Generators for Photon-Photon Physics

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New Vistas in Photon Physics in Heavy-Ion Collisions

Outline

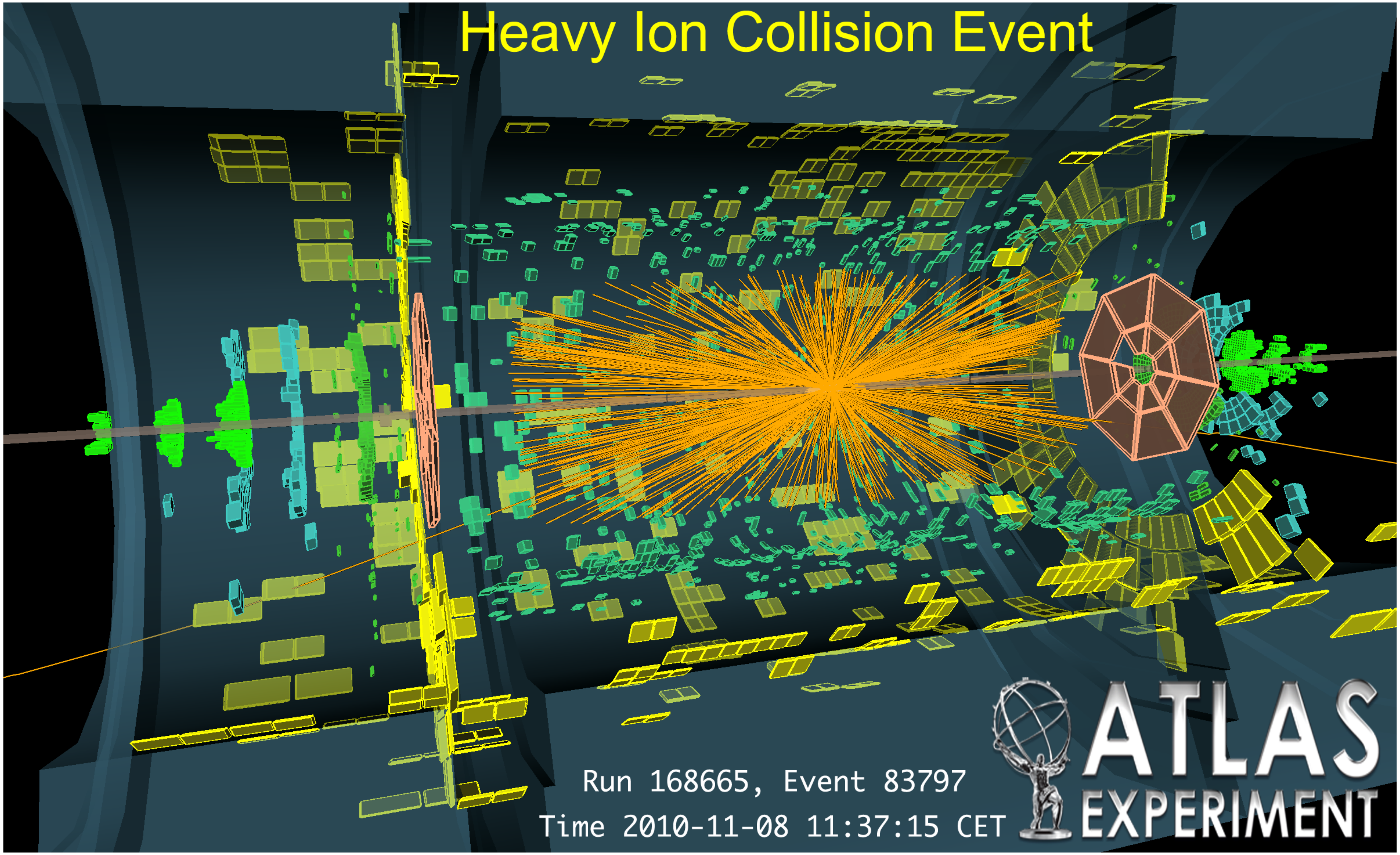
- **Motivation:** why study photon-photon physics in heavy collisions?

- How can we model $\gamma\gamma$ collisions in a heavy ion environment?

- What generators are available and how do they differ?

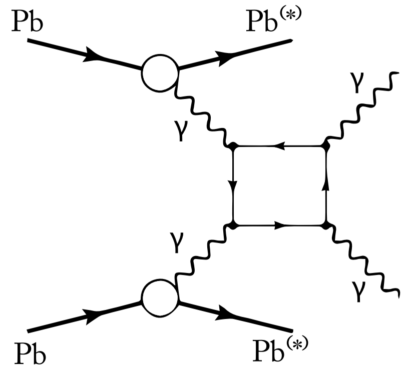
Motivation

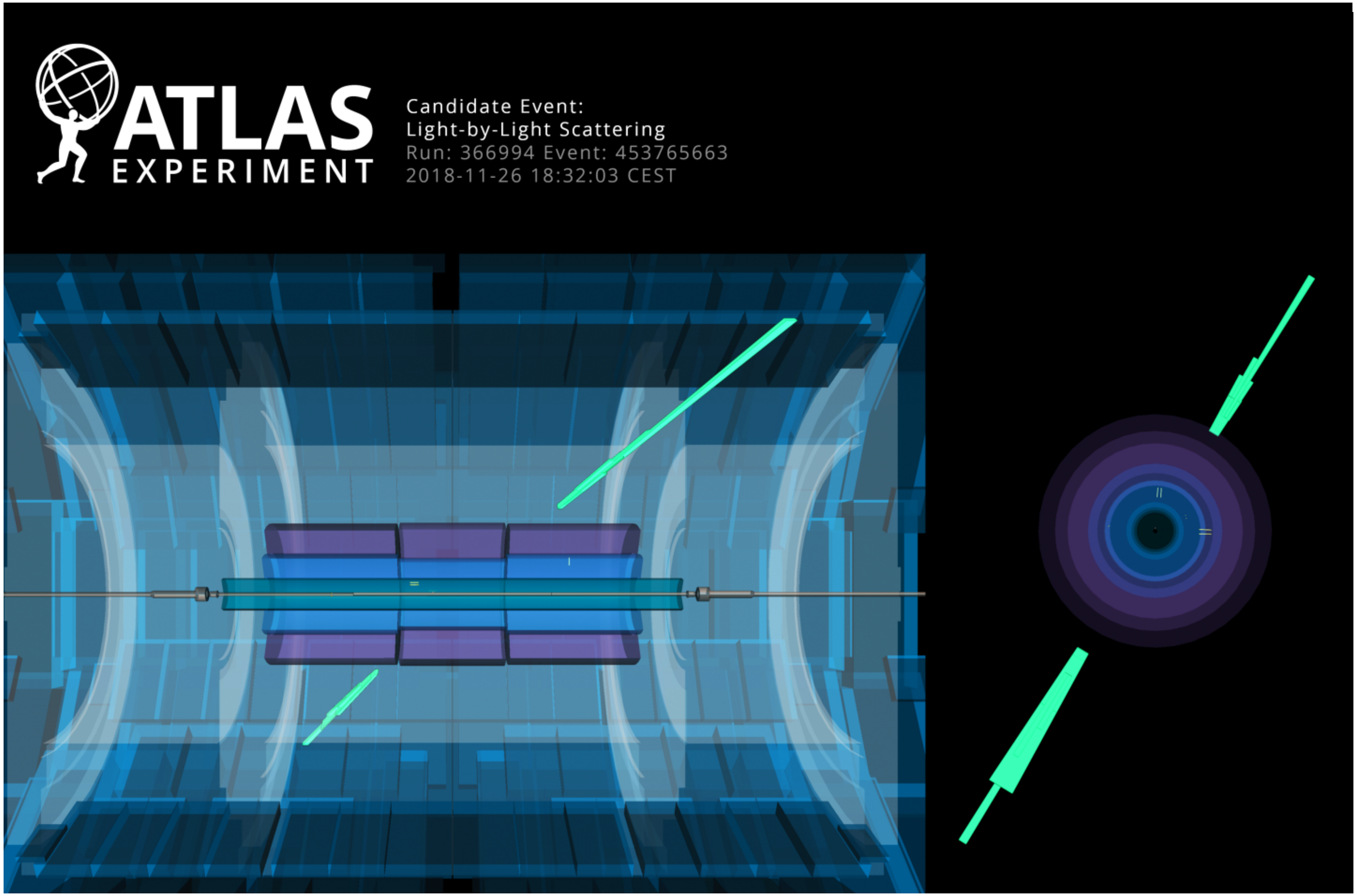
- A ‘standard’ heavy ion collisions looks like this:



- But not the only possibility…

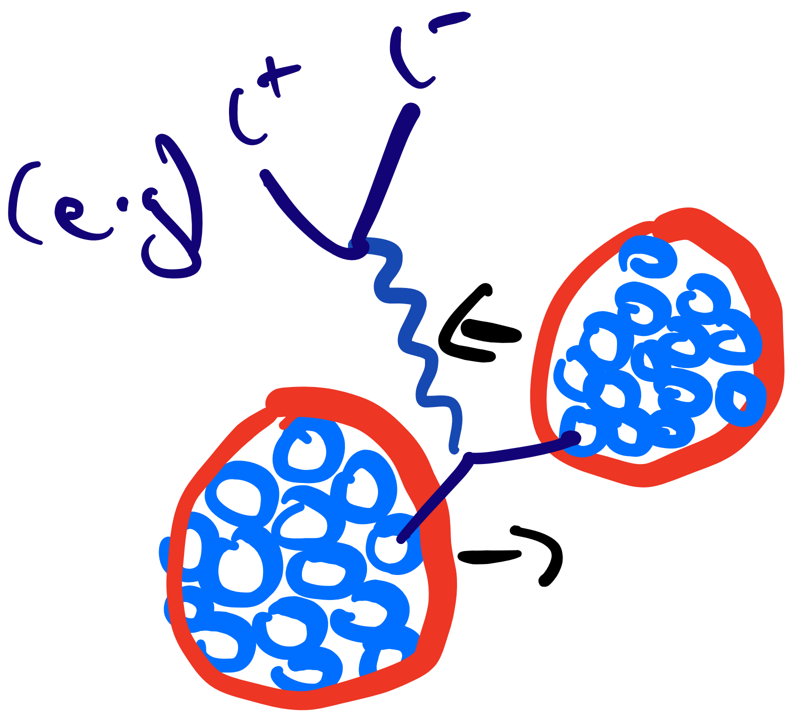
• Candidate `light-by-light' scattering event:





• How does this come about?

- In ‘standard’ heavy collision, large number of nucleons in initial state QCD particle production enhanced and multiplicity can be very high.



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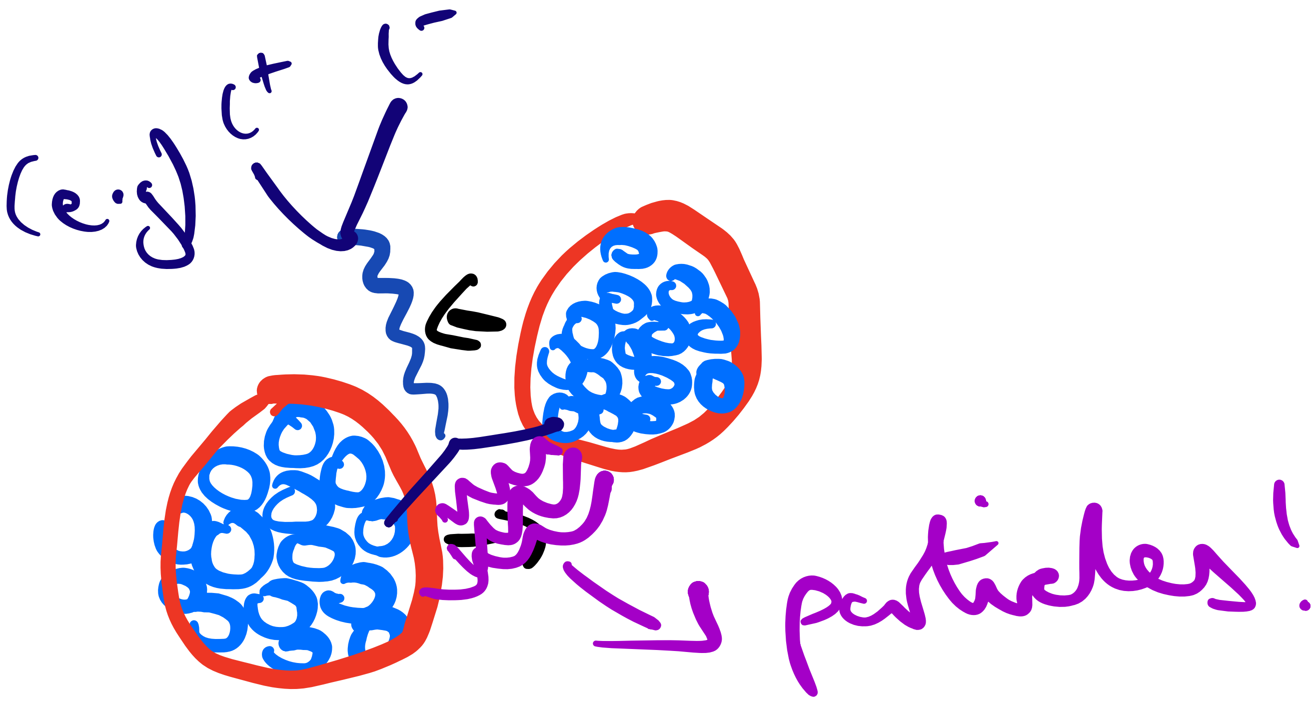

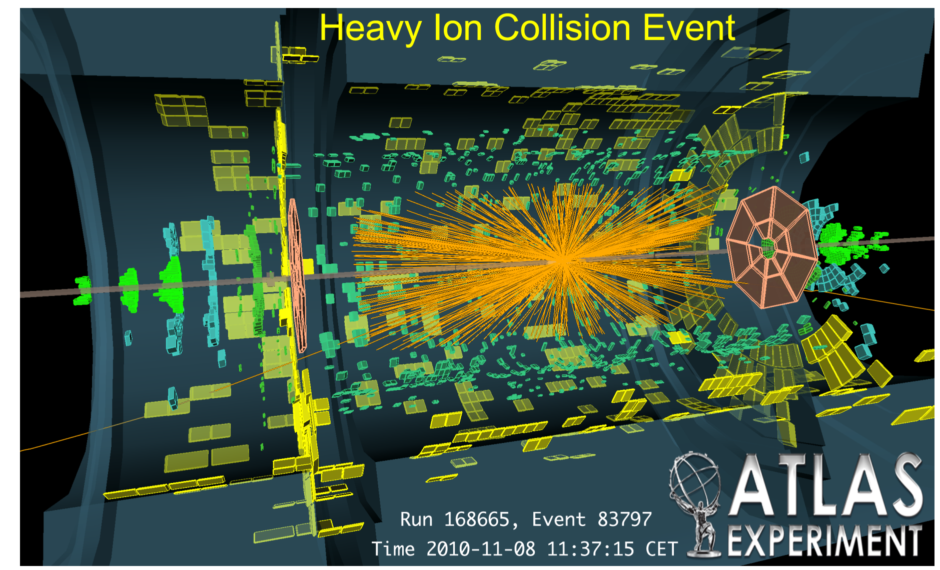

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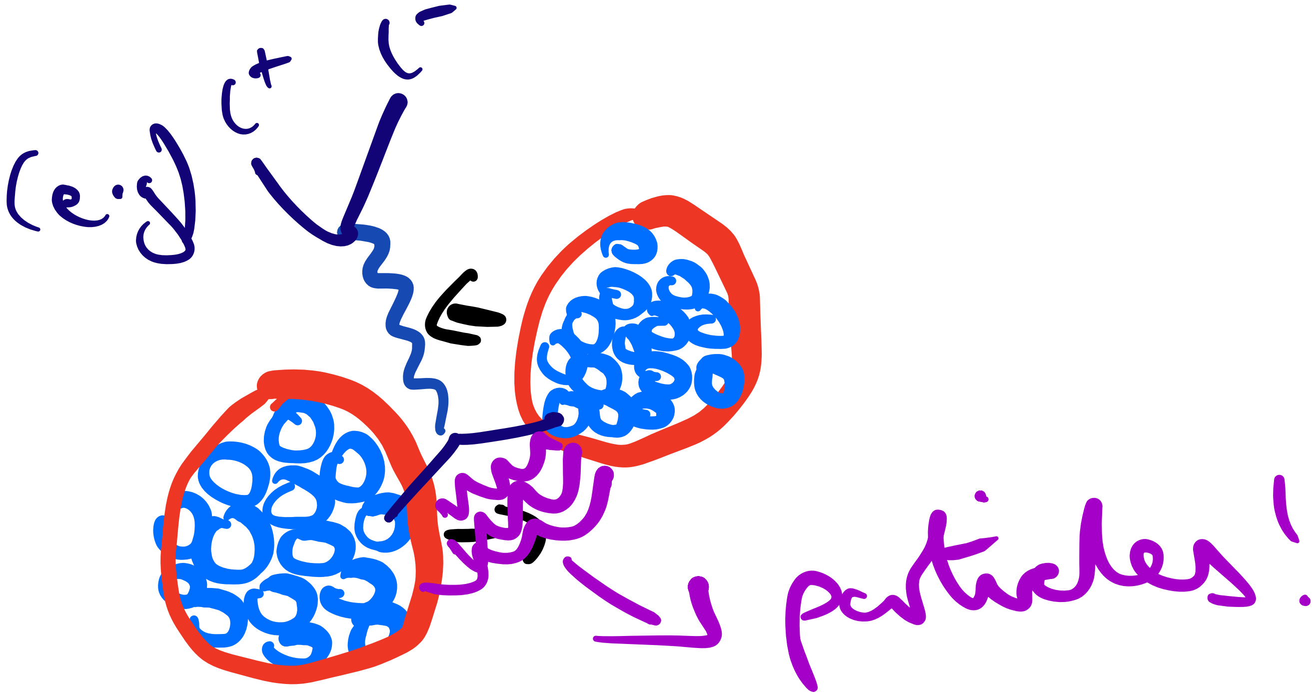
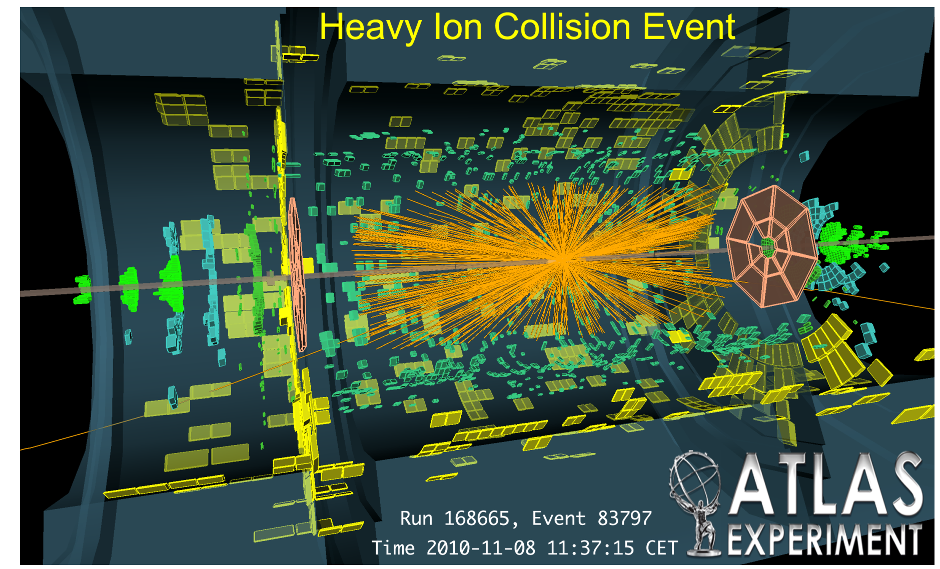
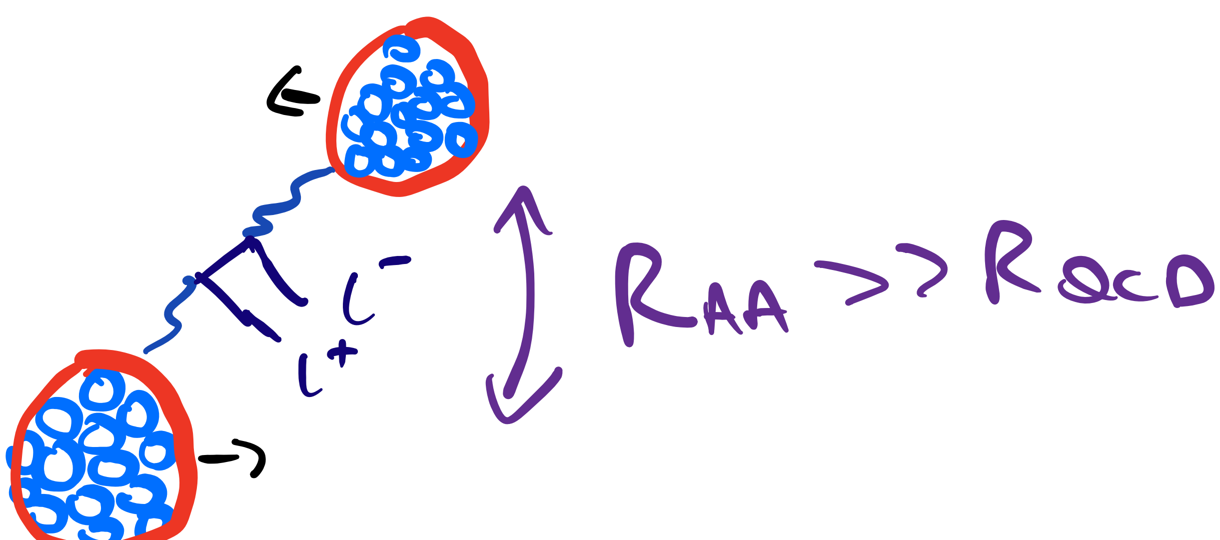
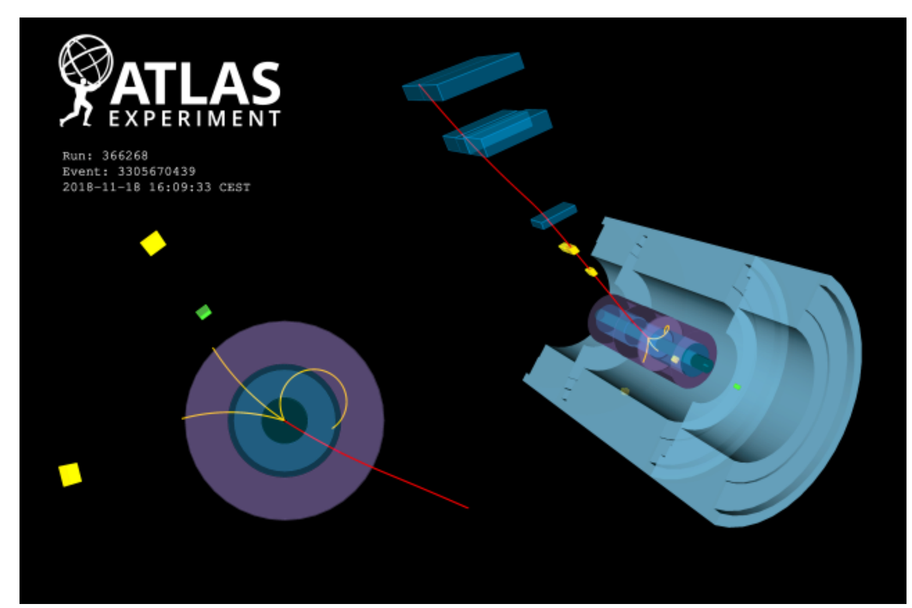




- However if colliding ions sufficiently separated in impact parameter ('ultraperipheral') does have to be the case:

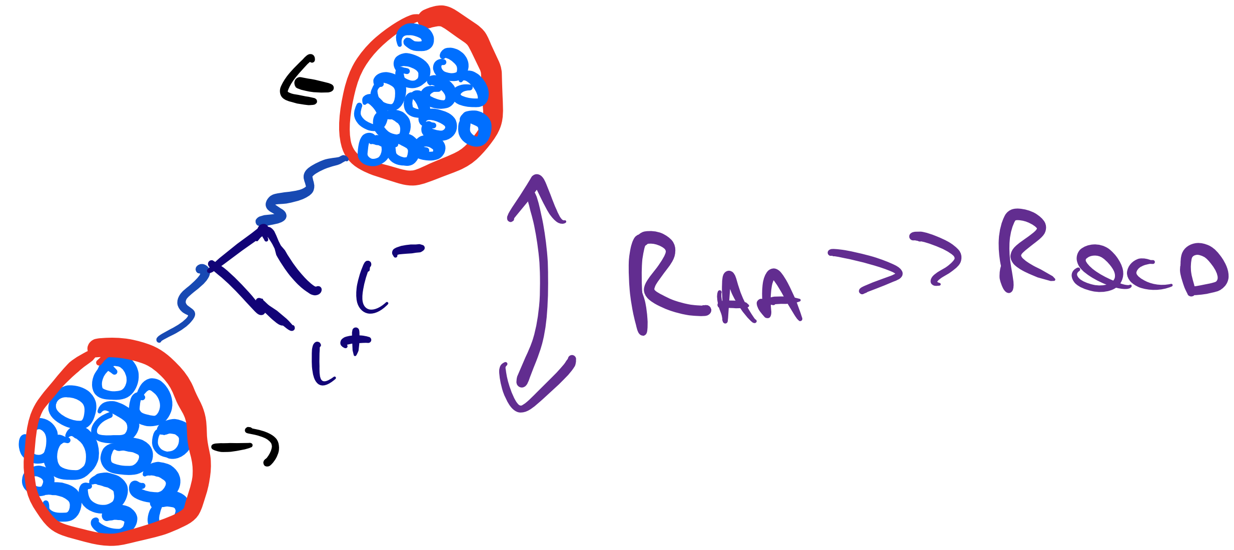




- Photon-initiated production naturally leads to this clean final-state:

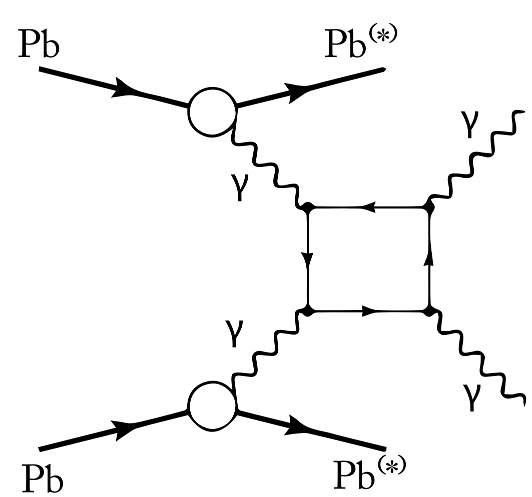
  ★ Long range QED interaction.

  ★ Colour singlet exchange.

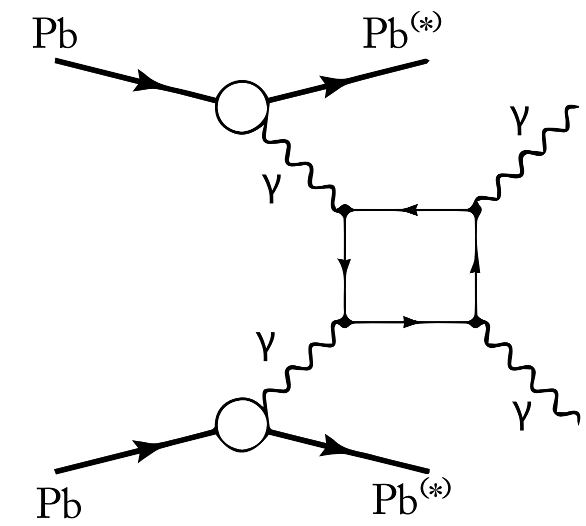


- Moreover heavy ions have large number (Z) of protons $\Rightarrow$ cross section enhanced by Z^4 !

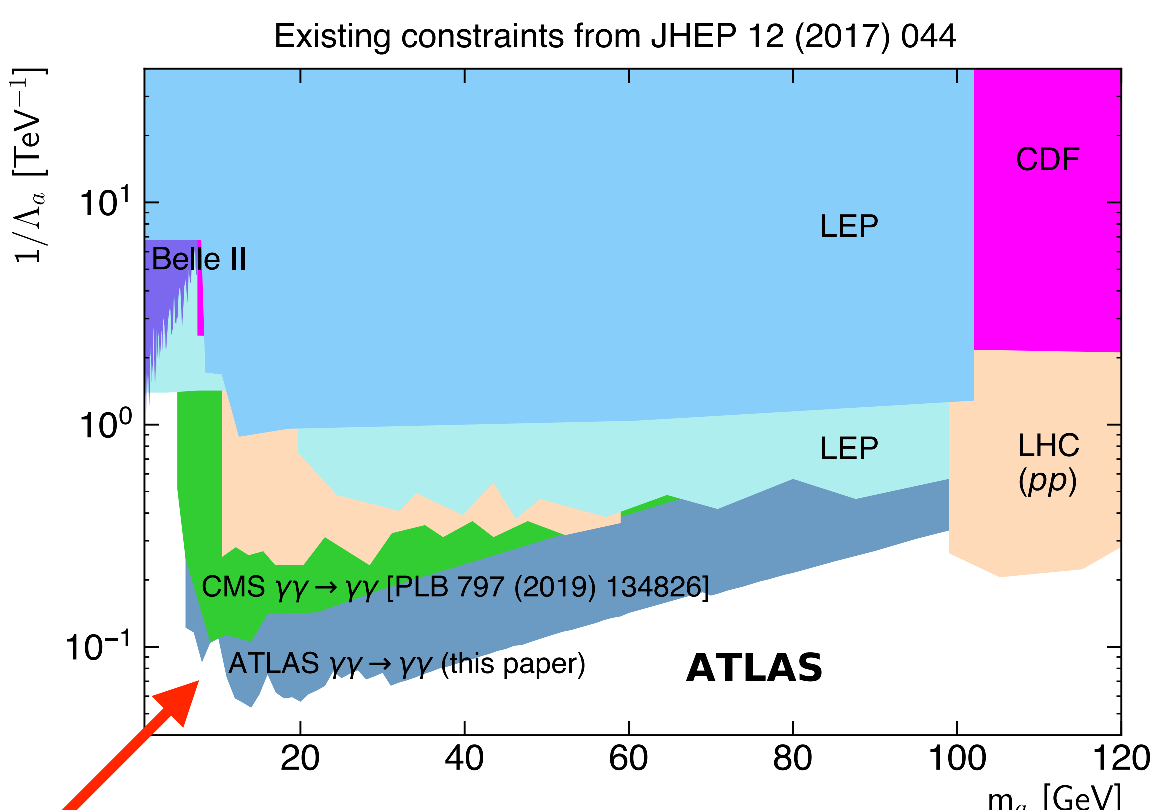
- Basic idea: effectively acts as a $\gamma\gamma$ collider, and with enhanced cross section due to large Z of ions.



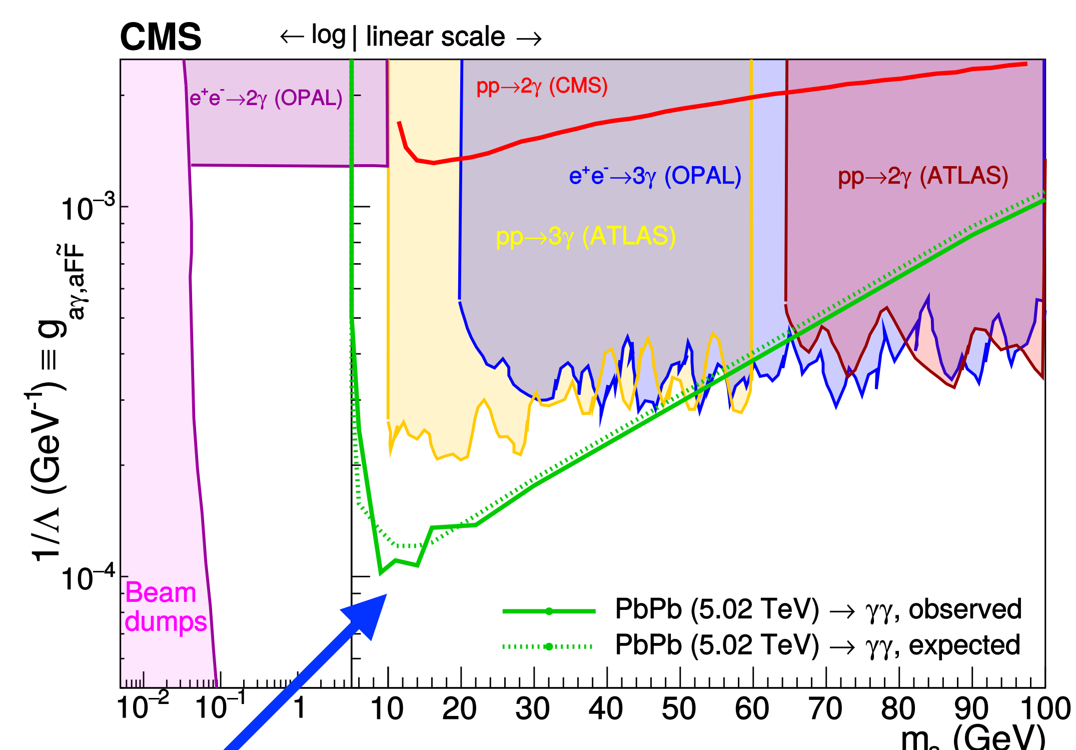
- Some examples…
  - ★ ‘Light-by-light’ scattering $\gamma\gamma \to \gamma\gamma$.
    - ✦ Rare loop-induced process in the SM. First direct observation in LHC PbPb collisions!
    - ✦ Sensitive to new particles in the loop and BSM `axion-like’ resonances.



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



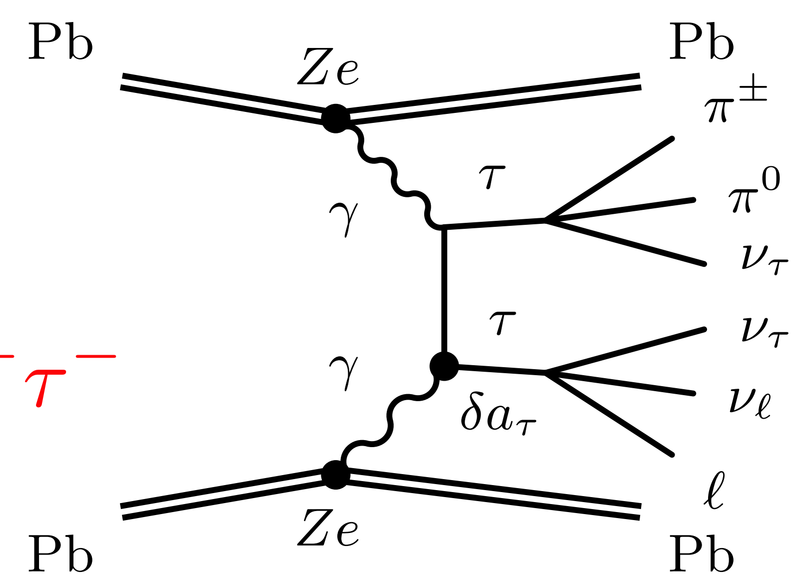
***JHEP* 11 (2021) 050, *JHEP* 03 (2021) 243**



***Phys.Lett.B* 797 (2019) 134826**

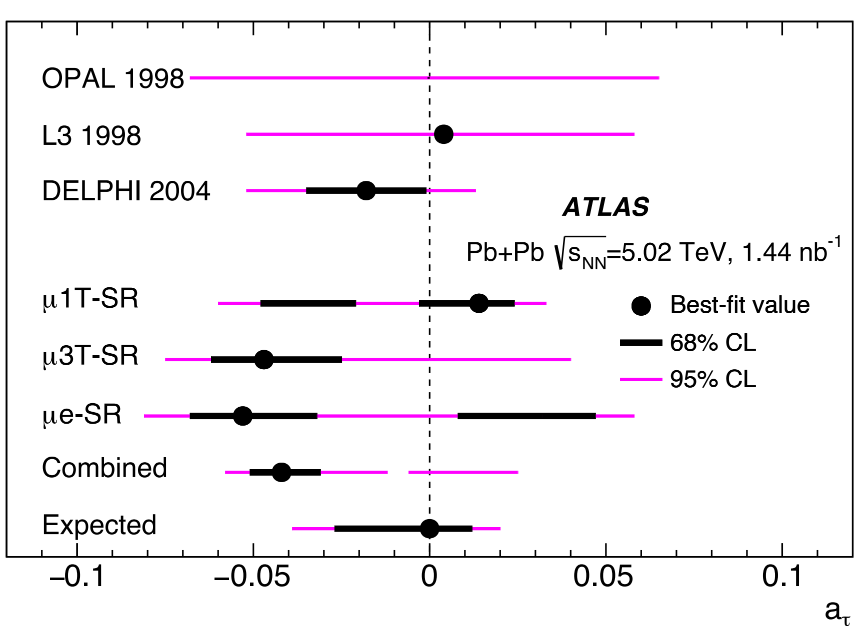
★ τ lepton pair production and the lepton anomalous magnetic moment.

- Z^4 enhanced rate $\Rightarrow$ significant $\gamma\gamma \to \tau^+\tau^-$ signal.
- High precision determination of cross section allows constraints on g-2 and hence BSM.

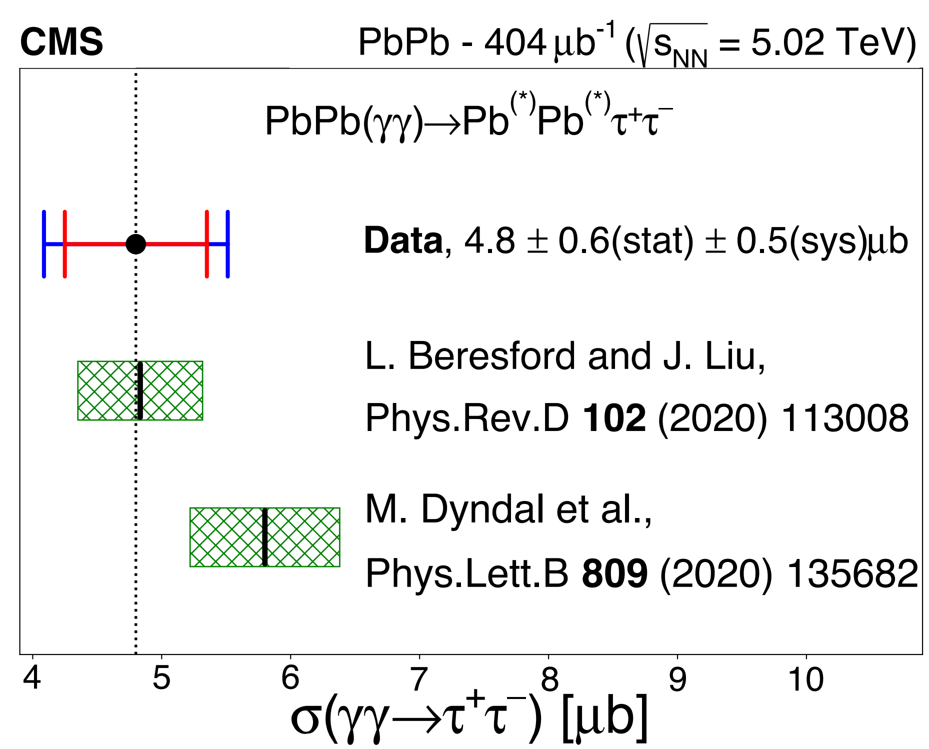


L. Beresford and J. Liu, PRD 102 (2020) 11, 113008

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



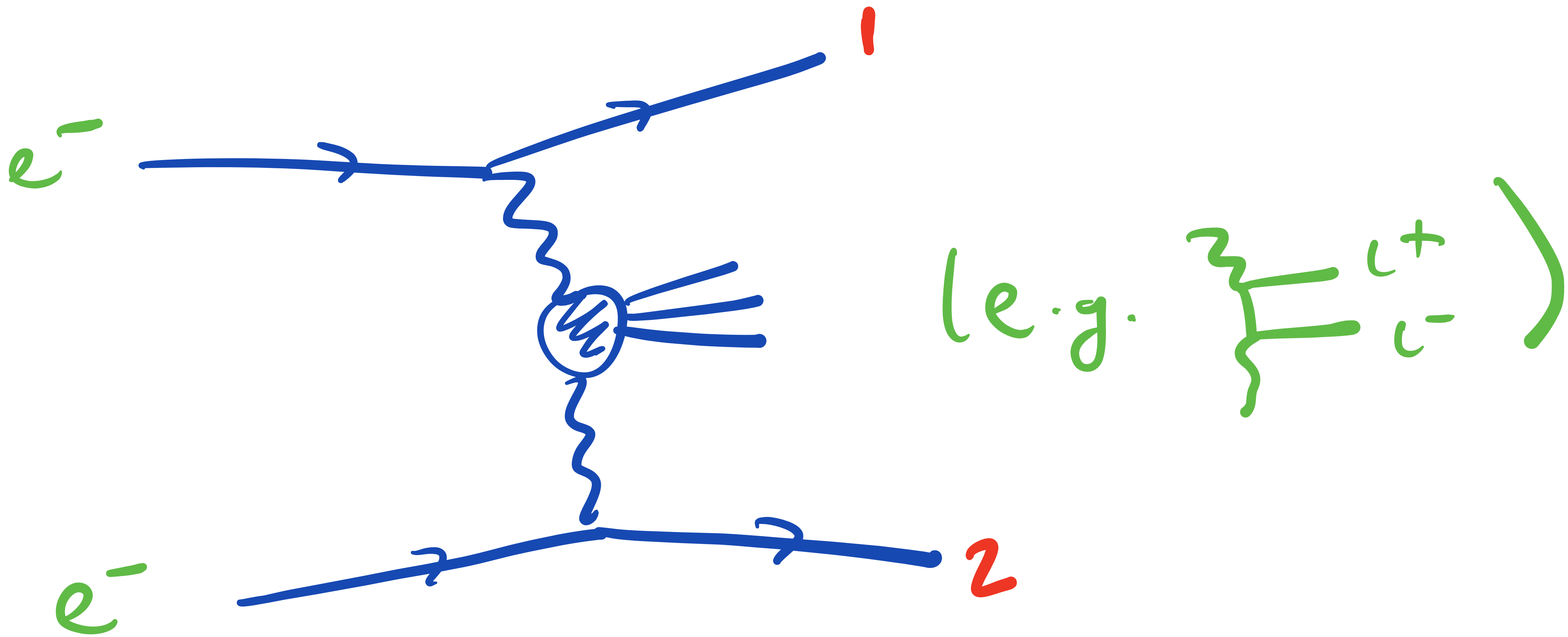
arXiv:2204.13478



arXiv:2206.05192

Modelling $\gamma\gamma$ production in heavy ions

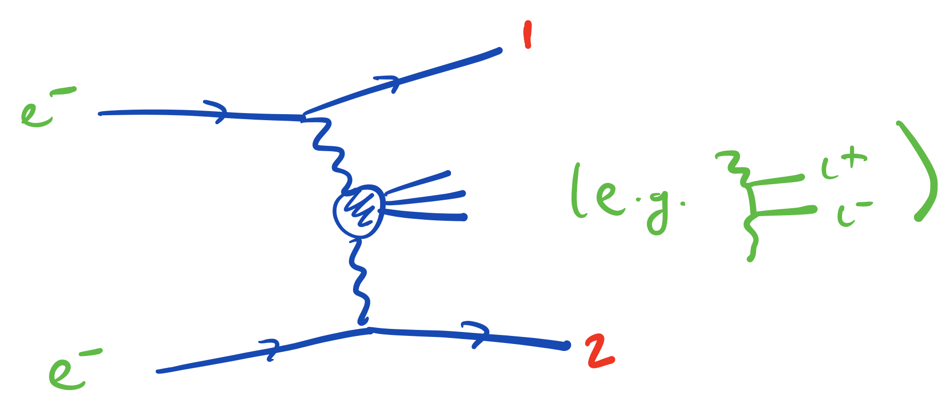
- How do we model photon-initiated production in heavy ion collisions?
- Consider simpler case of lepton-lepton collisions:



- Applying standard QED Feynman rules, cross section given by:

Phase space!

$$\sigma \sim \int d^2 q_{1\perp}\, d^2 q_{2\perp}\, \frac{dx_1}{x_1} \frac{dx_2}{x_2}\, dPS_{\gamma\gamma \to X}$$



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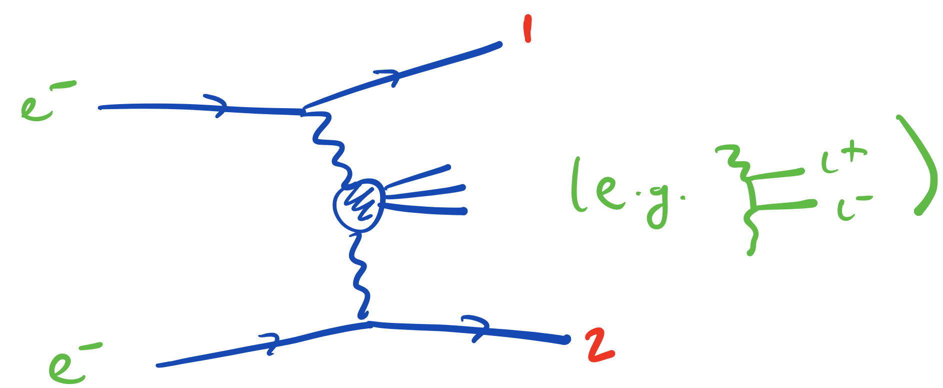

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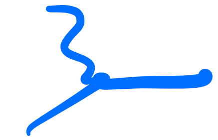

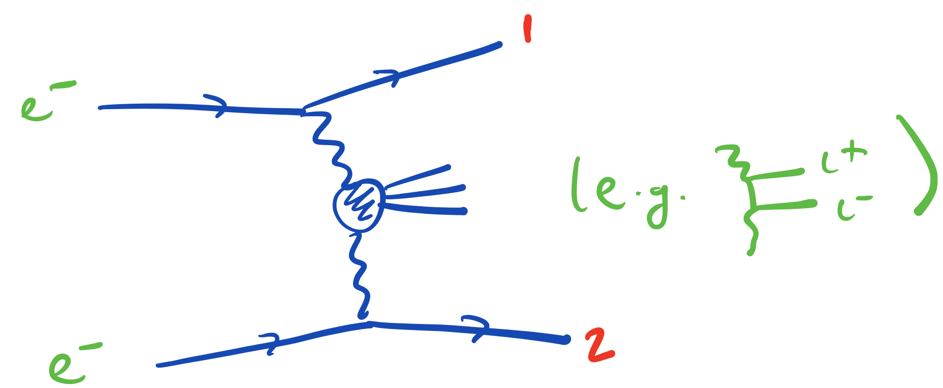

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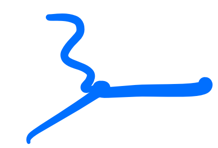
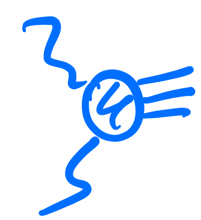
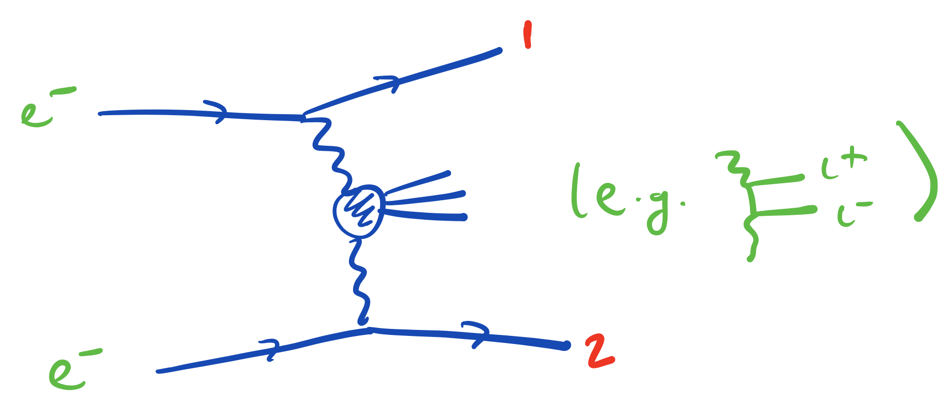
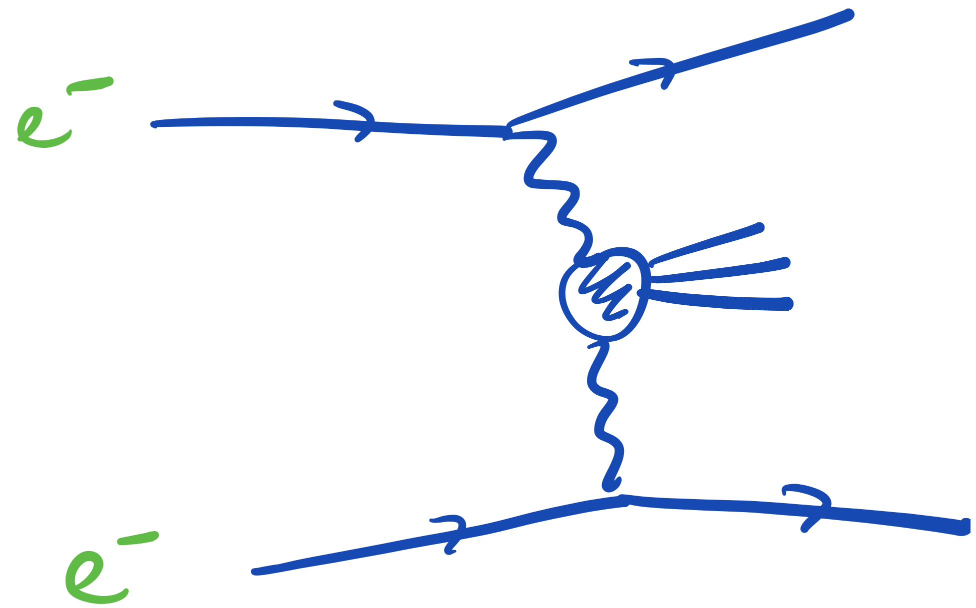
$$\cdot\ \alpha(Q_2^2)\,\frac{1}{Q_2^2}\left(\frac{q_{\perp 2}^2}{Q_2^2} + \frac{x_2^2}{2}\right) :$$ 

$$\cdot\ |M(\gamma\gamma \to X)|^2 :$$ 



- Aside: what would happen for e.g. charged (spinless) pions?



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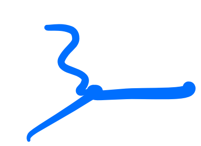

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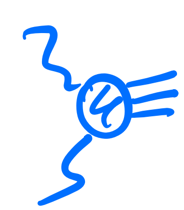

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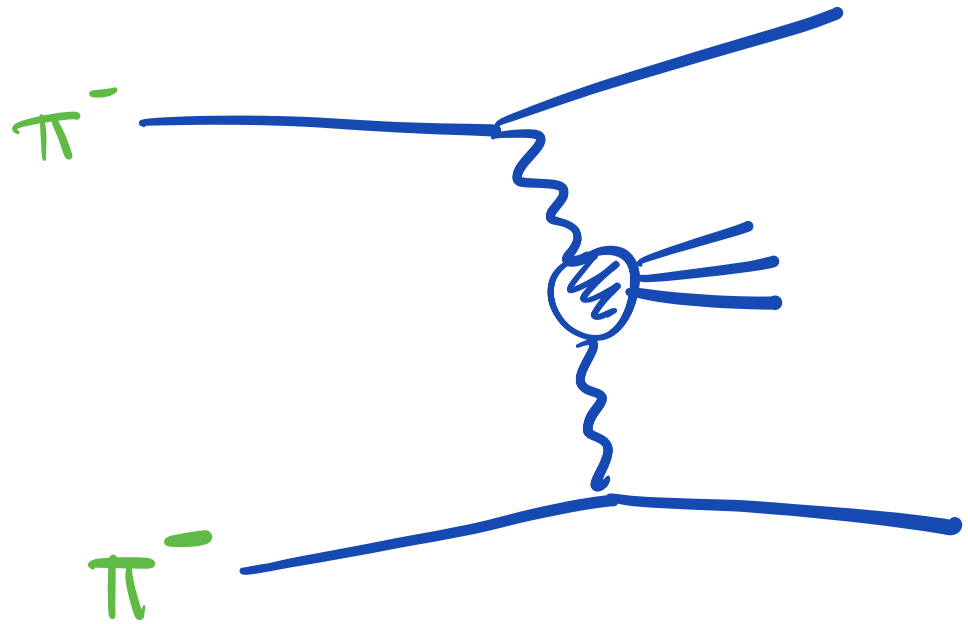

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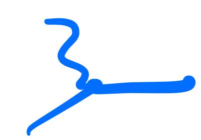
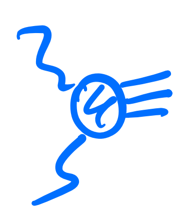
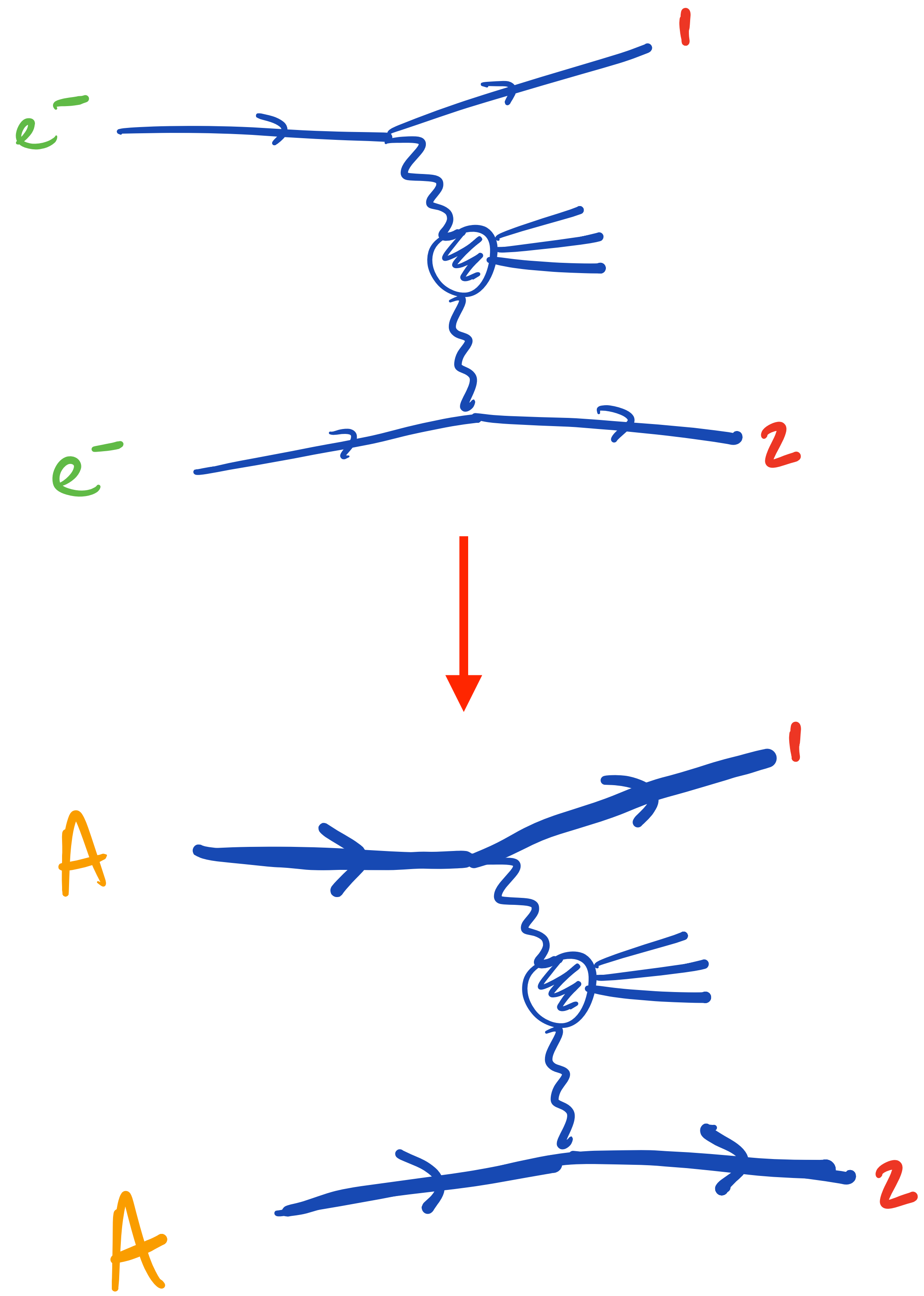
$\cdot\ \alpha(Q_2^2) \frac{1}{Q_2^2} \left(\frac{q_{\perp 2}^2}{Q_2^2} \cancel{+ \frac{x_2^2}{2}} \right)$: 

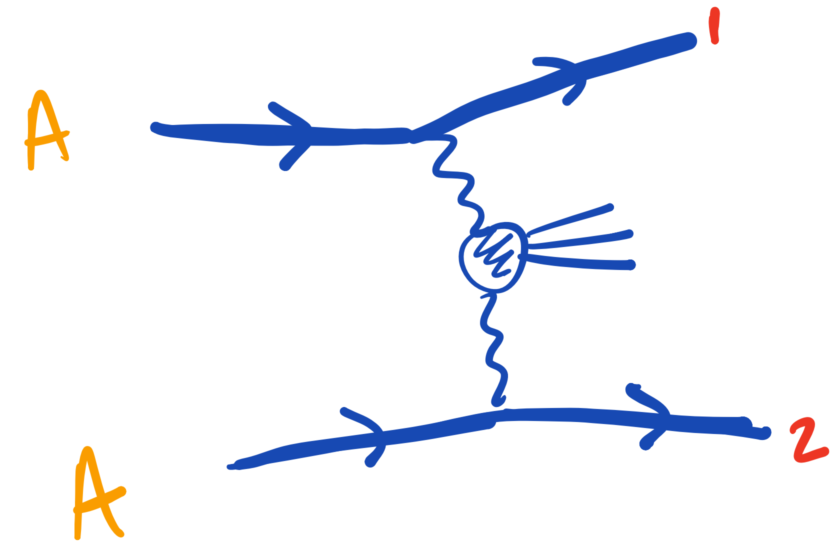
$\cdot\ |M(\gamma\gamma \to X)|^2$: 

- Second term due to magnetic (spin) interaction with photon.

- Now: what happens if we replace the leptons with heavy ions?



- Answer: cross section exactly as before, but with suitably modified $\gamma p \Rightarrow \gamma A$ vertex.



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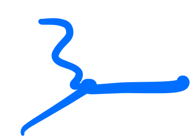
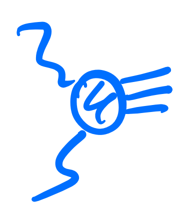
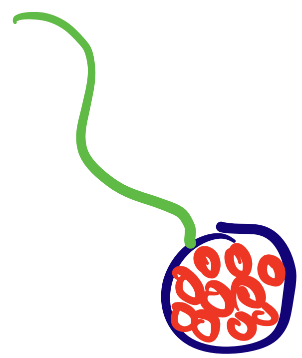
$\cdot\ \alpha(Q_2^2)\, \frac{1}{Q_2^2} \left(\frac{q_{\perp 2}^2}{Q_2^2} + \frac{x_2^2}{2} \right)$: 

Needs modification!

$\cdot\ |M(\gamma\gamma \to X)|^2$: 

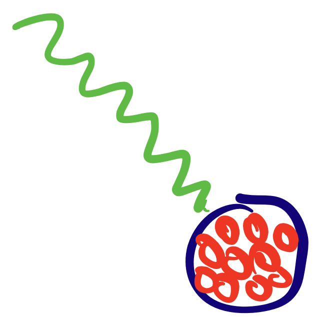
- For long enough photon wavelength (low enough Q^2) ion looks point-like:



$$: \quad \lambda \sim \frac{1}{Q} \gg R_A$$

$$\Rightarrow \mathcal{M} \sim Z$$

- But as we decrease wavelength (increase Q^2) probe internal ion structure:



$$: \quad \lambda \sim \frac{1}{Q} \lesssim R_A$$

$$\Rightarrow \mathcal{M} \sim Z \cdot F(Q^2)$$

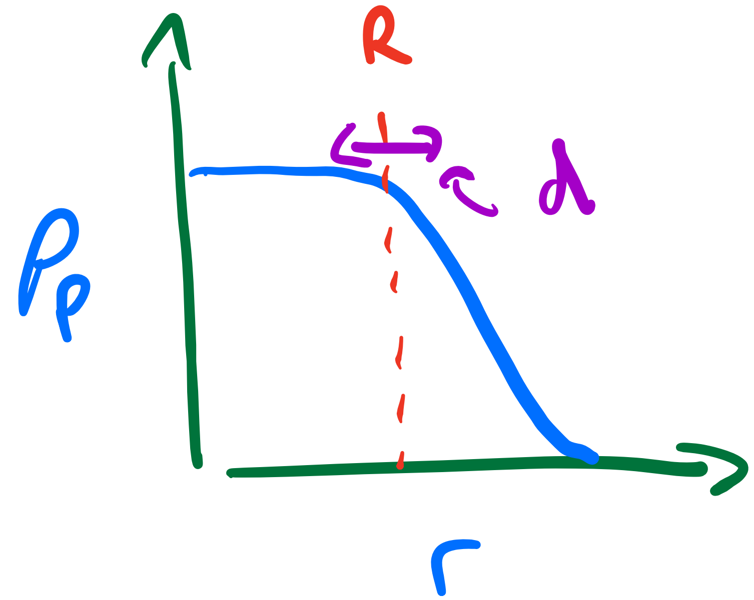
- This internal structure is encoded in ion EM form factor:

$$F(Q^2) = \int d^3\vec{r}\, e^{i\vec{q}\cdot\vec{r}} \rho_p(\vec{r})$$

Ion charge density

- What does ion charge density look like?

$\rho_p(\vec{r})$:



- Common & accurate to use Woods-Saxon parameterisation:

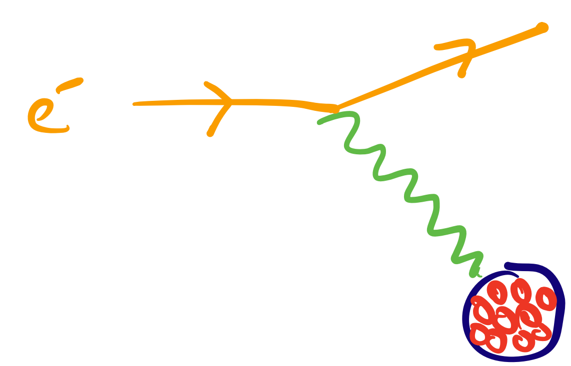
$$\rho_p(r) = \frac{\rho_0}{1 + \exp{(r - R)/d}},$$

'Skin thickness'

Charge radius

N.B $F(Q^2 = 0) = \int d^3\vec{r}\, \rho_p(\vec{r}) \equiv Z$

- Key point: the parameters of the charge density are determined with sub-percent level precision from wealth of e-A scattering data!

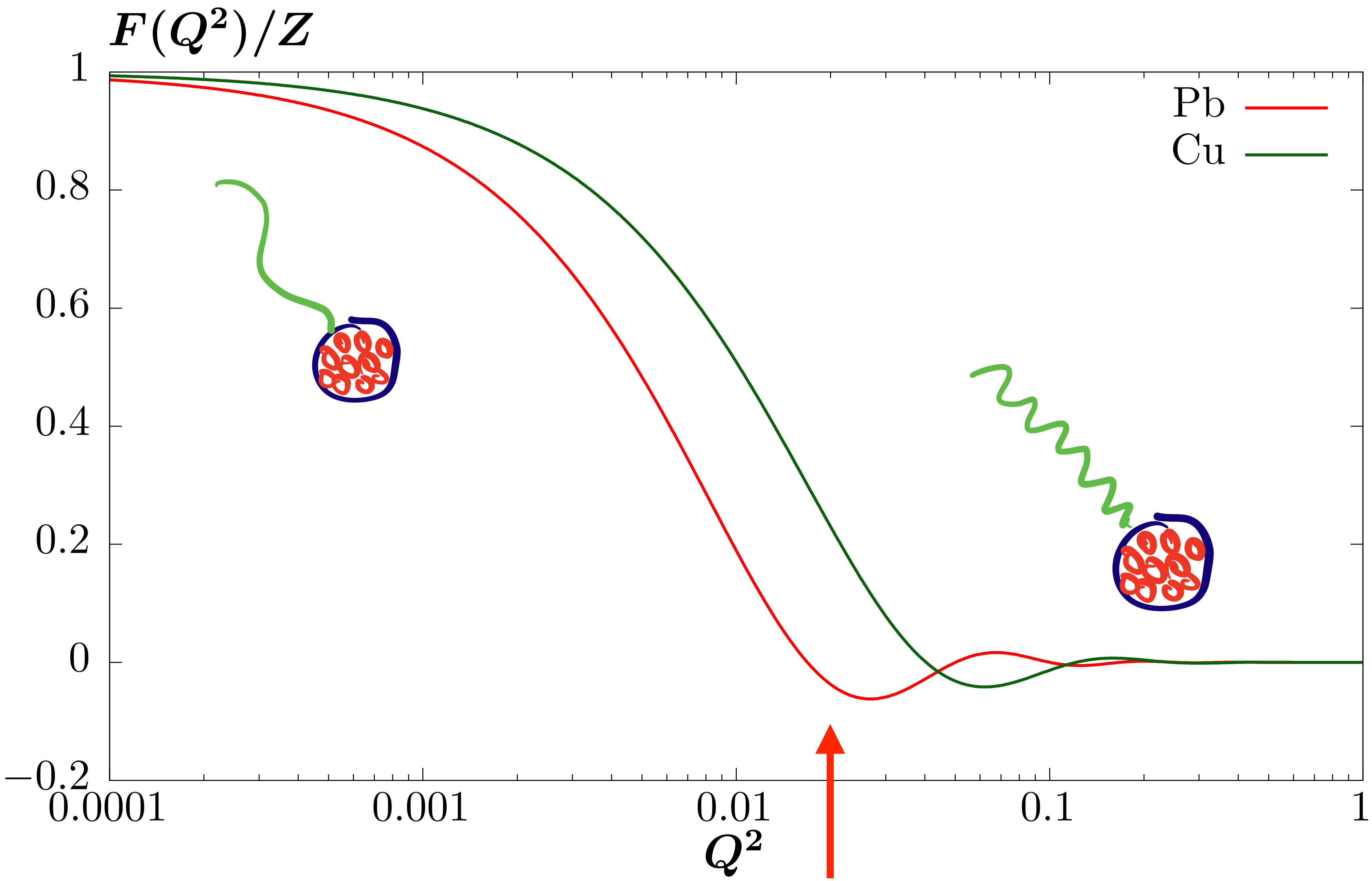


- What does this form factor look like?

$F(Q^2) = \int d^3\vec{r}\, e^{i\vec{q}\cdot\vec{r}} \rho_p(\vec{r})$

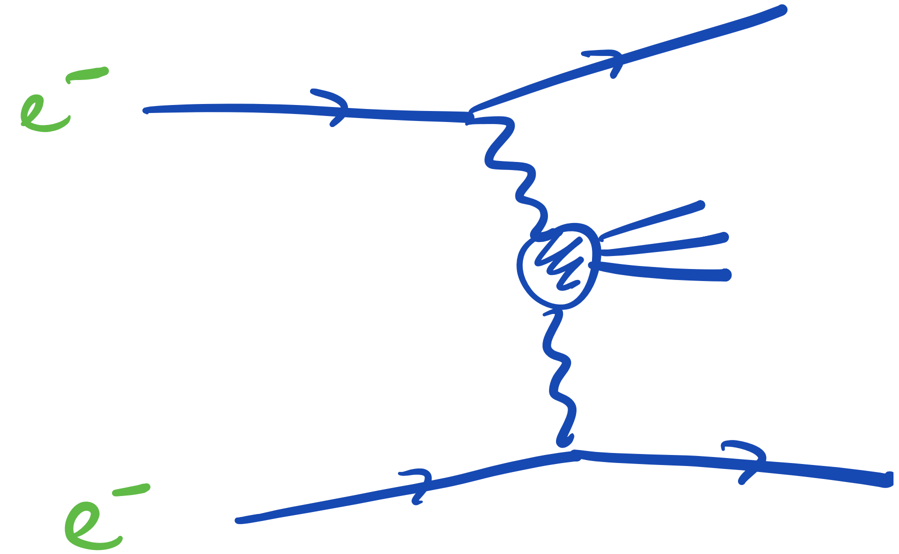
★ Low Q^2 : constant ($\sim Z$)

★ Higher Q^2: falls off as substructure probed.



$\sqrt{Q^2} \sim 3/R \sim 0.1$ GeV

- So we have:



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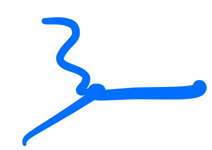

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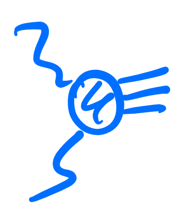
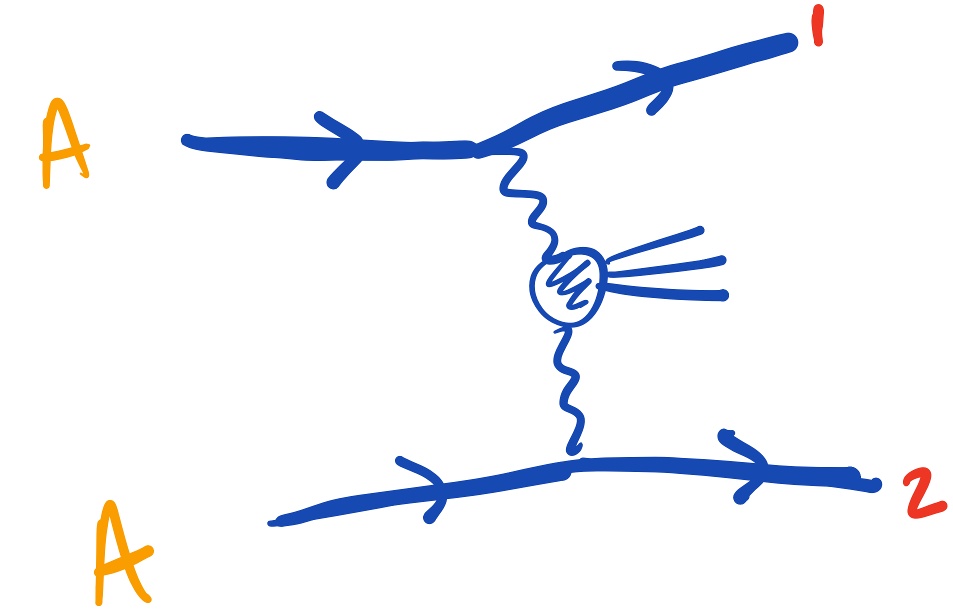


- Becomes:



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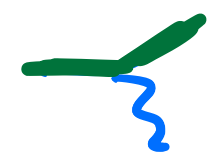

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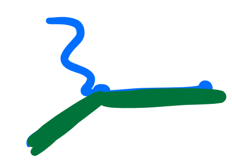

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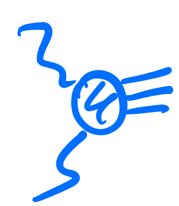
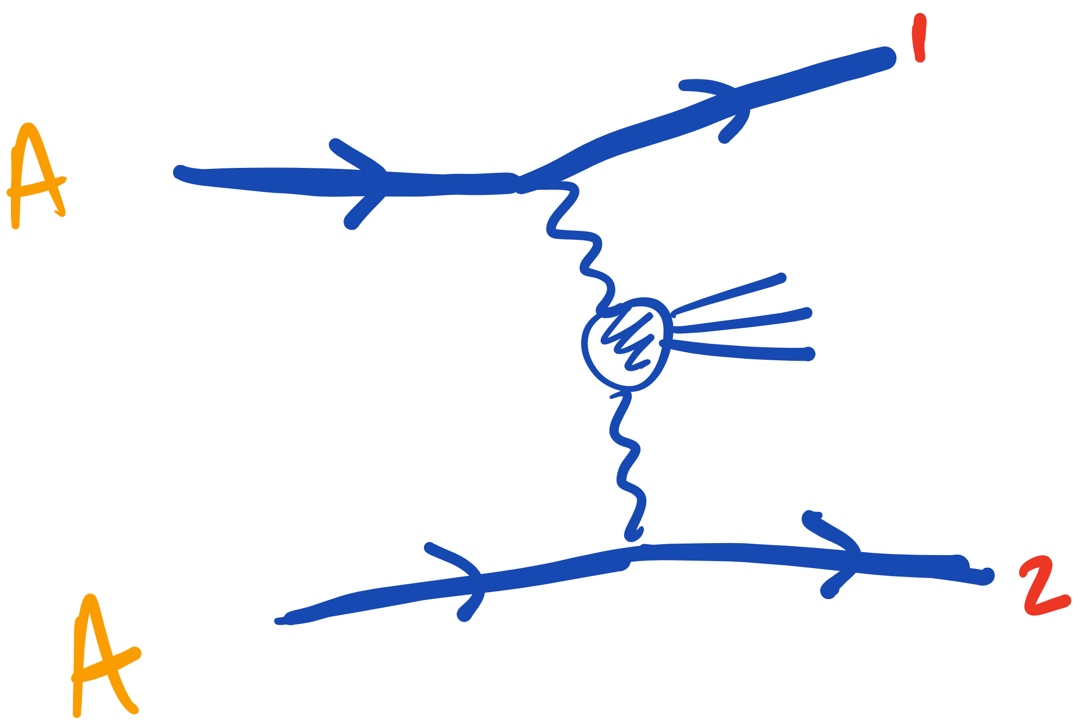
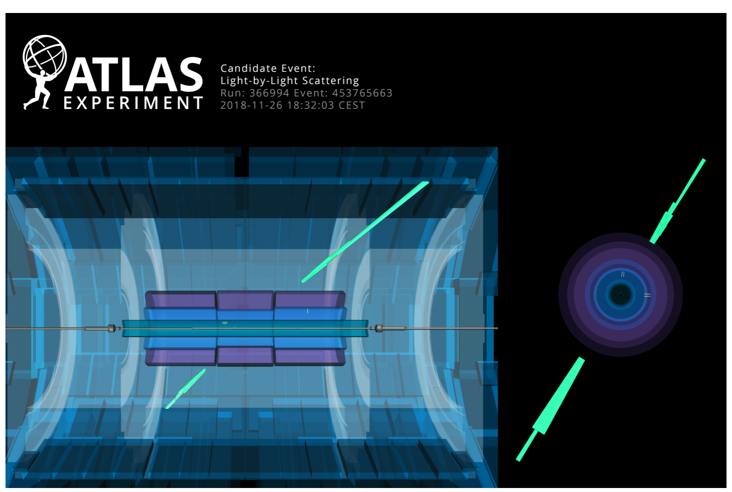


N.B. no magnetic form factor as suppressed by Z

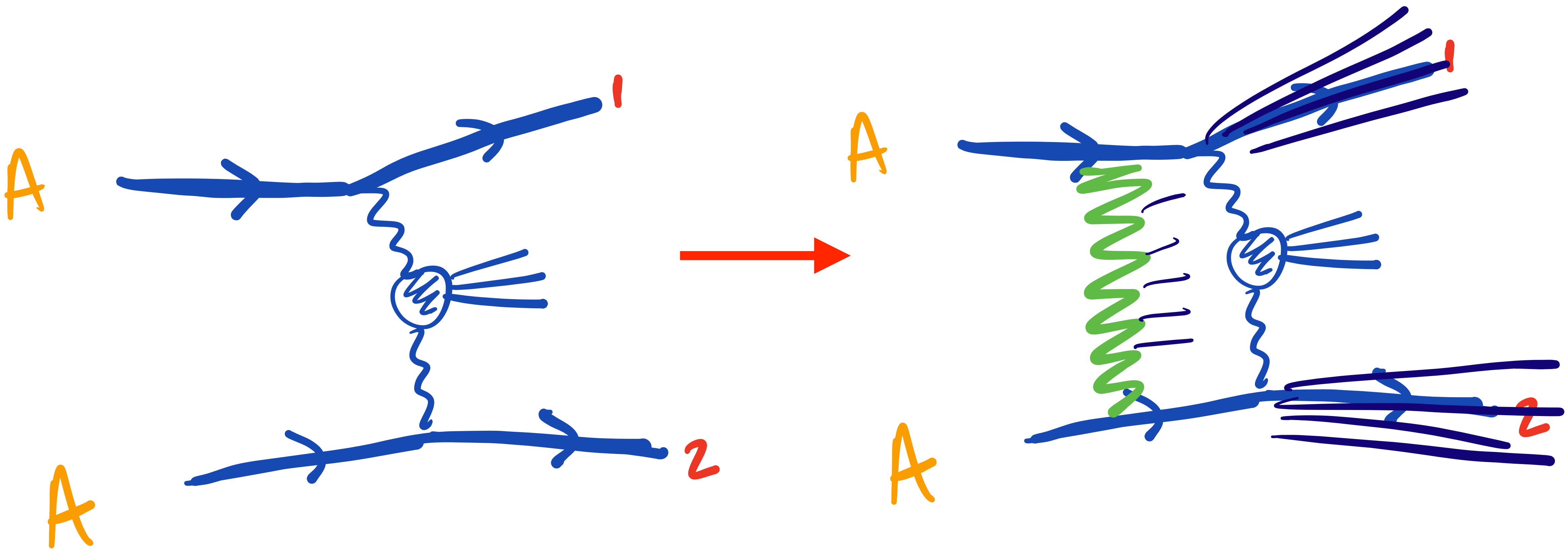
- With form factor given as before. **Is that it?**

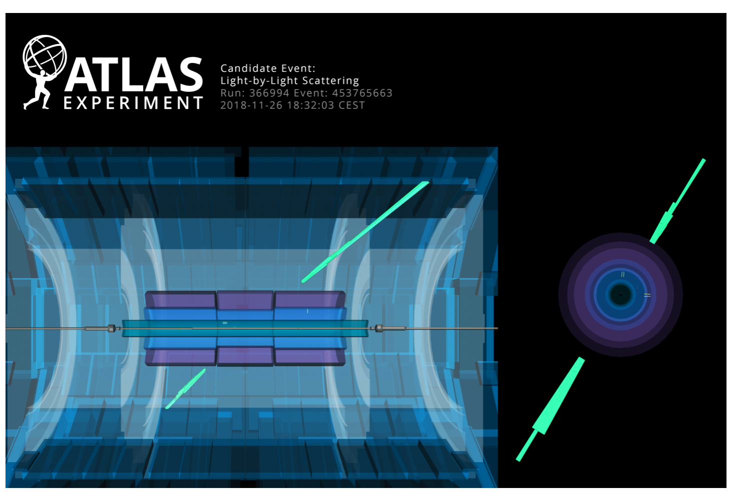
- Answer: no! We must account for possibility of inelastic ion-ion interactions in addition to this.

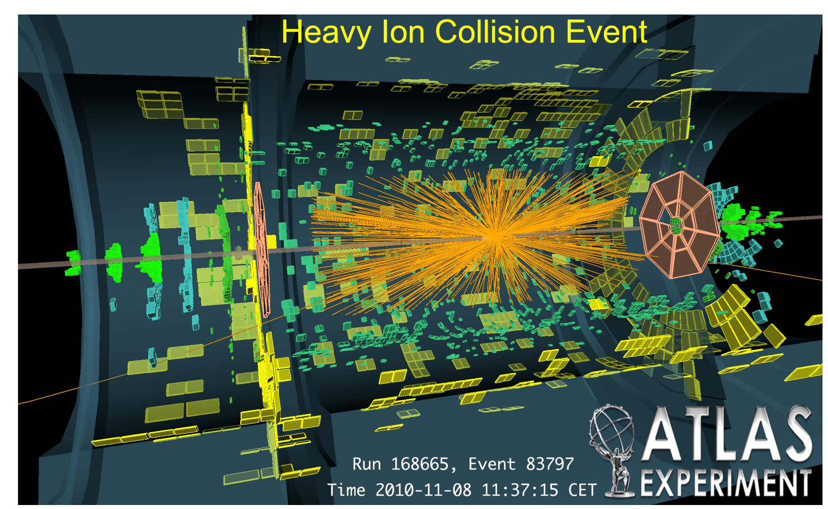




- Answer: no! We must account for possibility of inelastic ion-ion interactions in addition to this.

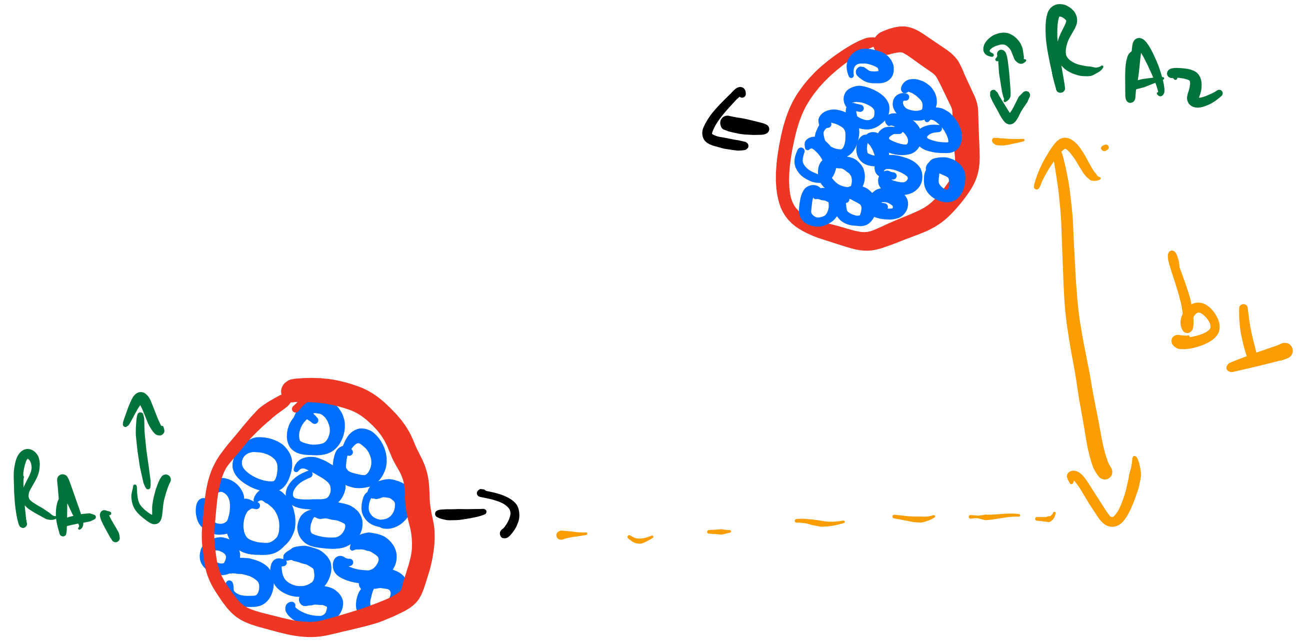






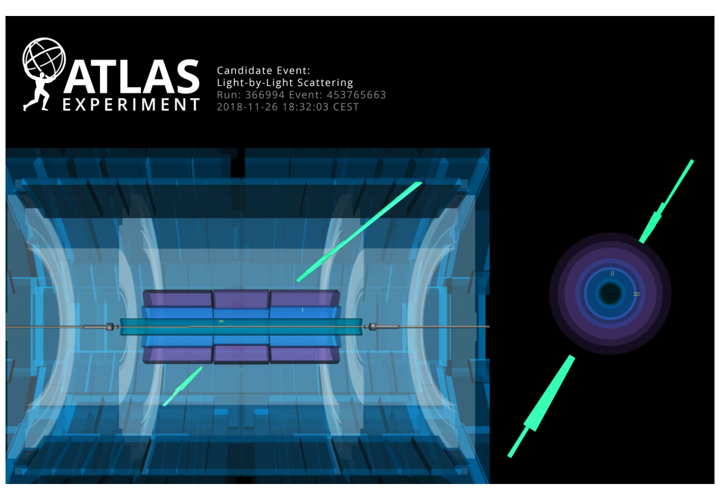
- Need to include **survival factor**: probability of no additional inelastic ion-ion interactions.

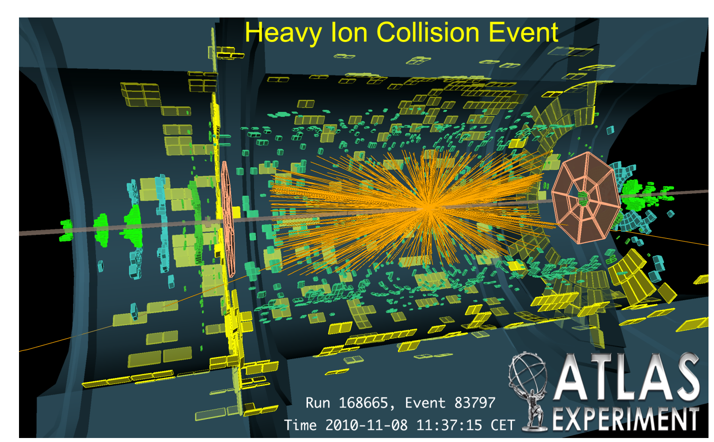
- How do we calculate survival factor? Simplest if we consider collision in terms of ion-ion impact parameter.



- Basic idea: if ions overlap then they will interact inelastically.

$$b_\perp > R_{A_1} + R_{A_2} \qquad\qquad b_\perp < R_{A_1} + R_{A_2}$$

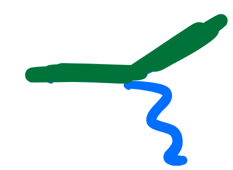




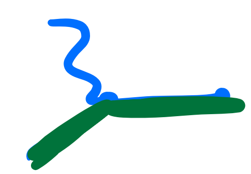
- Mathematically, achieve this by going to impact parameter space, i.e. taking Fourier Transform.
- Writing schematically:

$$\sigma \sim \int d^2 q_{1\perp}\, d^2 q_{2\perp}\, \frac{dx_1}{x_1} \frac{dx_2}{x_2}\, dPS_{\gamma\gamma \to X}$$

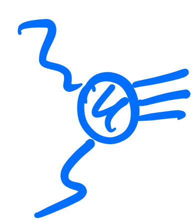
$$\cdot\ \alpha(Q_1^2) \cdot \frac{1}{Q_1^2} \left(\frac{q_{\perp 1}^2}{Q_1^2} \cdot F^2(Q_1^2) \right) :$$

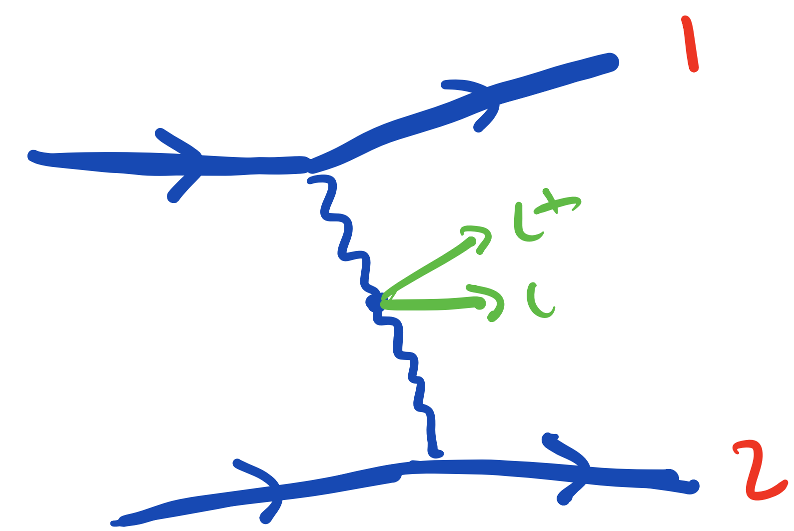


$$\cdot\ \alpha(Q_2^2) \frac{1}{Q_2^2} \left(\frac{q_{\perp 2}^2}{Q_2^2} \cdot F^2(Q_2^2) \right) :$$



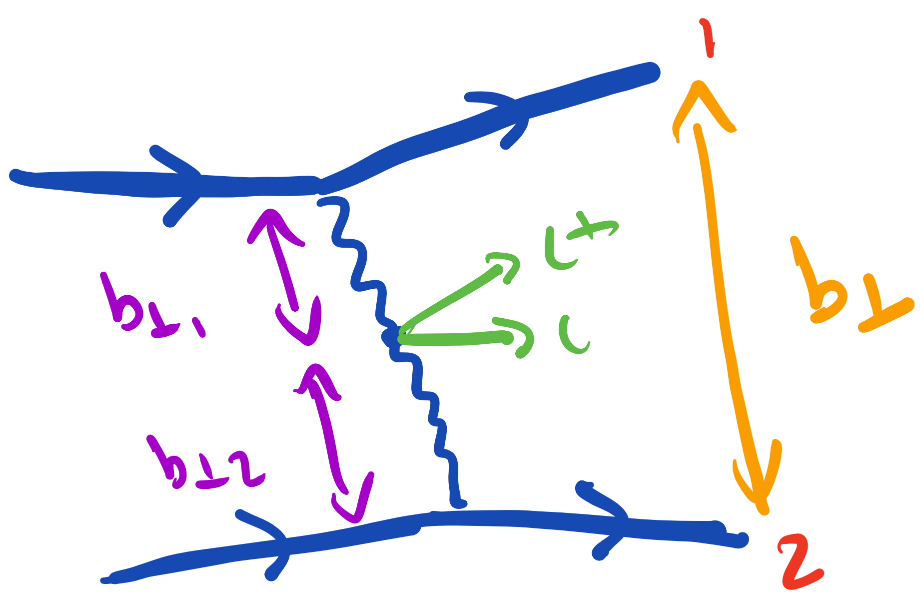
$$\cdot\ |M(\gamma\gamma \to X)|^2 :$$





- Mathematically, achieve this by going to impact parameter space, i.e. taking Fourier Transform.
- Writing schematically:

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



- Mathematically, achieve this by going to impact parameter space, i.e. taking Fourier Transform.
- Writing schematically:

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

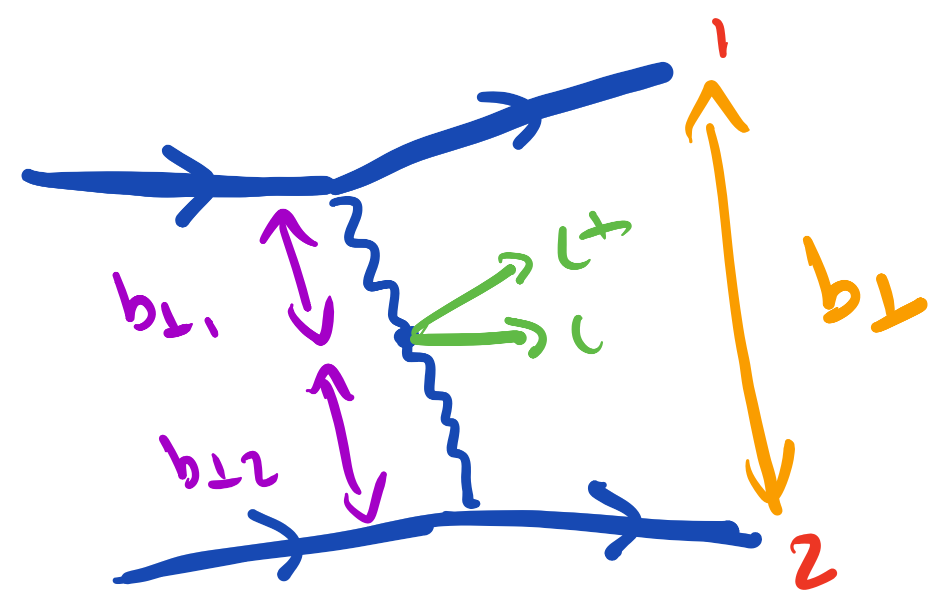
- We can write this as integral over ion impact parameters:

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

- Where:

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

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



- To first approximation, we then simply require:

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

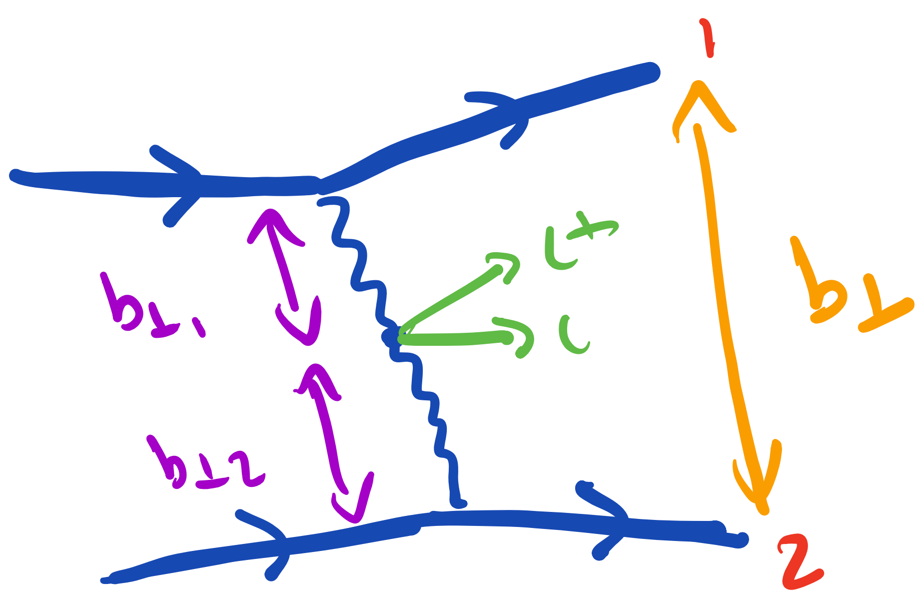
$$\downarrow$$

$$\sigma = \int d^2 b_{1\perp}\, d^2 b_{2\perp} \cdot \Theta(b_\perp - R_{A_1} - R_{A_2}) \cdot |\tilde{M}(\vec{b}_{1\perp}, \vec{b}_{2\perp}, \ldots)|^2$$

- That is, only integrate over impact region where:

$$b_\perp > R_{A_1} + R_{A_2}$$

holds!



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

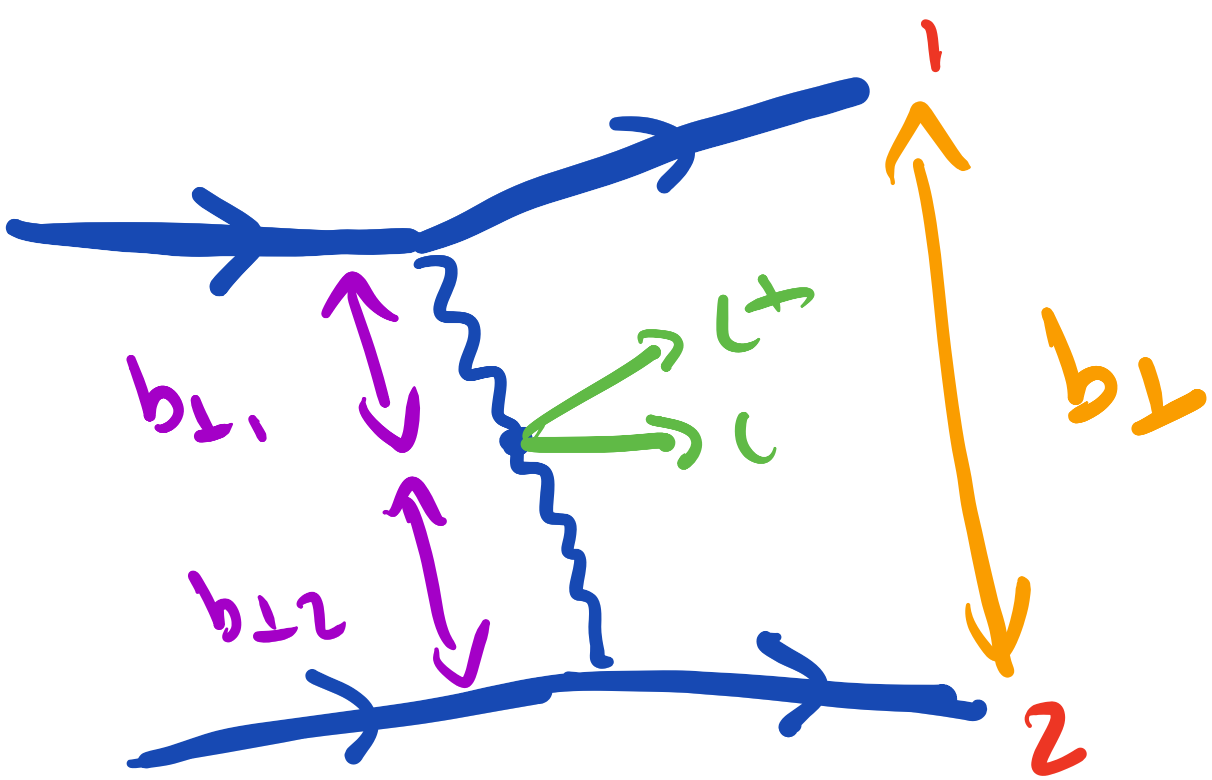
Schematically:

$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp} ...)|^2 e^{-\Omega_{A_1 A_2}(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}$$

$e^{-\Omega_{A_1 A_2}(\vec{b}_{1\perp} - \vec{b}_{2\perp})}$: survival factor - probability for no additional particle production at impact parameter $b_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$. Roughly:

$$e^{-\Omega_{A_1 A_2}(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})} \approx \theta(b_\perp - R_{A_1} - R_{A_2})$$

but not exact!



Ion-ion survival factor

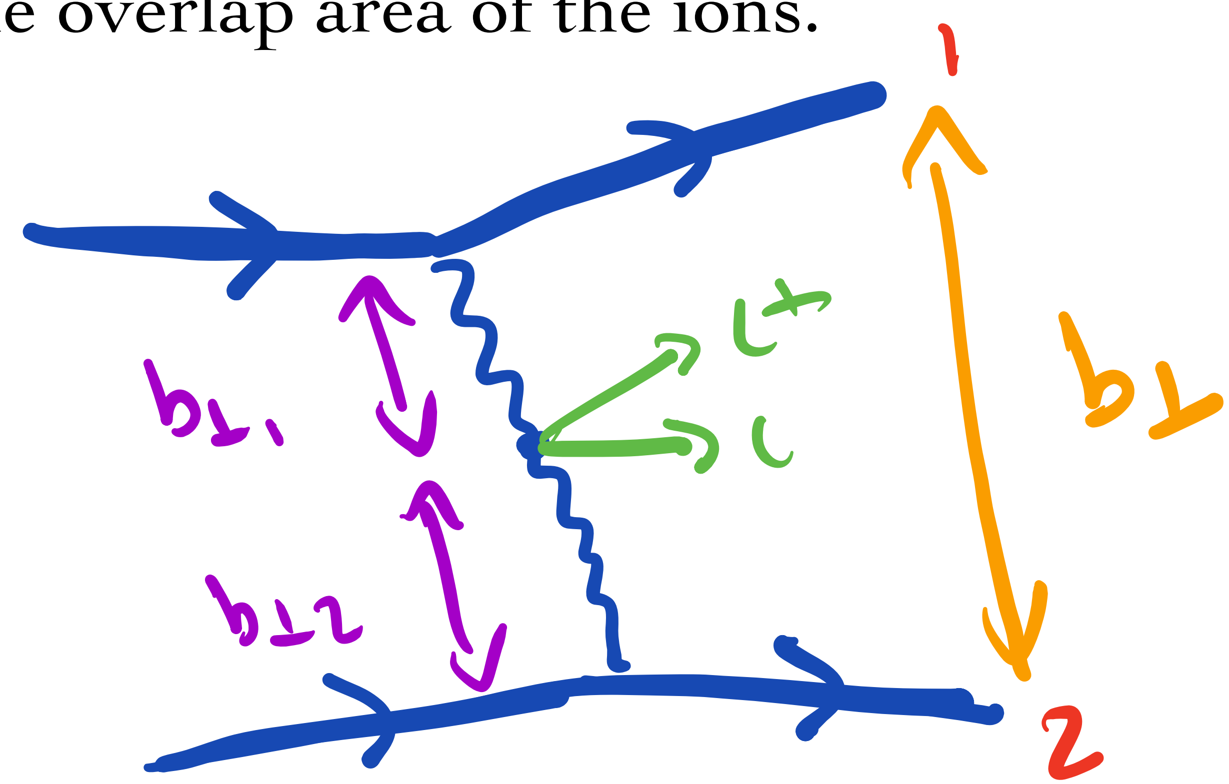
- In more detail, we have:

$$\Omega_{A_1A_2}(b_\perp) = \int \mathrm{d}^2 b_{1\perp} \mathrm{d}^2 b_{2\perp} T_{A_1}(b_{1\perp}) T_{A_2}(b_{2\perp}) A_{nn}(b_\perp - b_{1\perp} + b_{2\perp})$$

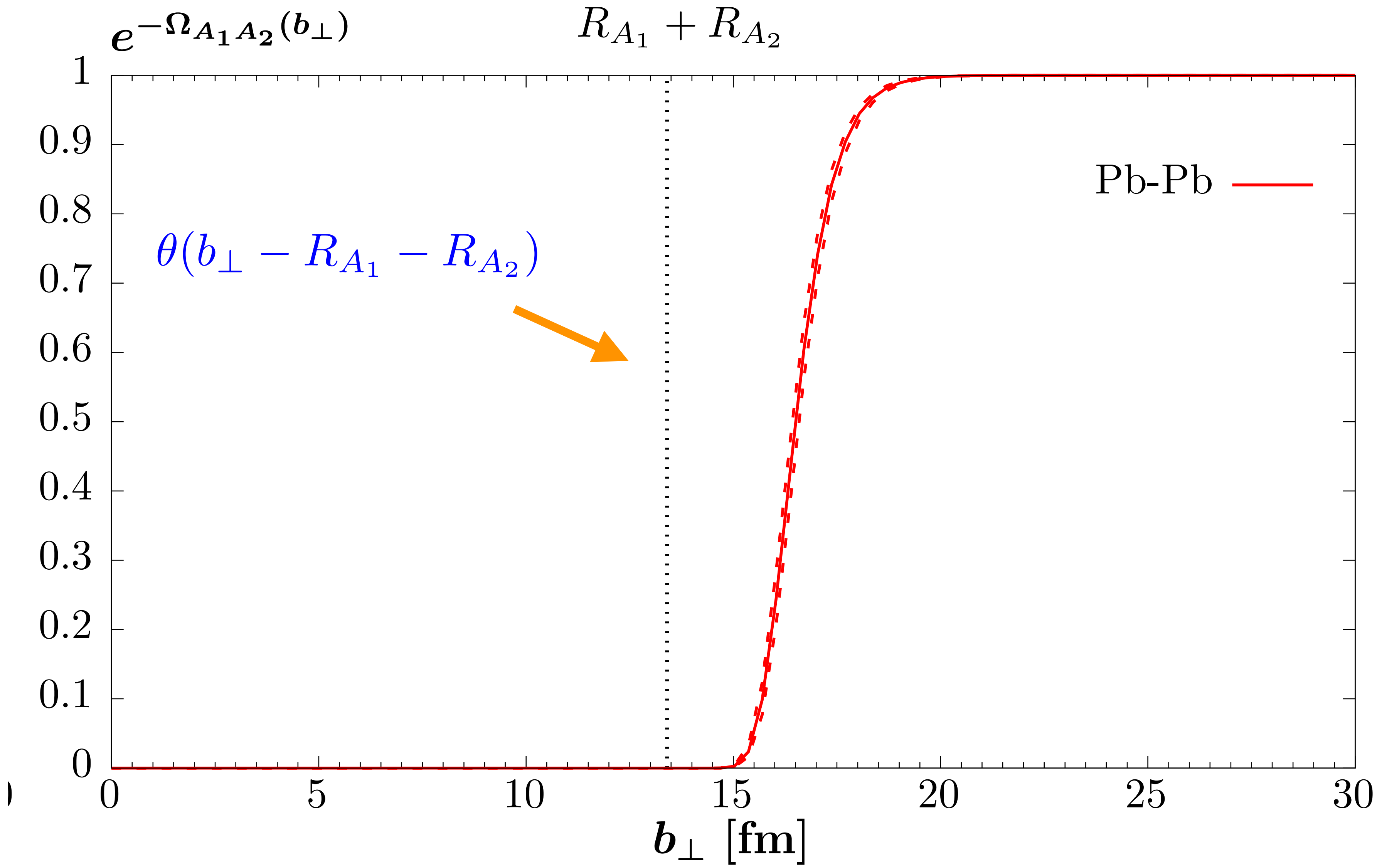
where: $T_A(b_\perp) = \int \mathrm{d}z\, \rho_A(r) = \int \mathrm{d}z\, (\rho_n(r) + \rho_p(r))$, is transverse nucleon density.

$A_{nn}(b_\perp) = 2(1 - e^{-\Omega(b_\perp)/2})$: nucleon-nucleon scattering amplitude.

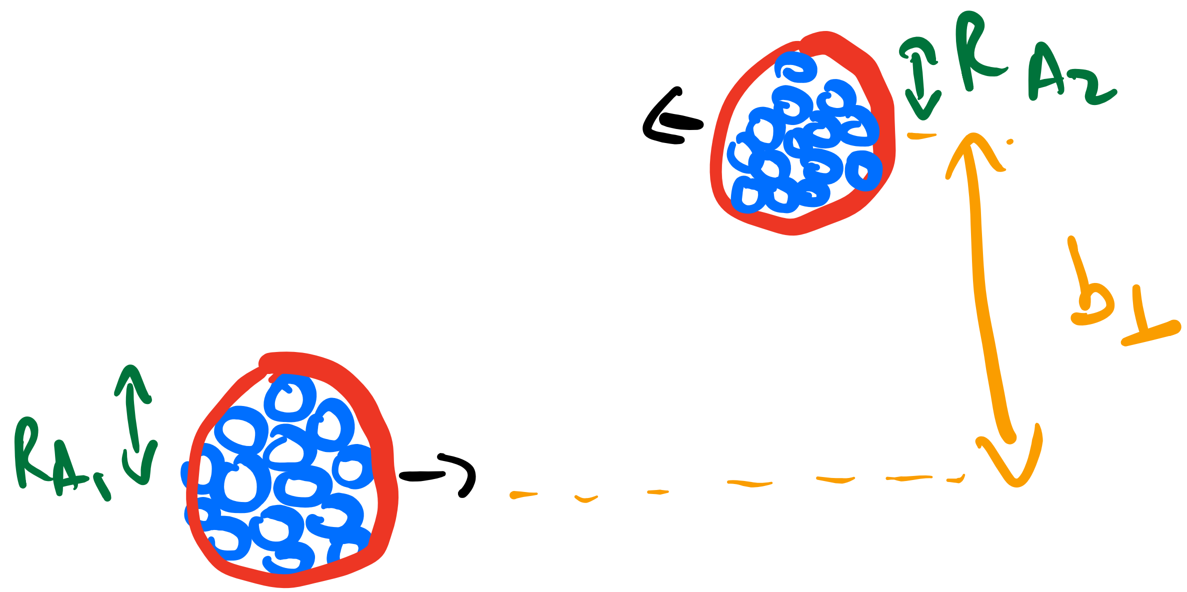
i.e. schematically given in terms of integrating individual nucleon-nucleon scatterings over the overlap area of the ions.



- Result for Pb-Pb:



$\Rightarrow$ expect larger suppression vs. simple $b_\perp > R_{A_1} + R_{A_2}$ cut, as QCD has finite range.

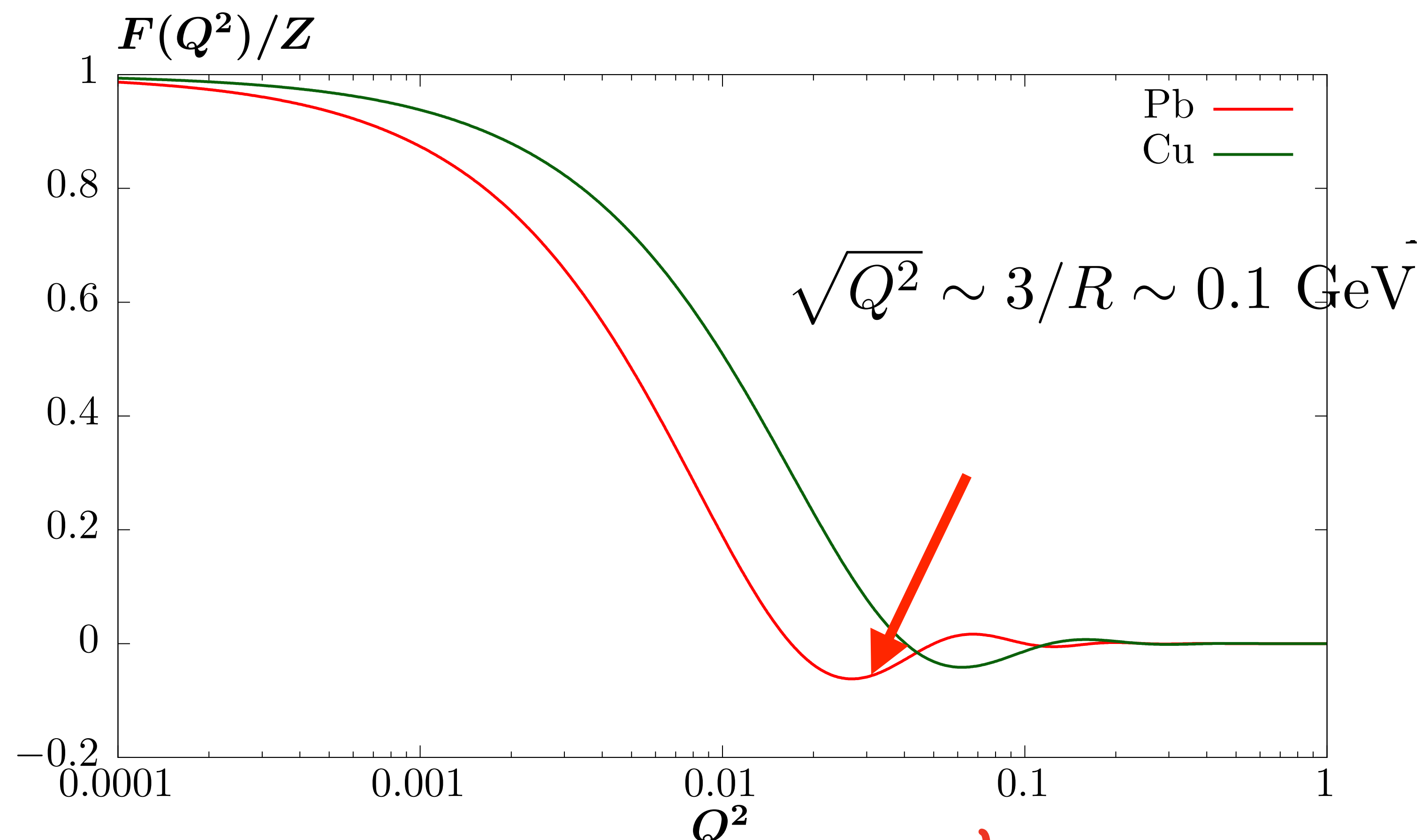


$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp} ...)|^2 e^{-\Omega_{A_1 A_2}(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}$$

- How significant is the survival factor? How much does it reduce cross section by?

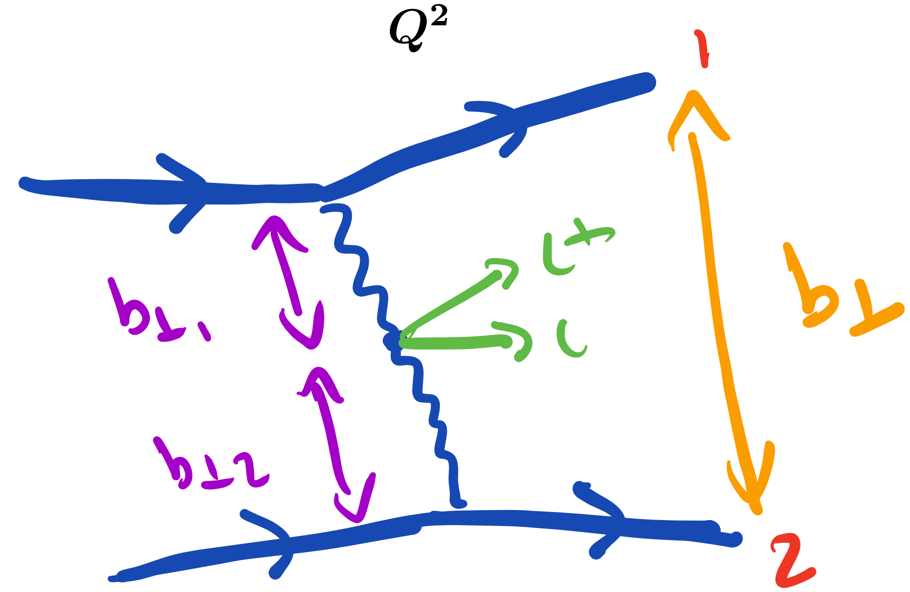
$$S^2 = \frac{\int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp} ...)|^2 e^{-\Omega_{A_1 A_2}(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}}{\int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp} ...)|^2}$$

- Key point: ion-photon form factor $F(Q^2)$ steeply falling at higher Q^2 .



- Higher $Q^2 \Rightarrow$ lower impact parameter $b_\perp$

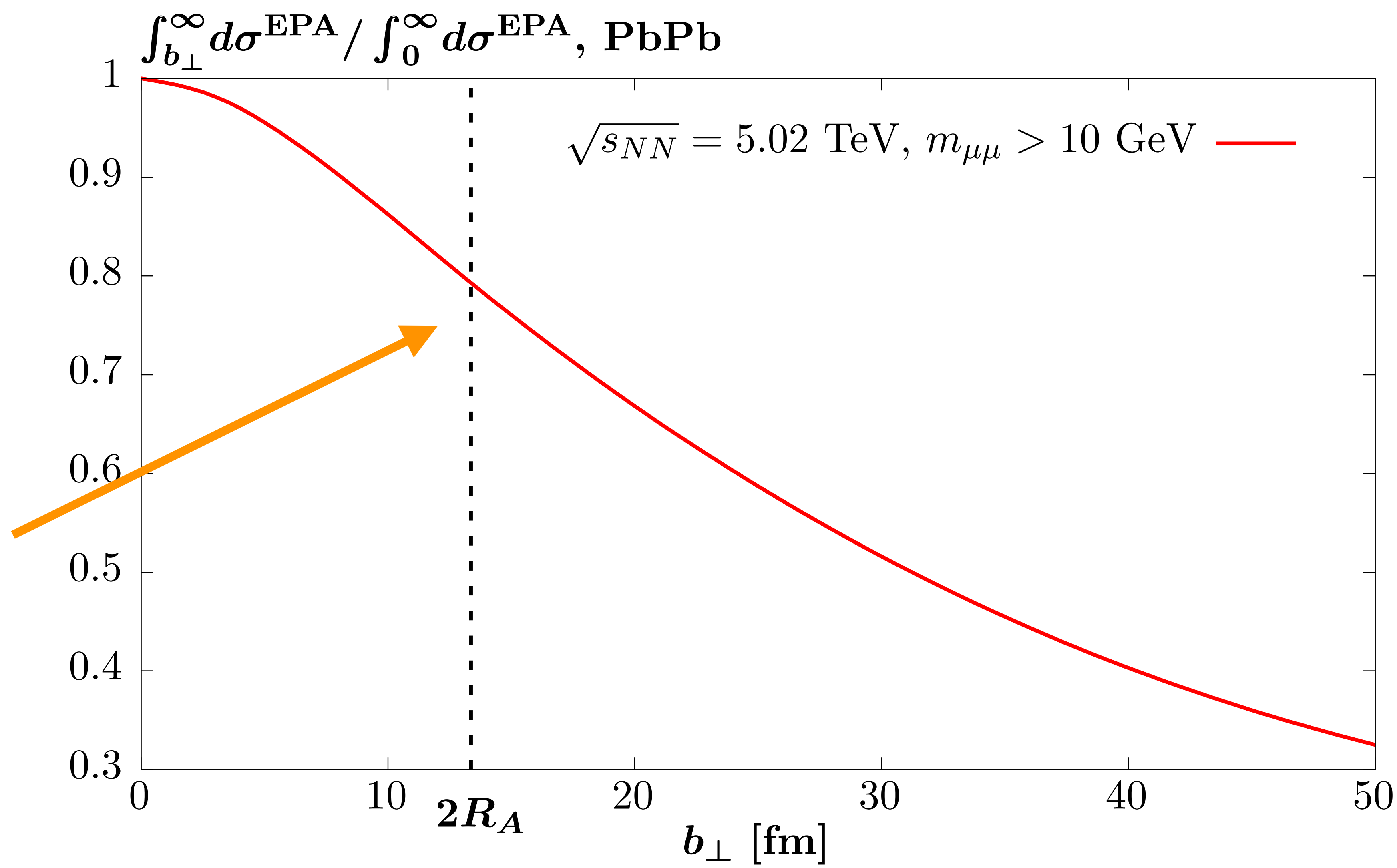
$\Rightarrow$ low $b_\perp$ region already suppressed by elastic photon-ion interaction.



- Have a look at ratio:

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

~ 80% of cross section lies outside $b_\perp > R_{A_1} + R_{A_2}$

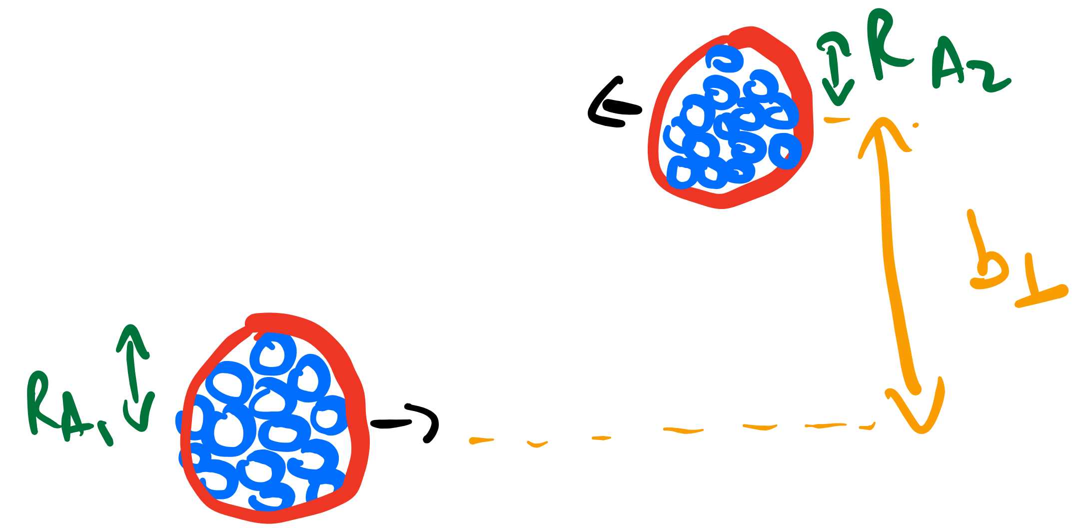


- Elastic photon-photon production is a **special case**: quasi-real photon corresponds to large average ion-ion impact parameter $\Rightarrow$ outside range of QCD interactions between ions!

- Depending on precise process/ kinematics have:

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

- What about uncertainties?

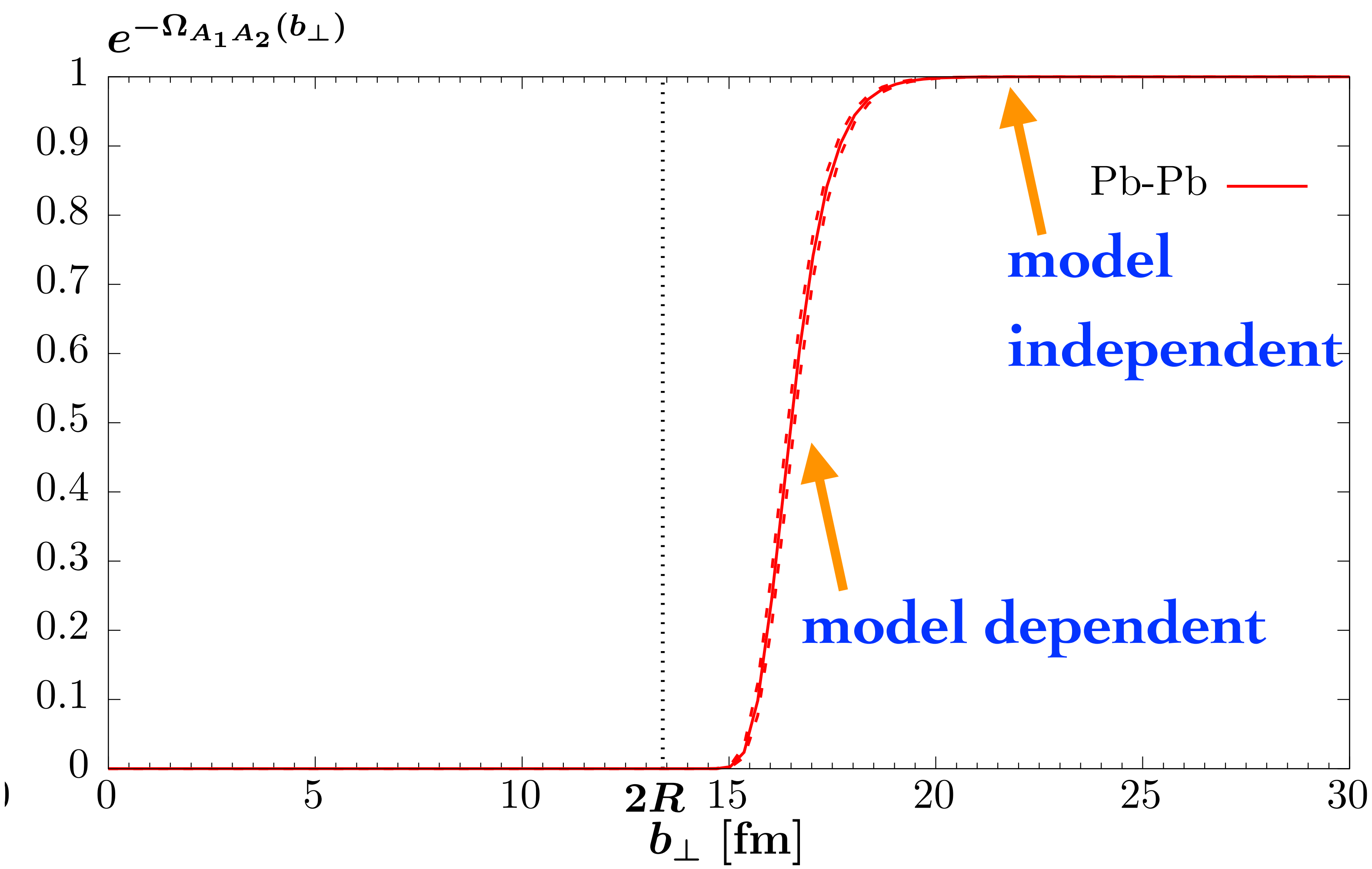


- Naively might assume inelastic ion-ion interactions has large uncertainties - requires knowledge of non-perturbative QCD/nuclear physics.

- However, not the case: majority of interaction occurs for

$$b_\perp > R_{A_1} + R_{A_2}$$

where $S^2 \sim 1$ independent of QCD modelling.



$\longrightarrow$ Uncertainty on S^2 small, at % level.

- Other effects?

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

$$\langle S^2 \rangle = \frac{\int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp} \ldots)|^2 e^{-\Omega_{A_1 A_2}(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}}{\int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp} \ldots)|^2}$$

$b_\perp \leftrightarrow q_\perp$

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

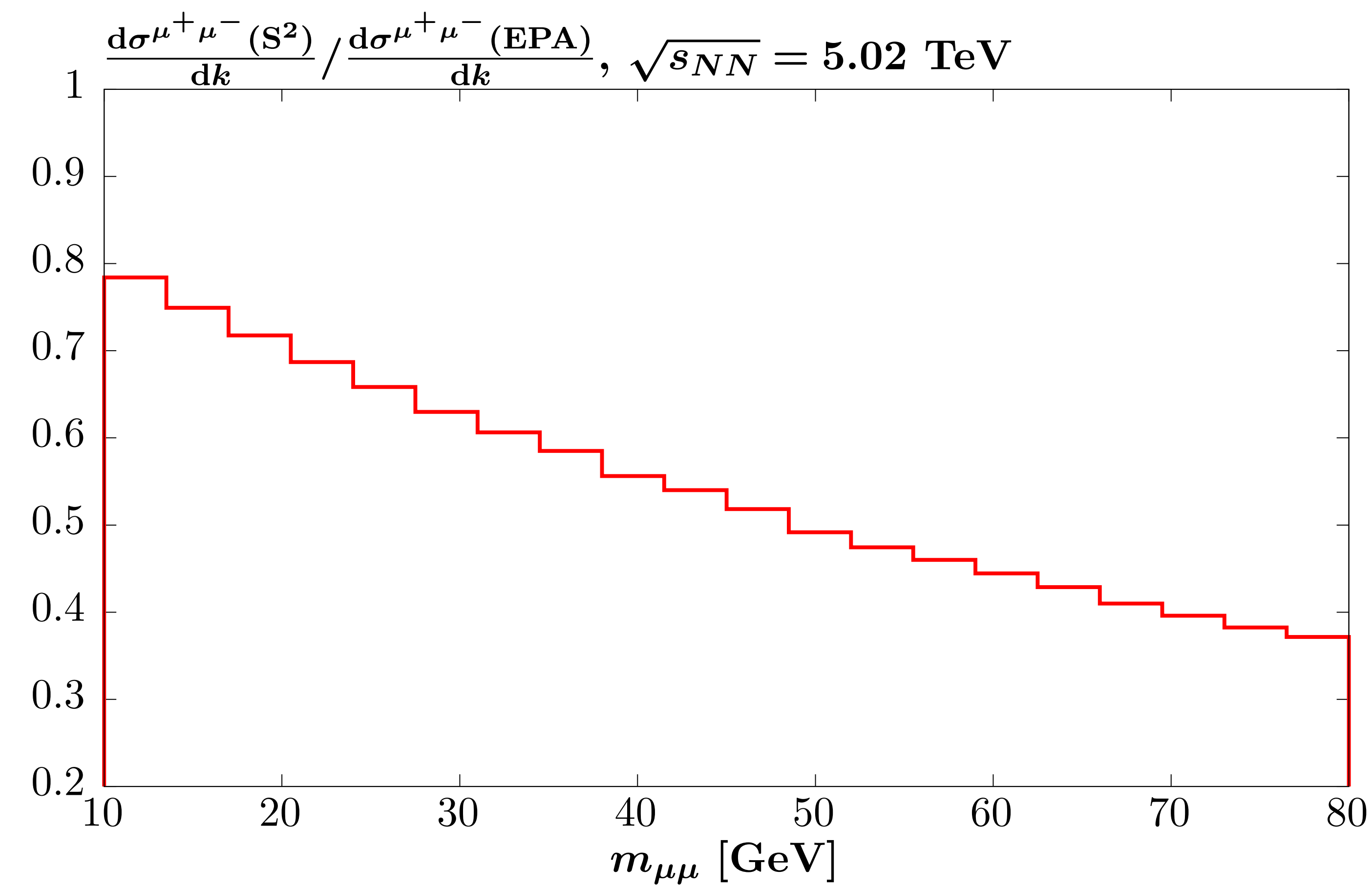
Kinematics

Process

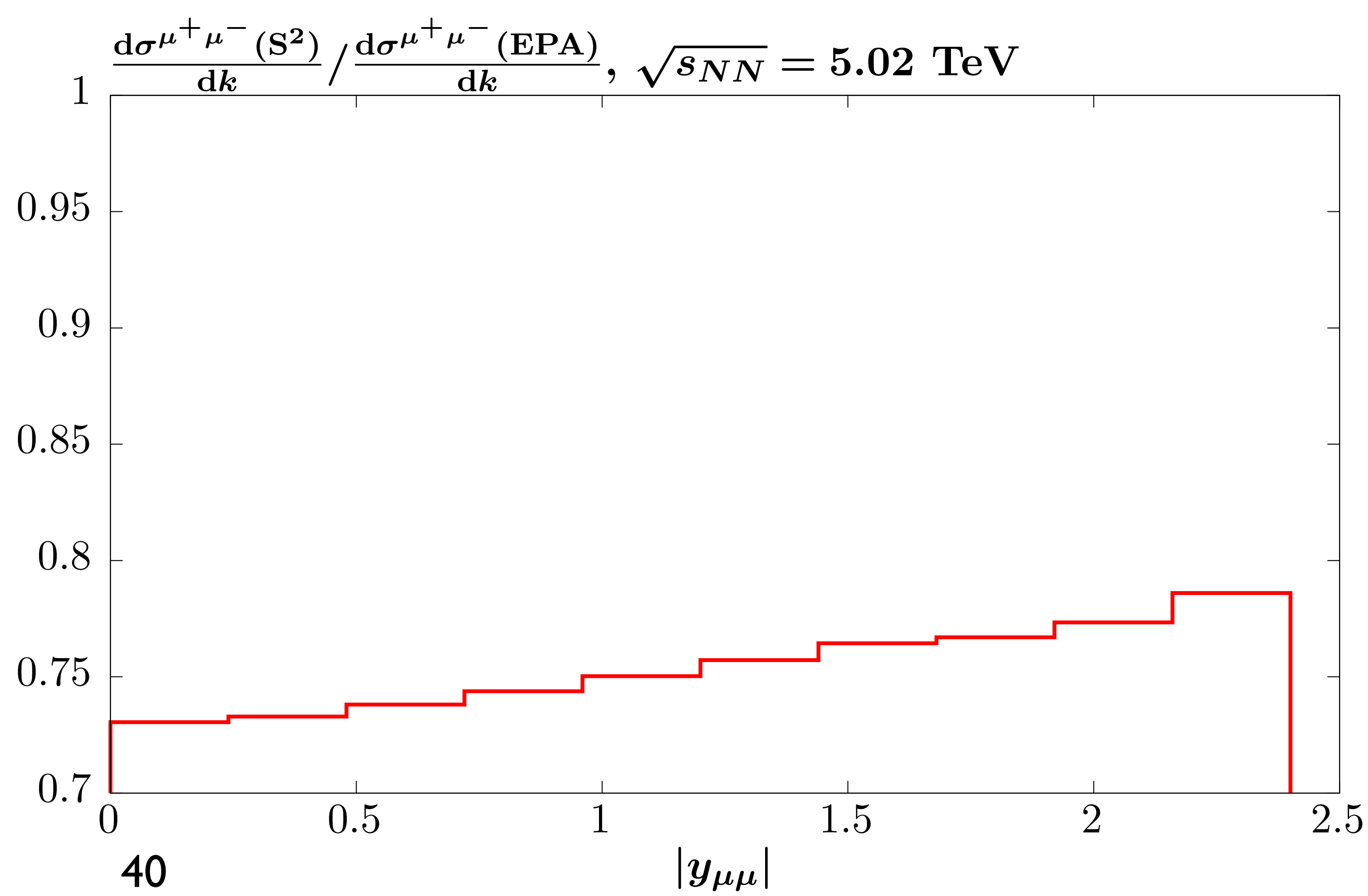
$T \sim n(x_1) n(x_2) V(\gamma\gamma \to X)$

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

- For example, consider **dimuon** production in PbPb.
- Survival factor ~ 0.7-0.8 at low mass, but lower at high mass.



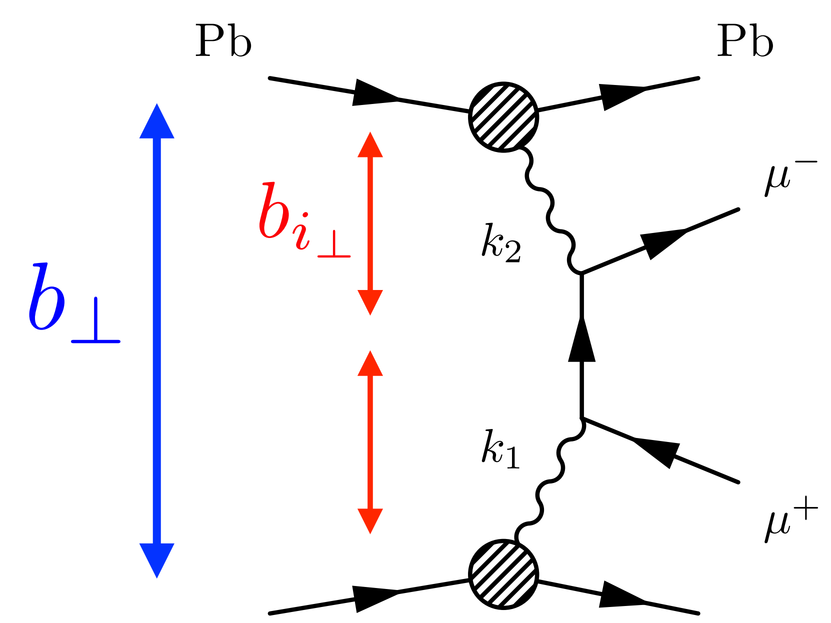
- Some (mild) dependence on rapidity.



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

- Survival factor due to hadron-hadron interactions - expressed ~ as a cut on the hadron-hadron impact parameter:

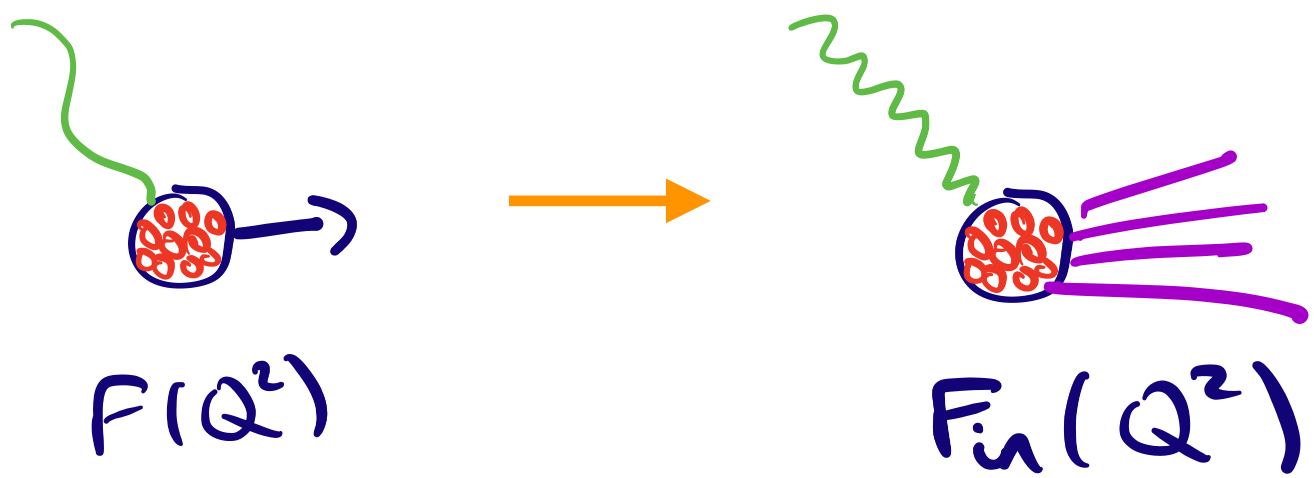
$$S^2(b_\perp) \approx \theta(b_\perp - 2r_A)$$



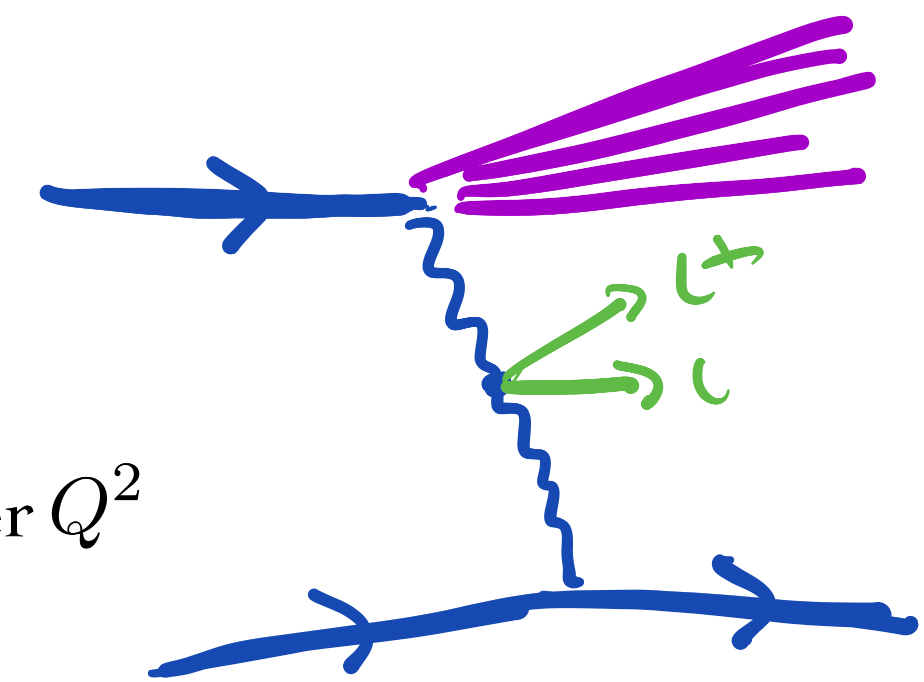
- However, in some MCs an additional cut on the dilepton-hadron impact parameter is imposed: $b_{1,2\perp} > R_A$
- This is unphysical: no lepton-hadron QCD interaction. HO QED interactions small and not to be included in this way.
- Indeed recent ATLAS data on dimuon production in PbPb disfavours such a cut.

Ion Dissociation

- Assume interaction is peripheral - no QCD ion-ion interactions. Can still have inelastic photon-ion interaction.
- How to include this? Suitably modified form factor:

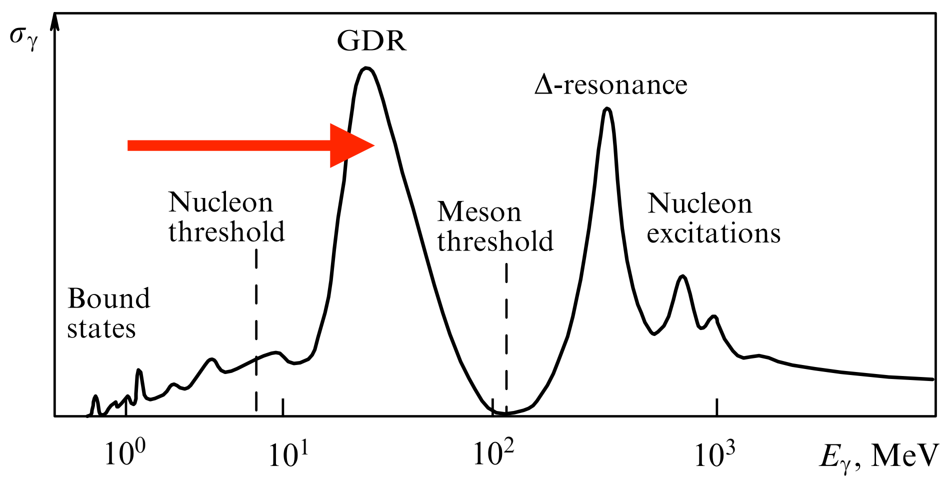


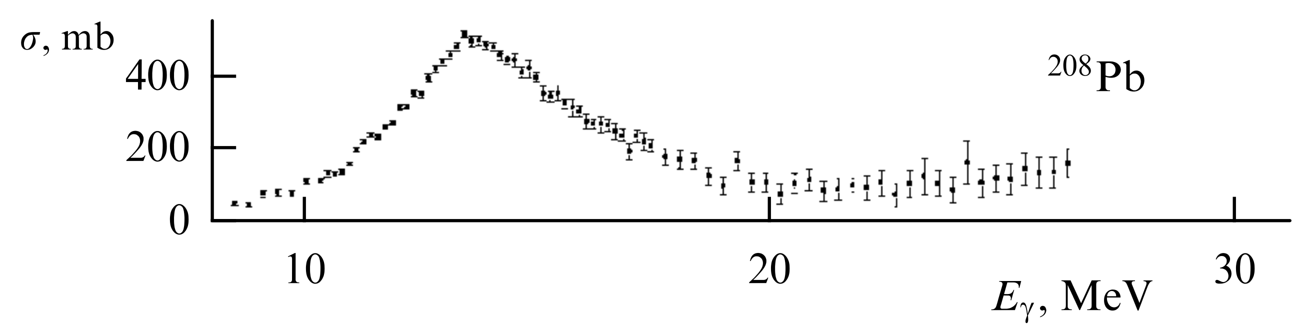
- But for inelastic emission photon no longer feels coherent charge Z of ion $\Rightarrow$ suppressed by factor of Z.

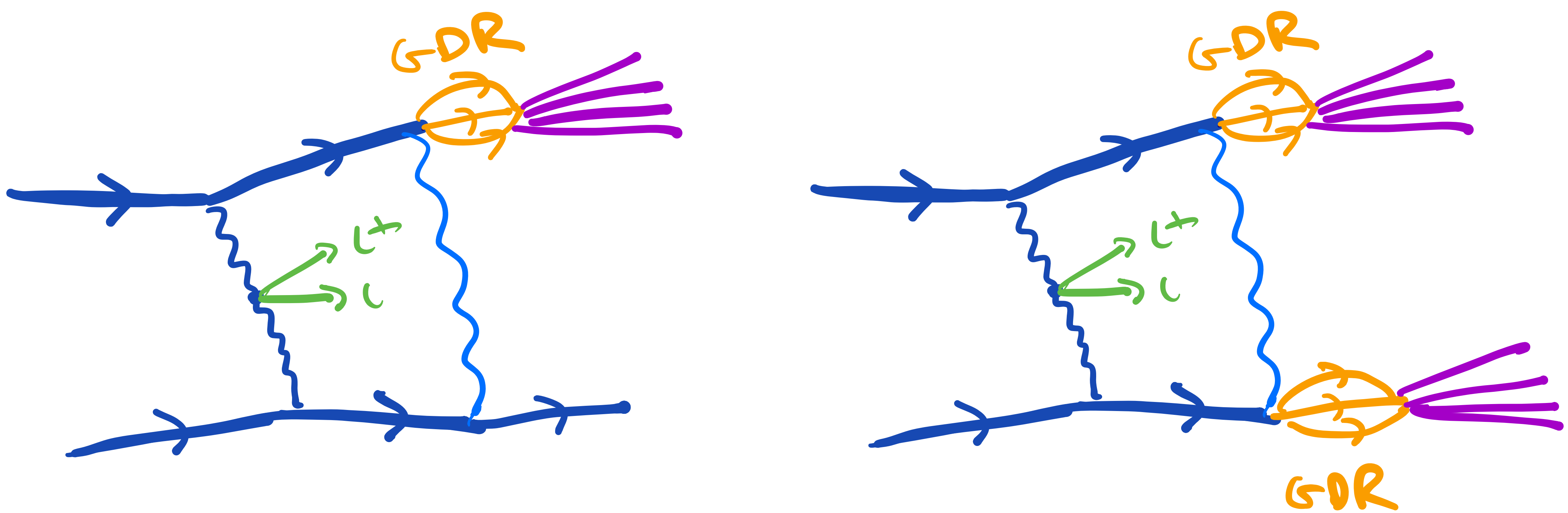


$\longrightarrow$ % level correction, and with broader Q^2 distribution.

- In fact this is not the dominant source of ion dissociation for ultra-peripheral ion-ion collisions.
- This comes from addition ion-ion photon exchanges. Can in particular excite ion into higher energy state: 'Giant Dipole Resonance'.





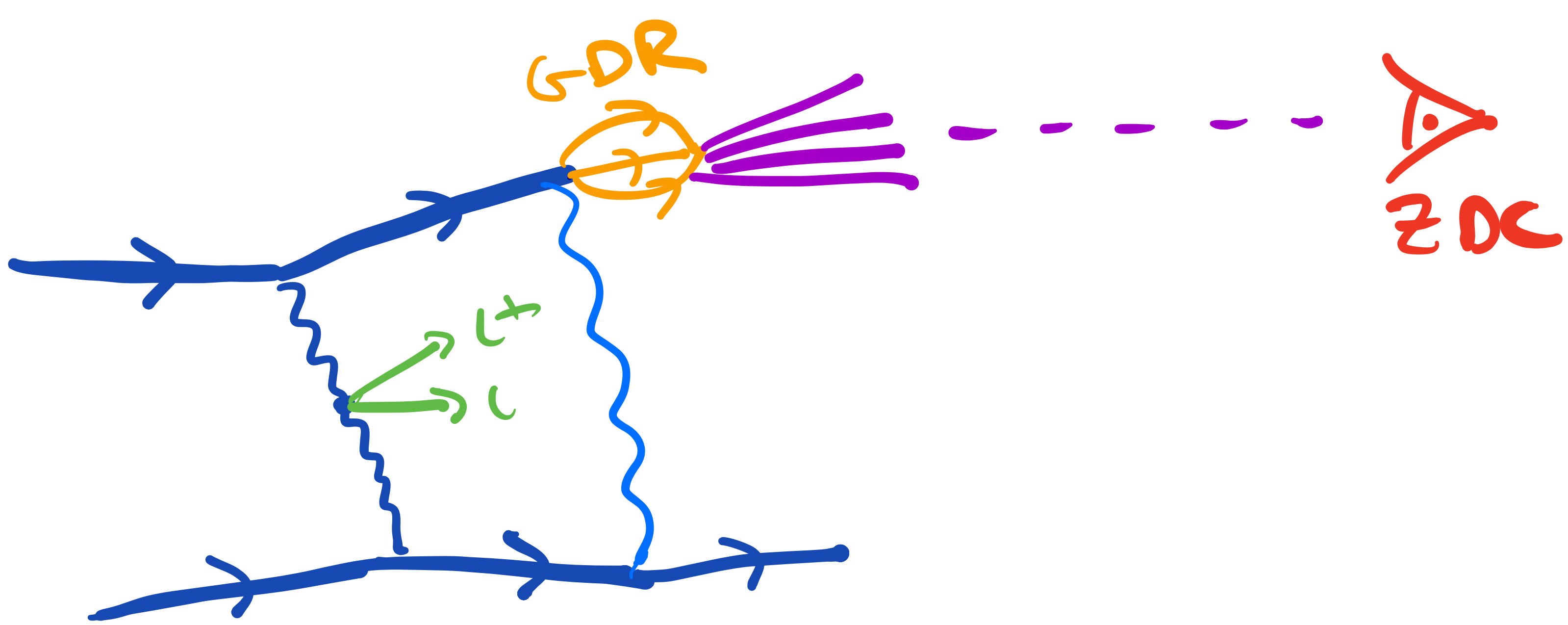


- GDR excitation assumed to happen independently of photon-photon cross section:

$$\sigma \sim \int d^2 b_\perp \, \sigma_{\gamma\gamma}(b_\perp) \cdot P_{\gamma A \to A^*}(b_\perp)$$

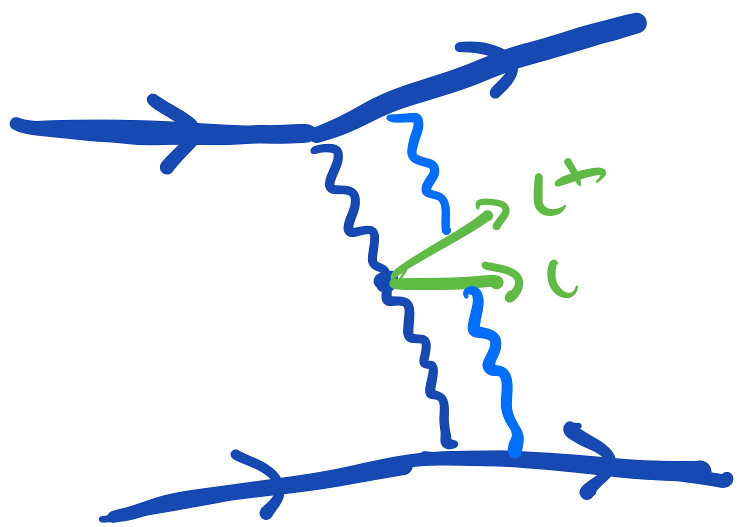
- Total probability sums to unity $\Rightarrow$ if MC excludes this effect will get rate correct. $\sum_{A^*} P = 1$

- However some distributions (e.g. dilepton acoplanarity) can be sensitive.
- In addition, can distinguish experimentally by measuring decay neutron in 'Zero Degree Calorimeters' (ZDCs).



Higher order QED effects

- Lepton pair production: the Z^2 enhancement of elastic photon-ion interaction implies that additional ion-lepton QED exchanges no necessarily negligible.

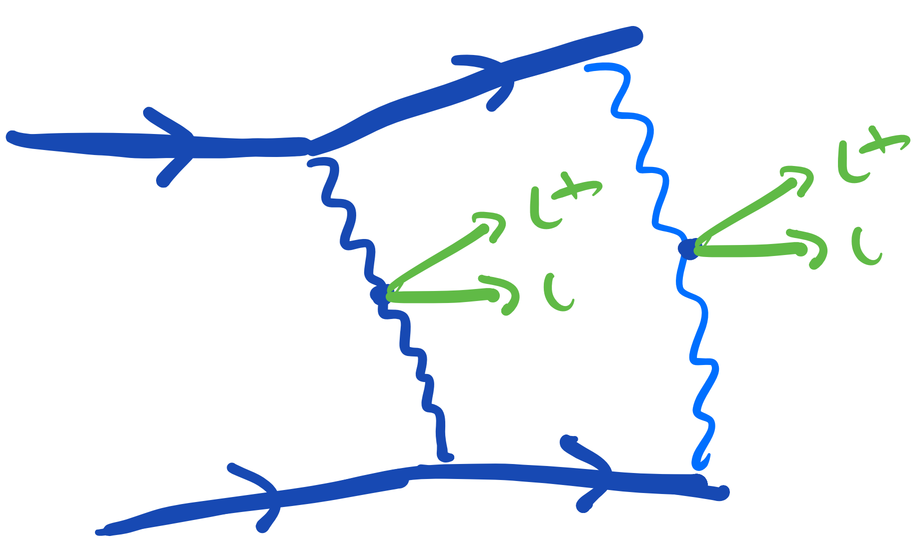


- Size of effect no settled matter: differing studies give differing results, from < 1% to ~ 10%.

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

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

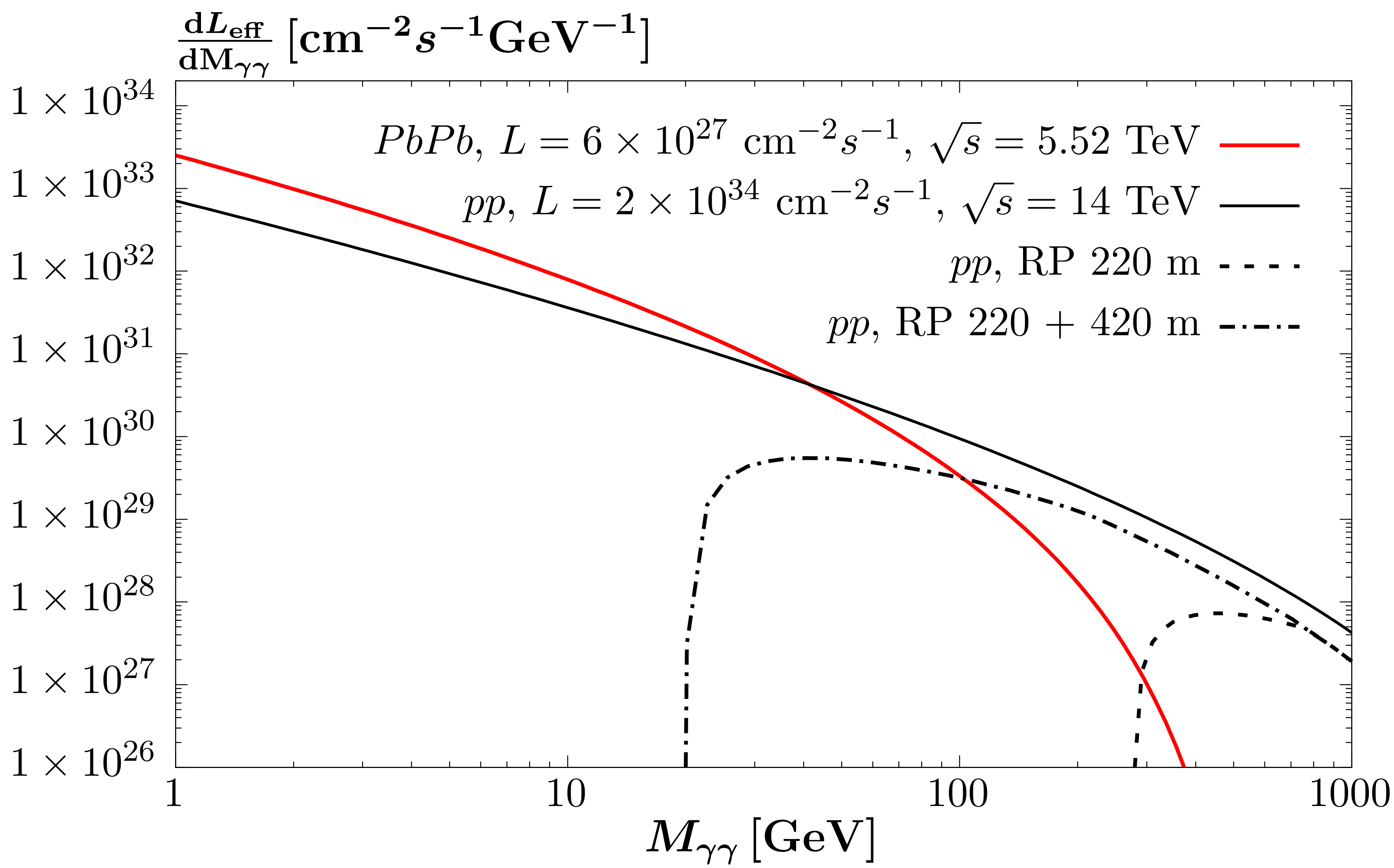
- Additional lepton pair production also not neligible:



- Studies suggest ~ 50% events accompanied by additional e^+e^- pairs.
- Strongly peak at v. low energy, so impact depends on detail of experimental veto.

What are heavy ion collisions good for?

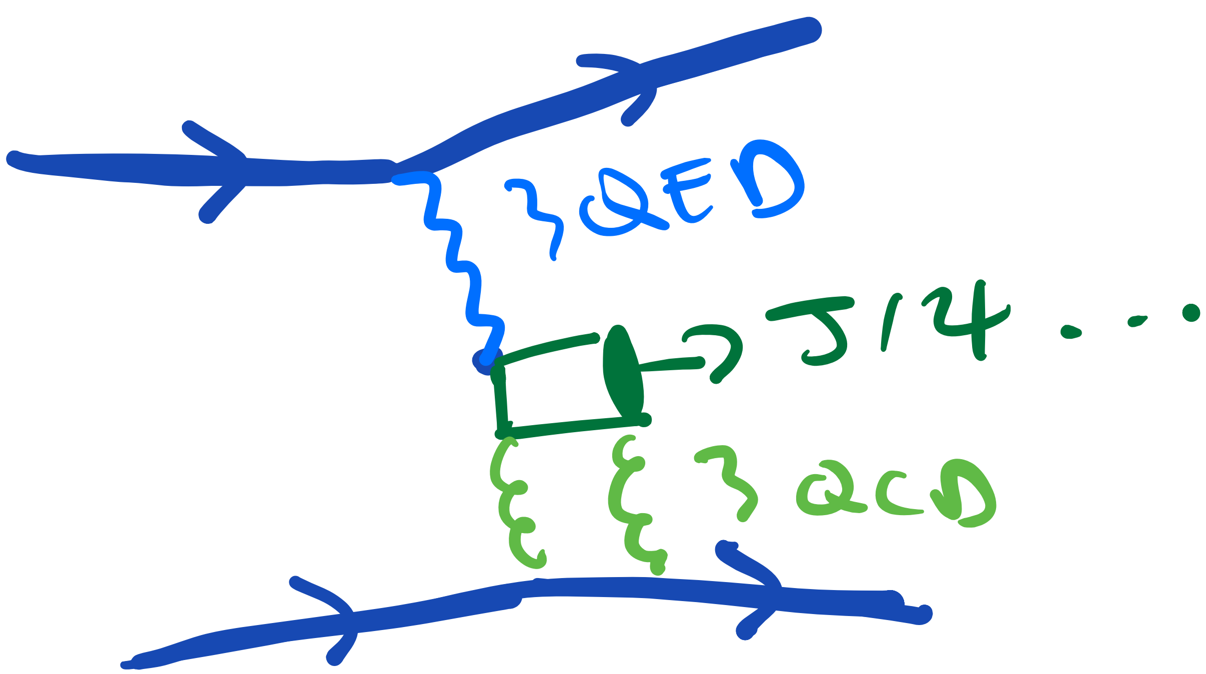
- At lower masses, Z^4 enhancement wins: PbPb larger effective luminosity than pp.
- However PbPb rate sharply falling with $m_{\gamma\gamma}$: larger $m_{\gamma\gamma} \Rightarrow$ larger $x_\gamma \Rightarrow$ larger average photon Q^2 and ion will not remain intact.



$\longrightarrow$ Heavy ion collisions useful for lower mass production.

Aside: photoproduction

- Photon-photon collisions not the only process of interest: production of strongly interacting objects via photoproduction also possible.
- Involves QCD interaction $\Rightarrow$ sensitive to nuclear structure, saturation effects…
- Photon emission on one side $\Rightarrow$ ultraperipheral interaction still possible.
- Can also consider pA collisions.
- Will not discuss in detail here (time), but worth bearing in mind!



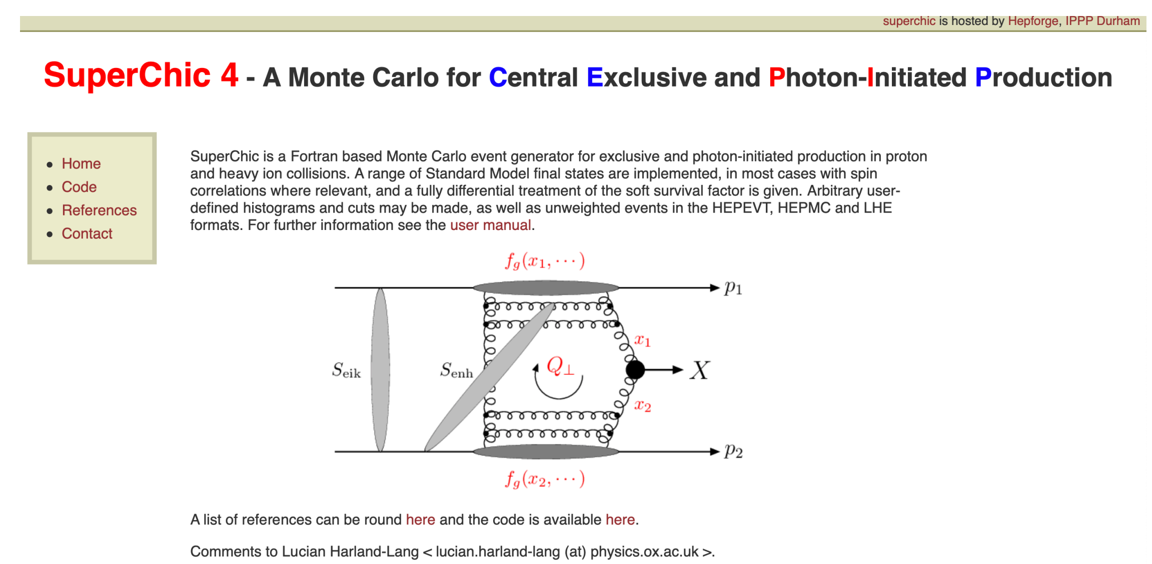
MCs on the Market

- Principle MCs on the market: ★ **SuperChic**

- 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.

- In heavy ions, currently implemented of most relevance:
  - Lepton pairs.
  - Light-by-light scattering.
  - ALPs.
  - Monopoles.
  - Vector meson photoproduction.



`https://superchic.hepforge.org`

- Currently only elastic production implemented: no dissociation.

★ Starlight

- Dedicated MC for heavy ion collisions.

- Range of two-photon processes implemented:

Two-Photon Channels

	Particle	Jetset ID
lepton pairs	e^+e^- pair	11
	$\mu^+\mu^-$ pair	13
	$\tau^+\tau^-$ pair	15
	$\tau^+\tau^-$ pair, polarized decay	10015*
vector mesons	ρ^0 pair	33
	$a_2(1320)$ decayed by PYTHIA	115
	η decayed by PYTHIA	221
	$f_2(1270)$ decayed by PYTHIA	225
	η' decayed by PYTHIA	331
	$f_2(1525) \rightarrow K^+K^-(50\%), K^0\bar{K}^0(50\%)$	335
	η_c decayed by PYTHIA	441
	$f_0(980)$ decayed by PYTHIA	9010221

- As well as vector meson photoproduction.
- Nuclear breakup is included - both single and multiple neutron emission.
- **But** unphysical $b_\perp > R_A$ cut always applied.
- Process dependence of survival factor not included.

`https://starlight.hepforge.org`

★ gamma-UPC

- New MC for photon-photon production in heavy ion ultra-peripheral collisions (UPCs).

- Makes use of MadGraph: in principle any arbitrary $\gamma\gamma \to X$ process can be simulated, e.g.:

$\gamma\gamma \to e^+e^-, \mu^+\mu^-$

$\gamma\gamma \to \tau^+\tau^-$

$\gamma\gamma \to \gamma\gamma$

$\gamma\gamma \to \mathcal{T}_0$

$\gamma\gamma \to (c\bar{c})_{0,2}, (b\bar{b})_{0,2}$

$\gamma\gamma \to \mathrm{XYZ}$

$\gamma\gamma \to \mathrm{VM\,VM}$

$\gamma\gamma \to \mathrm{W^+W^-,\ ZZ,\ Z}\gamma, \cdots$

$\gamma\gamma \to \mathrm{H}$

$\gamma\gamma \to \mathrm{HH}$

$\gamma\gamma \to t\bar{t}$

$\gamma\gamma \to \tilde{\ell}\tilde{\ell}, \tilde{\chi}^+\tilde{\chi}^-, \mathrm{H^{++}H^{--}}$

$\gamma\gamma \to a, \phi, \mathcal{MM}, G$

- Currently only elastic production implemented: no dissociation.
- Process dependence of survival factor not included.

https://hshao.web.cern.ch/hshao/gammaupc.html

→ Selection of MCs publicly available that model photon-photon production in heavy ion collisions.

- All broadly use the same underlying theory:

$$\sigma \sim \int d^2q_{1\perp}\, d^2q_{2\perp}\, \frac{dx_1}{x_1} \frac{dx_2}{x_2}\, dPS_{\gamma\gamma\to X}$$

$\cdot\ \alpha(Q_1^2) \cdot \frac{1}{Q_1^2} \left(\frac{q_{\perp 1}^2}{Q_1^2} \cdot F^2(Q_1^2) \right)$:

$\cdot\ \alpha(Q_2^2)\, \frac{1}{Q_2^2} \left(\frac{q_{\perp 2}^2}{Q_2^2} \cdot F^2(Q_2^2) \right)$:

$\cdot\ |M(\gamma\gamma \to X)|^2$:

$$\sigma = \int \mathrm{d}^2 b_{1_\perp} \mathrm{d}^2 b_{2_\perp} |\tilde{M}(\vec{b}_{1_\perp}, \vec{b}_{2_\perp} ...)|^2 e^{-\Omega_{A_1 A_2}(\vec{b}_{1_\perp} - \vec{b}_{2_\perp})}$$

but with (important) differences in implementation/processes generated.

★ Full treatment of survival factor.

★ Ion dissociation.

★ Unphysical $b_\perp > R_A$ cut.

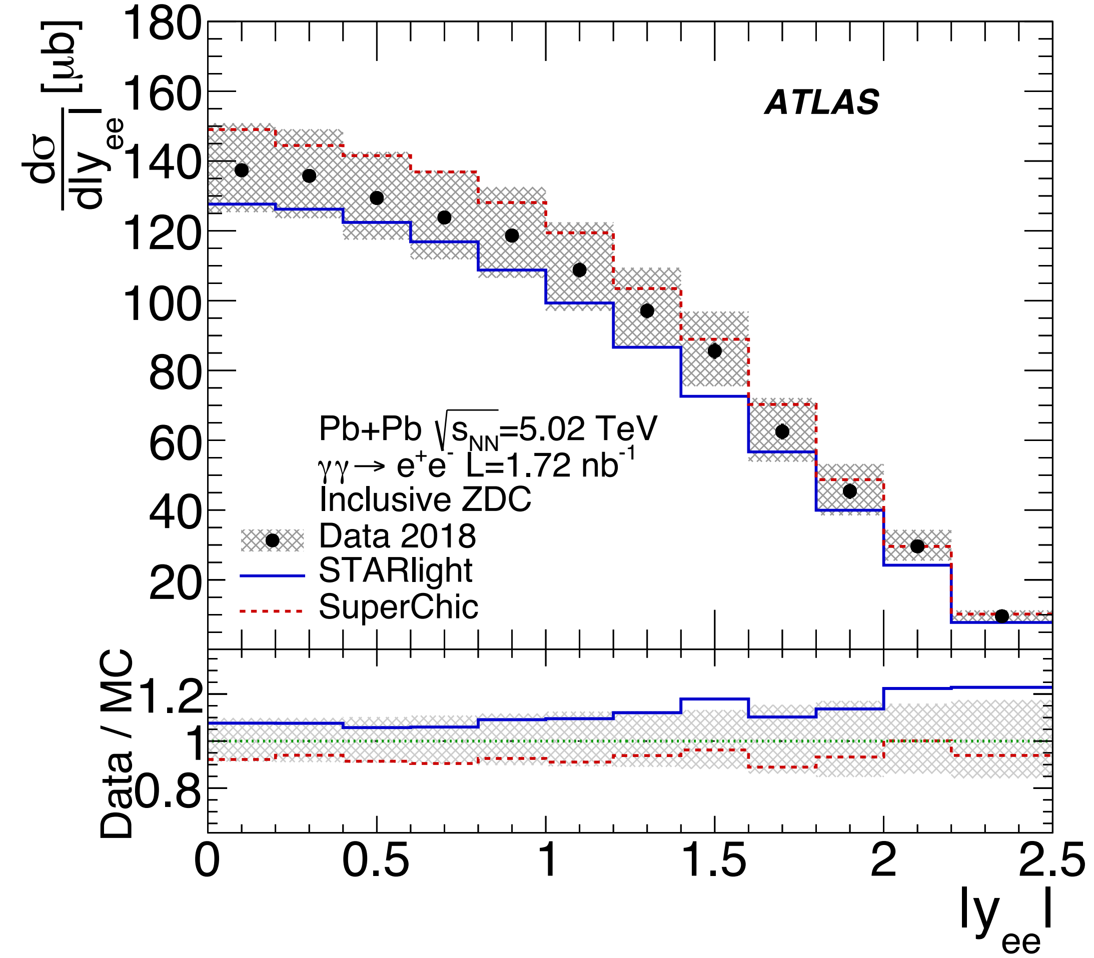
★ Automated process generation.

★...

Where do we stand?

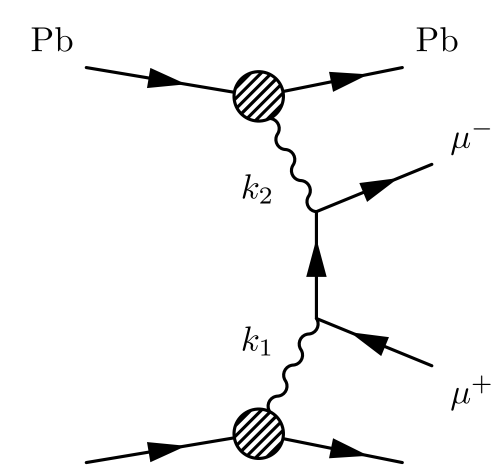
- Measurements of lepton pair production broadly agree with Superchic/ Starlight predictions, but not entirely:

  ★ Unphysical $b_\perp > R_A$ cut disfavoured by differential data.



- But tendency for SuperChic predictions to undershoot dimuon data (better for electrons).

	ATLAS data [24]
σ [μb]	34.1 ± 0.8

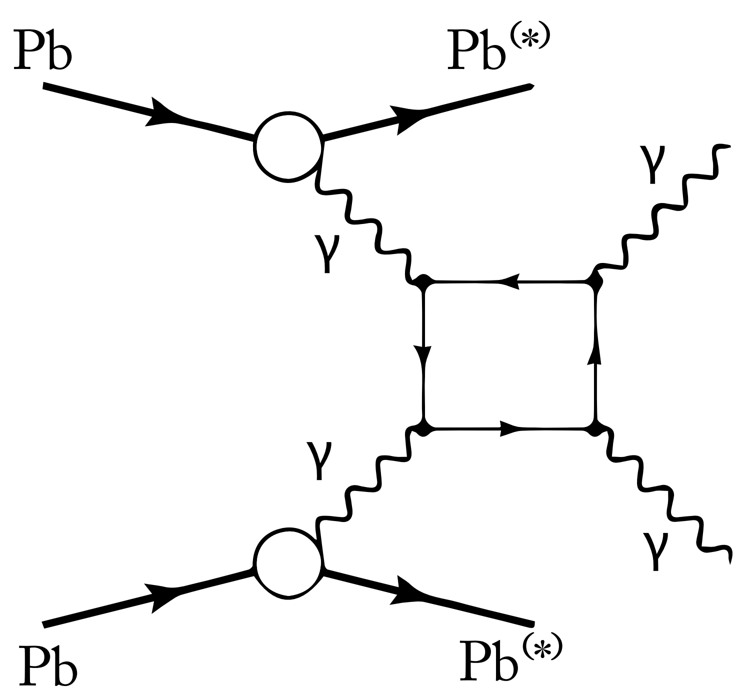


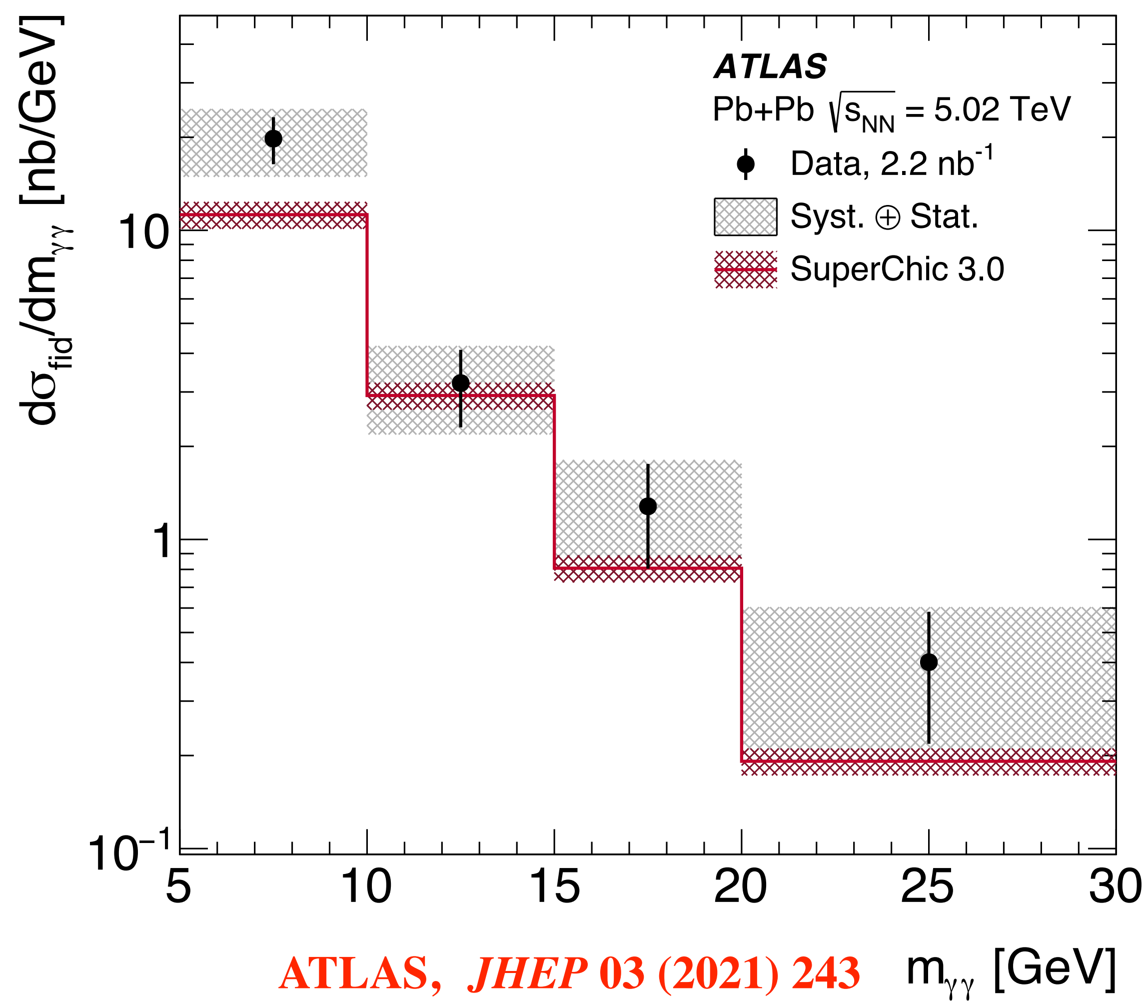
Light-by-Light Scattering

- 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

Outlook

- Basic theory for modelling two-photon interactions in heavy ion collisions well established.
- Range of MCs on the market that implement this.
- But none so far are complete:

  ★ Full treatment of survival factor.

  ★ Inclusion of ion dissociation.

  ★ Higher order QED effects.

- To do high precision physics in heavy ion collisions including all of this well be key: more work to do!

Thank you for listening