U.S. DEPARTMENT OF ENERGY

Office of Science

UPCs and electromagnetic probes

Daniel Tapia Takaki

Quark Matter 2023 - Lecture at Student Day

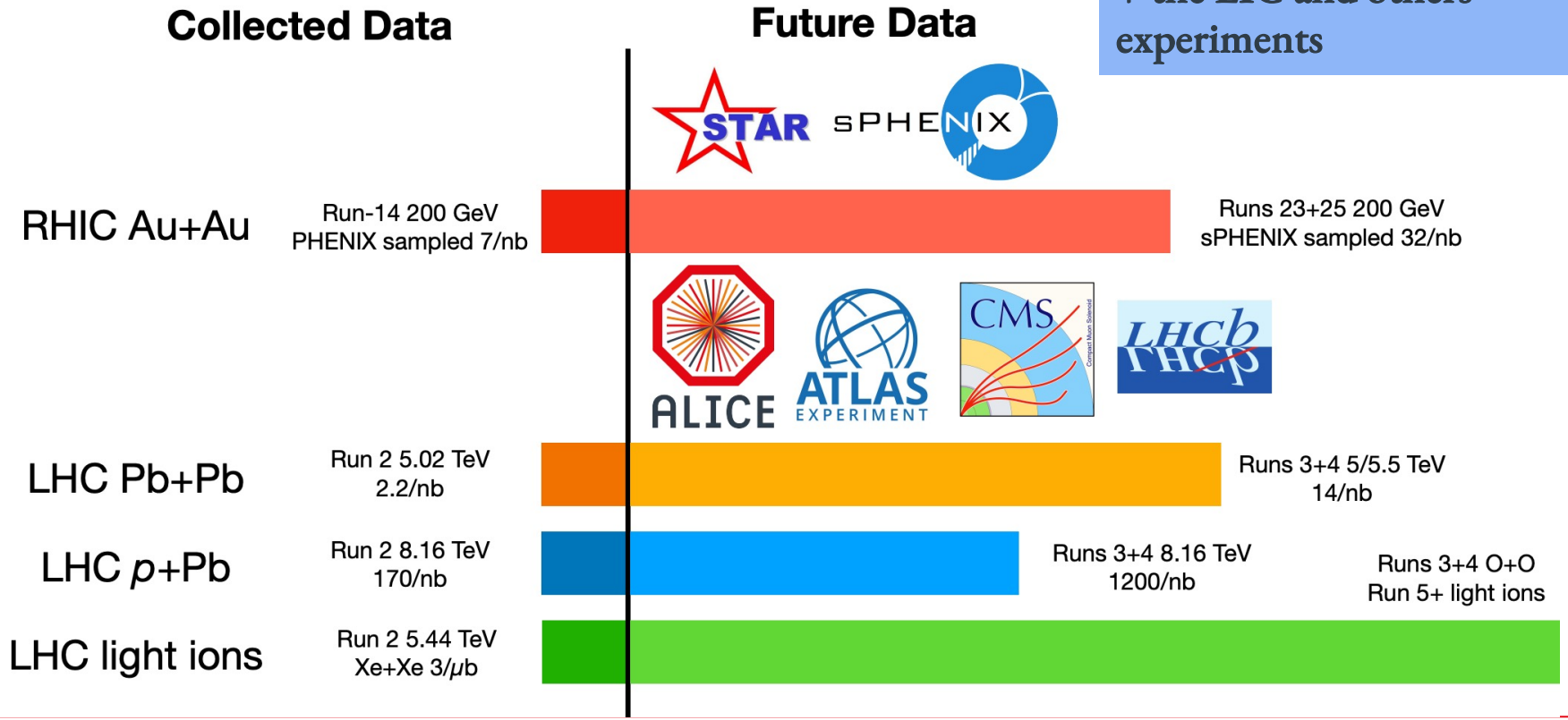
Houston, Texas – September 3, 2023

KU THE UNIVERSITY OF KANSAS

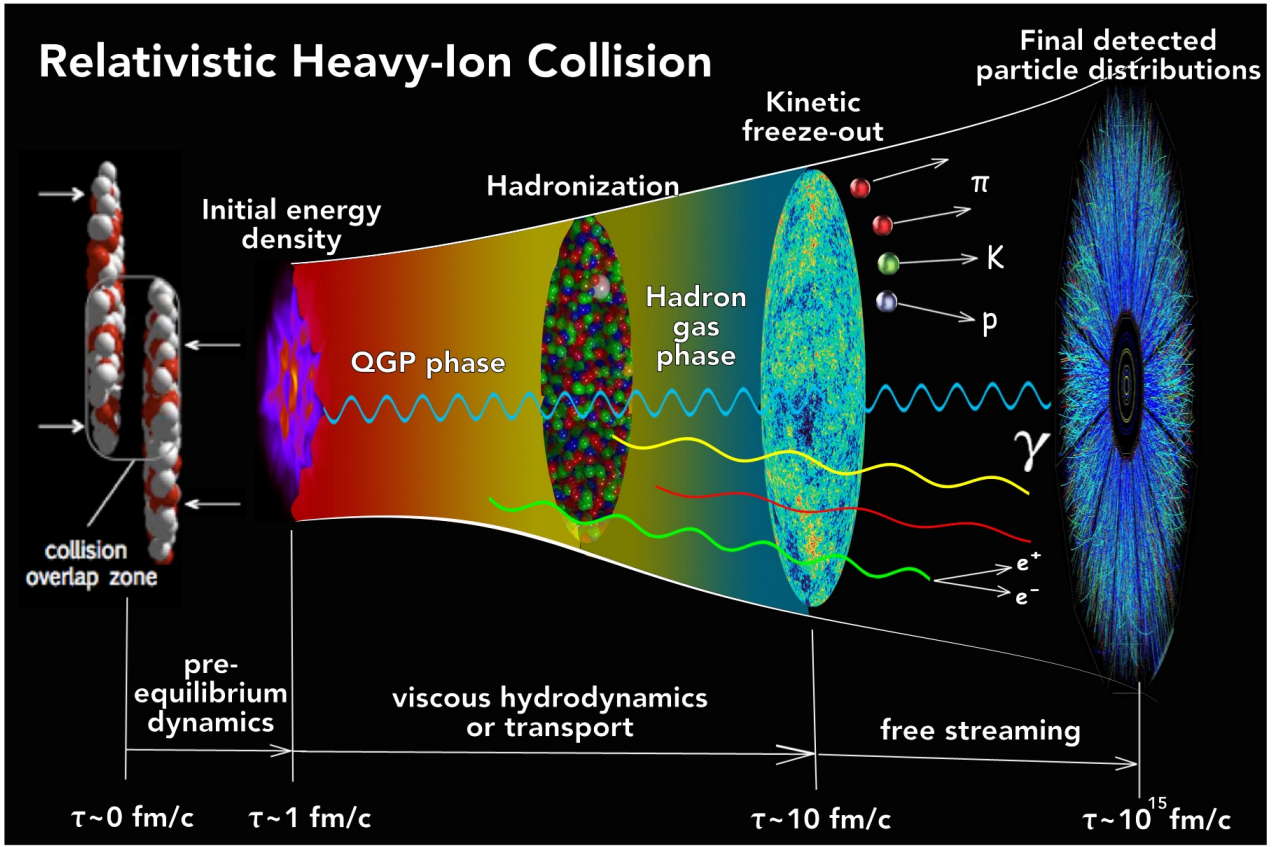
A great time to be in the field of heavy ion physics

Dennis V. Perepelitsa
QCD Town Hall meeting 2022

+ the EIC and others experiments



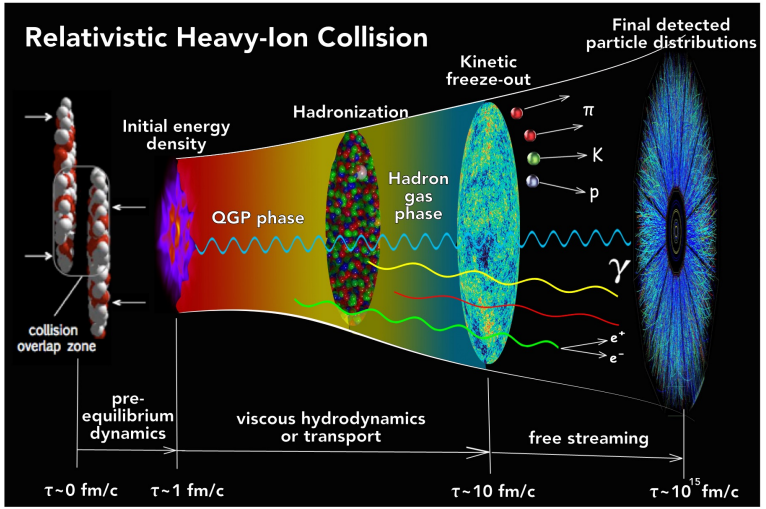
Stages of a heavy ion collision



Heavy-ion collisions

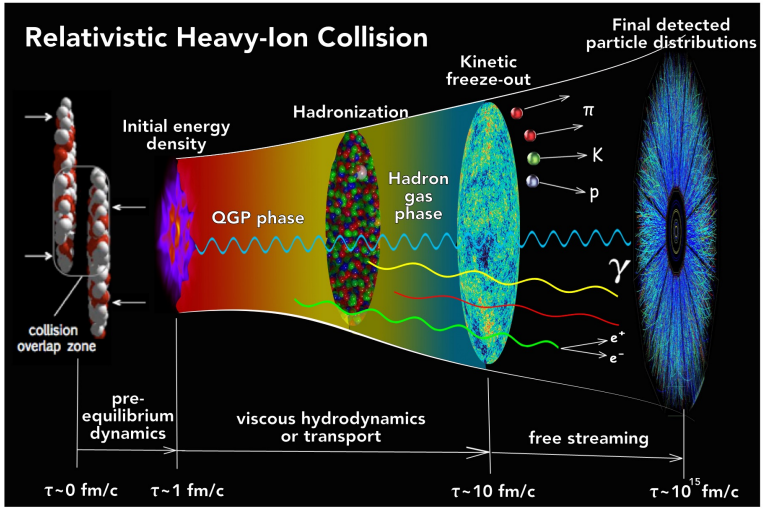
- **What are the properties of the hot and dense QGP:** equation of state, transport properties

- How to measure the QGP experimentally?
- The theory and phenomenological modeling of the QGP?
- How to compare theory and experimental results?



Heavy-ion collisions

- **What are the properties of the hot and dense QGP:** equation of state, transport properties



- How to measure the QGP experimentally?
- The theory and phenomenological modeling of the QGP?
- How to compare theory and experimental results?

- **Besides the QGP, what other (QCD) phenomena we could learn in heavy-ion collisions?**

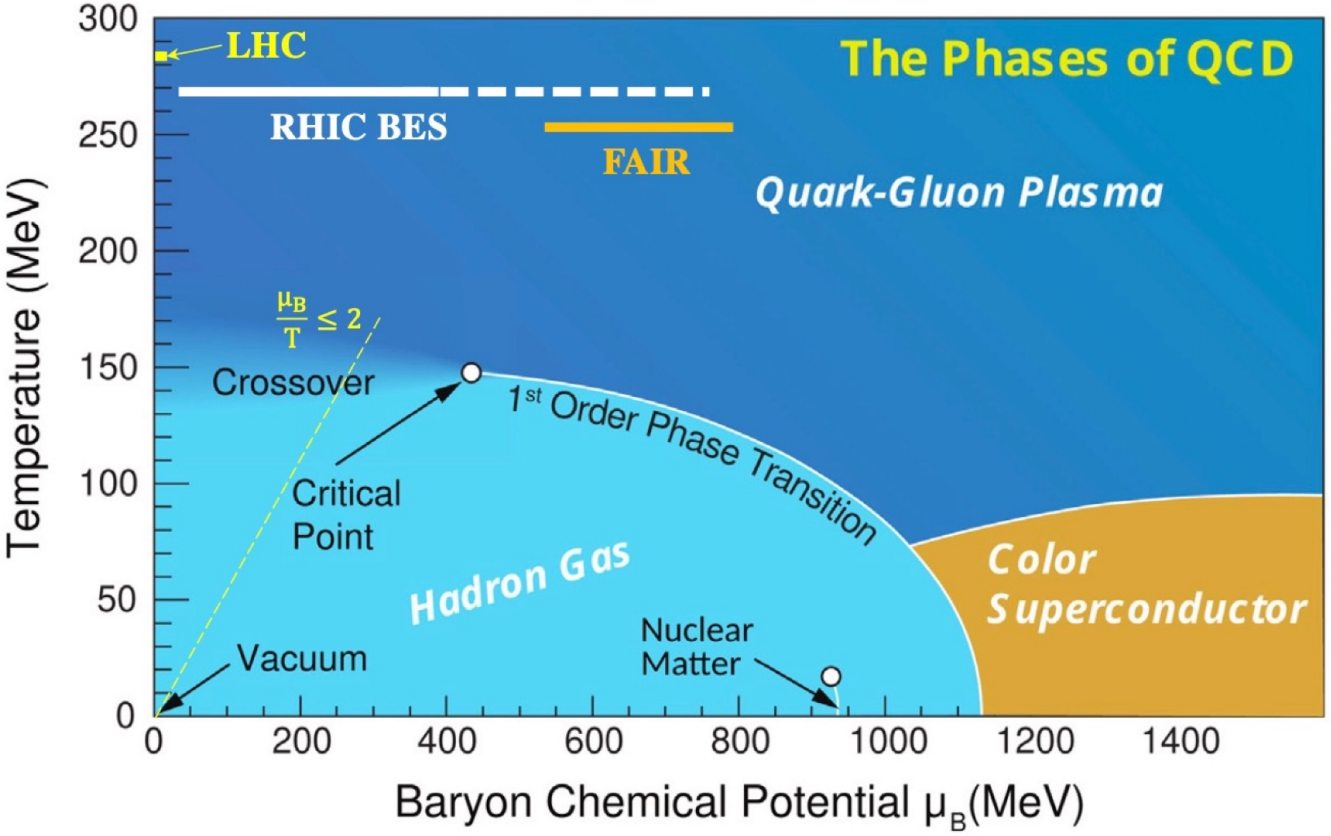
Electromagnetic probes: early times and time evolution

Electromagnetic probes: early times and time evolution

Thermal properties of the QGP:
Low-energy photons and low-mass dileptons radiated from the plasma, but they do not have further interactions

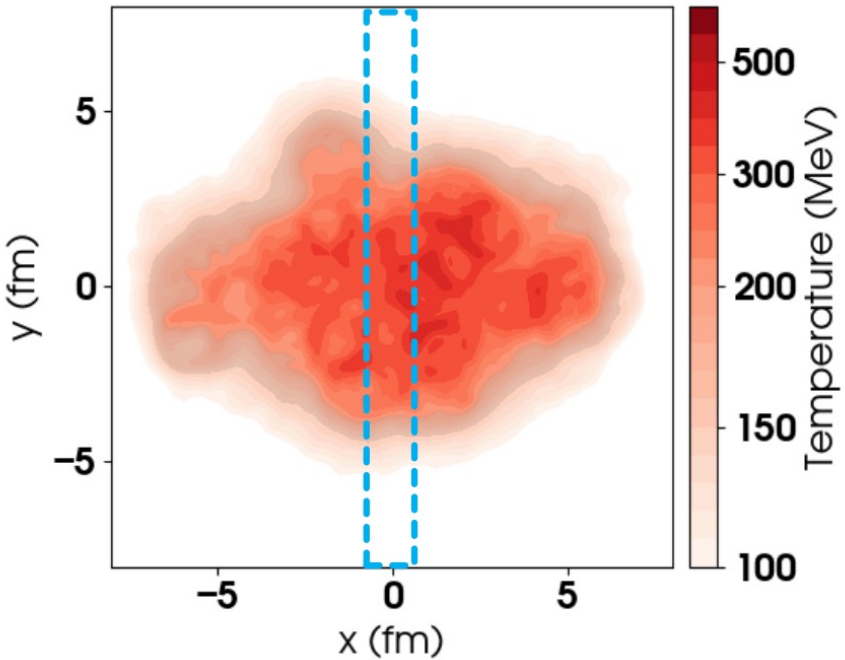
Initial properties of the collision:
High-energy photons, dileptons and weak bosons are mainly produced when the nuclei initially collide

What are the conditions for the QCD phase transition?



Temperature profile

Jean-François Paquet
https://arxiv.org/pdf/2307.09967.pdf

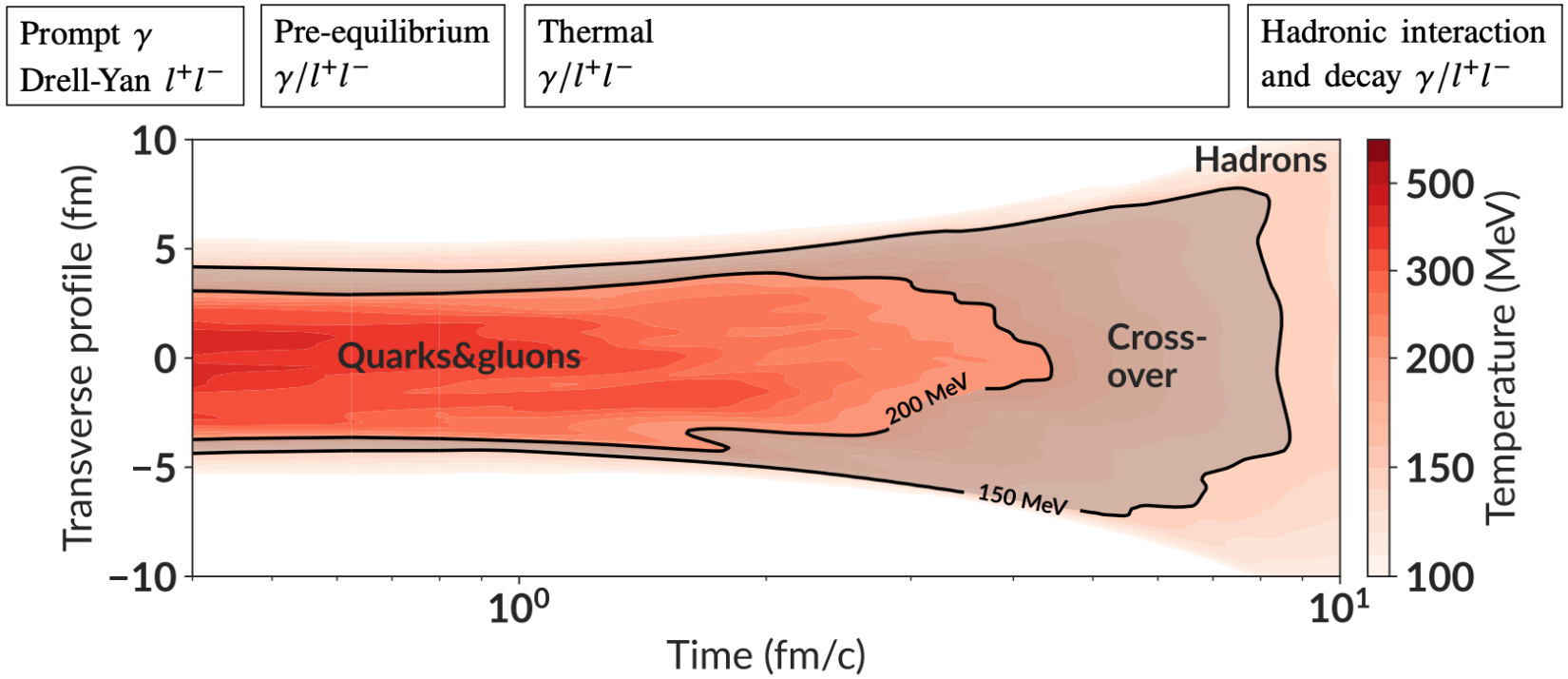


$$\frac{d\,Volume}{d\,T} \sim T^{-\left(2c_s^{-2}+1\right)} \sim T^{-9}$$

[c_s^2 is speed of sound]

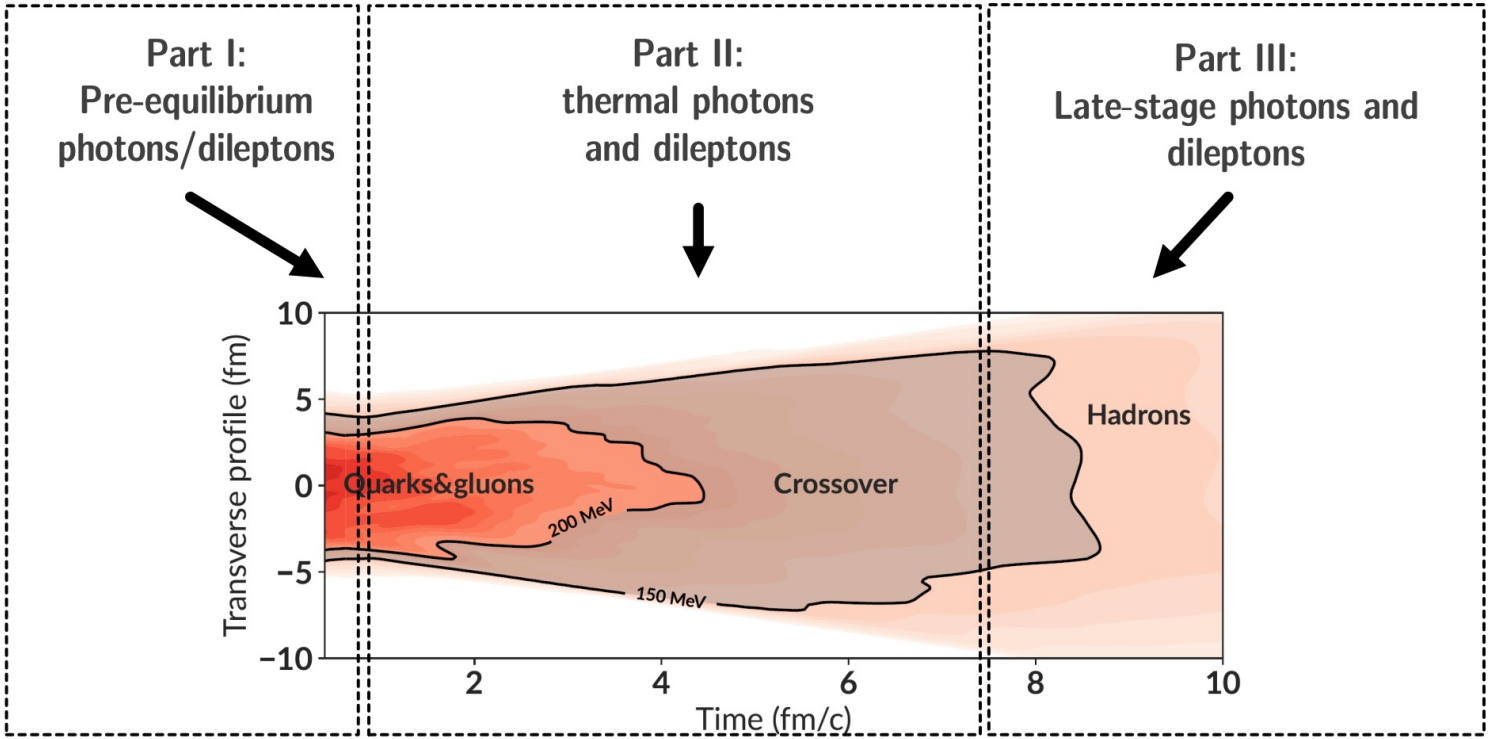
Electromagnetic radiation produced early

Jean-François Paquet
https://arxiv.org/pdf/2307.09967.pdf



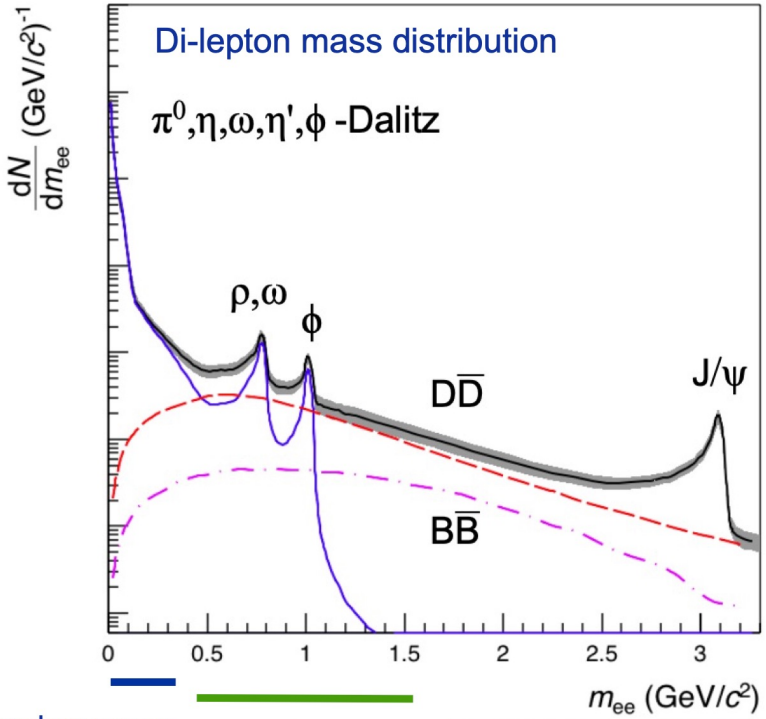
Electromagnetic radiation produced early

Jean-François Paquet
Hard probes 2023



Challenging measurements

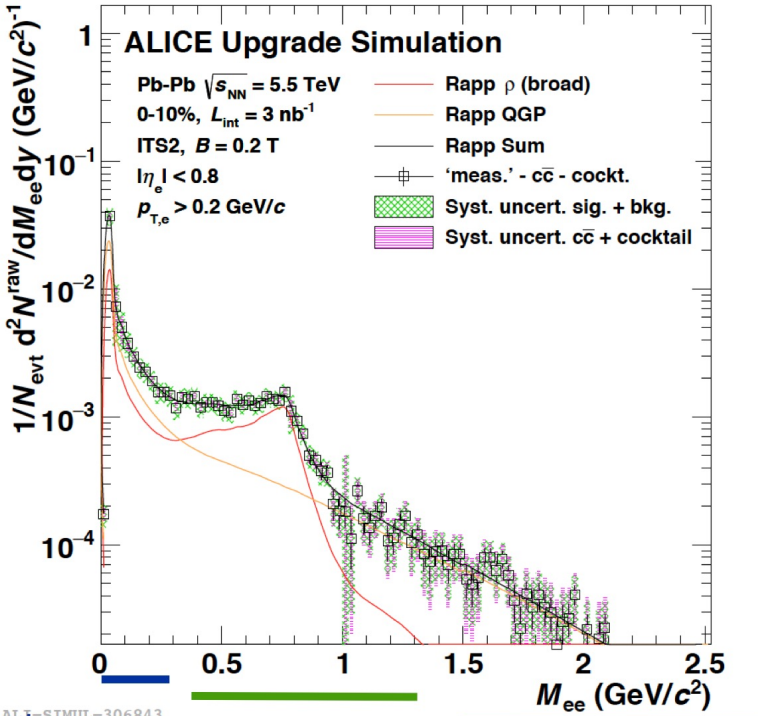
Francesca Bellini
CERN student lectures



Very low mass: conductivity

omega/phi region: chiral symmetry and rho-a_1 mixing

Large mass: very early times



Very low mass: conductivity

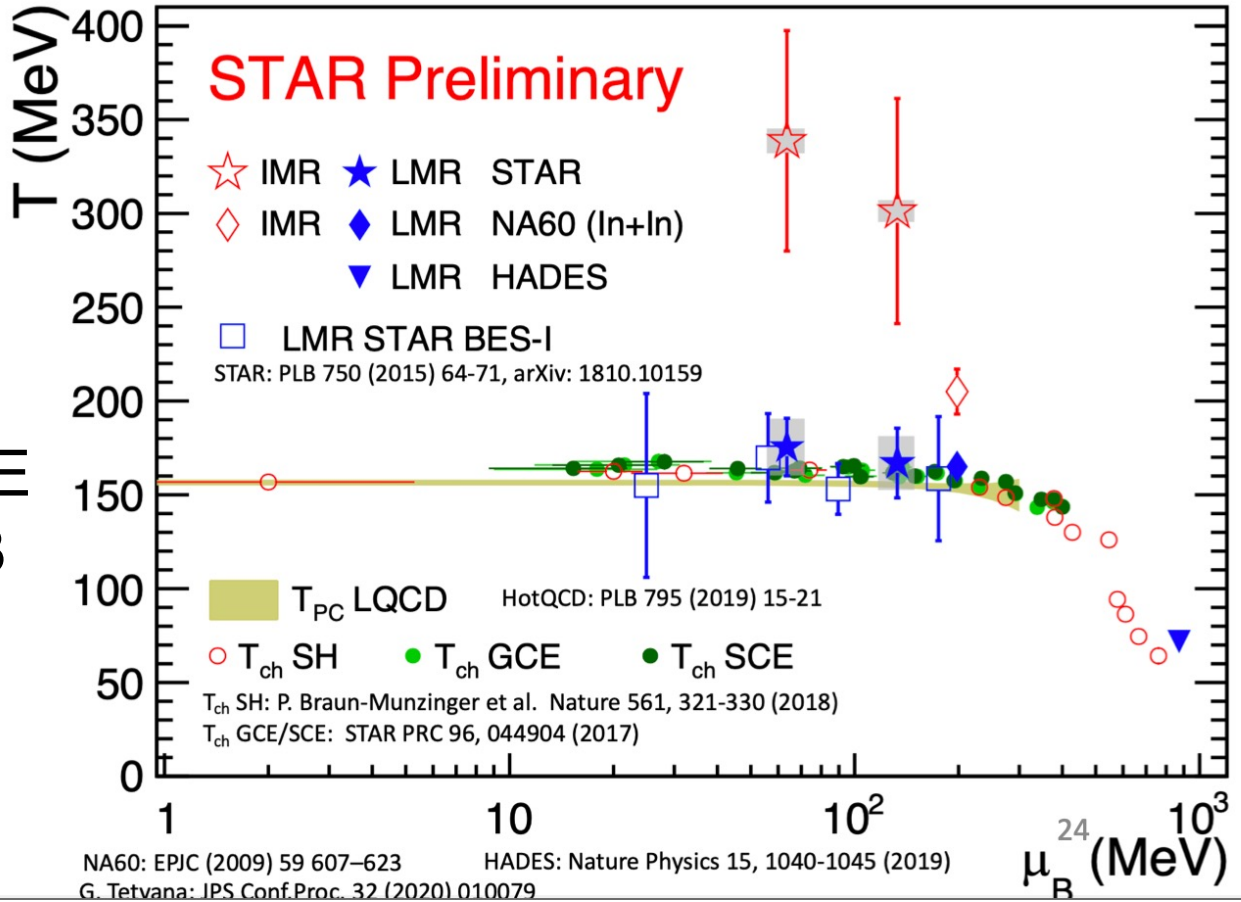
omega/phi region: chiral symmetry and rho-a_1 mixing

Large mass: very early times

Lots of future potential

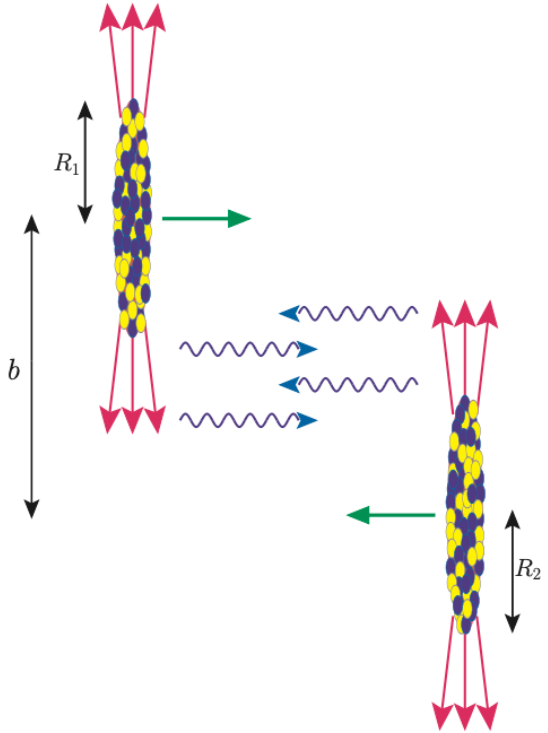
Lijuan Ruan
QM'23 student lecture

BESII and future NA60+, CBM, and Run 3 and 4 in ALICE (FoCal), and ALICE3



UPCs: Ultra-peripheral heavy ion collisions

UPC: Ultra peripheral collisions

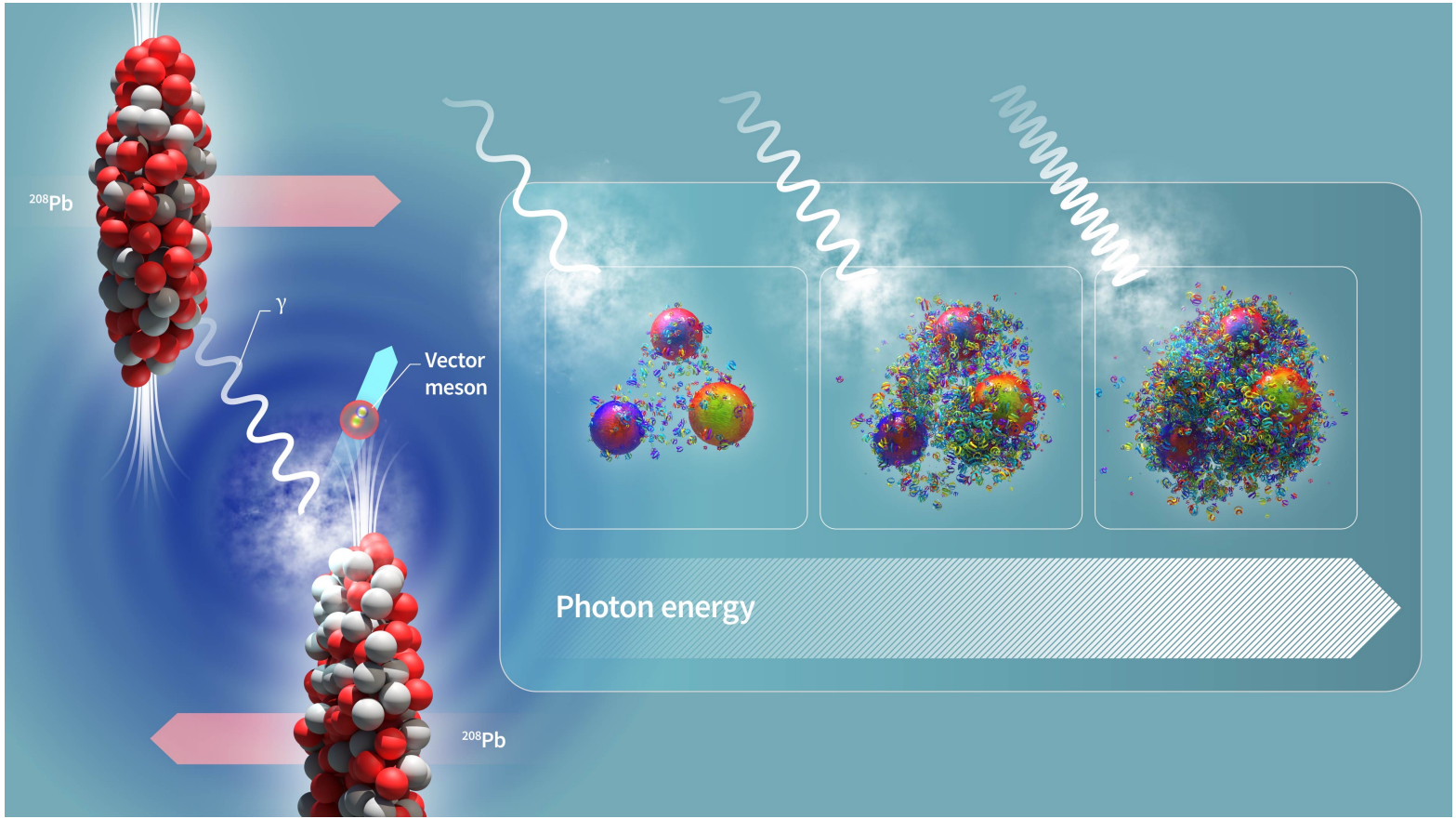


Two heavy nuclei in the sky
Were speeding on their way
They met upon a common course
But did not touch that day

They did not know what they would make
A photon or a pair
They only knew they had to shake
The fields that made them glare

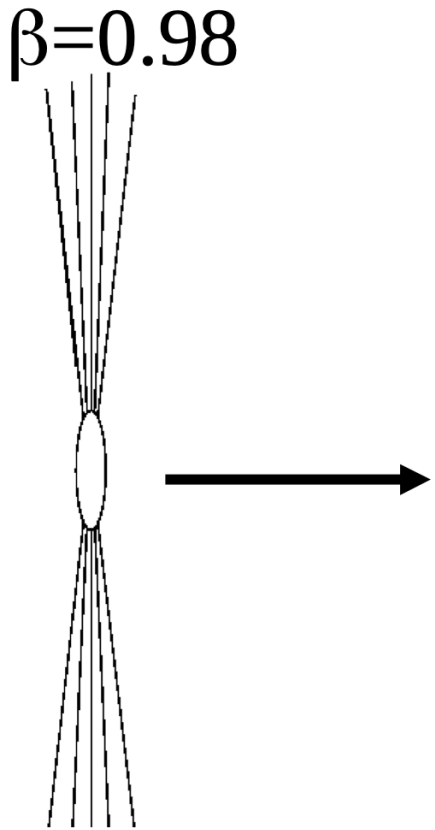
A poem generated by Bing AI

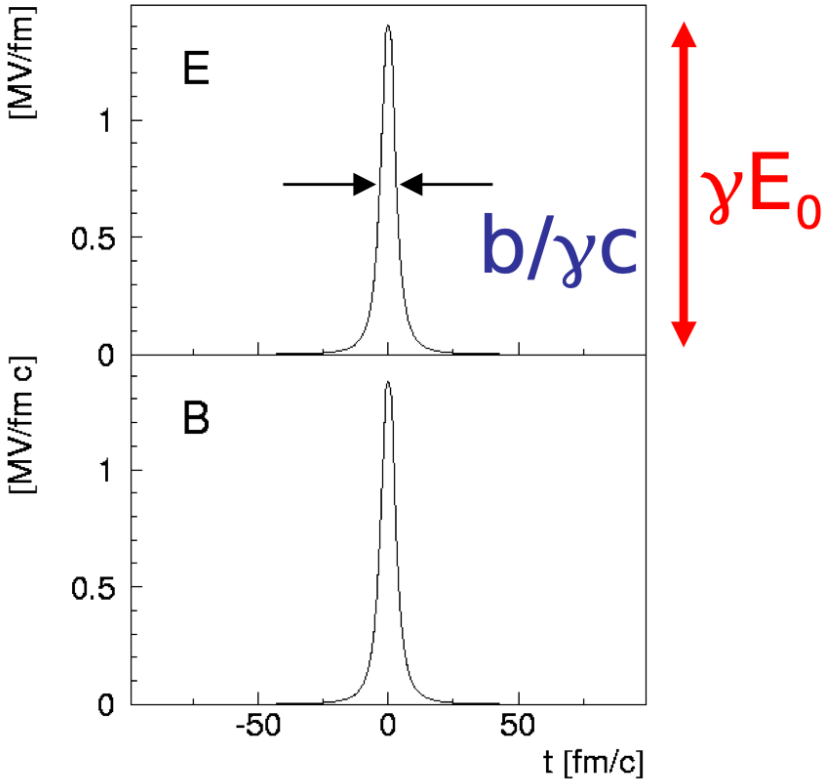
Ultra peripheral collisions



EM fields of a charged particle

Joakim Nystrand
Student lectures at
Forward QCD 2022





Pulse width

The photon flux can be computed through a Fourier transform
Weizsäcker-Williams method (1934)

RHIC and LHC as Photon Colliders

- **Ultra Peripheral Collisions (UPC)** can explore a wide range of energies using almost real photons

  $k = \gamma M_V \exp(\pm,y)$

  Up to several TeV in γp

  Up to ~ 700 GeV/nucleon in γA

  Up to ~ 150 GeV in $\gamma\gamma$ using UPC PbPb,

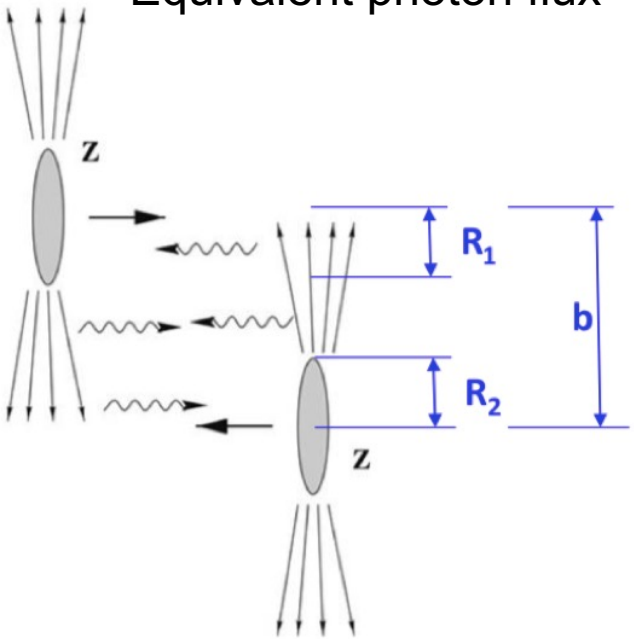
  ~ 4 TeV in in $\gamma\gamma$ using UPC pp

- UPCs at the LHC probe the hadronic structure over broad and unique Bjoren *x* region, yet the precision not compatible to DIS machines like the EIC

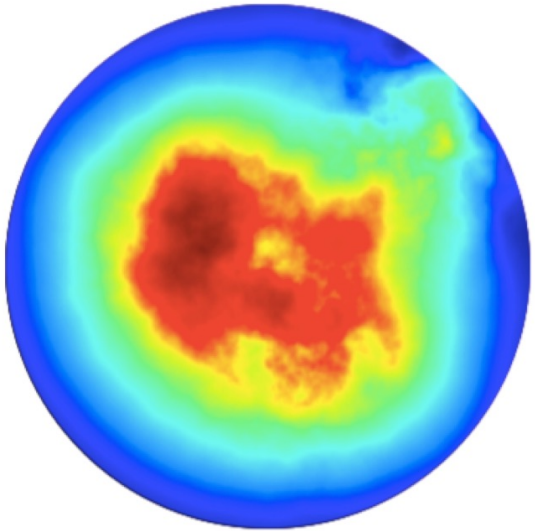
  $x = M_V/\gamma m_p \exp(\pm,y)$

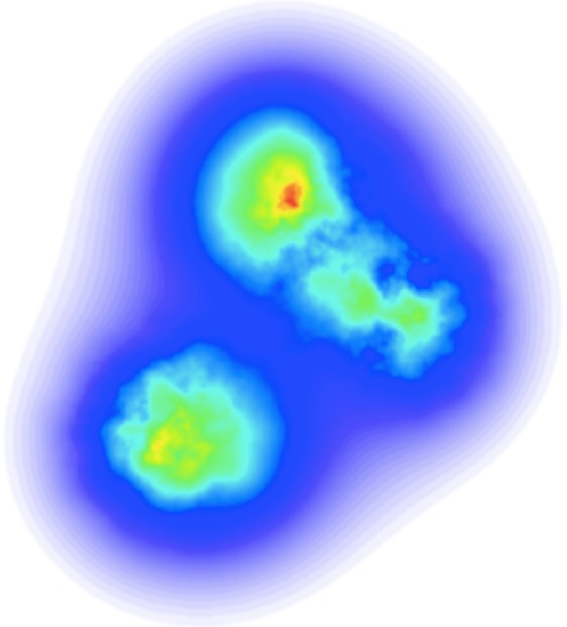
Interactions mediated by the EM interactions

Equivalent photon flux



The structure and dynamics of hadrons

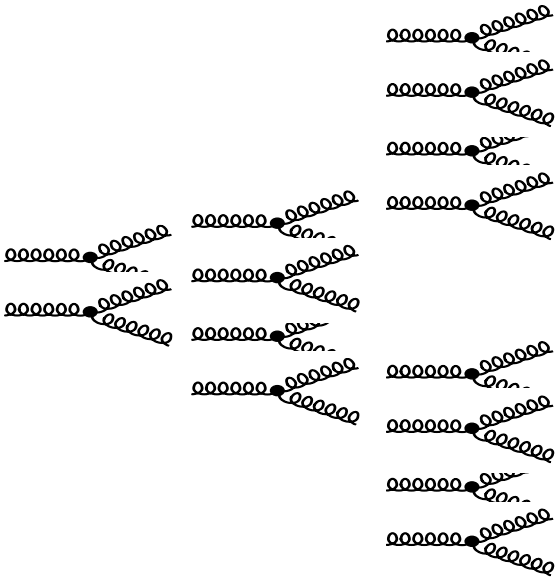




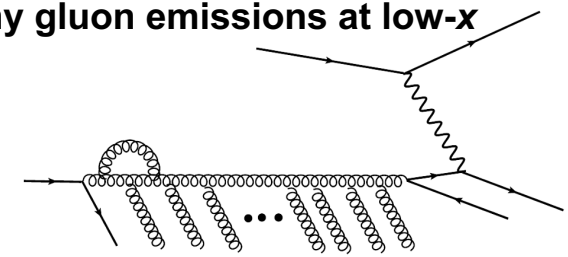
Gluons matter

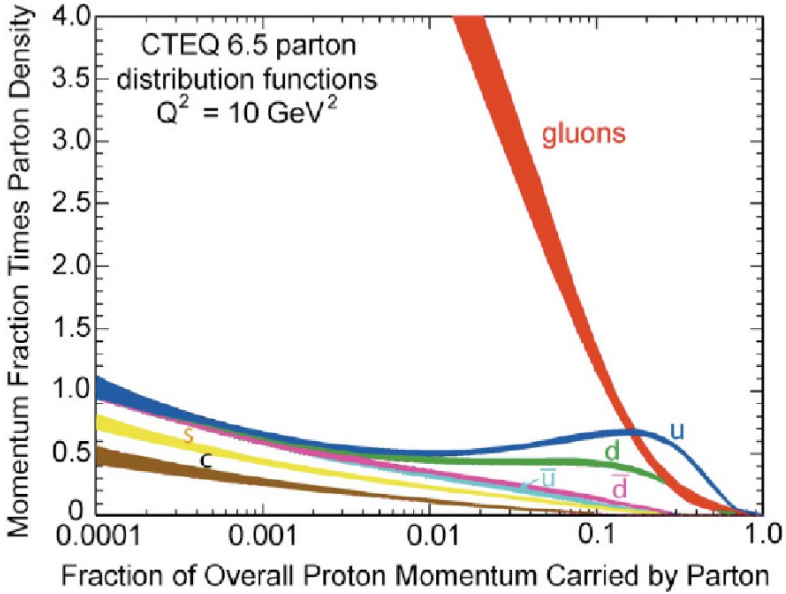
Quarks and gluons dynamics described by QCD

Gluons carry color, thus self-gluon interactions



Many gluon emissions at low-*x*





Gluon saturation

At high energies, or for heavy nuclei at lower energies, gluon saturation is predicted

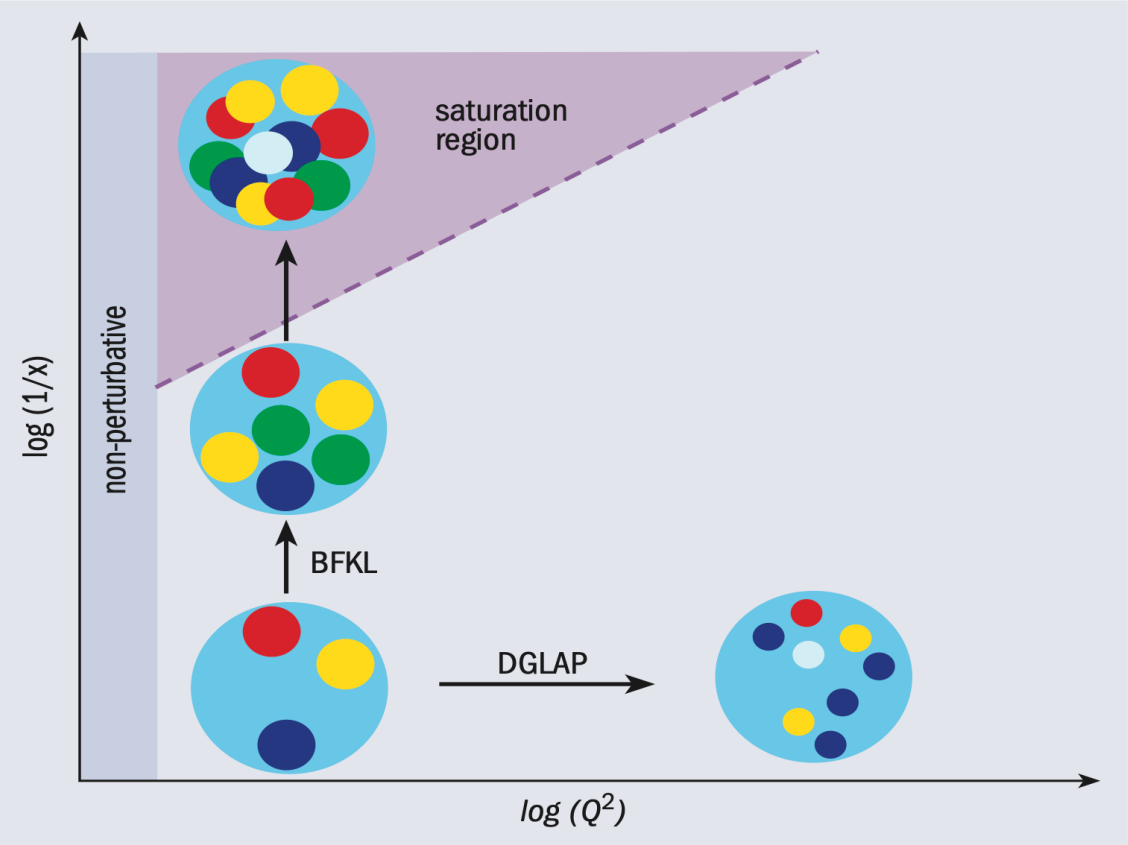
gluon emission

gluon recombination

Dynamical equilibrium of gluon saturation state reached

- Non-linear QCD evolution equations introduced, but how is gluon saturation triggered?
- Can we determine experimentally the saturation scale (Q_S)?
- Is there a state of matter formed by gluon saturated matter with universal properties?

Evolution of the hadronic structure with Bjorken-x and Q^2

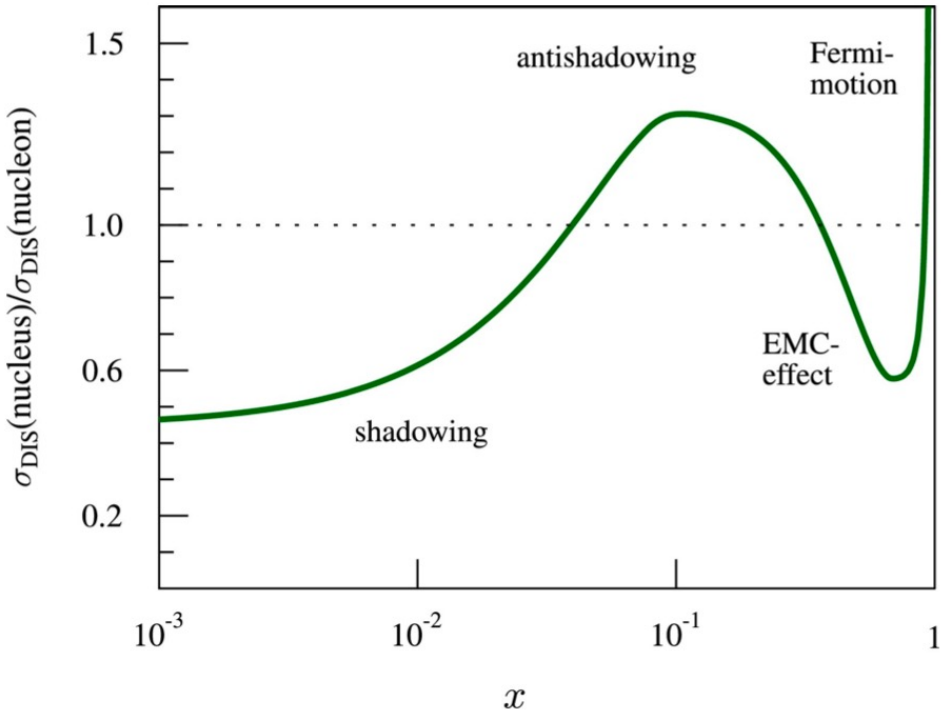


- Experimental observables needed to map out the transition between the dilute and saturation regimes
- For nuclei, the saturation scale is enhanced by a $A^{1/3}$ factor

$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

Nuclear shadowing experimentally confirmed, but not fully understood

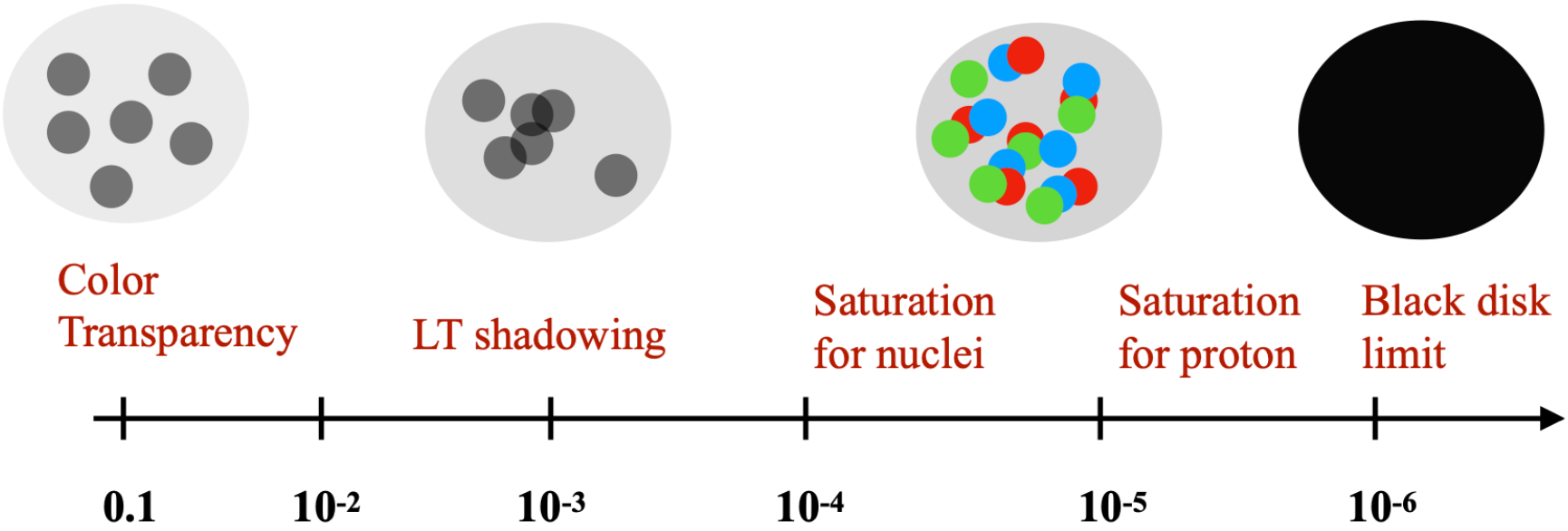
$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$



- Experimental observation that parton distributions are different for protons and nuclei
- What's the mechanism responsible for shadowing? How is gluon saturation related?
- The knowledge of the initial state of nuclei also needed for understanding the QGP evolution

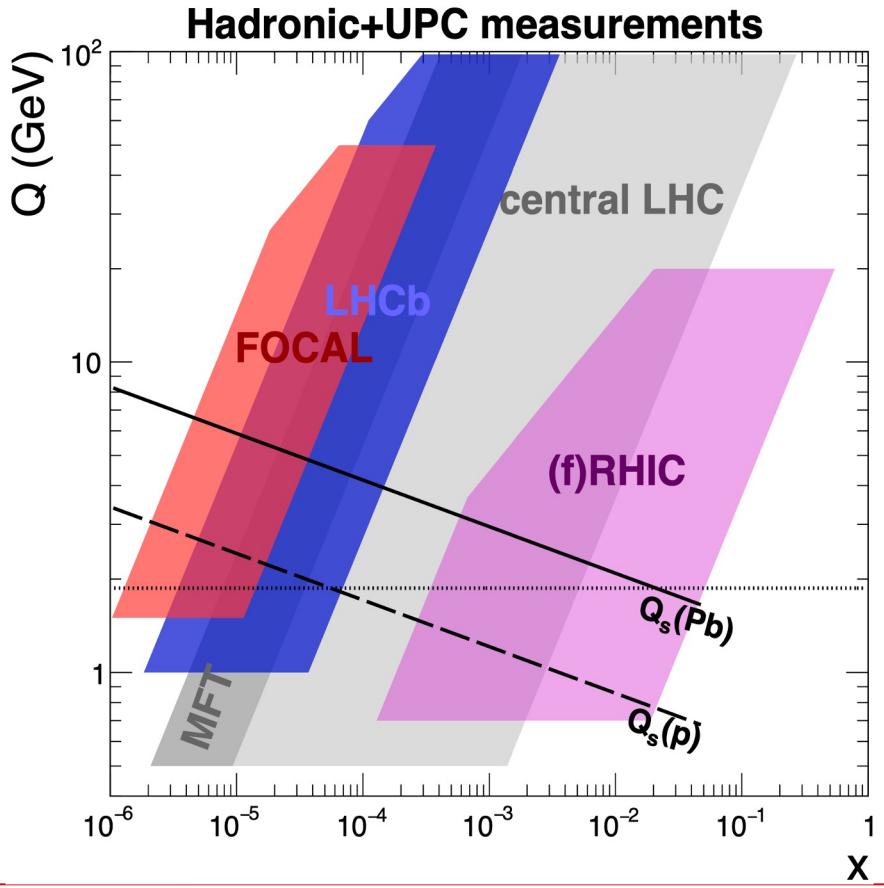
Possible stages?

Vadim Guzey
Hard Probes 2023



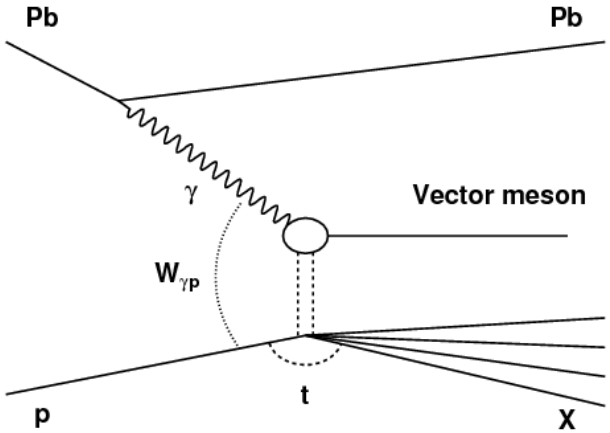
Experimental program

- The Electron-Ion Collider will be a dedicated QCD machine with the precision and control capabilities for studying gluon saturation and shadowing in a systematic way like never before.
- The LHC explores the high energy domain for both hadronic and photon-induced reactions
- FoCal at ALICE will explore a unique low-*x* regime reaching $x \sim 10^{-6}$



Vector meson (VM) photoproduction in UPCs

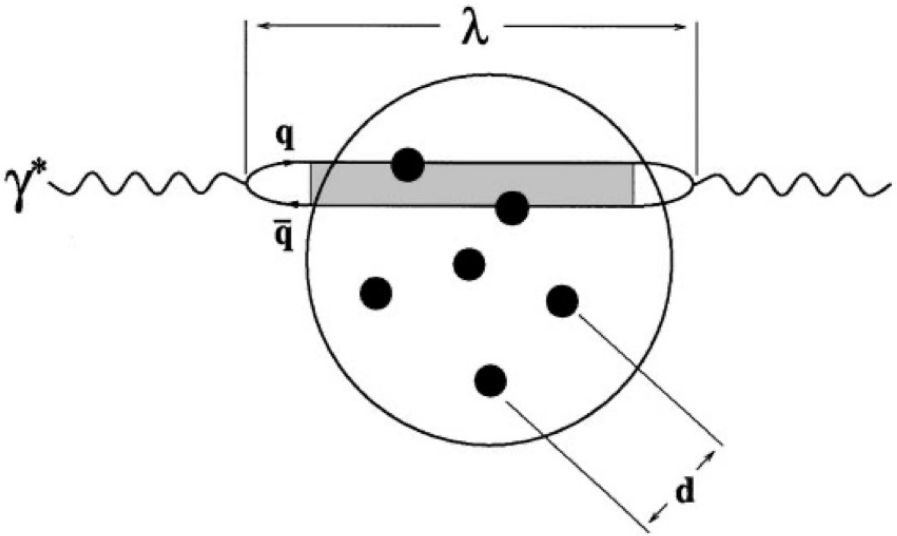
$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$



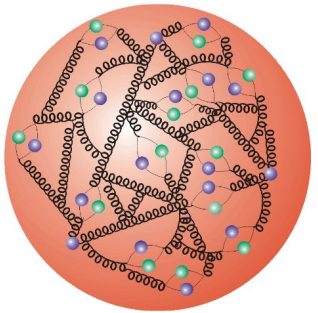
- As in DIS, several reactions are possible in UPCs:

  -Exclusive photoproduction
  -Semi-exclusive photoproduction
  -Inclusive photoproduction

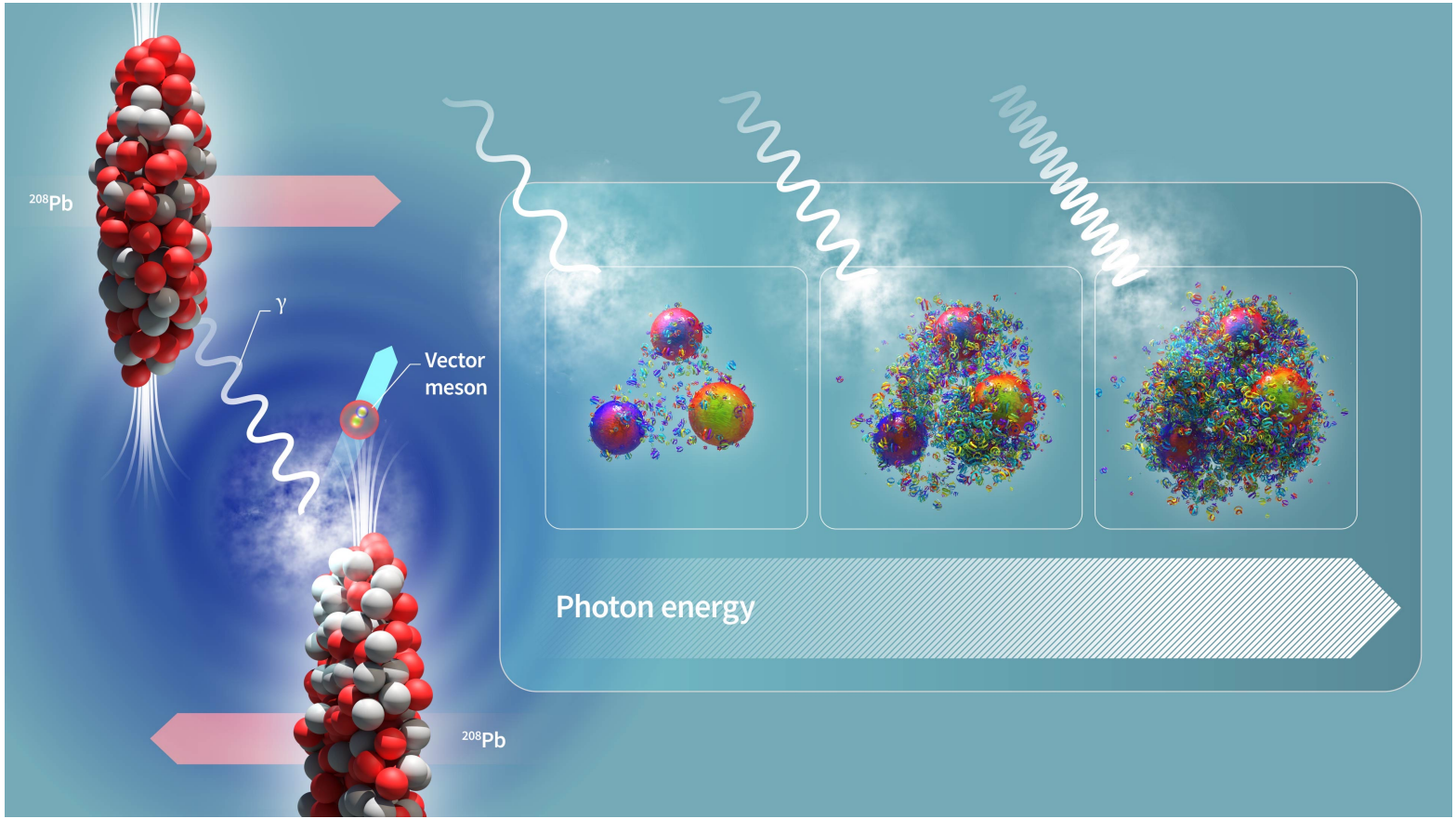
Vector meson (VM) photoproduction in UPCs



- By studying various VMs, it is possible to study the Q^2 dependence
- In the dipole approach, the light VMs (ϕ, ρ^0) are more sensitive to saturation because of the larger dipole, but pQCD methods not applicable

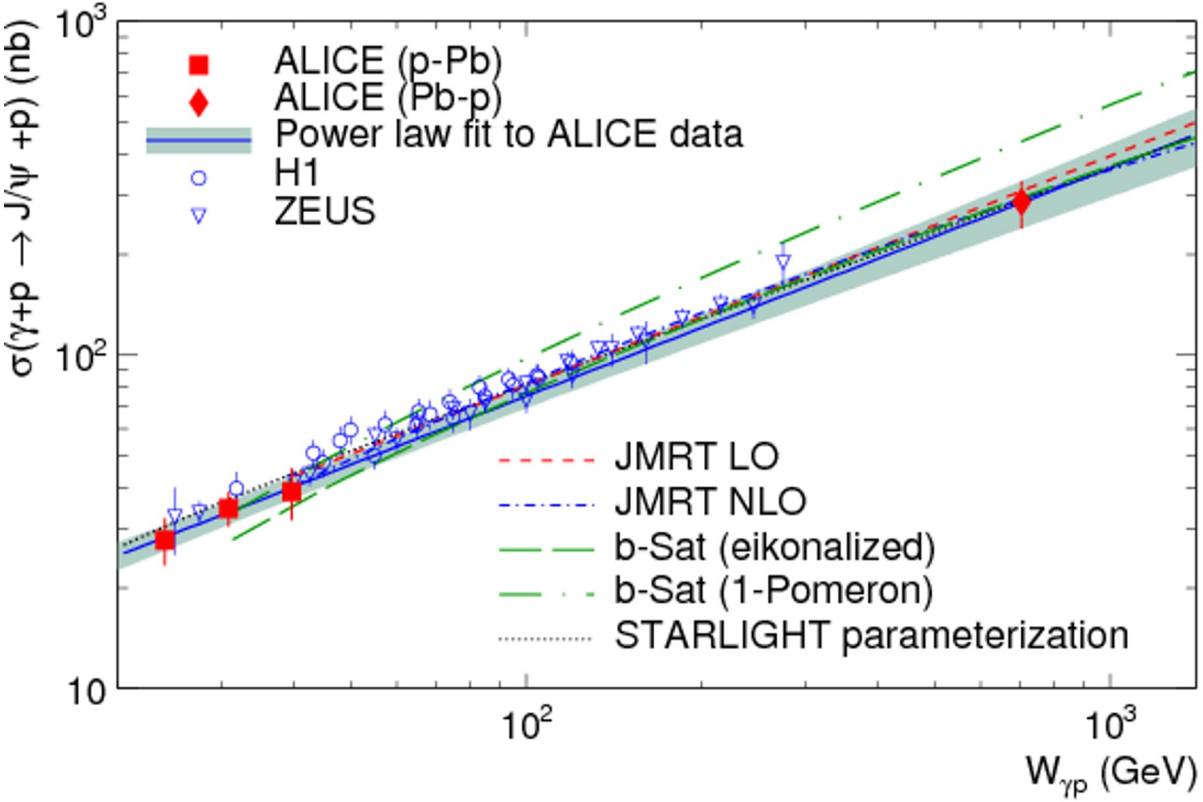


Ultra peripheral collisions



First exclusive J/ψ measurements by ALICE using Run 1 (2013)

Phys. Rev. Lett. 113 (2014) 23, 232504



- No change with respect to HERA power-law growth observed at low energies up to 700 GeV
- UPC pPb collisions have no ambiguity on the photon energy

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

Two-fold ambiguity on the photon direction in symmetric systems

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

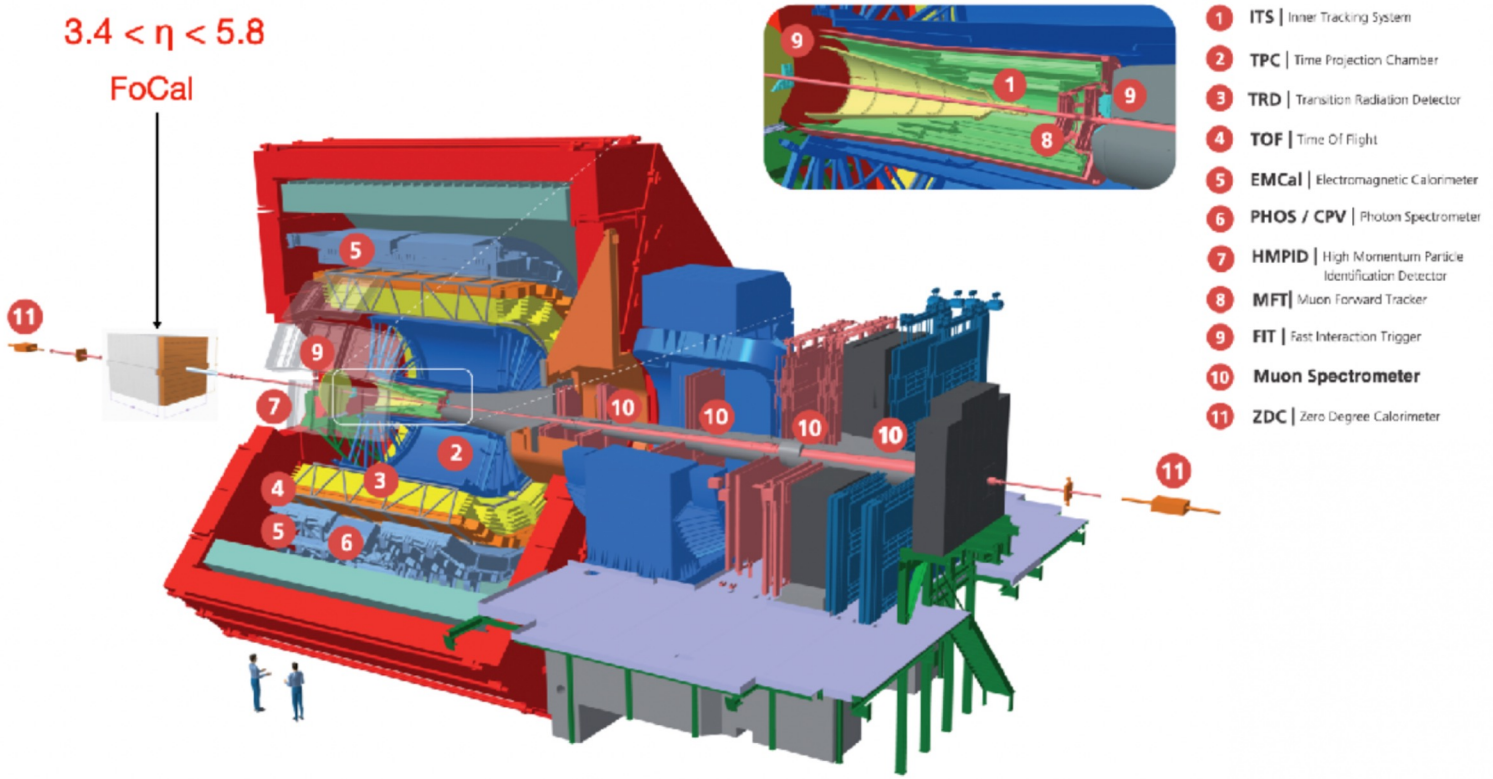
Symmetric systems (pp, A-A) suffer from the two-fold ambiguity on the photon direction

Positive rapidity Negative rapidity

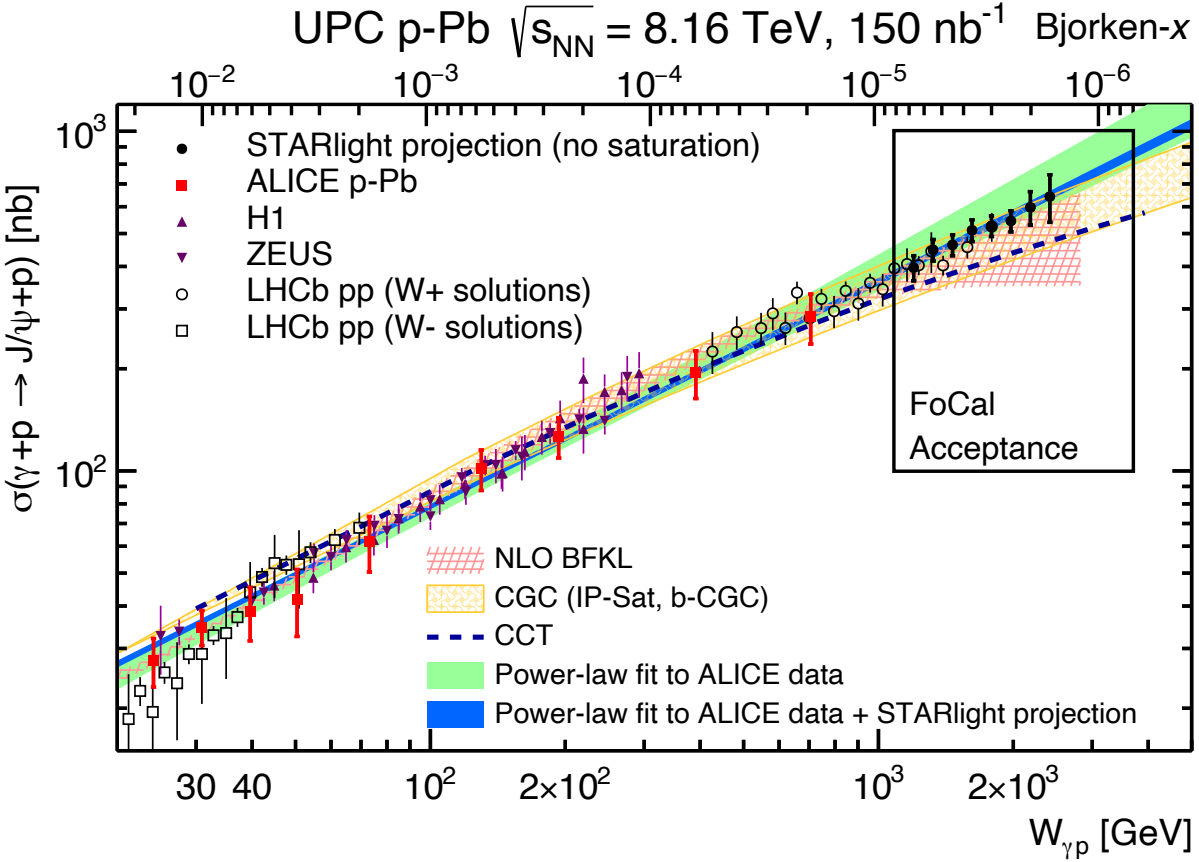
$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma p, +y) + n(-y)\sigma(\gamma p, -y)$$

Only UPC asymmetric systems (p-Pb) analyses provide a model independent way of the energy dependence of $\sigma(\gamma p)$

The ALICE FoCal project for Run 4



Projections for exclusive J/ψ off protons

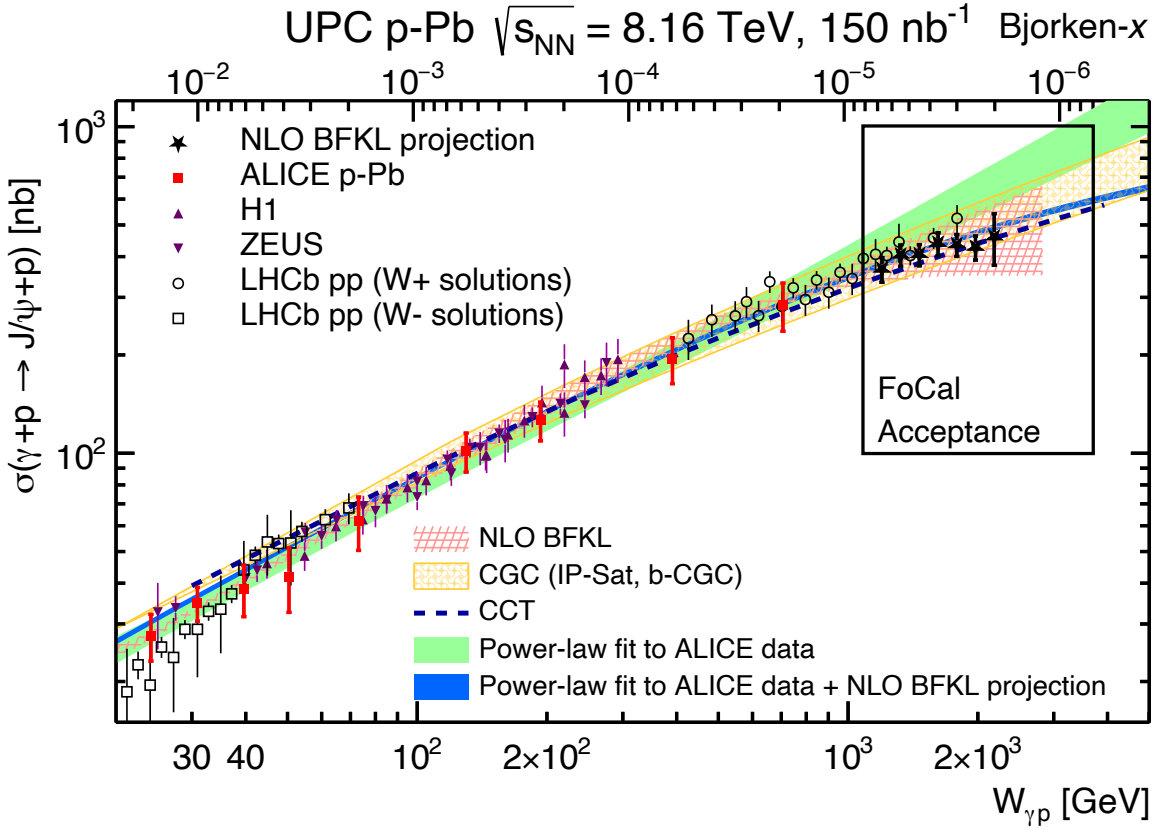


- Deviations from a power-law trend should signal non-linear QCD dynamics
- Here, projections based on STARlight which uses a parametrization based on HERA data

$$\sigma_0 \left(W_{\gamma p} / W_0 \right)^{\delta}$$

- For all figures, 60% efficiency. Conservative assumption after acceptance selection

Projections for exclusive J/ψ off protons

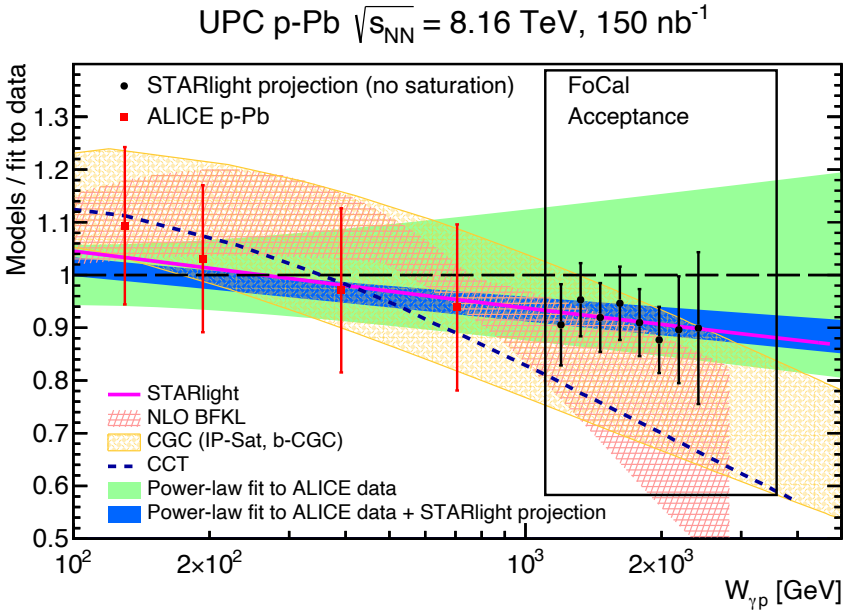


- Projections assuming a broken power-law
- Projected points based on NLO BFKL calculation

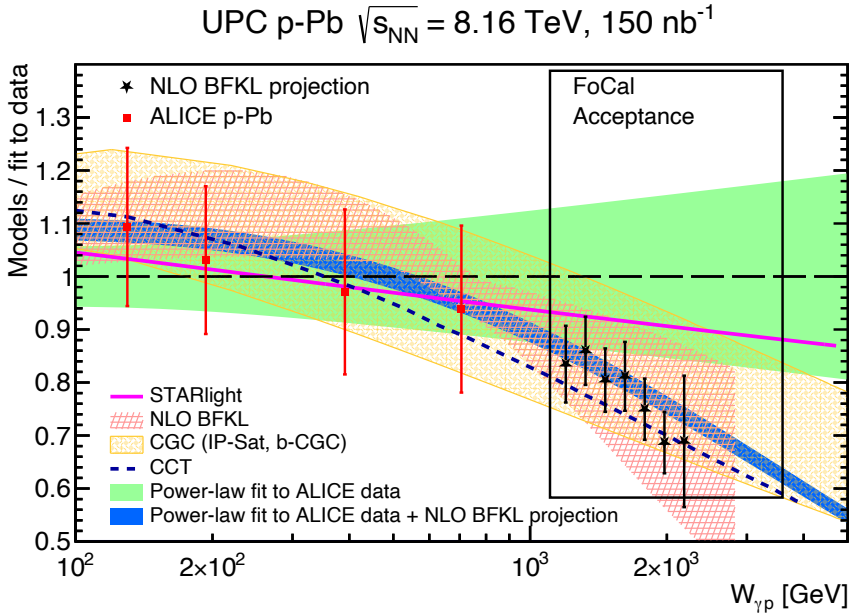
$$\sigma(\gamma p) \approx \frac{\sigma_0}{\frac{1}{W_{\gamma p}^{\delta}} + A}$$

Projections for exclusive J/ψ off protons

Power-law behavior (STARlight)



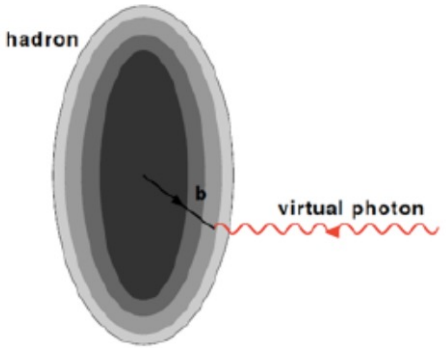
Broken power-law behavior (NLO BFKL)



FoCal measurement would be sufficient to observe a deviation from a power law behavior, if exists

Transverse profile of the target

- t-differential measurements give a gluon tranverse mapping of the hadron/ nucleus.

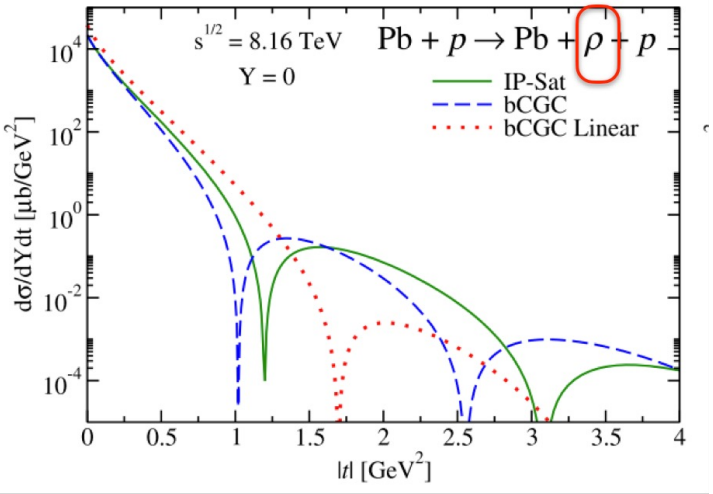


The study of the t-distribution

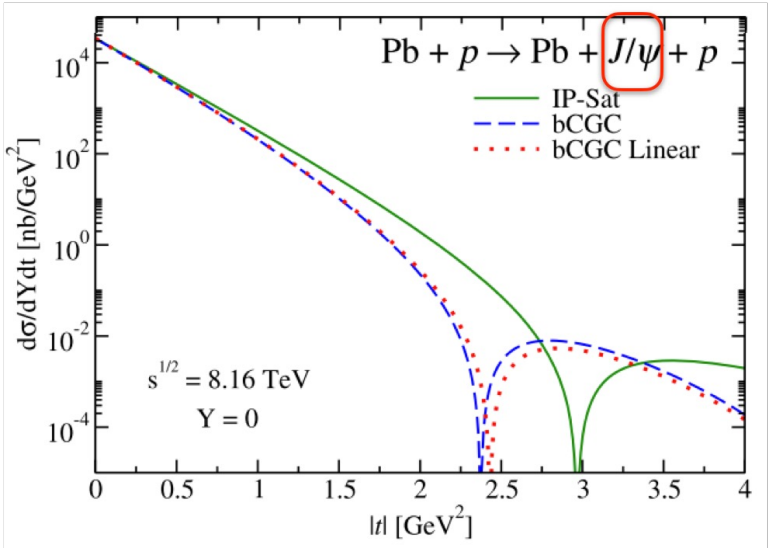
Appearance and location of diffractive dips: signature of gluon saturation

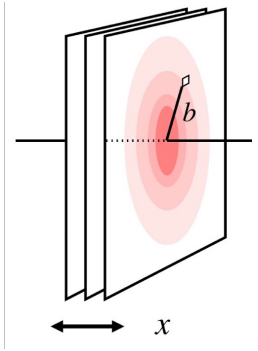
V. Goncalves, et al.
Phys. Lett. B791 (2019) 299-304

Signature of gluon saturation



Study of ρ^0 is very promising since diffractive dips expected at lower t values

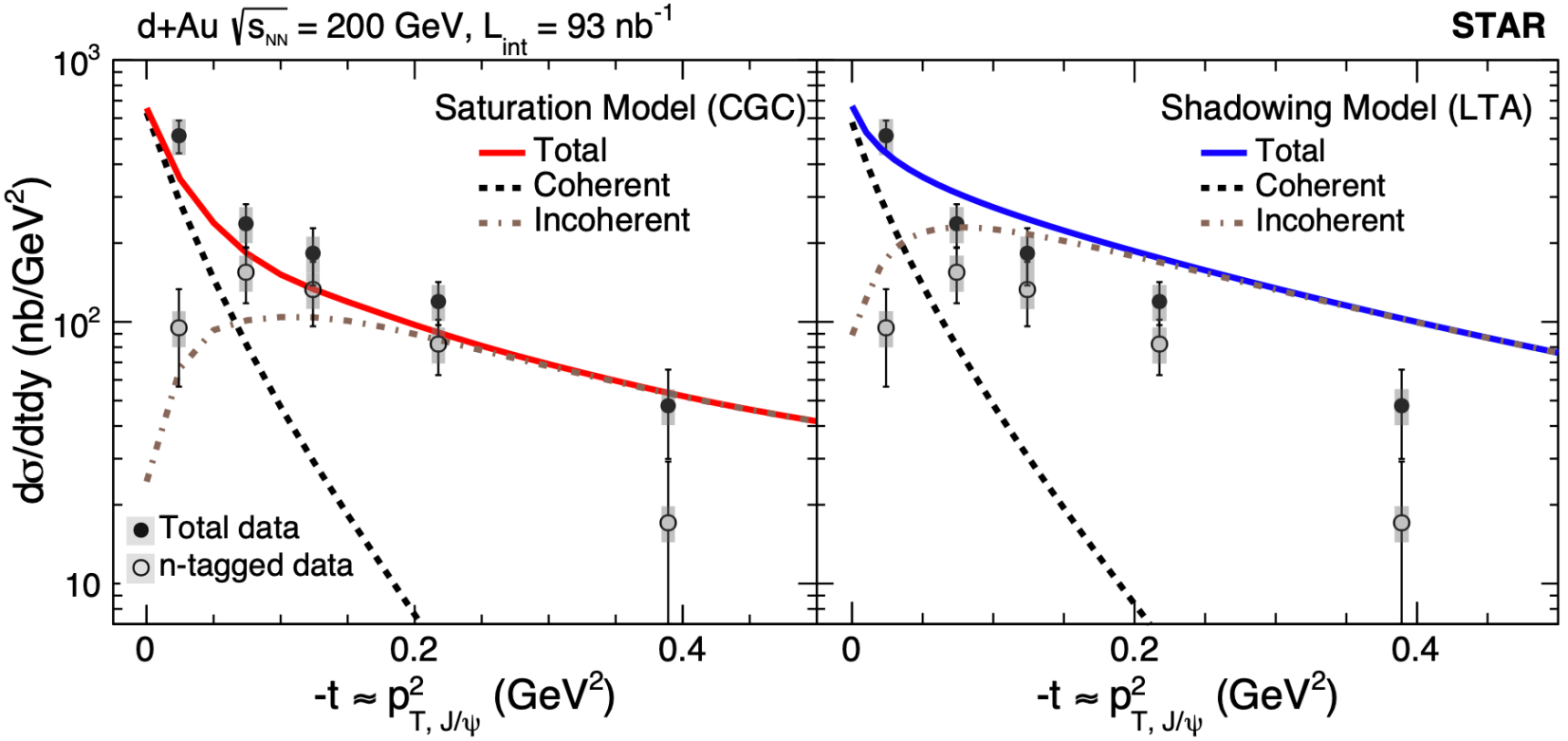




Location of the Diffractive dips:
Different for IP-Sat and bCGC

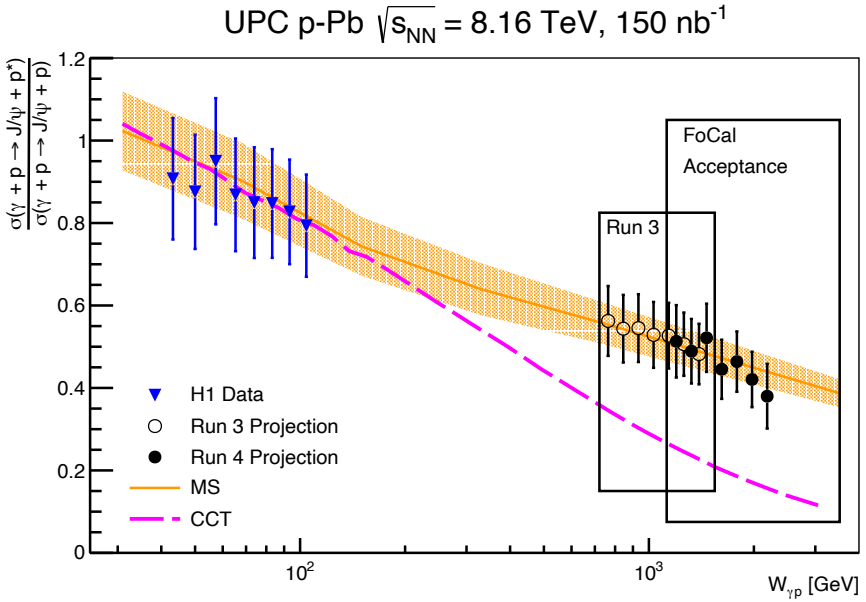
Energy dependence of the t-distribution: onset of gluon saturation

J/ψ photoproduction in d+Au

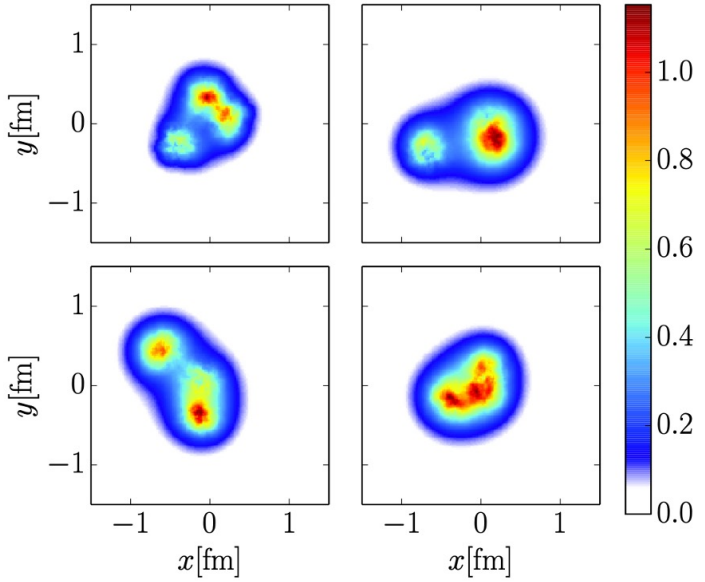


Projections for dissociative J/ψ cross section ratio in γp

J. Cepilia, J.G. Contreras and DTT
Phys. Lett.B 766 (2017) 186-191



Projections here based on the MS model
Event-by-event fluctuations



Mantysaari and Schenk, PRD 94, 034042 (2016)
S. Klein arXiv:2301.014018

In the Good-Walker approach, sensitive to subnucleonic fluctuations of the gluon density

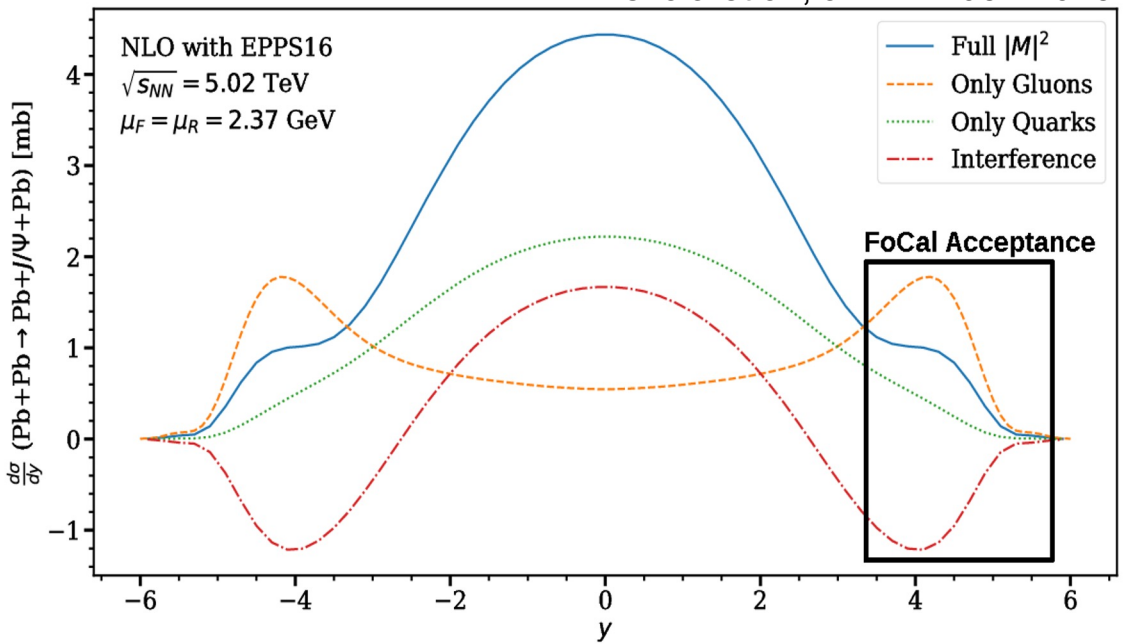
$$\frac{d\sigma(\gamma p \to \mathrm{J}/\psi Y)}{dt} = \frac{R_g^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2\right)$$

Projections for VMs in γPb

Recent NLO calculations indicate importance of quark contribution and large scale uncertainties

The FoCal region is gluon dominated

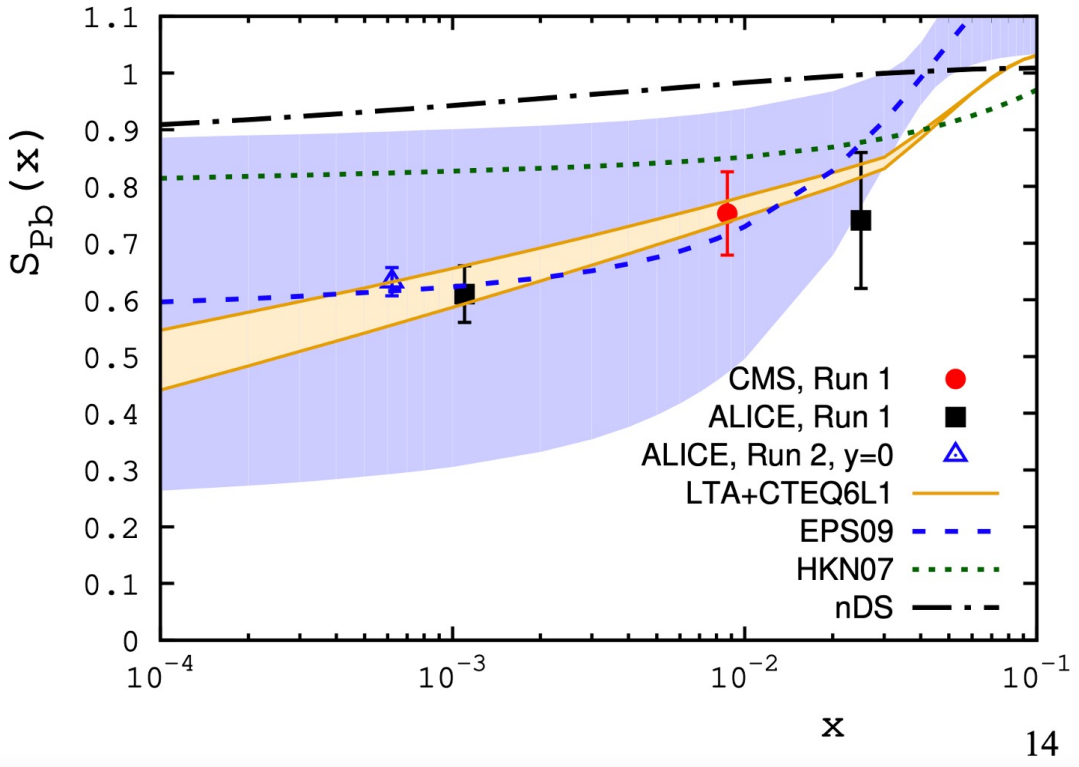
K. Eskola et al., arXiv:2203.11613



- At LO predicted to be proportial to the square of the gluon density (Z. Ryskin Phys. C 57, 89 (1993), but several caveats
- UPC J/ψ also described by Generalized Parton Distributions (GPDs), with some theory considerations

Nuclear suppression factor for UPC J/ψ: Comparing γPb to γp

V. Guzey et al. PLB 726 (2013)



An experimental definition, which can be linked to PDFs at LO

$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A \to J/\psi A}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma A \to J/\psi A}(W_{\gamma p})}} = \kappa_{A/N} \frac{x g_A(x,\mu^2)}{A x g_N(x,\mu^2)}$$

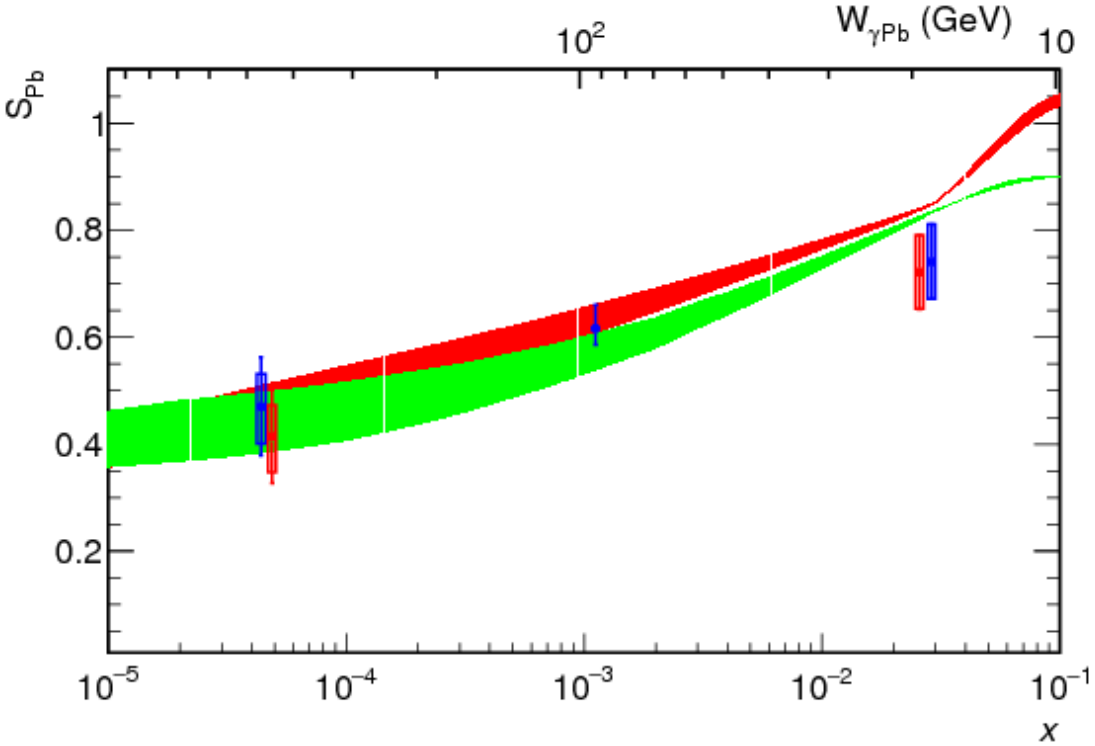
Run 1 data from ALICE was the first at indicating nuclear gluon shadowing at x ~ 10^{-3}

Large scale NLO uncertainties should cancel in the $S_{Pb}(x)$ ratio

ALICE results at y=0 have no ambiguity on the photon energy determination

Nuclear suppression factor for peripheral (not UPC) J/ψ

J.G. Contreras, *Phys. Rev .C* 96 (2017) 1, 015203



Run 1 data from ALICE observed Coherent-like J/ψ from peripheral hadronic PbPb events. Process later confirmed by STAR

The photon flux depends on the impact parameter, these peripheral J/ψ explore γP energies beyond coherent J/ψ at the same y interval at the same cms energy

Sensitivity to x ~ 10^{-5}

Neutron-dependence of coherent J/ψ in γPb

The photon flux (n) depends on the impact parameter

Decomposed in terms of neutron configurations emitted in the forward region

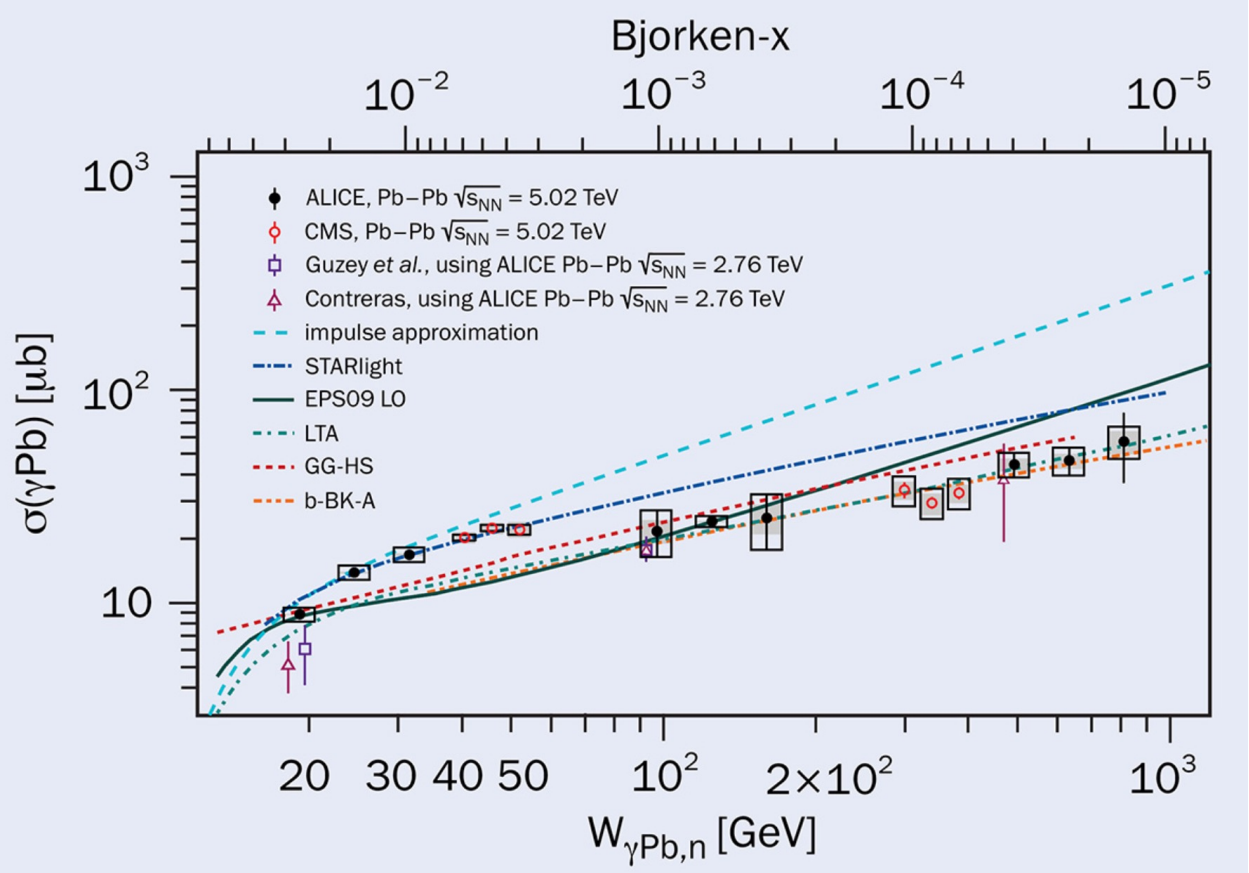
$$\frac{d\sigma}{dy} = \frac{d\sigma(0\mathrm{n}0\mathrm{n})}{dy} + 2\frac{d\sigma(0\mathrm{n}\mathrm{X}\mathrm{n})}{dy} + \frac{d\sigma(\mathrm{X}\mathrm{n}\mathrm{X}\mathrm{n})}{dy}$$

Solving the linear equations resolves the two-photon ambiguity for VMs at y ≠ 0

Positive rapidity Negative rapidity

$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma\mathrm{p}, +\mathrm{y}) + \mathrm{n}(-\mathrm{y})\sigma(\gamma\mathrm{p}, -\mathrm{y})$$

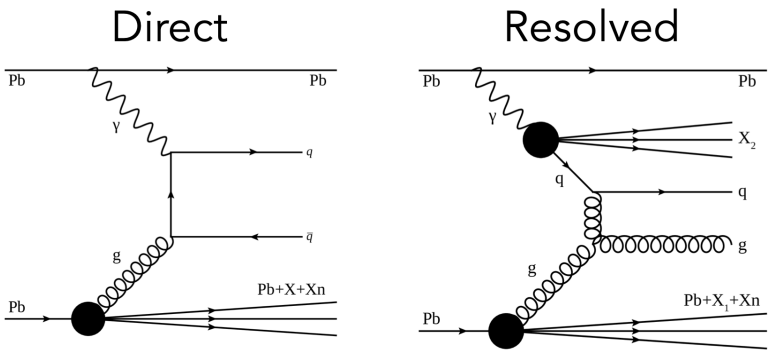
Energy dependence of coherent J/ψ in γPb



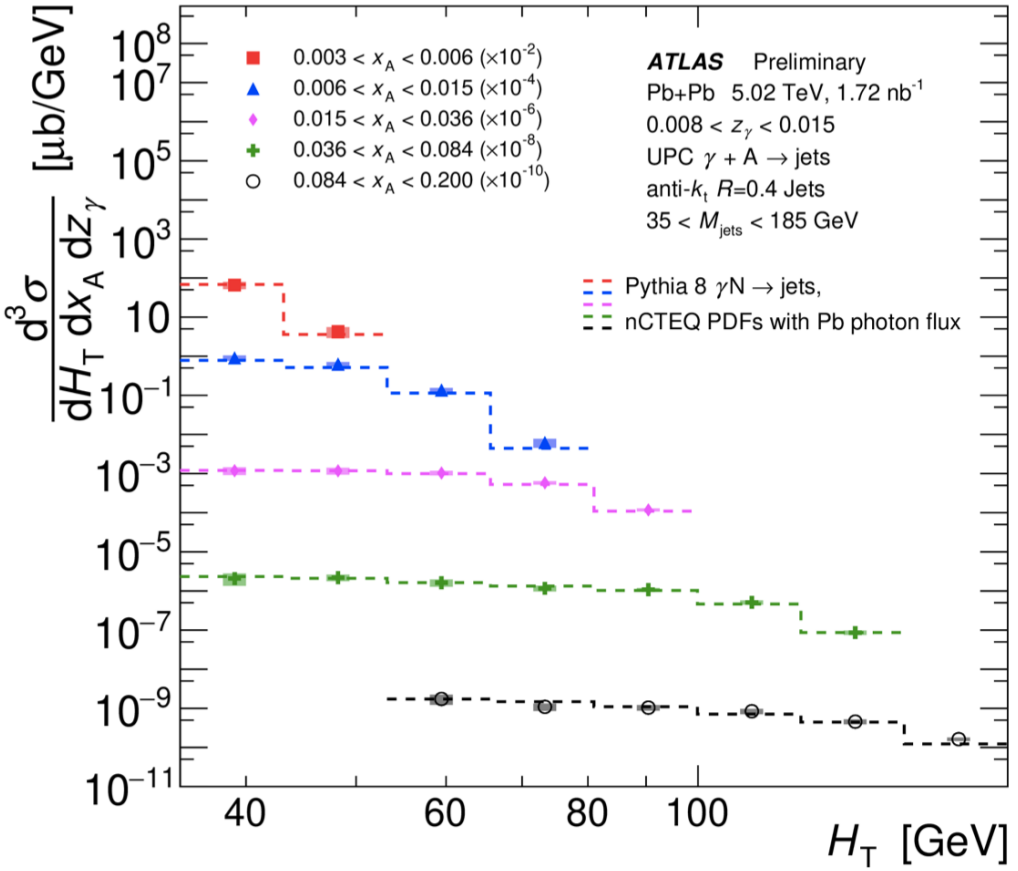
Both gluon saturation and shadowing describe the data at high energies

At low energies the data cannot be described by these models

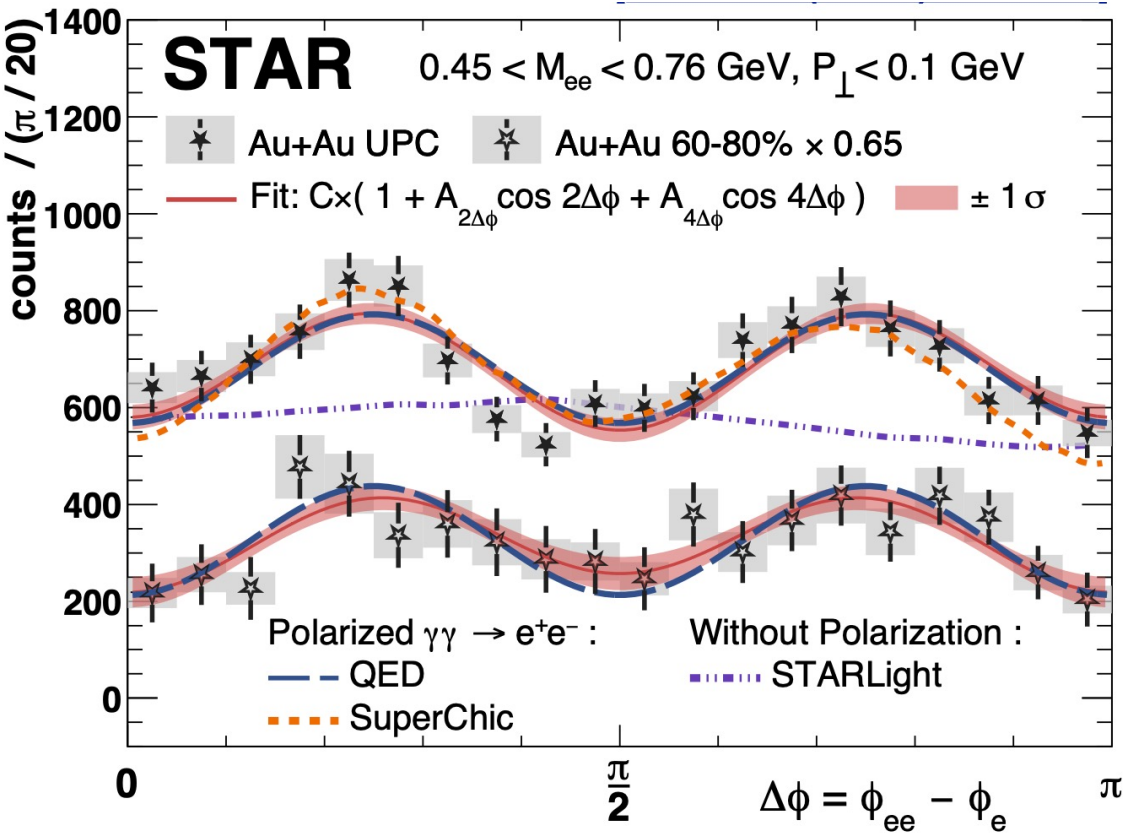
Photonuclear jets

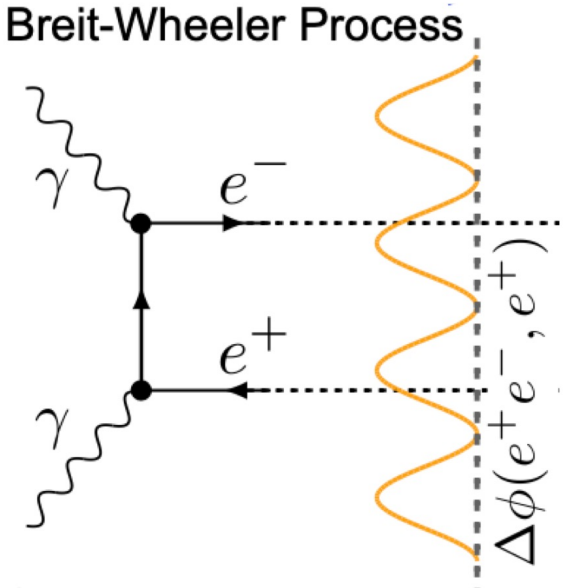


Sensitivity to nuclear modification, including from PDFs



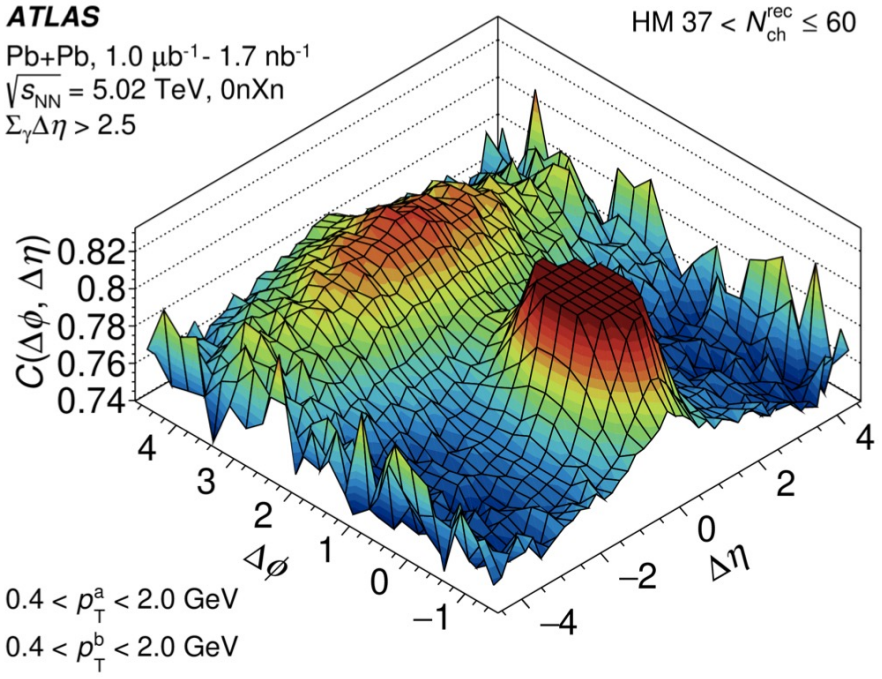
Linear polarization

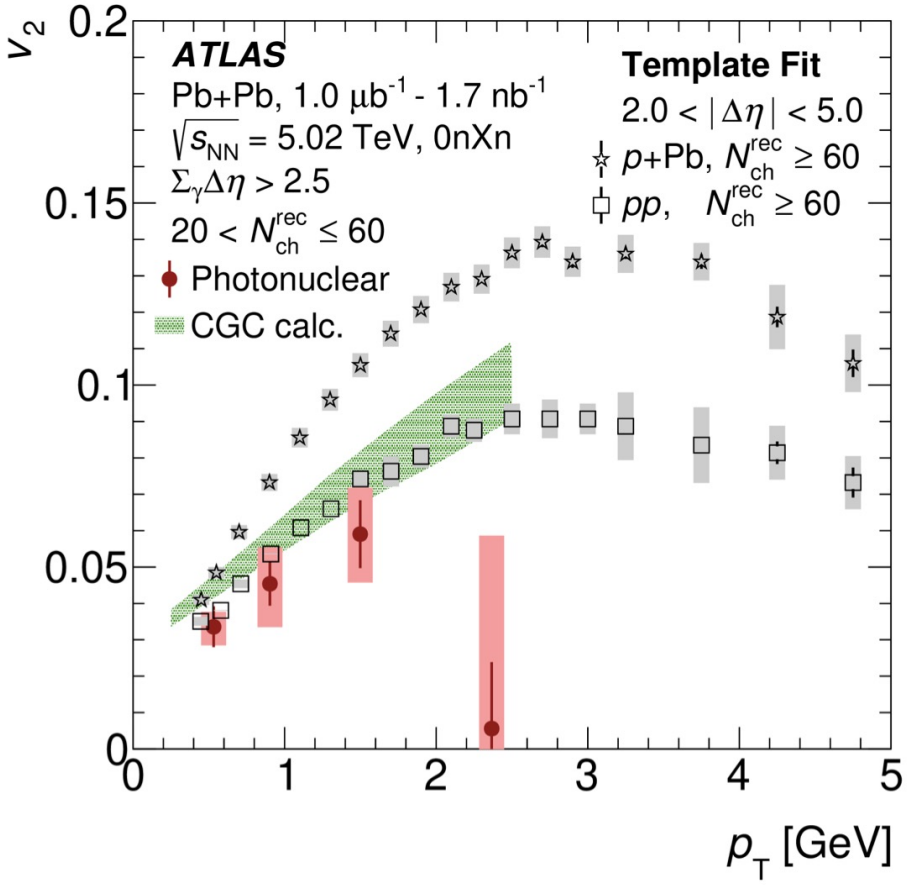




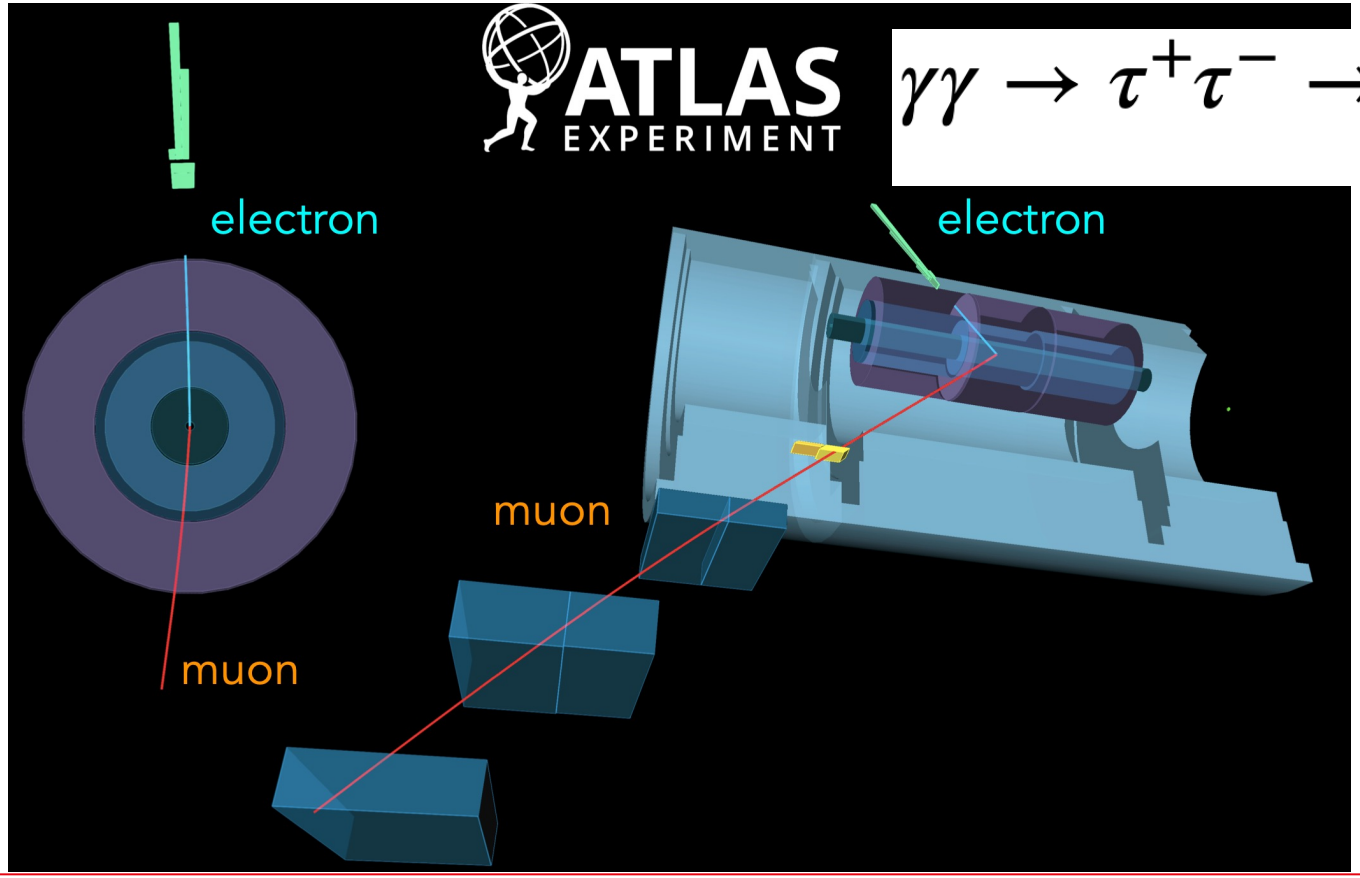
Polarization properties in UPCs is a new tool to study QCD, probing QM at the smallest scale available

Flow studies from UPCs

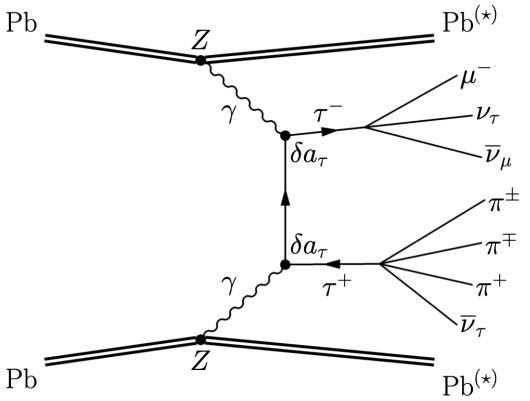




UPCs and searches for new physics

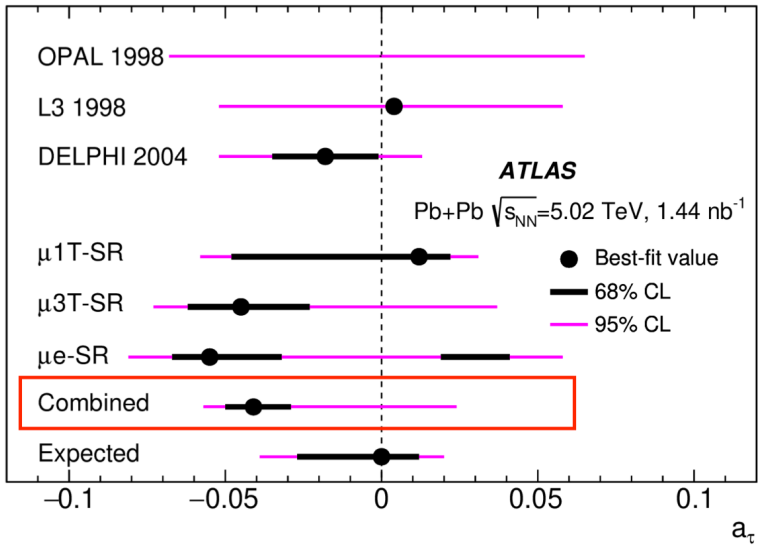


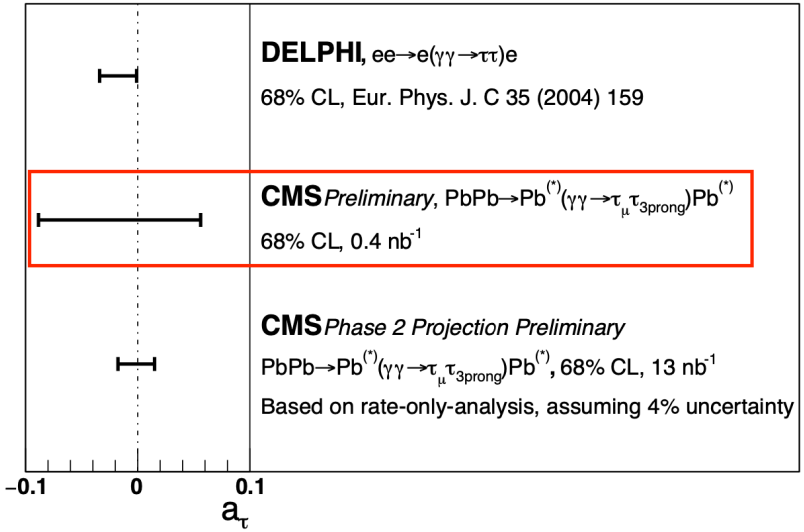
$$\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow e^+\nu_e\nu_\tau\mu^-\nu_\mu\nu_\tau$$



UPCs and searches for new physics

The tau anomalous magnetic momentum





UPCs is opening new directions of investigation for QCD, heavy ions, electromagnetic and BSM physics

https://indico.cern.ch/event/1263865

Registration and abstract deadline: September 15

Student day on December 10

We have some limited funding for students. Contact us !

Thanks!