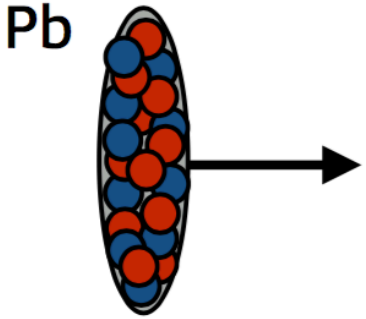
Photo-production at LHC and EIC

Yongsun Kim

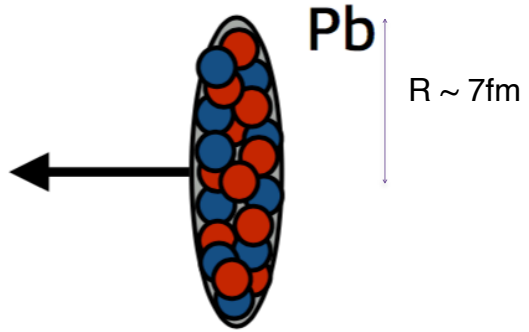
1 Oct 2022

ExHIC meeting

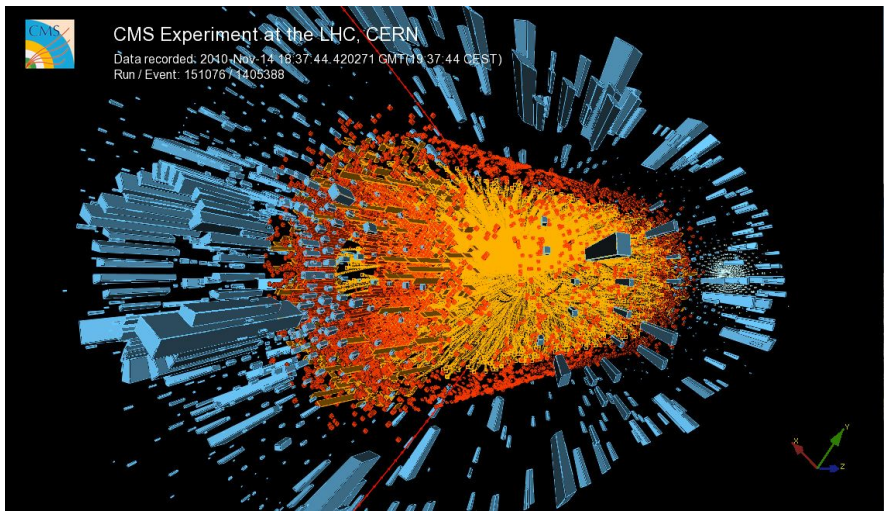
Hadronic heavy ion collision at LHC



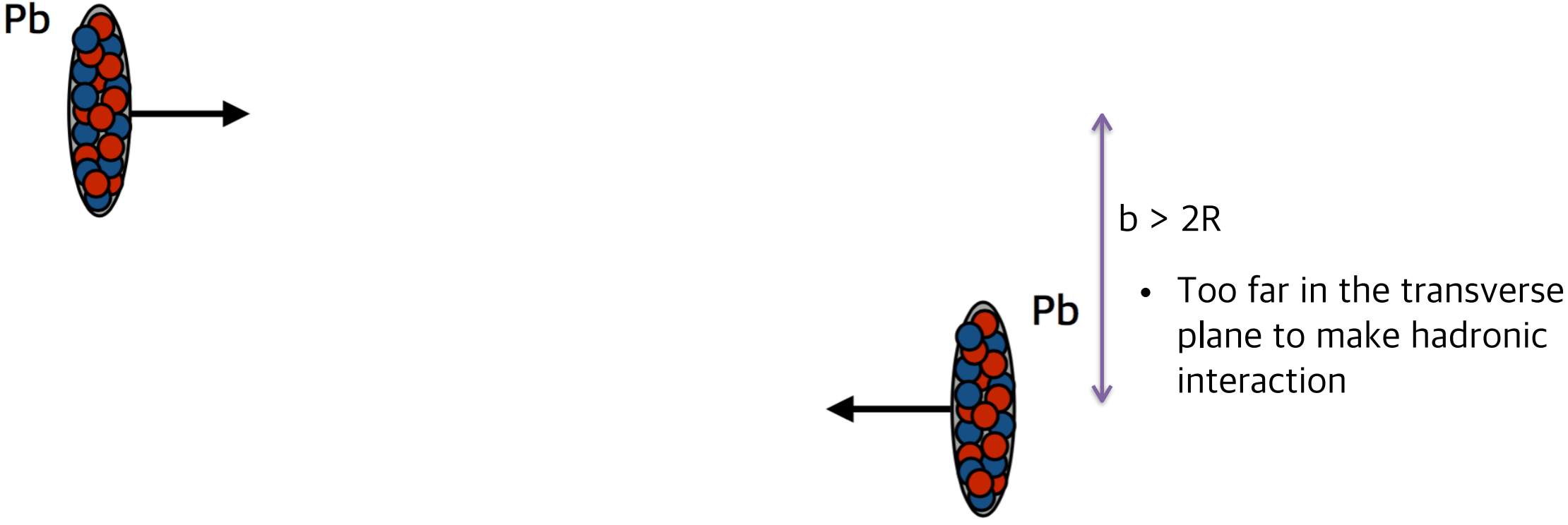
$b \lesssim 2R$



Hadronic A+A collision



Ultra peripheral collision at LHC

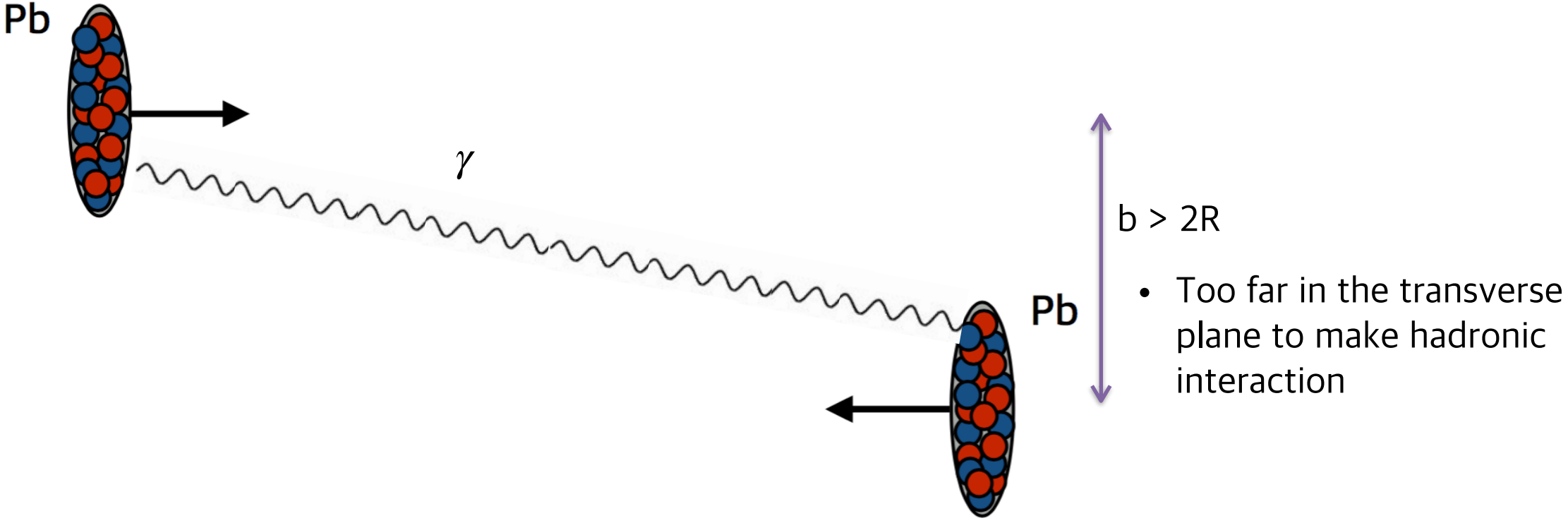


- Too far in the transverse plane to make hadronic interaction

Ultra Peripheral Collision (UPC)

- quasi-elastic and diffractive collision
- Occasionally neutrons are emitted from excited ions

Ultra peripheral collision at LHC



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Ultra Peripheral Collision (UPC)

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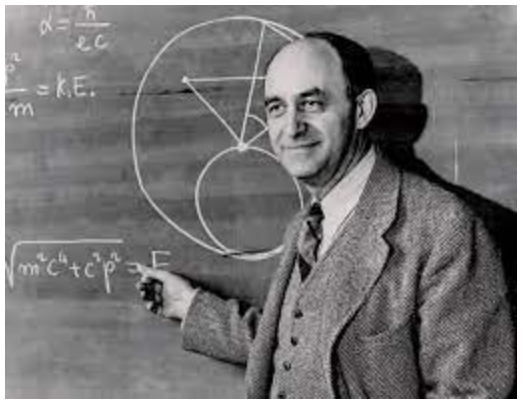
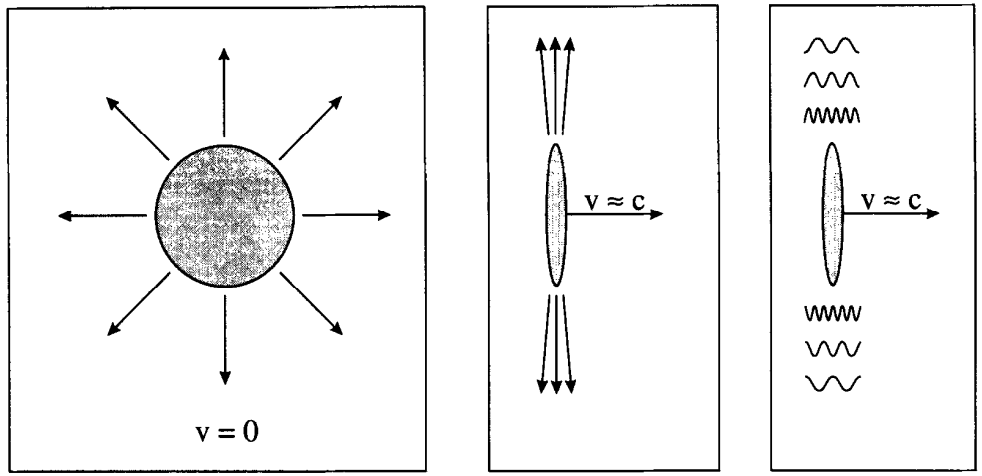
Equivalent Photon Approximation



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)

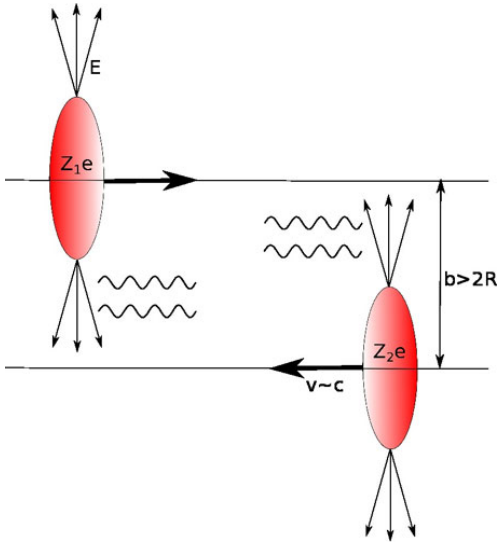


- Trajectory of fast moving charged particle is equivalent to a flux of photons (Fermi, 1924)
- Later, extended to relativistic regime by Weizsacker[1] and Williams[2]
- At LHC, photon energy can reach up to 80 GeV, and at RHIC up to 3 GeV
- We can practice high energy γ + (p or A) and γ + γ collisions by triggering non-hadronic collisions
- These events are called ultra-peripheral collisions, or **UPC**

[1] Z. Phys. 88, 612 (1934)

[2] Kgl. Danske Videnskab. Selskab Mat.-Fys. Medd. 13, 4 (1935)

LHC, the most powerful photon collider



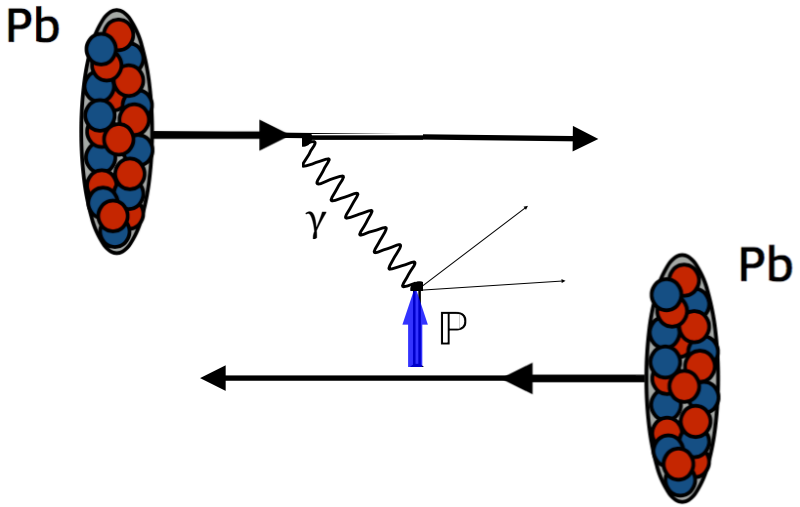
$$\omega^{\max} = \frac{\hbar}{\Delta t} \sim \frac{\gamma \hbar v}{b},$$

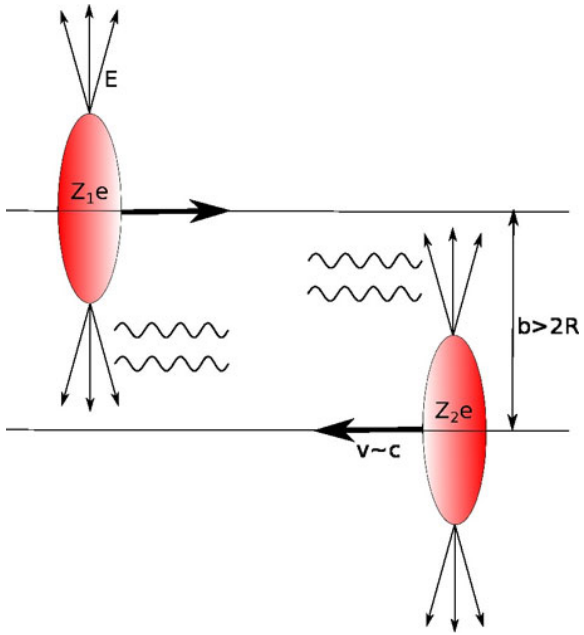
$$N(\omega, b) = \frac{Z^2 \alpha \omega^2}{\pi^2 \gamma^2 \hbar^2 \beta^2 c^2} \left(K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right)$$

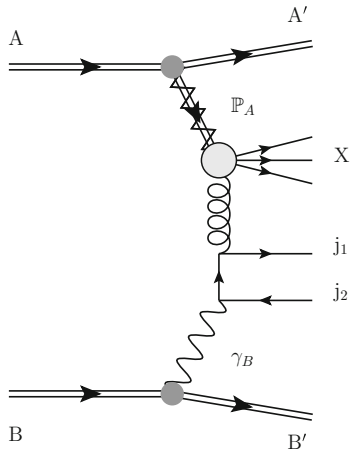
Annu. Rev. Nucl. Part. Sci. 2005. 55:271

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

UPC can tell us…

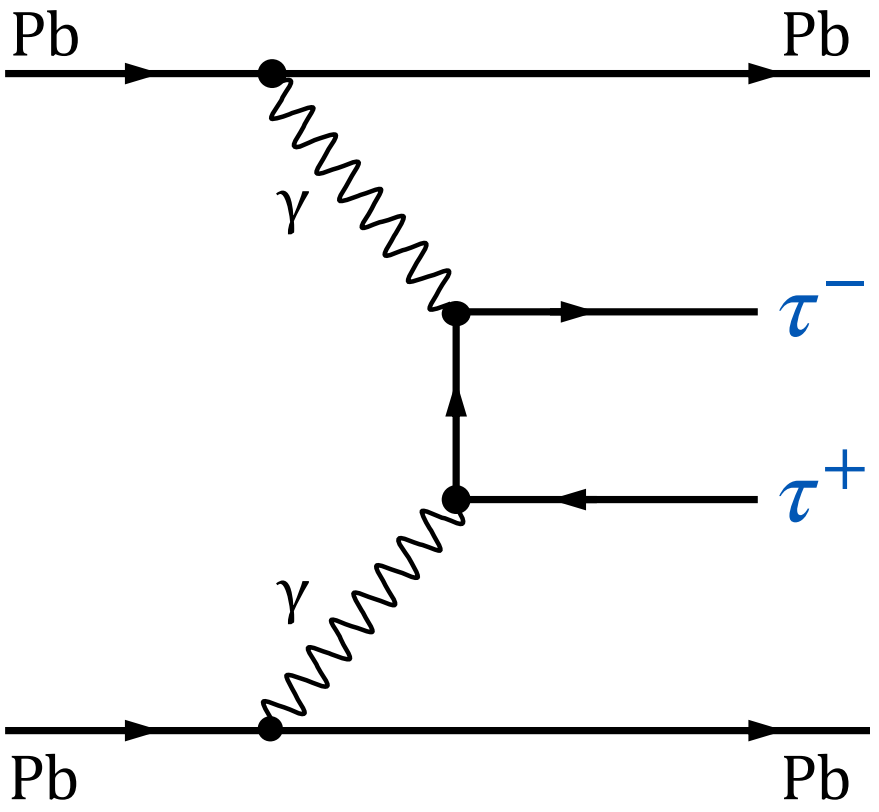




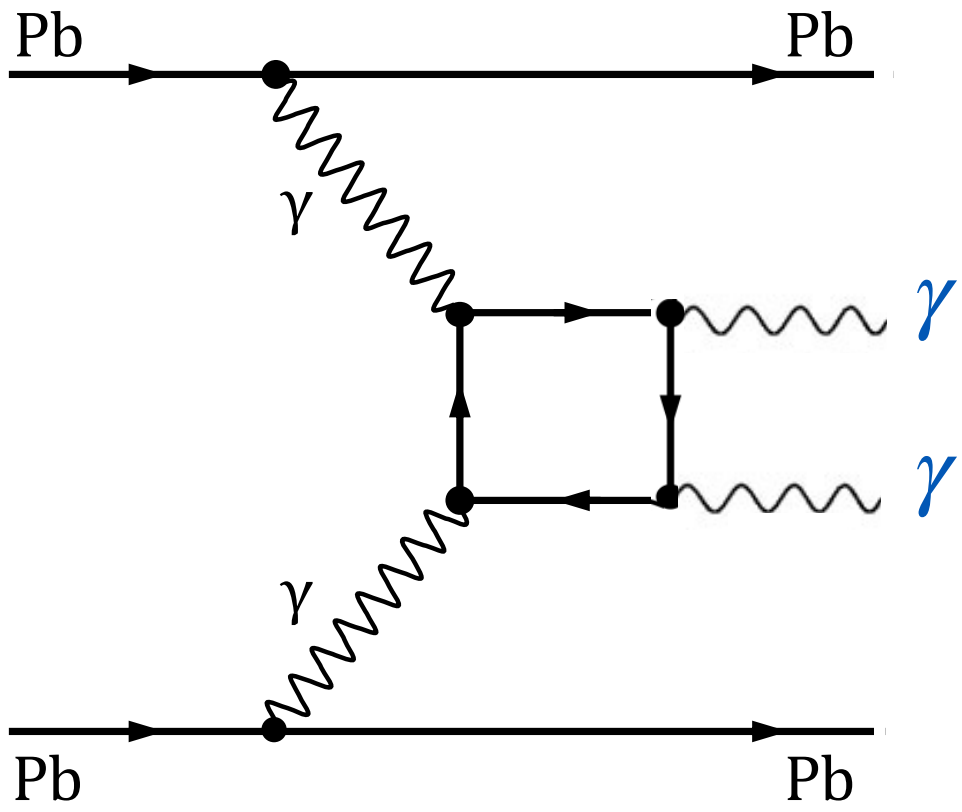


- The smallest (or non-) QCD system made by hadronic collision
  - γ + A $\simeq$ vector meson + A collision in the vector-meson dominance picture
- Control measurement for study of quark gluon plasma
- gluon momentum distribution at very low x
- Low background provides precise test for Beyond Standard Model

UPC for BSM search



$$\gamma + \gamma \rightarrow \tau^+ + \tau^-$$

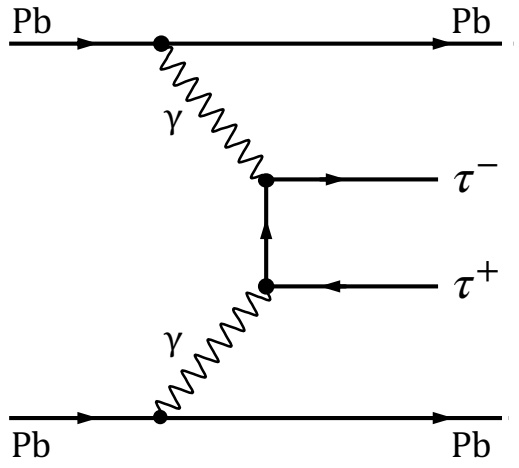


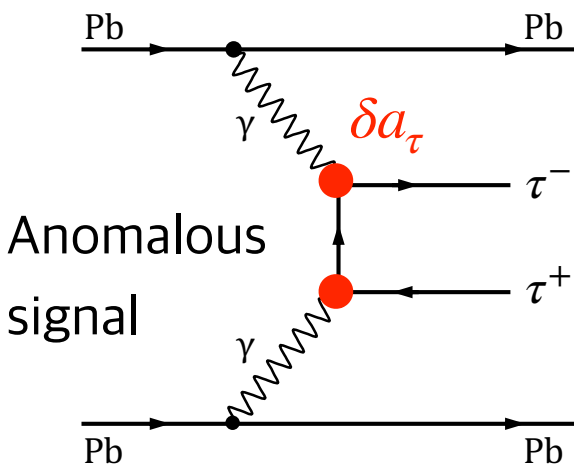
$$\gamma + \gamma \rightarrow \gamma + \gamma$$

UPC for BSM search

$\gamma + \gamma \rightarrow \tau^+ + \tau^-$

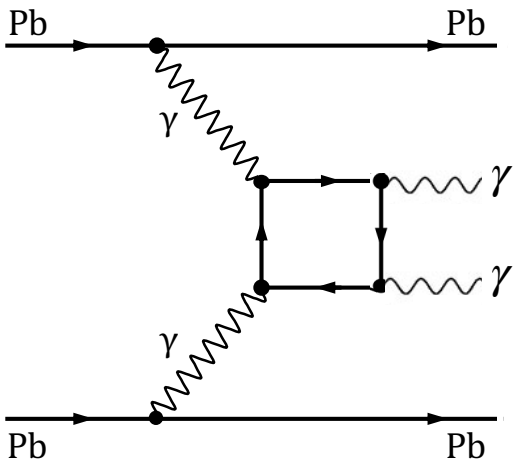
PLB 797 (2019) 134826, CMS
JHEP 03 (2021) 243, ATLAS

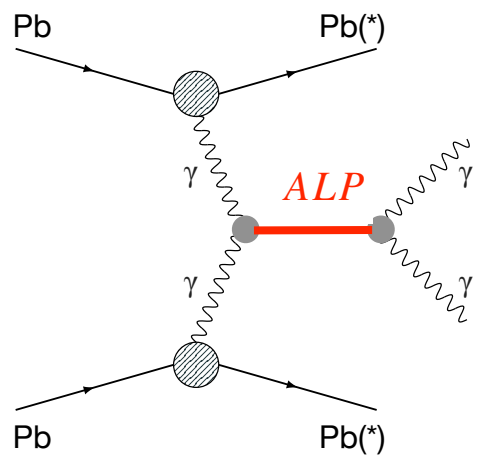




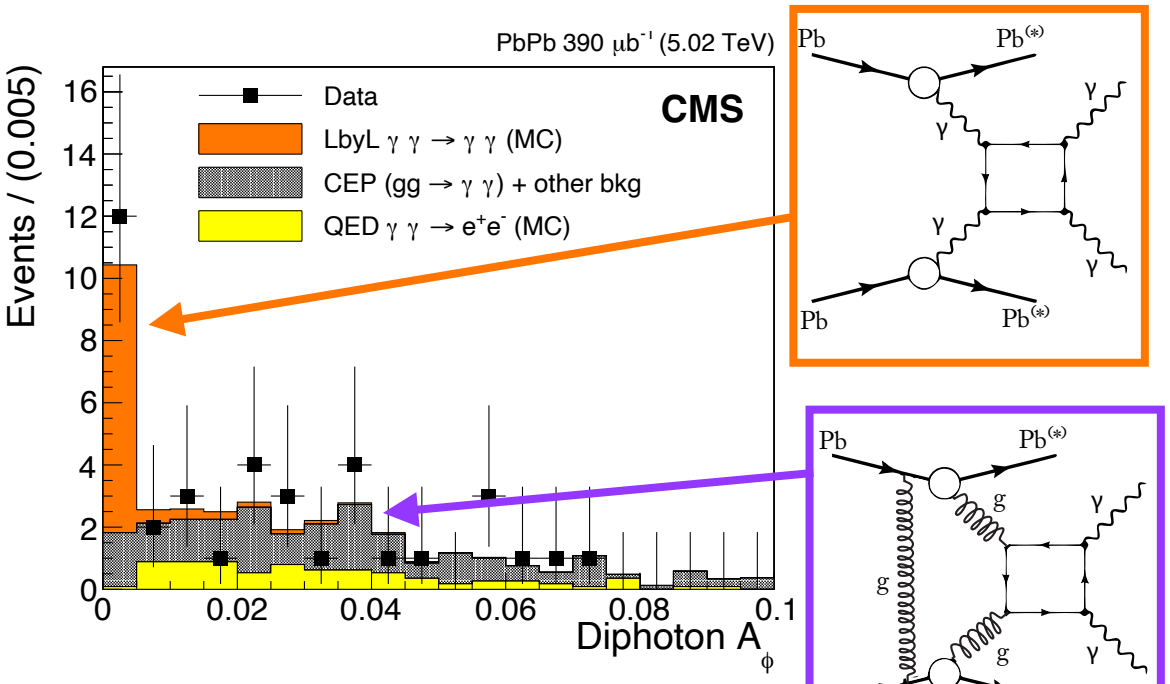
$\gamma + \gamma \rightarrow \gamma + \gamma$

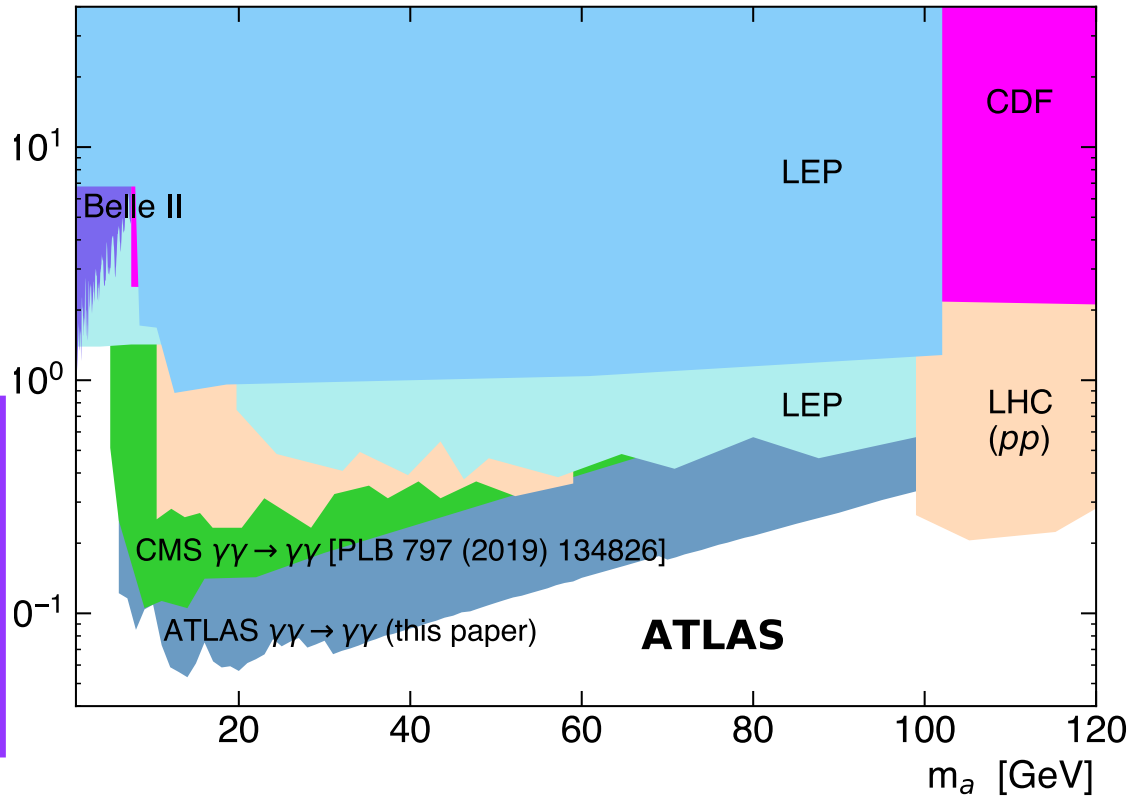
Nature Phys. 13 (2017) 852, ATLAS
PLB 797 (2019) 134826, CMS
JHEP 03 (2021) 243, ATLAS





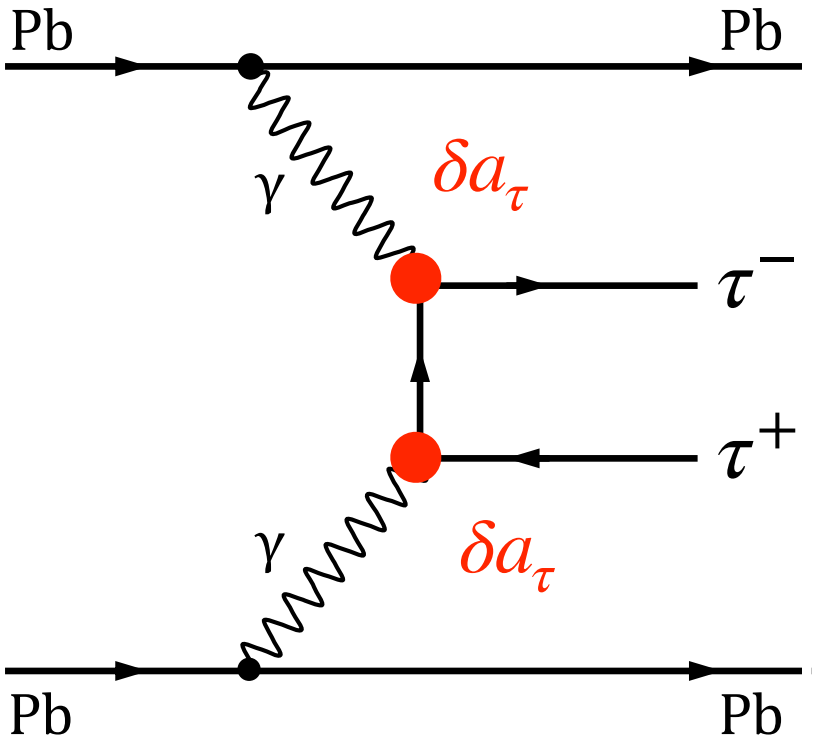
$\gamma + \gamma \rightarrow \gamma + \gamma$



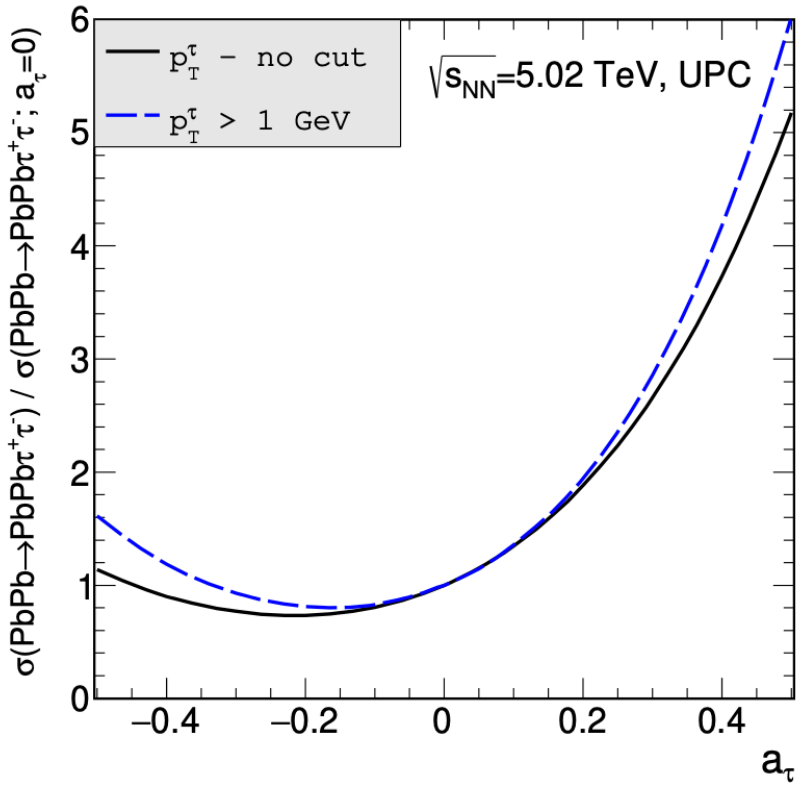


- QED + CEP backgrounds are also well described by acoplanarity nature
- No deviation from SM was observed
- The strongest constraints for the mass rages $6 < m_a < 100$ GeV

$\gamma + \gamma \rightarrow \tau + \tau$

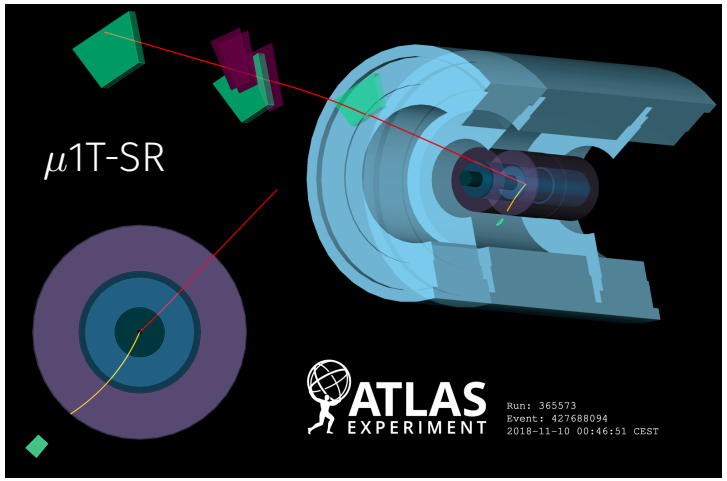


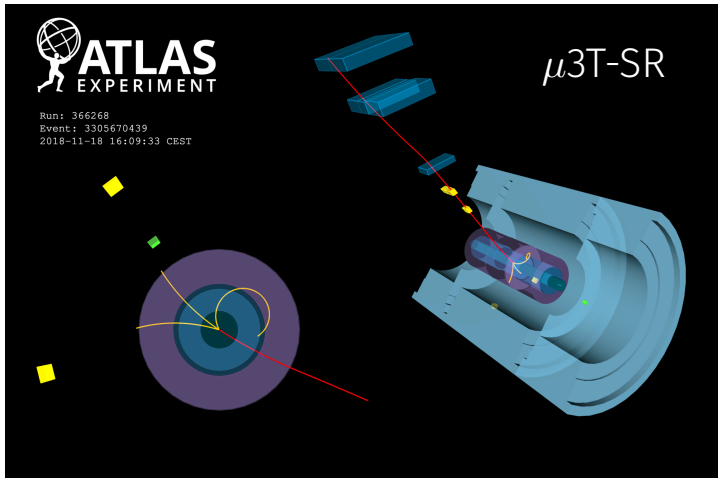
PLB 809 (2020) 135682

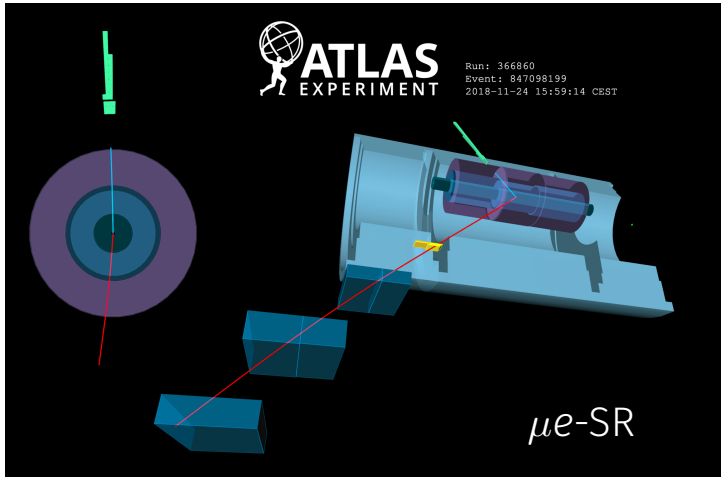


- Deviation from calculation can be a signal for anomalous magnetic moment $a_\tau = (g_\tau - 2)/2$
- UPC at LHC is great laboratory by virtue of small backgrounds
- Cross section scales by Z^4 ~ 40,000,000 compared to pp

$\gamma + \gamma \rightarrow \tau + \tau$



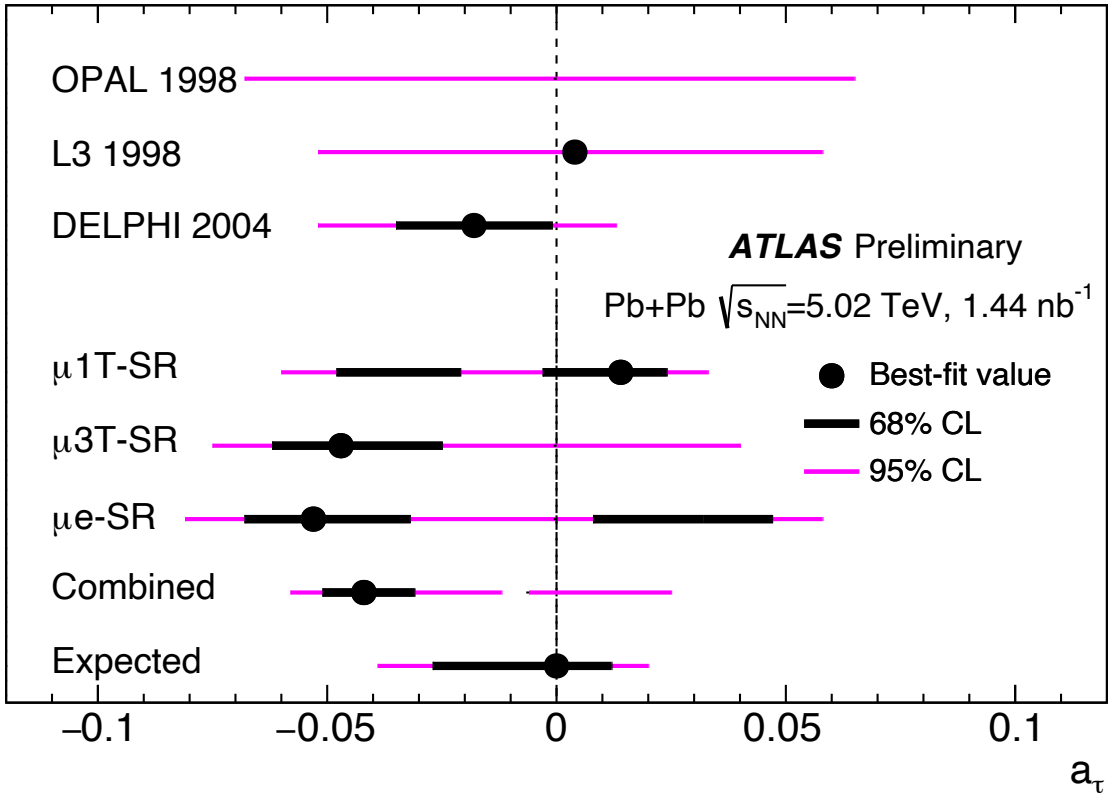


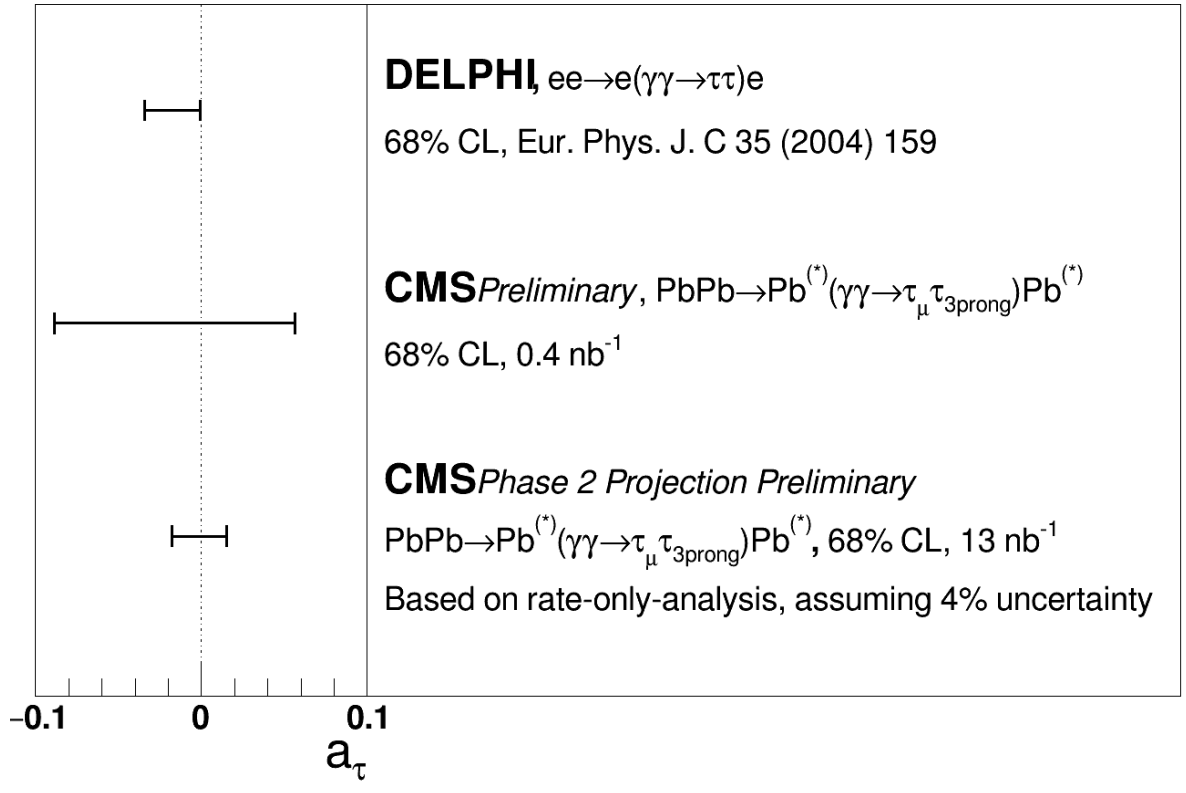


Muon + 1 track | Muon + 3 tracks | electron + Muon

- ATLAS measured all three channels above with full Run II data
  - Analyzed the p_T shape to find the best fit with a_τ as a parameter
  - a_τ : **(–0.058, – 0.012) ∪ (–0.006, 0.025) in 95% CL**
- CMS measured Muon + 3 tracks with partial Run II data (full stat. in preparation)
  - Cross section with efficiency correction: σ_{fiducial} **= 4.8 ±0.6(*stat*) ±0.5(*sys*)**$sys\ \mu b$
  - Compared $\sigma_{fiducial}$ with theoretical calculation to extract a_τ

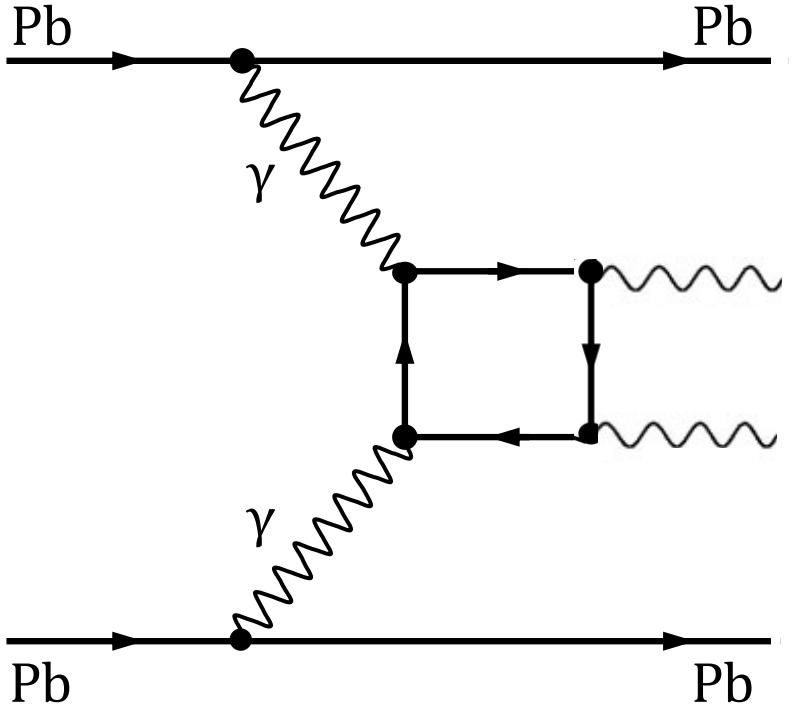
$\gamma + \gamma \rightarrow \tau + \tau$





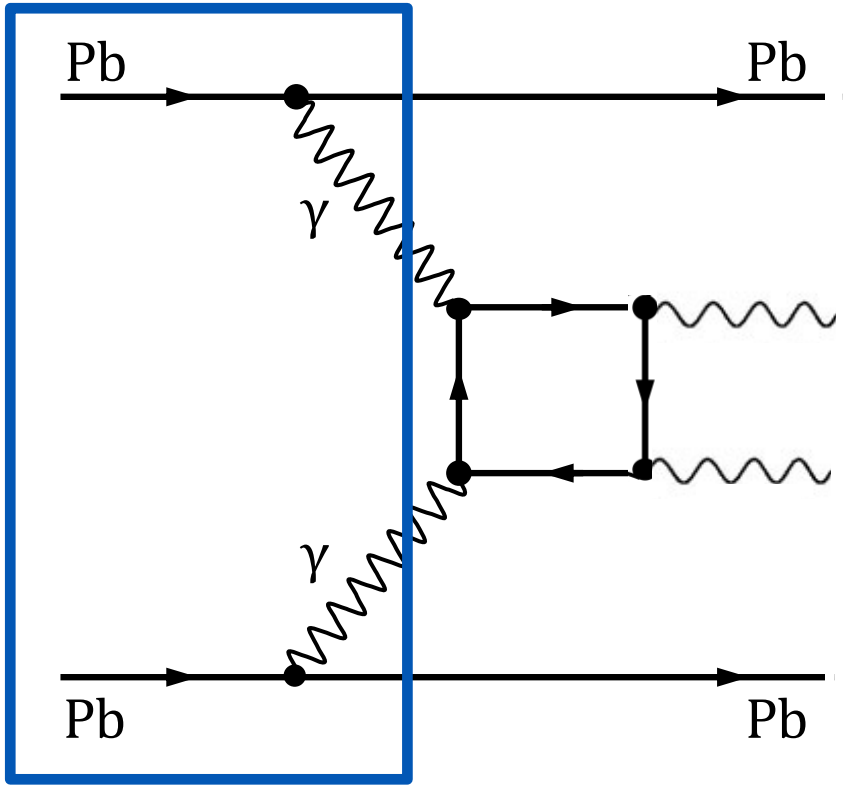
- Compared to DELPHI, better resolution is expected with Run3 + Run4 data, PbPb with L= 13 nb^{-1}

Photon flux measurement



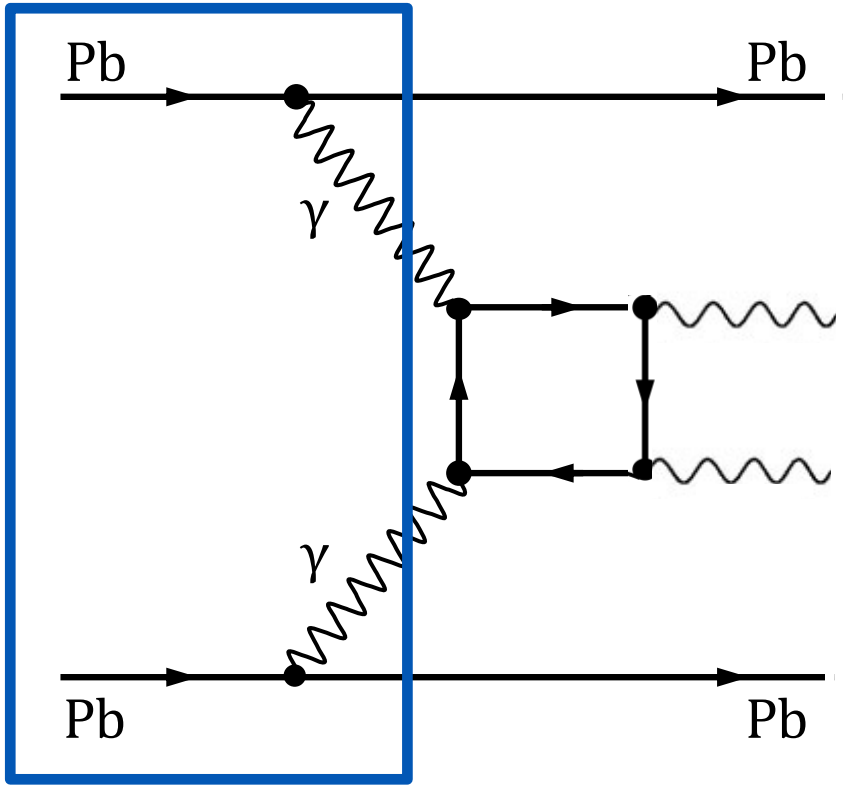
- Is our understanding of QED in UPC perfect?

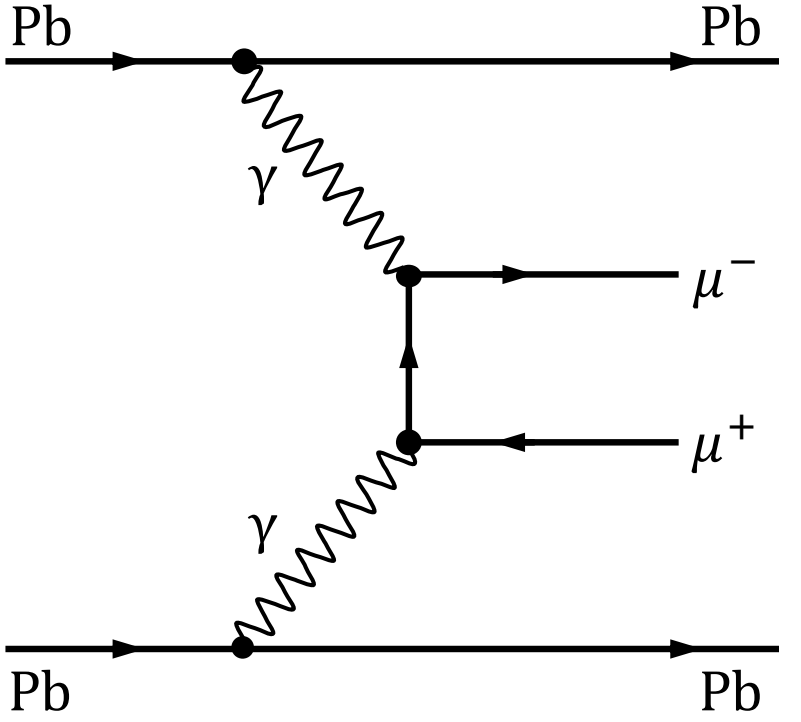
Photon flux measurement



- Is our understanding of QED in UPC perfect?
- Do we have good estimate for the initial photon flux?

Photon flux measurement



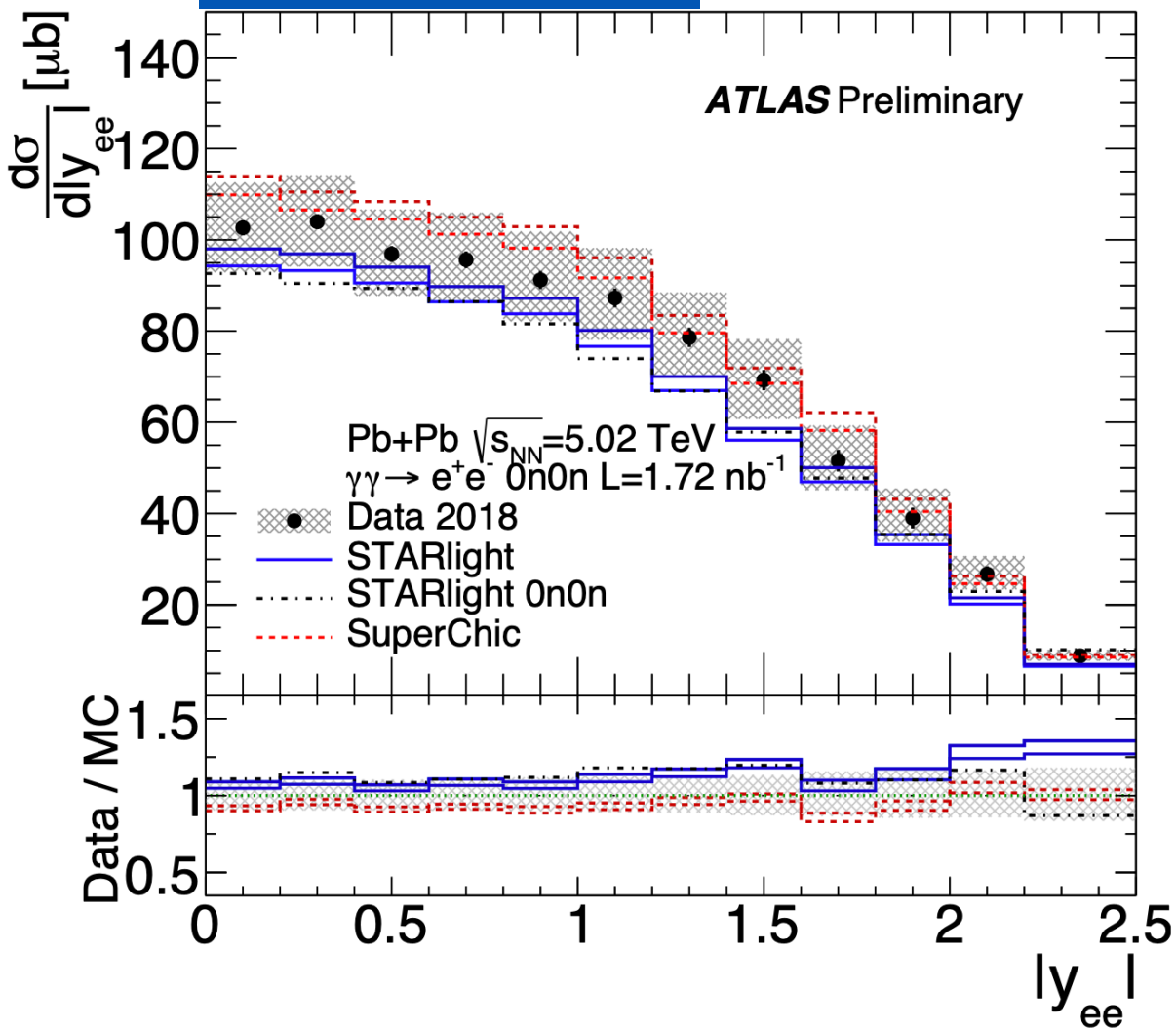


- Is our understanding of QED in UPC perfect?
- Do we have good estimate for the initial photon flux?

- $\gamma + \gamma \rightarrow \mu + \mu$ may answer

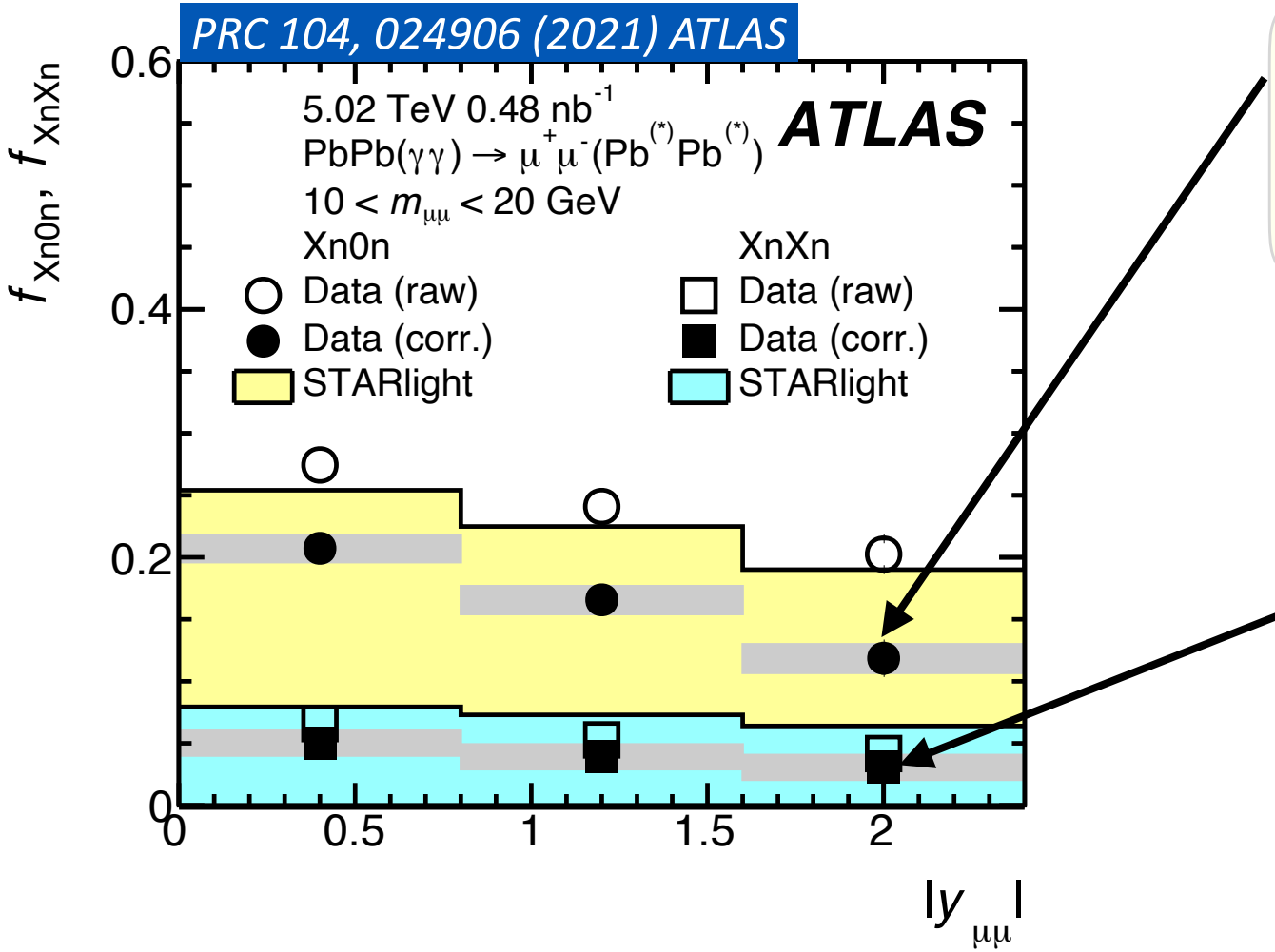
Cross section of $\gamma\gamma \rightarrow \mu\mu(ee)$ in PbPb UPC

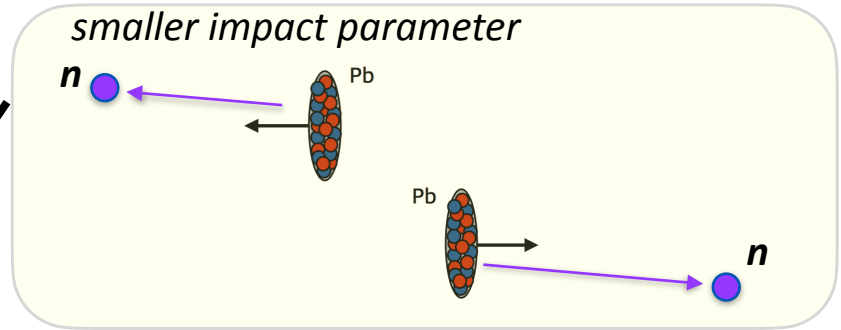
ATLAS-CONF-2022-025

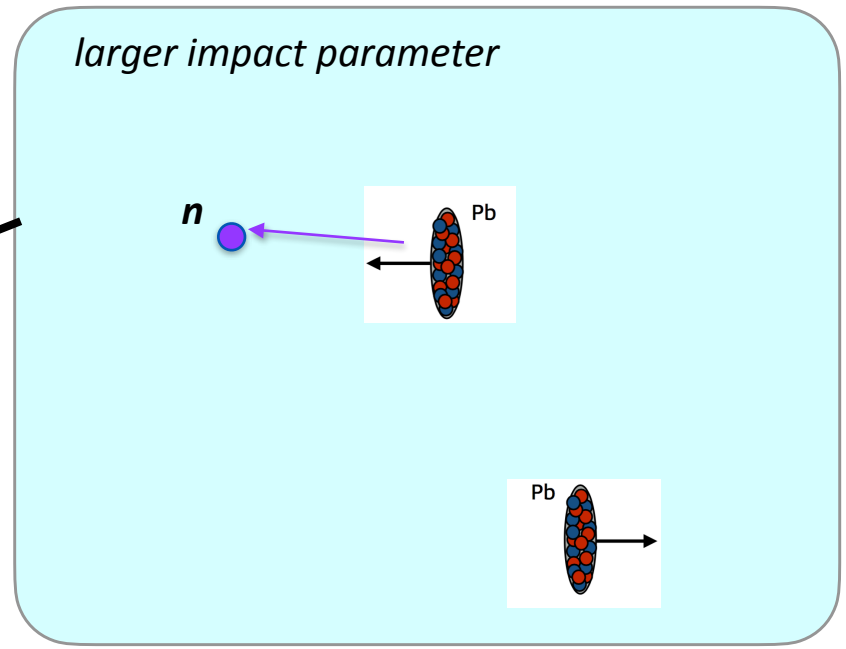


- Cross section is proportional to the incoming photon flux
- Thus useful for calibration of photon flux
- Monte Carlo simulation, like SuperChic and STARLIGHT, calculate inclusive cross section within uncertainties

Cross section of $\gamma\gamma \rightarrow \mu\mu(ee)$ in PbPb UPC

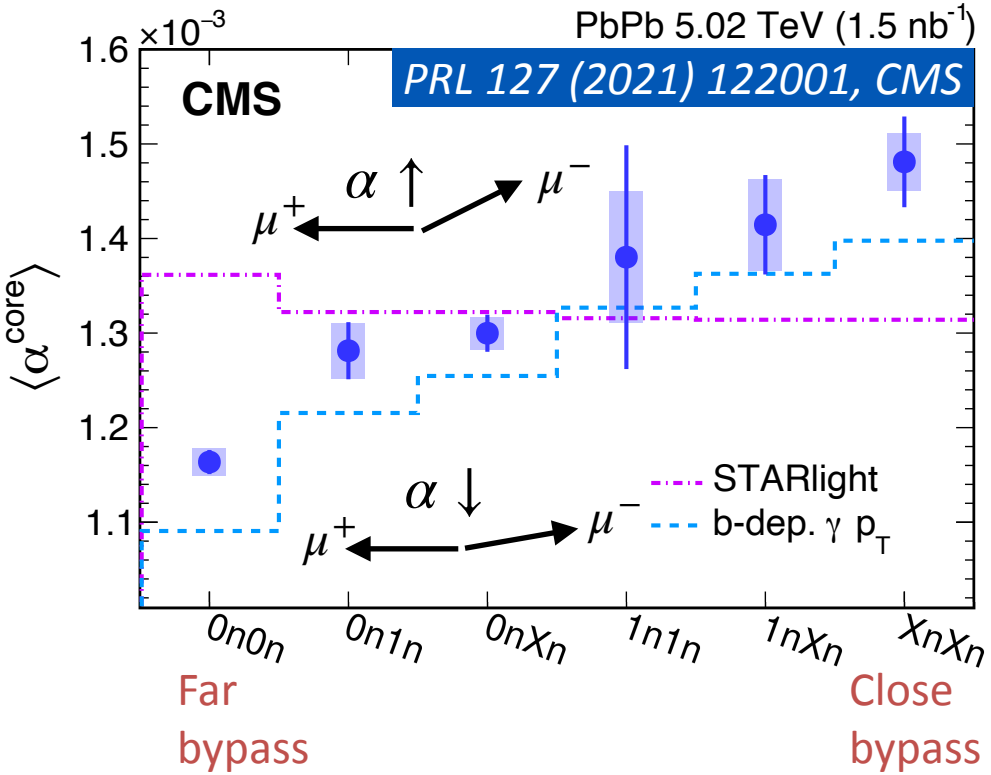


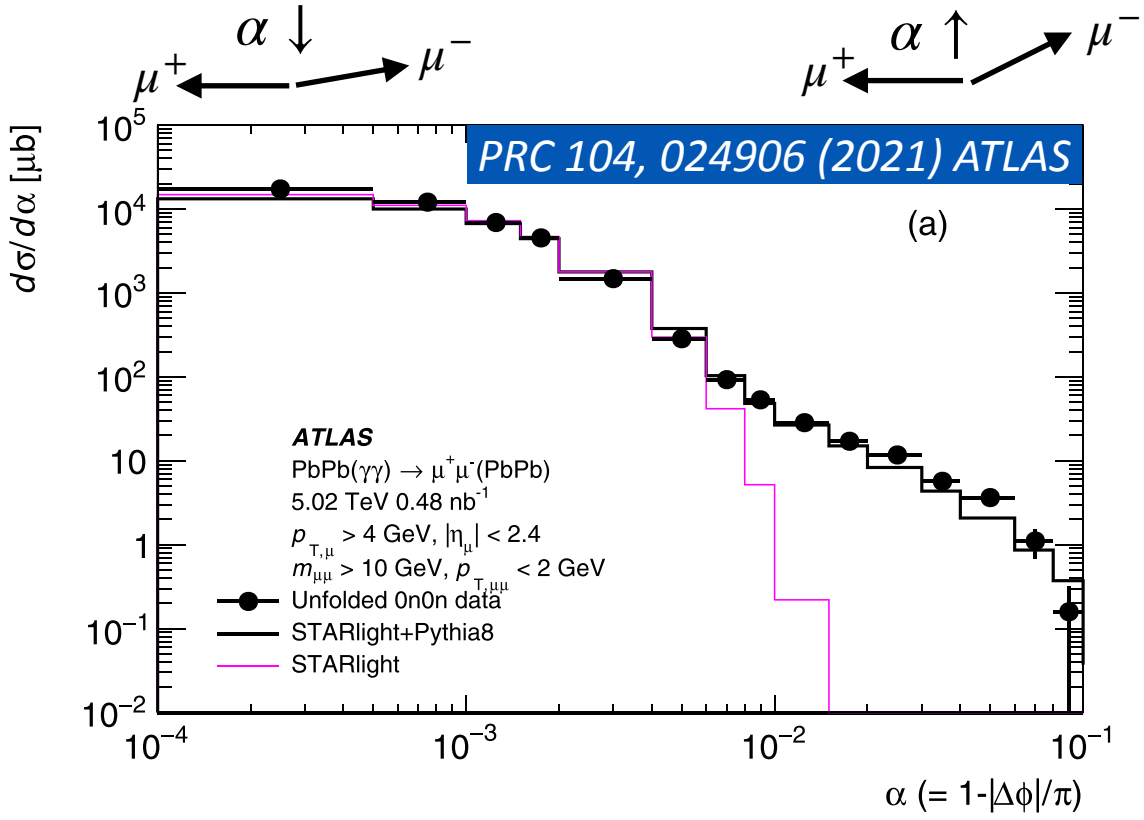




- Data and MC (STARlight) have different f_{Xn0n} and f_{nxnx}

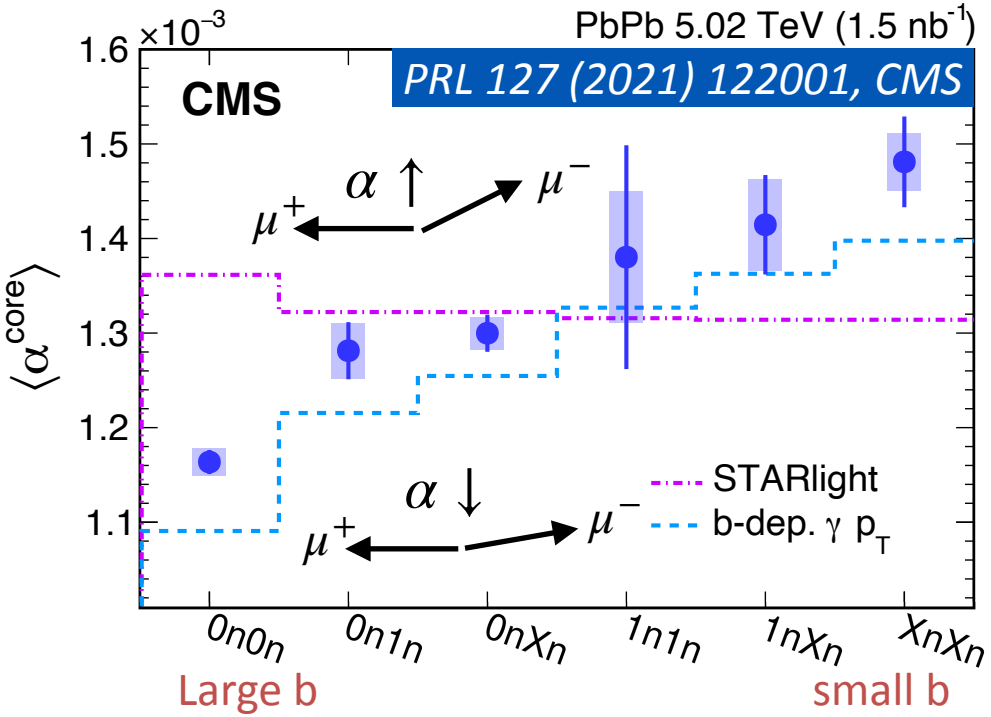
Dimuon acoplanarity in UPC

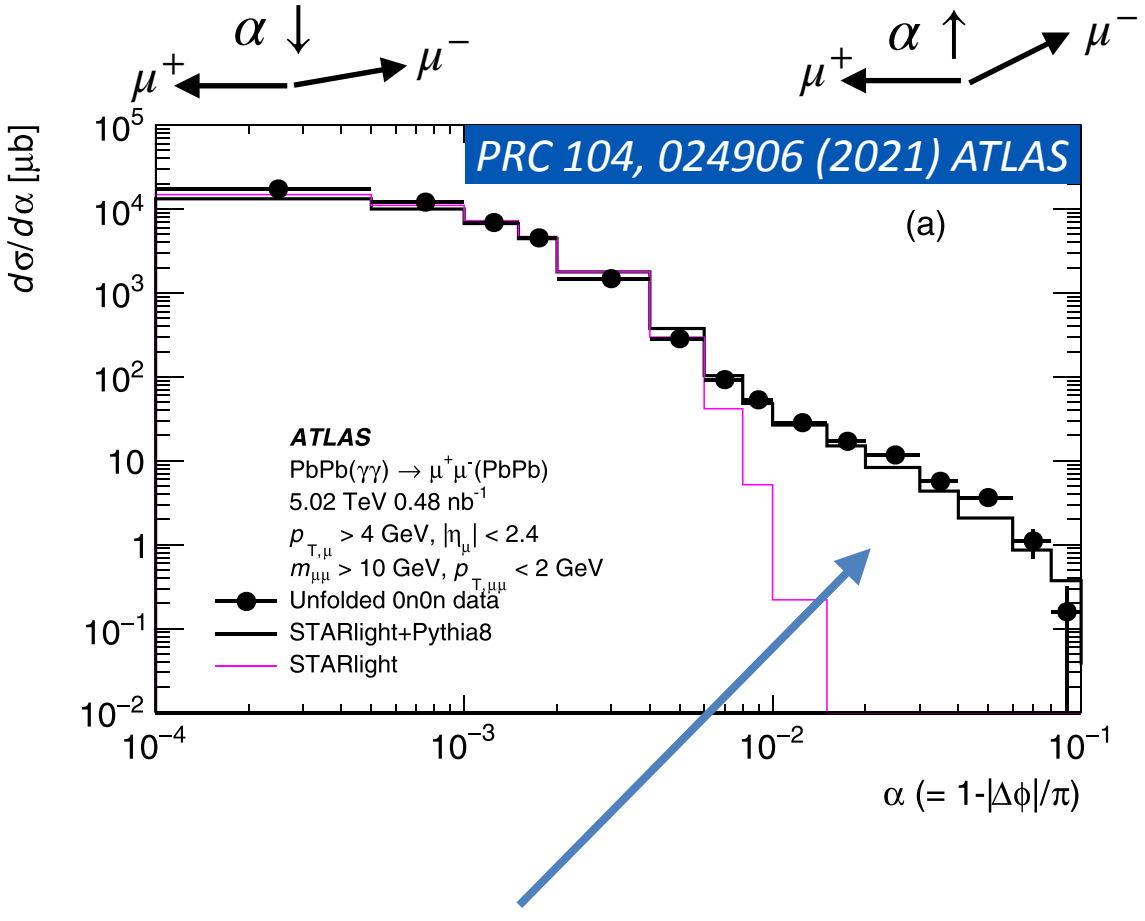




- Photo-produced dimuon pairs had acoplanarity depending on the impact parameter
- Theory compatible with data when the b-dependent photon p_T is considered *[arXiv.2006.07365]*

Dimuon acoplanarity in UPC

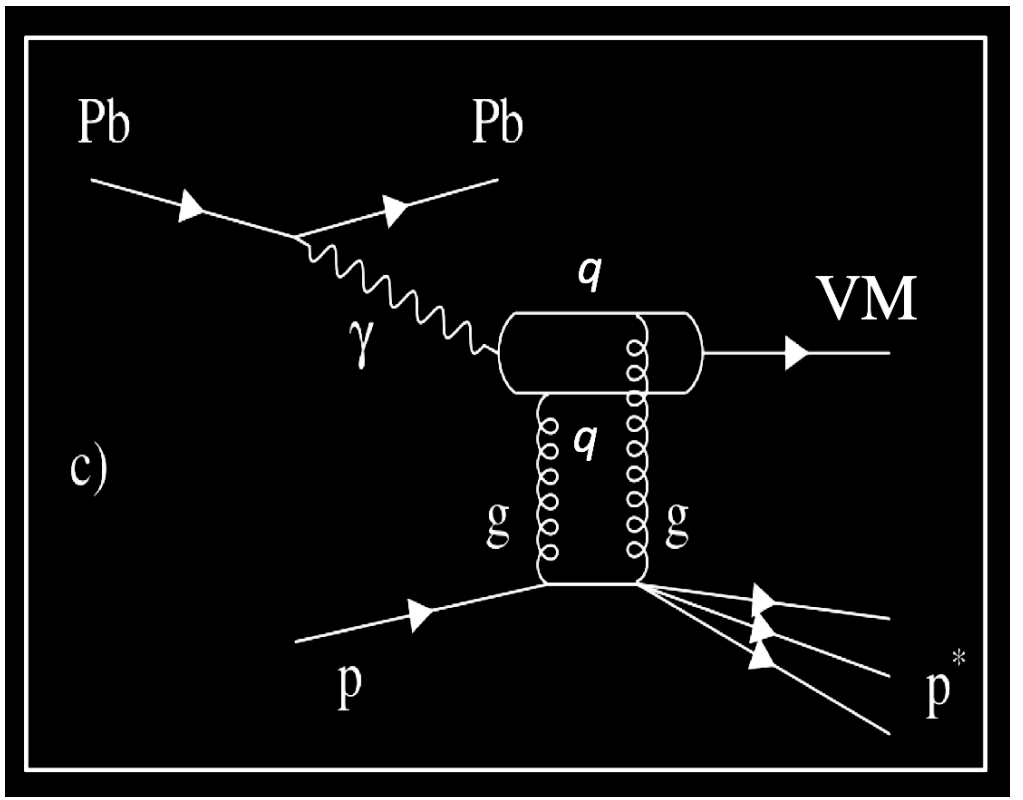


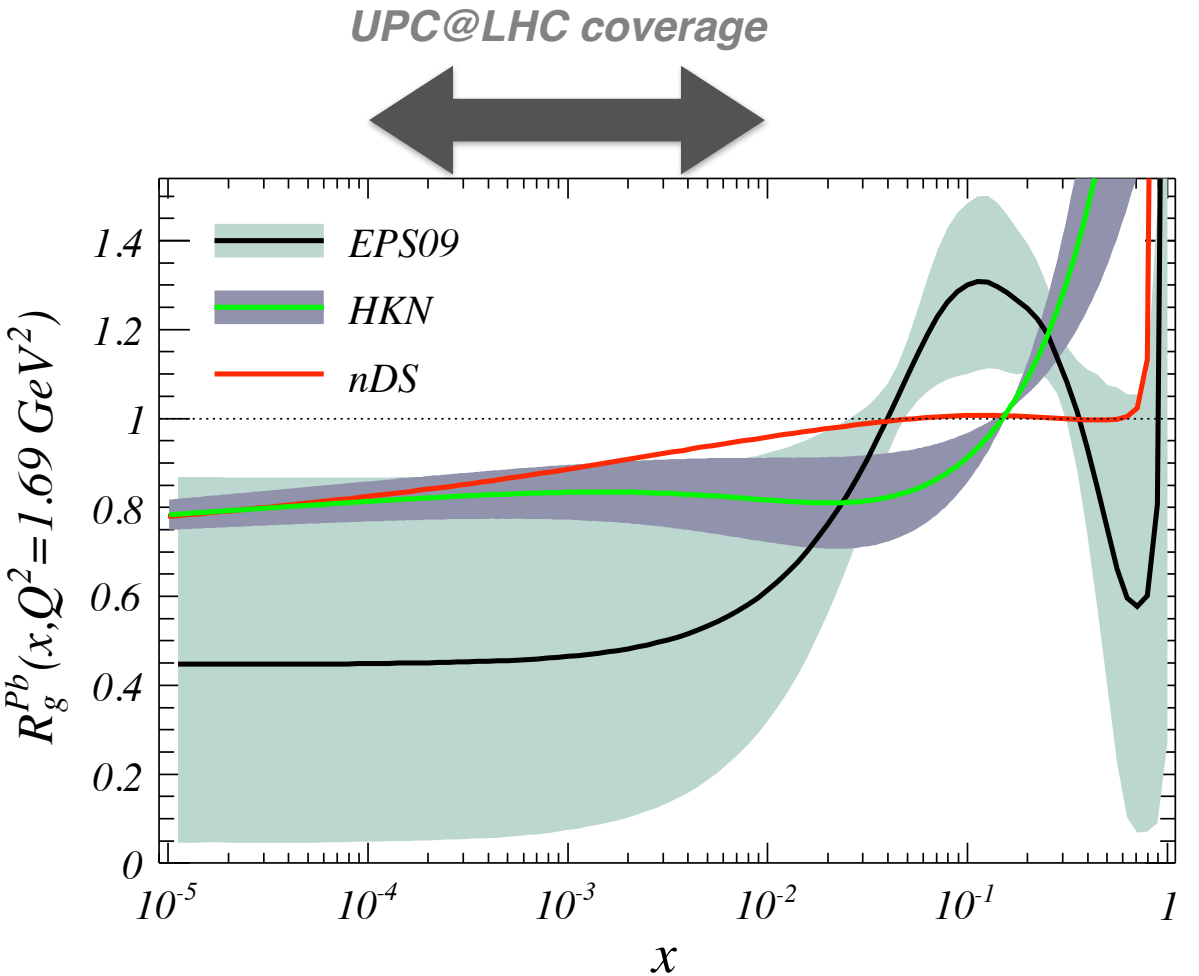


- ATLAS observed the excess of high acoplanarity events (α>0.01) which is not in STARlight
- Need for NLO calculation
- UPC is great tool to validate QED!

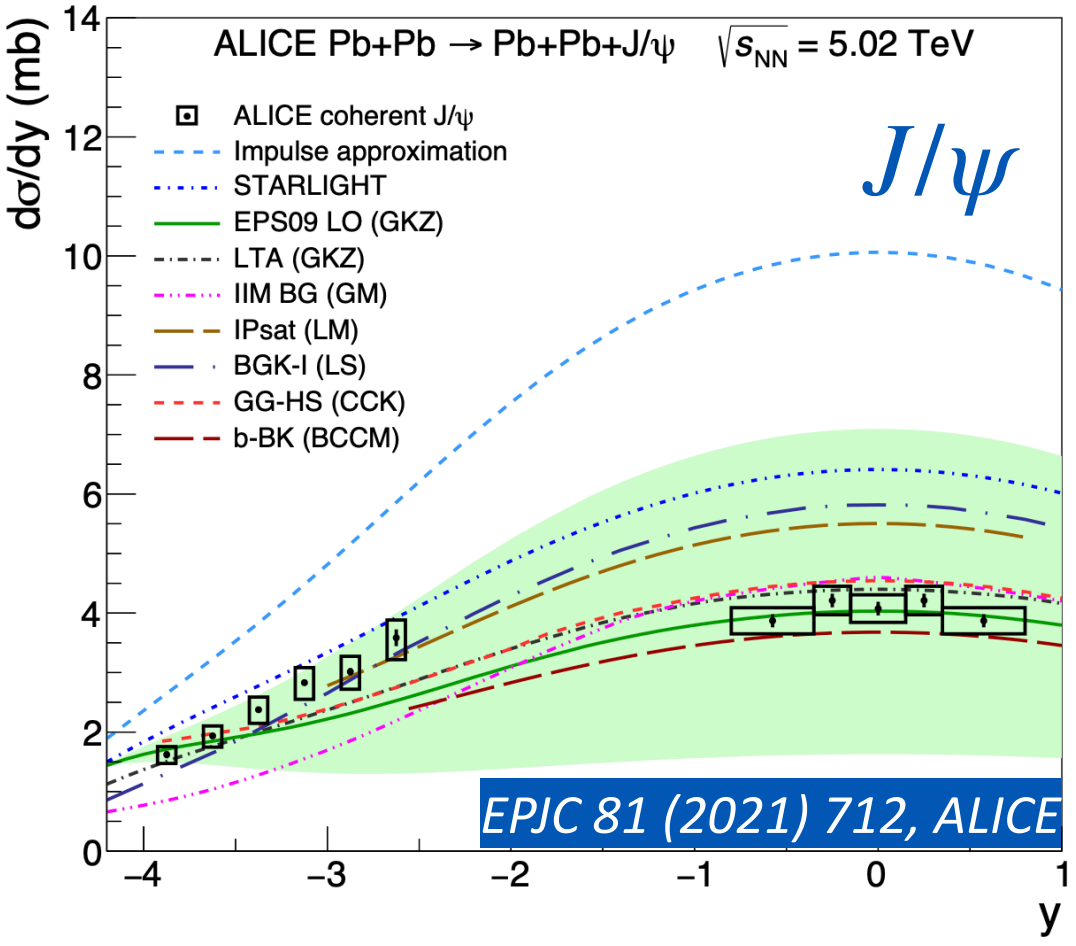
Vector meson in UPC

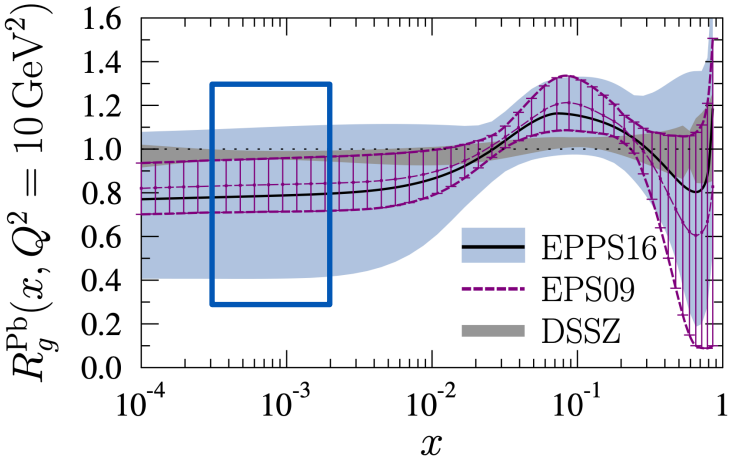
- $\rho(770)$, J/ψ, $\psi(2S)$, Υ(nS), ϕ
- Test for pQCD and nuclear structure





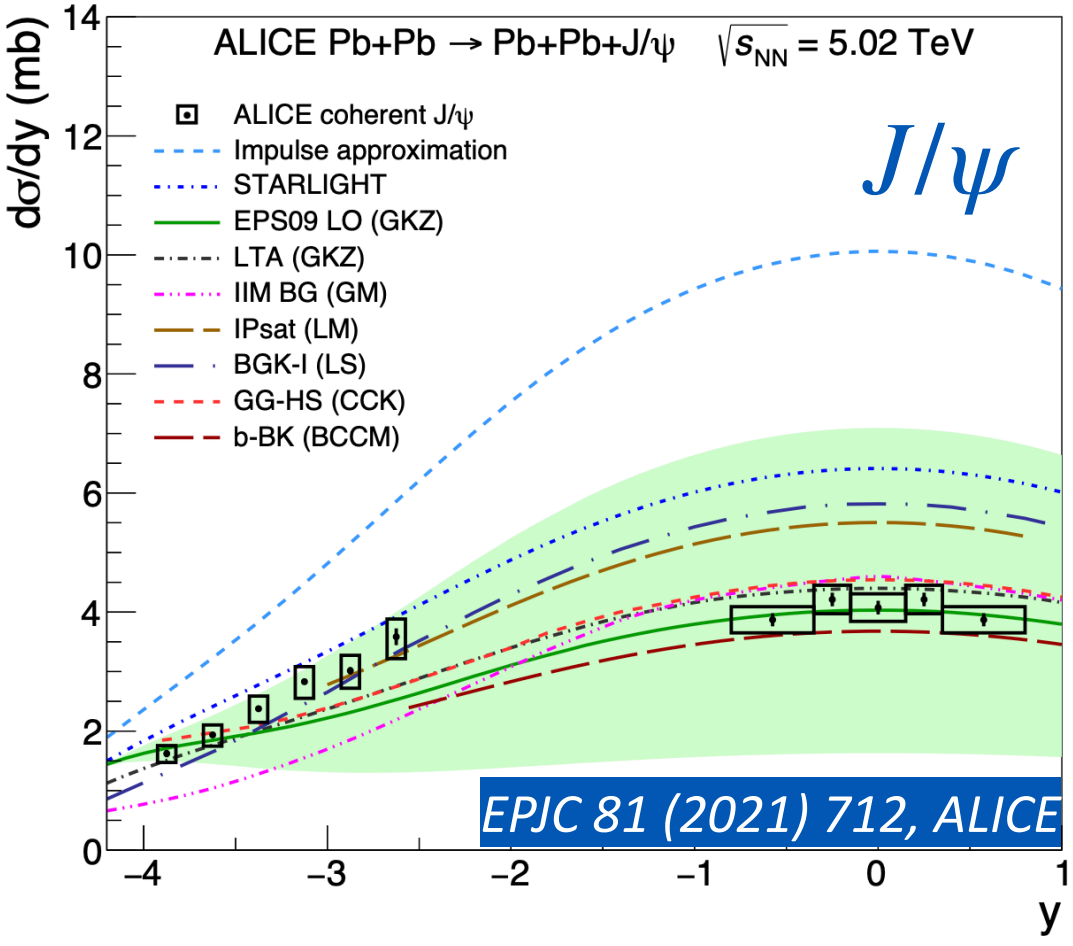
J/ψ probes gluon distribution in Pb

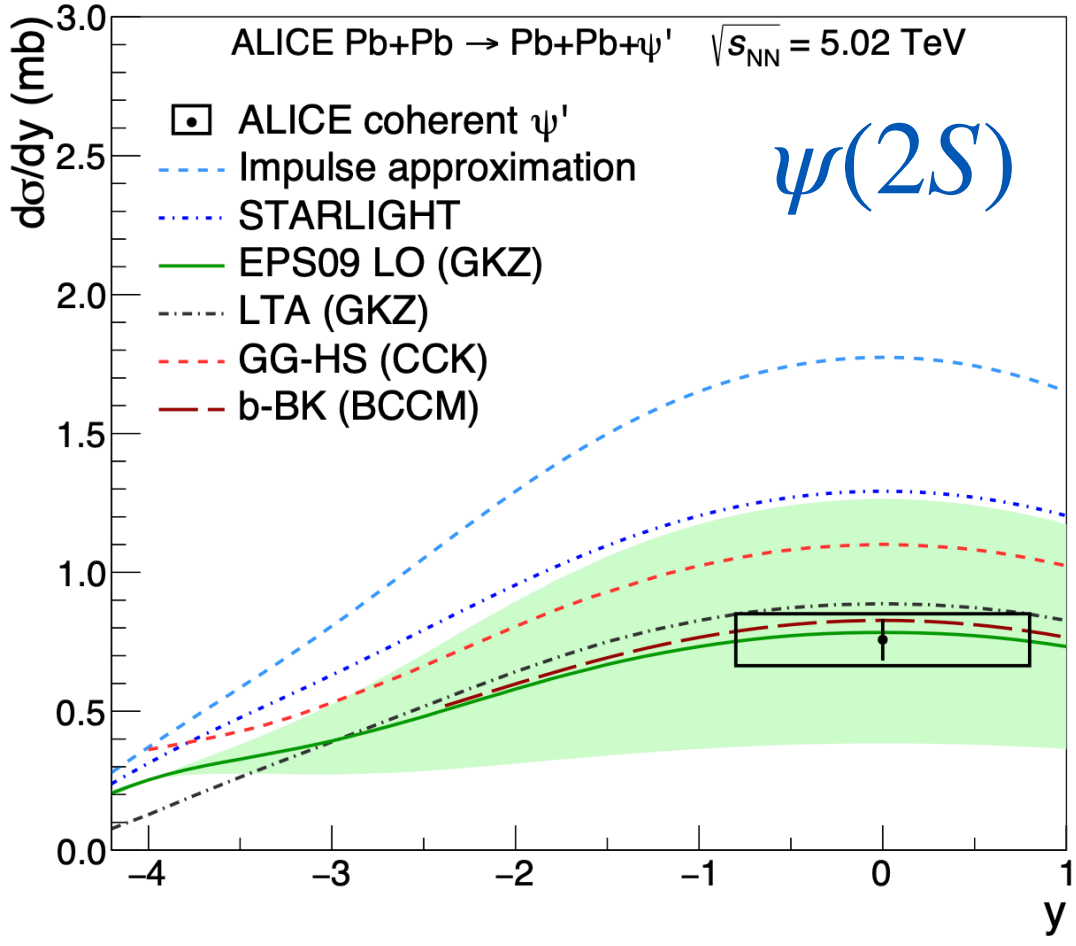




- J\ψ was suppressed by more than factor of 2 when compared to normalized γ+p calculation with impulse approximation
- Models with shadowing and saturation effects better describes data
- Yet, none can reproduce the rapidity distribution in *-4 < y < 1*

J/ψ probes gluon distribution in Pb



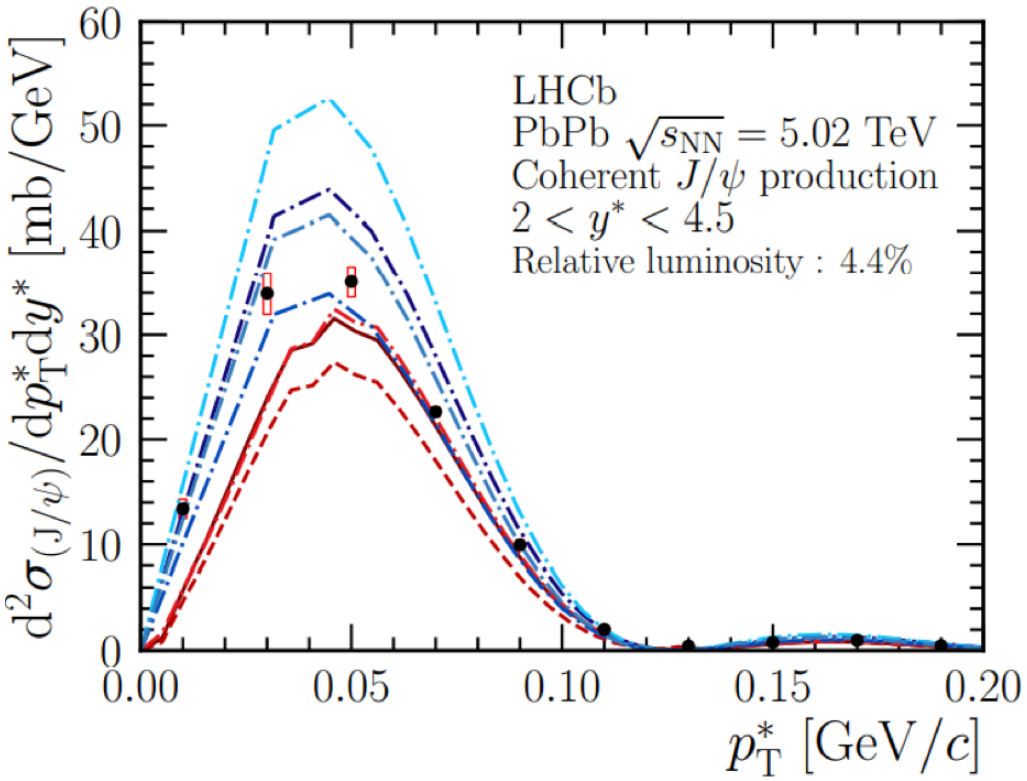


- The suppression of ψ(2S) level is same to J/ψ in UPC
- Confirms that the suppression occurs by gluon distributions in A

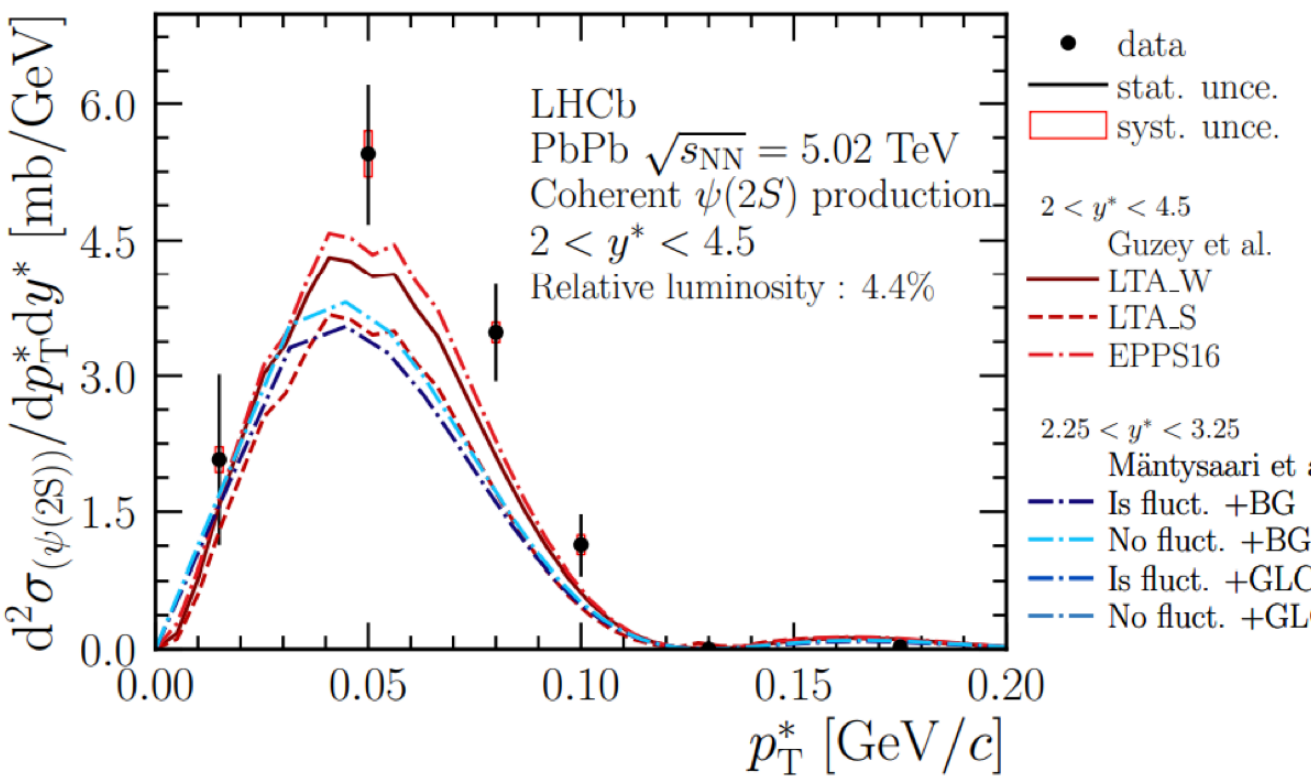
J/ψ probes gluon distribution in Pb

LHCb-PAPER-2022-012, LHCb

J/ψ



$\psi(2S)$

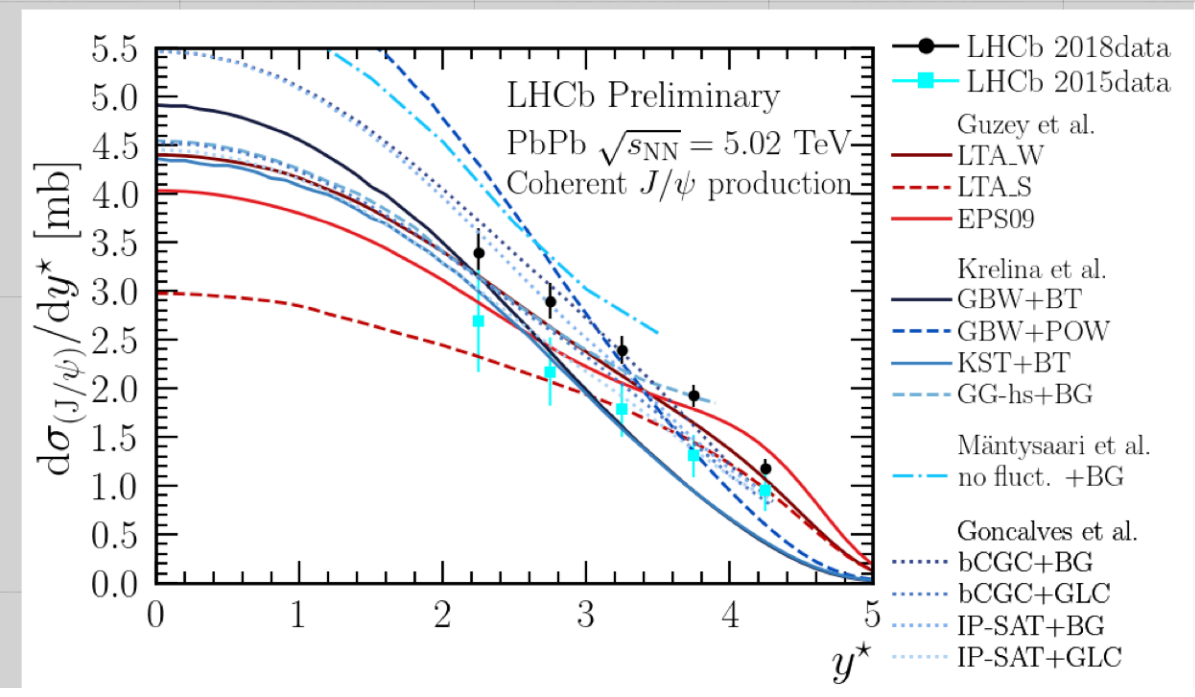


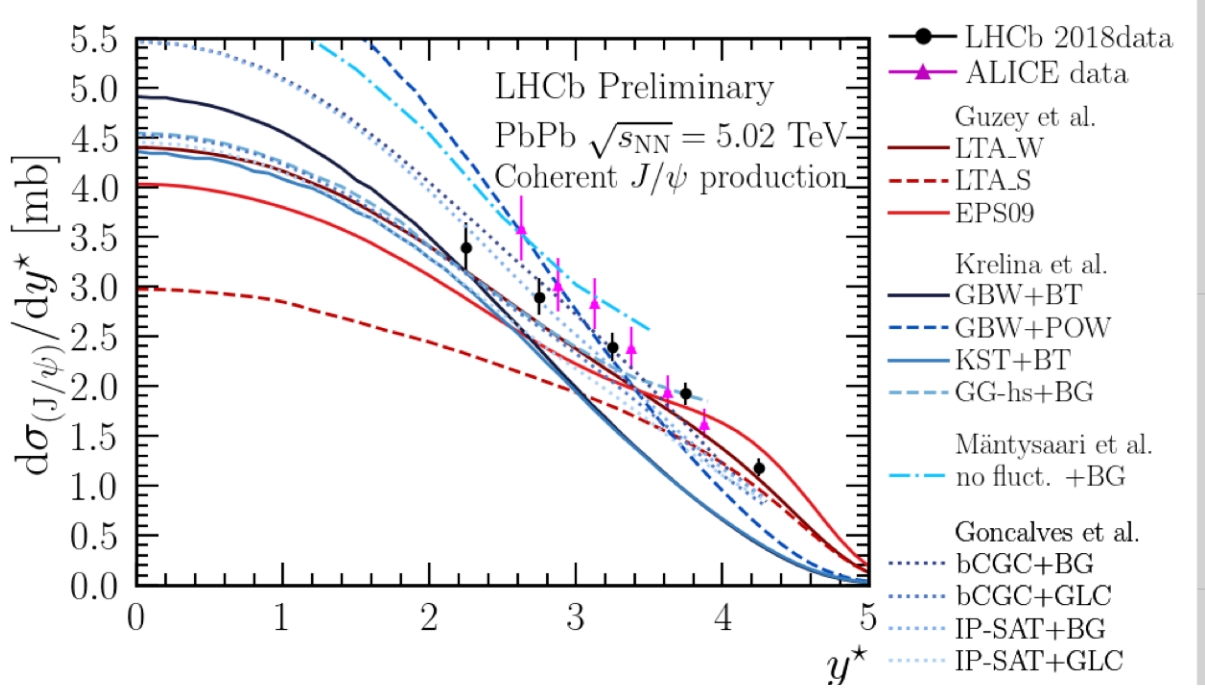
- First measurement of charmonia spectra vs p_T

J/ψ probes gluon distribution in Pb

LHCb-PAPER-2022-012, LHCb

J/ψ $\psi(2S)$

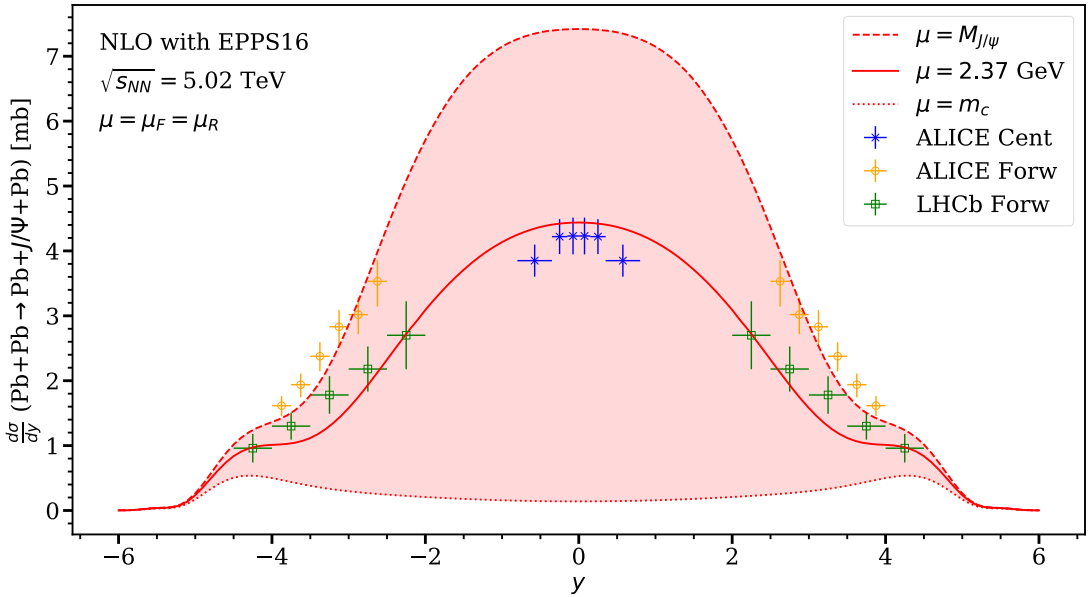


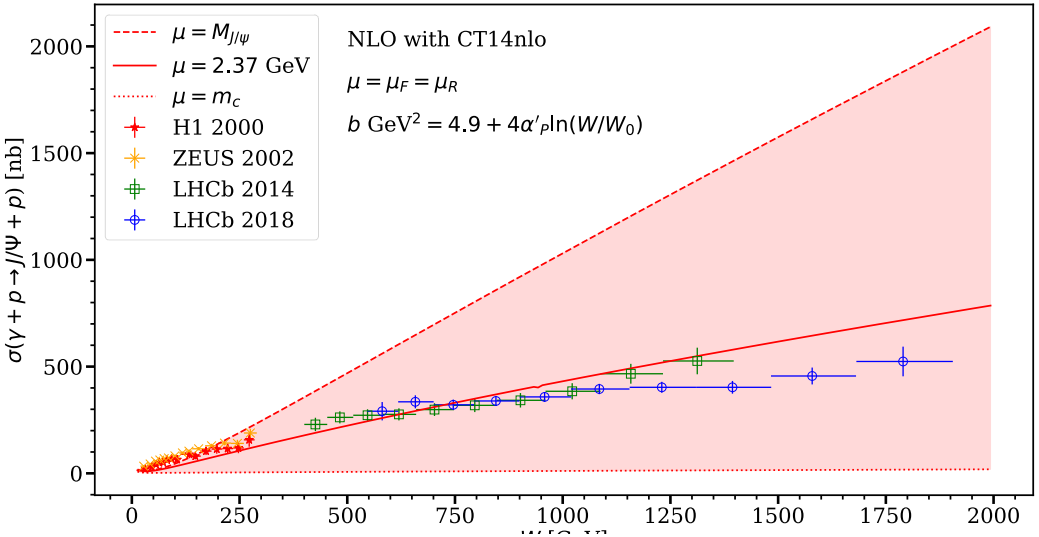


- LHCb also measured rapidity-differential cross section and single ratio of J/ψ and $\psi(2S)$, providing input for pQCD models

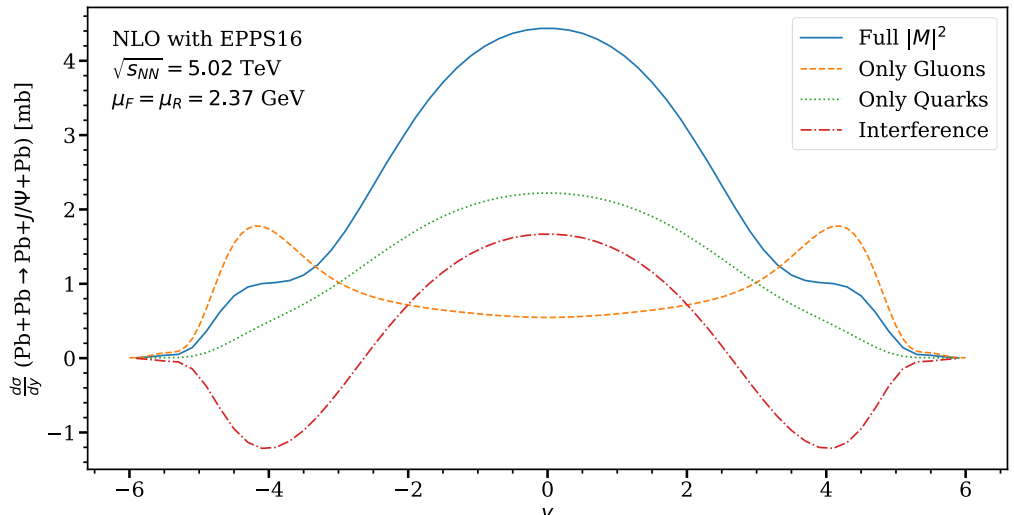
NLO calculation looks promising for J/ψ phenomenology

Löytäinen's slides in QM22





- Sensitive to the scale, but can find an optimal value that reproduces $\gamma + p$ and $\gamma + Pb$ results simultaneously



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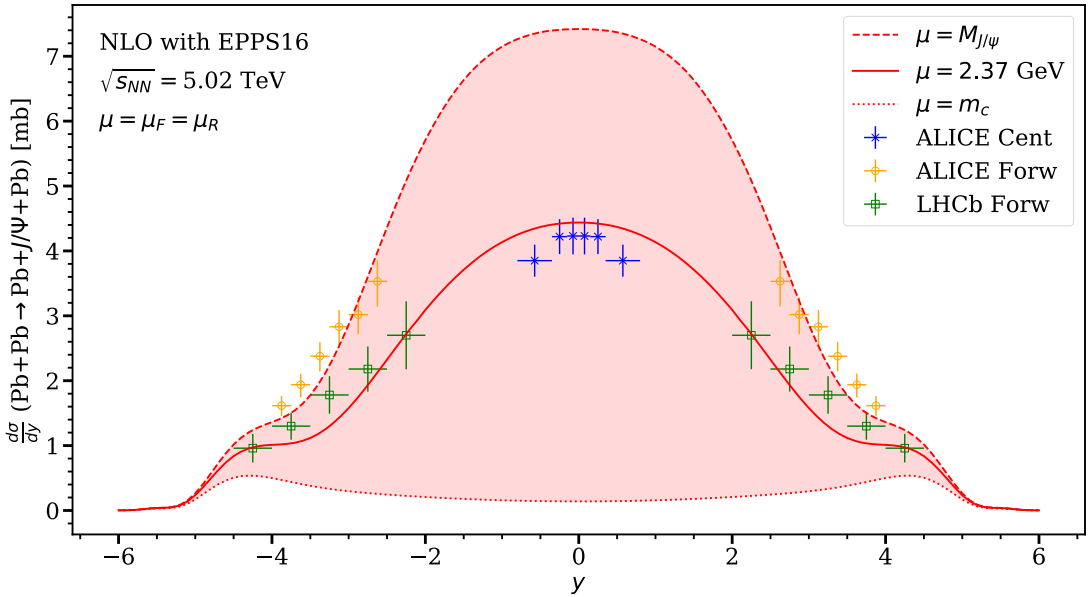
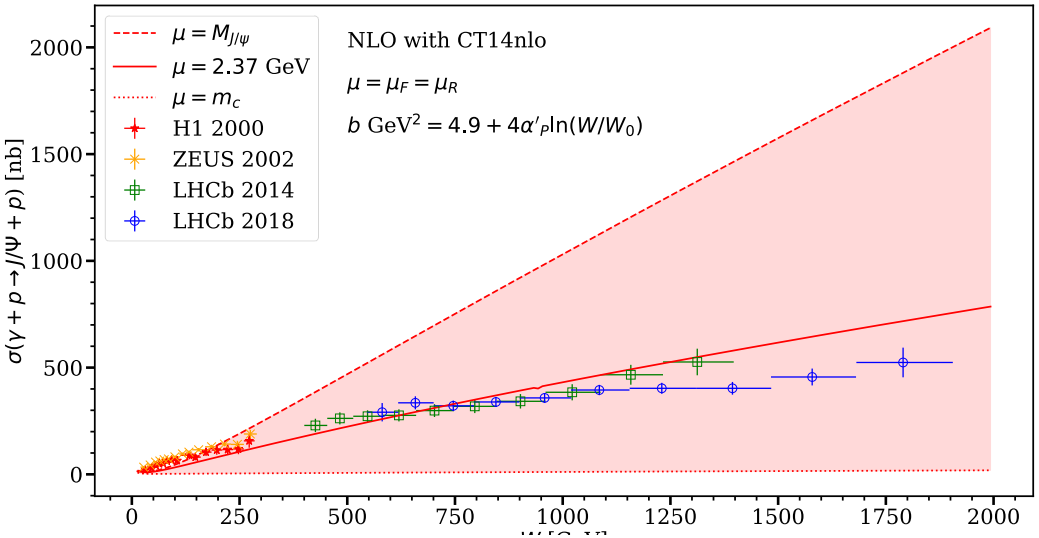
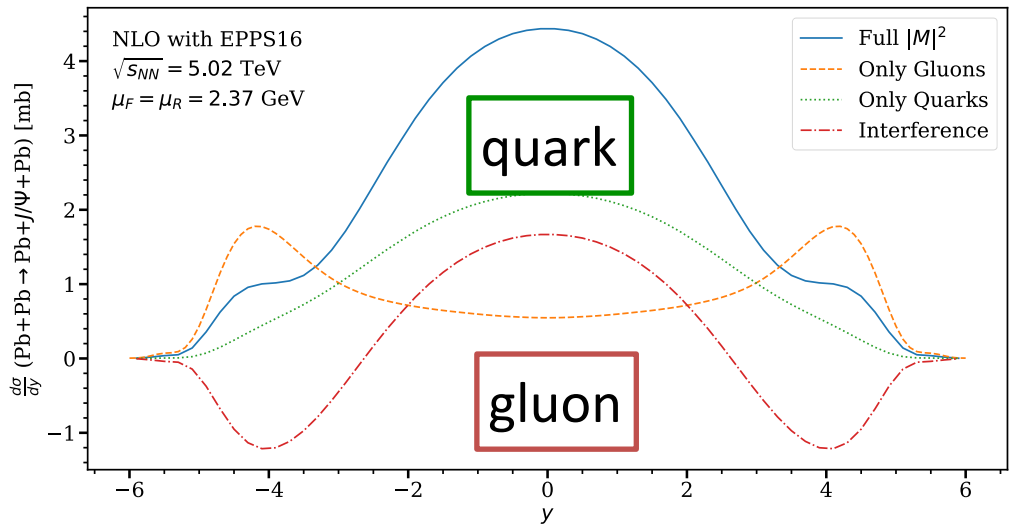


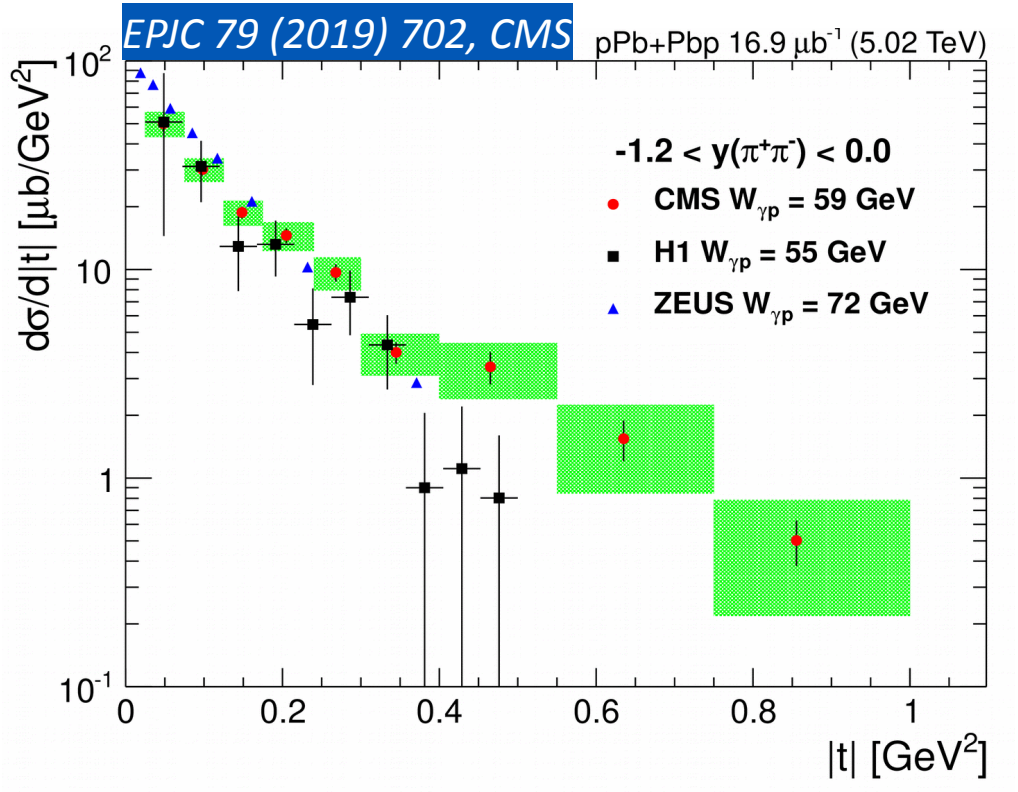


- Sensitive to the scale, but can find an optimal value that reproduces $\gamma + p$ and $\gamma + Pb$ results simultaneously
- At mid rapidity, quark contribution is dominant because gluon's amplitudes cancel for LO and NLO

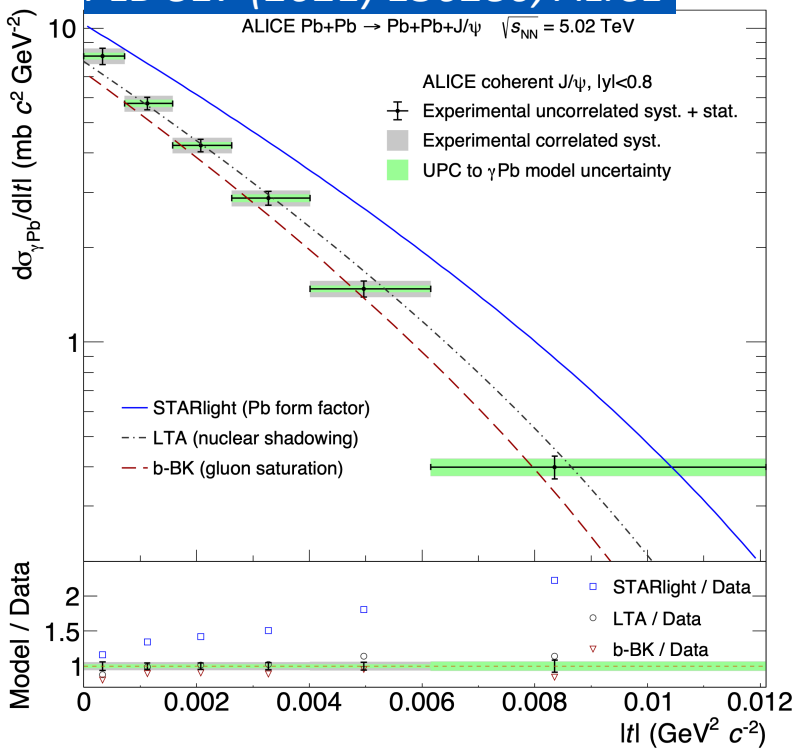


Exclusive $\rho(770)$ in pPb collision at 5.02 TeV

EPJC 79 (2019) 702, CMS

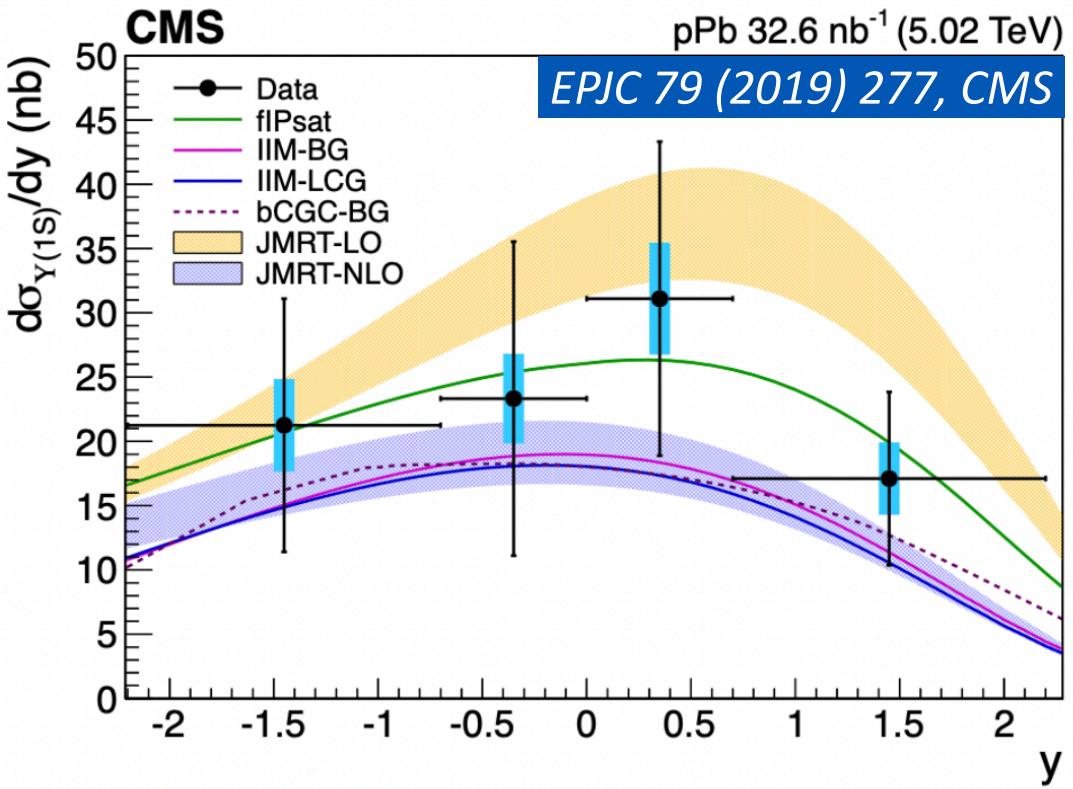


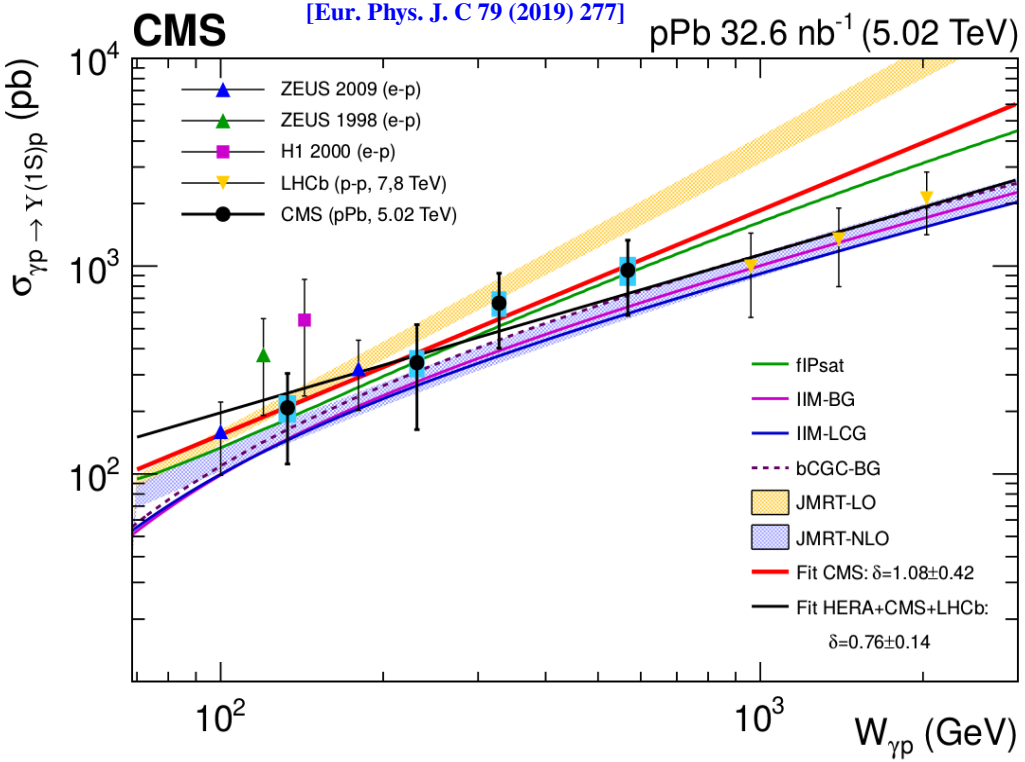
PLB 817 (2021) 136280, ALICE



- |t| dependence shows proton density profile
- Diff. cross section of ρ in $\gamma + p$ agrees well with HERA data
- Diff. cross section of J\ψ in $\gamma + Pb$ agrees well with nuclear shadowing models

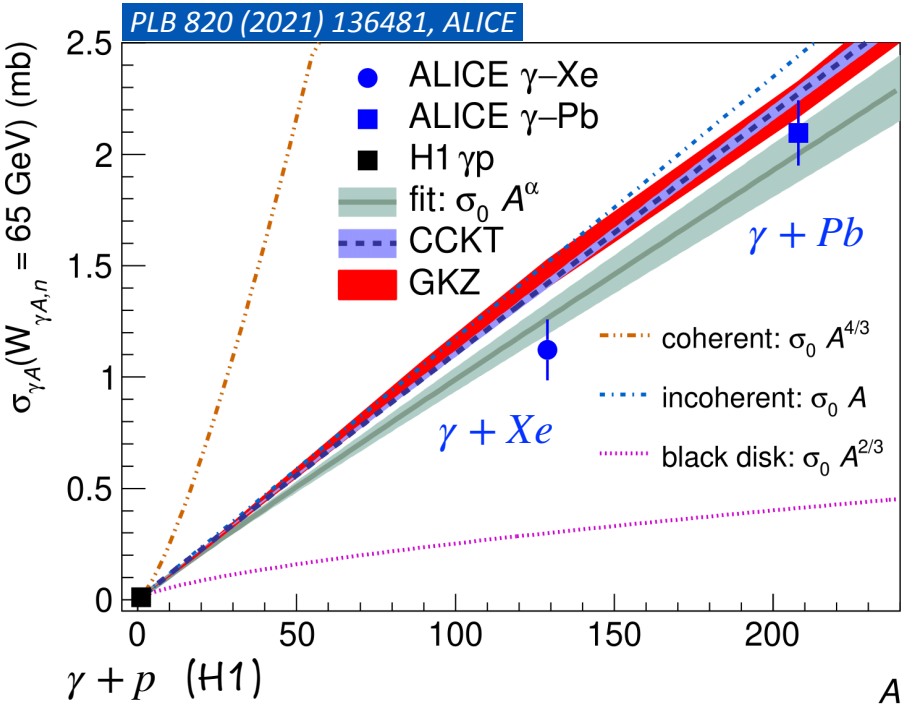
Exclusive Υ(1S) in pPb collision at 5.02 TeV





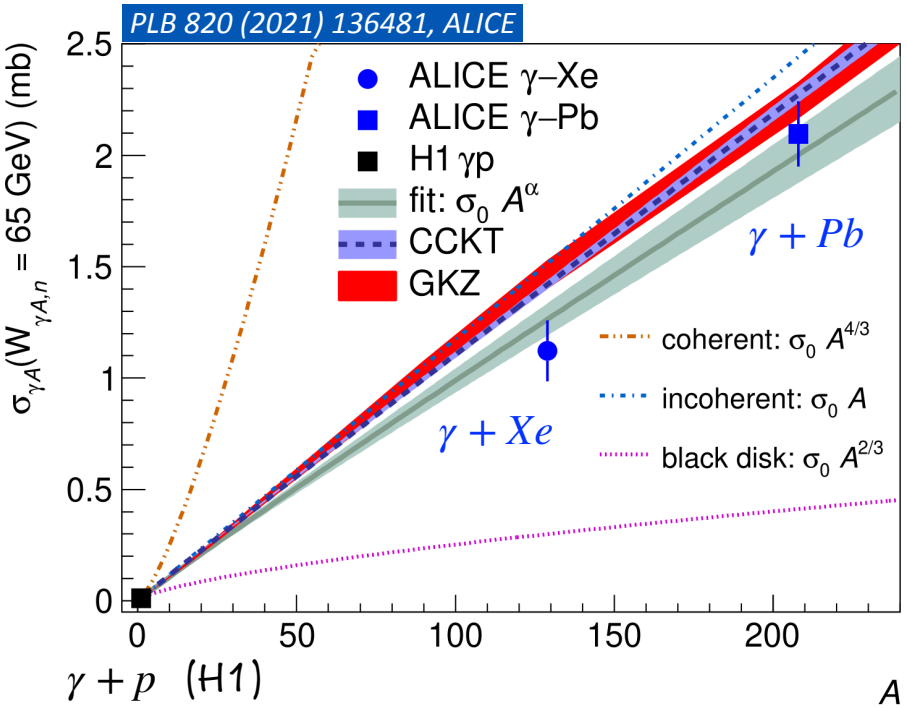
- Exclusive Y(1S) in γ+p was measued as a function rapidity
- Compared with saturation deployed models CGC model **(fIPsat)**, Color dipole formalism **(IIM)**, and pQCD calculation with DGLAP formalism **(JMRT)**
- $W_{\gamma p}$ dependence, power-law, is compatible with H1 and ZEUS

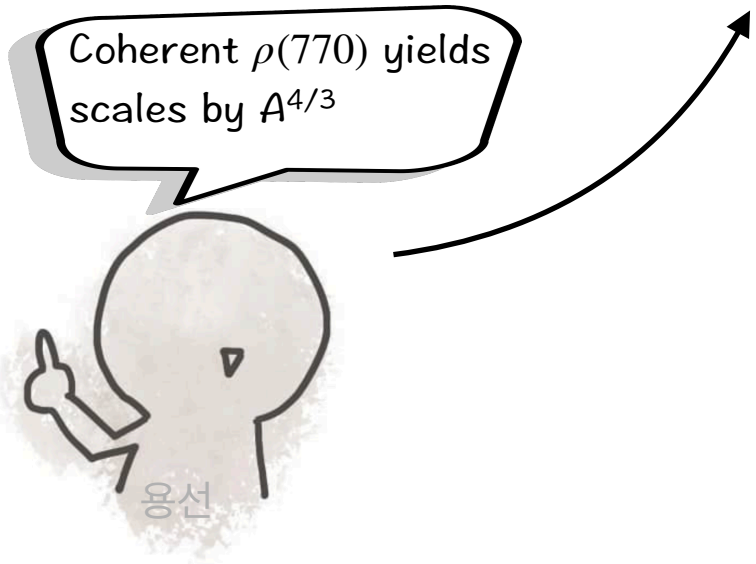
Exclusive $\rho(770)$ in XeXe

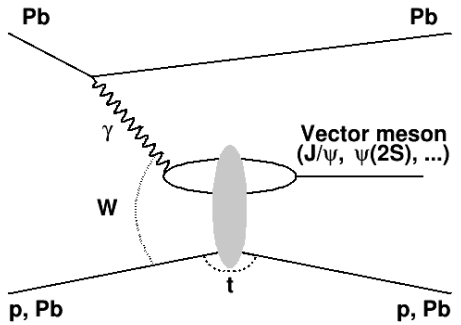


- Study of target species dependence
- Power law fit α ~ 0.96 $\pm$ 2
- Coherent VM cross section is expected to scale by $A^{4/3}$, however, the nPDF cancel this out, as suggested by CKZ (shadowing) and CCKT (saturation)

Exclusive $\rho(770)$ in XeXe







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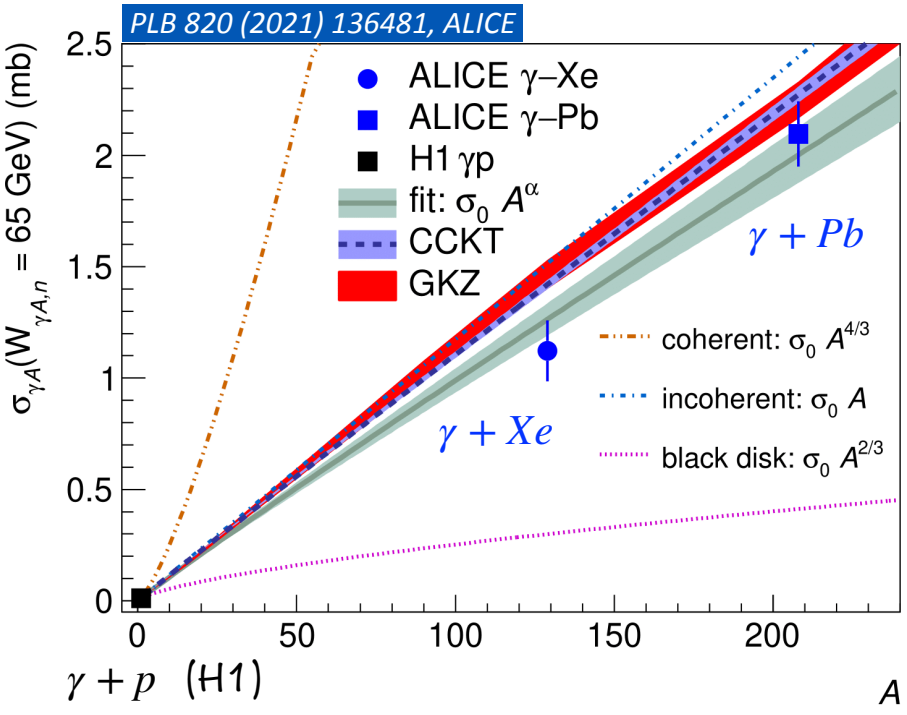

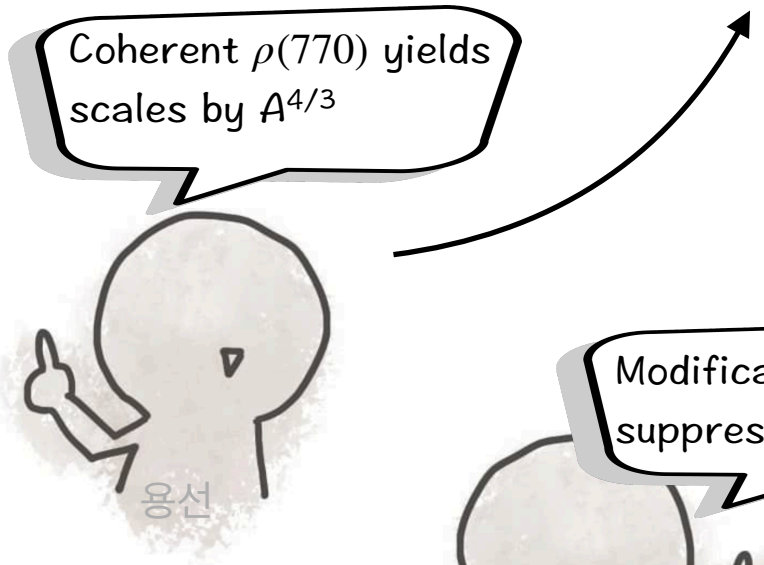

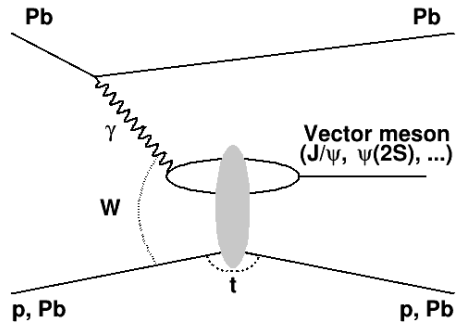

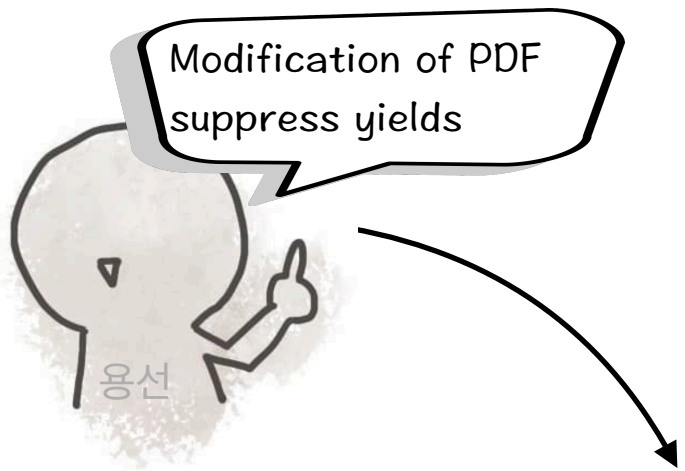

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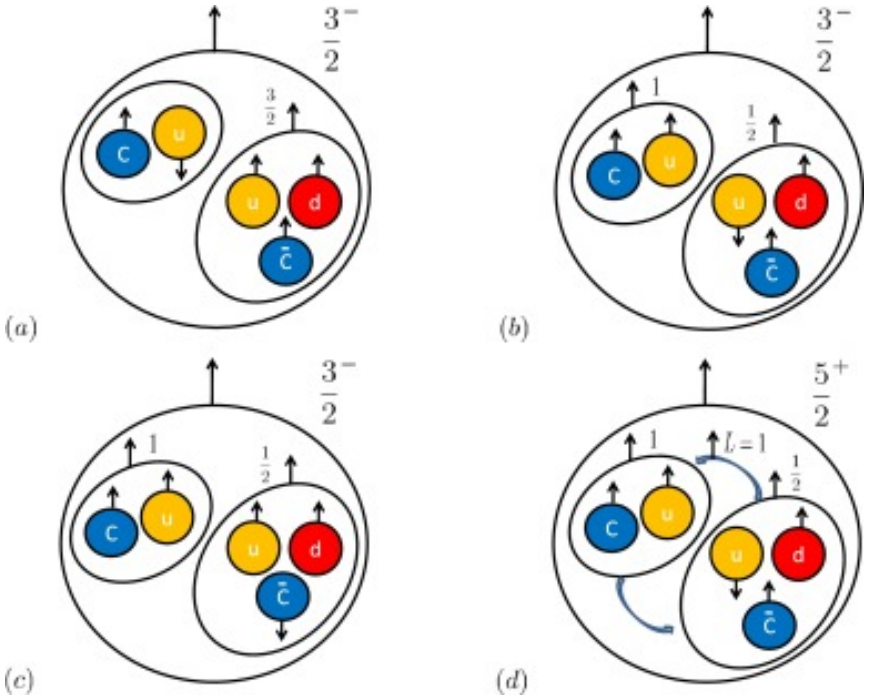
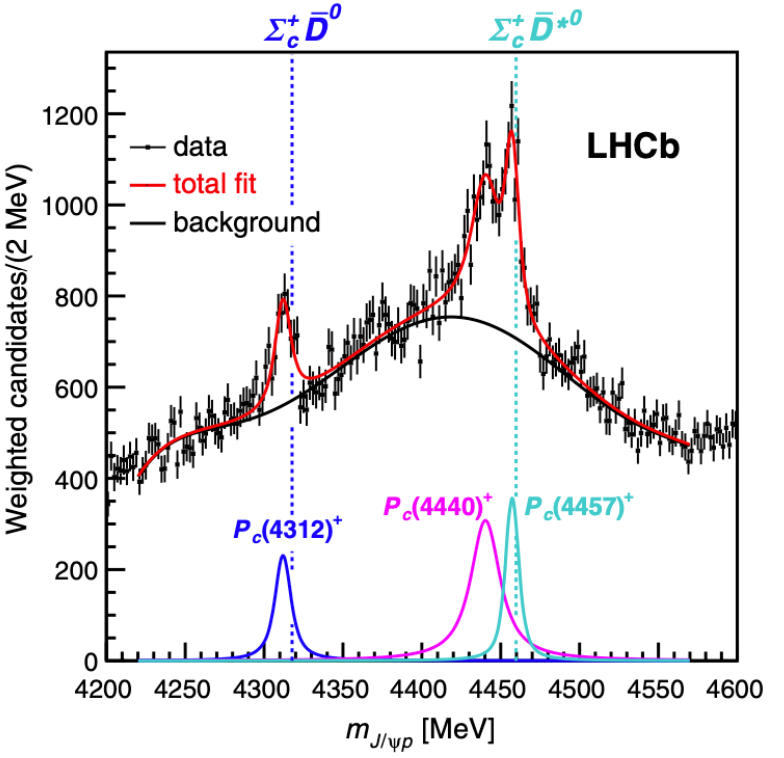
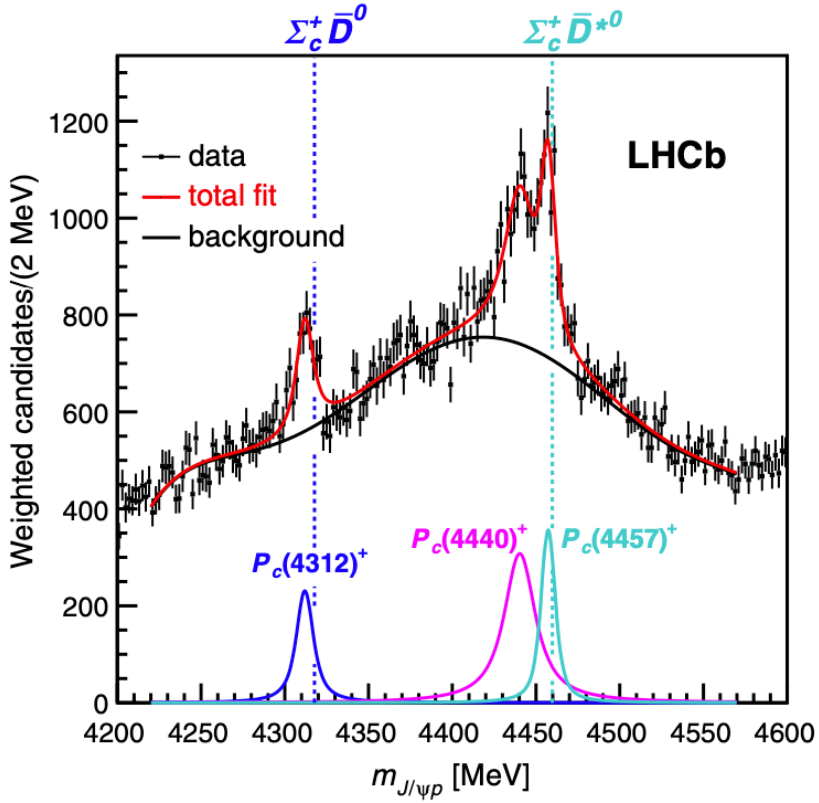
Photoproduction of Exotic particles at EIC



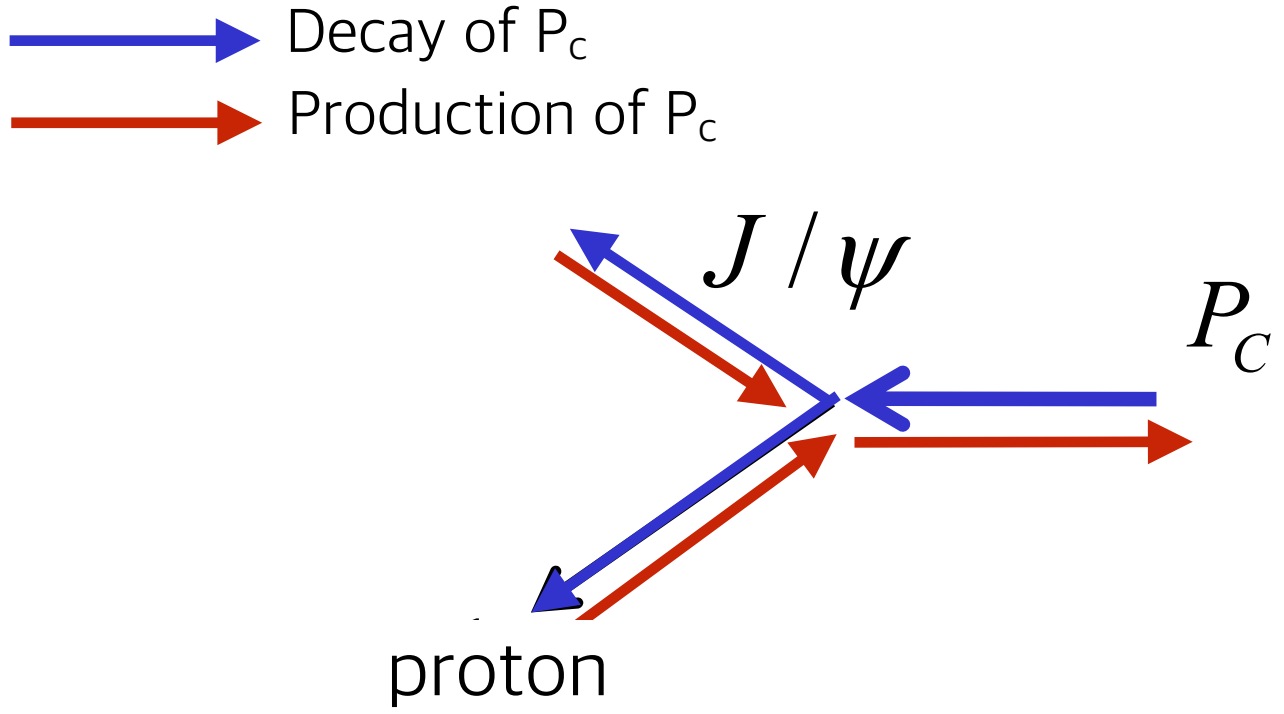


Decay width for P_c measured by LHCb (2018)



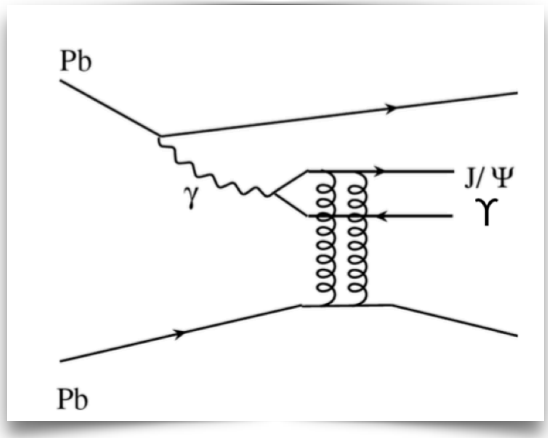
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

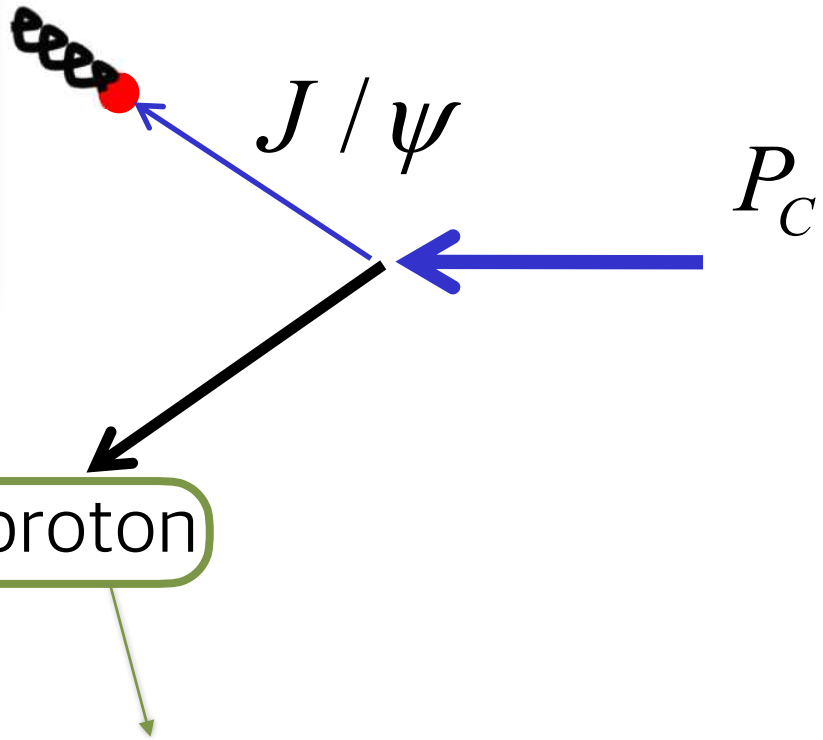
Decay width for P_c measured by LHCb (2018)



Perhaps we can create a pentaquark by coalesce J/ψ and proton at collider

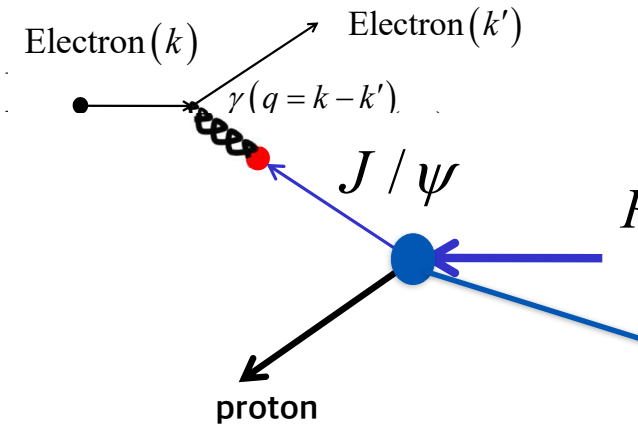
Decay width for P_c measured by LHCb (2018)





from proton beam

Decay width for P_c measured by LHCb (2018)



Vector meson dominance model

- Z.Phys. A356 (1996) 193-206, Klingl et al.
- Currents and Mesons (1969), Sakurai

$$\mathcal{L}_{\rm int} = \begin{cases} \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \sigma^{\mu\nu} F^J_{\mu\nu} \psi_{P_c} & J^P = \frac{1}{2}^+, \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma_5 \sigma^{\mu\nu} F^J_{\mu\nu} \psi_{P_c} & J^P = \frac{1}{2}^-, \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma_5 \gamma^\mu F^J_{\mu\nu} \psi^\nu_{P_c} & J^P = \frac{3}{2}^+, \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma^\mu F^J_{\mu\nu} \psi^\nu_{P_c} & J^P = \frac{3}{2}^-. \end{cases}$$

Interaction strength J/ψ, proton and P_c is computed from the decay width measured bu LHCb

J^P	$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$
g_{JpP_c}	0.379	0.169	1.47	0.599

Interaction strength in 4 spin x parity cases

Cross section of $P_c(4312)$ in EIC

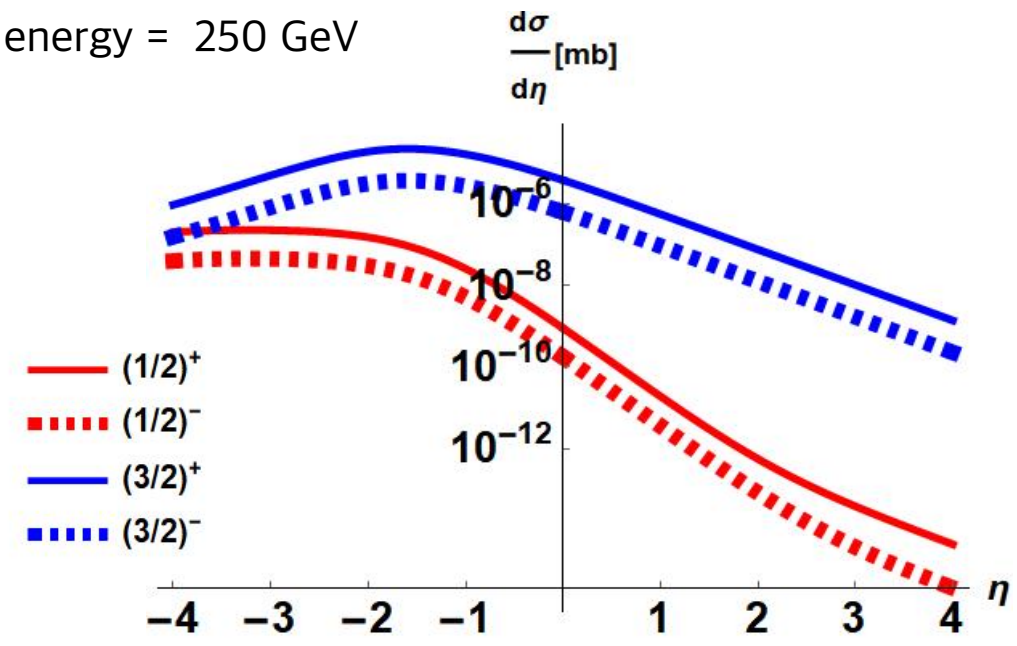
	e	p	$^3He^{2+}$	$^{197}Au^{79+}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		122.5	81.7	63.2
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge, nC	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron rms norm. emittance, μm		0.27	0.20	0.20
Electron rms norm. emittance, μm		31.6	34.7	57.9
Beta*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.015	0.014	0.008
Electron beam disruption		2.8	5.2	1.9
Space charge parameter		0.006	0.016	0.016
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak luminosity, 10^{33} $cm^{-2}s^{-1}$		1.5	2.8	1.7

Peak lumi updated to 10^{34} $cm^{-2}s^{-1}$ => 10 fb^{-1} per month is

Cross section of $P_c(4312)$ in EIC

Electron energy = 16 GeV

Proton energy = 250 GeV



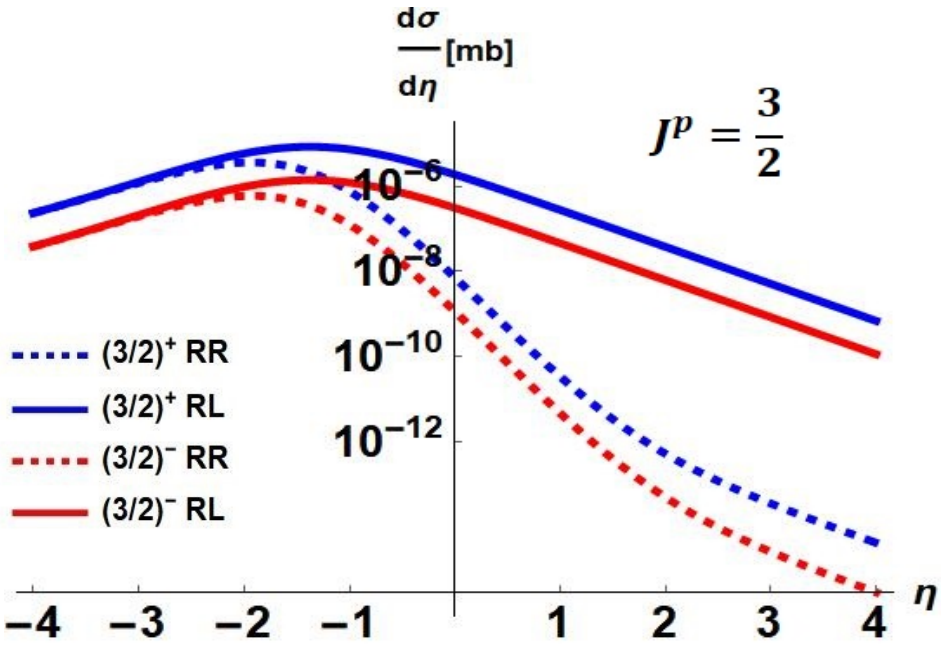
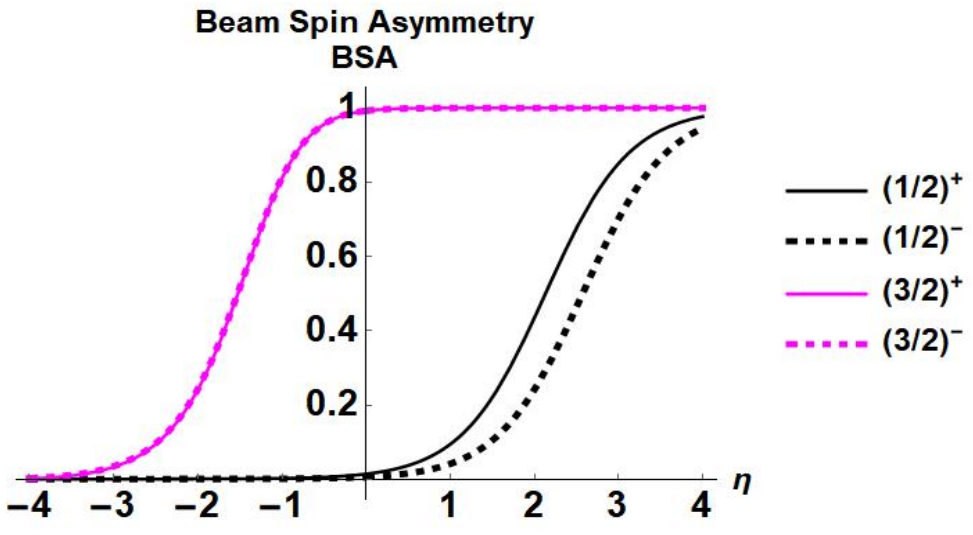


TABLE II. Expected number of $P_c(4312)$ produced at the EIC with 10 fb^{-1}.

J^P of P_c	$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$
Yield	5.09×10^6	1.01×10^6	4.51×10^8	7.46×10^7

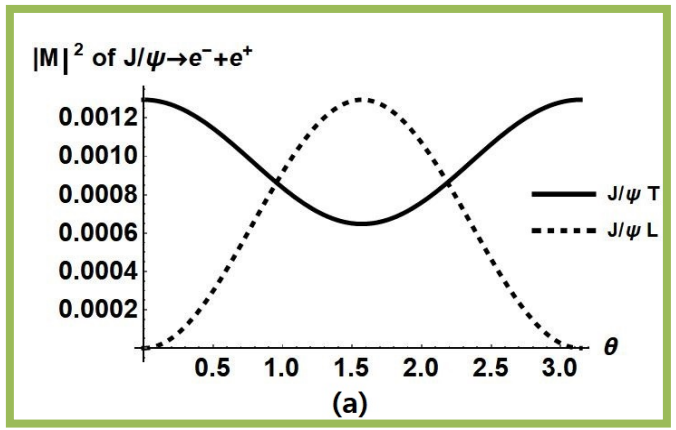
PRD 105, 114023
I. Park, S. Cho, S. Lee, Y. Kim

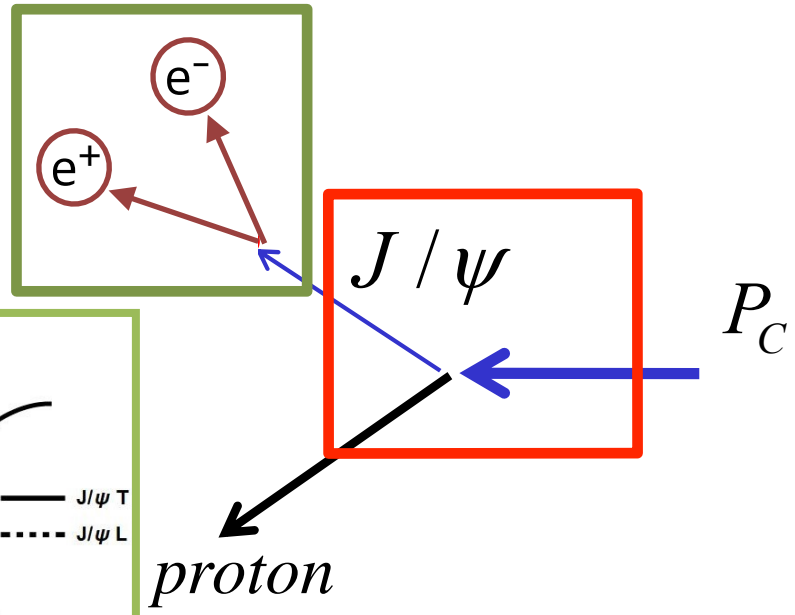
Cross section of $P_c(4312)$ in EIC

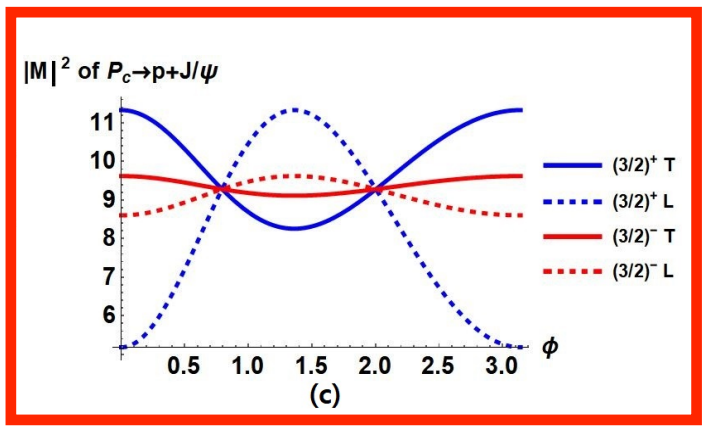


$$BSA\ (\eta) = \frac{d\sigma/d\eta\ [RL] - d\sigma/d\eta\ (RR)}{d\sigma/d\eta\ [RL] + d\sigma/d\eta\ [RR]}$$

- BSA says the spin
- angular correlation says the parity







Take home message

UPC, sic parvis magna

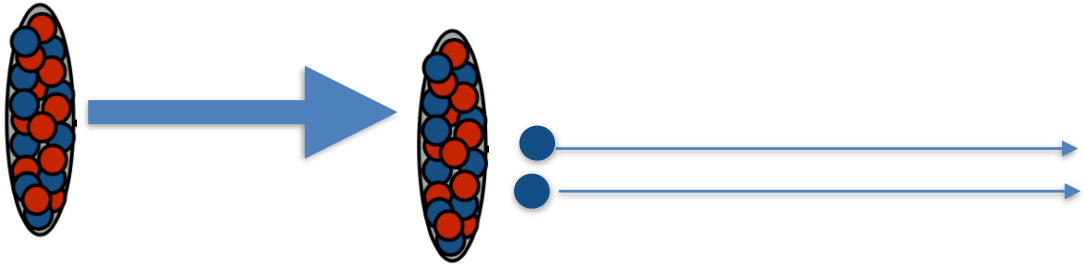
- UPC program at LHC was initially motivated for nuclear shadowing in heavy ion
- Proved to be useful for the search for new physics
- Exclusive channels for gluon polarization

Prospective probes at the LHC and EIC

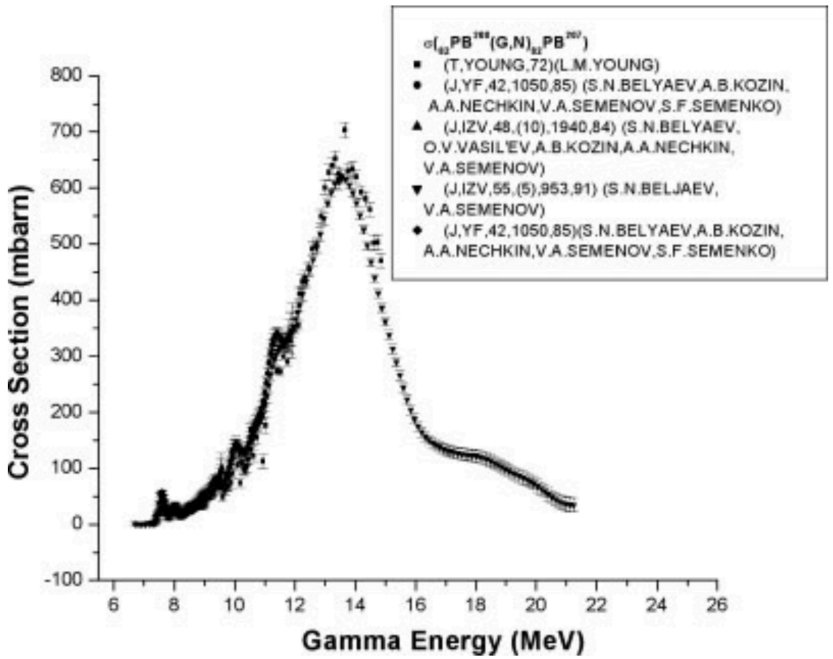
- VM - VM pairs - double J/ψ or double Υ events
- X(3872) is also a probable particle produced from UPC
- Huge chance for the study of Exotic particles at EIC

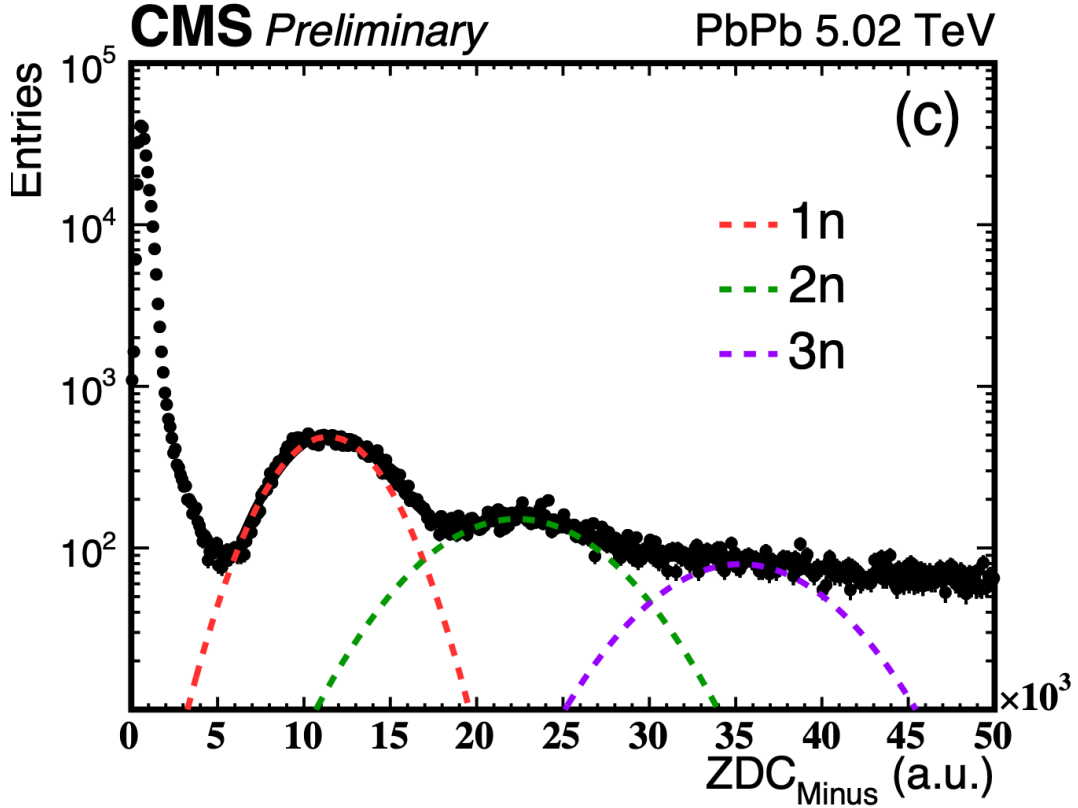
BACKUP

Impact parameters of photo-interaction



Emitted neutrons move almost forward and detected by Zero Degree Calorimeter





- **Giant dipole resonance** knocks out neutrons
- Measured by Zero Degree Calorimeters