

In Search of Saturation

Probing the Frontier of High-Energy Hadron Scattering

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Penn State University

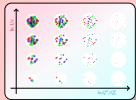
March 20, 2014

based on

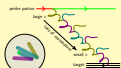
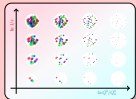
PRL **112** 012302 (2014)

and work in progress

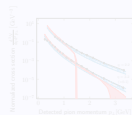
Parton model of proton structure



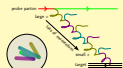
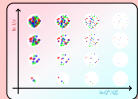
Outline



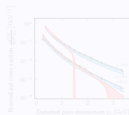
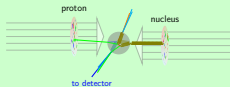
QCD and partons

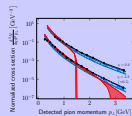
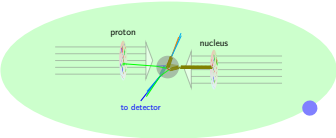
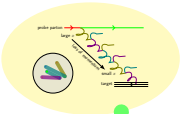
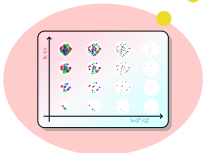


Outline



Relating theory
to experiment





What's in a proton?

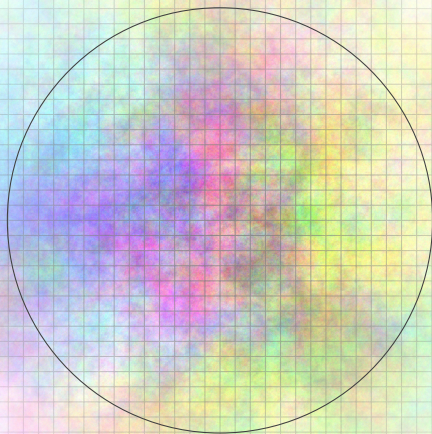
1 of 19



What's in a proton?

1 of 19

Quantum fields



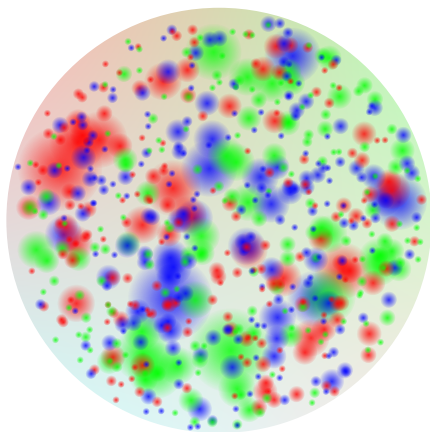
...not directly observable



What's in a proton?

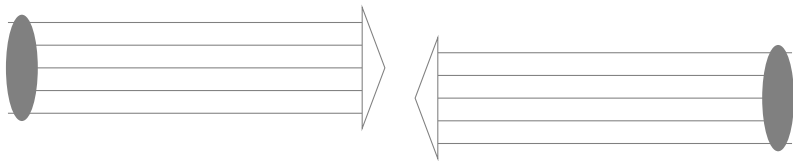
Acts like a collection of particles, or **partons**

quarks
gluons
photons
electrons
W bosons
Z bosons
Higgs bosons
etc.



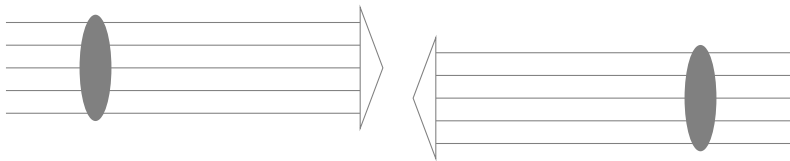
Observing the proton's structure

Information about proton's structure comes from collisions



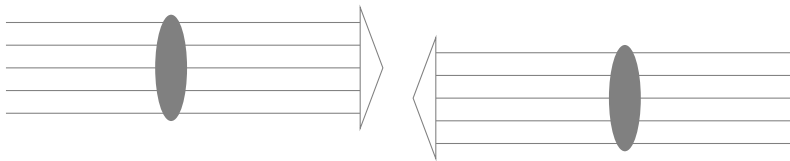
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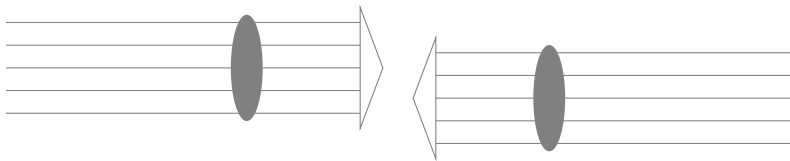
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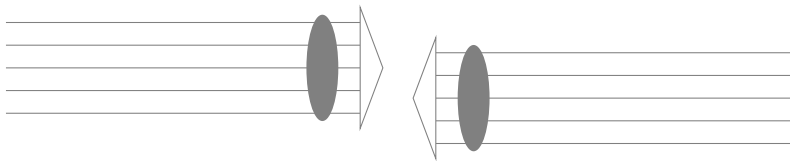
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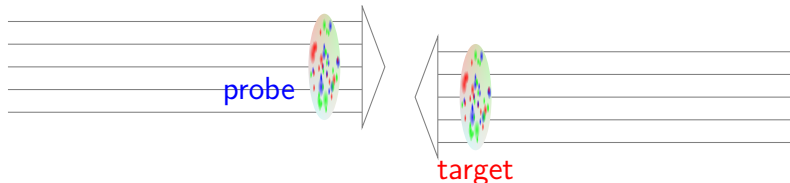
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Observing the proton's structure

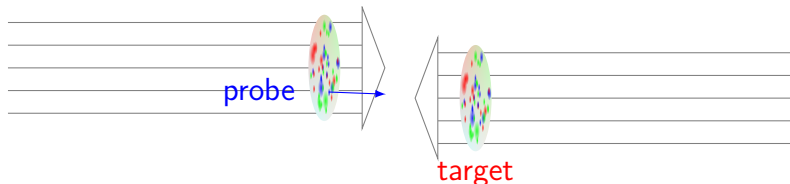
Information about proton's structure comes from collisions



Observing the proton's structure

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Information about proton's structure comes from collisions

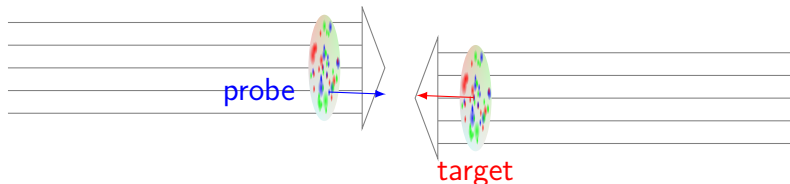


One parton from the probe proton

$$x_p = \frac{\text{forward momentum of parton}}{\text{forward momentum of proton}}$$

Observing the proton's structure

Information about proton's structure comes from collisions



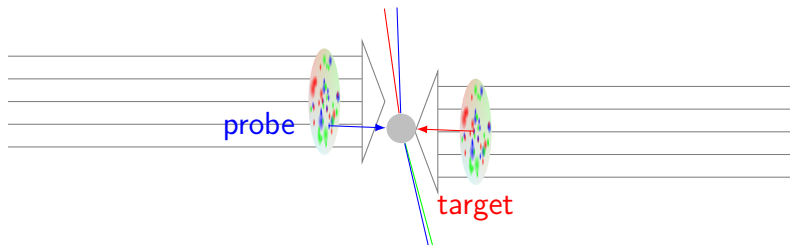
One parton from the target proton

$$x_t = \frac{\text{forward momentum of parton}}{\text{forward momentum of proton}}$$

Observing the proton's structure

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Information about proton's structure comes from collisions

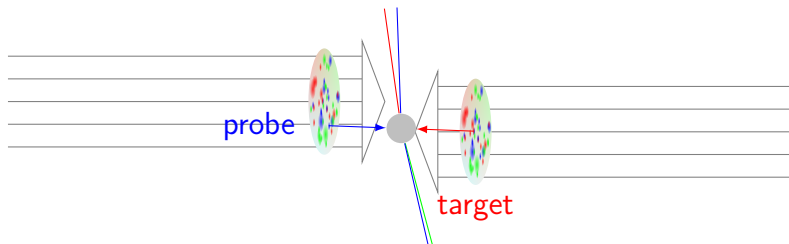


Particles come out and hit the detector

$Q \sim$ transverse (sideways) momentum transfer between partons

Observing the proton's structure

Information about proton's structure comes from collisions

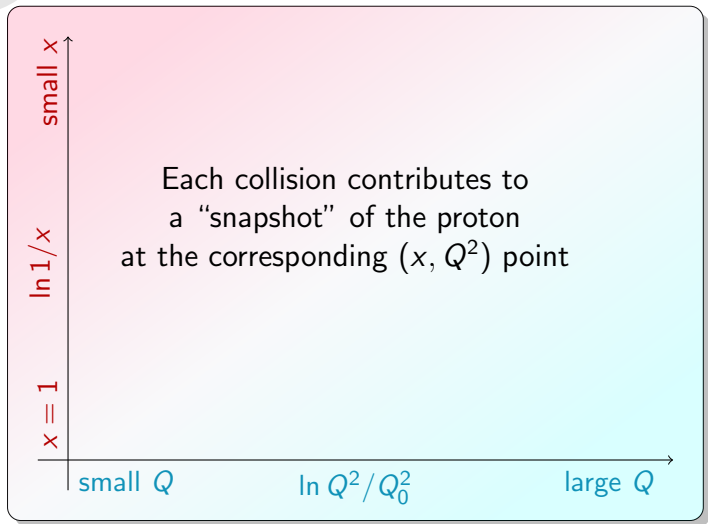


Behavior of target classified by

- x_t : forward momentum fraction
- Q : transverse momentum transfer

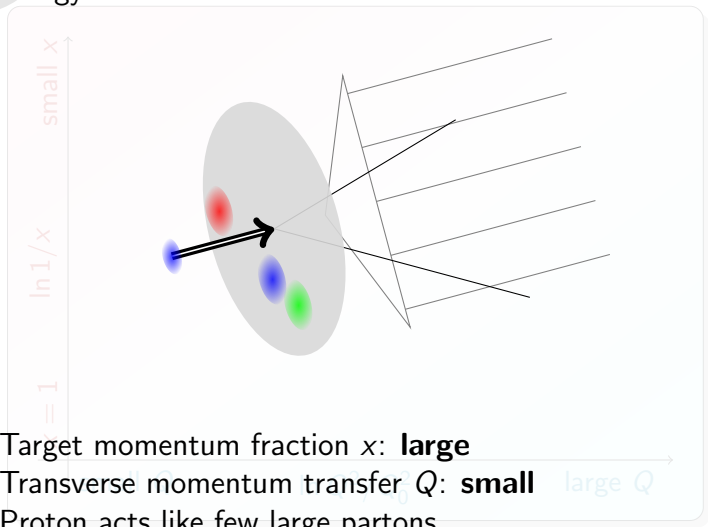
which are calculated from measurements of outgoing particles

Classifying collisions



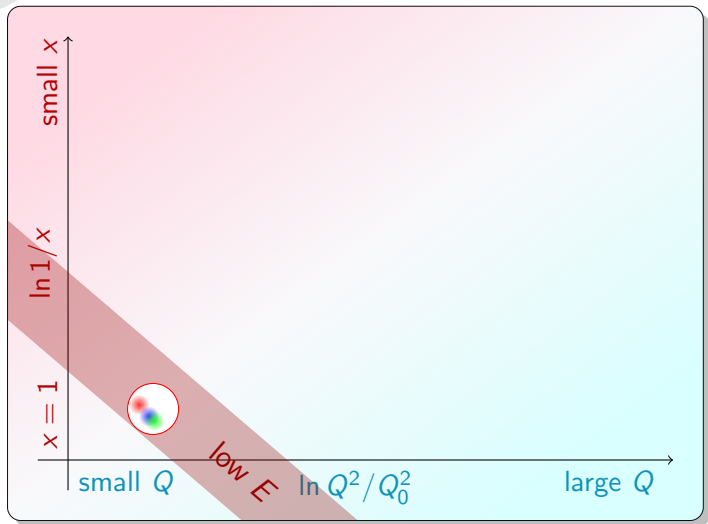
Classifying collisions

Low energy collision:



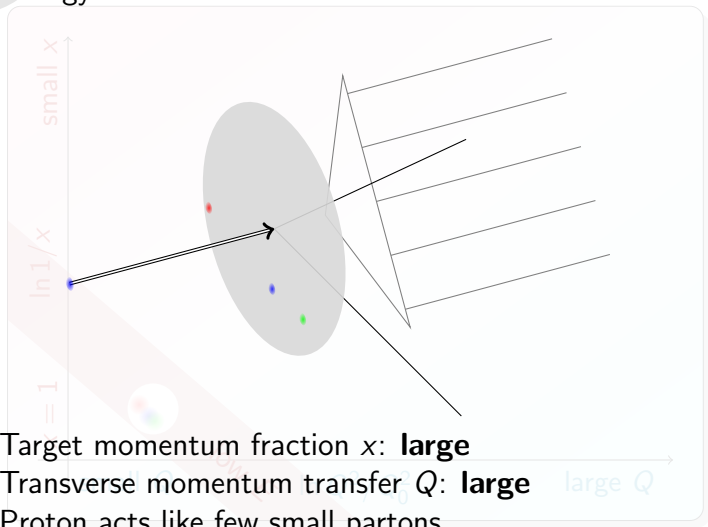
Classifying collisions

3 of 19



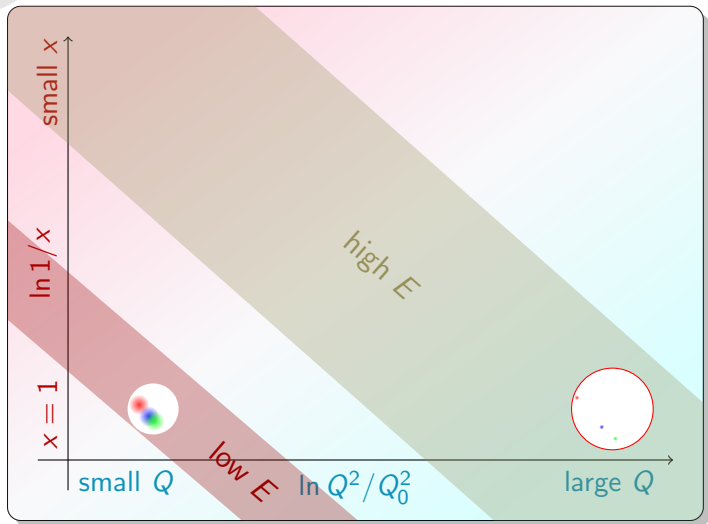
Classifying collisions

High energy collision:



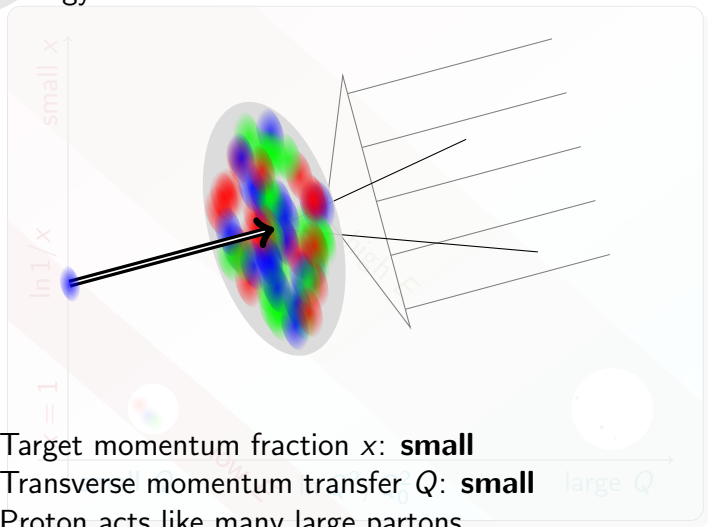
Classifying collisions

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Classifying collisions

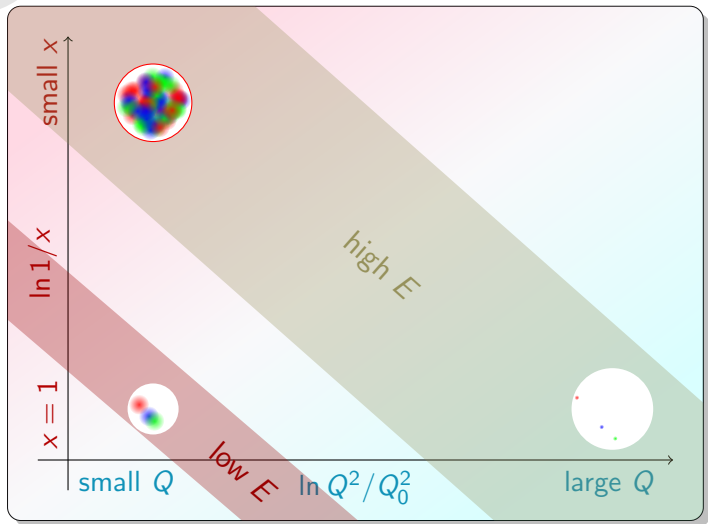
High energy collision:



- Target momentum fraction x : **small**
- Transverse momentum transfer Q : **small**
- Proton acts like many large partons

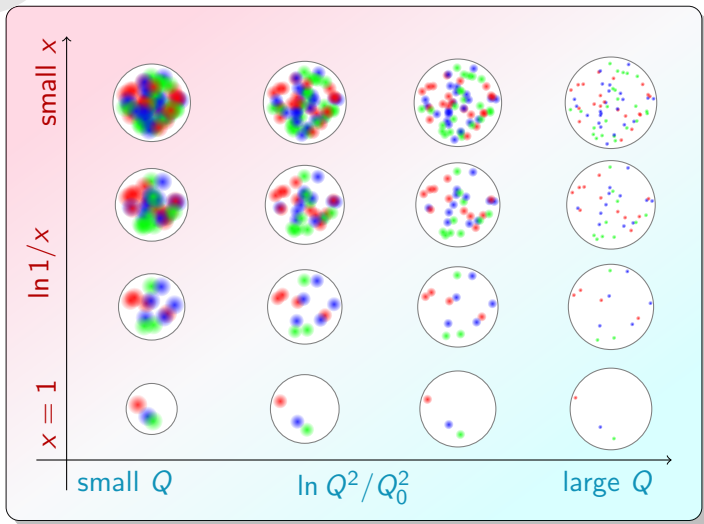
Classifying collisions

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Internal structure of a proton

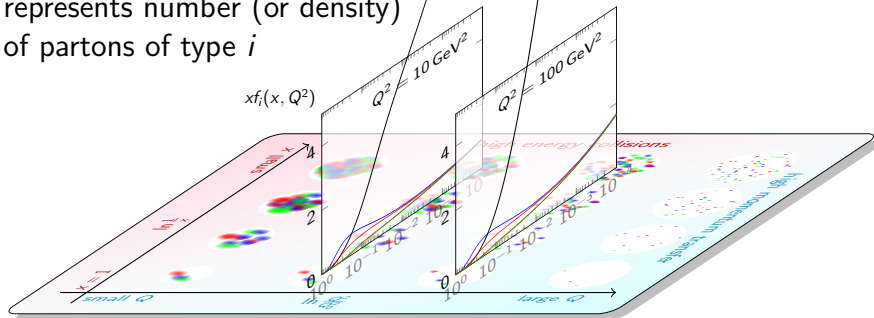
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Parton distributions

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Parton distribution function (PDF) $xf_i(x, Q^2)$ roughly represents number (or density) of partons of type i

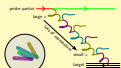
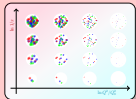


Shown for some types of partons:

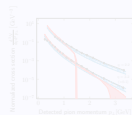
— gluon — up — down — antiup — antidown

This effective description is the **parton model**

Outline



QCD and partons



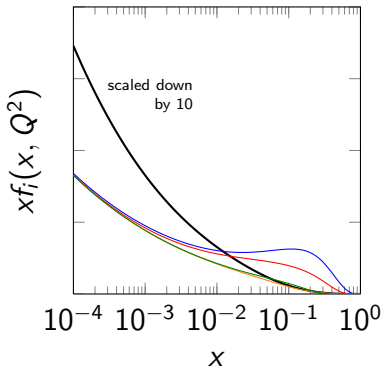
The parton model and QCD

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Quantum chromodynamics (QCD):

theory of strong interactions

Can we derive parton distributions from QCD?



The parton model and QCD

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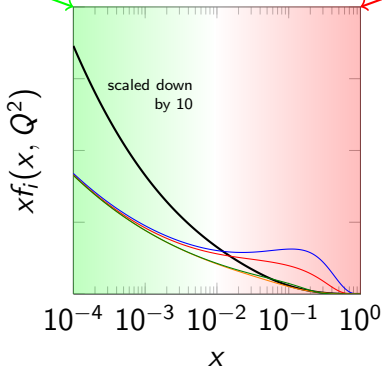
Quantum chromodynamics (QCD):

theory of strong interactions

Can we derive parton distributions from QCD?

yes

no(ish)

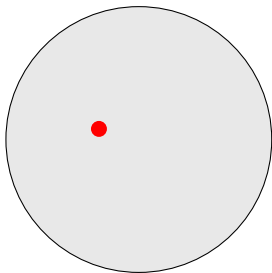


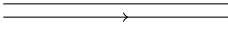
Parton branching

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Here's what happens under the hood:

probe parton 

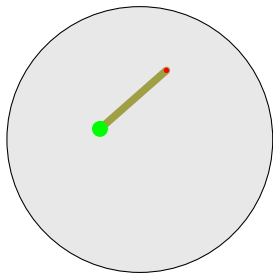


target 

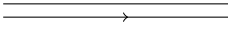
Parton branching

7 of 19

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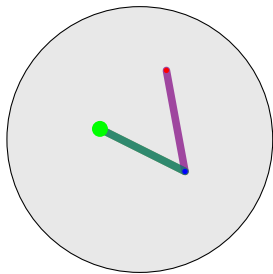
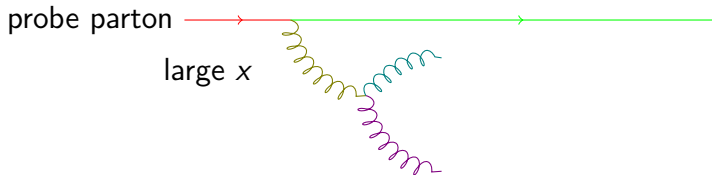


The diagram shows two parallel horizontal lines representing a parton. An arrow points to the right between the two lines.

Parton branching

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Here's what happens under the hood:



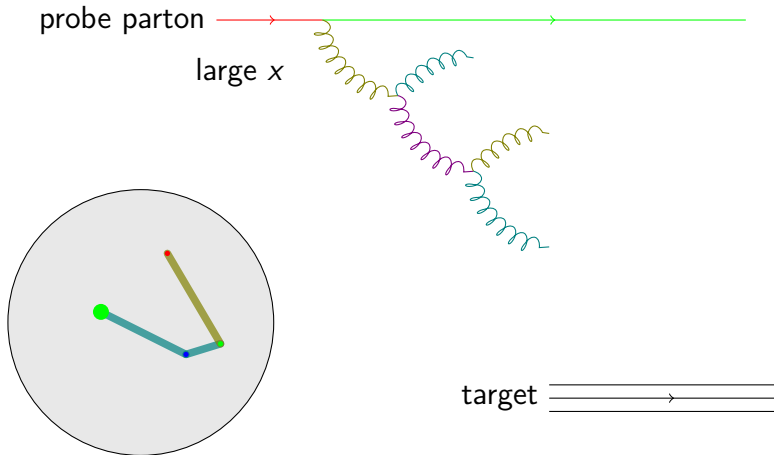
target

The target is represented by two horizontal parallel lines with an arrow pointing to the right, indicating the direction of the target's motion.

Parton branching

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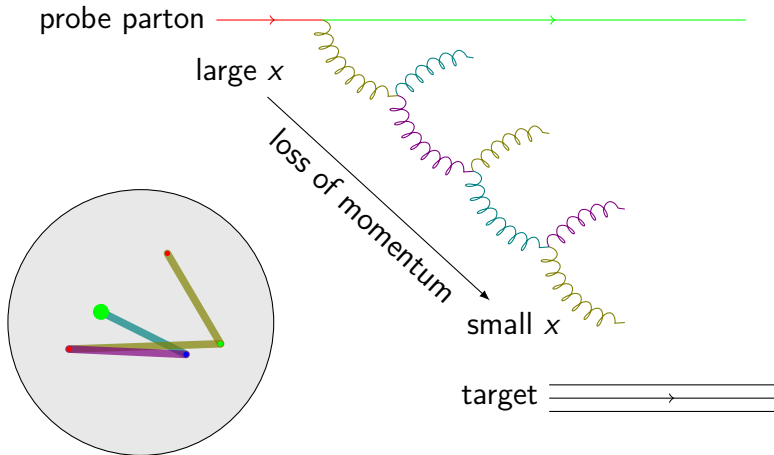
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Parton branching

7 of 19

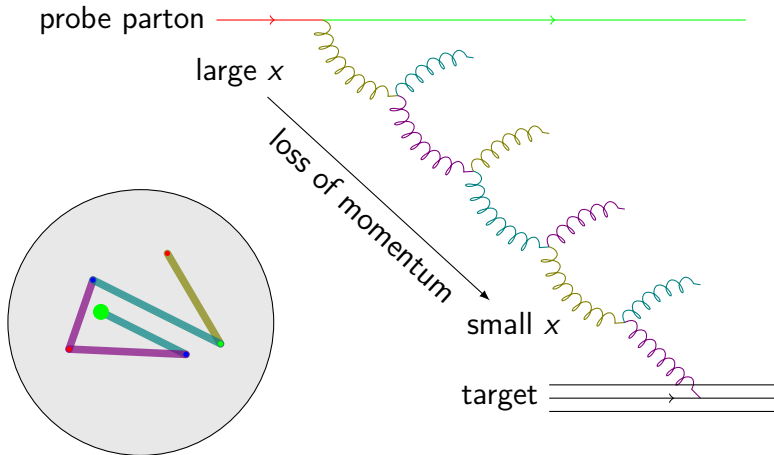
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Parton branching

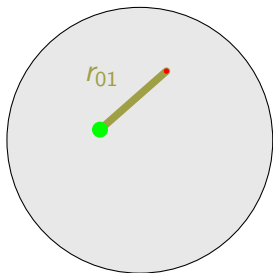
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Here's what happens under the hood:



Translation into math: **BFKL equation**

$$\frac{\partial S(x, r_{01}^2)}{\partial \ln \frac{1}{x}} = \frac{\alpha_s N_c}{2\pi^2} \int d^2 \mathbf{r}_2 \frac{r_{01}^2}{r_{02}^2 r_{12}^2} [S(x, r_{02}^2) + S(x, r_{12}^2) - S(x, r_{01}^2) - 1]$$



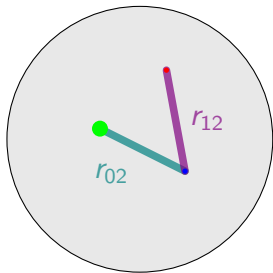
where

$$F(x, k_{\perp}^2) = \frac{d}{dQ^2} [xf_i(x, Q^2)] \Big|_{k_{\perp}^2}$$

$$S(x, r^2) = \int d^2 \mathbf{k}_{\perp} e^{-i\mathbf{k}_{\perp} \cdot \mathbf{r}} F(x, k_{\perp}^2)$$

Translation into math: **BFKL equation**

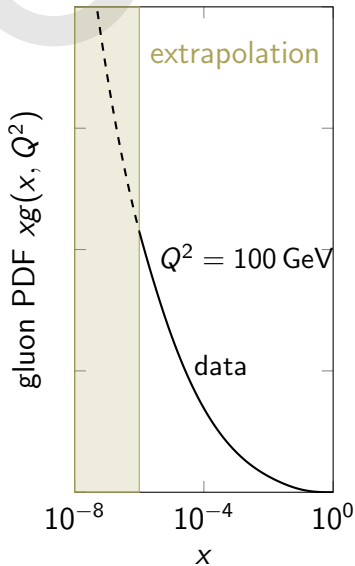
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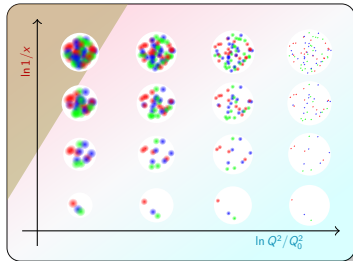
$$F(x, k_{\perp}^2) = \frac{d}{dQ^2} [xf_i(x, Q^2)] \Big|_{k_{\perp}^2}$$

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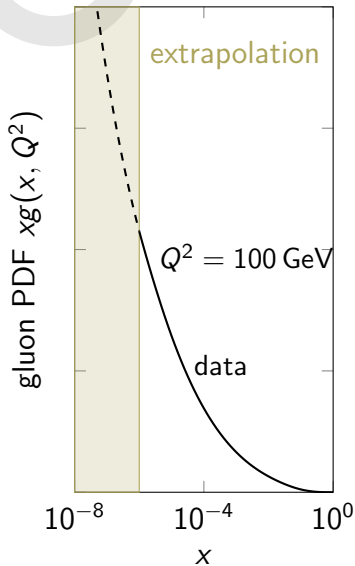
Problem:

- As $xg(x, Q^2)$ increases, so does gluon interaction probability
- At very small x , trend breaks probability conservation!

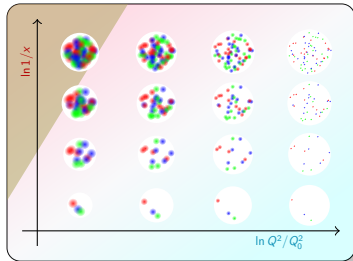


Runaway growth

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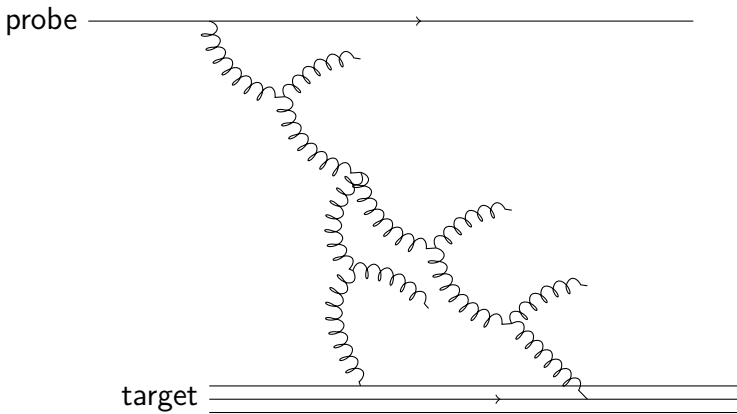


AHHHHHHHHH
PARTICLE PHYSICS IS BROKEN



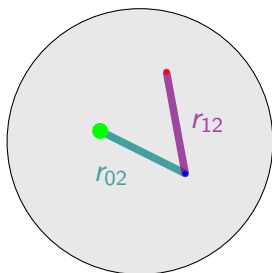
Multiple scattering

Multiple interactions occur with lots of partons in the target



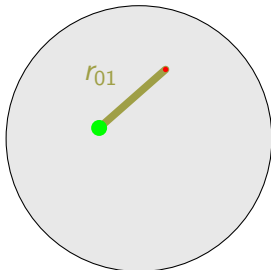
Translation into math: **BK equation**

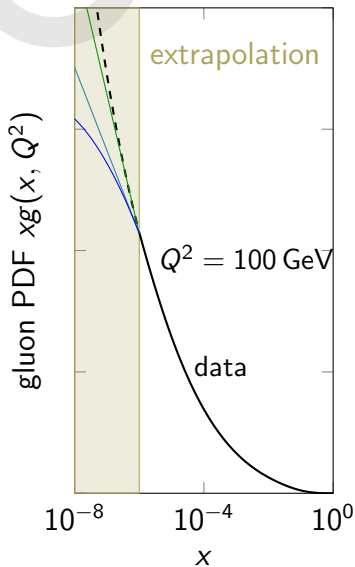
$$\frac{\partial S(x, r_{01}^2)}{\partial \ln \frac{1}{x}} = -\frac{\alpha_s N_c}{2\pi^2} \int d^2 \mathbf{r}_2 \frac{r_{01}^2}{r_{02}^2 r_{12}^2} [S(x, r_{01}^2) - S(x, r_{02}^2) S(x, r_{12}^2)]$$



Translation into math: **BK equation**

$$\frac{\partial S(x, r_{01}^2)}{\partial \ln \frac{1}{x}} = -\frac{\alpha_s N_c}{2\pi^2} \int d^2 \mathbf{r}_2 \frac{r_{01}^2}{r_{02}^2 r_{12}^2} [S(x, r_{01}^2) - S(x, r_{02}^2) S(x, r_{12}^2)]$$

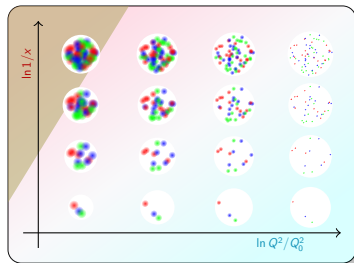




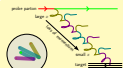
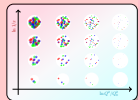
BK predicts slower growth

This is called **saturation**

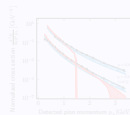
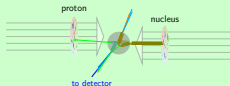
Details depend on parameters in the equation



Outline

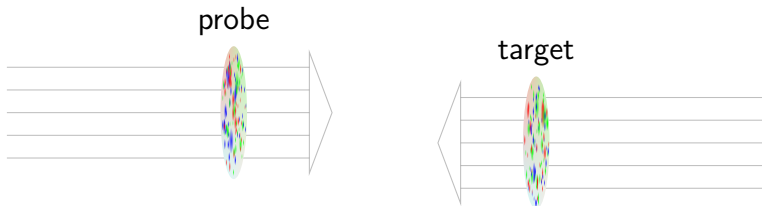


Relating theory
to experiment



Cross section calculation

To connect gluon distribution to measurable cross section:



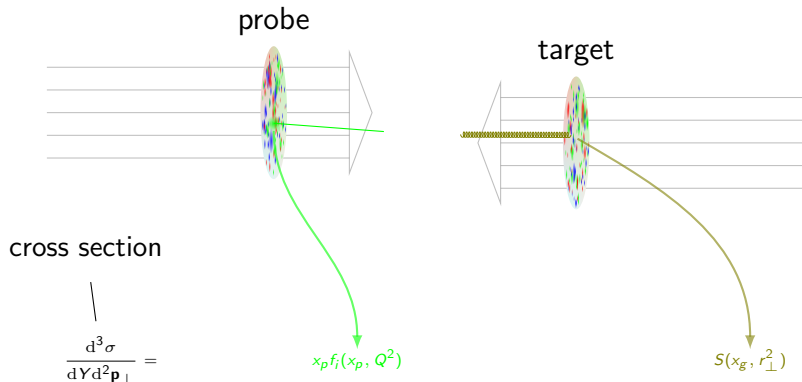
cross section

$$\frac{d^3\sigma}{dY d^2\mathbf{p}_\perp} =$$

Cross section calculation

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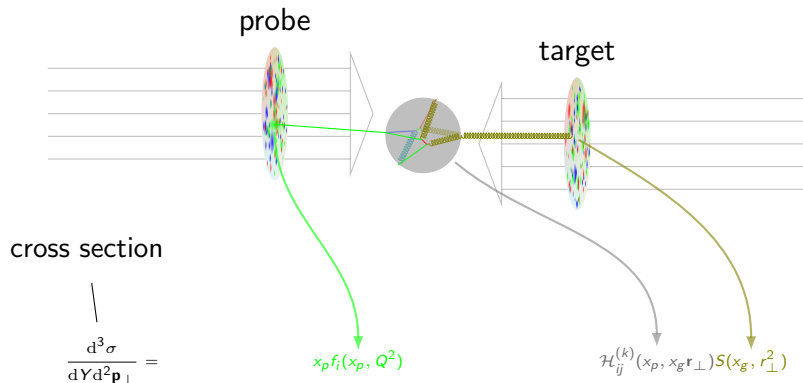
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Cross section calculation

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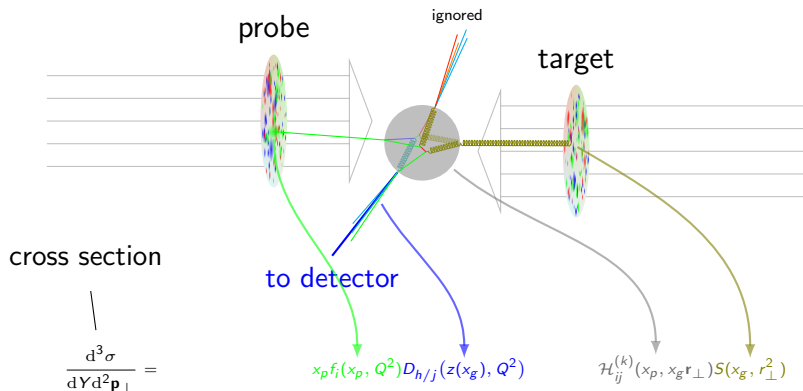
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Cross section calculation

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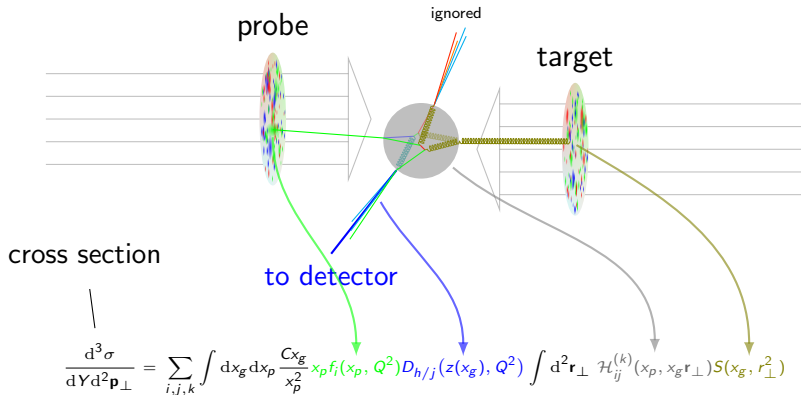
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Cross section calculation

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
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


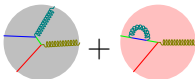
$$\frac{d^3\sigma}{dY d^2\mathbf{p}_\perp} = \sum_{i,j,k} \int dx_g dx_p \frac{C_{xg}}{x_p^2} x_p f_i(x_p, Q^2) D_{h/j}(z(x_g), Q^2) \int d^2\mathbf{r}_\perp \mathcal{H}_{ij}^{(k)}(x_p, x_g \mathbf{r}_\perp) S(x_g, r_\perp^2)$$

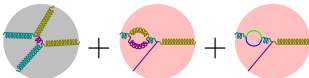
Leading order:


Next to leading order:


$$\mathcal{H}_{qq}^{(0)} \leftrightarrow$$


$$\mathcal{H}_{gg}^{(0)} \leftrightarrow$$


$$\mathcal{H}_{qq}^{(1)} \leftrightarrow$$


$$\mathcal{H}_{gg}^{(1)} \leftrightarrow$$


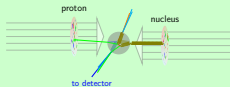
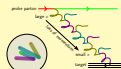
$$\mathcal{H}_{qg}^{(1)} \leftrightarrow$$


$$\mathcal{H}_{gq}^{(1)} \leftrightarrow$$


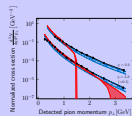
only in our
calculation

But are these contributions enough?

Outline



Results of our calculation



Determining the gluon distribution

- 1 Postulate a form for gluon distribution $S(x, r^2)$ using e.g. BK equation (section 2)
- 2 Plug in to cross section formula (section 3)
- 3 Compare results to data

Two reasons it might not match:

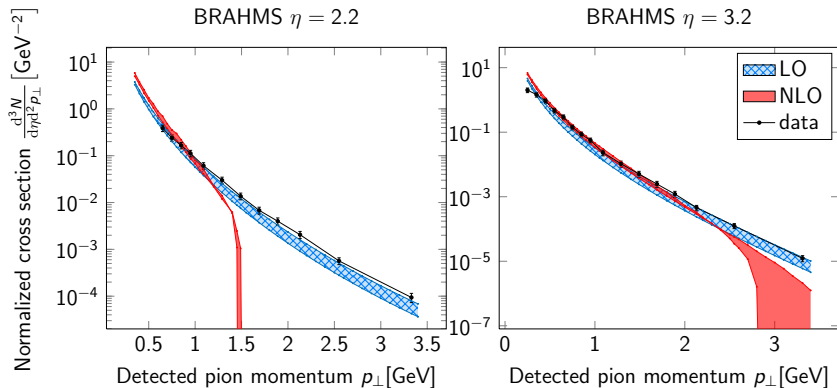
- Proposed model of gluon distribution is not accurate; or
- Cross section formula is not precise enough



Comparison with data

16 of 19

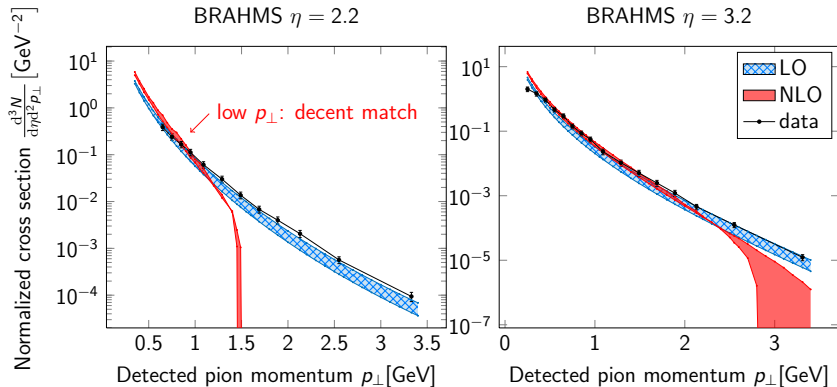
Best available: from BRAHMS @ RHIC (Brookhaven)



Comparison with data

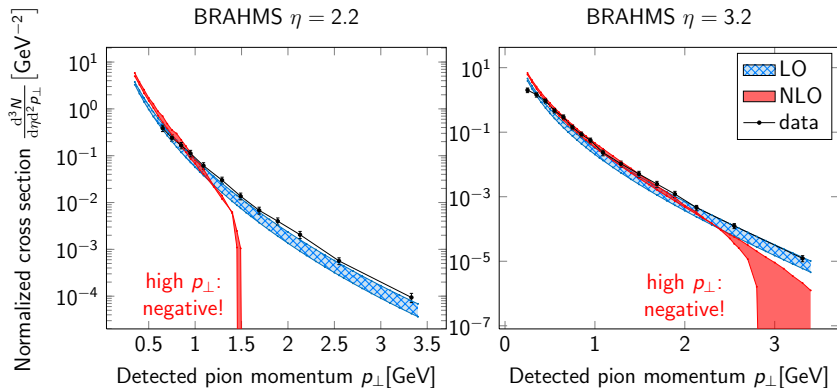
16 of 19

Best available: from BRAHMS @ RHIC (Brookhaven)



Comparison with data

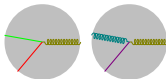
Best available: from BRAHMS @ RHIC (Brookhaven)



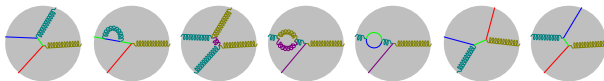
Strongly suggests the LO+NLO terms are insufficient!

What next?

If the leading order



and next to leading order terms



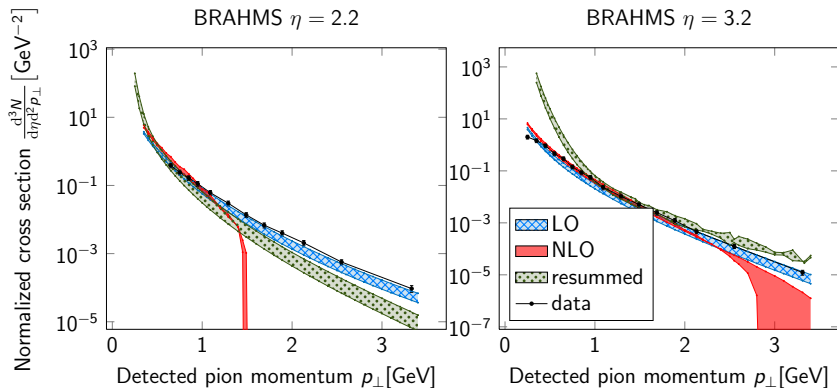
don't work, look for largest terms at higher orders.

Like  but with more loops.

Resummation results

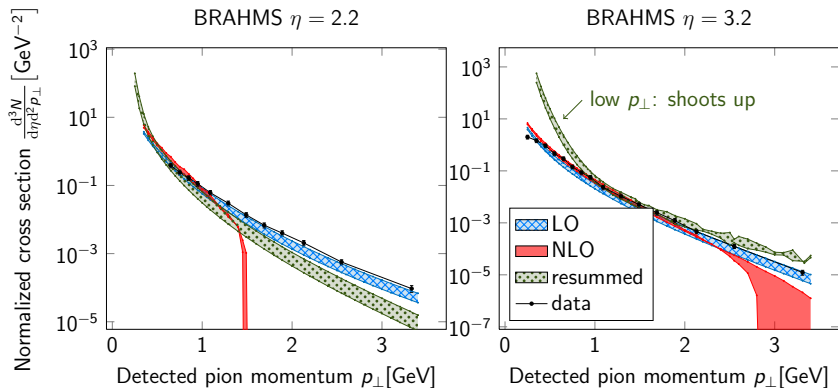
18 of 19

Simplest resummation scheme:



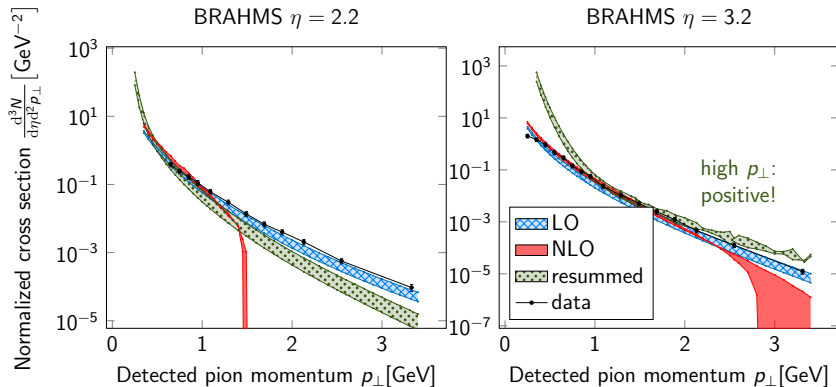
Resummation results

Simplest resummation scheme:



Resummation results

Simplest resummation scheme:

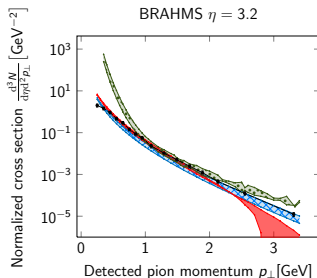


This is promising! But needs better tuning.

What does this tell us?

Three possible conclusions:

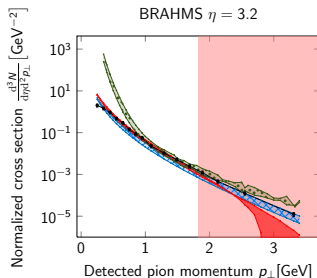
- Cross section formula is not precise enough
- Model of gluon distribution is not accurate, or
- Model of gluon distribution is accurate



What does this tell us?

Three possible conclusions:

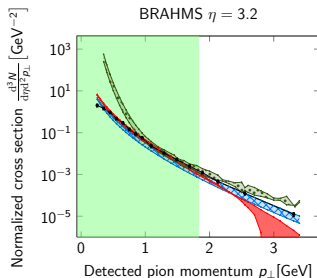
- Cross section formula is not precise enough
- Model of gluon distribution is not accurate, or
- Model of gluon distribution is accurate



What does this tell us?

Three possible conclusions:

- Cross section formula is not precise enough
- Model of gluon distribution is not accurate, or
- **Model of gluon distribution is accurate**



NLO formula is useful for looking for saturation

Acknowledgments

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- Bowen Xiao
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- Milton Cole
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- Jorge Sofo
- Anna Staśto
- Mauricio Terrones

And
YOU

for staying awake