The LHC as a photon-photon collider

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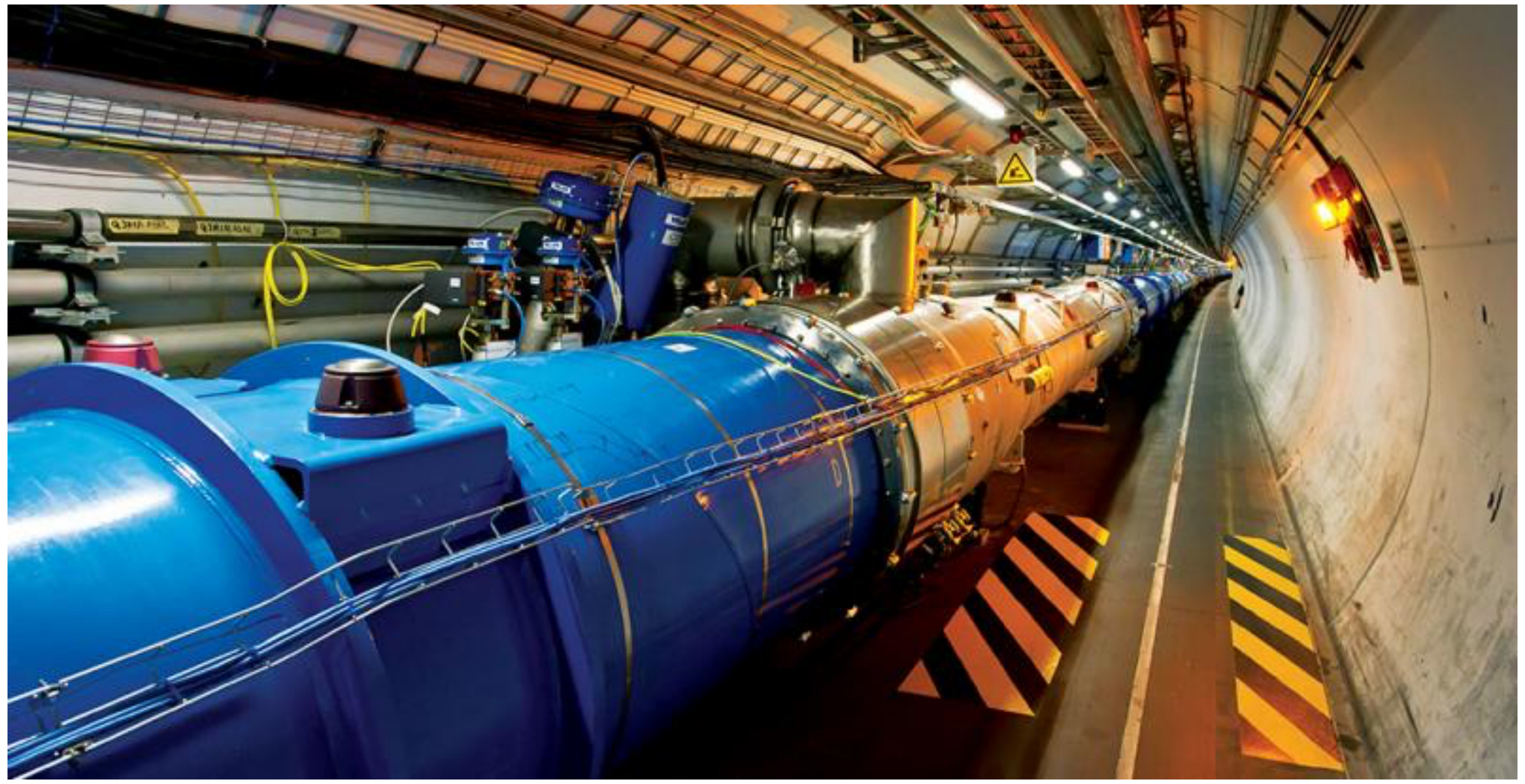
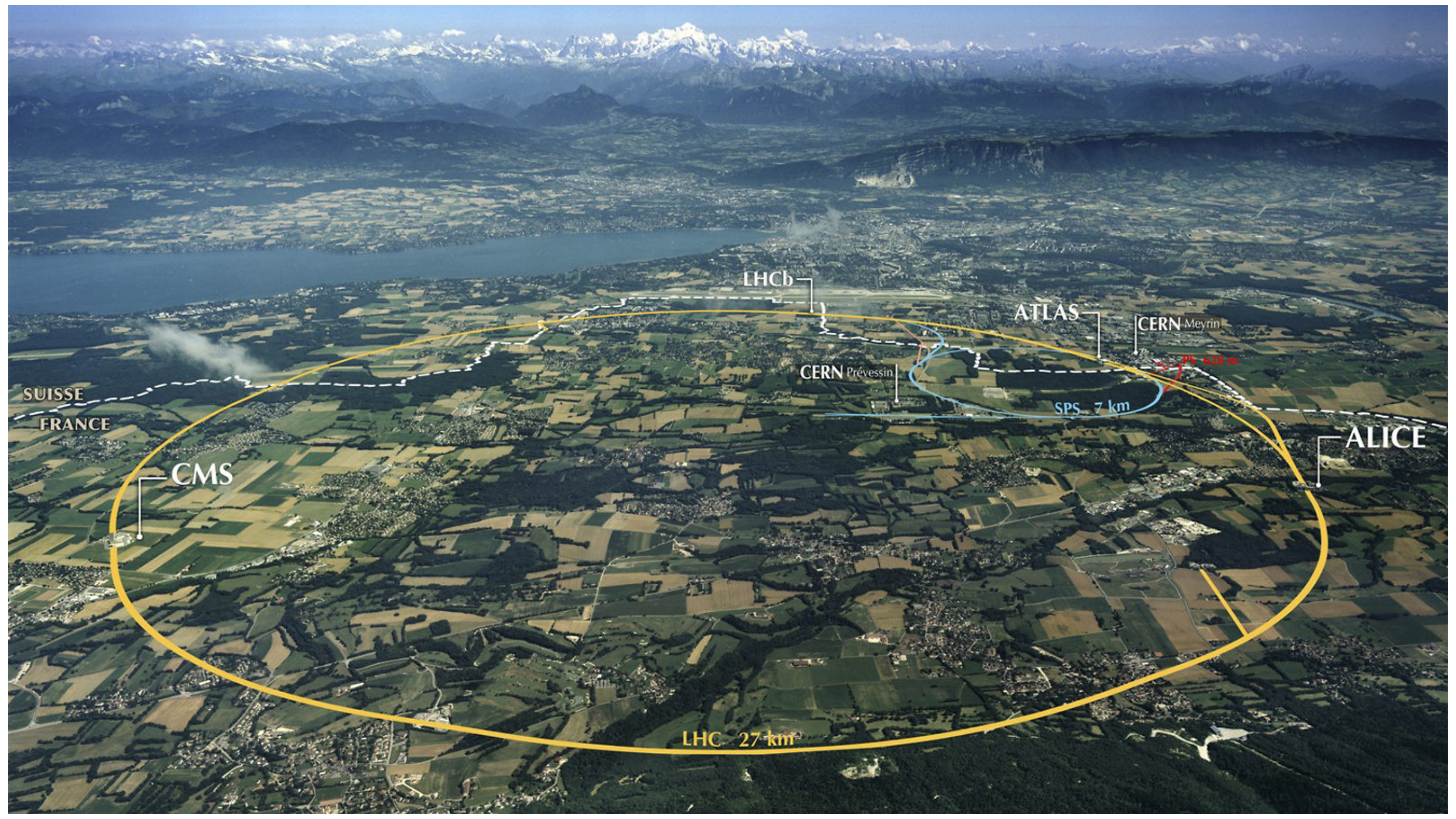
Particle Physics Seminar, Birmingham, May 22

The LHC: a hadron-hadron collider

- The **LHC** works by colliding hadron beams head on at high energy.
- We examine the debris of these interactions in order to probe the Higgs sector, look for physics beyond the Standard Model and to understand the SM better.
- It is both a **discovery** and a **precision** measurement machine.
- Before doing any of that that: we need to understand what we are colliding: the **proton.**

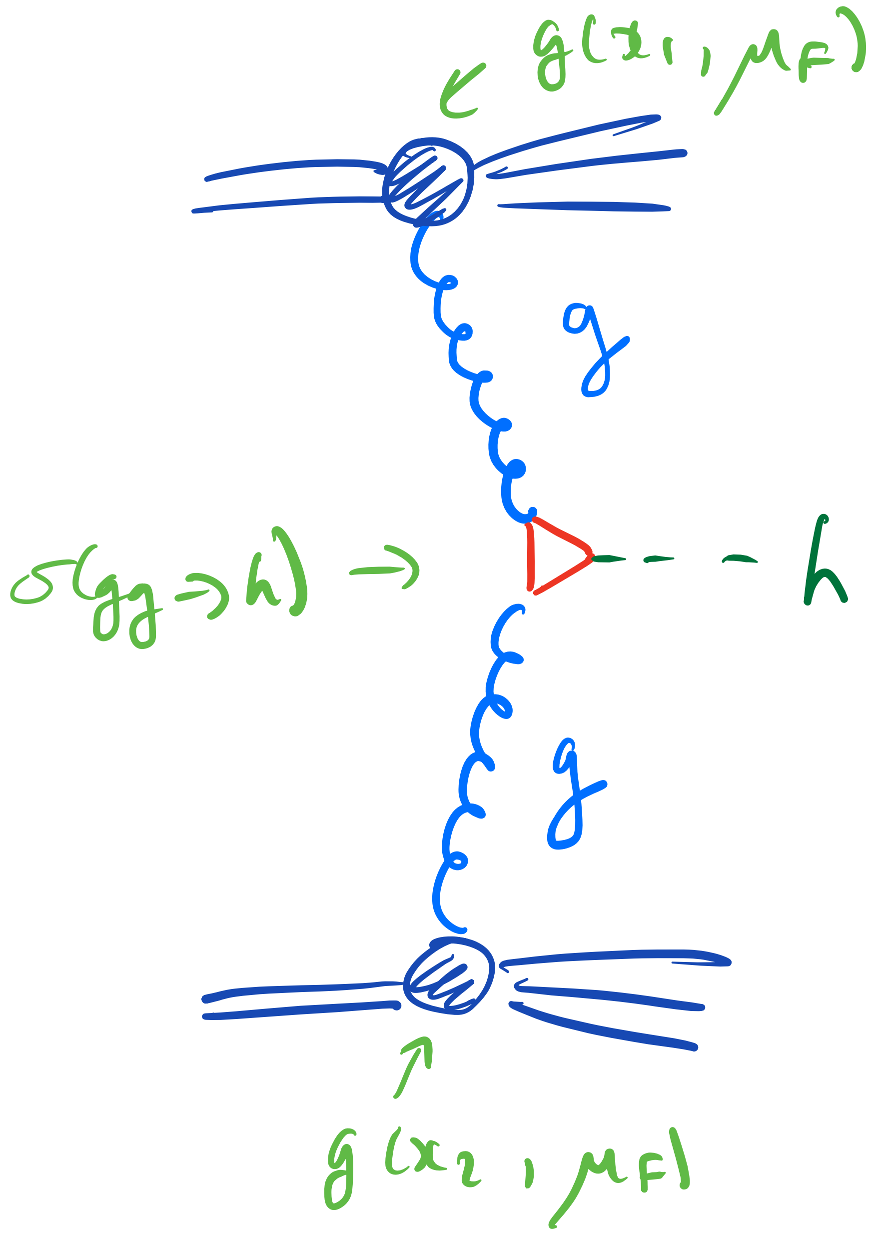


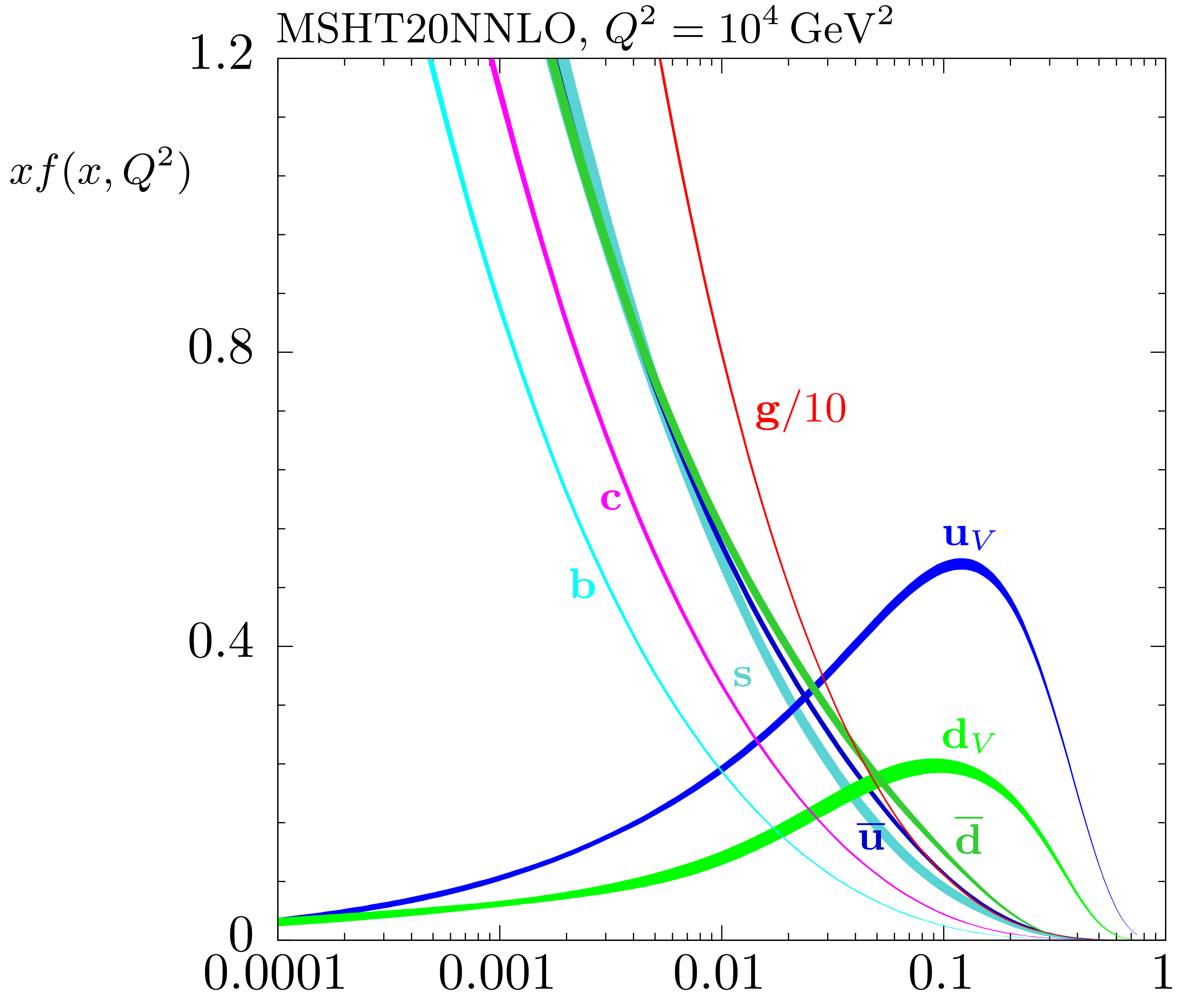


The LHC: a parton-parton collider

- Proton-proton collision modelled in terms of interactions of fundamental QCD degrees of freedom: quark + gluon '**partons**' in proton.

$$\sigma(pp \to X) \sim \hat{\sigma}(ij \to X) \otimes f_i(x_1, \mu^2) \otimes f_j(x_2, \mu^2)$$

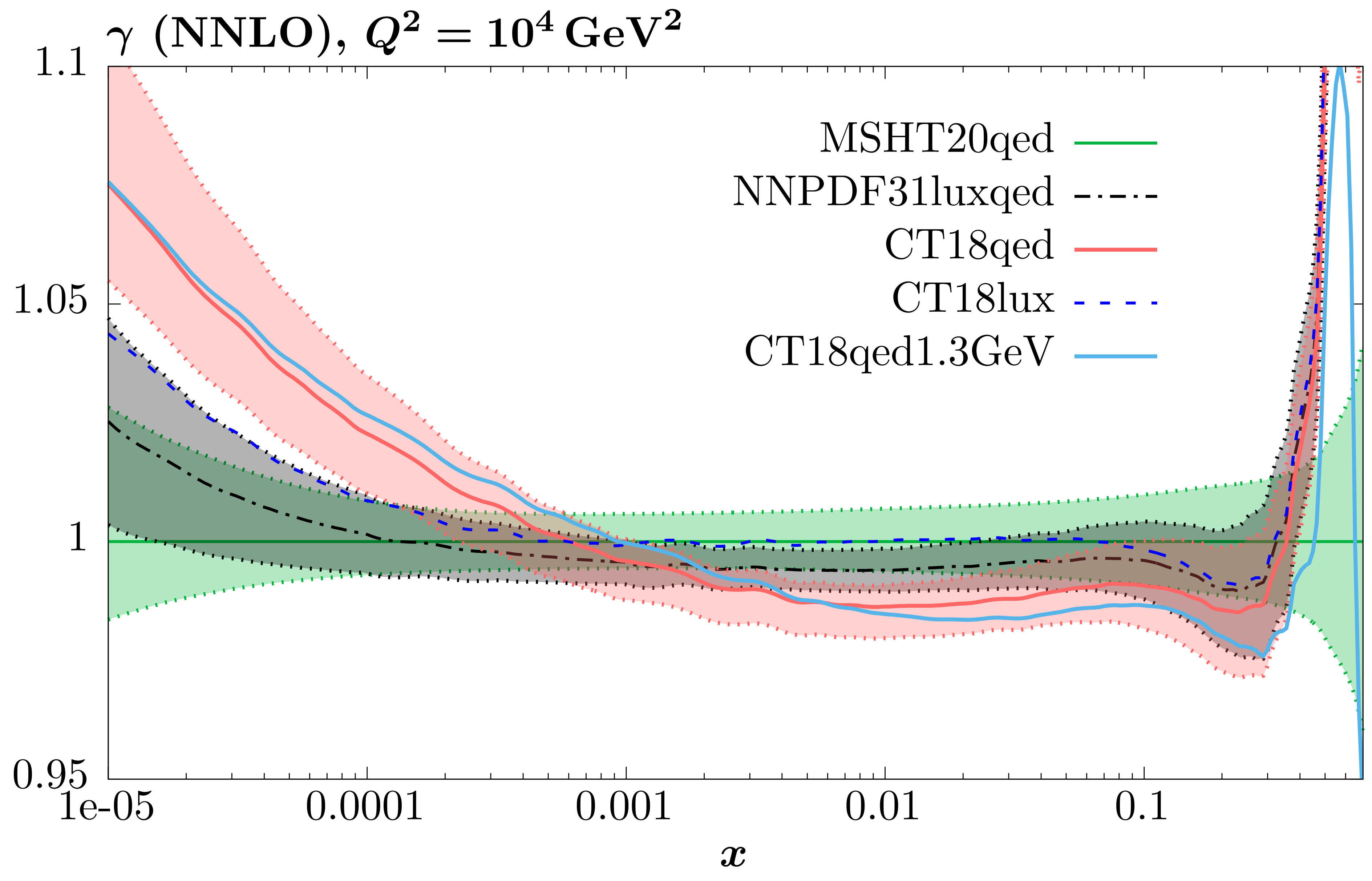


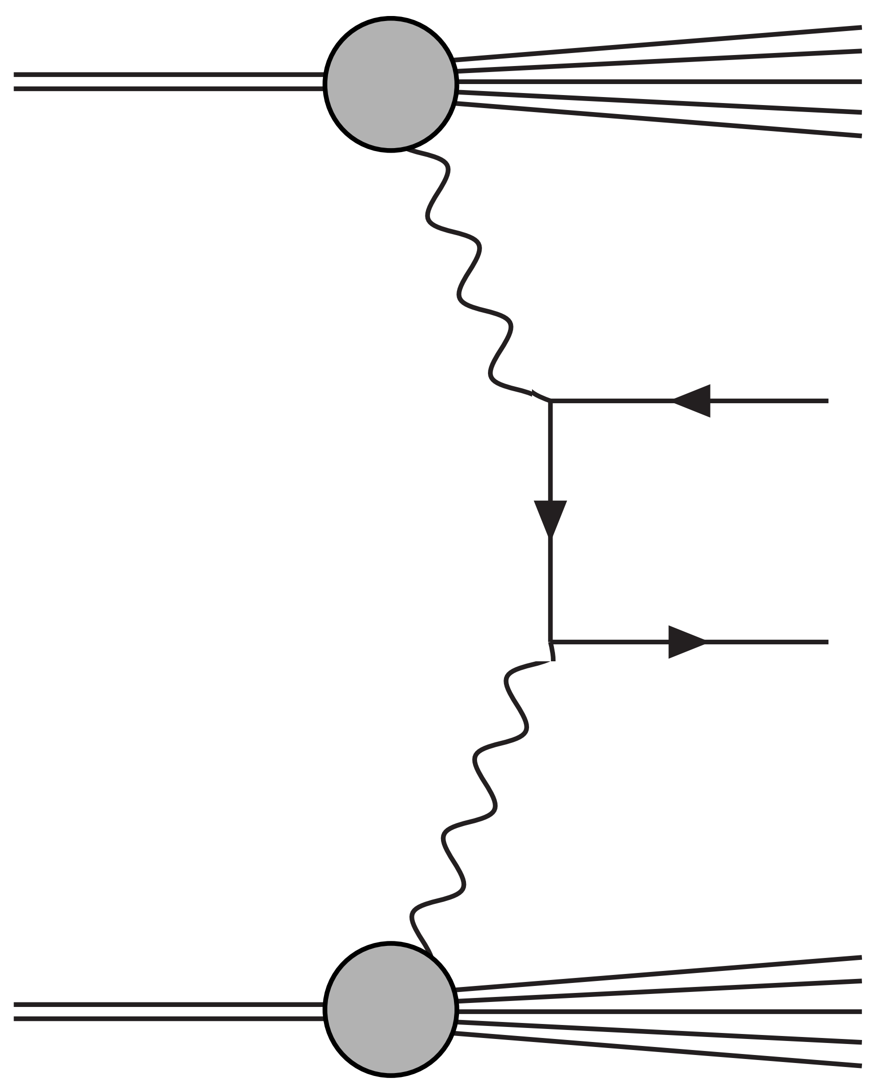


- Density of partons encoded in `parton distribution functions' (PDFs).
- Story for another seminar. Question: are quark/gluons all there is?

The LHC: a photon-photon collider

- **No!** Protons and their quark constituents also have QED charge: photons are a proton constituent. **Photon-initiated** production possible.

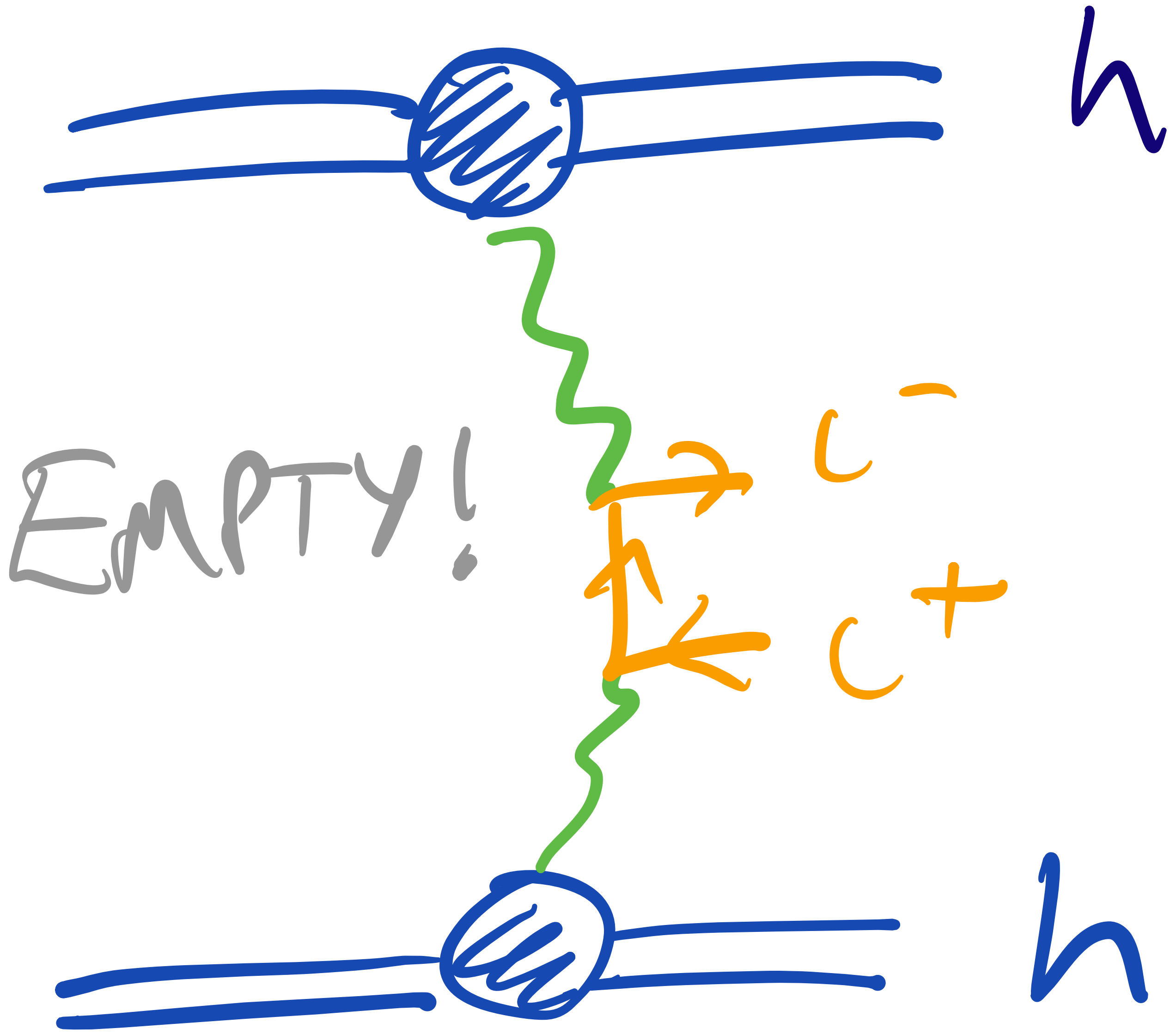




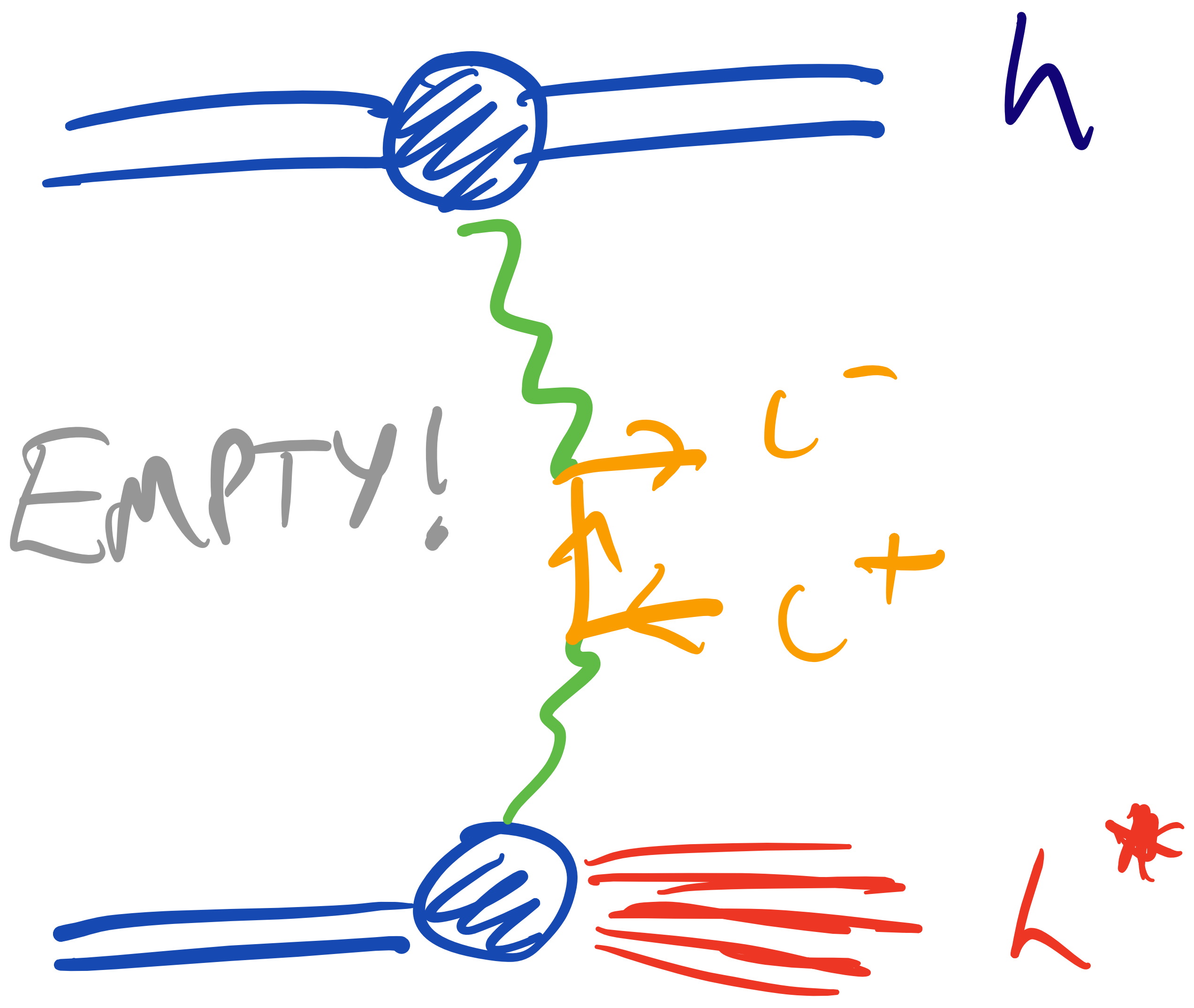
- Initial-state photons can be accounted for in proton PDFs. Generally ~ % level contributions to inclusive LHC cross sections.
- Essential component of high precision theoretical calculations - % level corrections. **End of story?**

The (semi) exclusive photon

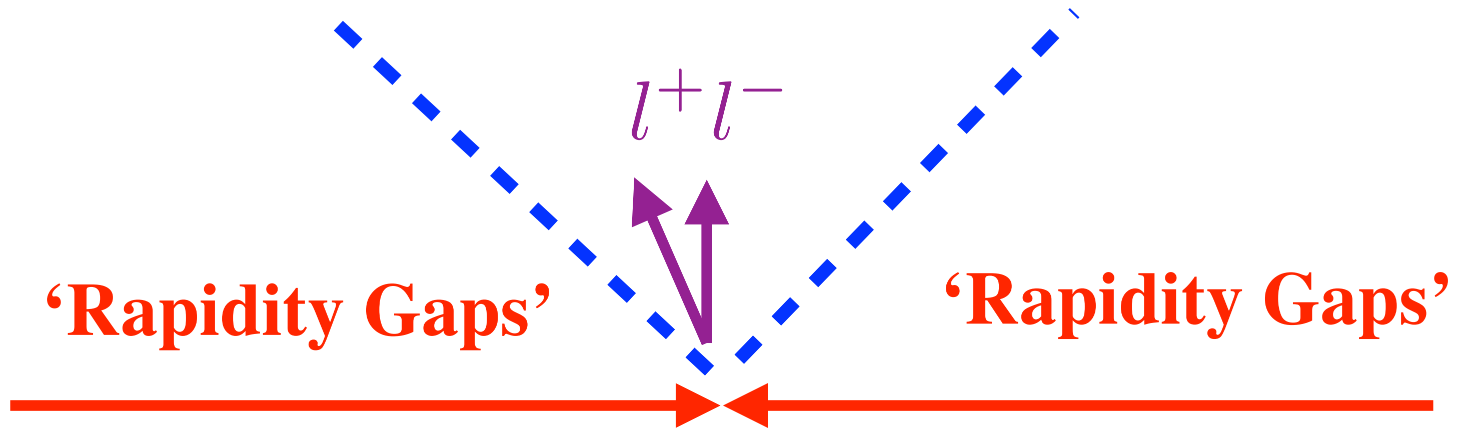
- **Exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state:



Exclusive



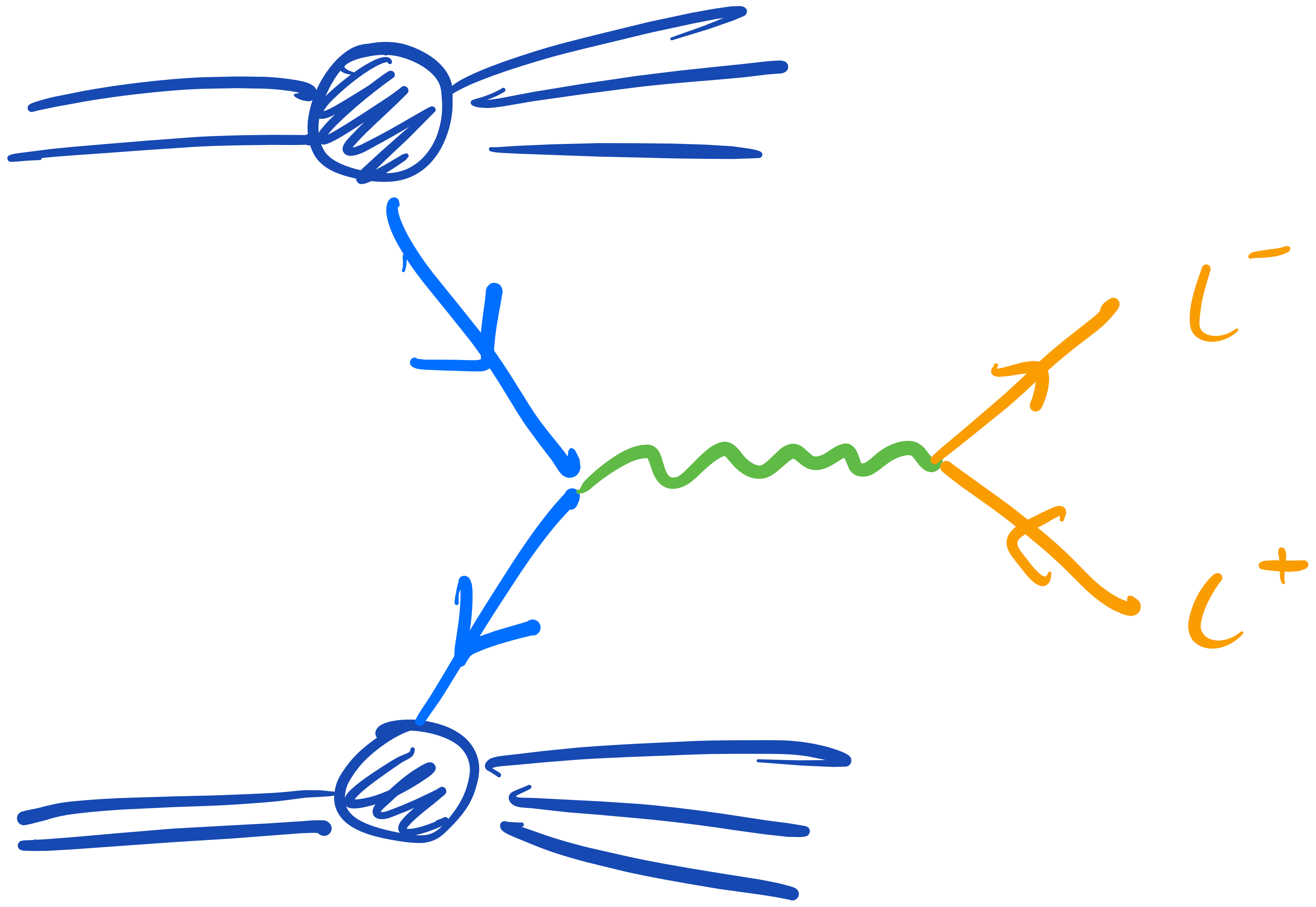
Semi-exclusive



$\Rightarrow$ The LHC as a $\gamma\gamma$ collider! How does this differ from `standard' LHC collisions?

Inclusive Production

- **Key point:** quark/gluon-initiated production leads to colour flow between protons $\Rightarrow$ these break up + significant amount of additional particles present in detector.



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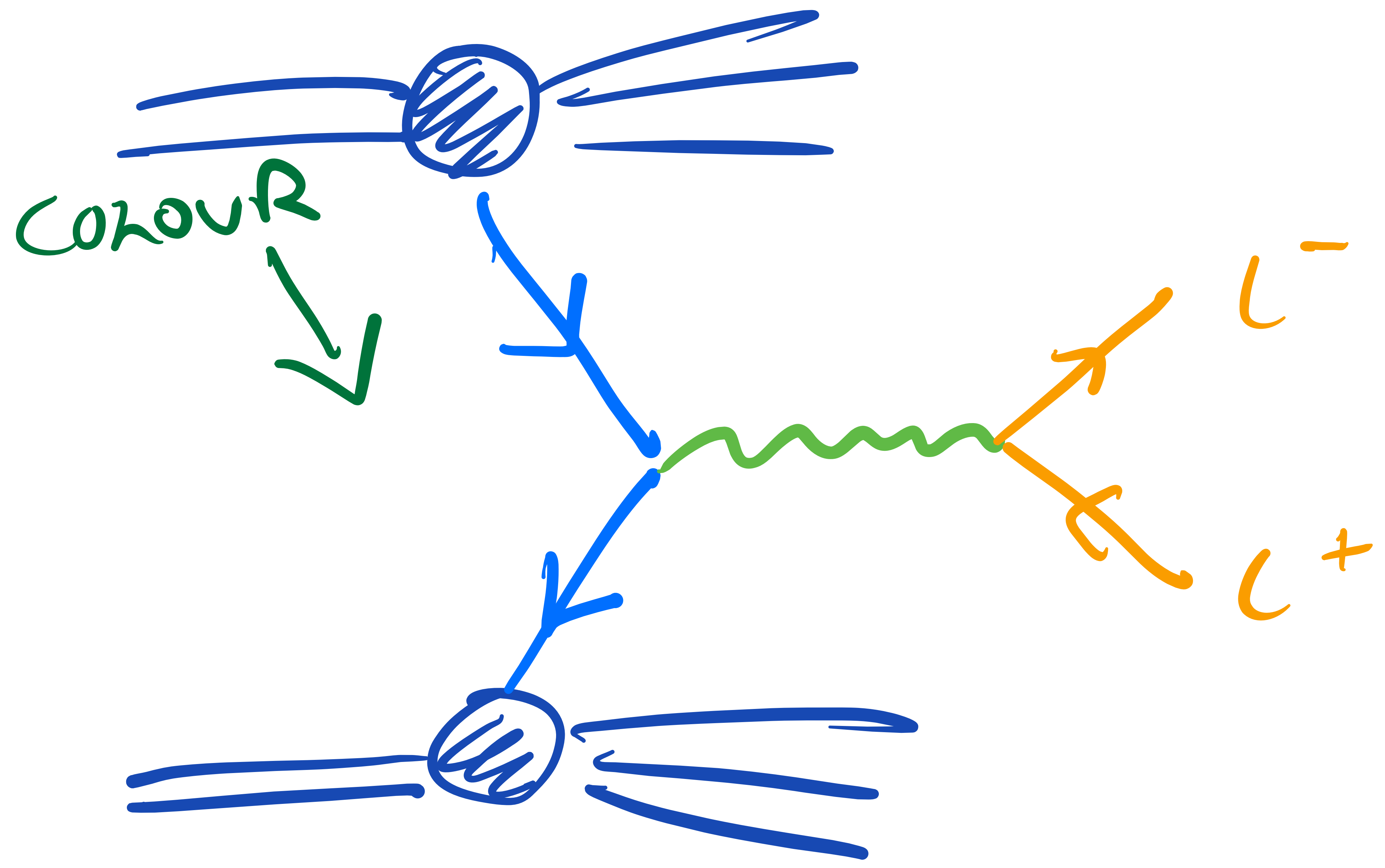

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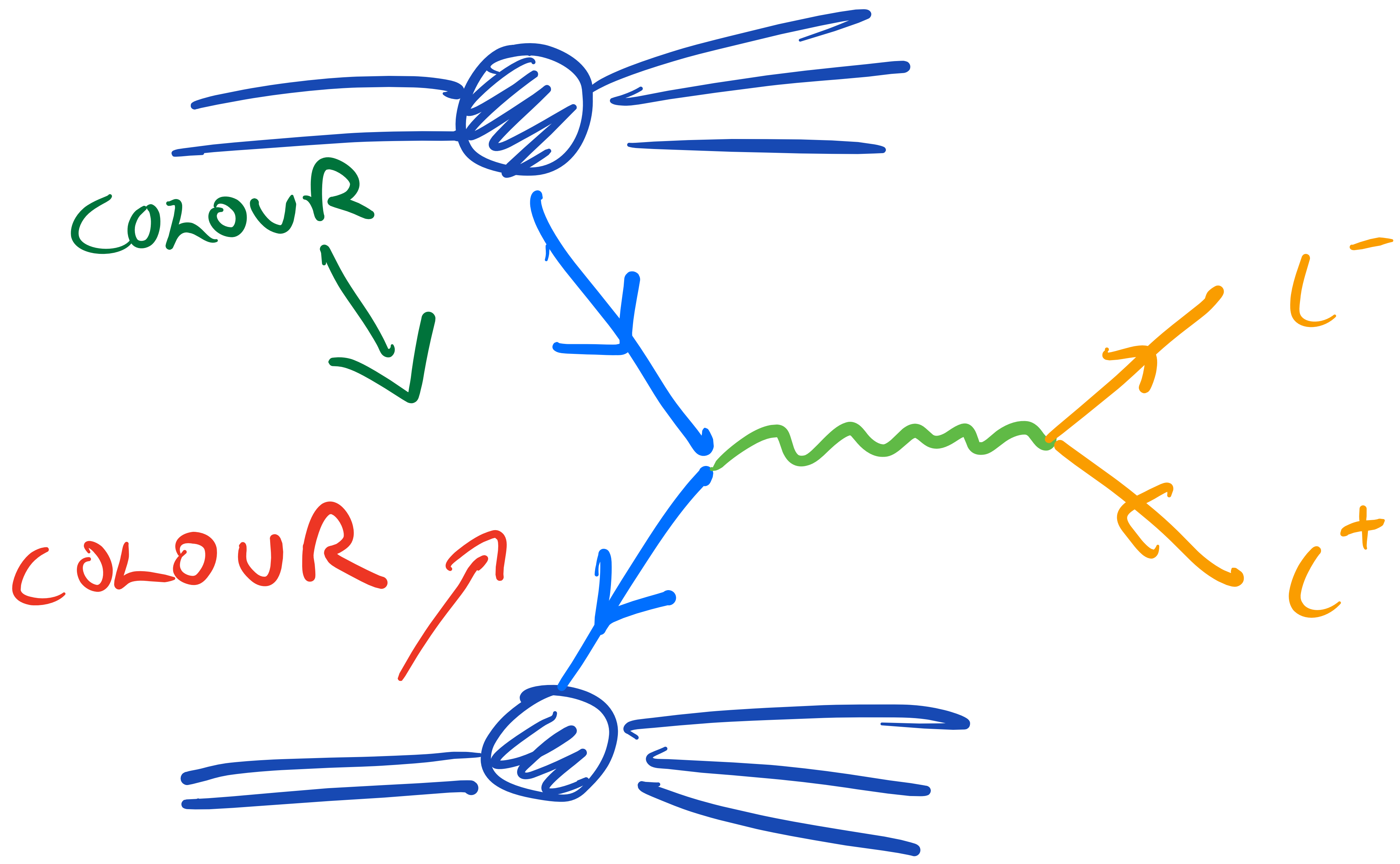

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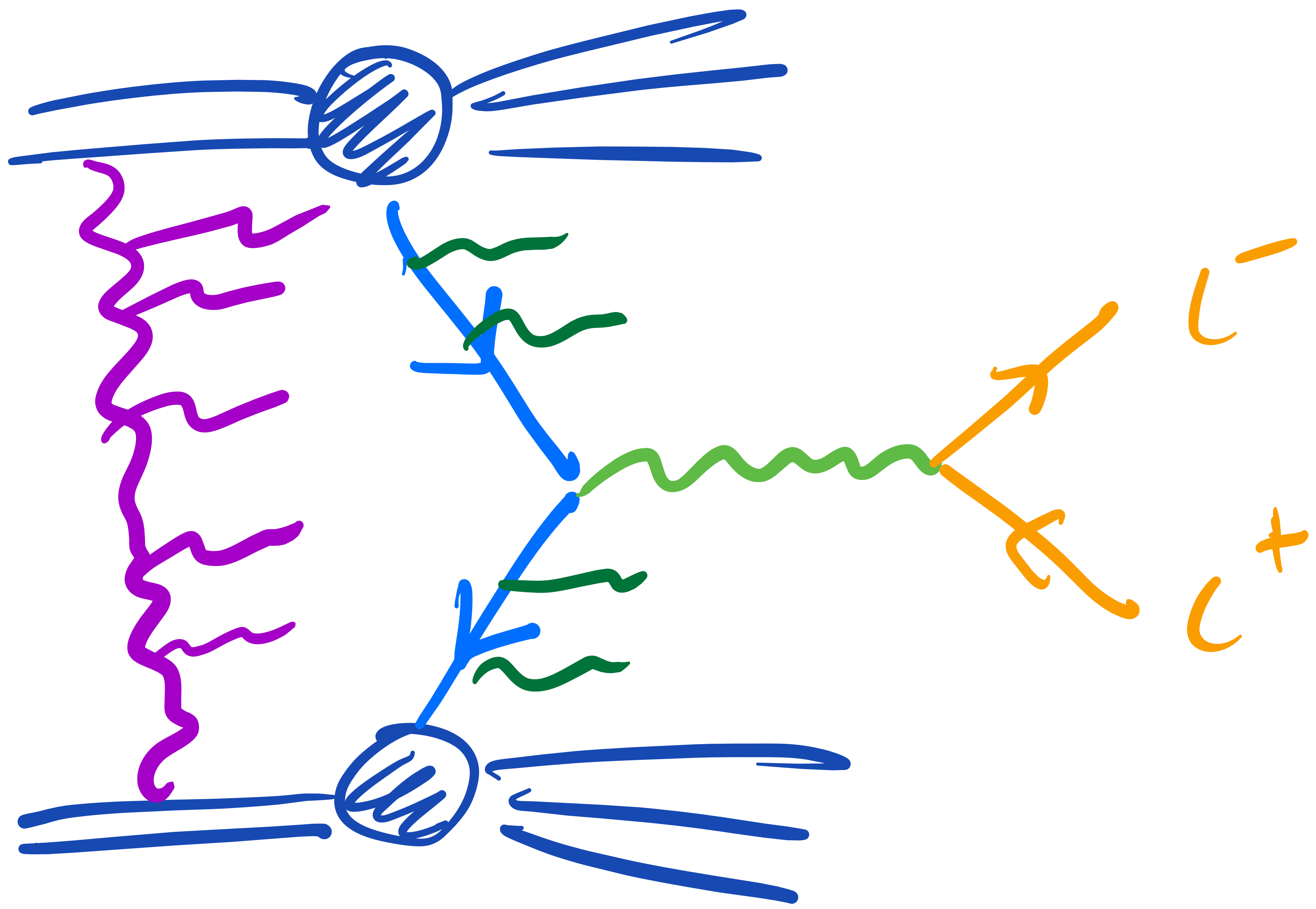

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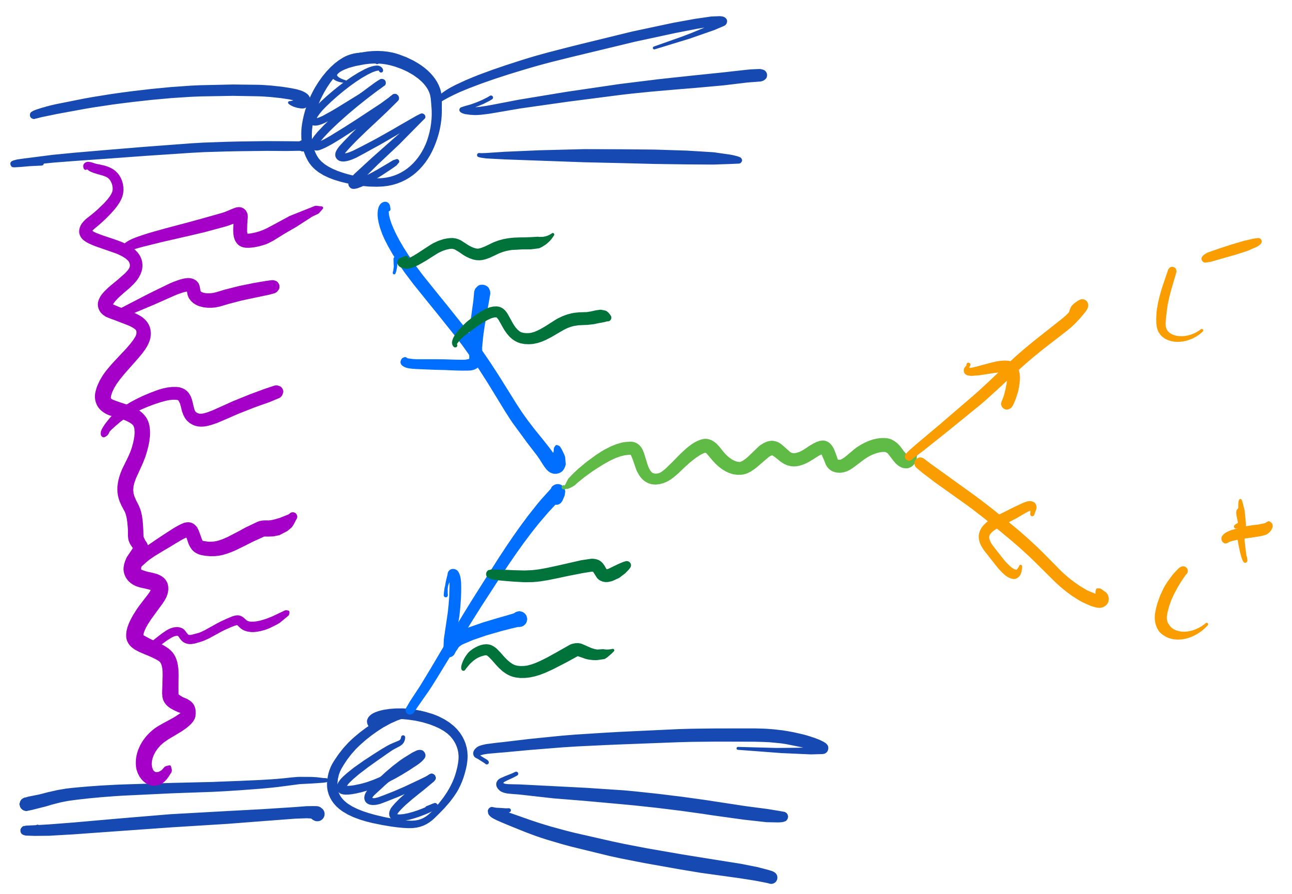
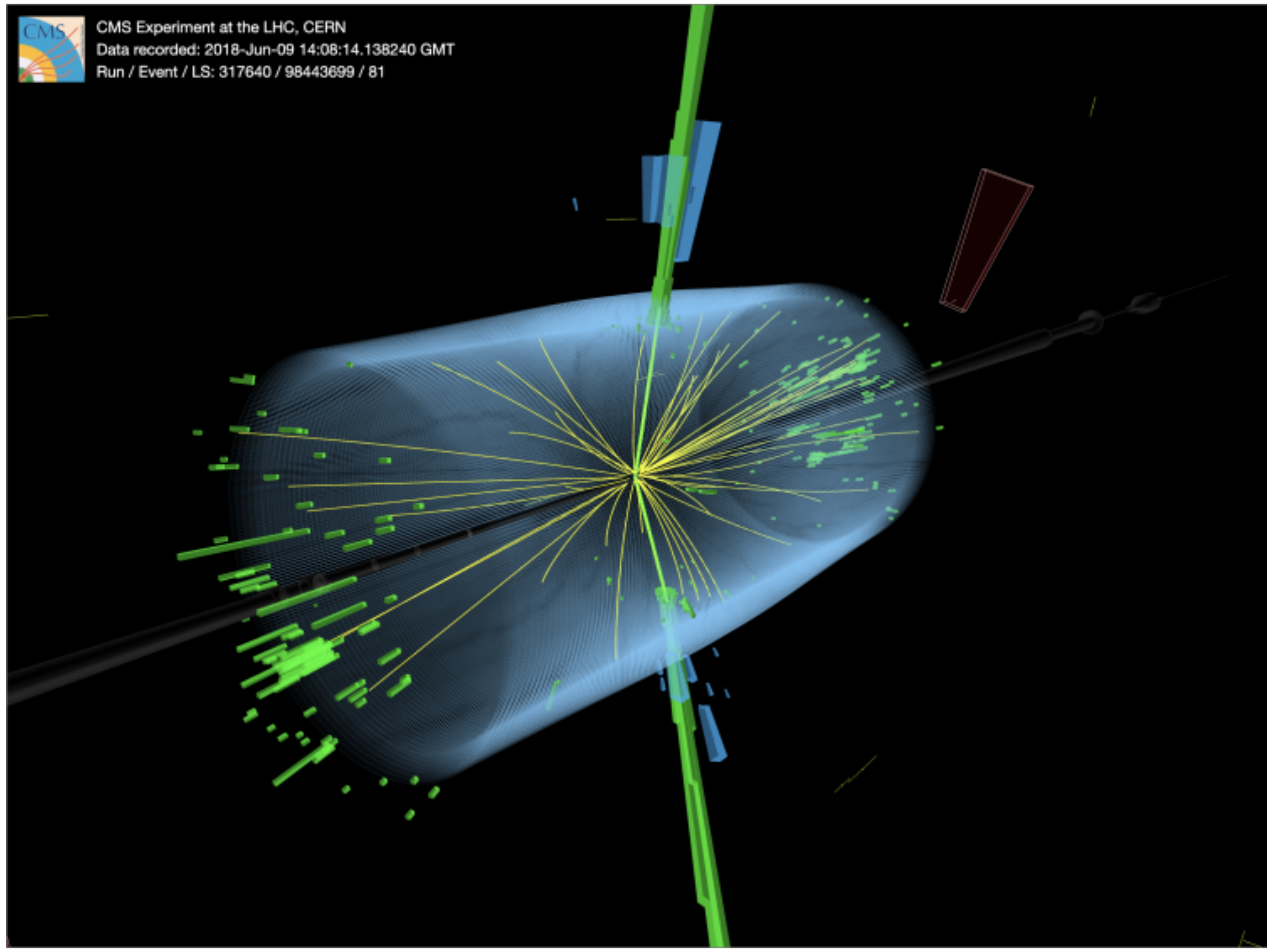
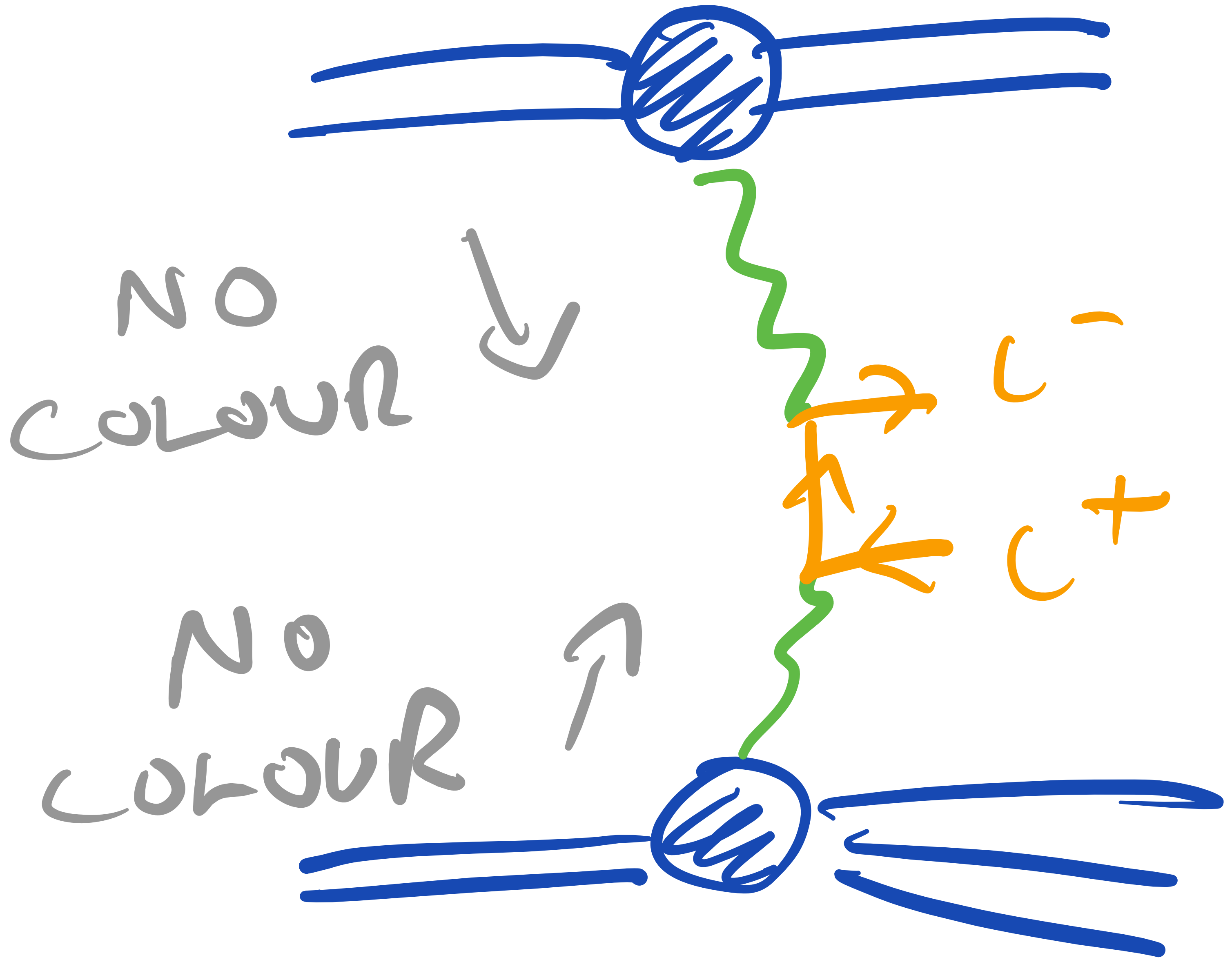




Semi-exclusive production

- For photon-initiated production no longer the case: colour flow not necessary.



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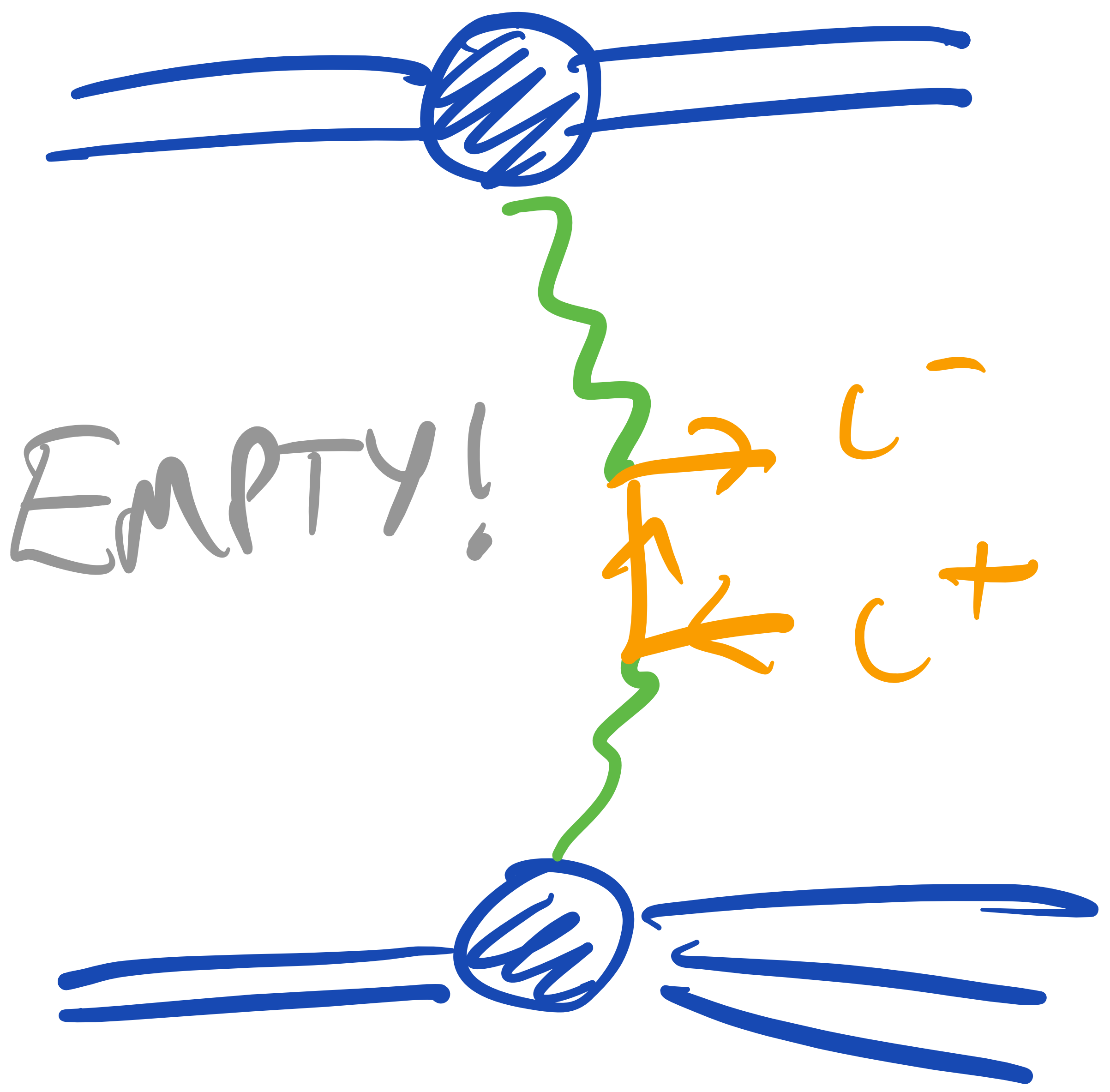

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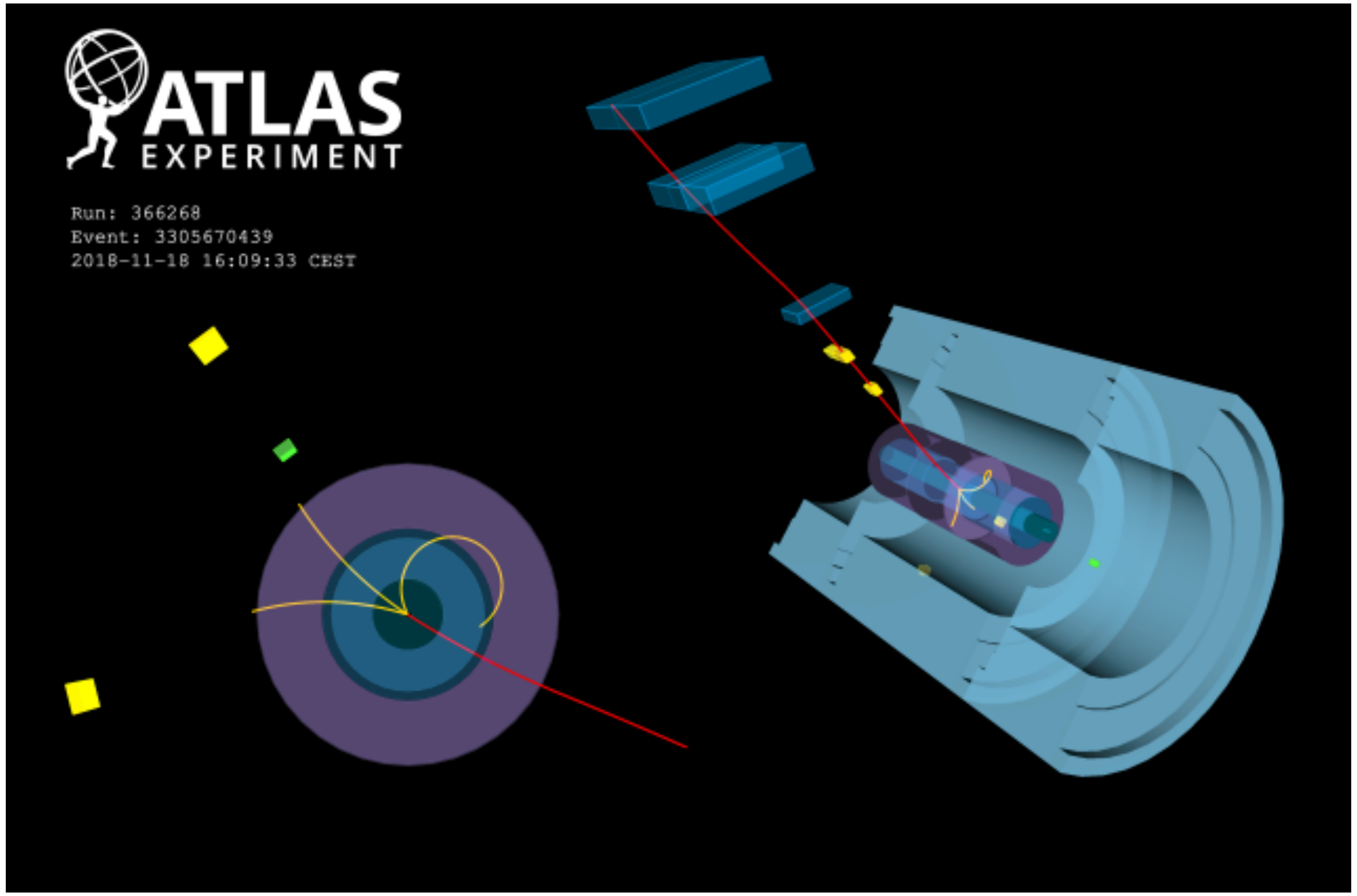
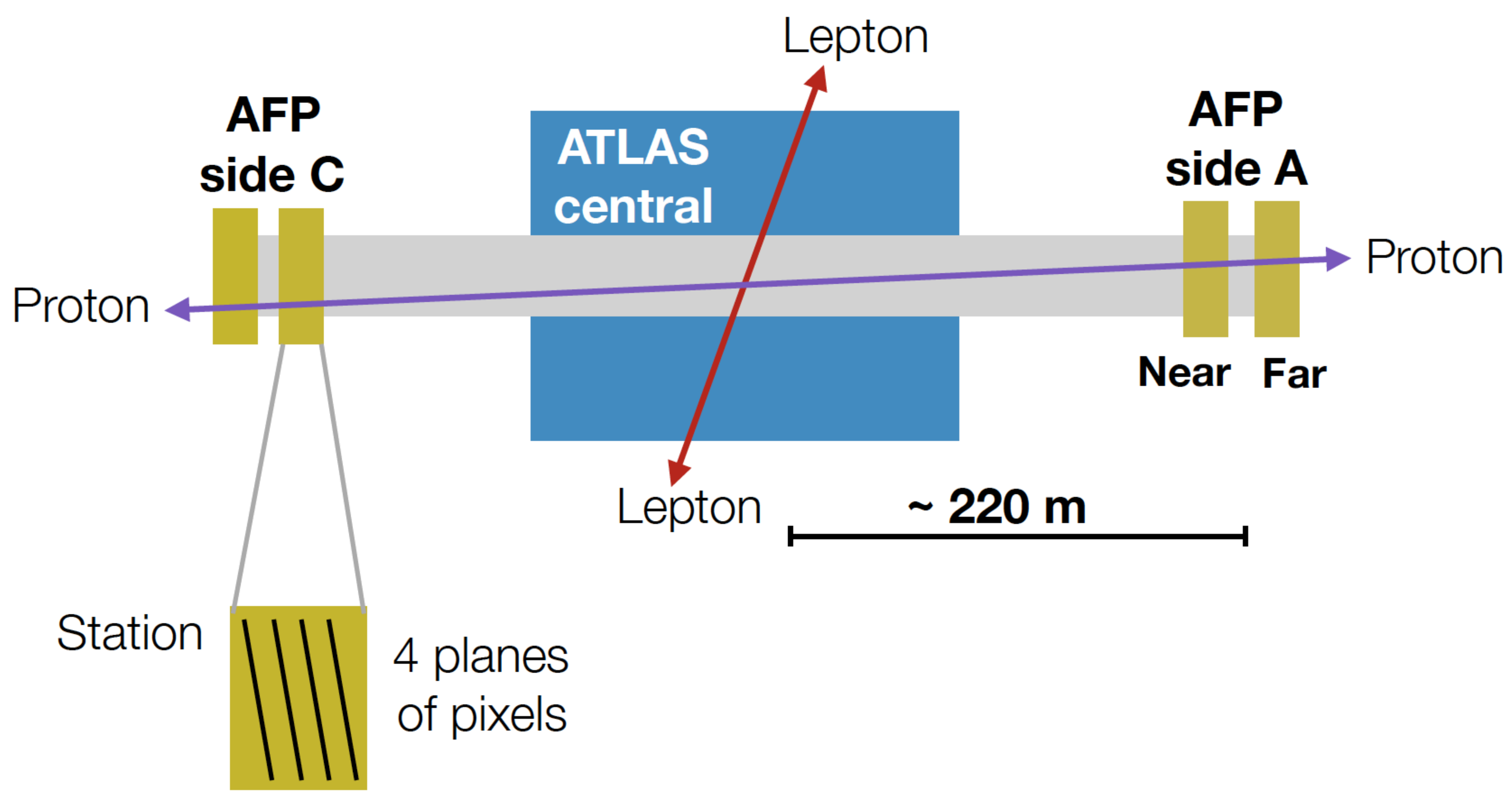
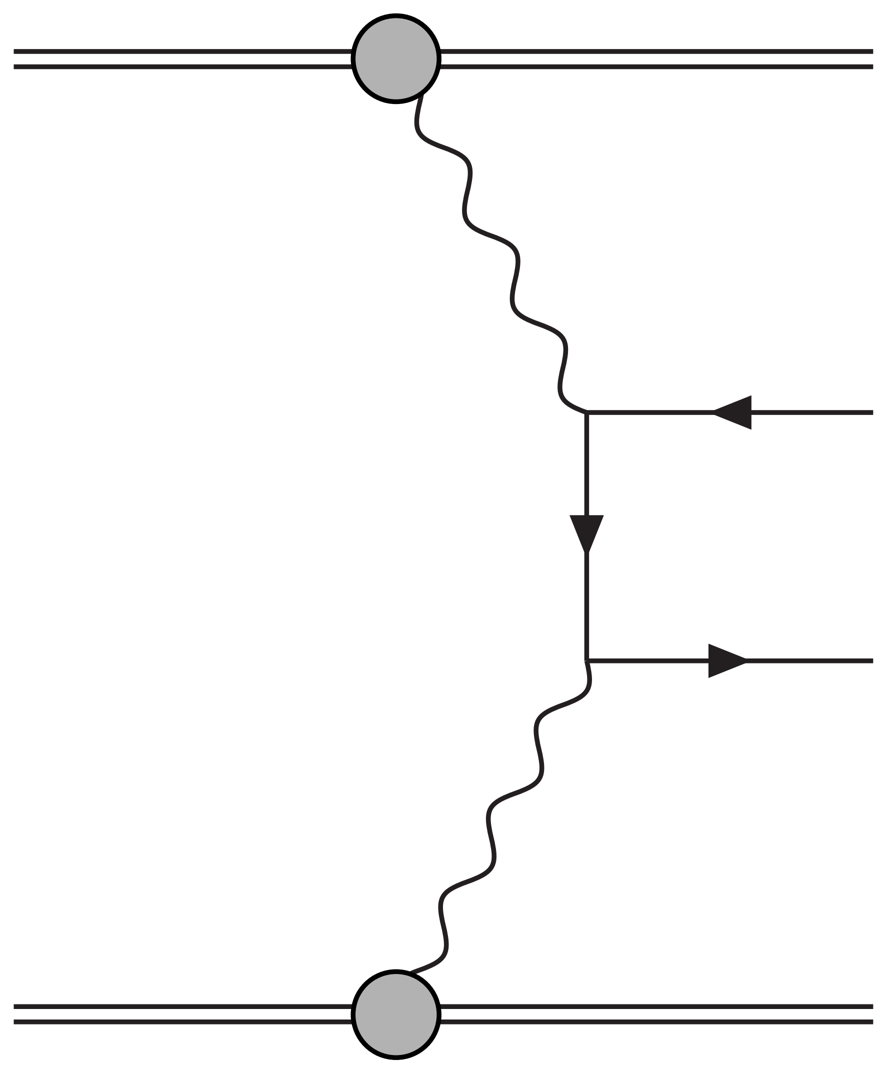


N.B. for experts - this is not a pp event…

The elastic photon

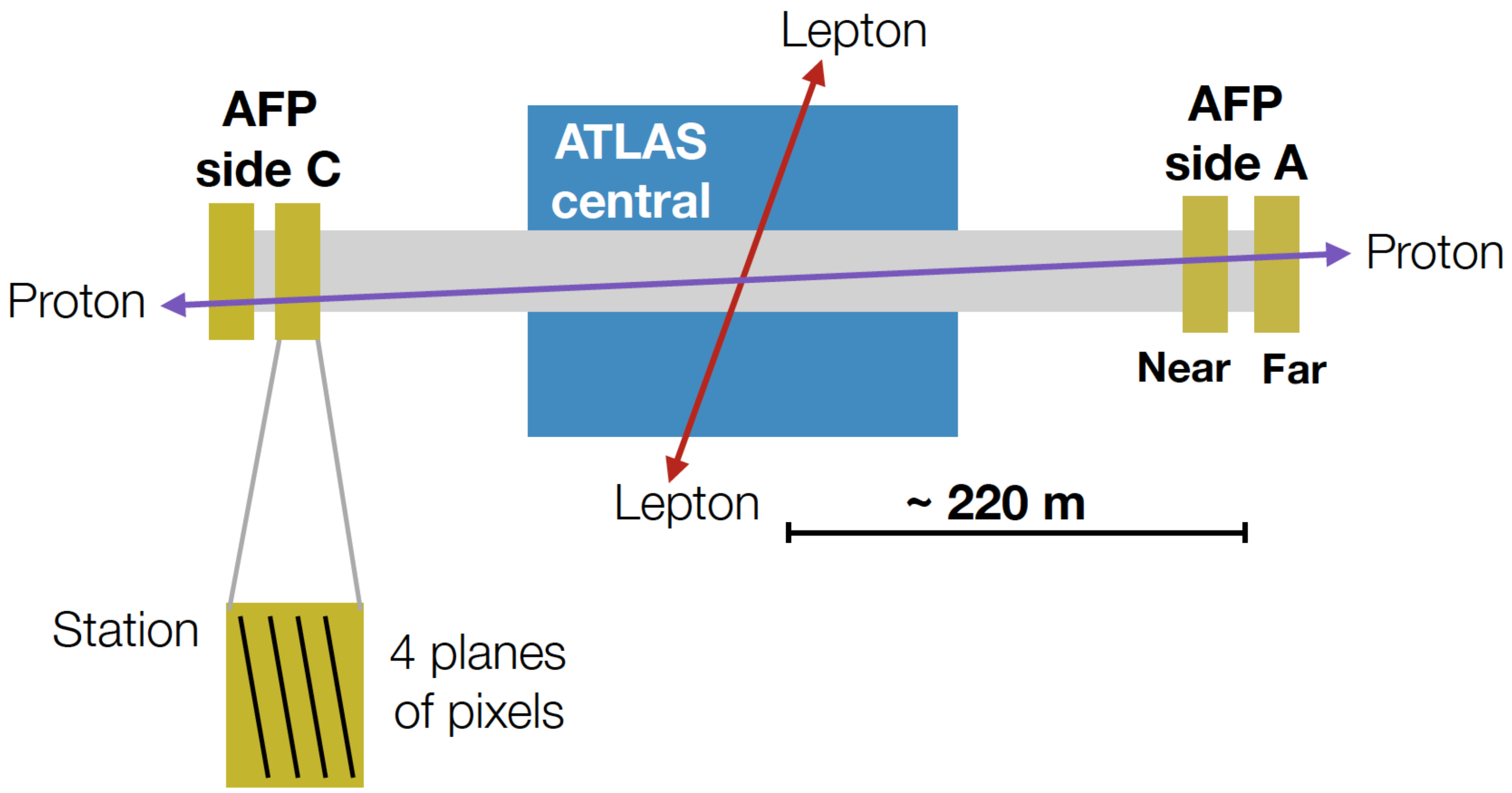
- If proton remains intact will continue down the beam line but with lower energy $E < \sqrt{s}/2$: will be bent out of beamline by LHC magnets.
- Can measure with dedicated detectors ~ 200m (+): proton taggers.



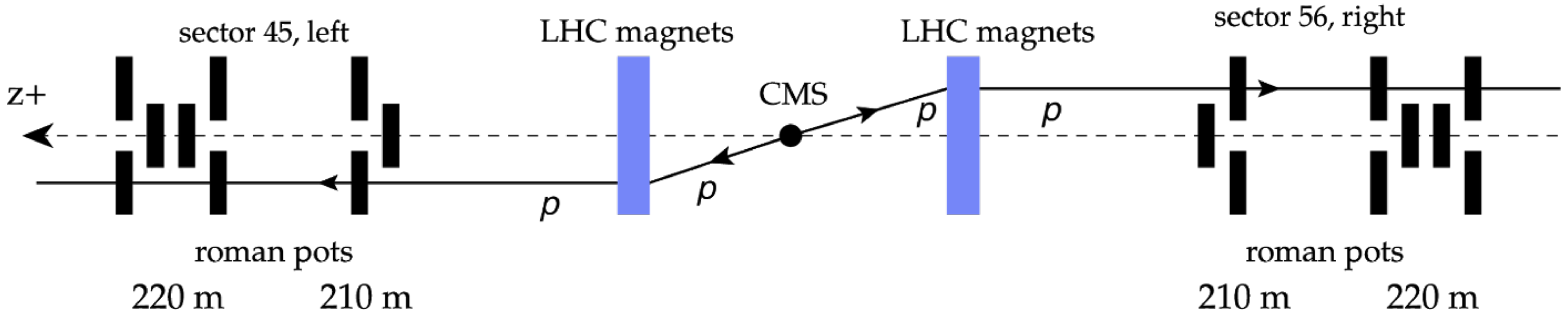


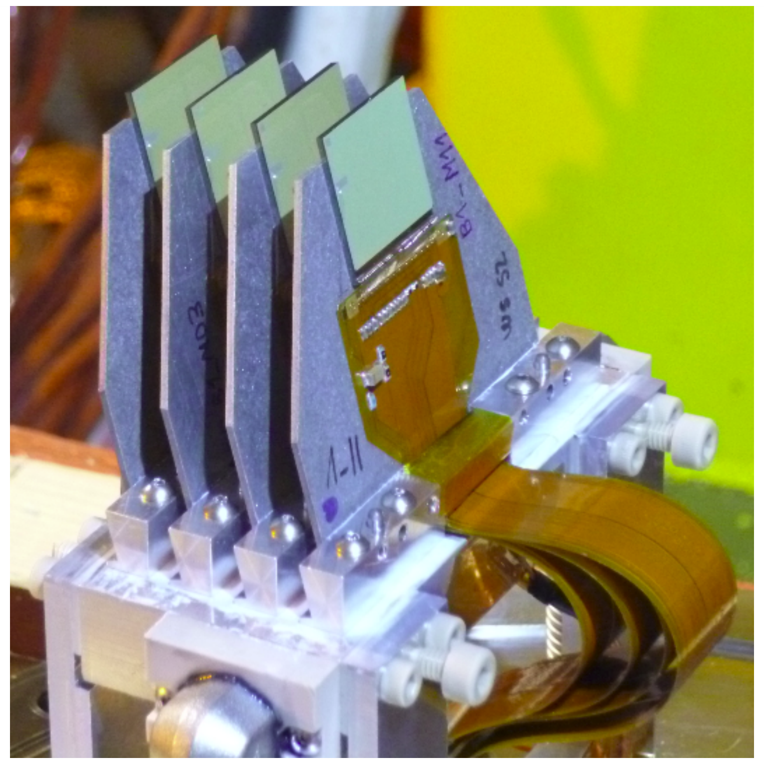
- Allows exclusive events to be selected, and momentum of proton to be reconstructed.
- These are installed and running in association with ATLAS and CMS…

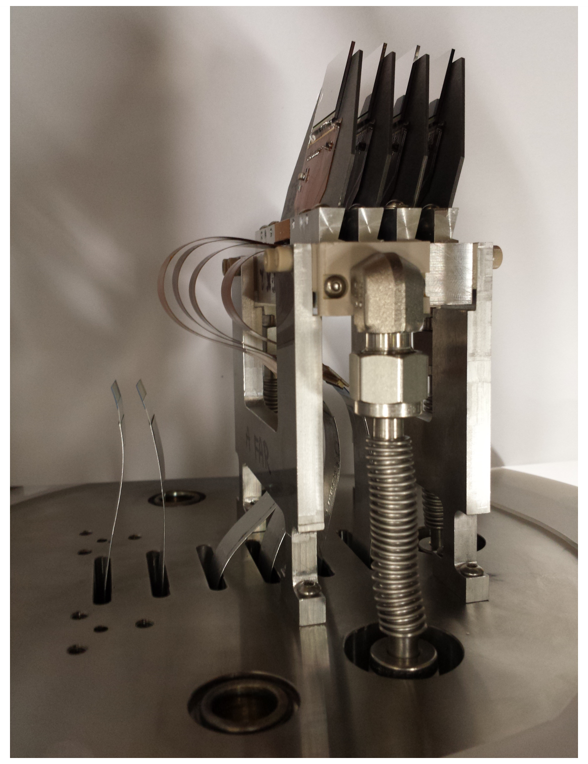
AFP



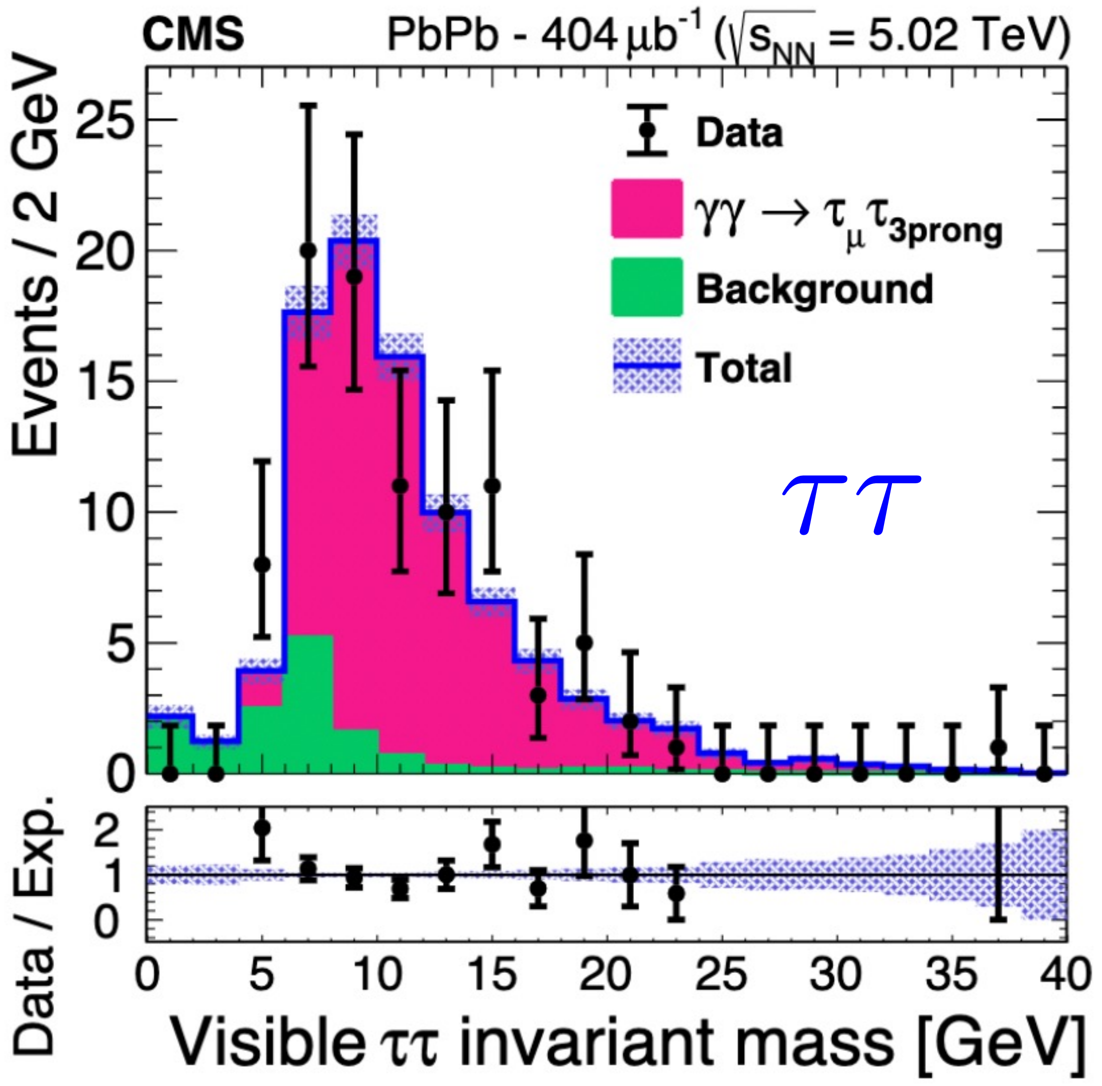
CT-PPS

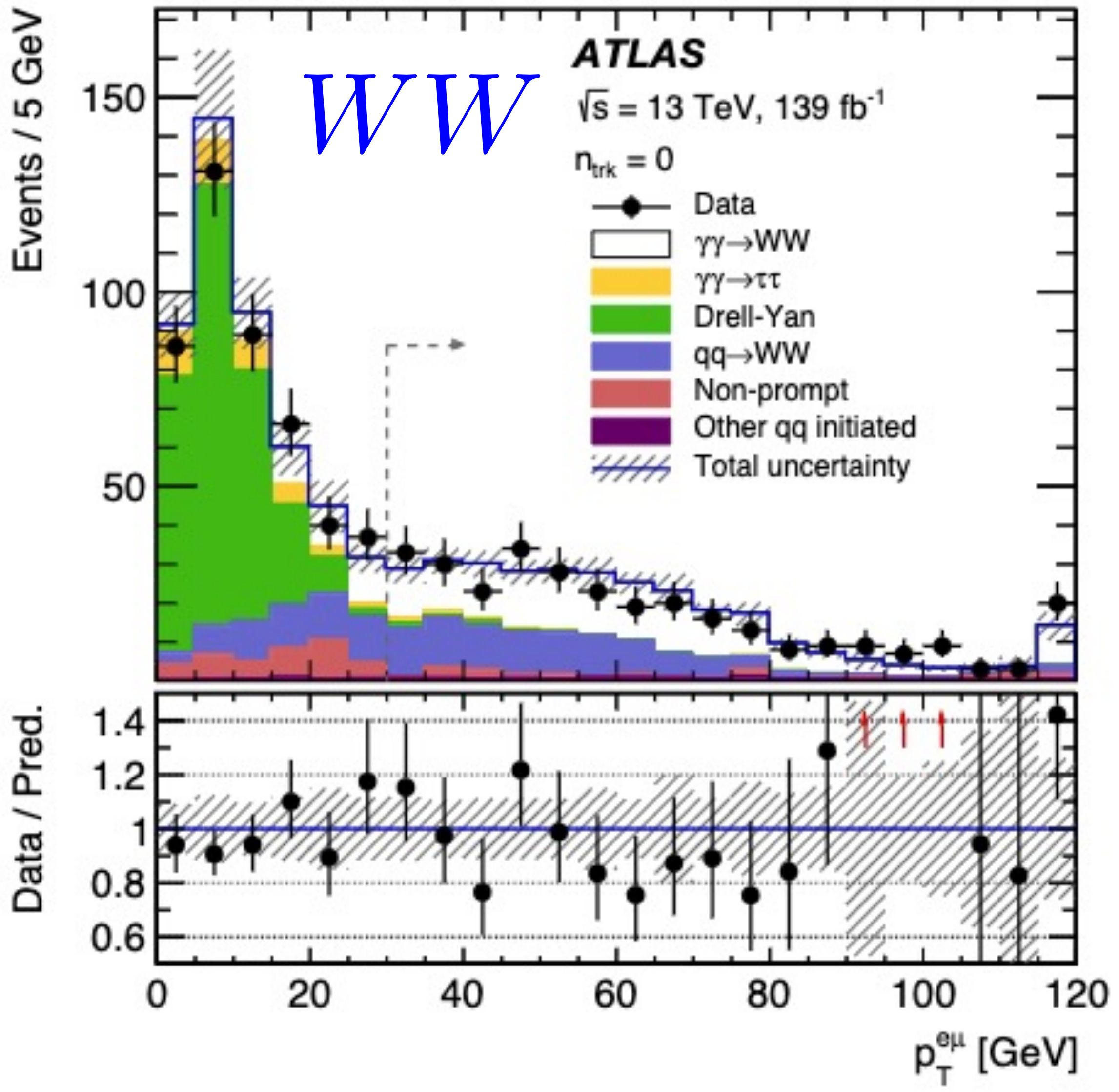


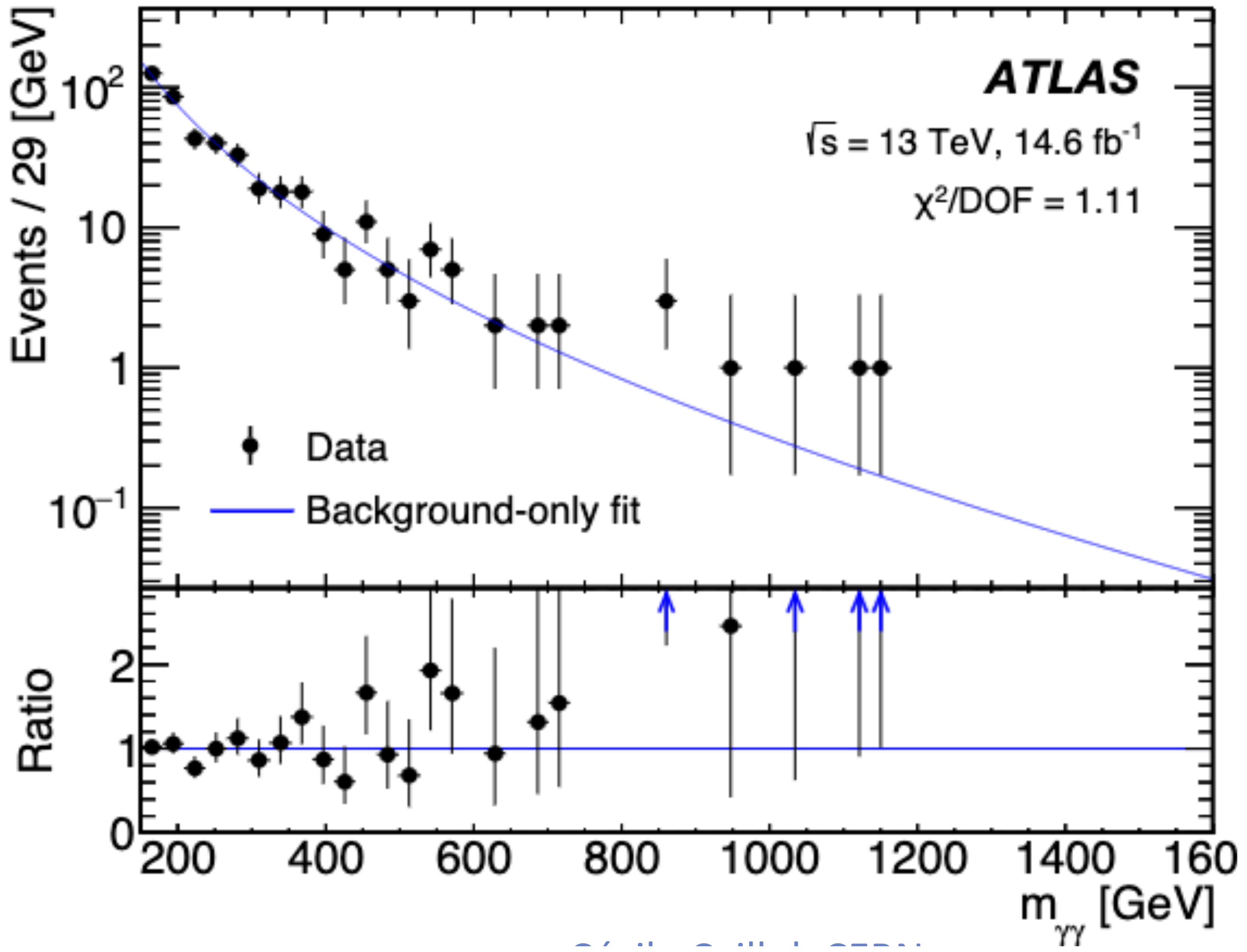




- Proton taggers ~ 200m from ATLAS/CMS.
- Many measurements/searches data already…







$\gamma\gamma$

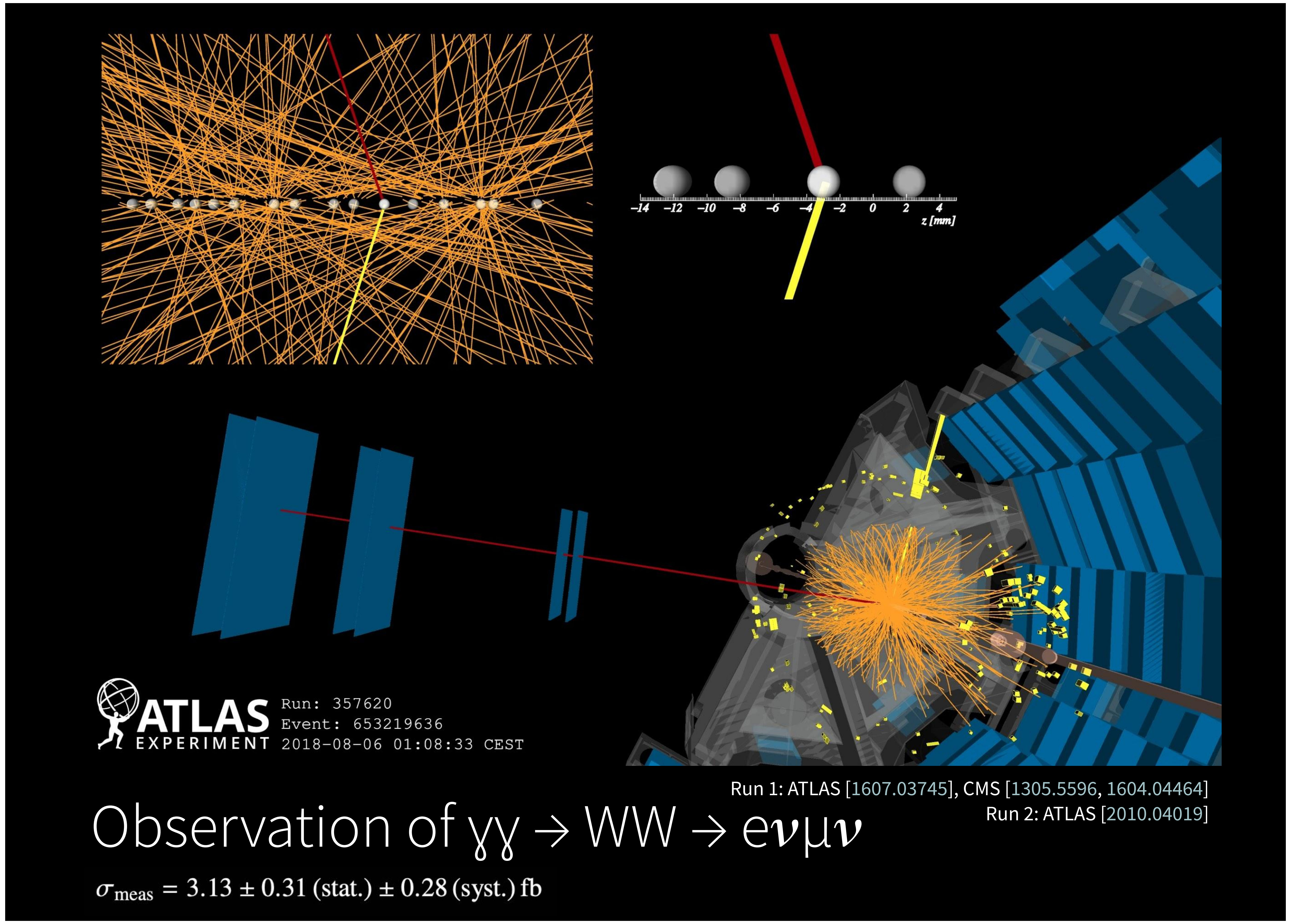
C. Caillol, Moriond EW 2024

- With prospects for HL-LHC running being pursued.

CT-PPS, arXiv:2103.02752

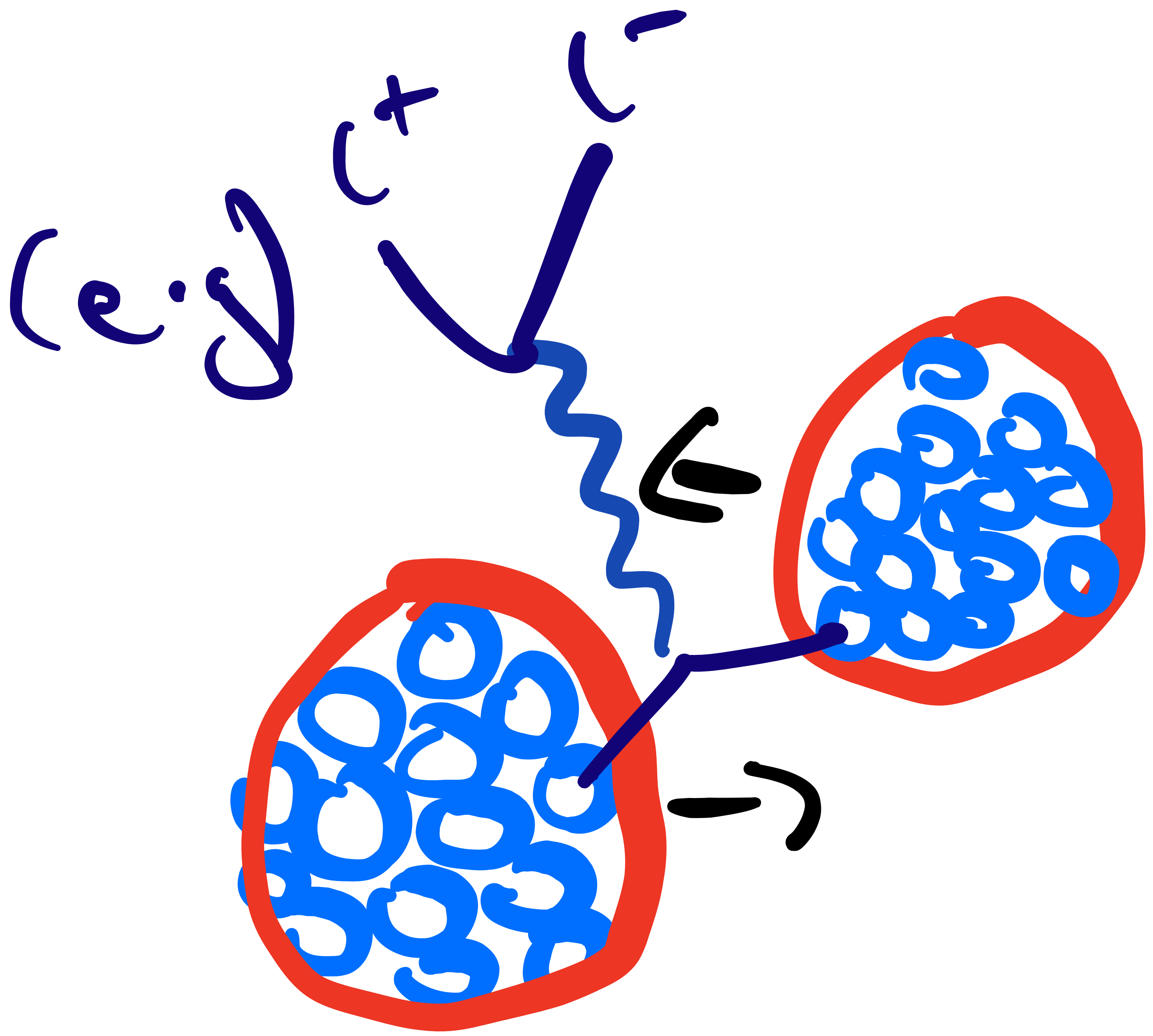
Selecting semi-exclusive production

- Proton tagging useful but not essential.
- During normal LHC pp running multiple (10s) of collision events during the same bunch crossing.
- Events can be selected by requiring no addition associated tracks in the (very) high multiplicity environment of the high pile-up LHC.



Heavy Ions

- Possibilities not limited to pp collisions. LHC also a **heavy ion collider**.
- In 'standard' heavy collision, large number of nucleons in initial state $\Rightarrow$ QCD particle production enhanced and multiplicity can be very high.



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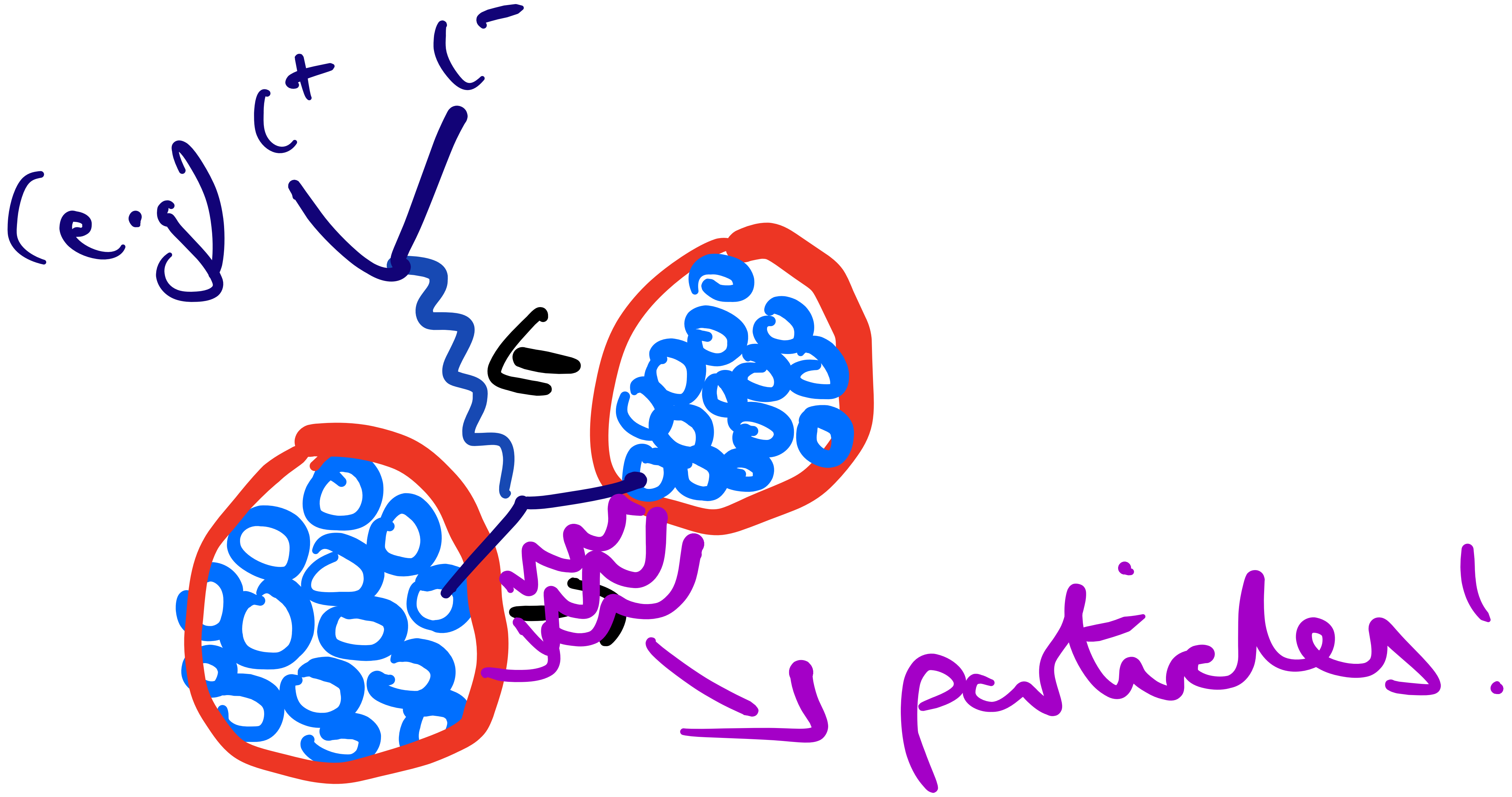
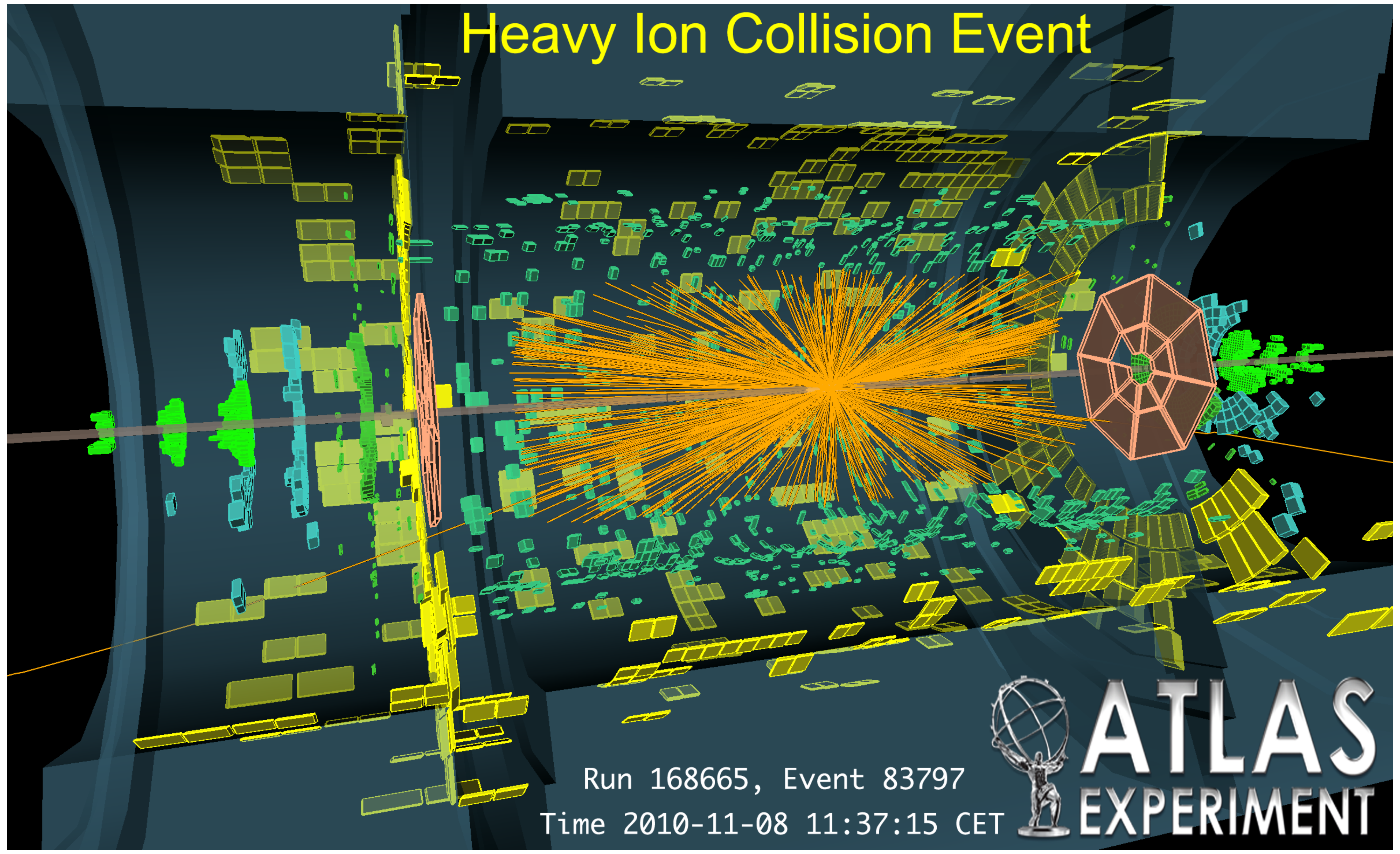
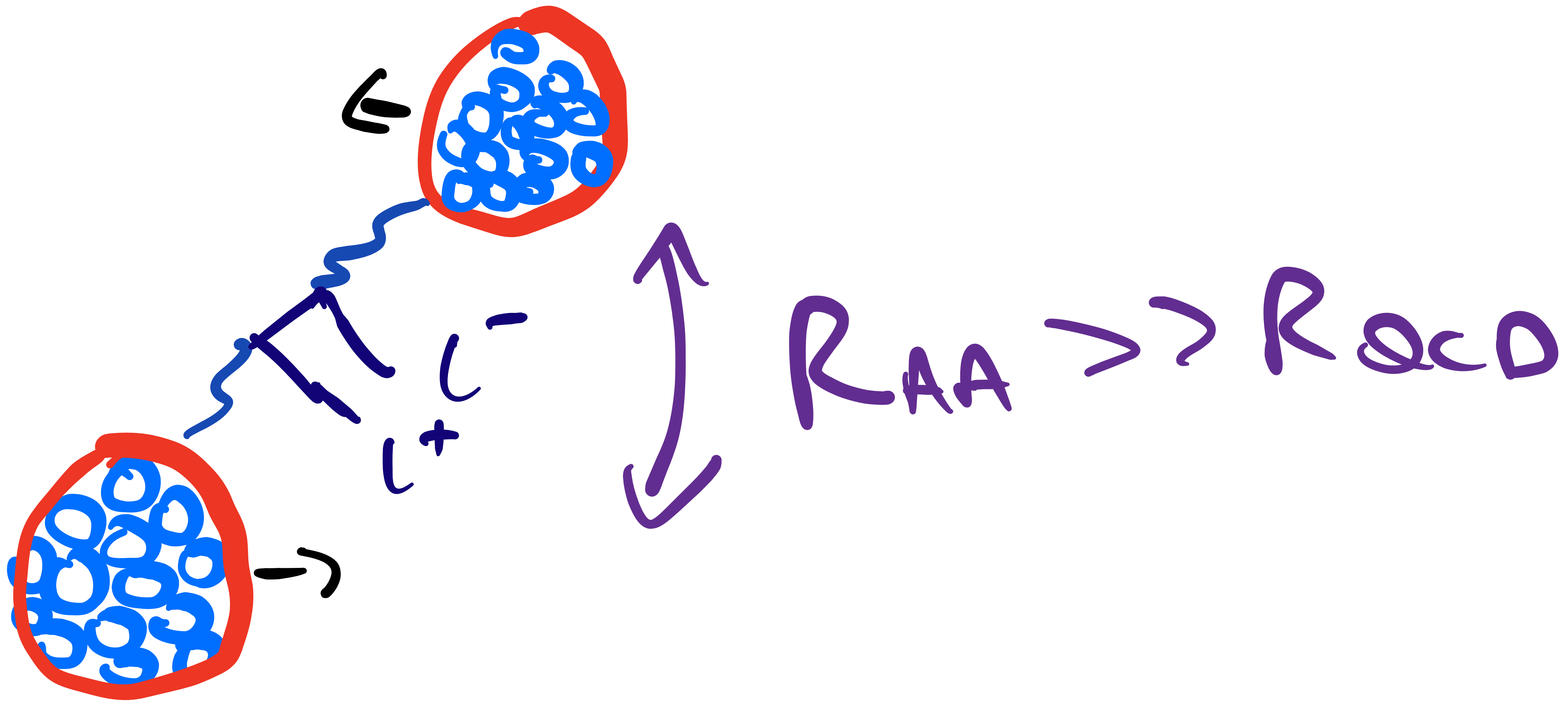
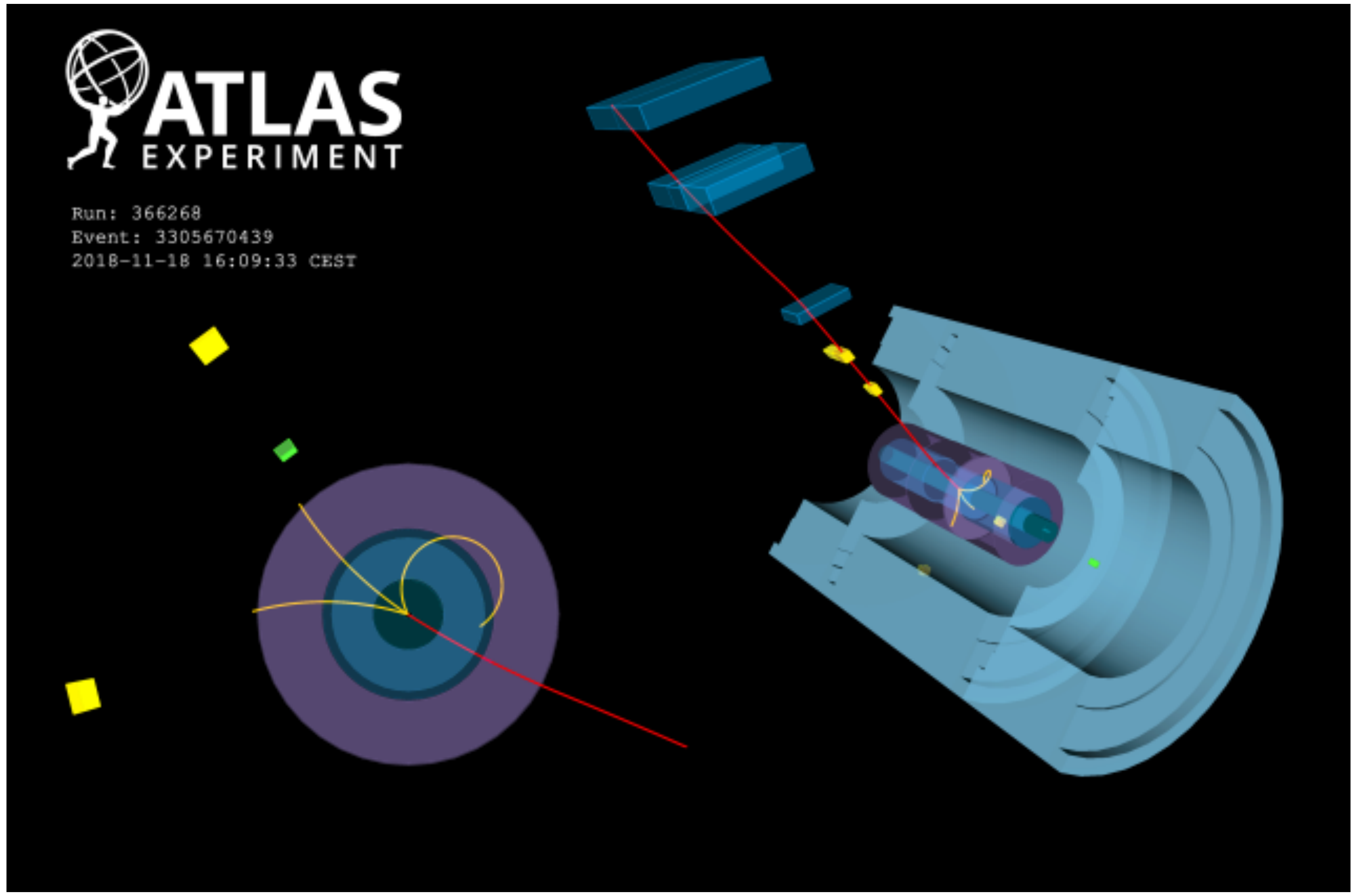


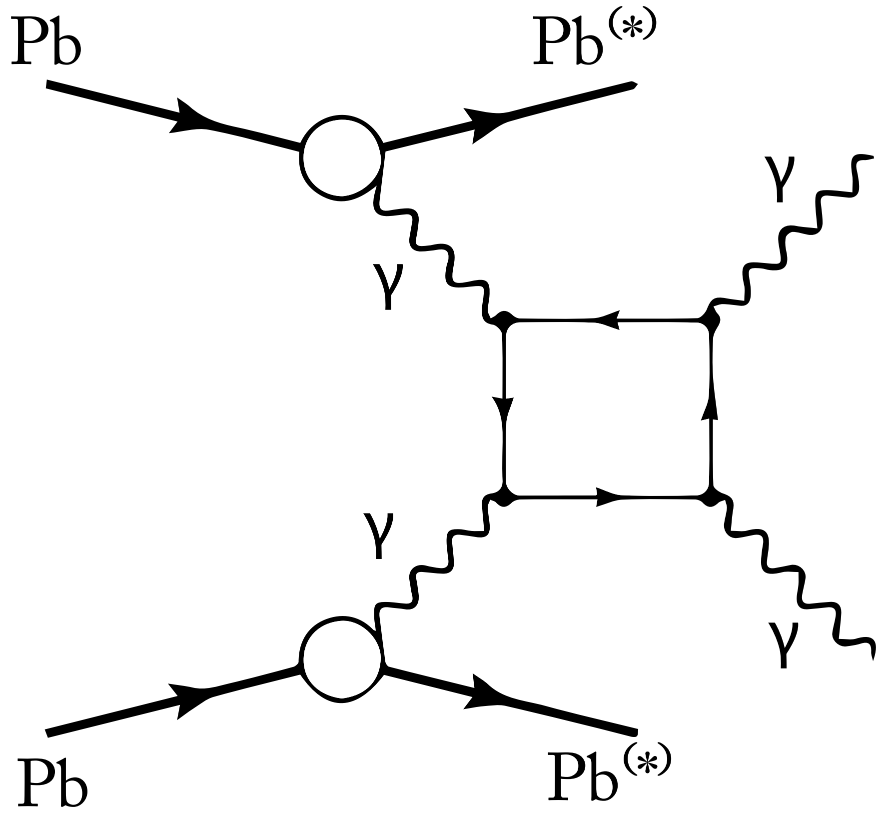


- Possibilities not limited to pp collisions. LHC also a **heavy ion collider**.
- However if colliding ions sufficiently separated in impact parameter ('ultraperipheral') does have to be the case:





- **Key point:** heavy ions have significant electric charge $Z_{\rm Pb} = 82$



nature physics ARTICLES

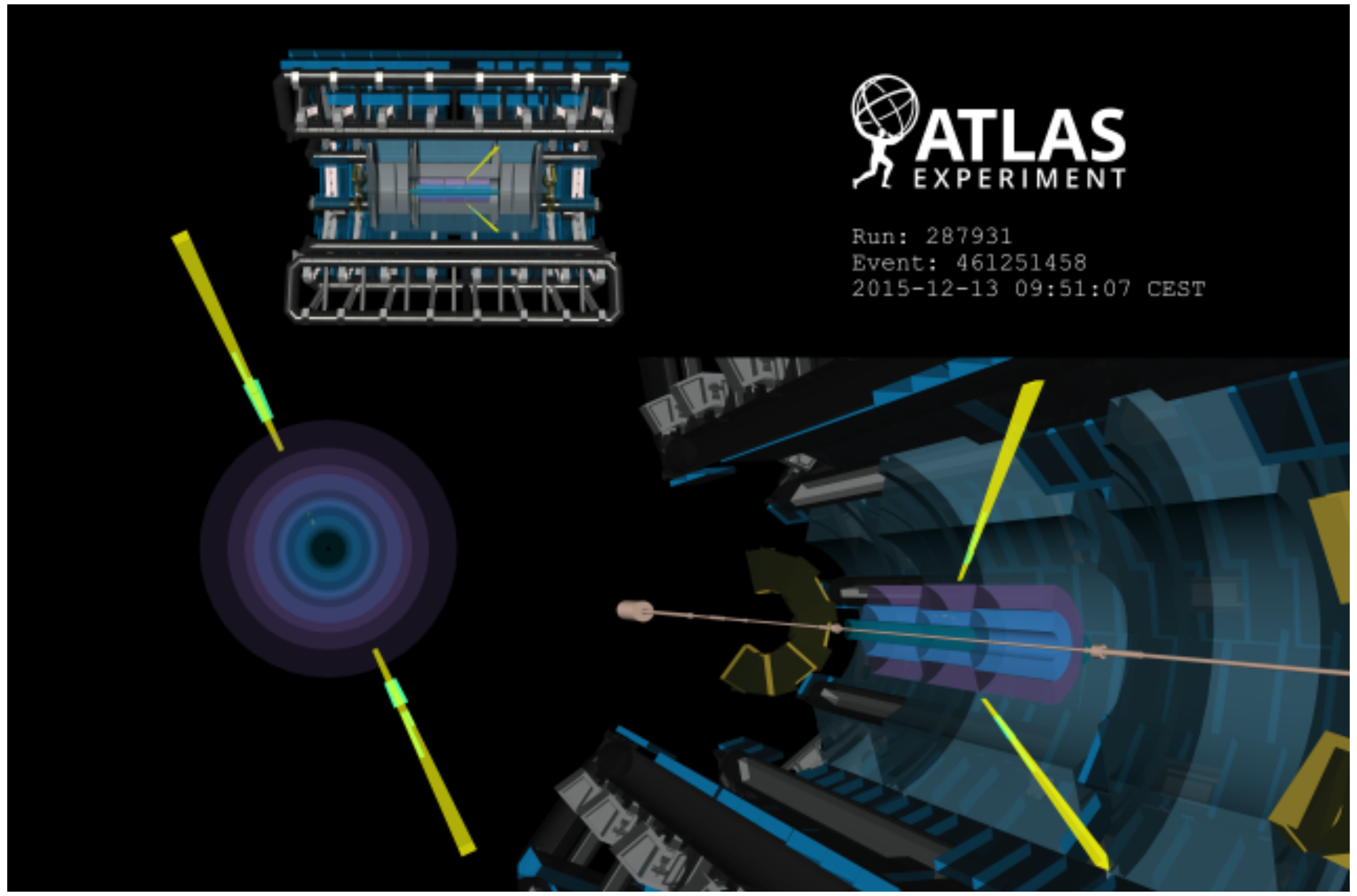
PUBLISHED ONLINE: 14 AUGUST 2017 | DOI: 10.1038/NPHYS4208

OPEN

Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration†

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



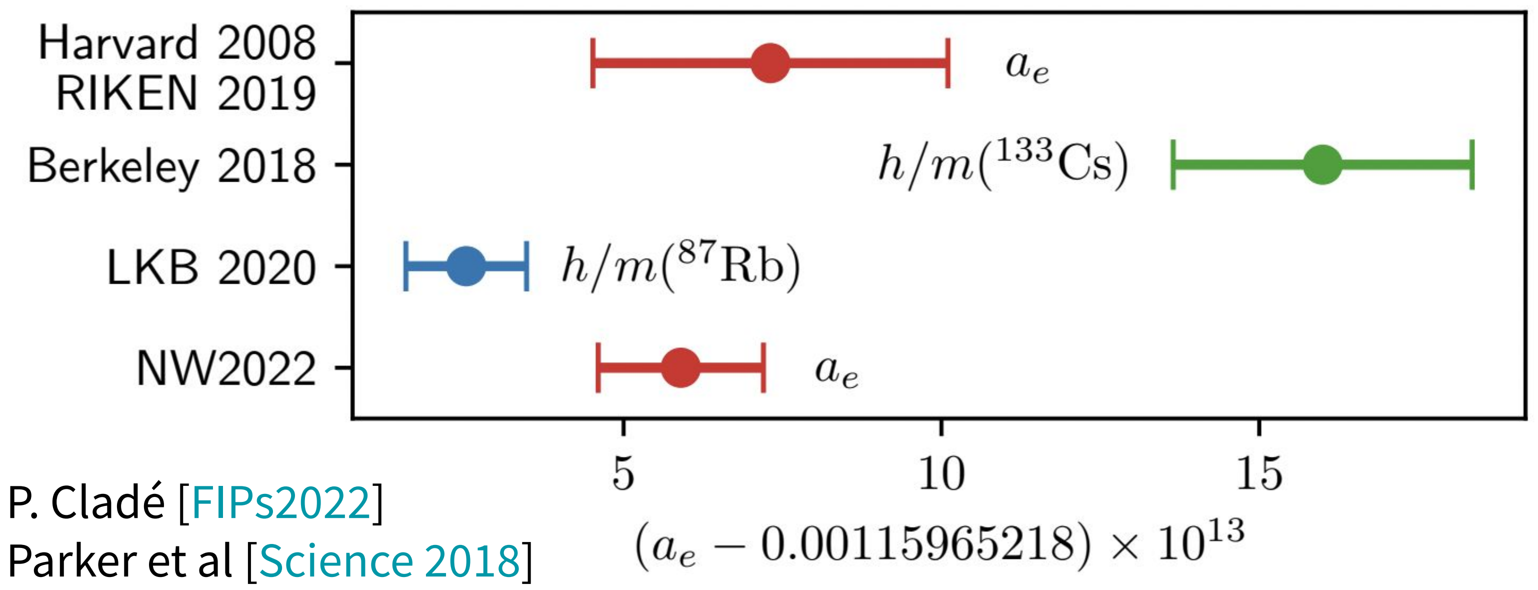
- Photons emitted coherently from colliding ions $\Rightarrow$ cross section enhanced by $Z^4 \gg 1$.
- For in particular light objects, this allows previously untested production to be probed, and with unprecedented precision.

Physics Cases: Some Examples

⋆ Probing the tau g-2:

- While experimental situation for lighter leptons well developed…

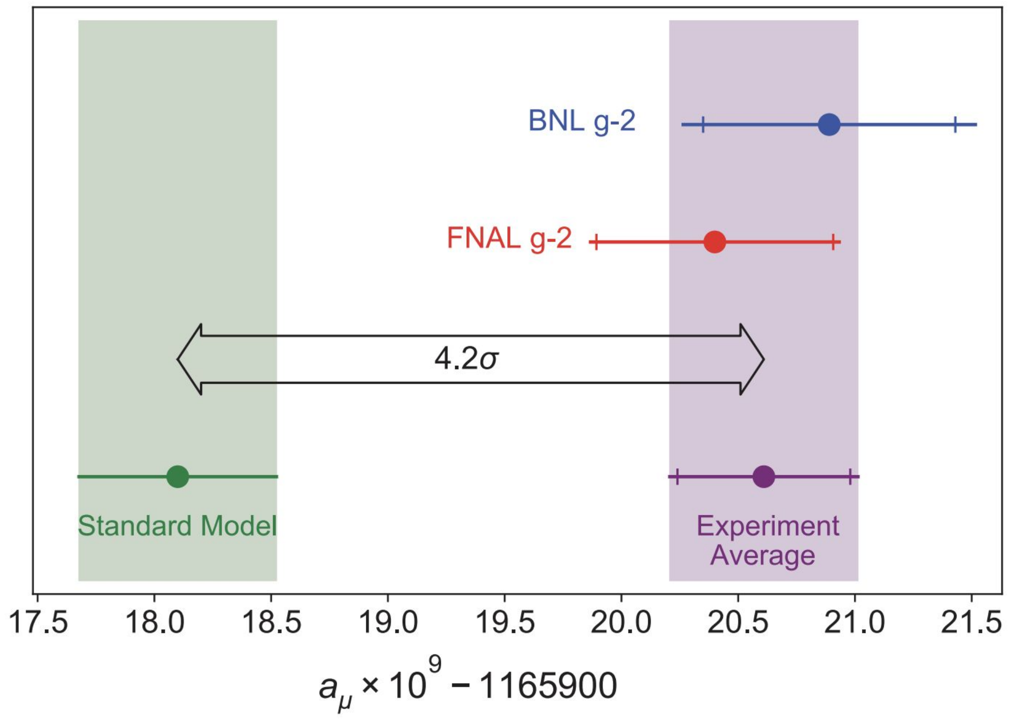
Electron $g - 2$ (−2.5σ?)



P. Cladé [FIPs2022]
Parker et al [Science 2018]
Morel et al [Nature 2022], Fan et al [2209.13084]

0.2 parts per billion

Muon $g - 2$ (+4.2σ?)



0.5 parts per million

- For the tau lepton surprisingly little is known!

$$a_\tau^{\mathrm{exp}} = -0.018\,(17)$$

DELPHI [hep-ex/0406010]

(Pre - LHC)

$$a_{\tau,\,\mathrm{SM}}^{\mathrm{pred}} = 0.001\,177\,21\,(5)$$

Eidelman, Passera [hep-ph/0701260]

- Does not even probe 1-loop QED:

$$\alpha/2\pi = 0.001162$$

Schwinger [1948]

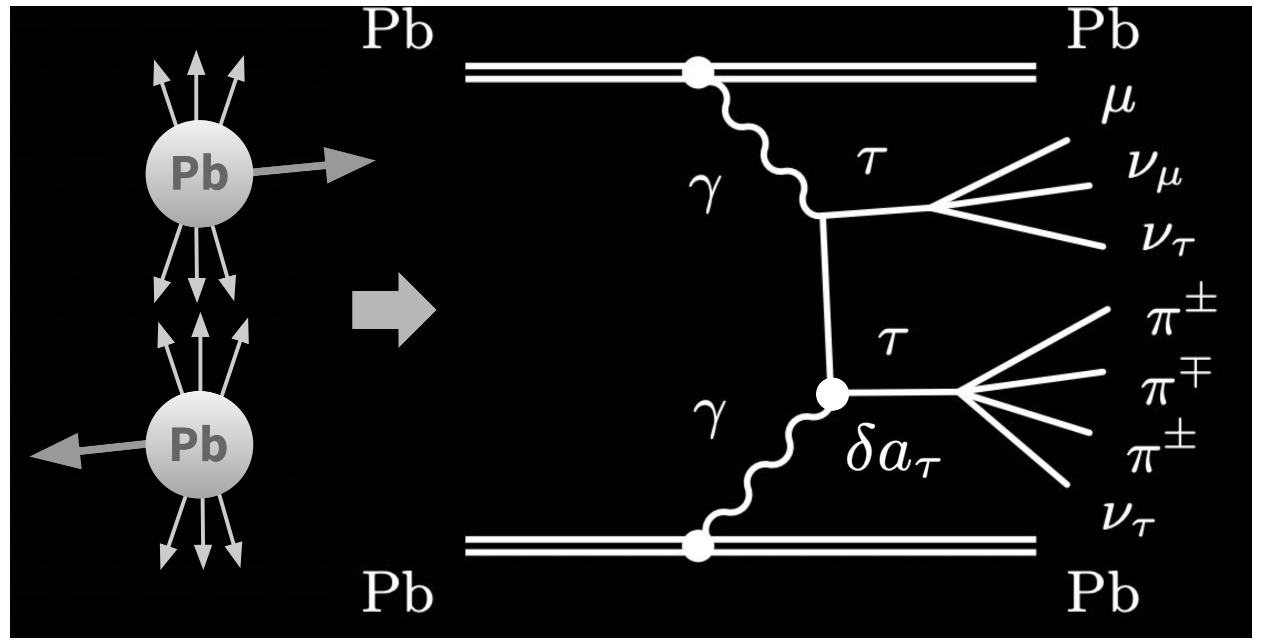
- Sensitivity to BSM unprobed:

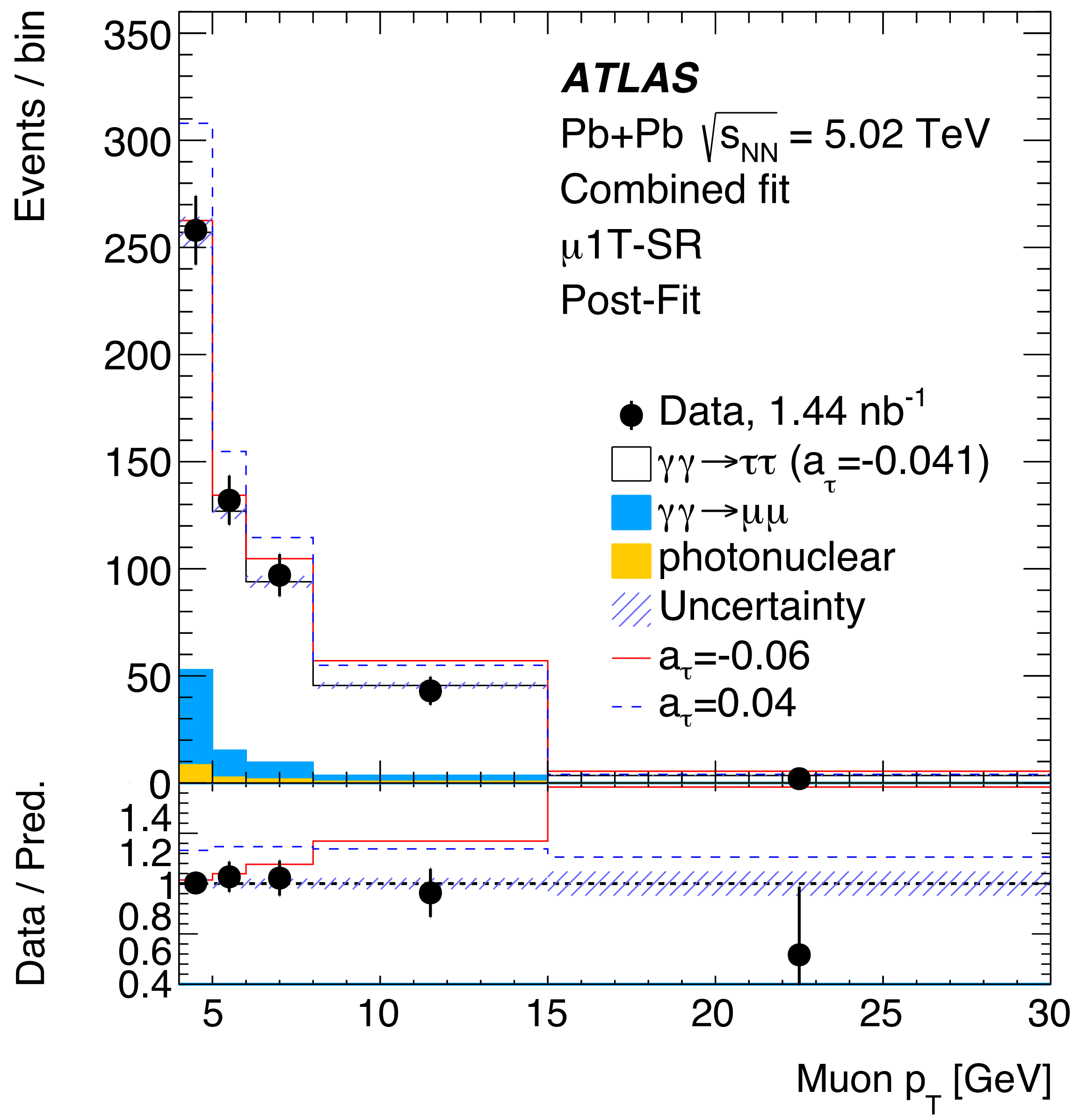
$$\delta a_\ell \sim m_\ell^2/M_{\mathrm{SUSY}}^2 \qquad m_\tau^2/m_\mu^2 \sim 280$$

Martin, Wells [hep-ph/0103067]

Figures curtesy of J. Liu

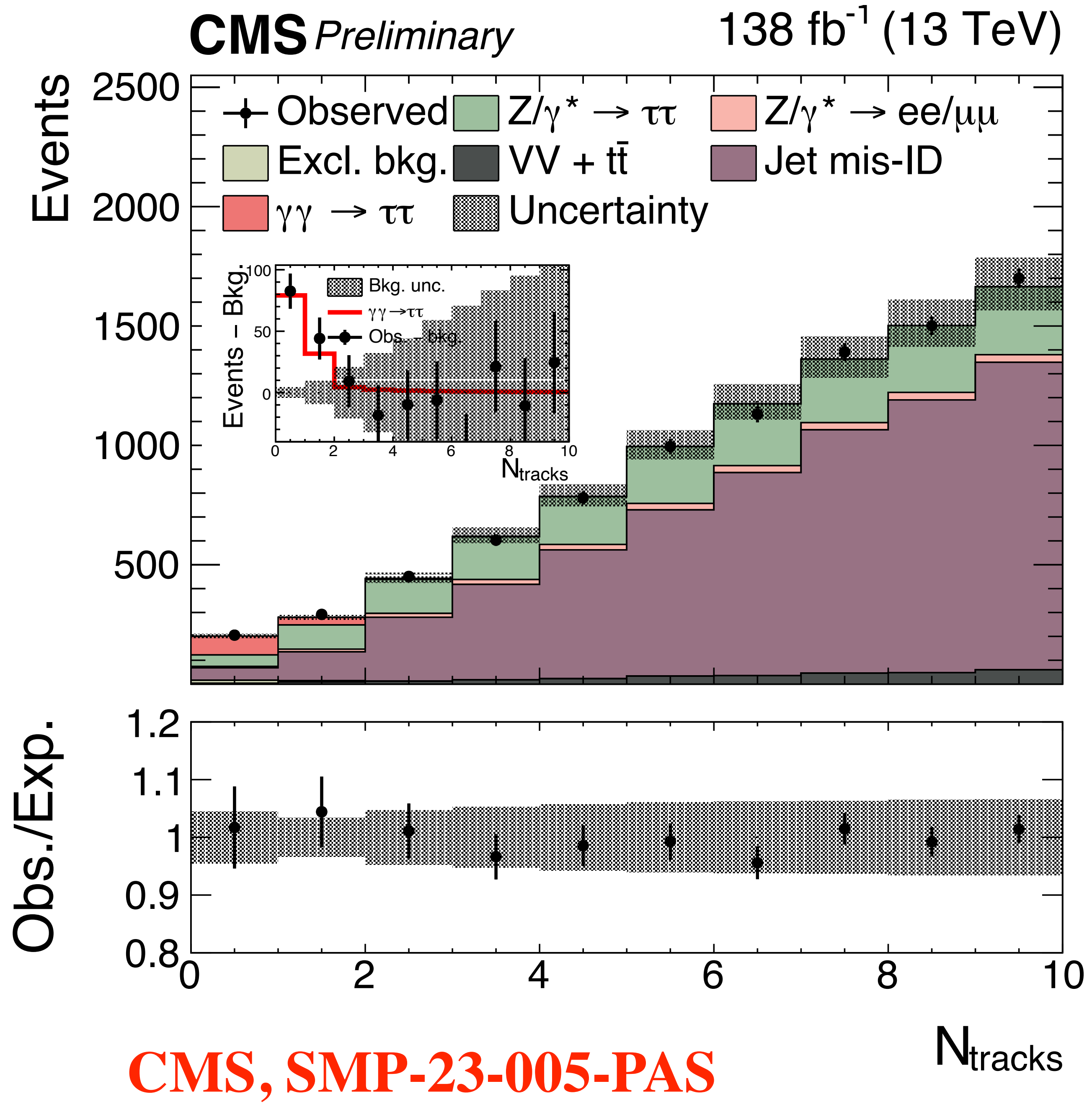
- Measured in both PbPb collisions ($Z^4 \gg 1$), and recently in pp - $\gamma - \tau$ coupling $\Rightarrow \tau$ g-2



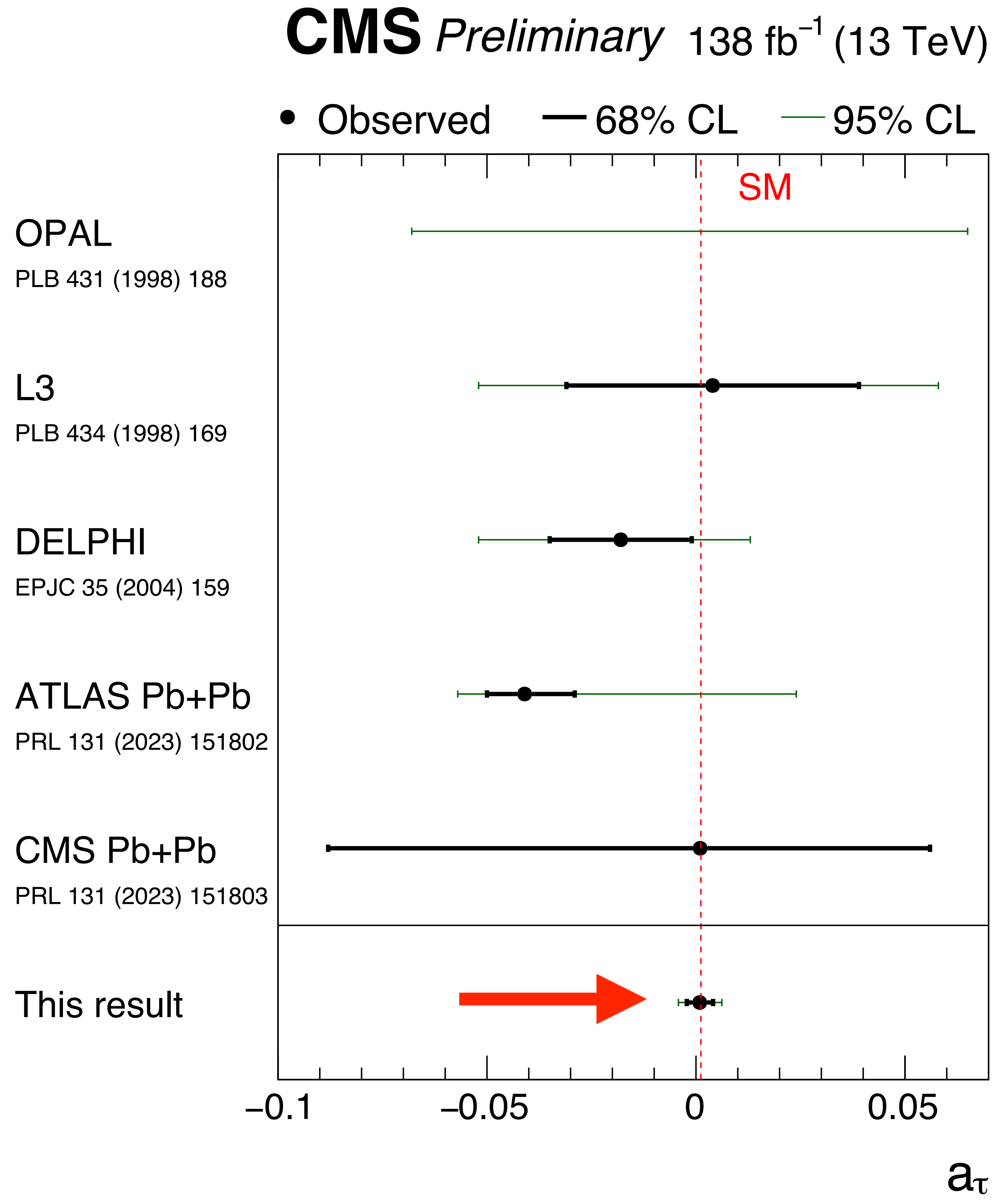


ATLAS, arXiv:2204.13478

- Sensitivity via differential cross section has already set new limits.



CMS, SMP-23-005-PAS



⋆ Vector boson production in pp collisions.

- **Vector Boson Scattering (VBS)**: broad class of process with sensitivity to the EW sector of the SM and BSM extensions of it.
- Often select events via VBS cuts: require two well separated jets (suppress s-channel $q\bar{q} \to VV$). However not the only way!

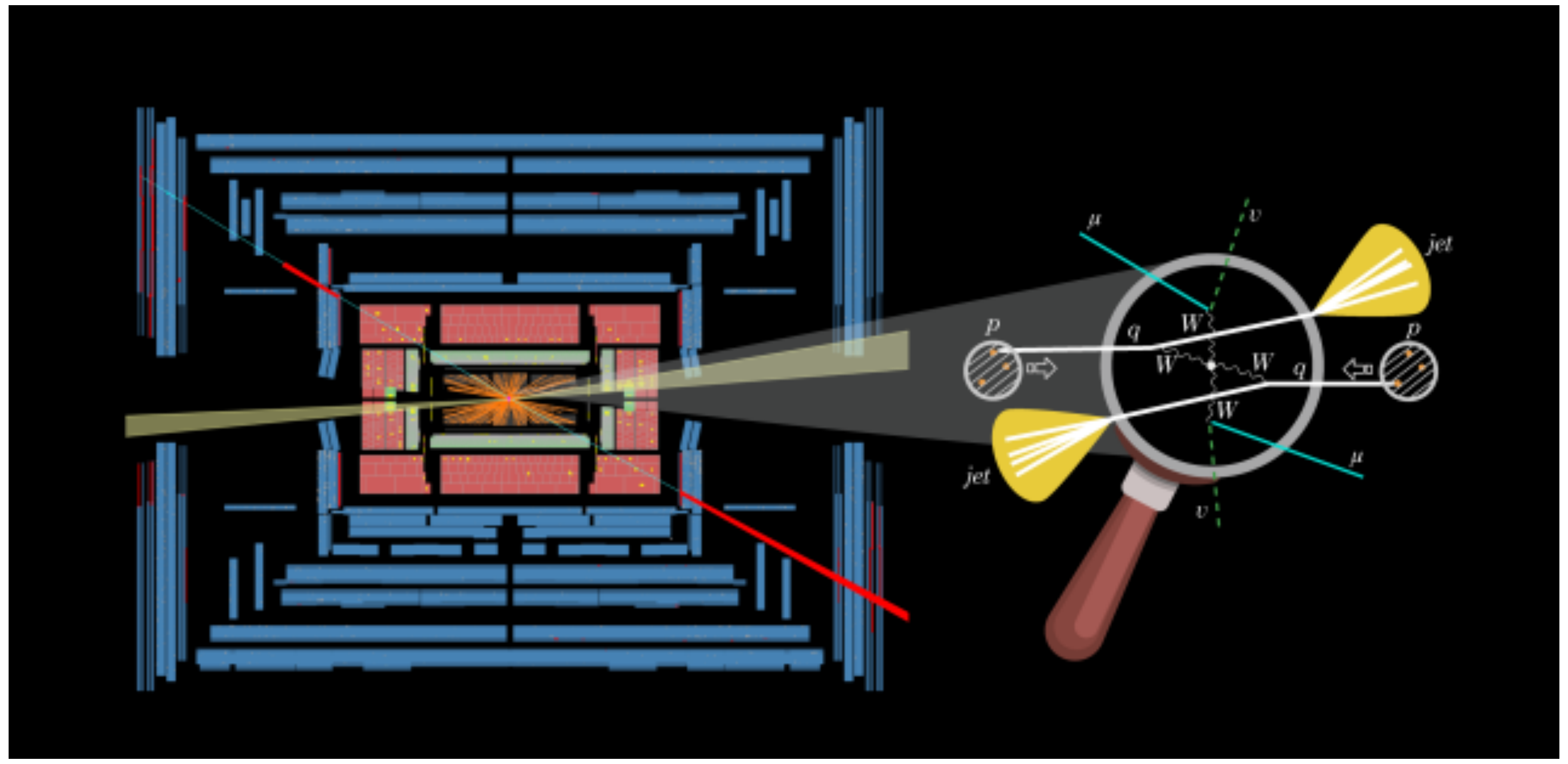
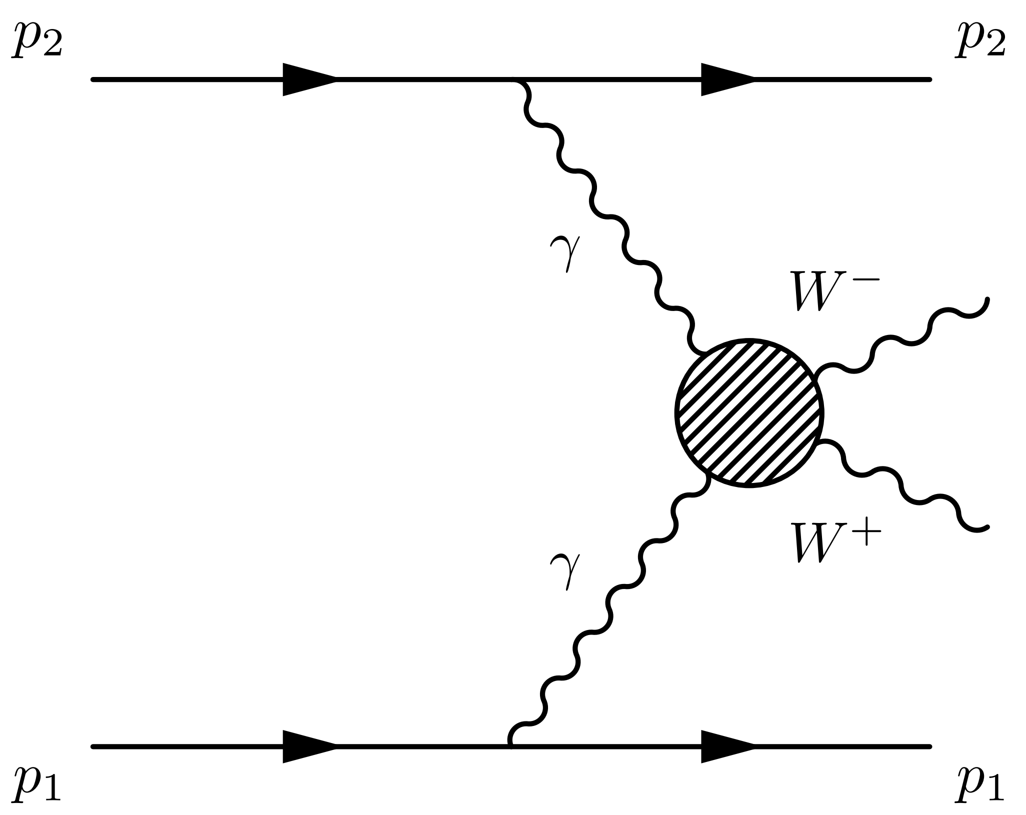
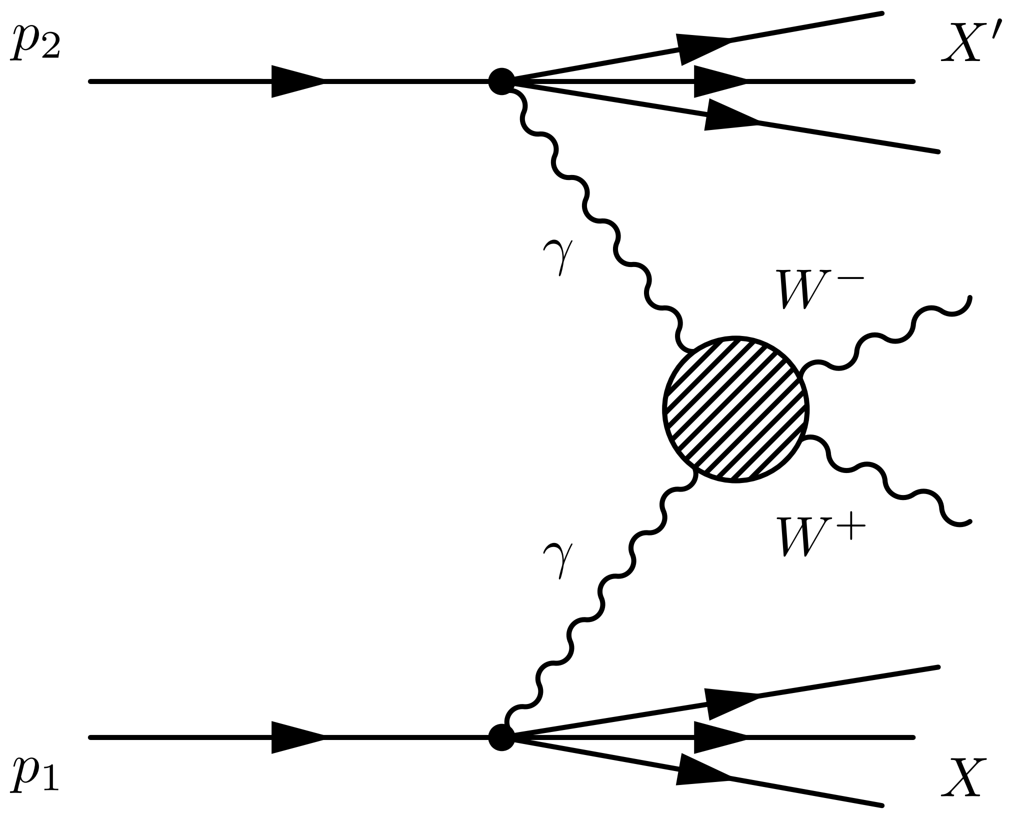


Image credit: Lucia Di Ciaccio, Simone Pagan Griso

- By selecting semi-exclusive VV events, focus in on underlying $\gamma\gamma \to VV$ process, e.g. W^+W^- :

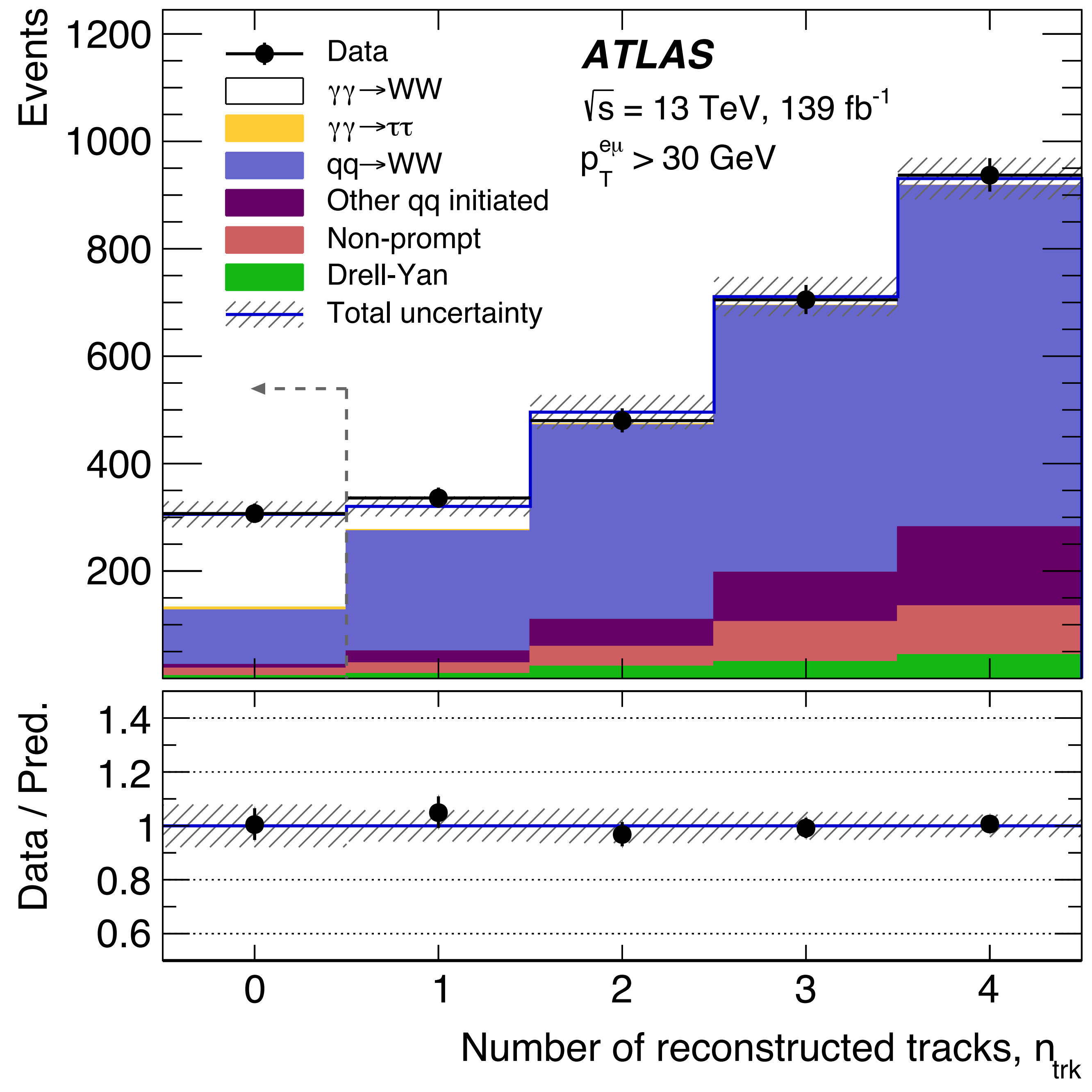




- 'Empty' event + VV final state $\Rightarrow \gamma\gamma \to VV$

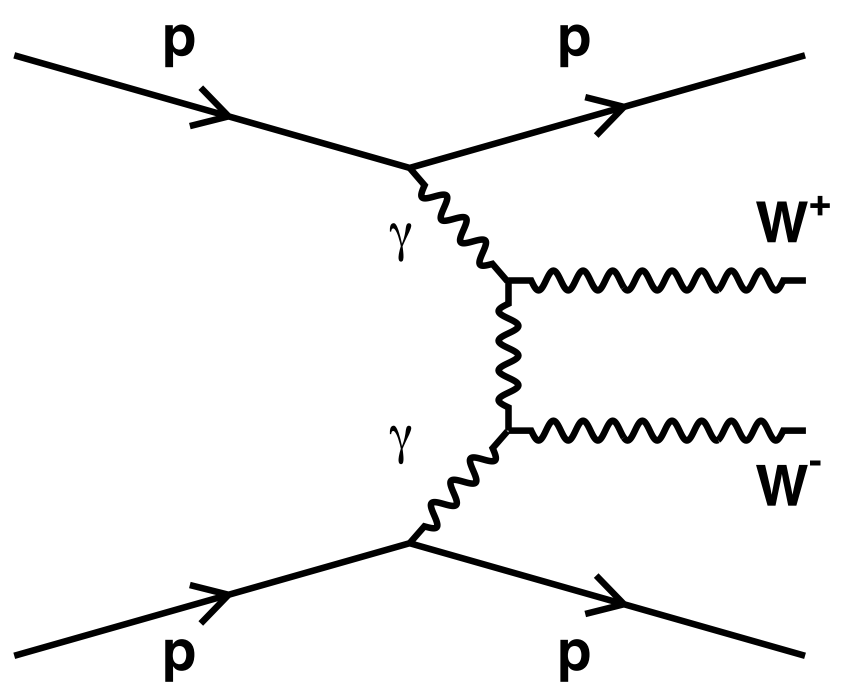
- First observation by ATLAS, by vetoing on additional associated tracks. Cross section agrees well with SM (within uncertainties).

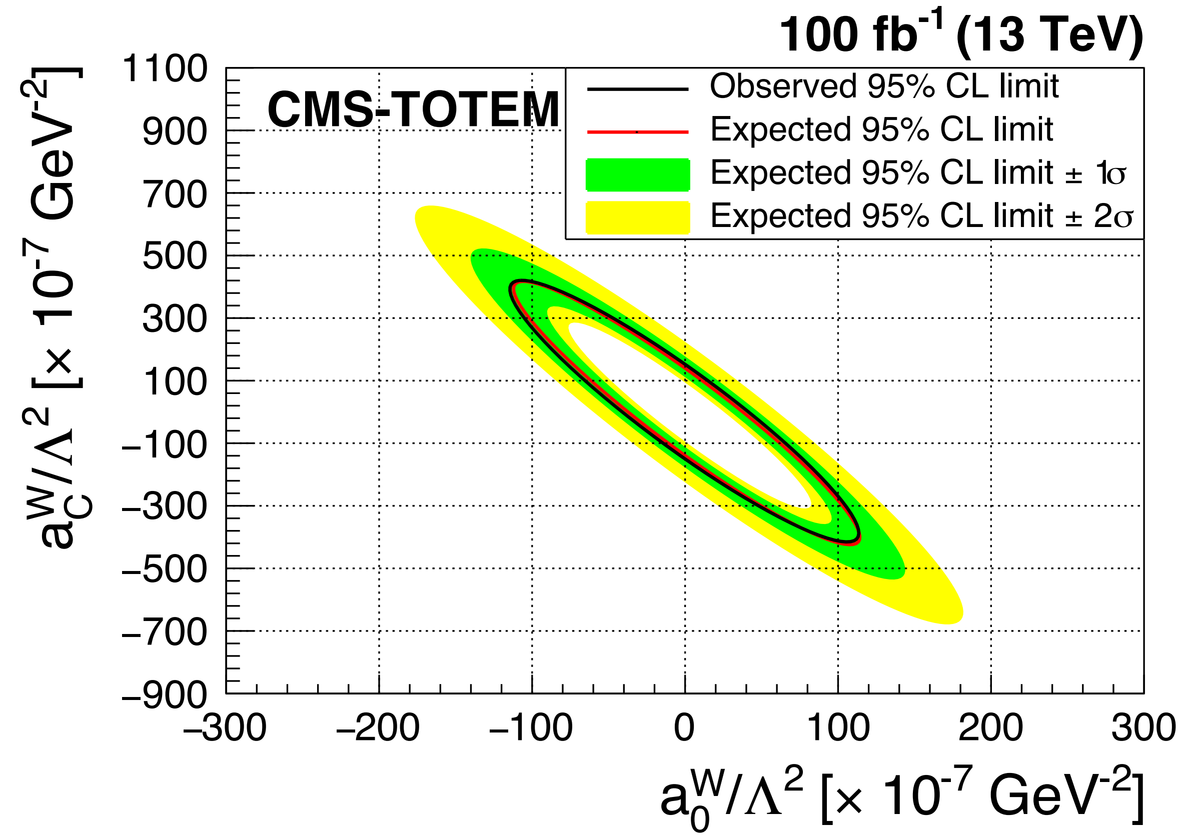
$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

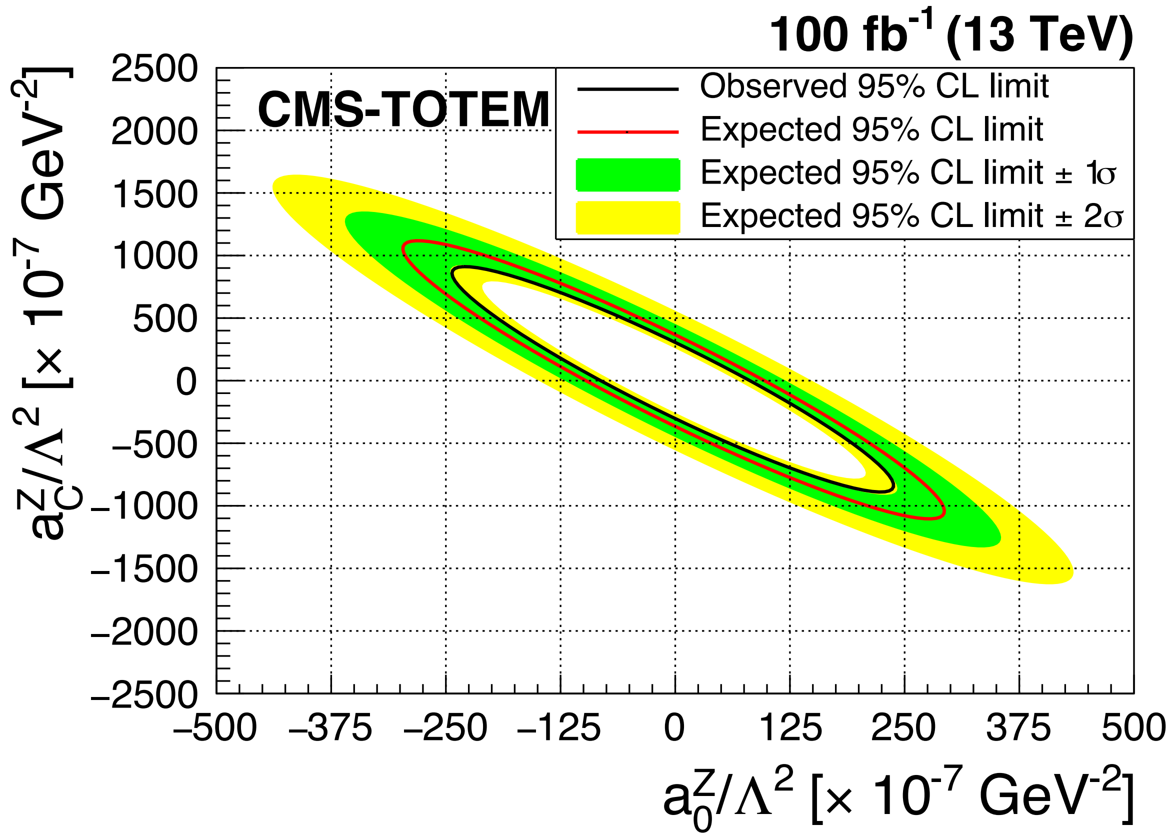


ATLAS, Phys. Lett. B 816, 136190 (2021)

- Searches have also been performed with tagged protons (hadronic decays).



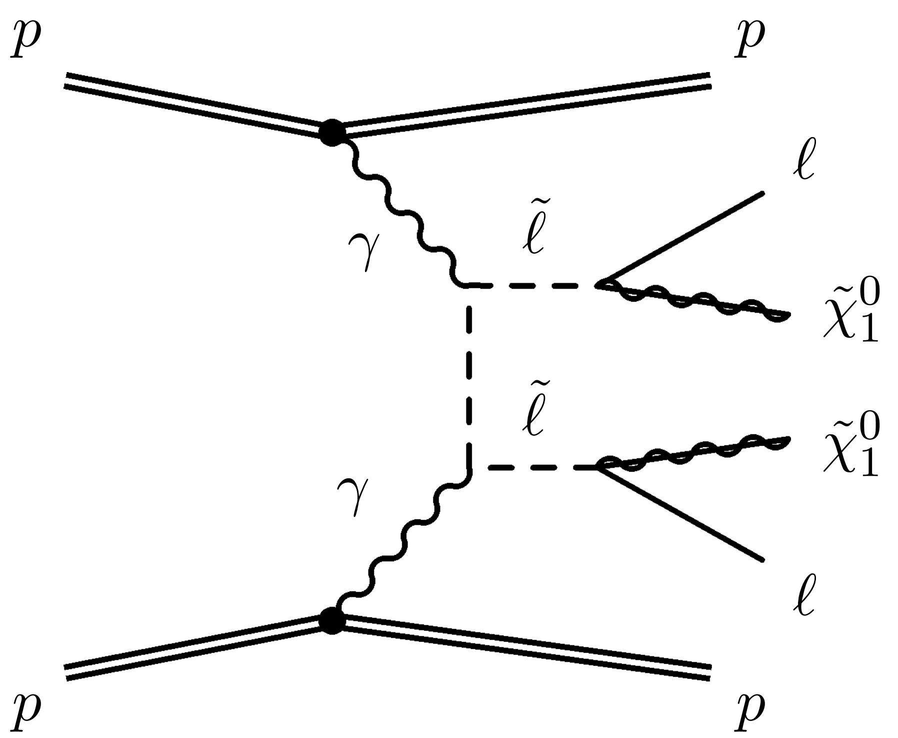




- Limits already competitive with other vector boson scattering results. Promising hunting ground for BSM.

★ Many physics cases of interest…can't mention them all.

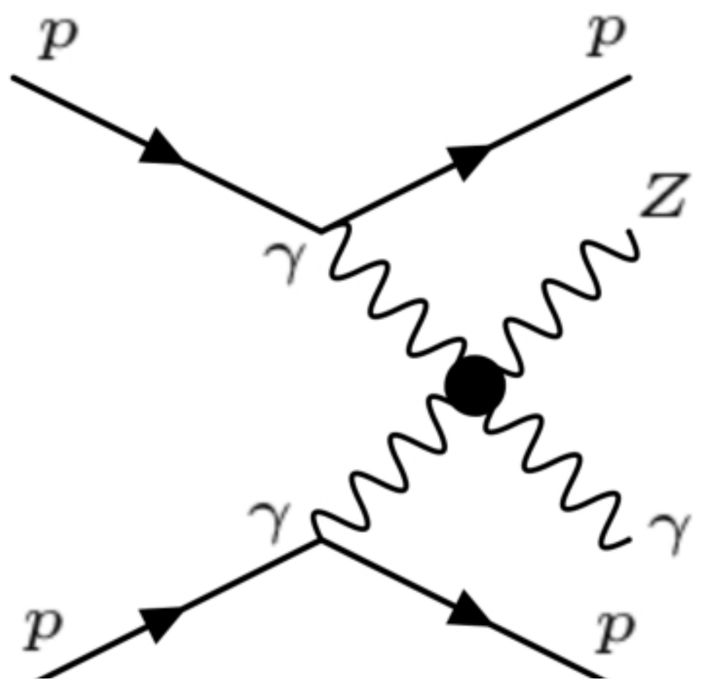
Compressed SUSY



LHL et al., JHEP 1904 (2019) 010

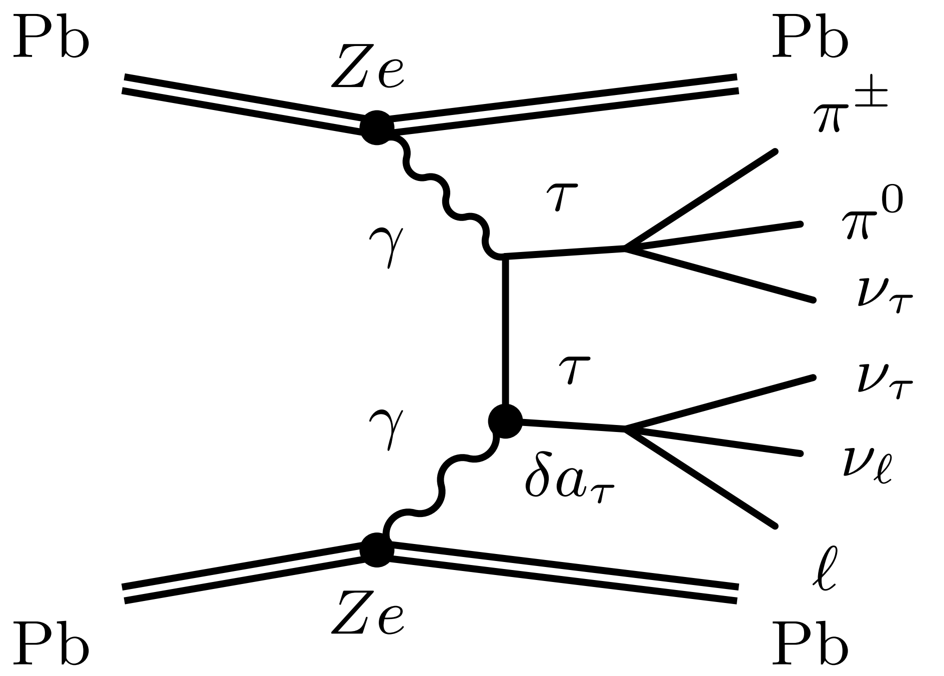
L. Beresford and J. Liu, PRL 123 (2019) no.14

Anomalous couplings



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

tau g-2



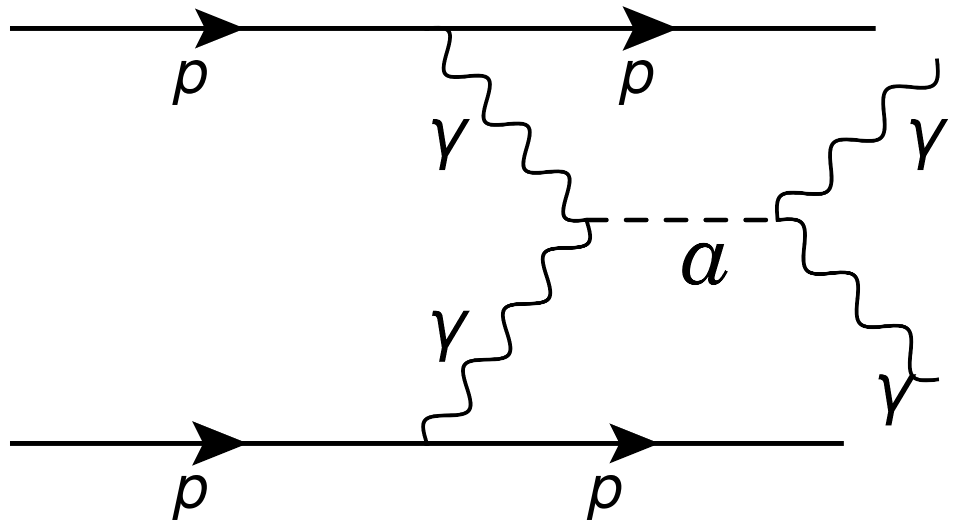
L. Beresford and J. Liu, PRD 102 (2020) 11, 113008

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

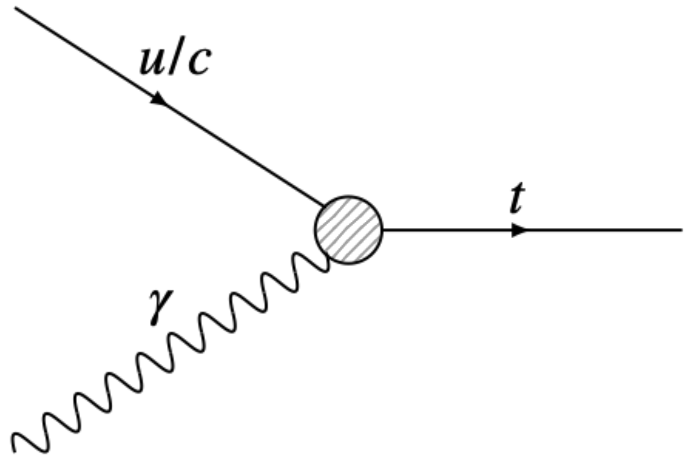
Axion-like Particles

LHL and M. Tasevsky, arXiv:2208.10526

C. Baldenegro et al., *JHEP* 06 (2018) 131



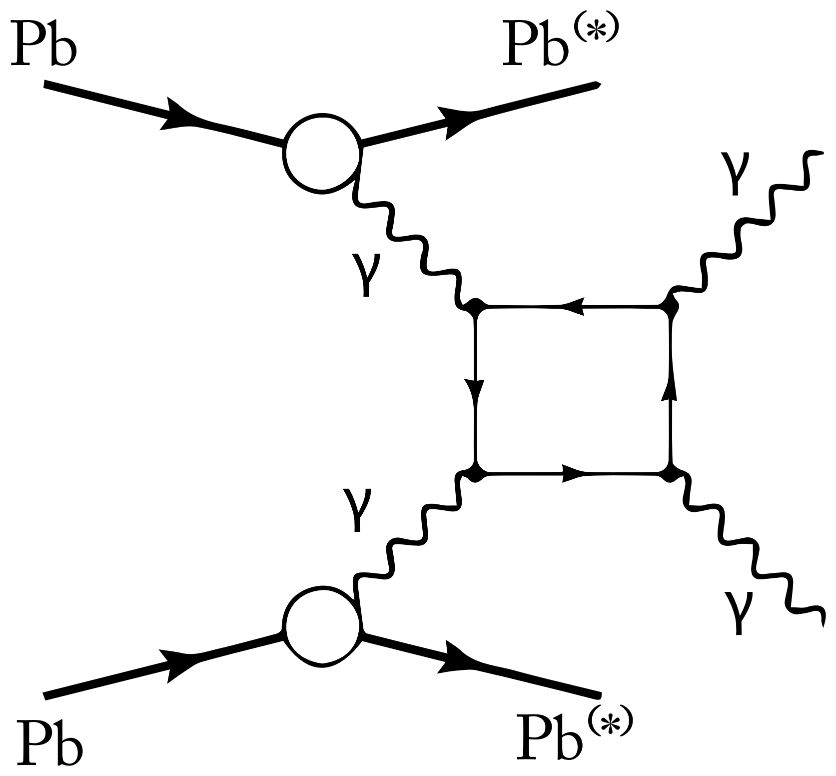
Top quarks



V. Goncalves et al., *Phys.Rev.D* 102 (2020) 7, 074014

J. Howarth, arXiv:2008.04249

LbyL scattering/ALPS



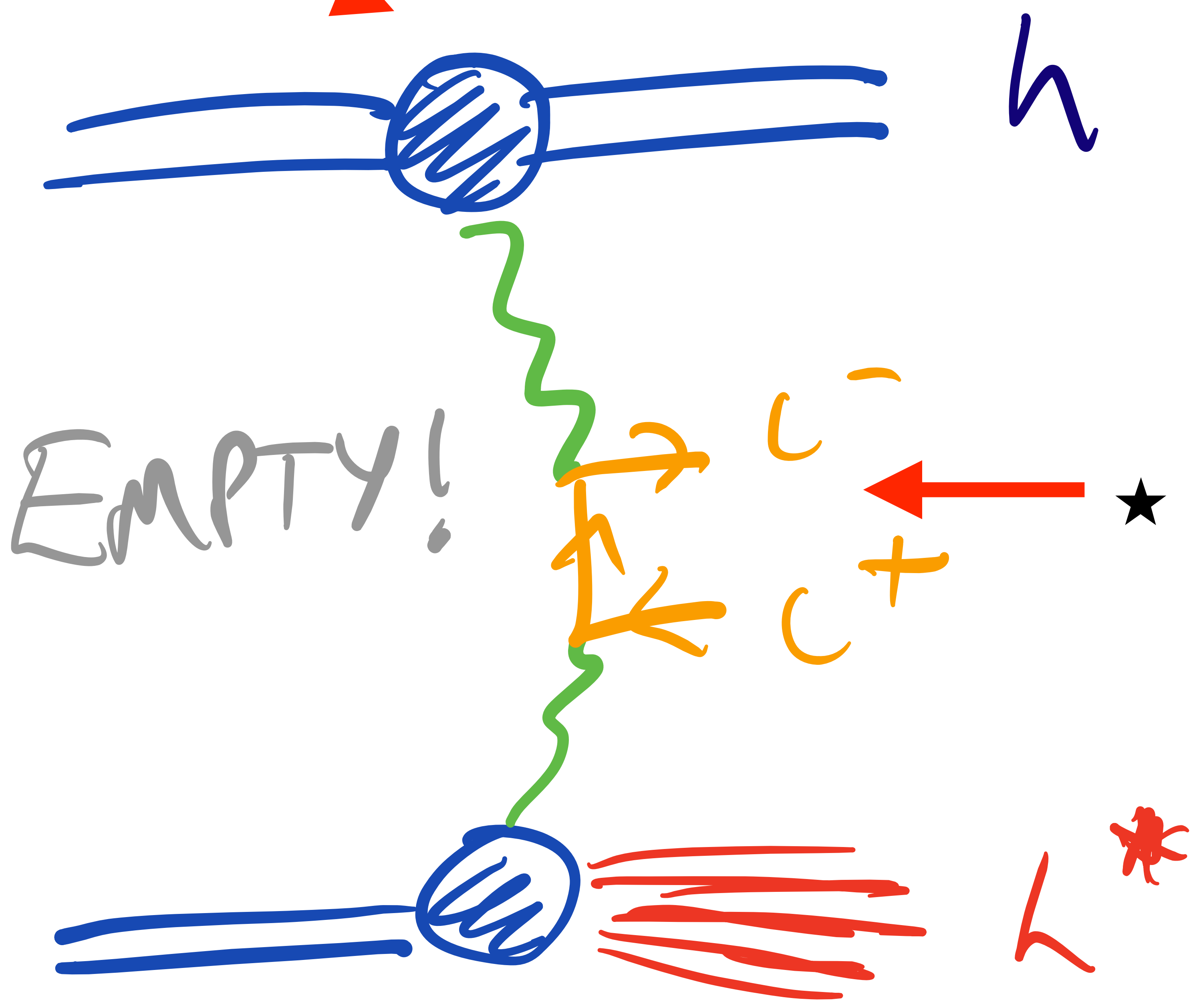
C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

Modelling PI Production (pp collisions)

PI production: building blocks

- (Semi)-Exclusive PI cross section given in terms of:

★ $p \to \gamma p(p^*)$ form factor.



★ $\gamma\gamma \to X$ cross section.

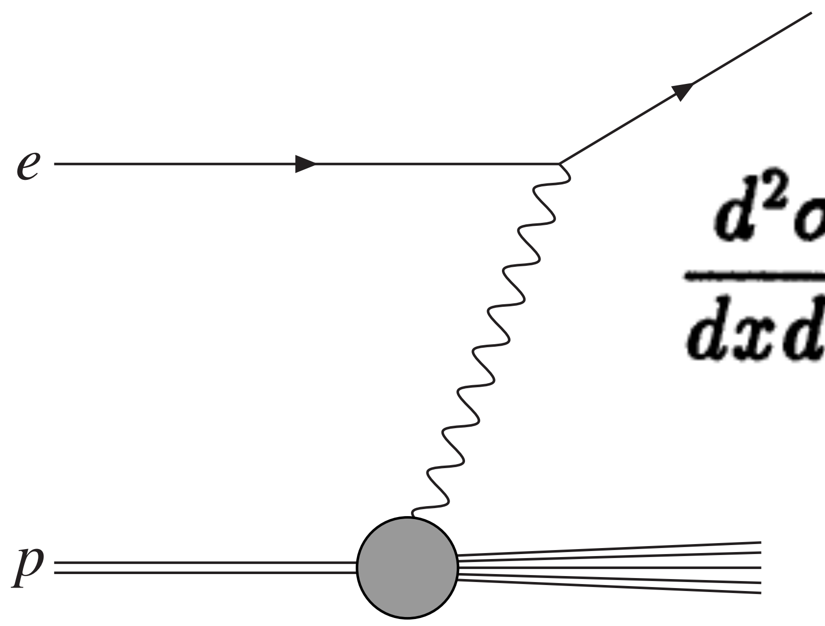
★ \`**Survival factor**' probability of no addition proton-proton interactions.

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

LHL, *JHEP* 03 (2020) 128

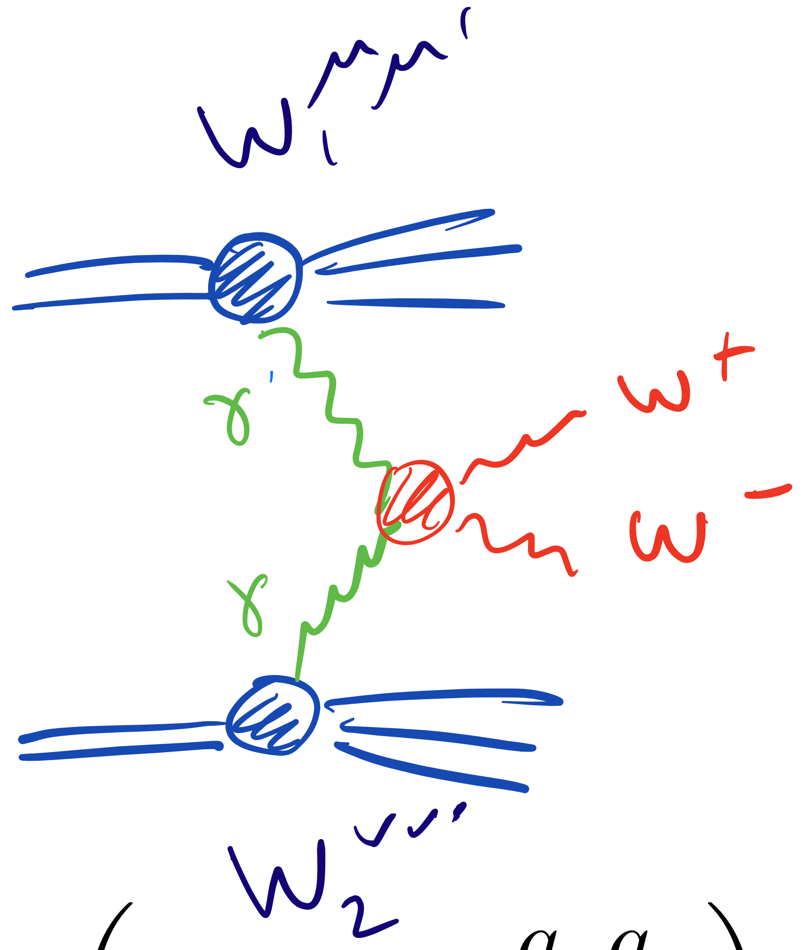
Structure Function Calculation

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



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

$W^{\alpha\beta}$



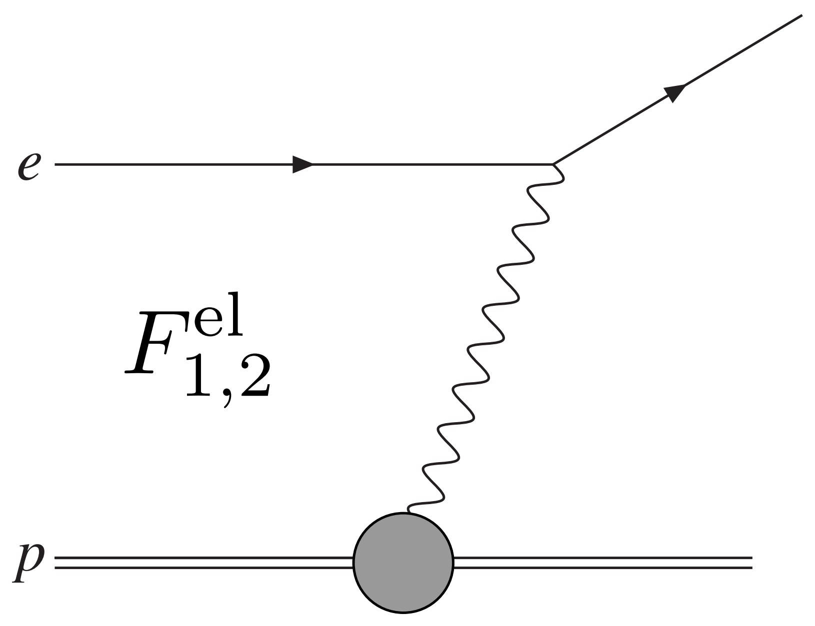
- Structure functions parameterise the $\gamma p \to X$ vertex: $W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} F_2(x,Q^2)$
- Use same idea as for DIS to write:

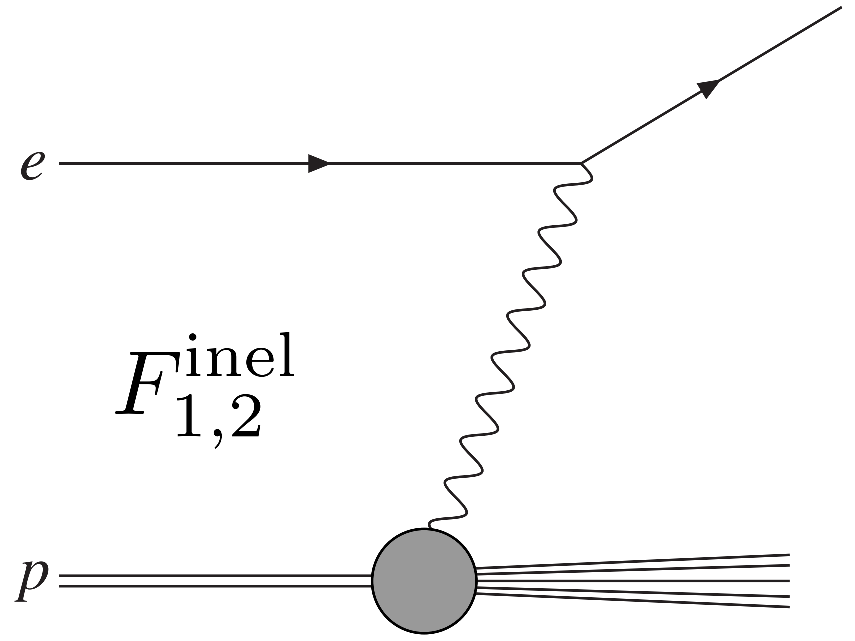
Photon x, Q^2 $\quad$ $\gamma^* p \to X$ $\quad$ $\sim \sigma(\gamma^*\gamma^* \to X)$ $\quad$ $(\rho_{\mu\nu} \sim W_{\mu\nu})$

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

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

- Both elastic and inelastic SFs accounted for:





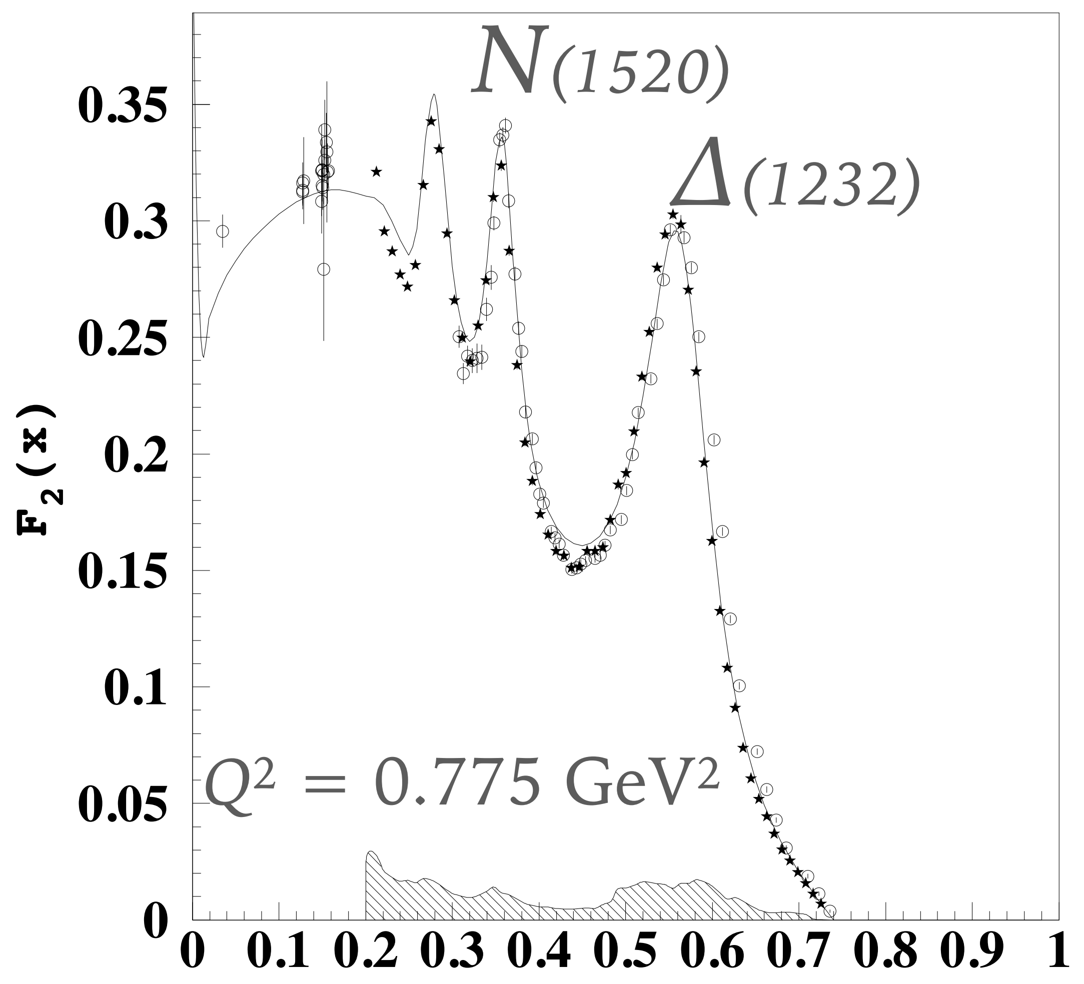
★ **Elastic**: precisely measured proton EM form factor.

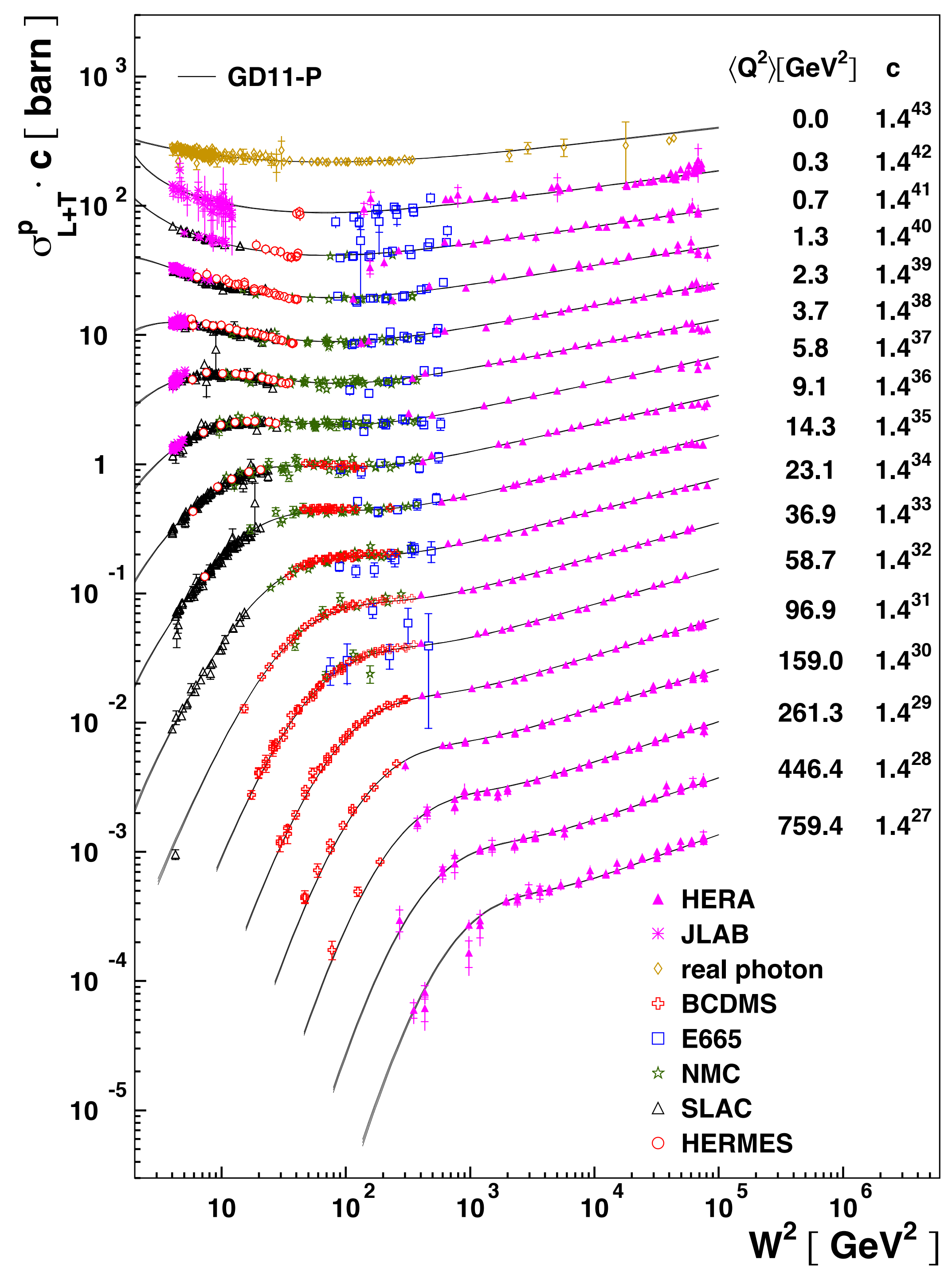
★ **Inelastic**:

$$Q^2_{\rm cut} = 1\,{\rm GeV}^2 \quad W^2_{\rm cut} = 3.5\,{\rm GeV}^2$$

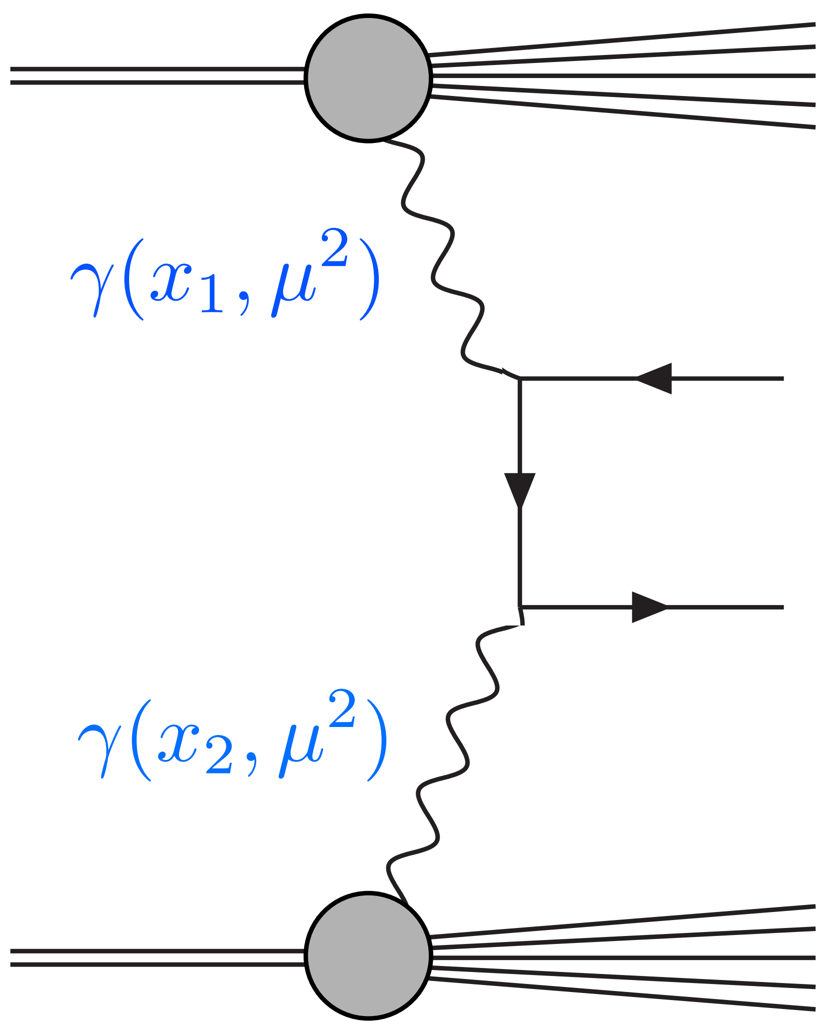
- High Q^2 region, simplest to calculate using (NNLO) pQCD + global PDFs.

- Low Q^2 and/or W^2 region: take direct experimental determinations.

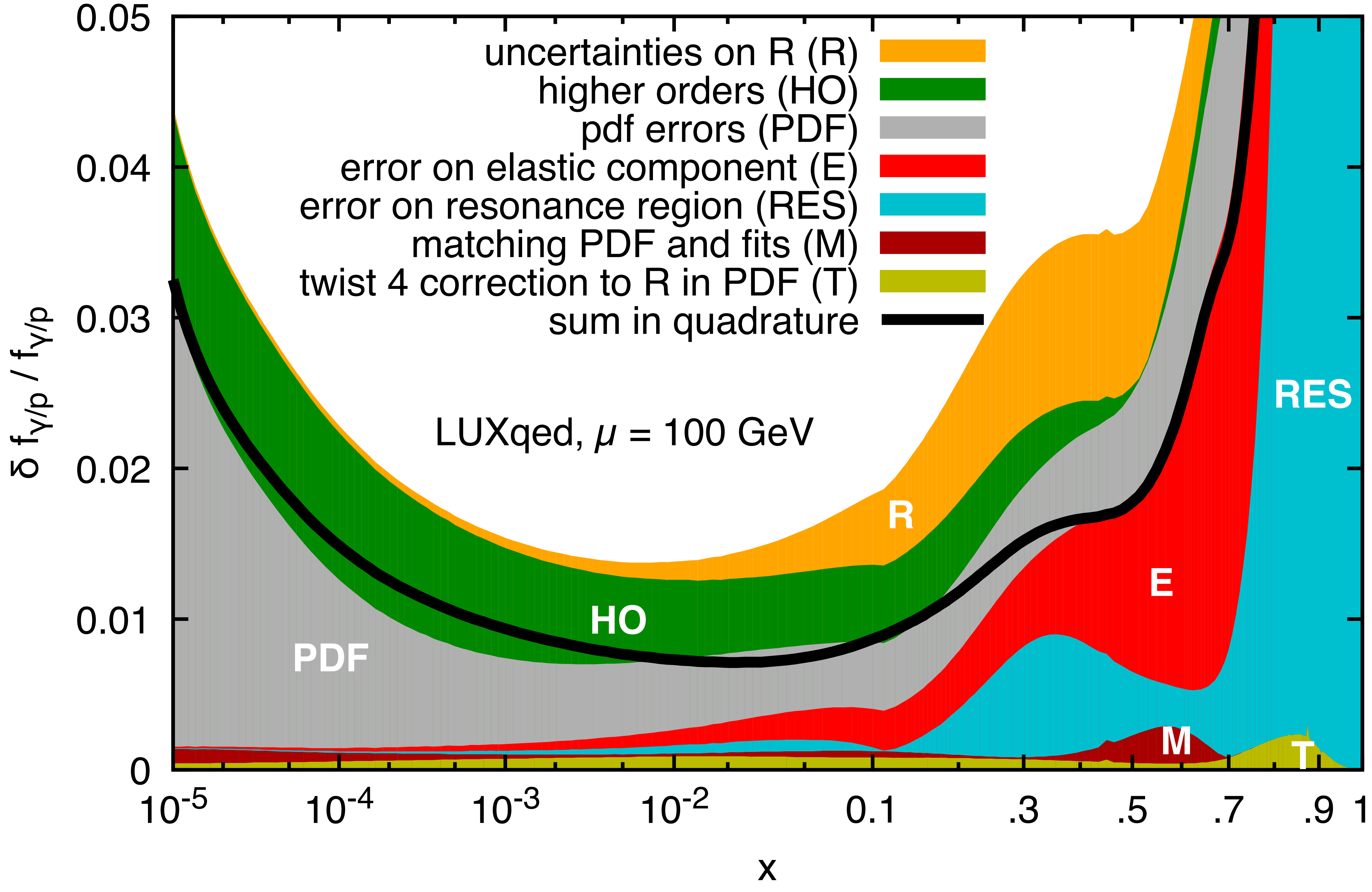




- These inputs are exactly as in the original `LUXqed' decomposition of the photon PDF.



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 calculation readily amenable to MC treatment:

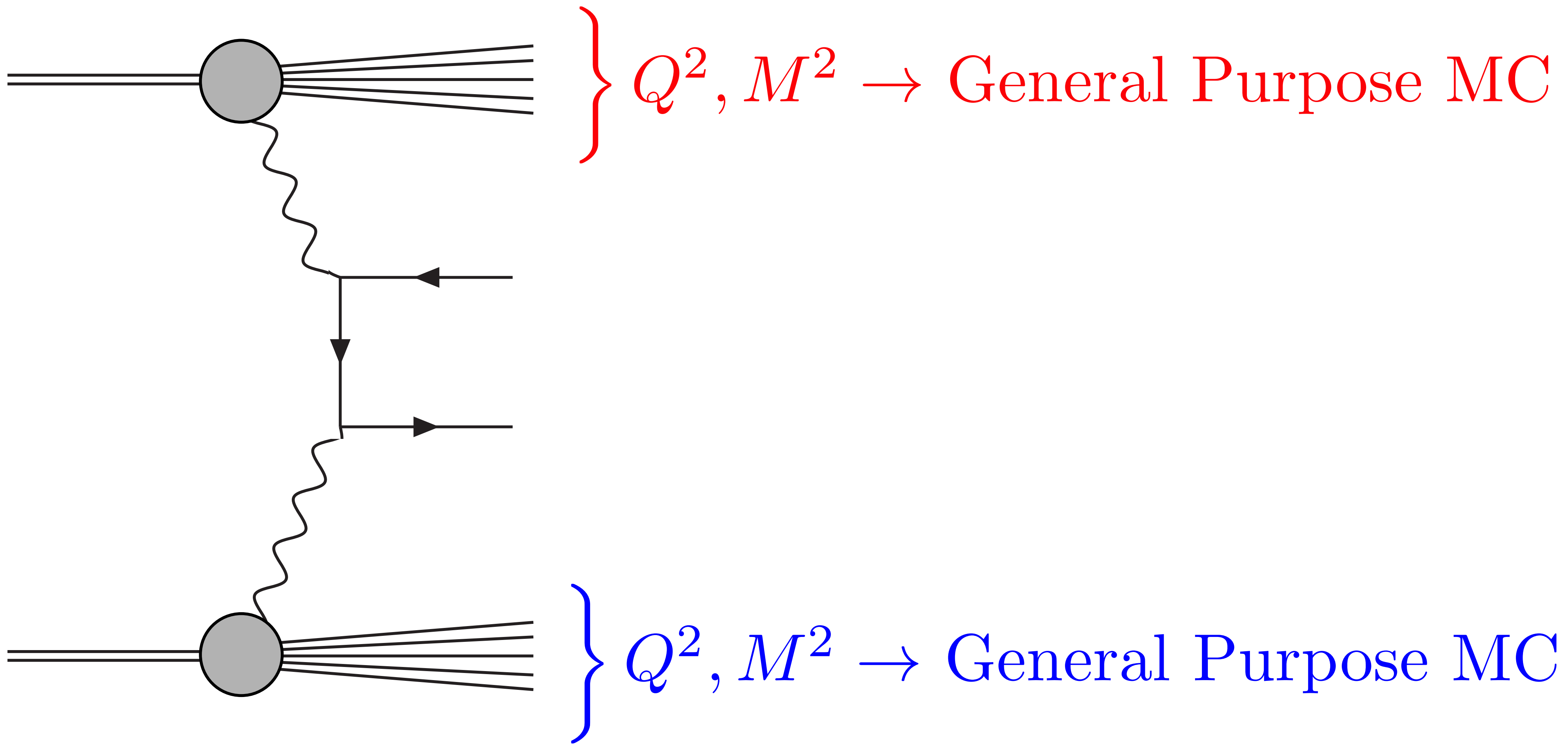
  ★ Can isolate elastic component of $F_{1,2}$ to give exclusive prediction.

  ★ 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

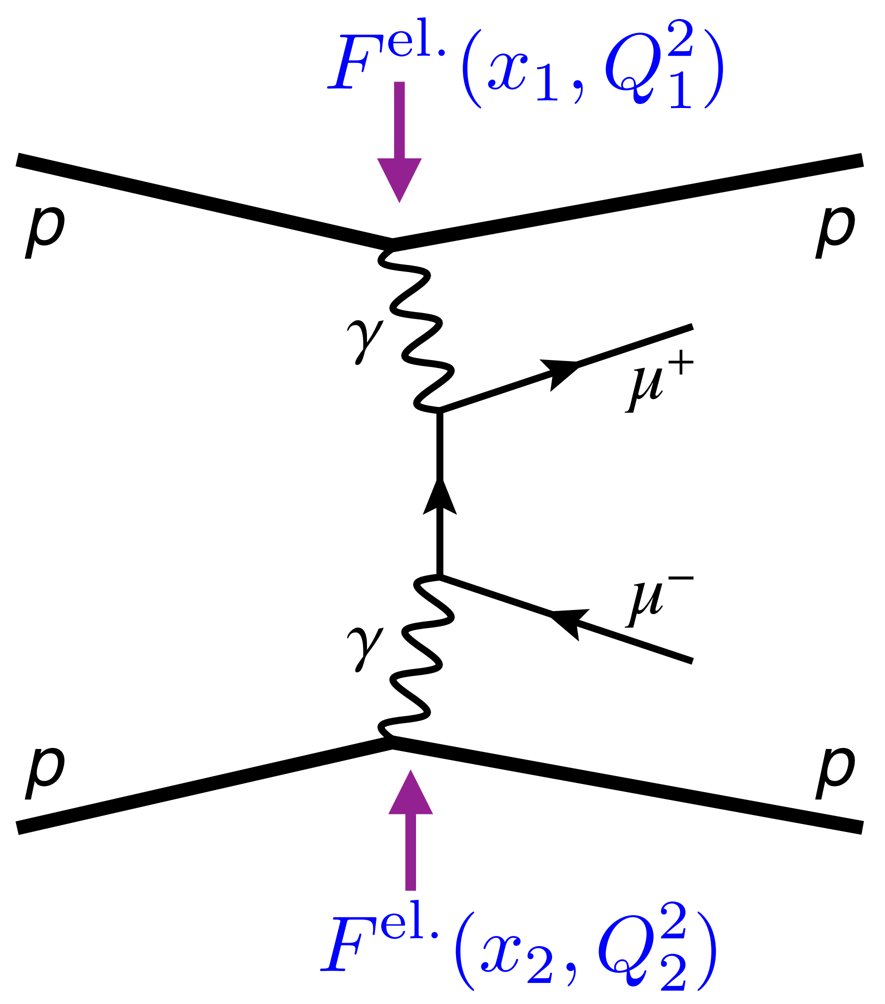


- **But not the end of the story**!

The Survival Factor

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

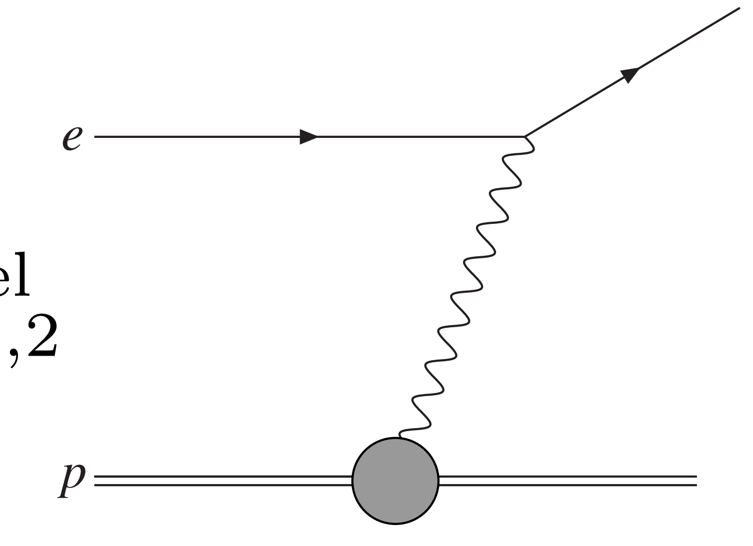
$$\sigma \sim F^{\mathrm{el.}}(x_1,Q_1^2)F^{\mathrm{el.}}(x_2,Q_2^2)$$



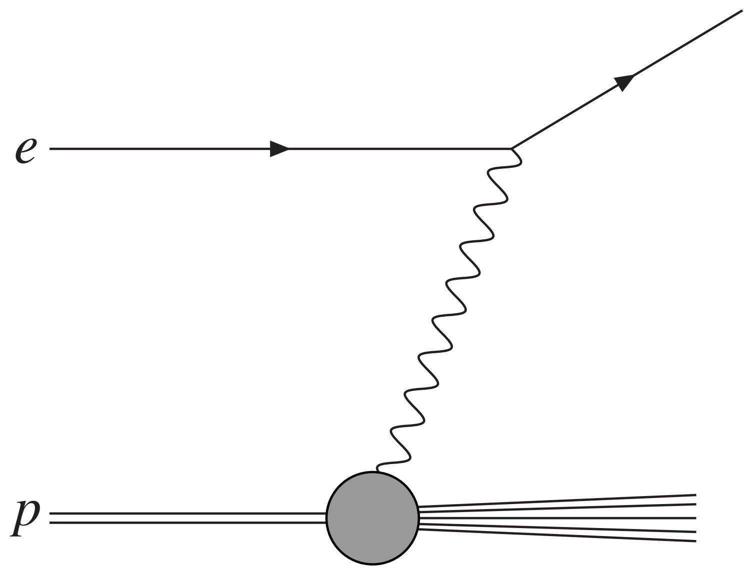
- Similarly for SD + DD, with $F^{\mathrm{el.}} \to F^{\mathrm{inel.}}$

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

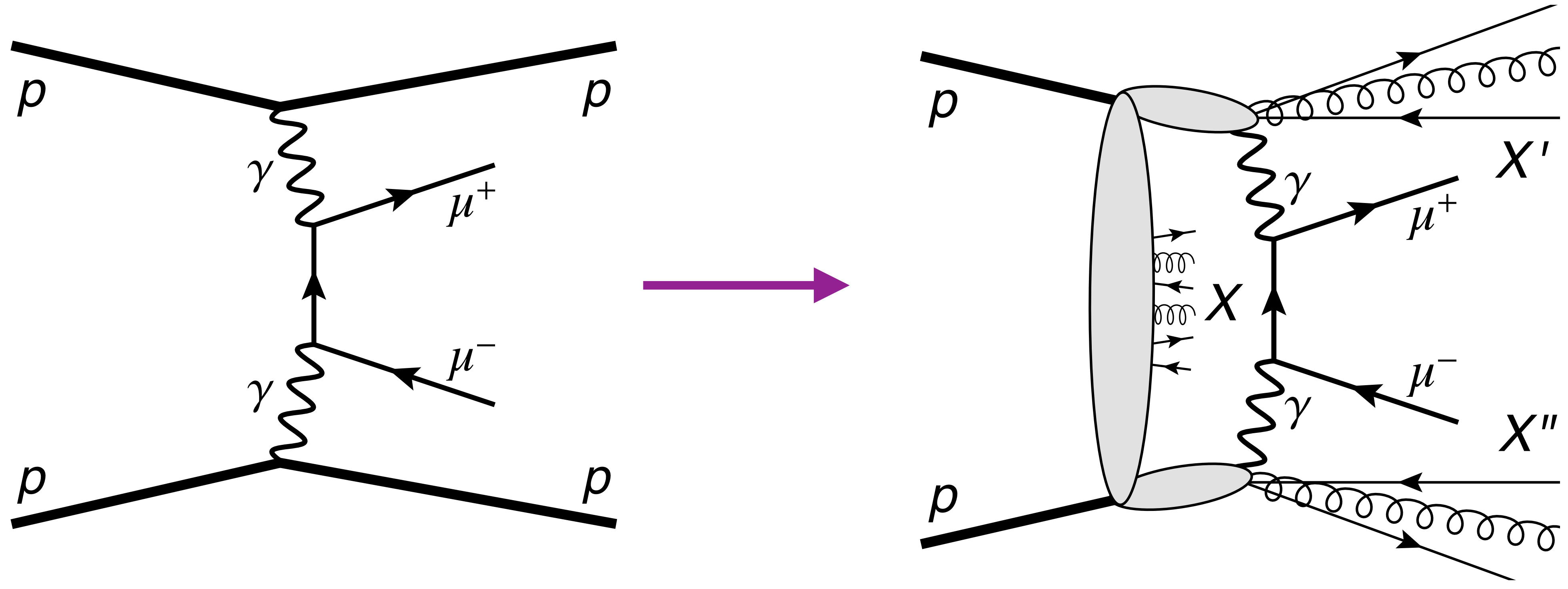
$F_{1,2}^{\mathrm{el}}$



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



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

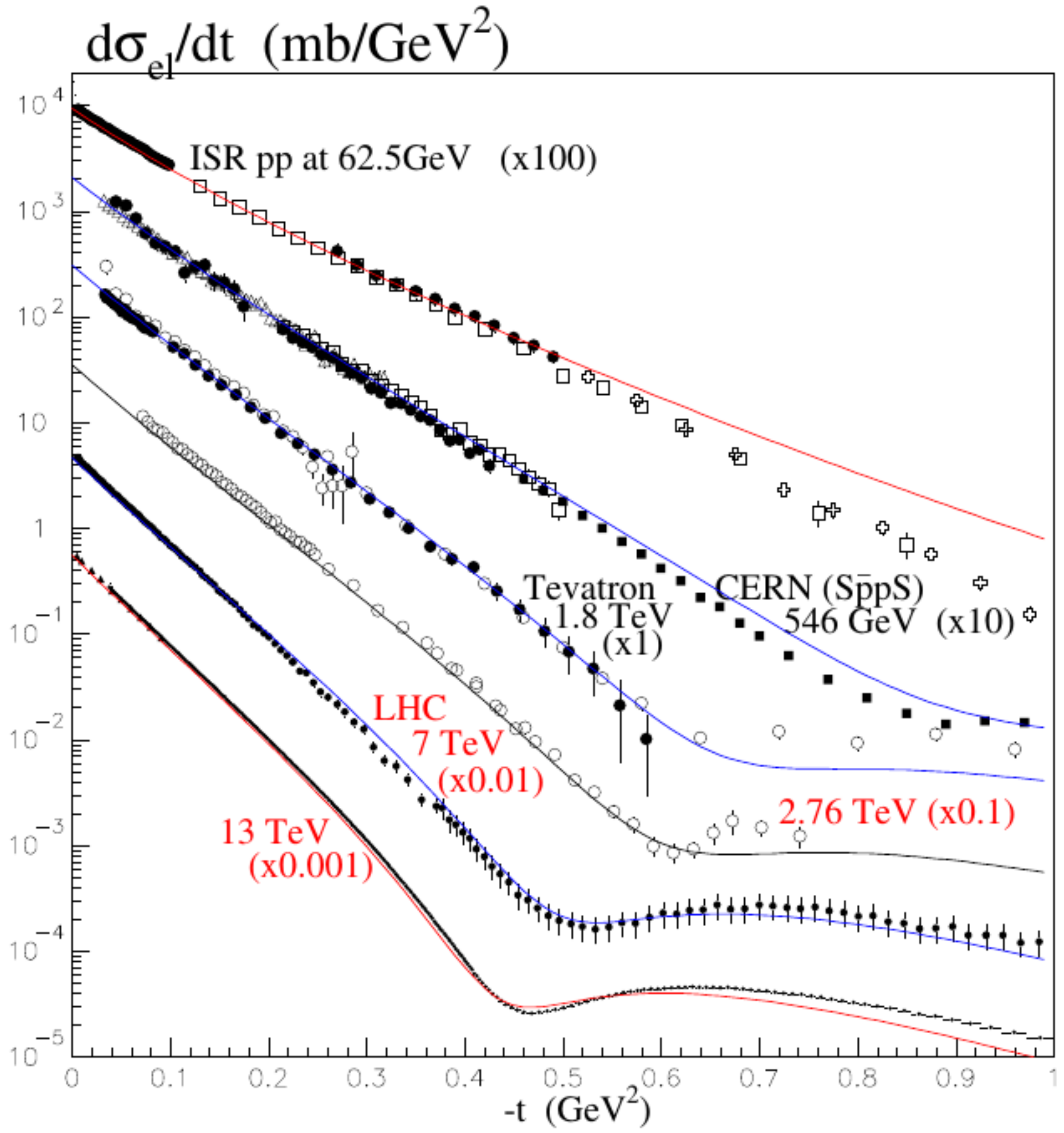


- ‘**Survival factor**’ = probability of no additional inelastic hadron-hadron interactions. Schematically:

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

- 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).

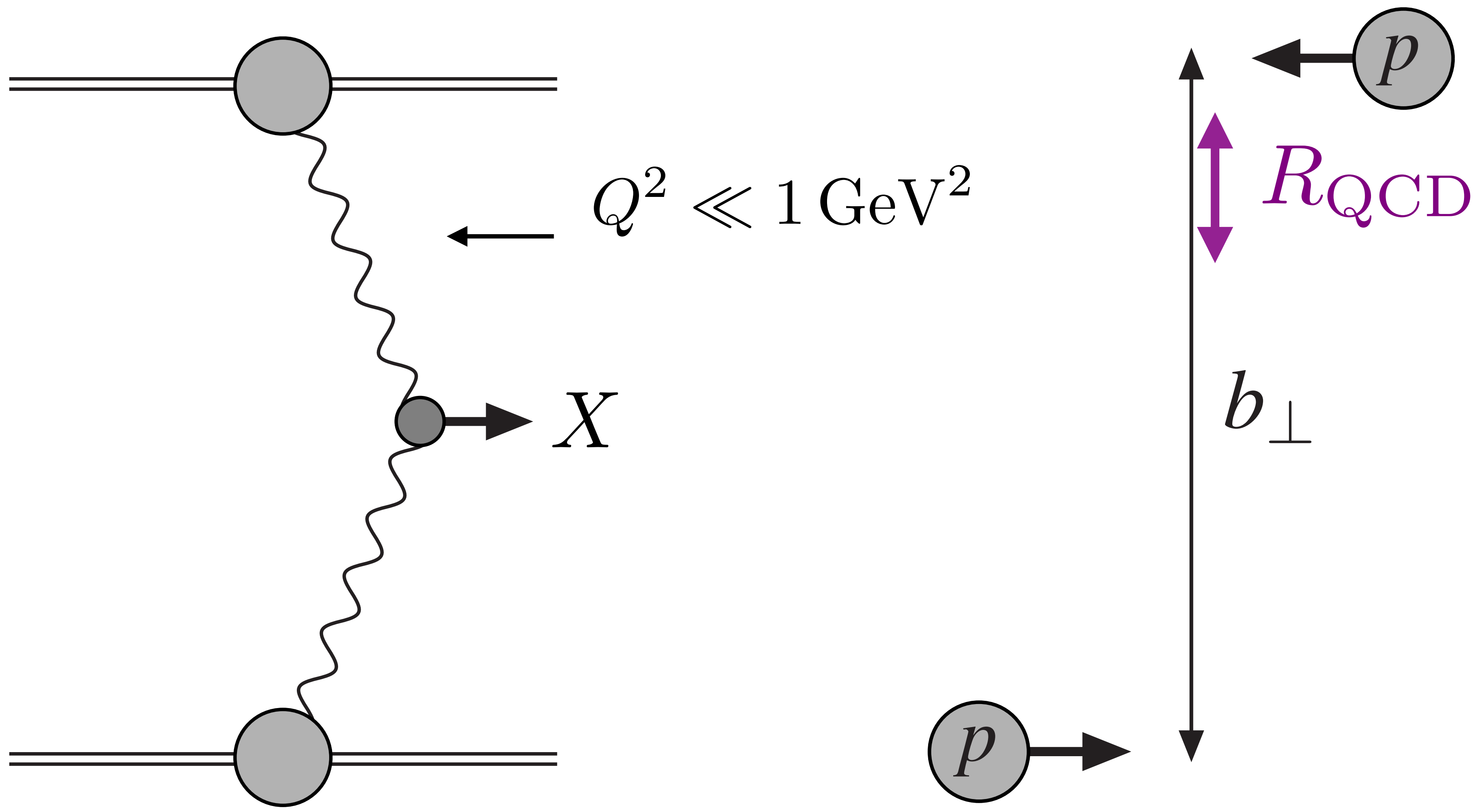
- In general source of **uncertainty**. Is this the case for photon-initiated production?



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

The Survival Factor in PI processes

- 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:

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

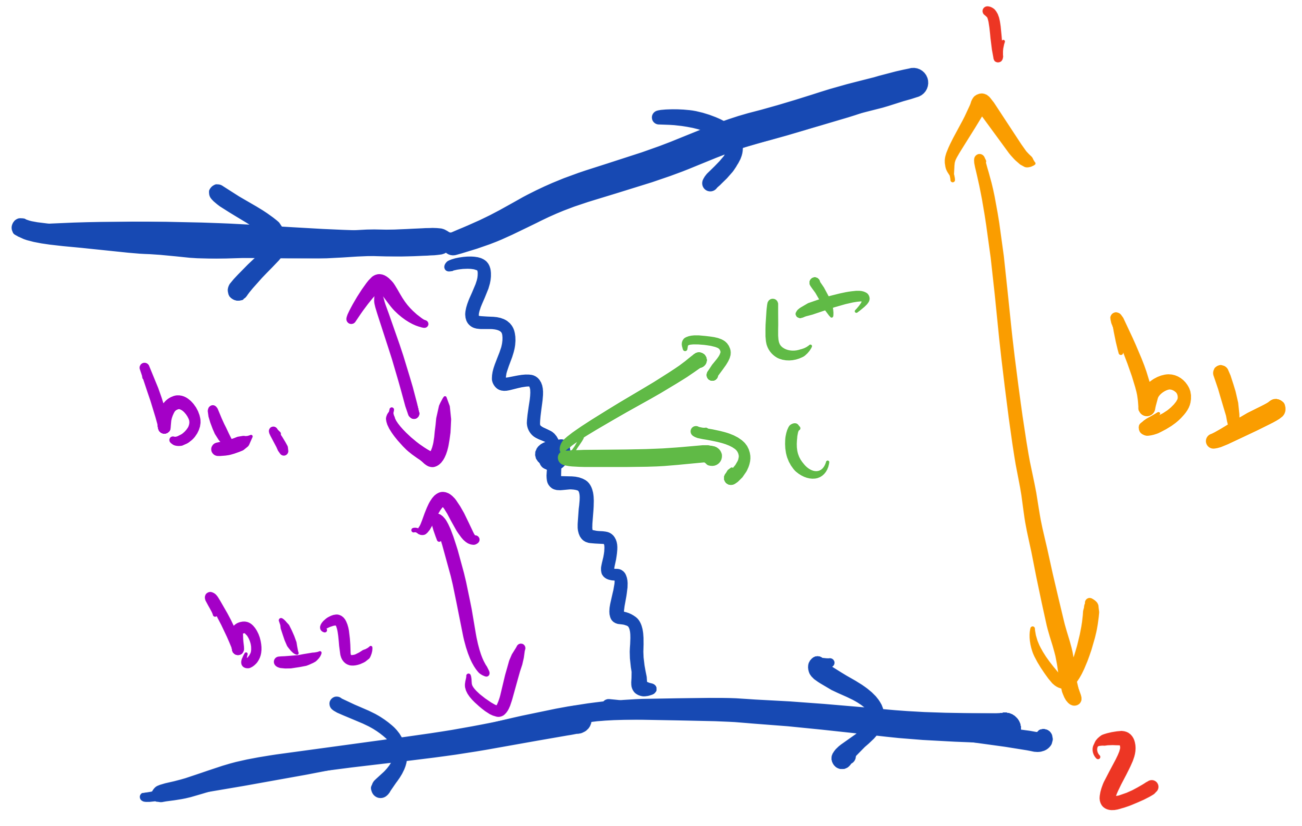
- We can write this as integral over proton impact parameters:

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

- Where:

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

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



- To first approximation, we then simply require:

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

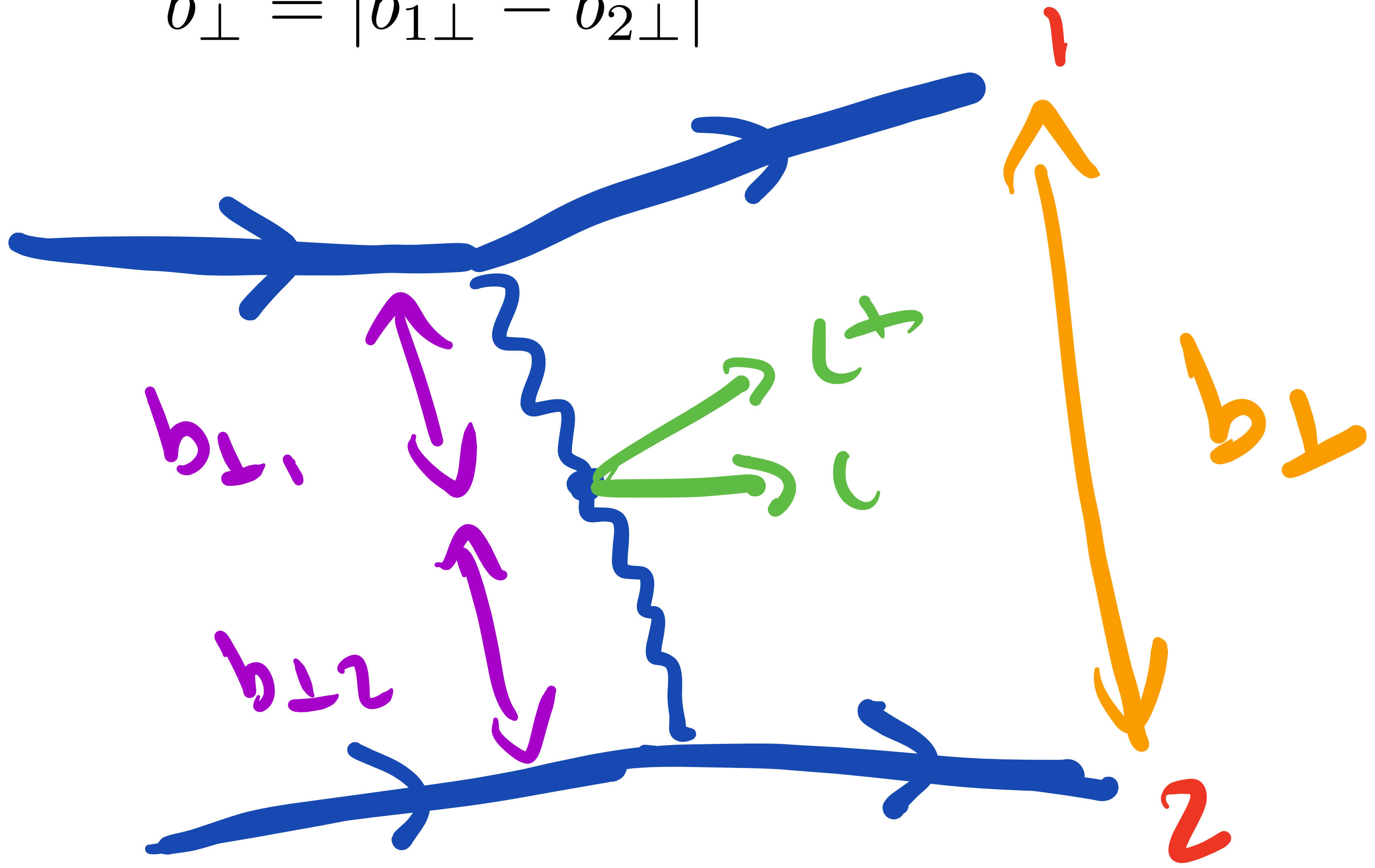
$$\downarrow$$

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

- That is, only integrate over impact region where:

$$b_\perp > 2r_p$$

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



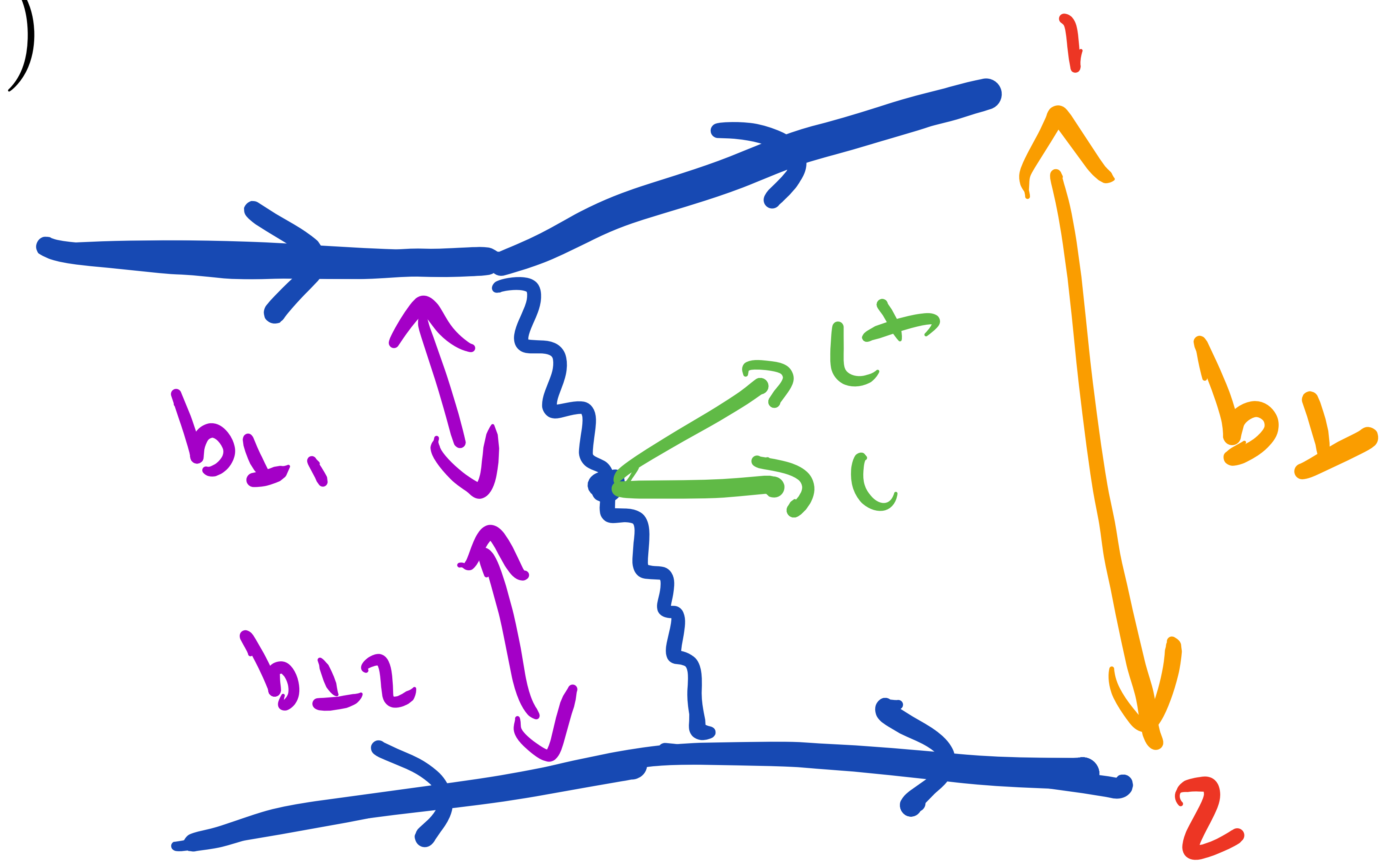
- In more detail, condition is not discrete - some overlap can occur. Schematically:

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

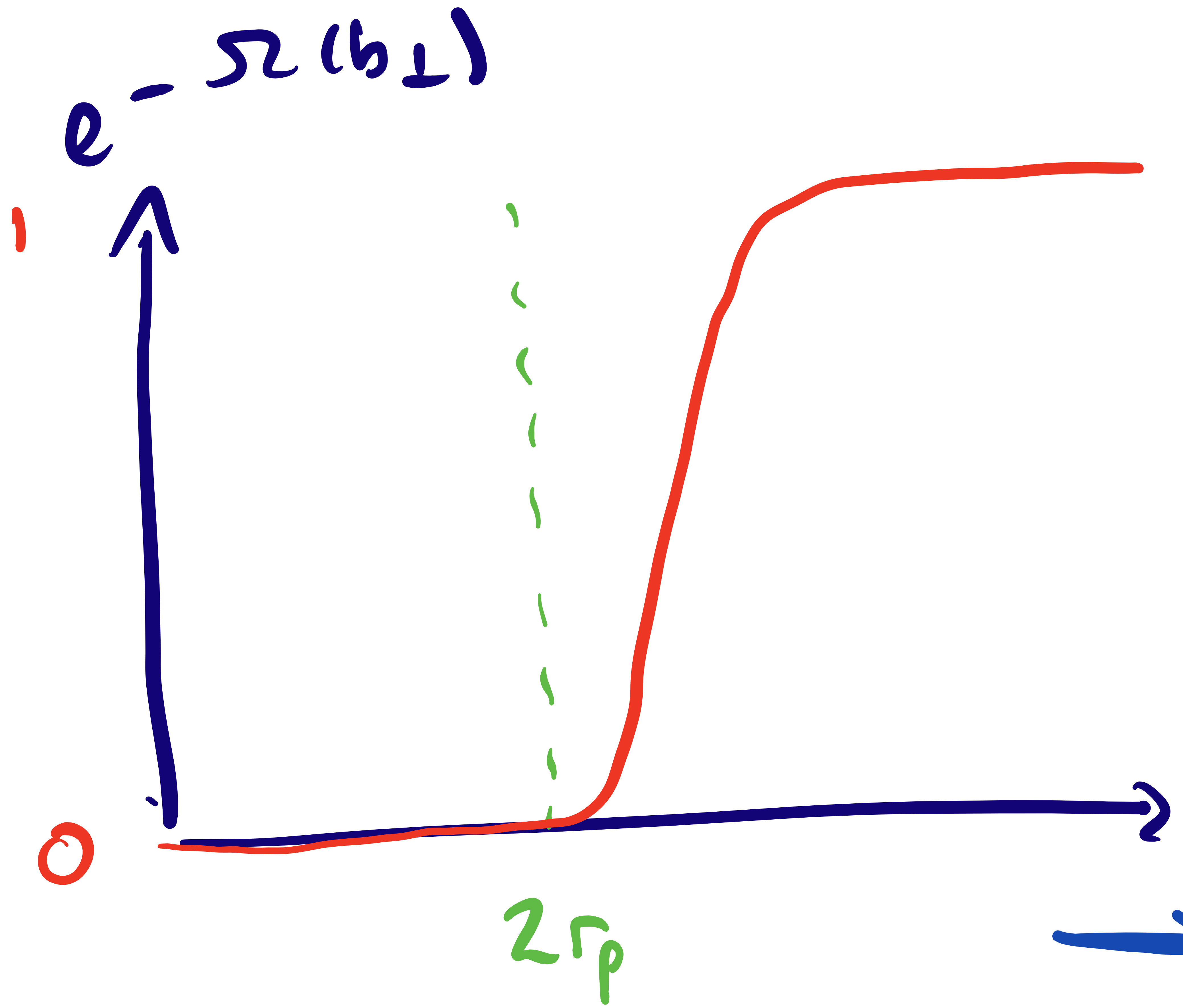
$e^{-\Omega(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}$: **survival factor** - probability for no additional particle production at impact parameter $b_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$. Roughly:

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

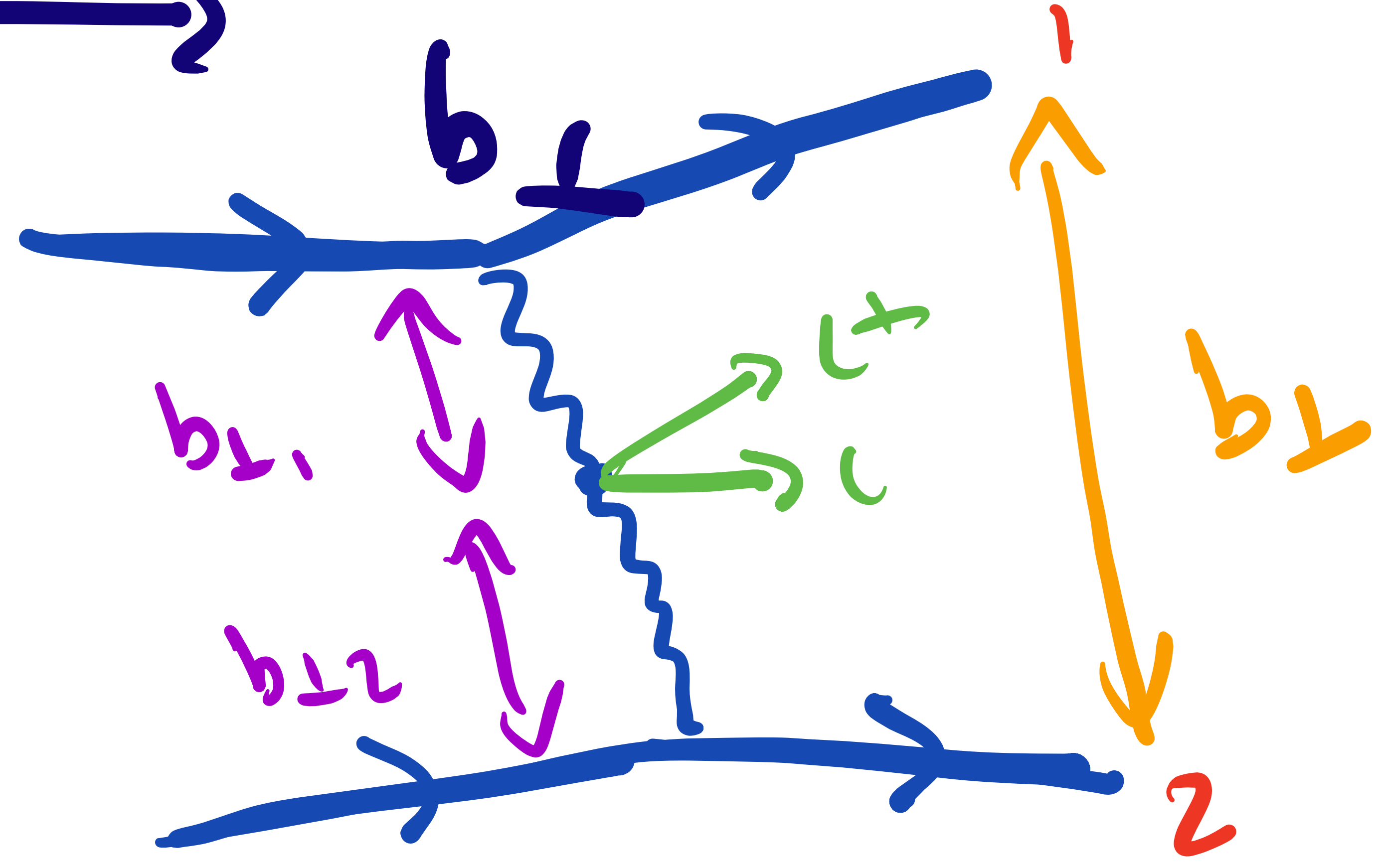
but not exact!



- Result for pp:



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



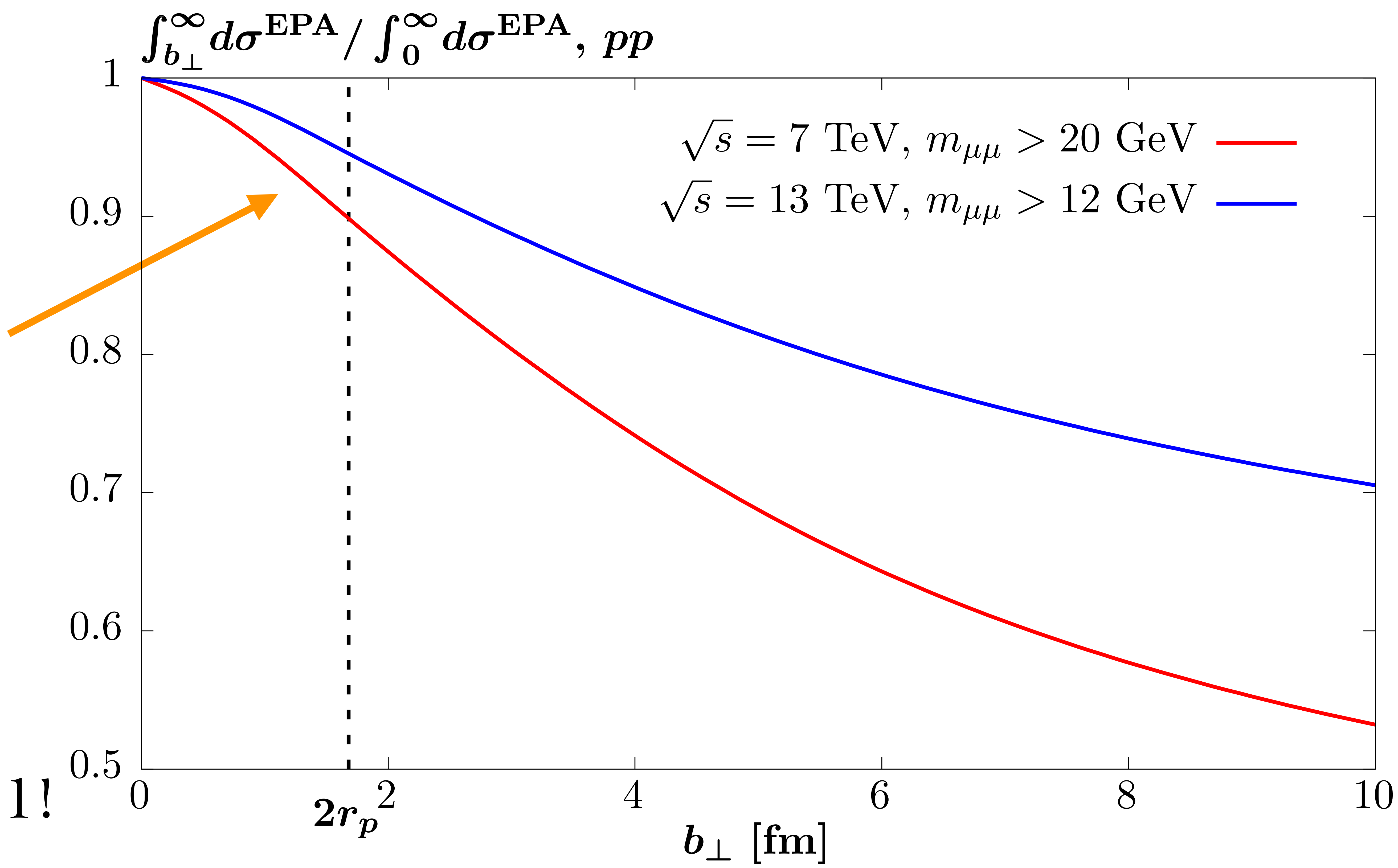
- What does this tell us about survival factor for purely elastic production?

- Have a look at ratio:

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

~ 90% of cross section lies outside

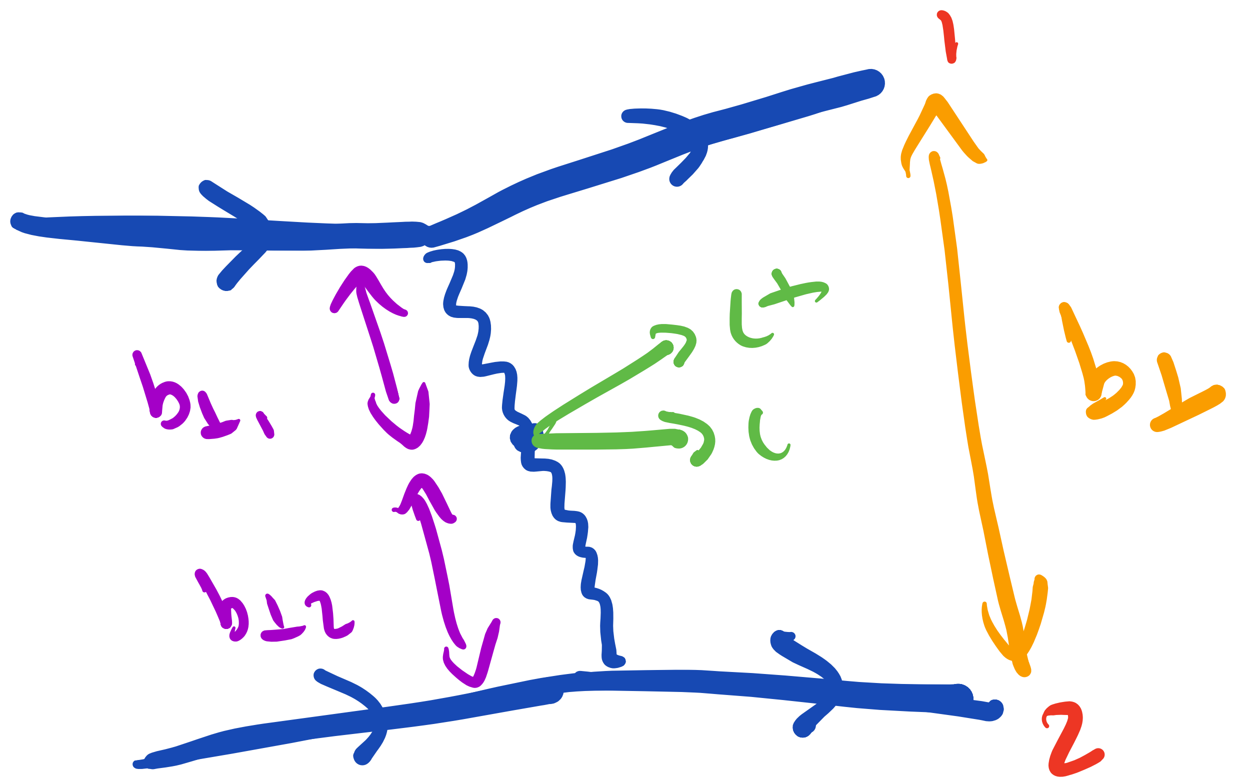
$$b_\perp > 2r_p$$



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

- Depending on precise process/ kinematics have:

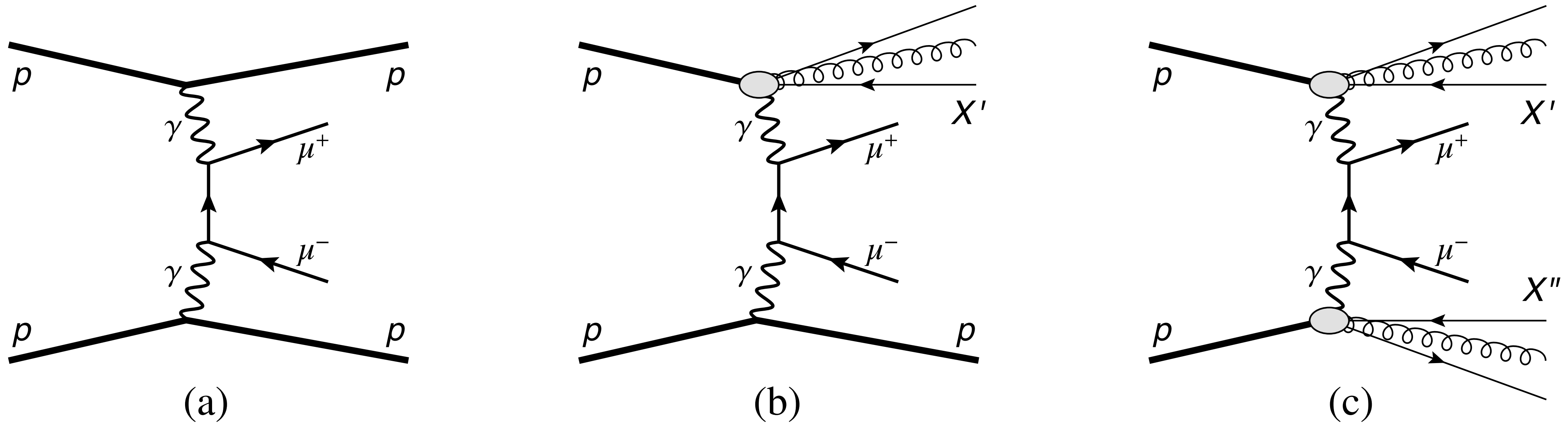
$$S^2 \sim 0.7 - 0.9$$



- What about dissociative production?

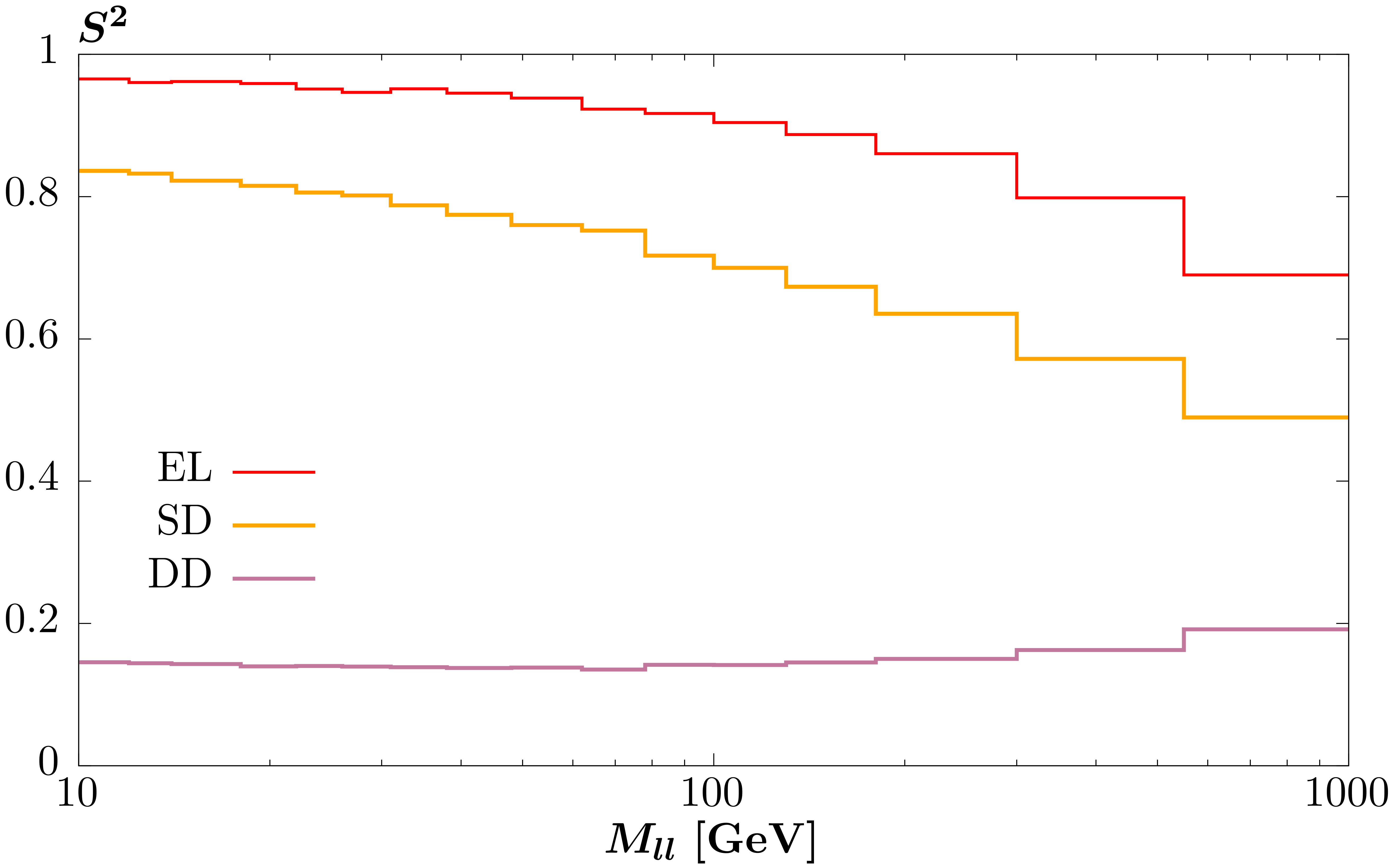
- Dissociation $\Rightarrow$ larger photon Q^2 $\Rightarrow$ smaller pp $b_\perp$ $\Rightarrow$ $S^2 \downarrow$

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



- For DD no longer case and

$$S^2 \sim 0.1$$

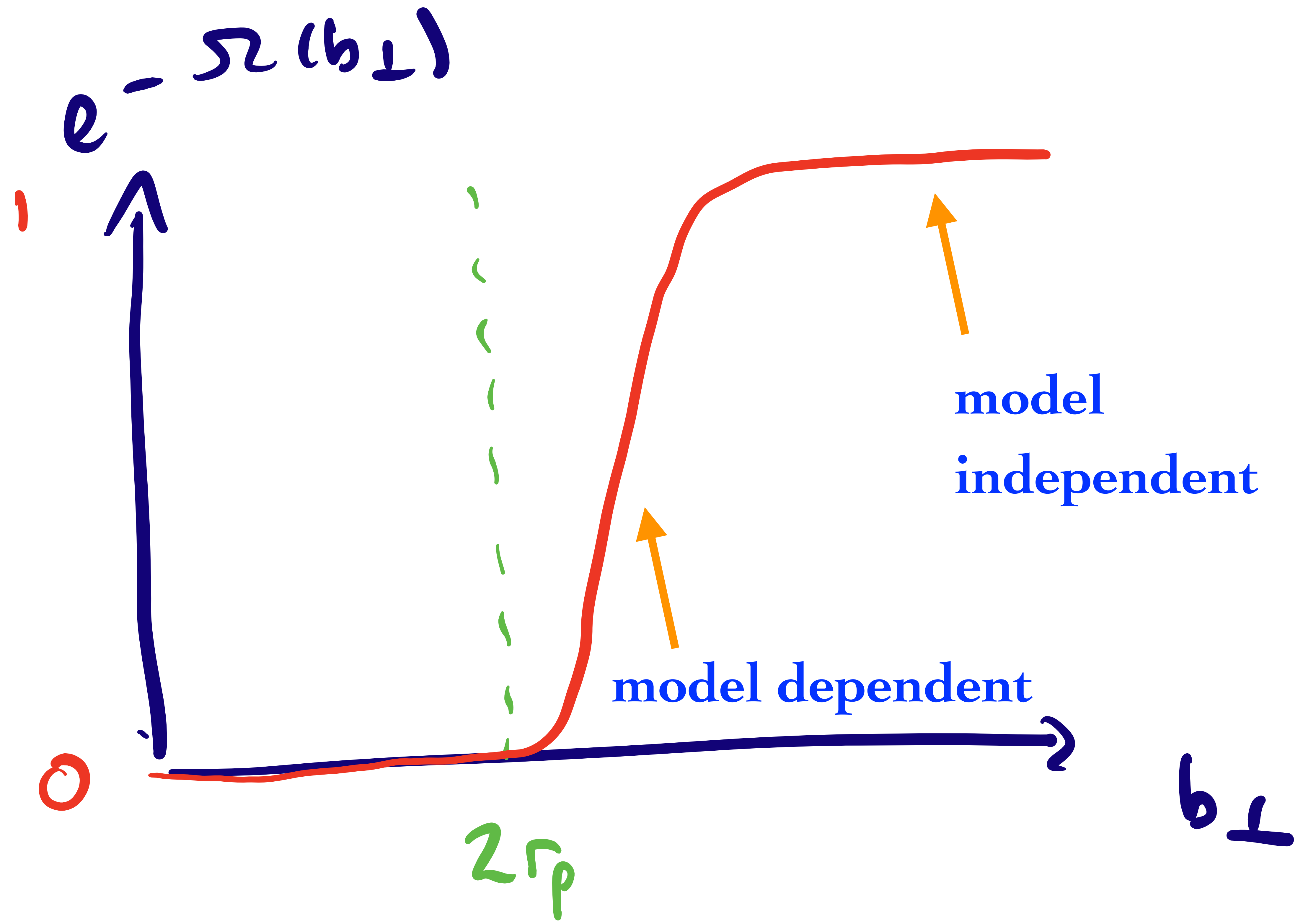


lepton pair production

- 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 - 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

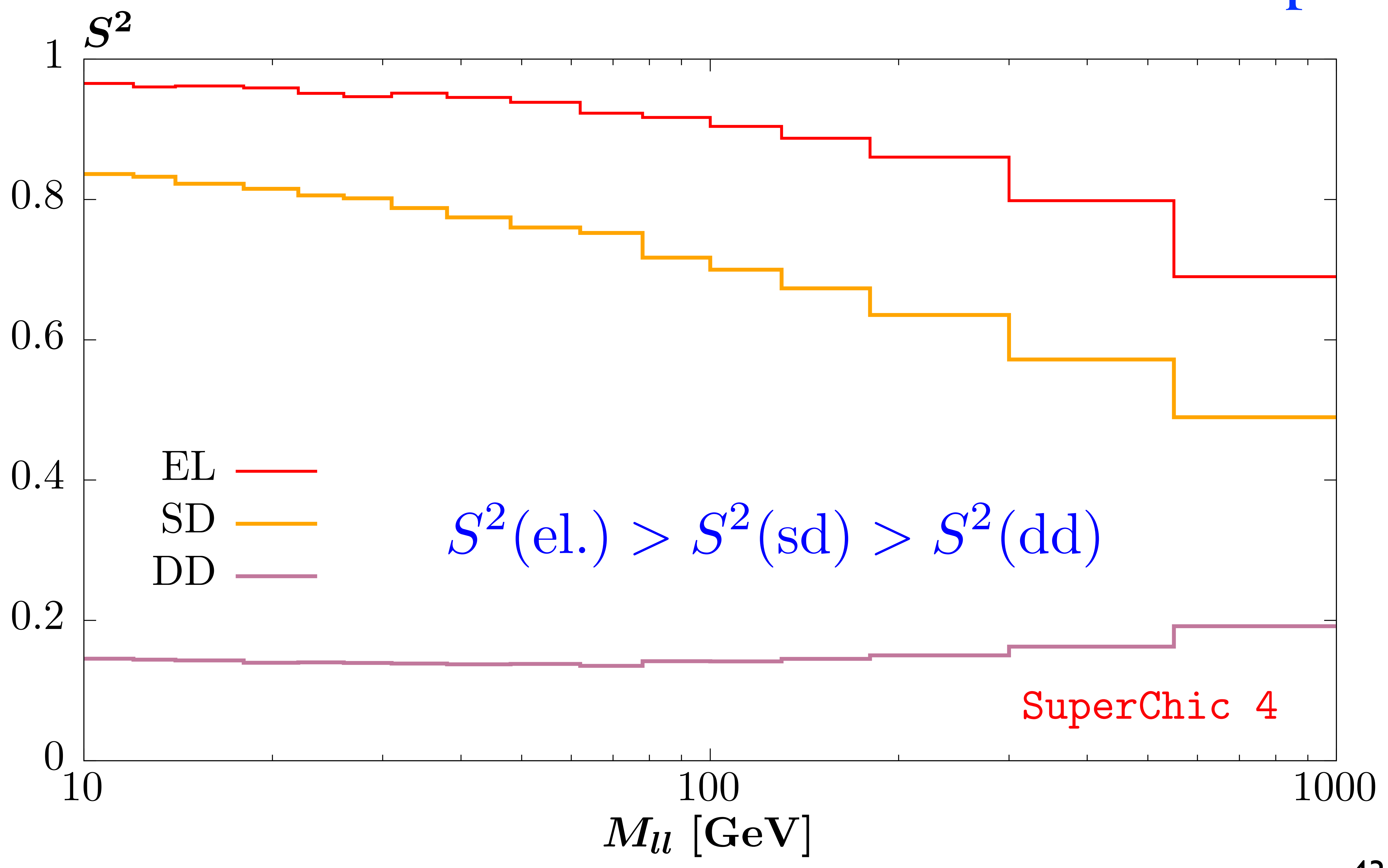
- NB: this process dependence is often (incorrectly) omitted in literature

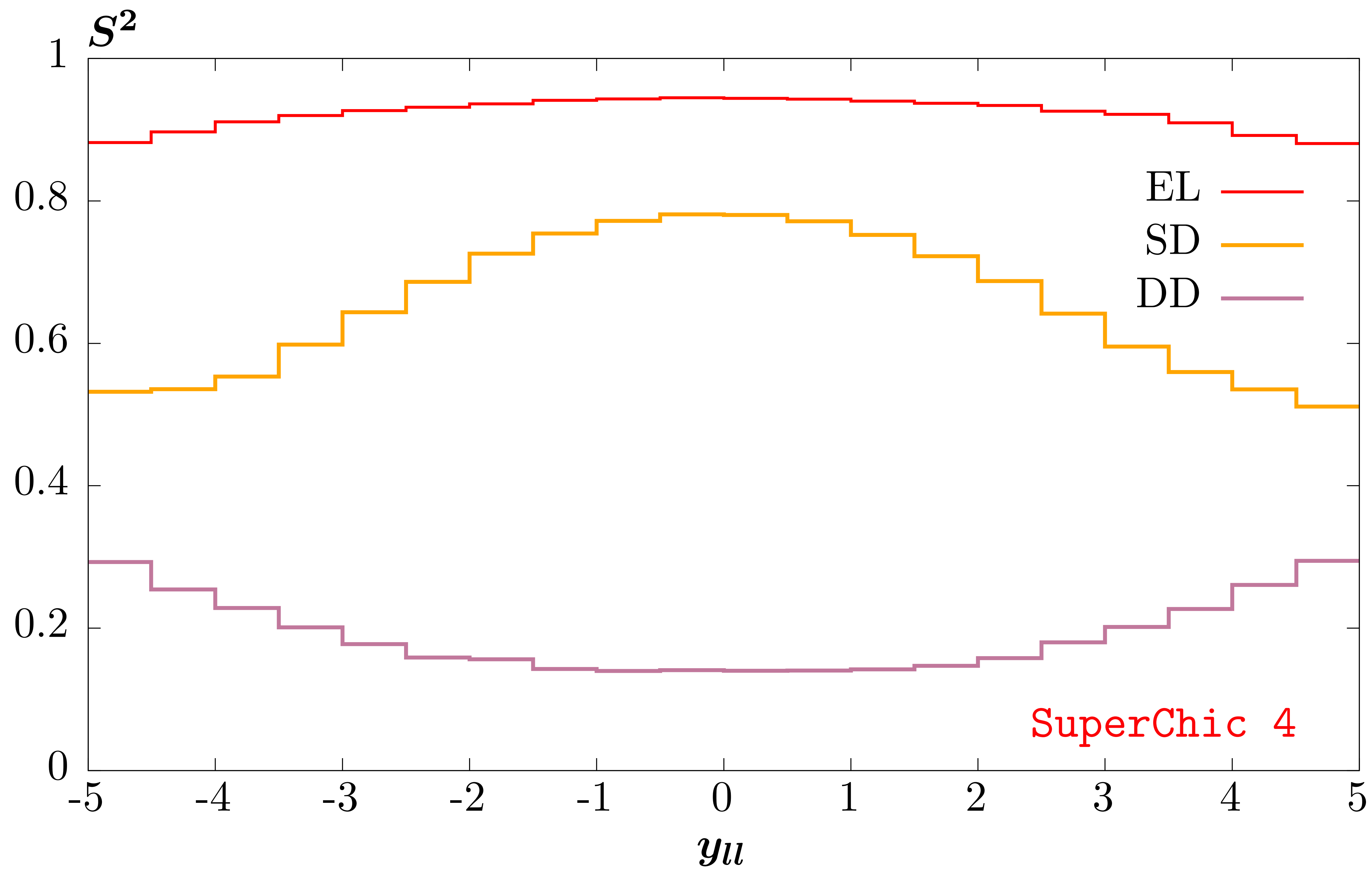
Results

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

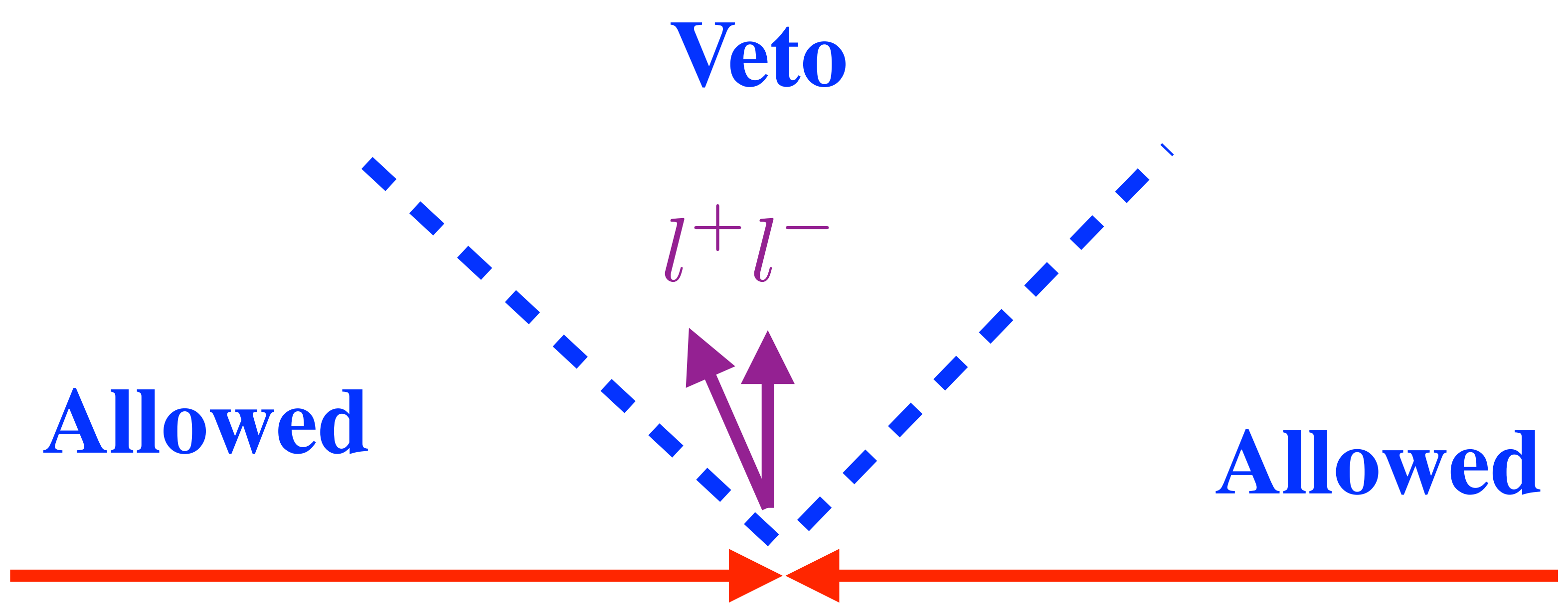
- Dependence on kinematics (e.g. y_{ll}, m_{ll}) also evident.

lepton pair production

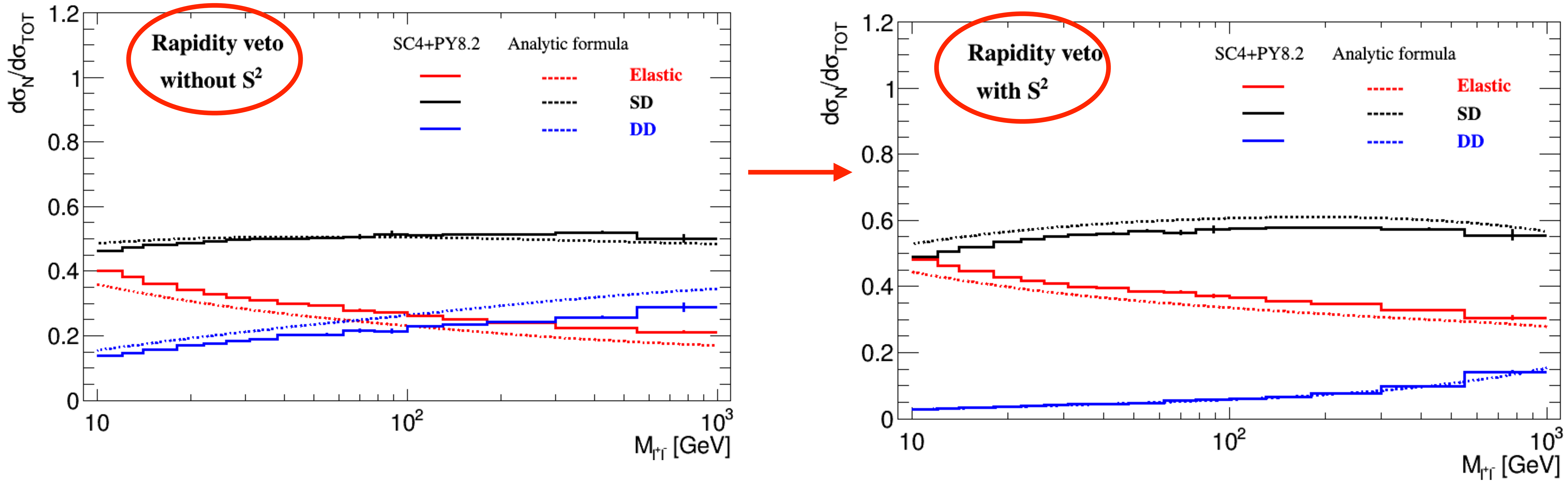




Veto Impact



- MC generation allows us to assess impact of rapidity veto on cross section and different (EL, SD, DD) components.

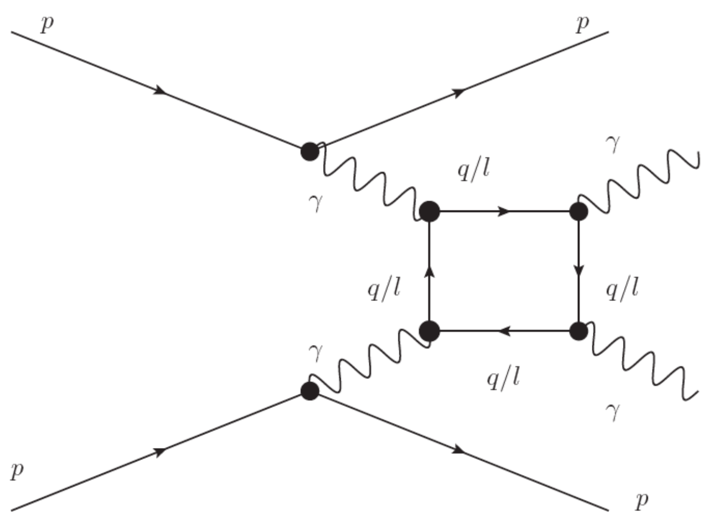


★ **Veto** : strong suppression in DD. Elastic and SD comparable at lower m_{ll} , SD dominant as m_{ll} increases.

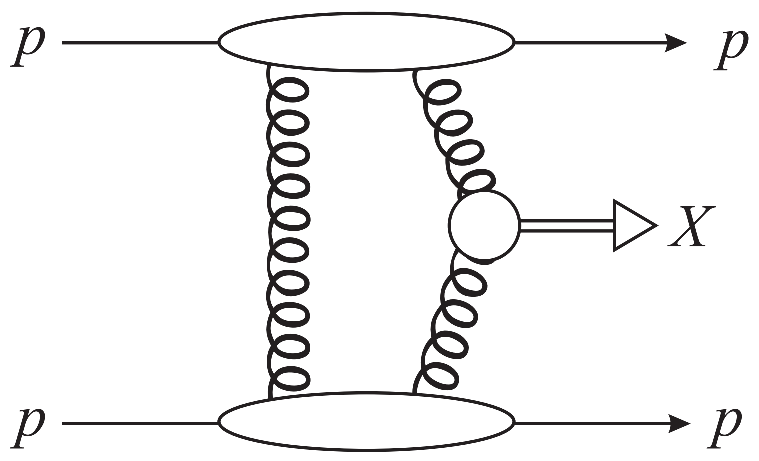
★ **Proton tagging** : single tag removes DD and double tag gives pure EL.

SuperChic MC Implementation

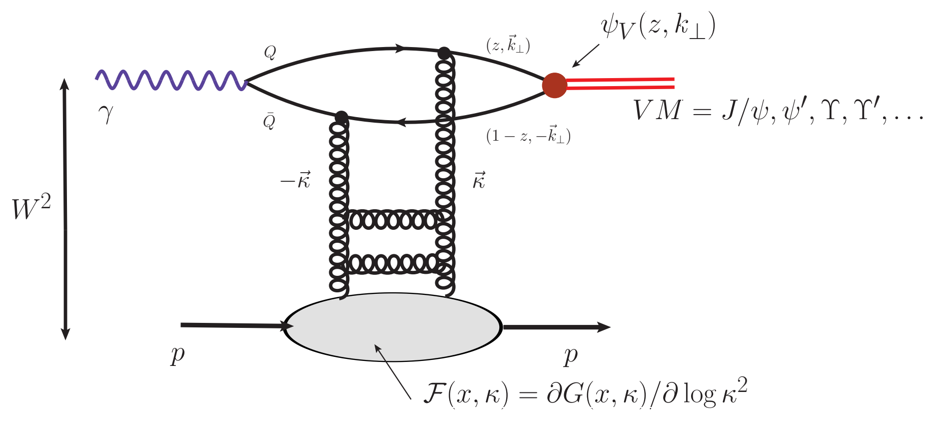
- A MC event generator for CEP processes. **Common platform** for:
  - QCD-induced CEP.
  - Photoproduction.
  - Photon-photon induced CEP.



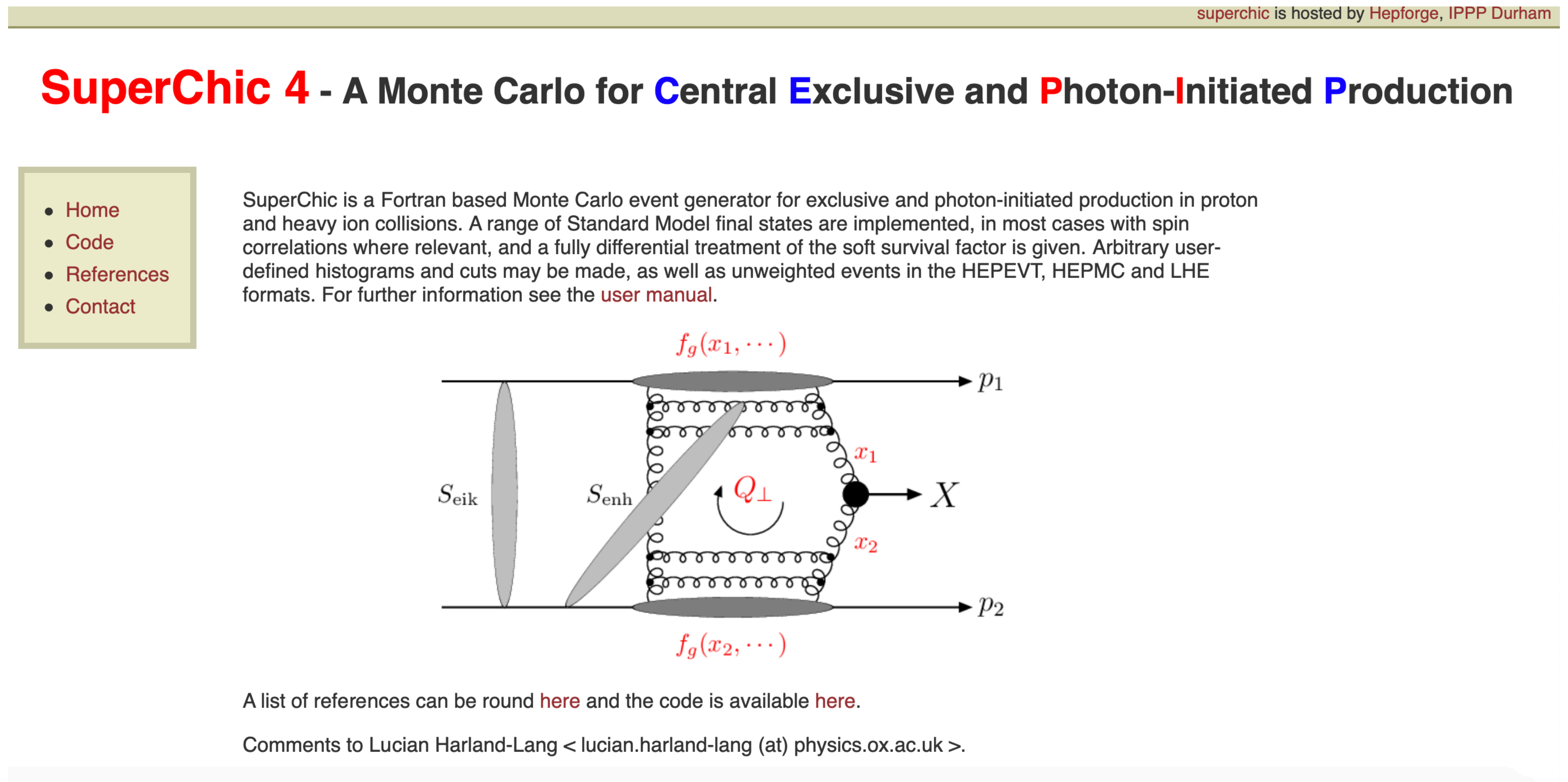
Photon-induced



QCD-induced



Photoproduction



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

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

SuperChic 5 - MC Implementation

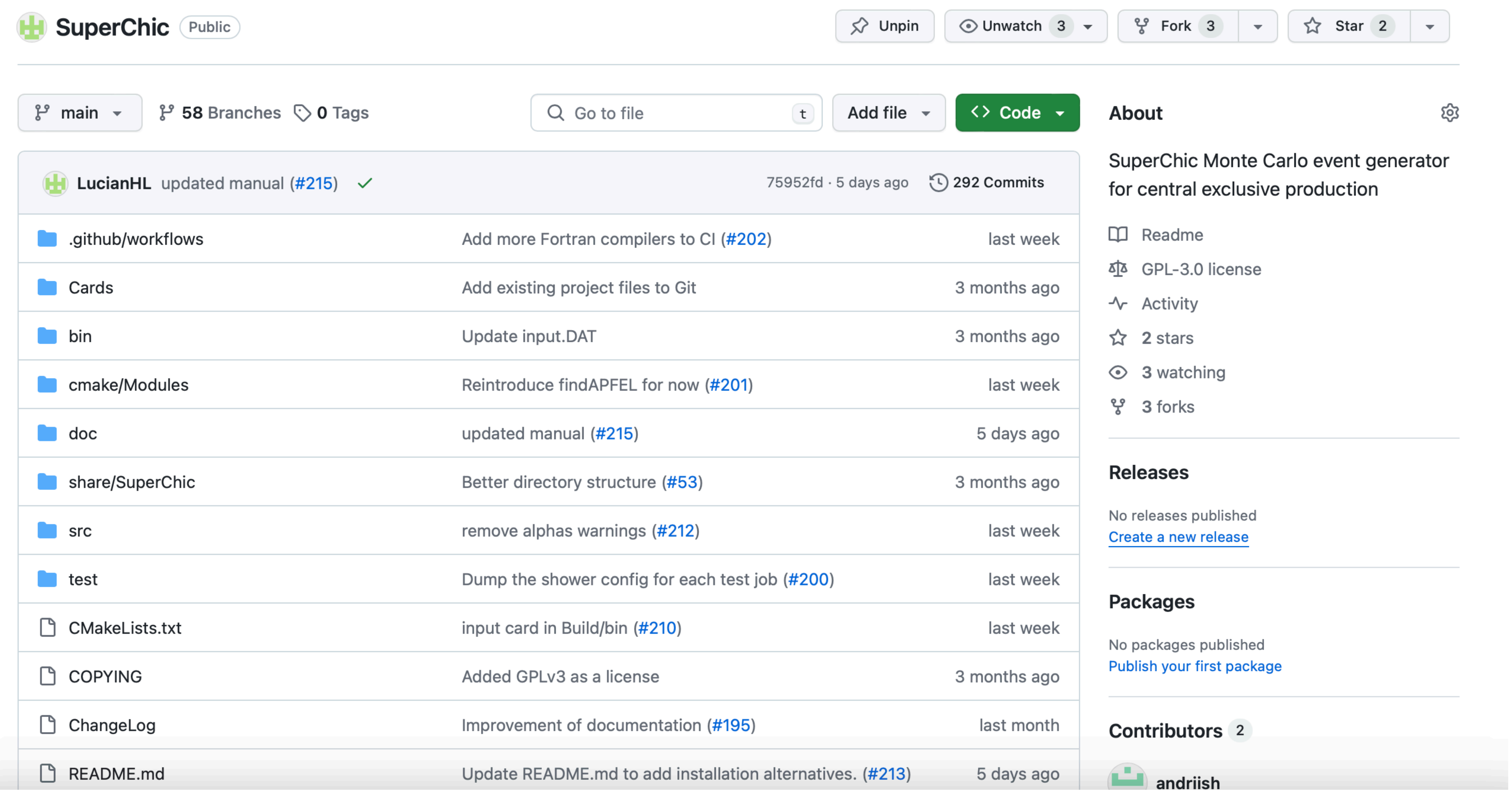
- Version 5 now released. Significant updates to code:

★HepMC output now properly supported.

★Full testing suite added + cmake build system.

★Various bug fixes + code improvements.

★ Future releases will be via github. Collaboration/PRs welcome!



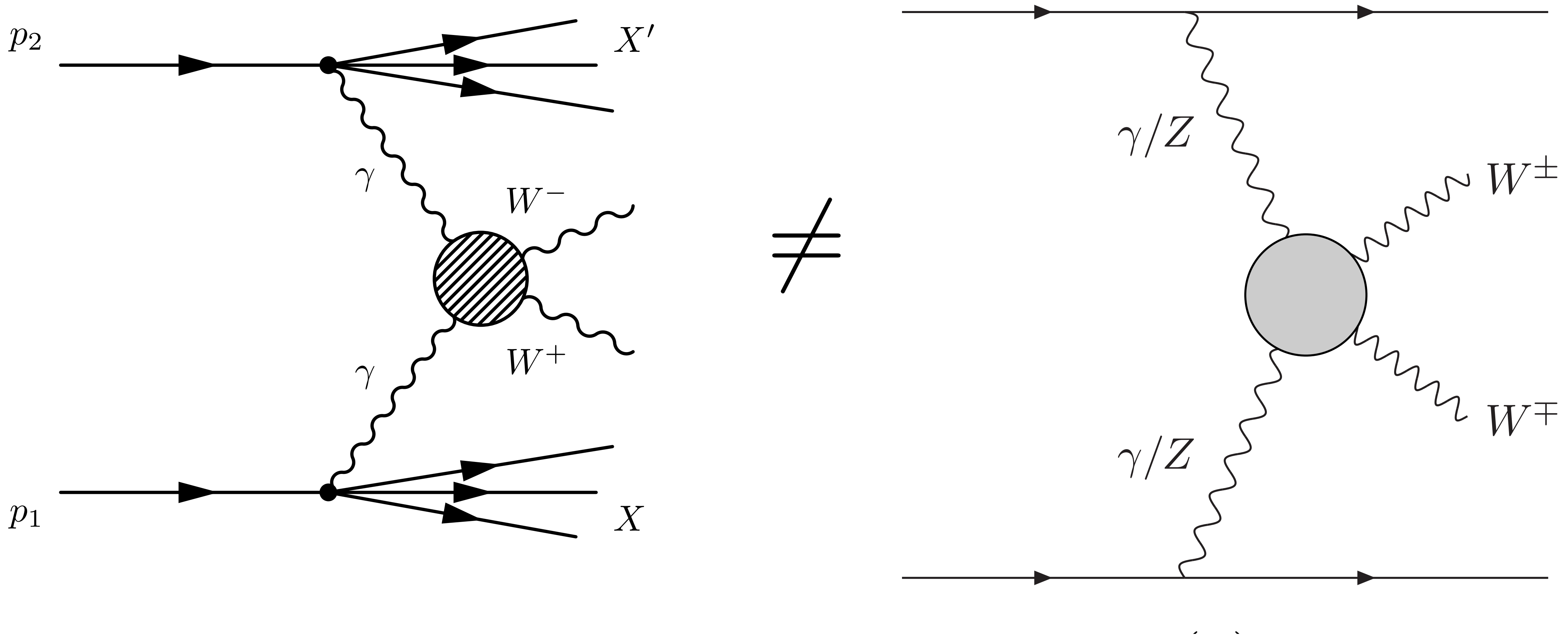
`https://github.com/LucianHL/SuperChic`

Where do we stand? Comparison to Data

WW production

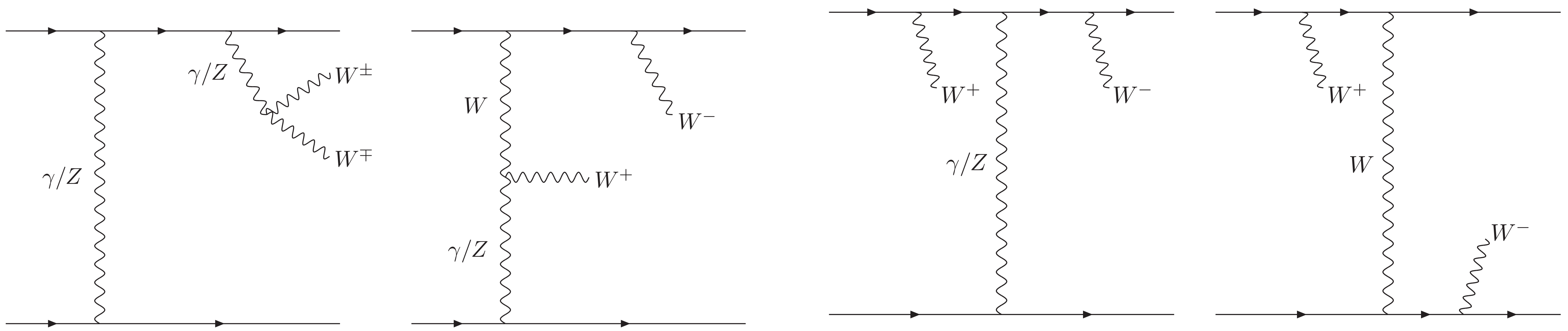
S. Bailey and LHL,*Phys.Rev.D* 105 (2022) 9, 093010

- Basica idea: ask for no activity to isolate semi-exclusive $\gamma\gamma \to WW$ signal.
- Only recently been fully understood. If both protons tagged we would isolate this alone. But otherwise non photon-initiated diagrams will enter

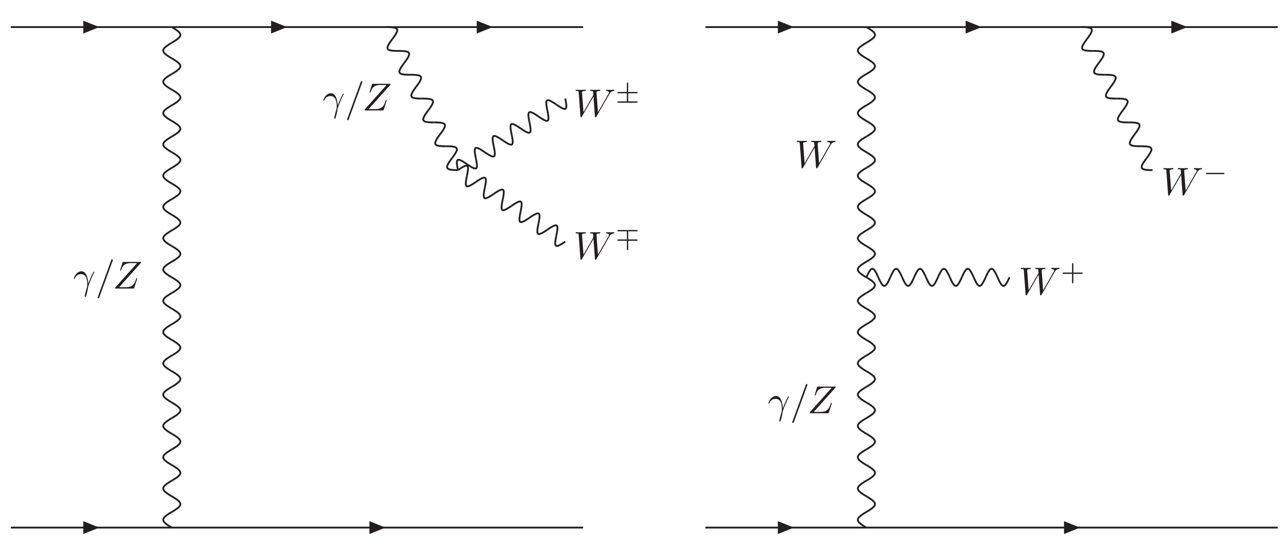


Alone!

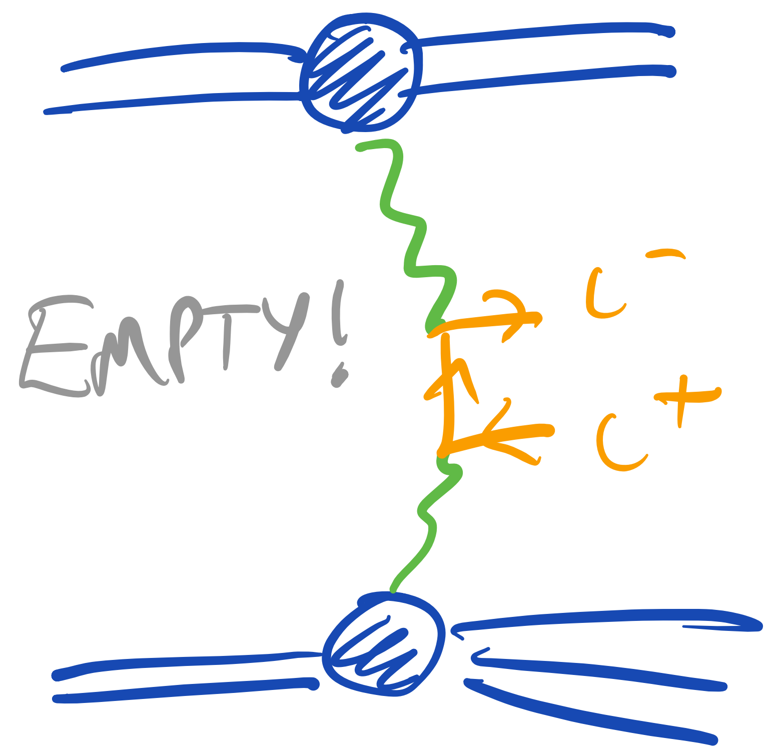
- Must include other diagrams:



- To get SM cross section right, need to include:
  - ★ All contributing diagrams (not just photon-initiated for SD and DD).

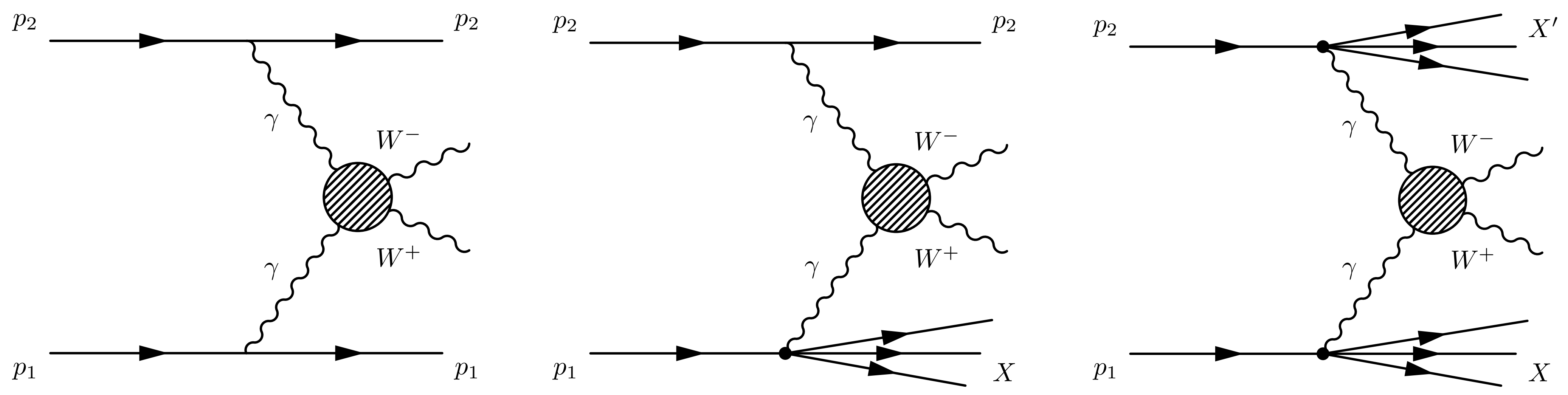


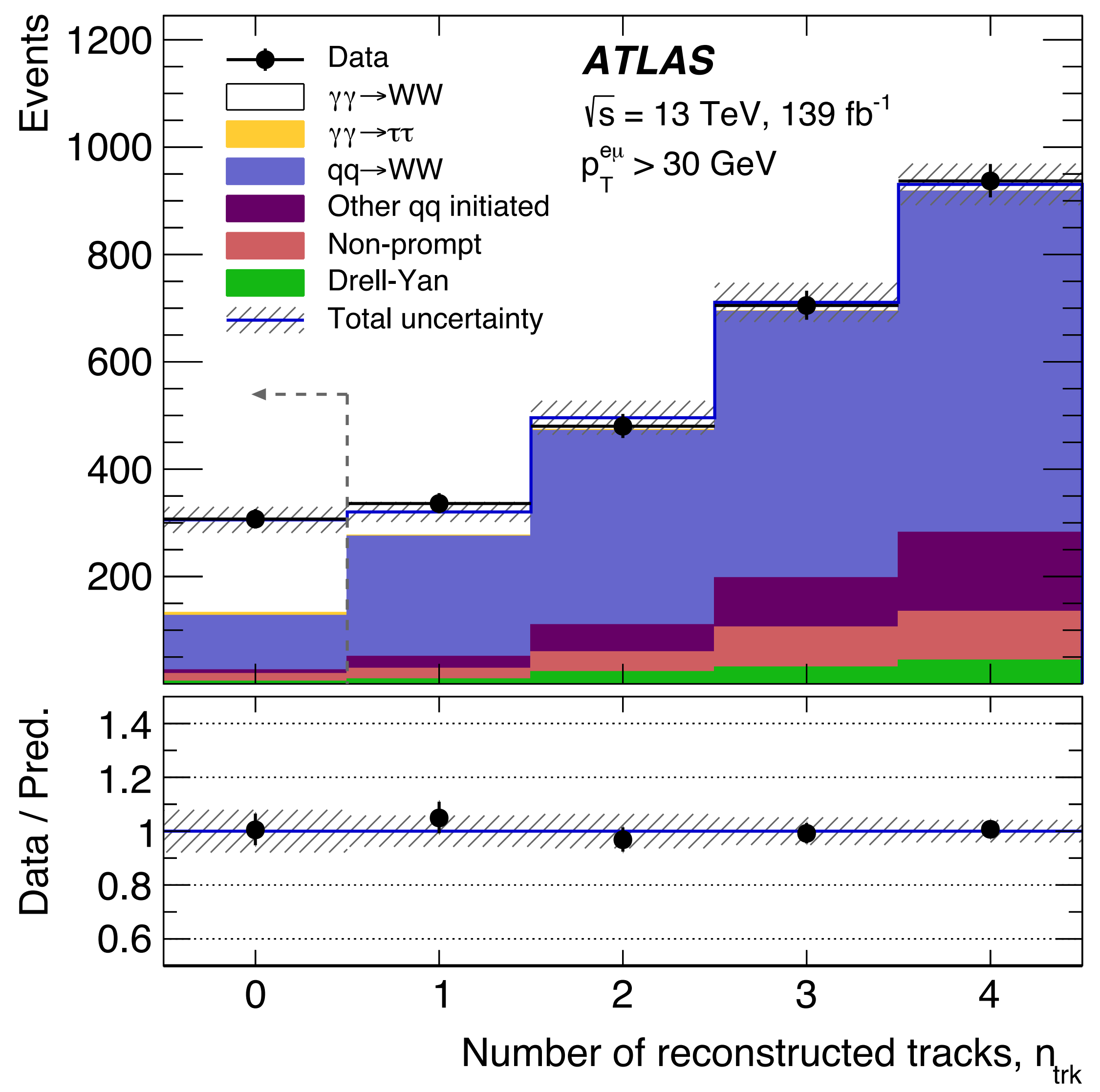
★ Survival factor



★ MC treatment - impact of veto on EL/SD/DD.

- First observation of semi-exclusive WW production by **ATLAS**, at 13 TeV, via rapidity veto.





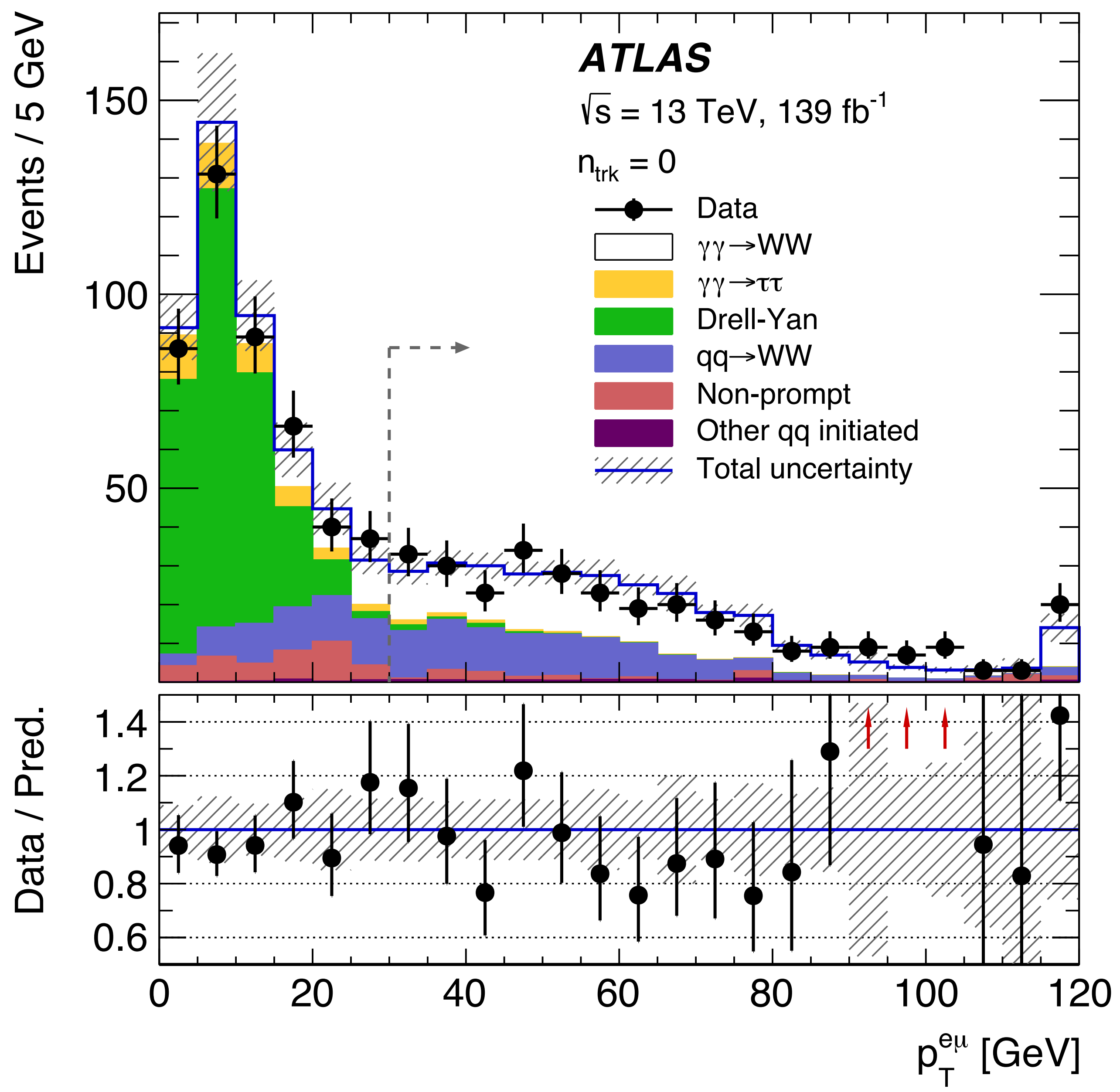
- All channels enter, and full treatment as above needed to match data!

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

- Find:

σ [fb] (σ_i/σ_{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: $\sigma_{meas} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})$ fb $\Rightarrow$ **Very good agreement!**
- Assuming relative SD + DD to EL components are as in e.g. dilepton production would miss contribution from non-PI diagrams - undershoot data by ~ 20%.
- Looking to the future. Go beyond one number and look at distributions - EFT analyses.
- Will require full treatments of subtleties described above - survival factor, non-PI diagrams etc all modify distributions! Much to do…



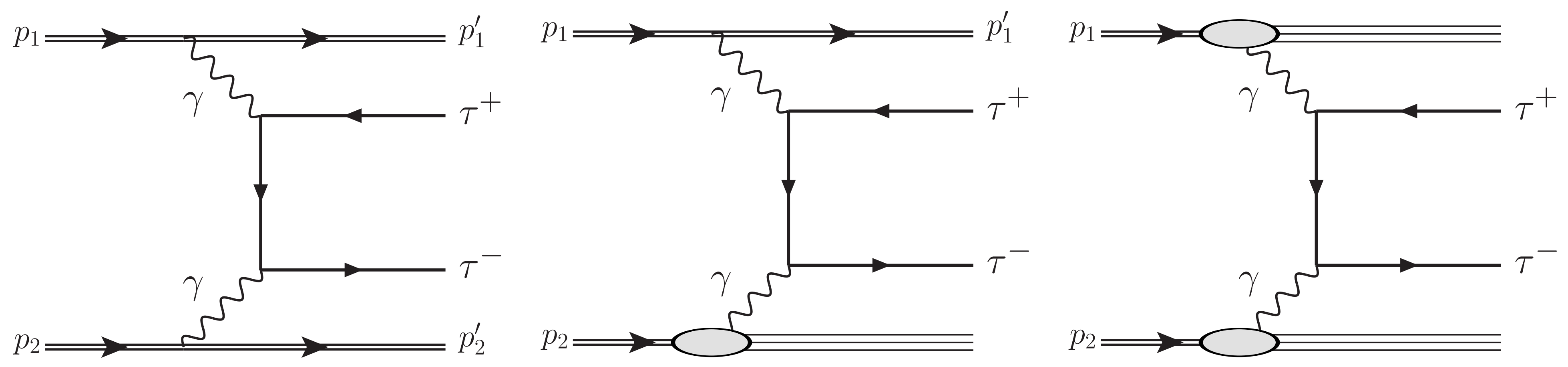
Exclusive tau pair production

CMS, SMP-23-005-PAS

- Recent first measurement of exclusive tau lepton pair production in pp by CMS, following data in PbPb by ATLAS/CMS.

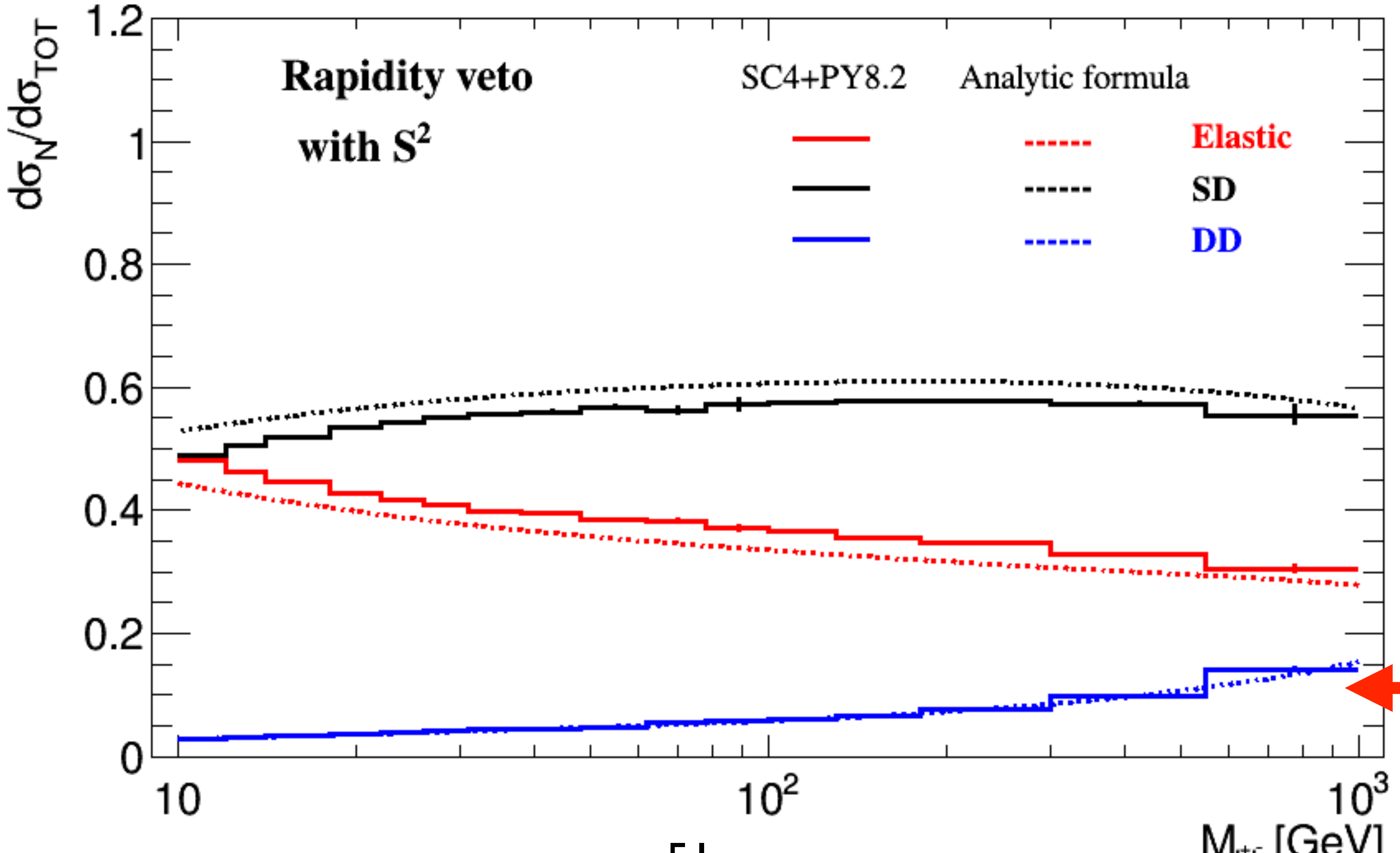
$e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h, \mu\mu$

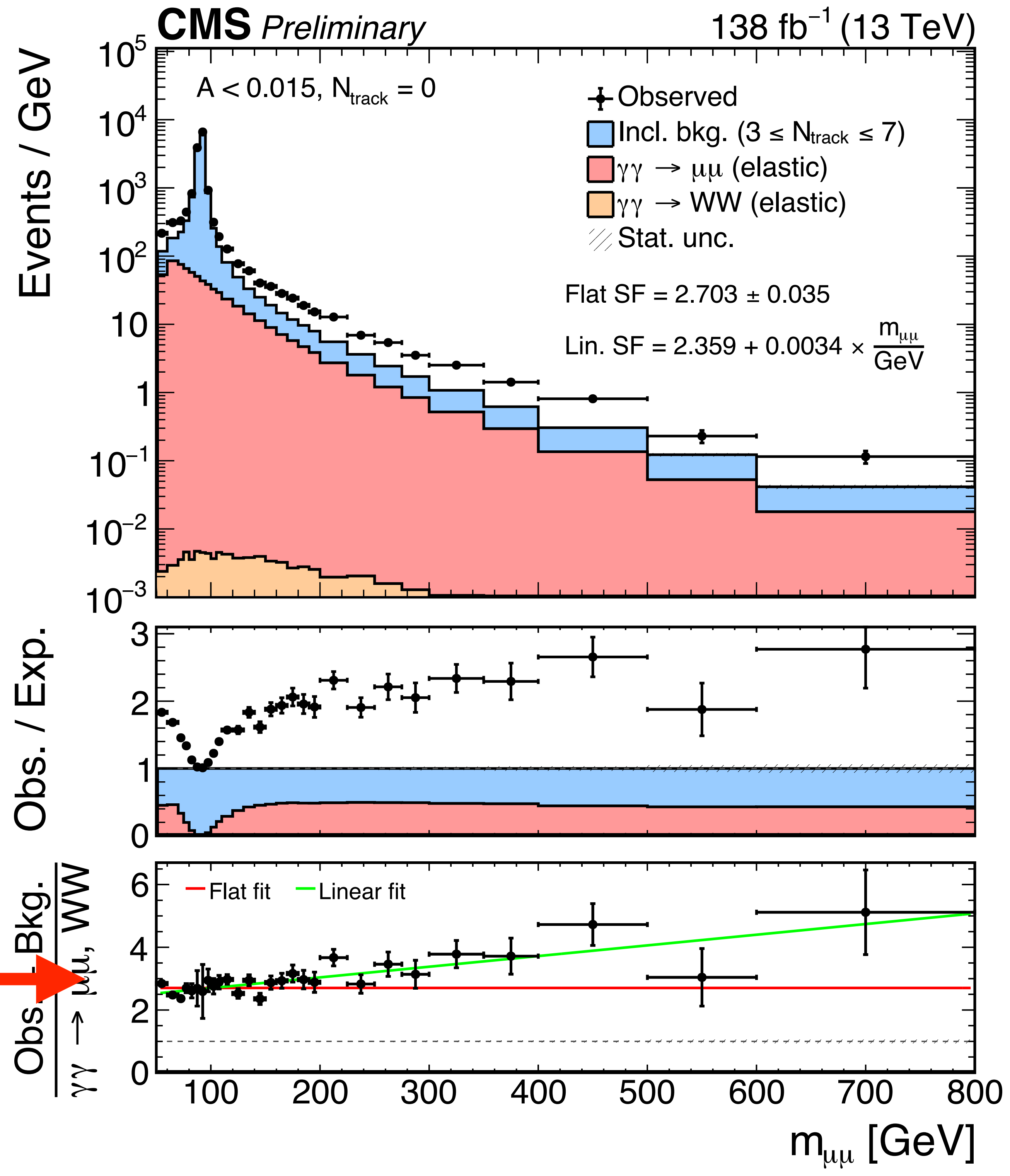
- As with ATLAS WW, selected via rapidity veto - no tagged protons. All components enter:



- Leptons somewhat simpler than W boson in SM, but complete modelling still essential here.

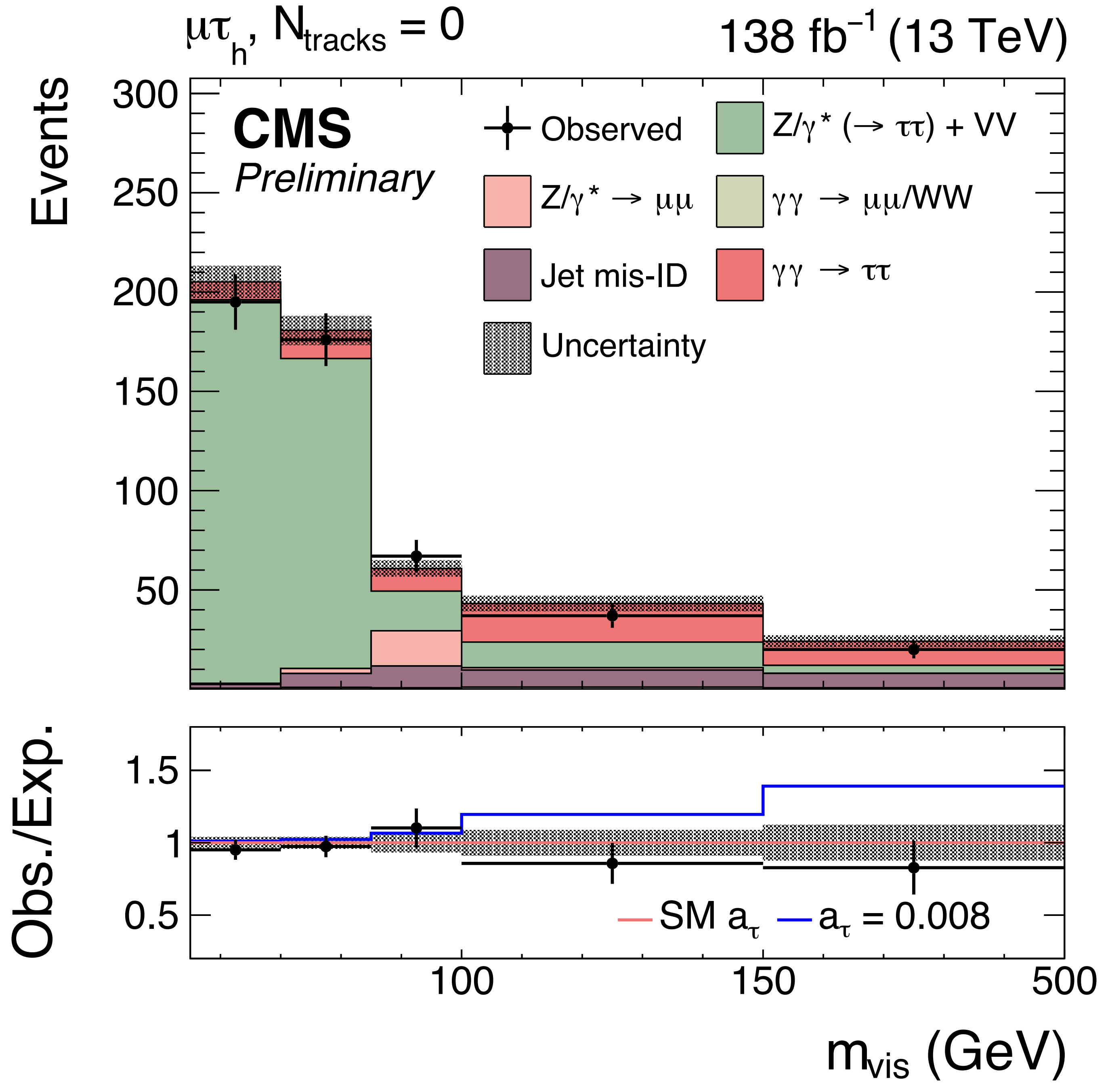
- Sizeable SD + DD contribution, in particular at higher masses (in line with expectations).

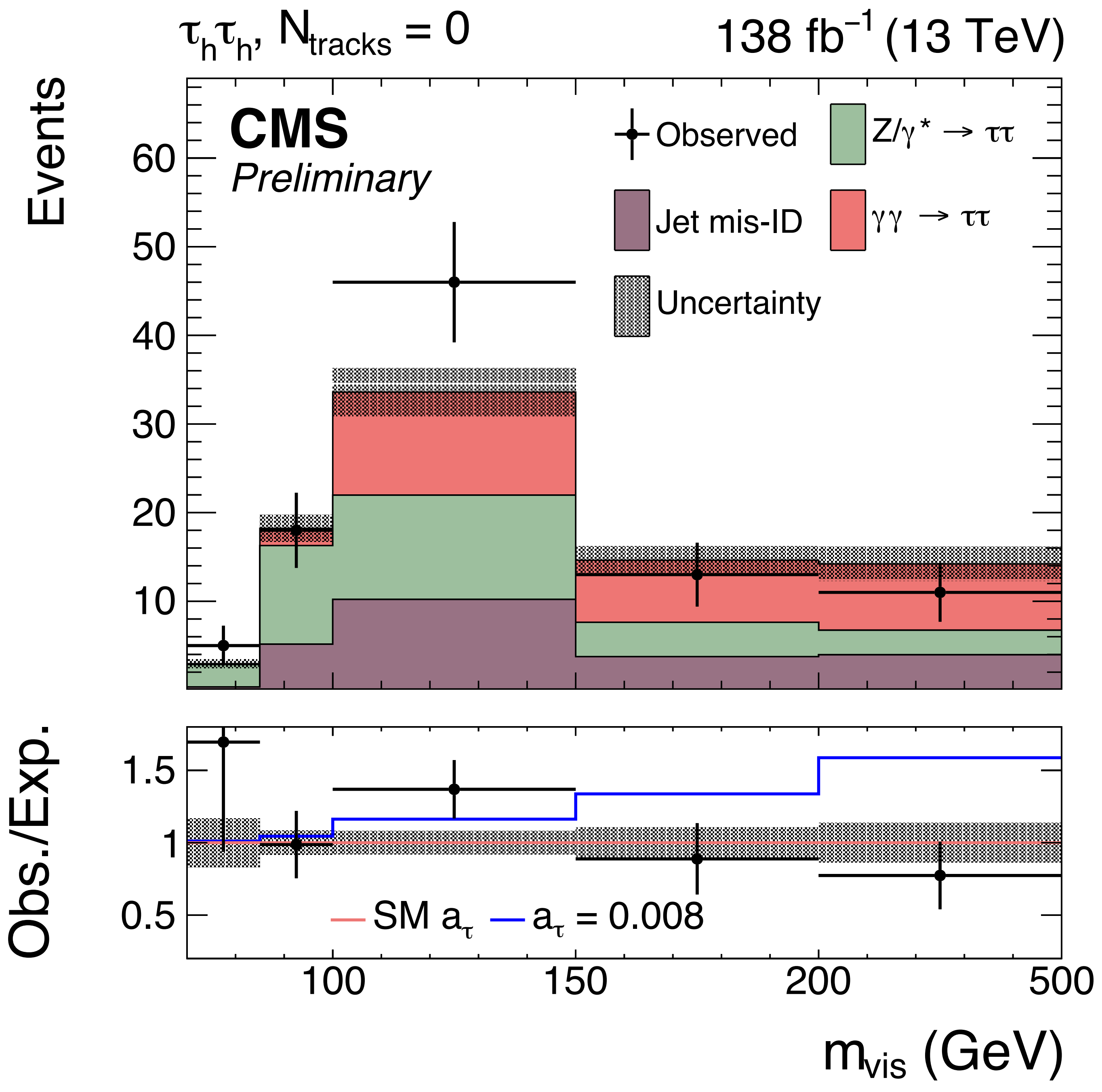


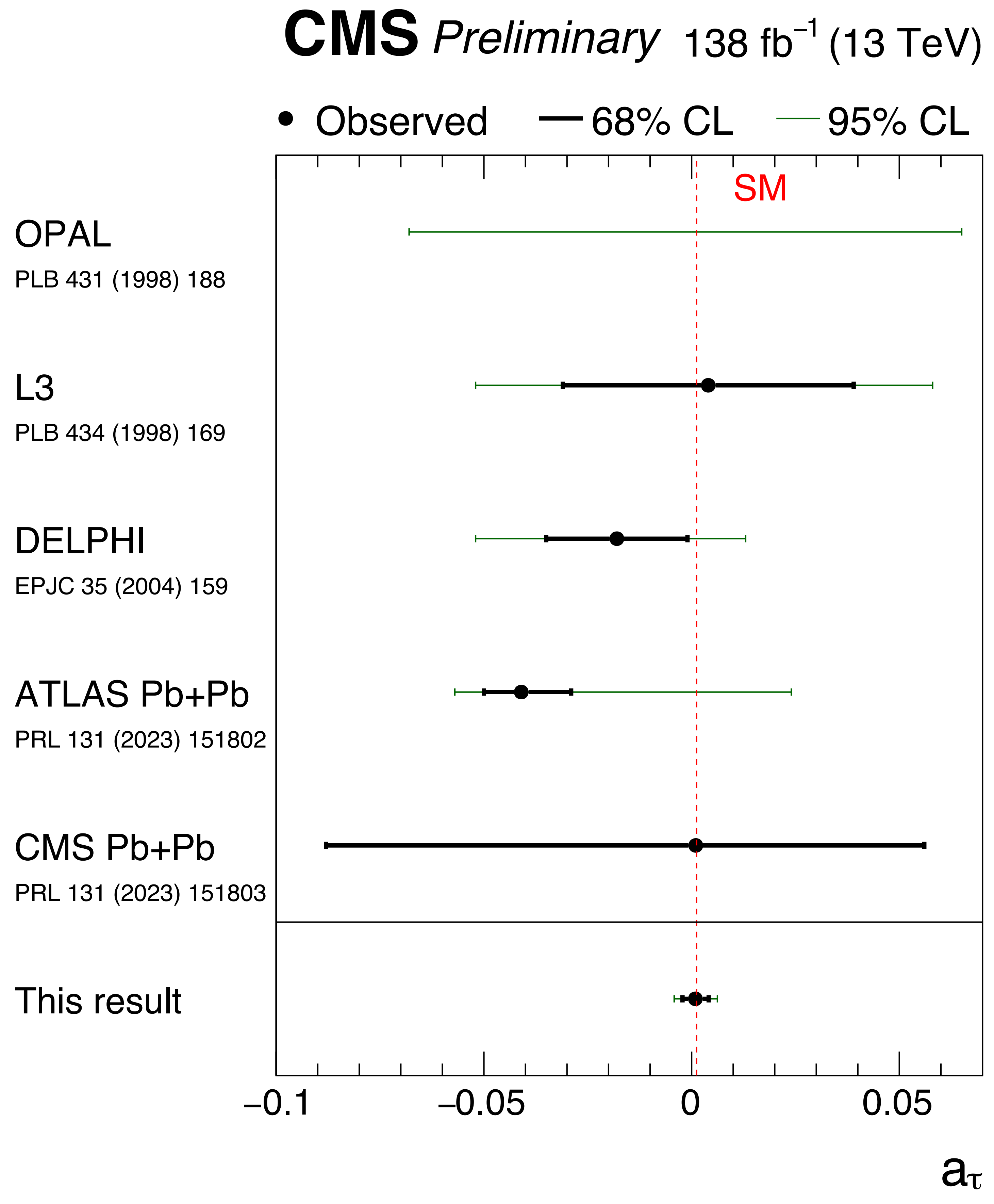


Exclusive tau pair production

- Data agrees well with SM expectation $\Rightarrow$ set limits on anomalous value of tau g-2.
- Sensitive to normalisation (ratio to $\mu\mu$) and shape of distributions.



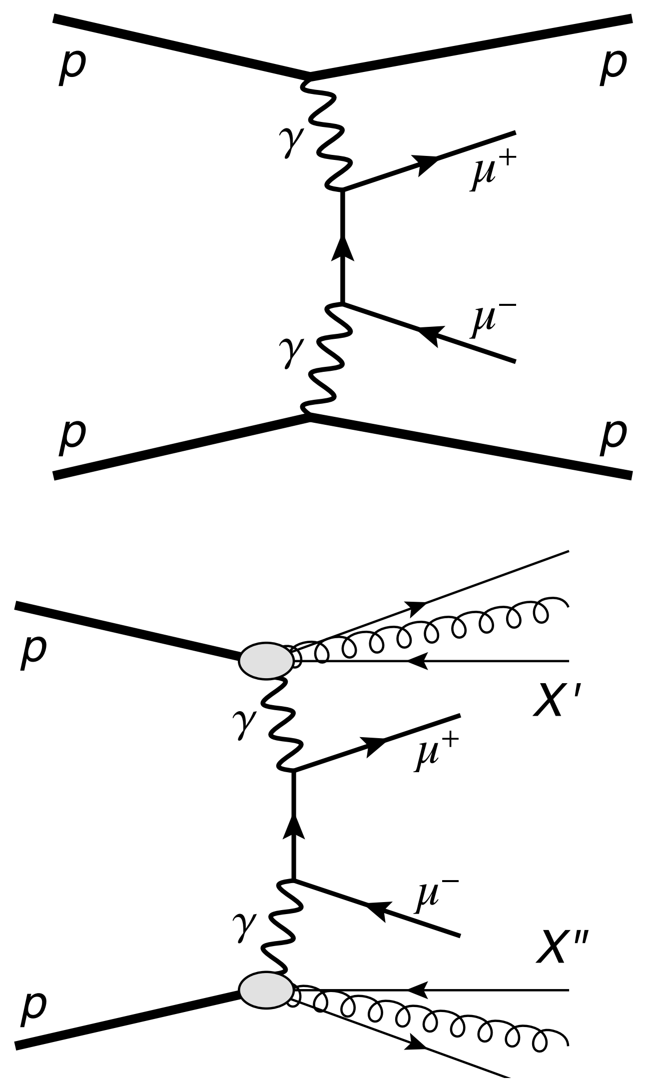




- As discussion before makes clear, to get this right need a proper handle of relevant elements (veto efficiency, survival factor…), all of which modify shape. How sensitive are limits to this?

Exclusive leptons: a caveat

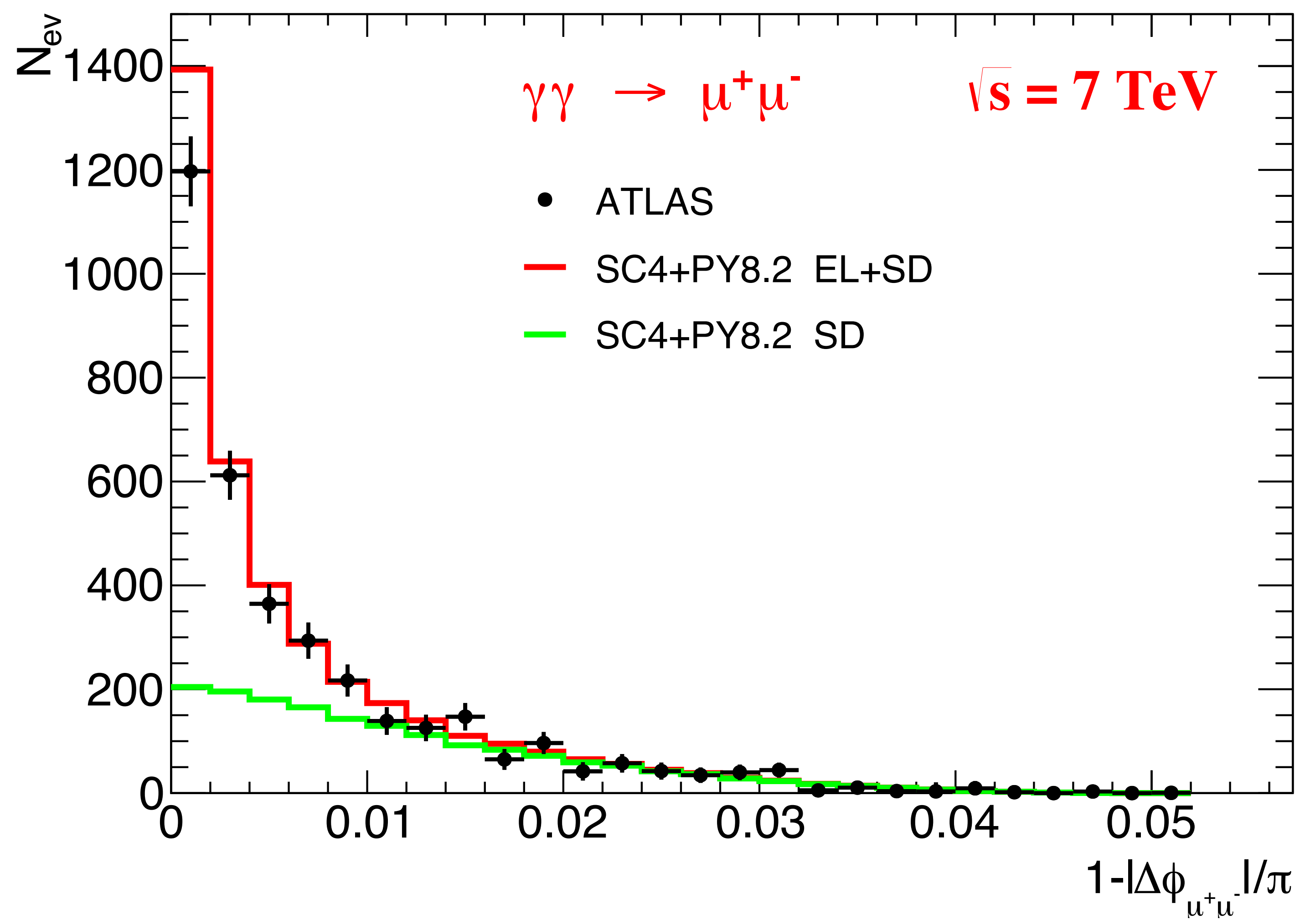
- For simplest 'standard candle' of lepton (muon, electron) pair production, data/theory agreement good but some trend for theory to overshoot data by O(10%).



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

- Selected via rapidity veto and/or single proton tag, as well as in PbPb.



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

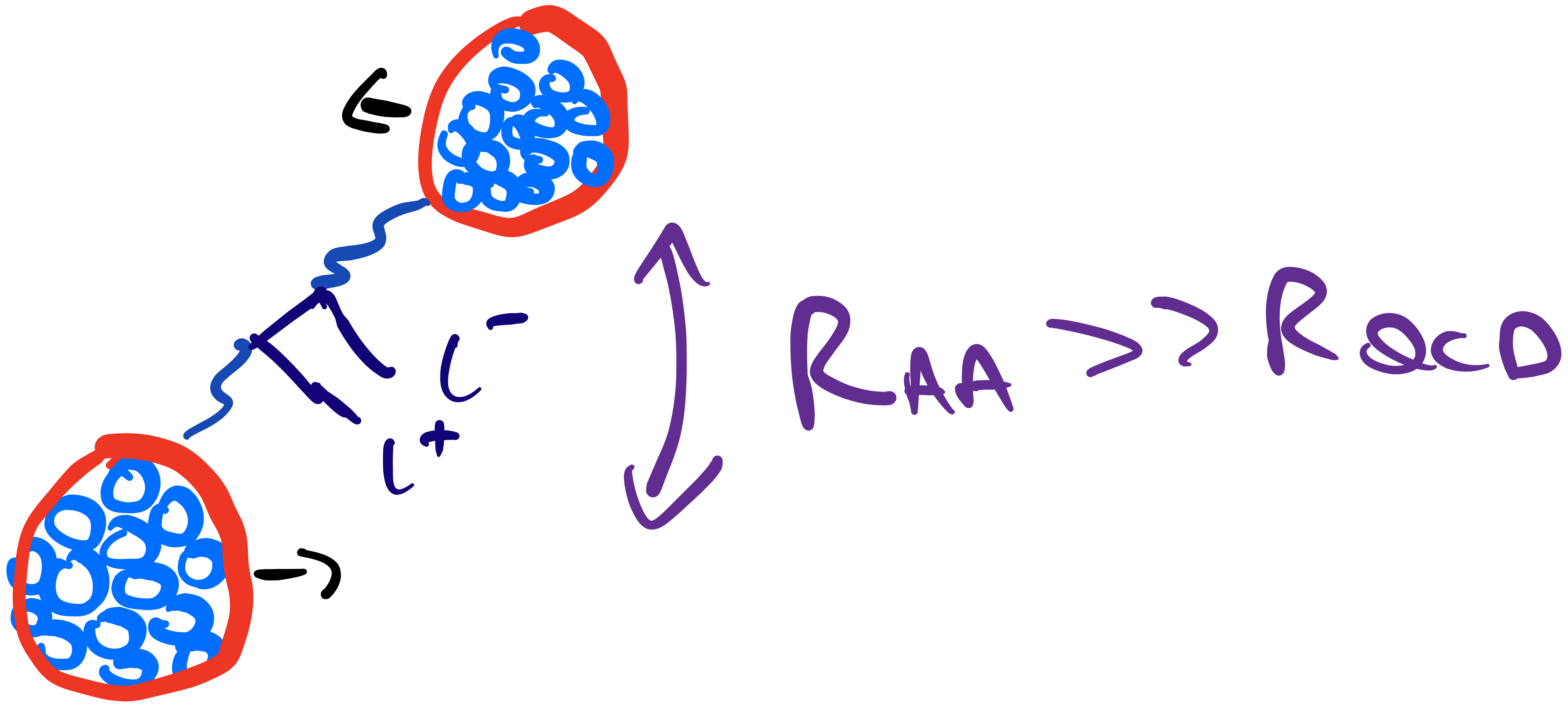
LHL, V.A Khoze, M.G. Ryskin, *SciPost Phys*. 11 (2021) 064

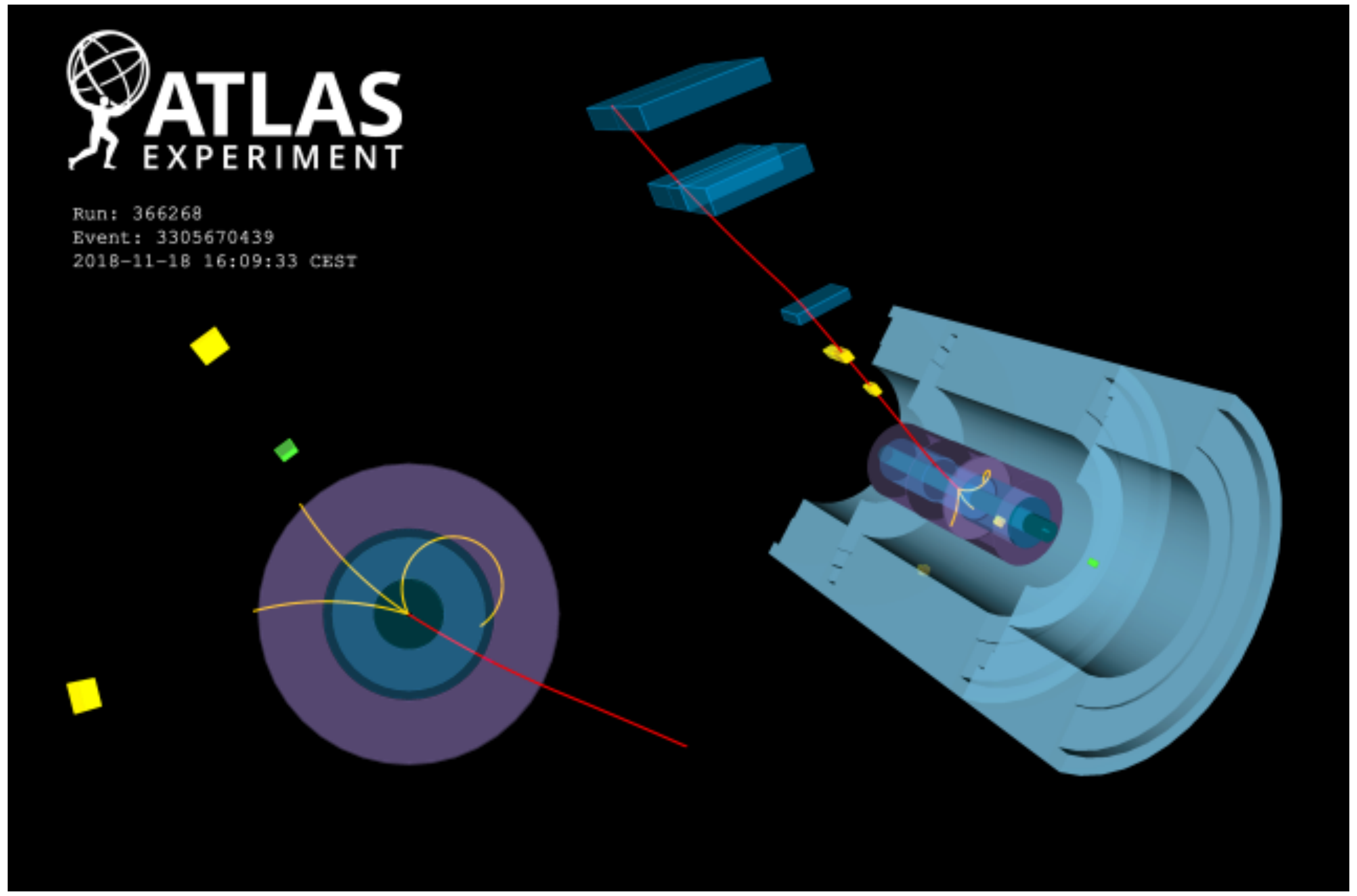
- Reasons for difference been considered in detail in literature, and so far not clear why.
- Futher more differential data and with different proton tags will help. Something to keep an eye on!

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).

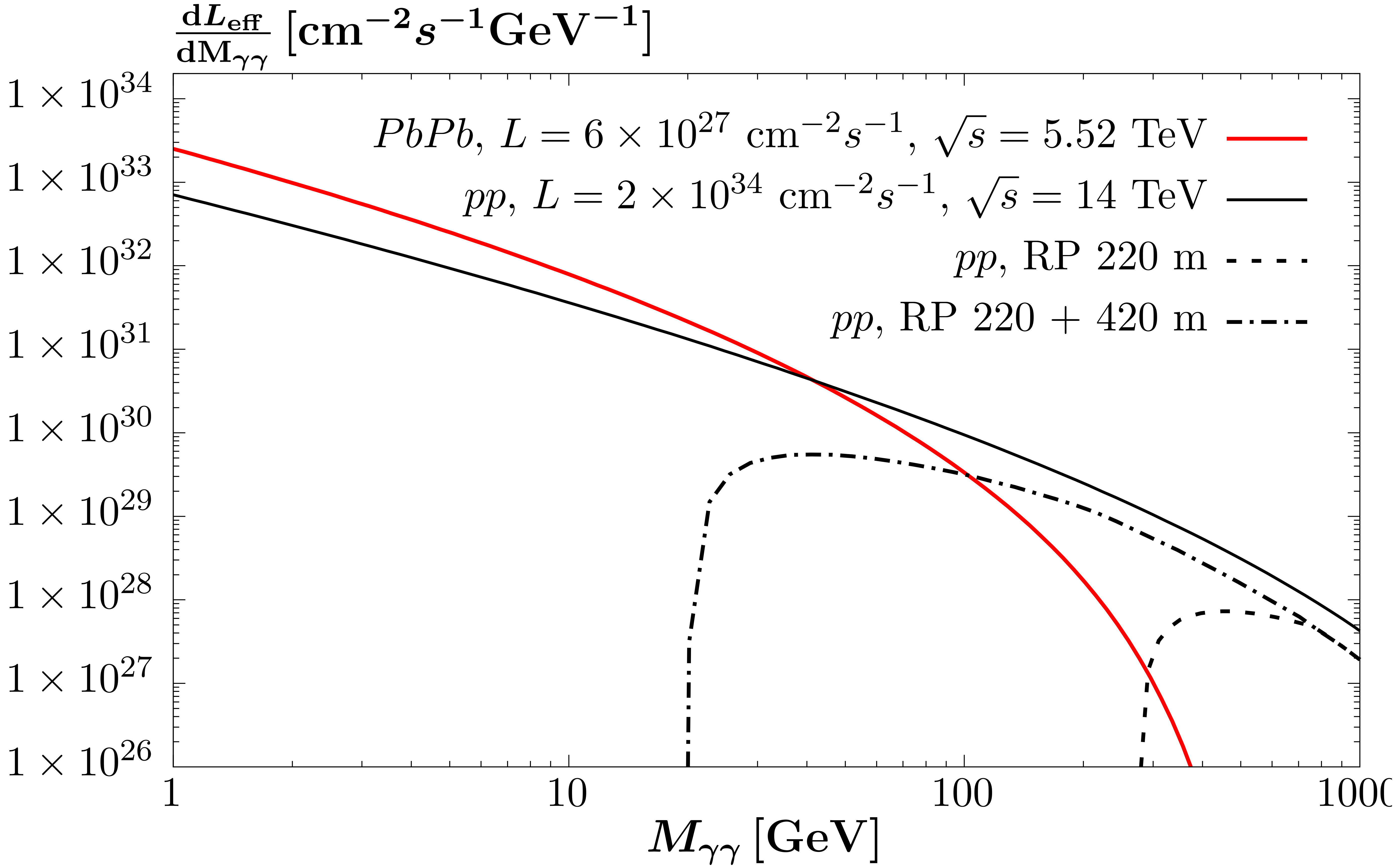




- Photon flux from ions falls v. quickly with central object mass but here great deal has been achieved…

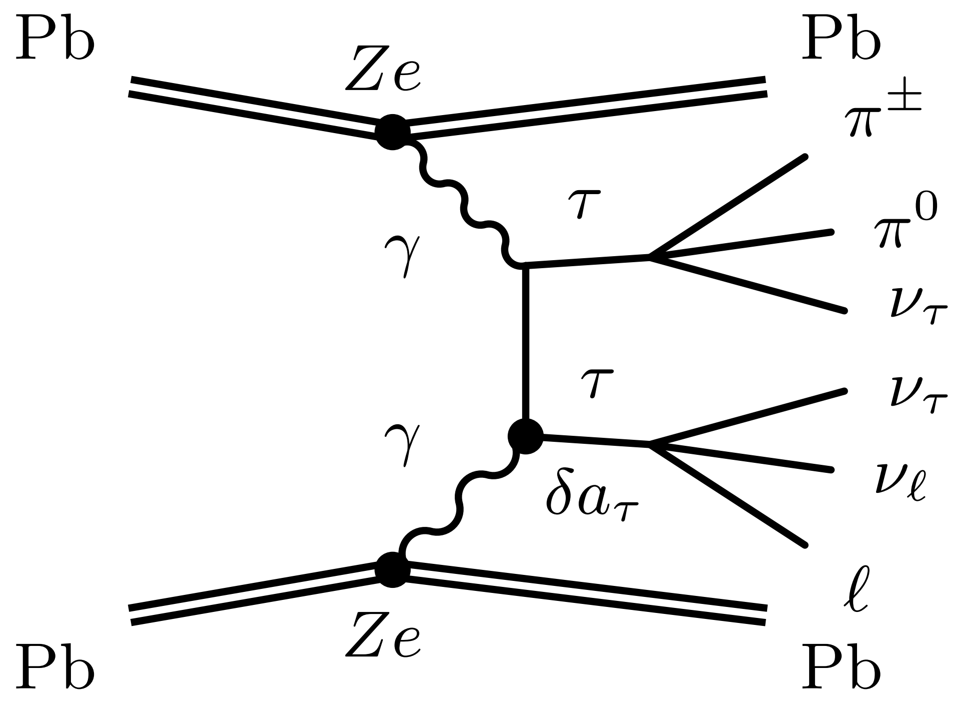
$$F_p \propto Z \Rightarrow \text{cross section} \propto F_p^4 \sim Z^4 \text{: strong enhancement} \qquad F_p(|\vec{q}|) = \int d^3r\, e^{i\vec{q}\cdot\vec{r}} \rho_p(r)$$

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



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

tau g-2

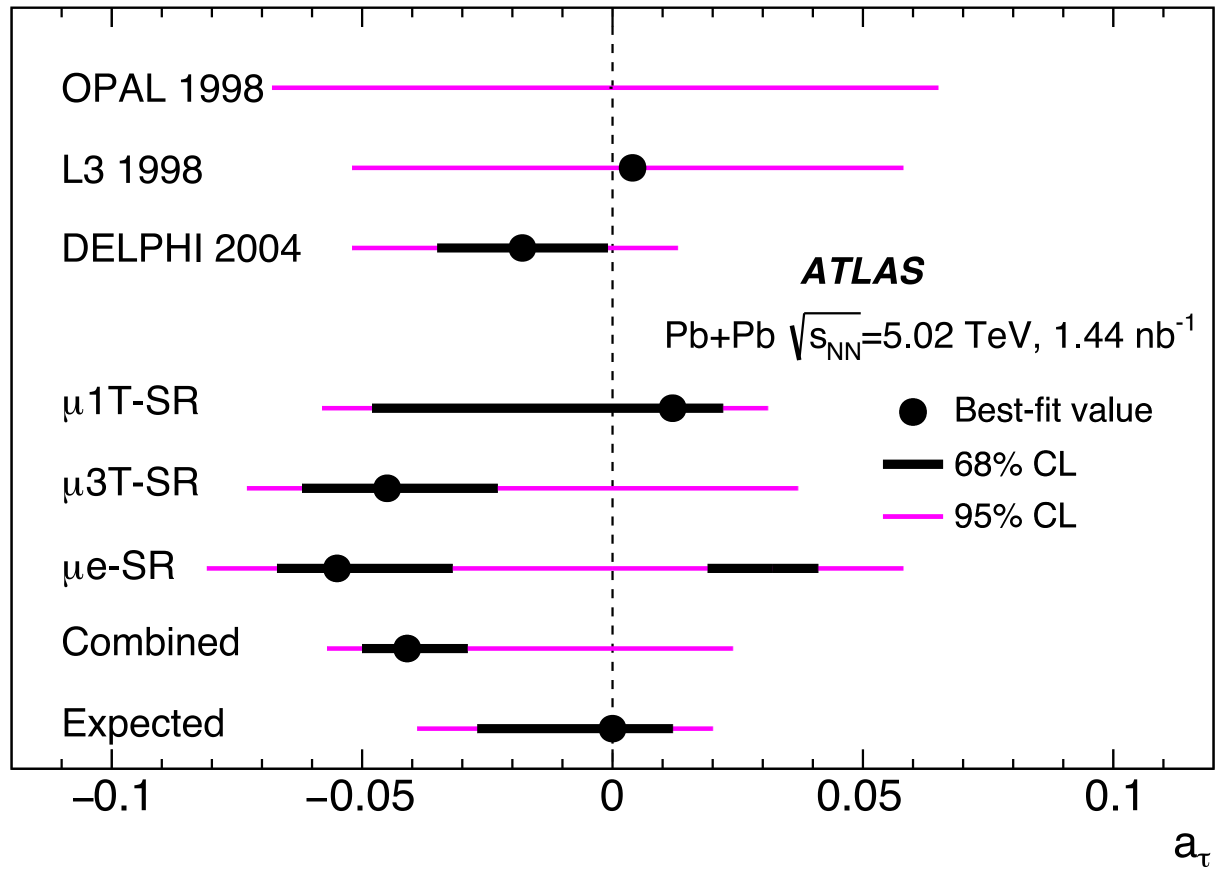


L. Beresford and J. Liu, PRD 102 (2020) 11, 113008

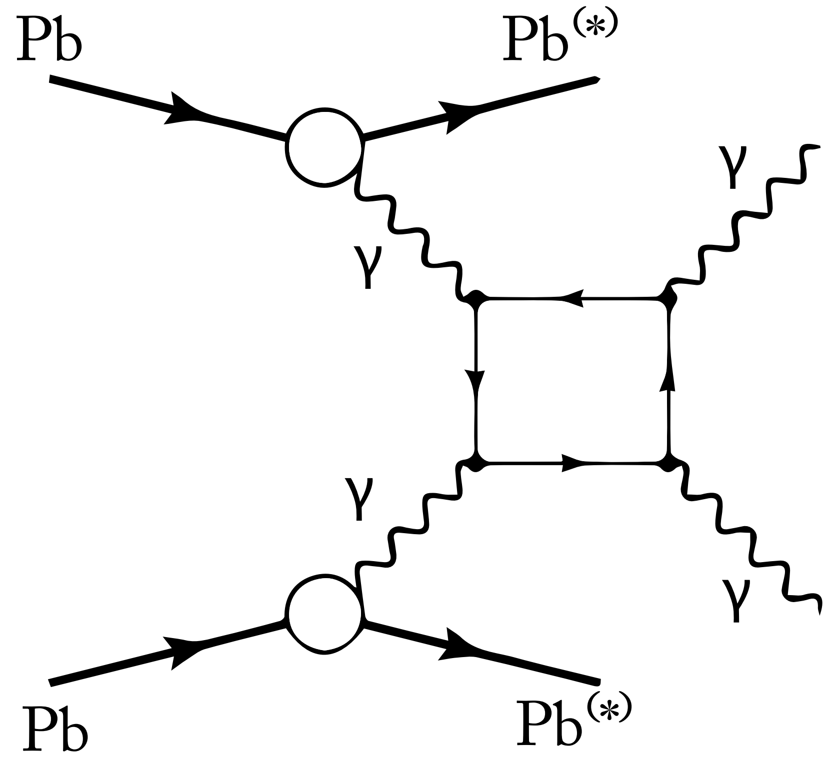
M. Dyndal et al., PLB 809 (2020) 135682

★ Tight constraints on tau g-2.

ATLAS, arXiv: 2204.13478 (accepted PRL)

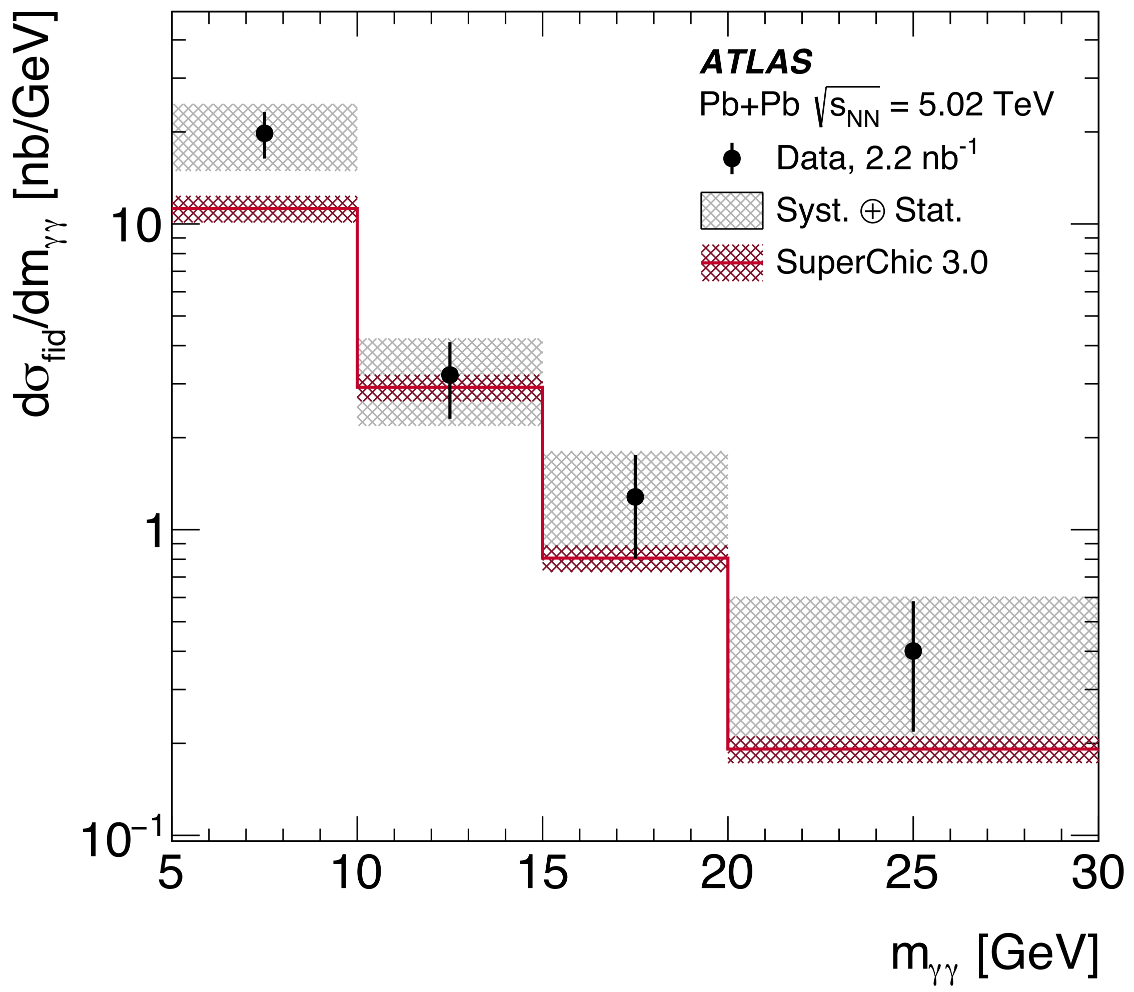


LbyL scattering

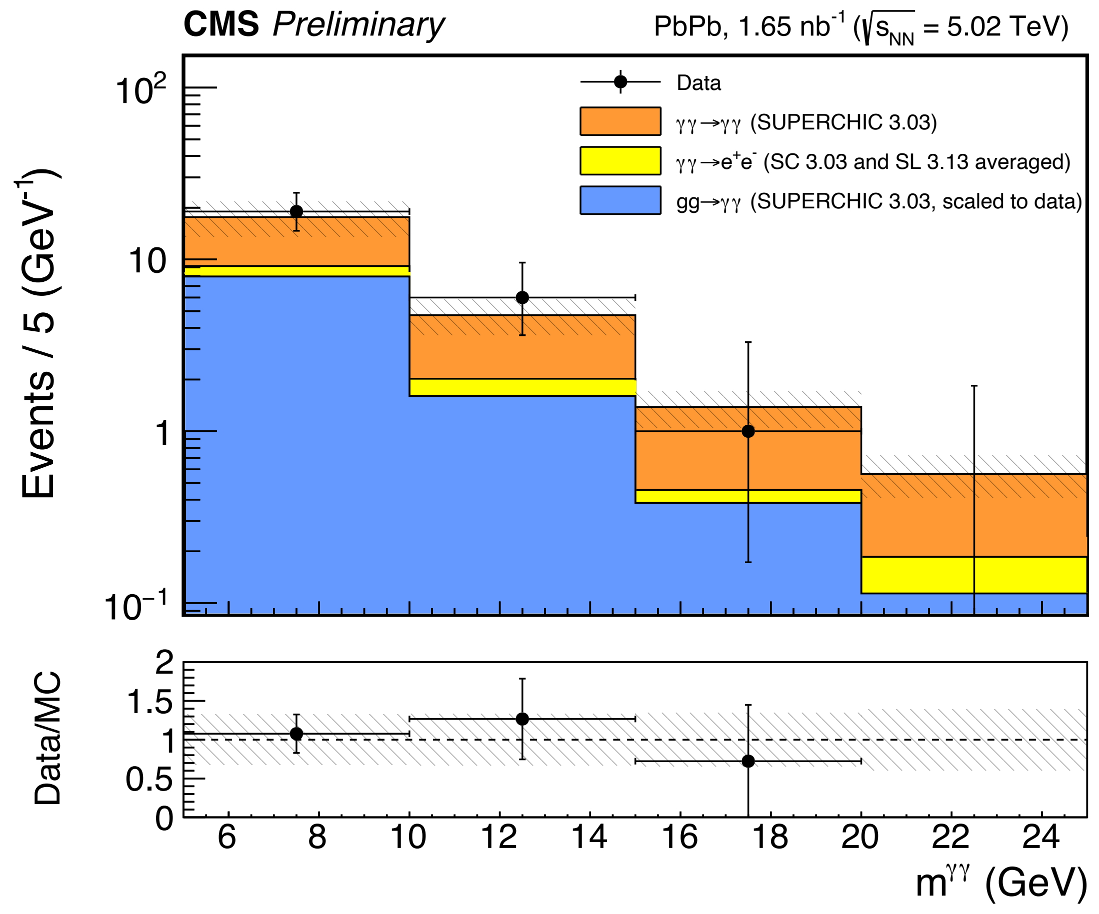


C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

★ First ever observation!



ATLAS, *JHEP* 03 (2021) 243



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

CMS, CMS PAS HIN-21-015

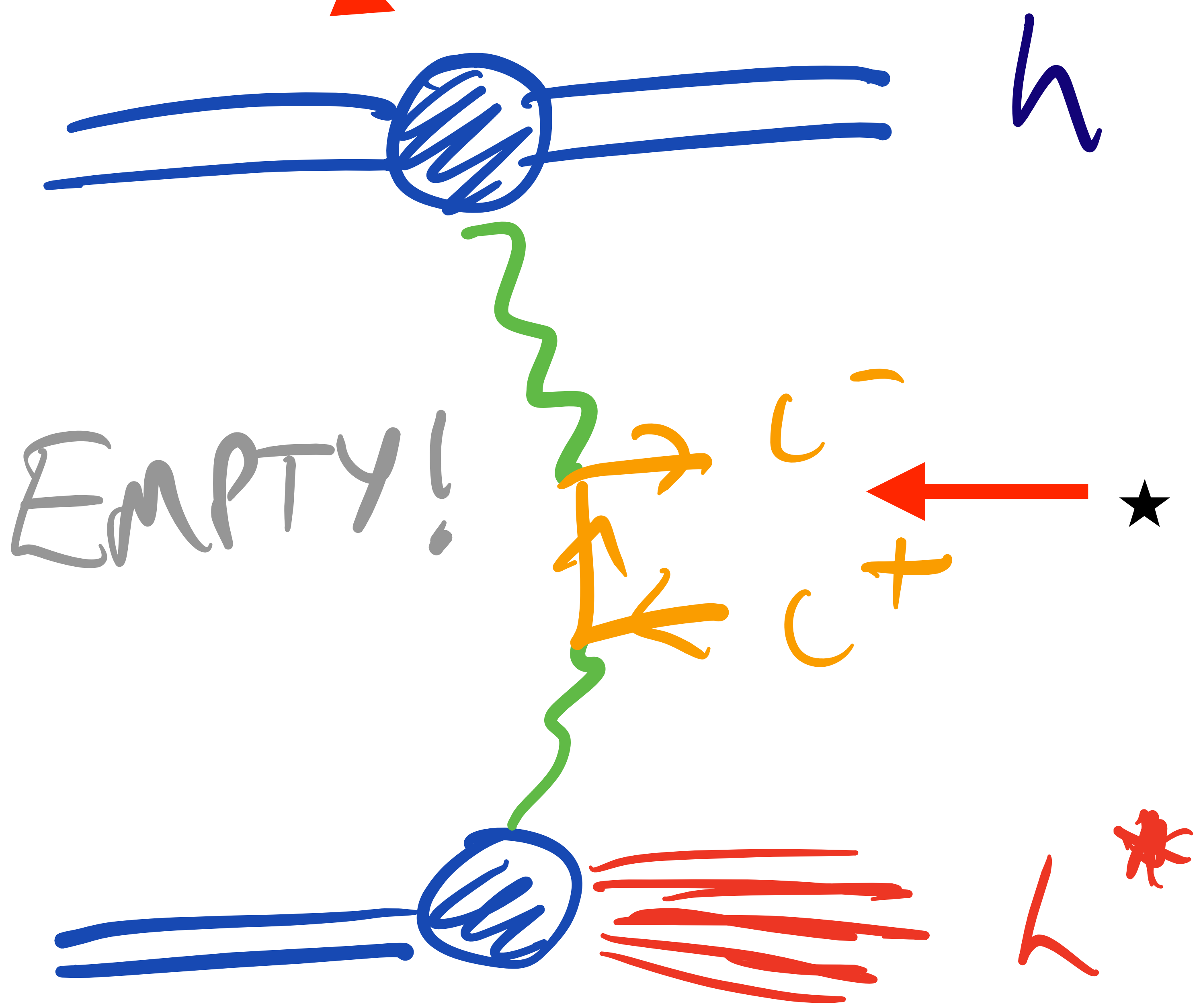
PI production: building blocks

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

★ $p \to \gamma p(p^*)$ form factor.

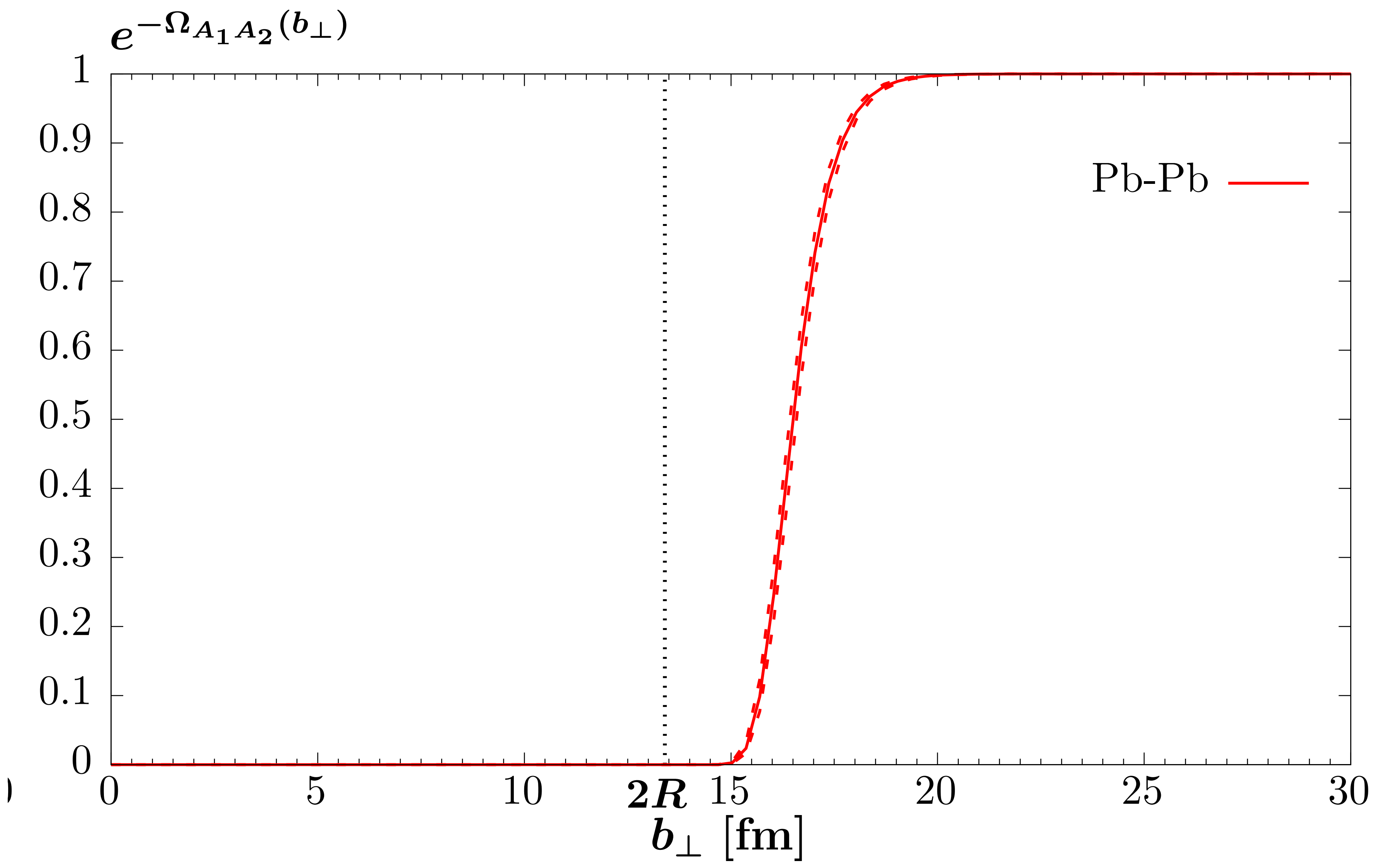
★ $\gamma\gamma \to X$ cross section.

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



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

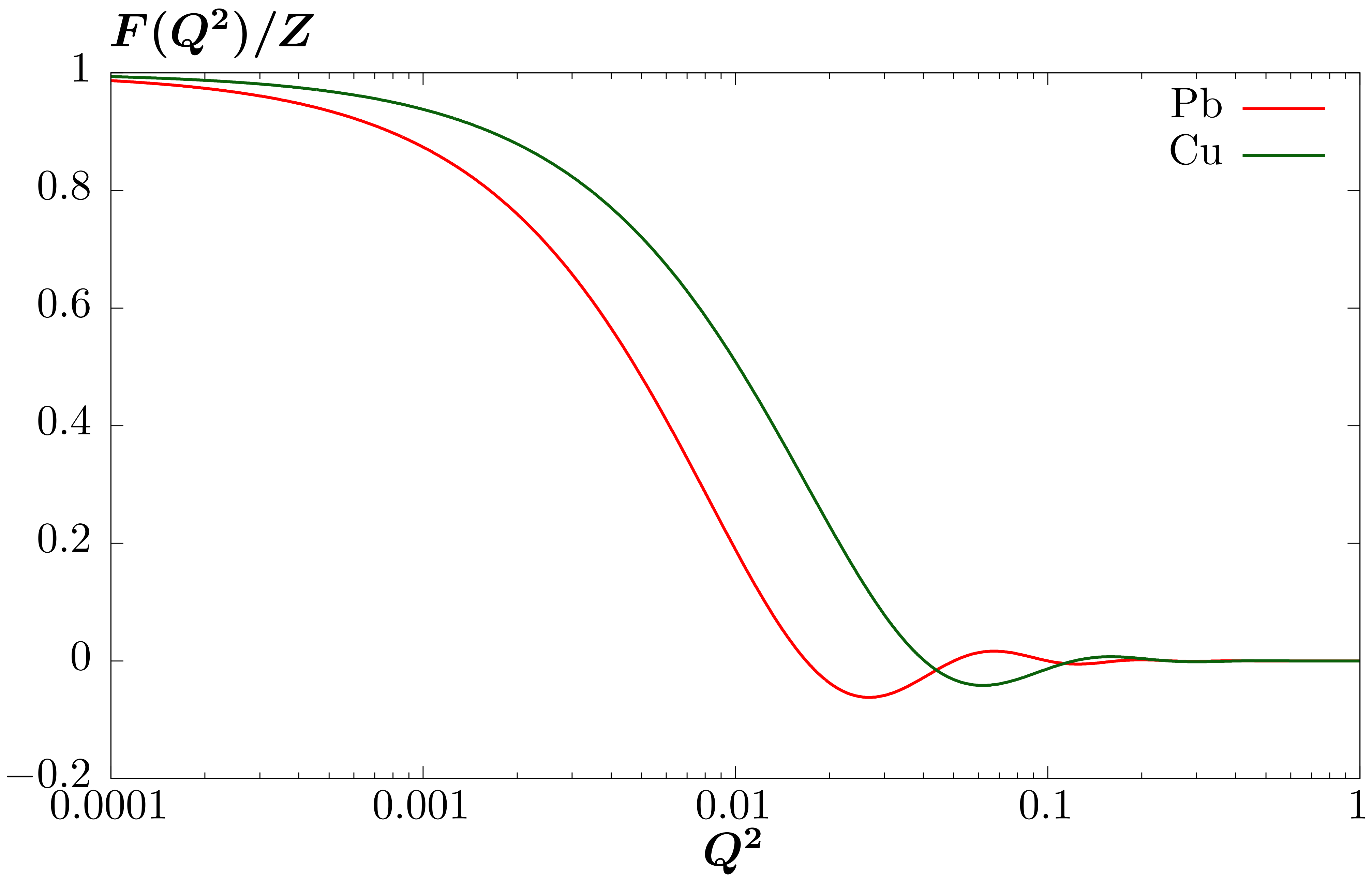
$\Rightarrow S^2 \sim 1$, with small uncertainty



★ Input for elastic form factors very well determined.

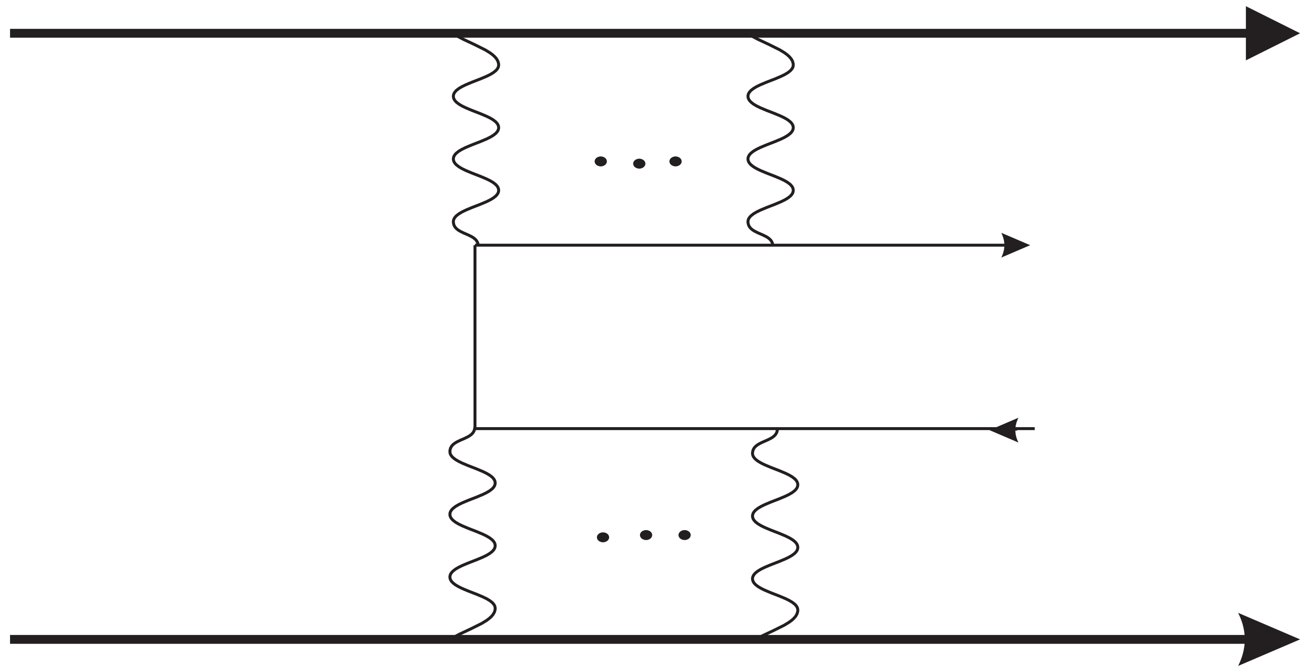
$$\rho_p(r) = \frac{\rho_0}{1 + \exp{(r-R)/d}} ,$$

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

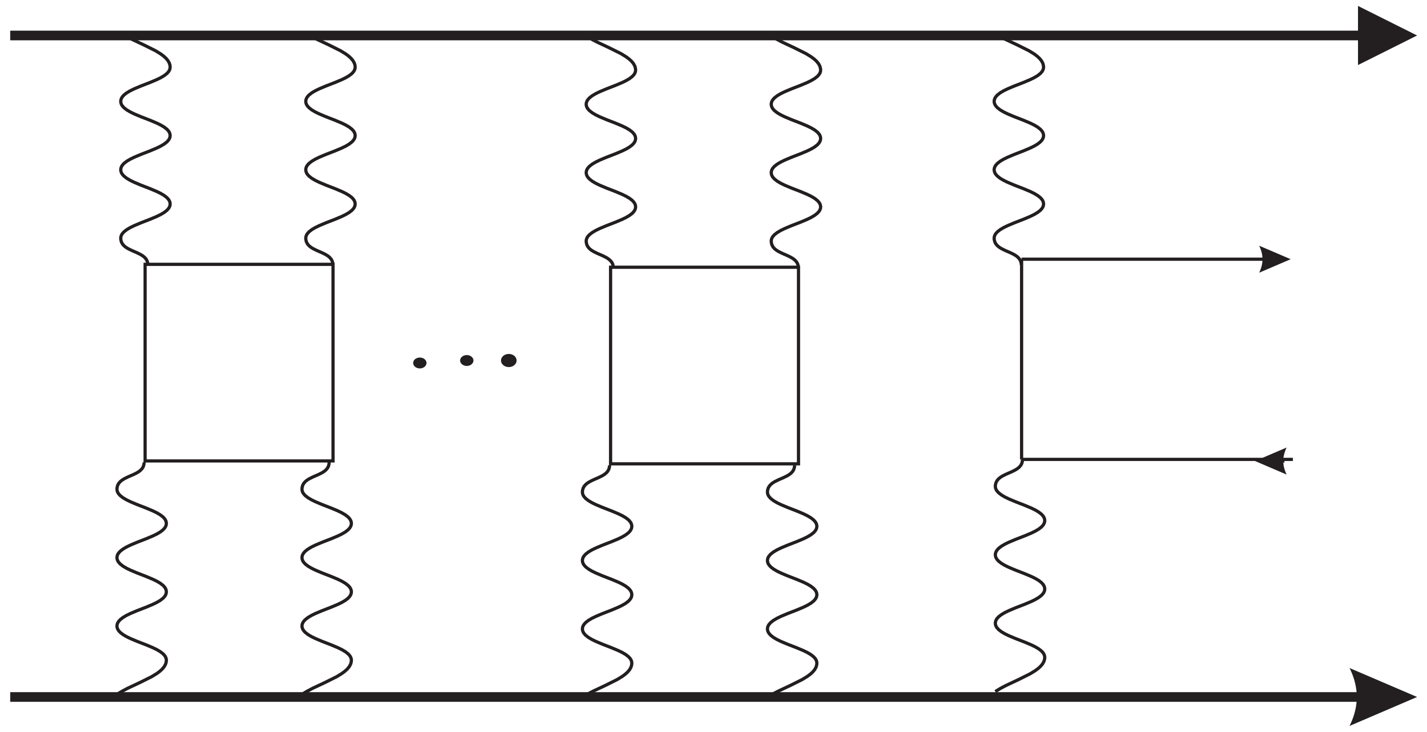


★ But also other features that enter only in heavy ion case….

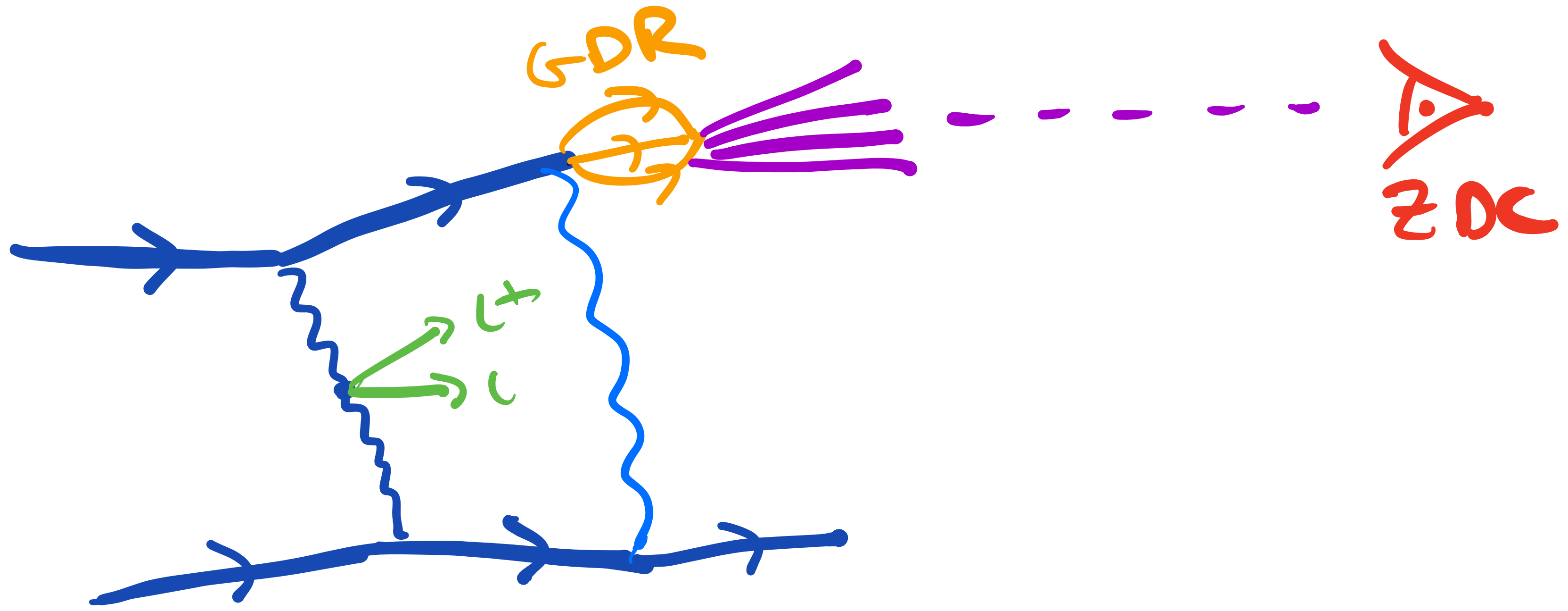
• **HO QED** effects?



• **Unitary corrections**?



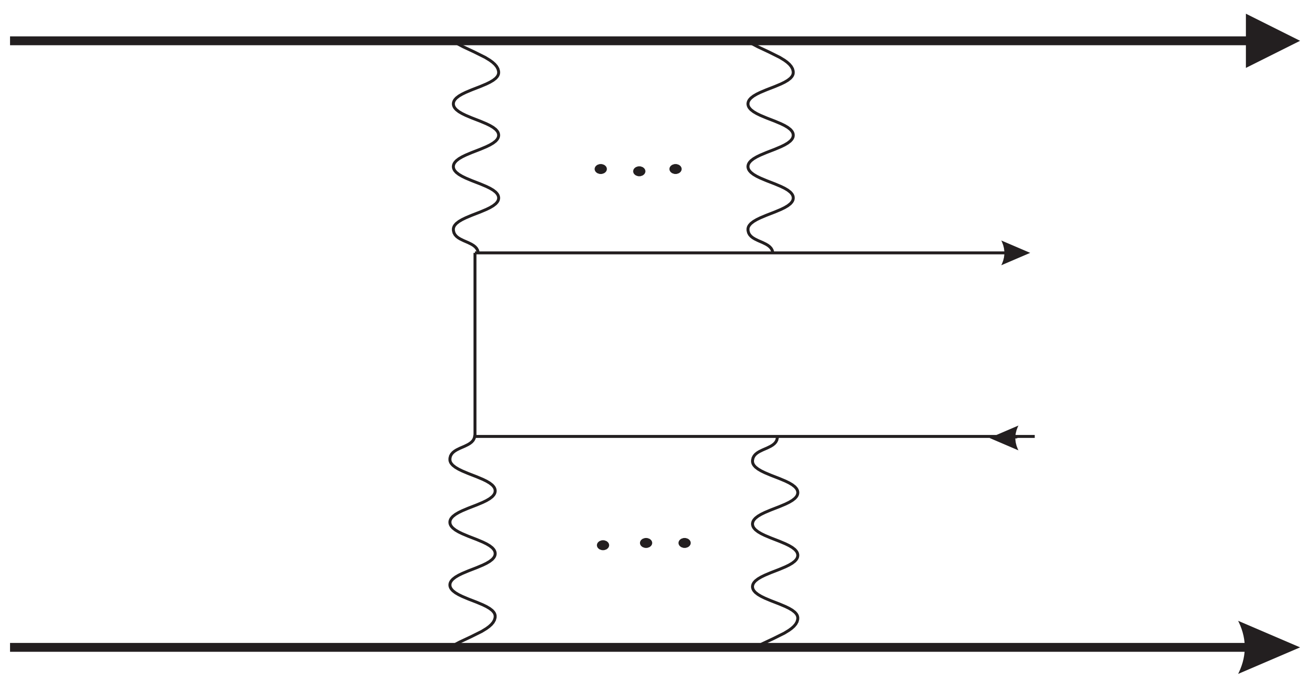
• **Ion dissociation**?



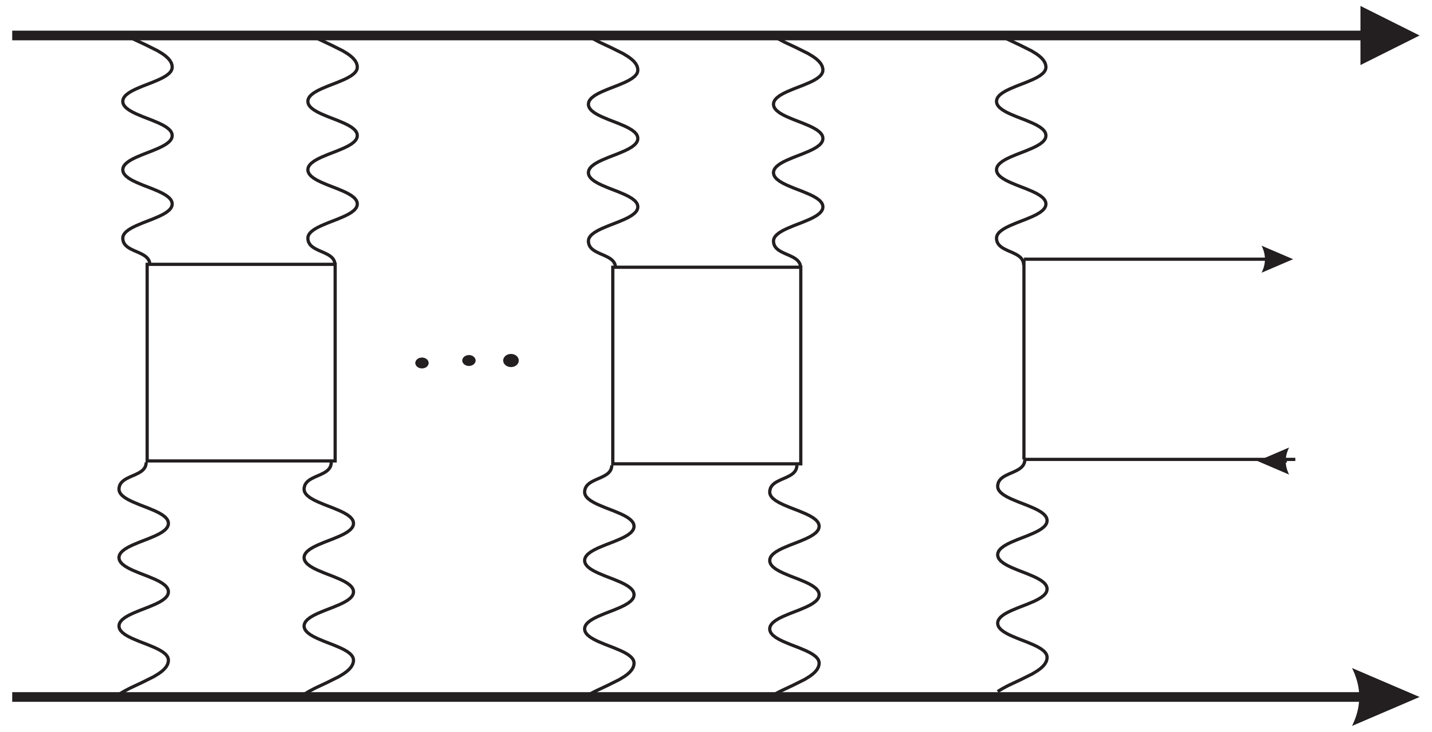
→ Each of these can play a role, but full picture yet to be developed. For precision physics much left to consider.

★ But also other features that enter only in heavy ion case….

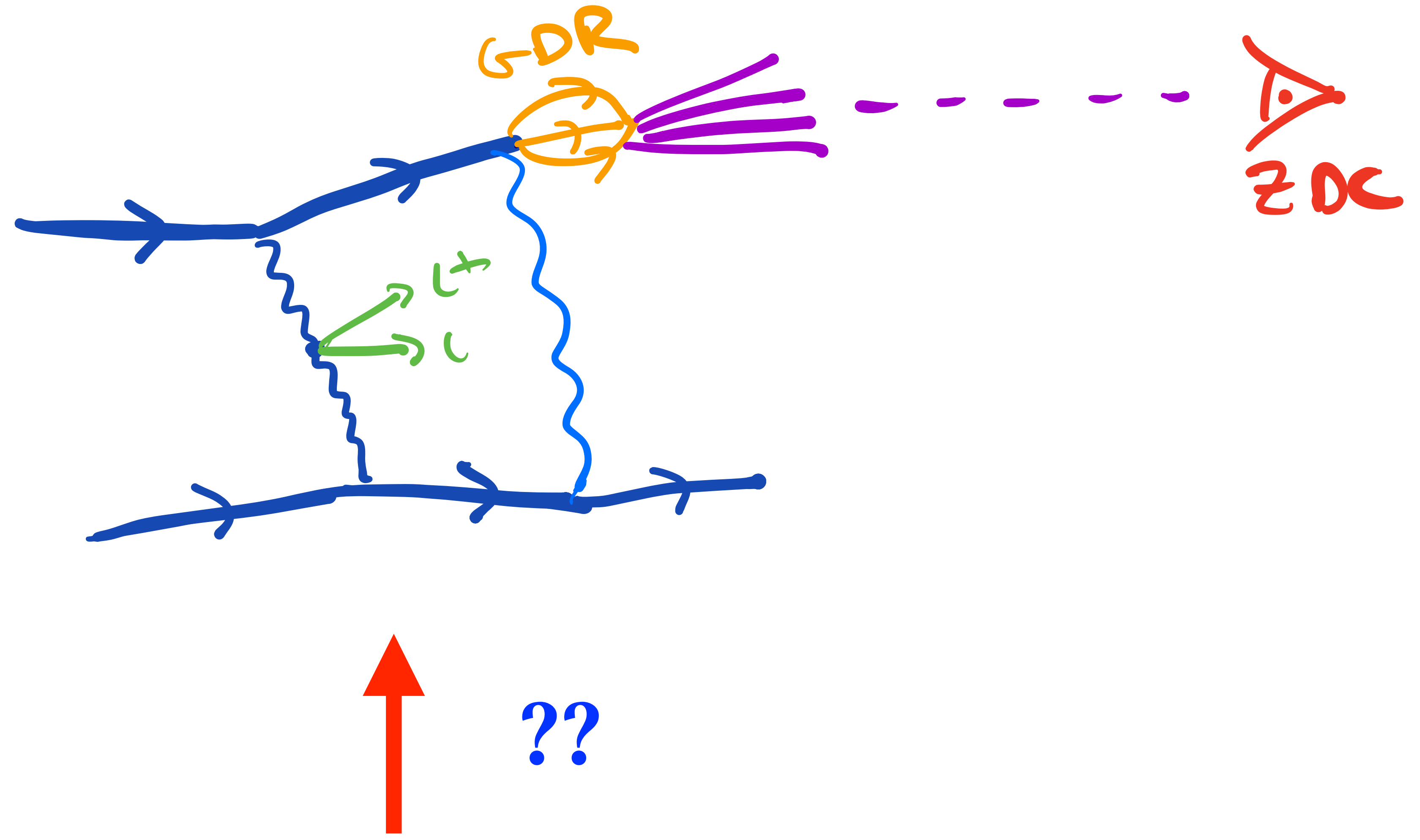
• **HO QED** effects?



• **Unitary corrections**?

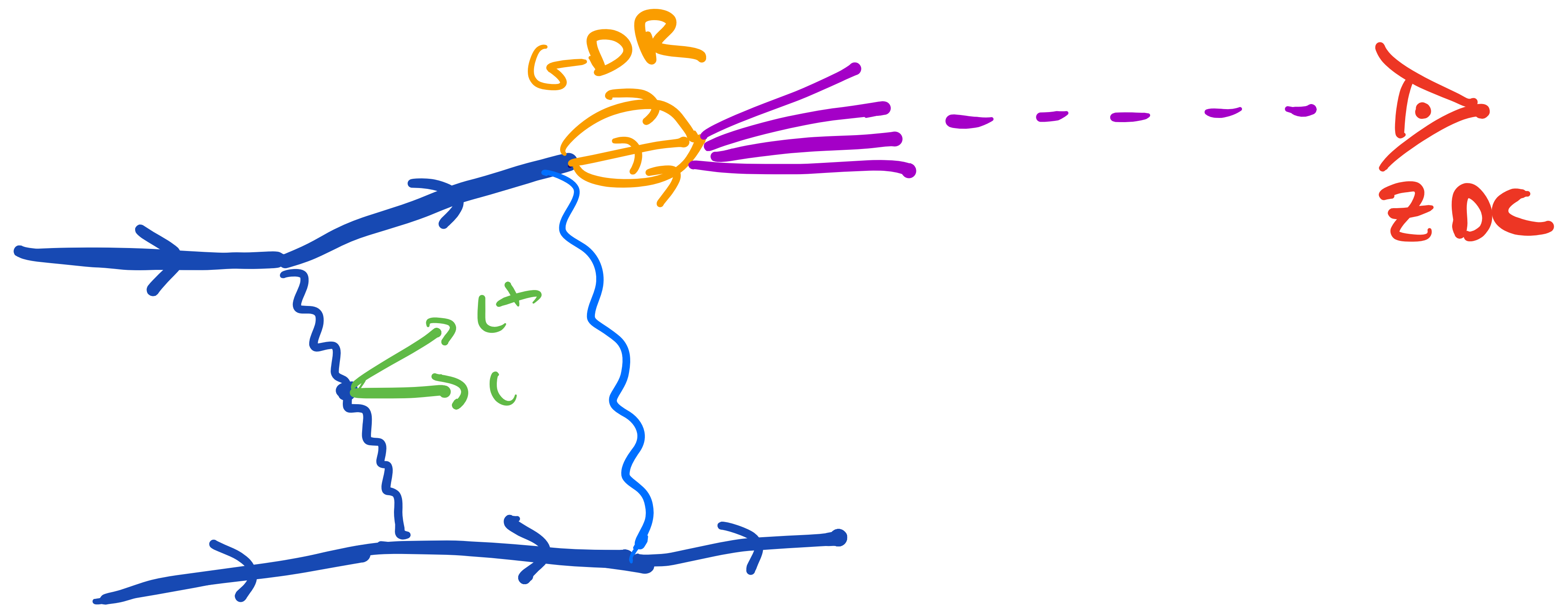


• **Ion dissociation**?

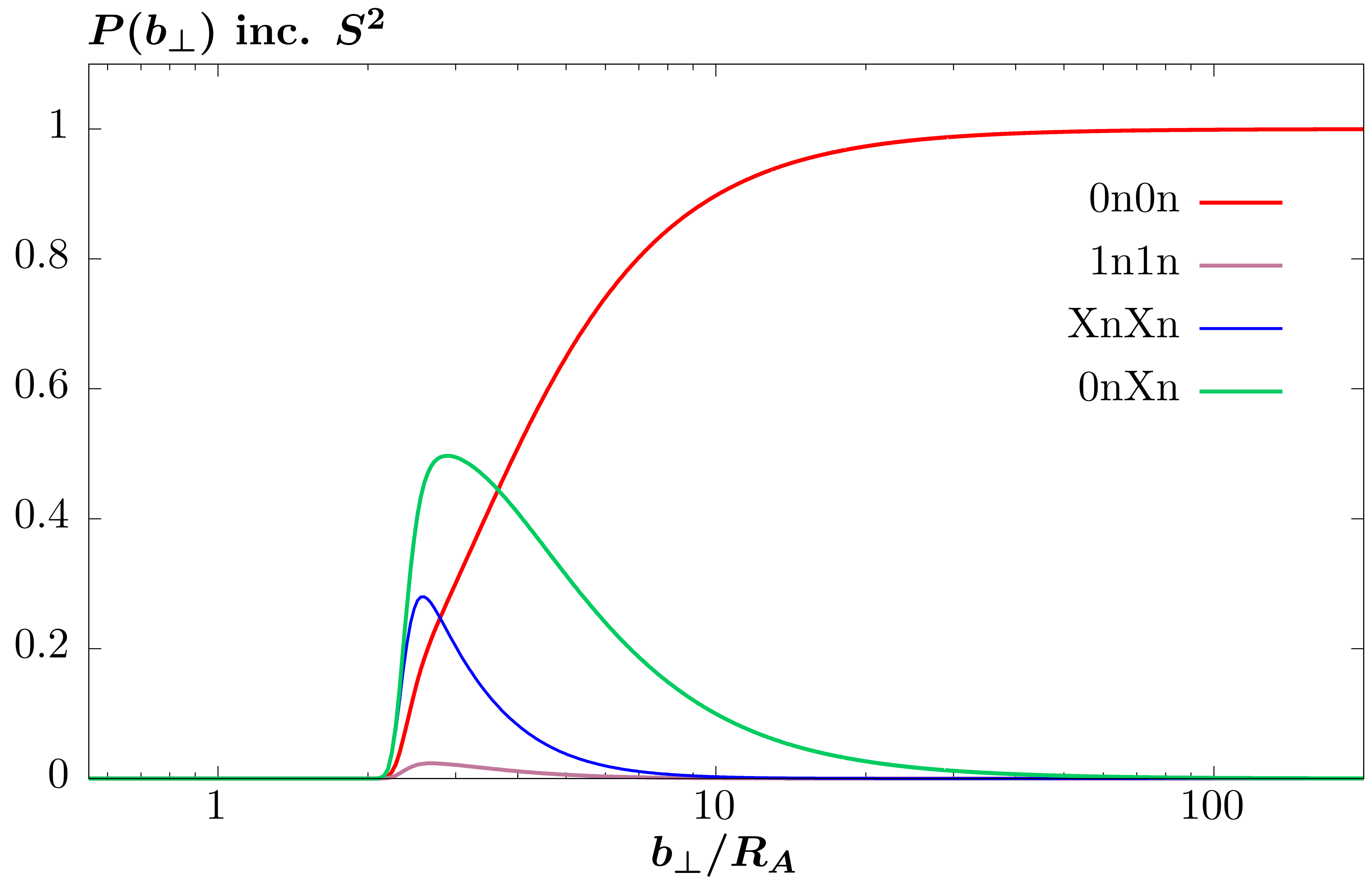


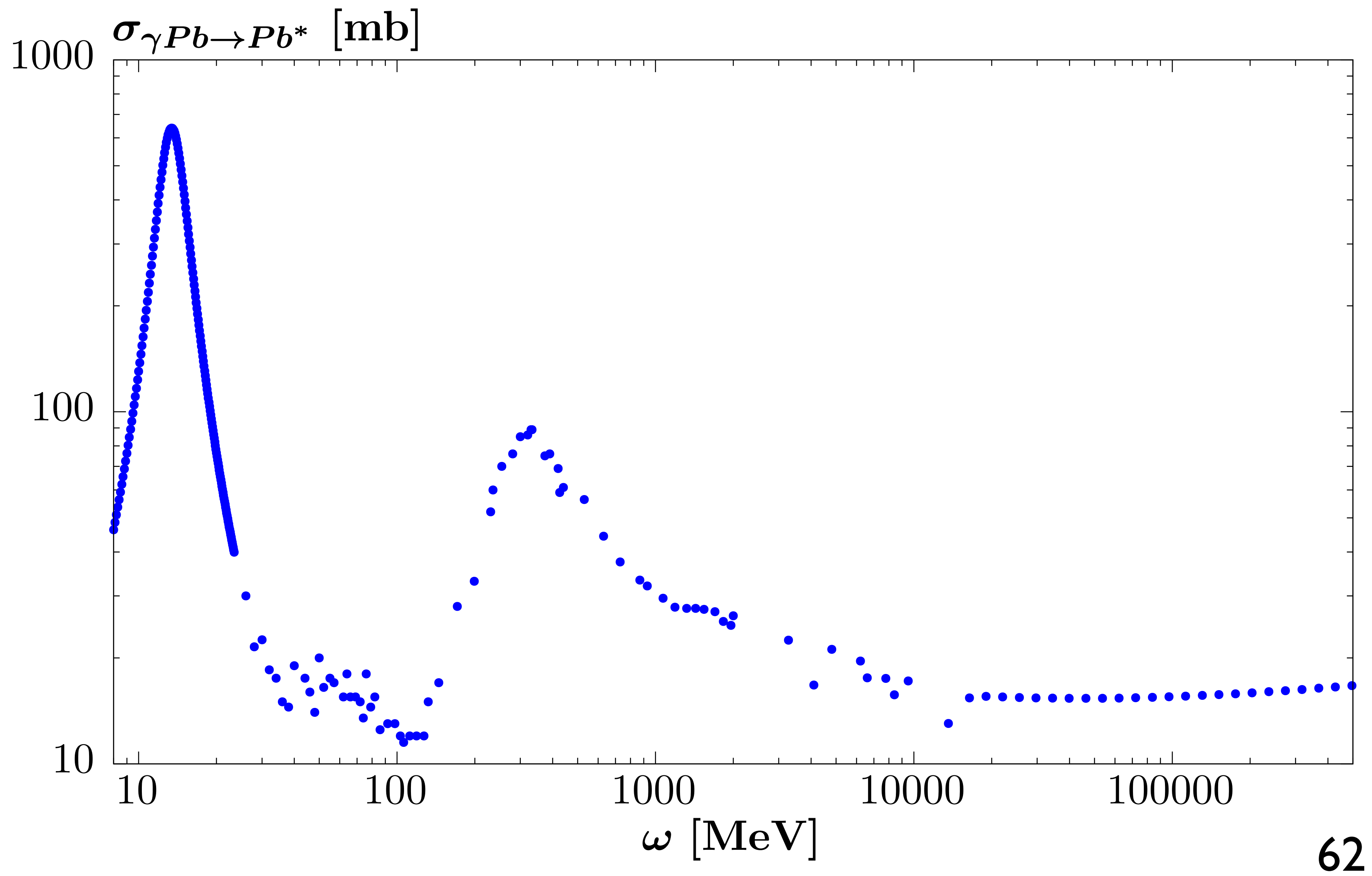
→ Each of these can play a role, but full picture yet to be developed. For precision physics much left to consider.

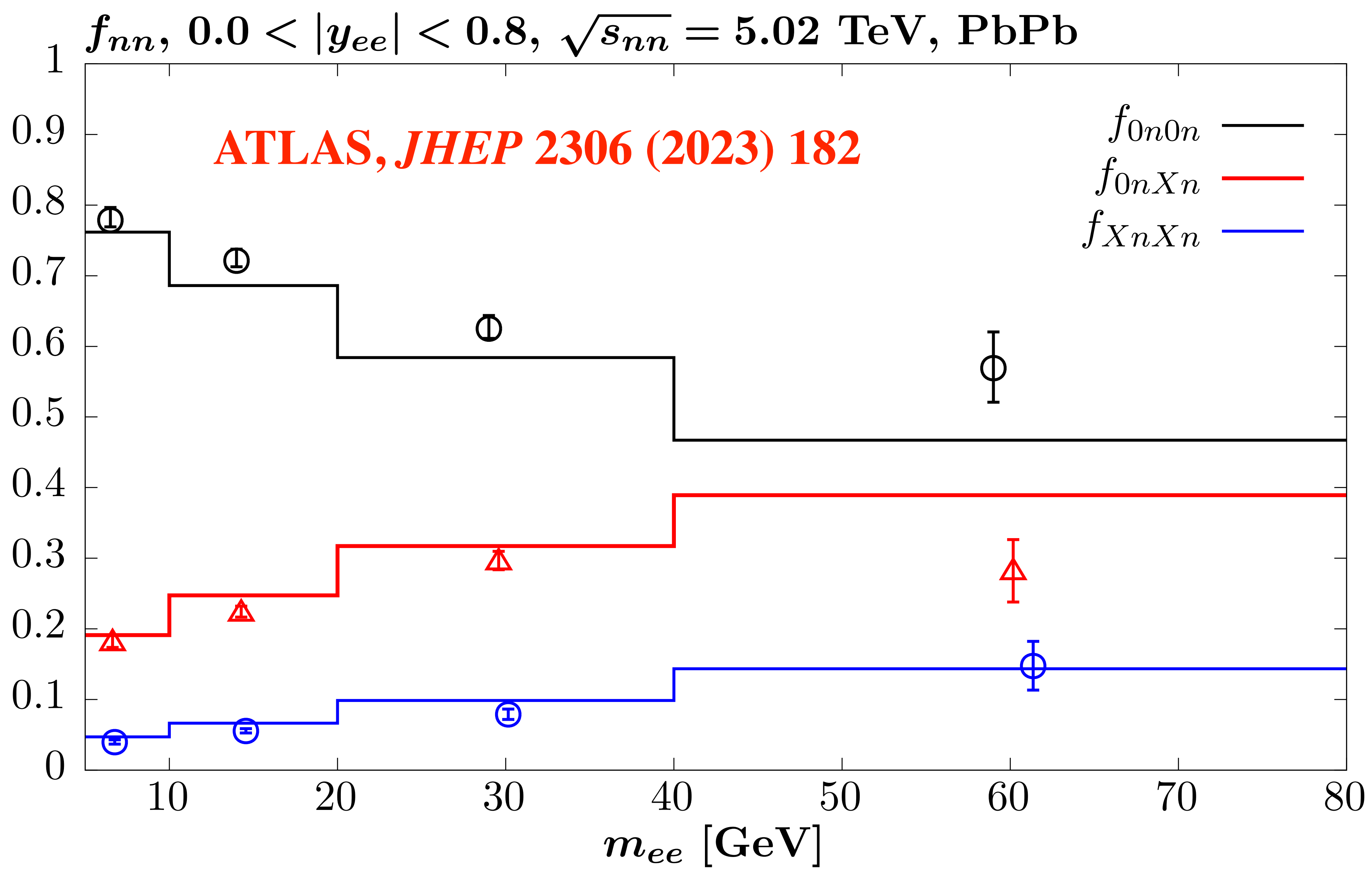
- As with pp purely elastic collisions not the only case of interest.
  - ★ Ions can dissociate: additional boosted neutron production measured by ATLAS/CMS Zero Degree Calorimeters detectors.
  - ★ Different neutron multiplicities have different impact parameter profiles → modifies central kinematics.



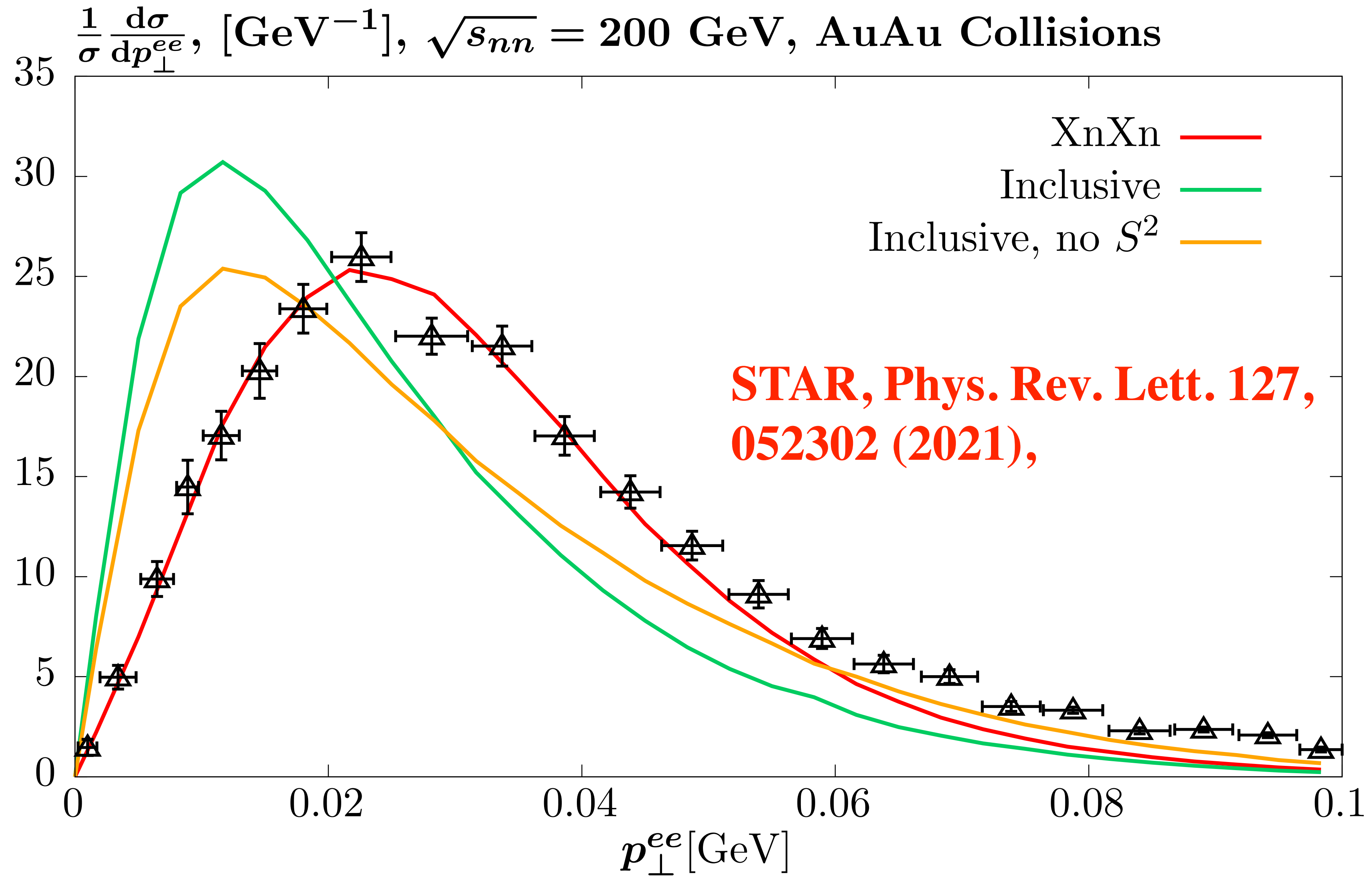
LHL, *Phys.Rev.D* 107 (2023) 9, 093004

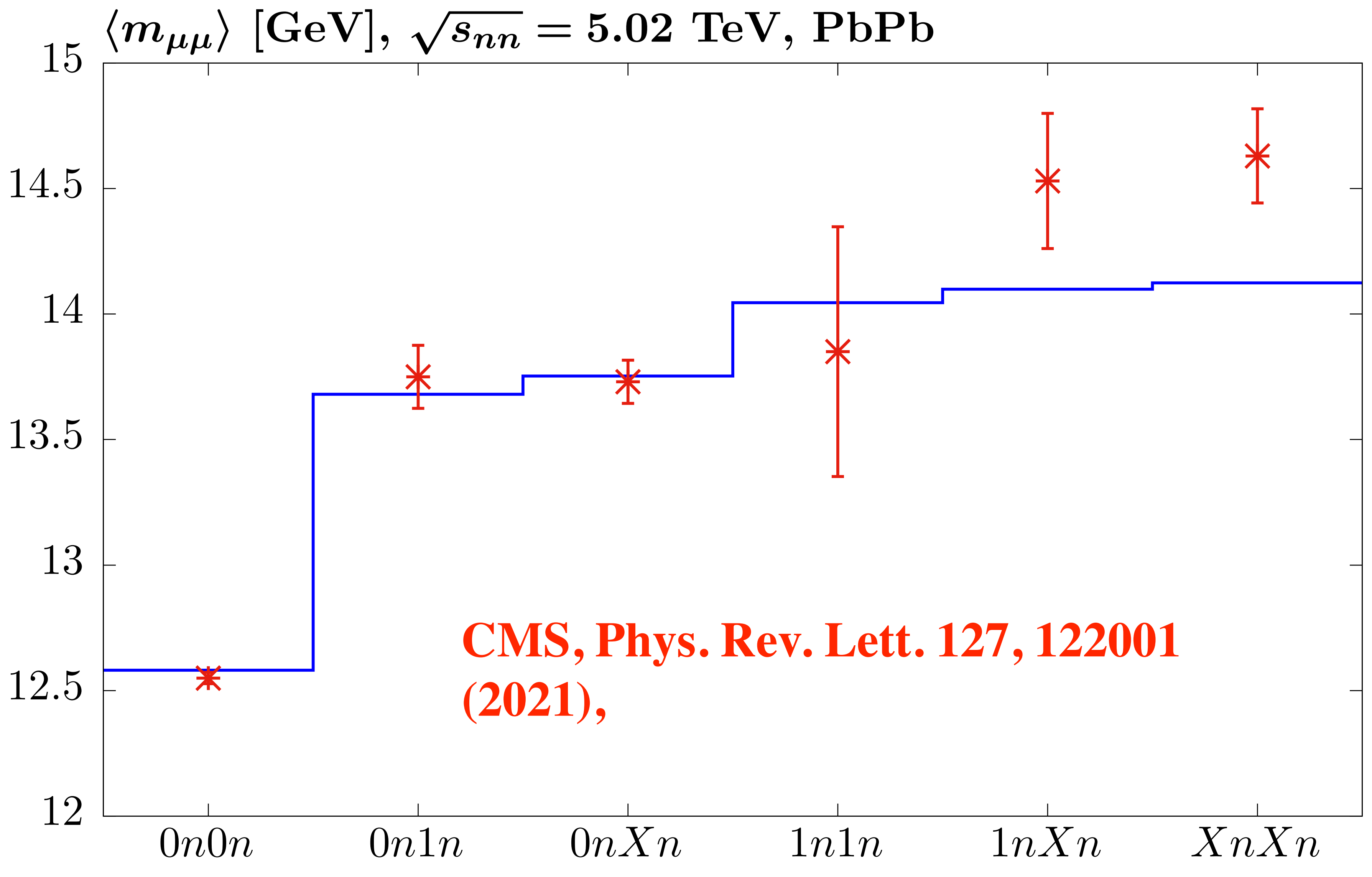






- ★ Broad agreement with range of LHC/RHIC data, but devil in detail!
- ★ Provides additional handle in measurements/searches.

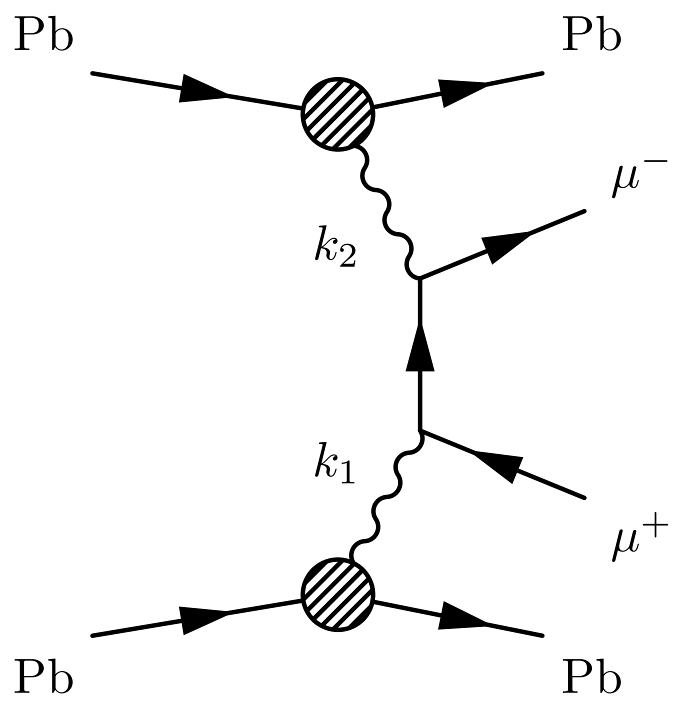




Comparison to data

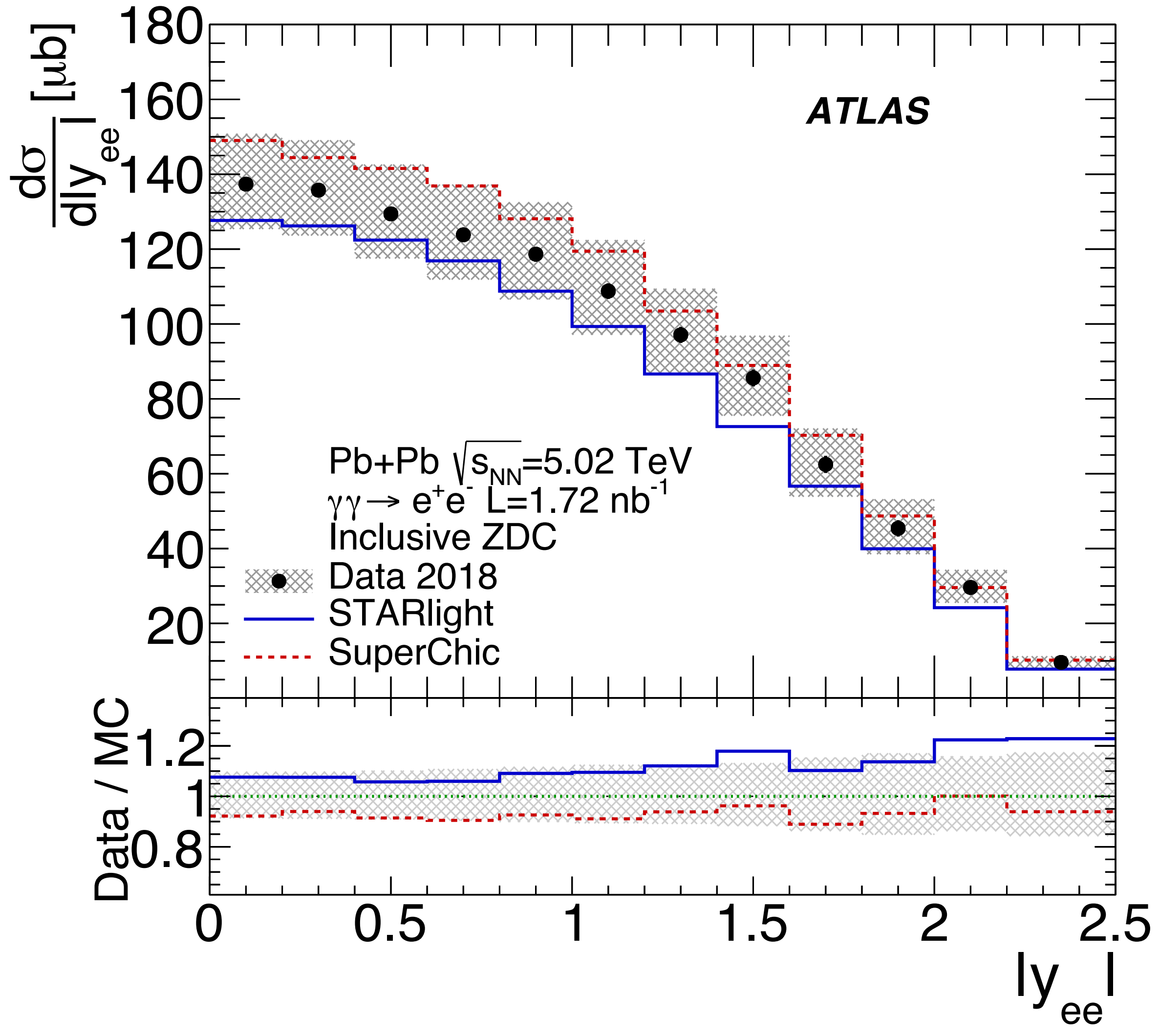
- All of the above relevant to fact that in dilepton channel (as in pp) some tendency to overshoot data:

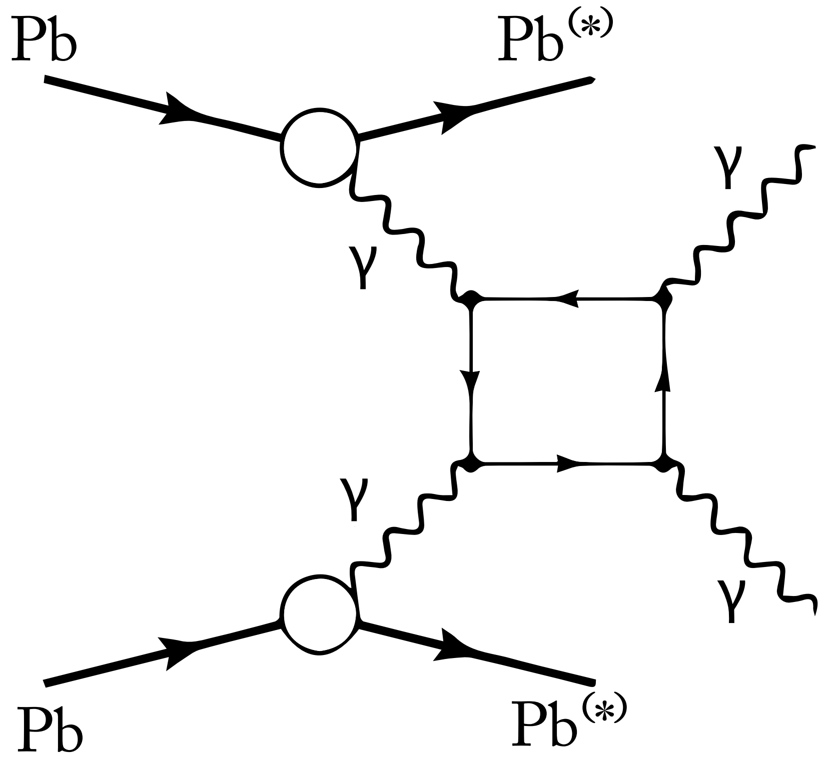
	ATLAS data [23]	Pure EPA	inc. S^2	inc. S^2 + FSR
σ [μb]	34.1 ± 0.8	52.2	38.9	37.3



ATLAS, *Phys.Rev.C* 104 (2021) 024906
ATLAS, *JHEP* 2306 (2023) 182

- Though distributions ~ well described.





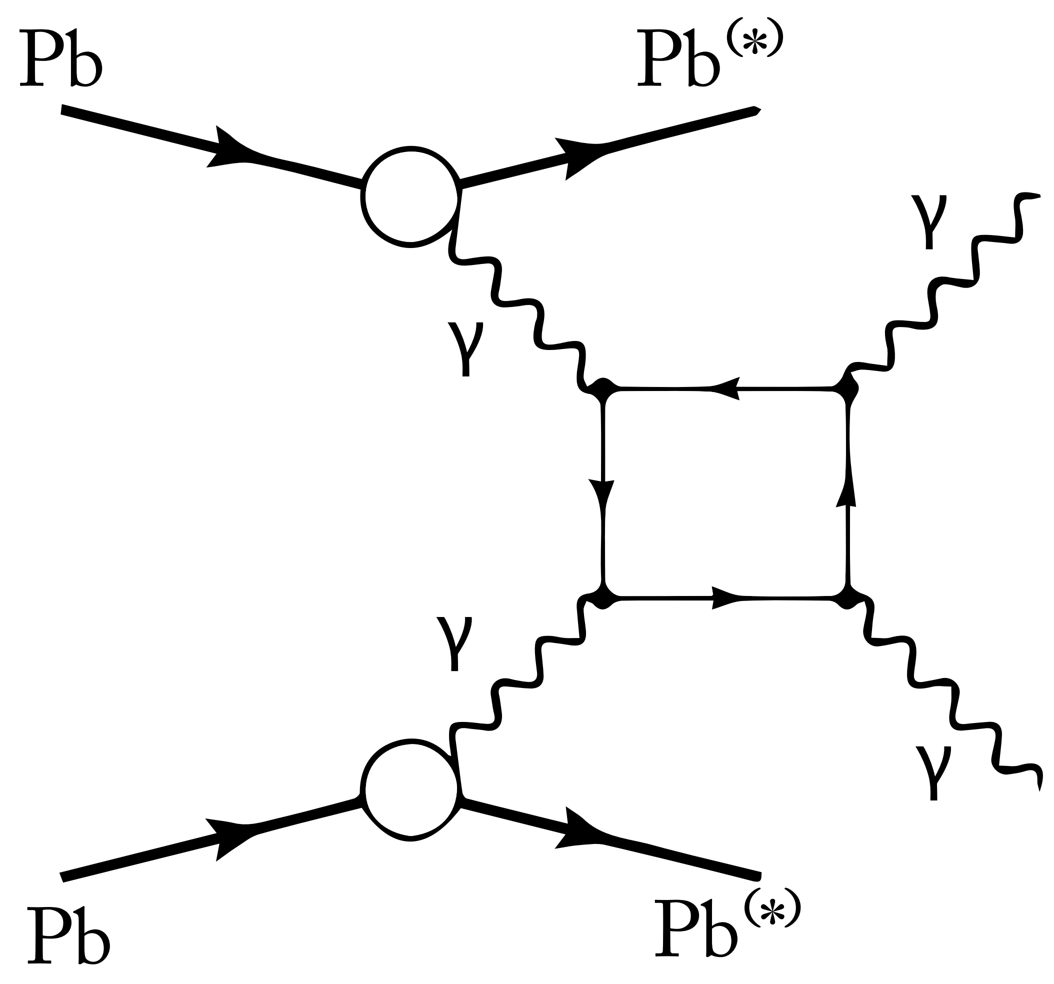
- What about Light by light scattering?

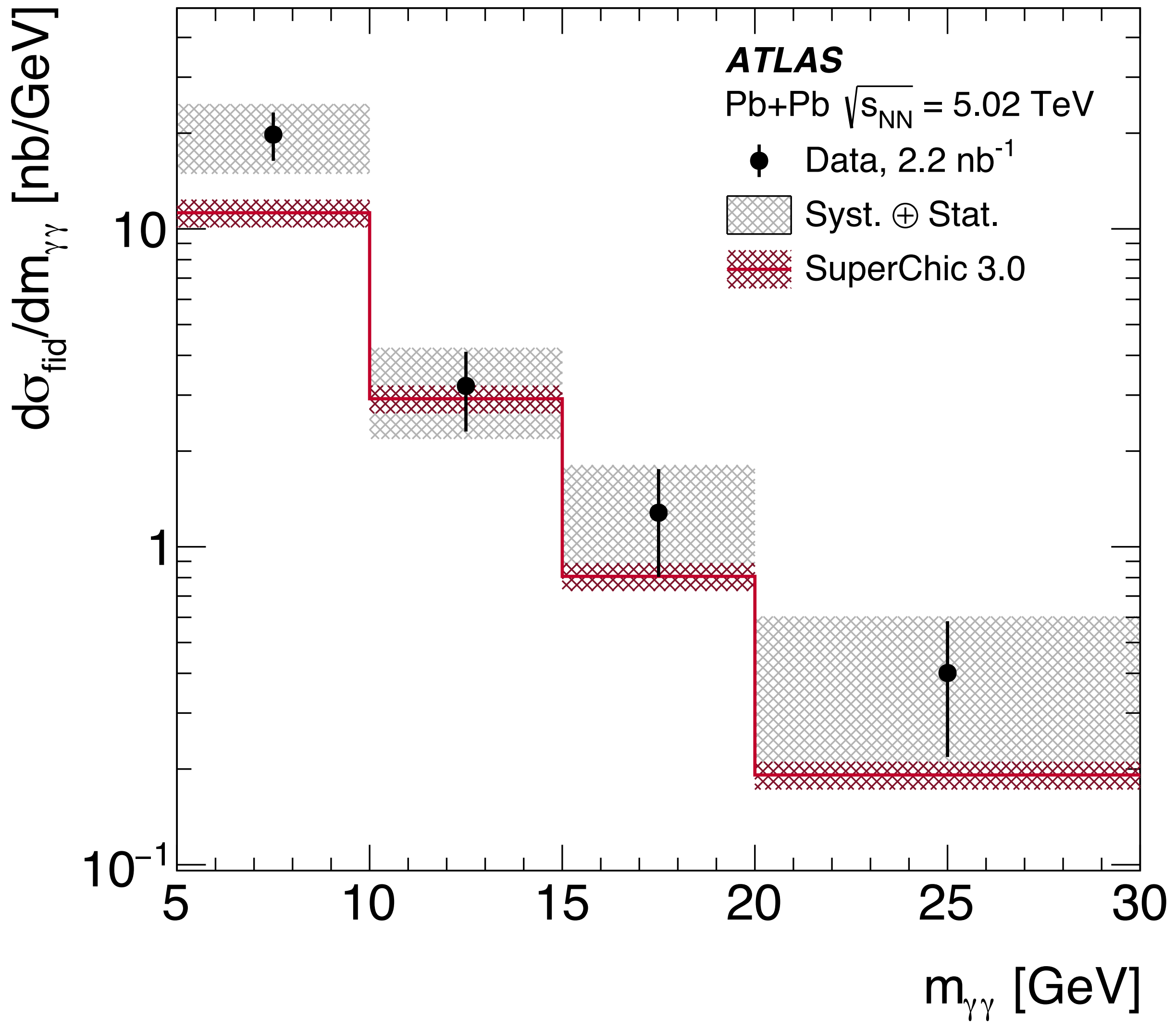
Light-by-Light Scattering

- MC prediction compared with ATLAS data on LbyL scattering:

$$\sigma_{\rm fid} = 120 \pm 17\ (\text{stat.}) \pm 13\ (\text{syst.}) \pm 4\ (\text{lumi.})\ \text{nb}.$$

- **SuperChic** central prediction: *78* nb, i.e. now **below** the data. Differentially:

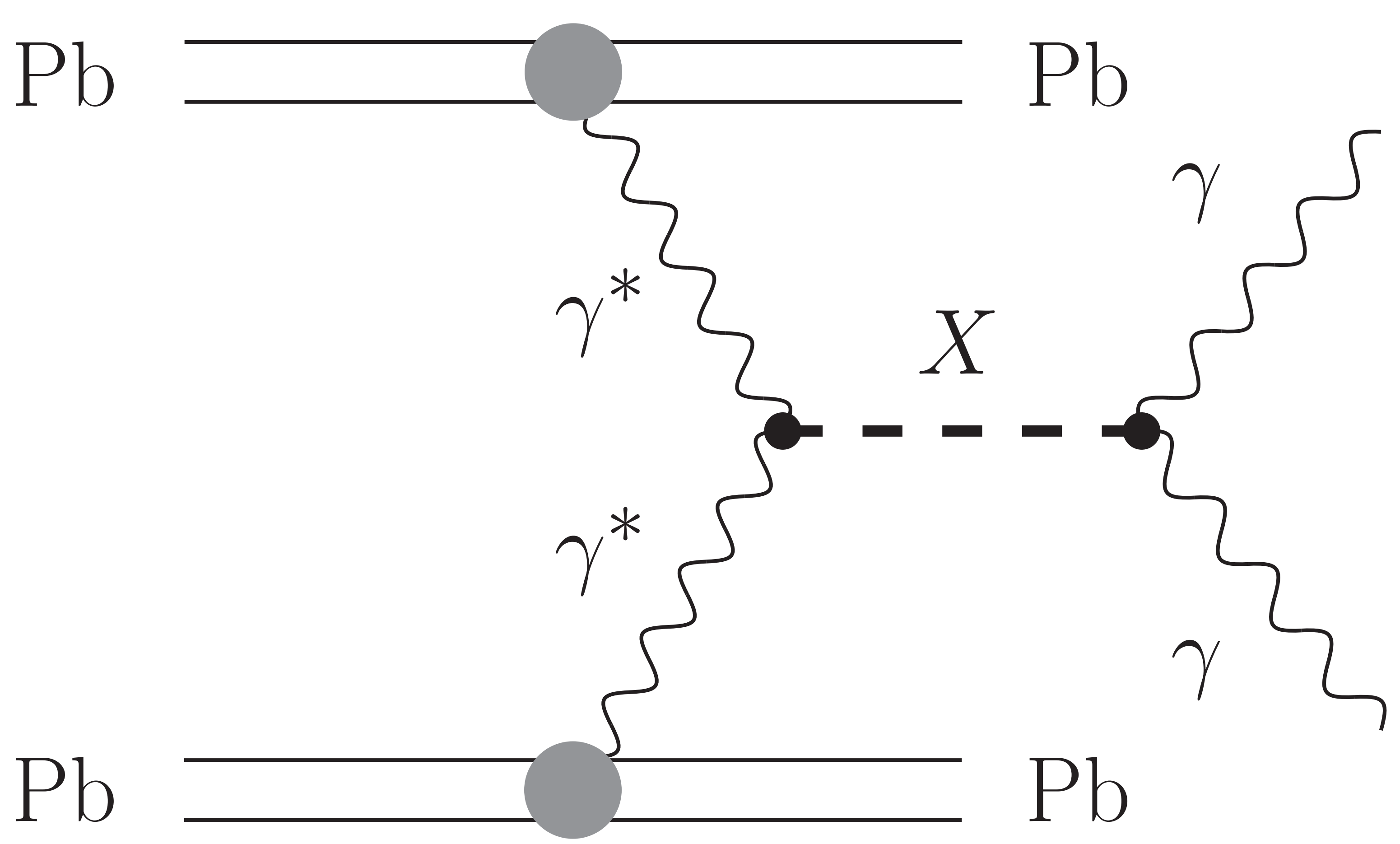




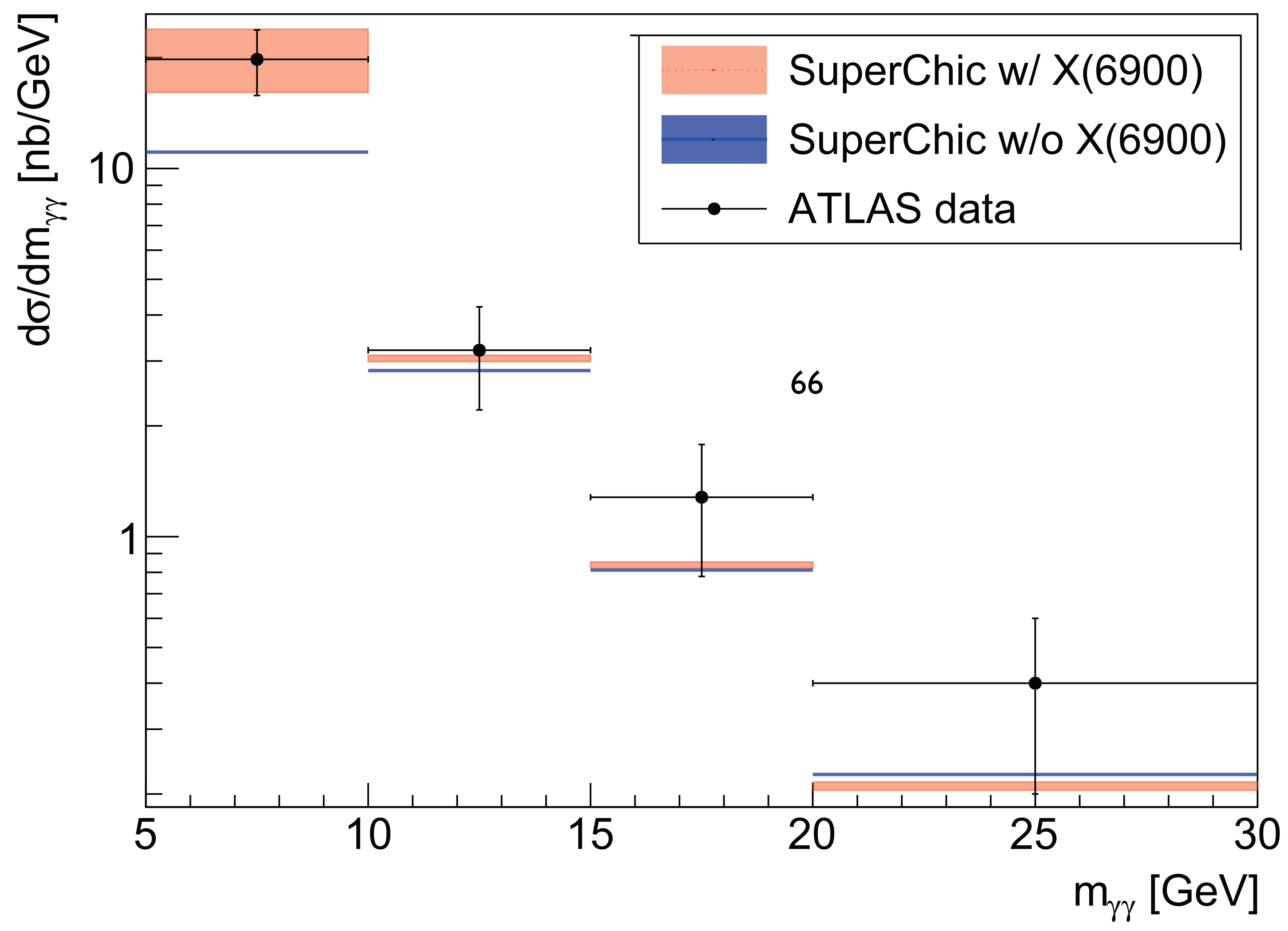
ATLAS, *JHEP* 03 (2021) 243

- Might something be going on in the lowest mass bin?

- In general sensitive to resonance production via decays to photons:



- Possible explanation of excess, exotic charmed `Tetraquark' ($cc\overline{cc}$) state at 6.9 GeV, seen in $J/\psi J/\psi$ decays at LHC in pp.

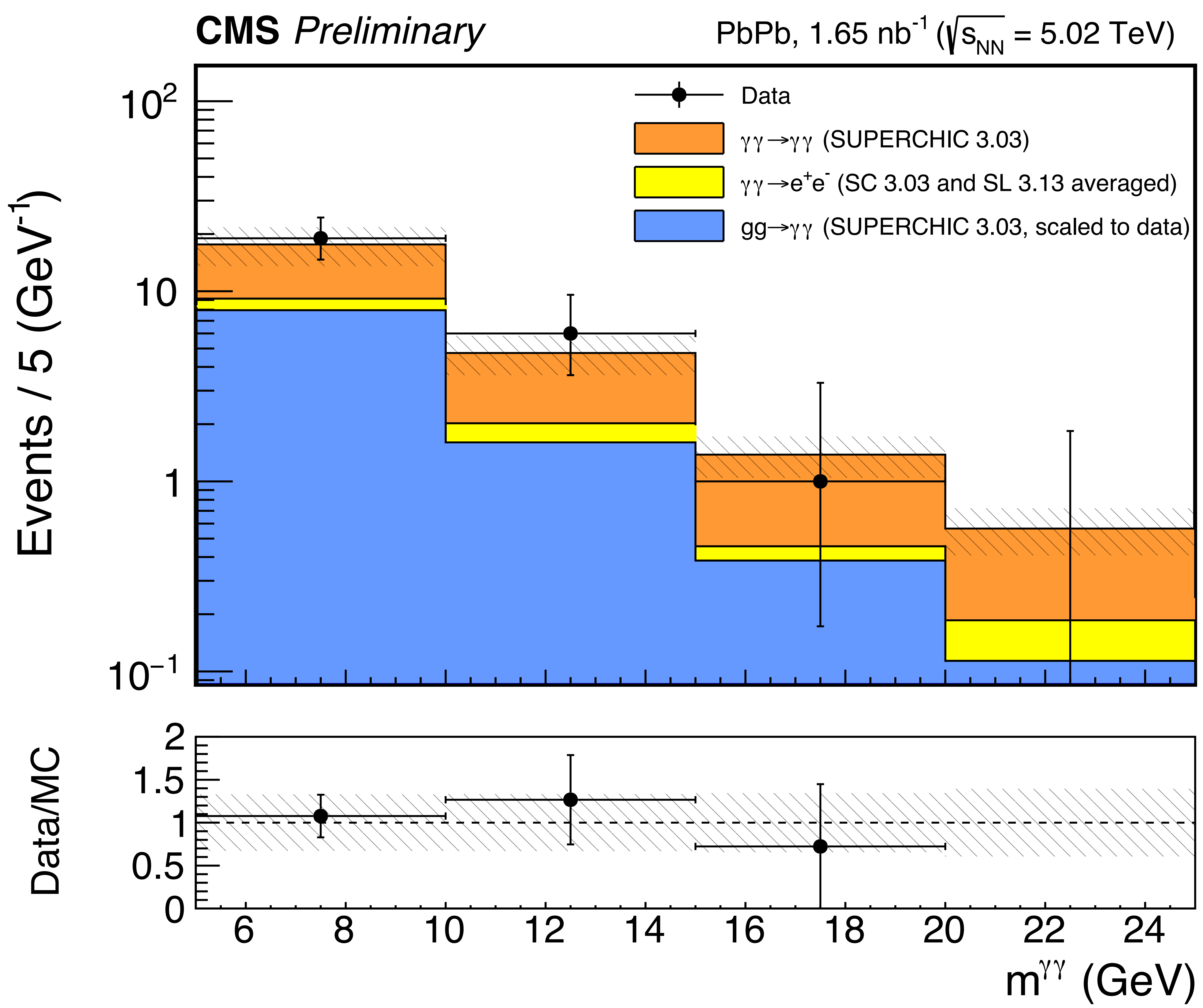


- Recent study data can be fit with this state and branching to $\gamma\gamma$ that is consistent with tetraquark hypothesis.

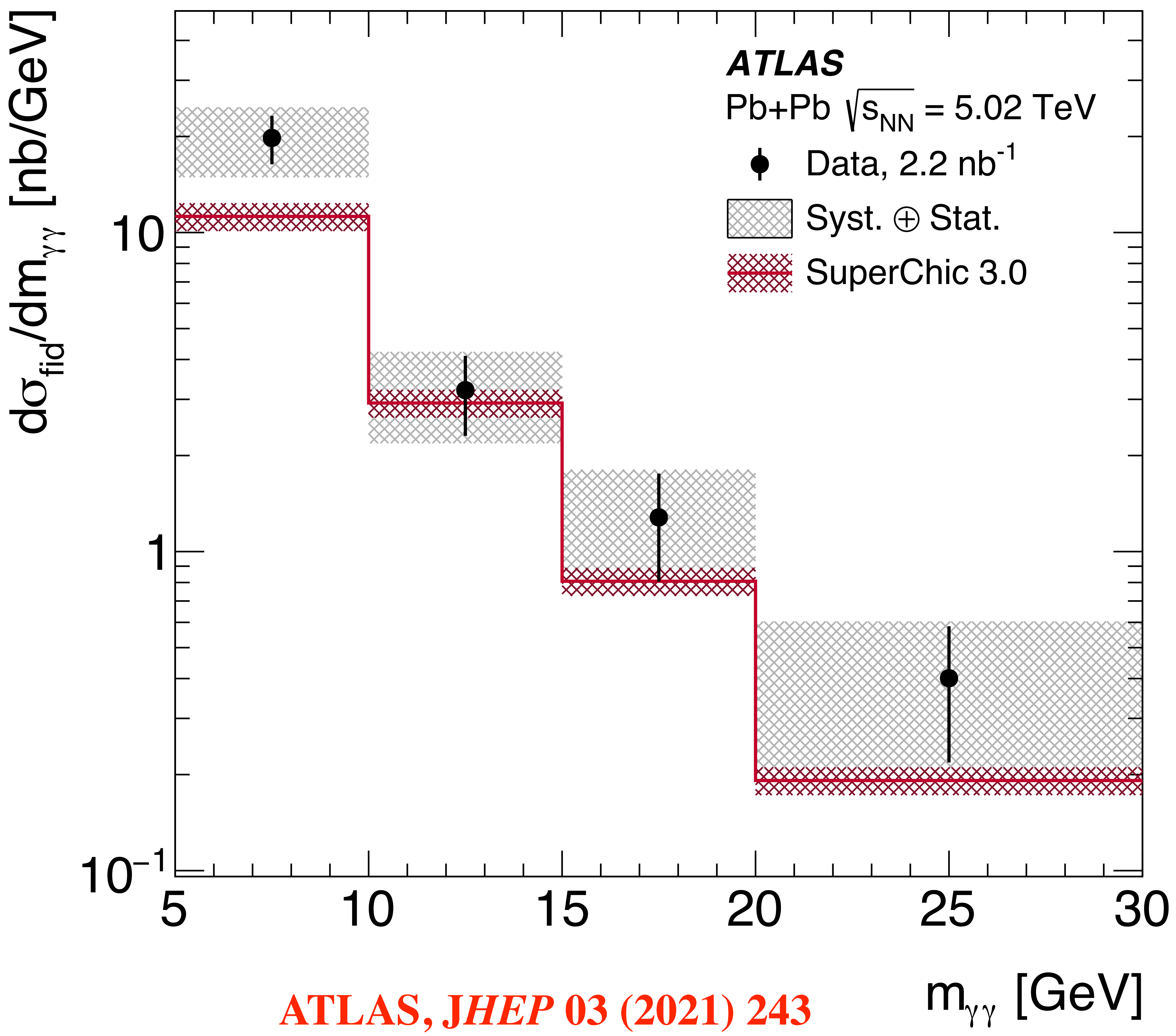
V. Biloshytskyi, V. Pascalutsa, LHL, B. Malaescu, K Schmieden, arXiv:2207.13623

- Statistical significance limited for now, but more data to come!...

- Recent CMS data does not confirm hint of excess (slightly larger errors):



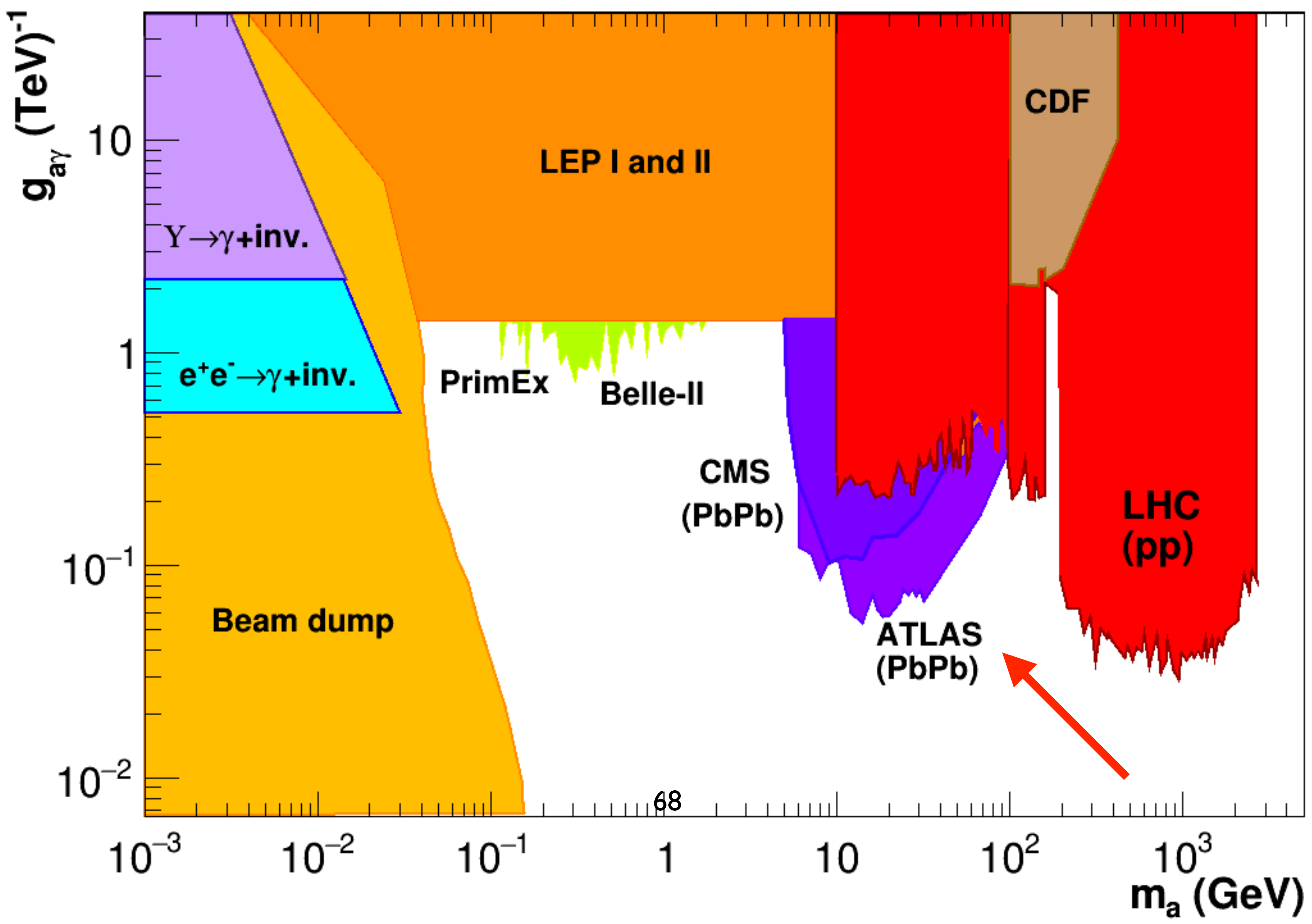
CMS, HIN-21-015-PAS



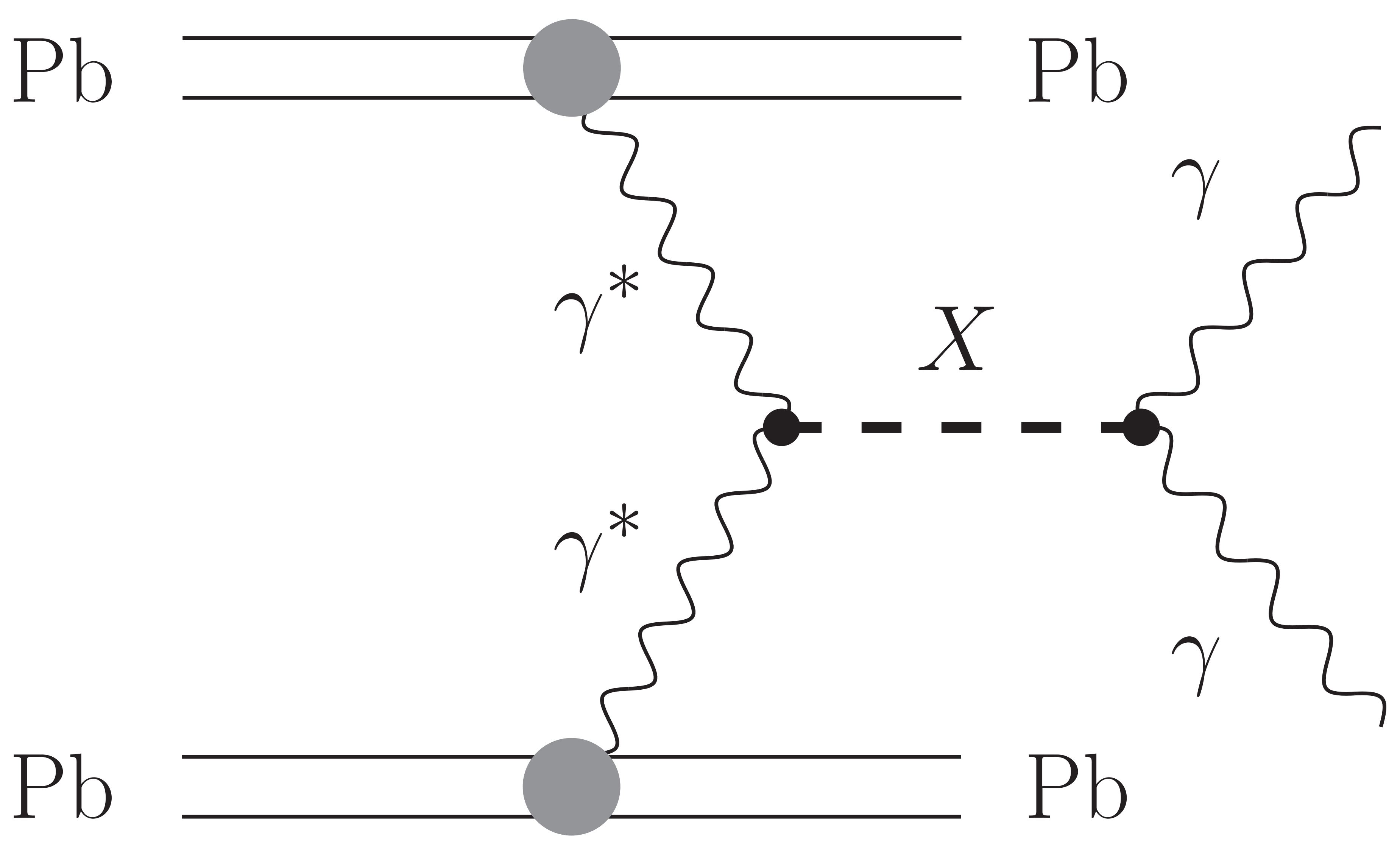
ATLAS, *JHEP* 03 (2021) 243

- Another one bites the dust?

- Such data also place the tightest constraints on **axion-like-particles** in the GeV region.



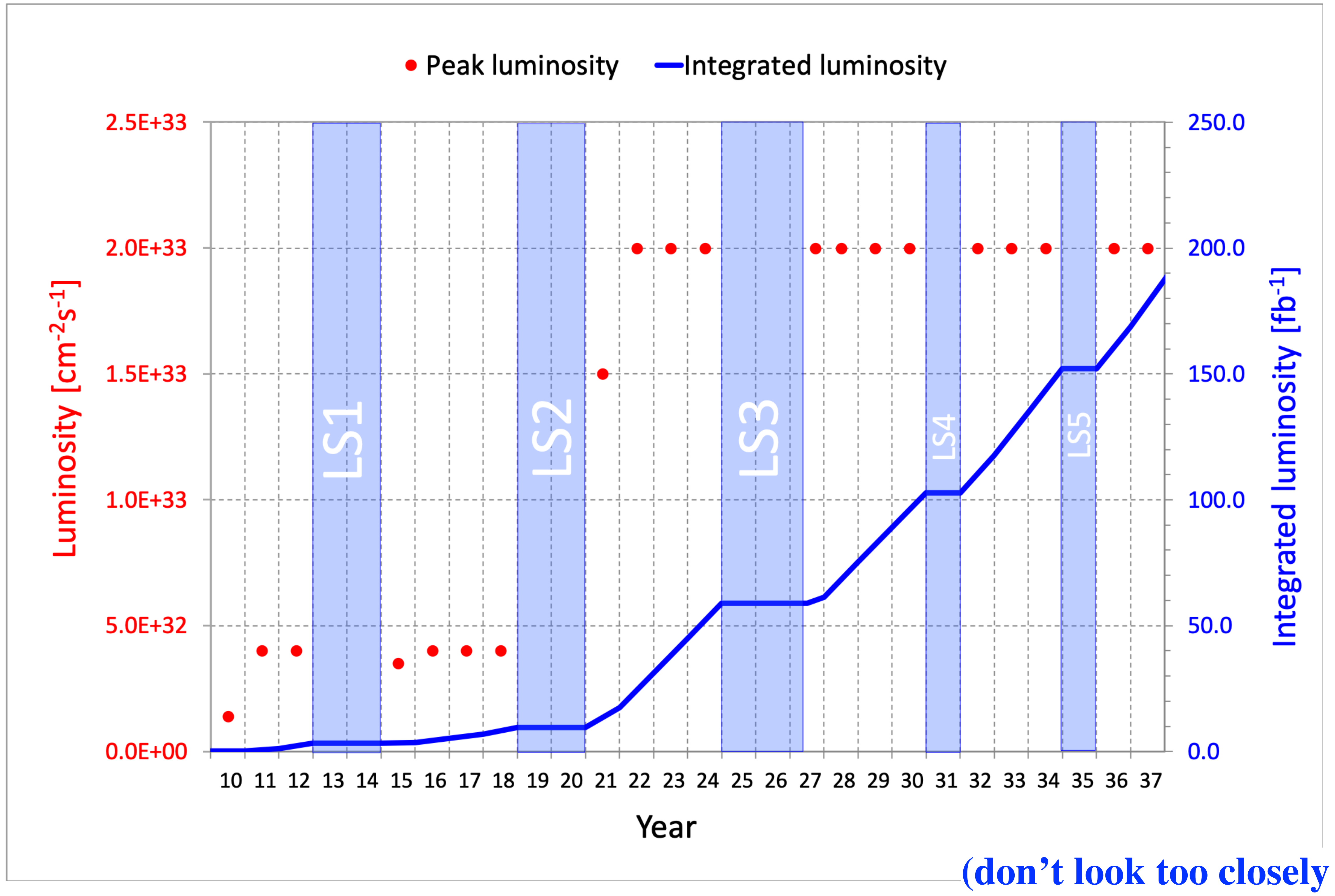
D. d'Enterria, arXiv:2102.08971



Looking to the future

- Already many new LHC measurements in the photon-initiated channel.
- But still in foothills of data taking.

- During Run 3 both **ATLAS** and **CMS** continuing to take semi-exclusive pp data with and without tagged protons.



(don't look too closely at the years!)

- Work towards HL-LHC running at **CMS** (and **ATLAS**) underway, with new taggers being proposed.

- Similarly in AA collisions, much new data to come, with **ALICE** and **LHCb** entering the game.

- So far statistics can limit things:

pp:

★ **More data** $\Rightarrow$ tighter constraints on vector boson production. Will go differential and with new channels to explore $\Rightarrow$ more BSM constraints/data.

★ Many other **searches** (SUSY, ALPs, monopoles…) to come.

AA:

★ Drill down on tau g-2, light-by-light…

- However many of these searches rely on precise **theoretical understanding** of underlying production process. Will become increasingly important.

- Much progress has been made here, but much more still to do…

- Much left to explore:

pp:

★ SM well modelled, but what about BSM? Full EFT analysis of possible BSM effects, using SuperChic machinery to model photon-initiated production (c.f. WW production).

★ Parton shower/hadronization of proton dissociation system and matching to MC. Approach so far relies on approximation, definite room for improvement.

★ Survival factor: allowing some additional particle production?

AA:

★ Ion dissociation.

★ Higher order QED effects and unitarisation.

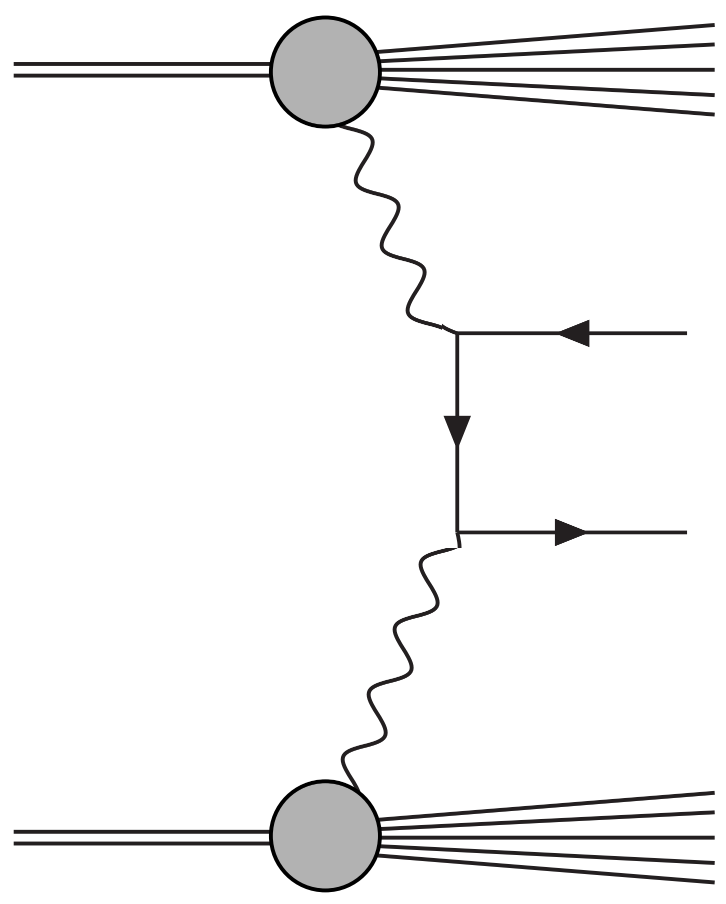
★ Soft photon resummation?

- And of course **new channels** out there! Much **physics** to come.

Thank you for listening!

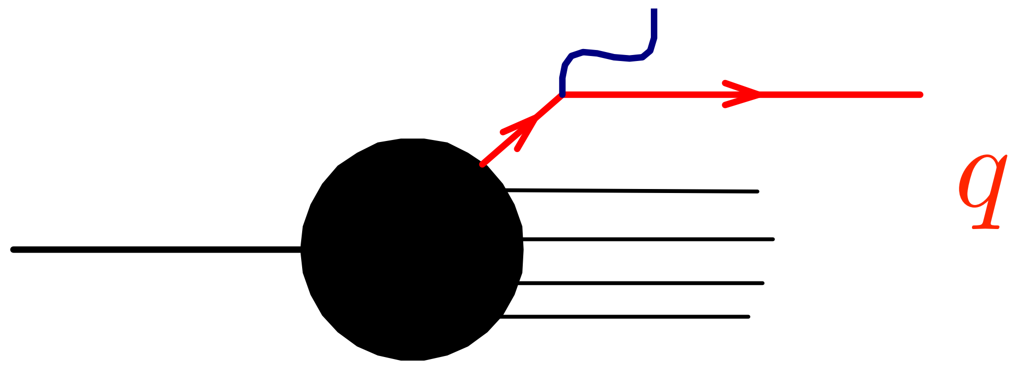
Backup

PI + ISR Showering



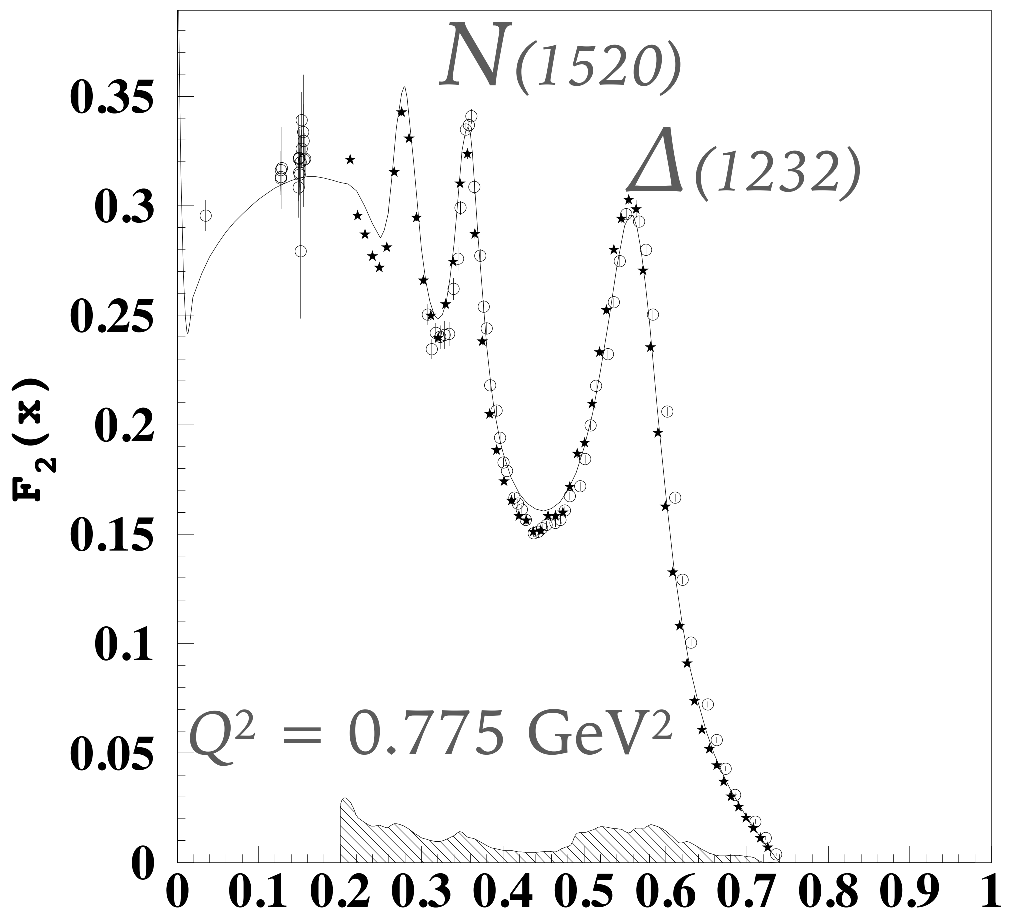
- SF calculation give precision prediction for photon x, Q^2 and we would like showering/hadronisation of dissociation system to respect this.

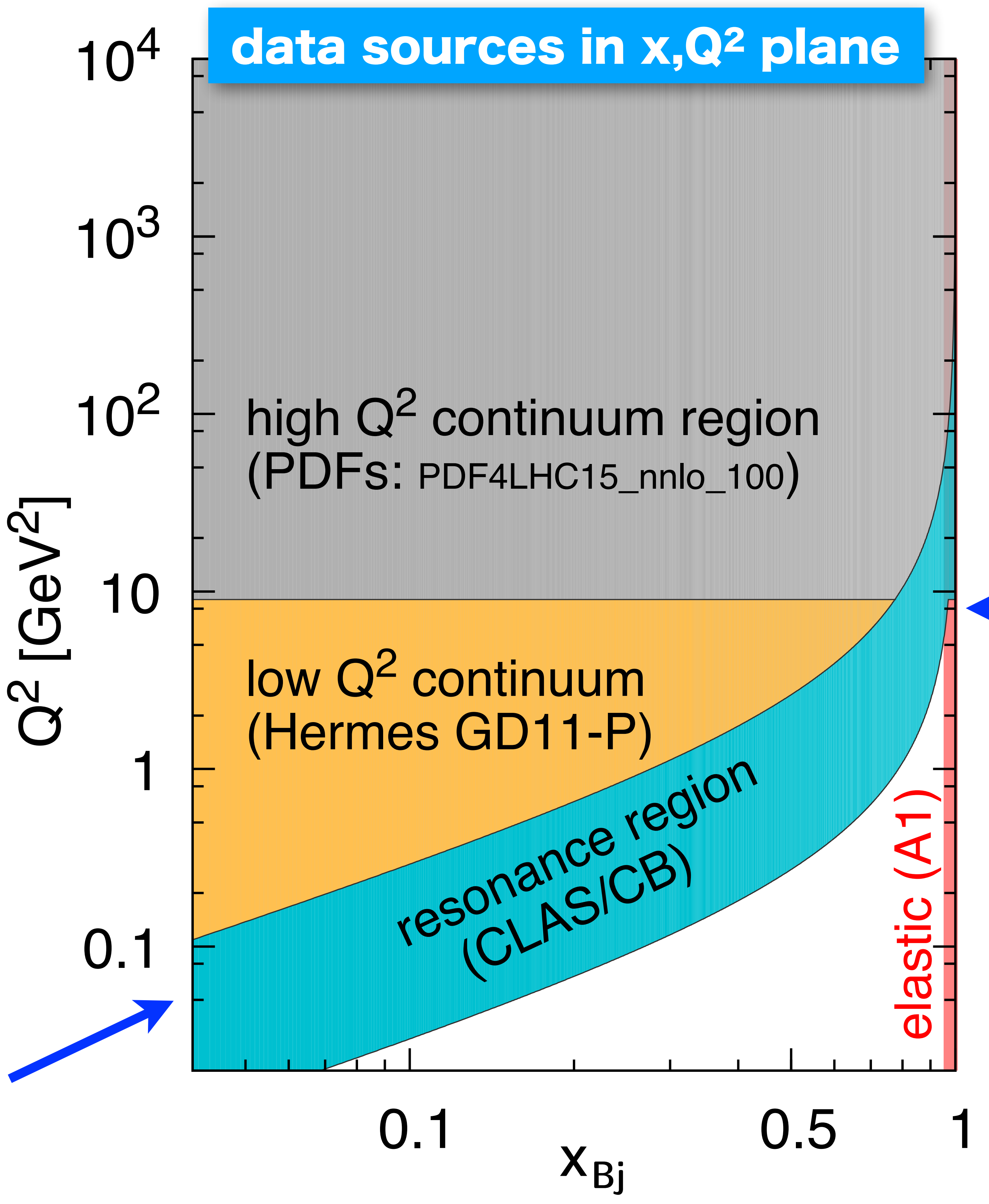
- No clear off-the-shelf way to do this, so take simplified approach:
    - ★ For purposes of LHE record, for inelastic emission take LO $q \to q\gamma$vertex
    - ★ Generate outgoing quark according to momentum conservation, preserving photon 4-momentum.

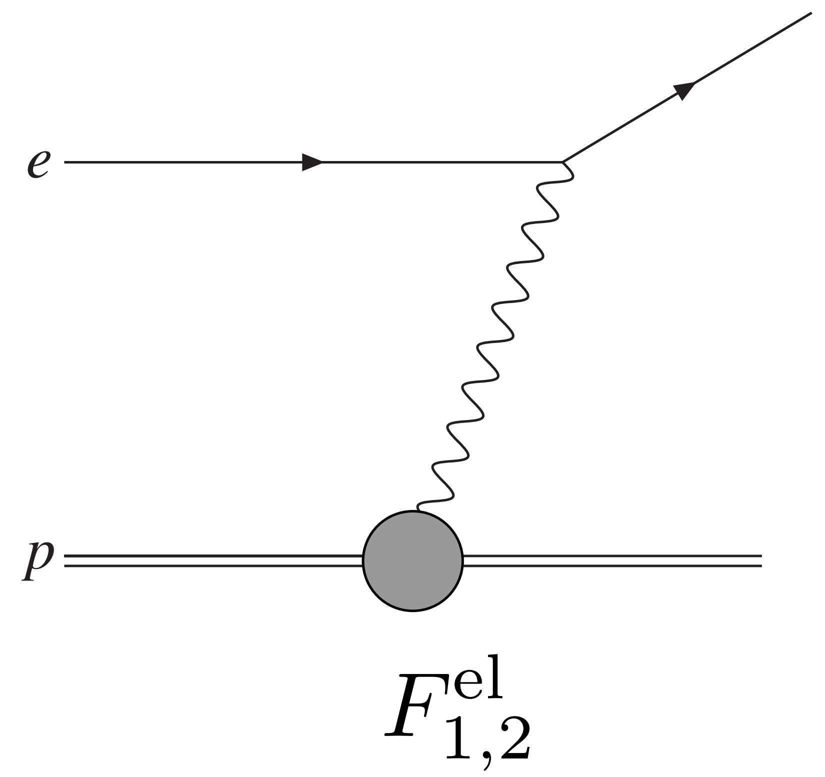


- ISR/FSR will then modify photon 4-momentum. Not ideal, but for purpose of current study sufficient.
- In addition, must turn off global recoil in Pythia to get realistic result (no colour connection between beams).

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



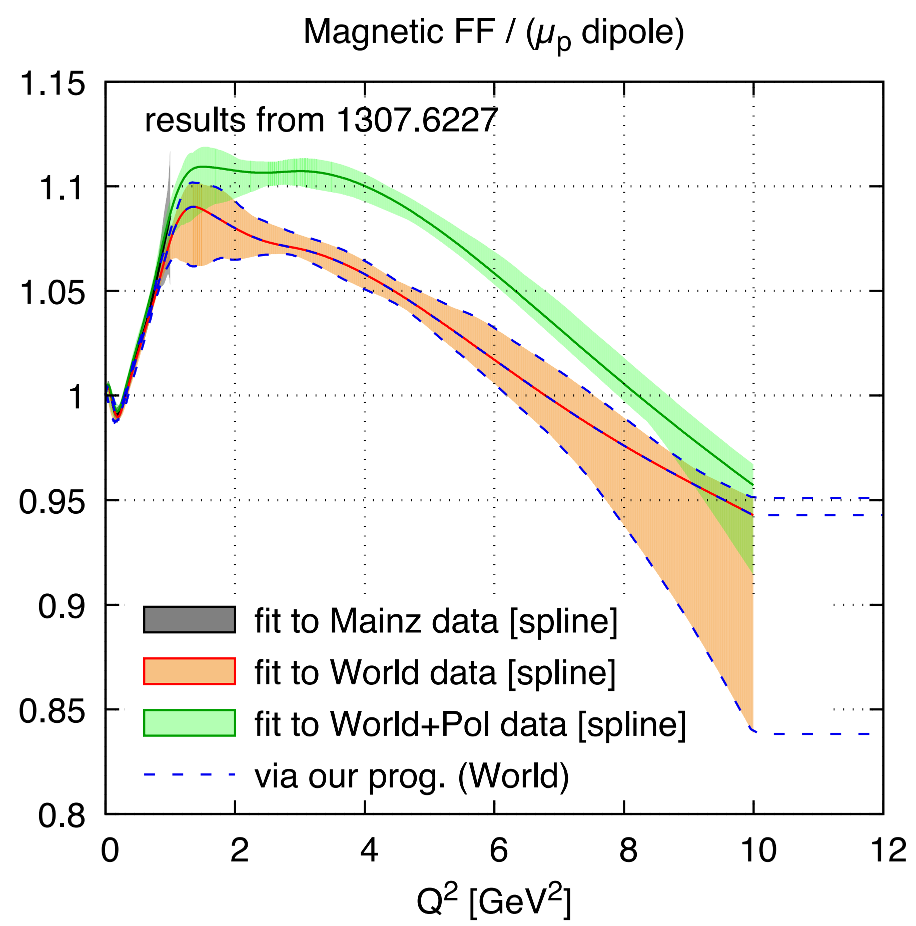




Inelastic resonant proton excitation. Precise parameterisations available.

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

Elastic scattering: from A1 collaboration.



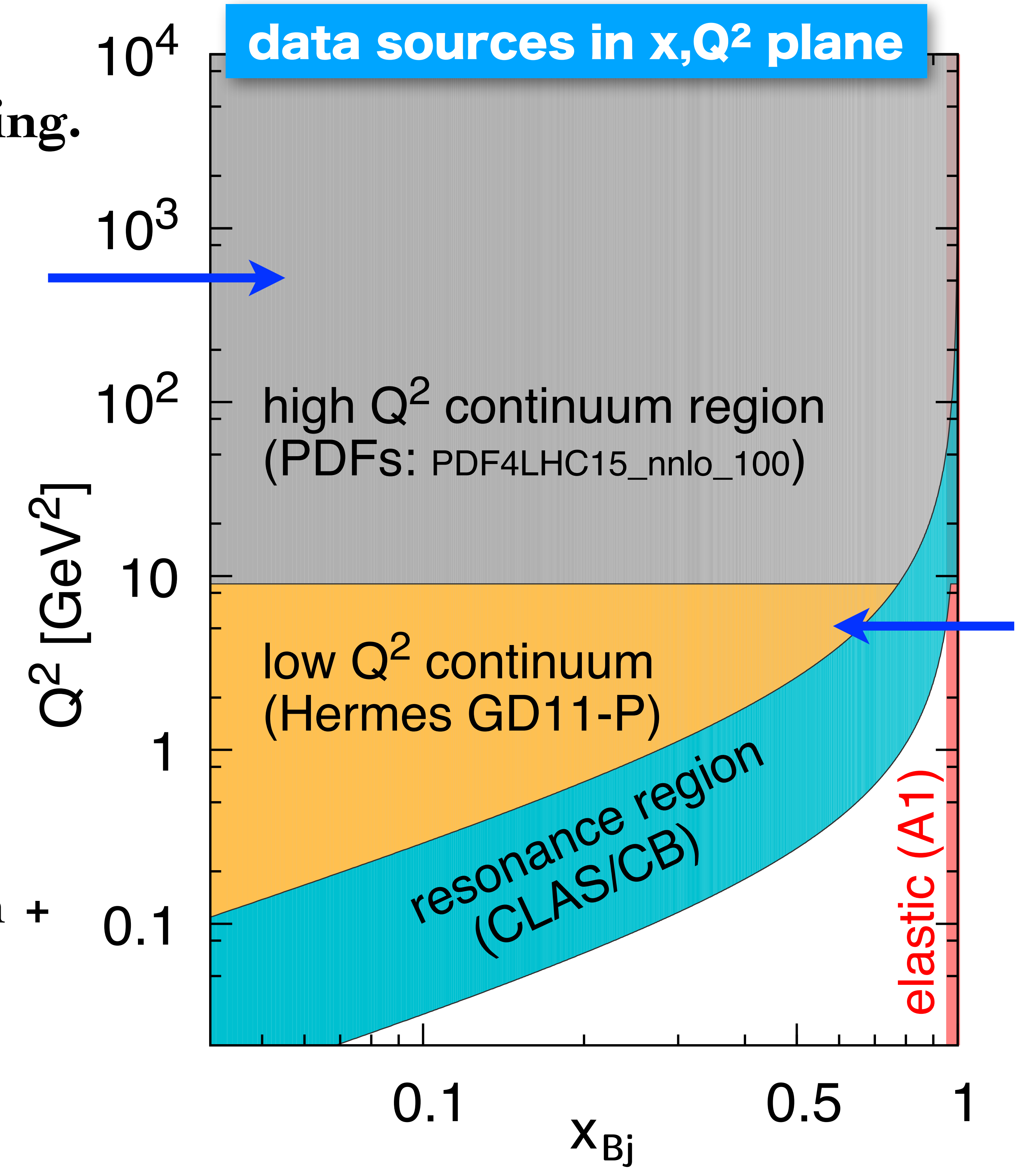
A1 Collaboration, Phys. Rev. C90, 015206 (2014)

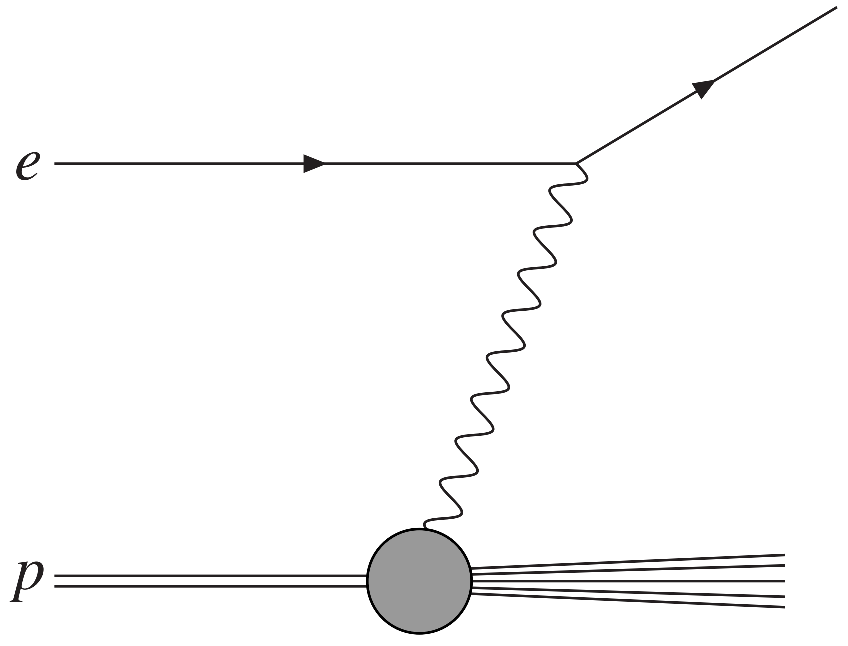
Image credits: Gavin Salam

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

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

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

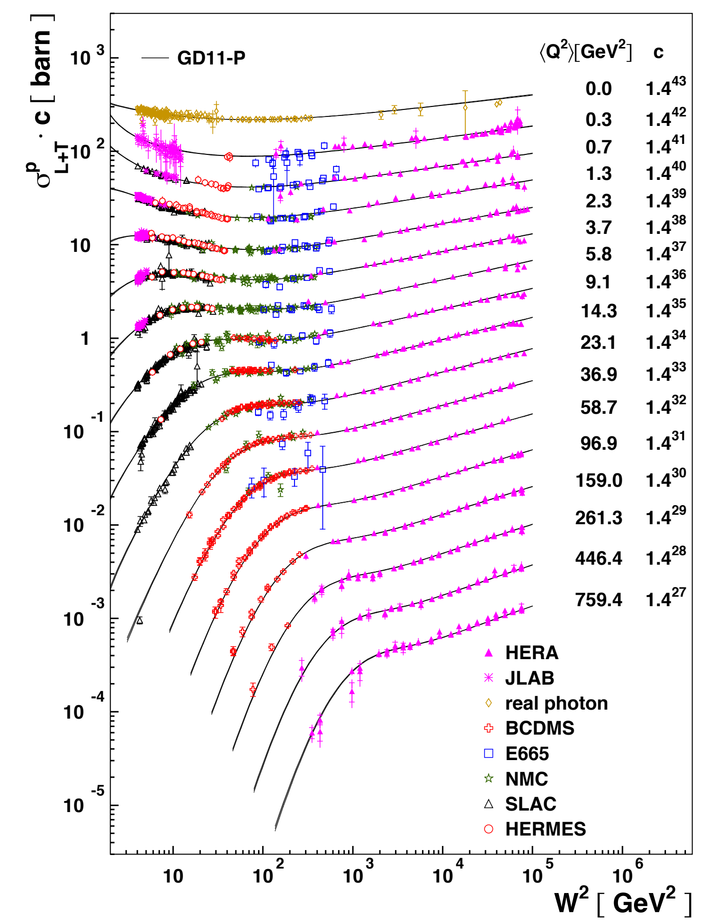




$F_{1,2}^{\text{inel}}$

Inelastic low Q^2 scattering. Precise parameterisation available.

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



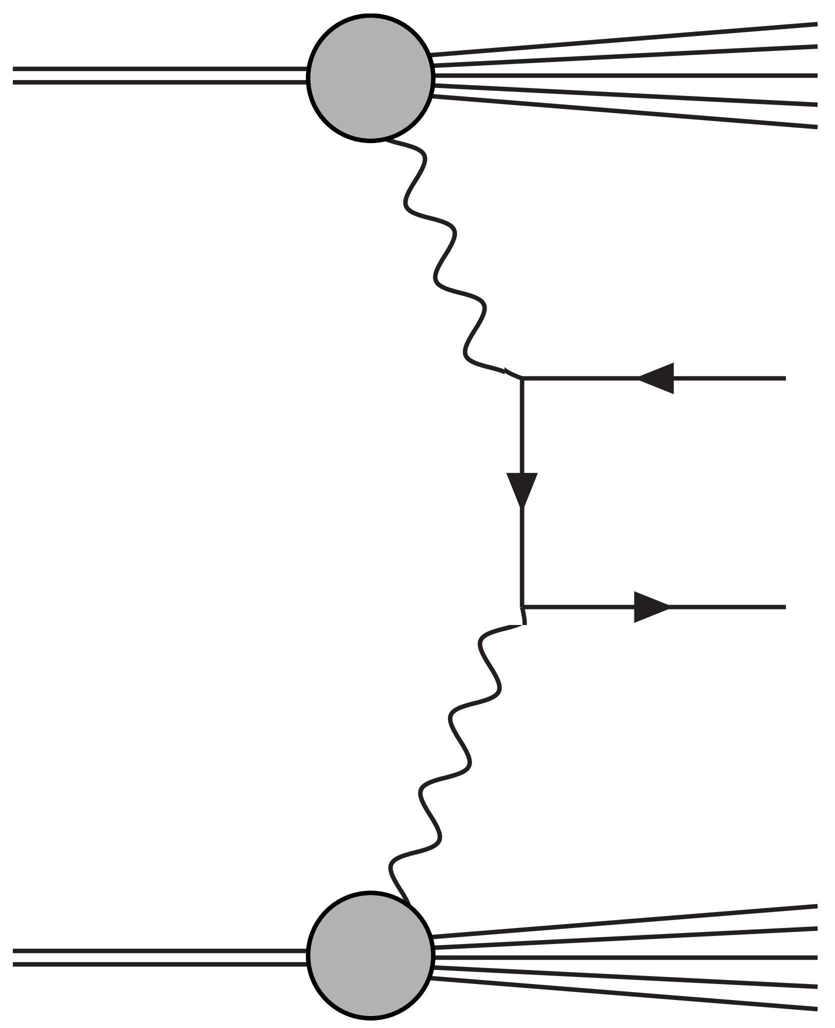
- Closely follow LUXqed inputs here.

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

Other Considerations

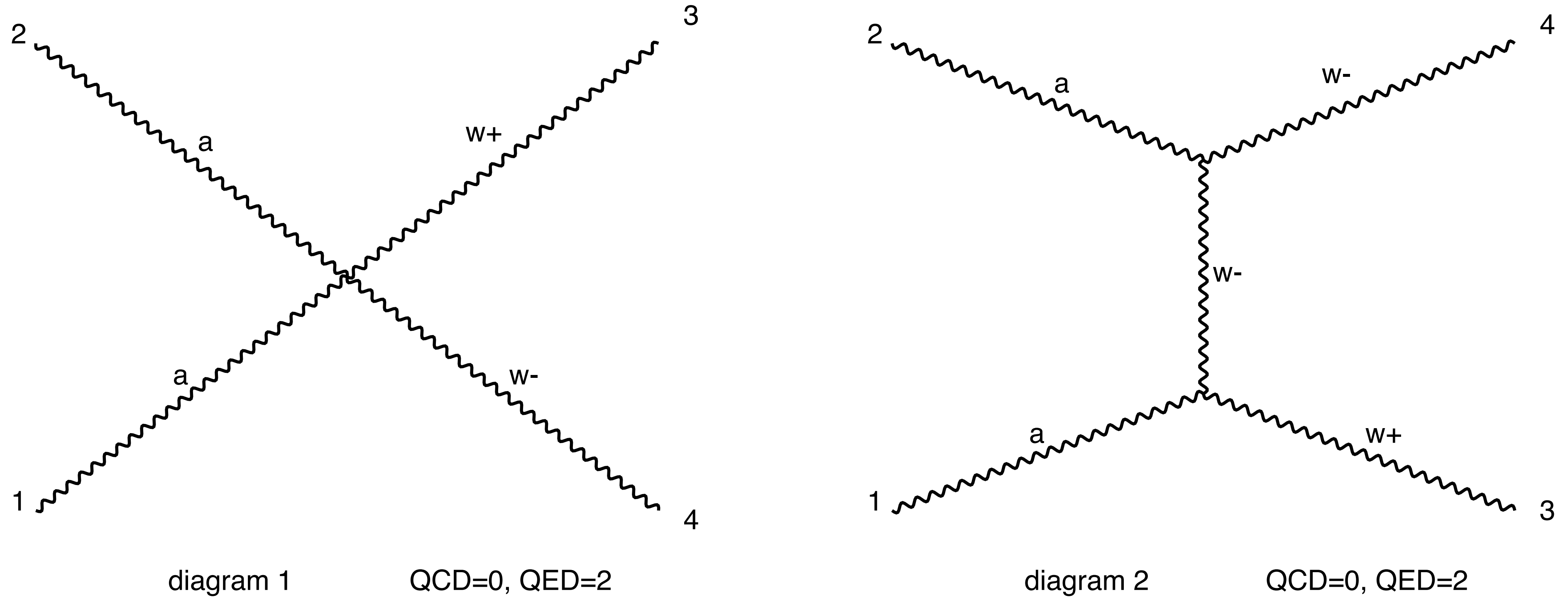
Collinear Calculation

- 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.

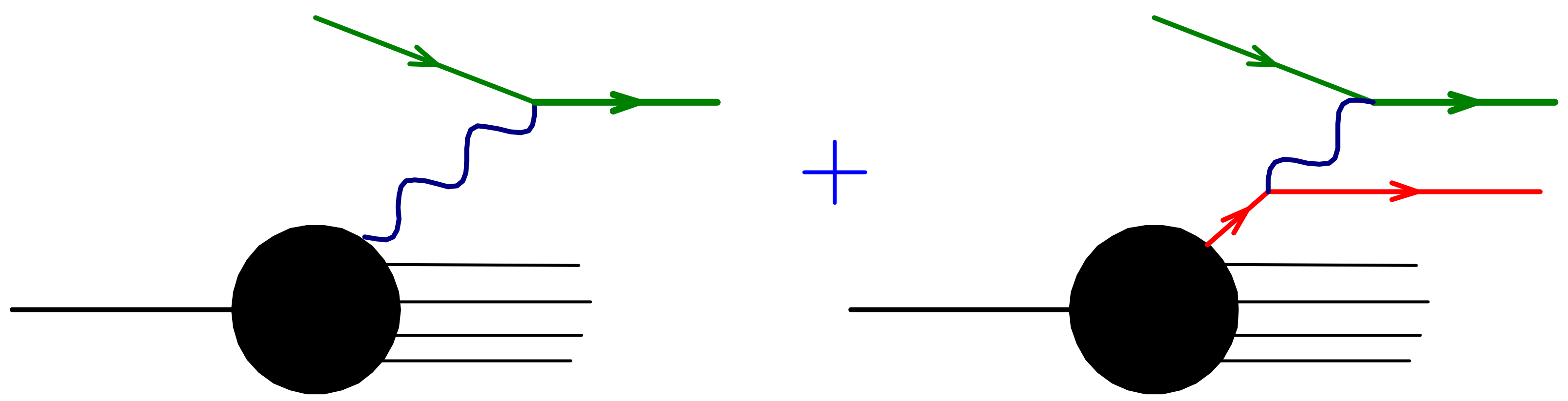


- Can show that collinear calculation is (approximately) equivalent to full structure function calculation for pure PI production:

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

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

- 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:

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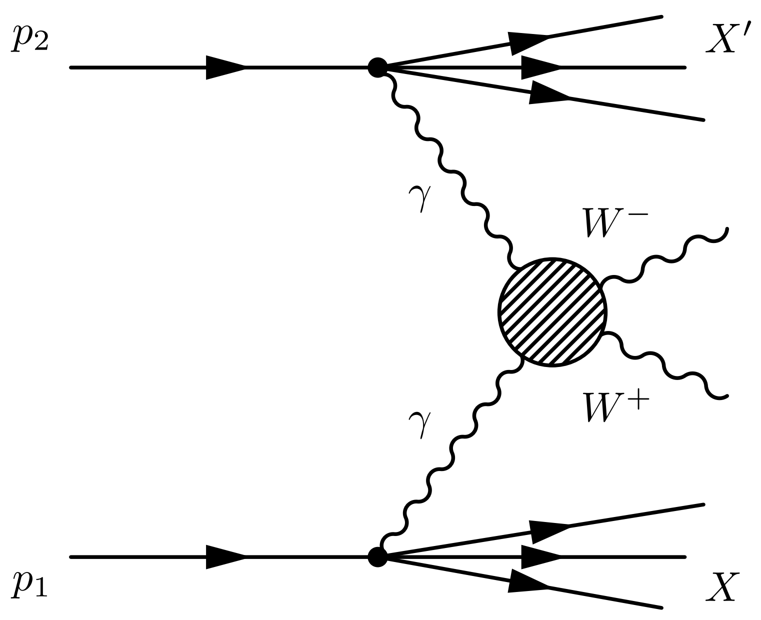

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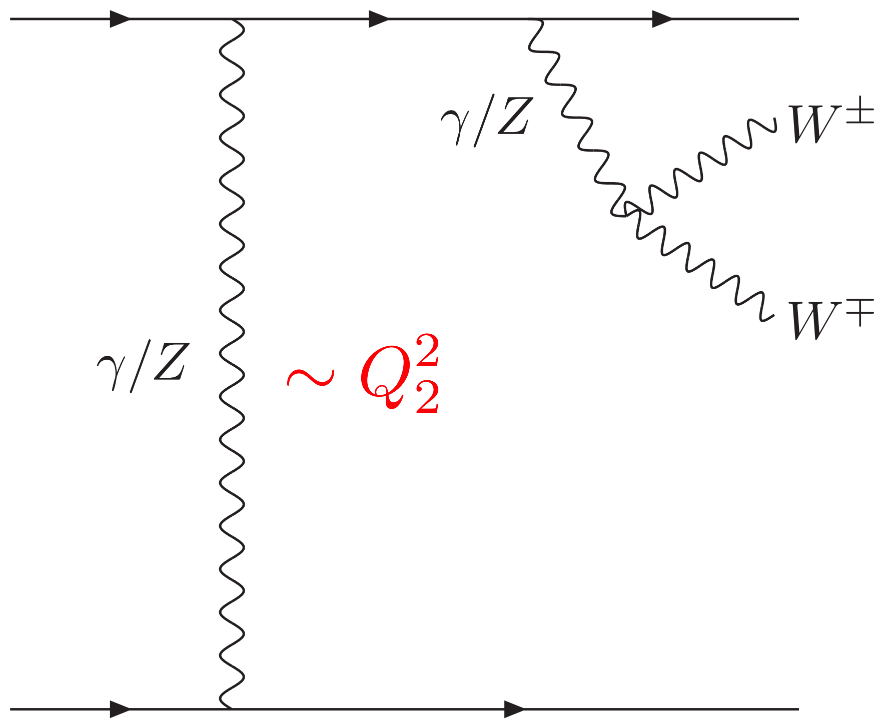
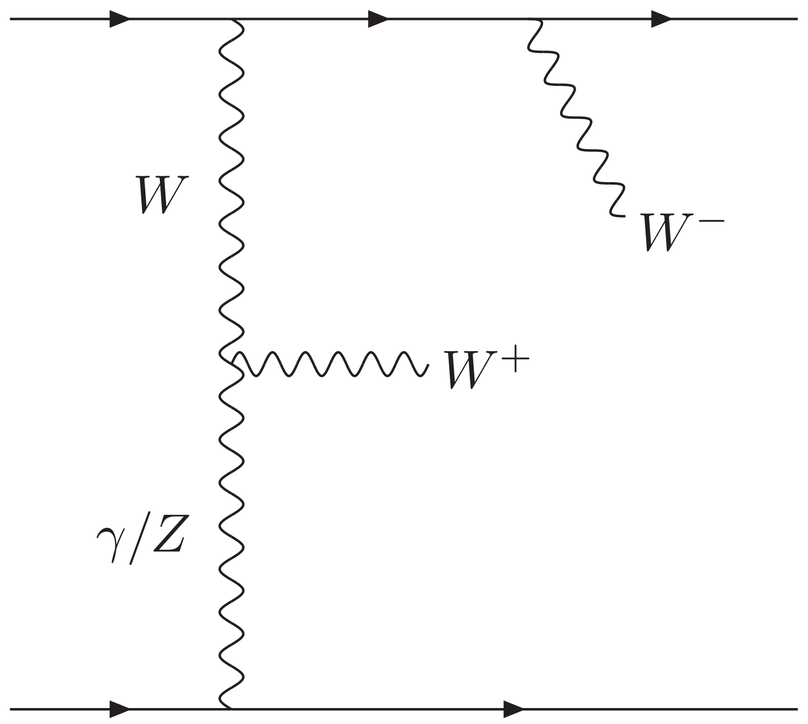
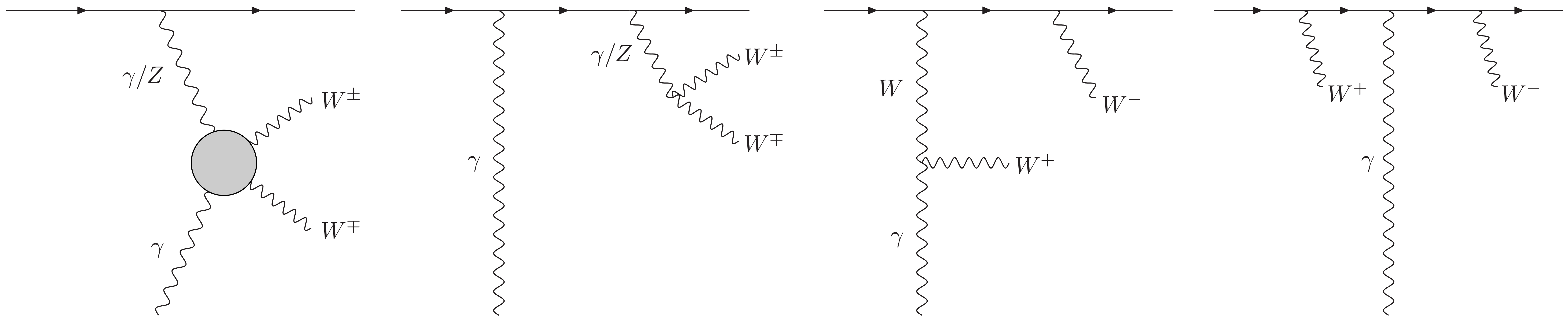




+ …

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

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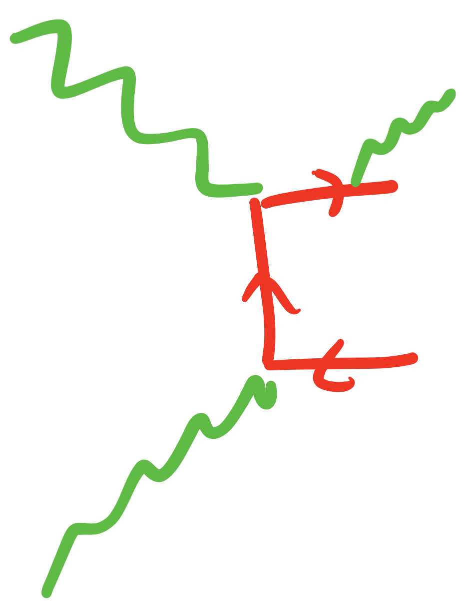
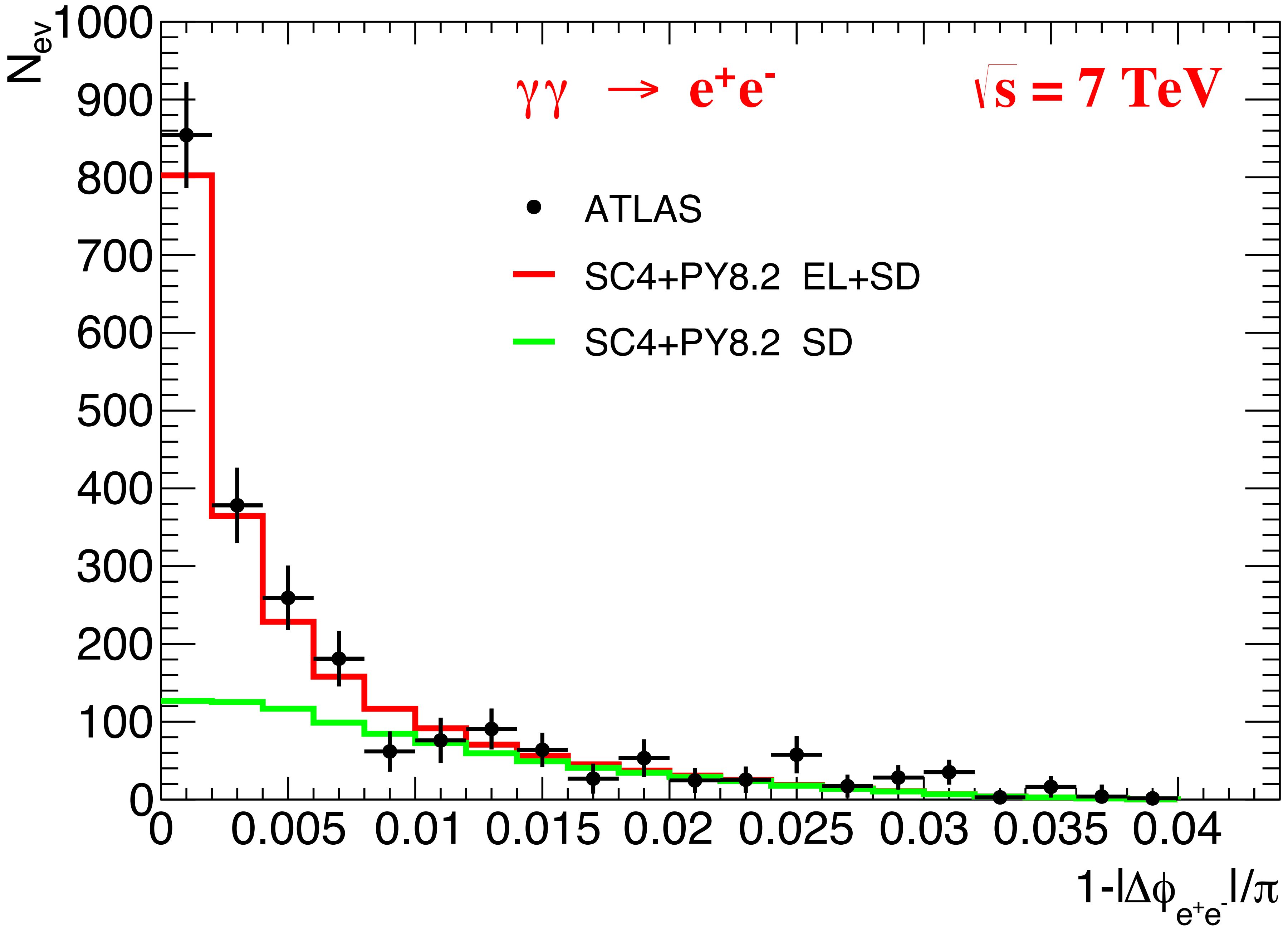
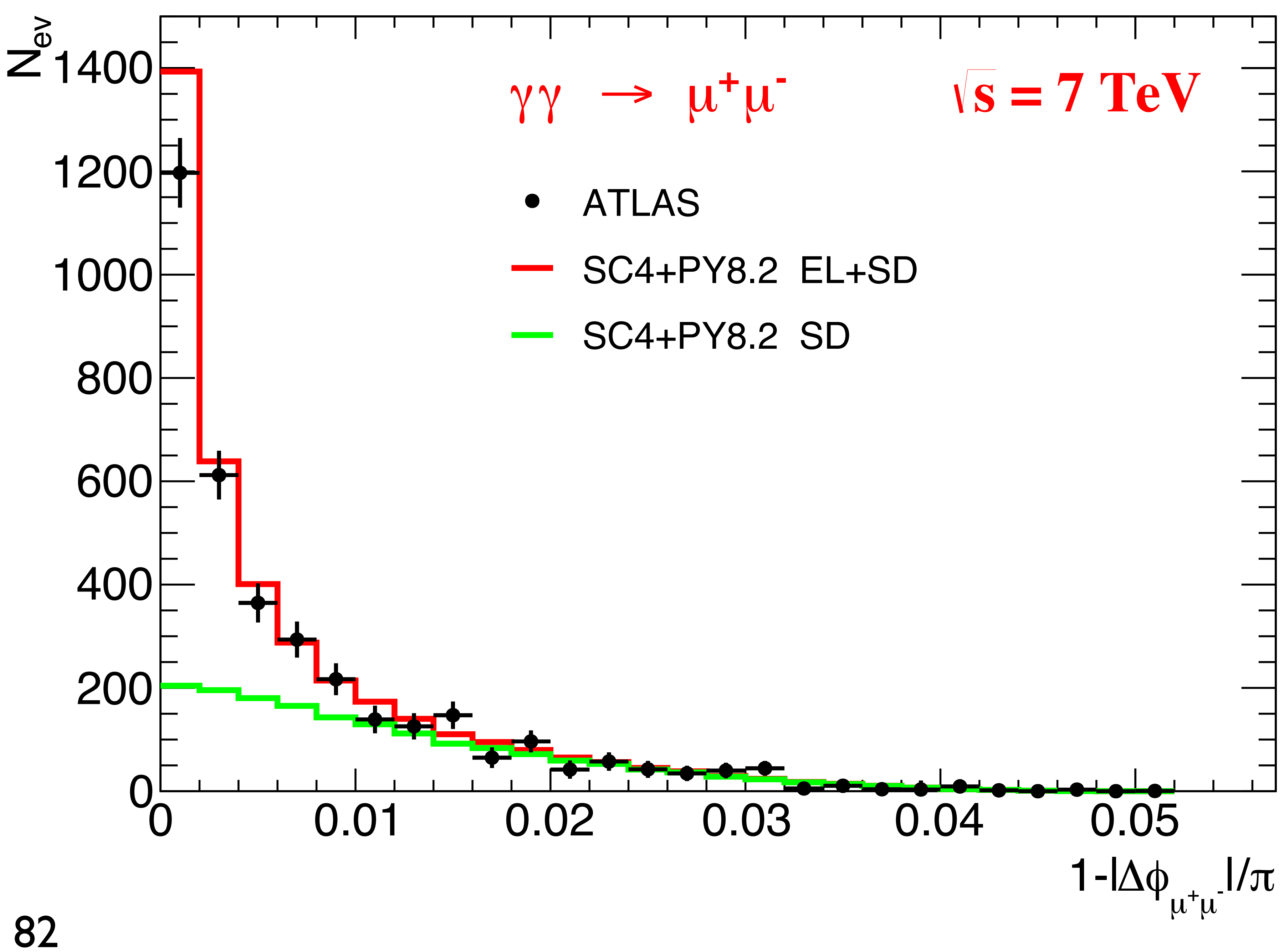
- Could also use (NLO…) collinear factorization although this comes with complications.
- Impact of non-PI production depends on experimental selection and process:
  - ★ W pair production: O(10%) correction.
  - ★ Lepton pair production: O(1%) correction.

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.



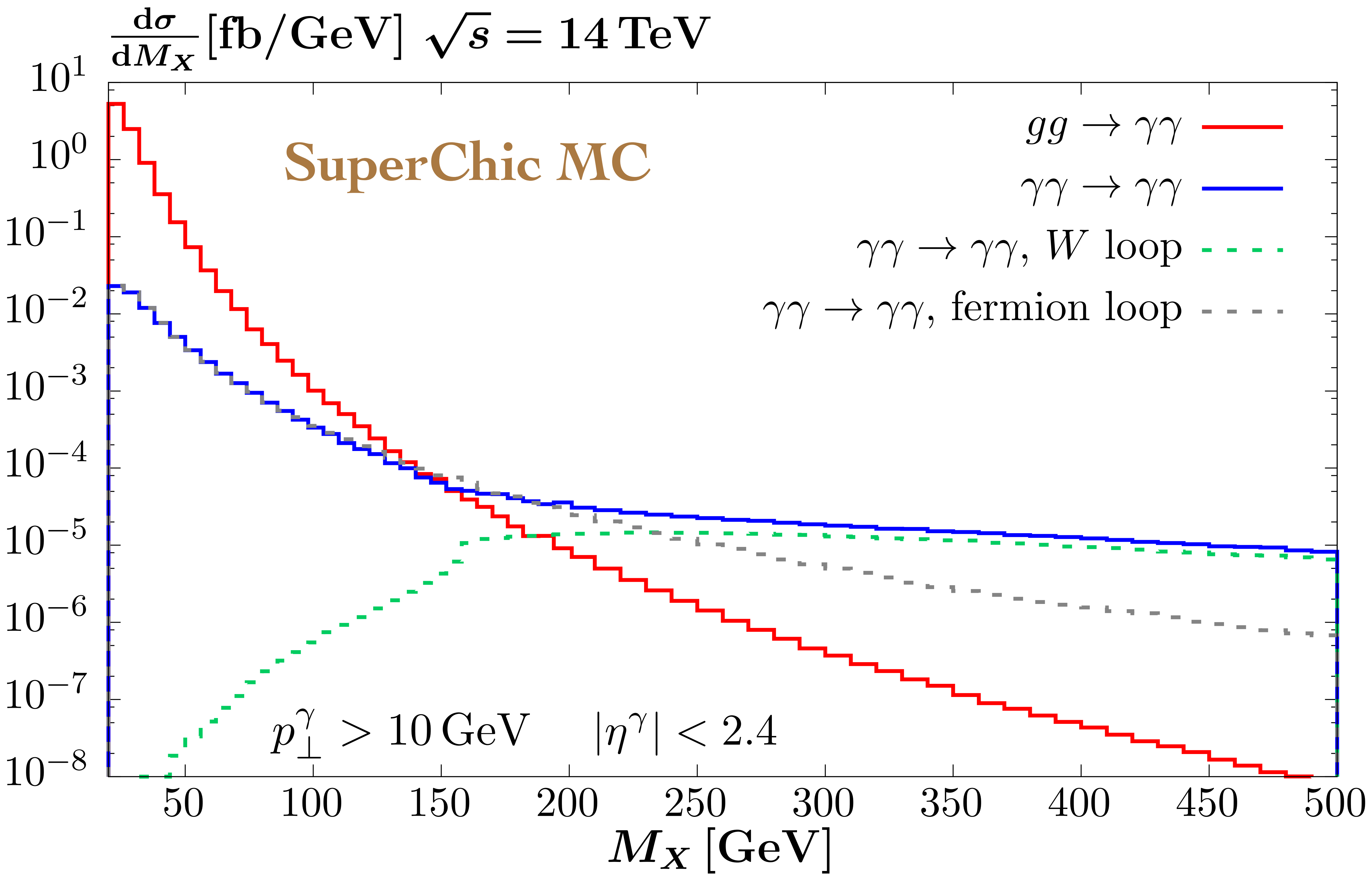


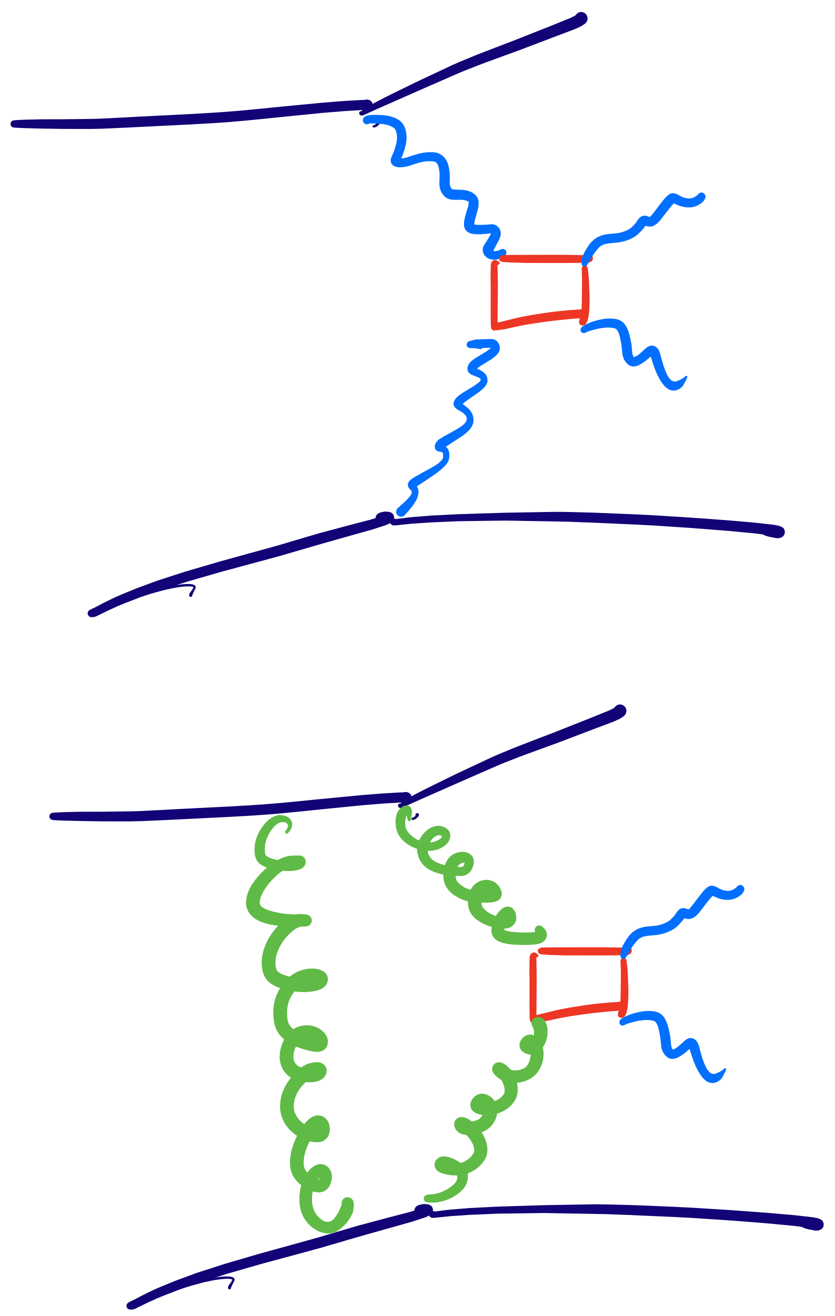


gg vs. $\gamma\gamma$

- 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.

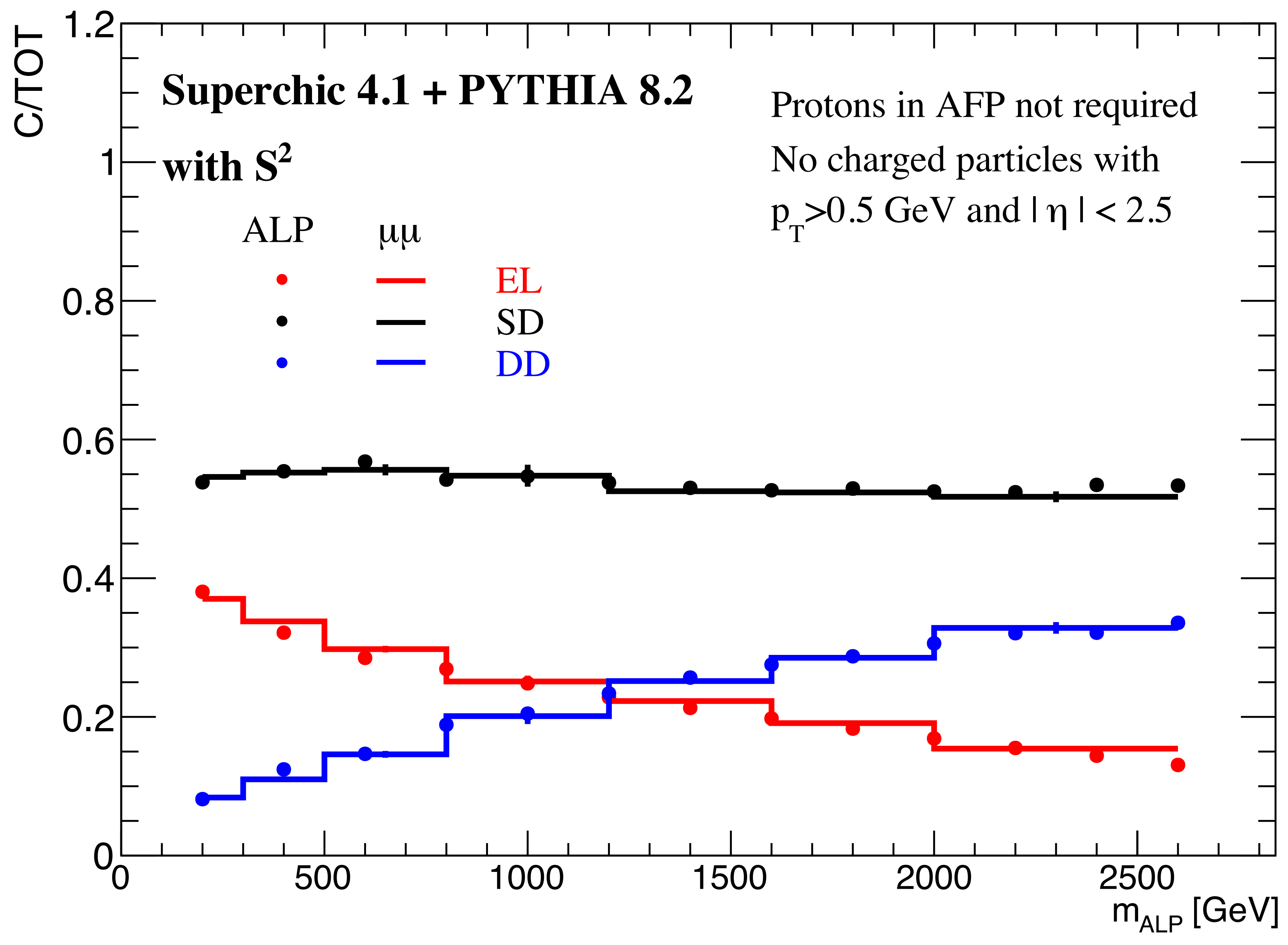
$\longrightarrow$ At higher mass PI production starts to dominate.

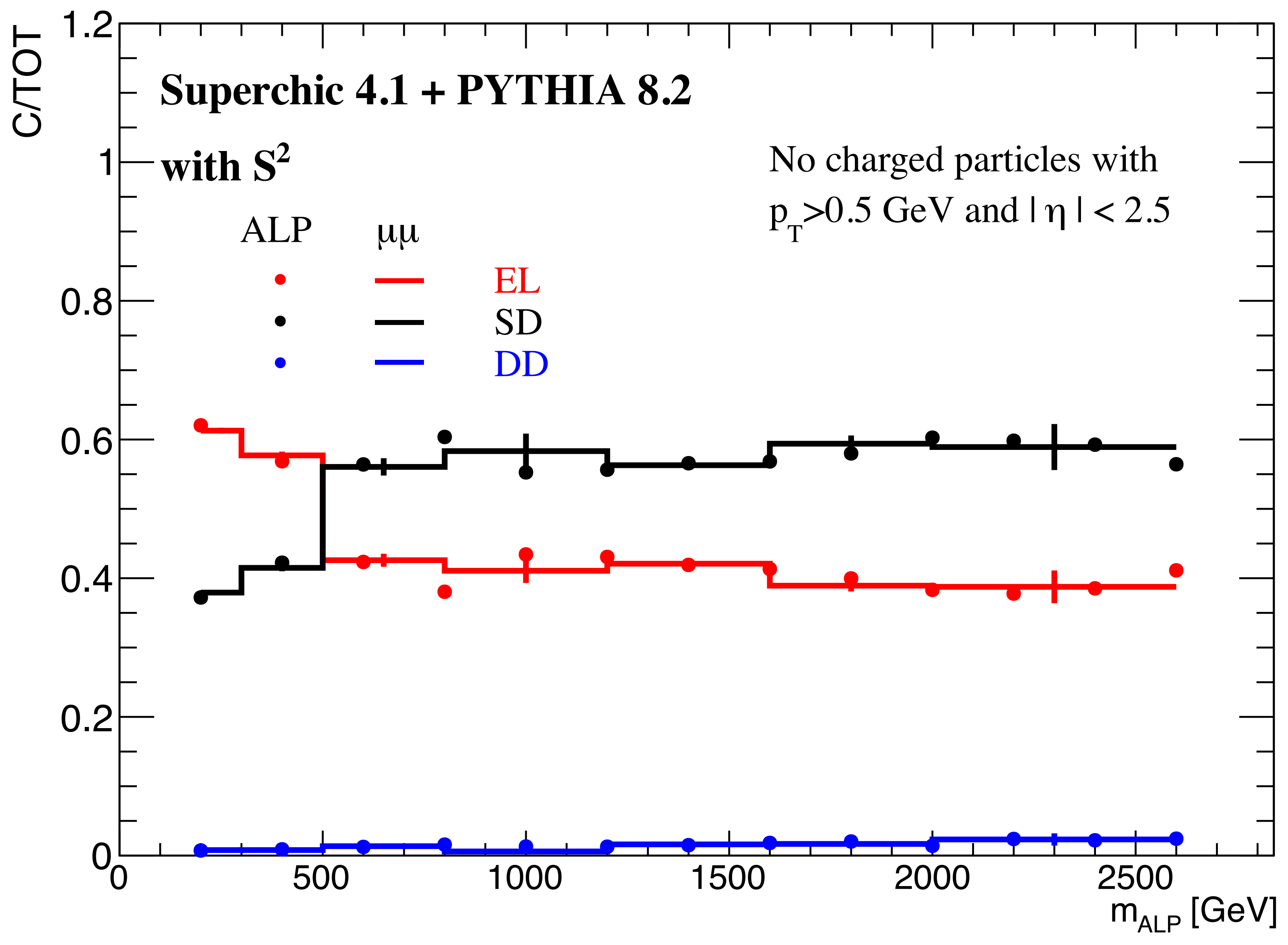




Proton Tag Impact

- 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