Theoretical advancements of relevance for heavy-ion interactions in Atlas and Alice

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NorCC Workshop, 14-15. September 2022

Outline of the talk

- Recent results from Atlas on $\gamma\gamma \to \tau\tau$ and $\gamma\gamma \to e^+e^-$. What to expect for Run 3?

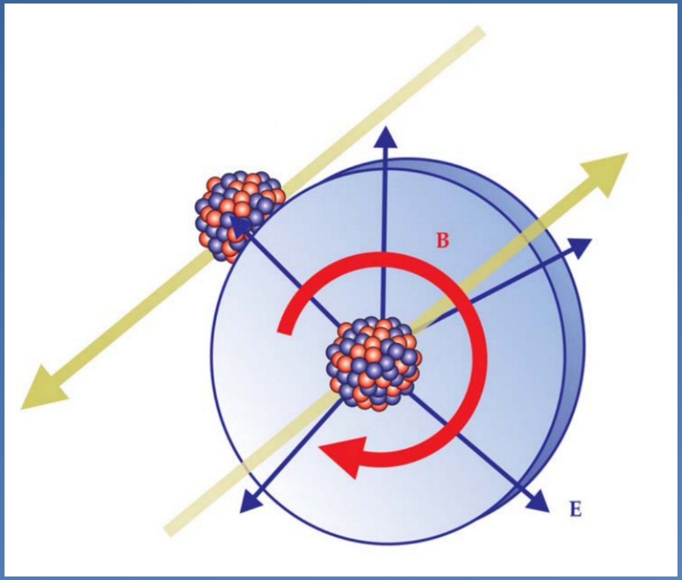
- Photoproduction in the very forward region. New addition to ALICE in Run 4 – the Forward Calorimeter (FoCal).

- How to measure nuclear stopping – a new idea using Bremsstrahlung emission.

Ultra-Peripheral Collisions

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

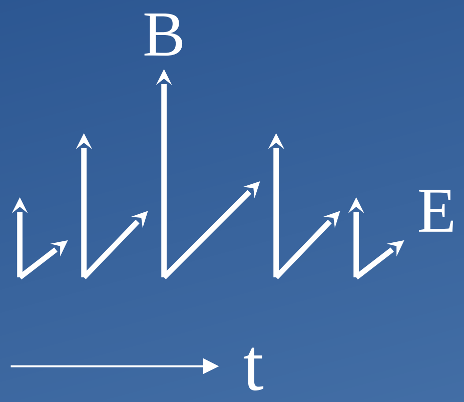
Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.



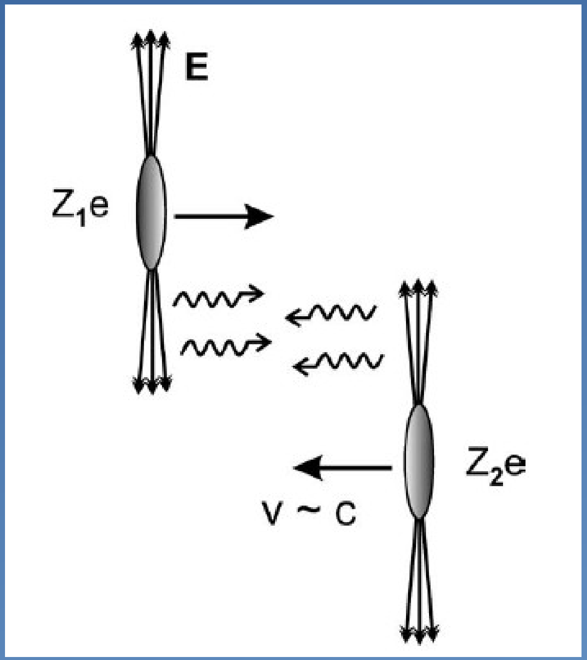
The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

The electromagnetic field of an ultrarelativistic, charged particle



1) $|E| \approx |B|$ 2) $(E \perp B)$ 3) $\Delta t \sim b/\gamma c$



Fermi 1924: The effect of the fields is equivalent to a flux of photons with a continous energy spectrum.

The spectrum extends to energies $\approx\gamma\hbar c/b_{min}$, where b_{min} is the minimum impact parameter.

This is in the 100 – 1000 GeV range at the LHC.

Two-photon interactions

Two recent papers from Atlas on ultra-peripheral collisions:

“Observation of the $\gamma\gamma \rightarrow \tau\tau$ process in Pb+Pb collisions and contraints on the τ-lepton anomalous magnetic moment with the Atlas detector”, arxiv:2204.13478.

“Exclusive dielectron production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with Atlas”, arxiv:2207.12781.

Both use the STARLight Monte Carlo to compare with the measured cross sections and to simulate events.

The starlight Monte Carlo

A Monte Carlo for exclusive two-photon and photonuclear interactions at hadron colliders.

Development started ~25 years ago in Berkeley (Spencer Klein, Joakim Nystrand).

Available on hepforge: http://starlight.hepforge.org/.

“Recent” write-up: S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, Comput. Phys. Commun. 212 (2017) 258.

Two-photon production of τ-pairs.

Two-photon production of dilepton pairs.

The cross sections $\gamma\gamma\to\tau\tau$ and $\gamma\gamma\to e^+e^-$ calculable from QED.

$$\sigma(\gamma\gamma \to l^+l^-) = \frac{4\pi\alpha^2}{W^2}\left[\left(2+\frac{8M^2}{W^2}-\frac{16M^4}{W^4}\right)\ln\frac{W+\sqrt{W^2-4M^2}}{2M} - \sqrt{1-\frac{4M^2}{W^2}}\left(1+\frac{4M^2}{W^2}\right)\right]$$

This is the Breit-Wheeler formula (1934). W - center-of-mass energy; M - lepton mass; α - fine structure constant.

This formula is derived assuming the standard QED vertex factor $ie\gamma_\mu$.

But leptons have spin and magnetic moments.

Two-photon production of τ-pairs.

The anomalous magnetic moment of leptons.

$$a_l = \tfrac{1}{2}(g_l - 2)$$

A Dirac particle will have a gyromagnetic ratio $g_l = 2$ and thus $a_l = 0$. Quantum field theory predicts a one-loop correction leading to

$$a_l = \alpha_{em}/2\pi \approx 0.00116$$

For the muon, a_μ has been measured with a precision of 1 part in 10^7, and there are tensions with the standard model.

Two-photon production of τ-pairs.

The effects of magnetic and electric dipole moments can be treated by adding two terms to the vertex factor

$$i\Gamma_{\mu}^{(\gamma\ell\ell)}(p',p) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\ell}\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{1}{2m_\ell}\gamma^5\sigma_{\mu\nu}q^\nu F_3(q^2)\right],$$

The photons here are nearly real ($Q^2 \sim (1/R)^2 \approx 0$).

The standard model predicts

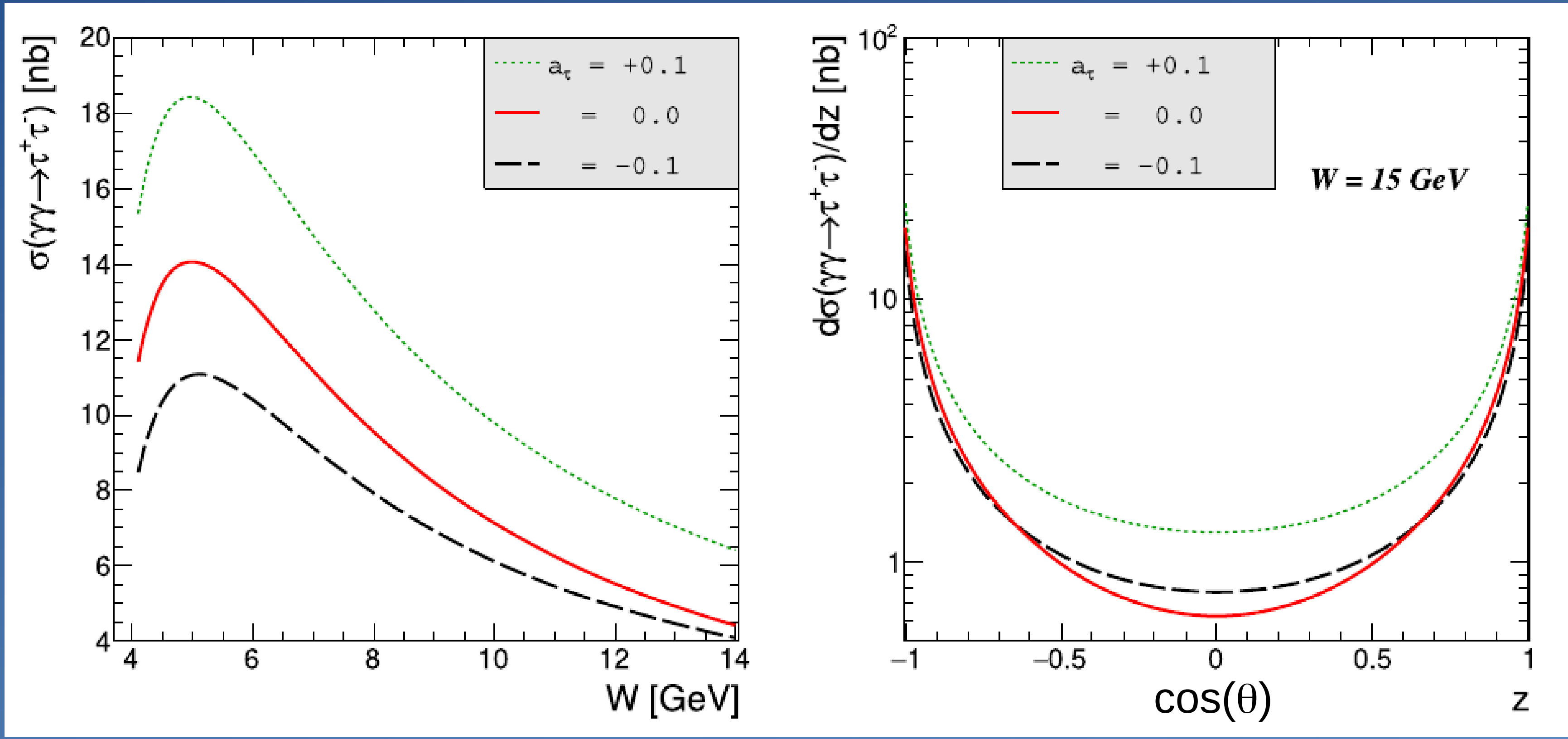
$F_1(0) = 1$

$F_2(0) = a_l$

$F_3(0) = 0$ - no electric dipole moment

The second term introduces a dependency on a_l.

Two-photon production of τ-pairs.

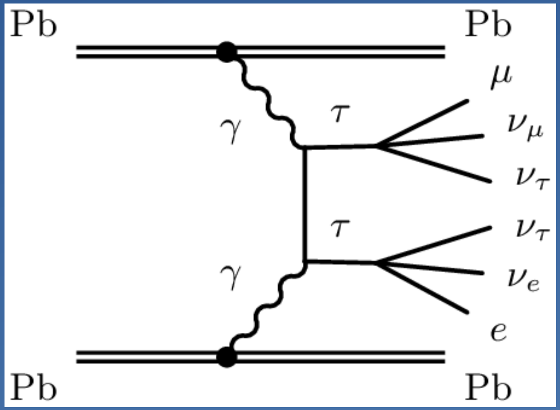


M. Dyndal, M. Klusek-Gawenda, A. Szczurek, M. Schott, Phys. Lett. B 809 (2020) 135682.

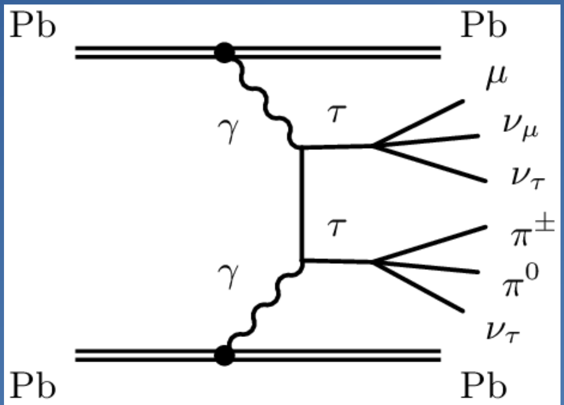
Including a non-zero a_l leads to a modification of the Breit-Wheeler formula.

Two-photon production of τ-pairs.

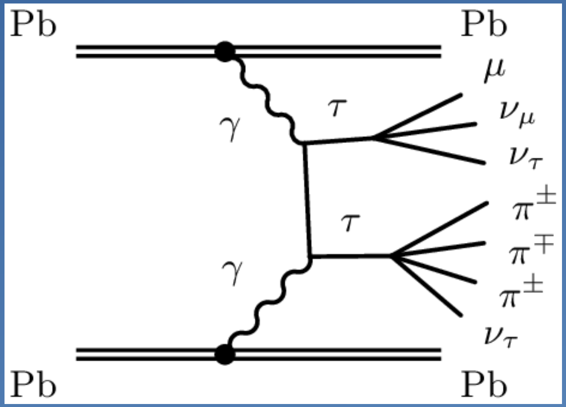
Measurement by Atlas in 3 decay channels of the τ, all requiring that one of the taus decays to a muon:



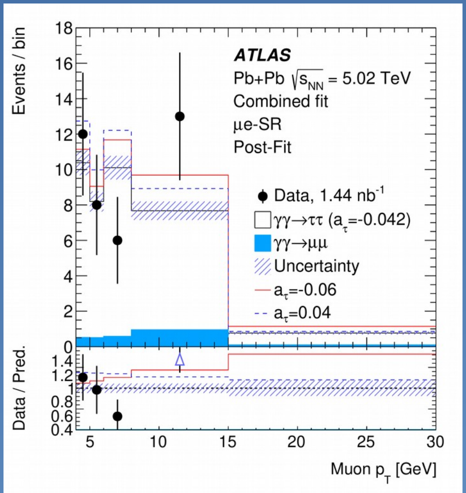
electron

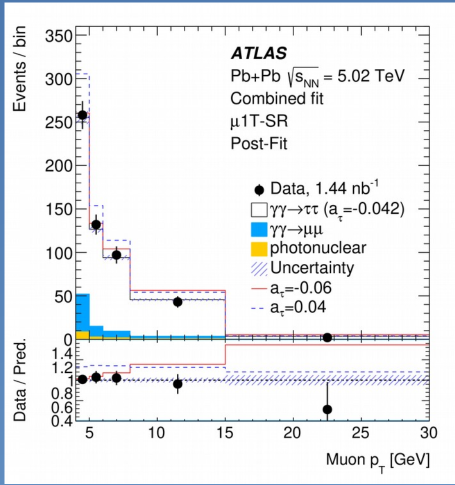


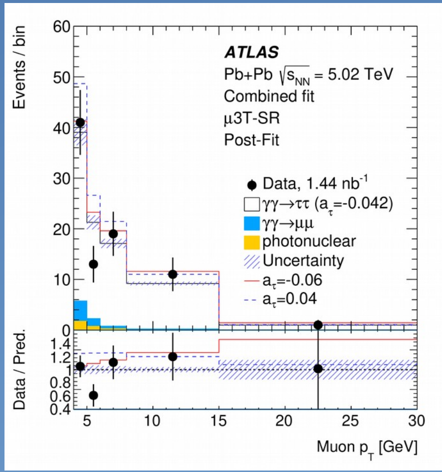
1 charged hadron



3 charged hadrons

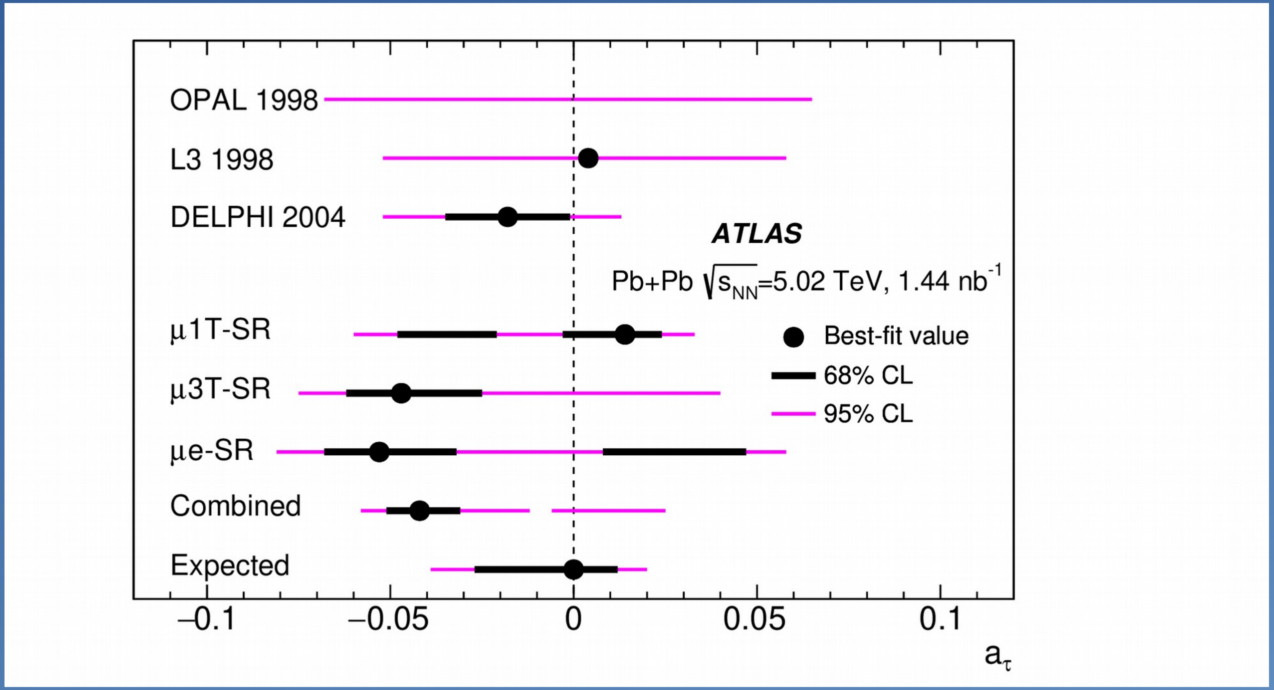






Two-photon production of τ-pairs.

The limit set on a_τ is compatible with previous measurments at LEP.



"The measurement precision is limited by statistical uncertainties". Can expect an increase in the statistics by a factor of 6 in Run 3.

Two-photon production of e+e- pairs.

Measuring the cross section for $\gamma\gamma \rightarrow e^+e^-$ important to understand the uncertainty of the normalization of QED processes at hadron colliders.

Comparison to two models: STARlight and SuperChic*.

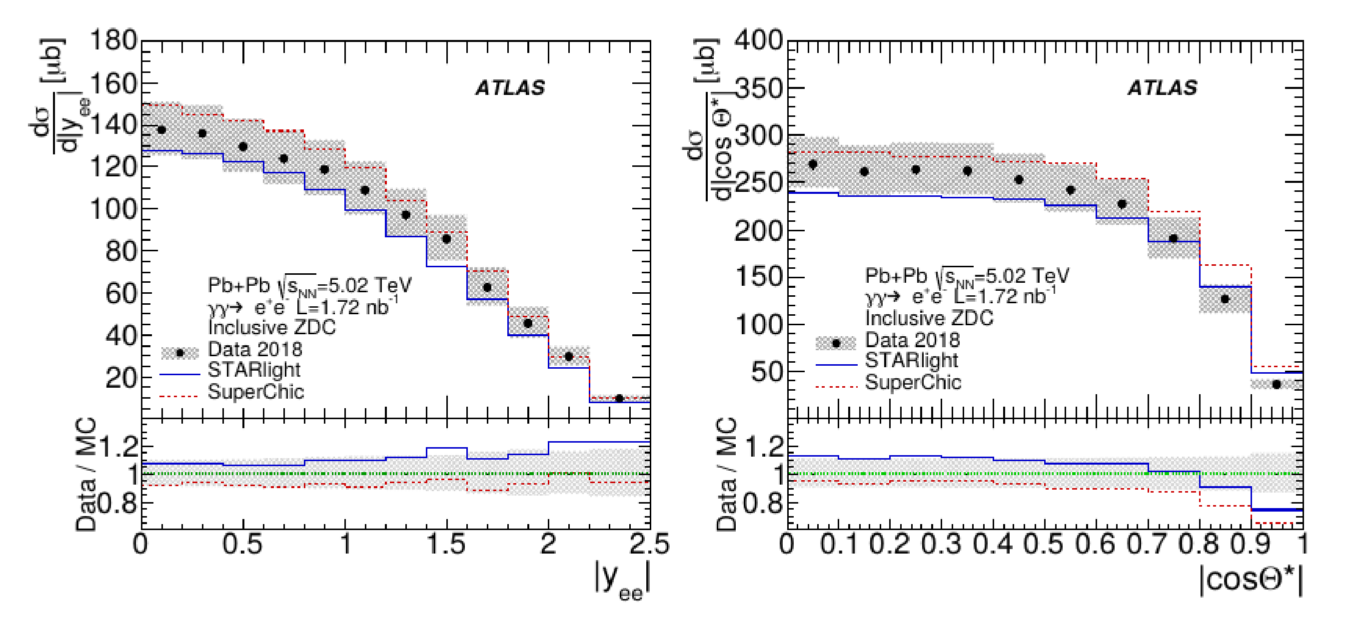
Total cross section in fiducial region (electron transverse momentum $p_T > 2.5$ GeV and pseudorapidity $|\eta_e| < 2.5$, dielectron invariant mass $m_{ee} > 5$ GeV, and transverse momentum $p_T < 2$ GeV):

Data:	$215 \pm 1(\text{stat}) \pm 22(\text{syst}) \pm 4(\text{lumi})$ μb
STARlight:	197 μb
SuperChic:	235 μb

*L. A. Harland-Lang, V. A. Khoze and M. G. Ryskin, Eur. Phys. J. C 79 (2019) 39.

Two-photon production of e+e- pairs.

The two models bracket the data.



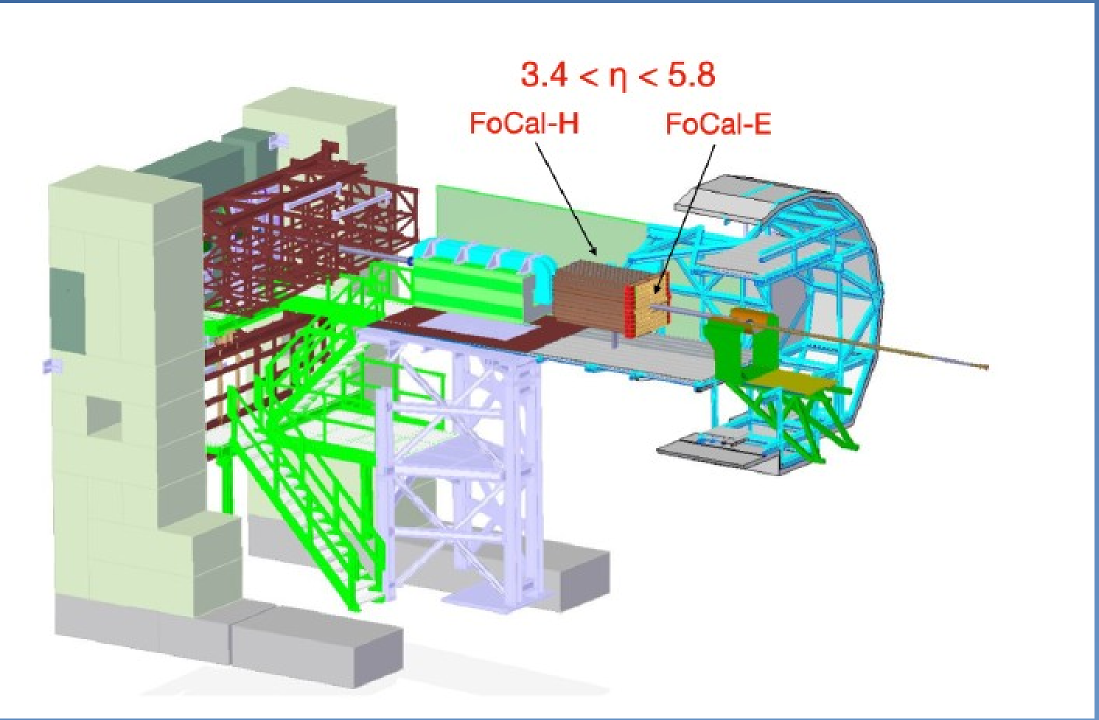
Note: QED is a very precise theory, but the sources of the fields are in this case not point particles!

Vector meson photoproduction in the forward direction

The Forward Calorimeter (FoCal) in ALICE.

A highly granular Si+W electromagnetic calorimeter combined with a conventional sampling hadronic calorimeter covering pseudorapidities of $3.4 < \eta < 5.8$.

Optimized to measure isolated photon spectra at forward rapidity in the range of about $4 < p_T < 20$ GeV/c.



- Located 7 m from the primary vertex.
- Radial distance from the beam 4 – 45 cm.
- To be installed in Run 4 (2029).
- Read-out electronics developed in Bergen.

Vector meson photoproduction in the forward direction

The Forward Calorimeter (FoCal) in ALICE. Main physics goals:

- Measure the gluon distribution functions at low x in protons and heavy nuclei.

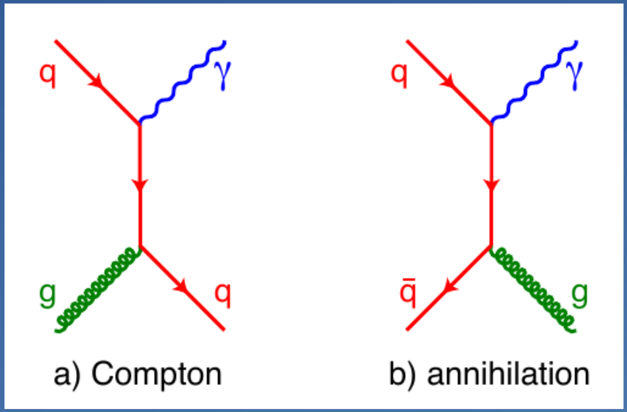
- Investigate the suppression of high-p_T hadrons in an unexplored region of phase space – aka “jet quenching” a strong quark-gluon plasma signature.

- Investigate long range correlations in η - the so called “ridge effect” - by combining measurements in FoCal and the central barrel.

Vector meson photoproduction in the forward direction

Measuring the gluon distributions using FoCal:

1) Direct and isolated photon production

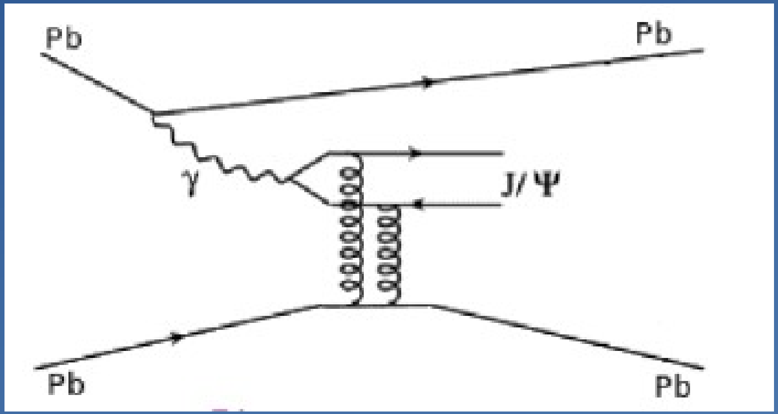


2) D-meson production, charm quark production dominated by $g+g \rightarrow c+cbar$.

3) Photoproduction of heavy vector mesons. Work in progress, together with Daniel Tapia Takaki and Alexander Bylinkin.

Vector meson photoproduction in the forward direction

Leading order contribution to exclusive vector meson production: Exchange of 2 gluons (colorless exchange).



Calculable from pQCD

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$

Ryskin 1993

Can be studied in ultra-peripheral Pb+Pb and p+Pb collisions.
Pb+Pb:Pb nucleus photon emitter and target
p+Pb: Pb nucleus photon emitter, proton target.

Vector meson photoproduction in the forward direction

Starting with p+Pb collisions:
Probes the reaction γ+p $\rightarrow$ J/ψ+p.

The γ-p center of mass energy given by

$$W_{\gamma p} = \sqrt{2E_p M_V e^y}$$

E_p – proton energy in laboratory frame; y – rapidity of the vector meson.

The Bjorken-x is then

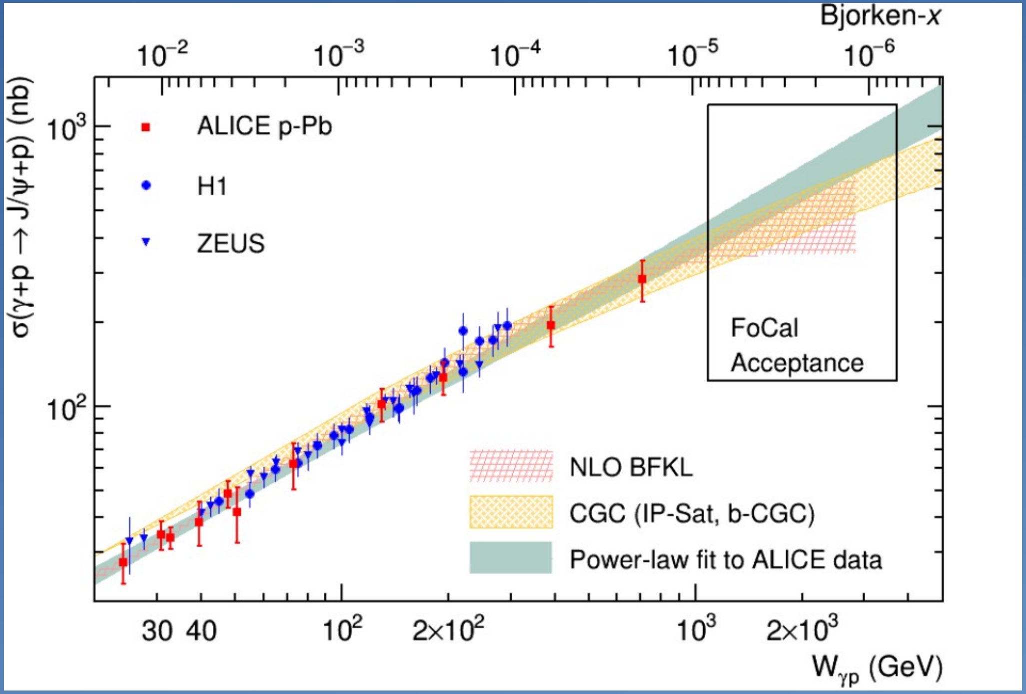
$$x = \frac{M_V^2}{W_{\gamma p}^2}$$

So, forward production ==> Large $W_{\gamma p}$ and small x.

Vector meson photoproduction in the forward direction

Measured by Zeus and H1 Collaborations at HERA and by ALICE in p+Pb collisions using the muon arm.

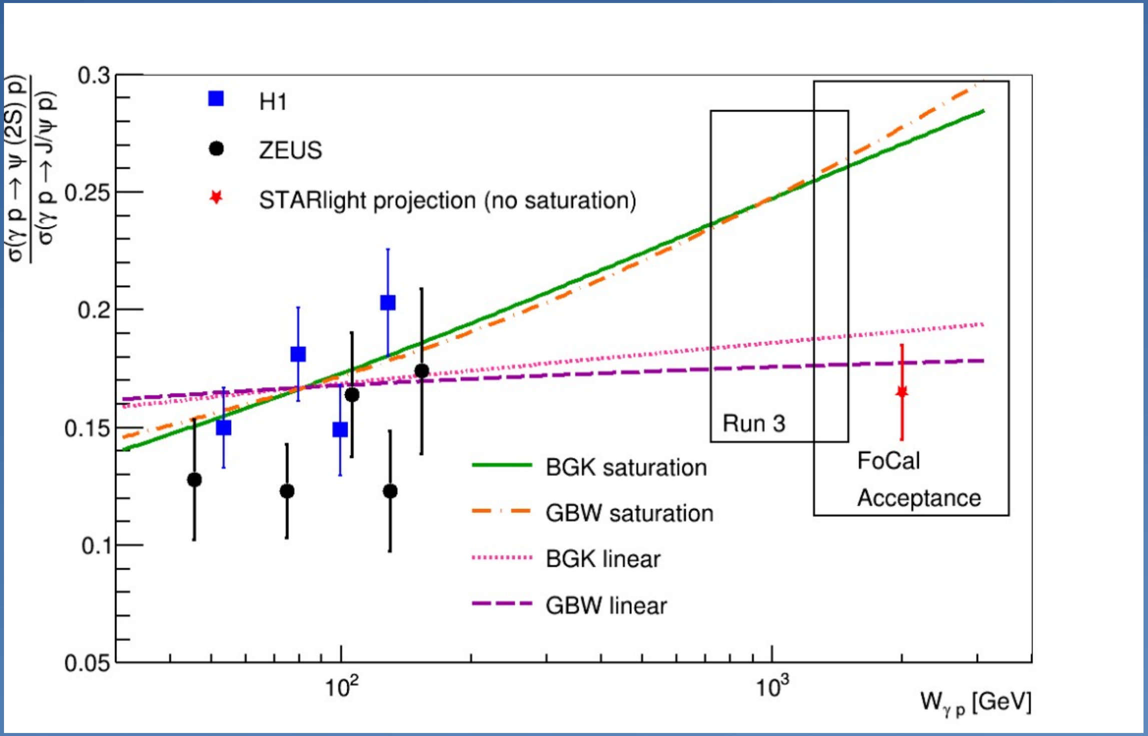
FoCal will significantly extend the range in γ-p center of mass energy



Saturation models predict a break down of the power law increase in the cross section at large $W_{\gamma p}$.

Vector meson photoproduction in the forward direction

Measuring the ratio $\sigma(\gamma+p \rightarrow \psi'+p)/\sigma(\gamma+p \rightarrow J/\psi+p)$ might improve the sensitivity to saturation.



M. Hentschinski et al., arxiv:2203.08129.

The STARlight point includes the expected statistical error.

Vector meson photoproduction in the forward direction

Estimates of the yield in FoCal for Pb+p, acceptance for electrons $3.4 < \eta < 5.8$, calculations with Starlight, for 150 nb^{-1}:

J/ψ:	5,400
ψ':	80

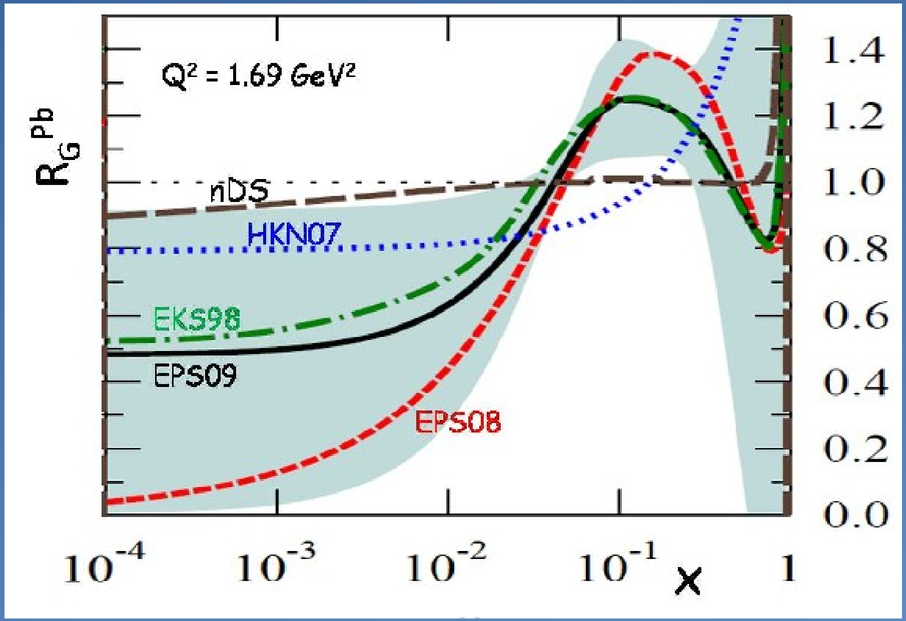
The uncertainty on the ratio dominated by the statistical error from the ψ', $\approx$11%.

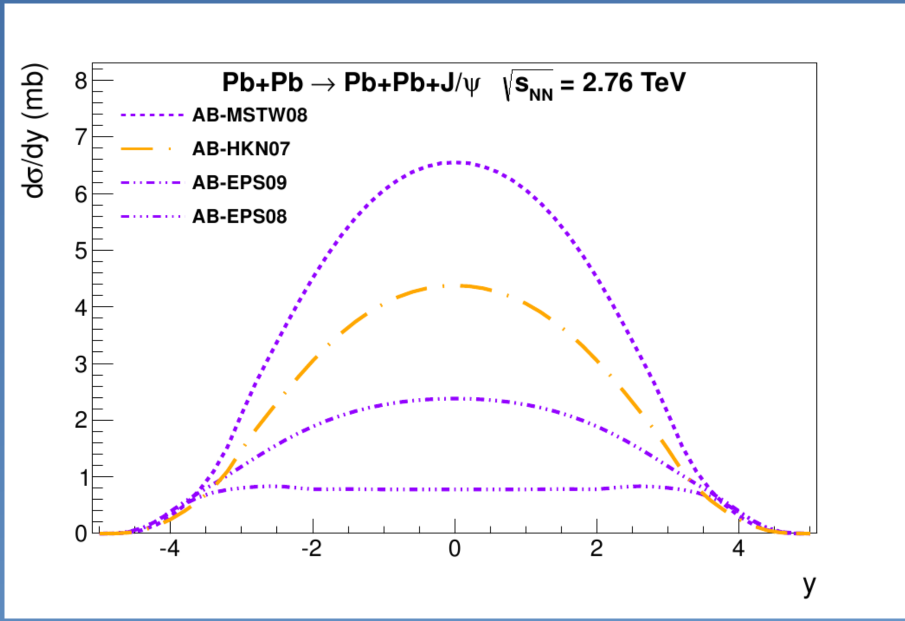
Vector meson photoproduction in the forward direction

Exclusive J/ψ production in Pb+Pb collisions. One nucleus emits the photon, the other is the target.

$$\frac{d\sigma}{dt}\bigg|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$

Ryskin 1993

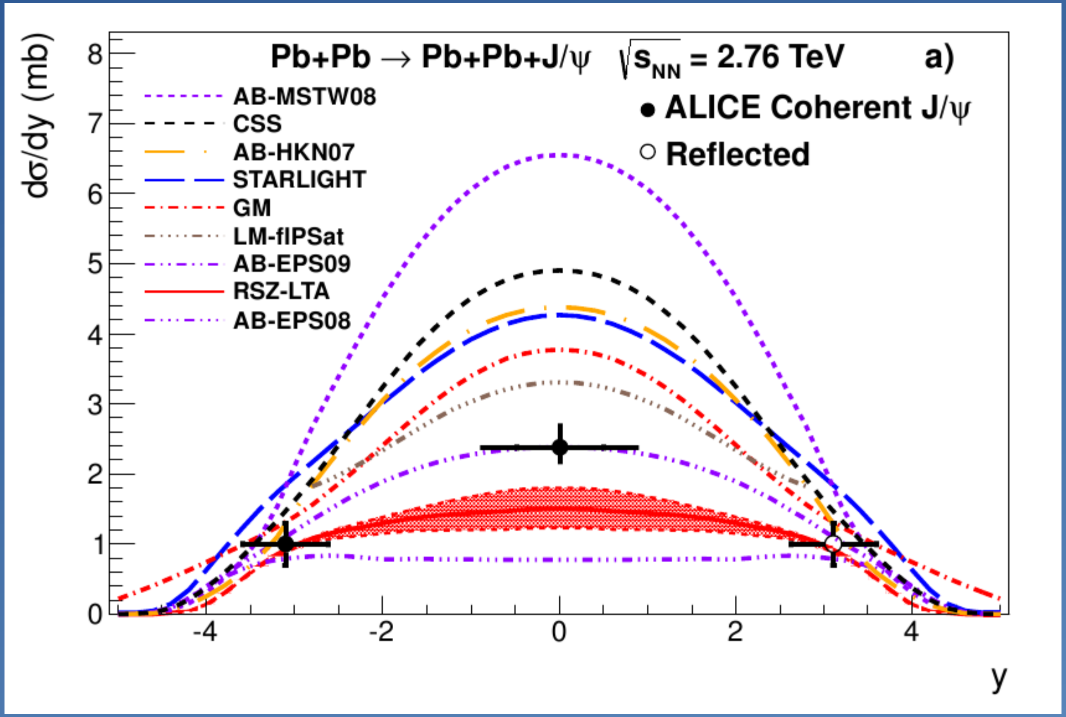




Adeluyi, Bertulani, Phys. Rev. C 85 (2012) 044904

Different gluon distributions translate into different cross sections.

Vector meson photoproduction in the forward direction



ALICE Collaboration

Phys. Lett. B 718 (2013) 1273

and

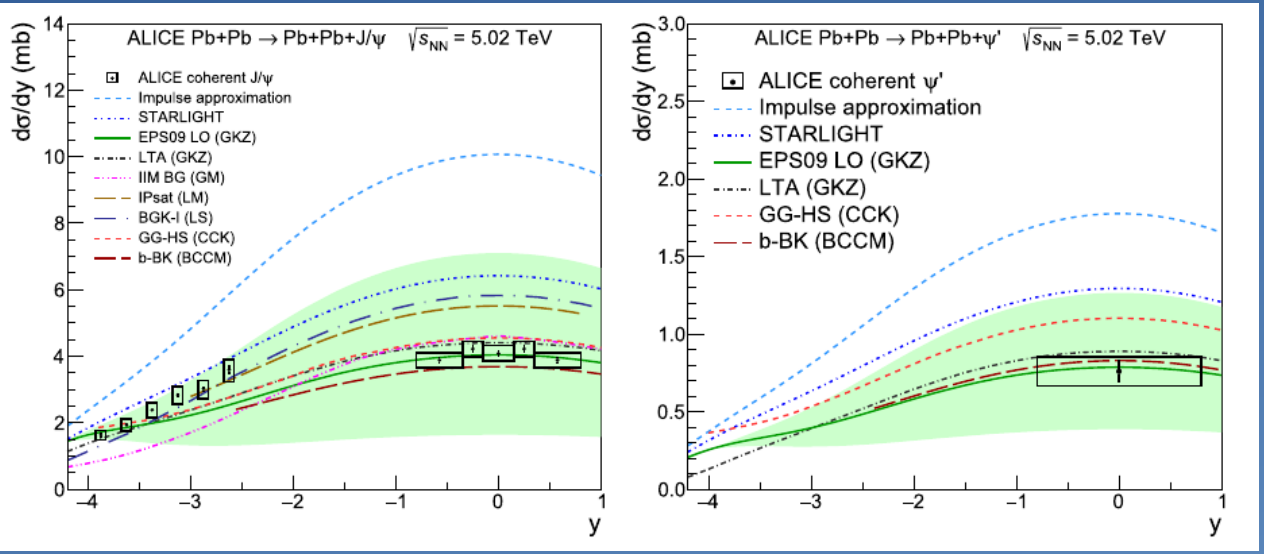
EPJC 73 (2013) 2617.

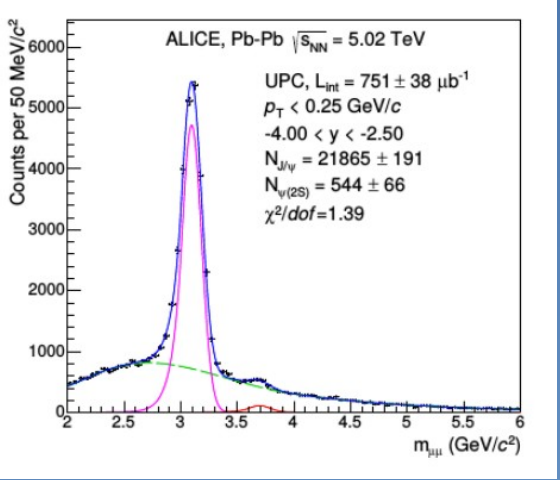
ALICE measurement from Run 1 consistent with moderate shadowing (EPS09 parameterization).

For exact references to the models, see Eur. Phys. J 73 (2013) 2617.

Vector meson photoproduction in the forward direction

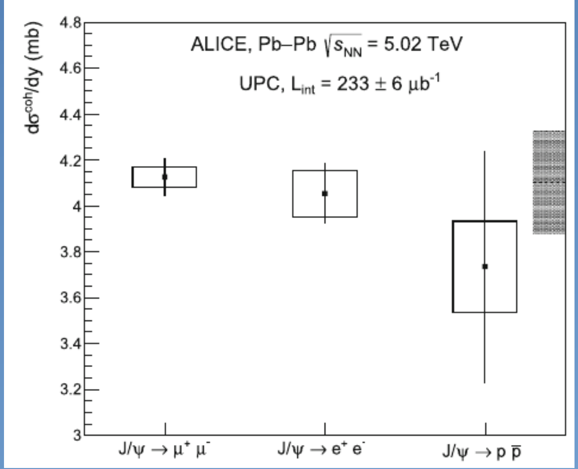
New results with much higher statistics, better binning in rapidity, now see also the ψ’. (“Coherent J/ψ and ψ photoproduction at midrapidity in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV”, Eur. Phys. J. C 82 (2021) 712)





The J/ψ is measured also through the J/ψ → $p\bar{p}$ decay channel.

2022.



Vector meson photoproduction in the forward direction

But why measure it in the forward region when the sensitivity is largest at mid-rapidity?

==> This is for Leading Order calculations.

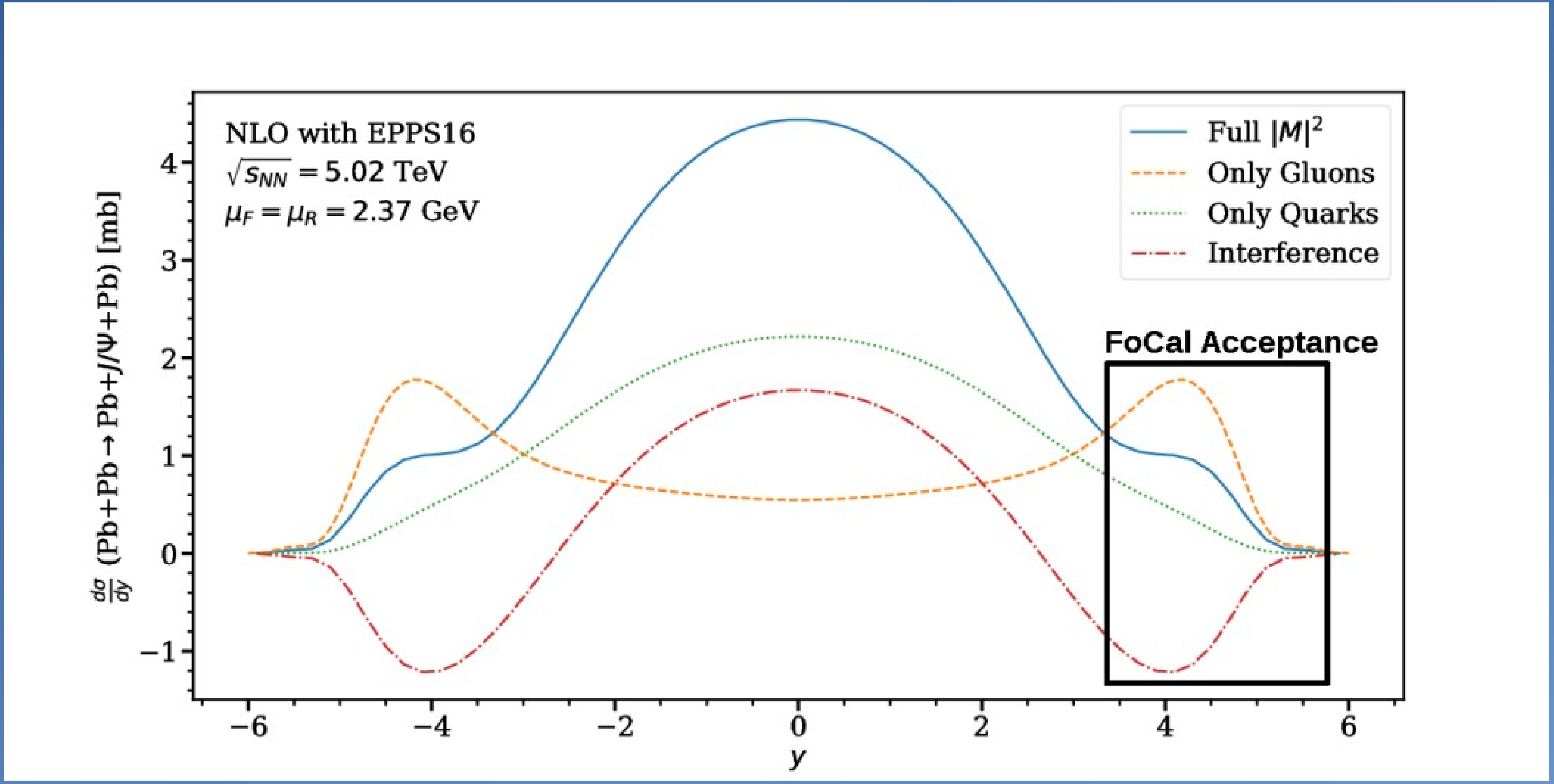
==> Recent paper by K.J. Eskola et al. arxiv:2203.11613, investigates Next-to-Leading Order and uncertainty on the scale, μ.

==> Find a strong dependence on the scale, but this should be constrained from γ+p data (in my opinion).

==> Strong contribution also from quarks, not just gluons, and interference between the two.

Vector meson photoproduction in the forward direction

The interference between these contributions largest at forward rapidity, right at the acceptance of FoCal.



Vector meson photoproduction in the forward direction

What can one expect to see in FoCal?

Some quick estimates for Pb+Pb, acceptance for electrons $3.4 < \eta < 5.8$, calculations with Starlight, for 10 nb^{-1}:

J/ψ: σ(Pb+Pb → Pb+Pb+J/ψ) = 39 mb;
both e+e- in FoCal, σ = 57 μb ==> yield 570,000 J/ψ

Ψ': σ(Pb+Pb → Pb+Pb+ψ') = 7.5 mb;
both e+e- in FoCal, σ = 1.3 μb ==> yield 13,000 ψ'

ϒ(1S): σ(Pb+Pb → Pb+Pb+ϒ(1S)) = 94 μb;
both e+e- in FoCal, σ = 23 nb ==> yield 230 ϒ(1S)

ALICE reconstructed ≈20,000 J/ψ from UPC in the muon arm in Run 2.

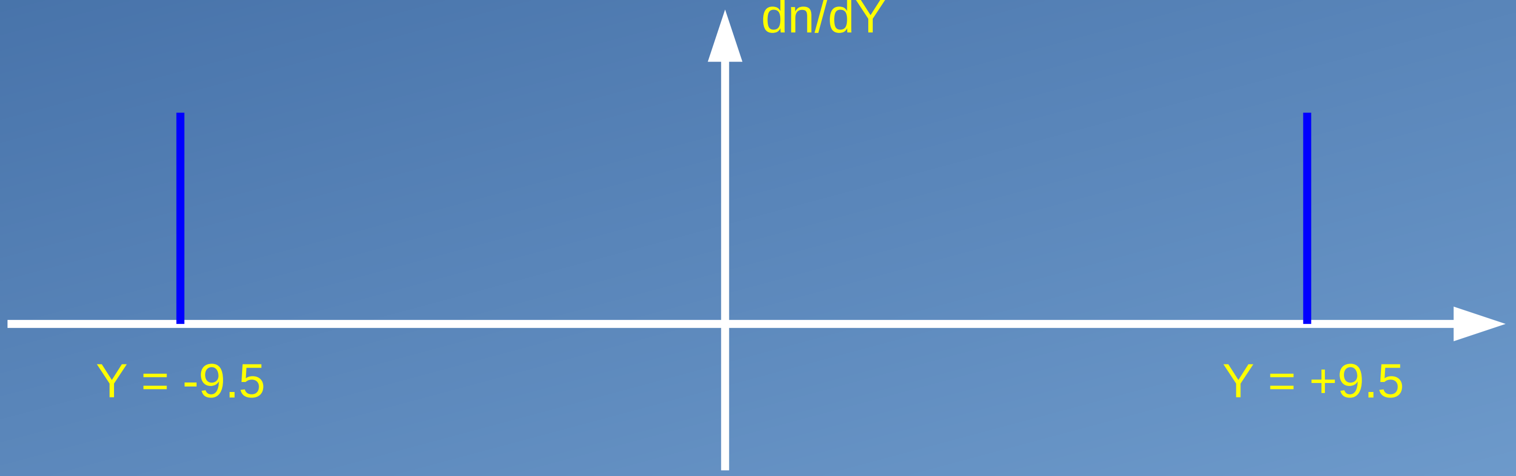
Bremsstrahlung emission in the forward direction

A fundamental question: How much energy do the protons/nucleons lose in a collision at the LHC?

The Standard Model does not give much guidance here.

Before the collision, the protons come in with rapidities $y = +9.5$ and $y = -9.5$ [+8.5/-8.5 for Pb nuclei].

Before the collision: Two δ-functions



Bremsstrahlung emission in the forward direction

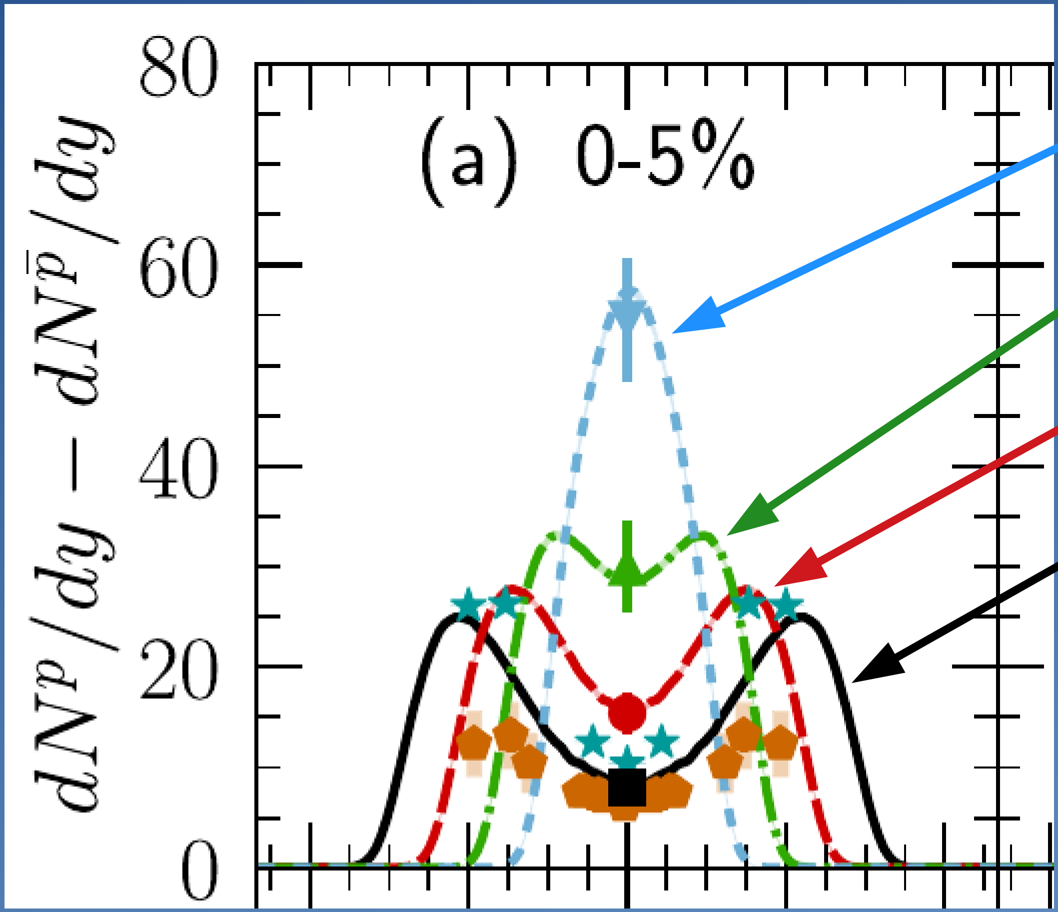
In the collision, pairs of protons and anti-protons are produced, but baryon number and electric charge is conserved.

What is the distribution of the net-number of protons (n(p)-n(pbar))?

Will focus on heavy-ion collisions from now on.

From measurements at lower energies, one knows that the stopping decreases with increasing collision energy.

Bremsstrahlung emission in the forward direction



√s = 7.7 GeV

√s = 19.6 GeV

√s = 62.4 GeV

√s = 200 GeV

5% most central
Au+Au collisions

C. Shen, B. Schenke, Phys. Rev. C 105 (2022) 064905.

Bremsstrahlung emission in the forward direction

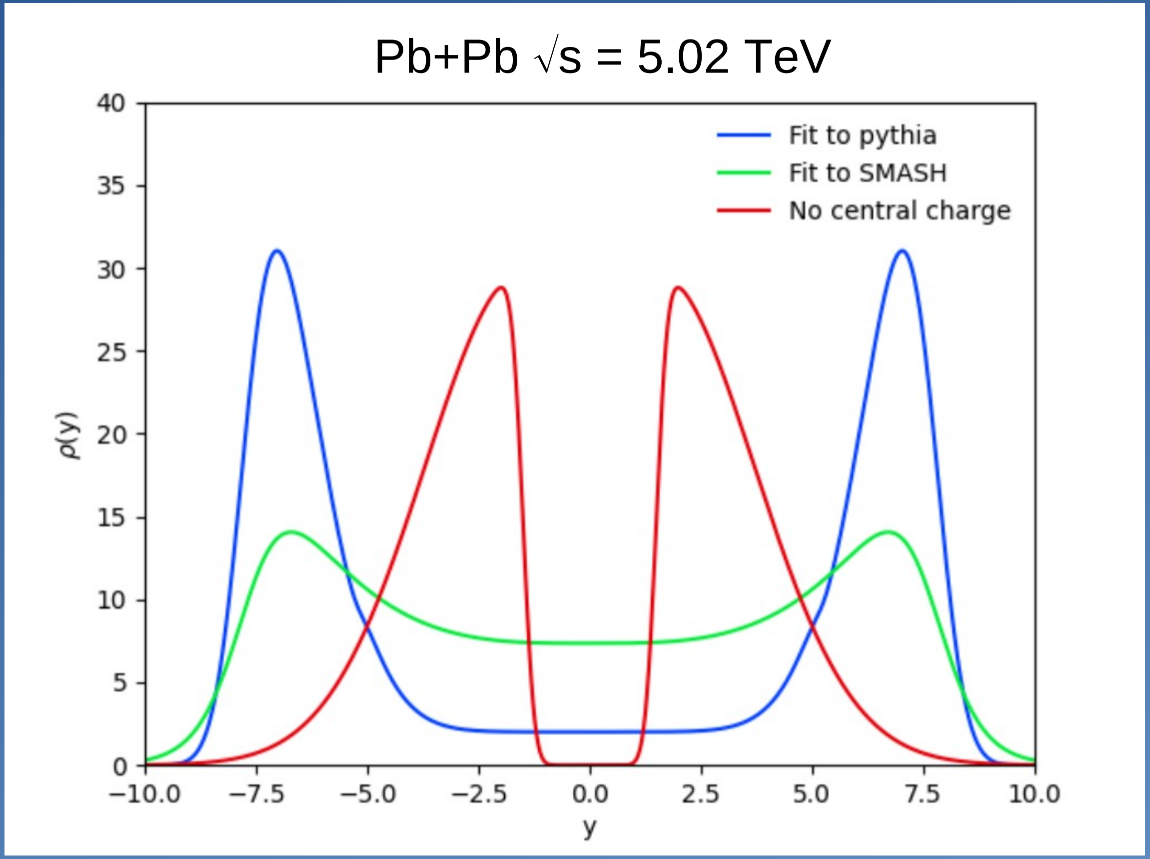
At the LHC, there are no measurement of the protons/anti-protons down to $p_T \approx 0$, except by ALICE at central rapidity.

Shows that the $|y| < 0.9$ region is baryon freee – no net protons!

But beyond that, there are no experimental constraints.

Bremsstrahlung emission in the forward direction

What do the models say?



Pythia for Heavy-Ions (Angantyr), JHEP 10 (2018) 134.

SMASH (a hadron transport model), J. Weil et al. Phys. Rev. C 94 (2016) 054905.

A phenomenological function which have no net-protons at midrapidity.

Bremsstrahlung emission in the forward direction

Alternative method to determine the amount of stopping?

As the protons slow down, they will emit bremsstrahlung photons. These are emitted at very small angles, $\theta \sim 1/\gamma$, where γ is the Lorentz factor of the beam.

Each of the stopping scenarios will give a distinct spectrum of Bremsstrahlung photons.

It might be possible to observe these in FoCal in the energy range $0.1 < \omega < 1$ GeV. Could also be done in ALICE-3 with photon energies as low as 50 MeV.

Work in progress, done together with Sigurd Nese. Hope to have some results to present in a month or so.

Conclusions

- Ultra-peripheral collisions have become a vivid research field at the LHC.

- Studied both by Atlas and Alice, so cross disciplinary collaboration should be possible.

- Seems one is now at the stage where one can use ultra-peripheral to set constraints on the standard model.

- Many of the observables are luminosity driven, so the outlook for Run 3 and 4 is bright.

- Bremsstrahlung might be used to determine the amount of stopping in heavy-ion collisions.