Studying gluon saturation and nuclear gluon effects using forward heavy-ion probes and UPCs

Daniel Tapia Takaki

Saturation: Recent developments, New Ideas and measurements
RIKEN BNL Research Center Workshop
April 26, 2017

Plan of this talk

- Highlights from the QM, INT workshop and DIS this year, focusing mainly on experimental measurements/ideas
- Lots of synergies with the EIC program and UPC at RHIC/LHC. Will mention it briefly but this is material for another talk….
- Discussions about new ideas …

INT workshop

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Application form
For full consideration, please apply by October 31, 2016.

Talks online

Exit report

Visitor Information

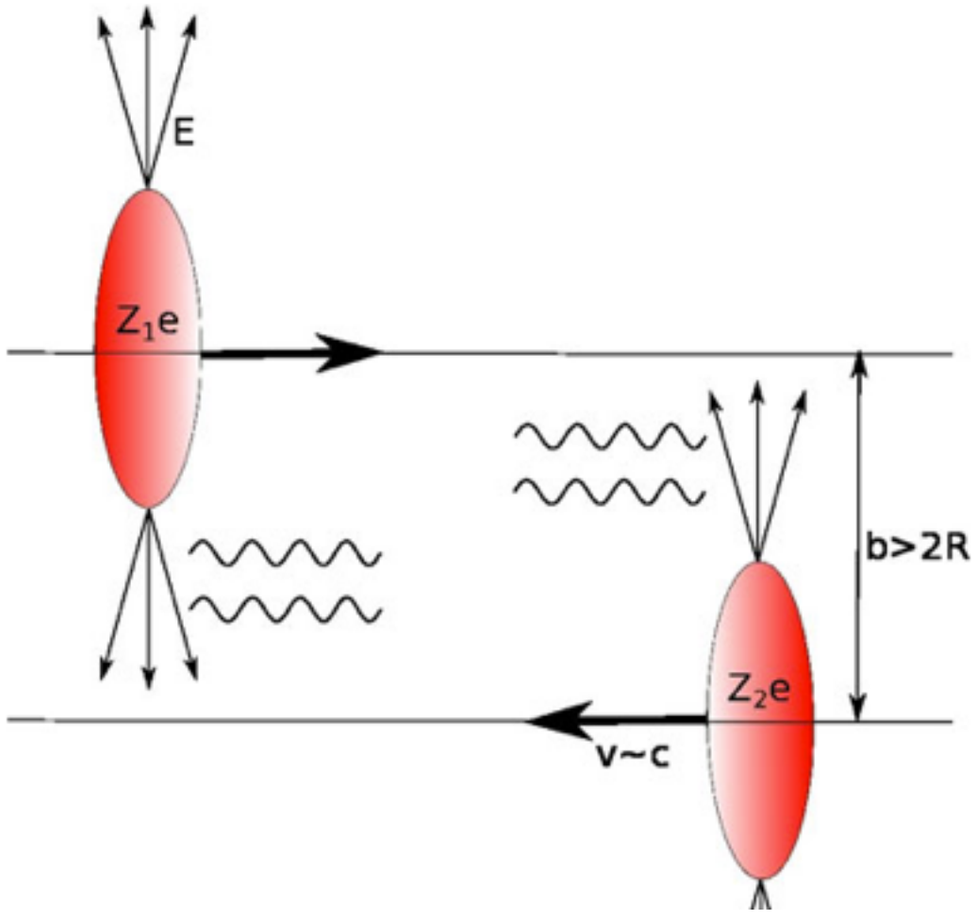
Friends of the INT

Obtain an INT preprint number

INT Workshop INT-17-65W

Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the Path to EIC

February 13 - 17, 2017



http://www.int.washington.edu/PROGRAMS/17-65w/

DIS 2017

WG2 conveners

Grzegorz Gach — AGH

Anna Staśto — PennState Eberly College of Science

Daniel Tapia Takaki — KU

INT workshop

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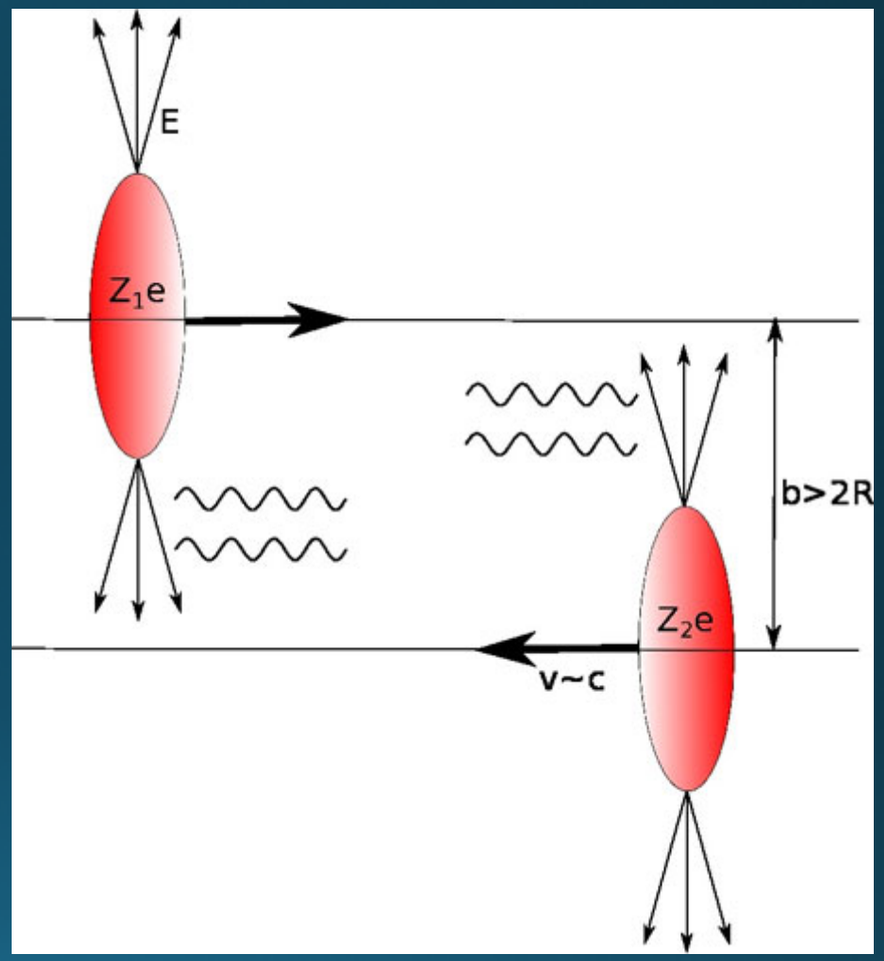
INT workshop

Overview

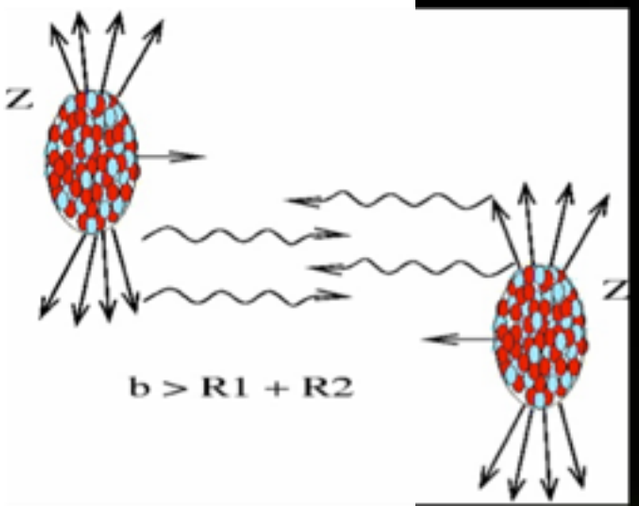
- High-energy photon-nucleon (nucleus) collisions offer us a unique opportunity to study the hadron and photon structure, QCD dynamics and small Bjorken-x gluon dynamics at photon intensities and energies that are unavailable elsewhere

- These interactions can already be studied in a wide energy range from W ~10 GeV (RHIC Au-Au) to W ~ 500 GeV (LHC Pb-Pb) using ultraperipheral collisions at hadronic colliders

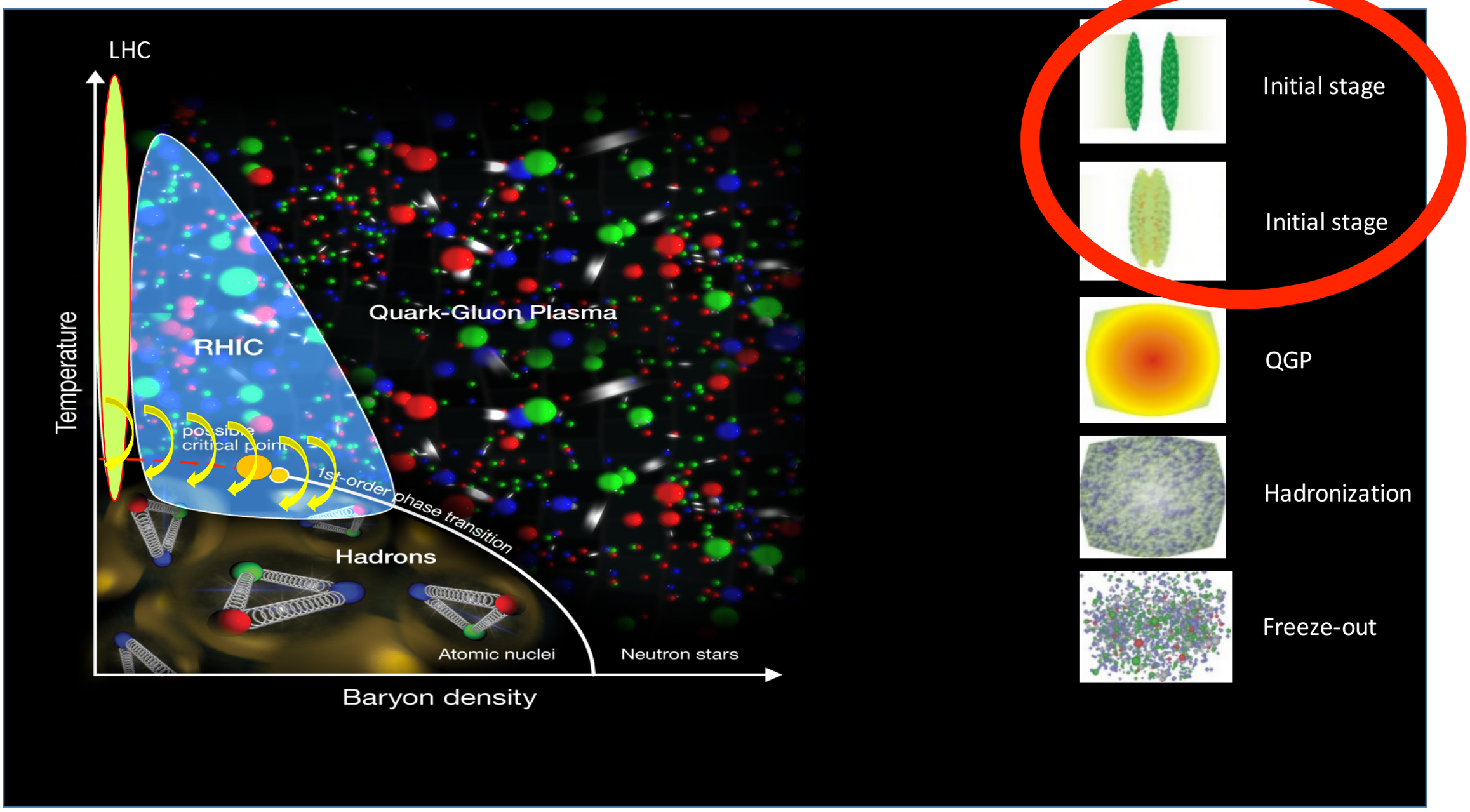


Ultra-peripheral collisions

UPC collisions: shedding light on the proton (pp or p-Pb) or nucleus (Pb-Pb)



Understanding the initial state



the nature of the initial state is one of the most important questions in high-energy nuclear physics

10 UPC studies with heavy ions at the LHC

- *Coherent J/ψ photoproduction in ultra-peripheral Pb-Pb collisions at sNN=2.76 TeV* Phys.Lett. B718 (2013) 1273-1283
- *Charmonium and e+e− pair photoproduction at mid-rapidity in ultra-peripheral Pb-Pb collisions at sNN√=2.76 TeV* Eur.Phys.J. C73 (2013) 11, 2617
- *Exclusive J/ψ photoproduction off protons in ultra-peripheral p-Pb collisions at sNN√=5.02 TeV* Phys.Rev.Lett. 113 (2014) 23, 232504
- *Coherent ρ0 photoproduction in ultra-peripheral Pb-Pb collisions at sNN =2.76 TeV* JHEP 1509 (2015) 095
- *Coherent ψ(2S) photo-production in ultra-peripheral Pb Pb collisions at sNN = 2.76 TeV* Phys.Lett. B751 (2015) 358-370
- *Measurement of an excess in the yield of J/\psi at very low pT in Pb-Pb collisions at sNN = 2.76 TeV* Phys. Rev. Lett.116 (2016) 22, 222301
- *Coherent J/ψ photoproduction in ultra-peripheral Pb-Pb collisions at sNN=2.76 TeV with the CMS detector* CMS-PAS-HIN-12-009. Submitted to PLB
- *Measurement of exclusive Upsilon in pPb collisions at sNN = 5.02 TeV* CMS-PAS-FSQ-13-009
- *Measurement of high-mass dimuon pairs from ultraperipheral lead-lead collisions at sNN =5.02 TeV with the ATLAS detector at the LHC* ATLAS-CONF-2016-025
- Light-by-light scattering in ultra-peripheral Pb+Pb collisions at sNN = 5.02 TeV with the ATLAS detector at the LHC ATLAS-CONF-2016-111

INT workshop

Overview

- ***UPC studies serve as a forerunner of the Electron Ion Collider (EIC) experiments.***
- The top of the energy range in UPCs at LHC is a factor of ten higher than that of the EIC, which offers a unique opportunity to explore this novel kinematic regime.
- At the same time, UPC collisions at RHIC and LHC have their own limitations, since it is not possible to study the Q^2 dependence systematically for most physics processes of interest.

INT workshop

Overview

- Despite the recent experimental progress, work on the theoretical side is clearly not at a similar level to that of inclusive hard scattering.

- ***The goal of this workshop is to identify and discuss the theoretical challenges of photon-induced physics, and how to use this knowledge for physics studies at the EIC.***

INT workshop

Topics (main focus)

- **Current status of nuclear PDFs and developments using photon-nucleus data**
- **Strategies for observing nonlinear and gluon saturation effects in photon - nucleus scattering**
- Progress in understanding heavy quark hadronization in exclusive processes.
- Models for coherent and incoherent soft photon - nucleon / nucleus interactions
- Predictions of the leading twist models, dipole models and CGC models for exclusive gamma-p and gamma A scattering.
- Exotic spectroscopy and searches for new physics

Overview

- **Studying QCD with high energy photon-photon, photon-proton and photon-nuclear interactions at RHIC and LHC**
  - **Searching for saturation effects in the proton**
  - **Nuclear effects at both low and high Bjorken-x**

- **So far, most analyses have been carried out for exclusive VM photoproduction but new studies possible and ongoing dijets, diphotons…**

- **Inclusive photo-nuclear and photon-proton reactions also possible and first studies ongoing**

INT workshop

PDFs

Ramona Vogt (LLNL)
Fred Olness (SMU)
Shunzo Kumano (KEK)

Diffraction, Jets, Saturation, and Dipoles

Beatriz Gay Ducati (UFRGS)
Anna Stasto (PSU)
Guangyao Chen (Iowa State)
Piotr Kotko (PSU)
Wolfgang Schaefer (Cracow)
Amir Rezaeian (Valparaiso)
Heikki Mantysaari (BNL)
Misak Sargsian (FIU)

Shadowing

Vadim Guzey (Petersburg
Leonid Frankfurt (Tel Aviv
Mark Strikman (PSU)
Boris Blok (Technion)

Polarization in UPCs and EIC

Maria Elena Tejeda-Yeomans (Sonora)
John Ralston (Kansas)

Path to EIC

Elke Aschenauer (BNL)
Christian Weiss (JLab)
Michael Lomnitz (LBNL)

Experiments at RHIC and LHC

Jarda Adam (Creighton)
Aaron Angerami (Columbia)
Evgeny Kryshen (Petersburg)
Michael Murray (Kansas)

INT workshop

48 participants at INT

Some selected slides….

DIS 2017

Working Group 2: Low x and Diffraction

9 sessions, 42 talks, 18 experiment, 24 theory/phenomenology

Speakers:

Marcin Guzik
Laurent Forthomme
Alexander Bylinkin
Bartłomiej Rachwał
Jesus G. Contreras Nuno
Frigyes Janos Nemes
Grzegorz Gach
Peter John Bussey
John Dainton
Karel Cerny
Kay Graham
Martin Hentschinski
Jan Cepila
Heikki Mantysaari
Radek Zlebcik
Renaud Boussarie
Yoshitaka Hatta
Oleg Kuprash
Benoit Roland
Gilvan Augusto Alves

Merijn van de Klundert
Jamal Jalilian-Marian
Mirko Serino
Oldrich Kepka
Grigorios Chachamis
Krzysztof Kutak
Agustin Sabio Vera
Victor Fadin
Sergey Bondarenko
Giovanni Antonio Chirilli
Guillaume Beuf
Tibor Zenis
Nestor Armesto Perez
Stephane Munier
Leszek Motyka
Bertrand Ducloue
Ian Balitsky
Elena Petreska
Aleksander Kusina

INT workshop

UPC in parallel with EIC

- UPCs and EIC complementary

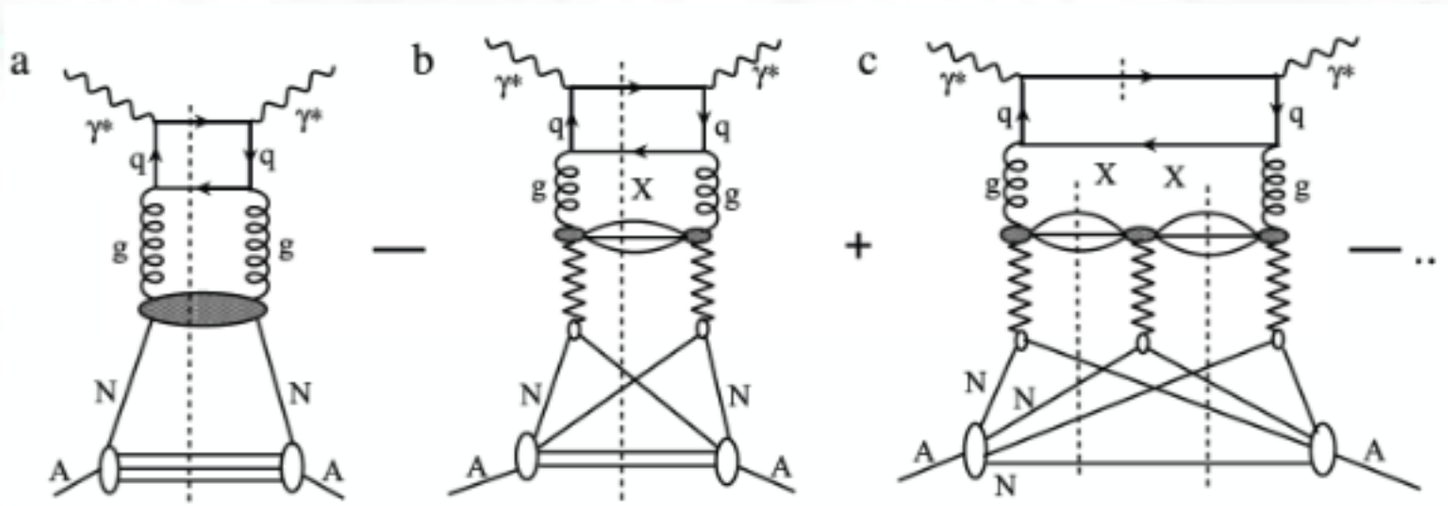
  Highest energy $\leftrightarrow$ control of hard-process kinematics

- Concrete possibilities for "joint" studies

  Mechanism of nuclear shadowing
  Nuclear quarks/gluons at larger x
  Transverse nucleon structure
  Unitarity limit in hard interactions

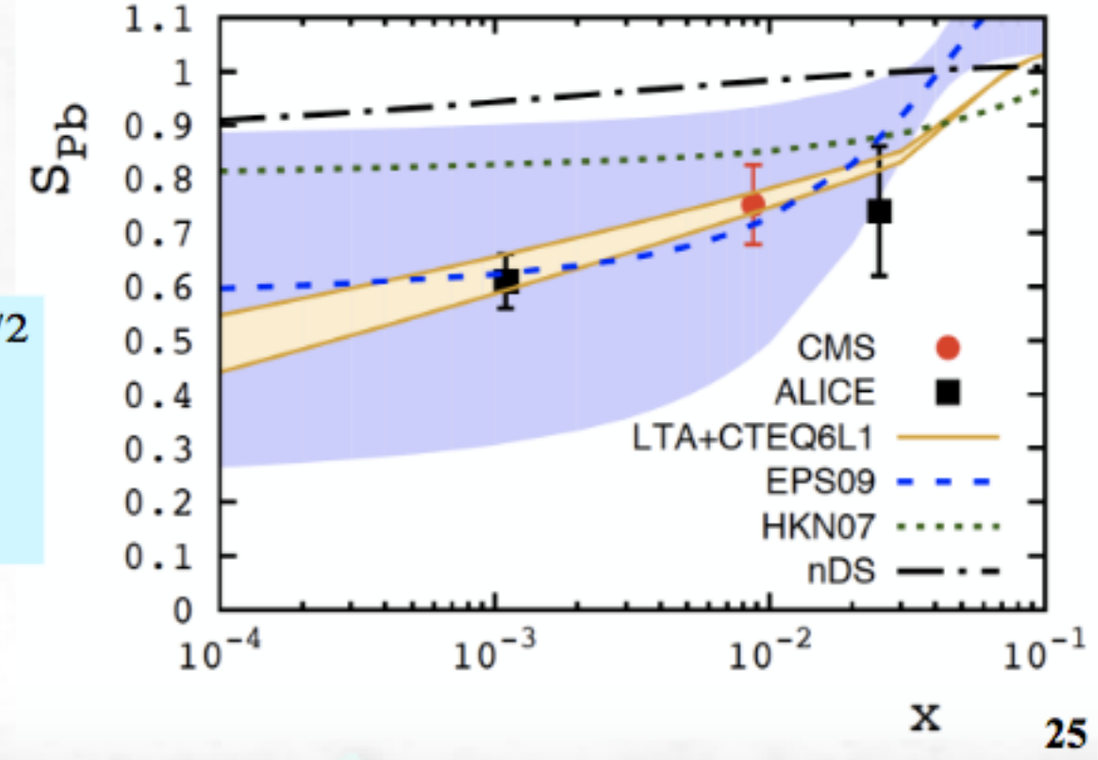
From Christian Weiss' talk

Leading Twist Shadowing Model



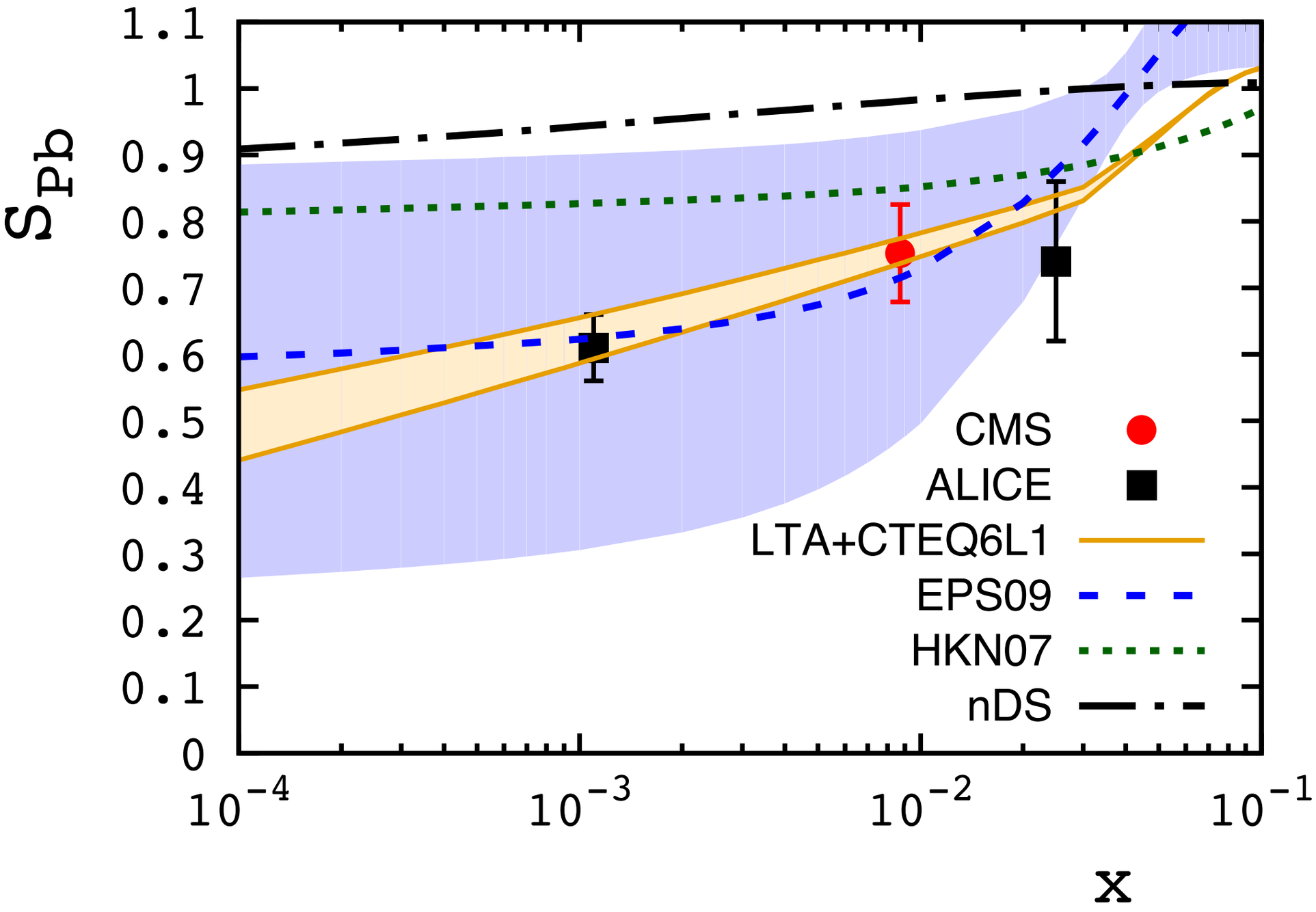
From Vadim Guzey's talk

$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb \to J/\psi Pb}}{\sigma^{IA}_{\gamma Pb \to J/\psi Pb}} \right]^{1/2}$$



Nuclear suppression factor in Pb (S)

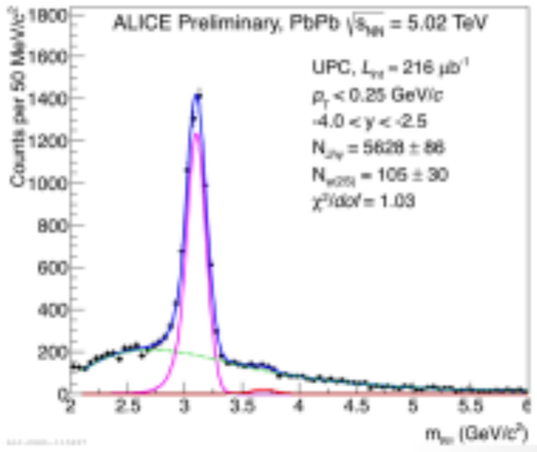
V. Guzey, et al.



Exclusive production of J/ψ and ψ(2S) in Pb+Pb

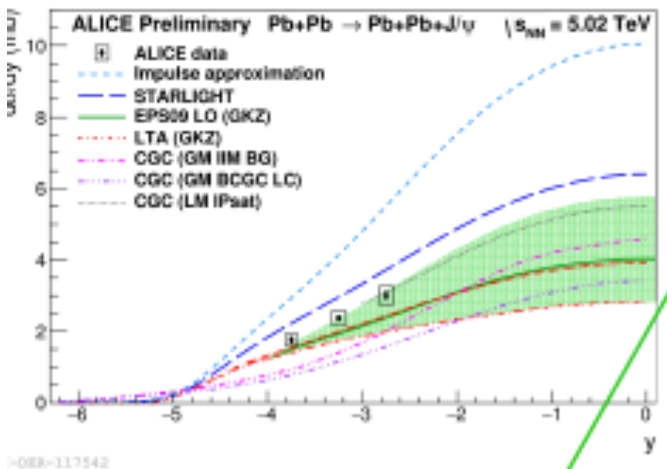
Kay Graham
ALICE

Run 2 data



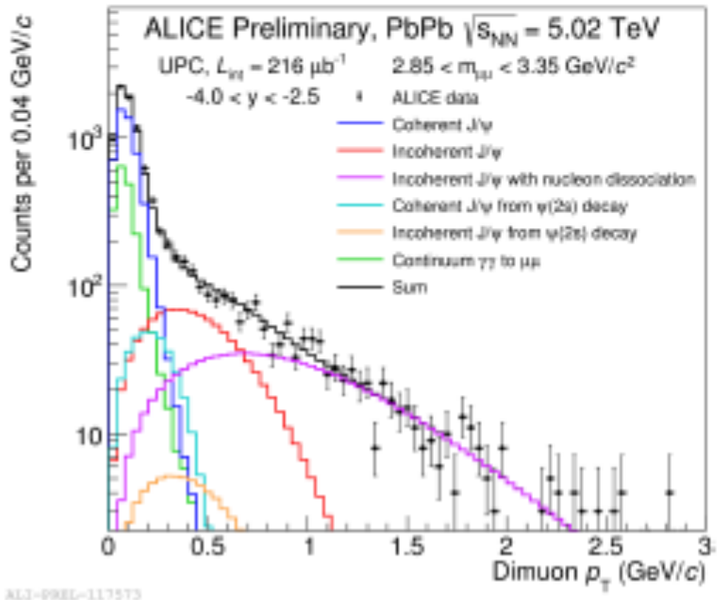
σ(ψ(2s))/σ(J/ψ) ≈0.166 ± 0.011 fits well with H1

data: 0.166 ± 0.007 (stat) ± 0.008 (syst) ± 0.007 (BR) [Phys.Lett.B541:251-264,2002]



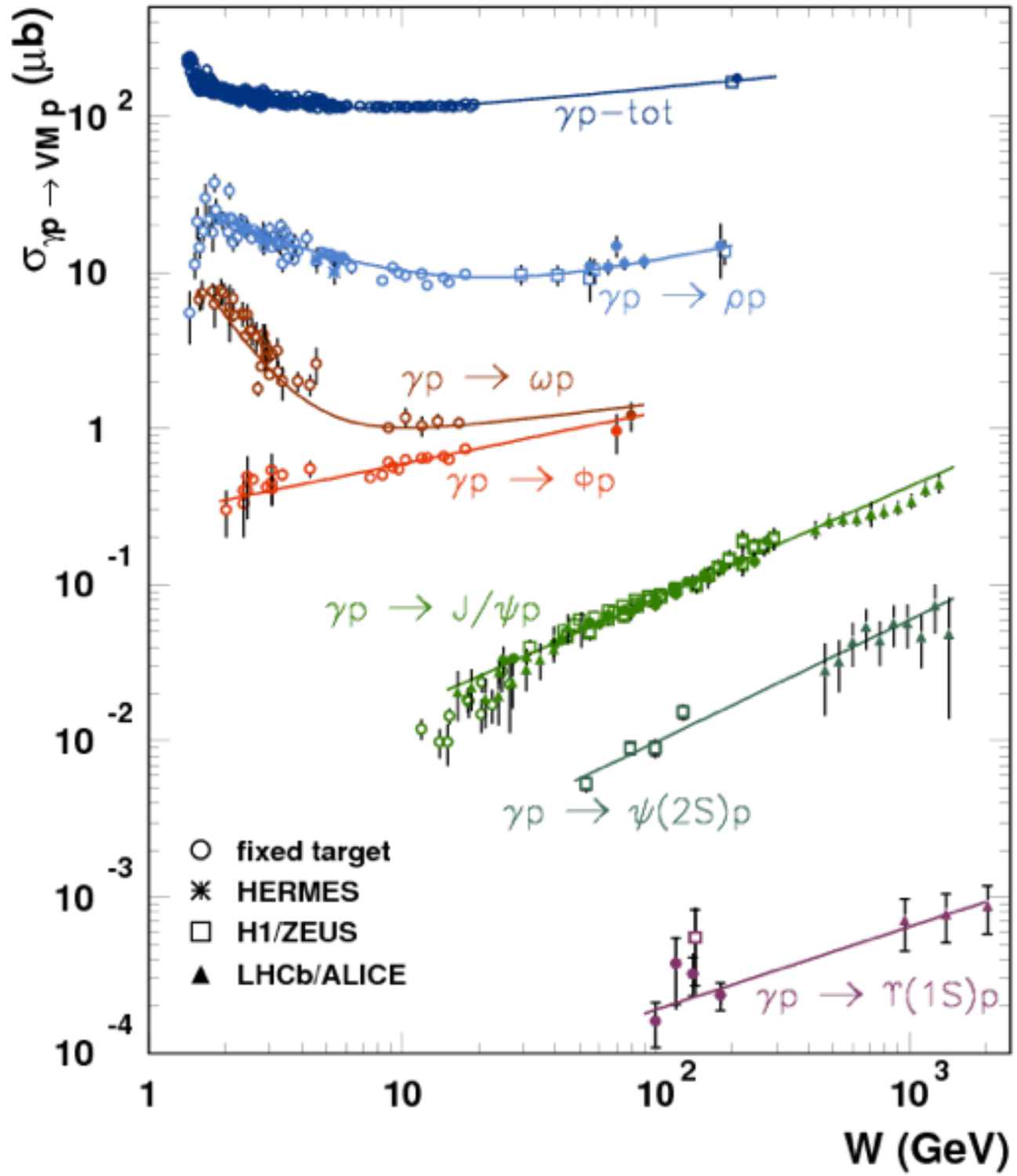
- Impulse approximation: no nuclear effects
- STARLIGHT: VDM + Glauber (Klein, Nystrand *et al* Comput. Phys. Commun. 212 (2017) 258)
- EPS09 L0: EPS09 shadowing (Guzey, Kryshen, Zhalov, PRC93 (2016) 055206)
- LTA: Leading Twist Approximation (Guzey, Kryshen, Zhalov, PRC93 (2016) 055206)
- CGC GM: color dipole model + IIM/BCGC (Goncalves, Machado *et al*, PRC 90 (2014) 015203, JPG 42 (2015) 105001)
- CGC LM: Color dipole model + IPSat (Lappi, H. Mäntysaari, PRC 83 (2011) 065202; 87 (2013) 032201)

Cross section consistent with moderate nuclear gluon shadowing

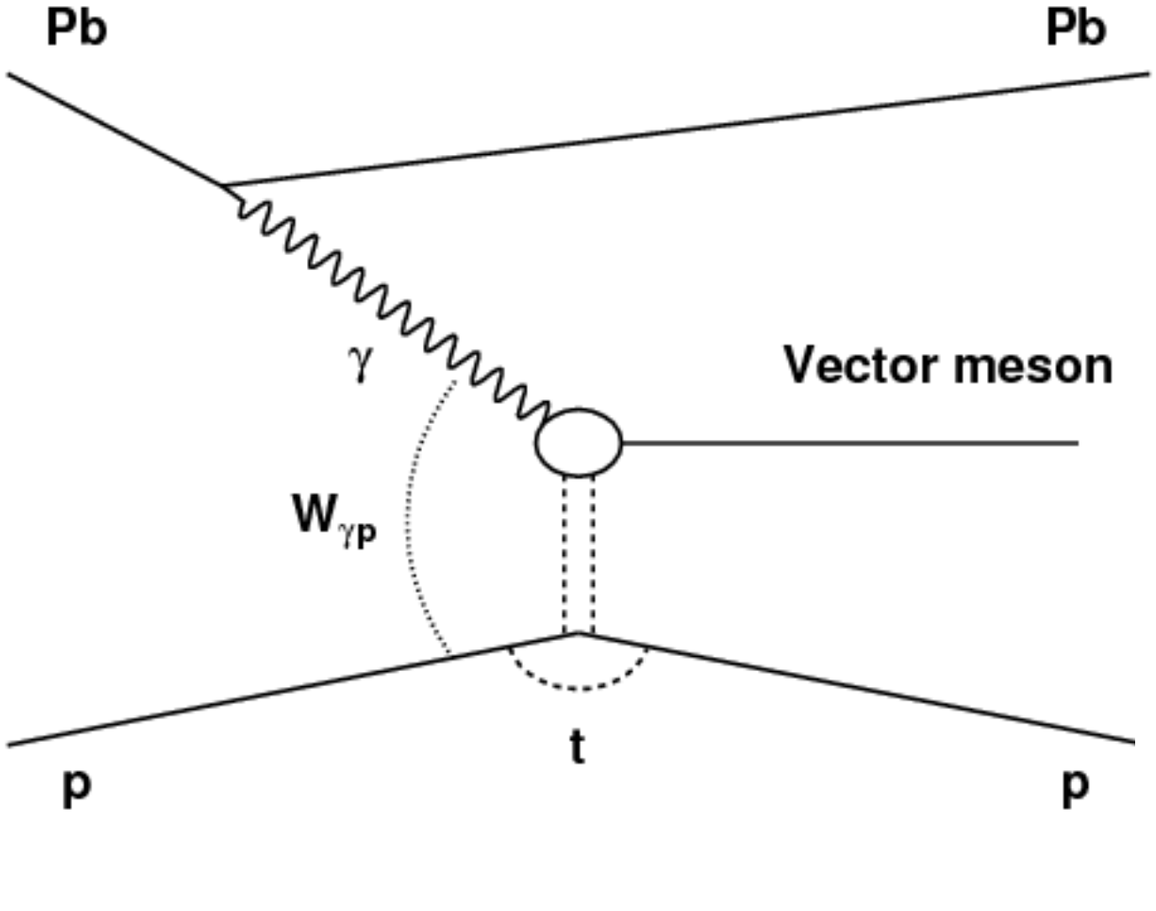


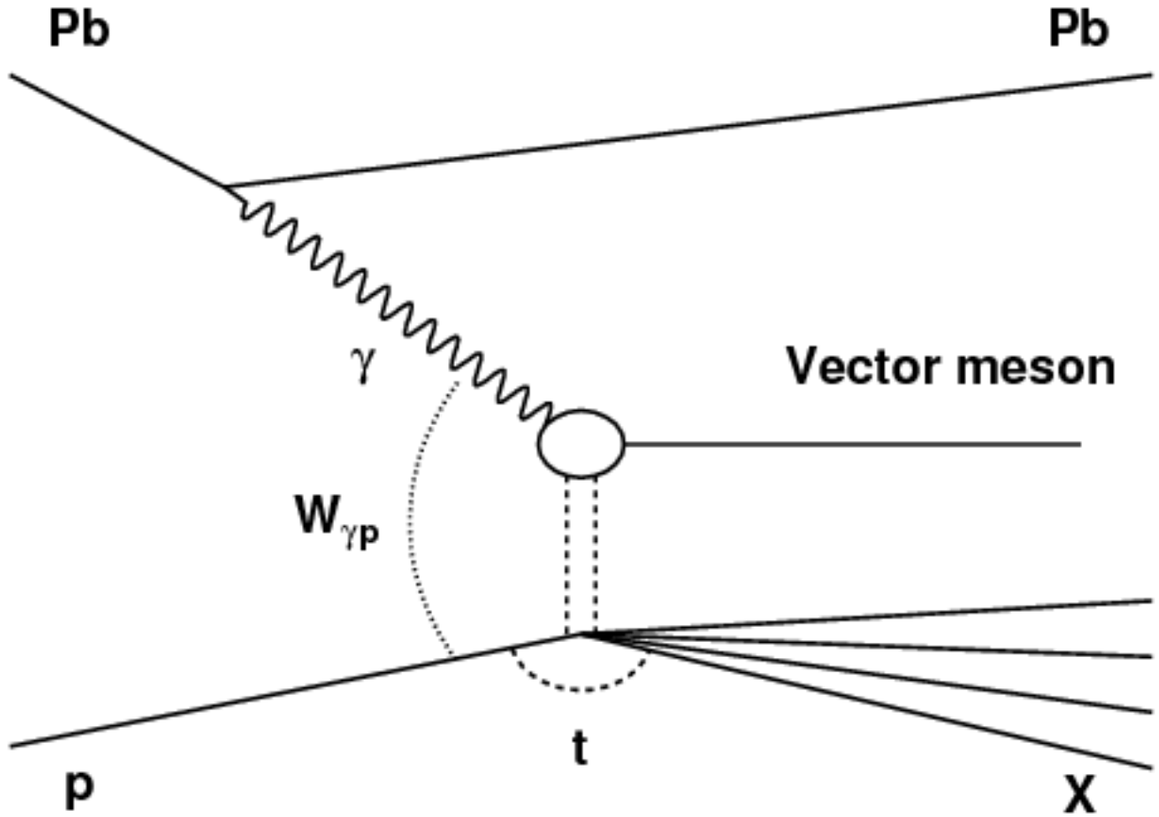
Both nucleon dissociation and incoherent production are needed to describe the data.

VM photoproduction data



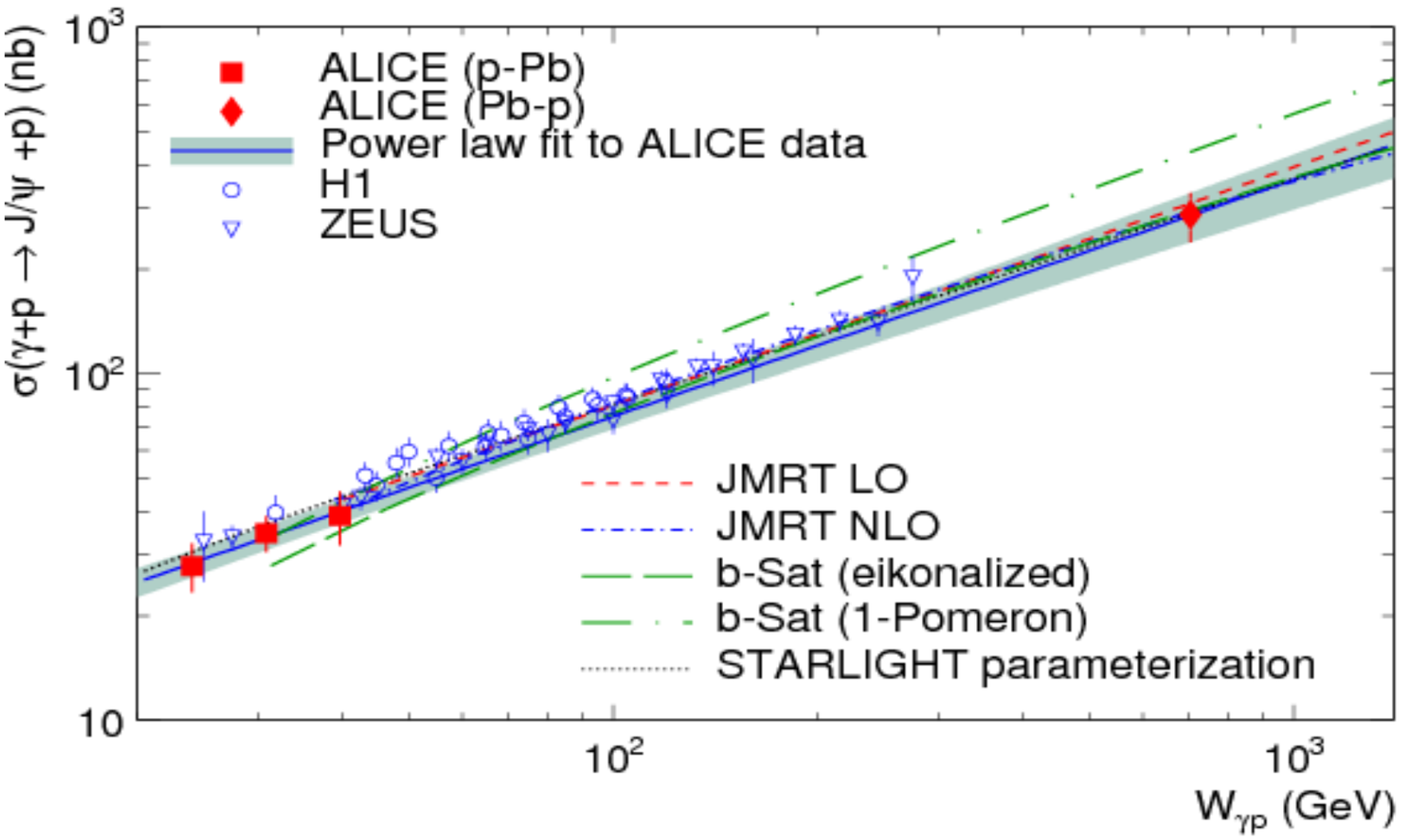
Vector meson photoproduction

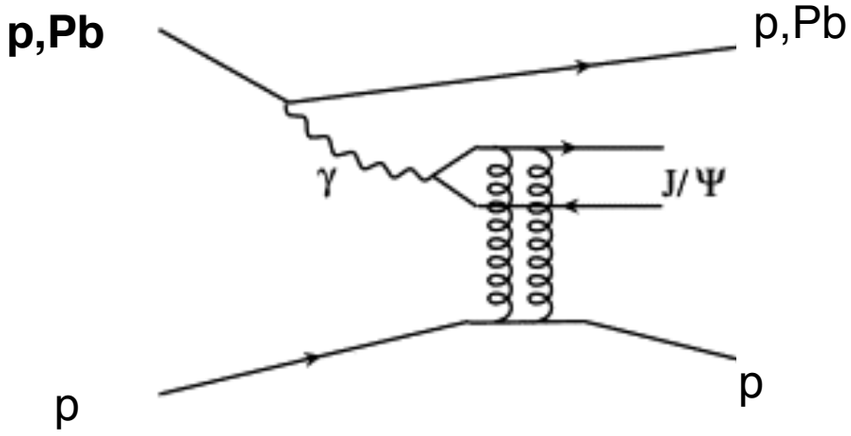




Exclusive J/psi photoproduction

Phys.Rev.Lett. 113 (2014) 23, 232504





$$\frac{d\sigma_{\gamma \mathrm{Pb} \to J/\psi \mathrm{Pb}}(t=0)}{dt} = \frac{16\,\Gamma_{ee}\pi^3}{3\alpha_{em}M_{J/\psi}^5}\left[\alpha_s(Q^2)xG_{\mathrm{Pb}}(x,Q^2)\right]^2$$

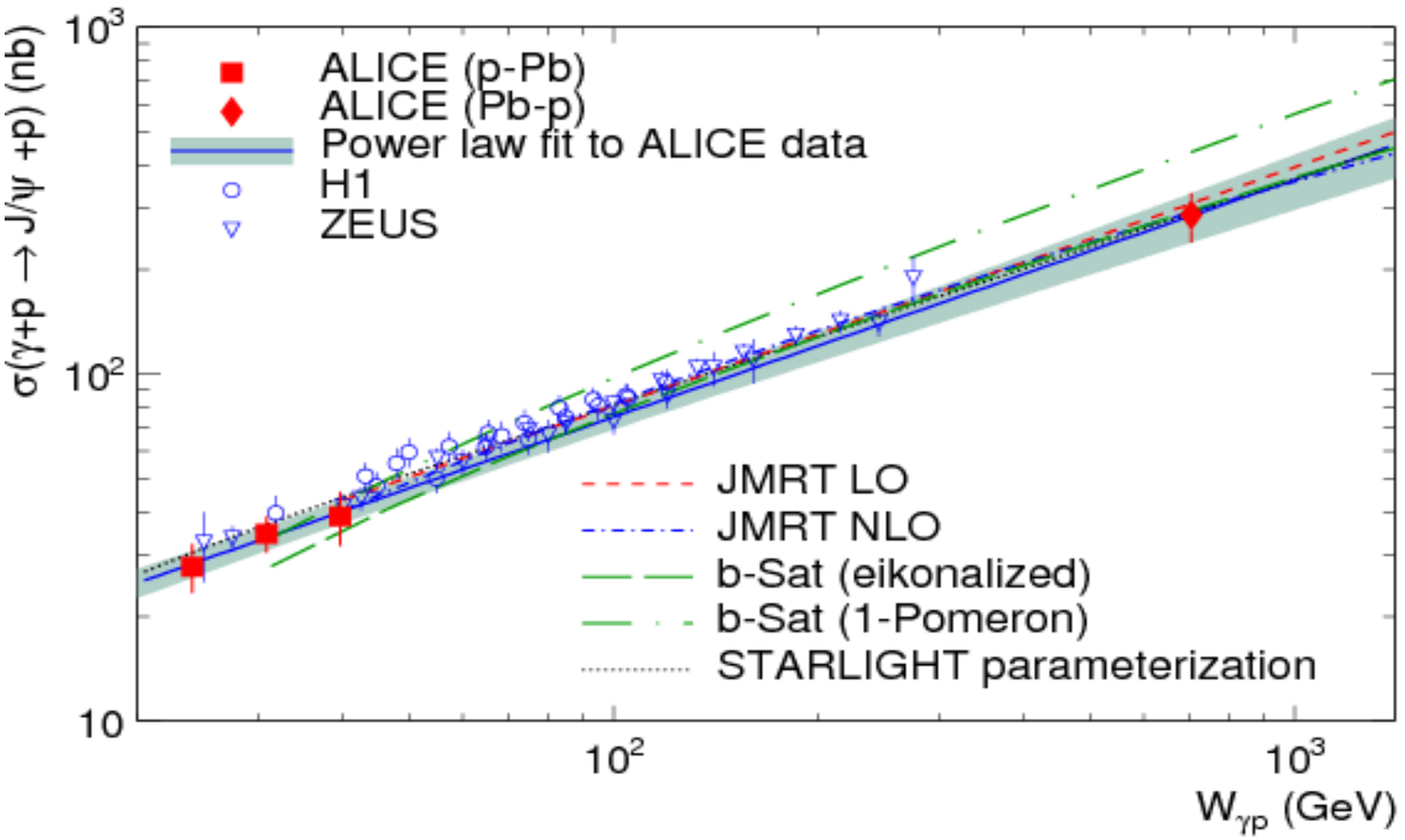
UPC VM in pp, p-Pb is a direct tool to measure saturation

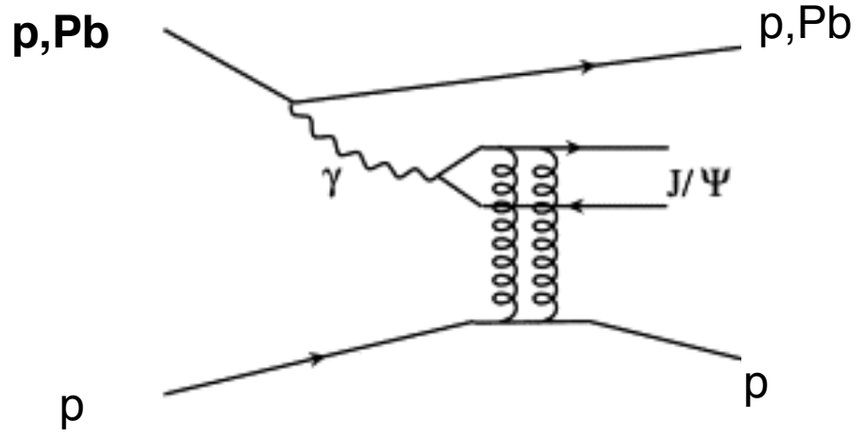
Bjorken $x \sim 10^{-2} - 10^{-5}$

accessible at LHC

Exclusive J/psi photoproduction

Phys.Rev.Lett. 113 (2014) 23, 232504





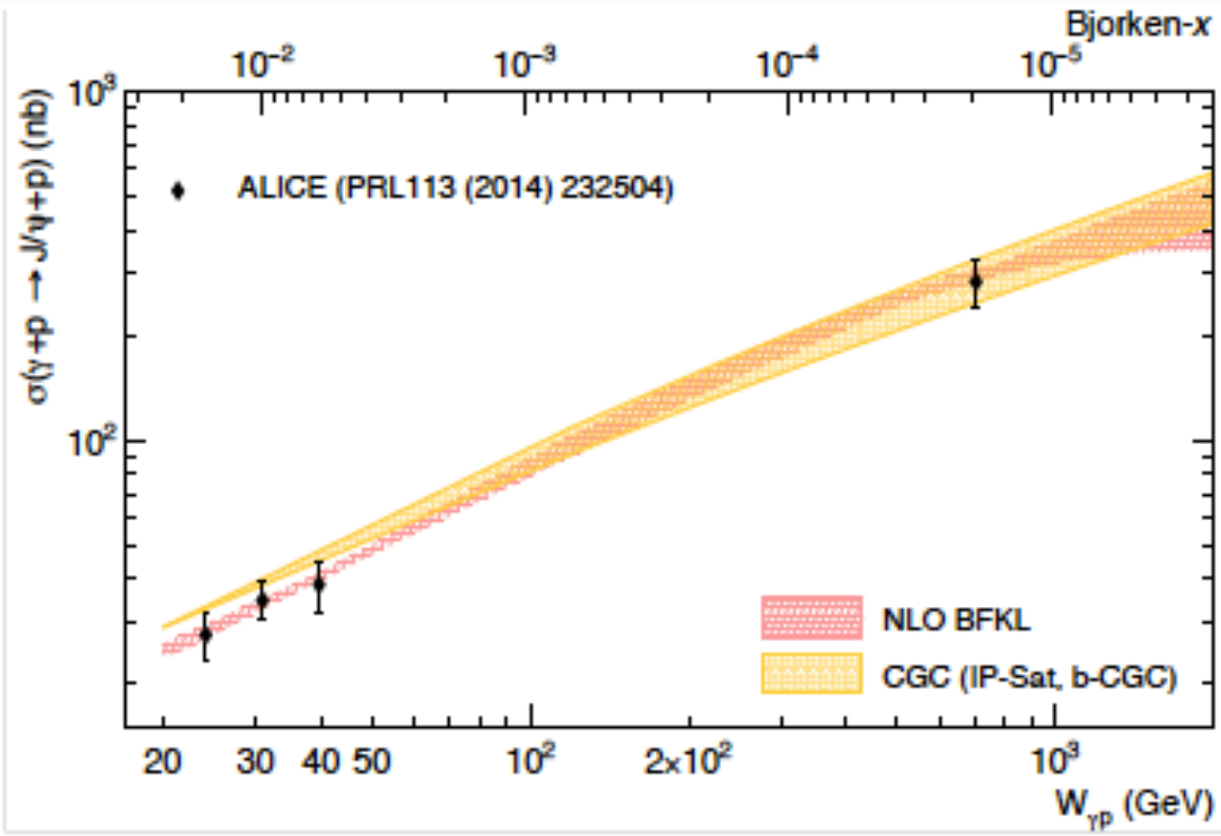
A natural explanation is that no change in the behaviour of the gluon PDF in the proton is observed between HERA and LHC energies" PRL 113 (2014) 232504.

Exclusive J/psi photoproduction

Phys.Rev.Lett. 113 (2014) 23, 232504

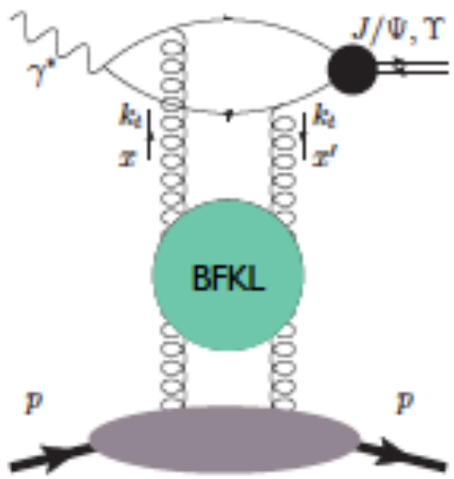
p,Pb

In pPb in ALICE, $W_{\gamma p}$ from 20 GeV to 1.5 TeV



Martin Hentschinski

NLL BFKL calculation - no saturation
Very good description of the data
Approaches with saturation work well too..



WG2: Low x and Diffraction

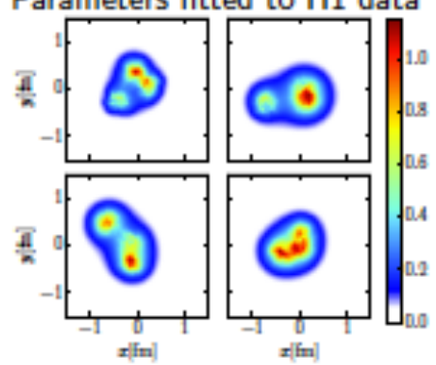
VM exclusive and dissociative production

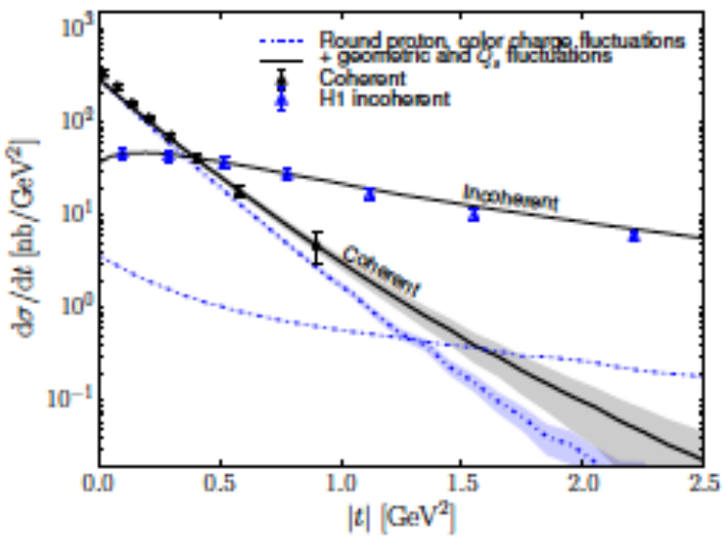
...so we do not know if gluon density *saturates* (yet), but maybe it *fluctuates*?

Heikki Mantysaari

Model the geometric fluctuations of density inside the proton

Parameters fitted to H1 data





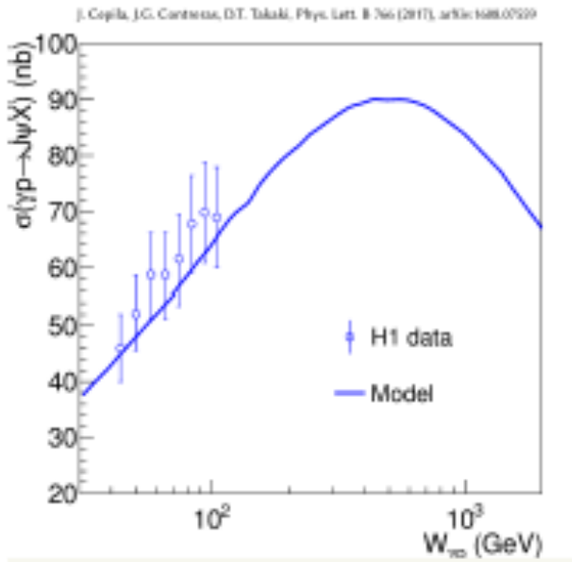
Coherent VM production: target stays intact

$$\frac{d\sigma^{\gamma^* p \to Vp}}{dt} \sim |\langle A(x, Q^2, t)\rangle|^2$$

Incoherent VM diffraction: target breaks up.

$$\frac{d\sigma^{\gamma^* p \to Vp^*}}{dt} \sim \langle |A(x, Q^2, t)|^2\rangle - |\langle A(x, Q^2, t)\rangle|^2$$

Jan Cepila

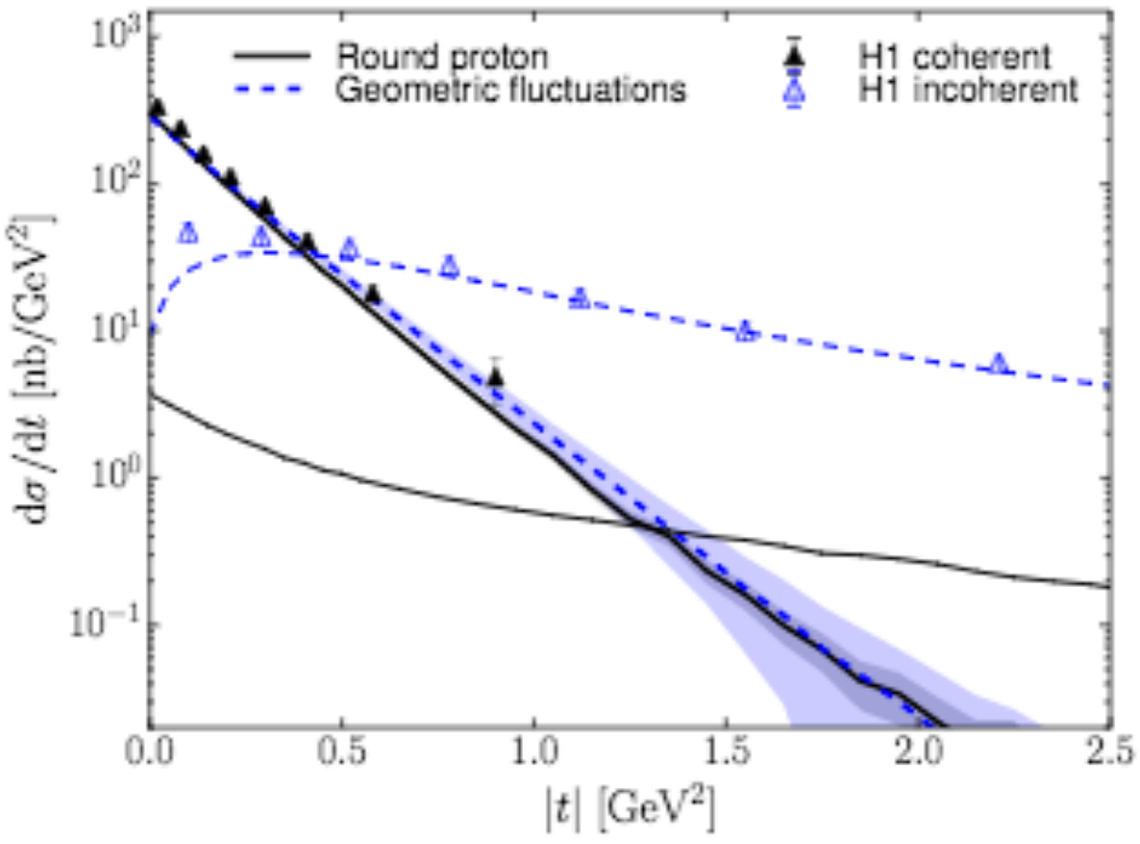


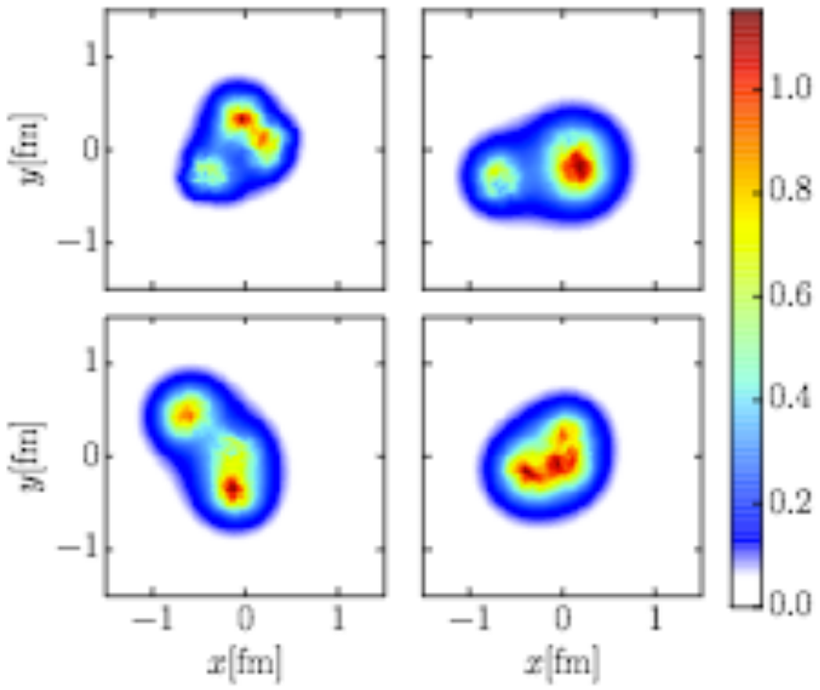
At high energies the incoherent cross section decreases with energy, due to increase and overlap of hotspots

WG2: Low x and Diffraction

IP-Glasma and HERA data

Include color charge fluctuation, parameters fitted to H1 data

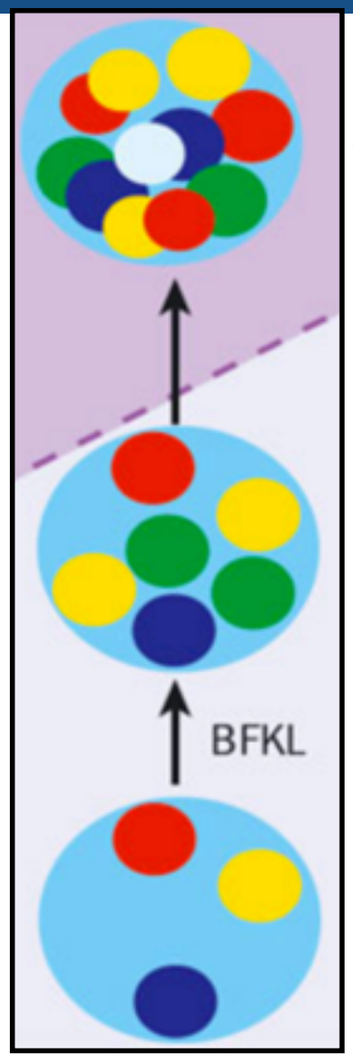


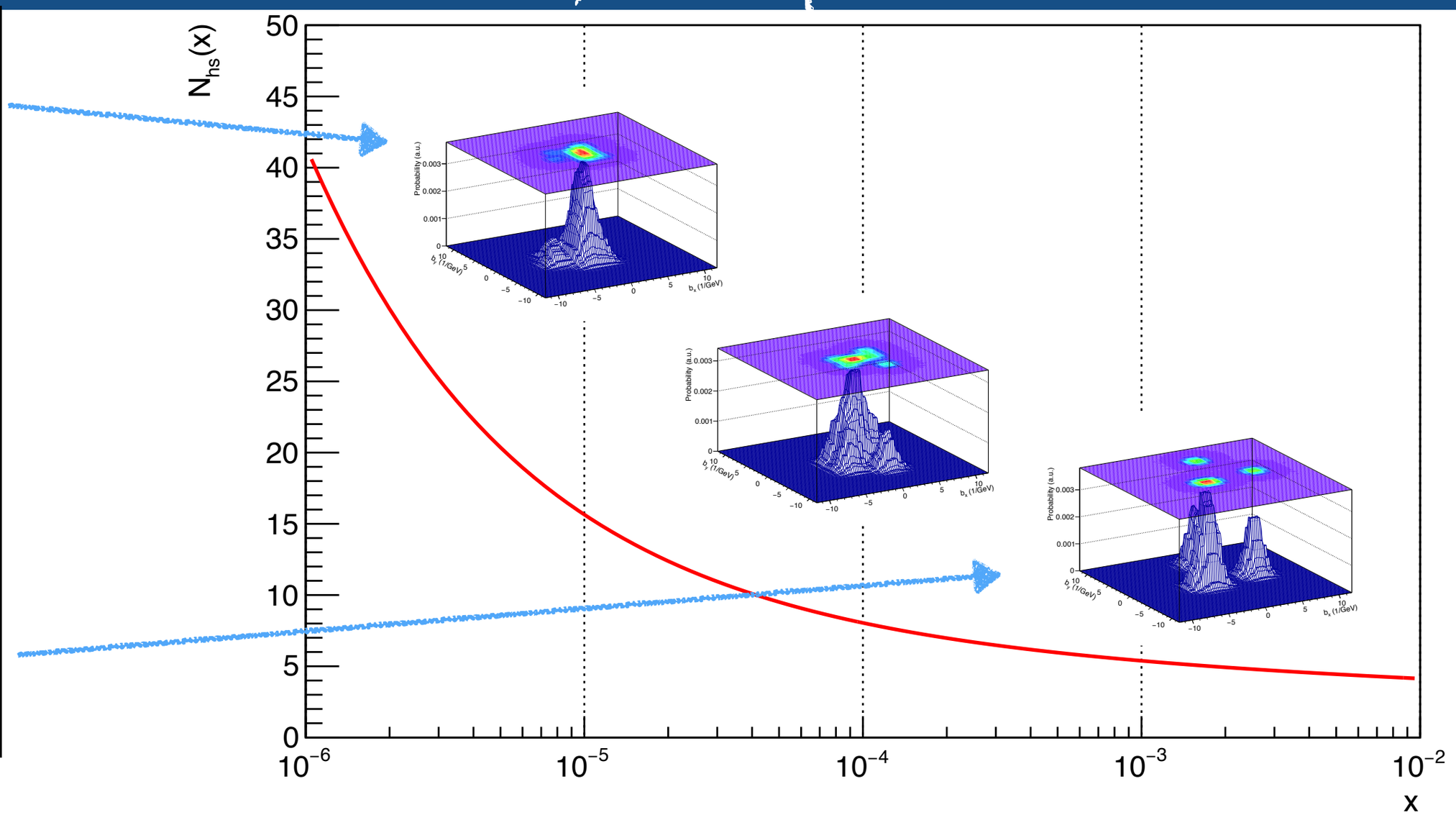


H.M., B. Schenke, PRD94 (2016), 034042

- Initial condition for pA hydro, good description of v_2 and v_3 data!

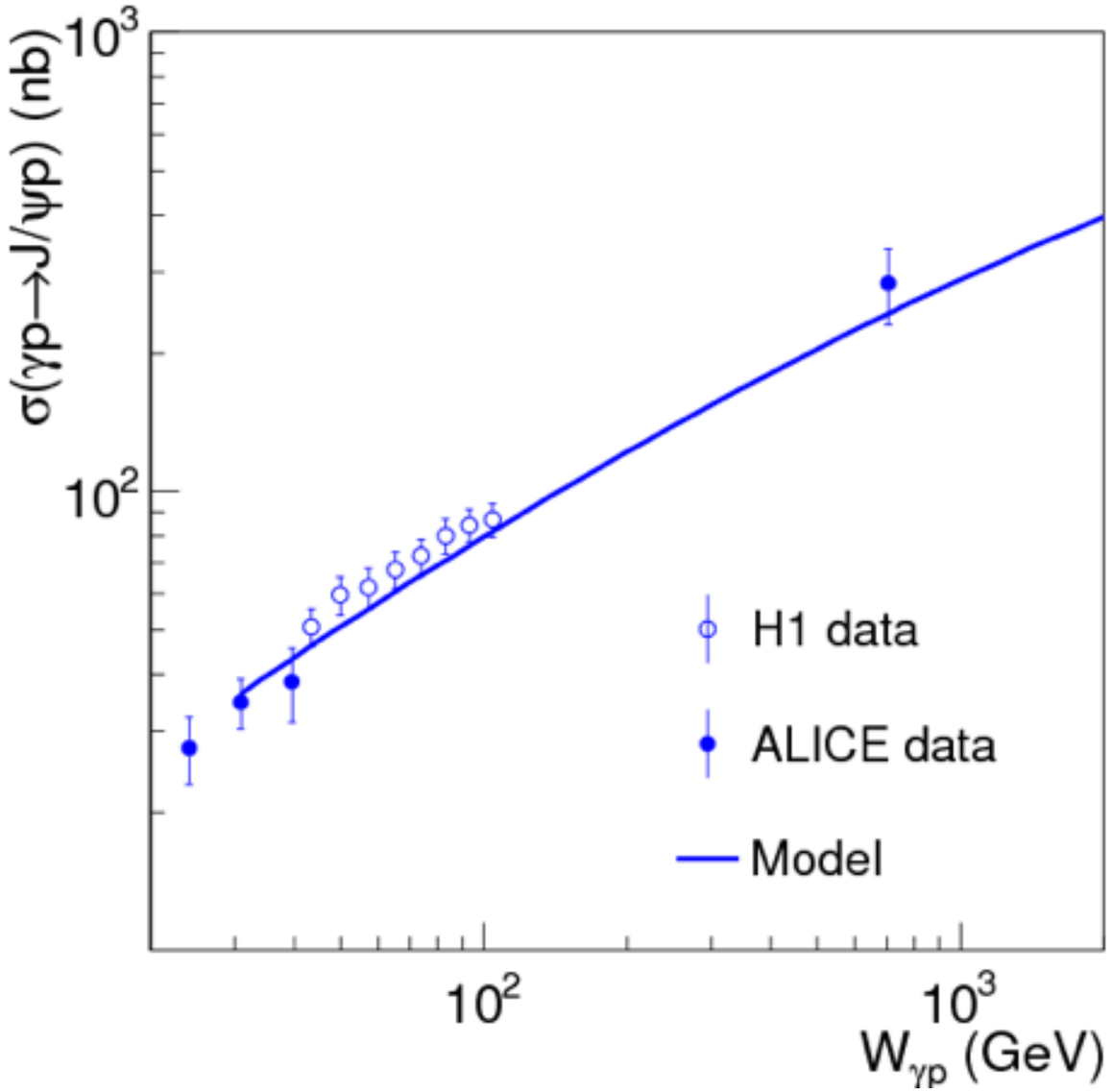
Number of hot spots

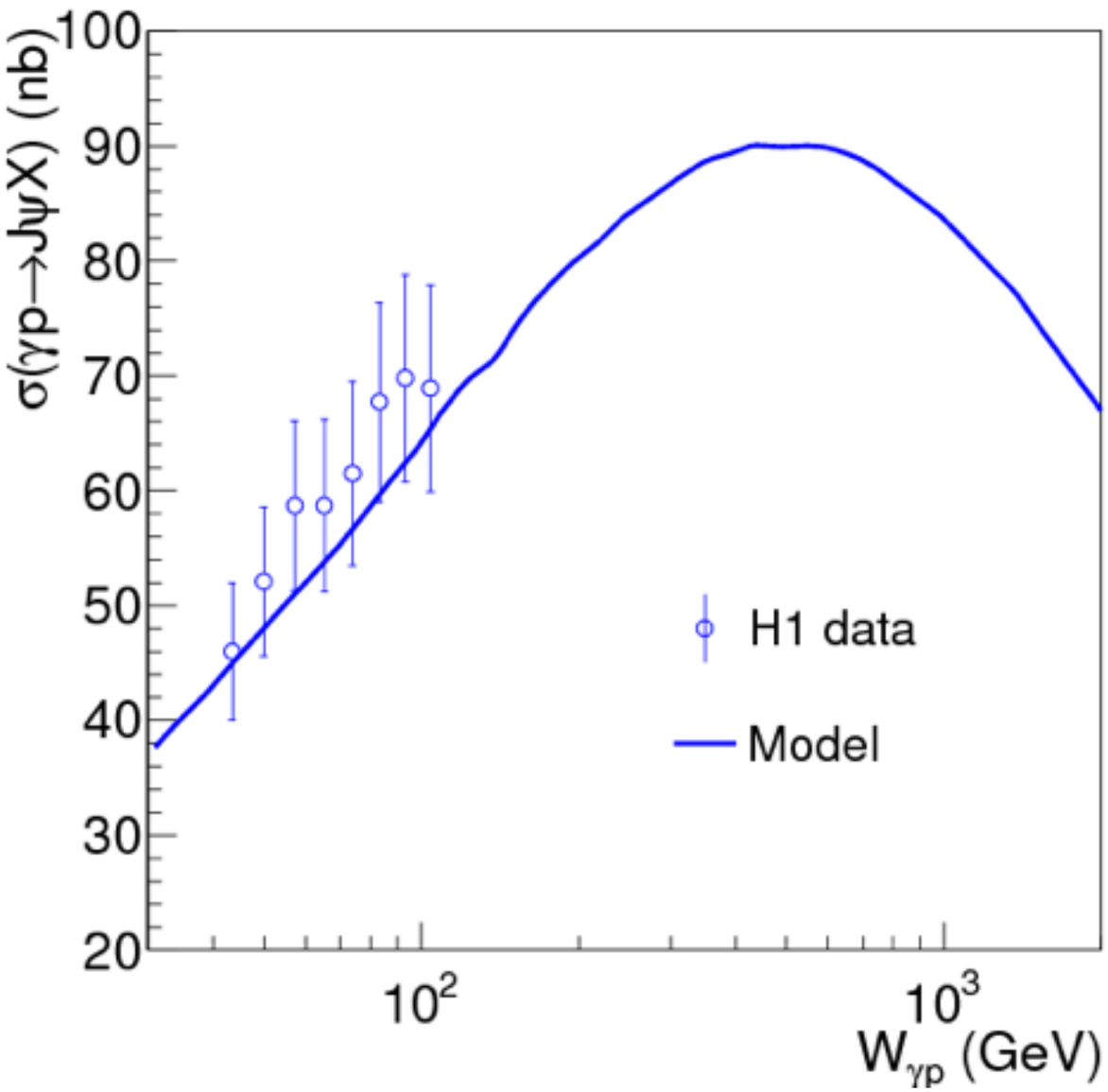




Energy dependence of dissociative photoproduction: ***signature of gluon saturation***

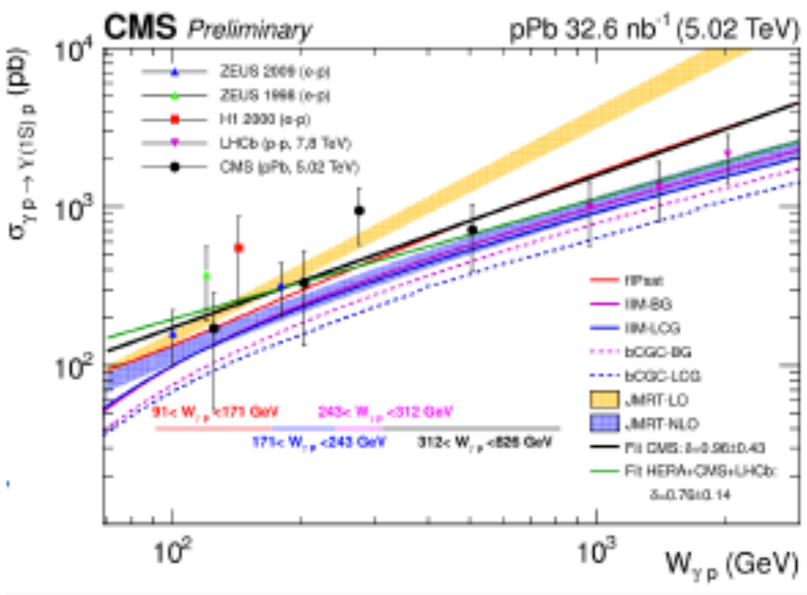
J. Cepina et al. Phys. Lett. B766 (2017) 186-191





Exclusive production of ψ(2s) and ϒ

Alexander Bylinkin
CMS



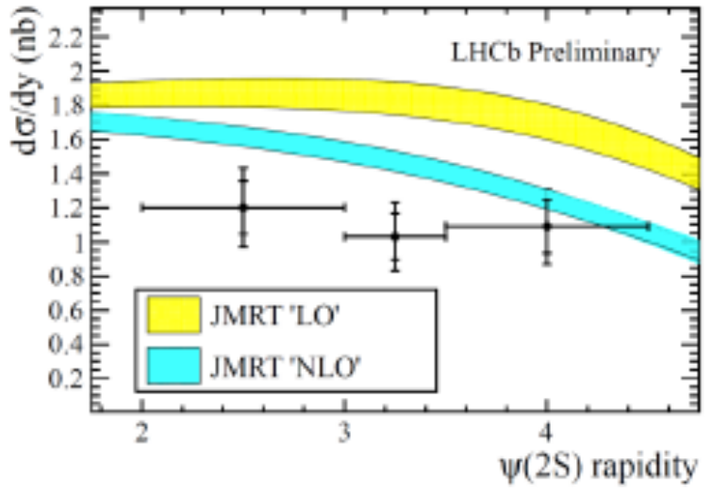
A fit with power-law **A X (W/400)$^{\delta}$** to the CMS data
δ = (0.96 ± 0.43) , A = 655 ± 196
Data compatible with power-law dependence of σ($W_{\gamma p}$), disfavours LO pQCD predictions

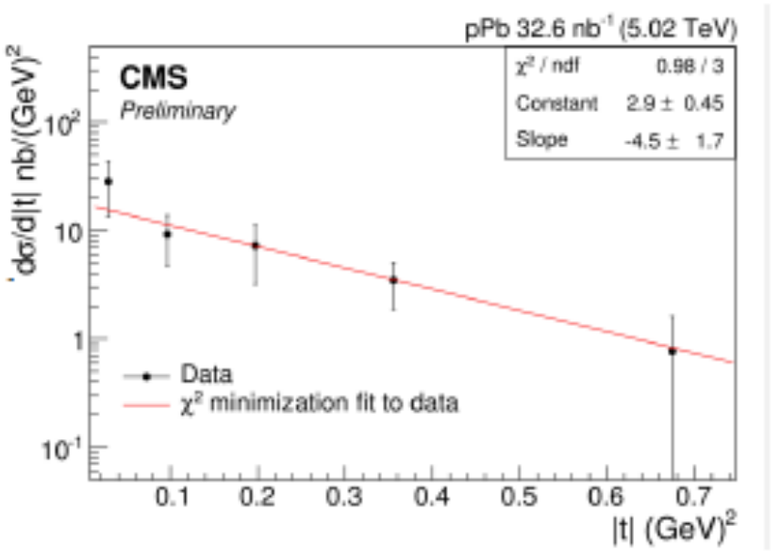
Still missing: energy dependence of t distribution for vector meson

Bartłomiej Rachwał
LHCb

Exclusive production ψ(2s) at 13 TeV

$\sigma_{\psi(2S)\to\mu^+\mu^-}\ (2.0 < \eta(\mu^{\pm}) < 4.5) = 9.4 \pm 1.3(stat) \pm 0.5(sys) \pm 0.4\text{pb}$

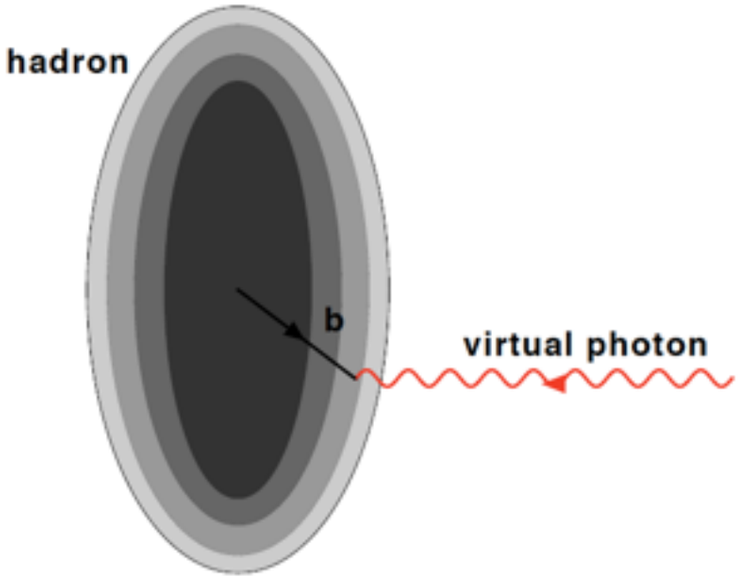


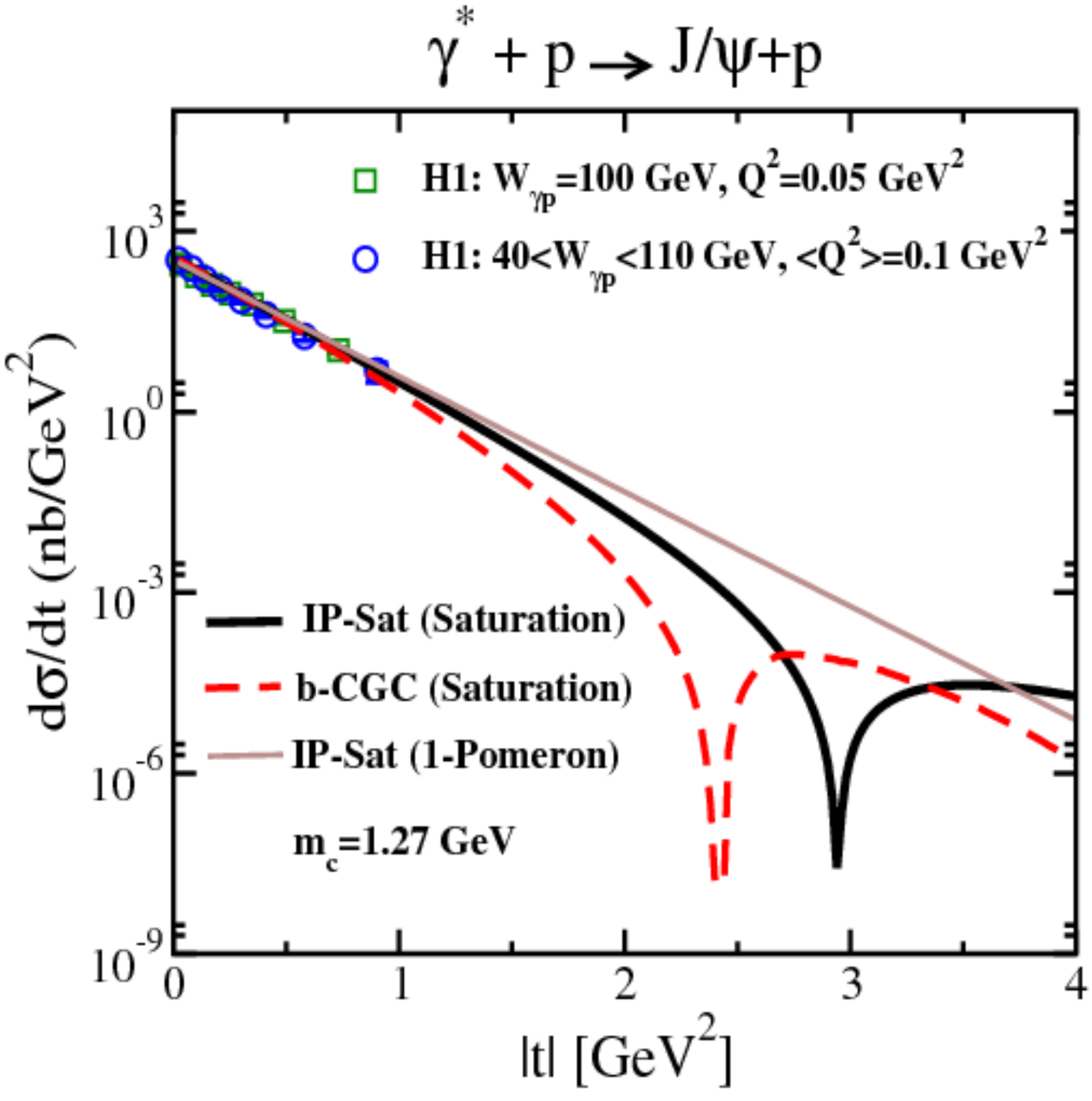


WG2: Low x and Diffraction

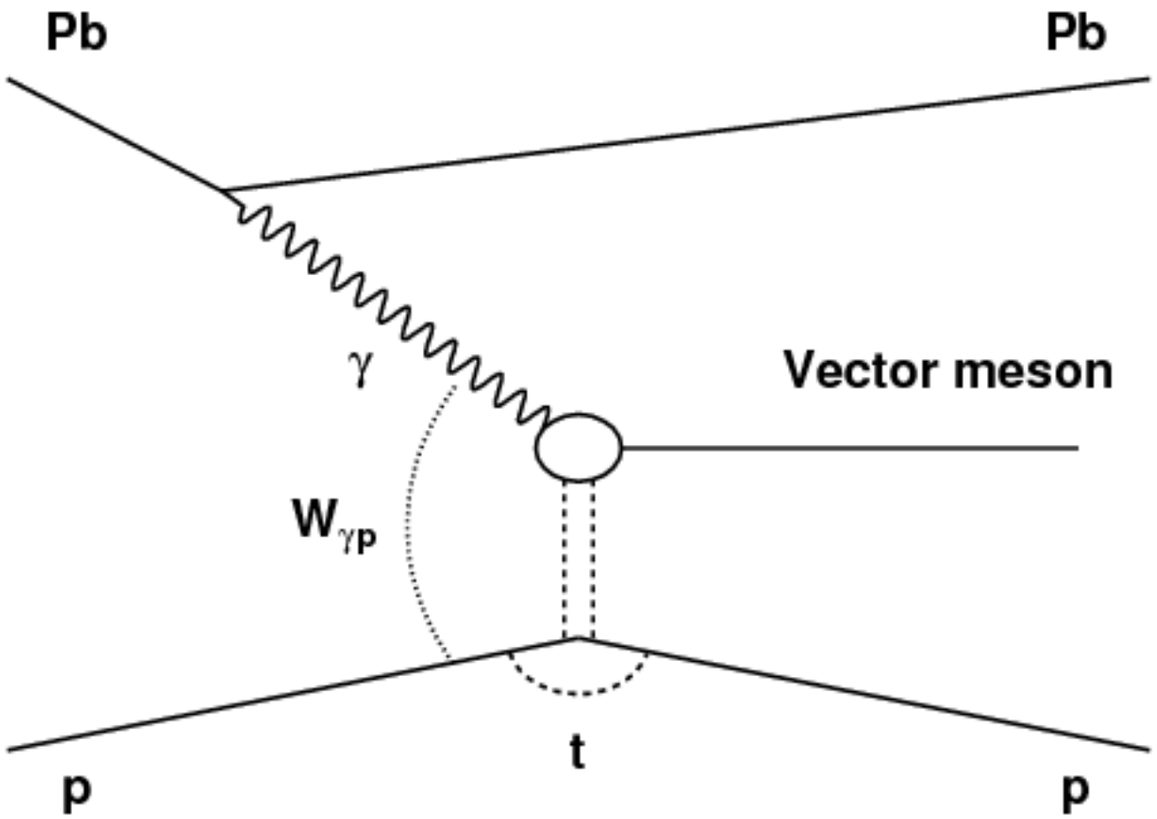
t-distribution

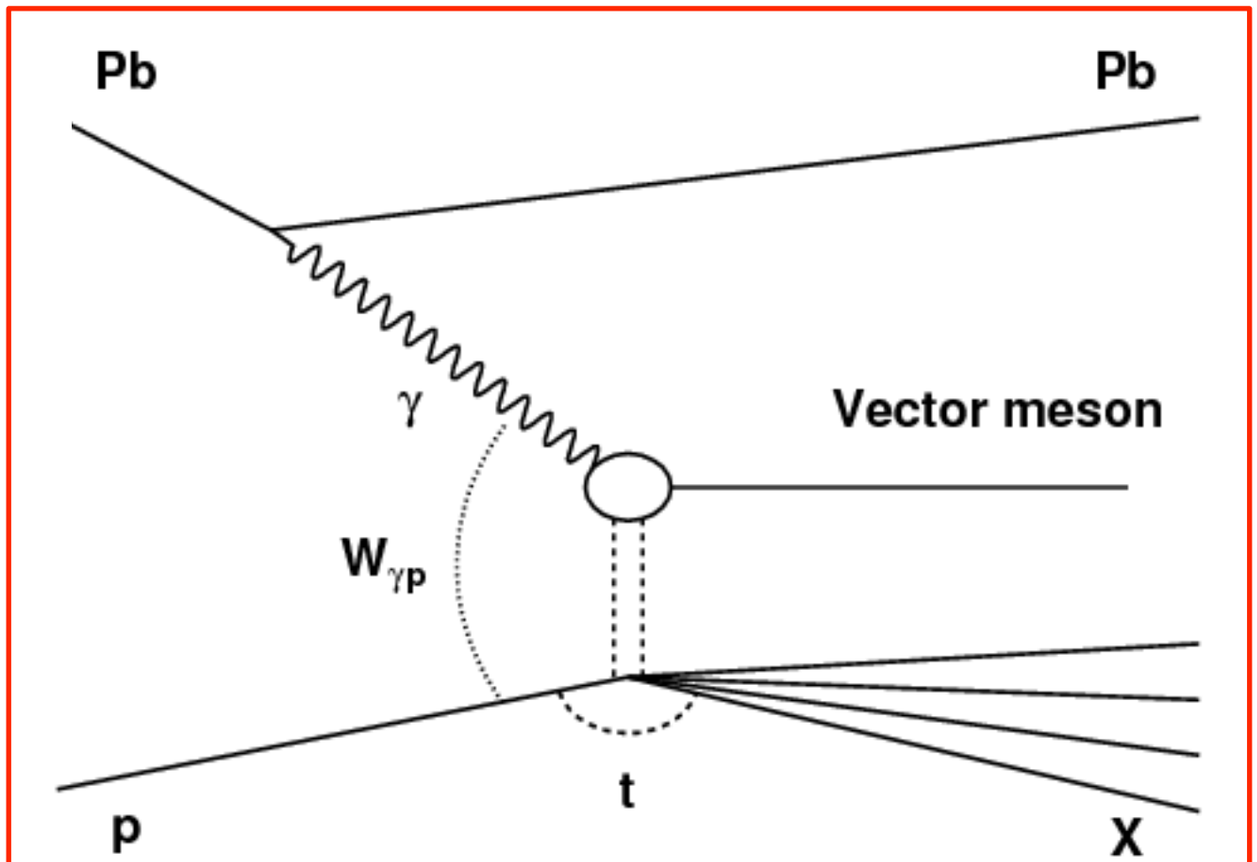
- t-differential measurements give a gluon tranverse mapping of the hadron/ nucleus.



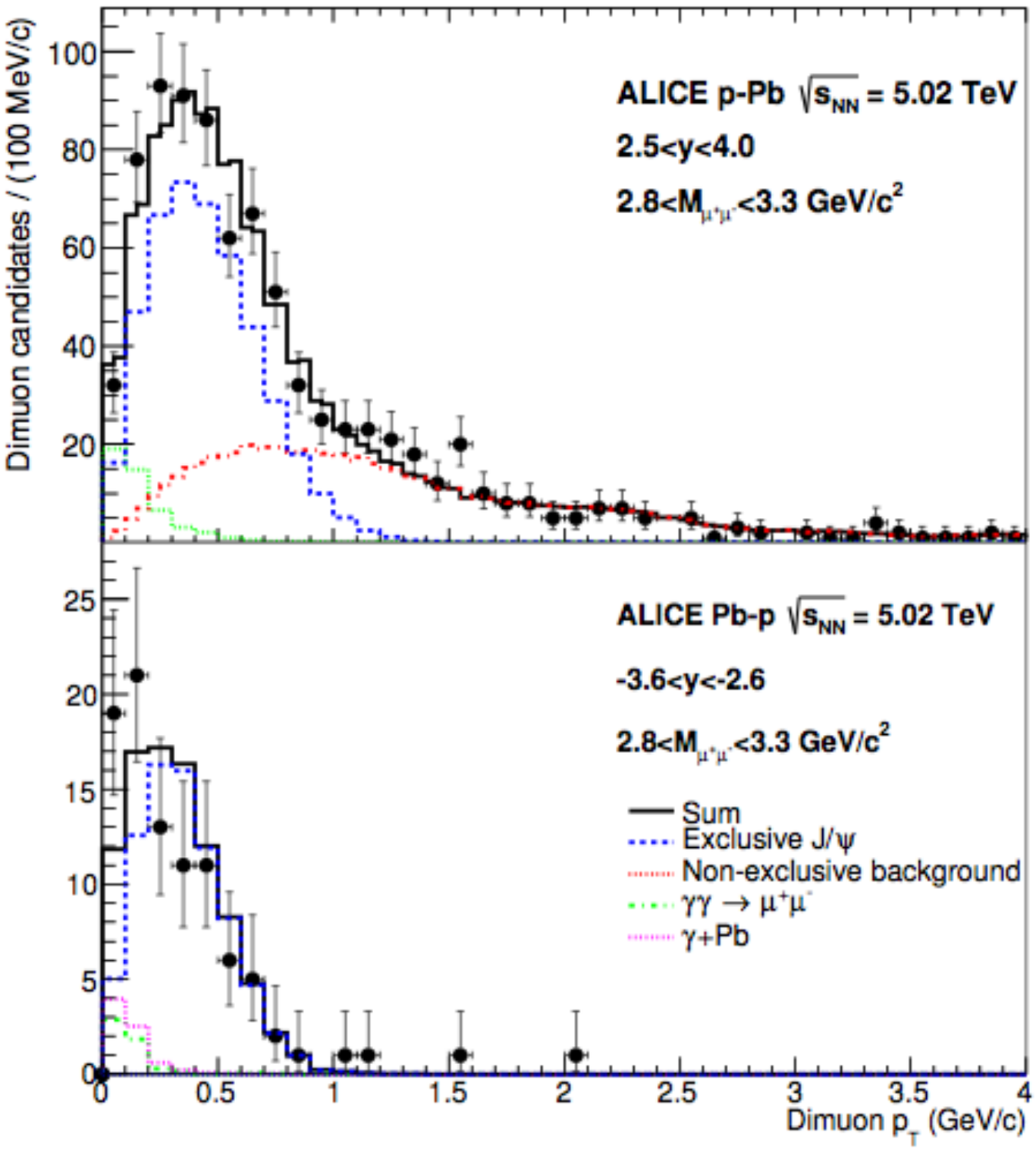


Vector meson photoproduction





Exclusive J/psi in p-Pb



Phys.Rev.Lett. 113 (2014) 23, 232504

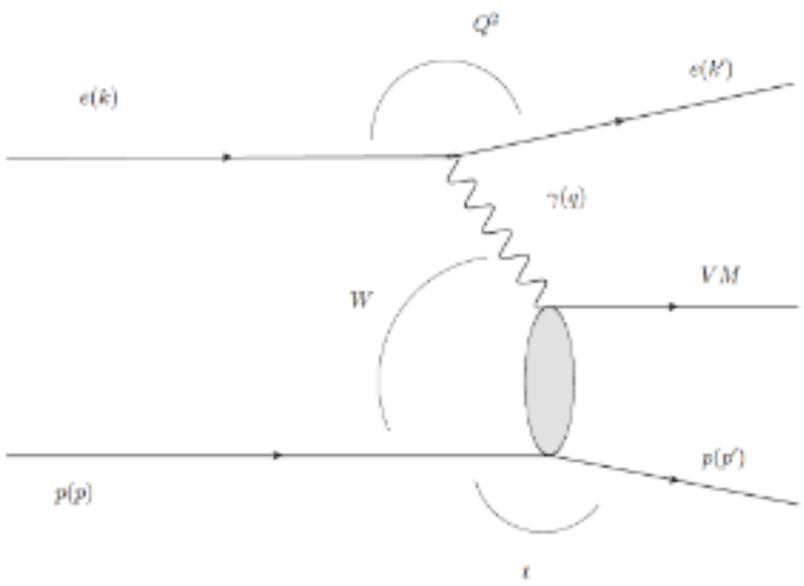
Data well described by templates

Energy dependence is clearly visible

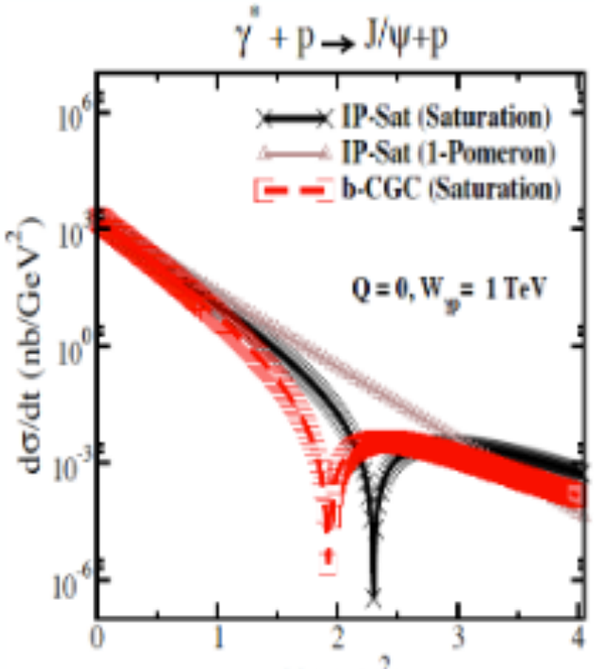
Low W_{gp} energy point
$\langle W_{gp} \rangle \sim 30$ GeV

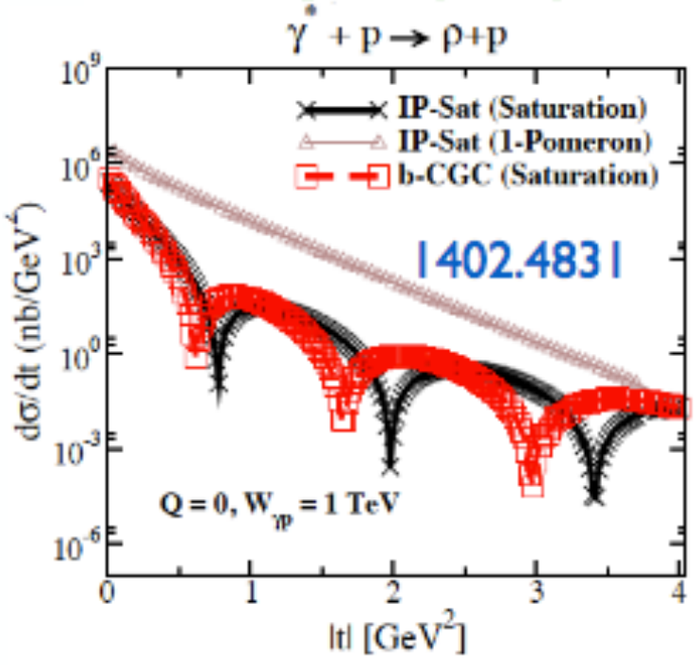
High W_{gp} energy point
$\langle W_{gp} \rangle \sim 700$ GeV

Elastic VM production in ep (III):

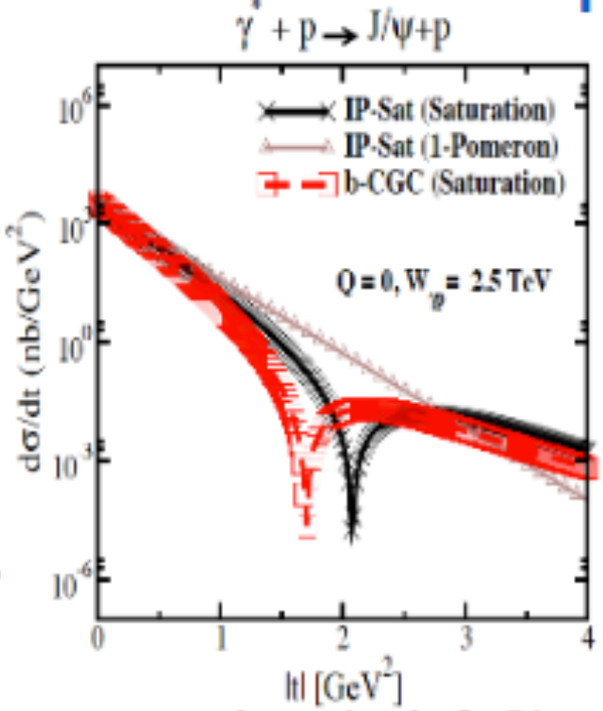


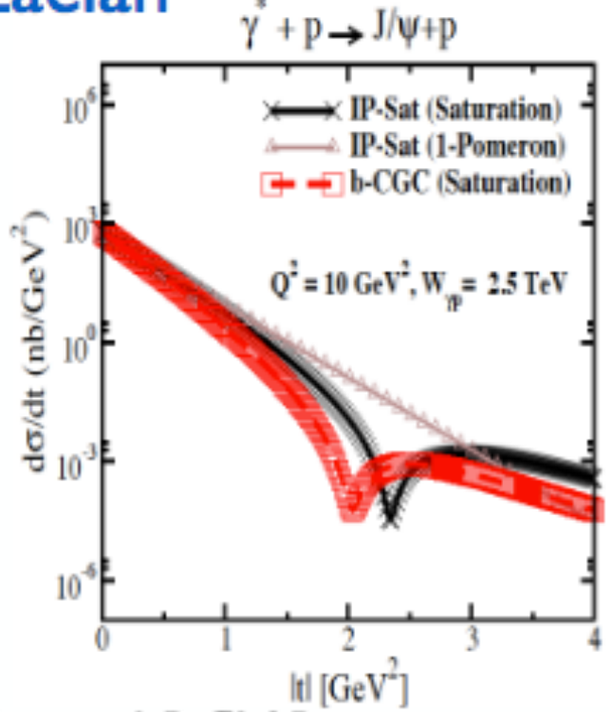
- Position of the dip and its evolution determined by the transverse structure of proton/ nuclei; its shrinking is natural in non-linear evolution towards the black disk (unitarity) limit.





Rezaeian





N.Armesto, 16.01.2017 - Small-x Physics in ep, eA and pA: 3. Physics beyond DGLAP. 17

Vector meson photoproduction in UPC Pb-Pb

Neutron dependence

$$d\sigma(\text{total})/dy = d\sigma(0\text{n}0\text{n})/dy + 2d\sigma(0\text{n}\text{X}\text{n})/dy + d\sigma(\text{X}\text{n}\text{X}\text{n})/dy$$

There is a factor 2 since the neutron and the coherent J/ψ are independent processes (confirmed by data)

Two components:

High-x: **J/ψ and the emitted neutrons: same rapidity hemisphere**

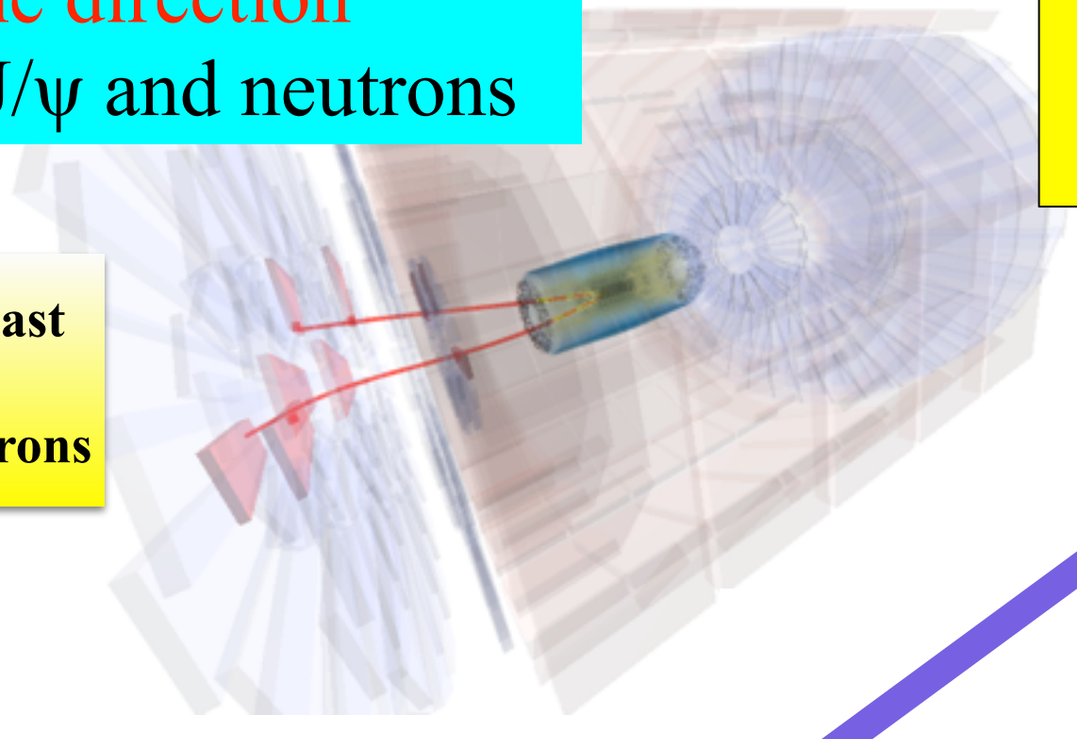
Low-x: **J/ψ and the emitted neutrons: opposite rapidity hemisphere**

Two different type of topologies

Same direction
for J/ψ and neutrons

No neutrons

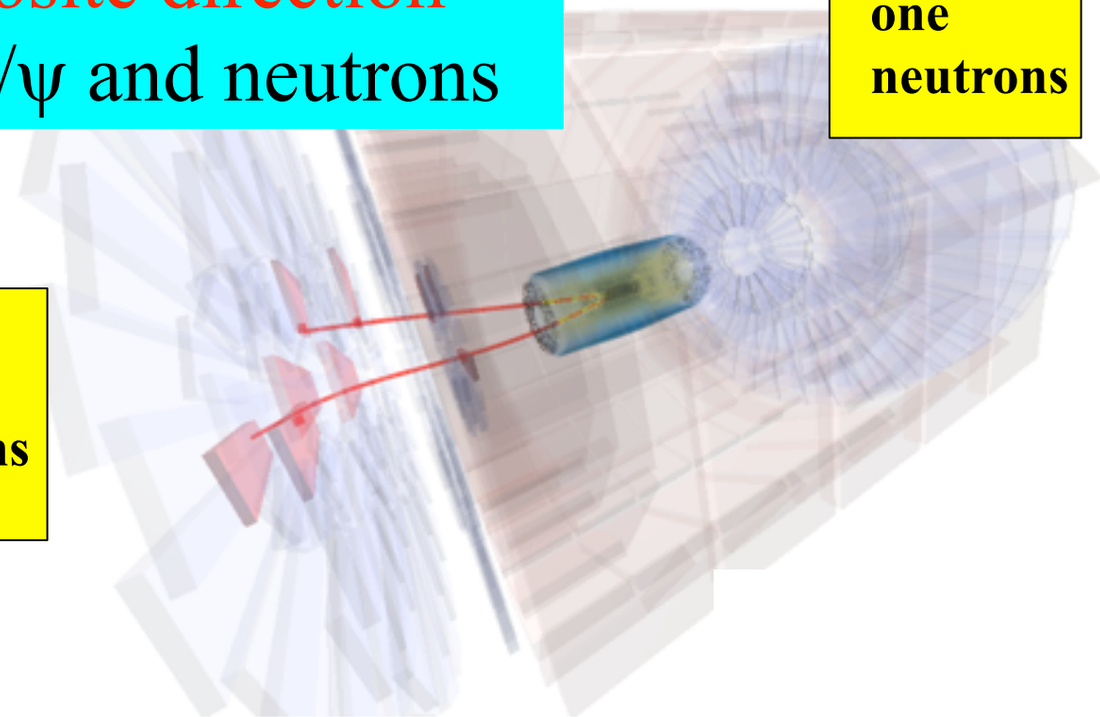
At least one neutrons



Opposite direction
for J/ψ and neutrons

At least one neutrons

No neutrons

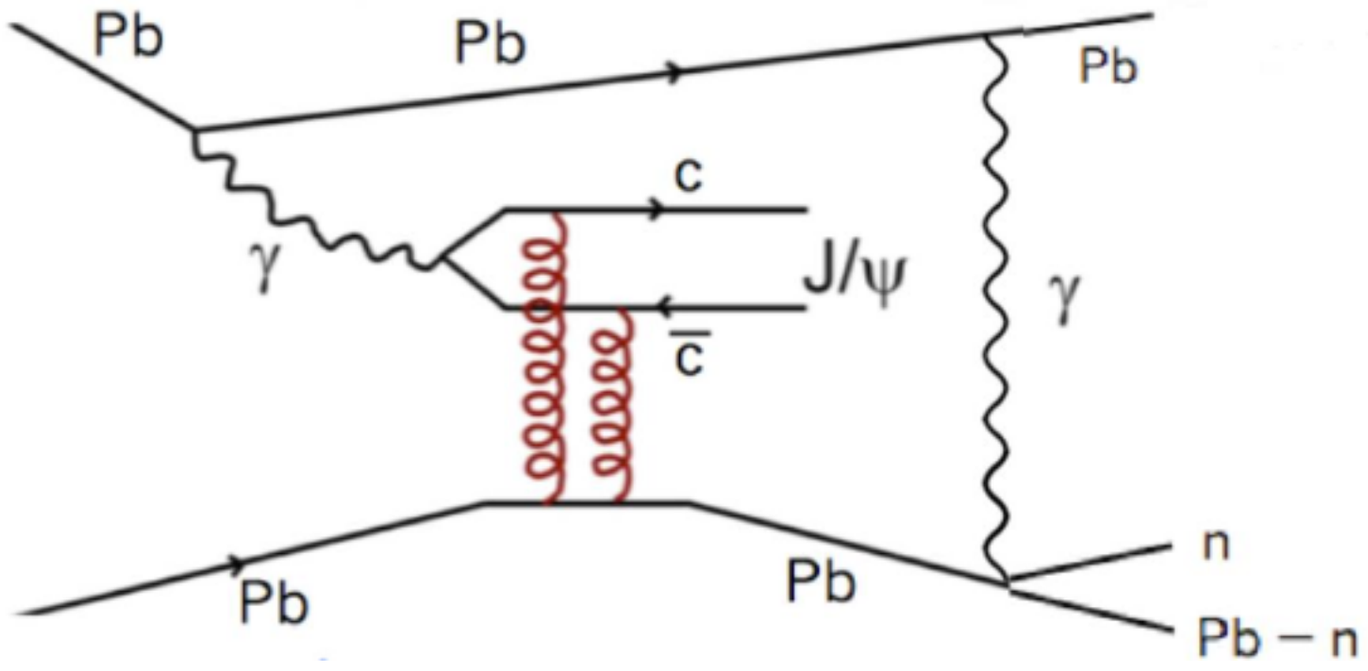


Incoherent photoproduction in UPC Pb-Pb

Total cross section

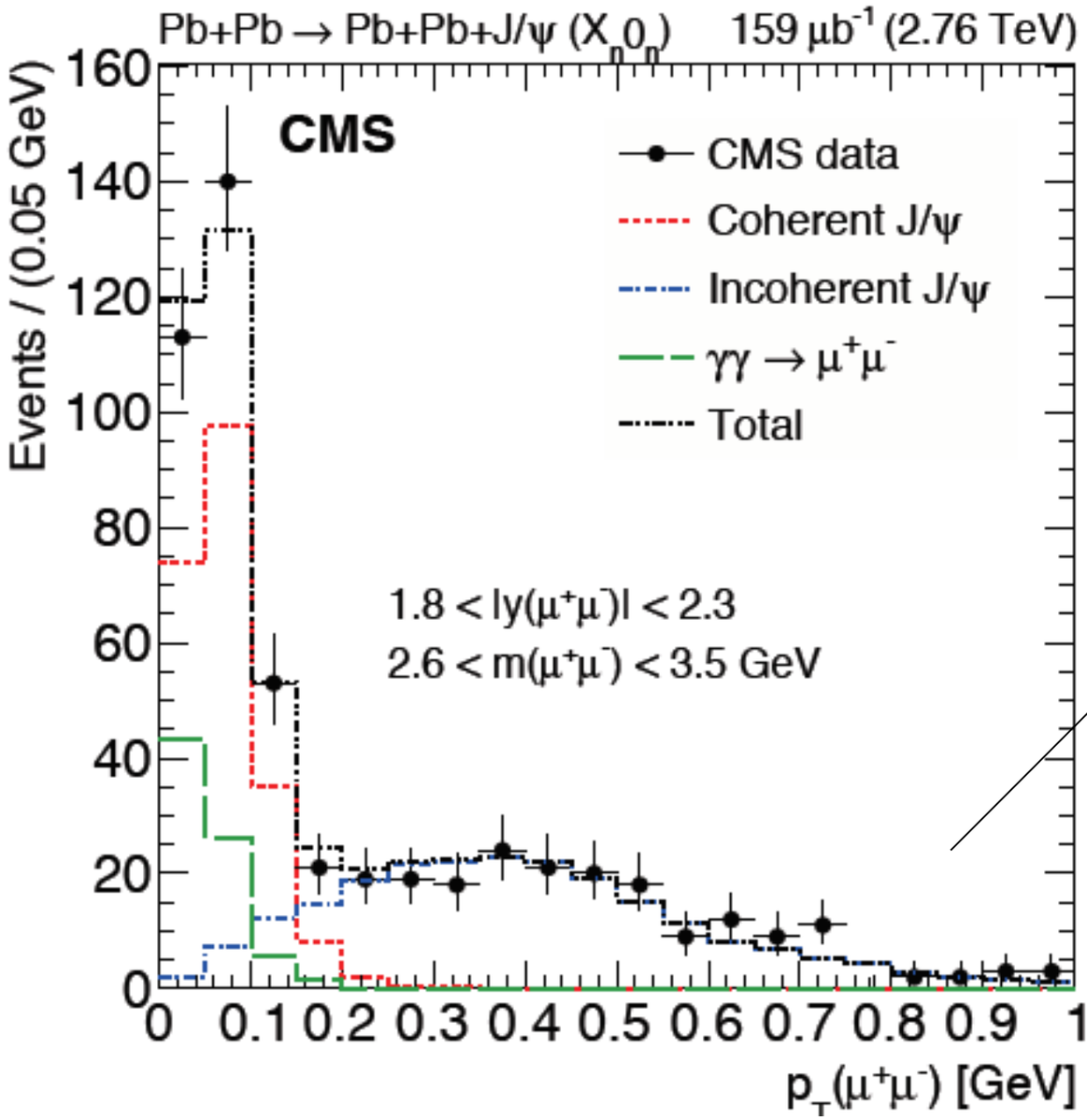
Low W: **x~ 10-2** **High W:** **x~ 10-4**

$$\frac{d\sigma_{\mathrm{PbPb}}(y)}{dy} = N_{\gamma/\mathrm{Pb}}(y, M)\sigma_{\gamma\mathrm{Pb}}(y) + N_{\gamma/\mathrm{Pb}}(-y, M)\sigma_{\gamma\mathrm{Pb}}(-y)$$



Incoherent production is expected to be more sensitive to the photon direction (energy dependence). Here 0nXn and Xn0n will unfold the two x-values

Energy dependence of Incoherent J/ψ



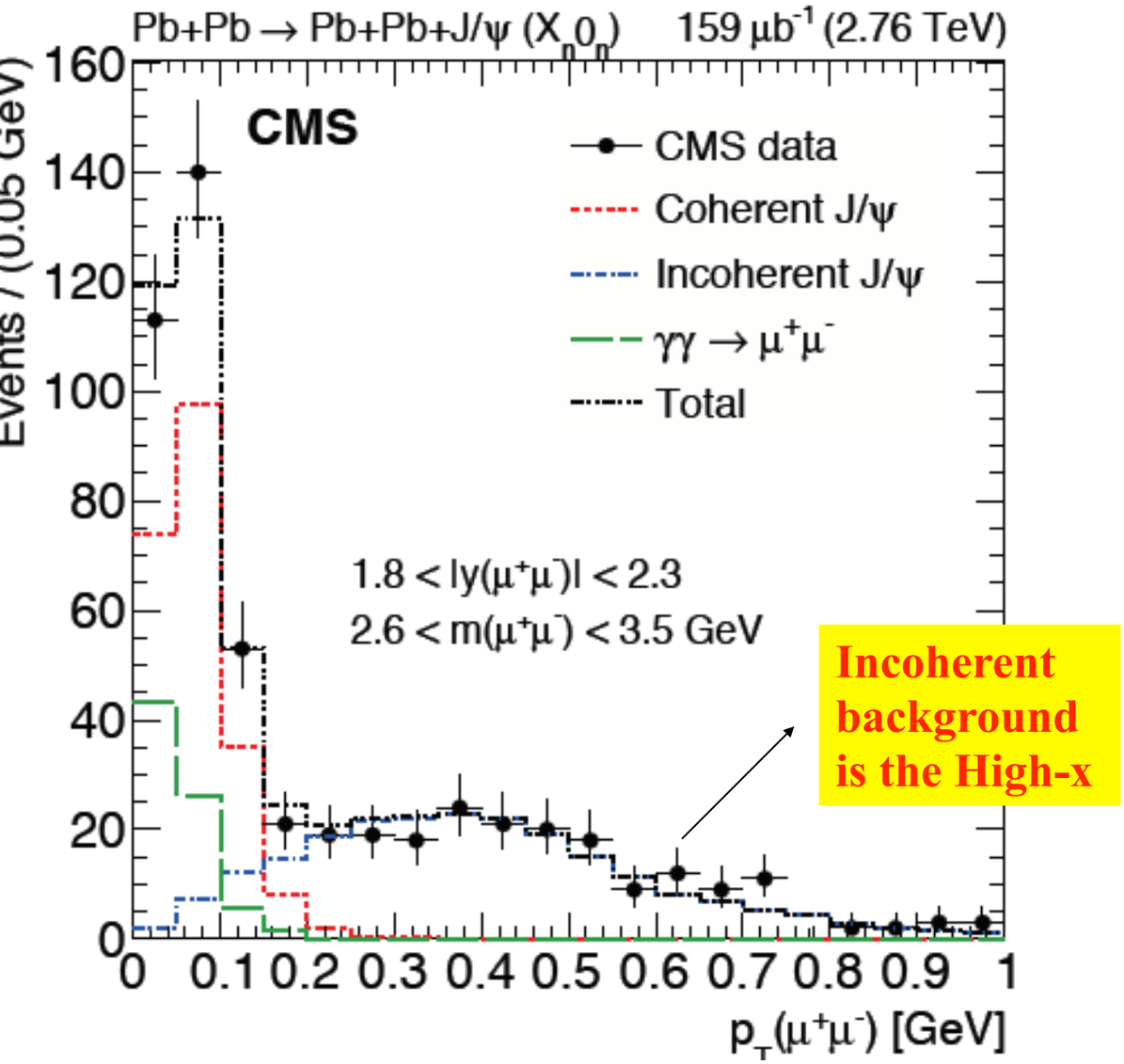
Incoherent background is the High-x region

Incoherent J/ψ background (Xn0n): ***Events are in the High-x region.***

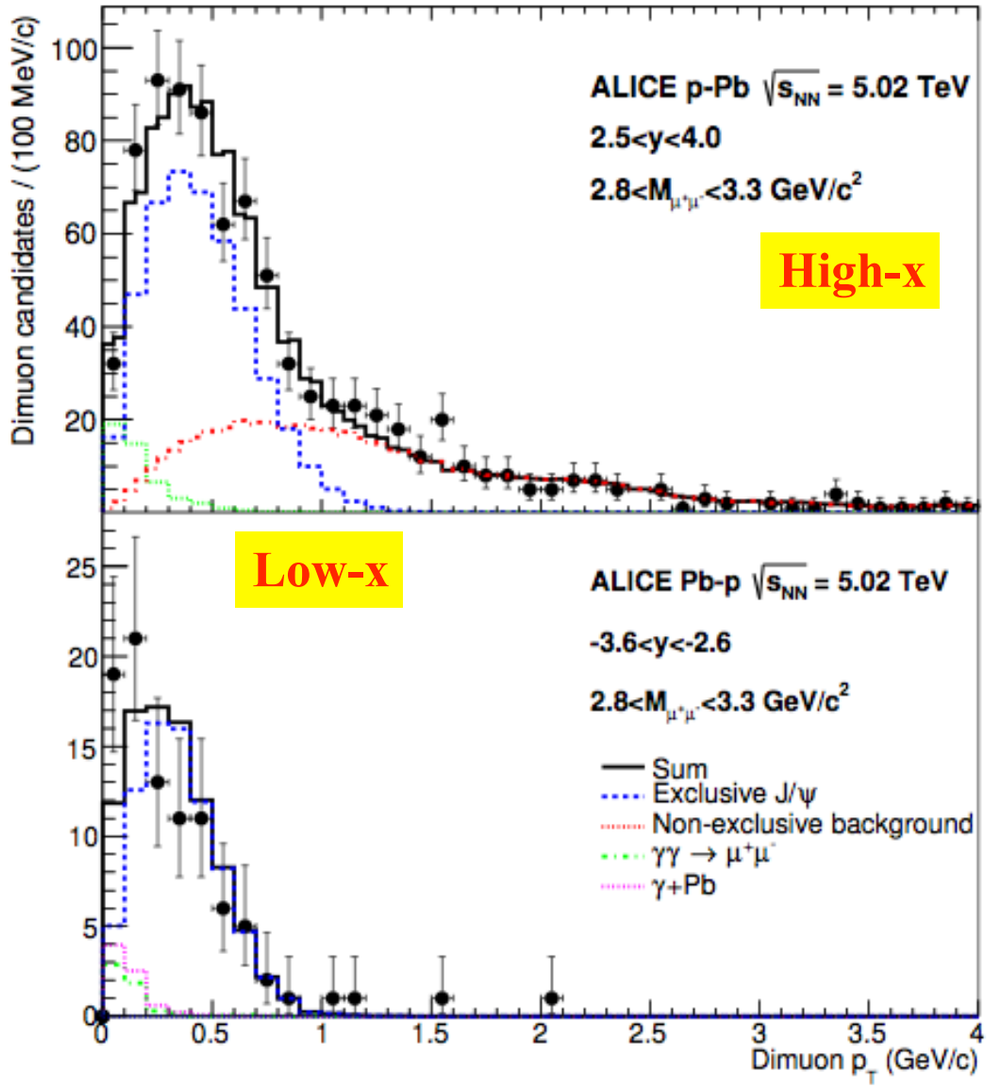
At Low-x, incoherent production is very strongly suppressed wrt to High-x region - First time seen in γ+Pb interactions

Energy dependence of Incoherent J/ψ

γ+Pb interactions



γ+p interactions

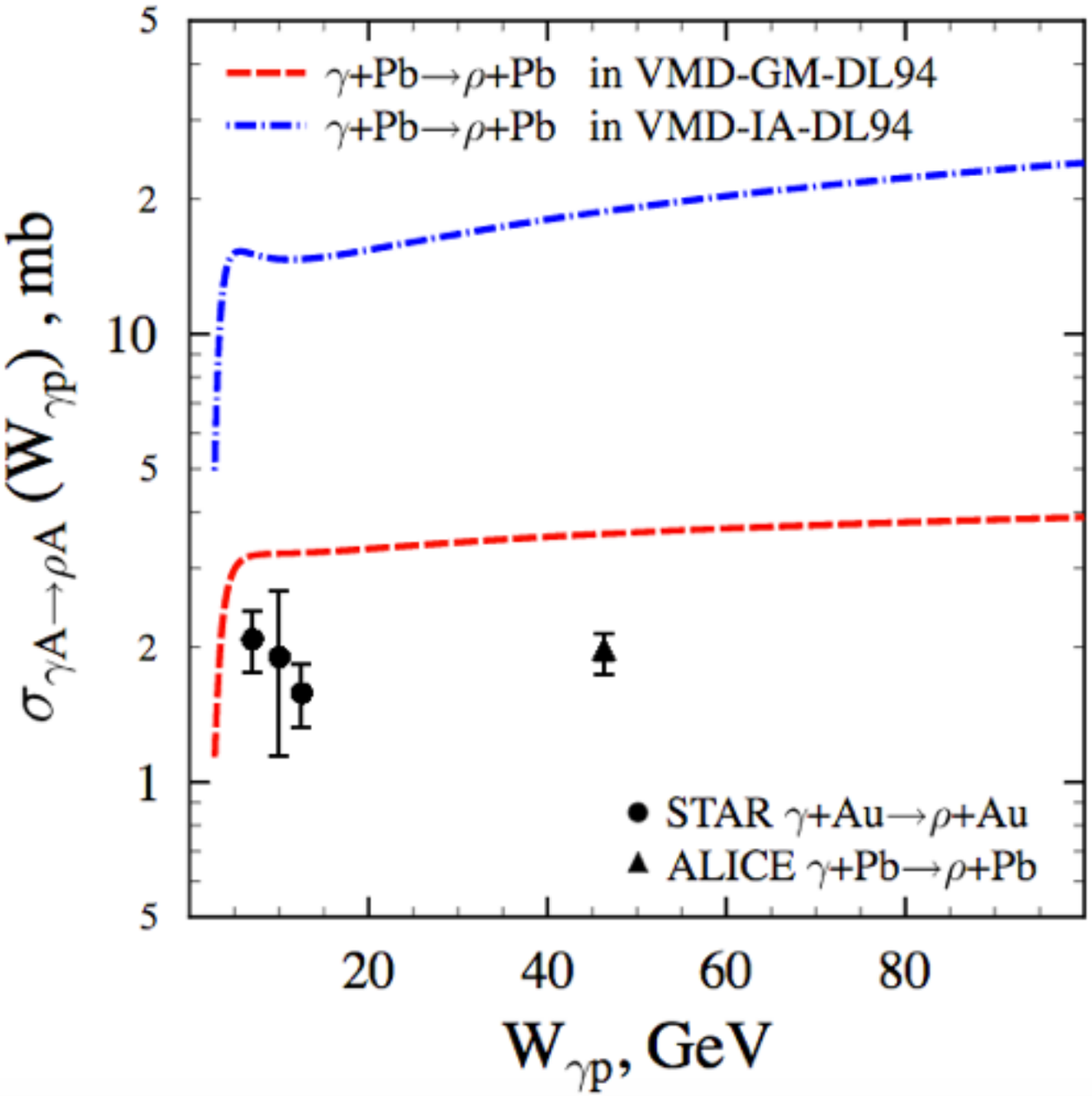


Incoherent J/ψ background (Xn0n): ***Events are in the High-x region. At Low-x incoherent background is heavy suppressed***

In qualitative agreement with ALICE Collaboration. Phys. Rev. Lett. 113 (2014) 23, 232504 (see also J. Cepina et al. Phys. Lett. B766 (2017) 186-191)

Coherent Rho0

ALICE
JHEP 1509 (2015) 095



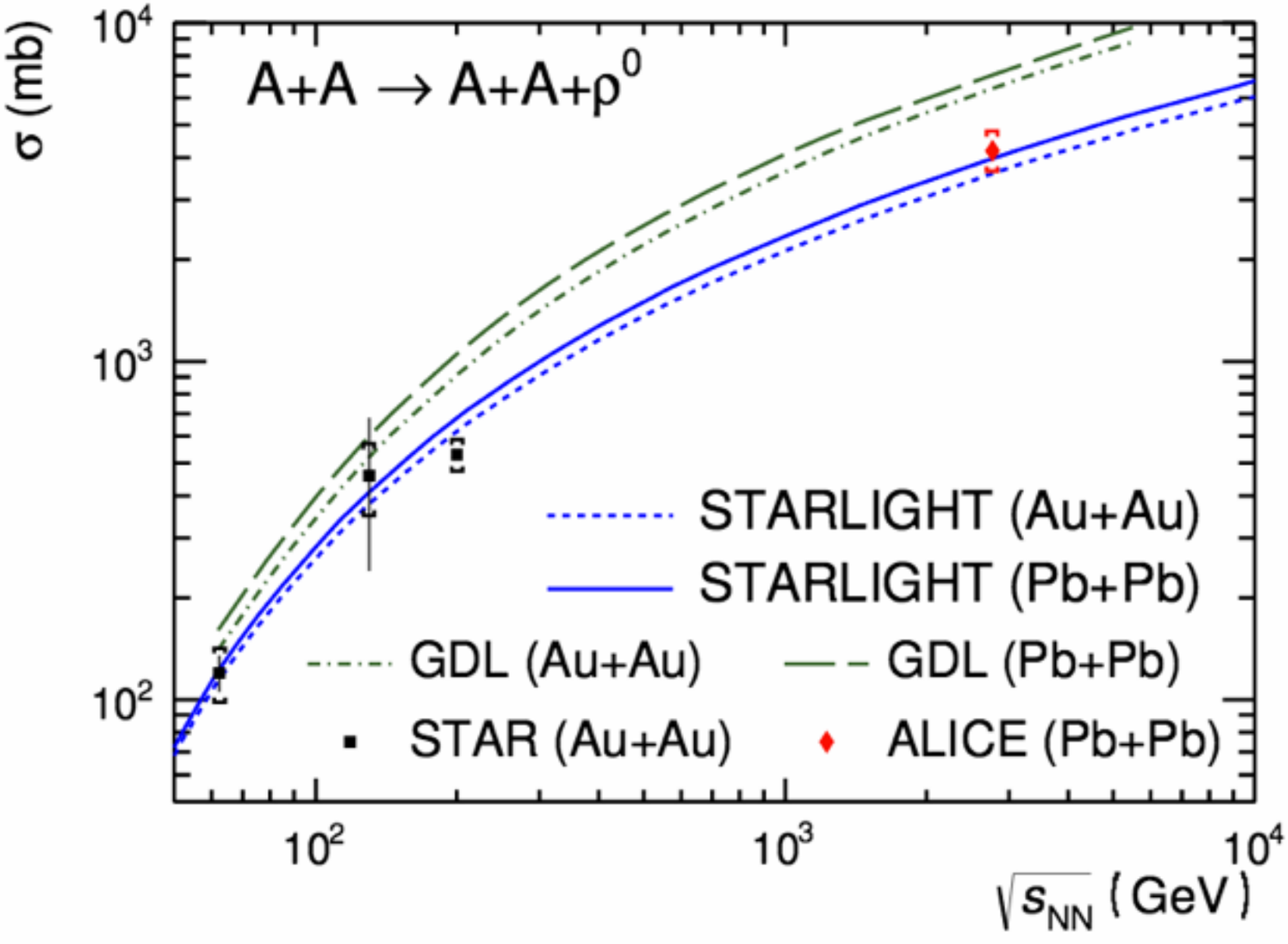
L. Frankfurt et al.
Phys.Lett. B752 (2016) 51-58

Both ALICE and STAR find measured cross section ~40% lower than predicted by Glauber, ….although works fine at fixed-target experiments

Nuclei does not behave like individual nucleons?

Coherent Rho0

JHEP 1509 (2015) 095

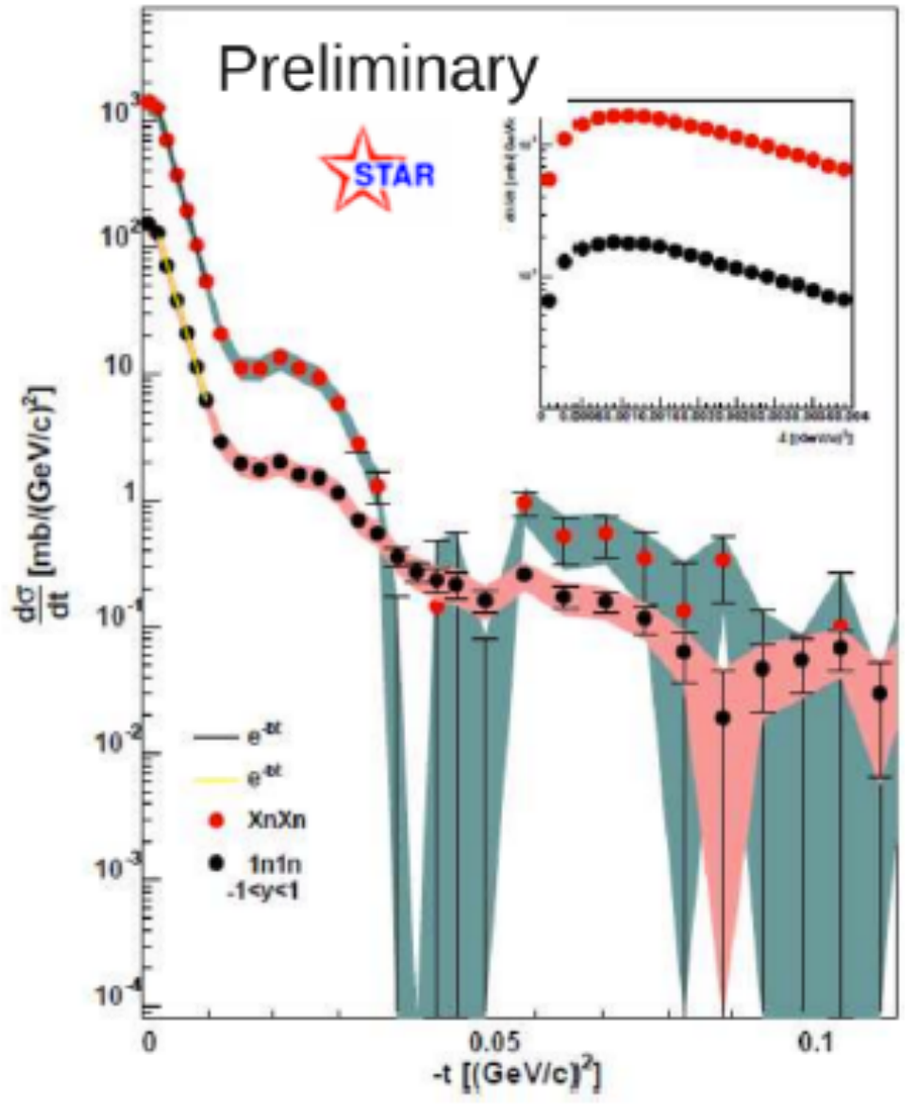


Both ALICE and STAR find measured cross section ~40% lower than predicted by Quantum Glauber, ….although works fine at fixed-target experiments

Nuclei does not behave like individual nucleons?

Coherent ρ^0 cross section

- Characteristic diffraction dips visible, positions:
  - 1^{st} : $-t = 0.018 \pm 0.005$ GeV^{-2}
  - 2^{nd} : $-t = 0.043 \pm 0.01$ GeV^{-2}
- Expected when approaching black disk limit
- Partially washed out due to photon p_T distribution and detector resolution
- Consistent with Normalized nuclear form factor, mVMD-GGM lower by $\sim 1\sigma$
- Interference between the two production nuclei makes downturn at $|t| < 10^{-3}$ GeV^2

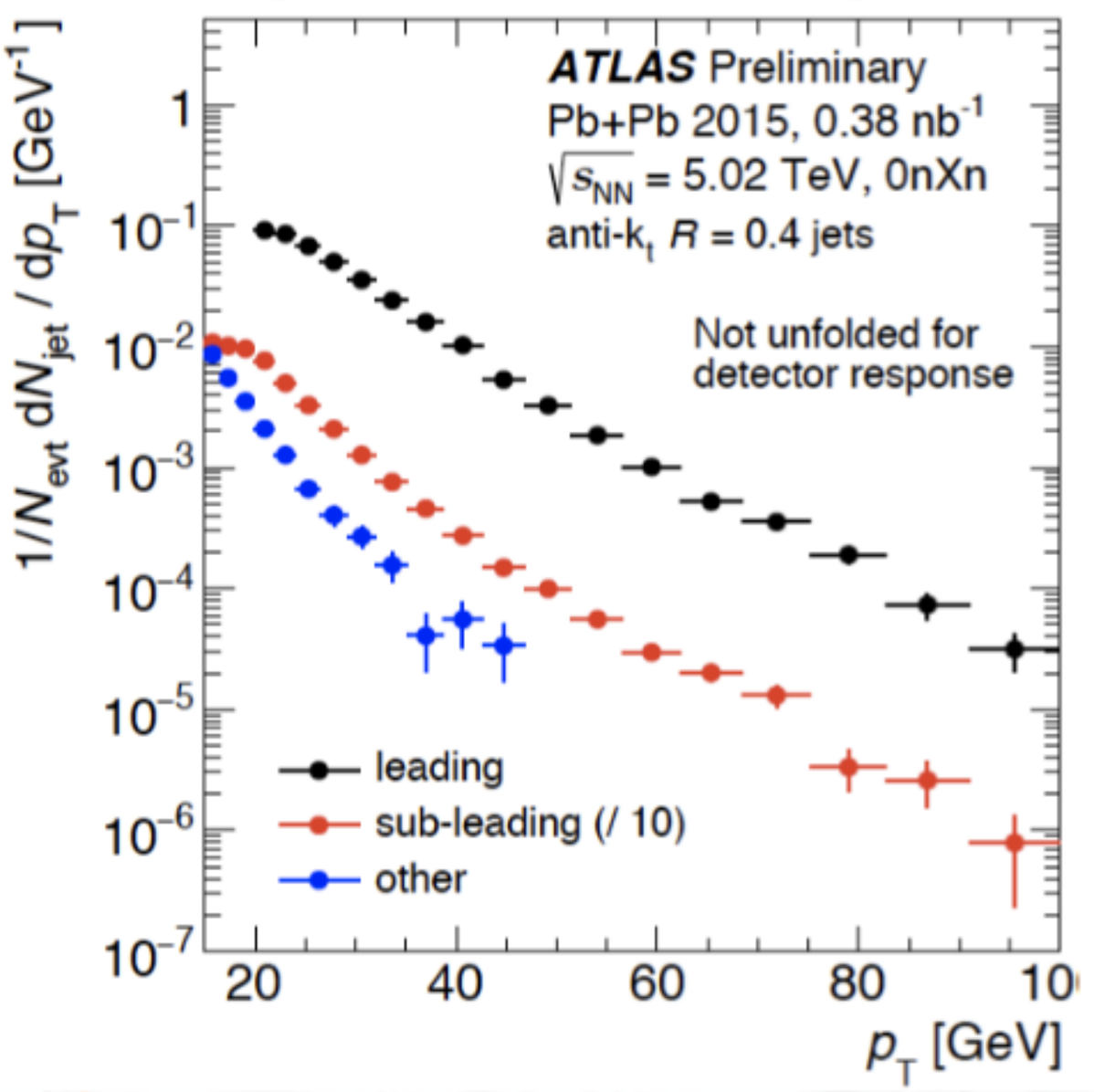


Norm nucl form factor: Atom. Data Nucl. Data Tabl. 36, 495 (1987), mVMD-GGM: Phys. Lett. B 752, 51 (2016), calculations: arXiv:1611.05471

INT workshop

Jets

From
Aaron Angerami's
talk



Measurement Coverage

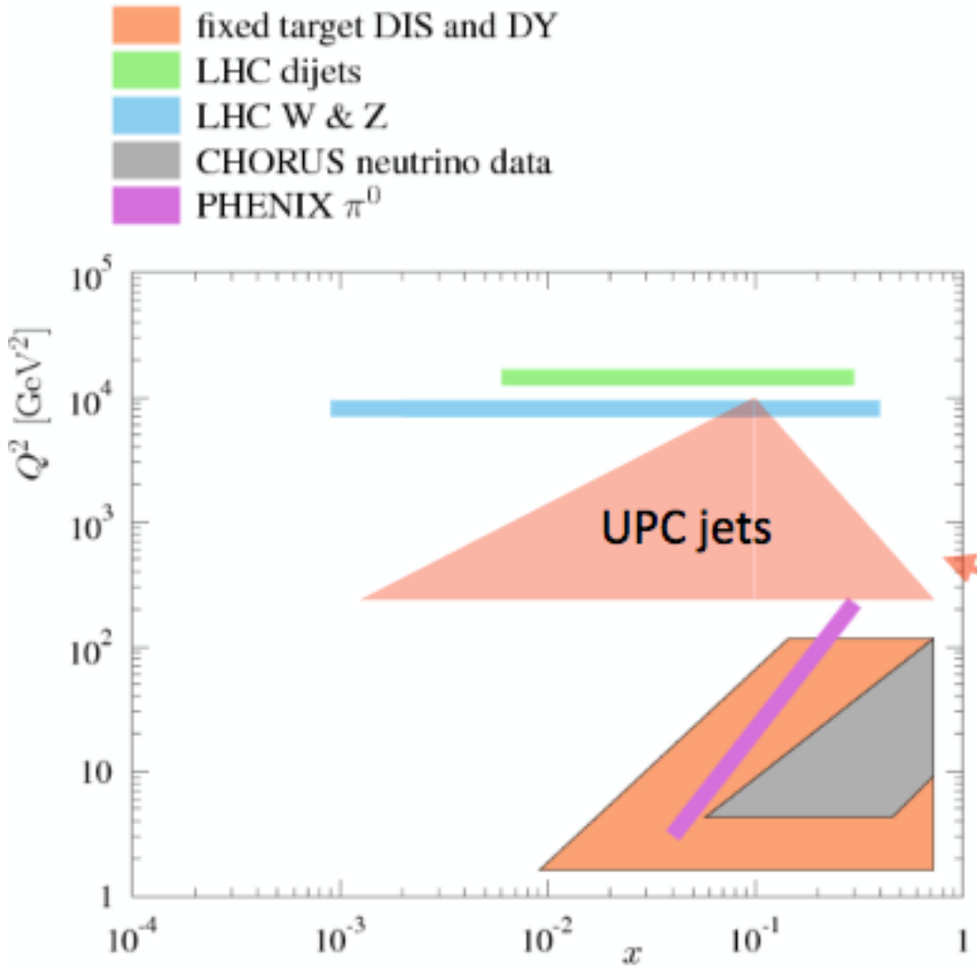
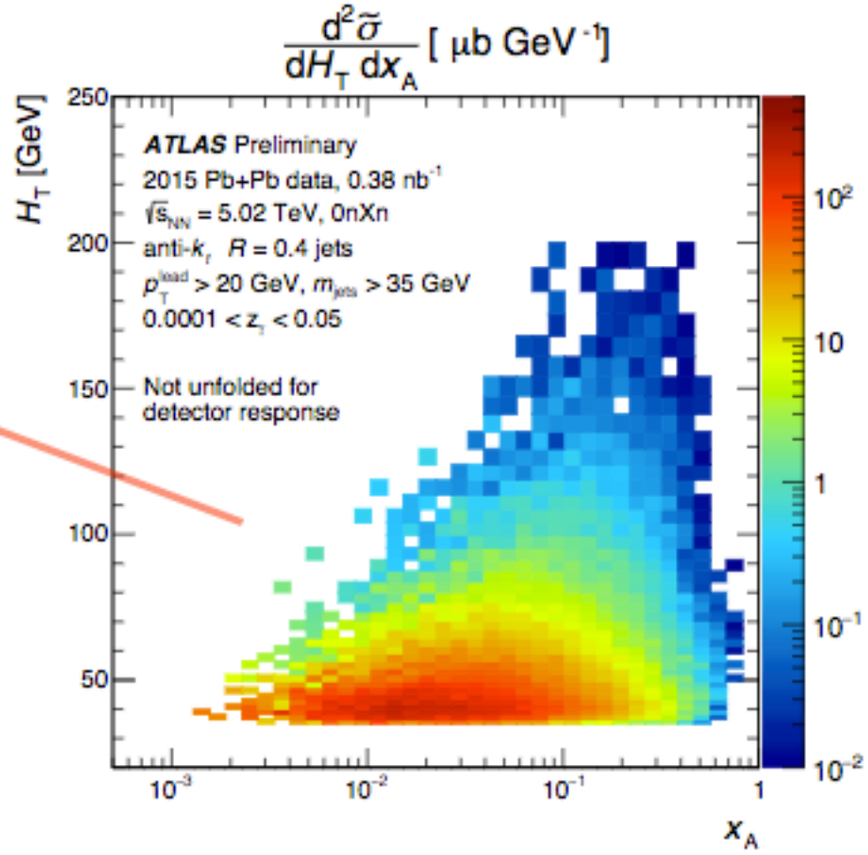


Figure adapted from EPPS16
1612.05741 [hep-ph]

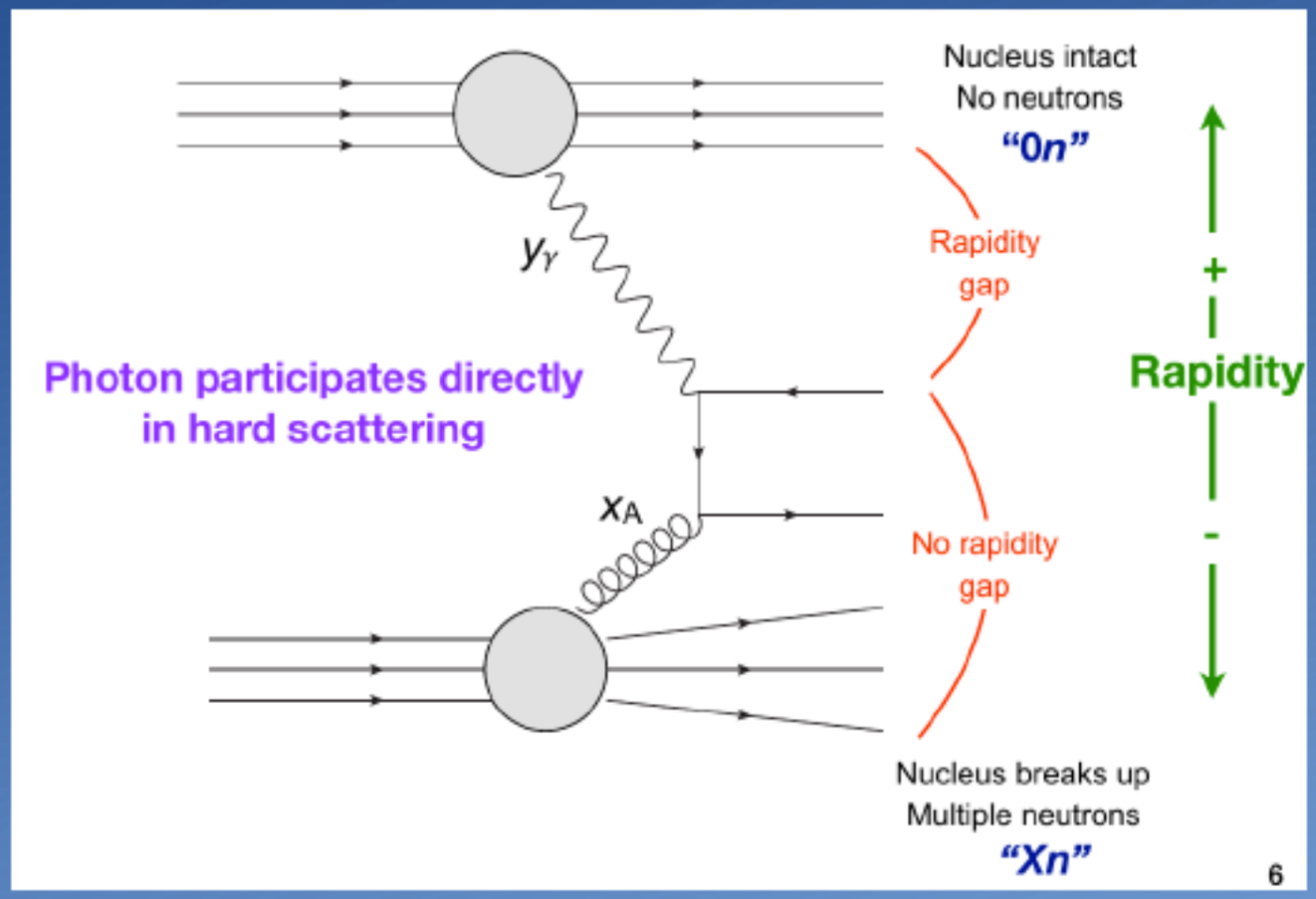


- **ATLAS-CONF-2017-011**

Cross section depends linearly on nuclear PDFs.

Photonuclear jet-production at the LHC

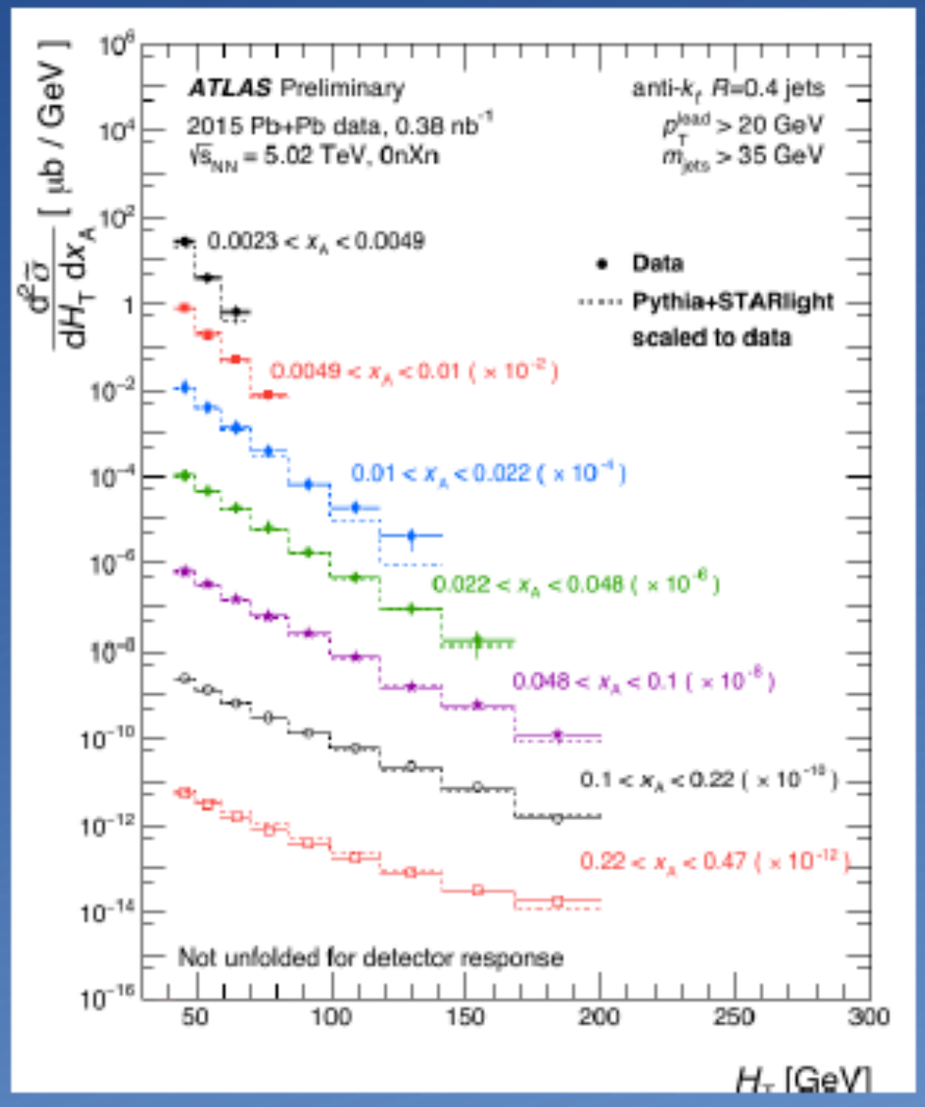
One rapidity gap between photon emitting nucleus and "target" nucleus.



A. Angerami, Quark Matter 2017.

Cross section depends linearly on nuclear PDFs.

Photonuclear jet-production at the LHC



A. Angerami, Atlas Collaboration, Quark Matter 2017.

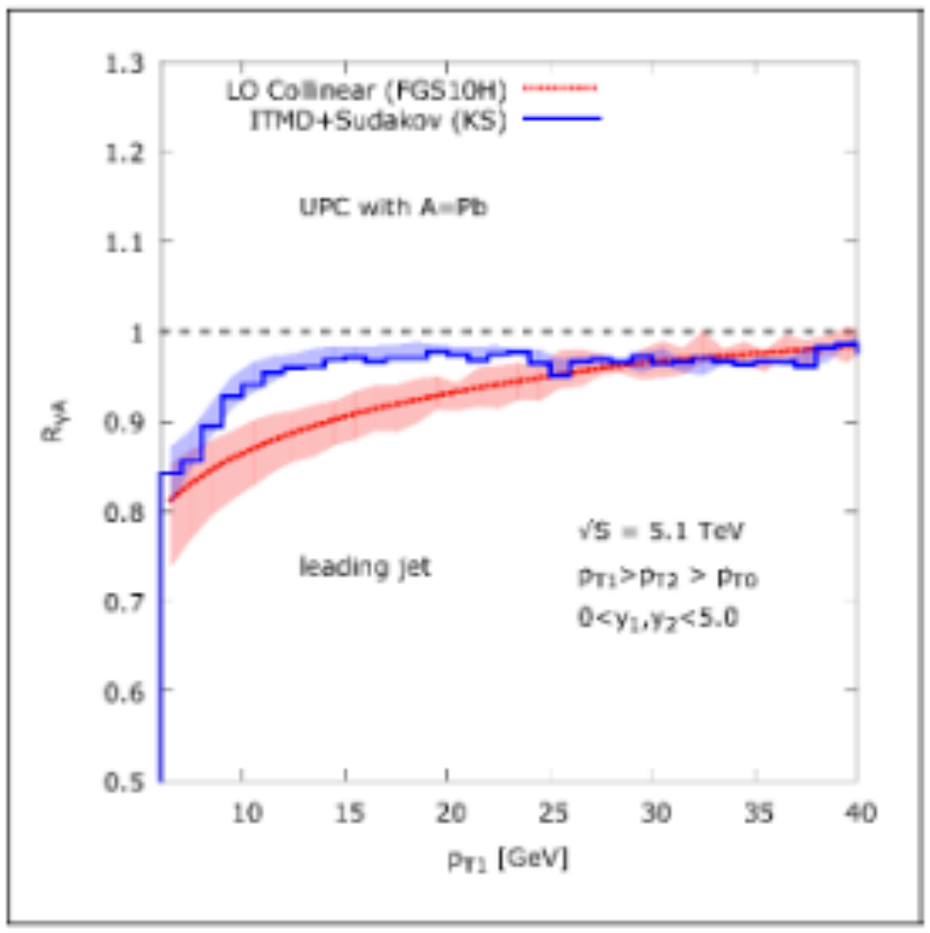
Rather good agreement with Pythia, if photon spectrum is adjusted to that of STARLIGHT (photon spectrum in Pythia is for a lepton beam).

Results for dijets in UPC

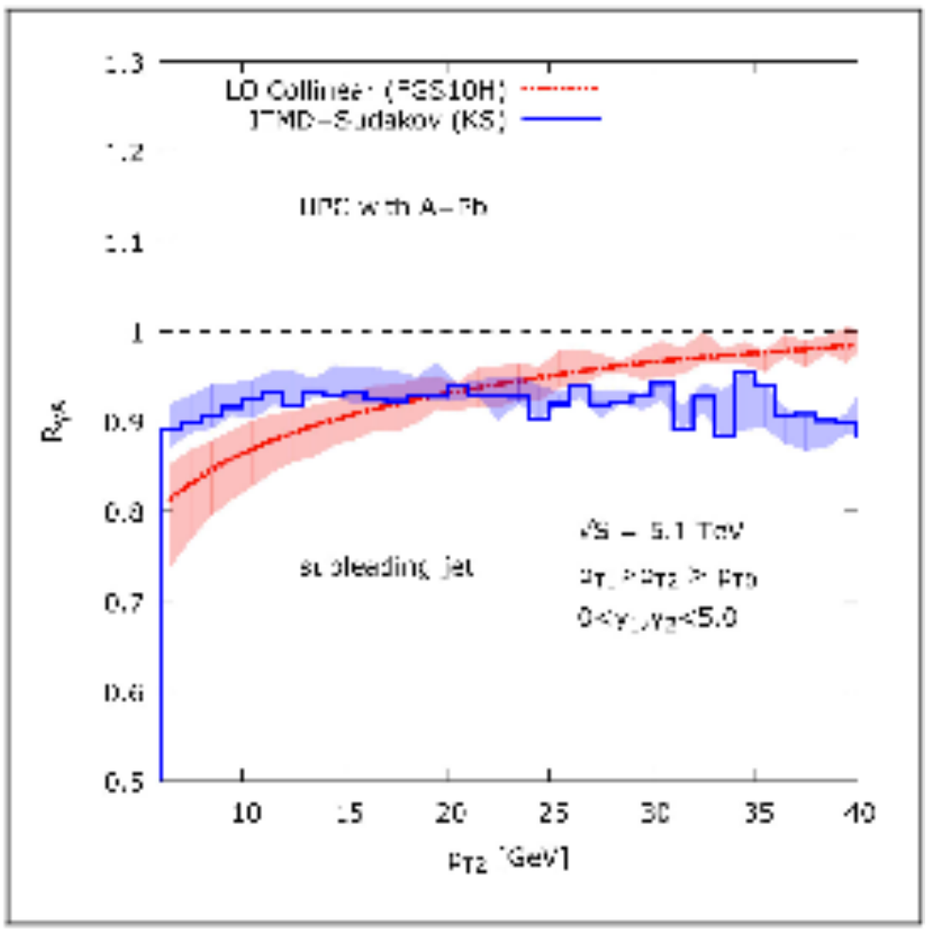
P. Kotko, A. Stasto, M. Strikman

Nuclear modification factor R_{yA}

leading jet p_T

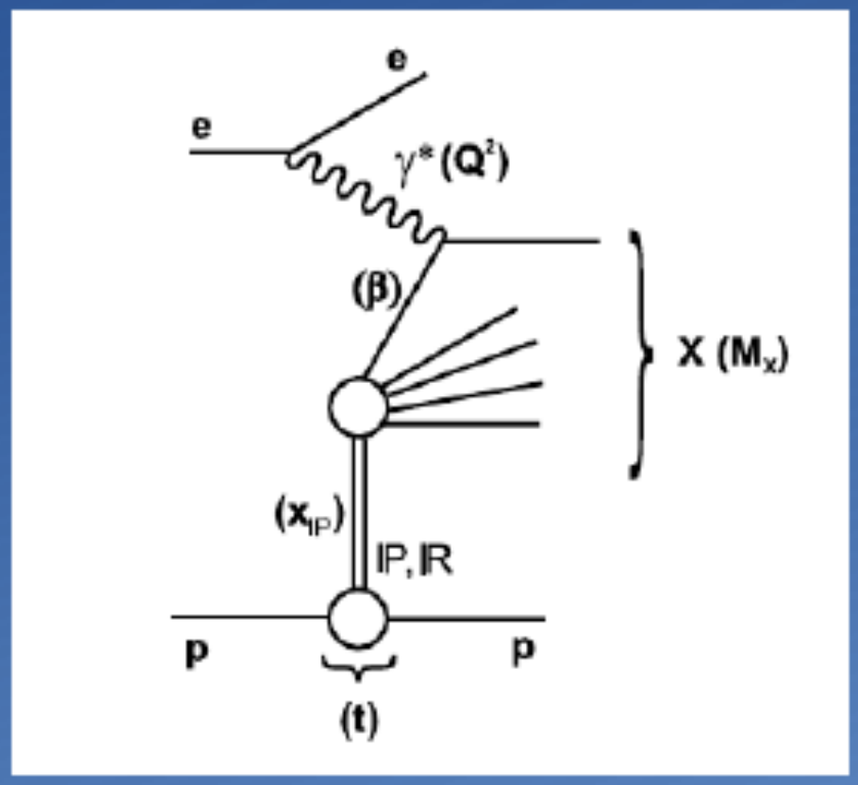


subleading jet p_T



Photonuclear jet-production at the LHC

Photonuclear jets can also be studied in “diffractive” events.



Rapidity gap between both nuclei and the produced state.

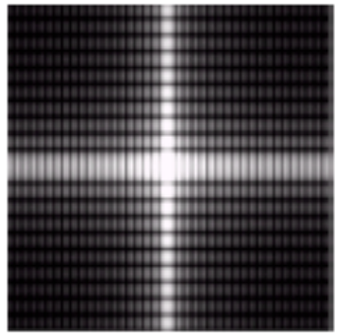
- Has been studied at HERA with proton target.
- Nothing done with nuclear targets.

Diffractive dijets in DIS and UPC

Diffractive VM production, especially t - dependence, can provide with the valuable information about the spatial distribution of the target.

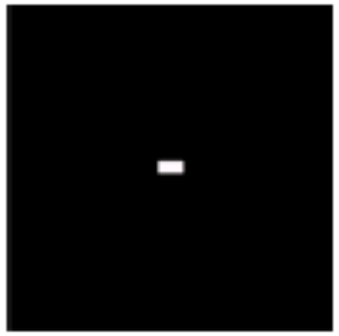
It is similar to image processing:

Fourier image

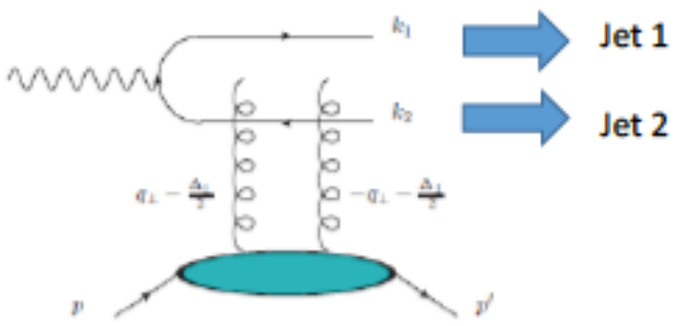


inverse 2-dim FT transform

Real space



Yoshitaka Hatta



Jet 1

Jet 2

$$\vec{\Delta}_\perp = -(\vec{k}_{1\perp} + \vec{k}_{2\perp})$$

Proton recoil momentum

$$\vec{P}_\perp = \frac{1}{2}(\vec{k}_{2\perp} - \vec{k}_{1\perp})$$

Dijet relative momentum

Diffractive dijets provide access to Wigner distribution or Generalized Transverse Momentum Distribution

$$W(x, \vec{k}, \vec{\Delta})$$

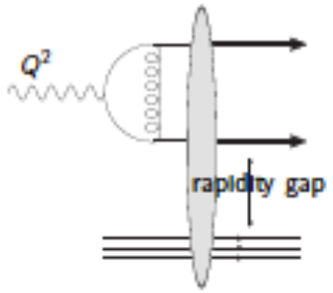
WG2: Low x and Diffraction

Diffractive dijets: higher order calculations

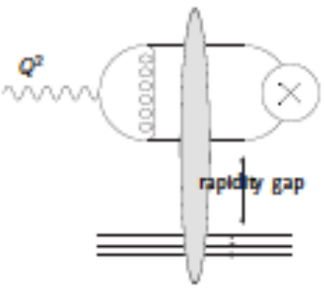
Higher order corrections to diffractive dijets

Renaud Boussarie

Diffractive dijet in CGC formalism at NLO



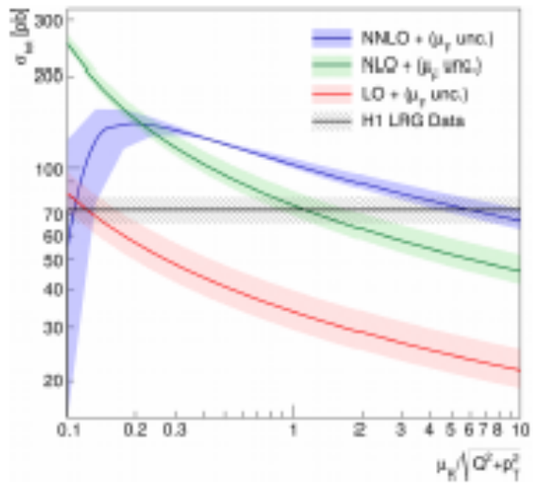
Diffractive VM production in CGC formalism at NLO



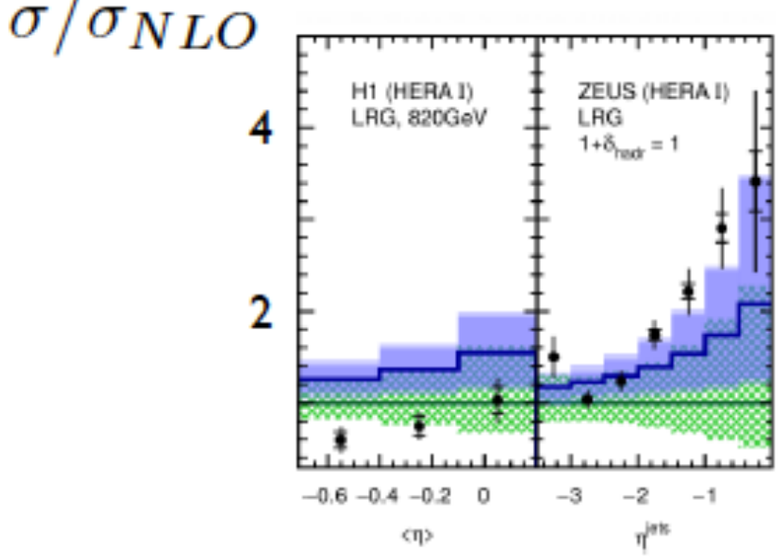
Radek Zlebcik

First study of diffractive dijets in collinear formalism at NNLO!

Renormalization scale dependence



Reduction of the renormalization (and factorization) scale dependence at NNLO

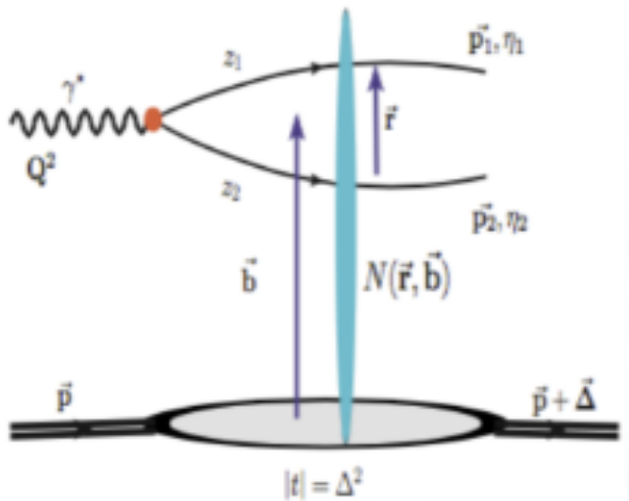


Higher order corrections are large: NNLO substantially higher than NLO for some distributions.
Need more detailed study, NNLO DPDFs?

WG2: Low x and Diffraction

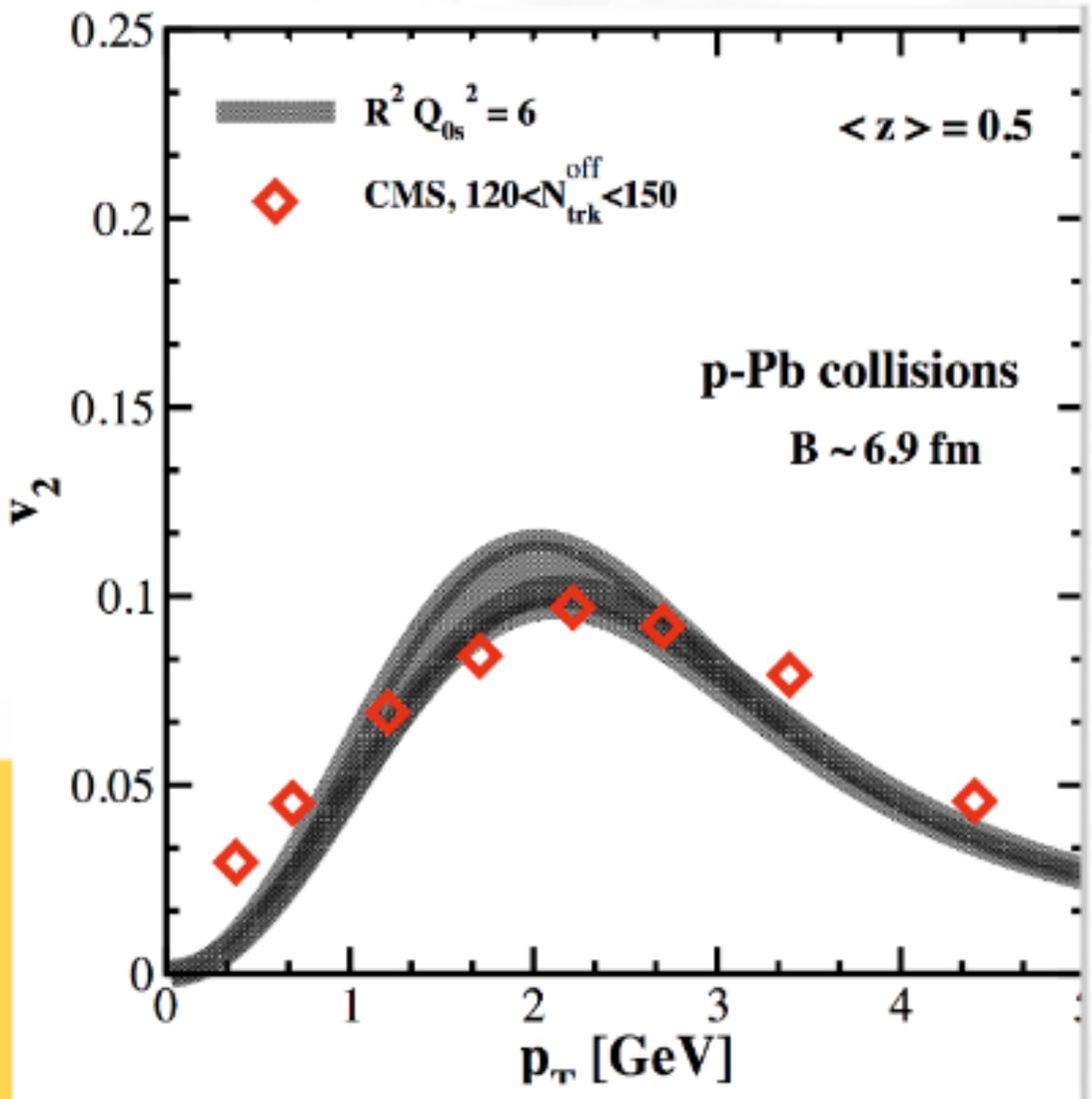
13

Motivation:
Test gluon saturation model

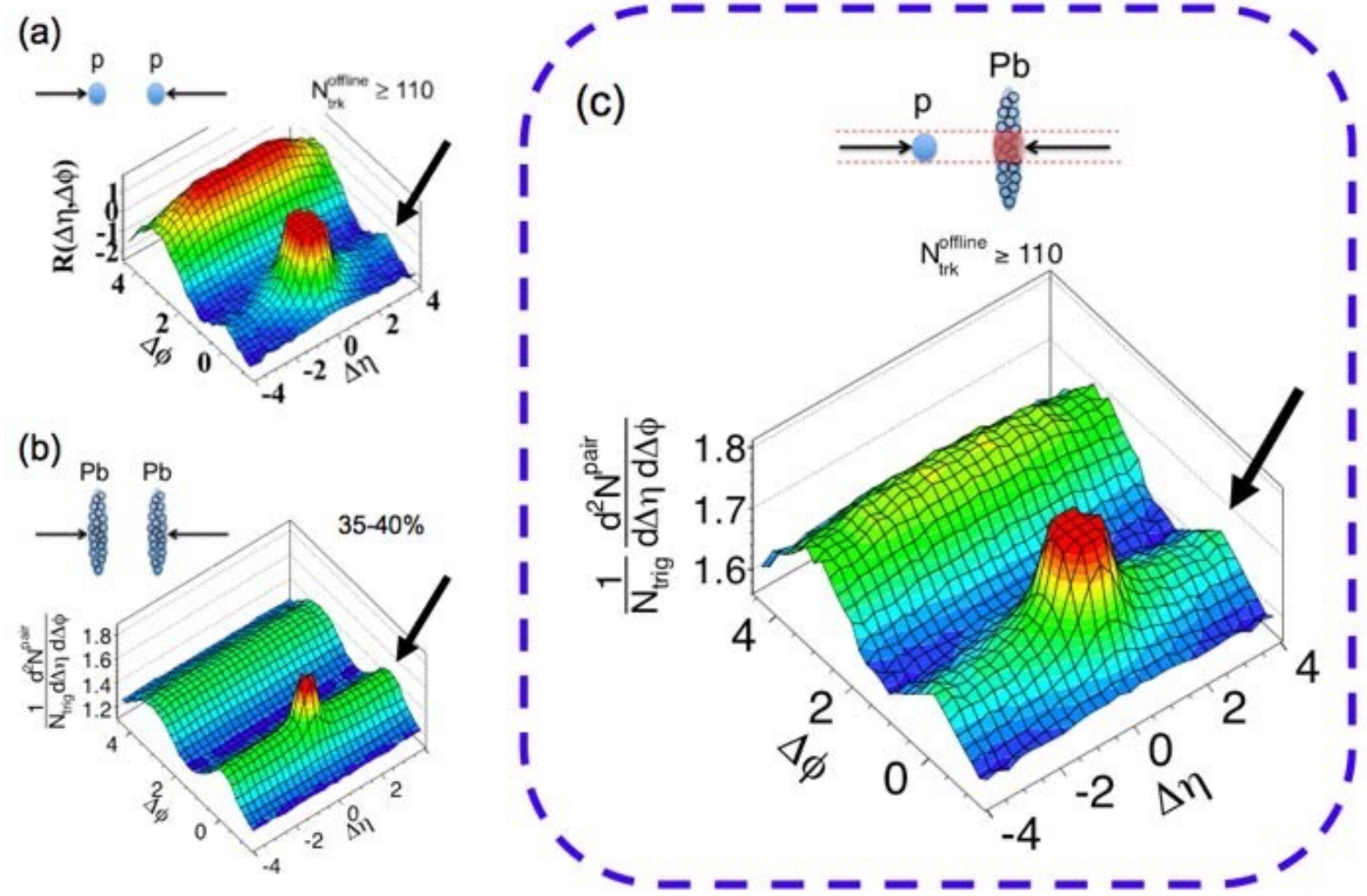


From Amir Rezaeian's talk

Since jet is color neutral, jet production dominated by q-qbar pairs of smaller transverse size with increasing saturation

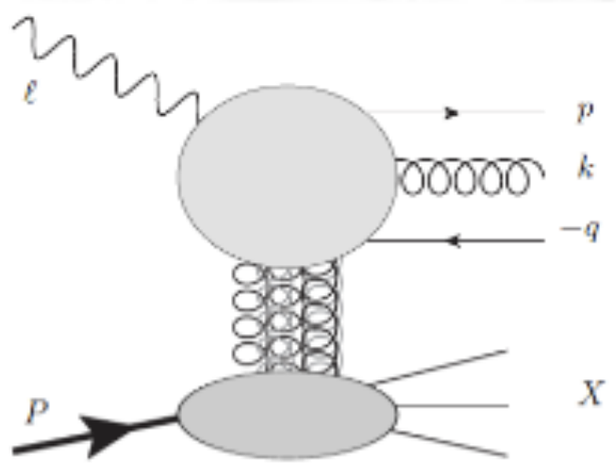


21



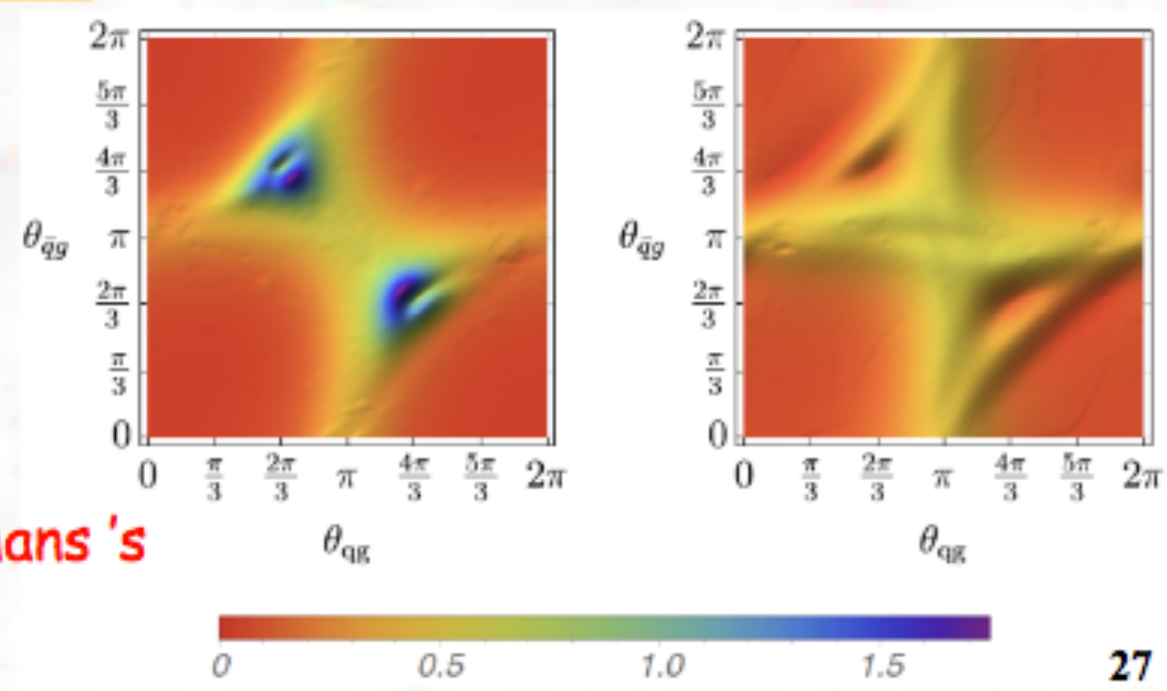
2-particle correlations in UPC collisions?

Polarization in UPCs and EIC



Motivation: use azimuthal angular correlations of 3 partons in inclusive DIS to explore the dynamics of saturated partonic matter

Azimuthal correlations between 3 partons in DIS

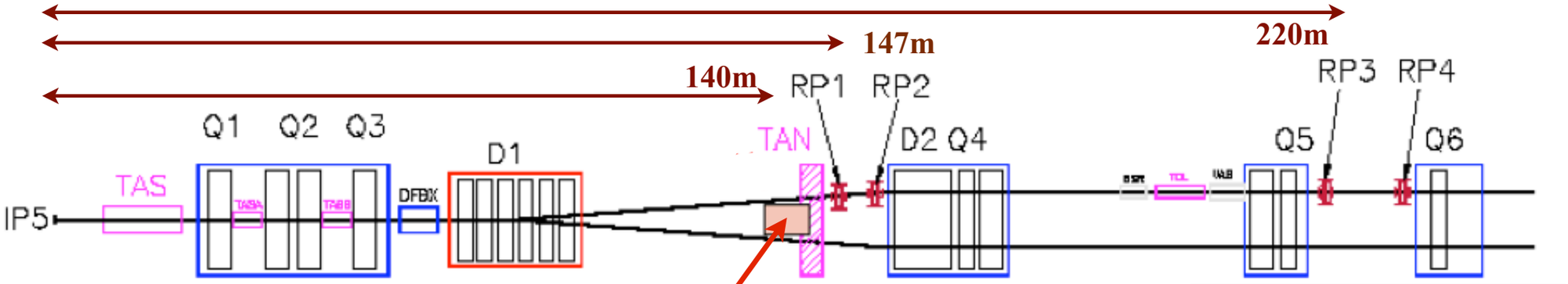


From Maria Elena Tejeda-Yeomans 's talk

27

One more thing …

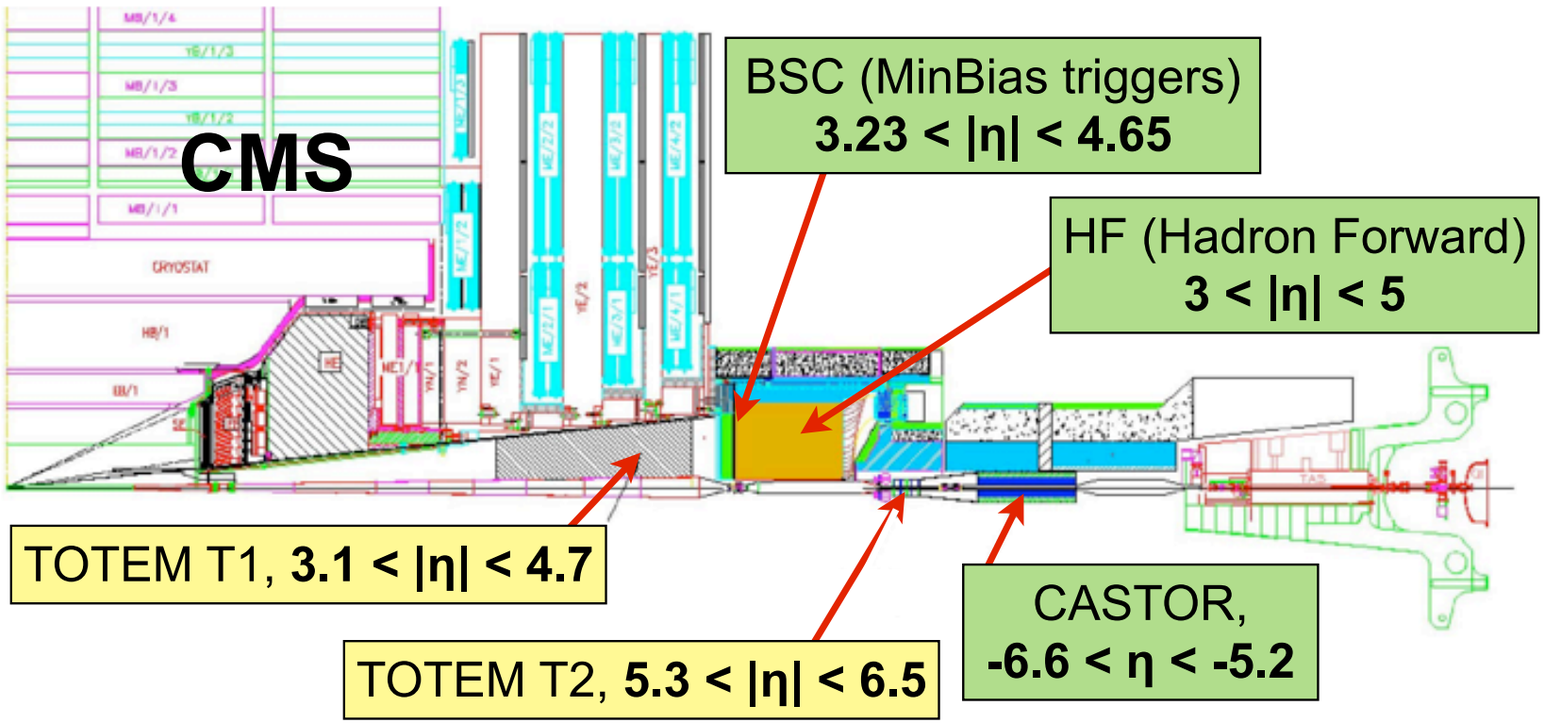
Forward detectors at CMS



Forward Shower Counters
6 < |η| < 8

Zero Degree Calorimeter
|η| > 8.1

TOTEM Roman Pots
±147m, ±220m



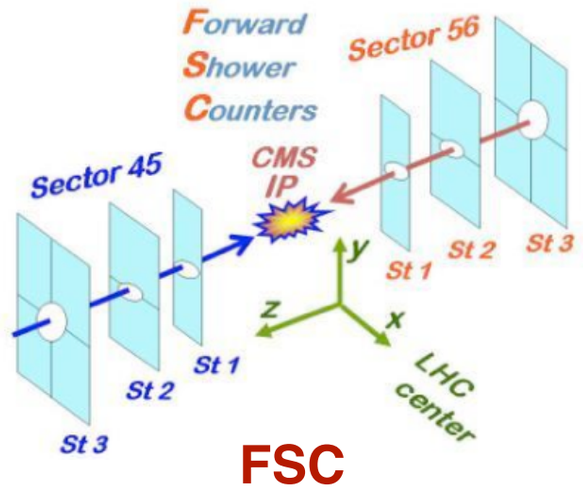
BSC (MinBias triggers)
3.23 < |η| < 4.65

HF (Hadron Forward)
3 < |η| < 5

TOTEM T1, **3.1 < |η| < 4.7**

TOTEM T2, **5.3 < |η| < 6.5**

CASTOR,
-6.6 < η < -5.2

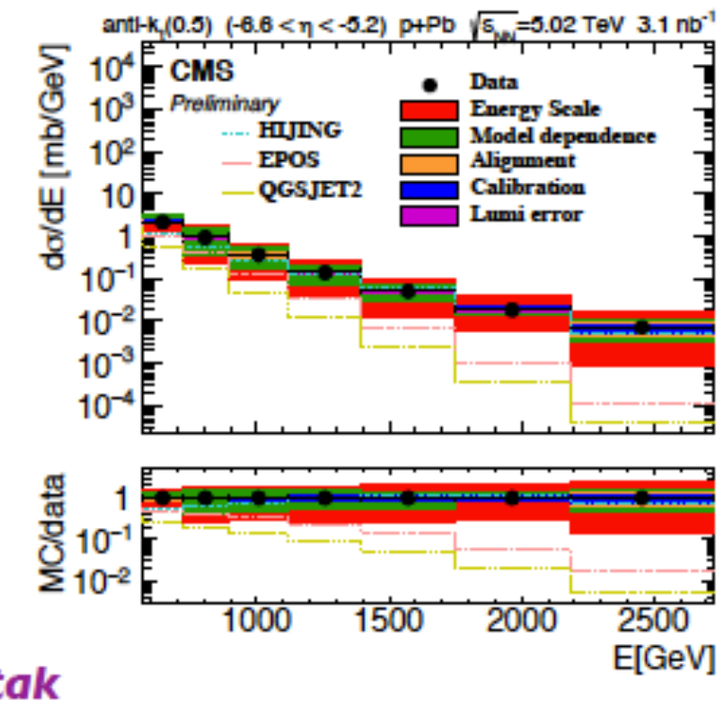


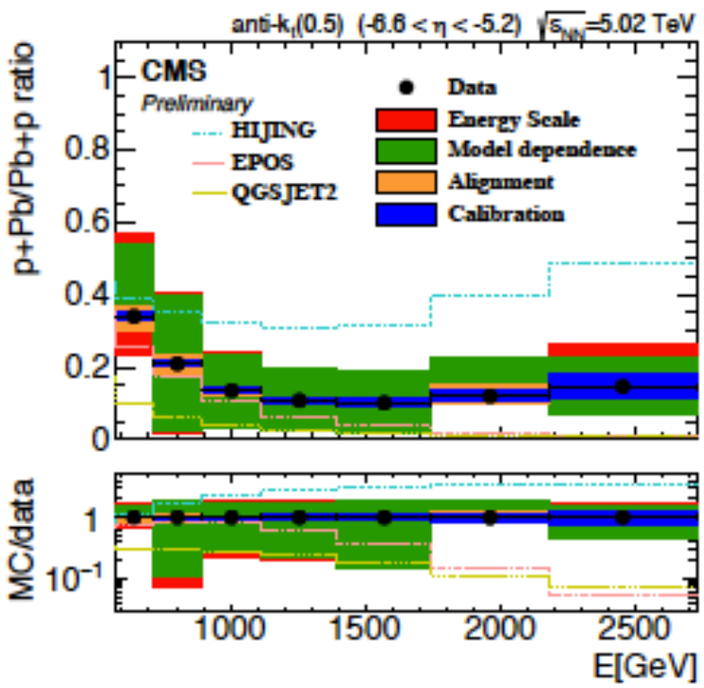
FSC

From DIS 2017 —sensitive to saturation …Not UPCs but possible to use CASTOR in UPC studies in the future

Very forward jets in p+Pb and Pb+p with CASTOR

Merijn van de Klundert
CMS

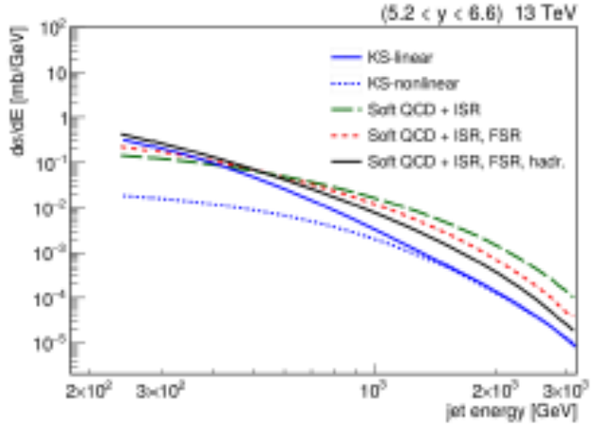




Krzysztof Kutak

Calculation of very forward inclusive jet in pp using formalism
of hybrid factorization for CASTOR kinematics.
Comparison of calculations with and without the gluon saturation.
Strong suppression expected at low transverse momenta even in the proton - proton case.

Very strong suppression of the p+Pb/Pb+p ratio
Caveat: compromised by boost of center of mass frame



WG2: Low x and Diffraction

14

White paper

- Following the INT workshop, a White Paper on photon-nucleus/proton will be prepared

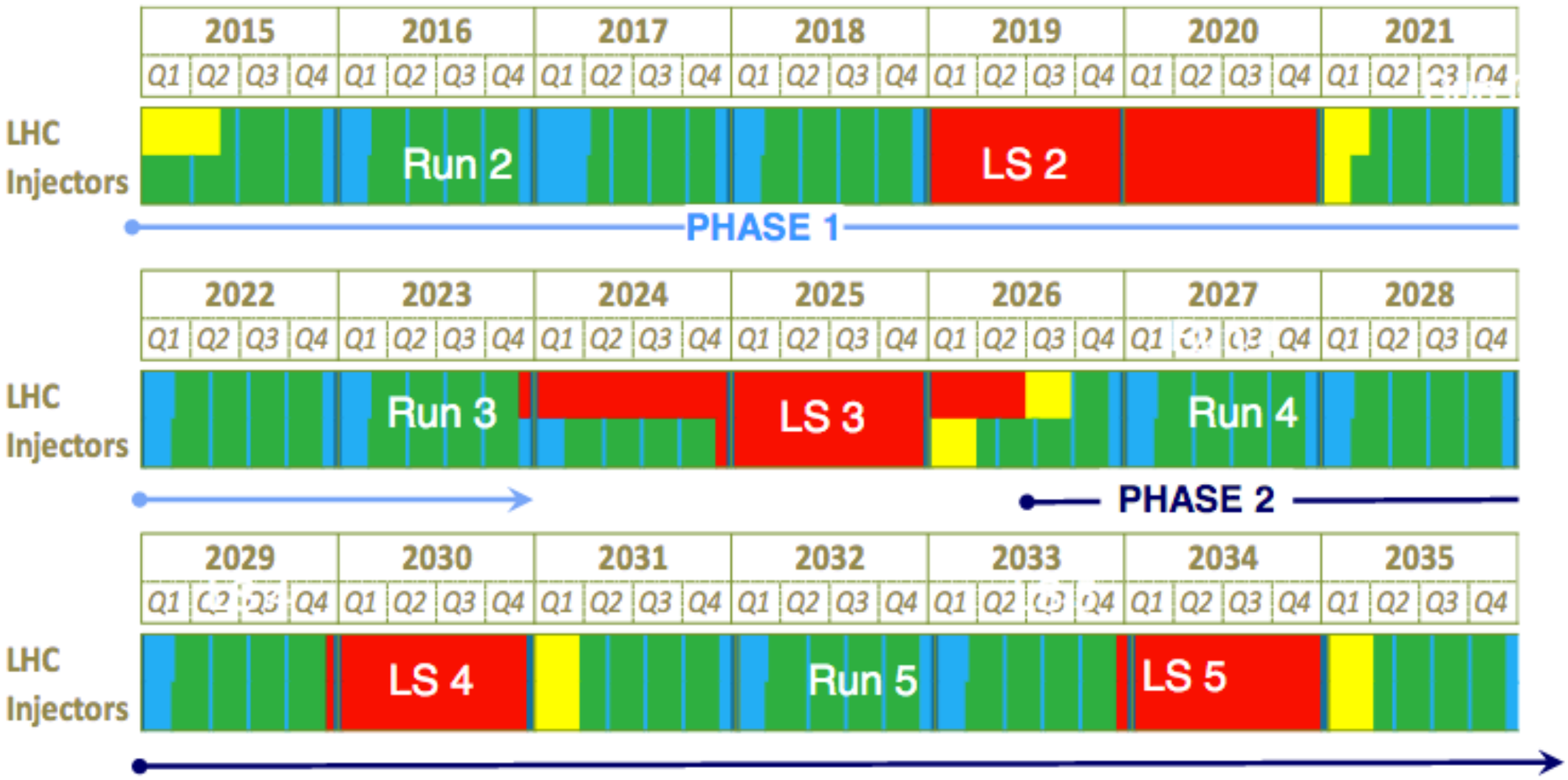
Coordinated by DTT and in preparation…

LHC schedule

CERN Yellow Report: *CERN-PH-LPCC-2015-001*

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



Summary and outlook

- **Studying QCD with high energy photon-photon, photon-proton and photon-nuclear interactions at the LHC**
  - **Searching for saturation effects in the proton**
  - **Nuclear effects at both low and high Bjorken-x**

- **So far, most analyses have been carried out for exclusive VM photoproduction but new studies possible for other final states (dijets, double VM, diphoton, etc)**

- **Inclusive photo-nuclear and photon-proton reactions also possible**

Summary and outlook

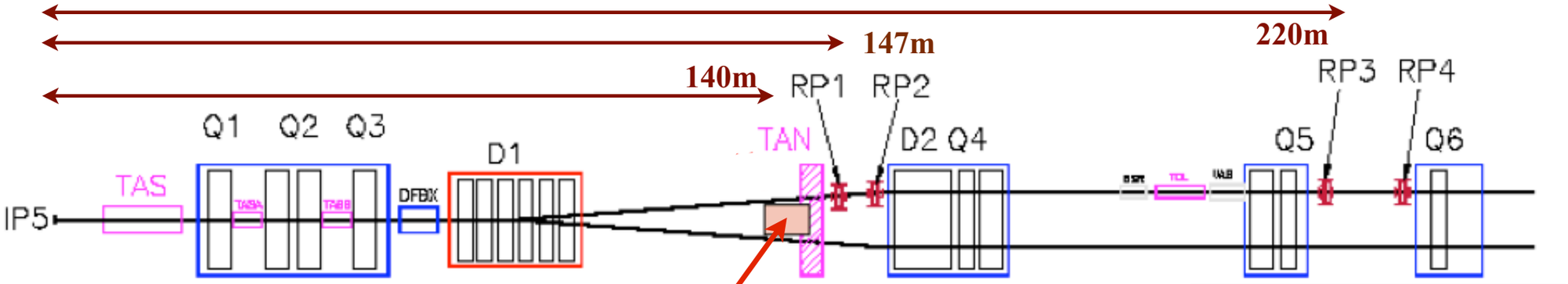
- **UPC studies at RHIC/LHC, some new energy regime. Despite the limitations in terms of statistics and precision, there are lots of synergies with the EIC program**

- **New saturation studies ongoing**

- **Community building around these topics from both the theory and experimental side**

Additional slides

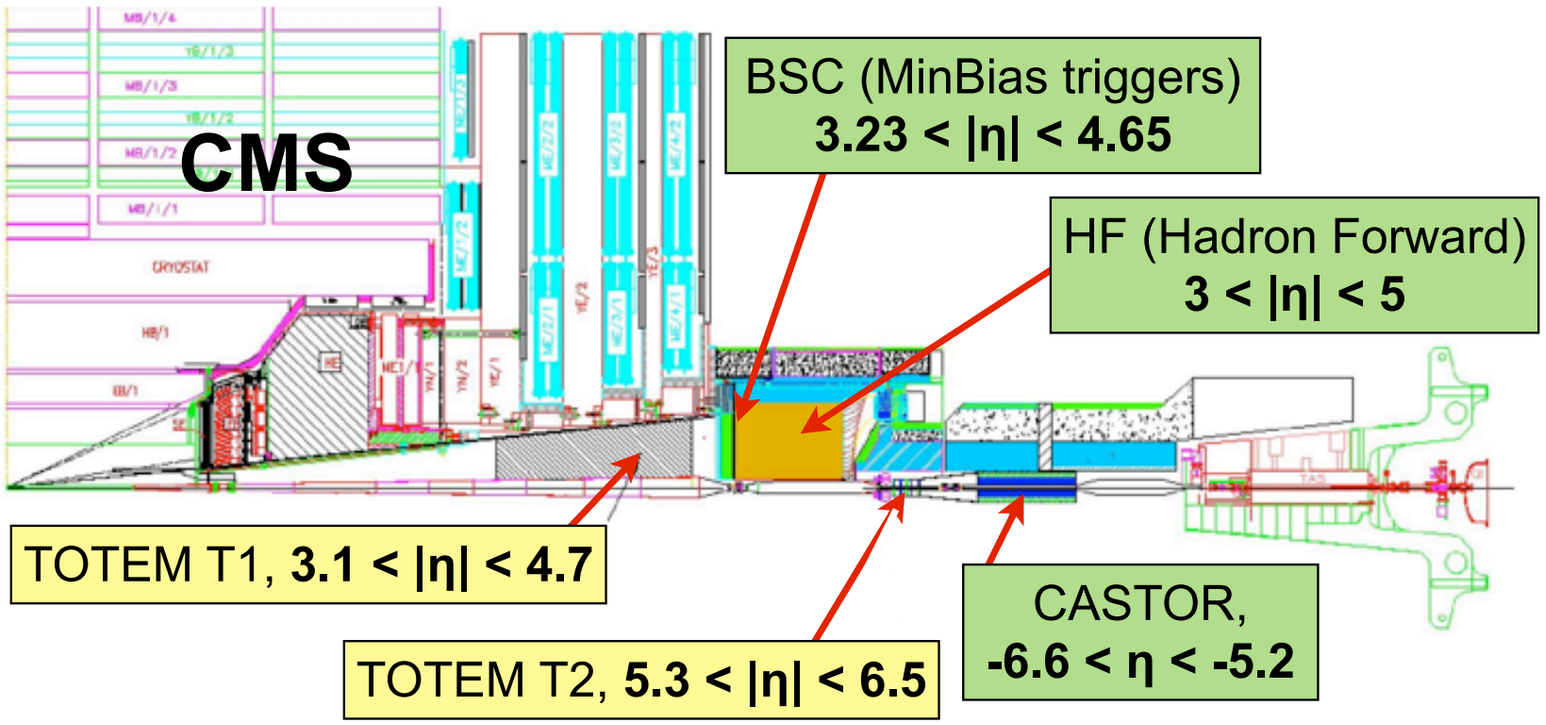
Forward detectors at CMS



Forward Shower Counters
6 < |η| < 8

Zero Degree Calorimeter
|η| > 8.1

TOTEM Roman Pots
±147m, ±220m



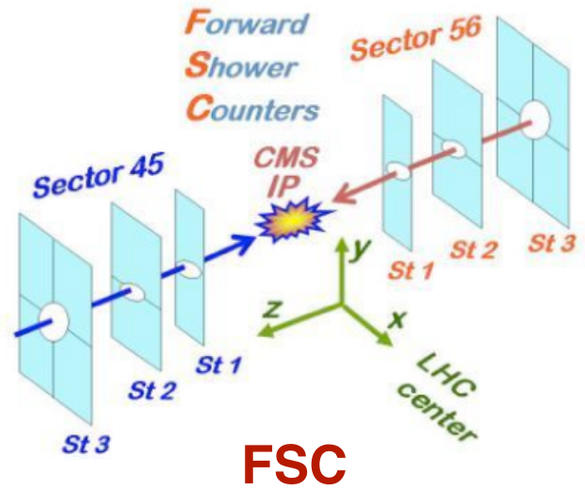
BSC (MinBias triggers)
3.23 < |η| < 4.65

HF (Hadron Forward)
3 < |η| < 5

TOTEM T1, **3.1 < |η| < 4.7**

TOTEM T2, **5.3 < |η| < 6.5**

CASTOR,
-6.6 < η < -5.2



FSC

Forward detectors at CMS