Photon-Initiated Production: Theory Overview

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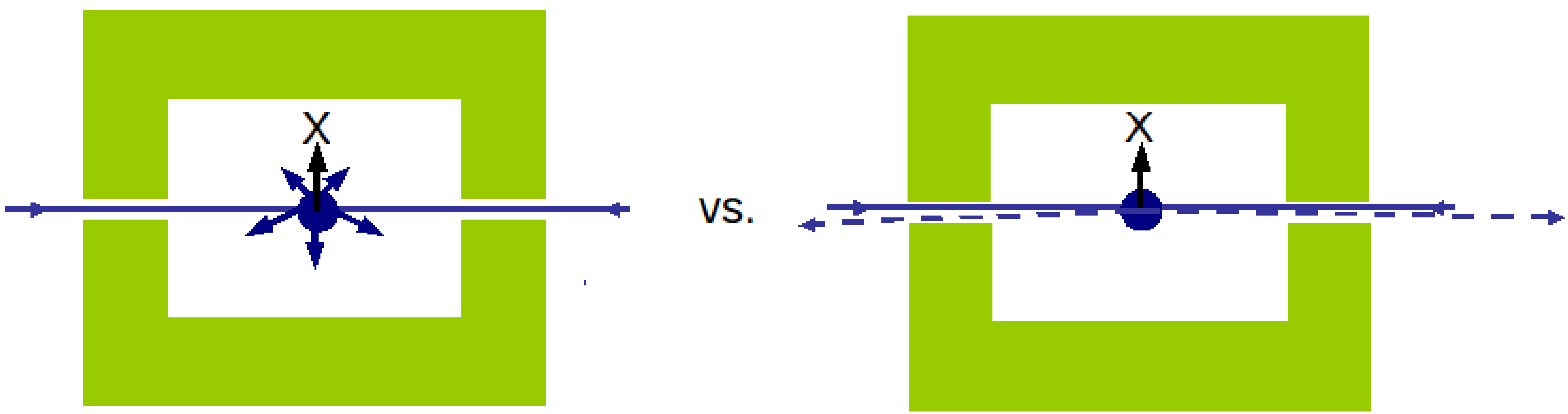
Workshop on Photon-Induced Processes, IPPP
Durham, Nov 3 2022

Central Exclusive Production

Central Exclusive Production (CEP) is the interaction:

$$hh \to h + X + h$$

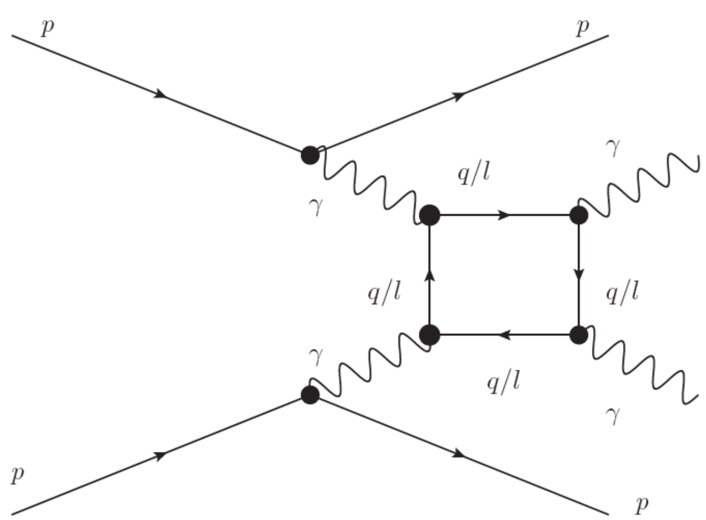
- Diffractive: colour singlet exchange between colliding protons, with large rapidity gaps ('+') in the final state.
- Exclusive: hadron lose energy, but remain intact after the collision.
- Central: a system of mass M_X is produced at the collision point and only its decay products are present in the central detector.



Production Mechanisms

Exclusive final state can be produced via three different mechanisms, depending on kinematics and quantum numbers of state:

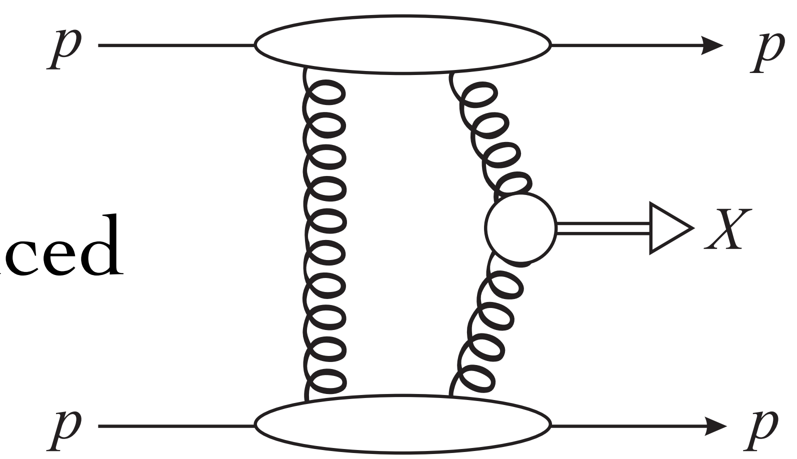
C-even, Couples to photons



Photon-induced

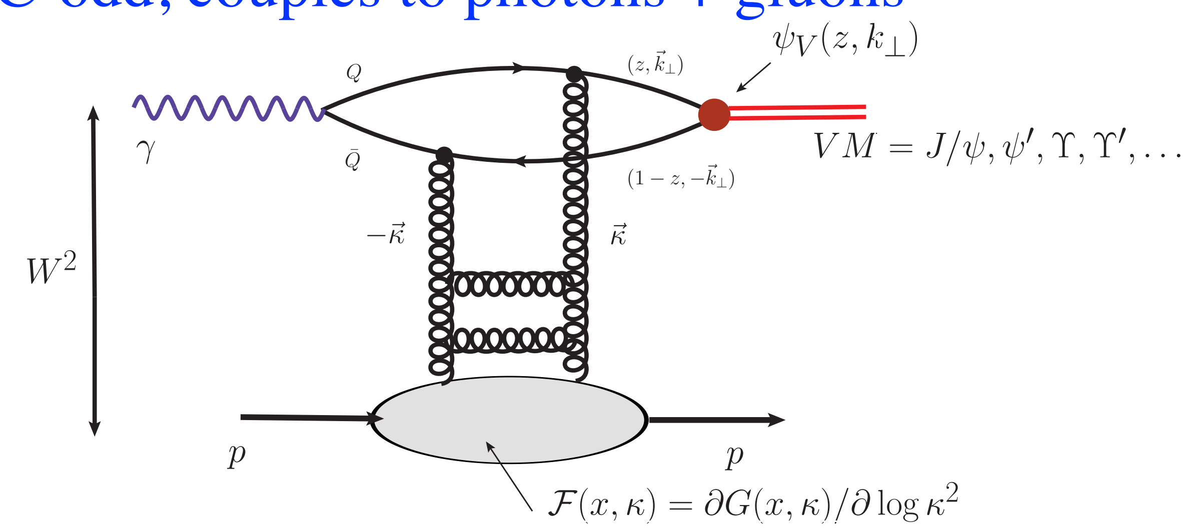
C-even, couples to gluons

QCD-induced



C-odd, couples to photons + gluons

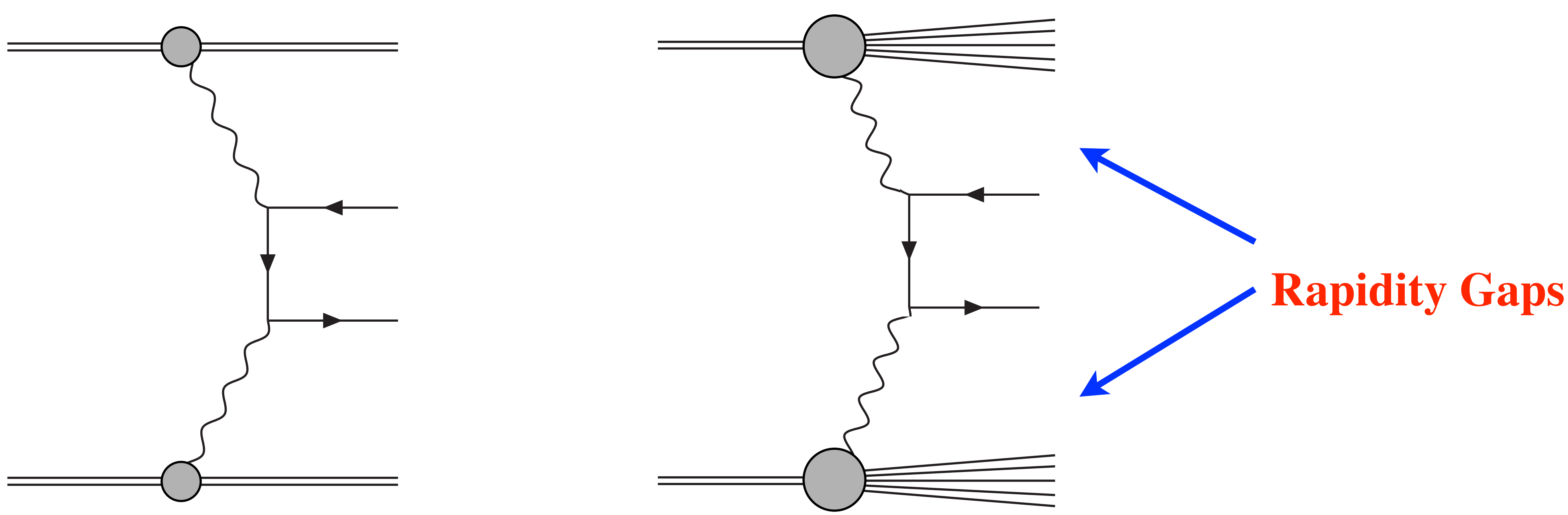
Photoproduction



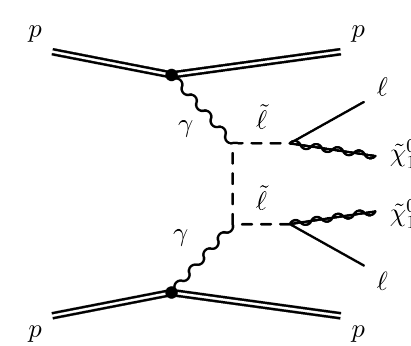
Focus here on photon-induced (PI) production, though other mechanisms of course of broader interested in CEP programme.

PI Production @ LHC

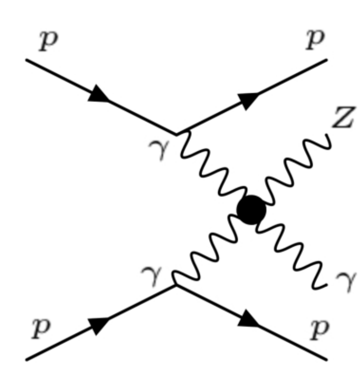
- **Exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state.
- Can be selected either with proton tagging or via rapidity gap vetos (i.e. elastic + inelastic = semi-exclusive production).



- Clean, ~ pure QED process:

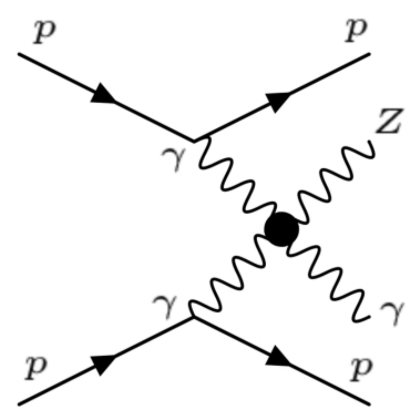


$\Rightarrow$ The LHC as a $\gamma\gamma$ collider!



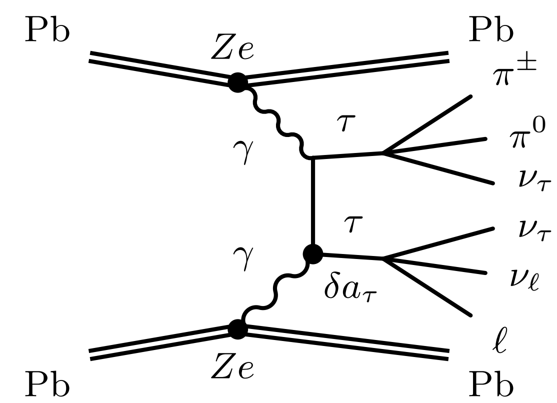
★ Probe of BSM:

Anomalous couplings



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

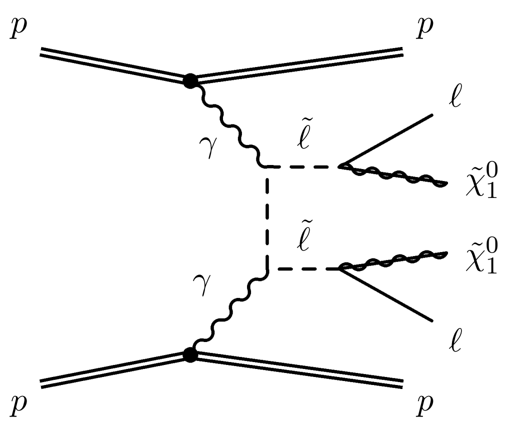
tau g-2



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

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

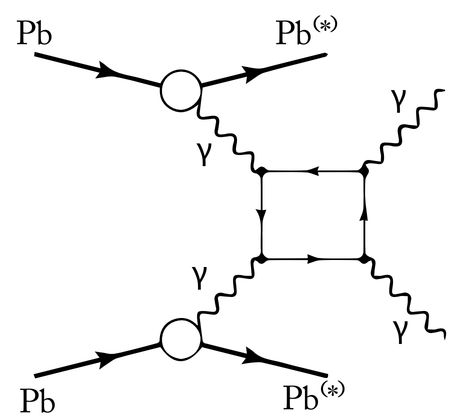
Compressed SUSY



LHL et al., JHEP 1904 (2019) 010

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

LbyL scattering/ALPS

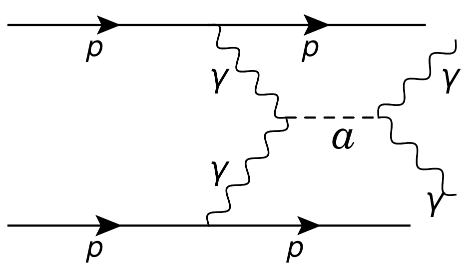


C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

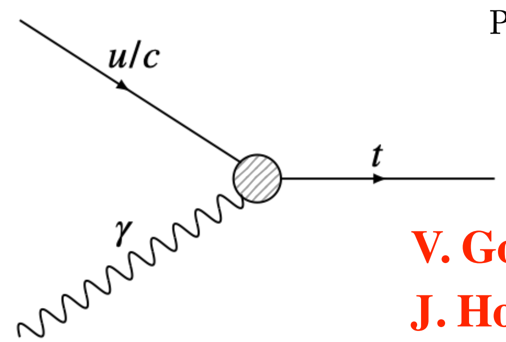
Axion-like Particles

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

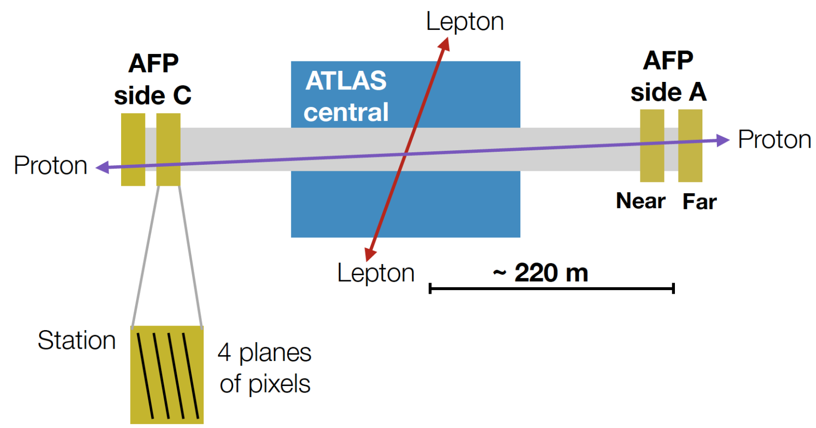
J. Howarth, arXiv:2008.04249

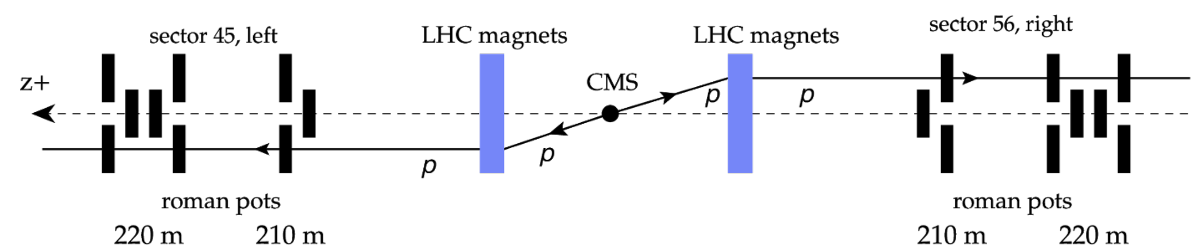
★ Laboratory to test our models of proton dissociation + proton-proton MPI effects.

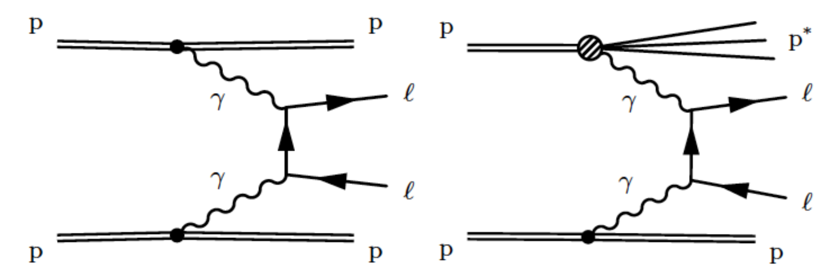
LHL et al., EPJC 76 (2016) no. 5, 255, LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925

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

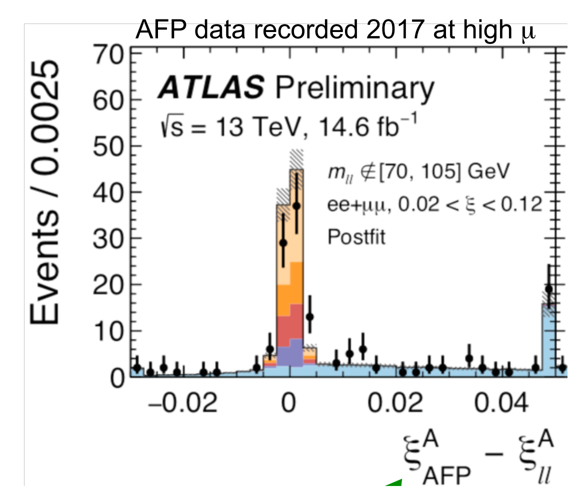
The elastic proton



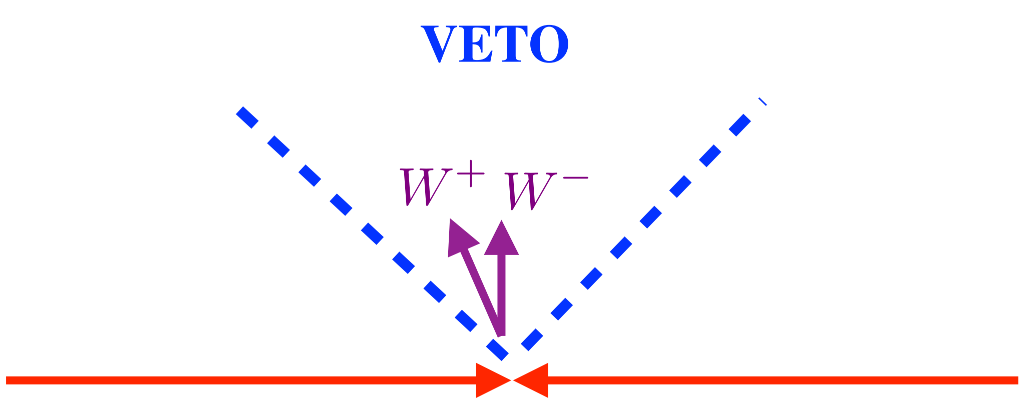




- Proton tagging detectors at ATLAS/CMS allow exclusive events with intact protons in final state to be selected during **nominal running**.



- Alternatively/in conjunction can use track veto:

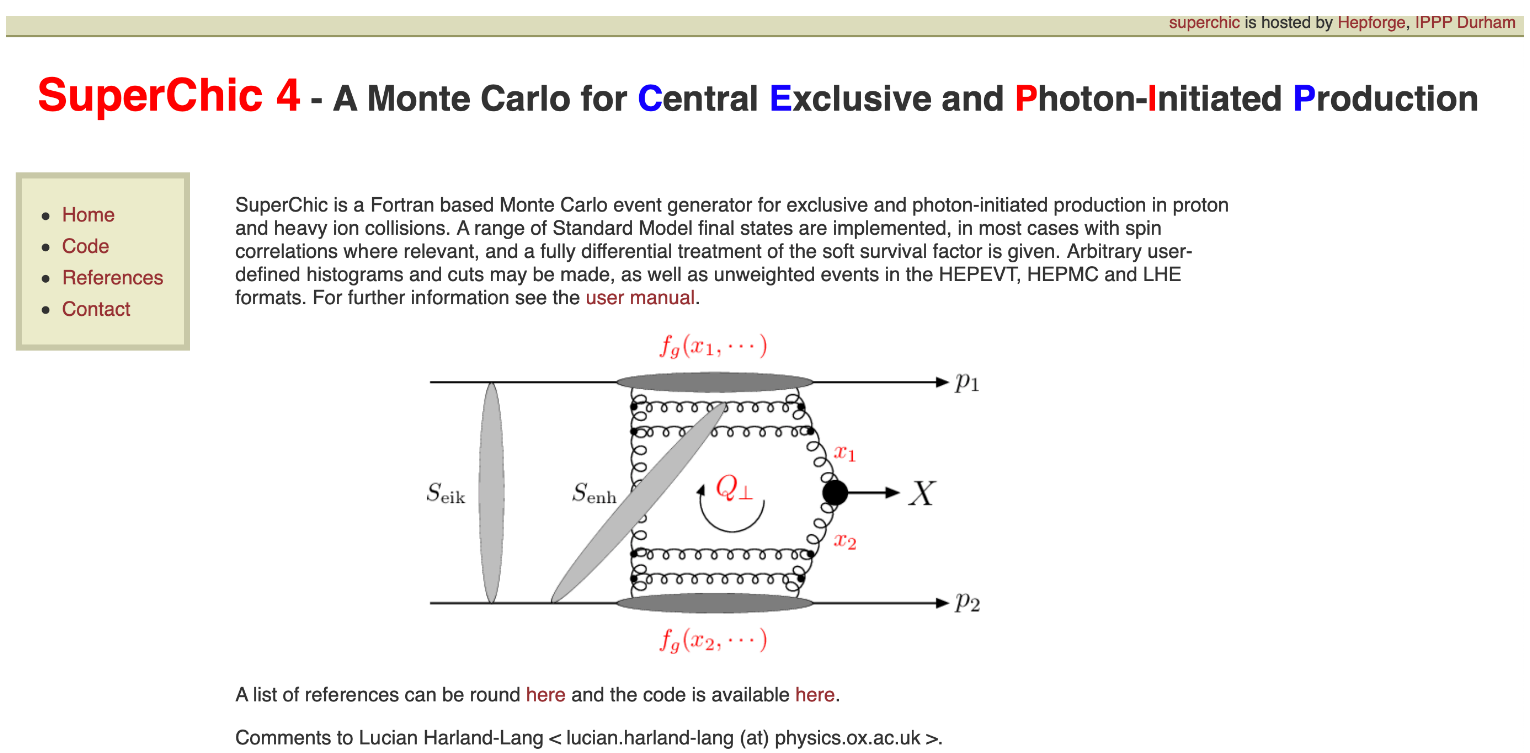


- In which case both elastic and dissociative production can enter.
- How do we model this process theoretically? And how well can we model it?

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.



- **N.B.**: discussion here will follow the theory implementation of the SC4 MC.

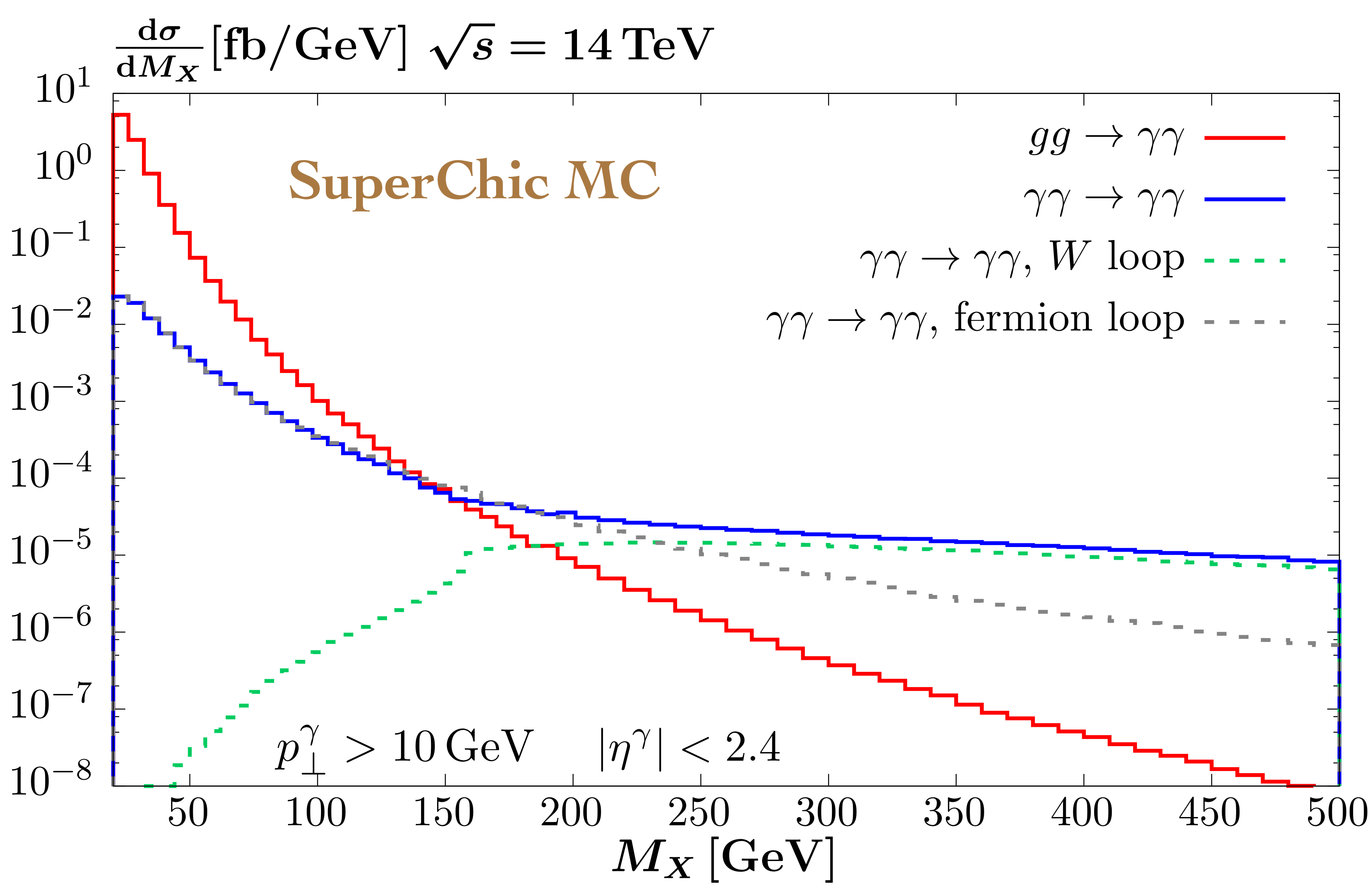
`https://superchic.hepforge.org`

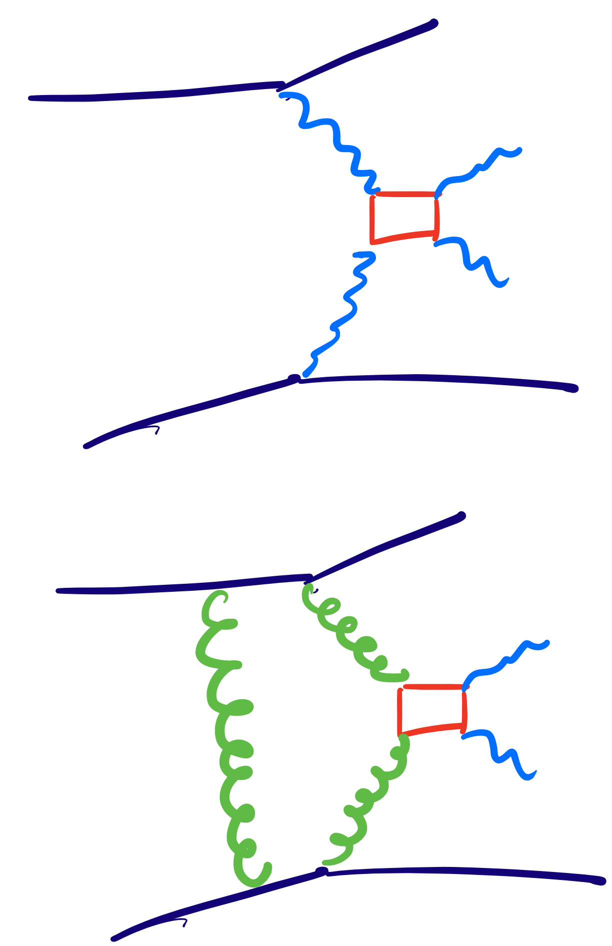
LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925

gg vs. $\gamma\gamma$

- For some processes both QCD and photon initiated production can contribute.
- However, for higher masses QCD production strongly suppressed by no radiation probability from initial-state gluons.

$\longrightarrow$ At higher mass PI production starts to dominate.





Modelling PI Production (pp collisions)

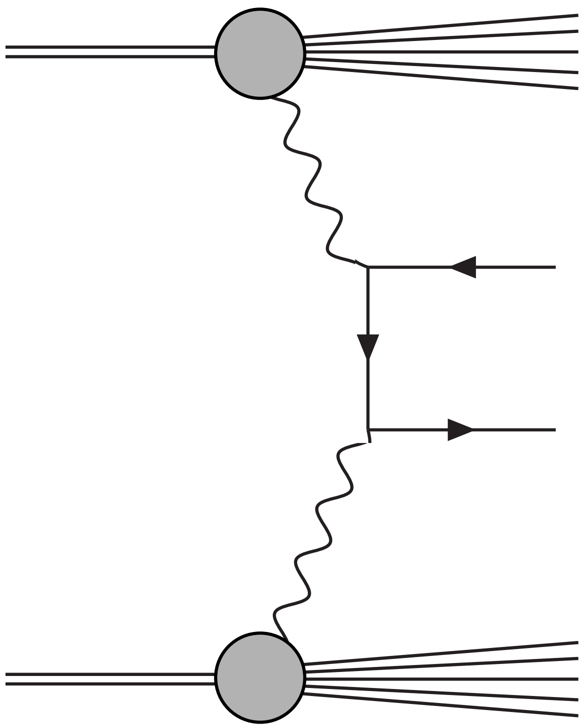
PI production: building blocks

- PI cross section given in terms of:

  ⋆ $p \to \gamma p(p^*)$ form factor.

  ⋆ $\gamma\gamma \to X$ cross section.

  ⋆ `**Survival factor**' probability of no addition proton-proton interactions.

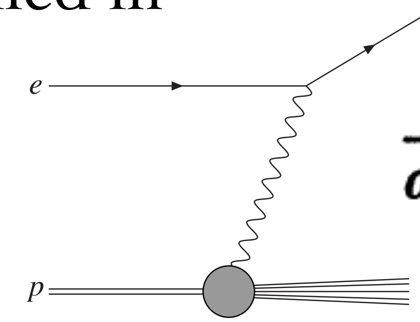


- Will consider each in turn.

LHL, *JHEP* 03 (2020) 128

Structure Function Calculation

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



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

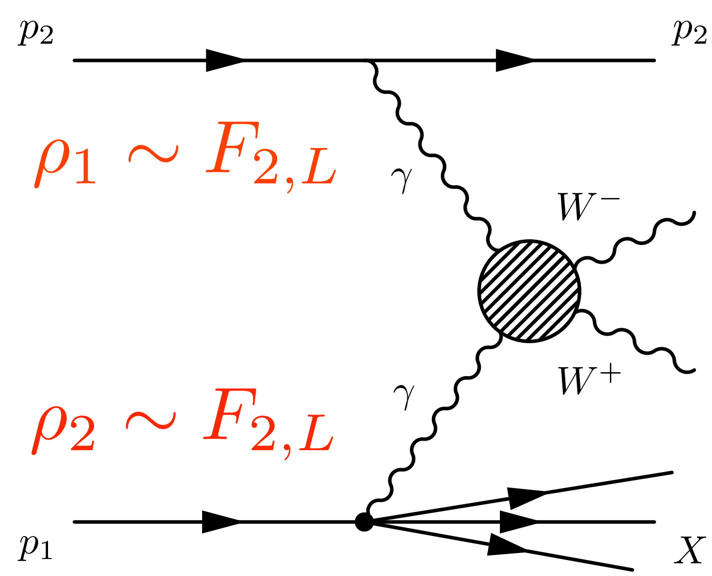
- Structure functions parameterise the $\gamma p \to X$ vertex.

- Use same idea as for DIS to write:

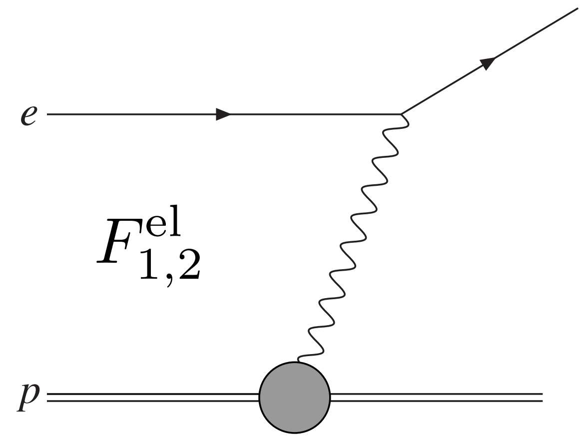
$$W^{\alpha\beta}(p,q) = \left(g^{\alpha\beta} - \frac{q^\alpha q^\beta}{q^2}\right) W_1(x,Q^2) + \left(p^\alpha + \frac{1}{2x}q^\alpha\right)\left(p^\beta + \frac{1}{2x}q^\beta\right) W_2(x,Q^2)$$

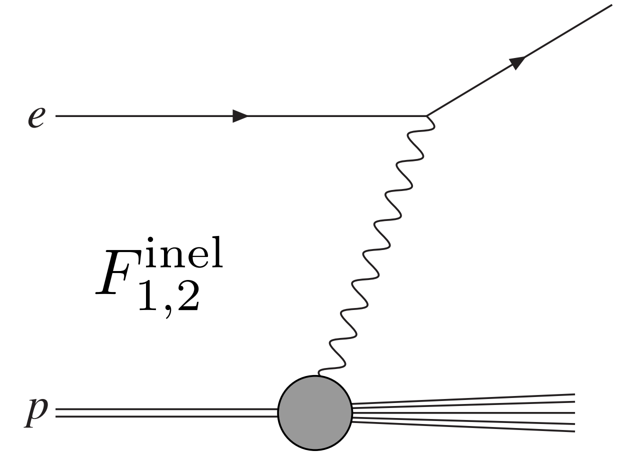
$$\sigma_{pp} = \frac{1}{2s}\int \overbrace{\mathrm{d}x_1 \mathrm{d}x_2\, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp}}^{\textbf{Photon}\ x,\,Q^2} \mathrm{d}\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\overbrace{\rho_1^{\mu\mu'}\,\rho_2^{\nu\nu'}}^{\gamma^* p \to X}\, \overbrace{M^*_{\mu'\nu'} M_{\mu\nu}}^{\sim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

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



- Both elastic and inelastic SFs accounted for:

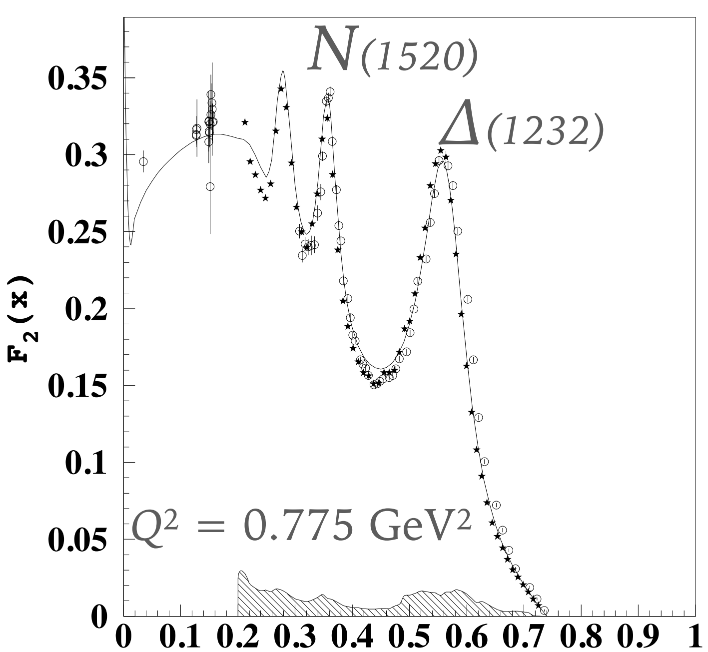


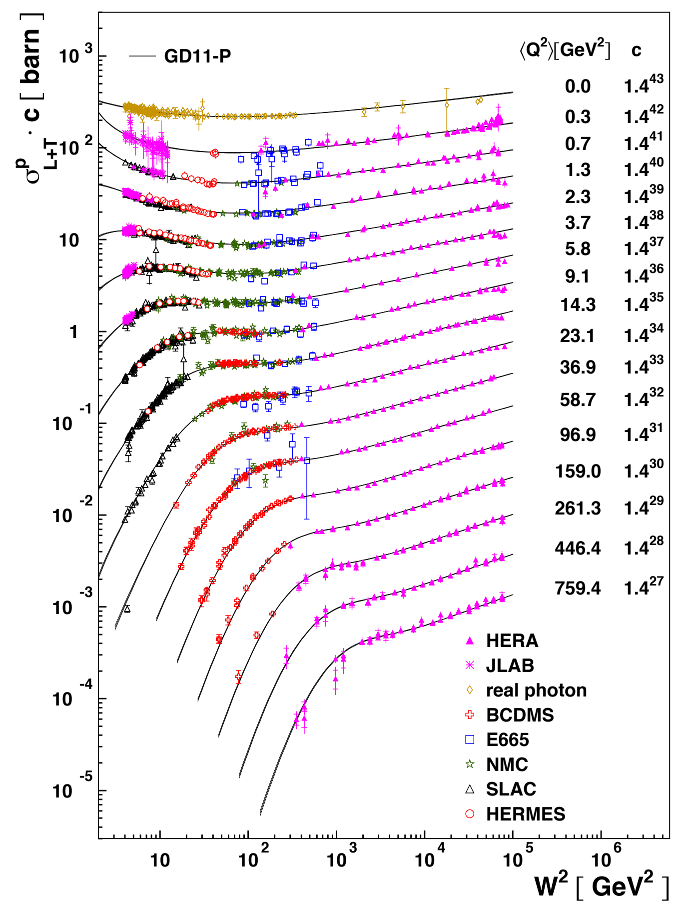


★ **Elastic**: precisely measured proton EM form factor.

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

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

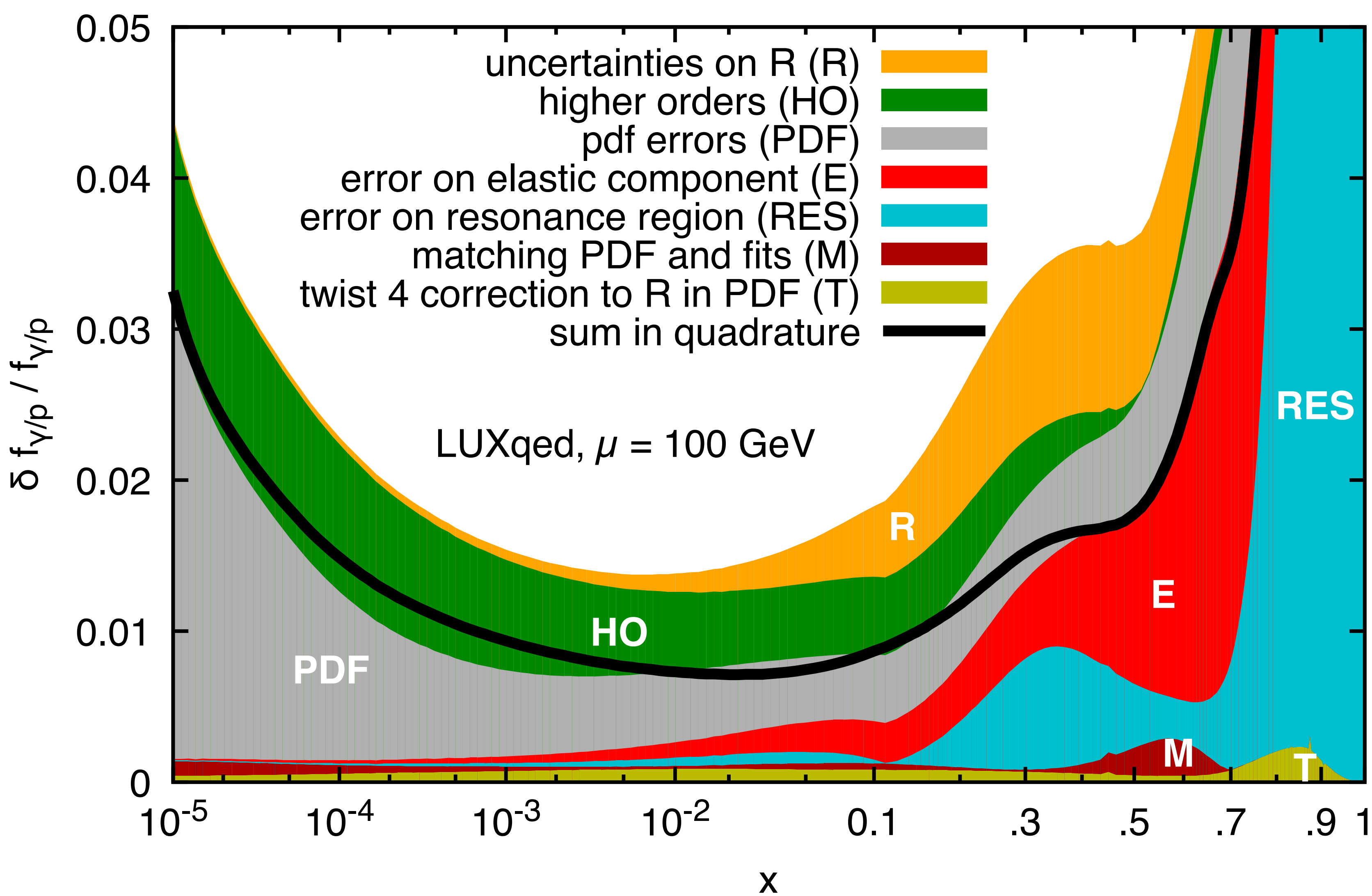


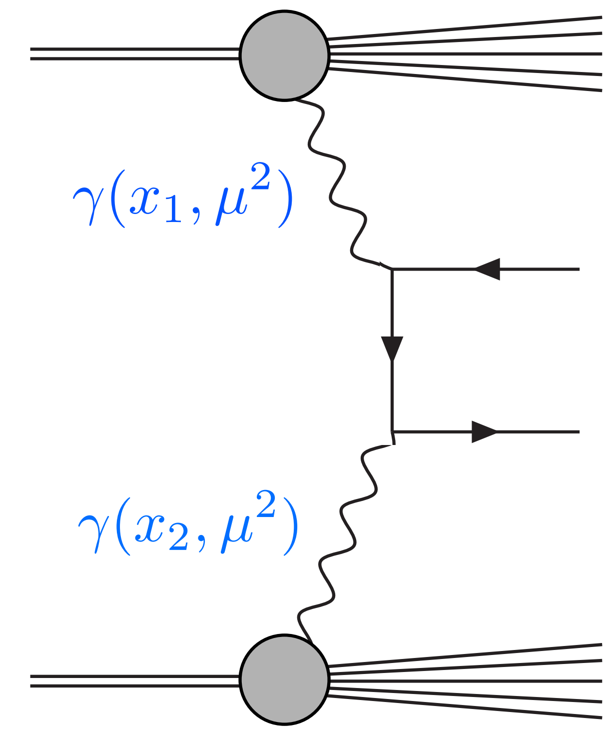


- High Q^2 region, simplest to calculate using (NNLO) pQCD + global PDFs.

- 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).

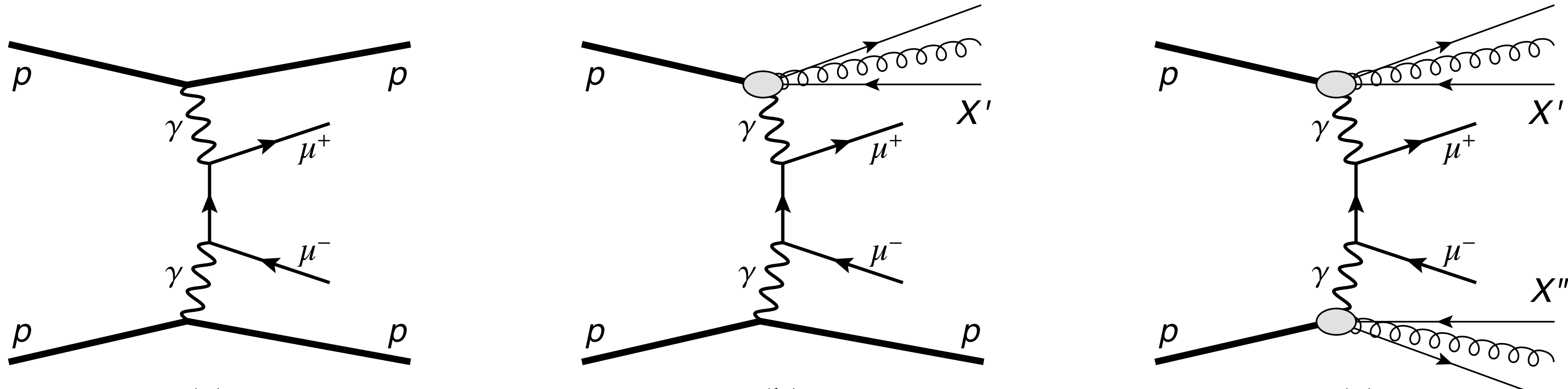
LHL, *JHEP* 03 (2020) 128,
Phys.Rev.D 104 (2021) 7, 073002

- SF approach can provide high precision predictions for inclusive PI production.
- But also 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).



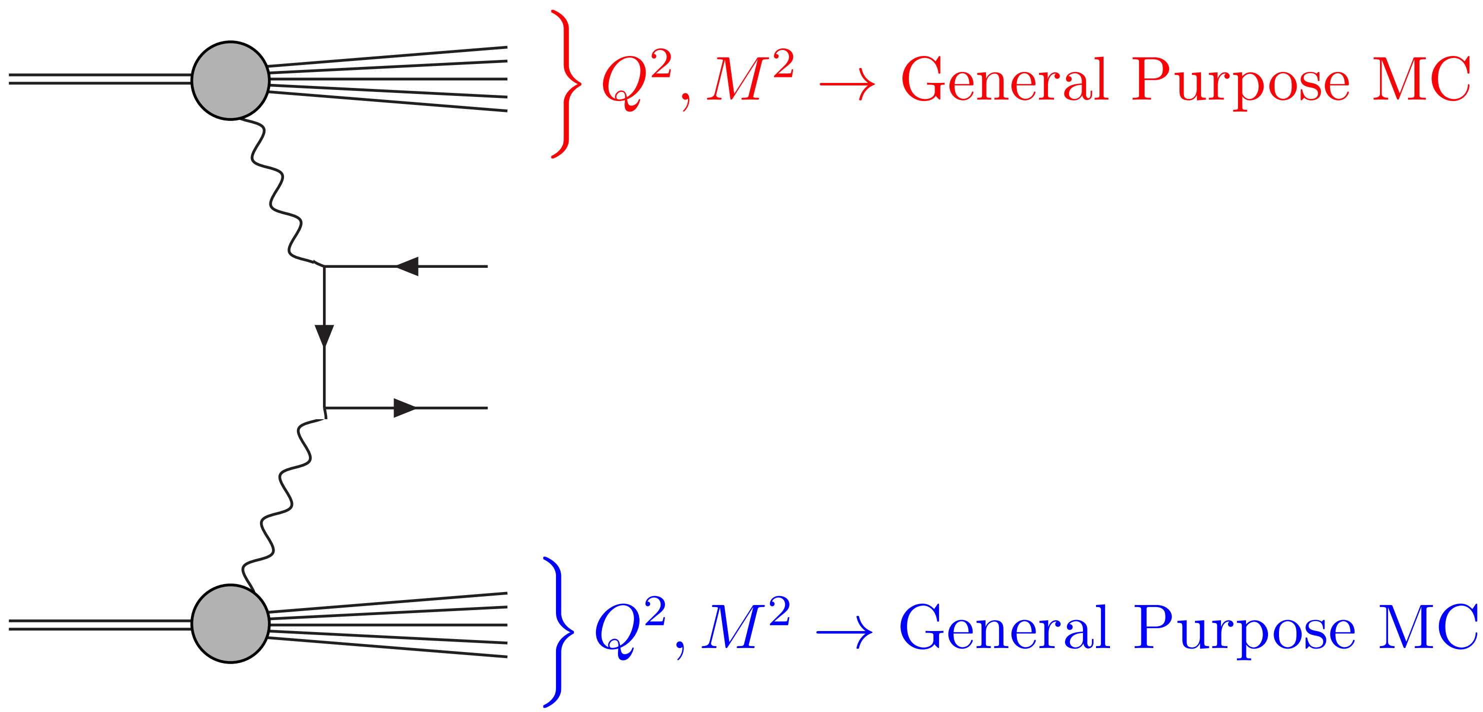
(a) $\rho_{1,2} \sim F^{\rm el}(x, Q^2)$

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

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

- Having generated exclusive/semi-exclusive events, pass to general purpose MC for showering/hadronisation of dissociation system.

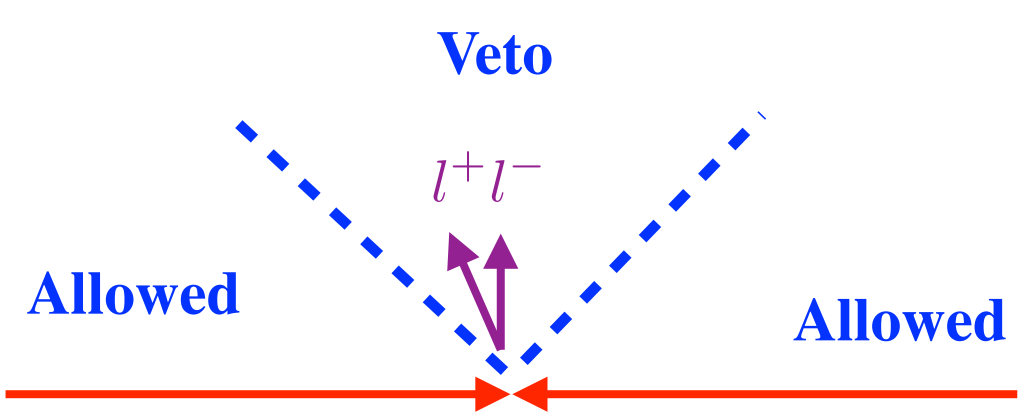
Backup



- Then simply impose veto at particle level.
- 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. $A^{\rm dd} < A^{\rm sd} < 1$

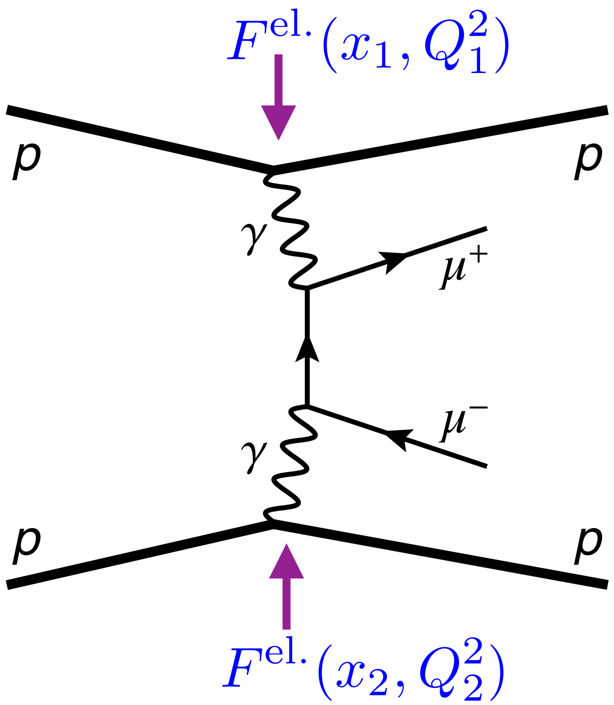


- **But not the end of the story**!

The Survival Factor

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

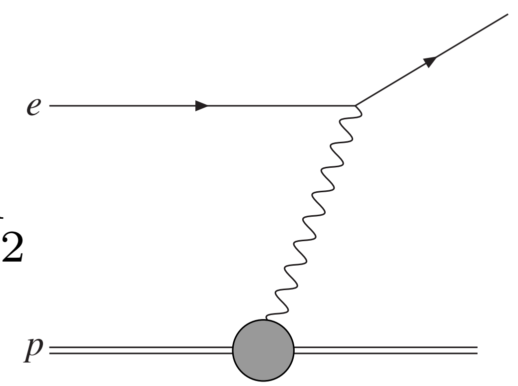
$$\sigma \sim F^{\rm el.}(x_1, Q_1^2) F^{\rm el.}(x_2, Q_2^2)$$



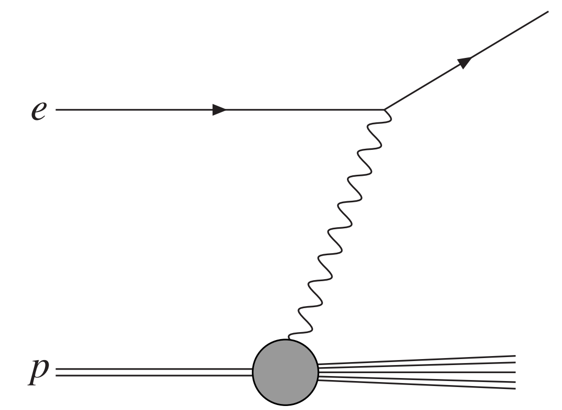
- Similarly for SD + DD, with $F^{\rm el.} \to F^{\rm inel.}$

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

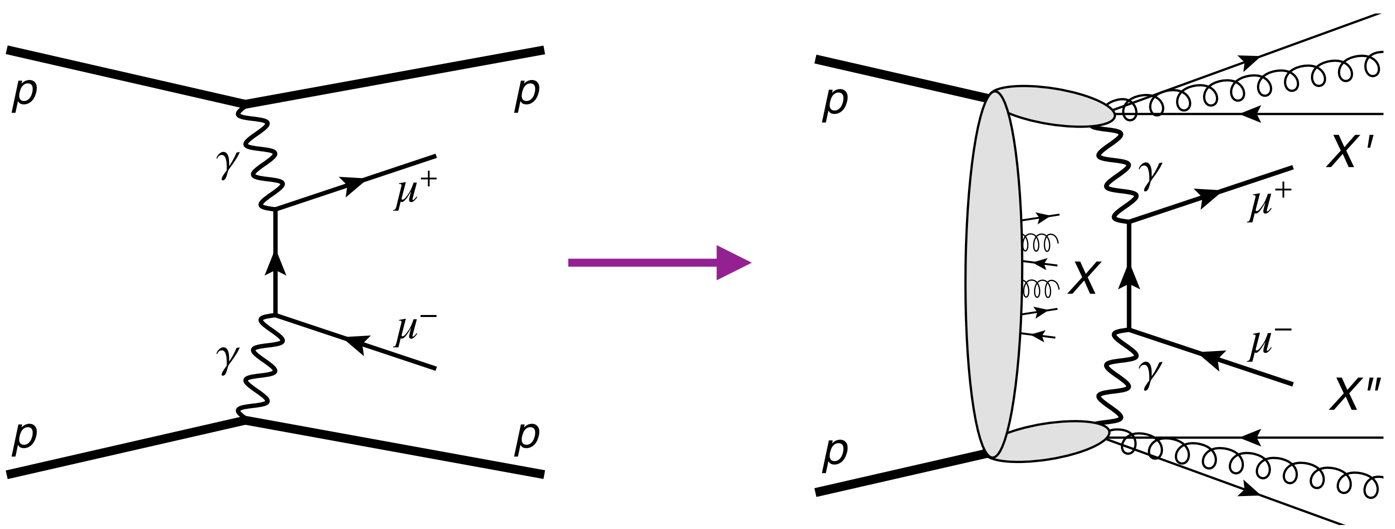
$F_{1,2}^{\rm el}$



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



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

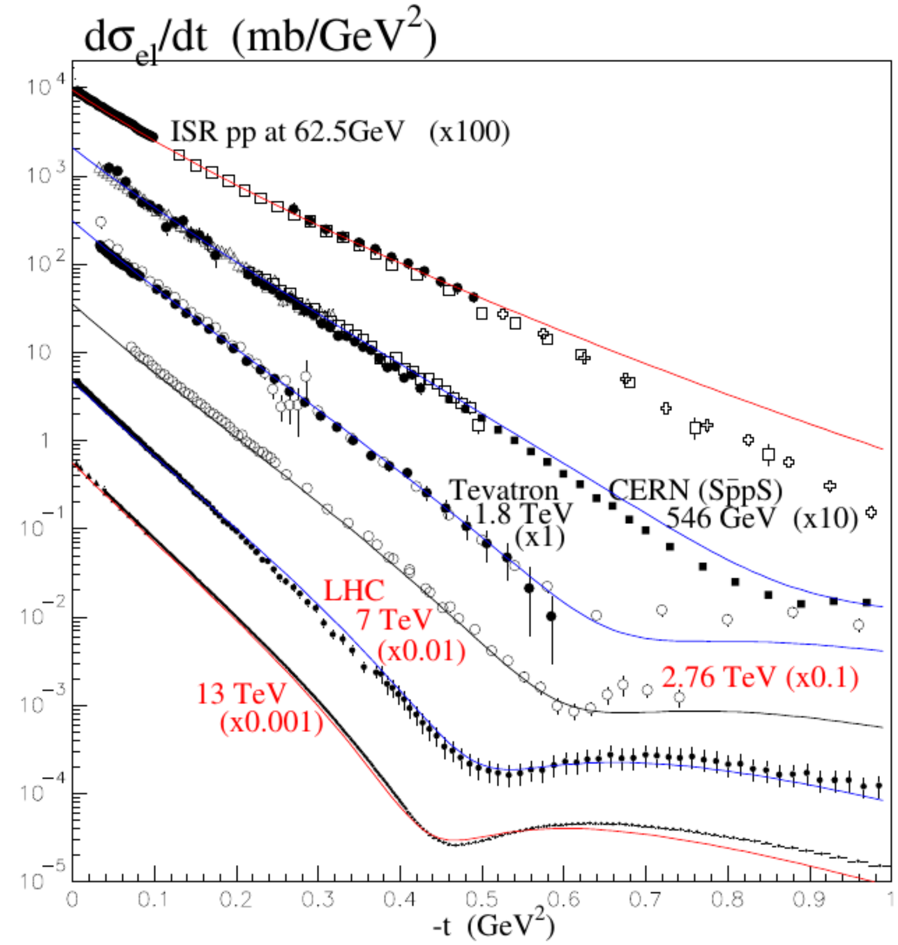


- '**Survival factor**' = probability of no additional inelastic hadron-hadron interactions. Schematically:

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

- 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).

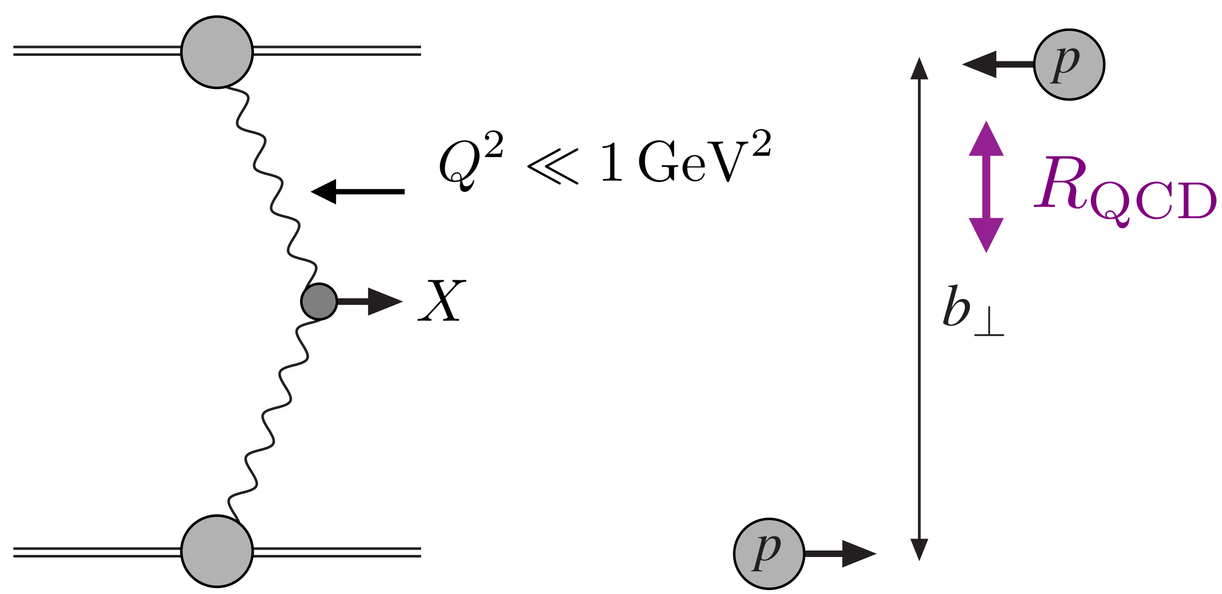
- In general source of **uncertainty**. Is this the case for PI production?



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!

- In more detail…

- How do we calculate survival factor for PI production? Simplest if we consider collision in terms of proton-proton impact parameter.
- Writing schematically:

$$\sigma = \int \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp} |M(\vec{q}_{1_\perp}, \vec{q}_{2_\perp}, ...)|^2$$

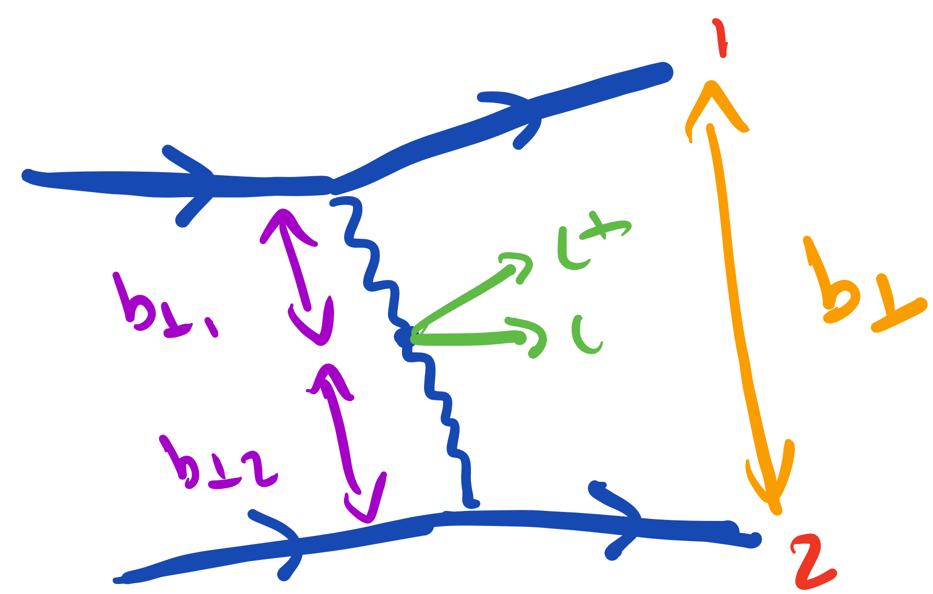
- We can write this as integral over ion impact parameters:

$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp}, ...)|^2$$

- Where:

$$\tilde{M}(\tilde{b}_{1\perp}, \tilde{b}_{2\perp} ..) = FT(M(\vec{q}_{1\perp}, \vec{q}_{2\perp} ..))$$

$$\tilde{M}(\tilde{b}_{1\perp}, \tilde{b}_{2\perp} ..) \sim \int d^2 q_{1\perp} d^2 q_{2\perp} e^{-i\vec{q}_{1\perp}\cdot b_{1\perp}} e^{i\vec{q}_{2\perp}\cdot \vec{b}_{2\perp}} \cdot M(\vec{q}_{1\perp}, \vec{q}_{2\perp}, ...)$$



- To first approximation, we then simply require:

$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp}, ...)|^2$$

$$\downarrow$$

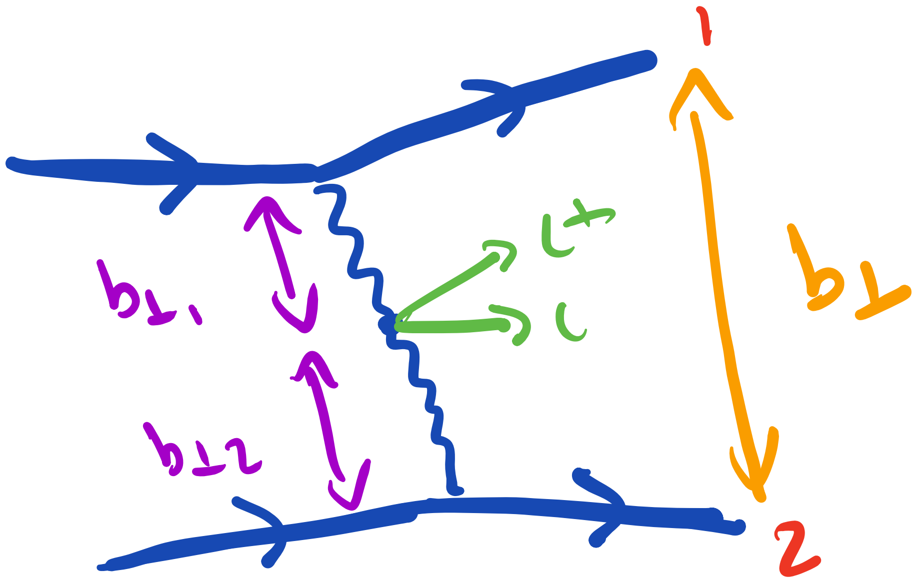
$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp}, ...)|^2 \Theta(b_\perp - 2r_p)$$

$$b_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$$

- That is, only integrate over impact region where:

$$b_\perp > 2r_p$$

holds!



- In more detail, condition is not discrete - some overlap can occur.

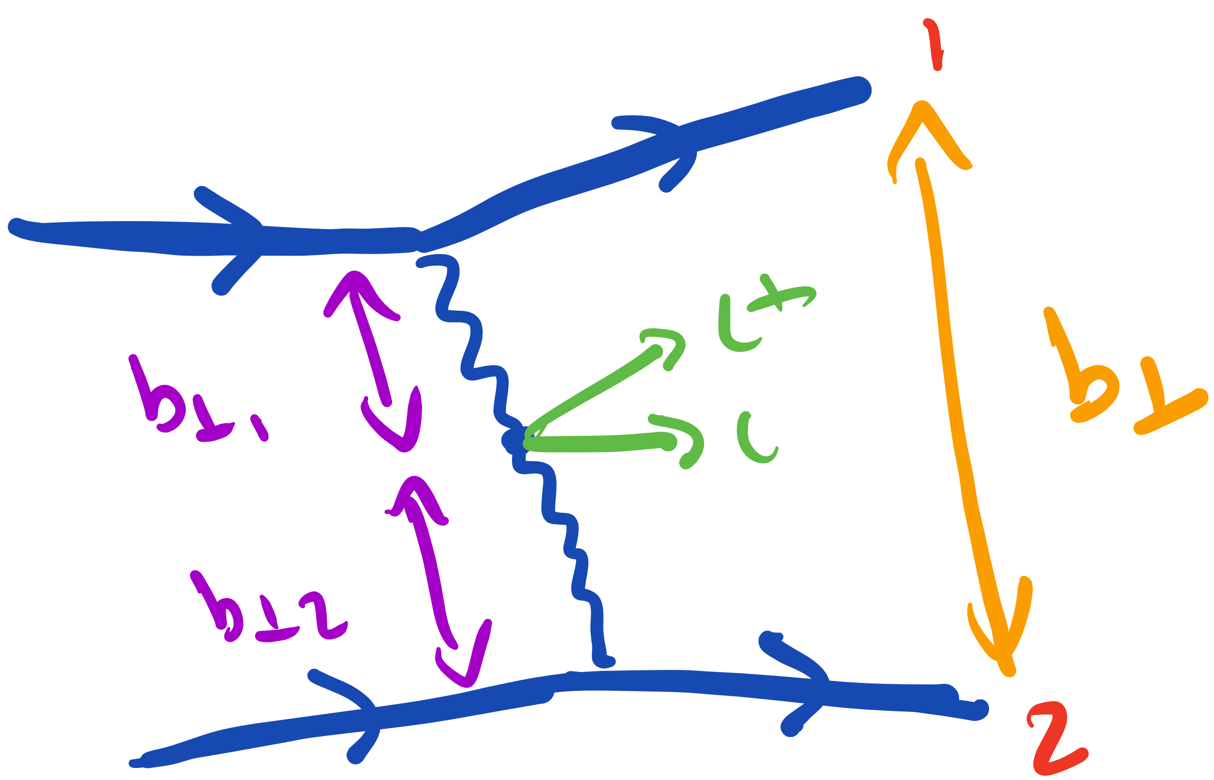
Schematically:

$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp}, ...)|^2 e^{-\Omega(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}$$

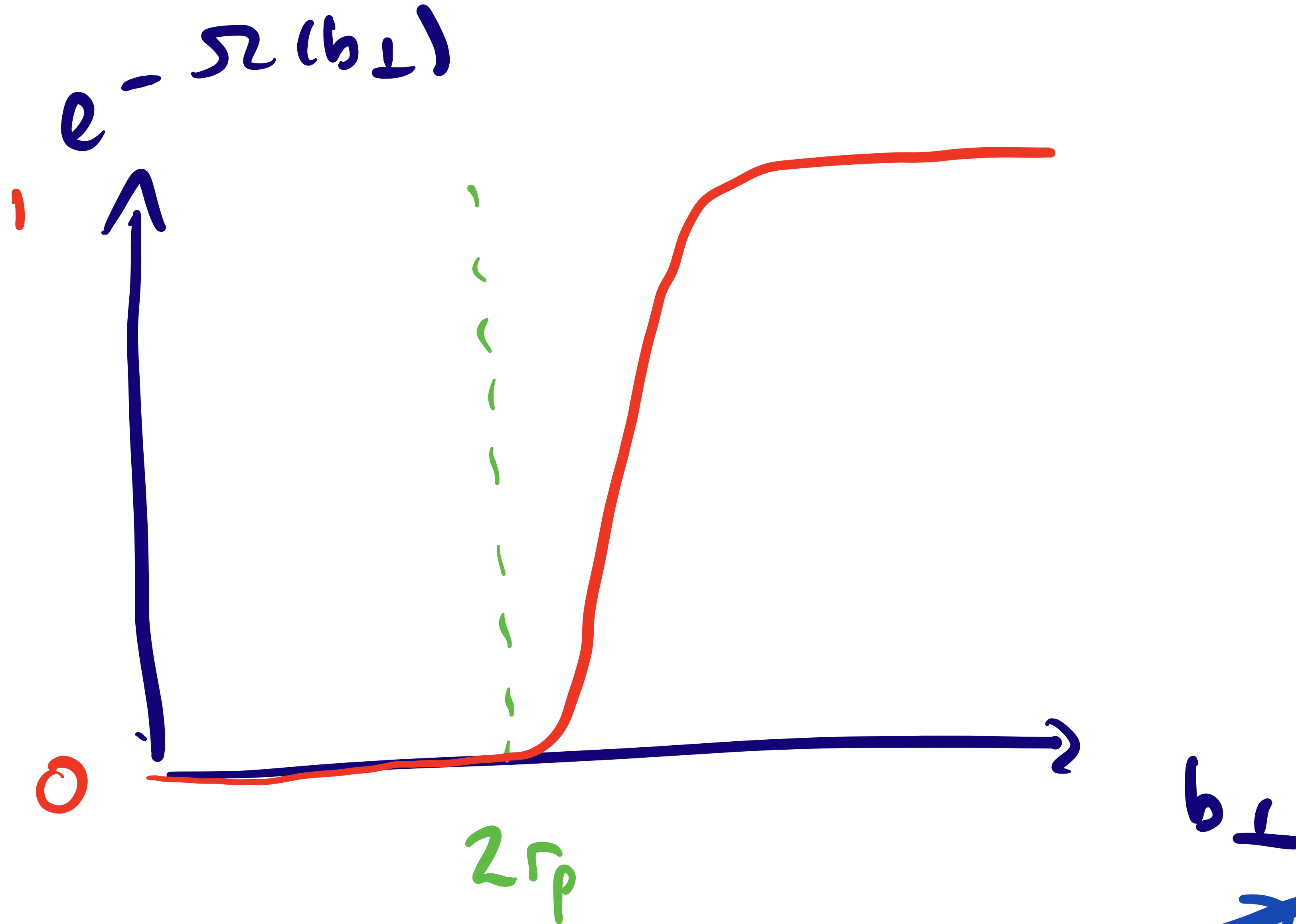
$e^{-\Omega(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}$: survival factor - probability for no additional particle production at impact parameter $b_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$. Roughly:

$$e^{-\Omega(b_\perp)} \approx \Theta(b_\perp - 2r_p)$$

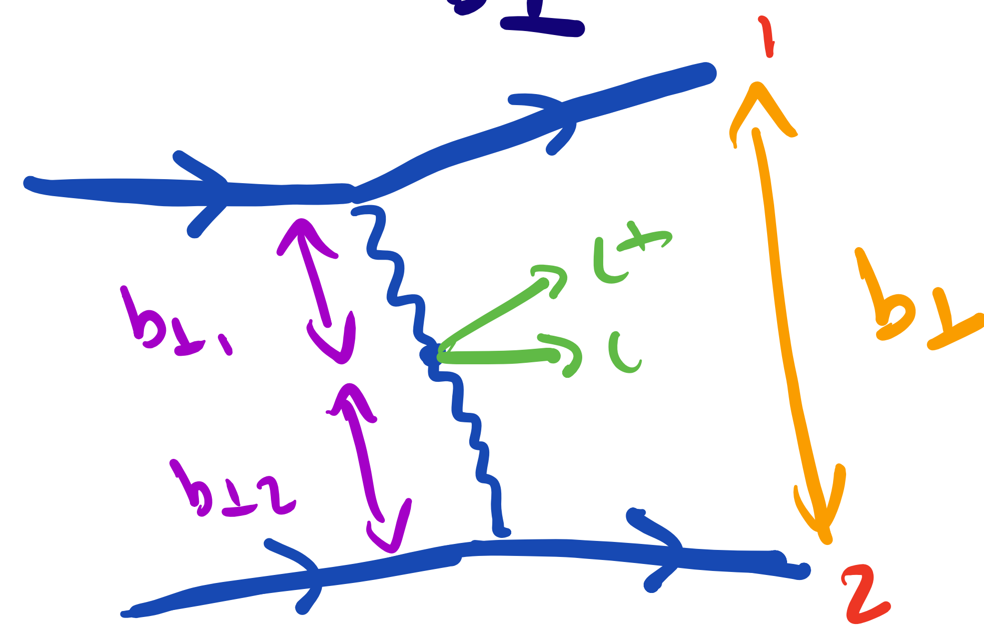
but not exact!



- Result for pp:



$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp}, \ldots)|^2 e^{-\Omega(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}$$



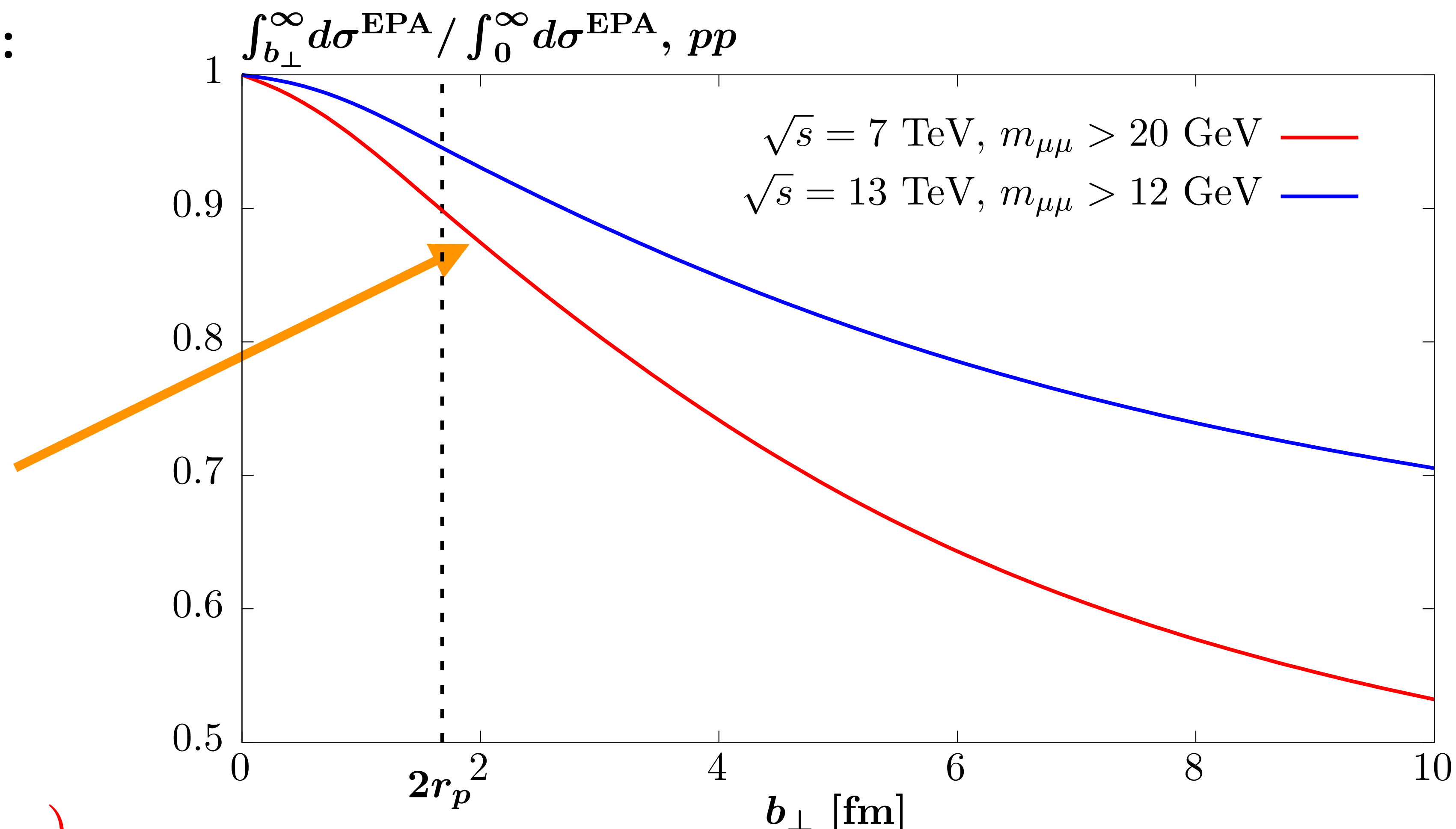
- What does this tell us about survival factor for purely elastic production?

- Have a look at ratio:

$$\frac{\sigma(b_\perp > b_\perp^{\rm cut})}{\sigma(b_\perp > 0)}$$

~ 90% of cross section lies outside

$$b_\perp > 2r_p$$

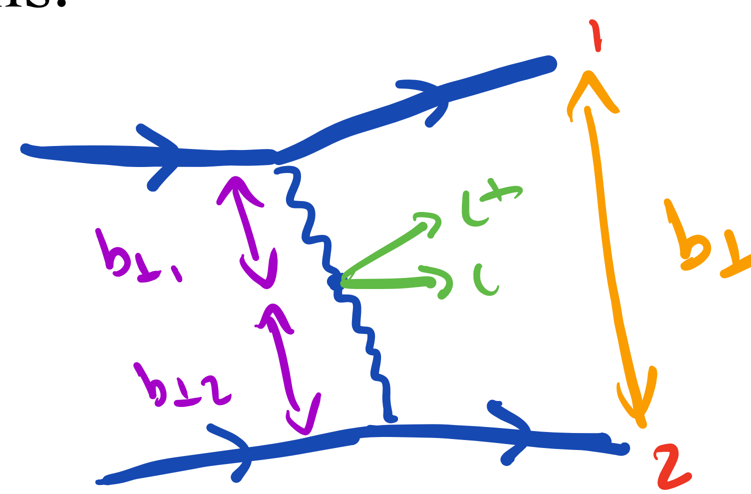


where $e^{-\Omega(\vec{b}_{1\perp} - \vec{b}_{2\perp})}$ is ~ 1!

- Elastic PI production: quasi-real photon Q^2 corresponds to large average pp impact parameter $\Rightarrow$ outside range of QCD interactions.

- Depending on precise process/ kinematics have:

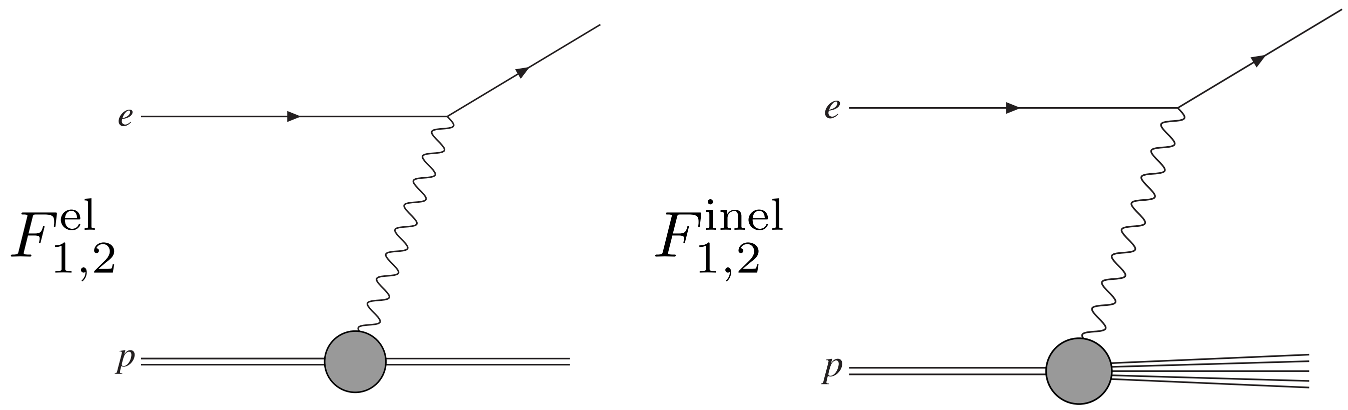
$$S^2 \sim 0.7 - 0.9$$



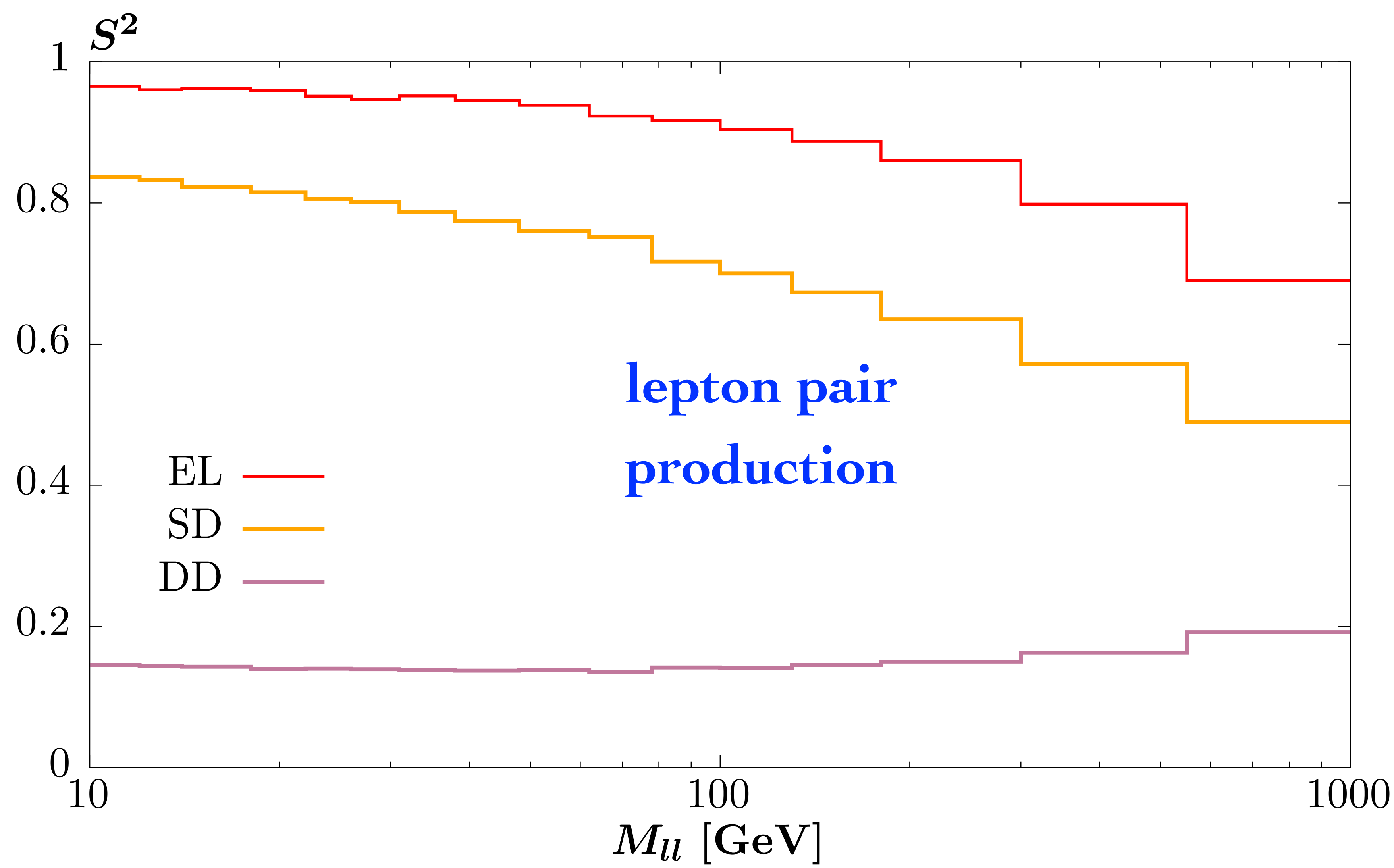
- What about dissociative production?

- 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^2 still rather high.



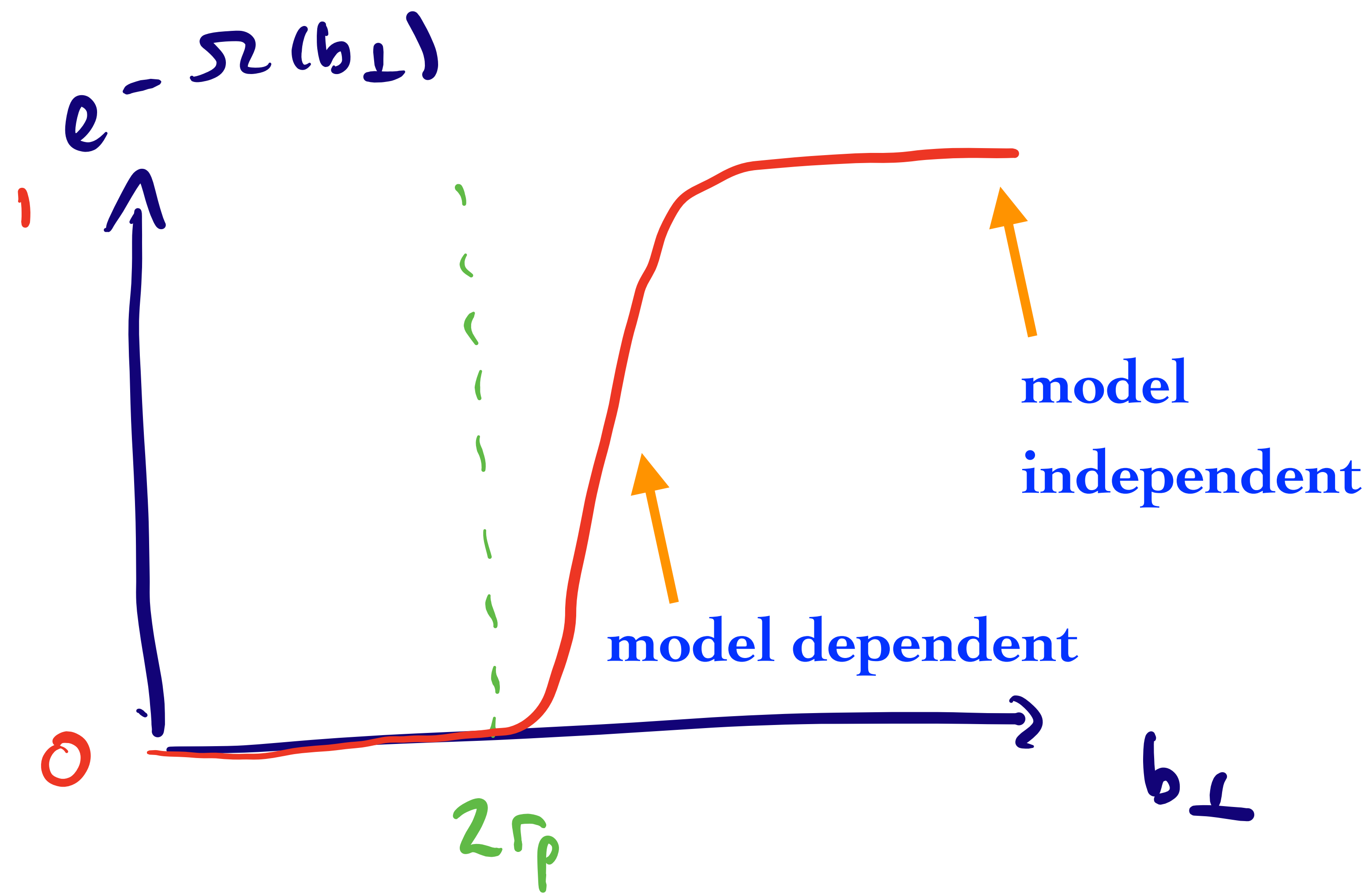
- For DD no longer case and $S^2 \sim 0.1$.



- 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).

- Other effects?

- Survival factor not constant: depends on process/kinematics.

$$\langle S^2 \rangle = \frac{\int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp}, \ldots)|^2 e^{-\Omega(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}}{\int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp}, \ldots)|^2}$$

$b_\perp \leftrightarrow q_\perp$

$$\langle S^2 \rangle = \frac{\int \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp} |M^{\mathrm{inc.}S^2}(\vec{q}_{1_\perp}, \vec{q}_{2_\perp}, \ldots)|^2}{\int \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp} |M(\vec{q}_{1_\perp}, \vec{q}_{2_\perp}, \ldots)|^2}$$

Kinematics

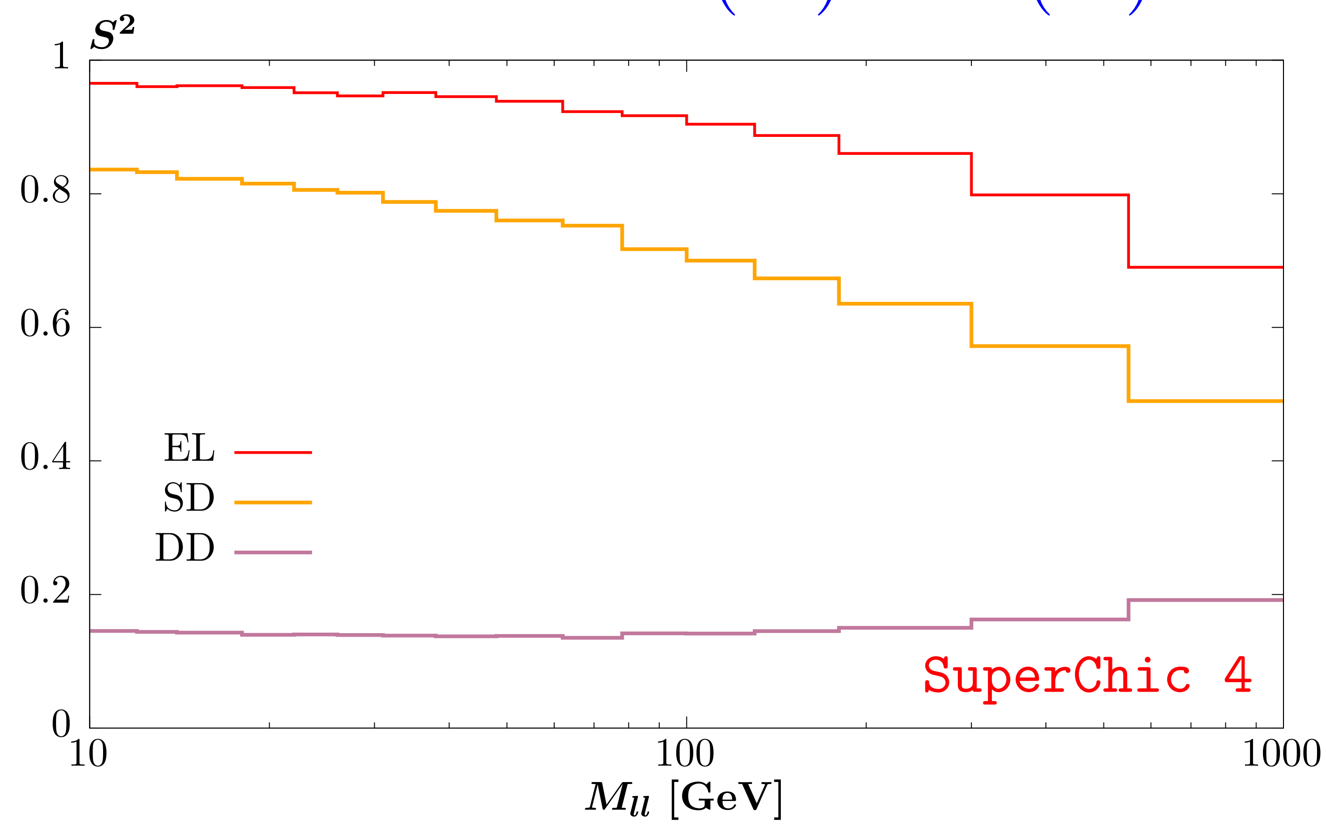
Process

- NB: this process dependence is often (incorrectly) omitted in literature

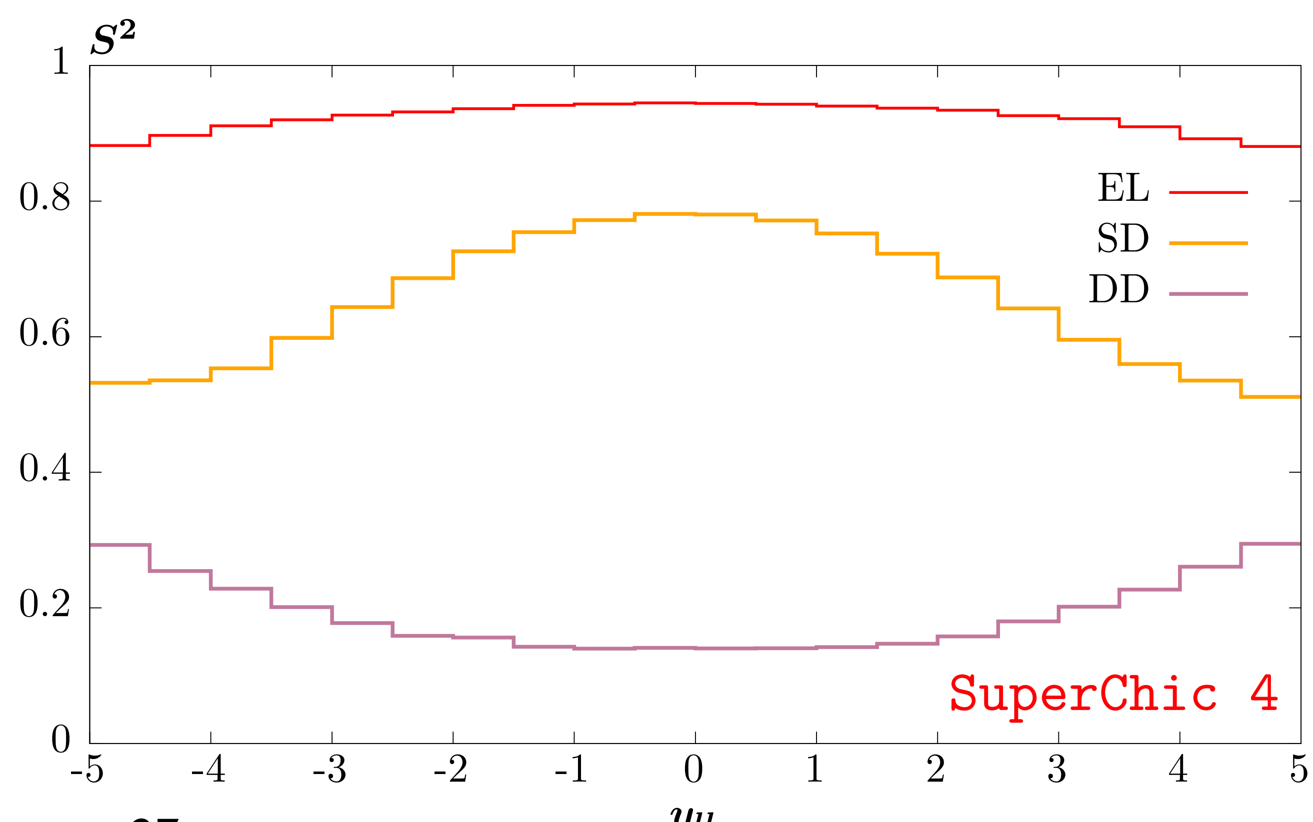
Results

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

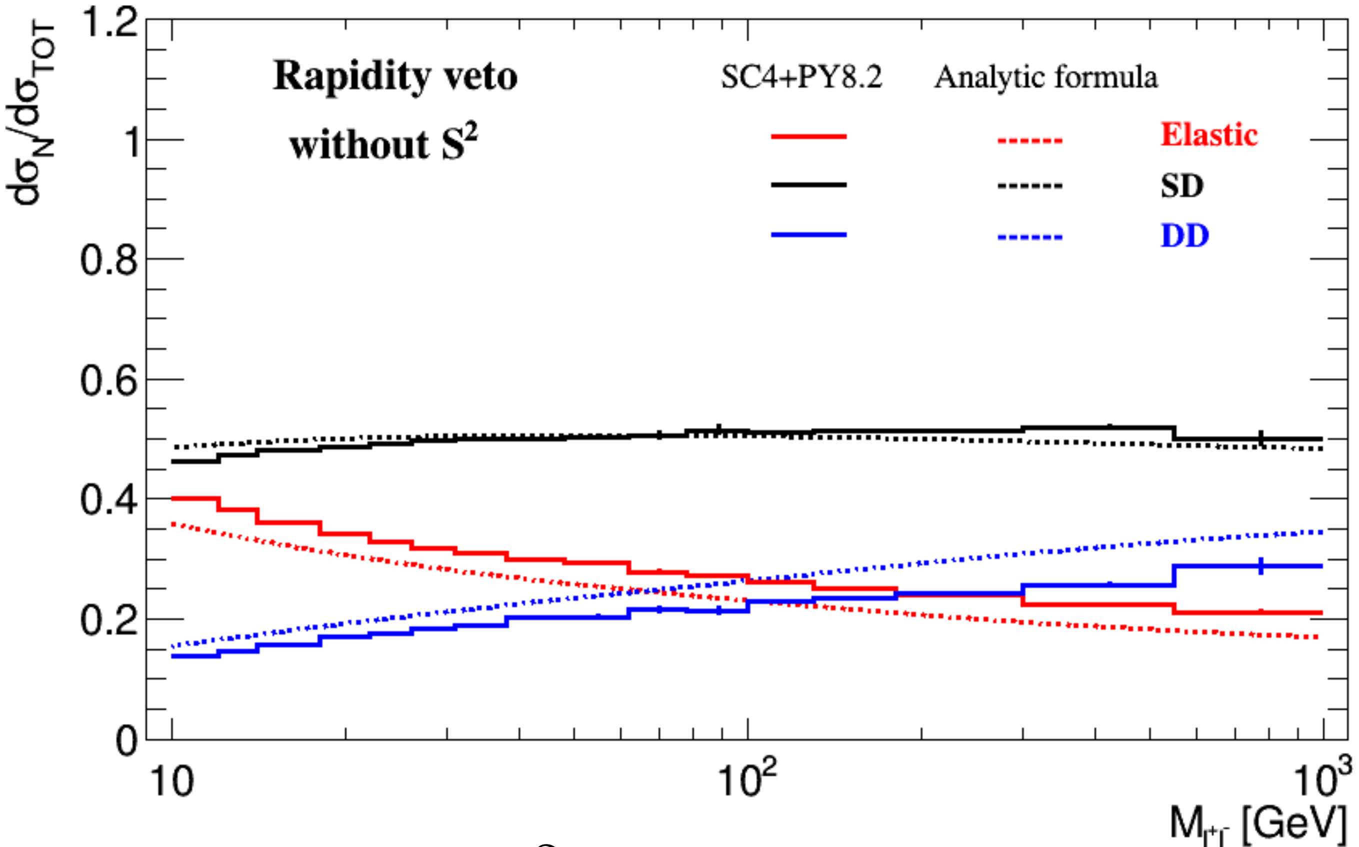
- (Again) scaling with elastic vs. dissociative clear.
- For SD case, $S^2 \sim 1$ still generally true as one proton elastic.

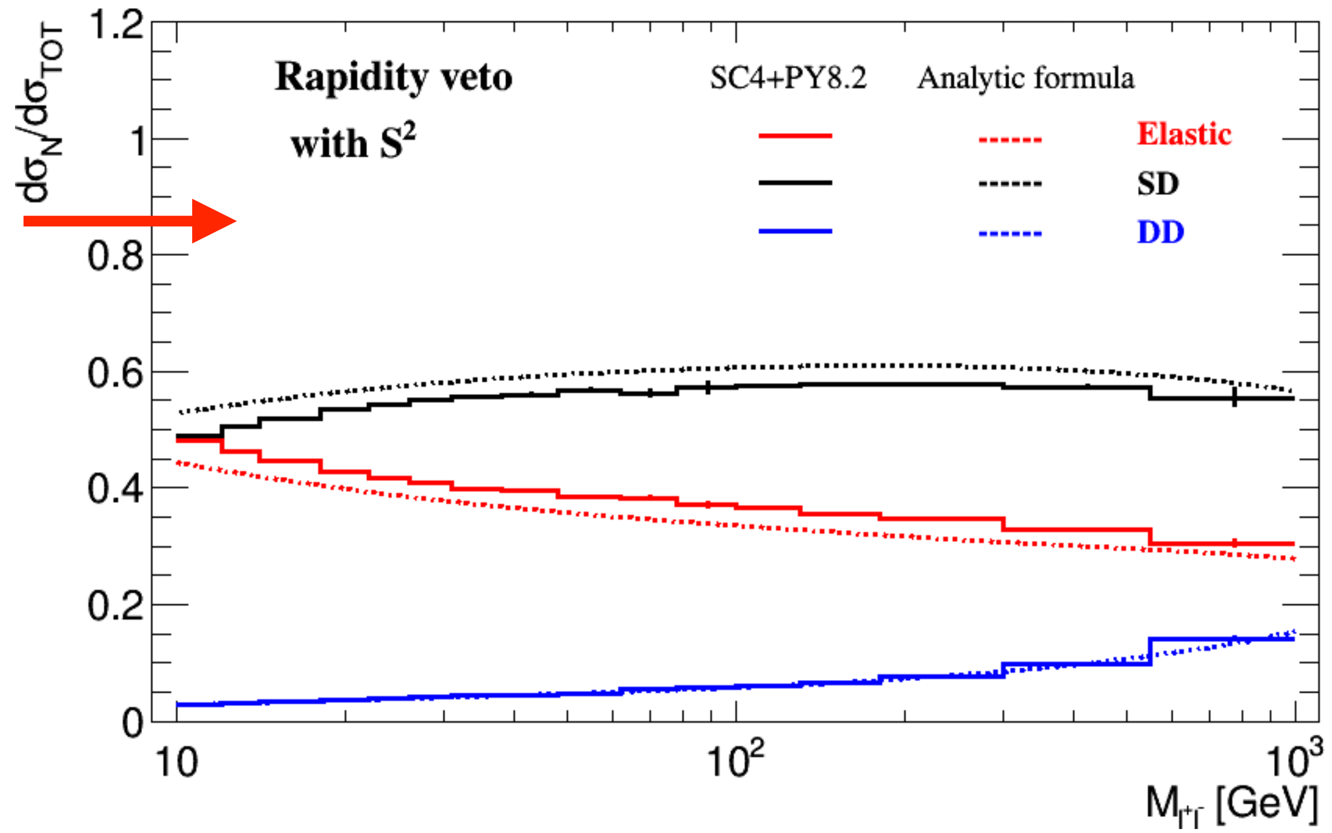


- Dependence on kinematics (e.g. y_{ll}, m_{ll}) also evident.



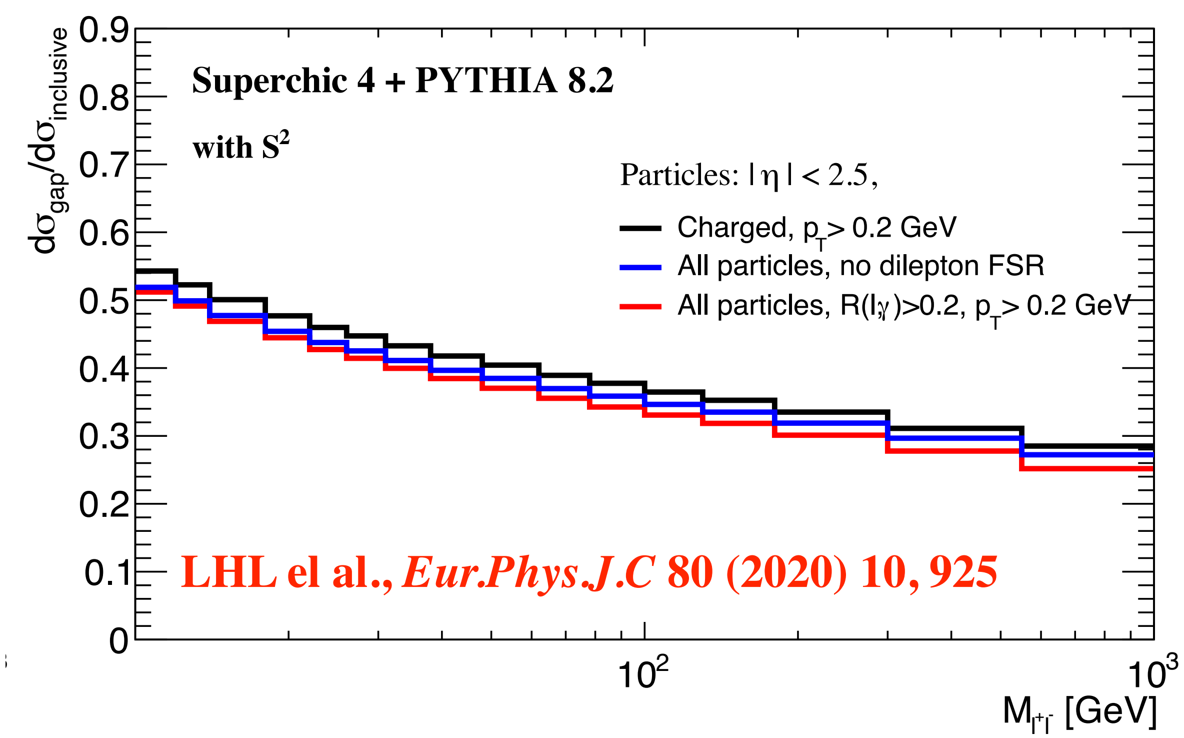
Veto Impact





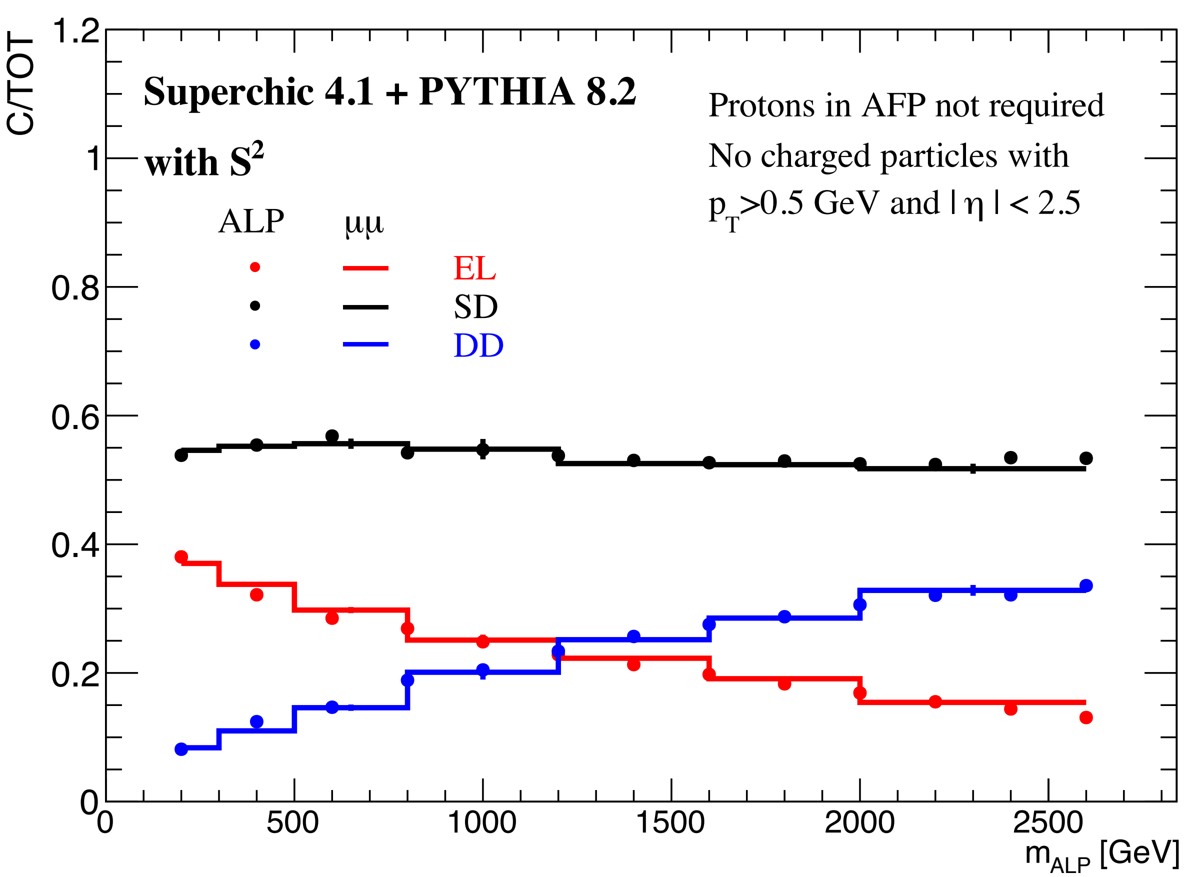
★ **Veto** + S^2 : strong suppression in DD. Elastic and SD comparable at lower m_{ll}, SD dominant as m_{ll} increases.

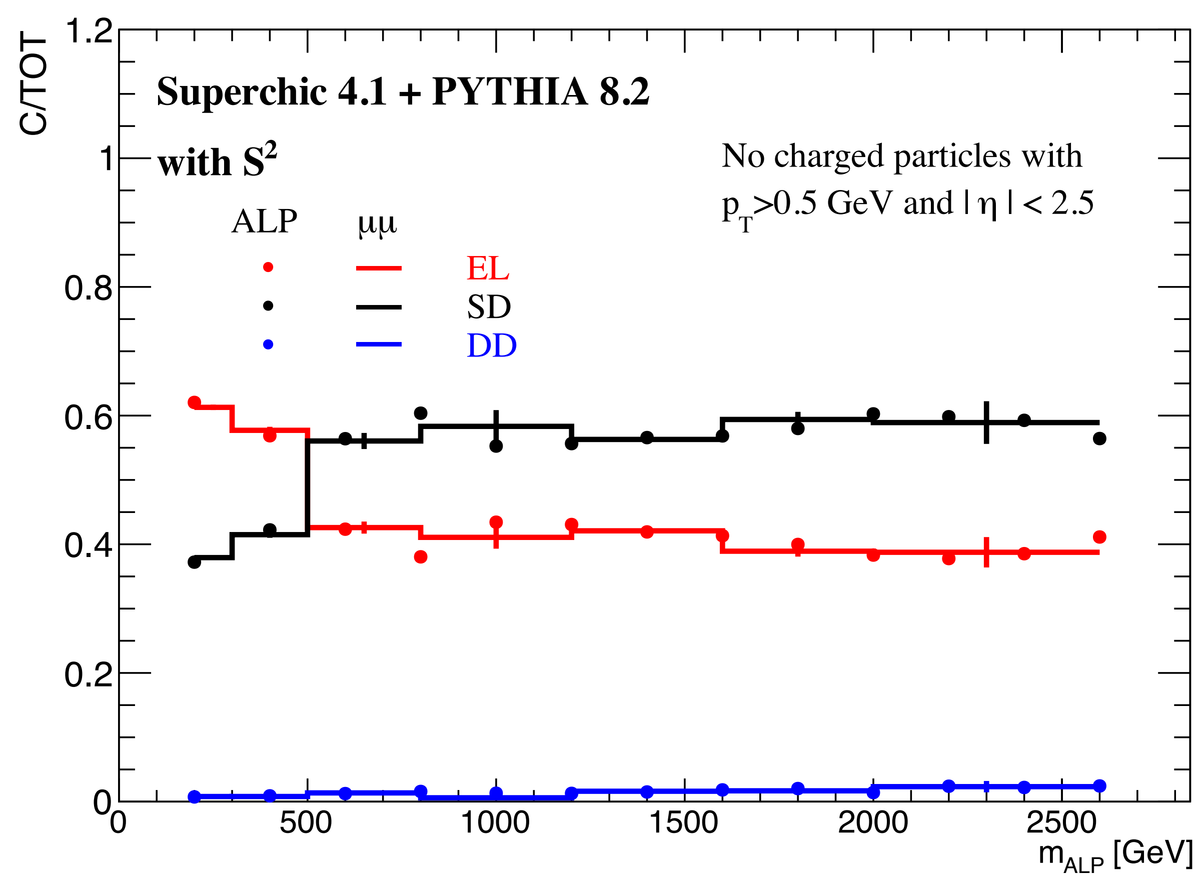
- Above result ~ close to analytic expectation (LO kinematics).
- Vetoing on charged particles only + realistic threshold gives **similar results**.



Proton Tag Impact

- Proton tag can be included at MC level (here for ALP production).
- As expected dissociation suppressed by even single tag.



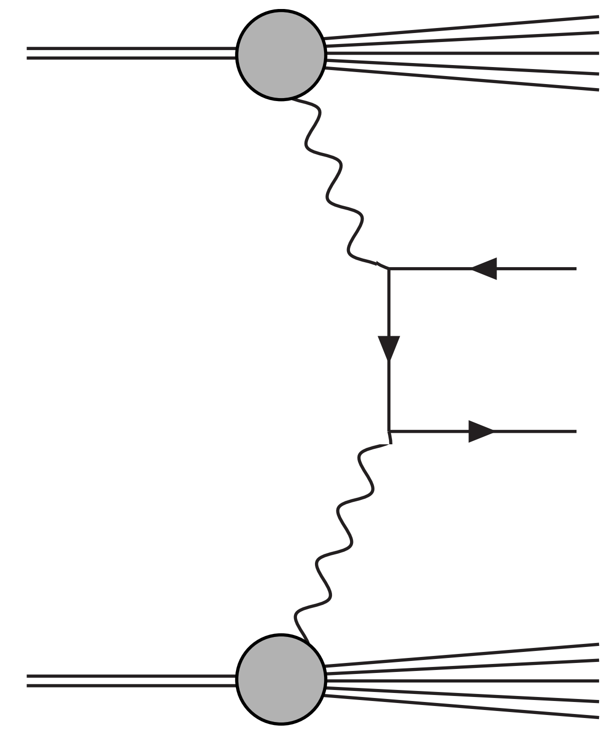


LHL and M. Tasevsky, arXiv:2208.10526

Other Considerations

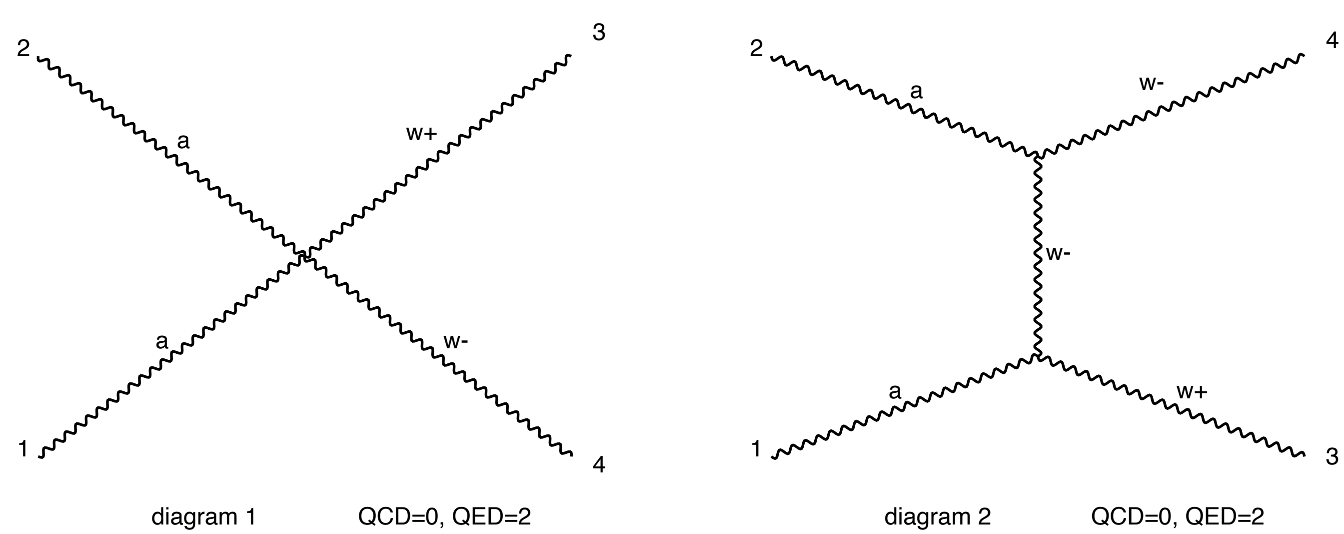
Collinear Calculation

- Also possible/relatively common to calculate PI cross section in collinear factorization. Given in terms of photon PDF



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

- This is what comes out of e.g. MG5 generator.

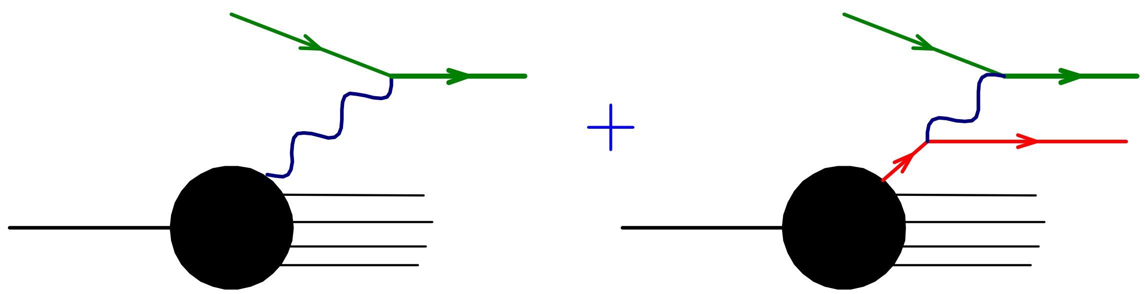


- Can show that collinear calculation is (approximately) equivalent to full structure function calculation for pure PI production:

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

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

- Approximate equivalence manifests itself in μ_F dependence of collinear result (absent in SF result).
- For LO collinear, this dependence is **large** (i.e. approximation relatively poor). Can improve agreement with SF by including higher order diagrams:

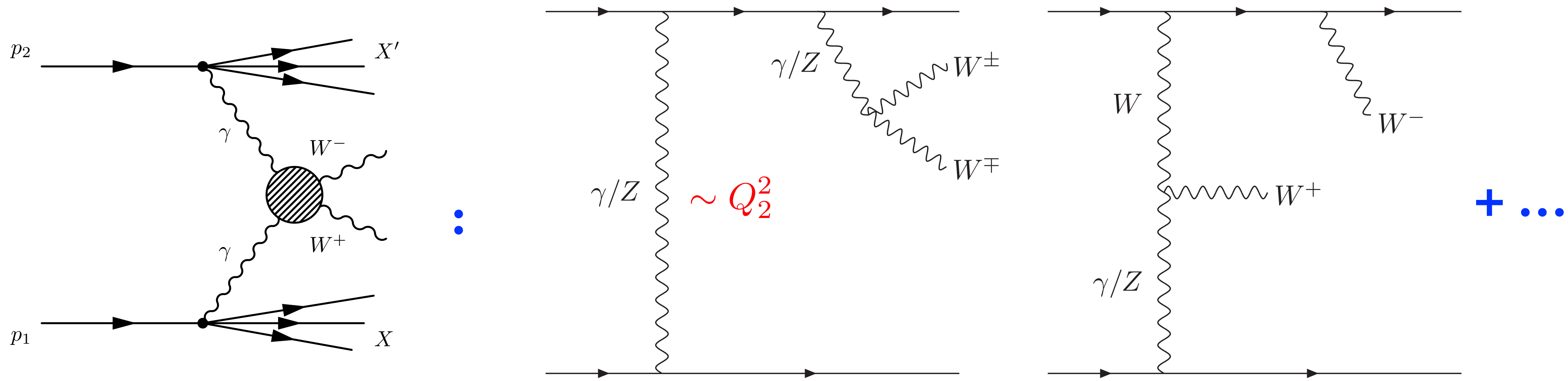


- But fore pure PI this is automatically accounted for in SF calculation.
- Moreover SF calculation (unintegrated in photon $k_\perp$) fundamental to calculation of survival factor.

However…

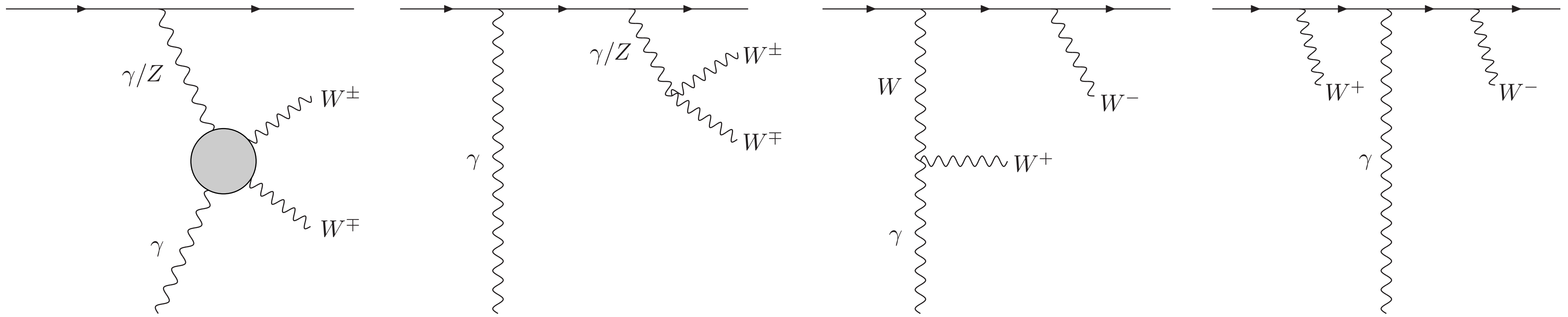
- SF calculation only accounts for pure PI (+ Z-initiated) production.
- For dissociative production this is not the only contribution. Discussed in detail for the case of WW production in **arXiv:2201.08403**.
- For e.g. the DD case also have:

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



- These non-PI diagrams are suppressed by at least $\sim Q^2/M_{W,Z}^2$ and so on principle **subleading**. But:
  - ⋆ The contribution is not necessarily negligible - to be determined.
  - ⋆ More importantly, the pure PI (+Z) contribution is **not individually gauge invariant** away from collinear limit.

- In general necessary to include both PI and non-PI diagrams when considering data without tagged protons.



- Accounted for in **arXiv:2201.08403** via so-called `hybrid' approach:

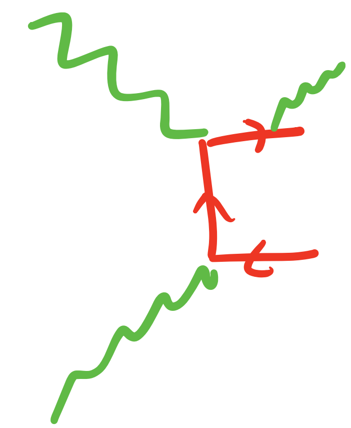
LHL, ***Phys.Rev.D*** **105 (2022) 9, 093010**

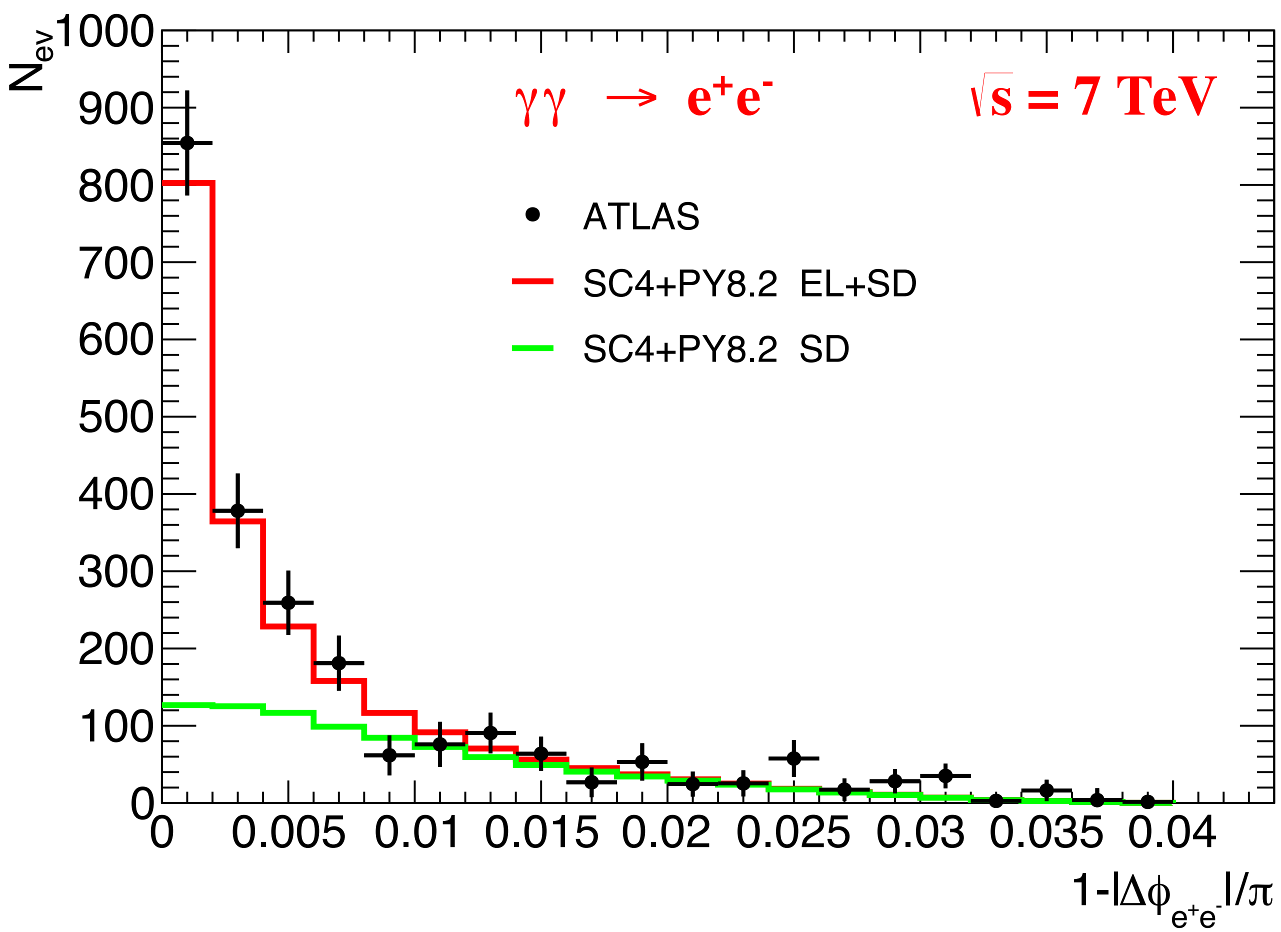
  - ⋆ SF calculation used in low photon Q^2 region.
  - ⋆ Full set of non-PI diagrams included in higher photon Q^2 region.

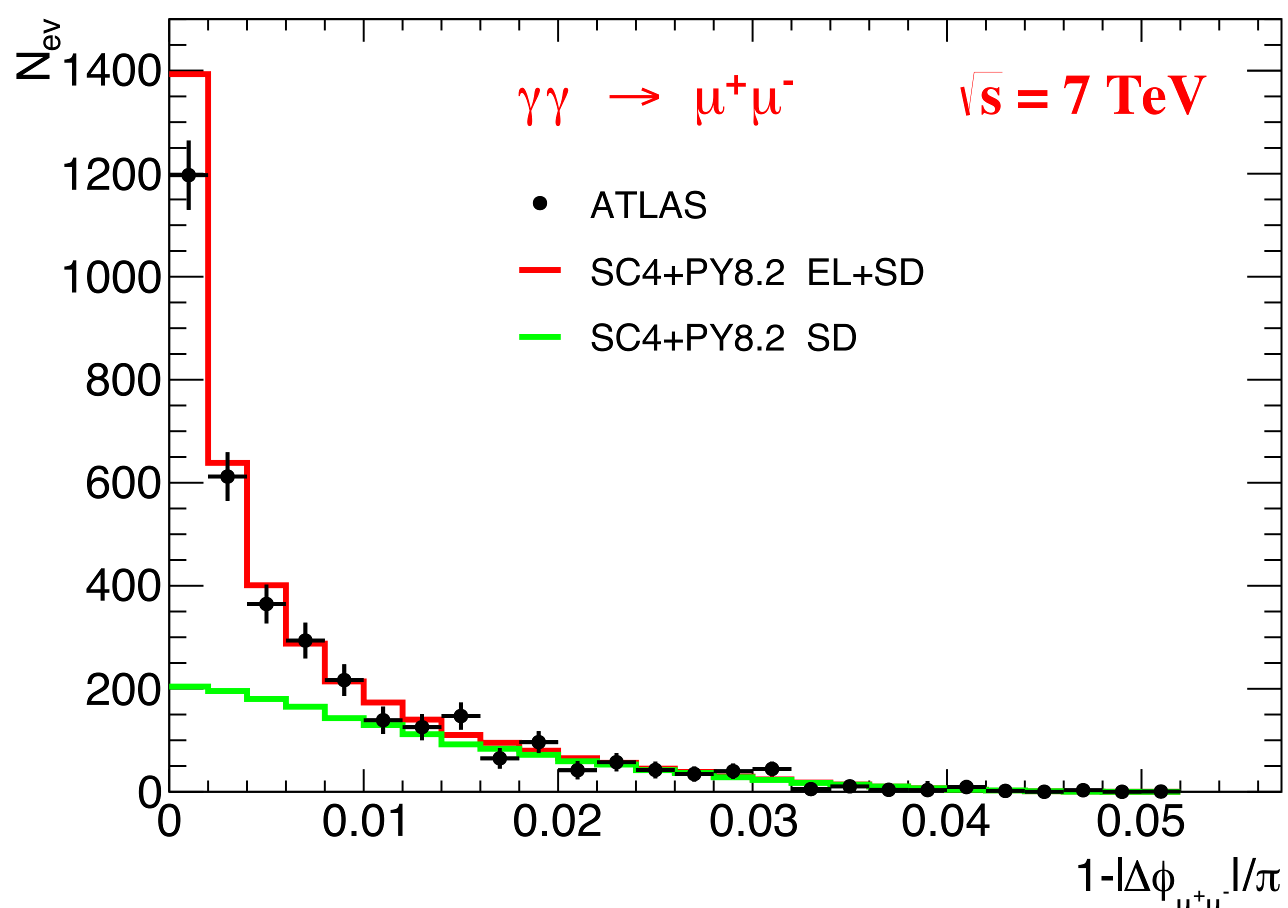
- Could also use (NLO…) collinear factorization although this comes with complications.
- Impact of non-PI production depends on experimental selection and process:
  - ⋆ W pair production: O(10%) correction.
  - ⋆ Lepton pair production: O(1%) correction.

Higher order QED?

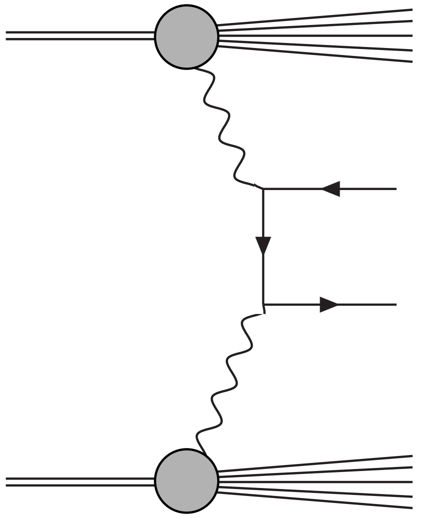
- Final consideration: $\gamma\gamma \to X$ subprocess.
- In general QED corrections should be 1% level - under good control.
- Only remark: if experimental cuts placed on acoplanarity $\Rightarrow$ sensitivity to system $p_\perp$. May enhance this.
- E.g. FSR in case of dilepton production, though can account after passing to general purpose MC.







Summary/Recap



- Basic ingredients for modelling PI production:

  ⋆ $p \to \gamma p(p^*)$ form factor. **: very well determined: % level uncertainties.**

  ⋆ \`**Survival factor**' probability of no addition proton-proton interactions. **: moderate effect for EL, SD with % level uncertainties**

  large reduction for DD, with larger uncertainties

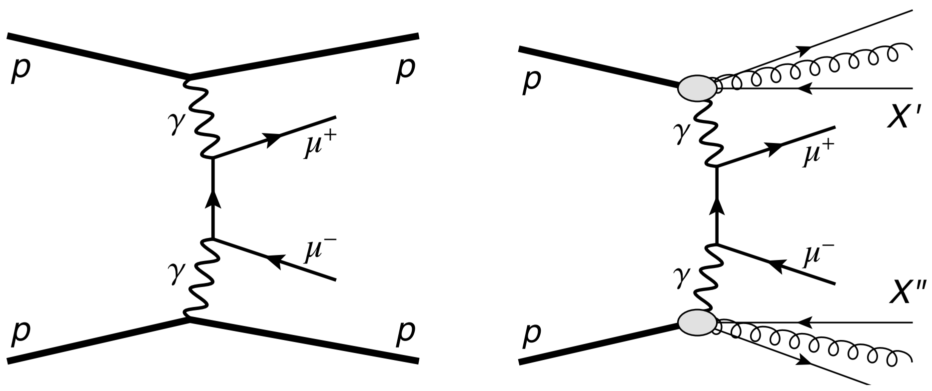
  ⋆ $\gamma\gamma \to X$ cross section. **: EW corrections may enter, though expectation is these are mild**

$\longrightarrow$ Theory under good control, ready for applications to BSM?

Where do we stand? Comparison to Data

What does the data say?

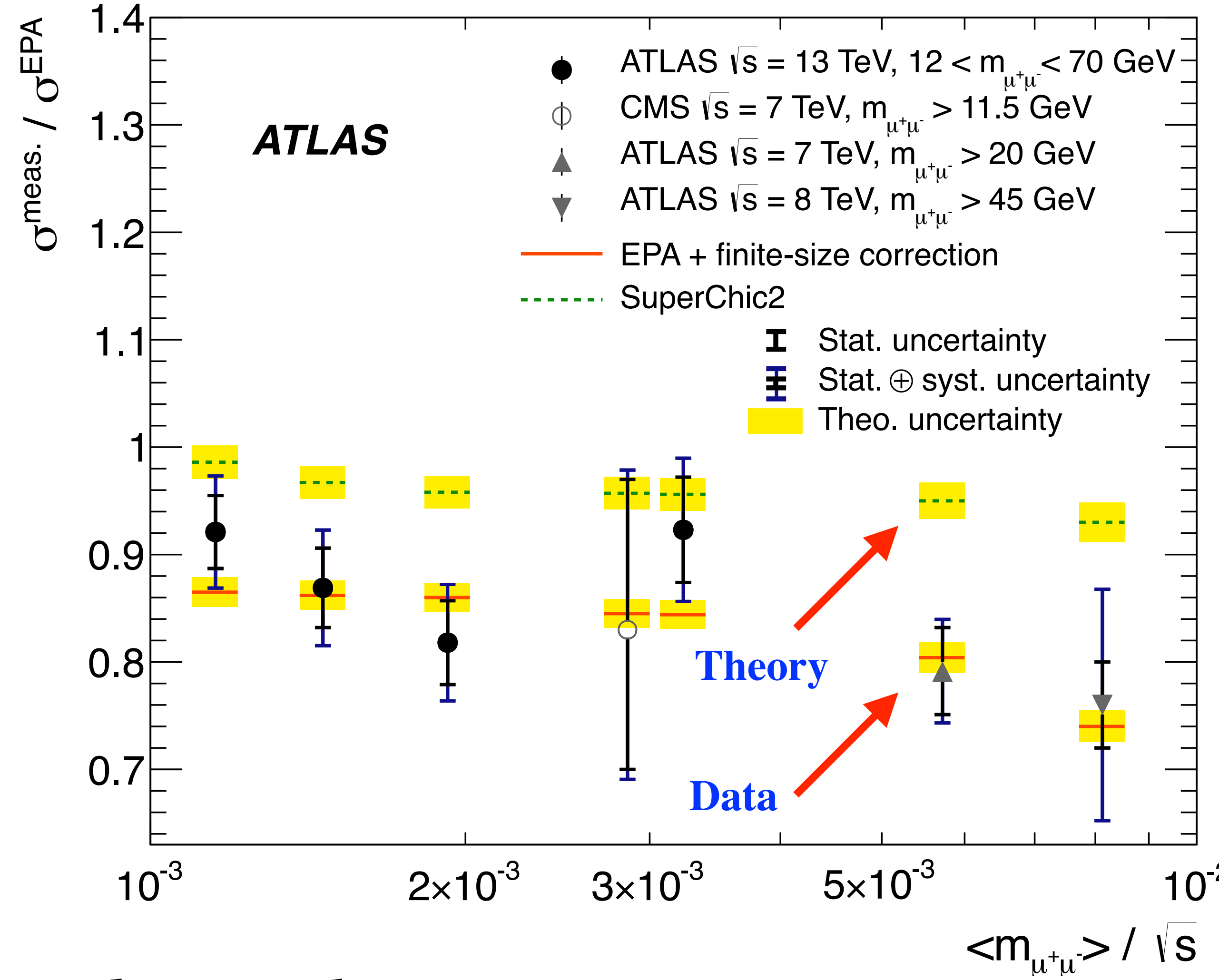
- Many BSM/SM scenarios to explore. First step: consider simplest 'standard candle' of **lepton pair** production.



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

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



- Multiple measurements of lepton pair production by **ATLAS/CMS**, selected via rapidity veto and/or single proton tag.
- Broad agreement, but SC predictions **overshoot** by O(10%) - 2-3 sigma.

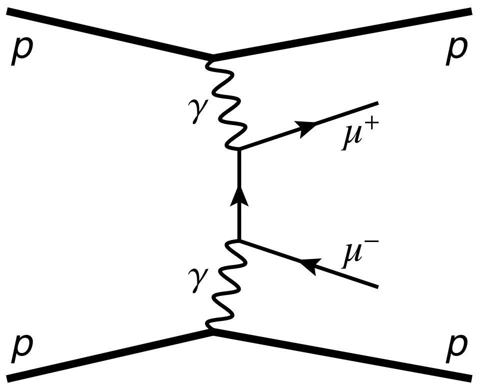
Theory vs. Data?

LHL, V.A Khoze, M.G. Ryskin, *SciPost Phys.* 11 (2021) 064

- This issue discussed in detail in recent paper: **arXiv:2104.13392**.

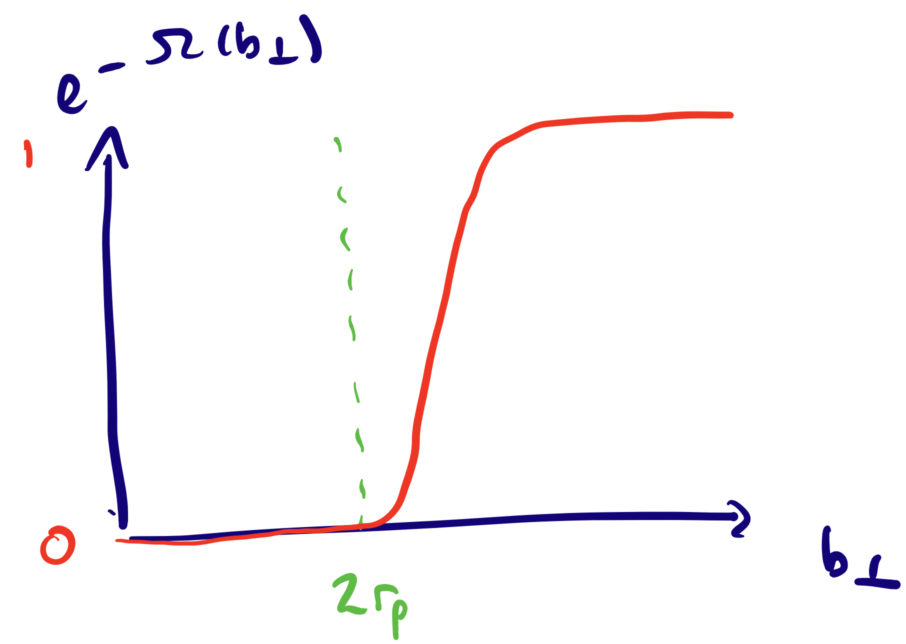
ATLAS, Phys. Lett. B 749, 242 (2015), Phys. Lett. B 777, 303 (2018)

	ATLAS data [14, 16]	Baseline	FF uncertainty	Dipole FF
σ [pb], 7 TeV	0.628 ± 0.038	0.742	$^{+0.003}_{-0.005}$	0.755
σ [pb], 13 TeV	3.12 ± 0.16	3.43	± 0.01	3.48



	ATLAS data [14, 16]	$\theta(b_\perp - 2r_p)$	$\theta(b_\perp - 3r_p)$
σ [pb], 7 TeV	0.628 ± 0.038	0.719	0.668
σ [pb], 13 TeV	3.12 ± 0.16	3.34	3.25

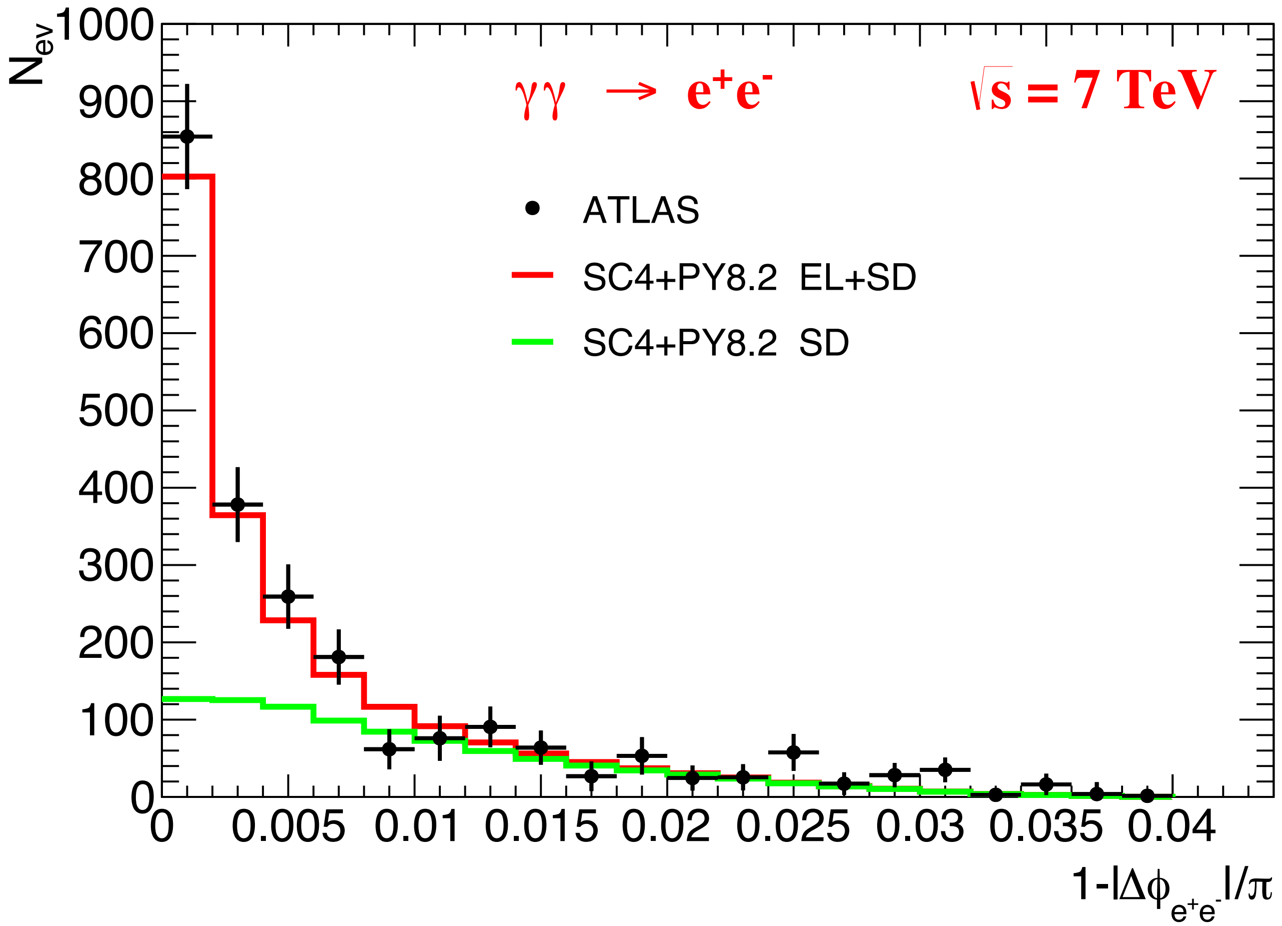
- Reasons for difference?
  - ⋆ Uncertainty from form factor: sub % level.
  - ⋆ Uncertainty from S^2 : even extreme (unrealistic) changes not sufficient.

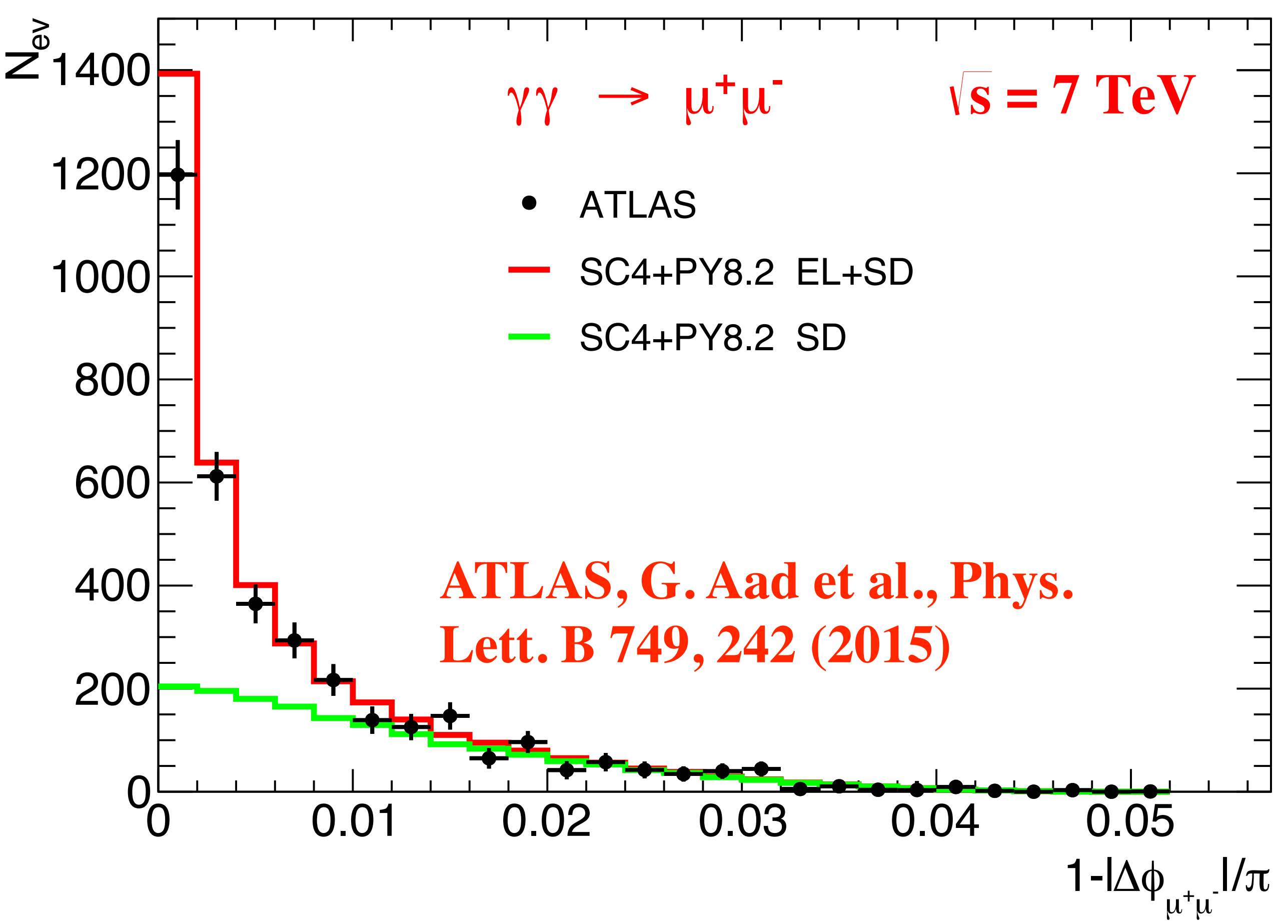


- Source of ~ 10% effect remains open question.

pp: other effects?

- ATLAS 7 TeV data suggests peaked at low dimuon acoplanarity.
- More differential data, including with proton tags will guide the way.
- Treatment of dissociative production (subtracted when quoting `El' result, sometimes with old MCs)? Higher order QED? No clear issue to point to.
- Electron data appear to be described better, but larger experimental errors.

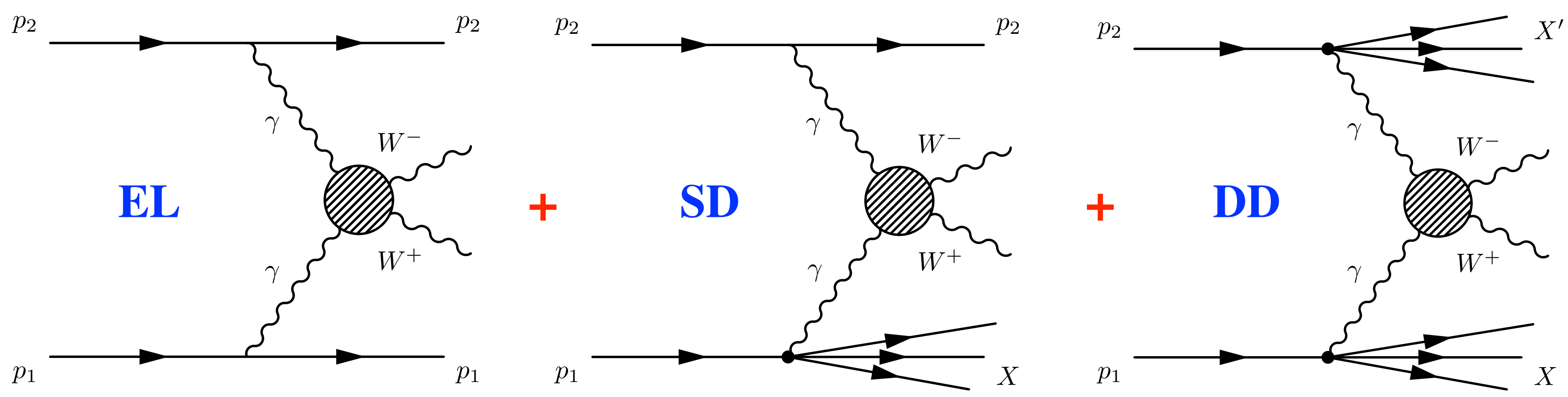




WW production

- **ATLAS 13 TeV** data, with lepton cuts + veto on associated tracks in: $p_\perp > 500\,\text{MeV},\ |\eta| < 2.5$

i.e. after subtracting BGs includes:



- We therefore need to evaluate all three contributions in SC:

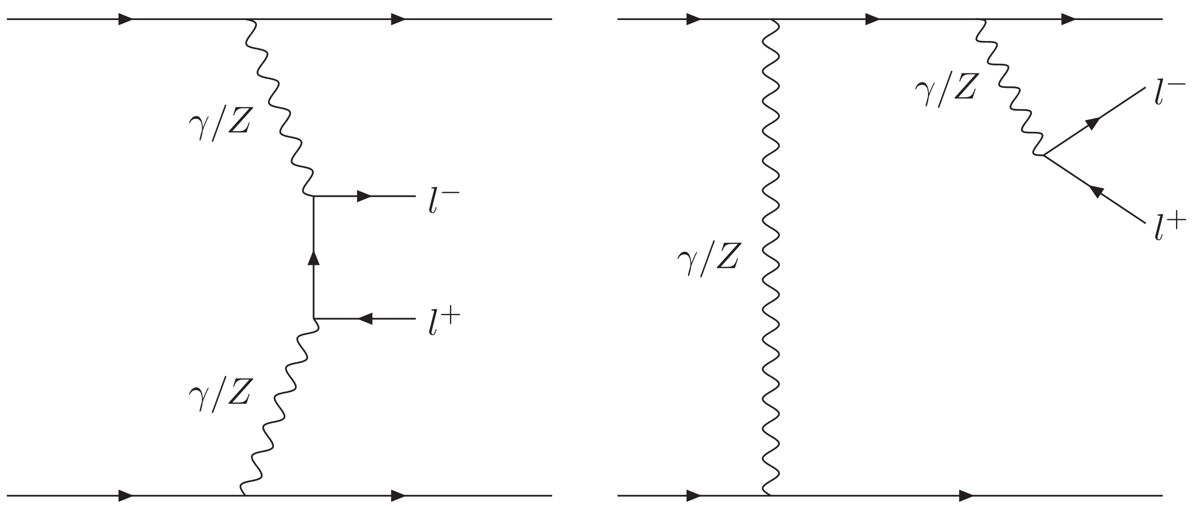
σ [fb] $(\sigma_i/\sigma_{\rm tot})$, W^+W^-	EL	SD	DD	Total
No veto, no S^2	0.701 (3.5%)	6.00 (30.3%)	13.1 (66.2%)	19.8
Veto, no S^2	0.701 (9.2%)	3.21 (42.3%)	3.68 (48.5%)	7.59
Veto, S^2	0.565 (18.6%)	1.87 (61.6%)	0.599 (19.8%)	3.03

- To compare with data: $\sigma_{\rm meas} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\,\text{fb}$

$\Rightarrow$ **Very good agreement**! In more detail….

- Impact of **non-PI**: compare with **lepton pair** production in similar kinematic region.

- Here impact of non-PI is found to be 1% level at most, and no issue with gauge invariance.



σ [fb] $(\sigma_i/\sigma_{\rm tot})$	EL	SD	DD	Total	f_γ^X
W^+W^-	0.565 (18.6%)	1.87 (61.6%)	0.599 (19.8%)	3.03	4.3
l^+l^-	9.61 (24.0%)	24.9 (62.5%)	5.42 (13.5%)	39.9	3.5

i.e. relative contribution from SD + DD is ~ 20% larger wrt pure EL in W^+W^- case. Dominantly due to **non-PI**.

$$f_\gamma^X \approx \frac{\sigma^{\rm EL} + \sigma^{\rm SD} + \sigma^{\rm DD}}{\sigma^{\rm EL}}$$

- Also leads to rather different breakdown between various channels. Crucial to account for - common previously to assume these are equal in extracting an 'exclusive' W^+W^- signal. In more detail…

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

σ [fb] ($\sigma_i/\sigma_{\rm tot}$)	EL	SD	DD	Total	f_γ^X
W^+W^-	0.565 (18.6%)	1.87 (61.6%)	0.599 (19.8%)	3.03	4.3
l^+l^-	9.61 (24.0%)	24.9 (62.5%)	5.42 (13.5%)	39.9	3.5

3.5 ± 0.5

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

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

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

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

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

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

- But we do not expect this to be true! **ATLAS** measure: $f_\gamma^{ll} = 3.59 \pm 0.15$

- Agrees well with our theory. But follow above procedure get:

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

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

Heavy Ion Collisions

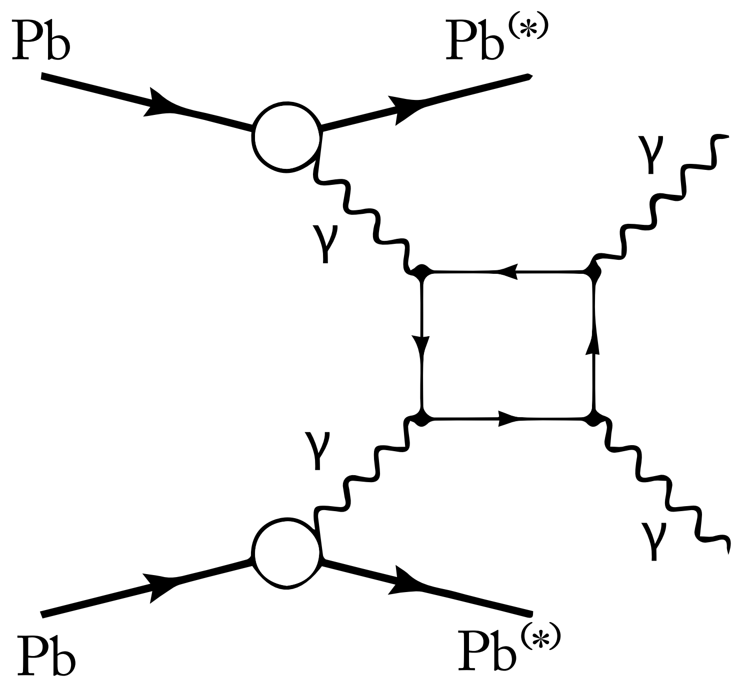
PI production and Heavy Ion Collisions

- PI production also key channel in heavy ion collisions.
- Theoretical framework broadly similar to pp case:

★ Elastic form factor.

★ $\gamma\gamma \to X$ cross section.

★ \`**Survival factor**' probability of no addition ion-ion interactions.



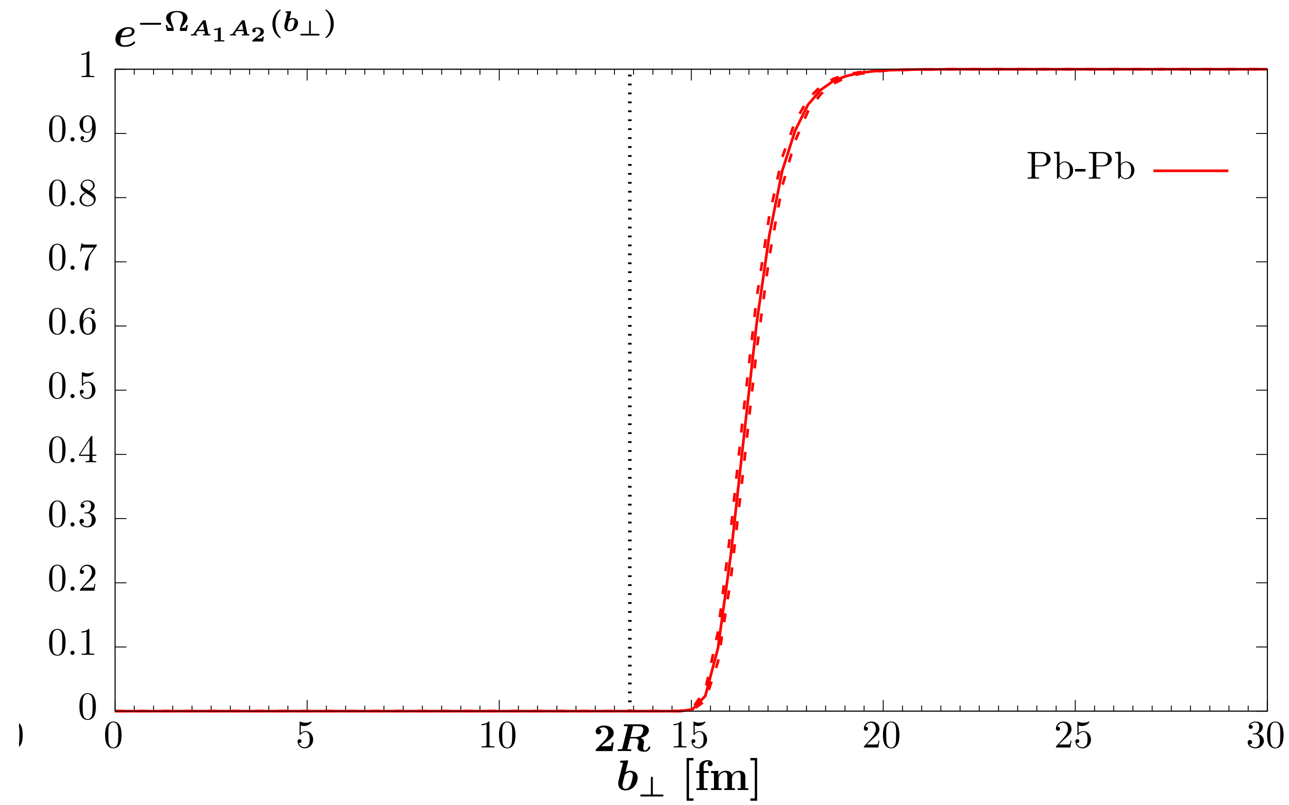
- Elastic form factor ~ ion charge density.

$$F_p(|\vec{q}|) = \int \mathrm{d}^3 r\, e^{i\vec{q}\cdot\vec{r}} \rho_p(r)$$

$$F_p \propto Z \Rightarrow \text{cross section} \propto F_p^4 \sim Z^4\text{: strong enhancement}$$

★ Survival factor: similar situation to pp, i.e. cross section dominantly occurs outside range of QCD.

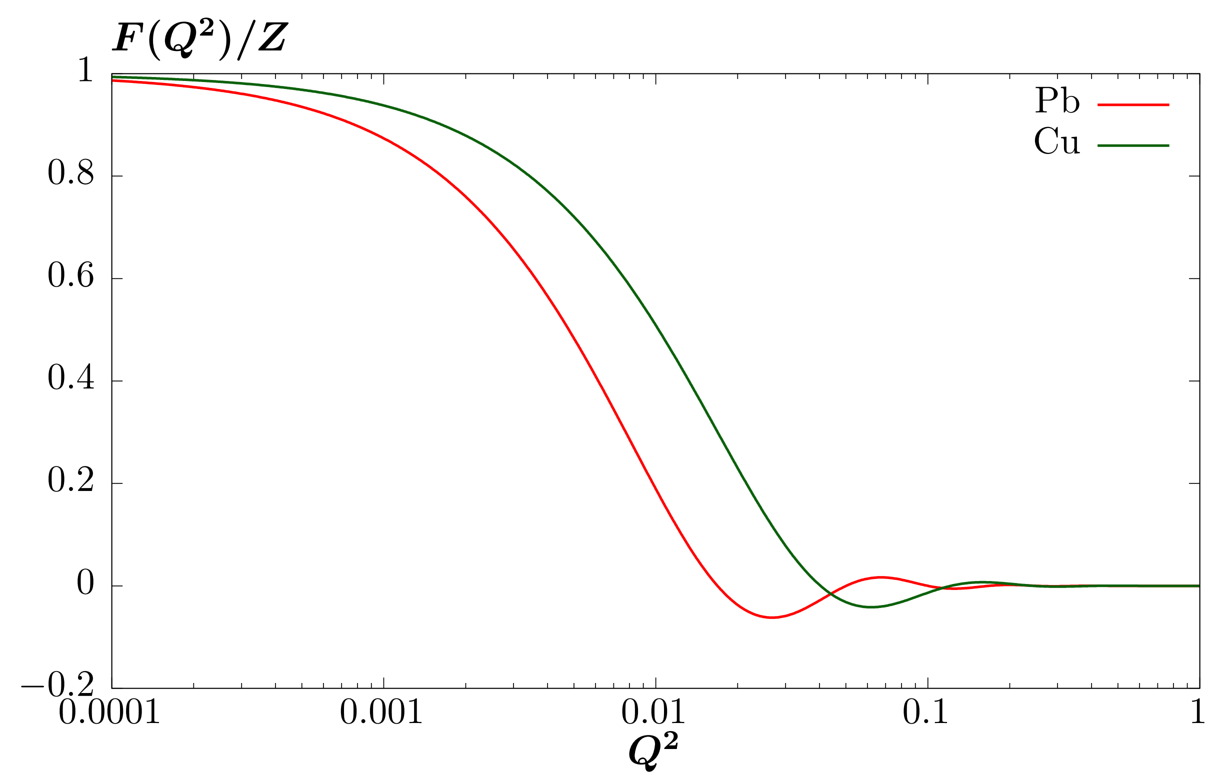
$\Rightarrow S^2 \sim 1$, with small uncertainty



★ Input for elastic form factors very well determined.

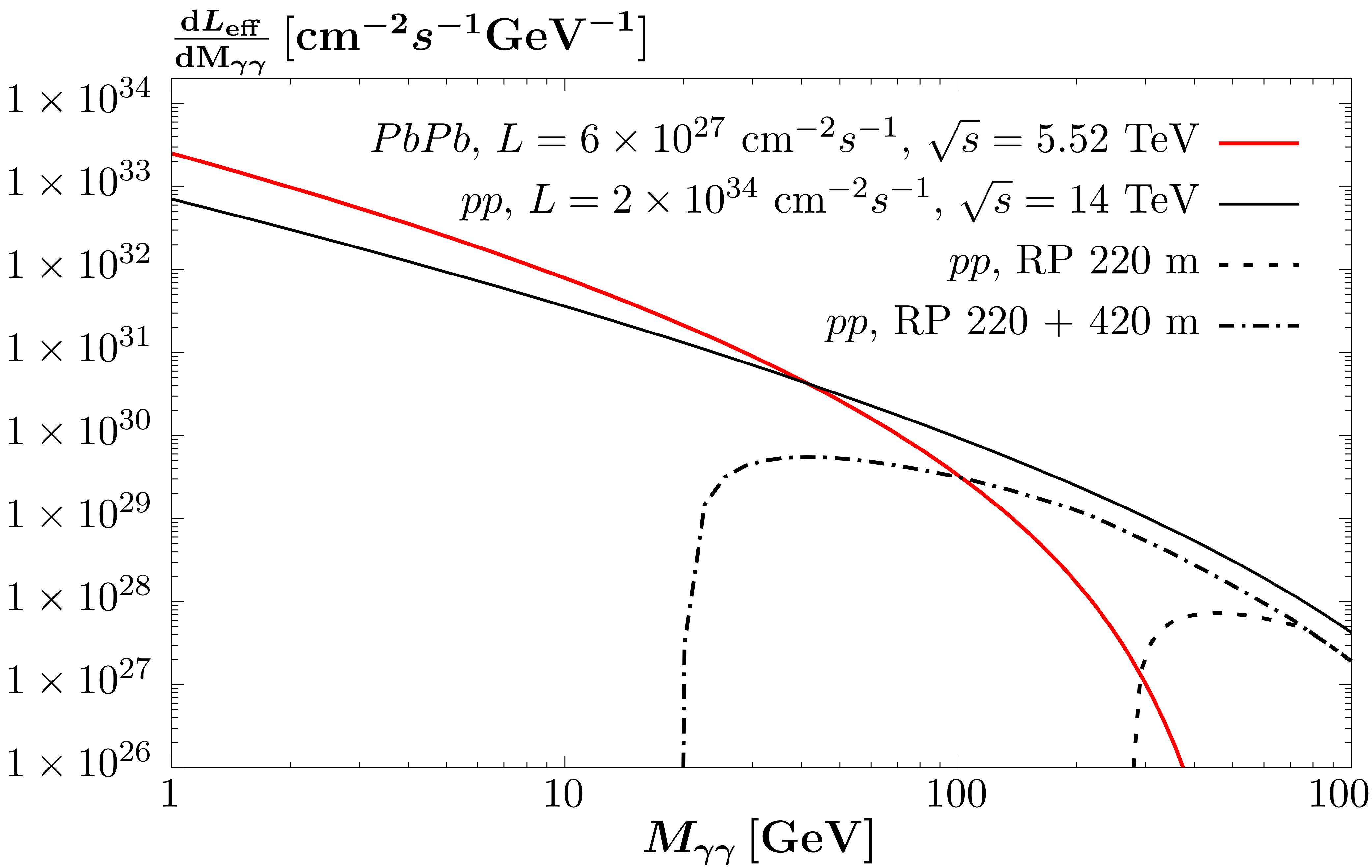
$$\rho_p(r) = \frac{\rho_0}{1 + \exp{(r - R)/d}} \; ,$$

$$R_p = 6.680\,\mathrm{fm} \; , \qquad d_p = 0.447\,\mathrm{fm} \; ,$$



★ Form factor peaked at very low photon Q^2 limits photon energy fraction x and hence $M_{\gamma\gamma}$ to be rather low…

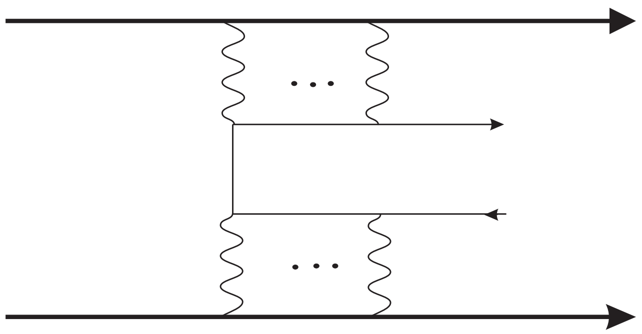
- Lower $M_{\gamma\gamma}$: heavy ions dominate.
- Higher $M_{\gamma\gamma}$: pp dominates.



- In addition, range of theoretical effects enter that play less of a role in pp case...

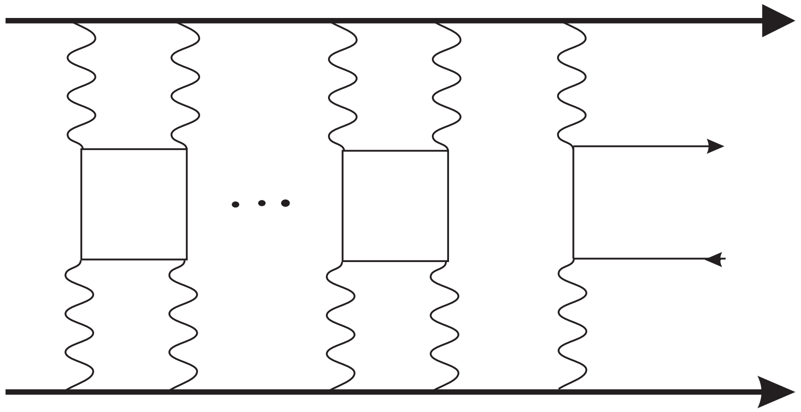
PbPb: other effects

W. Zha and Z. Tang, (2021), 2103.04605.



- **HO QED** effects? Recent paper suggests could act in this direction/with this size.
- But controversial. Previous studies predict much smaller effect, expect to be suppressed by $\sim Q^2/m_{\mu\mu}^2$

K. Hencken, E.A. Kuraev, V. Serbo, *Phys.Rev.C* 75 (2007) 034903…

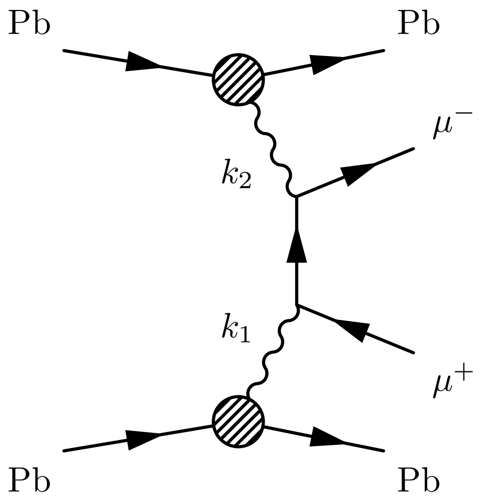


- **Unitary corrections**? Studies suggest ~ 50% events accompanied by additional e^+e^- pairs.
- Might these be vetoed on? Strongly peaked at low m_{ee} so perhaps not. But requires study.
- **Ion dissociation**? Not in SC (but in Starlight). Dominantly driven by additional ion-ion QED exchanges, i.e. unitary. Other inelastic emission subtracted from data.
- **QED FSR**? Included via Pythia in predictions, but worth recalling that production of such back-to-back leptons particularly sensitive to this.

$\longrightarrow$ Relevance of these effects clearly not limited to (SM) dimuon production!

Comparison to data

- All of the above relevant to fact that in dilepton channel (as in pp) some tendency to overshoot data:

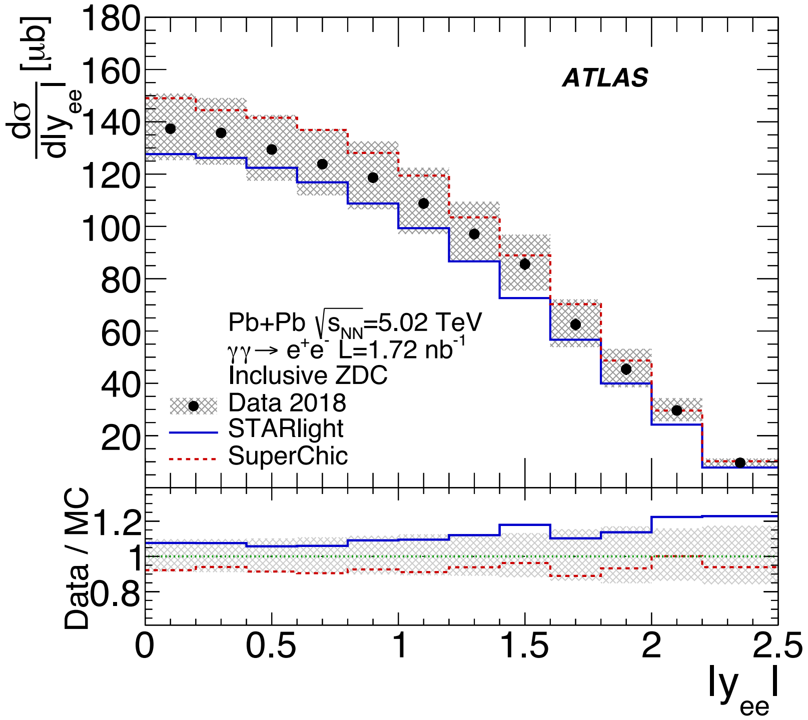


	ATLAS data [23]	Pure EPA	inc. S^2	inc. S^2 + FSR
σ [μb]	34.1 ± 0.8	52.2	38.9	37.3

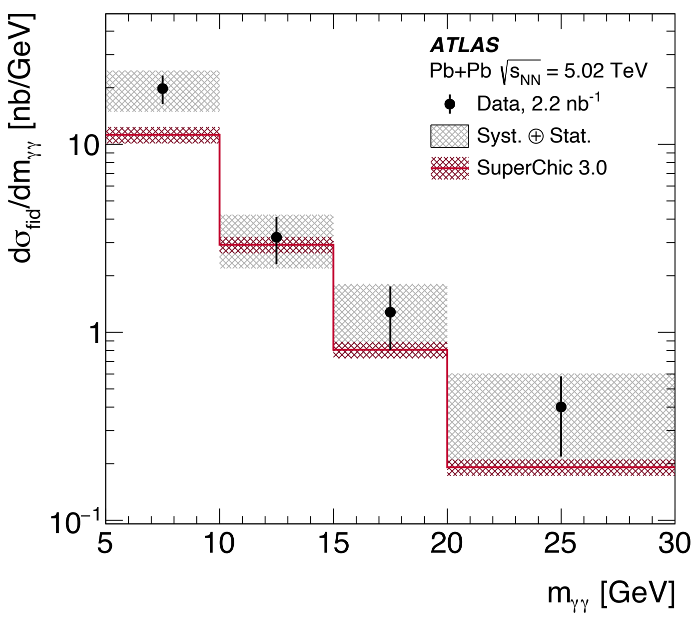
ATLAS, *Phys.Rev.C* 104 (2021) 024906

ATLAS, arXiv:2207.12781

- Though distributions ~ well described.



- For LbyL scattering on the other hand tendency to undershoot data!



ATLAS, *JHEP* 03 (2021) 243

Summary/Outlook

- ⋆ Robust theoretical framework + MC implementation for (semi -) exclusive photon-initiated production available.
- ⋆ Basic physics is well understood, impact of non-QED survival factor effects small but not negligible for EL and SD.
- ⋆ For DD strong suppression from survival factor, uncertainties larger.

$\longrightarrow$ Provides firm theoretical basis for BSM/EFT studies etc. Many promising channels with both double and proton single tags.

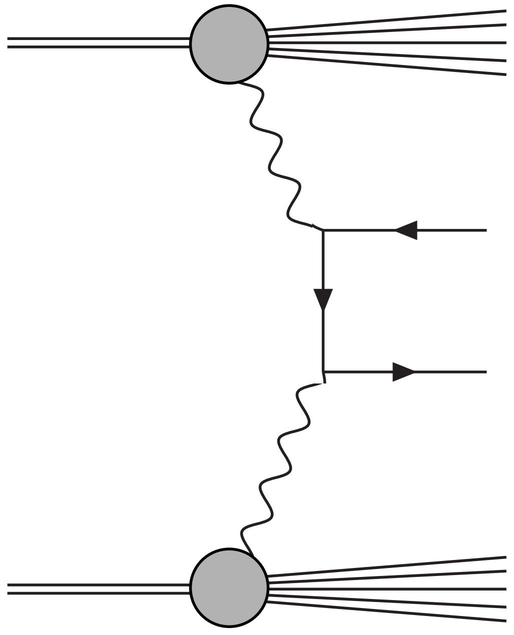
- On the other hand theoretical work not over:

    - ⋆ Small differences in data/theory?
    - ⋆ Higher-order QED?
    - ⋆ Going beyond 100% survival?
    - ⋆ Heavy ions: dissociation, higher order QED.
    - ⋆ …

Thank you for listening!

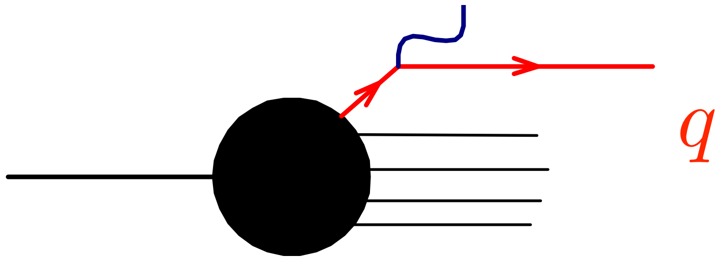
Backup

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.

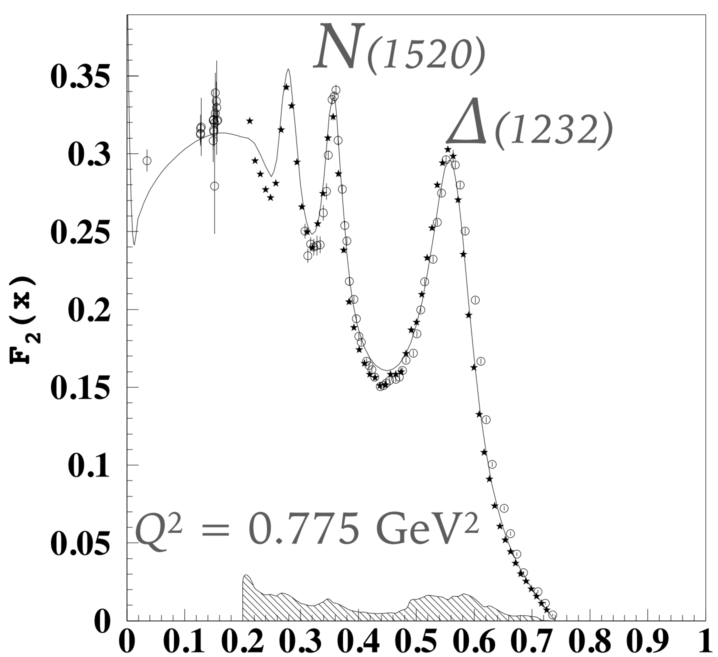
- No clear off-the-shelf way to do this, so take simplified approach:
    - ★ For purposes of LHE record, for inelastic emission take LO $q \to q\gamma$ vertex
    - ★ Generate outgoing quark according to momentum conservation, preserving photon 4-momentum.

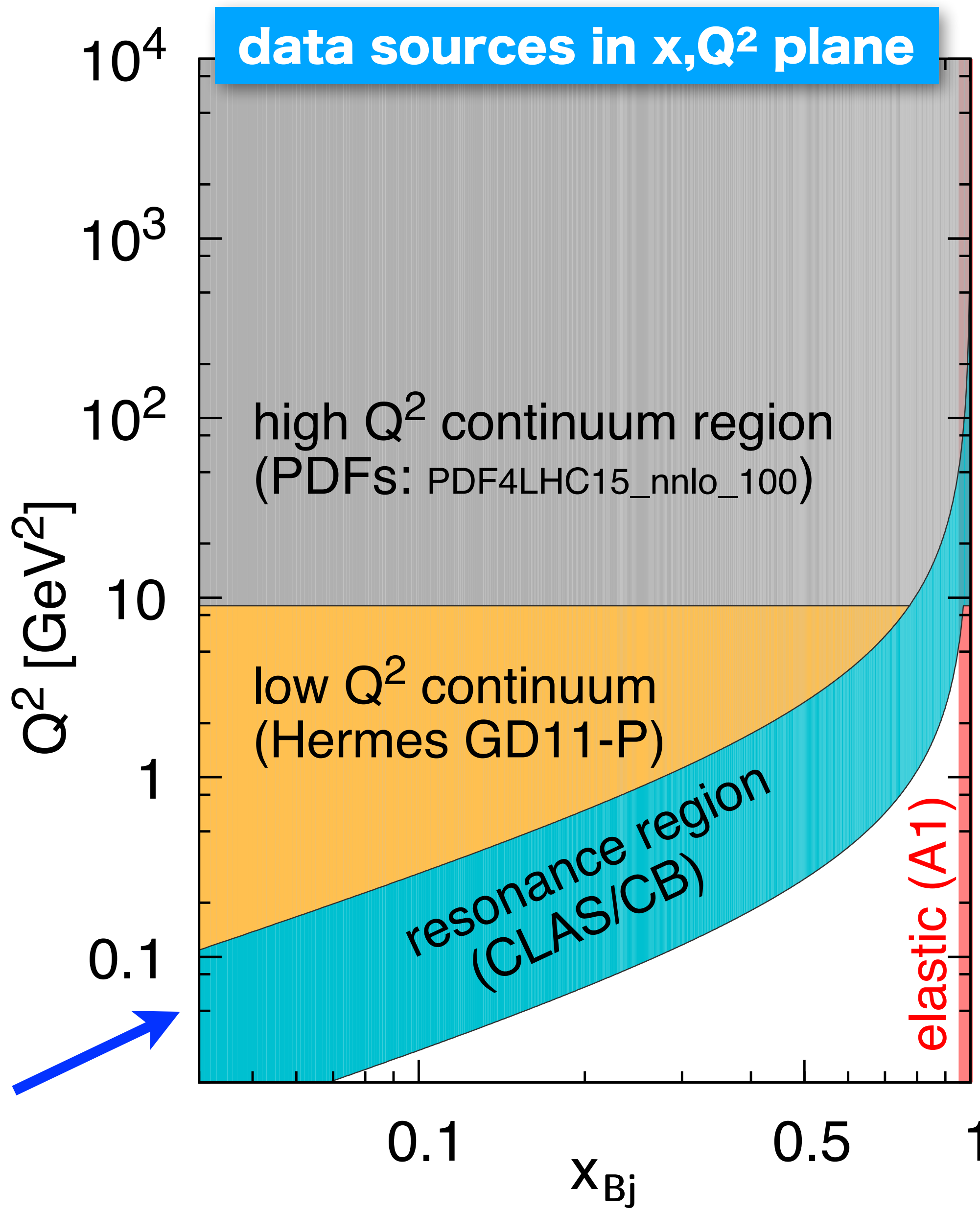


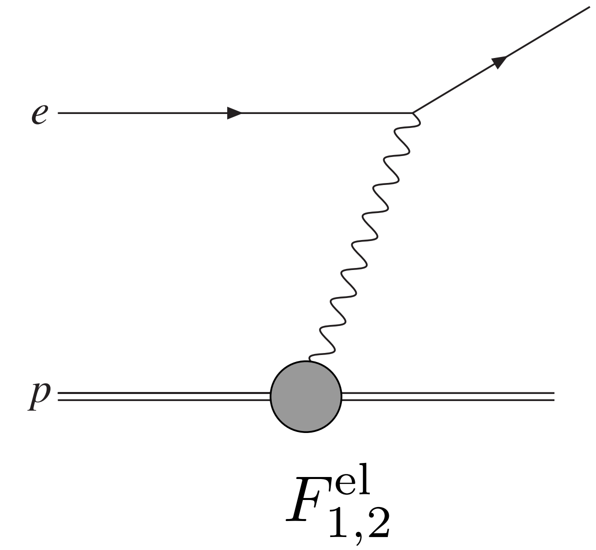
- ISR/FSR will then modify photon 4-momentum. Not ideal, but for purpose of current study sufficient.
- In addition, must turn off global recoil in Pythia to get realistic result (no colour connection between beams).

Image credits: Gavin Salam

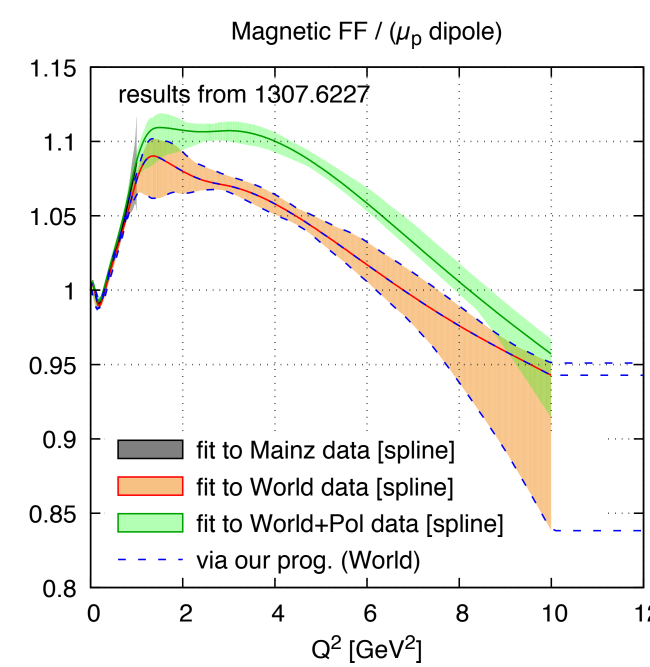
- In more detail, components of $F_{1,2}$ break up into four regions:







Elastic scattering: from A1 collaboration.



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

Inelastic resonant proton excitation. Precise parameterisations available.

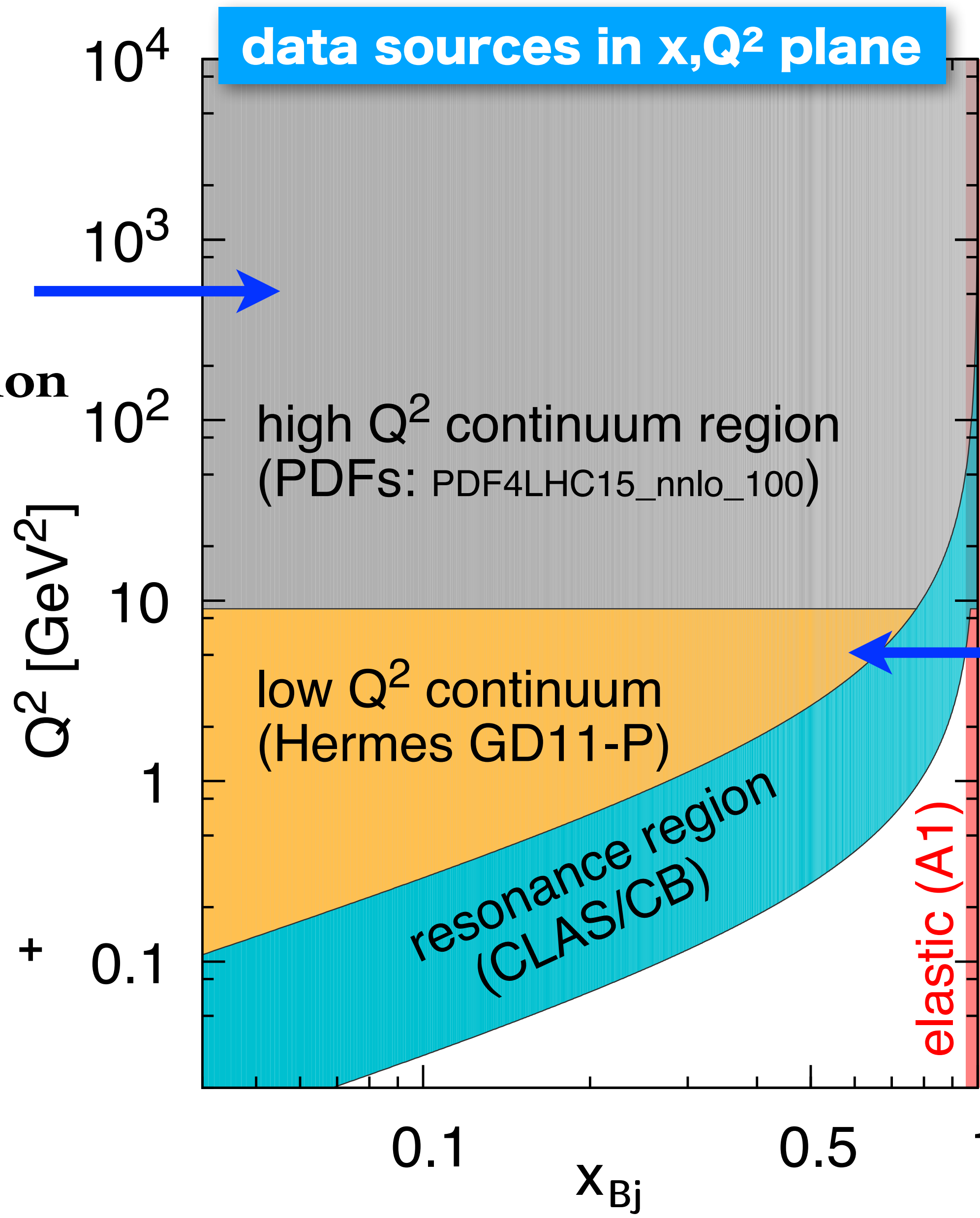
CLAS, M. Osipenko et al., Phys. Rev. D67, 092001 (2003)

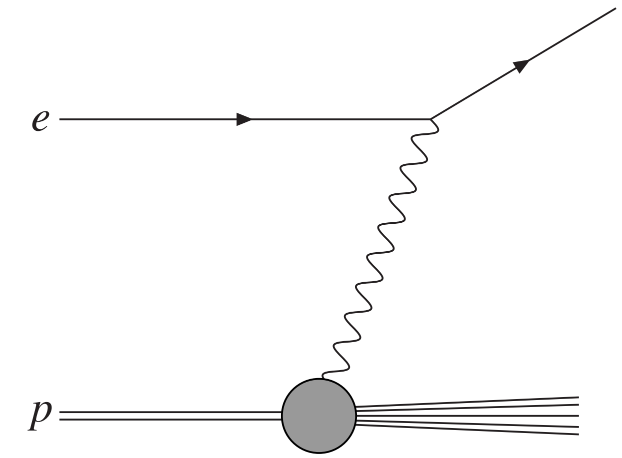
Image credits: Gavin Salam

- 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).

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

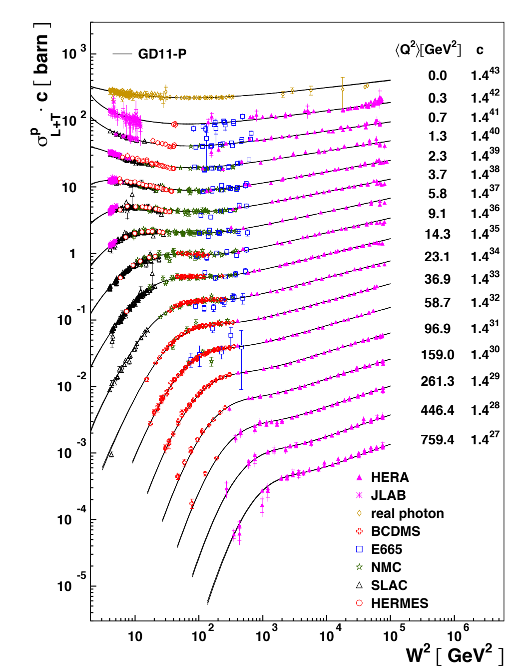




$F_{1,2}^{\rm inel}$

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 $Q^2 > 1{\rm GeV}^2$