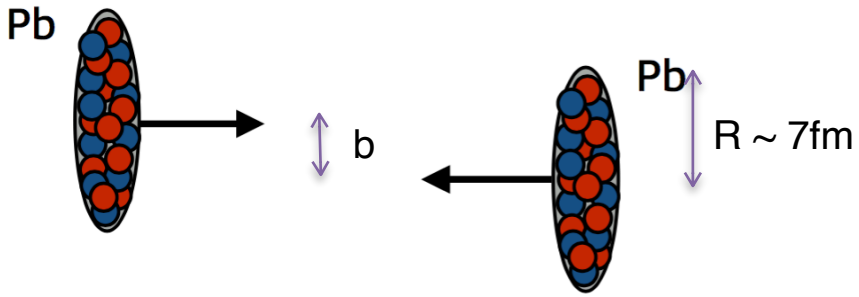
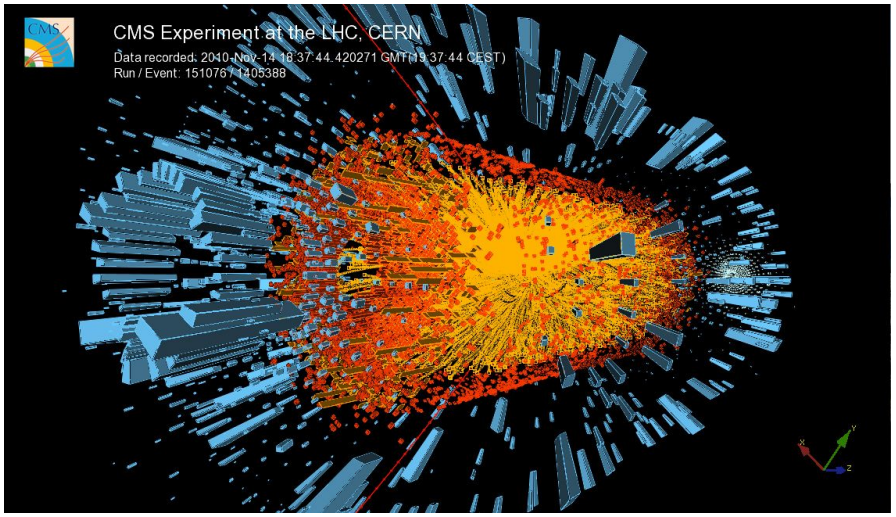
Photo-production in heavy ion collision

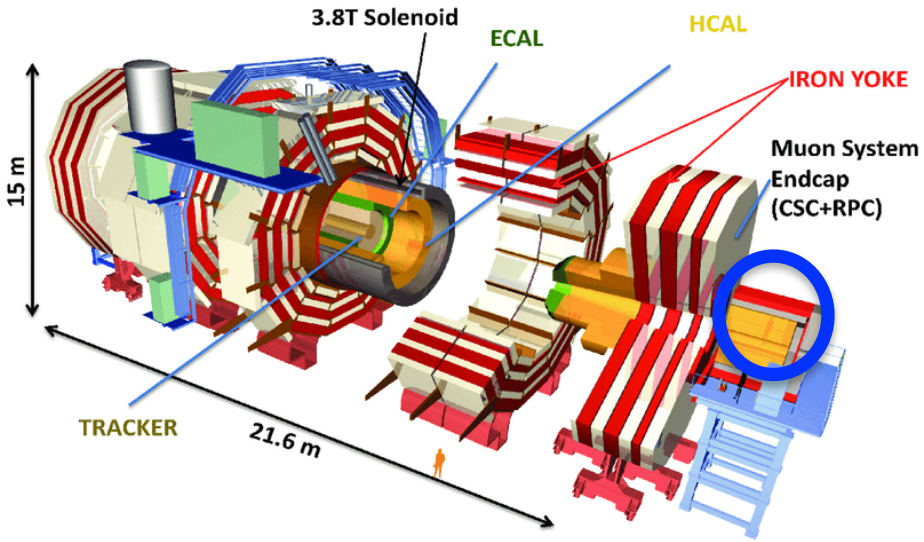
Yongsun Kim

Sejong University

All happening in HADRONIC collisions



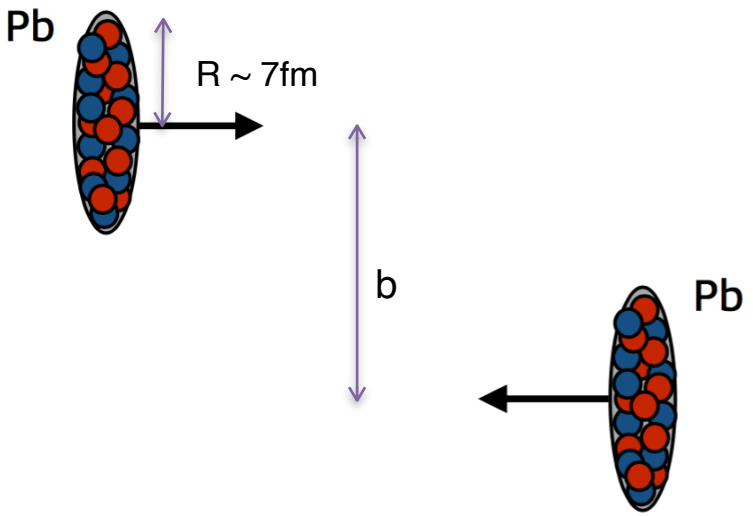


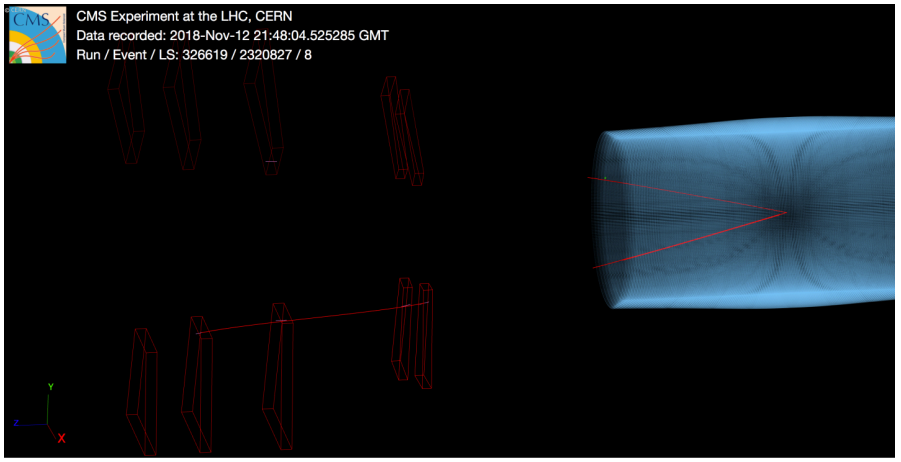


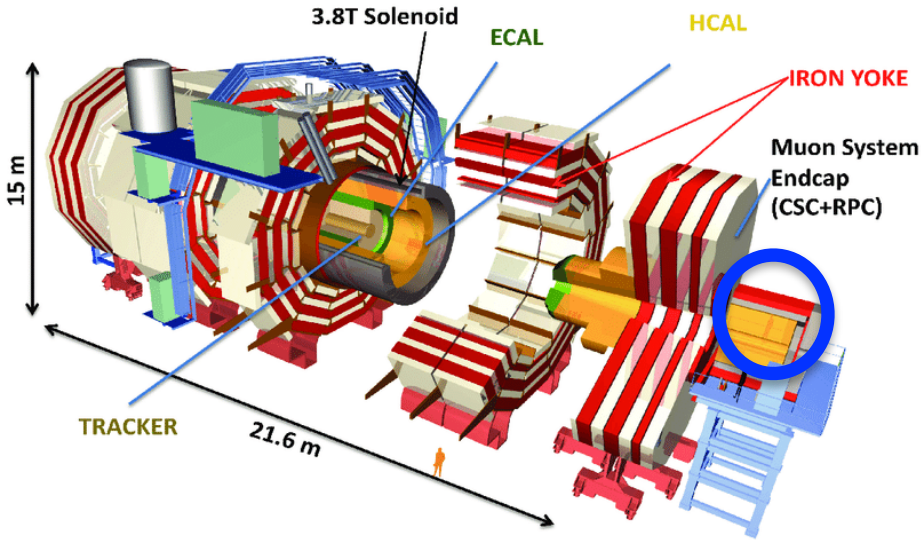
Forward Calorimeter(HF) signal

- Used for centrality classification

All happening in HADRONIC collisions



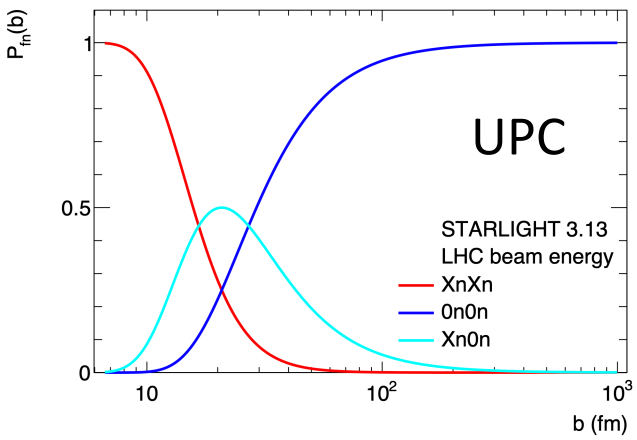


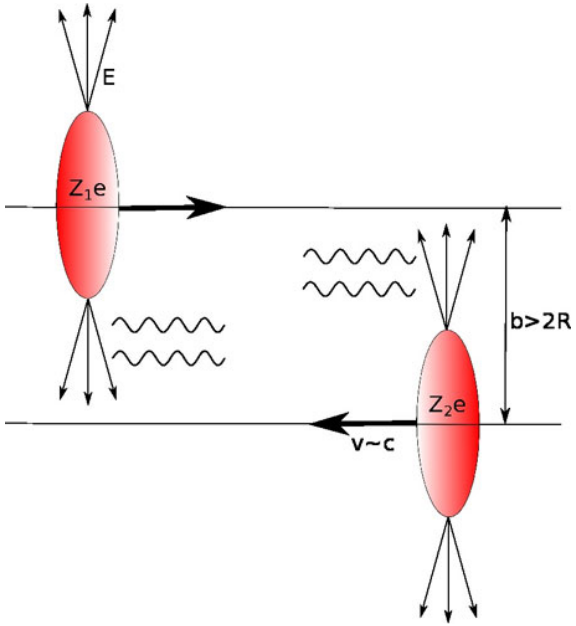


Forward Calorimeter(HF) signal

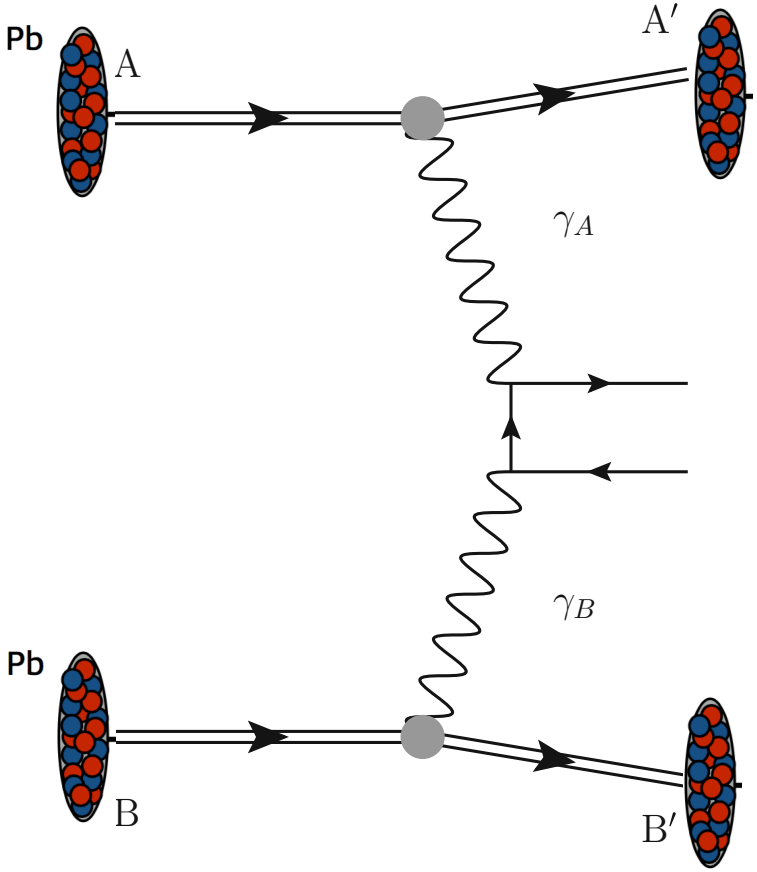
- No energy deposit at HF
- Very small hadronic activity in whole event

1. UPC and photon scattering

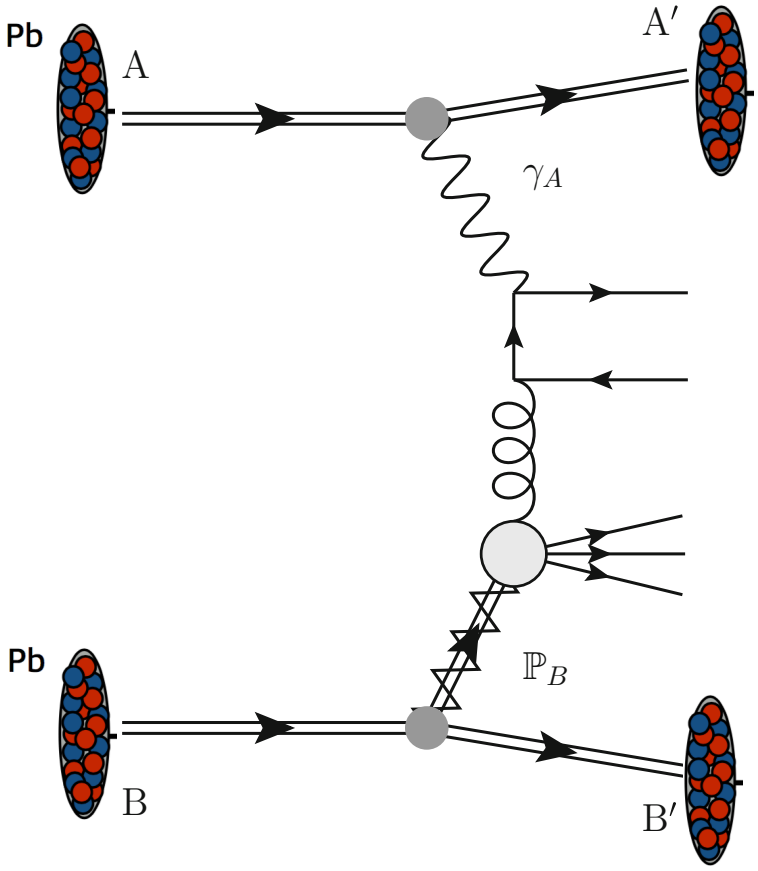




Di-jet from photo-production

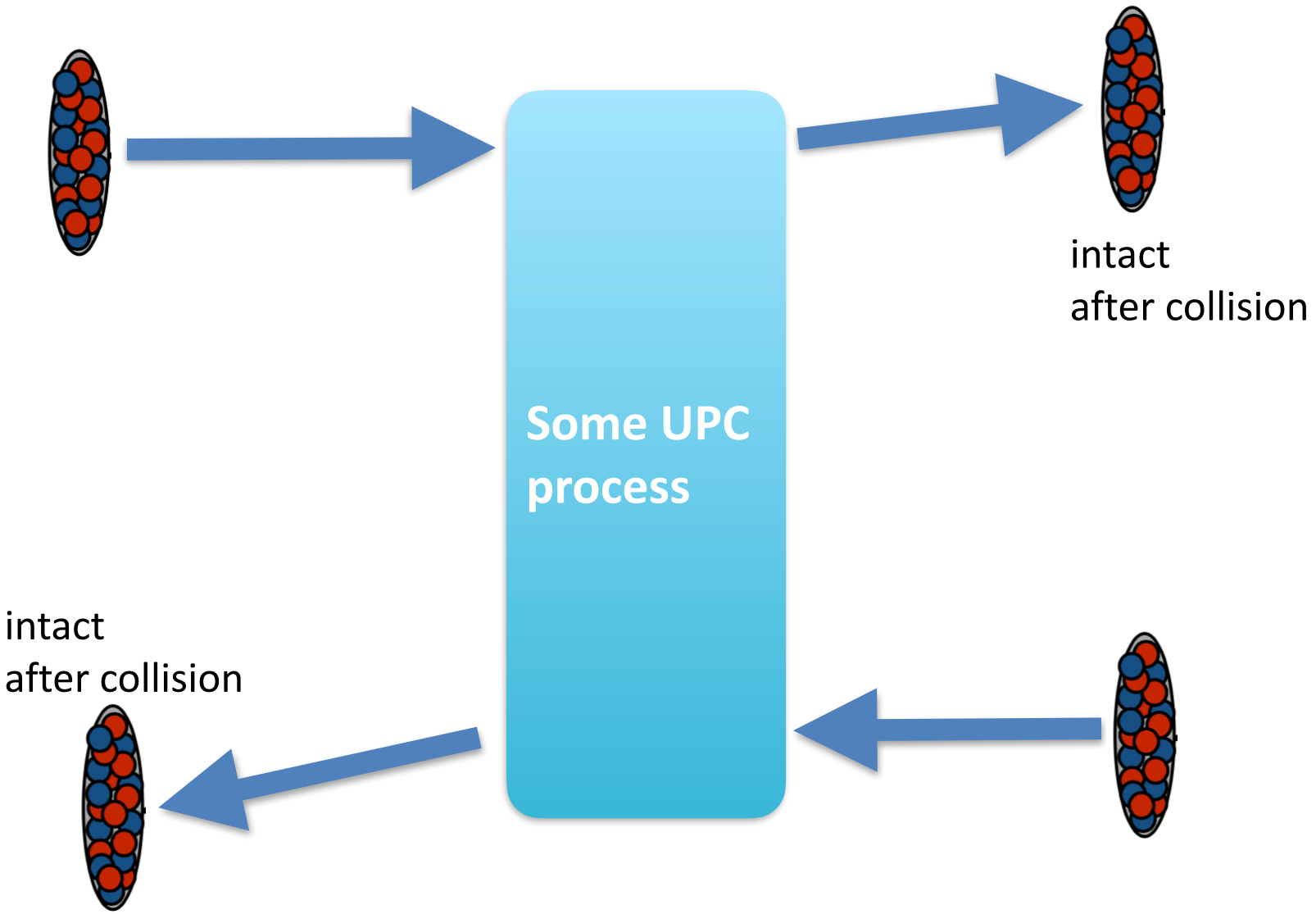


$\gamma + \gamma$ process

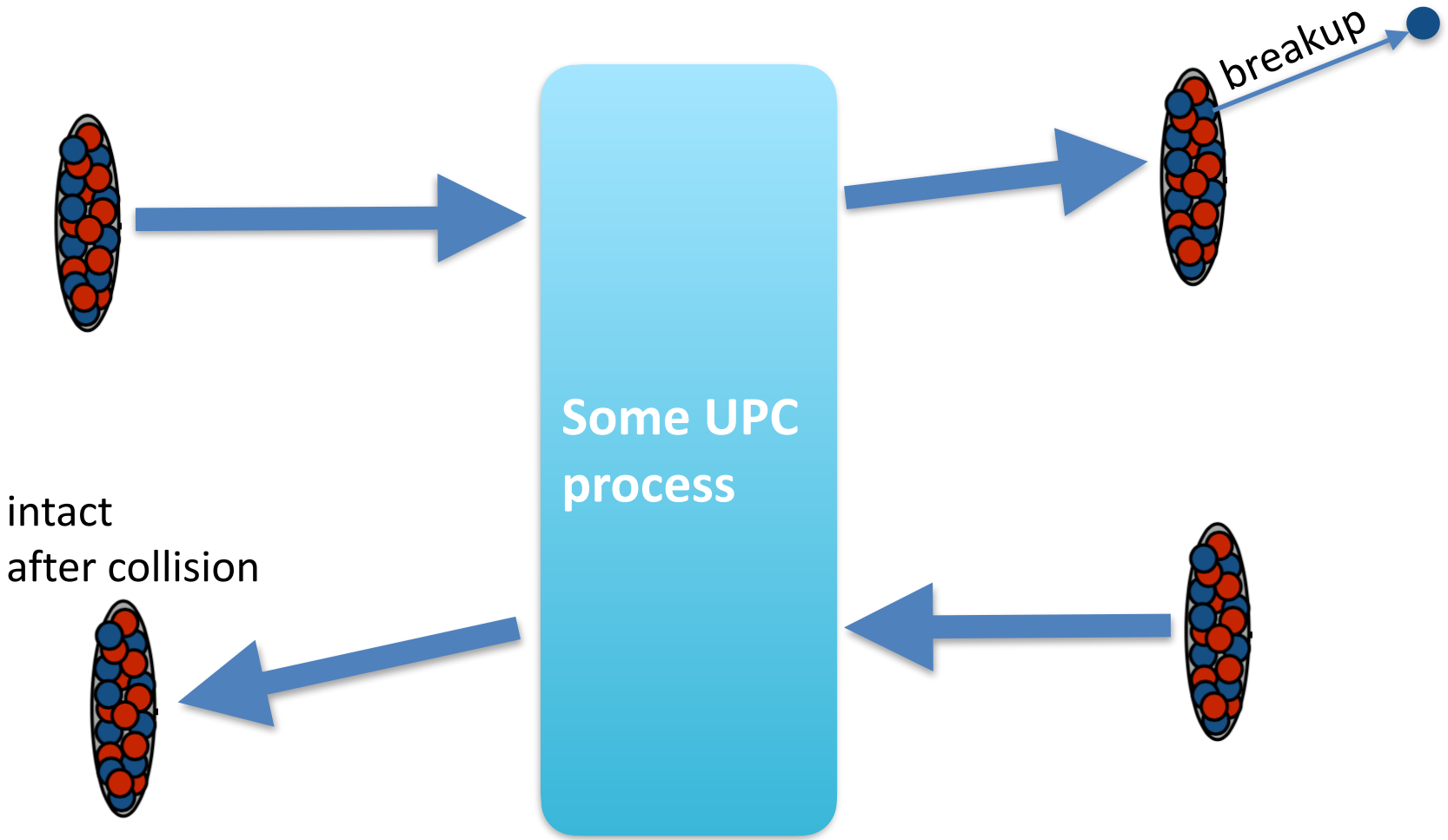


$\gamma +$ ***I\P*** process

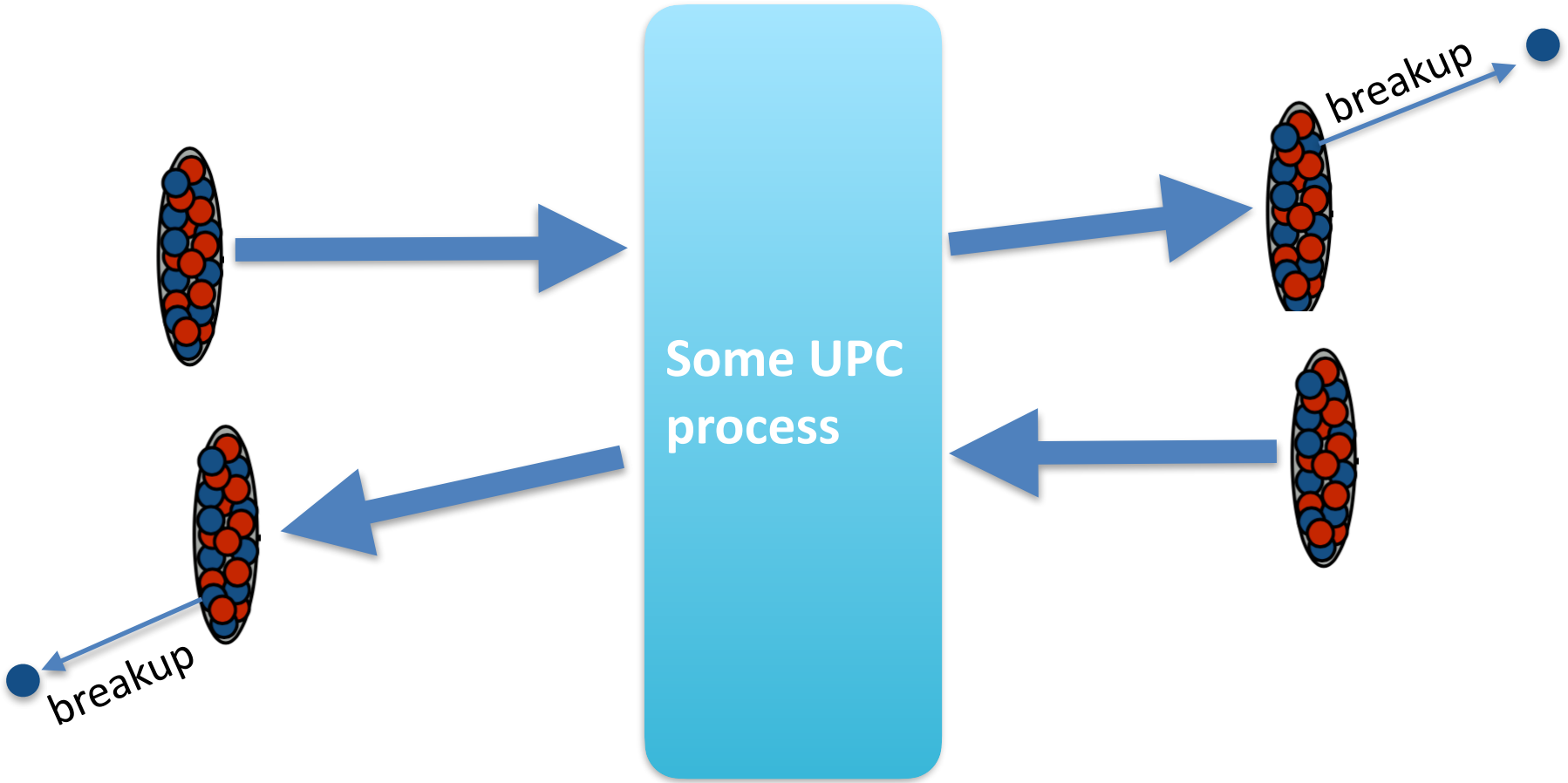
Di-muon production in UPC



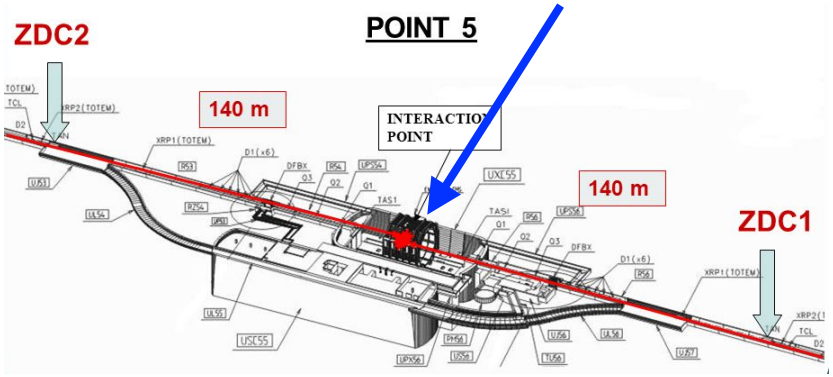
Di-muon production in UPC

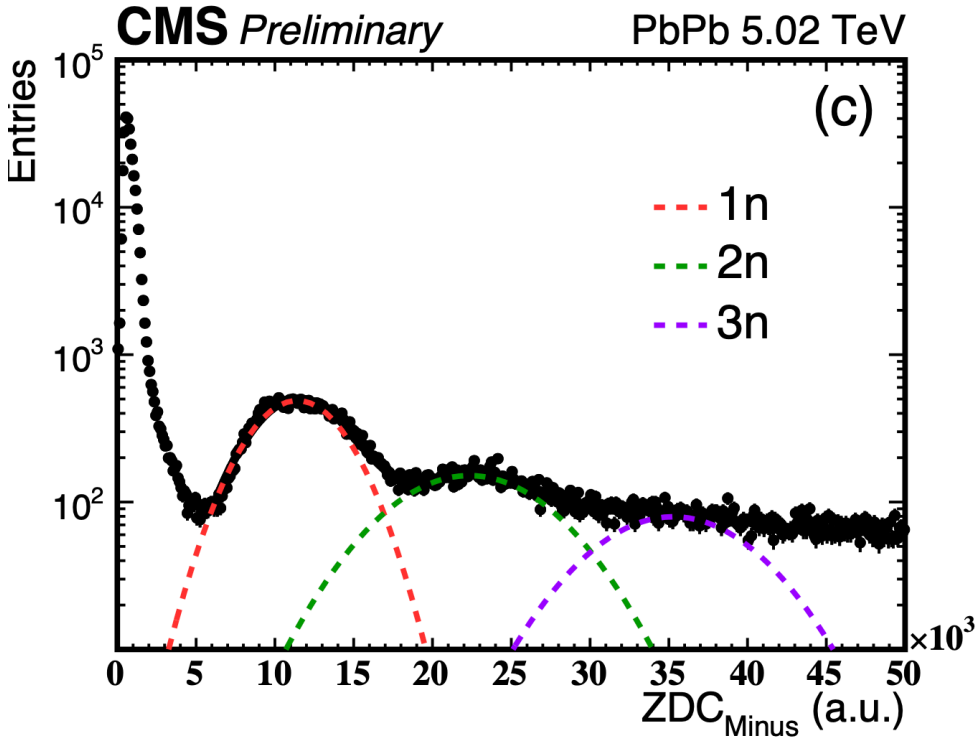


Di-muon production in UPC



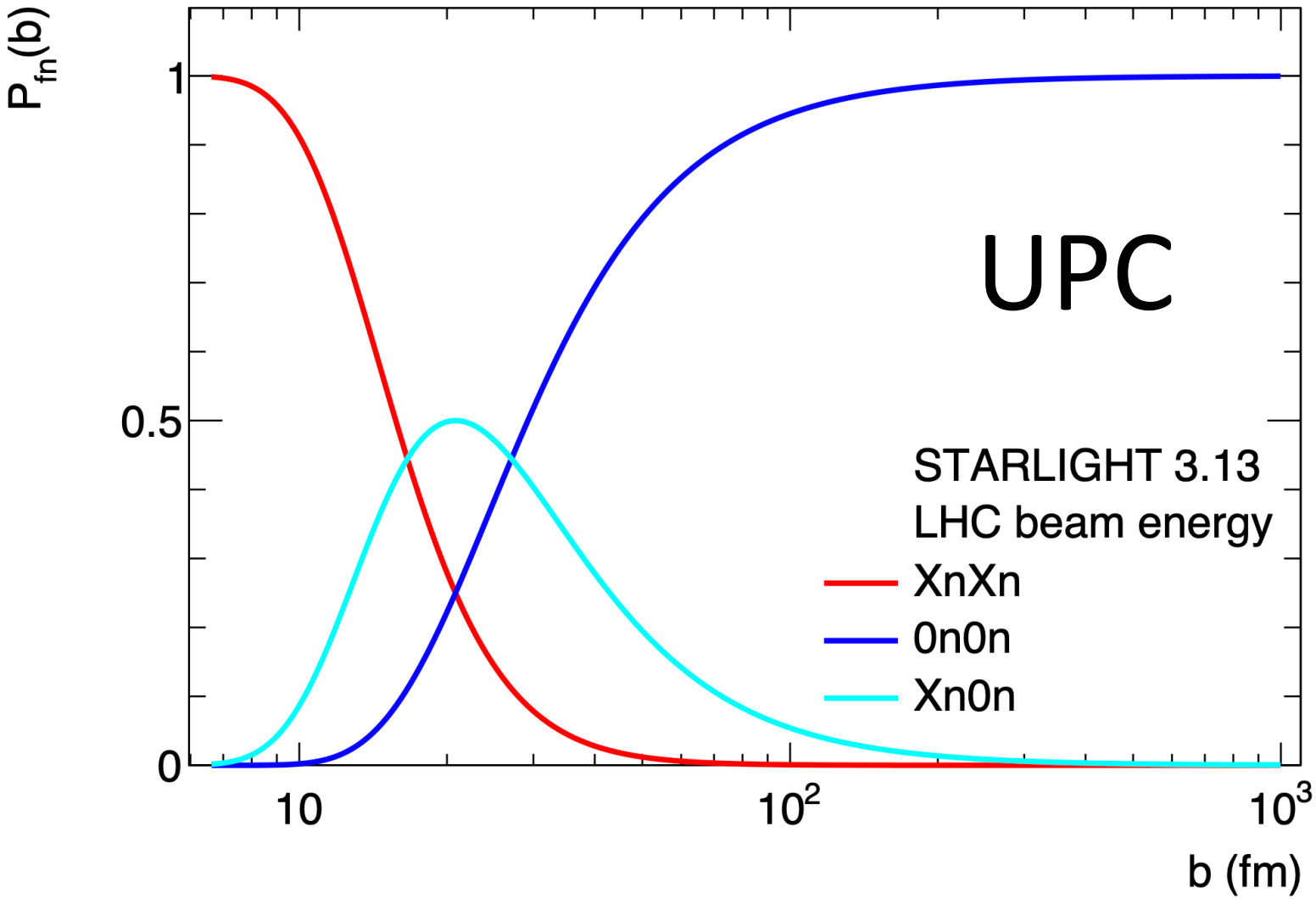
ZDC - neutron detector



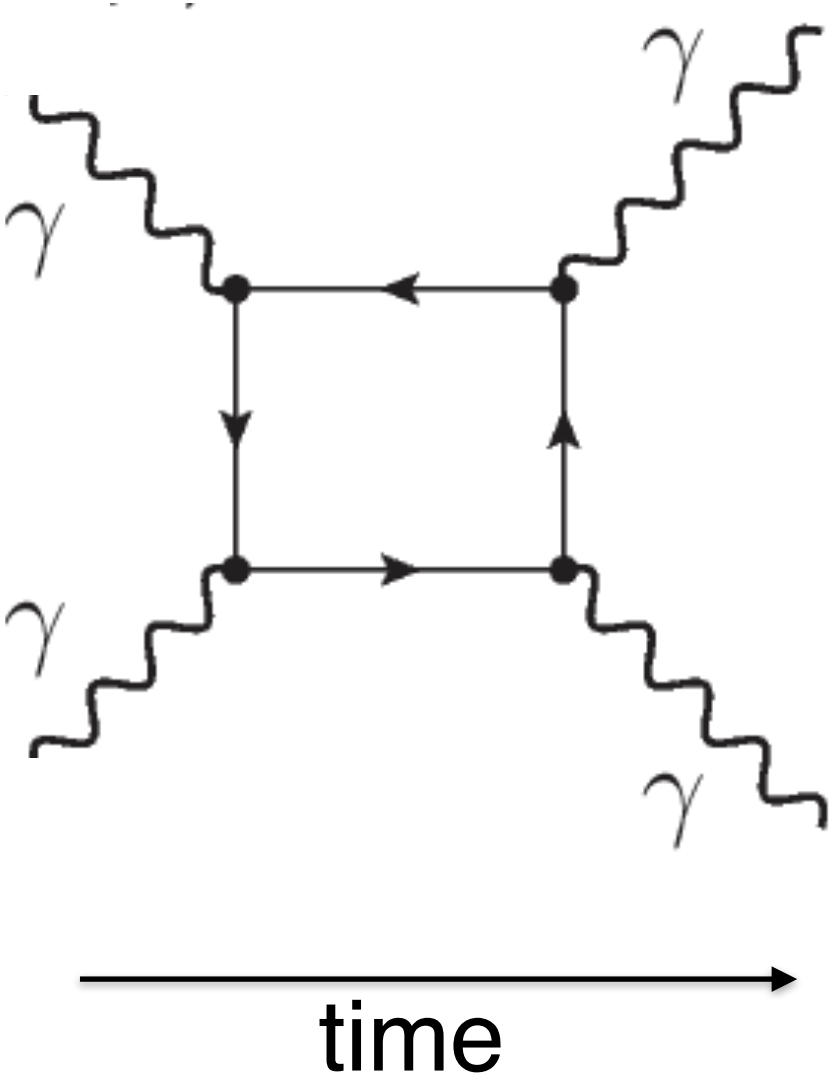


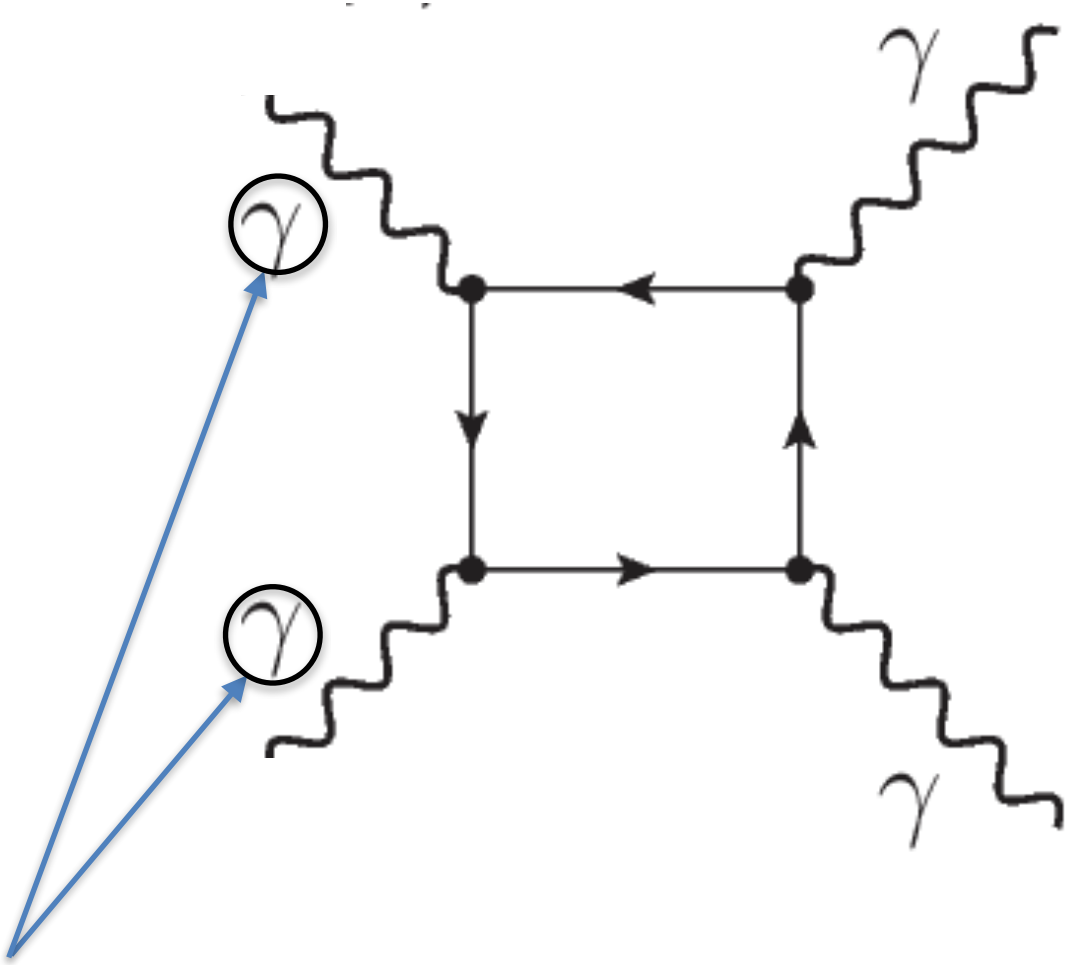
- Nuclear breakup measured by ZDC
- Number of neutrons = proxy for impact parameter
- CMS can catagorize events by 0n0n, 0nXn, XnXn

Di-muon production in UPC



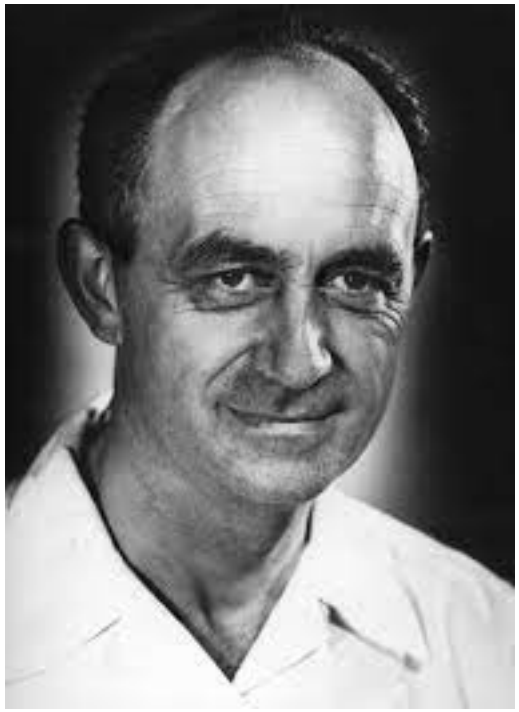
1. Light-by-light scattering





Photon from where?

Equivalent Photon Approximation (EPA)



E. Fermi suggested that trajectory of fast moving charged particle is equivalent to a flux of photons (1924)

Later, this method was extended to Ultra-relativistic regime by Weizsacker and Williams

Zweck der vorliegenden Arbeit ist, die Analogie zwischen diesen beiden Klassen von Erscheinungen zu präzisieren und die Erscheinungen bei dem Stoße quantitativ aus der Lichtabsorption abzuleiten.

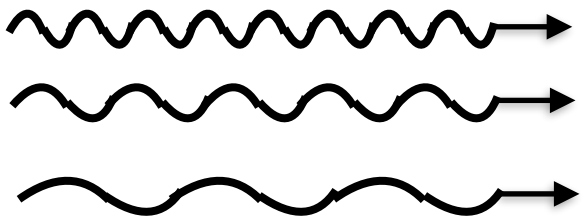
Wenn ein elektrisch geladenes Teilchen in der Nähe eines Punktes vorüberfliegt, entsteht in diesem Punkte ein veränderliches elektrisches Feld. Wenn wir nun dieses Feld durch ein Fouriersches Integral in harmonische Komponenten zerlegen, so sehen wir, daß es gleich dem Felde ist, das in dem Punkte sein würde, wenn es mit Licht von einer passenden kontinuierlichen Frequenzenverteilung belichtet würde. Denken

Nuovo Cim.,2:143-158,1925

(arXiv:hep-th/0205086 in English)

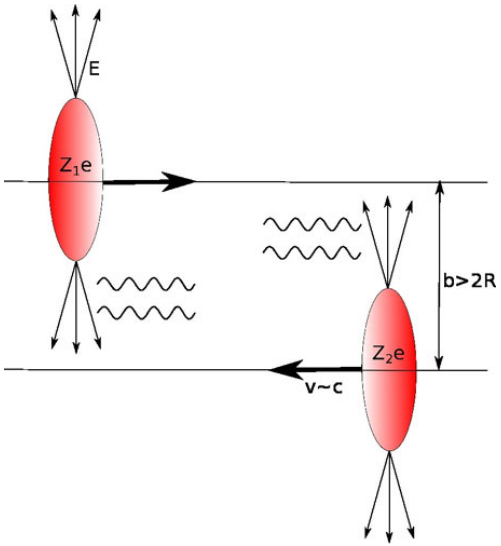
Fast moving charged particle

… is equivalent to photon flux



where N_γ proportional to Z^2

LHC, the most powerful photon collider



$$\omega^{\max} = \frac{\hbar}{\Delta t} \sim \frac{\gamma \hbar v}{b},$$

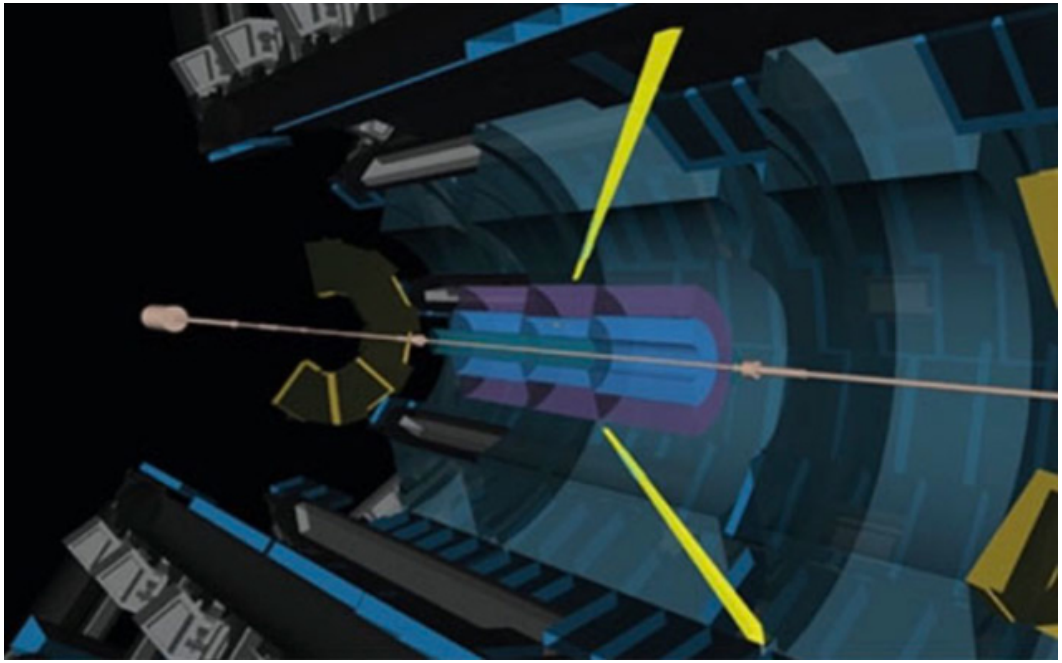
$$N(\omega, b) = \frac{Z^2 \alpha \omega^2}{\pi^2 \gamma^2 \hbar^2 \beta^2 c^2} \left(K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right)$$

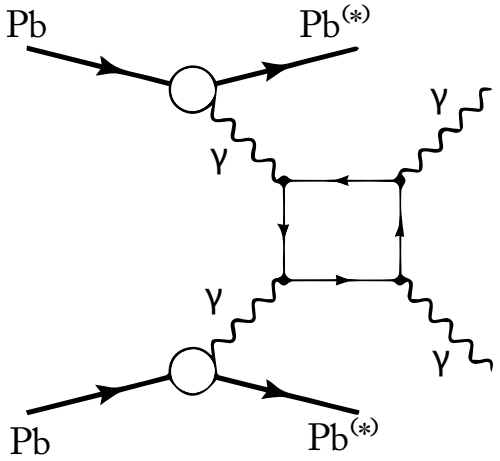
Annu. Rev. Nucl. Part. Sci. 2005. 55:271

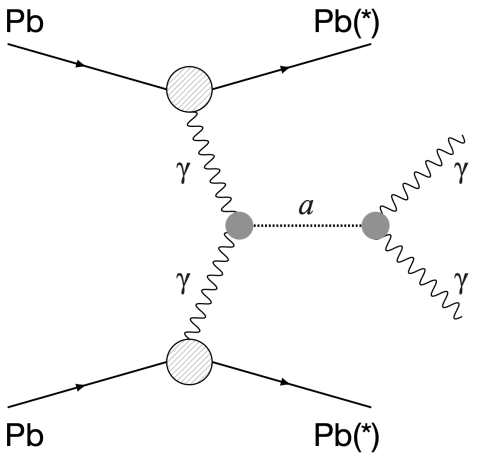
Accelerator	**Ions**	**Max. Energy per nucleon pair (CM)**	**Luminosity**	**Max. γp**	**Max. $\gamma\gamma$ energy**
CERN SPS	Pb+Pb	17 GeV	—	3.1 GeV	0.8 GeV
RHIC	Au+Au	200 GeV	4×10^{26} cm^{-2} s^{-1}	24 GeV	6.0 GeV
RHIC	p+p	500 GeV	6×10^{30} cm^{-2} s^{-1}	79 GeV	50 GeV
LHC	Pb+Pb	5.6 TeV	10^{27} cm^{-2} s^{-1}	705 GeV	178 GeV
LHC	p+p	14 TeV	10^{34} cm^{-2} s^{-1}	3130 GeV	1400 GeV
Tevatron	p+$\bar{p}$	20 TeV	5×10^{31} cm^{-2} s^{-1}	320 GeV	200 GeV

Light-by-light scattering

[*ATLAS, Nature Phys 13, 852–858 (2017)*]

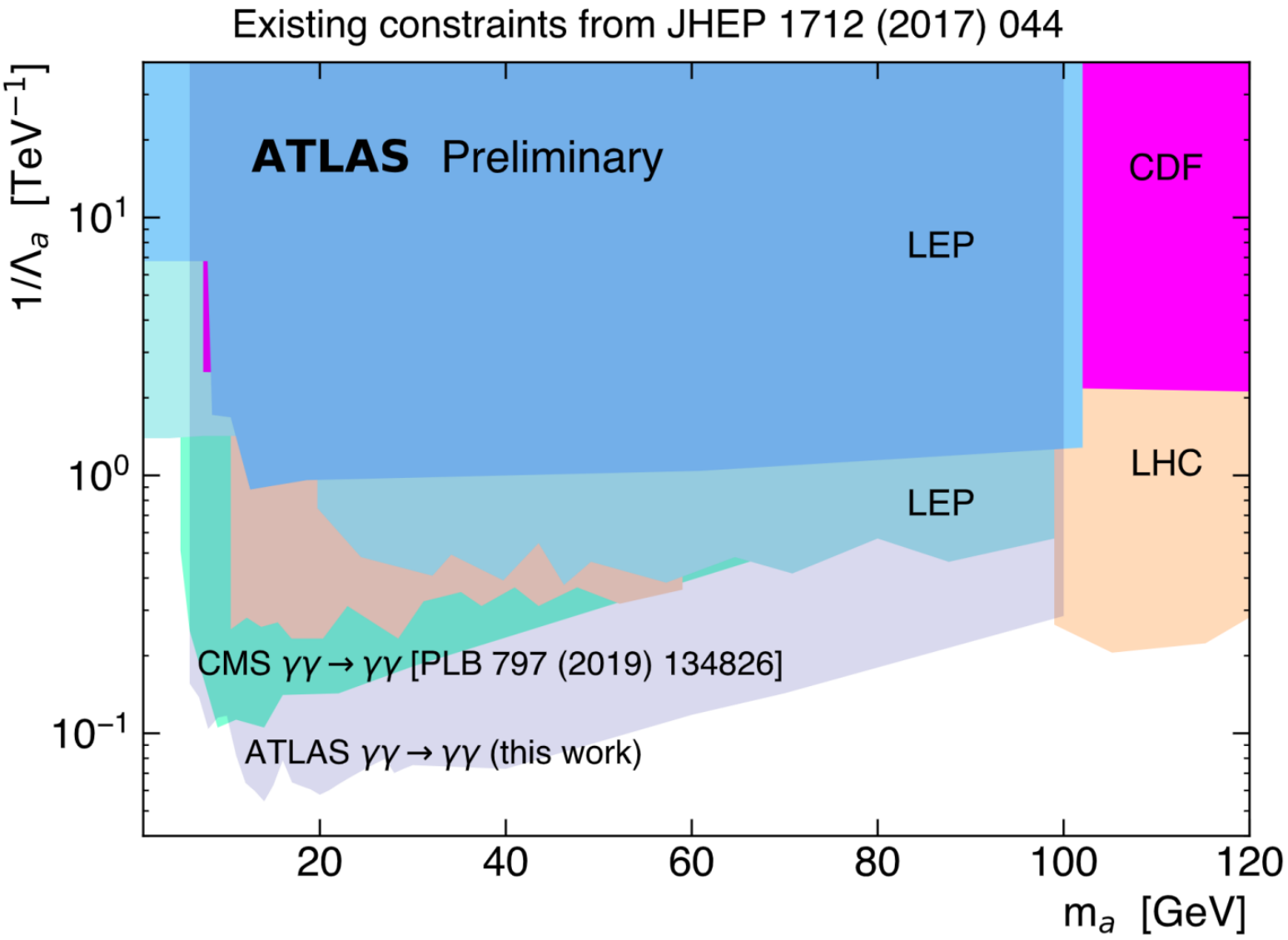






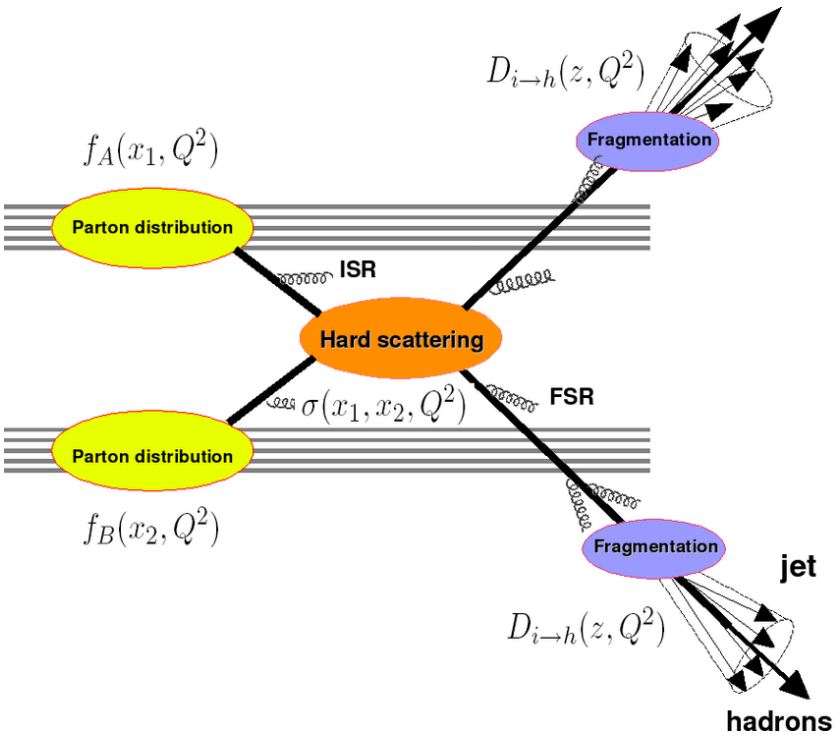
- Provides test for axion-like particles, relatively light and gauge-singlet in the form of narrow di-photon resonances
- LHC can search $6 < M_{ALP} < 100$ GeV/c^2

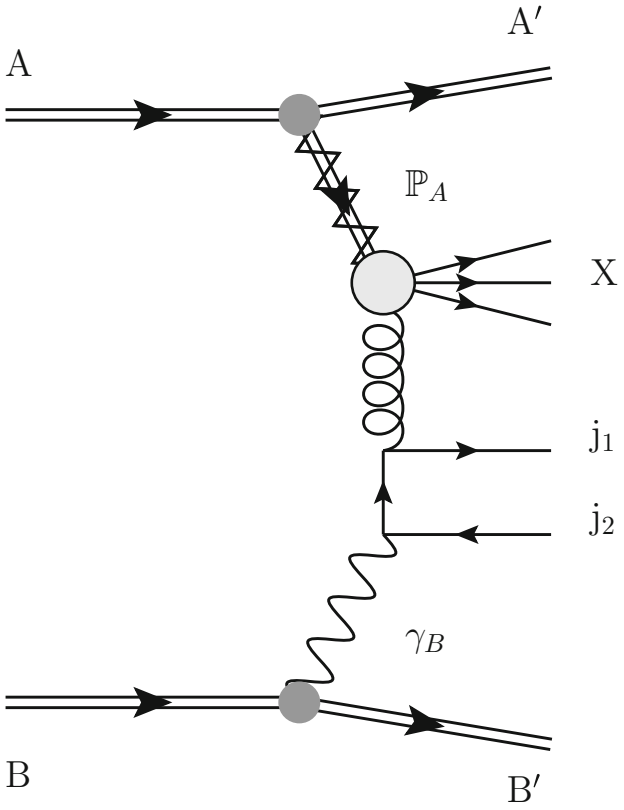
Constraints for ALP coupling to photons



2. Di-jet in UPC

Di-jet production in hadronic collisions





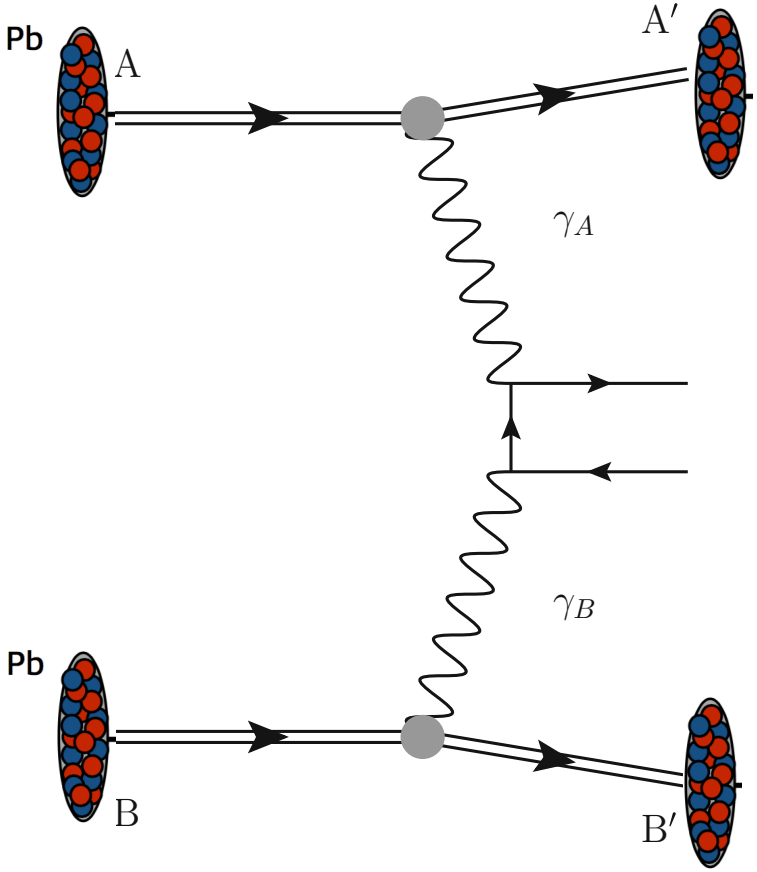
Hadronic collision

* Uncertainty in proton PDF
* complicated hard scattering calculation

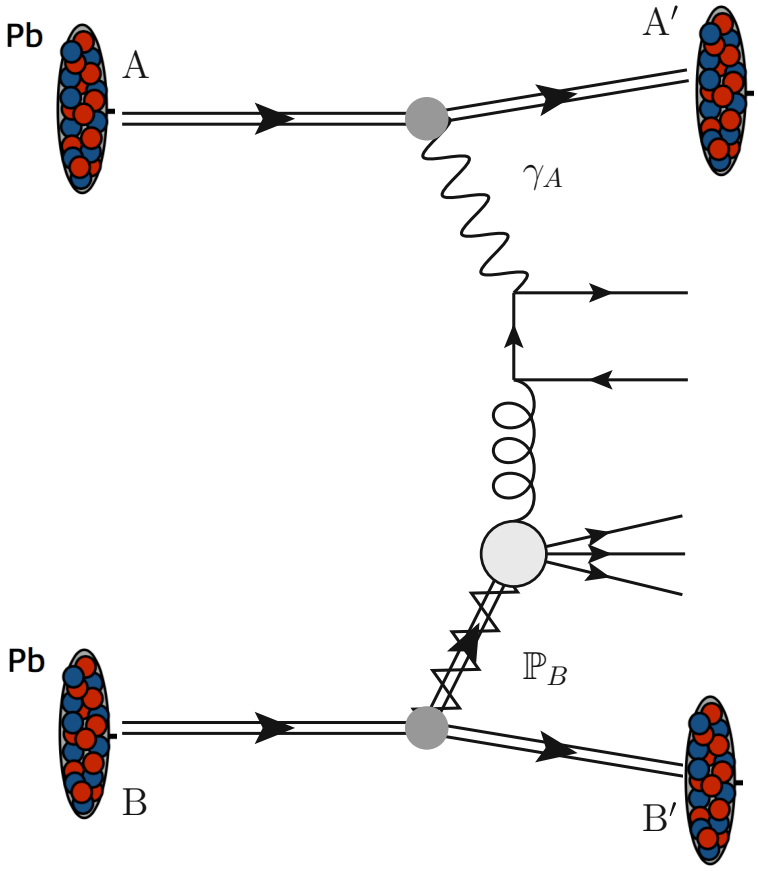
Ultra-Peripheral Collision (UPC)

* Free from projectile PDF
* Much smaller uncertainties
* Complementary kinematic region

Di-jet from photo-production

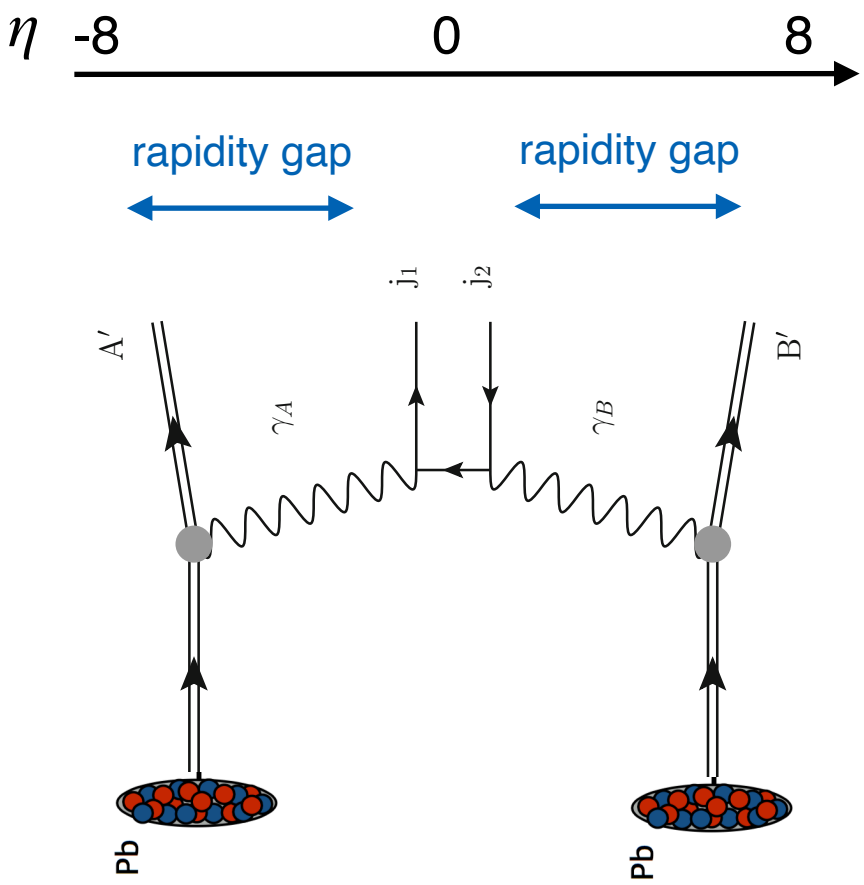


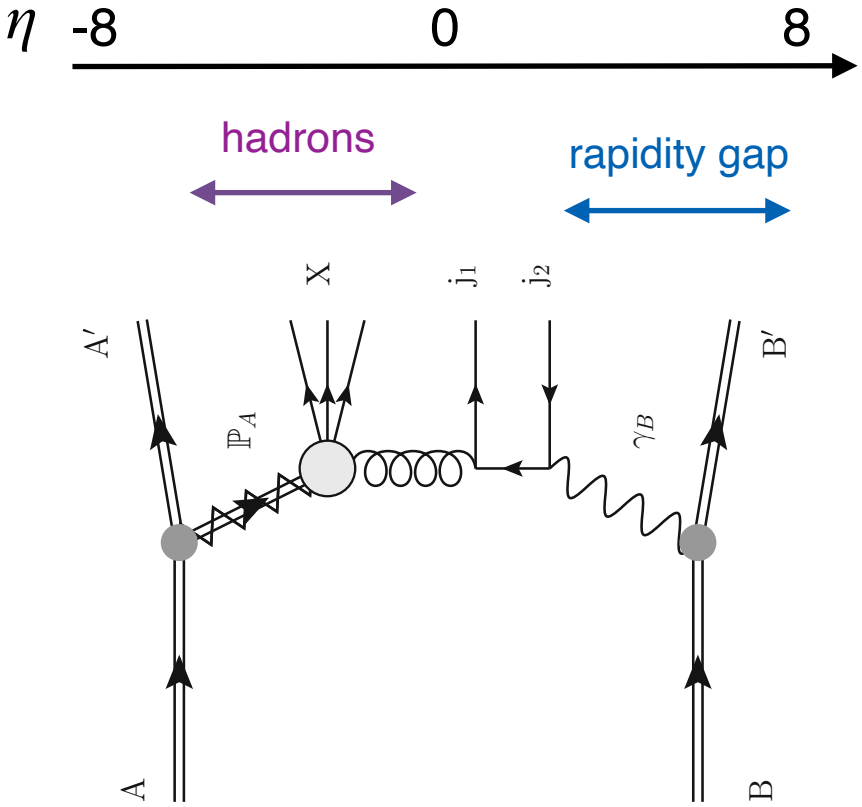
$\gamma + \gamma$ process



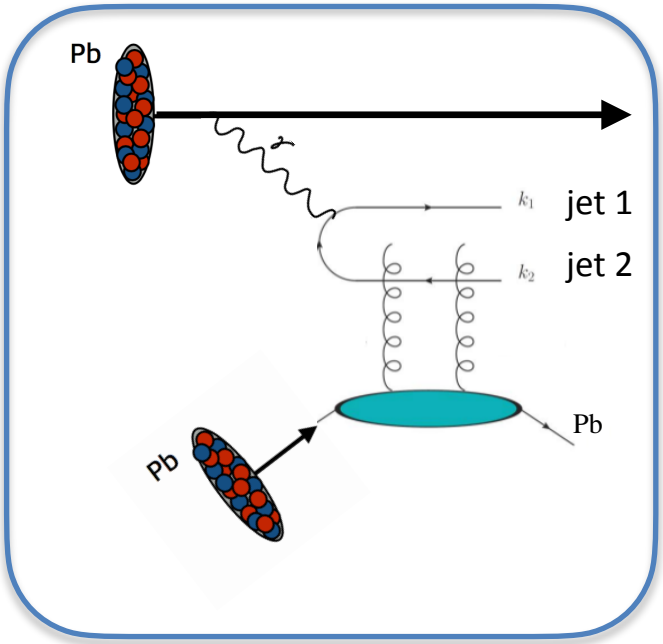
$\gamma +$ ***I\P*** process

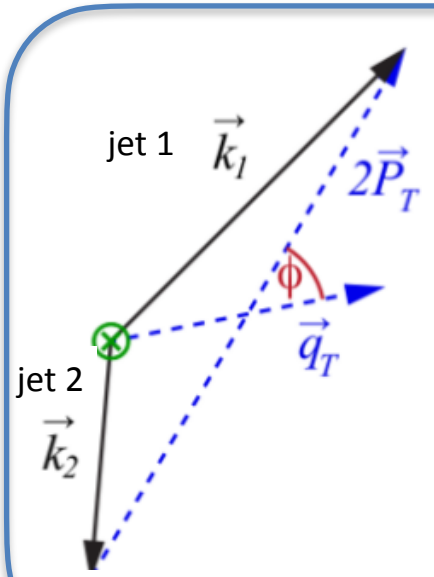
Di-jet from photo-production





Exclusive di-jet correlation





Vector sum of 2 jets:

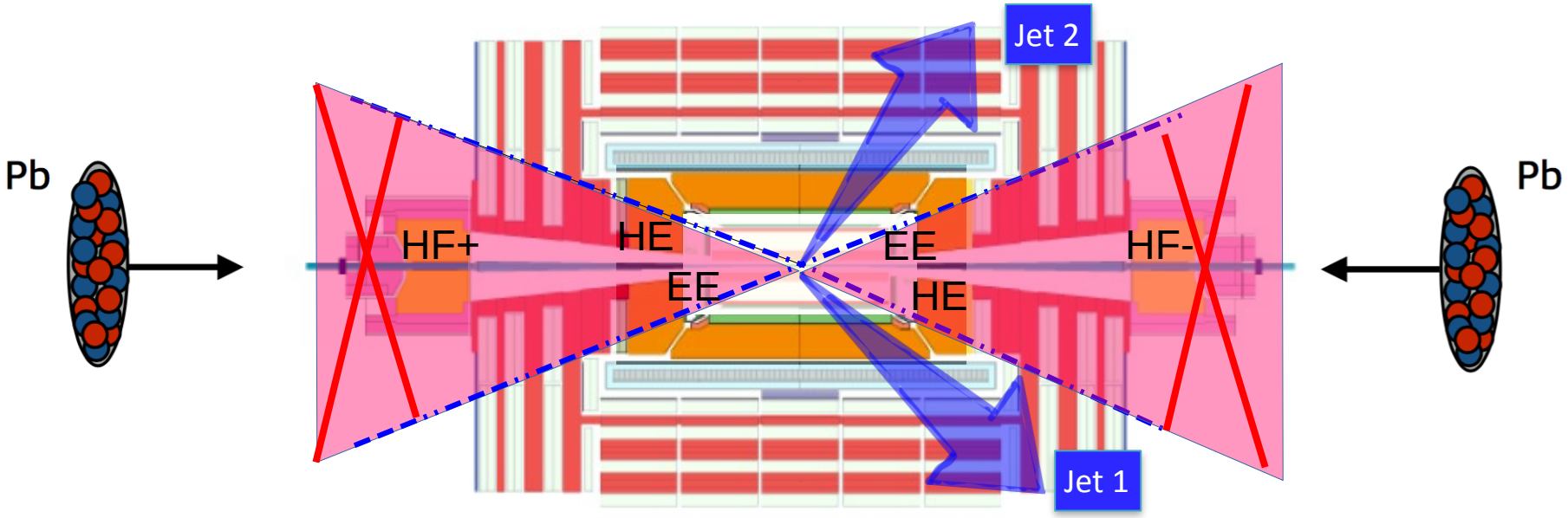
$$\vec{Q}_T = \vec{k}_1 + \vec{k}_2$$

Vector difference of 2 jets:

$$\vec{P}_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2)$$

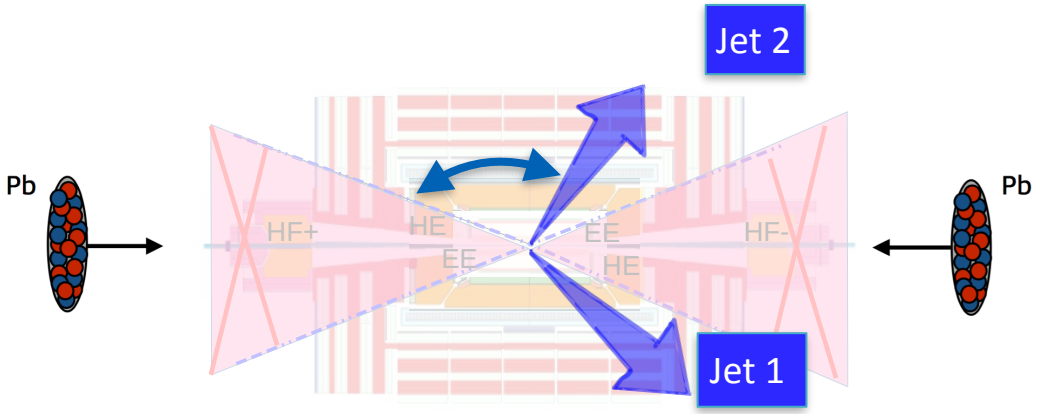
- *The only process which can directly access to the Wigner distribution* [PRL116, 202301 (2016)]
- Jets were used as the proxy of quarks decayed from the gluon
- Correlation between gluon and impact parameter vector due to dipole scattering amplitude in the small-x, so called "elliptic gluon" distribution
- Observable: $v_2 = < cos(2\phi) >$

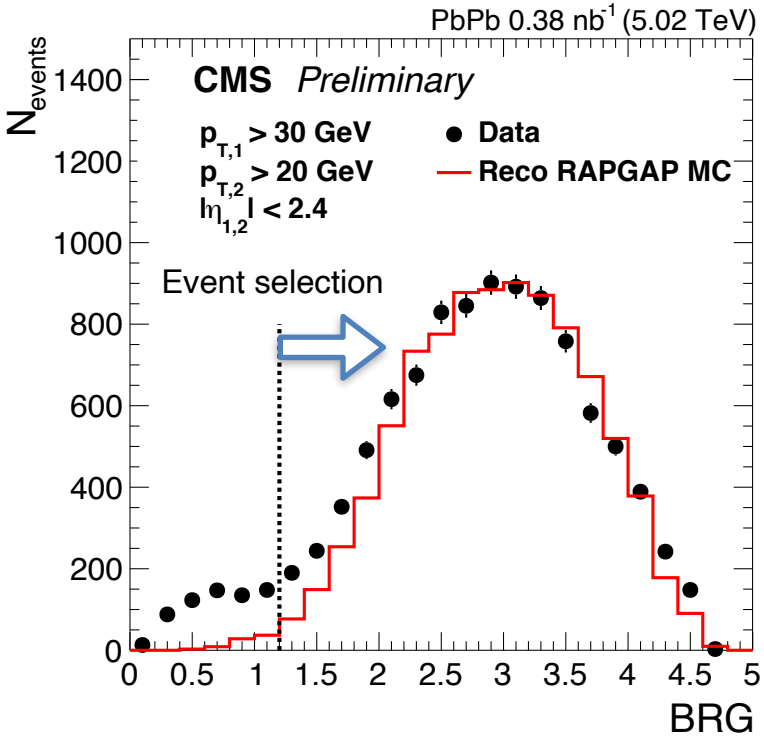
Exclusive di-jet correlation

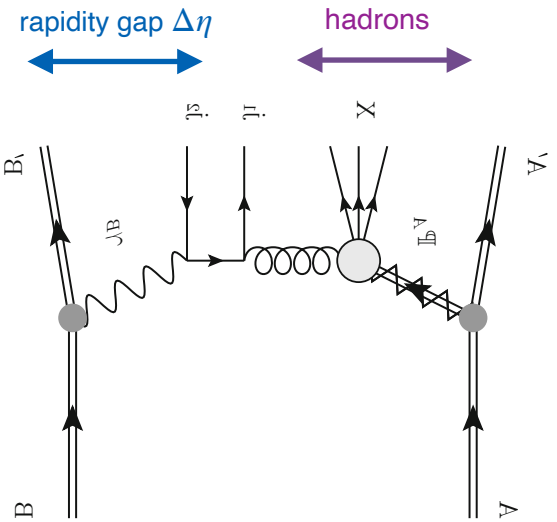


- UPC events are selected by
  - Veto activity in the forward and backward regions $2.8 < |\eta| < 5.2$
  - Existence of only two jets :
    - $|\eta_{lab}| < 2.4,\ \ p_{T,1} > 30GeV,\ \ p_{T,2} > 20GeV$
- Jets are reconstructed by anti-k_T algo with R=0.4
- ParticleFlow algo was used to provide input particles for jet finder

Exclusive di-jet correlation

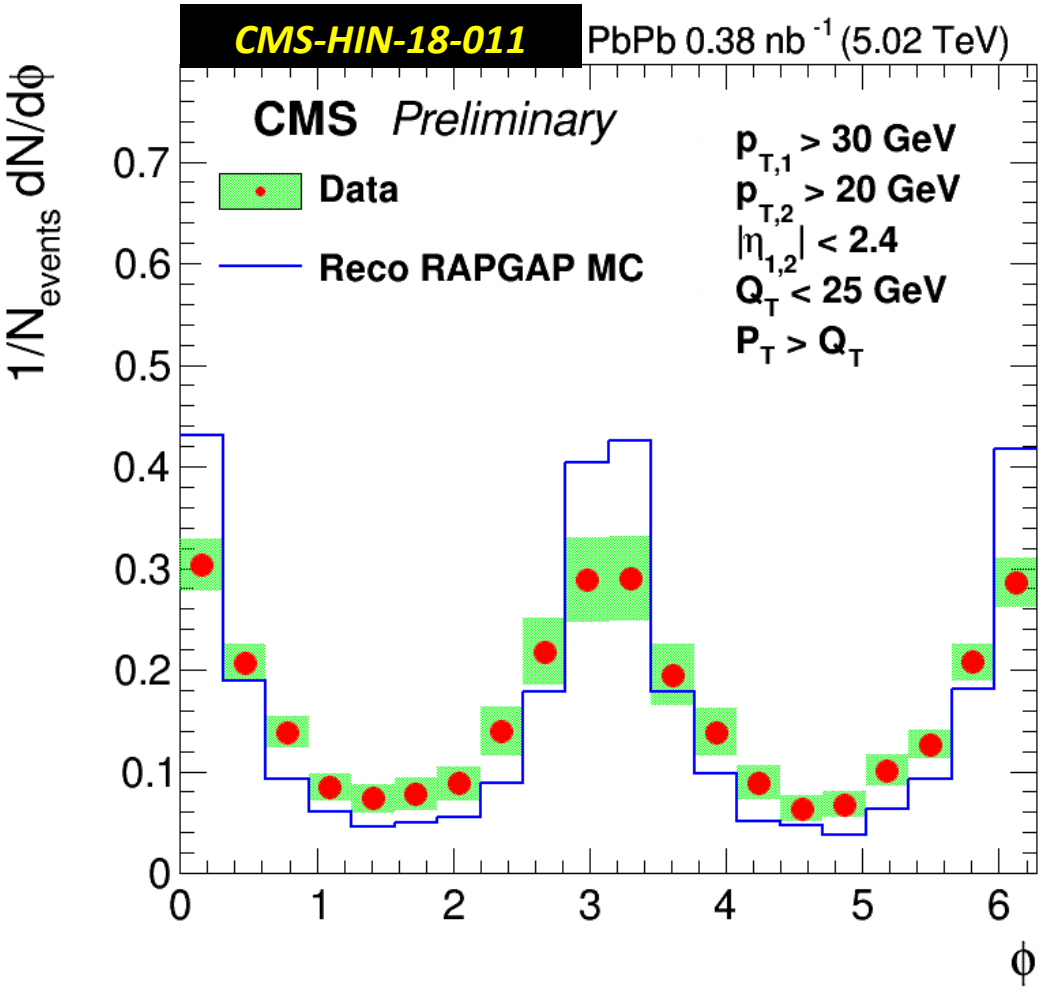


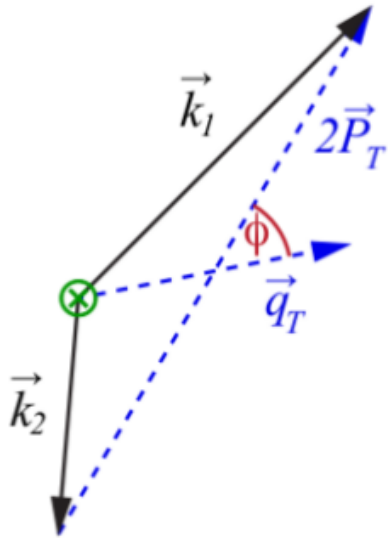




- Rapidity gap = $\Delta\eta$ between the forward calorimeter boundary and the closest track in the every
- Signature of exclusive di-jet process

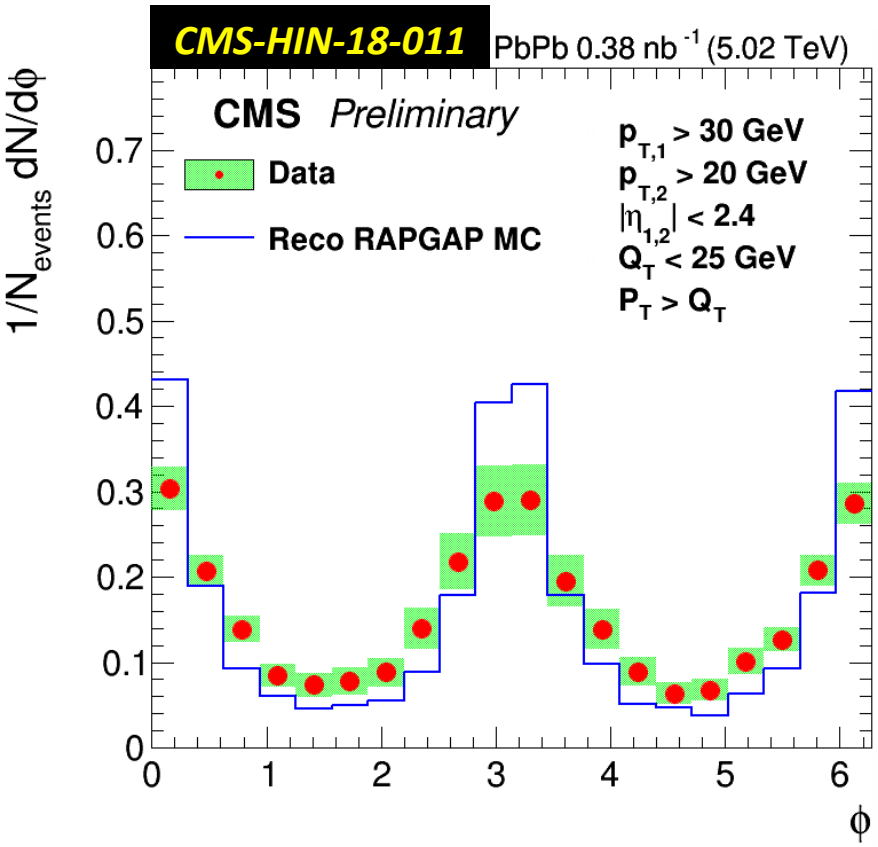
Exclusive di-jet correlation

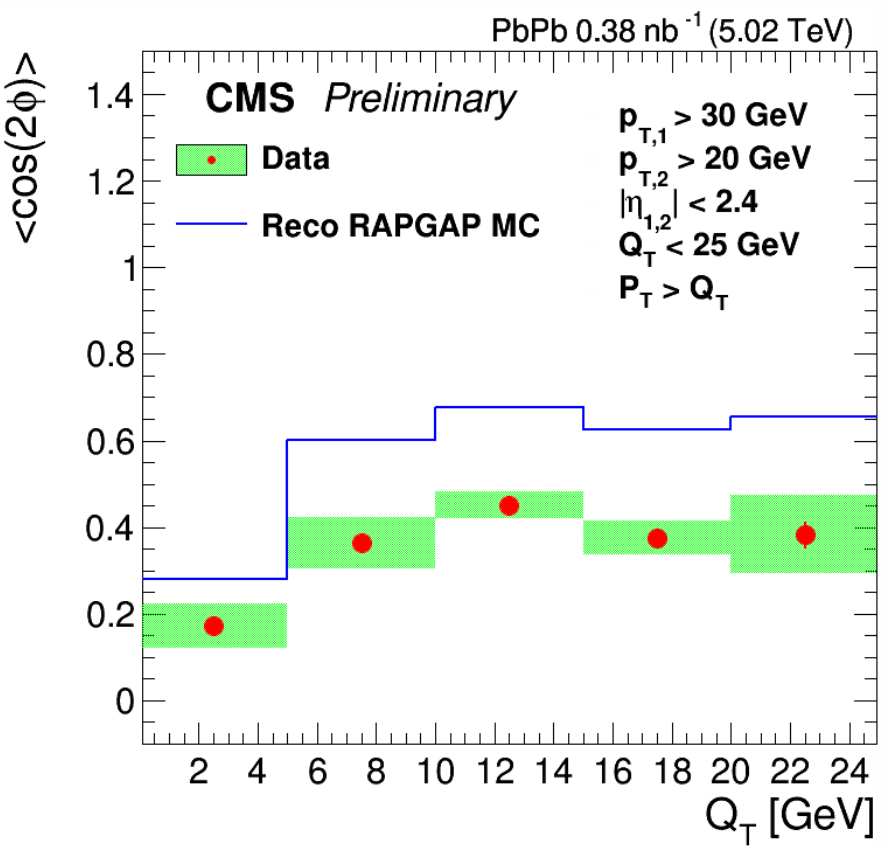




- Result shows a back-to-back correlation in both data and RAPGAP MC
- Positive v_2 (=<cos (2ϕ)>) values for all PT and QT bins

Exclusive di-jet correlation





- Result is compared with the RAPGAP simulation and toyMC models
- $< cos(2\phi) >$ in data is lower than in RAPGAP prediction by 20-30%, which provides input to the theory community

Feedback from theory society

- Theoretical developments are being made for our data
- In the following model, v_2 turns to be constant for QT > 5 GeV
- For better benchmarking, the unfolded data would be appreciated

Yuan, and Jian Zhou *arXiv:2010.10774 [hep-ph]*

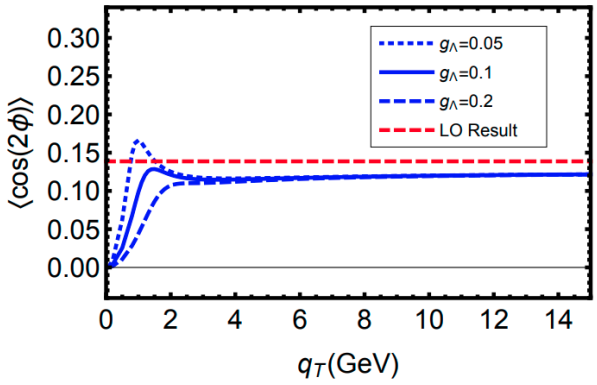
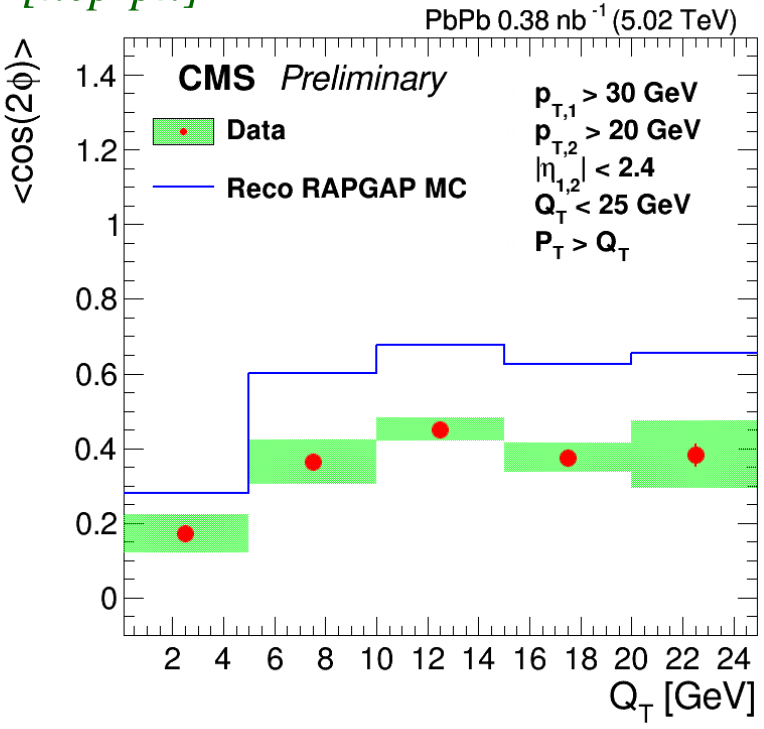
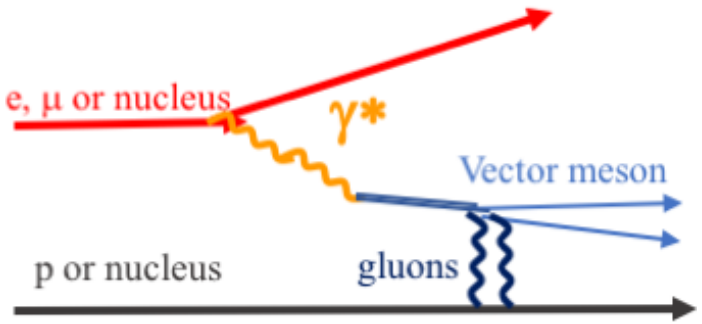


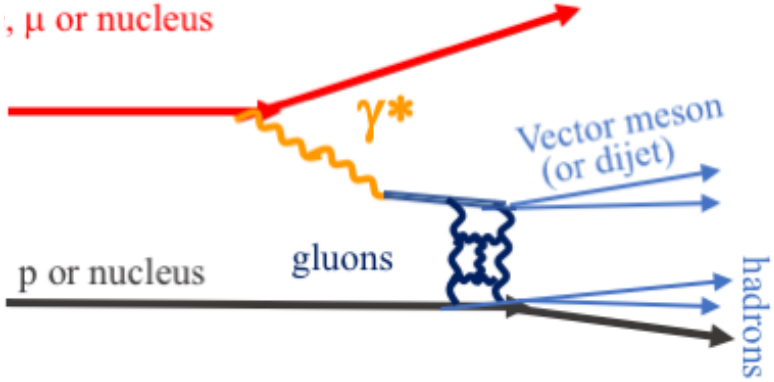
FIG. 2. Anisotropy in diffractive dijet production $\gamma + A \to q\bar{q} + A$ in ultra peripheral heavy ion collisions at the LHC. The kinematics correspond to the CMS measurements [34] with the leading jet $P_\perp = 35$GeV and the two jets are at the same rapidity $\Delta y_{12} = 0$. The figure shows $\langle\cos(2\phi)\rangle$ as a function of $q_\perp$, where ϕ is the azimuthal angle between $q_\perp$ and $P_\perp$.

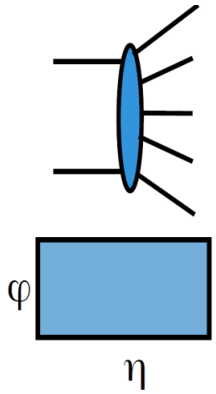


3. Characterization of Pomeron interaction

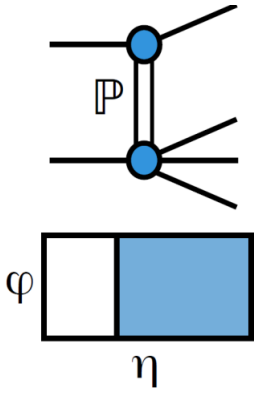
Diffraction phenomenology



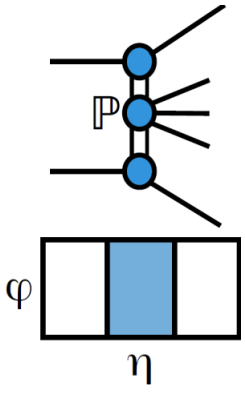




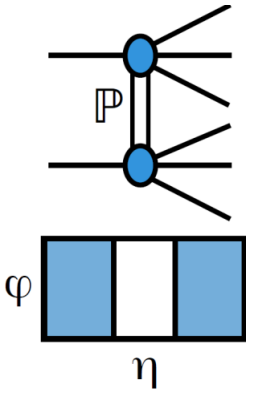
Non-Diffractive



Single Diffraction

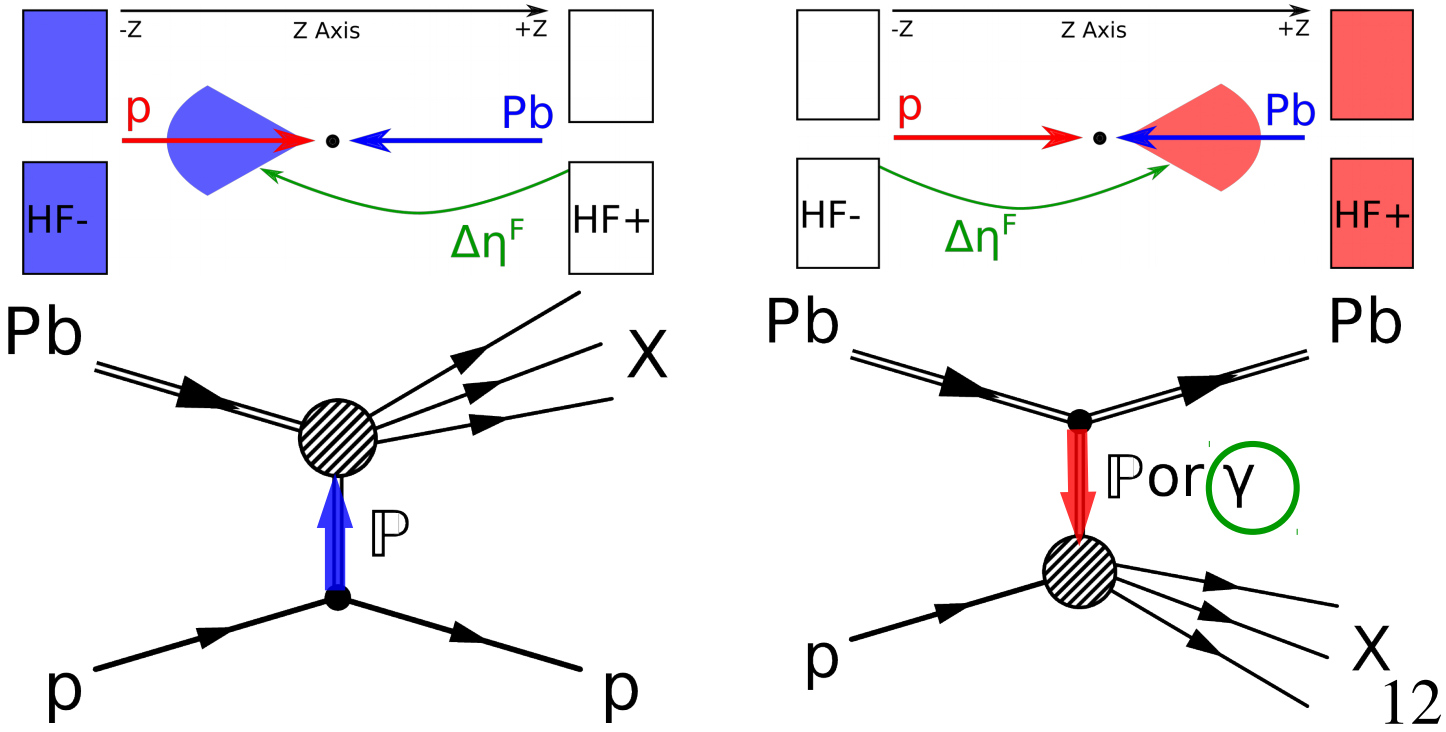


Central Diffraction



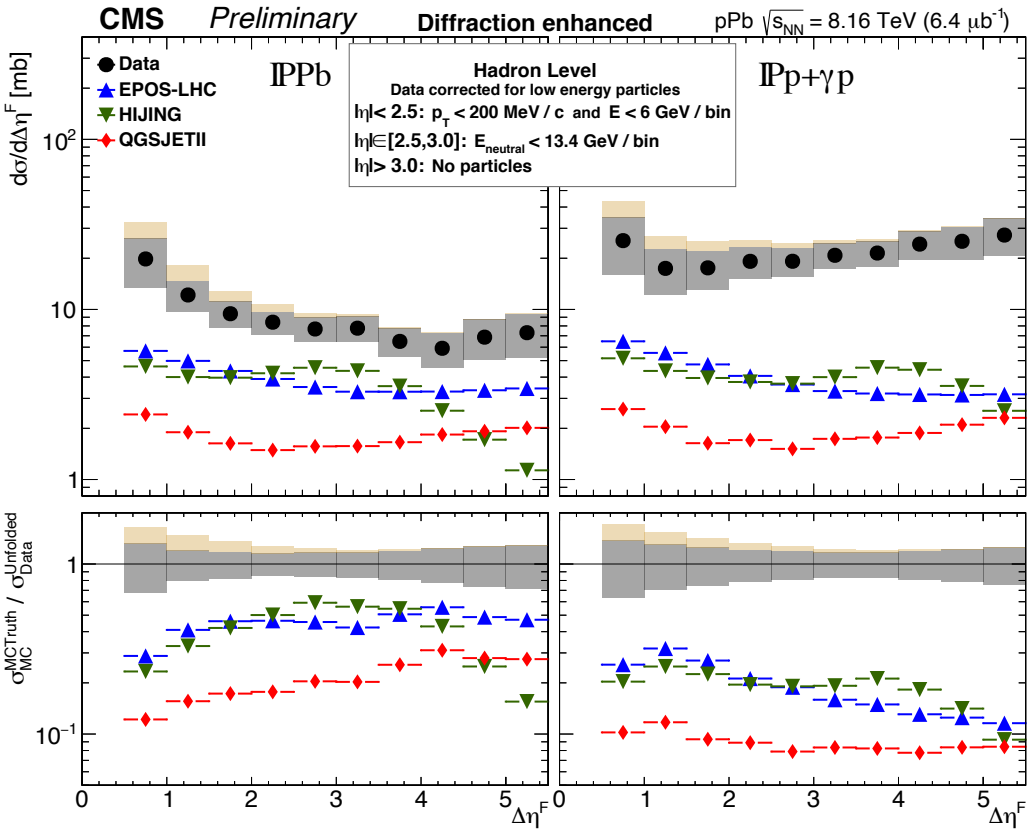
Double Diffraction

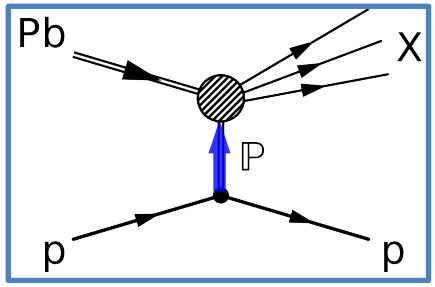
Diffraction phenomenology in pPb

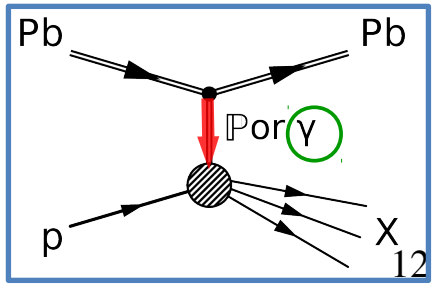


- Diffraction can be characterized by the rapidity gap
- Contribution from photon and Pomeron can be separated by comparing p-Pb and Pb-p collision
- CMS, as a hermetic & symmetric detector, is the best place for this test

Diffraction in pPb UPC







IP-Pb interaction

- Cross section in theoretical models are lower than data by factor of 2-4, but with similar shape as a function of $\Delta\eta$
- HIJIING model shows Large deficit for high $\Delta\eta$ due to the lack of low mass diffraction

IP-p interaction

- Neither normalization nor shape agree with data
- Significant contribution from γ +p is missing in MC simulations

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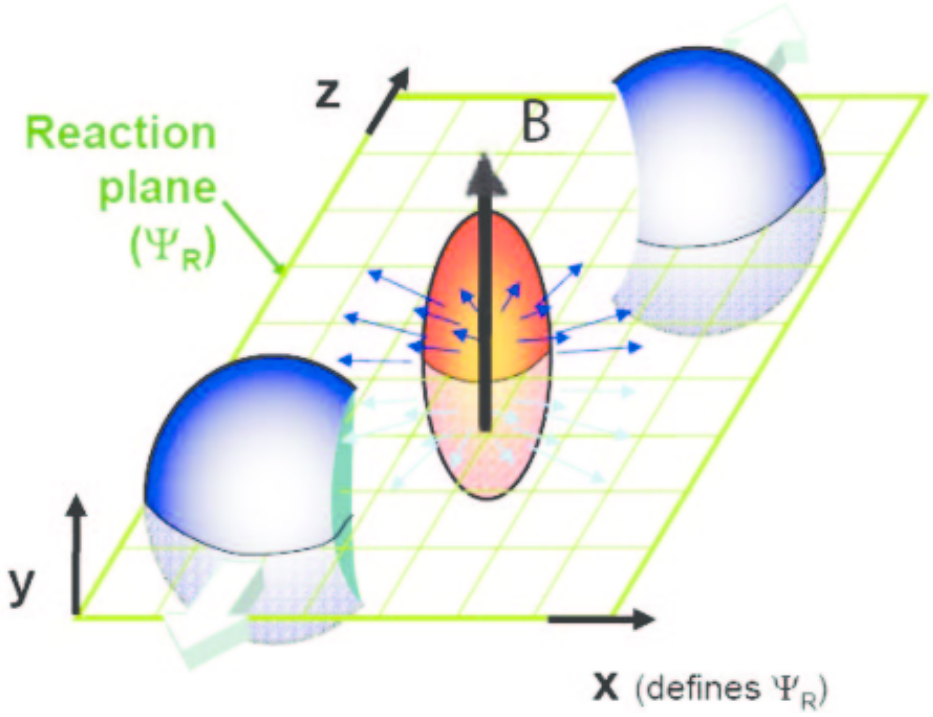
4. Di-lepton in UPC

Constraints for Electromagnetic field in QGP



Production of magnetic field

(B = 10^{15} T) in the medium?

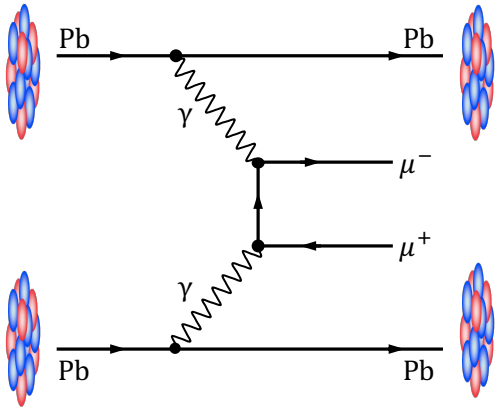
*PRL 121 (2018) 132301 by ***STAR***

*PRL 121 (2018) 212301 by ***ATLAS***

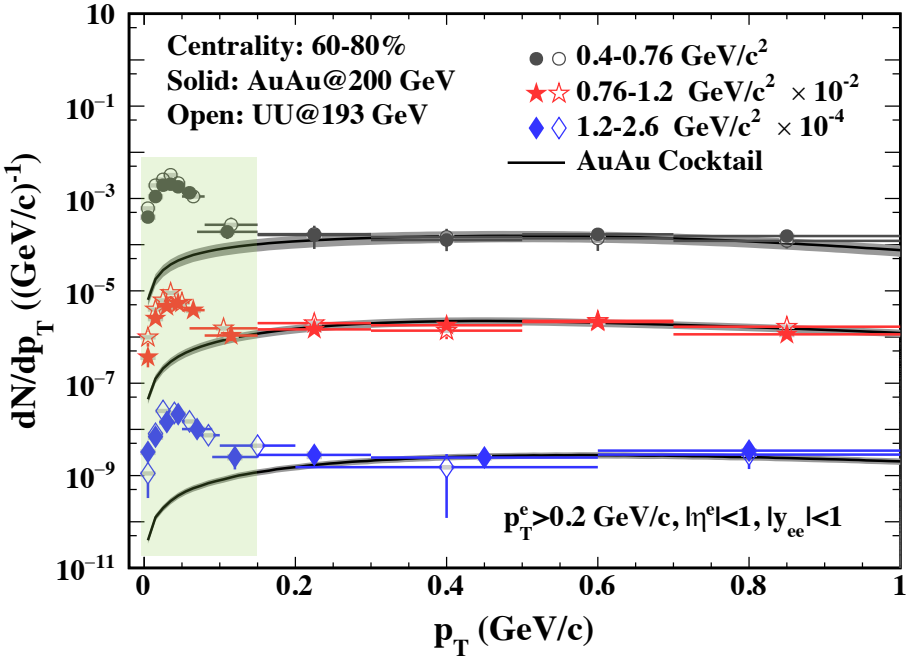
*PRL 127, 122001 (2021) by ***CMS***

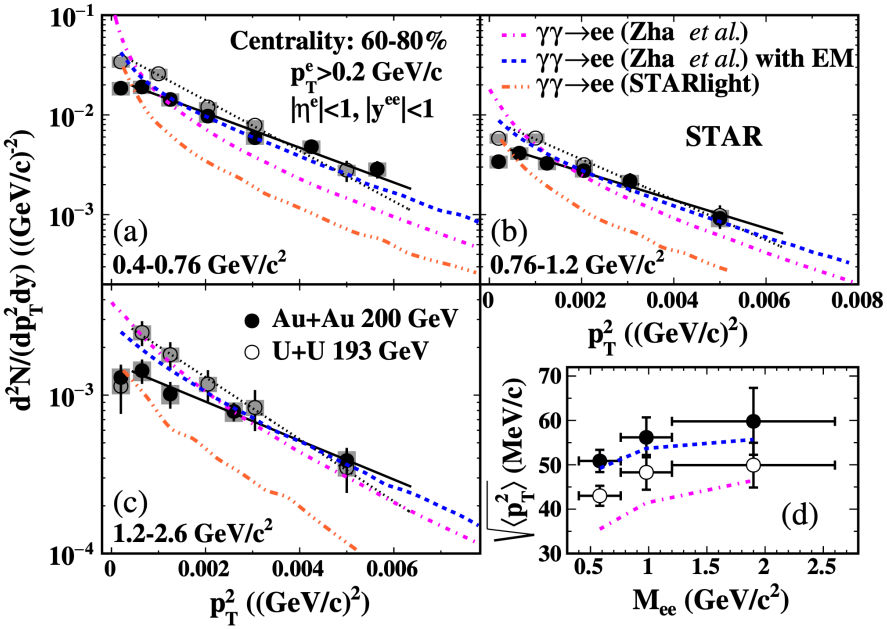
Di-lepton correlation

- $\gamma\gamma$ -> e^+e^- measured by STAR collaboration
  - Au+Au collision at $\sqrt{s_{NN}} = 200GeV$
  - U+U collision at $\sqrt{s_{NN}} = 193GeV$
- Data fits well with model with B = 10^{14} T
  - Evidence of formation of B field in heavy ion collision?



STAR PRL 121 (2018) 132301



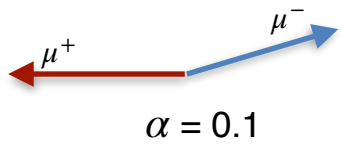


Angular correlation measured at the LHC

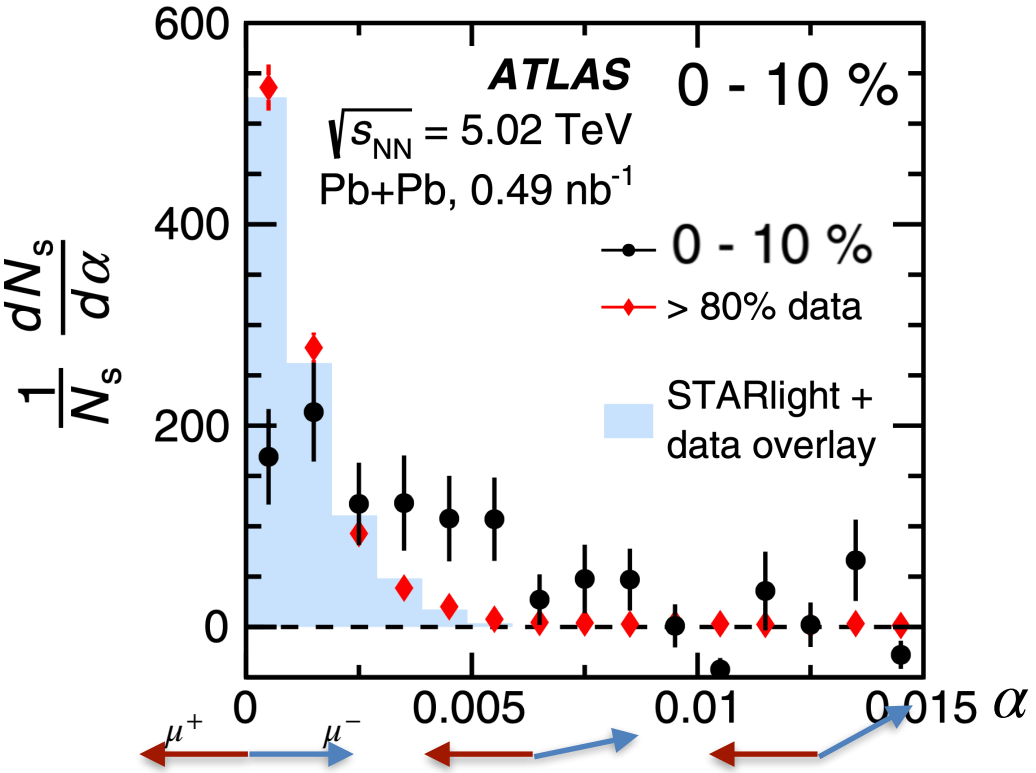
- ATALS collaboration
  - Pb+Pb collision at $\sqrt{s_{NN}} = 5.02\ TeV$

- Measured the azimuthal angular correlation of di-muon pairs

$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+ l^-}$$

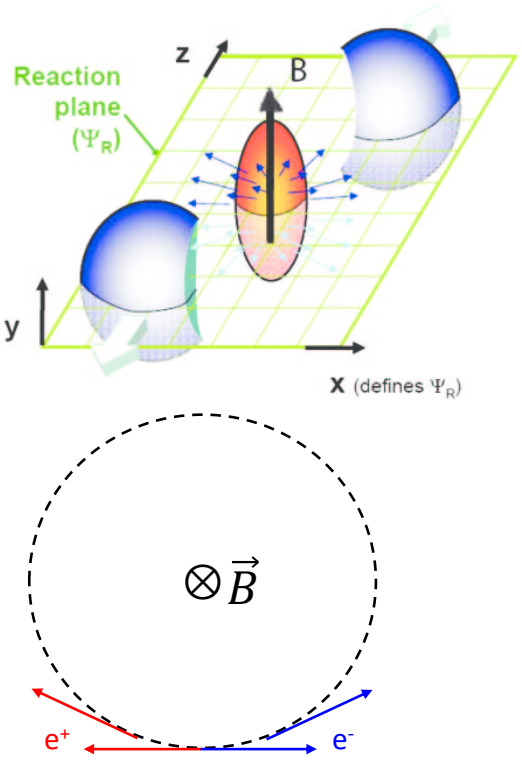


ATLAS, PRL 121 (2018) 212301



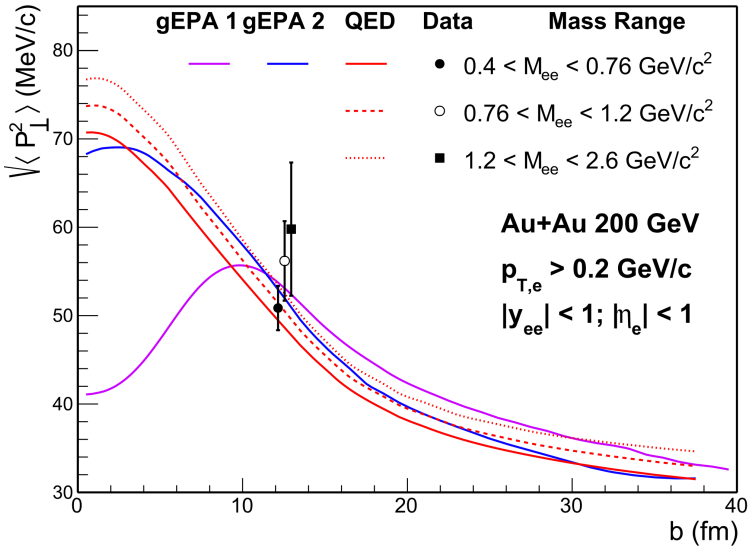
Interpretation of di-muon acoplanarity

Final state effect?



Formation of magnetic field?

Initial state effect?



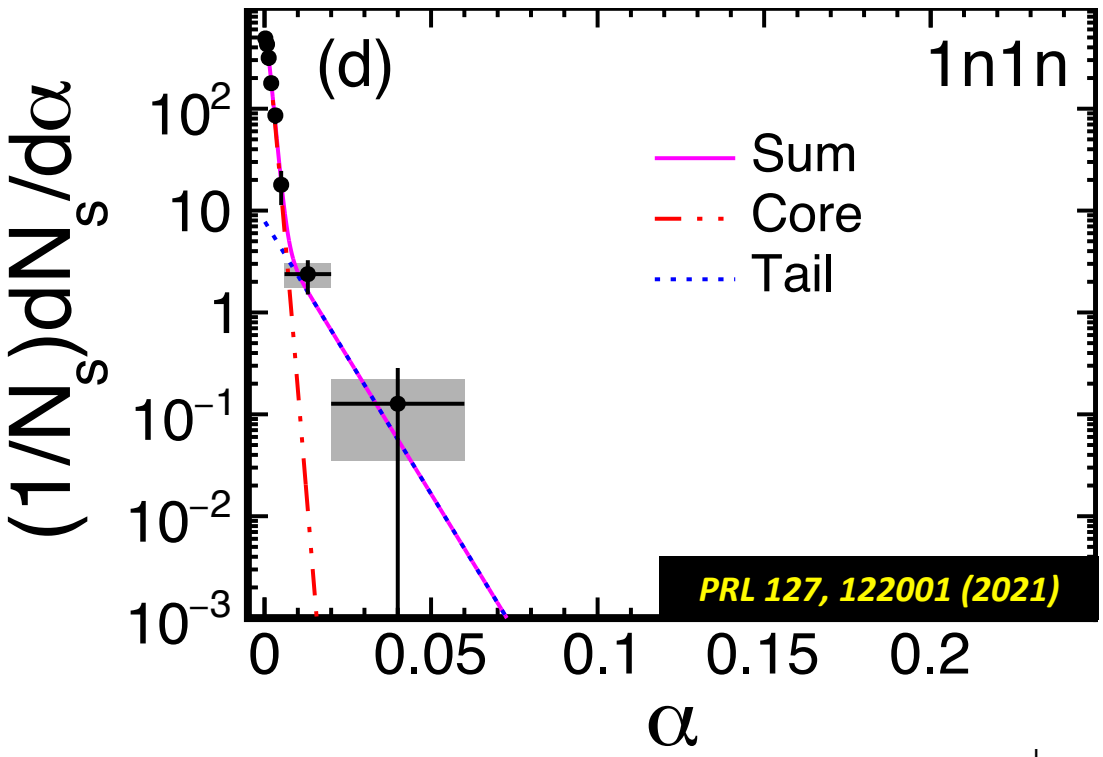
Pair $\langle p_T \rangle$ increases with ***b*** decreases

- Initial photon $\langle p_T \rangle$ increases with ***b*** decreases

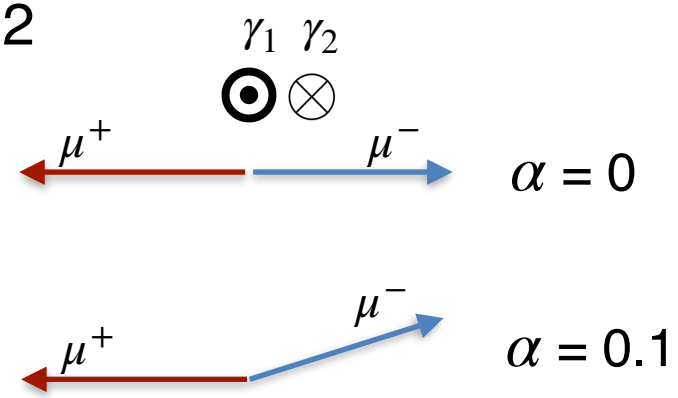
or, transverse momentum of initial photons?

UPC experiment can judge because there is no QCD medium produced in UPC

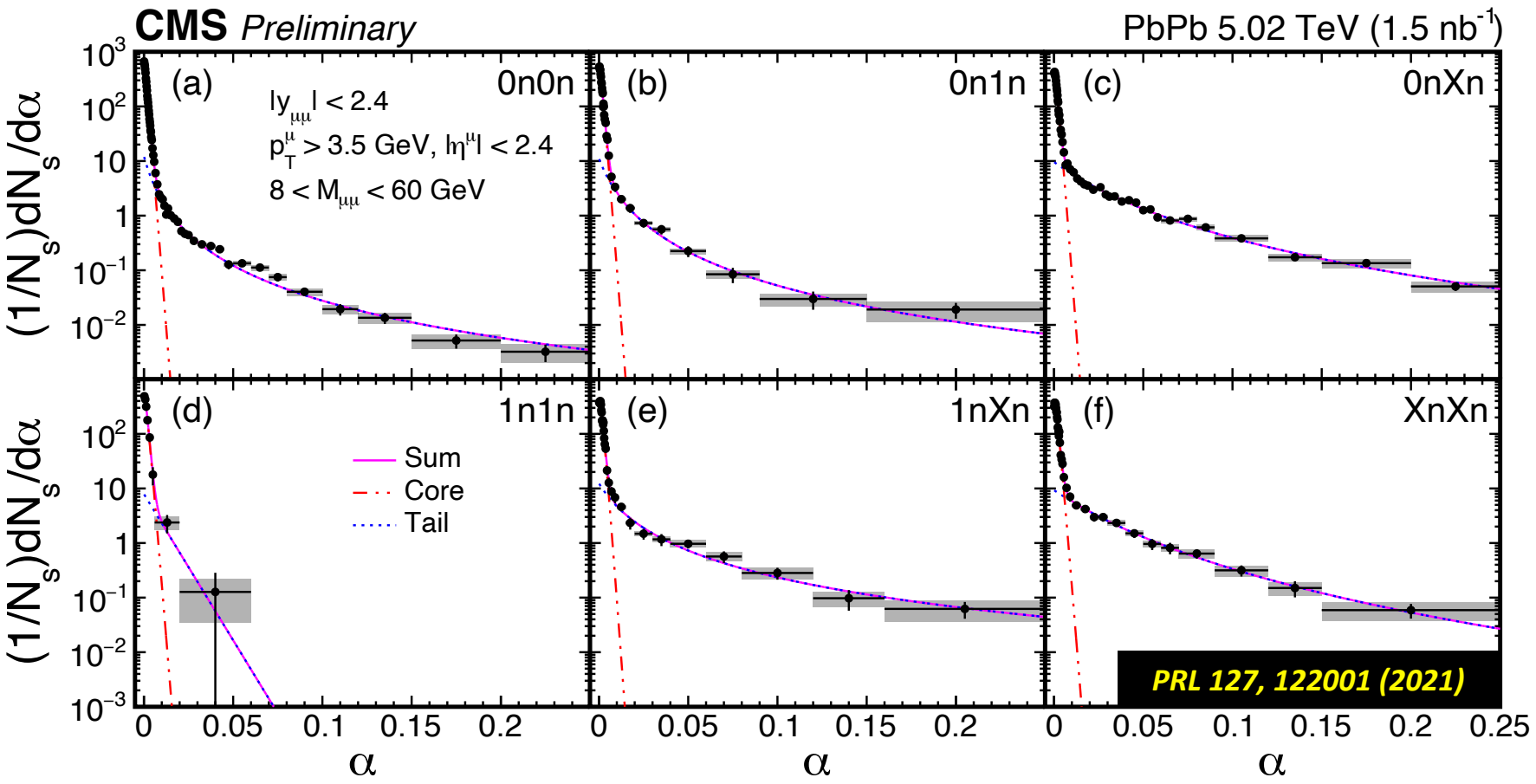
CMS result



$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+l^-}$$

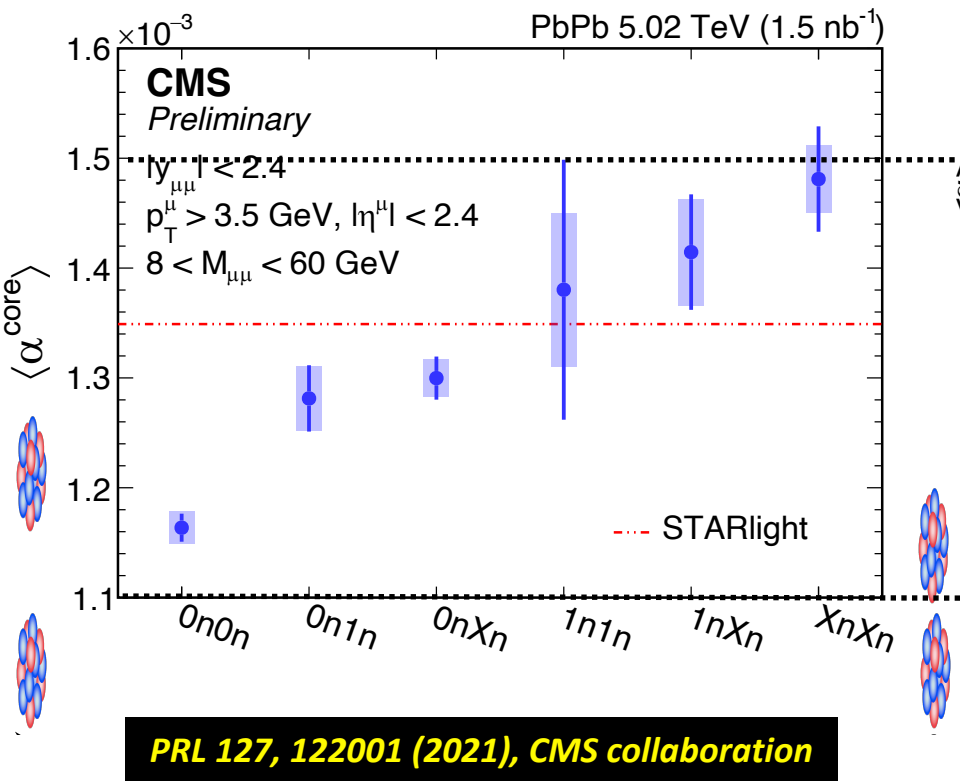


CMS result



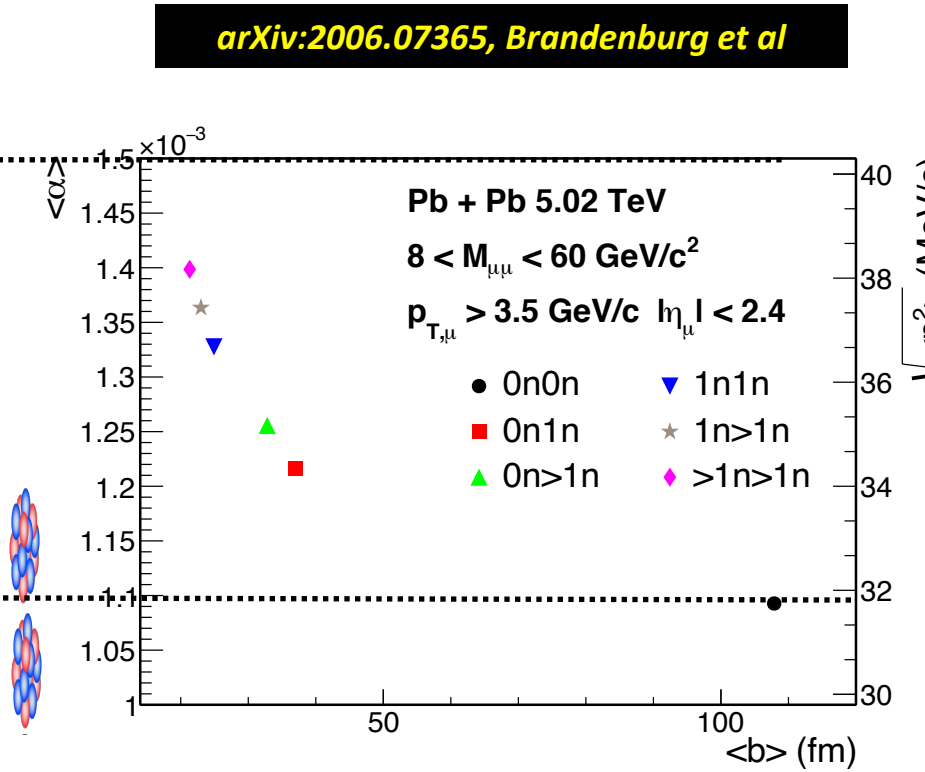
Core (red dashed line) structure is attributed to the leading order interaction, and the tail to the next to leading order

CMS result



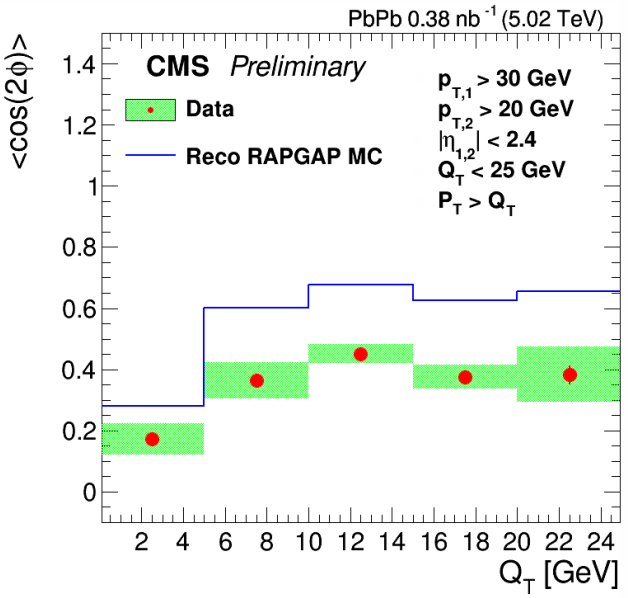
PRL 127, 122001 (2021), CMS collaboration

arXiv:2006.07365, Brandenburg et al



- Strong dependence of the di-muon acoplanarity on the impact parameter among UPC collisions
- Significant acoplanarity observed without production of QCD medium

Take home messages



- **UPC** in heavy ion experiments is useful to study photo-induced dynamics with very small noise
- Photon-photon scattering was recently measured by ATLAS and CMS and provided strong constraints for ALP production mechanism
- CMS made the first step to extract the Wigner/Husimi distribution of nucleus using di-jet correlation
- More interesting results are in the queue, including precision measurement of di-jet, τ g-2, etc, so please stay tuned

BACKUP