Photon-Initiated Production at the LHC: Theory Overview

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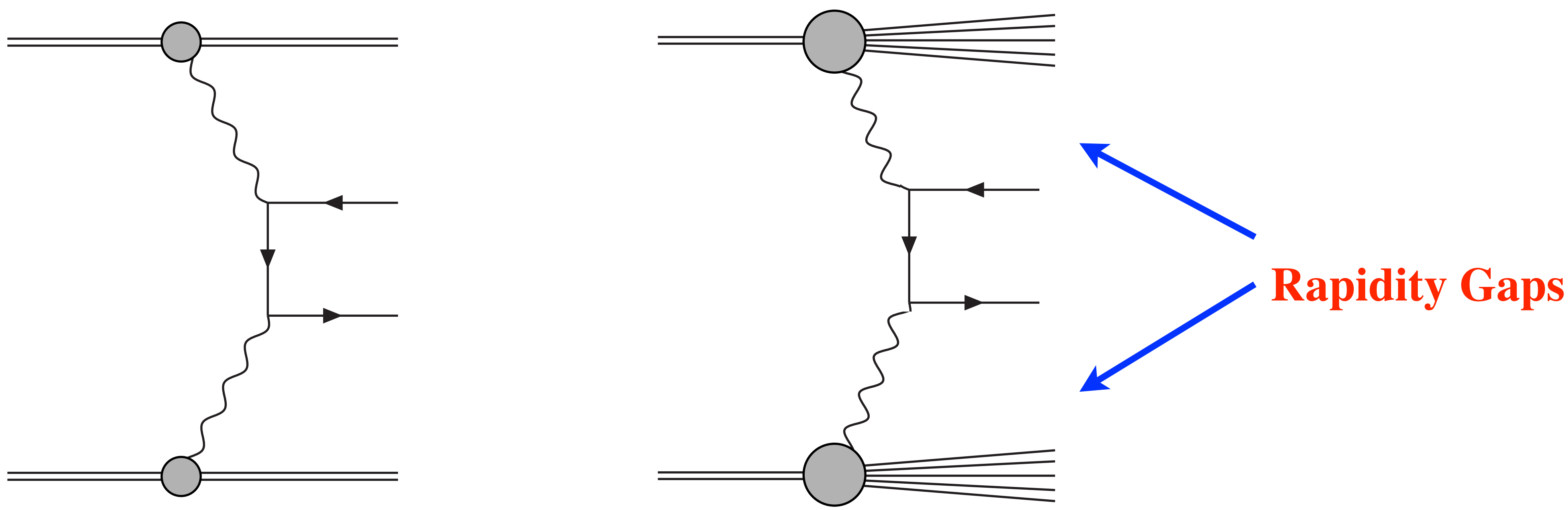
Forward Physics and QCD at the LHC and EIC,
Bad Honnef, Germany, Oct 26

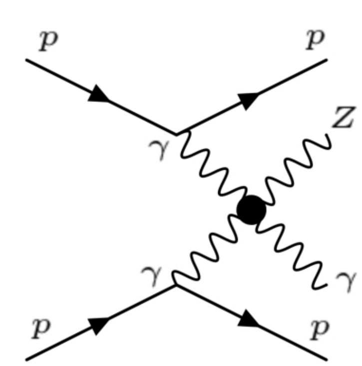
PI Production @ LHC

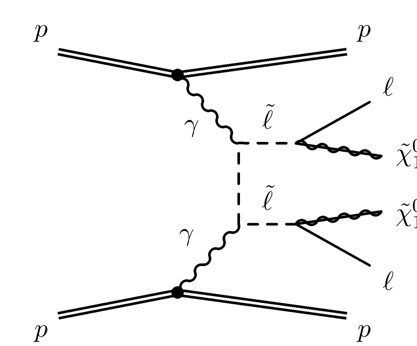
- **Exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact hadrons/rapidity gaps in final state.
- Can be selected either with proton tagging or via rapidity gap vetos (i.e. elastic + inelastic = semi-exclusive production).



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

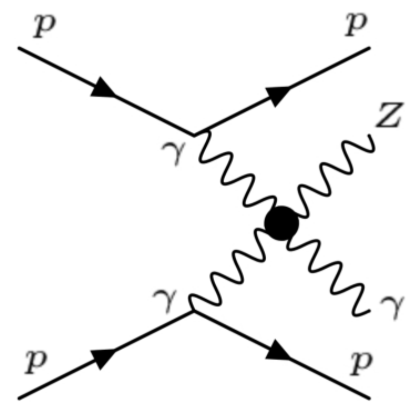
$\Rightarrow$ The LHC as a $\gamma\gamma$ collider!





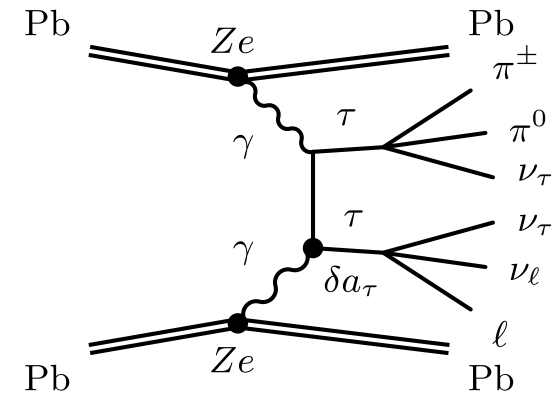
★ Probe of BSM:

Anomalous couplings



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

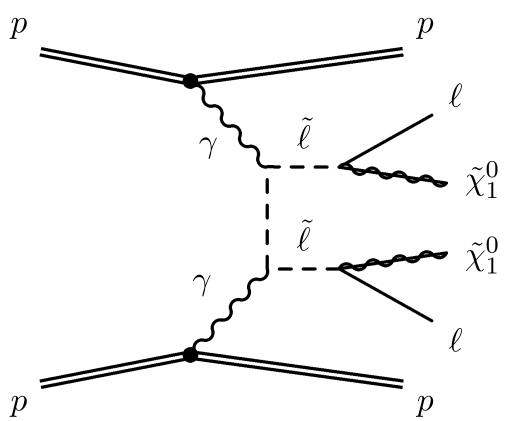
tau g-2



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

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

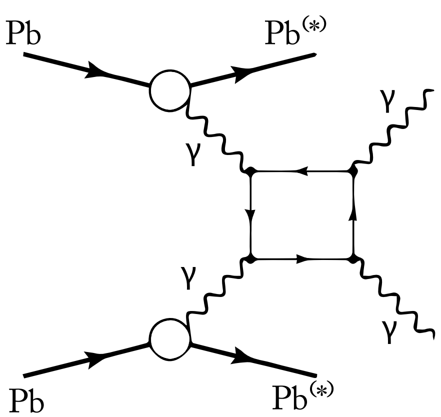
Compressed SUSY



LHL et al., JHEP 1904 (2019) 010

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

LbyL scattering/ALPS

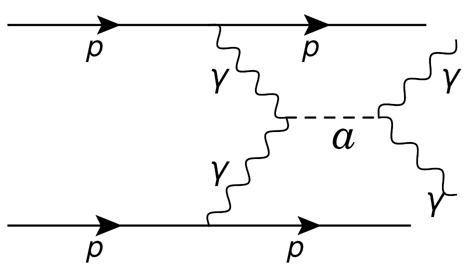


C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

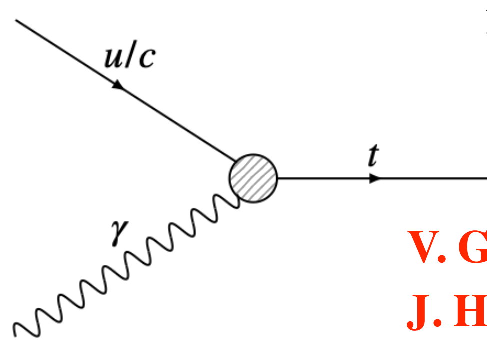
Axion-like Particles

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

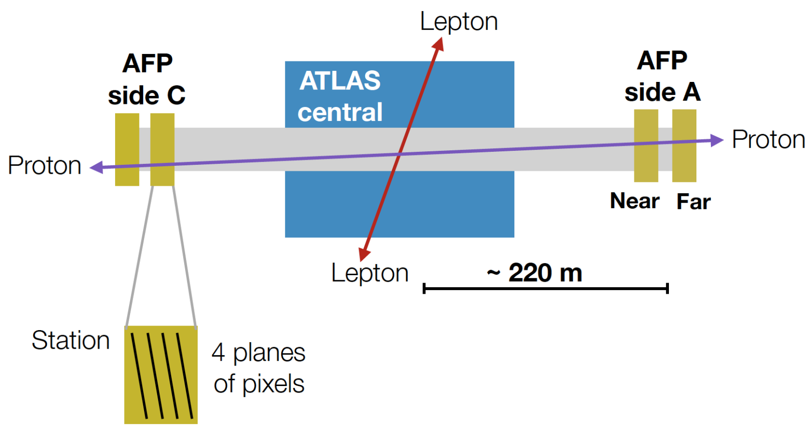
J. Howarth, arXiv:2008.04249

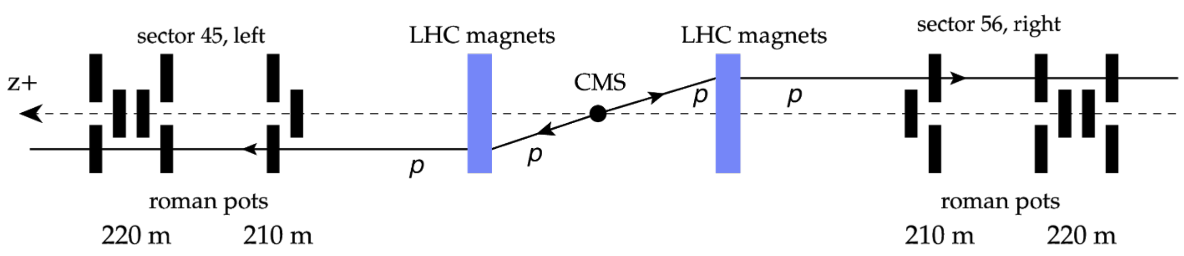
★ Laboratory to test our models of proton dissociation + proton-proton MPI effects.

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

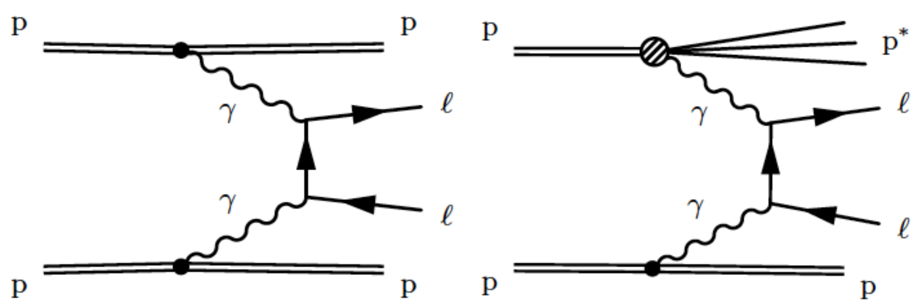
L. Forthomme et al., PLB 789 (2019) 300-307

The elastic proton

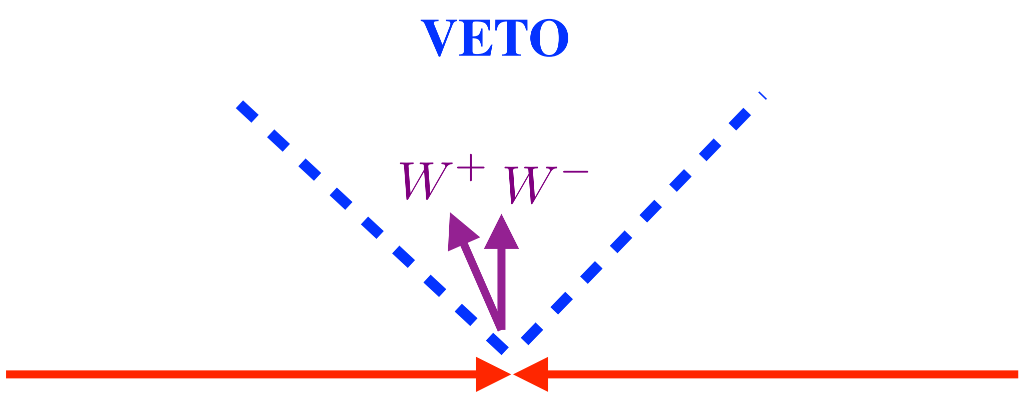


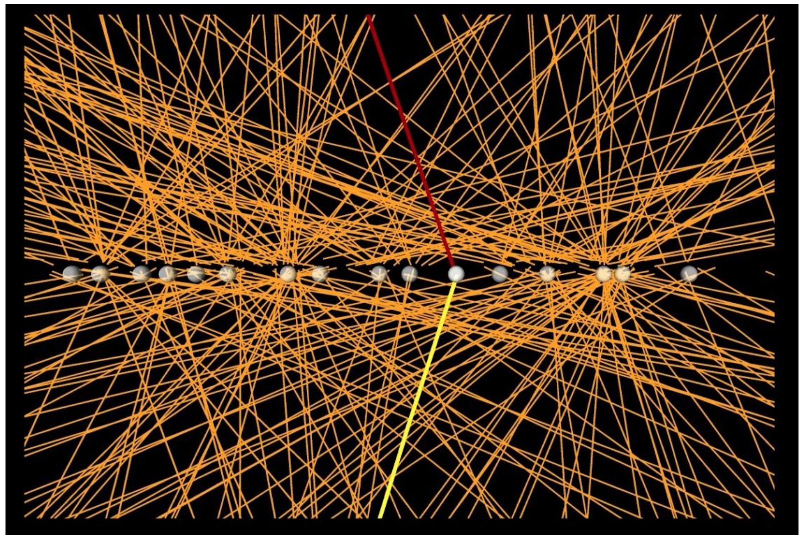


- Proton tagging detectors at ATLAS/CMS allow exclusive events with intact protons in final state to be selected during **nominal running**.



- Alternatively/in conjunction can use track veto:





- In which case both elastic and dissociative production can enter.

$\longrightarrow$ Any theoretical model has to account for both! How to do this?

SuperChic 4 - MC Implementation

- A MC event generator for CEP processes. **Common platform** for:
  - QCD-induced CEP.
  - Photoproduction.
  - Photon-photon induced CEP.

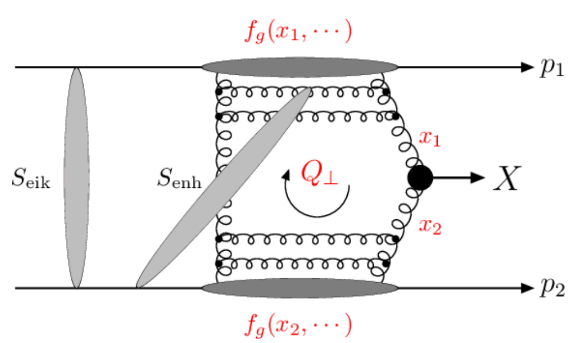
- For **pp**, **pA** and **AA** collisions. Weighted/unweighted events (LHE, HEPMC) available- can interface to Pythia/HERWIG etc as required.

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 >.

- **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

Modelling PI Production (pp collisions)

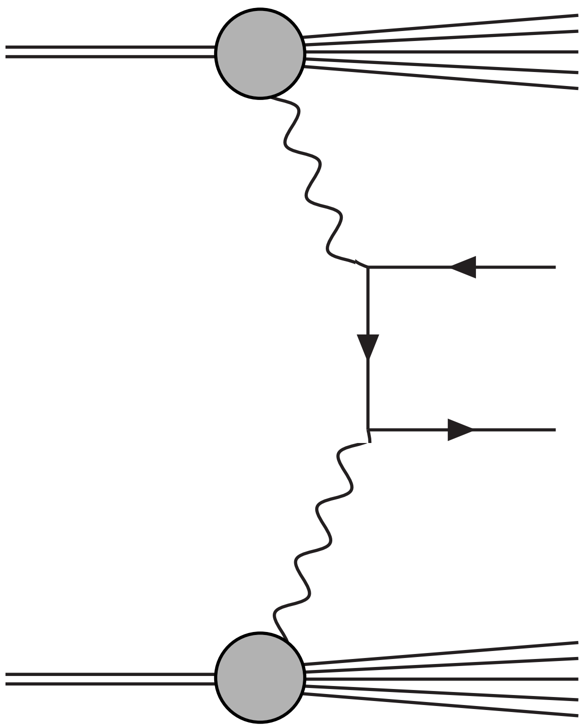
PI production: building blocks

- PI cross section given in terms of:

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

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

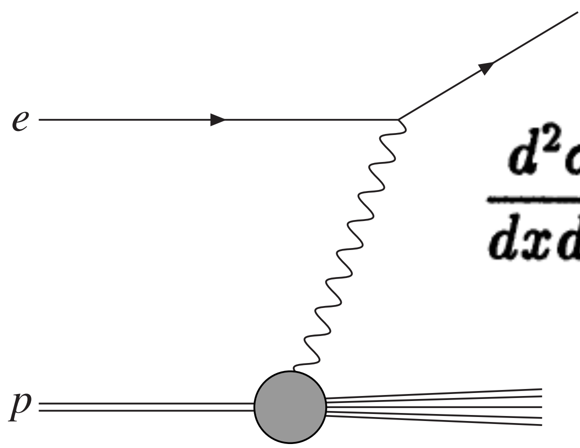
  ★ `**Survival factor**' probability of no addition proton-proton interactions.



- Start with $p \to \gamma p(p^*)$ form factor…

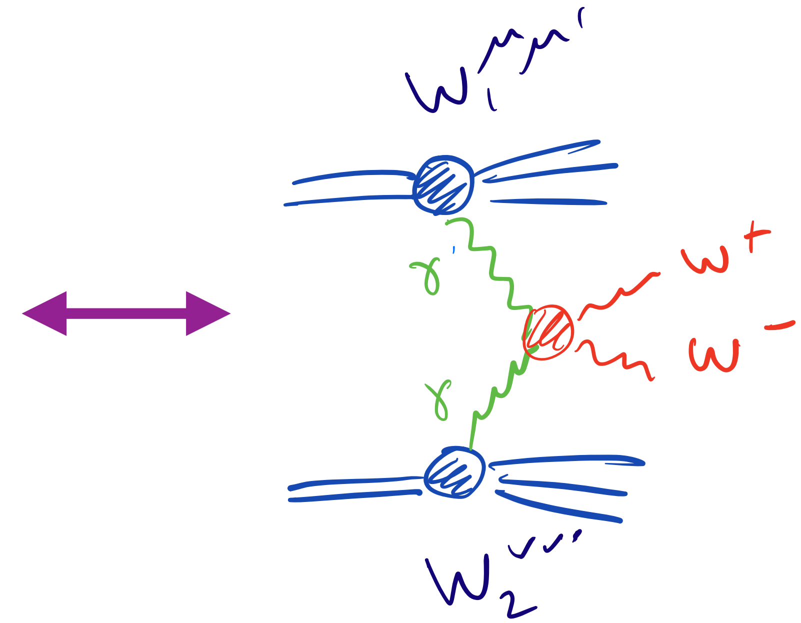
Structure Function Calculation

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



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

$W^{\alpha\beta}$



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

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} F_2(x,Q^2)$$

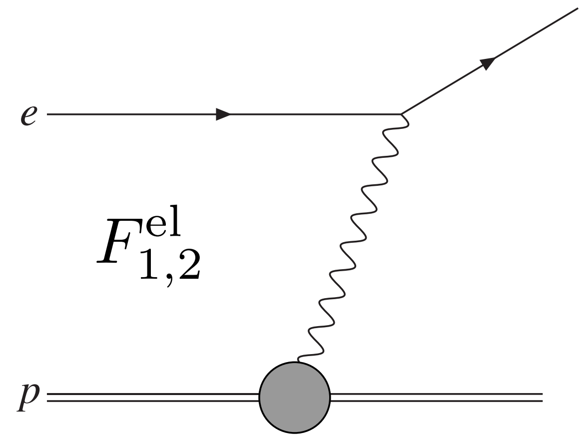
  - Use same idea as for DIS to write: $(\rho_{\mu\nu} \sim W_{\mu\nu})$

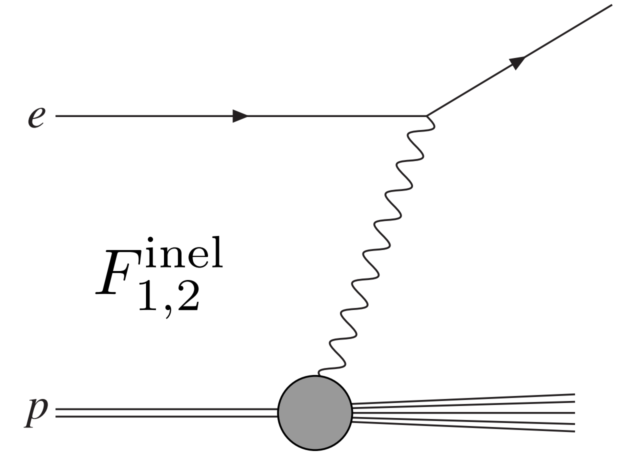
Photon x, Q^2 $\qquad$ $\gamma^* p \to X$ $\qquad$ $\sim \sigma(\gamma^*\gamma^* \to X)$

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

- Can relate to well known equivalent photon approximation, but more general/precise.

- Both elastic and inelastic SFs accounted for:

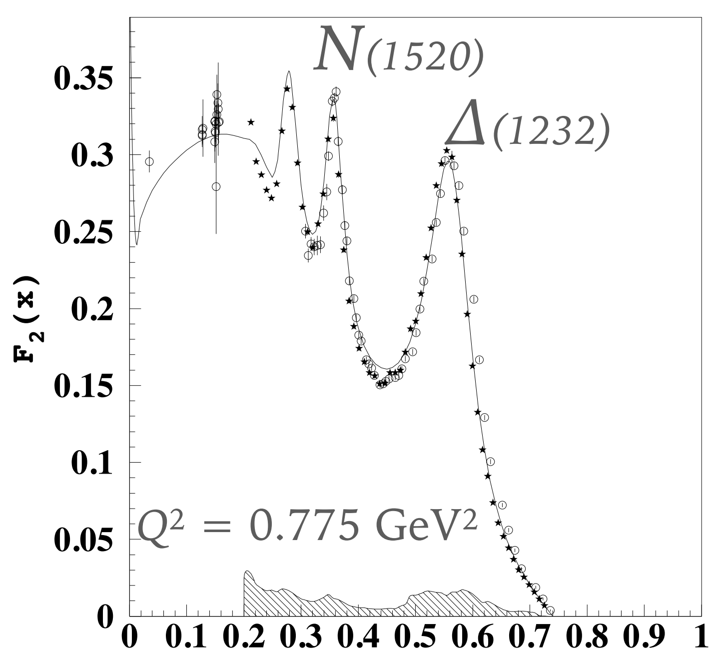


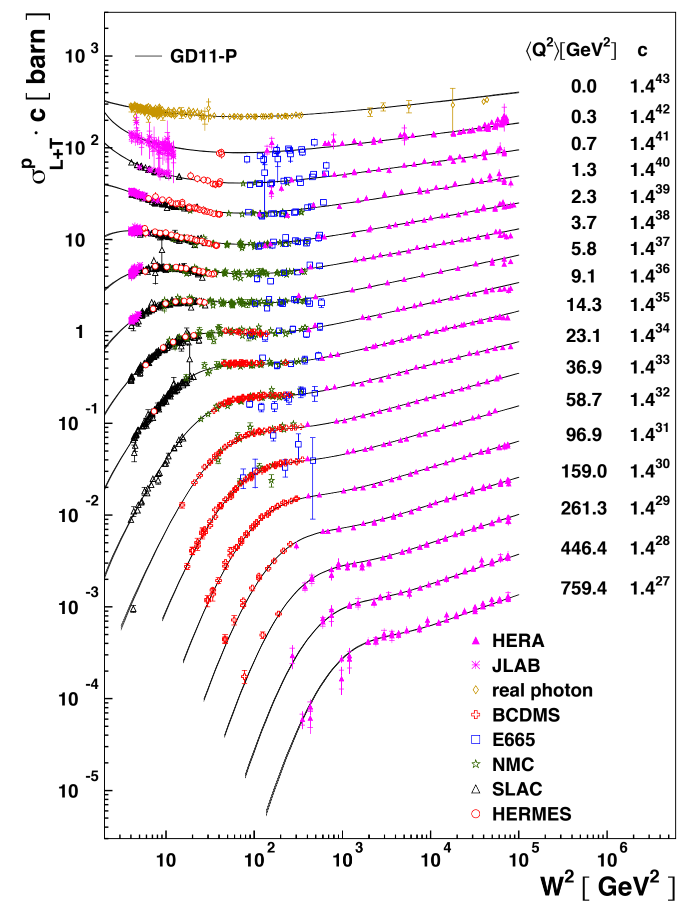


★ **Elastic**: precisely measured proton EM form factor.

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

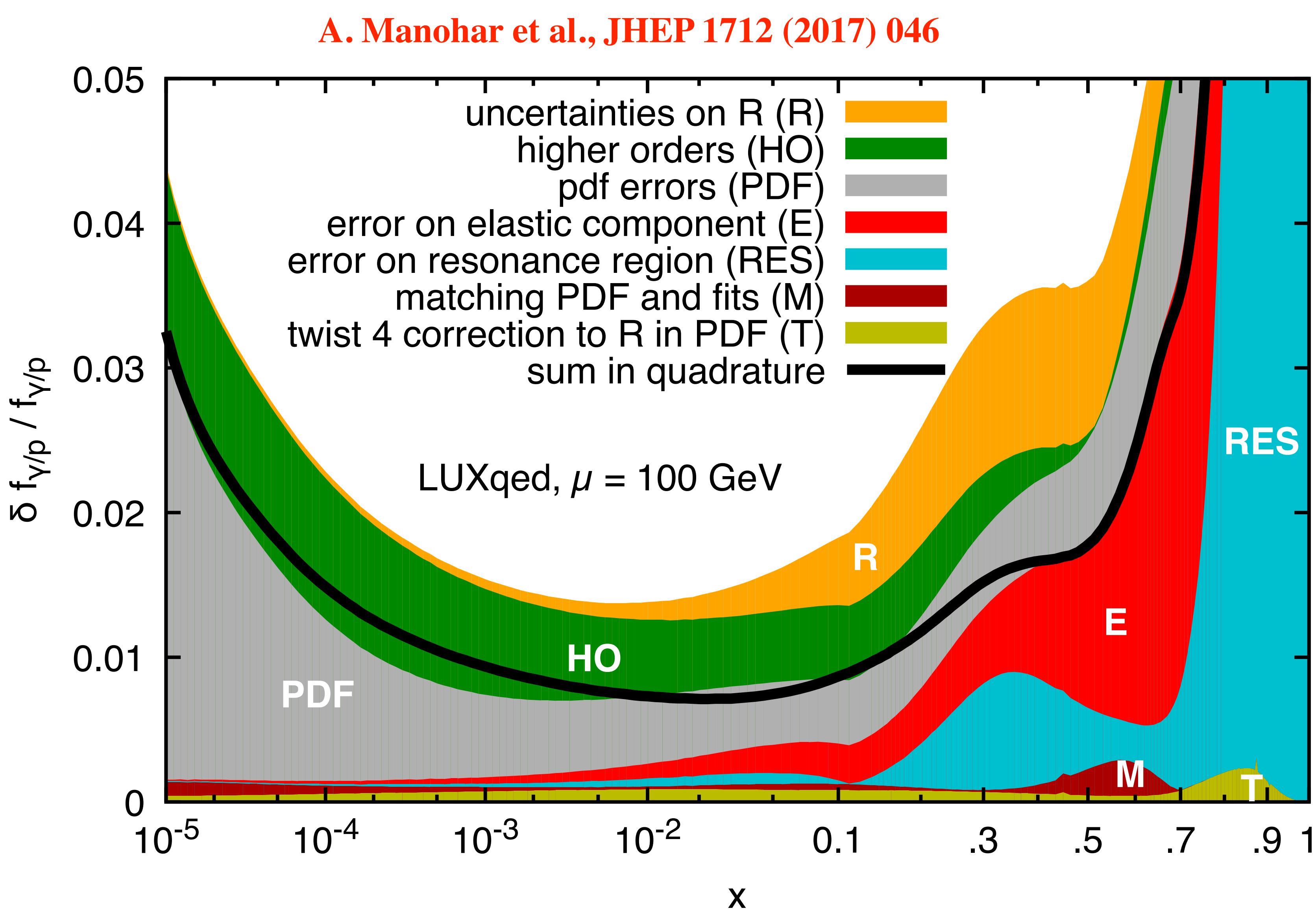
- Low (non-perturbative) Q^2 and/or W^2 region, take direct experimental determinations.

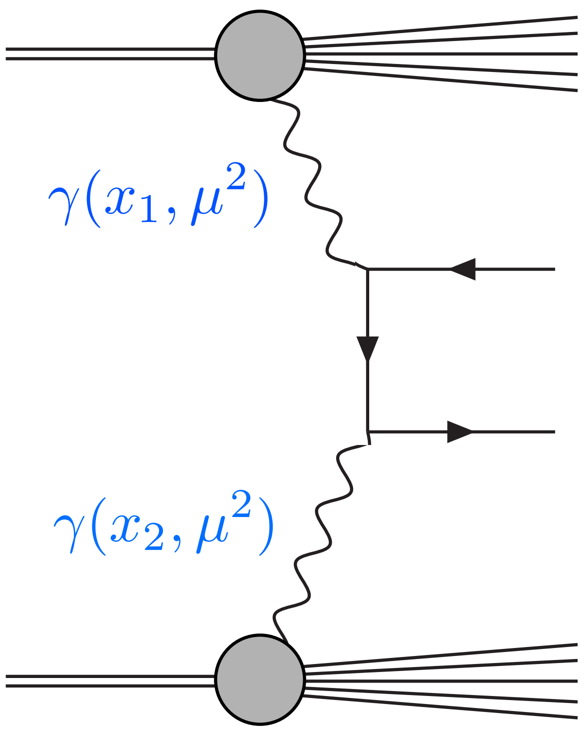




- High Q^2 region, simplest to calculate using (NNLO) pQCD + global PDFs.

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





- 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

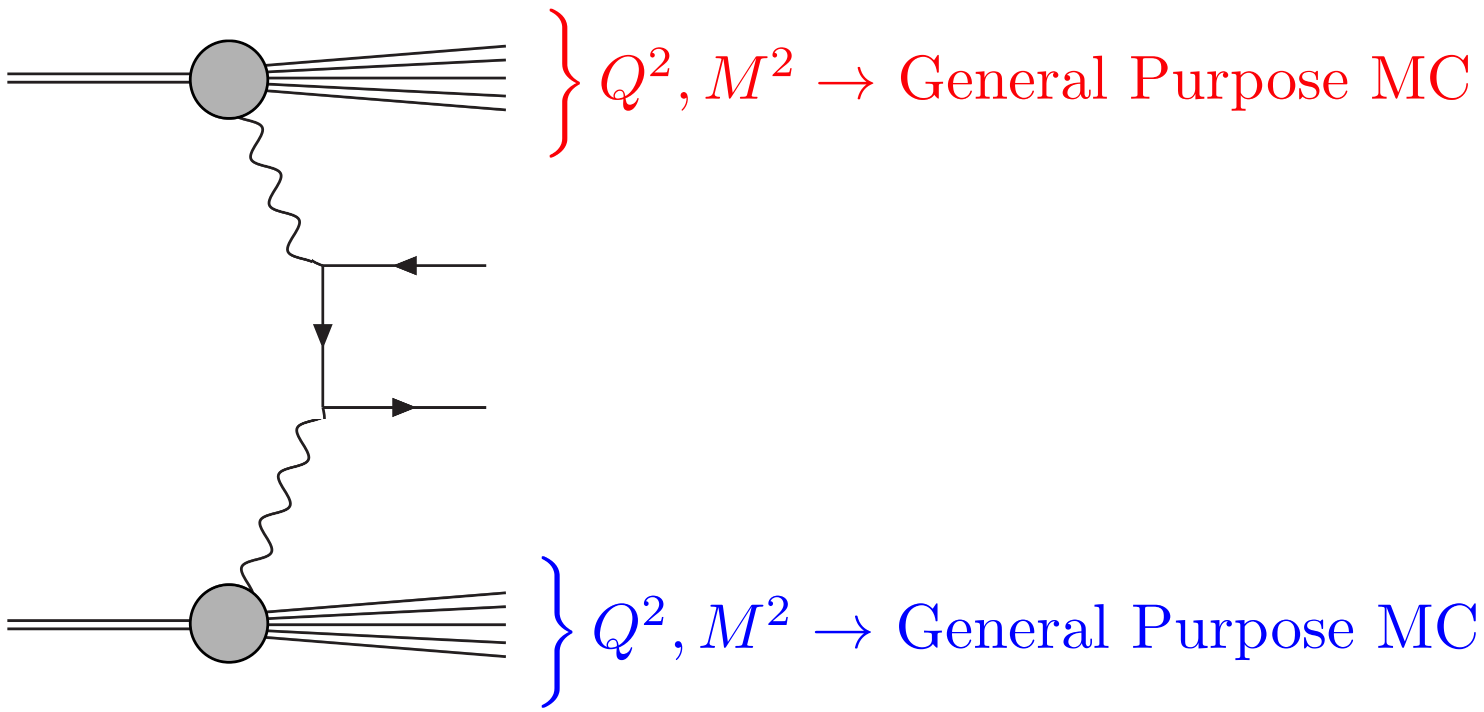
- SF calculation readily amenable to MC treatment:

  ⋆ 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).

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

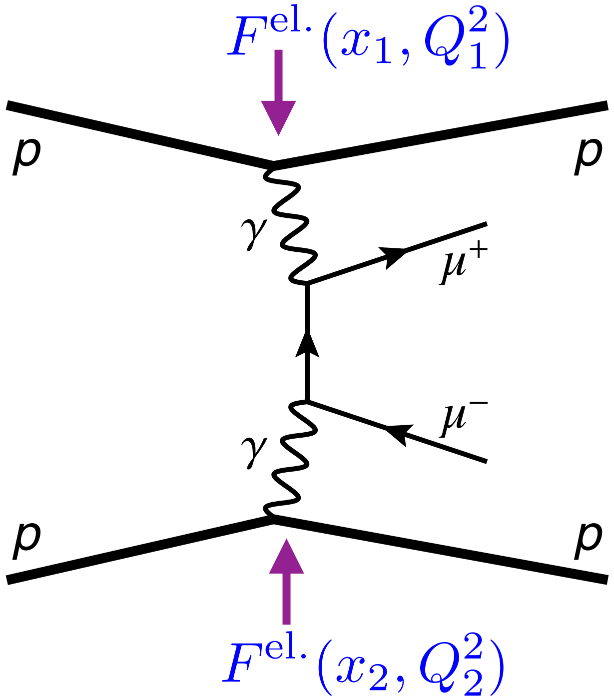
- Pass to general purpose MC for showering/hadronisation of dissociation system.
- Can evaluate impact of e.g. rapidity veto (proton tag) with this.



Backup

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

The Survival Factor

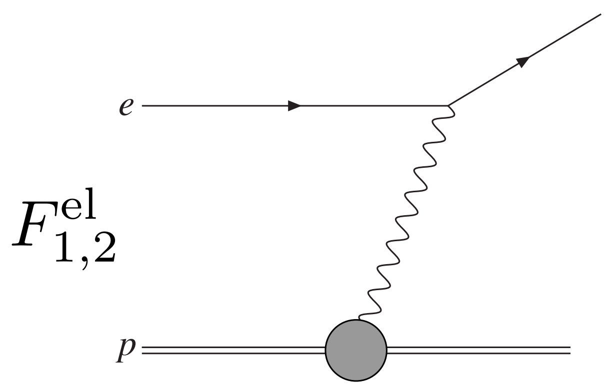


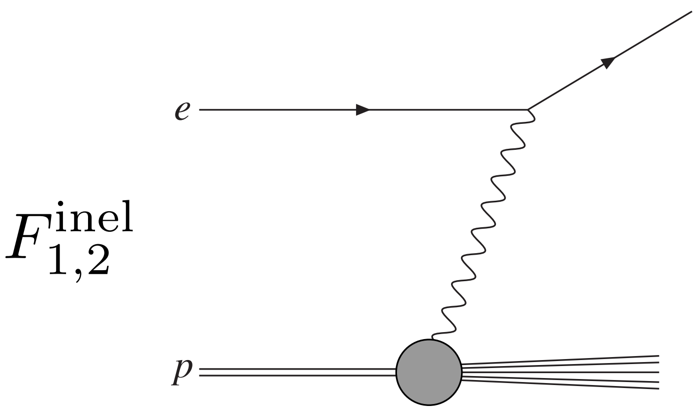
- Consider e.g. the exclusive process. So far we have (very) schematically:

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

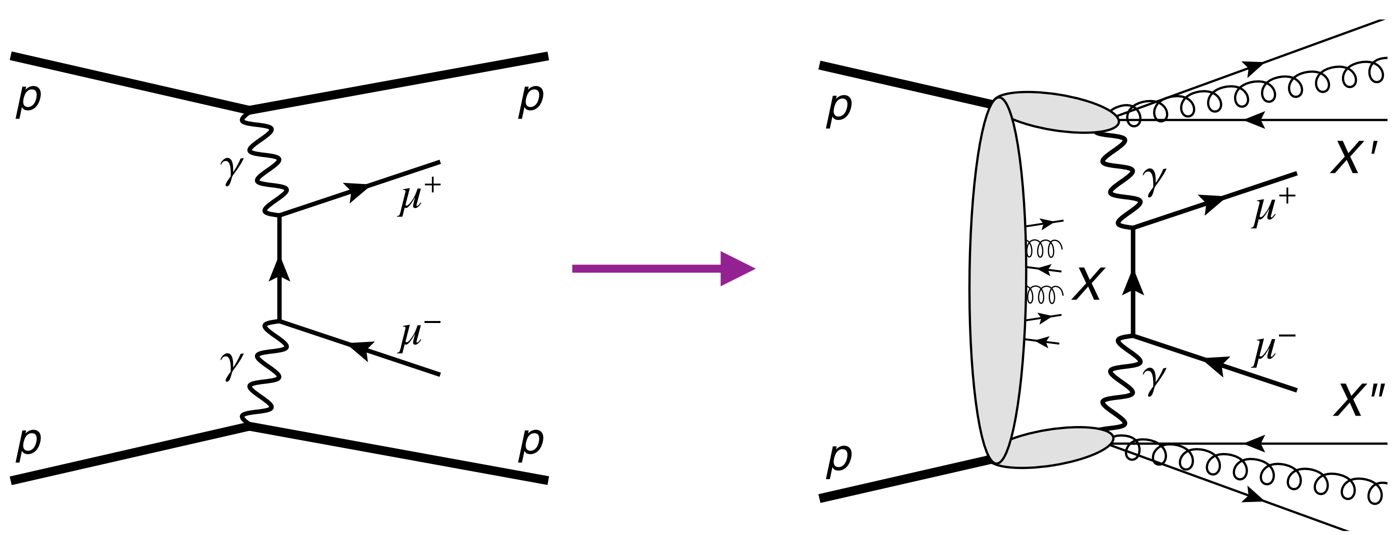
- Similarly for SD + DD, with $F^{\text{el.}} \to F^{\text{inel.}}$

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





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

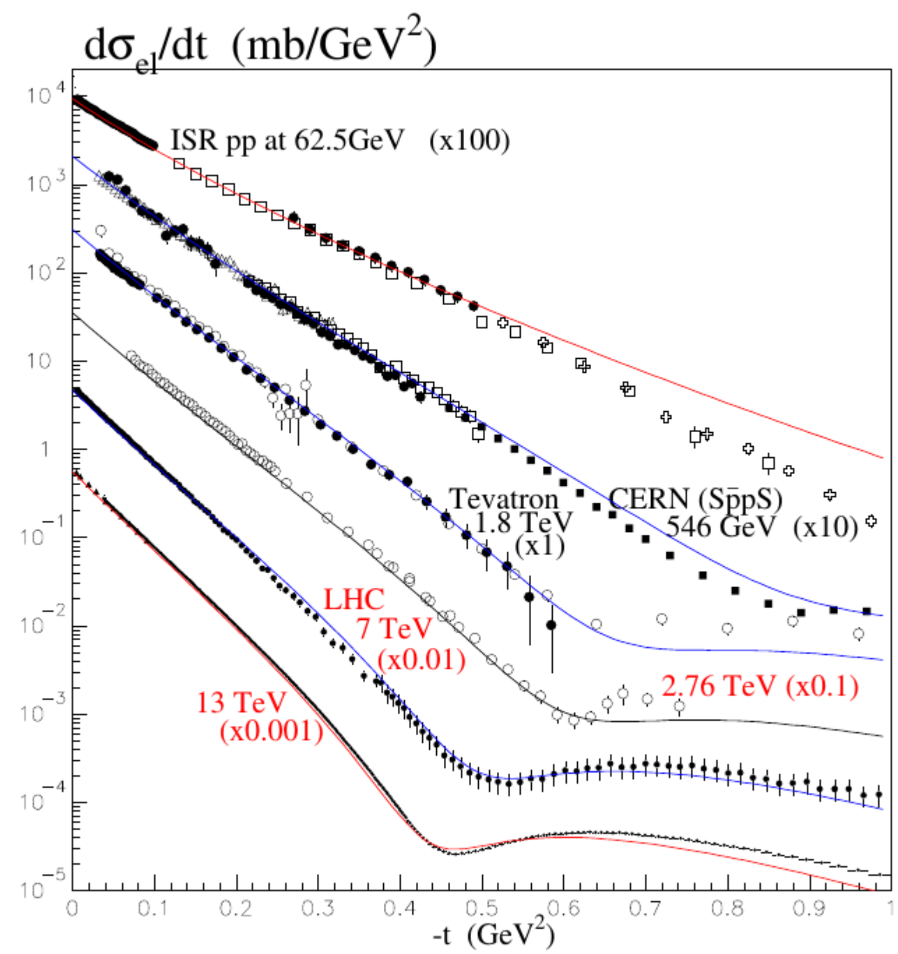


- '**Survival factor**' = probability of no additional inelastic hadron-hadron interactions. Schematically:

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

- 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).

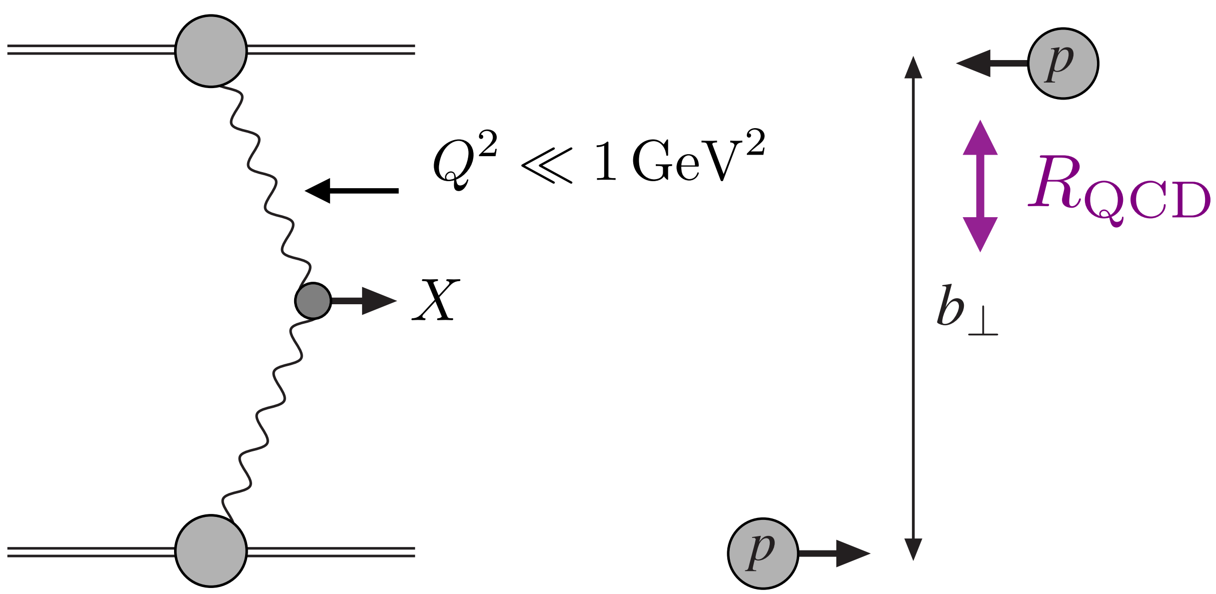
- In general source of **uncertainty**. Is this the case for PI production?



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

The Survival Factor in PI processes

- Again start with purely elastic case for simplicity.
- 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. Why we can say the LHC is 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:

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

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

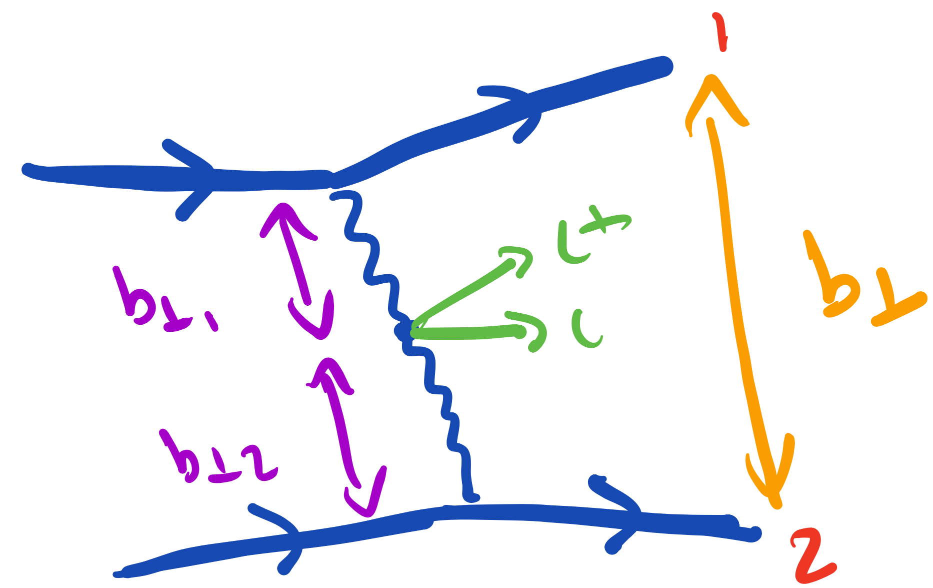
- We can write this as integral over ion impact parameters:

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

- Where:

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

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



- To first approximation, we then simply require:

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

↓

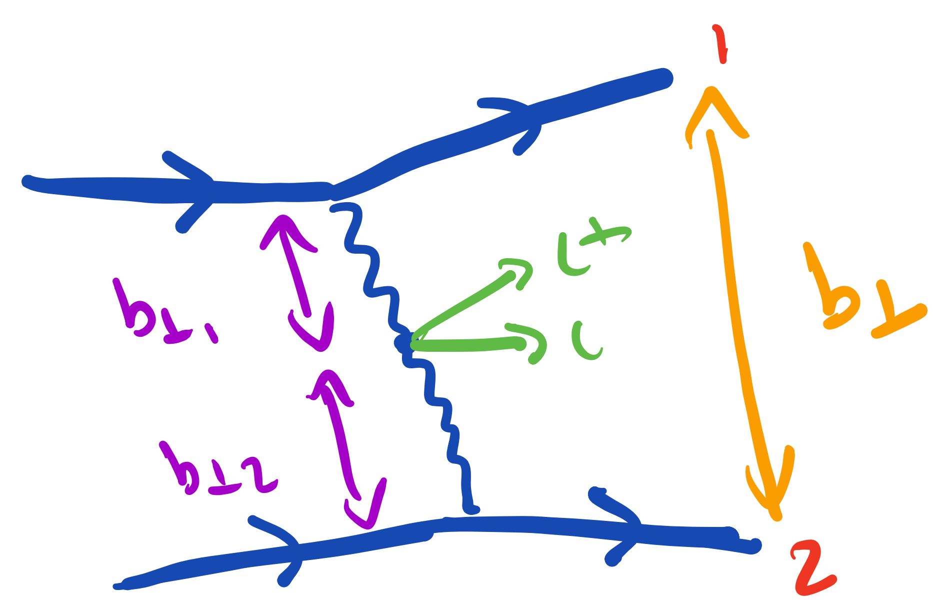
$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp}, ...)|^2 \Theta(b_\perp - 2r_p)$$

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

- That is, only integrate over impact region where:

$$b_\perp > 2r_p$$

holds!



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

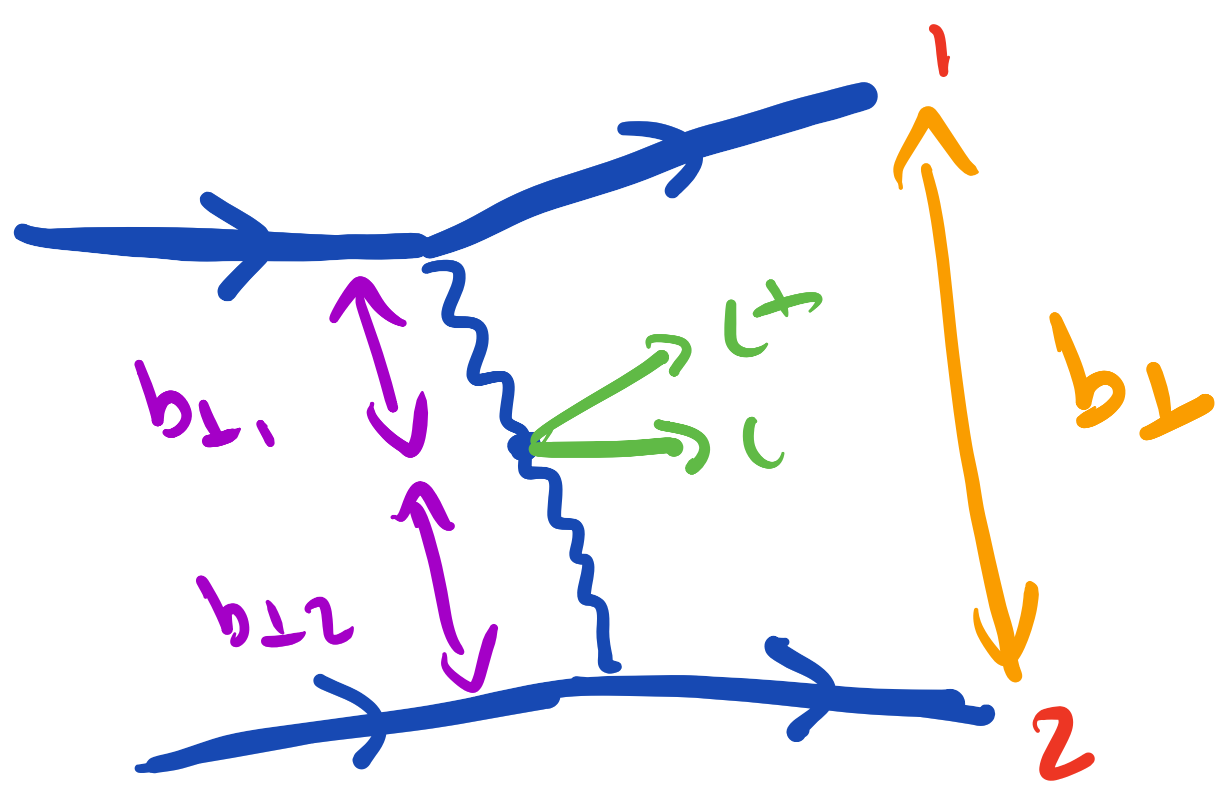
Schematically:

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

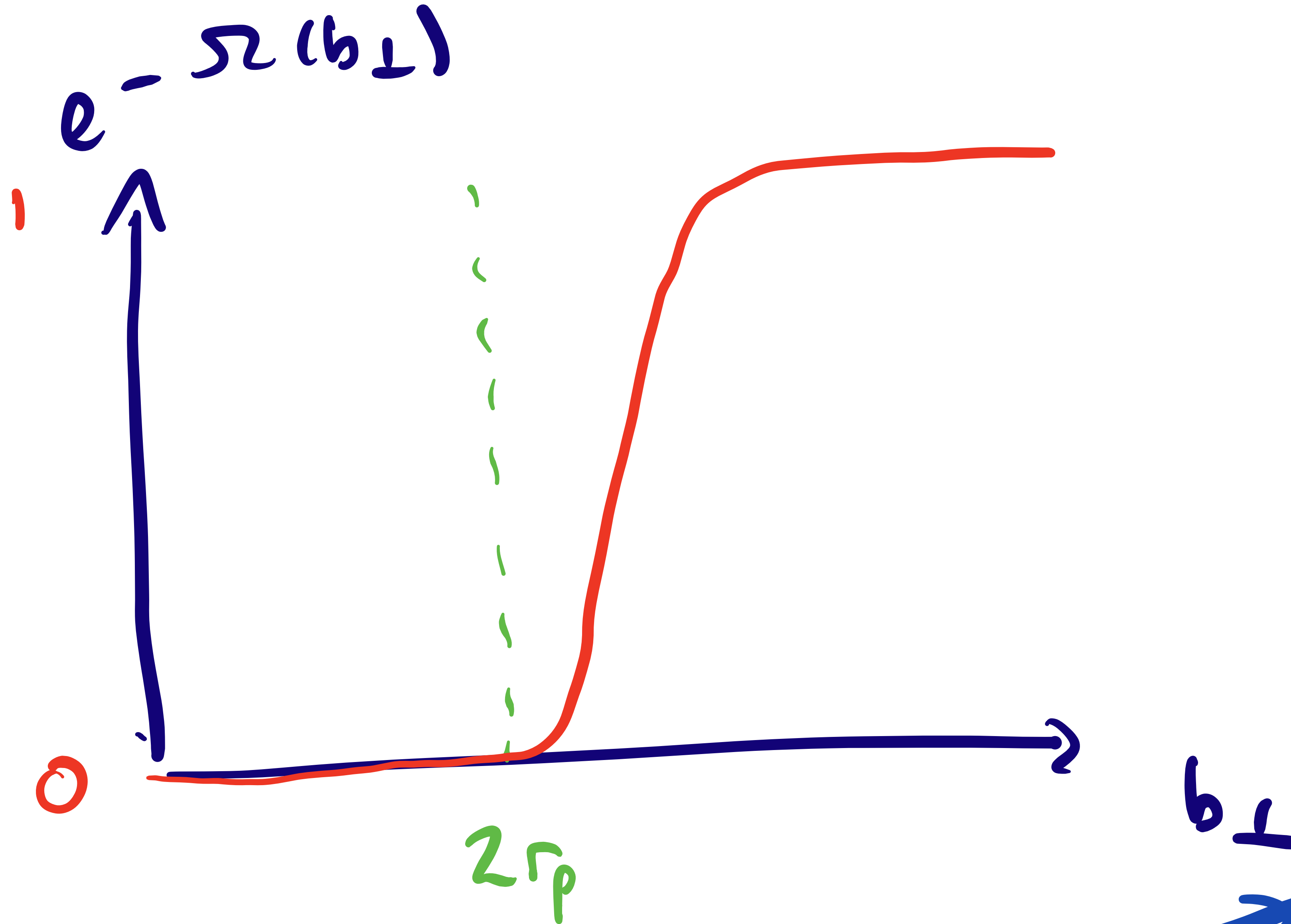
$e^{-\Omega(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}$: survival factor - probability for no additional particle production at impact parameter $b_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$. Roughly:

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

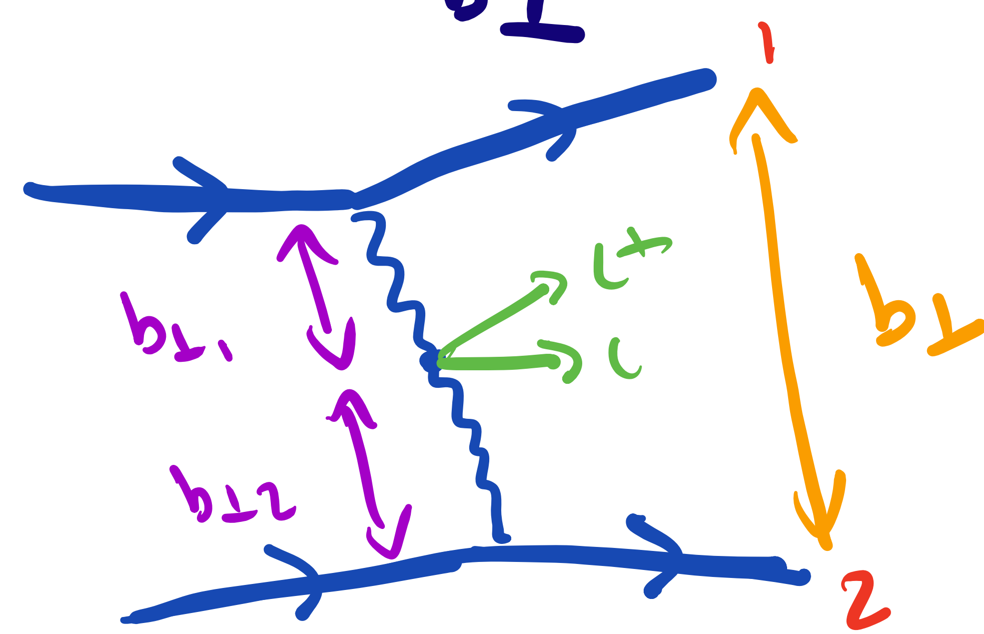
but not exact!



- Result for pp:



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



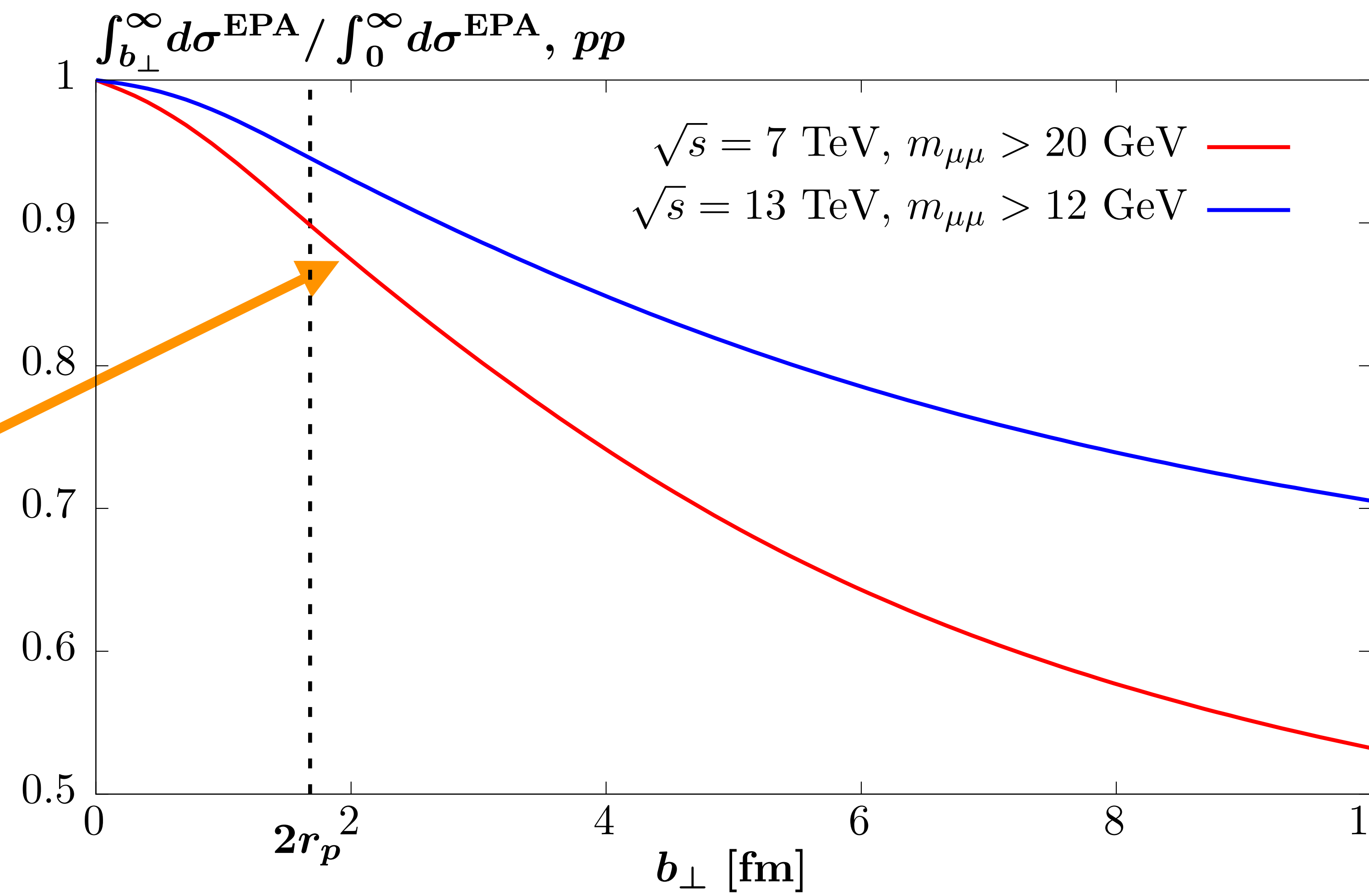
- What does this tell us about survival factor for purely elastic production?

- Have a look at ratio:

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

~ 90% of cross section lies outside

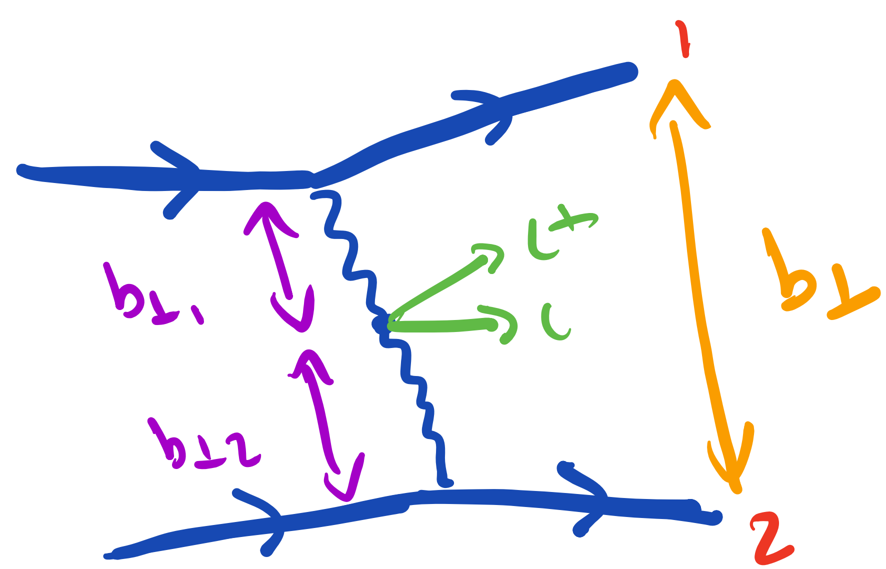
$$b_\perp > 2r_p$$



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

- Depending on precise process/ kinematics have:

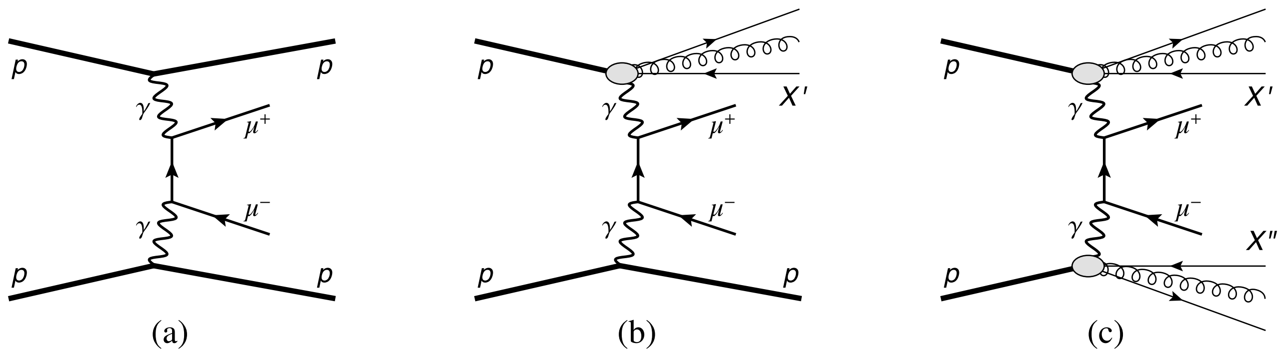
$$S^2 \sim 0.7 - 0.9$$



- What about dissociative production?

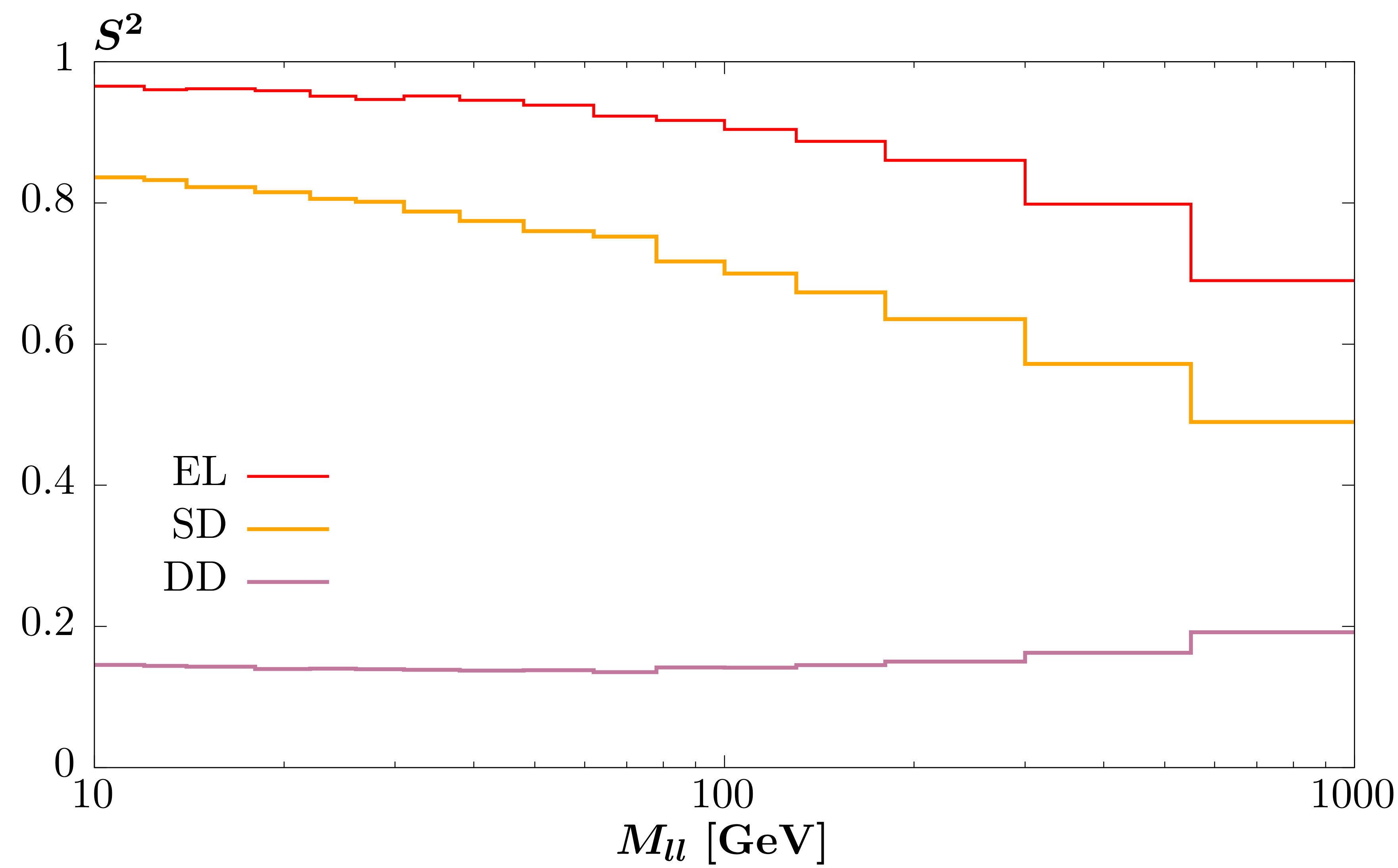
- Dissociation $\Rightarrow$ larger photon Q^2 $\Rightarrow$ smaller pp $b_\perp$ $\Rightarrow$ $S^2 \downarrow$

- For SD production elastic proton side results in ~ peripheral interaction and S^2 still rather high.



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

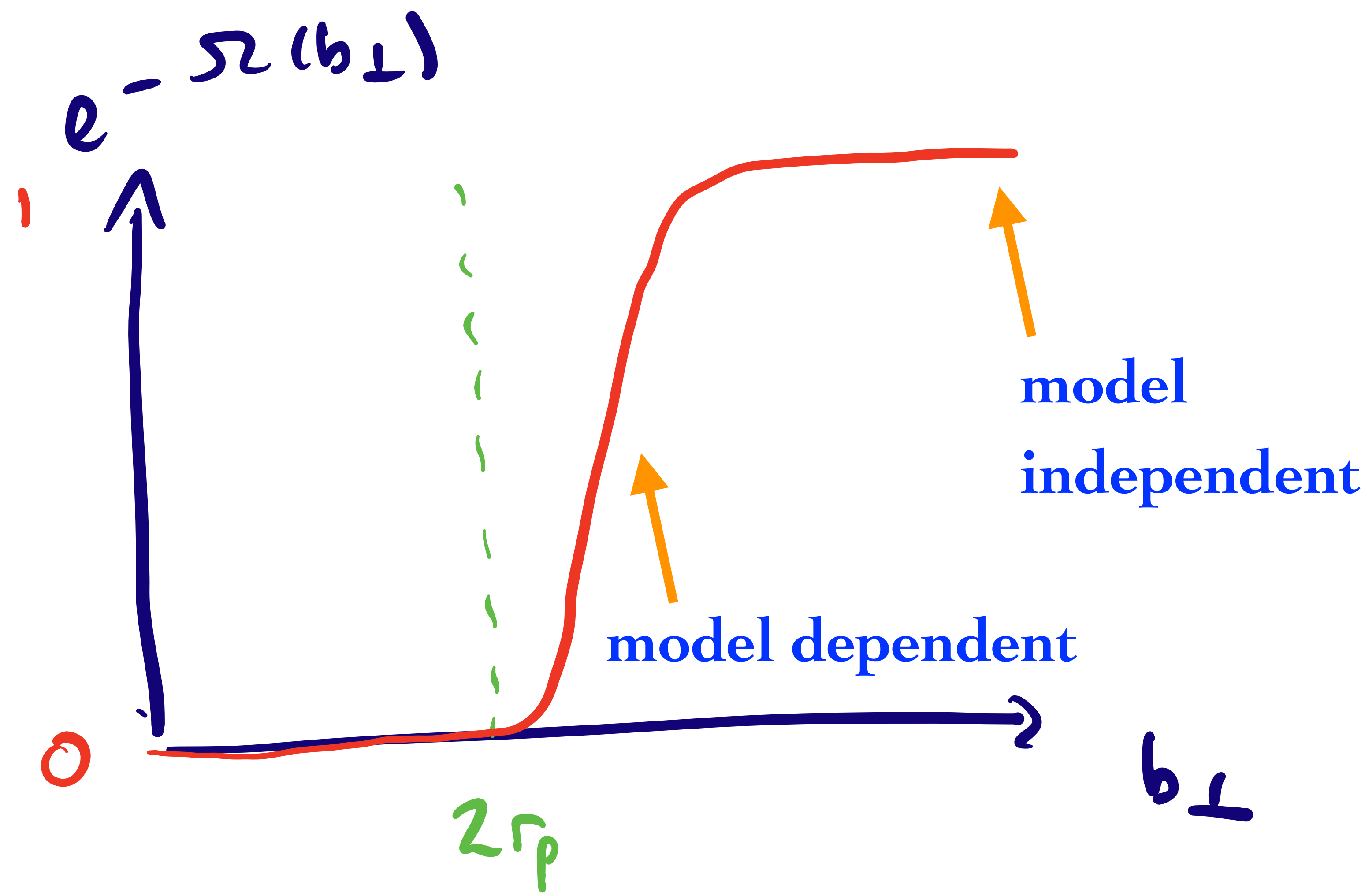
lepton pair production



- 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.

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

$$b_\perp \leftrightarrow q_\perp$$

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

Kinematics

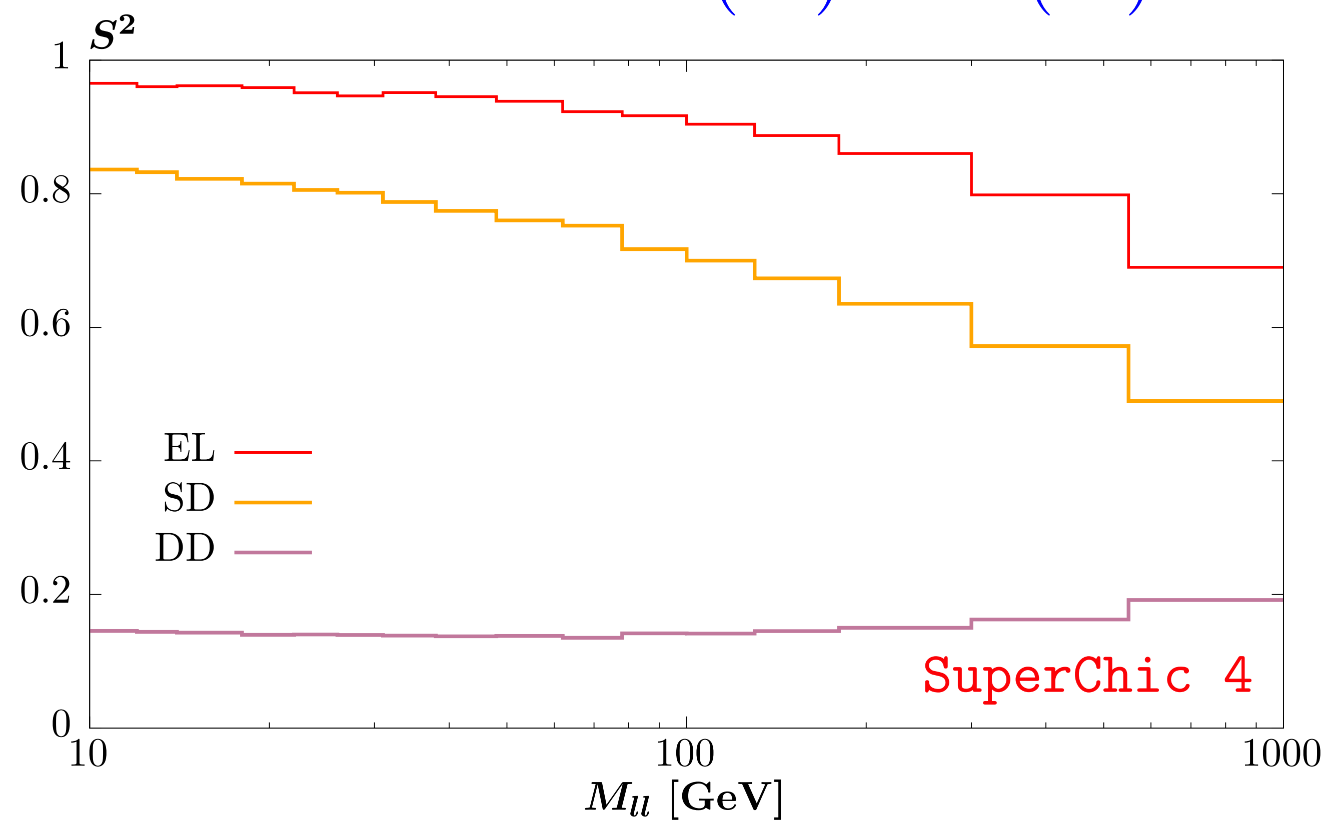
Process

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

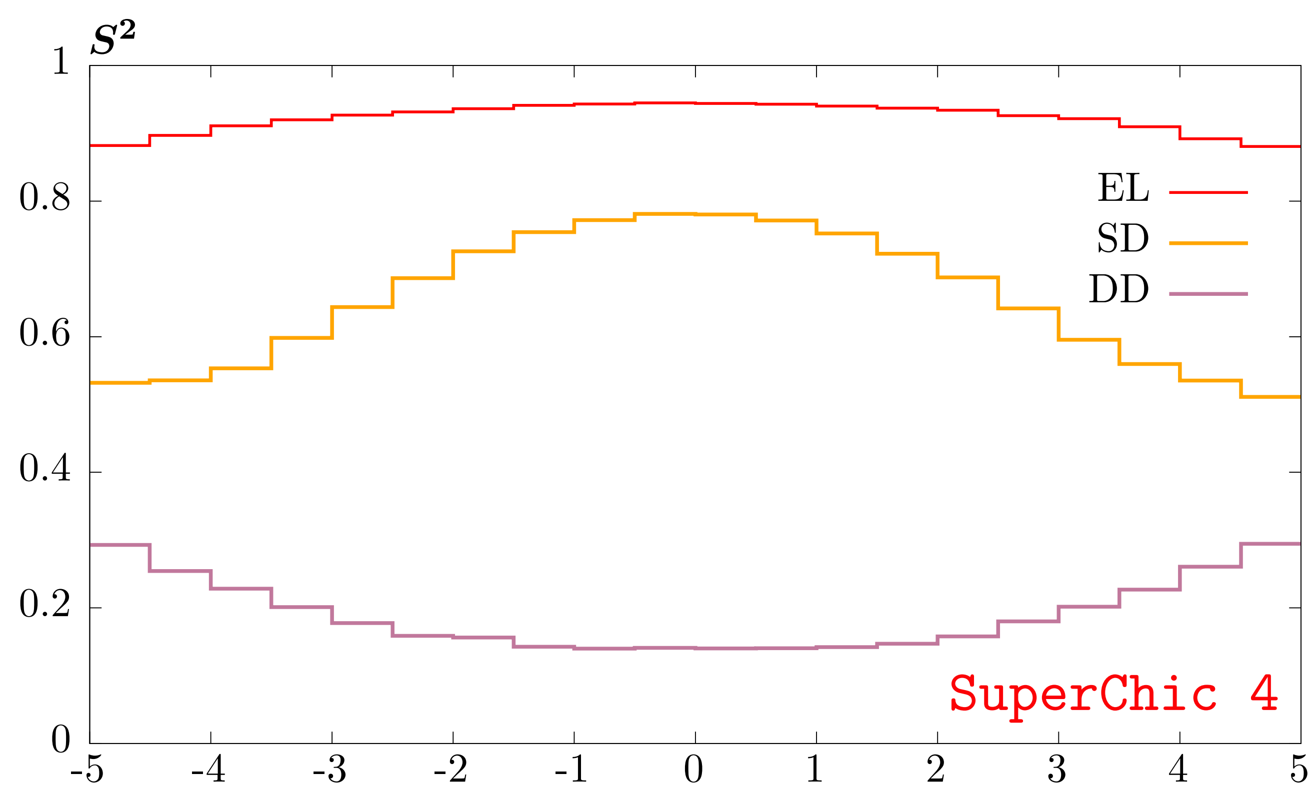
Results

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

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

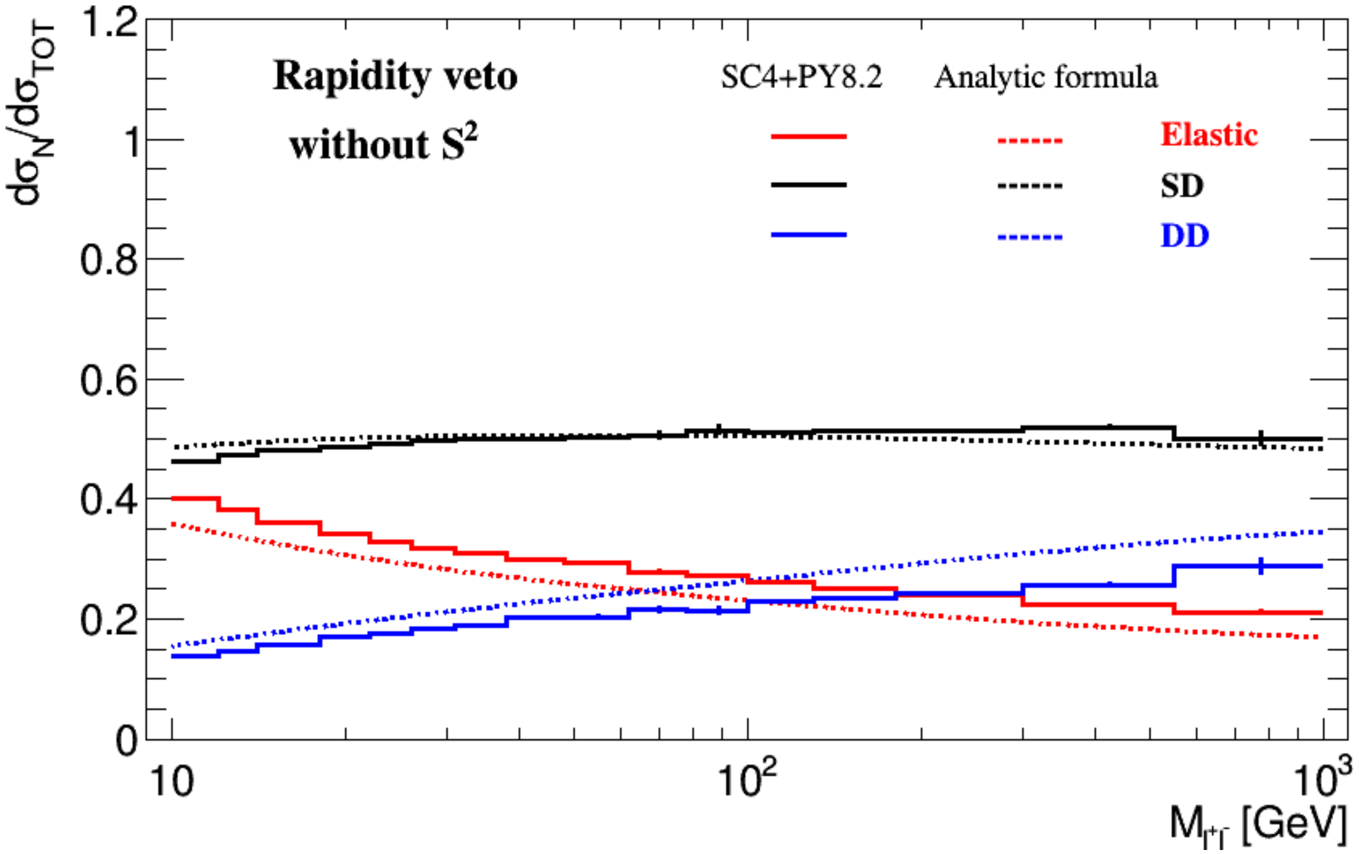


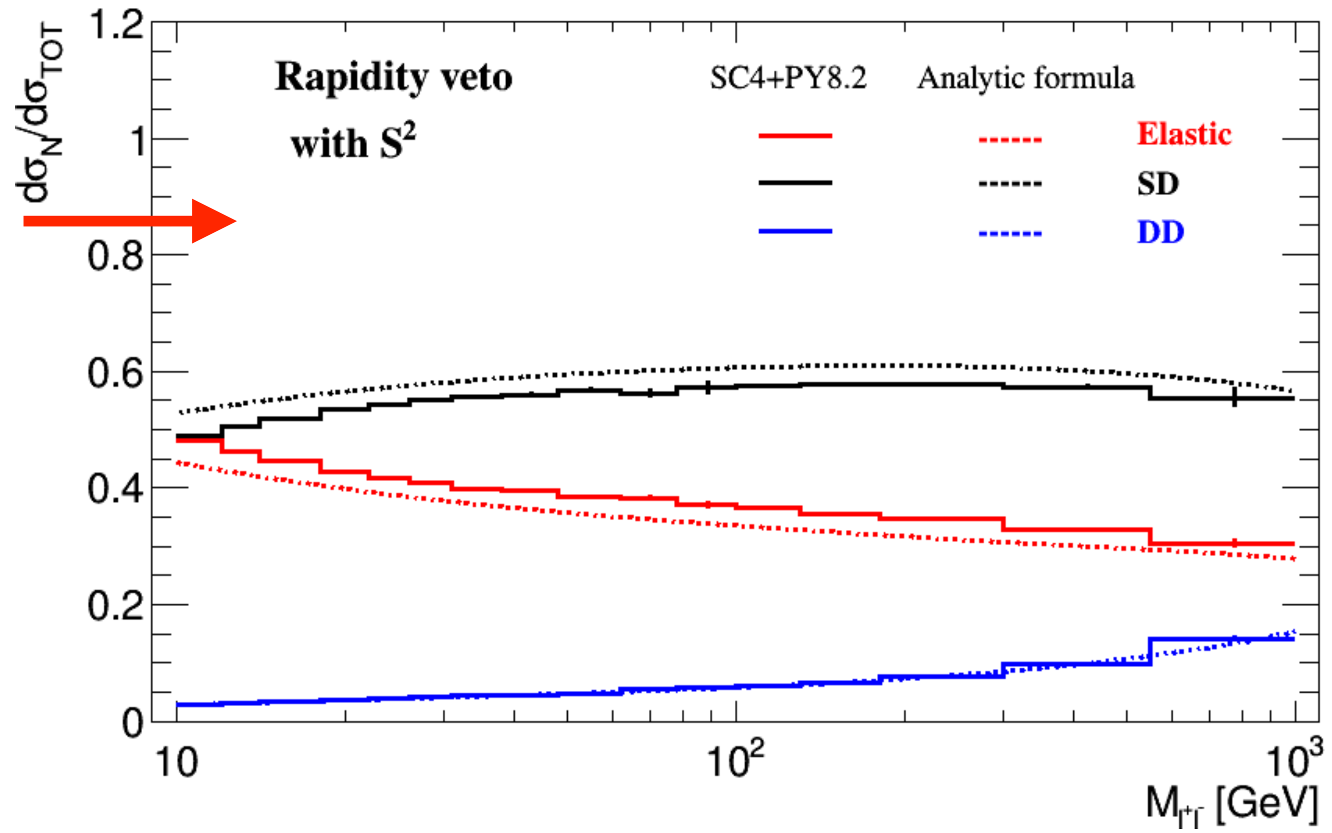
- Dependence on kinematics (e.g. y_{ll}, m_{ll}) also evident.



lepton pair production

Veto Impact

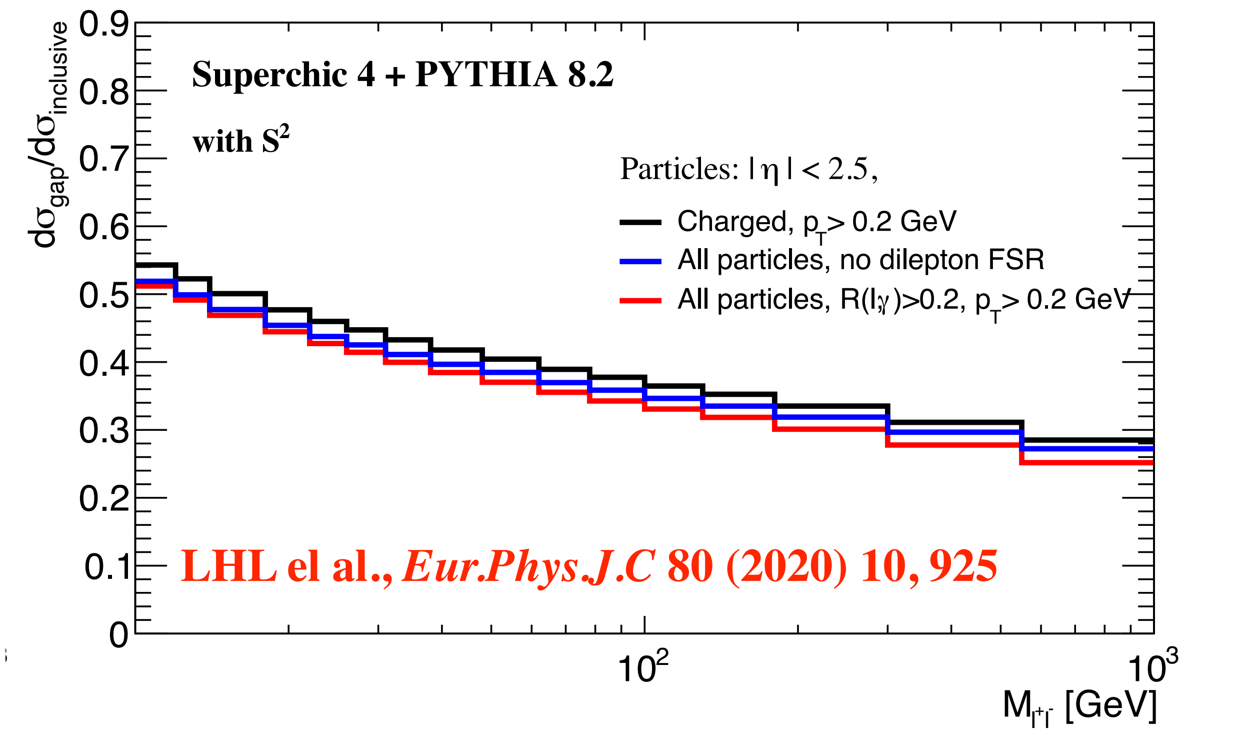




★ **Veto** + S^2 : strong suppression in DD. Elastic and SD comparable at lower m_{ll}, SD dominant as m_{ll} increases.

- Vetoing on charged particles only + realistic threshold gives **similar results**.

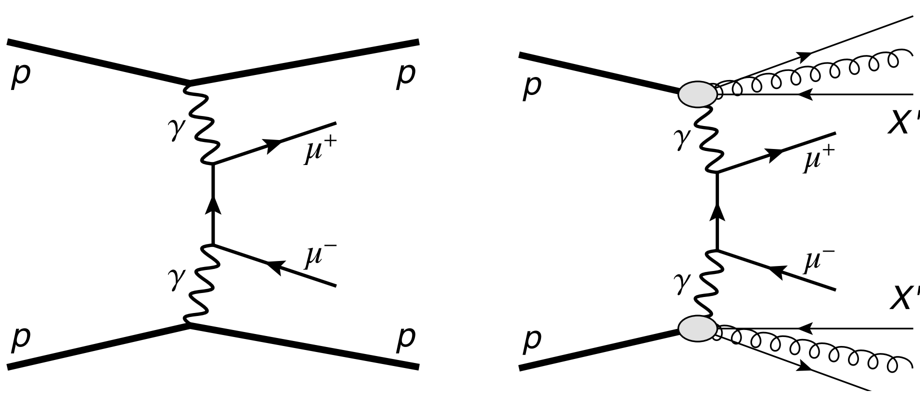
lepton pair production



Where do we stand? Comparison to Data

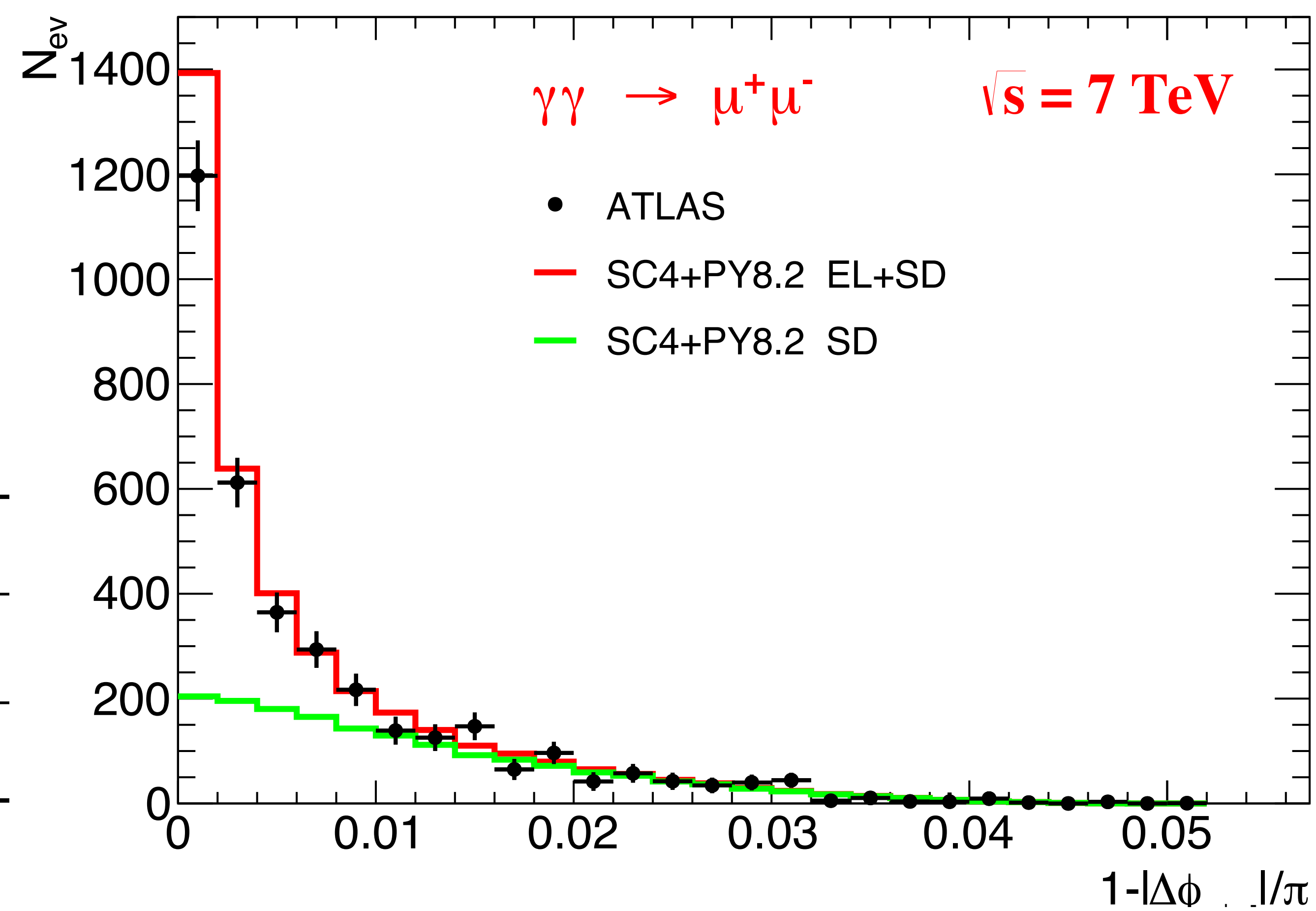
What does the data say?

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



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



LHL, V. A. Khoze, M. G. Ryskin, M. Tasevsky, *Eur.Phys.J.C* 80 (2020) 10, 925

- 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.

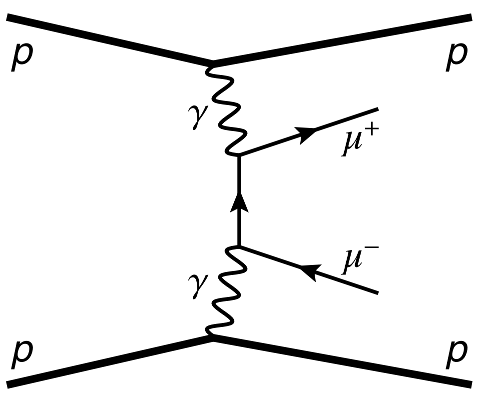
Theory vs. Data?

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

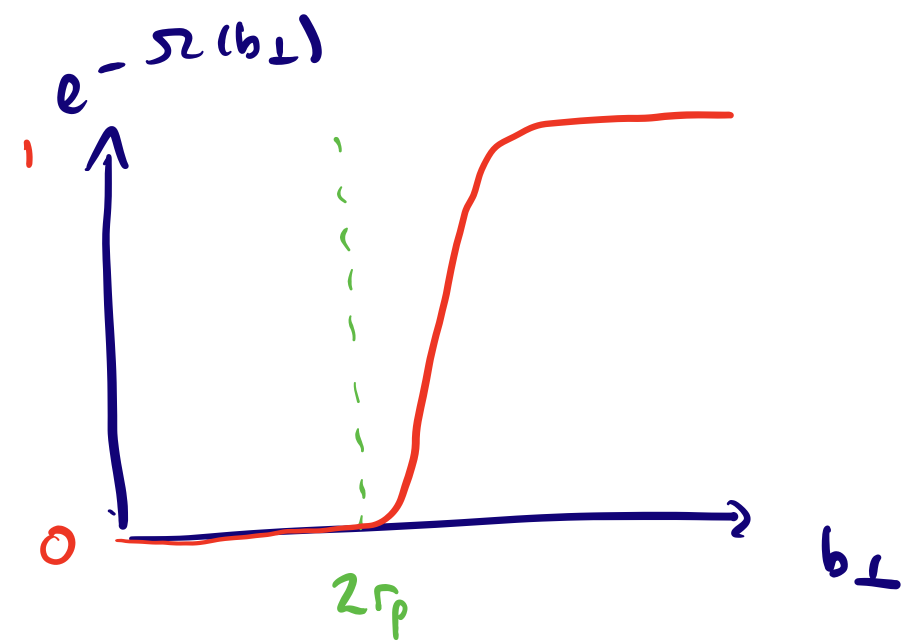
- This issue discussed in detail in recent paper: **arXiv:2104.13392**.

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

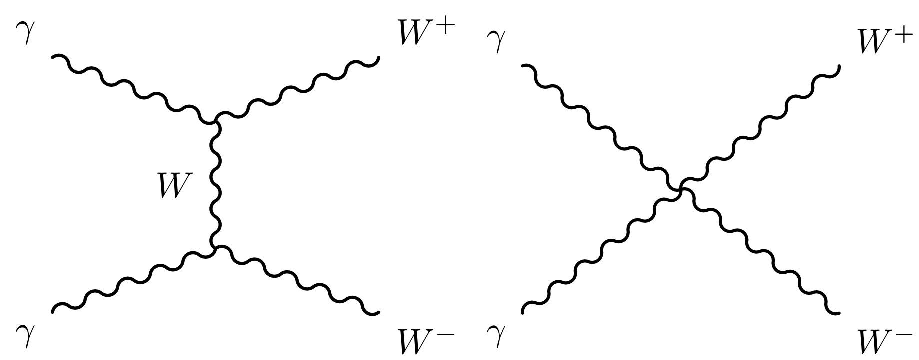


- Reasons for difference?
  - ⋆ Uncertainty from form factor: sub % level.
  - ⋆ Uncertainty from S^2 : even extreme (unrealistic) changes not sufficient.

- Source of ~ 10% effect remains open question.

WW production

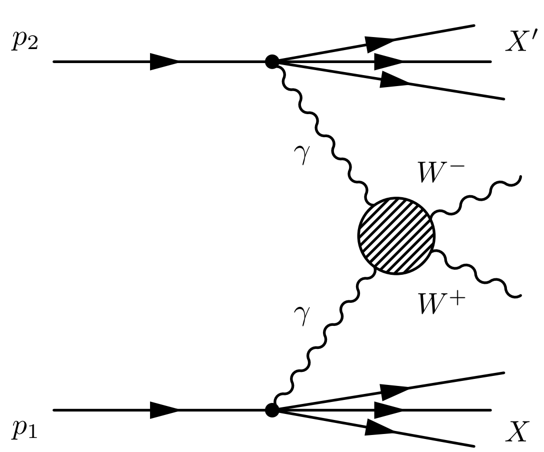
- Recent topical example. Effectively 'inverse VBS': instead of tagging jets ask for no activity to isolate:



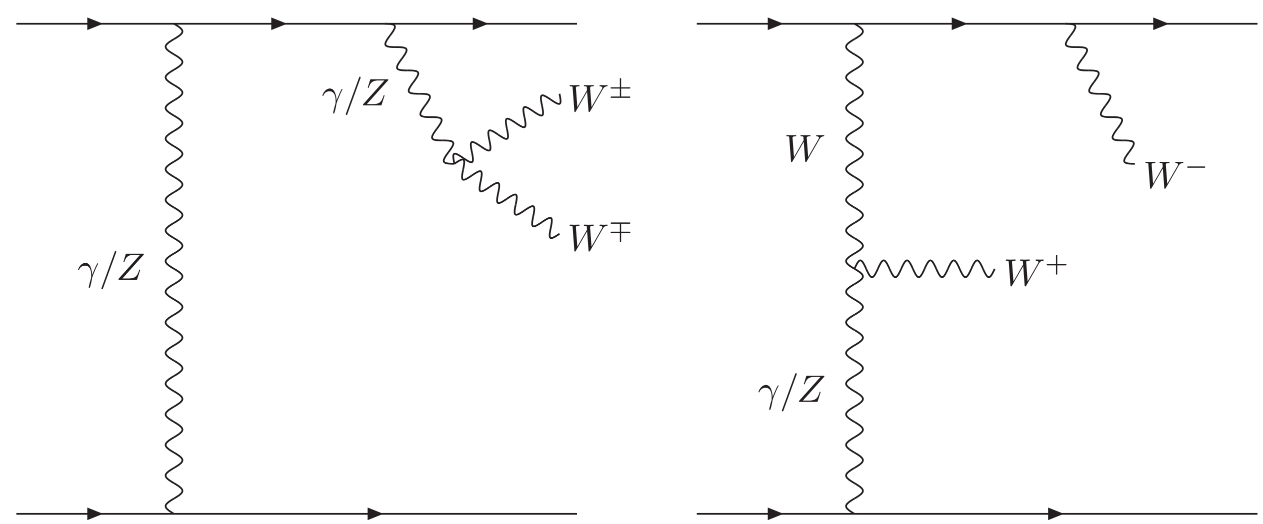
and probe (anomalous?) EW couplings of W.

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

- Only recently been fully understood. Subtleties related to non-PI diagrams:



:



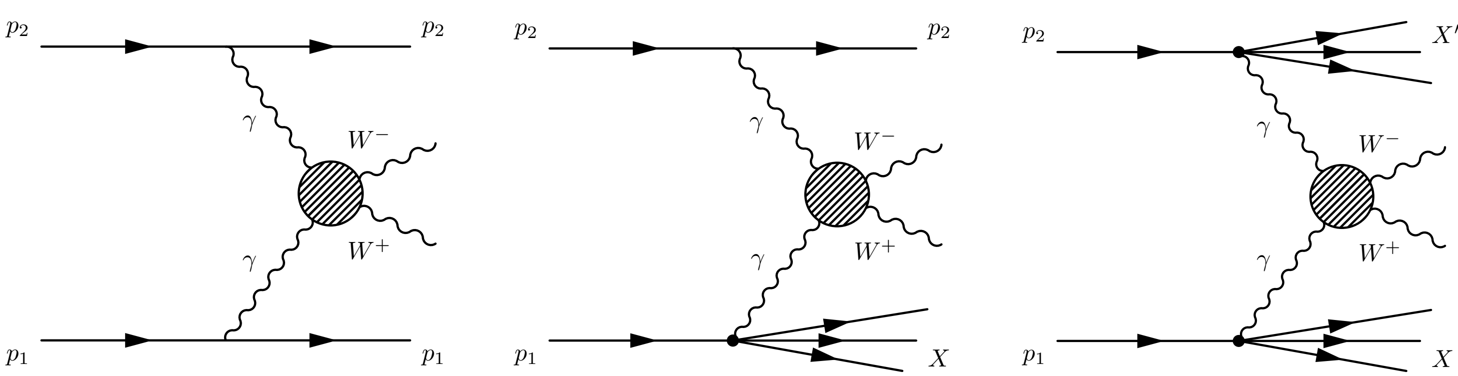
require some care, but can be accounted for, maintaining precision in predictions.

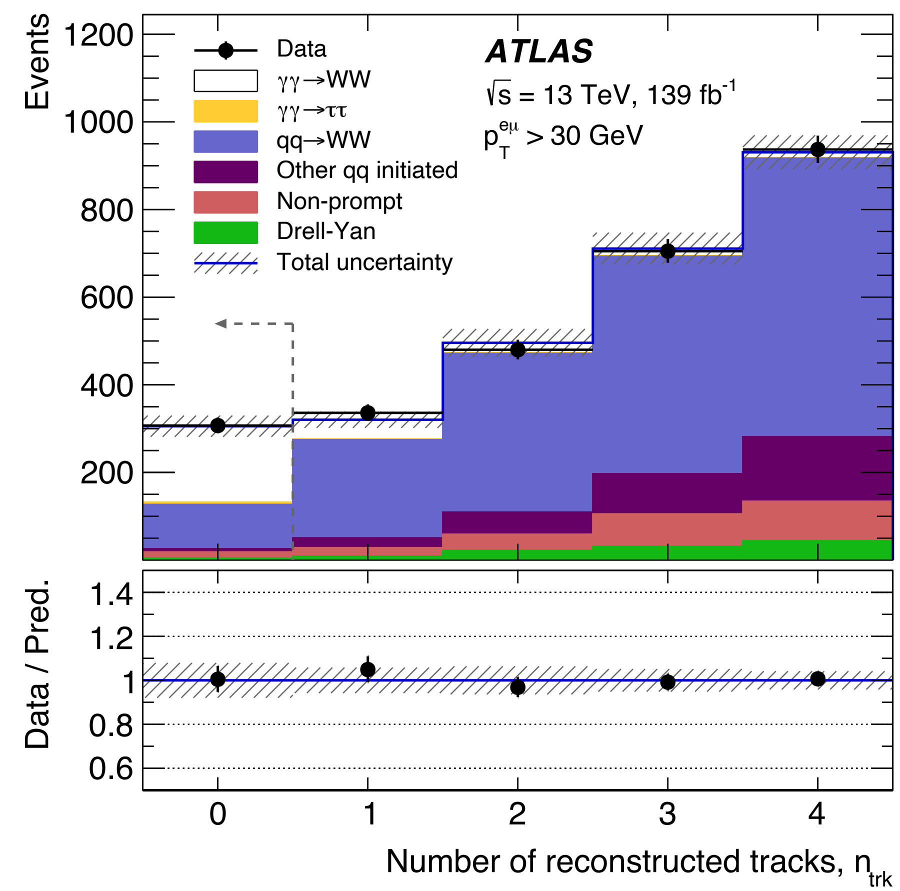
Recent data

- Evidence for such '**semi-exclusive**' W^+W^-production in leptonic channel seen by ATLAS + CMS previously.
- Recently: first observation by **ATLAS**, at 13 TeV, via rapidity veto.

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

Elastic | **Single Dissociative** | **Double Dissociative**





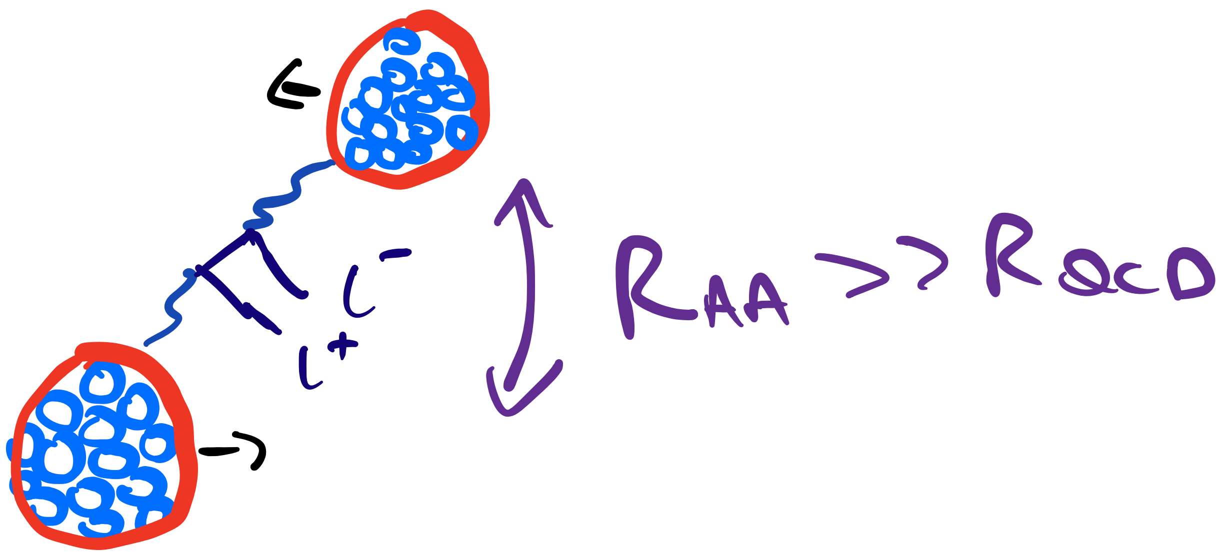
ATLAS, Phys. Lett. B 816, 136190 (2021)

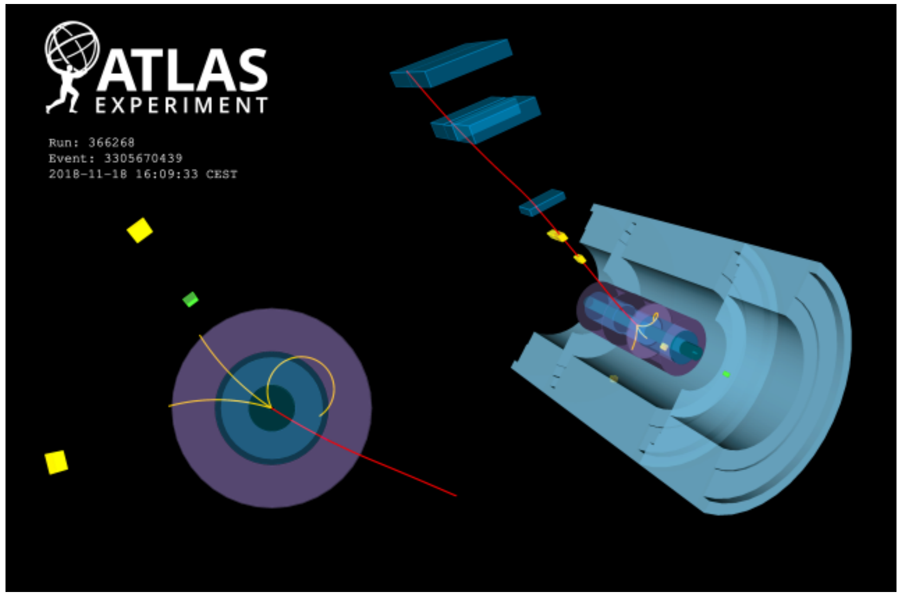
- Agrees well with theory, after including all diagrams.
- So far just a single number. Next steps: (multi)-differential, EFT analysis…

Heavy Ion Collisions

Heavy Ions

- Heavy ion collisions in fact natural arena for photon-initiated production.
- If photons emitted coherently from ions their virtuality Q^2 is very low and ion-ion impact parameter $b_\perp \gg R_{\rm QCD}$ $\Rightarrow$ clean, low multiplicity event. Known as ultraperipheral collisions (UPCs).





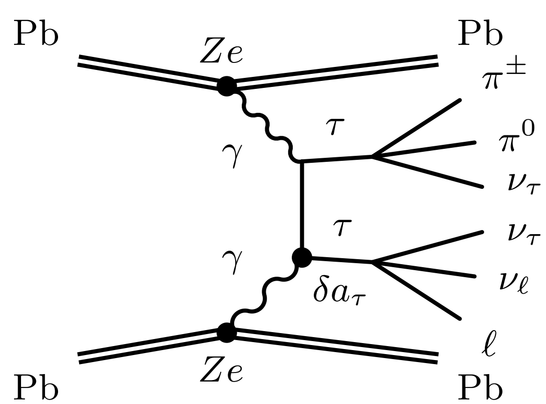
- Photon flux from ions falls v. quickly with central object mass M_X $\Rightarrow$ limited to $M_X \lesssim 50\,{\rm GeV}$, but here great deal has been achieved…

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

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

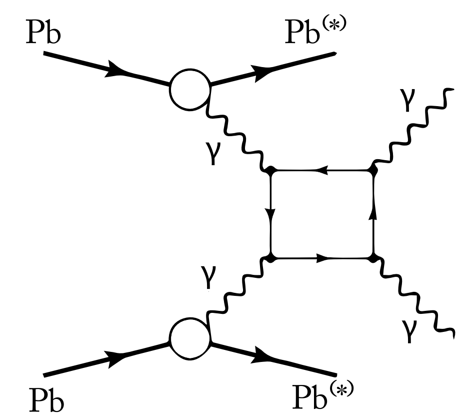
- Two flagship analyses - anomalous magnetic moment of the tau lepton and light-by-light scattering:

tau g-2



L. Beresford and J. Liu, PRD 102 (2020) 11, 113008
M. Dyndal et al., PLB 809 (2020) 135682

LbyL scattering



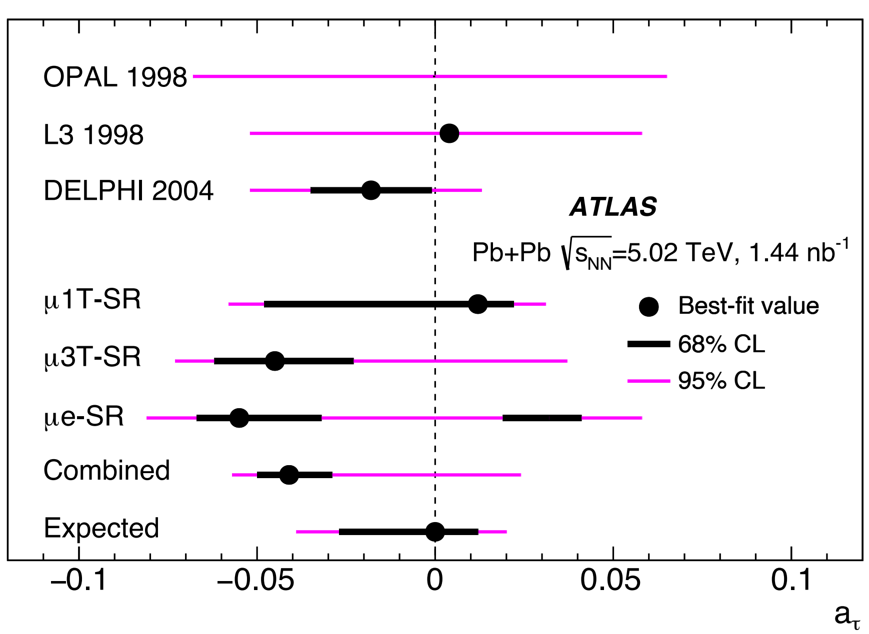
C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

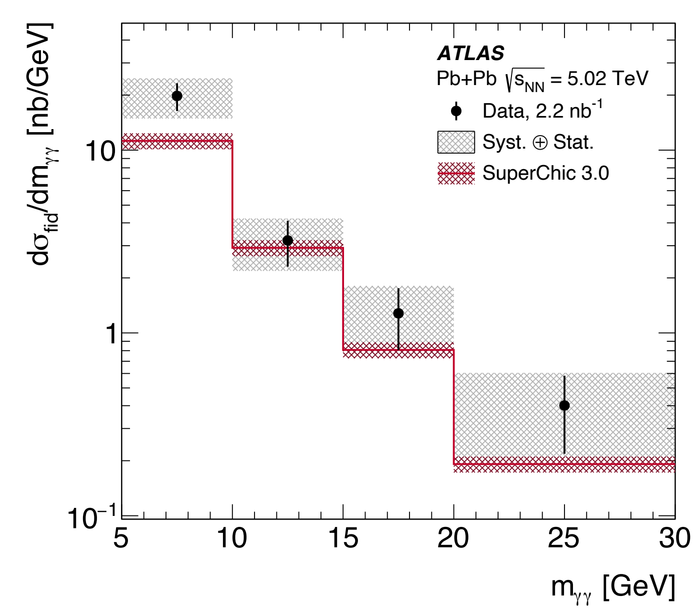
ATLAS, *Nature Phys*. 13 (2017) 9, 852-858

★ Tightest yet constraints on tau g-2.

★ First ever observation of this!

ATLAS, arXiv: 2204.13478 (accepted PRL)

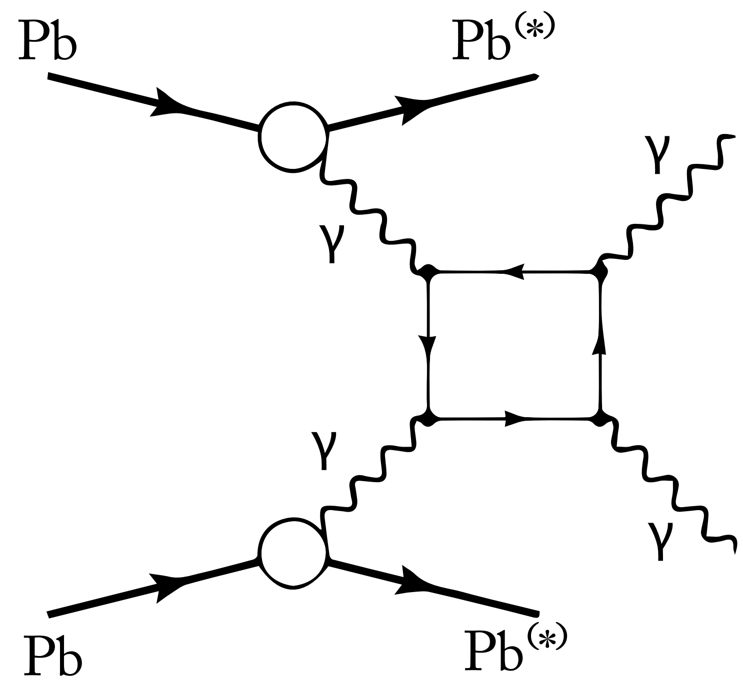




ATLAS, *JHEP* 03 (2021) 243

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.

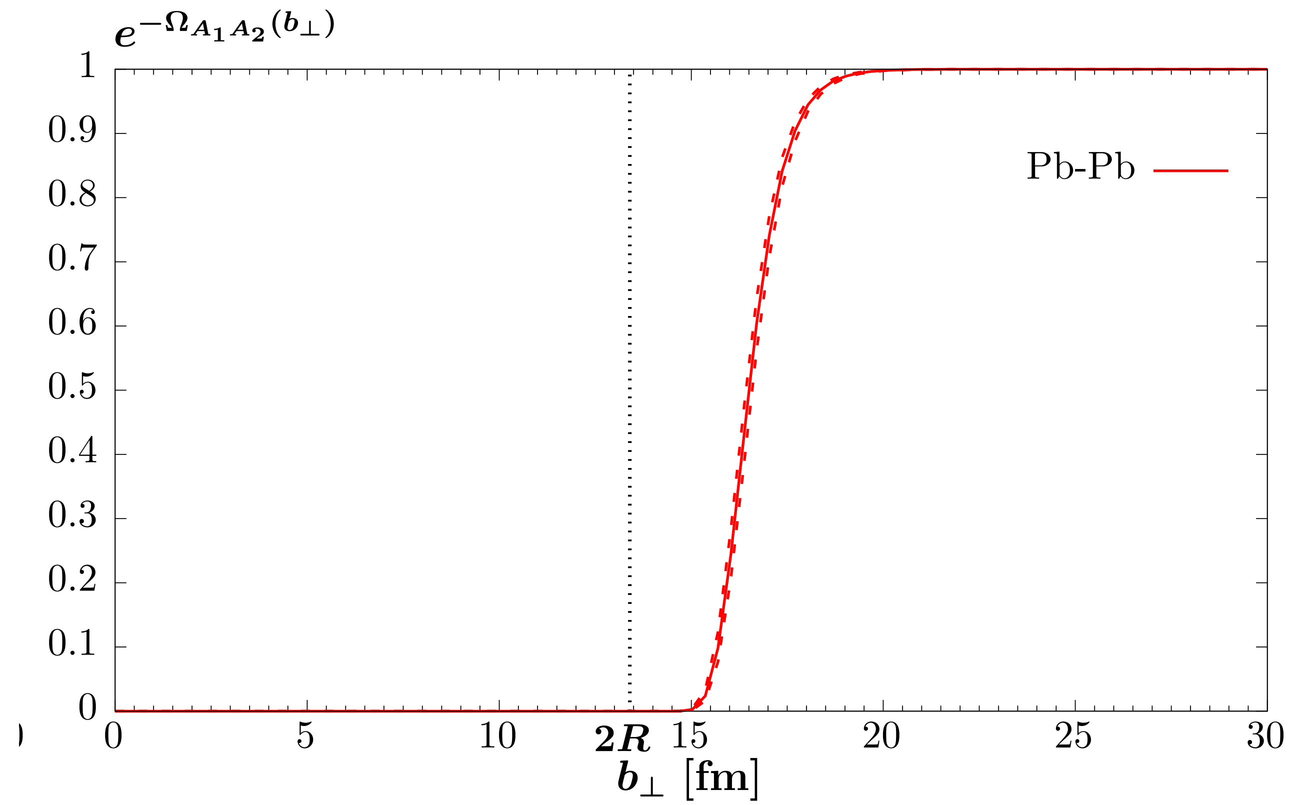
- Elastic form factor ~ ion charge density.

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

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

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

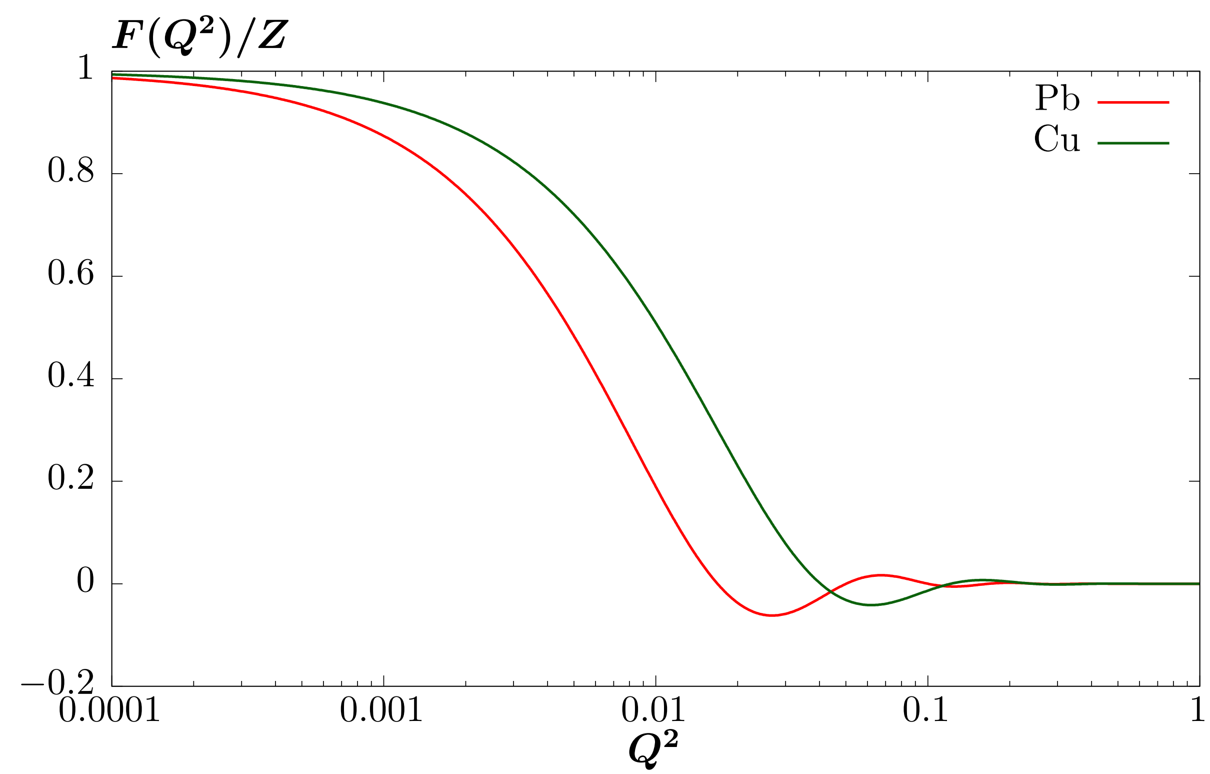
$\Rightarrow S^2 \sim 1$, with small uncertainty



★ Input for elastic form factors very well determined.

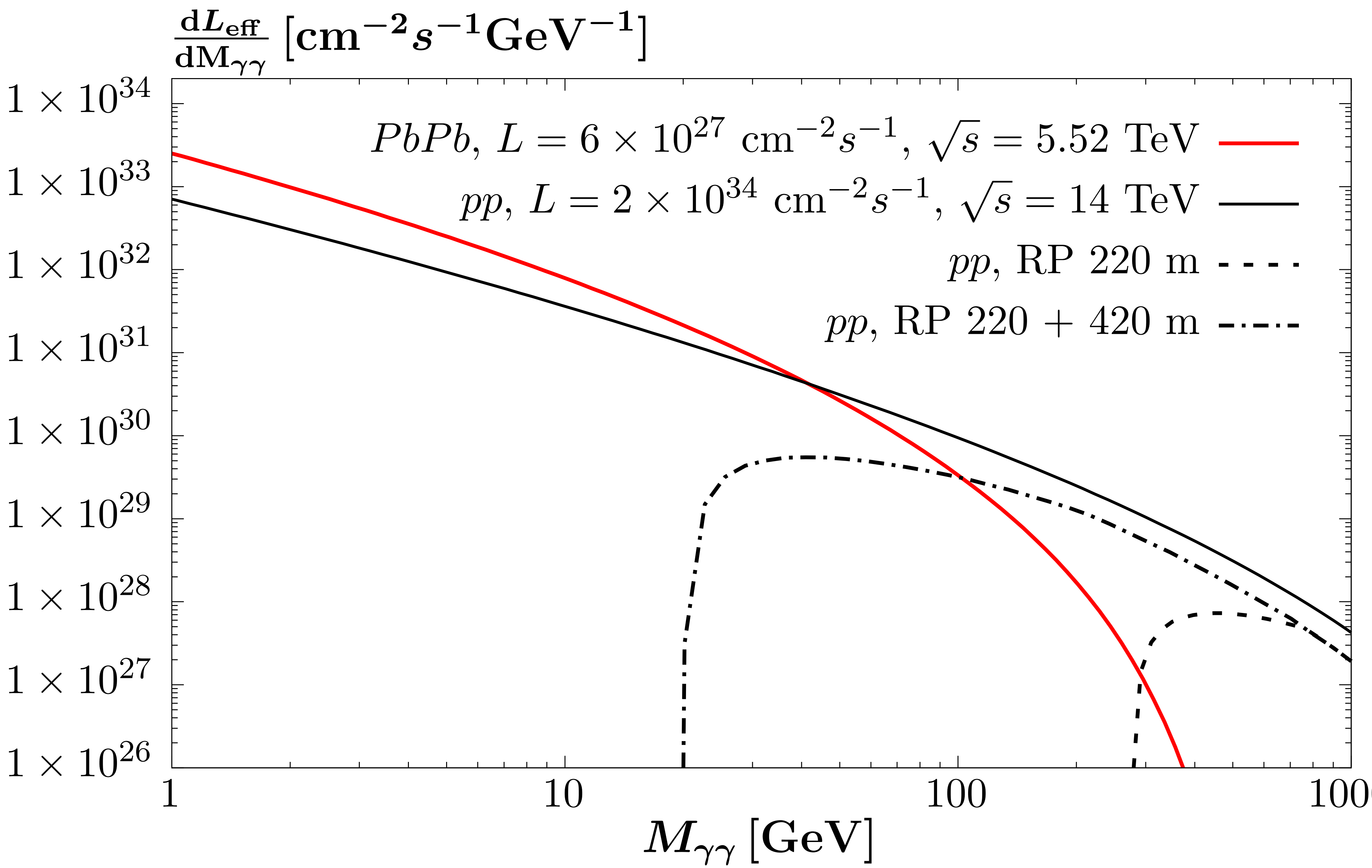
$$\rho_p(r) = \frac{\rho_0}{1 + \exp{(r-R)/d}} \, ,$$

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



★ 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.

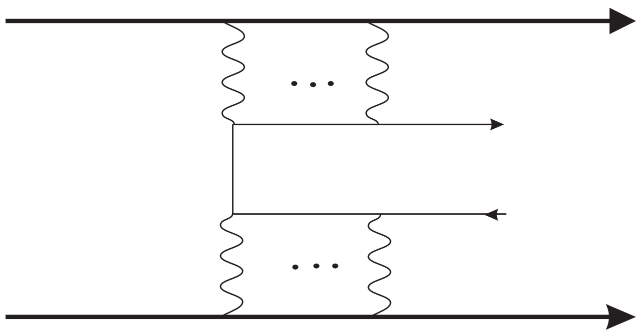


- In addition, range of theoretical effects enter that play less of a role in pp case...

PbPb: other effects

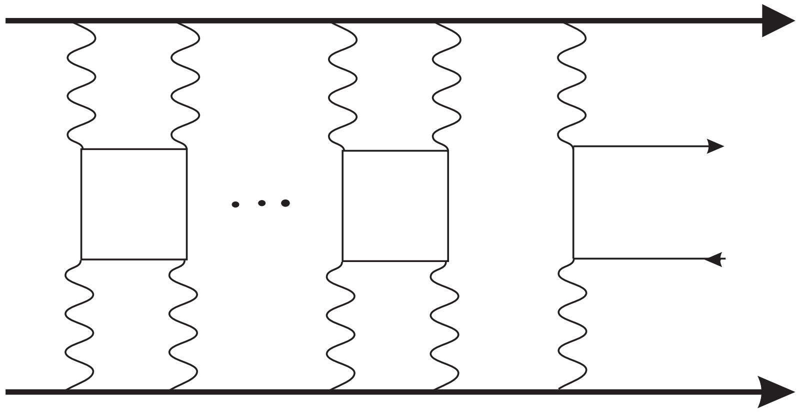
W. Zha and Z. Tang, (2021), 2103.04605.

- **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.



- **QED FSR**? Included via Pythia in predictions, but worth recalling that production of such back-to-back leptons particularly sensitive to this.

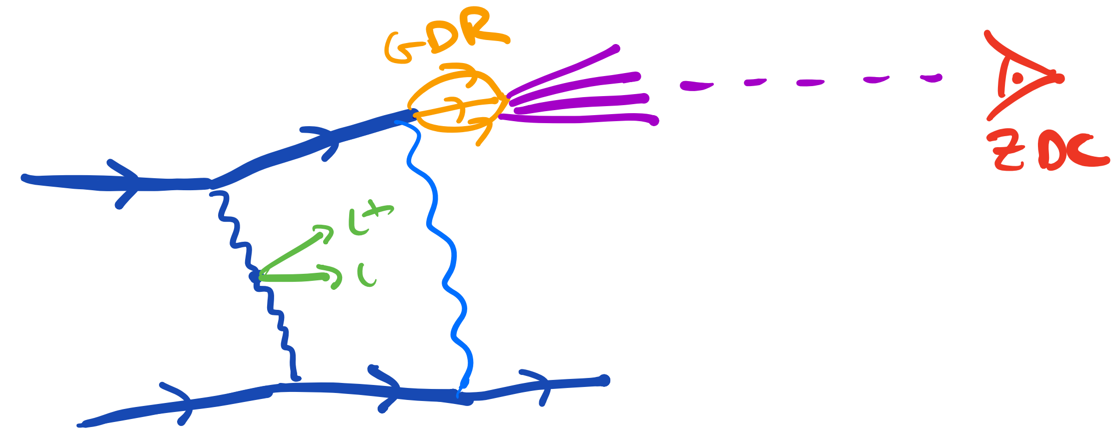
$\longrightarrow$ Relevance of these effects clearly not limited to (SM) dimuon production!

- As with pp purely elastic collisions not the only case of interest.

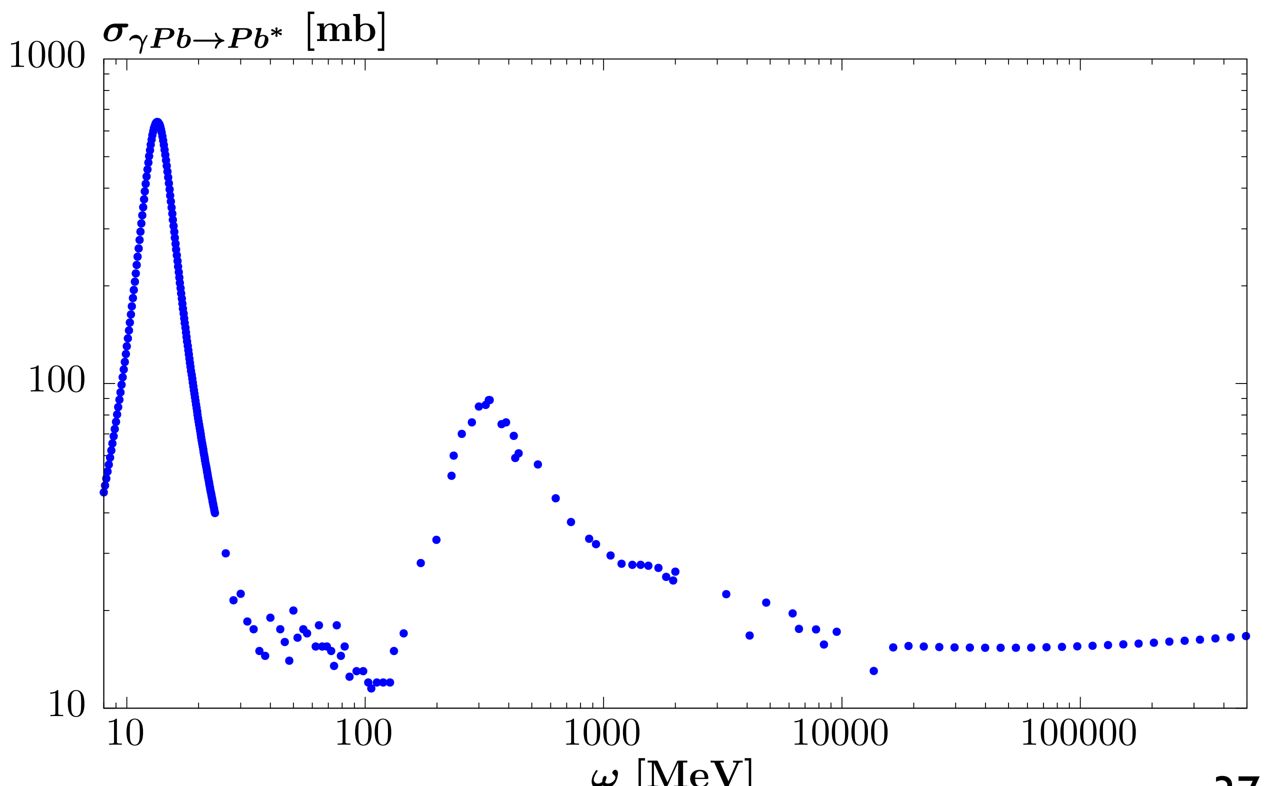
  ★ Ions can dissociate: additional boosted neutron production measured by ATLAS/CMS Zero Degree Calorimeters detectors.

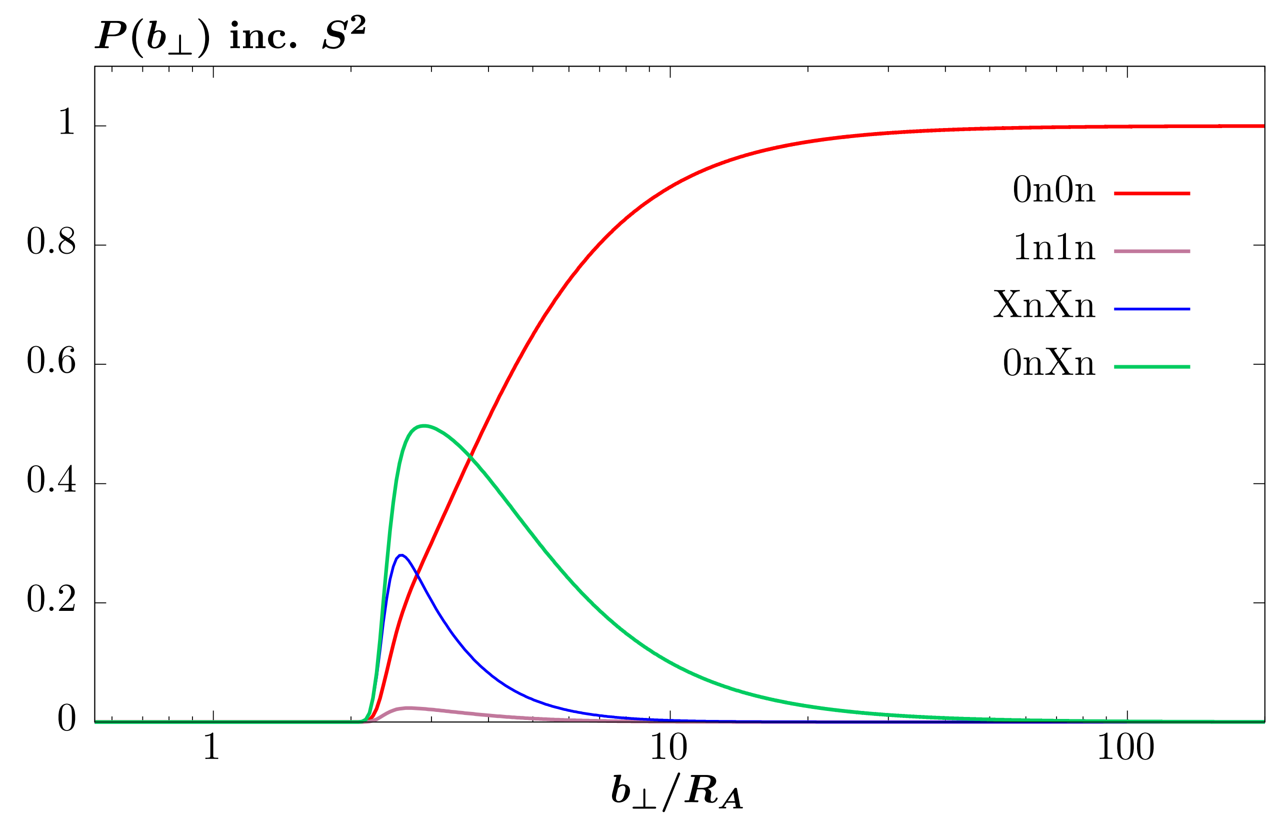
  ★ Different neutron multiplicities have different impact parameter profiles $\rightarrow$ modifies central kinematics.

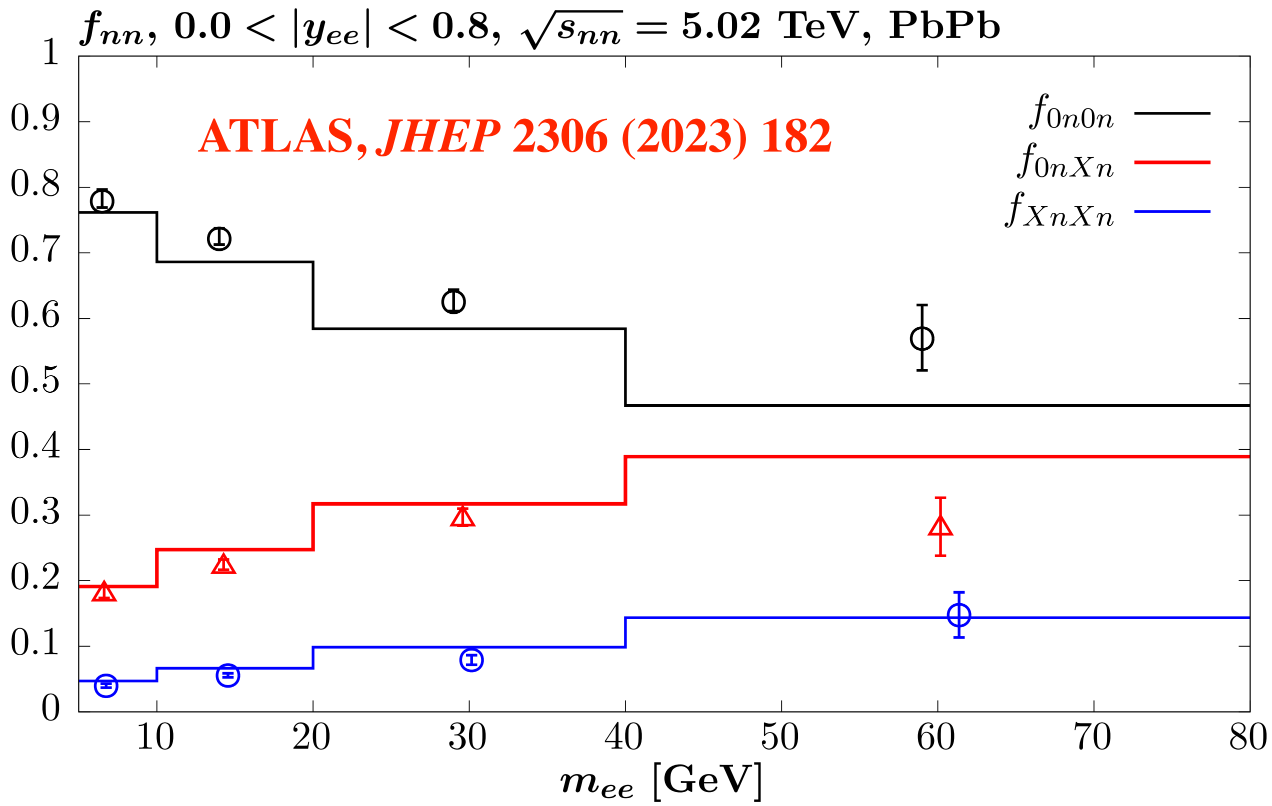
  ★ Accounted for in recent study…



LHL, *Phys.Rev.D* 107 (2023) 9, 093004

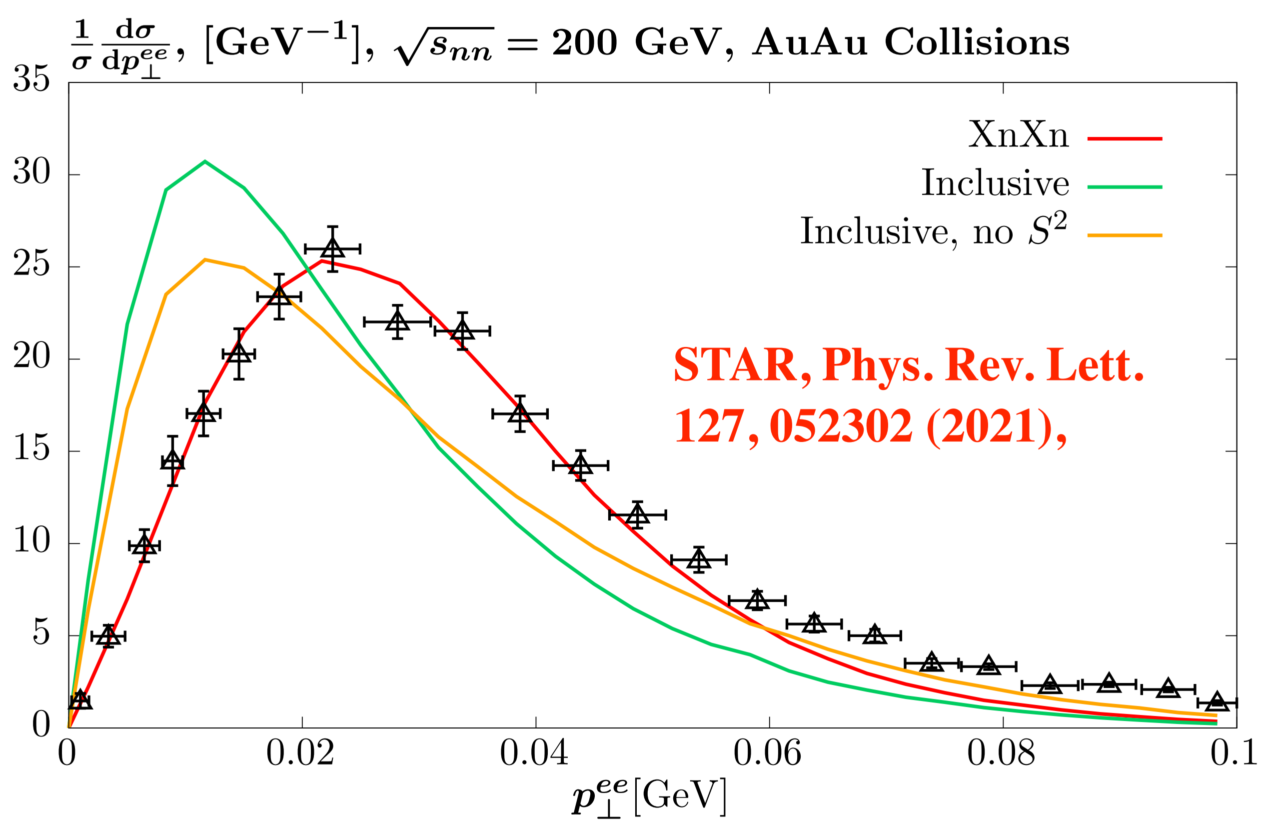


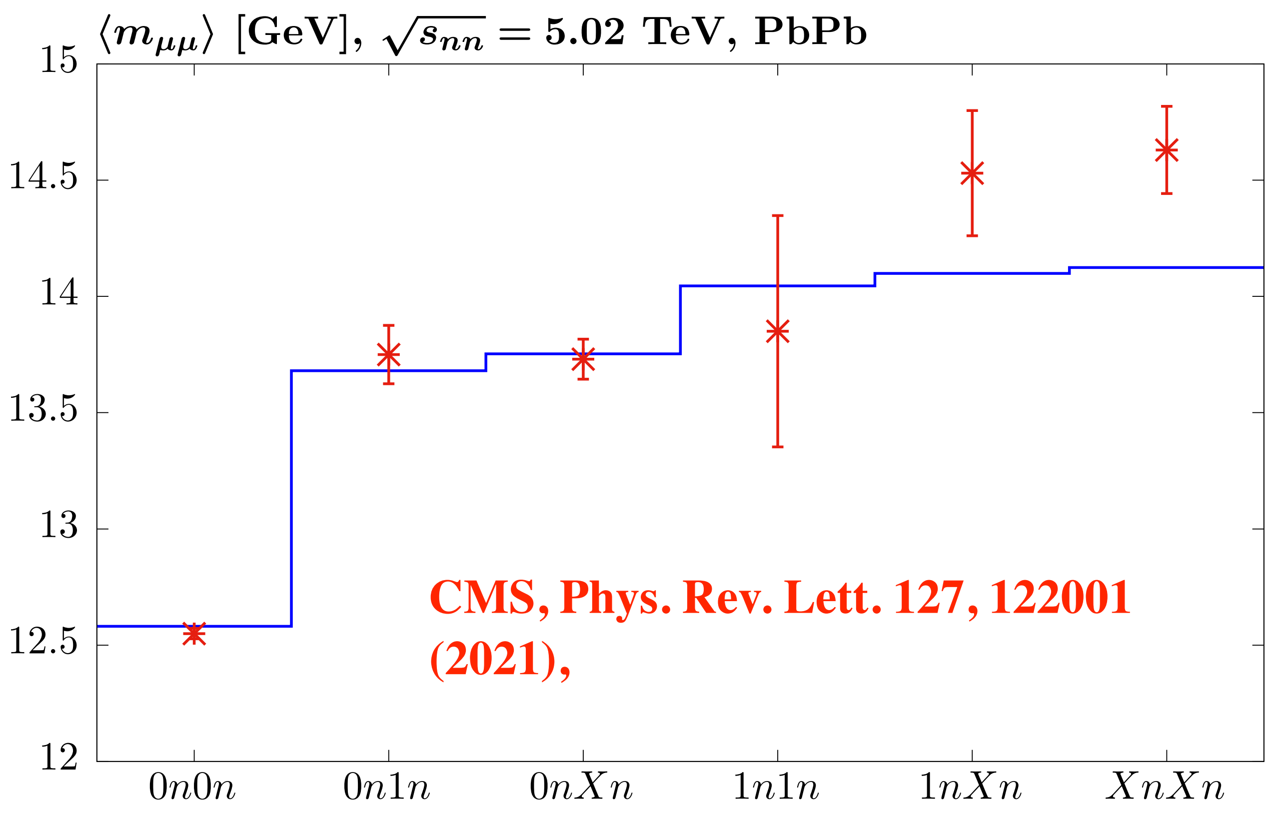




★ Broad agreement with range of LHC/RHIC data, but devil in detail!

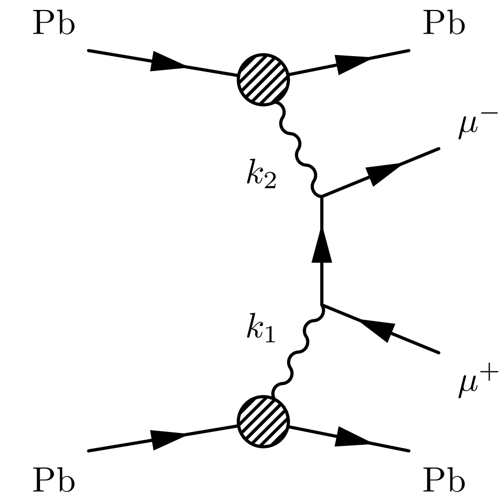
★ Provides additional handle in measurements/searches.





Comparison to data

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

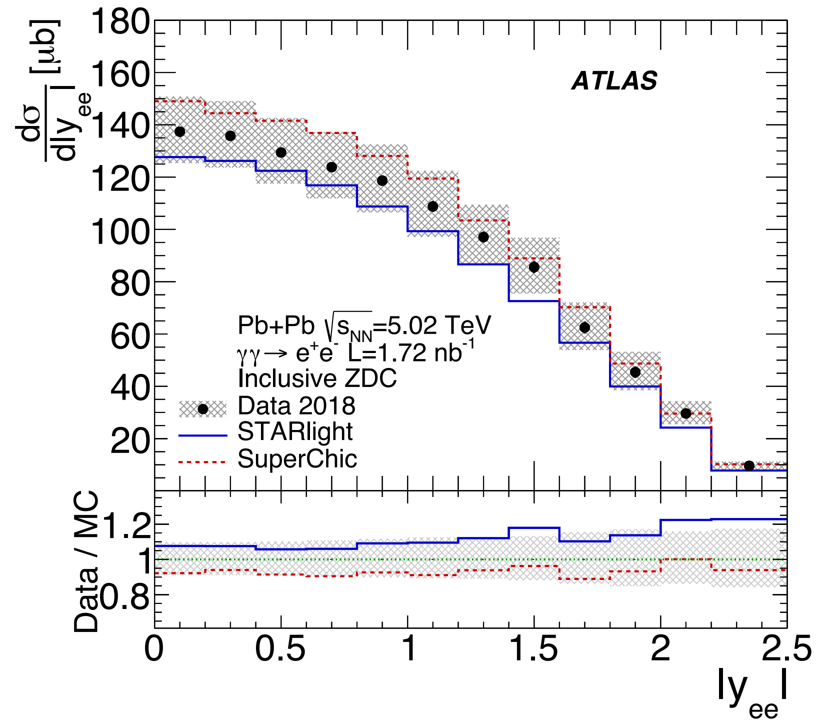


	ATLAS data [23]	Pure EPA	inc. S^2	inc. S^2 + FSR
σ [μb]	34.1 ± 0.8	52.2	38.9	37.3

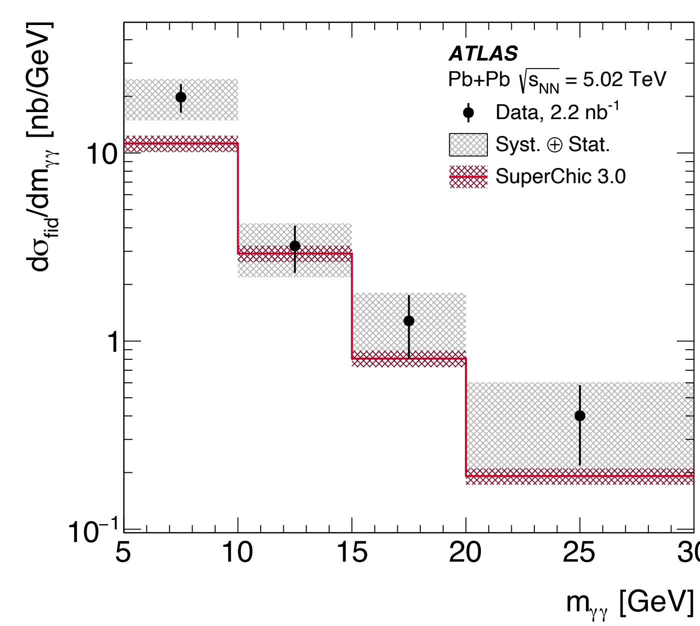
ATLAS, *Phys.Rev.C* 104 (2021) 024906

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?

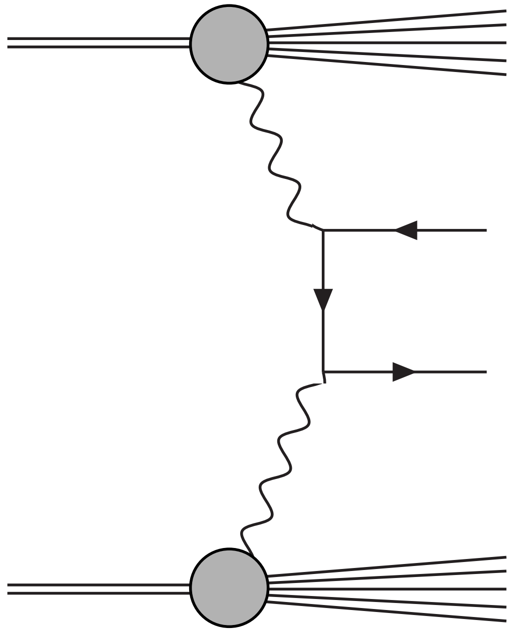
  ★ Heavy ions: higher order QED…

  ★ …

Thank you for listening!

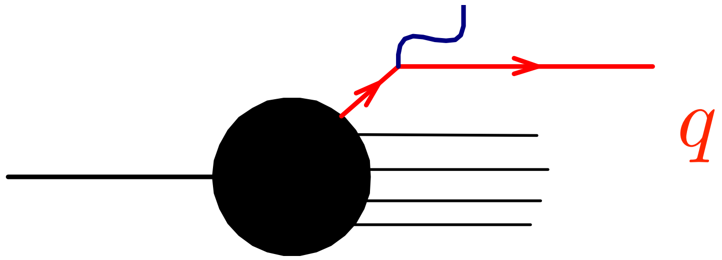
Backup

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.

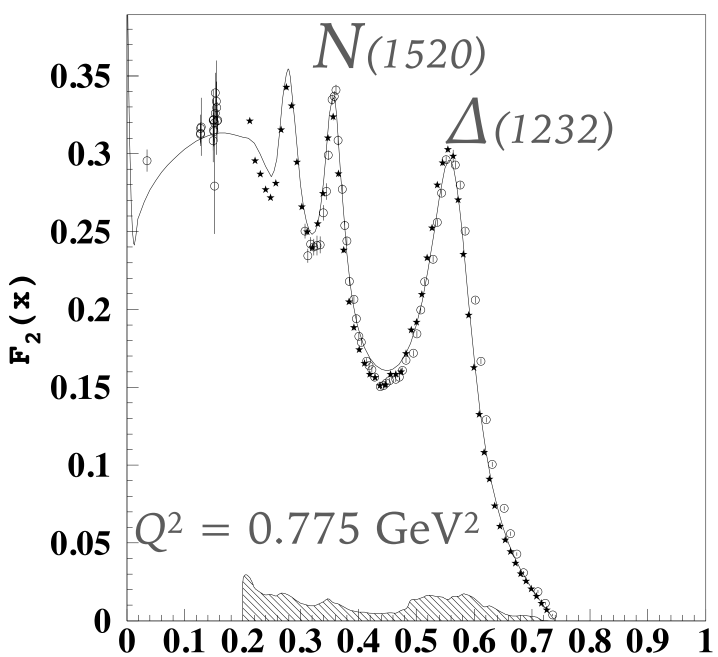
- No clear off-the-shelf way to do this, so take simplified approach:
  - ★ For purposes of LHE record, for inelastic emission take LO $q \to q\gamma$ vertex
  - ★ Generate outgoing quark according to momentum conservation, preserving photon 4-momentum.

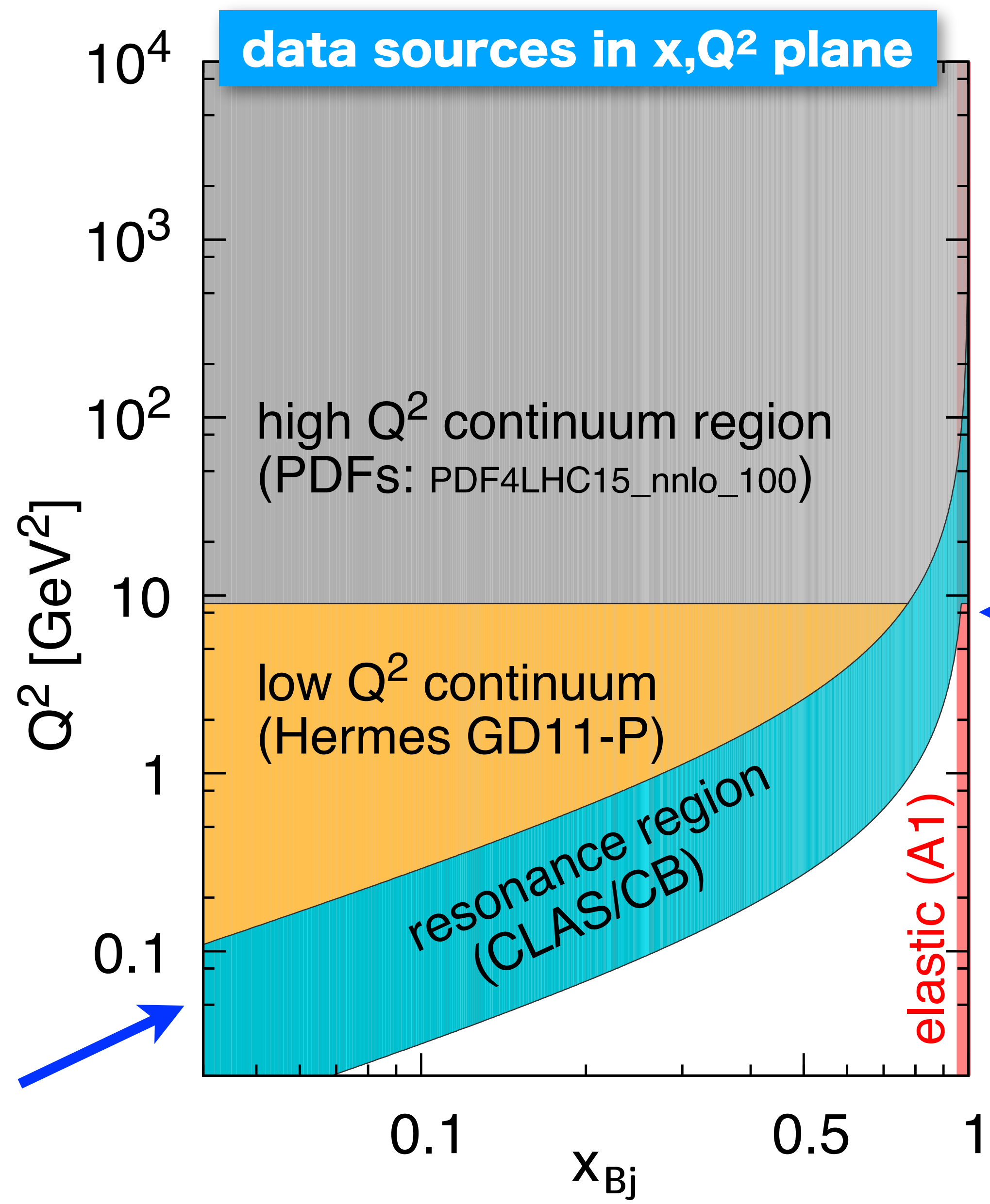


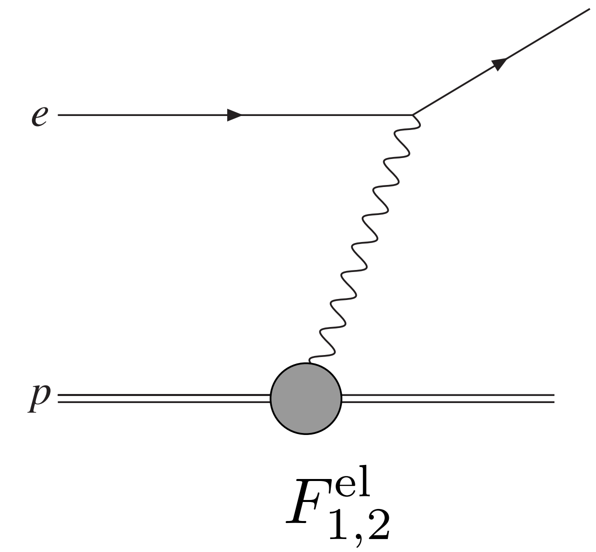
- ISR/FSR will then modify photon 4-momentum. Not ideal, but for purpose of current study sufficient.
- In addition, must turn off global recoil in Pythia to get realistic result (no colour connection between beams).

Image credits: Gavin Salam

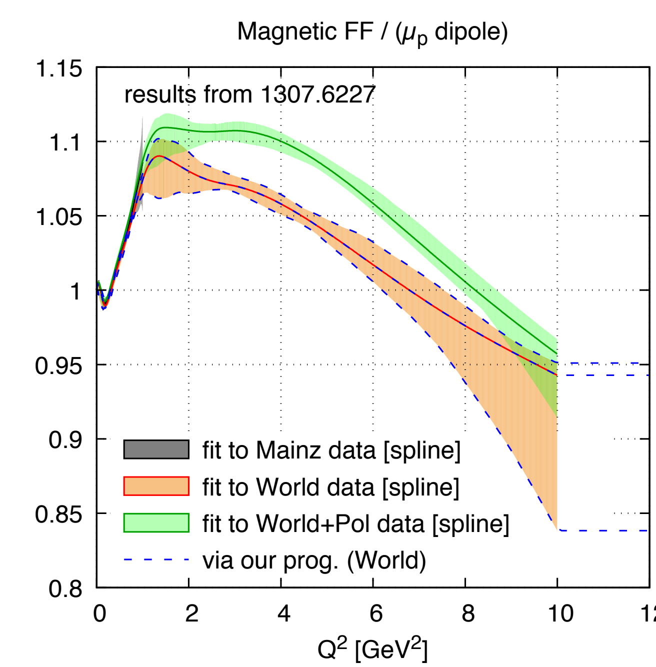
- In more detail, components of $F_{1,2}$ break up into four regions:







Elastic scattering: from A1 collaboration.



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

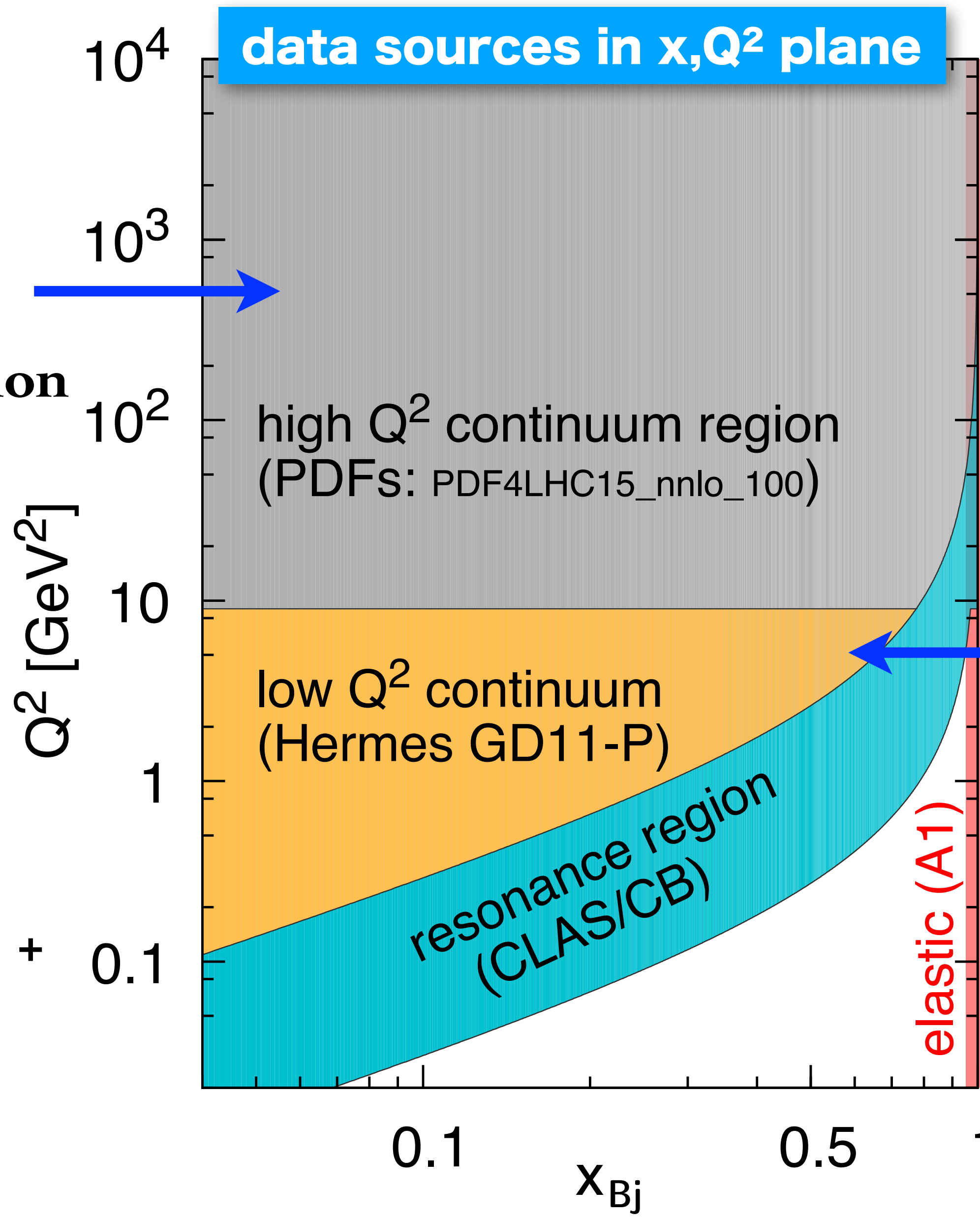
Inelastic resonant proton excitation. Precise parameterisations available.

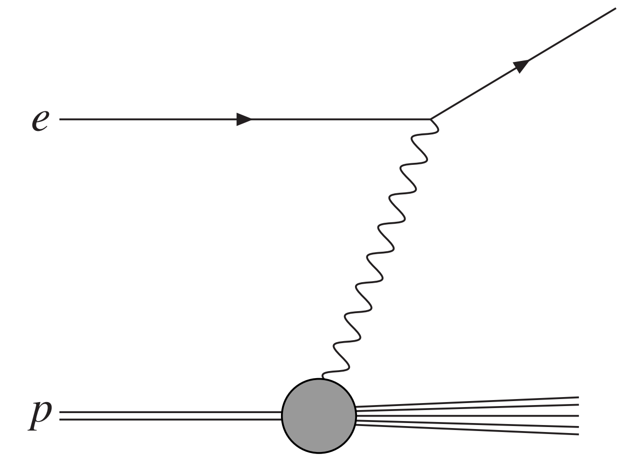
CLAS, M. Osipenko et al., Phys. Rev. D67, 092001 (2003)

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).



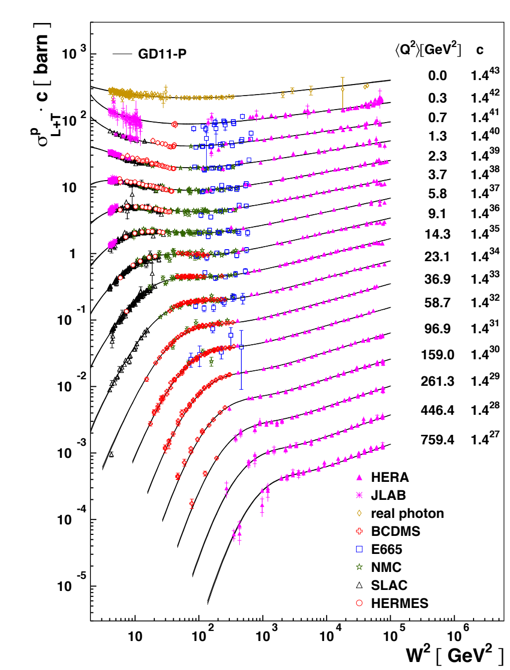


$F_{1,2}^{\rm inel}$

Inelastic low Q^2 scattering. Precise parameterisation available.

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

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



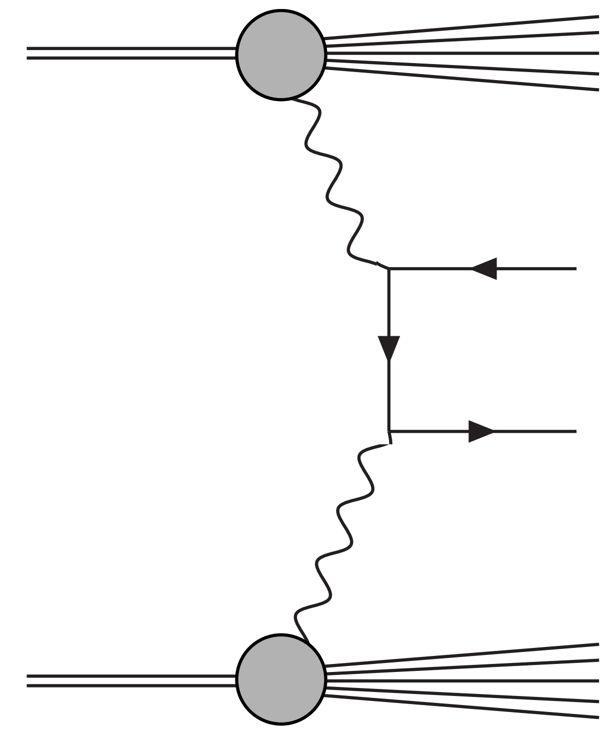
- Closely follow LUXqed inputs here.

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

Other Considerations

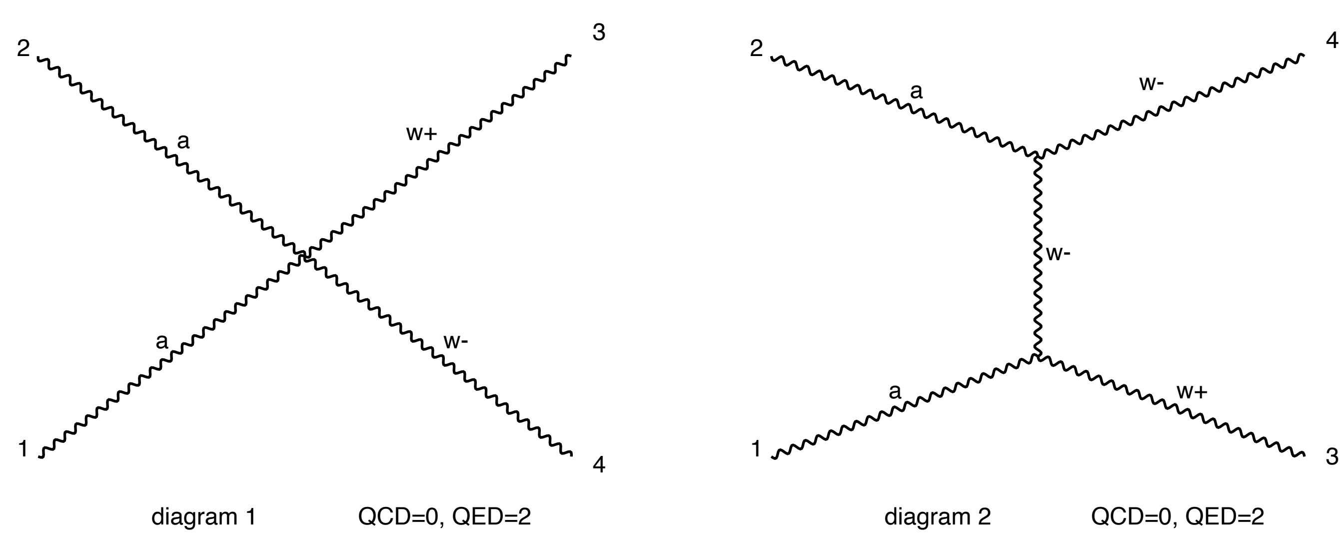
Collinear Calculation

- 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.

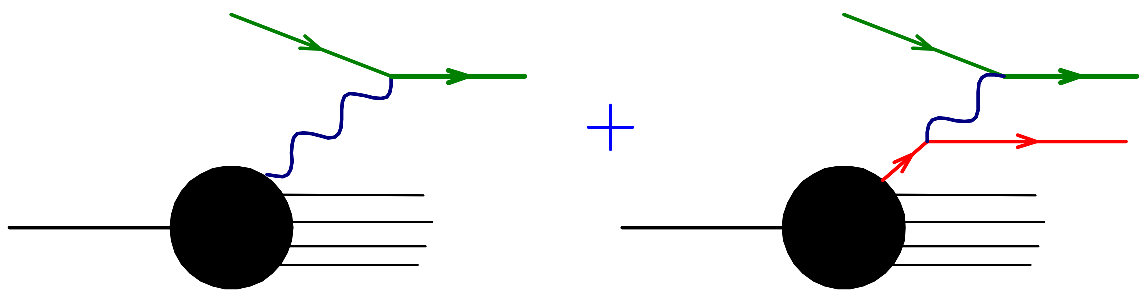


- Can show that collinear calculation is (approximately) equivalent to full structure function calculation for pure PI production:

$$\sigma_{pp} = \frac{1}{2s}\int dx_1 dx_2\, d^2 q_{1_\perp} d^2 q_{2_\perp} d\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\rho_1^{\mu\mu'}\rho_2^{\nu\nu'} M^*_{\mu'\nu'} M_{\mu\nu}}{q_1^2 q_2^2}\delta^{(4)}(q_1+q_2-p_X)\ ,$$

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

- 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:

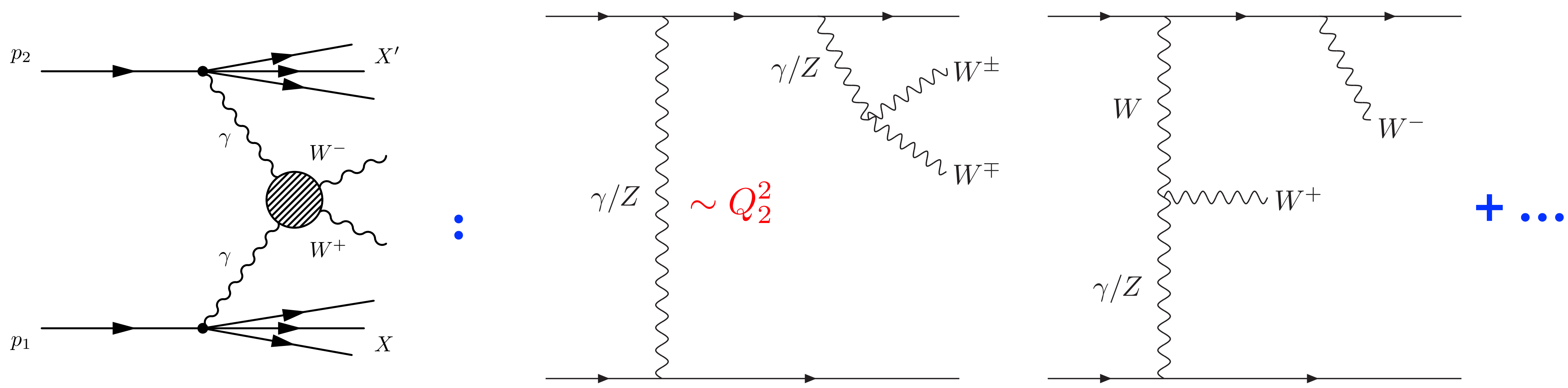


- But fore pure PI this is automatically accounted for in SF calculation.
- Moreover SF calculation (unintegrated in photon $k_\perp$) fundamental to calculation of survival factor.

However…

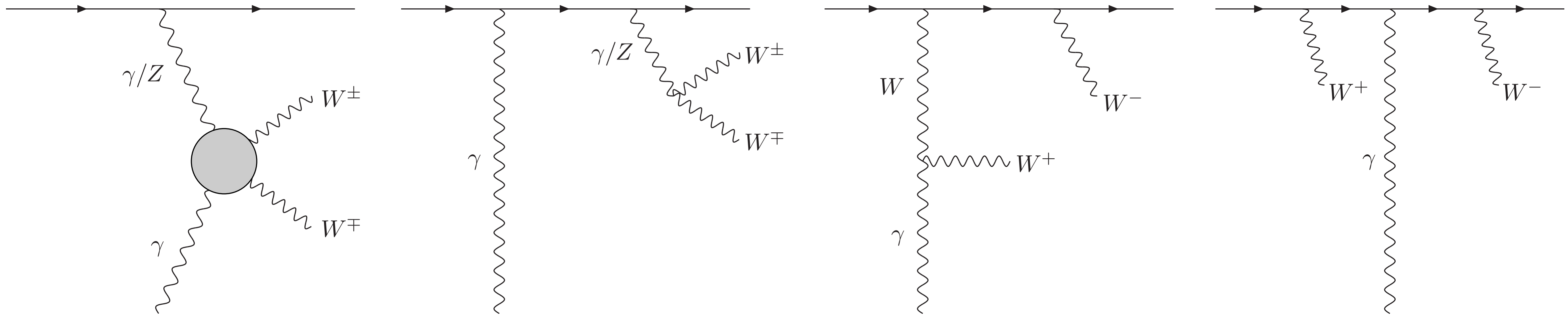
- SF calculation only accounts for pure PI (+ Z-initiated) production.
- For dissociative production this is not the only contribution. Discussed in detail for the case of WW production in **arXiv:2201.08403**.
- For e.g. the DD case also have:

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



- These non-PI diagrams are suppressed by at least $\sim Q^2/M^2_{W,Z}$ 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.

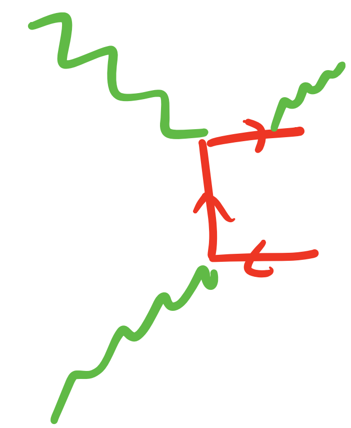
- Impact of non-PI production depends on experimental selection and process:

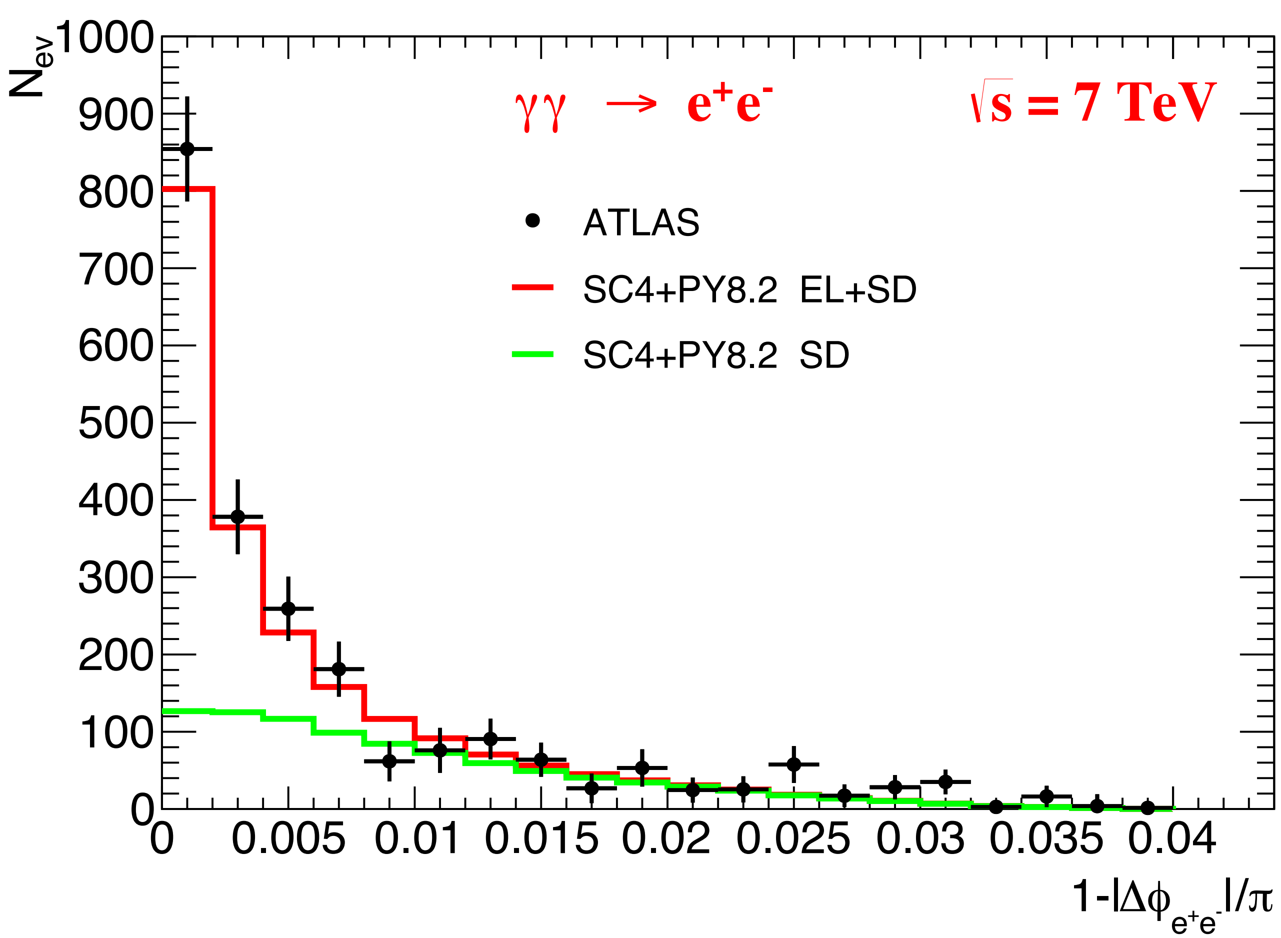
  ⋆ W pair production: O(10%) correction.

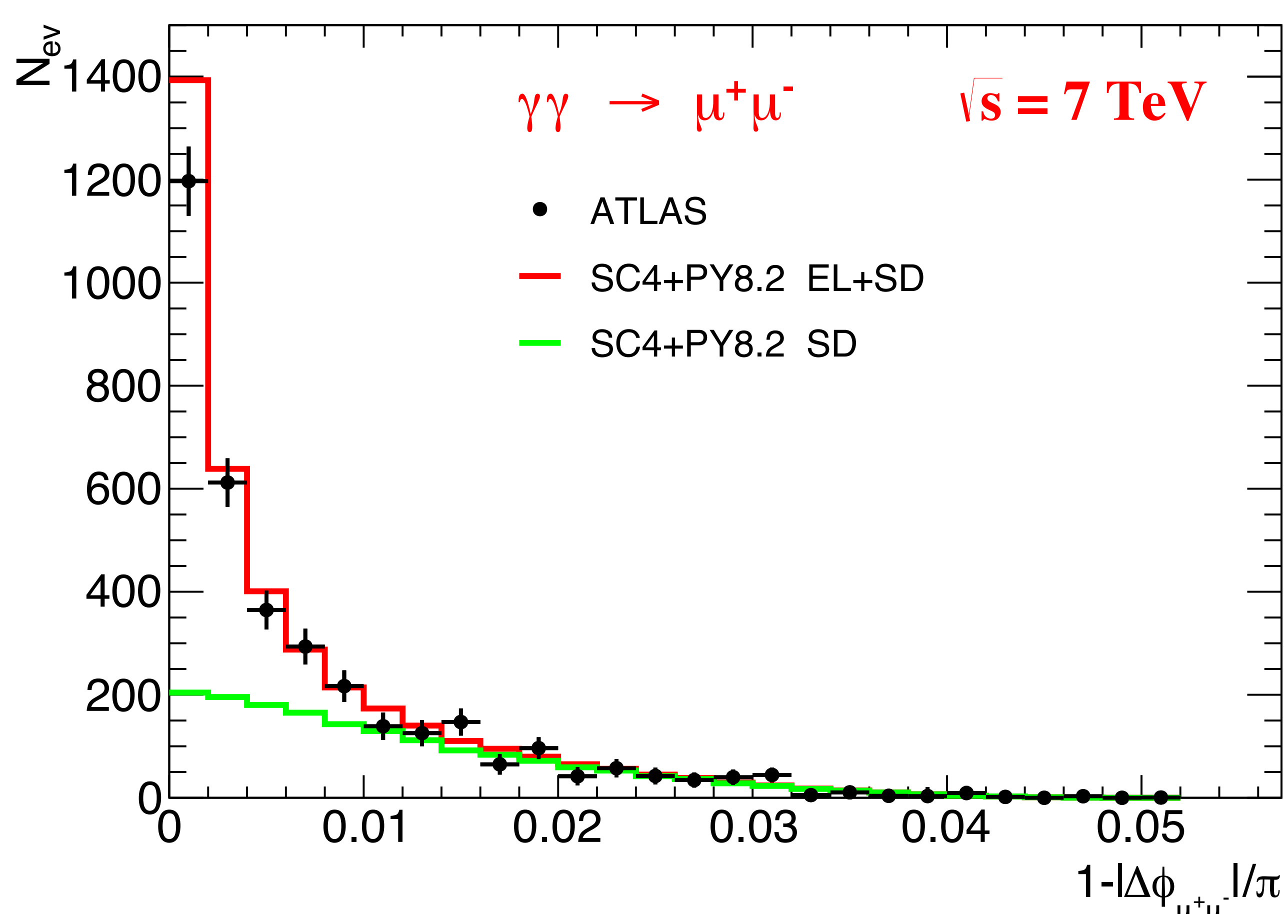
  ⋆ Lepton pair production: O(1%) correction.

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.



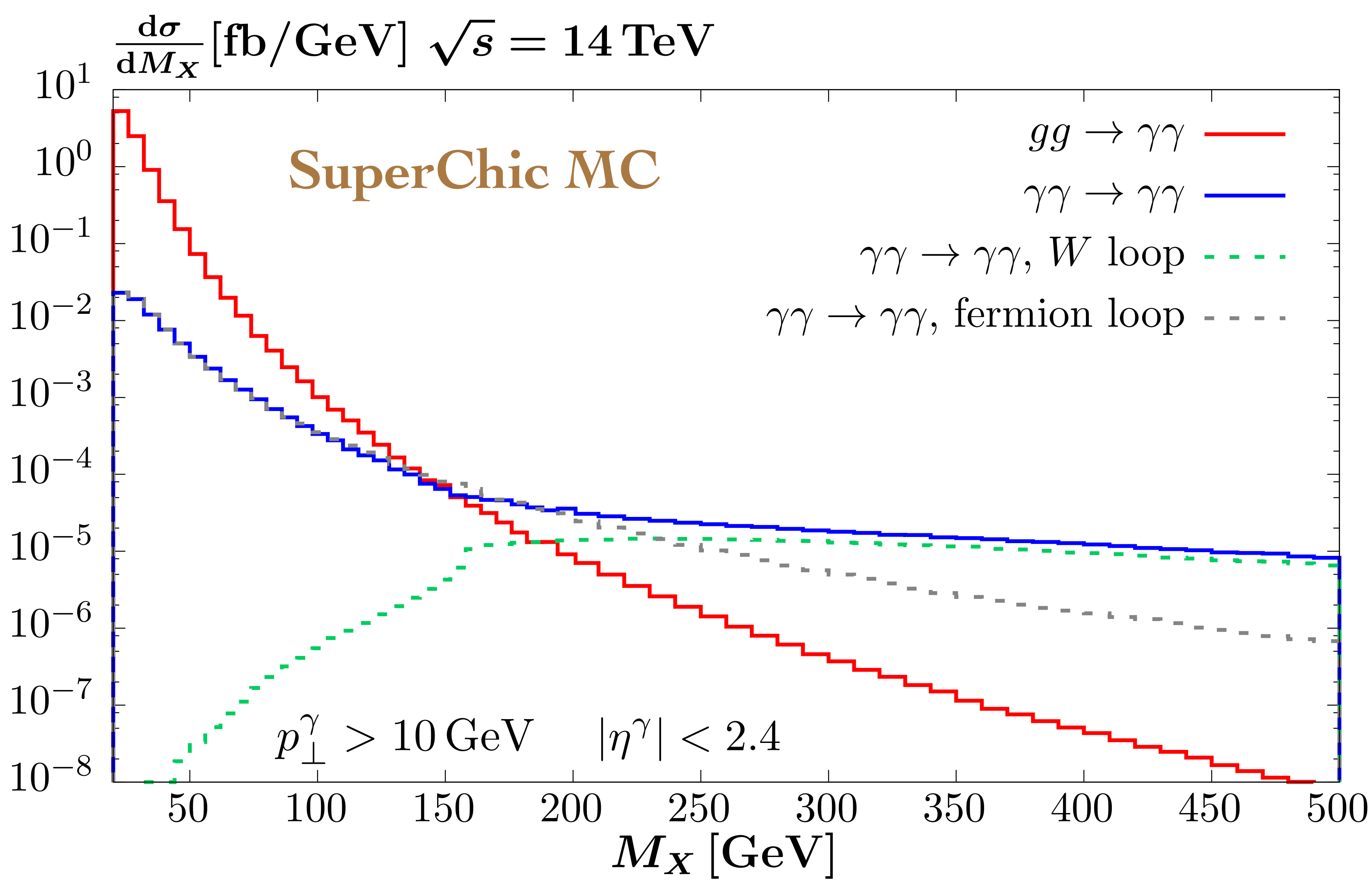


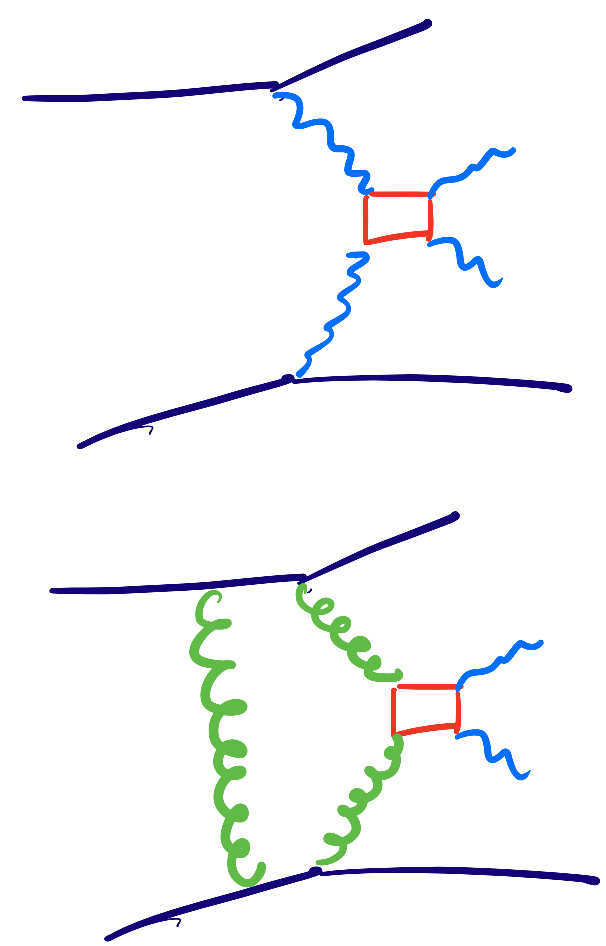


gg vs. $\gamma\gamma$

- 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.

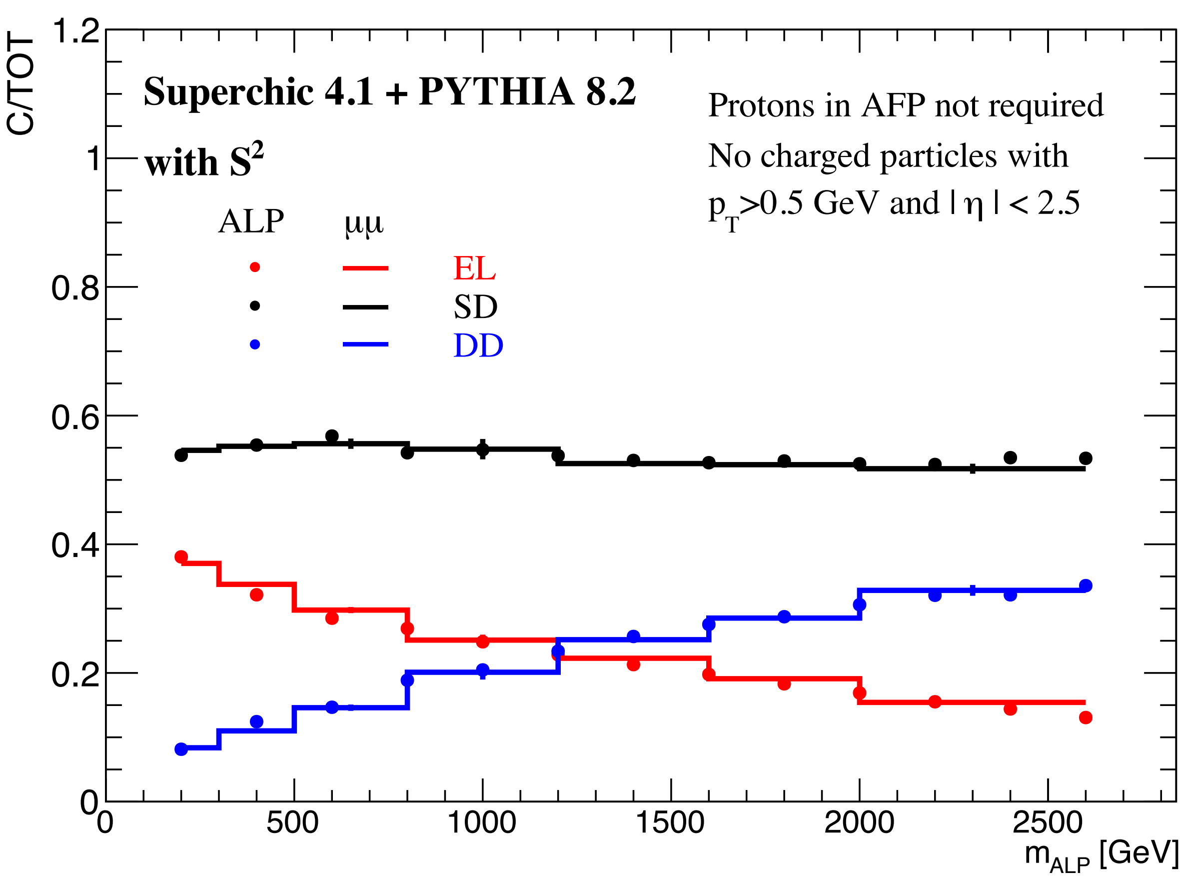
$\longrightarrow$ At higher mass PI production starts to dominate.

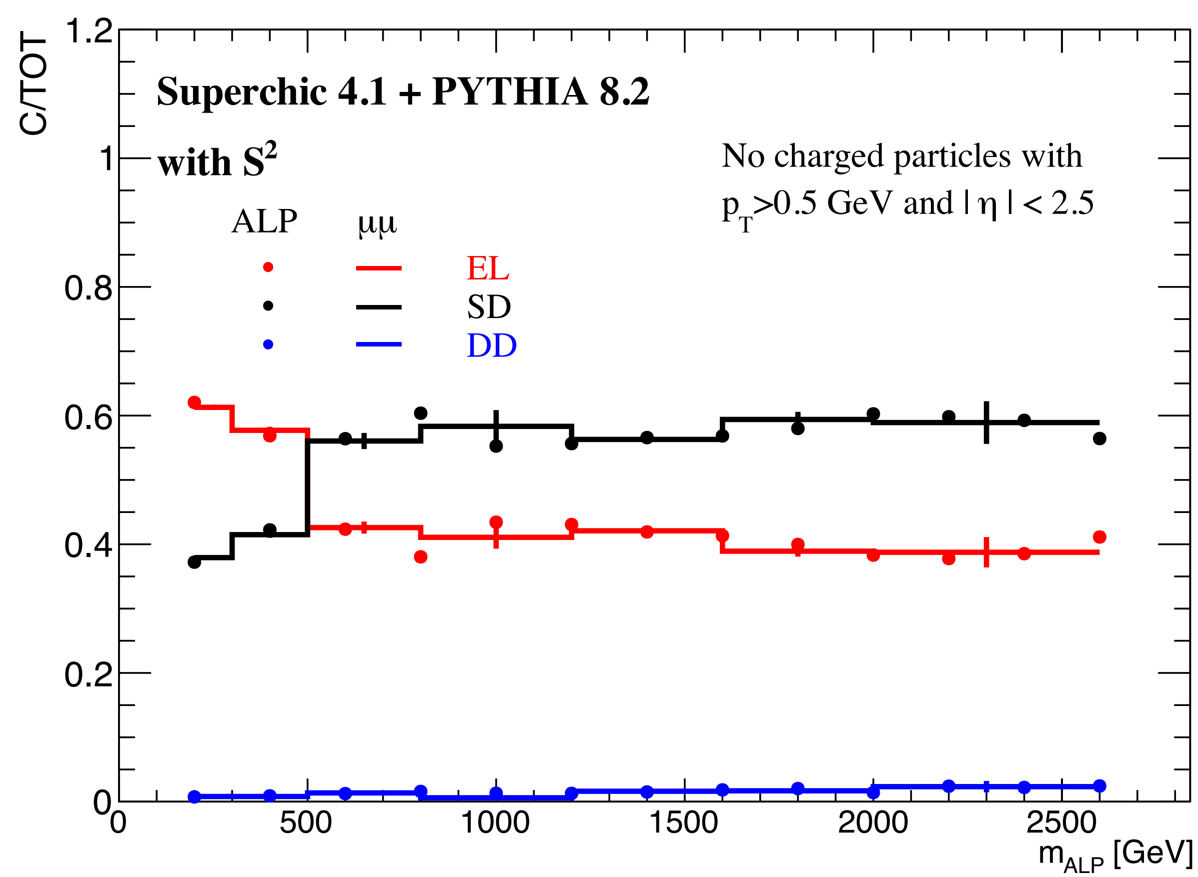




Proton Tag Impact

- 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

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.