Exciting Ions: Ultraperipheral Heavy Ion Collisions with Nuclear Breakup

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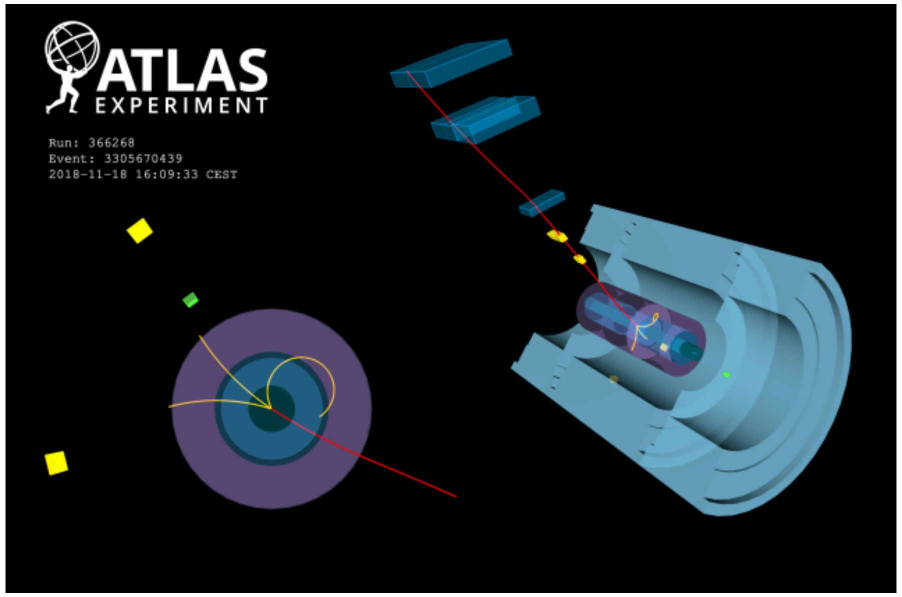
LHL, arXiv:2303.04826

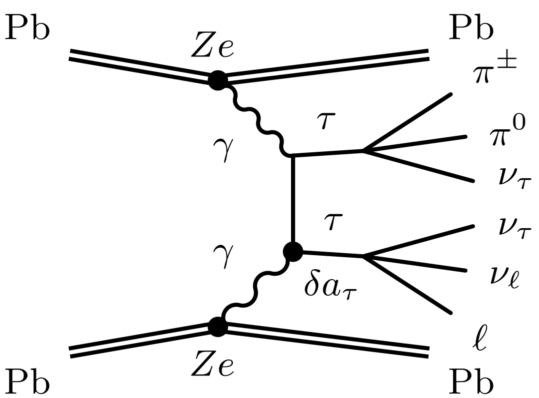
Motivation



- **Ultraperipheral** photon-initiated production: colour singlet photon naturally leads to events with intact ions/low multiplicity in final state.

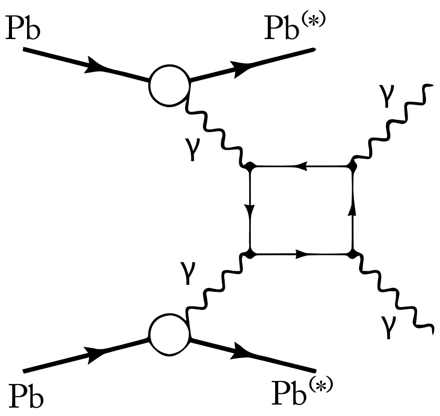
- **Clean** production mechanism and BSM probe.

tau g-2



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

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

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

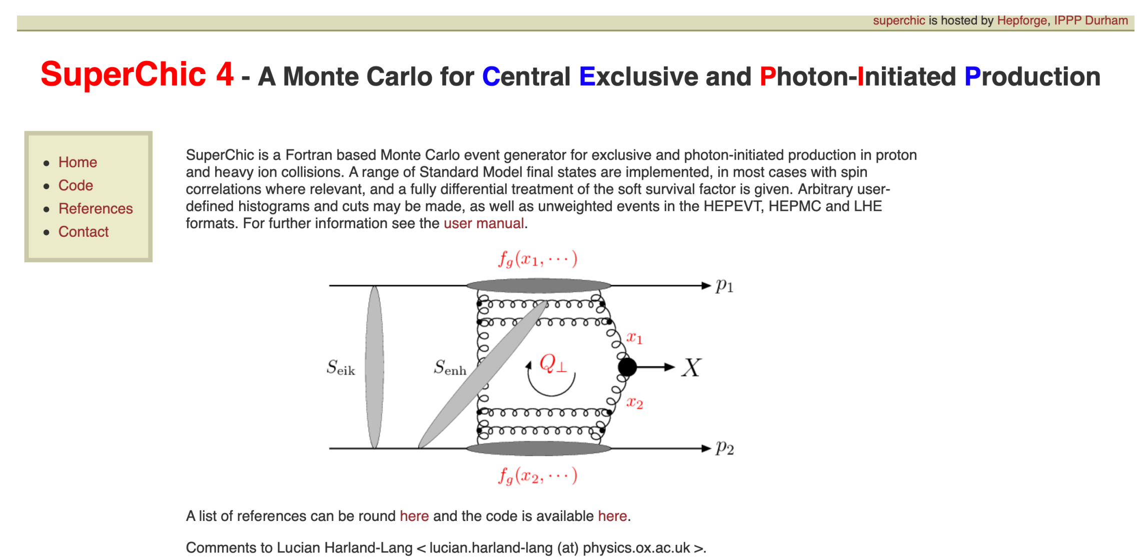
SuperChic 4.2

- 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.
  - LbyL scattering.
  - ALPs.
  - Monopoles

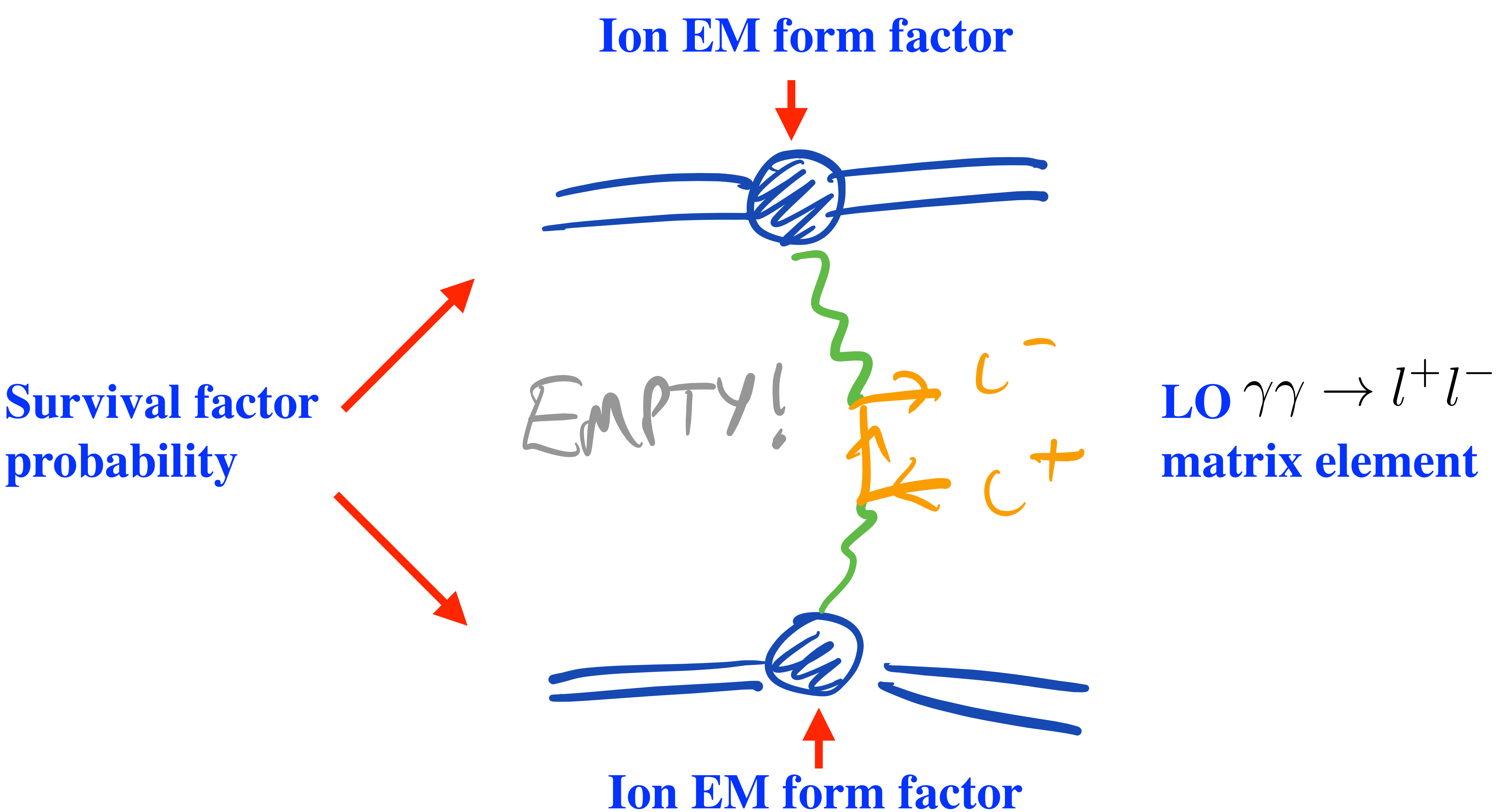
- But open to collaboration/discussion for including other channels!



https://superchic.hepforge.org

UPCs

- Consider e.g. lepton pair production. Key ingredients in **SC 4.2**:

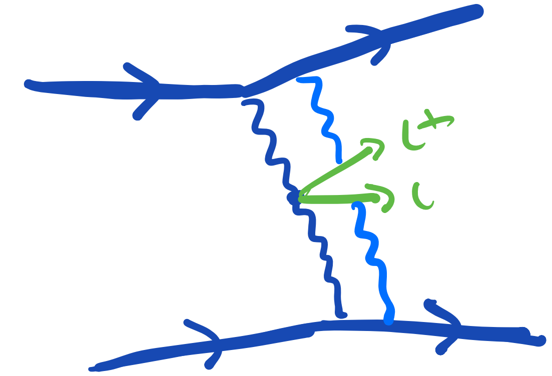


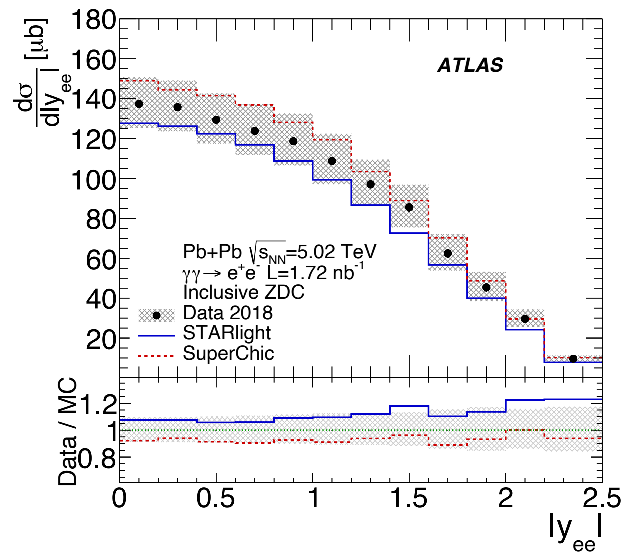
- Provides leading prediction for elastic process: $\mathrm{PbPb} \to \mathrm{Pb} + l^+l^- + \mathrm{Pb}$

- What else is missing?

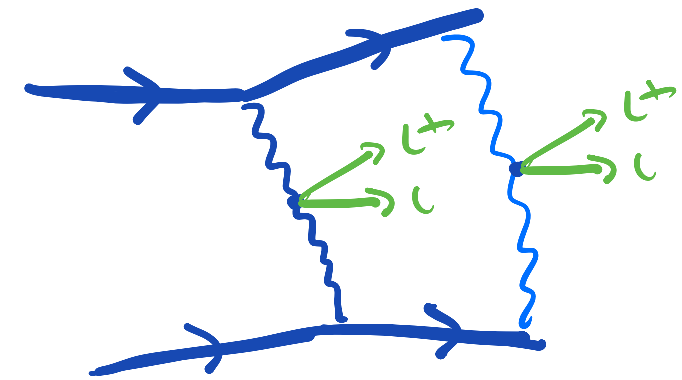
★ Higher order QED effects: some indication this might improve description of l^+l^-data.

Multiple scattering





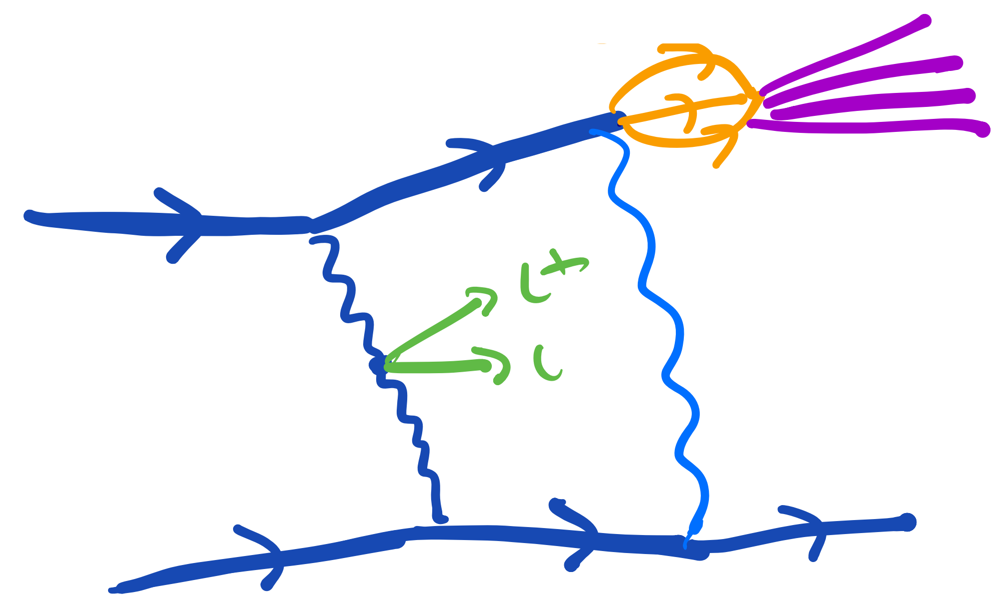
Unitary Corrections



Not Focus of this talk, but not to be ignored!

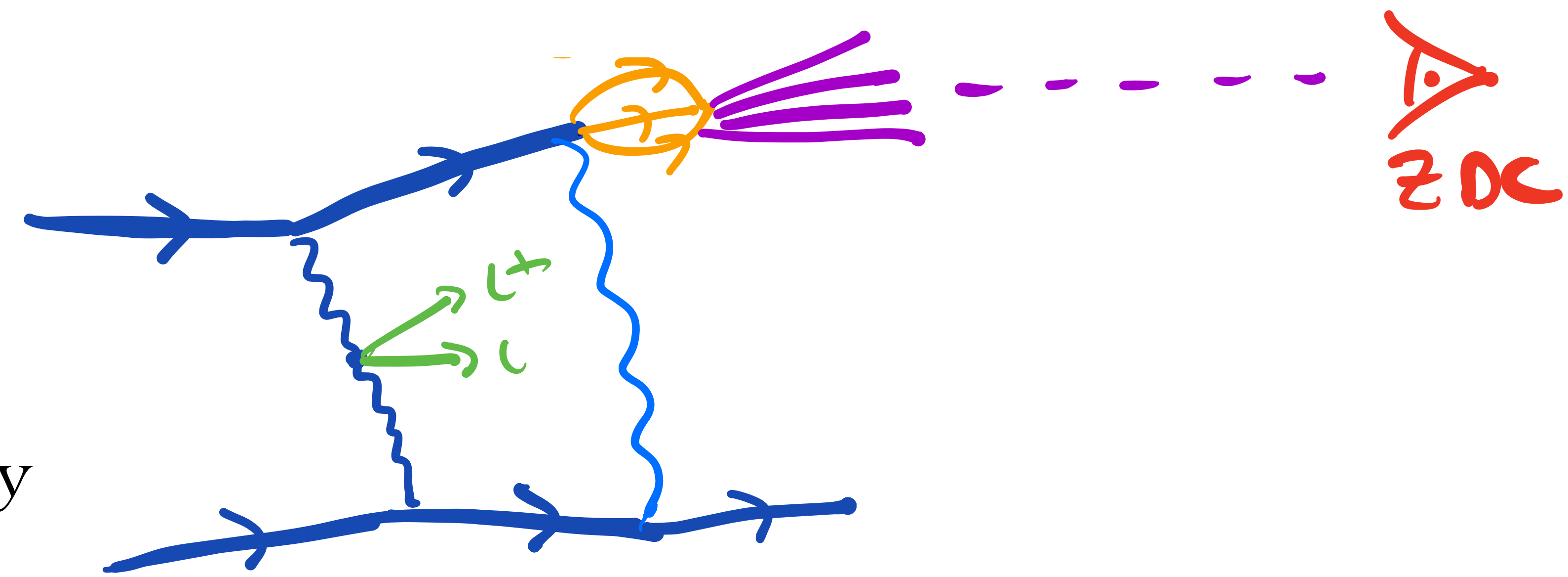
★ Focus here: ions can interact via additional QED exchanges and dissociate.

★ Accounted for in range of studies, but not complete MC treatment available (until now).

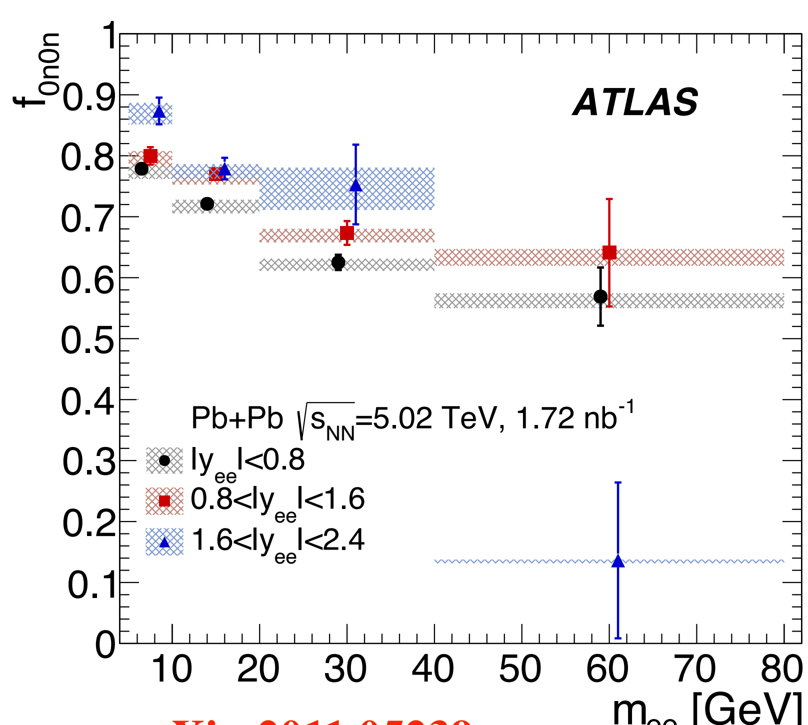


Mutual Ion Dissociation

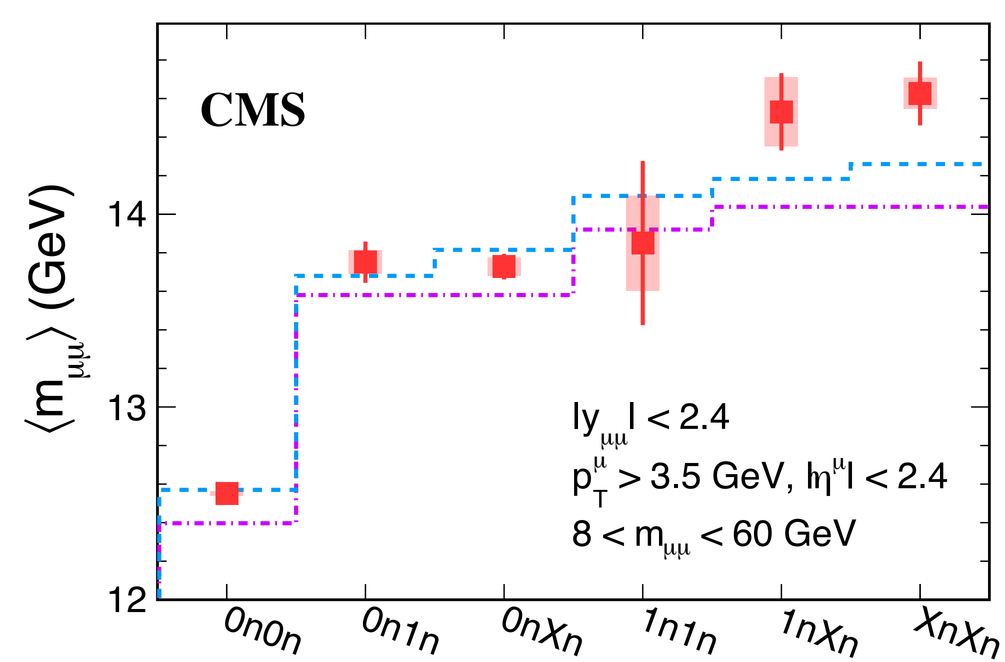
★ This dissociation leads to additional boosted neutron production: can be measured by Zero Degree Calorimeters.



★ As we will see, dilepton distributions also affected. Important to account for!



arXiv:2011.05239



arXiv:2207.12781

Modelling UPCs with Mutual Ion Dissociation

Modelling UPCs

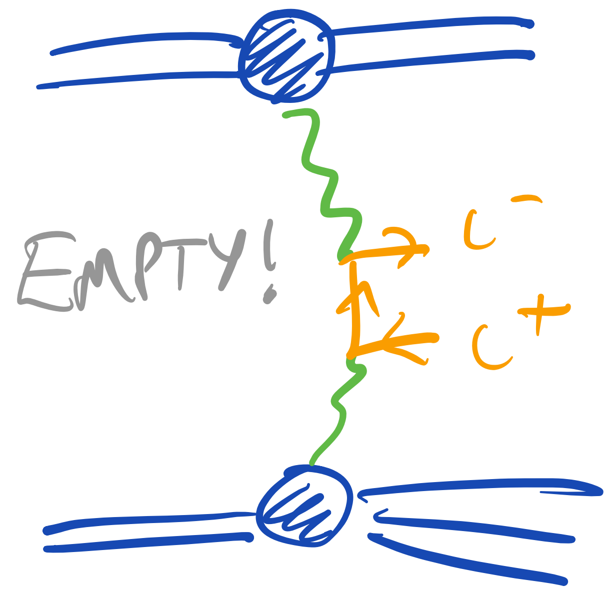
$b_\perp \gg r_{\rm QCD}$

- Basic idea: for UPCs ion-ion impact parameter $\gg$ range of QCD $\Rightarrow$ pure QED interaction.

- Consider e.g. lepton pair production.
Key ingredients:

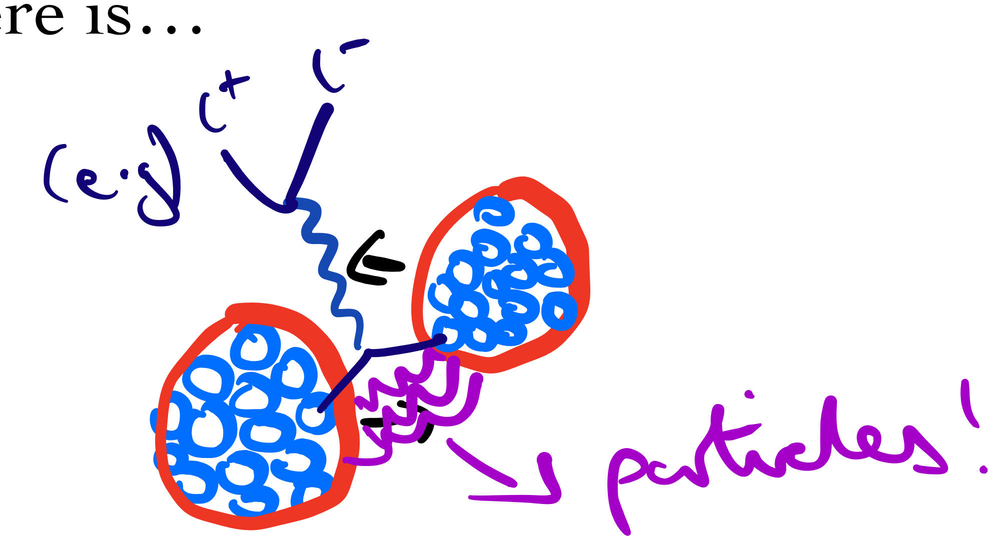
  ★ $\gamma\gamma \to l^+ l^-$ matrix element.

  ★ Ion EM form factor.



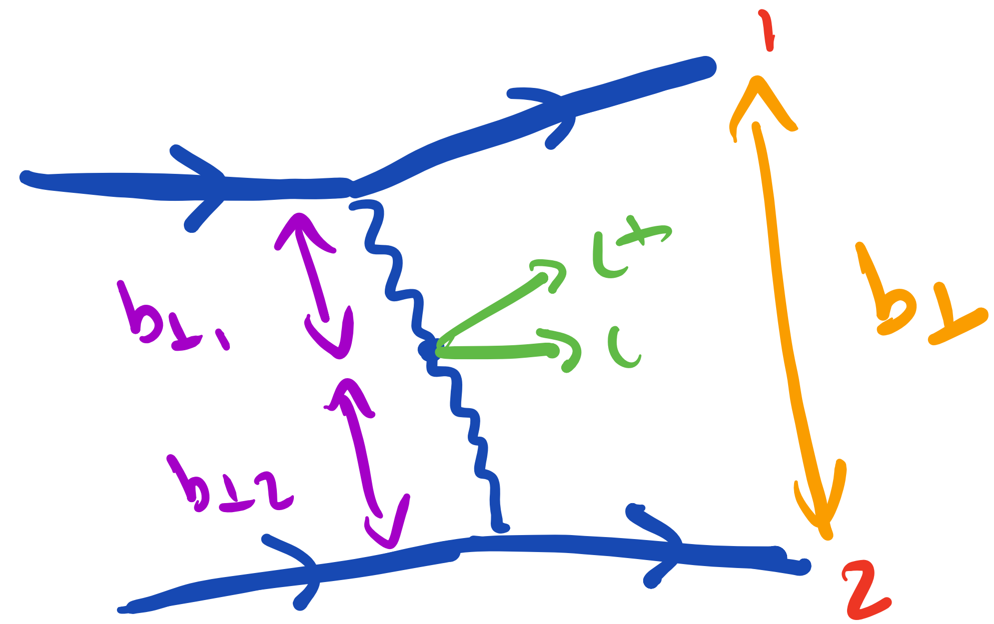
- Both well understood ✔. However not all there is…

- If $b_\perp \sim 2R_A$ additional strong ion-ion interactions cannot be ignored.



The Survival Factor

- Survival factor: probability of no additional strong ion-ion interactions.



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

- Can write cross section as integral over $b_{(1,2)_\perp}$

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

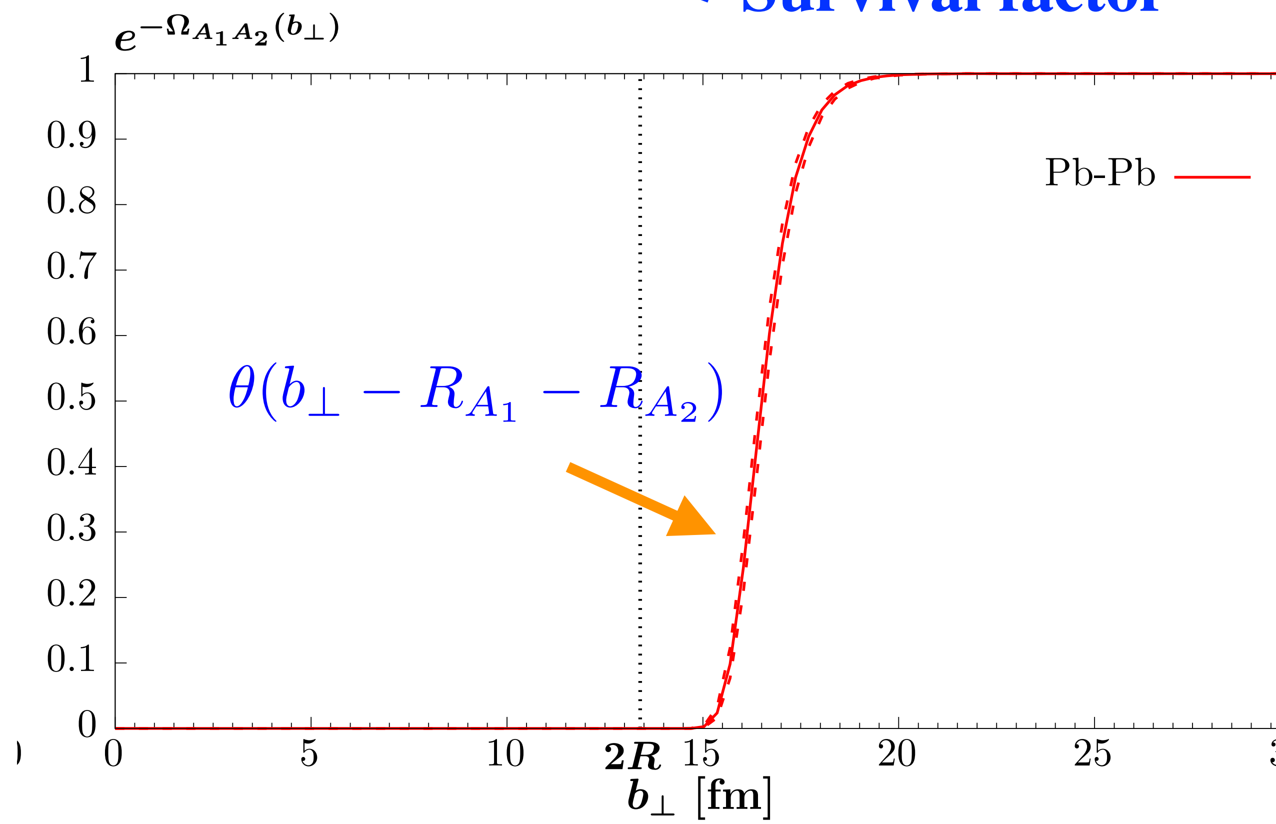
Amplitude for $l^+ l^-$ production in $b_\perp$ space.

- To first approximation survival factor included by requiring in integral:

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

$$d\sigma_{S^2} = \int d^2b_{1_\perp} d^2b_{2_\perp} |\tilde{T}(b_{1_\perp}, b_{2_\perp})|^2 e^{-\Omega_{A_1A_2}(b_\perp)}$$

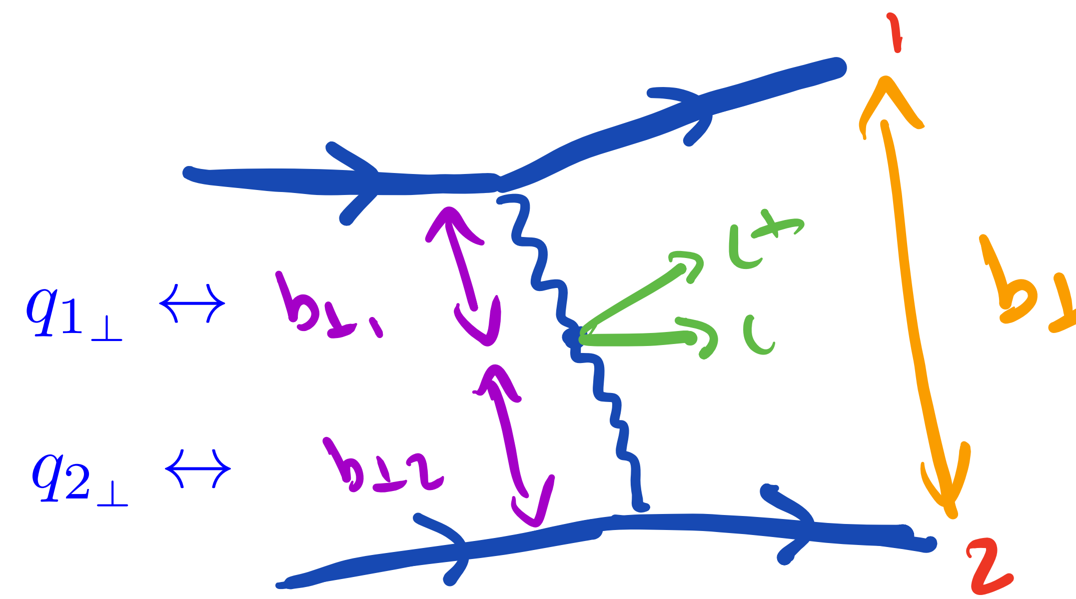
Survival factor



- More precisely can account for finite ion extent and non-zero range of QCD.

- Key point: impact parameters $b_{i_\perp}$ and photon $q_{i_\perp}$ are Fourier Conjugates.

- Survival factor → photon $q_{i_\perp}$ → dilepton kinematic distributions (backup).



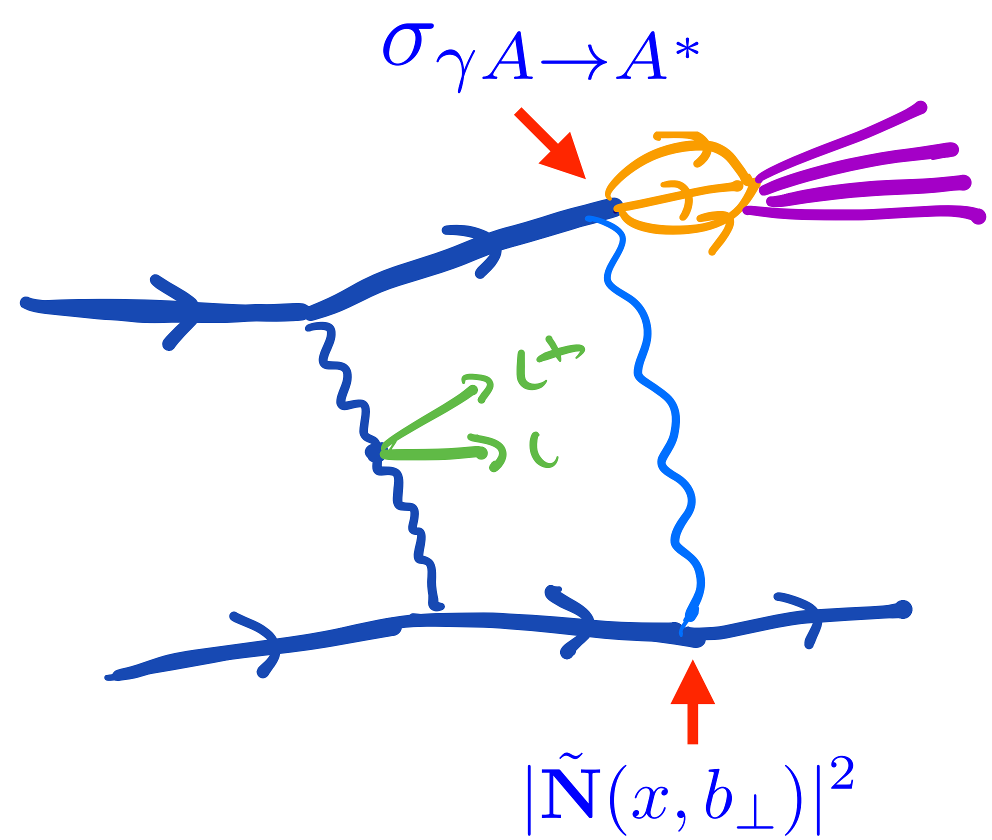
Mutual Ion Dissociation

- Account for this again in impact parameter space:

$$\mathrm{d}\sigma_{X_1 X_2} = \int \mathrm{d}^2 b_{1\perp}\, \mathrm{d}^2 b_{2\perp}\, \mathrm{d}\sigma_{\mathrm{S}^2}\, P_{X_1 X_2}(s, b_\perp)\ ,$$

where $P_{X_1 X_2}$ is the ion breakup probability, given in terms of factorized probabilities:

$$P_{X_1 X_2}(b_\perp) = P_{X_1}(b_\perp) P_{X_2}(b_\perp)\ .$$



- Individual probability given in terms of:

$$P^1_{Xn}(b_\perp) = \int \frac{\mathrm{d}\omega}{\omega} |\tilde{\mathbf{N}}(x, b_\perp)|^2 \sigma_{\gamma A \to A^*}(\omega)\ ,$$

$\gamma A \to \gamma A$ flux

$\gamma A \to A^*$ cross section

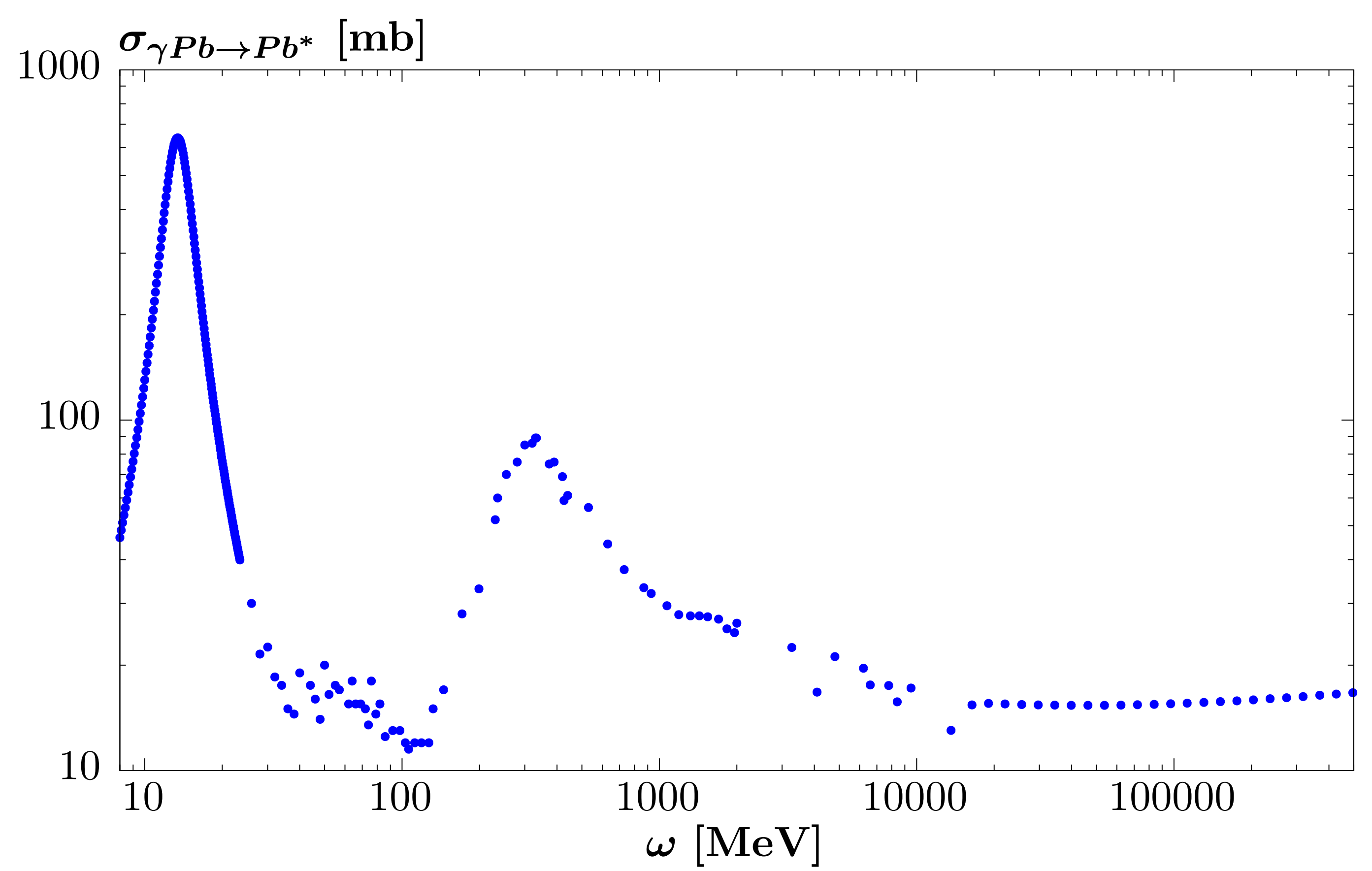
$$P^1_{Xn}(b_\perp) = \int \frac{\mathrm{d}\omega}{\omega} \, |\tilde{\mathbf{N}}(x, b_\perp)|^2 \sigma_{\gamma A \to A^*}(\omega) \; ,$$

$\gamma A \to \gamma A$ flux

$\gamma A \to A^*$ cross section

$\gamma A \to \gamma A$ flux : given as usual in terms of well known ion EM form factor.

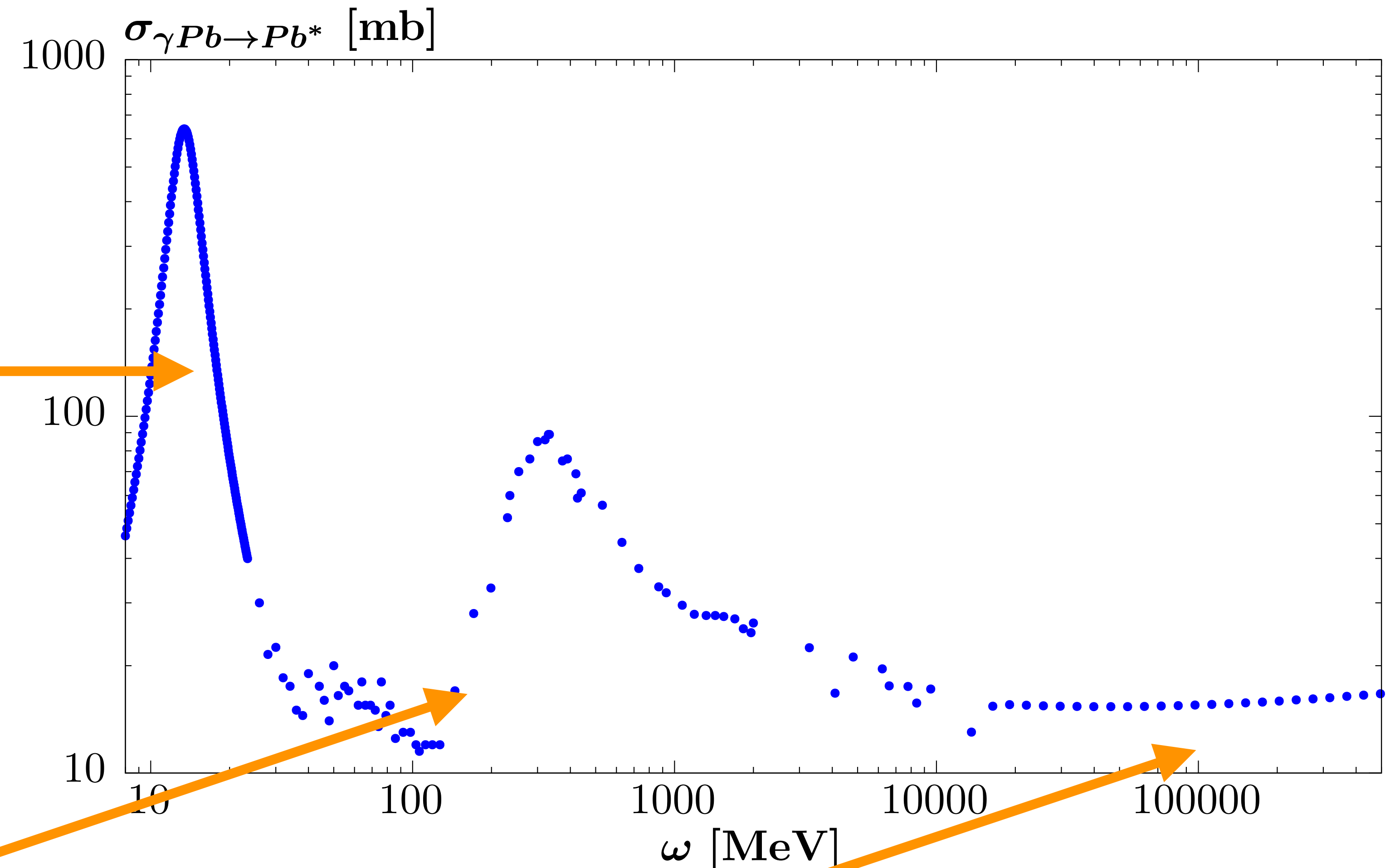
$\gamma A \to A^*$ cross section : taken from a range of γA and γn scattering data.



See e.g. S. R. Klein at al., Comput. Phys. Commun. 212, 258 (2017)

Data covers a range of photon energies ω , taken from range of experiments:

★ $\omega \lesssim 23\,\mathrm{MeV}$: `Giant Dipole Resonance' (GDR). 1n production dominant.



★ $23\,\mathrm{MeV} \lesssim \omega \lesssim 16\,\mathrm{GeV}$: Higher excitations. Range of direct data available.

★ $\omega \gtrsim 16\,\mathrm{GeV}$: data runs out. Use Regge Fit:

$$\sigma_{\gamma A} = A \cdot R_{\rm shad} \cdot \sigma_{\gamma n}$$

$$\sigma_{\gamma n} \propto s_{\gamma A}^{\delta}$$

- Biggest uncertainty from the high energy region. No direction data and ~ 25% of the cross section comes from it!
- For ω sufficiently high $y_{\gamma n}$ starts to enter into central detector $\Rightarrow$ may not pass exclusivity veto. We cut at $\omega < 500\,\mathrm{GeV}$ above which 15% of $\sigma_{\gamma A}$.

Kinematic Dependence

- Survival factor and kinematic impact accounted for using

$$T_{S^2}(q_{1\perp}, q_{2\perp}) = \frac{1}{(2\pi)^2} \int d^2 b_{1\perp} d^2 b_{2\perp}\, e^{i\mathbf{q}_{1\perp}\cdot\mathbf{b}_{1\perp}} e^{-i\mathbf{q}_{2\perp}\cdot\mathbf{b}_{2\perp}} \tilde{T}(b_{1\perp}, b_{2\perp})$$

Transverse momentum **Impact parameter**

with: $\tilde{T}(b_{1\perp}, b_{2\perp}) \to \tilde{T}(b_{1\perp}, b_{2\perp})\Gamma_{A_1A_2}(s, b_\perp)^{1/2}$, $\Gamma_{A_1A_2}(s, b_\perp) \equiv \exp(-\Omega_{A_1A_2}(s, b_\perp))$.

Survival Factor

- Ion dissociation accounted for in the same way. But now with:

$$\Gamma_{A_1A_2}(s, b_\perp)^{1/2} \to [\Gamma_{A_1A_2}(s, b_\perp) P_{X_1X_2}(b_\perp)]^{1/2} ,$$

- This then automatically accounts for kinematic dependence:

★ Ion dissociation → photon $q_{i_\perp}$ → dilepton kinematic distributions.

General Expectations

$$P_{X_1 X_2}(b_\perp) = P_{X_1}(b_\perp) P_{X_2}(b_\perp)\ .$$

- Look at dissociation probabilities for different neutron tags.

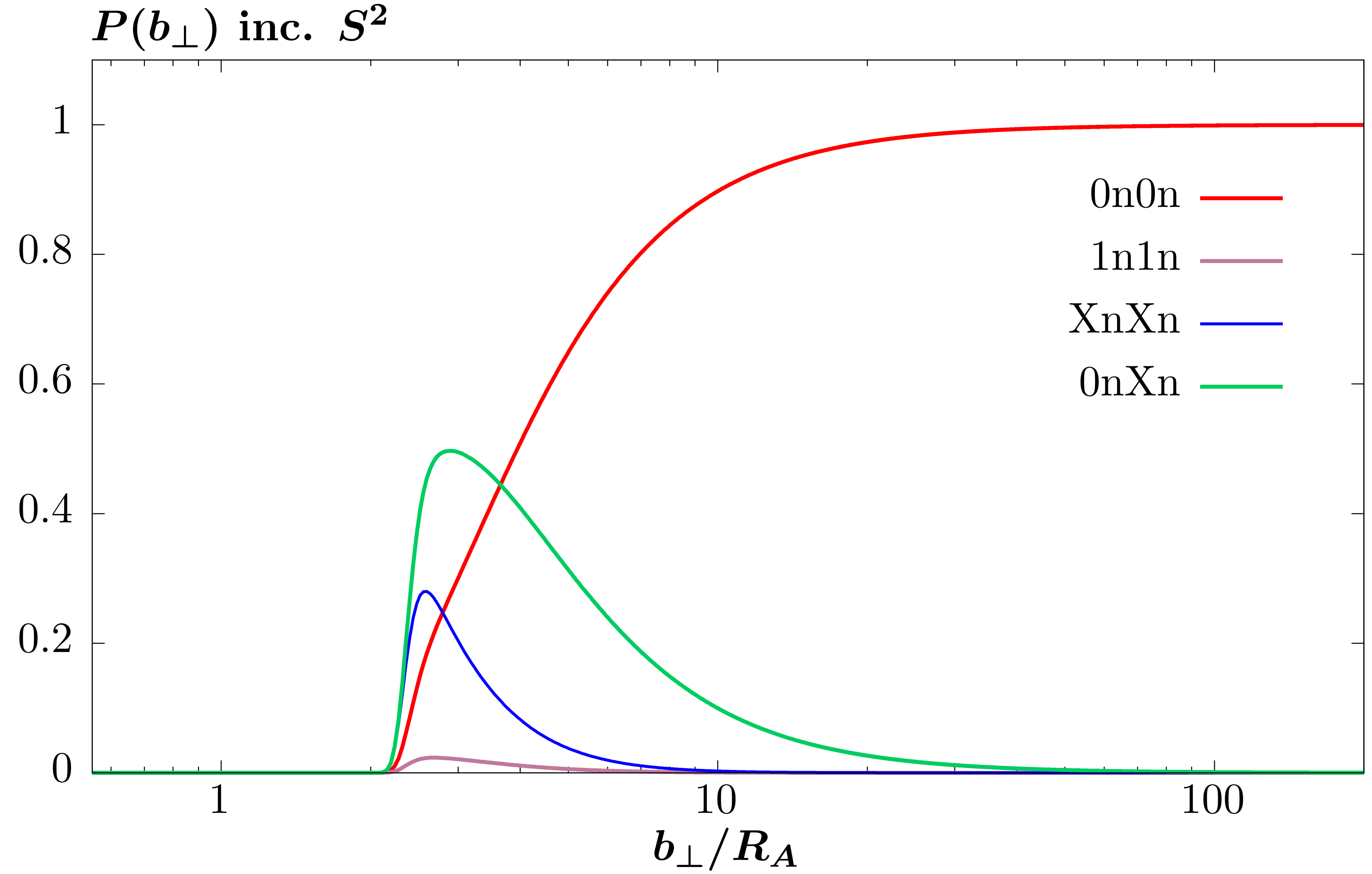
- Basic point: dissociation is peaked towards lower $b_\perp$: $P_{Xn}(b_\perp) \sim \dfrac{1}{b_\perp^2}$

- 0n veto ($\sim 1 - P_{Xn}(b_\perp)$ *) then peaked to larger $b_\perp$.

- Larger $q_\perp^{ll} \Rightarrow$ more dissociation.

- Larger $m_{ll} \Rightarrow$ more dissociation.

$$Q_i^2 = \frac{q_{i_\perp}^2 + x_i^2 m_{A_i}^2}{1 - x_i}$$



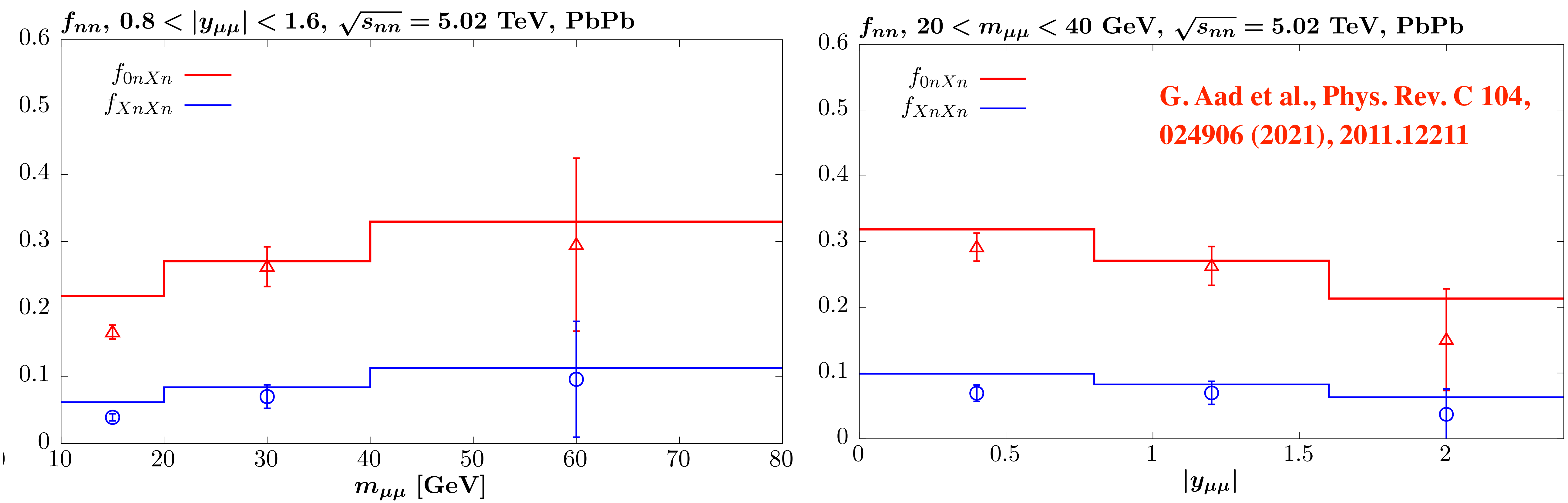
*To be precise account for unitarity (backup)

Comparison to data

ATLAS

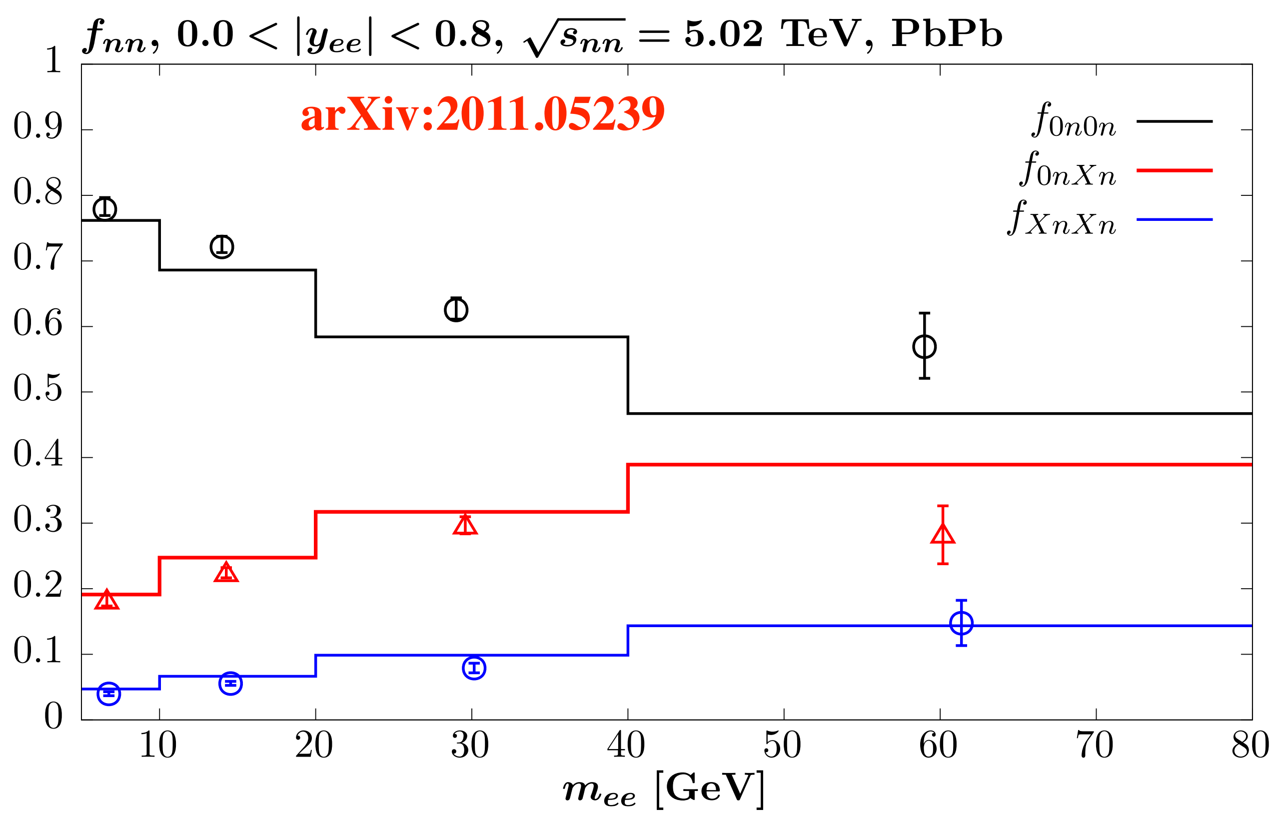
- ATLAS have measured dilepton (e, μ) UPCs for range of neutron tags, in terms of neutron tagged event fractions ($f_{0n0n} \cdots$).

★ Dimuon data:

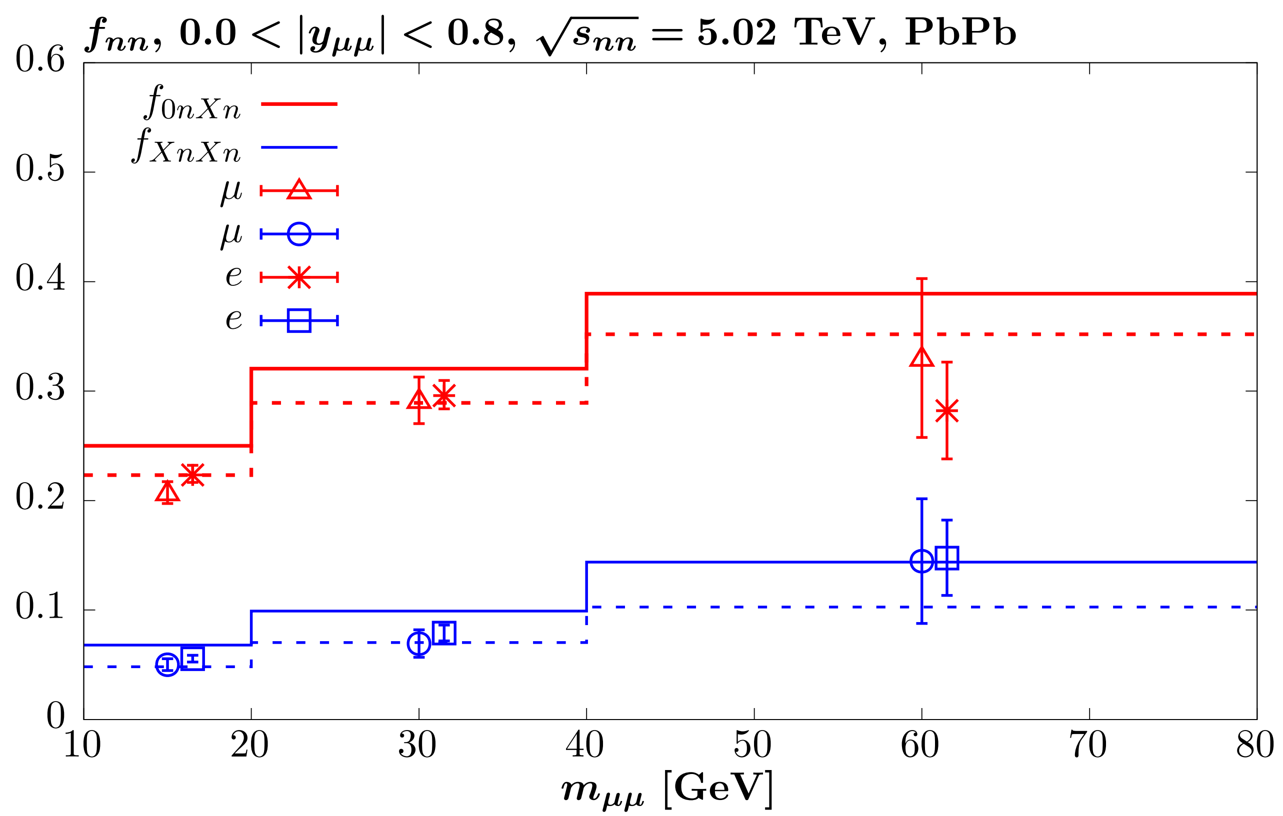


- Fractions show clear kinematic dependence, in line with expectations.
- Data/theory agreement in general encouraging, with some excess in lowest m_{ll} bin.

★Dielectron data:



- Basic trends again as expected, and matched by data.
- Quantitative agreement reasonable, with some difference in detail.

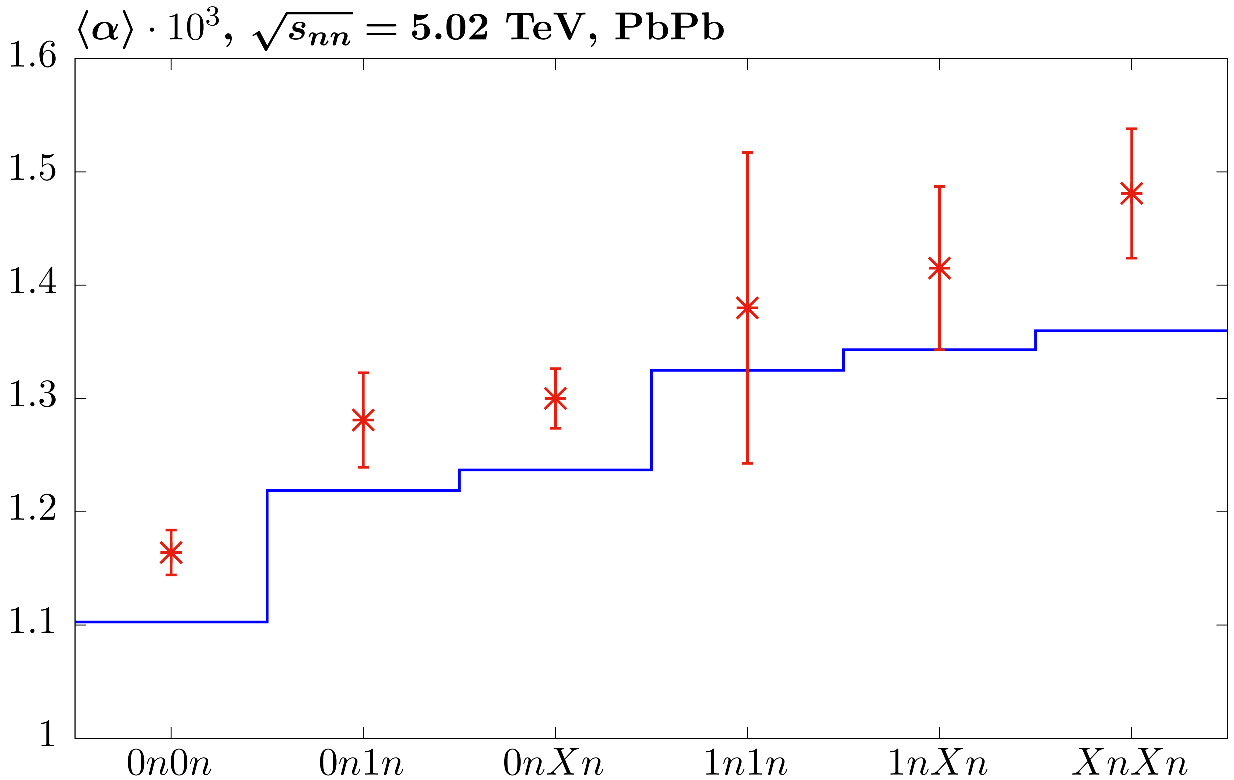


- Only with default prediction: there are uncertainties in $\sigma_{\gamma A}$.
- Tuning down by ~ 20% gives better agreement. Available as flag in MC.

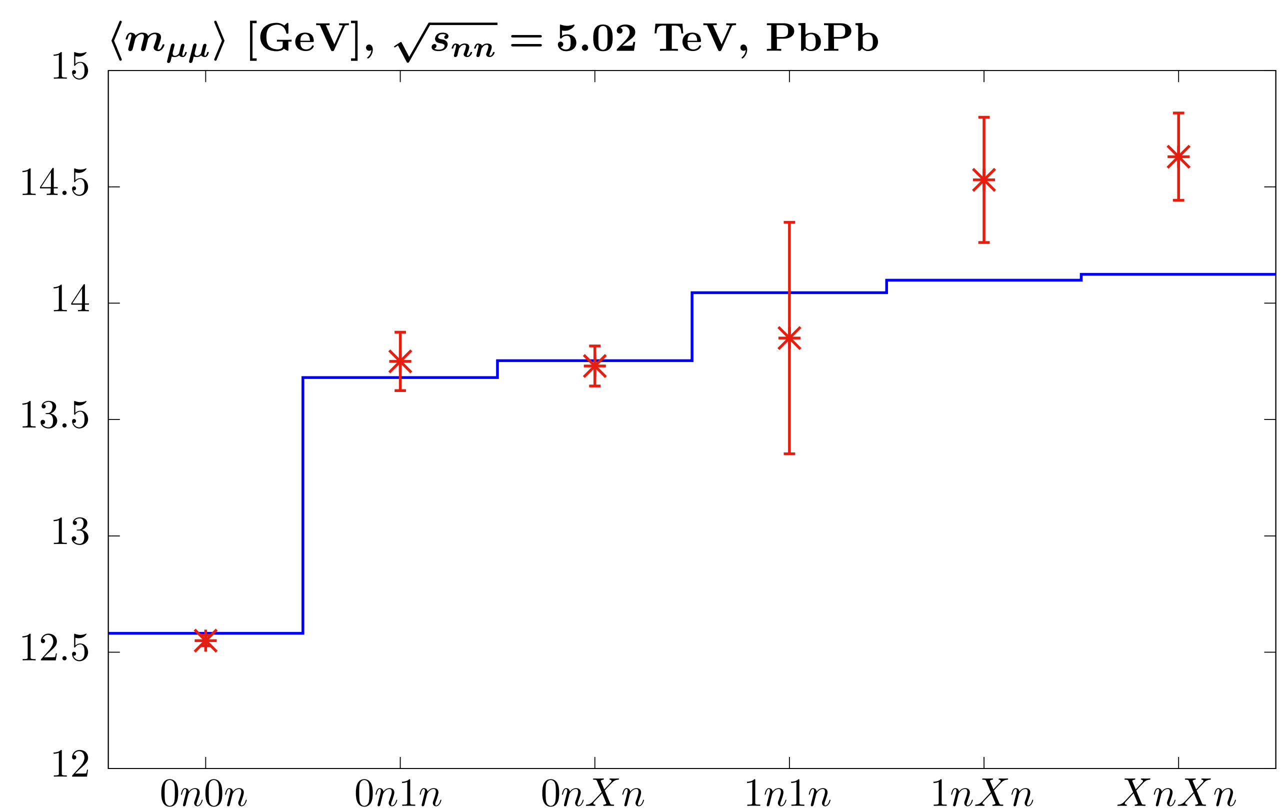
CMS

★ Dimuon acoplanarity distributions measured for range of neutron tags, fit in region where LO UPC mechanism dominates.

$$\alpha = 1 - \frac{\Delta\phi_{\mu\mu}}{\pi}$$



- Increase in $\langle\alpha\rangle$ with dissociation as expected, and matched by data.
- Some theory/data excess. Evidence due to FSR (backup).

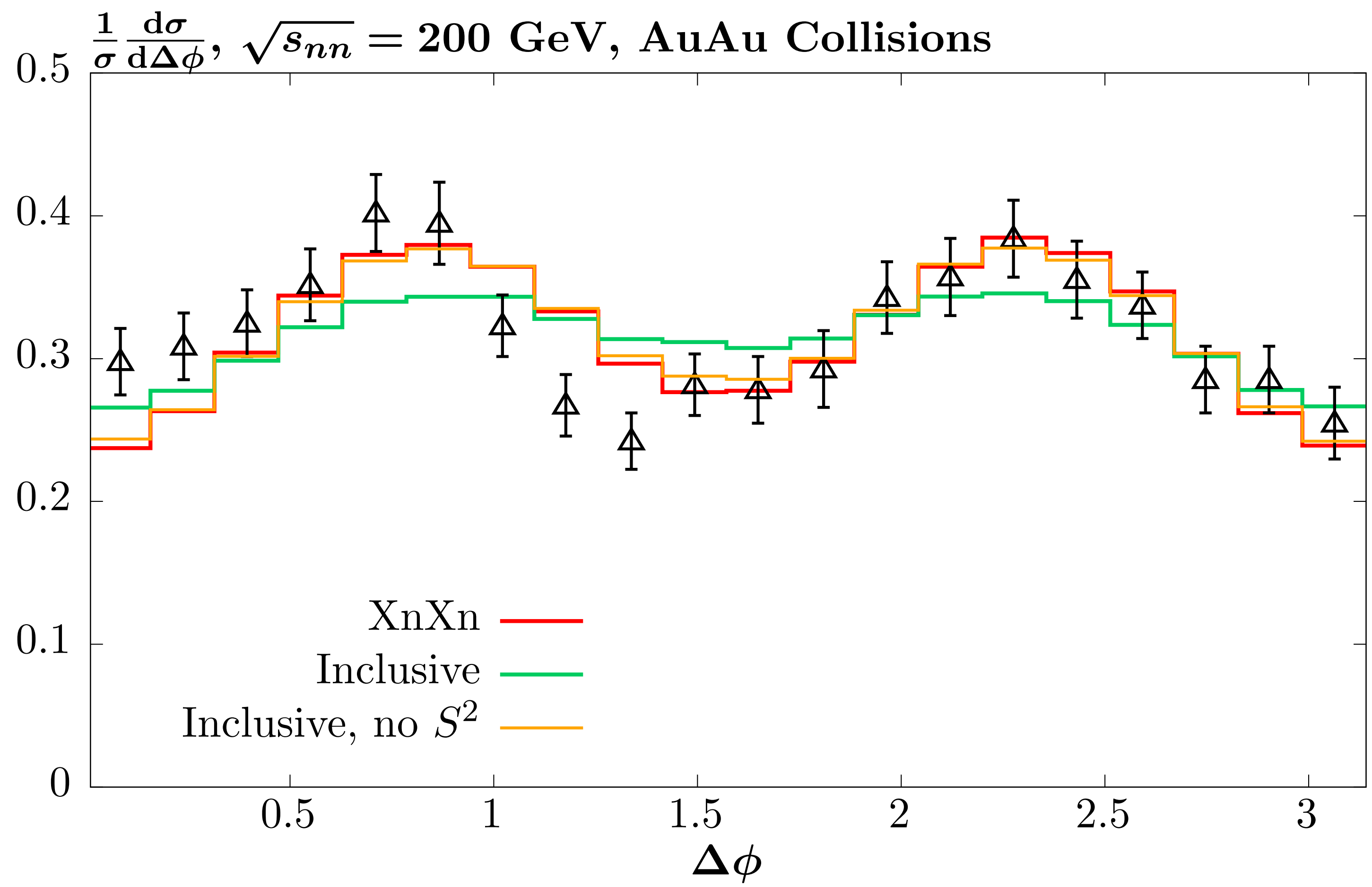


- Increase in $\langle m_{\mu\mu}\rangle$ with dissociation as expected, and matched by data.
- Data/theory agreement good!

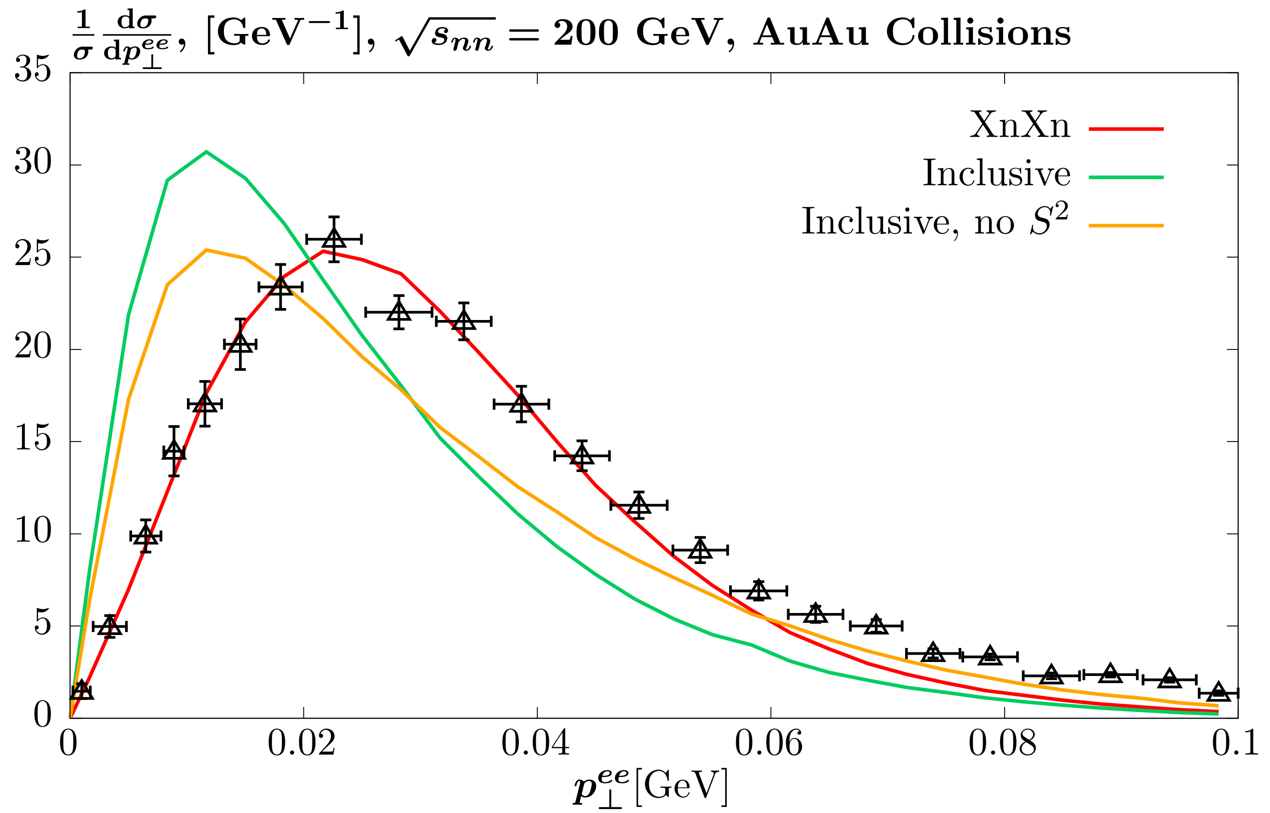
STAR

★ STAR data on dielectron production. Principle result: distribution w.r.t. azimuthal angle $\Delta\phi$ between $p_{e_\perp}$ and $p_\perp^{e^+e^-}$.

★ Data taken with XnXn tag: essential to account for mutual ion dissociation.



- Distribution in $\Delta\phi$ quite well matched (up to apparent data fluctuations).
- Impact of neutron tag on this is clear. Again comes from correct account of kinematic impact of mutual ion dissociation.



	SuperChic	Data
σ [μb]	240	261 ± 37
$\lvert A_{2\Delta\phi}\rvert$ (%)	6.2	2.0 ± 2.4
$\lvert A_{4\Delta\phi}\rvert$ (%)	20.1	16.8 ± 2.5
$\sqrt{\langle (p_\perp^{ee})^2 \rangle}$ [MeV]	36.1	38.1 ± 0.9

- Dielectron $p_\perp^{e^+e^-}$ again well matched. Reasonable agreement for extracted:

$$\frac{d\sigma}{d\Delta\phi} \propto 1 + A_{2\Delta\phi}\cos 2\Delta\phi + A_{4\Delta\phi}\cos 4\Delta\phi \ ,$$

- Final remarks:

  ★ Inclusion of ion dissociation key here. In original STAR study older version of SC without this is compared to and this is not made clear!

  ★ Analytic results predict $A_{2\Delta\phi} = 0$ up to $O(m_l^2/m_{ll}^2)$ but this does not account for specific STAR kinematics, where $p_\perp^e \gg p_\perp^{ee}$ not strictly valid.

Summary/Outlook/Final Remarks

★ **Superchic 4.2:** first complete Monte Carlo treatment of UPCs with mutual ion dissociation, including kinematic impact on central particles.

★ Treatment of ion dissociation (survival factor) in $b_\perp$ space, translated to $q_\perp$ space automatically accounts for this.

★ Data/theory comparison encouraging, but with some differences. May be that some fine tuning of $\sigma_{\gamma A}$ needed.

★ Future work: including FSR and further higher order QED effects essential for precision programme.

★ Results presented for dileptons here but of course applicable to other final-states.

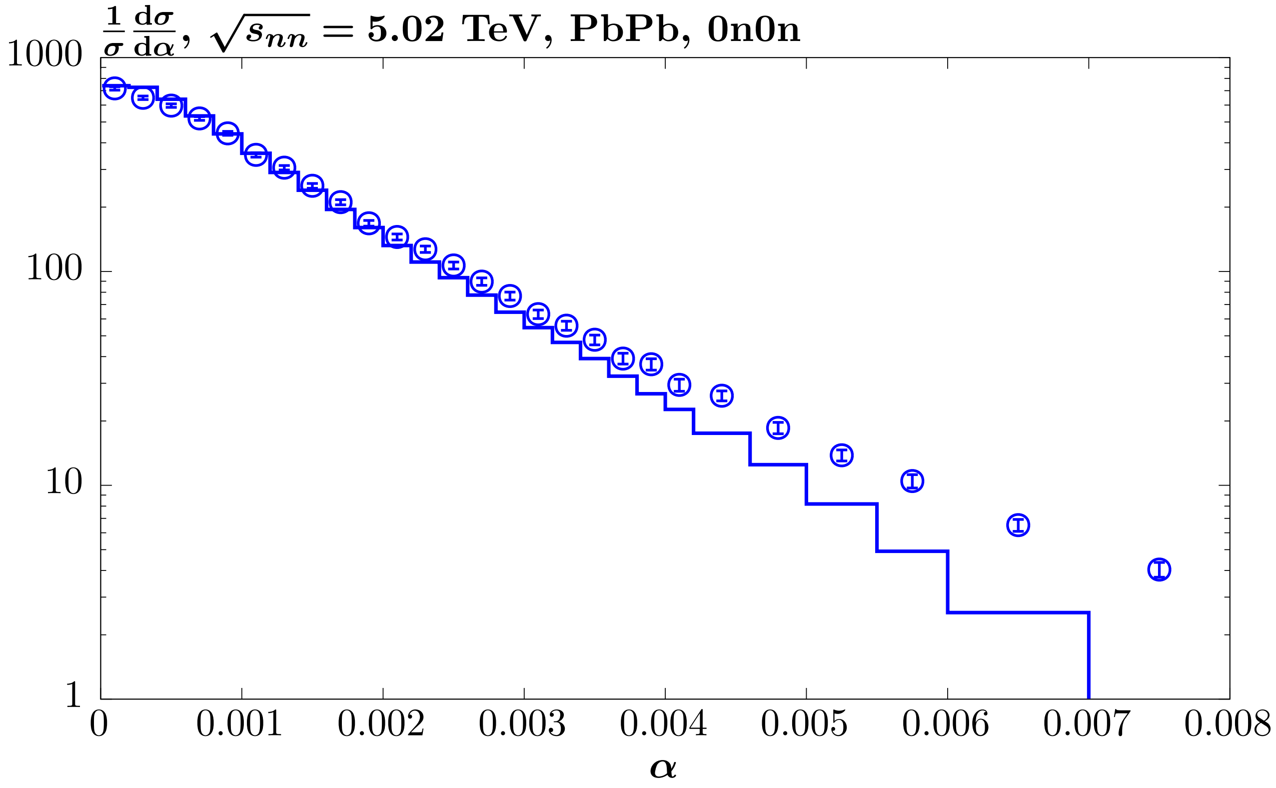
★ Indeed provides valuable tool for future SM/BSM studies in the fruitful UPC channel.

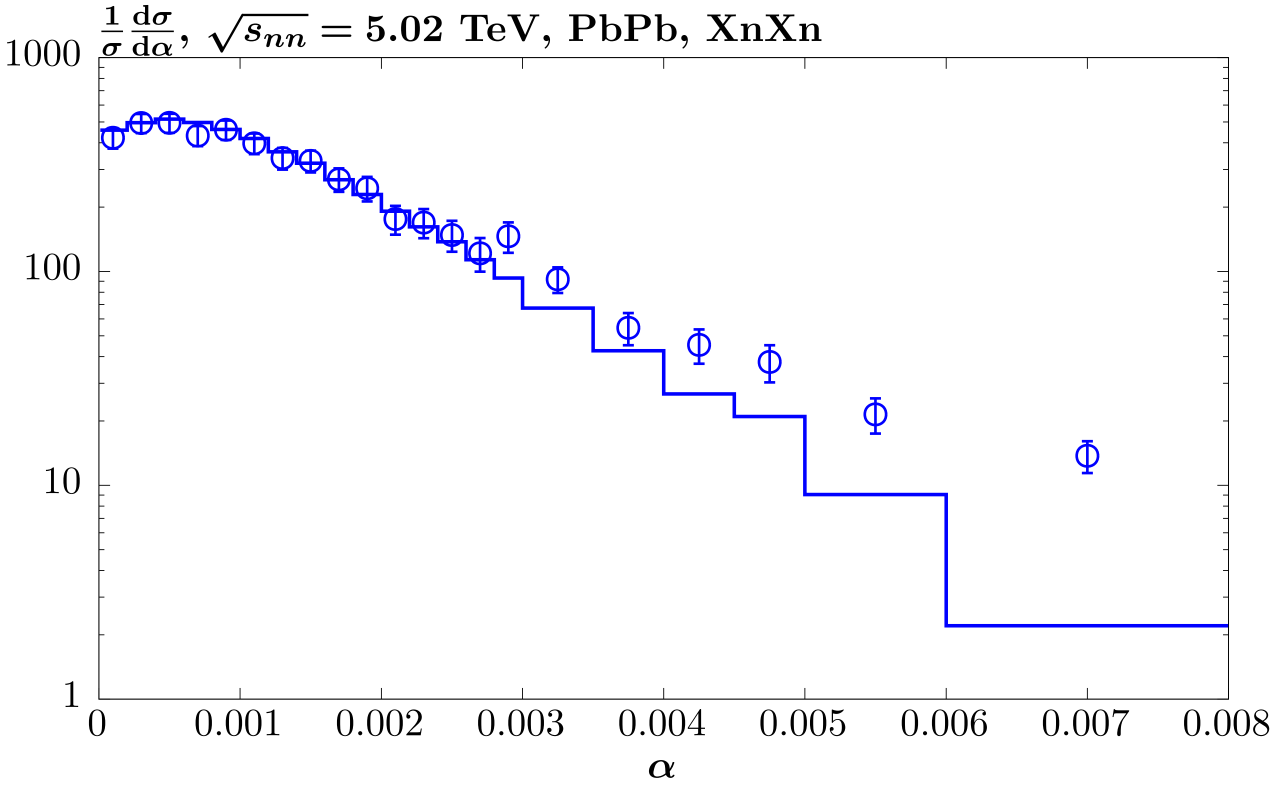
Thank you for listening!

Backup

CMS data

- Excess in theory over data in $\langle\alpha\rangle$ driven by tail of distributions, where FSR effects will be largest.
- Missing in theory $\Rightarrow$ indication this may be the culprit.





Unitarity

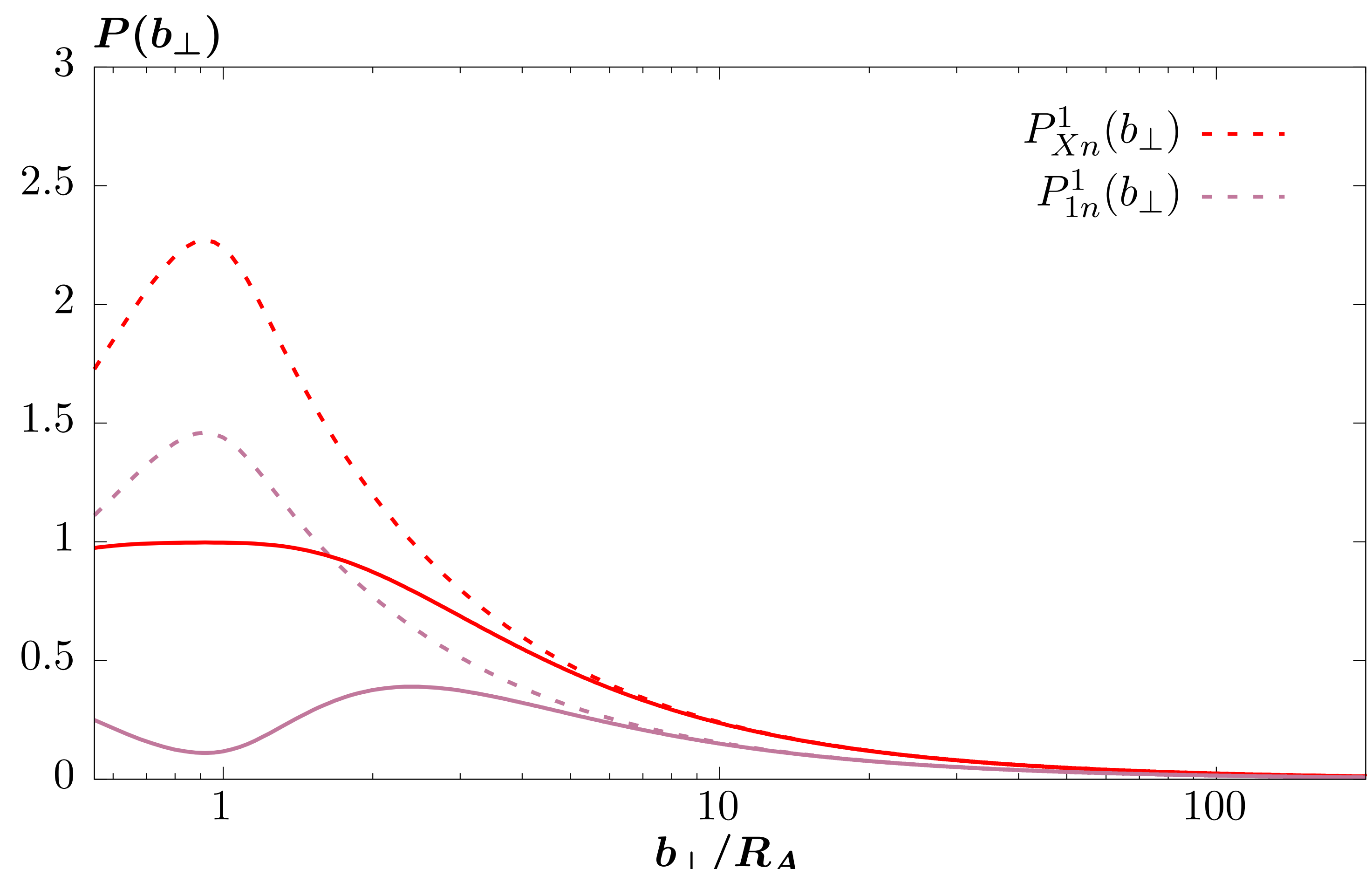
- Using naive ion dissociation probability: $$P^1_{Xn}(b_\perp) = \int \frac{\mathrm{d}\omega}{\omega} |\tilde{\mathbf{N}}(x, b_\perp)|^2 \sigma_{\gamma A \to A^*}(\omega) \ ,$$

this becomes > 1 at lower impact parameters.

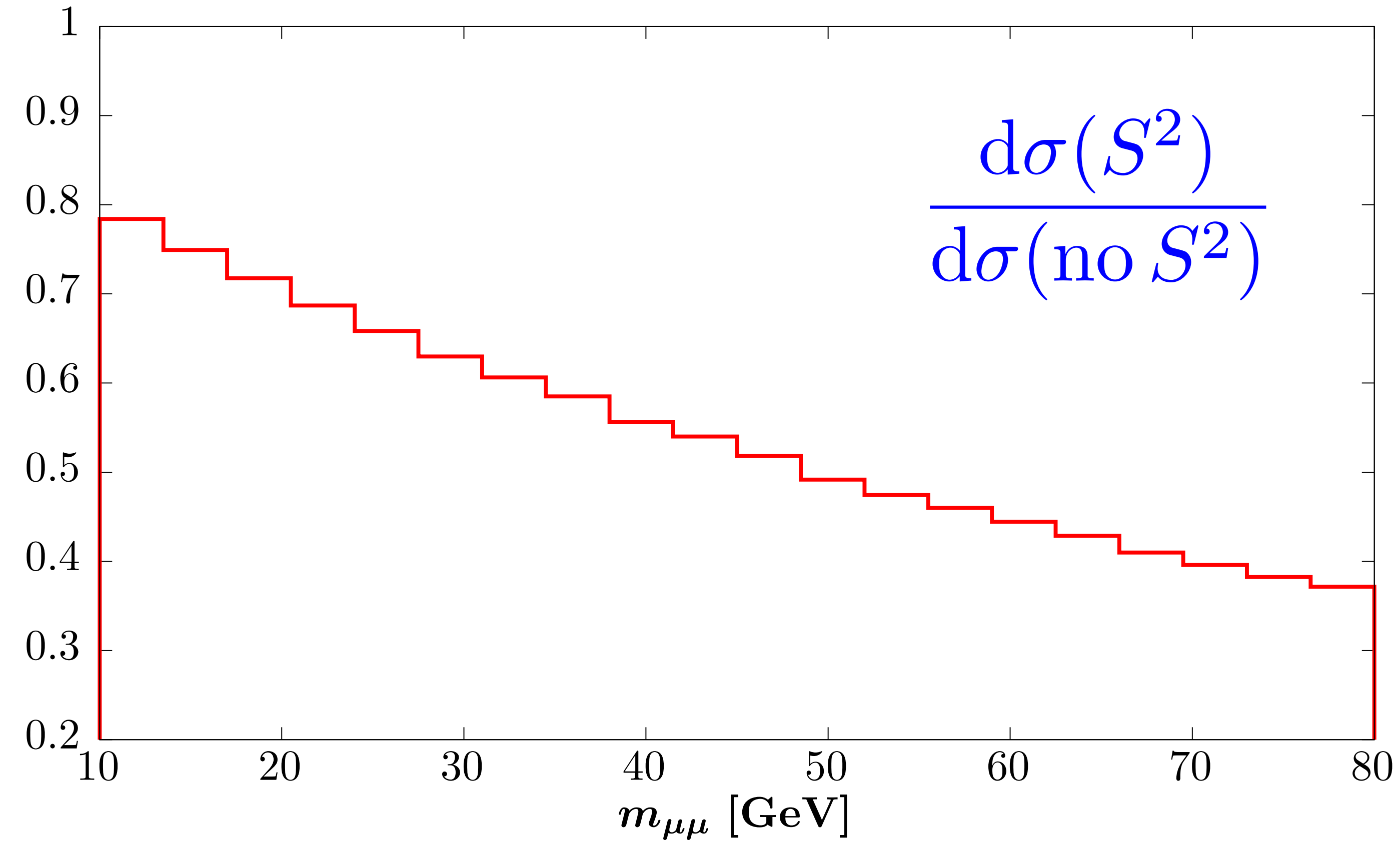
- Instead interpret as Poisson probability and use:

$$P_{0n}(b_\perp) = \exp(-P^1_{Xn}(b_\perp)) \ ,$$
$$P_{1n}(b_\perp) = P^1_{1n} \exp(-P^1_{Xn}(b_\perp)) \ ,$$
$$P_{Xn}(b_\perp) = 1 - \exp(-P^1_{Xn}(b_\perp)) \ .$$

- Probabilities by definition unitary.
- Reduces e.g. XnXn cross section by ~ 1-2.



- E.g. for dimuon production at 5.02 TeV.



- Clear impact on mass and rapidity distributions (and others).