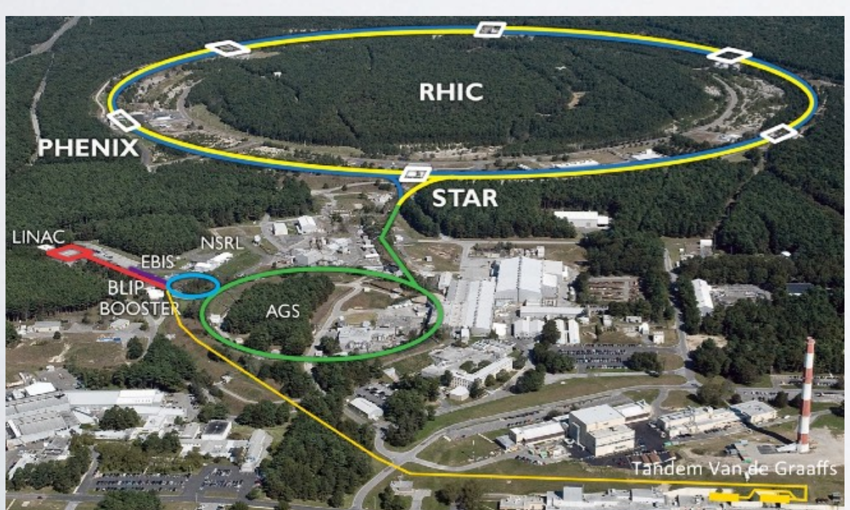
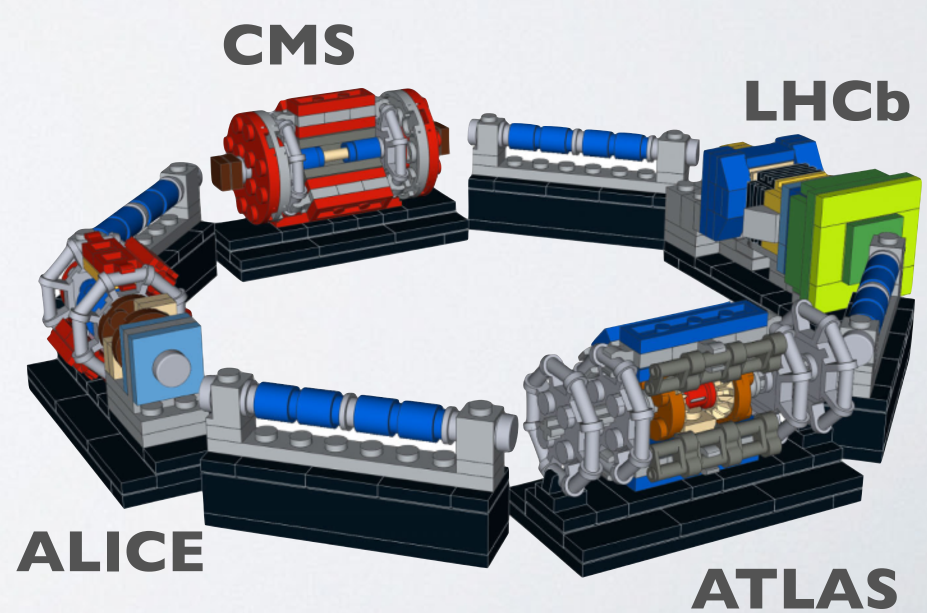
PHOTON PHOTON COLLISIONS AT RHIC & THE LHC

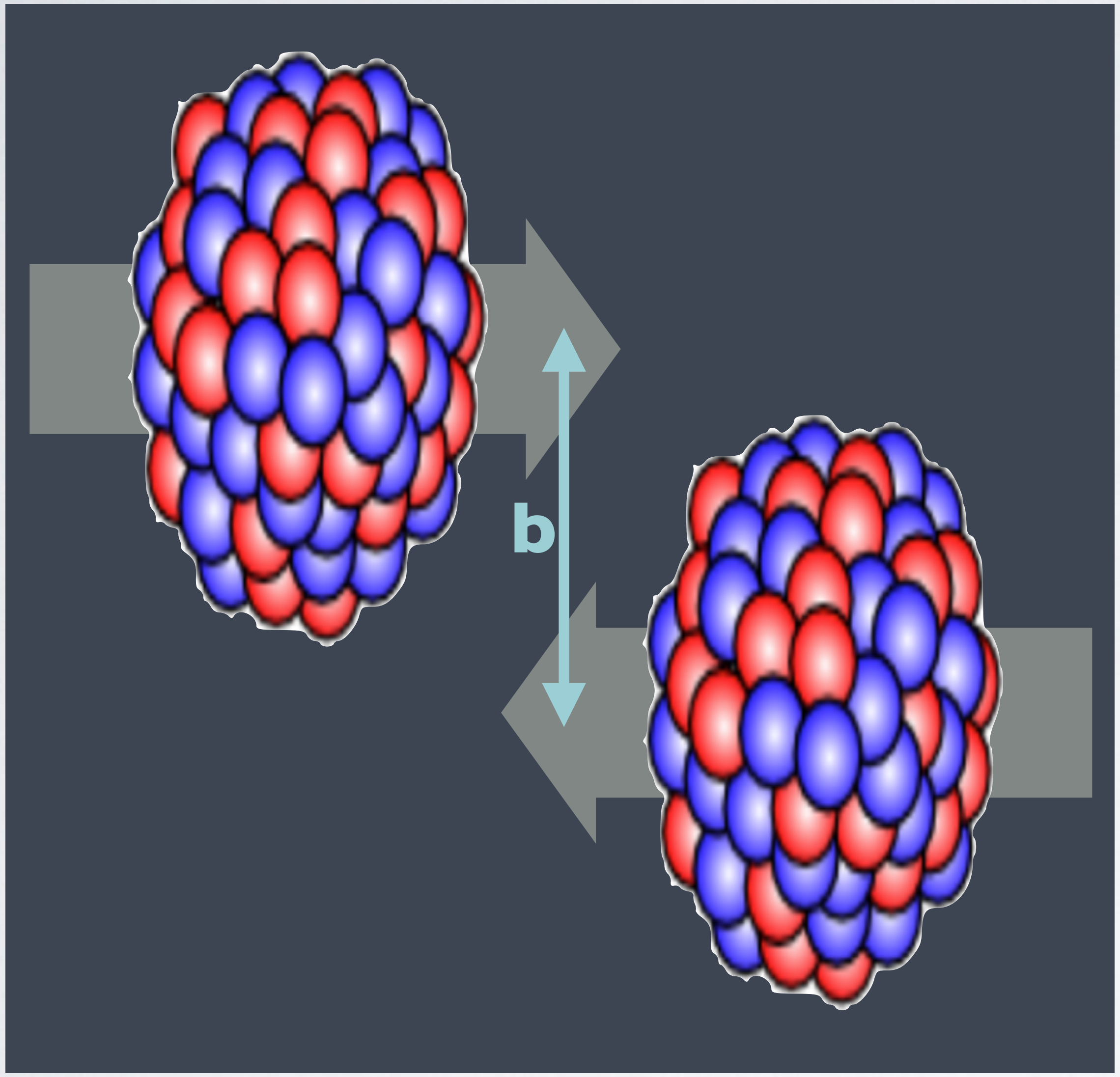
Peter Steinberg, BNL

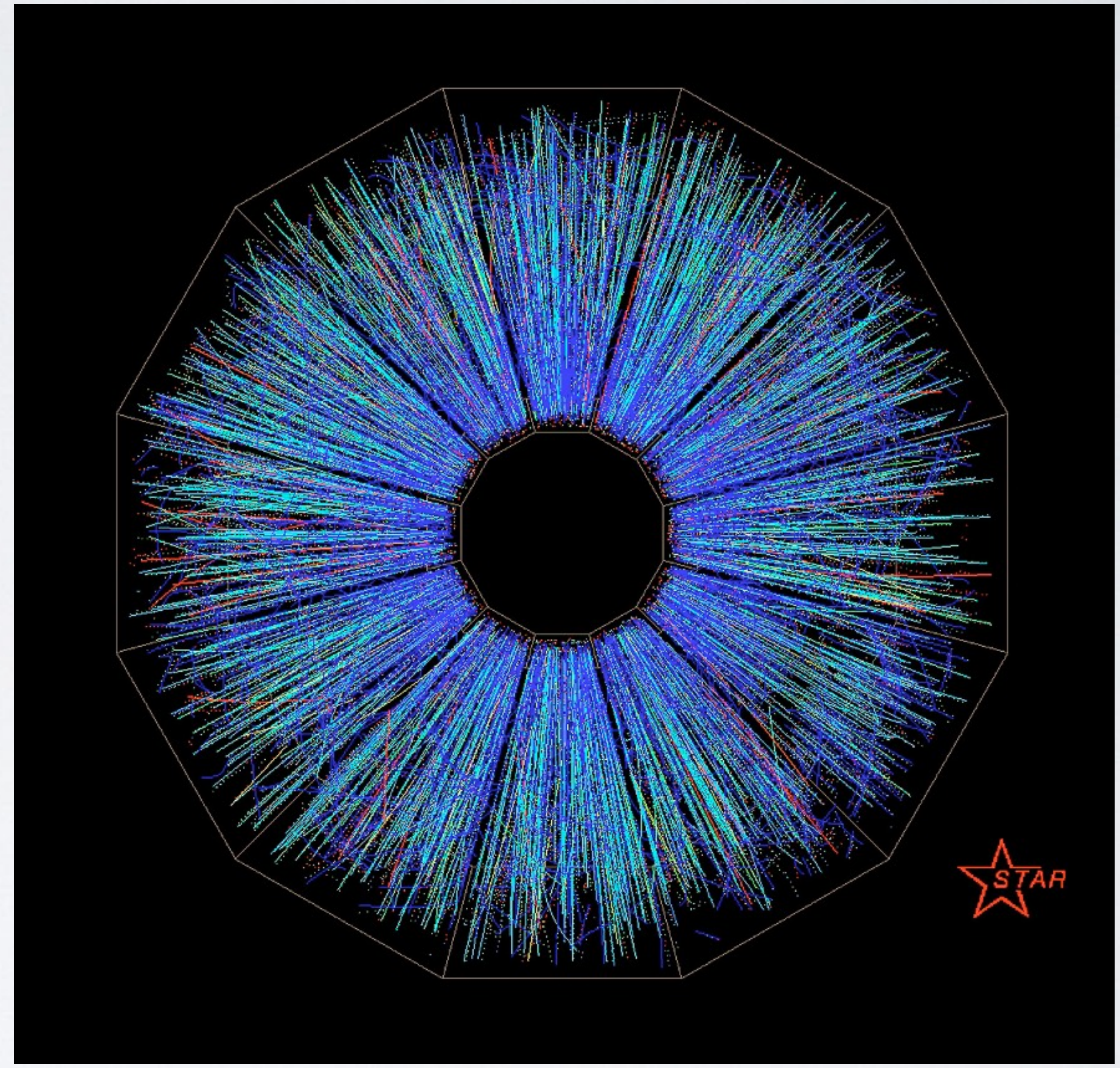


April 11, 2019
GHP2019
Denver, Colorado



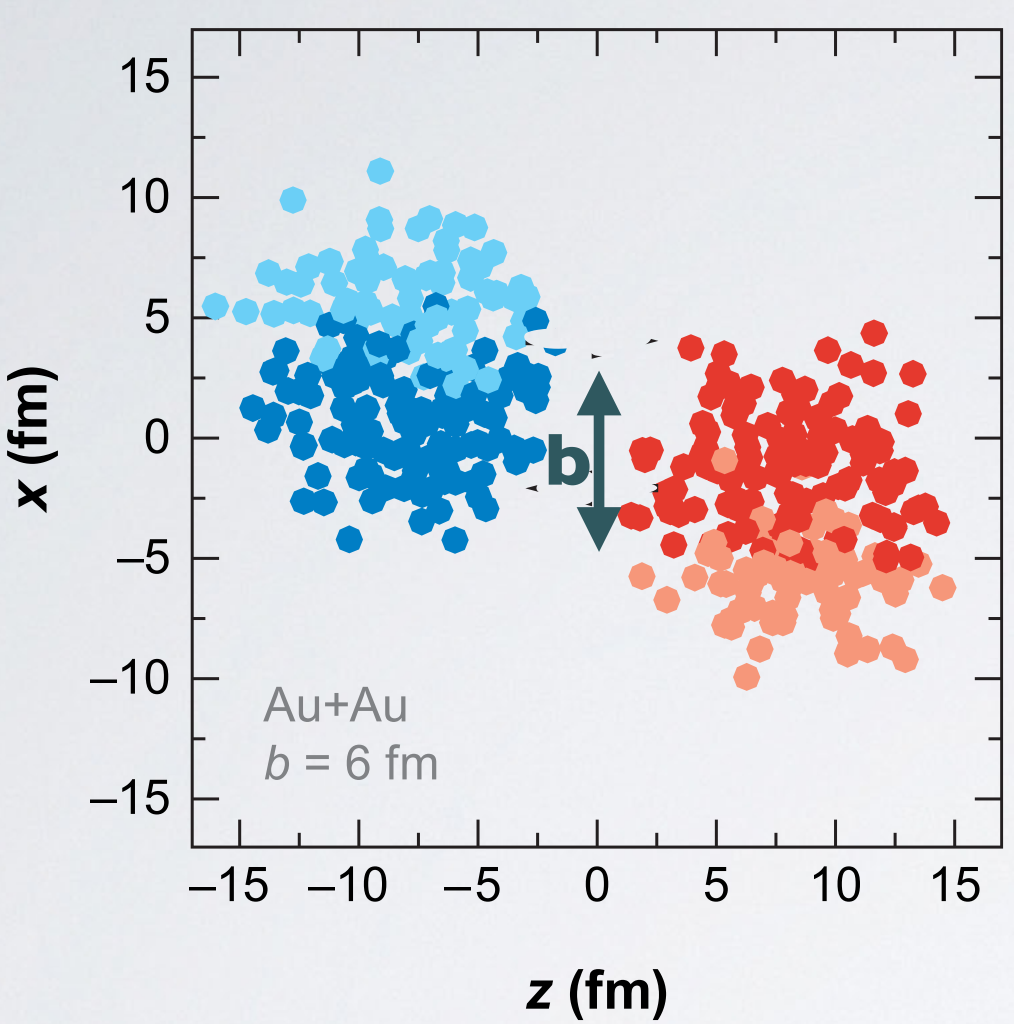
Heavy ion collisions

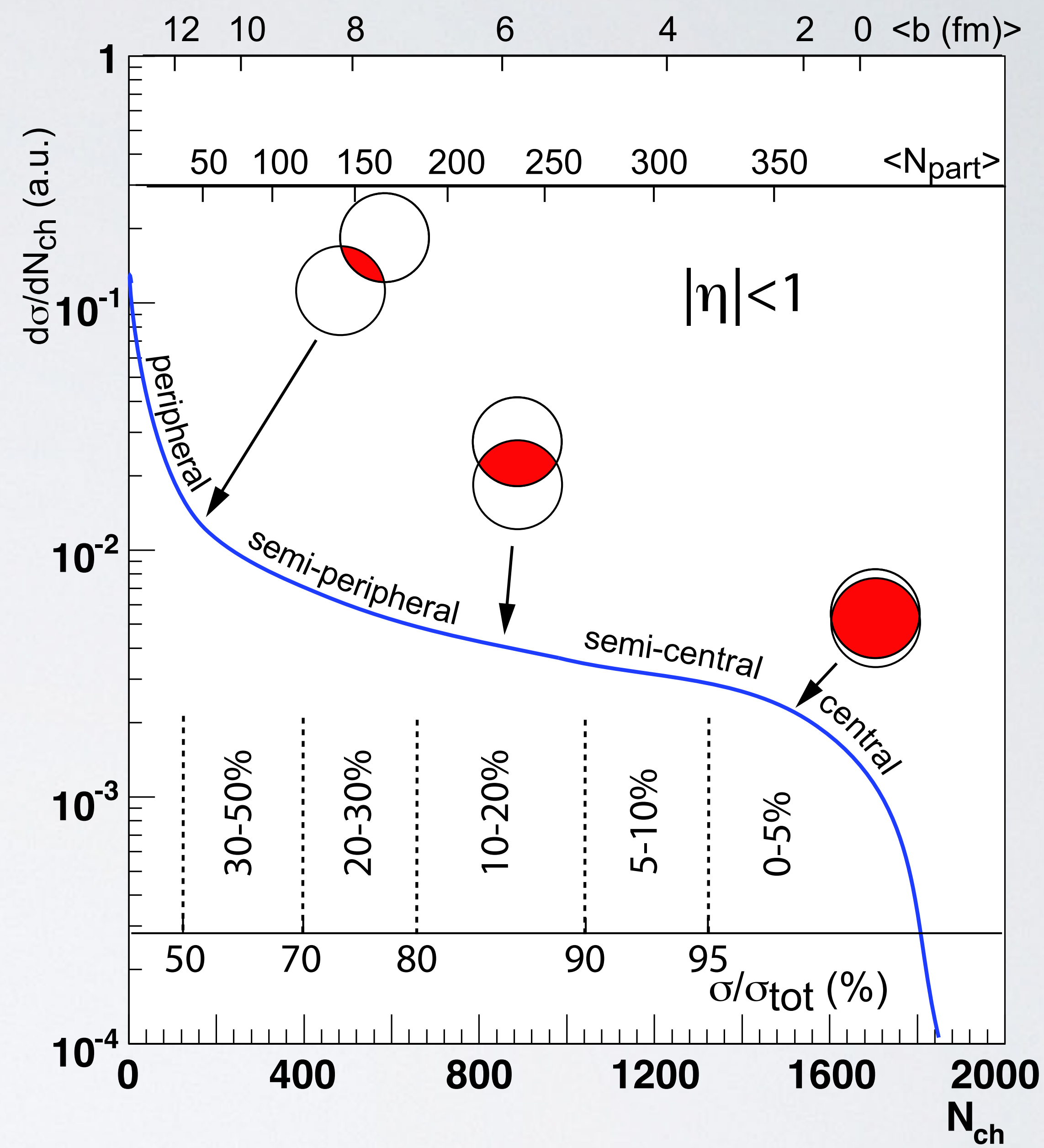




Many features of hadronic heavy ion collisions correlate strongly with the impact parameter between the nuclei: importance of nuclear geometry established by early RHIC program

Role of impact parameter





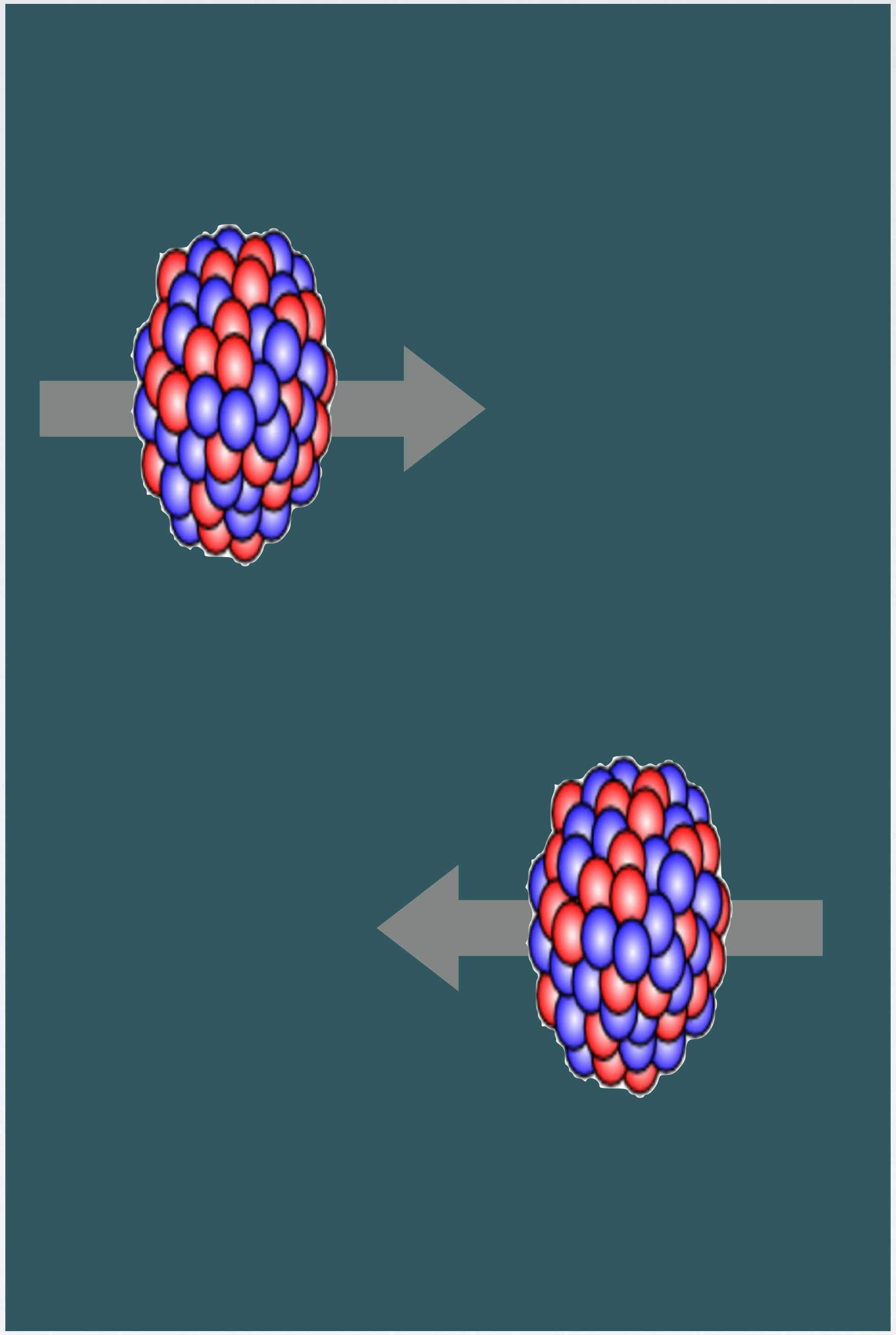
participants : N_{part} "volume $\frac{dN}{dy} \propto N_{\mathrm{part}}$

collisions : N_{coll}

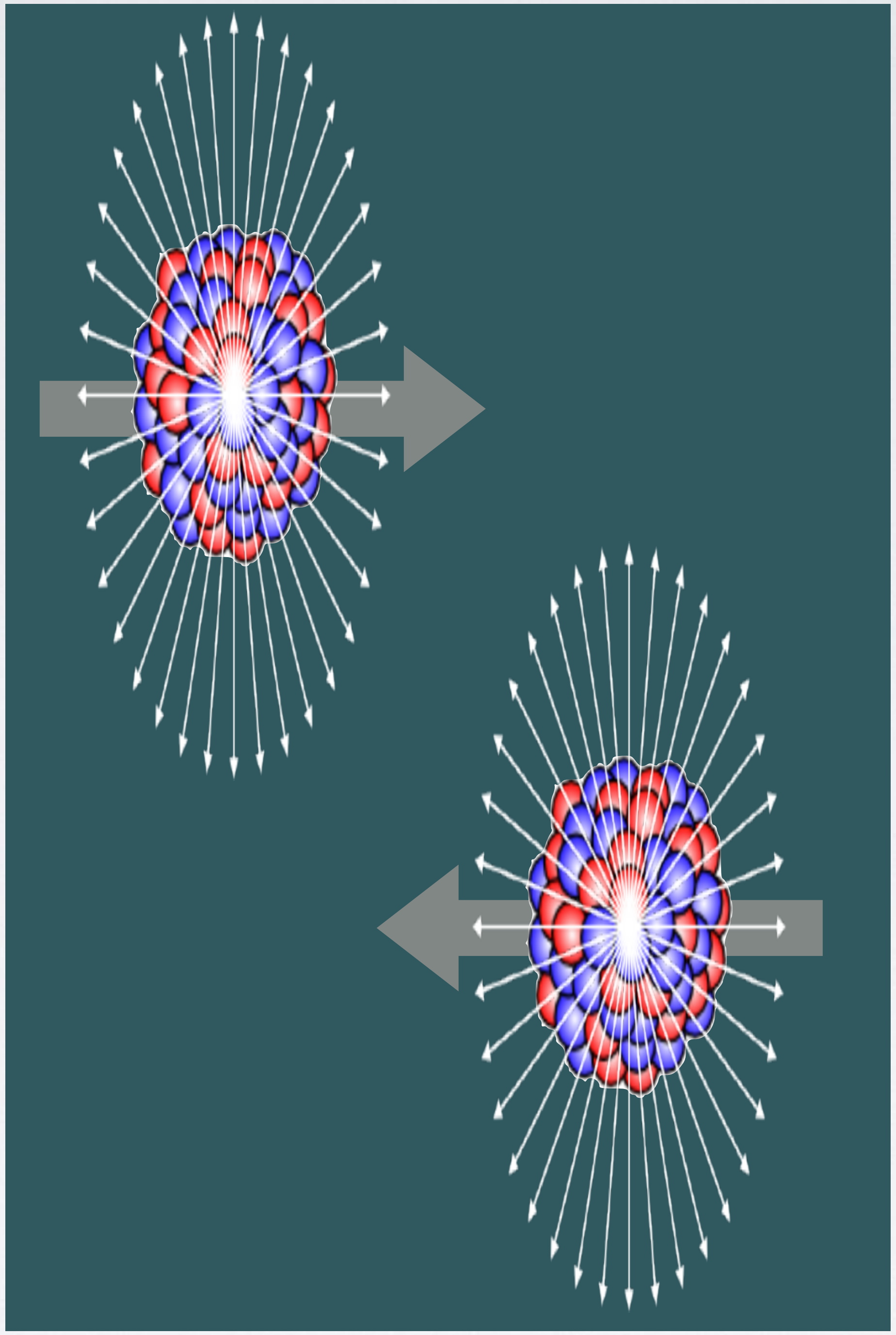
T_{AA} : $N_{\mathrm{coll}}/\sigma_{NN}$ "thickness", hard

Impact parameter & nuclear geometry control many (most) features of hadronic A+A collisions (multiplicity, hard process rates, collective flow): deviations from geometric scaling led to discoveries, e.g. jet quenching!

Wednesday:
Nagle & Majumder

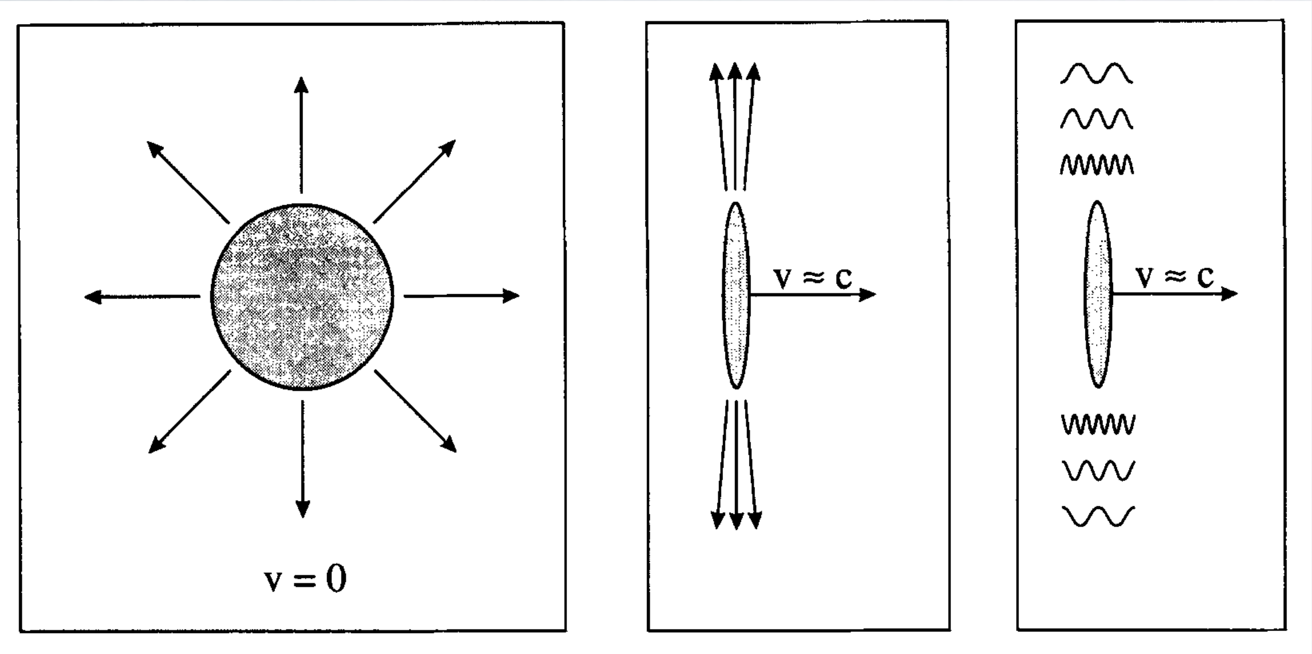


Ultra-peripheral collisions



When **b>2R**, ions “miss” but can still interact via EM processes: domain of “ultra-peripheral collisions” (UPC)

Ultra-peripheral collisions

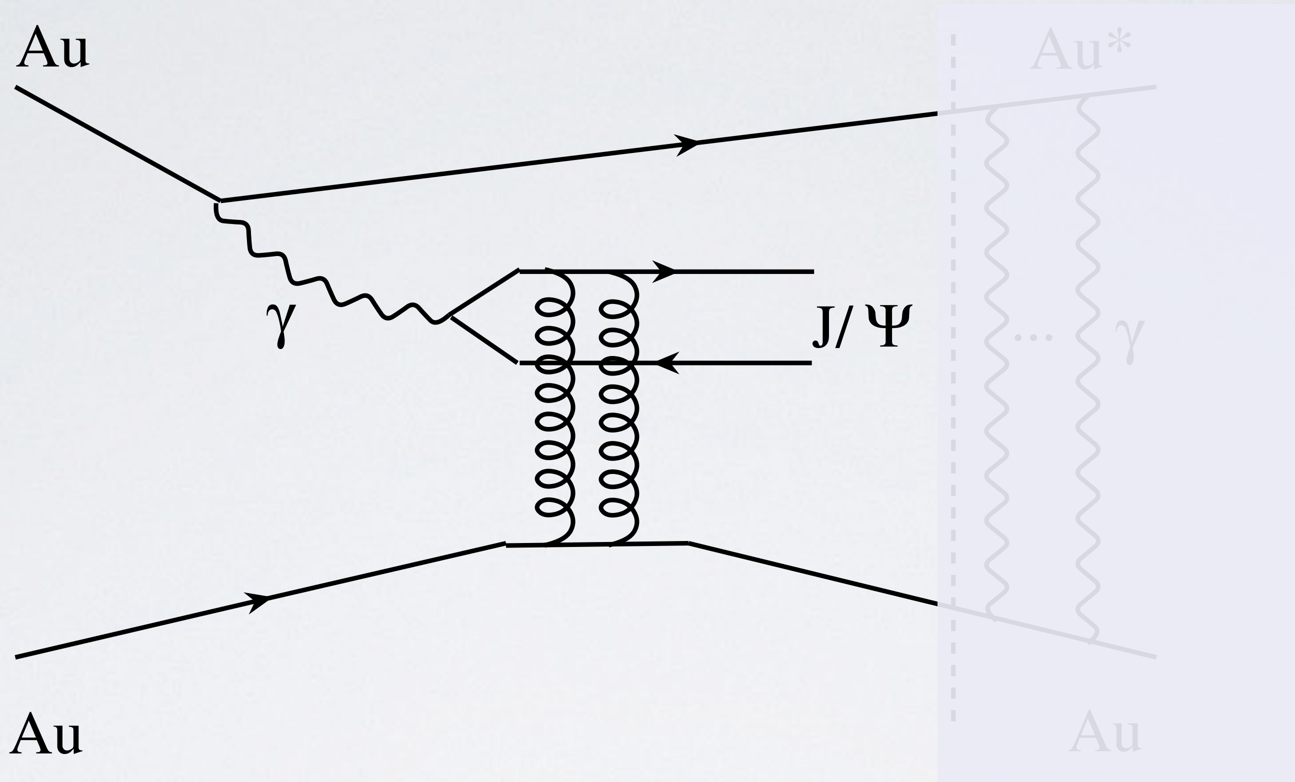


Lorentz-contraction of nuclear EM field "boosts" low energy quanta in nuclear Coulomb field to high energies

Weissacker-Williams approach: "equivalent photon approximation" used to derive *n*(k,b)

maximum energy $E_{\gamma,max} \sim \gamma(\hbar c/R)$	**80 GeV in Pb+Pb@LHC** **3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) $p_{Tmax} \sim \hbar c/R$	**O(30) MeV @ RHIC & LHC**
Coherent strengths (rates) scale as $\mathbf{Z^2}$: nuclei >> protons	Flux of photons on other nucleus ~ $\mathbf{Z^2}$, flux of photons on photons ~ $\mathbf{Z^4}$ **(45M!)**

Vector meson production



Coherent diffractive vector meson production has been the paradigmatic UPC measurement: accessible at RHIC & LHC

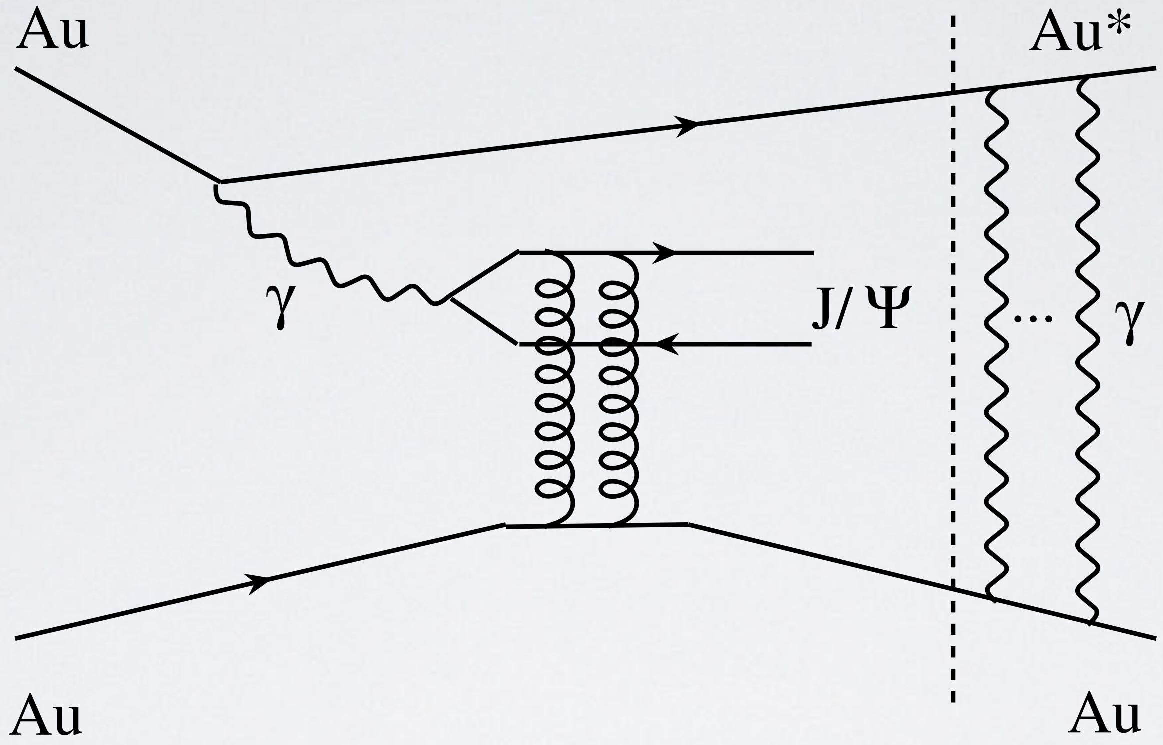
talks by
D. Tapia Takaki
J. Seger
C. Bertulani
this afternoon

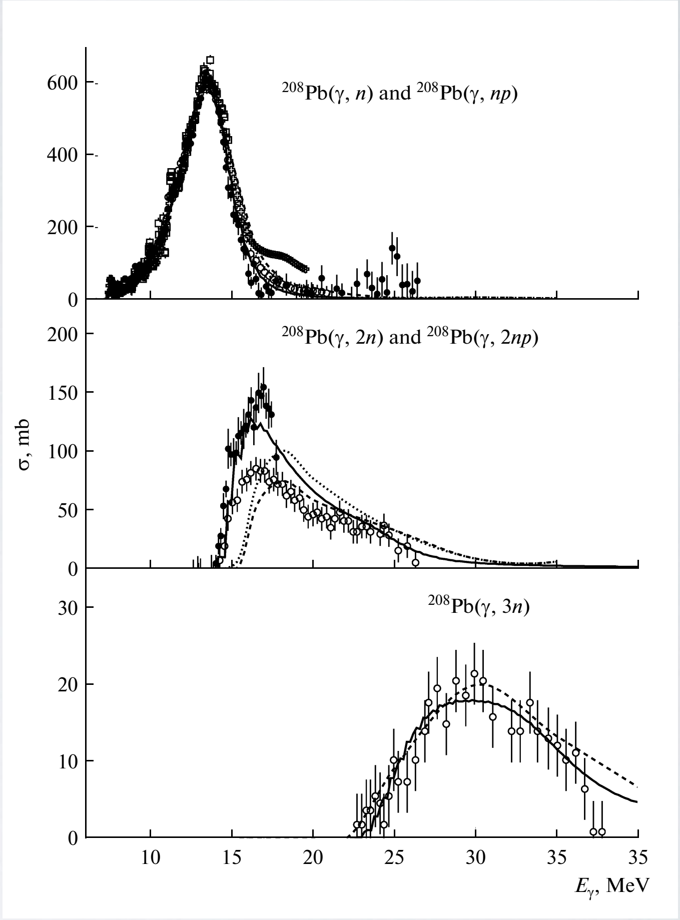
Photon from nucleus fluctuates to $q\bar{q}$ state
interacts with coherent pomeron (2 gluon) state from other nucleus:
final state is exclusive: oppositely-charged leptons with low p_T

No net color exchange: do nuclei stay intact?

Nuclear dissociation

Pschetnikov/RELDIS (2011)





Primary process leaves nuclei intact

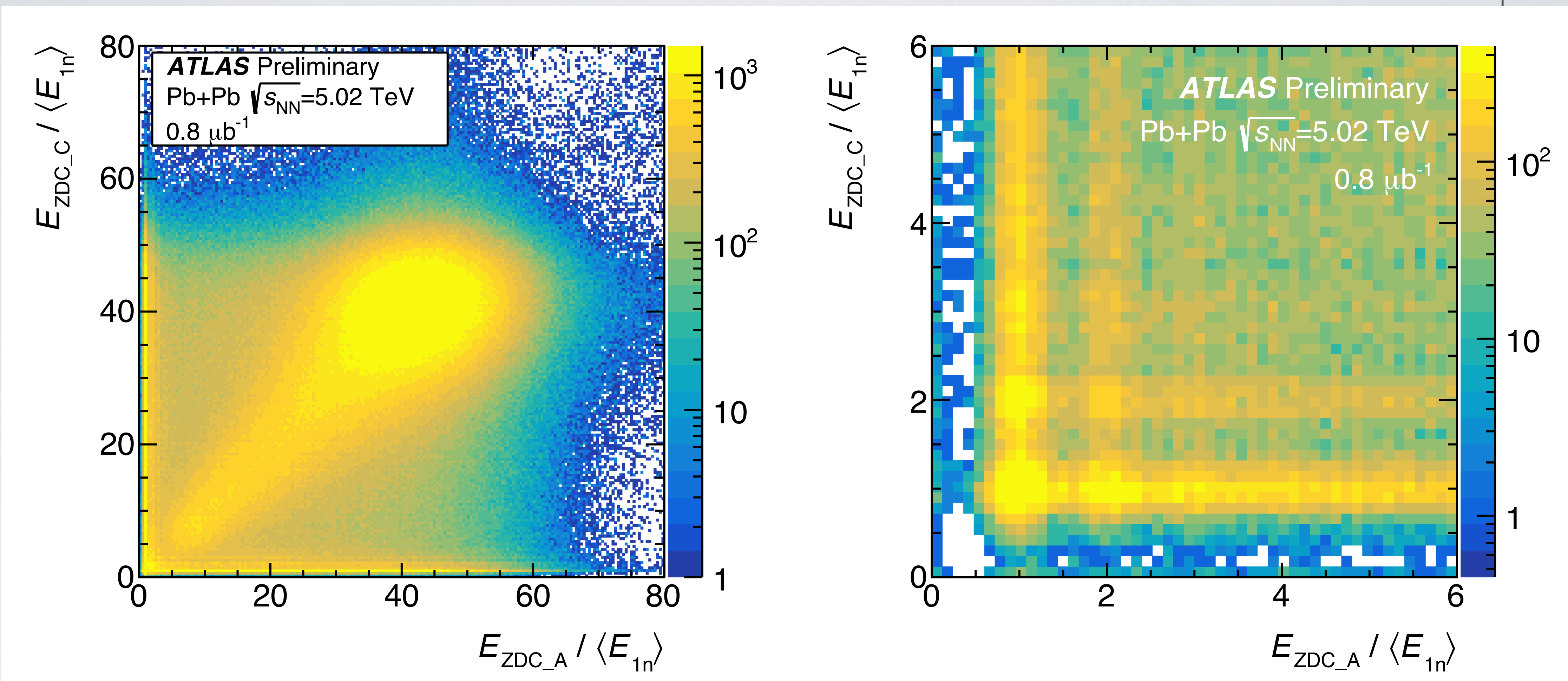
However *secondary* interactions of soft photons (10s of MeV) can break up other nucleus, e.g. via giant dipole resonance

⇒ exclusive processes can still break up nuclei!

STARLIGHT
RELDIS

Zero-degree calorimeters

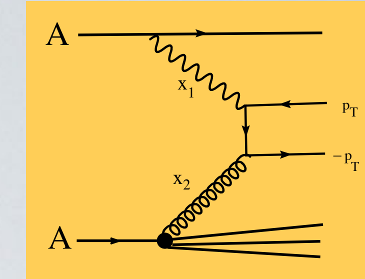
minimum bias Pb+Pb: 2 ZDCs required

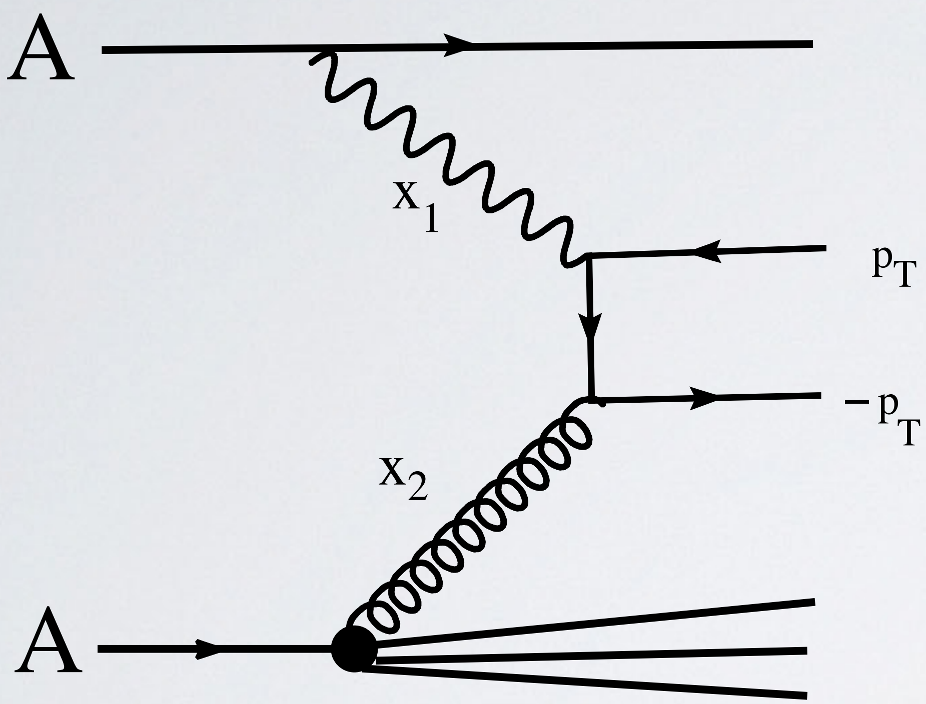


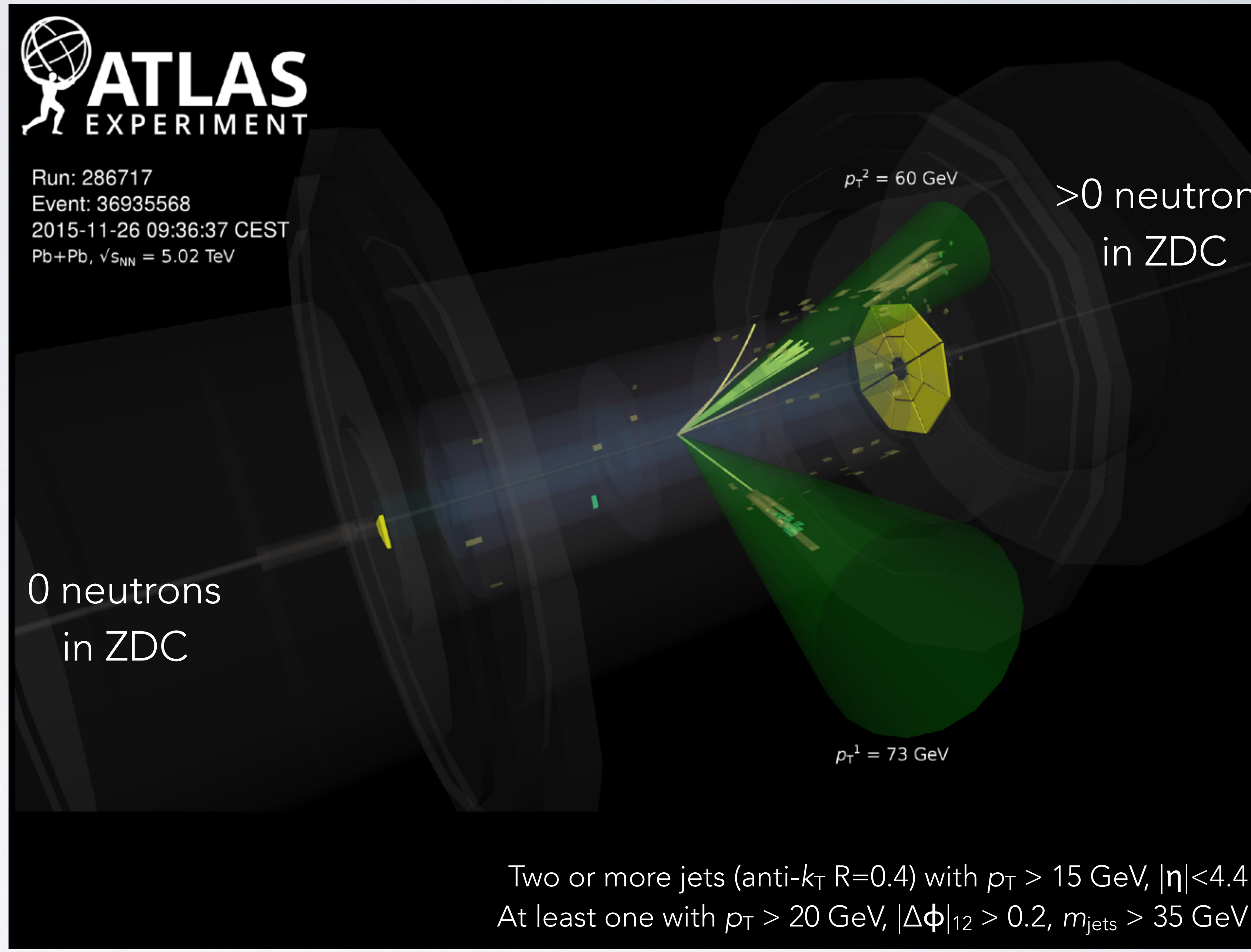
neutrons from nuclear fragmentation seen in far-forward
"Zero Degree Calorimeters" (ZDC):
symmetric (geometric) hadronic processes, asymmetric photonuclear processes

18m @ RHIC, 140m @ LHC

Photonuclear dijets





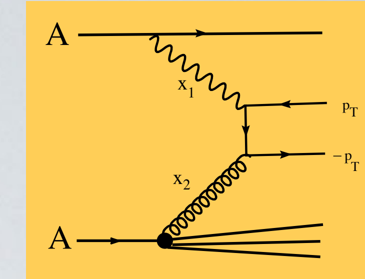


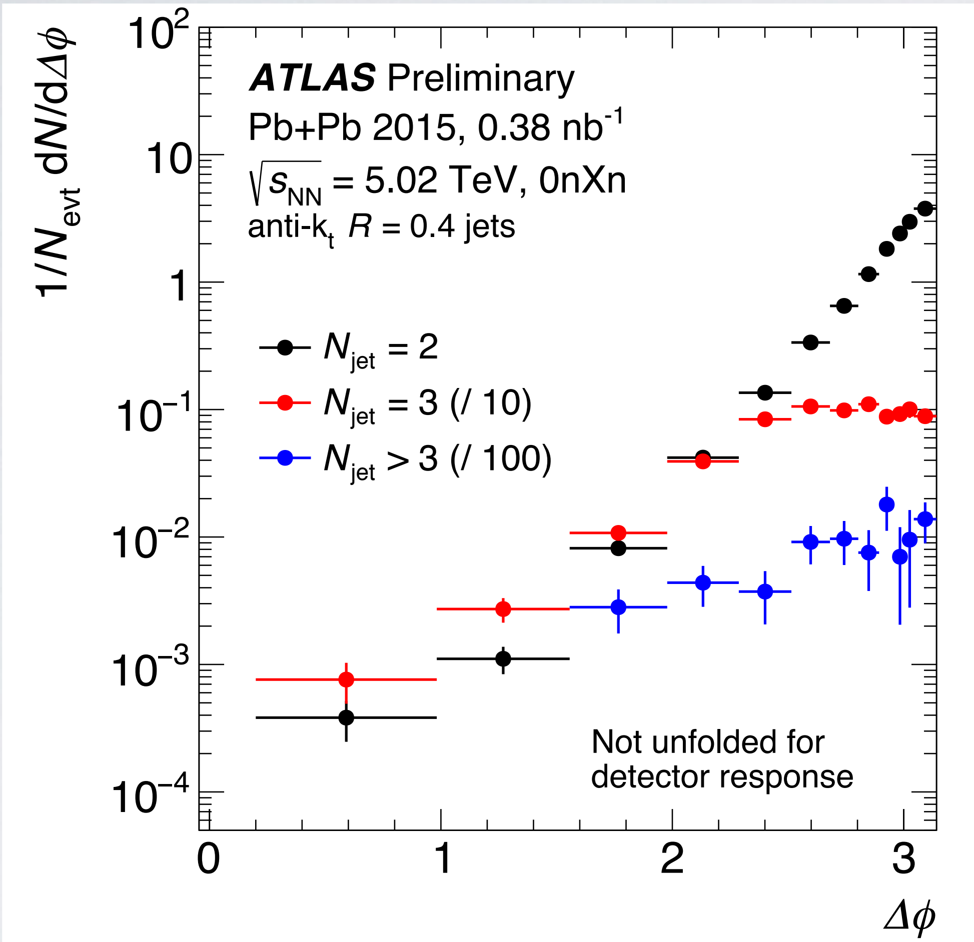
Inelastic photonuclear processes: $\gamma + A \rightarrow$ hadrons or jets & **rapidity gap**

Primary event topology: jets, energy in one ZDC & rapidity gap in calorimeter

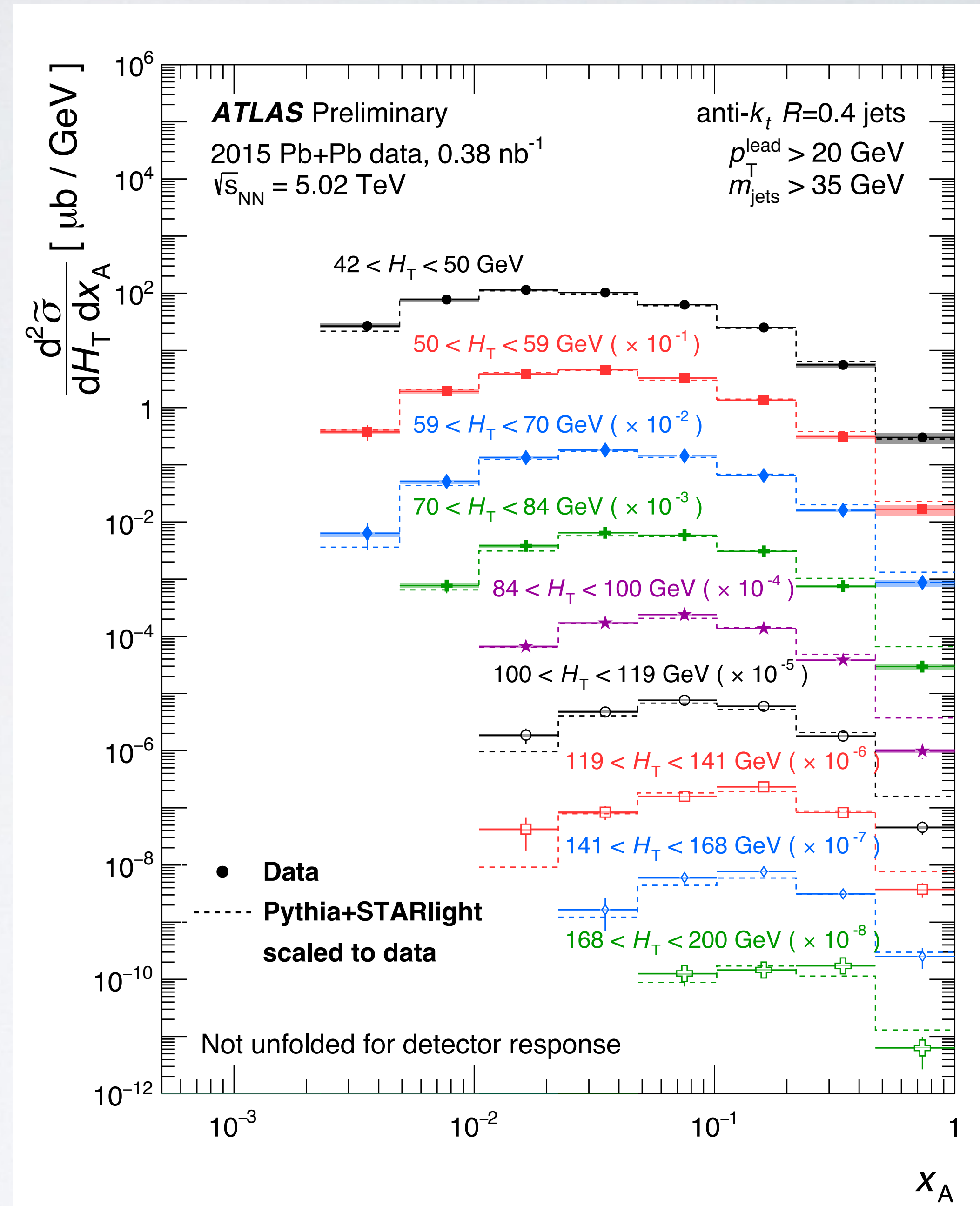
Photonuclear dijets

talk by Brian Cole, this afternoon





ϕ-balanced dijets↑

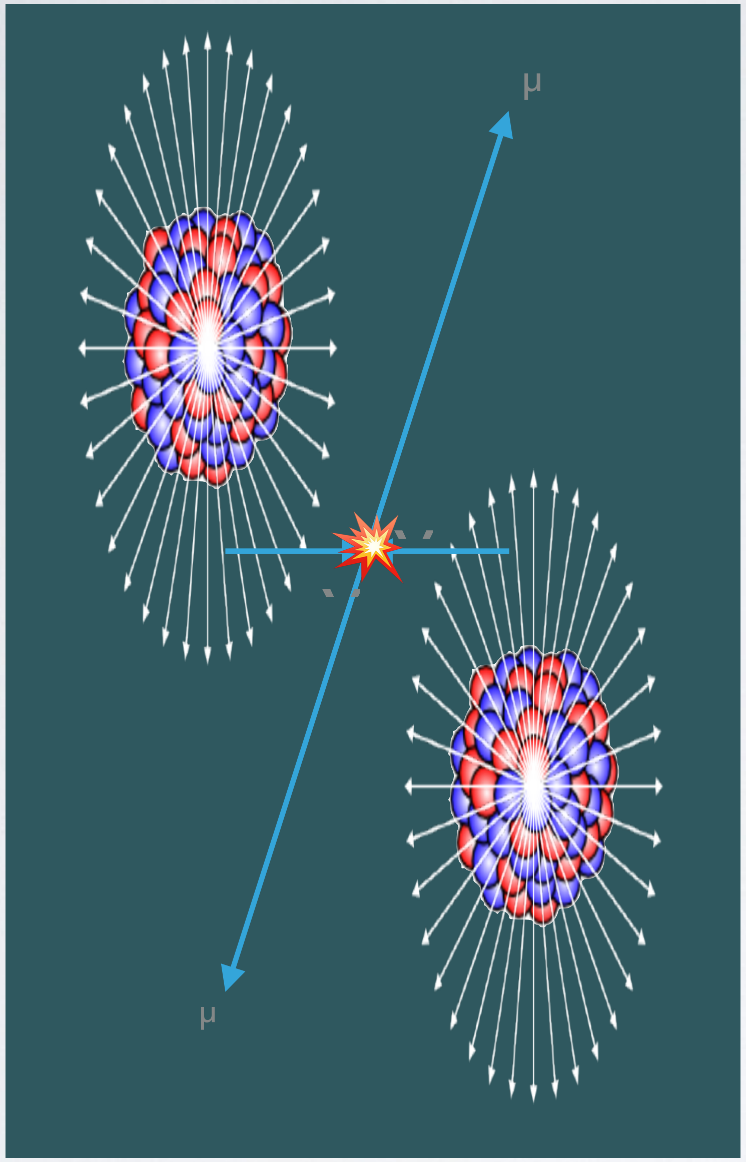


ATLAS-CONF-2017-011

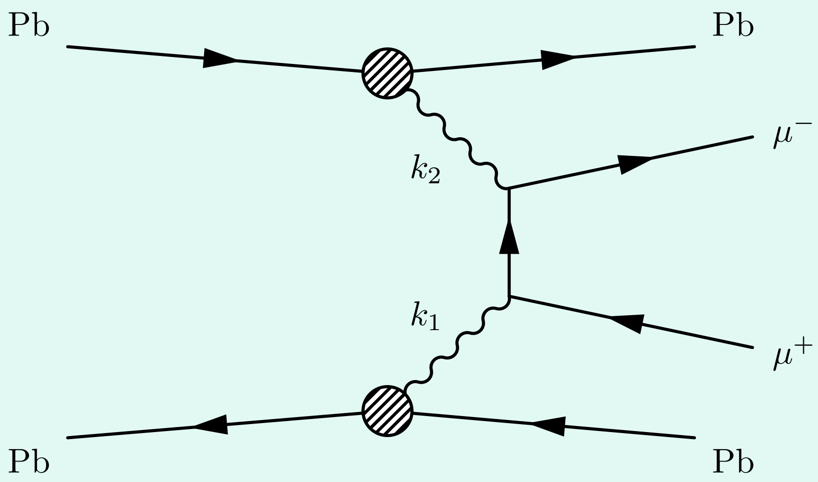
Differential (not unfolded) cross sections→
vs. DIS-like kinematic variables:
compared to PYTHIA photoproduction
w/ STARLIGHT EPA: **sensitive to nPDFs**

$$H_T \equiv \sum_i p_{T\,i}, \quad x_A \equiv \frac{m_{jets}}{\sqrt{s}} e^{-y_{jets}}$$

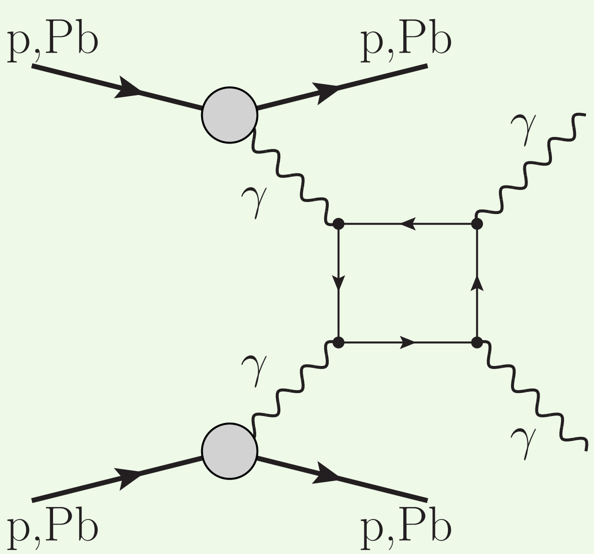
Gamma-gamma collisions



Pure EM process: interactions of photons from each nucleus

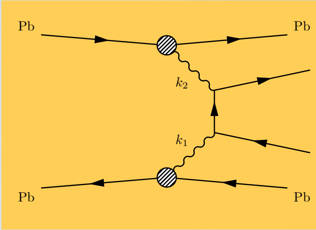


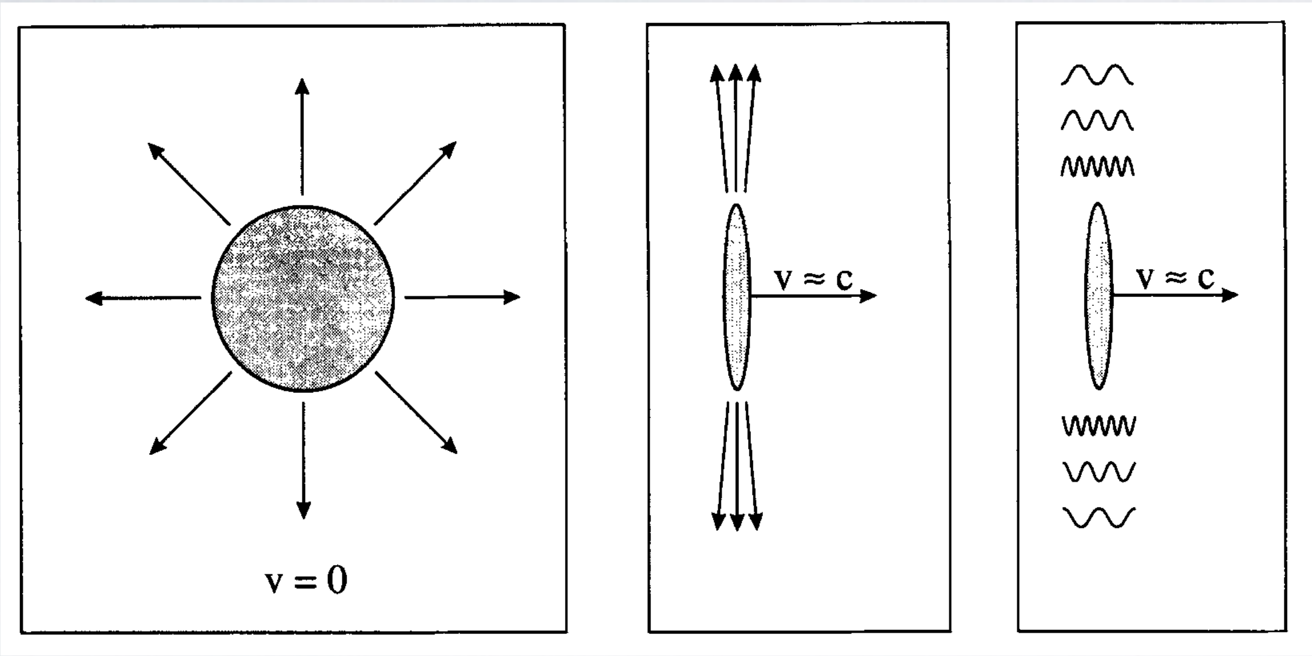
lepton pair production
(Breit-Wheeler formula, Brodsky et al 1971)



<u>photon</u> pair production
(via quark, lepton, W, BSM? loops)

Impact parameter dependence





Lorentz contraction of radial field lines induces impact parameter dependence of photon energy

$$n(k,b) = \frac{d^3n}{dk\,d^2b} = \frac{Z^2\alpha}{\pi^2 k b^2} x^2 K_1^2(x)$$

where $x = bk/\gamma$

This gives "two photon luminosity" an implicit b-dependence, formalism from PRC80 044902 (2009), used in STARLIGHT

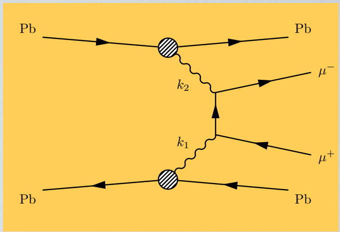
$$\frac{\mathcal{L}_{\gamma\gamma}}{dW\,dy} = \mathcal{L}_{AA}\frac{W}{2}\int_{b_1>R_A} d^2b_1 \int_{b_2>R_A} d^2b_2\, n(k_1,b_1)\,n(k_2,b_2)\,P(b)[1 - P_H(b)],$$

forward neutron topology ($P(b)$)

(no) hadronic interaction ($P_H(b)$)

impact parameter <u>correlates</u> incoming photon energies with breakup probabilities

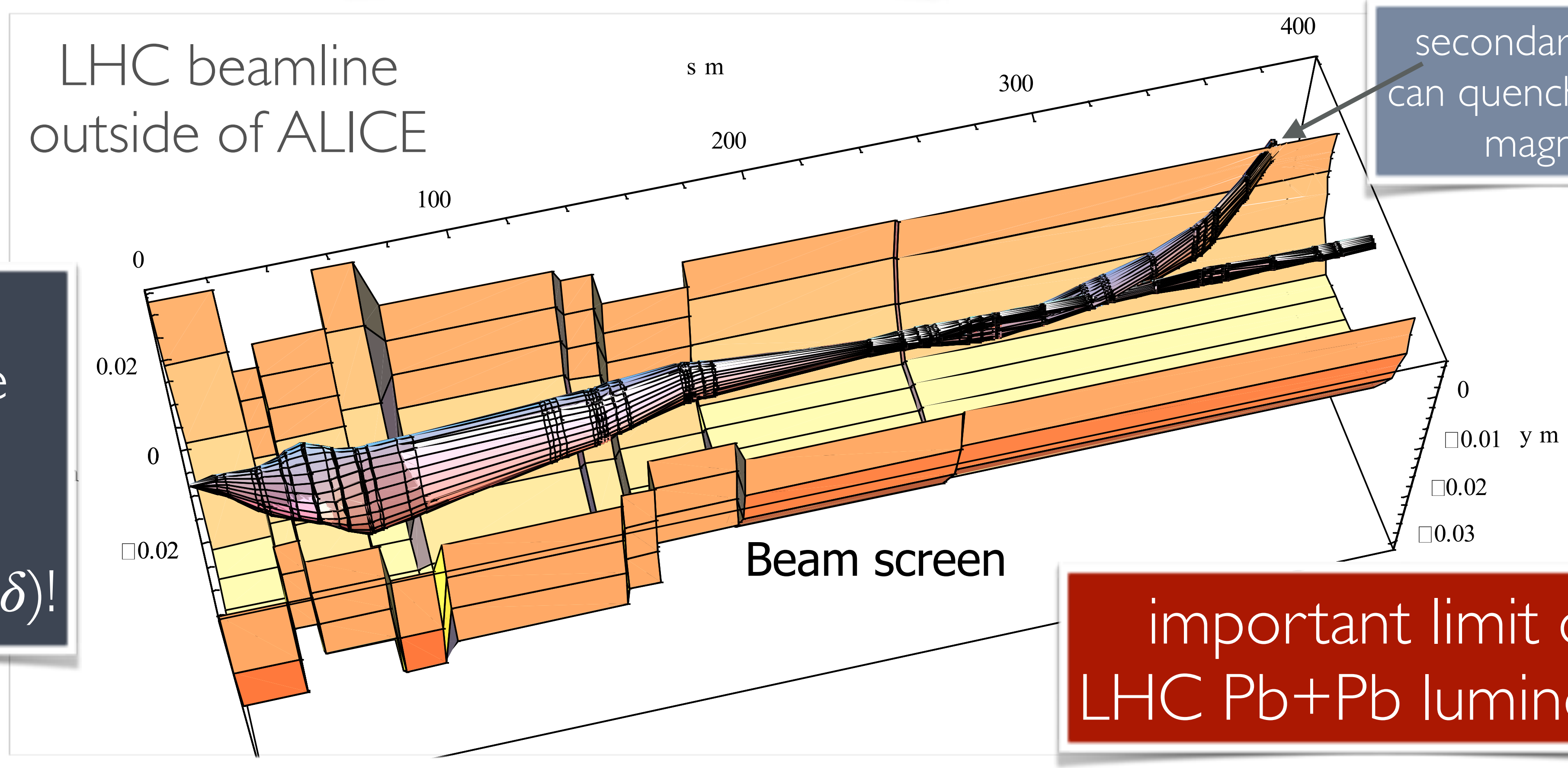
Exclusive dileptons: electrons



$$\text{BFPP: } {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$
$$\sigma = 281\ \text{b}, \quad \delta = 0.01235$$

$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

J. Jowett, CERN

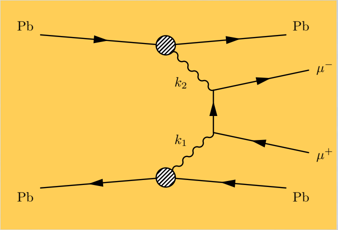


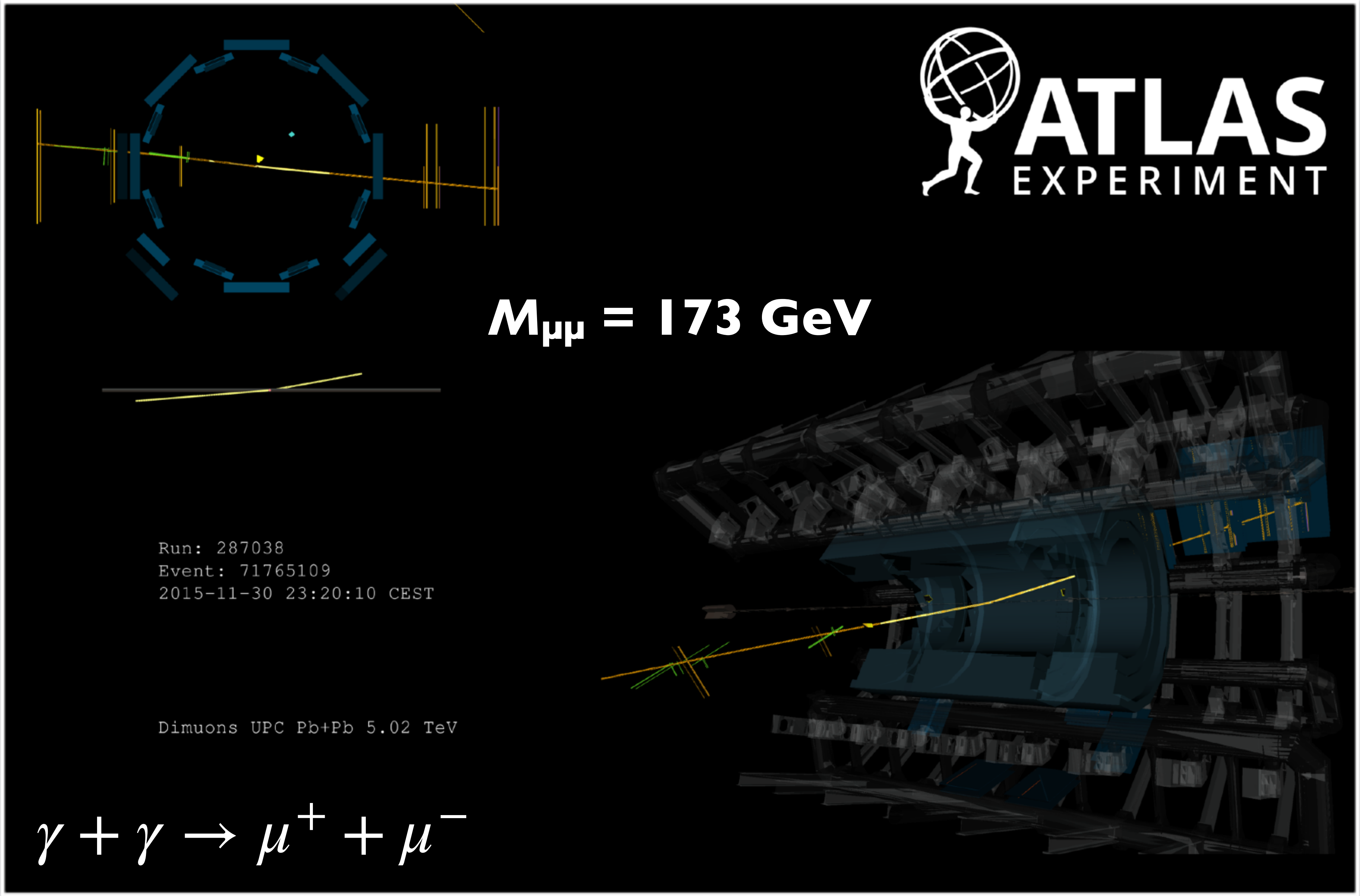
secondary beam can quench bending magnets!

Electron changes charge state of one or both ions: secondary beams w/ fixed rigidity shift(δ)!

important limit on LHC Pb+Pb luminosity!

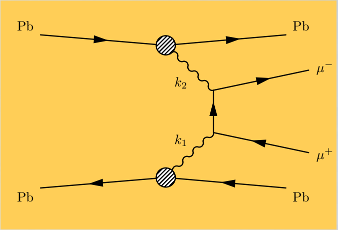
Exclusive dileptons: muons

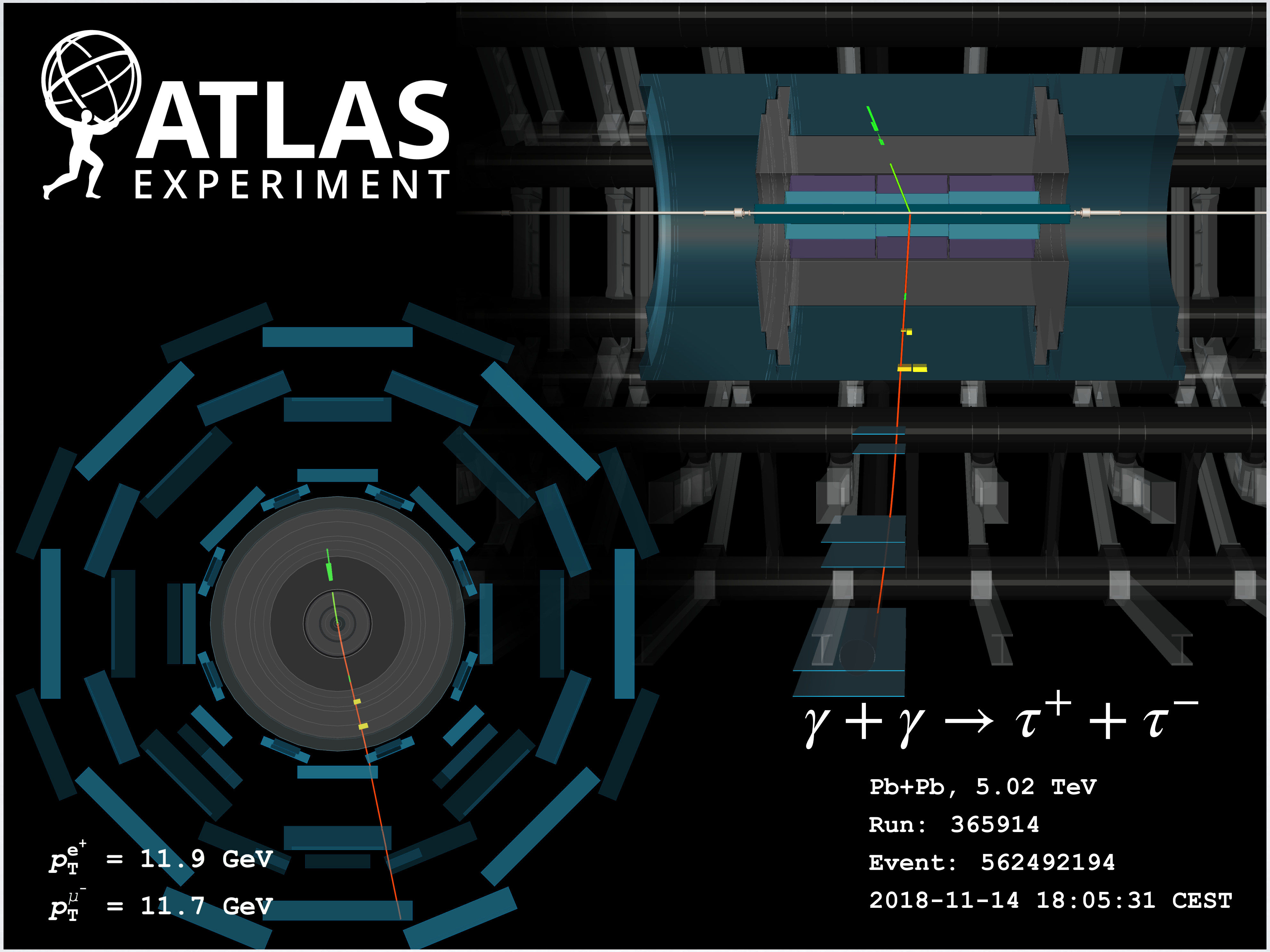




Back-to-back dimuons & no other activity in central detector:
fiducial acceptance $p_{T\mu}$>4 GeV, $|\eta_{\mu\mu}|$<2.4, $M_{\mu\mu}$ >10 GeV → σ ~ O(30 μb)

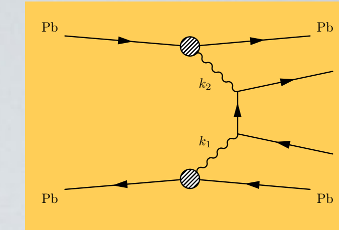
Exclusive dileptons: taus



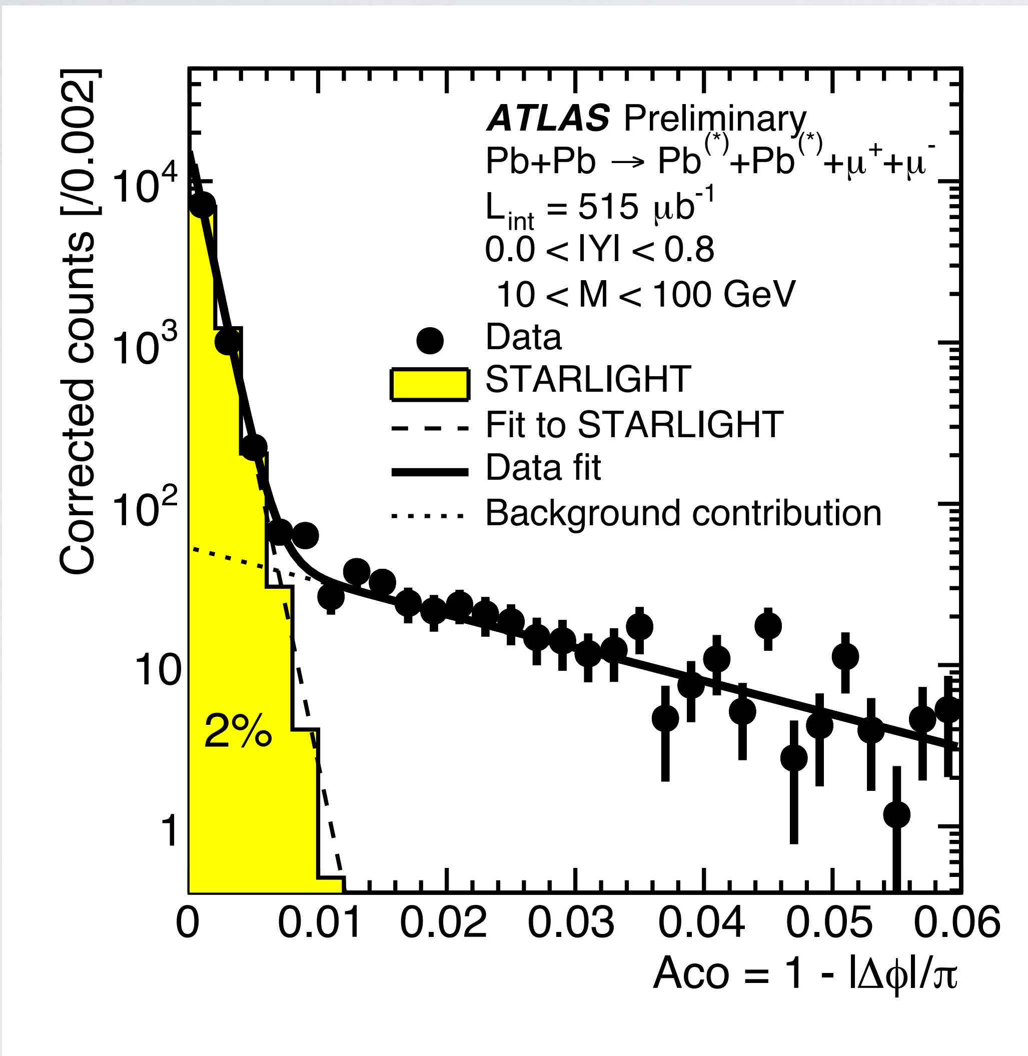


back-to-back electron & muon from tau decays

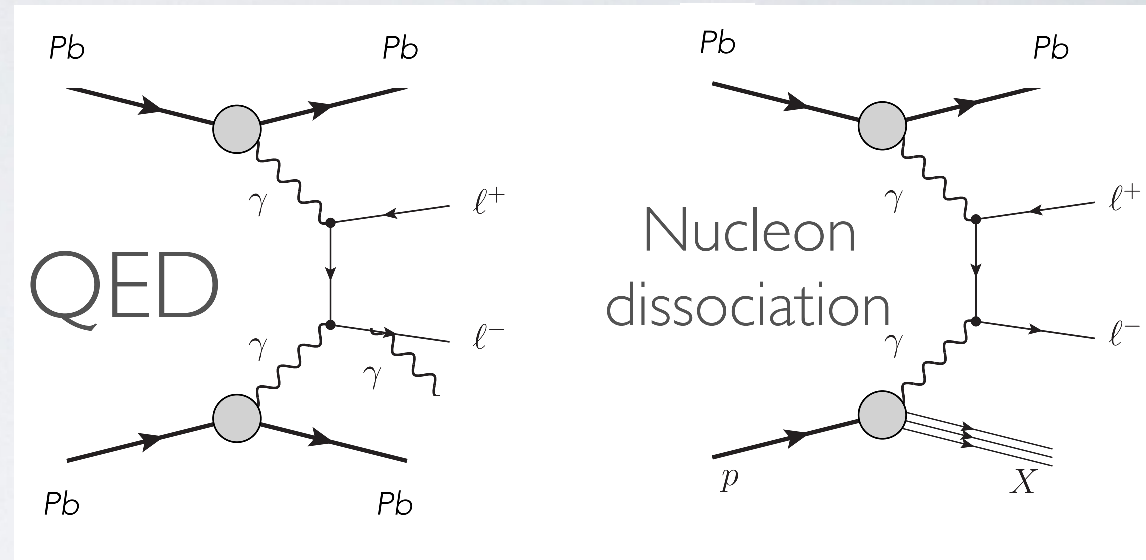
Dimuon acoplanarity

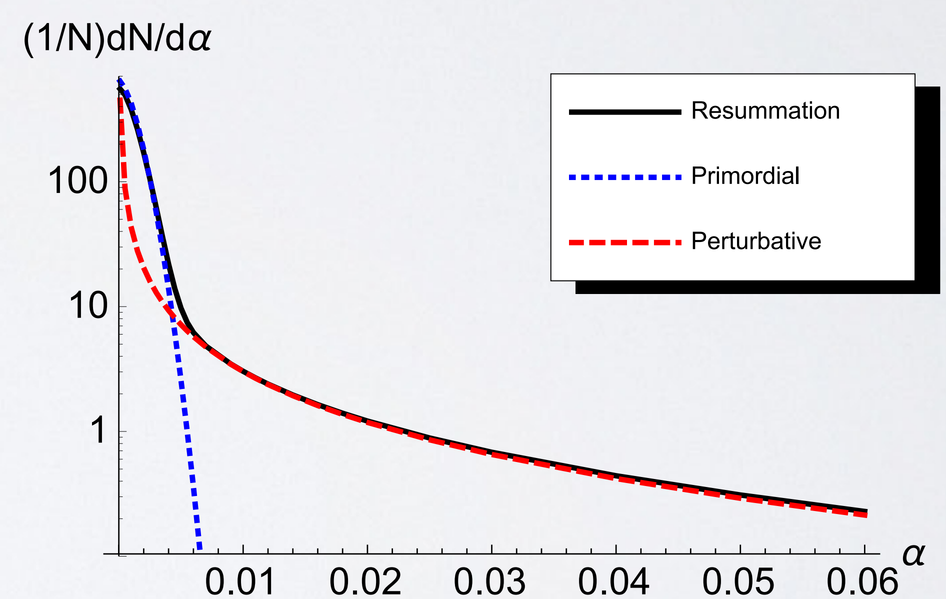


ATLAS-CONF-2016-025



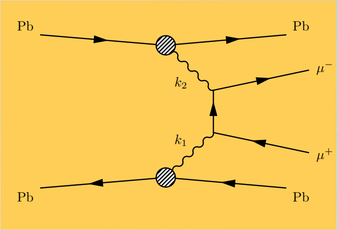
STARLIGHT has only implemented pure back-to-back dileptons (primordial μ p_T buried by Δp_T): comparison to ATLAS data (0.5 nb^{-1}) shows a "missing" tail



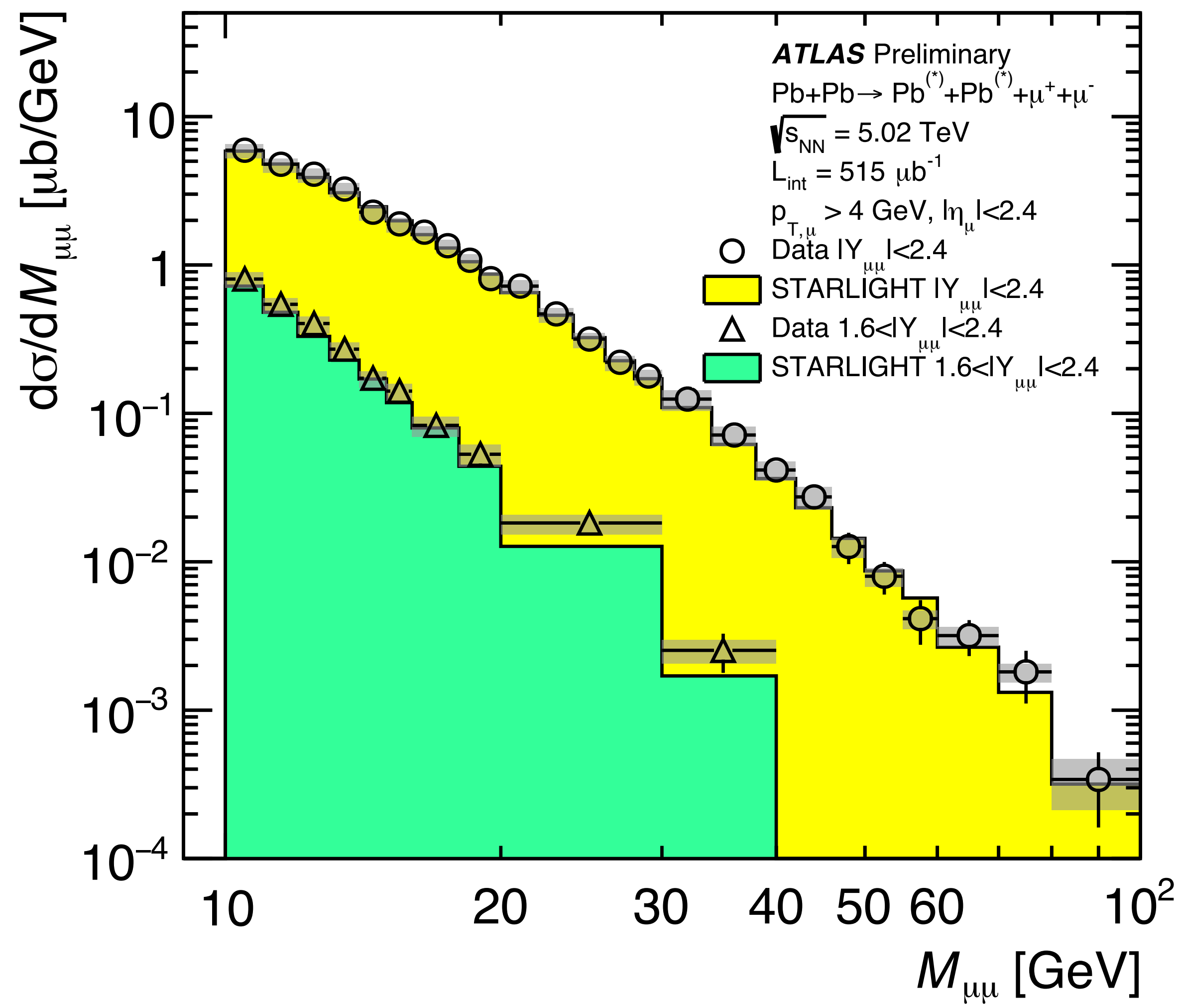


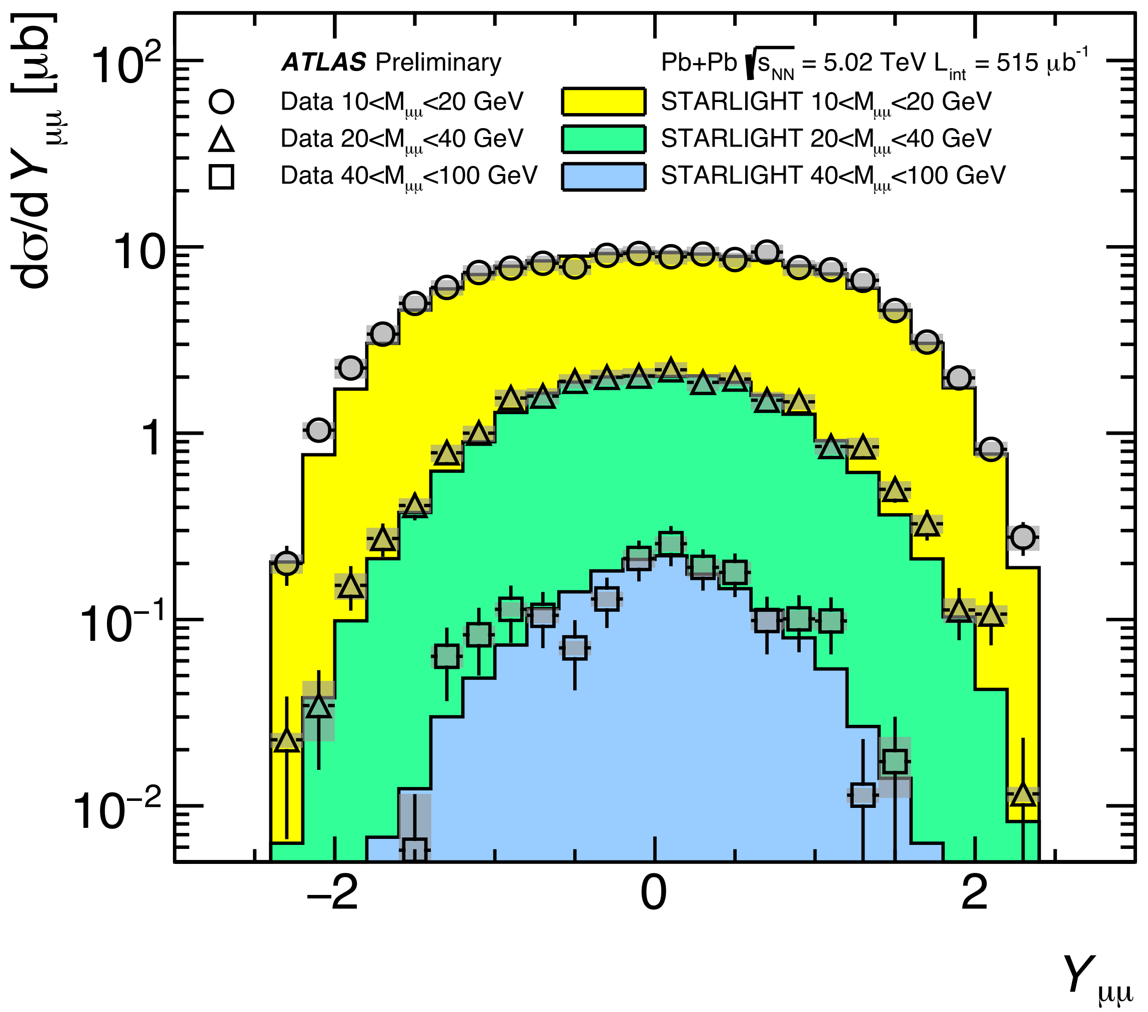
Inclusion of soft photons via Sudakhov formula provides long tail (1811.05519, Klein et al)

Dilepton yields vs. STARLIGHT



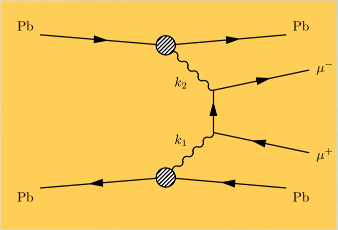
ATLAS-CONF-2016-025



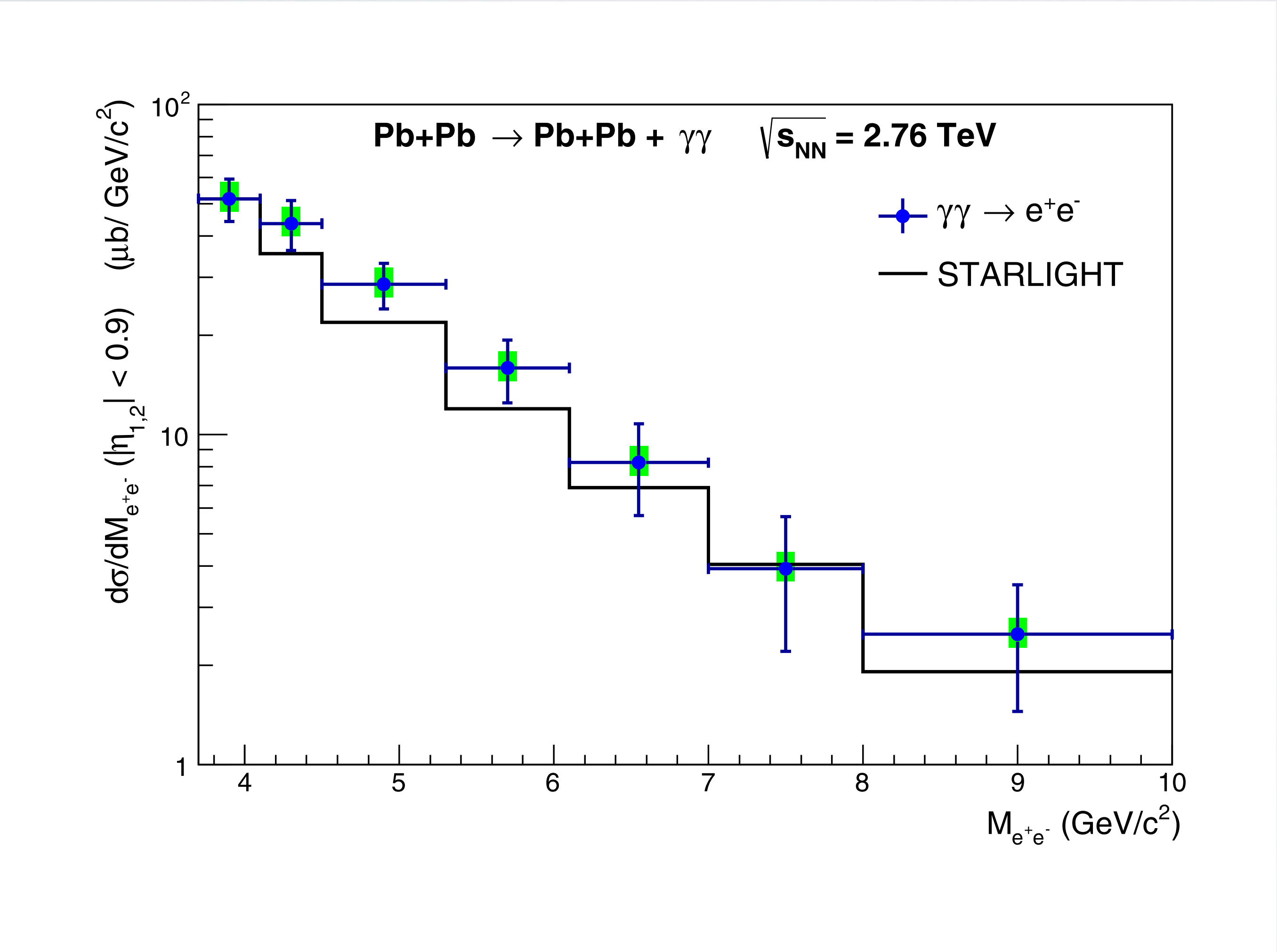


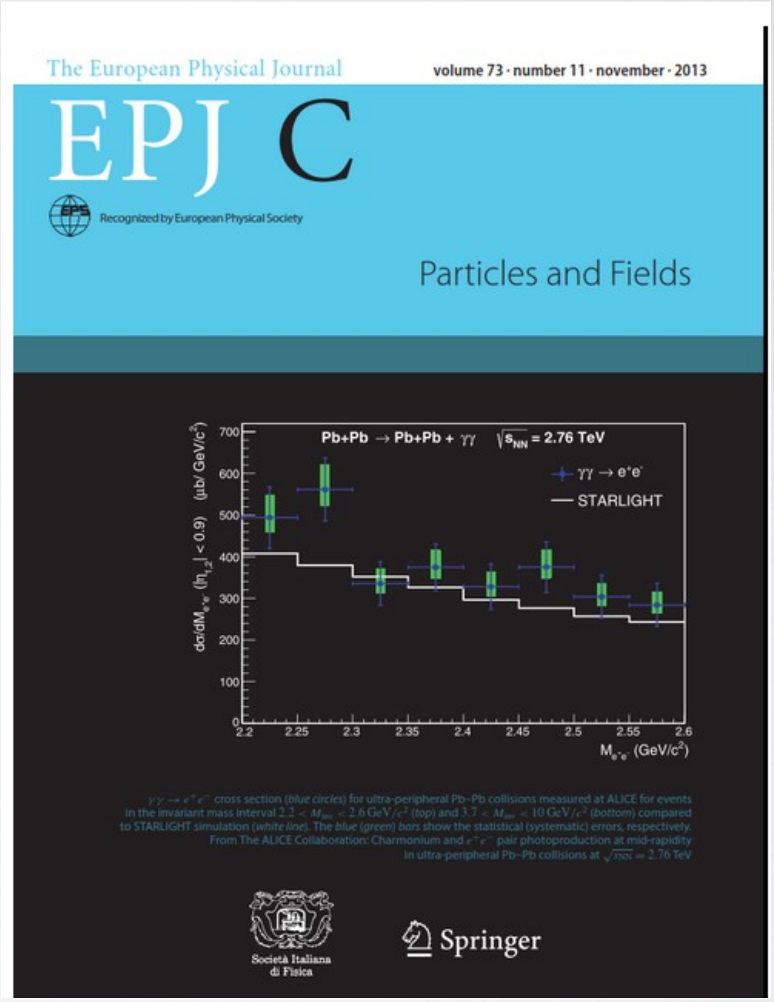
Even without full determination of contributions from QED & dissociation, STARLIGHT provides reasonable description of ATLAS & ALICE data

Dilepton yields vs. STARLIGHT



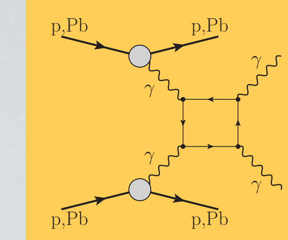
Eur. Phys. J. C (2013) 73:2617



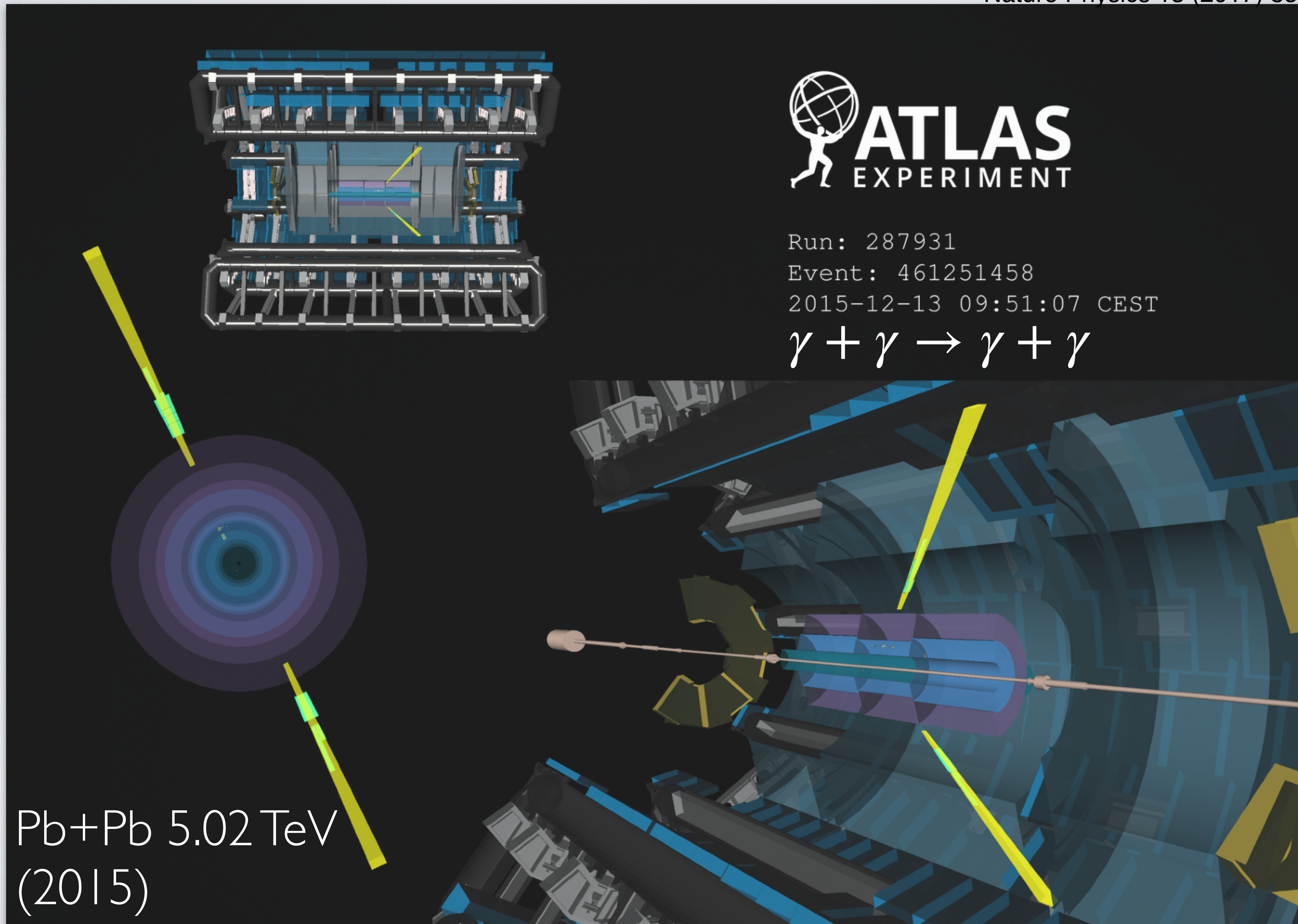


Even without full determination of contributions from QED & dissociation, STARLIGHT provides reasonable description of ATLAS & ALICE data: although data is systematically higher

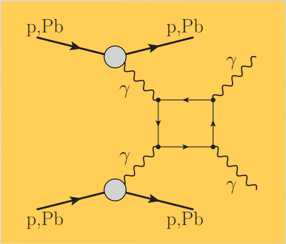
Light-by-light scattering (LbyL)



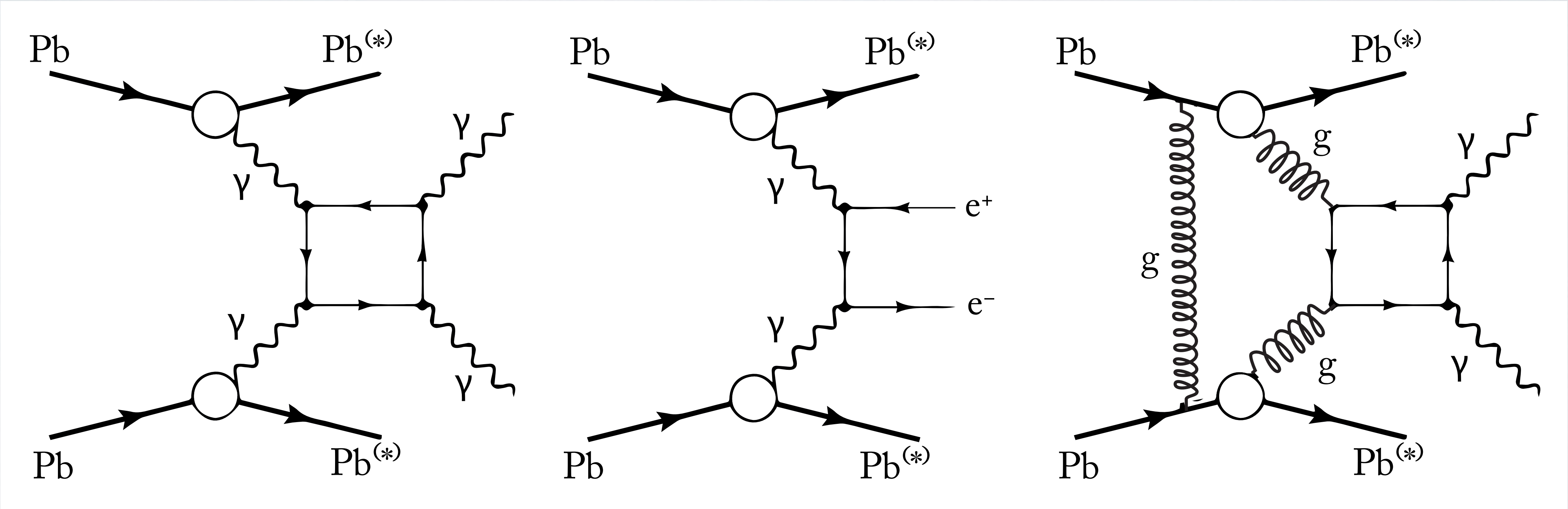
Nature Physics 13 (2017) 852



LbyL: Signal & backgrounds



CMS: 1810.04602



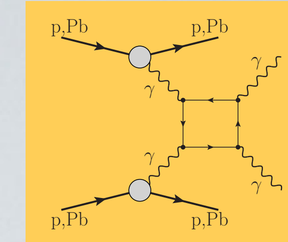
"LbyL":
including loops for leptons, quarks and W bosons

"QED":
dielectrons reconstructed as photons

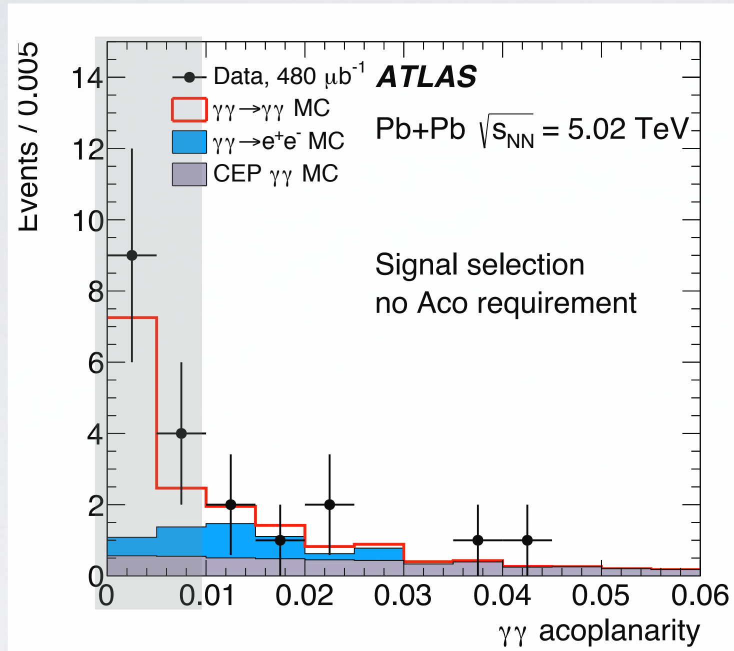
"CEP":
gluon exchange with photons produced through quark loops

SIGNAL | BACKGROUND

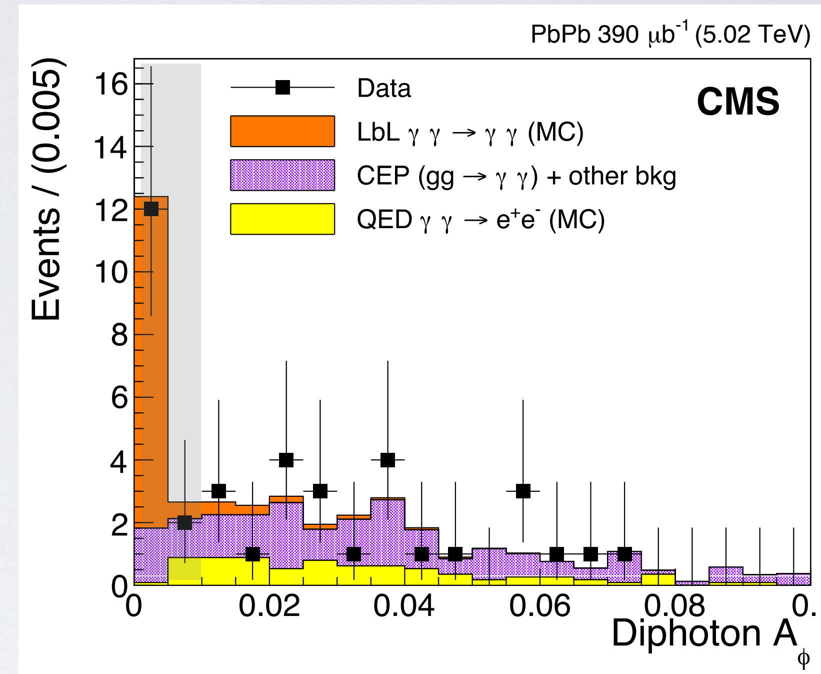
ATLAS & CMS data (2015)



2015 data set provided evidence (< 5σ significance) of light-by-light scattering



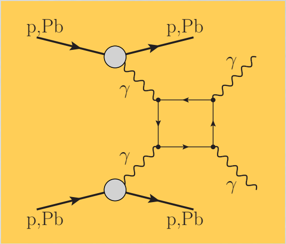
Nature Physics 13 (2017) 852



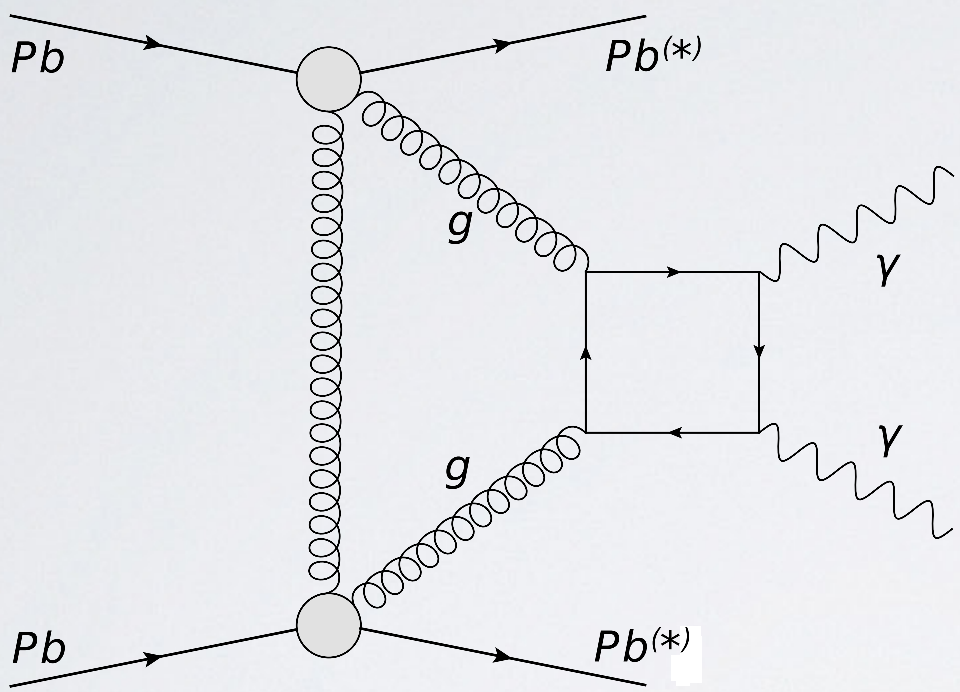
arXiv: 1810.04602

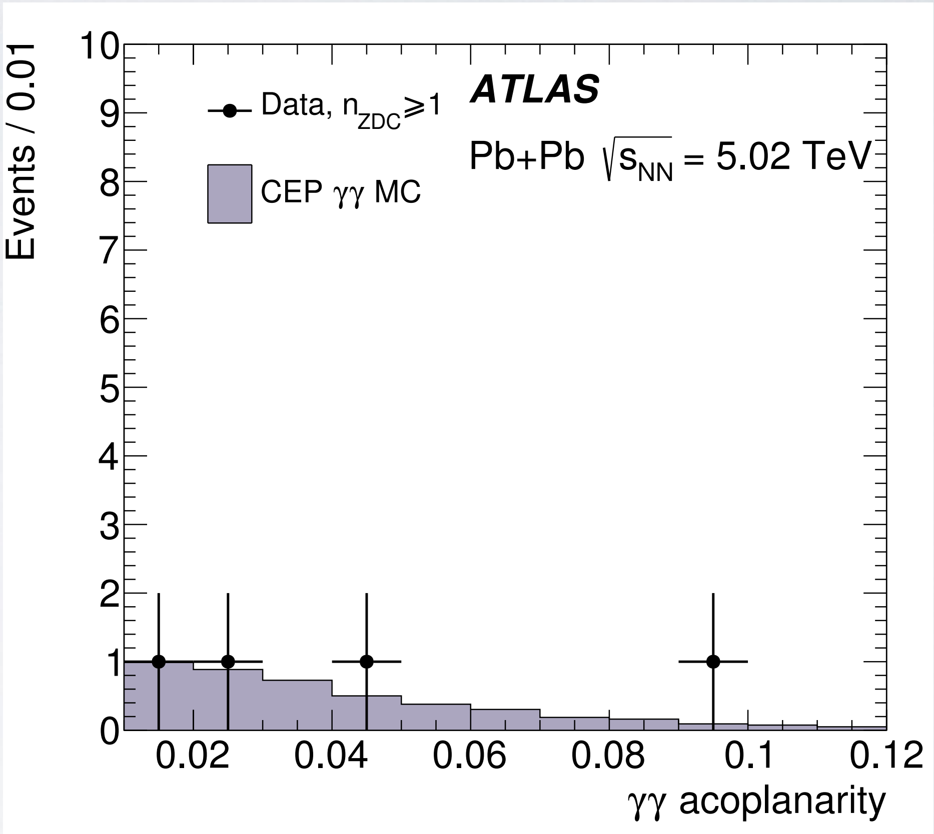
	ATLAS	CMS
Luminosity	0.48 nb^{-1}	0.39 nb^{-1}
Fiducial acceptance	$E_{T\gamma}$ > 3 GeV, $\|\eta\|$<2.37 $M_{\gamma\gamma}$ > 6 GeV, $p_{T\gamma\gamma}$ < 2 GeV, Aco < 0.01	$E_{T\gamma}$ > 2 GeV, $\|\eta\|$<2.4 $M_{\gamma\gamma}$ > 5 GeV, $p_{T\gamma\gamma}$ < 1 GeV, Aco < 0.01
Candidates / expected background	13 / 2.6±0.7	14 / 4.0±1.2
Signficance	4.4σ	4.1σ

ZDC & light-by-light



Supplemental material at
http://dx.doi.org/10.1038/nphys4208

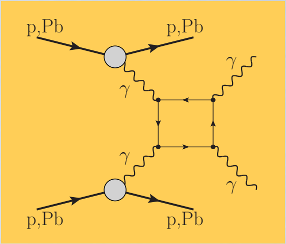




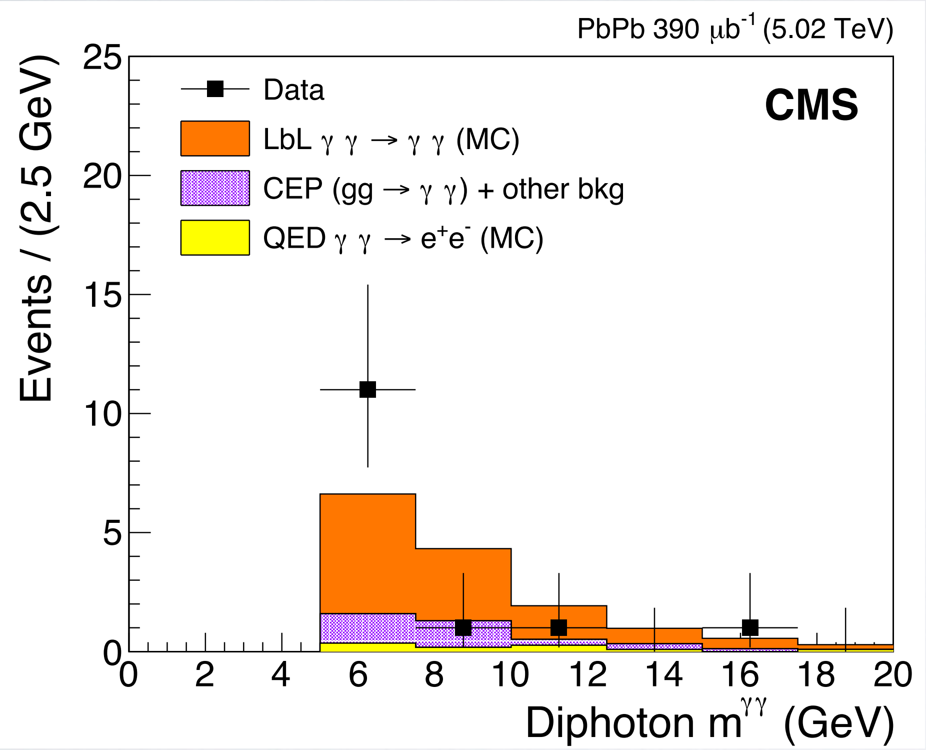
Light-by-light is pure γγ → no neutron production (modulo soft exchange)
background processes involving gluon exchange → neutrons in ZDC

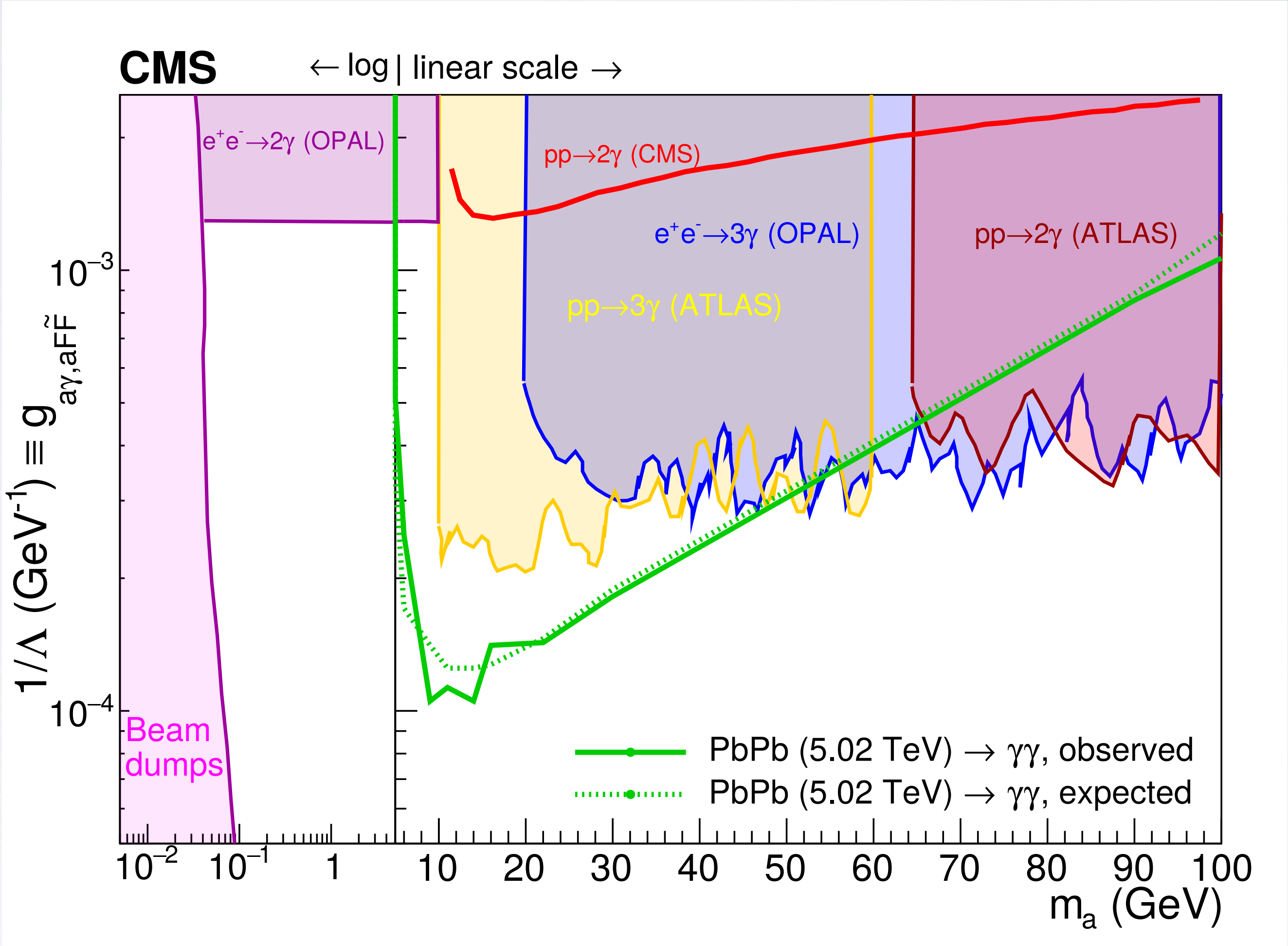
Events with ZDC activity show broad acoplanarity distribution
validates use of expectations from CEP MC (e.g. SuperChic)

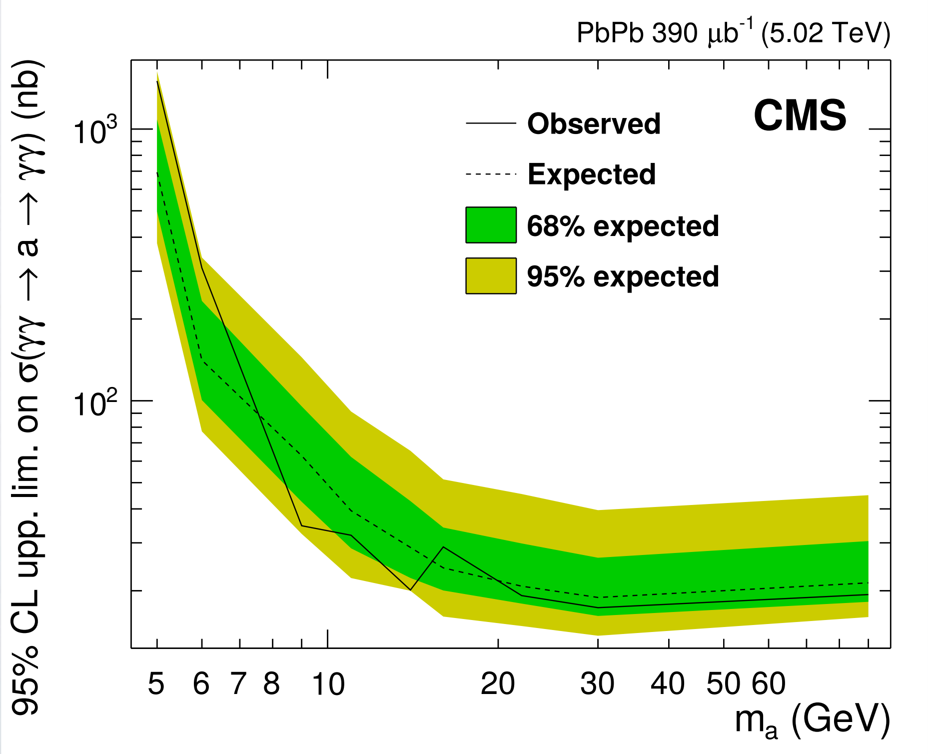
Searches for axion-like particles



arXiv: 1810.04602



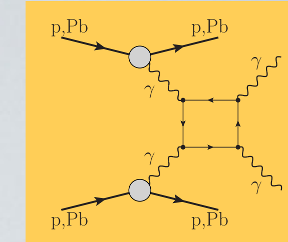


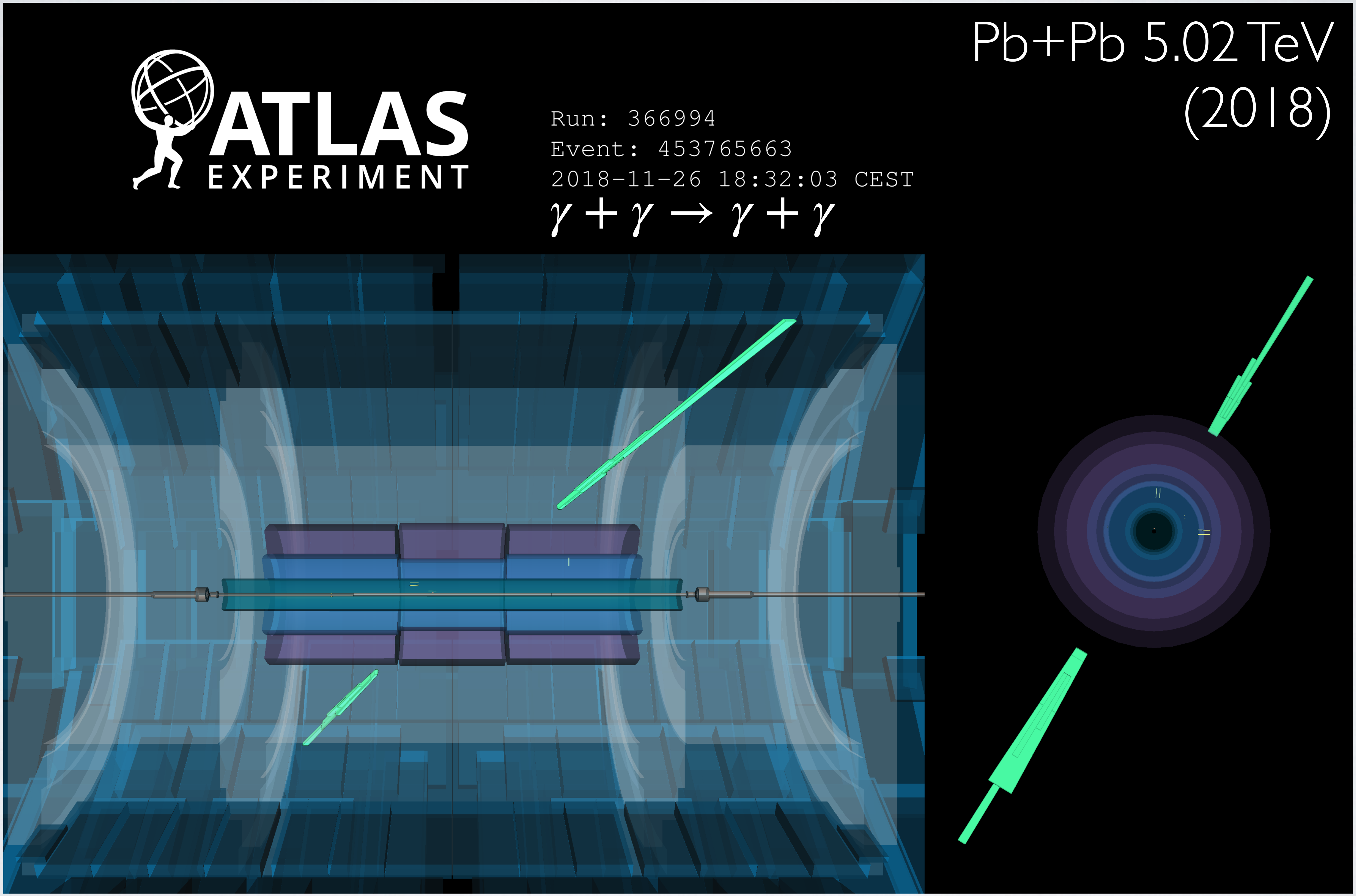


$$\gamma + \gamma \rightarrow a \rightarrow \gamma + \gamma$$

Limits on coupling of ALPs to photons: using LbyL in future searches is an active goal for LHC Runs 3 & 4 (10x luminosity over Run 2)

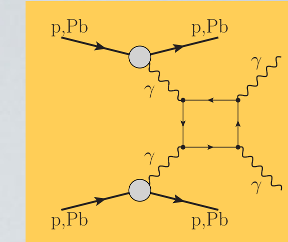
New 2018 data!

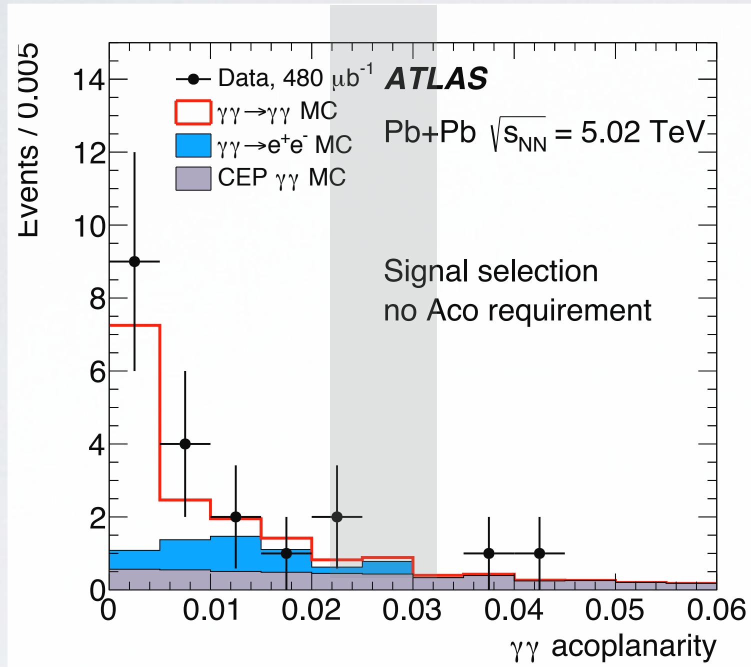




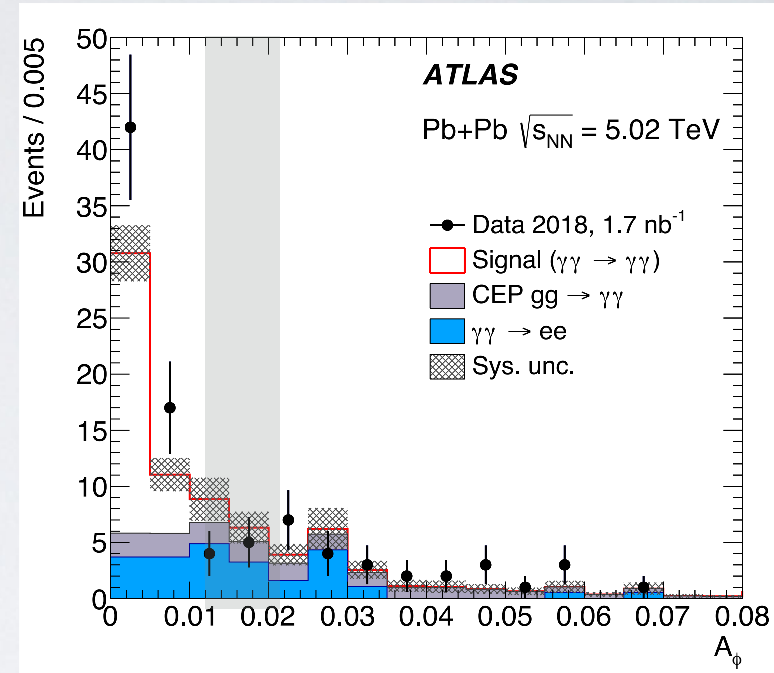
>3x 2015 dataset, improved analysis techniques

ATLAS: 2015 vs. 2018





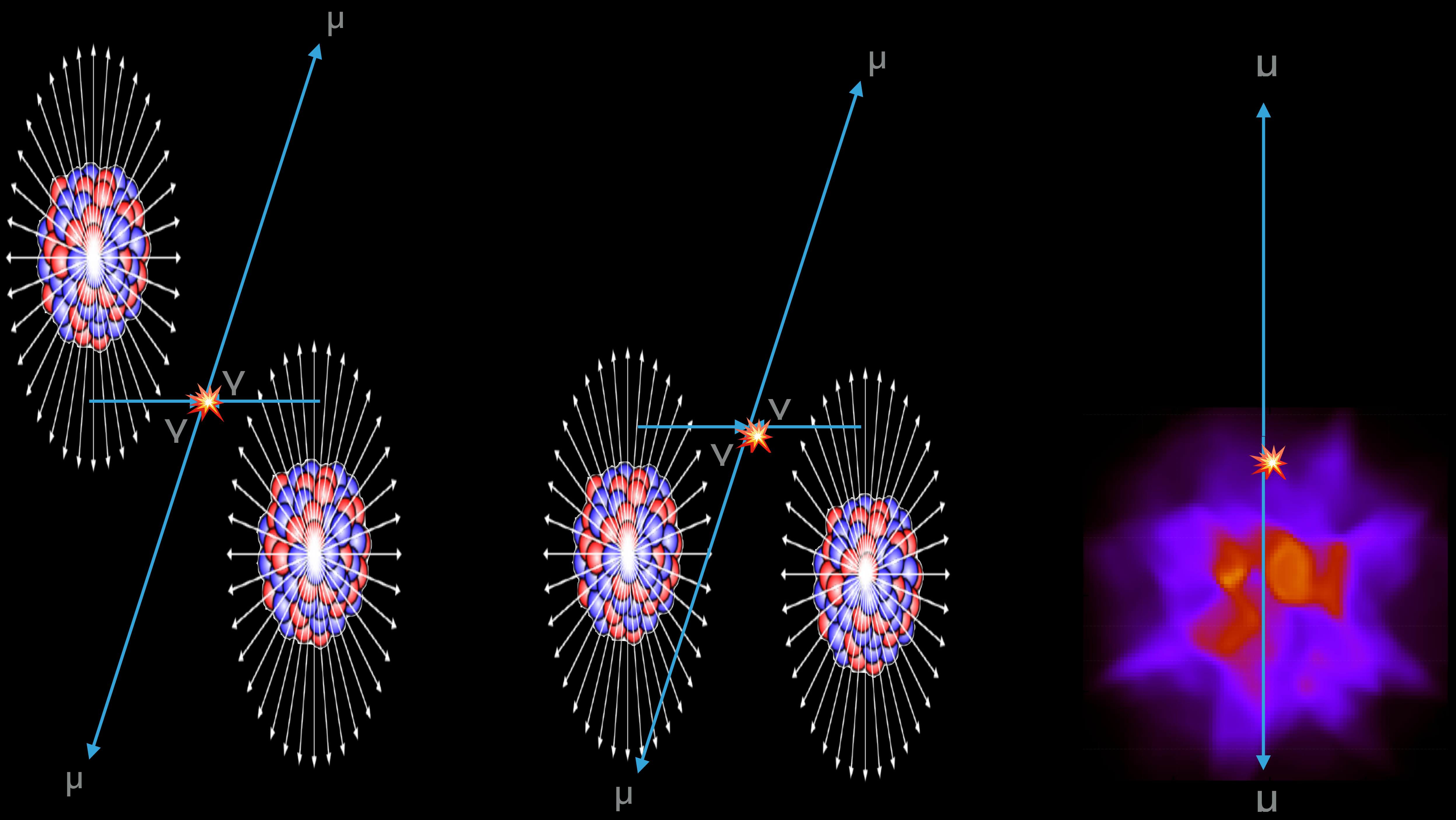
Nature Physics 13 (2017) 852



arXiv:1904.03536

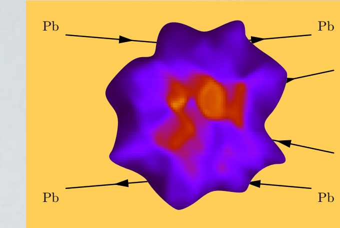
	ATLAS 2015	ATLAS 2018
Luminosity	0.48 nb^{-1}	1.7 nb^{-1}
Fiducial acceptance	$E_{T\gamma}$ > 3 GeV, $\lvert\eta\rvert$<2.37 $M_{\gamma\gamma}$ > 6 GeV, $p_{T\gamma\gamma}$ < 2 GeV, Aco < 0.01	$E_{T\gamma}$ > 3 GeV, $\lvert\eta\rvert$<2.37 $M_{\gamma\gamma}$ > 6 GeV, $p_{T\gamma\gamma}$ < 1-2 GeV, Aco < 0.01
Candidates / expected background	13 / 2.6±0.7	59 / 12±3
Signficance	4.4σ	**8.2σ** observation!

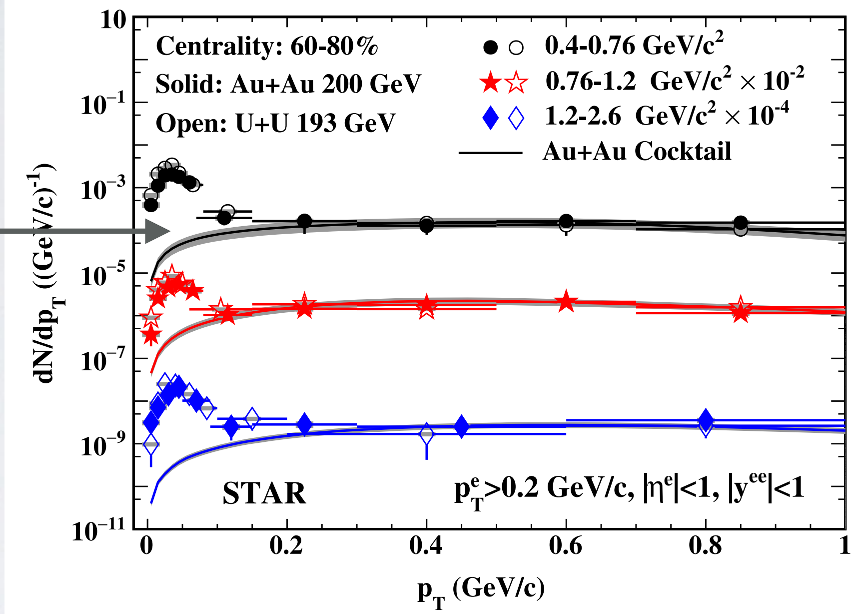
UPC dileptons in non-UPC events



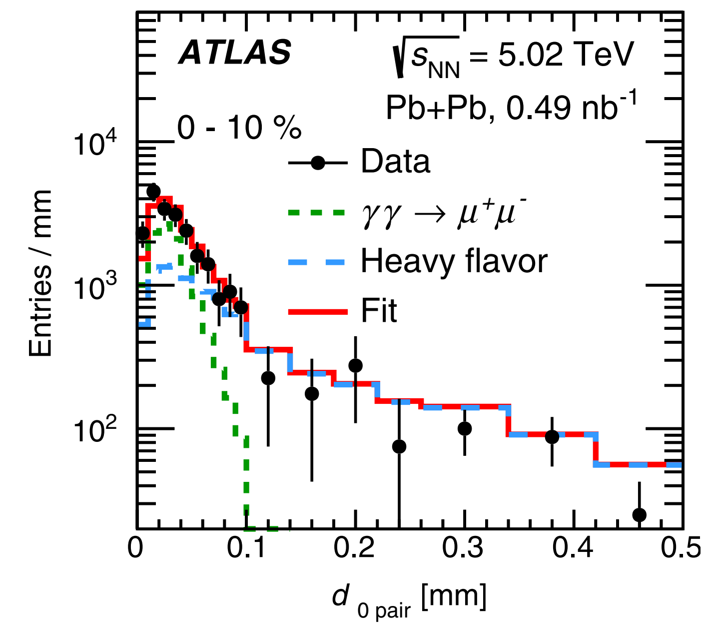
UPC nonUPC QGP?

ATLAS & STAR





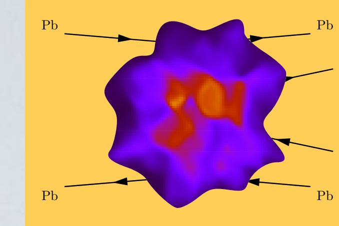
PRL 121 132301 (2018)



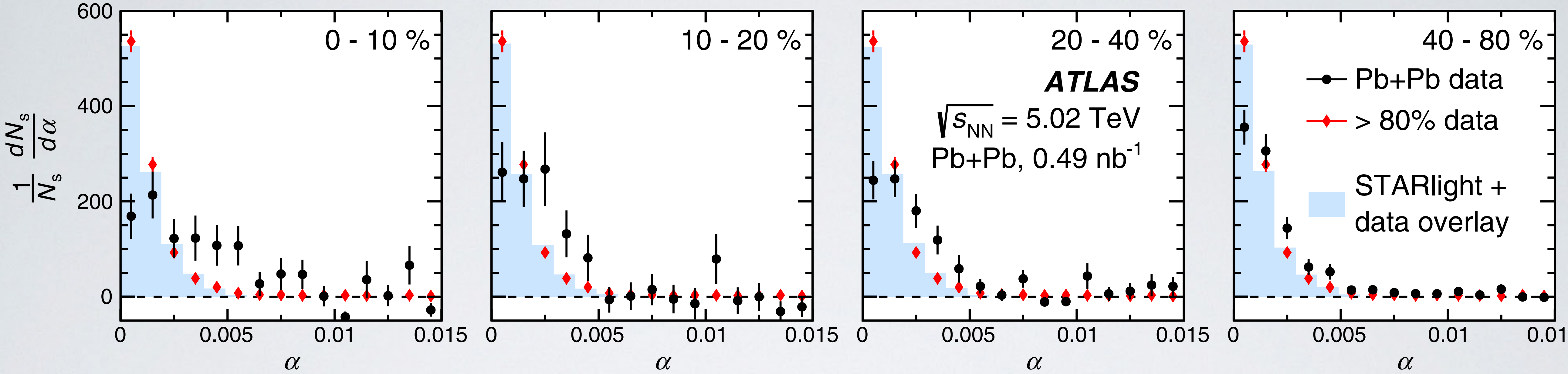
PRL 121 212301 (2018)

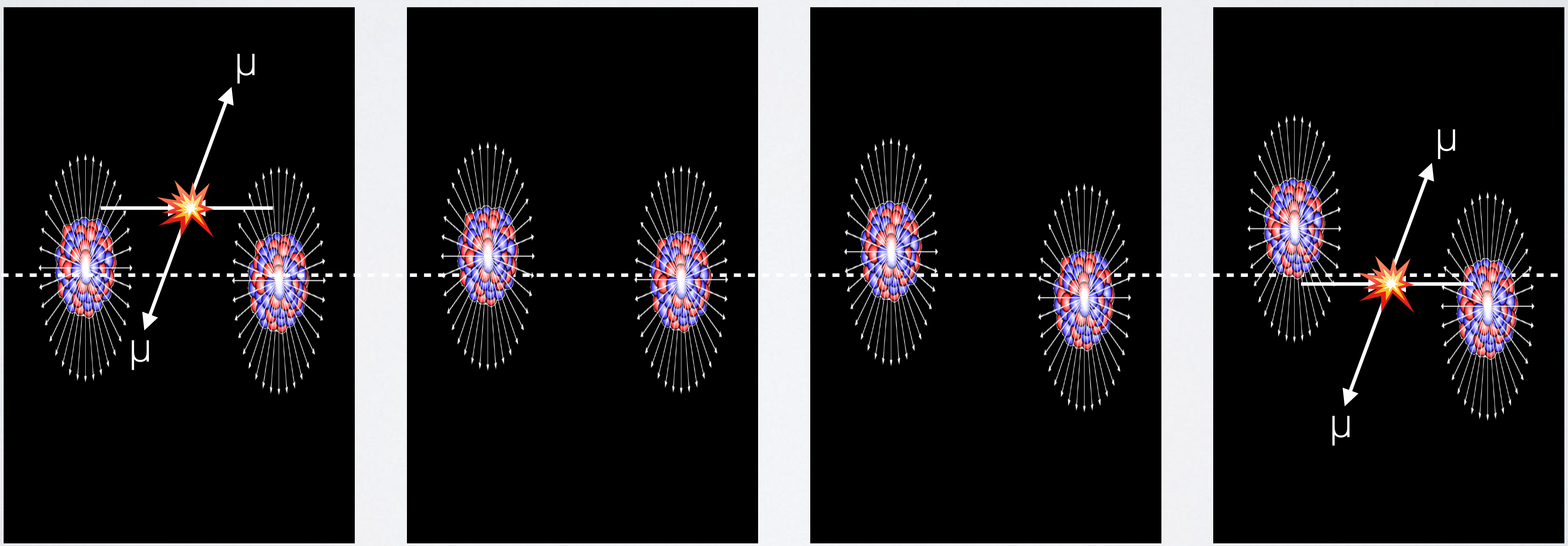
	STAR	ATLAS
Channel / System	e^+e^- pairs in Au+Au & U+U	$\mu^+\mu^-$ pairs in Pb+Pb
Dilepton mass	0.4-2.6 GeV	4-45 GeV
Primary backgrounds	Low mass resonances	Heavy flavor decays
Centrality range	60-80%	0-100%

ATLAS data



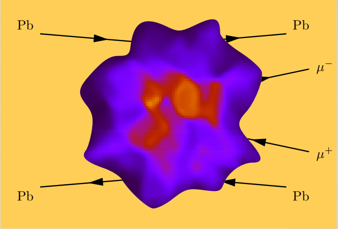
PHYSICAL REVIEW LETTERS **121,** 212301 (2018)



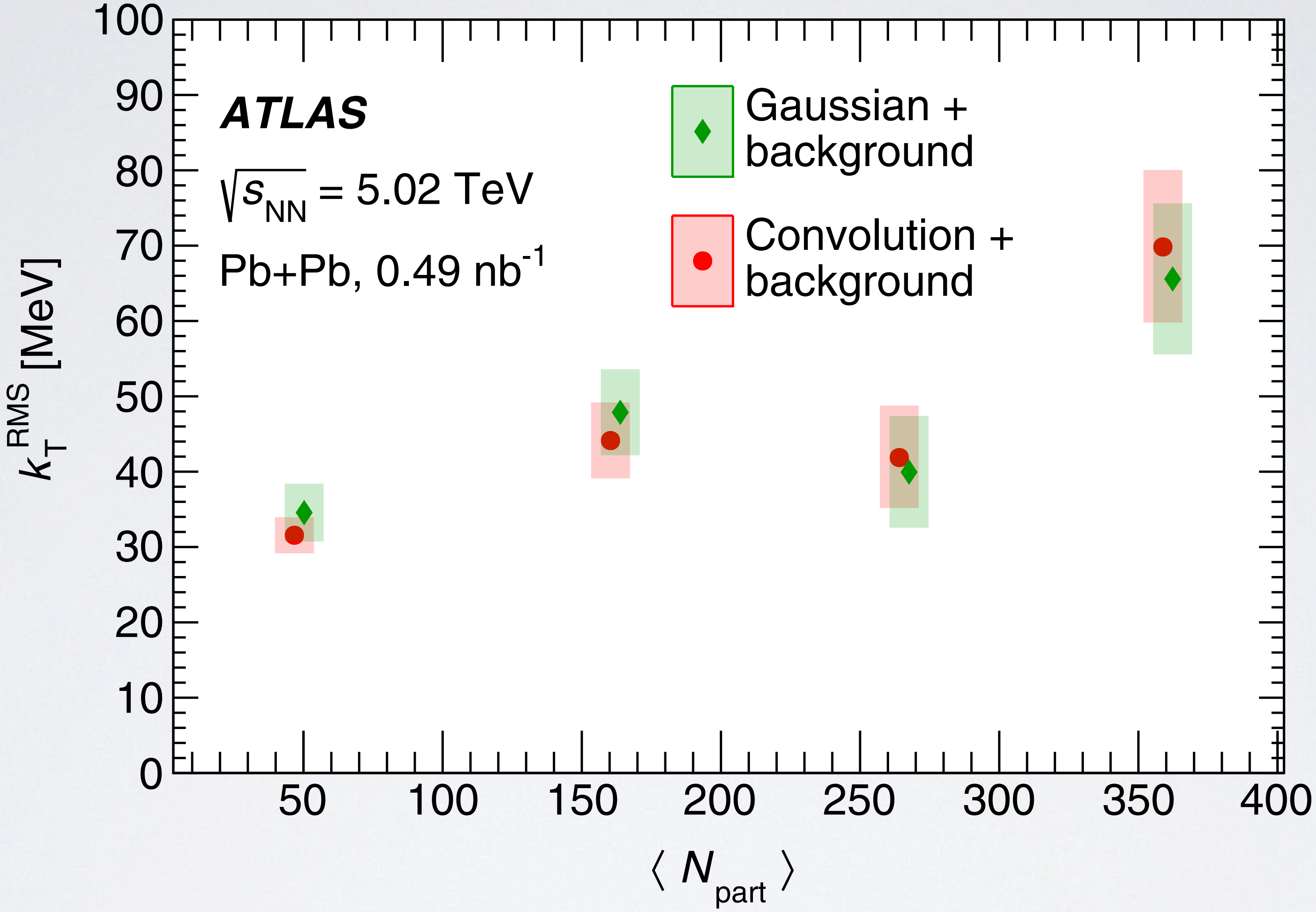


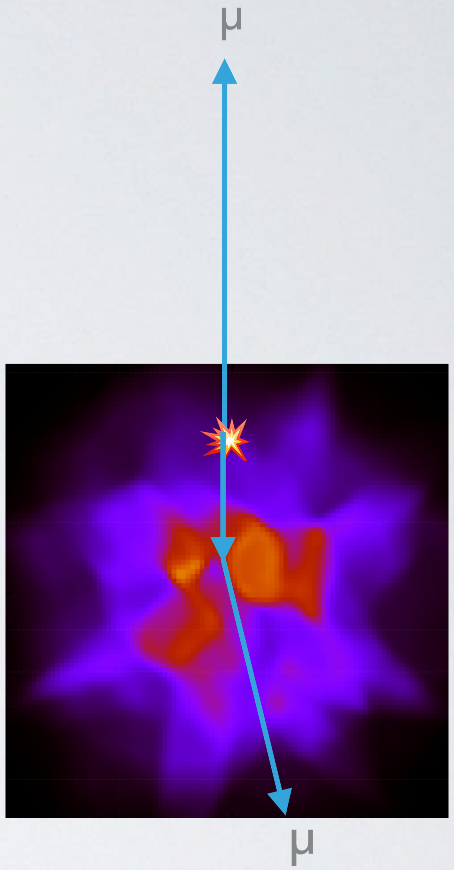
In peripheral collisions, similar to UPC/Starlight. In central, substantially broadened.

ATLAS data



PHYSICAL REVIEW LETTERS **121,** 212301 (2018)

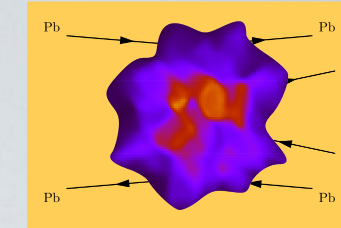




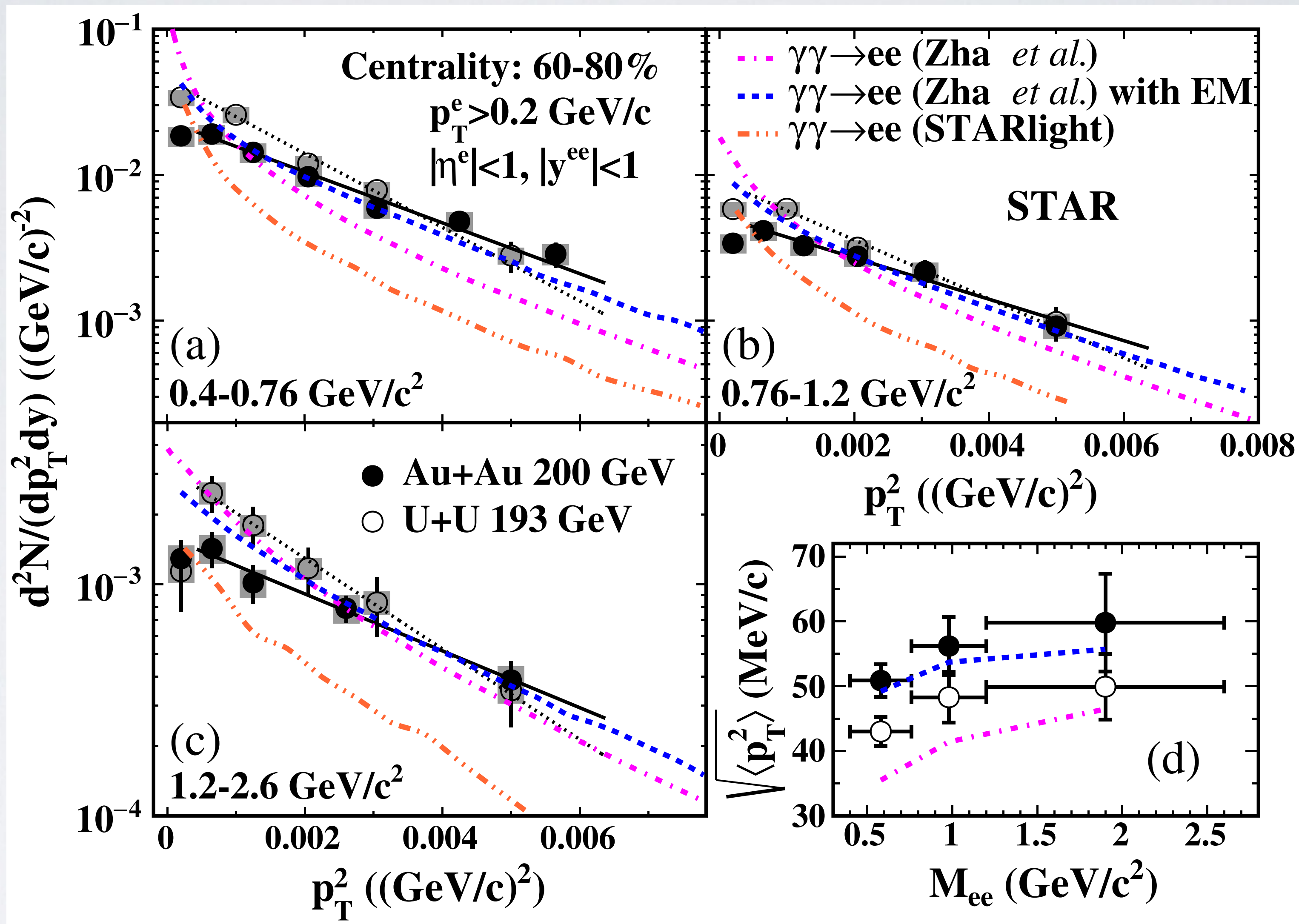
ATLAS extracts a per muon k_T broadening, relative to 80-100% centrality (UPC): 30-70 MeV

Is this rescattering of one or both muons in the QGP?

STAR data



PHYSICAL REVIEW LETTERS **121,** 132301 (2018)

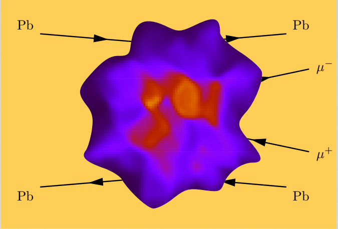


U+U/Au+Au ratio consistent w/ STARLIGHT

STAR yields and RMS(p_T) exceed STARLIGHT (red) and calculations including photon flux inside nucleus: **20-30 MeV p_T broadening**

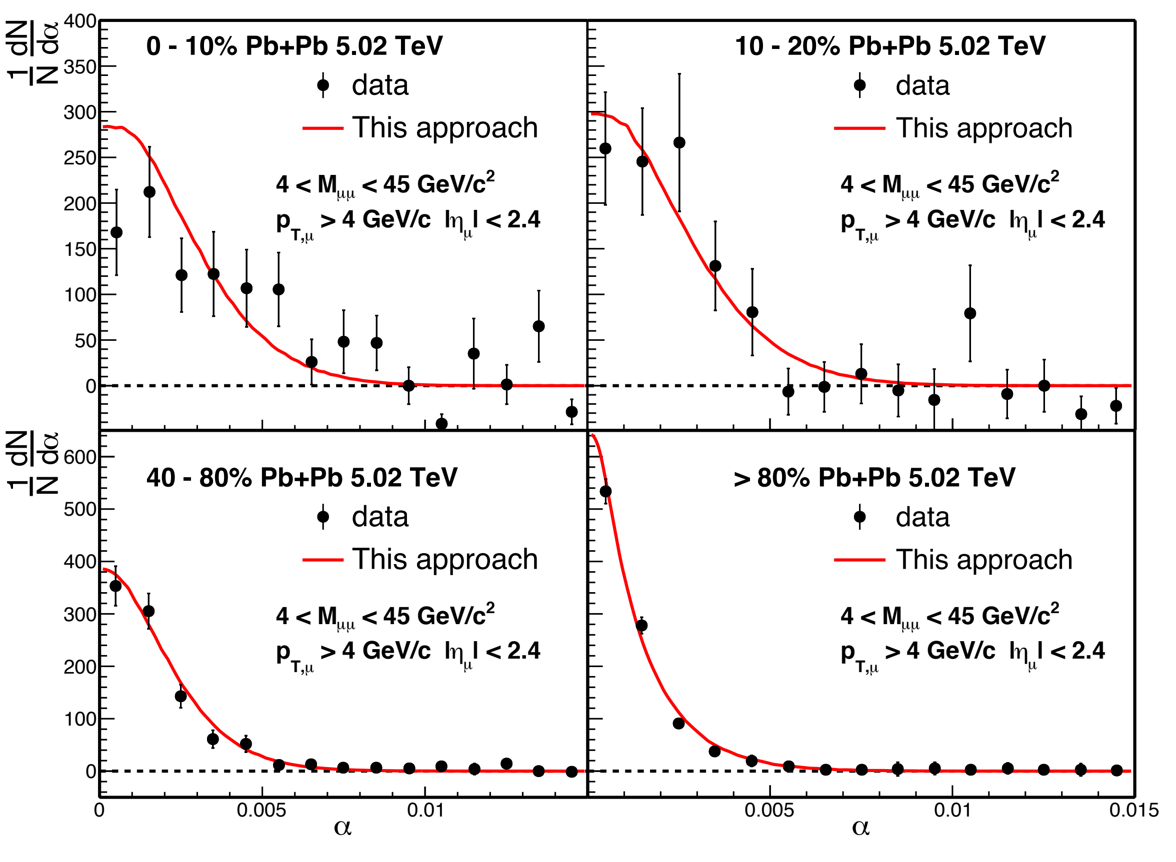
Better agreement assuming each electron passes through 1fm of magnetic field with B=10^{14} T perpendicular to beamline (blue)

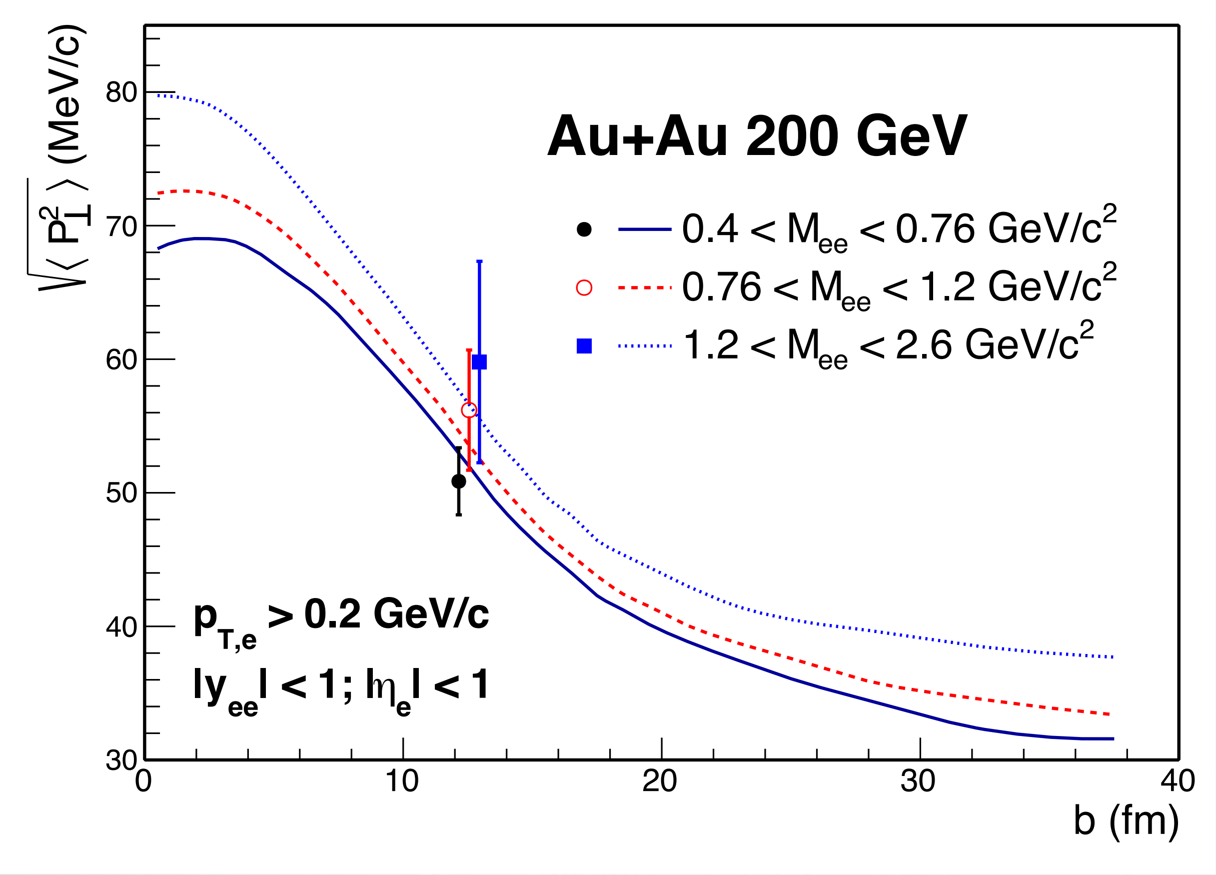
Impact parameter dependence of pair p_T



1812.02820 Zha et al - follow up to STAR paper

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int d^2b \int \frac{dw_1}{w_1}\frac{dw_2}{w_2}\frac{d^2k_{1\perp}}{(2\pi)^2}\frac{d^2k_{2\perp}}{(2\pi)^2}\frac{d^2q_\perp}{(2\pi)^2}$$
$$\times \frac{F(-k_1^2)}{k_1^2}\frac{F(-k_2^2)}{k_2^2}\frac{F^*(-k_1'^2)}{k_1'^2}\frac{F^*(-k_2'^2)}{k_2'^2} e^{-i\vec{b}\cdot\vec{q}_\perp}$$
$$\times \left[(\vec{k}_{1\perp}\cdot\vec{k}_{2\perp})(\vec{k}'_{1\perp}\cdot\vec{k}'_{2\perp})\sigma_s(w_1,w_2)\right.$$
$$\left.+ (\vec{k}_{1\perp}\times\vec{k}_{2\perp})(\vec{k}'_{1\perp}\times\vec{k}'_{2\perp})\sigma_{ps}(w_1,w_2)\right]$$





External classical field approach of Vidovic et al (1993):

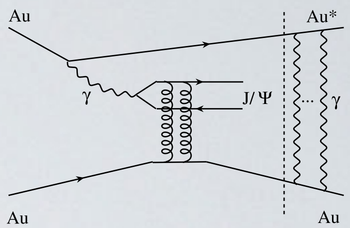
impact parameter and pair p_T are coupled in the full calculation

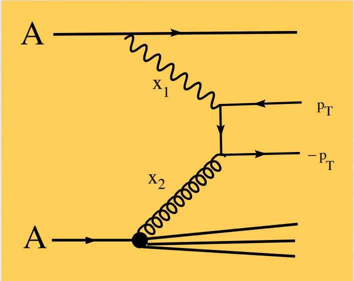
Induces broadening of same scale as seen in STAR & ATLAS data:

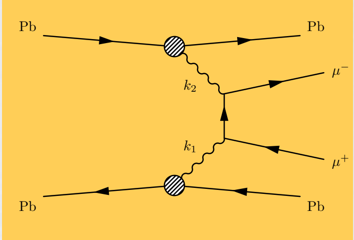
no need for rescattering or B

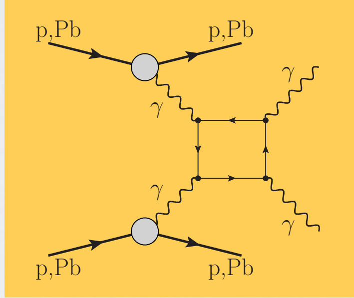
Conclusions

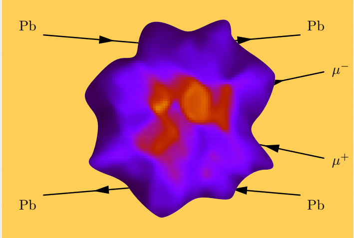
- Diverse program using electromagnetic interactions in ultra peripheral collisions
  - *Impact parameter plays important role in UPC, just as with hadronic collisions*
- In this talk, particular attention to photon-photon processes
  - *Variety of QED processes: dileptons, diphotons*
  - *Searches for new particles, esp. in loops*
  - *Possible new probes of QGP in "nonUPC" interactions*
  - *Very promising program in LHC Runs 3 & 4 (& forward RHIC program)*
- Increasing luminosity will require more sophisticated theoretical tools
  - *In particular, new data require more QED integrated into event generators*
  - *This applies both to initial state photons, and final state effects*
- Forward detectors are crucial for tagging different event topologies
  - *More data needed to understand how impact parameter modifies photon spectra*











Please see the parallel session today (14h00, Room I) for more results!