The STARLIGHT Monte Carlo

UPC 2023
Playa del Carmen 11-15 December, 2023

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Active collaborators: Spencer Klein, Janet Seger.

STARlight “Technical details”

STARlight paper: “STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions”, S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, Comp. Phys. Comm. 212 (2017) 258 – 268.

Code available here: https://github.com/STARlightsim/STARlight

STARlight calculates cross sections and phase space distributions (rapidity, p_T, ...) for various two-photon and photonuclear reaction channels.

It also generates events for these channels.

Outline

- Some historical notes.

- Two-photon interactions.

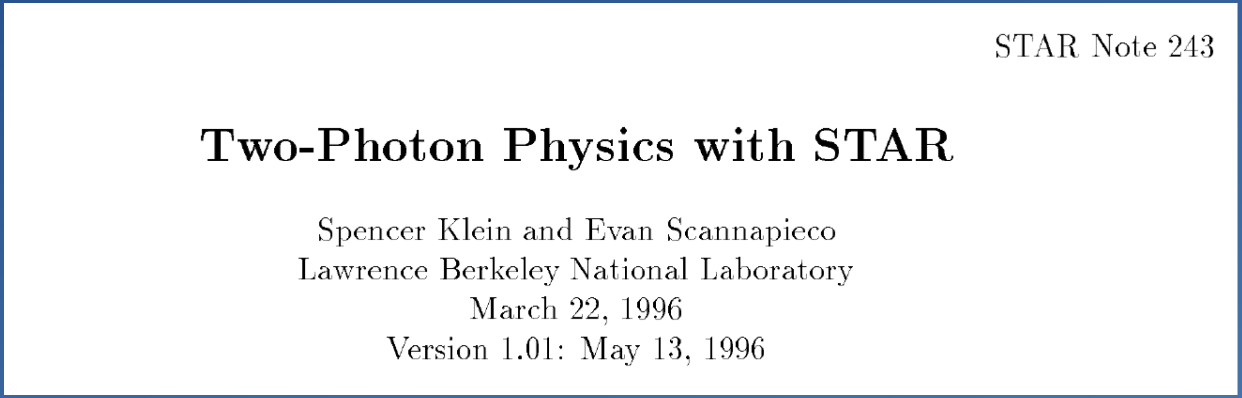
- Photonuclear vector meson production.

- UPCs with nuclear breakup.

- Interface with DPMJET.

- eSTARlight.

The STAR in STARlight



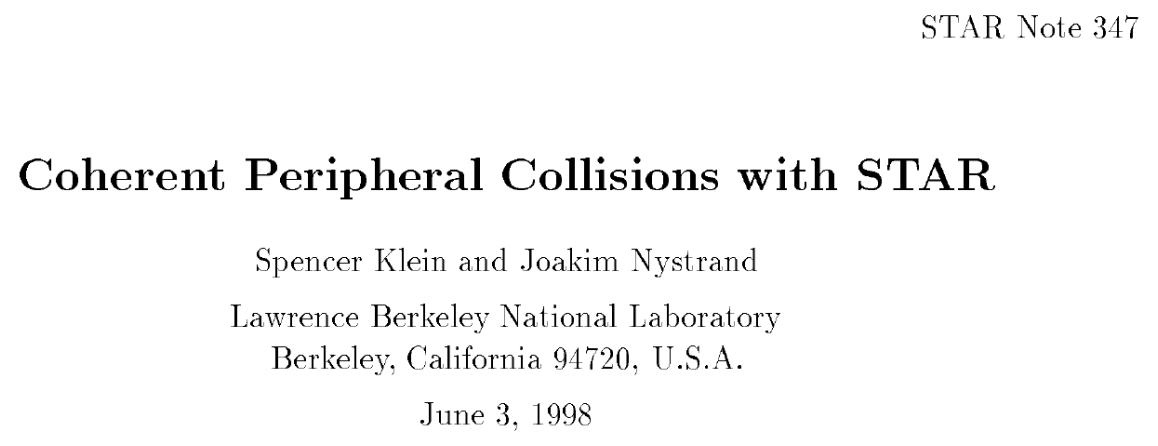
STAR Note 243

Two-Photon Physics with STAR

Spencer Klein and Evan Scannapieco
Lawrence Berkeley National Laboratory
March 22, 1996
Version 1.01: May 13, 1996

The STAR Collaboration at RHIC

While most of the STAR collaboration has focused on central collisions, we wish to point out that there is interesting physics present in peripheral collisions, and STAR is well suited to studying much of this physics.



STAR Note 347

Coherent Peripheral Collisions with STAR

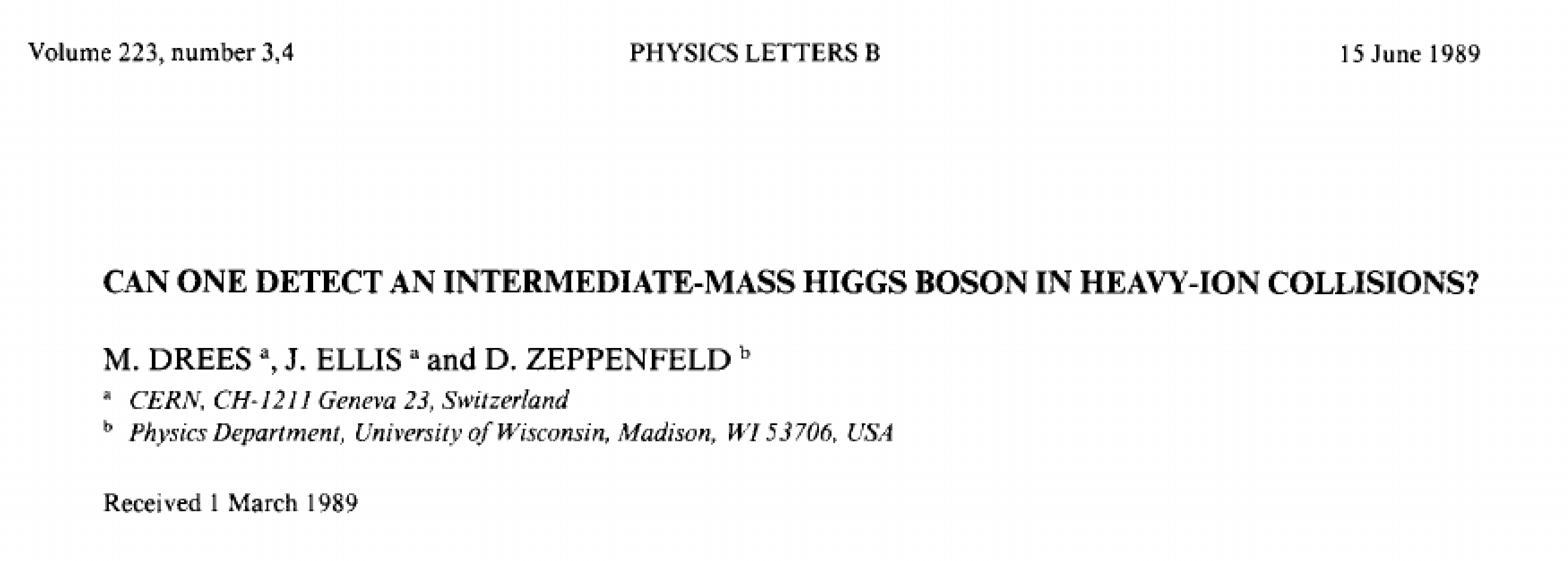
Spencer Klein and Joakim Nystrand

Lawrence Berkeley National Laboratory
Berkeley, California 94720, U.S.A.

June 3, 1998

The two-photon luminosity, RHIC production rates and early background estimates were discussed previously in STAR Note 243[2]. Here, we update that work and present new results on γ-Pomeron interactions and GEANT based simulations of two-photon events from STARLight.

Very early UPC calculations ~1990



Volume 223, number 3,4 PHYSICS LETTERS B 15 June 1989

CAN ONE DETECT AN INTERMEDIATE-MASS HIGGS BOSON IN HEAVY-ION COLLISIONS?

M. DREES [a], J. ELLIS [a] and D. ZEPPENFELD [b]

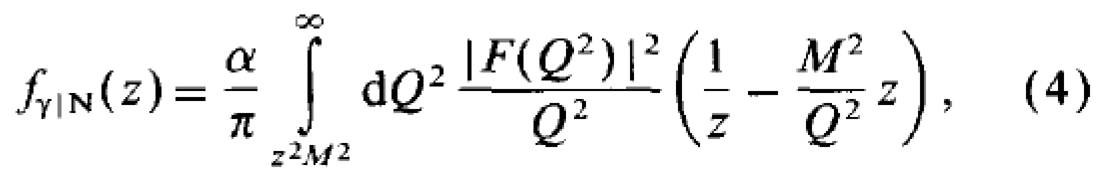
[a] *CERN, CH-1211 Geneva 23, Switzerland*

[b] *Physics Department, University of Wisconsin, Madison, WI 53706, USA*

Received 1 March 1989

But how to calculate the photon spectrum?

First approaches used a form factor



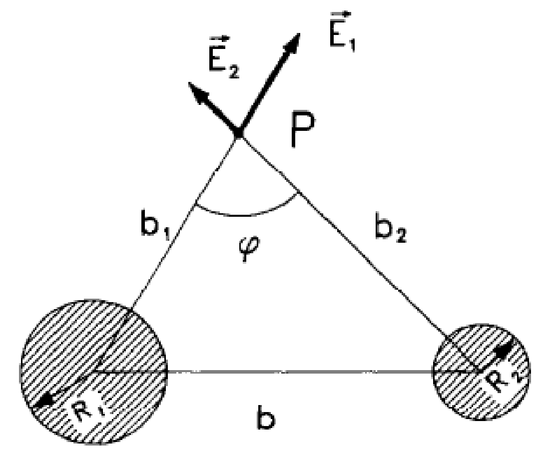
$$f_{\gamma|\mathrm{N}}(z) = \frac{\alpha}{\pi} \int\limits_{z^2M^2}^{\infty} \mathrm{d}Q^2 \, \frac{|F(Q^2)|^2}{Q^2} \left(\frac{1}{z} - \frac{M^2}{Q^2} z \right), \qquad (4)$$

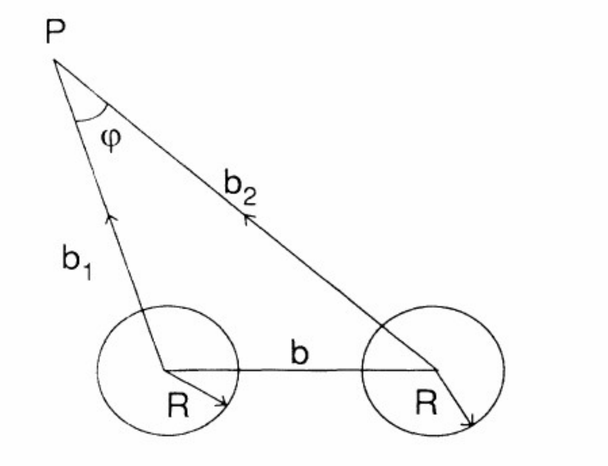
Very early UPC calculations ~1990

But to ensure only photon-induced interactions, the nuclei can’t interact hadronically. Must require impact parameters b > 2R.

==> Two papers by Cahn&Jackson (PRD 42 (1990) 3690) and Baur&Ferreira Filho (NPA 518 (1990) 786)

Do the calculations in impact parameter space, use the Weizsäcker-Williams photon fluxes as they can be found in the text book of Jackson!





The photon spectrum in STARlight

The photon spectrum is calculated in impact parameter space.

The energy/longitudinal momentum calculated from the Weizsäcker-Williams photon spectrum.

Transverse momentum added later through a nuclear form factor.

$$N(k,b) = \frac{Z^2\alpha}{\pi^2}\frac{k}{(\hbar c)^2}\frac{1}{\gamma^2}\left[K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right]$$

Impact parameter dependent photon spectrum.

$$\frac{dN_\gamma(k)}{dk} = \int d^2b P_{\mathrm{NOHAD}}(\vec{b})N(k,\vec{b})$$

$$\frac{d^2N_{\gamma\gamma}(k_1,k_2)}{dk_1dk_2} = \int\int d^2b_1 d^2b_2^2 P_{\mathrm{NOHAD}}(|\vec{b}_1 - \vec{b}_2|)N(k_1,\vec{b}_1)N(k_2,\vec{b}_2).$$

Two-photon interactions in STARlight

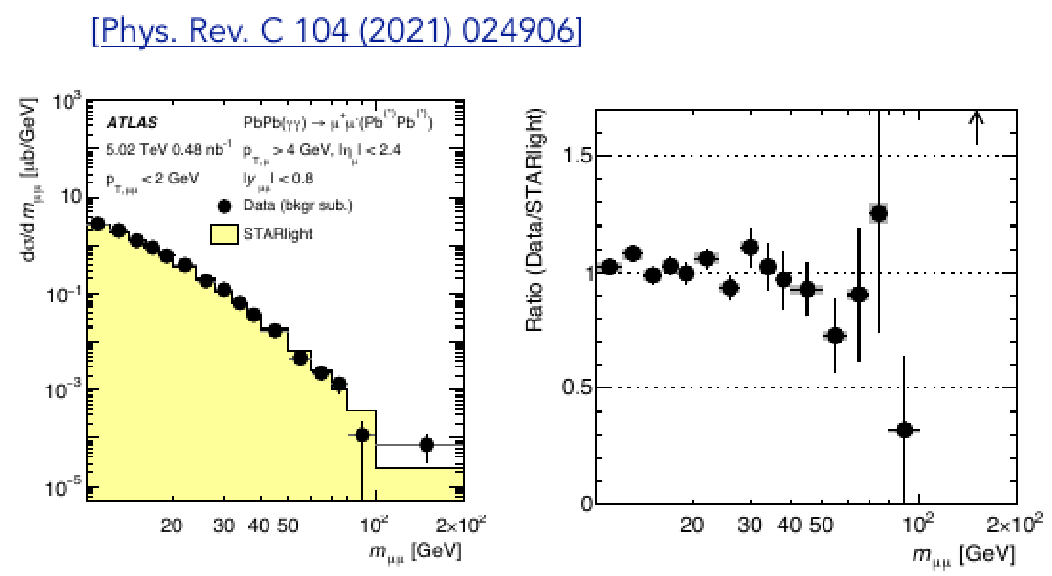
Two-photon interactions studied in UPC so far:

- two-photon production of dilepton pairs,
- no results on γγ→ single meson nor γγ→ X.

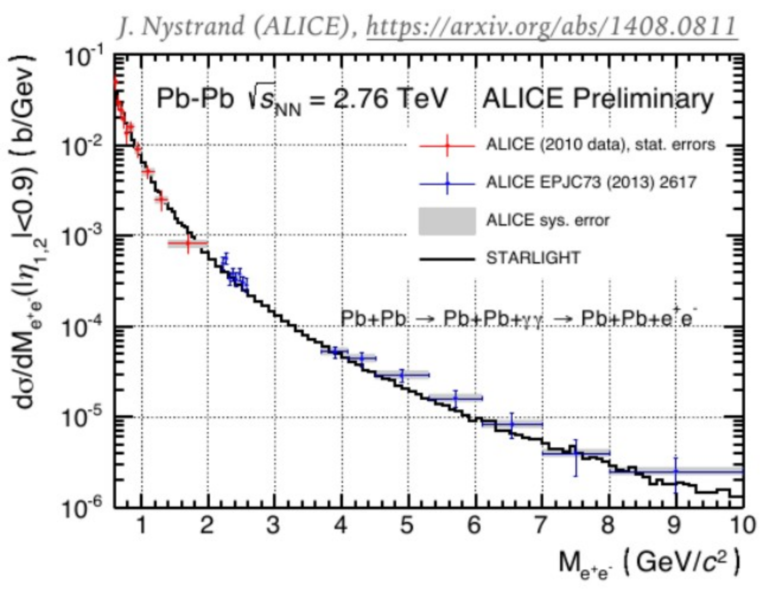
Criticism of STARlight in this context:

- cut-off $b_{1,2} > R$ (no production inside the nuclei),
- Form factor added ad hoc and not in an integrated way

But STARlight does rather well anyway:



[Phys. Rev. C 104 (2021) 024906]



J. Nystrand (ALICE), https://arxiv.org/abs/1408.0811

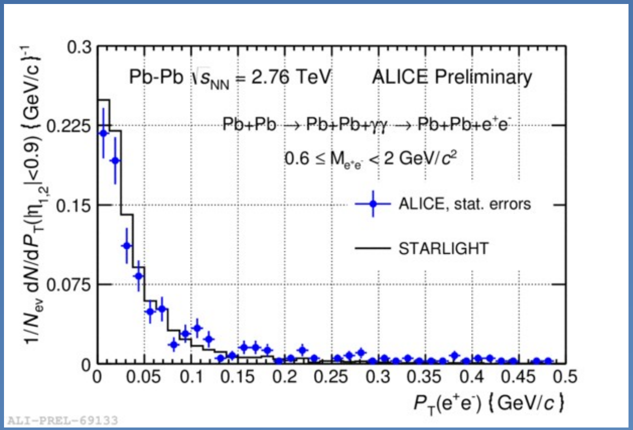
Two-photon interactions in STARlight

- Transverse momentum of photons determined by the nuclear Form Factor and the photon propagator:

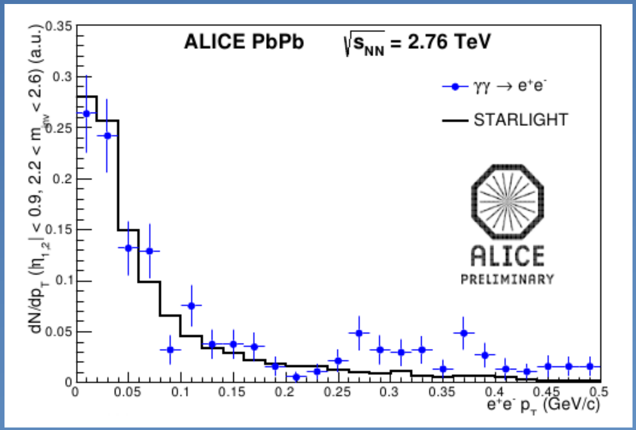
$$\frac{dN_\gamma}{dk_\perp} \propto \frac{|F((\omega/\gamma)^2 + k_\perp^2)|^2}{((\omega/\gamma)^2 + k_\perp^2)^2} k_\perp^3$$

- More narrow p_T distribution than for coherent vector meson production; distribution also depends on the invariant mass.

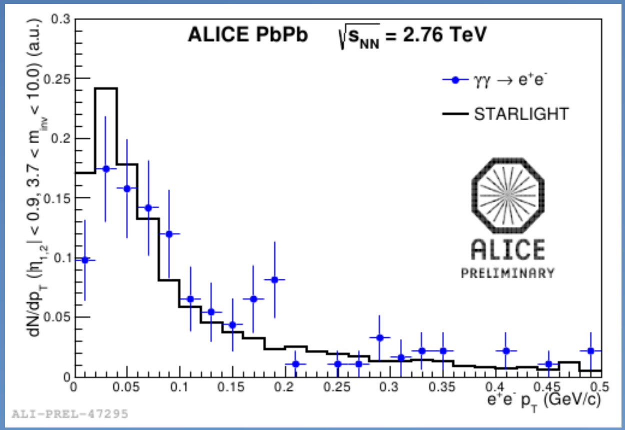
- Shape of p_T distribution well described by STARLIGHT.



$0.6 < M_{inv} < 2.0$ GeV/c^2



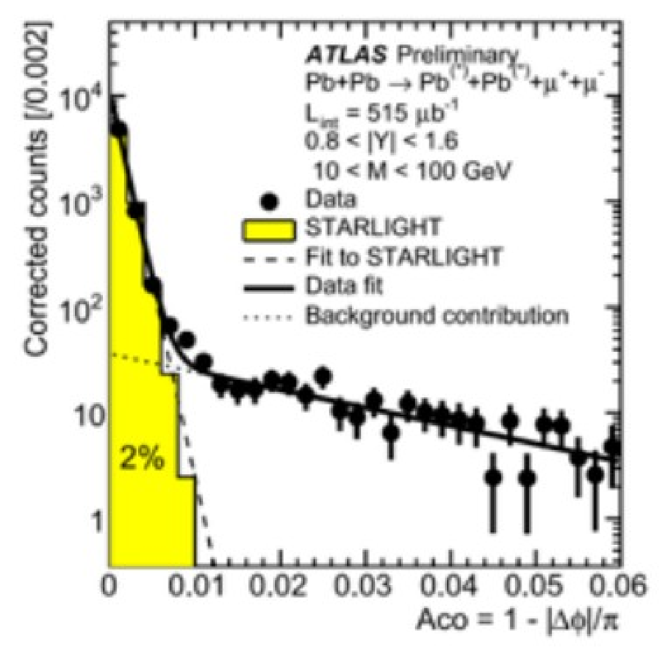
$2.2 < M_{inv} < 2.6$ GeV/c^2

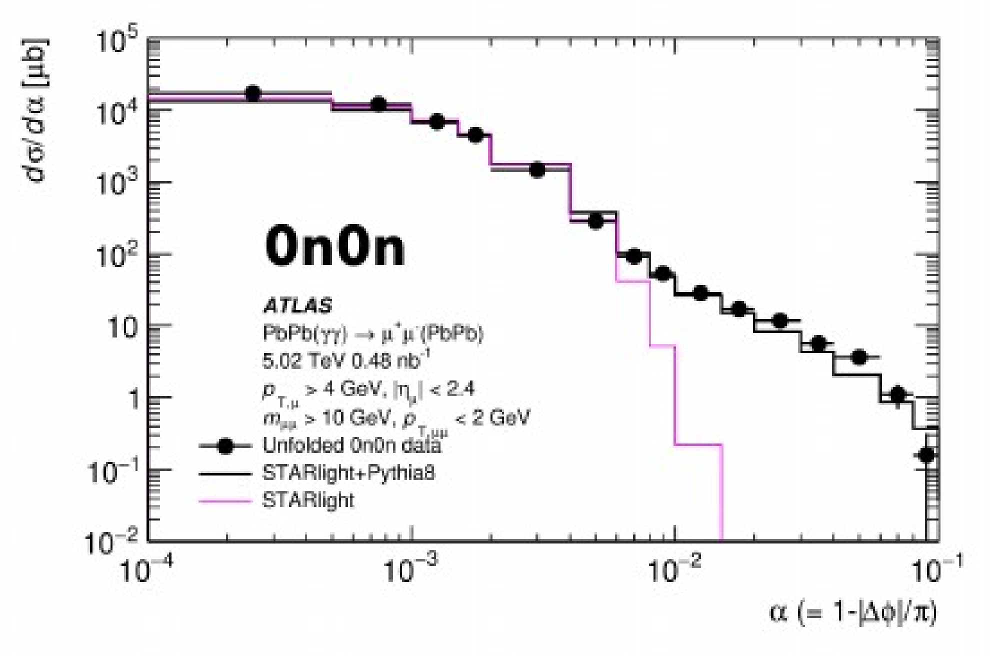


$3.7 < M_{inv} < 10.0$ GeV/c^2

Two-photon interactions in STARlight

An excess – not described by STARLIGHT – has been observed at high acoplanarities (↔ high pair p_T) by ATLAS.





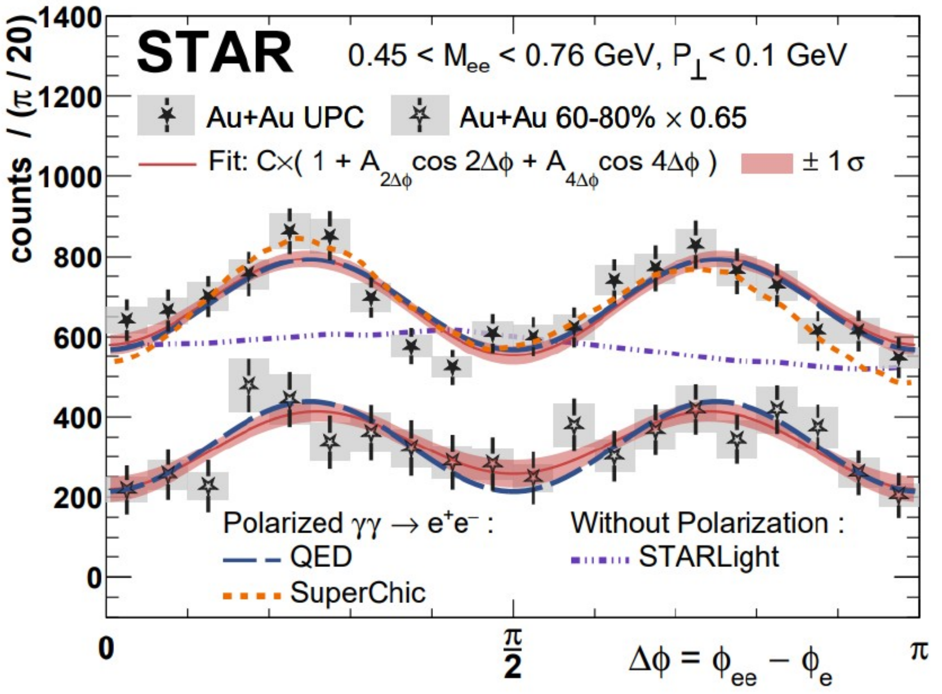
ATLAS-CONF-2016-025

JHEP 06 (2023) 182; presentation by Iwona Grabowska-Bold, Tuesday.

The excess can be explained by QED showering (FSR) as implemented in Pythia 8.

Two-photon interactions in STARlight

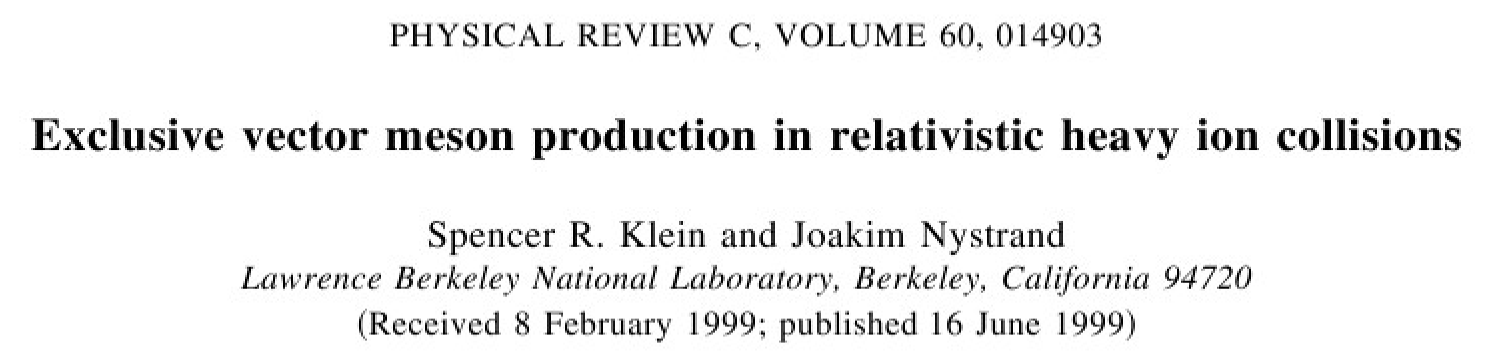
Polarization for low Q^2 photons not included, but can be implemented.



STAR Collaboration, Phys. Rev. Lett. 127 (2021) 052302

Presentations by Kaiyang Wang, Wangmei Zha, Tuesday.

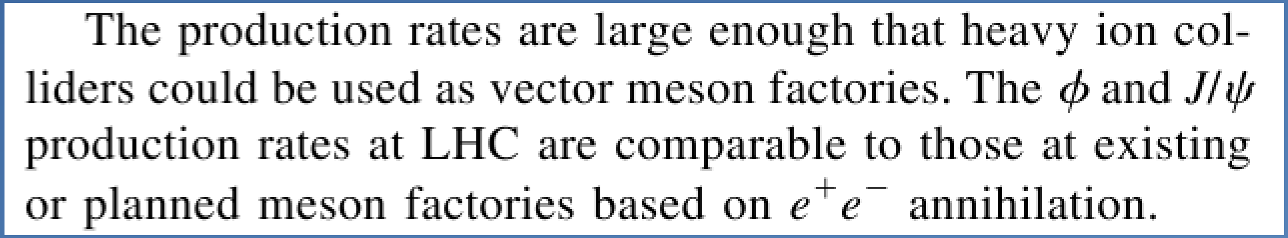
Exclusive vector meson production



PHYSICAL REVIEW C, VOLUME 60, 014903

Exclusive vector meson production in relativistic heavy ion collisions

Spencer R. Klein and Joakim Nystrand
Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 8 February 1999; published 16 June 1999)



The production rates are large enough that heavy ion colliders could be used as vector meson factories. The ϕ and J/ψ production rates at LHC are comparable to those at existing or planned meson factories based on e^+e^- annihilation.

For mesons of comparable masses, the cross sections are a factor 100 higher for exclusive photonuclear production compared with two-photon production.

Exclusive vector meson production

- The cross section $d\sigma(A+A \rightarrow A+A+V)/dy$ is the product of the photonuclear cross section and the photon flux:

$$\frac{d\sigma}{dy} = \omega_1 \frac{dn_\gamma}{d\omega_1} \sigma_{\gamma A \rightarrow VA}(\omega_1) + \omega_2 \frac{dn_\gamma}{d\omega_2} \sigma_{\gamma A \rightarrow VA}(\omega_2)$$

- The photon energy, ω, is given by the vector meson rapidity:

$$\omega_{1,2} = \frac{1}{2} M_V e^{\pm y}$$

- Away from $y=0$ there is a two-fold ambiguity in ω for symmetric systems.

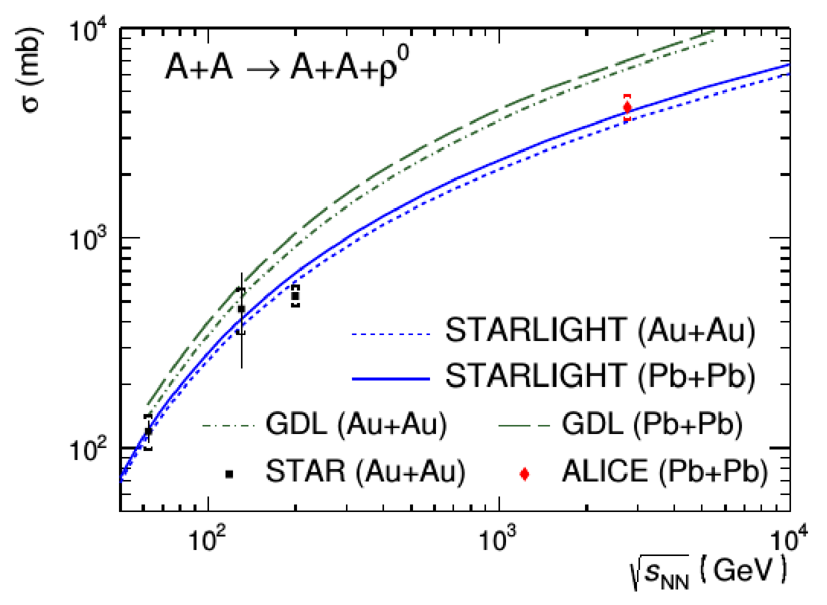
Exclusive vector meson production

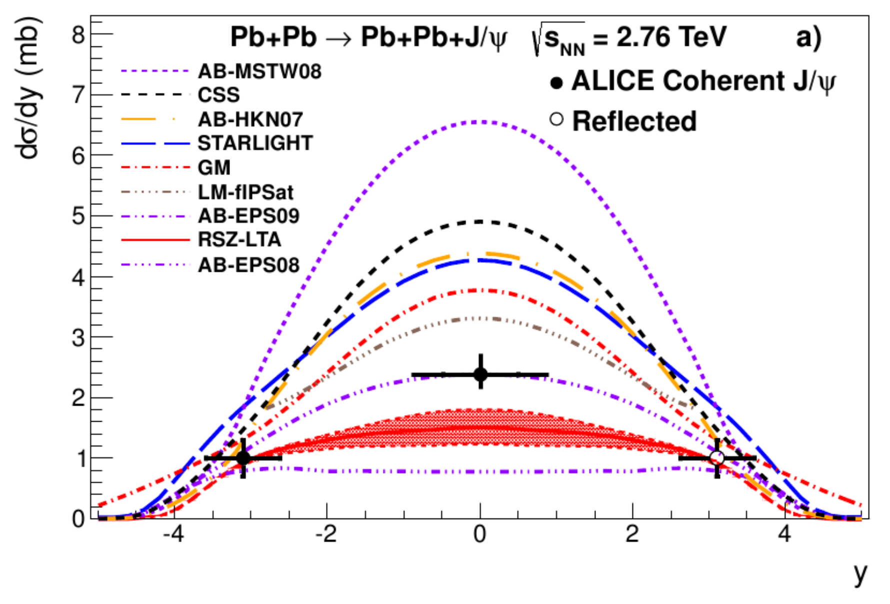
- Originally starlight used a simple, classical approach for the photonuclear cross section:

$$\sigma_{tot}(\rho A) = \int d\vec{b} \left\{ 1 - \exp\left[-\sigma_{\rho N} \int_{-\infty}^{\infty} \varrho(\vec{b}, z)\, dz \right] \right\}.$$

- Turned out to work surprisingly well for light vector mesons.

- Overestimates cross section for heavy vector mesons (J/ψ) because nuclear gluon shadowing not included.





Exclusive vector meson production

- Later a full quantum Glauber calculation was introduced as an option:

$$\sigma_{tot}^{qm}(\rho A) = 2\int d\vec{b}\left\{1 - \exp\left[-\frac{1}{2}\sigma_{\rho N} T_A(\vec{b})\right]\right\}.$$

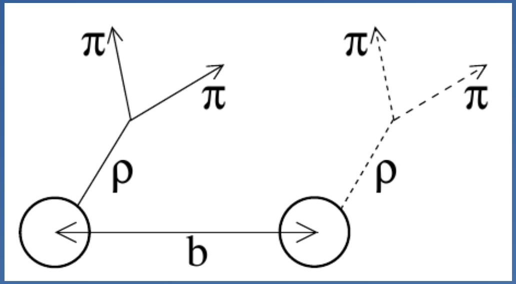
- Roughly doubles cross section for light vector mesons (and therefore disagrees with data) but has only a minor impact on the heavy vector mesons.

- Will also have an impact on the p_T spectrum; starlight per default uses a nuclear form factor.

- Focus mostly on coherent production, but incoherent (i.e. quasi-elastic γ+nucleon → V+nucleon) production included as well.

Exclusive vector meson production - Interference

A vector meson can be produced on either nucleus in a A+A → A+A+V reaction.



The cross section is the sum of the two possibilities

$$\frac{d\sigma}{dy\,dp_T} = \int_{b>2R} k_1 \frac{dN}{dk_1 d^2b}\,\sigma(\gamma A_2)\, f_{1,2}(p_T) \; + \; k_2 \frac{dN}{dk_2 d^2b}\,\sigma(\gamma A_1)\, f_{2,1}(p_T)\; d^2\vec{b}\,.$$

This can be written as the sum of two amplitudes squared

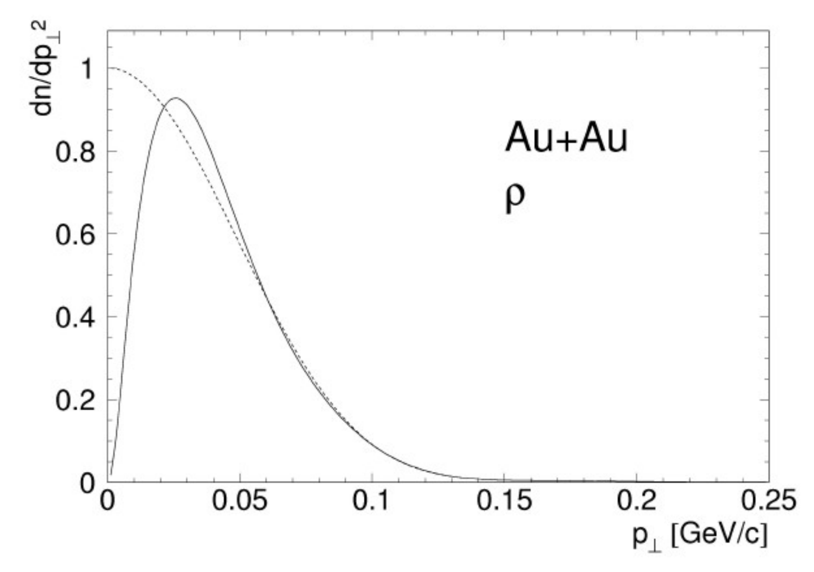
$$\frac{d\sigma}{dy\,dp_T} = \int_{b>2R} \left(|A_1|^2 + |A_2|^2\right) d^2\vec{b}\,,$$

But when p_T << 1/b, interference becomes important and one must add the amplitudes:

$$\frac{d\sigma}{dy\,dp_T} = \int_{b>2R} |A_1 + A_2|^2\, d^2\vec{b}\,.$$

Exclusive vector meson production - Interference

This leads to a modified p_T spectrum.



S.R. Klein, J. Nystrand, Phys. Rev. Lett. 84 (2000) 2330;
K. Hencken, G. Baur, D. Trautmann, Phys. Rev. Lett. 97 (2006) 012303.

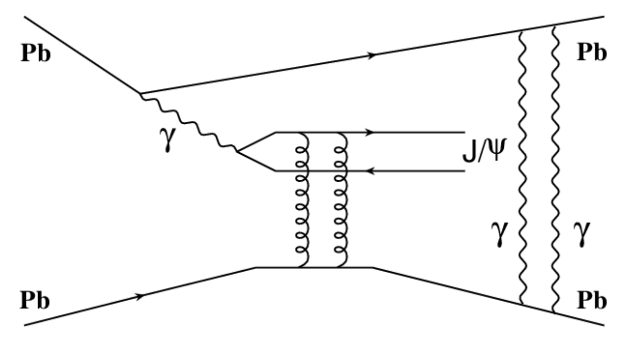
Median separation between nuclei for light vector meson production typically ≈ 50 fm at RHIC.

But the life-time of the ρ^0 is only 1 fm/c, so it will have decayed long before information is propagated from one source two the other.

One thus has “interferometry with short-lived particles”.

UPC with nuclear breakup

Strong EM fields ==> High probability to exchange one or more additional photons in a UPC.



Can divide events into breakup classes:

0n0n – no neutrons emitted.

0nXn – neutrons emitted in one direction but not in the other.

XnXn – neutrons emitted in both directions.

Typically low energy photons.

Dominating interaction for heavy nuclei: Excitation into a giant dipole resonance (GDR).

Leads to breakup of the nucleus.

Neutrons emitted in the forward direction.

Often used as an experimental signature/trigger for UPC.

UPC with nuclear breakup

- Starlight calculates the cross section with nuclear break under the assumption that the interaction probabilities factorize in impact parameter space (A.J. Baltz, S.R. Klein, J. Nystrand, PRL 89 (2002) 012301).

$$\sigma(AA \to A^*A^*V) = 2\int d^2b\, P_V(b)P_{XnXn}(b) \times \exp[-P_H(b)]\,.$$

- The interaction probability P(b) is calculated by changing the order of integration for the photon spectrum:

$$P^1_{C(Xn)}(b) = \int dk\, \frac{d^3n(b,k)}{dk\,d^2b}\, \sigma_{\gamma A \to A^*}(k)\,.$$

- The hadronic non-interaction probability $P_H(b)$ is calculated from the Glauber model:

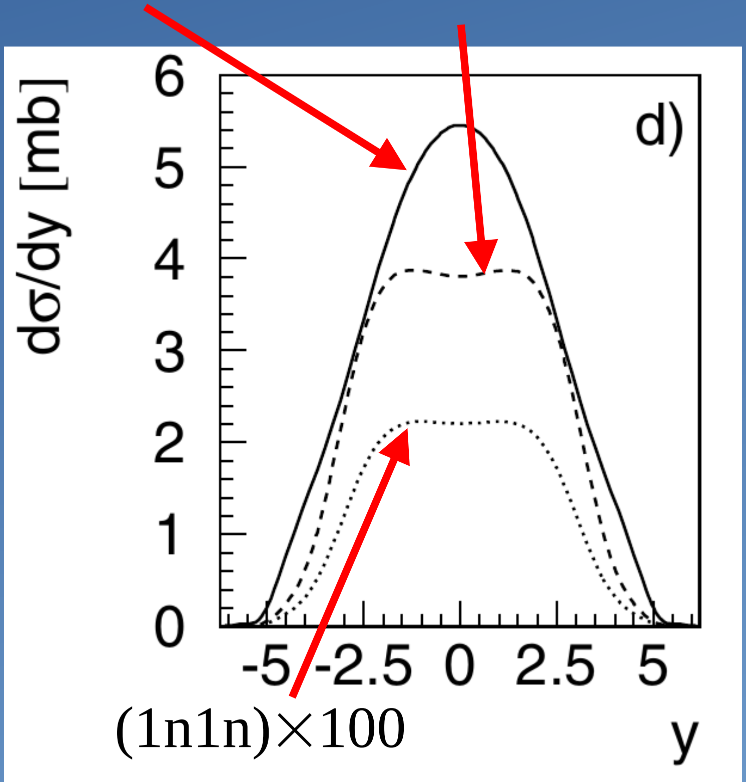
$$P_H(b) = \int d^2\vec{r}\, T_A(\vec{r} - \vec{b})\{1 - \exp[-\sigma_{NN} T_B(\vec{r})]\}\,.$$

UPC with nuclear breakup

The probability to emit additional photons is assumed to factorize in impact parameter space ⇒ modified impact parameter distributions for different breakup classes ⇒ modified photon spectrum (Baltz, Klein, Nystrand, PRL 89 (2002) 012301).

Leads to modified cross sections and rapidity/p_T distributions.

This is the basis for the separation of the low and high energy component in vector meson production at $y \neq 0$.



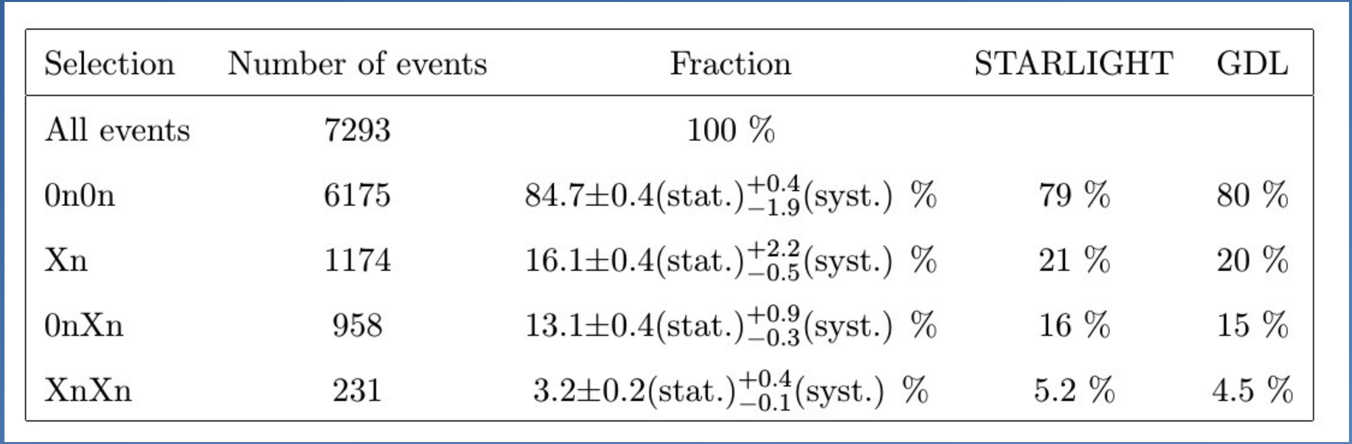
Pb+Pb → Pb*+Pb*+J/ψ
PRL 89 (2002) 012301.

UPC with nuclear breakup

- Not obvious that such a factorization scheme should work.

- But good agreement with data suggests that is does.

Photoproduction of ρ^0 with different breakup options (ALICE JHEP 09 (2015) 095)



Selection	Number of events	Fraction	STARLIGHT	GDL
All events	7293	100 %		
0n0n	6175	$84.7\pm0.4(\text{stat.})^{+0.4}_{-1.9}(\text{syst.})$ %	79 %	80 %
Xn	1174	$16.1\pm0.4(\text{stat.})^{+2.2}_{-0.5}(\text{syst.})$ %	21 %	20 %
0nXn	958	$13.1\pm0.4(\text{stat.})^{+0.9}_{-0.3}(\text{syst.})$ %	16 %	15 %
XnXn	231	$3.2\pm0.2(\text{stat.})^{+0.4}_{-0.1}(\text{syst.})$ %	5.2 %	4.5 %

0n no neutrons emitted in one direction.

Xn any number of neutrons emitted in one direction

ALICE PLB 751 (2015) 358

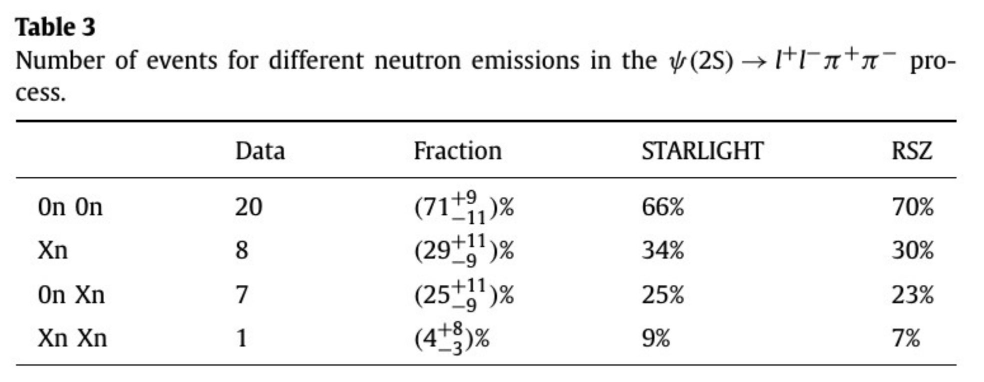


Table 3
Number of events for different neutron emissions in the $\psi(2S) \to l^+l^-\pi^+\pi^-$ process.

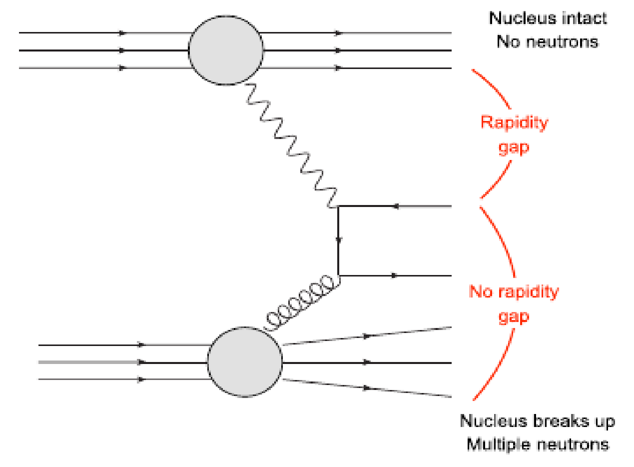
	Data	Fraction	STARLIGHT	RSZ
0n 0n	20	(71^{+9}_{-11})%	66%	70%
Xn	8	(29^{+11}_{-9})%	34%	30%
0n Xn	7	(25^{+11}_{-9})%	25%	23%
Xn Xn	1	(4^{+8}_{-3})%	9%	7%

Inelastic photonuclear interactions in UPC

STARlight has been interfaced with DPMJET 3.0-5 to simulate inelastic photonuclear interactions, γ+A → X, Ø. Djuvsland, J. Nystrand, Phys. Rev. C 83 (2011) 041901. (Attempts to include upgraded DPMJET ongoing.)

1) There is a rapidity gap on the side of the photon-emitting nucleus ==> main experimental signature.

2) The photon energy << beam energy ==> particle production is shifted in rapidity to the side of the target nucleus.



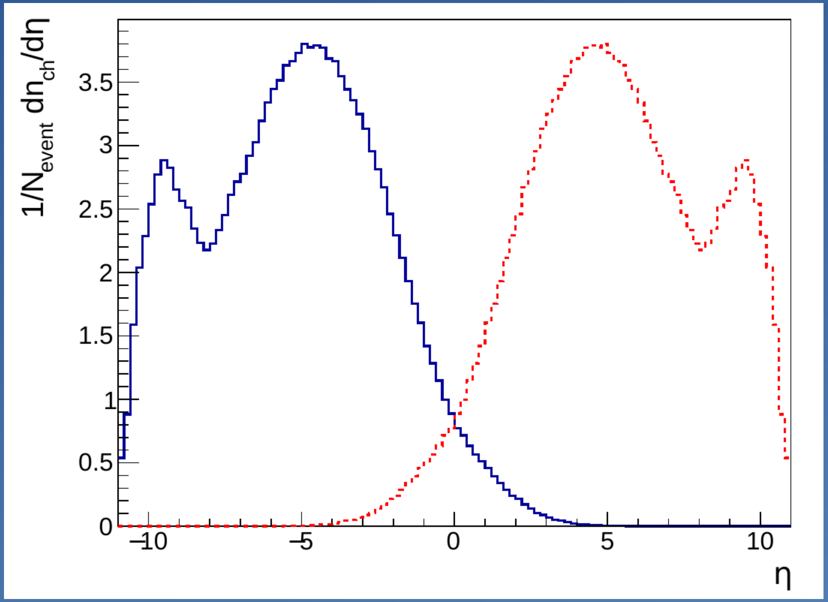
The total photonuclear cross sections for these photon energies is several barns (starlight+DPMJET):

$\sqrt{s}$ = 2.76 TeV	$\sqrt{s}$ = 5.36 TeV
σ(k > 1000 GeV) = 4.9 b	σ(k > 1000 GeV) = 8.9 b
σ(k > 10 000 GeV) = 0.9 b	σ(k > 10 000 GeV) = 2.9 b

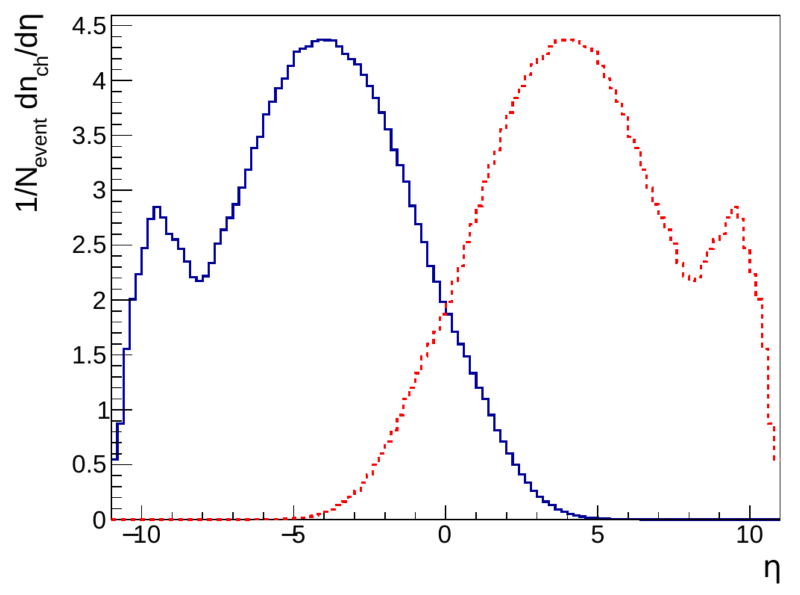
Inelastic photonuclear interactions in UPC

Pseudorapidity distributions of charged particles (π,K,p):

k > 1000 GeV



k > 10 000 GeV



Spectrum shifted away from y = 0, but each nucleus can emit the photon or act as target, so the total distribution includes the reflection.

Distribution shifted closer to mid-rapidity for higher k.

Increase in multiplicity with increasing k.

eSTARlight Monte Carlo for ep/eA collisions

Simulates exclusive vector meson production in ep/eA collisions

- Same final states as STARlight
- Plus backward meson production (related to baryon stopping)

STARlight was starting point

- Similar input/output format and code structure
- Virtual photons over arbitrary Q^2 range
- A completely new algorithm for sampling in W, Q^2 space

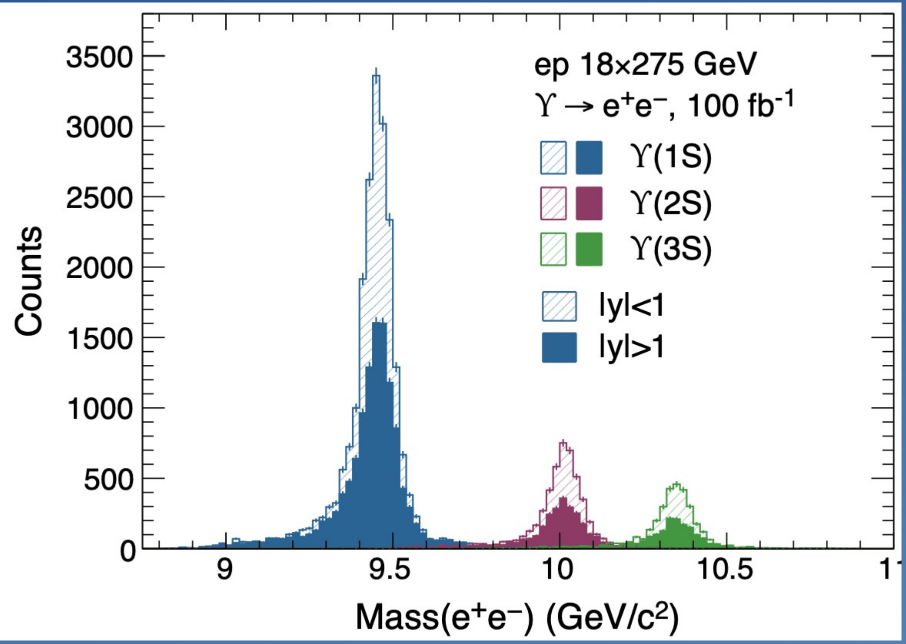
STARlight and eSTARlight internals are now very different

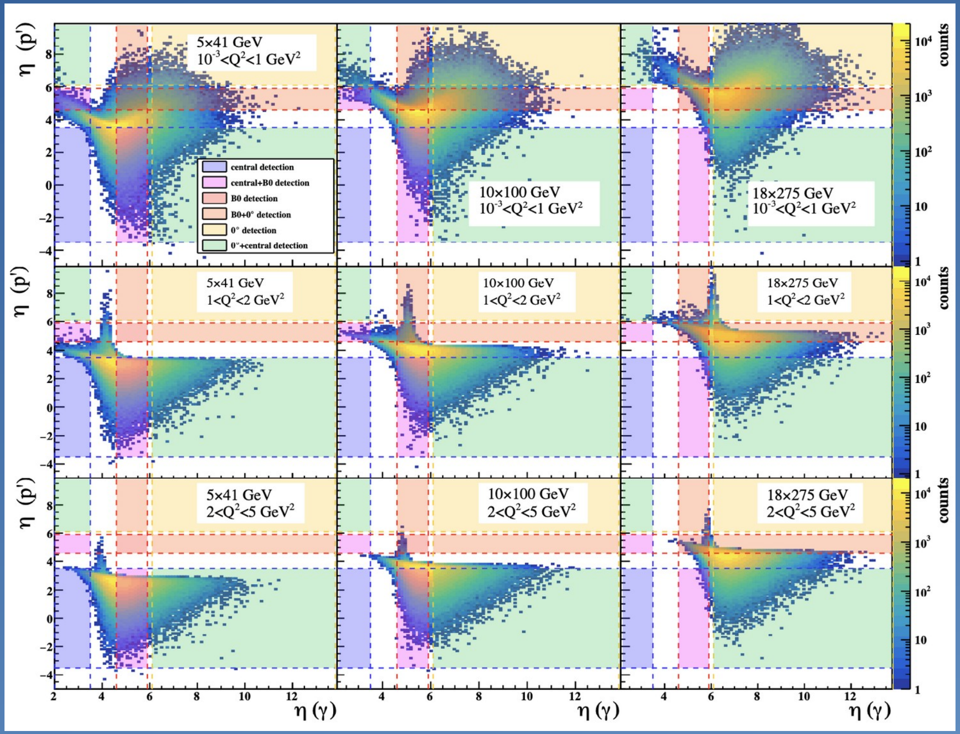
- dN_γ/dQ^2 is a rapidly varying function; $\sigma(\gamma A\text{->}VA)$ depends on Q^2.
- Limited data on Q^2 dependence of cross-sections; required judicious extrapolations
- VM Polarization changes from purely transverse at $Q^2=0$ to a mixture of transverse and longitudinal.

M. Lomnitz & S. Klein, Phys. Rev. **C99**, 015203 (2019)

eSTARlight usage

Select beam energies, (optionally) Q^2 range, process and desired final states





Separation of 3 ϒ states
ATHENA detector proposal
JINST **17,** P10019 (2022).

Backward Compton scattering, ep -> eγp
Proton is typically at midrapidity
Photon takes most of proton momentum
Z. Sweger et al., Phys. Rev. C **108** 055205 (2023).

Code available on github at https://github.com/eic/estarlight

Summary

- First version of STARlight was developed before the start of the heavy-ion program at RHIC and LHC.

- It has remained a stable reference for ultra-peripheral collisions.

- It has successfully PREdicted many UPC phenomena (coherent photoproduction of vector mesons, interference, photoproduction with nuclear breakup, two-photon production of dilepton pairs, …).

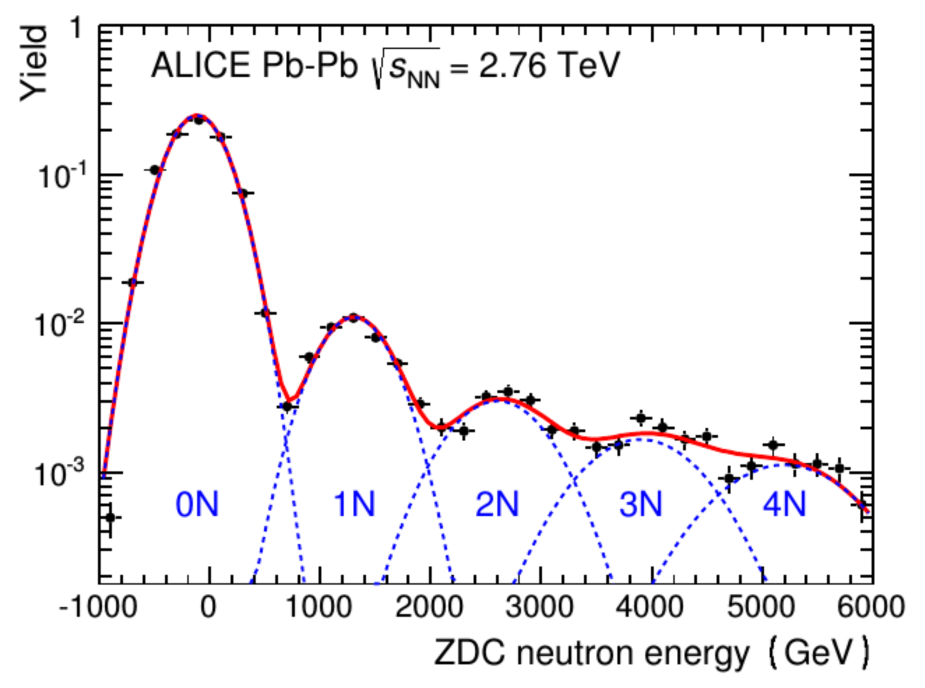
- It remains in use and is maintained today, and further developments are underway.

Backup Slide

UPC with nuclear breakup

Experimentally one could do a better estimate of the number of emitted neutrons than just 1n,Xn.

Energy deposit in the Zero-Degree Calorimeters when a ρ^0 is produced at midrapidity:



Peaks corresponding to 1n, 2n, 3n can be separated.

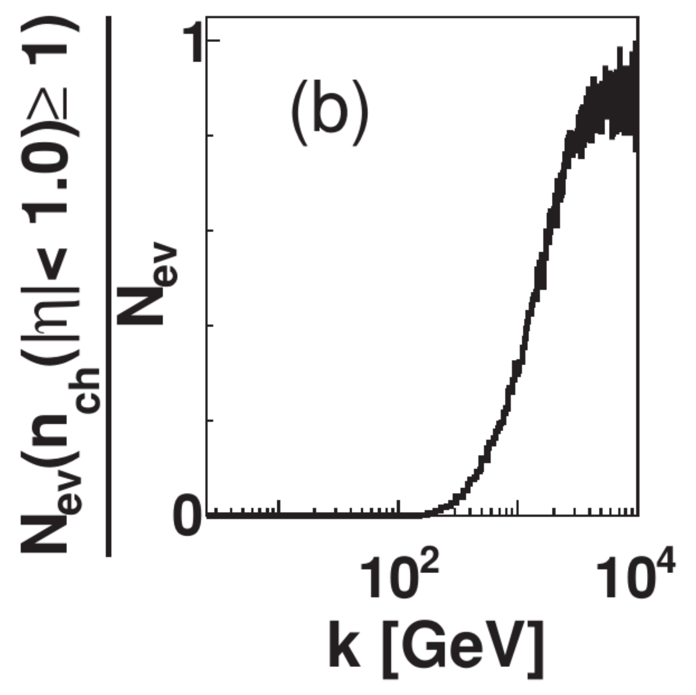
Input from theorists on this is welcome.

Models for photonuclear interactions in UPC

Use the photon spectrum from starlight and convolute it with DPMJET (Ø. Djuvsland, J. Nystrand, Phys. Rev. C 83 (2011) 041901).

The photon spectrum extends to infinity as the photon energy →0.

Has to define a meaningful minimum photon energy.



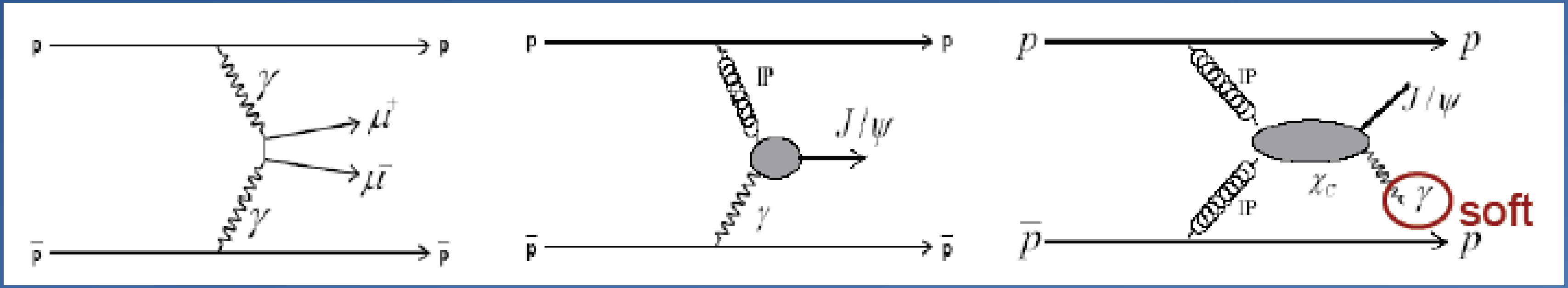
The probability to have at least one charged particle inside $|\eta| < 1$.

The photon energy is here in the rest frame of the nucleus.

This is in the region k ~ 1000 – 10 000 GeV.

6. Vector meson production in pp and pA collisions

Three possible contributions to the process $p+p \rightarrow p+p+\mu^+\mu^-$:

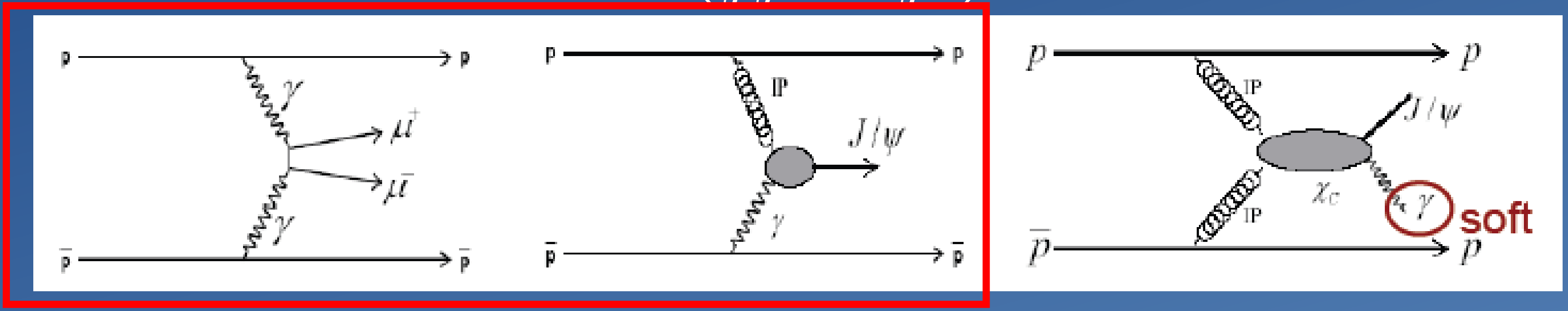


Note: no feed down from χ_c to Ψ'.

A contribution from Odderon+Pomeron also possible.

6. Vector meson production in pp and pA collisions

Calculations for the first two ($\gamma\gamma$ and γP) – STARLIGHT MC:



$\sigma(pp \to pp + J/\Psi(1S))$: 19.6 nb $\sigma \cdot Br(\mu\mu)$: 1.16 nb

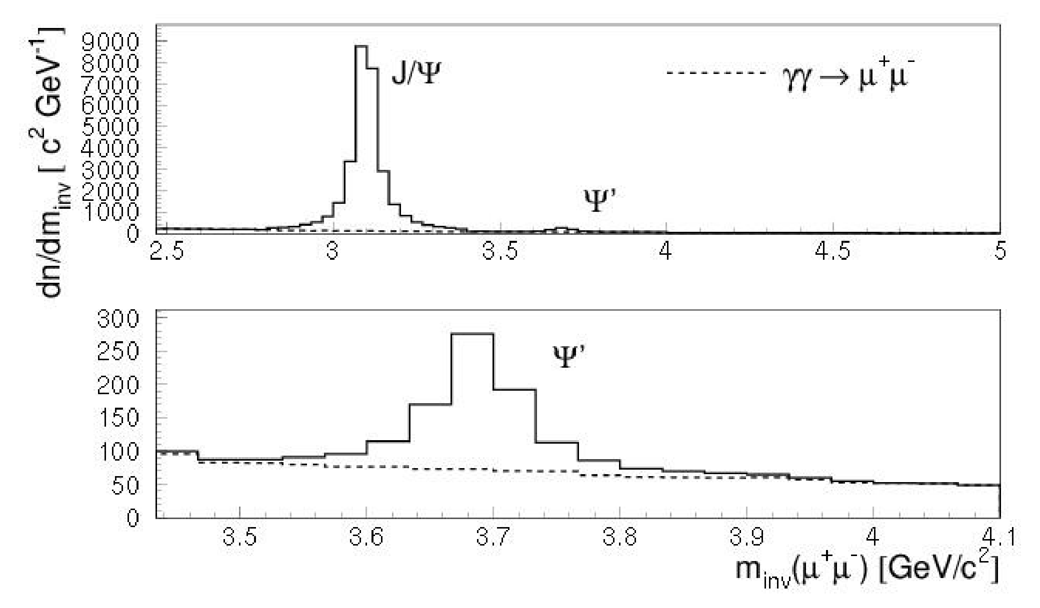
$\sigma(pp \to pp + \Psi'(2S))$: 3.2 nb $\sigma \cdot Br(\mu\mu)$: 23 pb

$\sigma(pp \to pp + \mu\mu)$: 2.4 nb ($m_{inv} > 1.5$ GeV/c^2)

Applying cuts on the $\mu^+\mu^-$:

$p_T > 0.5$ GeV/c

$|\eta| < 2.0$ $\Rightarrow$

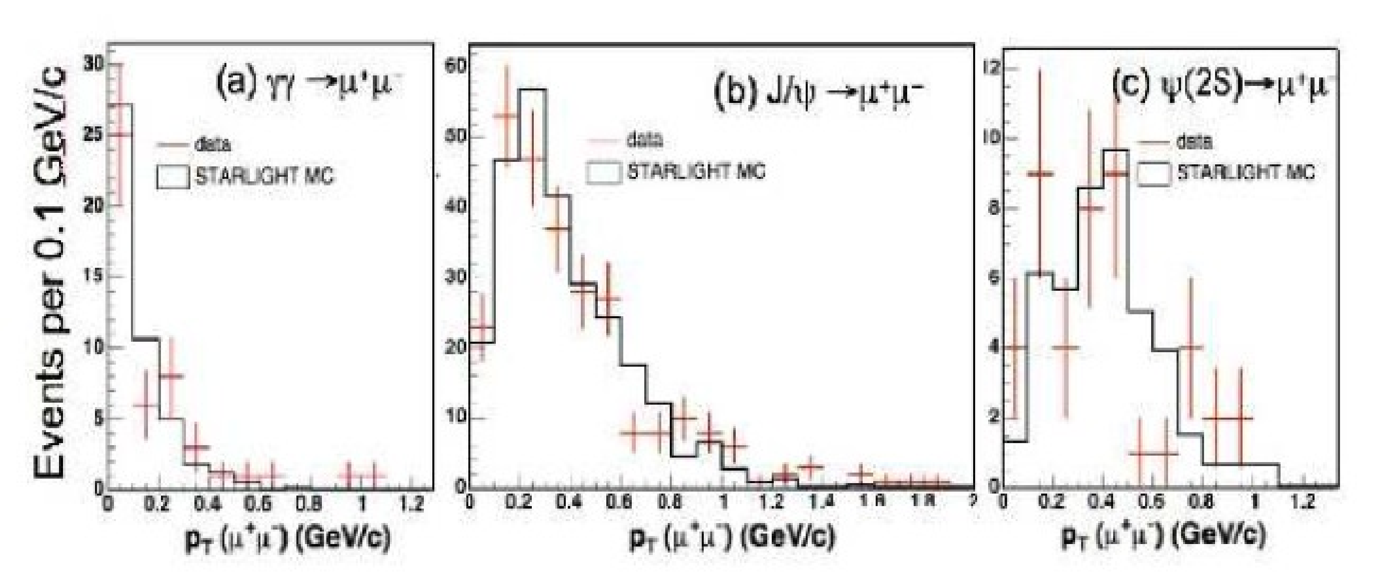


Yield(Ψ')/Yield(J/Ψ) ≈ 1:50

S.R.Klein, J.Nystrand, PRL 92 (2004) 142003 (J/Ψ only).

6. Vector meson production in pp and pA collisions

p_T distributions in agreement with expectations.



(T.Aaltonen et al. (CDF Collaboration) arXiv:0902.1271)

6. Vector meson production in pp and pA collisions

Comparison of cross sections:

	Theory	CDF (PRL 102 (2009) 242001)
J/Ψ:	$\frac{d\sigma(y=0)}{dy} = 2.7^{+0.6}_{-0.2}\,\mathrm{nb}$	$\frac{d\sigma(y=0)}{dy} = 3.92 \pm 0.62\,\mathrm{nb}$
Ψ':	$\frac{d\sigma(y=0)}{dy} = 0.46^{+0.11}_{-0.04}\,\mathrm{nb}$	$\frac{d\sigma(y=0)}{dy} = 0.53 \pm 0.14\,\mathrm{nb}$

Sets a limit on the Odderon contribution to the J/Ψ (95% c.l.):

$$\frac{d\sigma(y=0)}{dy} < 2.3\,\mathrm{nb}$$