QCD

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TAE (Taller de Altas Energias) - Workshop on High Energy Physics
Benasque September 2022

[Two lectures on selected topics]

Yocto/LHC
Yoctosecond imaging of QCD collectivity using jet observables
An ERC Advanced Grant 2019 · 2024
erc
European Research Council
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Outline

Lecture 1: QCD at colliders - *“gluon multiplication”*

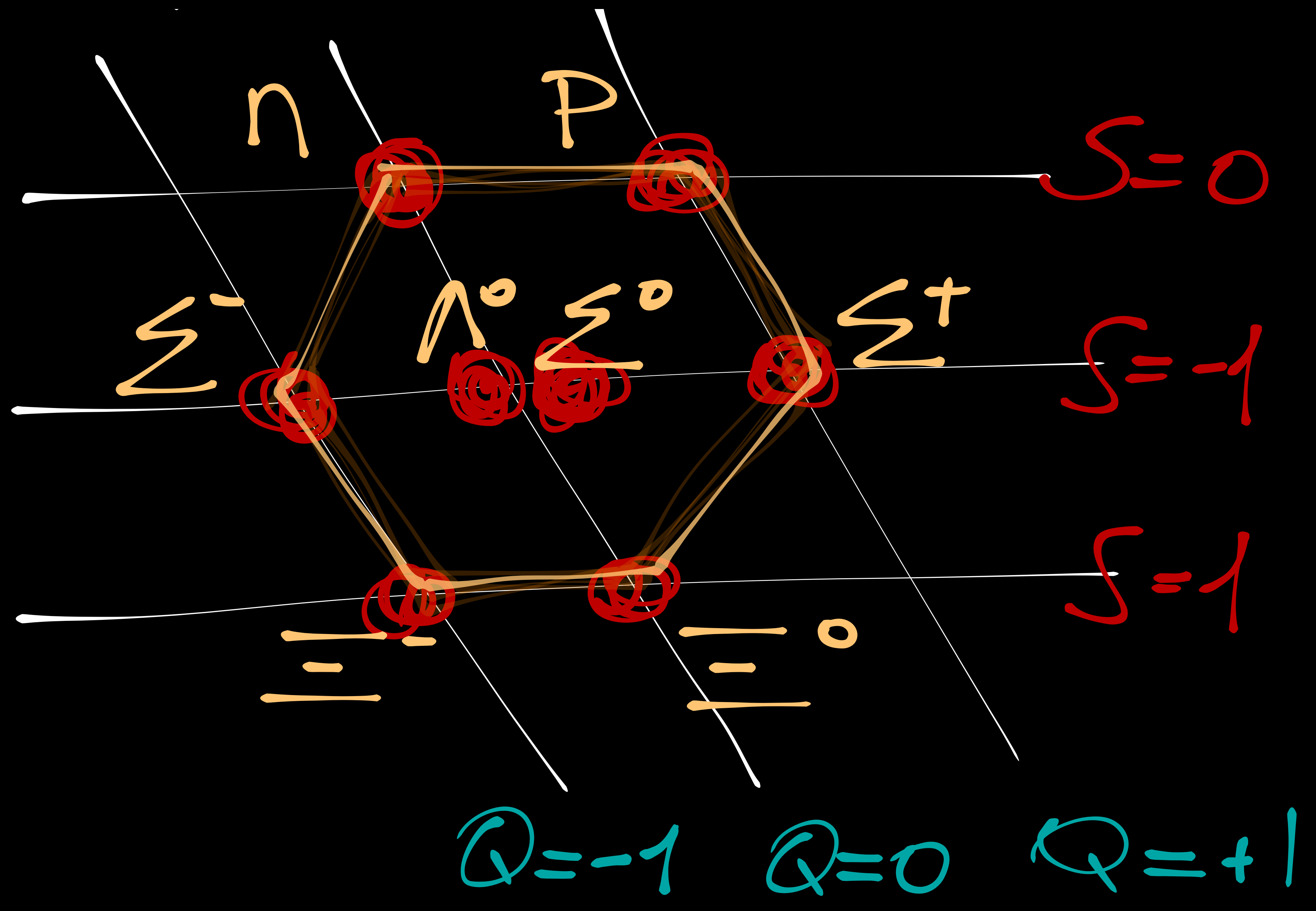
- Jets
- Parton Distribution Functions

Lecture 2: Hot and dense QCD

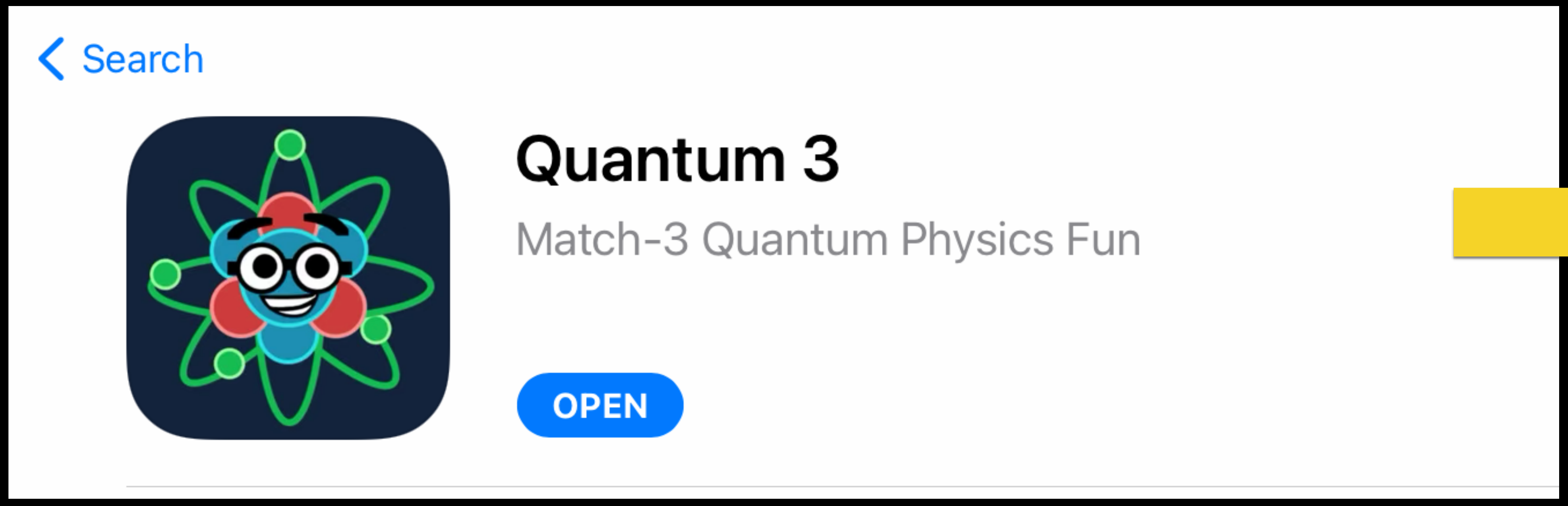
- The structure of matter in extraordinary conditions of temperature and density

Afternoon - two cases revealing quantum coherence

We are made of ~~stars~~ quarks



Hadrons are composite



The proton structure

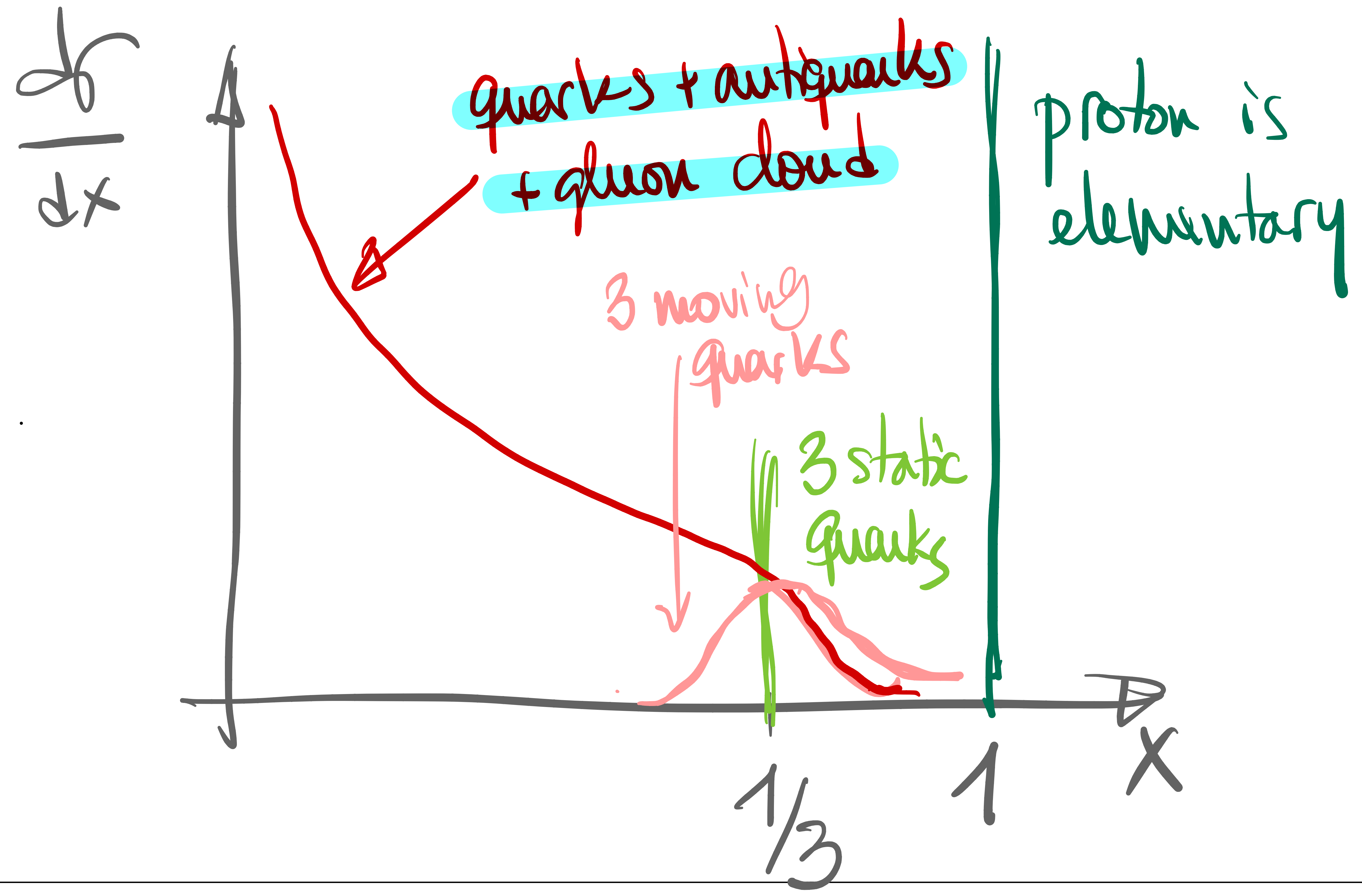
A proton seen in a lepton-proton scattering

Bjorken-x

$$x = \frac{Q^2}{2p \cdot q}$$

Can be written in terms of the lepton kinematics alone

[x=1 for elastic scattering]



QCD

QCD is the theory of the strong interaction

- Describes hadrons and their interactions
  - Asymptotic states
  - Nuclear matter (us)
  - Colorless objects
- However, quarks and gluons in the lagrangian
  - Fundamental particles
  - Color charge
- To build the Lagrangian proceed as for QED - gauge theory

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$$

The color charge is a vector

$$\mathcal{L} = \bar{\Psi}_a (i \not{D} - m) \Psi_a$$

Invariant under color "rotations" → SU(3)

$$\psi' = e^{i\alpha_a t^a}\psi$$

QCD

Color transformations with the Gell-Mann matrices $t_a = \frac{1}{2}\lambda_a$

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$

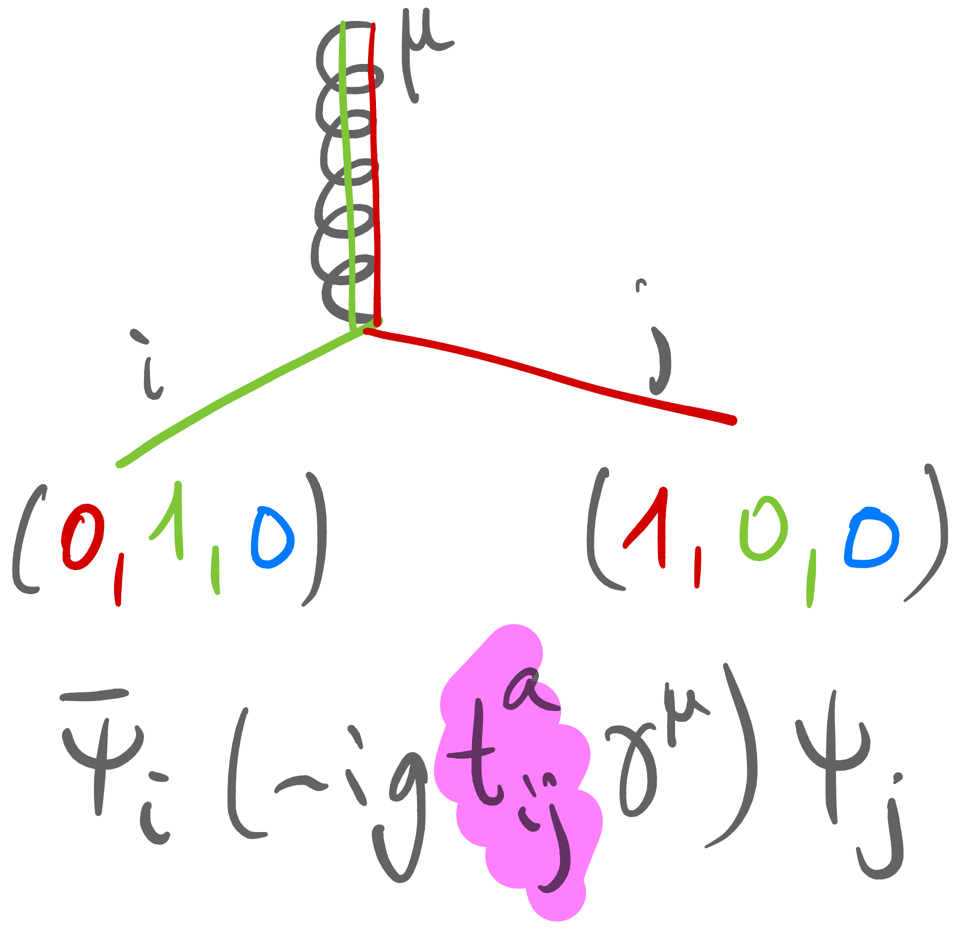
$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & \frac{-2}{\sqrt{3}} \end{pmatrix},$$

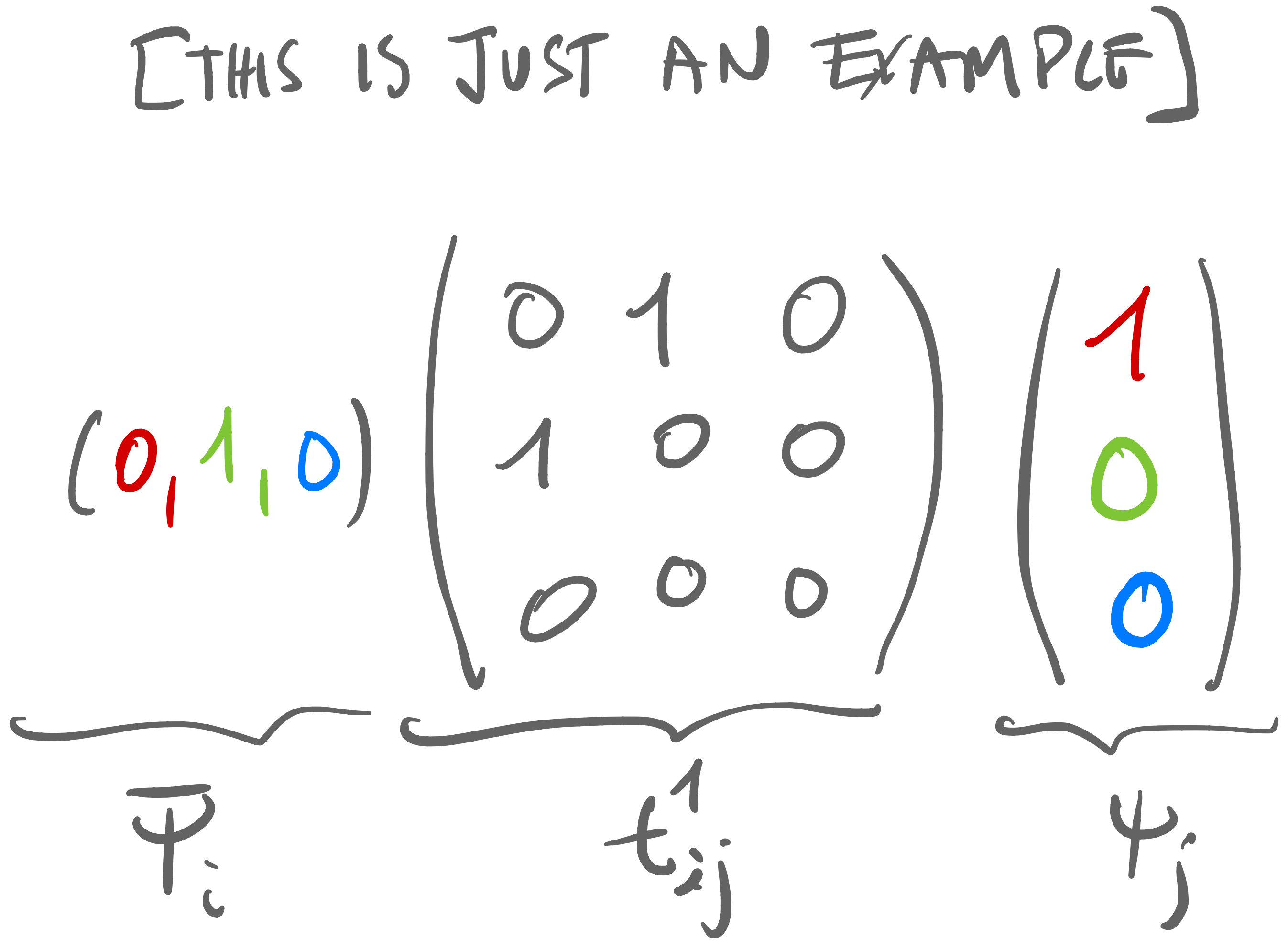
Quark's color - fundamental representation of SU(3)

$$[t^a, t^b] = i f_{abc} t^c$$

Gluons change the color of the quark

[the corresponding vertex in QED does not change the charge of the electron]

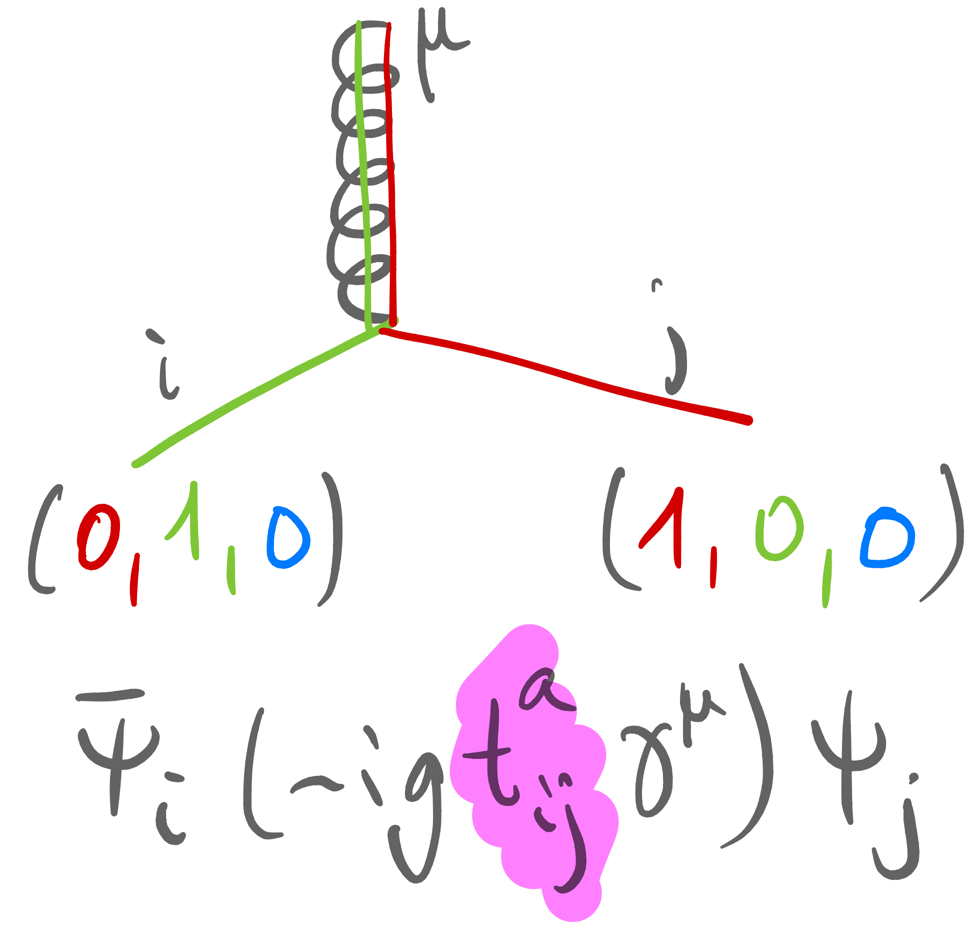




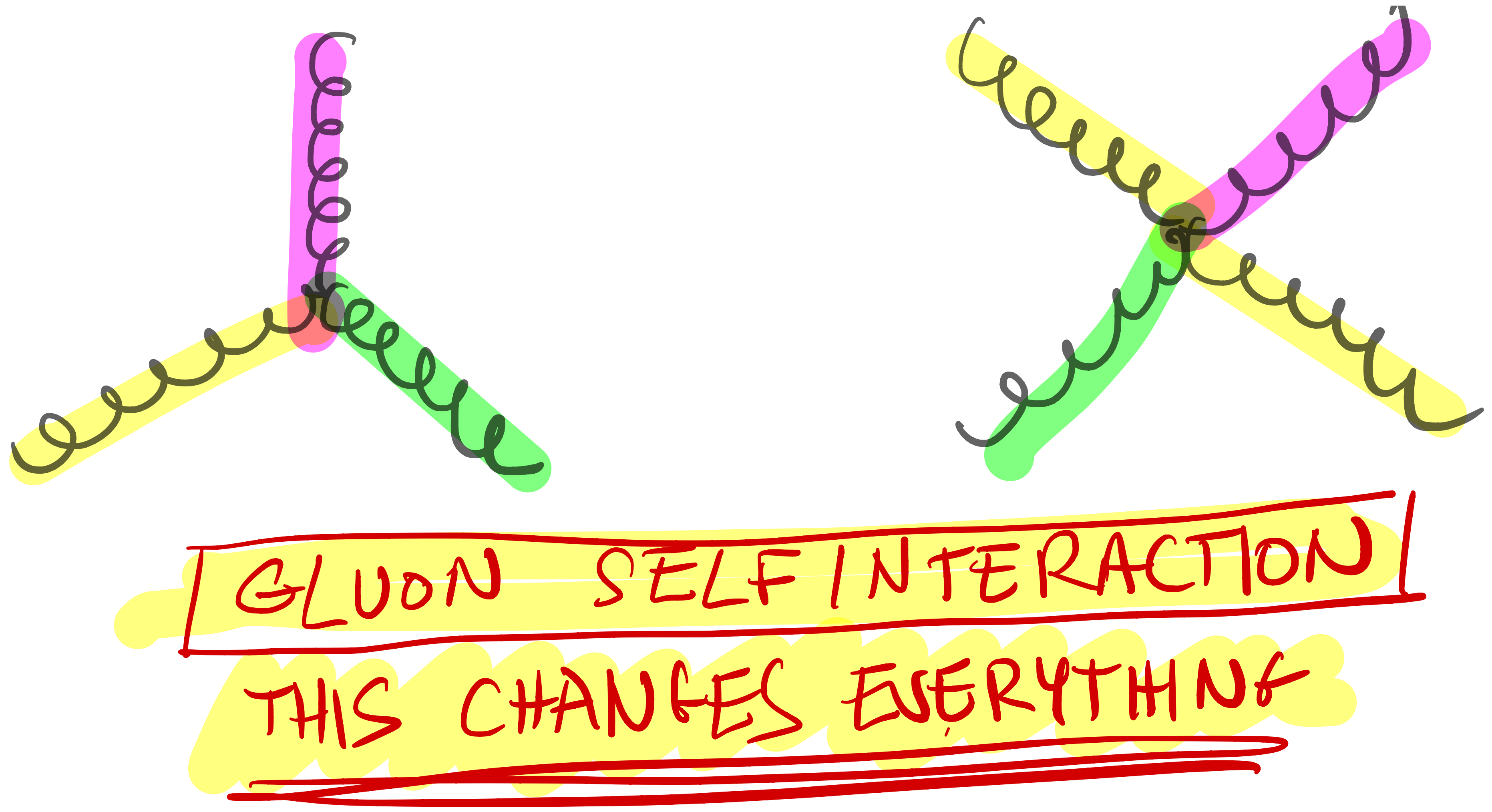
QCD

Gluons change the color of the quark ::: **gluons are colored**

[the gluons have the 8 possible colors of the adjoint representation of SU(3)]



This is similar to QED

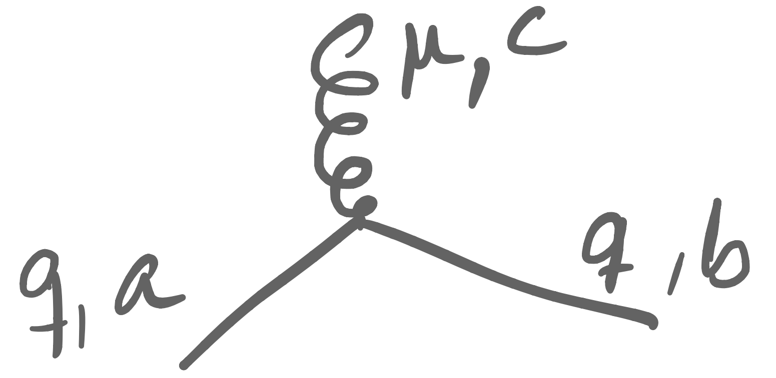


But gluon self-interaction - asymptotic freedom, confinement,…

The QCD Lagrangian

quark propag. $i\frac{\not p}{p^2+i\epsilon}$

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}\,,$$



$-ig\,t^a\gamma^\mu$

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu\,,$$

ABSENT IN QED

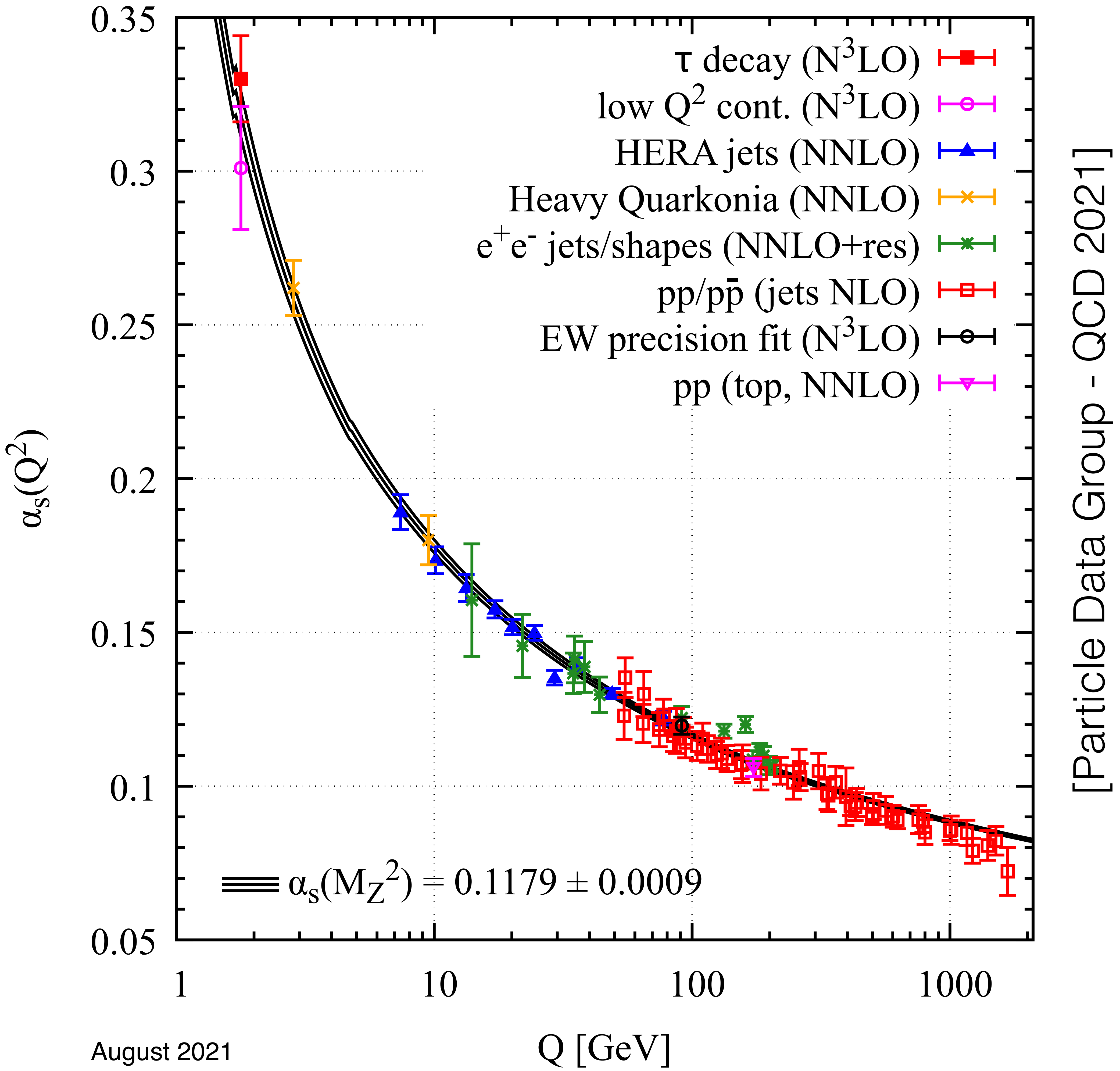
Use technology to build a gauge theory - with SU(3) group for color

The non-abelian nature of SU(3) - non-linear terms in $F^{\mu\nu}$

$F^A_{\mu\nu} F^{A\mu\nu}$

- Gluon kinetic term A^2 - propagator
- 3-gluon vertex A^3
- 4-gluon vertex A^4

Asymptotic freedom



$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$

Take $b_1 = b_2 = \cdots = 0$

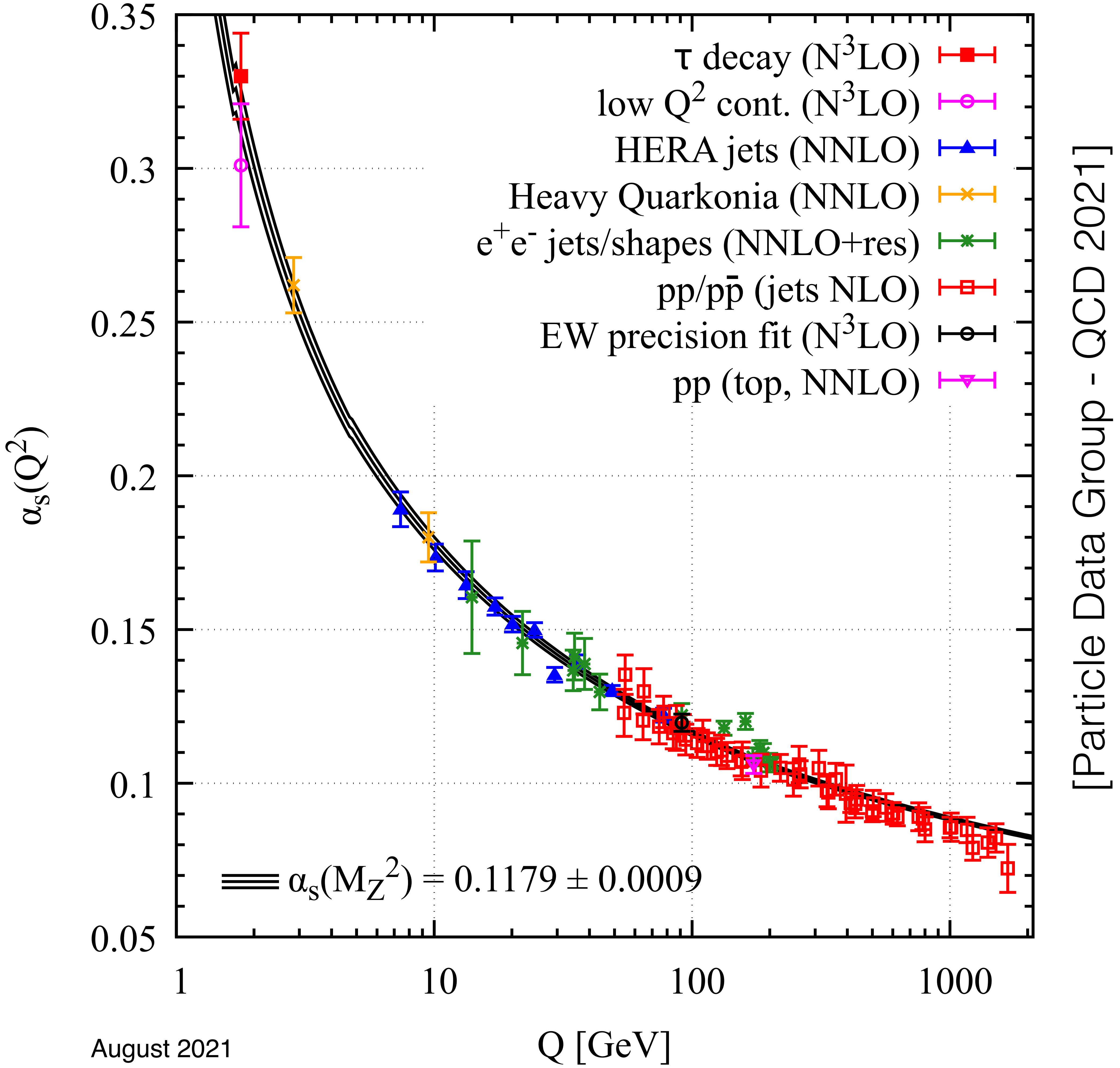
$$\frac{d\alpha_s}{d\log\mu_R} = -b_0\alpha_s$$

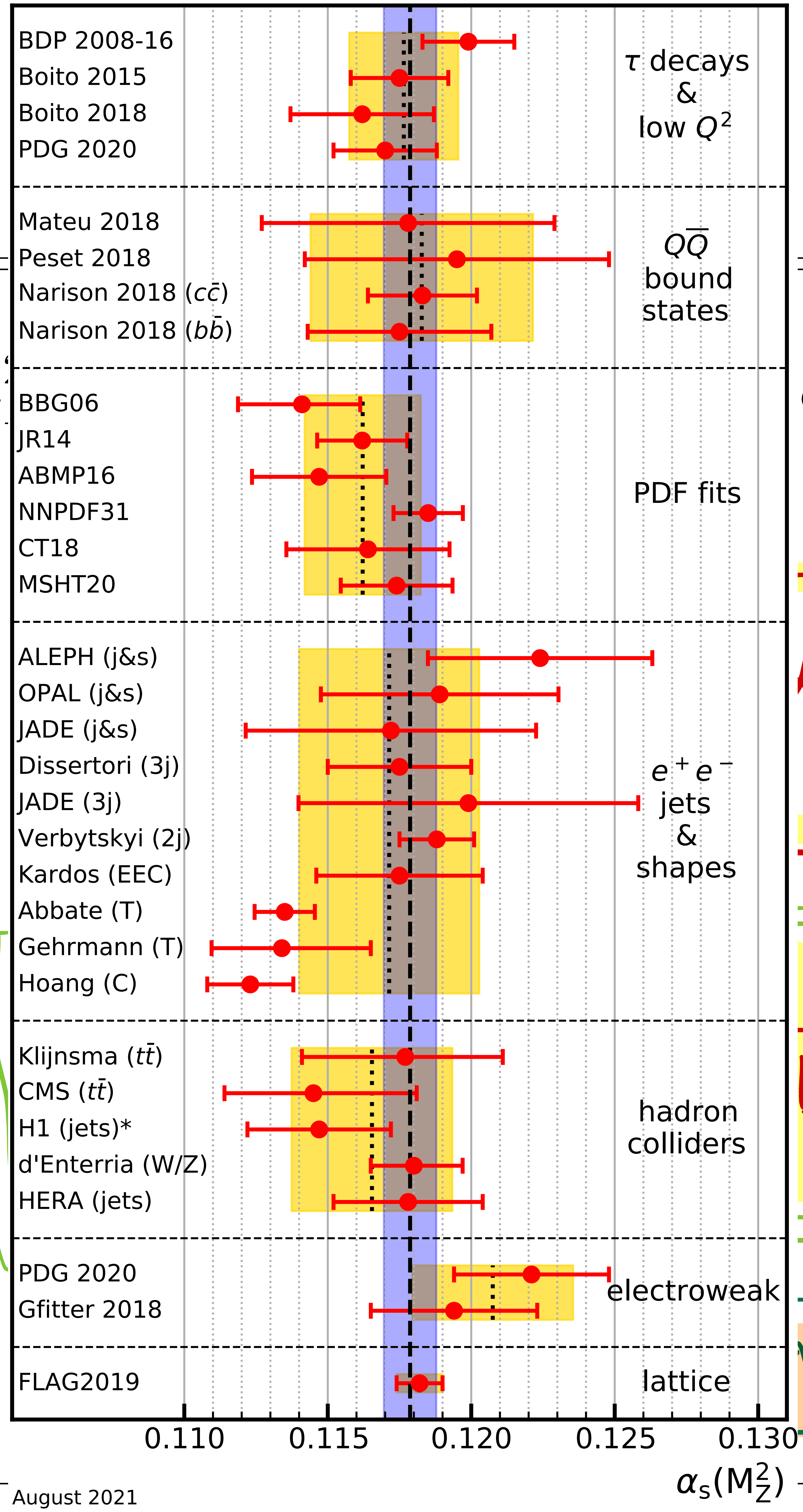
$$\alpha_s(\mu^2) = \frac{\alpha_s(\mu_0^2)}{1 + b_0\alpha_s(\mu_0^2)\log\frac{Q^2}{\mu_0^2}} \equiv \frac{1}{b_0\log^2\frac{Q^2}{\Lambda_{QCD}^2}}$$

$\alpha_s \ll 1$ FOR $Q^2 \gg \Lambda_{QCD}^2$

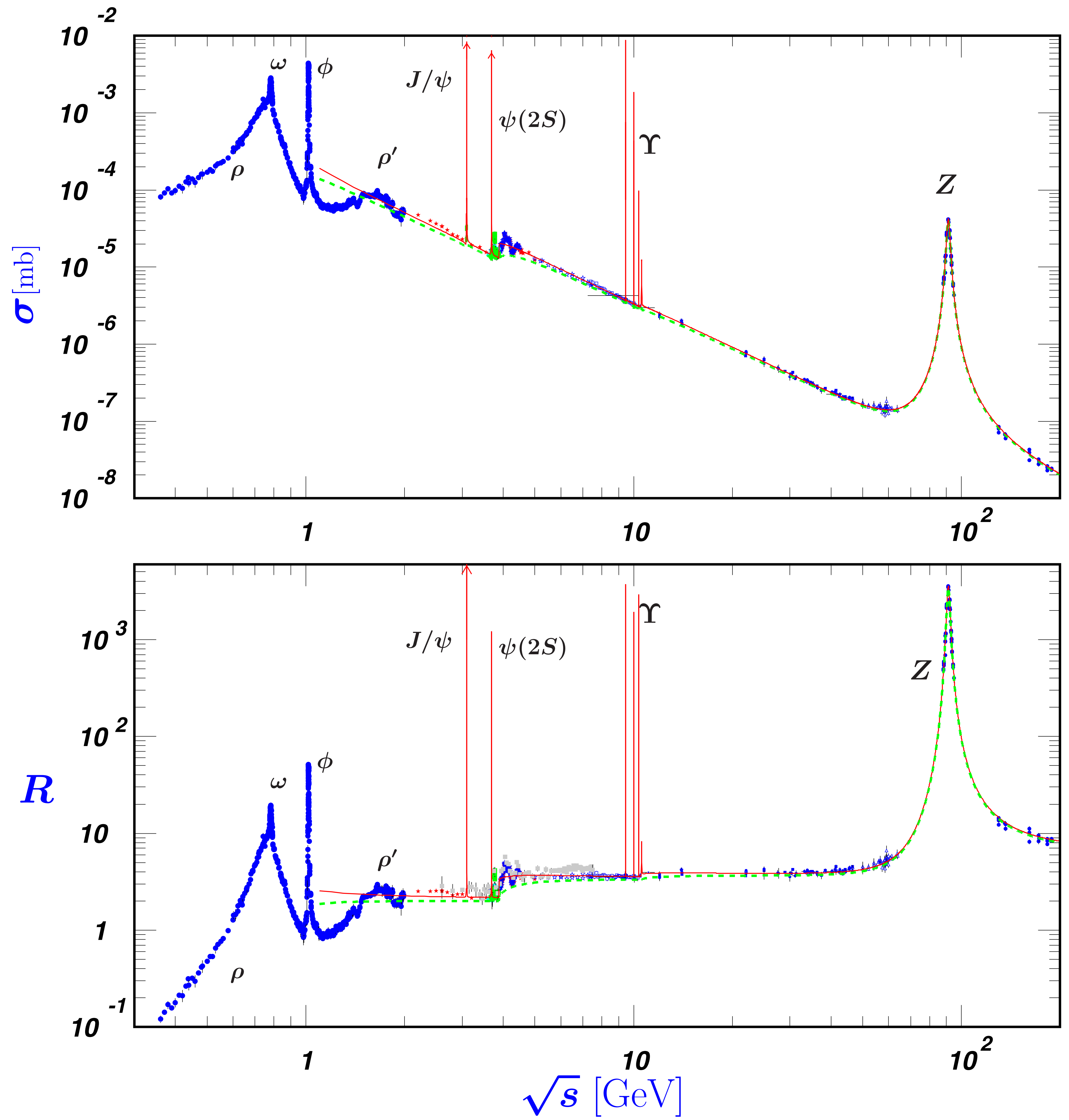
Asymptotic

μ ... $\alpha_s^3 + b_2\alpha_s^4 + \cdots)$

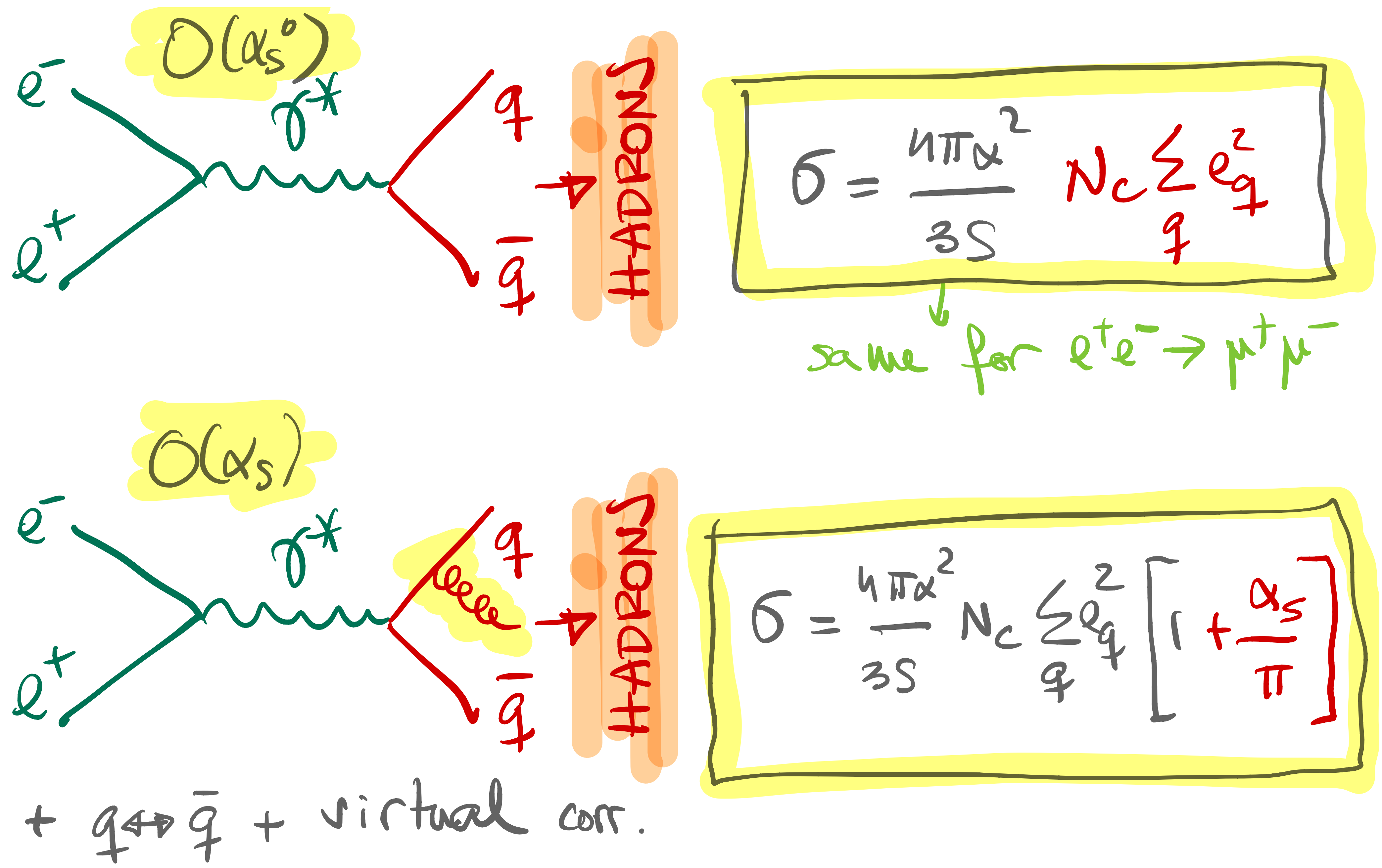




QCD perturbative at large scales



Example: e^+e^- annihilation into hadrons

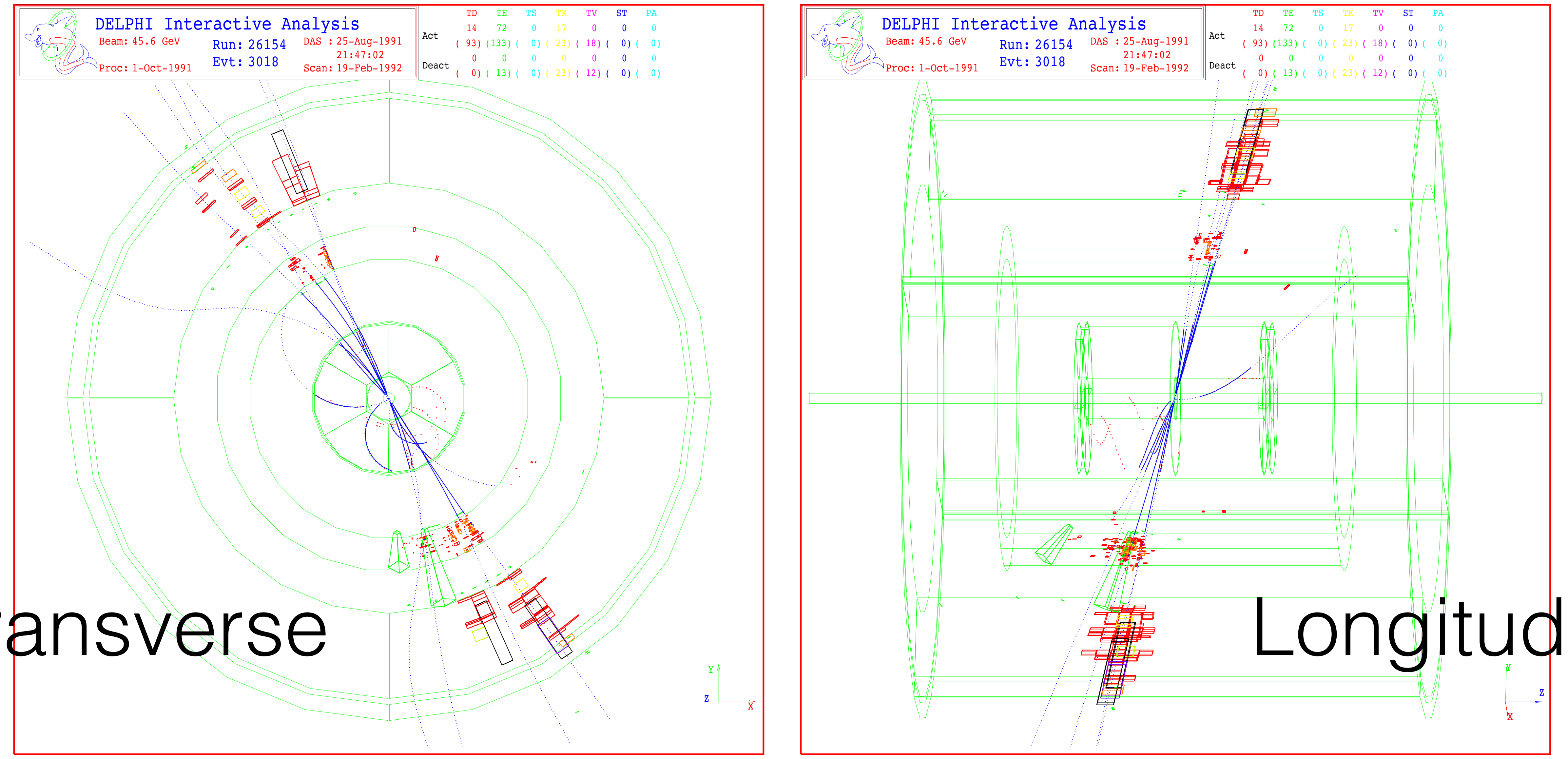


$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_q e_q^2 \left[1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

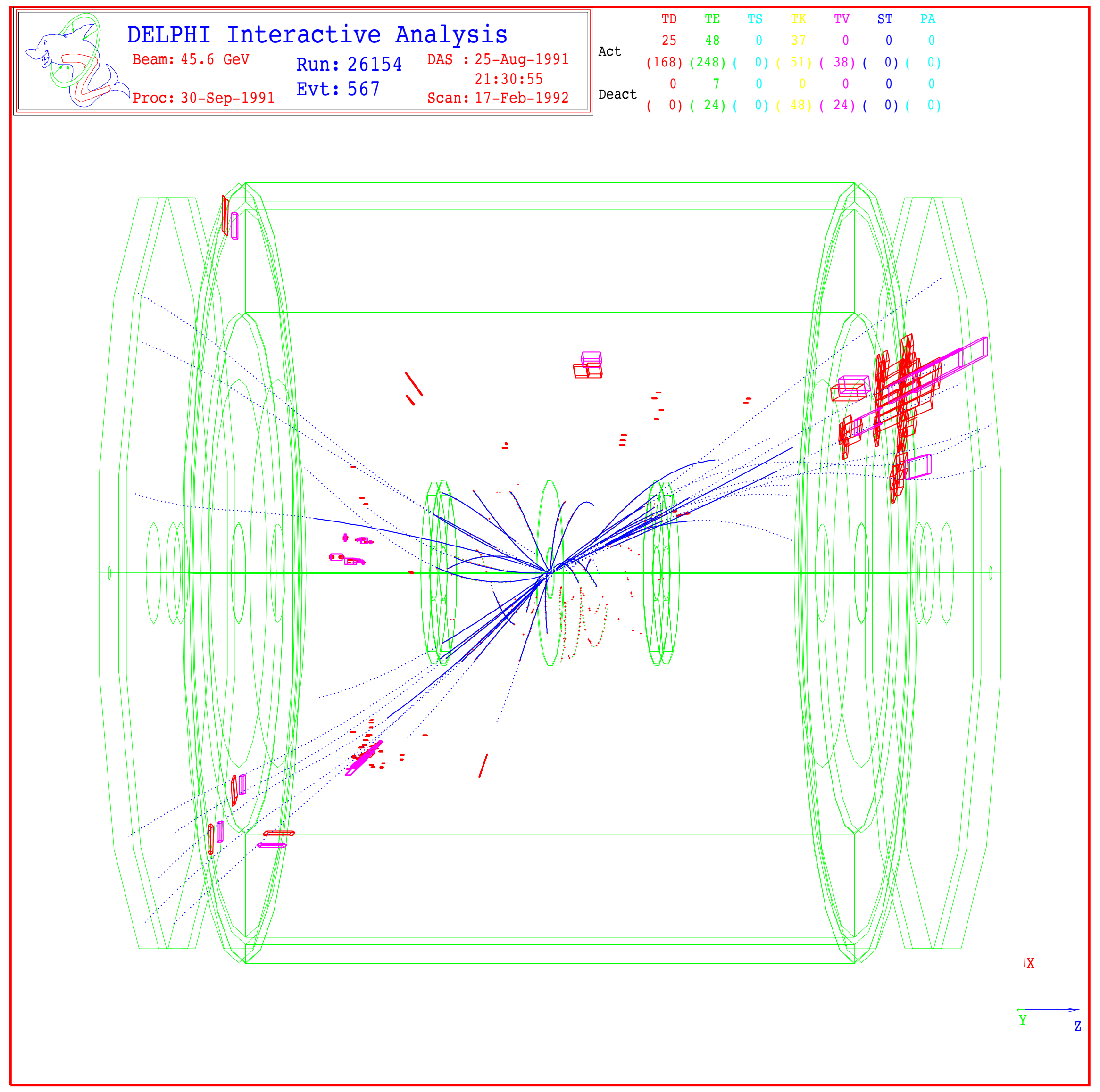
Less inclusive now…

What if, e.g., we want to know the angular distribution? **JETS**

- ☐ Hadronization - long distance / non perturbative
- ☐ **Gluon multiplication**

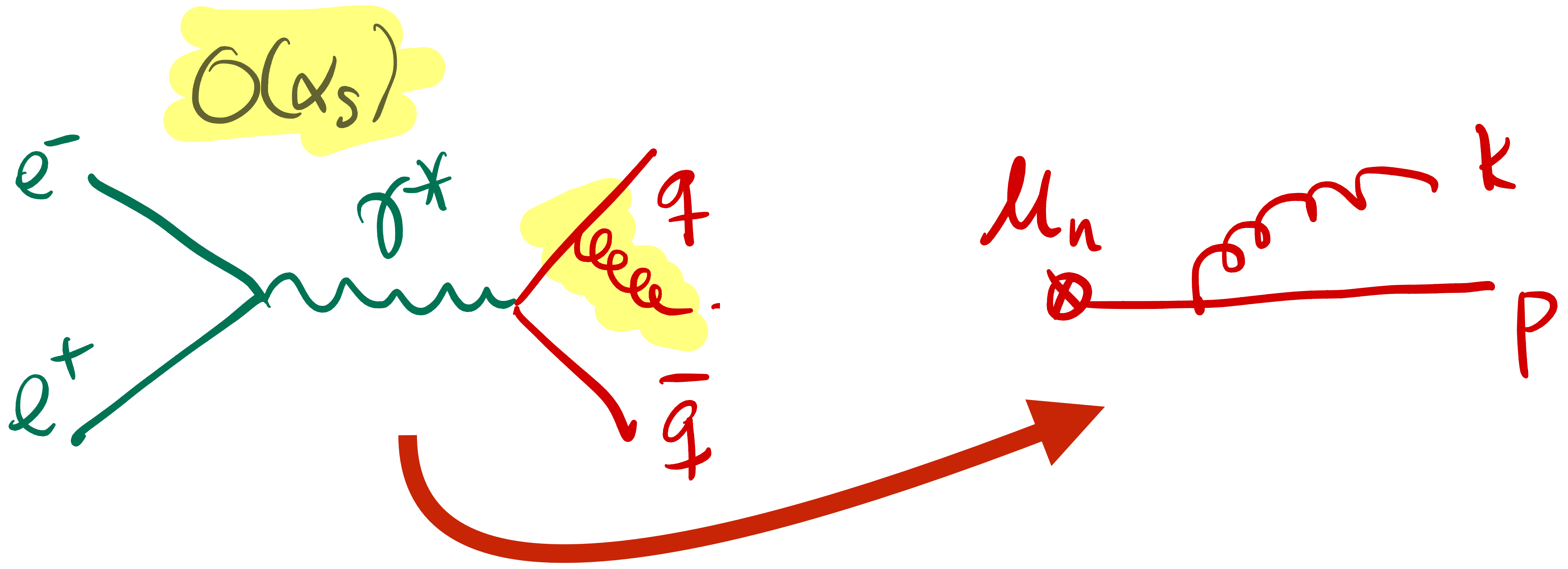


A 2-jet event at LEP



A 3-jet event at LEP

Gluon (and quark) multiplication



Soft radiation

$$\mathcal{M}_{n+1} = \bar u(p)\, i g t^a \not\epsilon(k)\, i \frac{\not p + \not k}{(p+k)^2}\, \mathcal{M}_n$$

[Exercise] SOFT RADIATION LIMIT $\omega \ll E$

$$\mathcal{M}_{n+1} = -g t^a \frac{p\cdot\epsilon}{p\cdot k}\, \bar u(p)\, \mathcal{M}_n$$

FOR QUARKS $C_F = \frac{2N_c}{N^2-1} = \frac{3}{4}$

FOR GLUONS $N_c = 3$

$$\frac{d\sigma^{n+1}/d\Phi^{n+1}}{d\sigma^n/d\Phi^n} \equiv \omega \frac{dN}{d\omega\, dk_\perp^2} = C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_\perp^2}$$

$$\frac{dN}{d\omega\, d\theta} = \frac{2\alpha_s C_F}{\pi} \frac{1}{\omega} \frac{1}{\theta}$$

Soft and collinear divergent

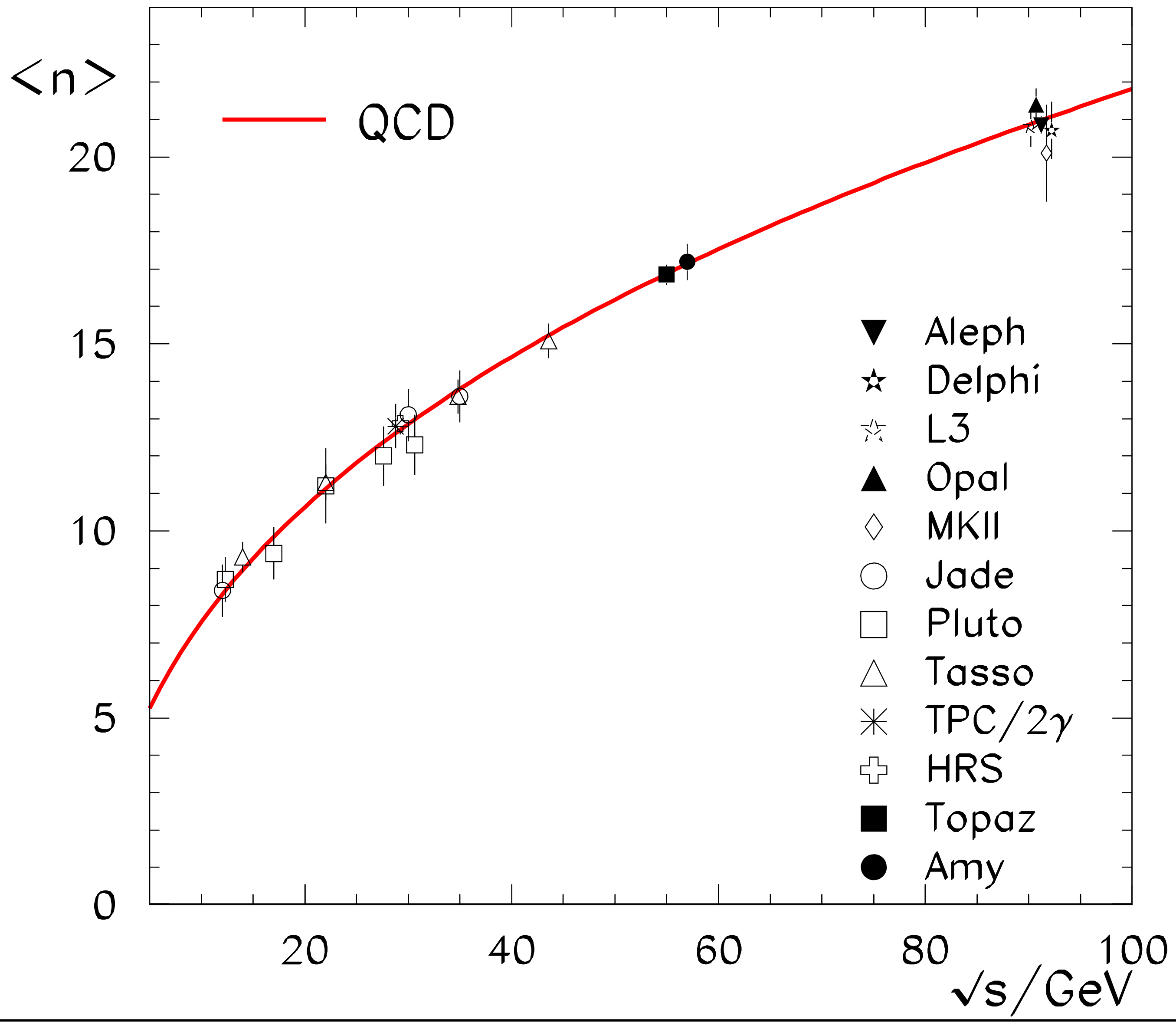
Gluon (and quark) multiplication

→ small-ω, small-θ compensate small-α_s

Counting gluons (naively) $\frac{1}{n!}\int_{Q_0}^{E}\frac{d\omega_1}{\omega_1}\int_{Q_0}^{\omega_1}\frac{dk_1}{k_1}\times\cdots\times\int_{Q_0}^{E}\frac{d\omega_n}{\omega_n}\int_{Q_0}^{\omega_n}\frac{dk_n}{k_n}$

For large $\alpha_s \log\omega \log\theta$

Exponential growth

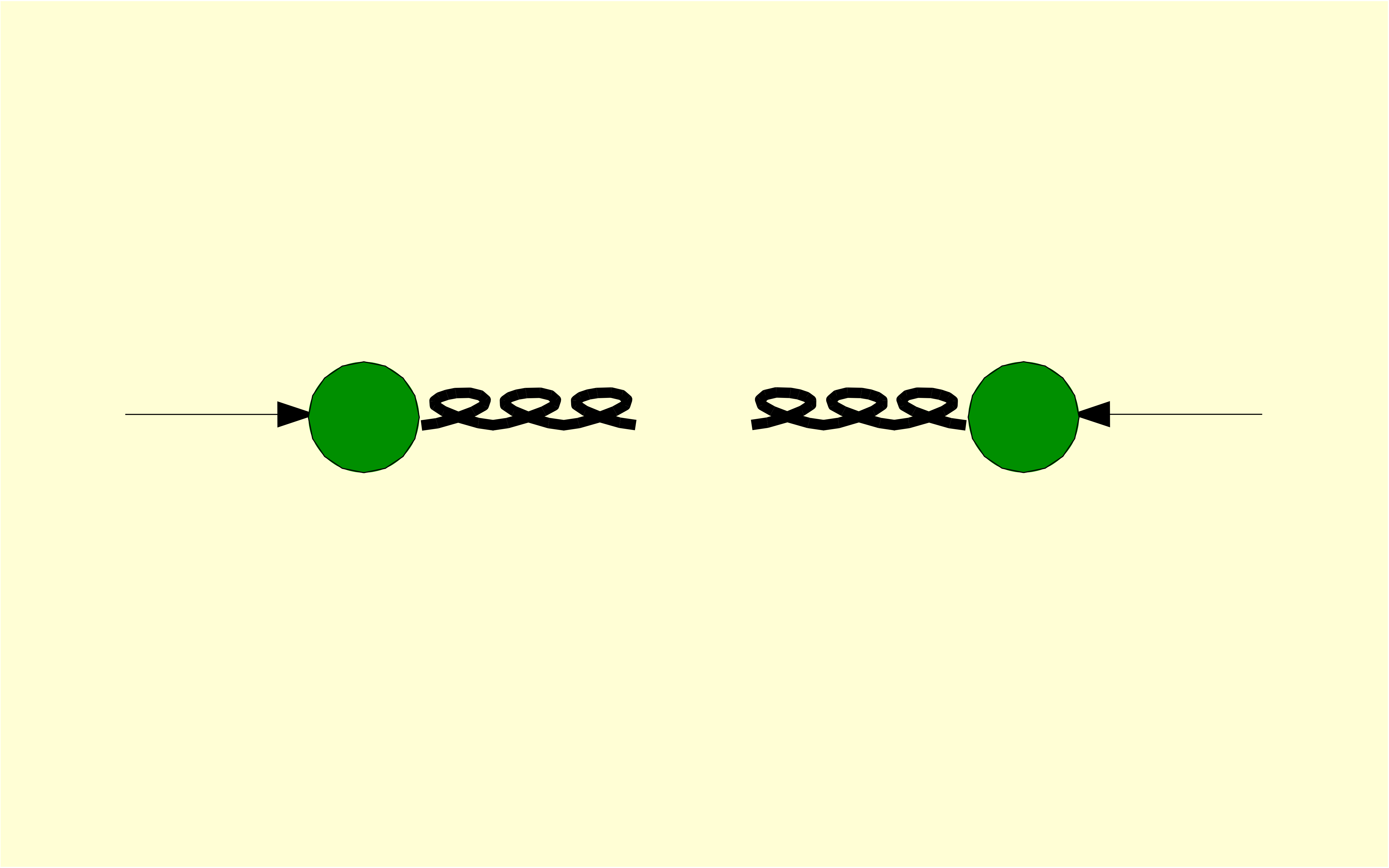


Resummation needed - **gluon multiplication**

$$\langle N_g\rangle \sim \frac{C_F}{C_A}\sum_{n=1}^{\infty}\frac{1}{(n!)^2}\left(\frac{C_A}{2\pi b^2\alpha_s}\right)^n \sim \frac{C_F}{C_A}\exp\left(\sqrt{\frac{2C_A}{\pi b^2\alpha_s(Q)}}\right),$$

G. Salam CERN Yellow Rep. School Proc. 5 (2020) 1-56

Jets: simple picture



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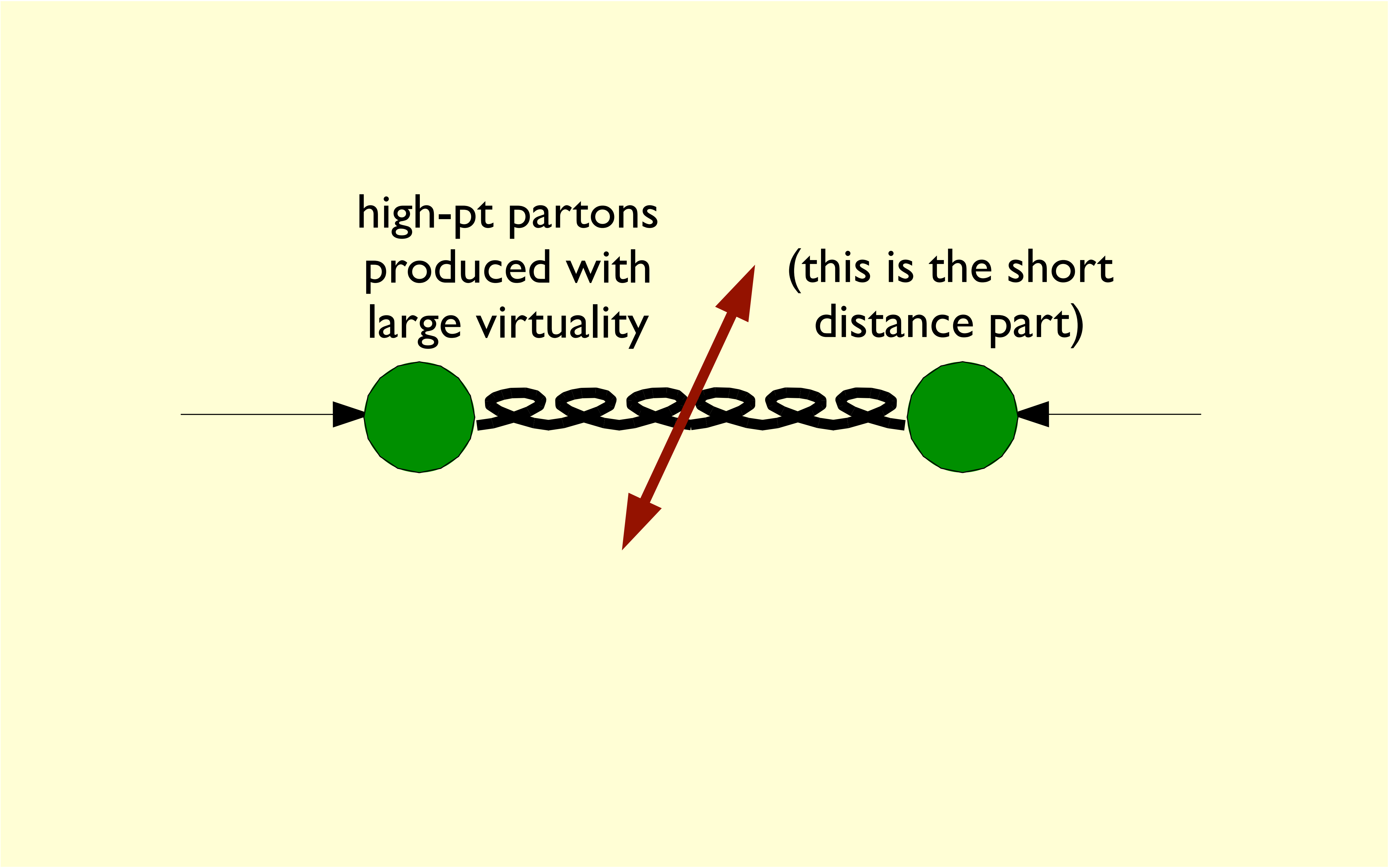

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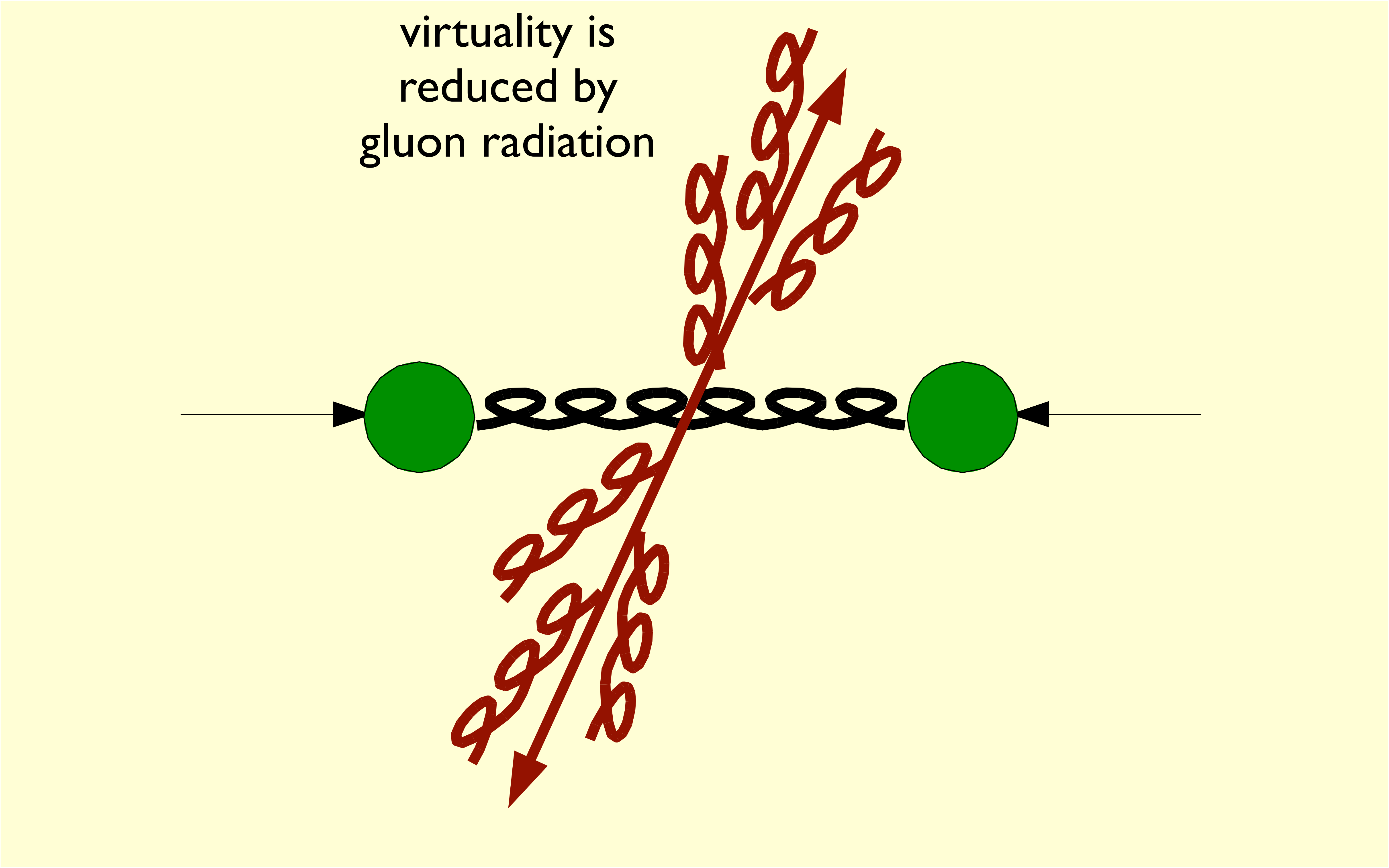

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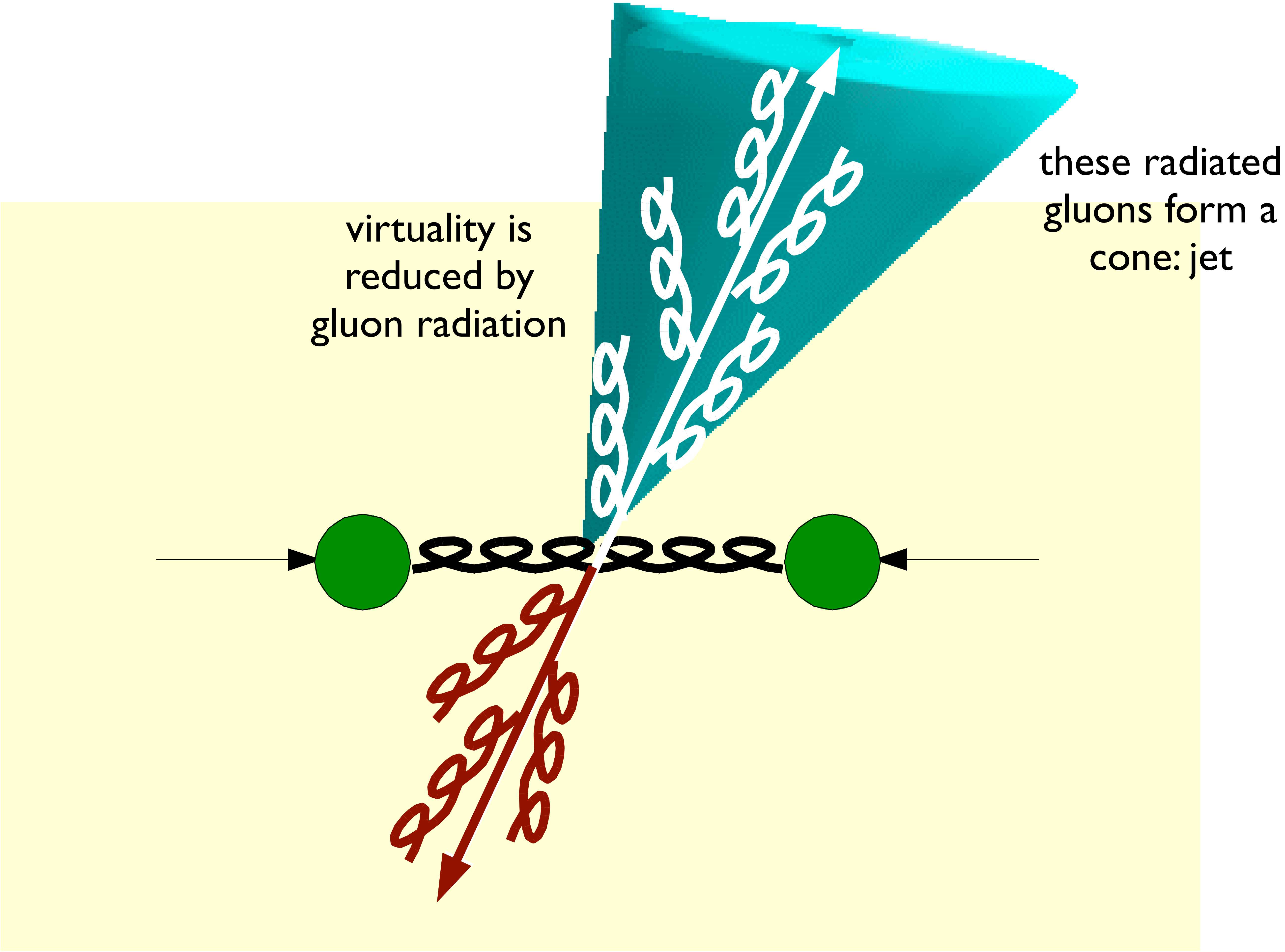

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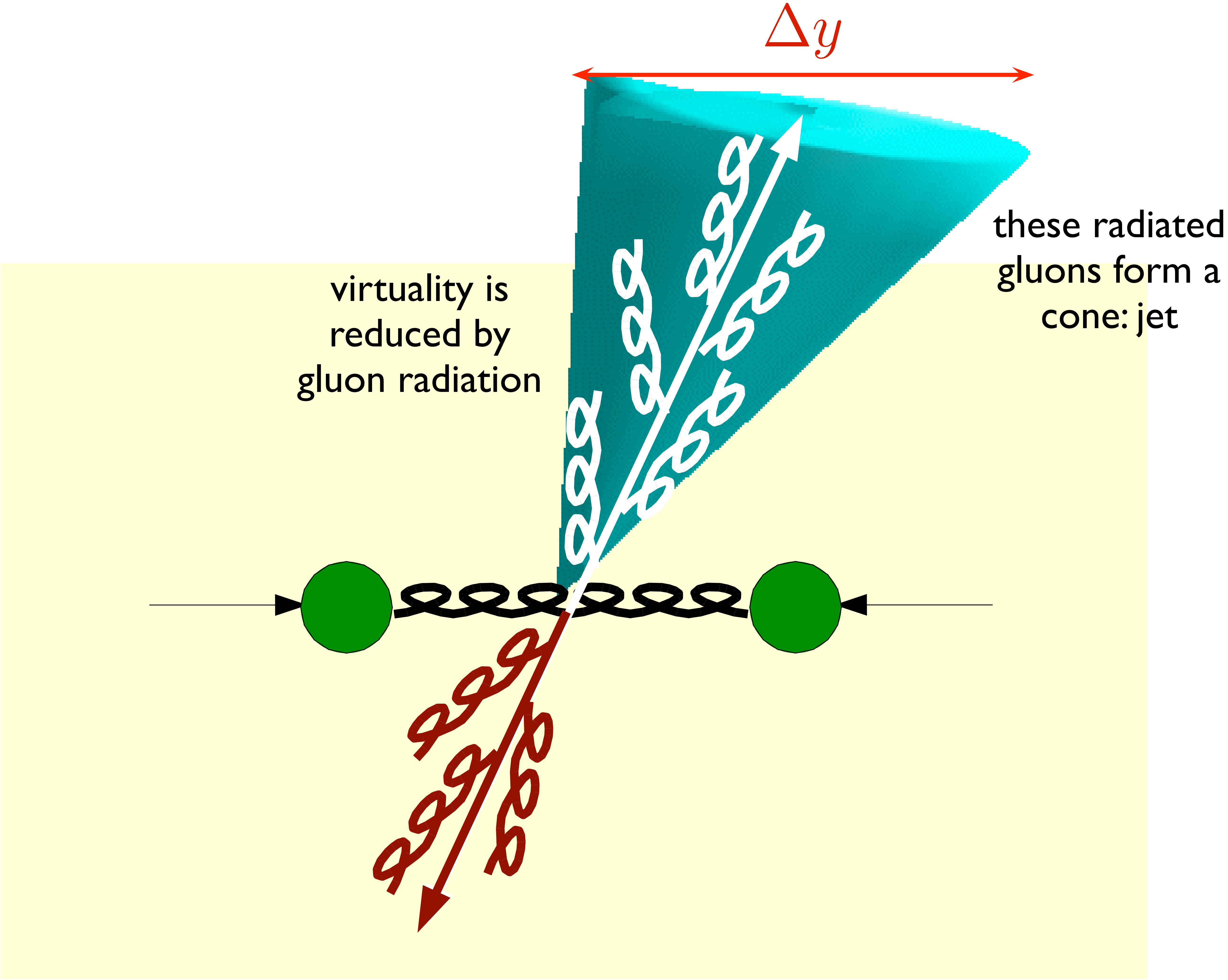

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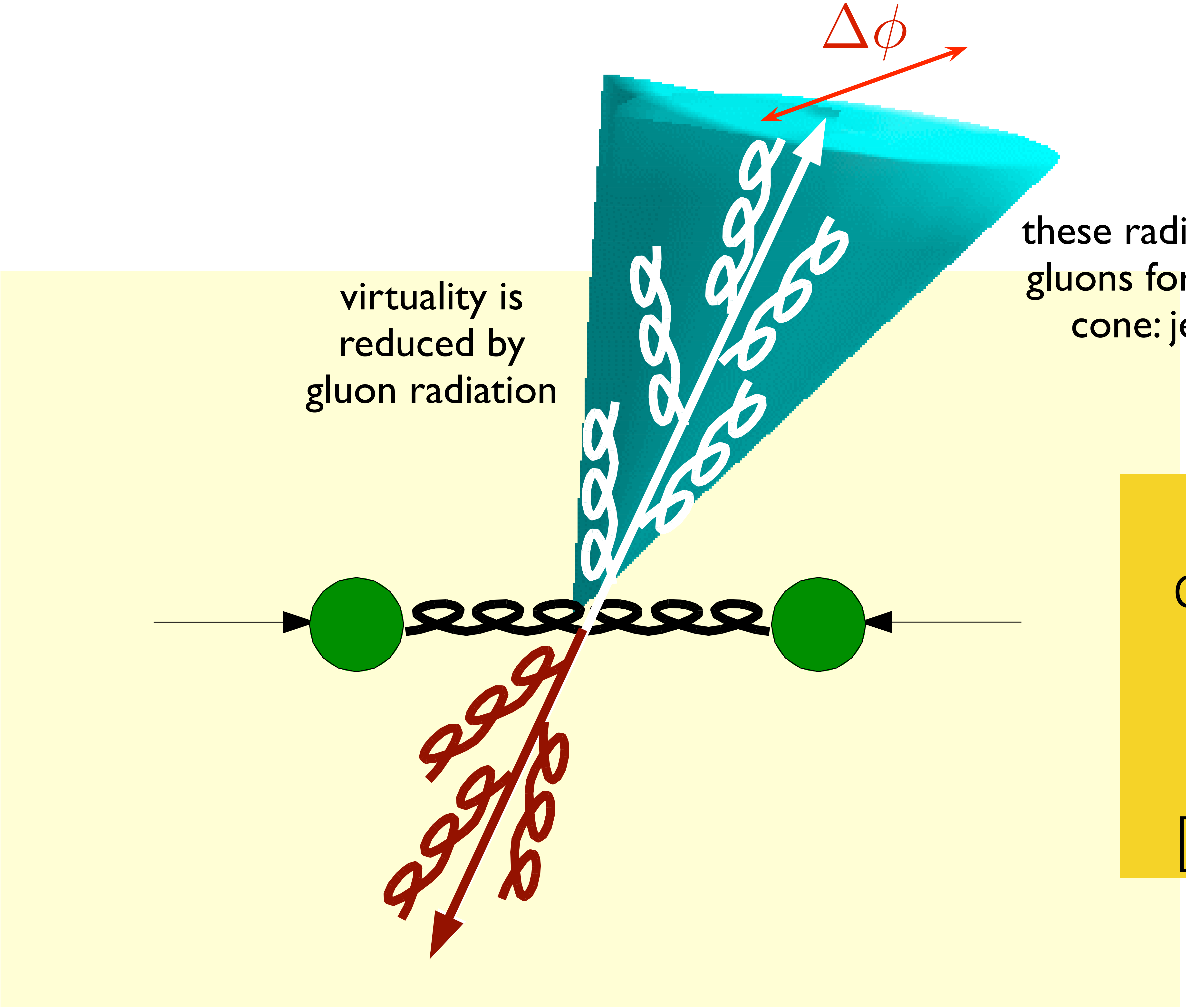
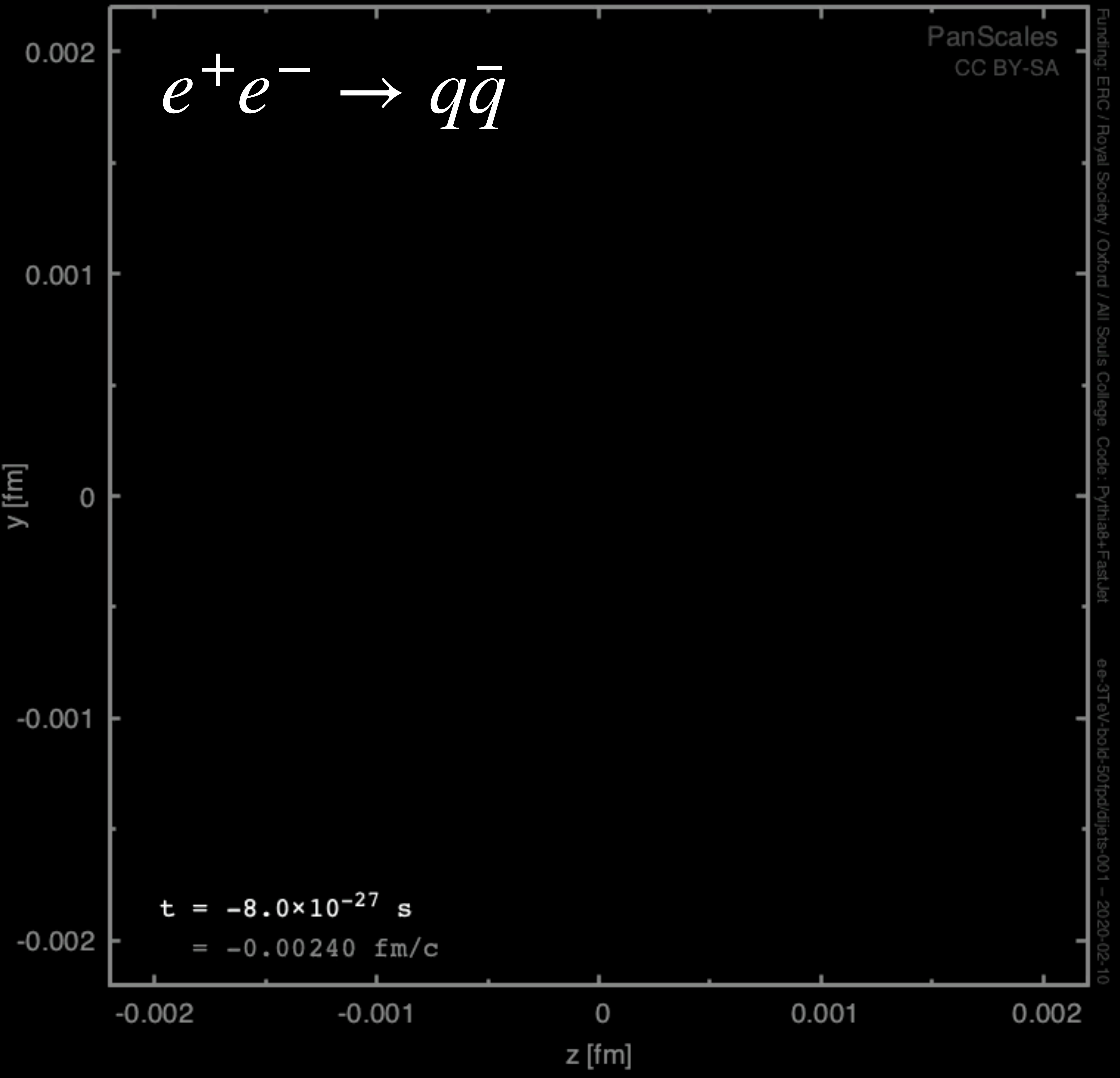


"Parton shower" can be described perturbatively

Included in Monte Carlo generators

[Pythia, Herwig, Sherpa]

https://gsalam.web.cern.ch/panscales/videos.html



3TeV e^+e^- events

Initial particles in yellow
Intermediate particles in blue
Final particles in red

[Simulation of the events are produced with Pythia 8
times estimated by clustering algorith
- see details in the web page]

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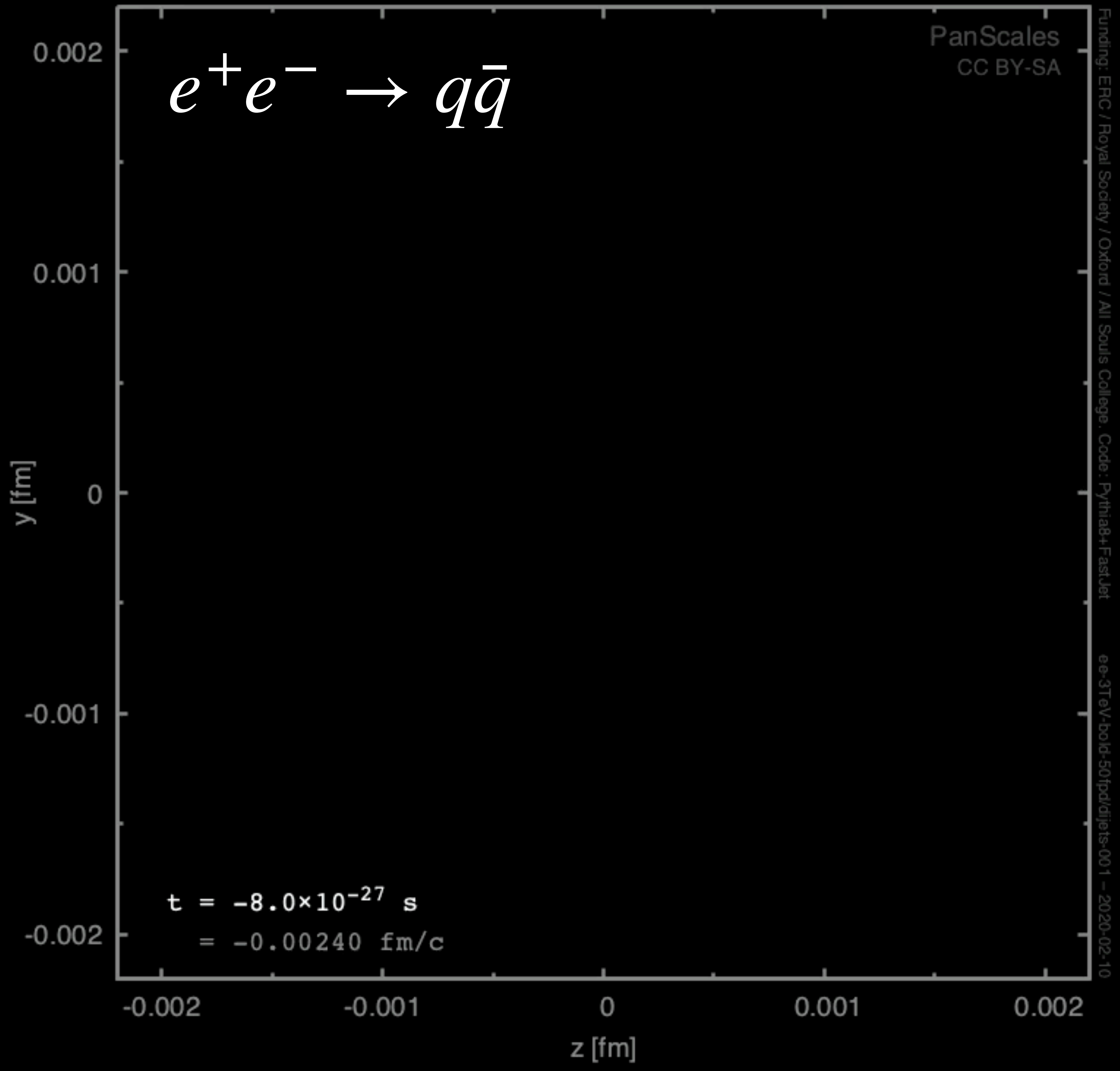

3TeV e^+e^- events

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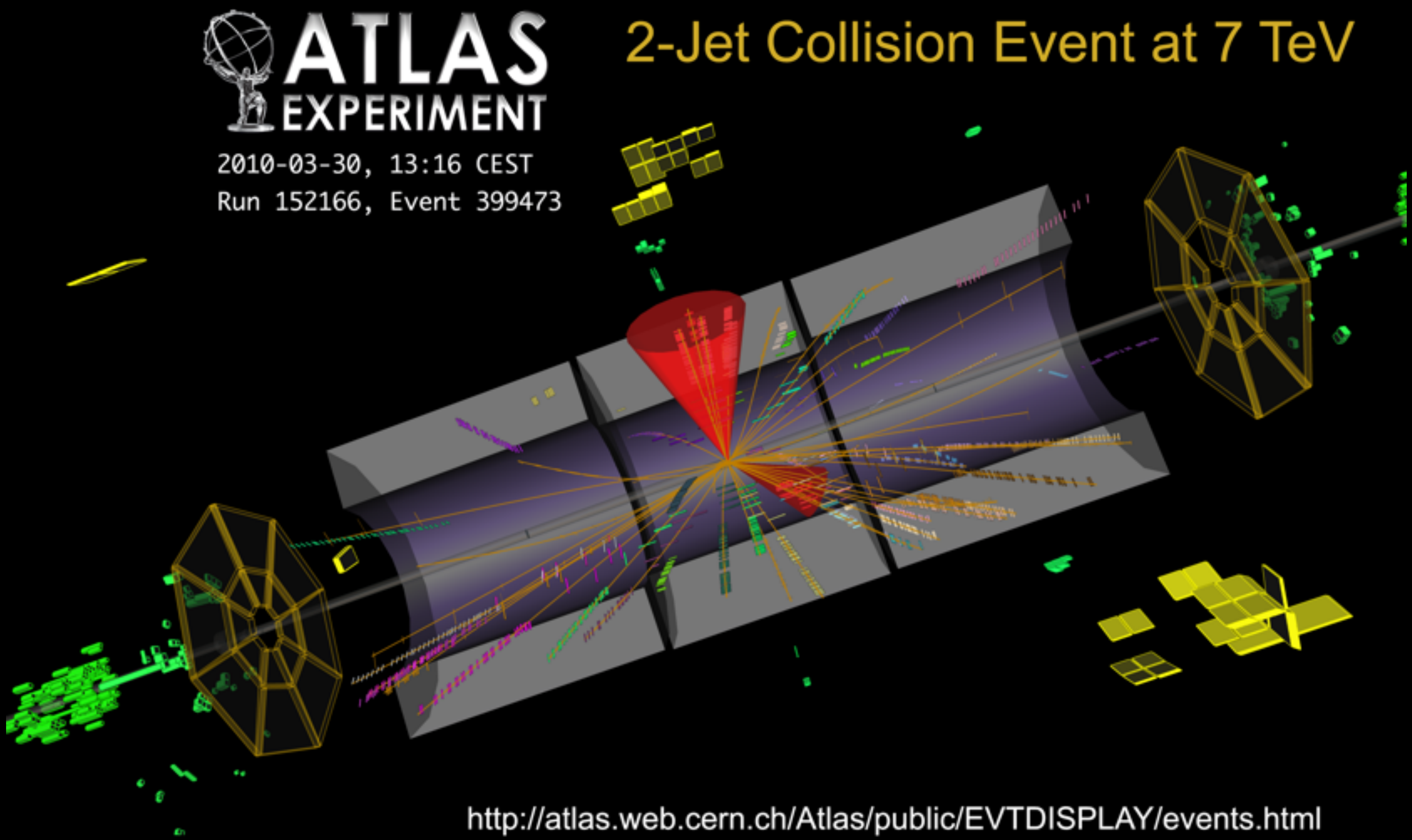
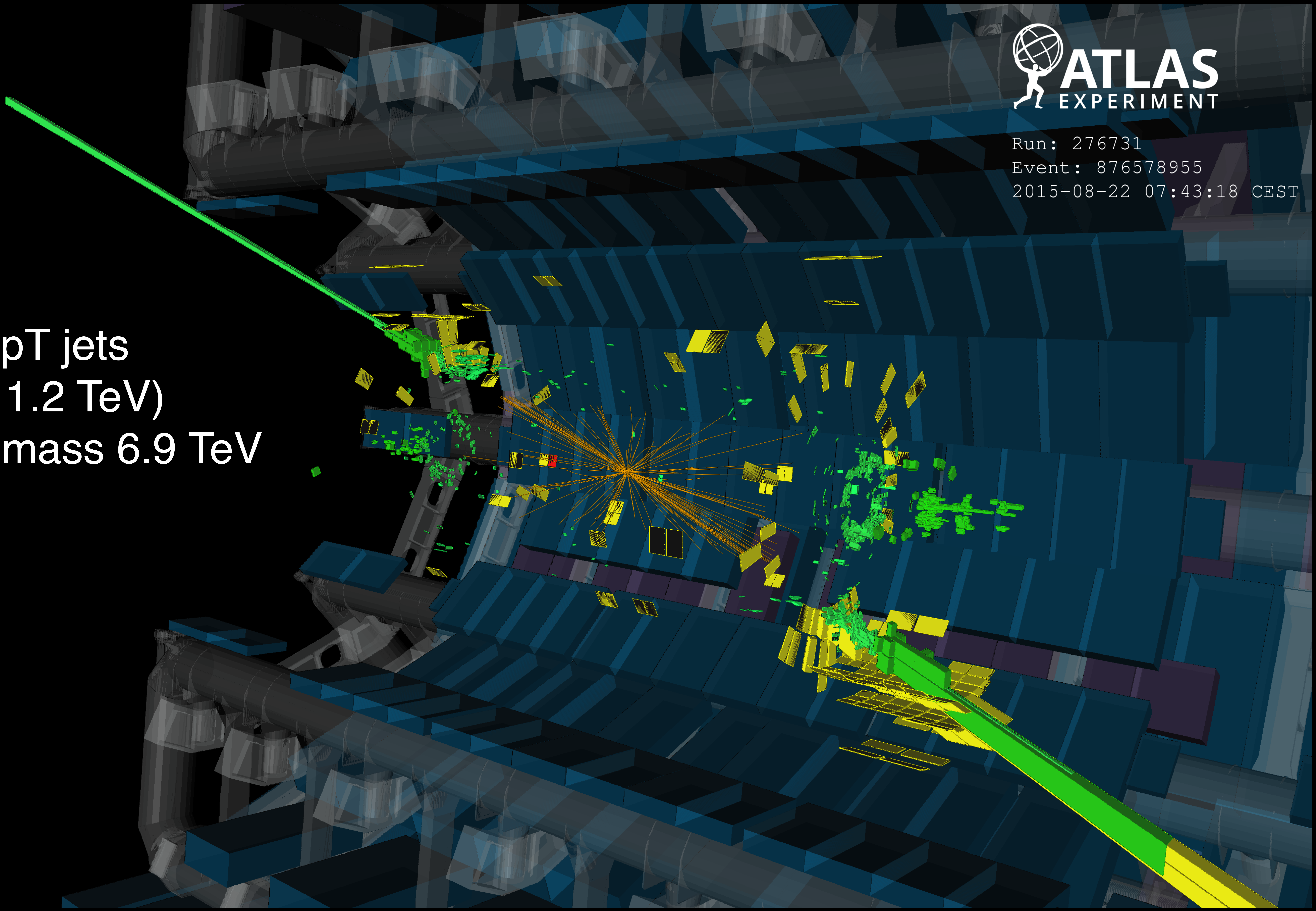
Jets in hadronic colliders



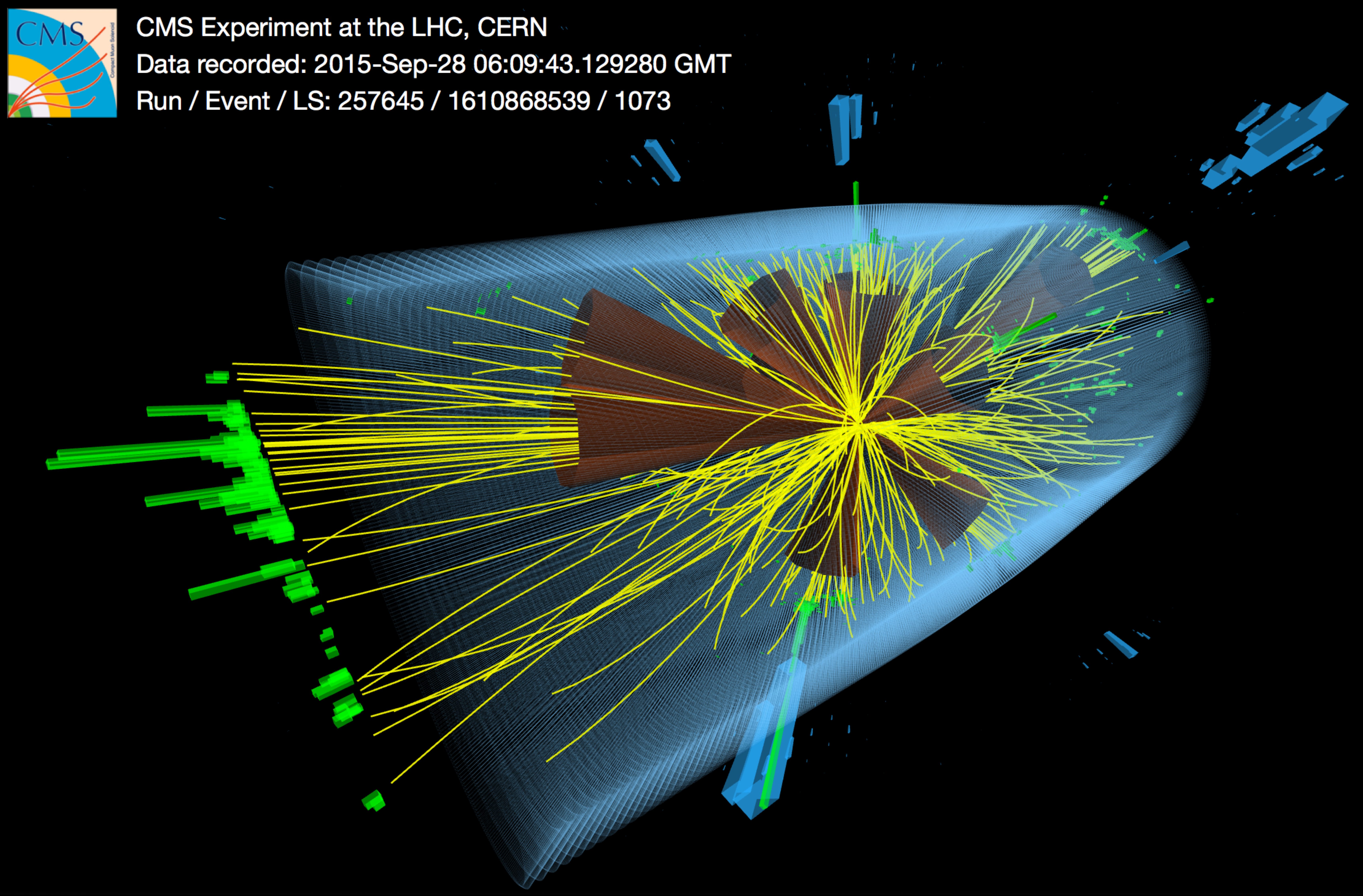
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Jets in hadronic colliders

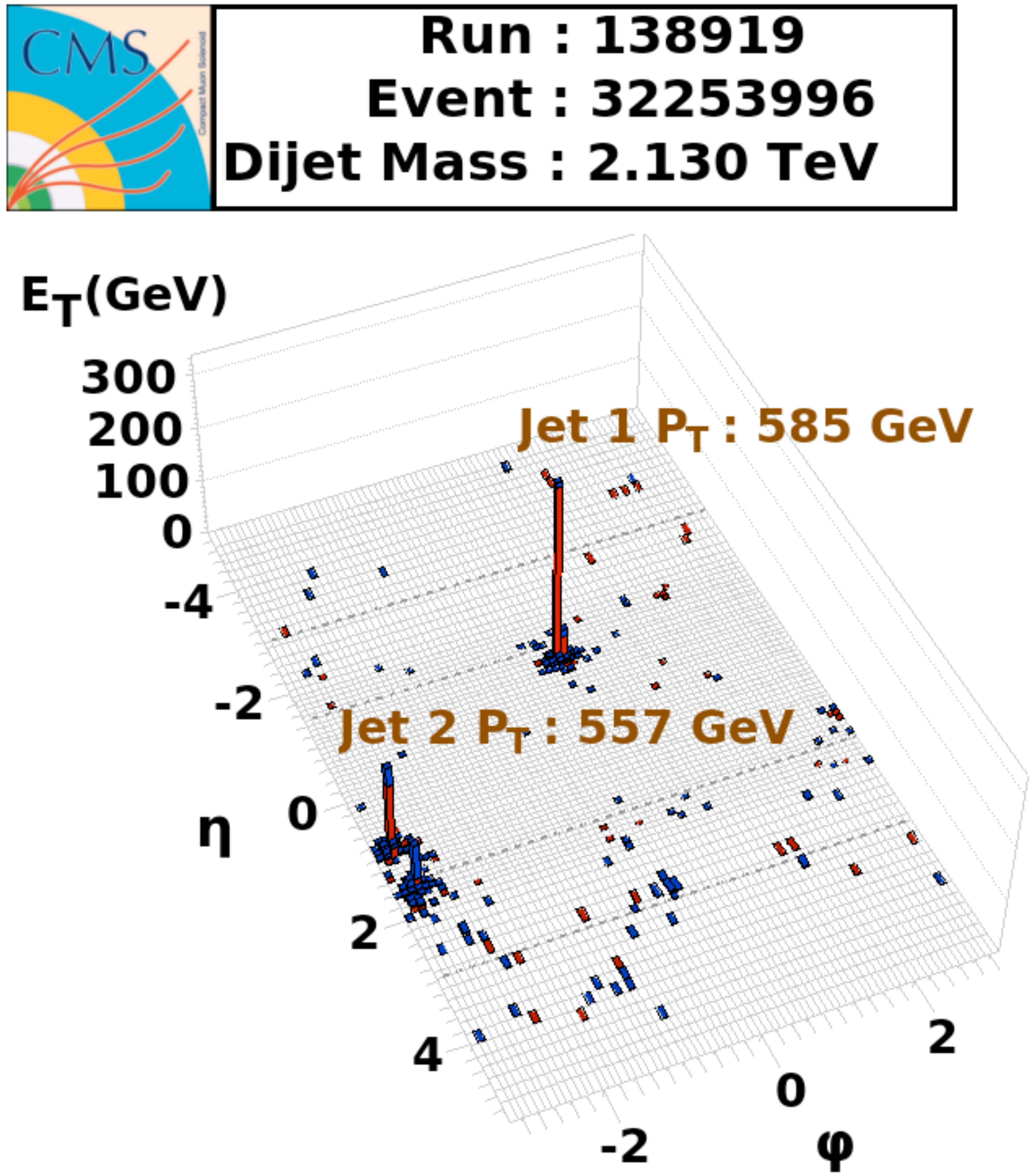
2 high pT jets
(1.3 and 1.2 TeV)
with invariant mass 6.9 TeV

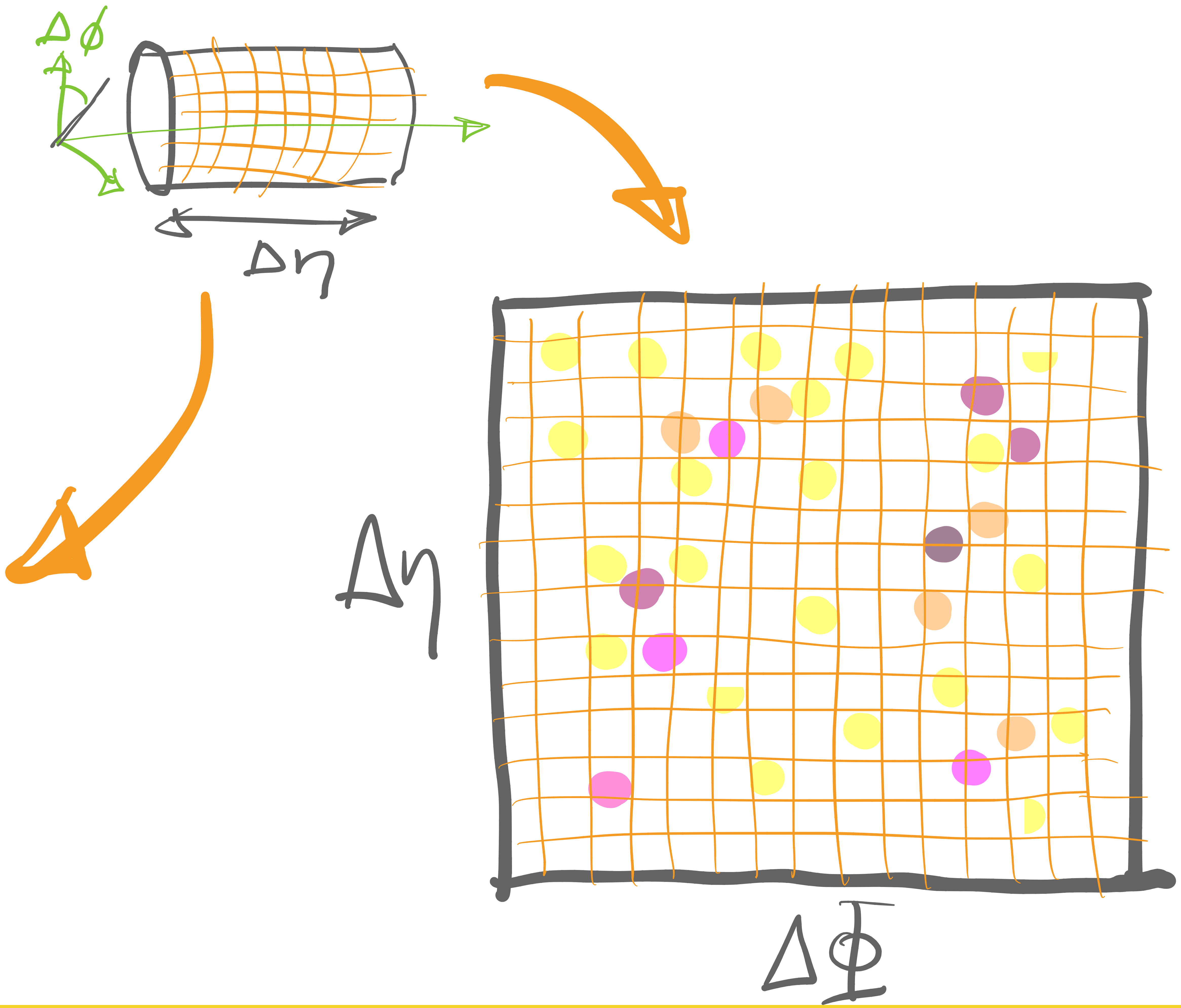


A multijet event at the LHC@13TeV



How to identify jets?





Number of jets depend on the definition - jet finding algorith

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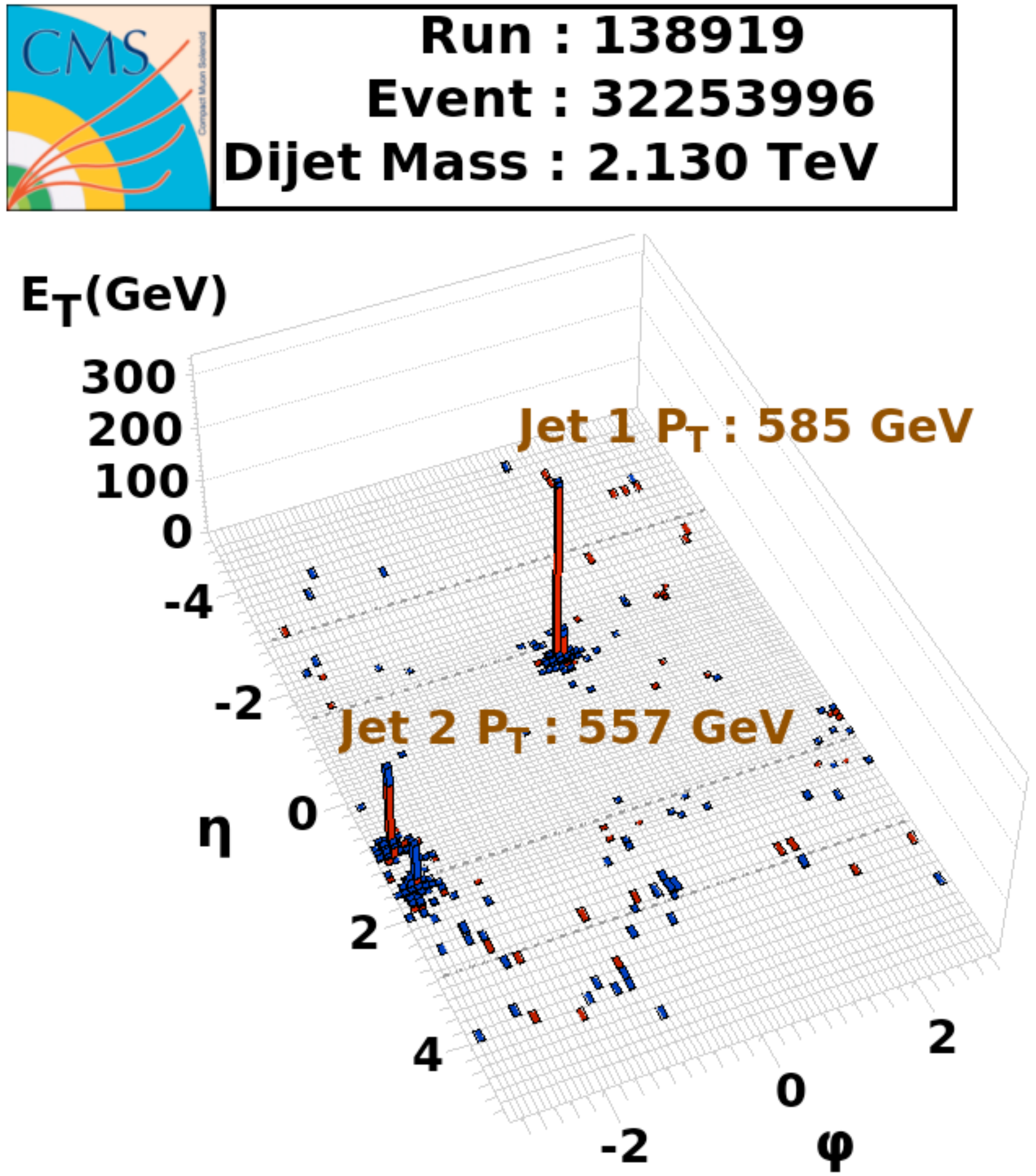

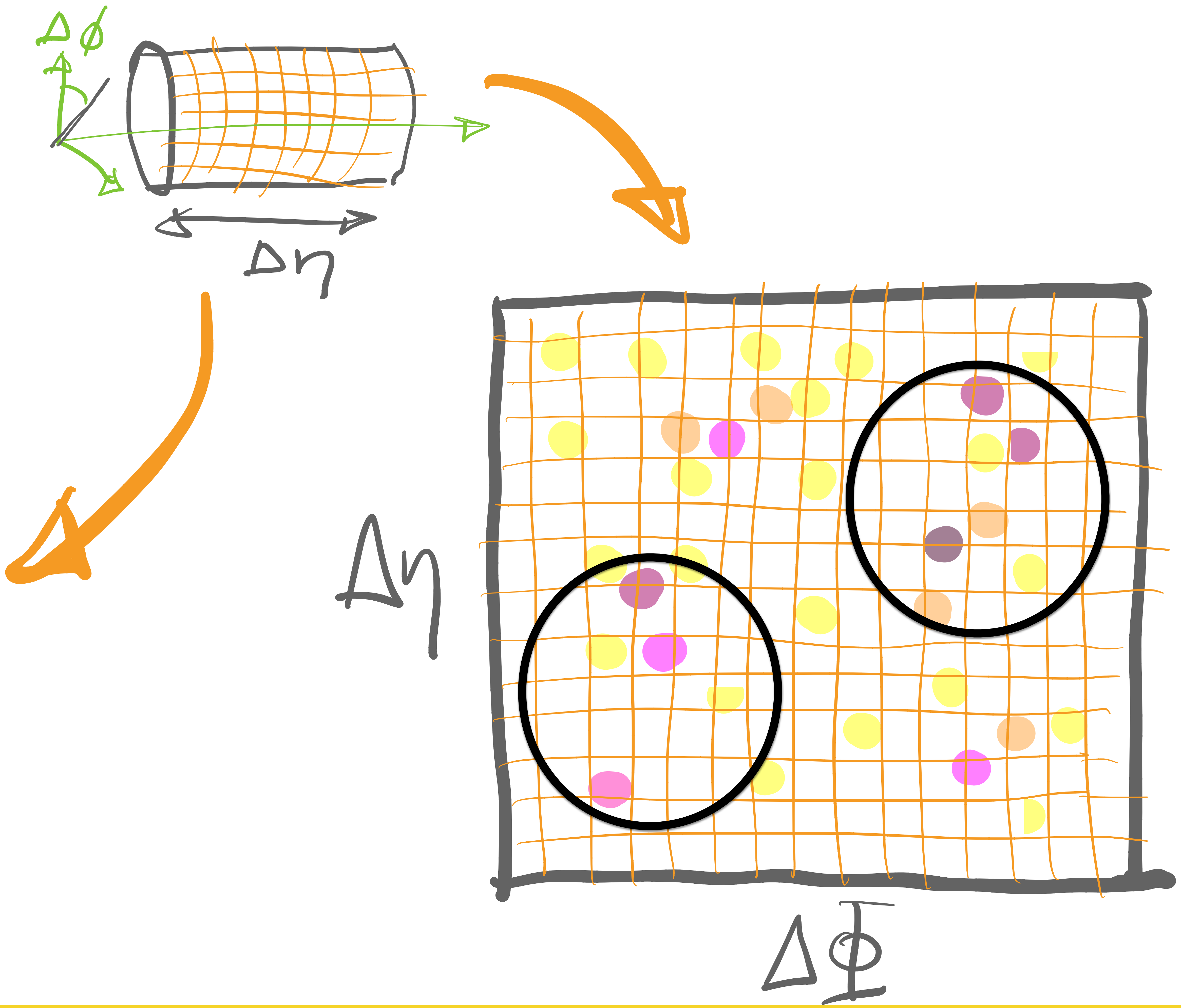

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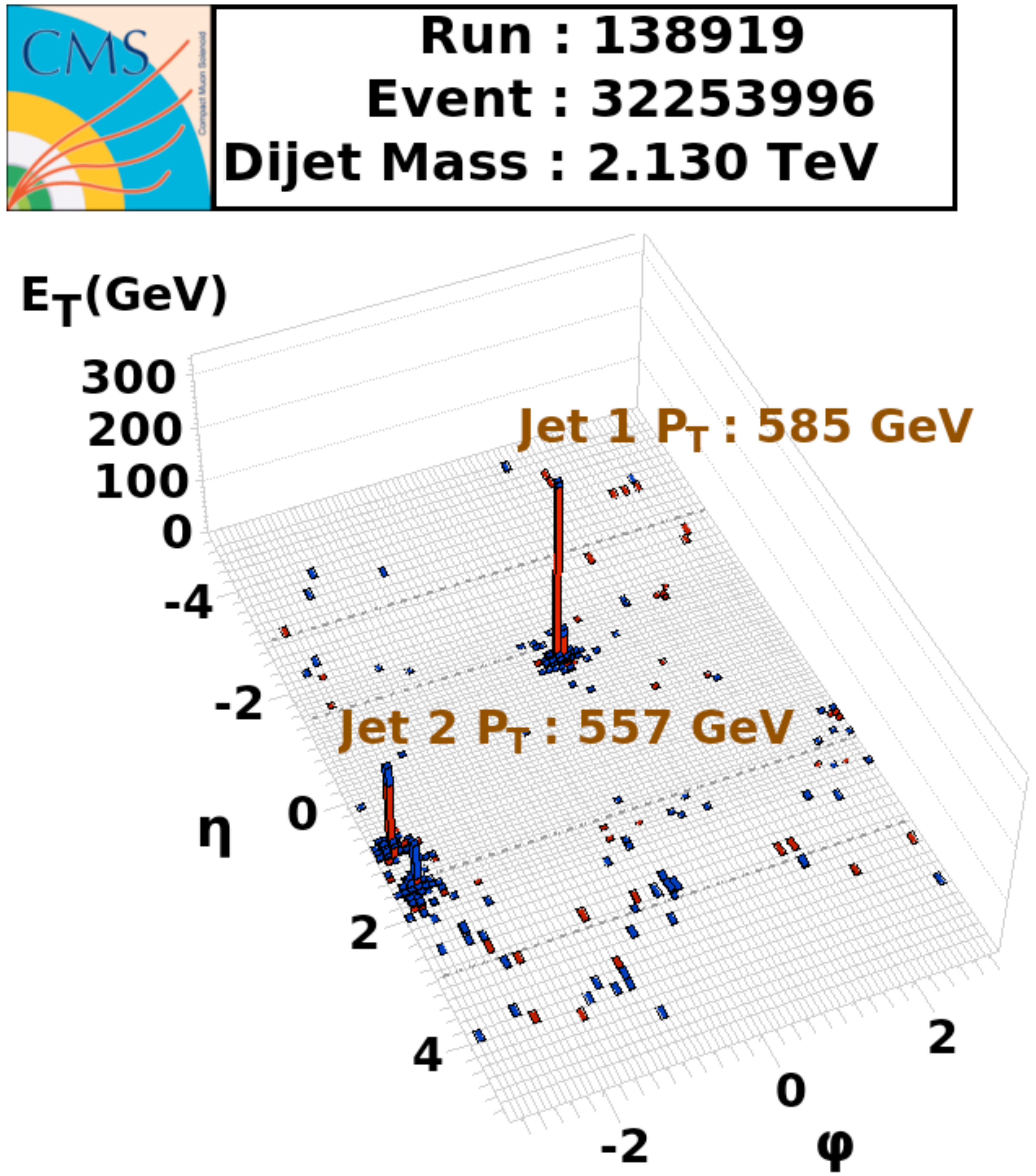
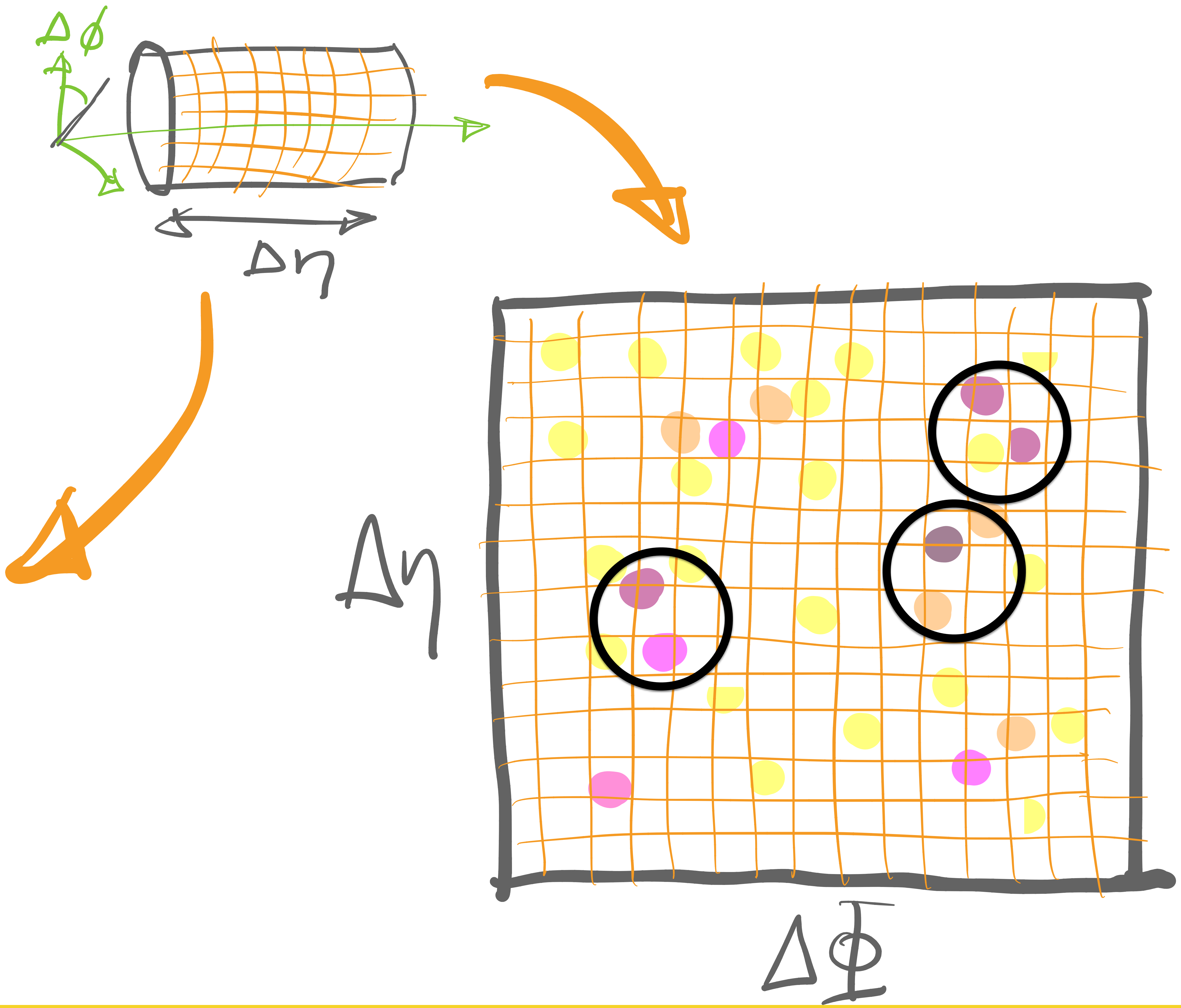
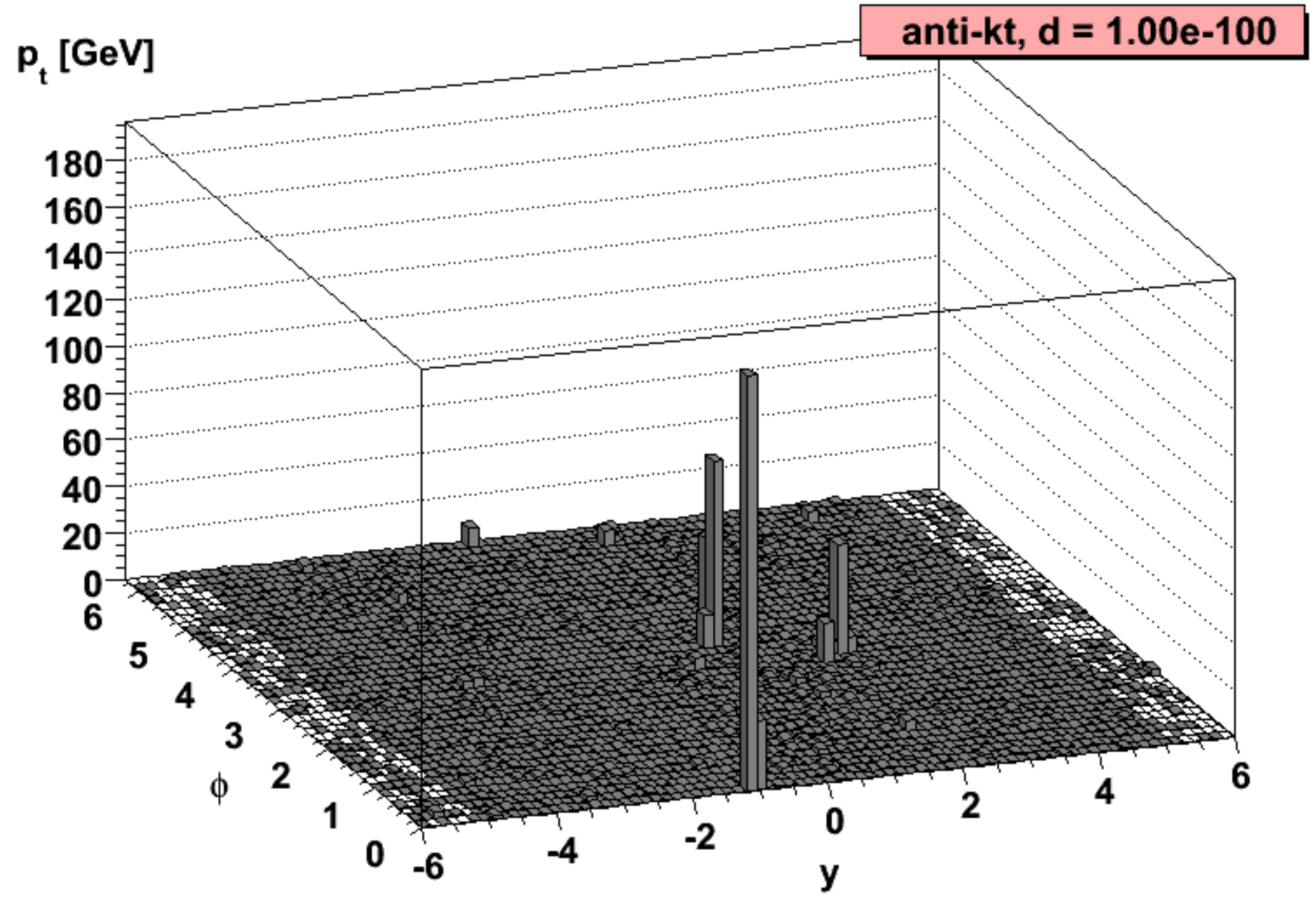




Number of jets depend on the definition - jet finding algorith

Jet clustering



Anti-kt has become the most widely used jet-finding algorithm at LHC

Sequential recombination. Define:

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = \frac{1}{p_{ti}^2}$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- ☐ Find smallest of d_{ij} and d_{iB}
- ☐ If ij, recombine them
- ☐ If iB, call it a jet and remove from the list
- ☐ Repeat until no particles left

[From https://gsalam.web.cern.ch/gsalam/teaching/PhD-courses.html]

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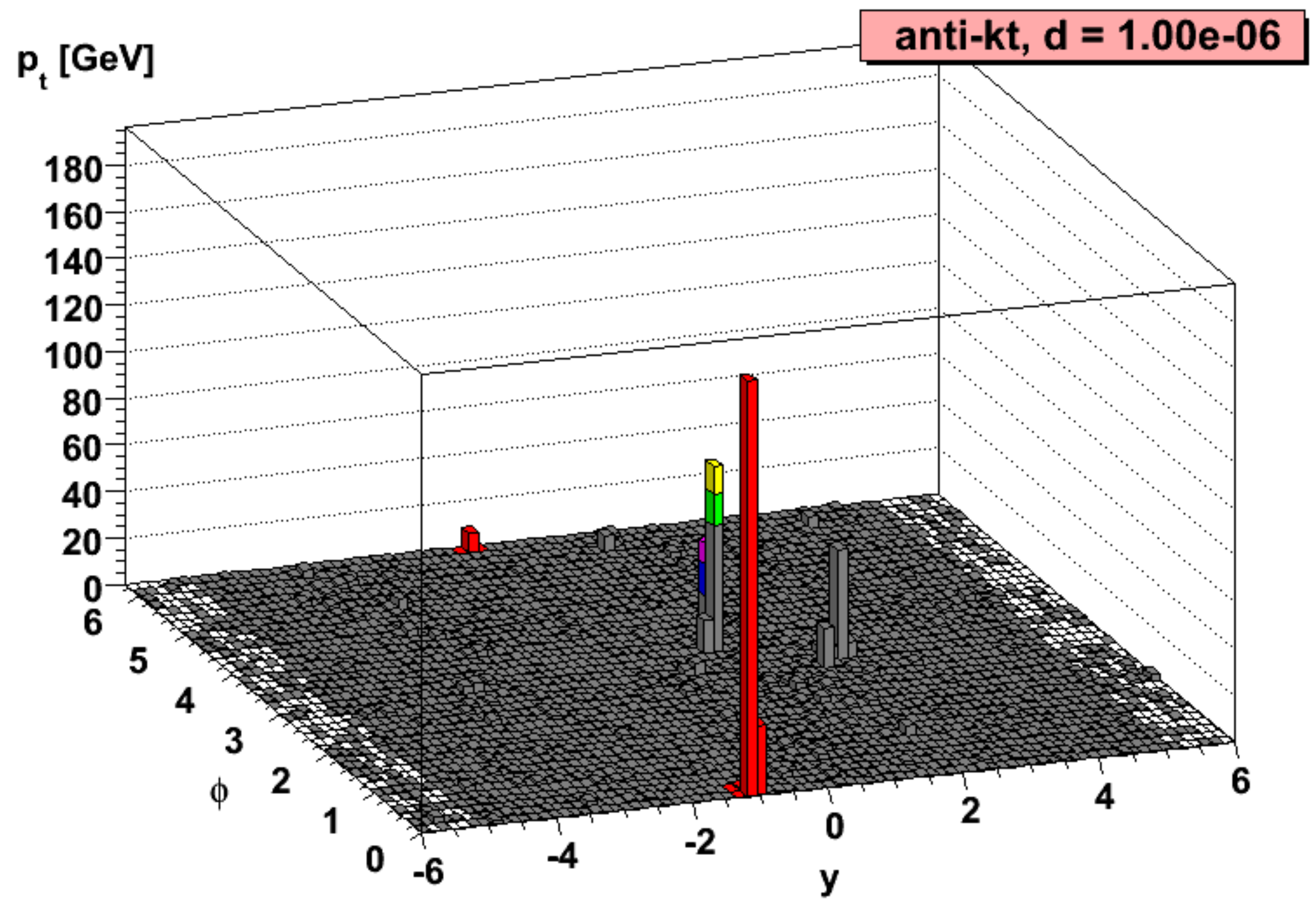

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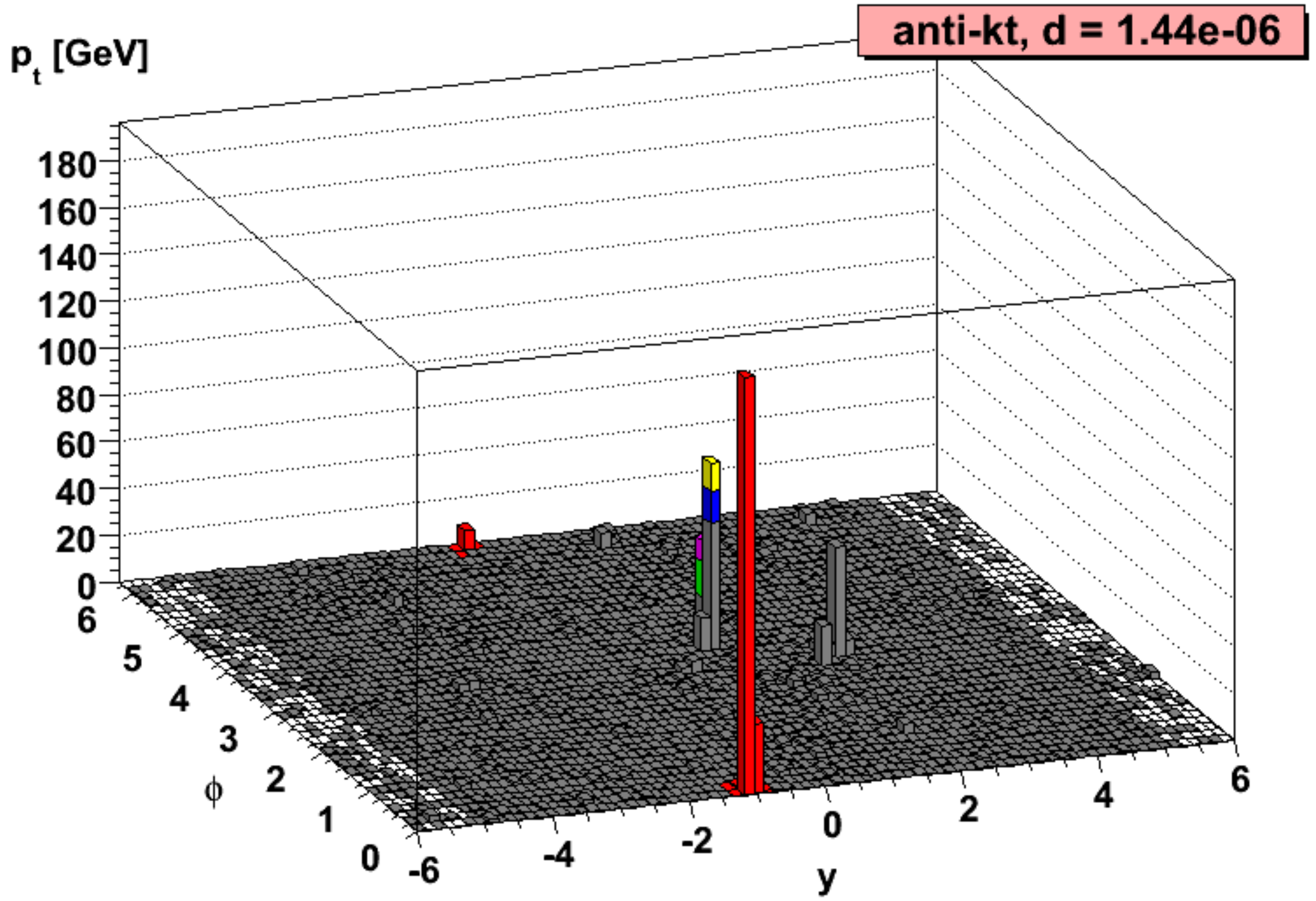

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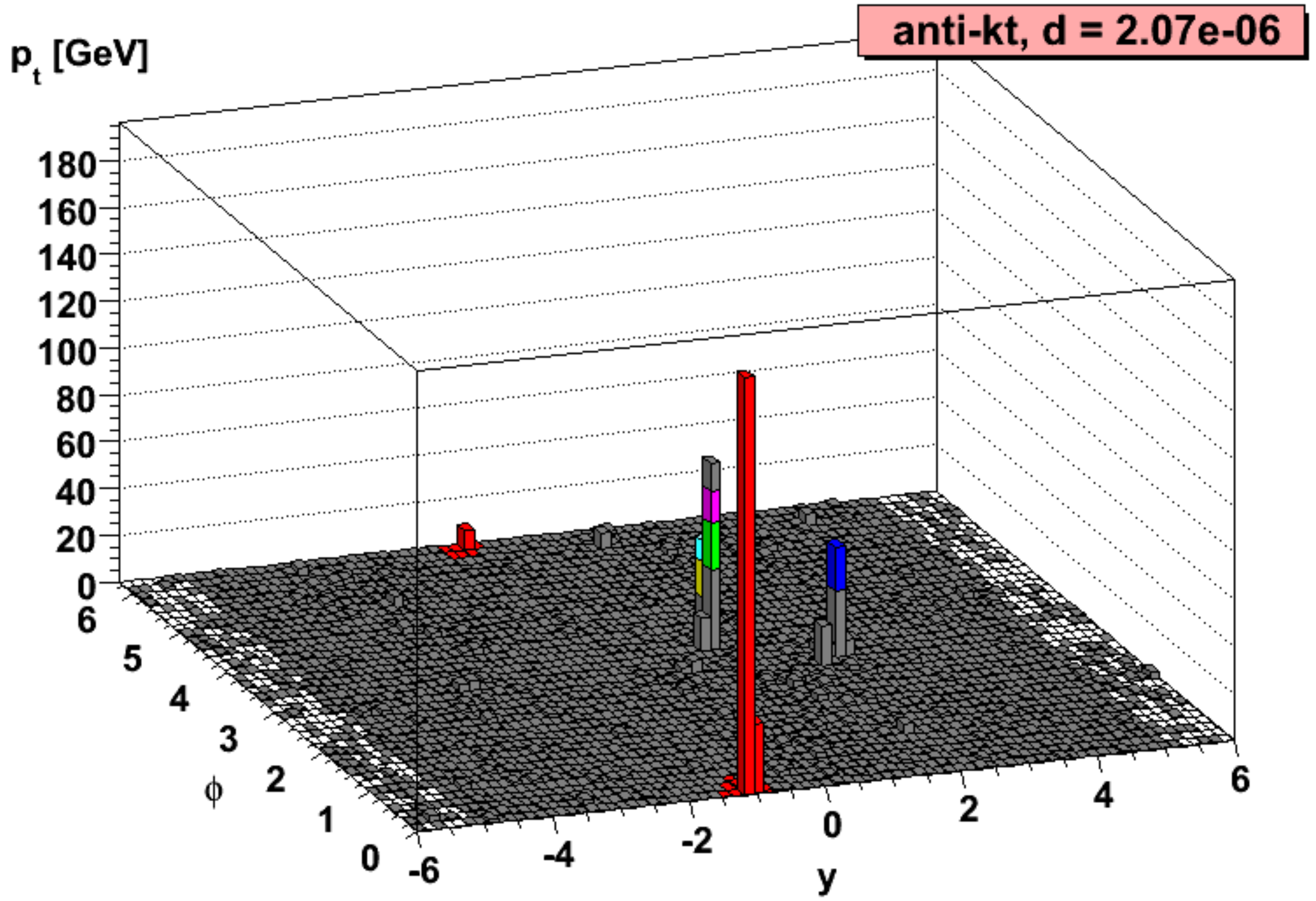

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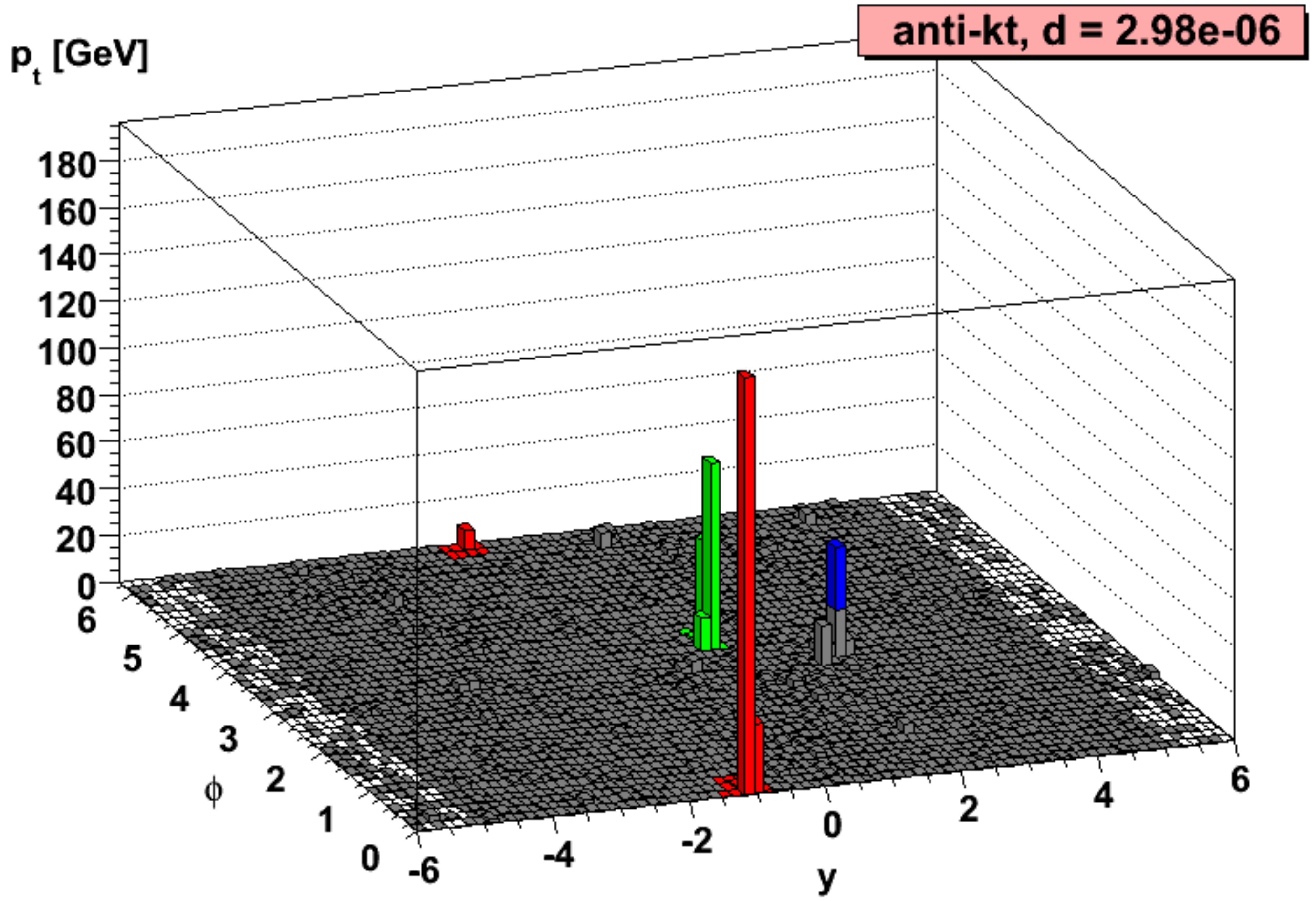

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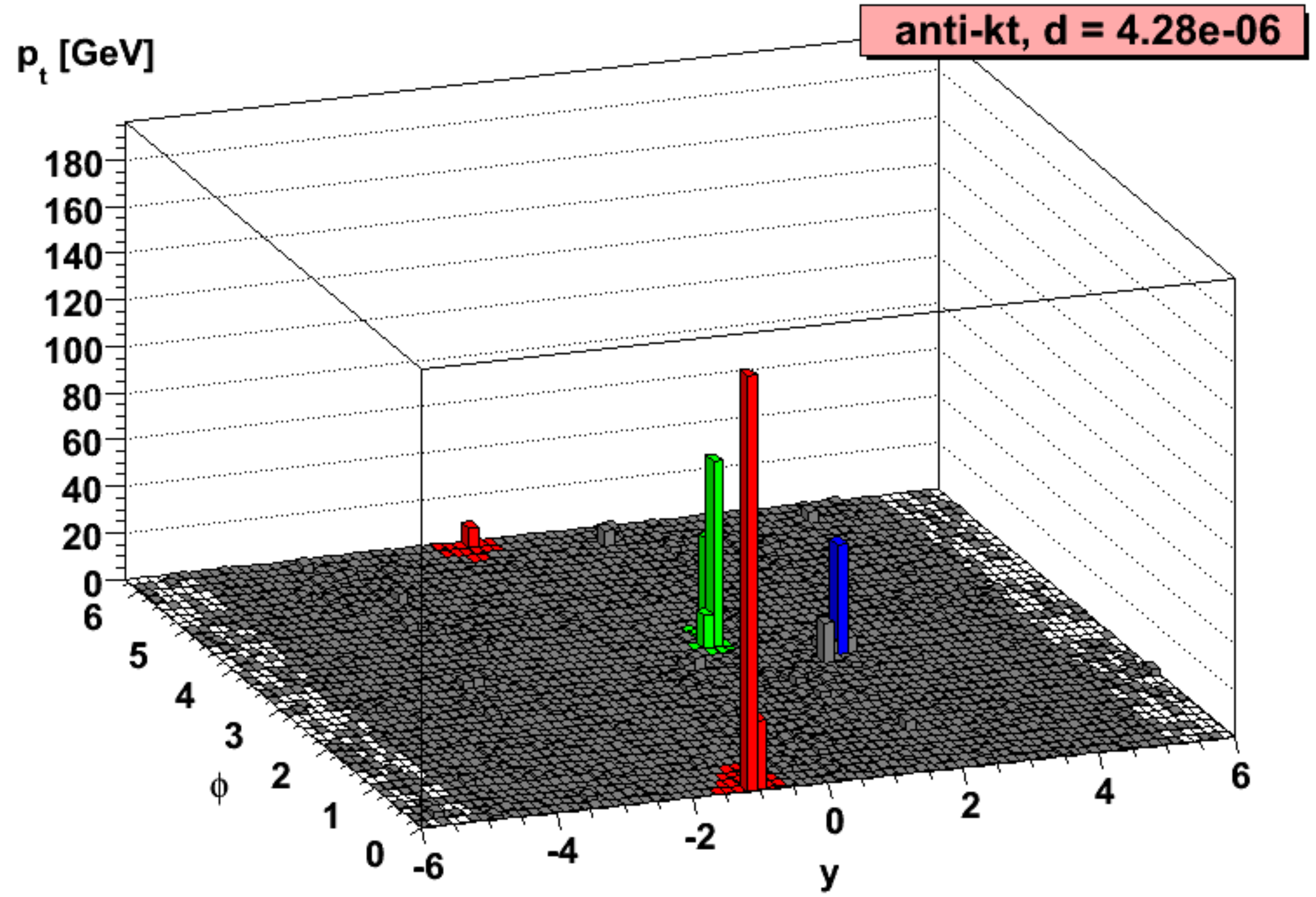

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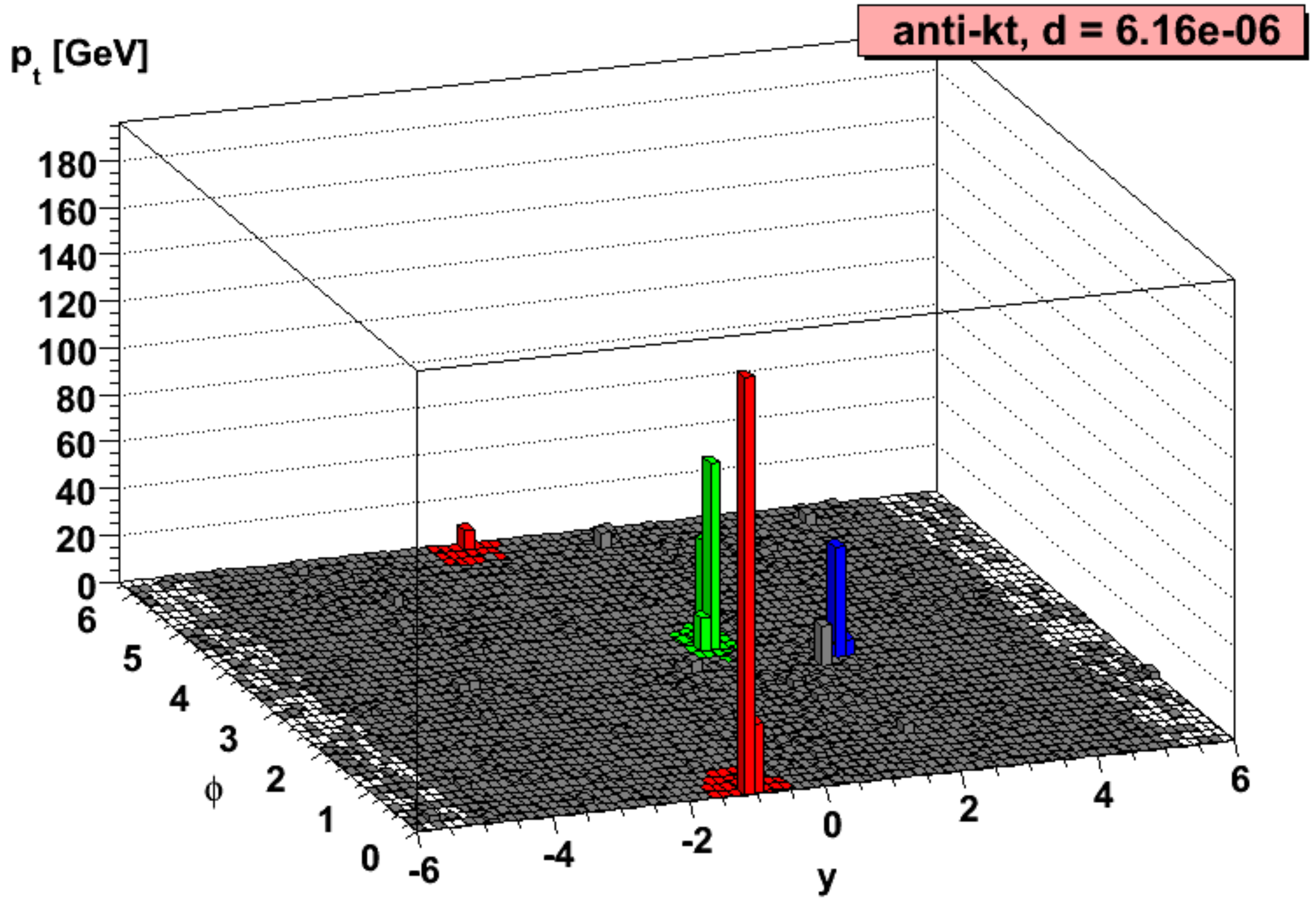
Jet clustering



Anti-kt has become the most widely used jet-finding algorithm at LHC

Sequential recombination. Define:

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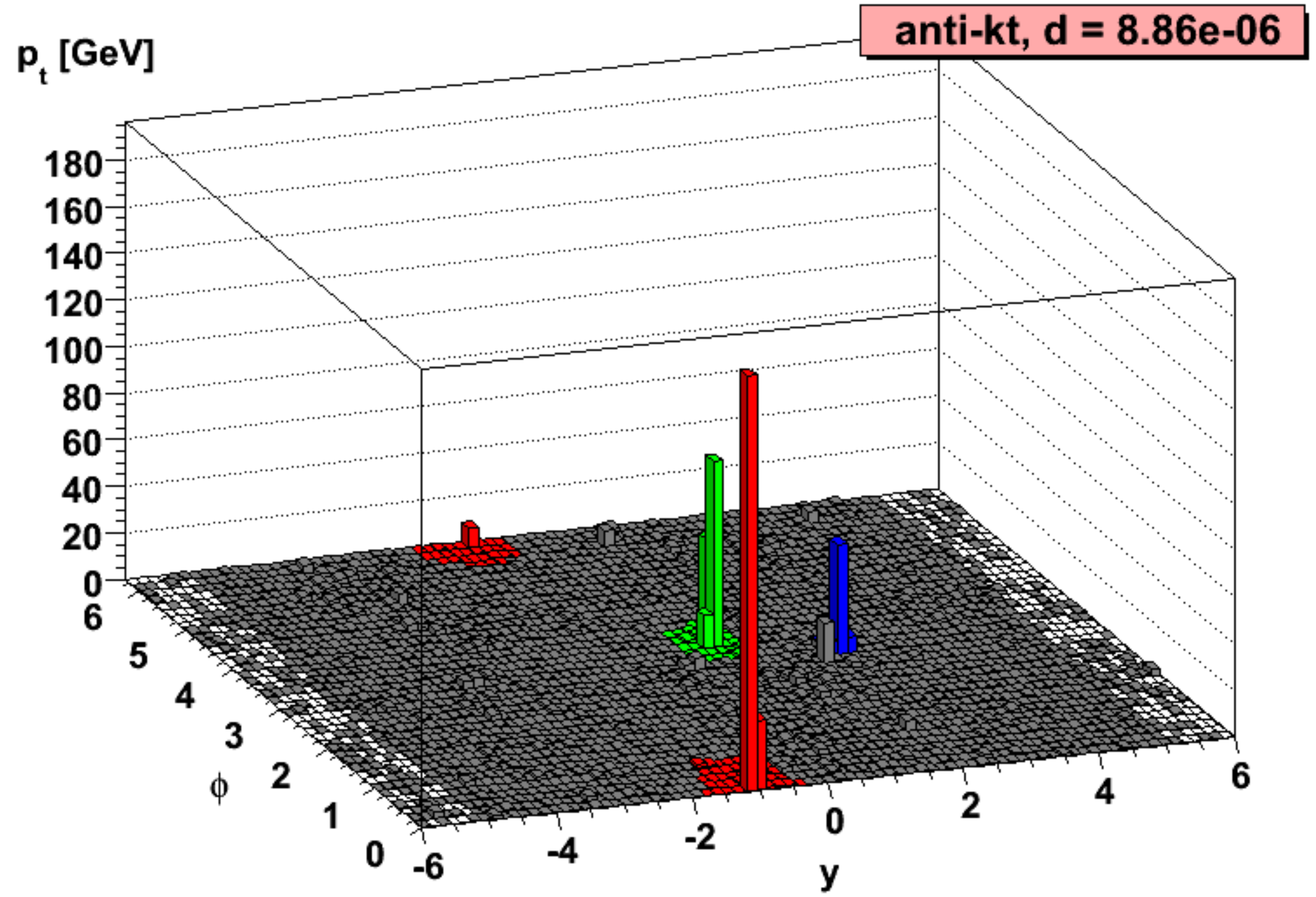

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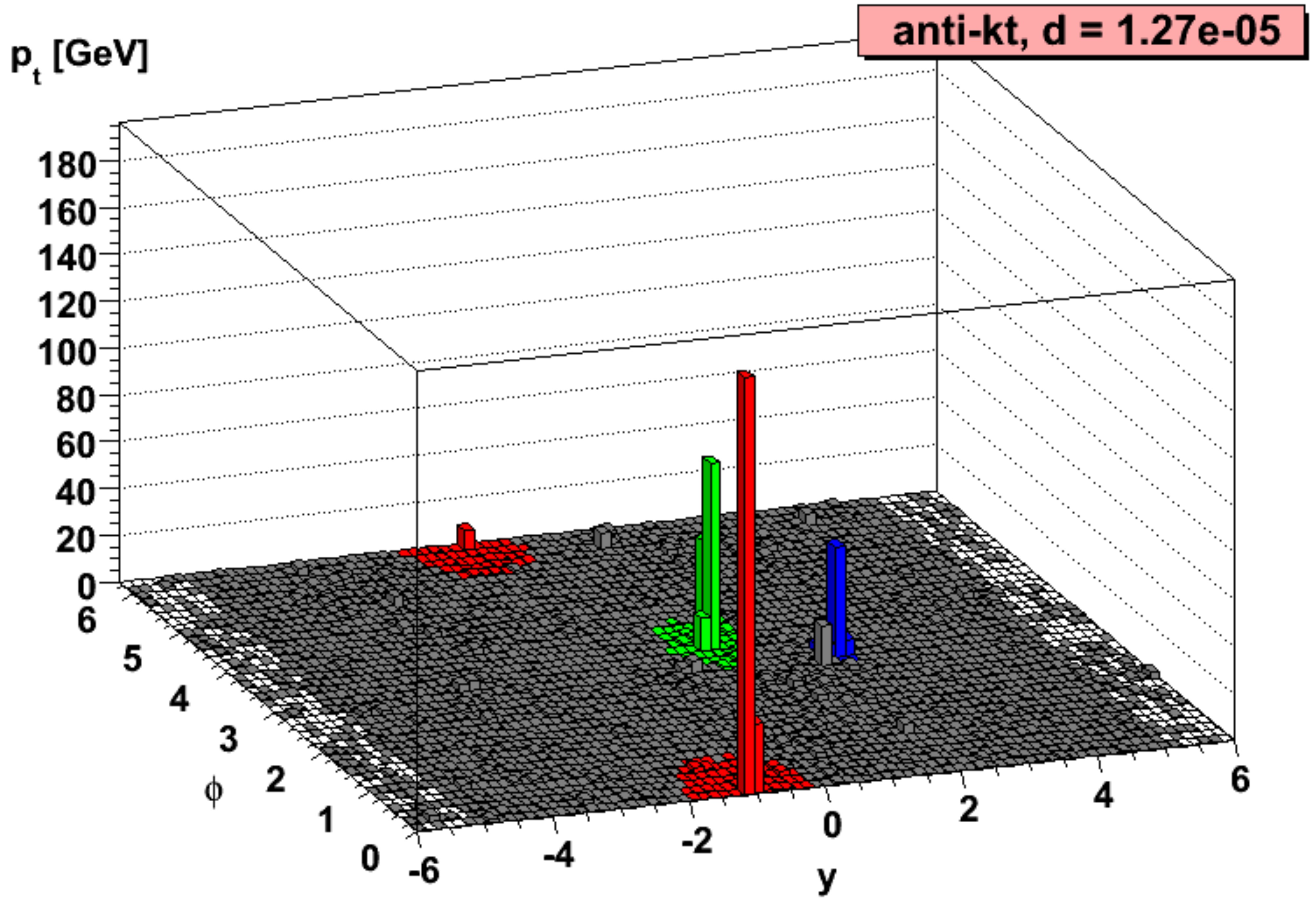

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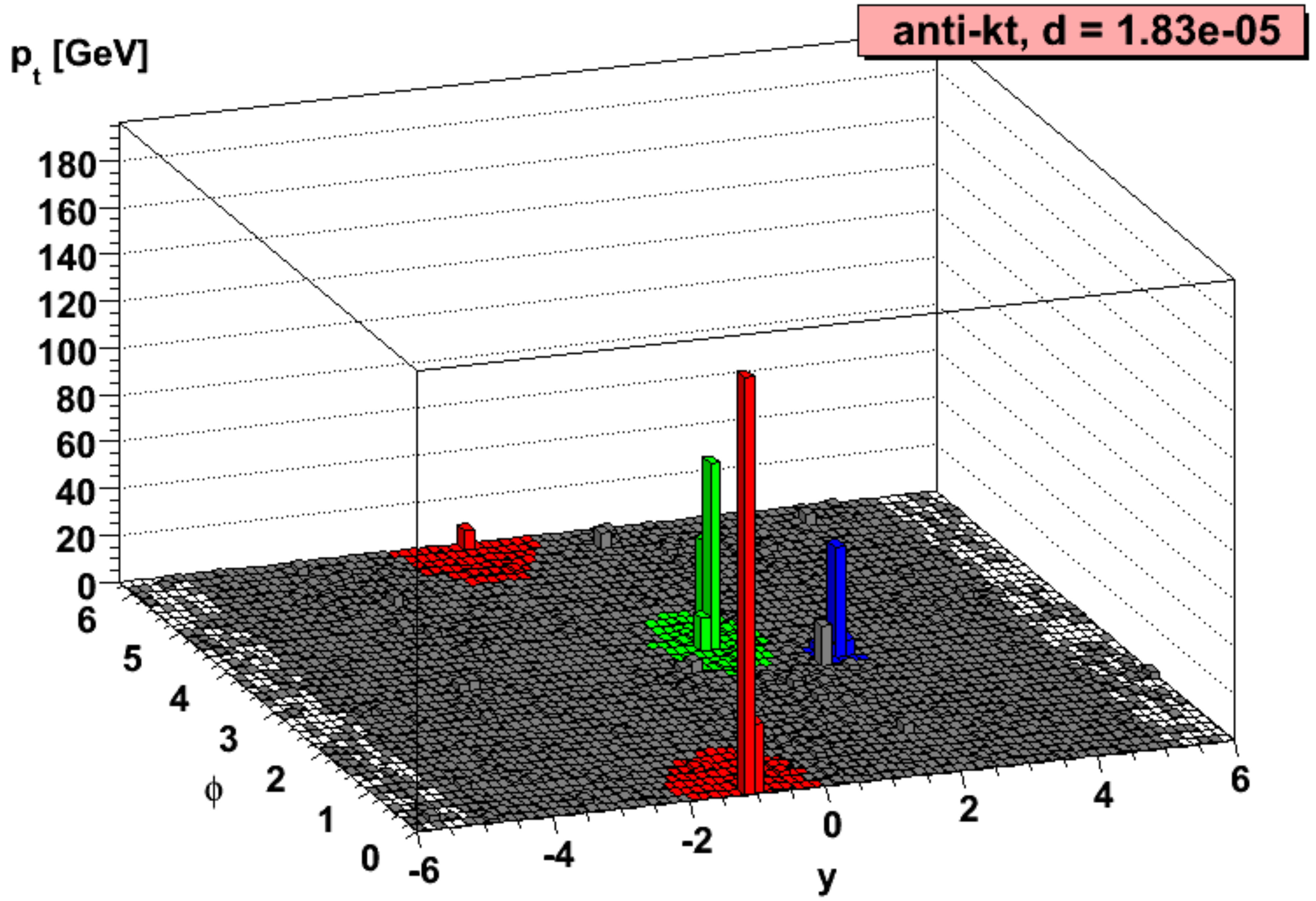

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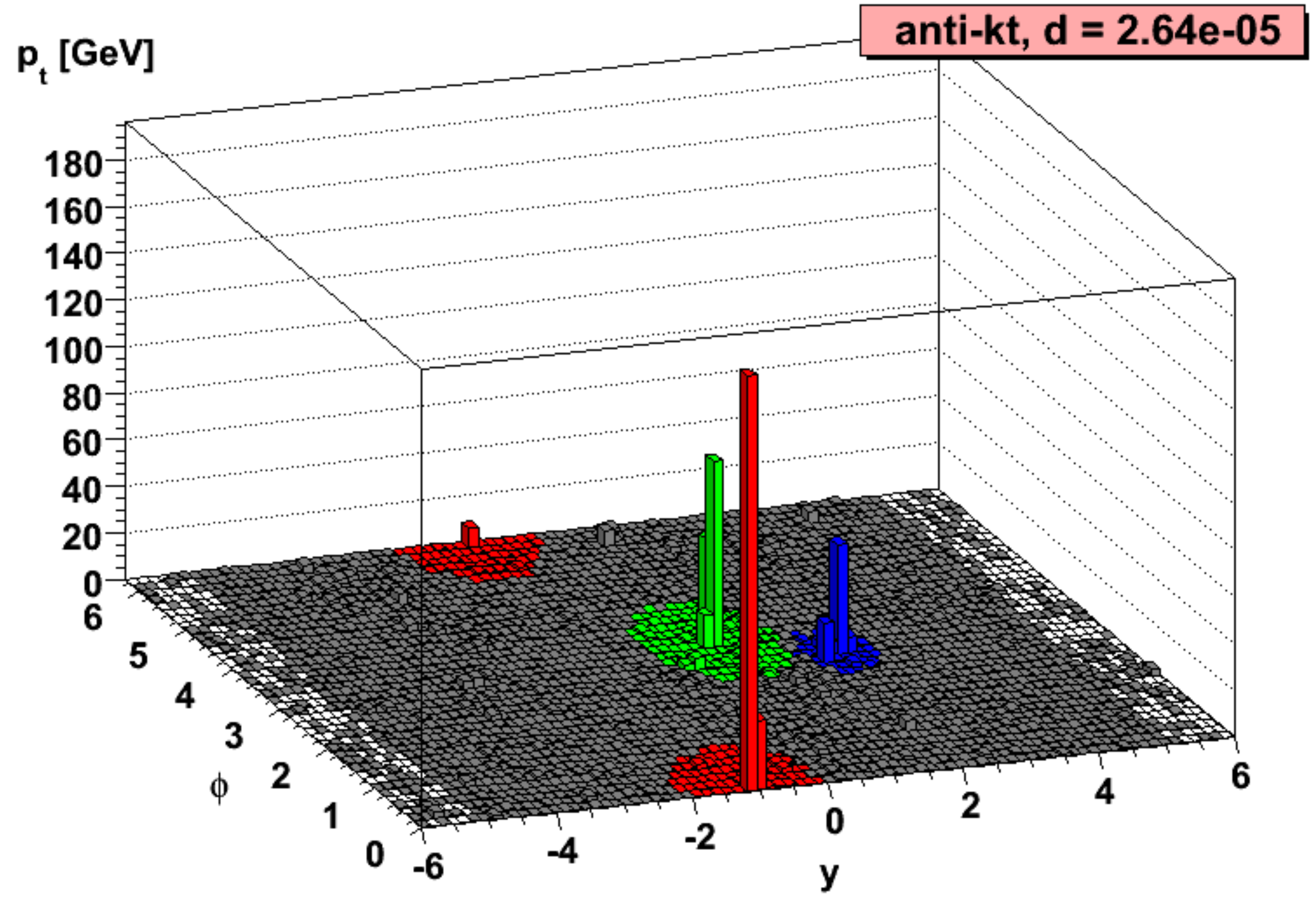

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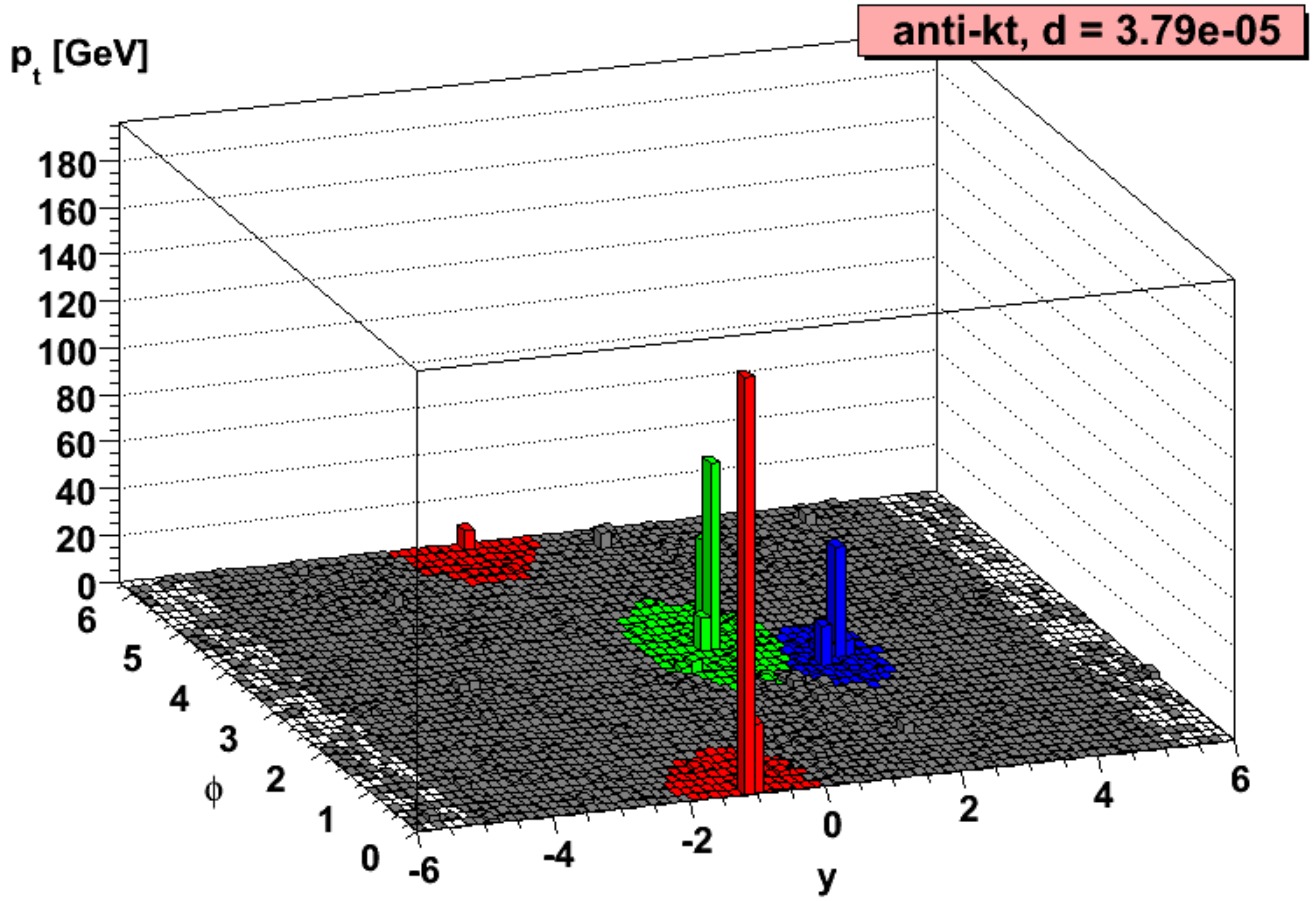

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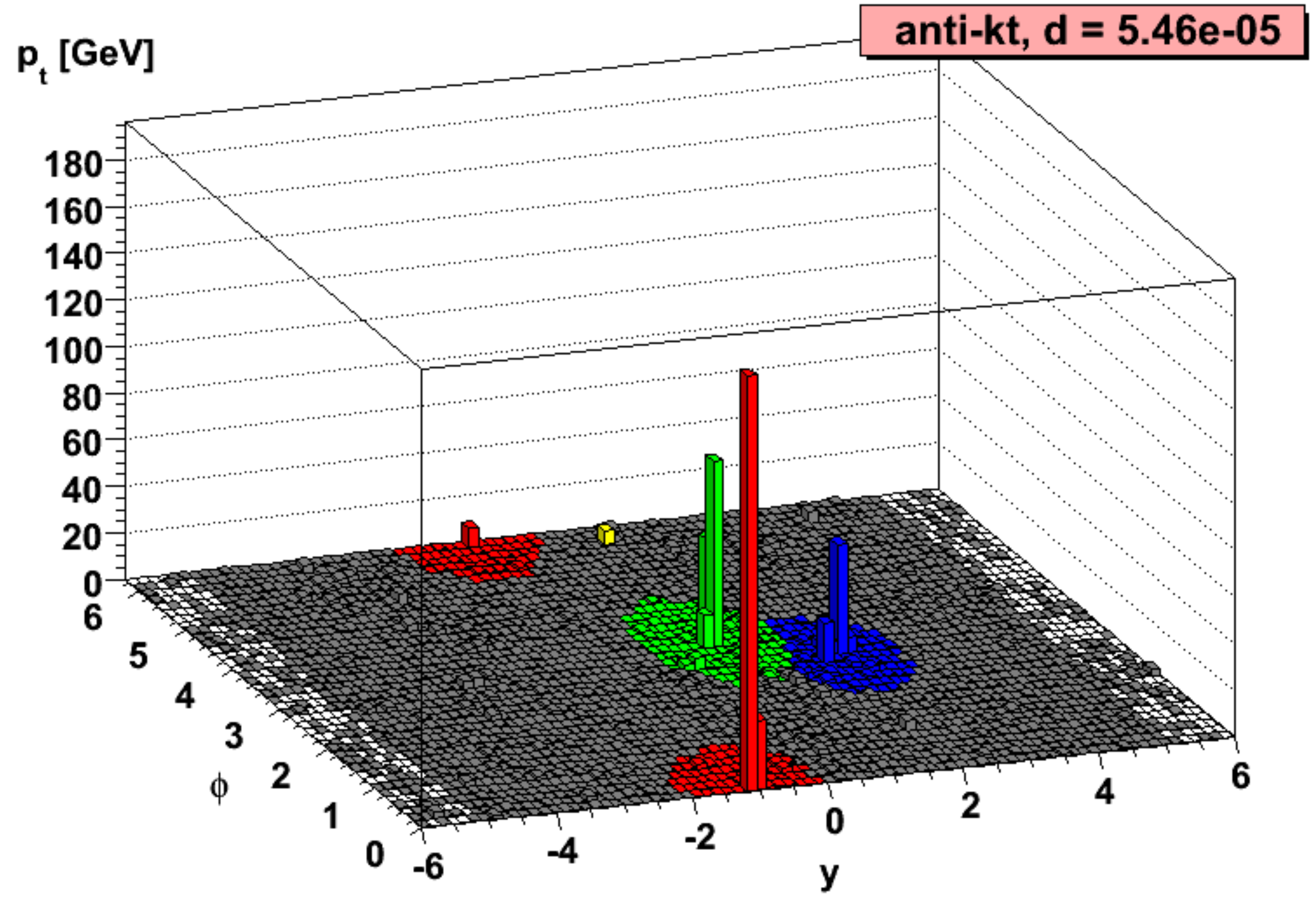

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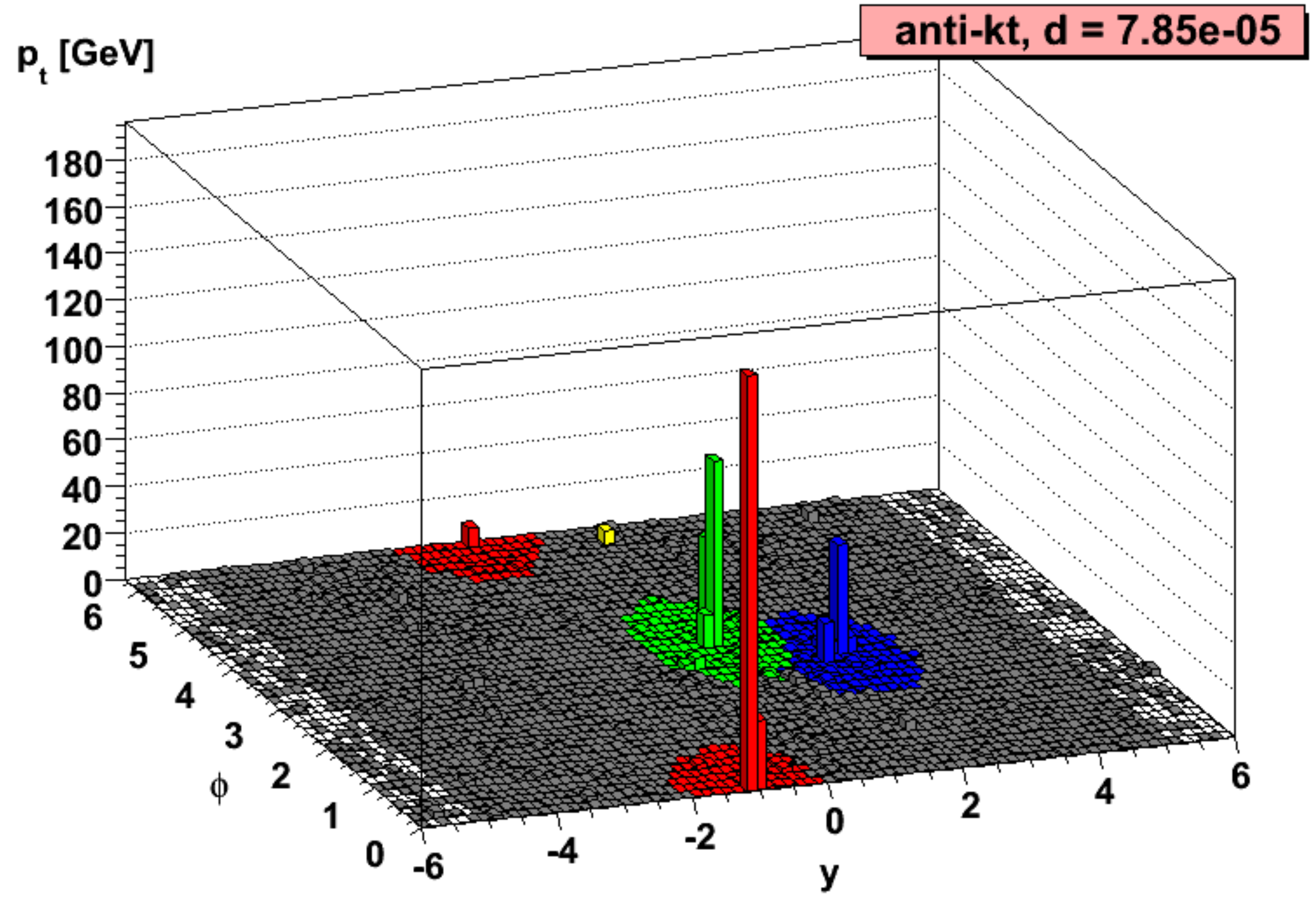

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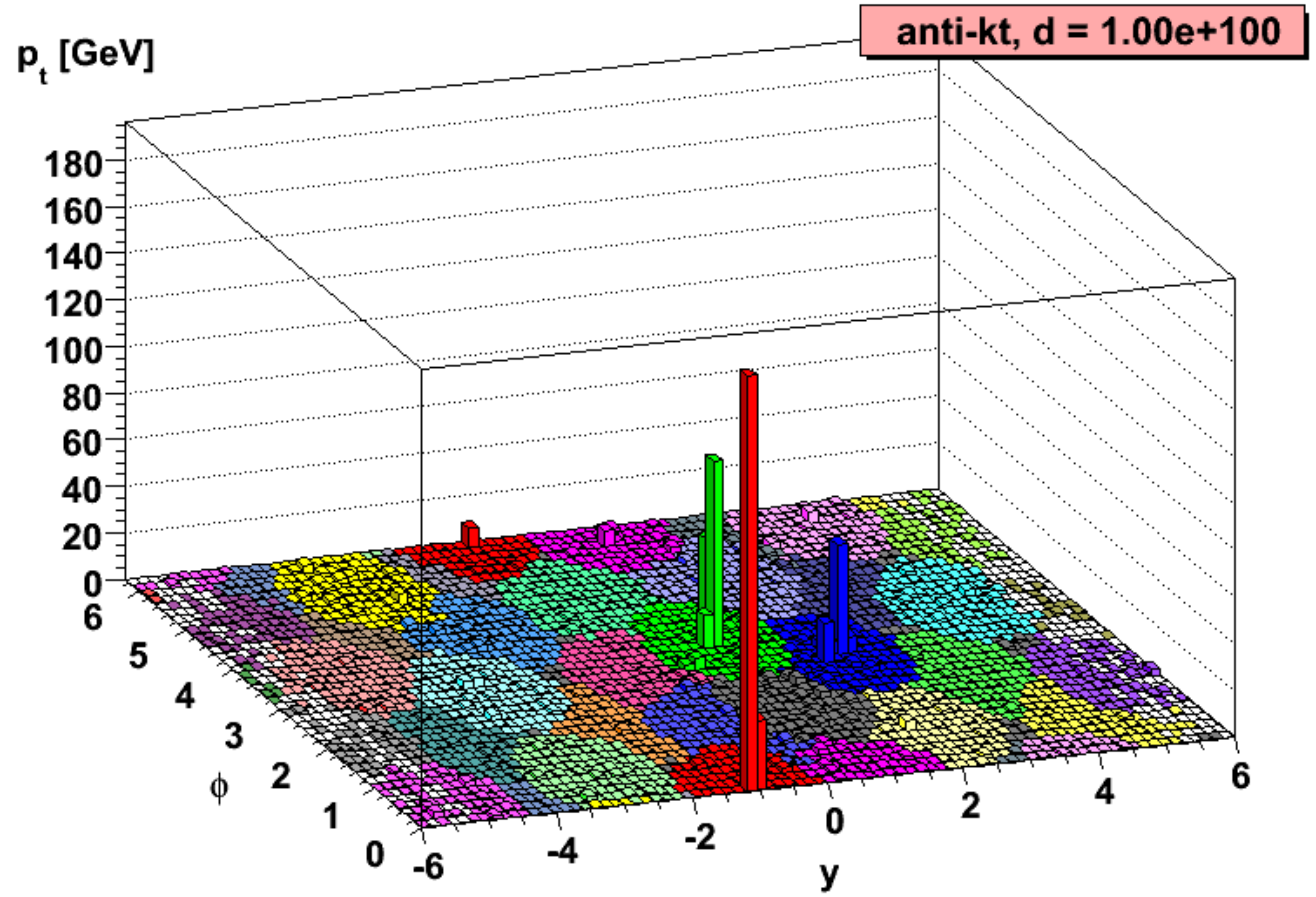

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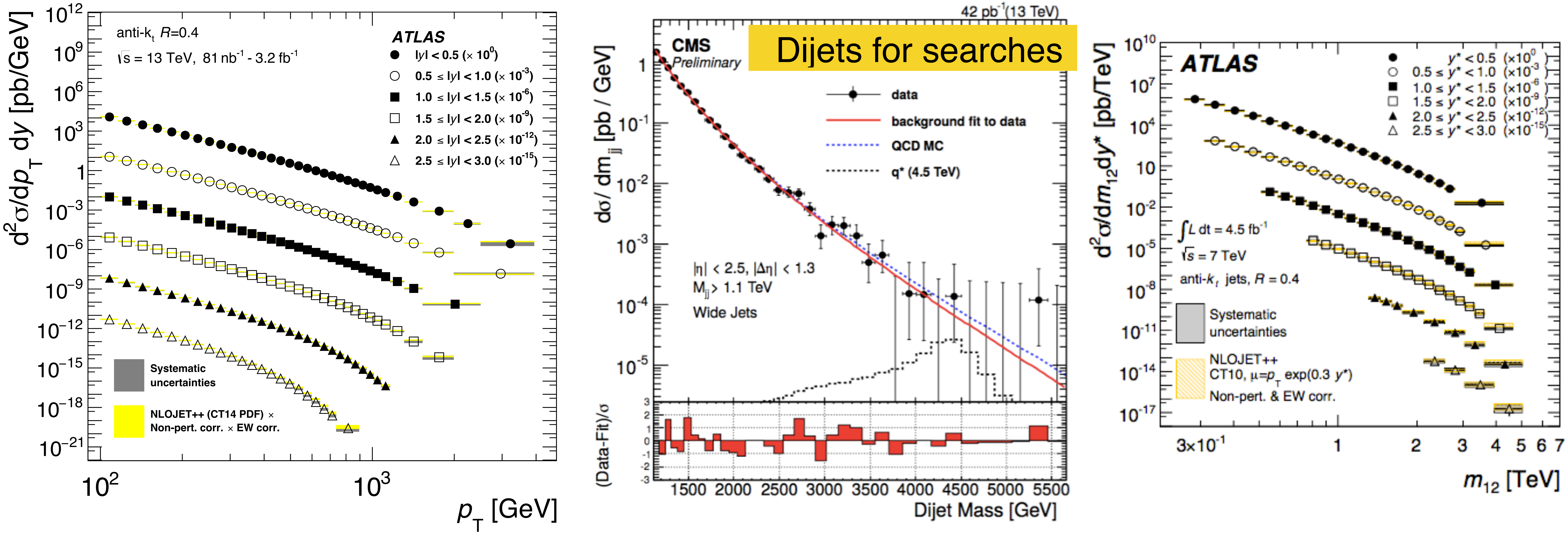
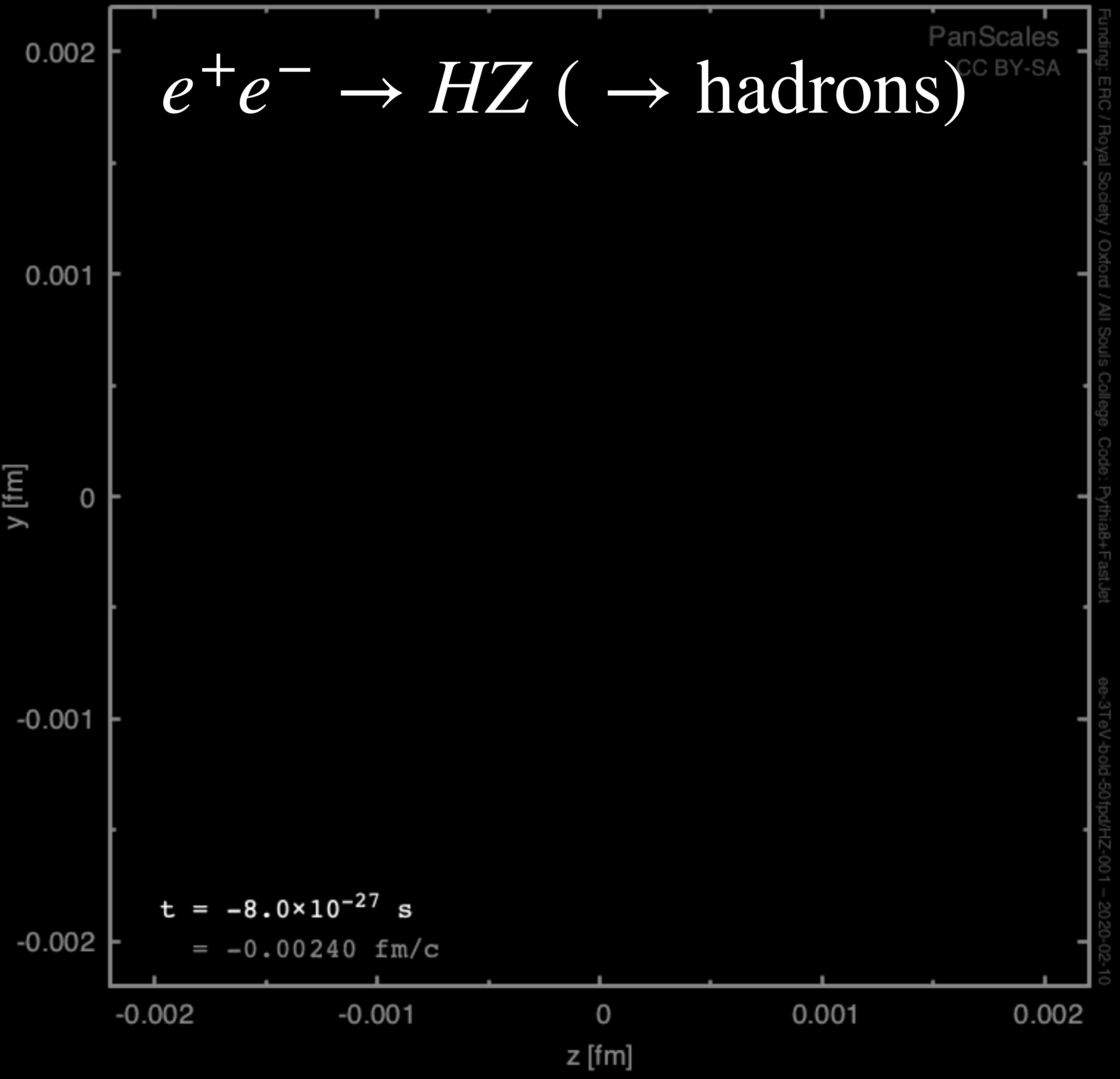
Some results from LHC



Excellent agreement with QCD - strong constraints to PDFs [later]

https://gsalam.web.cern.ch/gsalam/panscales/videos.html



3TeV e^+e^- events

Initial particles in yellow
Intermediate particles in blue
Final particles in red

Boosted H and Z decay
into **collimated jets**

[Simulation of the events are produced with Pythia 8
times estimated by clustering algorith
- see details in the web page]

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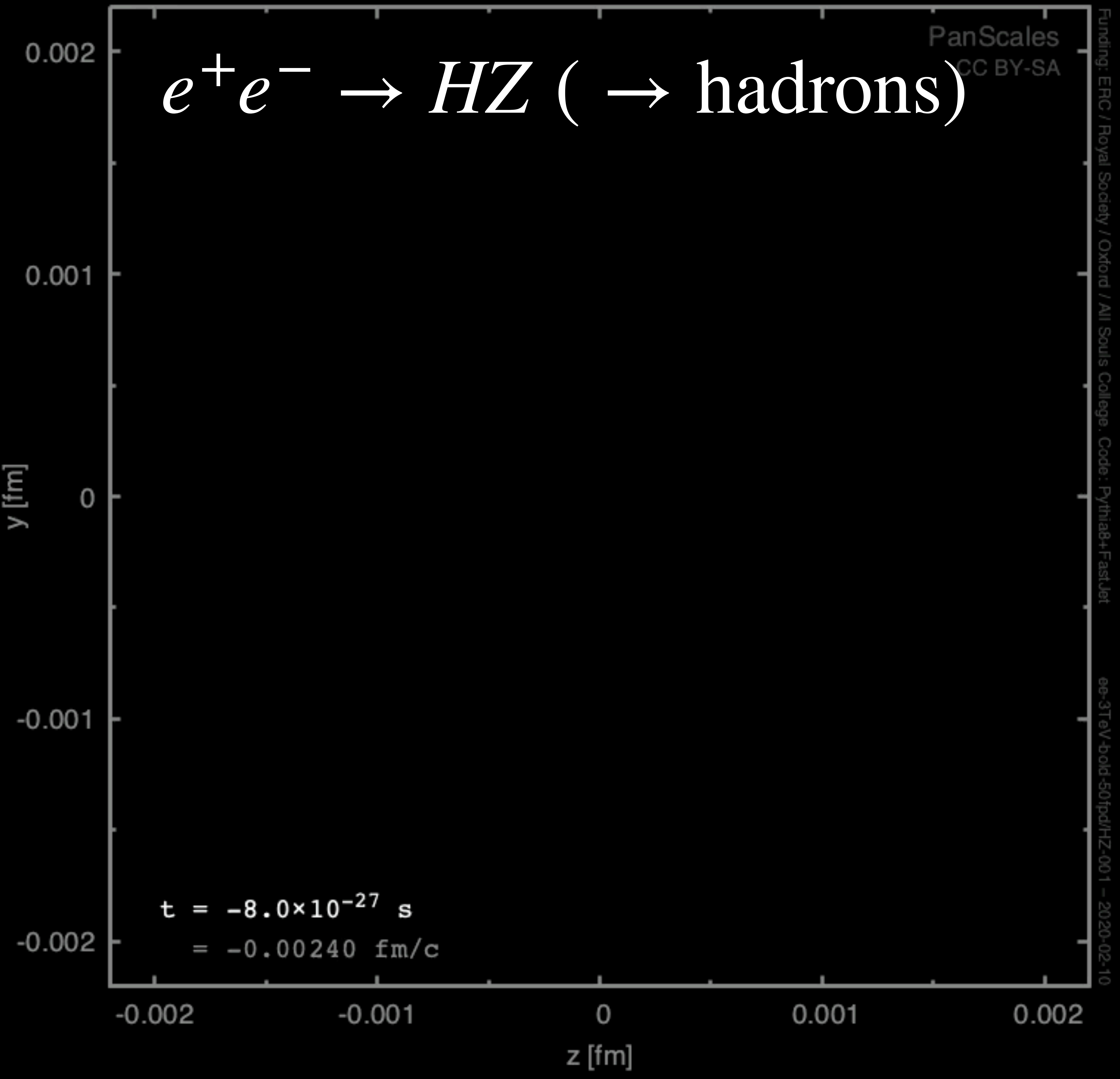

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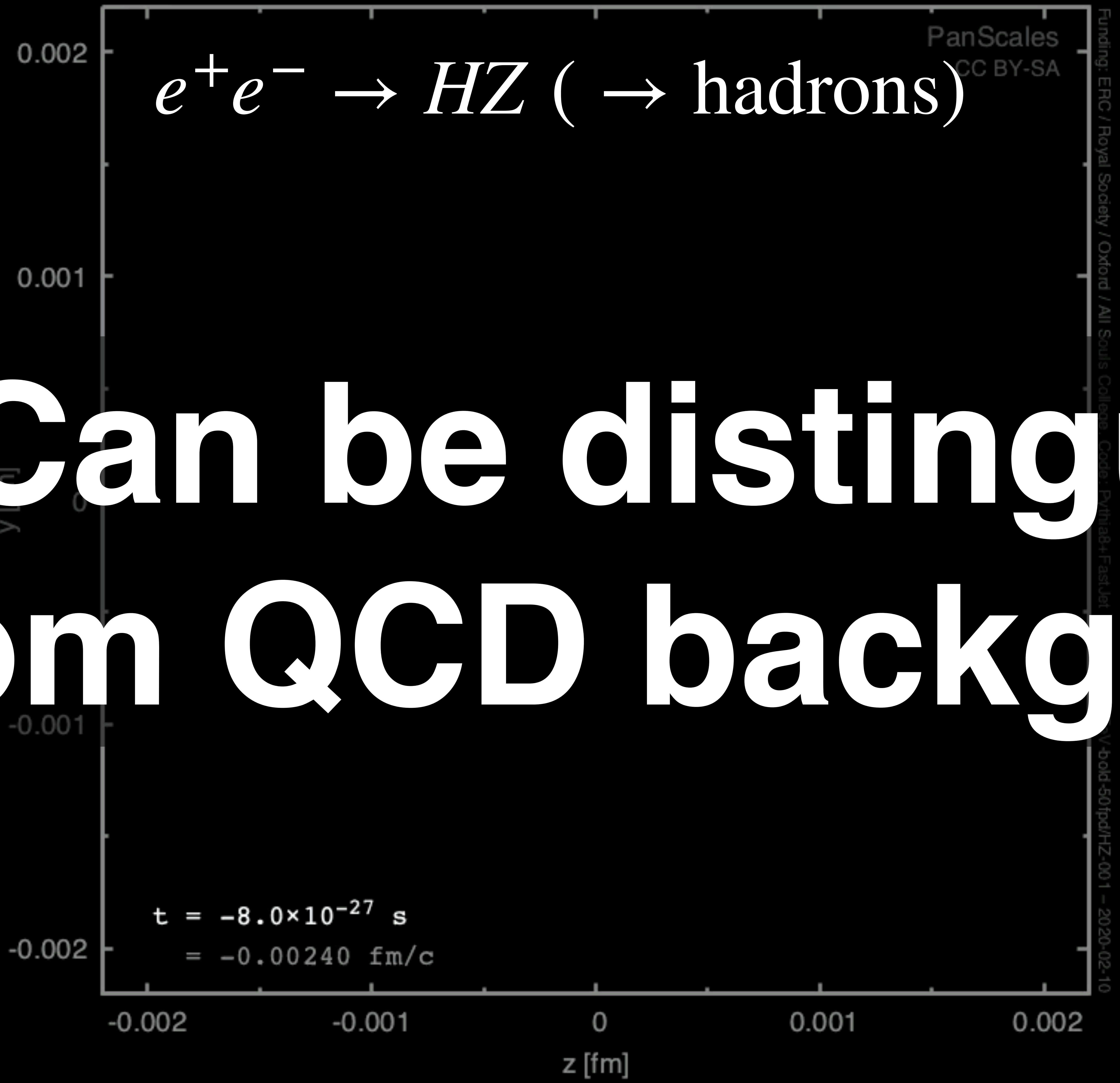
$e^+e^- \to HZ\ (\to \text{hadrons})$



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Can be distinguished from QCD background??

Boosted H and Z decay into **collimated jets**

[Simulation of the events are produced with Pythia 8
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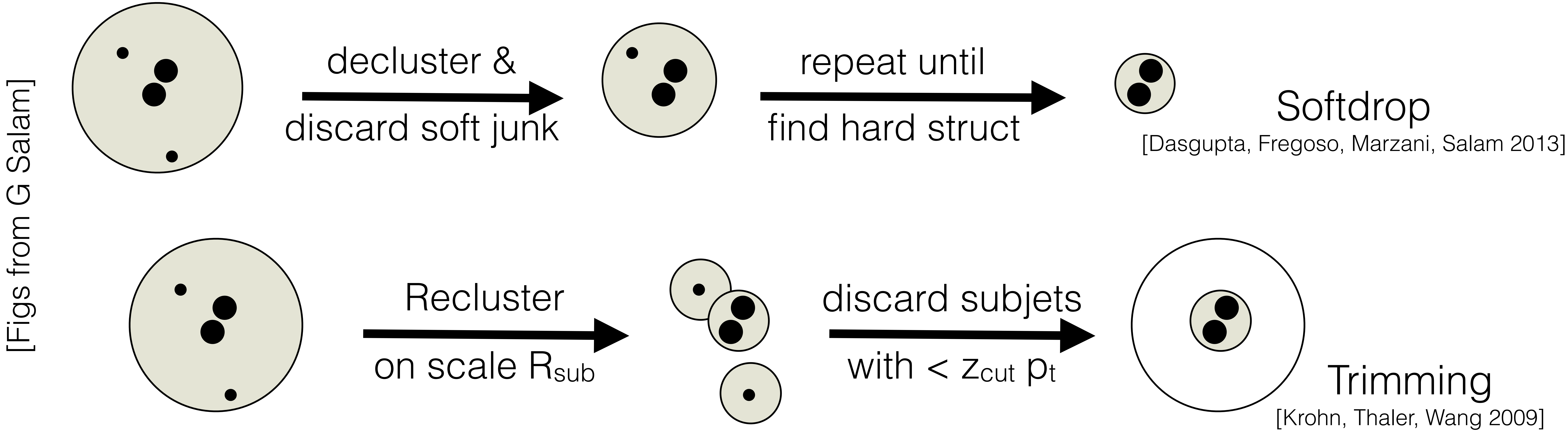
Jet substructure

Find different substructures in identified jets

[very active area, lots of results in the last years]



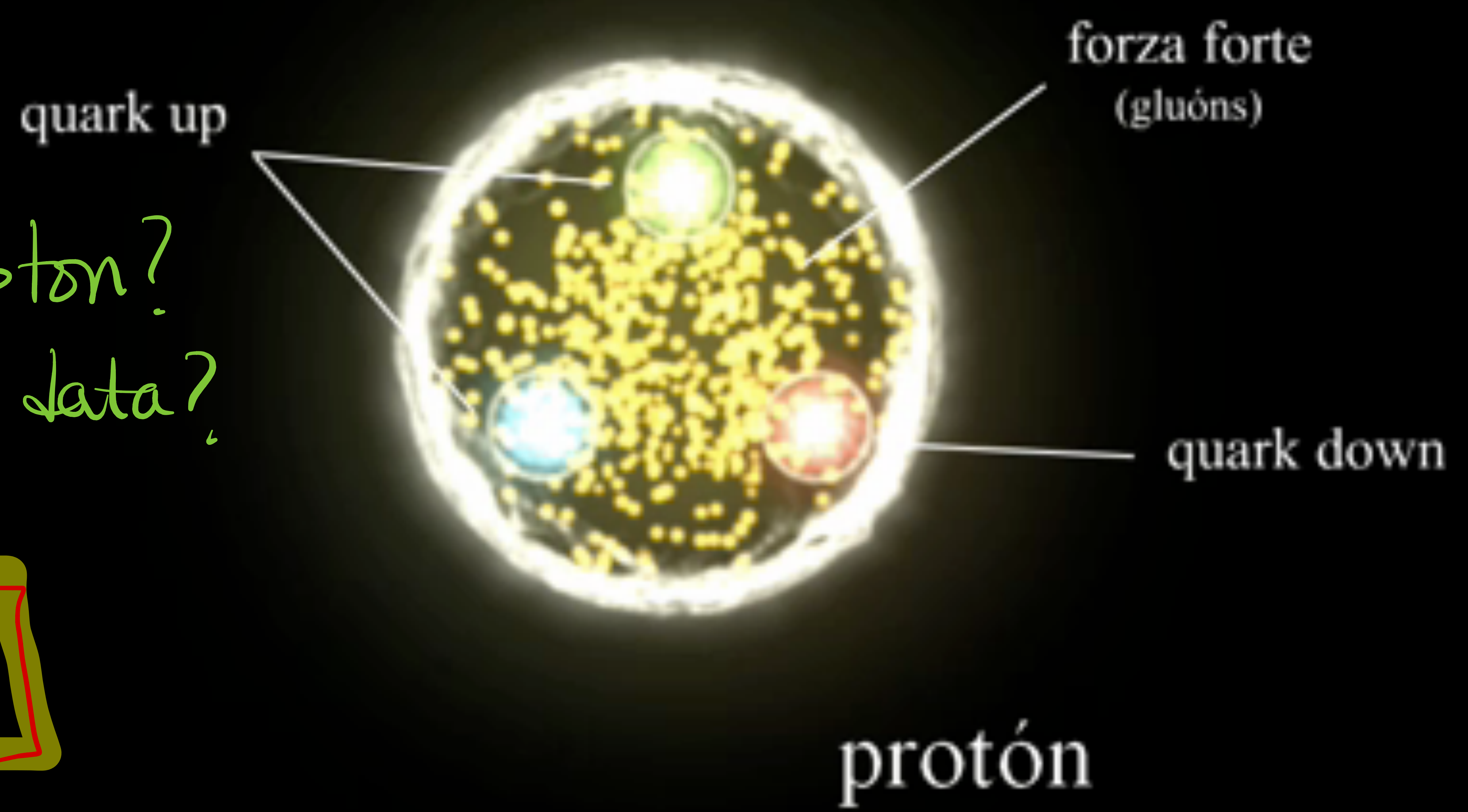
Also to identify two-pronged jet structures - boosted H/W/Z

QCD is a Quantum Field Theory

↳ Quantum fluctuations ↔ virtual particles

* What is the structure of the proton?
* How do we extract it from data?

GLUON MULTIPLICATION



See e.g. arxiv:1709.04922 for a review

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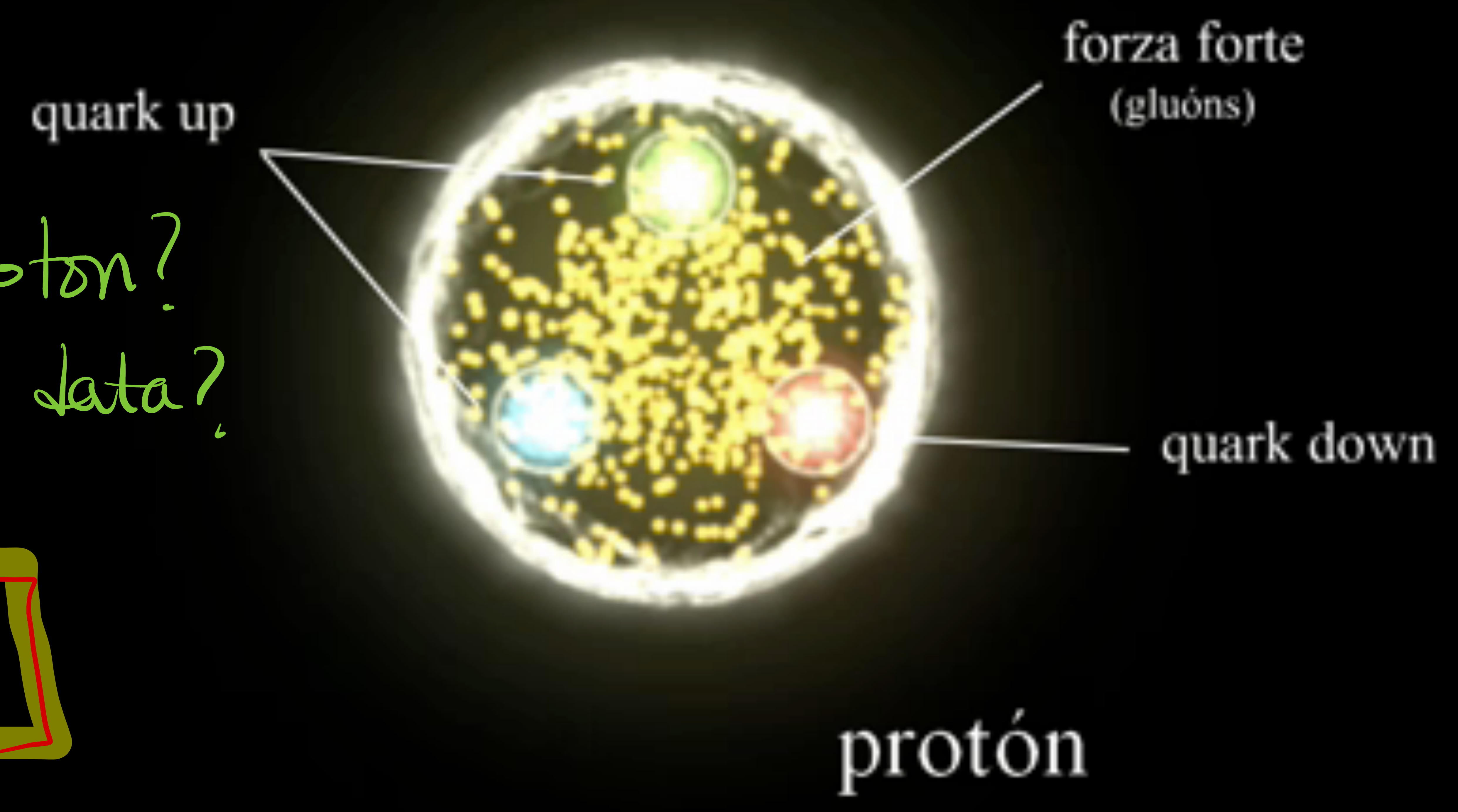

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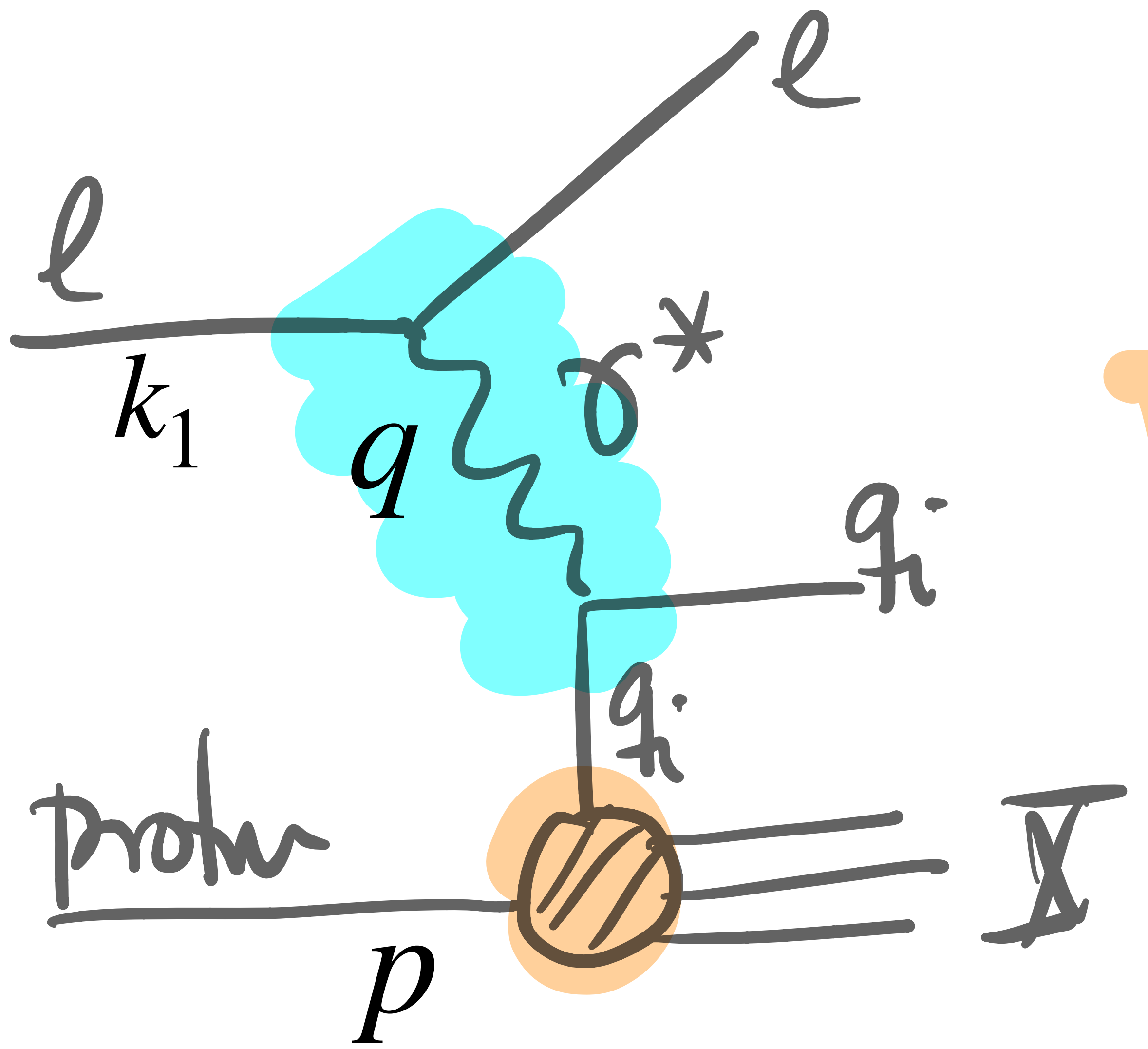
DIS - parton model



PARTON MODEL

$f_{q_i}(x)$ Probability to find q_i with fraction of momentum x **PDF**

$$\frac{d\sigma}{dx\,dQ^2} = \sum_i \int dx\, f_{q_i}(x) \frac{d\hat{\sigma}_i}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[1+(1-y)^2\right] F_2(x)$$

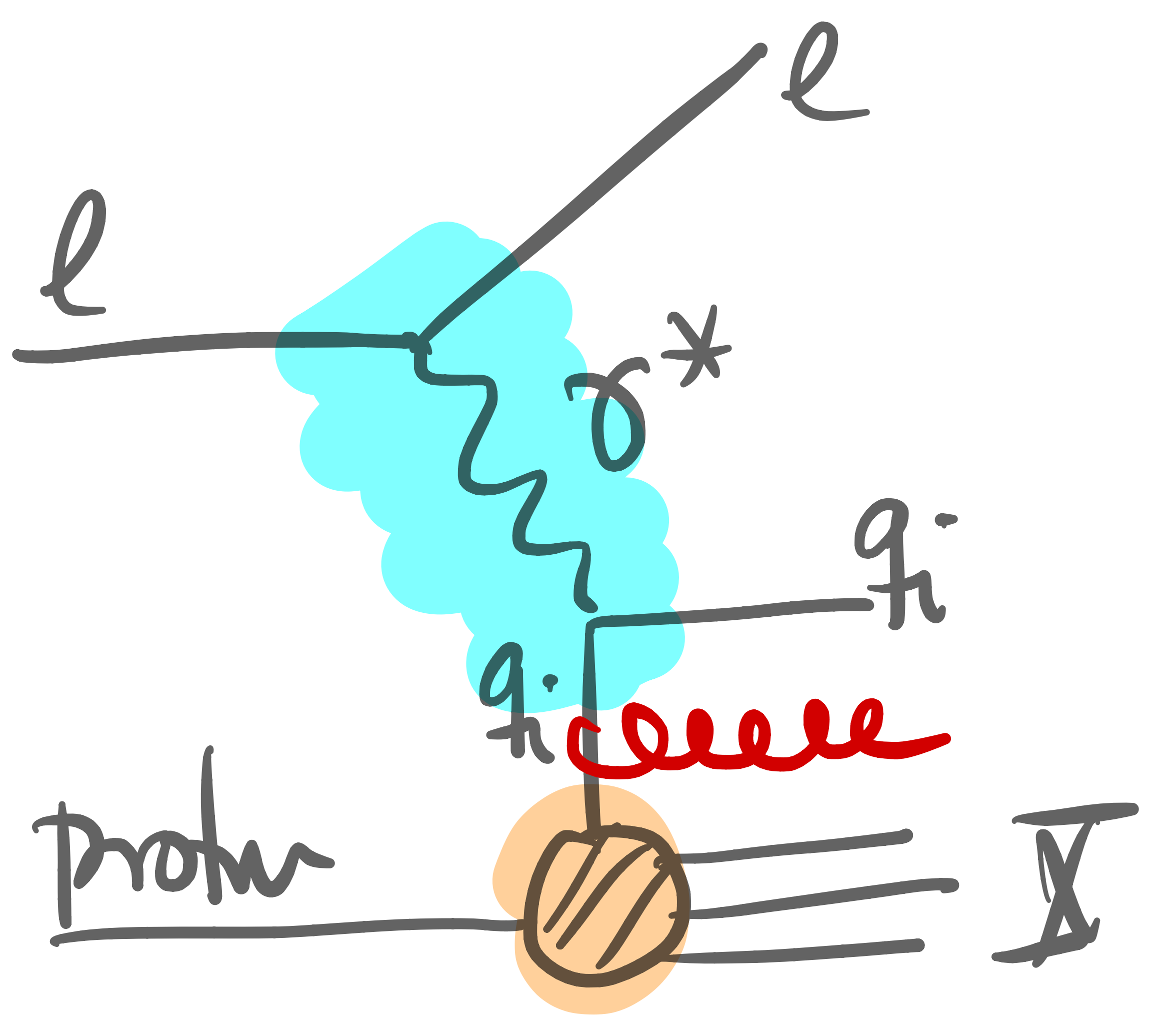
Kinematics — Structure of the proton

Structure function [Bjorken scaling]

$$F_2(x) = x \sum_{q_i} e_{q_i}^2 f_{q_i}(x) = x\left[\frac{4}{9}\left(u(x)+\bar{u}(x)\right) + \frac{1}{9}\left(d(x)+\bar{d}(x)+s(x)+\bar{s}(x)\right)+\ldots\right]$$

Kinematical variables $Q^2 \equiv -q^2, \quad x = \dfrac{Q^2}{2p\cdot q}, \quad y = \dfrac{p\cdot q}{p\cdot k_1}$

Parton model + QCD



PARTON MODEL + SOFT GLUON

Now $\frac{d\hat{\sigma}}{dx\,dQ^2} \to \frac{d\hat{\sigma}}{dx\,dQ^2}\left[1 + \frac{2\alpha_s C_F}{\pi}\frac{1}{k_\perp^2}P(x)\right]$

$P(x) \xrightarrow[x\to 0]{} \frac{1}{x}$

We have to integrate in $k_\perp$ & x

$$\int_{\mu_0}^{Q^2}\frac{dk_\perp^2}{k_\perp^2} = \log\frac{Q^2}{\mu_0^2} \xrightarrow{\mu_0\to 0} \infty$$

Renormalization

$$\frac{\partial F_2(x,\mu^2)}{\partial \log\mu^2} = 0 \iff \frac{\partial f_q(x,\mu^2)}{\partial \log\mu^2} = \frac{\alpha_s}{2\pi}\int\frac{dy}{y}P(y)\,f_q\!\left(\frac{x}{y}\right)$$

[Dokshitzer, Gribov, Lipatov, Altarelli, Parisi - DGLAP - see next slide]

DIS - parton model

Full DGLAP are coupled integro-differential eqs.

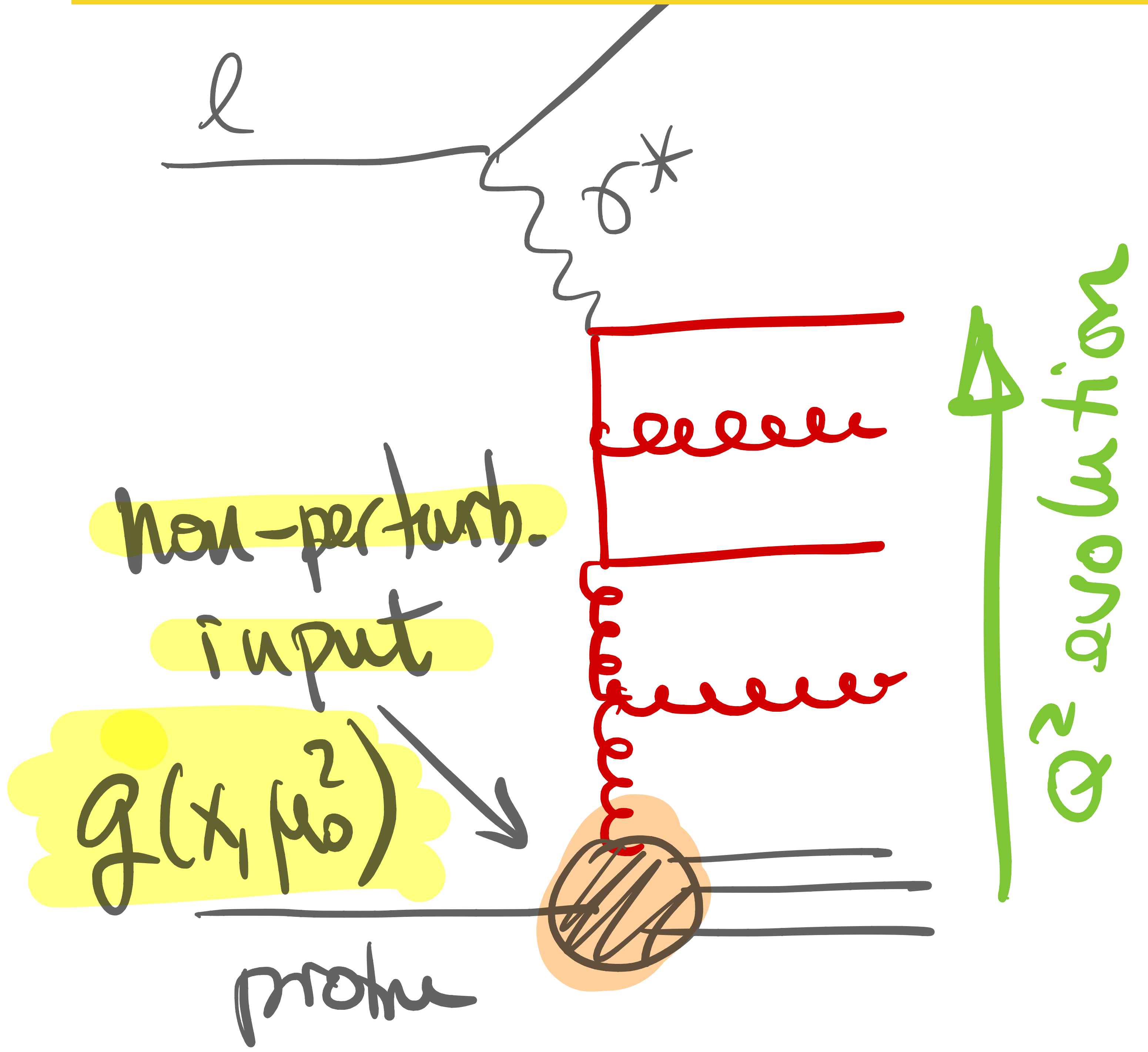
$$\frac{\partial q_i}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left[\sum_j P_{q_i q_j} \otimes q_j + P_{q_i g} \otimes g\right]$$

$$\frac{\partial g}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left[\sum_j P_{g q_j} \otimes q_j + P_{gg} \otimes g\right]$$

Initial conditions needed:
non-perturbative input at initial scale μ_0^2

$$u(x,\mu_0^2), \bar{u}(x,\mu_0^2), d(x,\mu_0^2), \bar{d}(x,\mu_0^2), s(x,\mu_0^2), \ldots, g(x,\mu_0^2)$$

Interpretation



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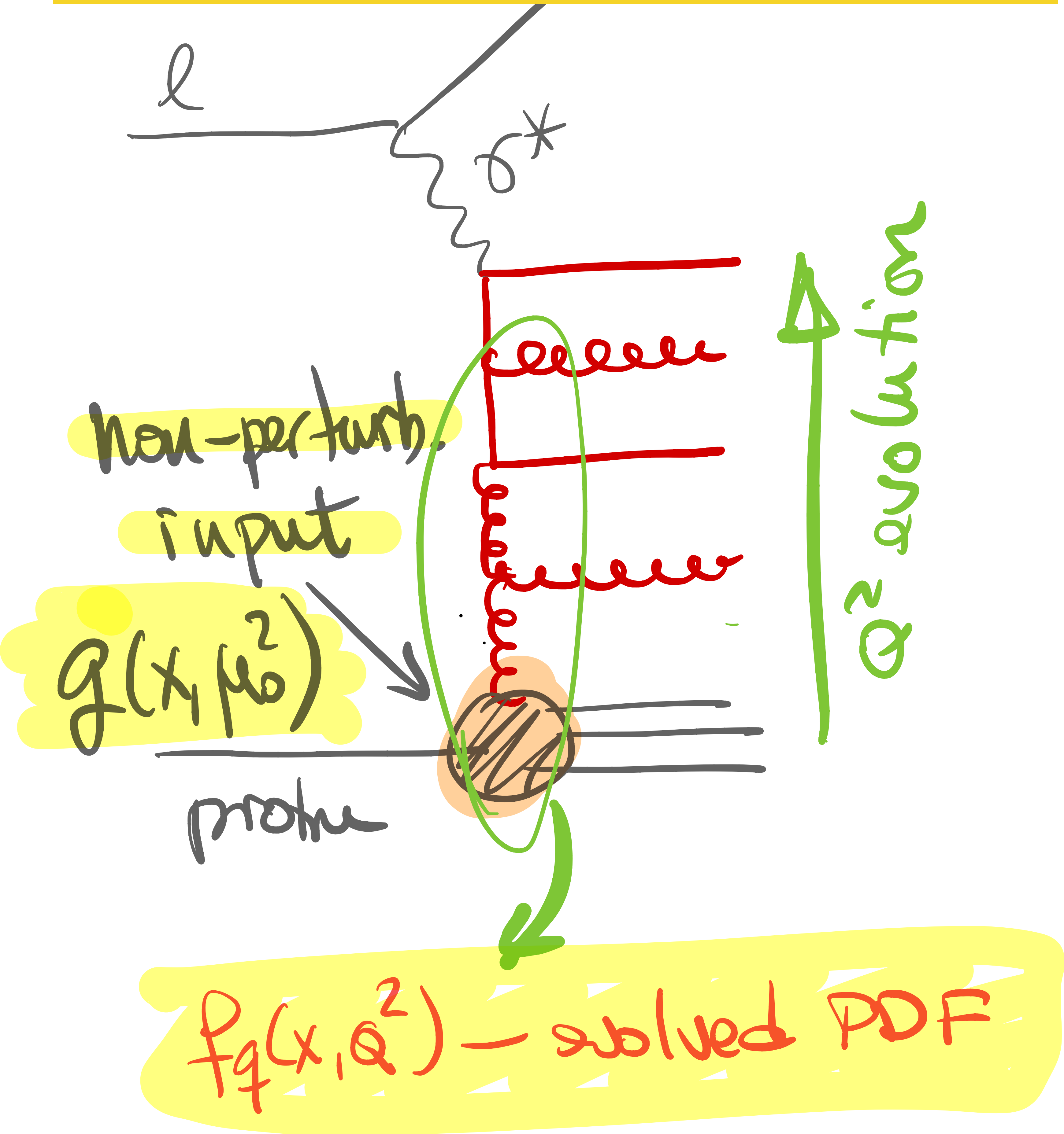


Splitting functions

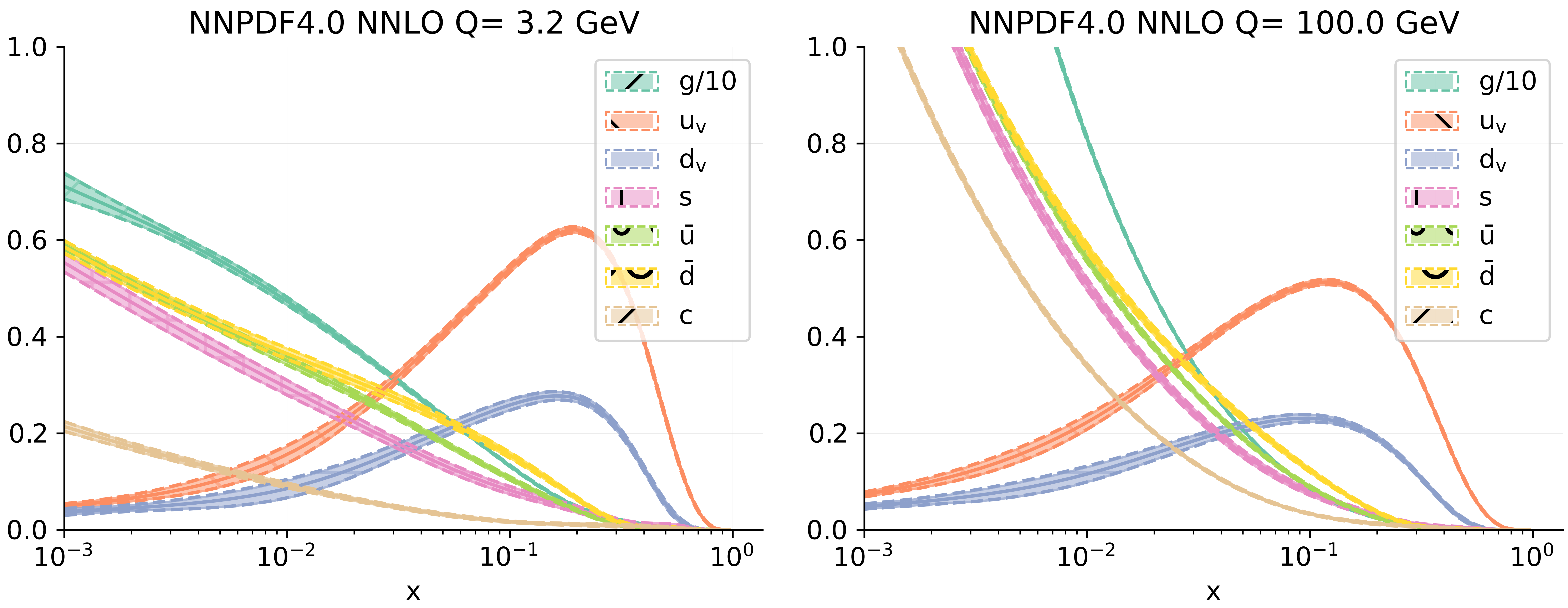
Building block of DGLAP equations: encode the probability of splitting [included here just for completeness]

$$\begin{aligned}
P_{q\leftarrow g}(z) =& T_F[z^2+(1-z)^2], \\
P_{q\leftarrow q}(z) =& C_F\left[\frac{1+z^2}{(1-z)_+}+\frac{3}{2}\delta(1-z)\right], \\
P_{g\leftarrow q}(z) =& C_F\left[\frac{1+(1-z)^2}{z}\right], \\
P_{g\leftarrow g}(z) =& 2C_A\left[\frac{1-z}{z}+\frac{z}{(1-z)_+}+z(1-z)\right]+\left(\frac{11}{6}C_A-\frac{2}{3}T_F n_f\right)\delta(1-z).
\end{aligned}$$

$$C_F=\frac{N_c^2-1}{2N_c}=\frac{4}{3}\,,\quad C_A=N_c=3 \quad \text{and} \quad T_R=\frac{1}{2}$$

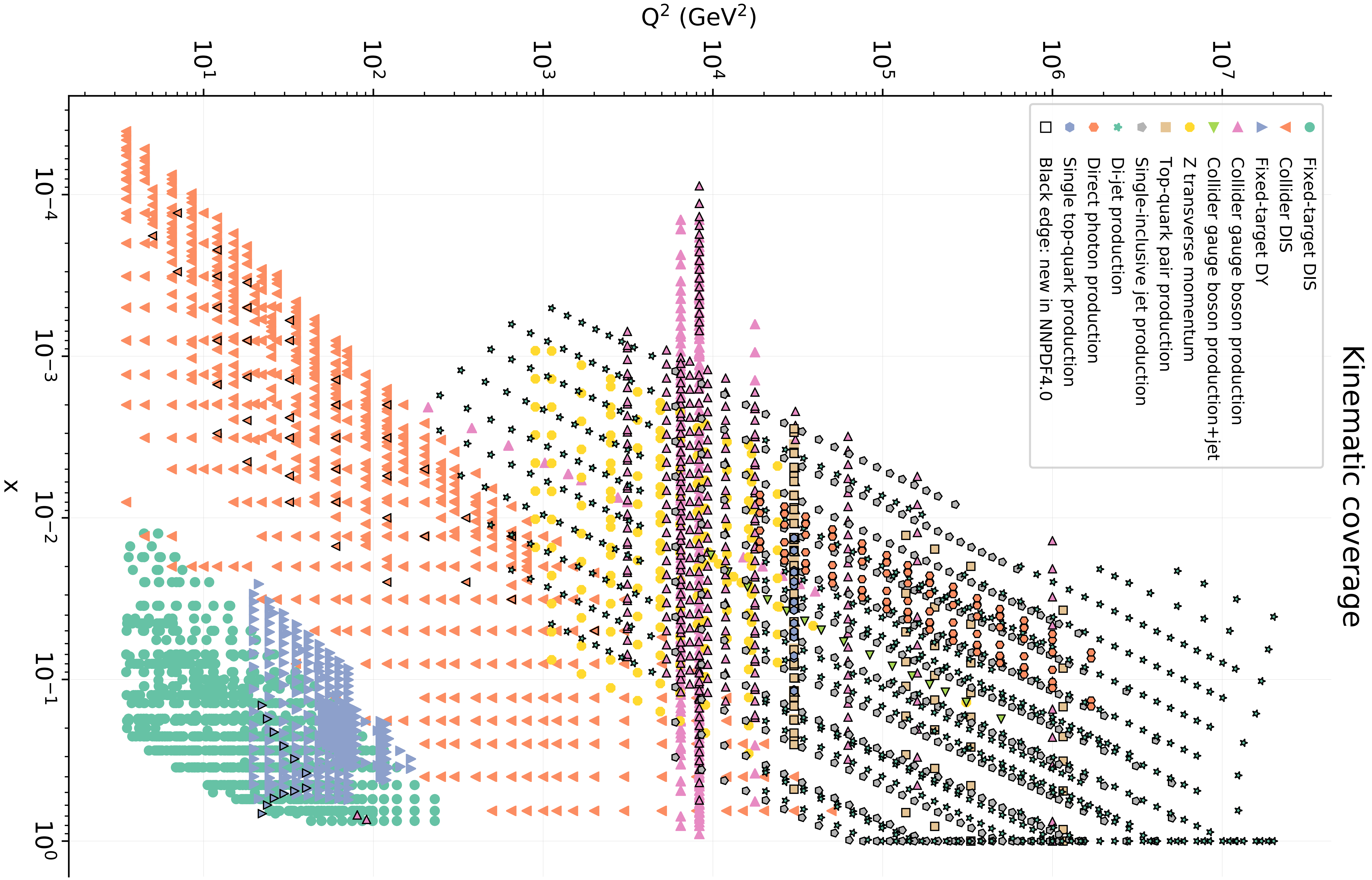
NNPDF4.0 set

Parton Distribution Functions for the proton from NNPDF global analysis



Huge number of data needed to achieve this degree of precision

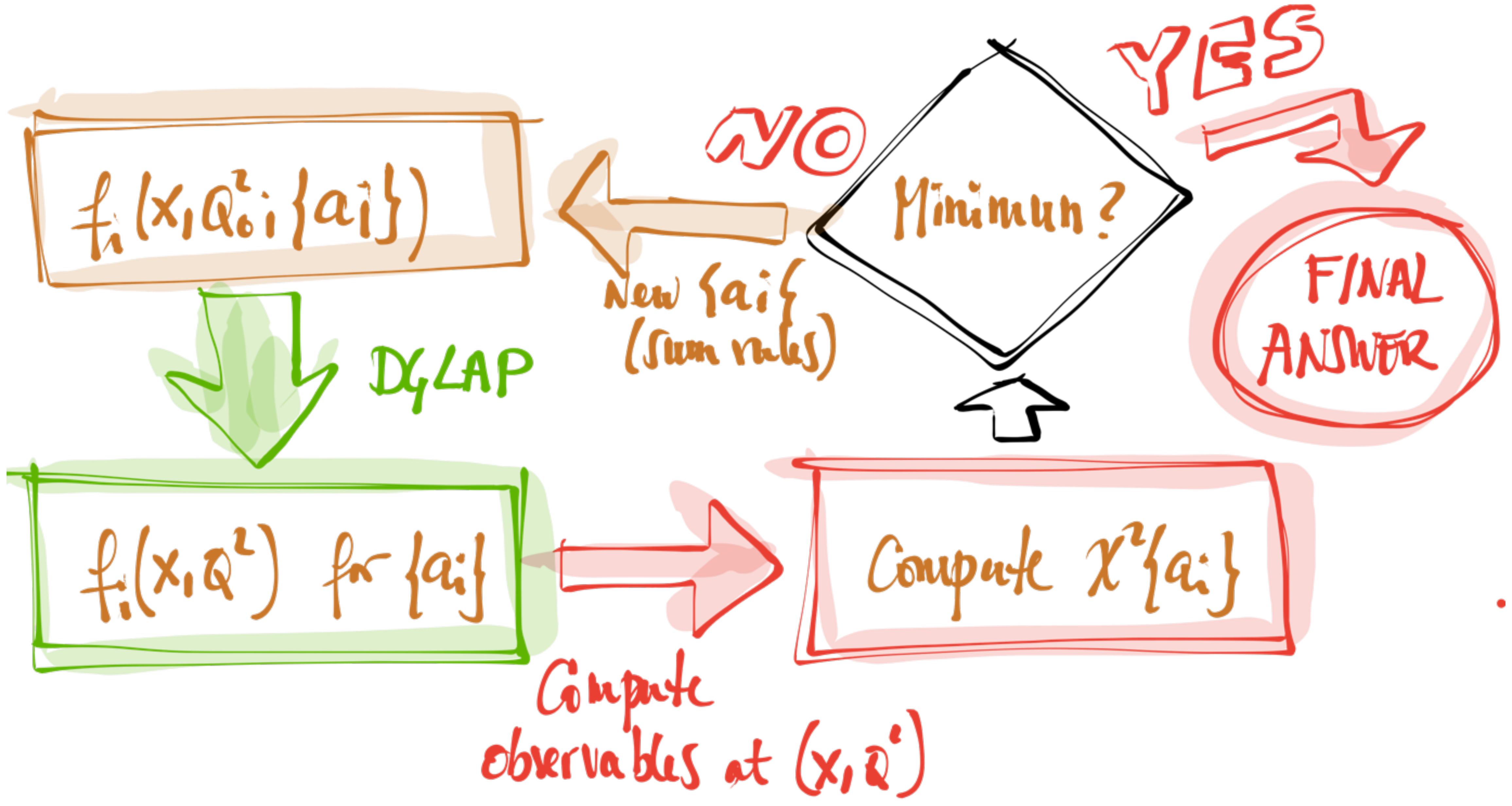
Kinematic coverage by data



NNPDF4.0

Global PDF fits

- **One of the most standardized procedures in High-Energy Physics.**
- Main goal: provide a set of Parton Distribution Functions (PDFs)



Different sets differ mostly on how I.C. are parametrized and how to treat the error analysis

Global PDF fits

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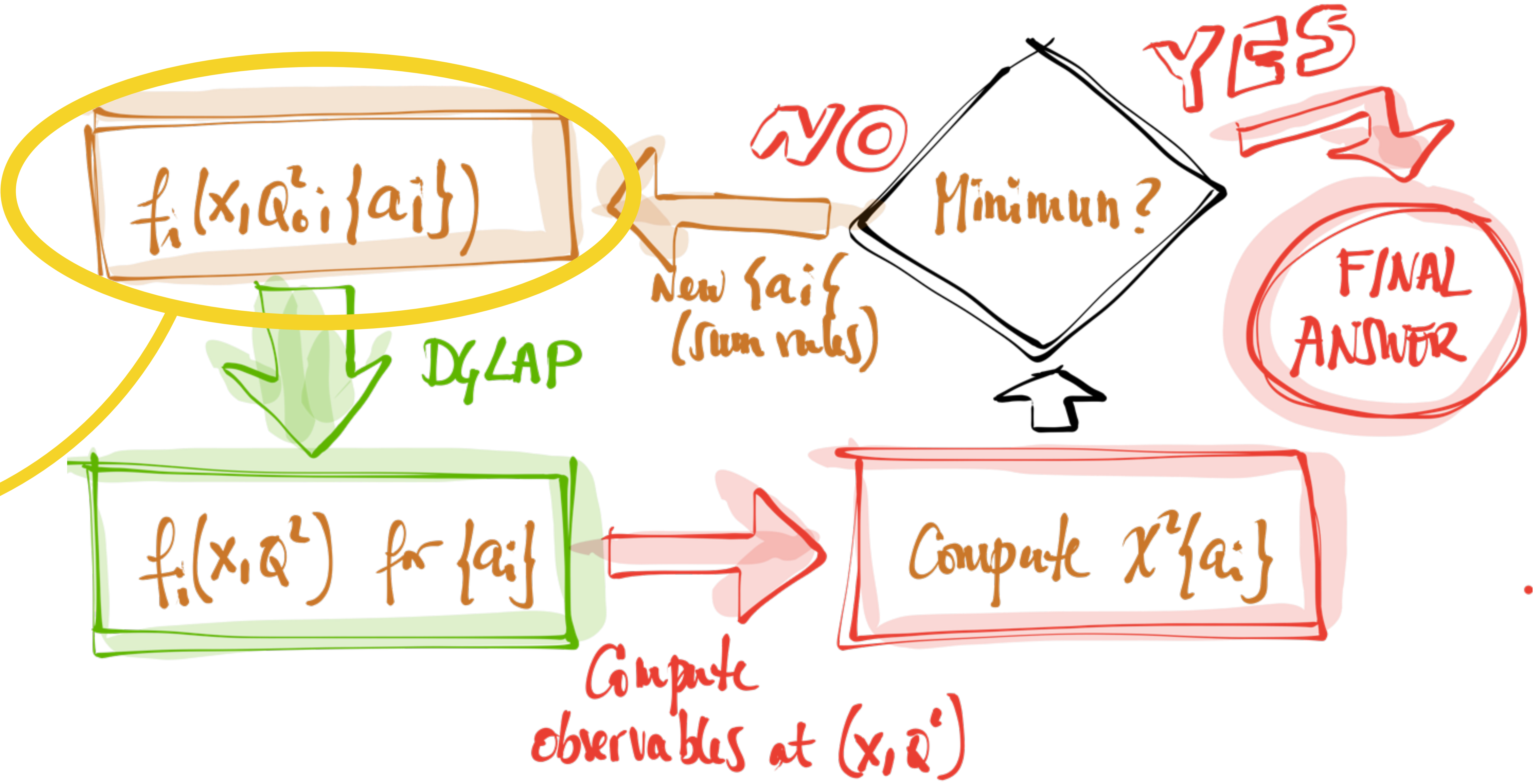
Input is a set of PDFs at an initial scale Q_0

This is the fitting function



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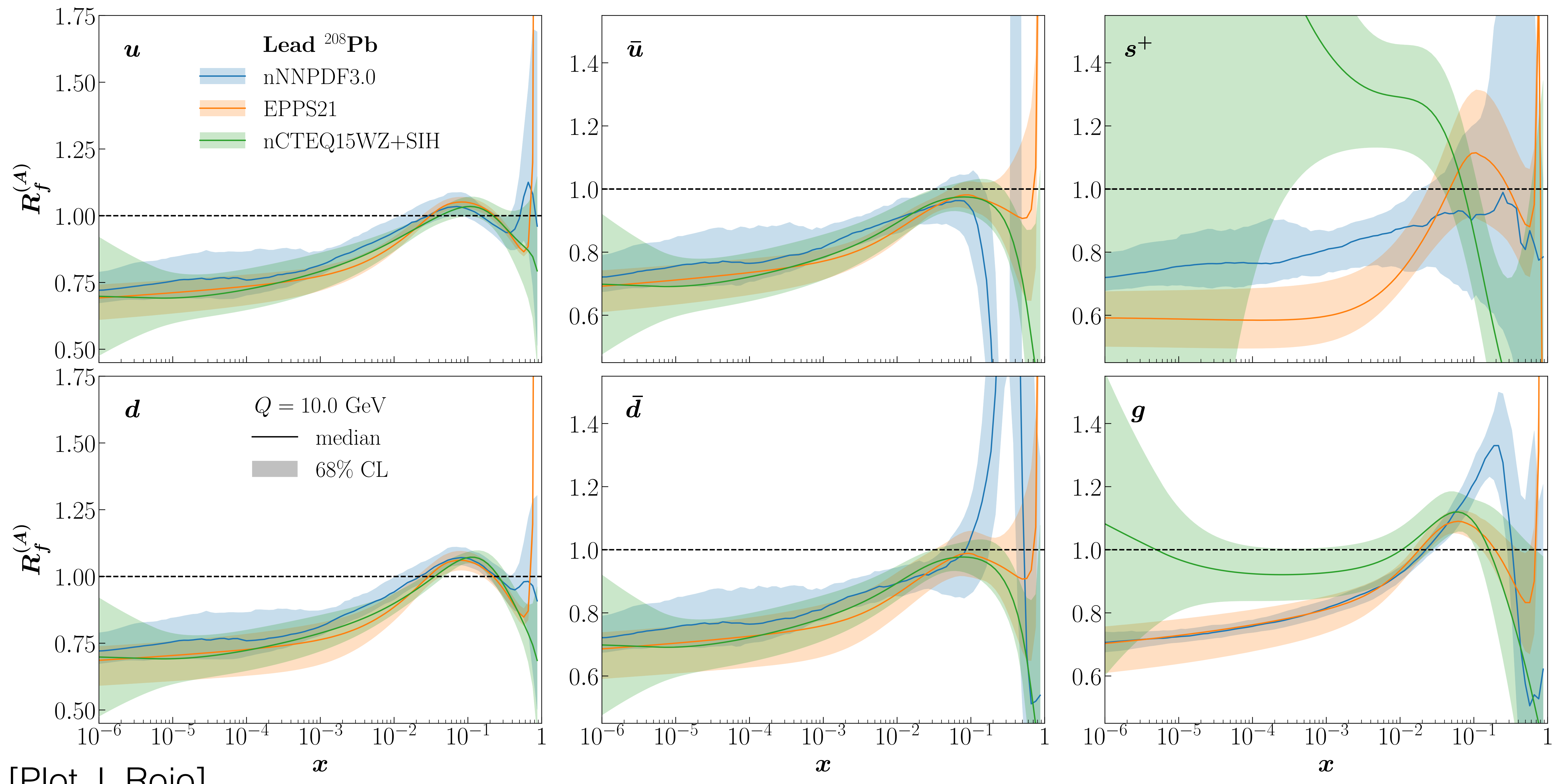
Nuclear PDFs

Similar analyses performed for nuclei - especially Pb



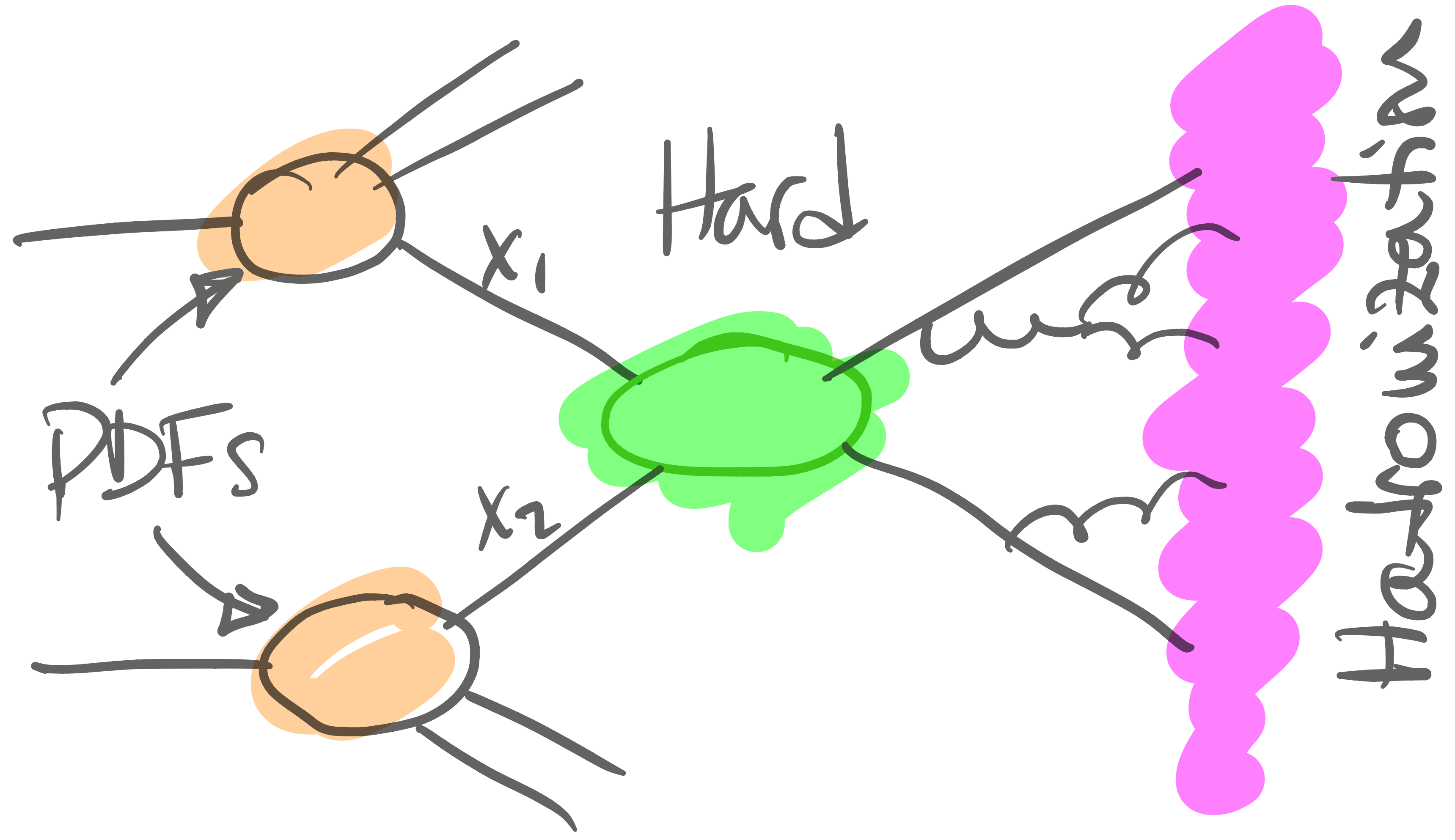
[Plot J. Rojo]

In terms of ratios to a known set of proton PDF

$$R_i(x, Q^2) = \frac{f_i^A(x, Q^2)}{f_i^p(x, Q^2)}$$

Two new analyses EPPS21, nNNPDF3.0

Factorization



QCD factorization between small and long distance processes

- **Long distance**: non-perturbative (PDFs and hadronization)
- **Short distance**: perturbative elementary cross section

Example: $$\frac{d\sigma^{pp\to h}}{dp_t} = f_i^p(x_1,Q^2)\otimes f_j^p(x_2,Q^2)\otimes \frac{d\hat{\sigma}^{ij\to k}}{dt}\otimes D^{k\to h}(z,Q^2)$$

Region between small- and long-distance: parton resummation (e.g. DGLAP)

This formalism/procedure allows to compute any cross section at LHC involving large scales: jets, H/W/Z (+jets), etc… [any cross section need long-distance information: PDFs]

Summary

QCD is the theory of strong interations

- **QCD has a rich dynamical content well within experimental reach**
- Needed for all phenomenology at hadron colliders (and most of other colliders as well)

Asymptotic freedom allows to perform perturbative computations at large scales

- However, non-perturbative contributions always present (due to confinement)
- Large regions of phase-space need to resum large logarithms - gluon multiplication

Jets and Parton Distribution Functions (PDFs) two main tools at the LHC

- Parton shower and DGLAP evolution

Huge effort in precision computations at NNLO and more [not mentioned here]