U.S. DEPARTMENT OF ENERGY

Office of Science

Ultra-peripheral heavy-ion collisions at the LHC selected results

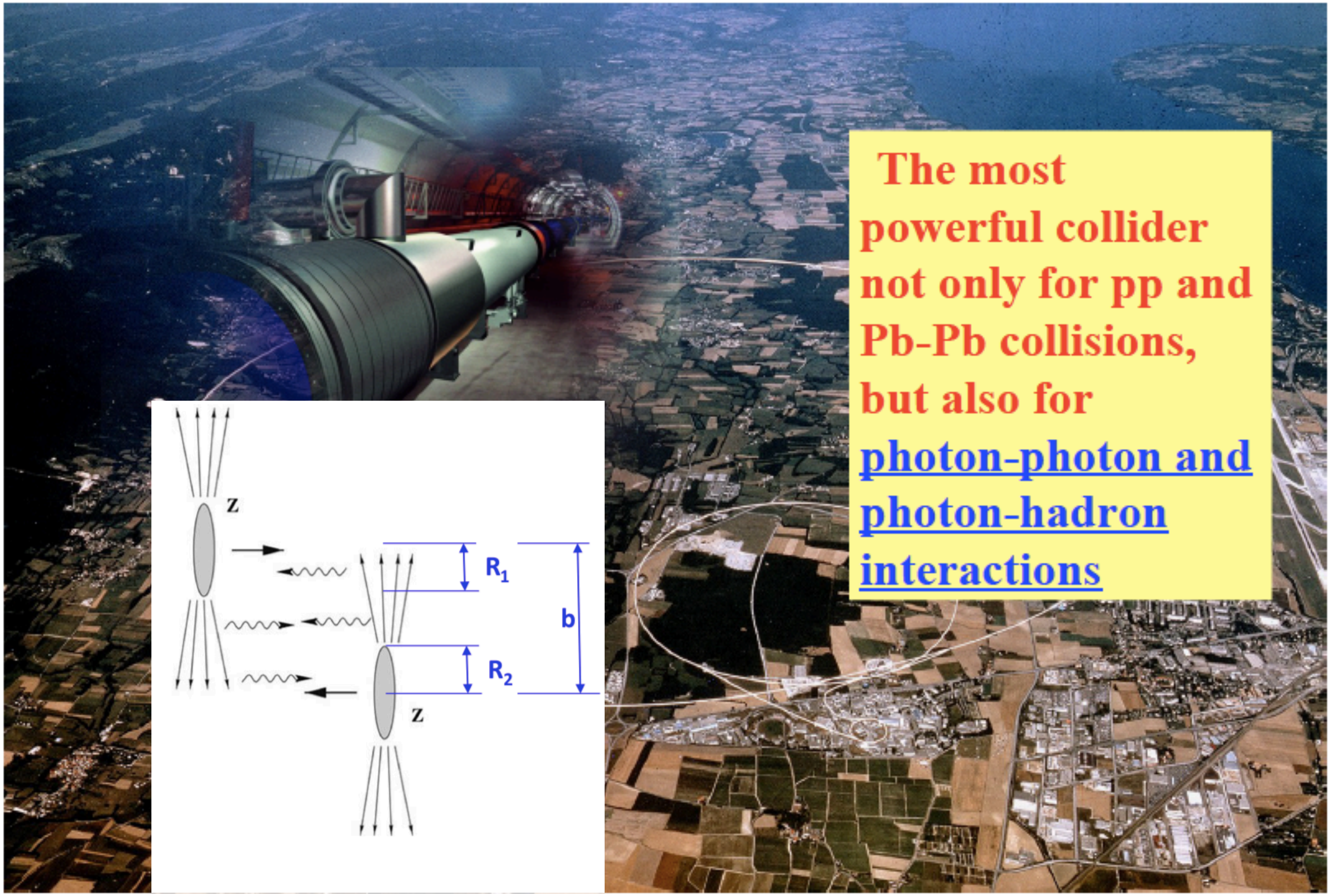
Daniel Tapia Takaki

University of Kansas

37th Winter Workshop on Nuclear Dynamics

Puerto Vallarta, Mexico - March 3, 2020

Photon-photon, photon-p, photon-A collider

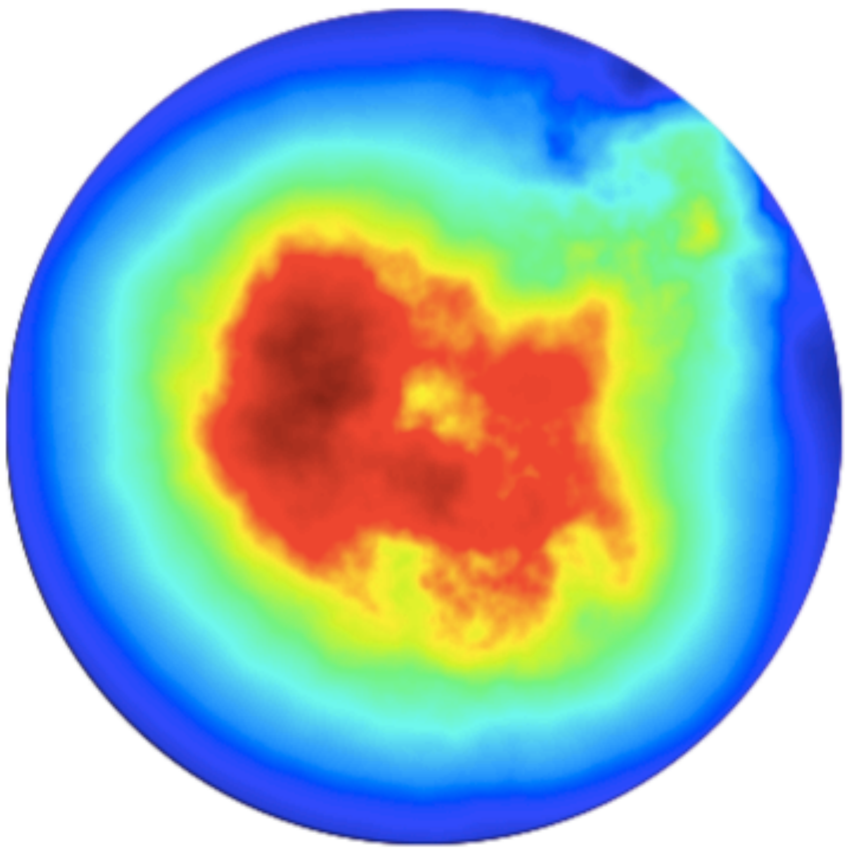


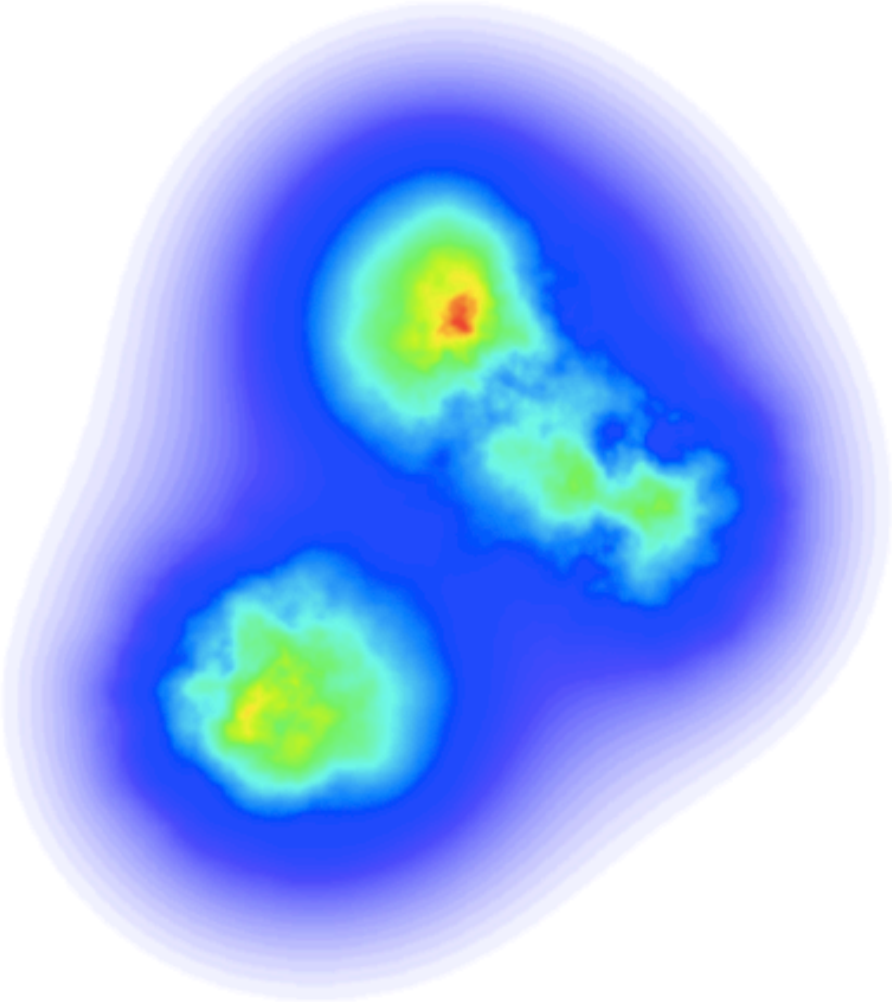
Energy systems

Facility	System	$\sqrt{s_{NN}}$ or $\sqrt{s_{eN}}$	Max. E_γ	Max. $W_{\gamma p}$	Max $\sqrt{s_{\gamma\gamma}}$
RHIC	AuAu	200 GeV	320 GeV	25 GeV	6 GeV
	pAu	200 GeV	1.5 TeV	52 GeV	30 GeV
	pp	500 GeV	20 TeV	200 GeV	150 GeV
LHC (17)	PbPb	5.1 TeV	250 TeV	700 GeV	170 GeV
	pPb	8.16 TeV	1.1 PeV	1.5 TeV	840 GeV
	pp	14 TeV	16 PeV	5.4 TeV	4.2 TeV
FCC-hh (18)	PbPb	40 TeV	13 PeV	4.9 TeV	1.2 TeV
SPPC (7)	pPb	57 TeV	58 PeV	10 TeV	6.0 TeV
	pp	100 TeV	800 PeV	39 TeV	30 TeV
eRHIC (19)	eAu	89 GeV	4.0 TeV	89 GeV	15 GeV
LHeC (20)	ePb	820 GeV	360 TeV	820 GeV	146 GeV

Review by S. Klein

What does the proton look like?





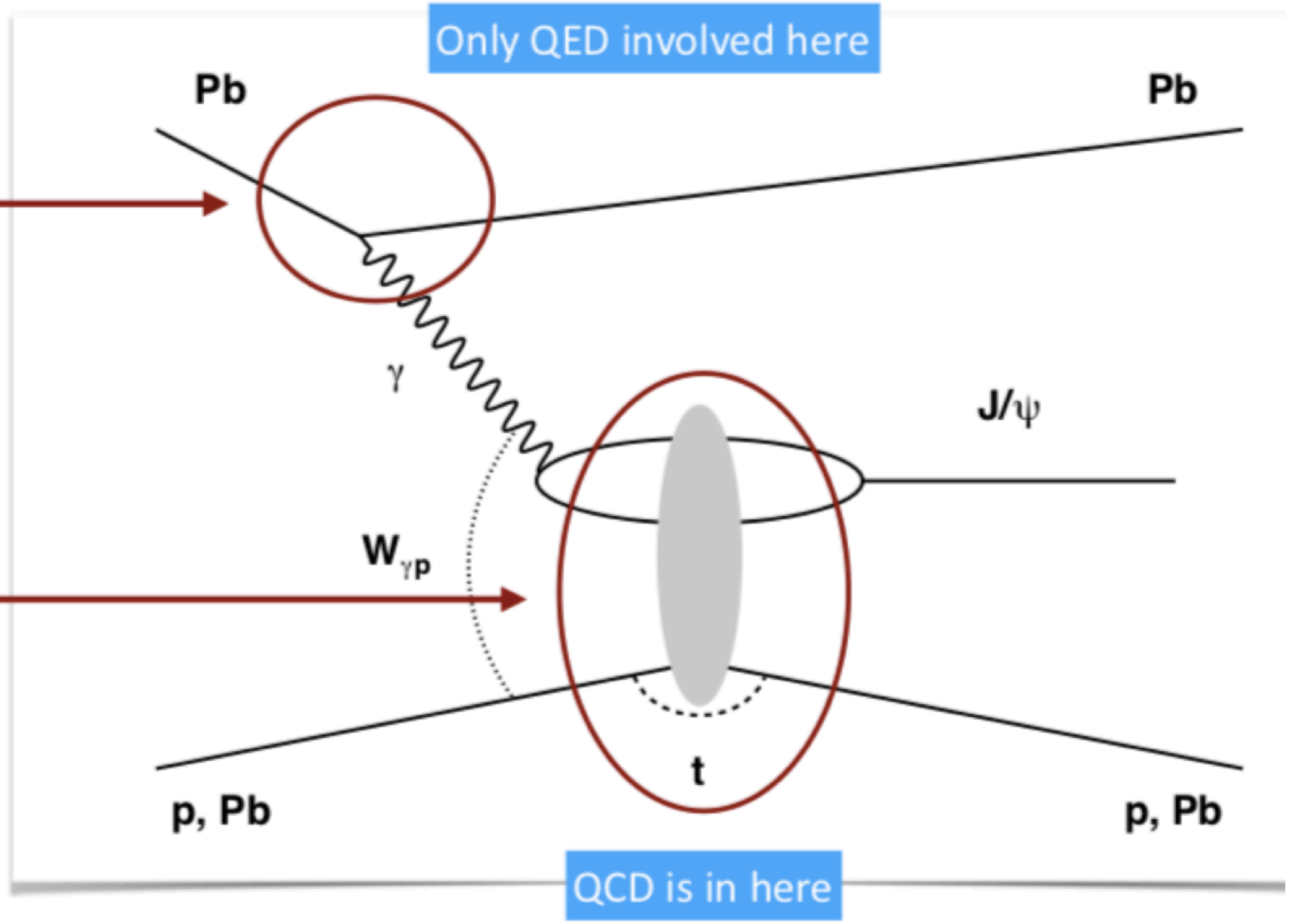
Nuclear gluon dynamics, saturation …

and the Pb?

UPC VM photoproduction

The process can be factorised in two parts:

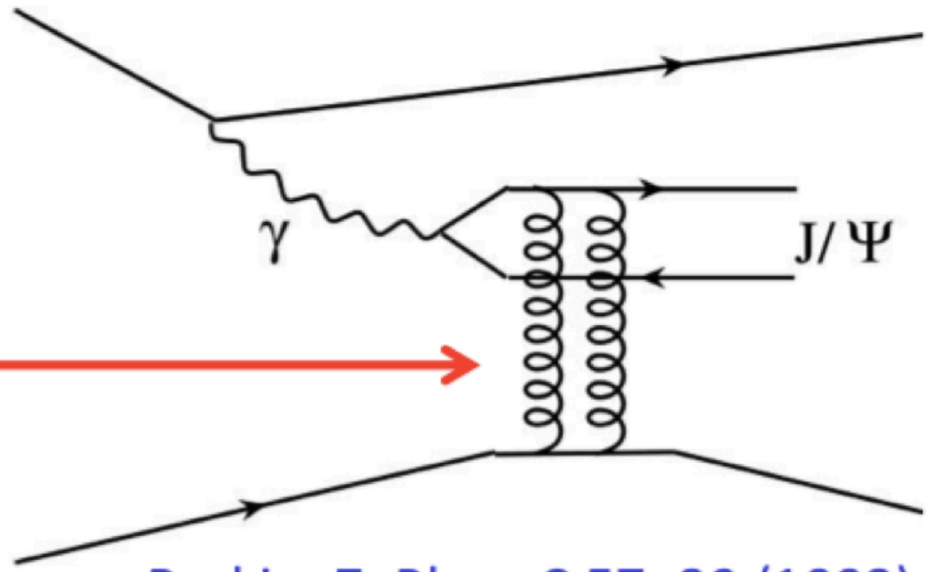
- Emission of the photon.
- Interaction of the photon with the target.



Exclusive VM photoproduction

- LO pQCD: exclusive J/ψ photoproduction cross section is proportional to the **square of the gluon density in the target**:

$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$



Ryskin: Z. Phys. C 57, 89 (1993)

- J/ψ mass serves as a hard scale:

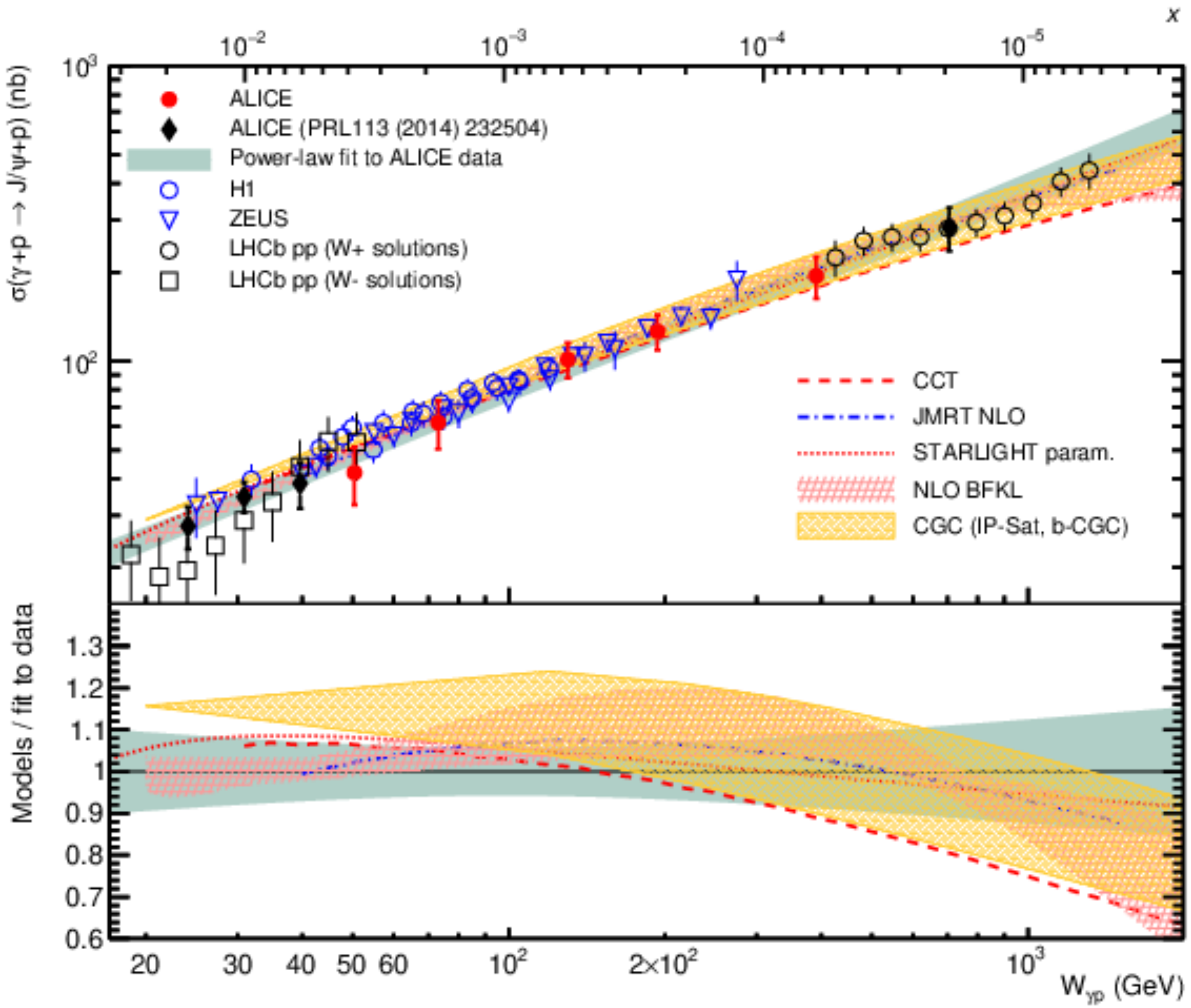
$$Q^2 \sim \frac{M^2_{J/\psi}}{4} \sim 2.5\ \mathrm{GeV}^2$$

- Bjorken x ~ $10^{-2} – 10^{-5}$ accessible at LHC:

$$x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}} = \frac{M_{J/\psi}}{2E_p}\exp(\pm y)$$

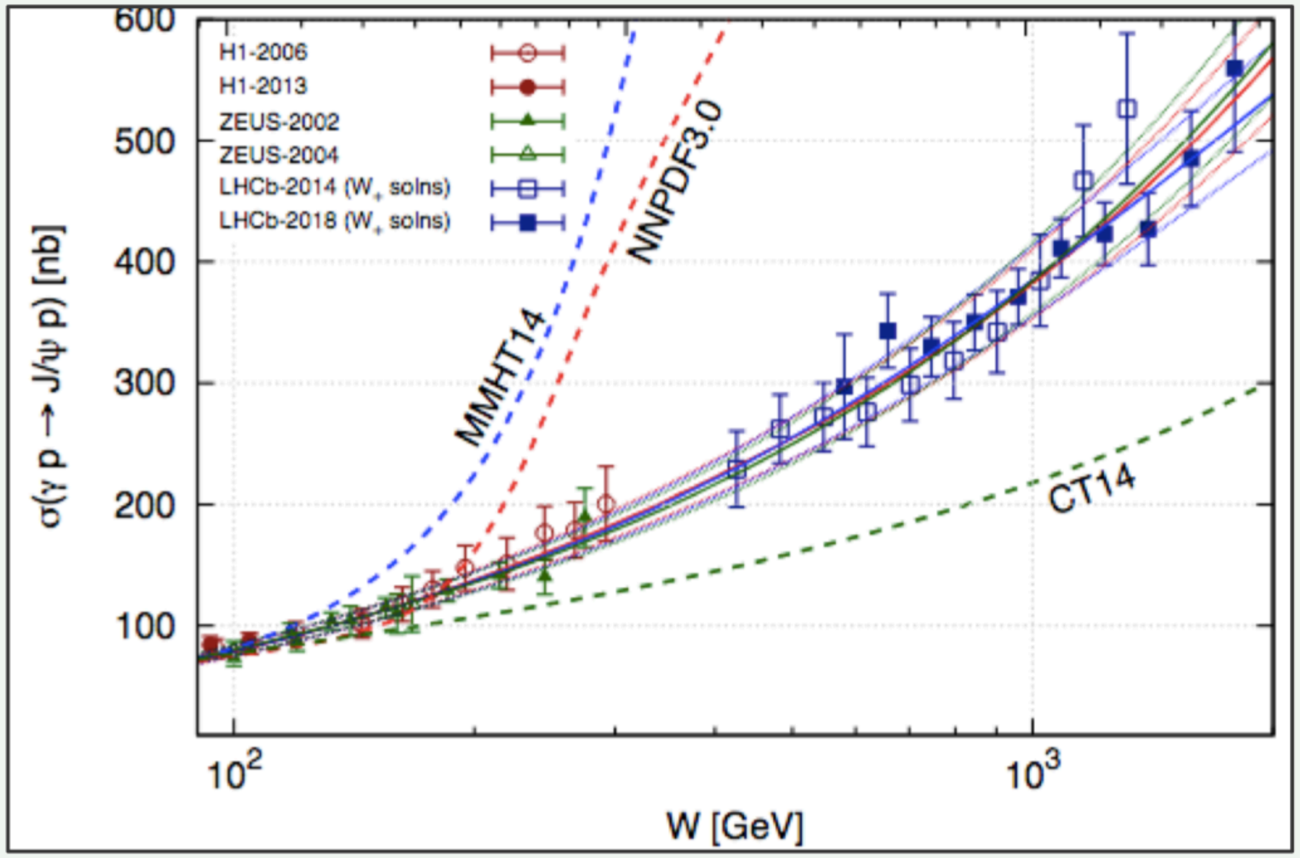
Recent Run 2 results

Eur. Phys. J. C 79 (2019) 5, 402

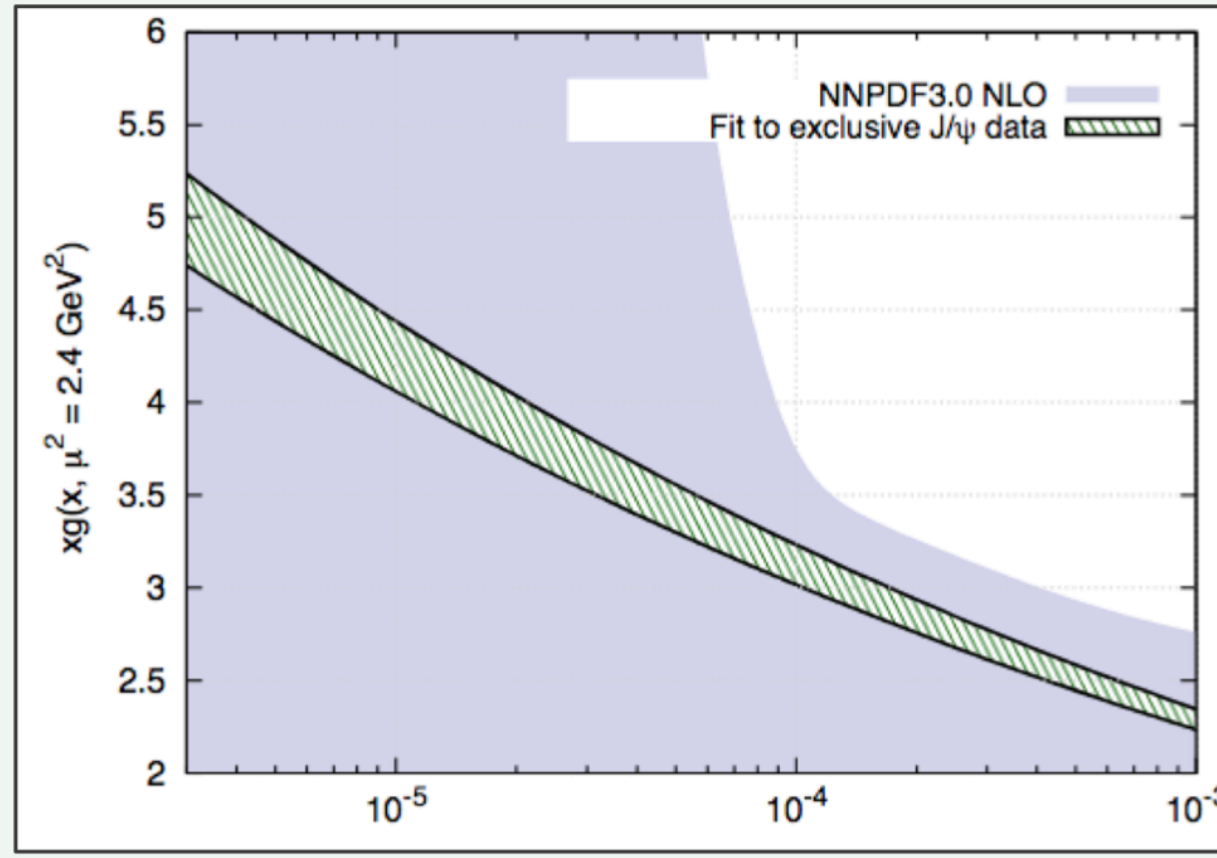


Gluon parton density

Central values of three global PDF fitting groups



Improvement in the gluon PDF with J/ψ data

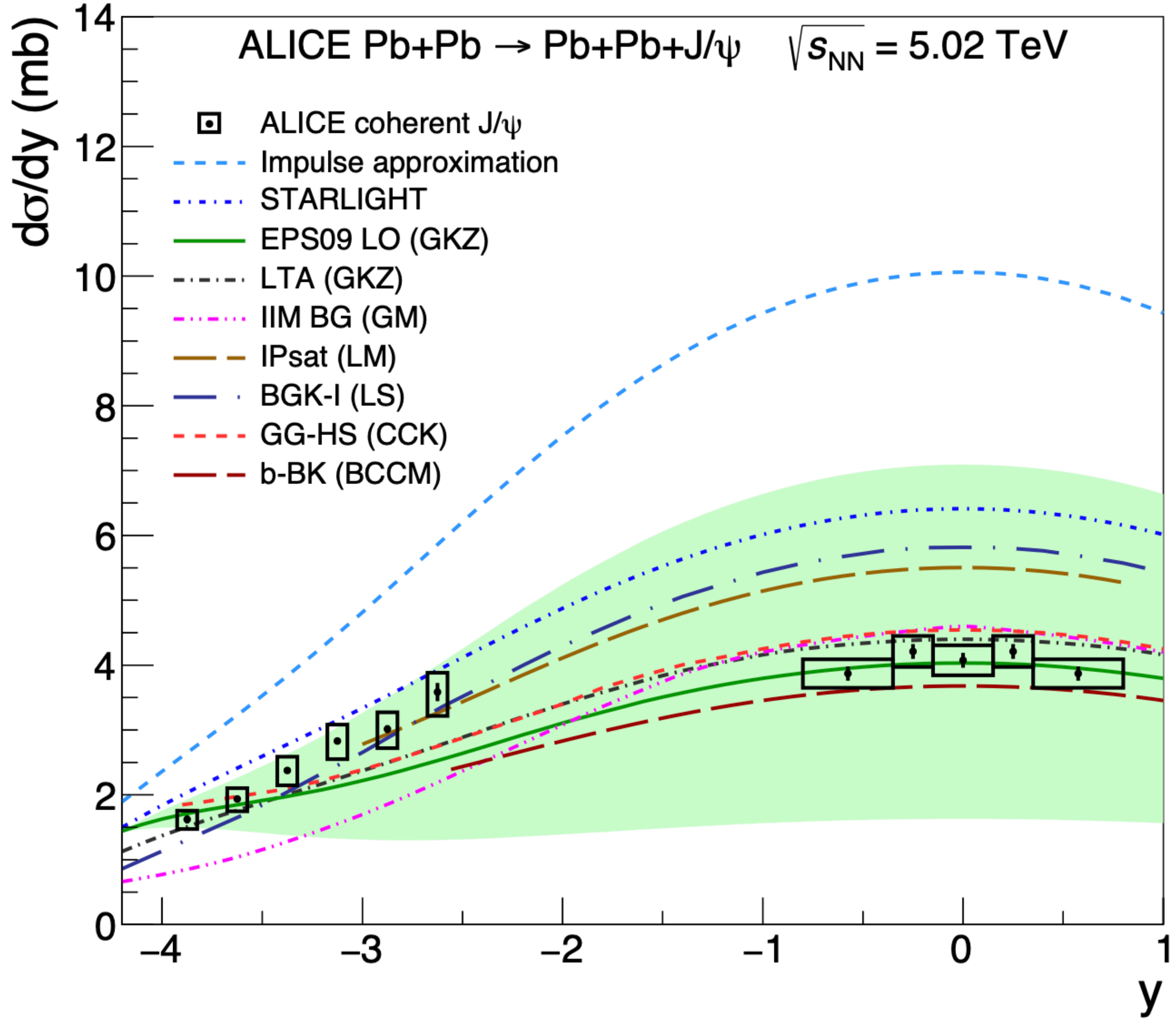


C. Flett et al., Phys.Rev.D 102 (2020) 114021

R. McNulty

Recent Run 2 results

Eur. Phys. J. C 81 (2021) 8, 712



UPC VM in photon-A

V. Guzey et al. PLB 726 (2013)

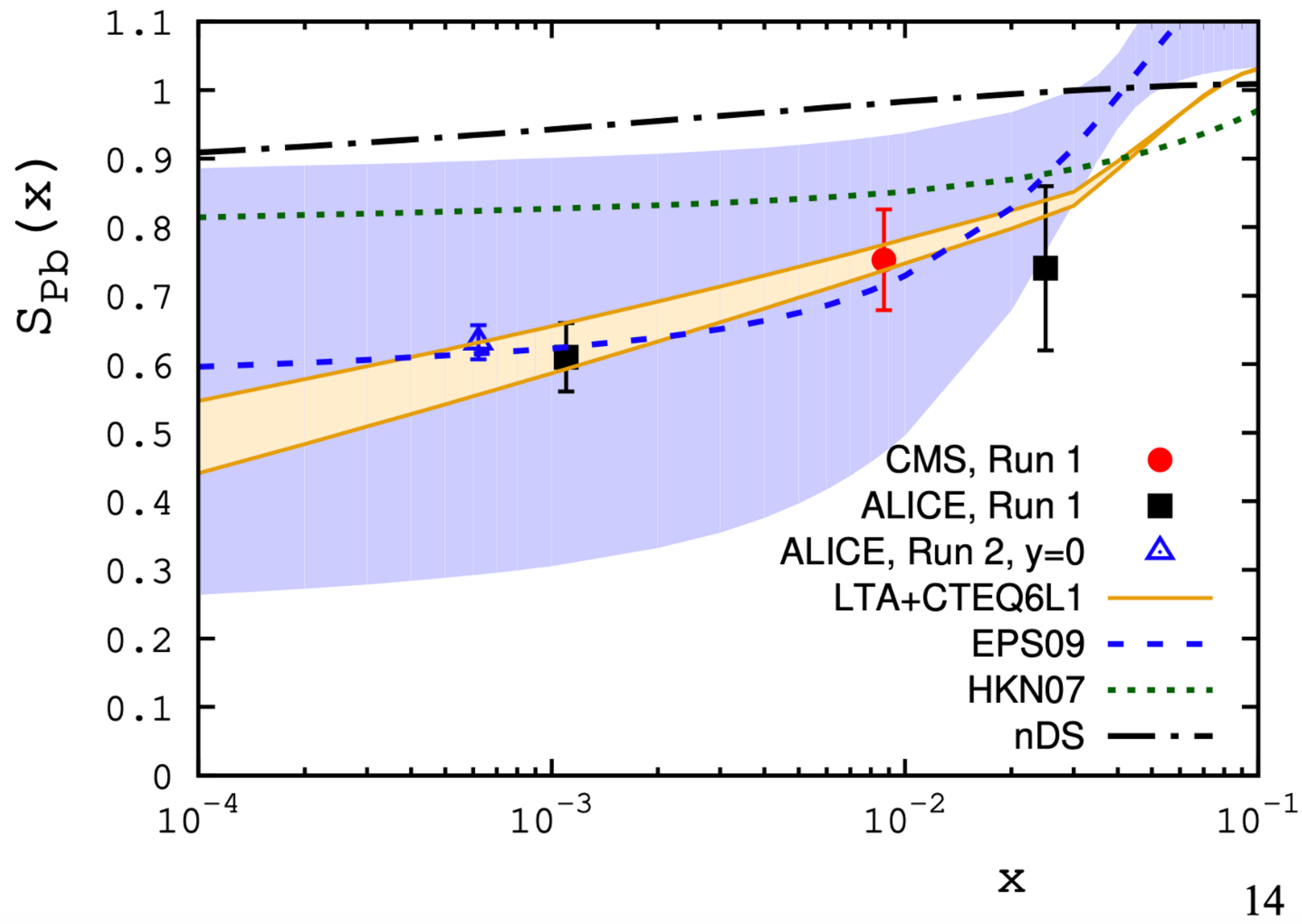
- The nuclear suppression factor

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

Nuclear suppression factor

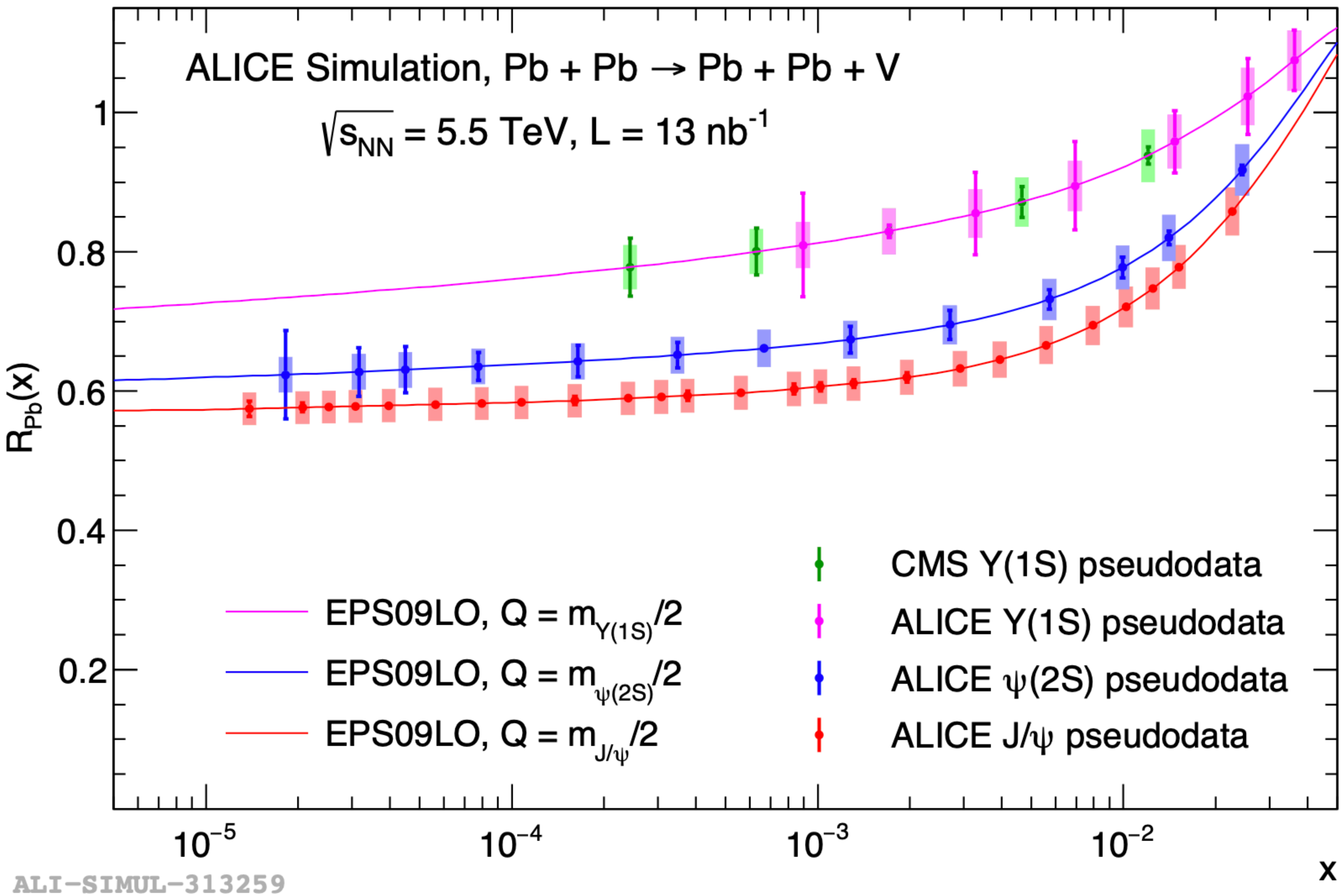
Updated with new Run 2 data

V. Guzey's nuclear fragmentation 2022



Nuclear Suppression factor at LHC
vector mesons

Projections for Run 3+4



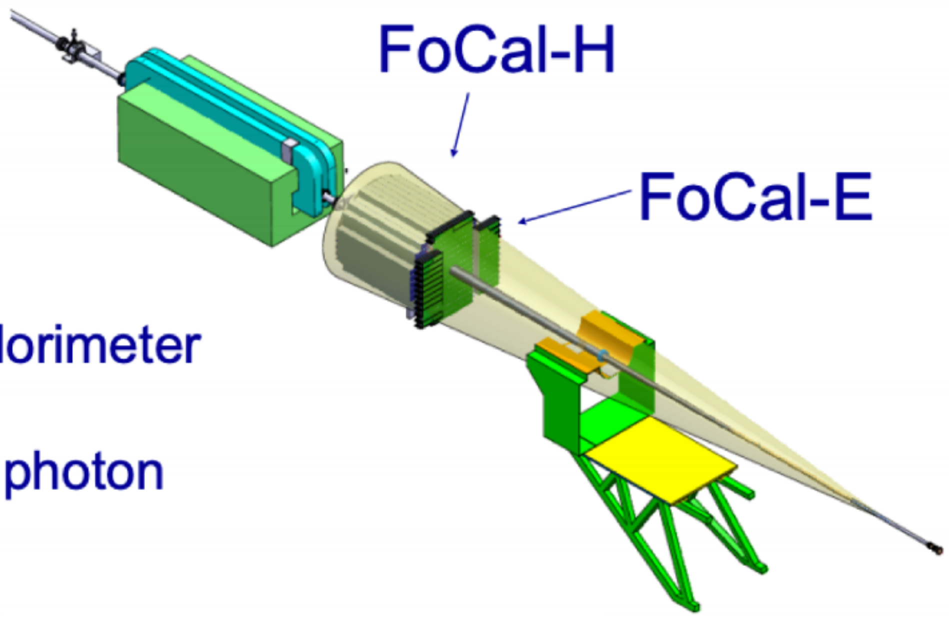
Nuclear Suppression factor at LHC
vector mesons

Projections for Run 3+4

PbPb						
Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$Y(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

pPb - lead shine, γp								
Meson	σ	All Total	Ctl. 1 Total	Ctl. 2 Total	FW 1 Total	FW 2 Toal	BW 1 Total	BW 2 Total
$\rho \to \pi^+\pi^-$	35 mb	70 B	3.9 B	15 B	2.0 B	5.5 B	850 M	2.0 B
$\phi \to K^+K^-$	870 μb	1.7 B	65 M	290 M	22 M	120 M	9.7 M	52 M
$J/\psi \to \mu^+\mu^-$	6.2 μb	12 M	1.0 M	5.2 M	260 K	800 K	180 K	430 K
$\psi(2S) \to \mu^+\mu^-$	134 nb	270 K	22 K	110 K	6.0 K	18 K	3.2 K	7.7 K
$Y(1S) \to \mu^+\mu^-$	5.74 nb	11 K	1.1 K	5.4 K	310	880	41	100

FoCal detector at ALICE



$3.2 < \eta < 5.8$

FoCal-E: high-granularity Si-W calorimeter for photons and π^0

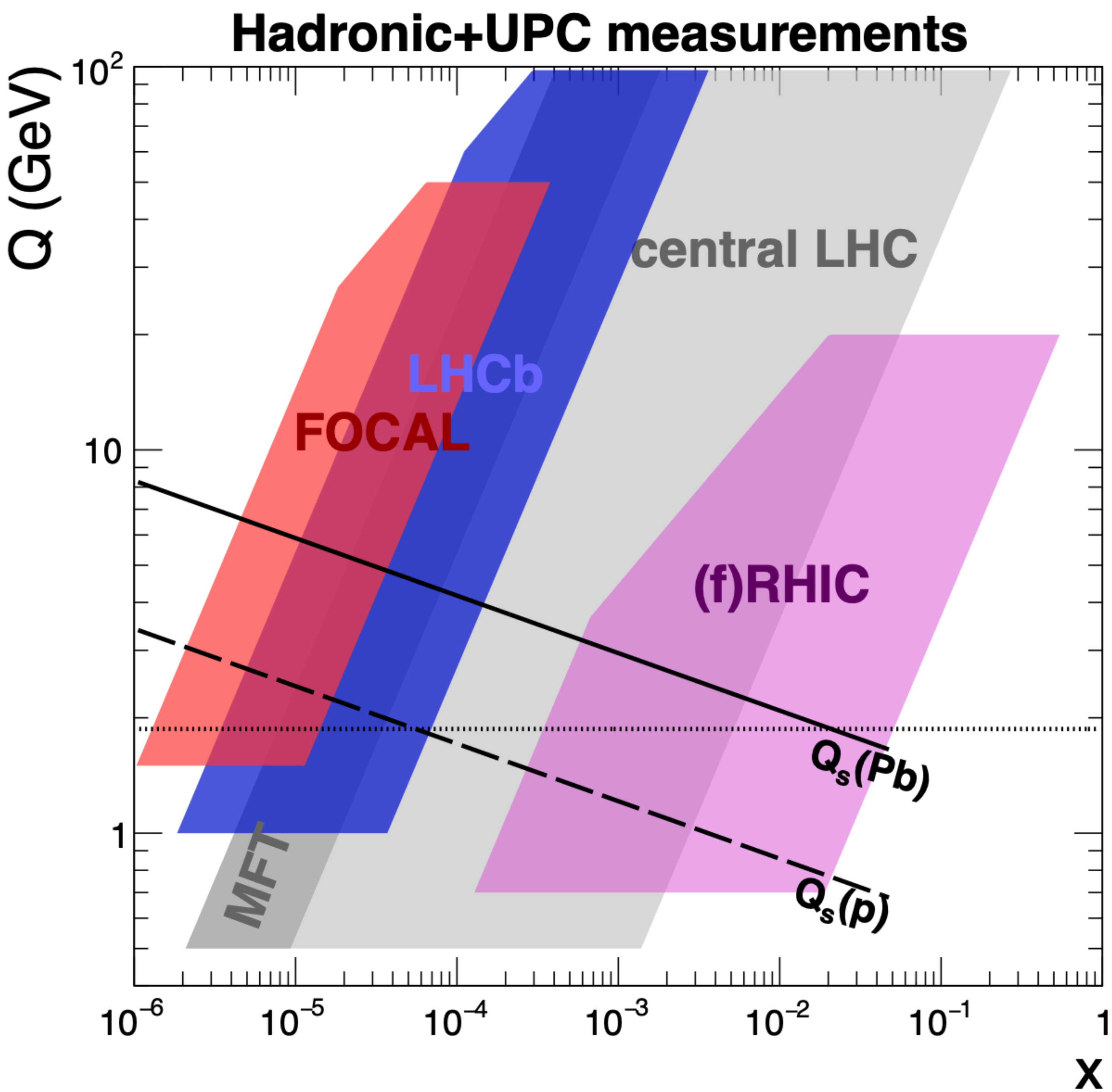
FoCal-H: hadronic calorimeter for photon isolation and jets

Observables:

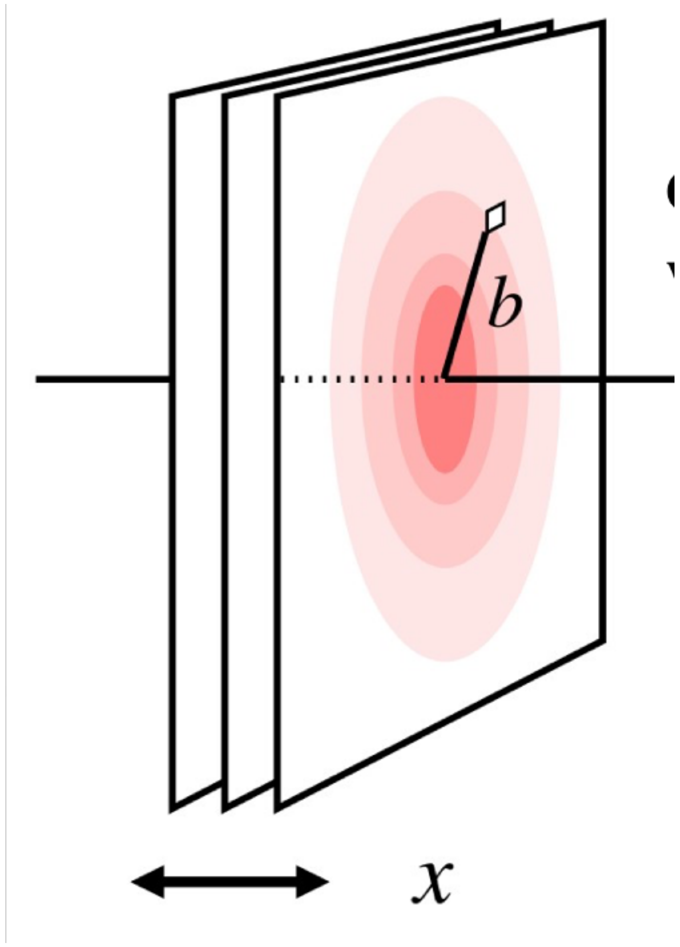
- π^0
- Direct (isolated) photons
- Jets

Advantage in ALICE:
forward region not instrumented;
'unobstructed' view of interaction point

FoCal kinematic coverage

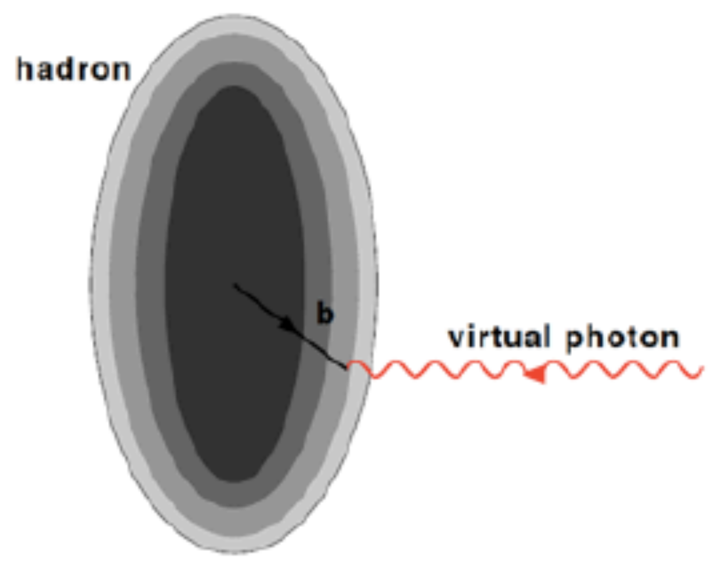


Transverse profile of the target



t-distribution

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



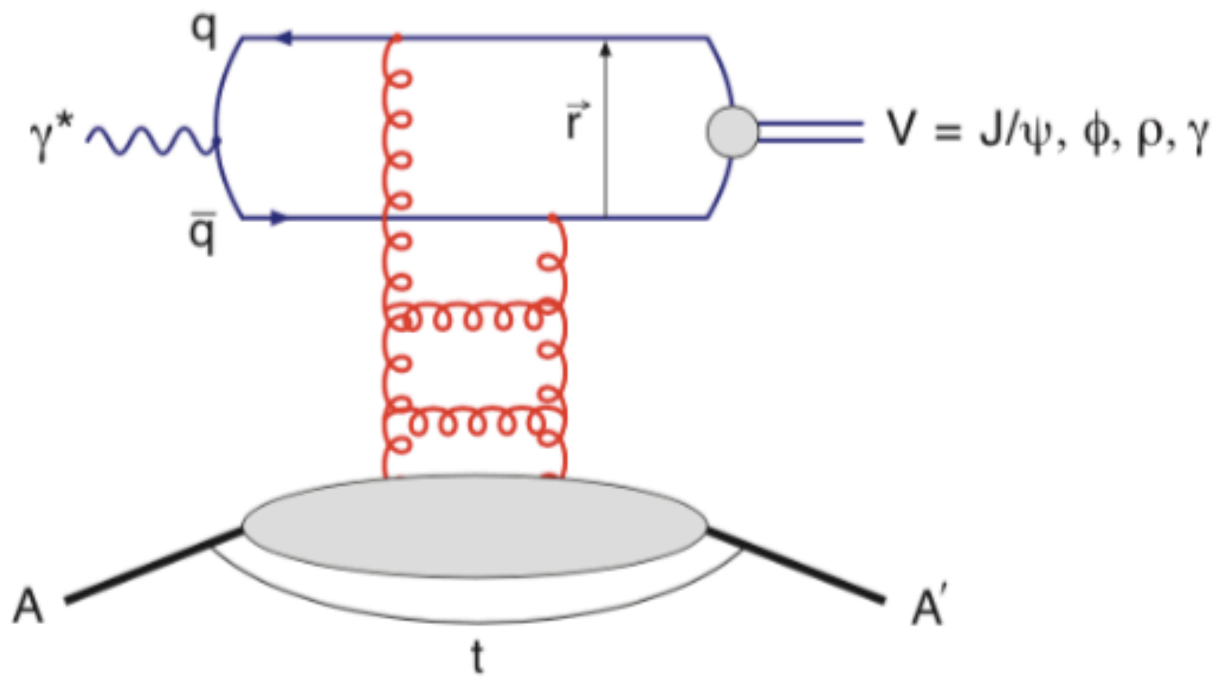
The study of the t-distribution

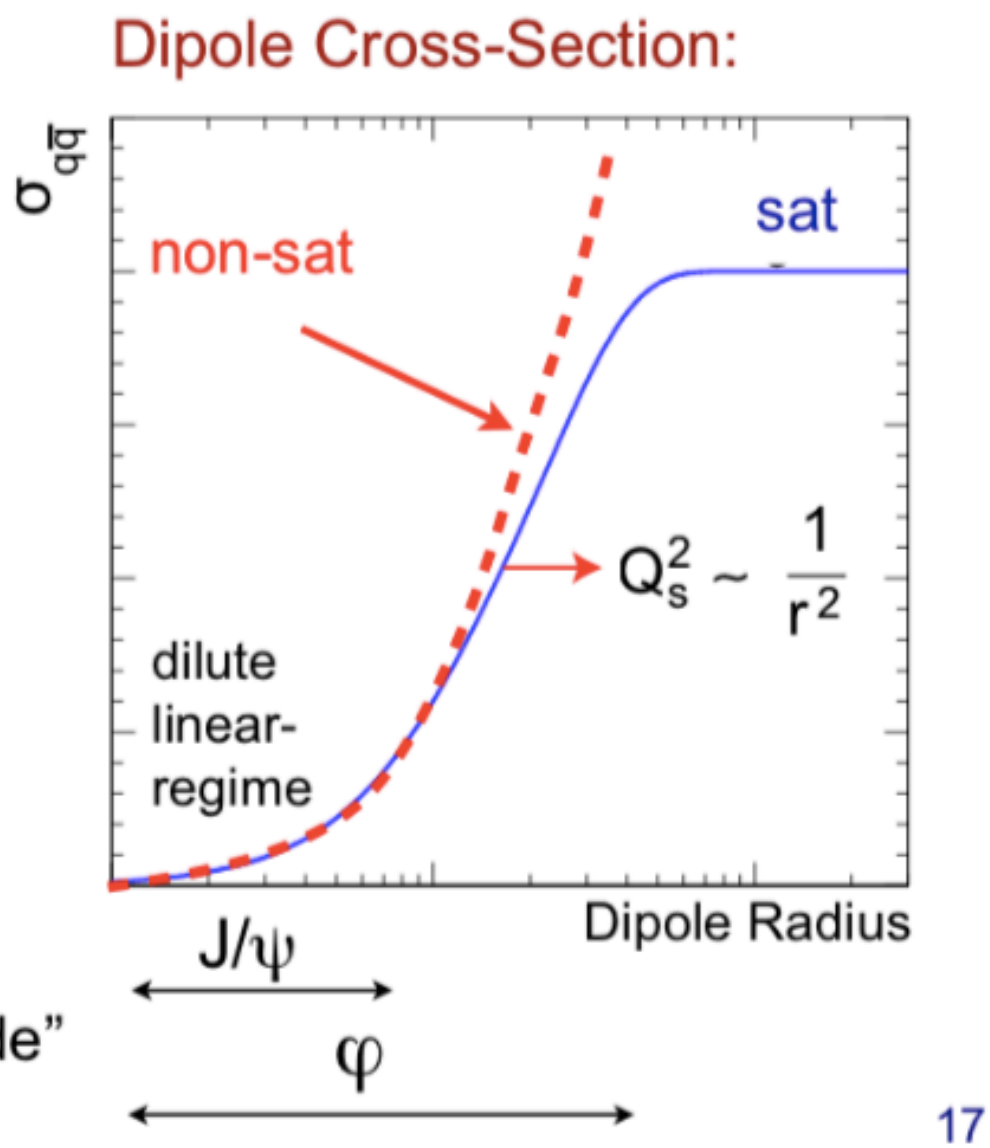
Appearance and location of diffractive dips: signature of gluon saturation

t-distribution

Here:

$$t = (\boldsymbol{p}_A - \boldsymbol{p}_{A'})^2 = (\boldsymbol{p}_{\rm VM} + \boldsymbol{p}_{e'} - \boldsymbol{p}_e)^2$$

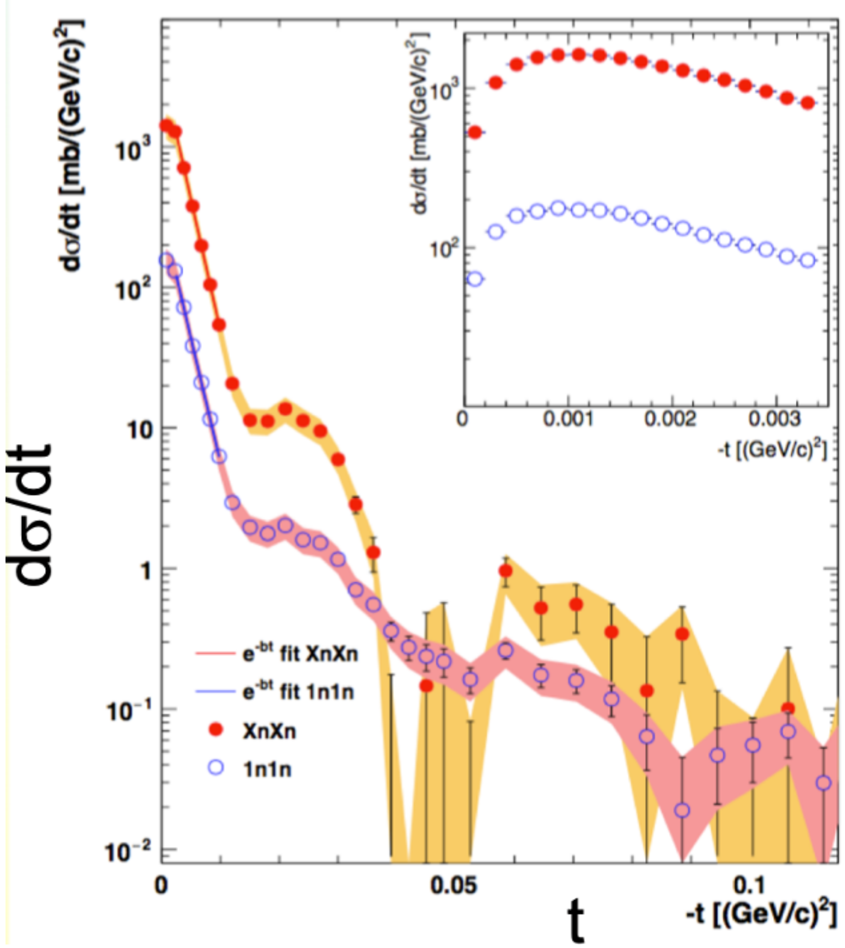




small size (J/Ψ): cuts off saturation region
large size (φ,ρ, ...): "sees more of dipole amplitude"
→ more sensitive to saturation

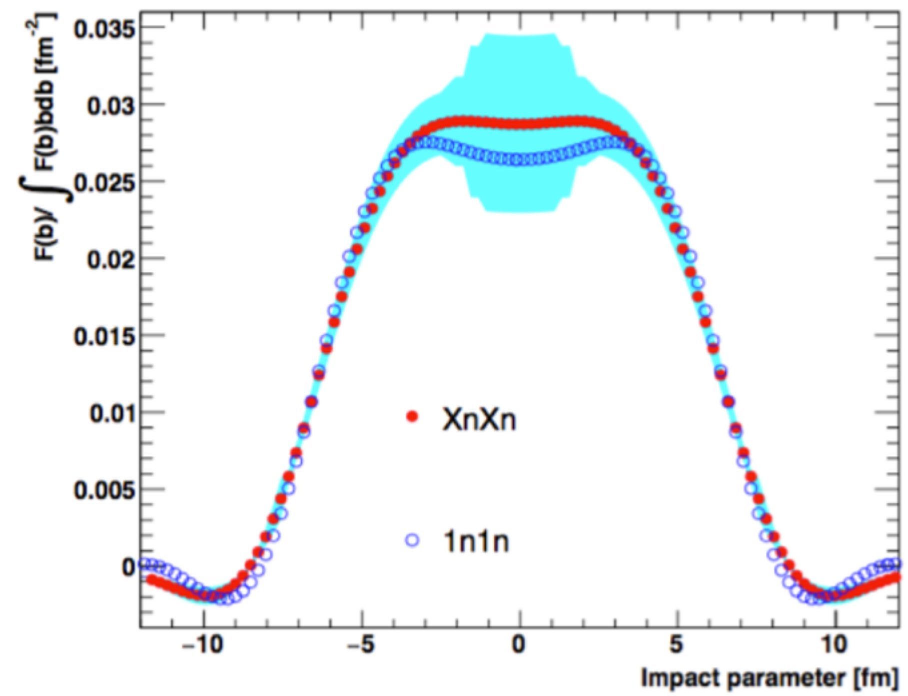
From T. Ullrich, IS 2017

Transverse profile of the target



STAR ρ^0

$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T p_T J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$

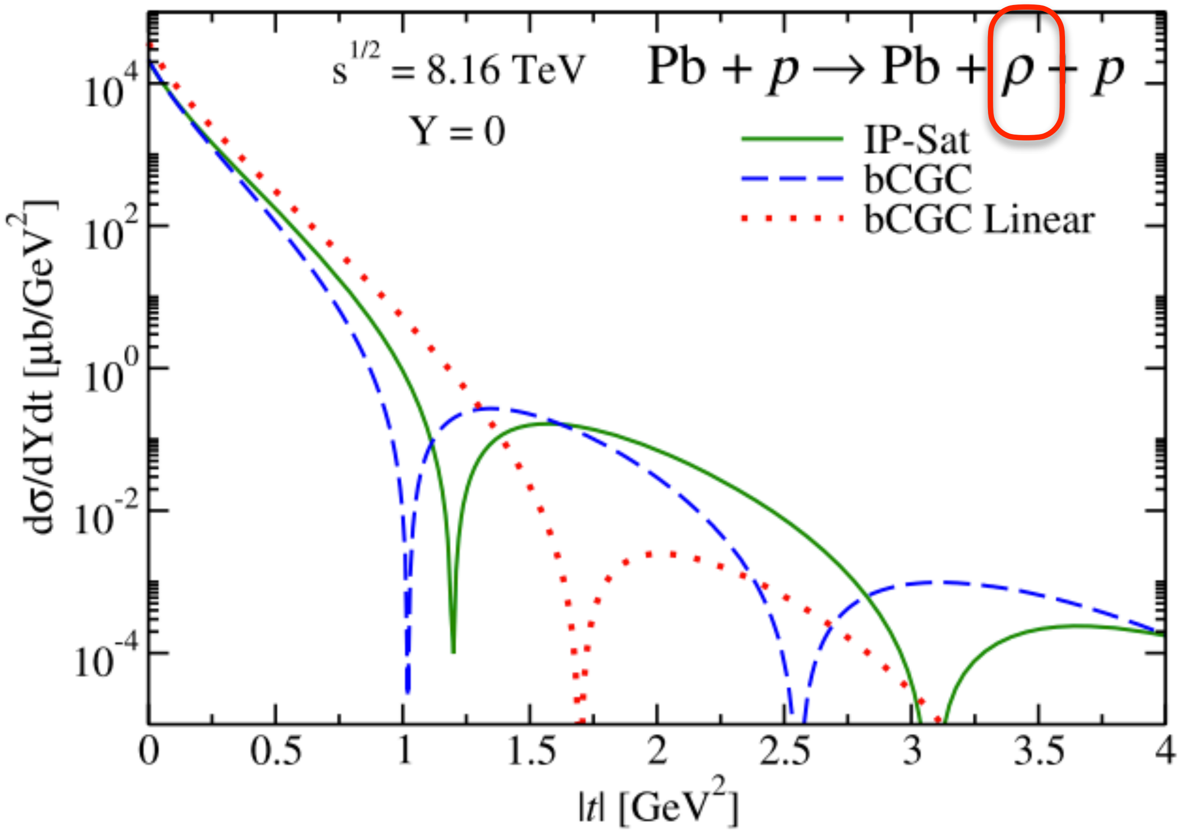


STAR, Phys. Rev. **C96**, 054904 (2017)

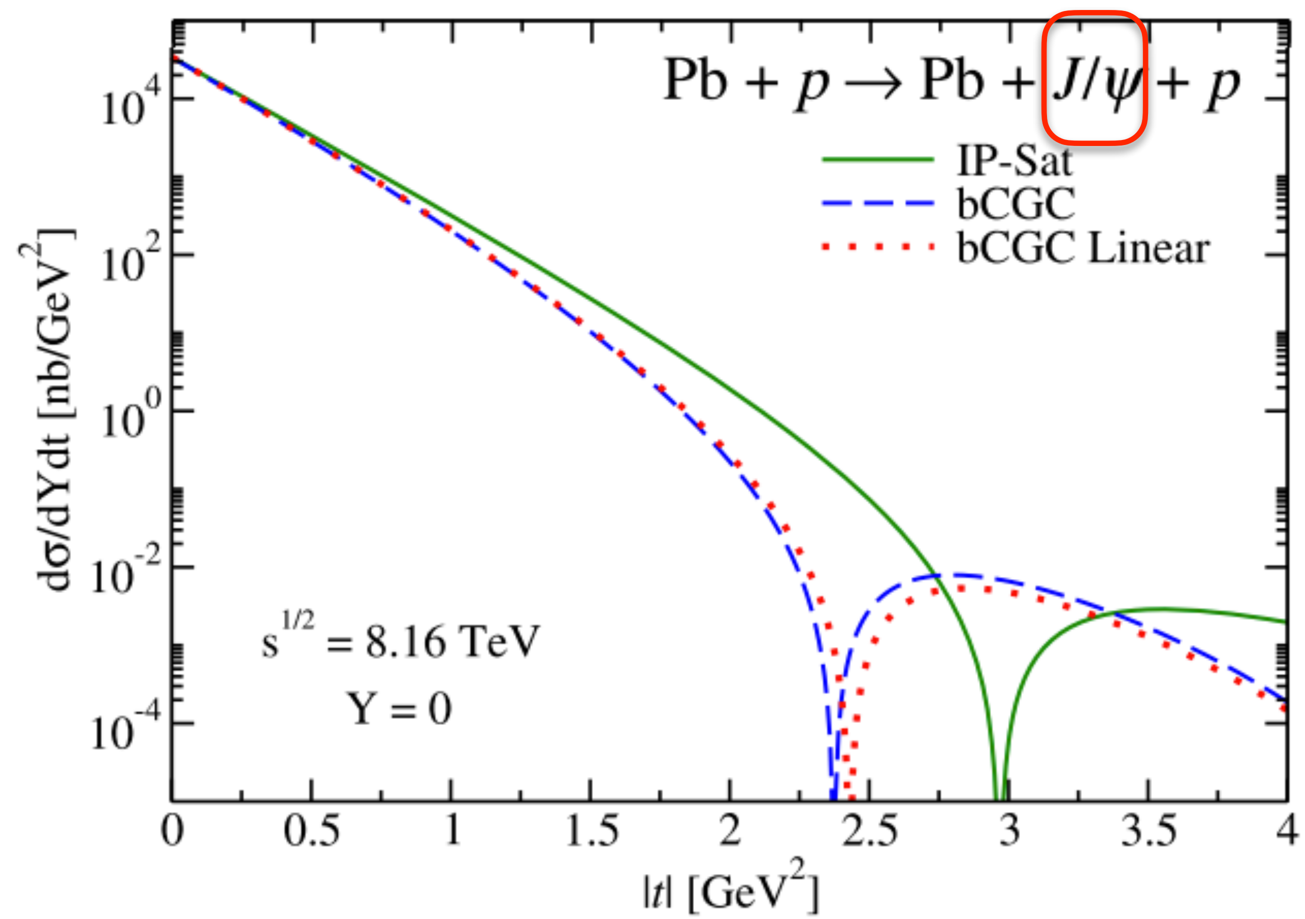
t-distribution
Exclusive vector mesons in γp

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

Signature of gluon saturation



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



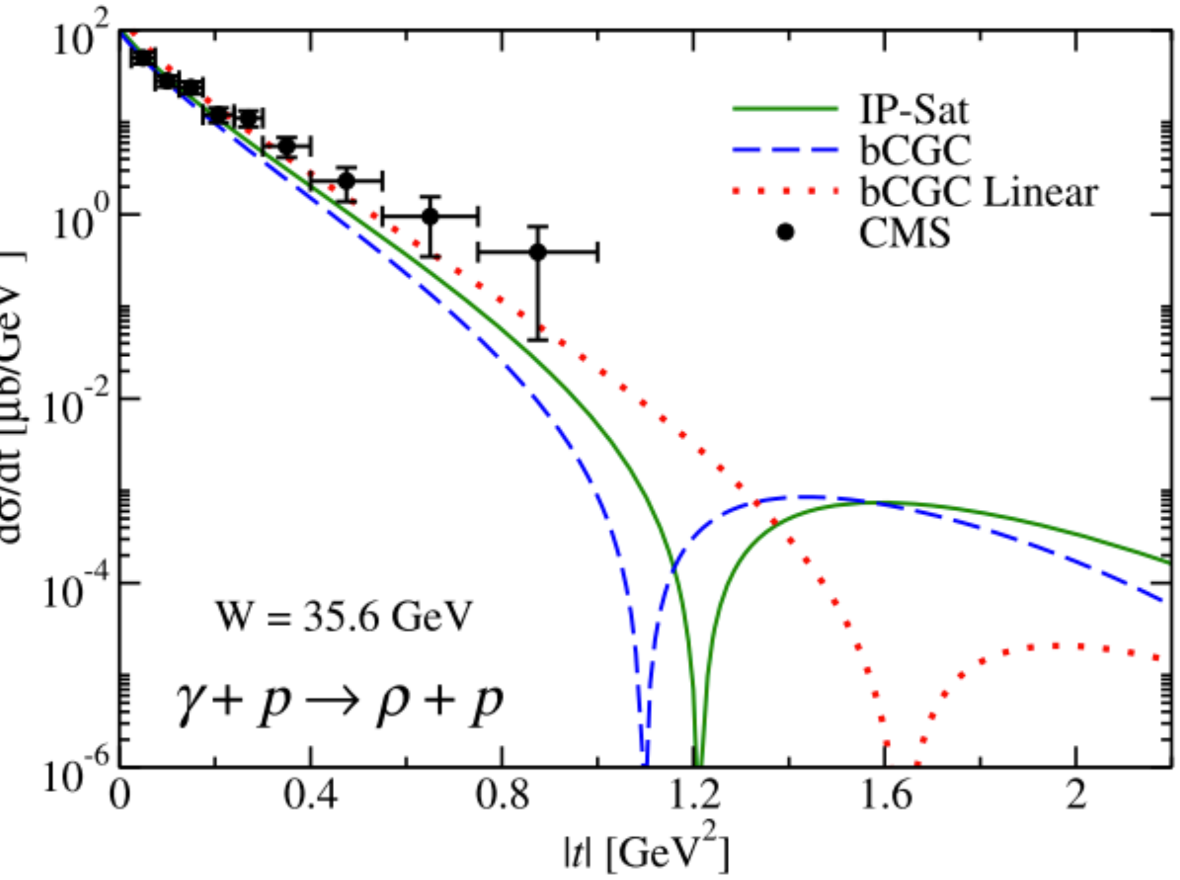
Location of the Diffractive dips: Different for IP-Sat and bCGC

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

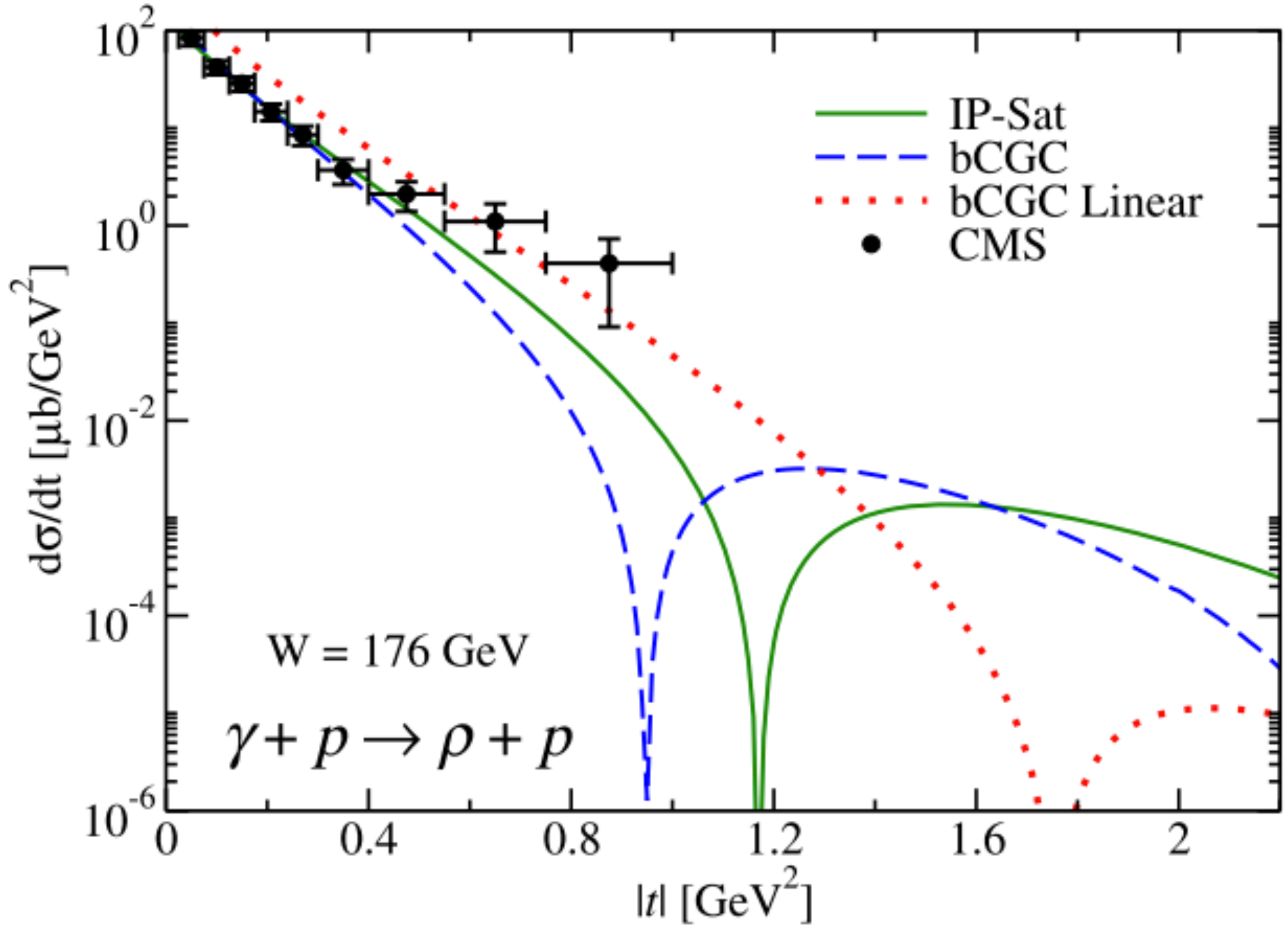
Exclusive ρ^0 in γp

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

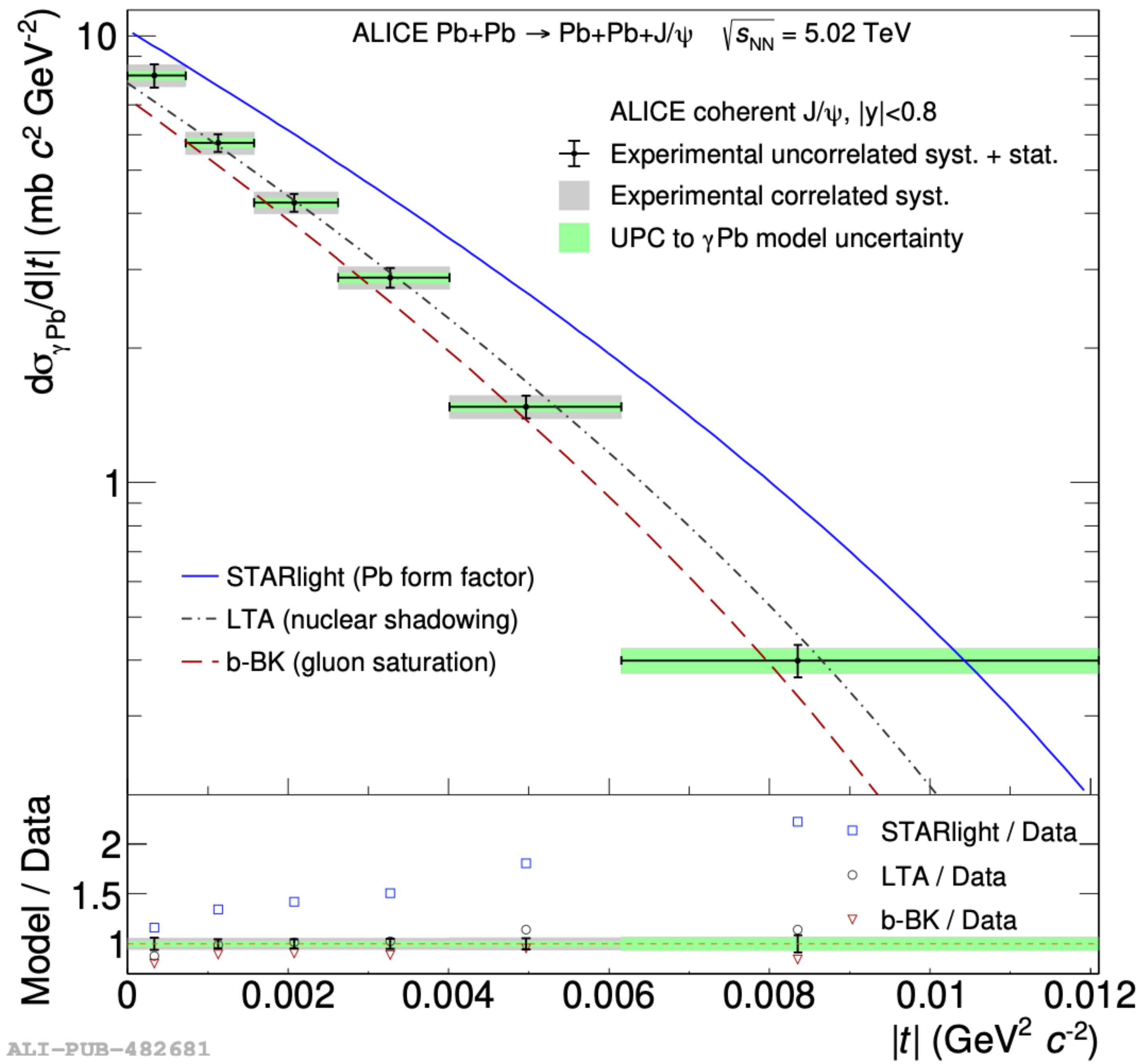
36 Gev



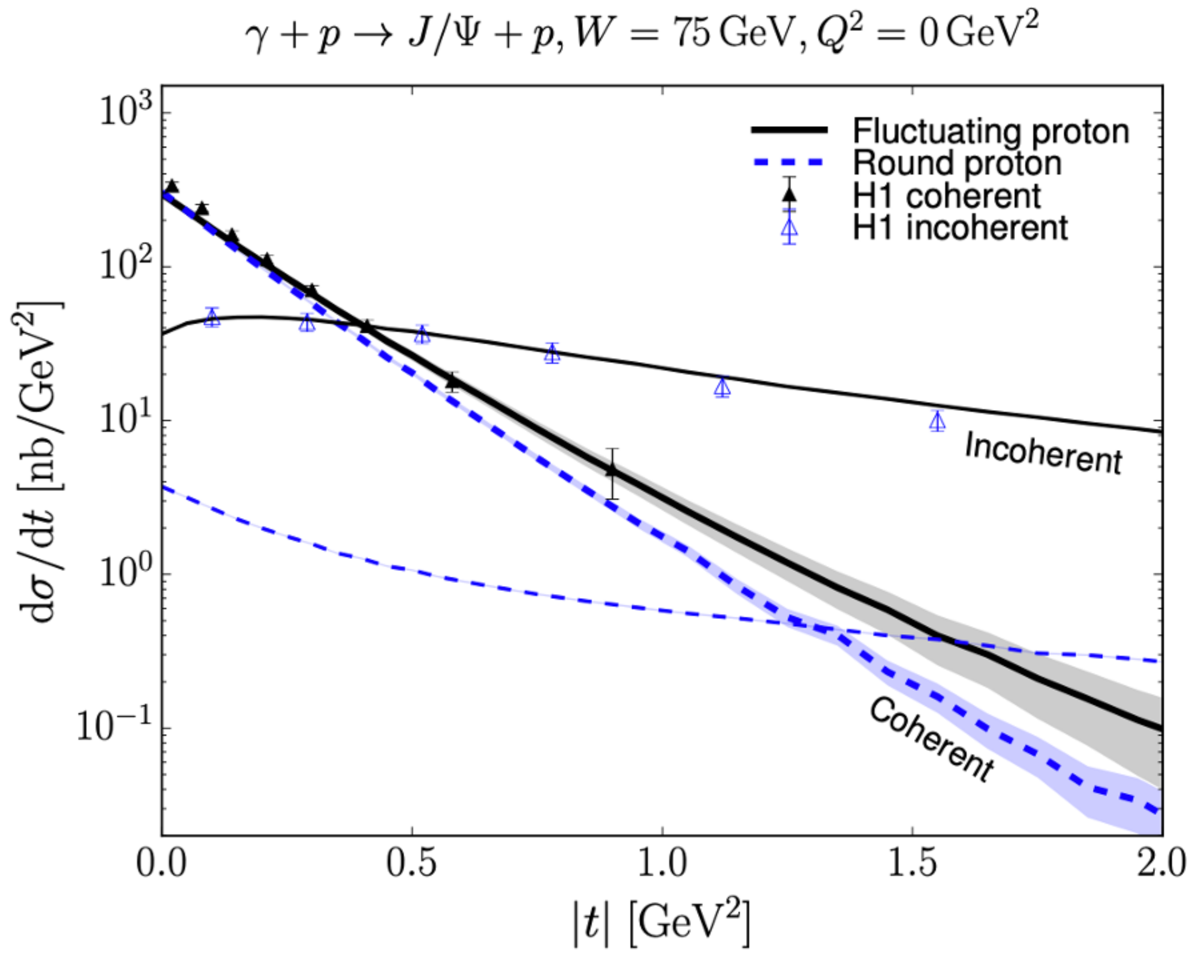
176 Gev

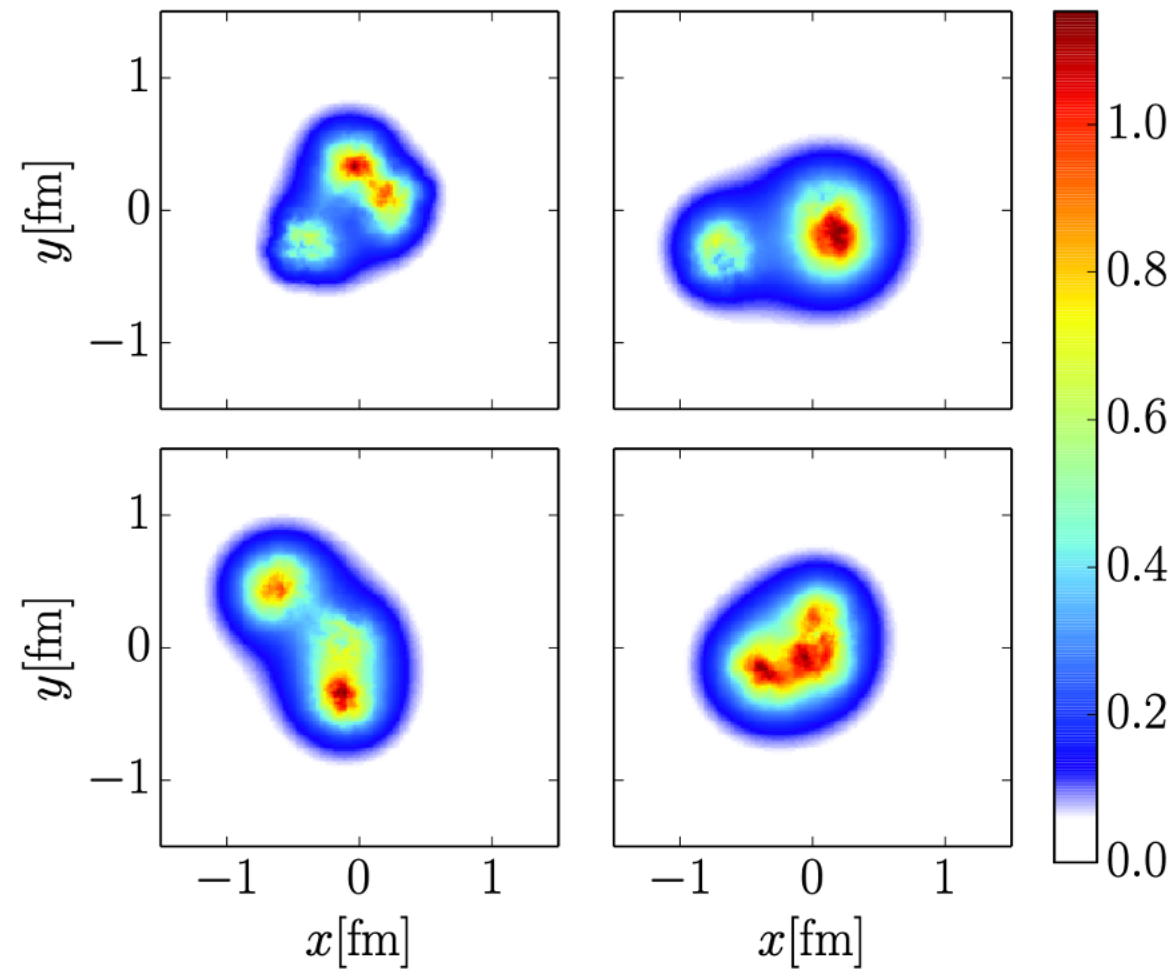


Transverse profile of the target



Gluon fluctuations

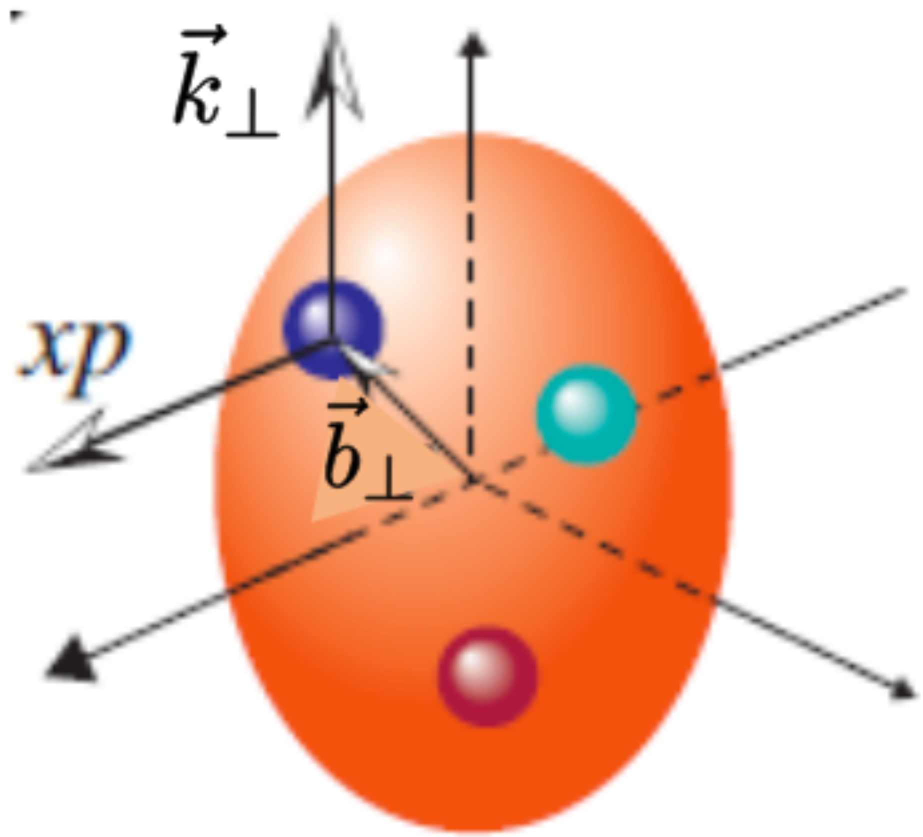




Gluon distributions are multidimensional

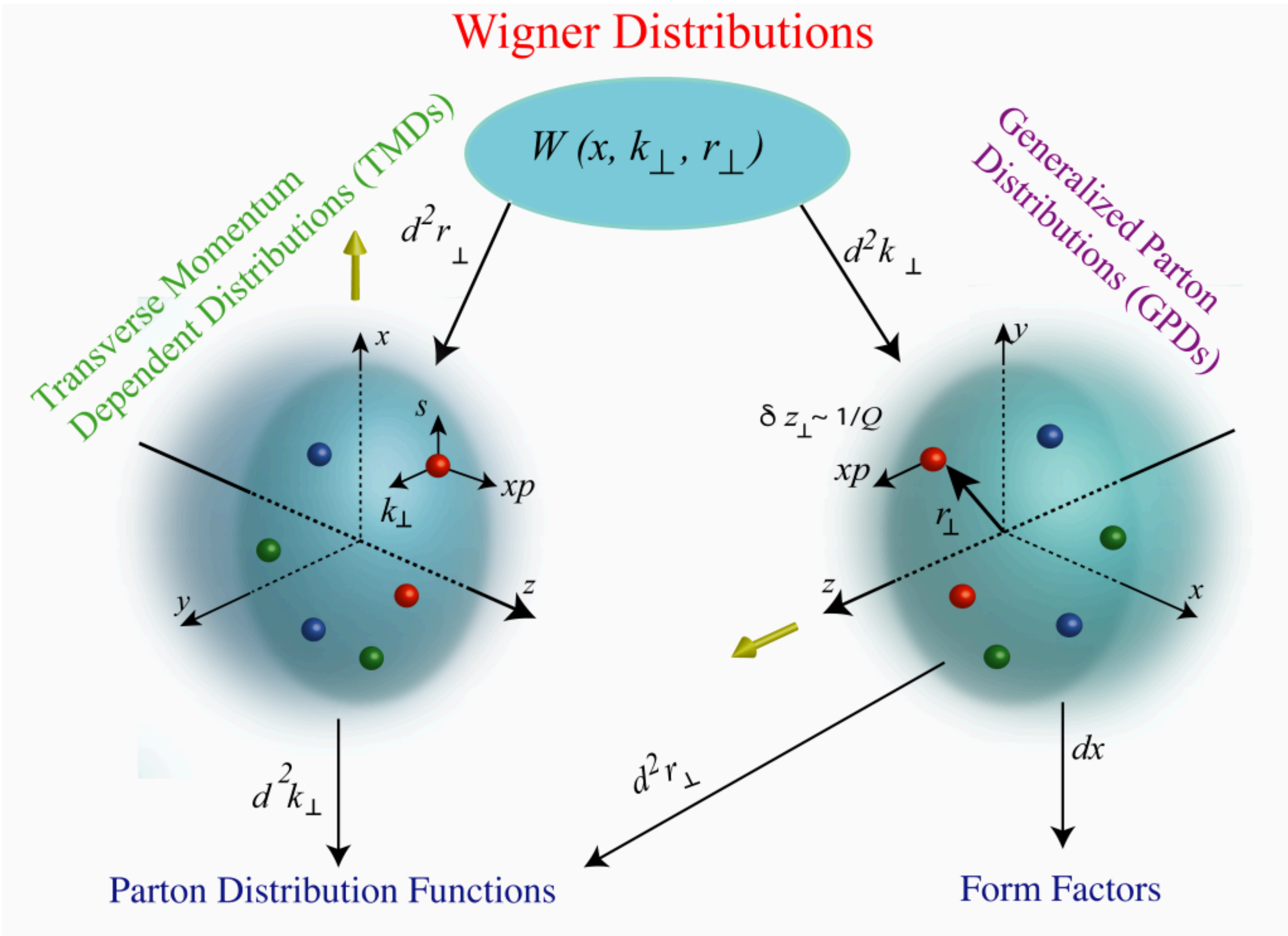
Azimuthal anisotropies of jets in UPC or eA

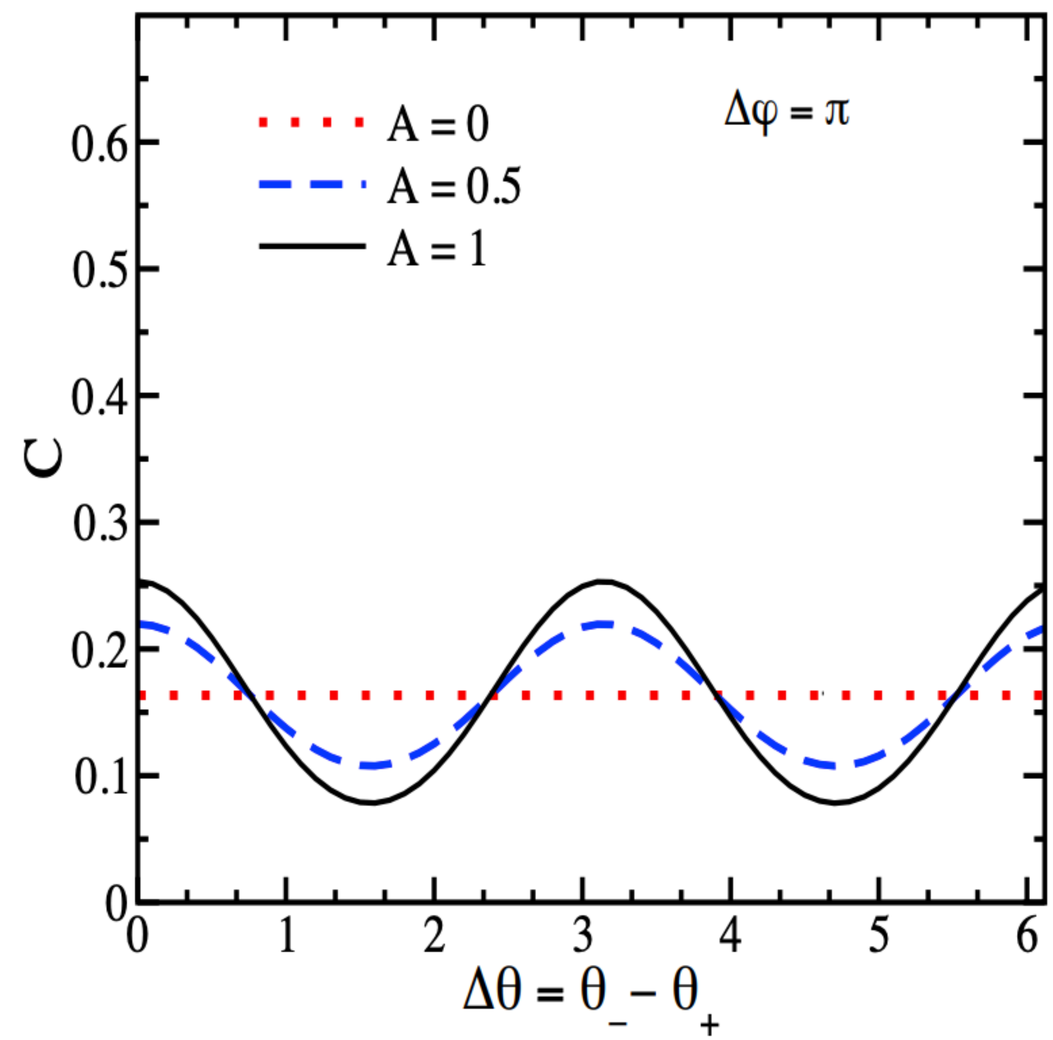
The Wigner or Husimi distribution go beyond the PDFs, GPDs and TMDs



Beyond Nuclear PDFs

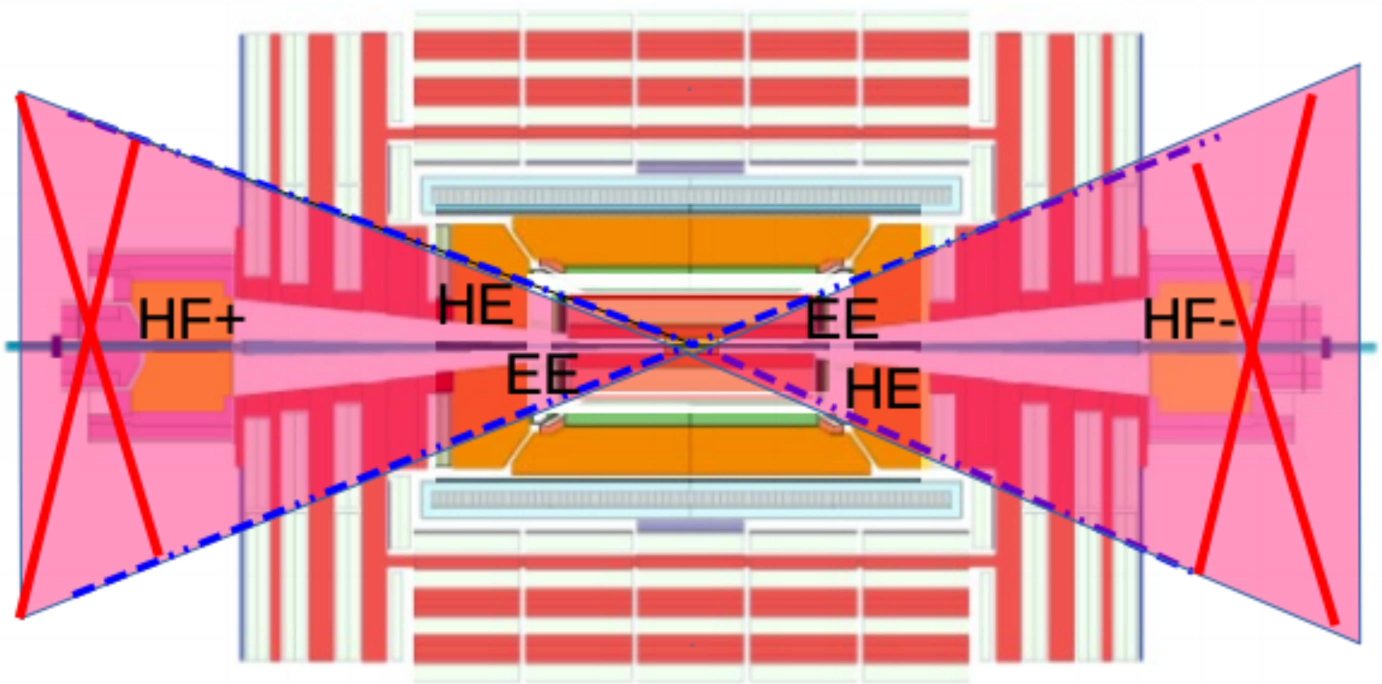
T. Altinoluk, N. Armesto, G. Beuf, and A. H. Rezaeian, Phys. Lett. B758, 373 (2016), arXiv:1511.07452 [hep-ph].

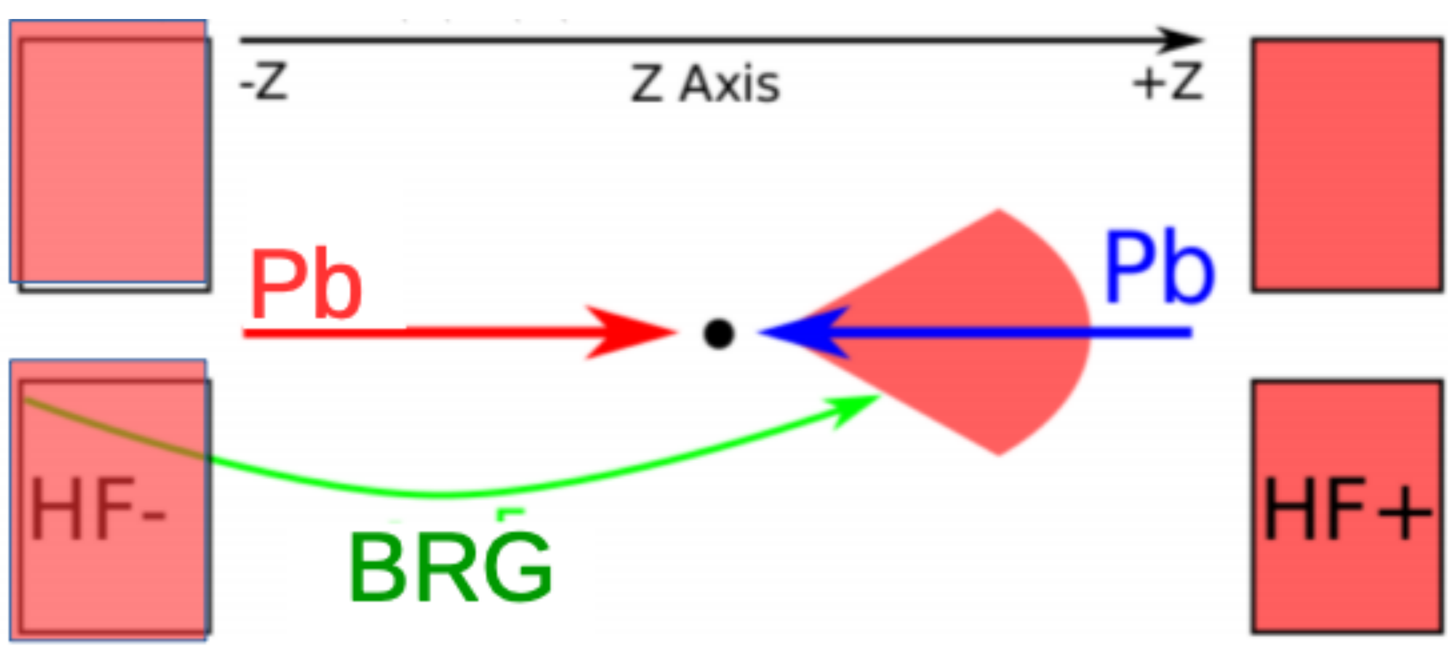




Exclusive dijets process known to be directly sensitive to the gluon Wigner distribution

Exclusive diffractive dijets in γA

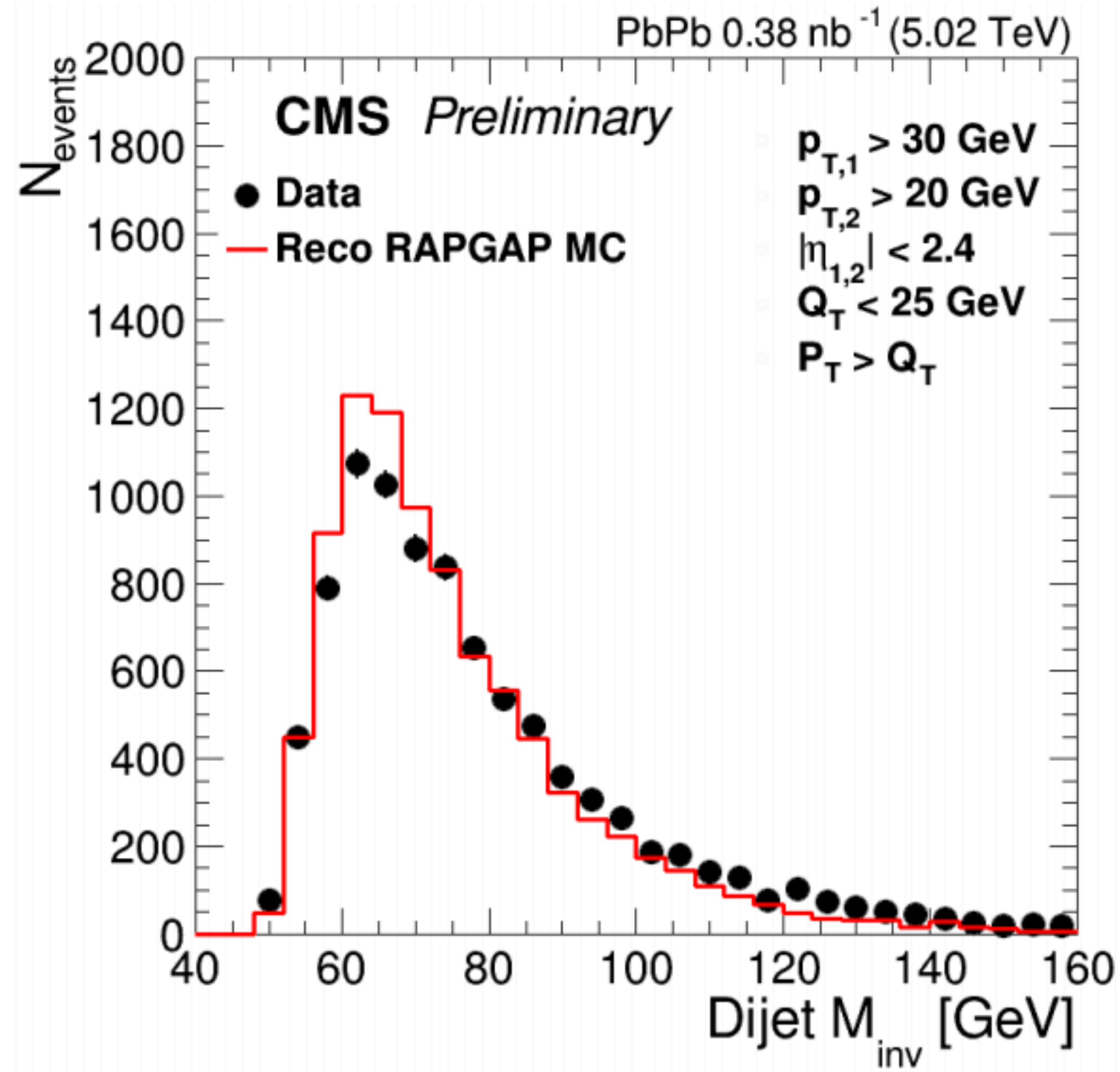


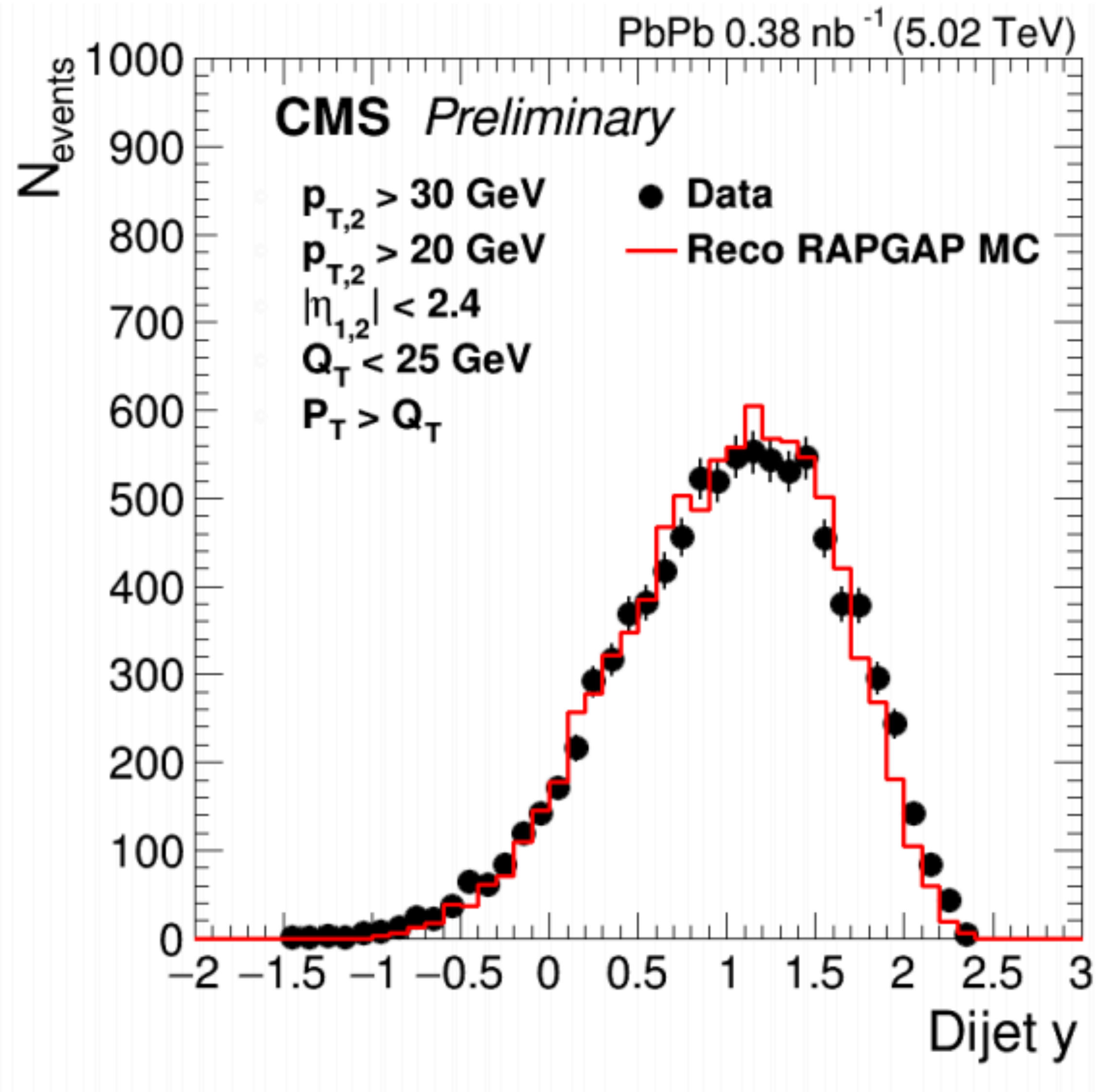


Exclusive diffractive dijets in γA

(CMS-PAS-HIN-18-011)

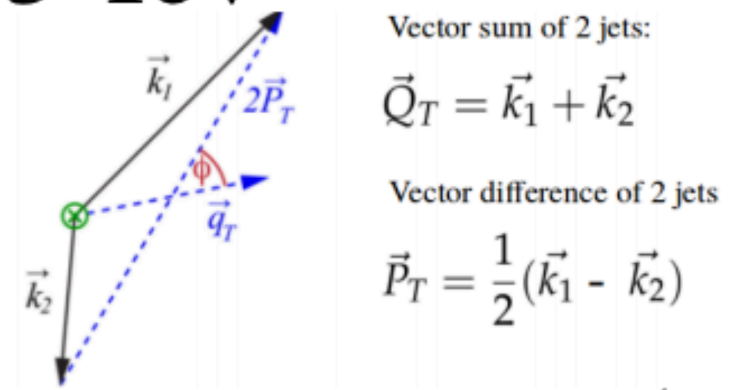
Dijet kinematics

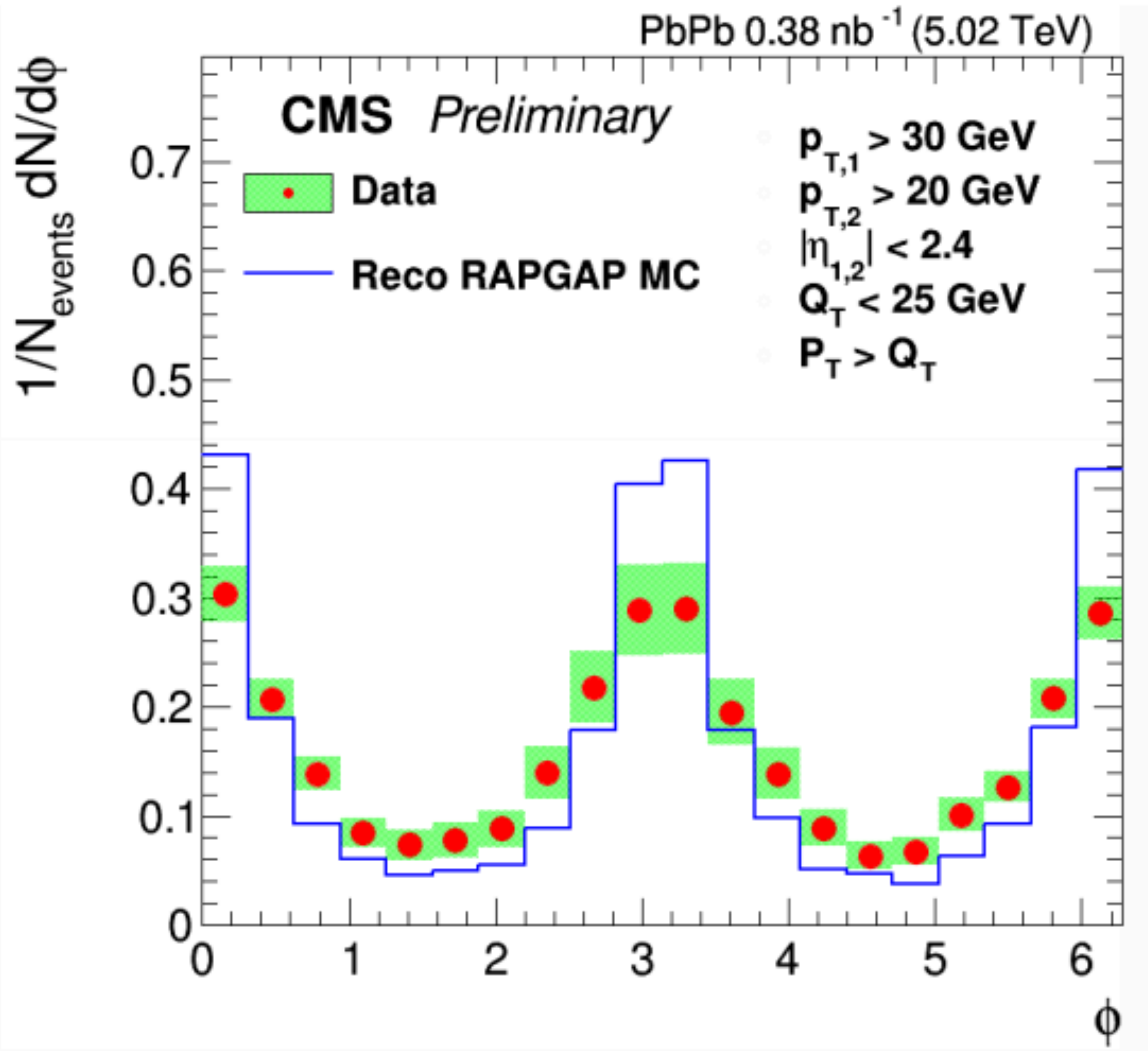


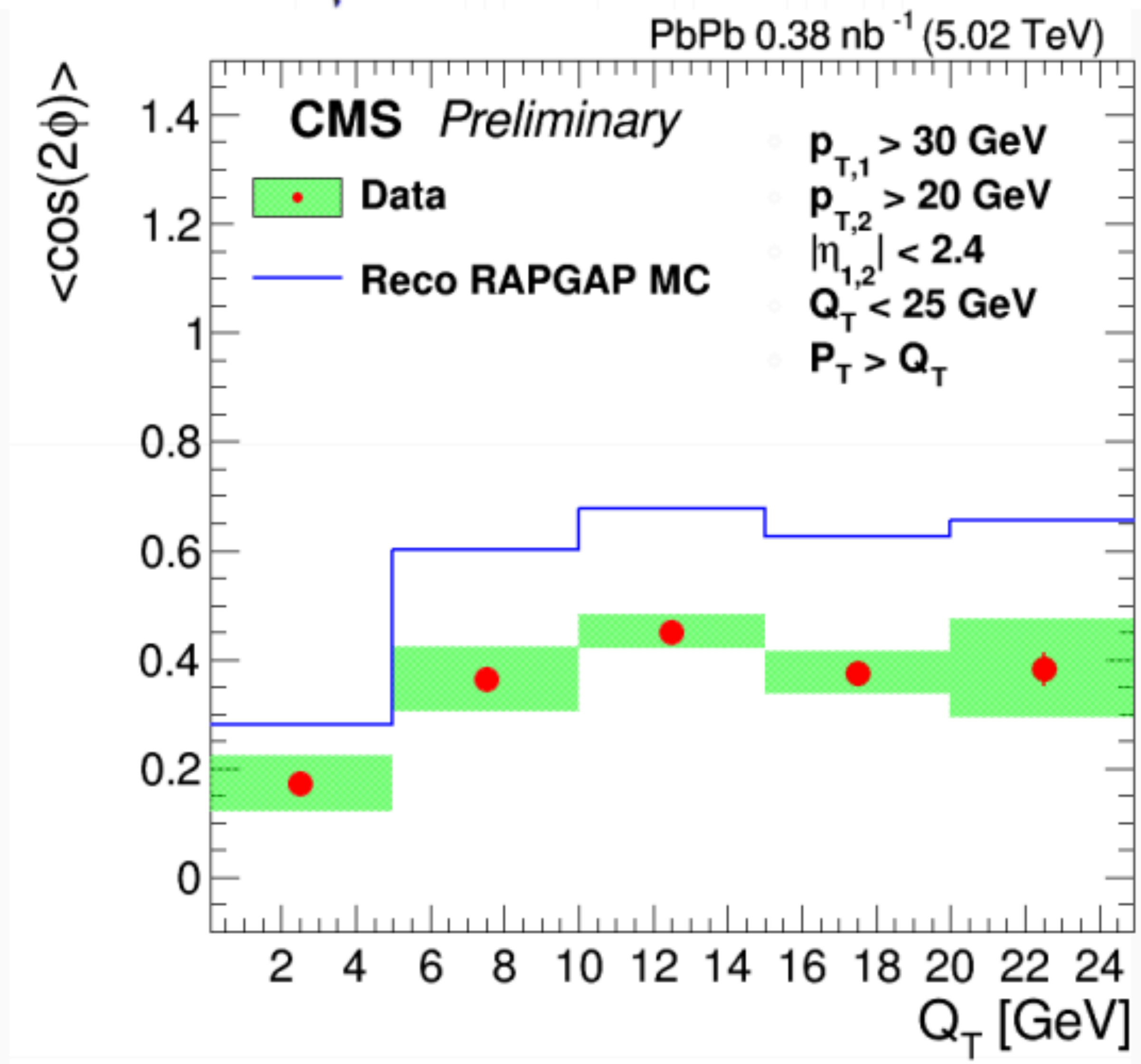


Exclusive diffractive dijets in γA

Exclusive dijets in UPC PbPb @5 TeV
(CMS-PAS-HIN-18-011)

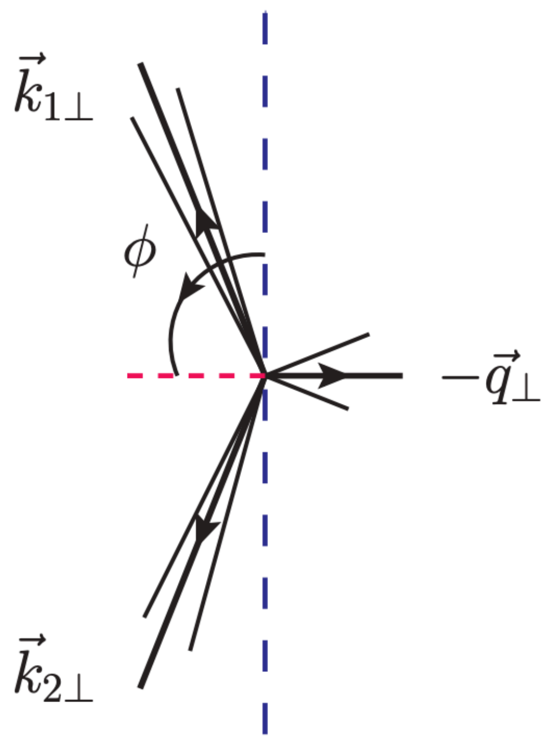






Soft-gluon radiation from final state jets

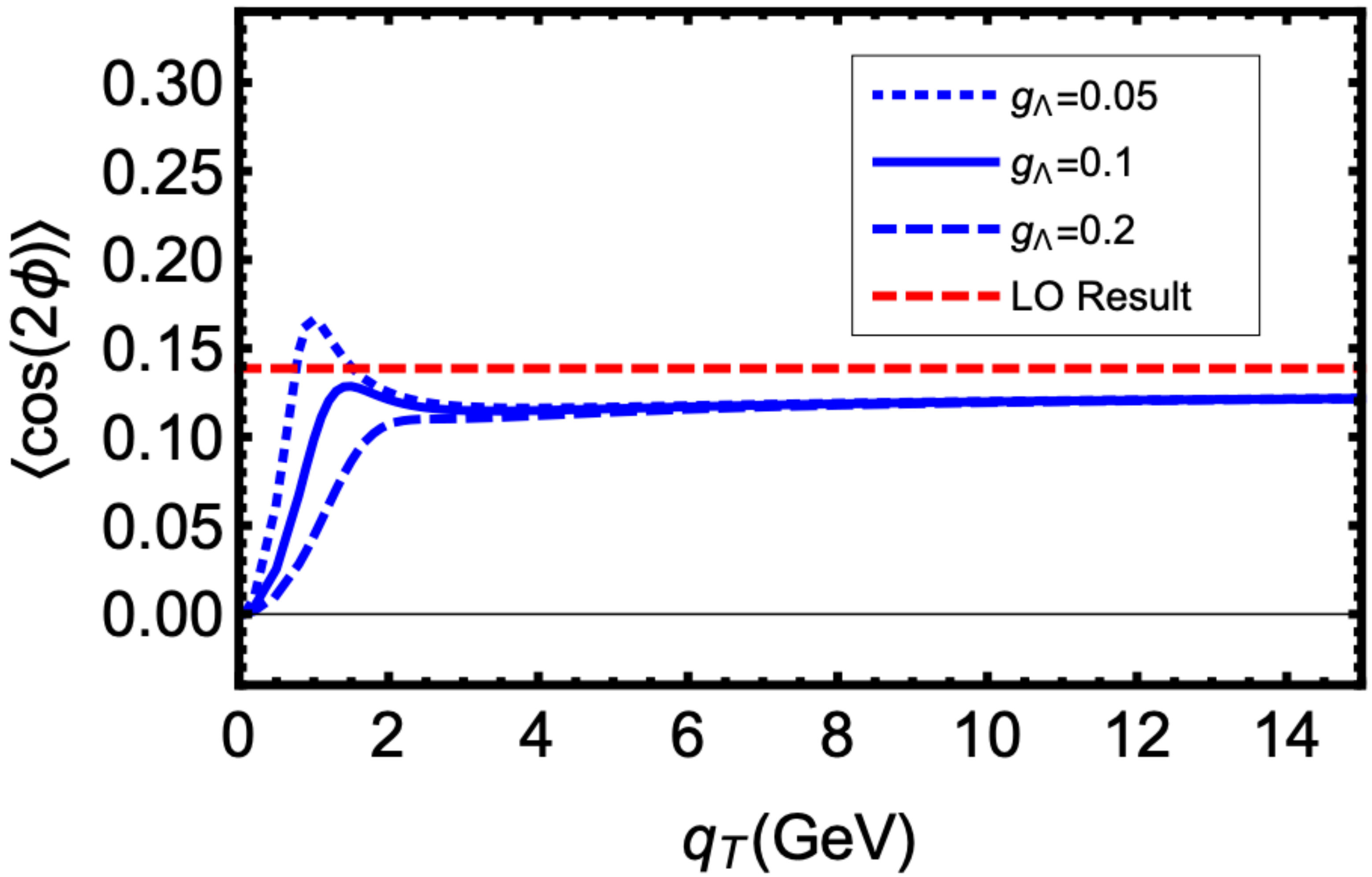
Yoshitaka Hatta, Bo-Wen Xiao, Feng Yuan and Jian Zhou
arXiv:2010.10774 [hep-ph]



They found soft gluon radiations from final state jets tend to be aligned with the jet direction and produce some angular anisotropies reflected in <cos(2phi)>

All the theory calculations considered soft gluon radiations to be suppressed
This could partly explained the CMS results

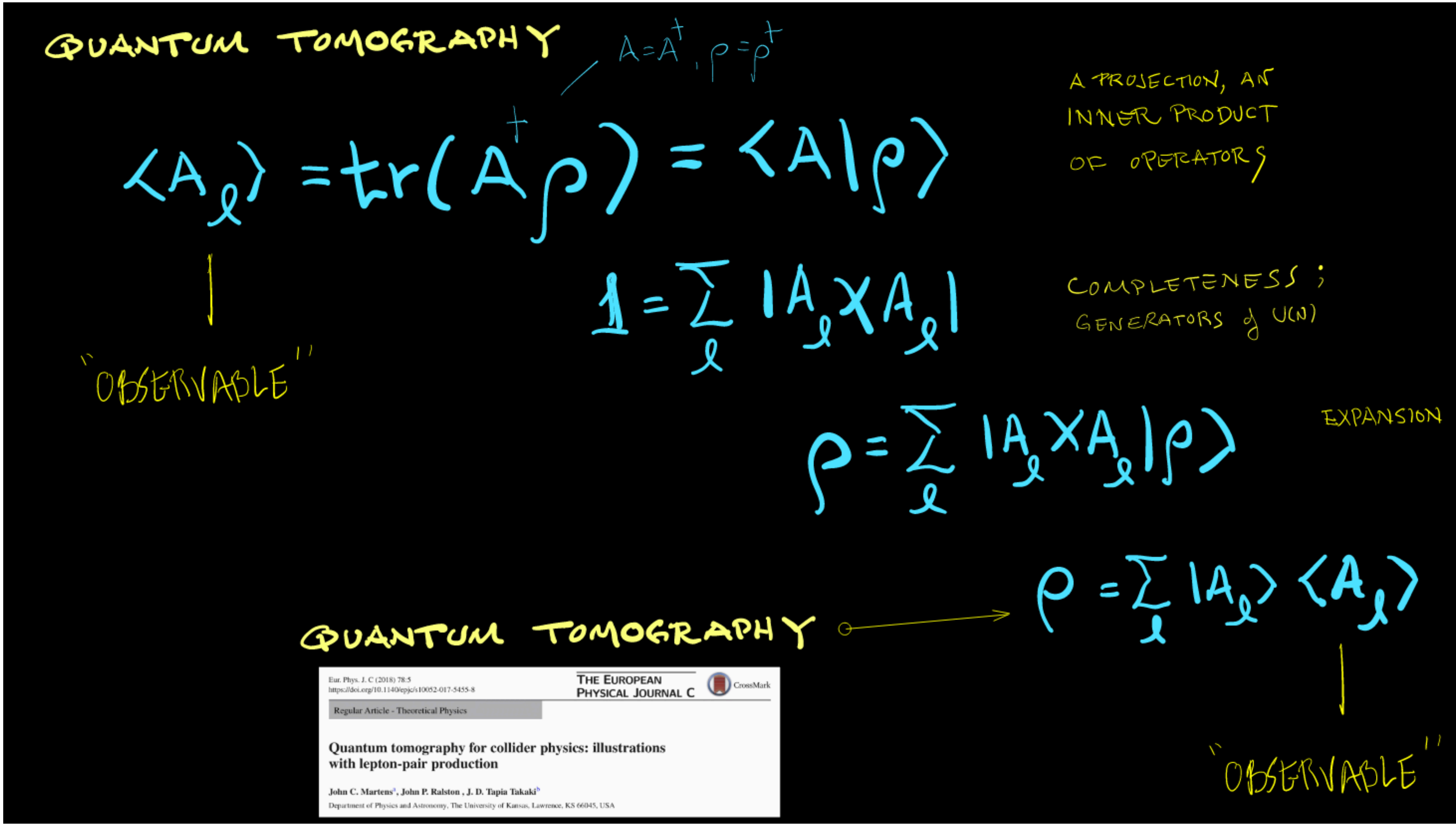
CMS kinematics



Could we now use this process to study medium energy loss with inclusive dijets in AA collisions?

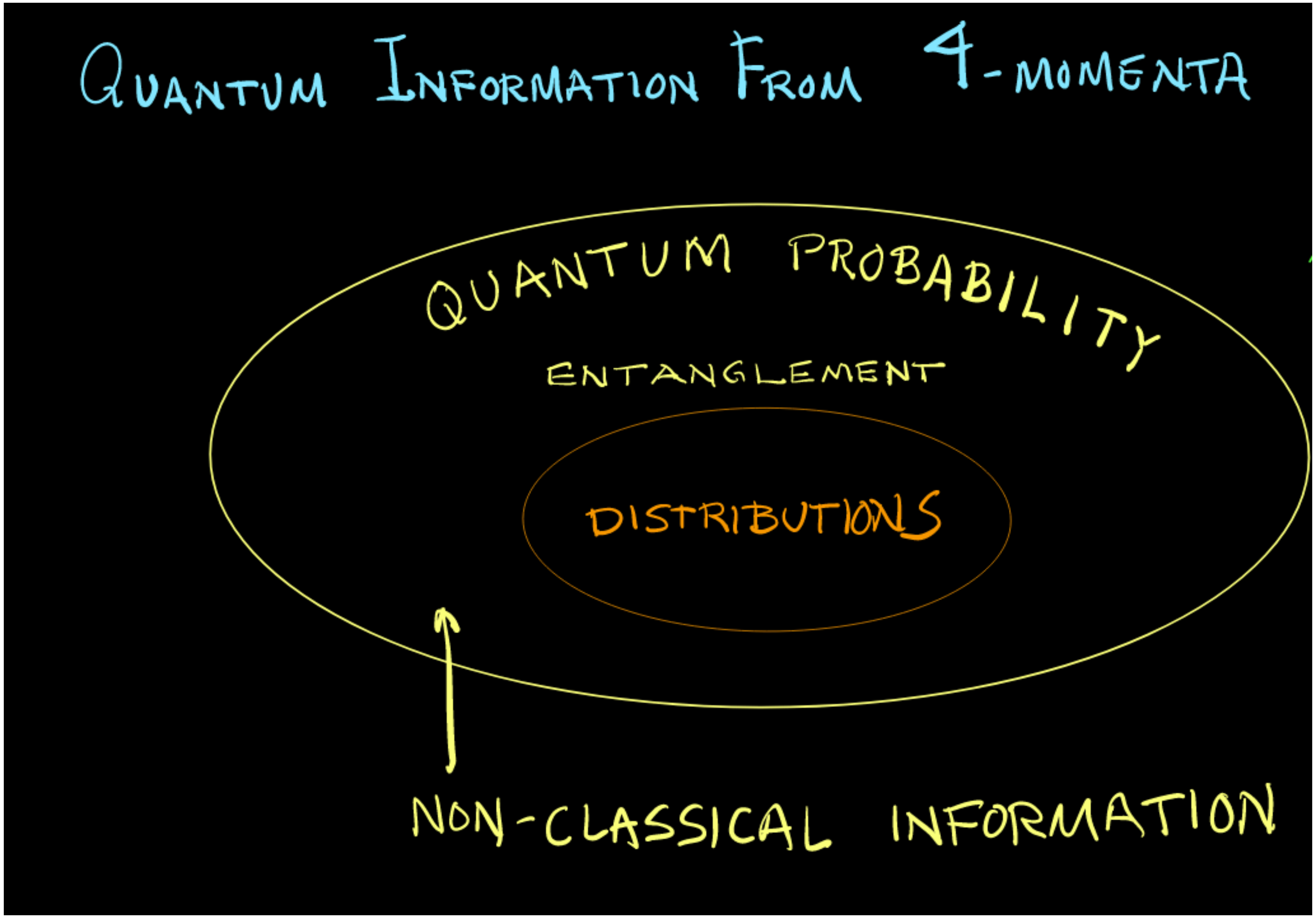
New approach

Quantum tomography



Martens, Ralston, Tapia Takaki Eur. Phys. J. C78, 5, 2018

Quantum tomography



Martens, Ralston, Tapia Takaki Eur. Phys. J. C78, 5, 2018

Quantum tomography

THE DENSITY MATRIX

$\rho = \rho^\dagger > 0$ POSITIVE EIGENVALUES

$\langle \hat{A} \rangle = \mathrm{tr}(\rho \hat{A})$

PURE STATE IS EXCEPTIONAL

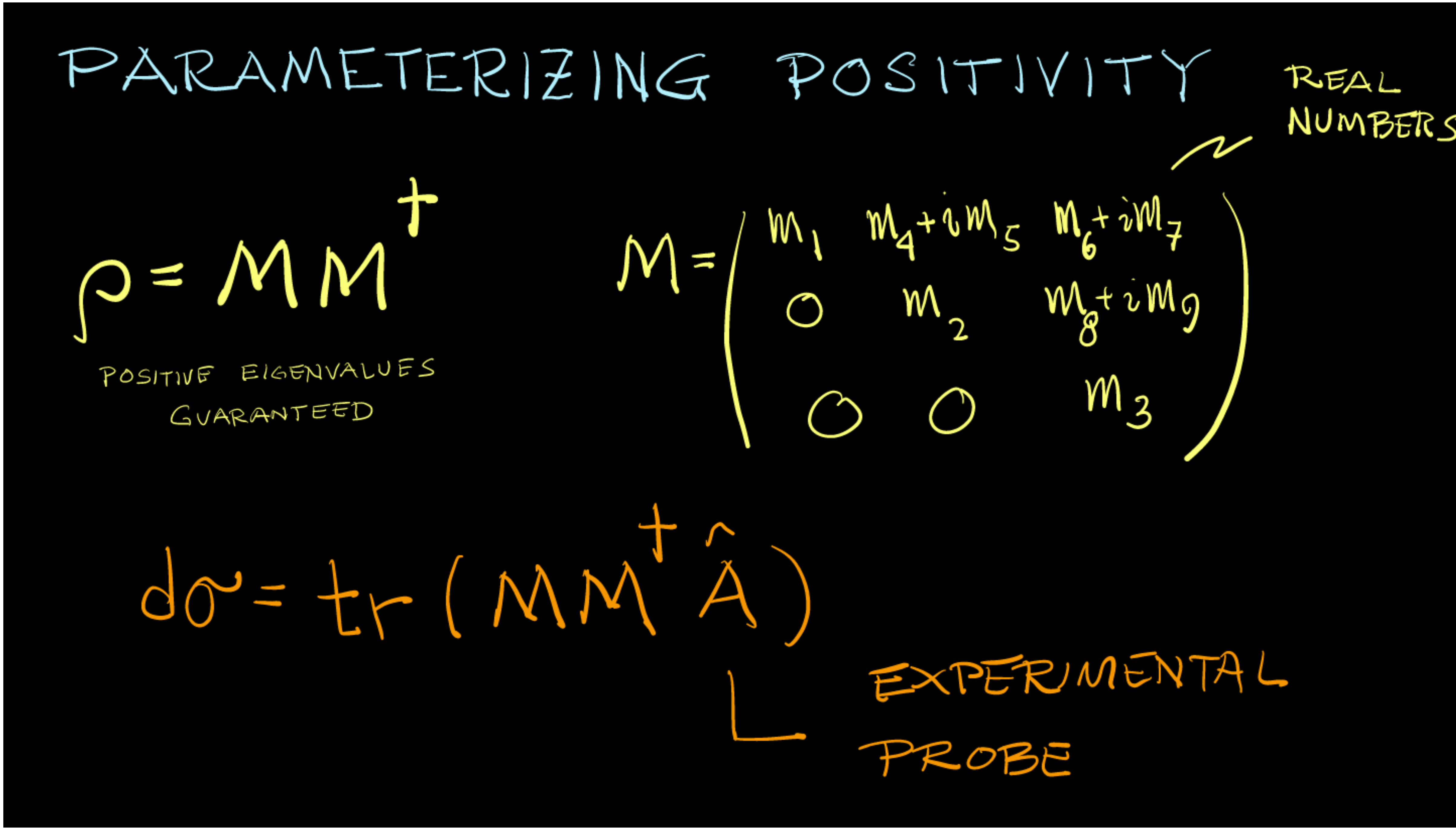
$\rho \to |\psi\rangle\langle\psi|$

$\langle \hat{A} \rangle \Rightarrow \mathrm{tr}(|\psi\rangle\langle\psi|\hat{A}) = \langle\psi|\hat{A}|\psi\rangle$

TEXTBOOKS SHOW THE EXCEPTION

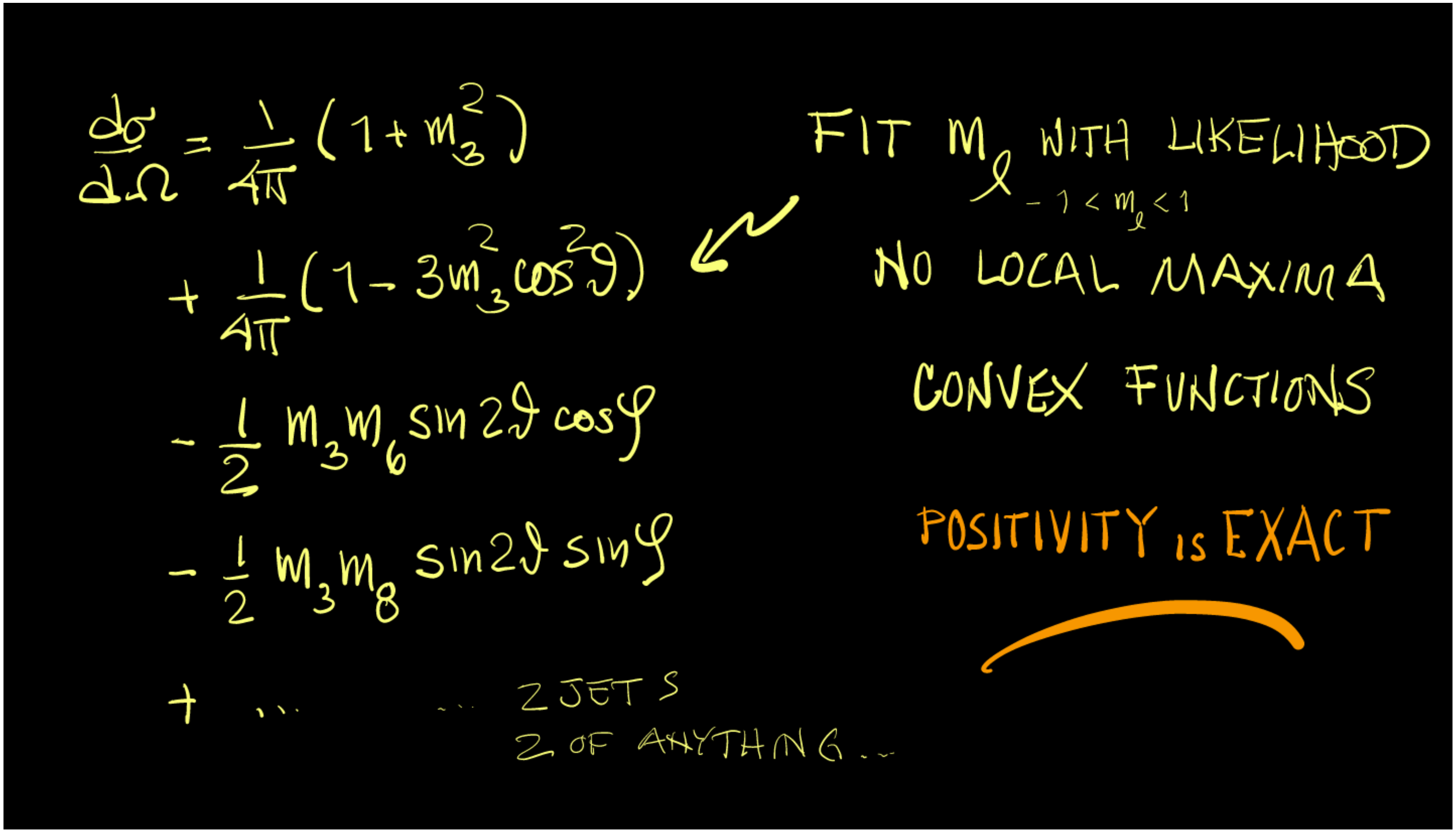
Martens, Ralston, Tapia Takaki Eur. Phys. J. C78, 5, 2018

Quantum tomography



Martens, Ralston, Tapia Takaki Eur. Phys. J. C78, 5, 2018

Quantum tomography



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Dijet angular correlation

histograms show a Lorentz-invariant angular distribution of jet1 v jet 2

measuring a density matrix

Quantum tomography Prediction

from MC generated events of DIS (RAPGAP)

We note that the polarization and transverse momentum degrees of freedom are entangled. No possibility to describe the system as separable. Need a more general description

$$\rho_X(Q_T) = \sum_{\alpha} |\psi_\alpha > \rho_\alpha < \psi_\alpha|$$

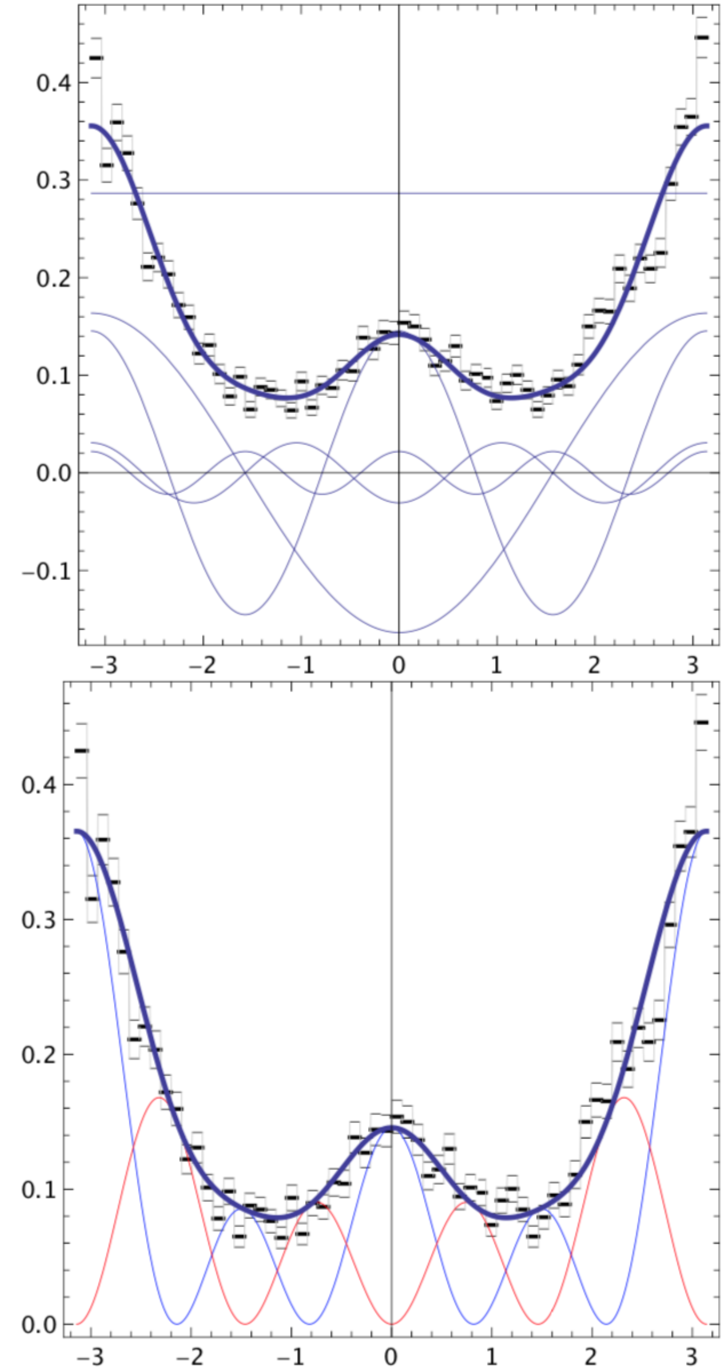

FIG. 4: Top: Maximum likelihood fit, with the contributions of $\cos m\phi$ for $m = 0-4$. Bottom: Two weighted distributions defined by $f_+(\phi) = Re(\psi)^2$ (blue) and $f_-(\phi) = Im(\psi)^2$ (red), coming from the eigenstates of the rank two density matrix.

Summary

- New data from nergy dependent studies of the t-distribution of UPC ρ0 in γp promising for determining the onset of gluon saturation

- Angular correlations of diffractive dijets.
  Soft-gluon radiation in final state jets.
  New techniques like Quantum tomography.

Altogether promising results that can have a broader impact beyond UPC studies

Additional slides

EIC Yellow Report

Topics \ Processes	Inclusive	Semi-Inclusive	Jets, Heavy Quarks	Exclusive	Diffractive, Forward Tagging
Global properties & parton structure	**incl. SF**	**h, hh**	**jet, Q**	**excl. $Q\overline{Q}$**	**incl. diffraction, tagged DIS on D/He**
Multidimensional Imaging		**h**	**jet, di-jet, jet+h, Q, $Q\overline{Q}$**	**DVCS, DVMP, elast. scattering**	
Nucleus	**incl. SF**	**h, hh**	**jet, di-jet, Q, $Q\overline{Q}$**	**coh. VM, di-jet, h, hh, D/He FF**	**diffr. SF, incoh. VM, di-jet, h, hh, nucl. fragments**
Hadronization		**h, hh, jet+h**	**jet, Q, $Q\overline{Q}$**		
Other fields	**incl. SF with e^+, $\sigma_{\gamma A}^{tot}$**	**charged curr. DIS, $\sigma_{\gamma A \to hX}$**		$\sigma_{\gamma A}^{elast}$	$\sigma_{\gamma A}^{diffr}$

DIS on nuclei