

VM photoproduction at the LHC as a probe of nuclear structure

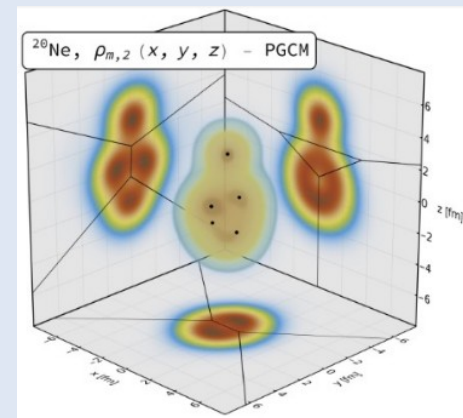
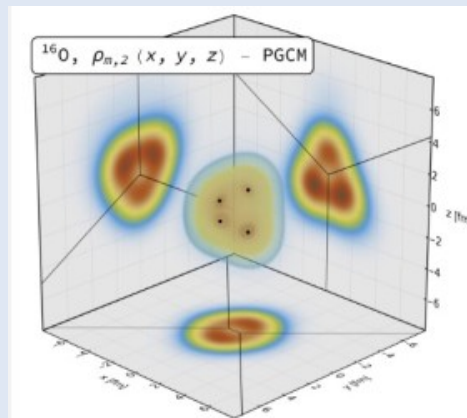
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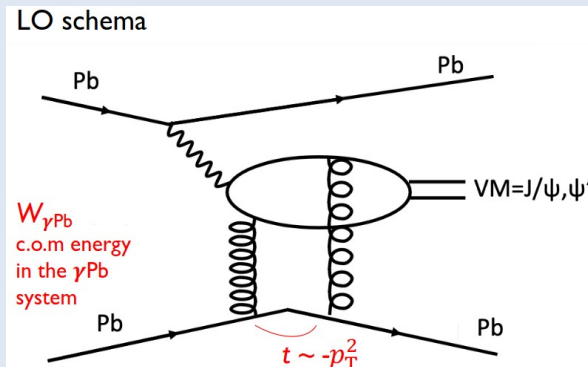
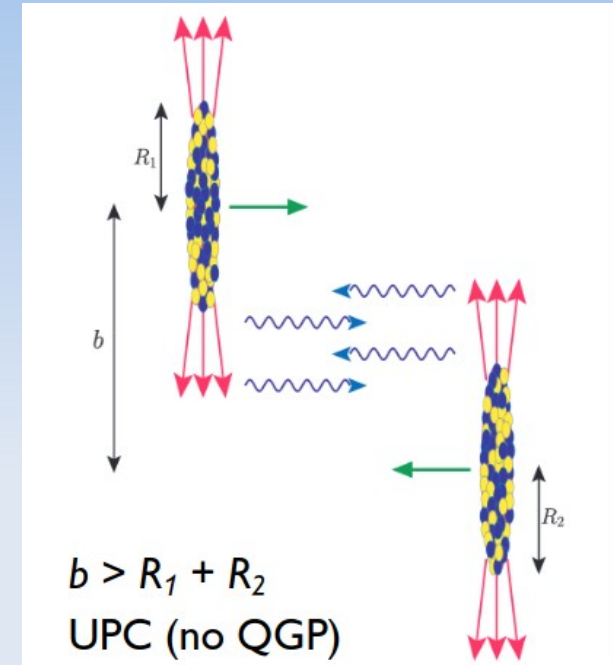
Assemblée Générale du GdR QCD, 7/10 2026

Outline

- **Theoretical** background for **vector meson (VM) photoproduction**
- My simulation-based feasibility study with Laure Massacrier:
 - Exploring the feasibility to measure photoproduced ρ and J/ψ mesons at LHCb in both collider and fixed target mode in Run 3
 - Can we see effects of **geometrical structure** in VM photoproduction measurements at the LHC?
 - In close contact with authors of the hot spot model in Prague
- **New ions**: cases to study at the LHC in the **future** with VM photoproduction
 - Benefiting from exchanges with nuclear physicists at Orsay, Saclay
 - Considering LHCb and ALICE acceptance regions

Photon-induced processes at the LHC

- The nuclei can interact **electromagnetically**:
 - Separation of pair of nuclei $>$ sum of their radii = **ultra-peripheral collisions** (UPC)
 - Extremely strong EM fields from ultra-relativistic highly charged ions described as a beam of quasi-real **photons**, number of photons $\propto Z^2$
- The LHC as a photon-hadron collider (**QCD**)
- Transverse **structure** from **diffraction** pattern

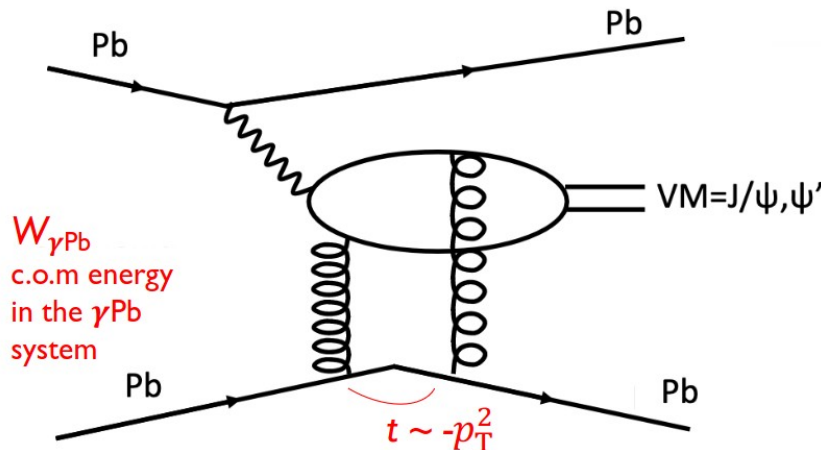


Complementarity with flow

- VM photoproduction probes **initial state**, flow probes deformation through final state particle-correlations generated by the QGP response
- More statistics needed for UPC measurements
- Different dependencies of observables on **modelling** (hydro models vs photoproduction models)

Vector meson photoproduction: some definitions

LO schema

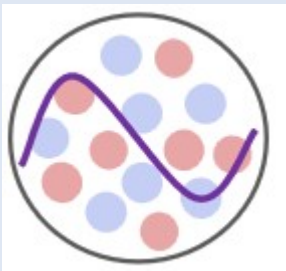


t : 4-momentum transfer
to target ion

- E.g. for J/ψ : Quasi-real **photon** fluctuates into a colour **dipole**
- Interaction with the target nucleus via **gluon exchange**
- Dipole rescatters $\rightarrow$ on-shell **VM**
- The rapidity y of the VM is related to **Bjorken-x**

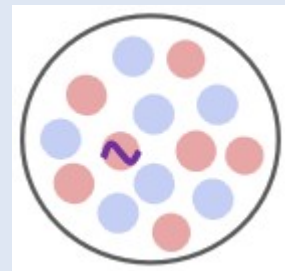
$$x_{\pm} = \frac{m_{J/\psi}}{\sqrt{s_{NN}}} e^{\pm y}$$

In **coherent** VM photoproduction,
the photon interacts coherently
with the **whole** target **nucleus**



$$\langle p_T^{\text{VM}} \rangle \sim 1/\text{Radius} \sim 60 \text{ MeV for Pb}$$

Incoherent VM photoproduction
occurs via the interaction of the
photon with a **single nucleon** or
subnucleonic structure



$$\langle p_T^{\text{VM}} \rangle \sim 500 \text{ MeV}$$

Nuclear imaging with VMs: target profile

$$\begin{array}{ccccccc}
 & & \text{Dipole-nucleus x-sec} & & \text{UPC x-sec} & & \\
 \text{Nuclear structure} & \rightarrow & T_A(\vec{b}) & \rightarrow & \frac{d\sigma_A^{\text{dip}}}{d\vec{b}} & \rightarrow & \mathcal{A}_{T,L}(x, Q^2, \vec{\Delta}) \rightarrow \frac{d\sigma}{d|t|} \\
 & & \text{Transverse target profile} & & \text{VM amplitude} & &
 \end{array}$$

In the hot spot model, the transverse profile of the gluonic **colour field** is constructed from **nucleons** and **sub-nucleonic hot spots**:

transverse position w.r.t
center of target nucleus

nucleons

transverse position of nucleon i

$$T_A(\vec{b}) = \frac{1}{2\pi B_{\text{hs}}} \sum_{i=1}^A \frac{1}{N_{\text{hs}}} \sum_{j=1}^{N_{\text{hs}}} \exp \left(-\frac{(\vec{b} - \vec{b}_i - \vec{b}_j)^2}{2B_{\text{hs}}} \right)$$

hot spot width

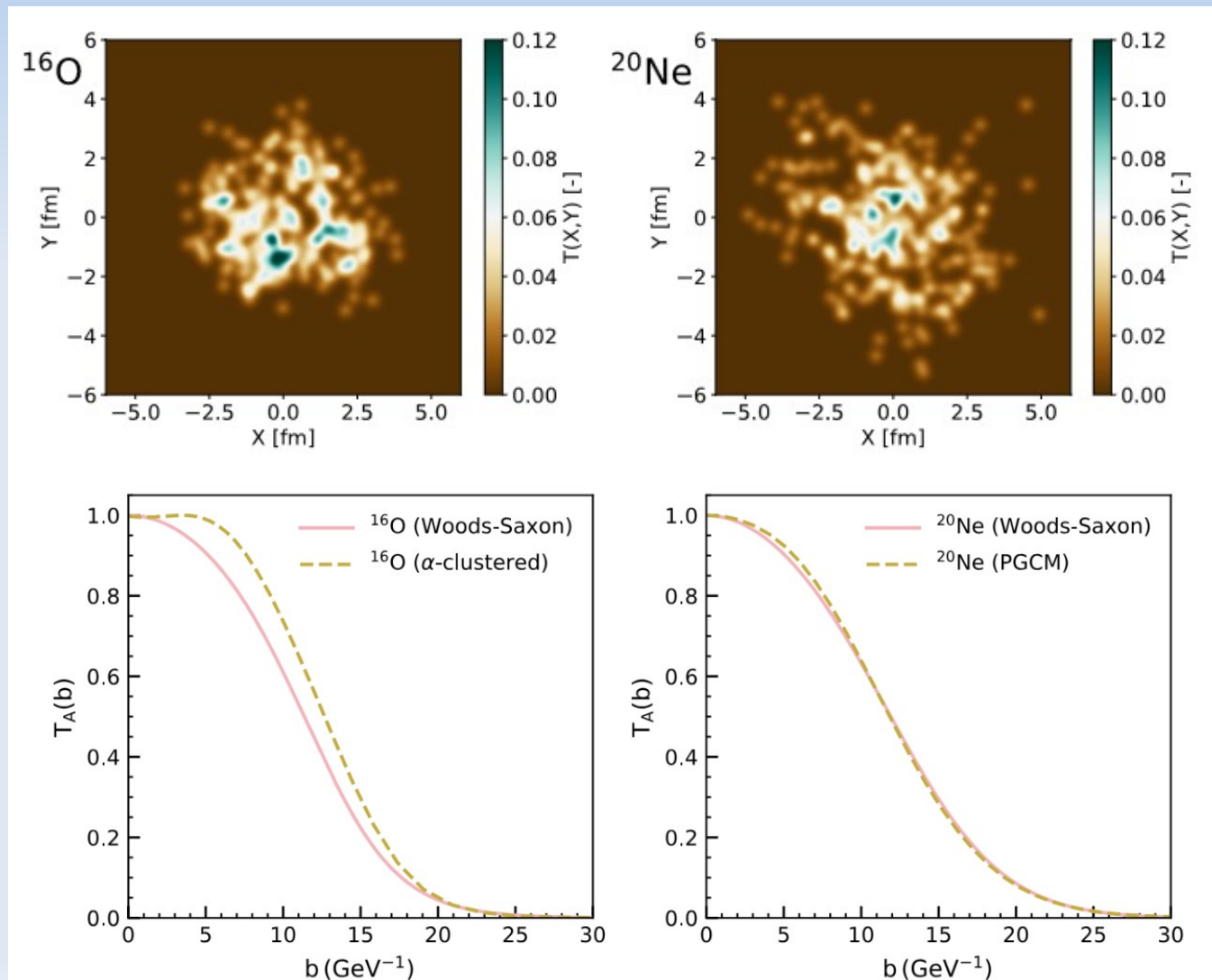
hot spots

transverse position
of hot spot j

J. Cepila et al., Phys. Rev. C. 113 (2026) 2, 025202

Nuclear imaging with VMs: hot spot distributions

Example **hot spot configurations** for ^{16}O and ^{20}Ne with α clusters and the transverse profiles (1D) from α -clustering or a deformed Woods-Saxon



Nuclear imaging with VMs: dipole-nucleus cross section

$$\text{Nuclear structure} \rightarrow T_A(\vec{b}) \rightarrow \frac{d\sigma_A^{\text{dip}}}{d\vec{b}} \rightarrow \mathcal{A}_{T,L}(x, Q^2, \vec{\Delta}) \rightarrow \frac{d\sigma}{d|t|}$$

dipole-nucleus cross section

target profile, encoding
nuclear structure

$$\left(\frac{d\sigma_A^{\text{dip}}}{d\vec{b}} \right) = 2 \left[1 - \left(1 - \frac{1}{2A} \sigma_0 N(x, r) T_A(\vec{b}) \right)^A \right]$$

dipole scattering amplitude related to small-x QCD dynamics

- depends on Bjorken-x and the transverse size of the dipole
- Includes cold nuclear matter effects (shadowing, saturation)

Nuclear imaging with VMs: vector meson amplitude

$$\text{Nuclear structure} \rightarrow T_A(\vec{b}) \rightarrow \frac{d\sigma_A^{\text{dip}}}{d\vec{b}} \rightarrow \mathcal{A}_{T,L}(x, Q^2, \vec{\Delta}) \rightarrow \frac{d\sigma}{d|t|}$$

dipole extension

VM wave function

Dipole-nucleus interaction profile

$$\mathcal{A}_{T,L}(x, Q^2, \vec{\Delta}) = i \int d\vec{r} \int_0^1 \frac{dz}{4\pi} \int d\vec{b} |\Psi_V^* \Psi_{\gamma^*}|_{T,L} \exp \left[-i \left(\vec{b} - \left(\frac{1}{2} - z \right) \vec{r} \right) \cdot \vec{\Delta} \right] \frac{d\sigma_H^{\text{dip}}}{d\vec{b}}$$

VM production amplitude,
dependent on Bjorken- x ,
photon virtuality Q^2 and t

dipole wave function

Momentum transfer
to target ion, $\Delta^2 = |t|$

The **spatial structure** in $\vec{b}$ is related to the
momentum transfer $\vec{\Delta}$ via a Fourier transform

Nuclear imaging with VMs: t-differential UPC cross section

$$\text{Nuclear structure} \rightarrow T_A(\vec{b}) \rightarrow \frac{d\sigma_A^{\text{dip}}}{d\vec{b}} \rightarrow \mathcal{A}_{T,L}(x, Q^2, \vec{\Delta}) \rightarrow \frac{d\sigma}{d|t|}$$

Good-Walker approach

Coherent VM cross section

- Proportional to the **average** over possible configurations of the colour field

$$\left. \frac{d\sigma^{\gamma^*H \rightarrow VH}}{d|t|} \right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} |\langle \mathcal{A}_{T,L} \rangle|^2$$

- Gives **average transverse nuclear structure**
- Encodes the nucleon **one body density**

Incoherent VM cross section

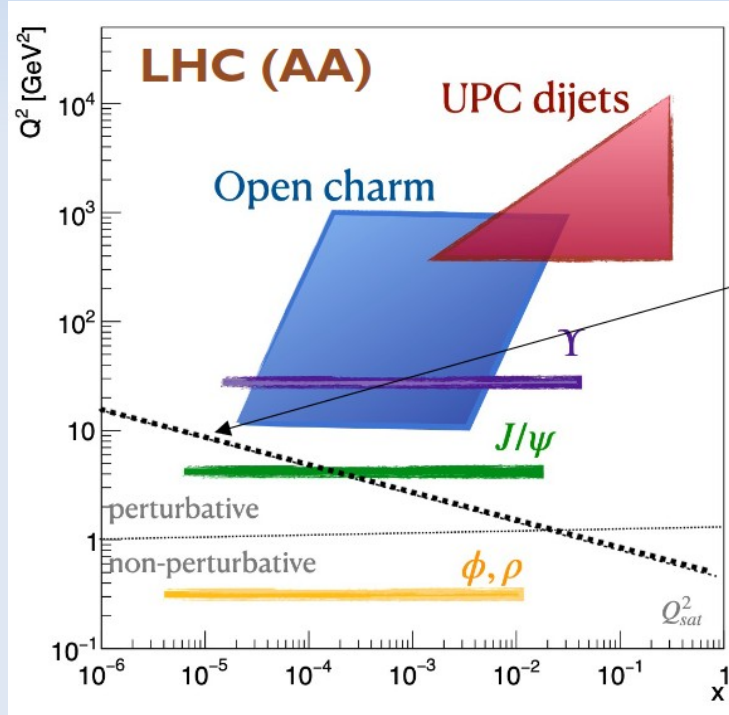
- Proportional to the **variance** of possible configurations of the colour field

$$\left. \frac{d\sigma^{\gamma^*H \rightarrow VY}}{d|t|} \right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} (\langle |\mathcal{A}_{T,L}|^2 \rangle - |\langle \mathcal{A}_{T,L} \rangle|^2)$$

- Probes internal gluonic **fluctuations** and the **substructure** of nuclei
- Contains the **two-body density**

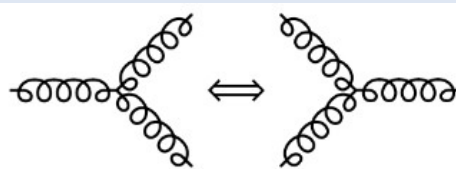
Complementarity of VM photoproduction measurements

- Using **different VMs** changes the spatial resolution of the probe
 - Same nuclear geometry, hot spot model, formalism
 - But different VM wave function, different dipole sizes, pdf sensitivity

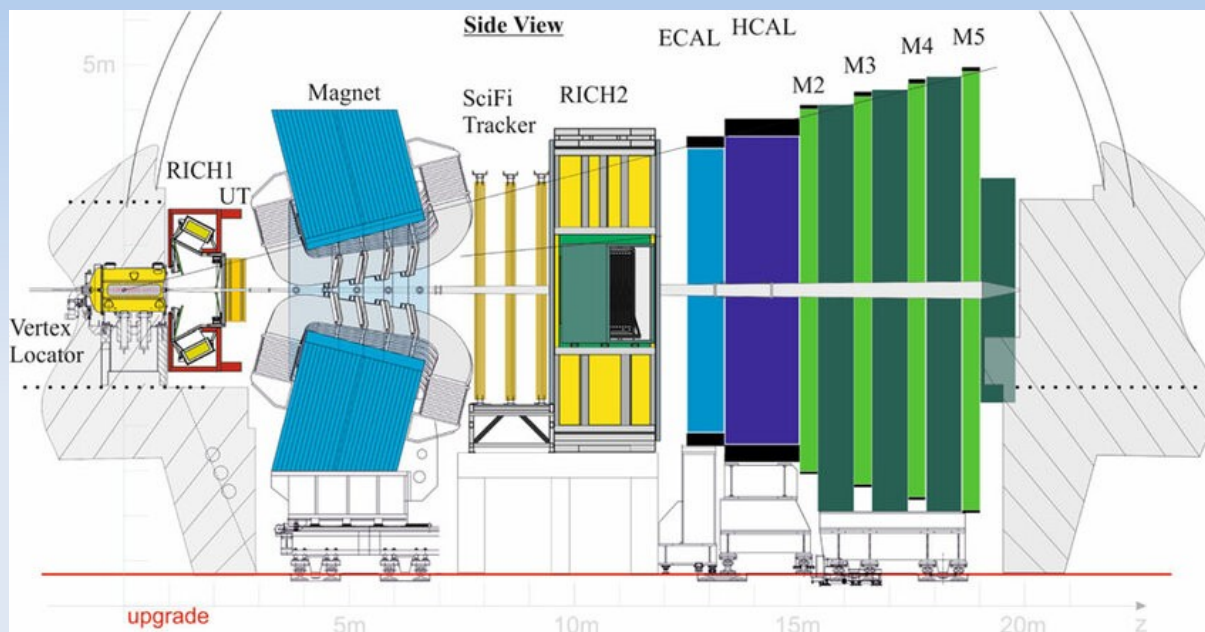


N. Burmasov LHCP 2026

Vector meson	ρ^0	J/ψ
Quark content	light (u, d)	charm pair ($c\bar{c}$)
Mass	0.77 GeV	3.1 GeV
Dipole size	large	small
Typical Q^2	small $\sim 0.3 \text{ GeV}^2$	larger $\sim 4 \text{ GeV}^2$
Typical x range	$7 \cdot 10^{-5} - 10^{-2}$	$5 \cdot 10^{-5} - 10^{-2}$
Interaction regime	Non-perturbative	More perturbative
Saturation sensitivity	Stronger	Weaker; non-negligible at small x

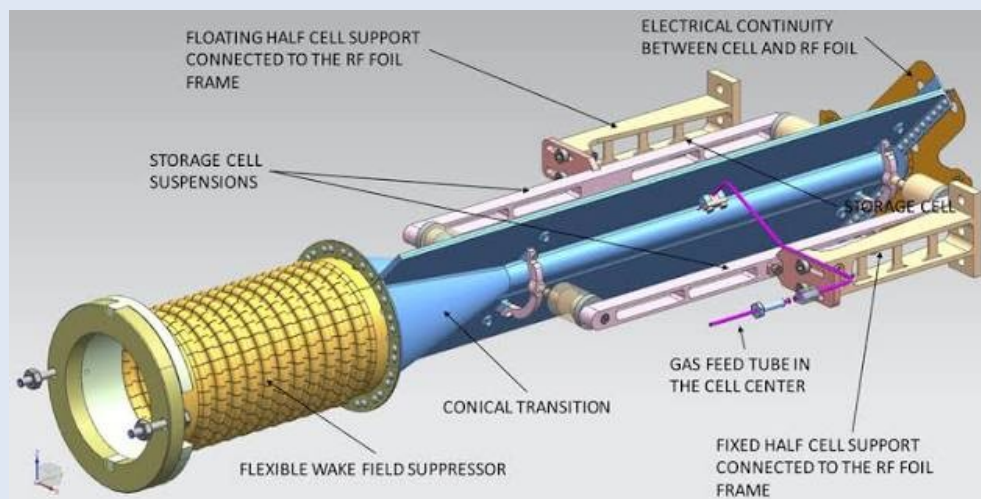


The LHCb experiment



LHCb is a forward single-arm spectrometer, covering $2 < \eta < 5$

- Provides **excellent p_T resolution**



- **Fixed target mode with SMOG2**
 - large flexibility in choice of gas target
- Typical c.o.m. energies: ~ 5 TeV for collision mode, ~ 70 GeV for fixed target

Strategy for feasibility study

Feasibility study of $\rho \rightarrow \pi^+\pi^-$ and $J/\psi \rightarrow \mu^+\mu^-$ photoproduction in UPC events at LHCb

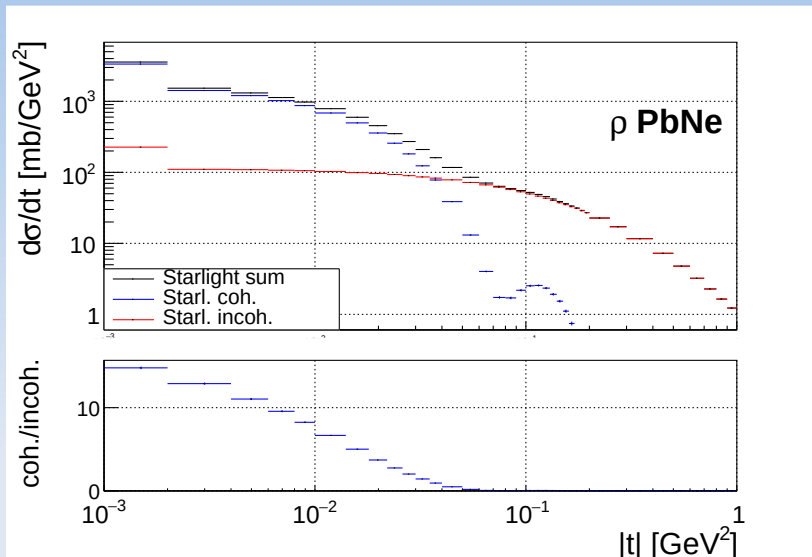
- Using the STARLIGHT event generator: applying the LHCb selection and estimating the number of events
 - Acceptance cuts: $2 < \eta(\pi, \mu) < 5$, $p_T(\pi, \mu) > 0.2 \text{ GeV}$, $2 < y(VM) < 5$
 - Assuming 100% acceptance*efficiency in this phase space
 - Assigning a **statistical uncertainty** of $\sqrt{N_{\text{LHCb}}}$ bin-wise and propagating it to the cross section (N_{LHCb} : upper limits), assuming that the statistical uncertainty dominates the uncertainty on the cross section
- **Fixed target** mode, $\sqrt{s_{\text{NN}}} = 70.9 \text{ GeV}$ with SMOG2 in Run 3 (many collision systems available)
- **Light ions** in symmetrical **collision** mode, $\sqrt{s_{\text{NN}}} = 5.36 \text{ TeV}$ in Run 3, including predictions from the hotspot model with variations of the **geometrical structure**, comparison to expected precision

Cross sections in fixed target mode

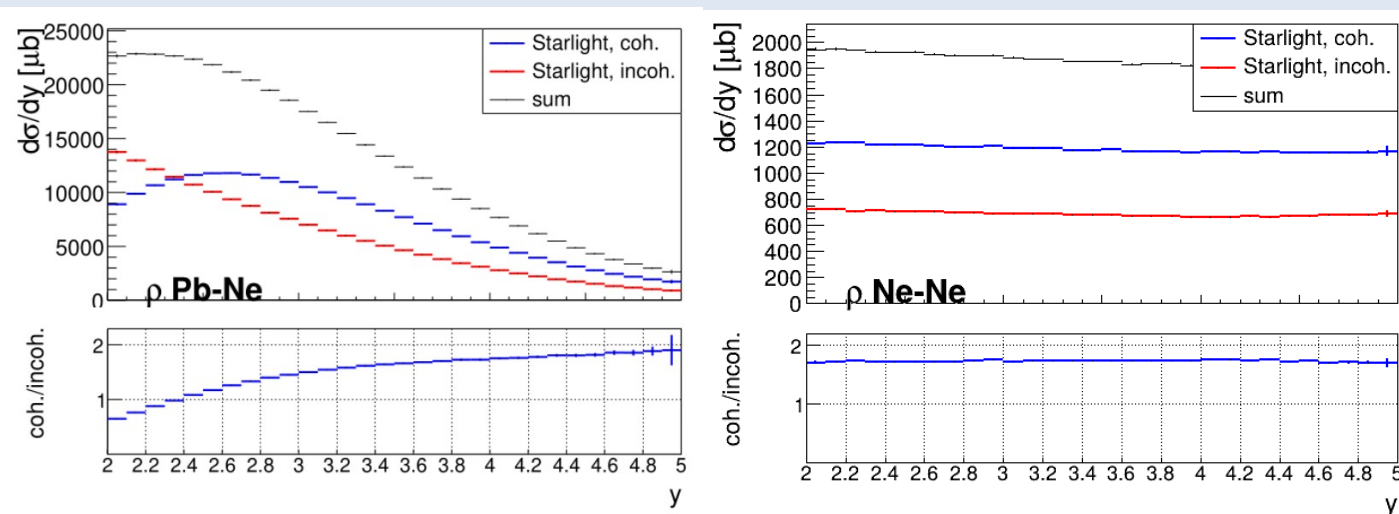
fid: $2 < y_{VM} < 5$, $p_{T, \text{daughters}} > 0.2 \text{ GeV}$ $2 < \eta_{\text{daughters}} < 5$	Pb-Ar, 71 GeV 2 nb^{-1}		Pb-Ne, 71 GeV 0.02 nb^{-1}		O-O, 5.36 TeV 5.5 nb^{-1}		Ne-Ne, 5.36 TeV 0.6 nb^{-1}	
	$\sigma_{\text{fid.}} \cdot \text{Br}$	N_{LHCb}	$\sigma_{\text{fid.}} \cdot \text{Br}$	N_{LHCb}	$\sigma_{\text{fid.}} \cdot \text{Br}$	N_{LHCb}	$\sigma_{\text{fid.}} \cdot \text{Br}$	N_{LHCb}
$\rho \rightarrow \pi\pi \text{ coh.}$	25.8 mb	52M	16.3 mb	980k	1.31 mb	7.2M	2.44 mb	1.5M
$\rho \rightarrow \pi\pi \text{ incoh.}$	15.5 mb	31M	10.1 mb	610k	0.69 mb	3.8M	1.23 mb	0.7M
$J/\psi \rightarrow \mu\mu \text{ coh.}$	52 nb	100	38 nb	2	145 nb	790	276 nb	170
$J/\psi \rightarrow \mu\mu \text{ incoh.}$	199 nb	400	125 nb	7	160 nb	860	285 nb	170

- In **fixed target** mode, ^{208}Pb is the **beam** and most interactions **probe** the **lighter nucleus**, with the heavier nucleus emitting the photon.
- **High statistics** for ρ photoproduction expected from collected data
- Inclusive **J/ψ** photoproduction measurements in **Pb-Ar, Ne-Ne** should be **feasible**, possibly differential J/ψ measurement in O-O
- Symmetrical light-ion collisions compared to fixed target Pb-X: higher energy and smaller system size (competing effects on σ)
 - Different collision energy dependence for ρ and J/ψ photoproduction

Fixed target & symmetrical collisions

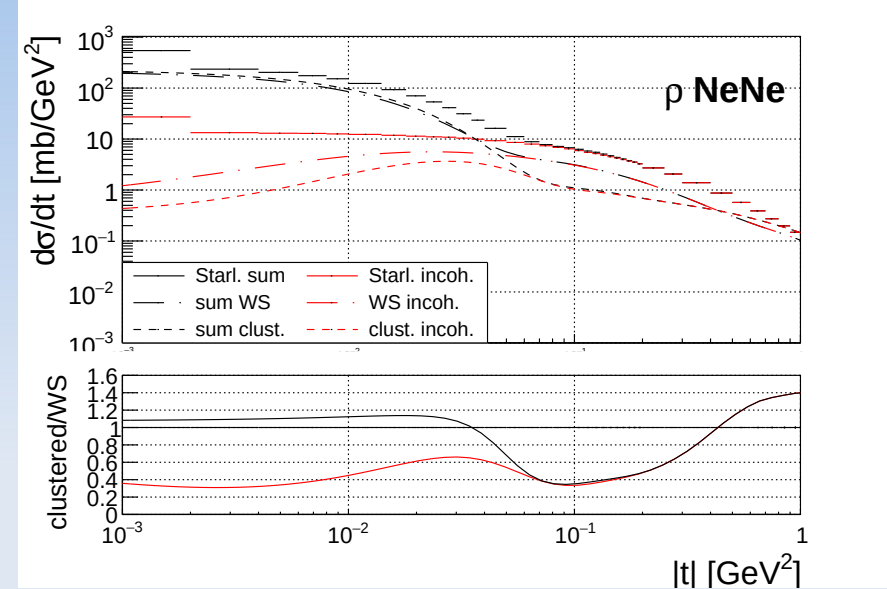
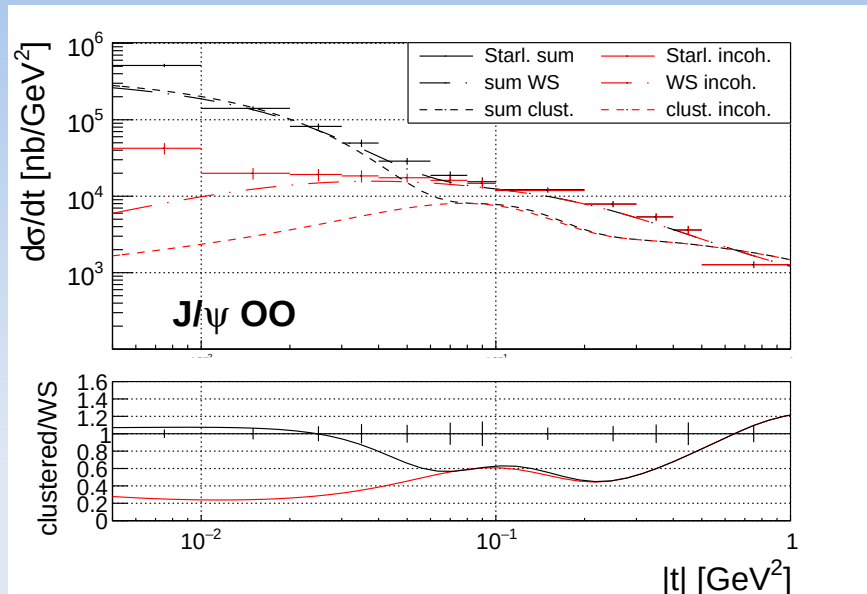


- The **nuclear structure** imprints on the **t**-distribution ($\sim$ momentum transfer to the target ion), evaluated as $|t| \sim p_T^2$ of the VM
- As expected, **coherent** photoproduction of VMs results in a much **lower average transverse momentum** than incoherent
 - The 2nd coherent diffractive peak is buried underneath the incoherent process



In **fixed target** kinematics: the **coherent** contribution is expected to peak at **larger rapidity** than the incoherent one

Adding the coherent and incoherent cross sections



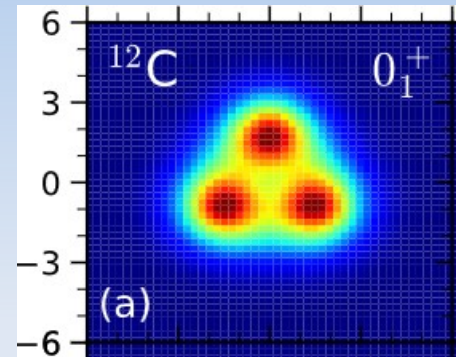
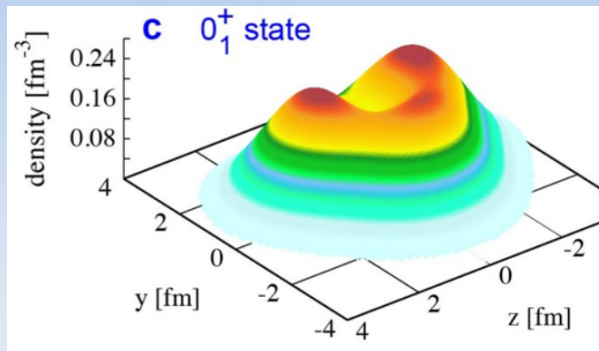
- The statistical uncertainty is shown as errorbars in both panels
- Sizeable **impact** from **structure** in the **incoherent prediction**
 - Better **separated** from the coherent process at **higher |t|**

$0.07 < t < 0.2 \text{ GeV}^2$	ρ O-O	J/ψ O-O	ρ Ne-Ne	J/ψ Ne-Ne
difference in pred.	35%	43%	61%	65%
stat. precision	0.09%	6%	0.2 %	14%

- Should consider **luminosity** uncertainty $\sim 6\%$ or mitigate it with ratios

^{12}C and ^{24}Mg for New Ions@LHC

- Recent simulation studies suggest **clustering** component in the **ground state** of ^{12}C (in contrast with previous paradigm)

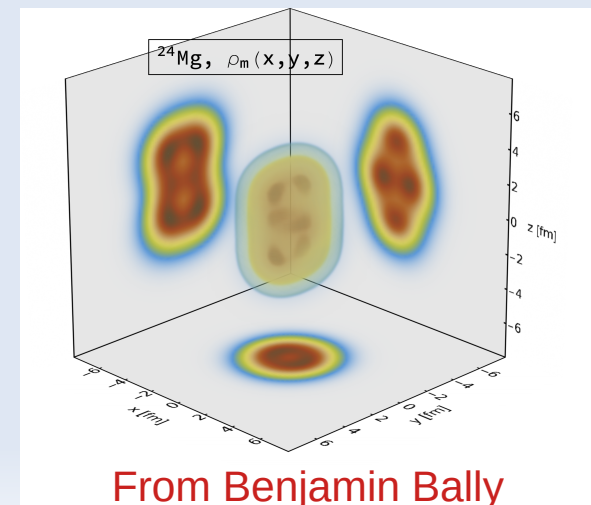


T. Otsuka et al, Nat Commun 13, 2234 (2022)

S. Shen et al, Nat. Commun. 14 (2023) 2777

- Recent **analyses** of low-energy ^{12}C reactions suggest presence of **clustering**
K. Yoshida, M. Kimura arXiv:2606.31437
W. Horiuchi, N. Itagaki Phys.Rev.C 107 (2023) 2

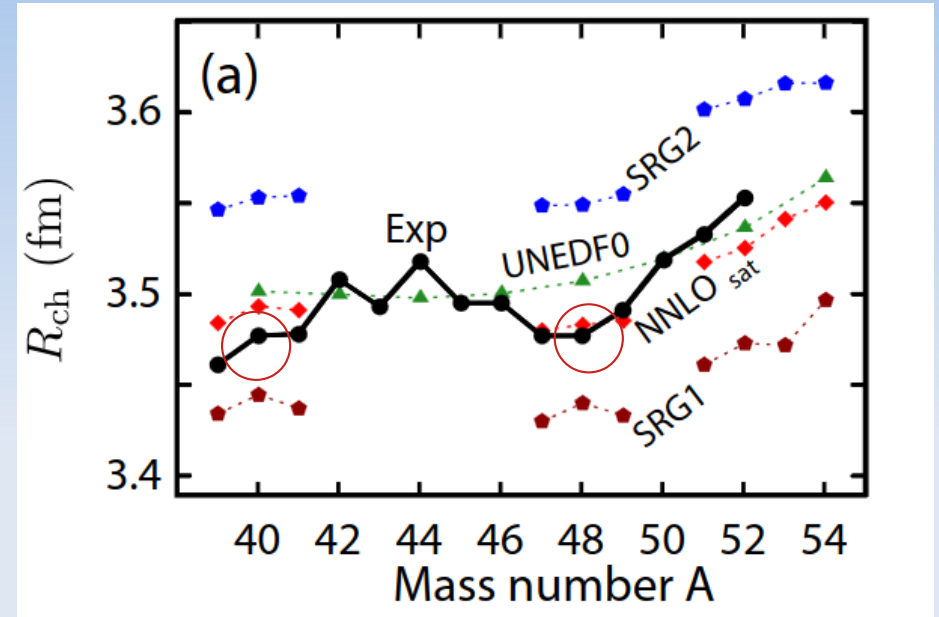
- Improving understanding of **transitions** to excited **Hoyle** state in ^{12}C and ^{24}Mg synthesis from ^{12}C in **supernovae**
- Studying **clustering** in both **small** and **intermediate** sized systems



From Benjamin Bally

Ca for New Ions@LHC

- Strange trend in **calcium charge radii**: similar size for $A=40$, $A=48$, and larger radii for intermediate even-even isotopes
- Understanding magic numbers in nuclear theory
- Benchmarks for ab initio models in nuclear theory
- **Ideally** would like to measure **2-3 isotopes** to test differences
- ^{40}Ca could have some clustering and is unusually small
- Currently, just one isotope is planned, with $A=48$ preferred, to measure the neutron skin → input to equation of state for **neutron stars**
 - Also this case would benefit from studying ^{40}Ca (cancellation of uncertainties)



Garcia Ruiz, R. *Nature Phys* 12, 594–598 (2016)

Expected #incoherent events @LHCb

Luminosities from <https://indico.cern.ch/event/1697777/>

System	$\text{lumi}_{\text{LHCb}} [\text{nb}^{-1}]$	$\sigma_{2 < y < 5} \rho \text{ incoh}$	$N_{\text{LHCb}} \rho \text{ incoh}$	$\sigma_{2 < y < 5} J/\psi \text{ incoh}$	$N_{\text{LHCb}} J/\psi \text{ incoh}$
$^{12}\text{C}-^{12}\text{C}$	2.78	272 μb	760k	61.6 nb	170
$^{24}\text{Mg}-^{24}\text{Mg}$	0.50	1.90 mb	950k	449 nb	220
$^{40}\text{Ca}-^{40}\text{Ca}$	0.69	7.20 mb	5.0M	1.75 μb	1200
$^{48}\text{Ca}-^{48}\text{Ca}$	0.79	8.10 mb	6.4M	2.01 μb	1600

A cut on daughter particles of $p_T > 0.2$ GeV is applied for the fiducial cross sections and number of events.

t-differential measurements should be **feasible** for ρ in C-C, Mg-Mg and Ca-Ca collisions **and** for **J/ψ in Ca**

Expected #incoherent events @ ALICE barrel

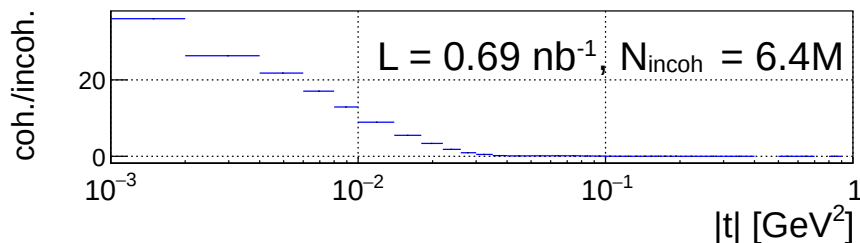
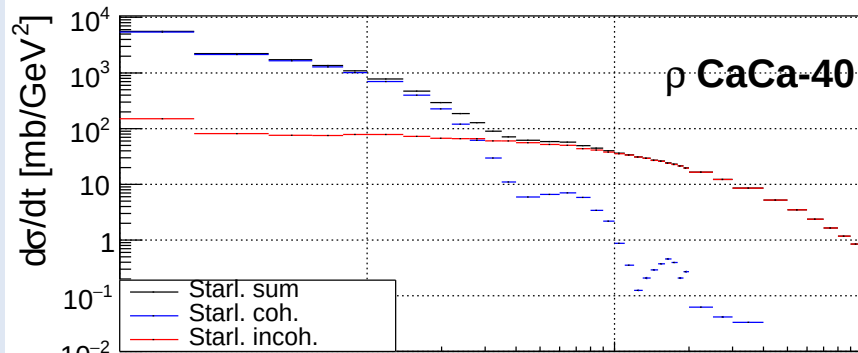
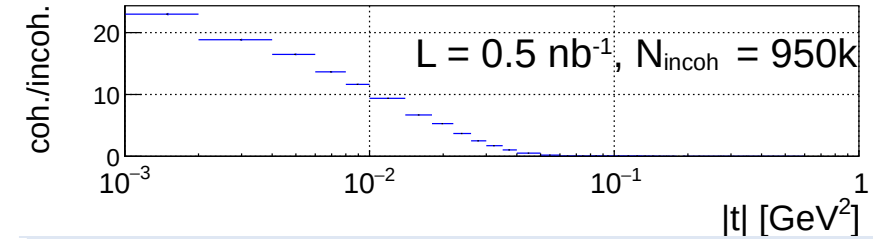
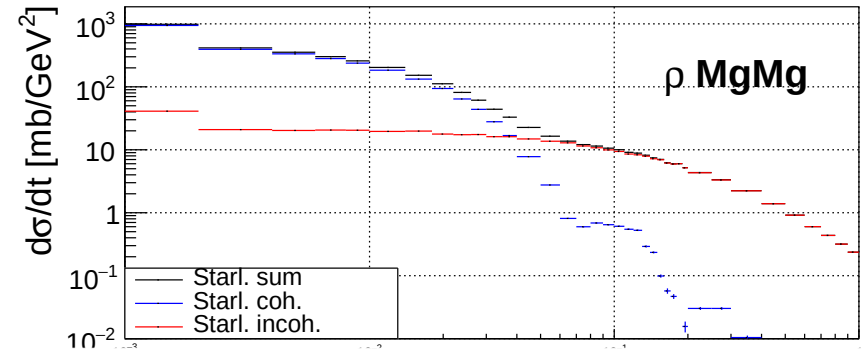
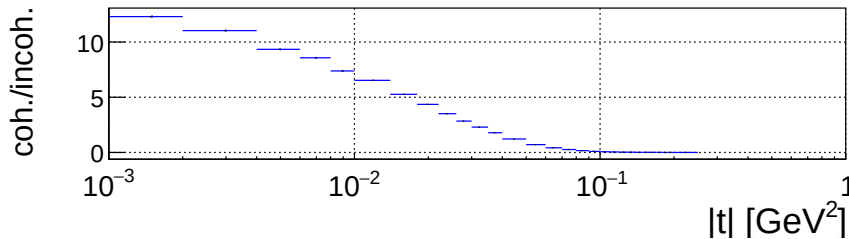
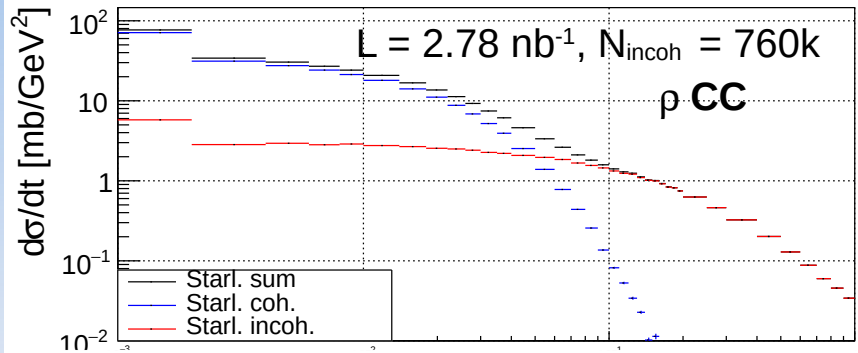
Luminosities from <https://indico.cern.ch/event/1697777/>

System	$\text{lumi}_{\text{ALICE}} [\text{nb}^{-1}]$	$\sigma_{ y <0.9} \rho \text{ incoh}$	$N_{\text{barrel}} \rho \text{ incoh}$	$\sigma_{ y <0.9} \text{J}/\psi \text{ incoh}$	$N_{\text{barrel}} \text{J}/\psi \text{ incoh}$
$^{12}\text{C}-^{12}\text{C}$	5.37	135 μb	730k	46.7 nb	250
$^{24}\text{Mg}-^{24}\text{Mg}$	0.97	965 μb	940k	370 nb	360
$^{40}\text{Ca}-^{40}\text{Ca}$	1.32	3.64 mb	4.8M	1.53 μb	2000
$^{48}\text{Ca}-^{48}\text{Ca}$	1.49	4.01 mb	6.0M	1.77 μb	2600

A cut on daughter particles of $p_{\text{T}} > 0.2 \text{ GeV}$ is applied for the fiducial cross section and number of events.

- Similar upper limits on N_{events} for LHCb and ALICE barrel region
- Note the different luminosities for ALICE and LHCb
- Acceptance x efficiencies should be estimated for more realistic projections

t-distributions within LHCb acceptance



$\langle p_T^{\text{VM}} \rangle$ decreases with **system size**
 for the **coherent** process → better
access to **incoherent** process at
lower $|t|$ at high A

What is our **sensitivity to structure?**
 Need theory input (in contact with
 the hot spot model team in Prague)

Summary and conclusions

- Investigating **feasibility** to measure **VM photoproduction** in light ion collisions and with SMOG2 in collected Run 3 data with LHCb
 - Millions of p events and hundreds of J/ψ in O-O, Ne-Ne and Pb-Ar runs
- **Diffraction** structure simulated in $|t|$, with a **softer coherent spectrum**
- Probing the **sensitivity to clustering** in O-O and Ne-Ne collisions, in the framework of the hot spot model
 - Looks **promising** in a region enriched in **incoherent** events
 - Ratios in $|t|$ intervals could cancel out the luminosity uncertainty
 - The uncertainty on the **modelling** should be kept in mind
- Preparing for the New Ions initiative, focusing on ^{12}C , ^{24}Mg , $^{40,44}\text{Ca}$ (^{76}Ge)
 - 3D density obtained for ^{24}Mg from Benjamin Bally, requested densities for ^{12}C from 2 groups, initiated discussion on Ca structure with theorists in Orsay/Saclay
 - In contact with authors of hot spot model, interested in IPGlasma model

Thank you!

Thank you to Laure Massacrier, J. Guillermo Contreras, Vladimir Manea, Didier Beaumel, David Verney, Thomas Duguet, Guiliano Giacalone and others for fruitful discussions!

Thank you to **Alexandra Ridzikova** for predictions in the LHCb acceptance region!

Thank you, all, for your attention!

Backup

Complementarity low-high energy

Low energy measurements

- Great **flexibility** in choice of nuclei to probe
- Ground and excited **states accessible**
- More **contamination** of the probed state from excitations
- Need to construct Kumar invariant by exciting to all states, measure and sum over results (not all states available)

T. Duguet, slide 37-39

Heavy ions at LHC

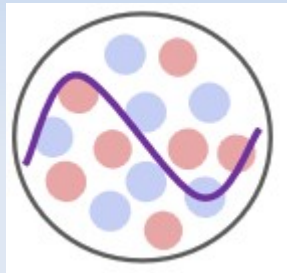
- Very **short interaction times** → clean ground state
 - Possible contamination from excited states if they are close in energy?
- **Expensive** beam time, with priority to pp/PbPb/pPb
 - Still, **new collision systems** possible for Run 4
 - Fixed (gas) target mode with **SMOG2** can provide larger **variety** of systems

Will we see the same thing at low and high energy?

Coherence of VM photoproduction

Coherent VM photoproduction

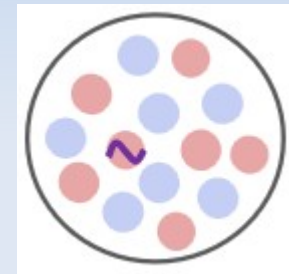
- The photon interacts coherently with the whole target nucleus



- $\langle p_T^{VM} \rangle \sim 1/\text{Radius} \sim 60 \text{ MeV}$ for Pb
- Usually no breaking of target nucleus
- Sensitive to **nuclear parton distribution functions**

Incoherent VM photoproduction

- A single nucleon emits the gluon

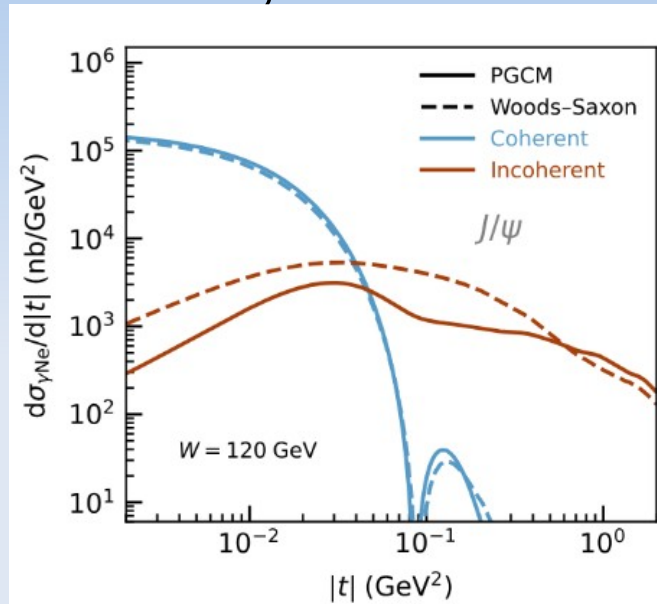


- **Higher** $\langle p_T^{VM} \rangle \sim 500 \text{ MeV}$
- Usually breaks the target nucleus
- Sensitive to nuclear **geometry**

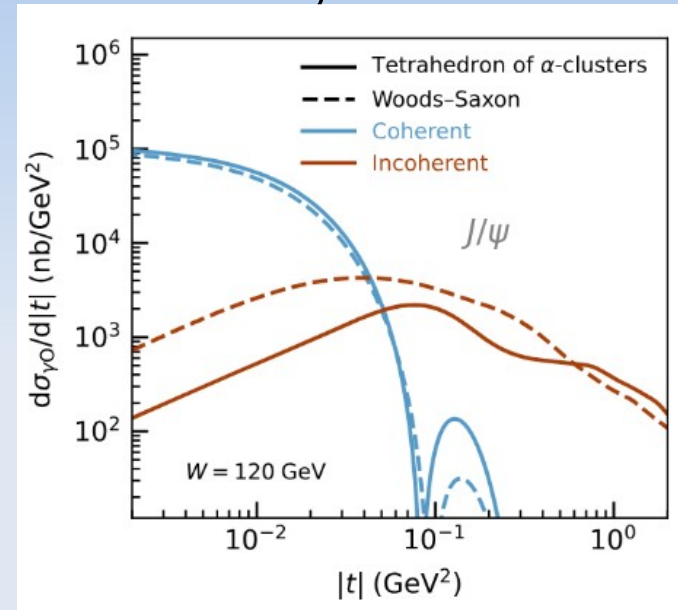
p_T : projection of the momentum on the plane transverse to the beam axis

How does nuclear structure affect the VM cross section?

O-O, 5.36 TeV



Ne-Ne, 5.36 TeV

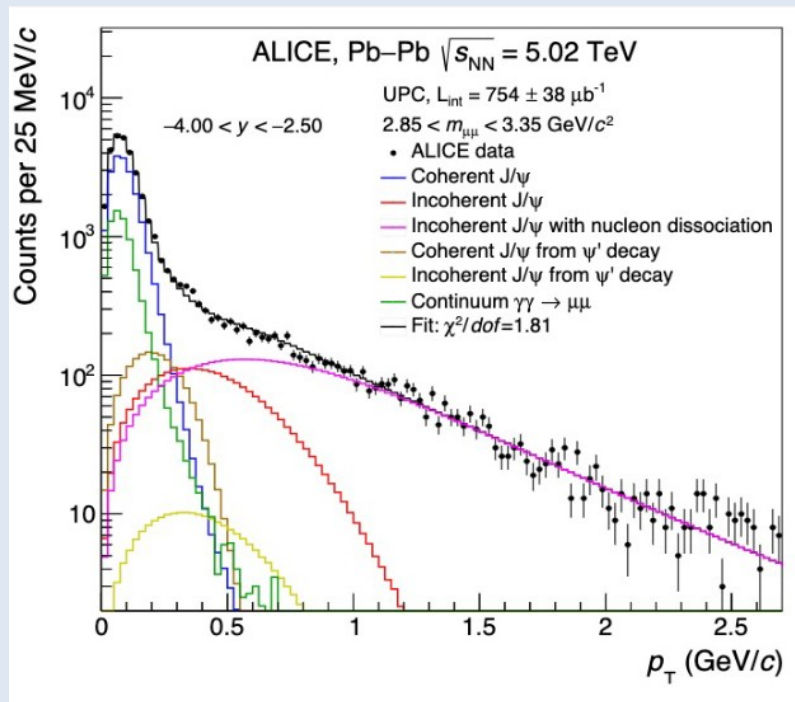


J. Cepila et al., Phys. Rev. C. 113 (2026) 2, 025202

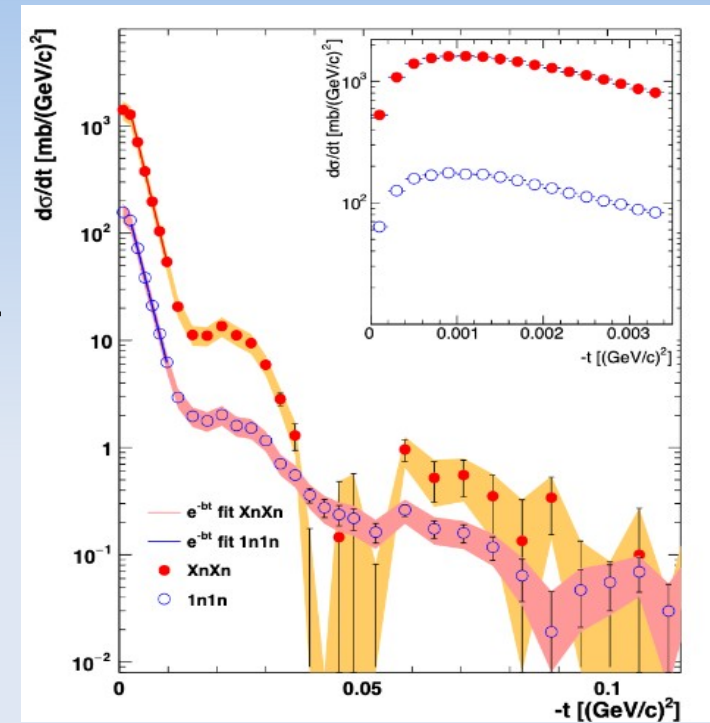
- **Coherent** process: main impact from nuclear structure is on the magnitude of the **second diffractive peak**
- **Incoherent** process: change in **shape** of the t-differential cross section and the **position** of the **dips**

Feasibility to constrain nuclear structure with VMs in UPC

- Extraction of second peak challenging in coherent VM photoproduction.
 - Measurements exist for the abundant ρ^0
- Clean coherent/incoherent separation (p_T cut or template fits of p_T distributions). Requires good $p_T(t)$ **resolution**



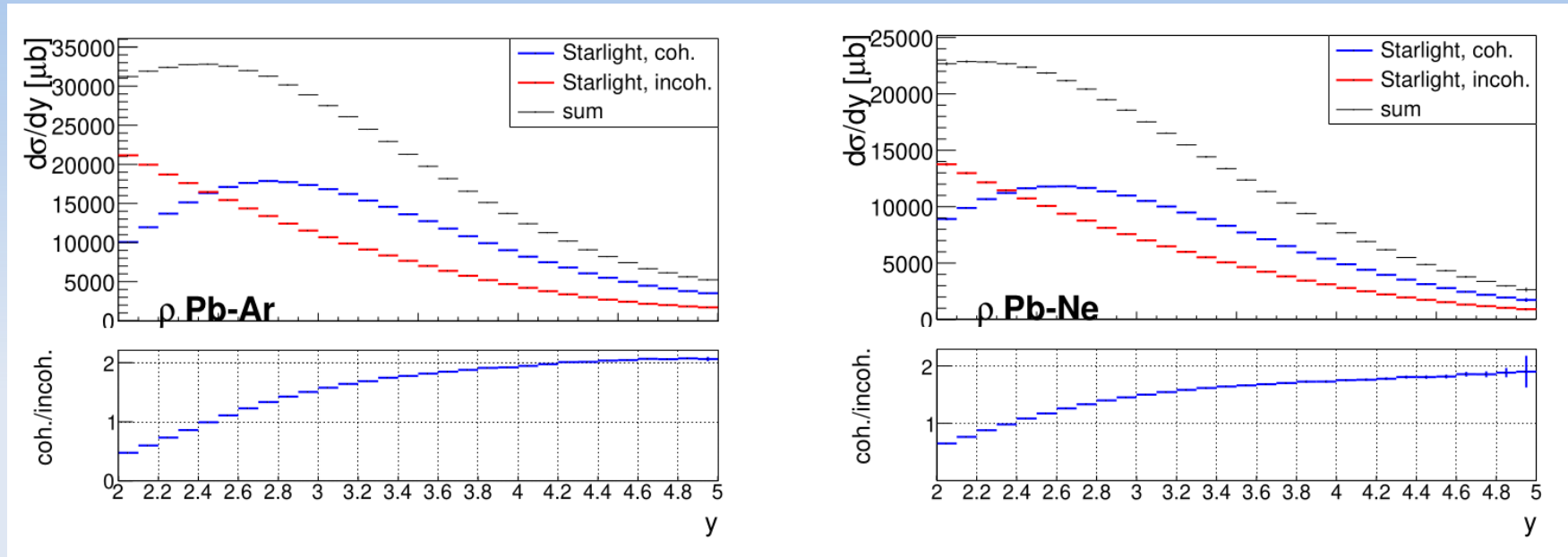
ALICE, Phys. Lett. B798 (2019) 134926



STAR, Phys. Rev. C. 96 054904

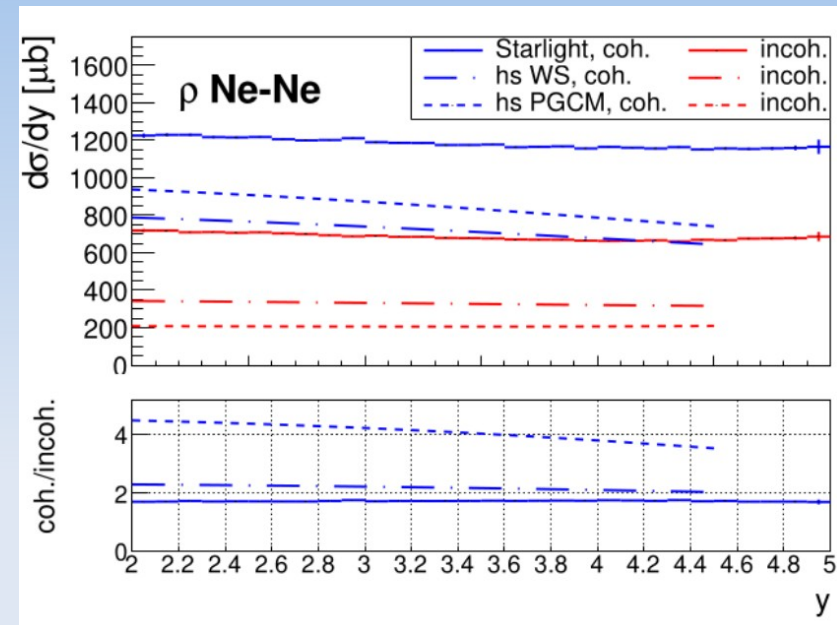
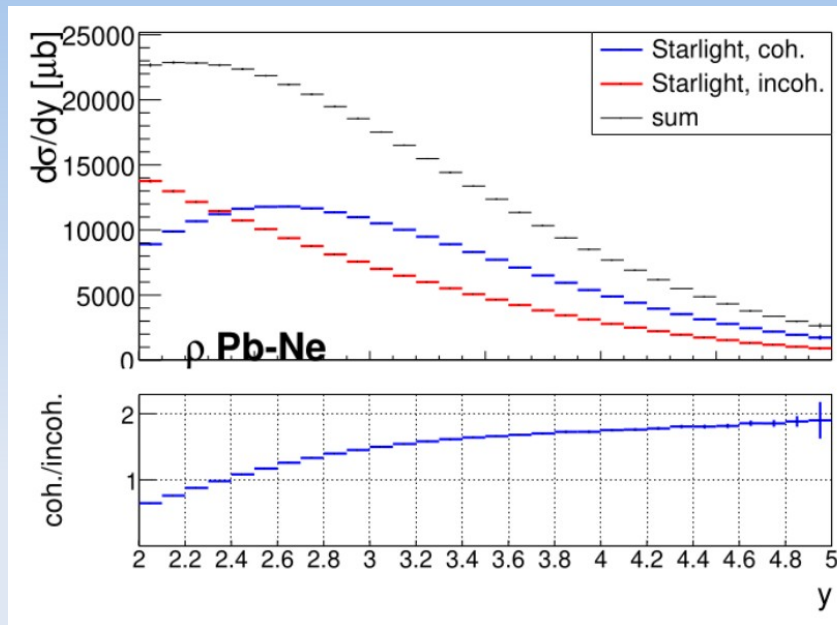
- I perform **projections** for some of the many available systems available at **LHCb**
 - **fixed target** and **collision** modes

Rapidity in fixed target events



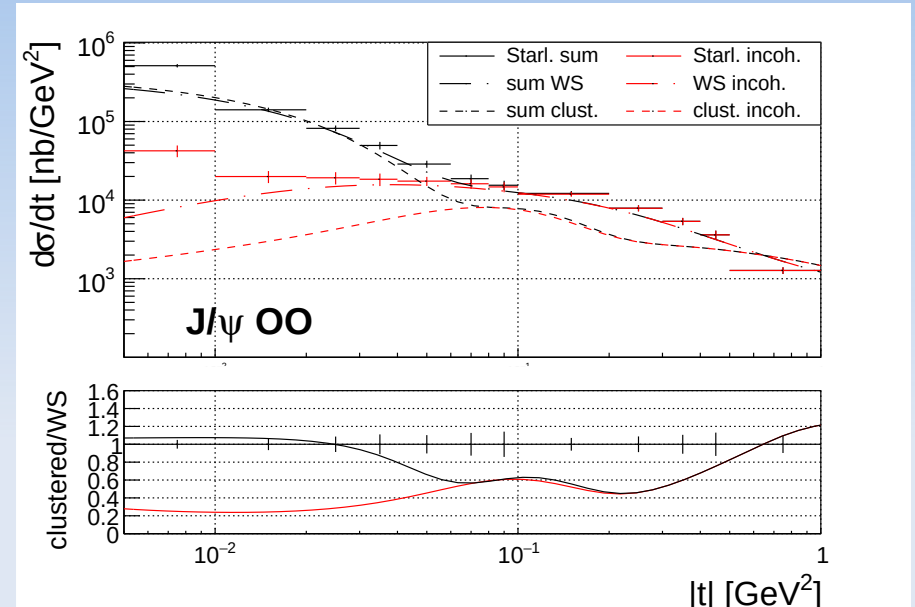
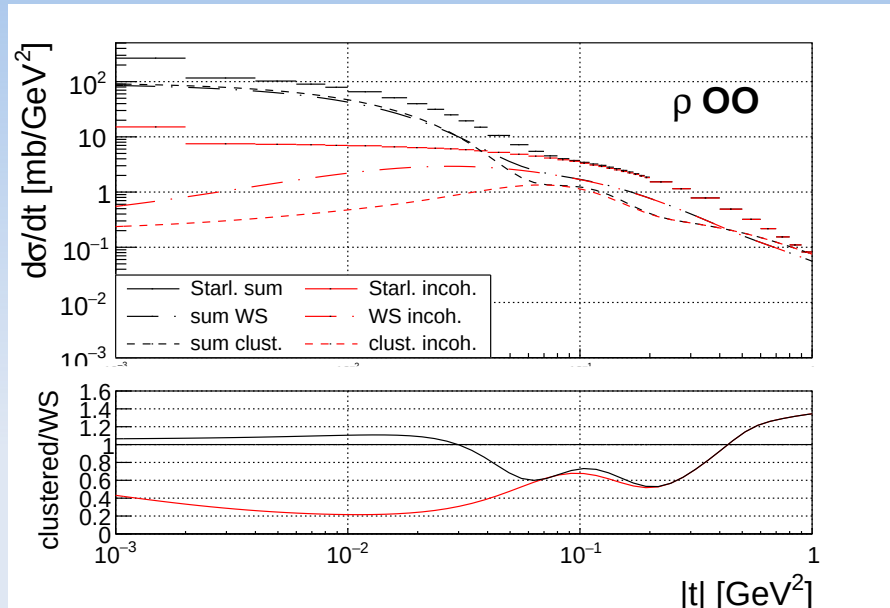
- The **coherent** process, which has lower p_T , and is **boosted** to **higher rapidity** than the incoherent one
- The LHCb acceptance cuts result in an enrichment of coherent events for fixed target interactions

Rapidity: fixed target vs symmetrical



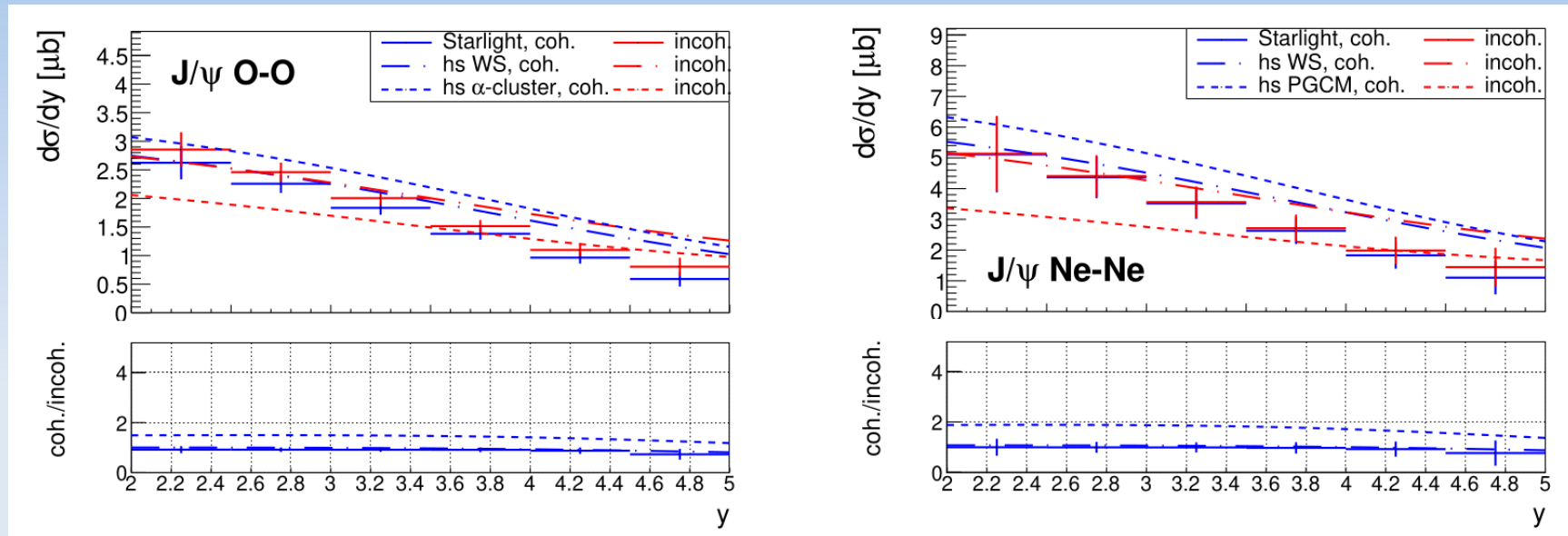
- The **coherent** process, which has lower p_T , and is **boosted** to **higher rapidity** than the incoherent one in fixed target events
- A small statistical uncertainty on ρ cross sections
- The Woods-Saxon and clustered predictions result in **different yields**, with no major impact on shape in y in Ne-Ne collisions.

Adding the coherent and incoherent cross sections, O-O



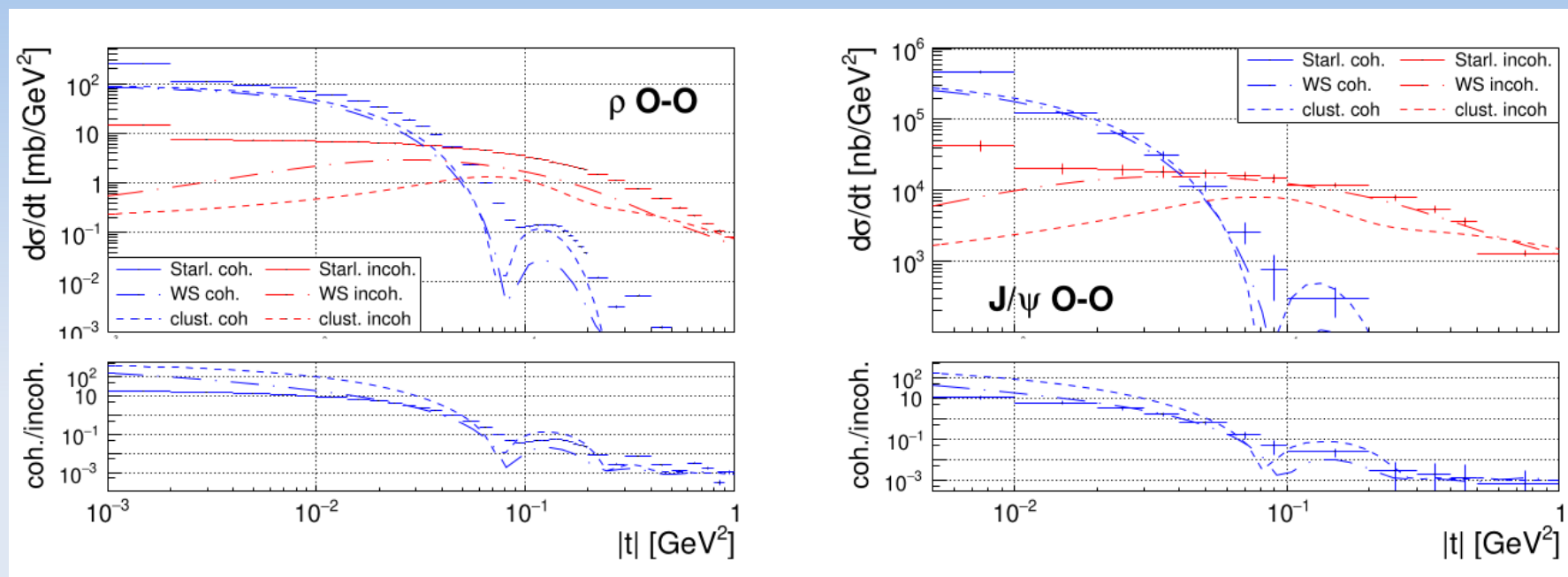
- Sizeable **impact** from **structure** in the **incoherent prediction**
 - Better **separated** from the coherent process at **higher $|t|$**
- Considering **sum** of the 2 processes rather than attempting separation
 - 30-40% lower clustered** prediction at **intermediate $|t|$** $\sim 10^{-1}$
- The statistical uncertainty is shown as errorbars in both panels
- Cold nuclear matter effects in the hot spot model are prominent at low $|t|$

γ distributions for J/ψ , light ions



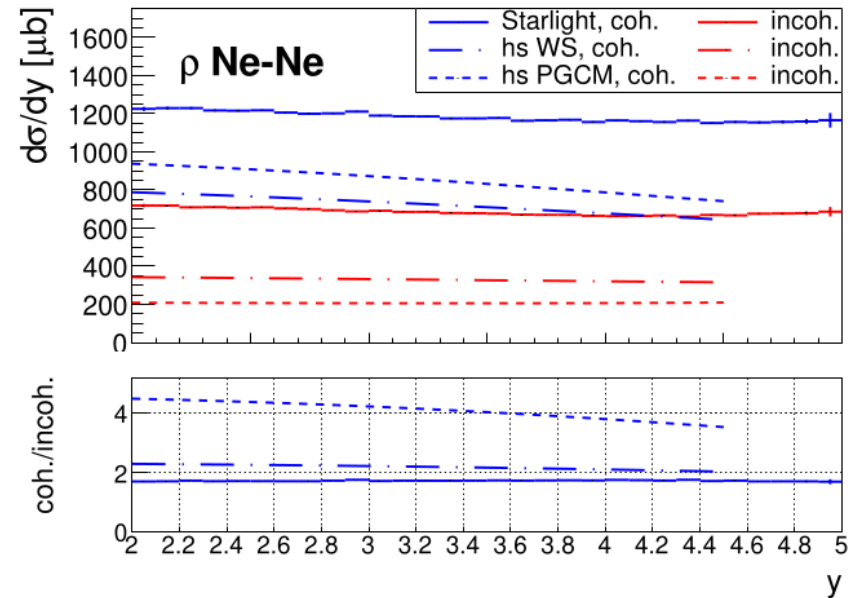
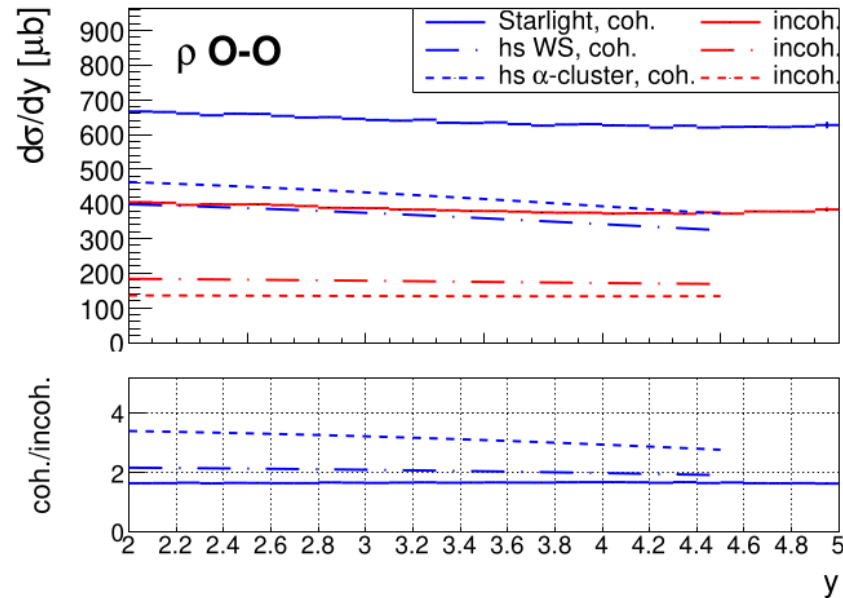
- Smaller statistical precision for J/ψ
- The coherent and incoherent predictions are very similar in the clustered case
- **Higher slope** than for ρ photoproduction

t distributions, O-O



- Cold nuclear matter effects (shadowing, saturation) are included in the hotspot model and are prominent at low $|t|$, resulting in a lower cross section than in the STARLIGHT simulation
- Second diffractive coherent peak buried under the incoherent process
- Sizeable **impact** from **structure** in the **incoherent prediction**
 - Better **separated** from the coherent process at **higher $|t|$**

y distributions for ρ , light ions



- Again, a **small statistical uncertainty** on the ρ cross sections.
- In collider mode with the same nuclei in both beams, we do not profit from the boost to separate the two processes in rapidity.
- The Woods-Saxon and clustered predictions result in **different yields**, with no major impact on shape in y .

t distributions for J/ψ, light ions

