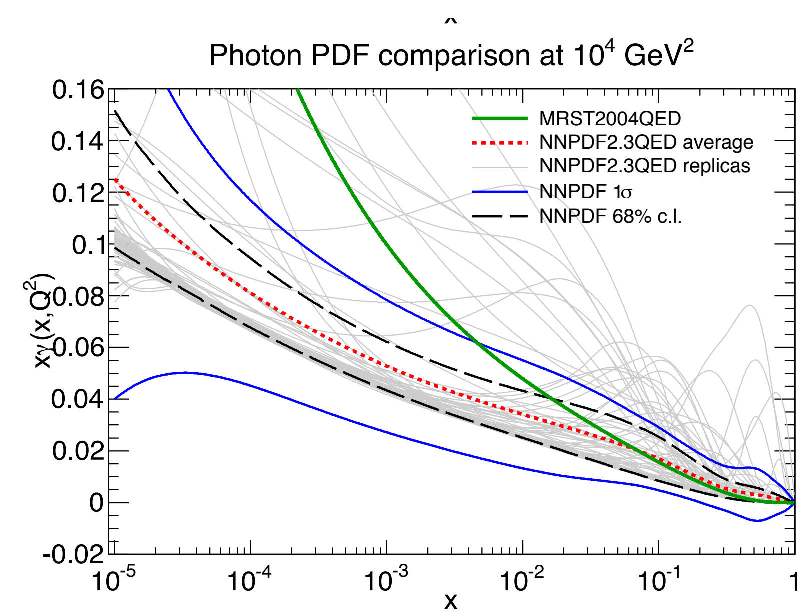
- Historically this was given in terms of:

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

  - 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)…

  - Completely **agnostic** fit: huge PDF uncertainties.



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

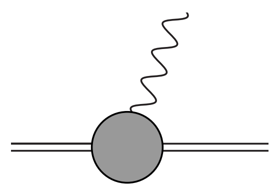
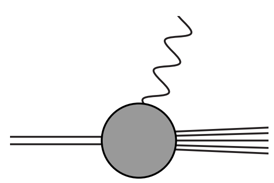
- A more precise evaluation of photon PDF given by well known **equivalent photon approximation** (EPA).
    - Cross section given in terms of:

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

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

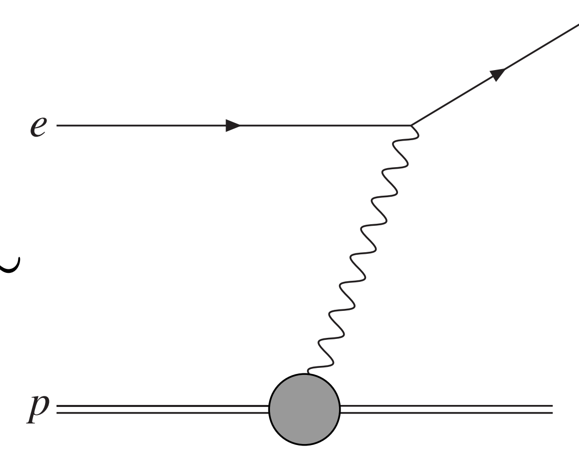
$$dn_i = \frac{\alpha}{\pi} \frac{d\omega_i}{\omega_i} \frac{d(-q_i^2)}{|q_i^2|} \left[\left| \frac{q_{i\perp}^2}{q_i^2} \right| D_i + \frac{\omega_i^2}{2E^2} C_i \right].$$

Table 8

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

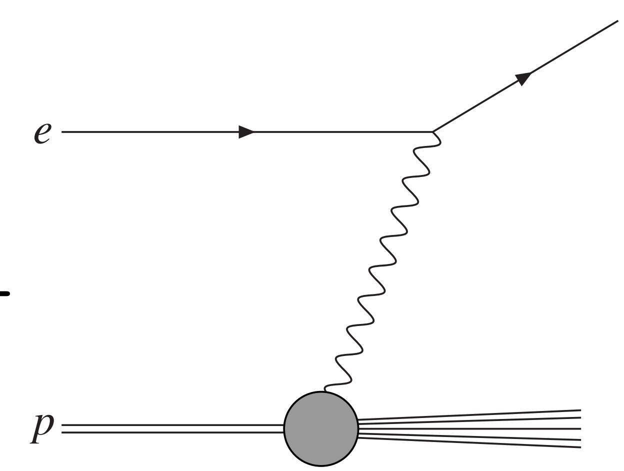
- Photon flux given in terms of proton EM form factors and inelastic **structure functions**.

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



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

$+$



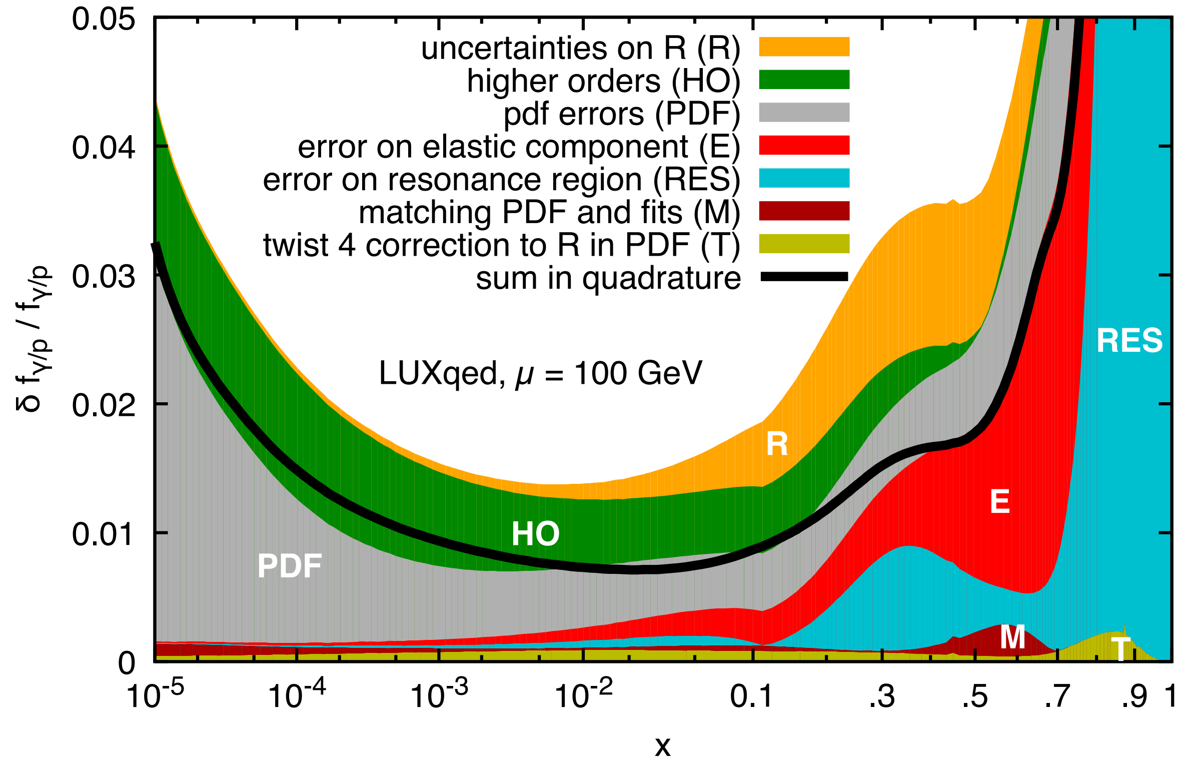
$F_{1,2}^{\rm inel}$

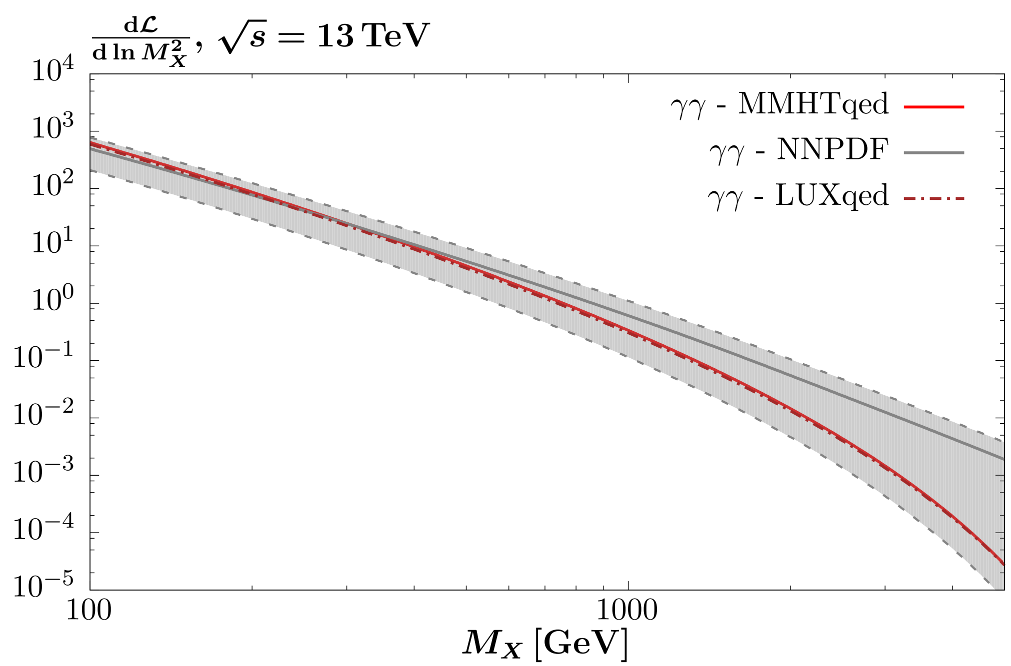
LUXqed

- 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

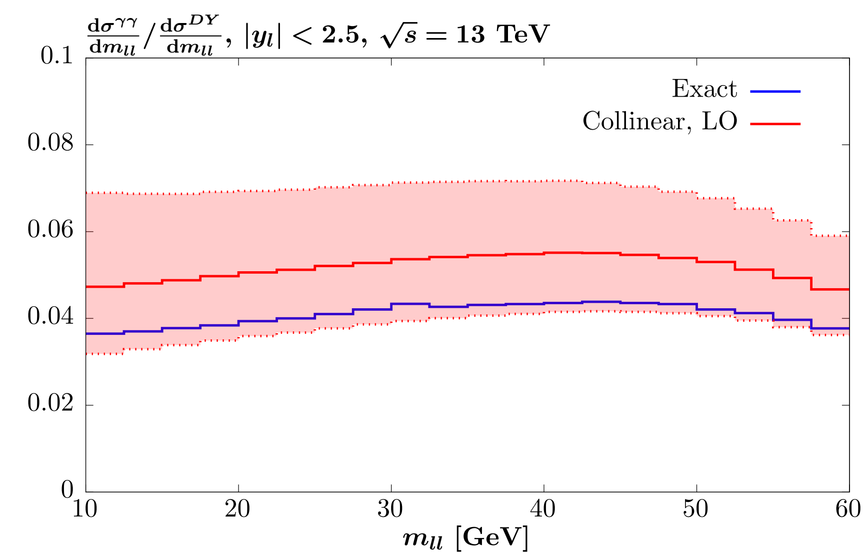




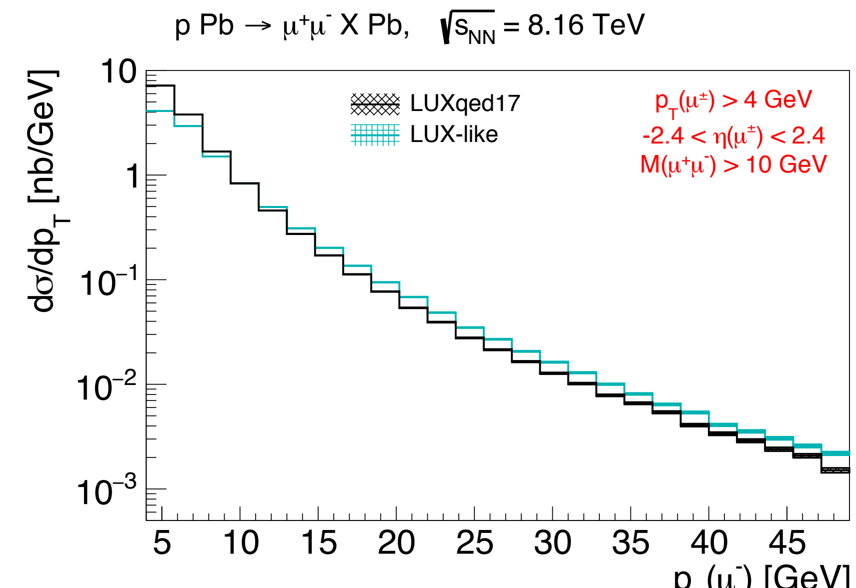
LHL eta al., Phys. Rev. D94 (2016) no.7, 074008

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

- Though in principle precise, there are **issues** with collinear approach:

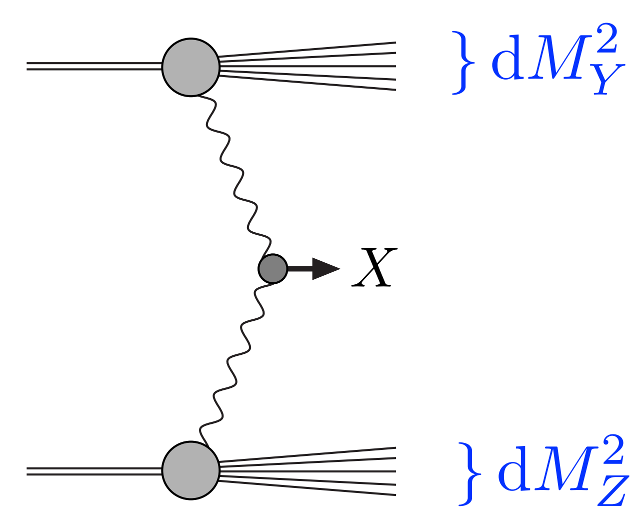


★ LO (in α) $\sigma^{\gamma\gamma}$ have v. large μ_F **uncertainty**.



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

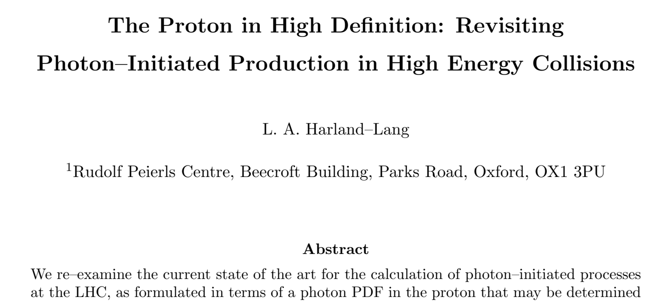
★ Sizeable **discrepancies** seen between $k_\perp$-factorization approach ($k_\perp$dependent photon PDF) and collinear.



★ If we want fully differential treatment of dissociation system need to go **beyond** LO **collinear** factorization.

A High Definition Picture

- **Solution** to all of these issues recently presented.
- Basic idea: apply '**structure function**' approach, well known from VBF Higgs.


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

LHL, arXiv:1910.10178

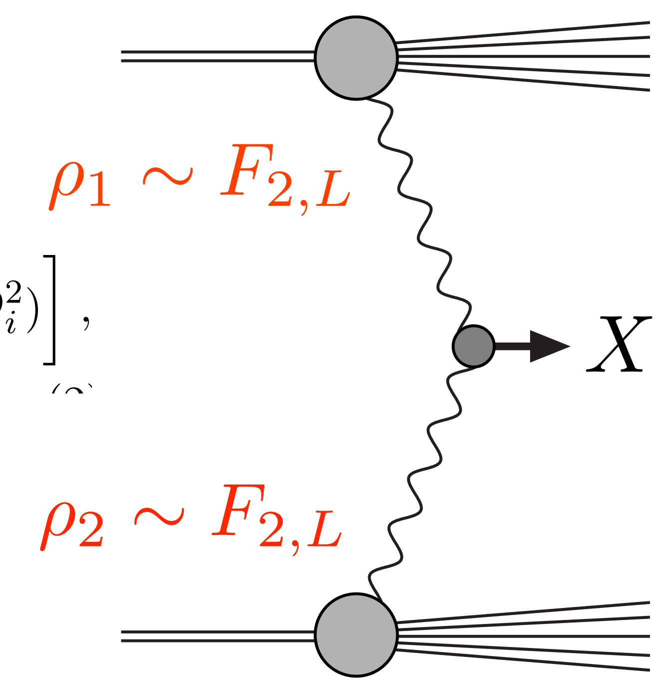
- PI cross section given directly in terms of proton structure functions:

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

via photon density matrix:

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

- With **no reference** to photon PDF at all*!



***True up to small (~0.5%) non-factorizeable corrections as in VBF Higgs. See arXiv:1910.10178 for further discussion.**

Relationship to Photon PDF

- Photon PDF enters by making **approximation** to full result:

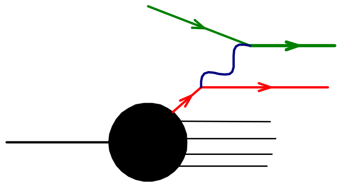
$$\dagger \quad \sigma_{pp} = \frac{1}{2s}\int \mathrm{d}x_1\mathrm{d}x_2\,\mathrm{d}^2q_{1_\perp}\mathrm{d}^2q_{2_\perp}\mathrm{d}\Gamma\,\alpha(Q_1^2)\alpha(Q_2^2)\frac{\rho_1^{\mu\mu'}\rho_2^{\nu\nu'}M^*_{\mu'\nu'}M_{\mu\nu}}{q_1^2q_2^2}\delta^{(4)}(q_1+q_2-p_X)\;,$$

- In $Q^2_{1,2} \ll M^2_{\gamma\gamma}$ (i.e. EPA) limit we find:

$$\ast \qquad \sigma_{pp} \approx \int \mathrm{d}x_1\mathrm{d}x_2\, f^{\rm PF}_{\gamma/p}(x_1,\mu^2)f^{\rm PF}_{\gamma/p}(x_2,\mu^2)\hat{\sigma}(\gamma\gamma\to X)\;,$$

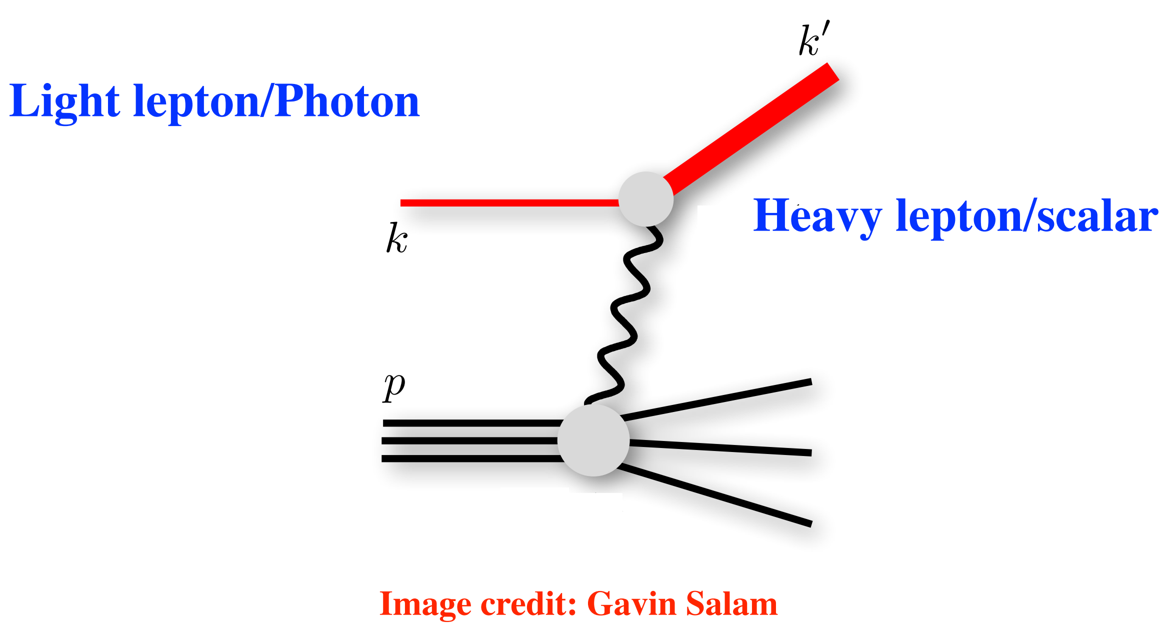
  with $f^{PF}_{\gamma/p} \sim$ photon PDF in LUXqed framework $\longrightarrow$ LO collinear PI cross section. But this is an approximation!

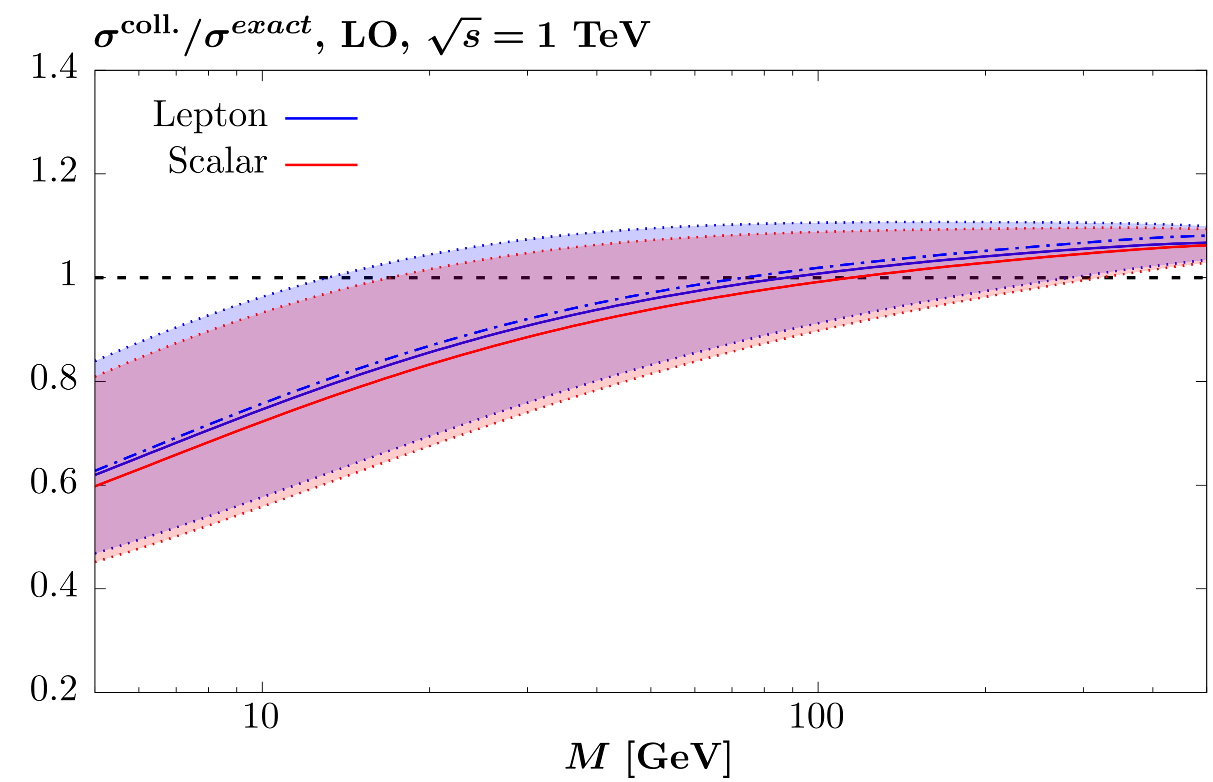
- Much better (**more precise**) to simply work with $\dagger$ directly. Presence of μ_F dependence in $\ast$ indicates this: entirely **artificial** (no control over $M^2_{\gamma\gamma} \sim Q^2_{1,2}$ region).
- Improve $\ast$ by going to higher order in α: include e.g. $q \to q\gamma \Rightarrow$ higher order terms in $Q^2/M^2_{\gamma\gamma}$. But $\dagger$ always more precise.



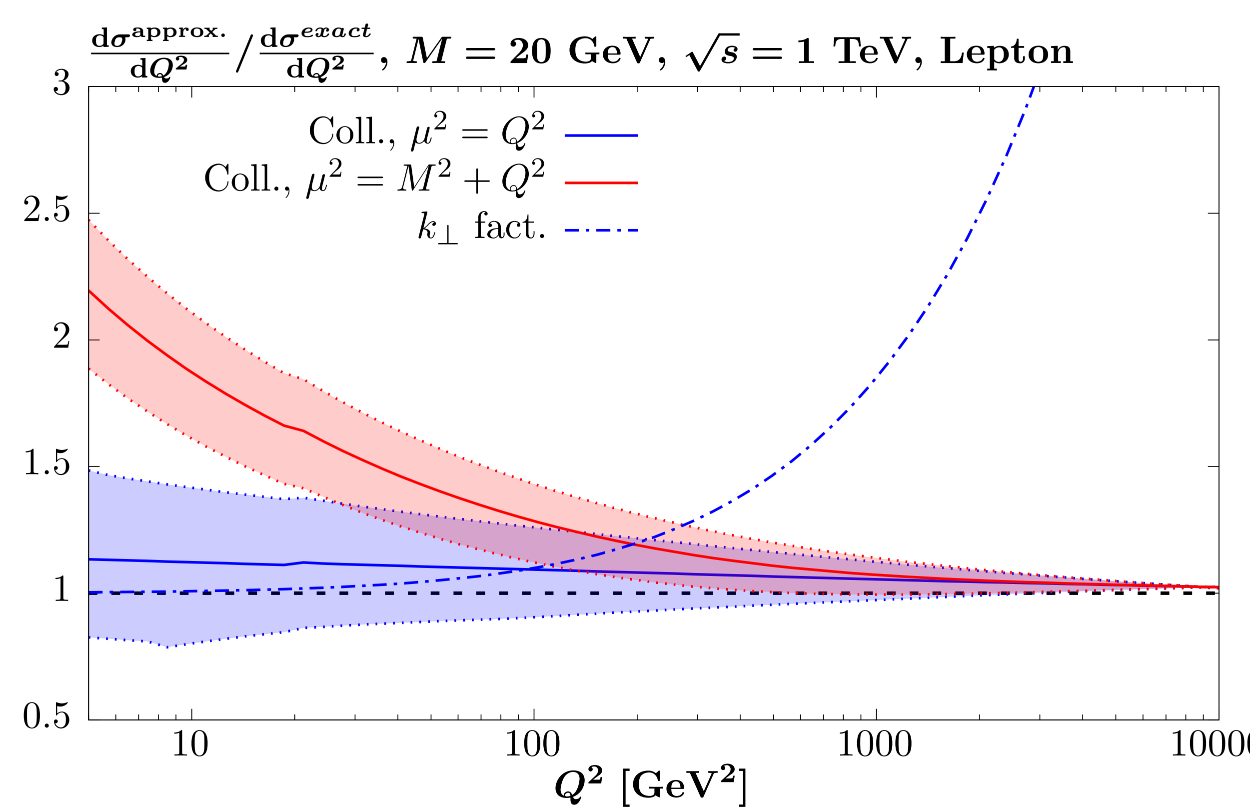
- Note: $Q^2_{1,2} \ll M^2_{\gamma\gamma}$ approx. also taken in $k_\perp$ factorization approach.

- As example, consider **toy processes**: heavy lepton/scalar production off one proton.





- Consider ratio of collinear/ $k_\perp$ -factorization approx. results to exact.
- See **clear deviations**, and large (artificial) μ_F variation uncertainty.



MC Implementation

- Master formula readily amenable to **MC implementation**:

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

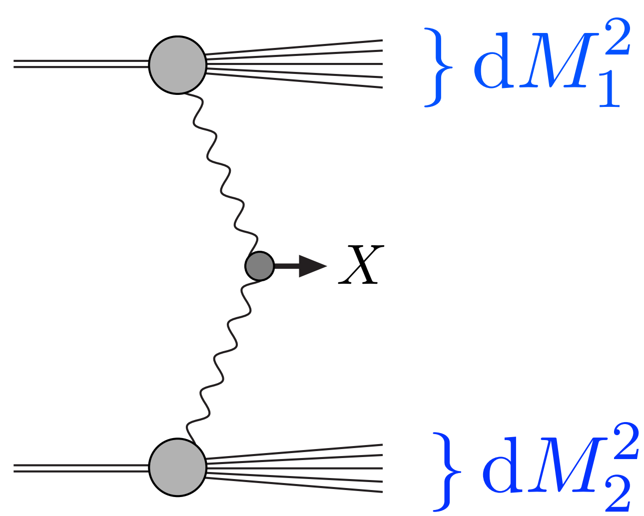
$M_{\mu\nu} :\sim \gamma^* \gamma^* \to X = l^+ l^-, W^+ W^- \dots$ LO (or beyond) amplitude.

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

↑

$$\int \frac{\mathrm{d}x_{B,i}}{x_{B,i}^2} = \int \frac{\mathrm{d}M_i^2}{Q_i^2}$$

Fully **differential** over invariant mass of dissociation system.



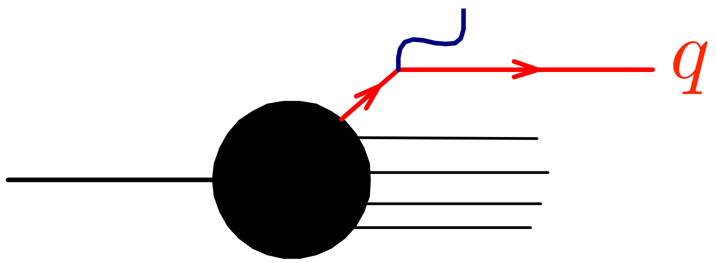
$F_{1,2}$ from elastic/ inelastic ep scattering data.

Treatment of Dissociation System

- MC produces outgoing dissociation system 4-momentum. Then need to decay so that we can interface to general purpose MC for **showering/ hadronisation**.
- **Two methods** for doing this being investigated:

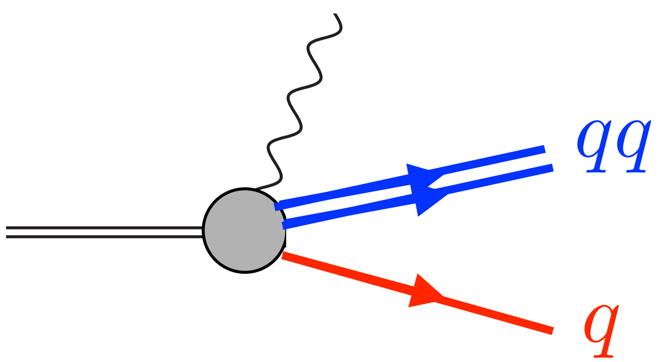
Forthomme et al., PLB 789 (2019) 300-307

★ Generate outgoing quark according to momentum conservation from (collinear) $q \to q\gamma$



Thanks to Radek Zlebcik

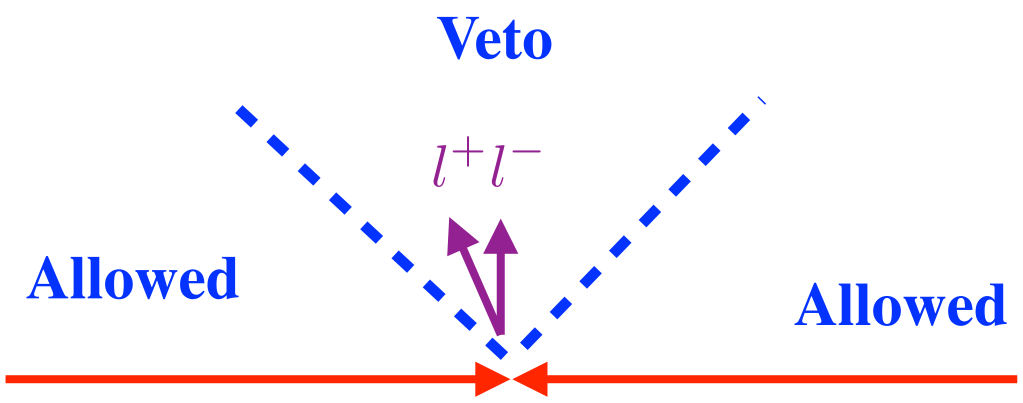
★ Decay dissociation system according to phase space into quark + diquark.



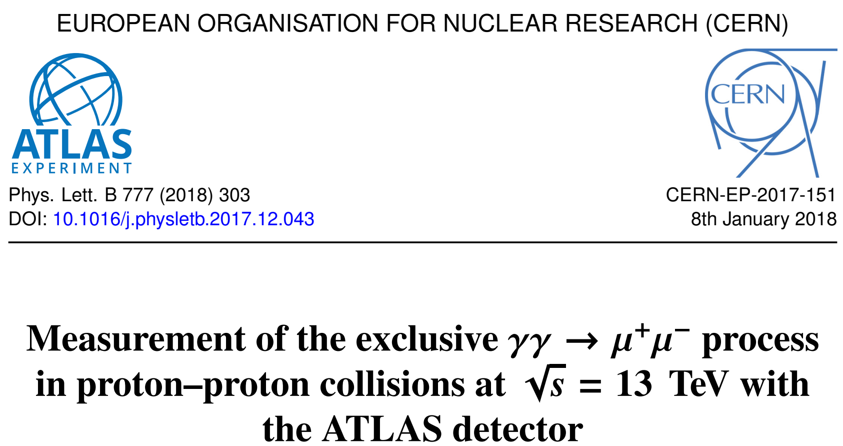
- Clearly a lot of variations even within these two approaches. Hope is that final results not too sensitive on specific choice: **to be investigated**.

Results

- 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 SD and DD events with dissociation outside veto region pass this:

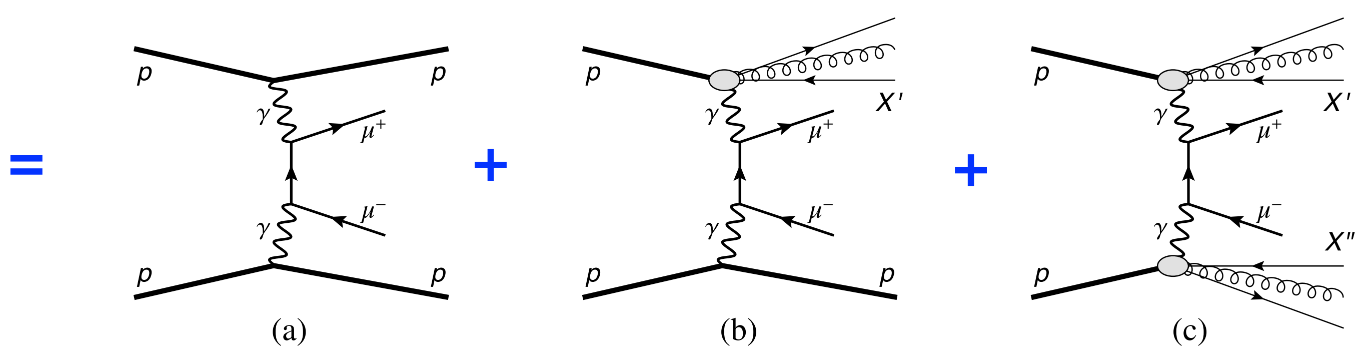

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

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

CERN-EP-2017-151
8th January 2018

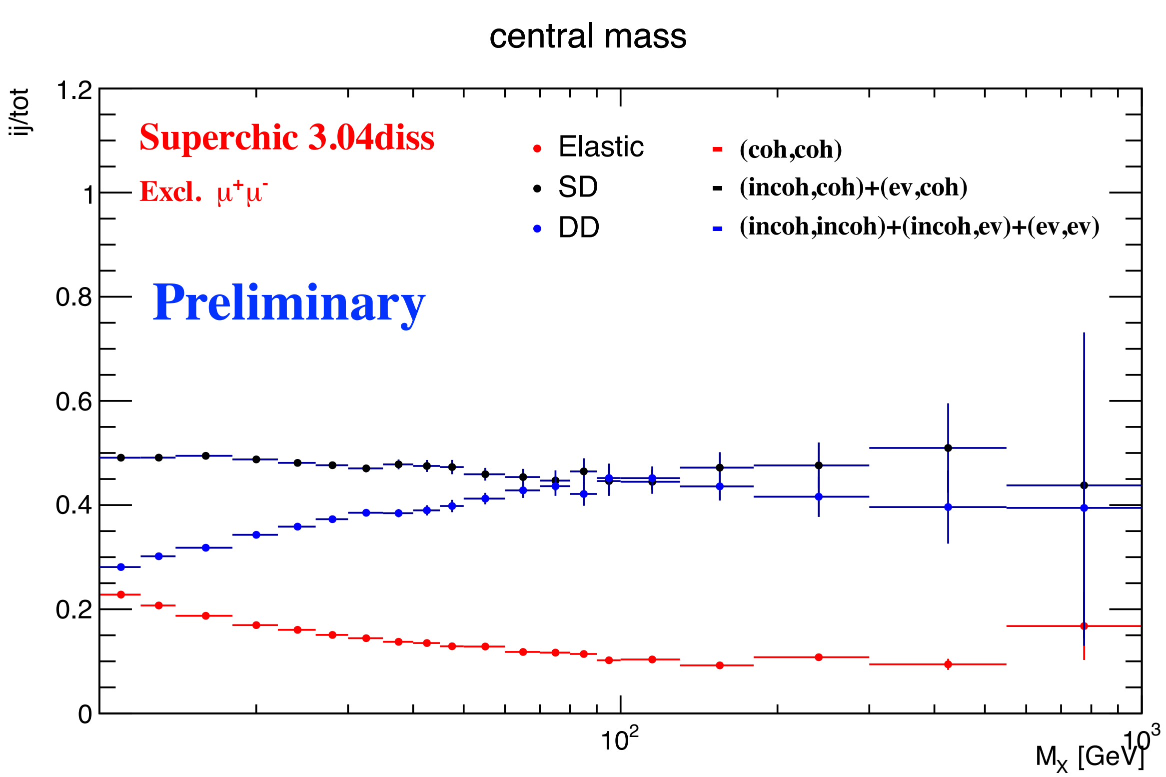
Measurement of the exclusive $\gamma\gamma \to \mu^+\mu^-$ process in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector



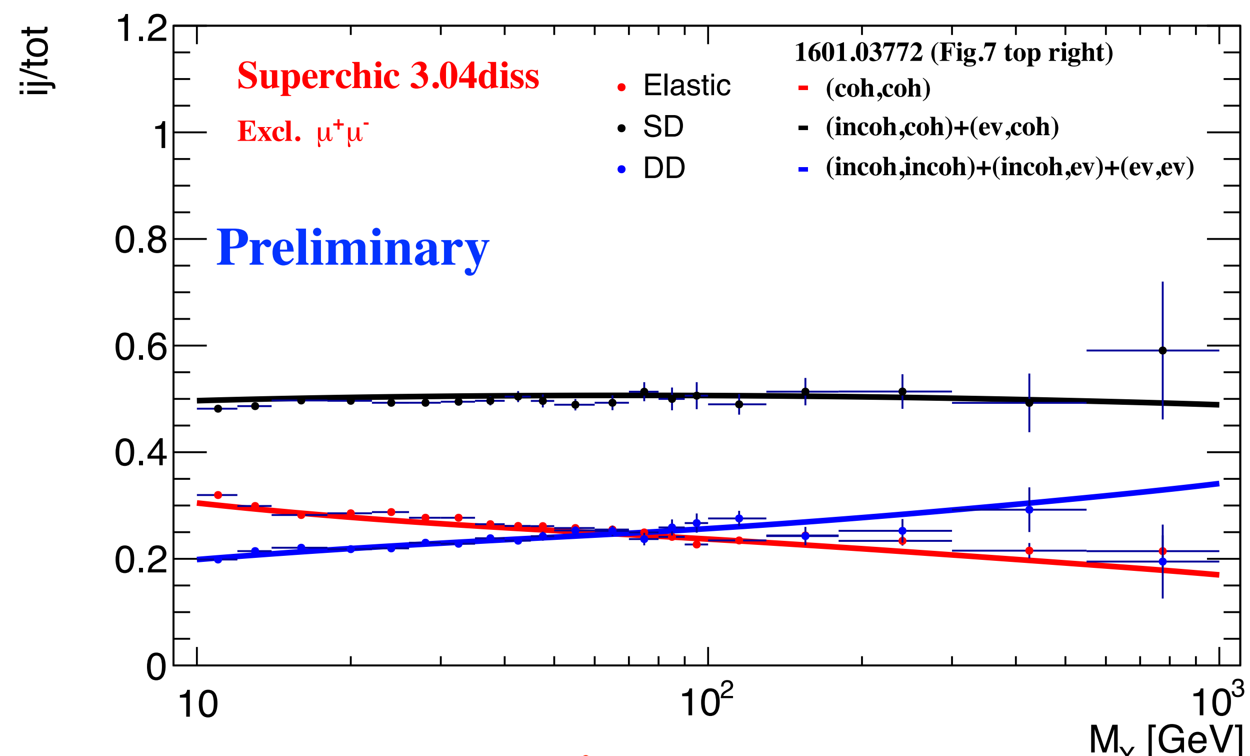
- Data-driven techniques applies to remove this BG, but simulation itself based on (**outdated**) LPAIR and NNPDF2.3 QED photon PDF.

Results

- Result **with/without veto**, corresponding to veto region out to $|\eta| \sim 5$.
- Relative fraction of elastic vs. single/double dissociation varies with central system mass (larger $m_{ll} \Rightarrow$ more dissociation).
- Imposing veto has impact on this. Gives e.g. larger relative elastic contribution.
- Also shown (with veto): approx. analytic result of **1601.03772**. Good agreement seen!



Without Veto

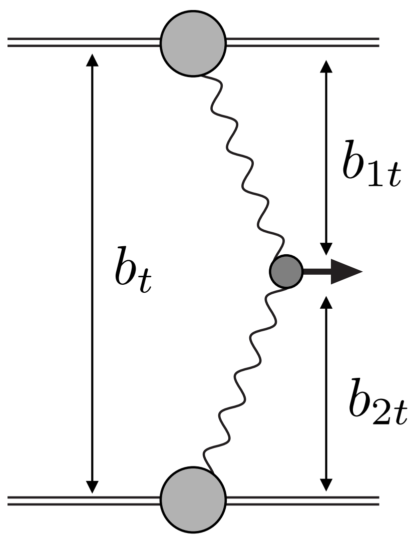


With Veto

Survival Effects

- Results so far for particles from dissociation system entering veto region.
- However additional inelastic pp interactions need to be included - can fill gap.
- Include '**survival factor**' = prob. of no additional inelastic pp interactions.
- Work in impact parameter space and apply 'eikonal' approach:

$$\langle S^2 \rangle = \frac{\int \mathrm{d}^2\mathbf{b}_{1t}\, \mathrm{d}^2\mathbf{b}_{2t}\, |T(s,\mathbf{b}_{1t},\mathbf{b}_{2t})|^2 \exp(-\Omega(s,b_t))}{\int \mathrm{d}^2\,\mathbf{b}_{1t}\mathrm{d}^2\mathbf{b}_{2t}\, |T(s,\mathbf{b}_{1t},\mathbf{b}_{2t})|^2}\,,$$



- Where denominator corresponds to σ_{pp} considered before (cross section with no survival effects).

Proton Opacity

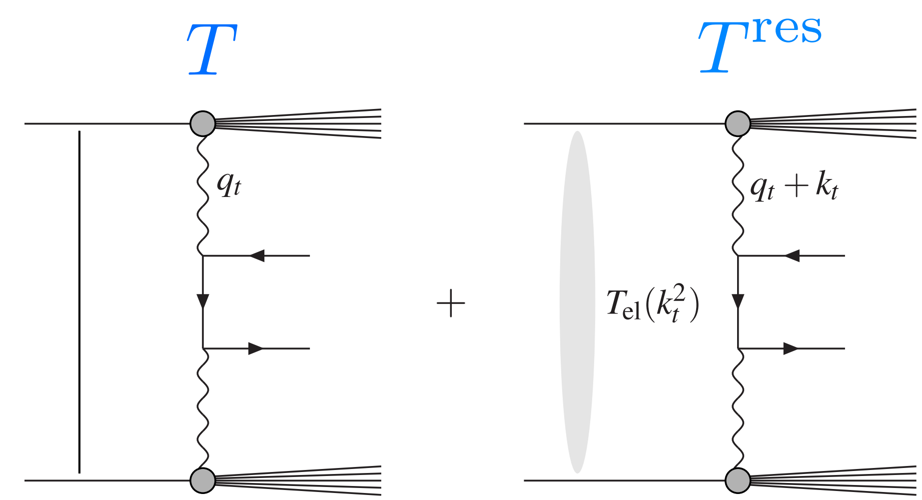
$\exp(-\Omega(s,b_t))$: Poissonian probability of no inelastic scattering at impact parameter b_t.

V.A. Khoze, A.D. Martin, M.G. Ryskin, EPJC73 (2013) 2503

- Apply phenomological **model** for this + fit to soft/diffractive data.

- All of the above well established for case of exclusive production. Need to **extend** formalism to case with proton dissociation.
- Not necessarily easy- must work at **amplitude** level. In momentum space:

$$\langle S^2_{\rm eik}\rangle = \frac{\int {\rm d}^2 q_{1t}\, {\rm d}^2 q_{2t}\, |T(q_{1t},q_{2t}) + T^{\rm res}(q_{1t},q_{2t})|^2}{\int {\rm d}^2 q_{1t}\, {\rm d}^2 q_{2t}\, |T(q_{1t},q_{2t})|^2} ,$$



- But master formulae only strictly valid at **cross section** level:

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

- For lower mass/Q^2 dissociation still relatively straightforward. Can isolate dominant contribution in photon density matrix to work at amplitude level:

$$\rho_1^{\mu'\mu} \rho_2^{\nu\nu'} M^*_{\mu'\nu'} M_{\mu\nu} \propto \big(\underbrace{q_{1\perp}^\mu q_{2\perp}^\nu M_{\mu\nu}}_{T}\big)\big(q_{1\perp}^{\mu'} q_{2\perp}^{\nu'} M^*_{\mu'\nu'}\big)$$

(Backup)

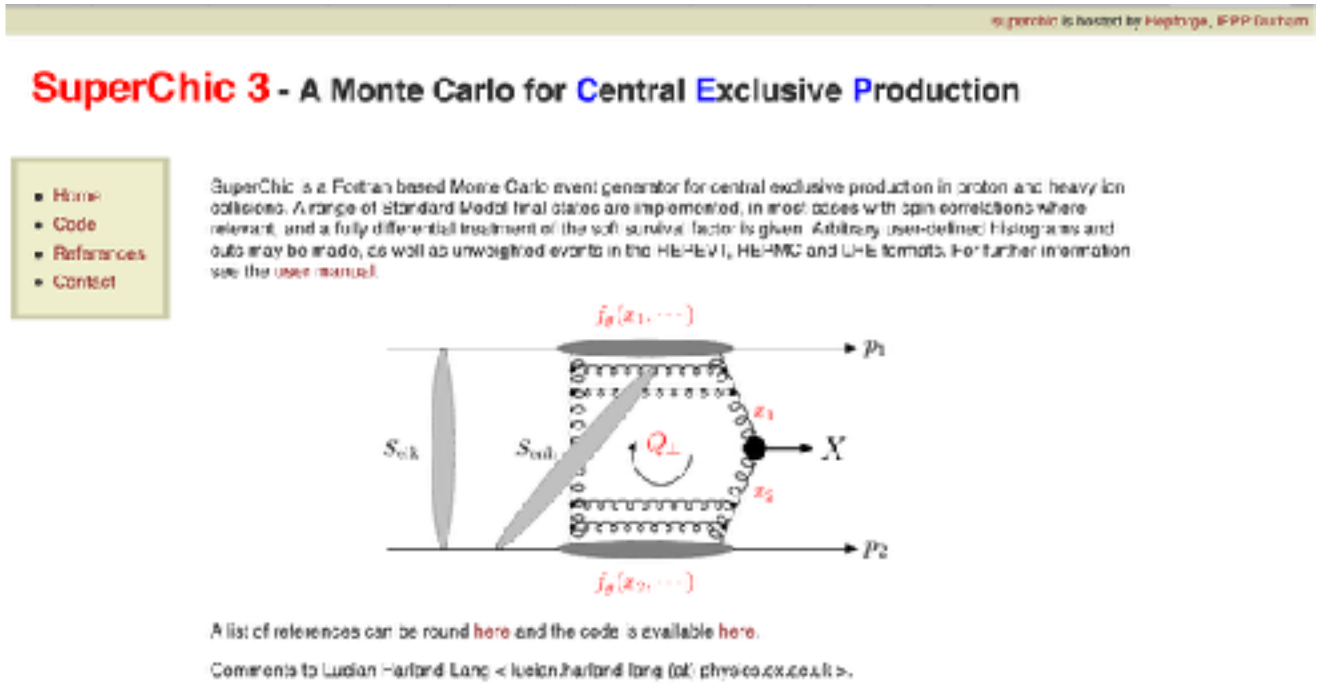
- For higher mass/ Q^2 cannot be done as easily, different approach needed.
- Full results in preparation - **stay tuned**!

SuperChic 3 - 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.

- Update with full treatment of proton dissociation for photon-initiated production in pp collisions **in preparation**.



https://superchic.hepforge.org

Summary/Outlook

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

★ New developments in calculation of PI processes allow high precision cross section calculation.

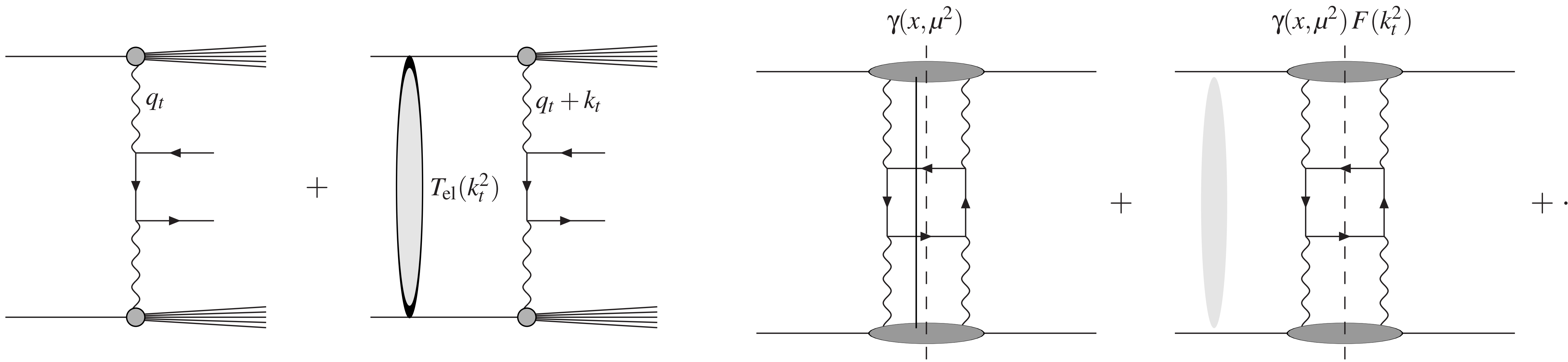
★ Unified MC treatment in inclusive/exclusive cases desirable and achievable. Work ongoing - stay tuned!

Thank you for listening!

Backup

High Mass Dissociation + Survival Factor

- For high Q^2 case the $k_\perp^2 \sim 2/B_{\rm el} \sim 0.1\,{\rm GeV}^2$ in Pomeron loop (generating screening correction) is $\ll$ photon $q_\perp$.
- Helps simplify calculation, even if cannot write directly at amplitude level.



- For screened case, we effectively need: $x\gamma(x,\mu^2) \to H^\gamma(x,\xi=0,t;\mu^2)$

GPDF

- We assume: $H^\gamma(x,\xi=0,t;\mu^2) = x\gamma^{\rm evol}(x,\mu^2;\delta)\,F_1(t)$,

Proton Dirac FF

- And cross section including survival effects takes relatively simple form:

$$\sigma^{\rm scr.} \sim 1 + \frac{2i}{s}\int \frac{{\rm d}^2 k_t}{8\pi^2}\,T_{\rm el}(k_t^2)F_1^2(k_t^2) - \frac{1}{s^2}\int \frac{{\rm d}^2 k_t\,{\rm d}^2 k_t'}{8\pi^2\;\;8\pi^2}\,T_{\rm el}(k_t^2)T_{\rm el}(k'^2_t)F_1^2((k_t+k_t')^2)\ ,$$