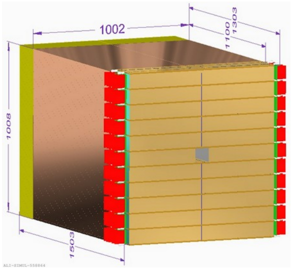
A Forward Calorimeter in ALICE (FoCal)

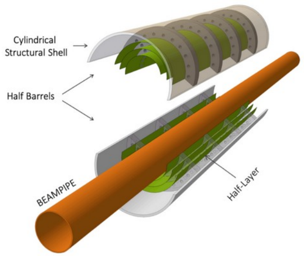
Ionut-Cristian Arsene (University of Oslo)
on behalf of the ALICE Collaboration

UPC 2023, 10-15 December, Playa del Carmen, Yucatán, Mexico

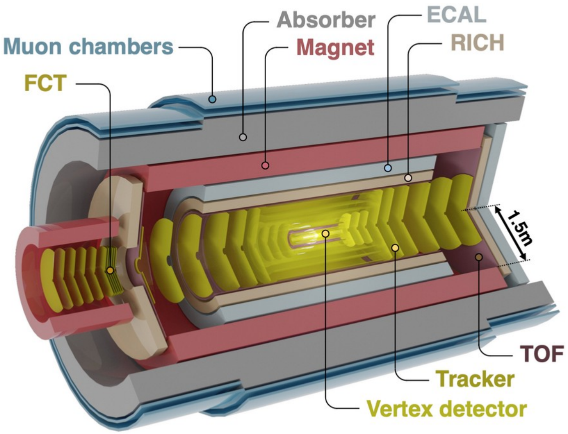
ALICE upgrades timeline

2022-2025 **2029-2032** **2035-2038** **2040-2041**





FoCal and ITS3



ALICE3

FoCal LoI: *ALICE, LHCC-I-036 (2020)*

ITS3 LoI: *CERN-LHCC-2019-018*

ALICE3 Loi: CERN-LHCC-2022-009

Why FoCal ?

Workshop: Exploration of small-x structure of nuclei and signals of saturation in forward measurements at the LHC

Wednesday 22 Jun 2022, 09:00 → 17:45 Europe/Zurich

40/S2-C01 - Salle Curie (CERN)

Description: Please register for this workshop if you intend to participate on site. If you are planning to participate online, no registration is needed.

Registration: You are registered for this event. Check details

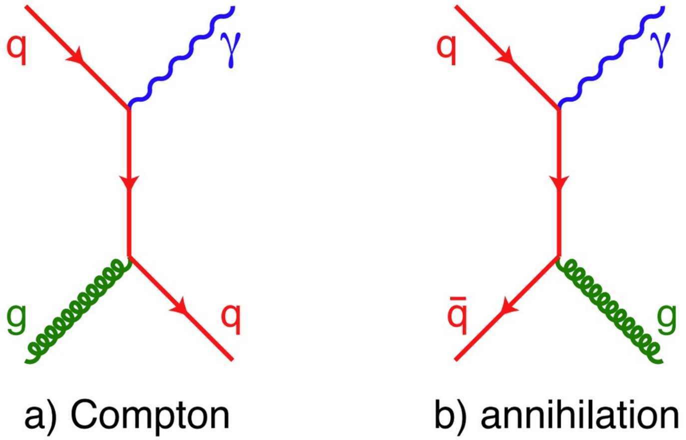
Time	Title	Duration	Material
10:30 → 10:35	**Introduction to the workshop** Speaker: Constantinos Loizides (ORNL)	5m	focal_ws_22june22....
10:40 → 10:55	**Physics Potential with the FOCAL Detector** Speaker: Ionut Cristian Arsene (University of Oslo (NO))	15m	IArsene_FOCALwork...
11:00 → 11:25	**Status of (n)PDFs and constraints from forward particle production** Speaker: Juan Rojo (VU Amsterdam and Nikhef)	25m	rojo-FoCal-smallxQ...
11:30 → 11:55	**Signatures of gluon saturation from structure-function measurements** Speaker: Heikki Mäntysaari (University of Jyvaskyla (FI))	25m	FOCAL_workshop_s...
12:00 → 12:25	**Particle Production from CGC - Photons, Hadrons, Dihadrons** Speaker: Jamal Jalilian-Marian	25m	cern-smallx-06-2022...
12:30 → 12:45	**Discussion**	15m	
13:45 → 14:00	**Forward dijet production in saturation formalism** Speaker: Piotr Kotko (AGH UST)	15m	Kotko_CERN_FoCal_...
14:05 → 14:20	**Heavy flavor and quarkonium production in the forward region** Speaker: Kazuhiro Watanabe (Subatech)	15m	Focal_Watanabe.pdf
14:25 → 14:50	**Why ALICE FOCAL may be interesting: Some loose thoughts of a theorist** Speaker: Antoni Szczurek	25m	szczurek_FOCAL_20...
14:55 → 15:10	**UPC, experimental overview and ALICE projections** Speaker: Joakim Nystrand (University of Bergen (NO))	15m	UPCFOCal.pdf
15:15 → 15:40	**Experimental forward results (LHC, RHIC) and (n)PDF sensitivity -- overview** Speaker: Norbert Novitzky (University of Tsukuba (JP))	25m	FoCalWorkshopNovi...
15:45 → 16:15	**Discussion**	30m	

- Main goal: **explore non-linear gluon evolution and nPDFs at low Bjorken-*x***

LoI: *ALICE, LHCC-I-036 (2020)*
Physics case: *ALICE-PUBLIC-2023-001*
Physics performance: *ALICE-PUBLIC-2023-004*

FoCal observables in hadronic collisions

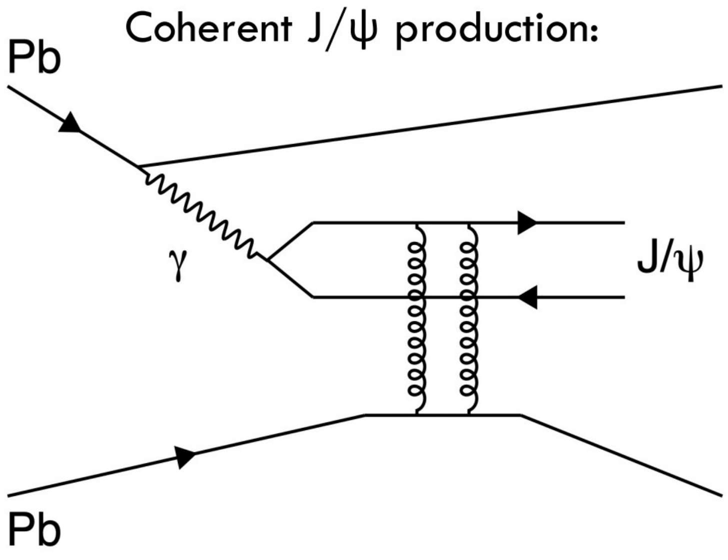
ALICE, LHCC-I-036 (2020)



- Main measurement: **isolated direct photons in pp and p-Pb collisions**
- Complementary observables:
  - π^0
  - Jets
  - Quarkonia, Z^0 and $W^{\pm}$
  - correlations

FoCal observables in UPC

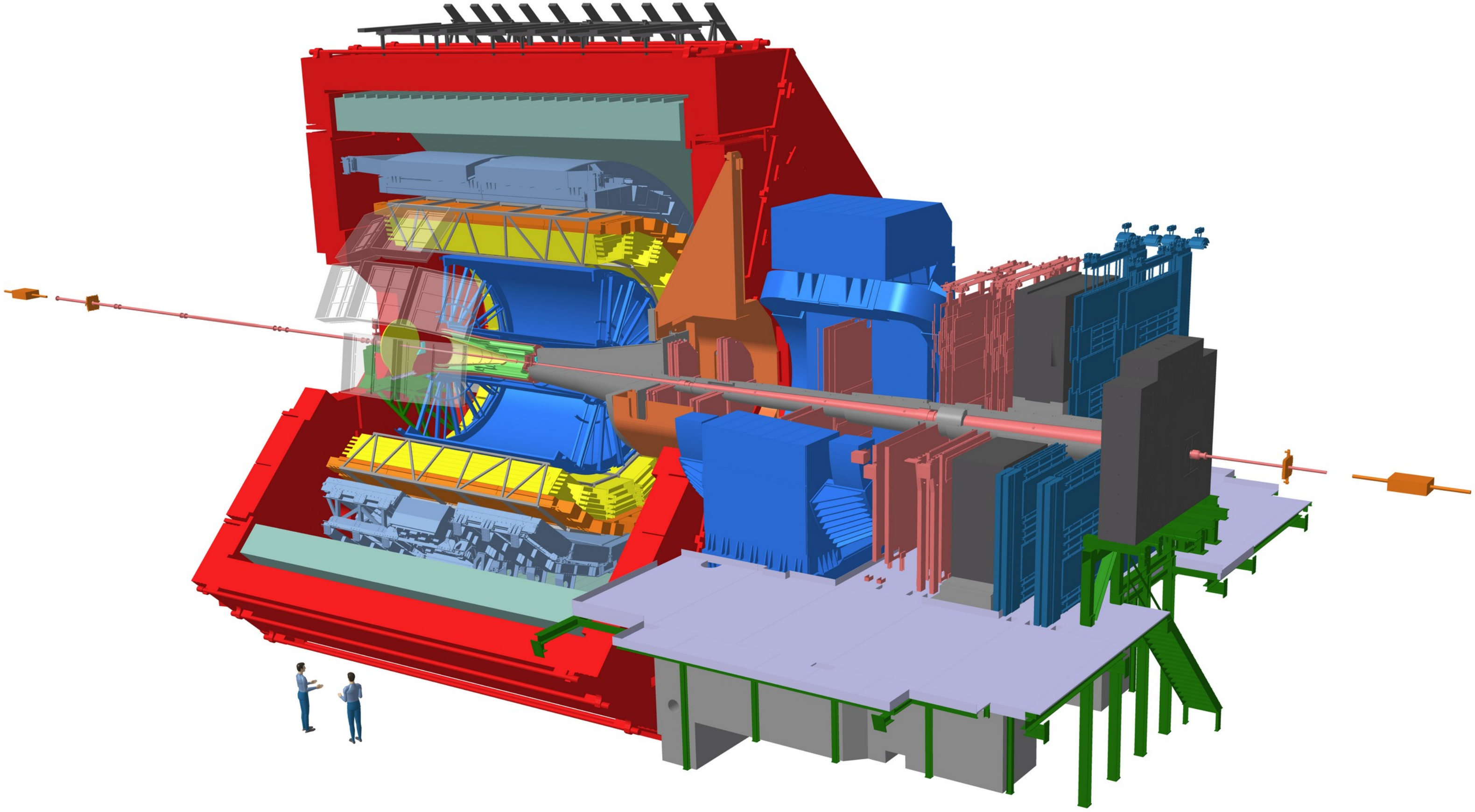
ALICE-PUBLIC-2023-001
Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107



- **Quarkonia (J/ψ, ψ') photoproduction**
  - Extension of photon-Pb and photon-proton cross-sections to very high and very low c.m. energy
  - Bjorken-*x* reach down to ~10^{-6}, discrimination power for saturation models
- Other photon induced processes also measurable:
  - Low mass vector mesons,
  - $\gamma\gamma \rightarrow ee$,
  - Inclusive photo-nuclear and diffractive di-jets,
  - Light-by-light scattering,...

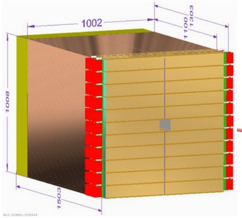
Many thanks to Alexander Bylinkin, Joakim Nystrand and Daniel Tapia Takaki !

The ALICE detector (Run 3 setup)

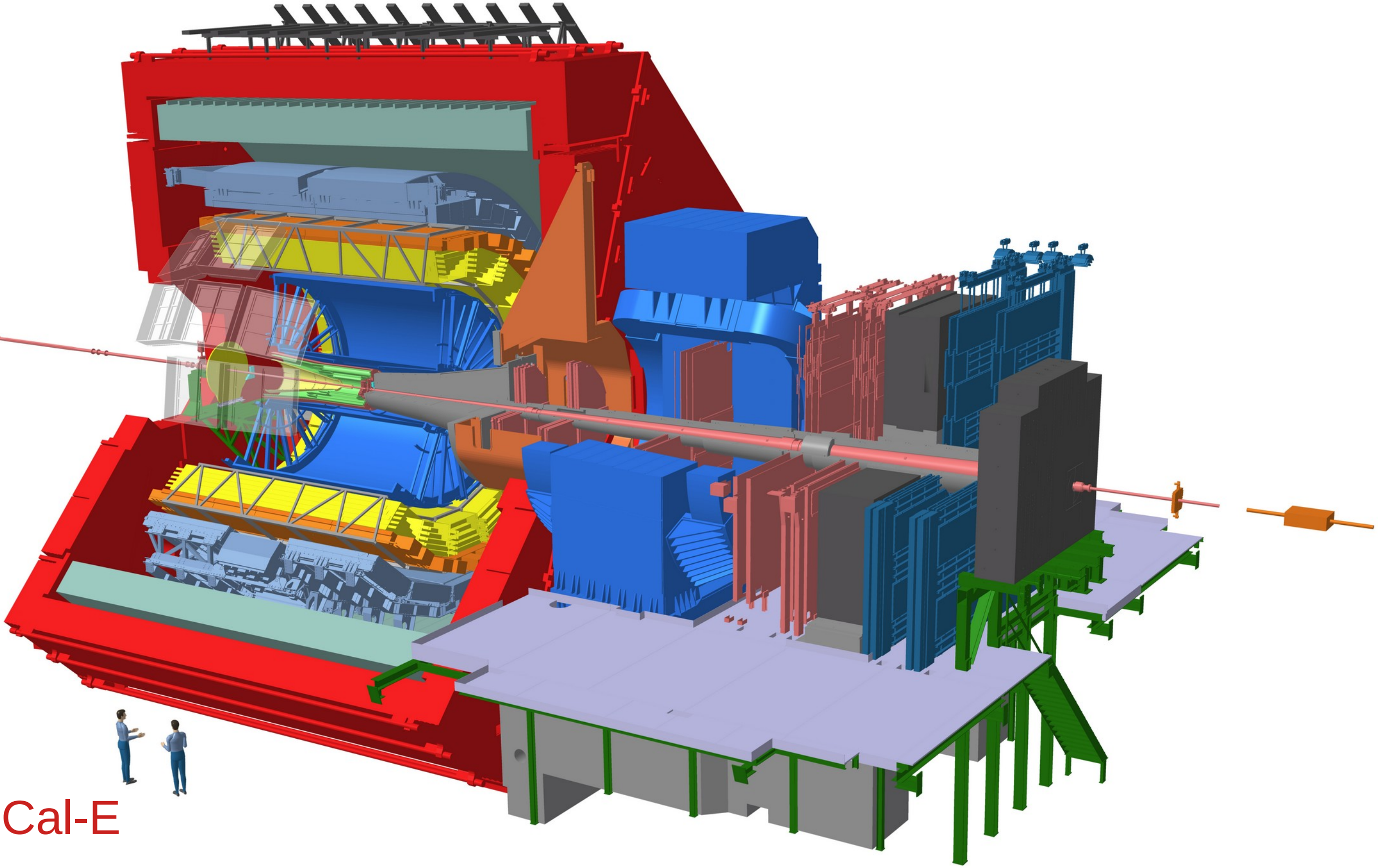


The ALICE detector + FoCal

(not to scale!)

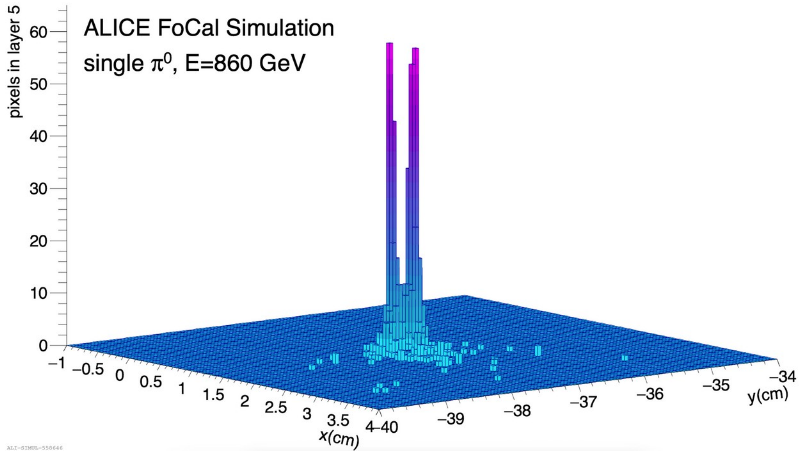


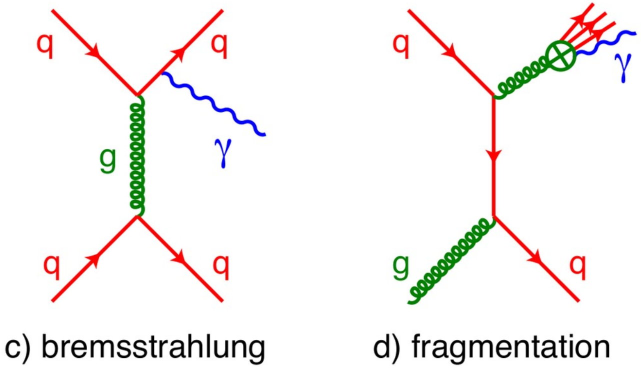
FoCal
3.2 < η < 5.8



- Forward calorimeter (3.2<η<5.8)
  - Electromagnetic: FoCal-E
  - Hadronic: FoCal-H

FoCal design challenges

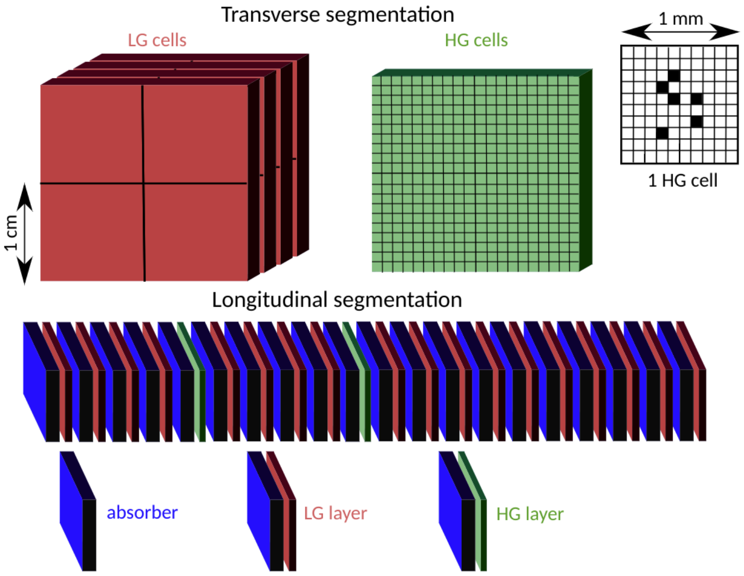




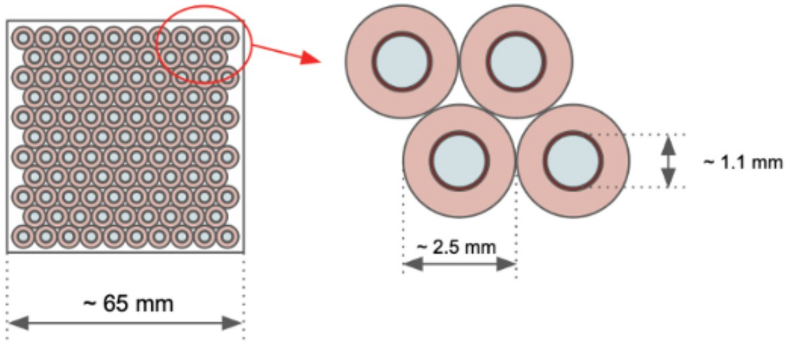
- Discriminate direct photons and decay photons (mainly from π^0)
  - Requires: small Moliere radius, high granularity readout

- Suppress bremsstrahlung and fragmentation photons
  - Requires: measurement of hadronic showers

FoCal structure

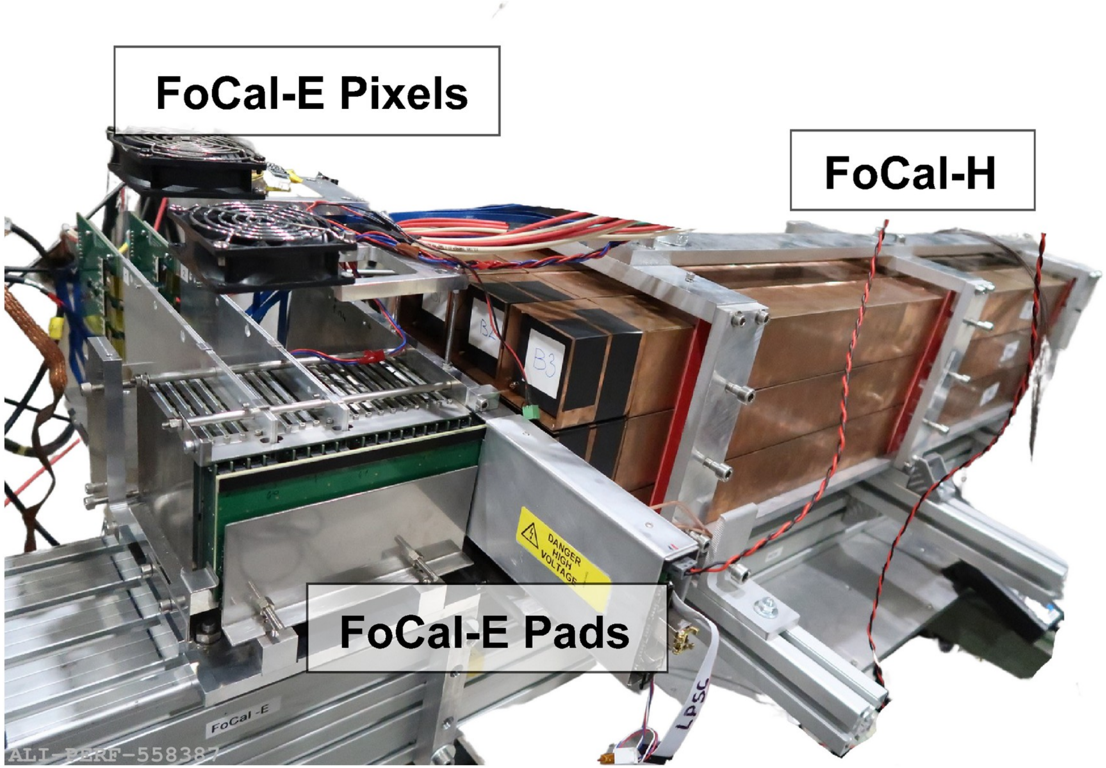


FoCal-E (electromagnetic)
- High granularity Si-W calorimeter
- Longitudinal segmentation (20 layers)
  - 3.5mm W in each layer (1 X_0)
  - 18 pad layers (1x1 cm^2)
    - Energy measurement
  - 2 pixel layers (30x30 μm^2)
    - Two shower separation



FoCal-H (hadronic)
- Metal-scintillator using “spaghetti” design
  - Scintillation fibers embedded in Cu tubes
- Photon isolation, hadronic jet components

FoCal prototype for test beams

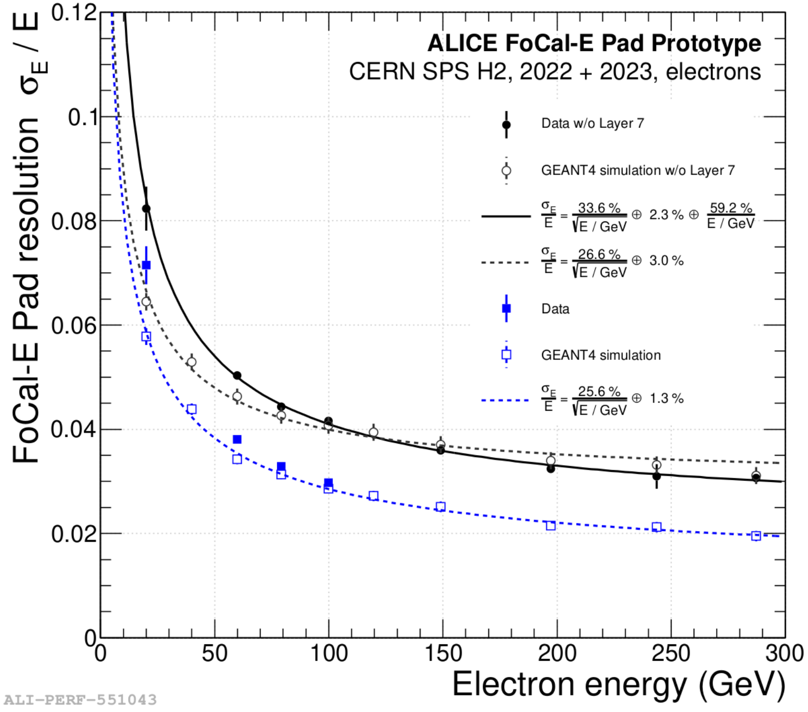


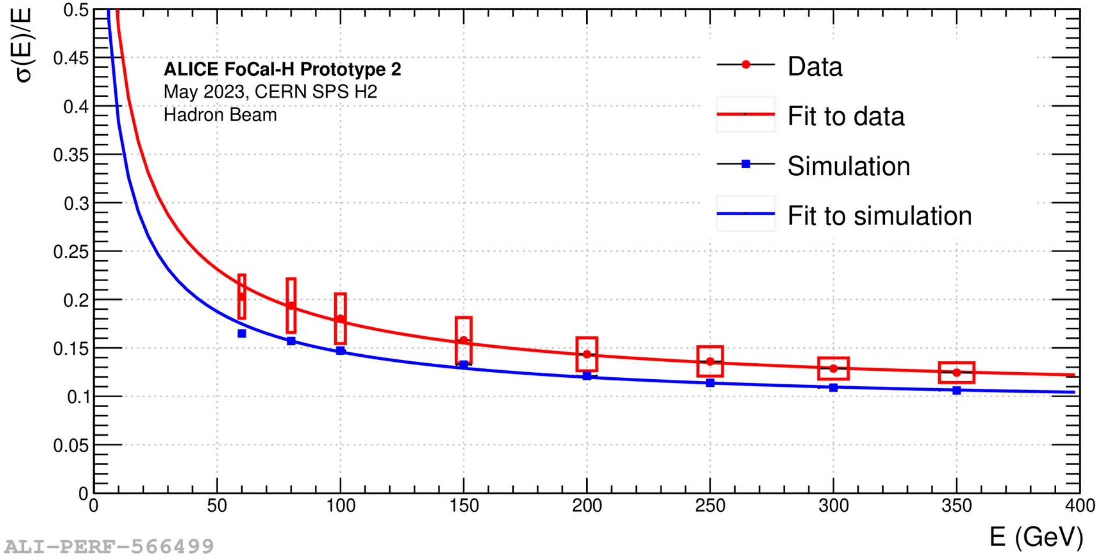
Small prototype built for performance tests

- FoCal-E
  - ~ 9 x 8 cm^2 transverse size
  - 18 pad layers
  - 2 pixel layers
- FoCal-H
  - 9 Cu-scintillator towers
  - ~ 20 x 20 cm^2 transverse size

FoCal prototype tested in electron/hadron beams at SPS in Nov 2022 and May 2023

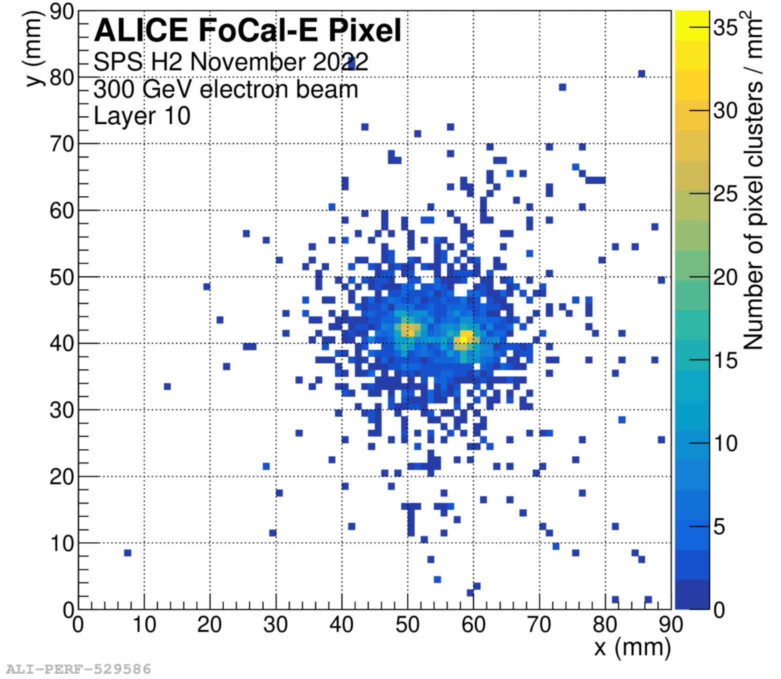
Energy resolution in beam tests

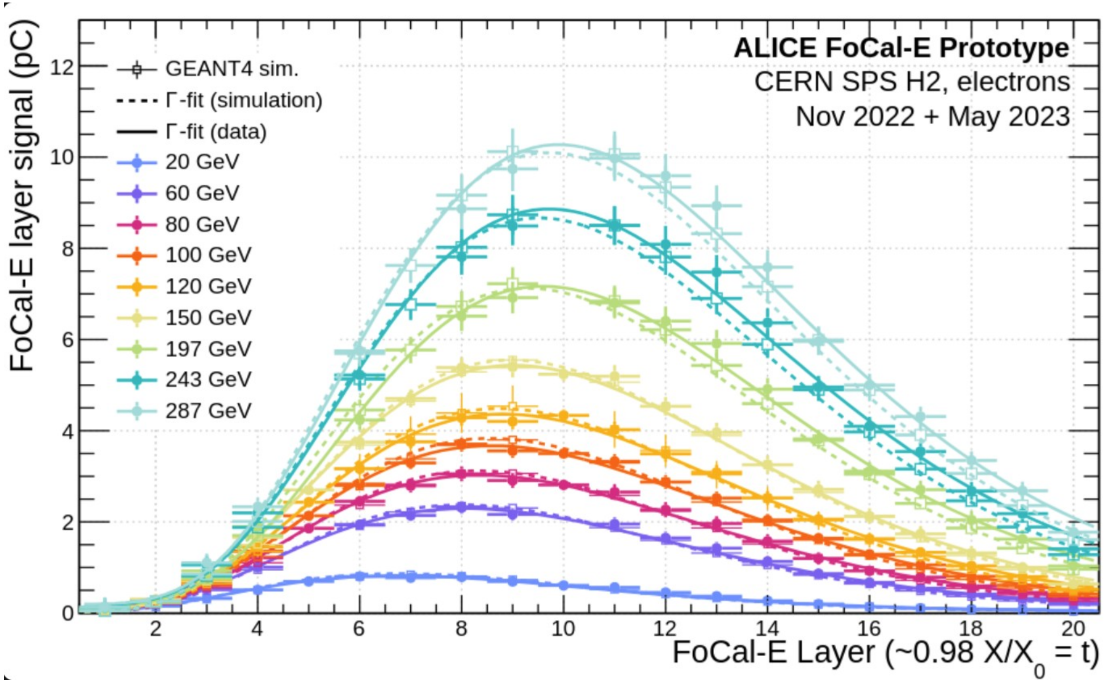




- FoCal-E: energy resolution < 4% at high energies
- FoCal-H: energy resolution < 15% at high energy
  - Disagreements with MC under investigation

Transverse and longitudinal shower profiles

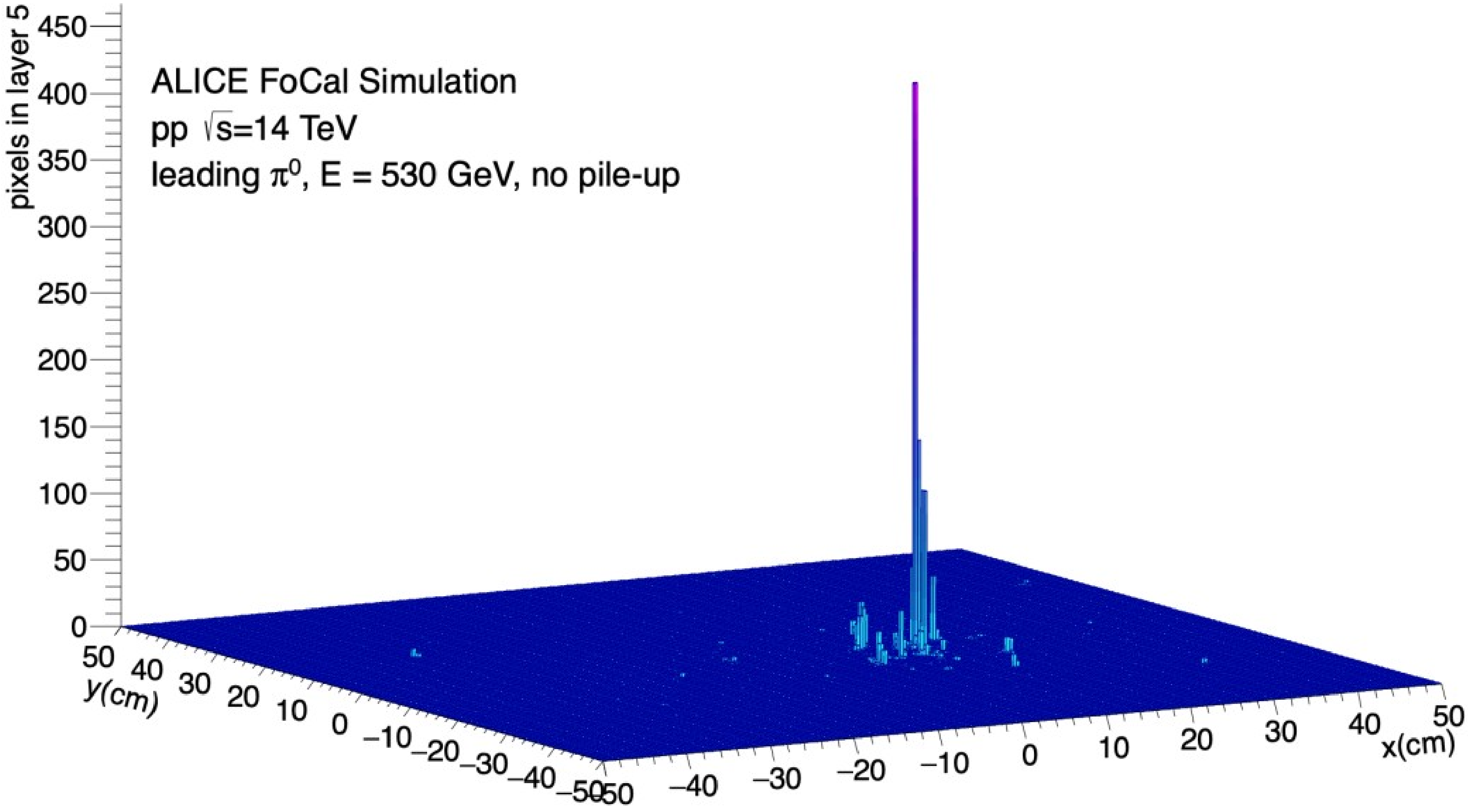




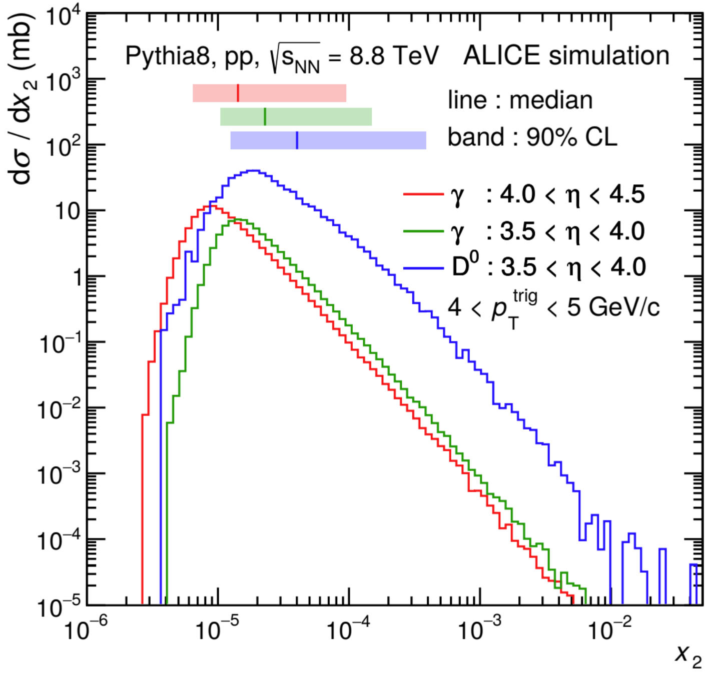
Two-shower separation in FoCal-E pixels

Longitudinal shower profile in FoCal-E

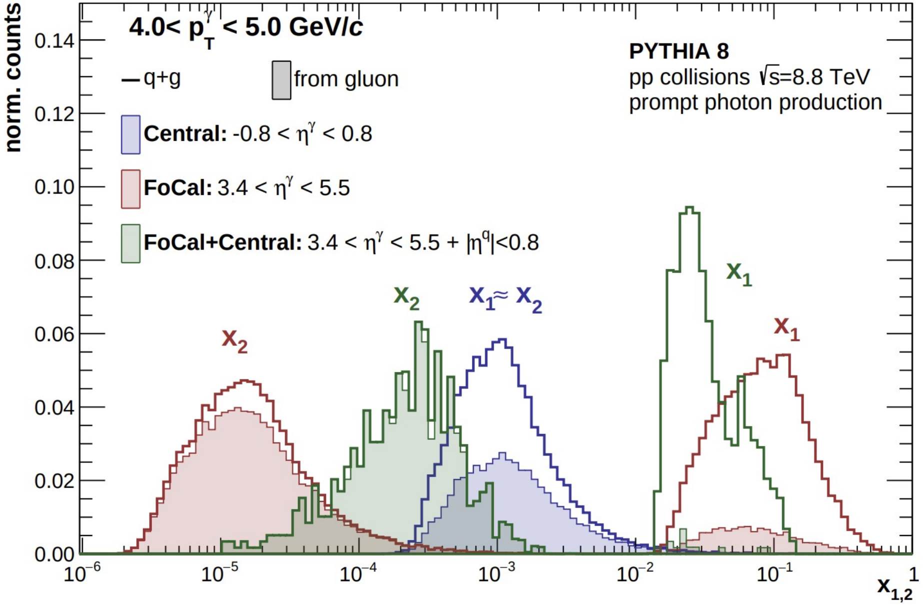
Performance in hadronic collisions



Phase-space coverage

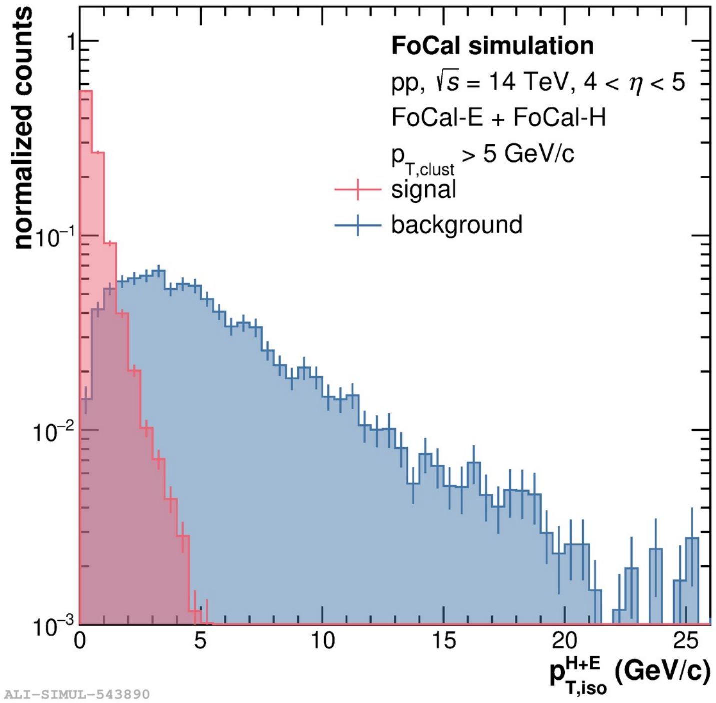


LHCb D⁰: JHEP10(2017)090

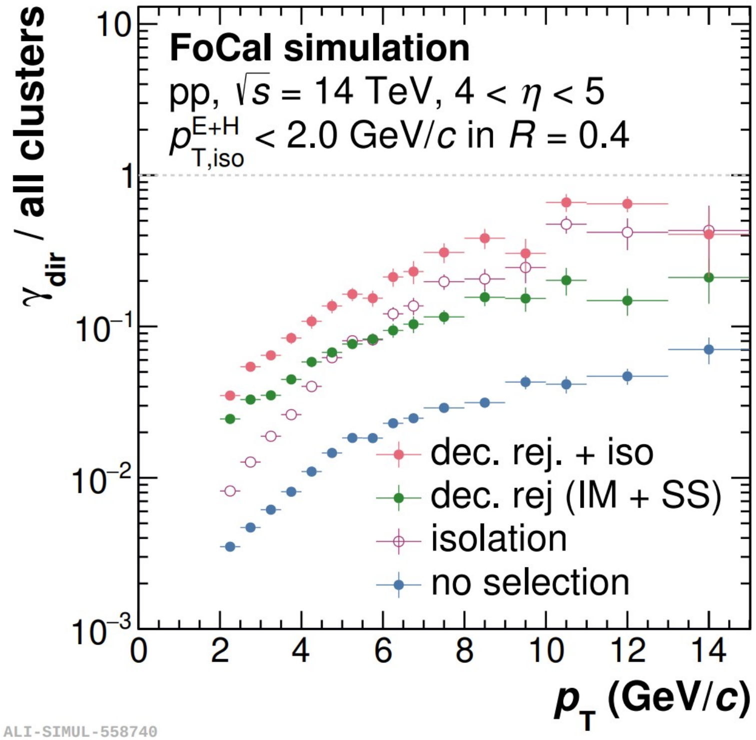


- Direct photons measured in FoCal vs. D-mesons in LHCb
- Photon-hadron correlations combining FoCal and central-rapidity acceptance significantly extends the coverage in x

Direct photons



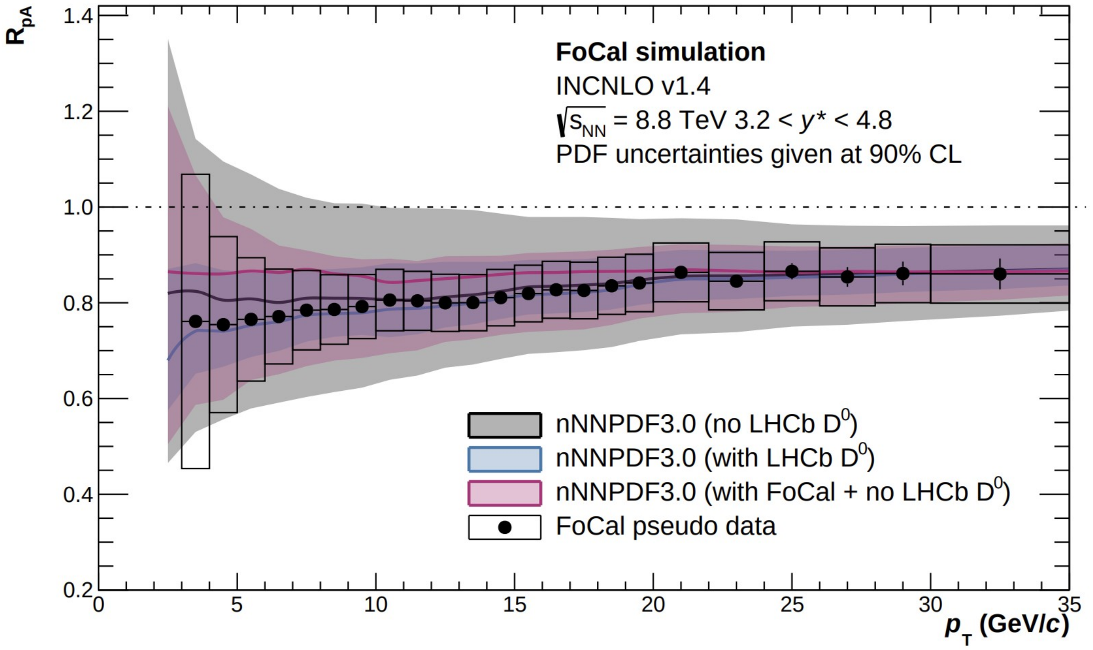
Isolation energy in FoCal-E and FoCal-H



Signal fraction up to ~70% at p_T~14 GeV/c

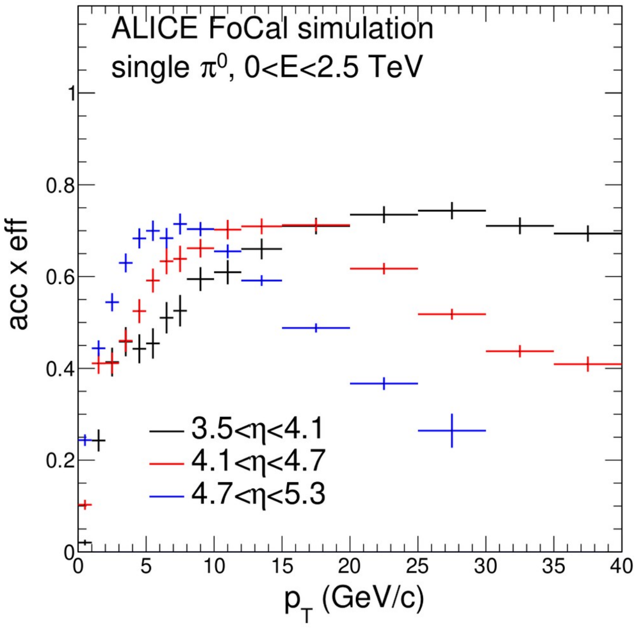
- Still untapped potential by using additional more sophisticated methods

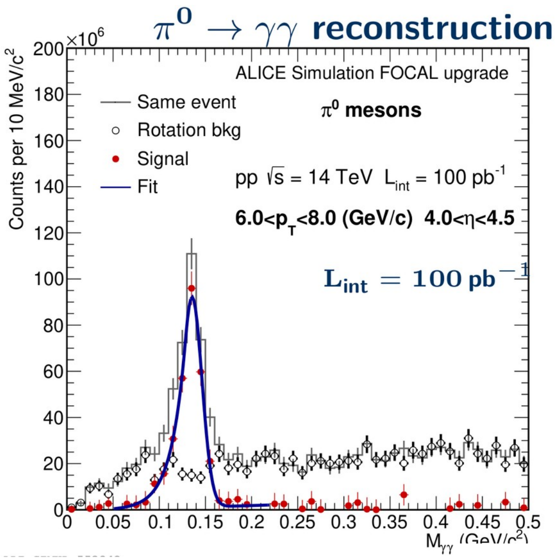
Prompt photon R_{pPb}

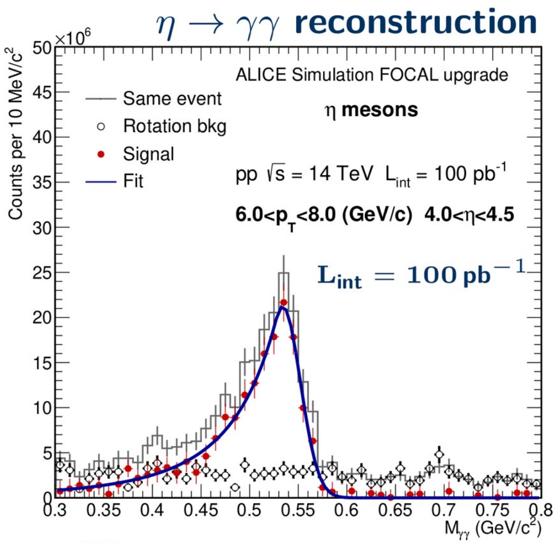


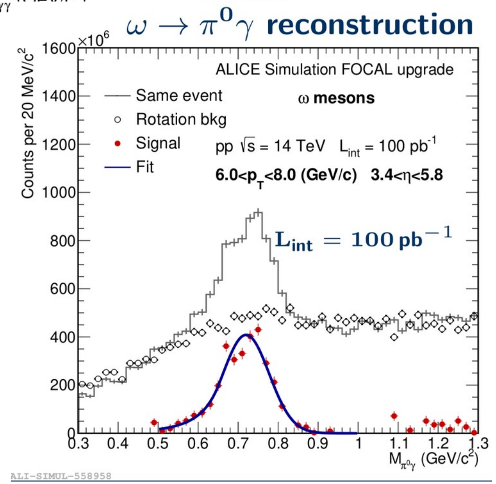
- nPDF+NLO R_{pPb} reweighted using FoCal pseudo data
- Reduction of nNNPDF30 uncertainties similar to LHCb D^0 mesons

Light mesons



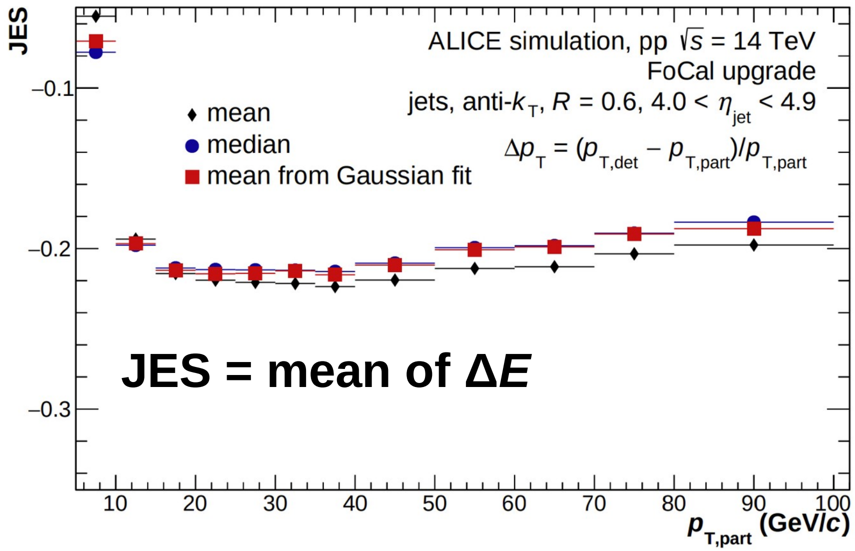


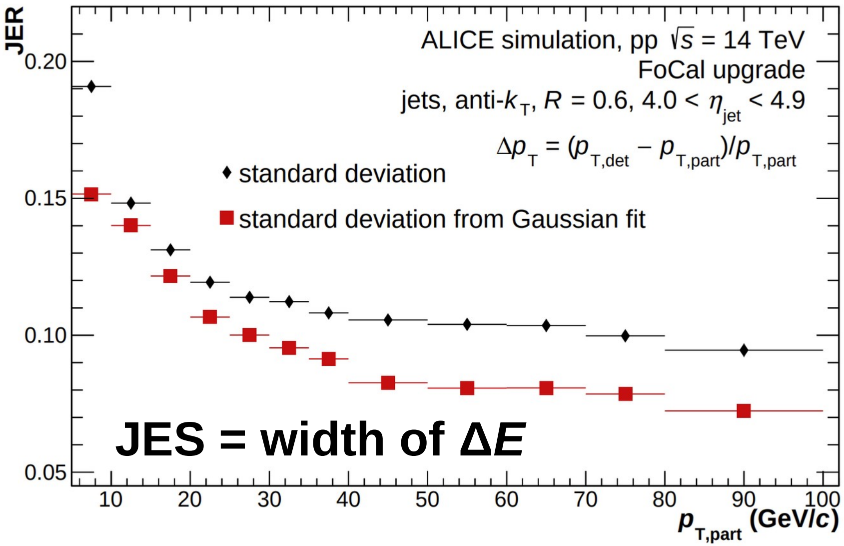




- Neutral pion efficiency of up to ~70%
- High efficiency for the reconstruction of other light mesons: η, ω

Jets

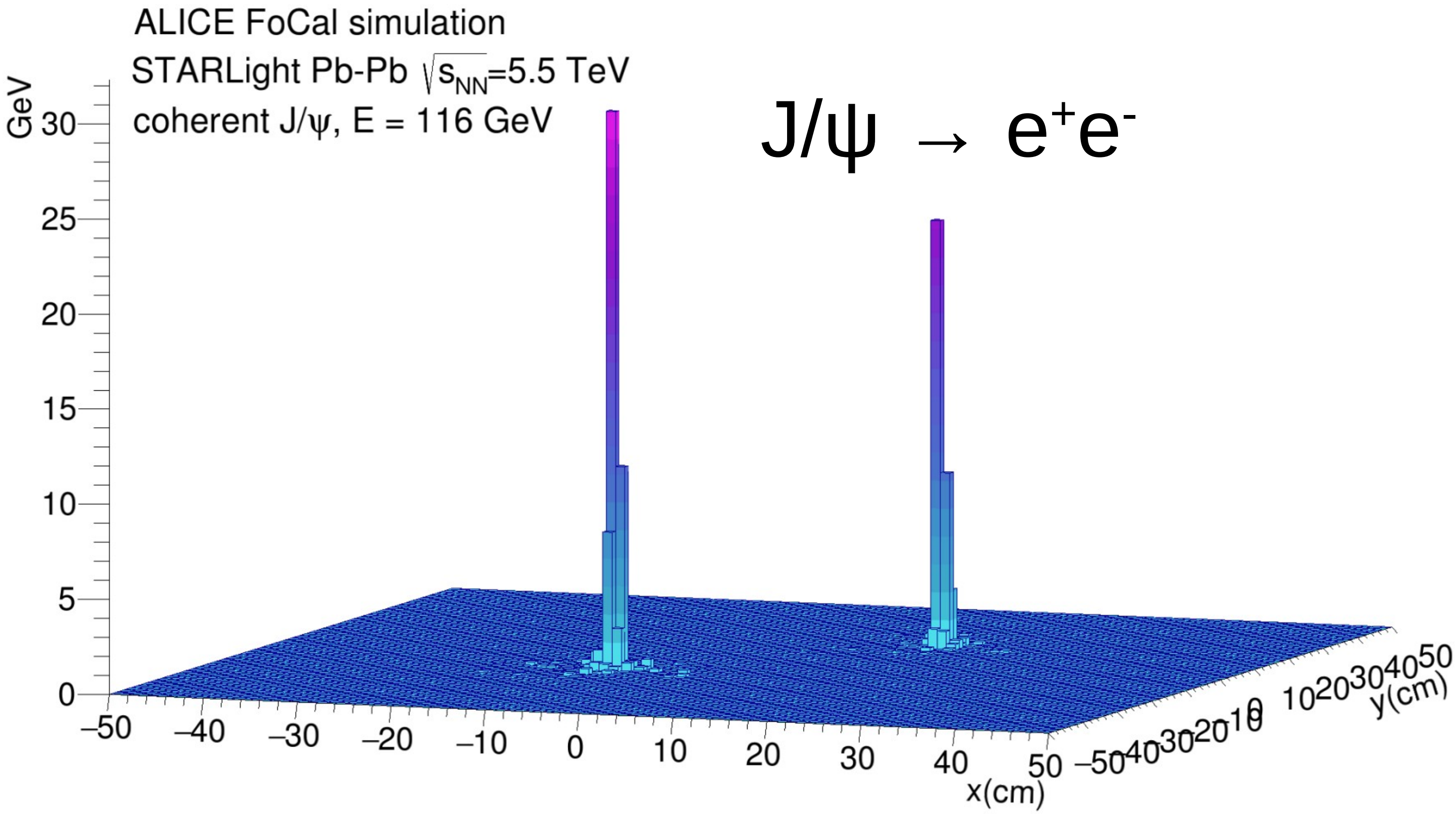




$$\Delta E = (E_{\mathbf{det}} - E_{\mathbf{part}})/E_{\mathbf{part}}$$

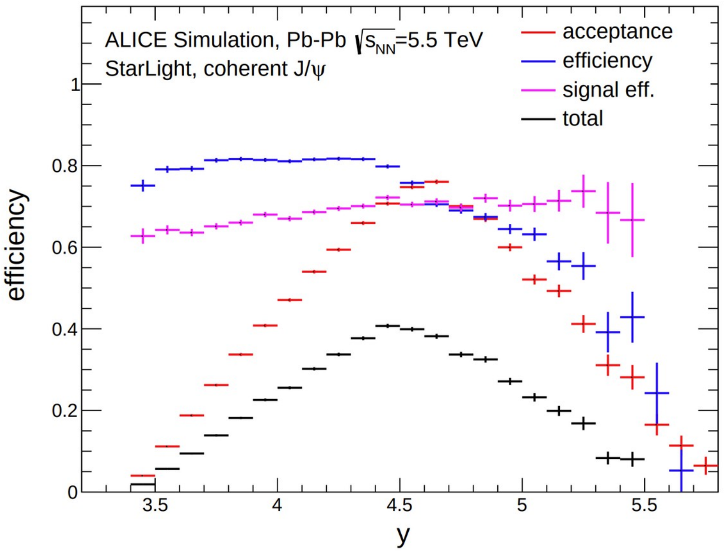
- Jet energy scale (JES) and jet energy resolution (JER) quantified using Pythia + GEANT for R=0.6 anti-k_T jets

Ultra-peripheral collisions



$J/\psi \rightarrow e^+e^-$

Vector meson photo-production in UPC



- High efficiency (~80%) for J/ψ measurement in e^+e^-
- Coverage up to *y*~5.5

Pb-Pb @ 5.36 TeV, L = 7/nb

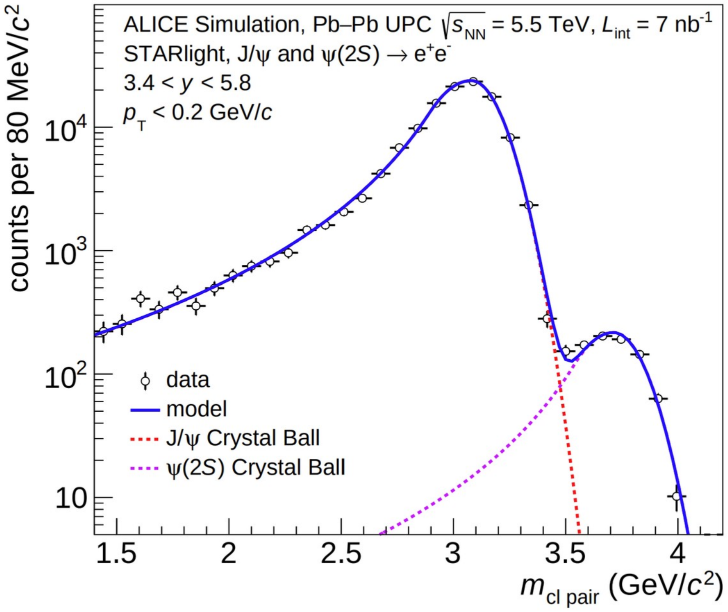
VM	$\sigma(\mathrm{Pb+Pb} \to \mathrm{Pb+Pb+VM})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
ρ^0	5.0 b	20 μb	140,000
ϕ	440 mb	10 μb	70,000
J/ψ	39 mb	53 μb	370,000
$\psi(2S)$	7.5 mb	1.1 μb	7,500
$\Upsilon(1S)$	94 μb	5.0 nb	35

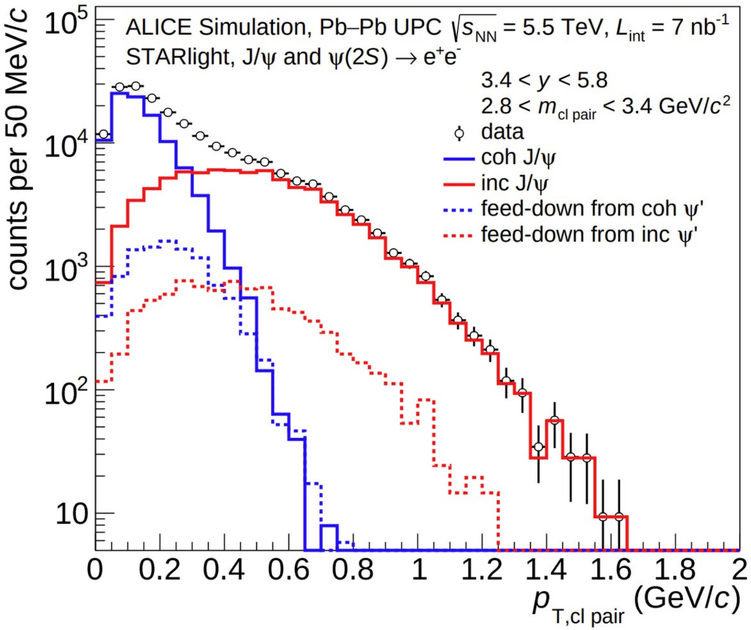
p-Pb, Pb-p @ 8.8 TeV, L = 150/nb

VM	$\sigma(\mathrm{p+Pb} \to \mathrm{p+Pb+VM})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$ p $\to$ FoCal	Yield p $\to$ FoCal
ρ^0	35 mb	140 nb	21,000
ϕ	1.7 mb	51 nb	7,700
J/ψ	98 μb	400 nb	60,000
$\psi(2S)$	16 μb	8.9 nb	1,300
$\Upsilon(1S)$	220 nb	0.38 nb	60
		Pb $\to$ FoCal	Pb $\to$ FoCal
ρ^0	35 mb	17 nb	2,600
ϕ	1.7 mb	5.3 nb	800
J/ψ	98 μb	36 nb	5,400
$\psi(2S)$	16 μb	0.53 nb	80
$\Upsilon(1S)$	220 nb	0.67 pb	~ 0

Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107

J/ψ and ψ(2S) reconstruction in Pb-Pb



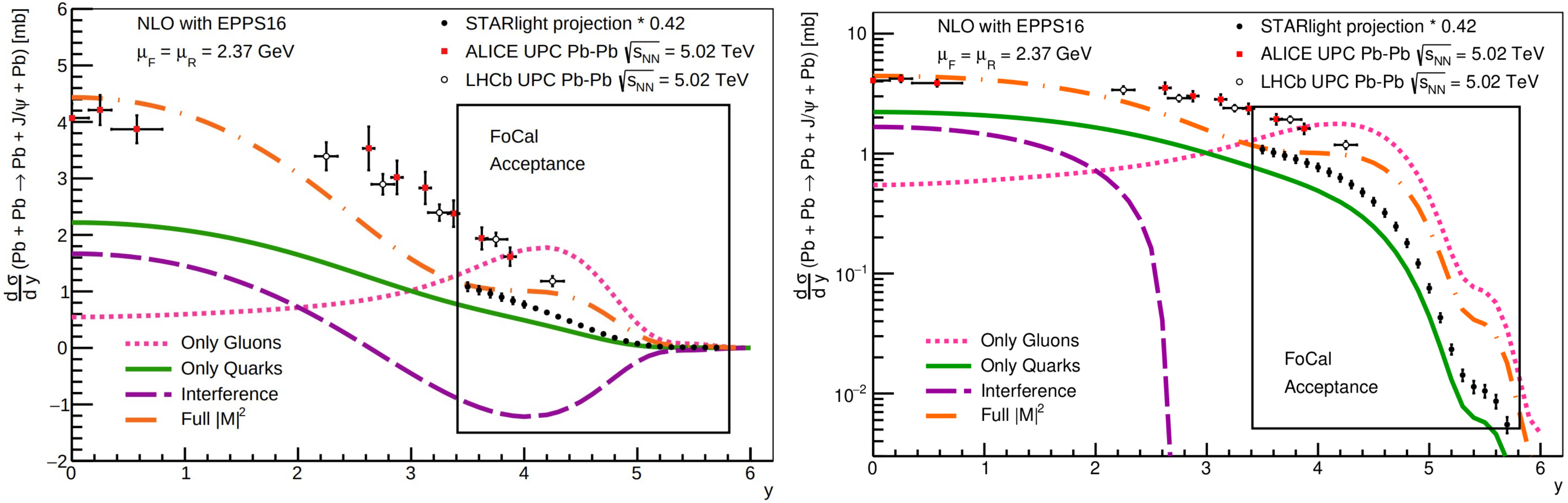


- Ground and excited charmonium states can be separated
- Coherent and incoherent components can be extracted from the p_T distribution
- Very large photoproduced quarkonia sample expected to be measured with FoCal
- Potential of improving the mass and p_T resolution

Coherent J/ψ photoproduction in Pb-Pb UPC

Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107

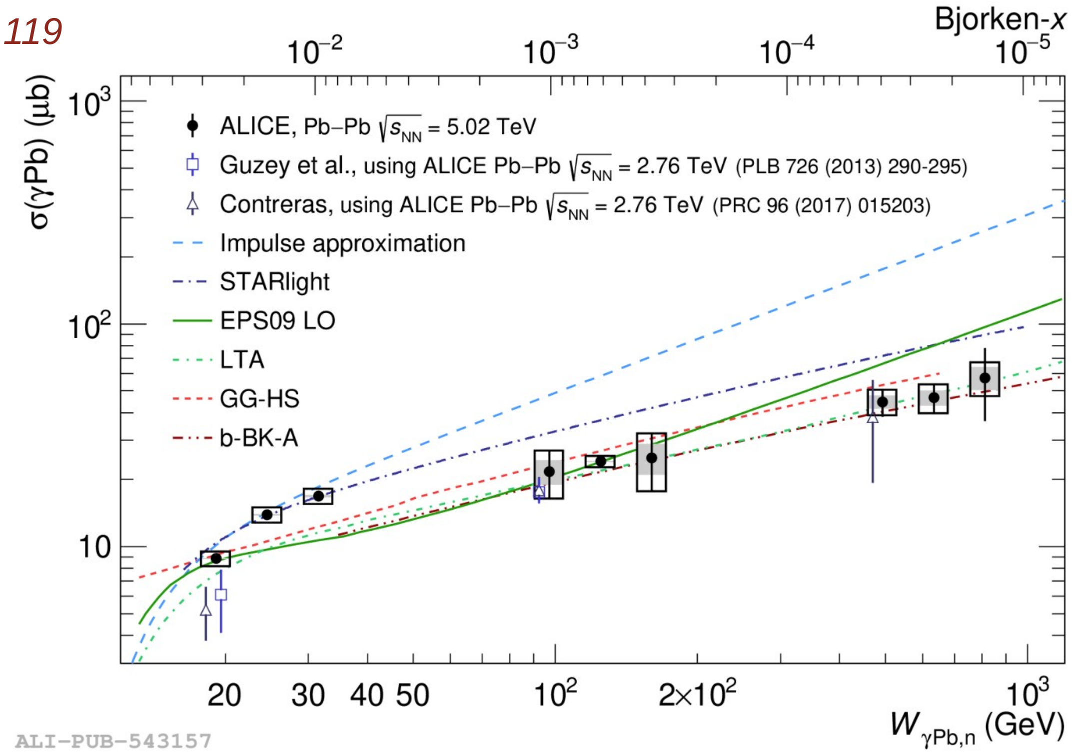
UPC Pb-Pb $\sqrt{s_{NN}}$ = 5.36 TeV, 7 nb^{-1}



- Extension of the measurement to y~5.5, very good stat. uncertainties
- Interference between quark and gluon contributions largest in the FoCal acceptance *Flett, Jones, Martin, Ryskin and Teubner, arXiv:1908.08398*

Photo-nuclear cross-section $\sigma(\gamma+Pb)$

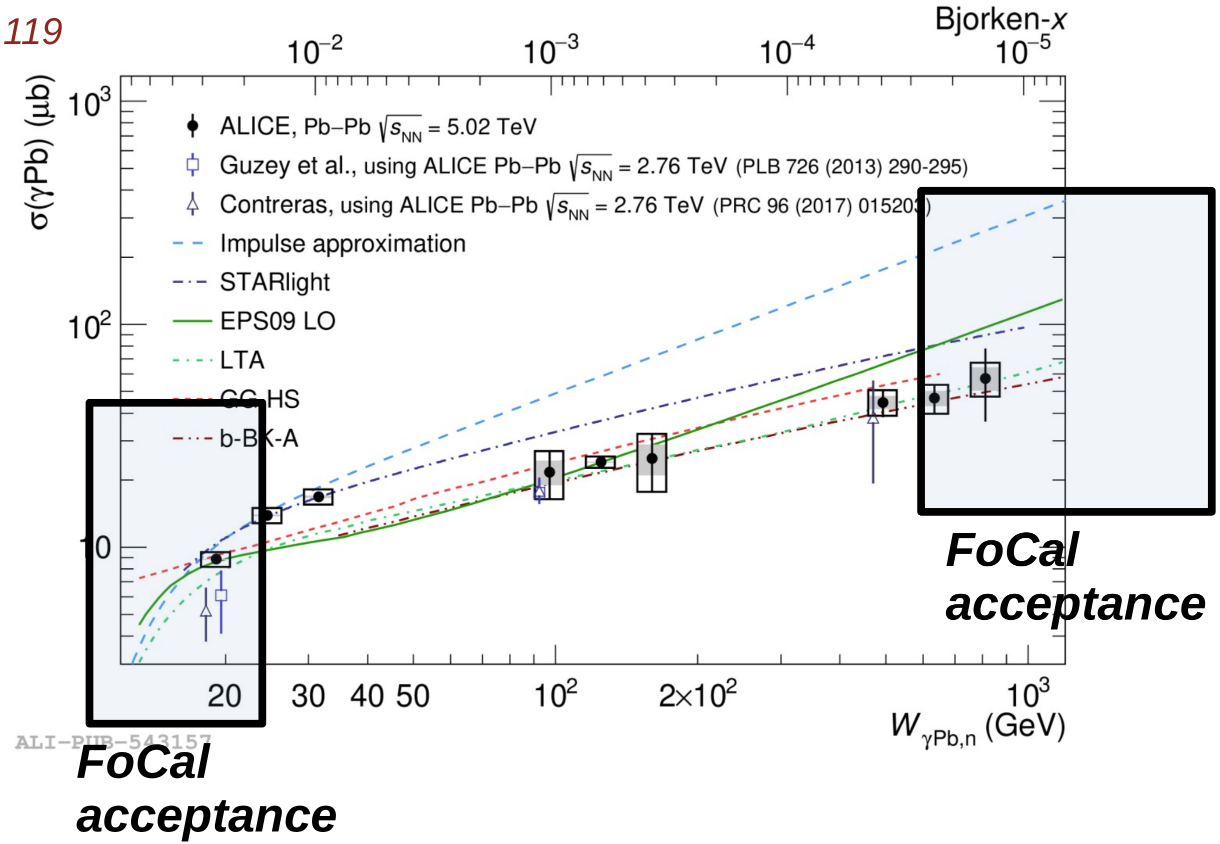
ALICE, JHEP 10 (2023) 119



- Emitter-target ambiguity solved using measurements in ZDC neutron emission classes

Photo-nuclear cross-section σ(γ+Pb)

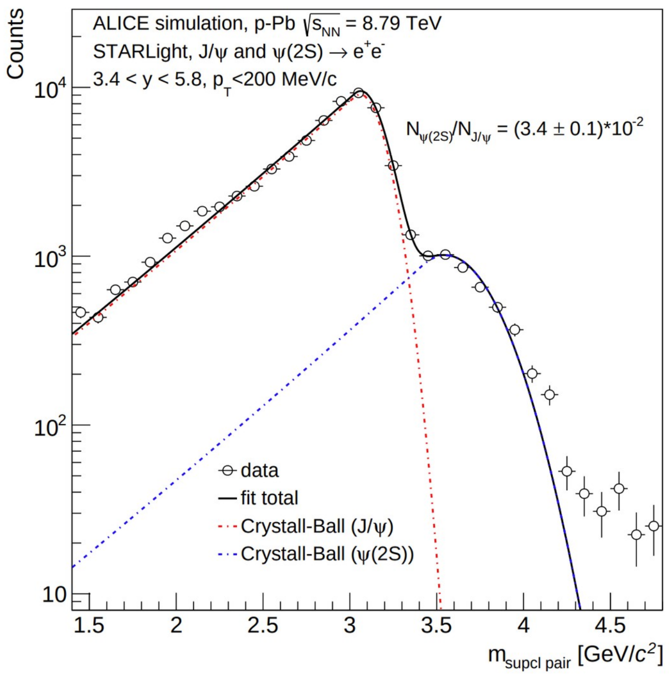
ALICE, JHEP 10 (2023) 119

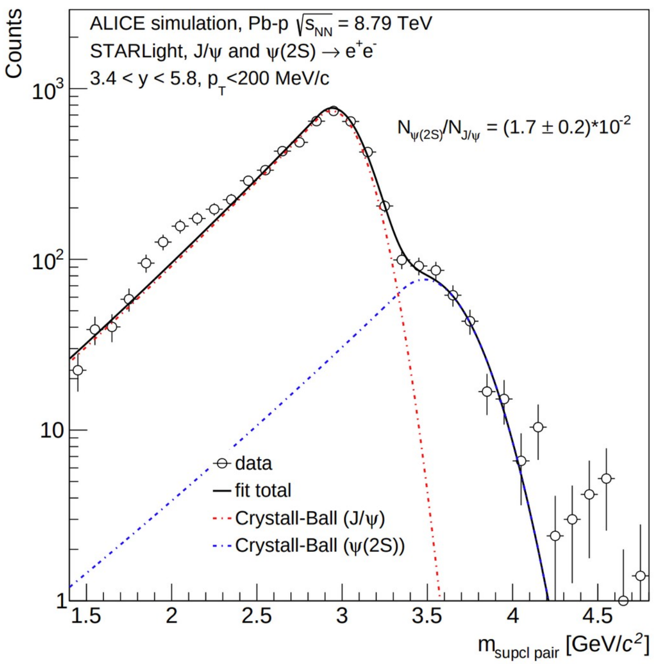


- Combined FoCal + ZDC analysis
  - coverage in W_{pPb} to be extended both towards low and high values

J/ψ and ψ’ reconstruction in p-Pb and Pb-p

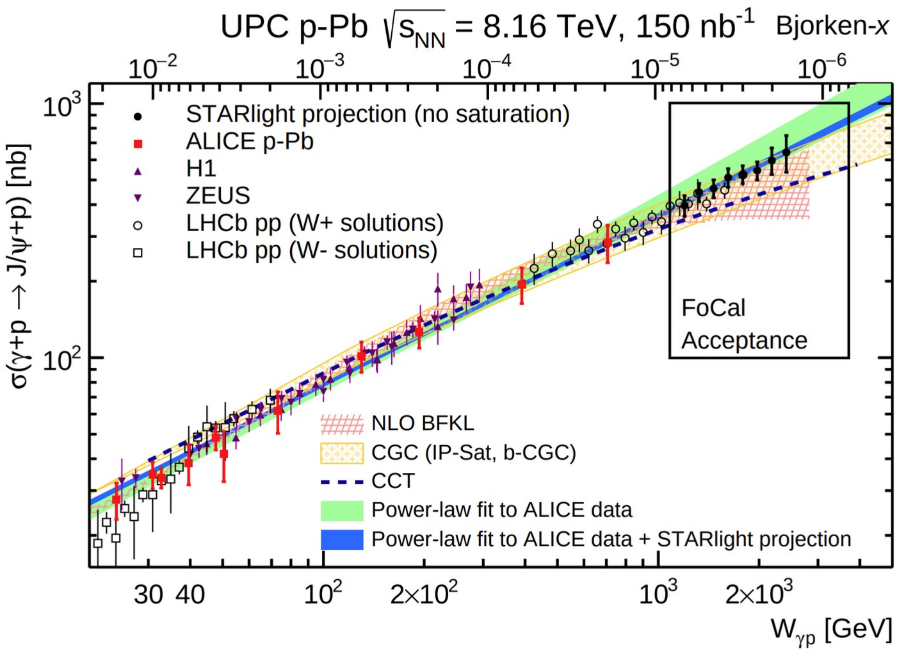
p-Pb (low-$W_{\gamma p}$) | Pb-p (high-$W_{\gamma p}$)

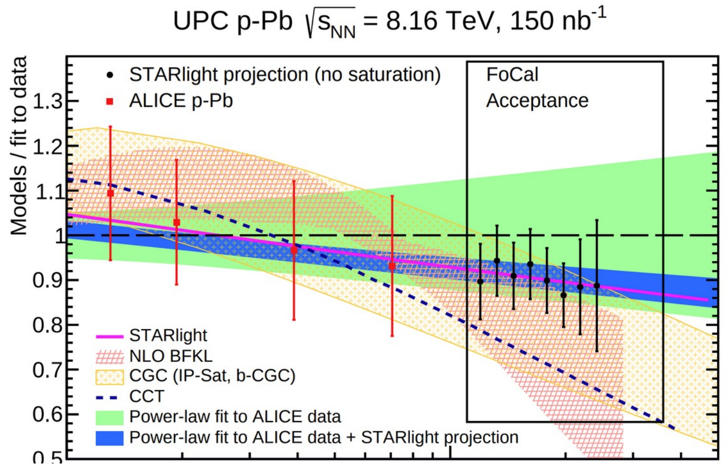


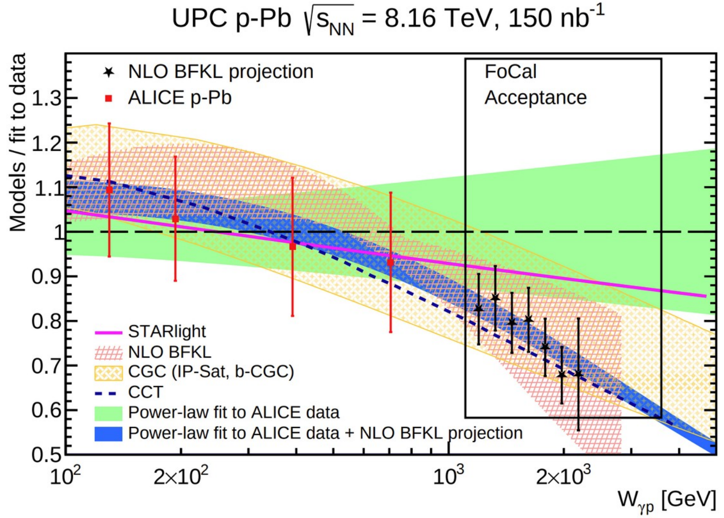


- Simulation studies done with realistic expectations of quarkonia yields
- ψ(2S)/J/ψ ratio expected to be measured with about **3%** and **12%** statistical uncertainty in **p-Pb (low-*W*)** and **Pb-p (high-*W*)**, respectively

Photoproduction off protons σ(γ+p) at high-W



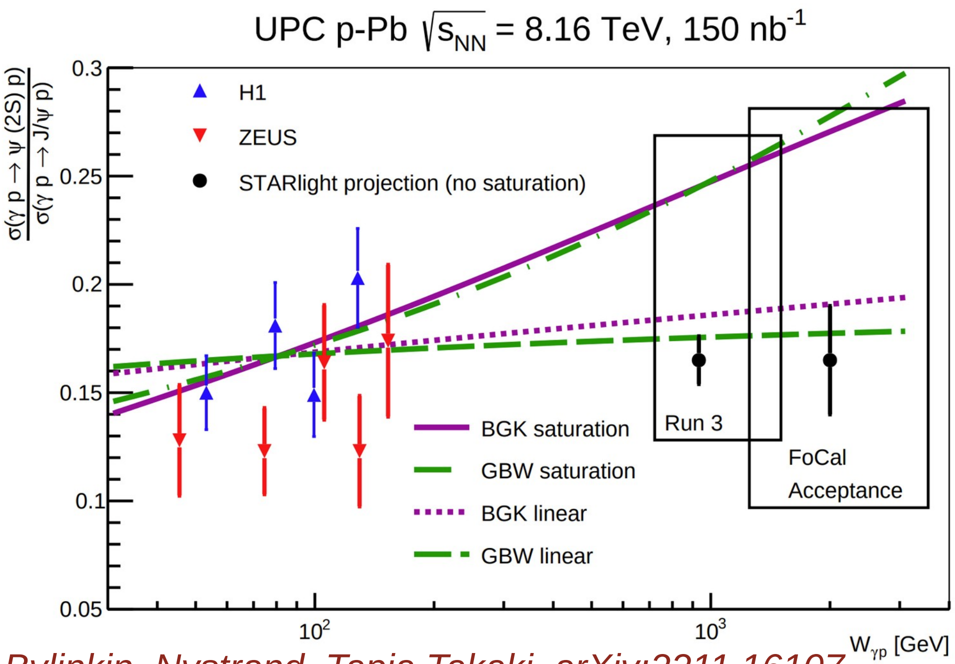




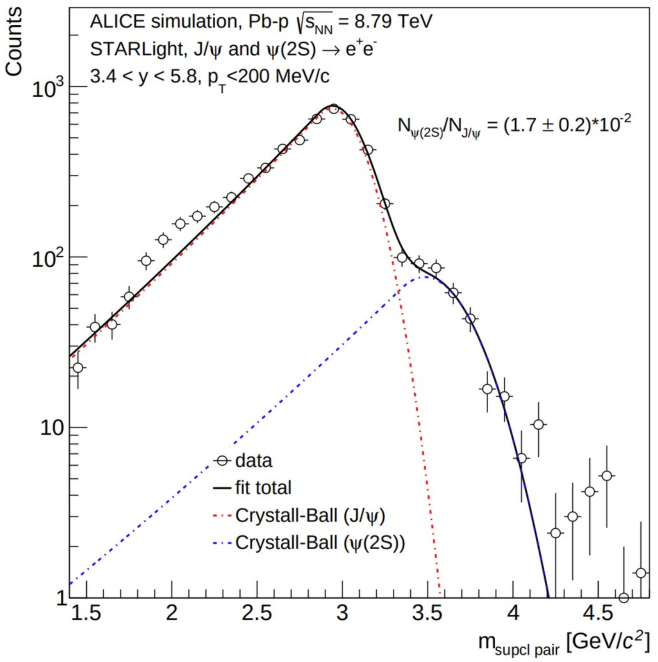
- FoCal extends coverage in $W_{\gamma p}$ up to about 2 TeV
- Large lever arm for discriminating linear vs saturation scenarios

Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107

Energy dependence of the ψ(2S)/J/ψ ratio



Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107

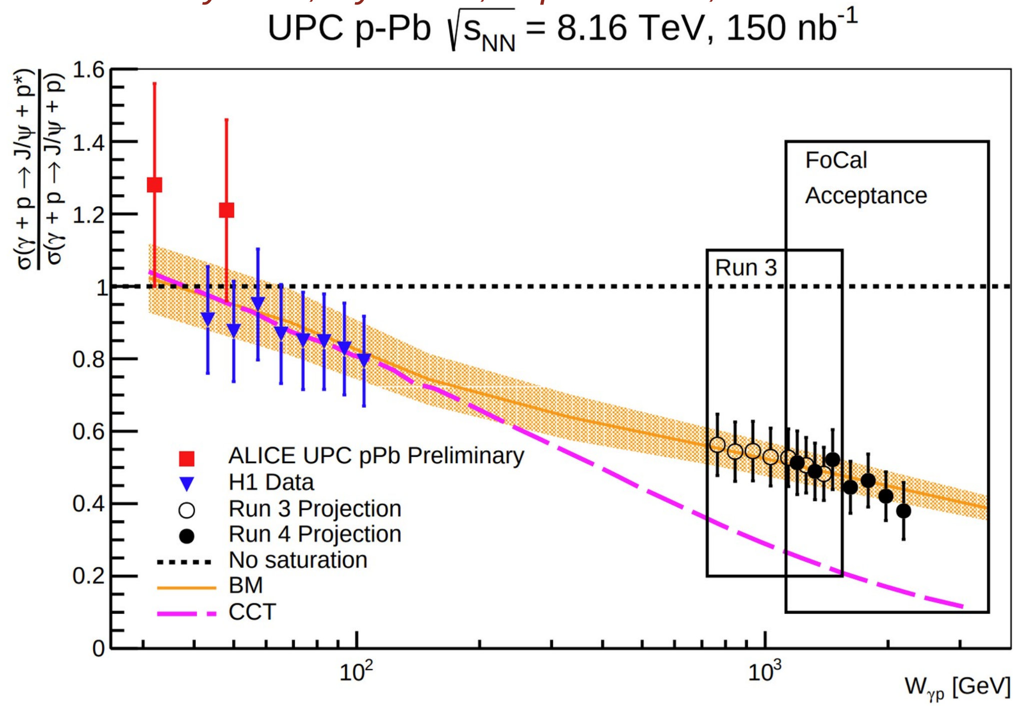


Ratio has a good discrimination power between linear vs saturation models in the range of very high-$W_{\gamma p}$

Limitation due to the expected low ψ(2S) yields (~12% stat.uncert.)

Dissociative to exclusive J/ψ photoproduction ratio

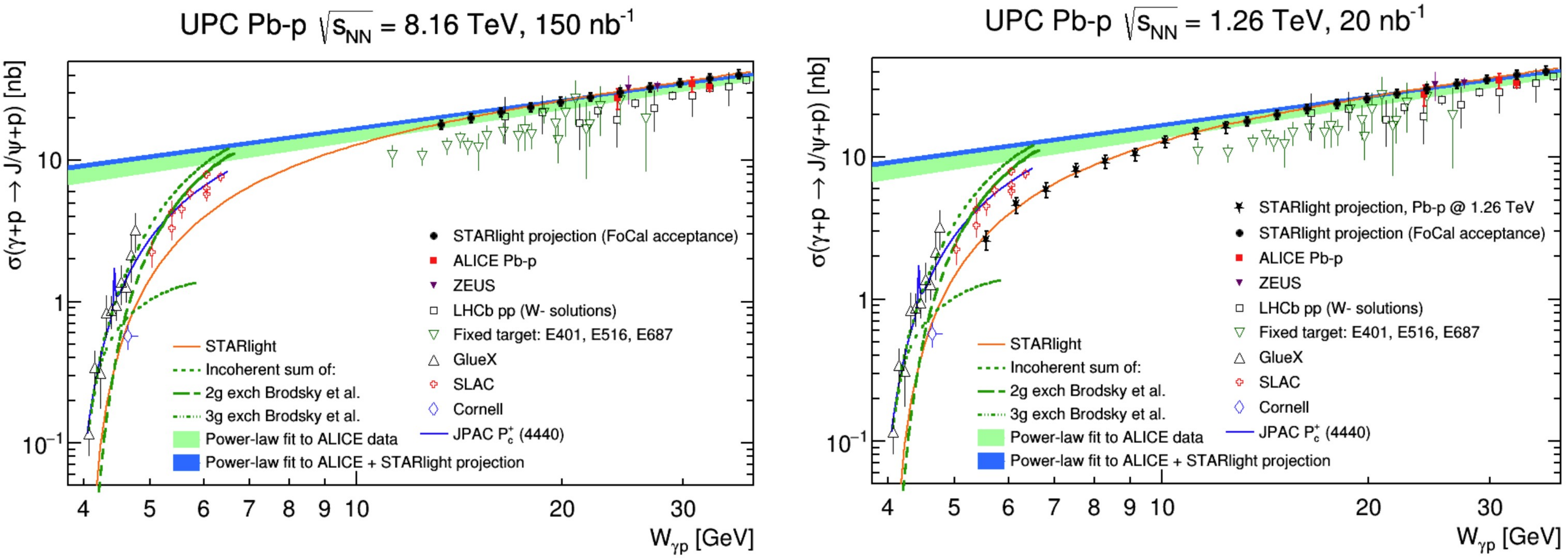
Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107



- Probe of the fluctuations in the proton target configurations
- Reduction of the dissociative/exclusive ratio towards high c.m. provides a signature of gluon saturation

Production off proton in Pb-p at low-$W_{\gamma p}$

Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107



- Coverage down to $W_{\gamma p}$~12 GeV with Pb-p at 8.16 TeV, overlap with E401 data
- With an eventual run at 1.26 TeV, measurements could fill the gap between low energy data points and LHC experiments

Summary

- FoCal is a planned ALICE upgrade for the LHC Run-4 covering forward rapidities
- Main goal: explore gluon content at low-x using multiple measurements
- Hadronic collisions
  - Isolated direct photons
  - Jets
  - Mesons, quarkonia, weak bosons
  - Correlations
- Main probes studied so far in UPC (Pb-Pb, p-Pb, Pb-p)
  - Coherent and incoherent J/ψ and ψ(2S)
  - Combined FoCal with ZDC and other ALICE detectors to tag neutron emission and dissociative production off protons

Backup