Workshop: Open questions in photon-induced interactions from relativistic nuclear collisions to the future EIC
April 26-28, 2021, Online meeting.

Vector Meson photoproduction in UPCs at the LHC

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Czech Technical University in Prague

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Some nice results from pp not mentioned

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Main focus on ALICE results … not all existing measurement are discussed …

Vector Meson photoproduction in UPCs at the LHC

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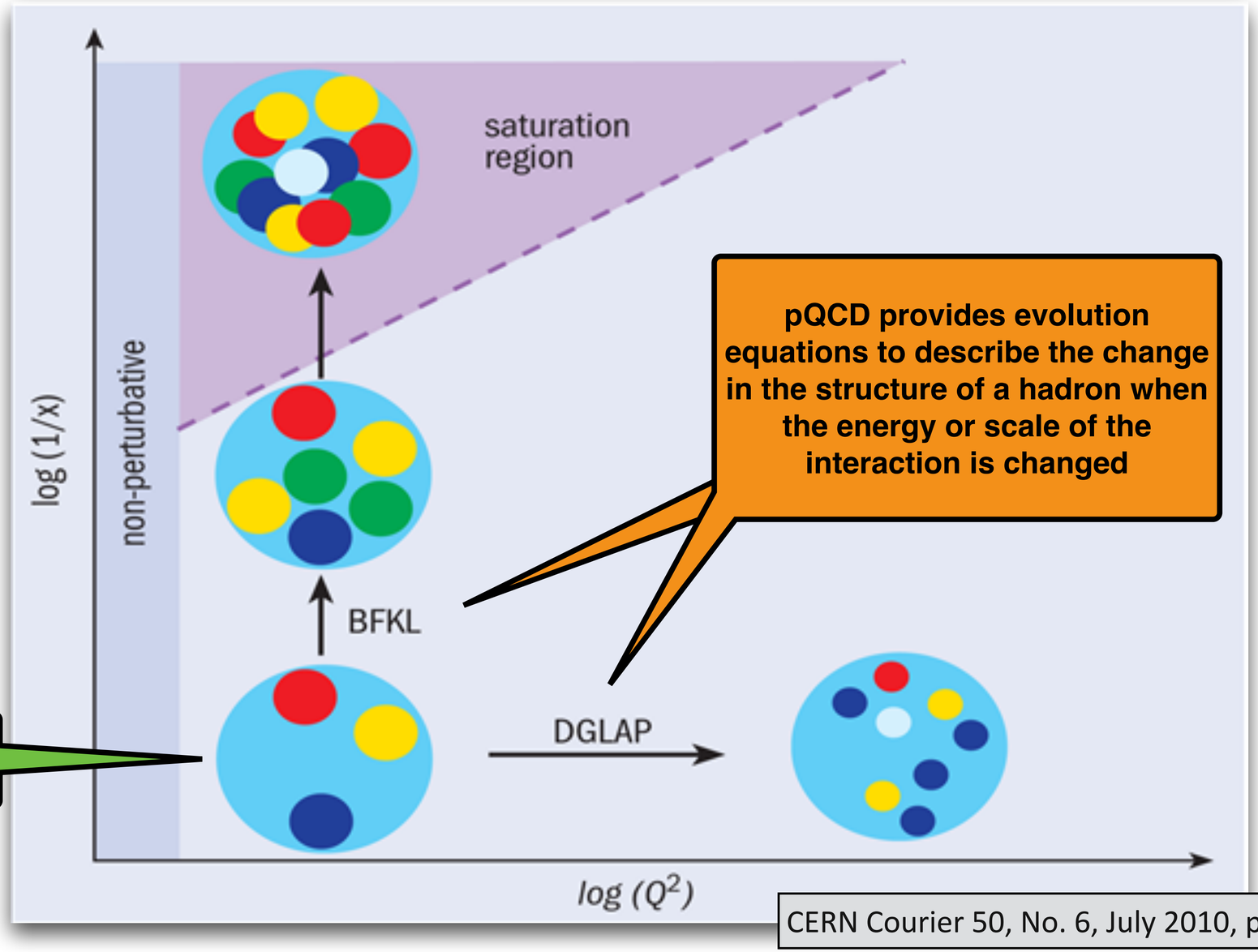
The physics we are interested in (in a nutshell)

pQCD



pQCD provides evolution equations to describe the change in the structure of a hadron when the energy or scale of the interaction is changed

Quarks and gluons bound in hadrons

CERN Courier 50, No. 6, July 2010, p.24

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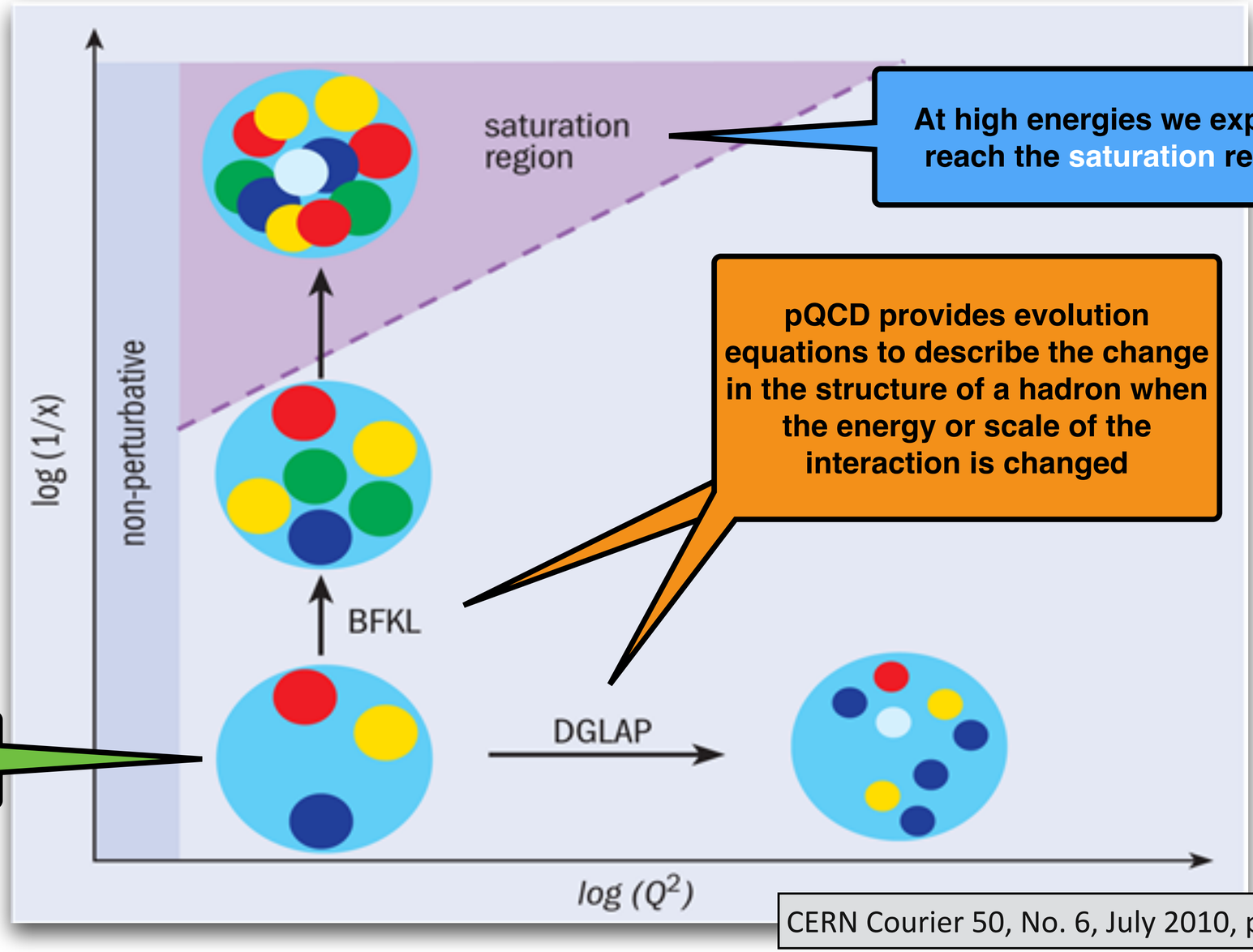

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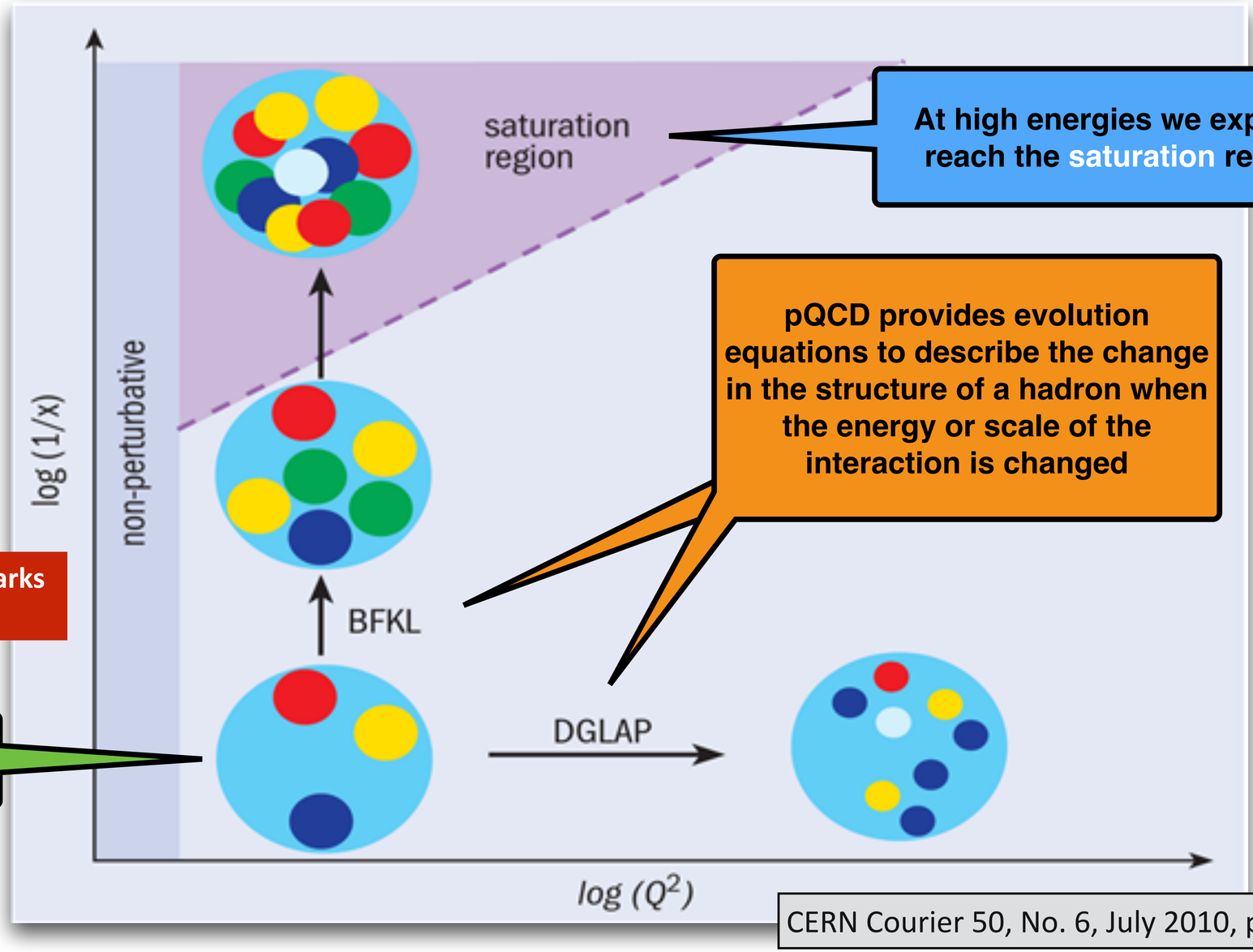
Measure the structure of hadrons in terms of quarks and gluons at different scales and energies



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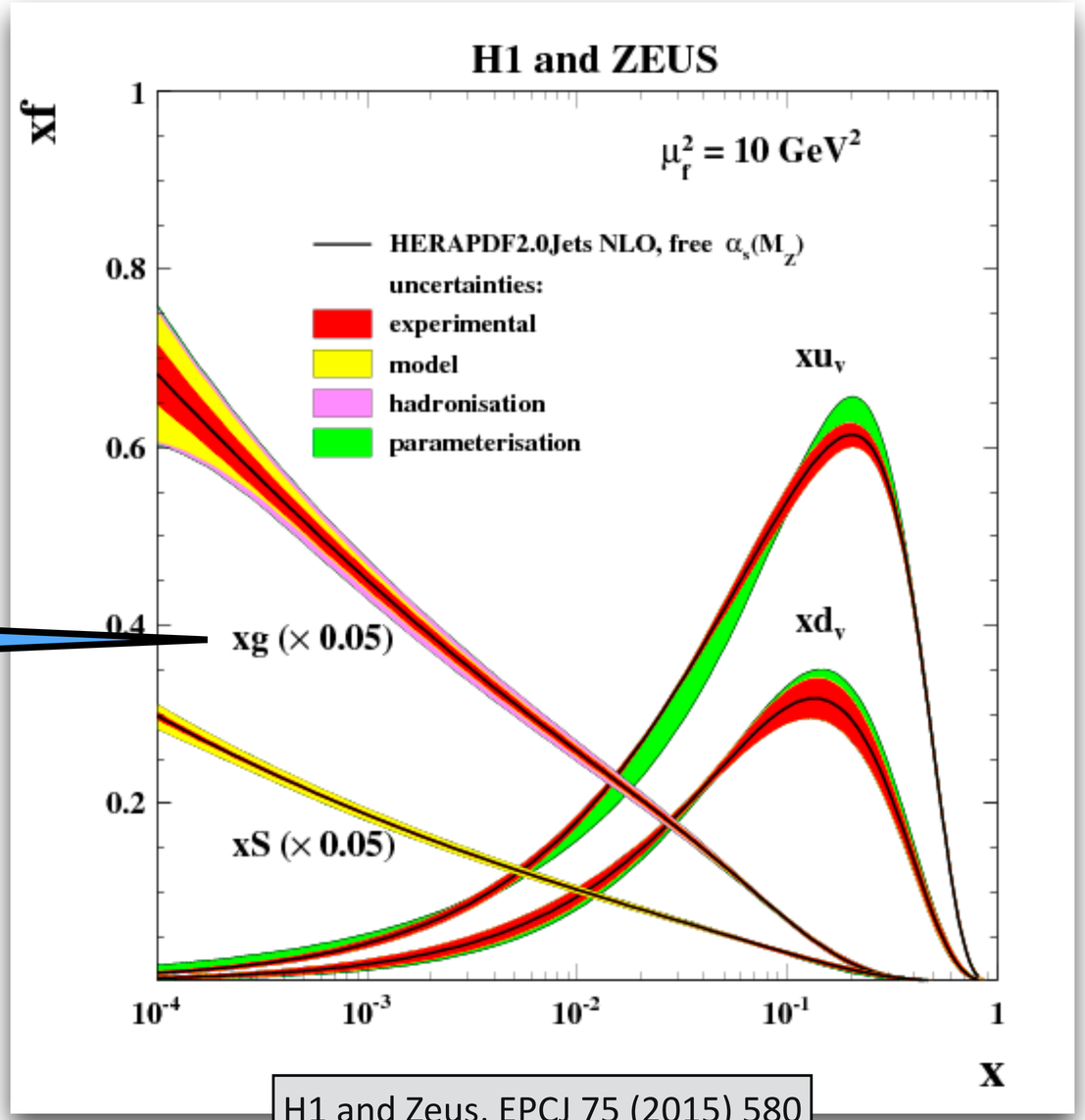
What do we know about the physics we are interested in ? (In a nutshell)

The gluon distribution in the proton dominates for decreasing x where it grows as a power law

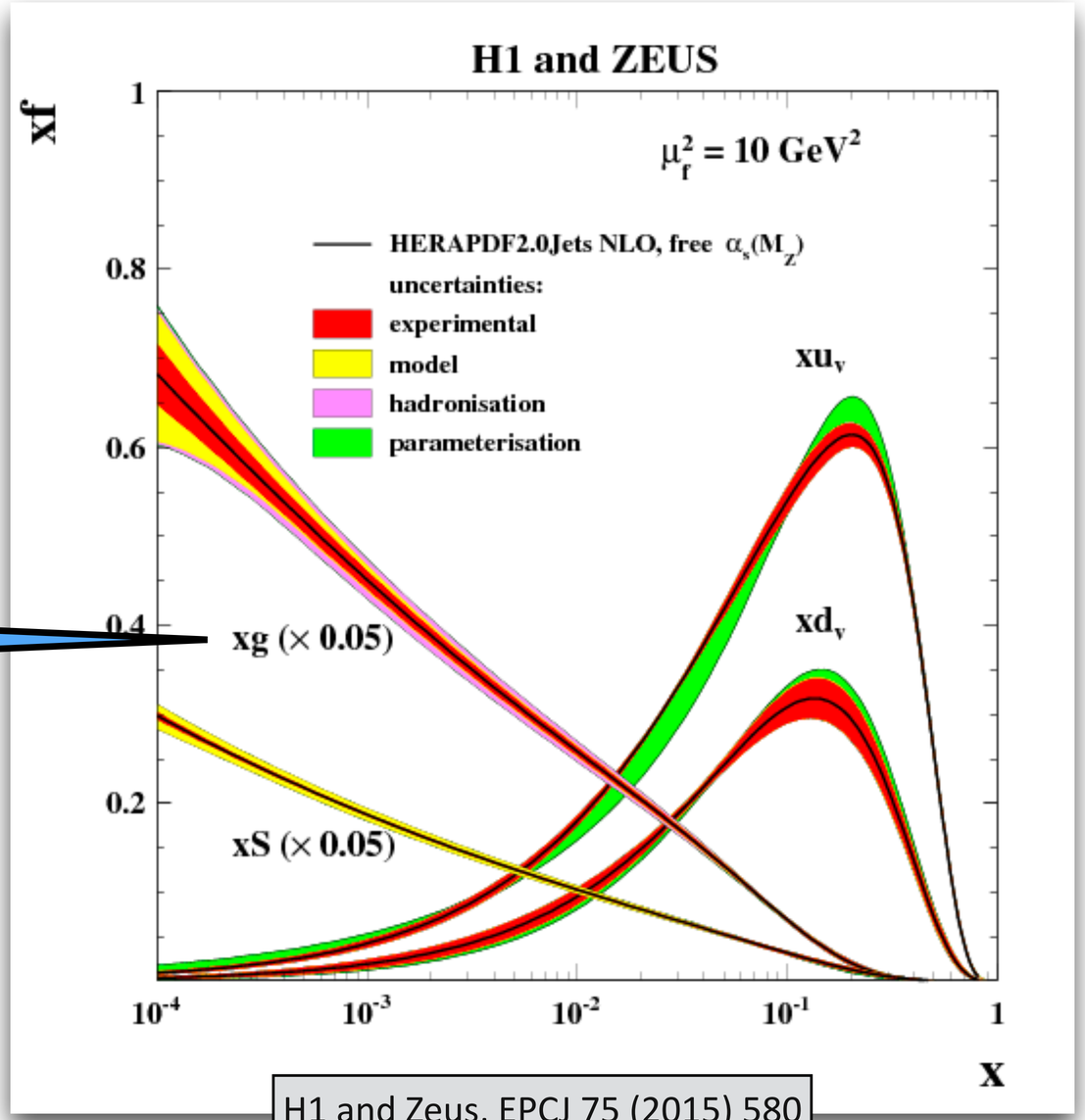


H1 and Zeus, EPCJ 75 (2015) 580

What do we know about the physics we are interested in ? (In a nutshell)

The gluon distribution in the proton dominates for decreasing x where it grows as a power law

Concentrate on processes highly sensitive to the gluon content in hadrons



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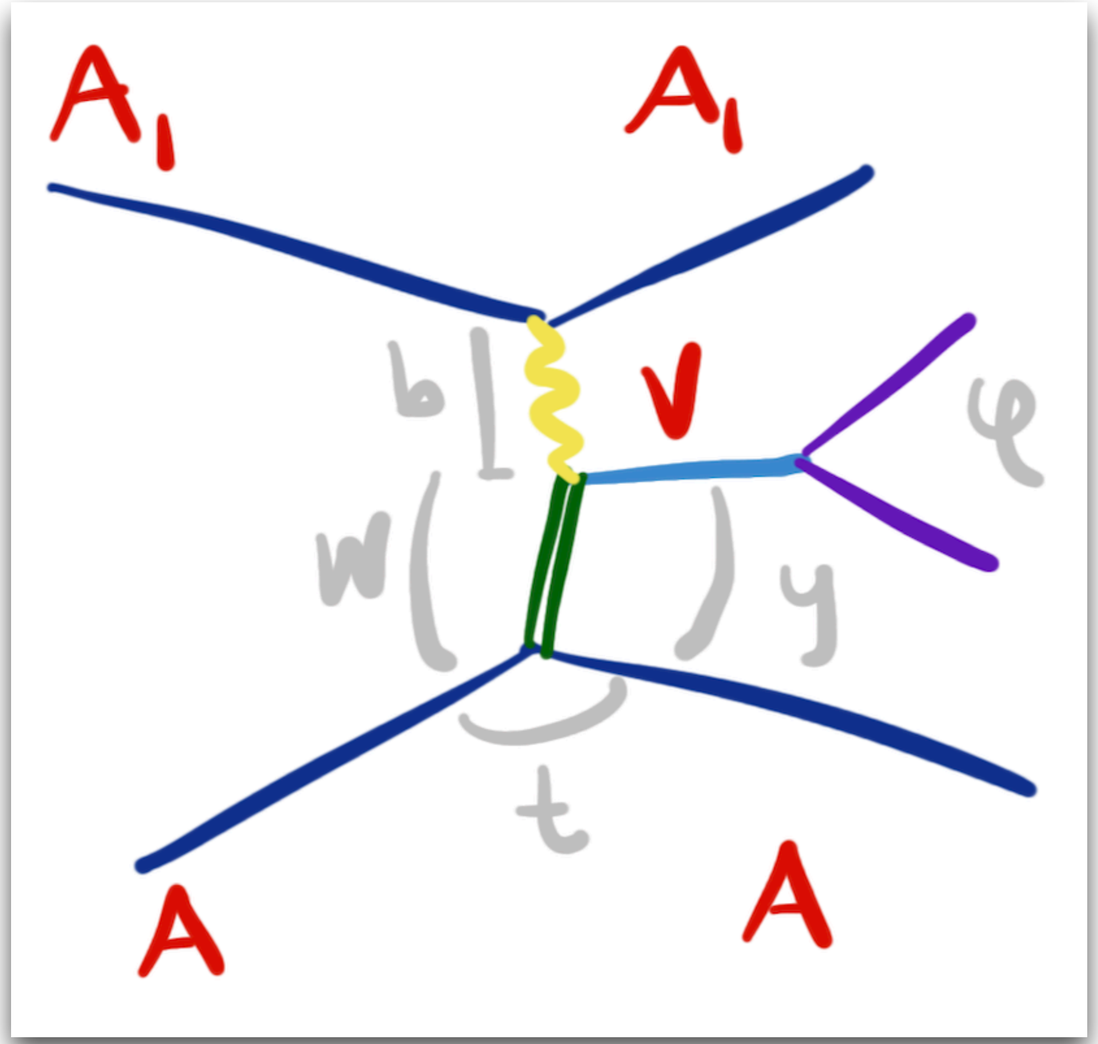

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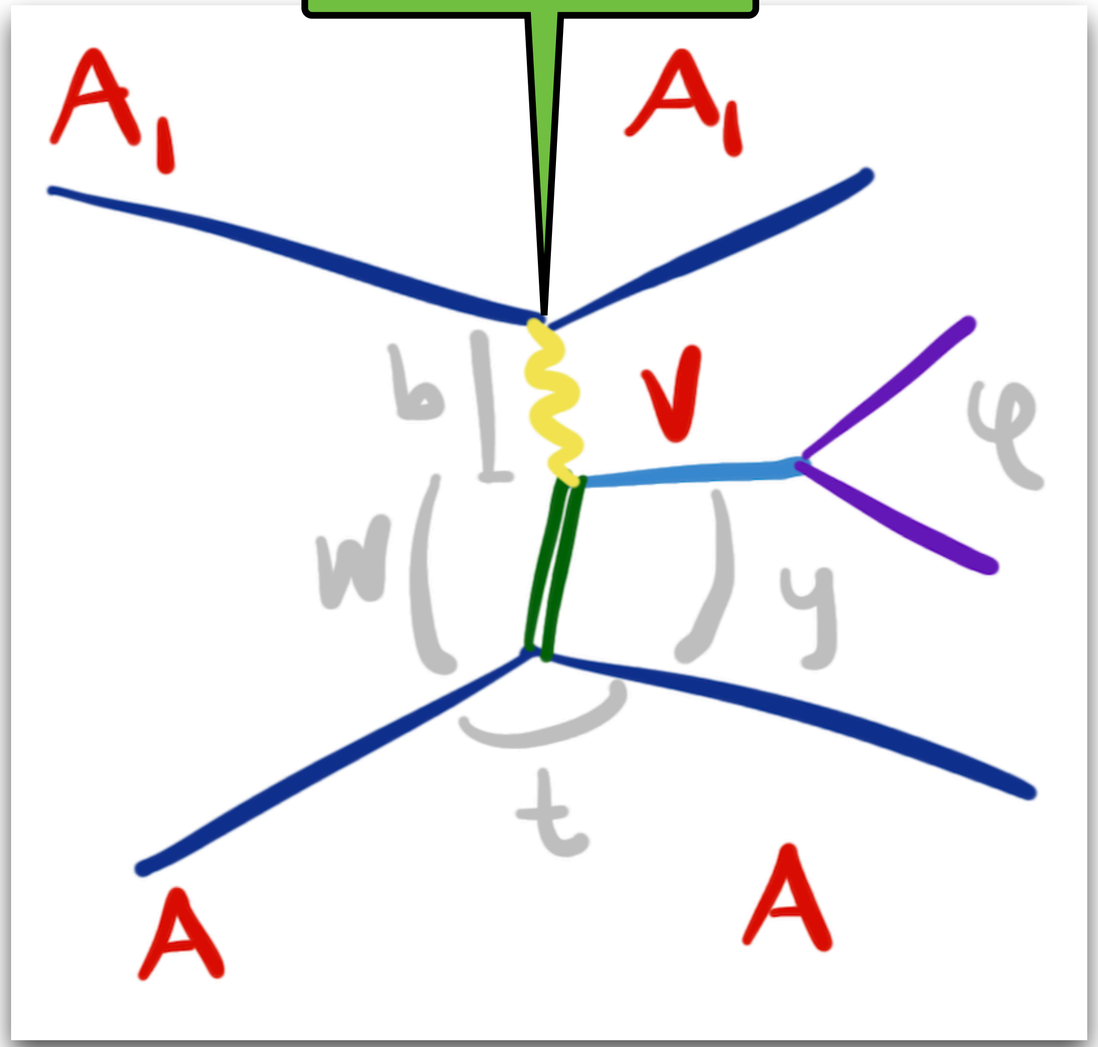
Interesting recent developments not covered here

QED is in here



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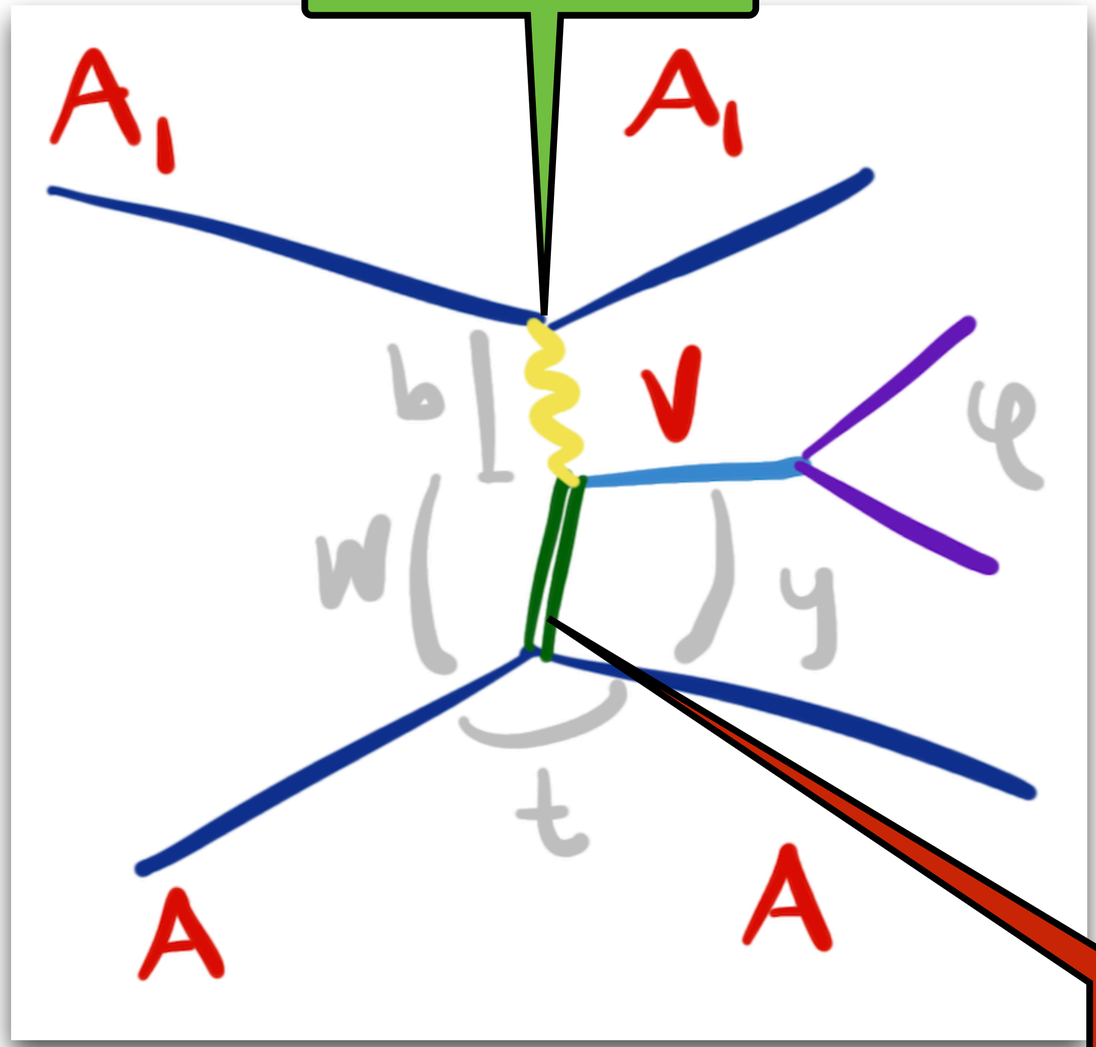

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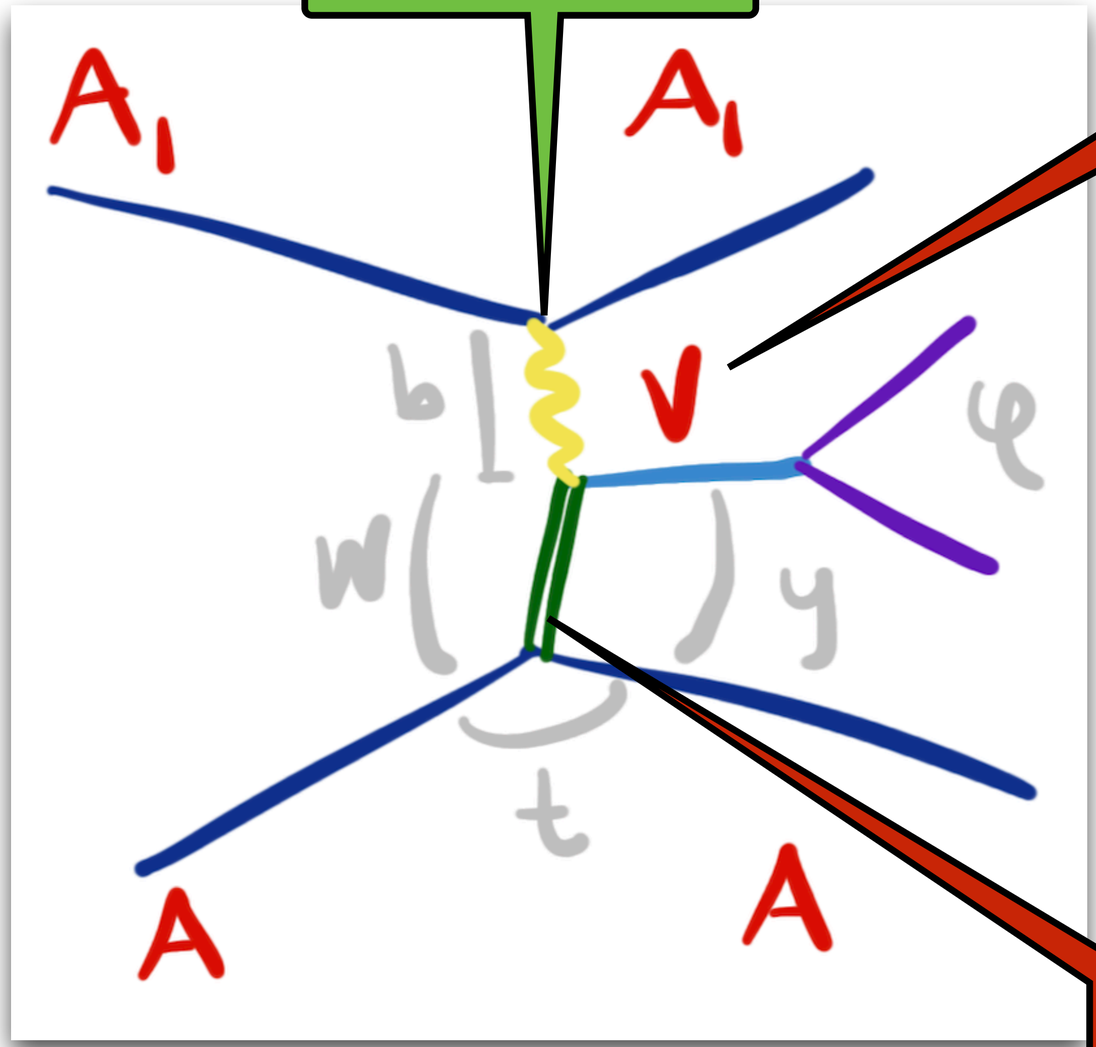

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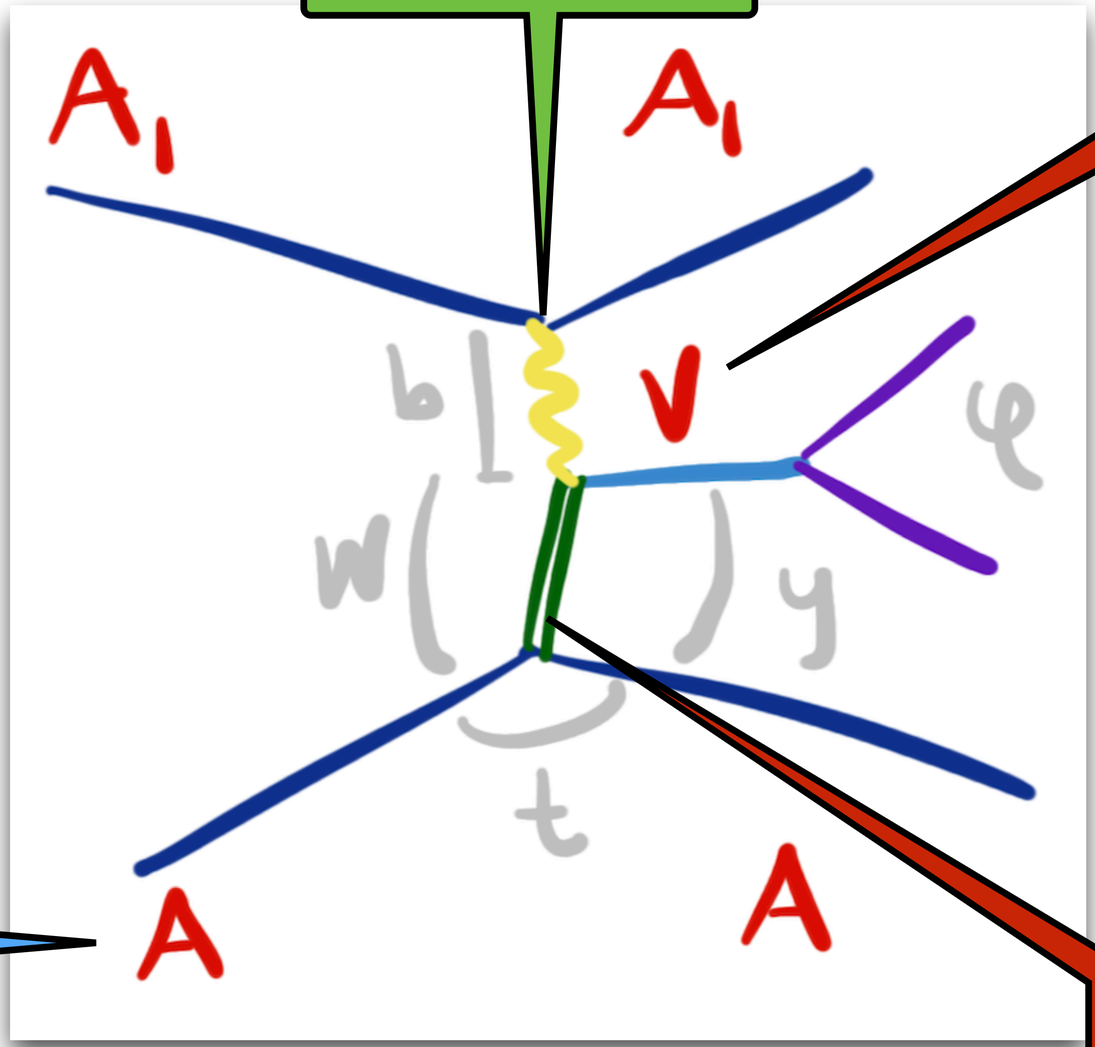

At the LHC A=p, Pb or Xe

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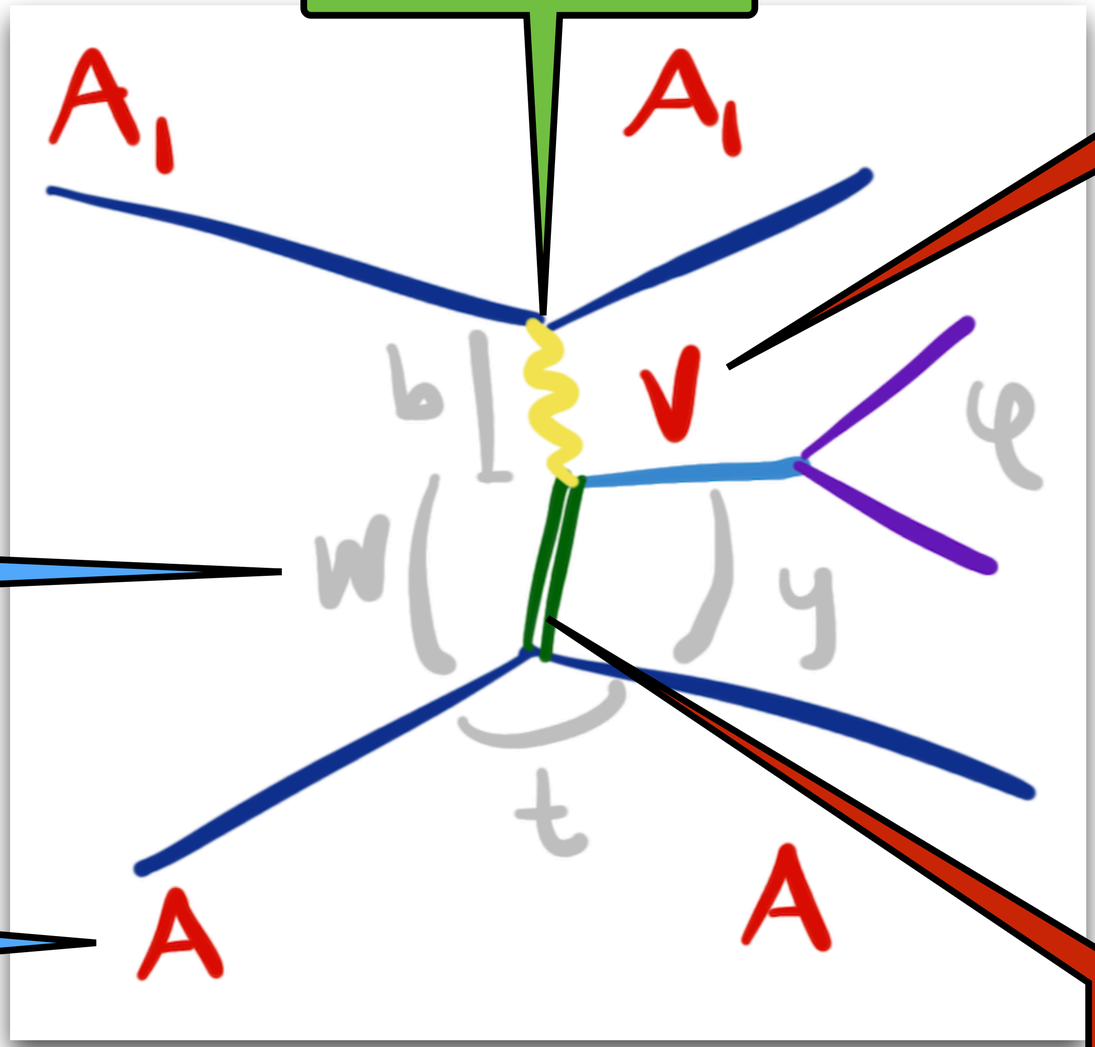

At the LHC W
up to ~1 TeV in γp
and
up to ~0.5 TeV in γPb

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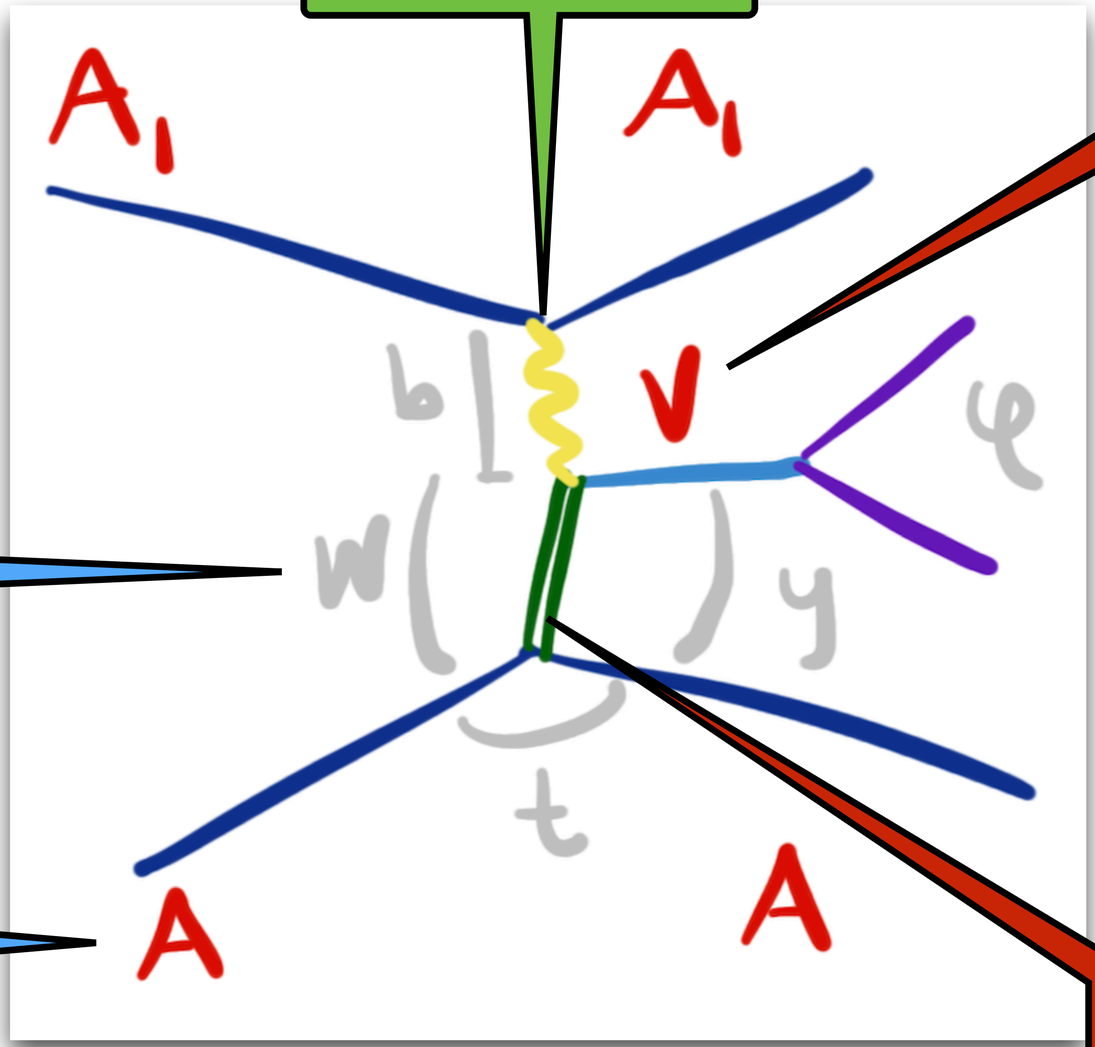
Current measurements based in a few hundreds to few thousand events.



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Run 3+4

Millions or even billions events expected In Run 3+4

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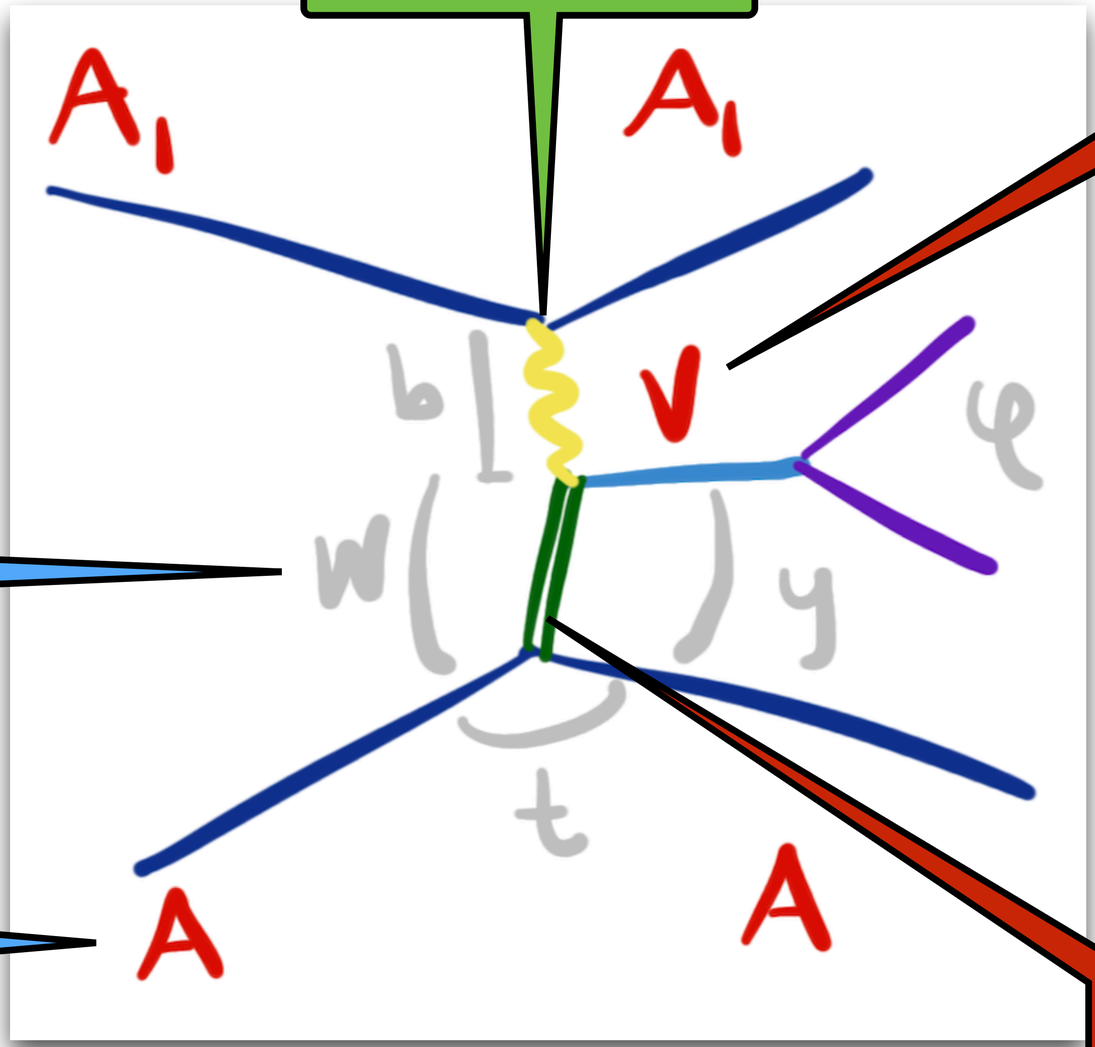

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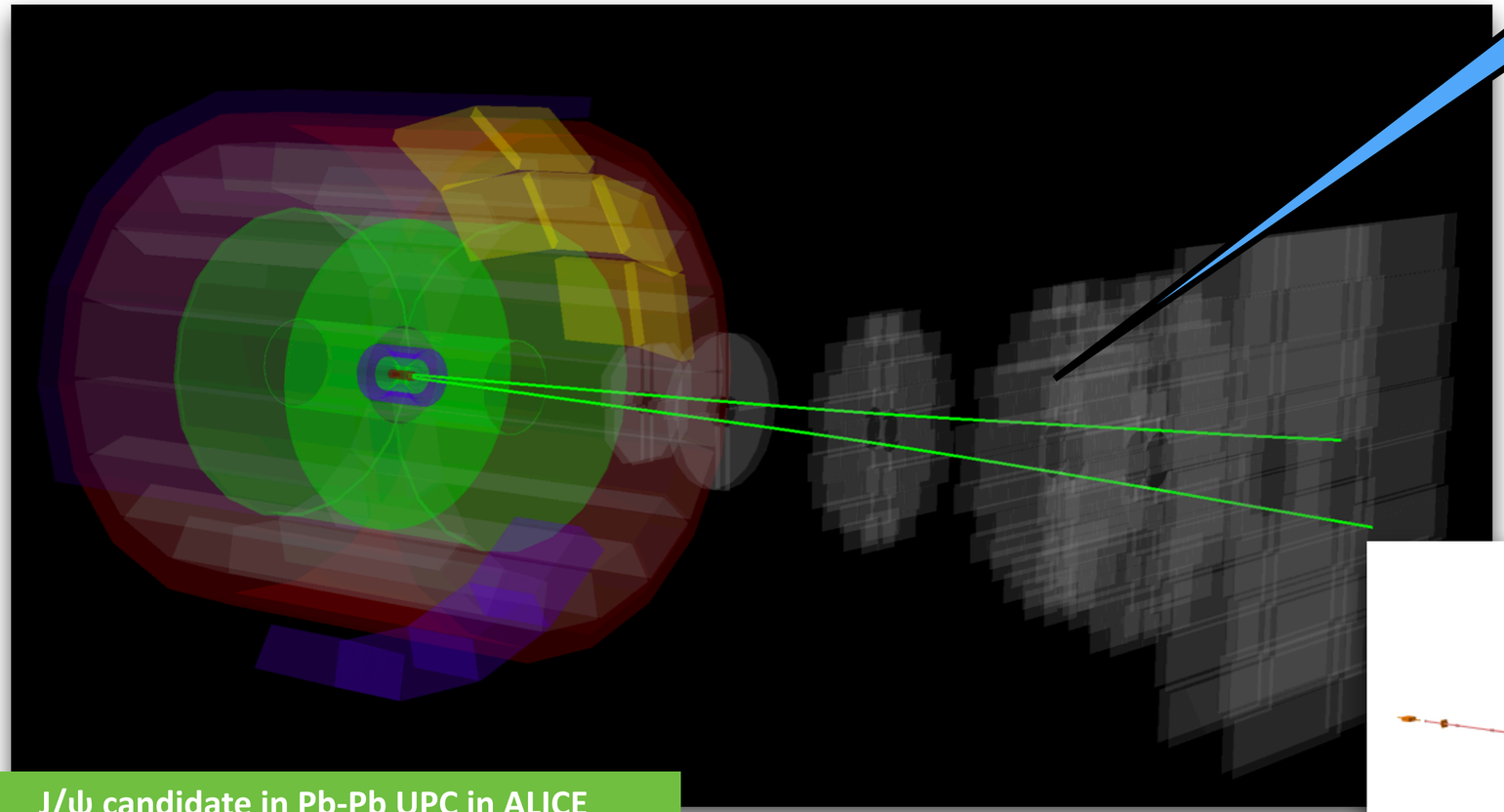
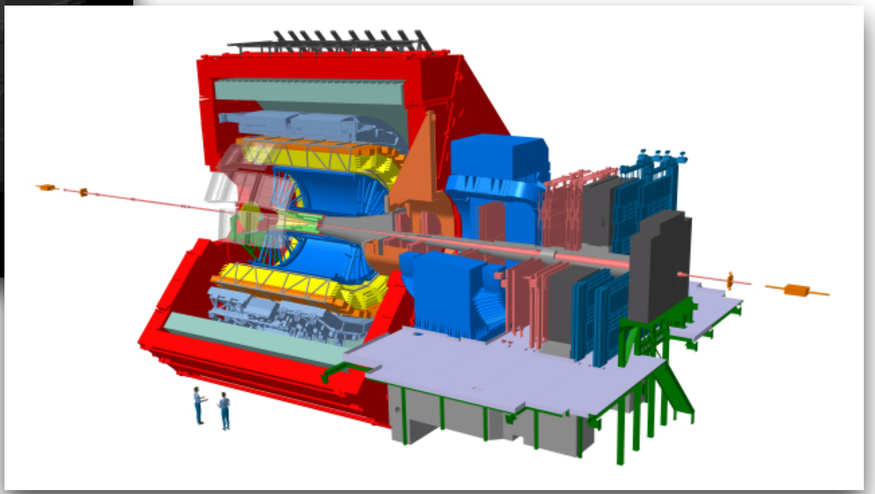
How does this process looks like in reality?

Two muons from the decay of the J/ψ and nothing else



J/ψ candidate in Pb-Pb UPC in ALICE



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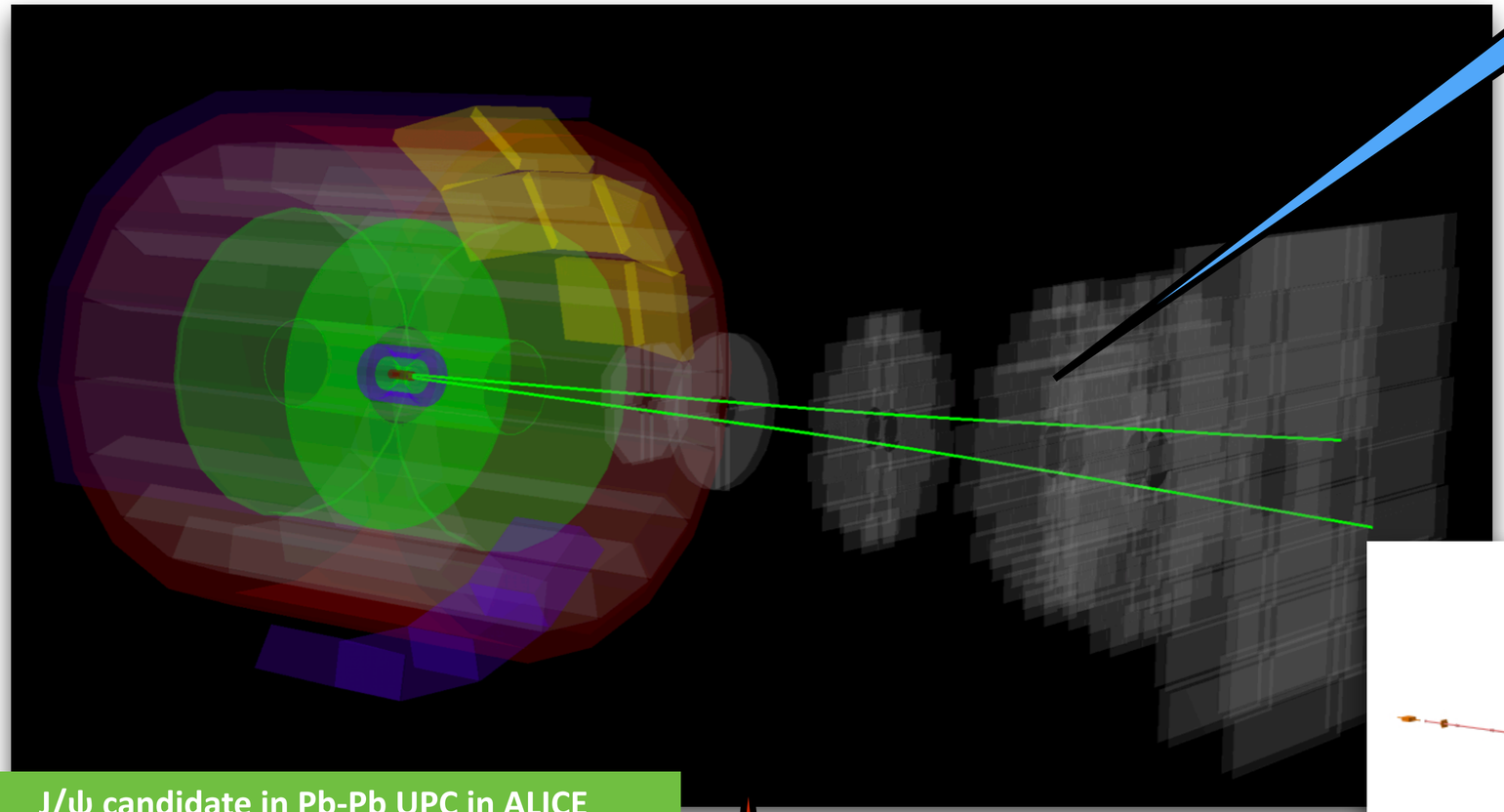

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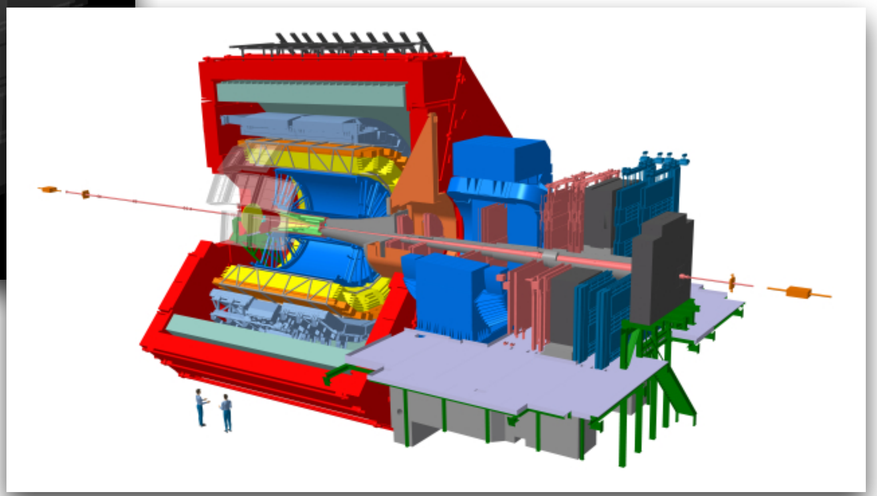

Open question:
How to trigger/select these events?

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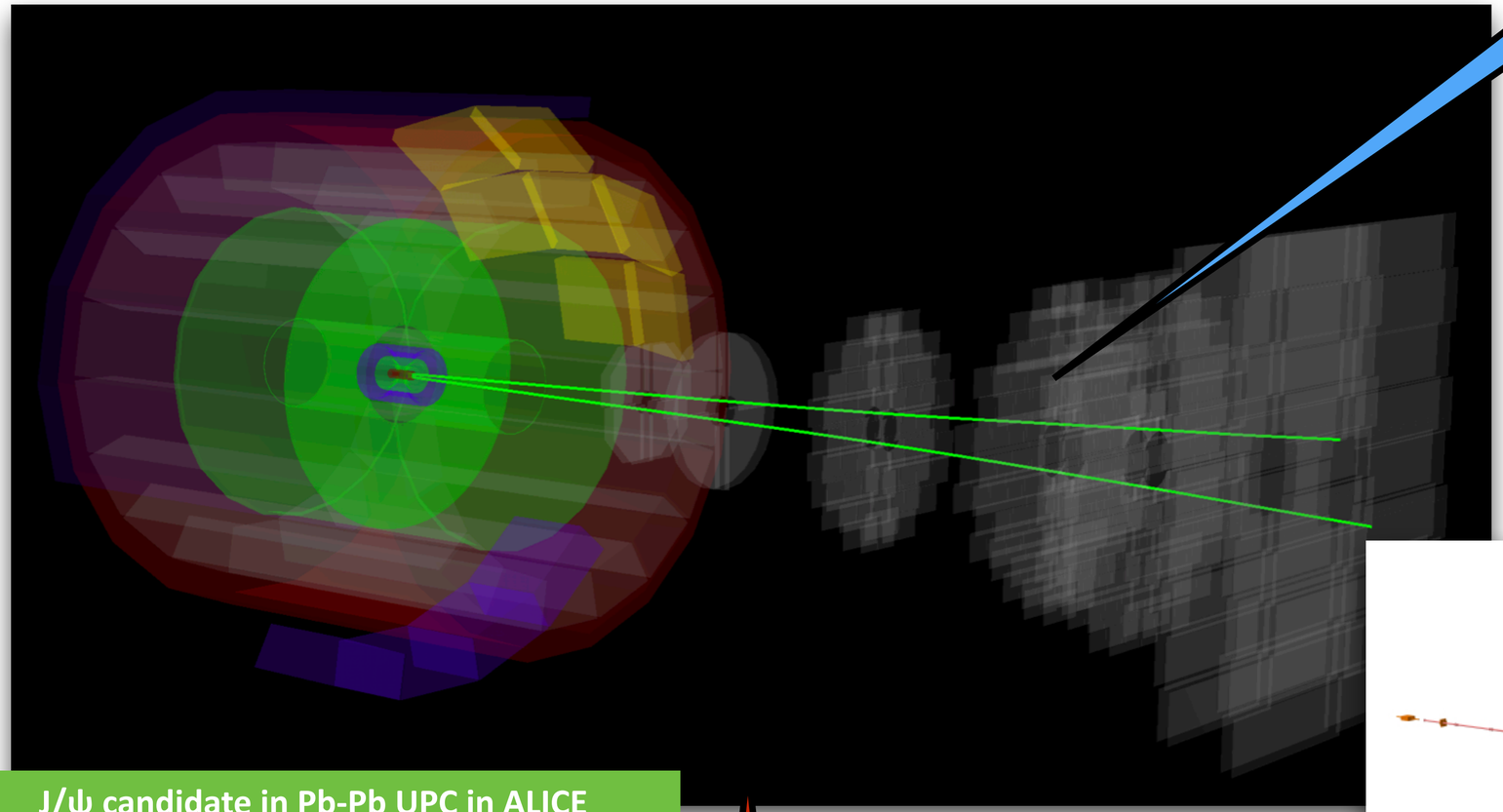
Open question:
How to ensure ‘nothing else’?



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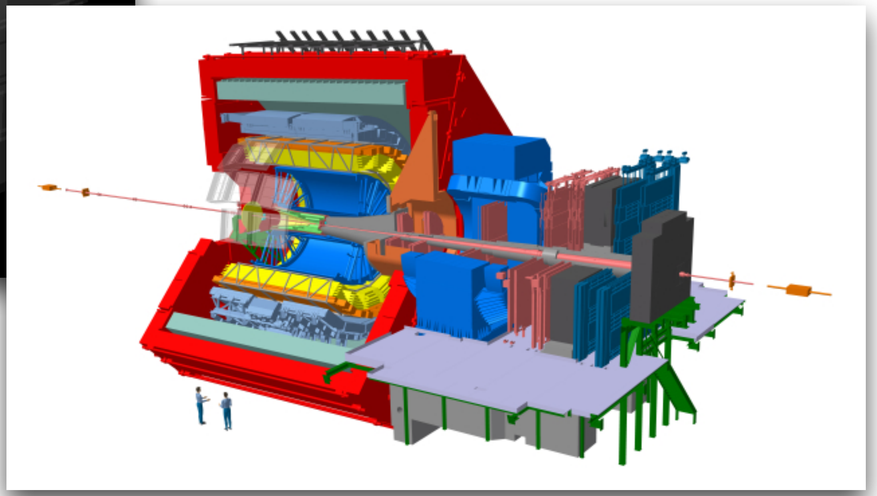

Open question:
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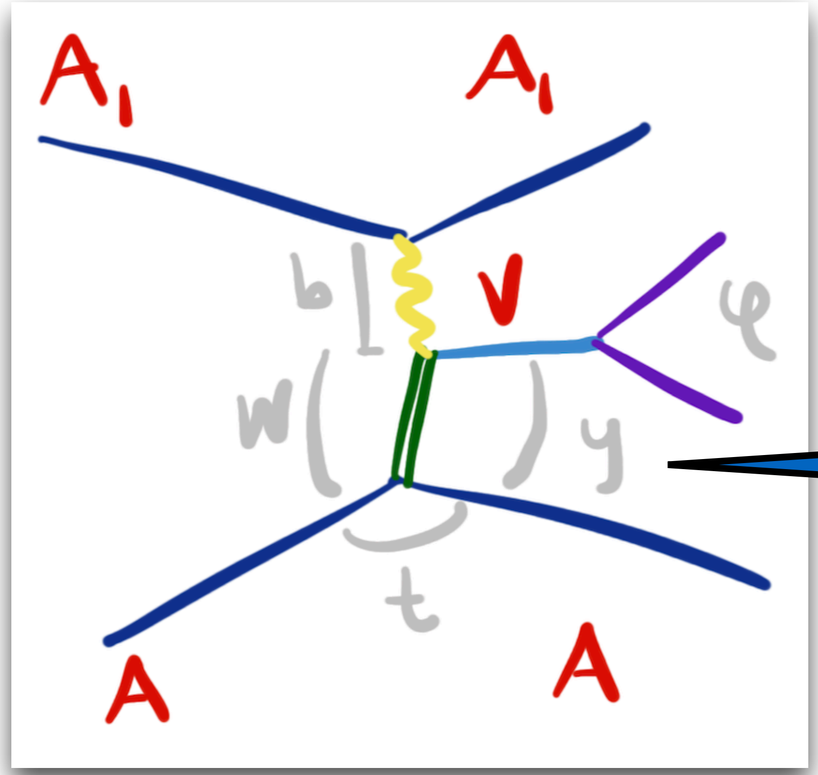
y

Rapidity dependence



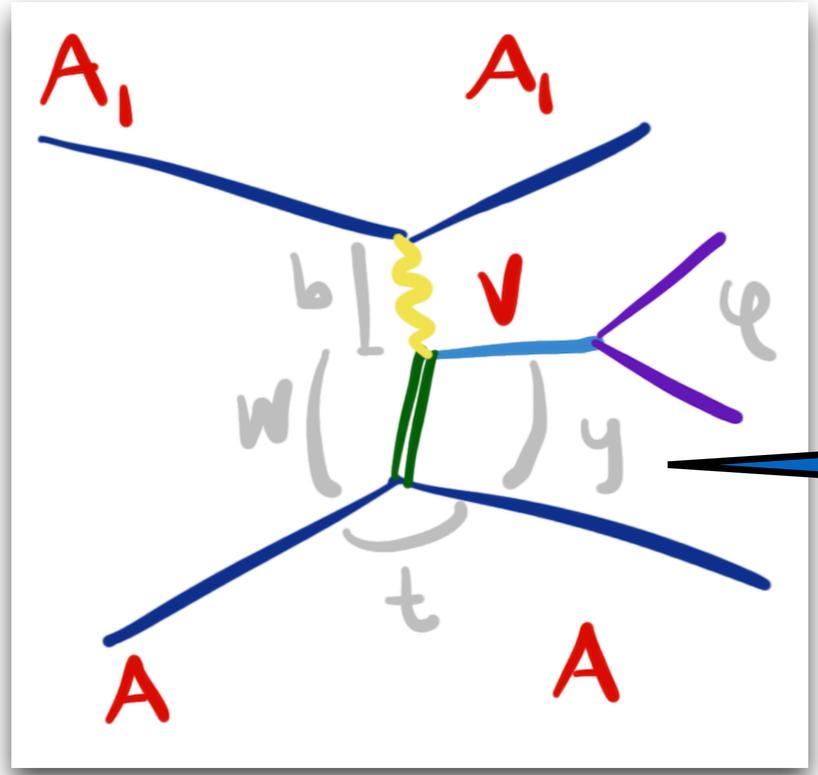
Rapidity dependence
⇨ x evolution

$$x = \frac{m}{\sqrt{s}} e^{y}$$

y

Rapidity dependence

Expectations:
The gluon distribution raises as a power law with decreasing x
⇨
The cross section raises as a power law until it saturates



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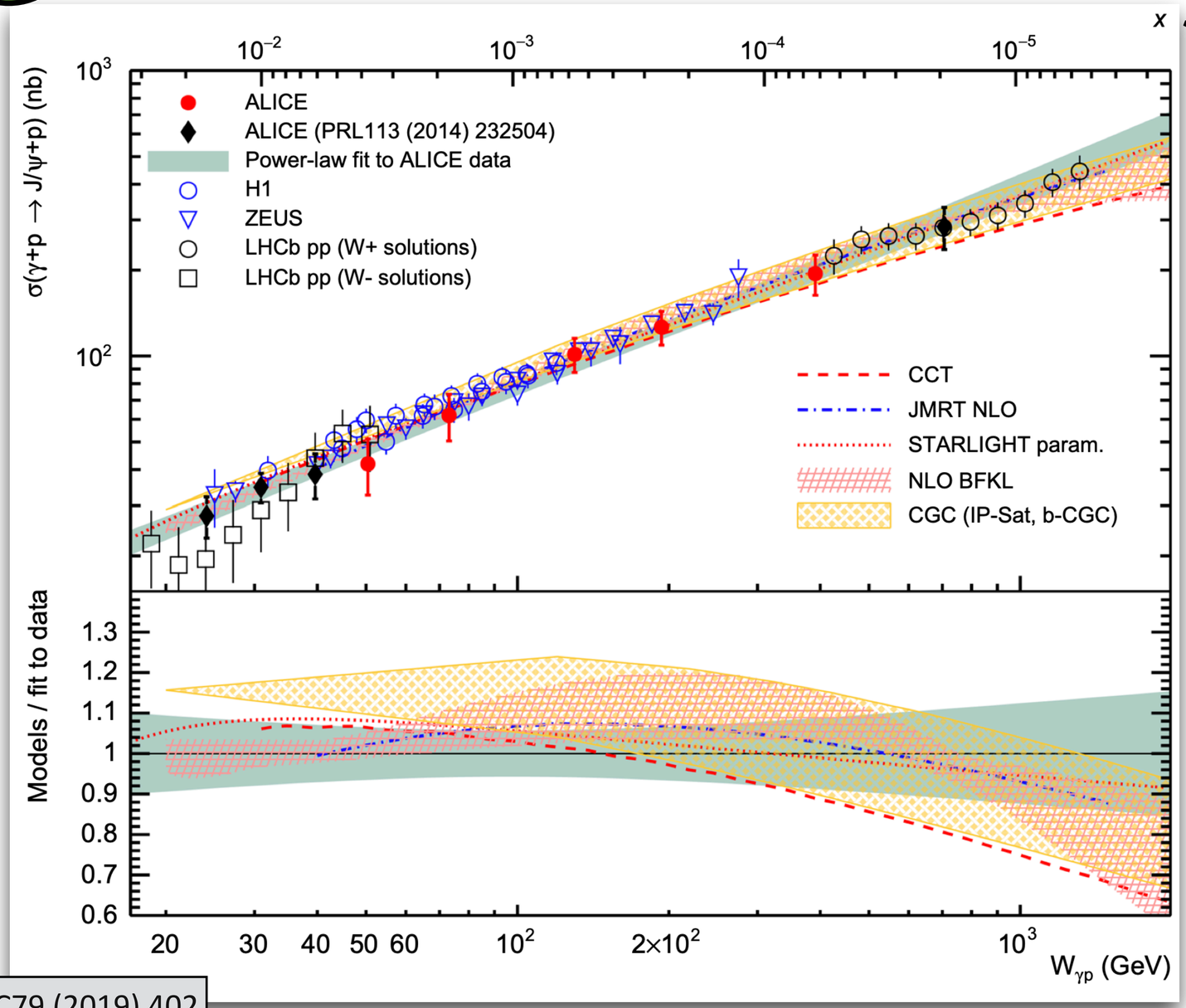
Rapidity dependence: p-Pb results from ALICE



3 orders of magnitude in x are covered with one detector!

ALICE, EPJ C79 (2019) 402

J/ψ

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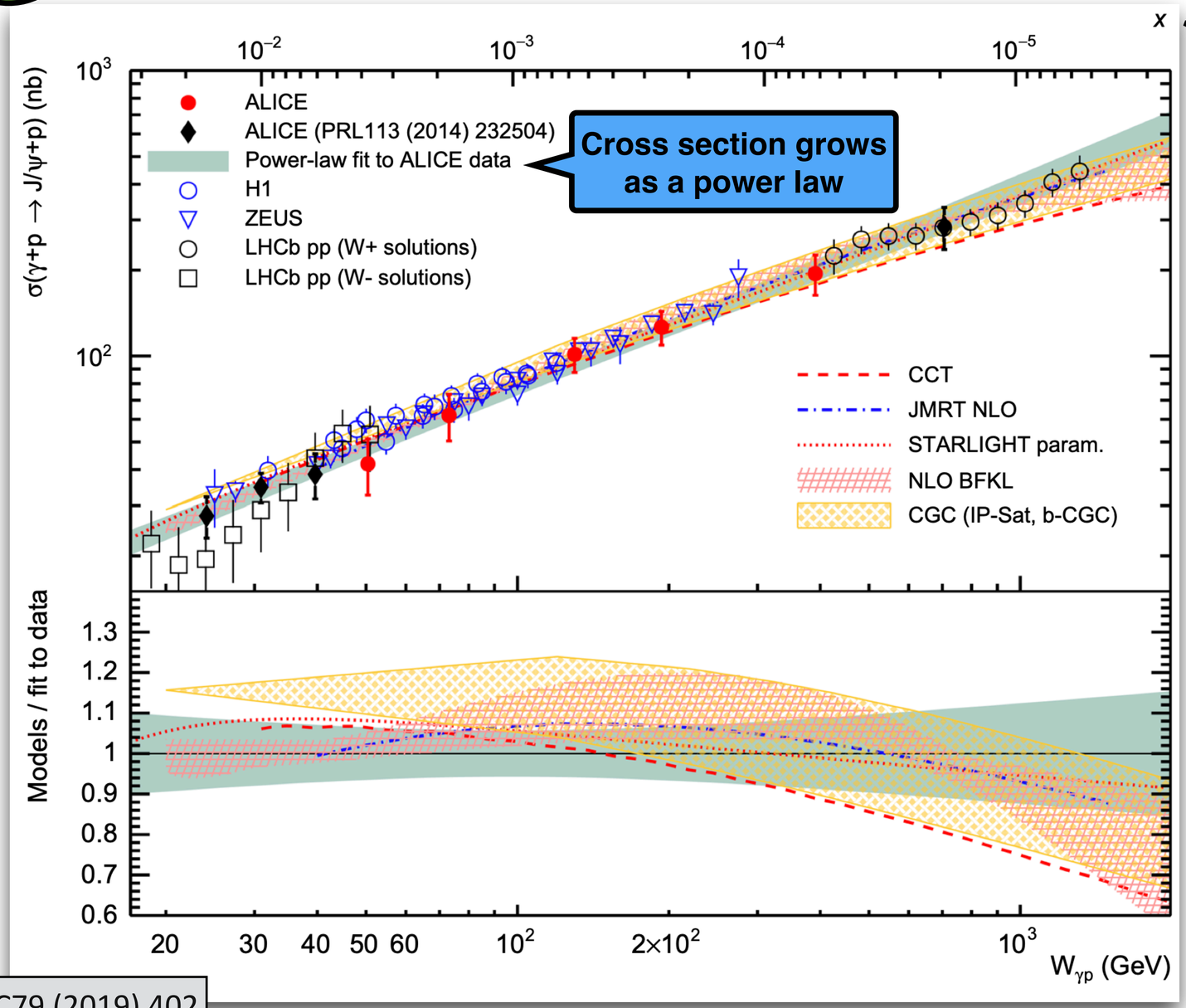

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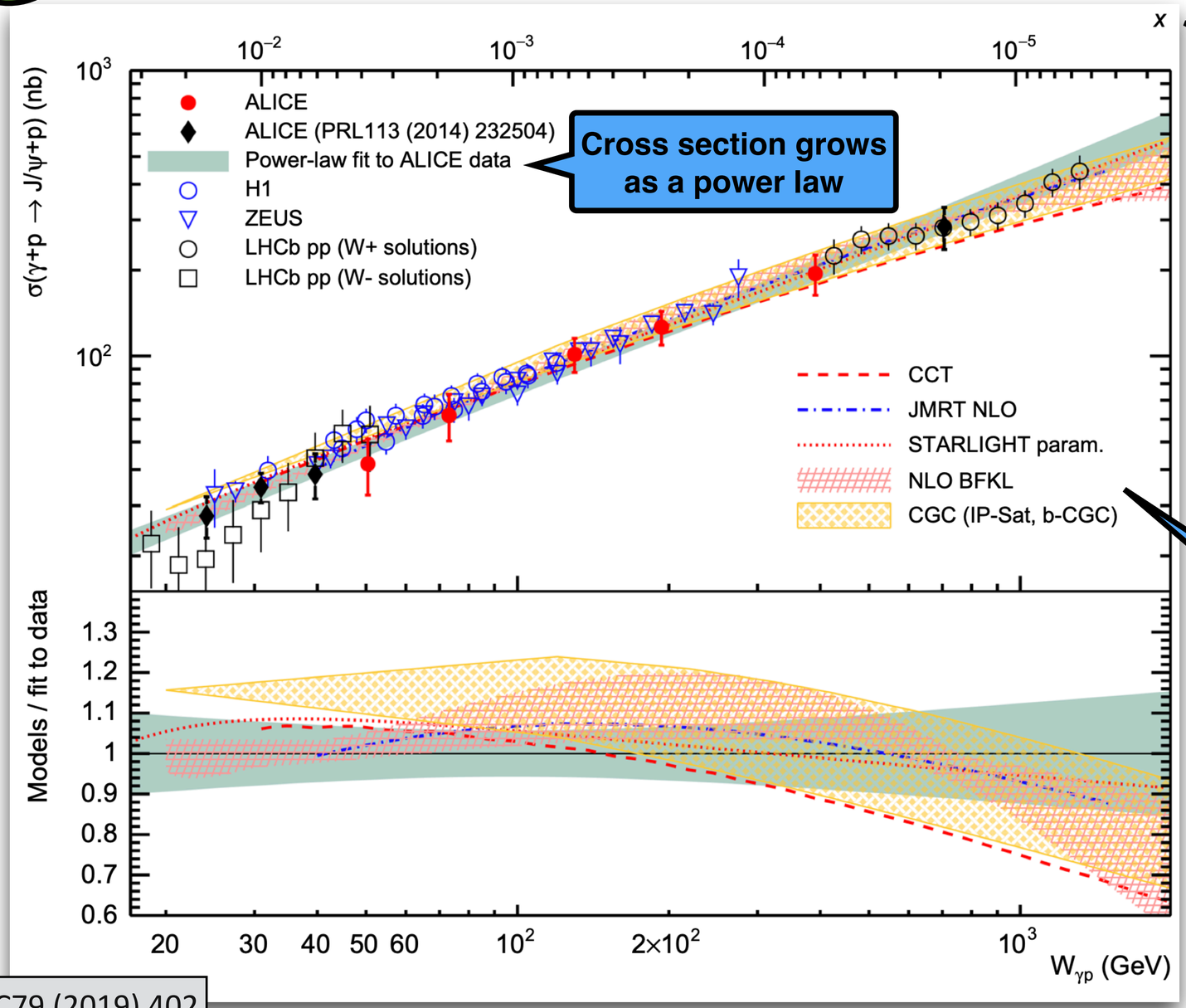

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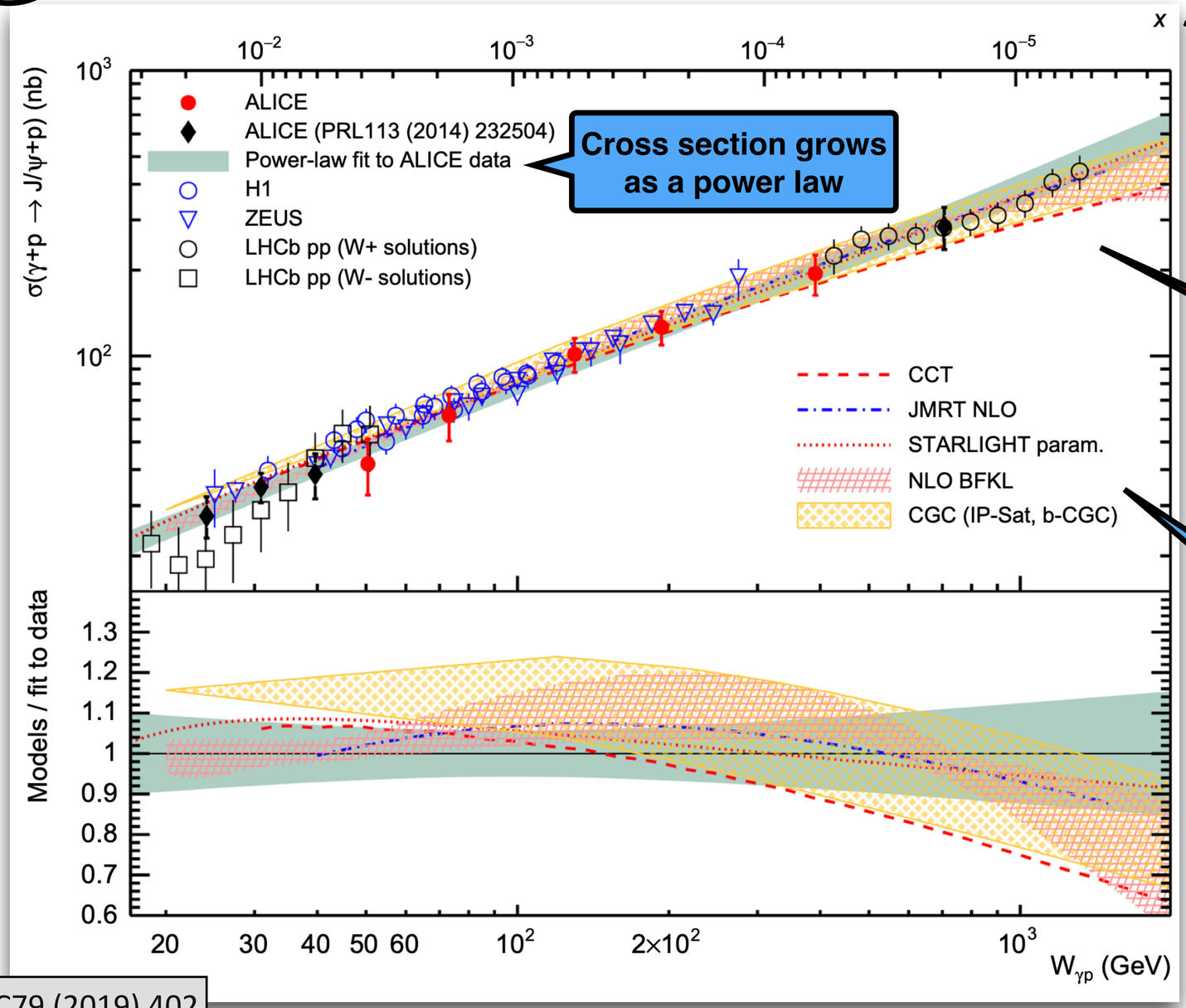

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Open question: Where is saturation?

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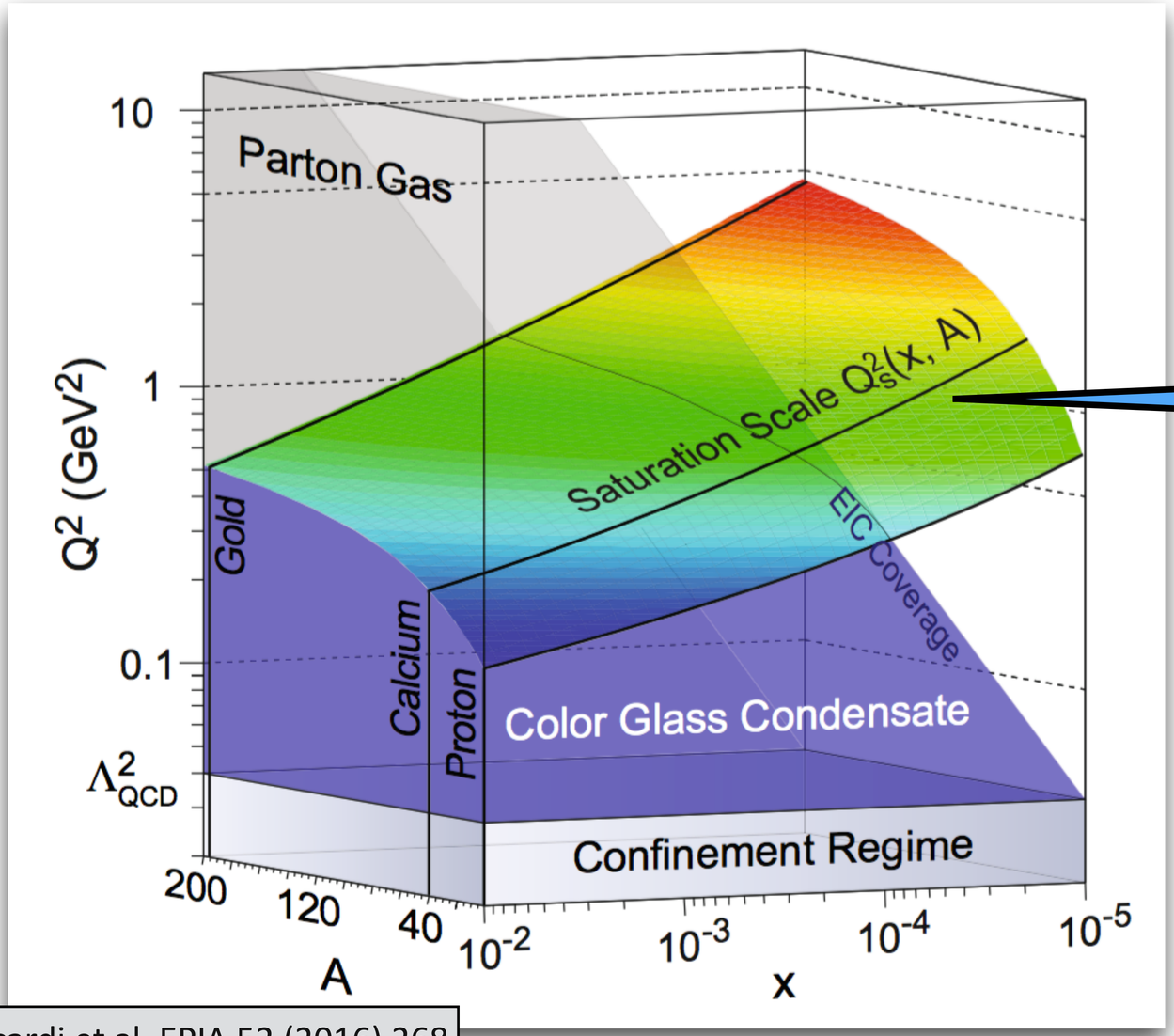
ALICE, EPJ C79 (2019) 402

Rapidity dependence: the case for nuclei

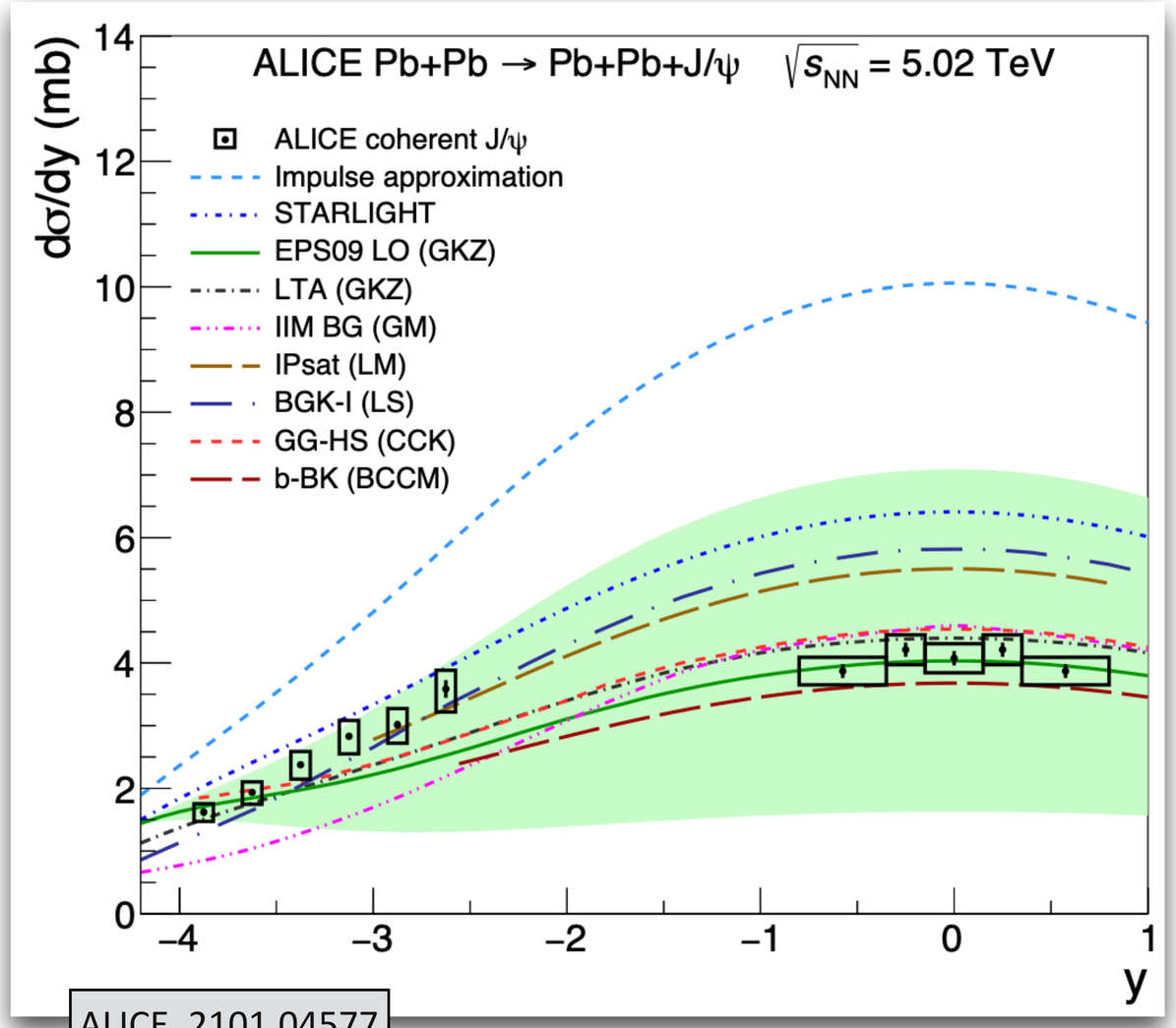


Accardi et al, EPJA 52 (2016) 268

Saturation is expected to set in earlier in heavier nuclei

J/ψ

Rapidity dependence: ALICE results in Pb-Pb



ALICE, 2101.04577

J/ψ

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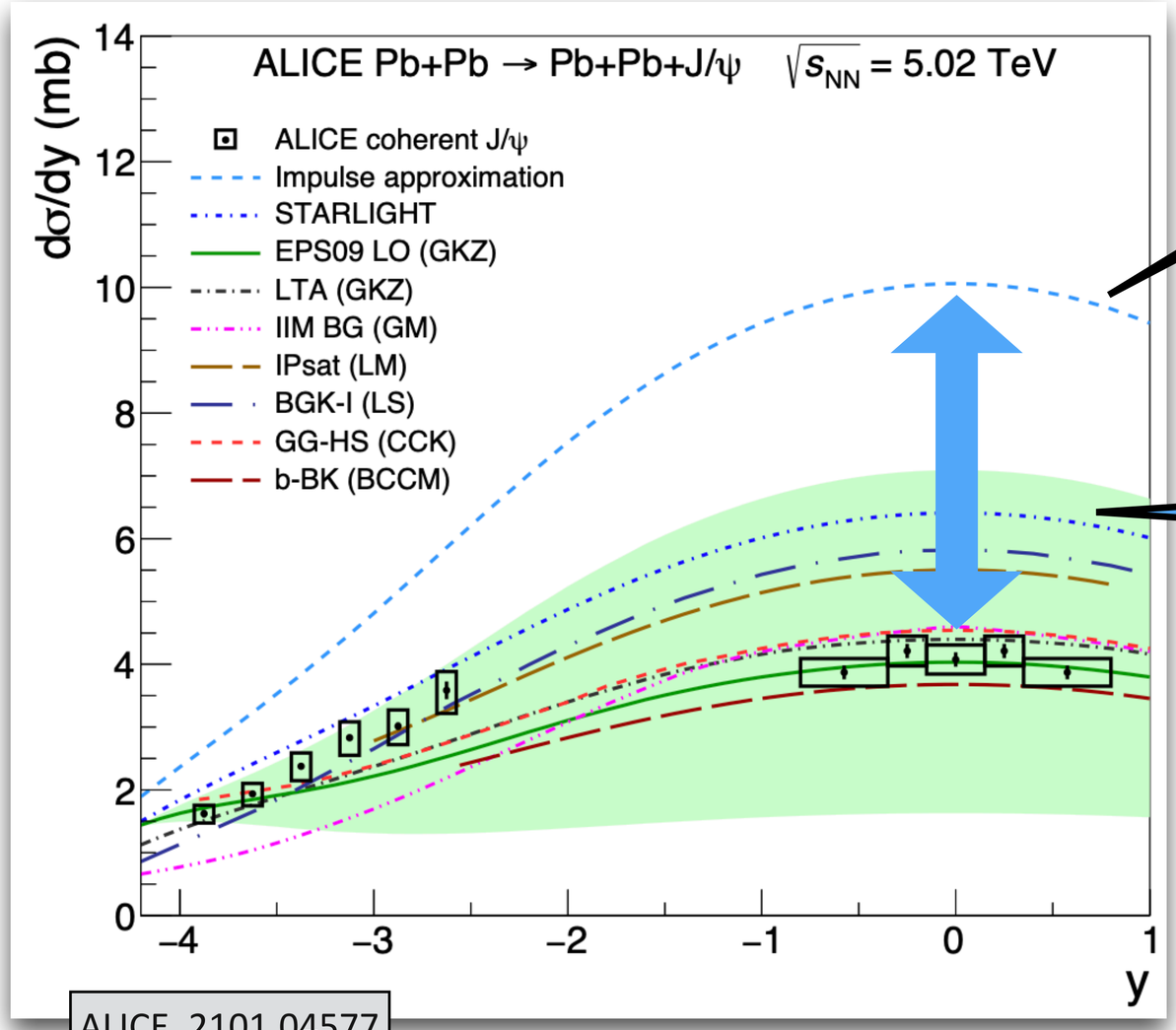

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Impulse approximation

Nuclear suppression factor for $x\sim10^{-3}$ is 0.65±0.03

J/ψ

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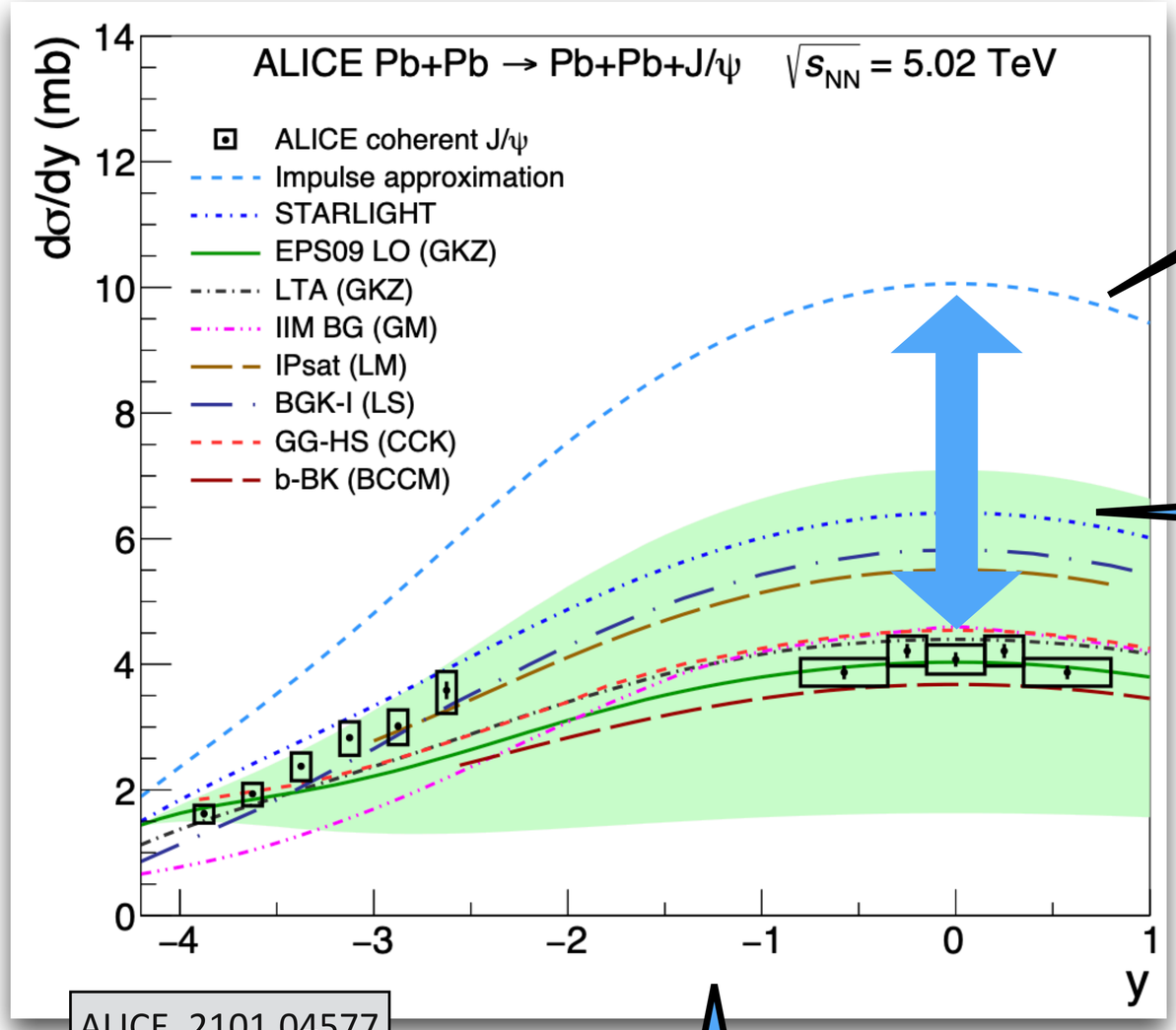

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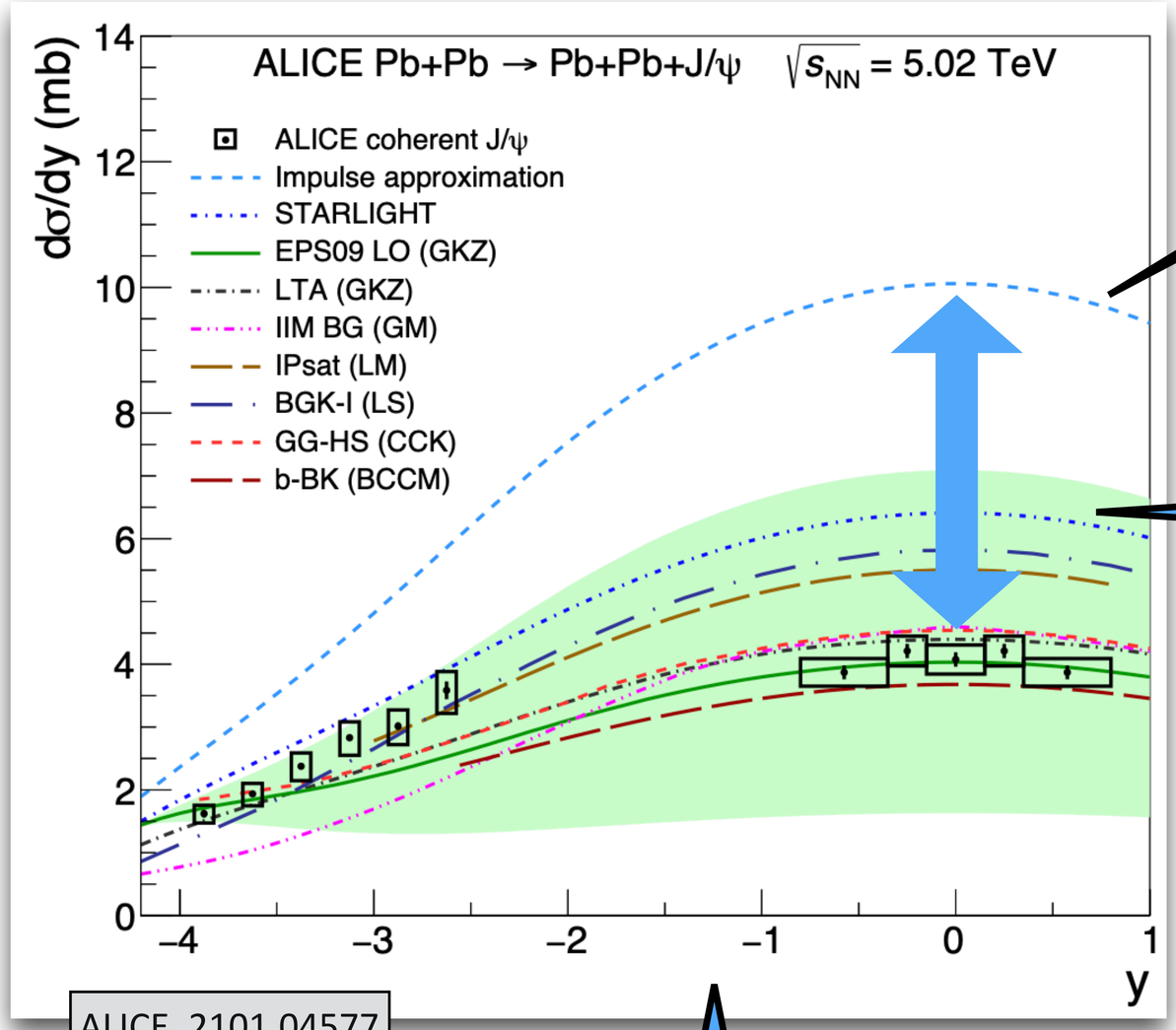

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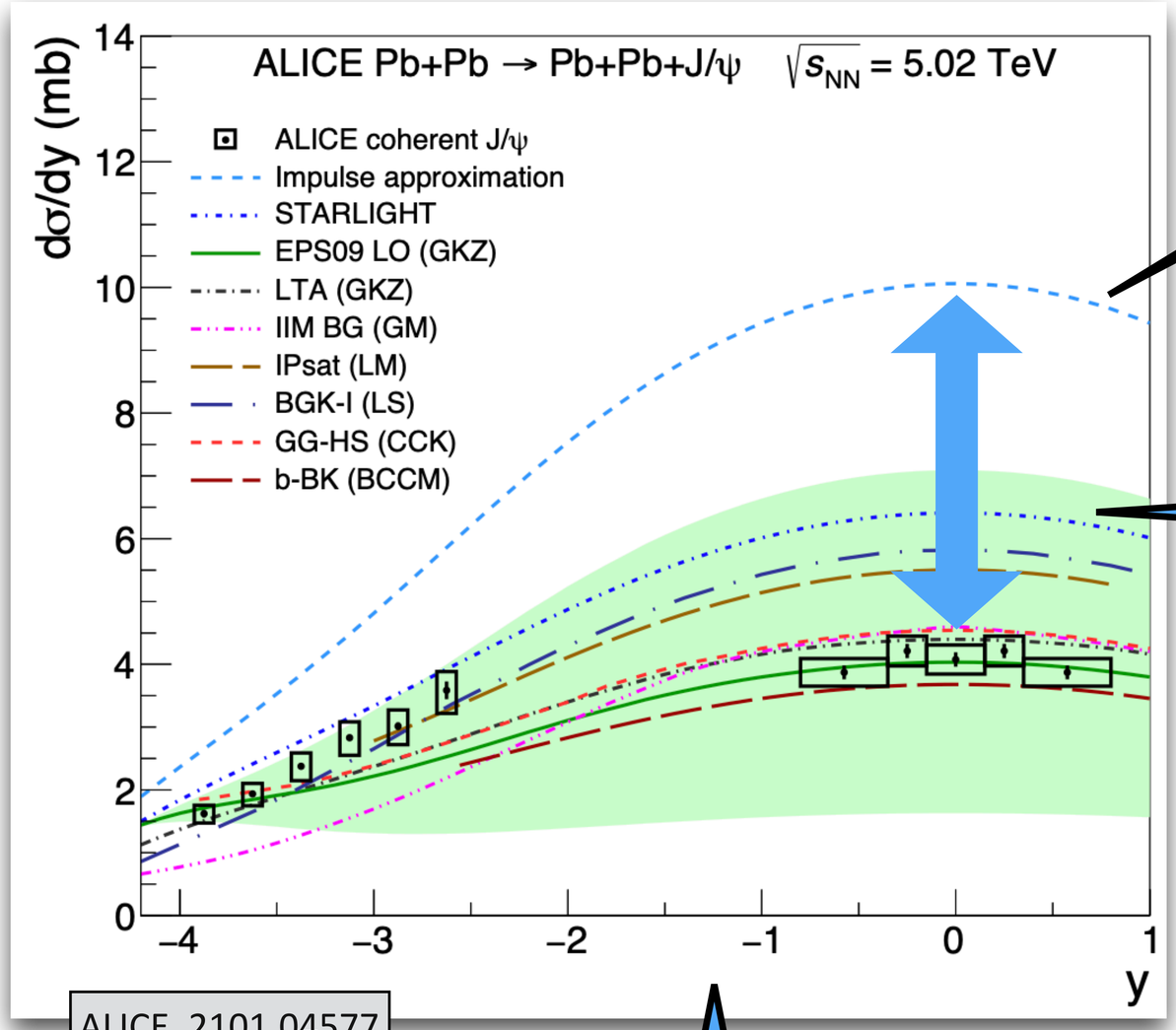

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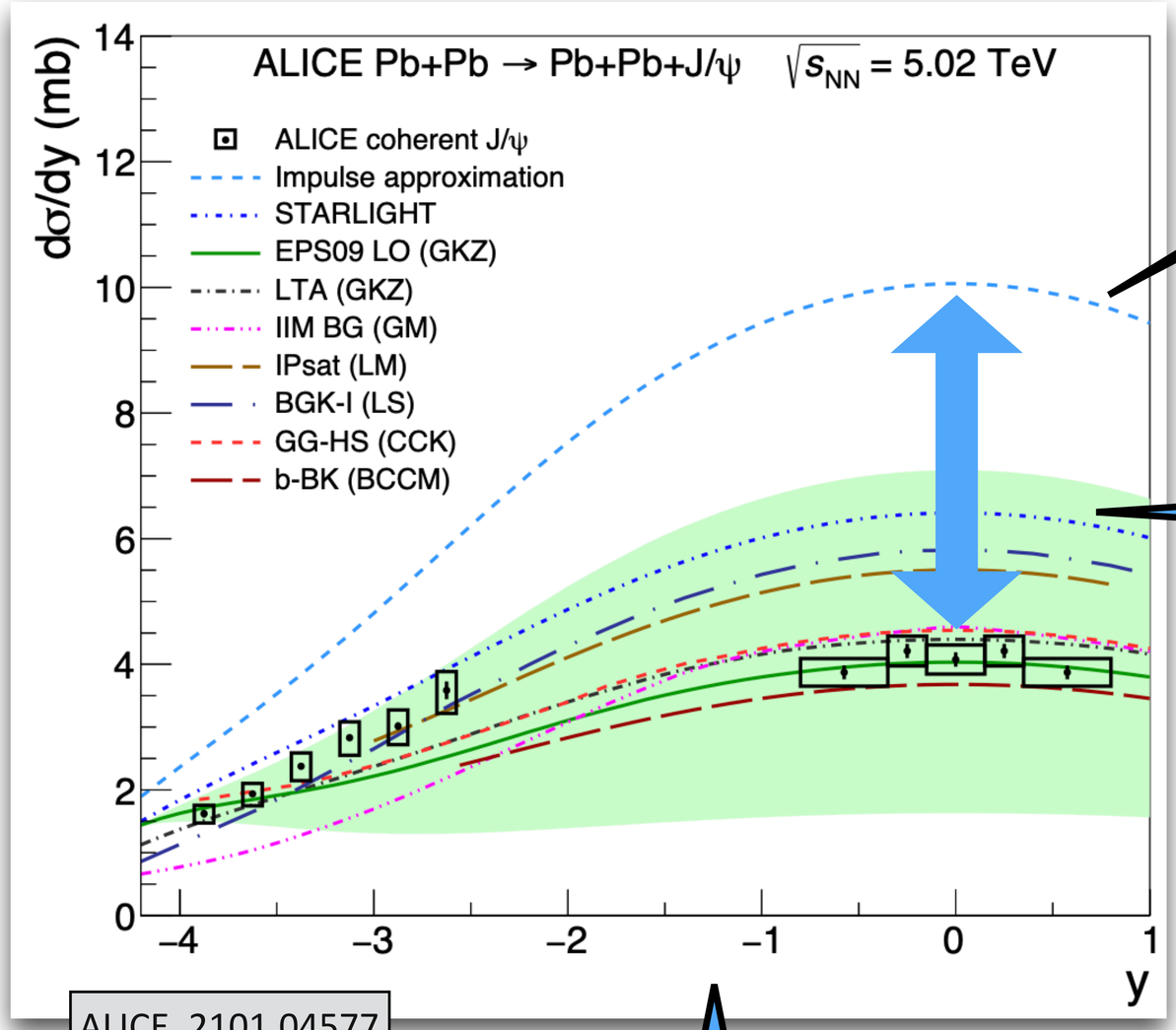

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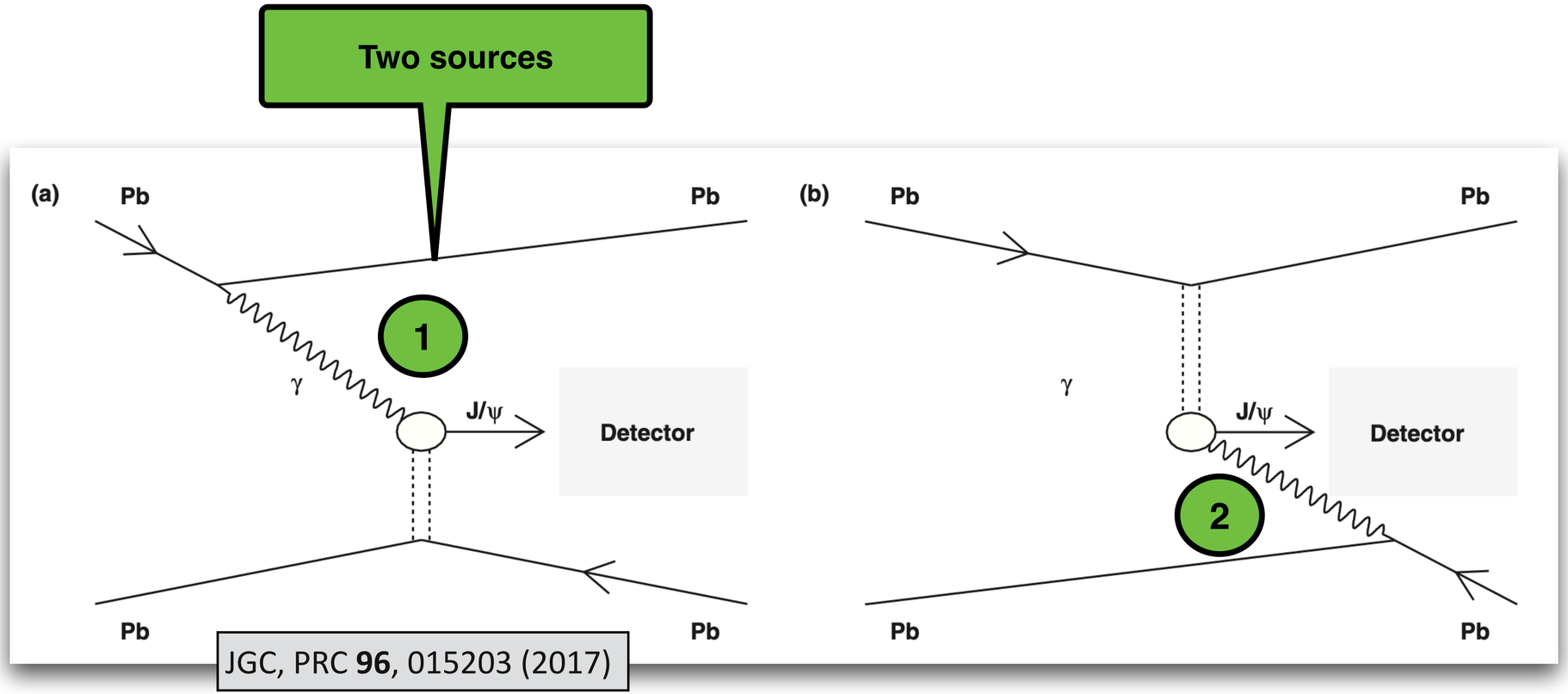
Try to plot vs x?

Rapidity dependence: ambiguity problem



JGC, PRC **96**, 015203 (2017)

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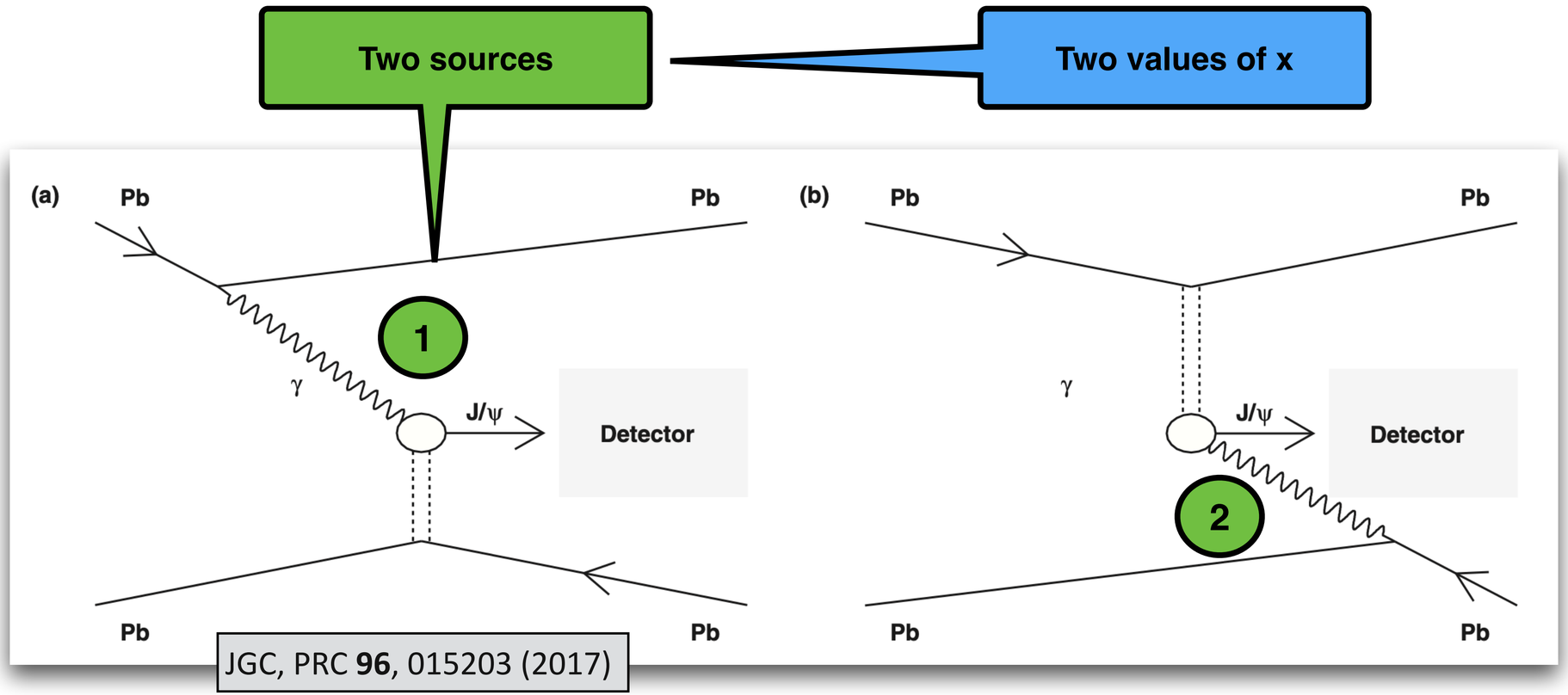

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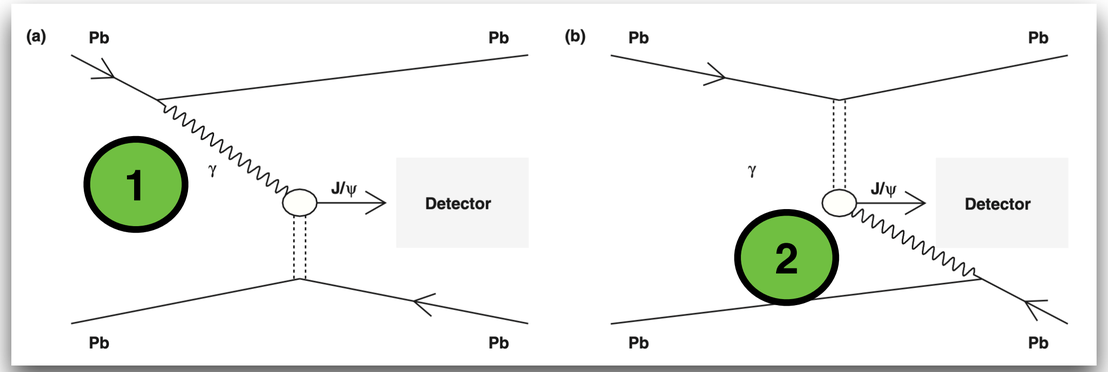
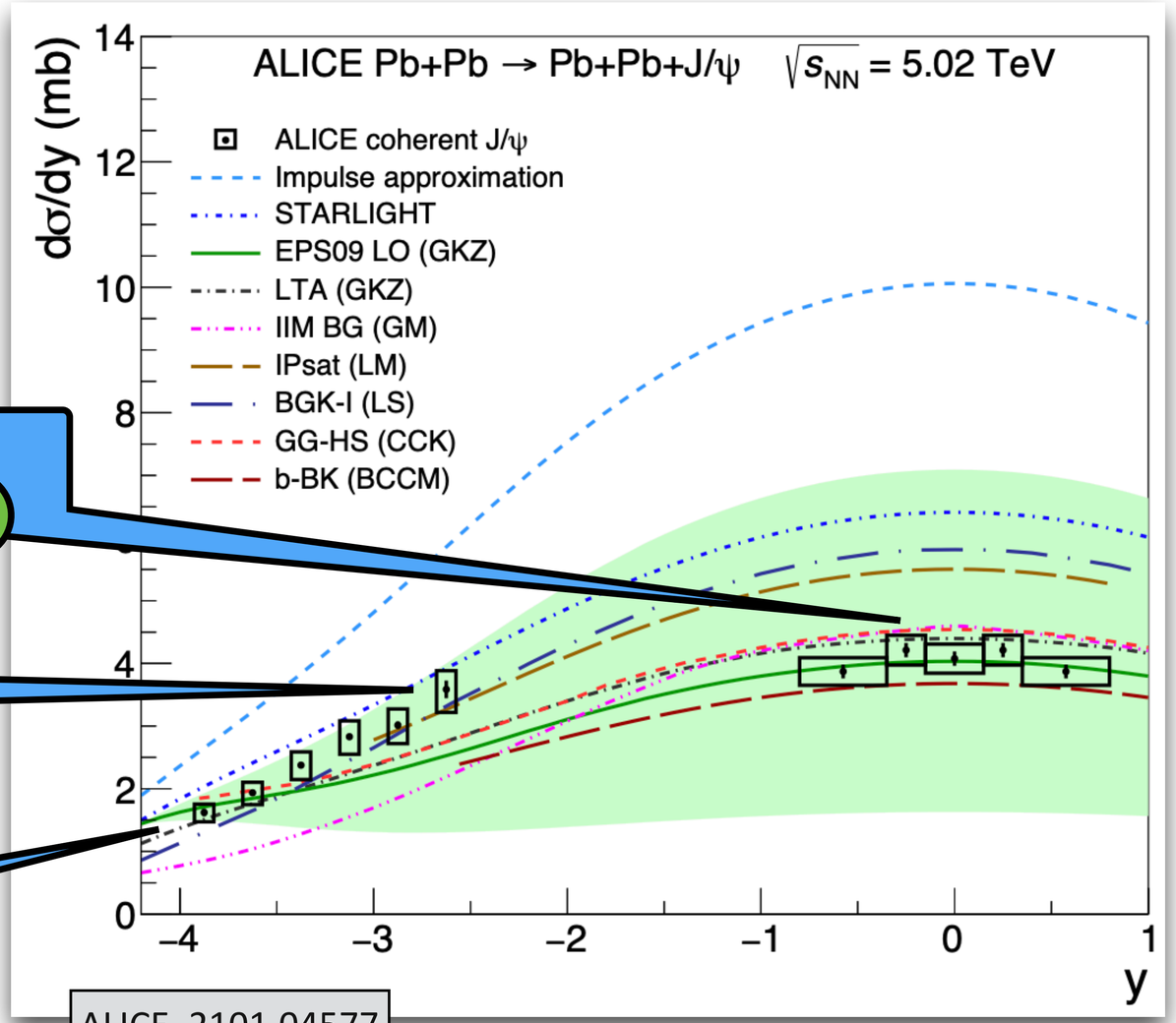


2
50% each x~1. 10^{-3}
1

2
60% x~0.7 10^{-2}
40% x~5.1 10^{-5}
1

2
95% x~3.3 10^{-2}
5% x~1.1 10^{-5}
1

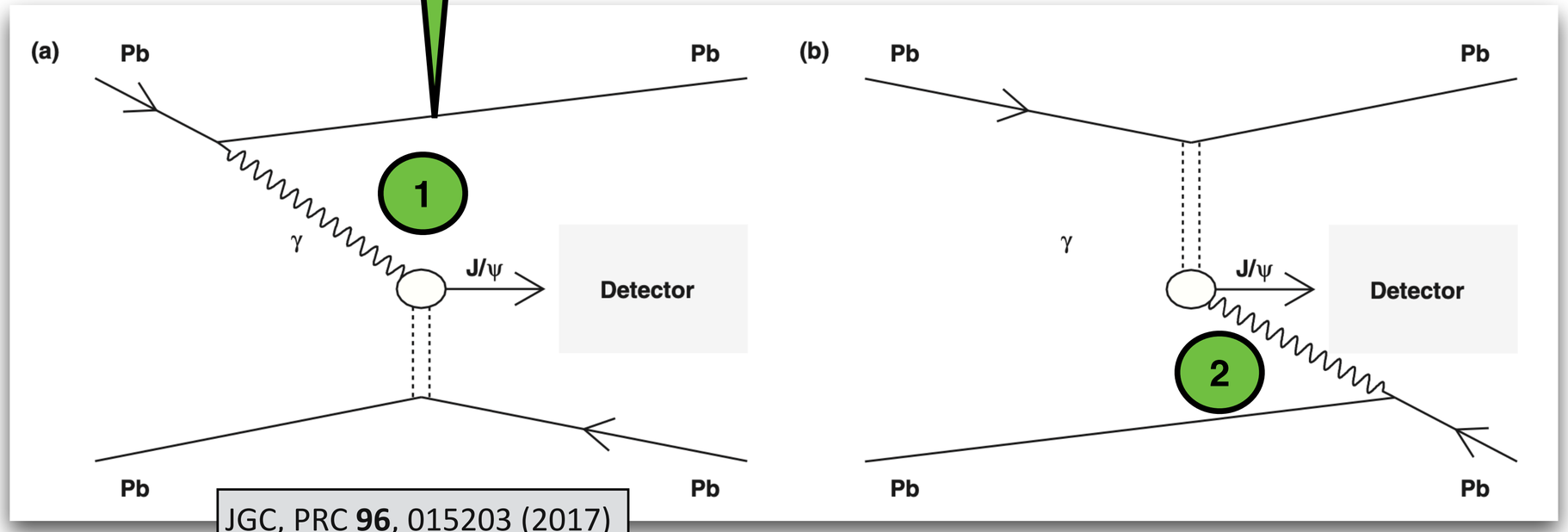


ALICE, 2101.04577

Rapidity dependence: ambiguity problem

Open question: how to disentangle both contributions?

Two sources



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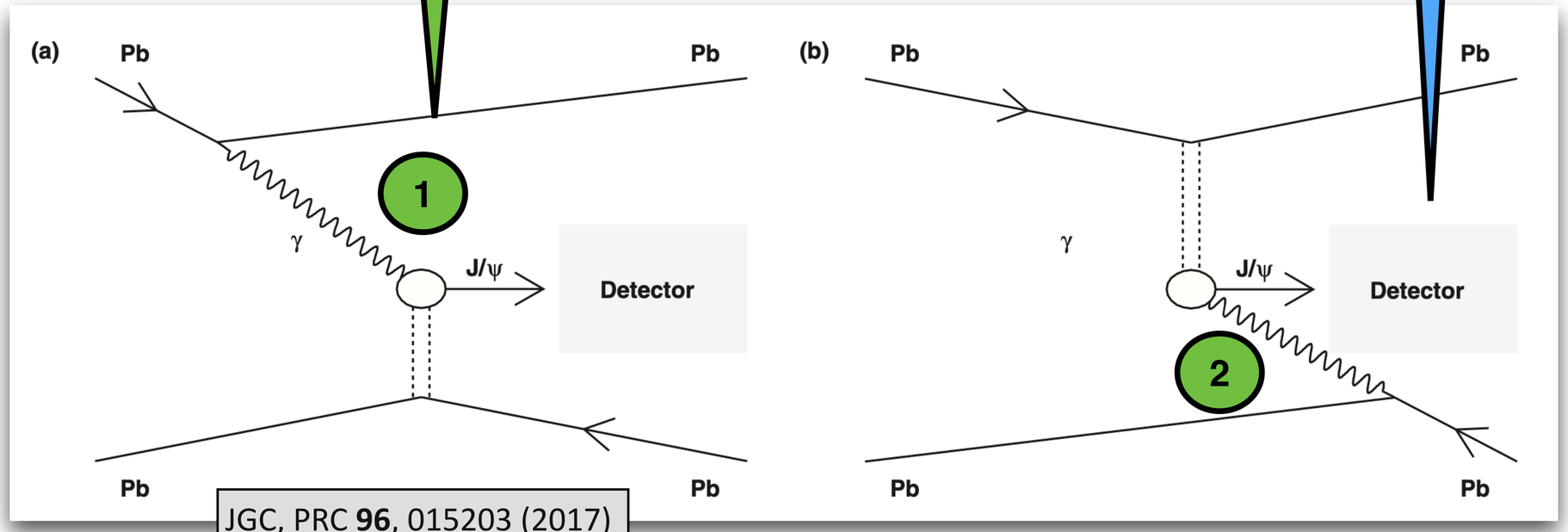
Another independent measurement needed at the same rapidity



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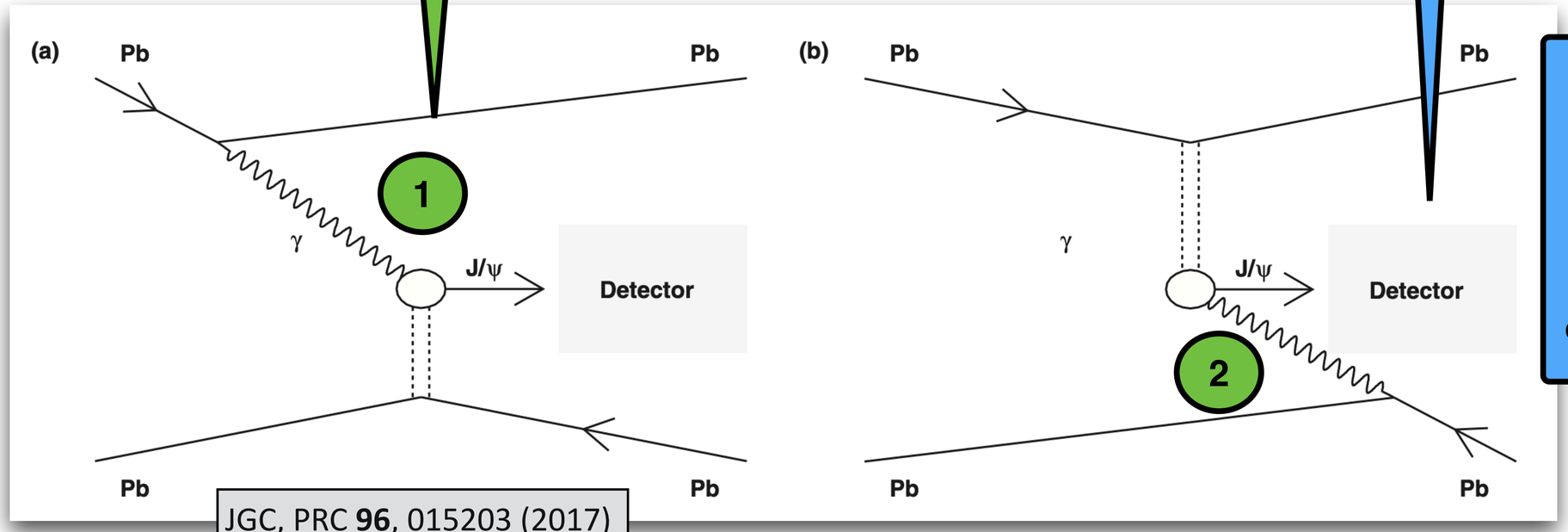


JGC, PRC **96**, 015203 (2017)

Another independent measurement needed at the same rapidity

Up to now, two options:

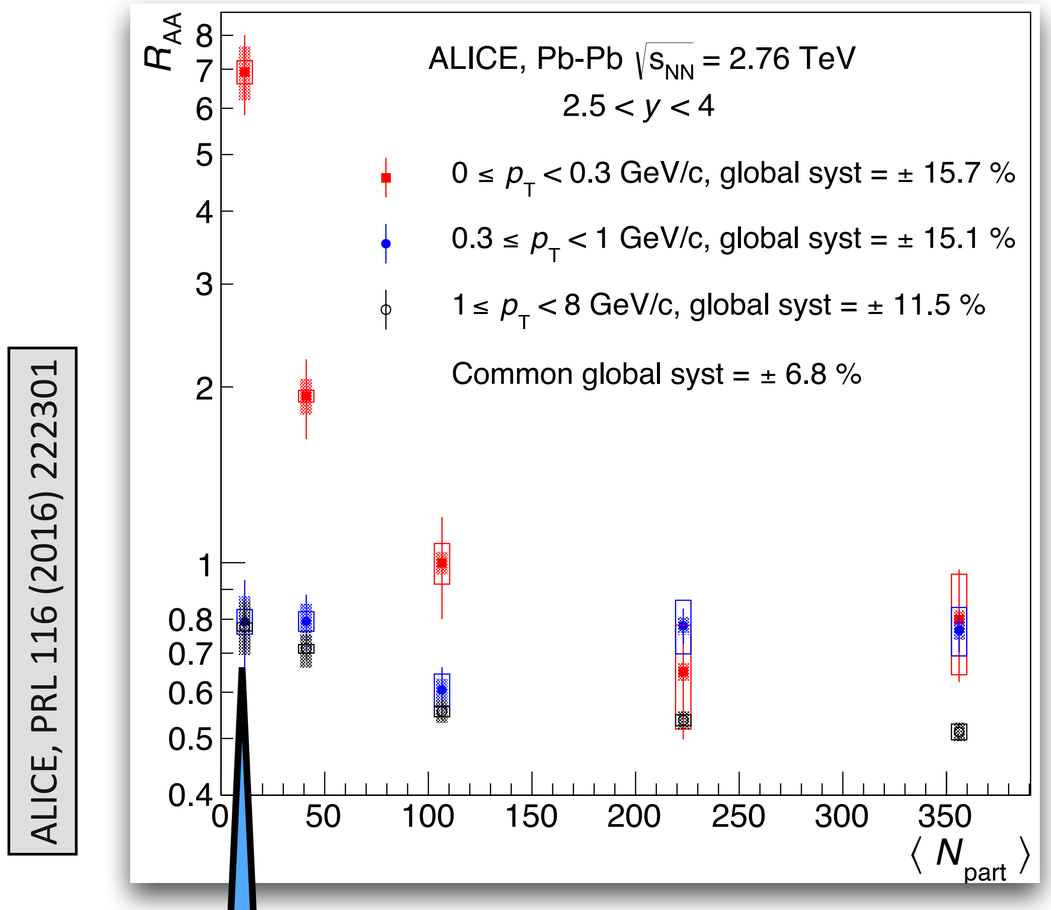
Measure the same process in peripheral collisions

Measure the same process with electromagnetic dissociation (EMD)

Both options select different regions of the impact parameter

J/ψ

Rapidity dependence: peripheral collisions

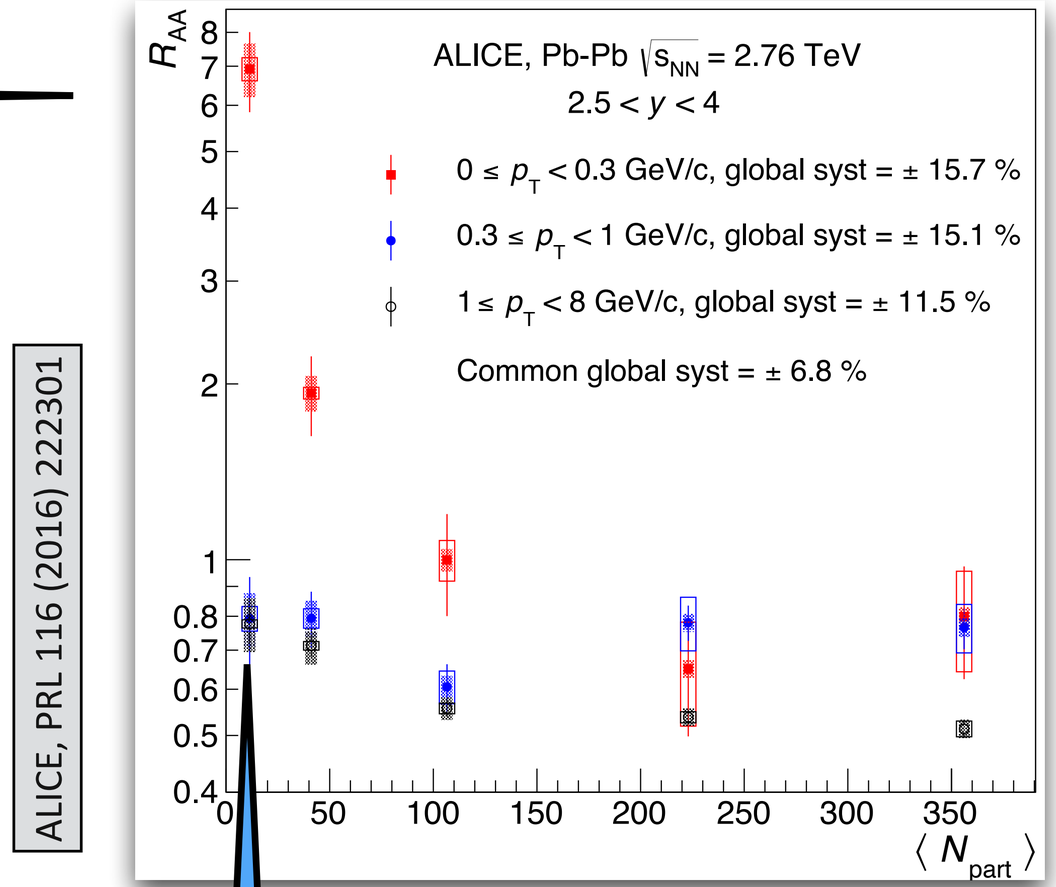


J/ψ production in Pb-Pb collisions: expected that RAA ~ 1 for <Npart> small

J/ψ

Rapidity dependence: peripheral collisions

At low pT, RAA values a lot larger then 1 have been measured
⇨ coherent photoproduction process!



ALICE, PRL 116 (2016) 222301

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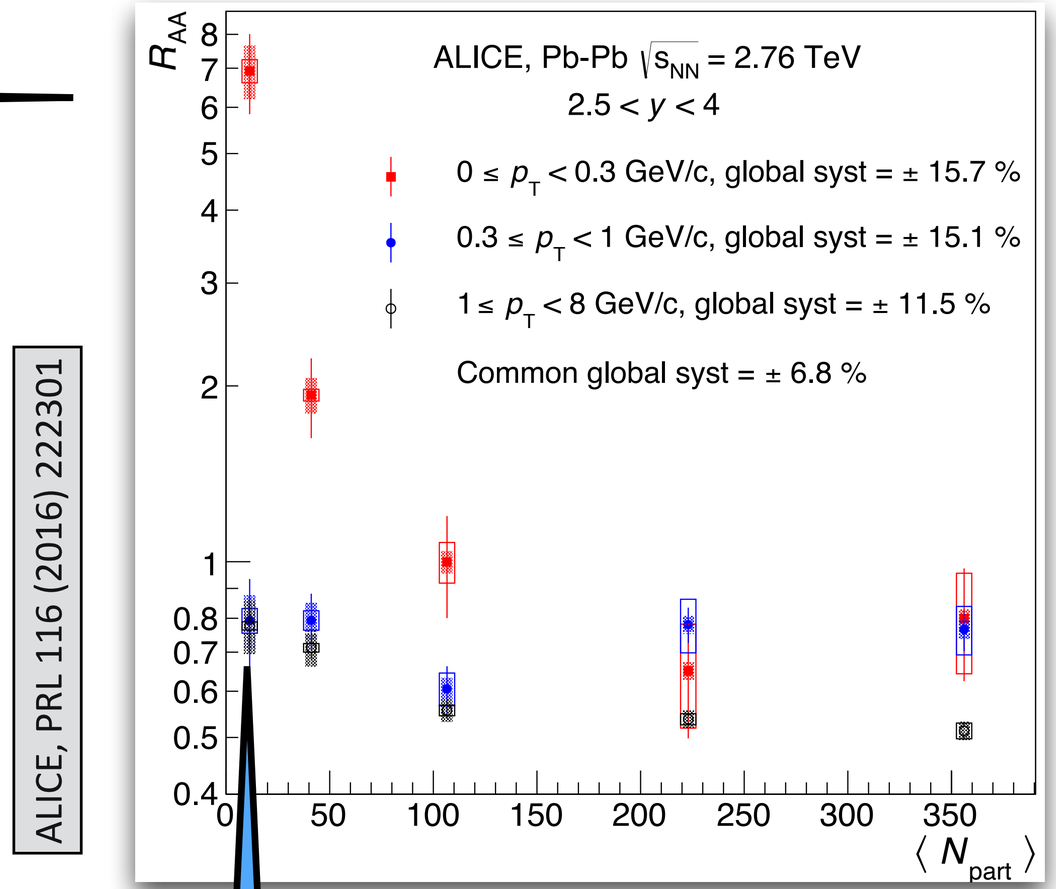


ALICE, PRL 116 (2016) 222301

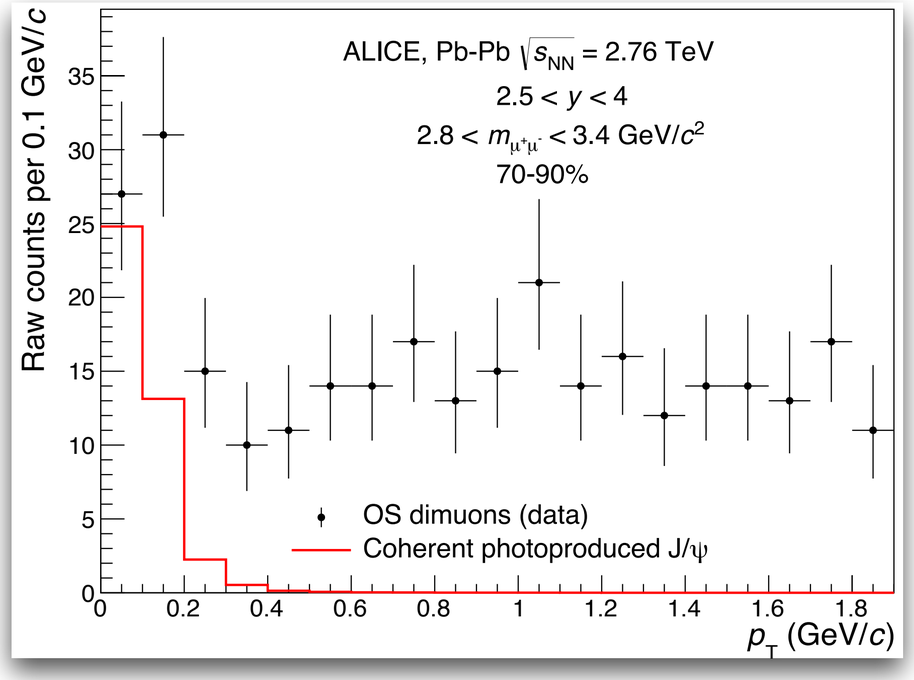
In coherent processes pT is related to the inverse of the size of the target hadron: expect very low pT off Pb ions

J/ψ production in Pb-Pb collisions: expected that RAA ~ 1 for <Npart> small

J/ψ

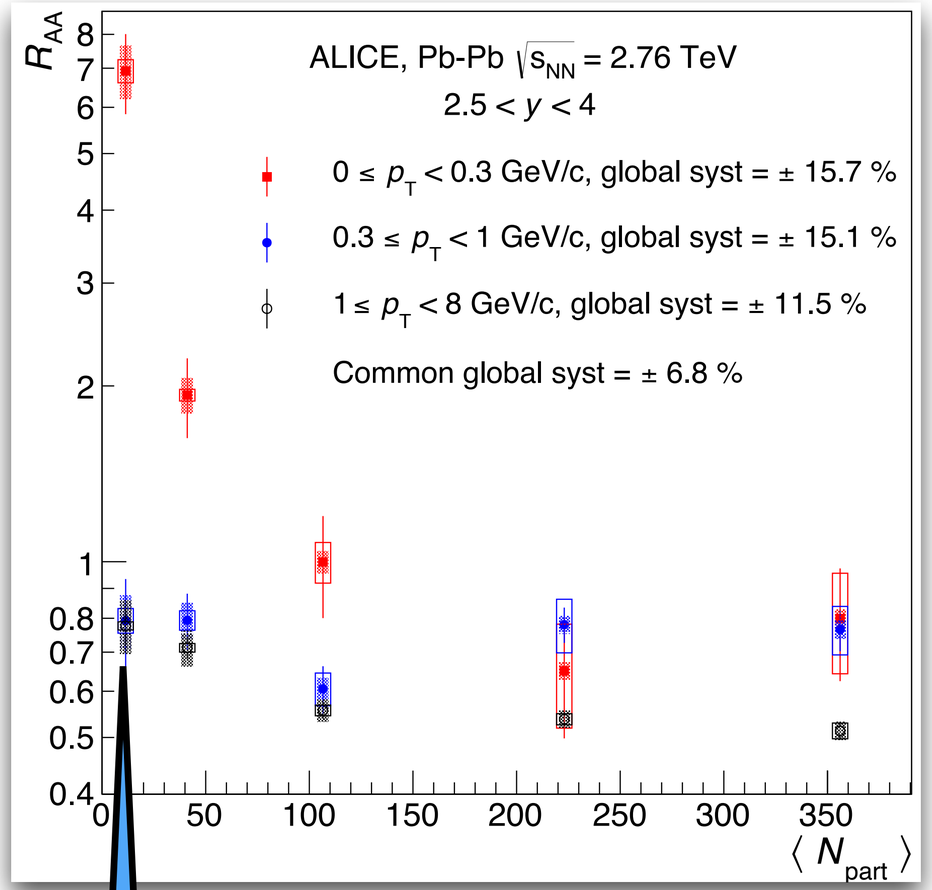
Rapidity dependence: peripheral collisions

At low pT, RAA values a lot larger then 1 have been measured
⇨ coherent photoproduction process!



In coherent processes pT is related to the inverse of the size of the target hadron: expect very low pT off Pb ions

ALICE, PRL 116 (2016) 222301

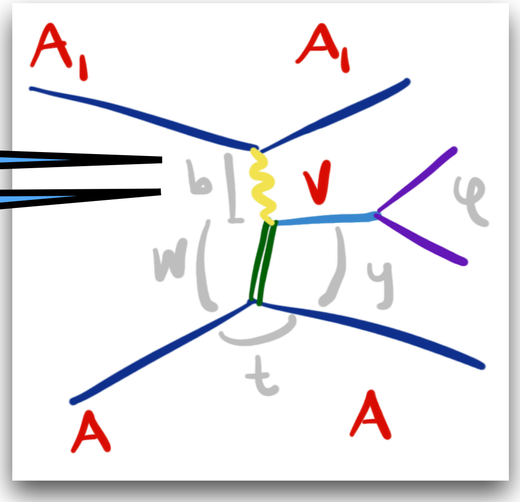


J/ψ production in Pb-Pb collisions: expected that RAA ~ 1 for <Npart> small

Rapidity dependence: From ultra + peripheral collisions measured by ALICE

Peripheral: small impact parameter

UPC: large impact parameter



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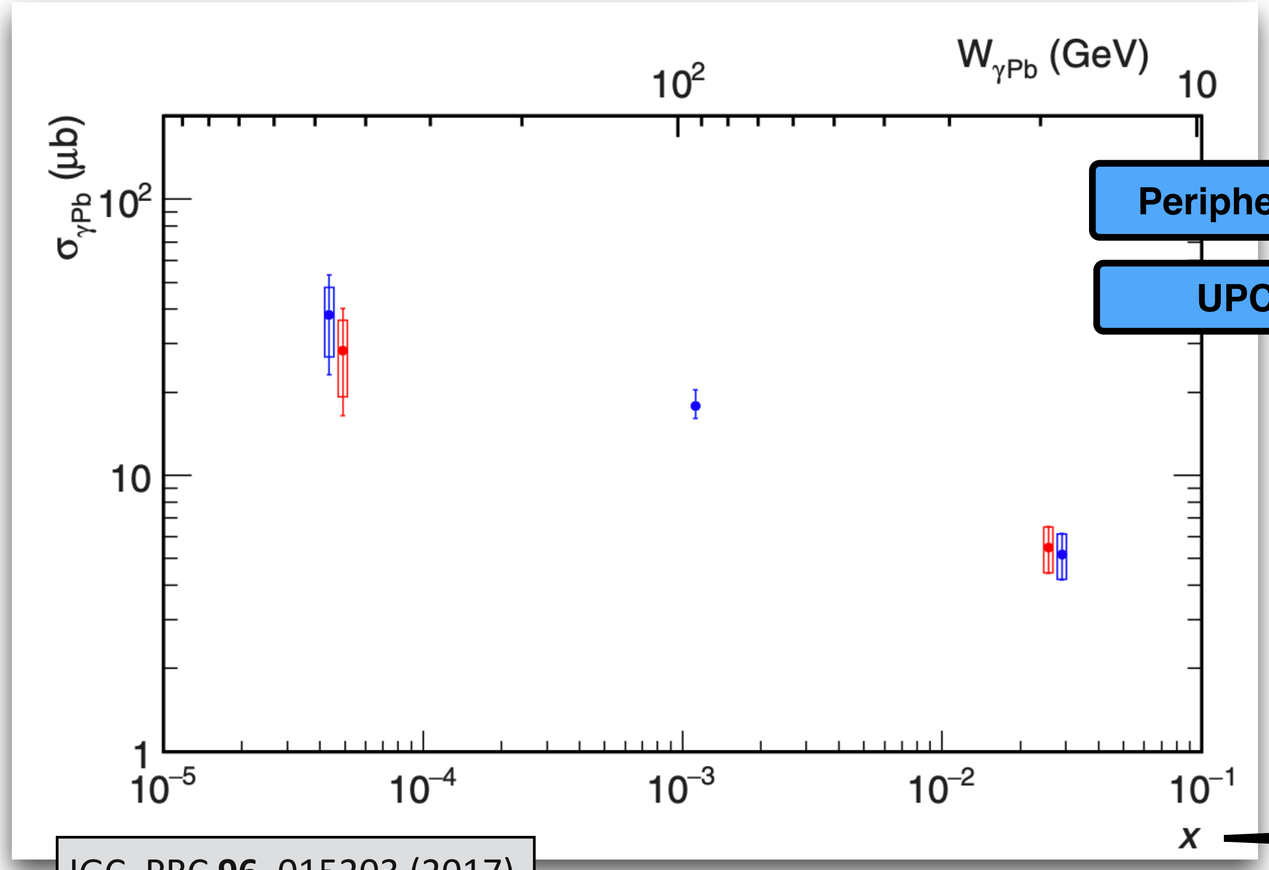

JGC, PRC **96**, 015203 (2017)

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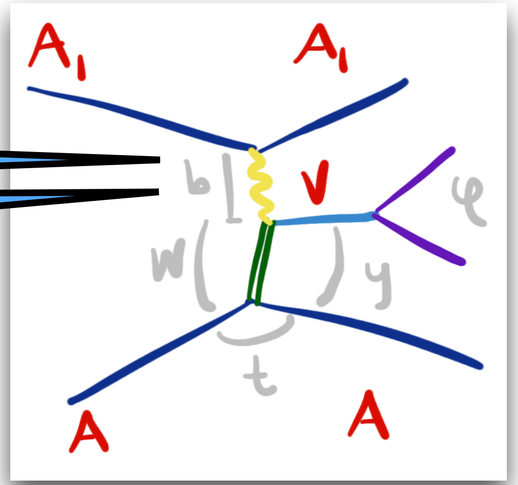
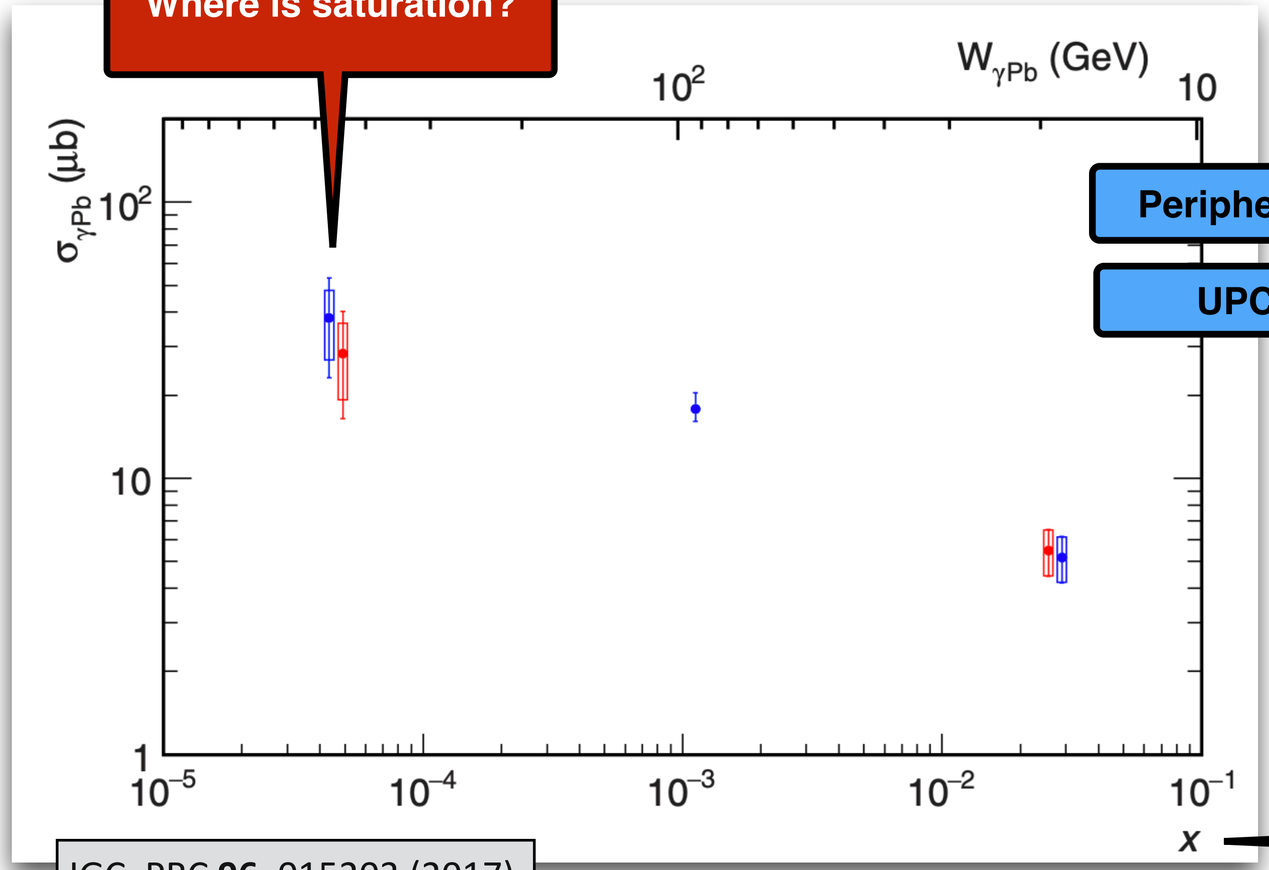


3 orders of magnitude in x are starting to be covered with one detector!

Rapidity dependence: From ultra + peripheral collisions measured by ALICE

Open question: Where is saturation?



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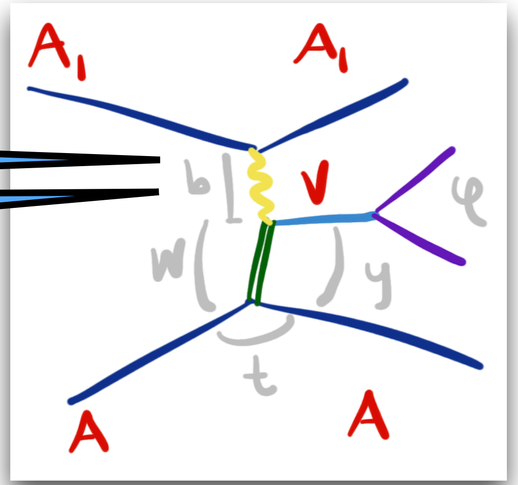

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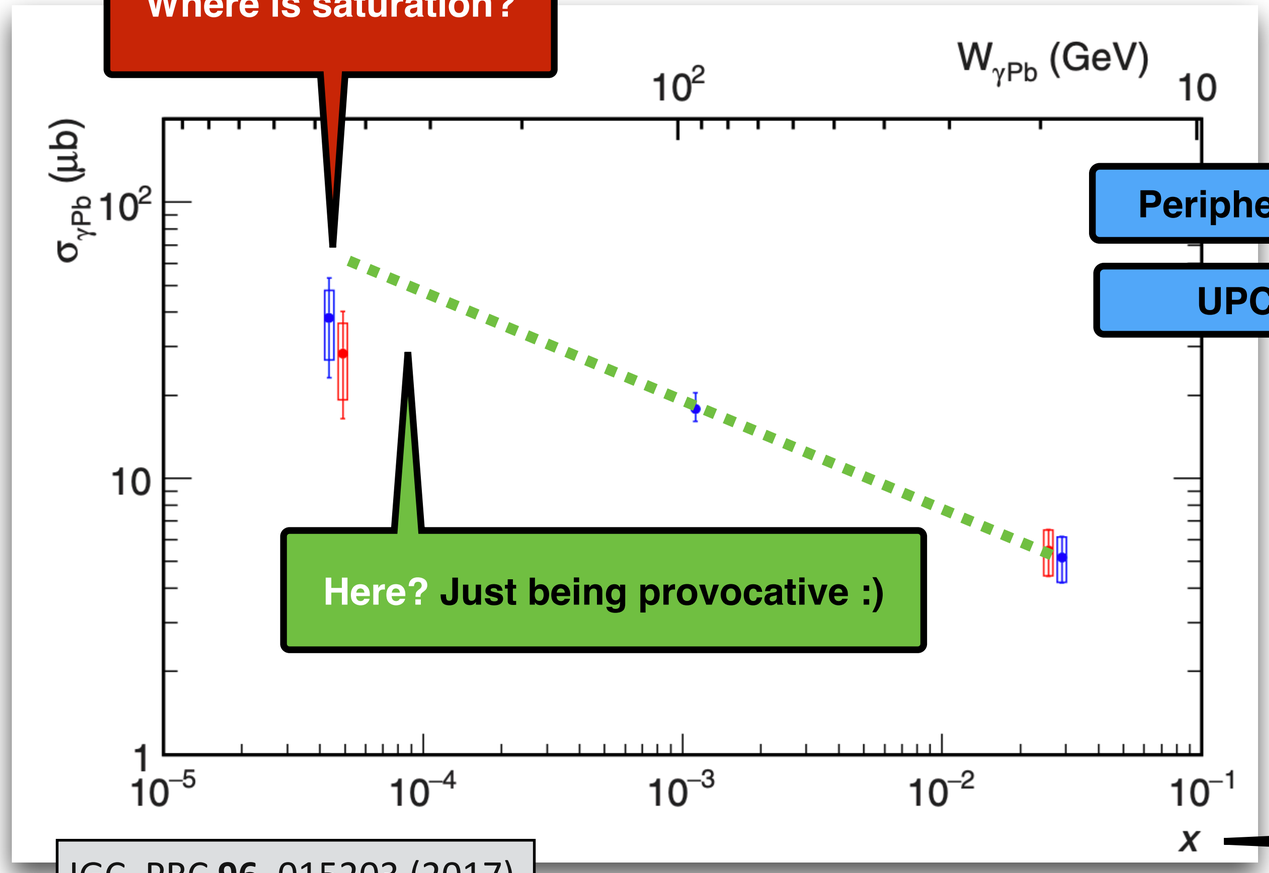

Here? Just being provocative :)

JGC, PRC **96**, 015203 (2017)

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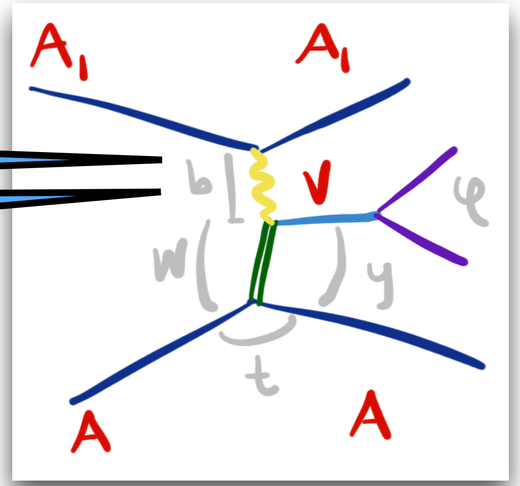

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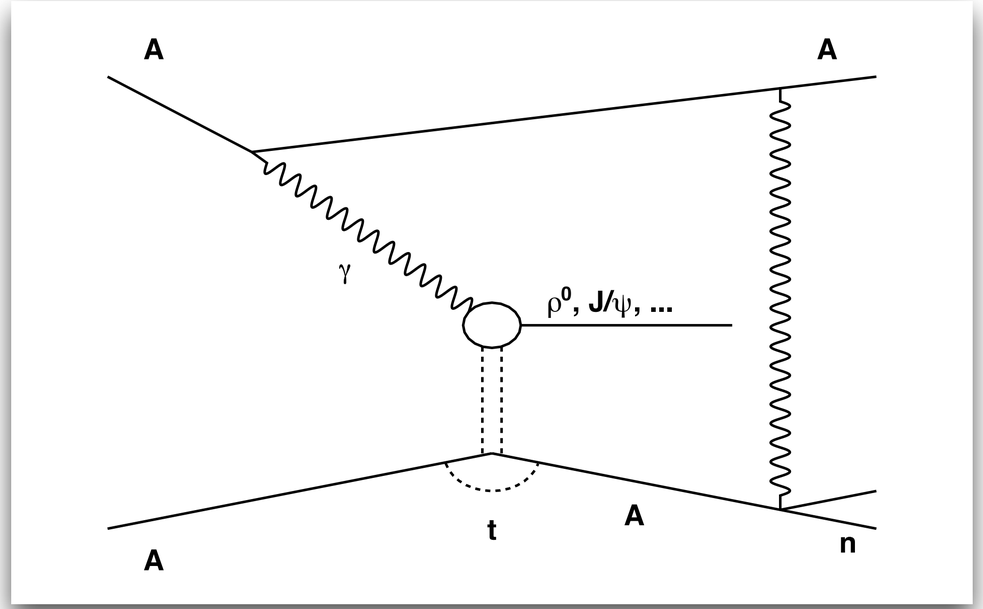
Rapidity dependence: Using EMD

Guzey, Strikman, Zhalov, EPJ C74 (2014) 2942



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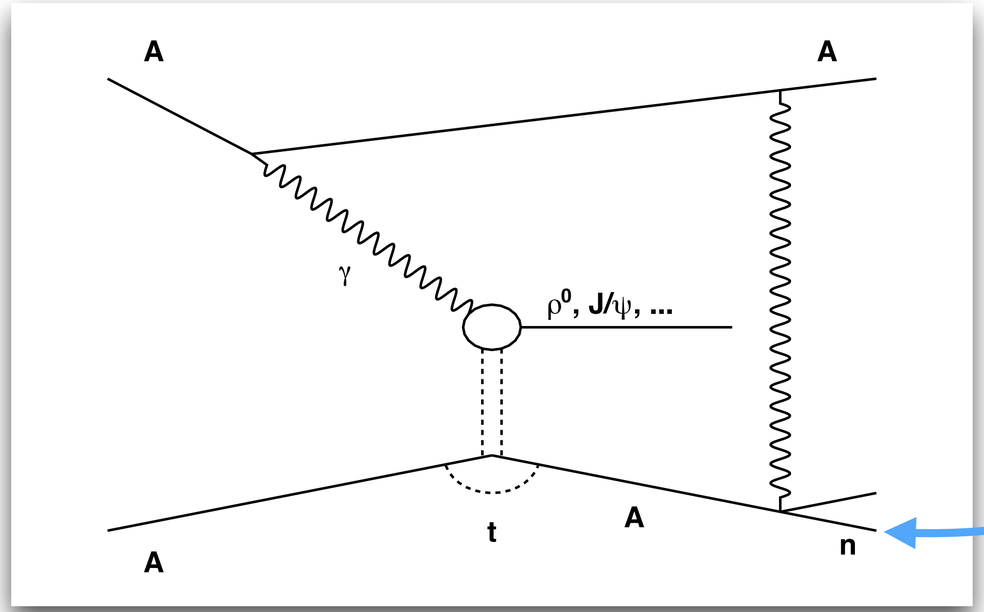
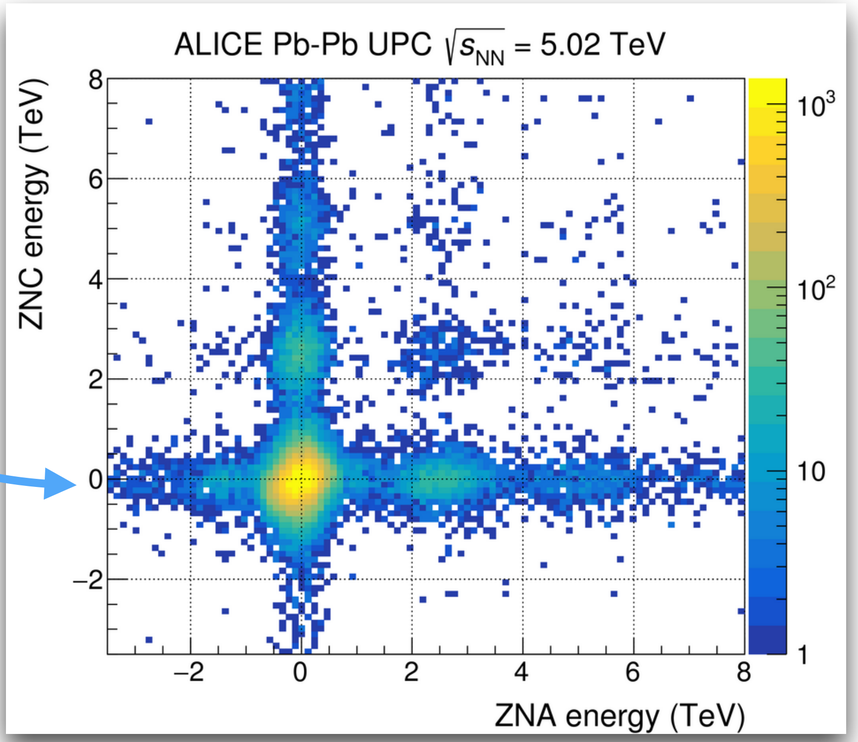


ZDC



ALICE, JHEP 06 (2020) 035

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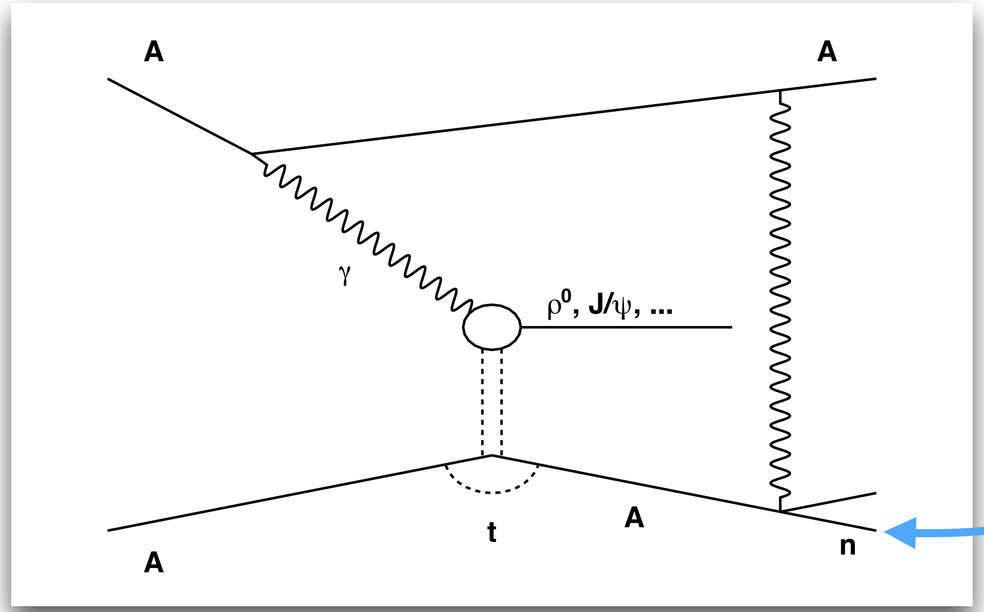

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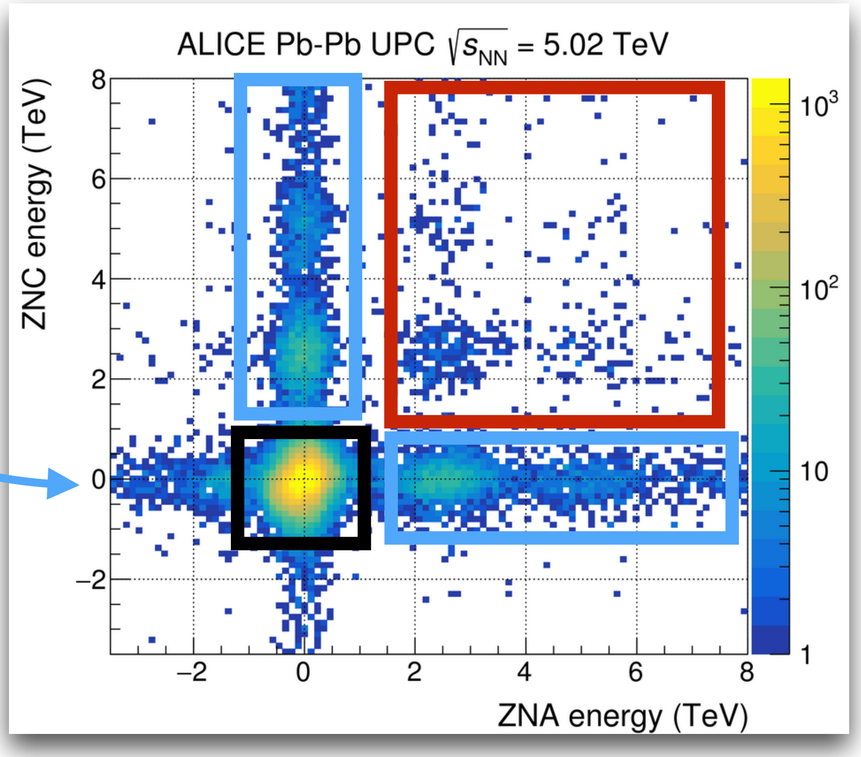

ALICE, JHEP 06 (2020) 035

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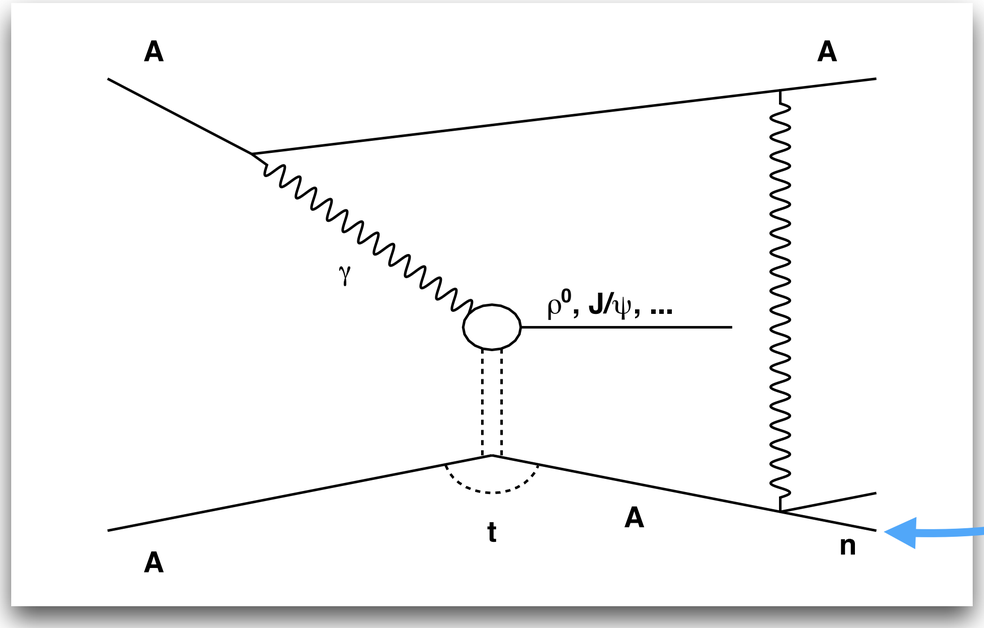

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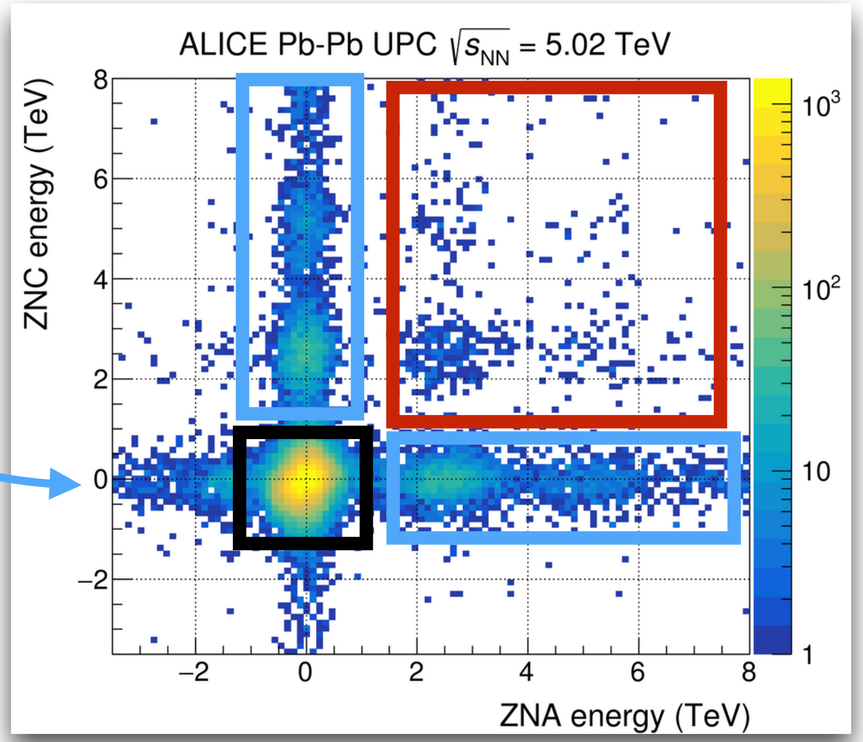
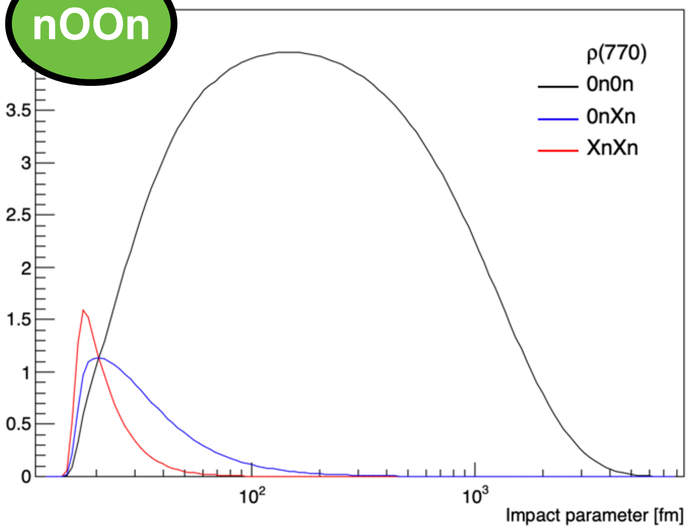


ALICE, JHEP 06 (2020) 035

nOOn



Broz et al., CPC 235 (2020) 107181

0n0n: large impact parameters
0nXn: smaller impact parameters
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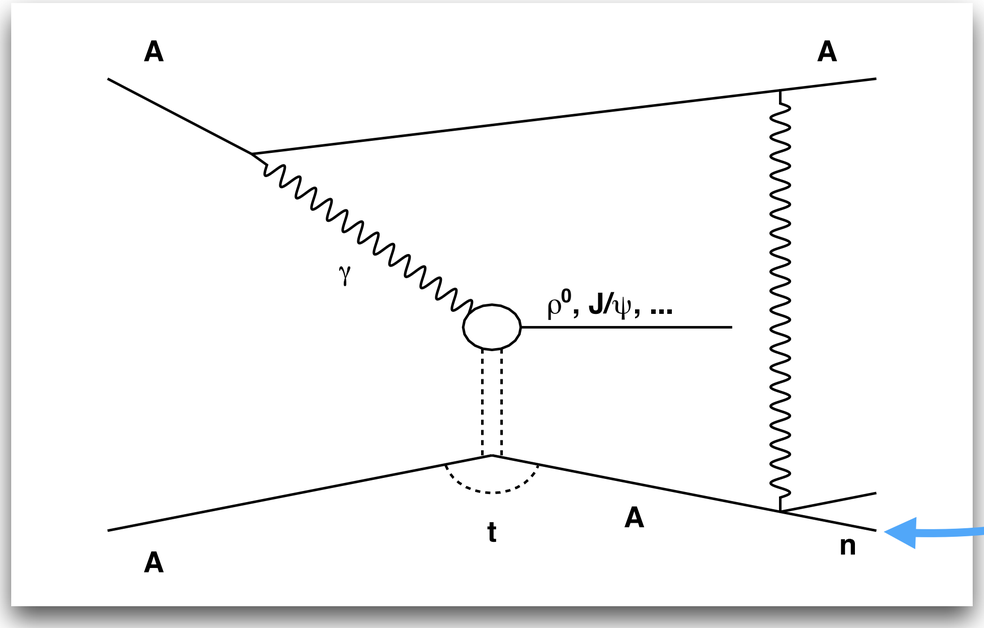

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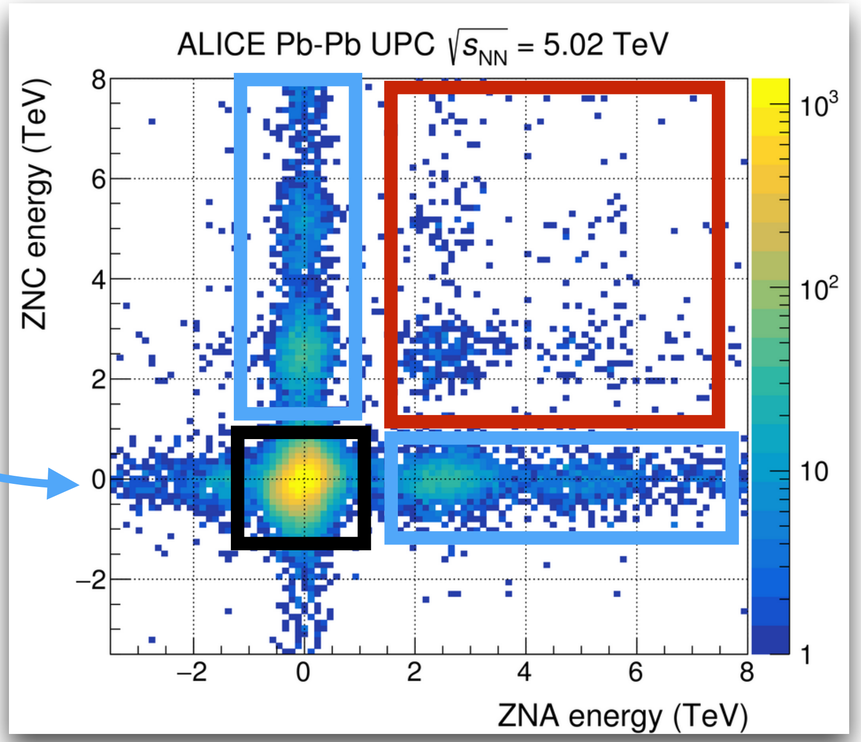
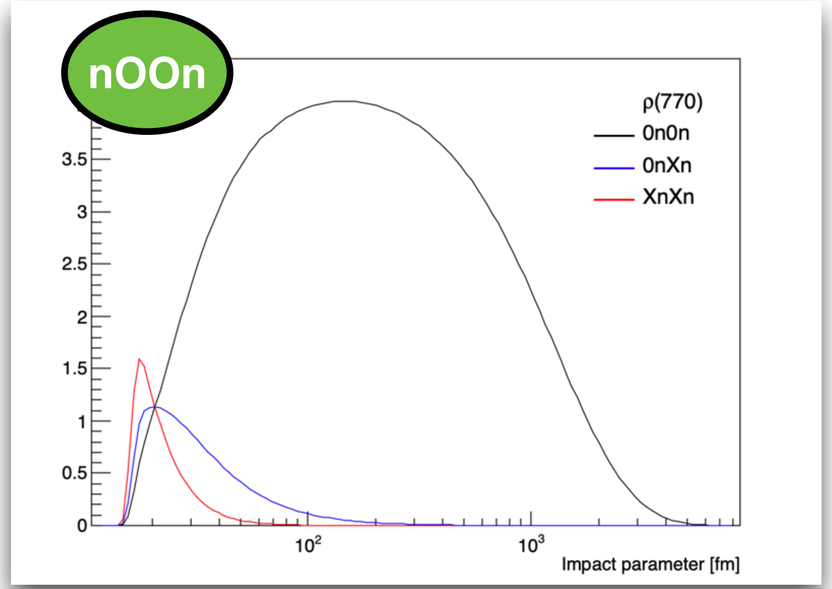


ALICE, JHEP 06 (2020) 035

nOOn



Broz et al., CPC 235 (2020) 107181

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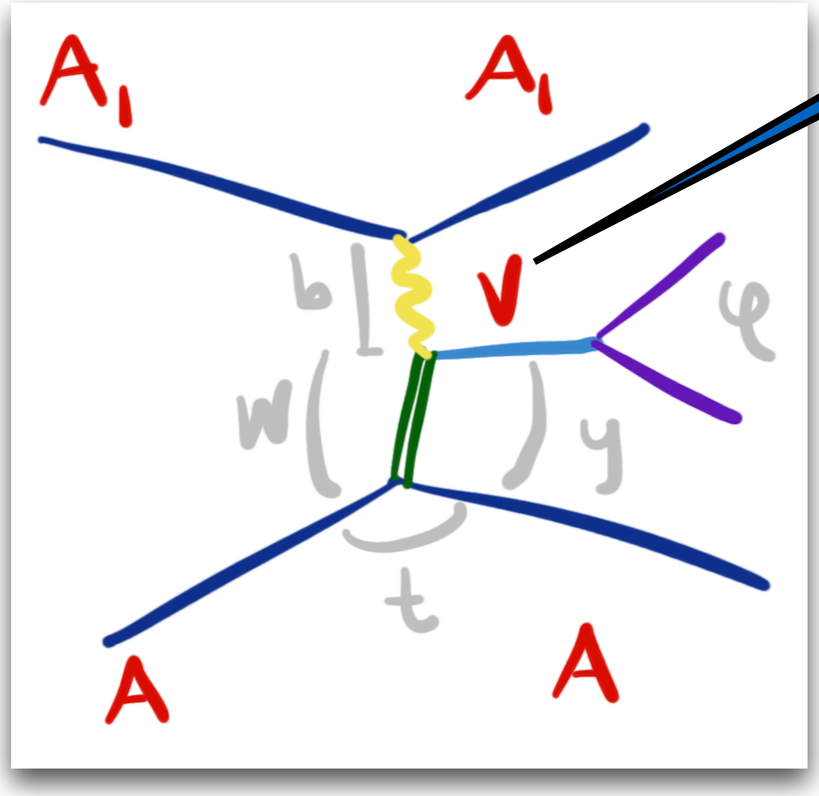
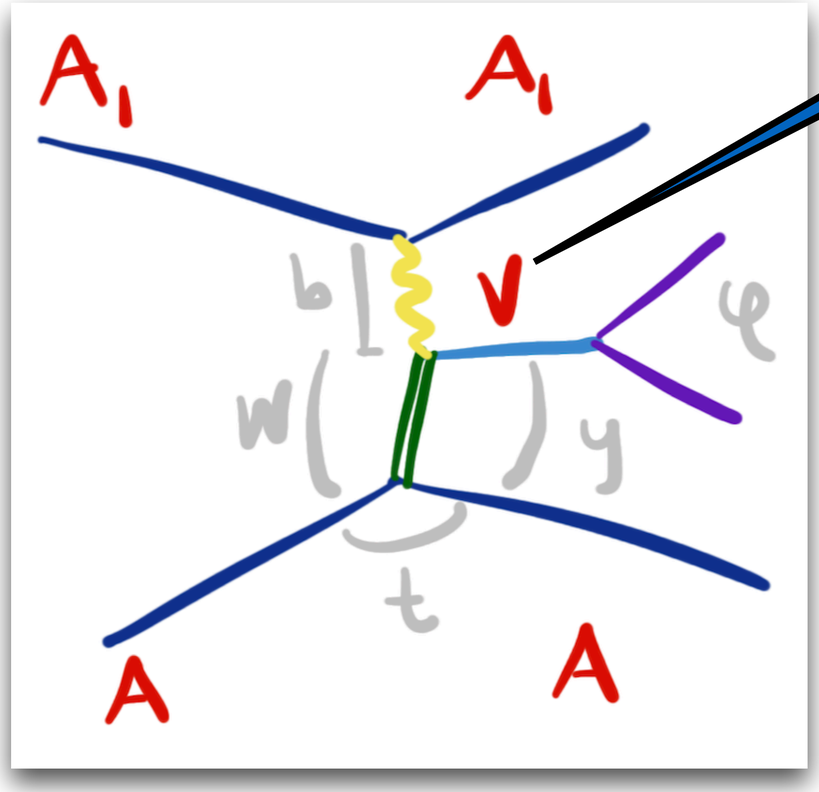
Few events in XnXn wrt 0n0n

Dependence on the scale of the process



Vector meson mass:
Lower the scale of the process

Dependence on the scale of the process



Vector meson mass:
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Expectations:
Saturation appears earlier at lower scales

m Dependence on the scale of the process

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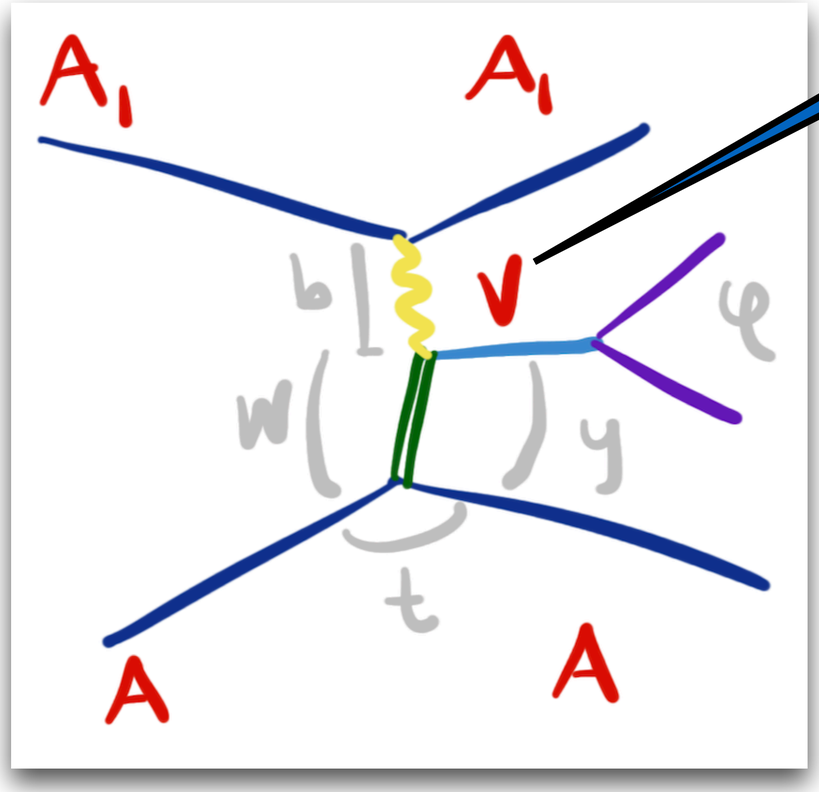

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EIC

Continuous variation of scale using the virtuality of the photon

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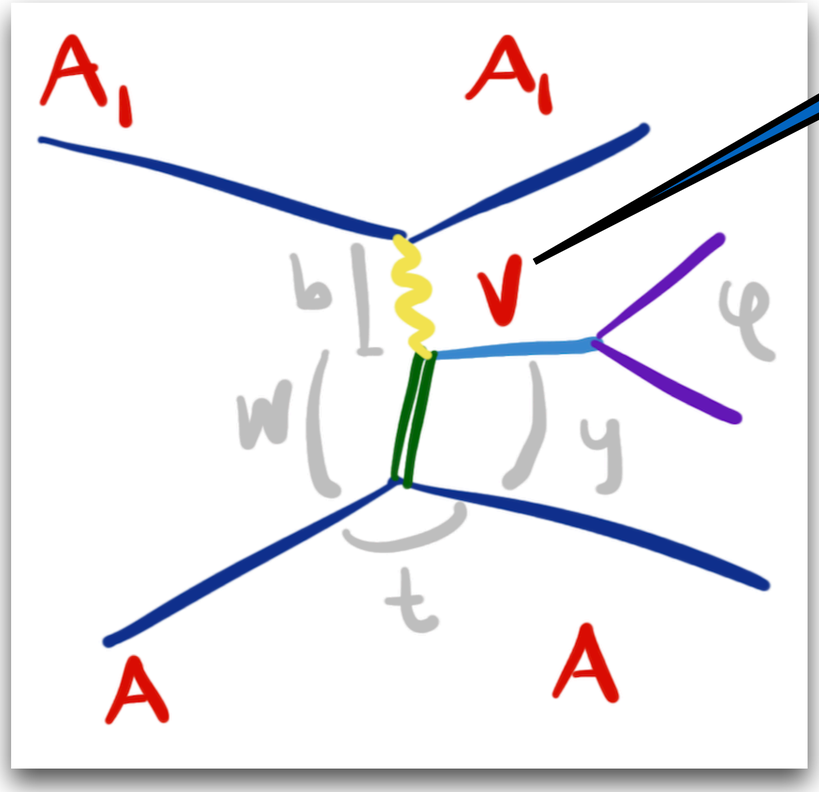

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But if the scale is too low, pQCD may not be applicable any more:
Semi-hard scale ⇨ approach to the black-disc limit of QCD

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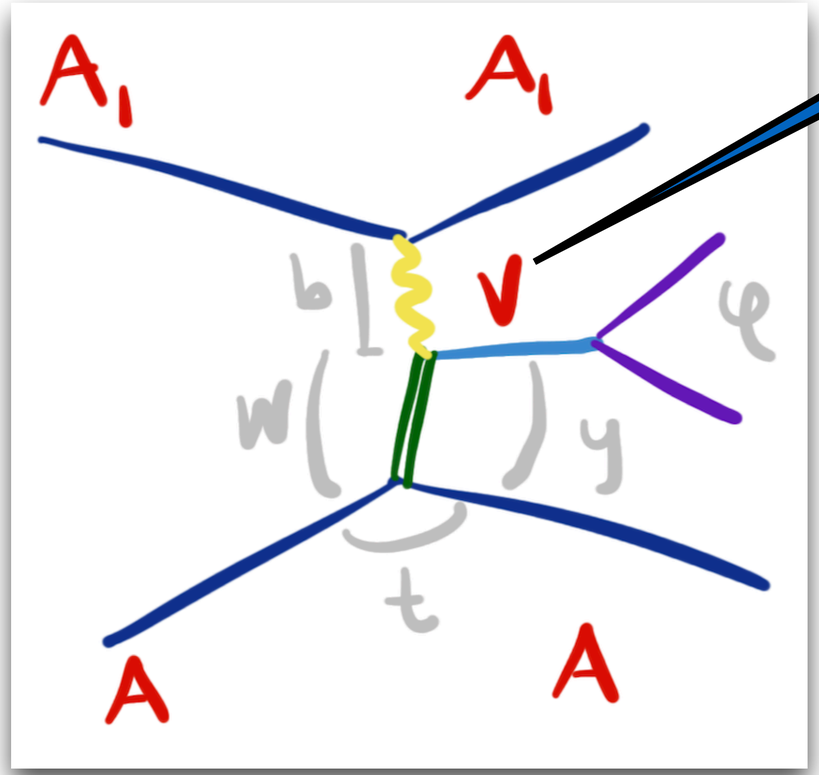

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Semi-hard scale ⇨ approach to the black-disc limit of QCD

Expectations:
Saturation appears earlier at lower scales

At low scales, the cross section is larger
⇨more events available

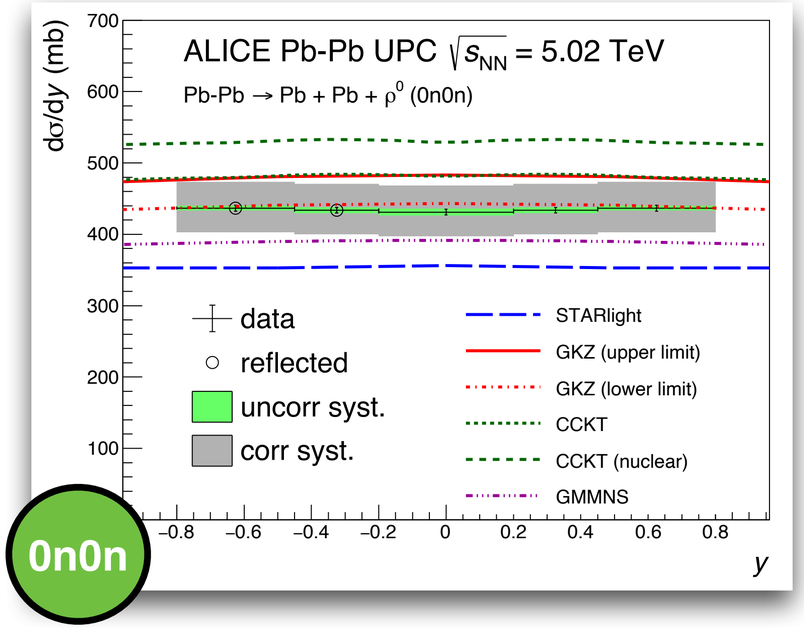
EIC

Continuous variation of scale using the virtuality of the photon

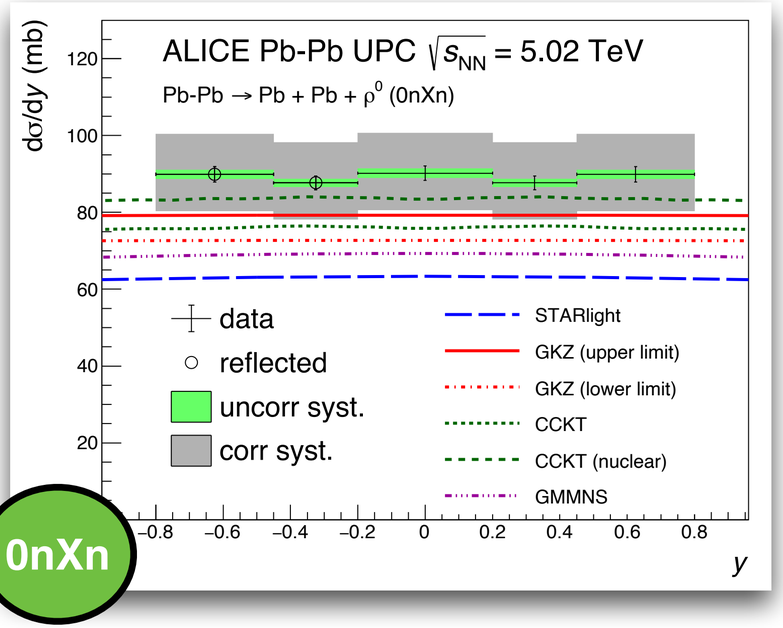
ρ(770)

ρ(770) in Pb-Pb as seen by ALICE

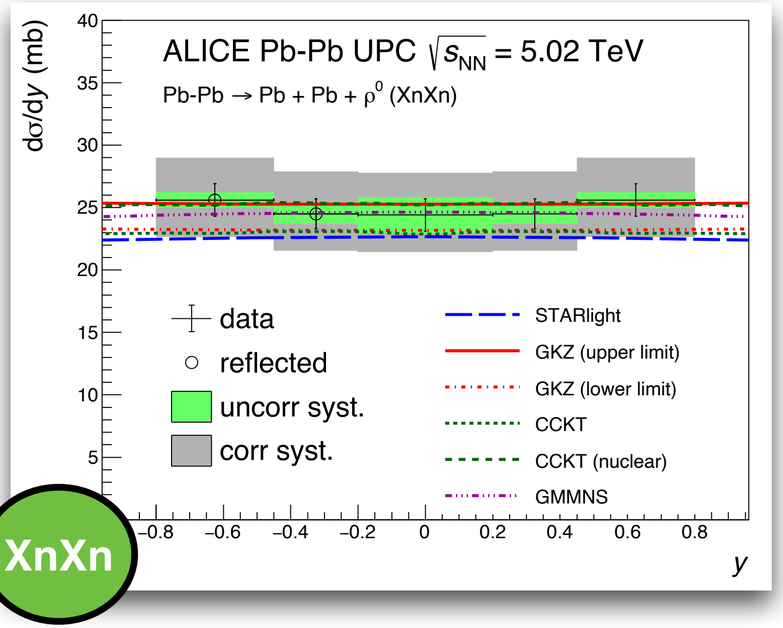
Testing the EMD method at midrapidity



0n0n



0nXn



XnXn

ALICE, JHEP 06 (2020) 035

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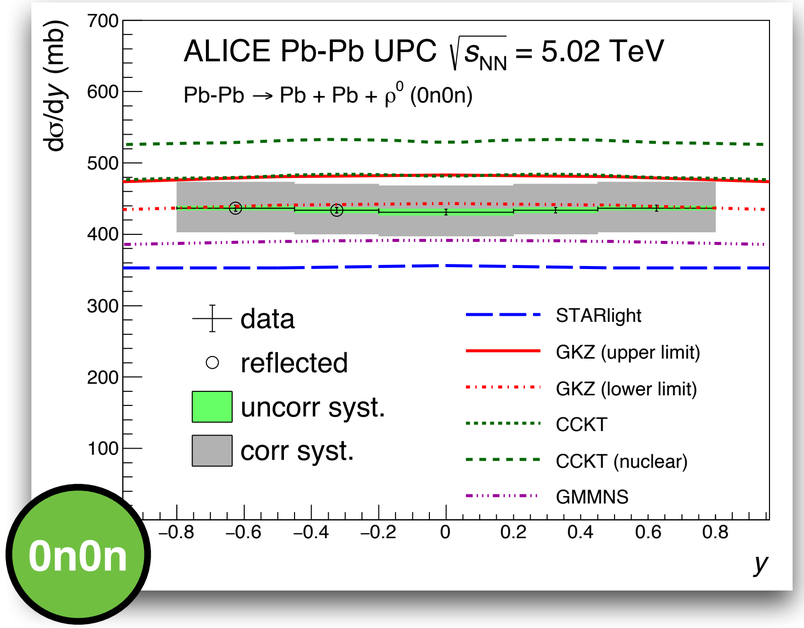

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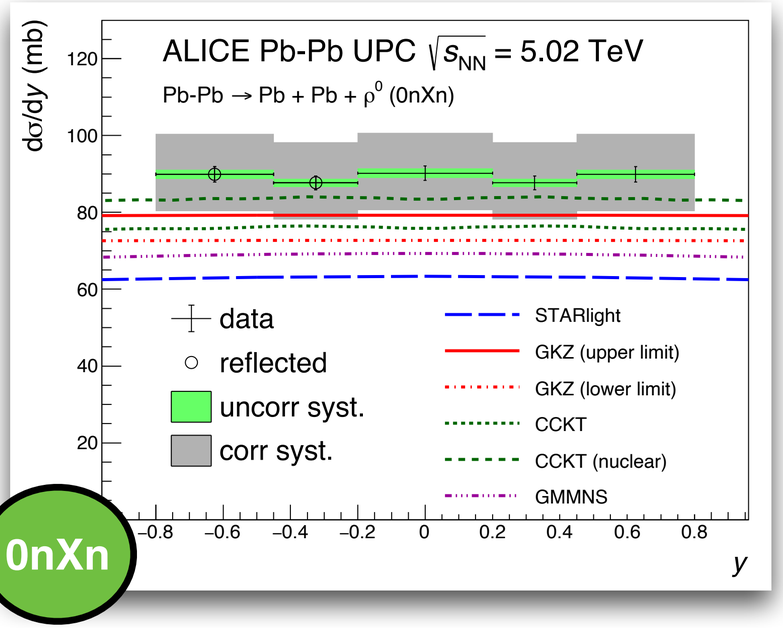

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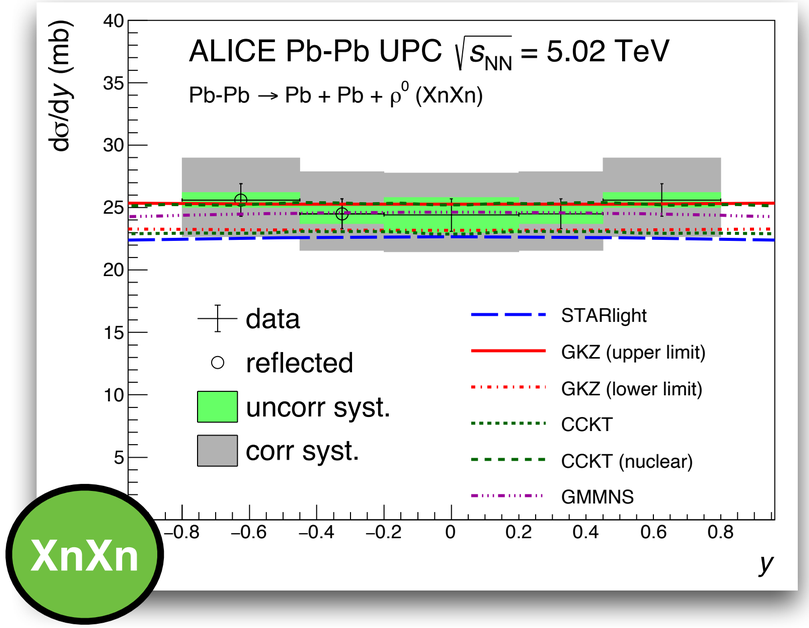

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ALICE, JHEP 06 (2020) 035

Models more or less follow the data, the idea seems to work!

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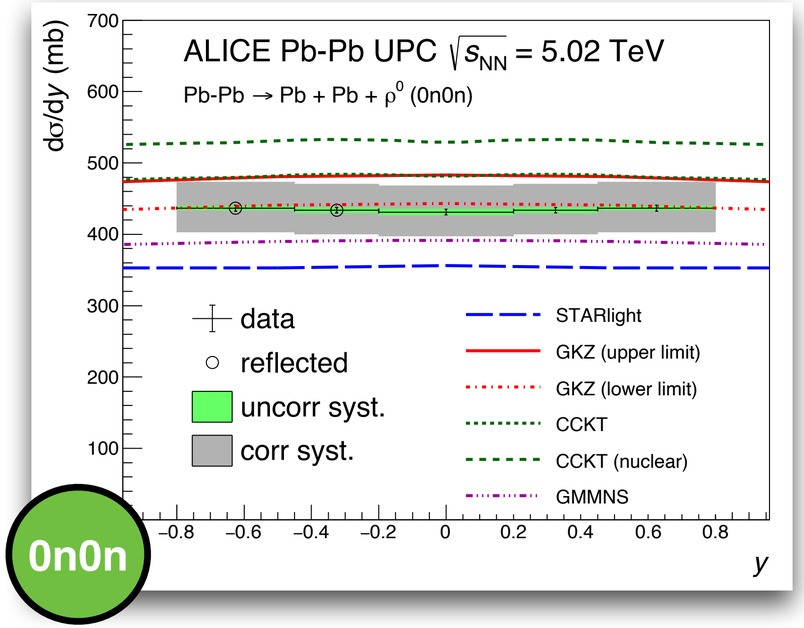

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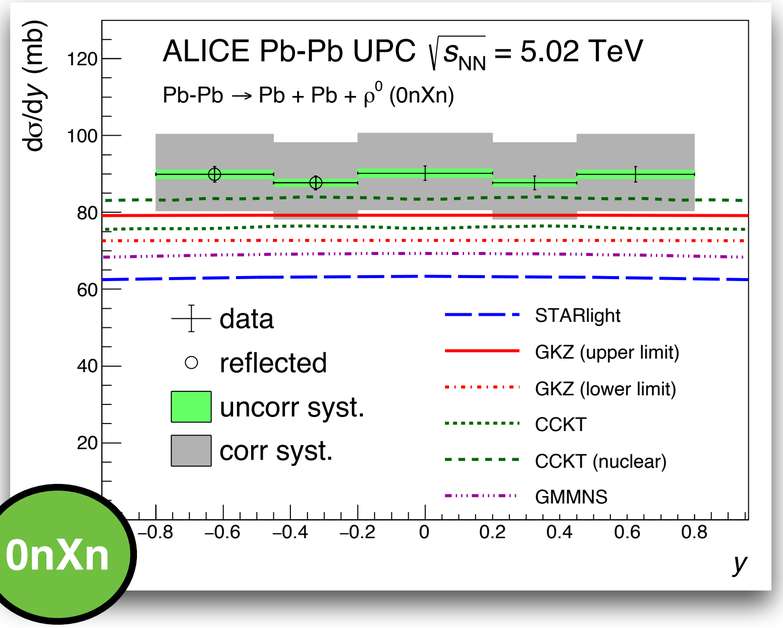

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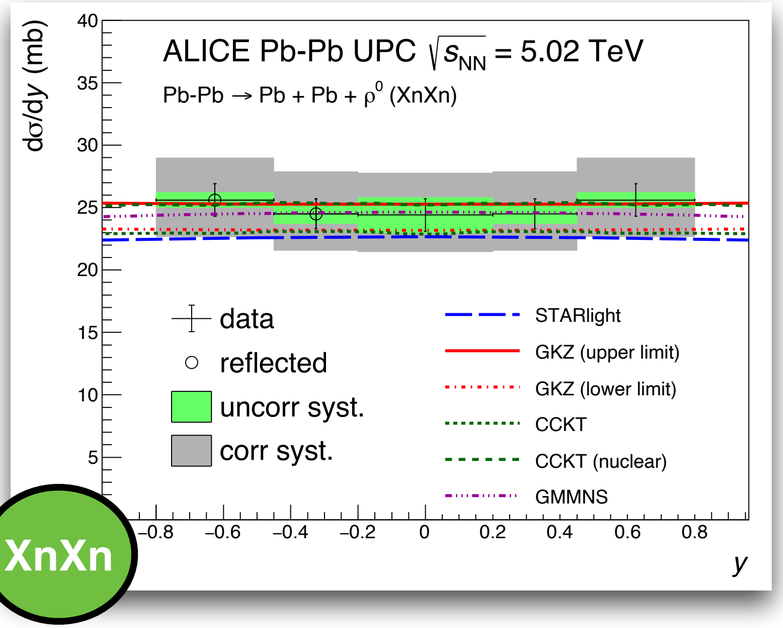

XnXn

ALICE, JHEP 06 (2020) 035

Models more or less follow the data, the idea seems to work!

Run 2

To be applied to J/ψ data at all rapidities

Parenthesis: a comment on the exclusivity condition

Once the precision of the measurement goes to the percent level, implementation of the exclusivity condition requires care

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The use of the same detector to measure UPCs and head-on Pb-Pb collisions, jeopardises single track sensitivity

⇨ the separation of peripheral and UPCs gets complicated

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Parenthesis: a comment on the exclusivity condition

The precision is increased with more events
⇨ In Run 3+4 this implies more pile-up

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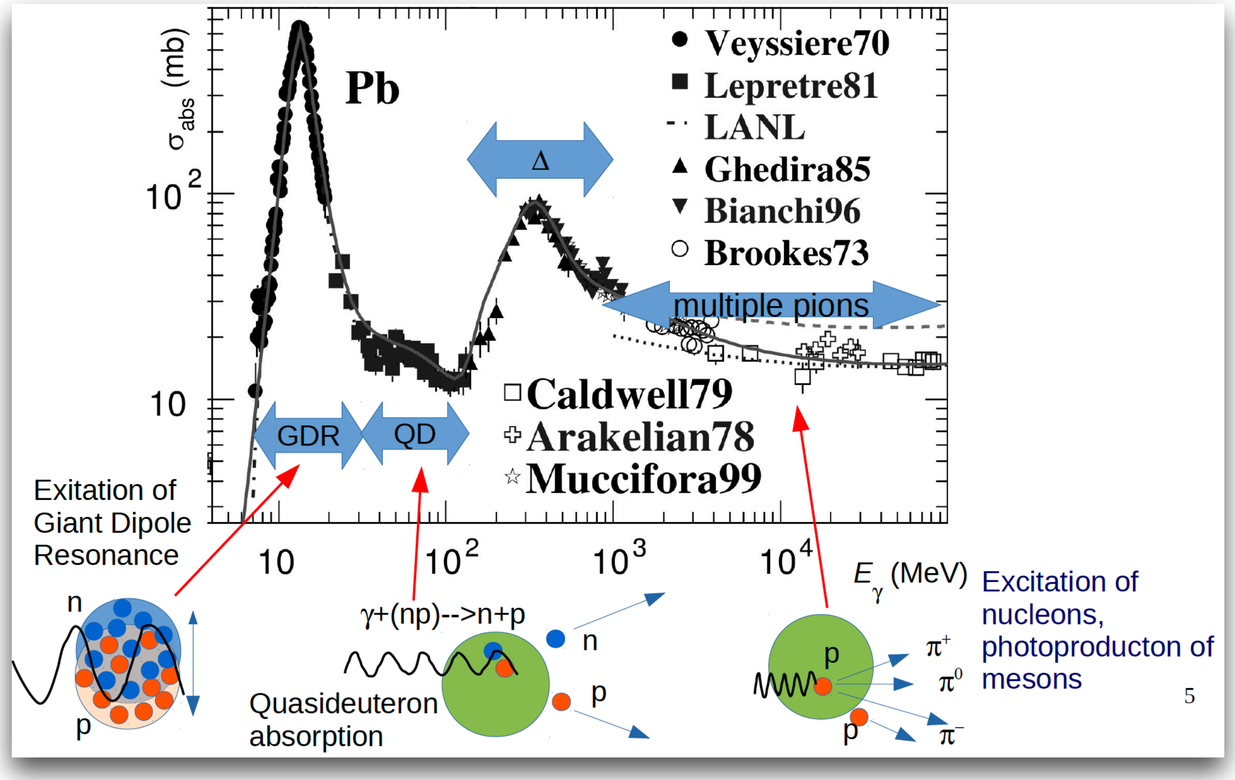
EMD also produces charged particles
⇨ activity vetoes are inefficient

Slide from Igor Pshenichnov



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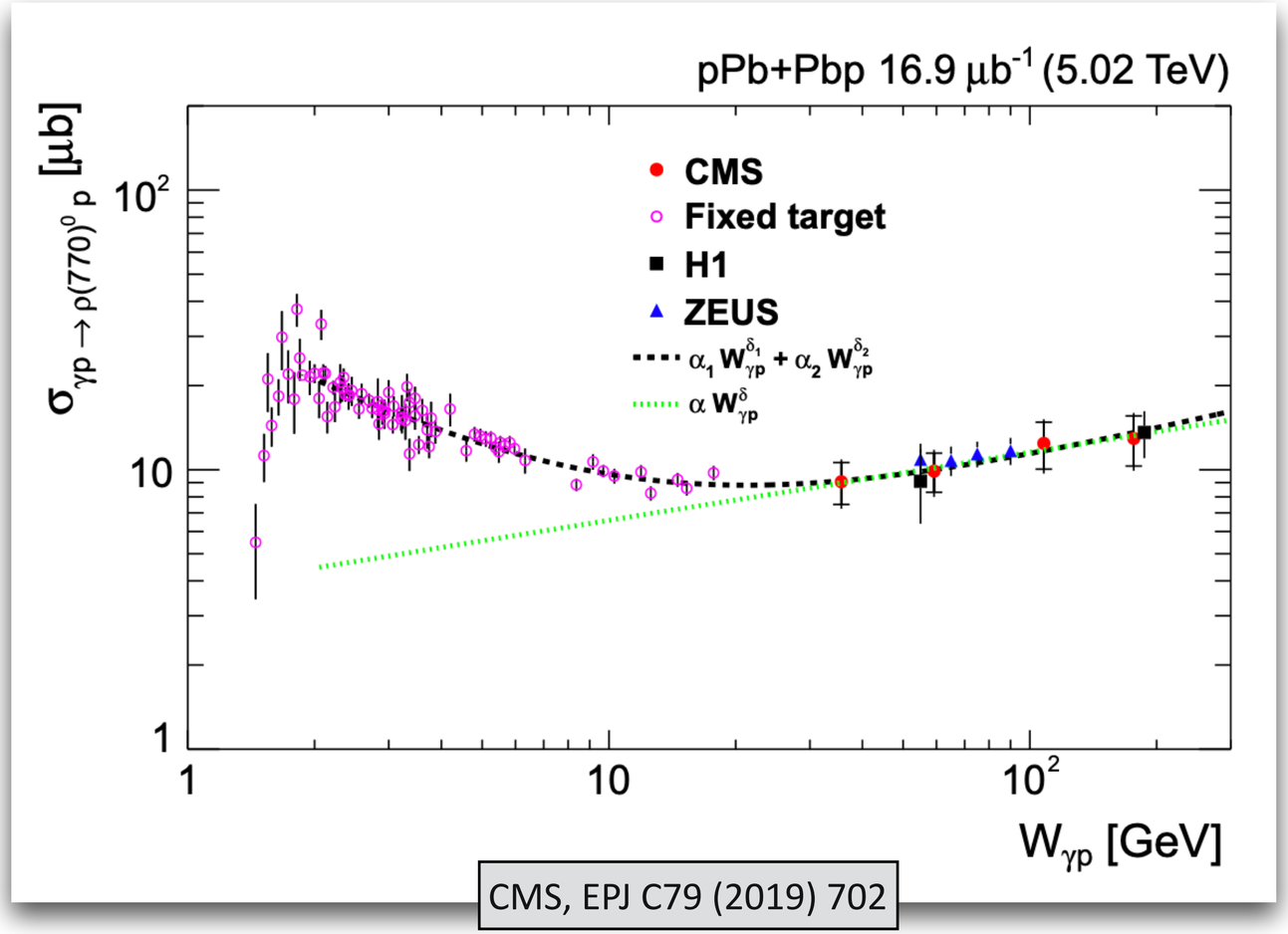
ρ(770) in p-Pb as seen by CMS: energy evolution



CMS, EPJ C79 (2019) 702

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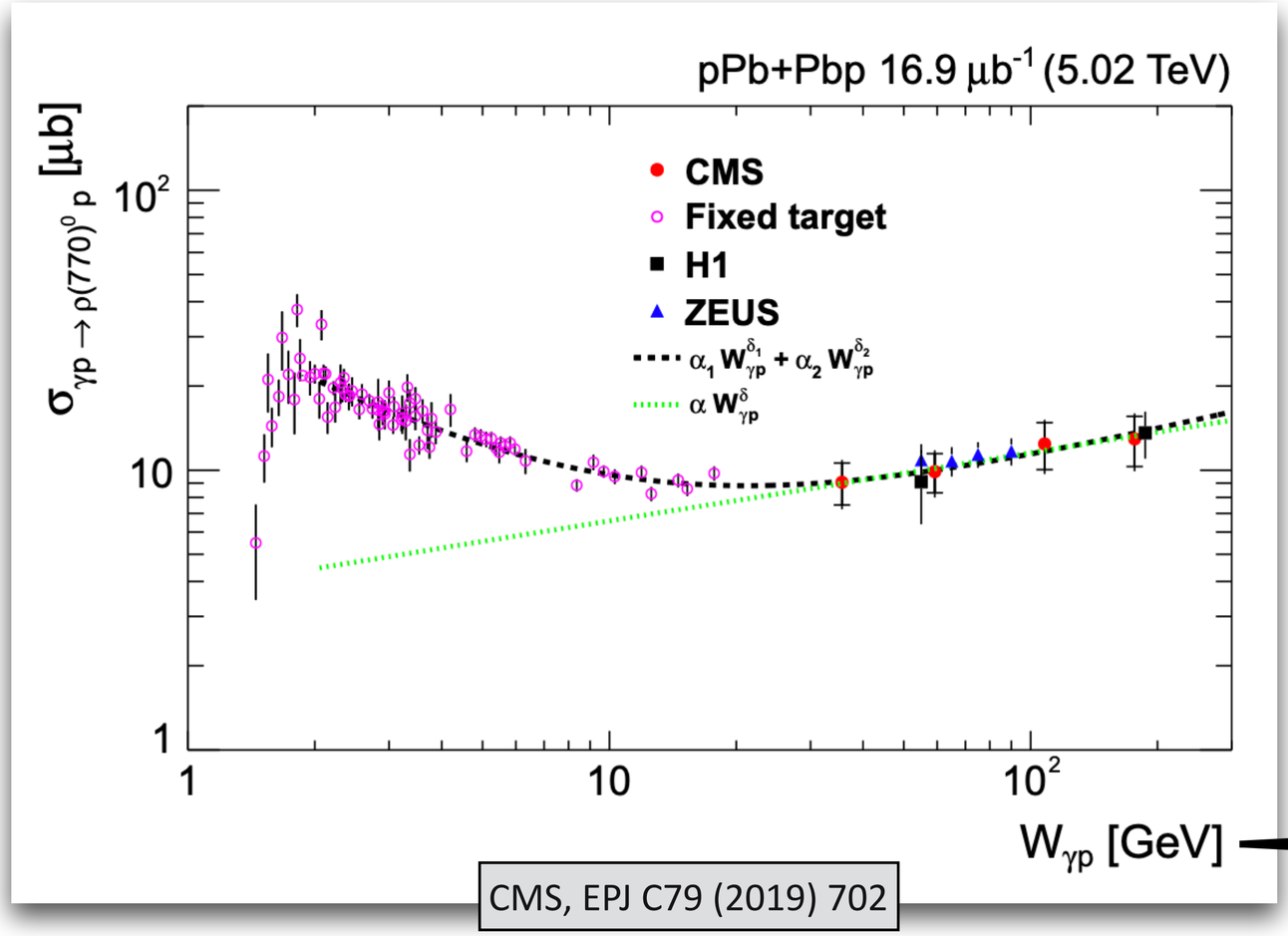

CMS, EPJ C79 (2019) 702

Up to now, similar energy range as in HERA
Cross section slowly growing

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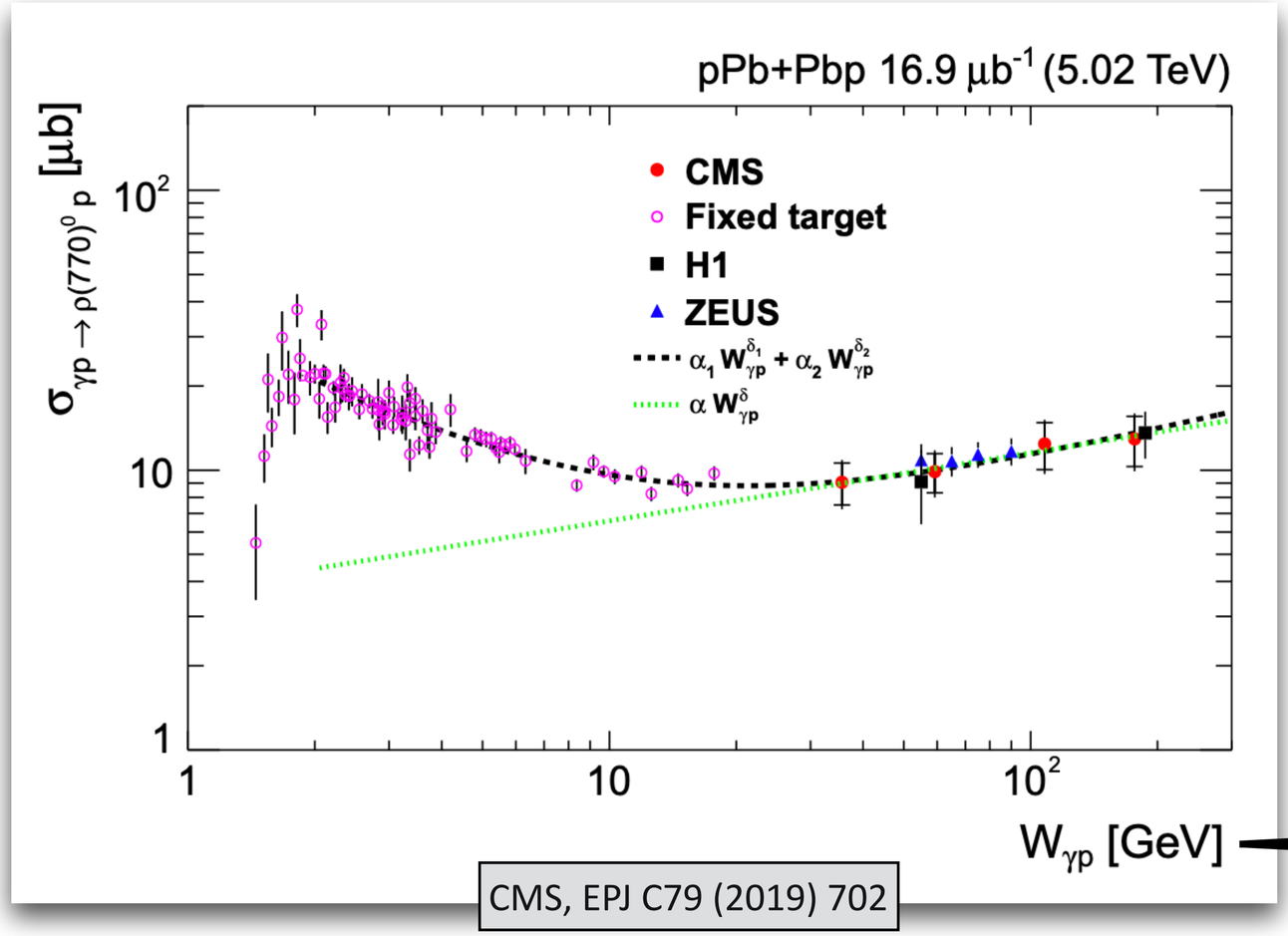

CMS, EPJ C79 (2019) 702

Run 3+4

LHCb and ALICE may be able to measure this at higher energies

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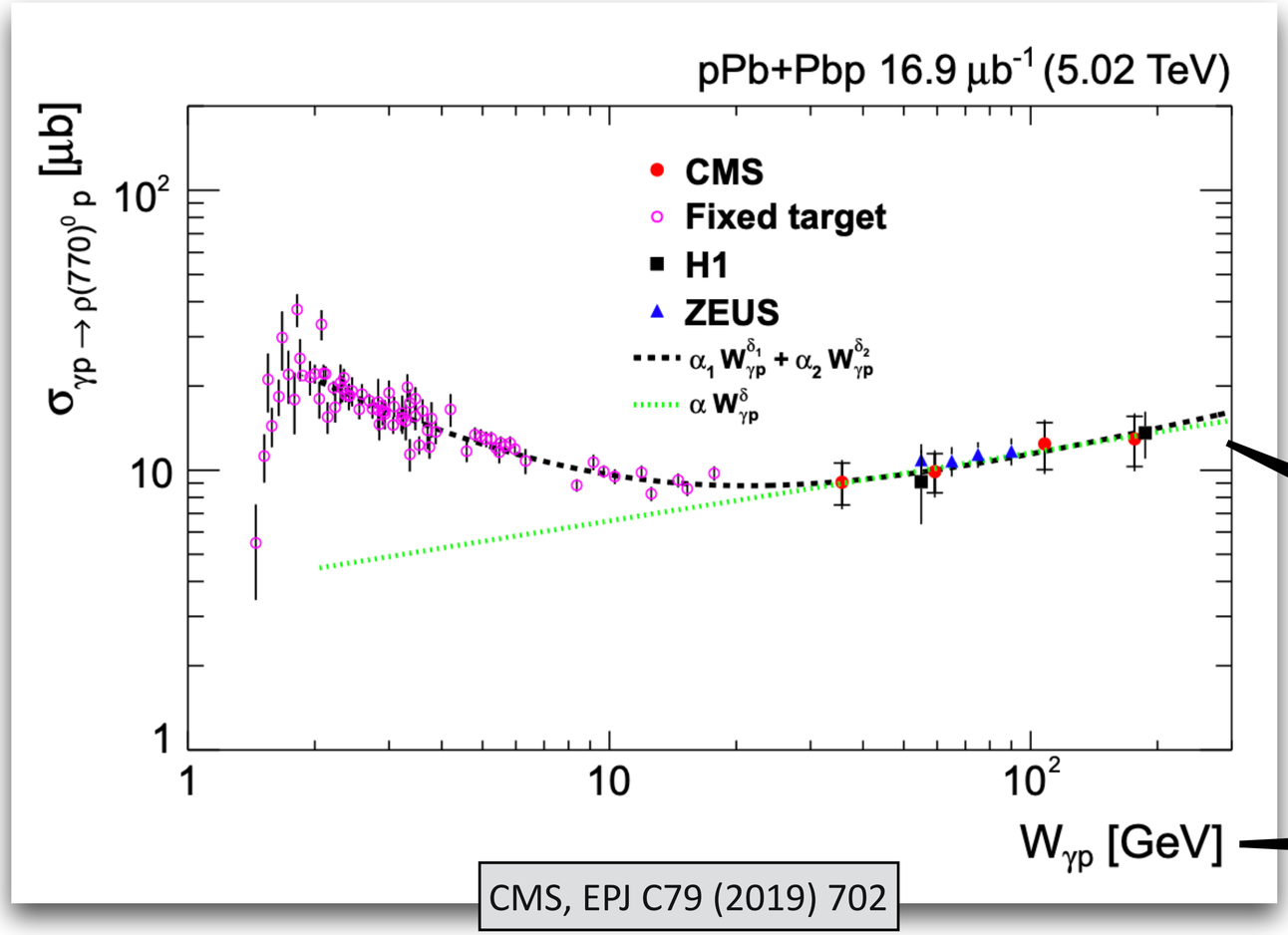


CMS, EPJ C79 (2019) 702

Run 3+4

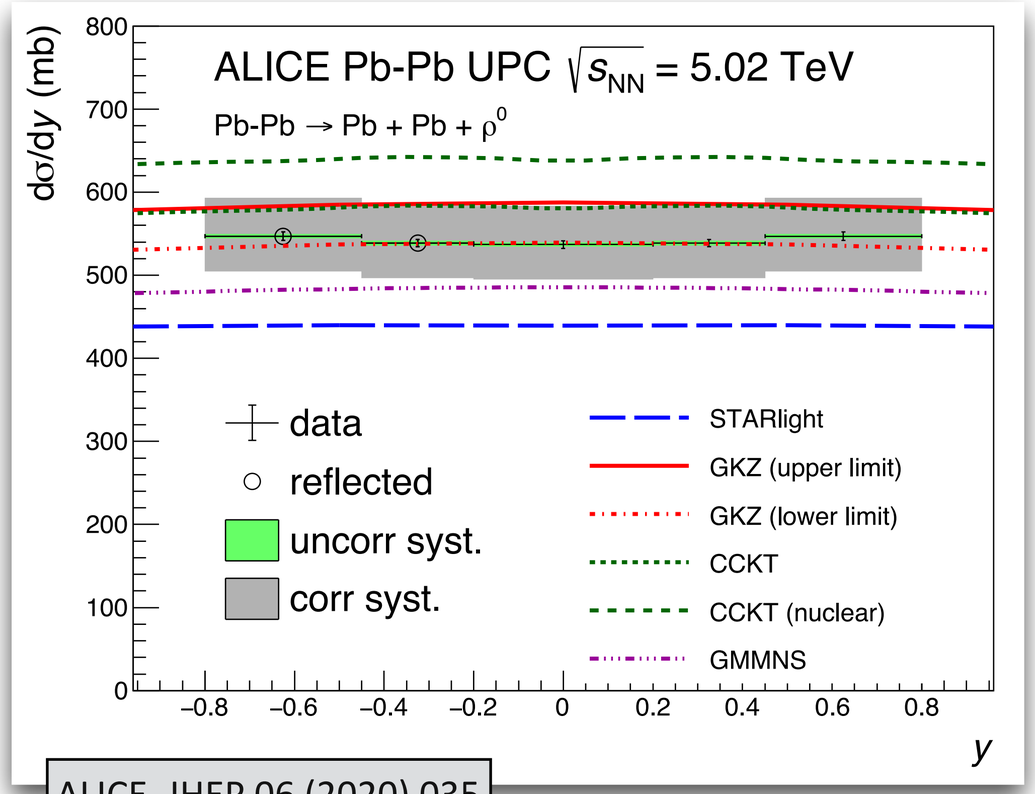
LHCb and ALICE may be able to measure this at higher energies

How does this rise with energy looks like for Pb?

Up to now, similar energy range as in HERA
Cross section slowly growing

ρ(770)

ρ(770) as seen by many experiments



ALICE, JHEP 06 (2020) 035

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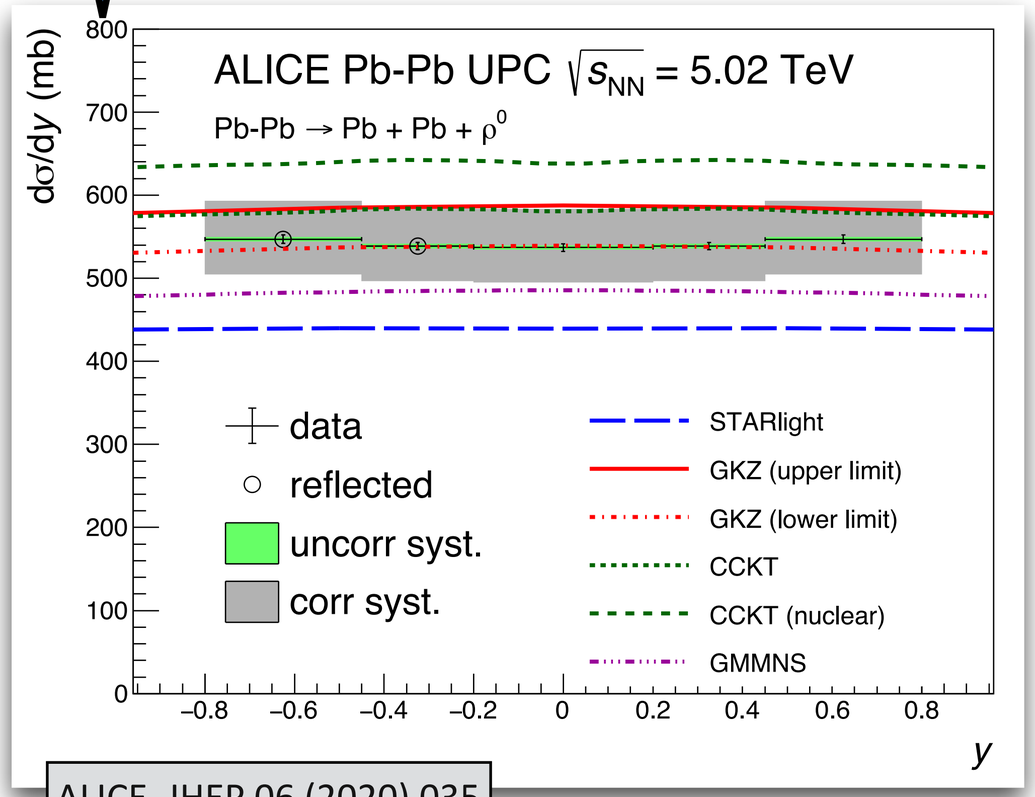
Huge cross section!



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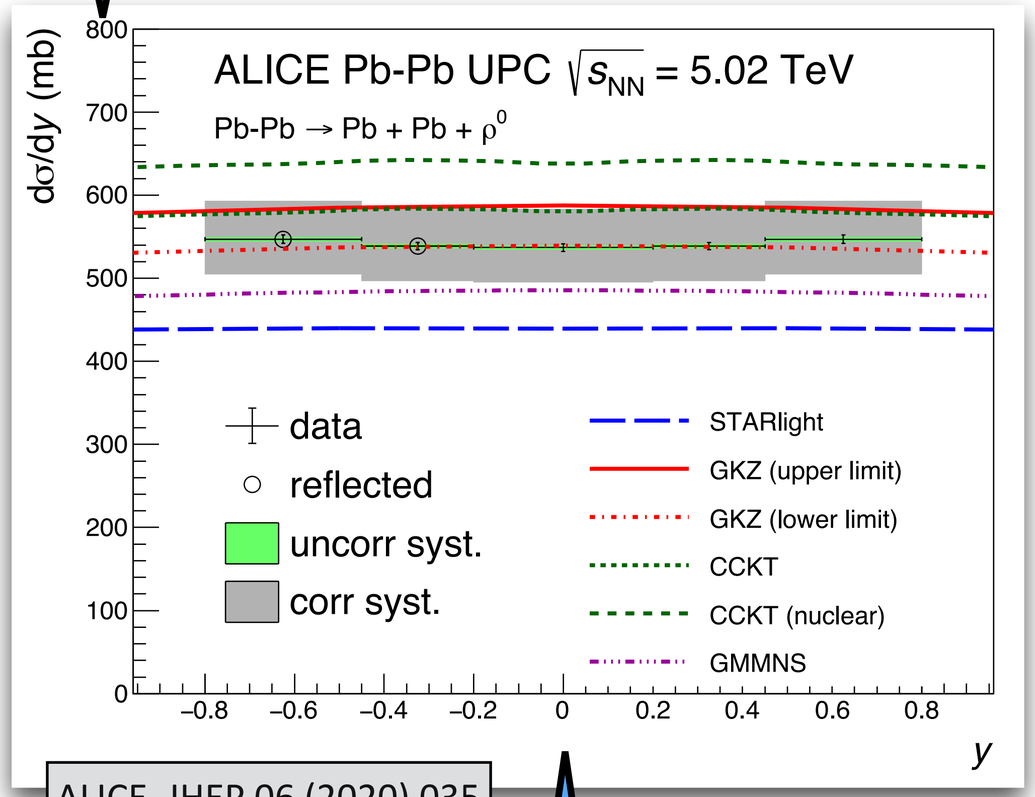

ALICE, JHEP 06 (2020) 035

Measurement at y=0
⇨ no ambiguity

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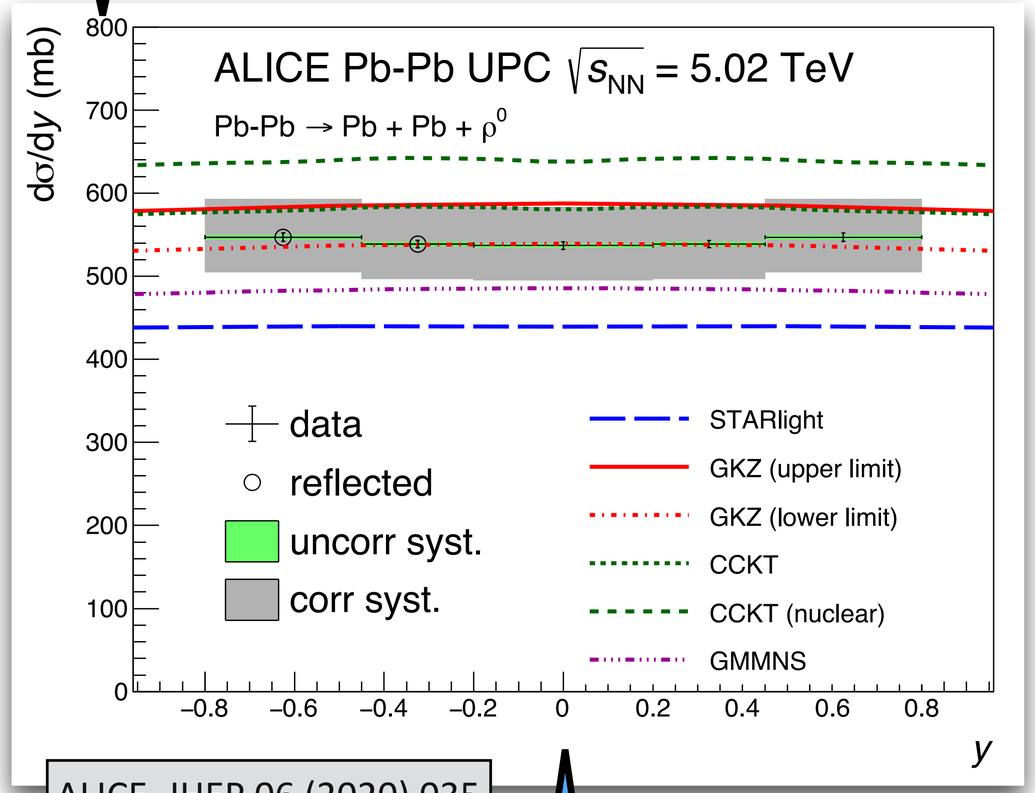

ALICE, JHEP 06 (2020) 035

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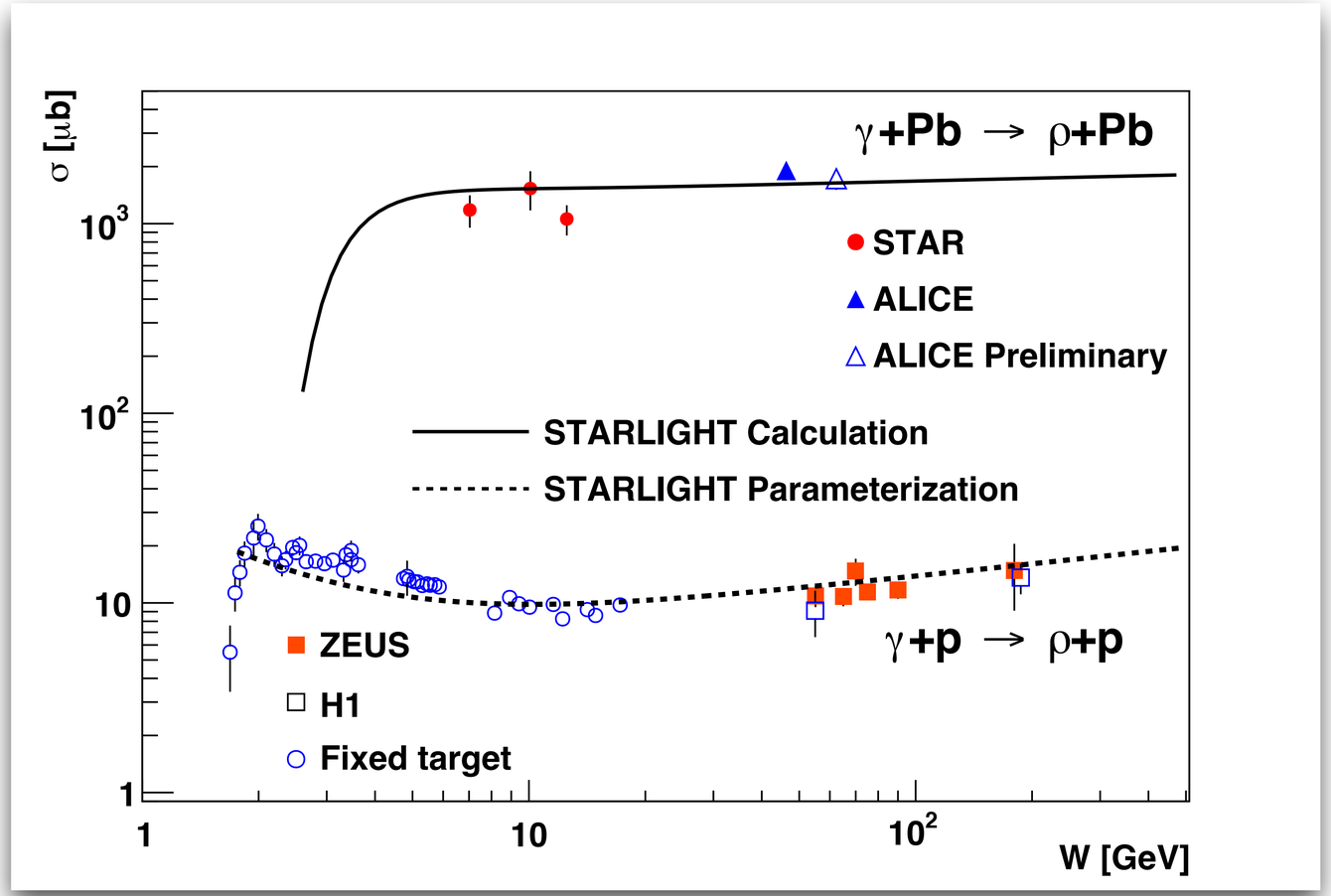

Plot produced by **Joakim Nystrand**
(personal communication, 2018)

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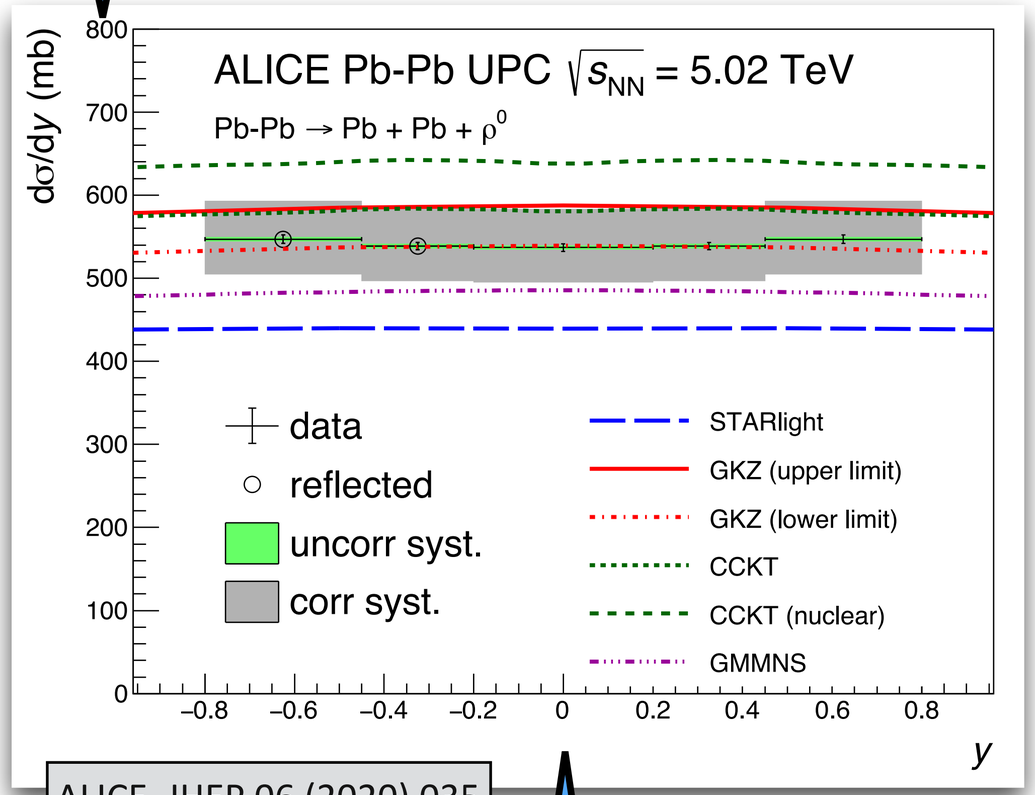

ALICE, JHEP 06 (2020) 035

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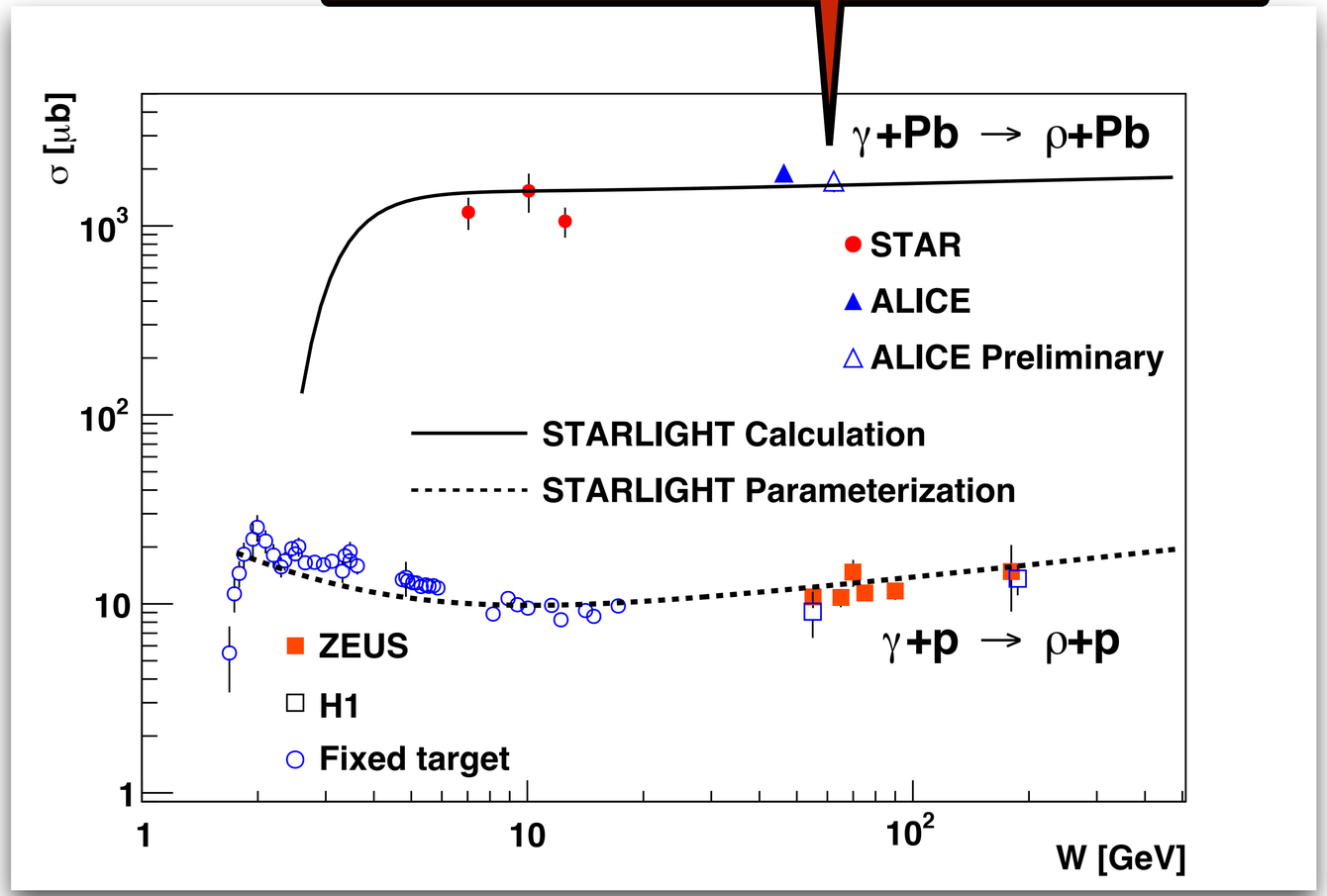
Open question:
Have we reached the black-disc limit?



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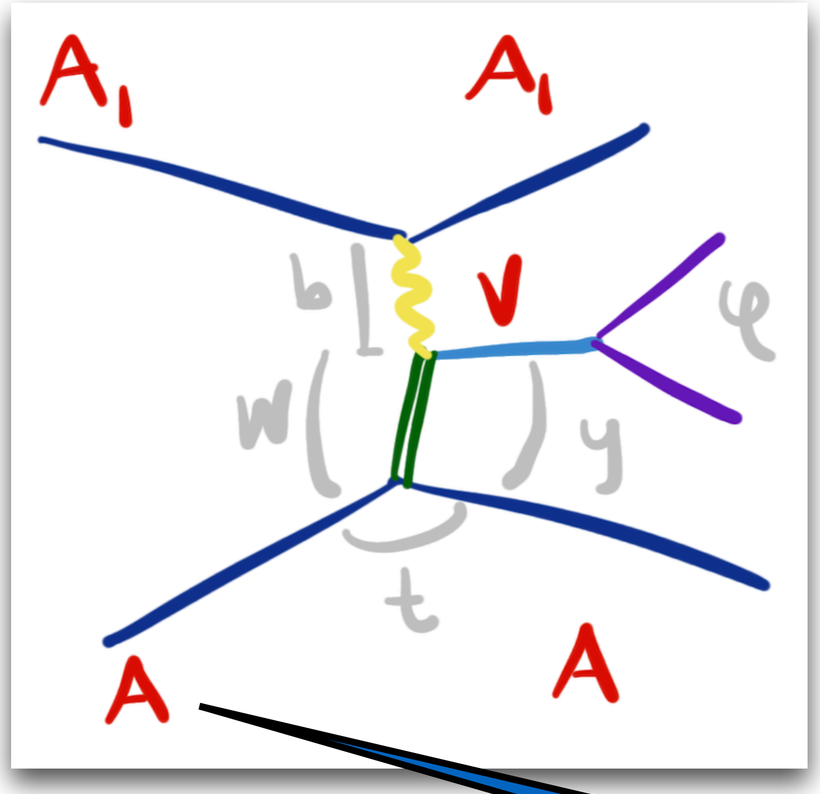
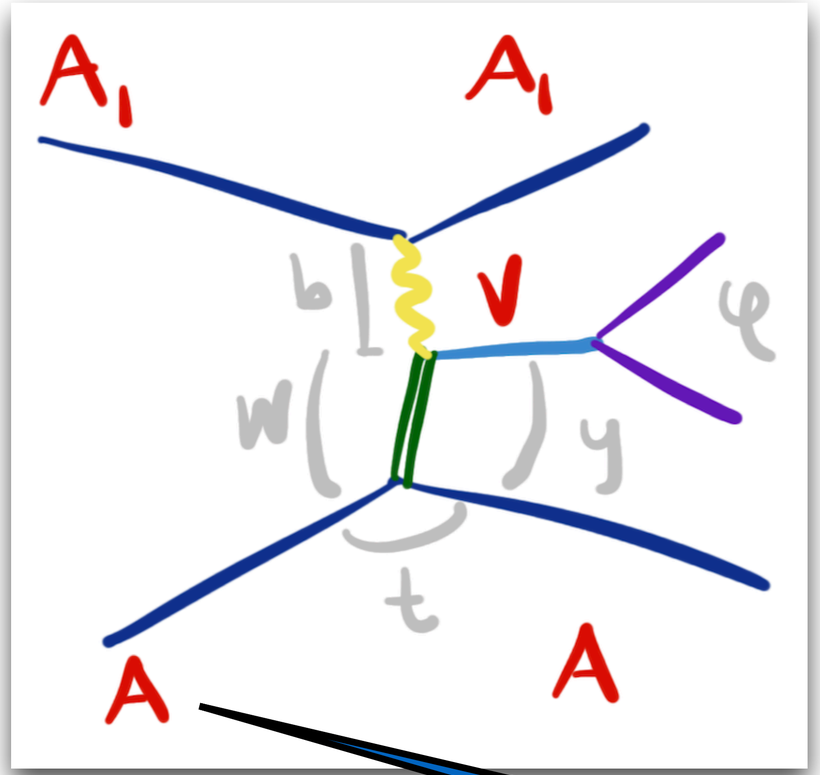
A

Dependence of the gluon distribution on A



Mass number dependence:
Early appearance of saturation?

A Dependence of the gluon distribution on A

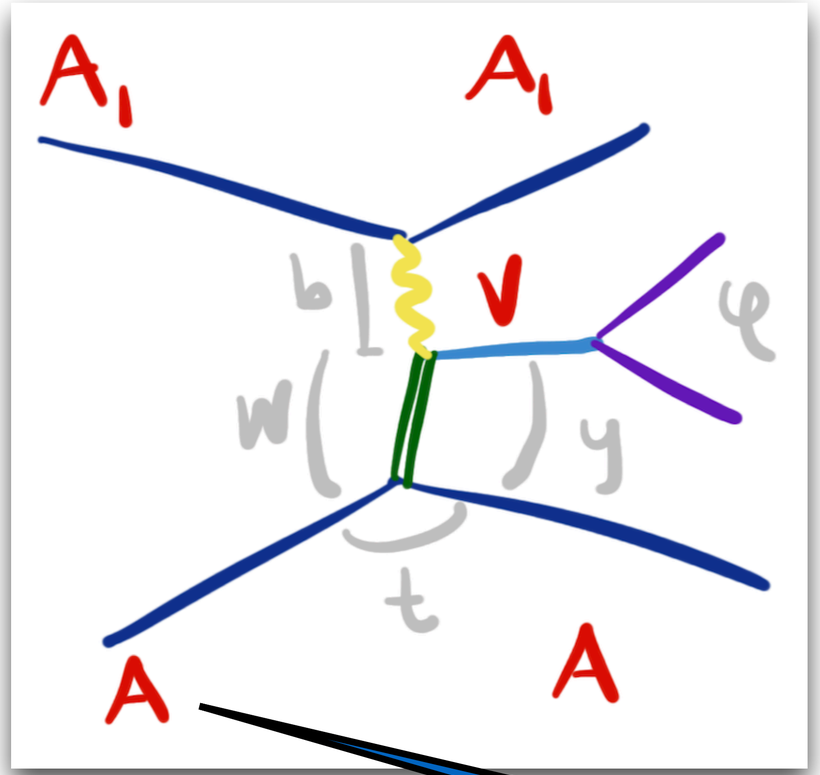


Expectations:
Different A dependence of a pure nuclear form factor and of the black-disc limit

Mass number dependence:
Early appearance of saturation?

A

Dependence of the gluon distribution on A



Expectations:
Different A dependence of a pure nuclear form factor and of the black-disc limit

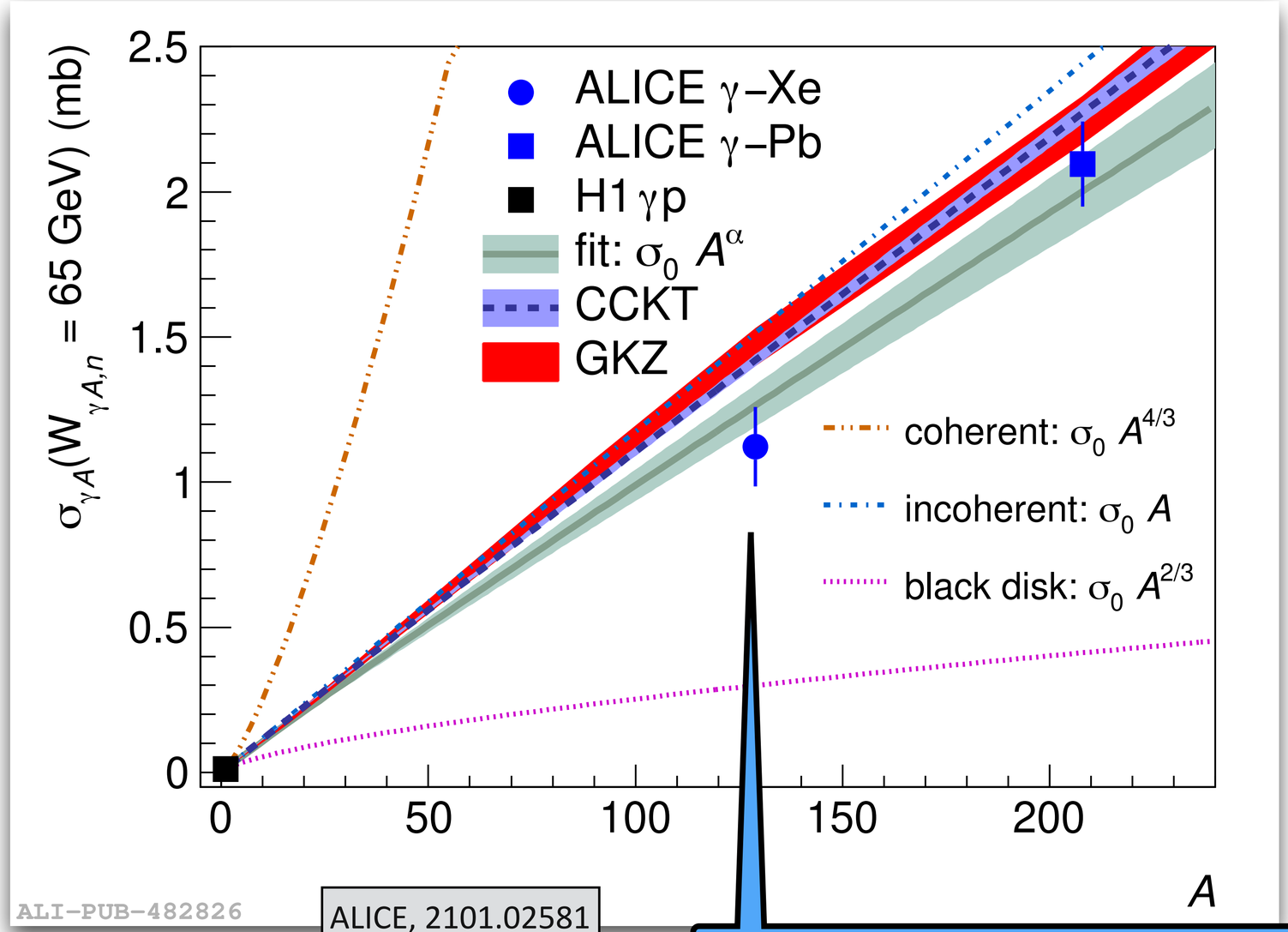
EIC

Many different nuclei can be studied

Mass number dependence:
Early appearance of saturation?

ρ(770)

A dependence of coherent ρ(770) photoproduction by ALICE

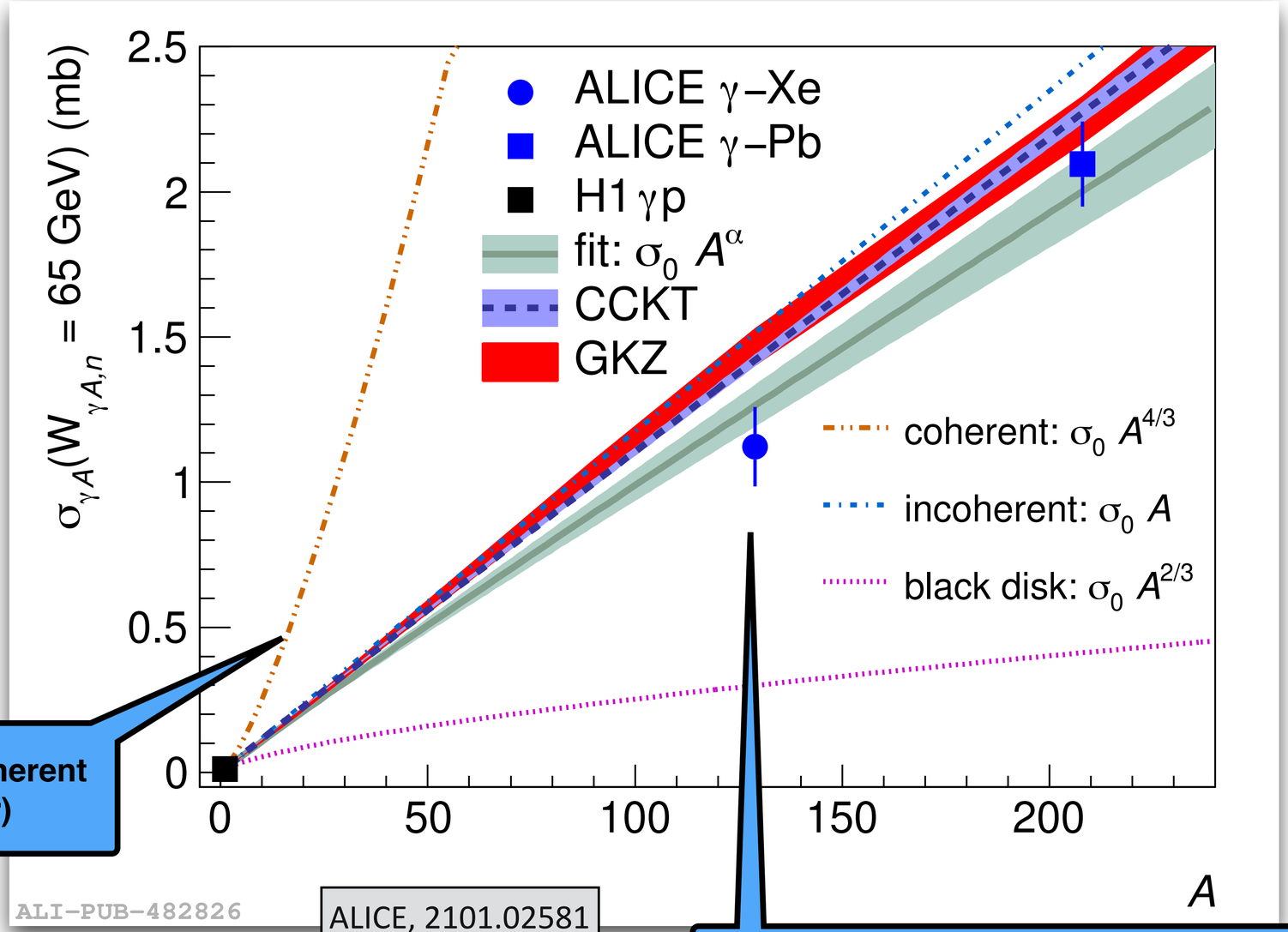


ALICE, 2101.02581

New measurement at y=0: Xe-Xe UPC

ρ(770)

A dependence of coherent ρ(770) photoproduction by ALICE



ALICE, 2101.02581

Expectation from coherent (just form factor)

New measurement at y=0: Xe-Xe UPC

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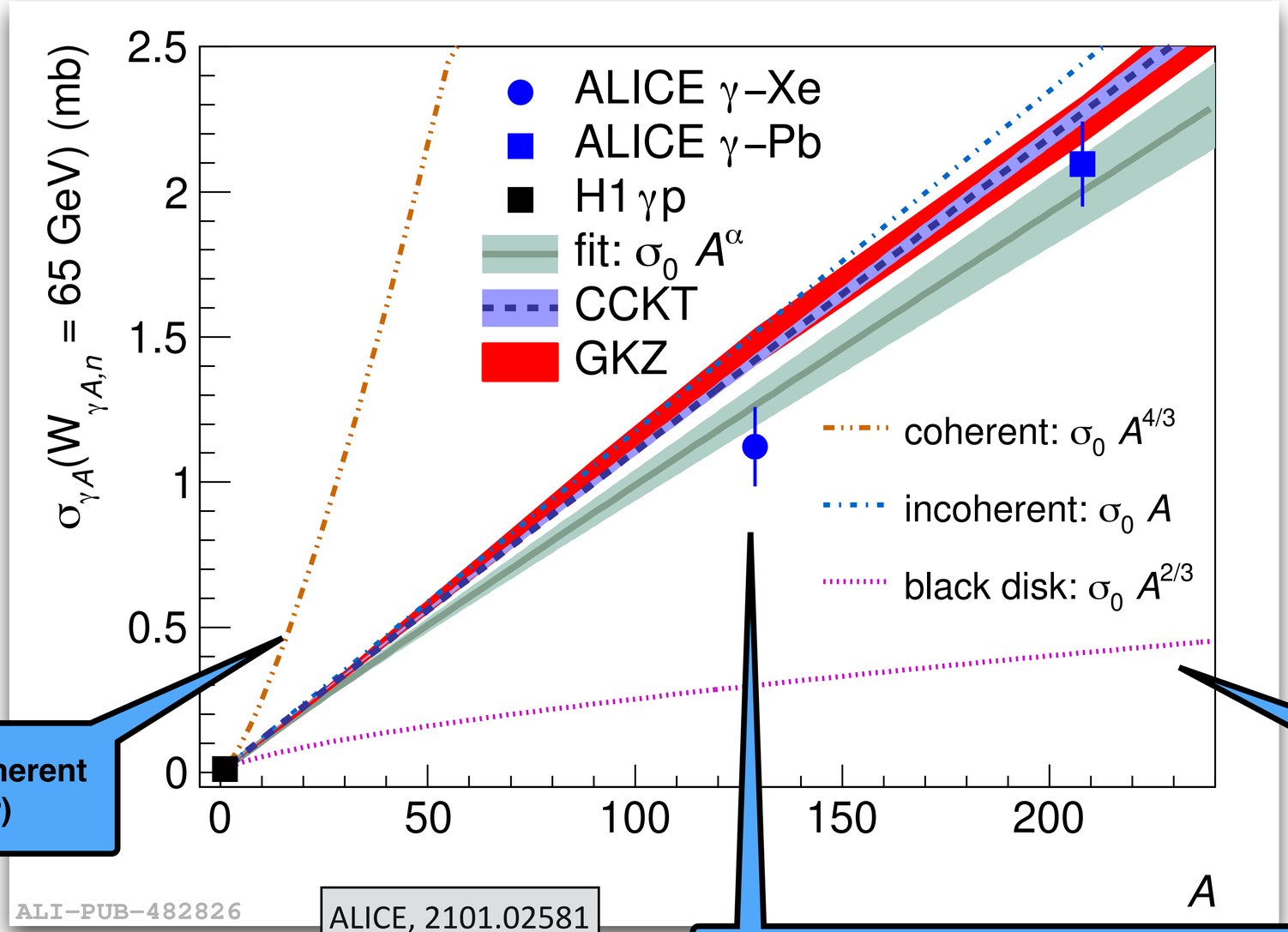

ALICE, 2101.02581

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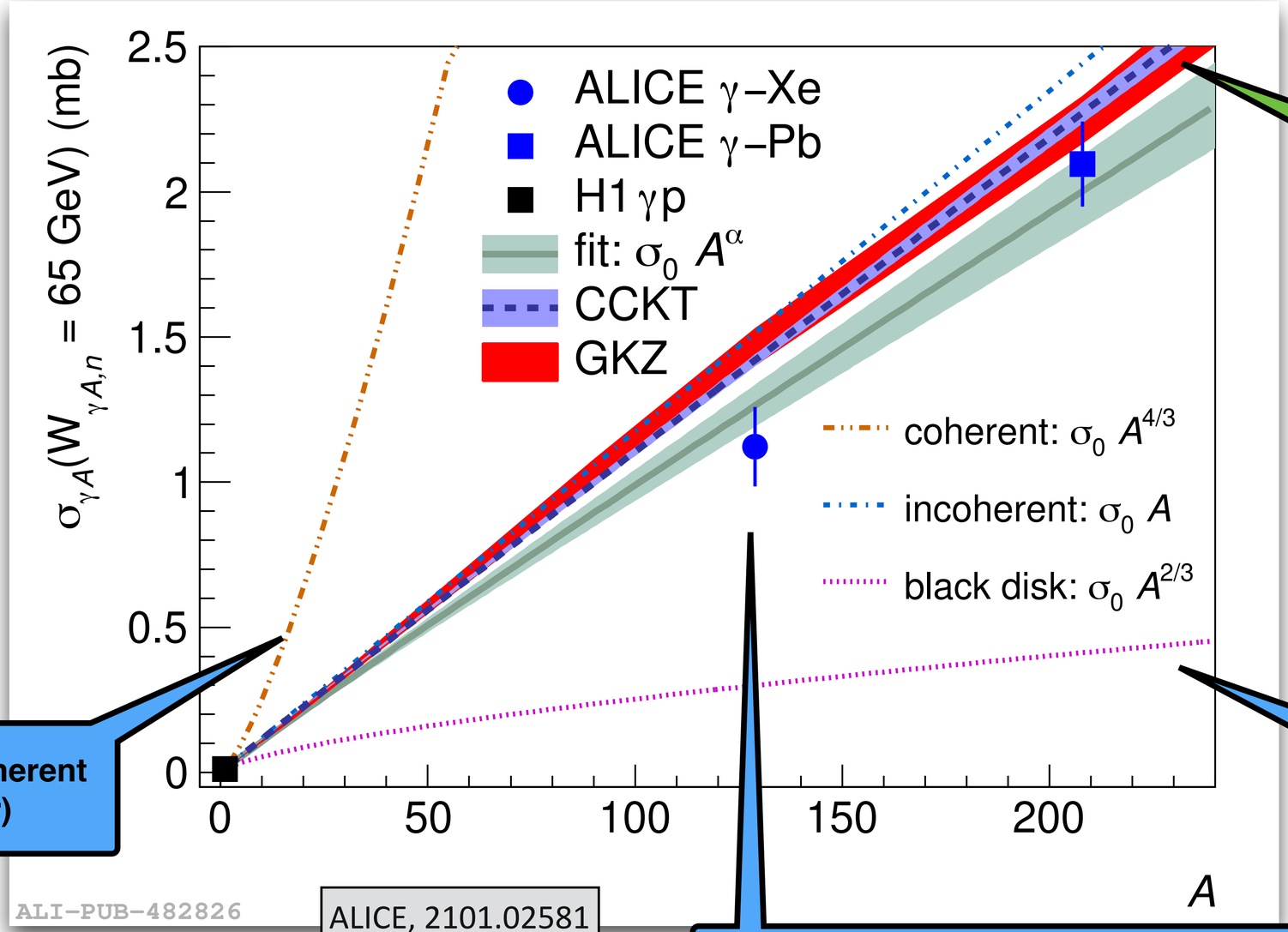


ALICE, 2101.02581

A shadowing based, and a colour dipole model with saturation and hot spots, close to data

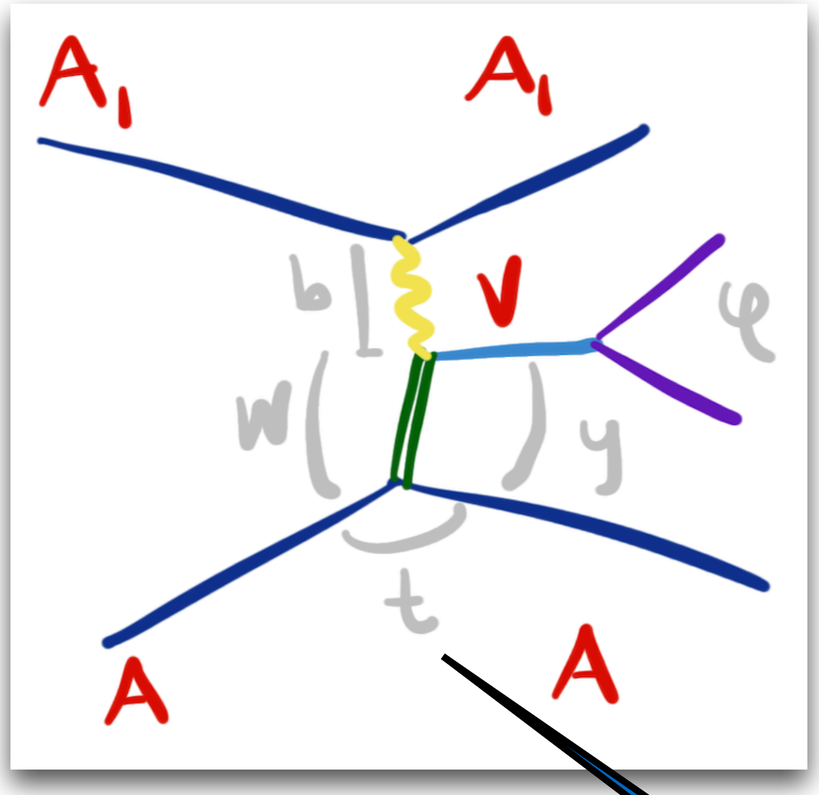
Expectation from coherent (just form factor)

Expectation from the black disc limit

New measurement at y=0: Xe-Xe UPC

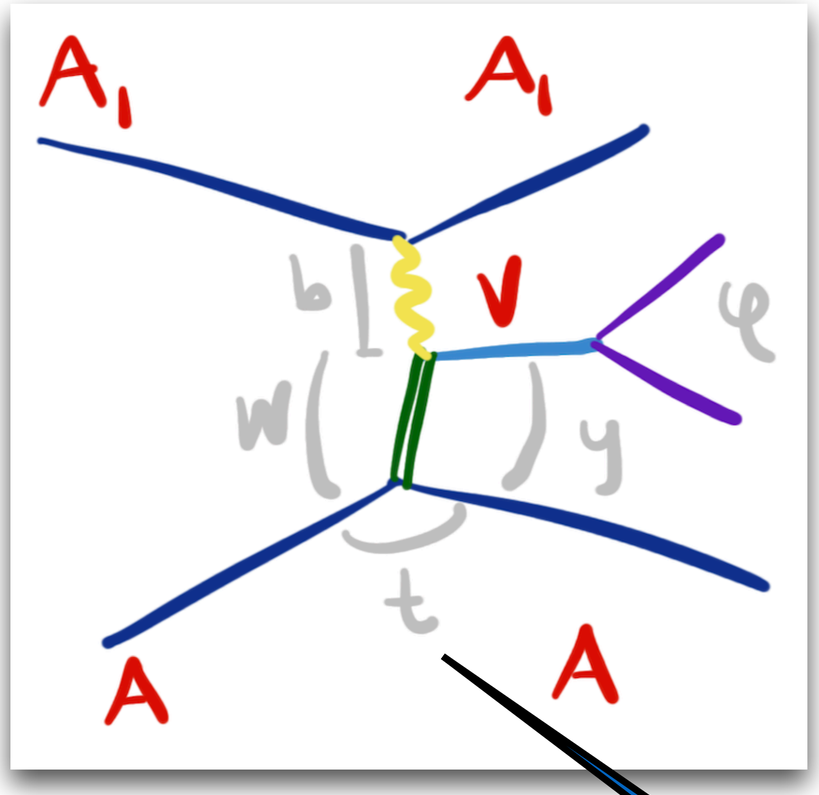
|t|

Momentum transferred at the target vertex



|t| dependence
⇨
A window to transverse structure

|t| Momentum transferred at the target vertex

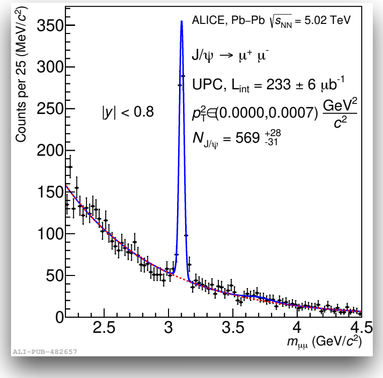


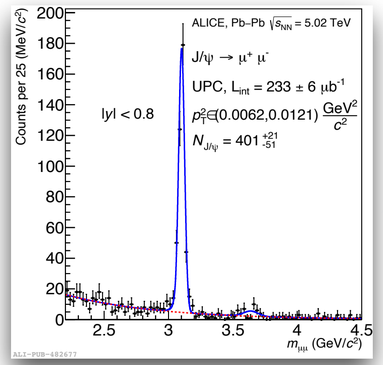
Expectations:
The distribution of gluons in the transverse plane is sensitive to saturation effects

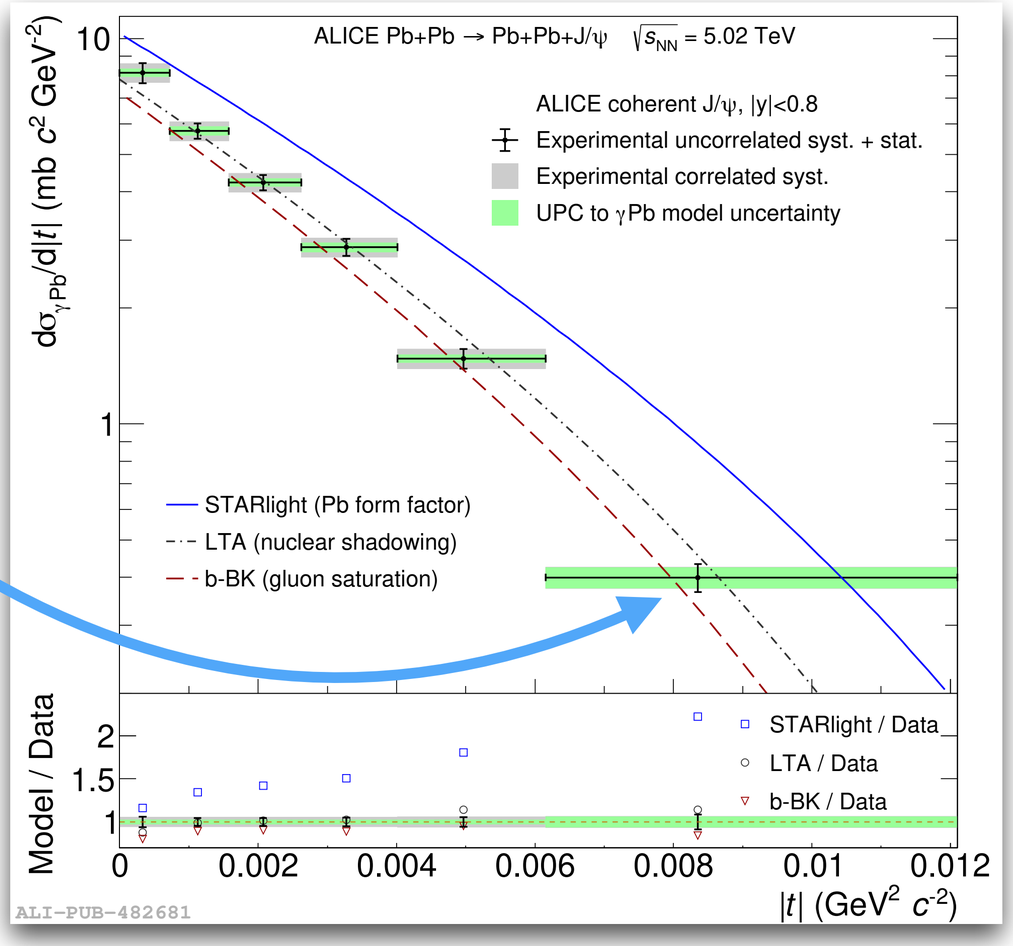
|t| dependence
⇨
A window to transverse structure

J/ψ

J/ψ in Pb-Pb UPC at midrapidity as seen by ALICE







Very clear signals

ALICE, PLB 817(2021) 136280

J/ψ

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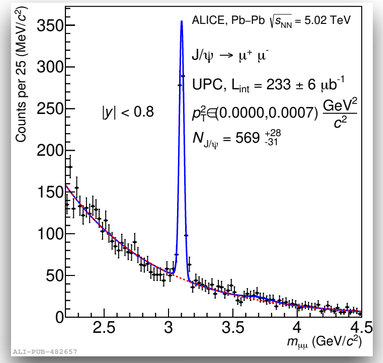
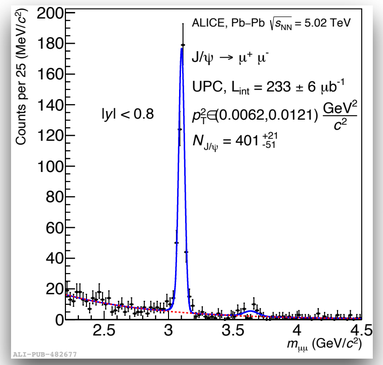
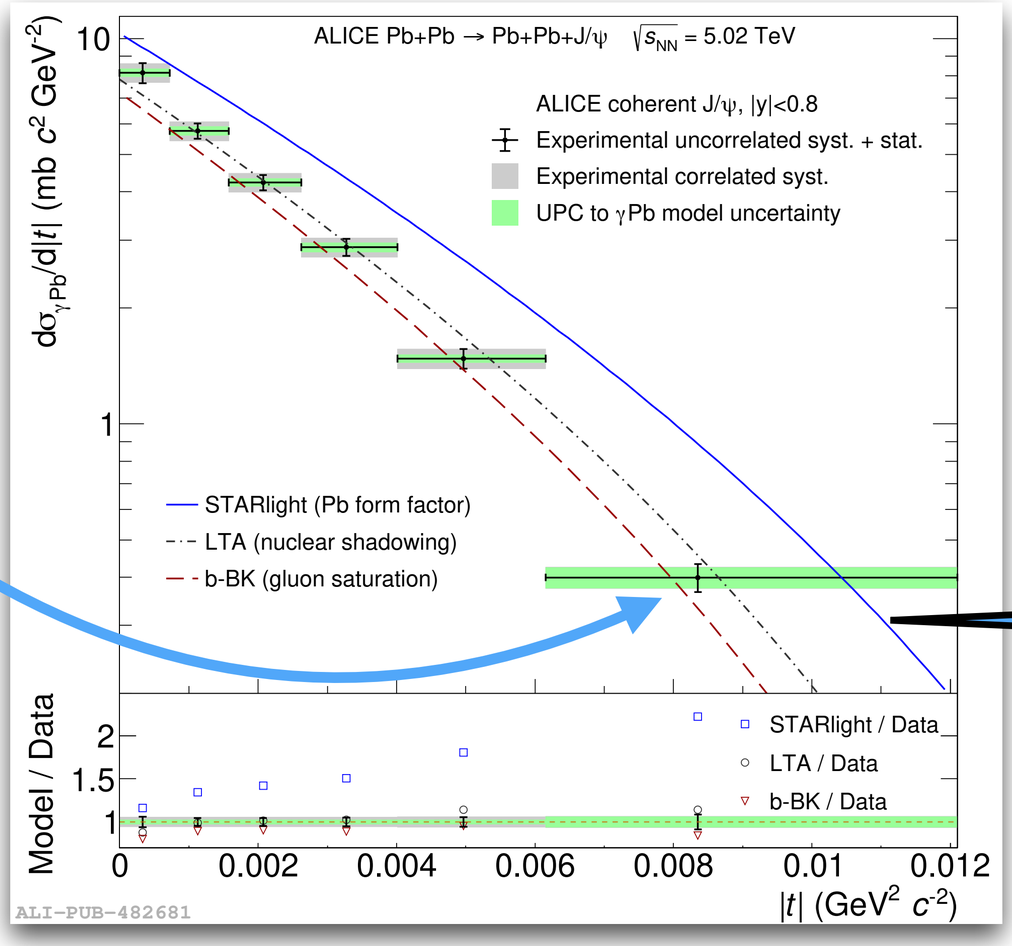






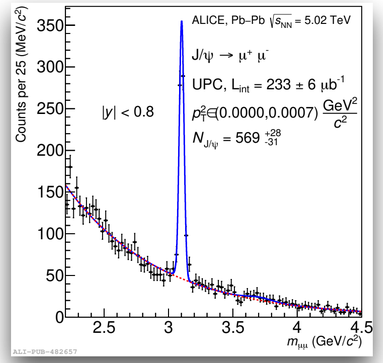
Very clear signals

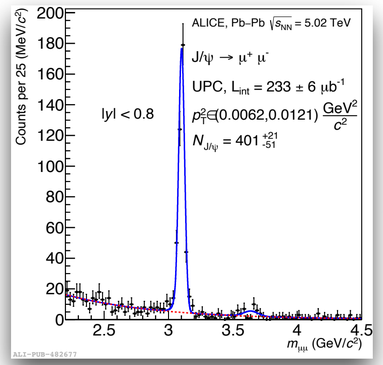
A model based on the form factor does not describe data

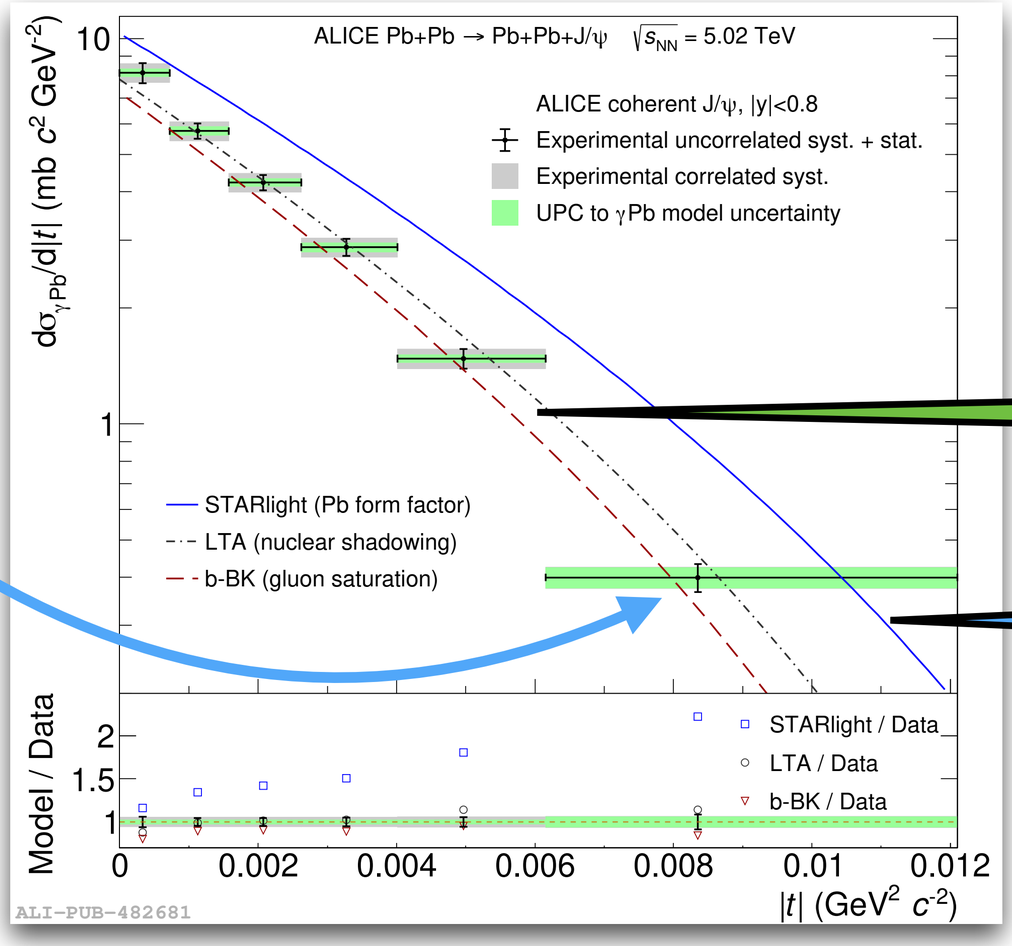
ALICE, PLB 817(2021) 136280

J/ψ

J/ψ in Pb-Pb UPC at midrapidity as seen by ALICE







A shadowing based, and a BK computation with impact-parameter dependence, close to data

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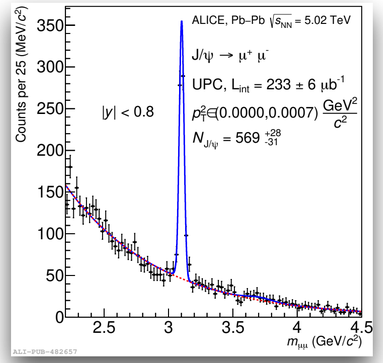
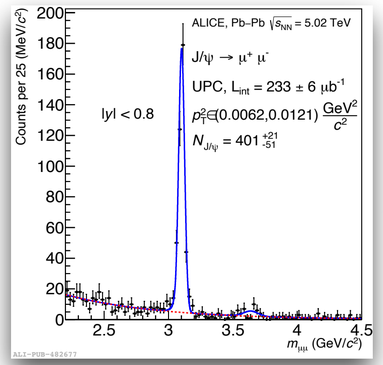
Very clear signals

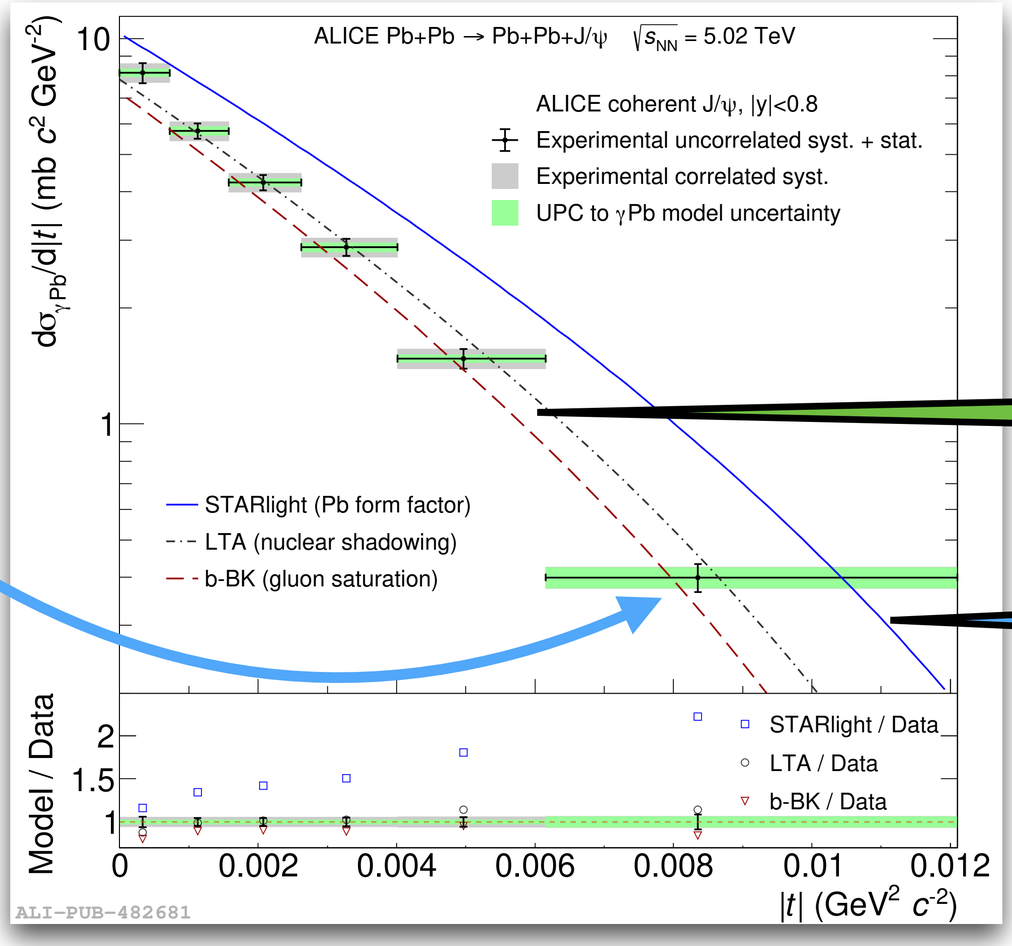
ALICE, PLB 817(2021) 136280

J/ψ

J/ψ in Pb-Pb UPC at midrapidity as seen by ALICE







Open question:
How much of shadowing is saturation?
Does the answer depend on |t|?

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ALICE, PLB 817(2021) 136280

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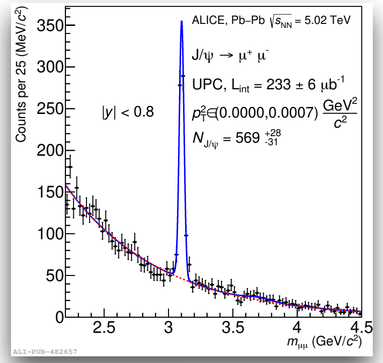

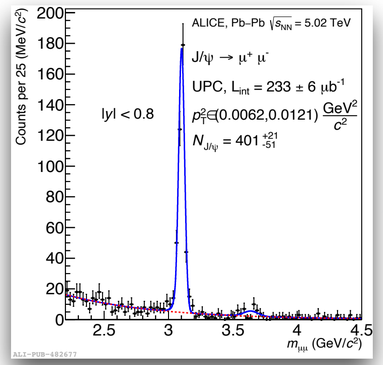

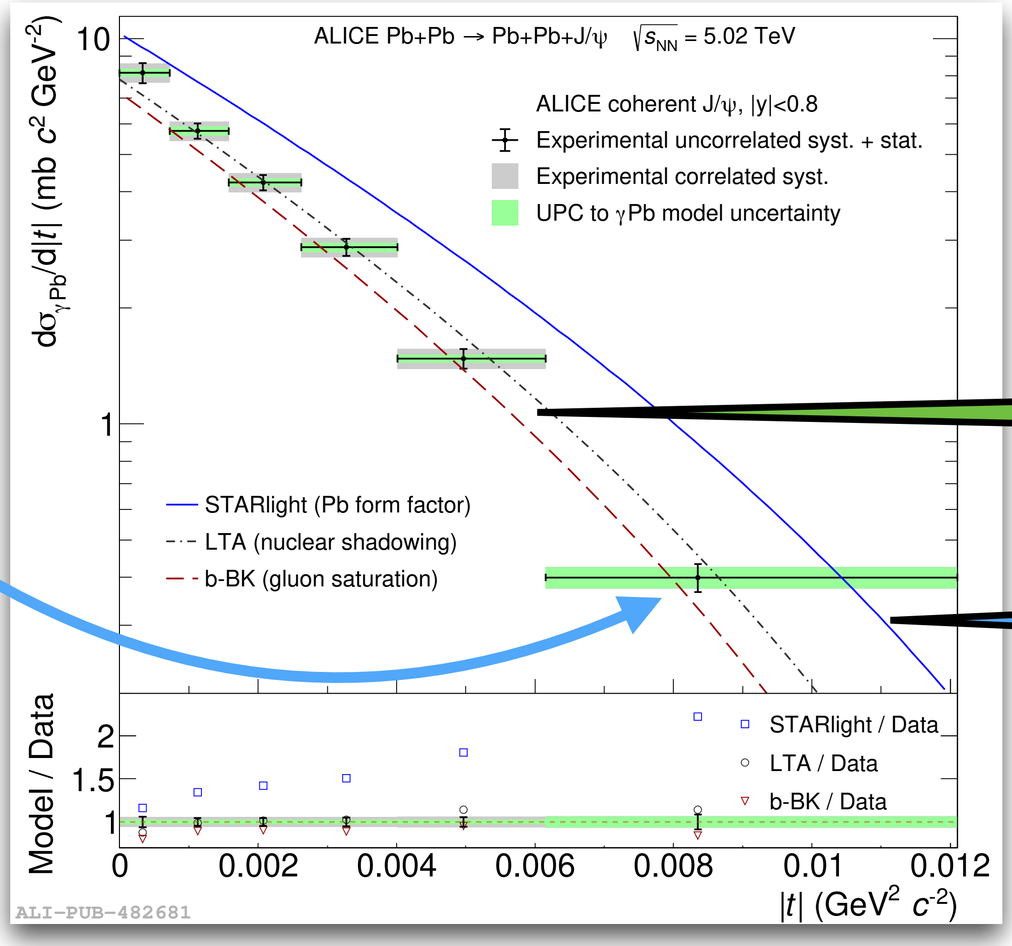

ALICE, PLB 817(2021) 136280

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A shadowing based, and a BK computation with impact-parameter dependence, close to data

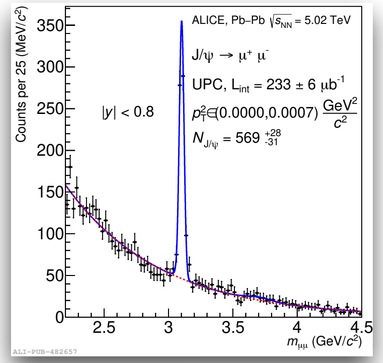
A model based on the form factor does not describe data

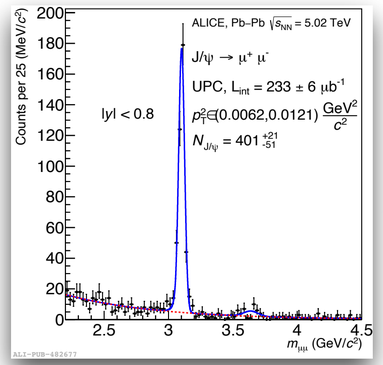
Open question:
Can we reach larger ltl at the LHC?

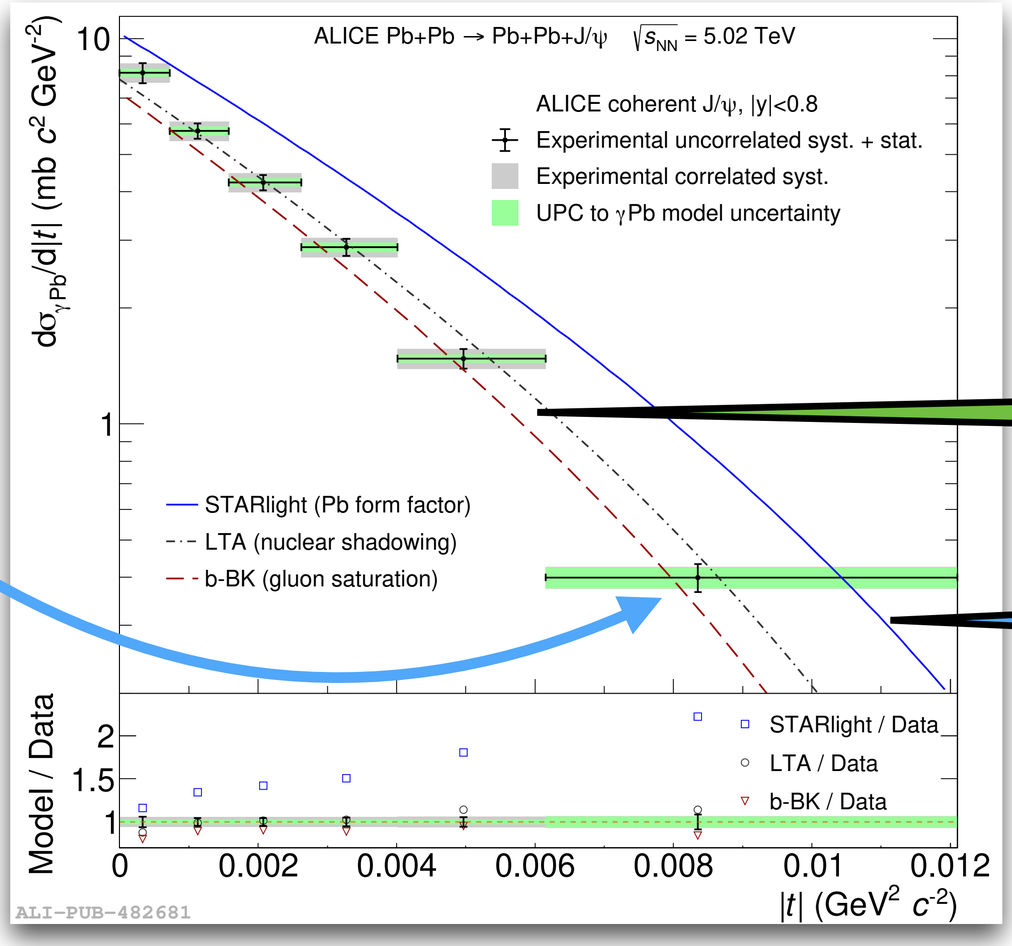
Very clear signals

J/ψ

J/ψ in Pb-Pb UPC at midrapidity as seen by ALICE







ALICE, PLB 817(2021) 136280

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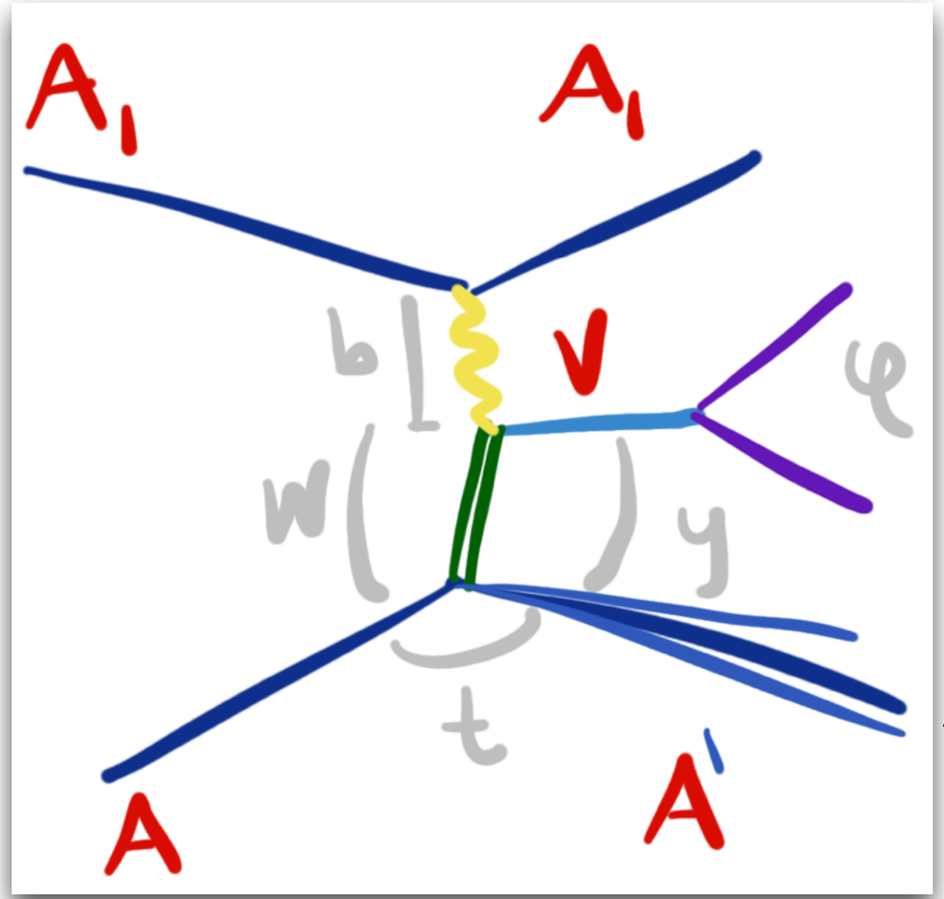
Open question:
Can we reach larger ltl at the LHC?

Use 0n0n events to suppress incoherent production

$\langle A^2 \rangle - \langle A \rangle^2$

Fluctuations of quantum fields

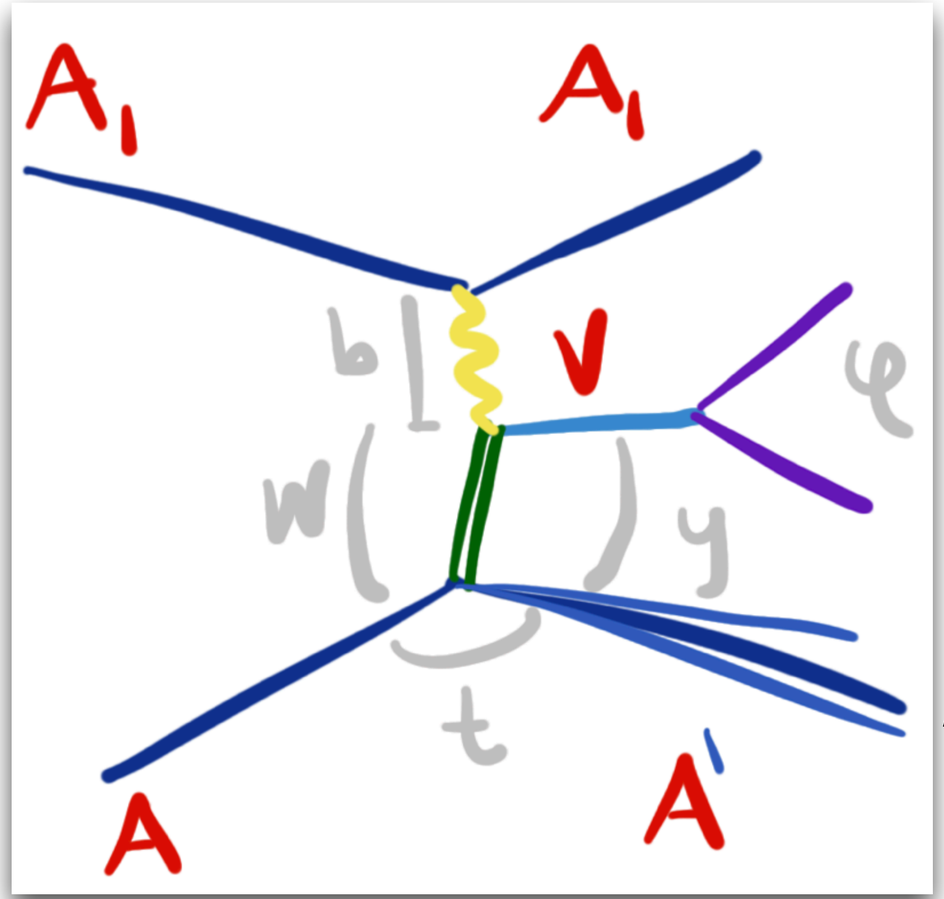


Incoherent production

⇨

Accessing quantum fluctuations

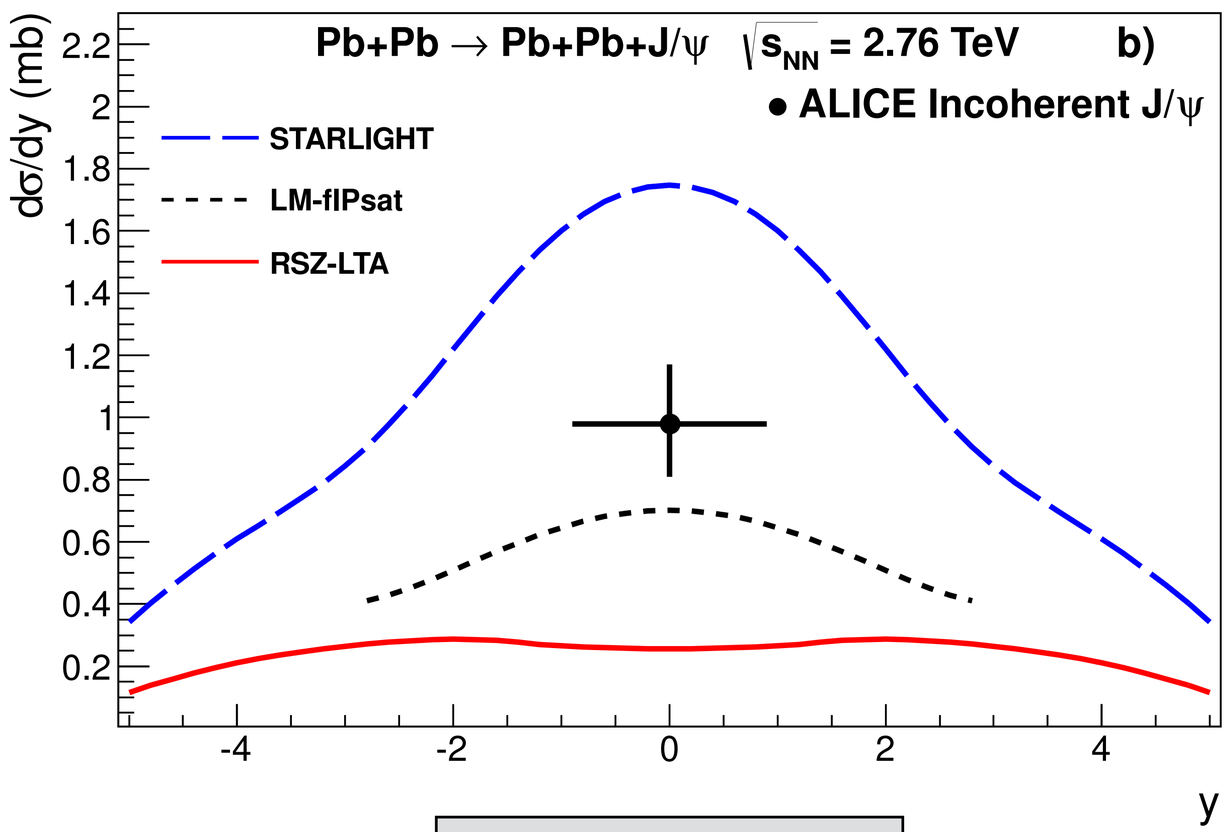
$\langle A^2 \rangle - \langle A \rangle^2$ Fluctuations of quantum fields



Expectations:
The variance of fluctuations provides new signals of saturation

Incoherent production
⇨
Accessing quantum fluctuations

Incoherent J/ψ as seen by ALICE

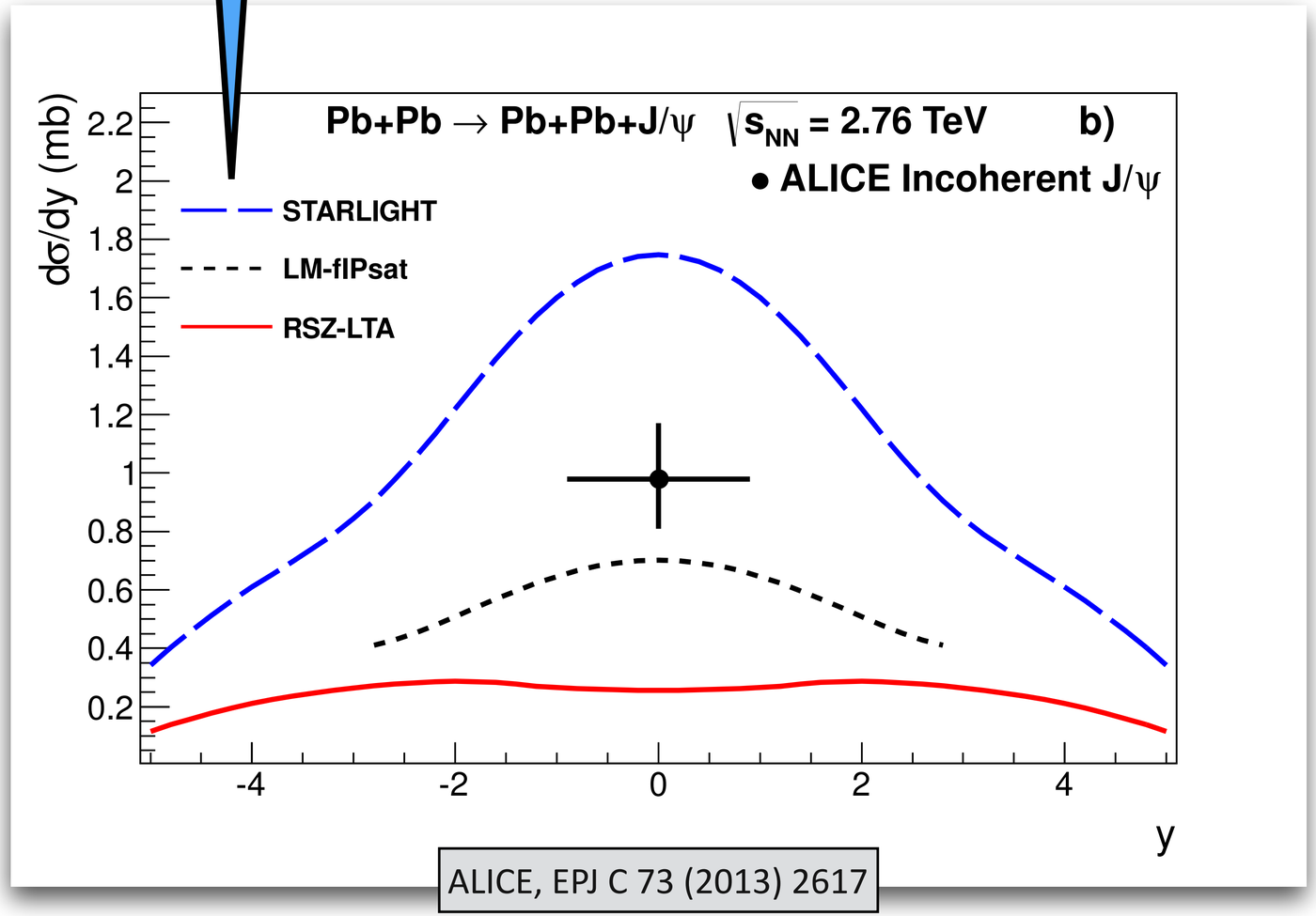


ALICE, EPJ C 73 (2013) 2617

J/ψ

Incoherent J/ψ as seen by ALICE

Models do not describe data, but large uncertainties in models and in data



ALICE, EPJ C 73 (2013) 2617

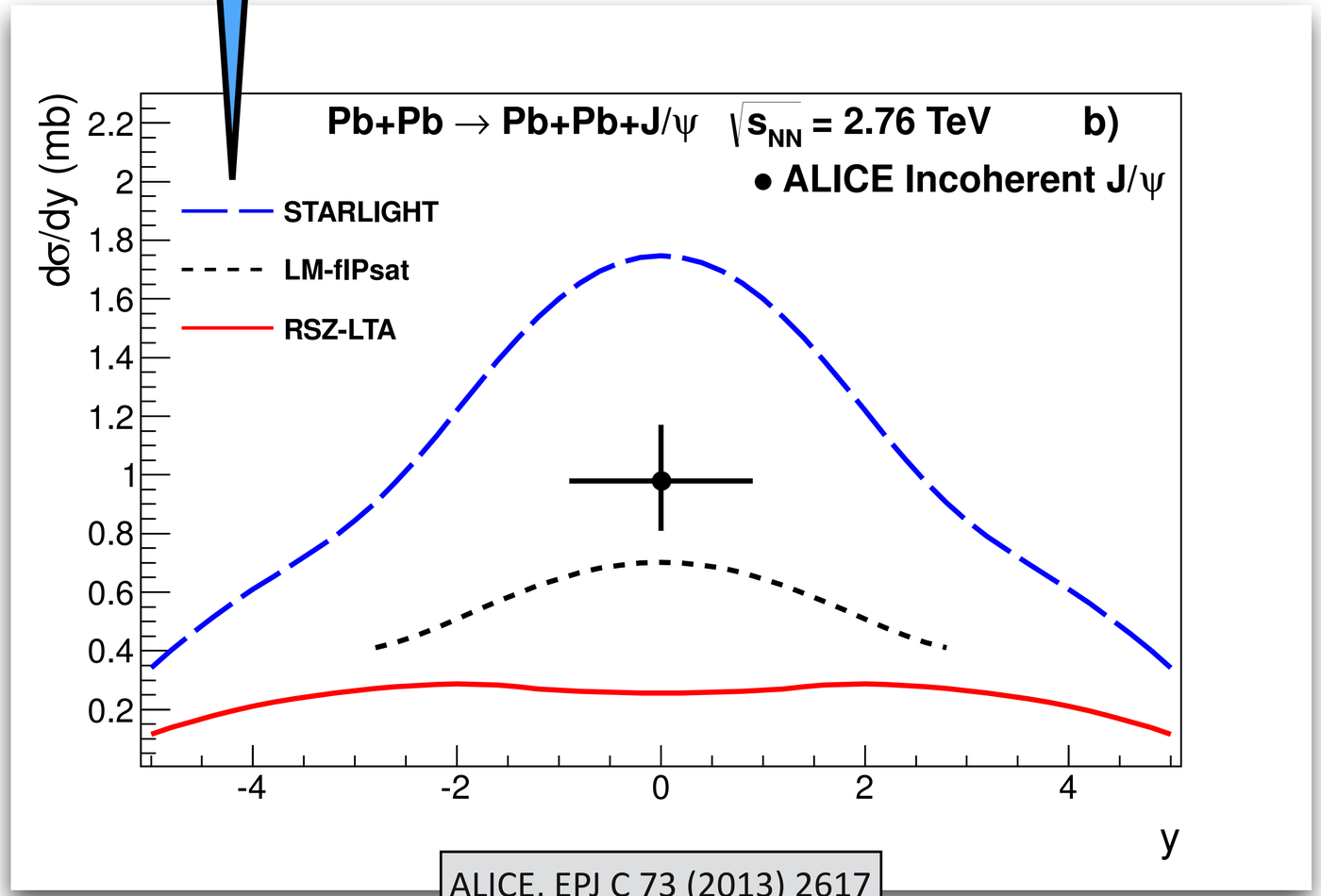
Incoherent J/ψ as seen by ALICE

J/ψ

Run 2

New data being analysed

Models do not describe data, but large uncertainties in models and in data



ALICE, EPJ C 73 (2013) 2617

Incoherent J/ψ as seen by ALICE

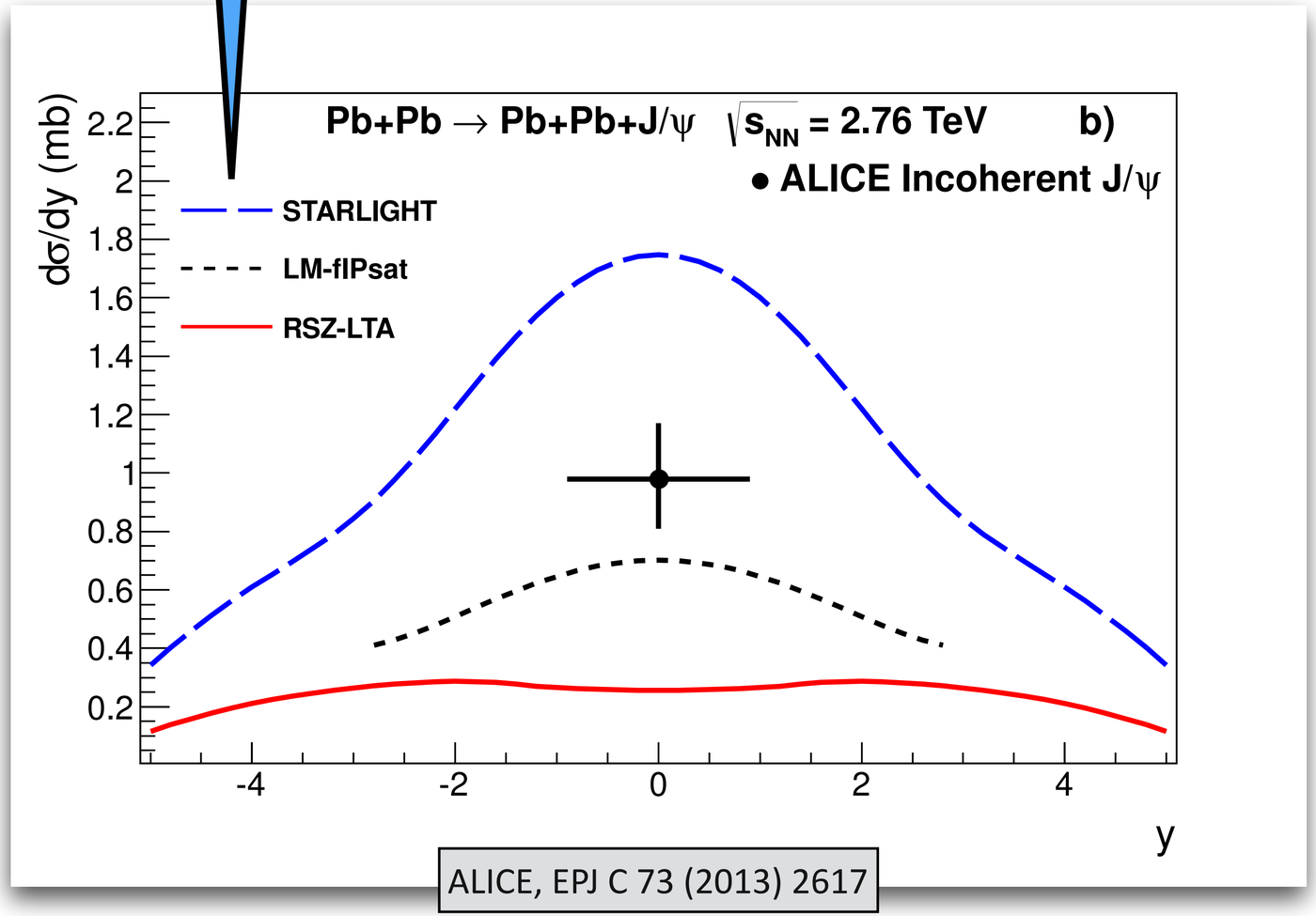
J/ψ

Models do not describe data, but large uncertainties in models and in data

Run 2

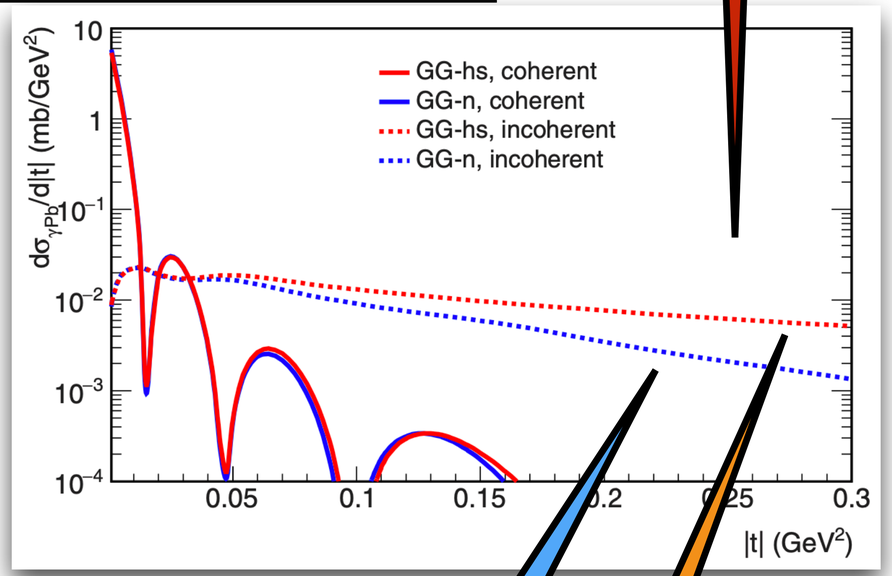
New data being analysed

Open question:
How much can we learn from the |t| dependence?



ALICE, EPJ C 73 (2013) 2617

JGC et al, PRC 97 (2018), 024901



Nucleon fluctuations

Sub-nucleon fluctuations

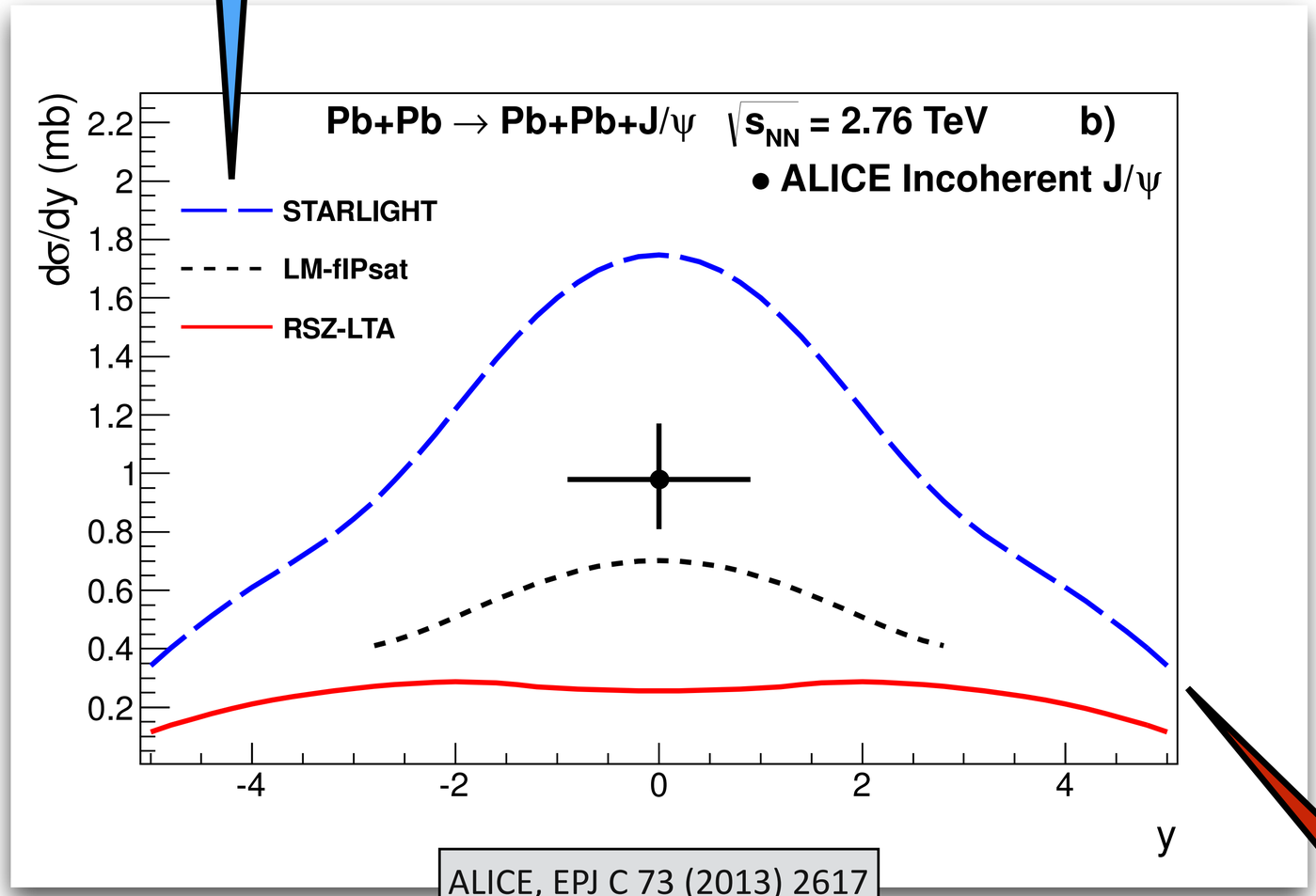
Incoherent J/ψ as seen by ALICE

J/ψ

Run 2

New data being analysed

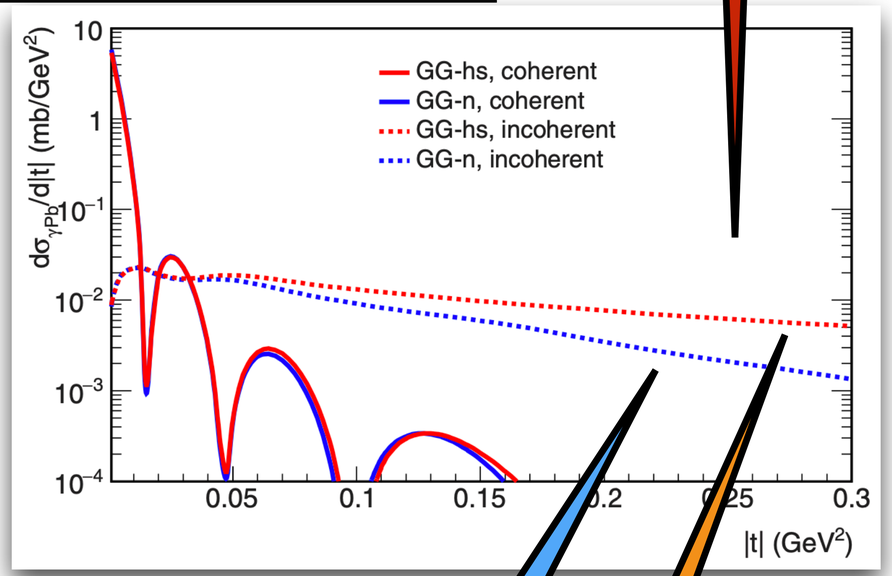
Models do not describe data, but large uncertainties in models and in data



ALICE, EPJ C 73 (2013) 2617

Open question:
How much can we learn from the ltl dependence?

JGC et al, PRC 97 (2018), 024901



Nucleon fluctuations

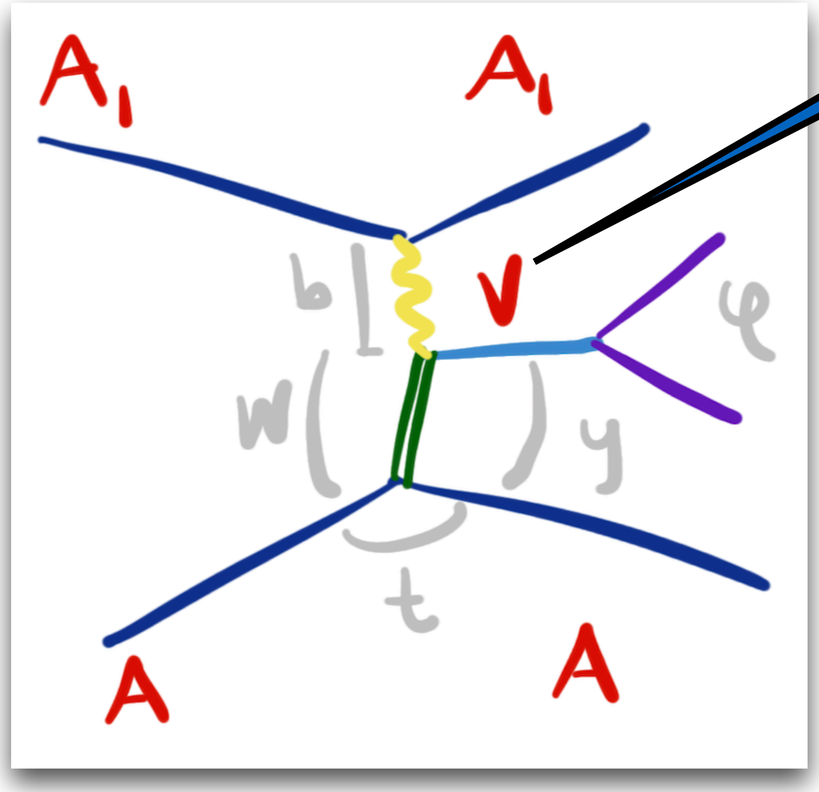
Sub-nucleon fluctuations

Open question:
Can we constraint the knowledge of the wave function?

2S

Wave functions of excited states

Excited states
Constraining the wave function



2S

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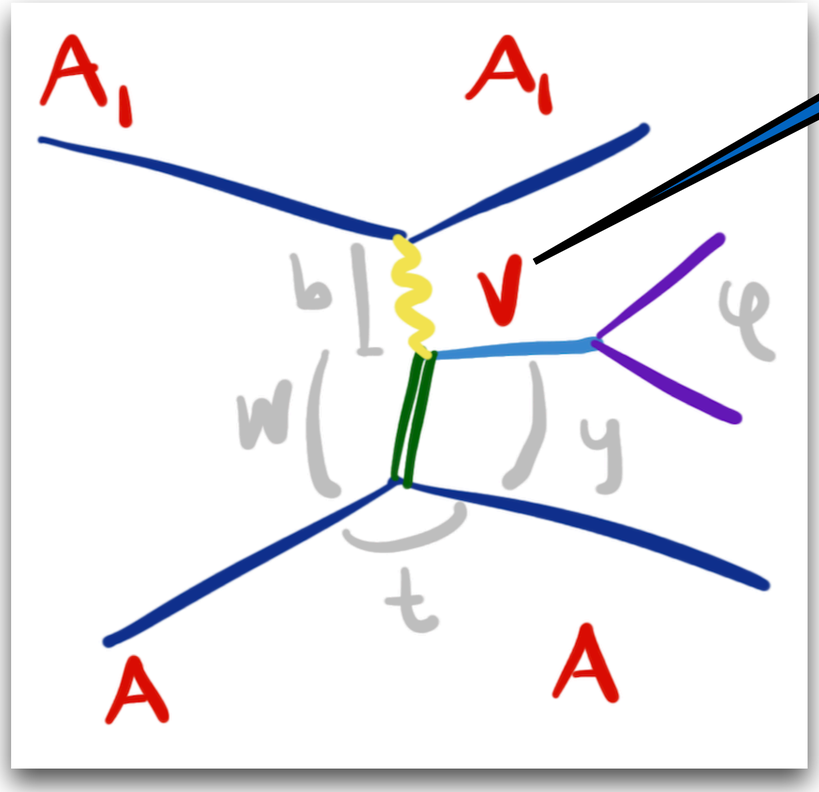
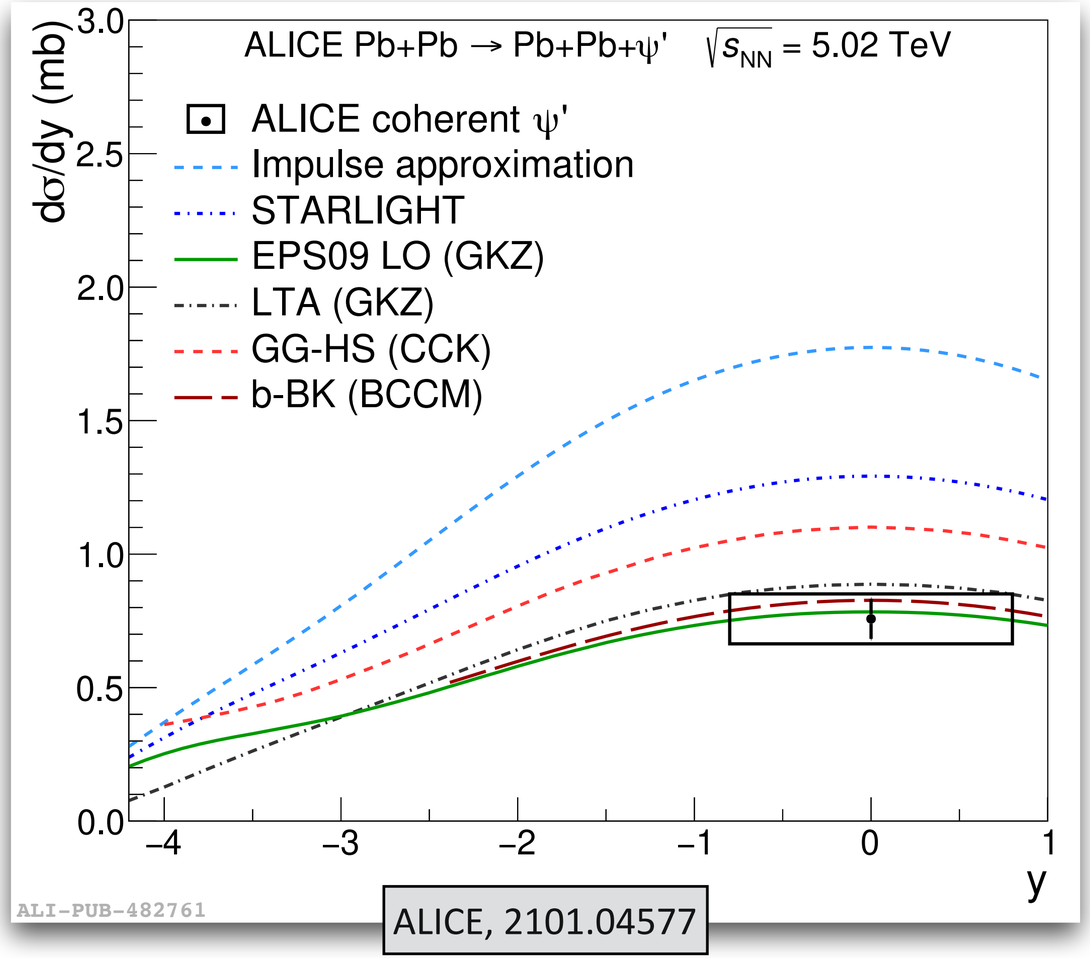


Expectations:
The angular momentum structure of the wave function may enhance/suppress some effects

ψ(2S)

ψ(2S) at midrapidity as seen by ALICE



ALICE, 2101.04577

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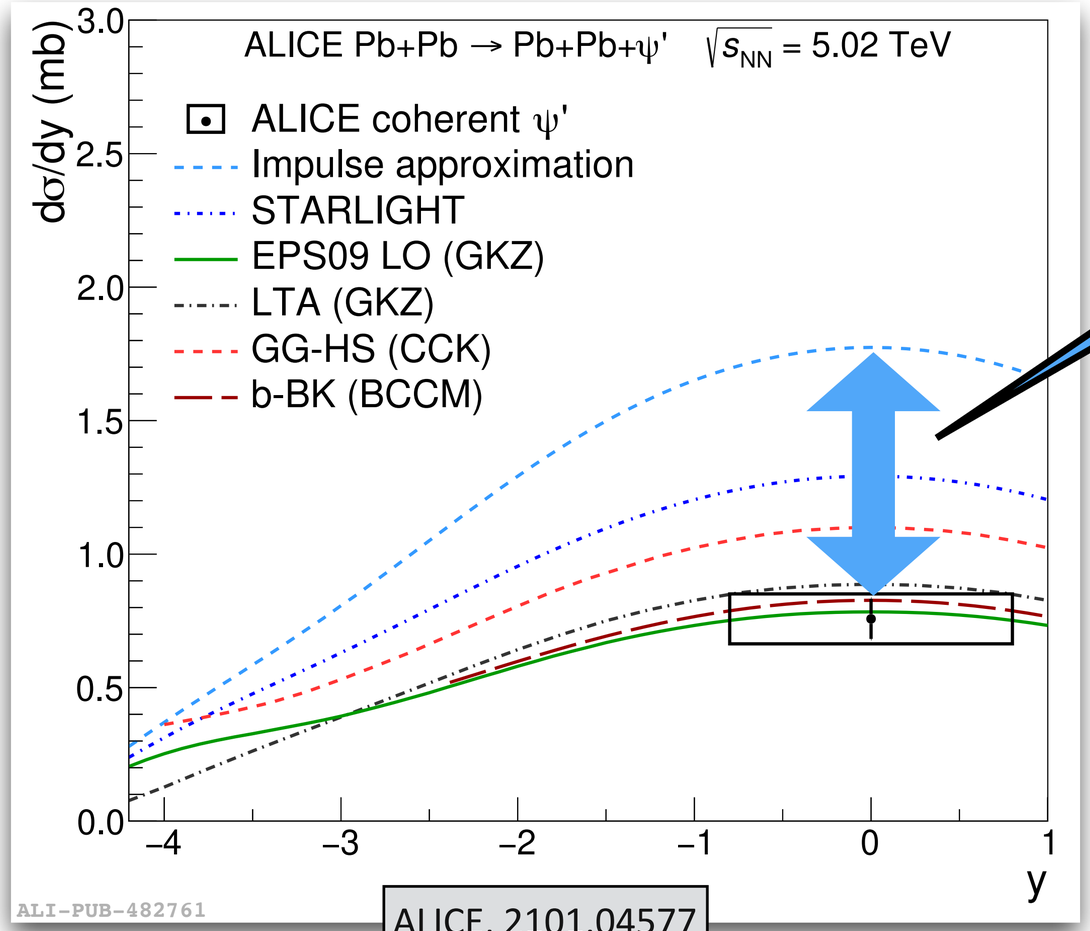

ALICE, 2101.04577

Same nuclear suppression factor as found for J/ψ

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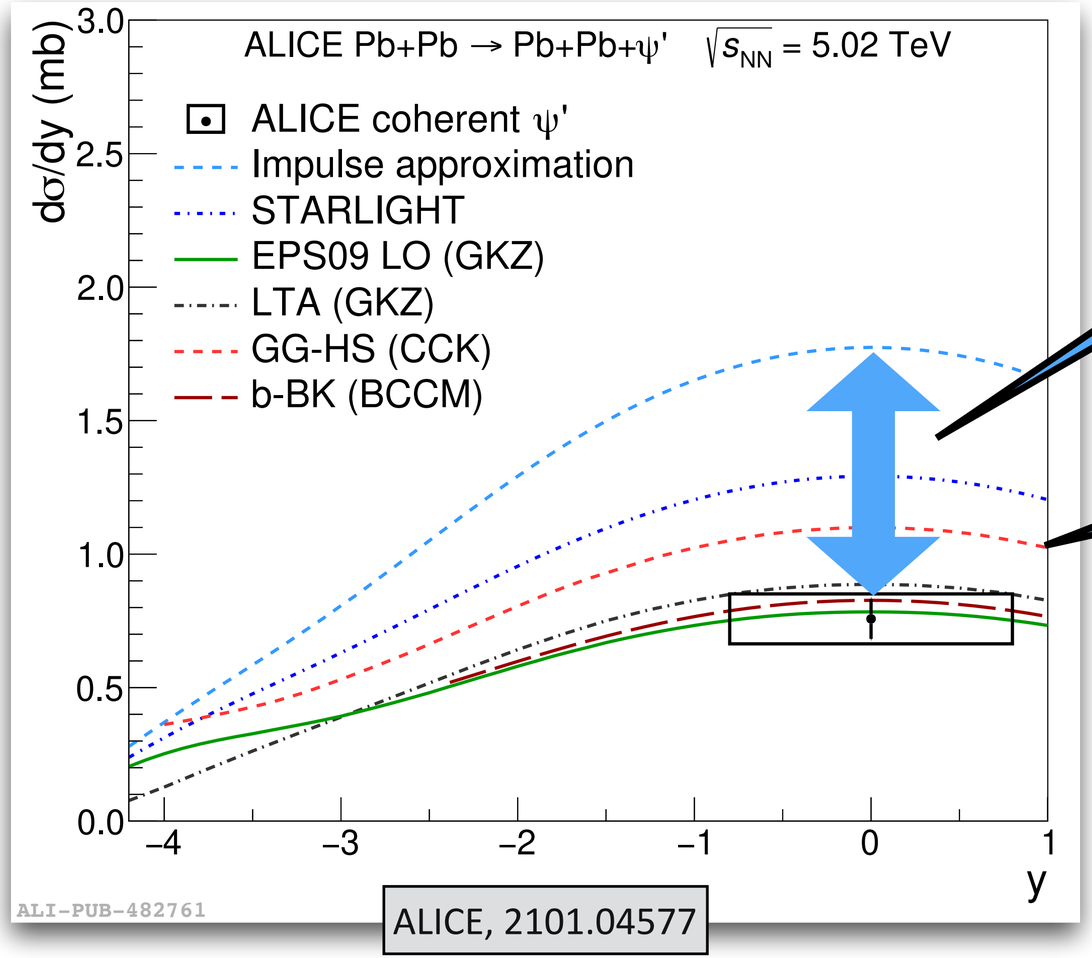


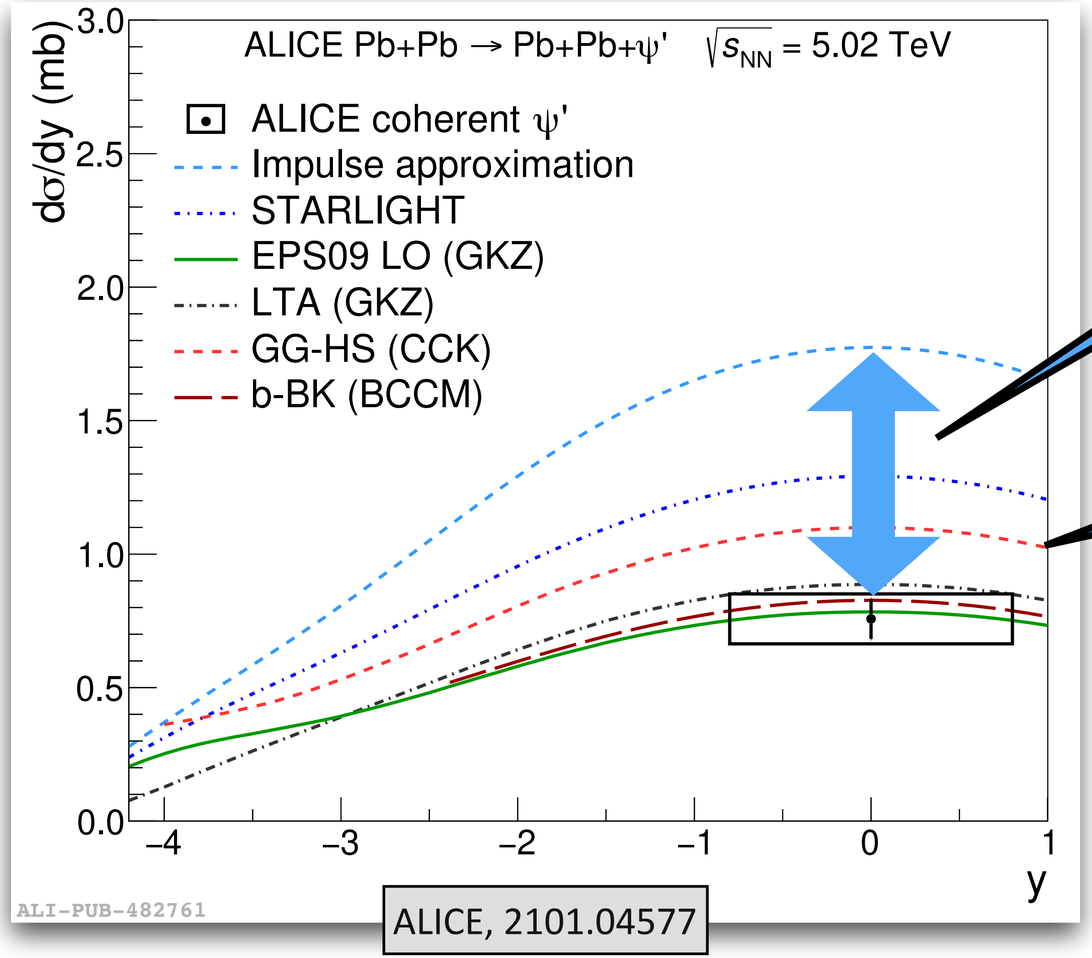
ALICE, 2101.04577

Same nuclear suppression factor as found for J/ψ

Some models that described the J/ψ cross section do not describe ψ(2S) so well

ψ(2S)

ψ(2S) at midrapidity as seen by ALICE



ALICE, 2101.04577

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Open question:
How much can we constrain the modelling of the wave function by comparing 1S and 2S states?

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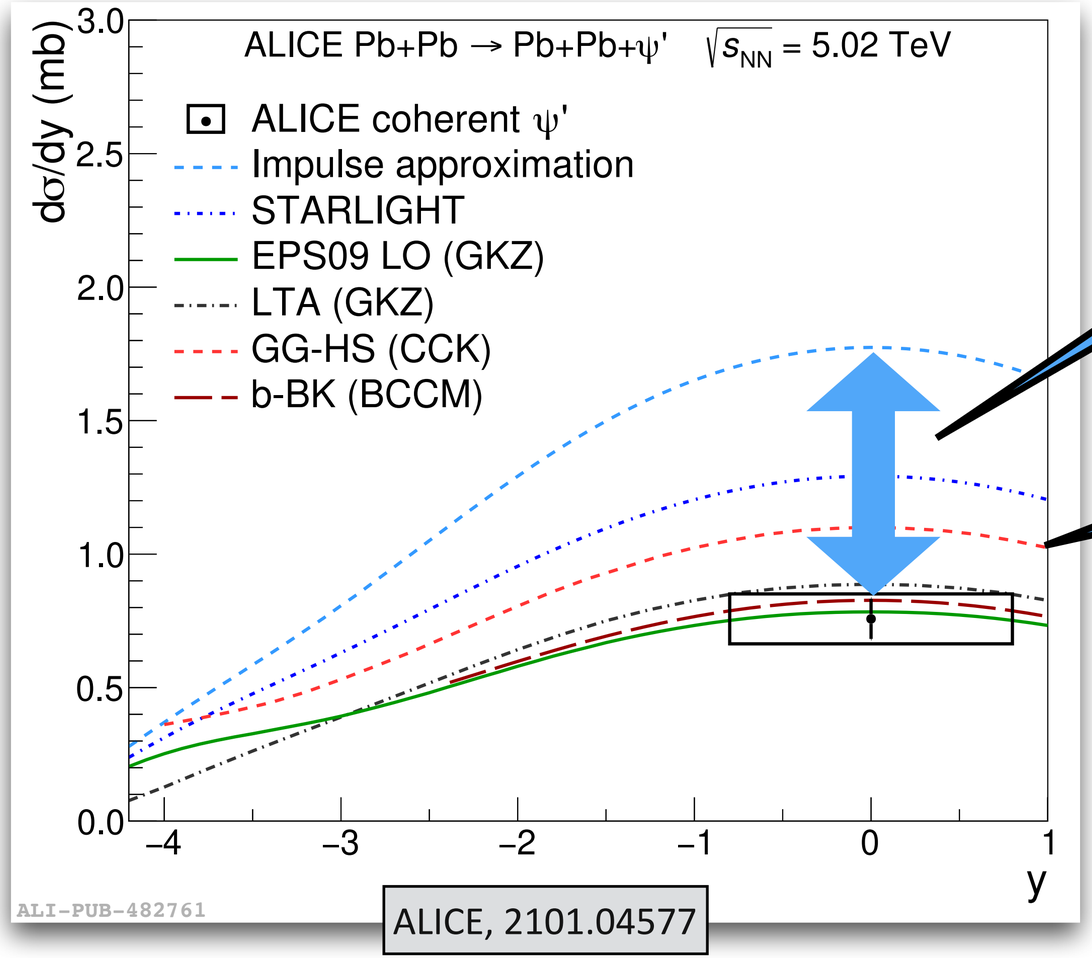

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EIC

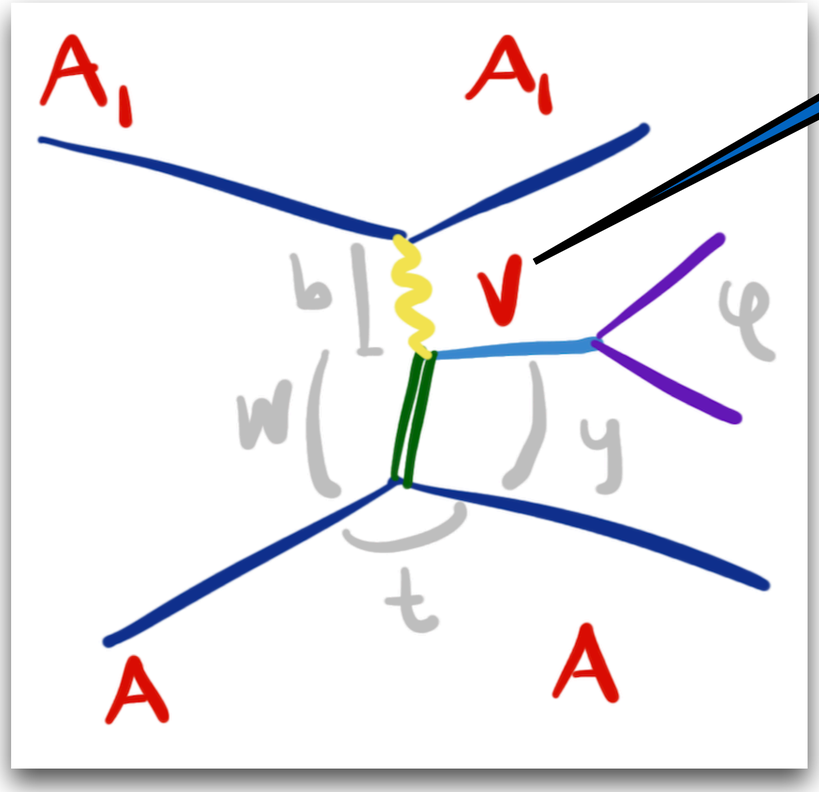
Q2 dependence important in this context

Cepila et al, EPJC 79 (2019) 6, 495

?

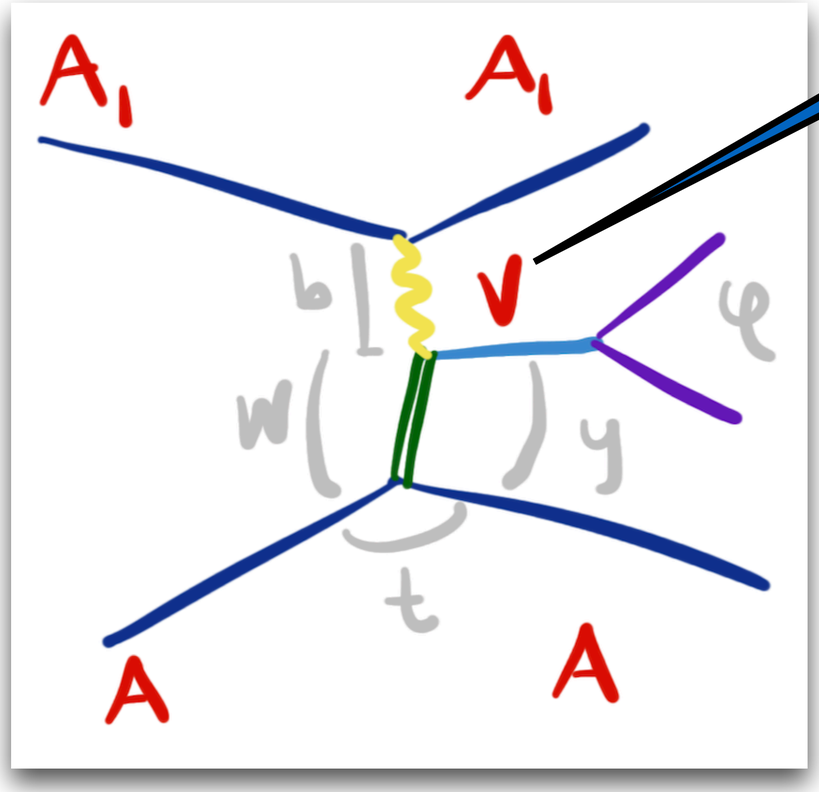
Studying new states

Vector meson mass:
Are there new photoproduced states?



?

Studying new states



Vector meson mass:
Are there new photoproduced states?

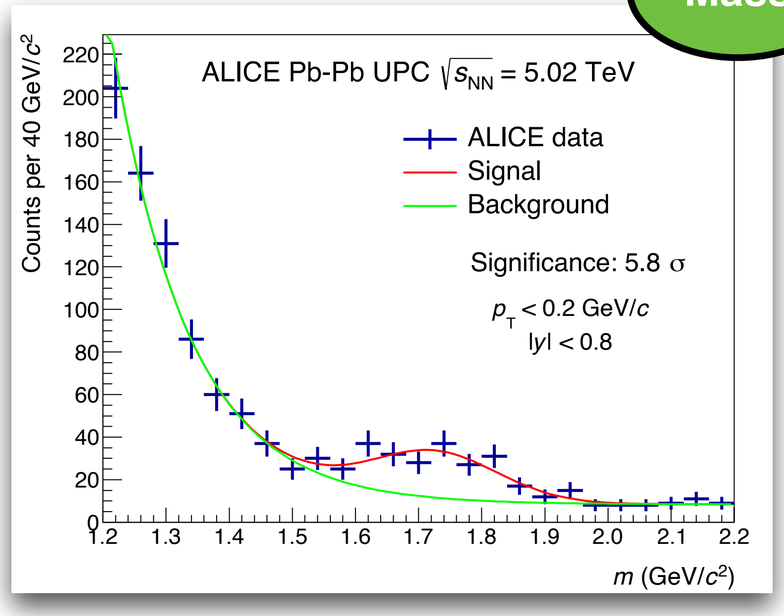
Expectations:
Such a clean environment should be ideal to spot new states

ρ’ (?)

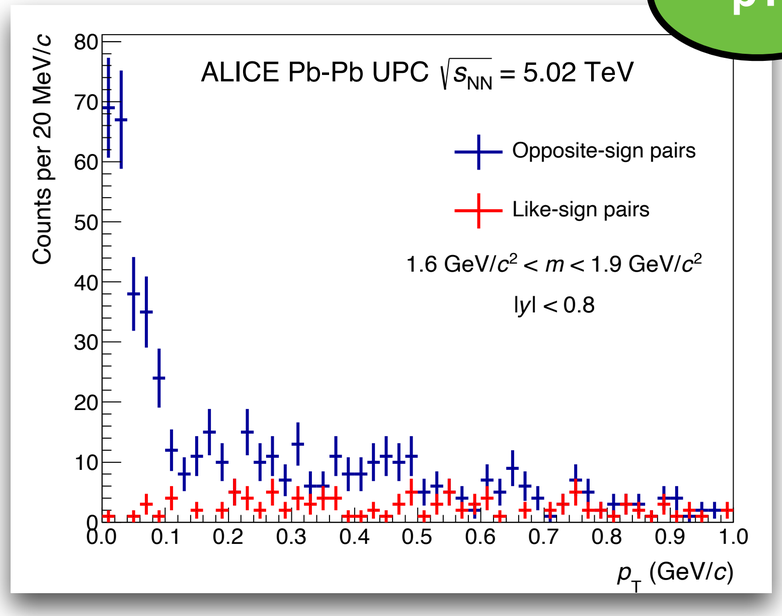
ππ pairs in Pb-Pb as seen by ALICE

ALICE, JHEP 06 (2020) 035

Mass



pT



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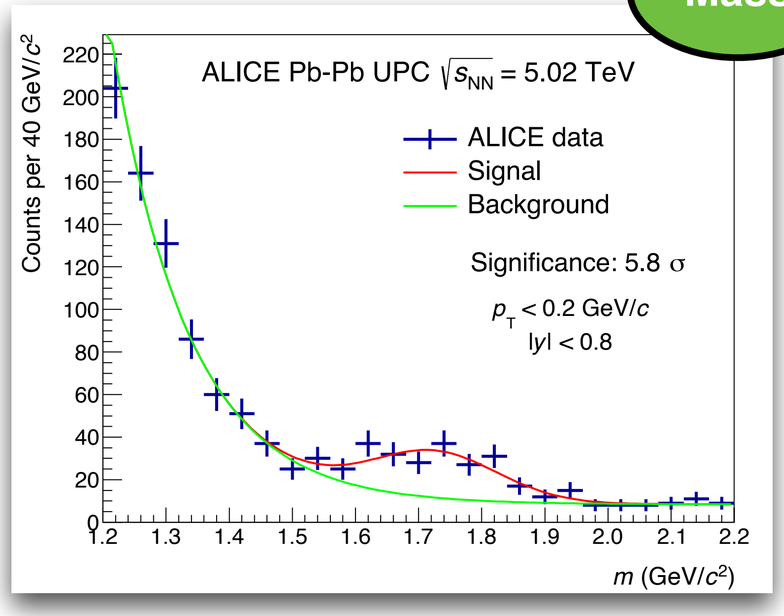
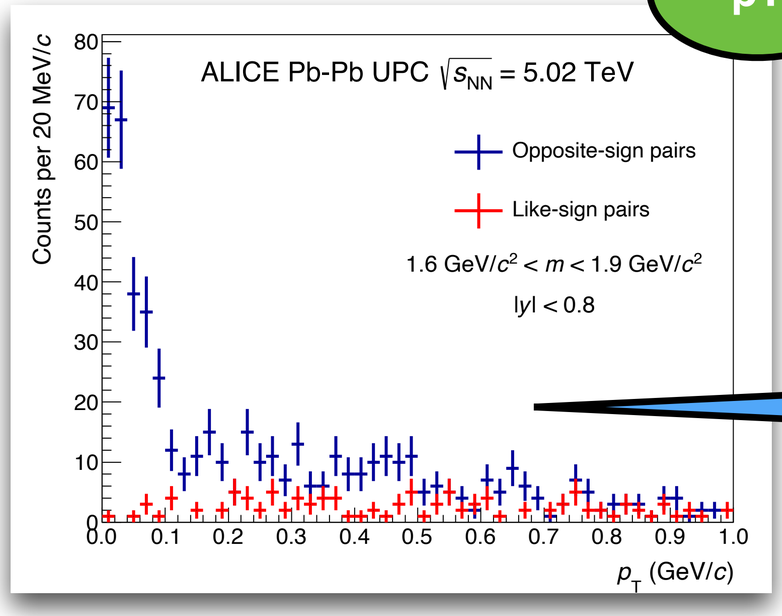


pT



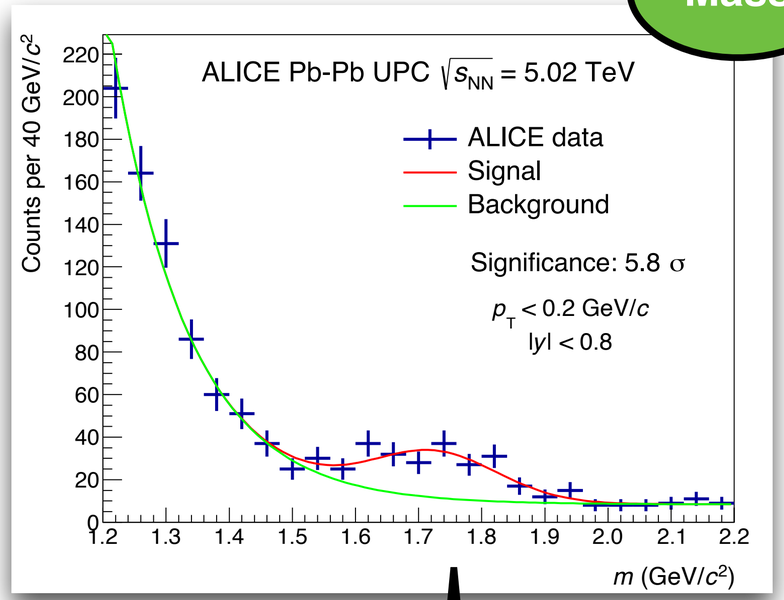
pT distribution typical of coherent photoproduction

ρ’ (?)

ππ pairs in Pb-Pb as seen by ALICE

ALICE, JHEP 06 (2020) 035

Mass



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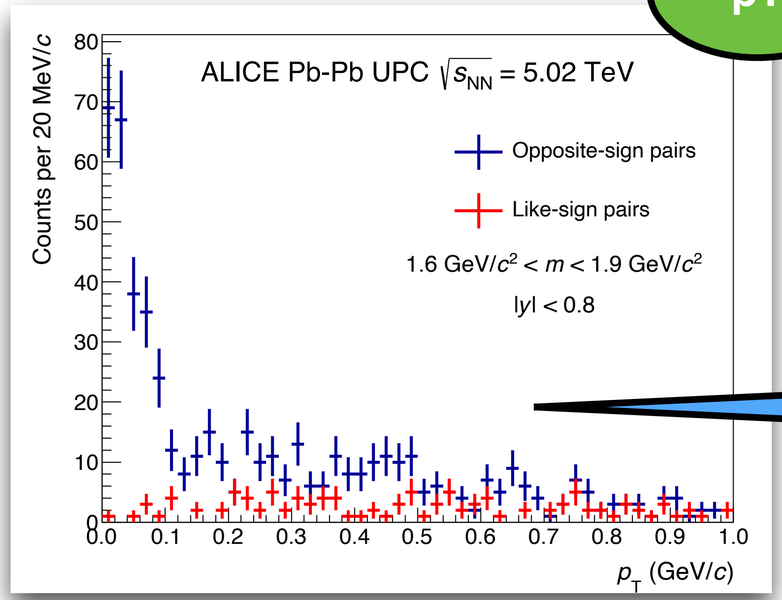


pT distribution typical of coherent photoproduction

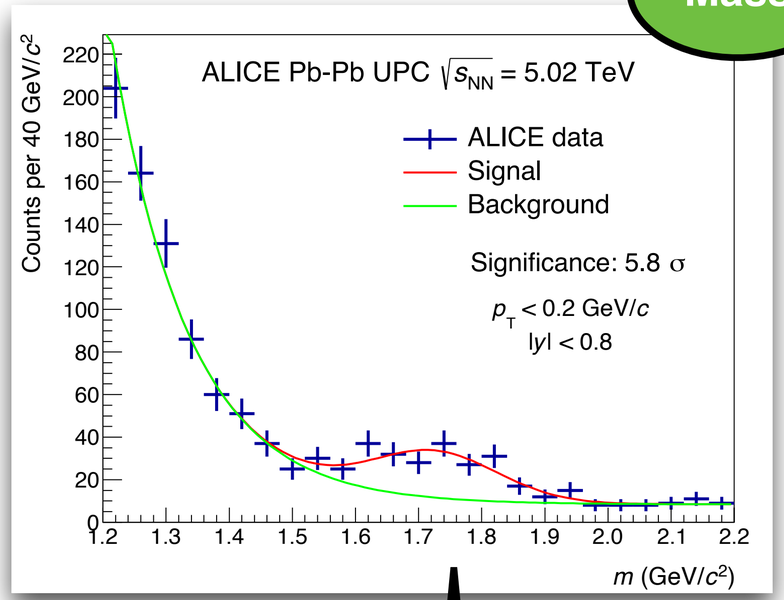
Bump seen in the invariant mass distribution. Similar (not 100% equal) bumps seen by H1 and STAR

ρ’ (?)

ππ pairs in Pb-Pb as seen by ALICE

ALICE, JHEP 06 (2020) 035

Mass



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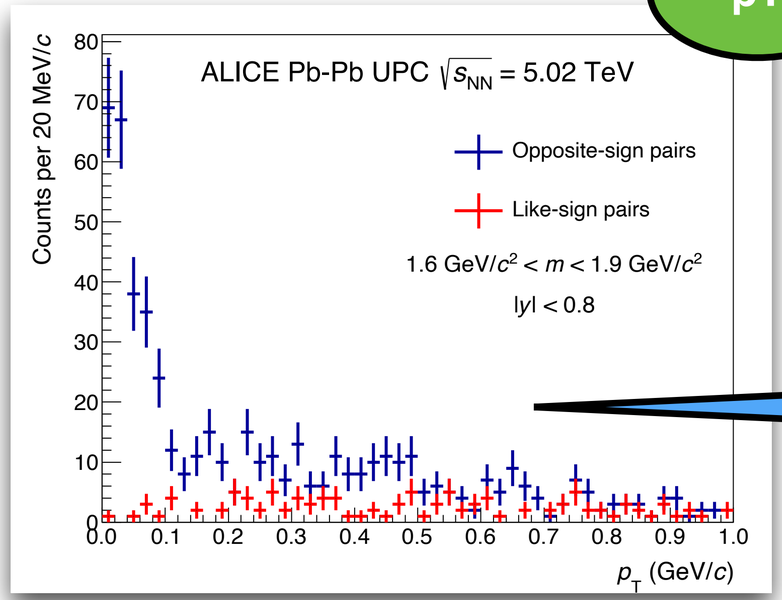


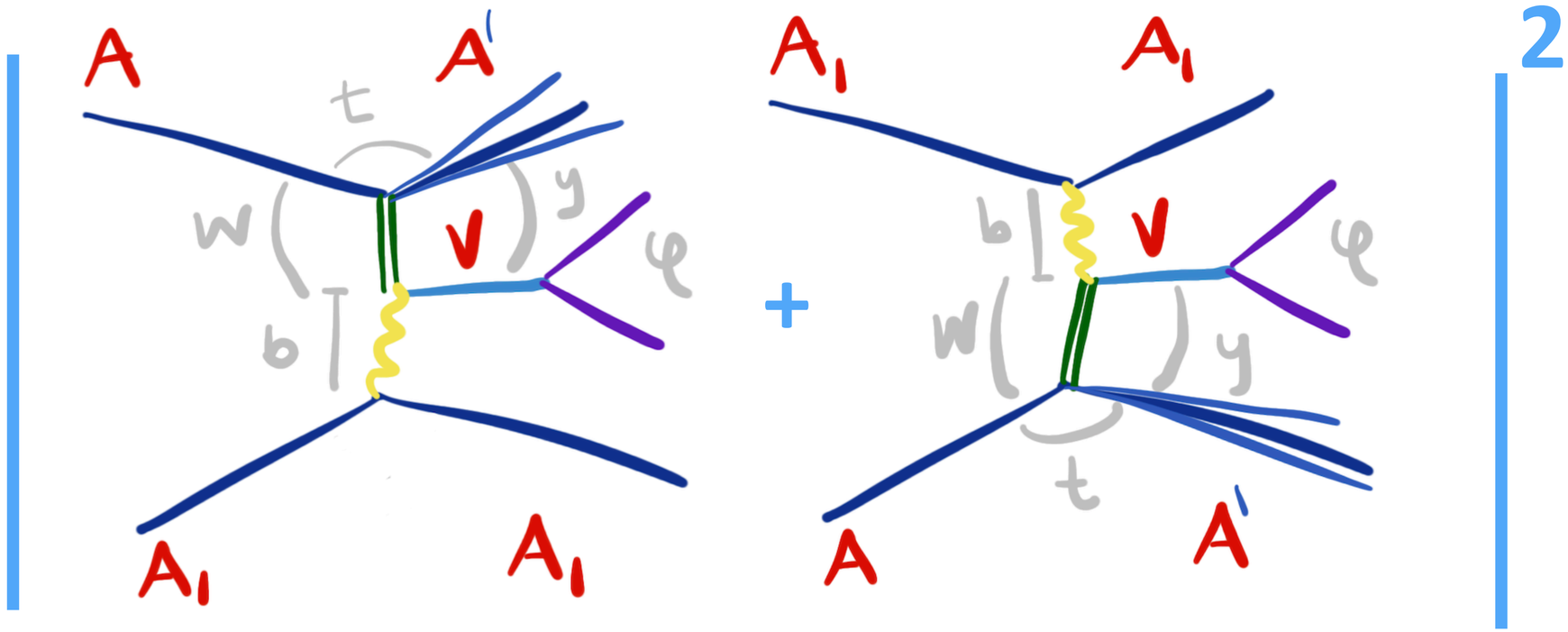
pT distribution typical of coherent photoproduction

Bump seen in the invariant mass distribution. Similar (not 100% equal) bumps seen by H1 and STAR

EIC

Should also be accessible at the EIC

Instead of a summary



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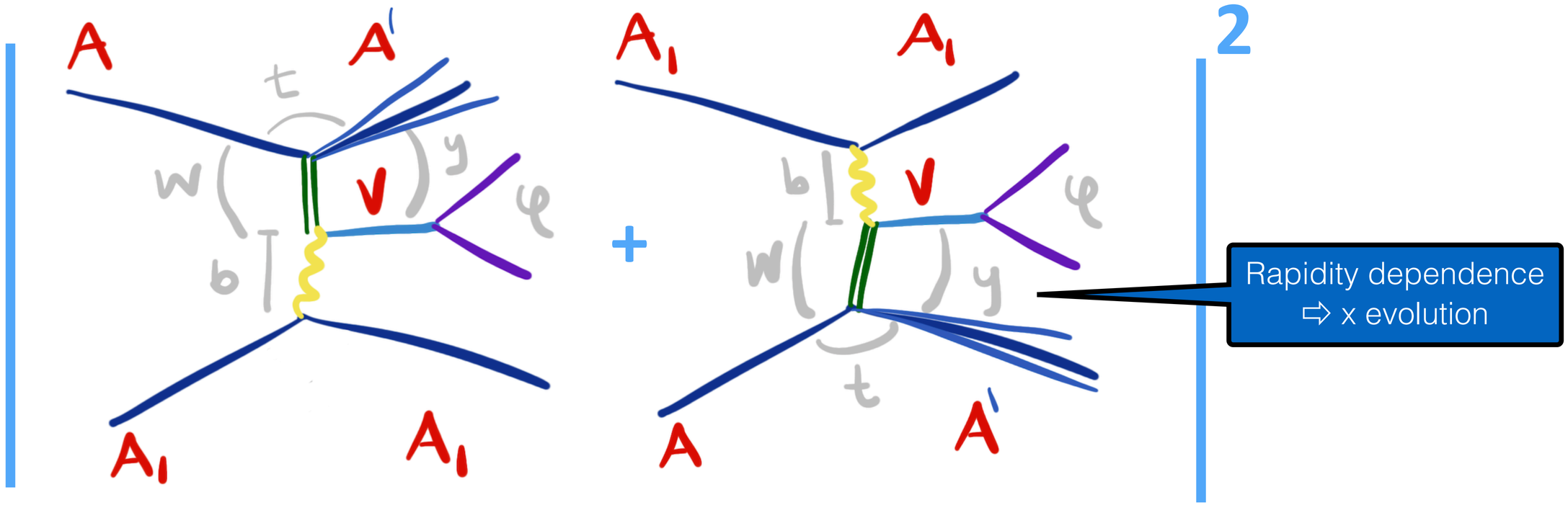

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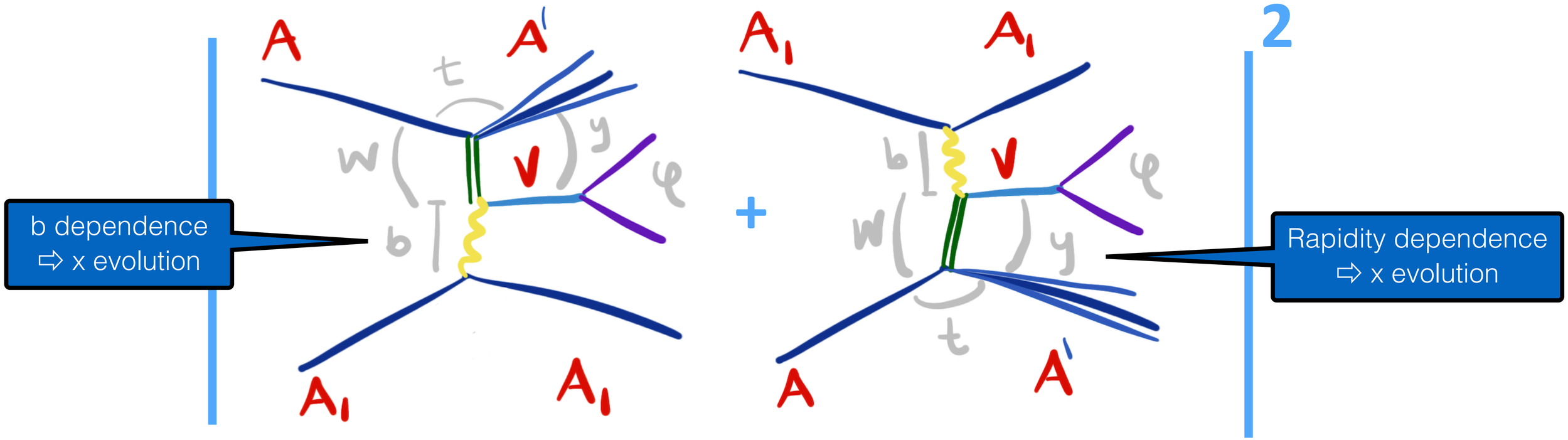

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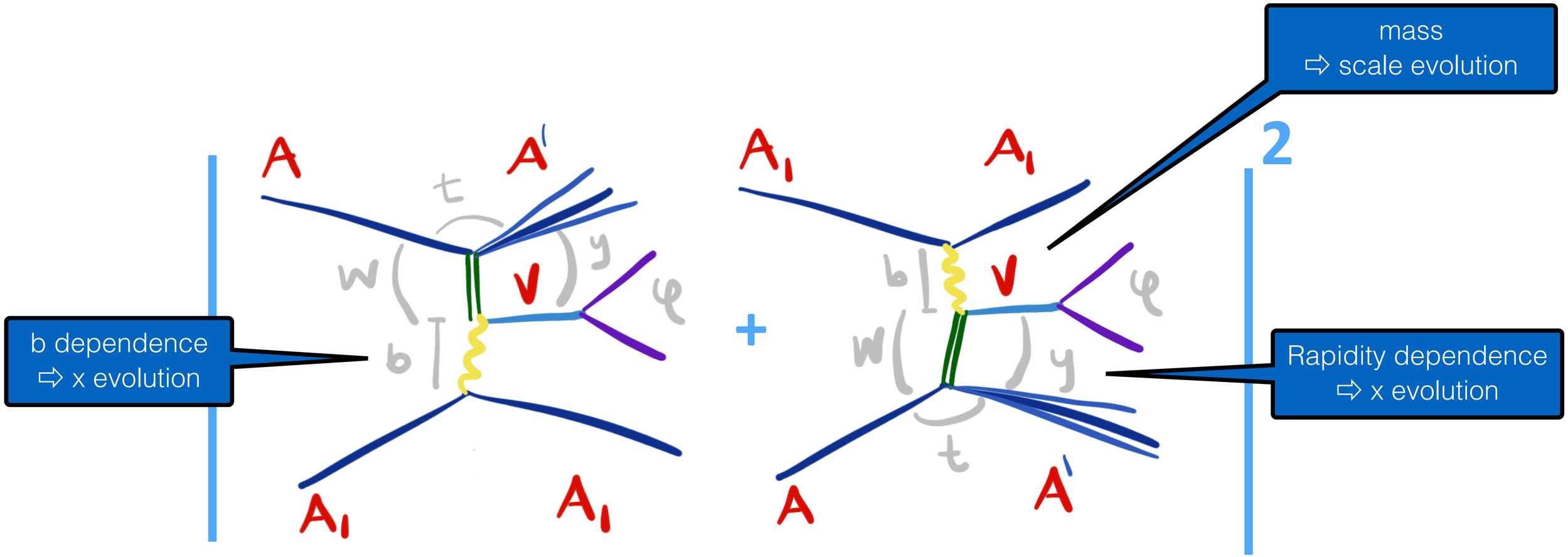

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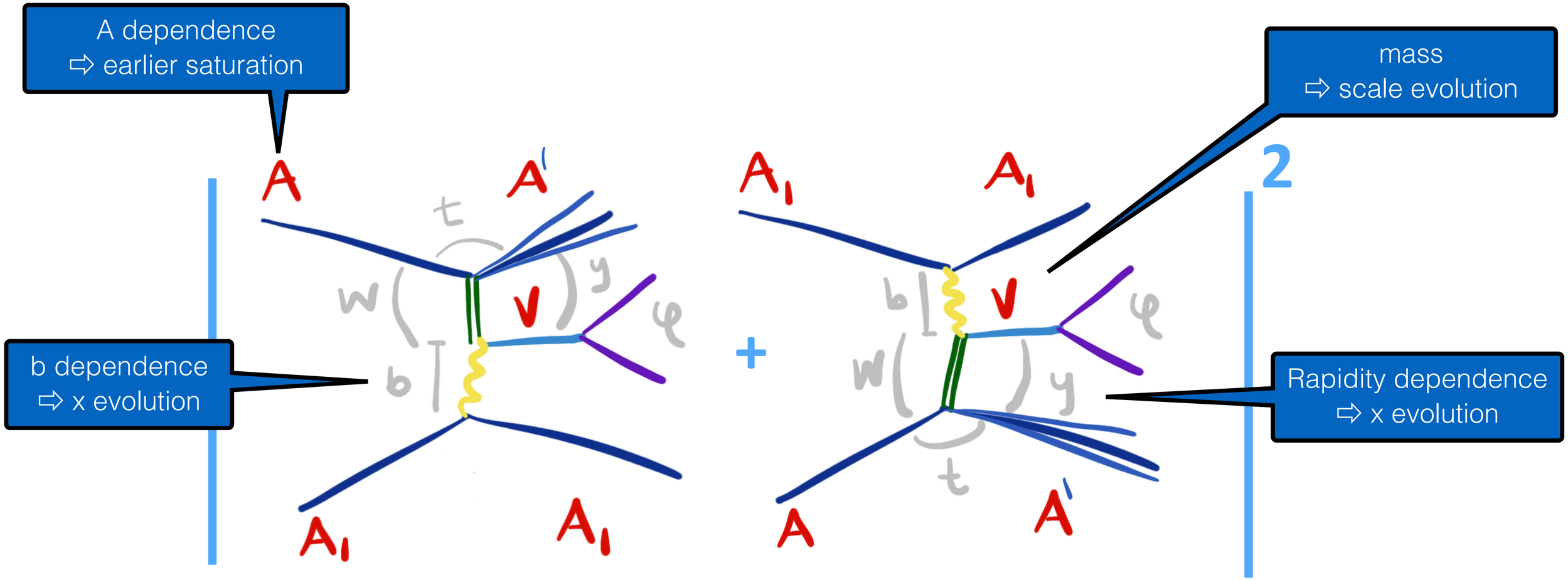
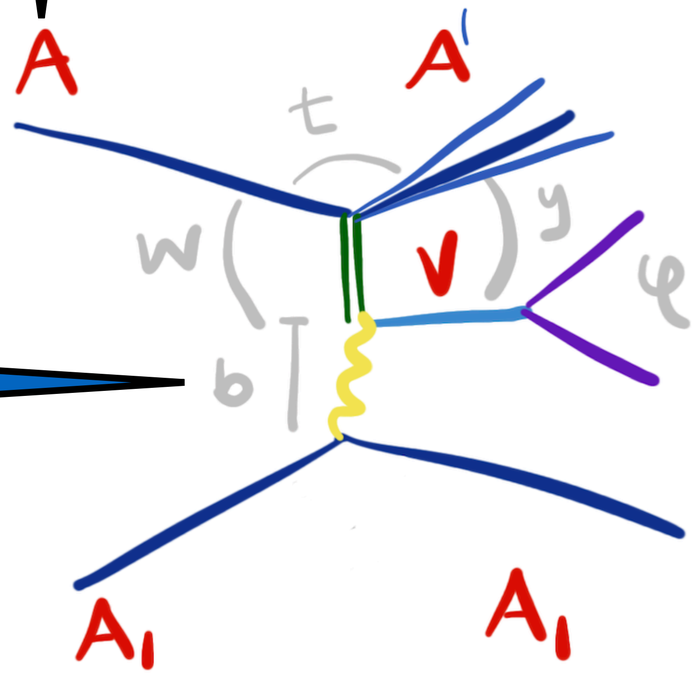


Instead of a summary

A dependence
⇨ earlier saturation

b dependence
⇨ x evolution



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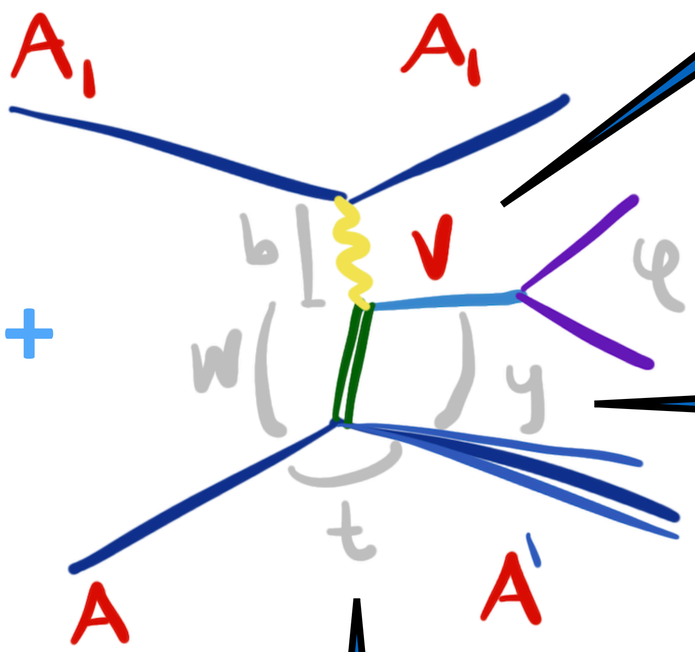


mass
⇨ scale evolution

2

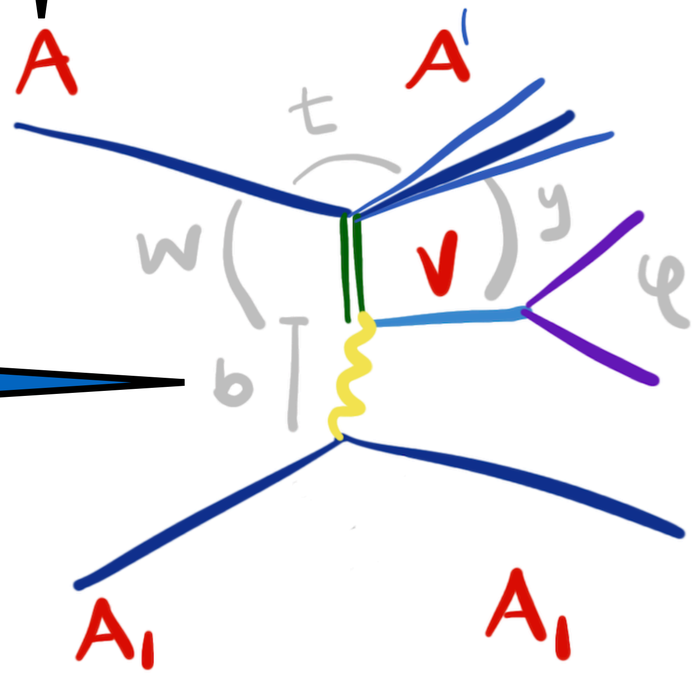
Rapidity dependence
⇨ x evolution

|t| dependence
⇨ transverse behaviour

Instead of a summary

A dependence
⇨ earlier saturation

b dependence
⇨ x evolution



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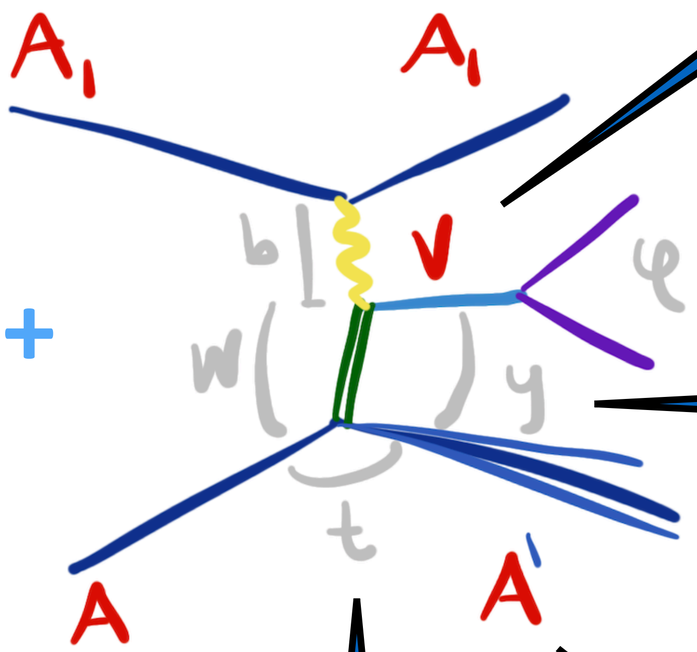


2

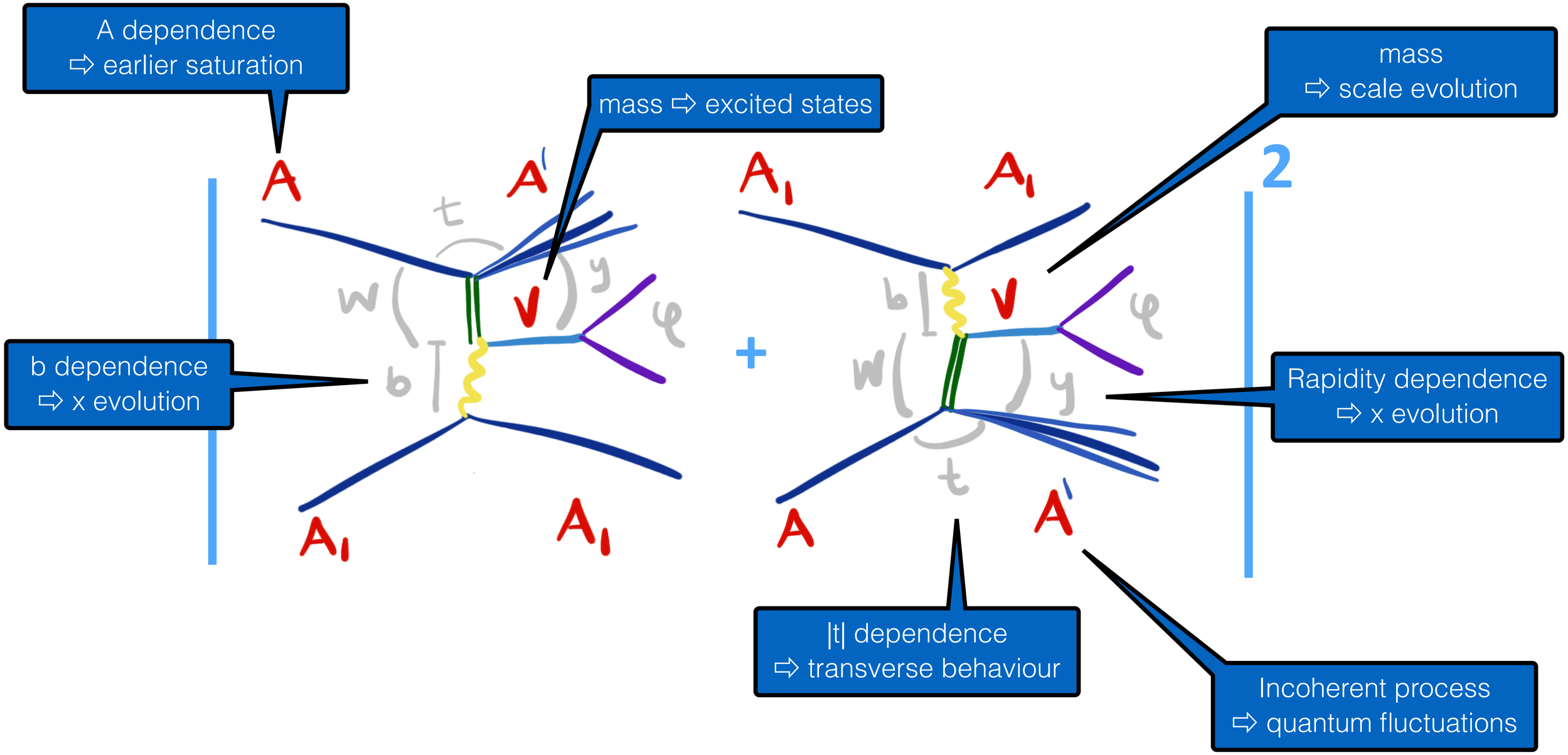
mass
⇨ scale evolution

Rapidity dependence
⇨ x evolution

|t| dependence
⇨ transverse behaviour

Incoherent process
⇨ quantum fluctuations

Instead of a summary



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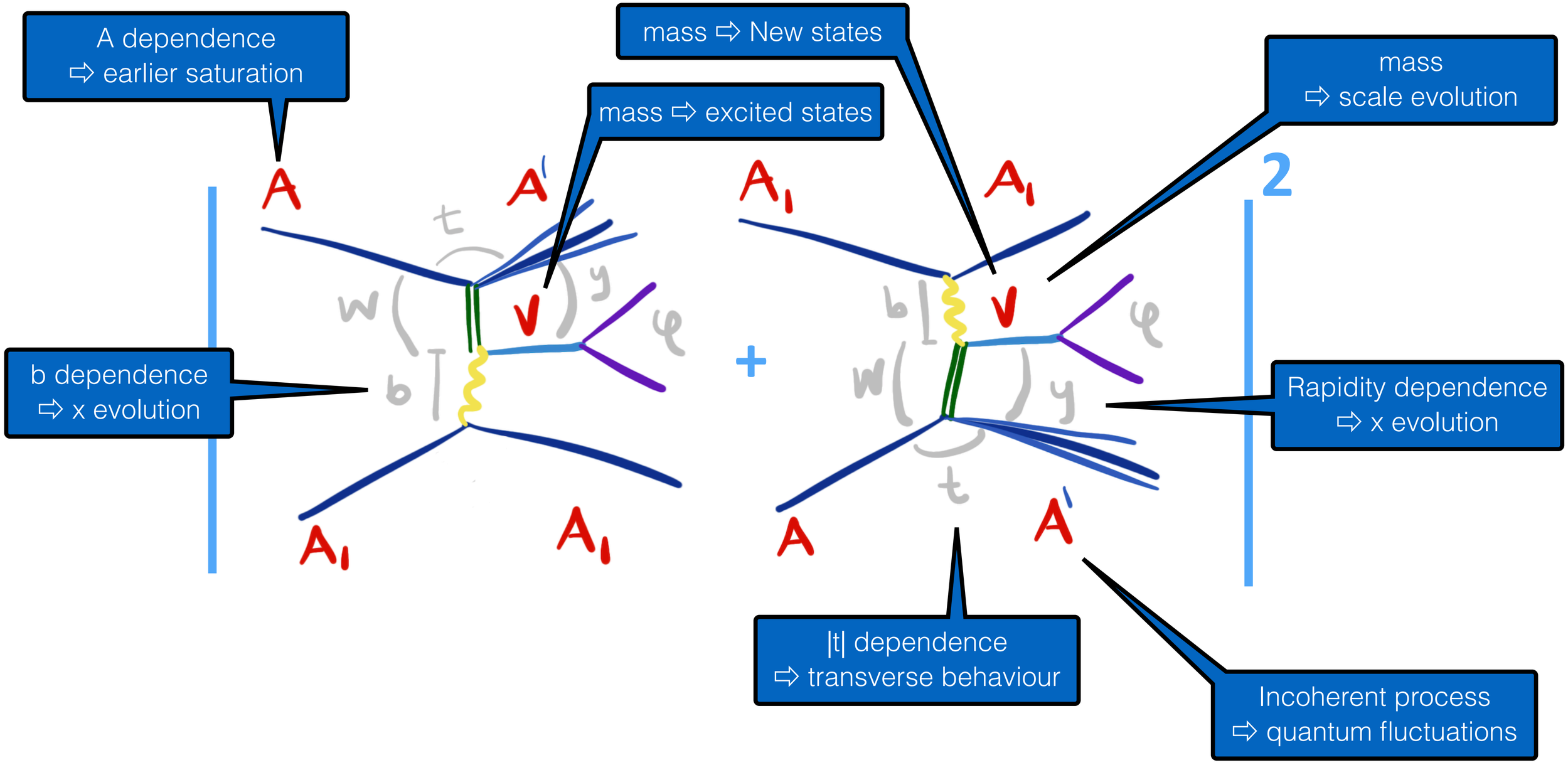

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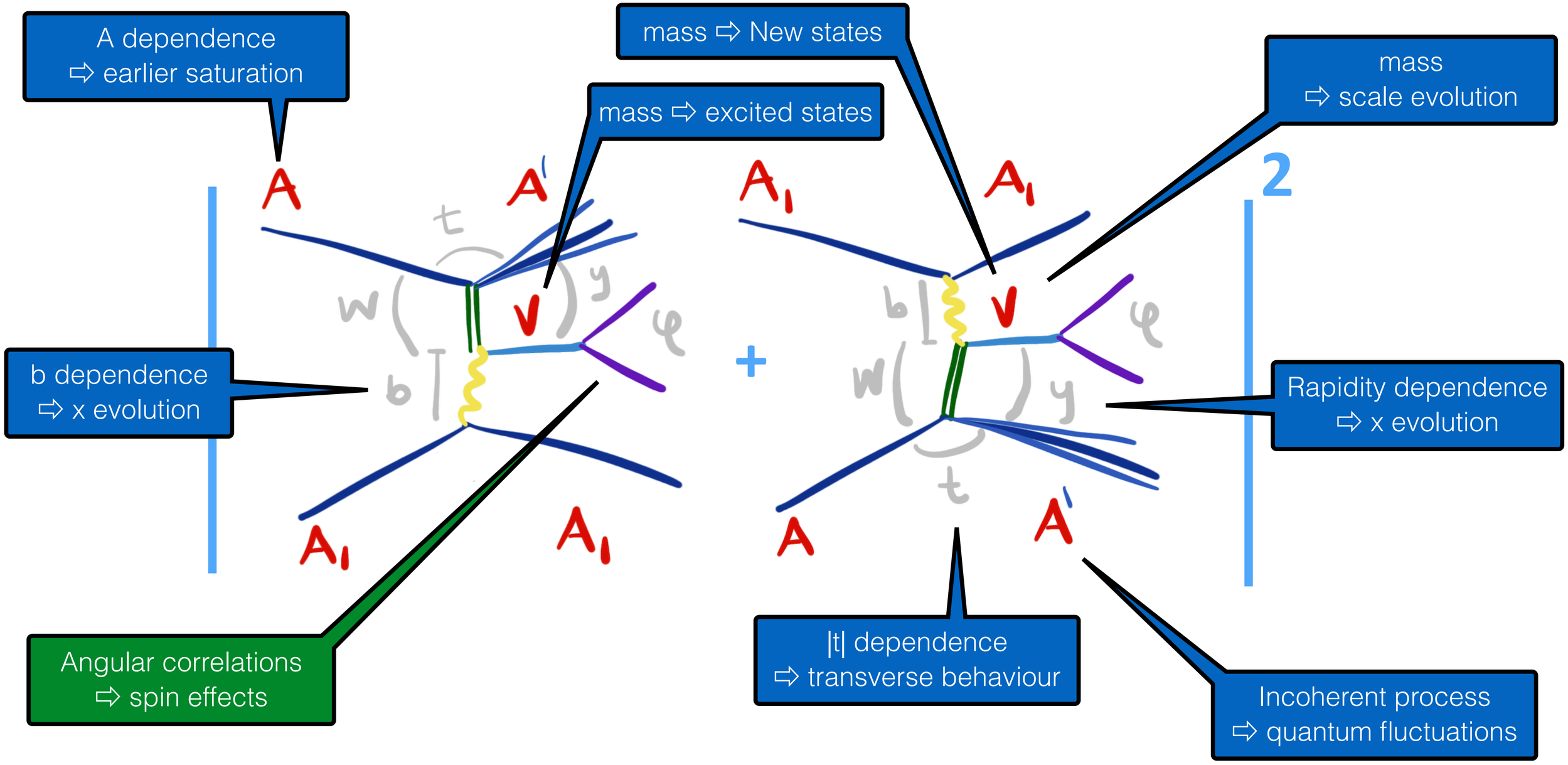
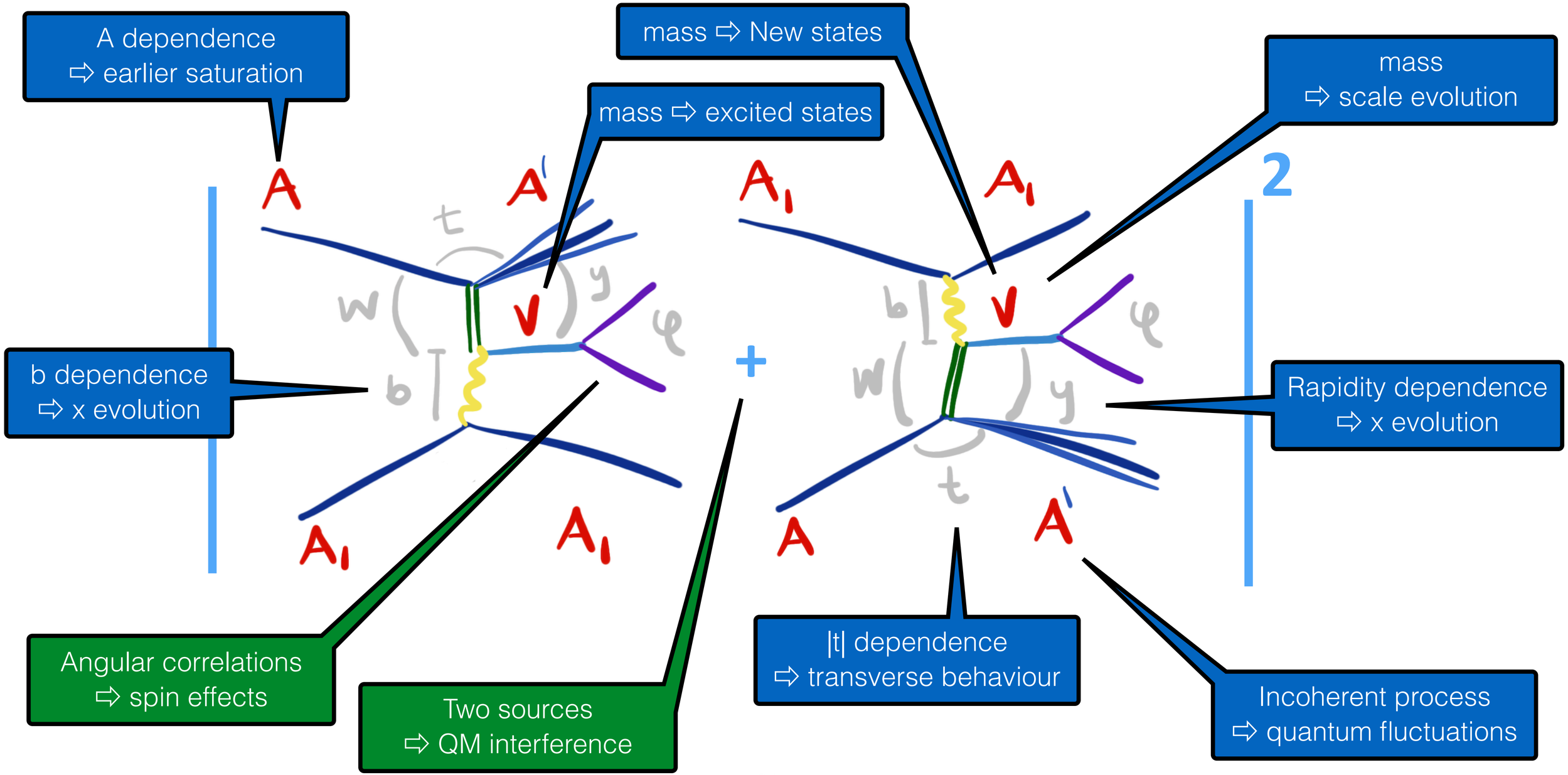


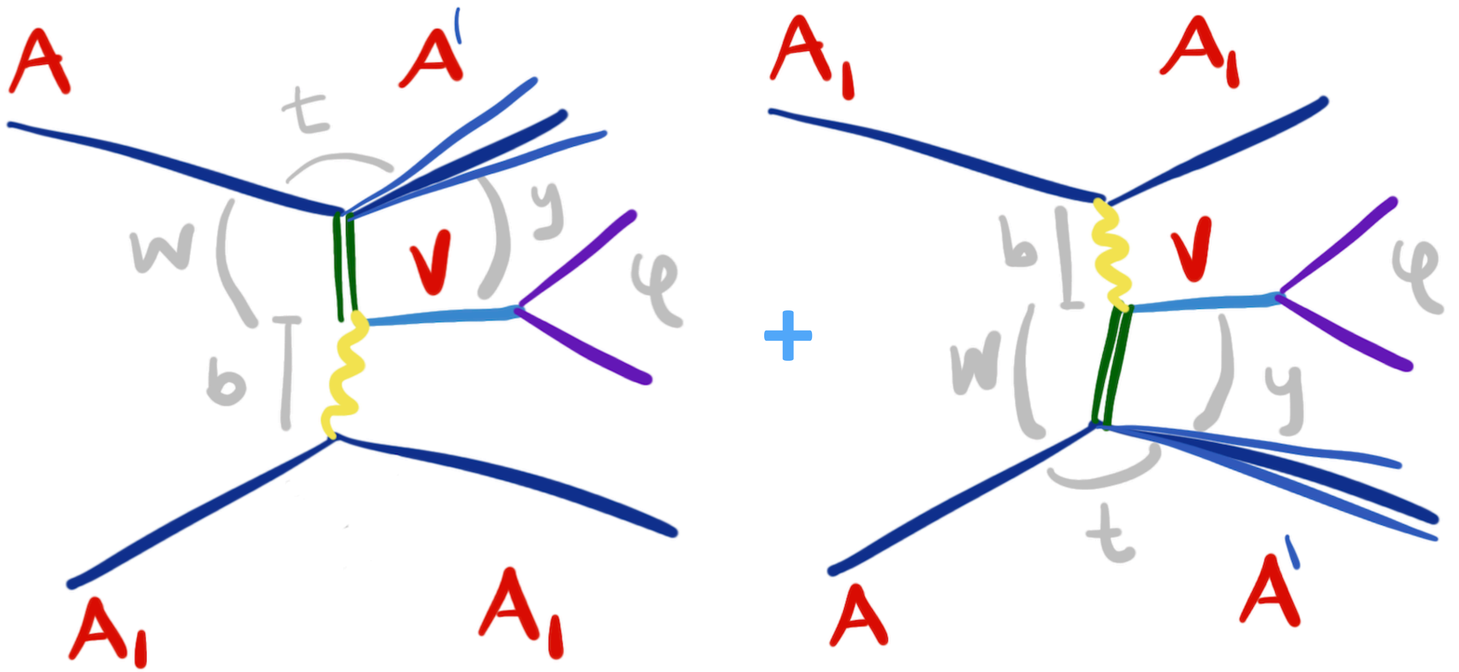
Instead of a summary



Instead of outlook

LHC/RHIC

Accelerator and detectors optimised for something else, nonetheless we have managed to measure this:



2

EICs

I am sure that measurements at EICs will be better than whatever we imagine today