The onset of gluon saturation at CERN LHC energies and new directions using quantum tomography

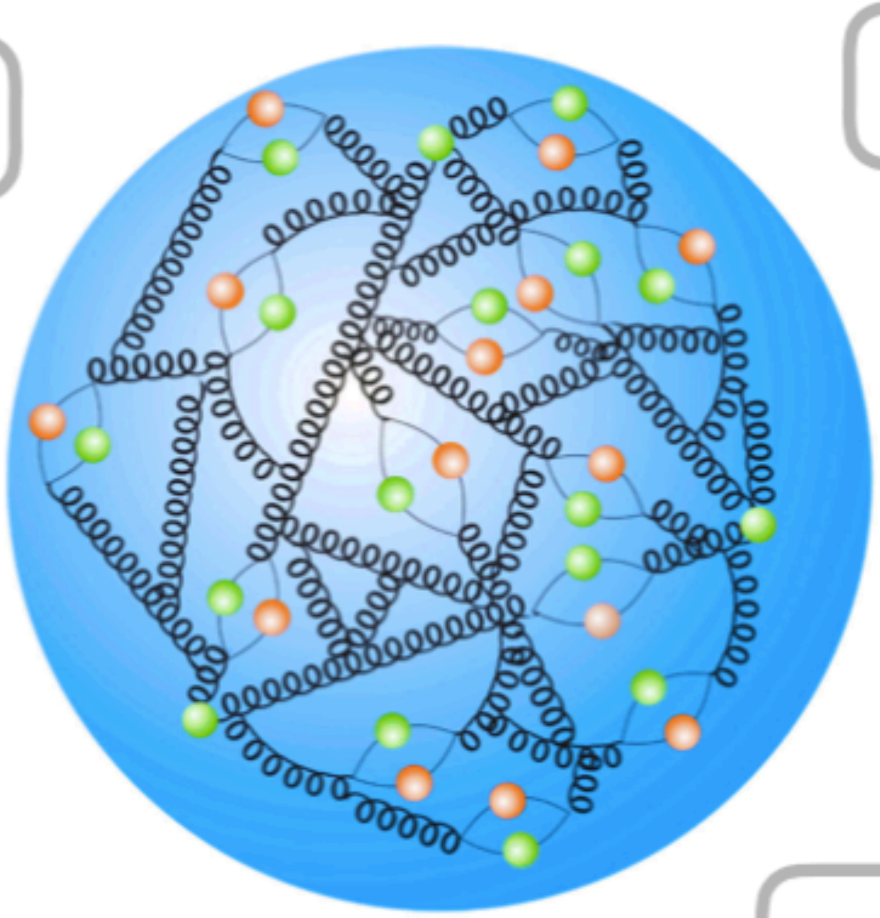
Daniel Tapia Takaki
University of Kansas

ICN and IF-UNAM High Energy Physics seminar
Mexico City - May 29, 2019

From yesterday in KS

The many faces of the proton

QCD bound state of **quarks** and **gluons**



Origin of mass?

Origin of spin?

Gluon-dominated matter?

3D imaging?

Heavy quark content?

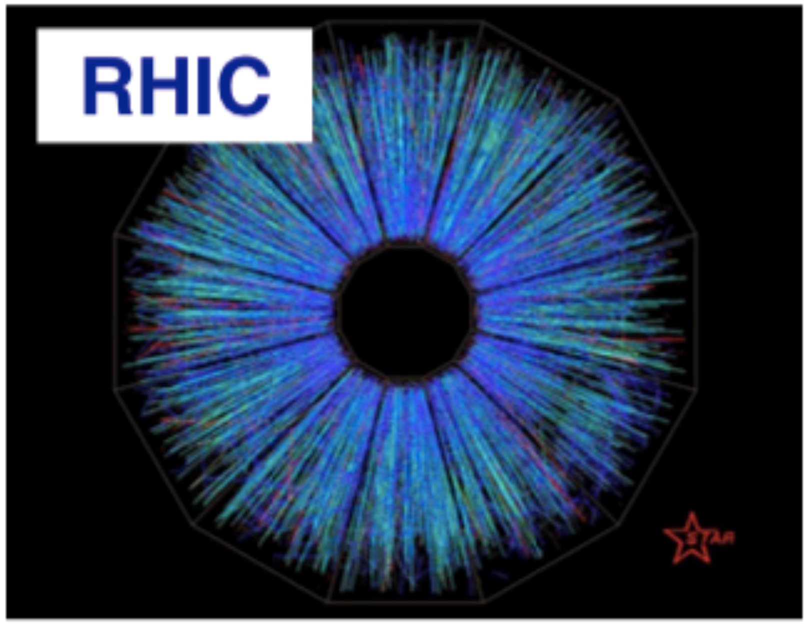
Nuclear modifications?

From J. Rojo. DIS 2019

From colliders to the cosmos

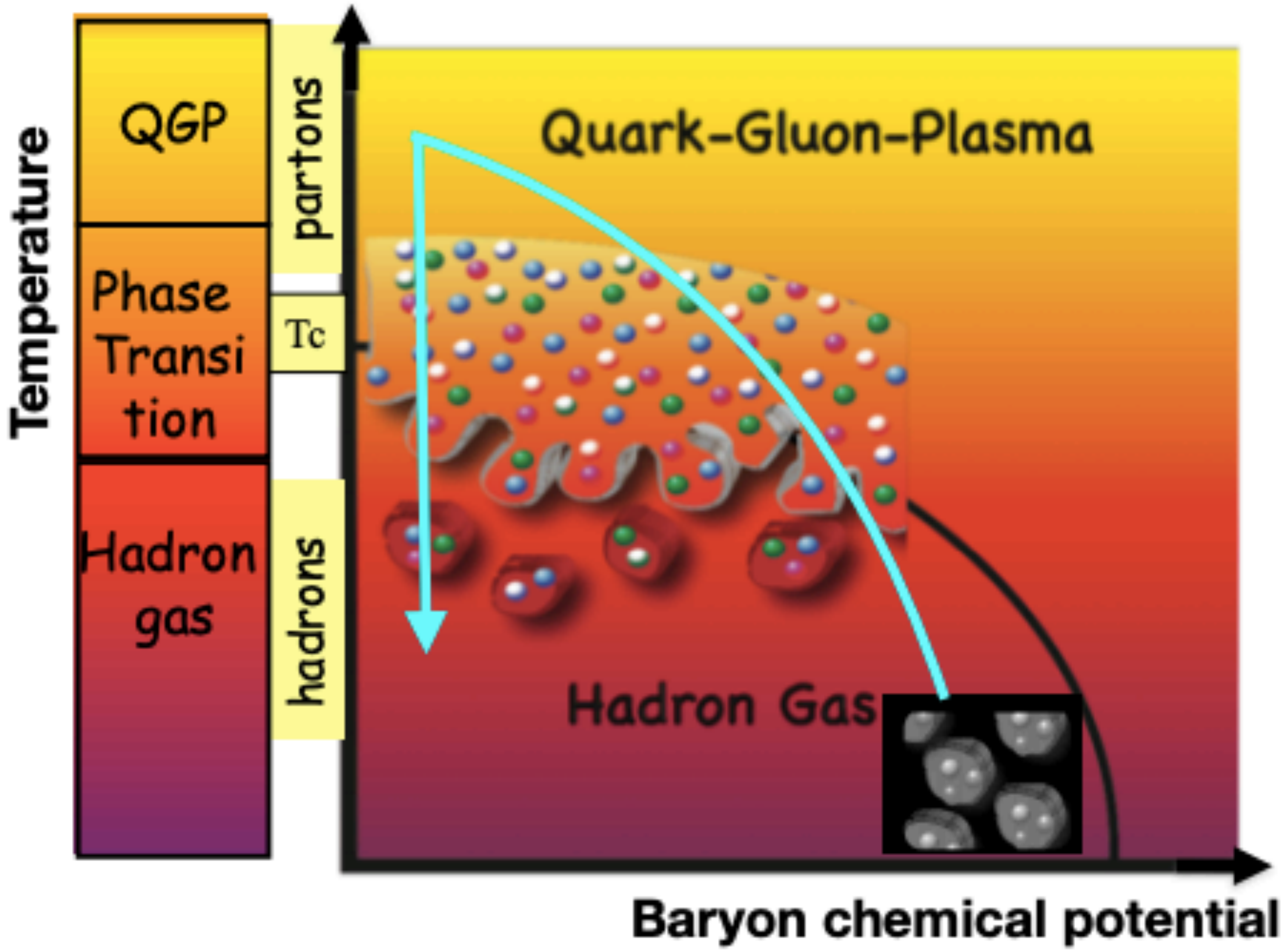
New **elementary particles** beyond the **Standard Model?**

Origins and properties of **cosmic neutrinos**?

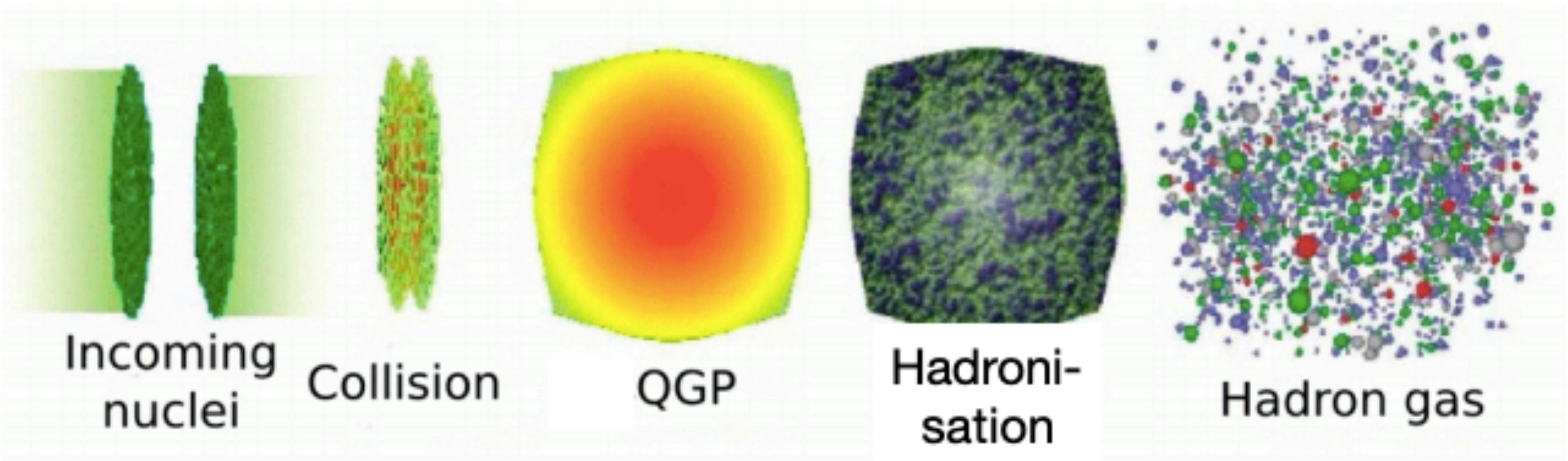


Nature of **Quark-Gluon Plasma** in **heavy-ion collisions?**

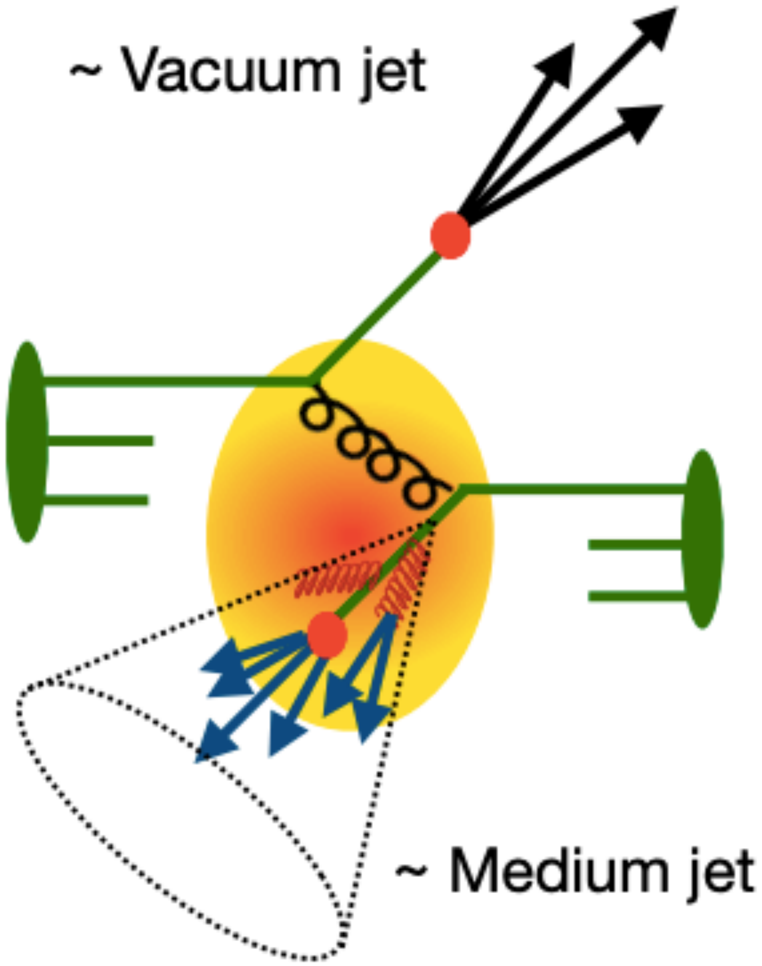
From J. Rojo. DIS 2019



- Hard scattering
- QCD medium: elastic and inelastic collisions (+radiation)
- Hadronisation
- Decoupling
  Freeze-outs (chemical + kinetic)

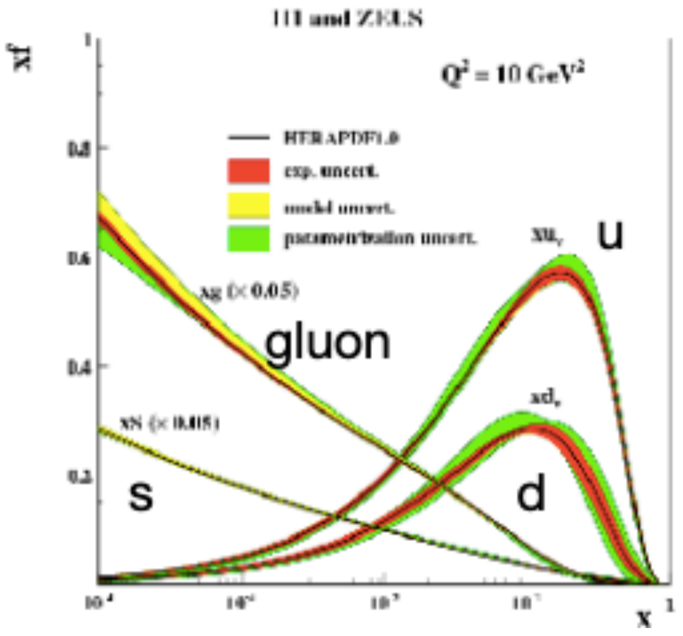


From C. Market. DIS 2019



- Initial conditions (+geometry)
- Initial hard and soft scatterings (qq,qg,gg) depending on: x (momentum fraction) gluon density (not well known)
- Energy dissipation by gluon radiation or parton scattering
- Modification of fragmentation ?

} jet



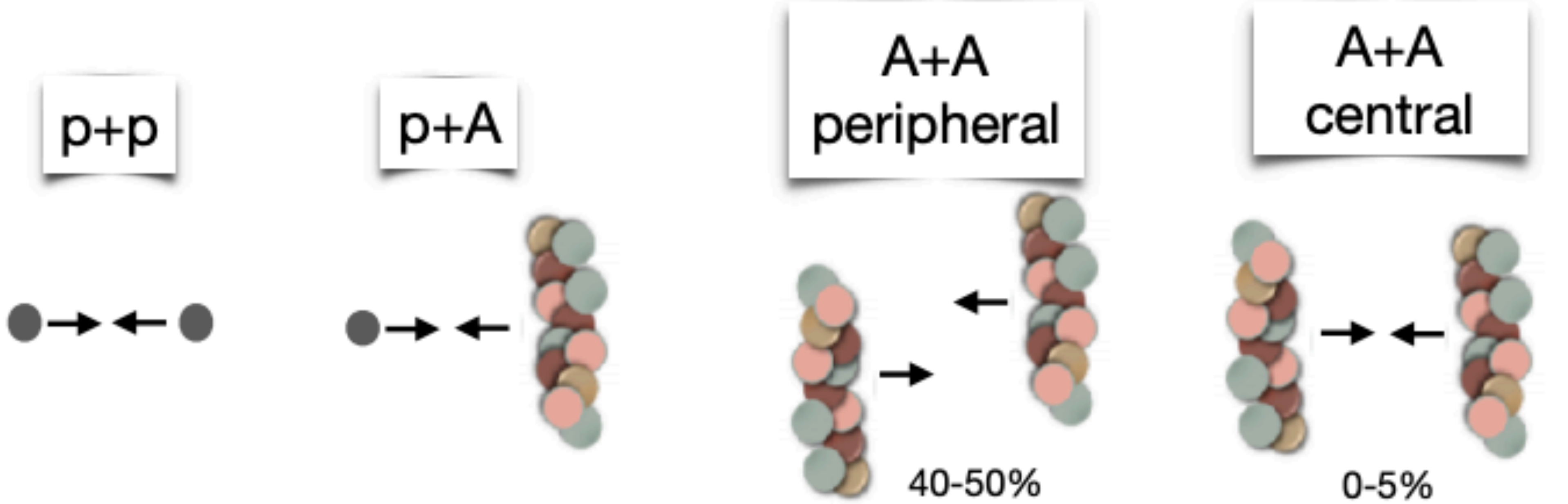
Energy dissipation: Where does the energy go?
—> It changes momentum of particles ?
—> It changes the particle angular distribution ?
—> It changes particle species ?

Questions:
What is the medium ?
How is the medium influenced by the jet ?
How is the jet influenced by the medium ?

From C. Market. DIS 2019

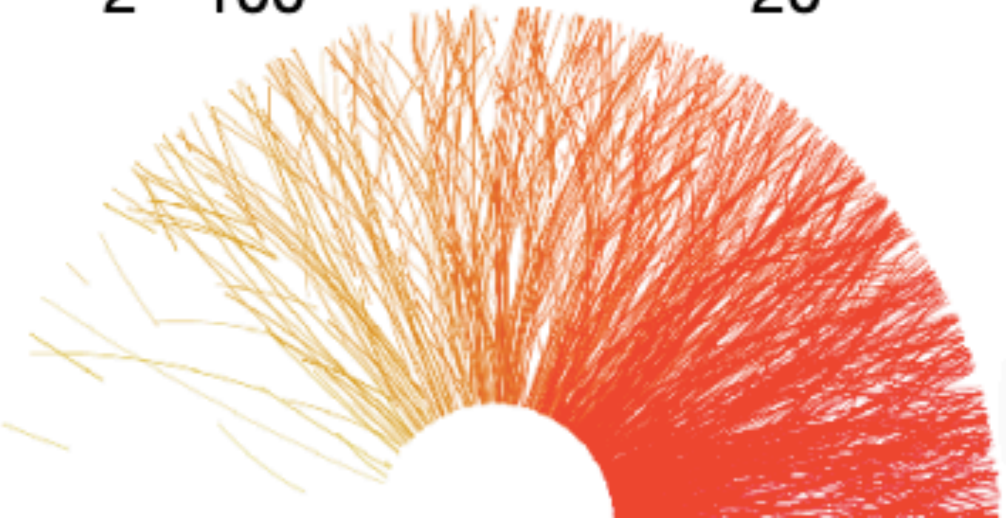
Vary system size of collision

(medium size)



Measure particle multiplicity (activity) at LHC energies (e.g. in TPC |eta| < 0.5)

2 - 100 2 - 100 20 - 2000



n_charge
N_part
centrality in %

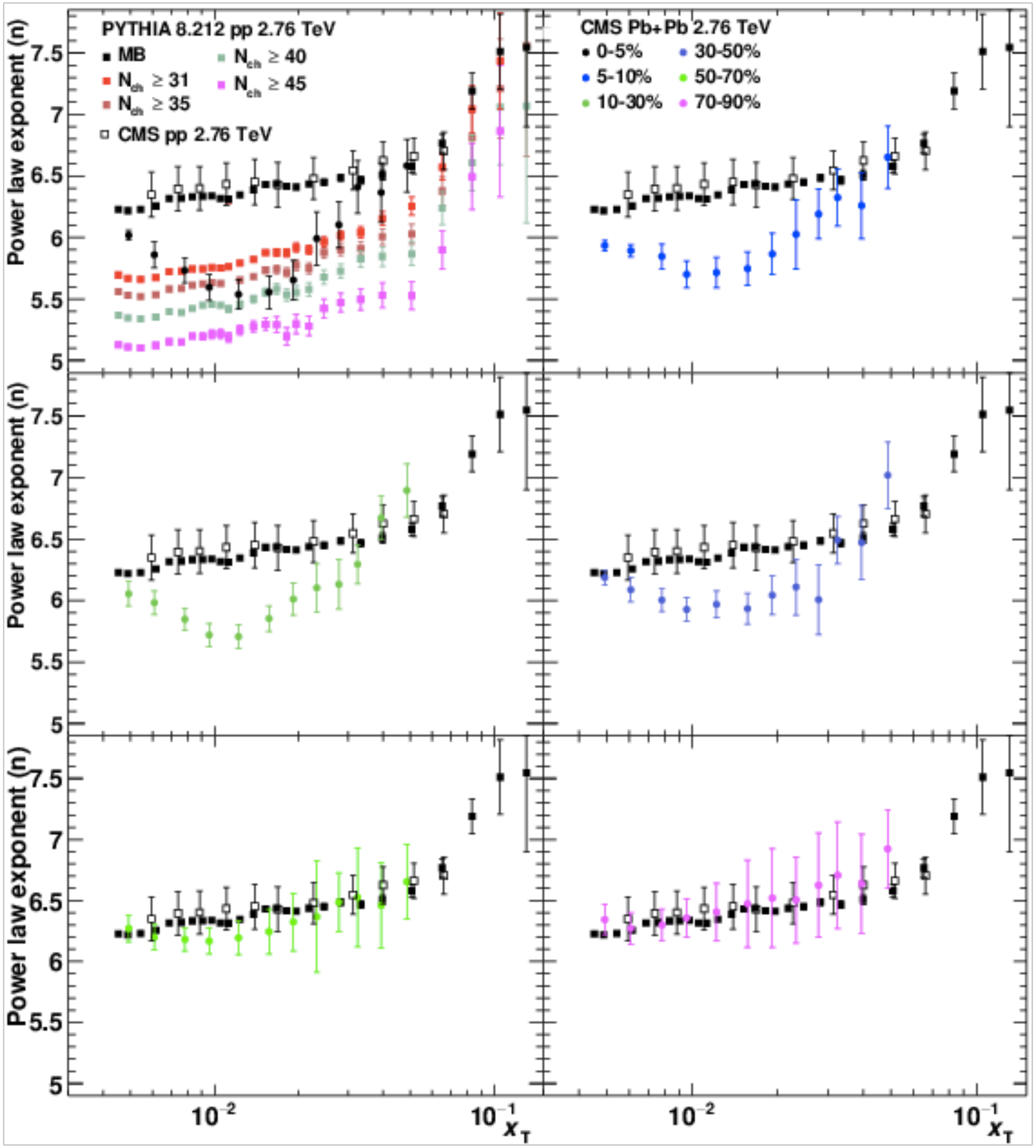
—>measurements: AA/pp

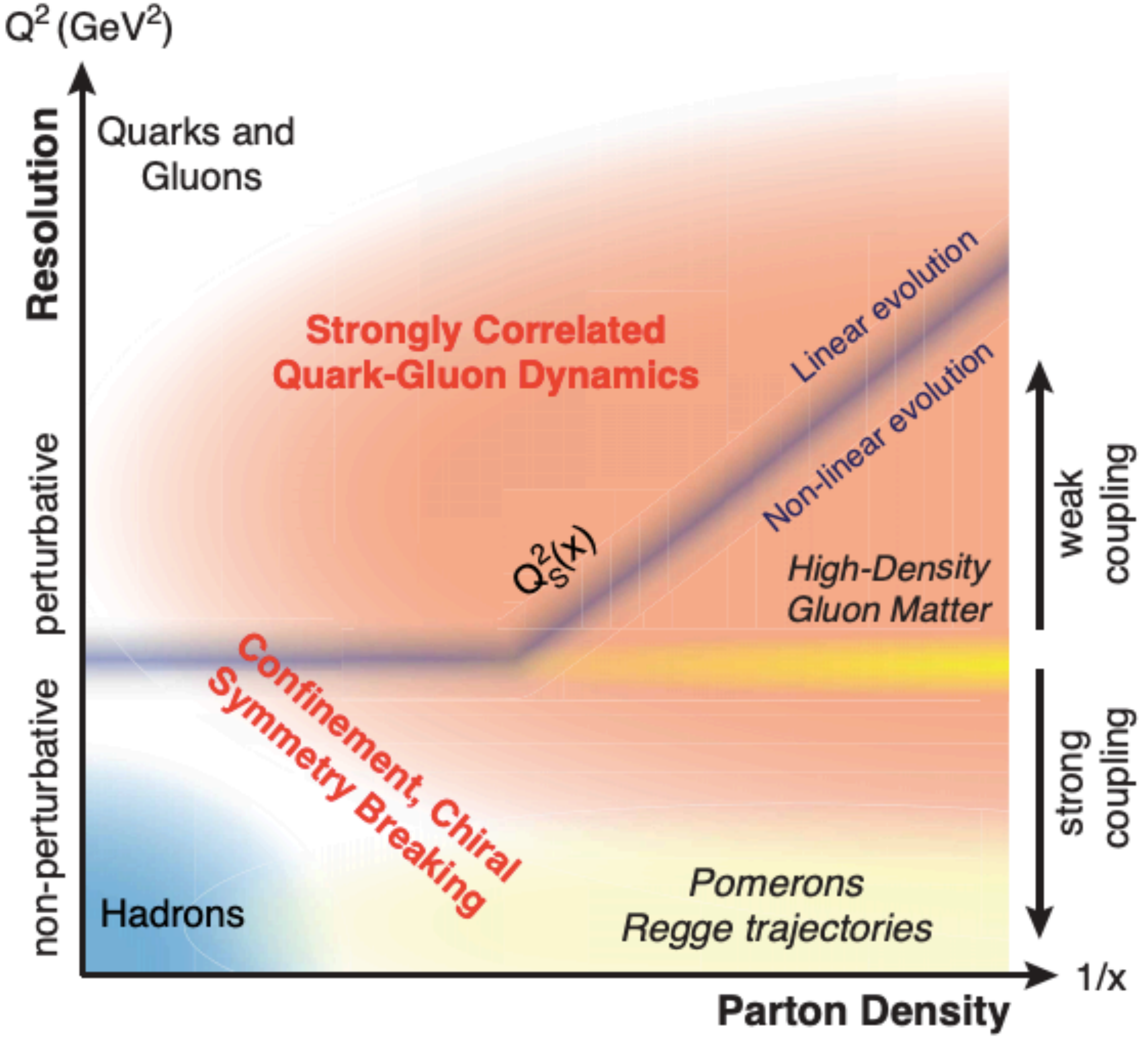
From C. Market. DIS 2019

Phys.Rev. C99 (2019) no.3, 034911

Aditya Nath Mishra, Antonio Ortiz and Guy Paic

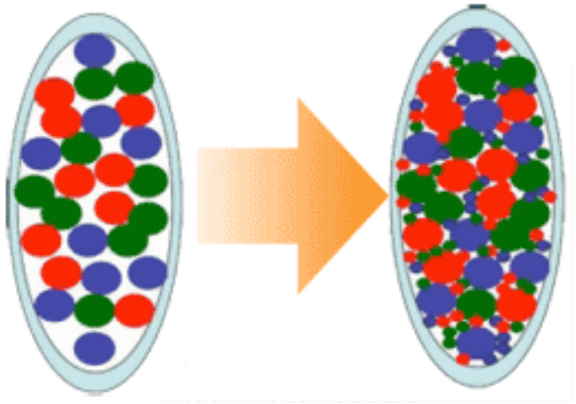
Intriguing similarities between high-pT particle production in pp and AA collisions

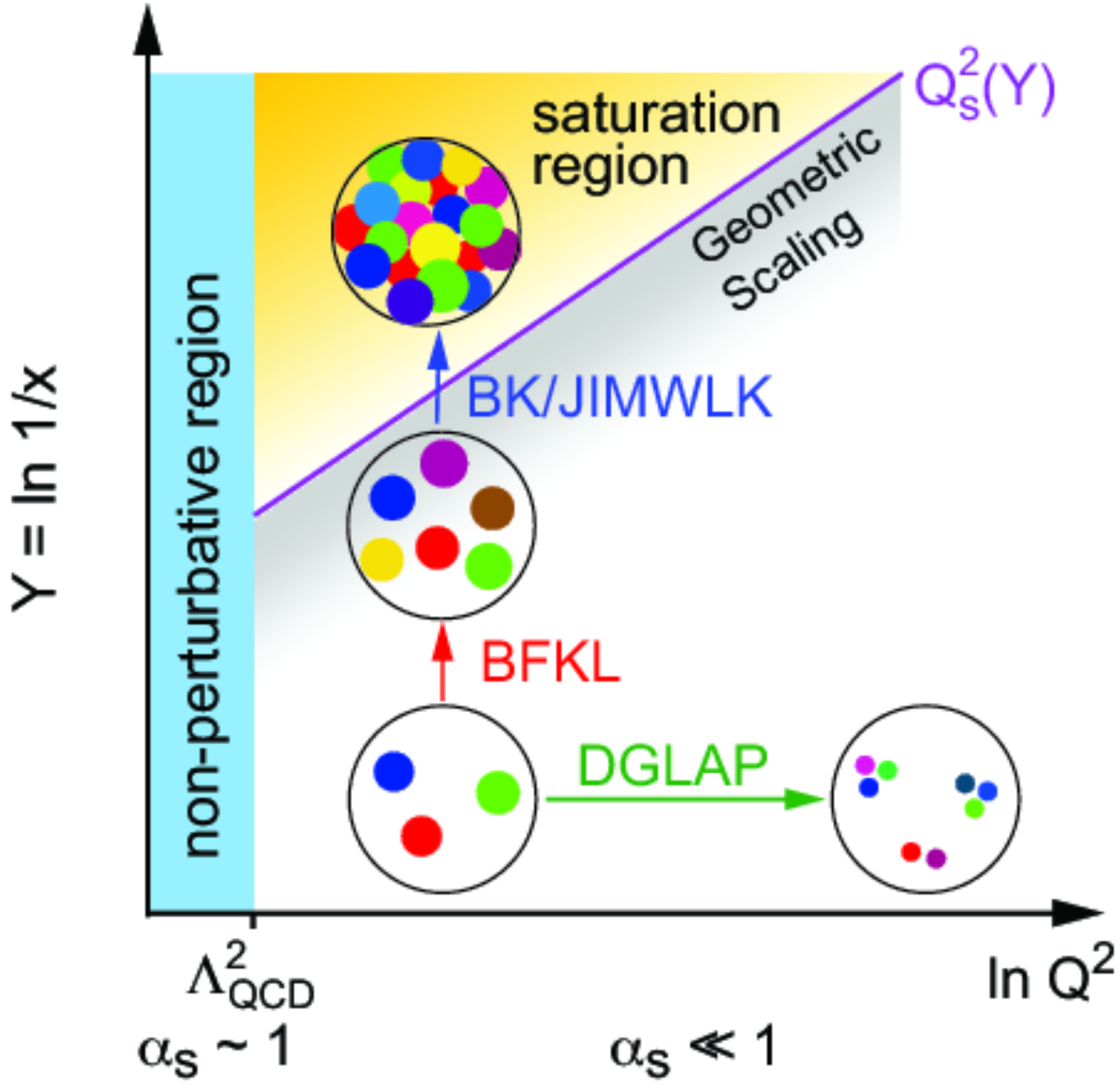




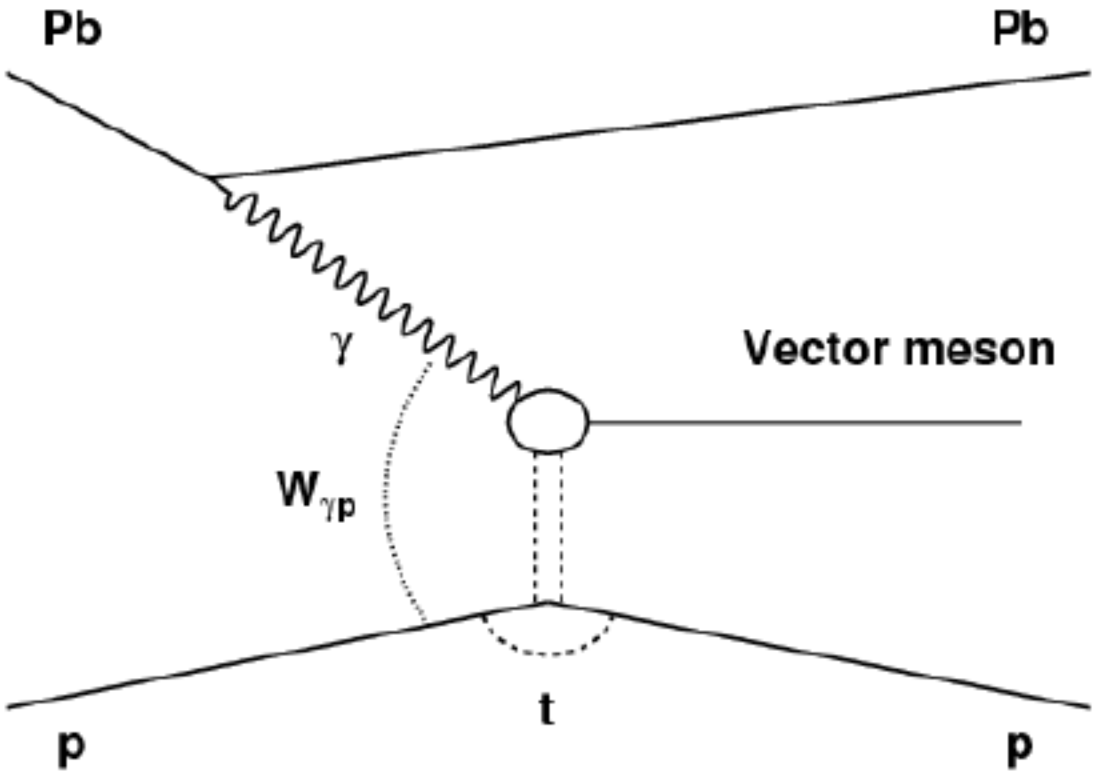
E. Aschenauer et al, arXiv:1708.01527

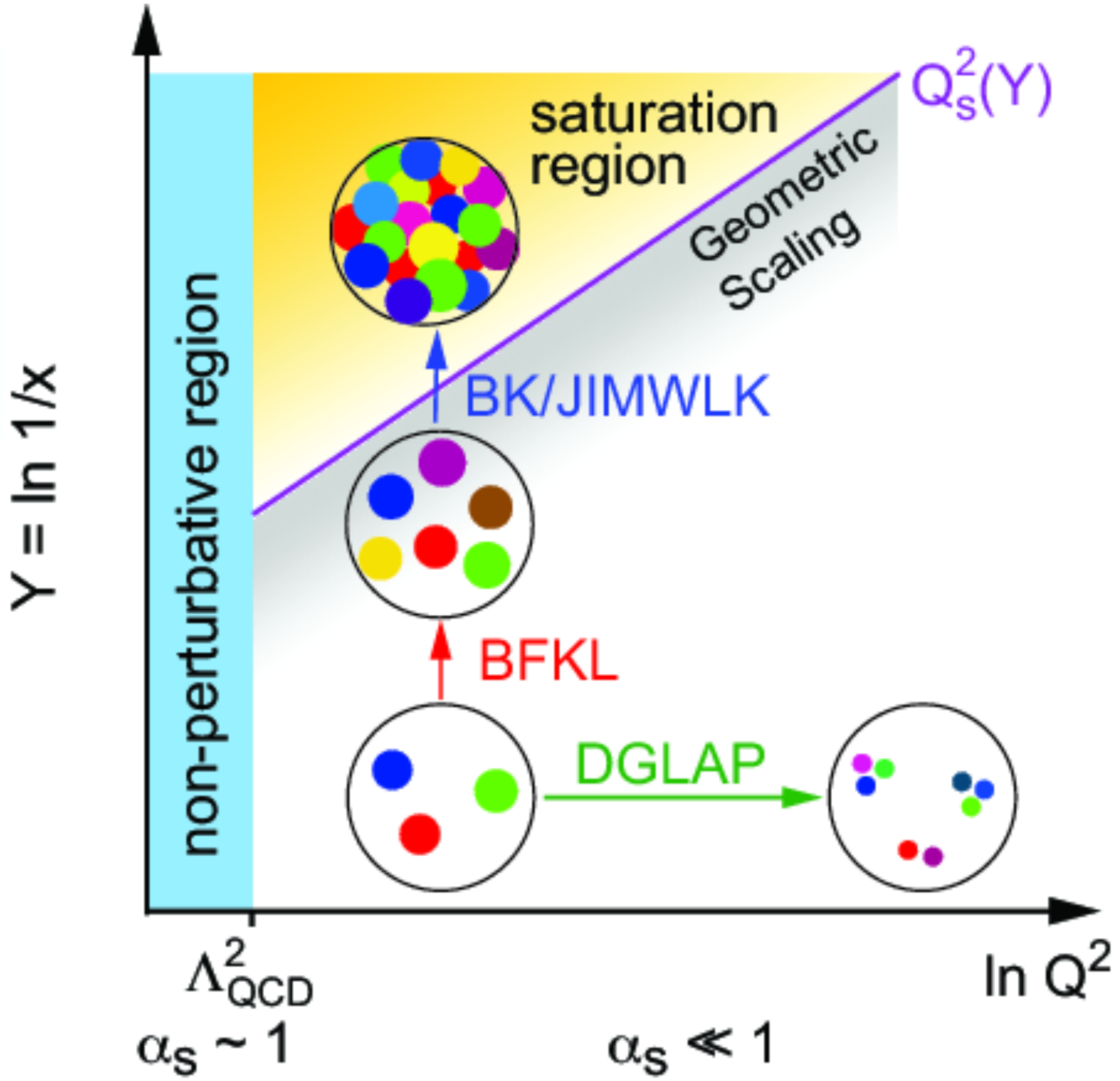
Gluon saturation

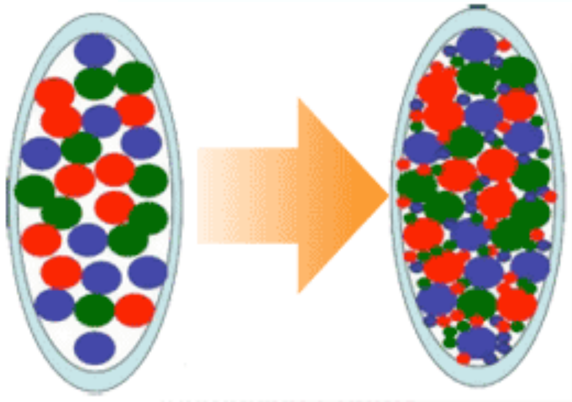




Exclusive VM photoproduction



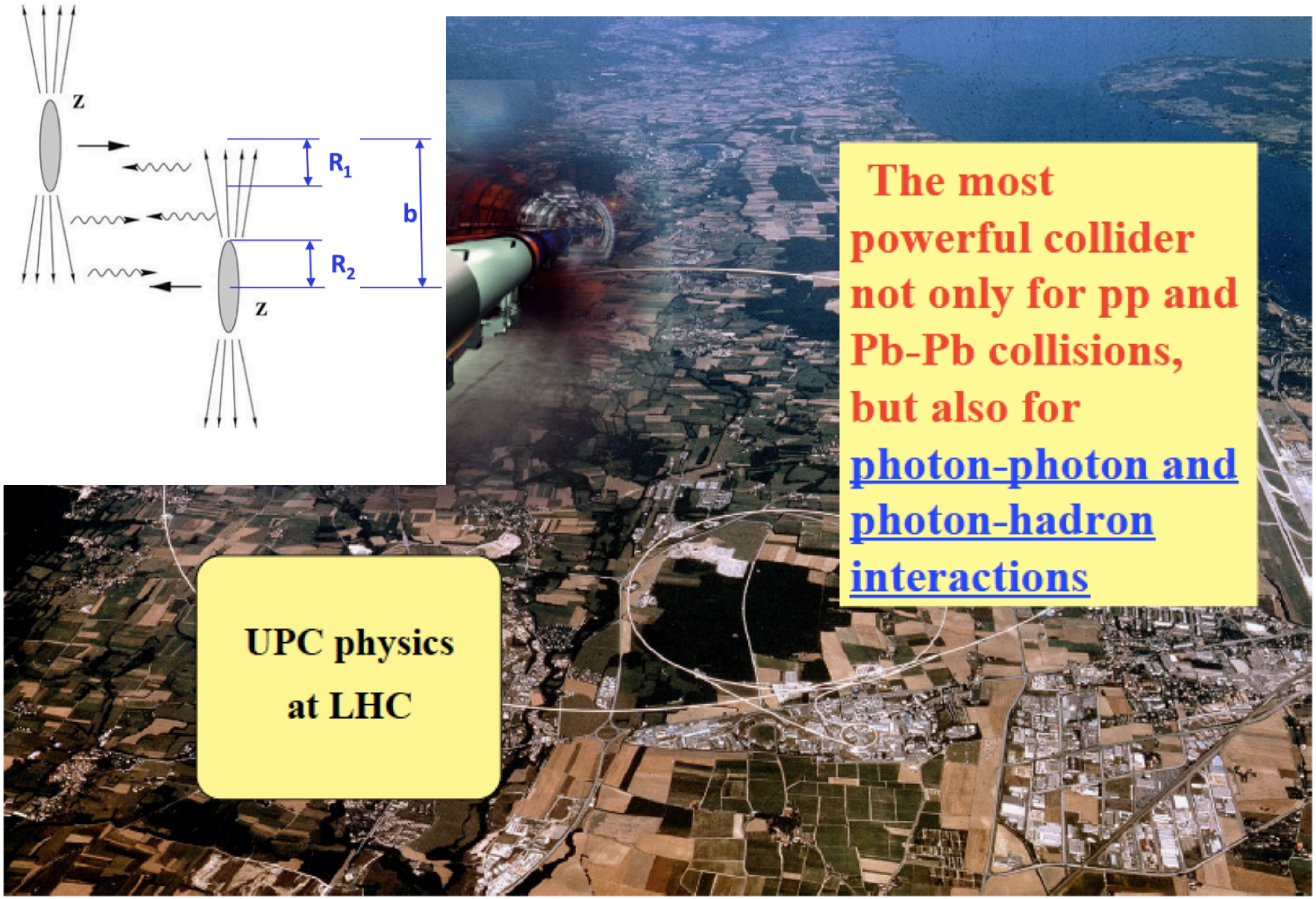




The energy dependance of the cross section

Suggested as a signature of gluon saturation

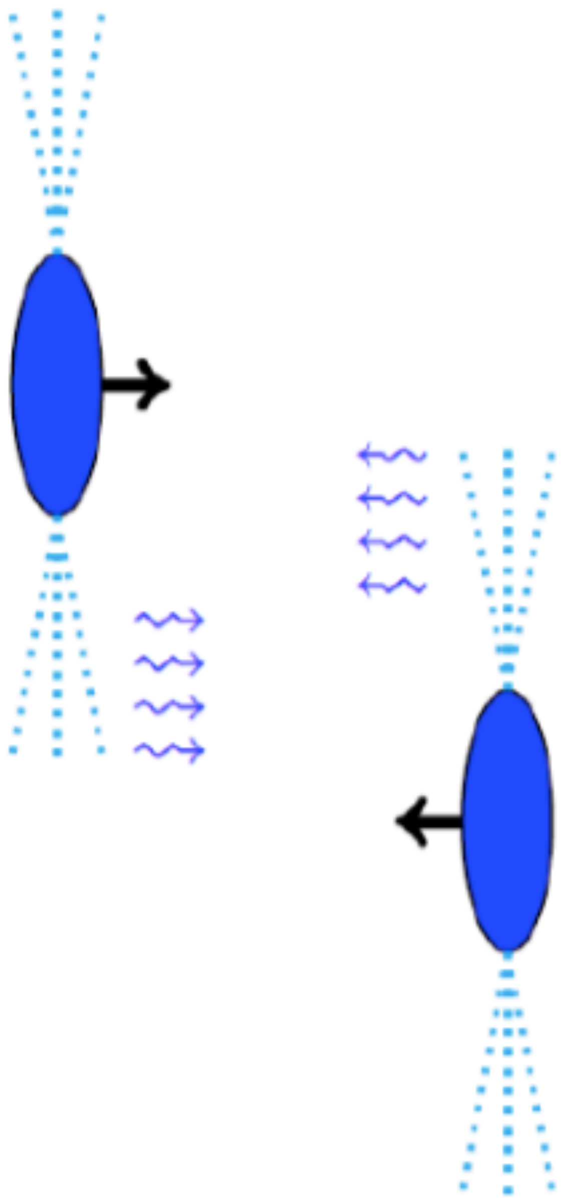
Photon-photon, photon-p, photon-A collider



The most powerful collider not only for pp and Pb-Pb collisions, but also for <u>photon-photon and photon-hadron interactions</u>

UPC physics at LHC

Ultra-peripheral collisions



Nuovo Cim.,2:143-158,1925

http://arxiv.org/abs/hep-th/0205086

Therefore, we consider that when a charged particle passes near a point, it produces, at that point, a variable electric field. If we decompose this field, via a Fourier transform, into its harmonic components we find that it is equivalent to the electric field at the same point if it were struck by light with an appropriate continuous distribution of frequencies.

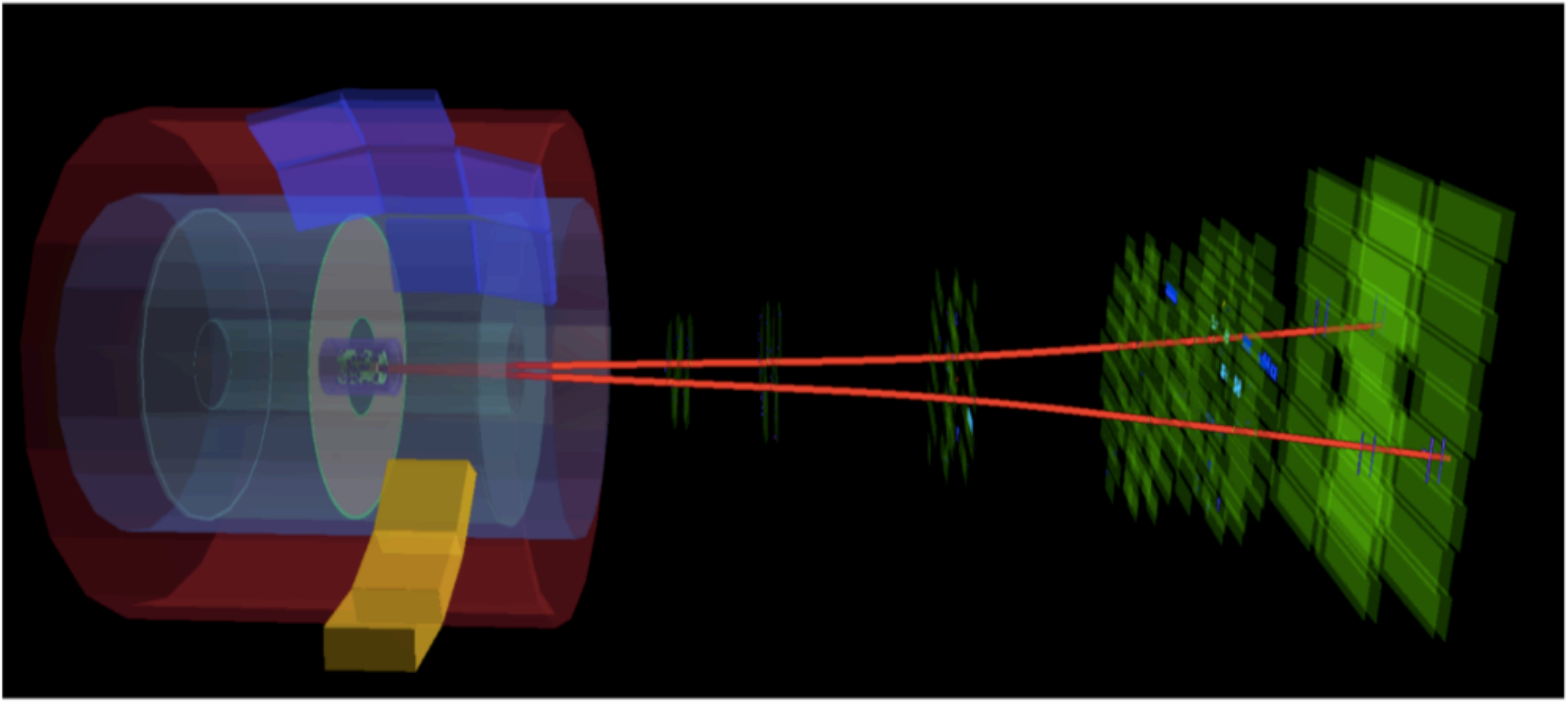
Enrico FERMI

The electromagnetic field surrounding these protons/ions can be treated as a beam of quasi real photons

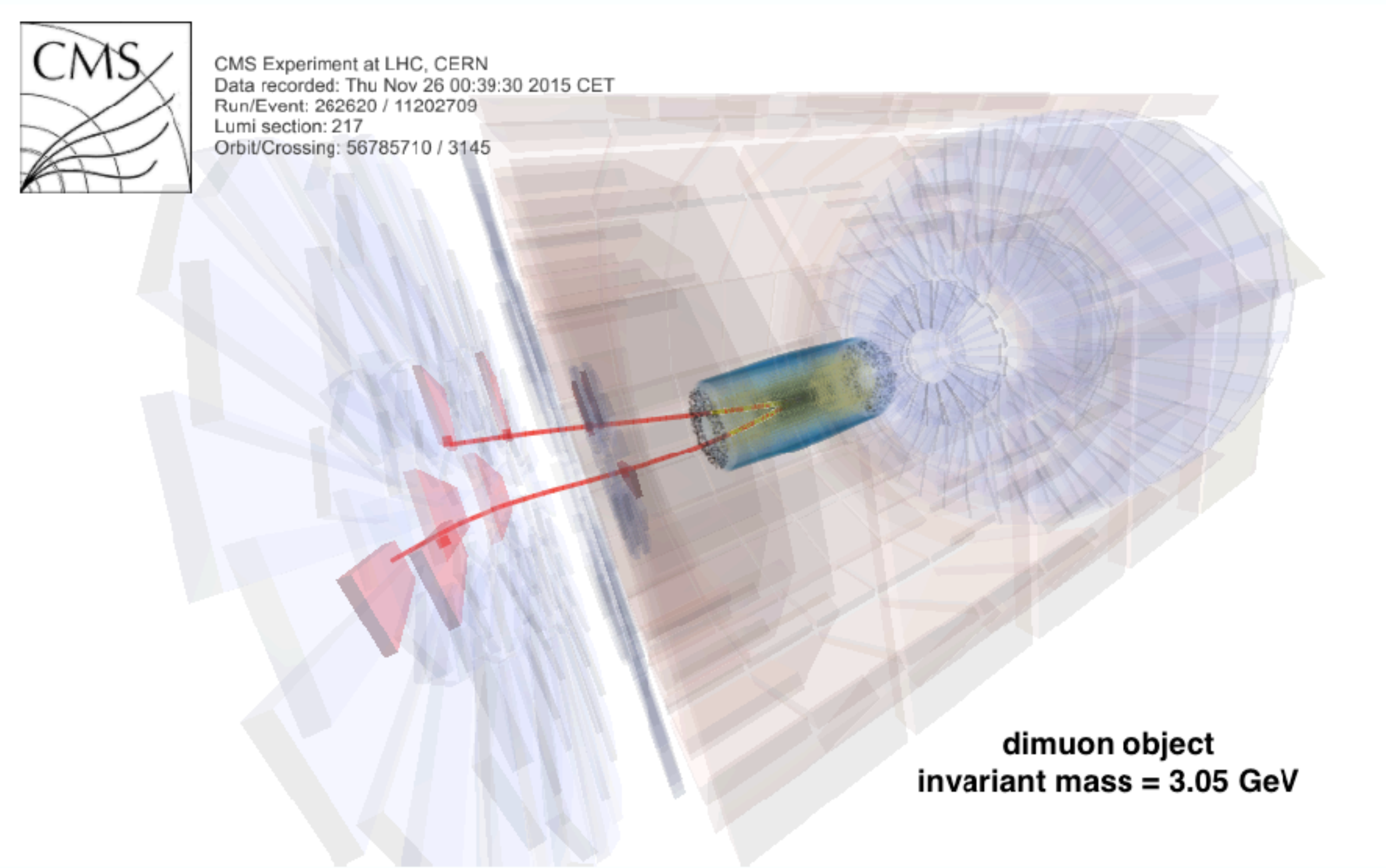
High photon flux ~ Z^2
→ well described by the Weizsäcker-Williams approximation

Two ions (or protons) pass by each other with impact parameters $b > 2R$. **Hadronic interactions are strongly suppressed**

UPC J/ψ at ALICE



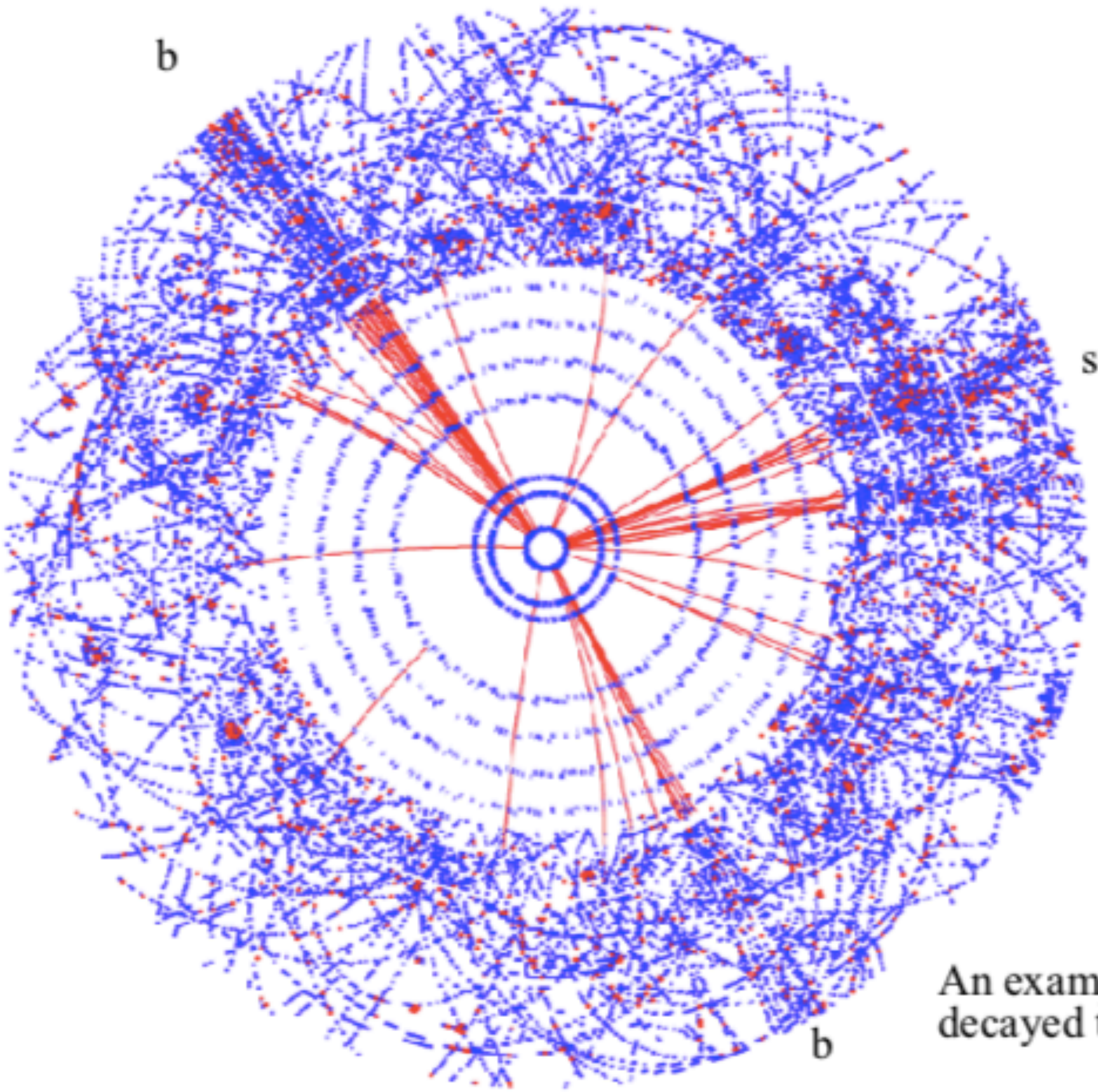
UPC event



CMS Experiment at LHC, CERN
Data recorded: Thu Nov 26 00:39:30 2015 CET
Run/Event: 262620 / 11202709
Lumi section: 217
Orbit/Crossing: 56785710 / 3145

dimuon object
invariant mass = 3.05 GeV

What events really look like scares me!

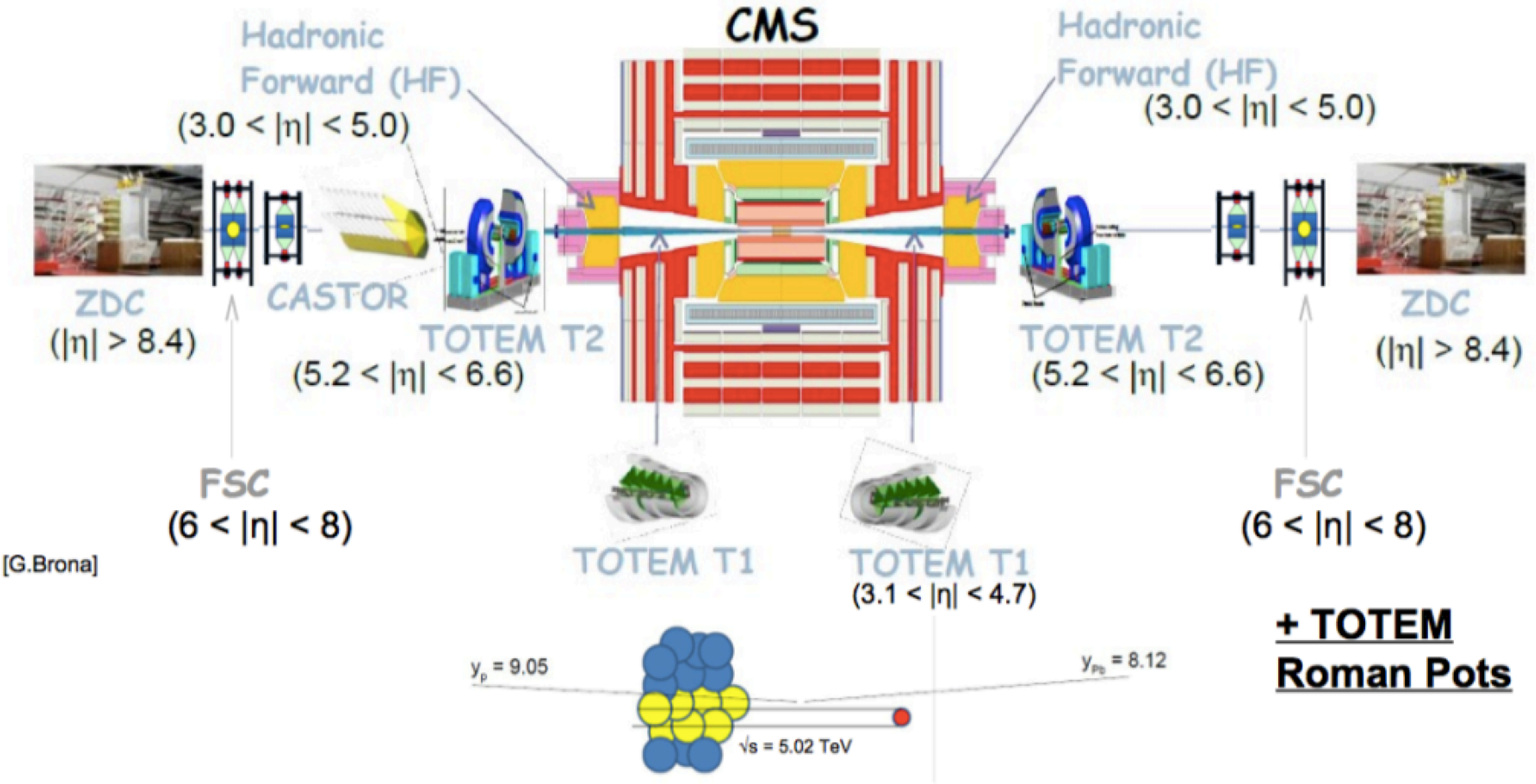


soft gluon radiation?

An example of an event where a higgs boson decayed to a pair of b-quarks/

From K. Kong SUSY 2019

UPCs at CMS

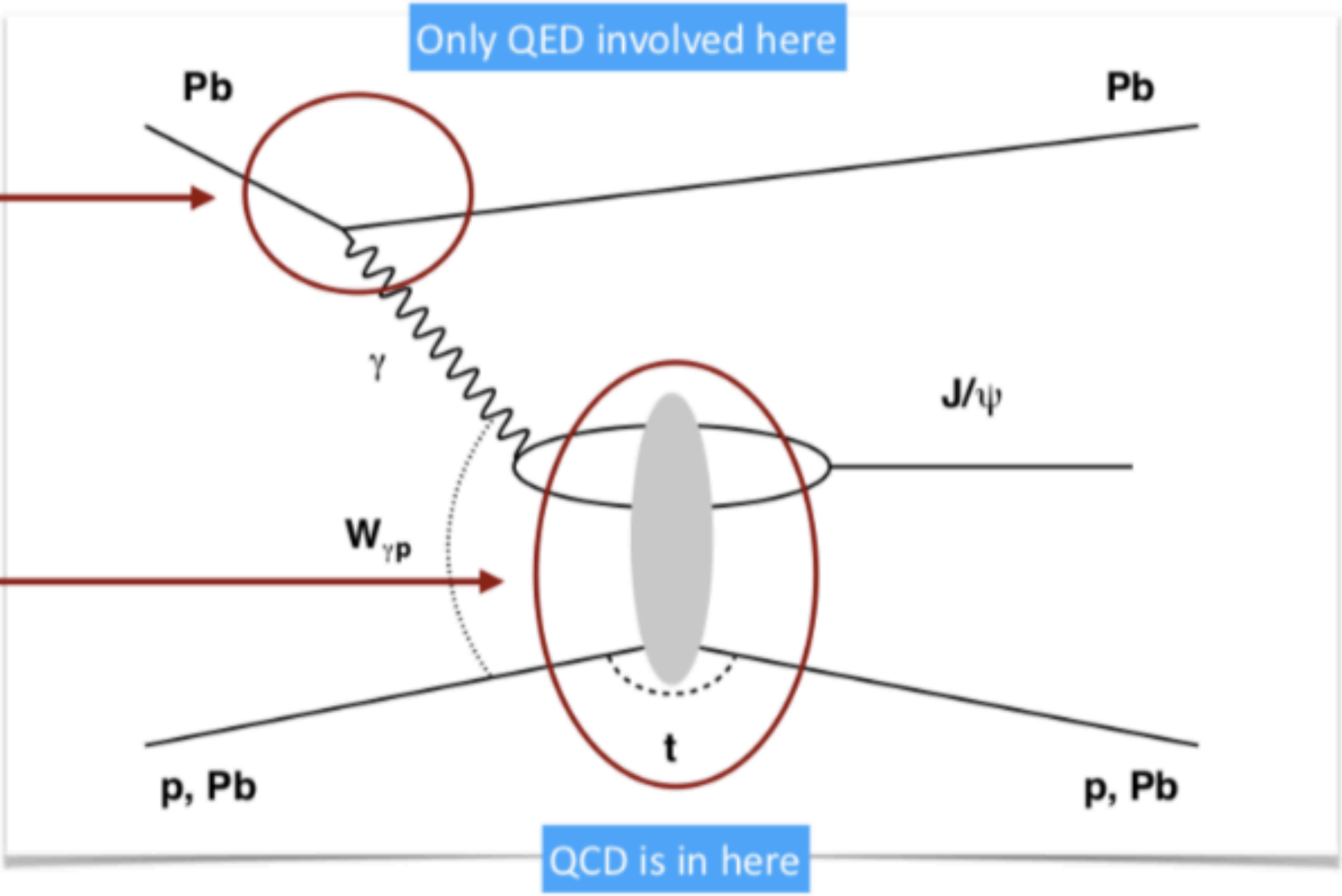


+ TOTEM Roman Pots

UPC VM

The process can be factorised in two parts:

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



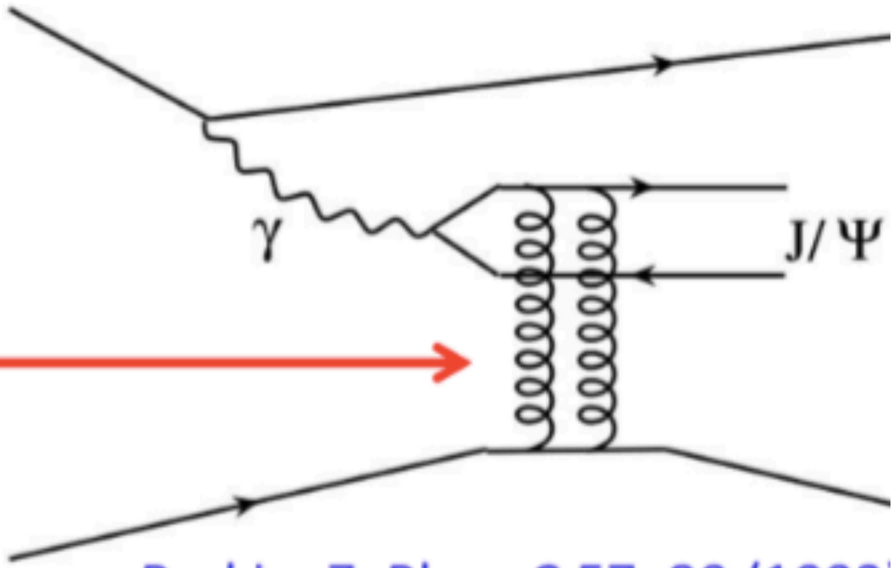
Only QED involved here

QCD is in here

Exclusive VM photo production

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

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



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:

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

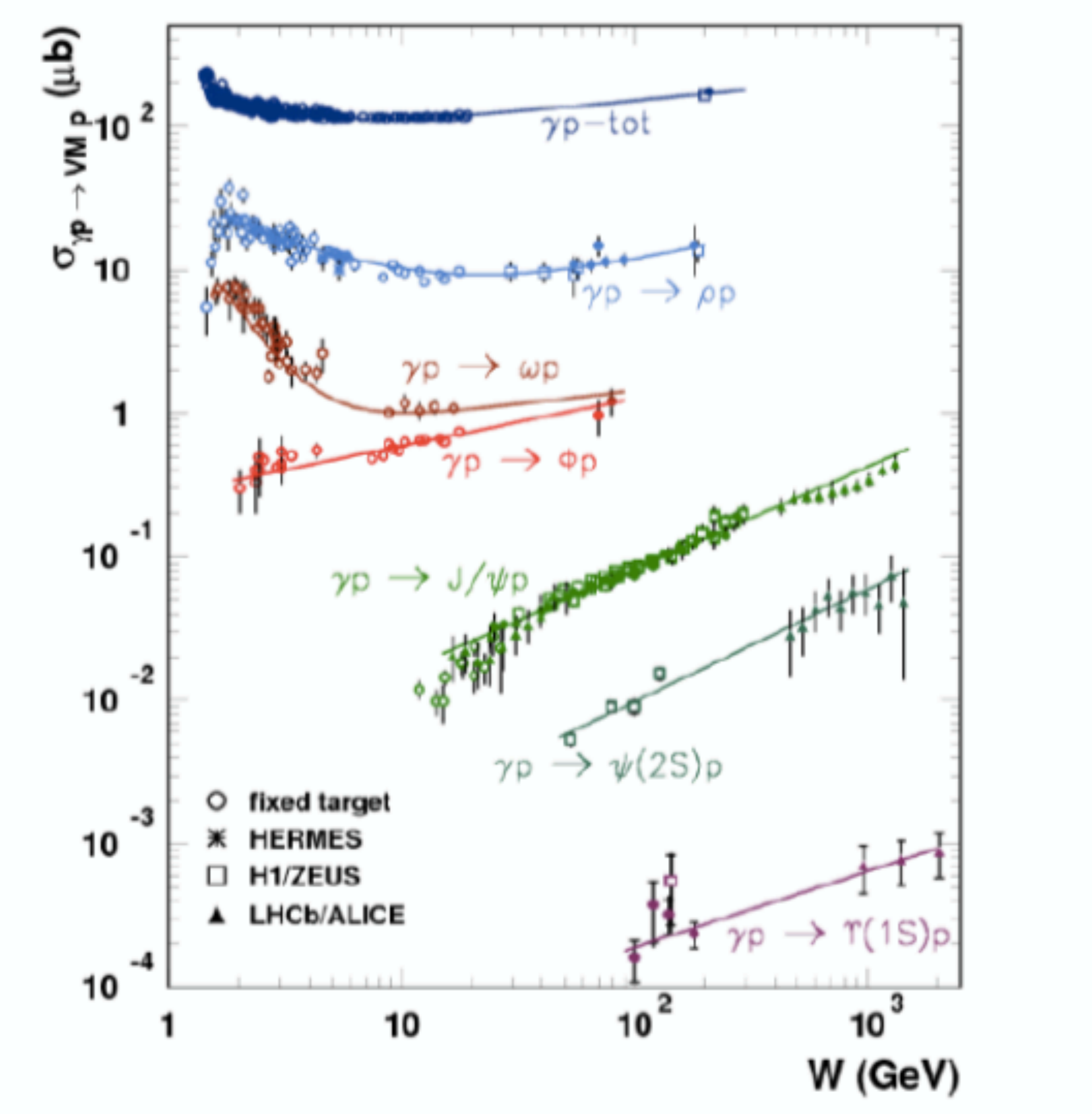
Exclusive VM photo production

Caveats:

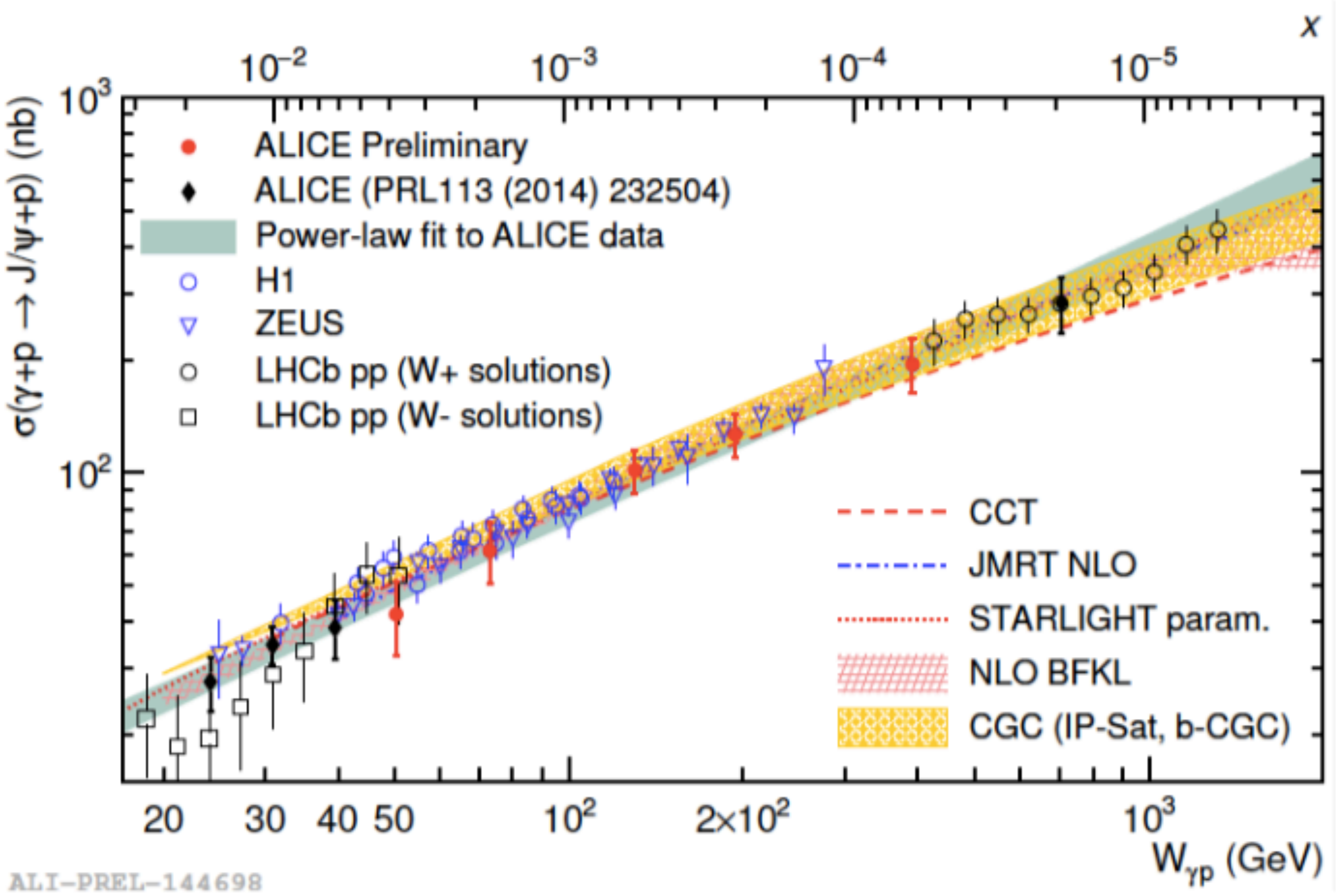
- J/ψ photoproduction probes generalized gluon distributions (two gluons have different x values):
  - Connected with collinear PDFs via Shuvaev transform: PRD 60 (1999) 014015
- Scale uncertainty (μ^2 ~ 2.4-3 GeV^2 is a reasonable choice)
- Large NLO contributions

Exclusive VM photo production

Eur. Phys. J. A52 (2016) no.6, 158

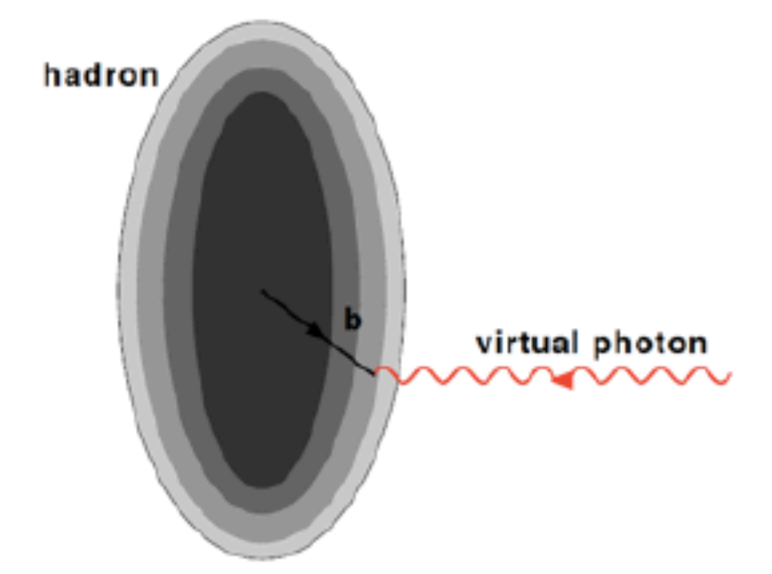


Exclusive J/ψ in γp



t-distribution

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

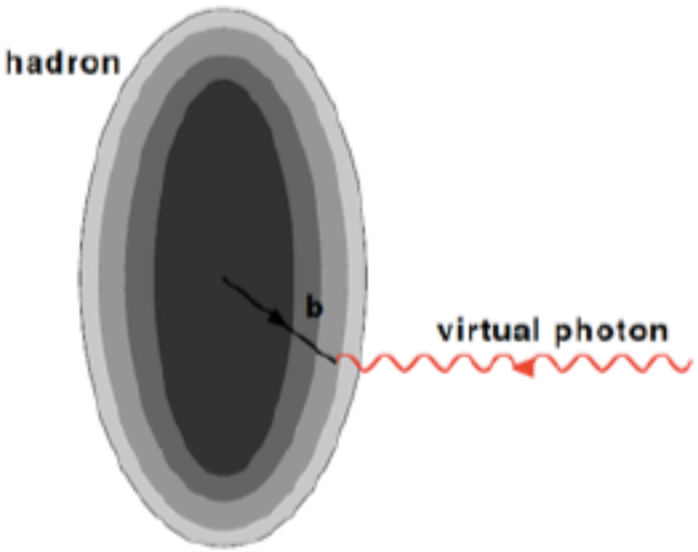


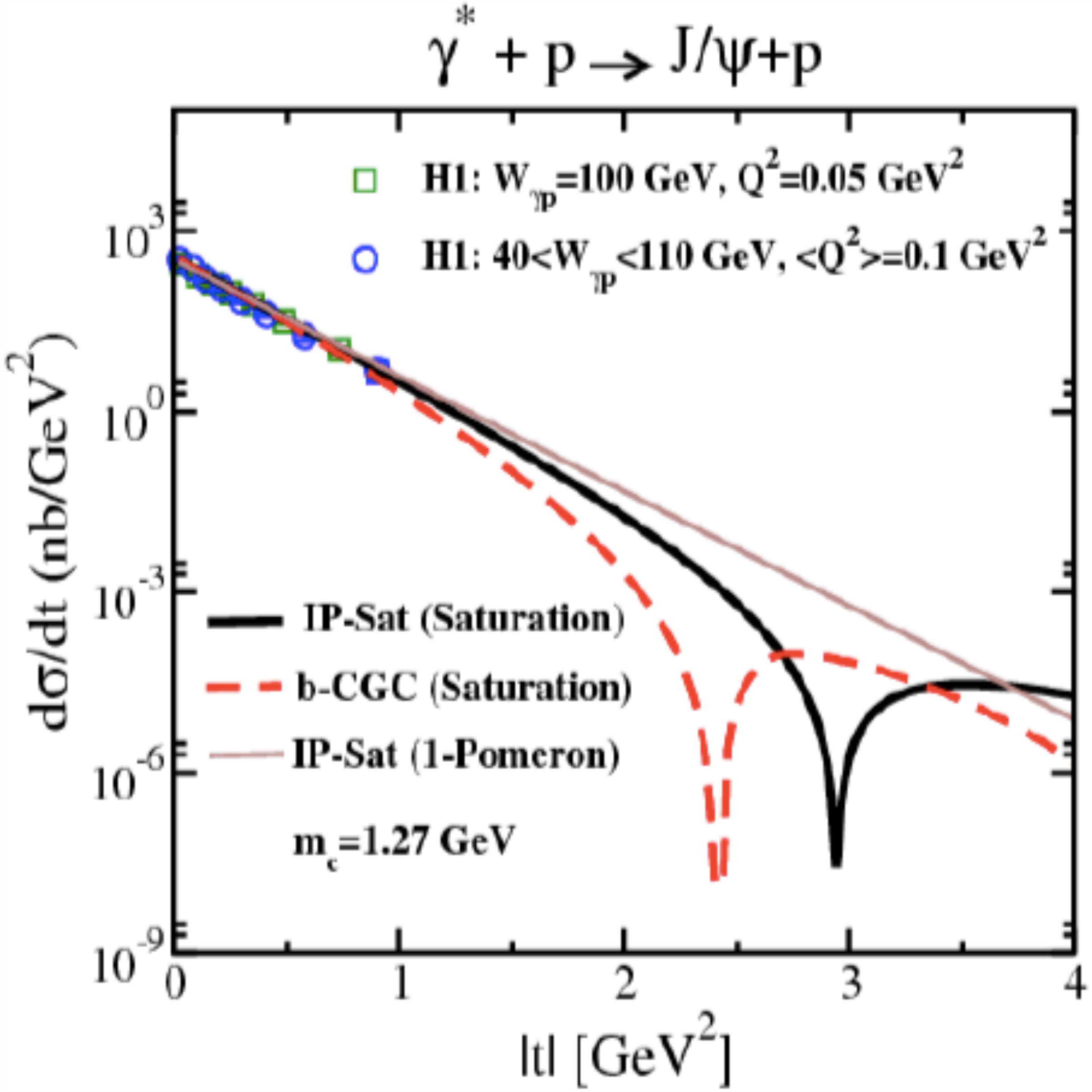
The study of the t-distribution

Appearance and location of diffractive dips: signature of gluon saturation

t-distribution

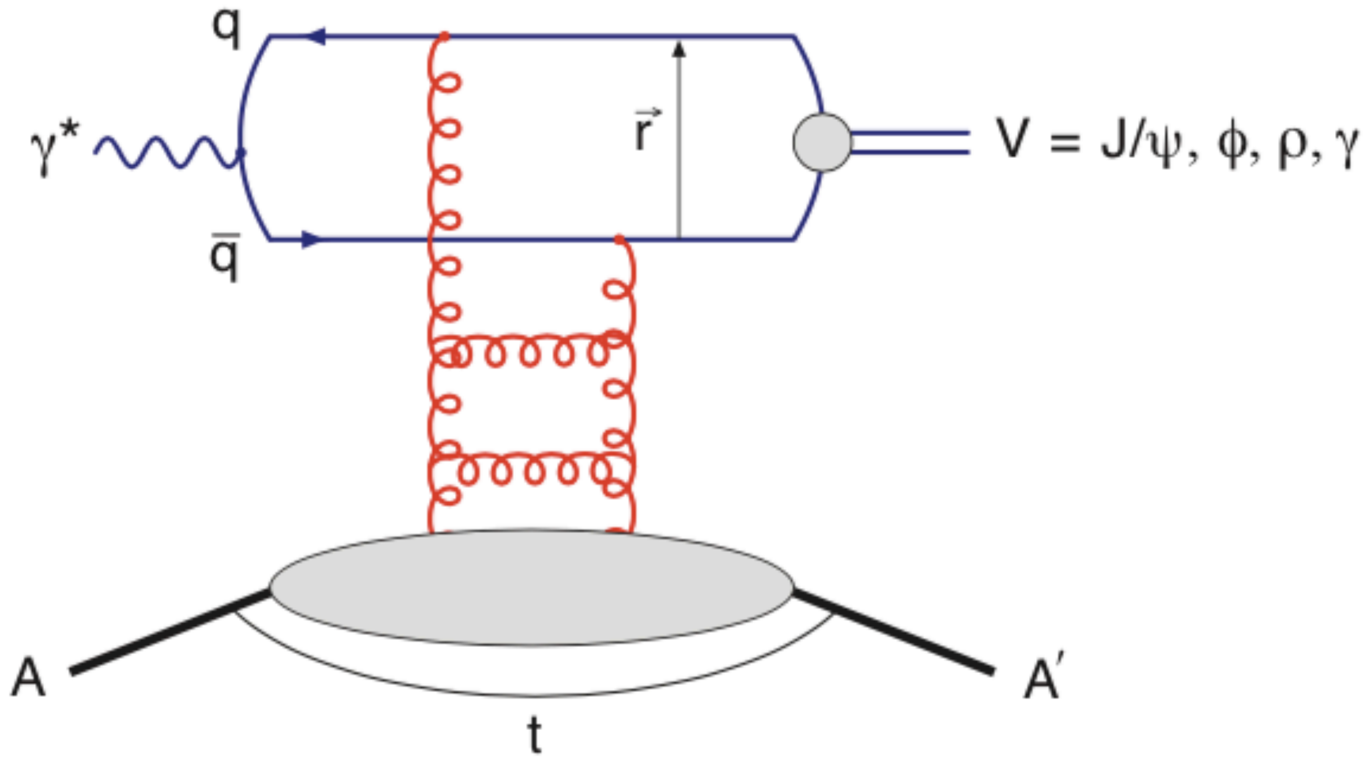
- t-differential measurements give a gluon tranverse mapping of the hadron/nucleus.



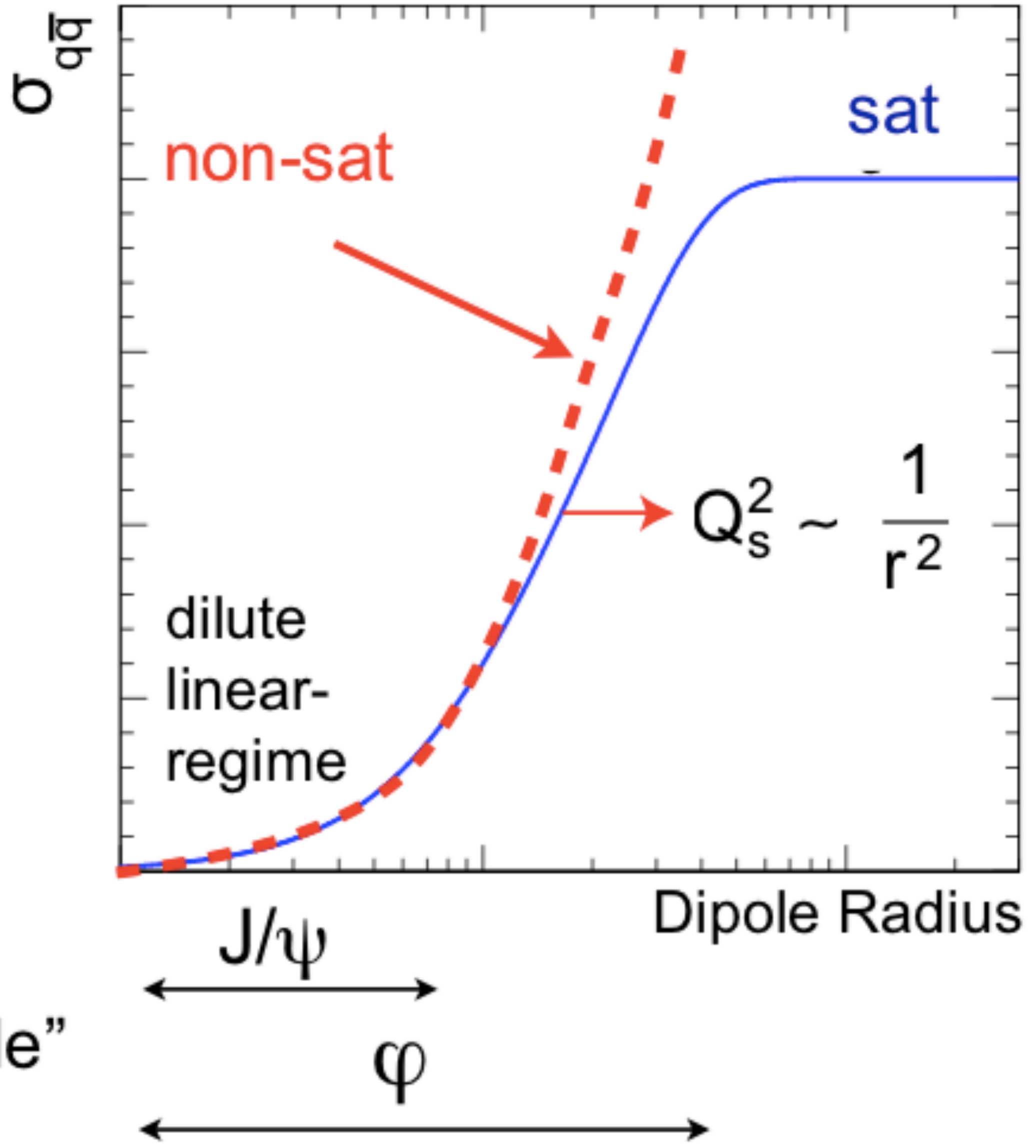


Here:

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



Dipole Cross-Section:



small size (J/Ψ): cuts off saturation region

large size (φ,ρ, ...): "sees more of dipole amplitude"

→ more sensitive to saturation

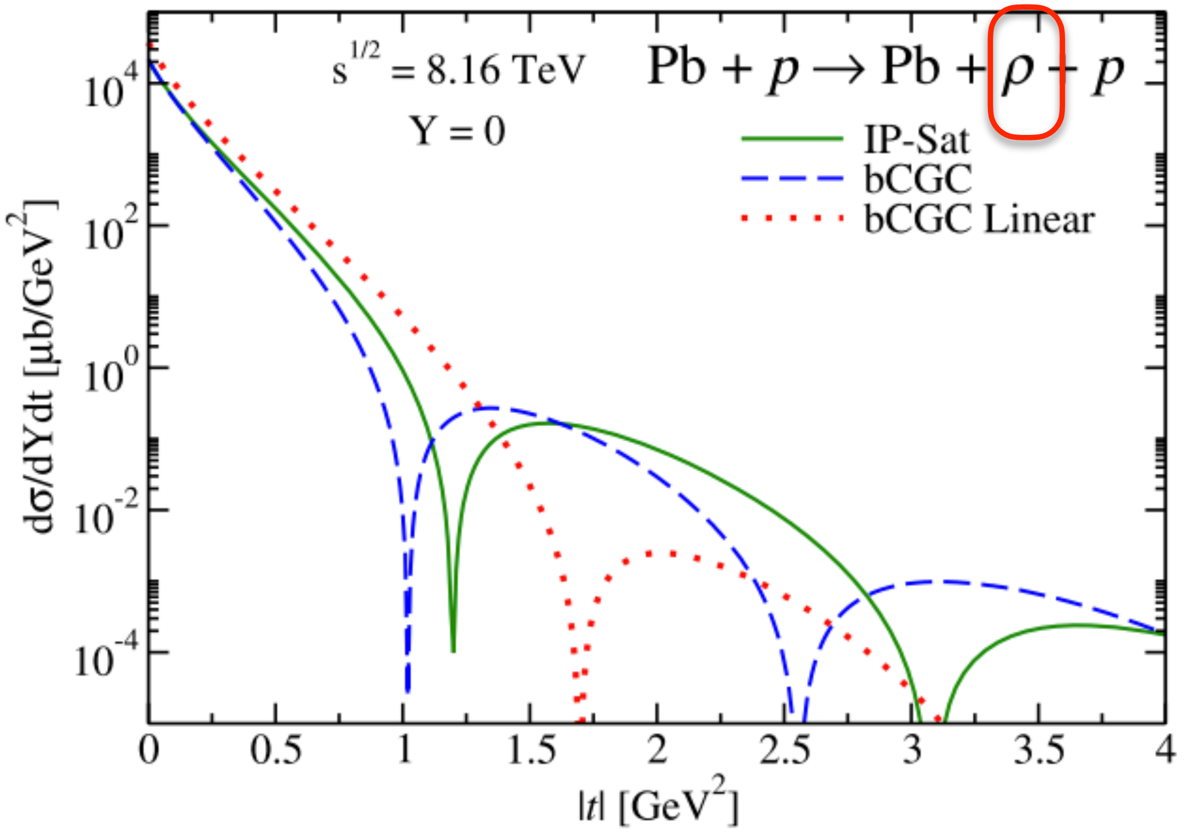
17

From T. Ullrich, IS 2017

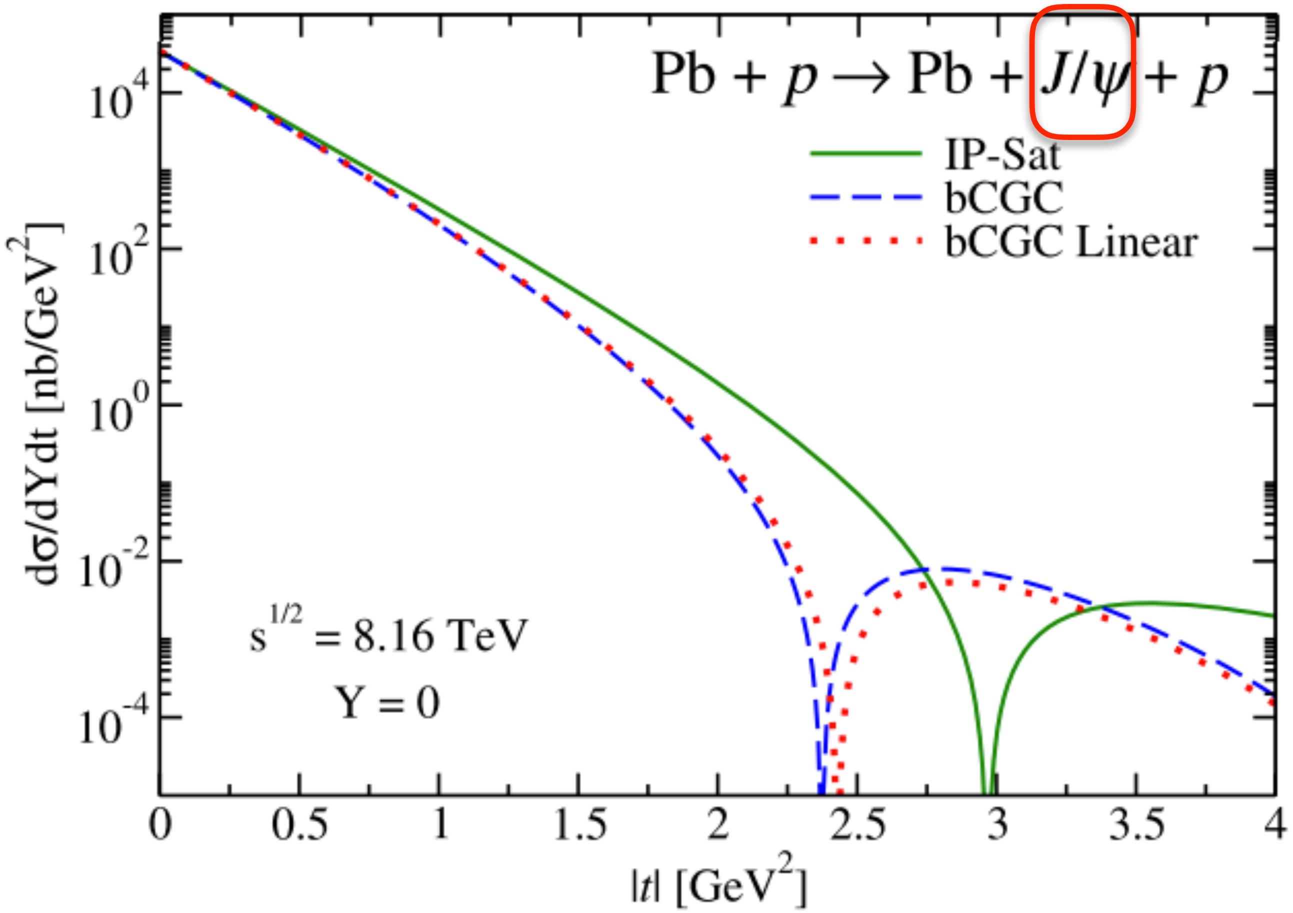
t-distribution
Exclusive VM in γp

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

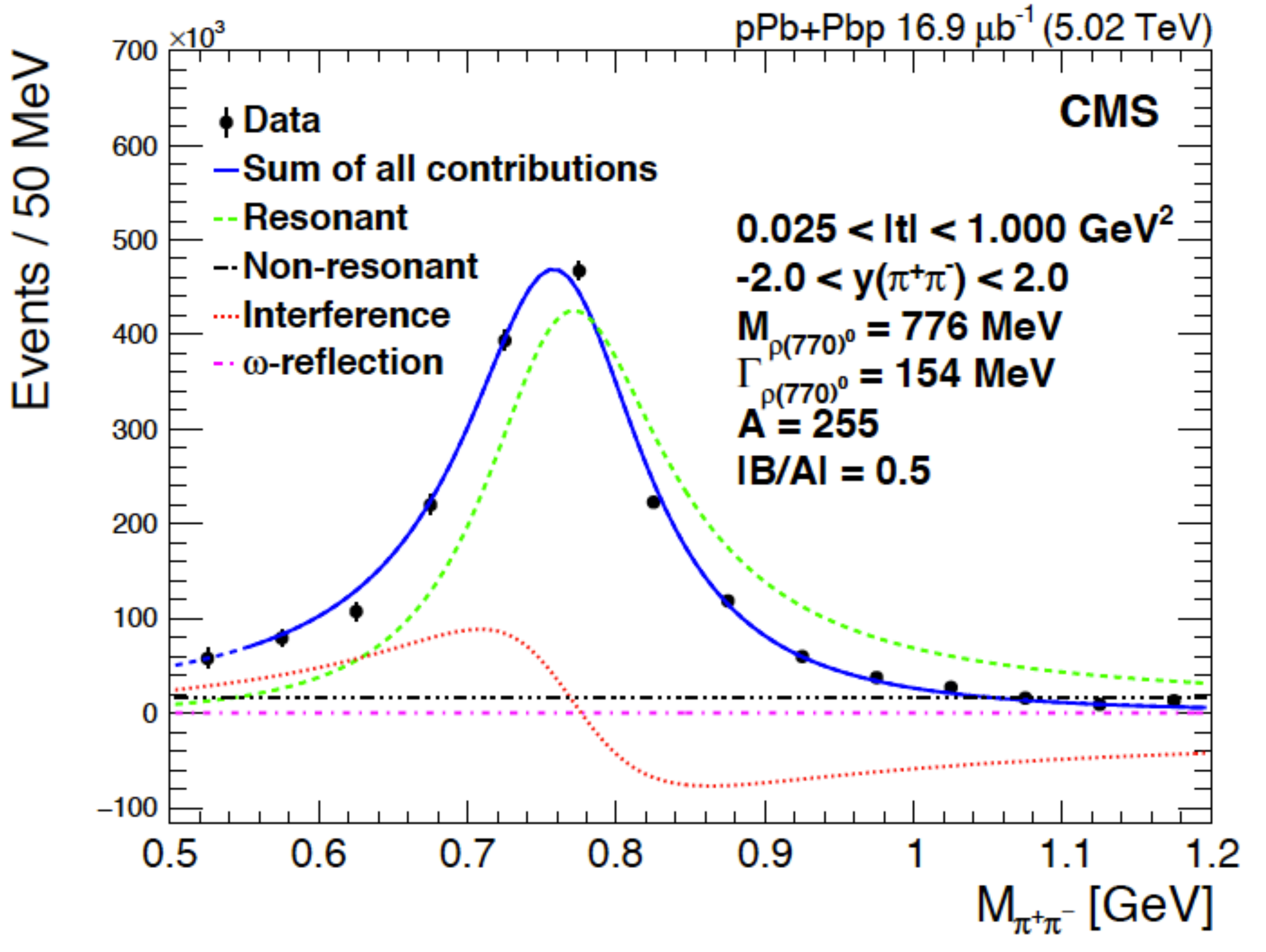


Location of the Diffractive dips:
Different for IP-Sat and bCGC

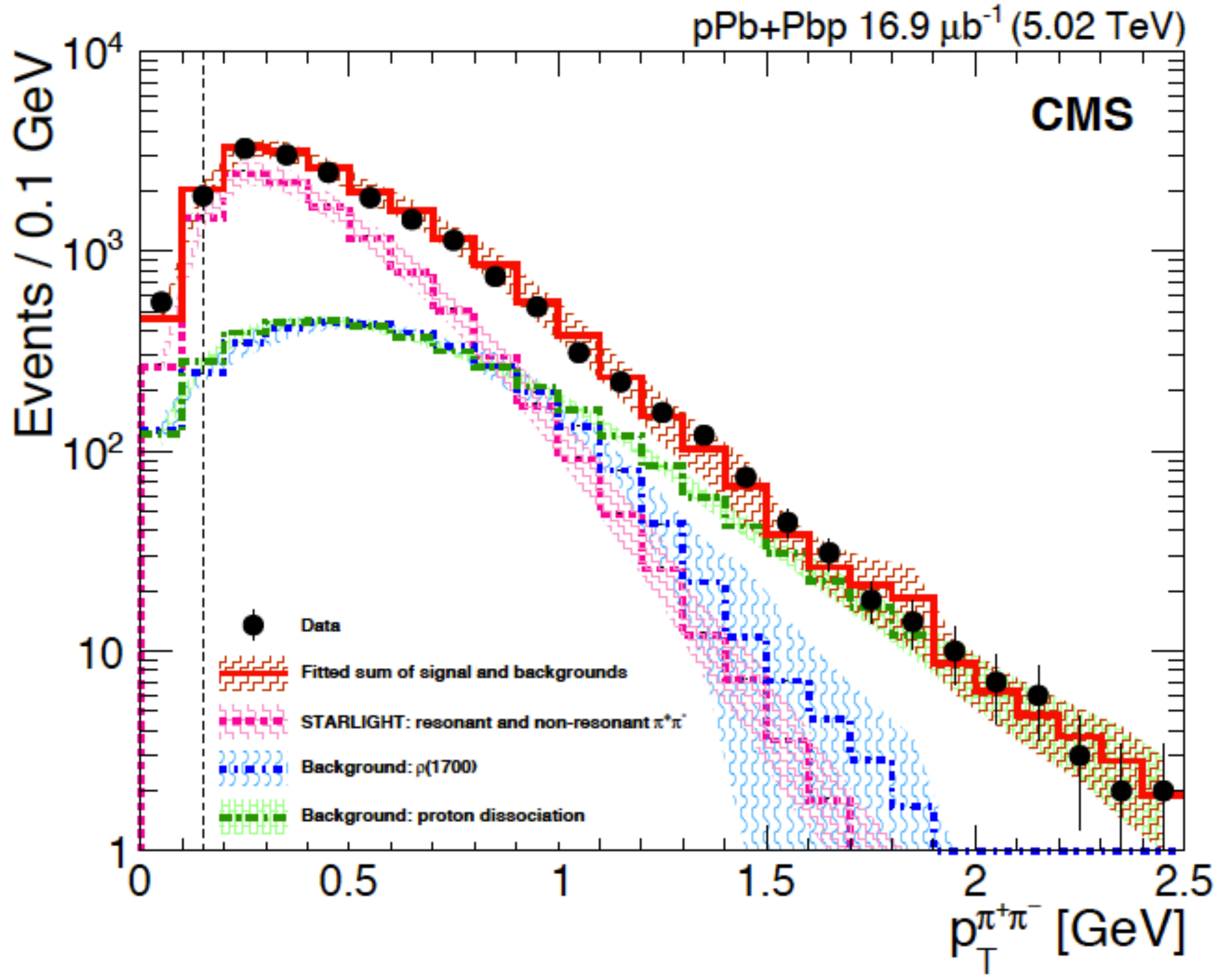
Energy dependence of the t-distribution: onset of gluon saturation

Exclusive ρ^0 in γp

arXiv:1902.01339
Submitted to EPJ C

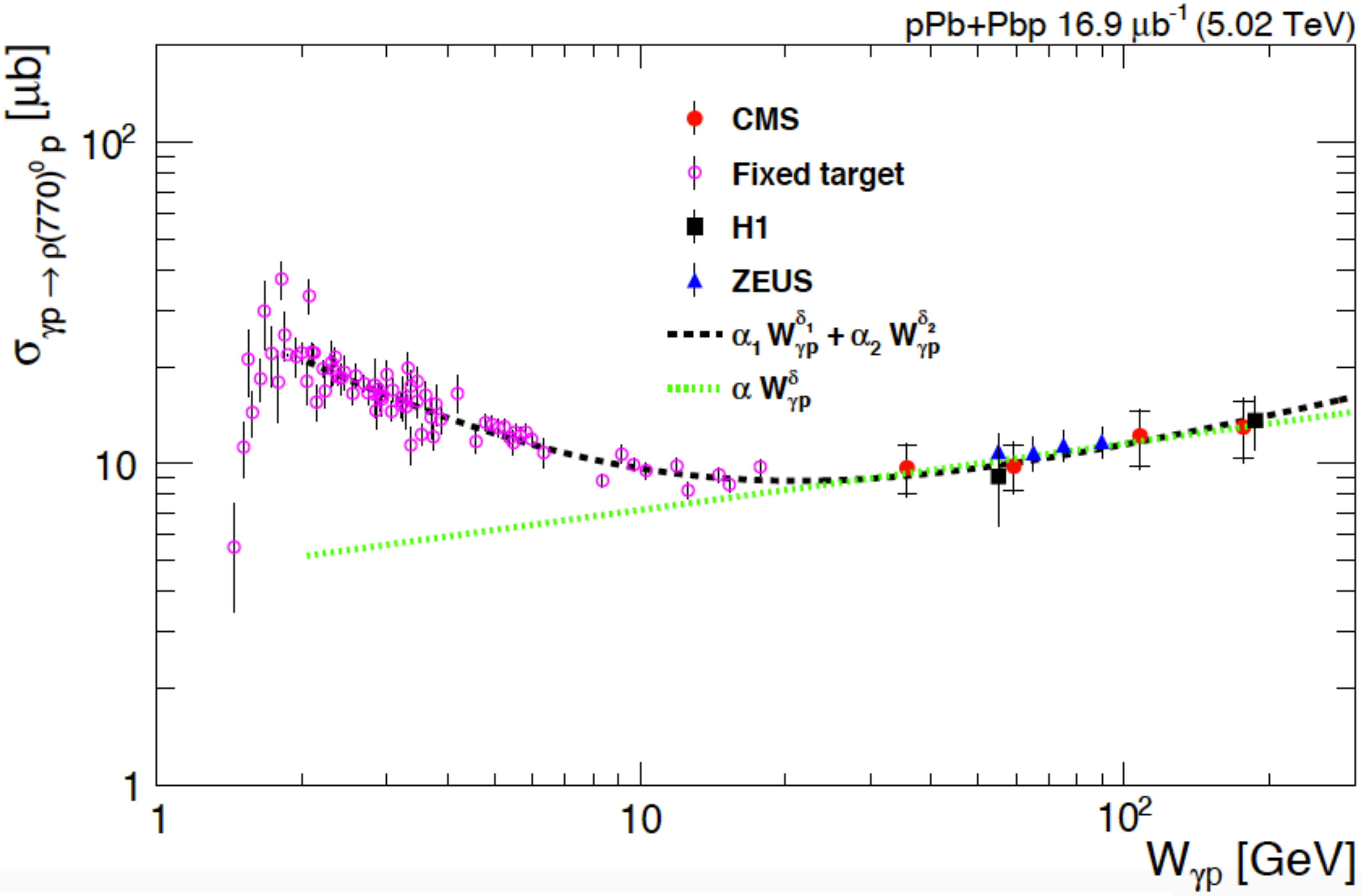


Data-driven approach for signal extraction



Exclusive ρ^0 in γp

arXiv:1902.01339
Submitted to EPJ C



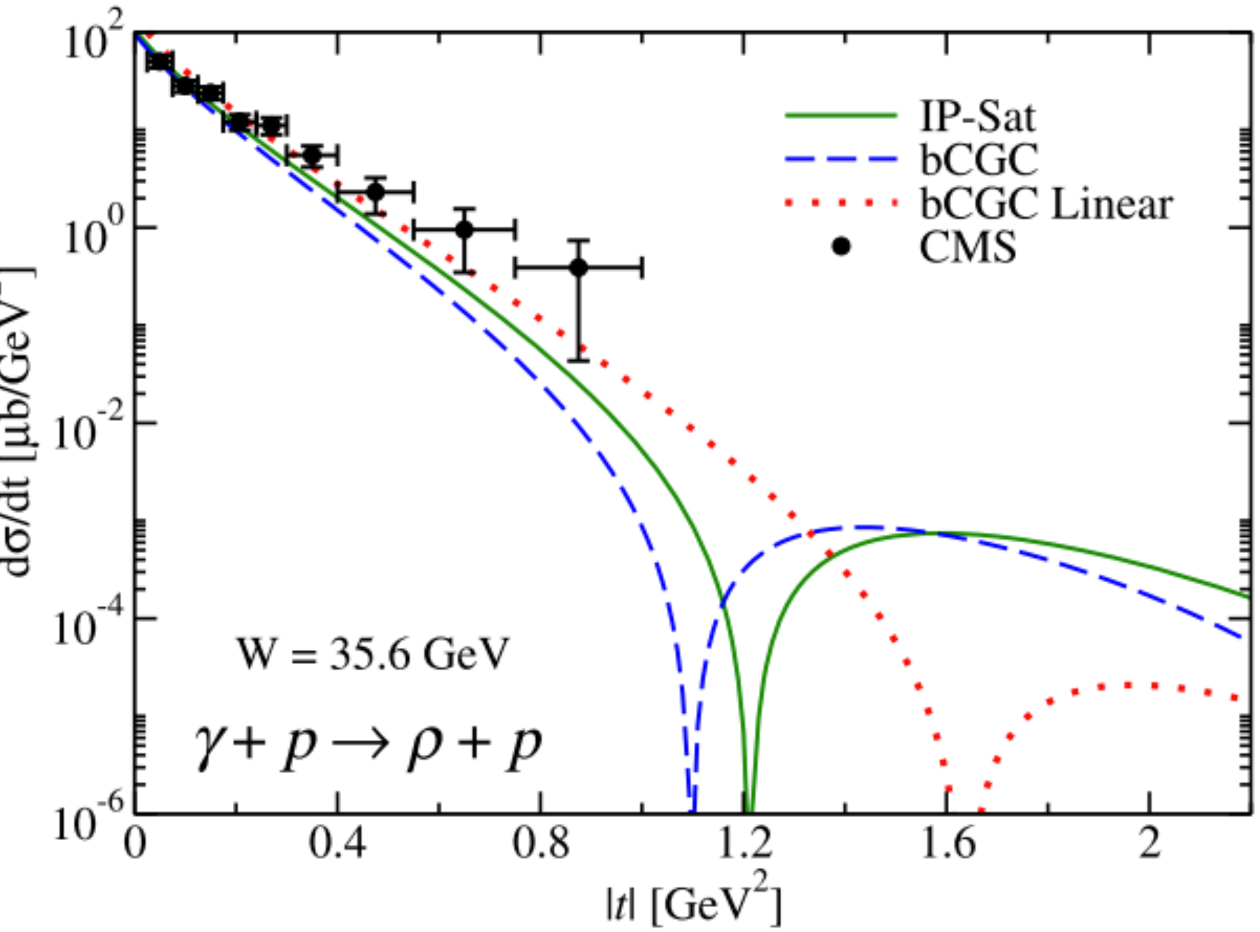
Good agreement with the HERA data and theoretical models

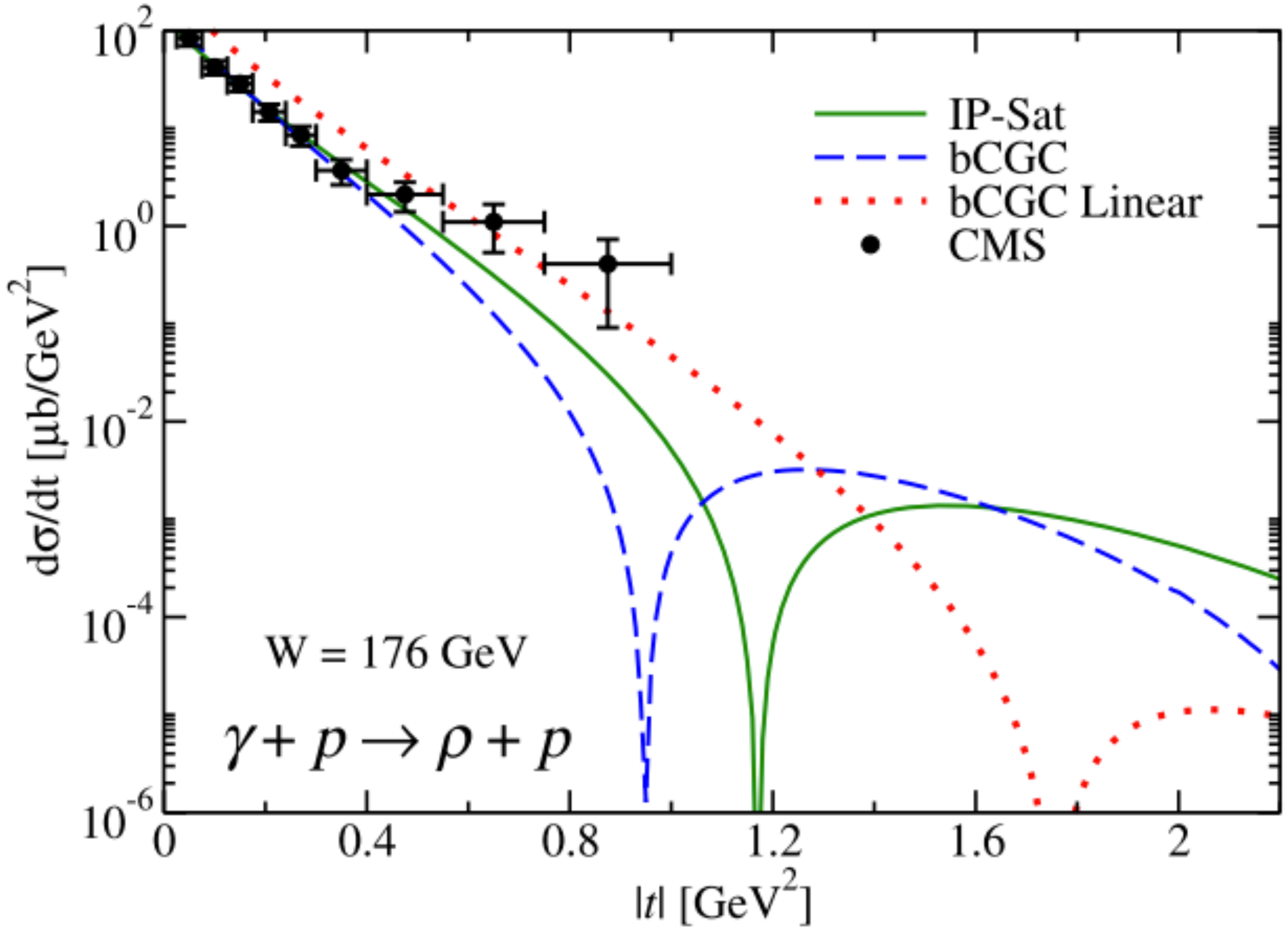
$$\delta = 0.23 \pm 0.14(\text{stat}) \pm 0.04(\text{syst})$$

Exclusive ρ^0 in γp

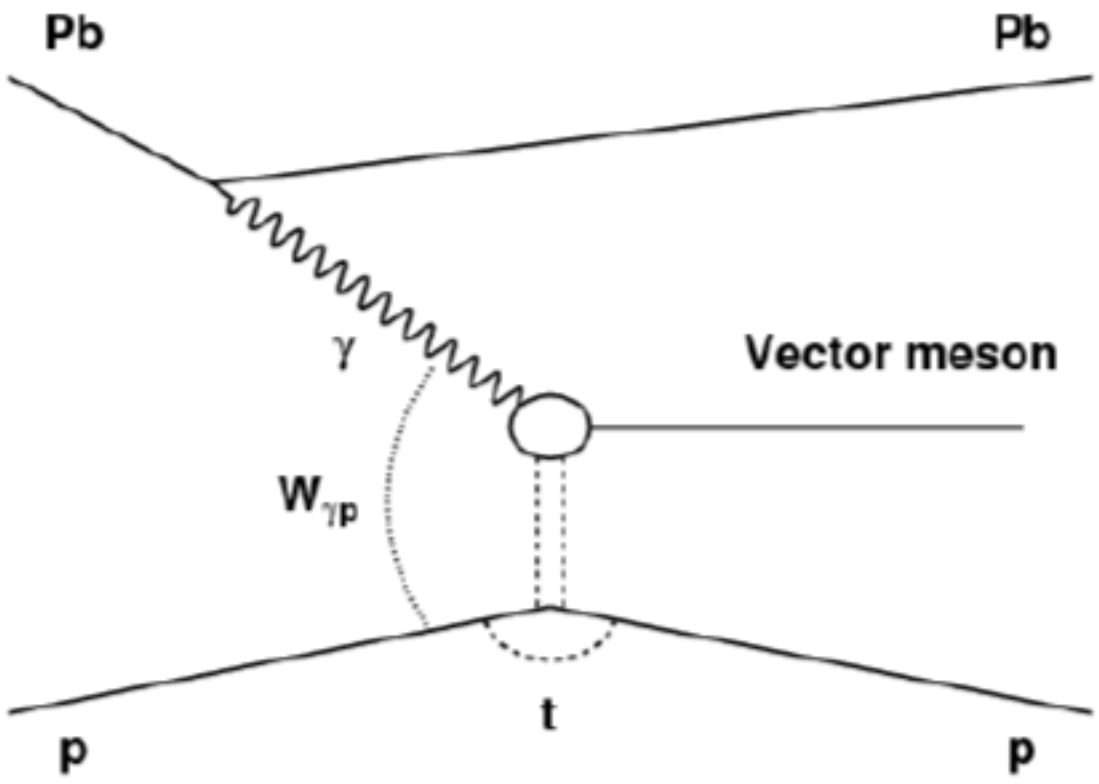
V. Goncalves, et al.
Phys. Lett. B791 (2019) 299-304

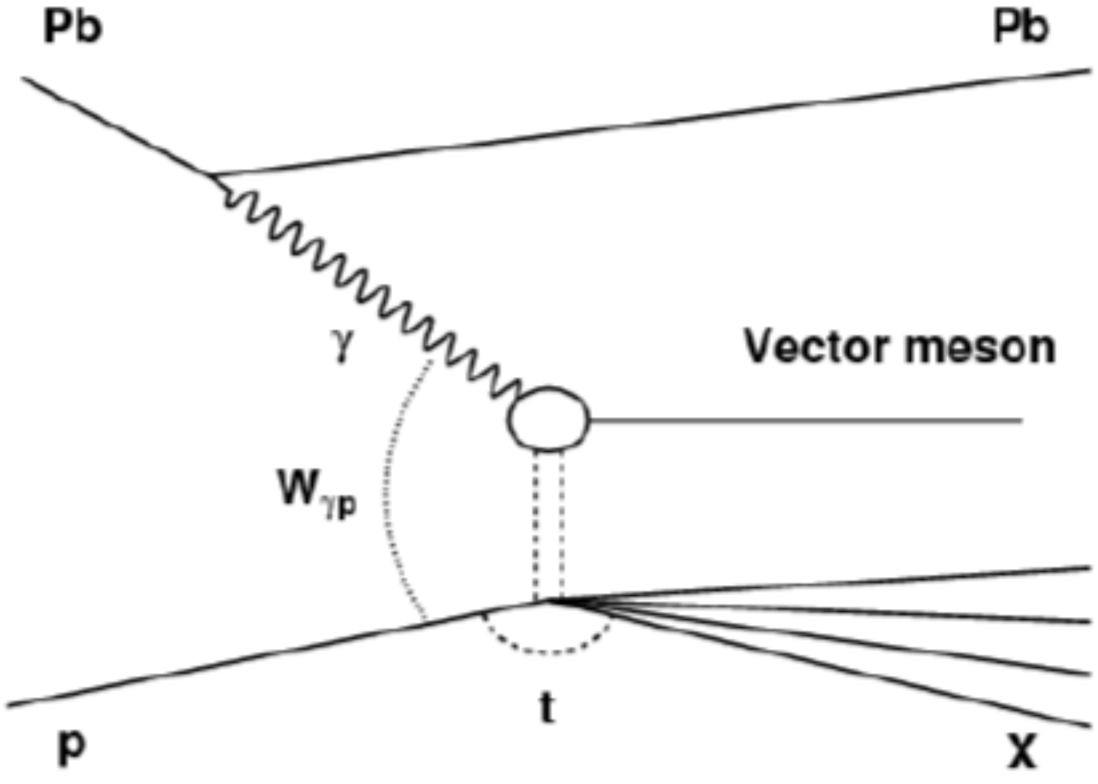
High energy points !





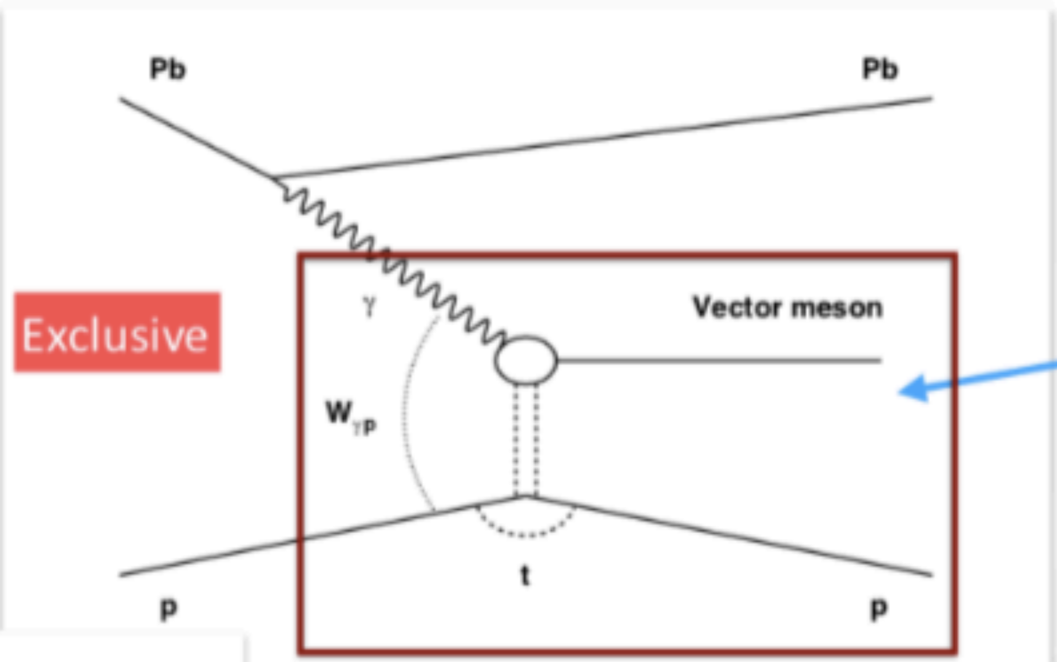
Dissociative/Incoherent production





Exclusive and dissociative production

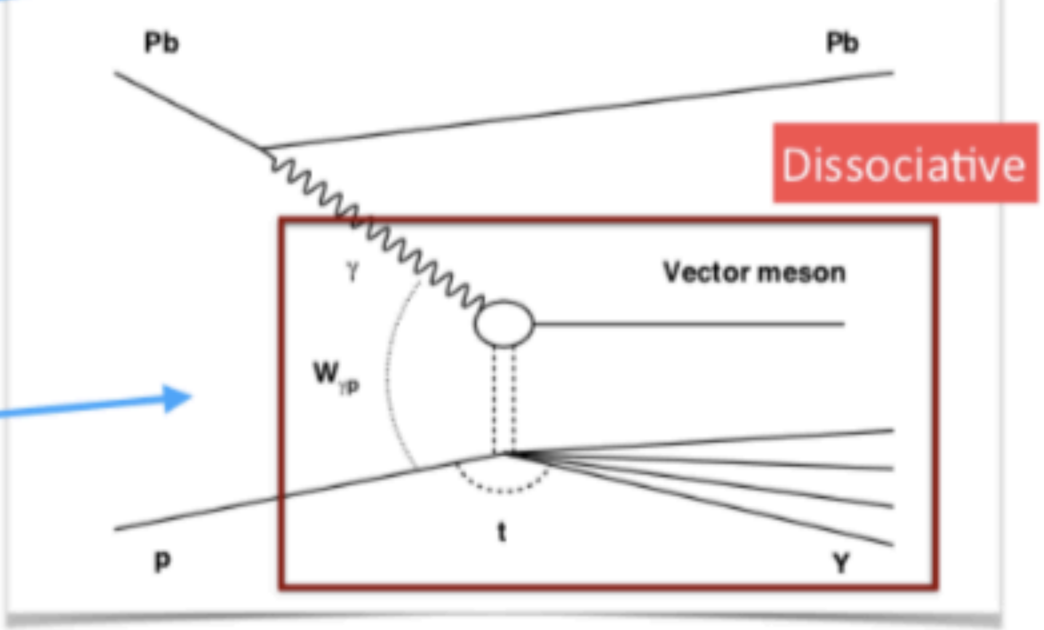
Exclusive

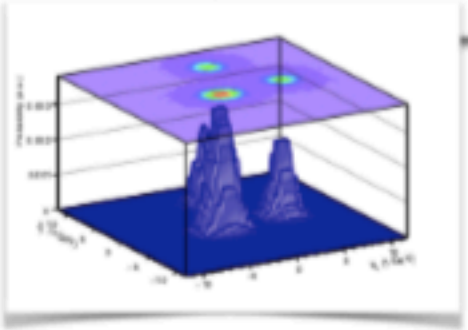


$$\frac{d\sigma(\gamma p \to \mathrm{J}/\psi p)}{dt} = \frac{R_g^2}{16\pi}\left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2$$

Average over configurations

Dissociative





Variance over configurations

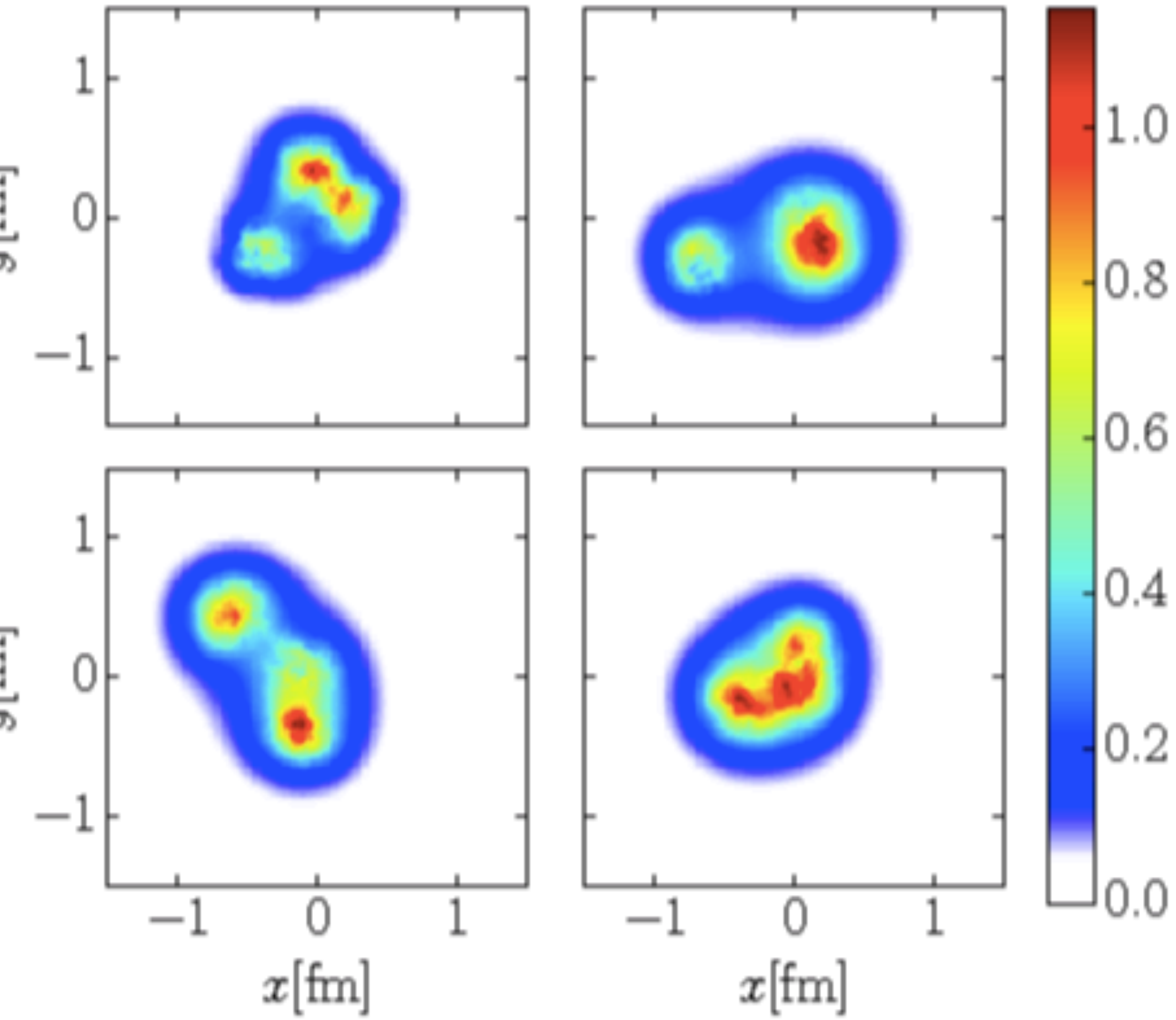
$$\frac{d\sigma(\gamma p \to \mathrm{J}/\psi Y)}{dt} = \frac{R_g^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2\right)$$

Good,Walker , PR 120 (1960) 1857

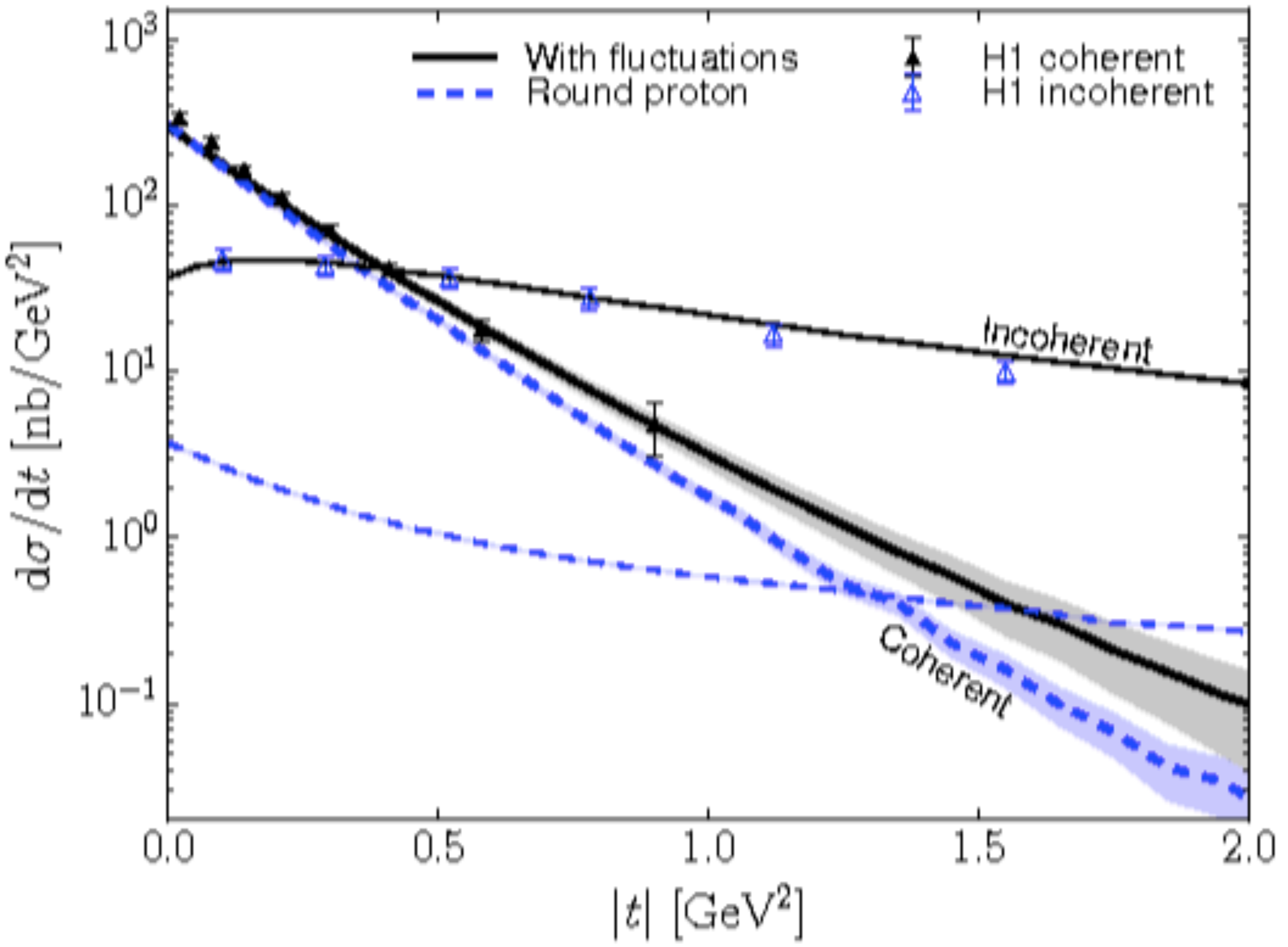
Miettinen, Pumplin, PRD18 (1978) 1696

Mantysaari, Schenke, PRL 117 (2016) 052301

t-dependance

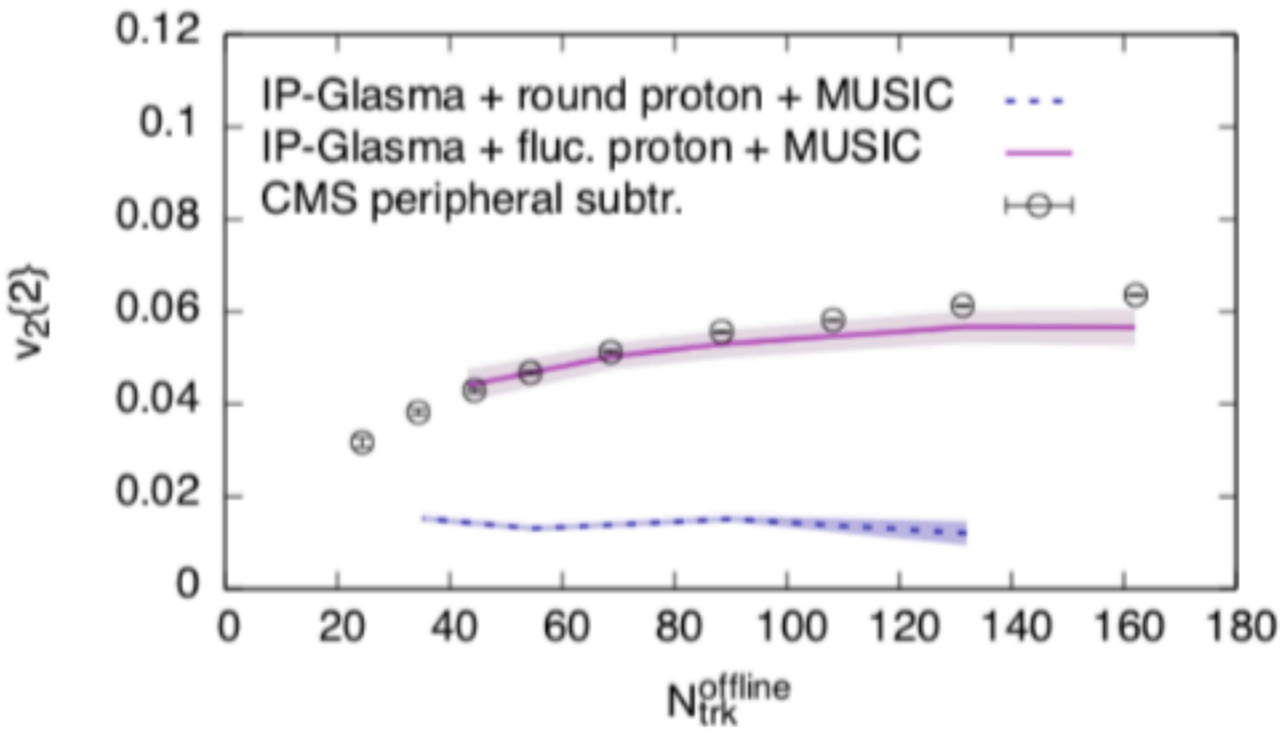


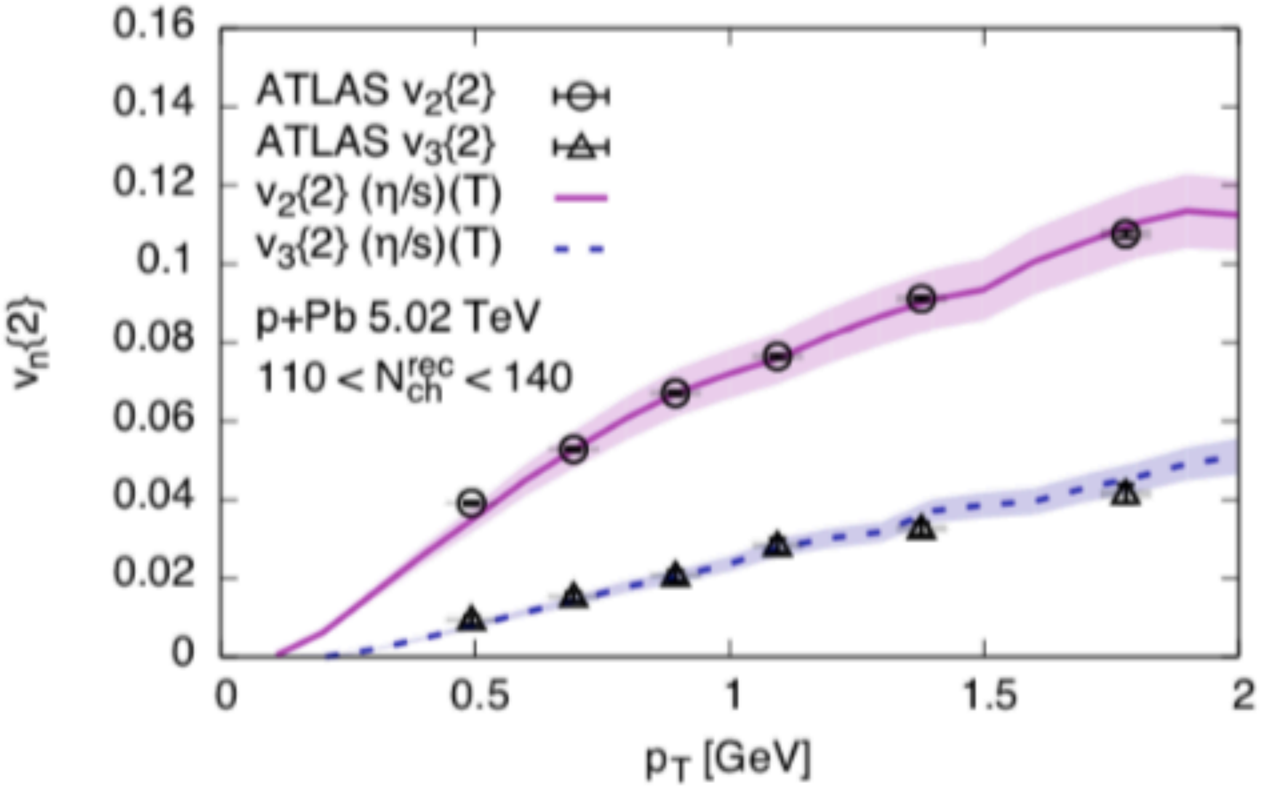
H. Mäntysaari



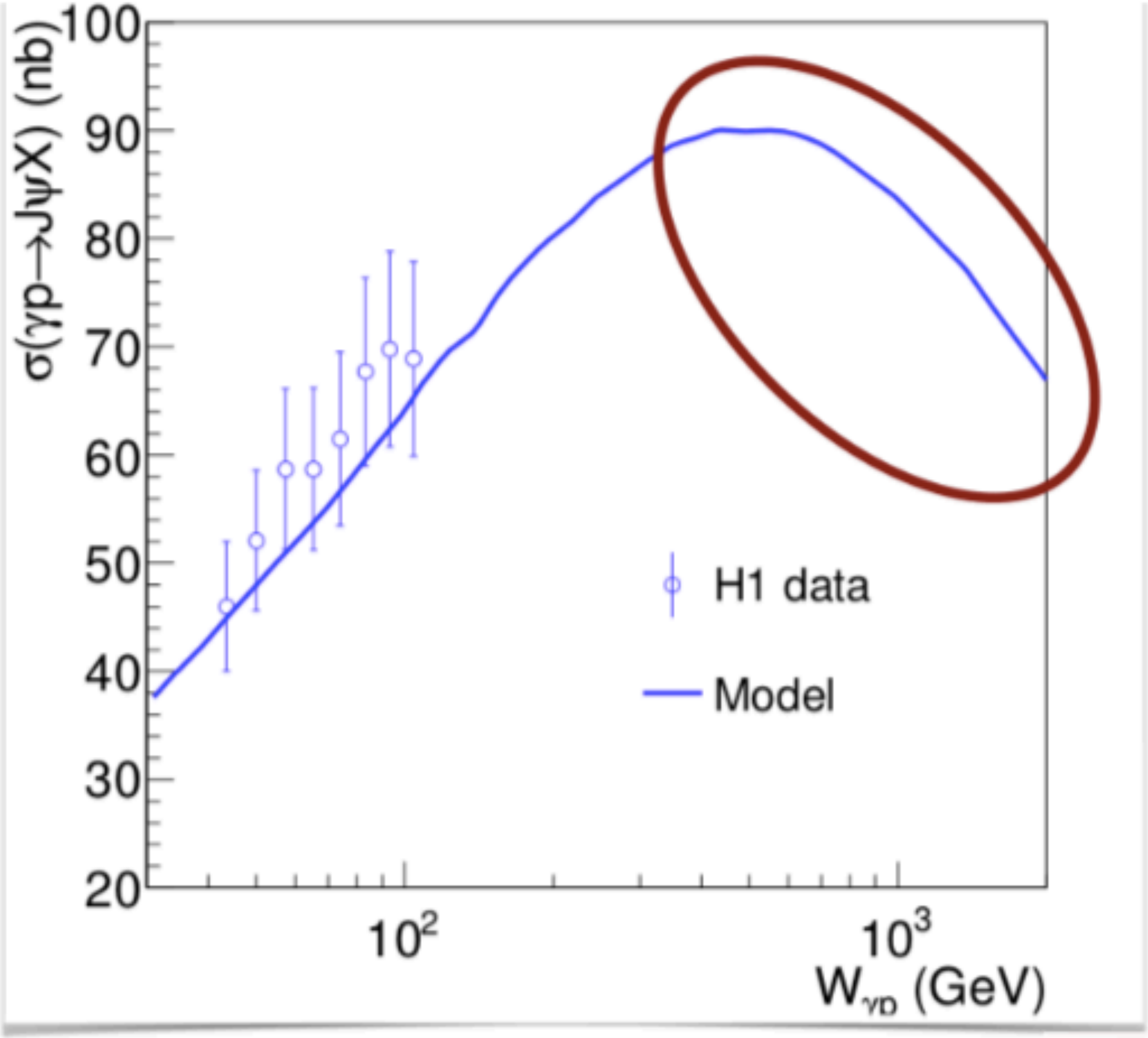
Results from t-dependance study

H. Mäntysaari





Energy dependance of the t-distribution for dissociative production



Phys. Lett. B766 (2017) 186-191

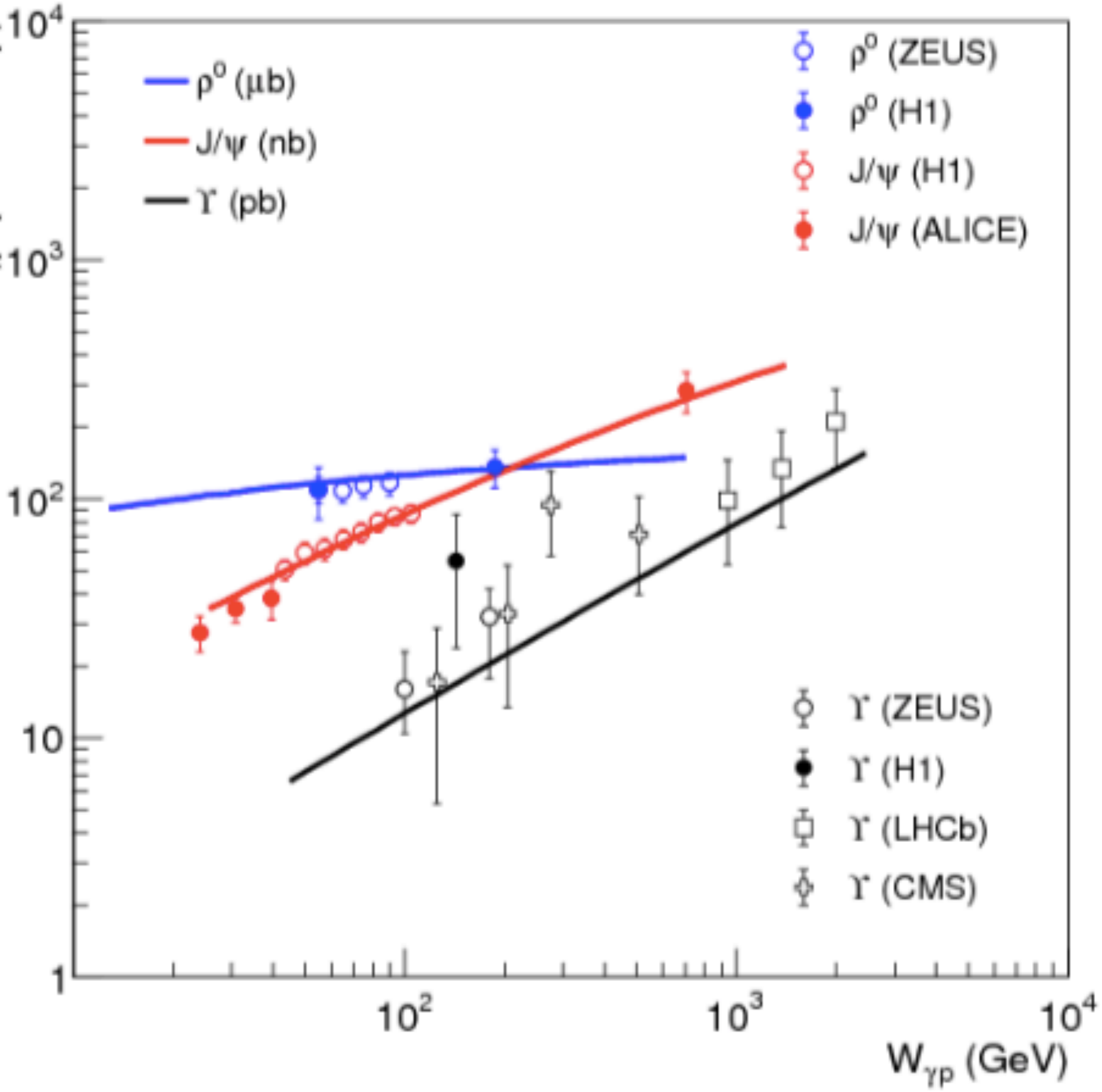
- The model predicts an **striking signature** for saturation:
  - As the number of hot spot grows, the hot spots fill up the proton.
  - When saturation is reached, all configurations are very similar and the variance over configurations tends to zero.

At the LHC we can measure J/ψ production accompanied by proton dissociation in this energy range!

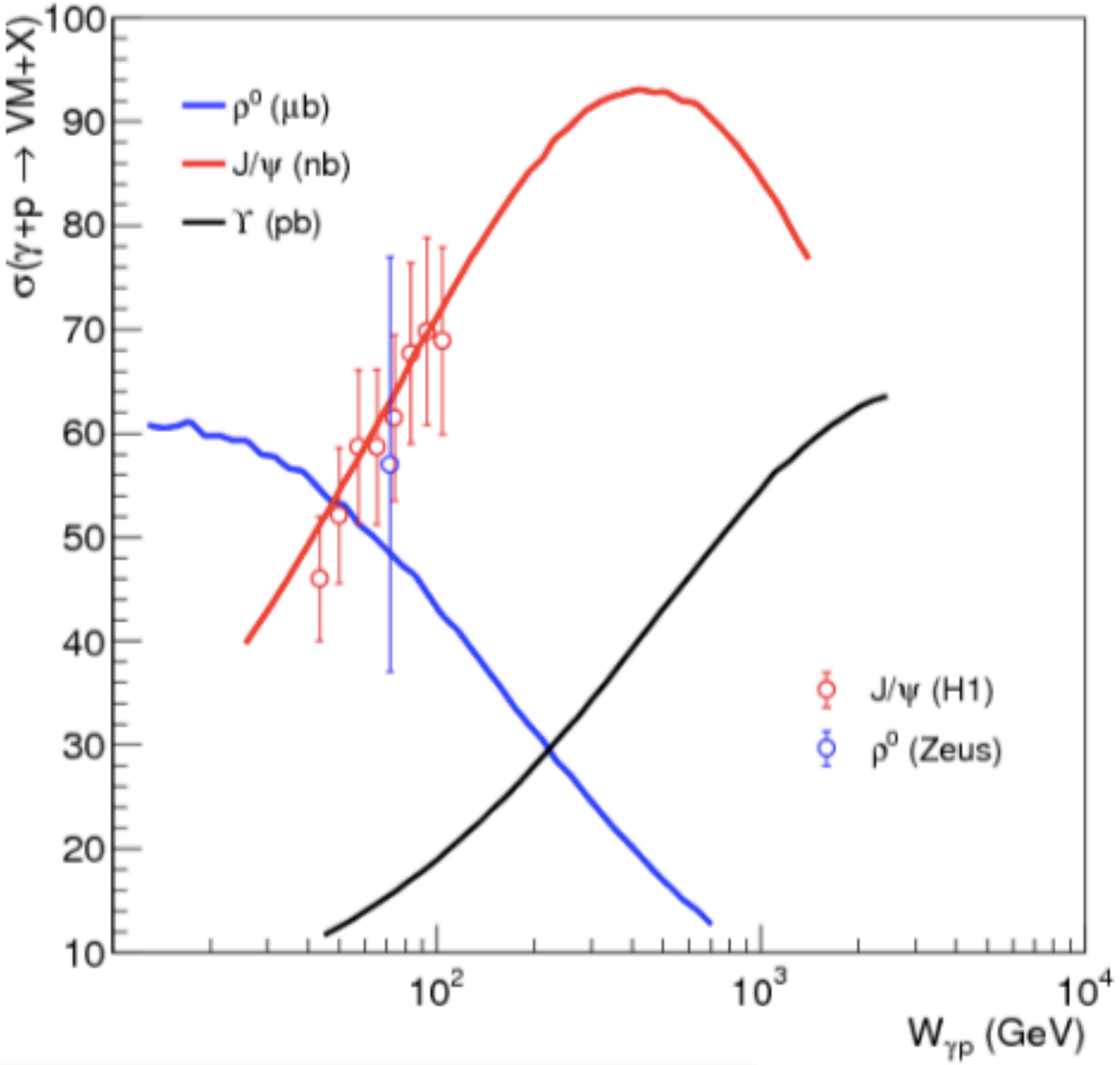
Mass dependance and energy dependance

Nucl. Phys. B934 (2018) 330-340

Exclusive

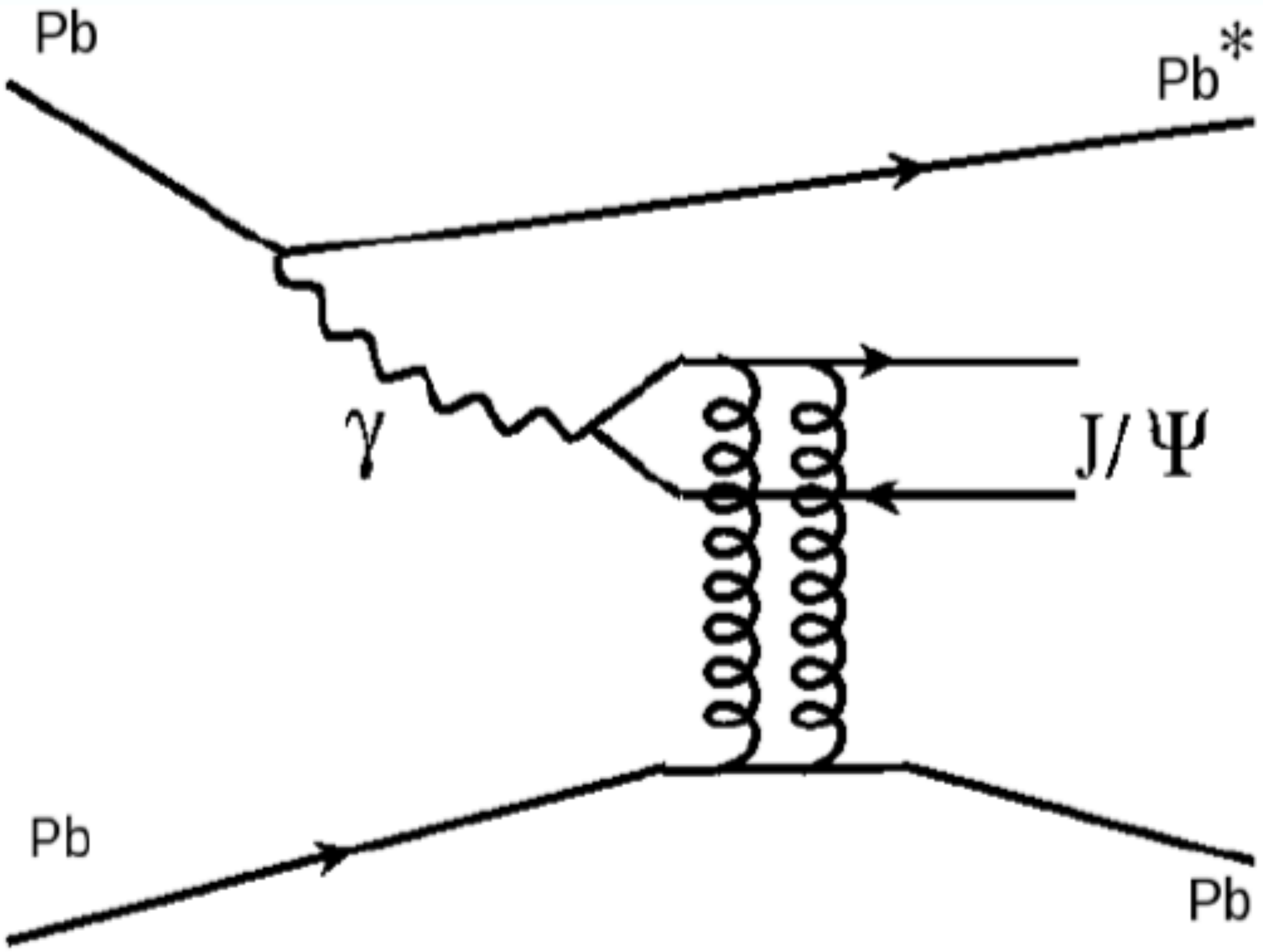


Dissociative

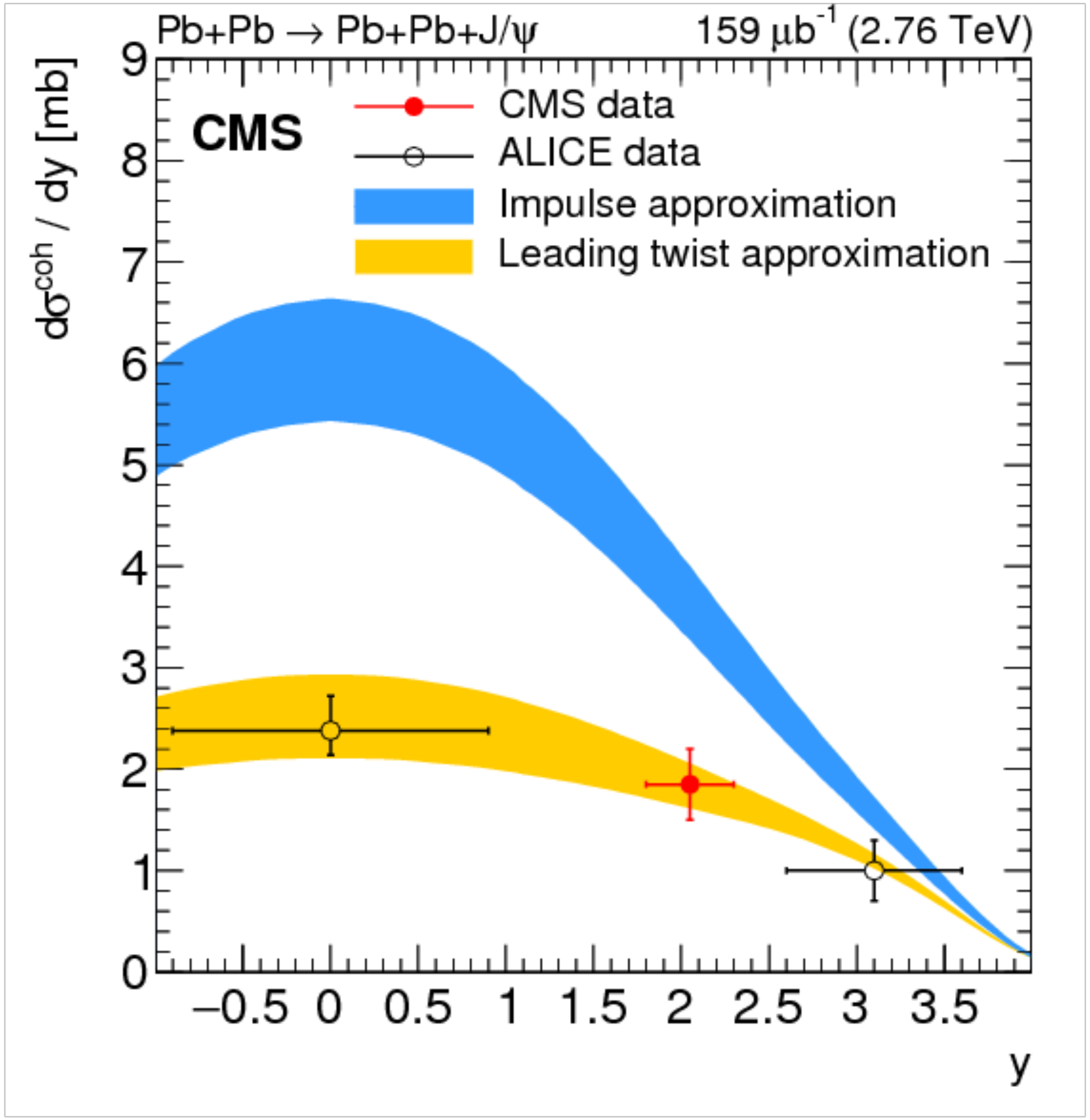


UPC J/ψ

$$\left.\frac{d\sigma_{\gamma A\to J/\Psi A}}{dt}\right|_{t=0} = \xi_{J/\Psi}\left(\frac{16\pi^3\alpha_s^2\Gamma_{l+l-}}{3\alpha M_{J/\Psi}^5}\right)\boxed{[xG_A(x,\mu^2)]^2}$$



Coherent J/ψ



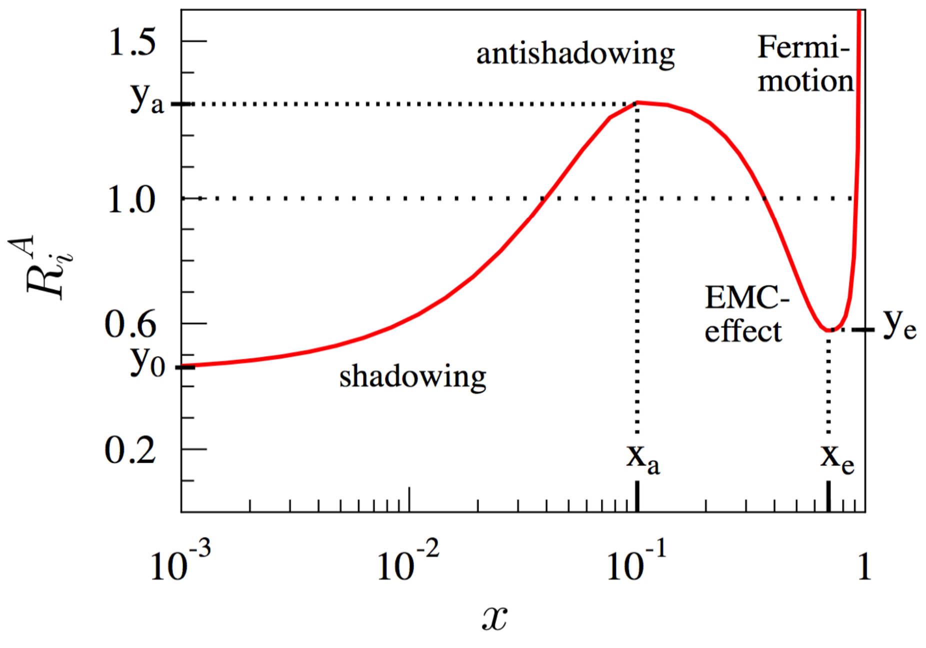
Phys. Lett. B772 (2017) 489-511

Model independent. Parametrization of exclusive J/Ψ data in gamma-protor

i.e. No nuclear effects

Experimental evidence of nuclear gluon shadowing

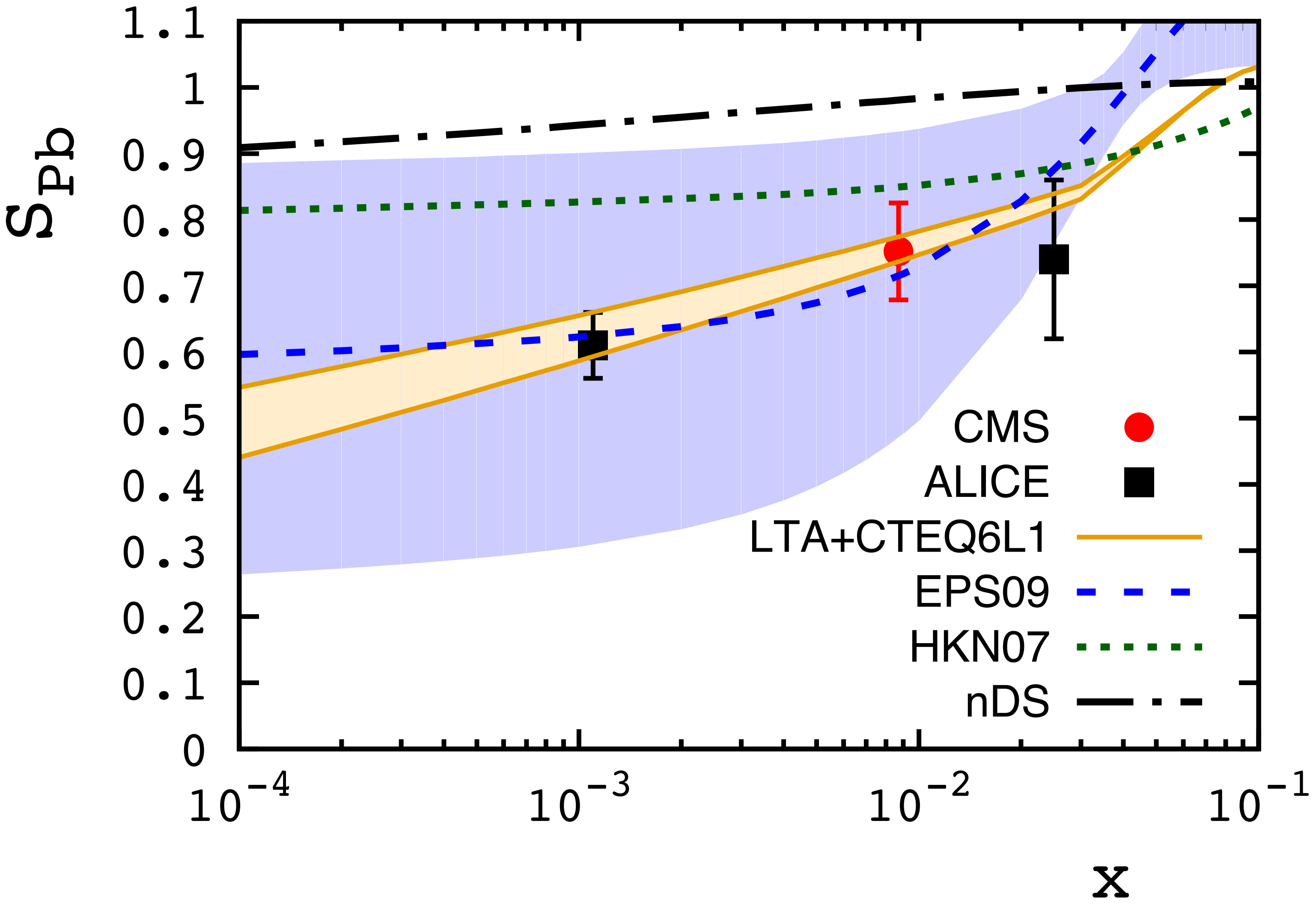
Nuclear effects at **Low x**



Coherent J/ψ photoproduction off Pb nuclei

By V. Guzey, et. al using Phys. Lett. B726 (2013) 290–295

and latest ALICE and CMS results



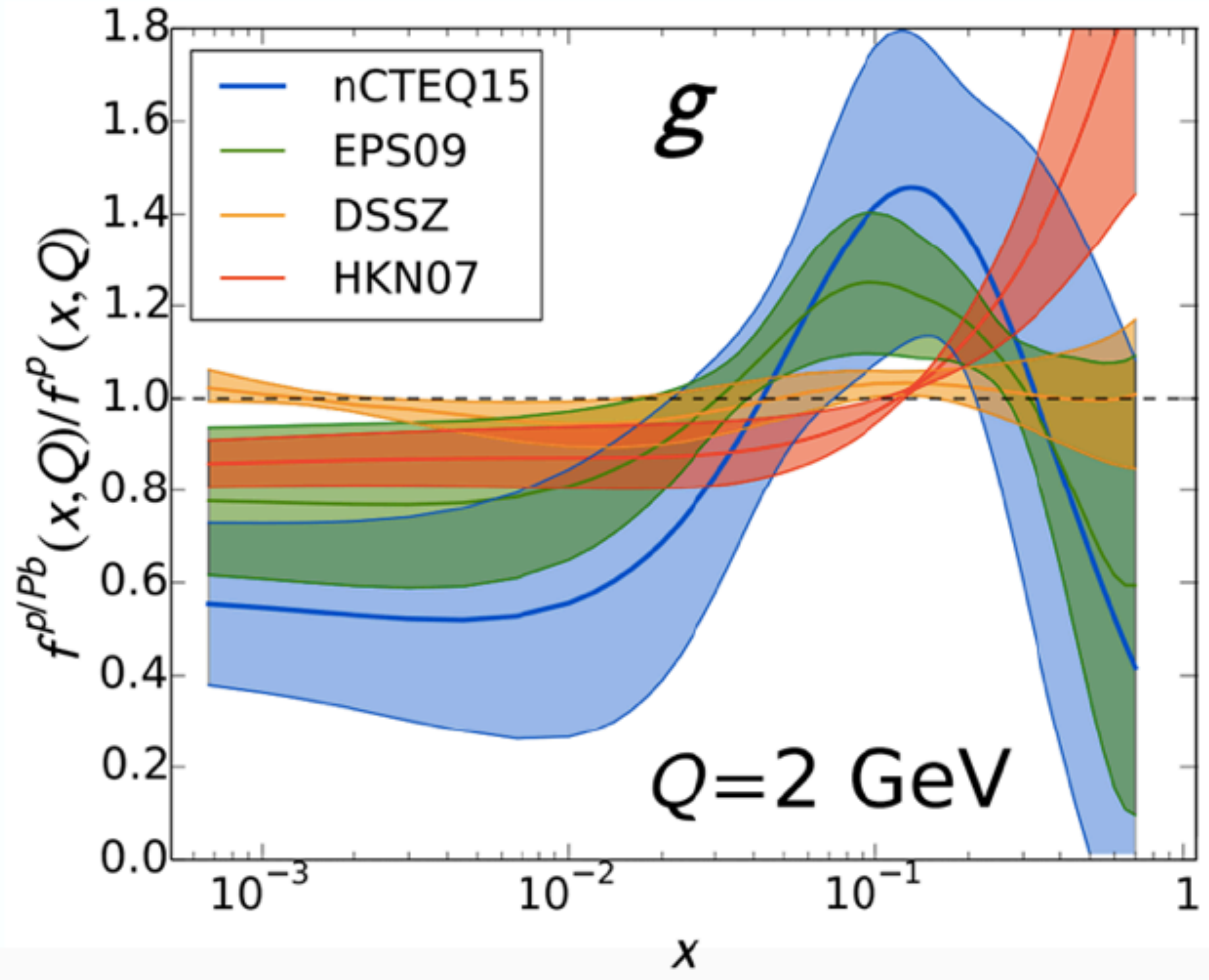
$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

Parton distributions

Parton Distribution Functions (PDFs)

Determined from data: Global QCD analysis

Nuclear gluon density



UPC studies provide the best information the community will get for the next 10 years before, the EIC turns on

Inclusive dijets in γPb

ATLAS-CONF-2017-011

$$z_\gamma \equiv \frac{m_{\rm jets}}{\sqrt{s}} e^{+y_{\rm jets}}, \quad x_{\rm A} \equiv \frac{m_{\rm jets}}{\sqrt{s}} e^{-y_{\rm jets}}.$$

Sensitive to nPDF

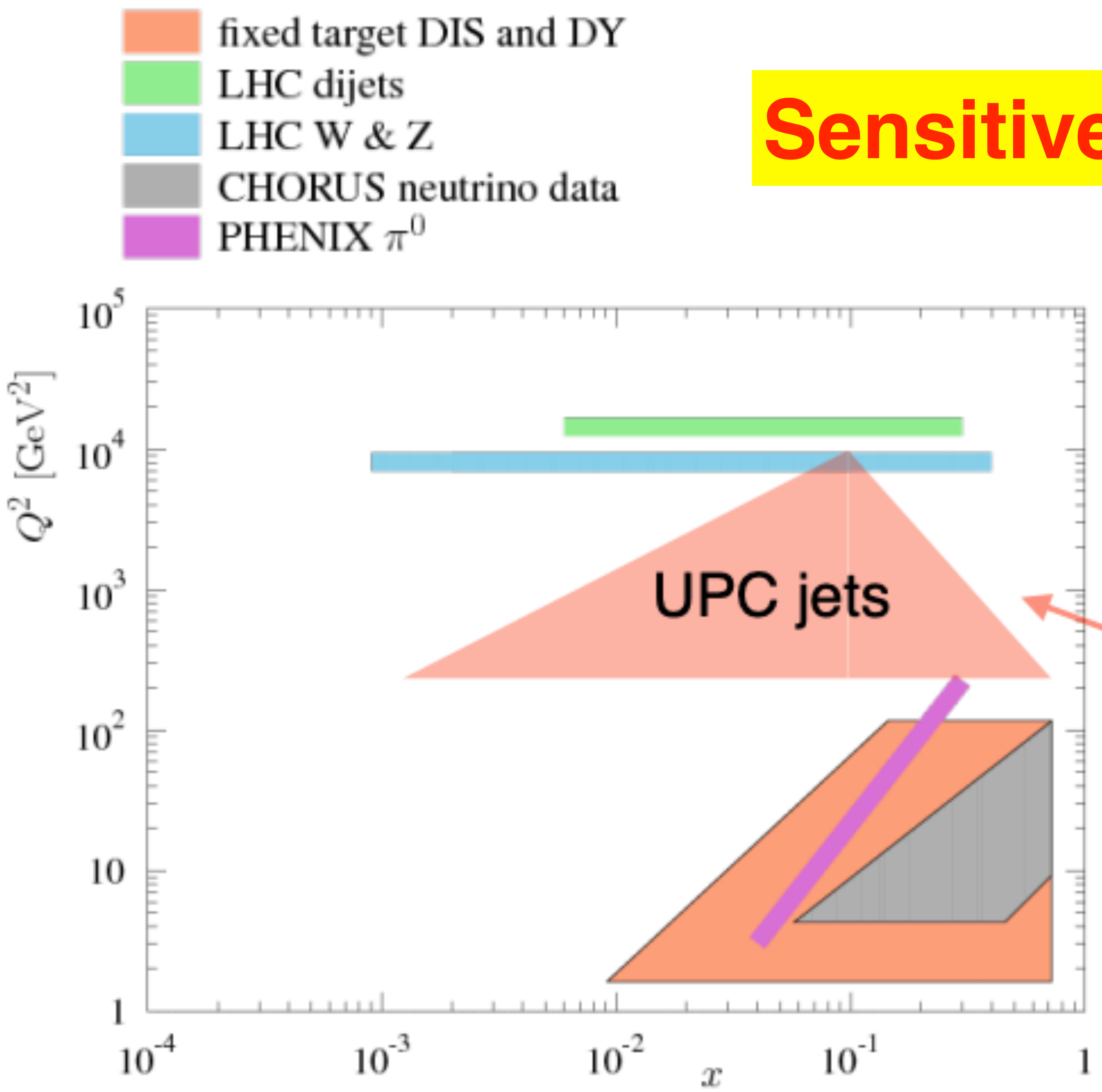
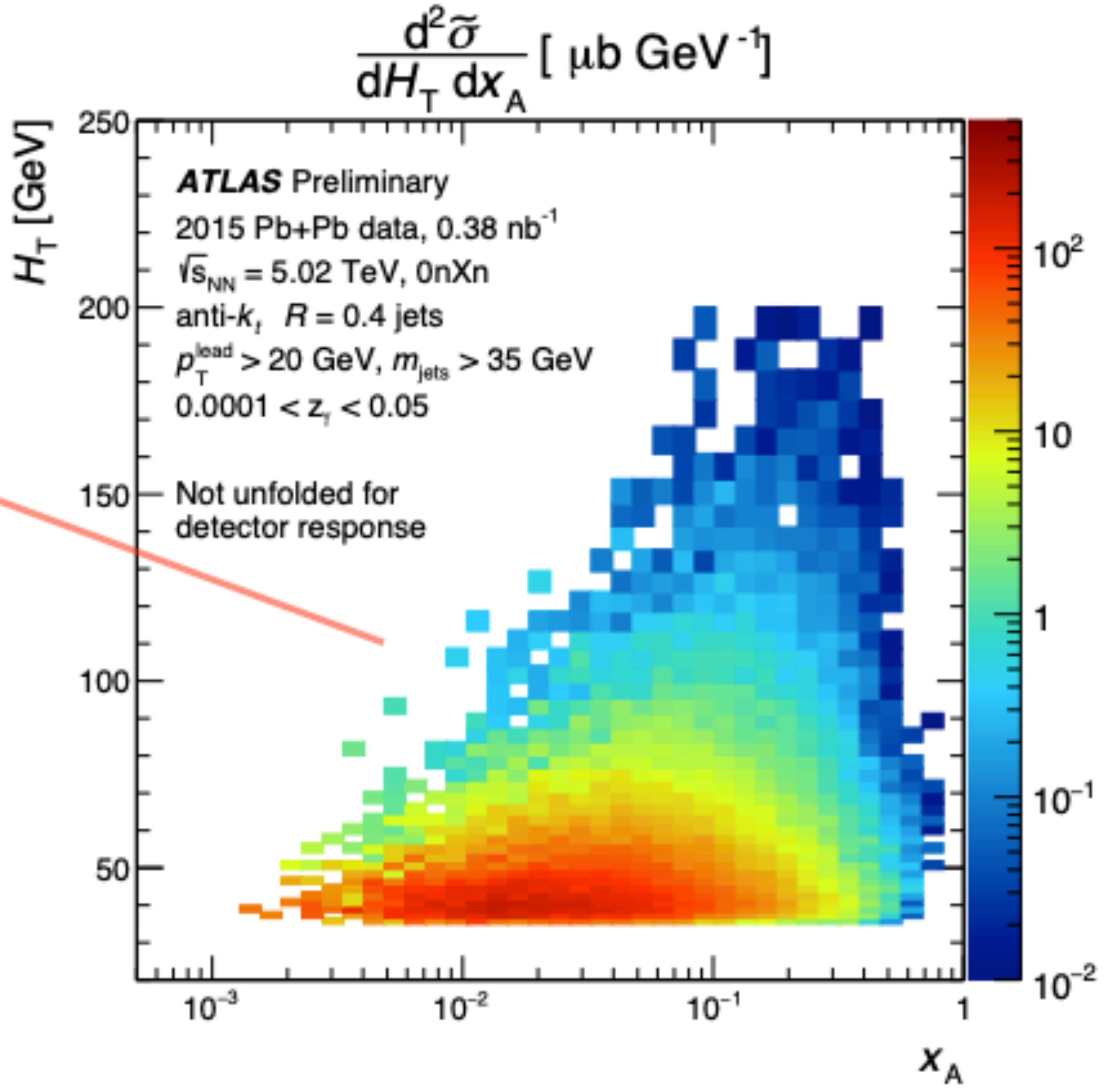


Figure adapted from EPPS16
1612.05741 [hep-ph]

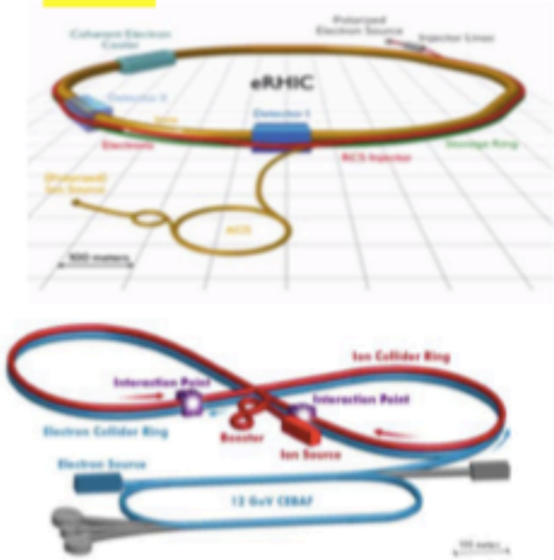


Planned DIS Colliders around the world

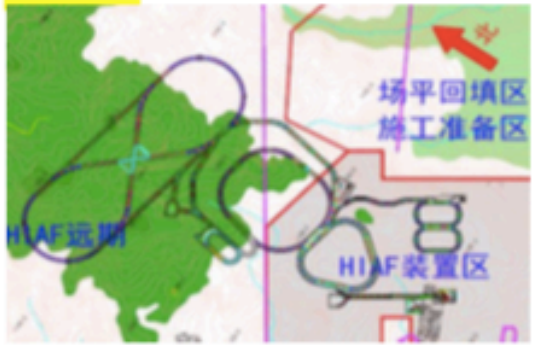
Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33} cm^{-2} s^{-1}$)	Ions	Polarization
EIC in US	> 2028	20 - $100 \rightarrow 140$	2 - 30	$p \rightarrow U$	e, p, d, ^{3}He, Li
EIC in China	> 2028	16 - 34	$1 \rightarrow 100$	$p \rightarrow Pb$	e, p, light nuclei
LHeC (HE-LHeC)	> 2030	200 - 1300 (1800)	10	depends on LHC	e possible
PEPIC	> 2025	$530 \rightarrow 1400$	$< 10^{-3}$	depends on LHC	e possible
VHEeP	> 2030	1000 - 9000	$10^{-5} - 10^{-4}$	depends on LHC	e possible
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible

EPPSU DIS Input

EIC

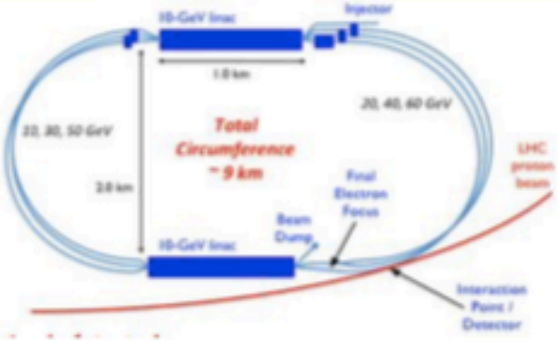


EicC

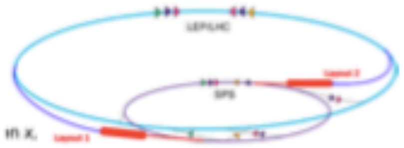


LHeC

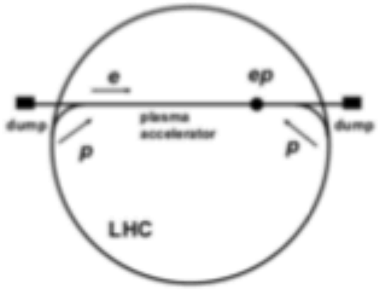
FCC-eh



PEPIC

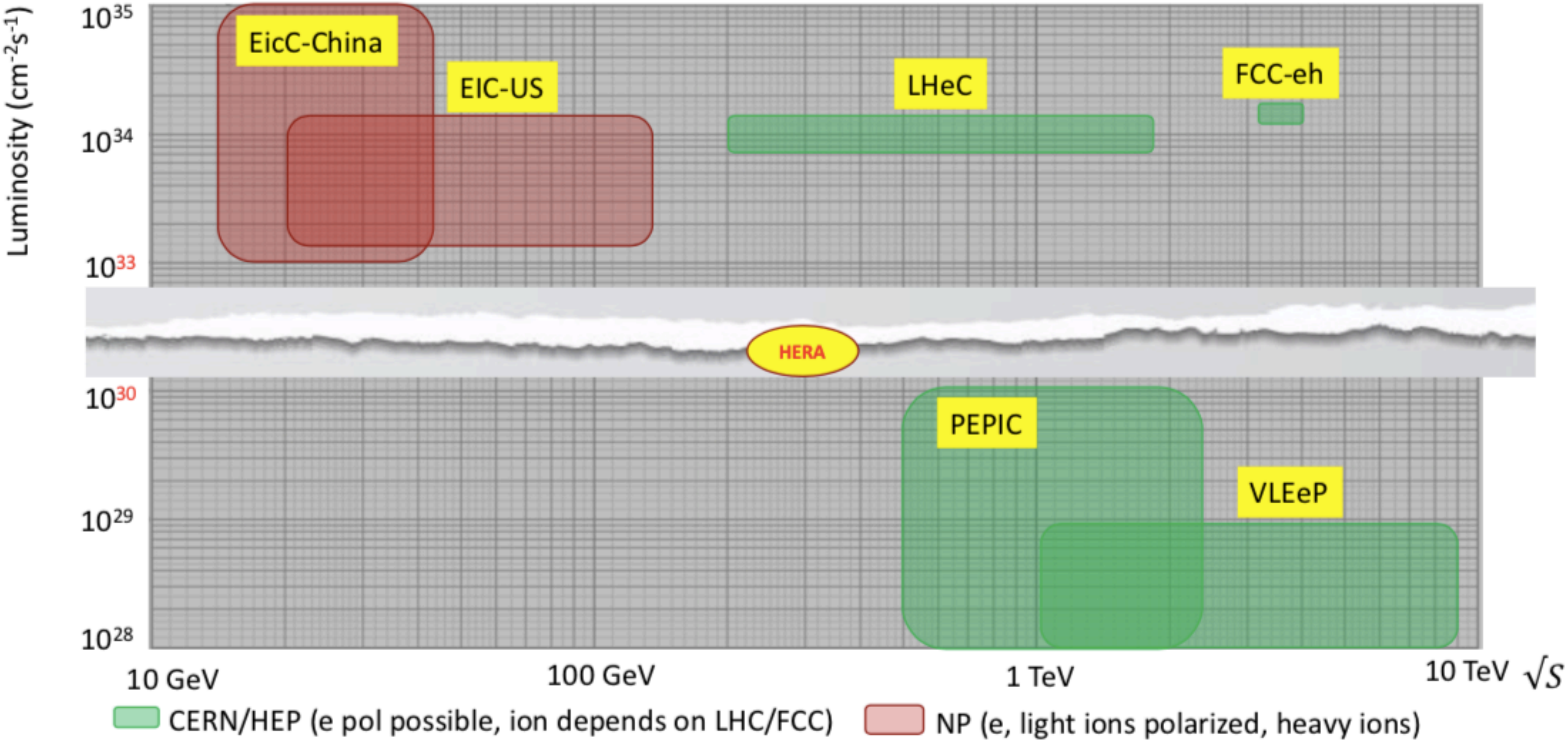


VLEeP



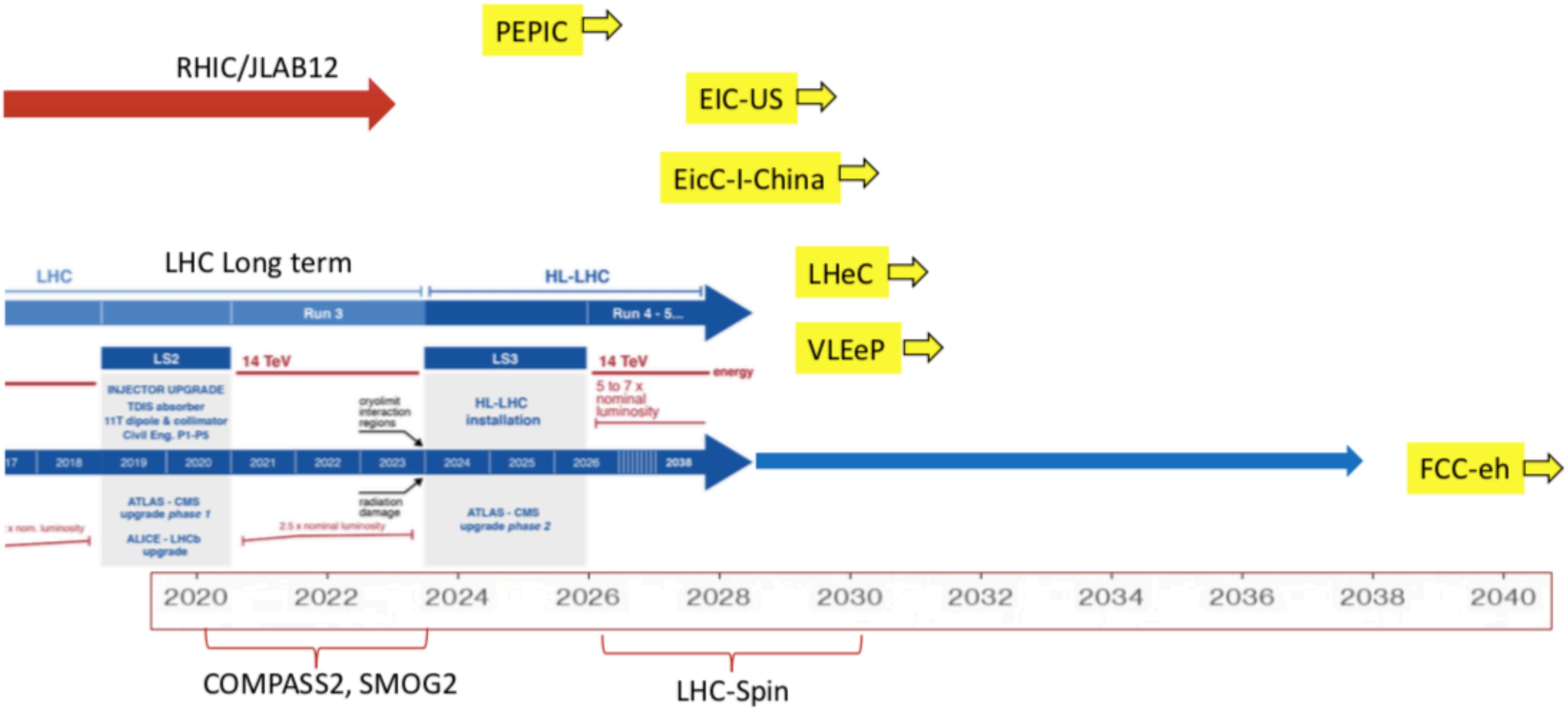
From R. Yoshida. DIS 2019

DIS Collider Plan Comparison (from EPPSU DIS document)



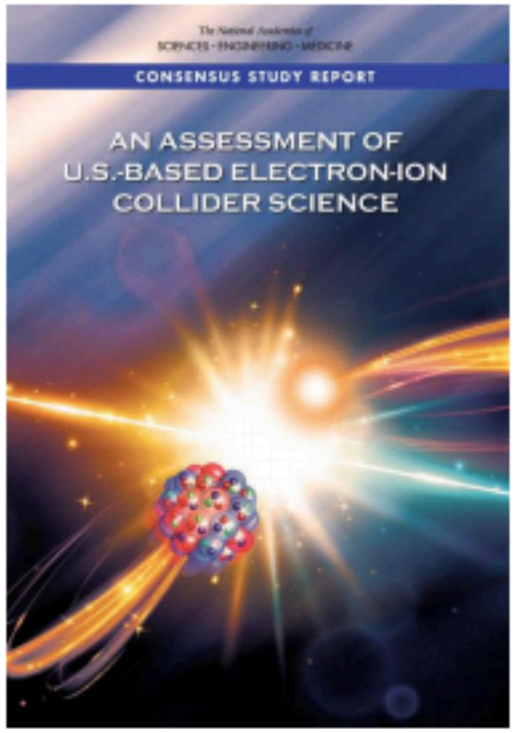
From R. Yoshida. DIS 2019

DIS Collider Earliest Possible Timelines (EPPSU DIS Document)



From R. Yoshida. DIS 2019

US EIC



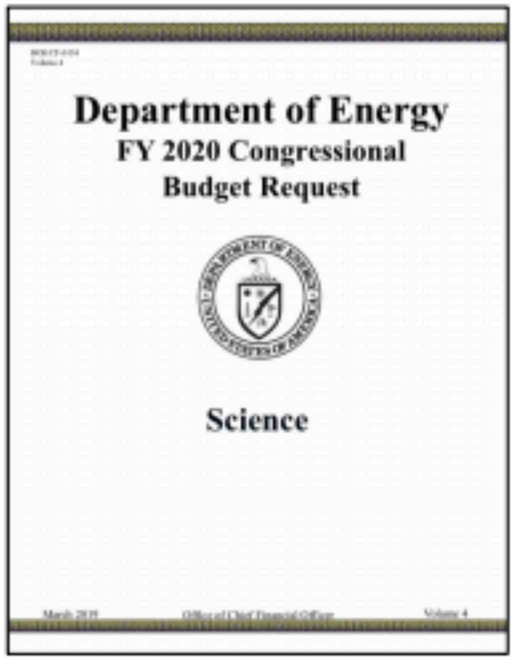
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE

National of Academy of Sciences : 2018 Assessment of US EIC
In summary, the committee finds a **compelling scientific case for such a facility**.

FY2020 US Budget Justification



Department of Energy
FY 2020 Congressional
Budget Request

Science

Approval needed in FY2019 to justify budget in FY2020

Volume 4, Page 272:
"The Request for Construction and Major Items of Equipment (MIEs) includes:"
…
"Other Project Costs (OPC) funding to support high priority, critically needed accelerator R&D to retire high risk technical challenges for the proposed U.S.-based EIC. Subsequent to the FY 2018 National Academy of Science Report confirming the importance of a domestic EIC to sustain U.S. world leadership in nuclear science and accelerator R&D core competencies. Critical Decision-0, Approve Mission Need, is planned for FY 2019."

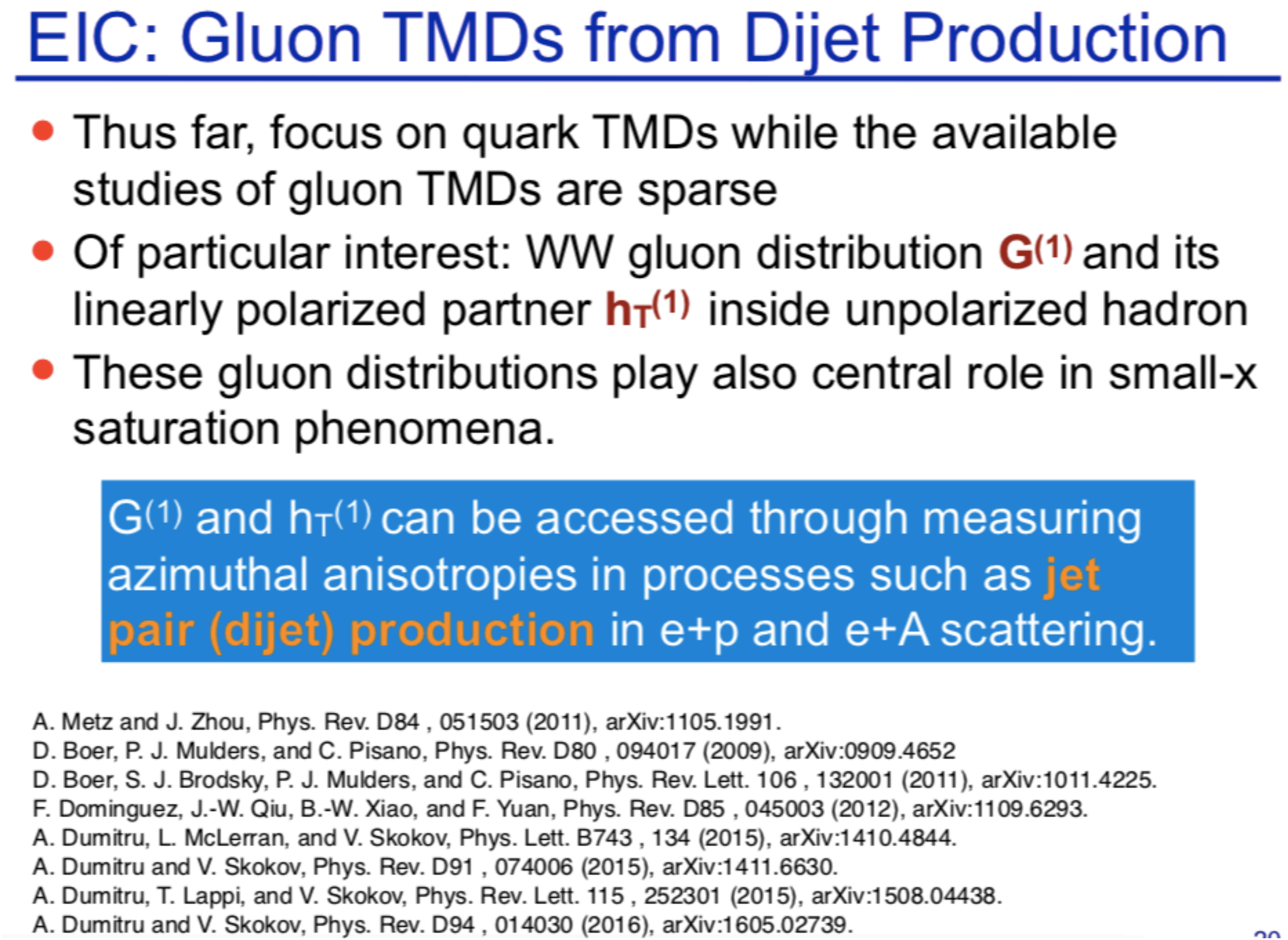
From R. Yoshida. DIS 2019

5D tomography:
Wigner distribution— the “mother distribution”

Belitsky, Ji, Yuan (2003);

$$W(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \int \frac{dz^- d^2 z_\perp}{16\pi^3} e^{ixP^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp} \langle P - \frac{\Delta}{2}|\bar{q}(-z/2)\gamma^+ q(z/2)|P + \frac{\Delta}{2}\rangle$$

$$\begin{tikzcd}
 & W(x,\vec{k}_\perp,\vec{b}_\perp) \arrow[dl, "\int d\vec{b}_\perp"'] \arrow[dr, "\int d\vec{k}_\perp"] & & \\
\text{TMD}\quad f(x,\vec{k}_\perp) \arrow[dr, "\int d\vec{k}_\perp"'] & & \text{GPD}\quad f(x,\vec{b}_\perp) \arrow[dl, "\int d\vec{b}_\perp"] \arrow[dr, "\int dx"] & \\
 & \underset{\text{PDF}}{f(x)} \arrow[dr, "\int dx"'] & & F(\vec{b}_\perp)\quad \text{Form factor} \arrow[dl, "\int d\vec{b}_\perp"] \\
 & & \underset{\text{charge}}{Q} &
\end{tikzcd}$$



EIC: Gluon TMDs from Dijet Production

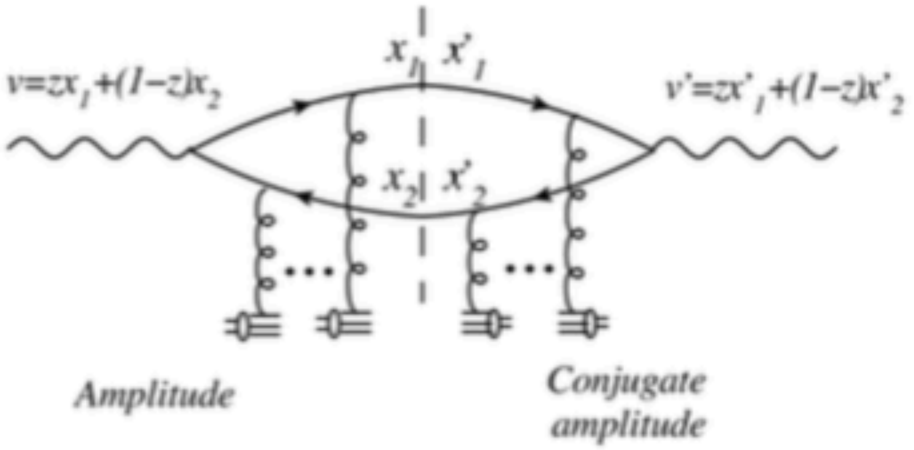
- Thus far, focus on quark TMDs while the available studies of gluon TMDs are sparse
- Of particular interest: WW gluon distribution **$G^{(1)}$** and its linearly polarized partner **$h_T^{(1)}$** inside unpolarized hadron
- These gluon distributions play also central role in small-x saturation phenomena.

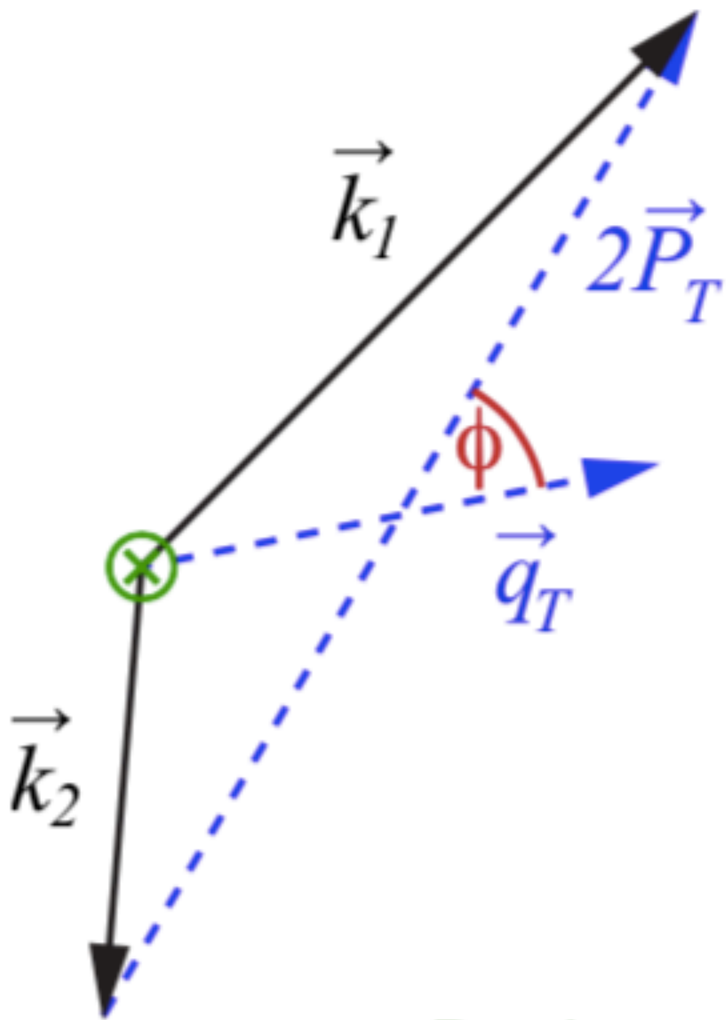
$G^{(1)}$ and $h_T^{(1)}$ can be accessed through measuring azimuthal anisotropies in processes such as **jet pair (dijet) production** in e+p and e+A scattering.

A. Metz and J. Zhou, Phys. Rev. D84 , 051503 (2011), arXiv:1105.1991.
D. Boer, P. J. Mulders, and C. Pisano, Phys. Rev. D80 , 094017 (2009), arXiv:0909.4652
D. Boer, S. J. Brodsky, P. J. Mulders, and C. Pisano, Phys. Rev. Lett. 106 , 132001 (2011), arXiv:1011.4225.
F. Dominguez, J.-W. Qiu, B.-W. Xiao, and F. Yuan, Phys. Rev. D85 , 045003 (2012), arXiv:1109.6293.
A. Dumitru, L. McLerran, and V. Skokov, Phys. Lett. B743 , 134 (2015), arXiv:1410.4844.
A. Dumitru and V. Skokov, Phys. Rev. D91 , 074006 (2015), arXiv:1411.6630.
A. Dumitru, T. Lappi, and V. Skokov, Phys. Rev. Lett. 115 , 252301 (2015), arXiv:1508.04438.
A. Dumitru and V. Skokov, Phys. Rev. D94 , 014030 (2016), arXiv:1605.02739.

From T. Ullrich, IS 2017

Kinematics: Dijets in γ^*A





Key observables: P_T and q_T

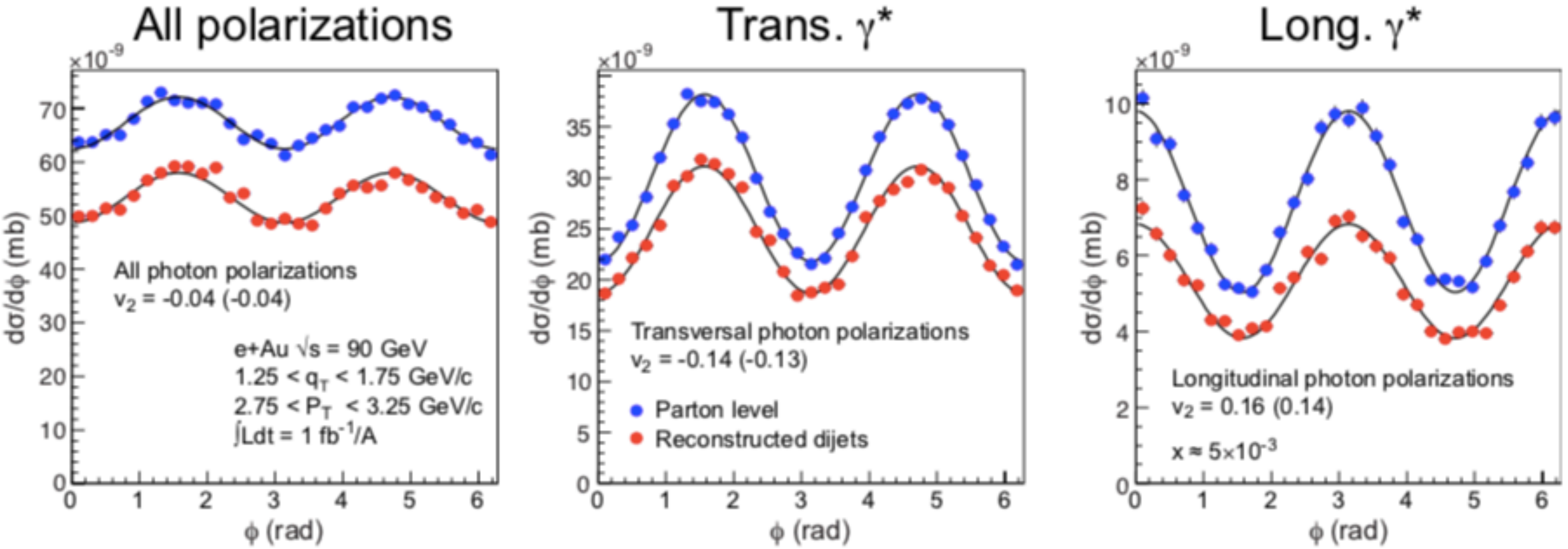
- the difference in momenta (imbalance)
  $$\vec{q}_T = \vec{k}_1 + \vec{k}_2$$
- the average transverse momentum of the jets
  $$\vec{P}_T = (1-z)\vec{k}_1 - z\vec{k}_2$$
- ϕ is angle between P_T and q_T
- work in "correlation limit" $P_T >> q_T$
- azimuthal asymmetry arising from the linearly polarized gluon distribution: $v_2 = \langle \cos 2\phi \rangle$

Dominguez, Marquet, Xiao, Yuan, PRD 2011

From T. Ullrich, IS 2017

Elliptic Anisotropy in DiJet Production (I)

- Dipartons from McDijet event generator (V. Skokov) → showers via Pythia → experimental cuts → jet-finding with ee-kt (FastJet)



- Dijets recover the anisotropy (v_2) quite well
- NOTE: phase shift between long. and trans. γ* (dominated by T)

Gluon TMDs via:
$$v_2^L = \frac{1}{2}\frac{h_\perp^{(1)}(x,q_\perp)}{G^{(1)}(x,q_\perp)} \quad , \quad v_2^T = -\frac{\epsilon_f^2 P_\perp^2}{\epsilon_f^4+P_\perp^4}\,\frac{h_\perp^{(1)}(x,q_\perp)}{G^{(1)}(x,q_\perp)}$$

A. Dumitru, T. Lappi, and V. Skokov, Phys. Rev. Lett. 115 , 252301 (2015), arXiv:1508.04438.

From T. Ullrich, IS 2017

It used to be like this …in the past

The experimentalist asks:	The theorist answers:
Is it possible to have a theory model which gives signature X?	Yes.
Are there any well motivated such models?	No. You bet. Let me tell you about those. Actually I have a paper…
Is there any Monte Carlo which can simulate those models?	I’m the wrong person to ask. Ask a phenomenologist.

From K. Kong SUSY 2019

Nowadays the tables have turned

- The stream of LHC data has changed the picture

Experimentalist answers:		**The theorist asks:**
Yes.	←	Can LHC be sensitive to model X?
Not this particular model. In our note we show plots in A model	←	Is there any analysis which is looking for this model?
Manpower. We do not have enough people to cover all possible theory models.	←	Why not?! It's a great model.

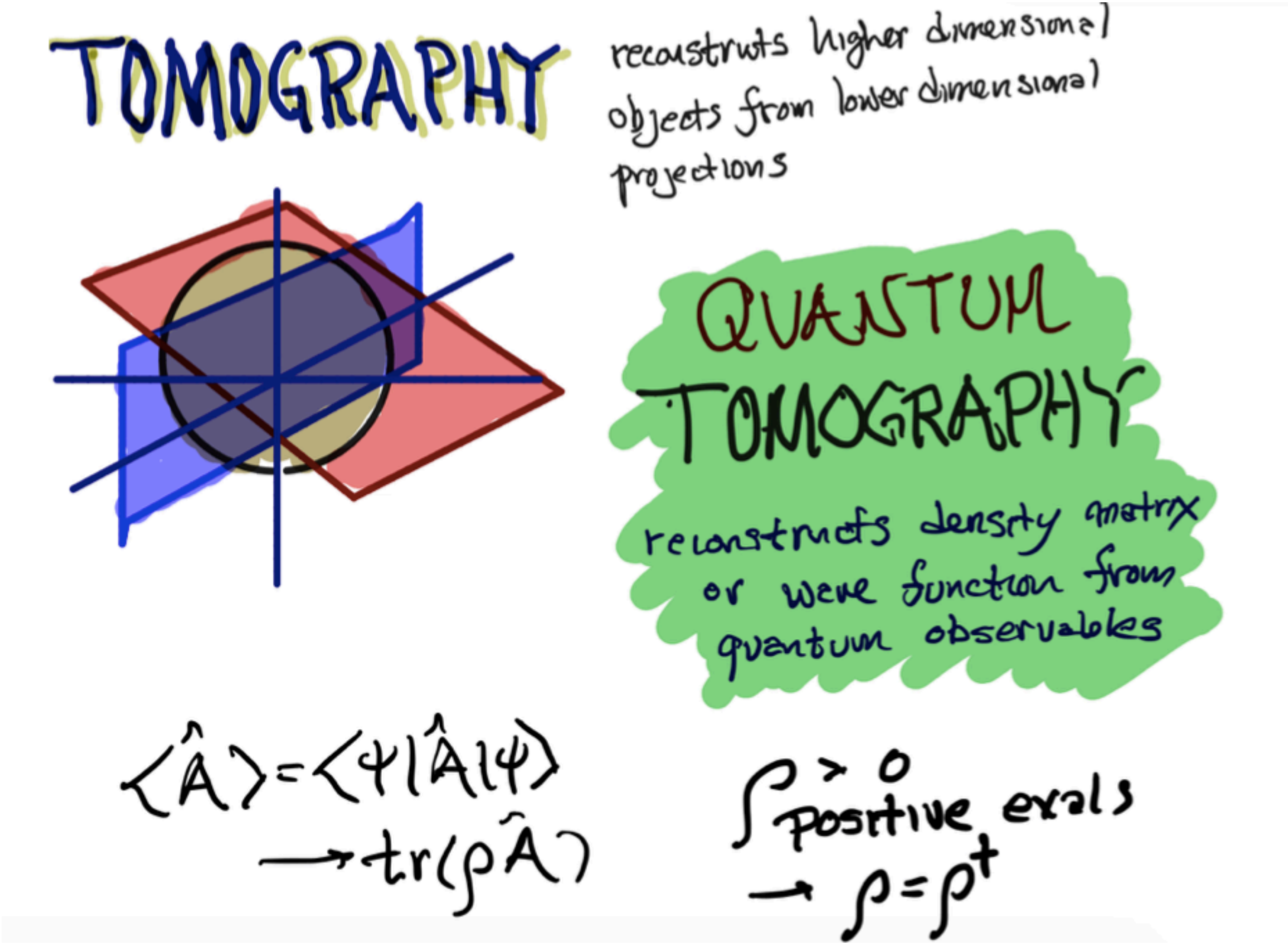
From K. Kong SUSY 2019

New directions in HEP

1. ***Machine learning***

2. ***Quantum information***

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



TOMOGRAPHY

reconstructs higher dimensional objects from lower dimensional projections

QUANTUM TOMOGRAPHY

reconstructs density matrix or wave function from quantum observables

$$\langle \hat{A} \rangle = \langle \psi | \hat{A} | \psi \rangle \rightarrow tr(\rho \hat{A})$$

$$\left\{ \begin{array}{l} \rho > 0 \\ \text{positive evals} \end{array} \right. \rightarrow \rho = \rho^{\dagger}$$

Begin with Some Results

"dijets" means
2 LHC jets, each
made of many particles
plus everything else not measured

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

measuring a density matrix

raw data processed,
bypassing 600 pages
of theory papers

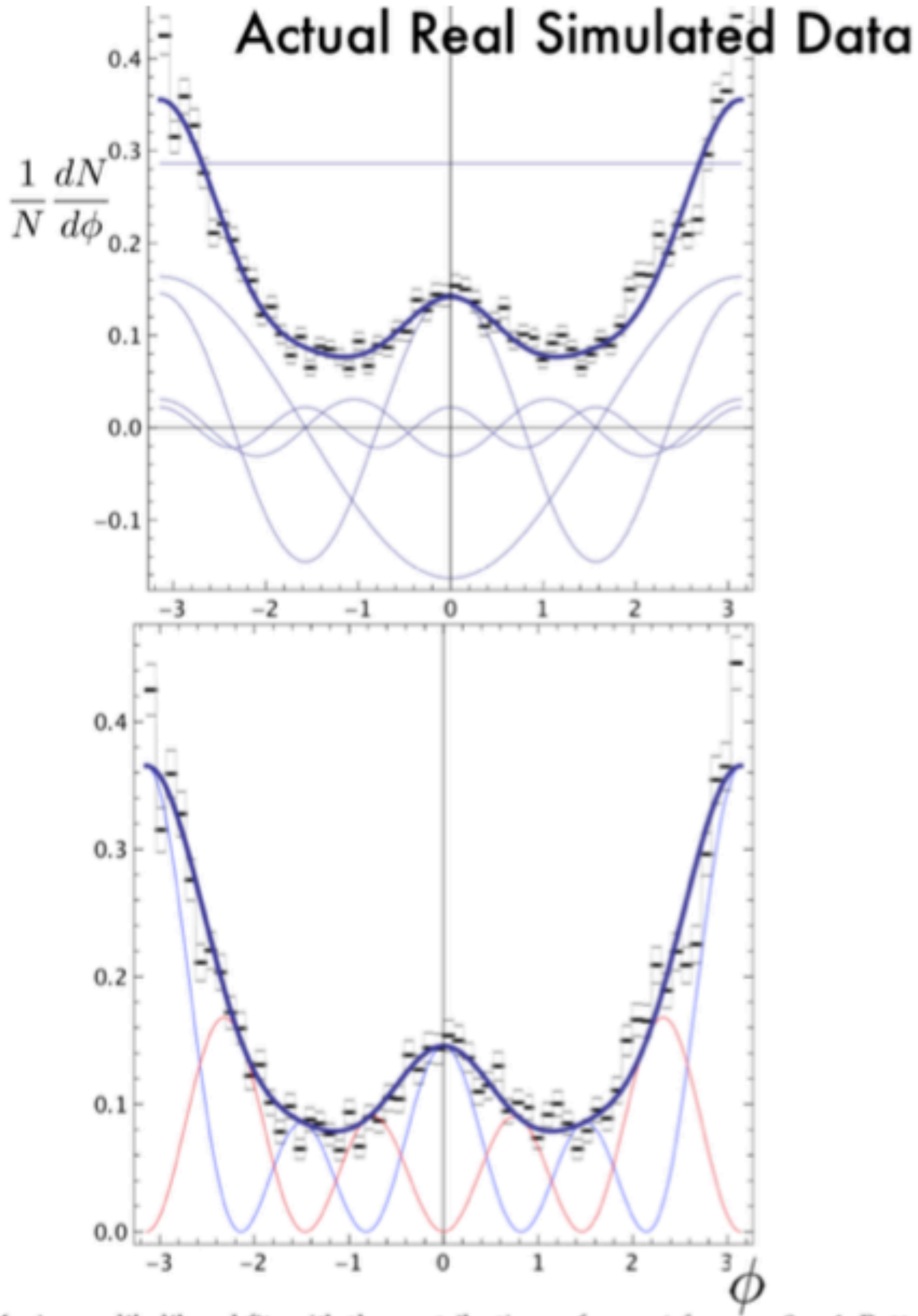
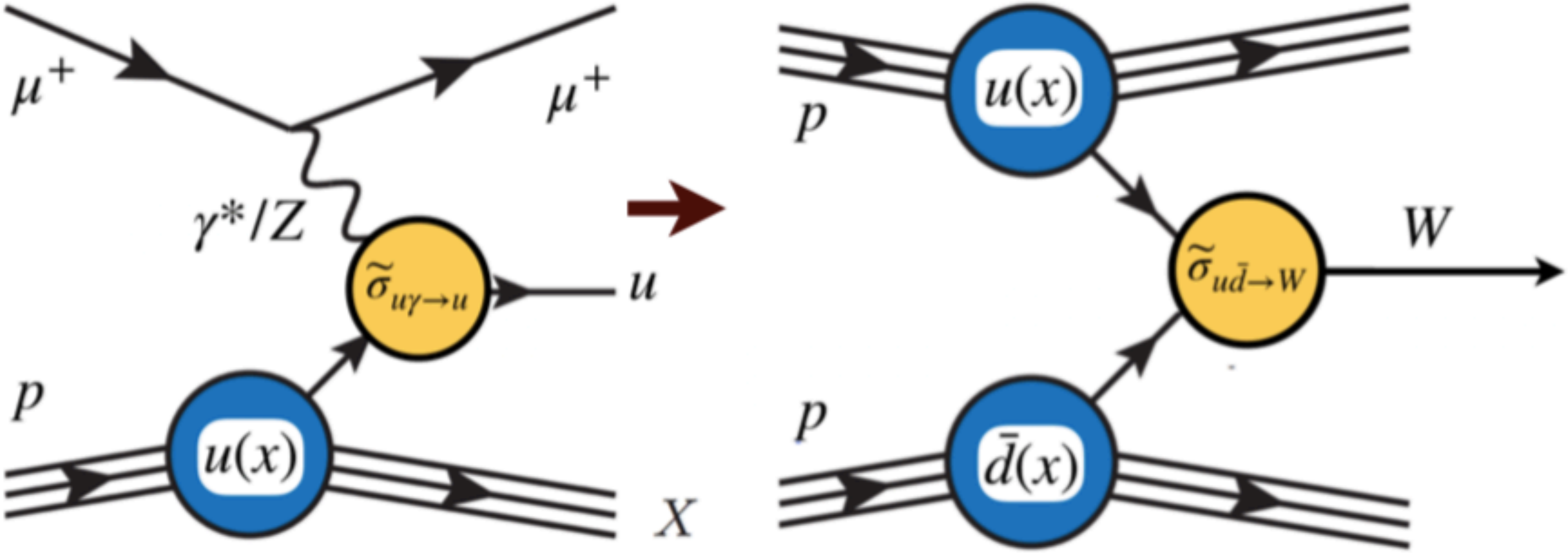


FIG. 4: Top: Maximum likelihood fit, with the contributions of cos $m\phi$ for $m = 0-4$. Bottom: Two weighted distributions defined by $f_+(\phi) = Re(\psi)^2$ (blue) and $f_-(\phi) = Im(\psi)^2$ (red), coming from the eigenstates of the rank two density matrix.

The Global QCD analysis paradigm

QCD factorisation theorems: **PDF universality**

$$\sigma_{lp\to\mu X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \quad \longrightarrow \quad \sigma_{pp\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$



Determine PDFs from ***deep-inelastic scattering****…*

… and use them to compute predictions for ***proton-proton collisions***

From J. Rojo. DIS 2019

mandatory diagram for collider theorists

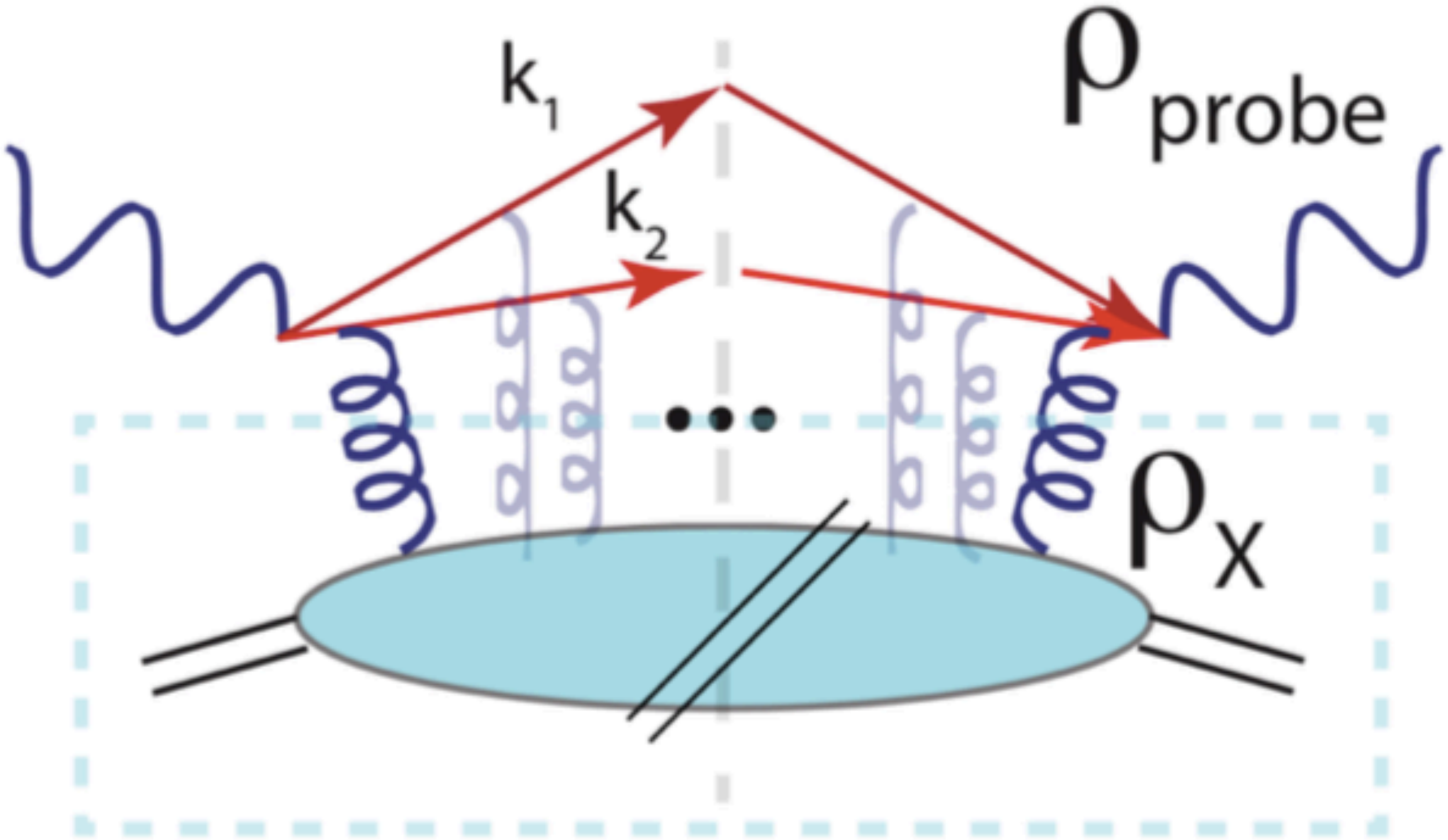


FIG. 1: By analogy with deeply inelastic scattering, a dijet probe replaces the handle of the handbag diagram with a shoulder strap (red) defining new elements of the probe density matrix ρ_{probe}. Each orthogonal element of ρ_{probe} can extract a corresponding projection of the unknown system density matrix ρ_X inside the dashed box. Unlike the deeply inelastic structure functions no assumptions of perturbation theory or one-photon exchange need be made.

EXAMPLE: Experimentally measure the polarization density matrix of a Z boson

$$\frac{dN}{d\cos\theta d\phi} \sim tr(\rho_{probe}\rho_X)$$

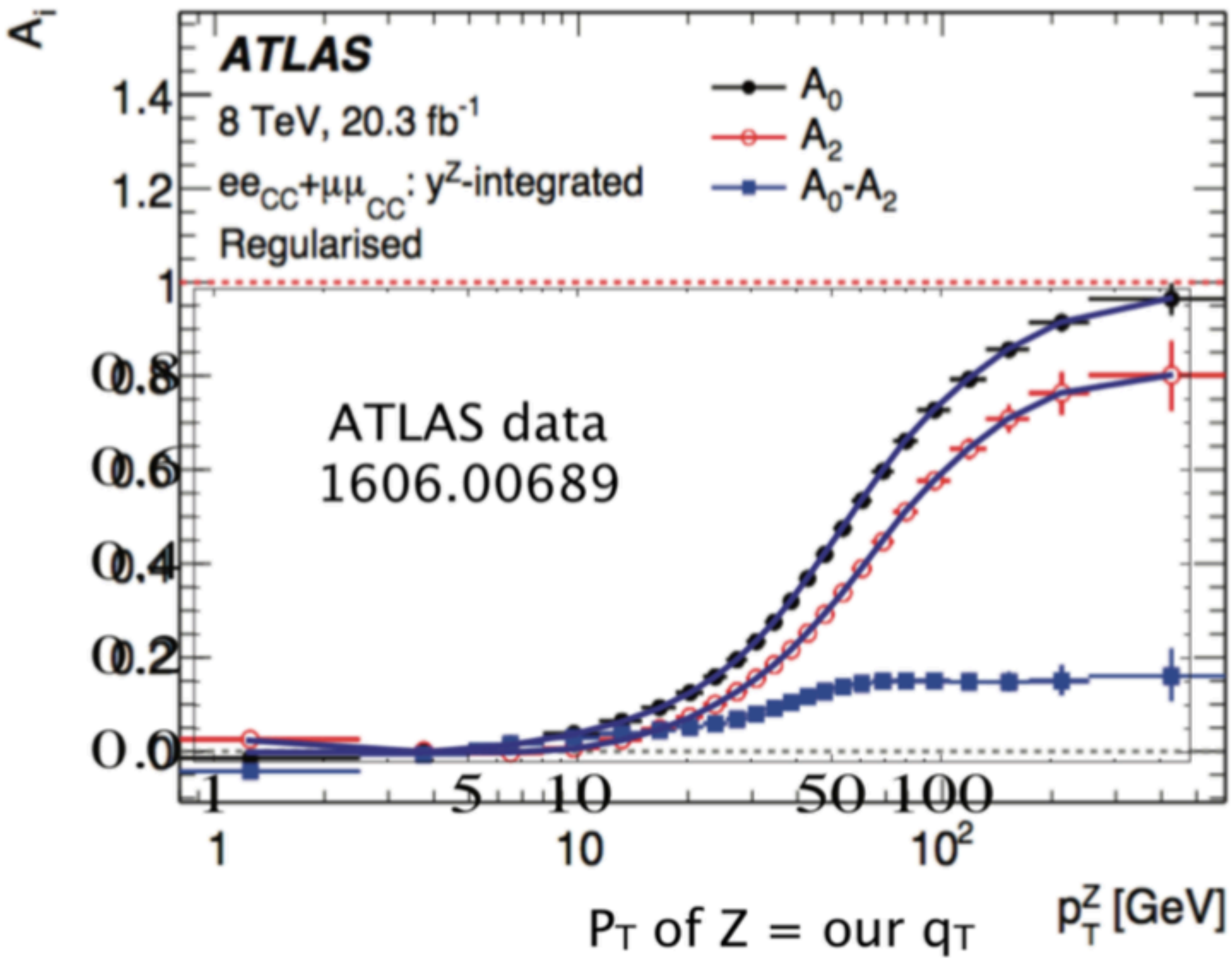
ρ_{probe} = known density matrix

ρ_X = unknown density matrix

The notation does not look Lorentz invariant, but the quantities are

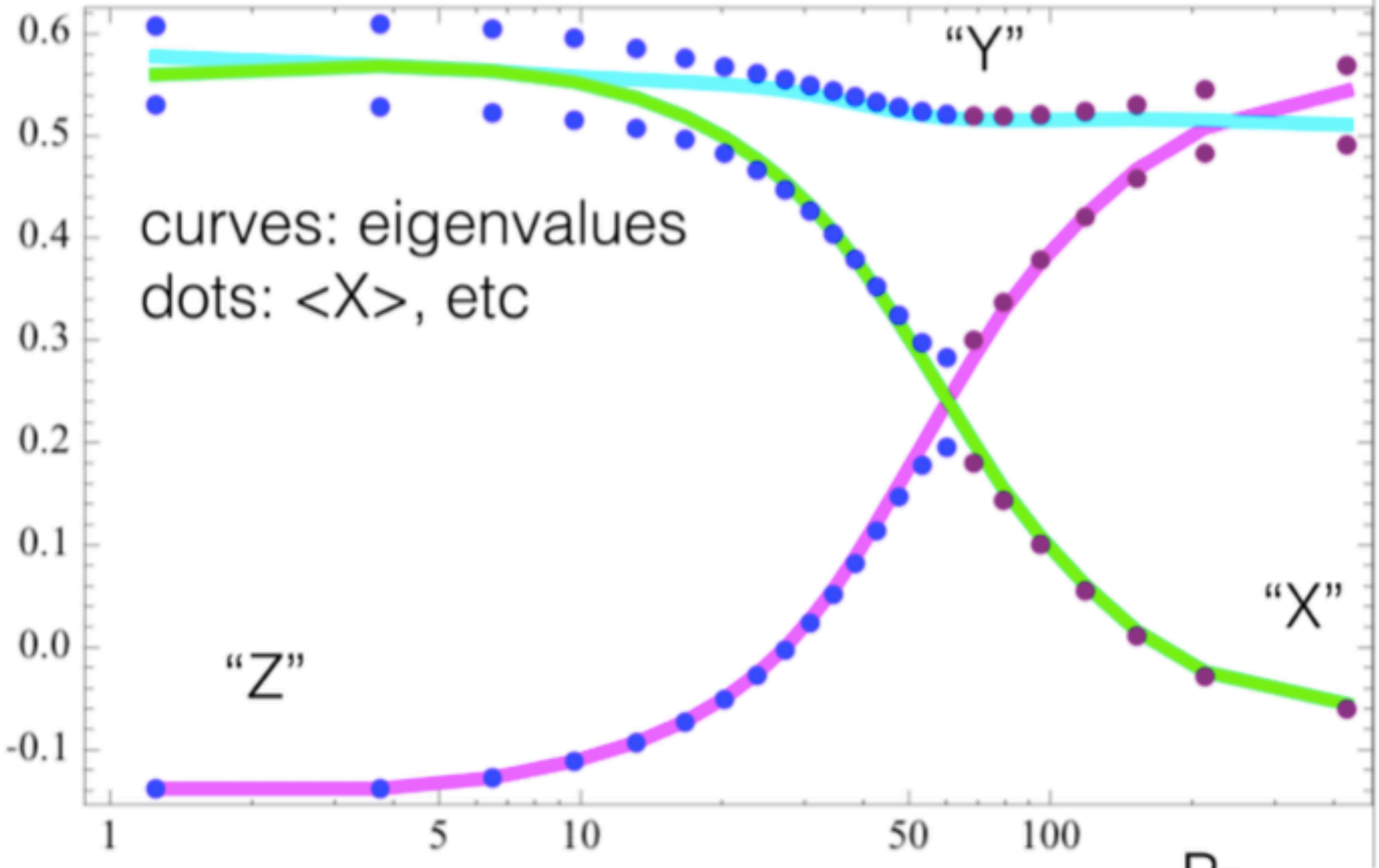
Quantum tomography

***We don’t need a theory,
sometimes less theory is better theory***


A_i
ATLAS
8 TeV, 20.3 fb^-1
ee_CC+μμ_CC: y^Z-integrated
Regularised
A_0
A_2
A_0-A_2
ATLAS data
1606.00689
1.4
1.2
1
0.8
0.6
0.4
0.2
0.0
1
5
10
50
100
10^2
P_T of Z = our q_T
p_T^Z [GeV]

Avoided level crossing; eigenvectors swap

true QM expectation values <X>, <Y>, <Z> v PT



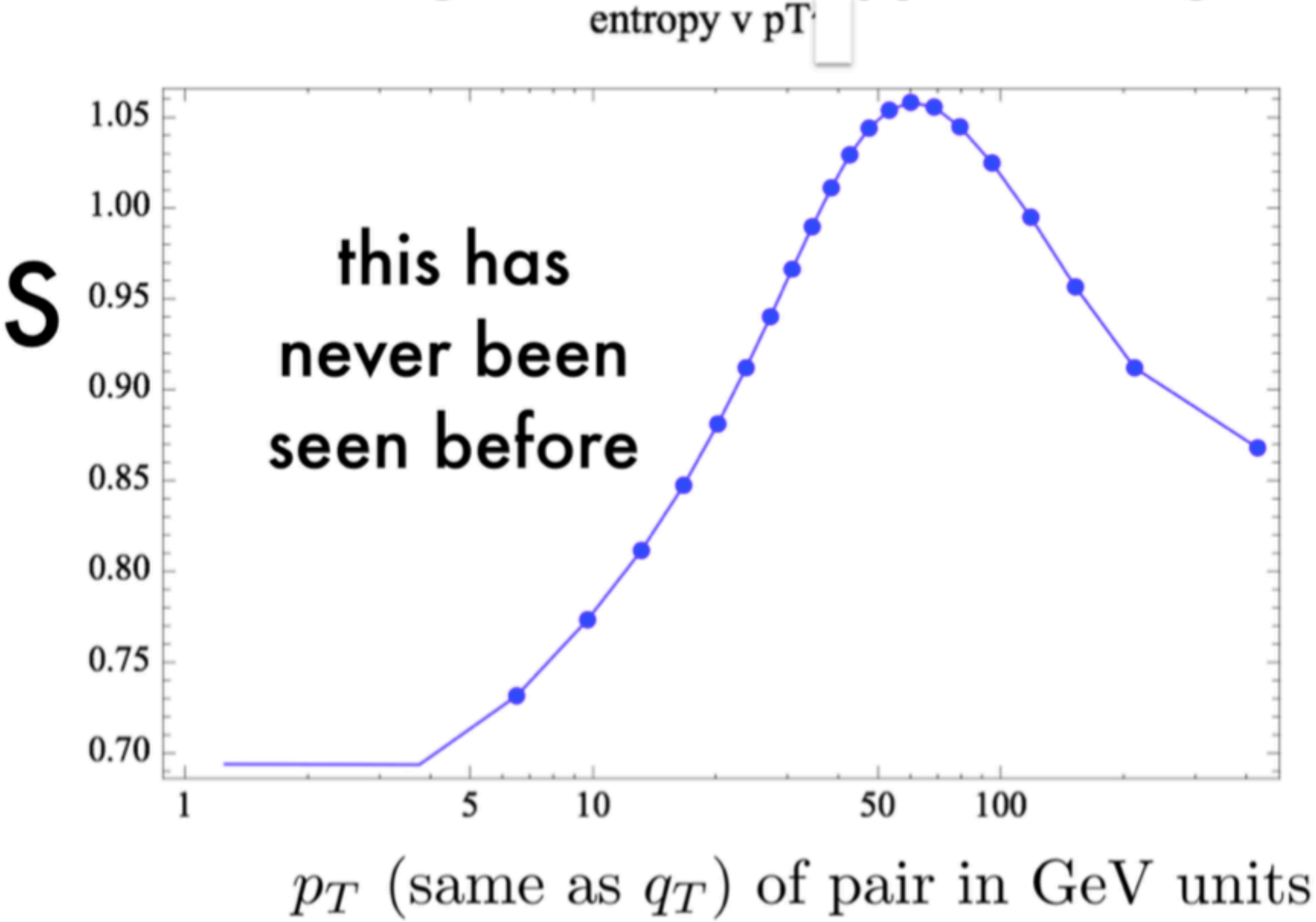
new: no precedent

P_T of Z = our q_T

the entanglement entropy

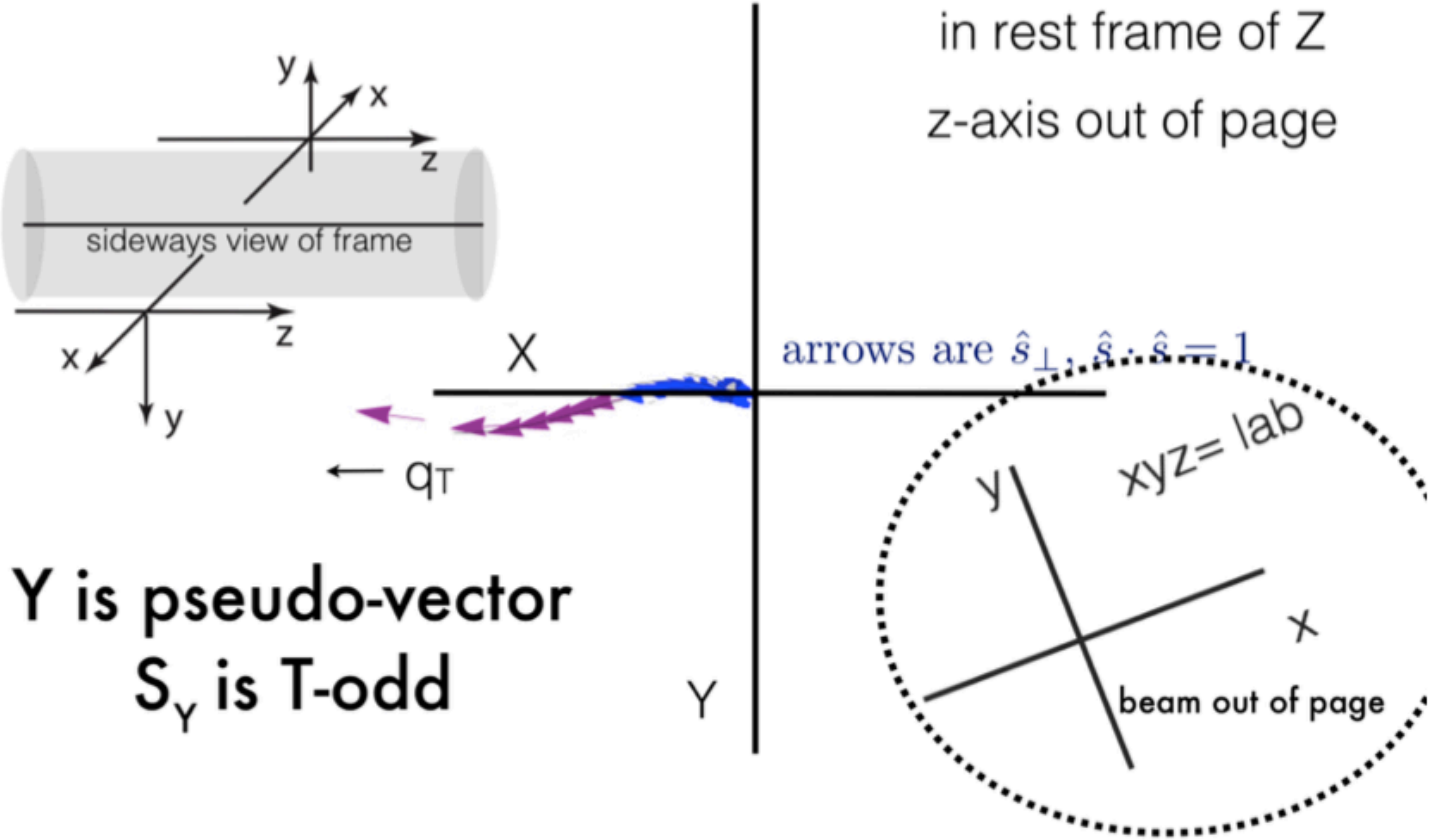
$$\mathcal{S} = -tr(\rho)log(\rho); \qquad \underset{\overset{|}{\text{pure}}}{0} < \mathcal{S} < \underset{\overset{|}{\text{unpolz}}}{log(N)}$$

The entanglement entropy is strange



this has never been seen before

Unexpected discovery in spin parameters of the Z

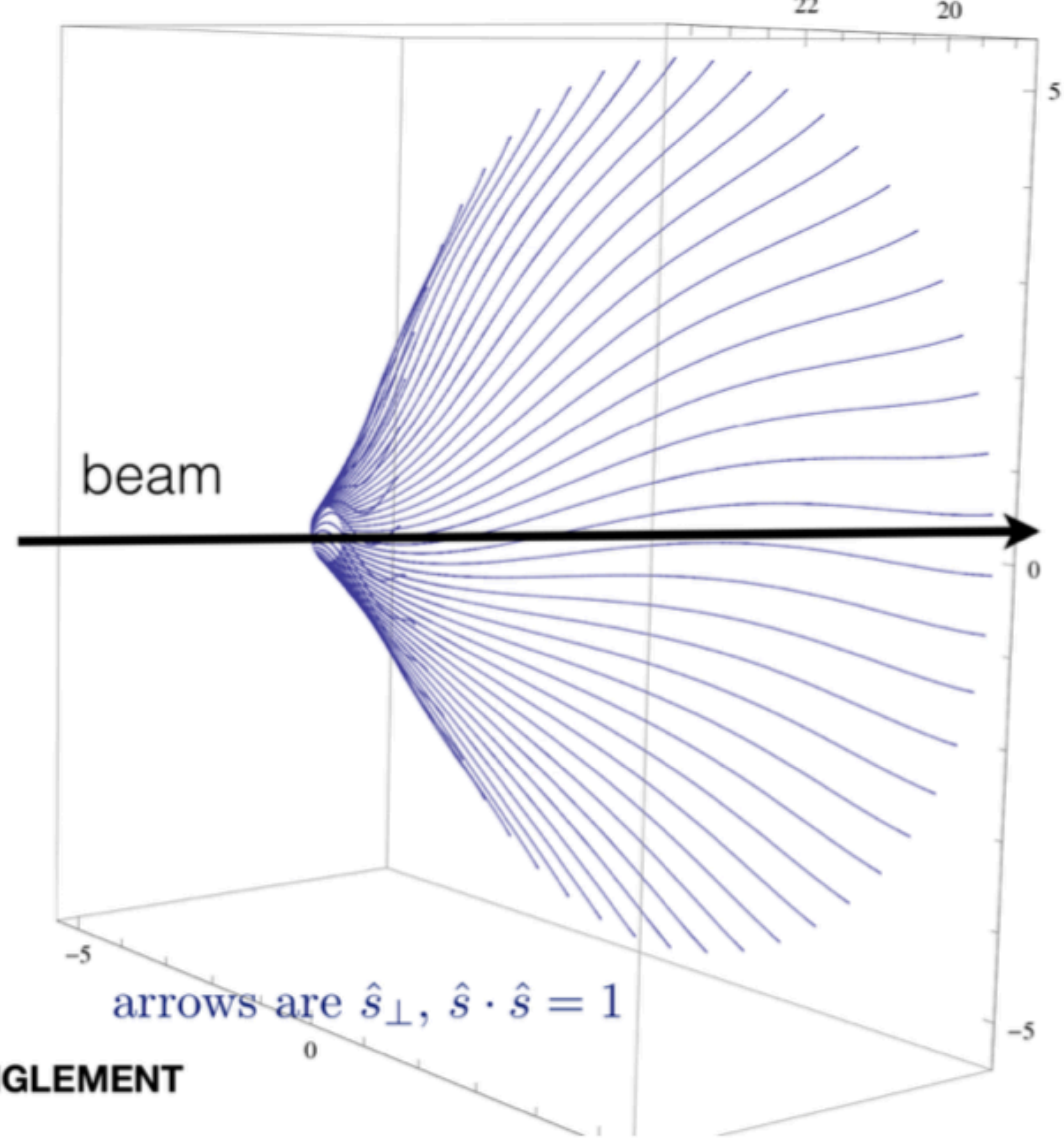


Y is pseudo-vector

S_Y is T-odd

3D
holography
of the
Z spin,
lab frame

(q_x, q_y, q_z)

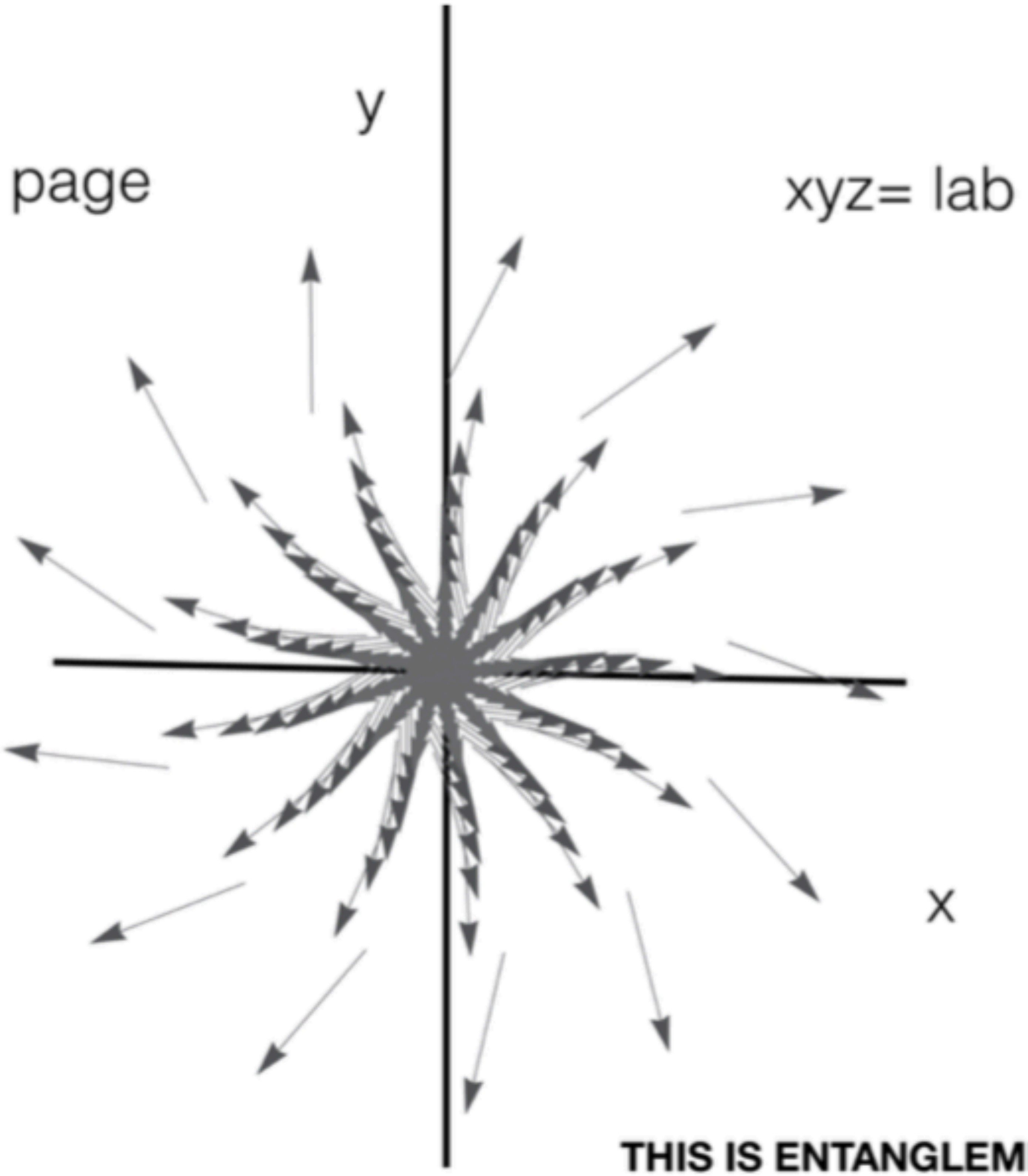


arrows are $\hat{s}_\perp$, $\hat{s} \cdot \hat{s} = 1$

2% of Z's are
polarized
pure state
spinning
as shown

THIS IS ENTANGLEMENT

beam-axis out of page



2% of Z's
are
polarized
pure state
spinning
as shown

THIS IS ENTANGLEMENT

arrows are $\hat{s}_{\perp}$, $\hat{s} \cdot \hat{s} = 1$

Summary

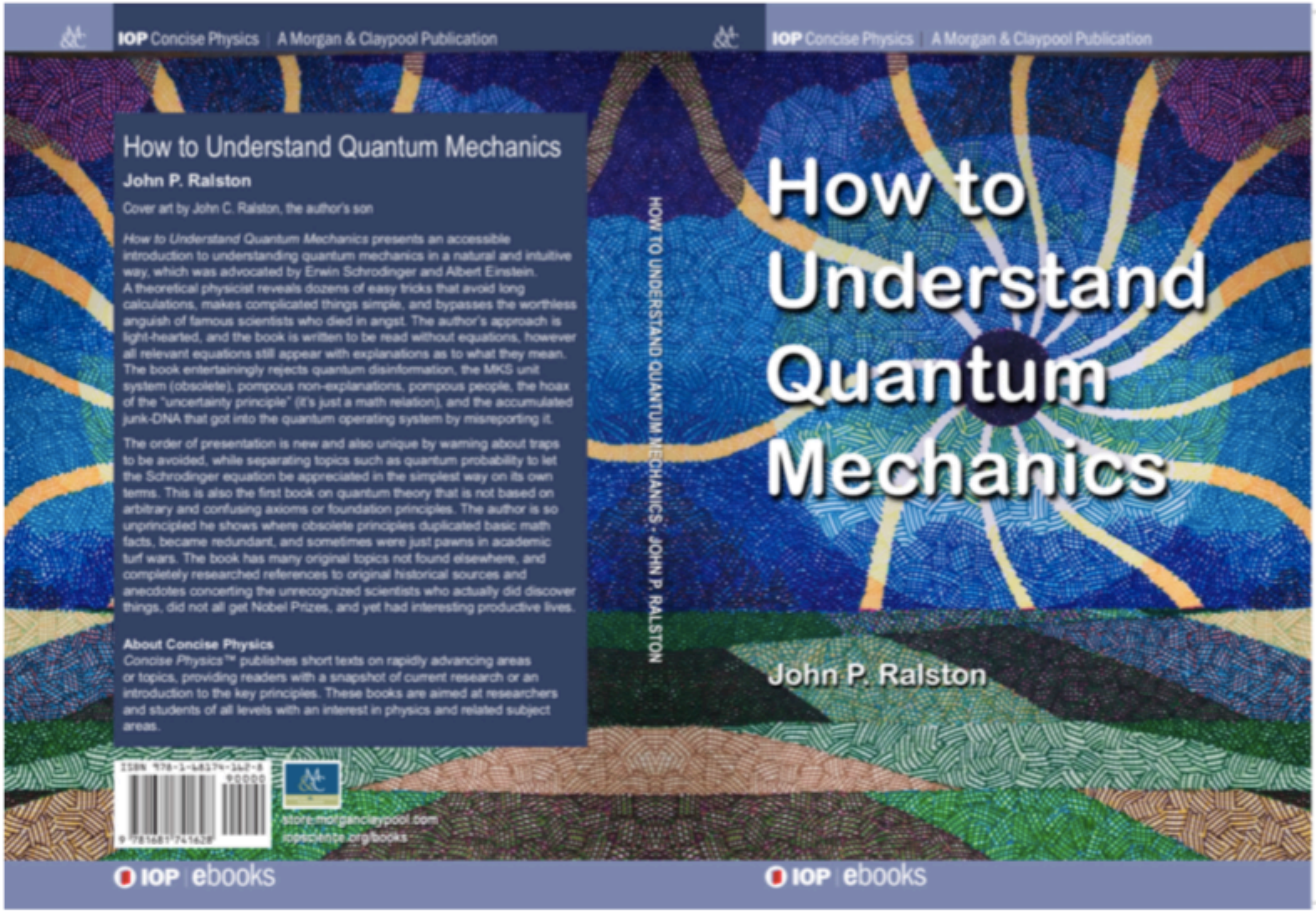
UPC studies at LHC- *covering an unexplored energy regime & synergies with the EIC.* **ATLAS and CMS studying a wide variety of physics topics in UPCs**

Results in UPC VMs by CMS (and ALICE), *studying UPC J/ψ in γPb already found evidence of nuclear gluon shadowing at low-x and Q^2*

Energy dependent studies of the t-distribution of UPC ρ^0 in γp promising for determining the onset of gluon saturation

New directions using Quantum Tomography for QCD (and BSM) studies very promising !

Research facilities such as EIC will open opportunities for fundamental physics studies



IOP Concise Physics | A Morgan & Claypool Publication

How to Understand Quantum Mechanics

John P. Ralston

Cover art by John C. Ralston, the author's son

How to Understand Quantum Mechanics presents an accessible introduction to understanding quantum mechanics in a natural and intuitive way, which was advocated by Erwin Schrodinger and Albert Einstein. A theoretical physicist reveals dozens of easy tricks that avoid long calculations, makes complicated things simple, and bypasses the worthless anguish of famous scientists who died in angst. The author's approach is light-hearted, and the book is written to be read without equations, however all relevant equations still appear with explanations as to what they mean. The book entertainingly rejects quantum disinformation, the MKS unit system (obsolete), pompous non-explanations, pompous people, the hoax of the "uncertainty principle" (it's just a math relation), and the accumulated junk-DNA that got into the quantum operating system by misreporting it.

The order of presentation is new and also unique by warning about traps to be avoided, while separating topics such as quantum probability to let the Schrodinger equation be appreciated in the simplest way on its own terms. This is also the first book on quantum theory that is not based on arbitrary and confusing axioms or foundation principles. The author is so unprincipled he shows where obsolete principles duplicated basic math facts, became redundant, and sometimes were just pawns in academic turf wars. The book has many original topics not found elsewhere, and completely researched references to original historical sources and anecdotes concerning the unrecognized scientists who actually did discover things, did not all get Nobel Prizes, and yet had interesting productive lives.

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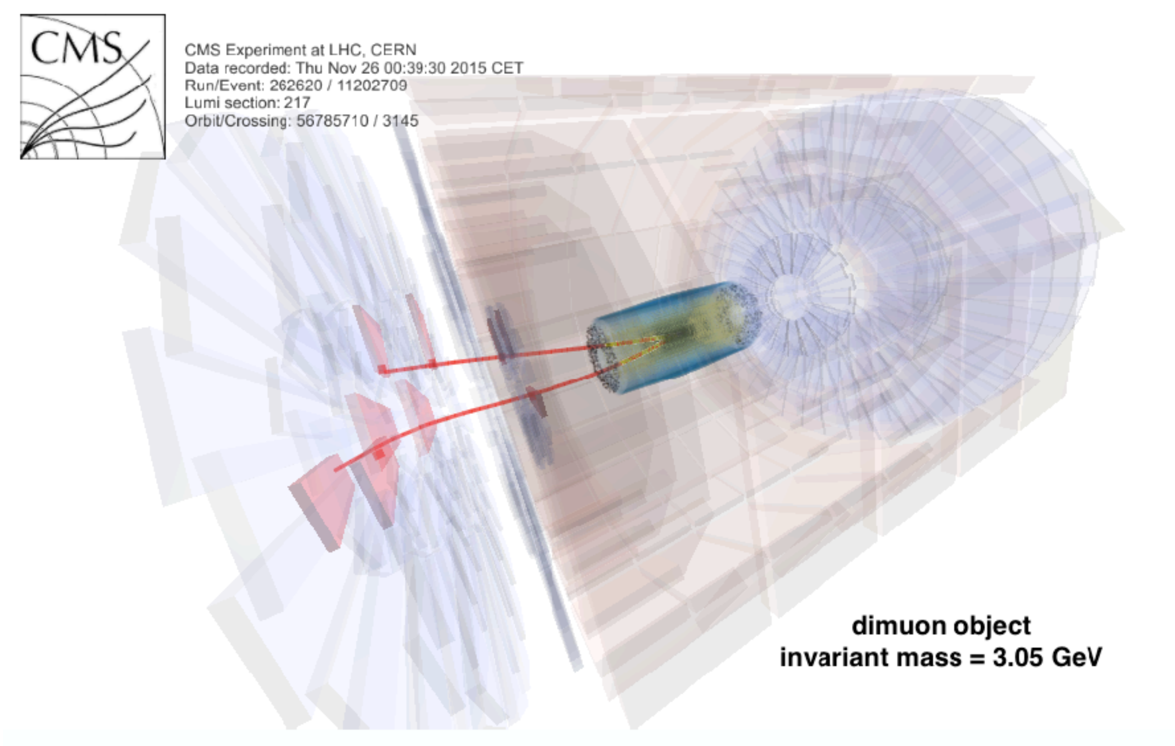
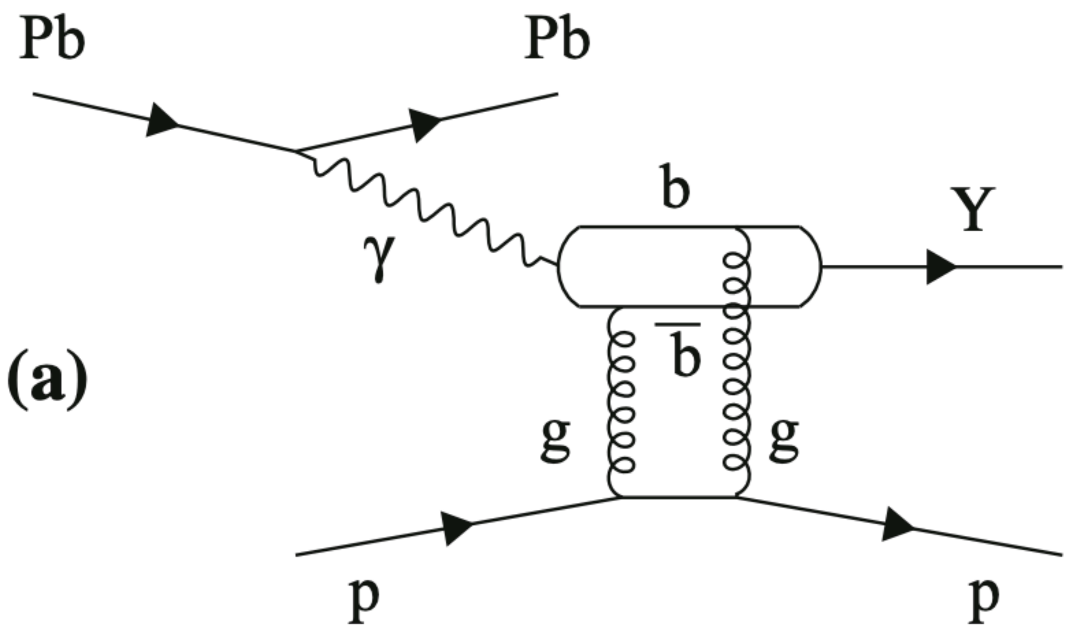
Additional slides

Exclusive Upsilon in γp

Eur. Phys. J. C 79 (2019) 277

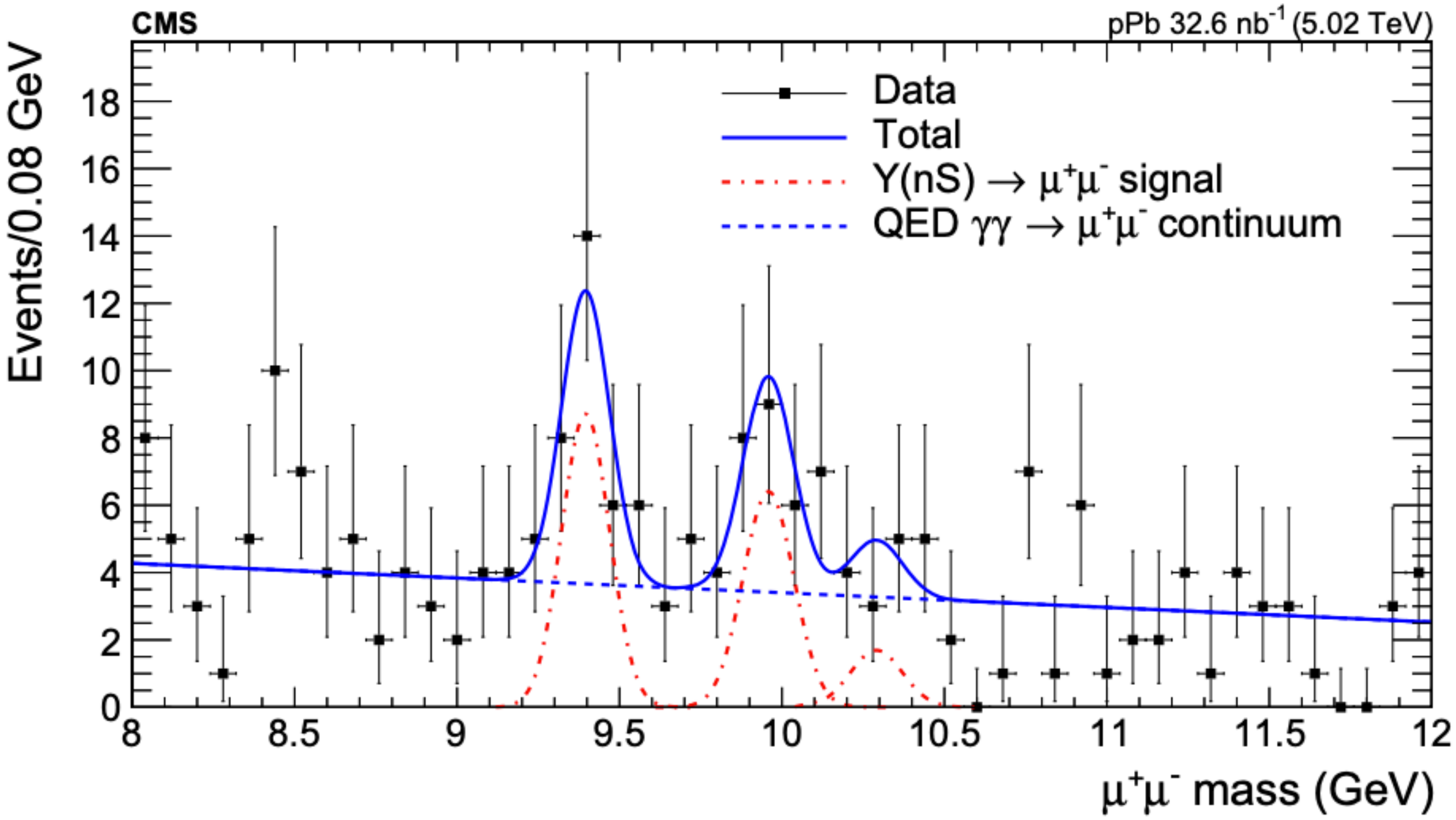


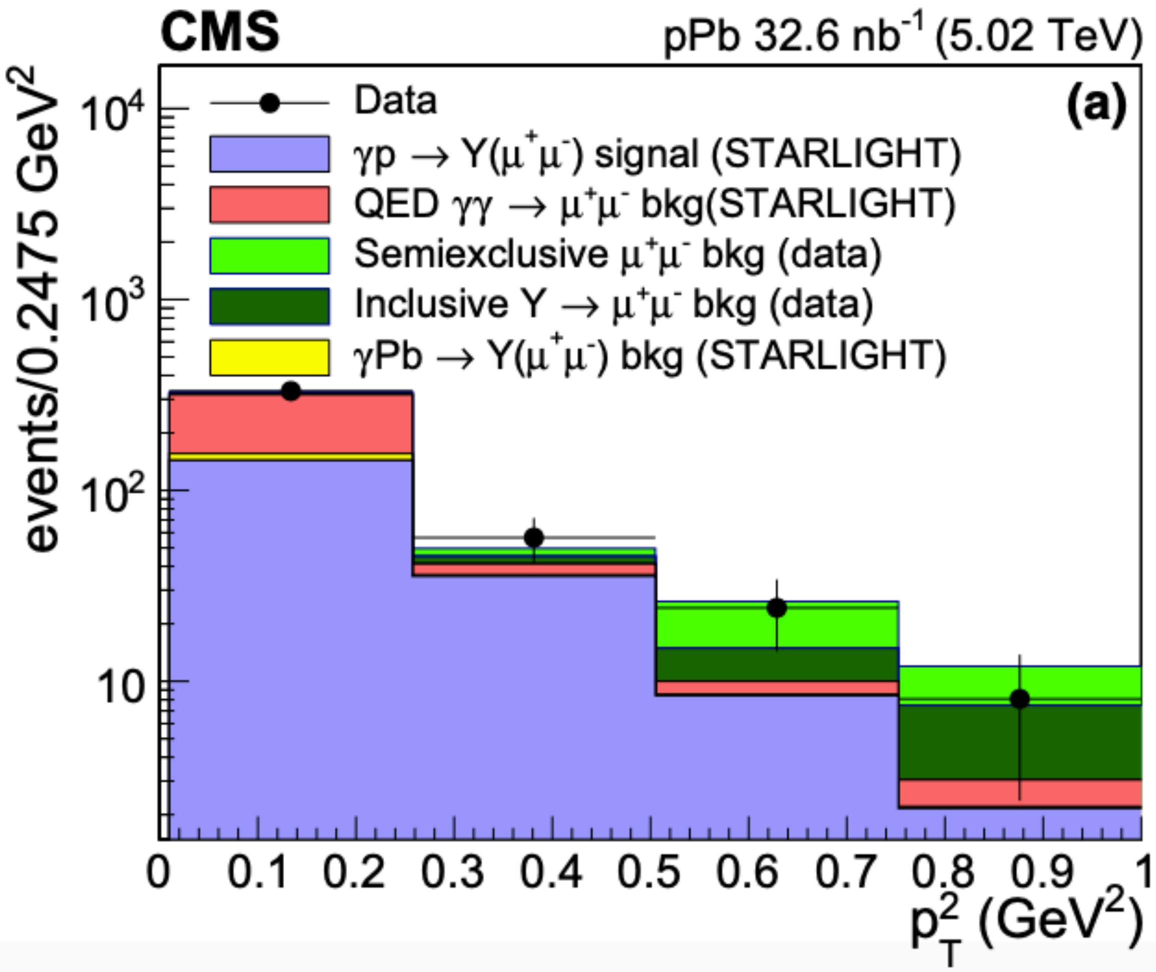
Exclusive Upsilon photoproduction



Exclusive Upsilon in γp

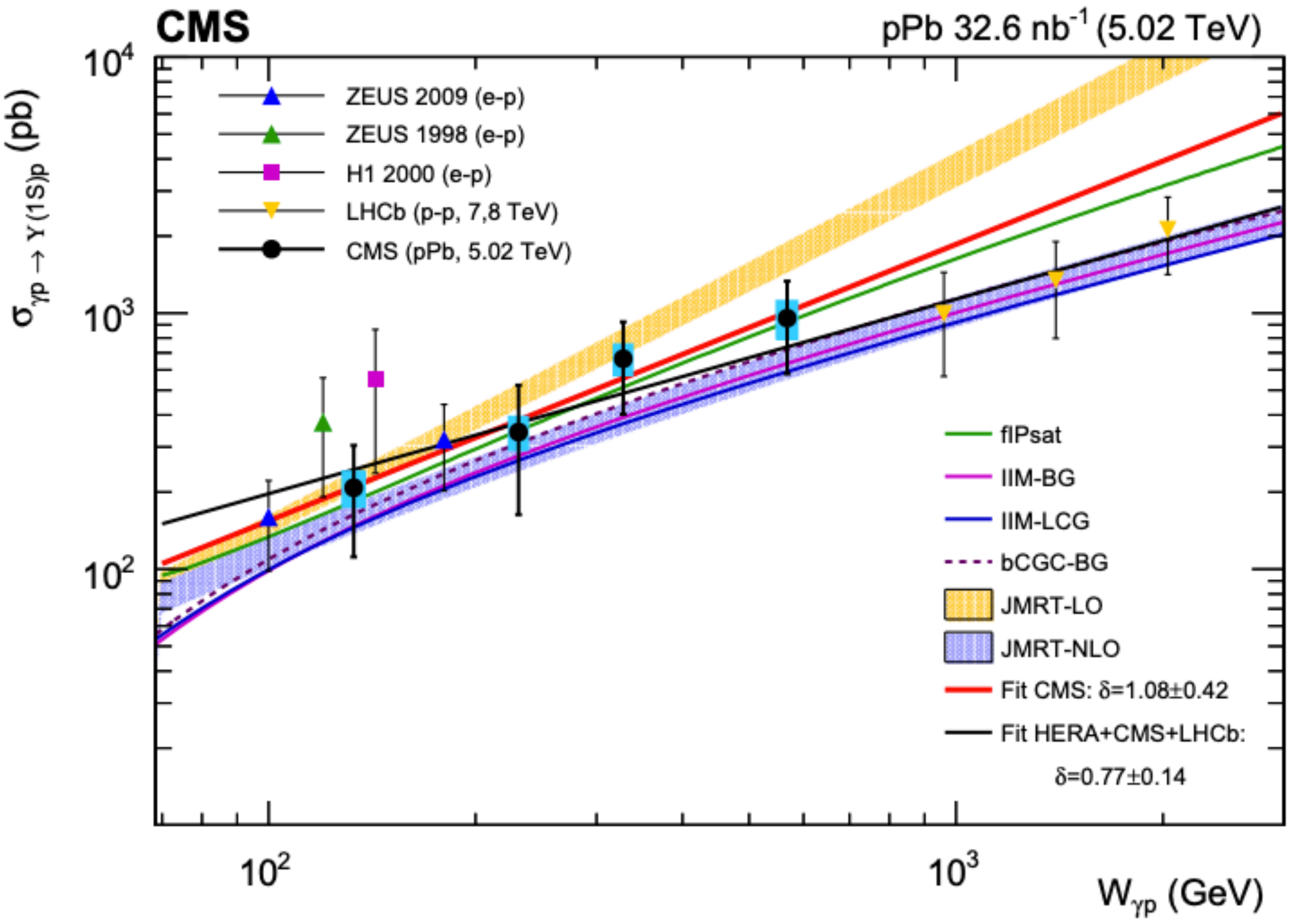
Eur. Phys. J. C 79 (2019) 277





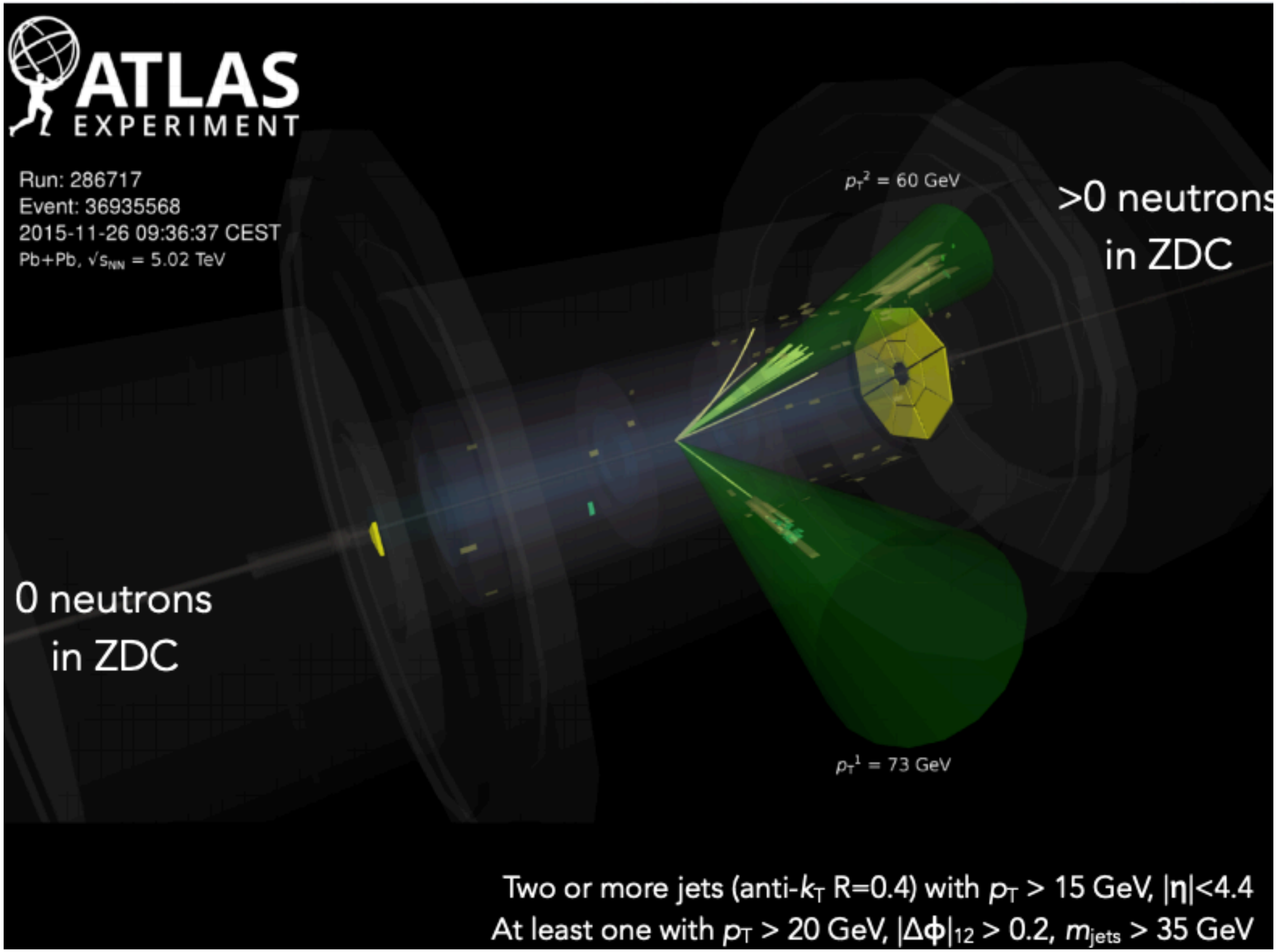
Exclusive Upsilon in γp

Eur. Phys. J. C 79 (2019) 277



Inclusive UPC Dijet at ATLAS

ATLAS-CONF-2017-011

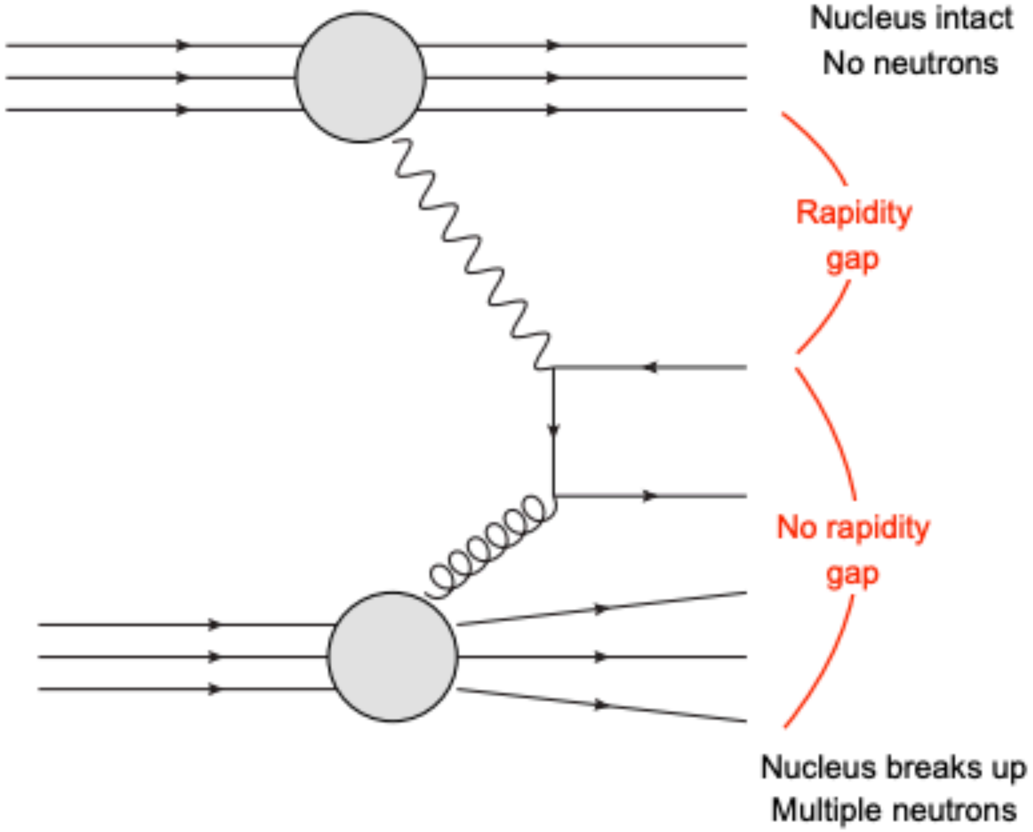


Two or more jets (anti-k_T R=0.4) with $p_T > 15$ GeV, $|\eta|<4.4$
At least one with $p_T > 20$ GeV, $|\Delta\phi|_{12} > 0.2$, $m_{jets} > 35$ GeV

Inclusive dijets in γPb

ATLAS-CONF-2017-011

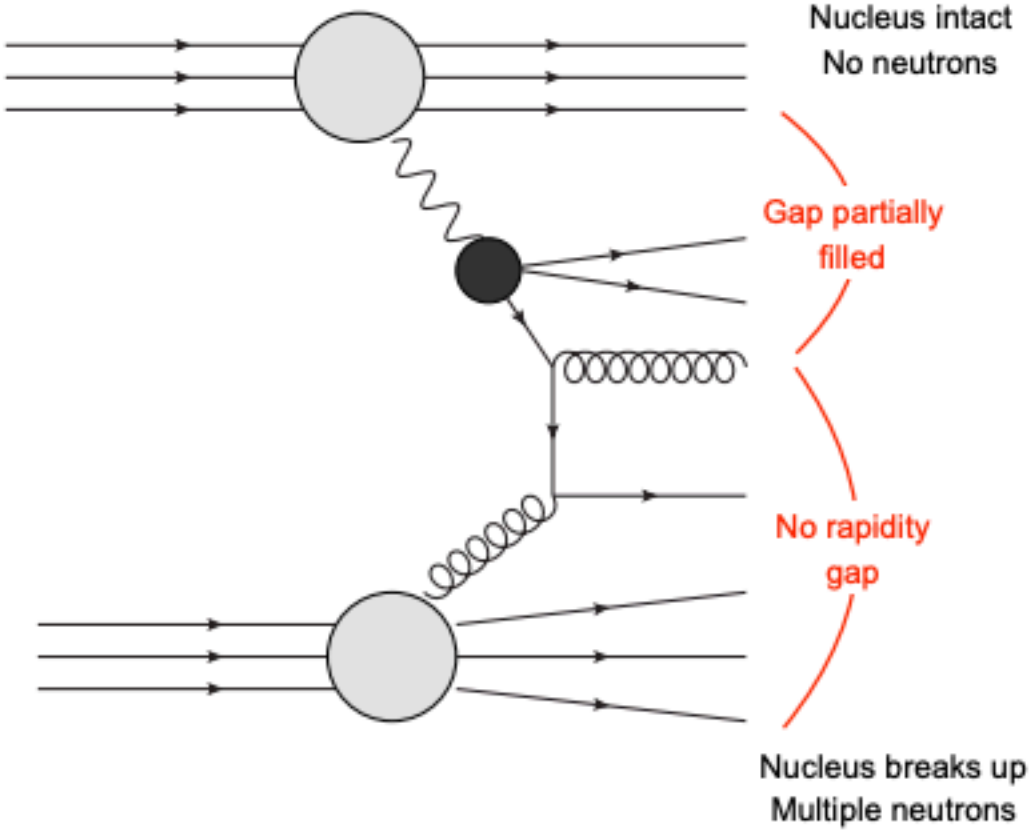
Direct process



“0n”

“Xn”

Resolved process



$$H_\mathrm{T} \equiv \sum_i p_{\mathrm{T}\,i}\,, \quad m_\mathrm{jets} \equiv \left[\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2\right]^{1/2}, \quad y_\mathrm{jets} \equiv \frac{1}{2}\ln\left(\frac{\sum_i E_i + \sum_i p_{z\,i}}{\sum_i E_i - \sum_i p_{z\,i}}\right),$$

Inclusive dijets in γPb

ATLAS-CONF-2017-011

$$z_\gamma \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{+y_{\text{jets}}}, \quad x_{\text{A}} \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}.$$

Sensitive to nPDF

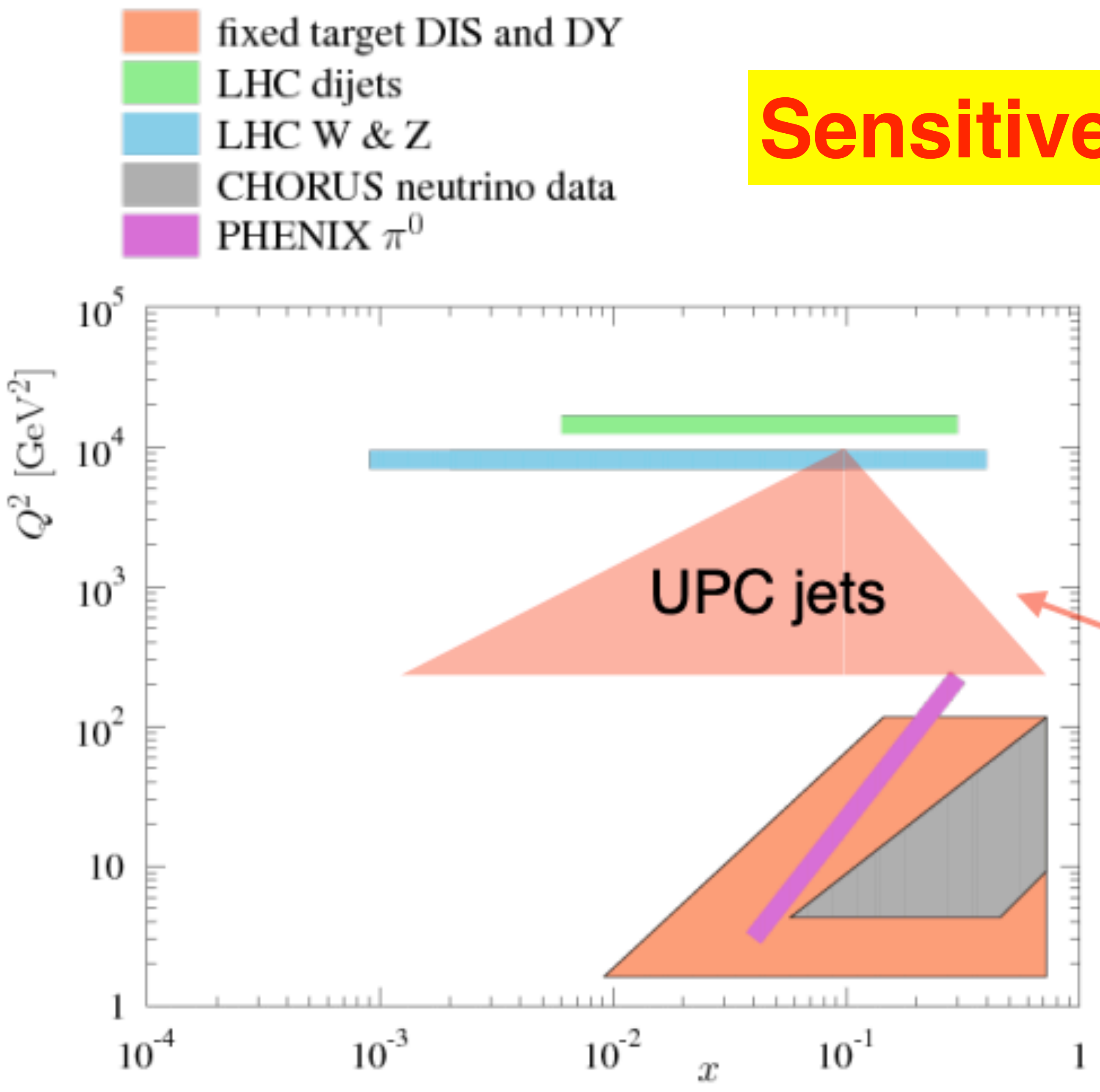
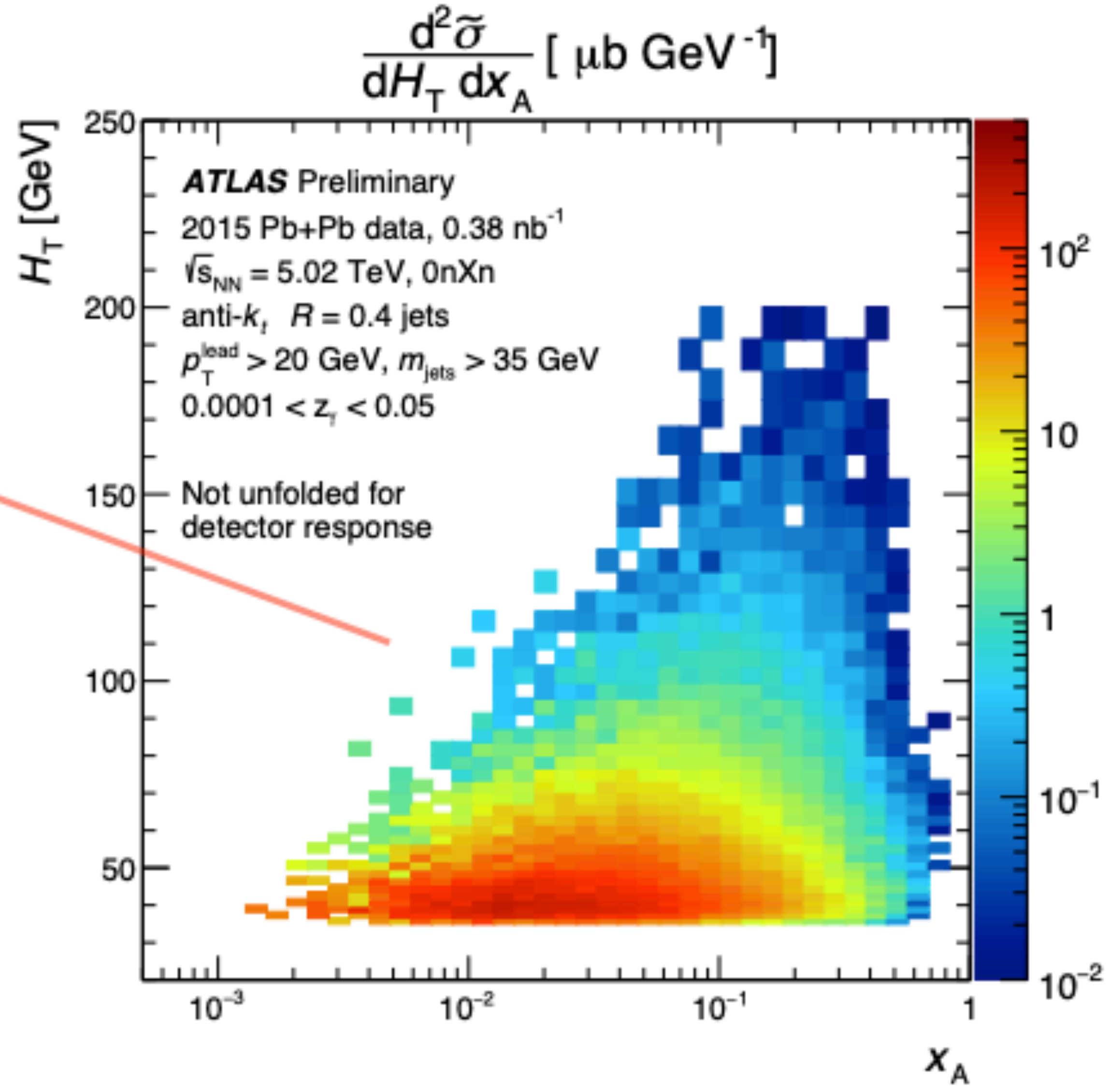


Figure adapted from EPPS16
1612.05741 [hep-ph]



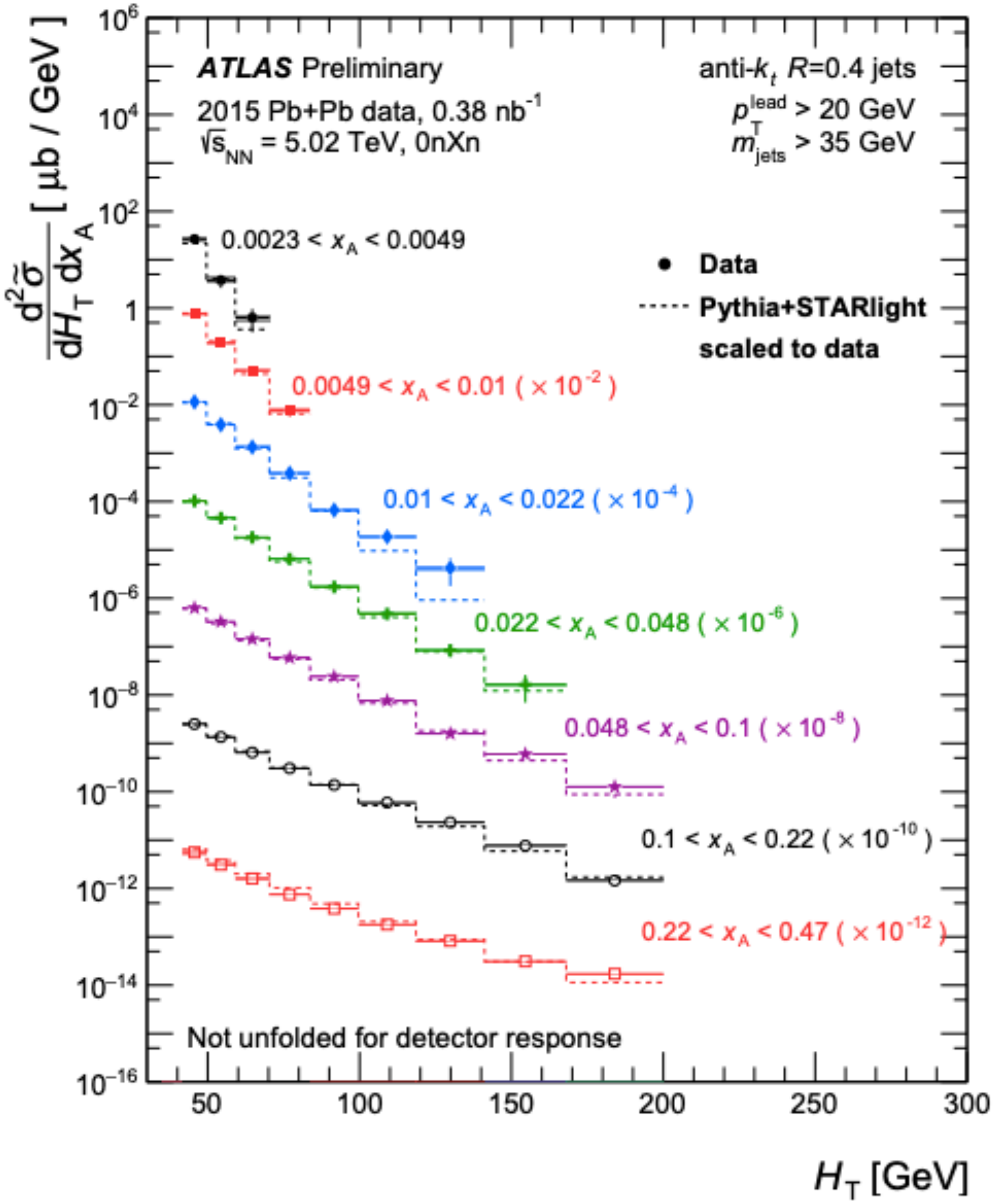
Inclusive dijets in γPb

ATLAS-CONF-2017-011

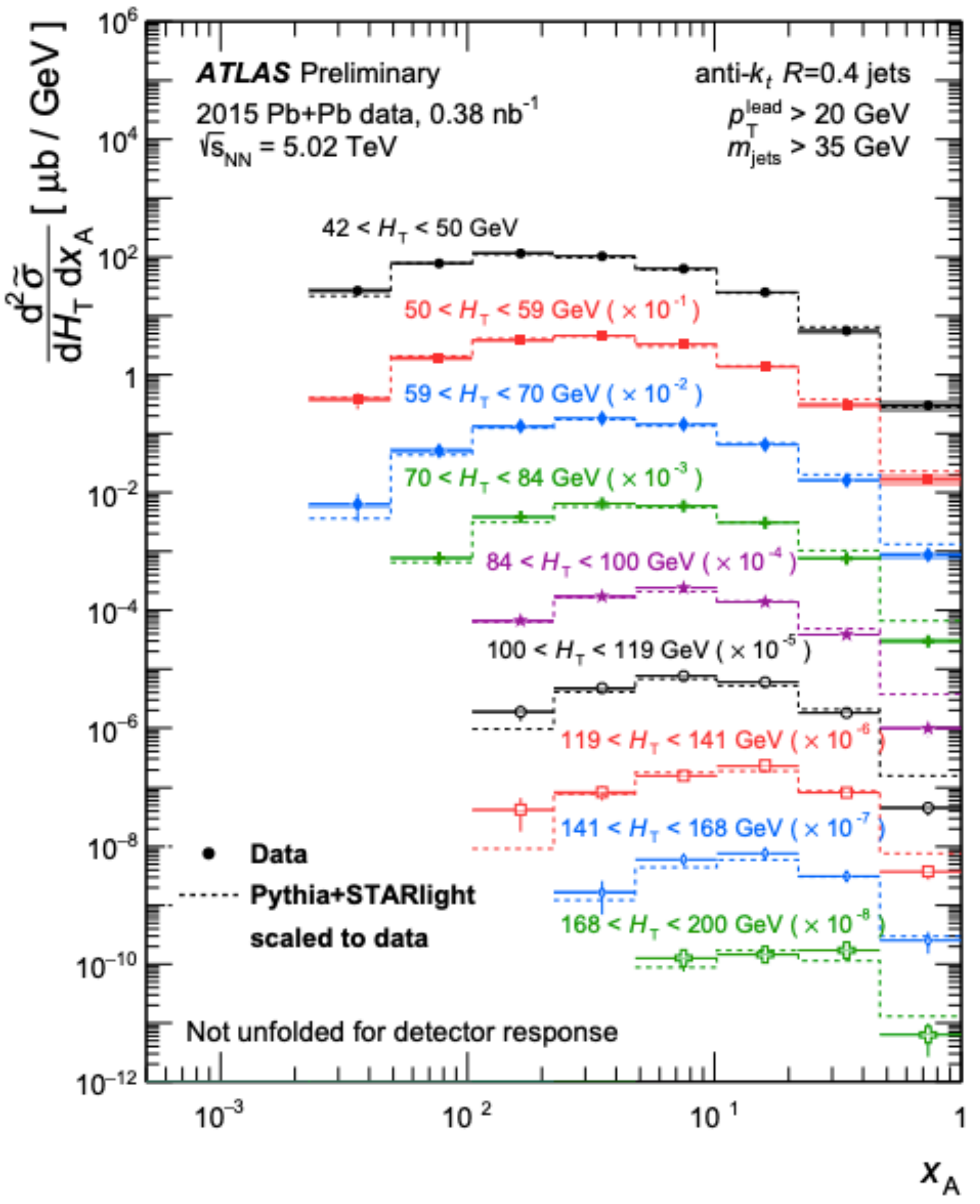
Differential (not unfolded) cross sections vs. DIS-like kinematic variables

Not exactly same as $F_2(x,Q^2)$

Data compared to PYTHIA + STARLIGHT(EPA)



Inclusive dijets in γPb



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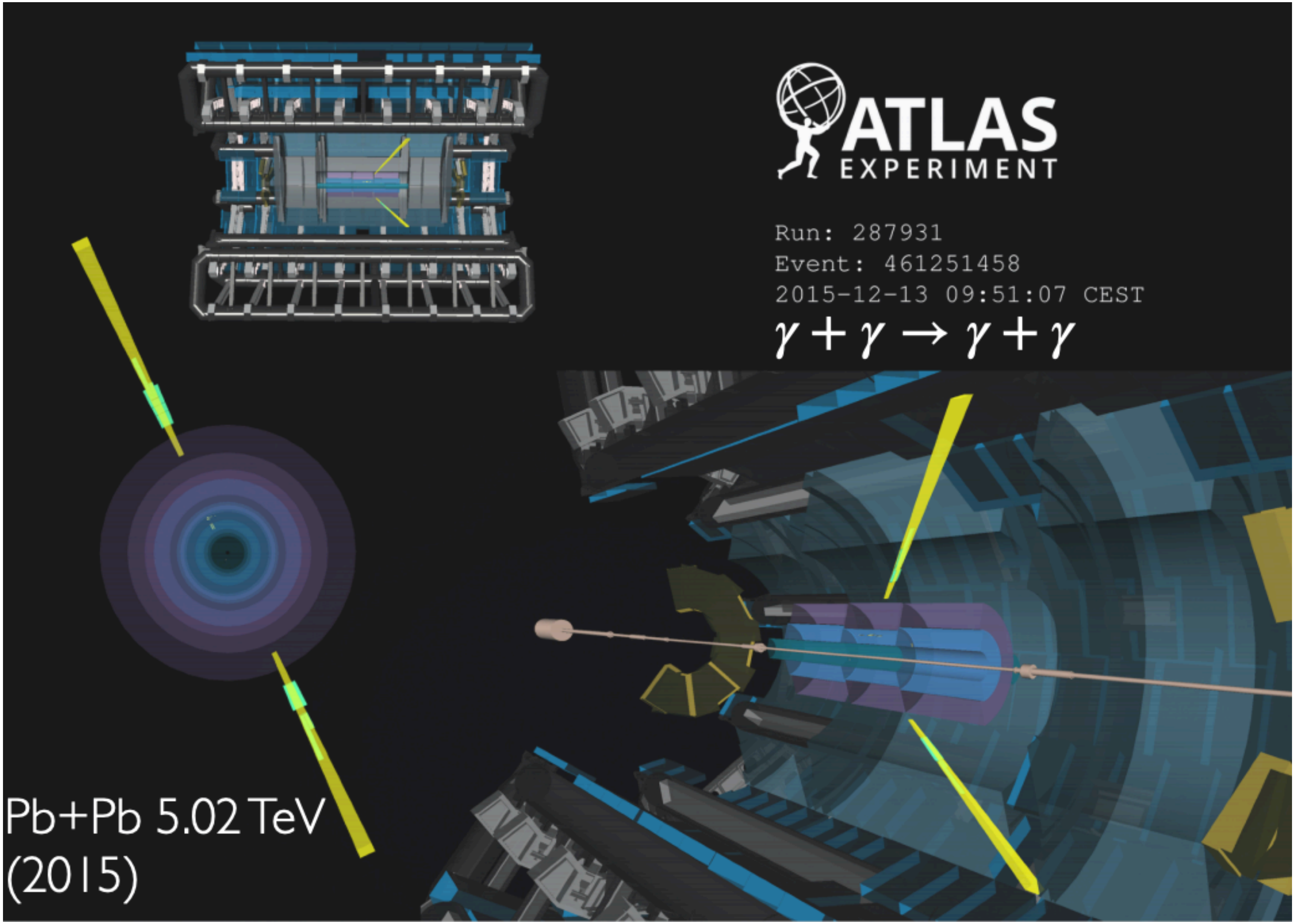
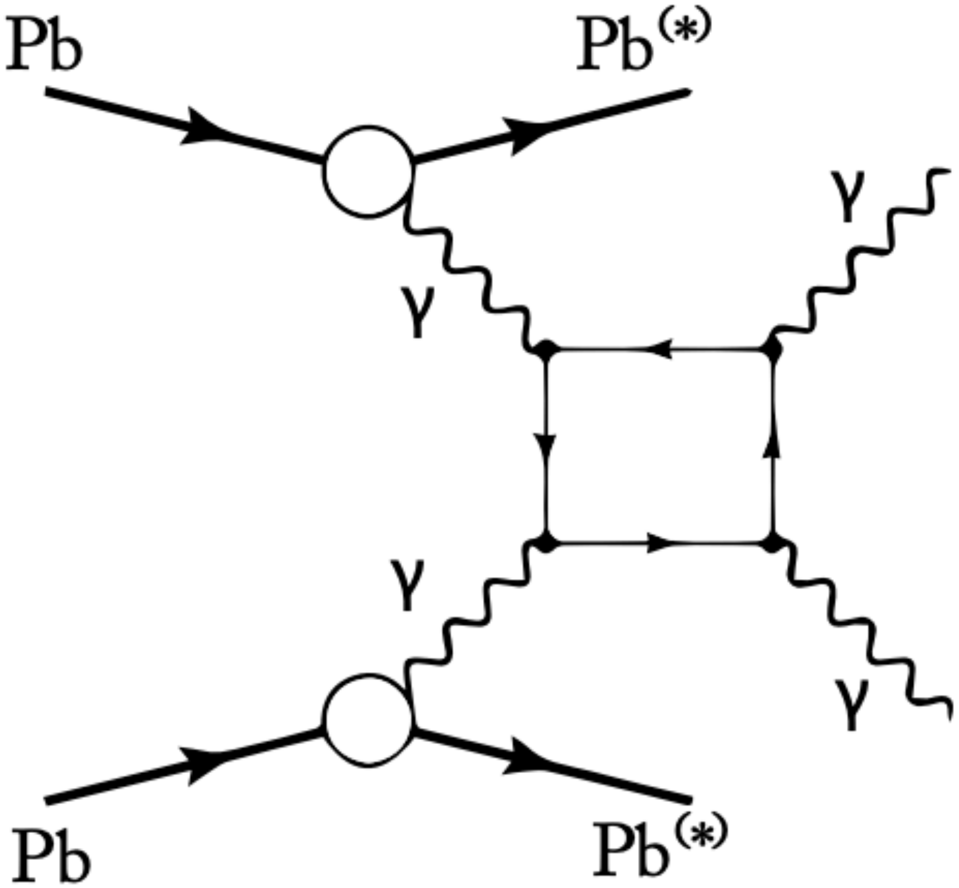
Data agrees with MC over most of acceptance

Next step: provide measurements that are <u>unfolded for detector response</u> and that can be compared directly to theoretical calculations

Nature Phys. 13 (2017) no.9, 852-858



Light-by-light scattering



Signal

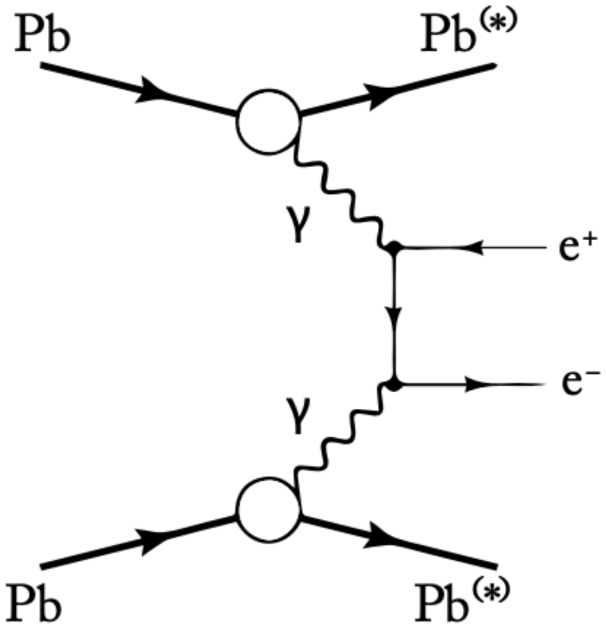
Main backgrounds

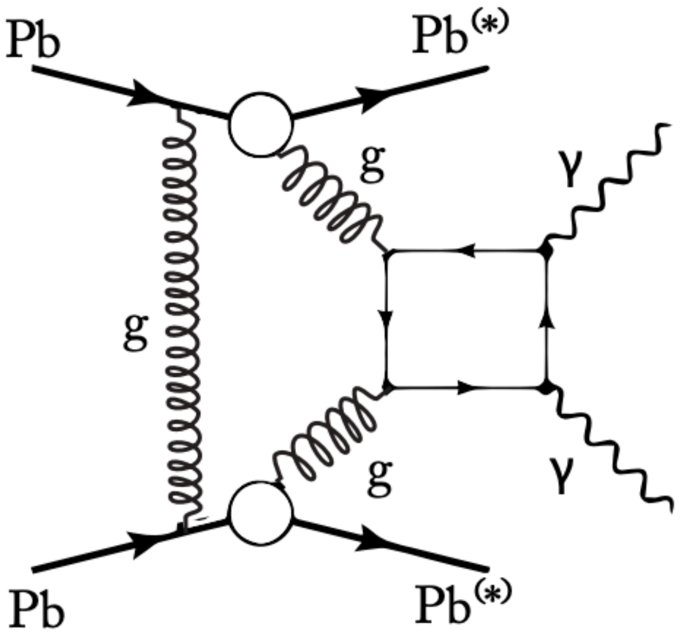
QED

two-photon process

CEP

Central Exclusive Productio

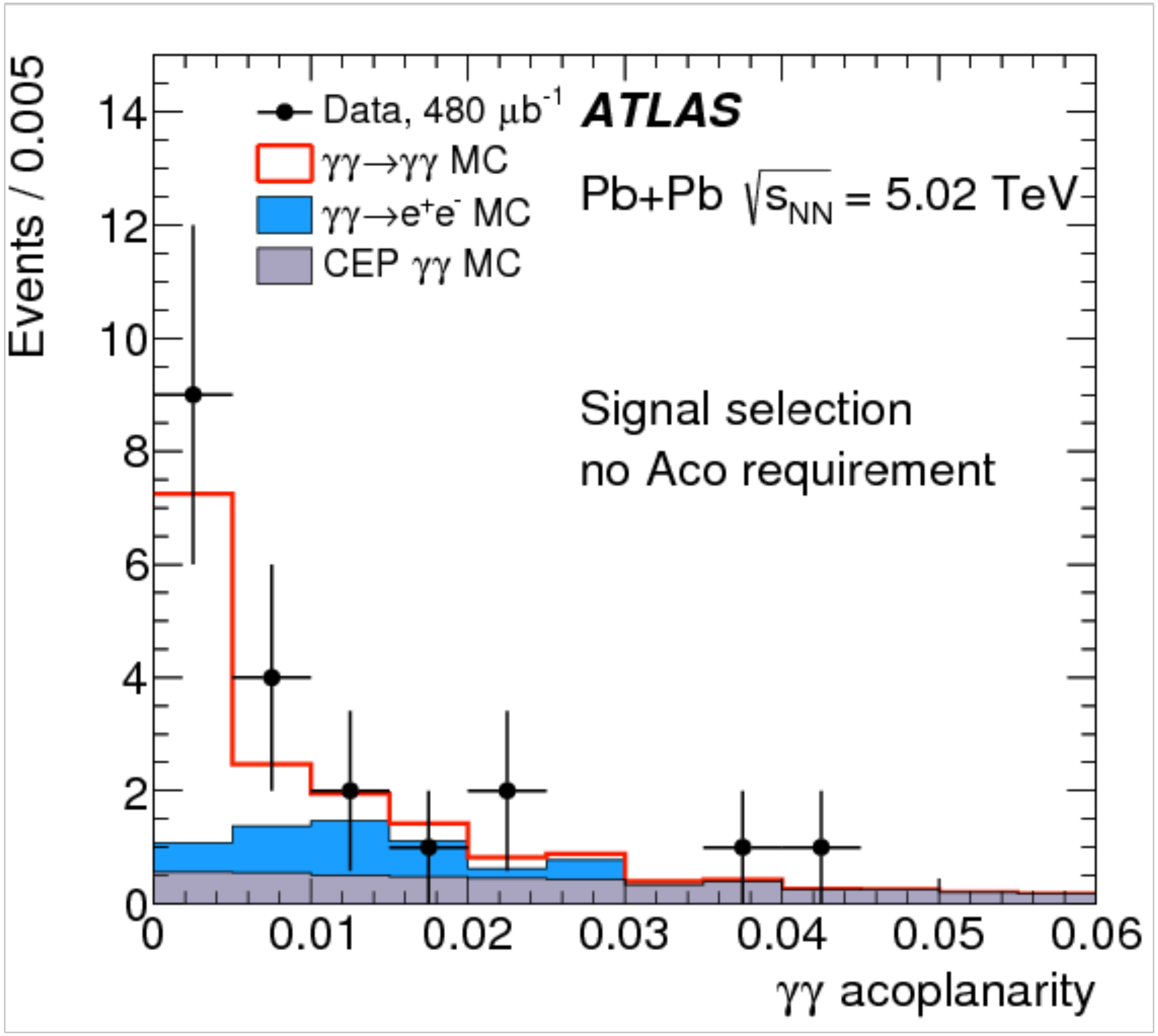




Light-by-light scattering
2015 PbPb data set

ATLAS Collaboration
Nature Phys. 13 (2017)
no.9, 852-858

4.4 σ significance



$E_T\gamma > 3$ GeV
$|\eta| < 2.37$

$M\gamma\gamma > 6$ GeV,

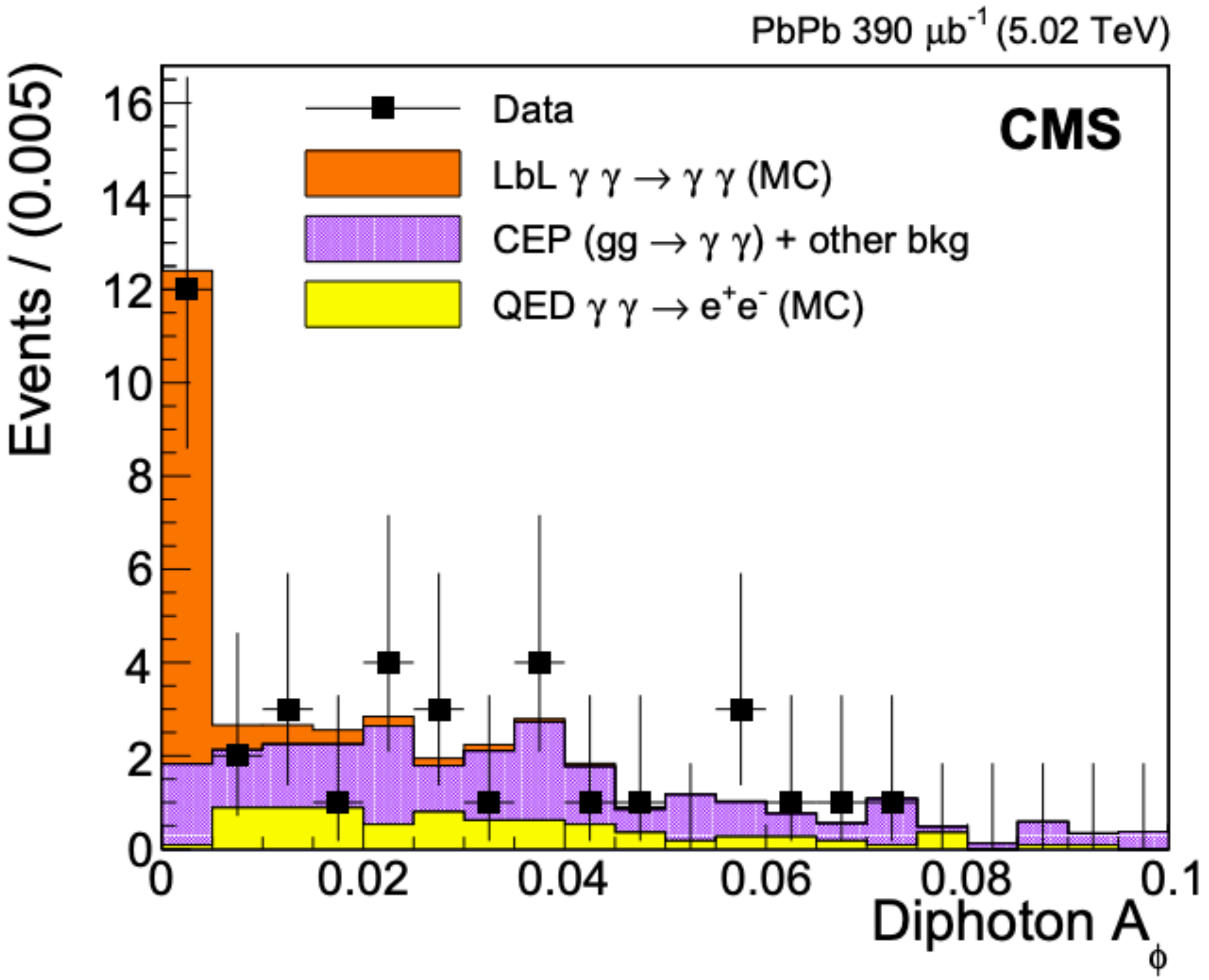
$p_T(\gamma\gamma) < 2$ GeV

Acoplanarity
$A_\phi < 0.01$

Light-by-light scattering
2015 PbPb data set

CMS Collaboration
arXiv:1810.04602
Submitted to PLB

4.1 σ significance



$E_T\gamma > 2$ GeV
$|\eta| < 2.4$

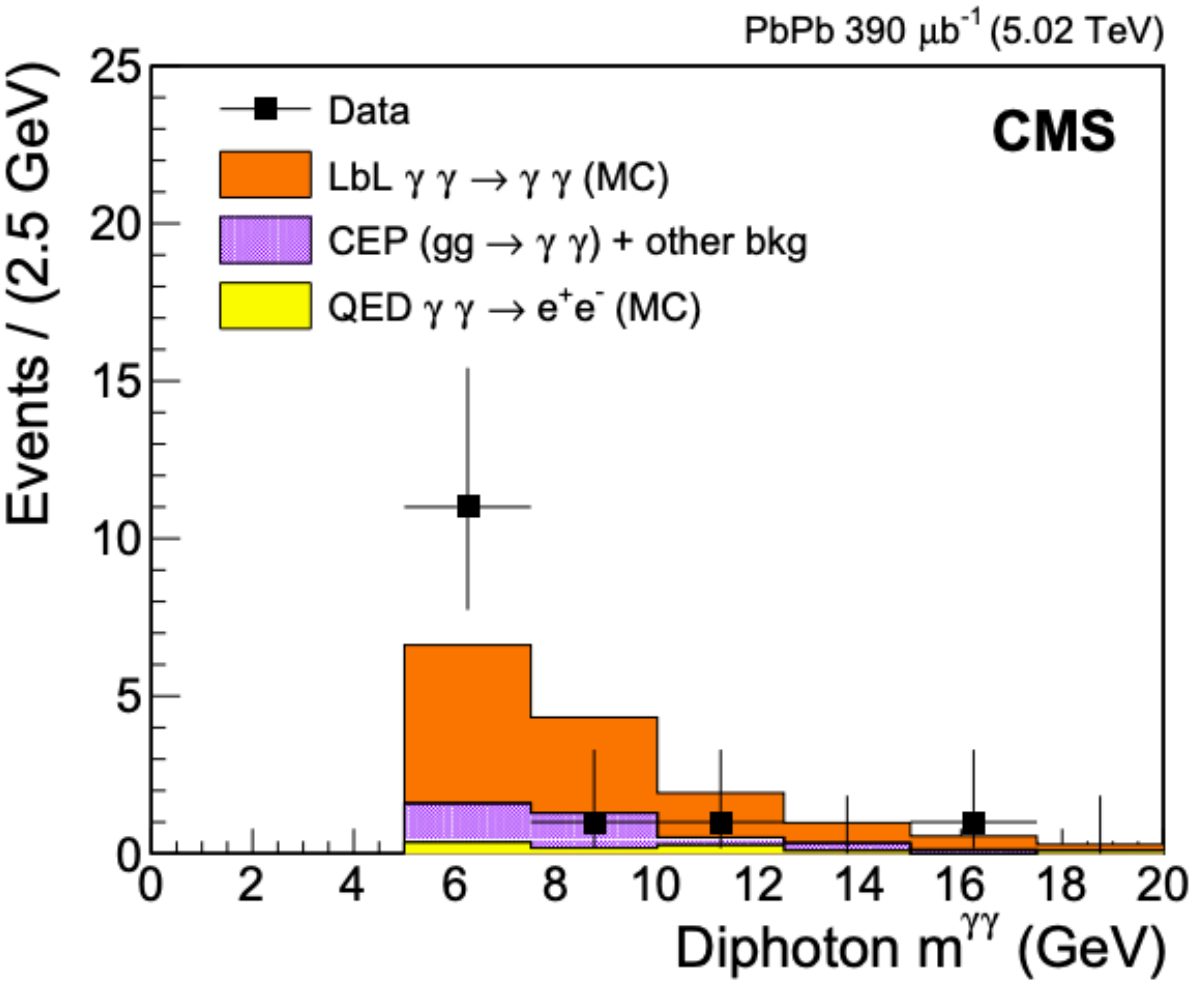
$M\gamma\gamma > 5$ GeV,

$p_T(\gamma) < 1$ GeV

Acoplanarity
$A_\phi < 0.01$

Light-by-light scattering
2015 PbPb data set

CMS Collaboration
arXiv:1810.04602
Submitted to PLB

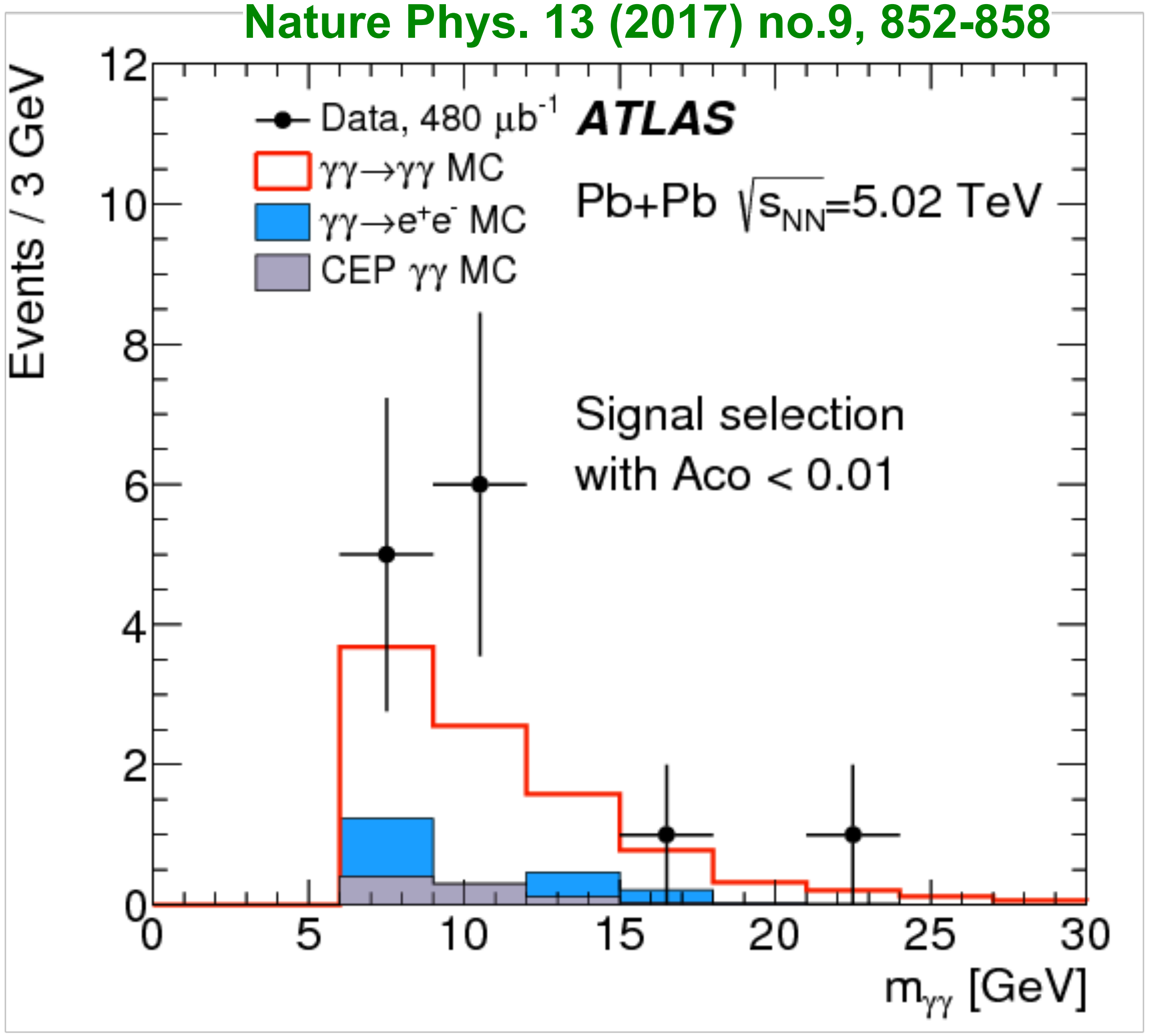


Evidence for light-by-light scattering

4.1 (4.4)σ observed (expected)

14 LbyL events observed -
consistent with the SM prediction

ATLAS Collaboration
Nature Phys. 13 (2017) no.9, 852-858



Evidence for light-by-light scattering

4.4 σ observed

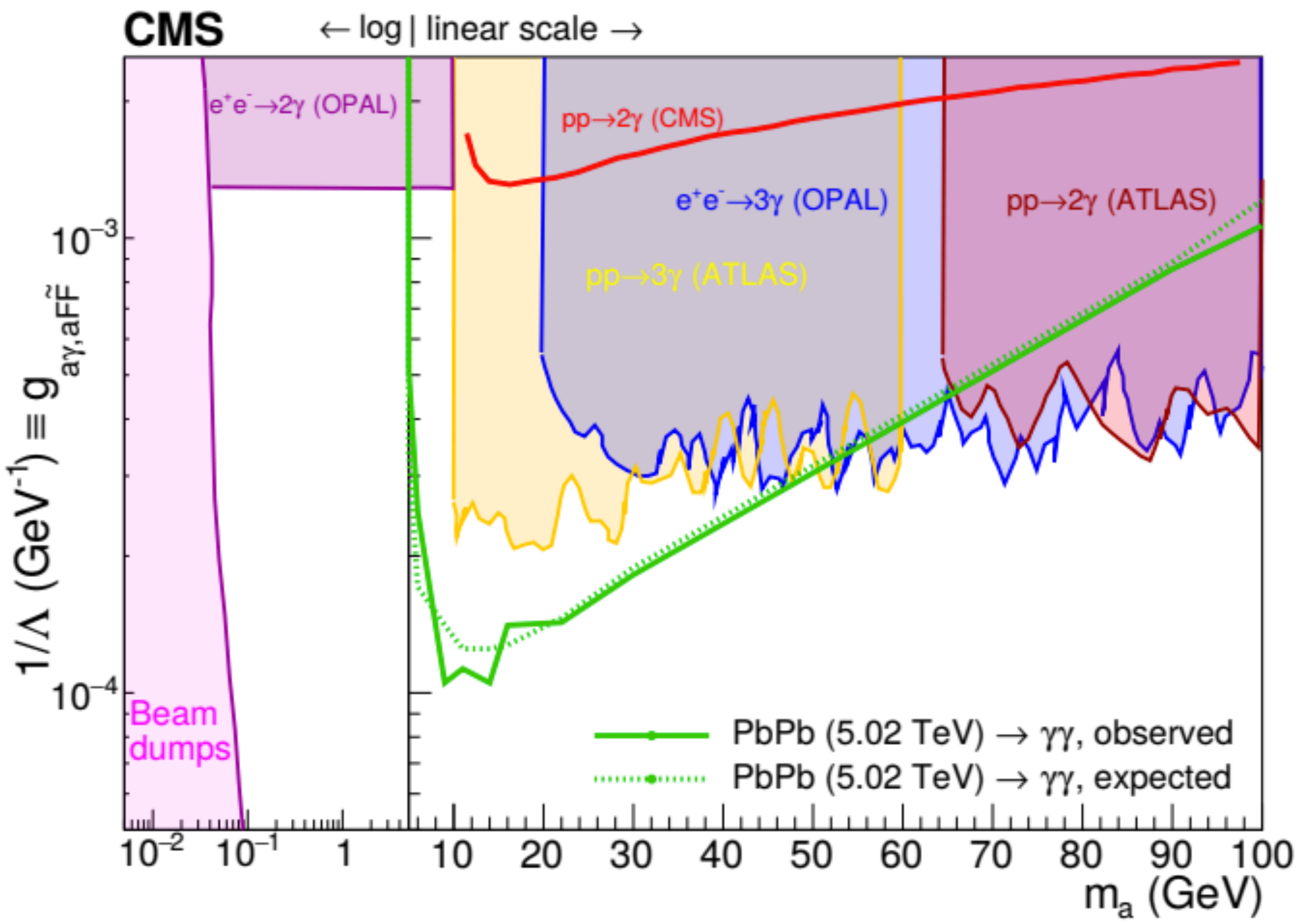
13 LbyL events observed -
2.6 ± 0.7 expected background

Axion-Like Particle Limits (ALP)

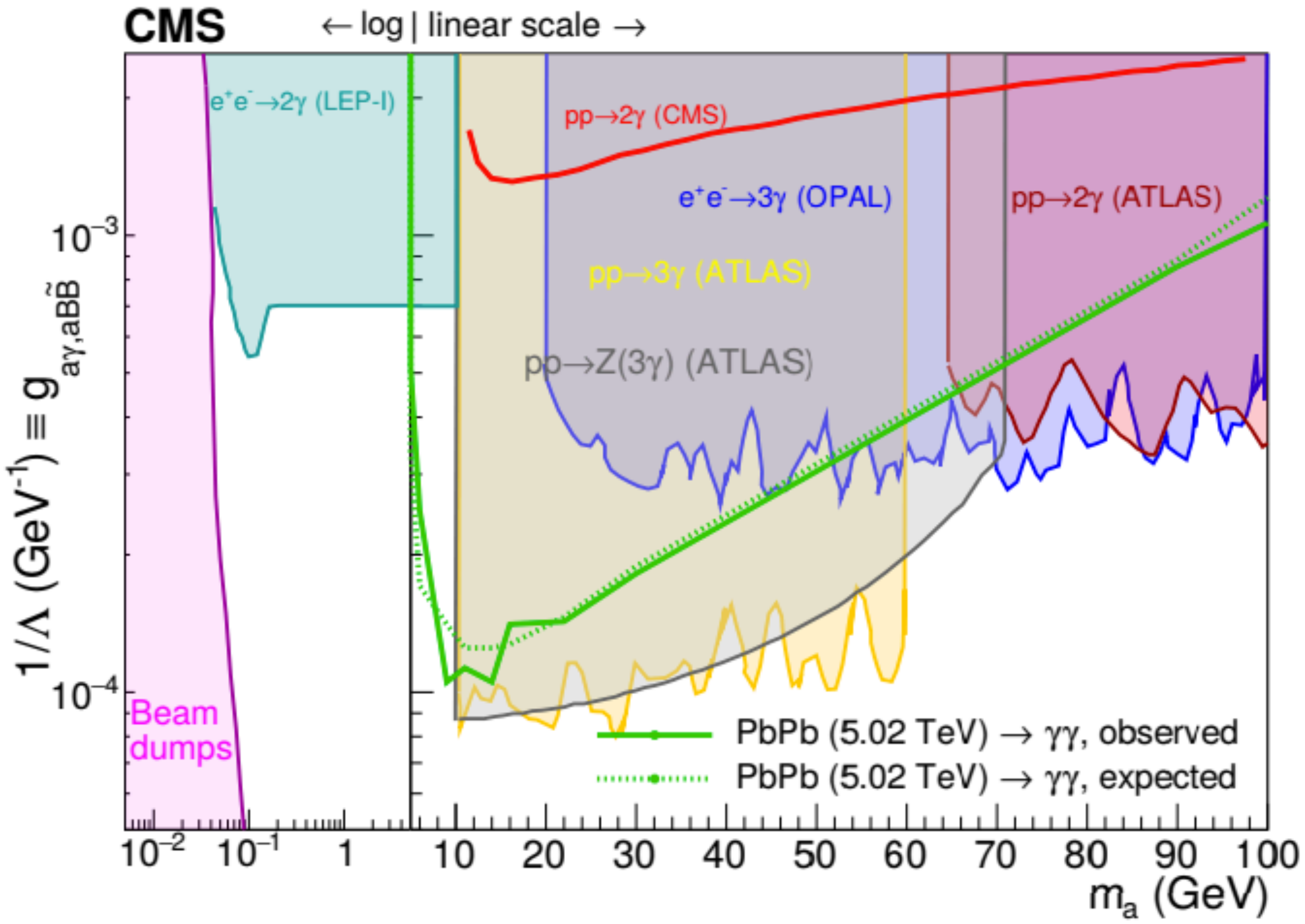
Light-by-light scattering - 2015 PbPb data set

CMS Collaboration
arXiv:1810.04602
Submitted to PLB

ALP coupling to photons only



ALP coupling to photons or hypercharge

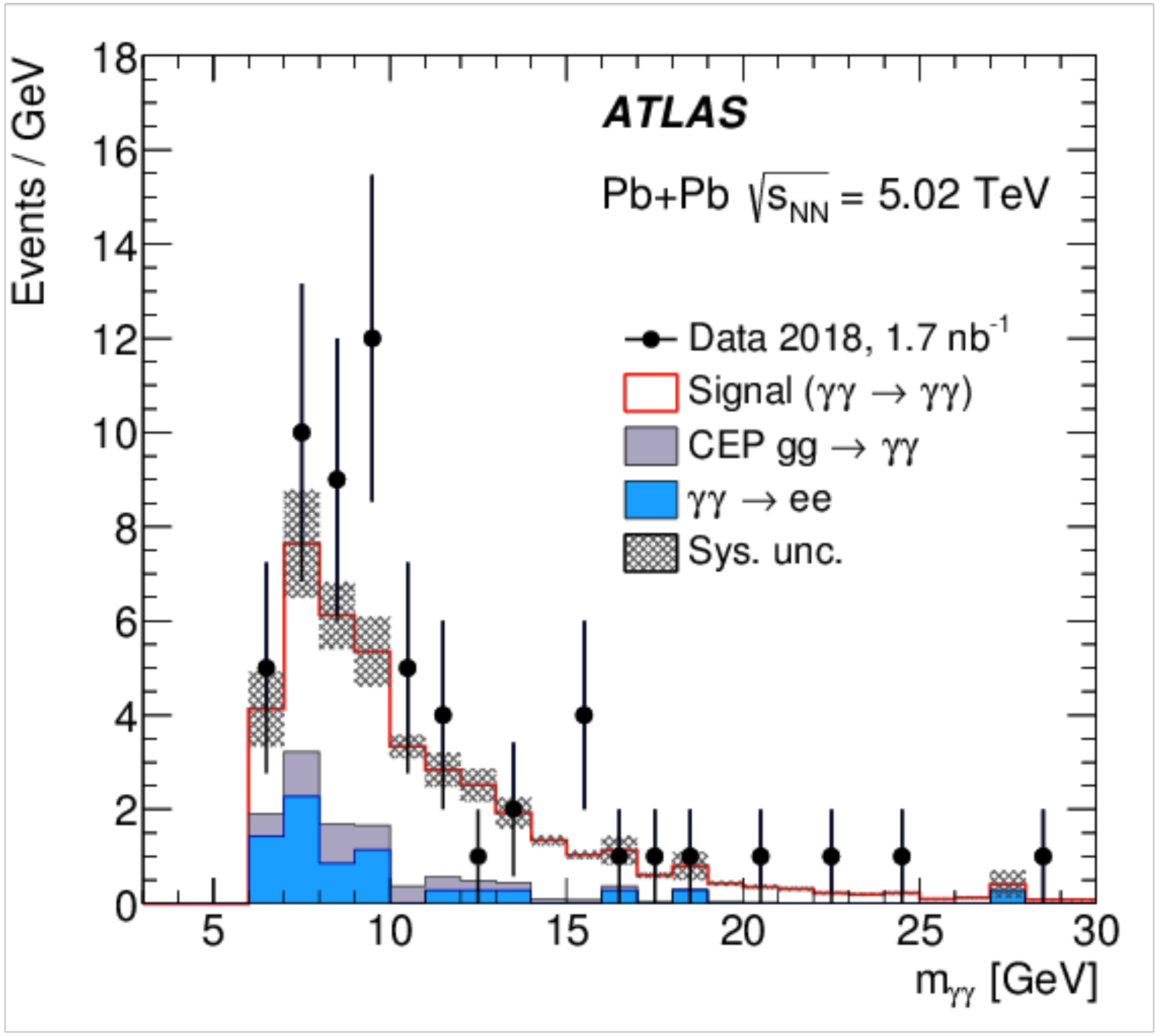


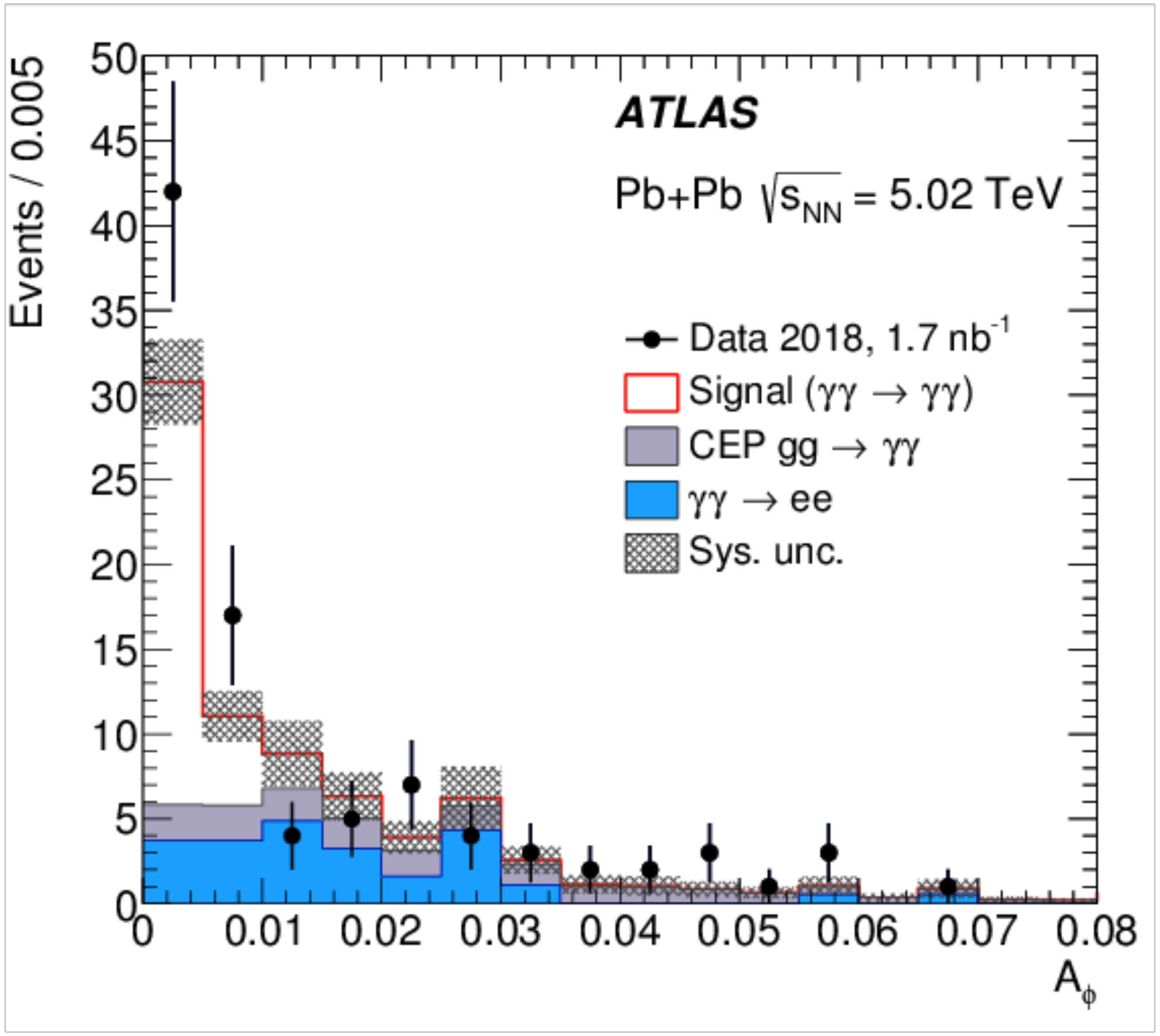
No significant excess observed

First observation - **2018 PbPb data set**
Light-by-light scattering

8.8 σ observation

ATLAS Collaboration
arXiv:1904.03536
Submitted to PRL





59 candidates out of 12 ± 3 expected background