Student Lectures - HP2023 - Aschaffenburg

11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

Theory of hard processes in heavy ion collisions

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Yocto/LHC
Yoctosecond imaging of QCD collectivity using jet observables
An ERC Advanced Grant 2019 · 2024

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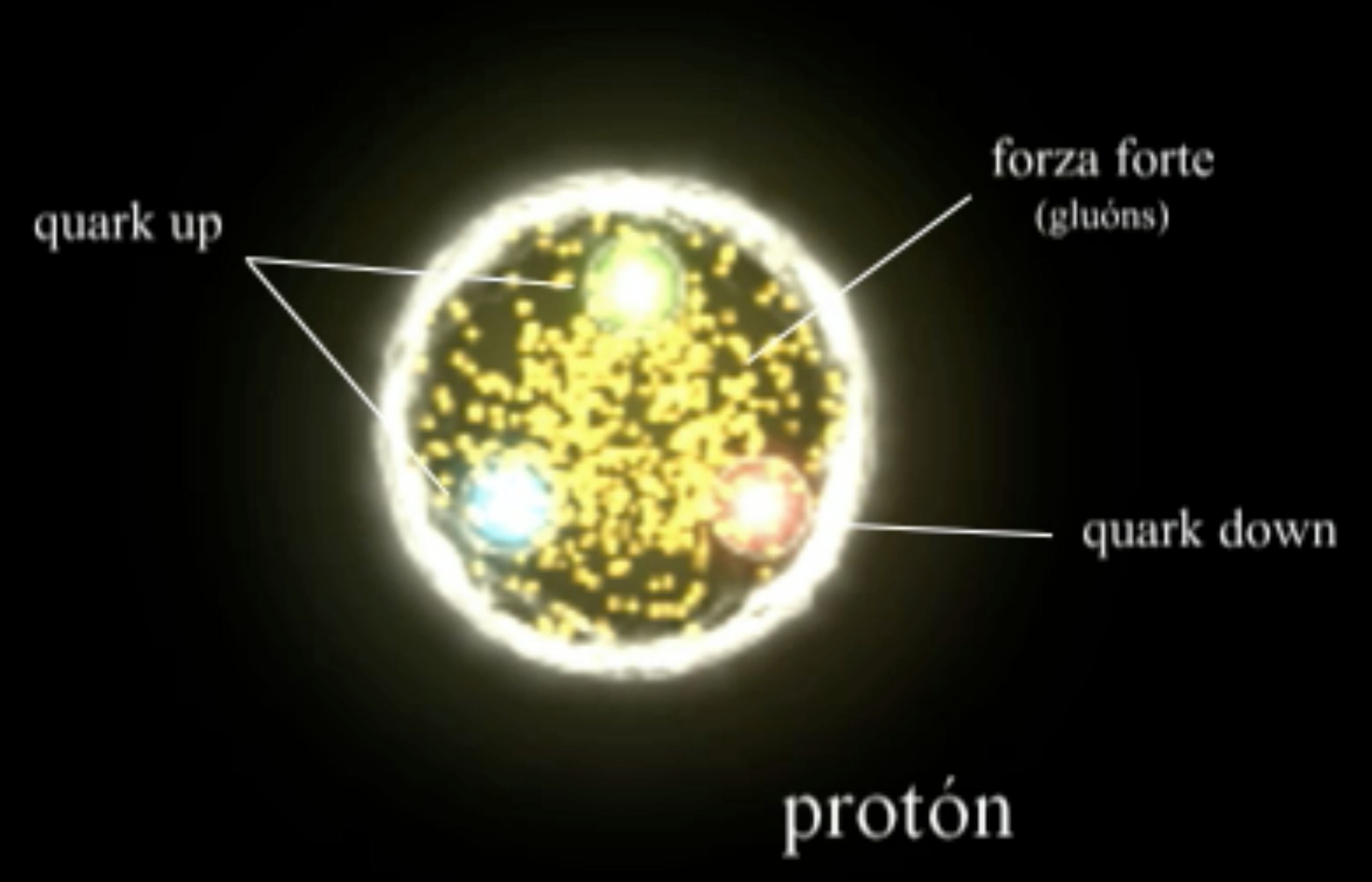
High energy heavy ion collisions: Collectivity and new phases of QCD

QCD: first levels of complexity at the most fundamental level
at scales easy to reach in collider experiments



[Confinement; chiral symmetry breaking and mass generation; new phases of matter; hadronic spectra; non-trivial vacuum structure; asymptotic freedom…]

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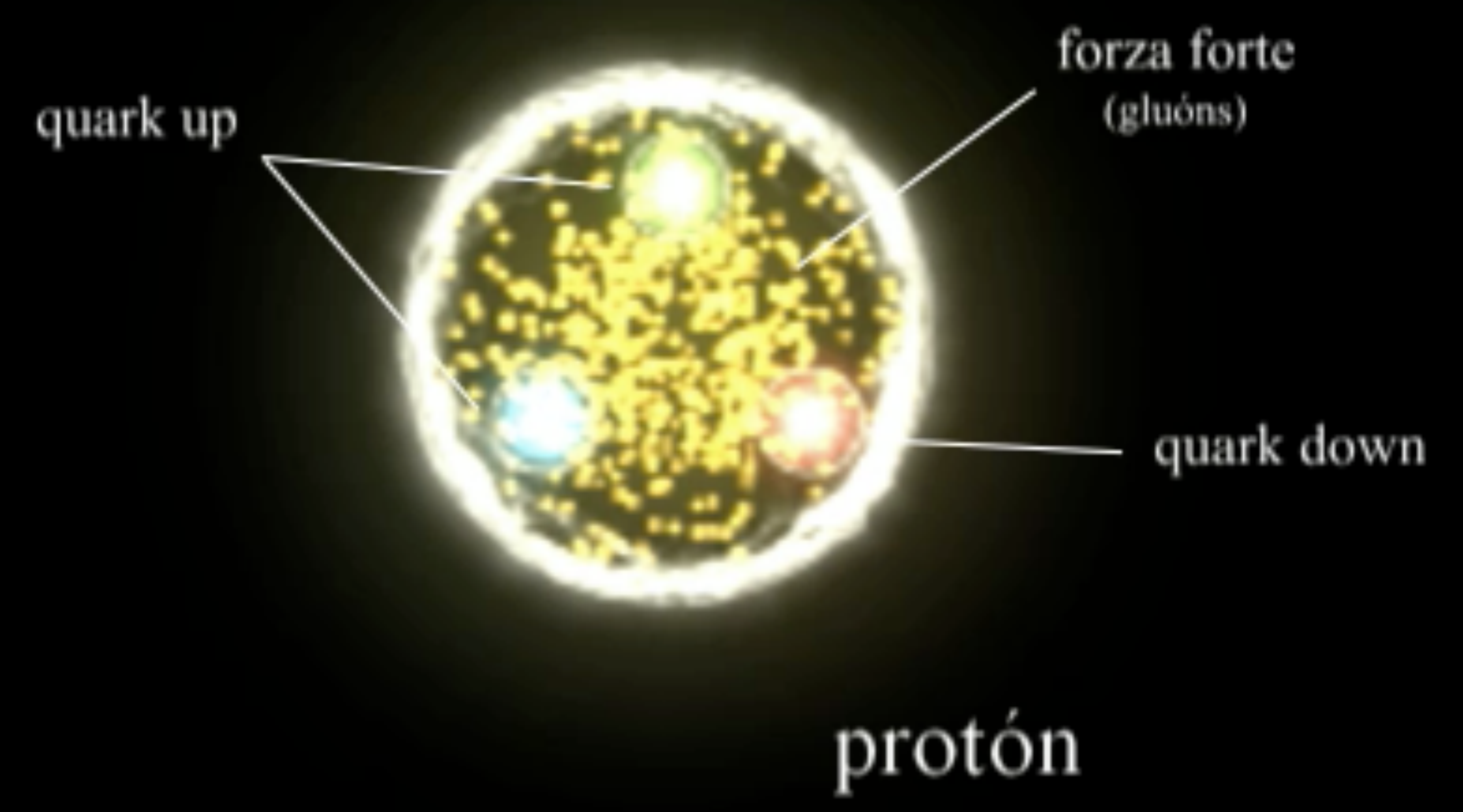
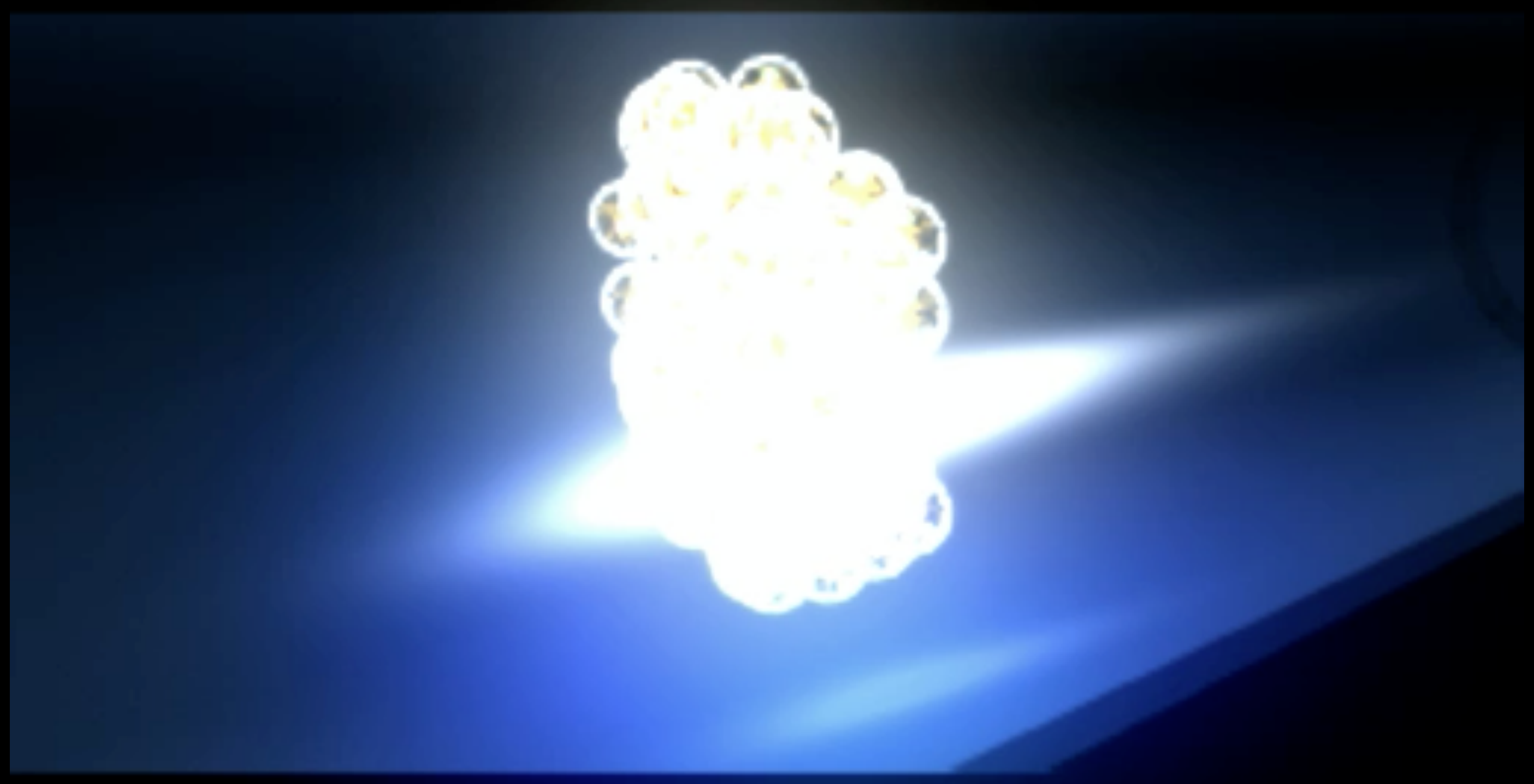
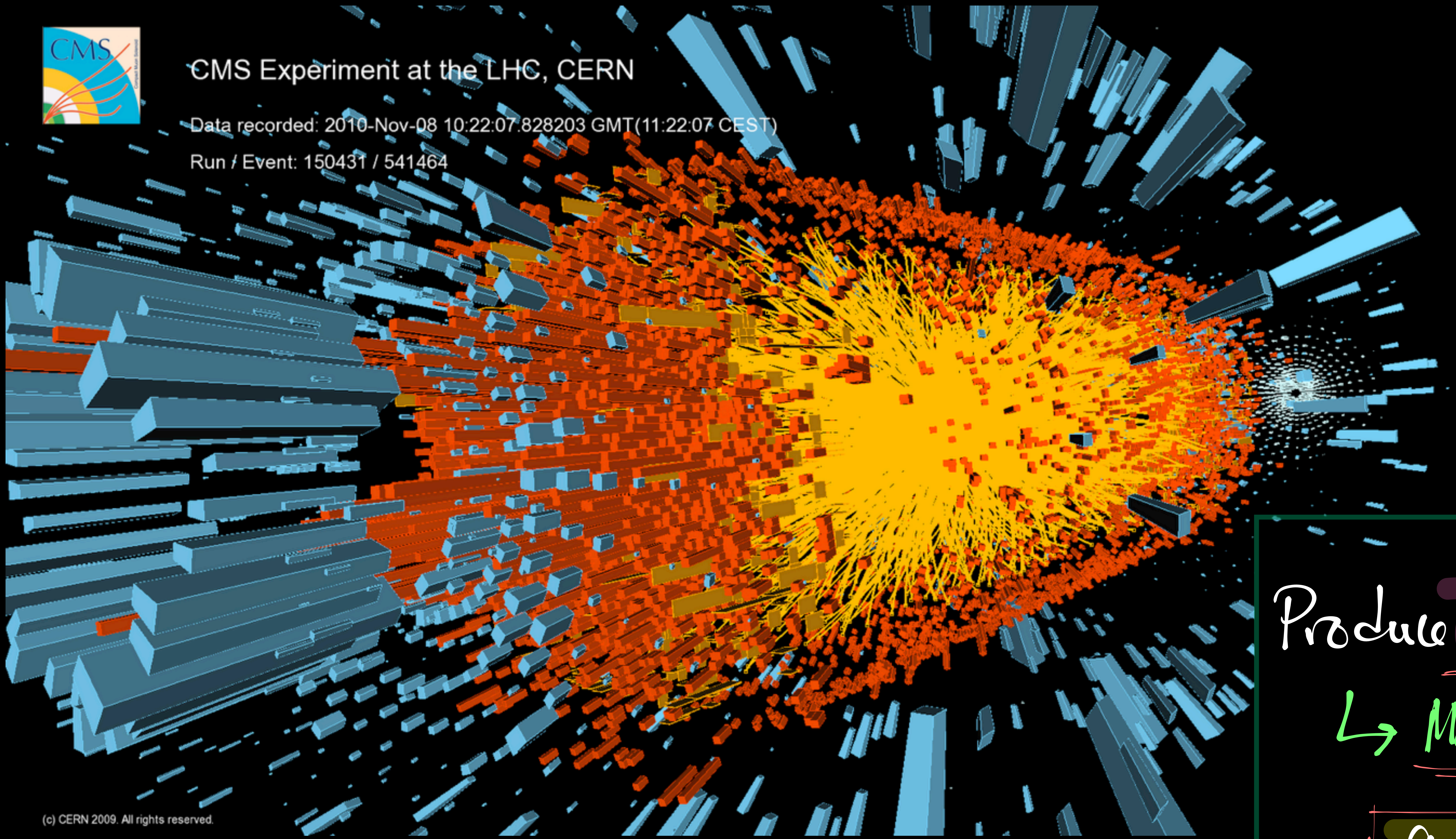




[Confinement; chiral symmetry breaking and mass generation; new phases of matter; hadronic spectra; non-trivial vacuum structure; asymptotic freedom…]

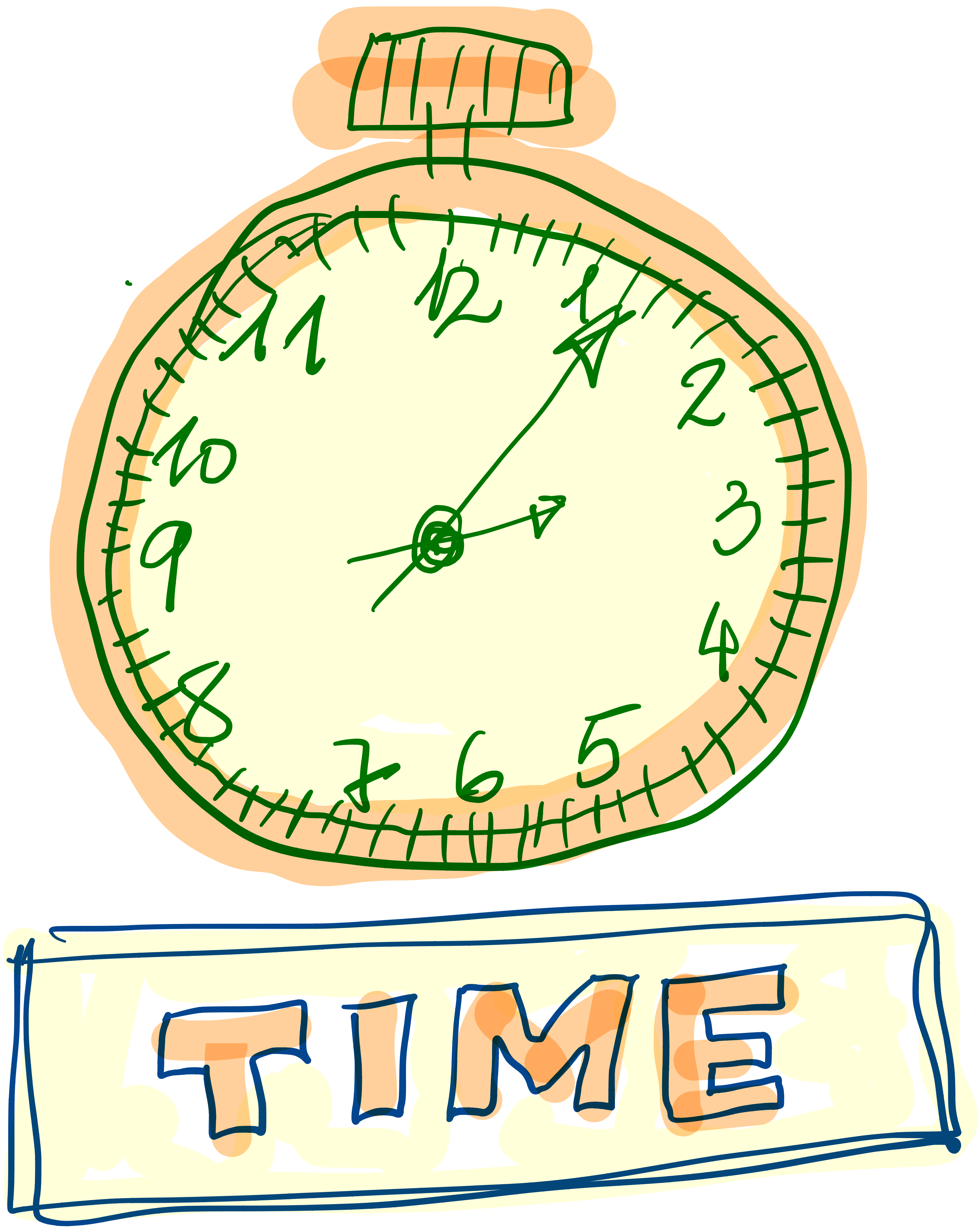


Produce "large" objects

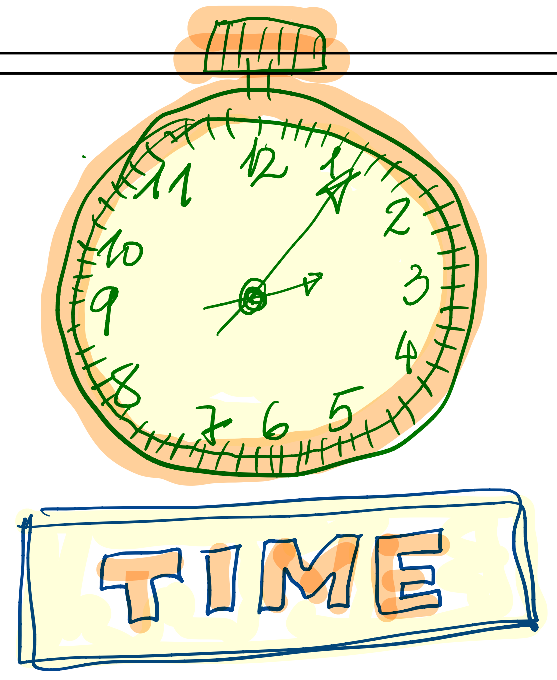
↳ Macroscopic in QCD scale

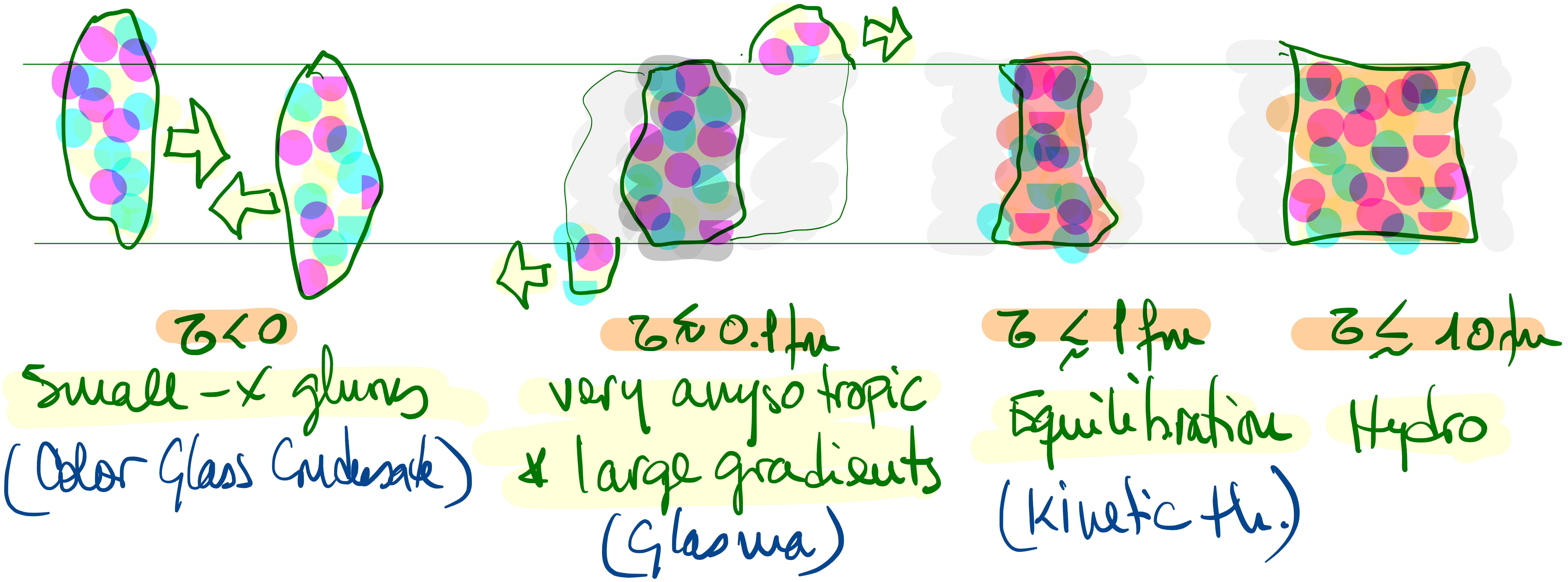
Collide heavy nuclei

But also…



(A possible) Time evolution of a HIC

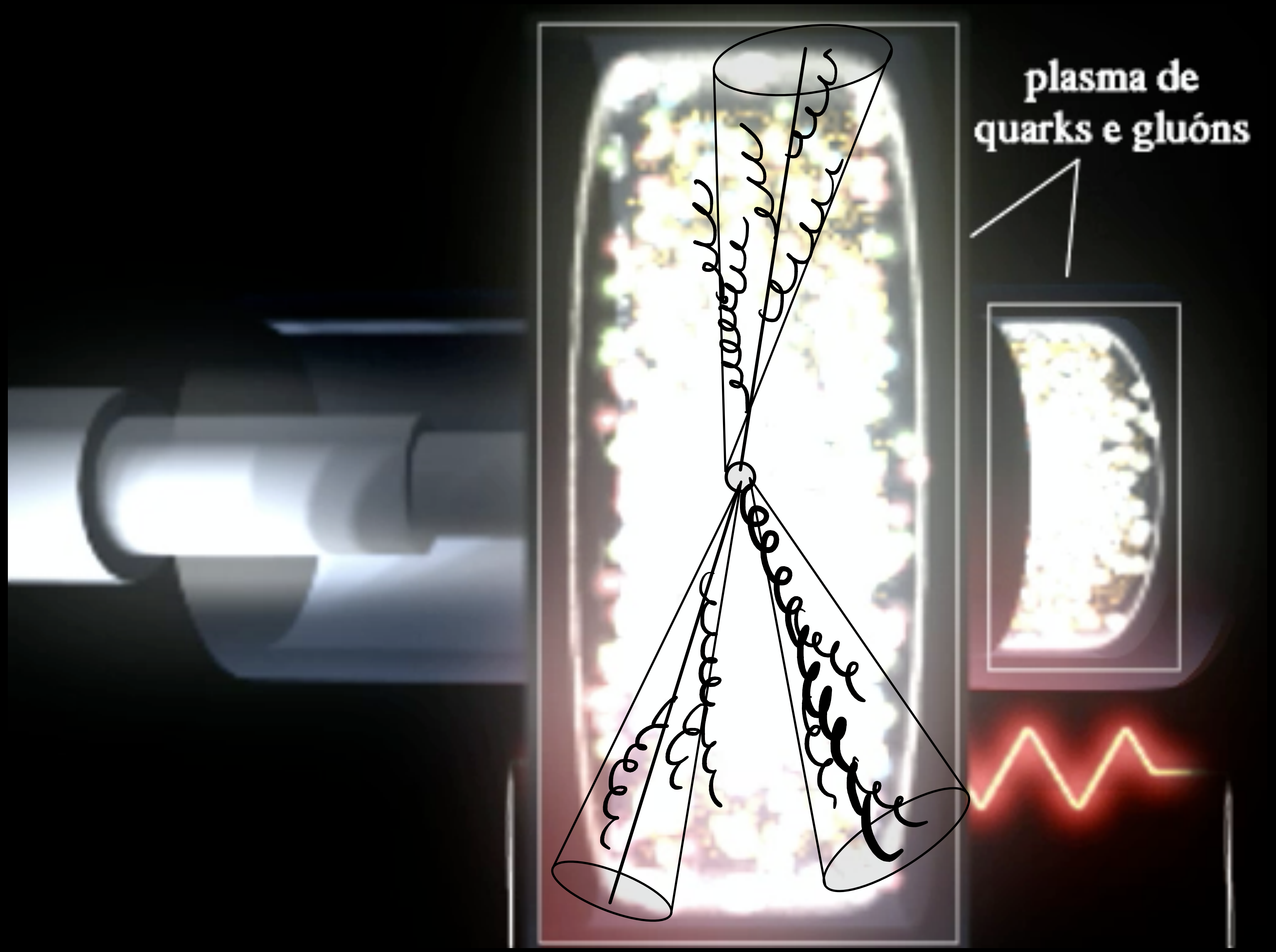


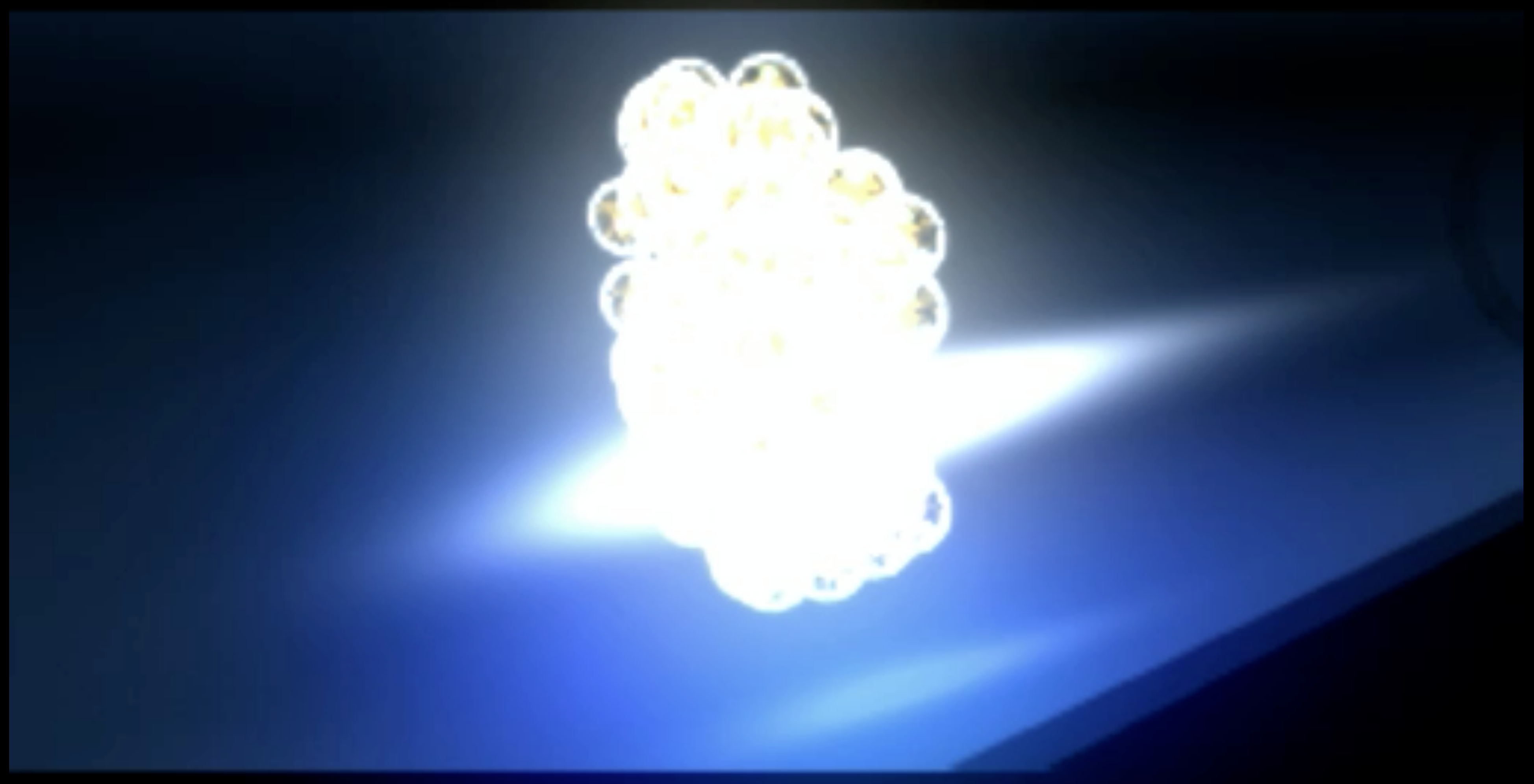


In contrast to usual HEP, **time and distance are relevant variables** in heavy-ion collisions

Building collectivity in extended (macroscopic) systems

Hard processes

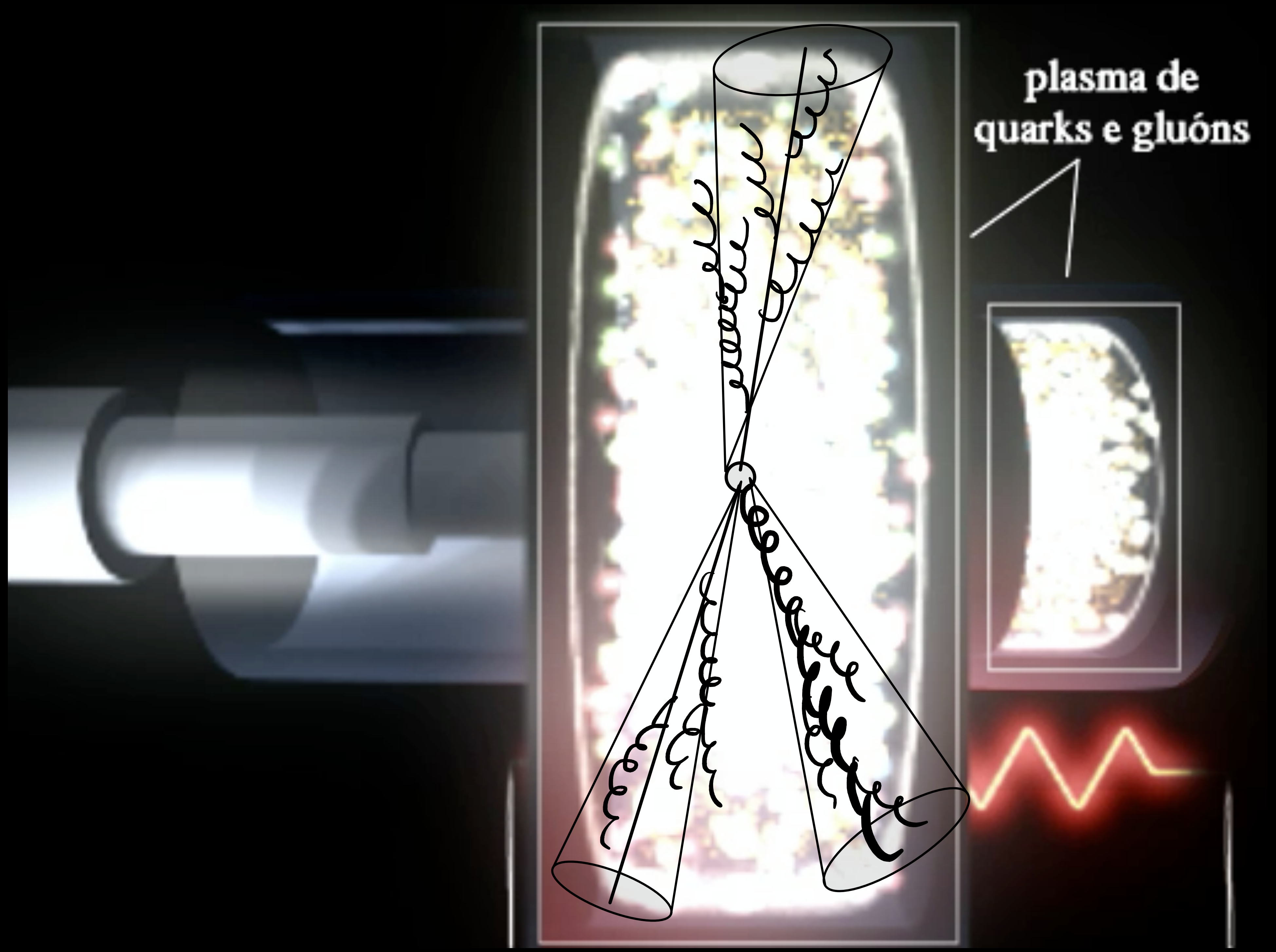


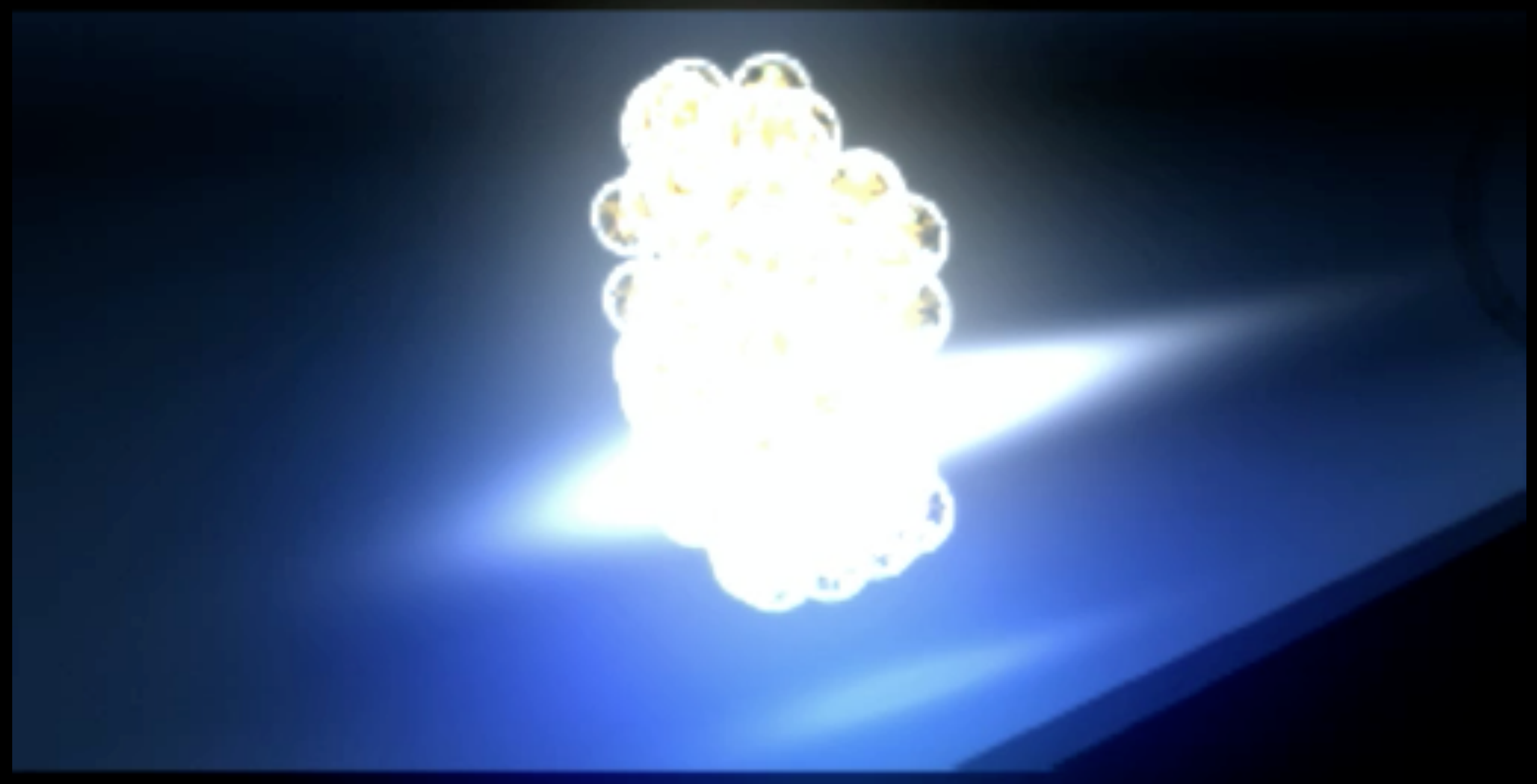


Excellent probes

- Produced very early $\sim 1/Q$ — production computed in pQCD
- Many different probes and scales
- Jets are extended objects that evolve in times $1/E_{jet} < t \lesssim 1\mathrm{fm/c}$

Hard processes





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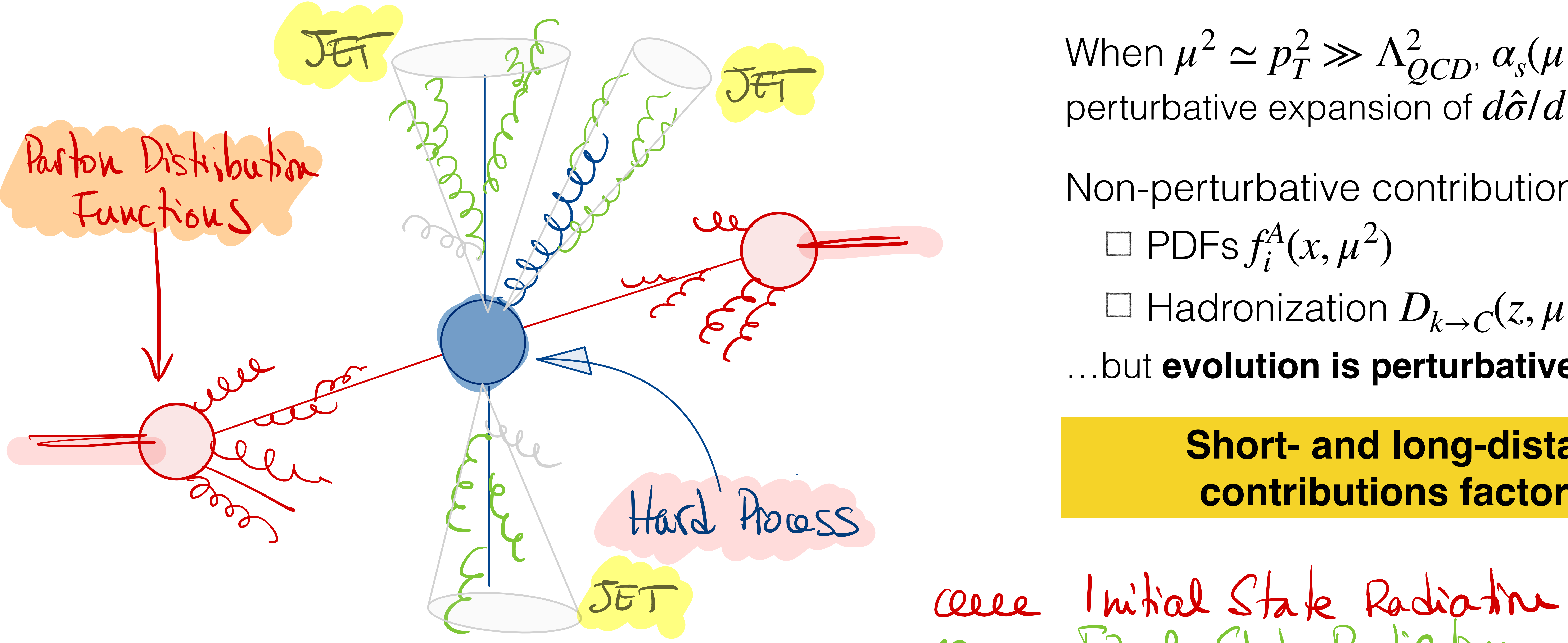
Hard processes in QCD

$$\frac{d\sigma^{AB\to C+X}}{dp_T} = f_i^A(x_1,\mu^2) \otimes f_j^B(x_2,\mu^2) \otimes \frac{d\hat{\sigma}^{i,j\to k}}{d\hat{t}} \otimes D_{k\to C}(z,\mu^2)$$



When $\mu^2 \simeq p_T^2 \gg \Lambda^2_{QCD}$, $\alpha_s(\mu^2) \ll 1$ perturbative expansion of $d\hat{\sigma}/d\hat{t}$ possible

Non-perturbative contributions:

- ☐ PDFs $f_i^A(x,\mu^2)$
- ☐ Hadronization $D_{k\to C}(z,\mu^2)$

…but **evolution is perturbative** (DGLAP…)

Short- and long-distance contributions factorize.

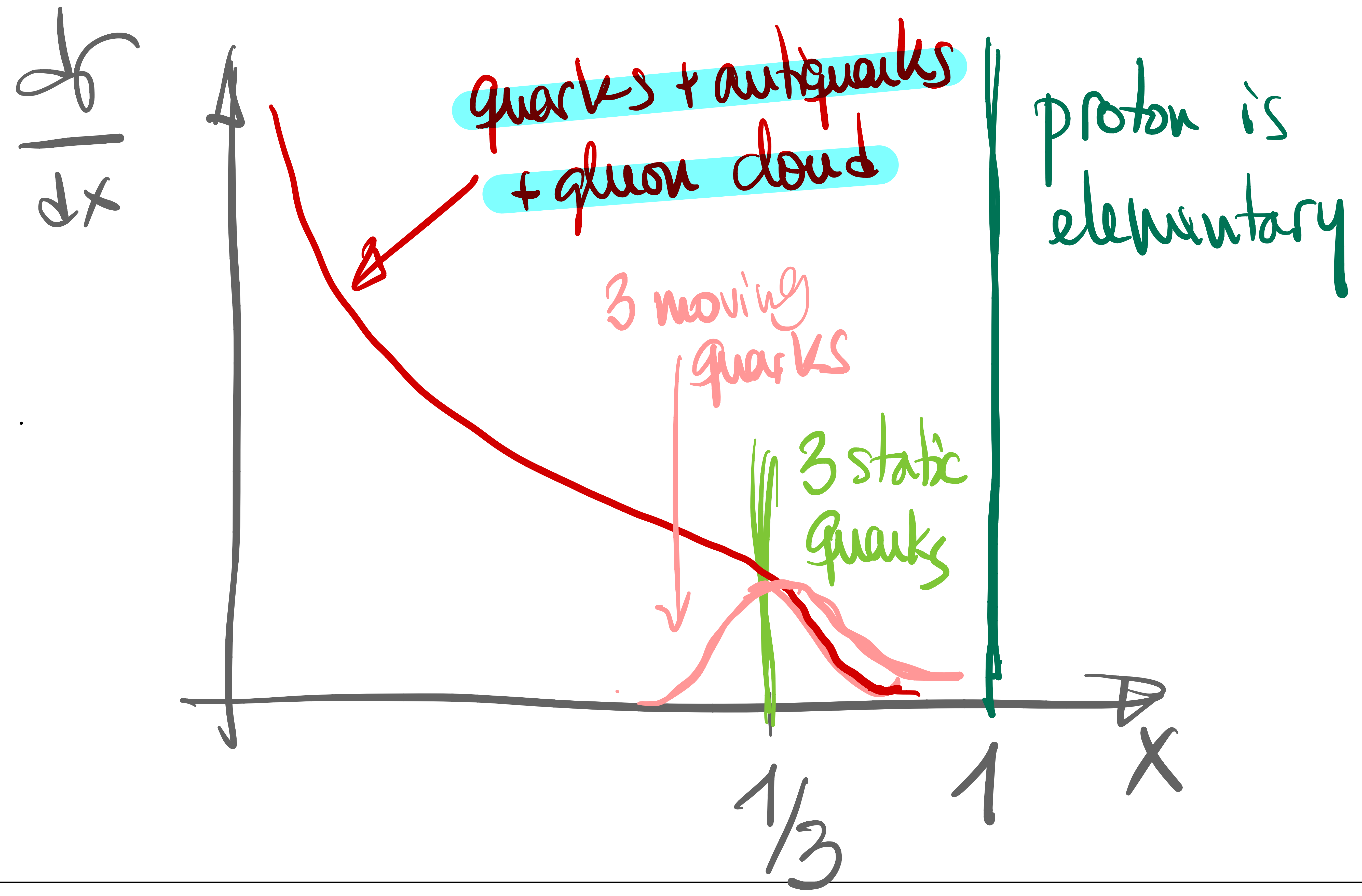
The hadron structure

A proton seen in a lepton-proton DIS (same applies to other hadrons or nuclei)

Bjorken-x

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

Can be written in terms of the lepton kinematics alone
[x=1 for elastic scattering]



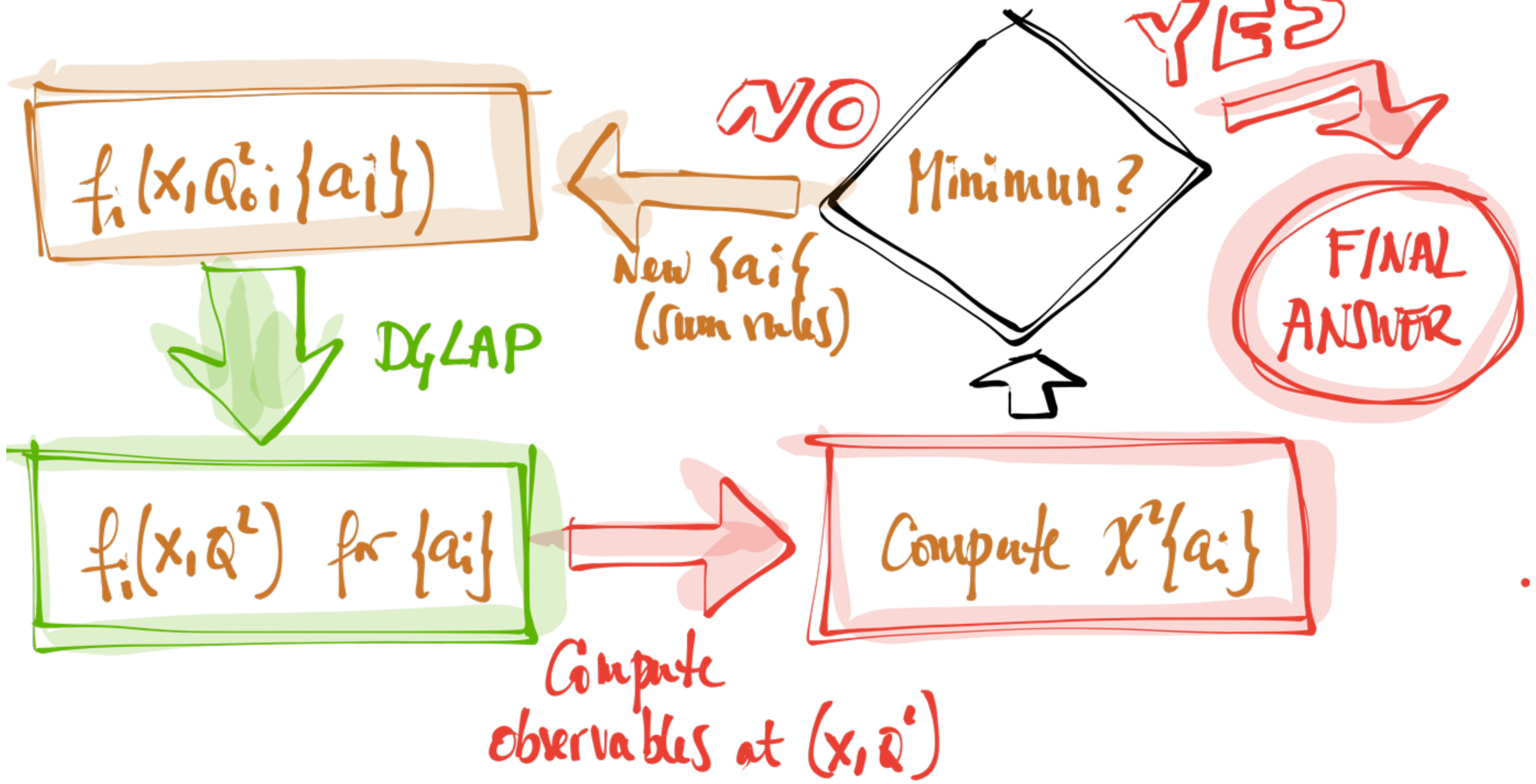
“Dilute” regime - usual DGLAP

Nuclear PDFs extracted in DGLAP global fits - as usual proton PDFs

$$\frac{\partial q_i}{\partial \log\mu^2} = \frac{\alpha_s}{2\pi}\left[P_{qq}\otimes q_i + P_{qg}\otimes g\right]$$

$$\frac{\partial g}{\partial \log\mu^2} = \frac{\alpha_s}{2\pi}\left[P_{gq}\otimes q + P_{gg}\otimes g\right]$$

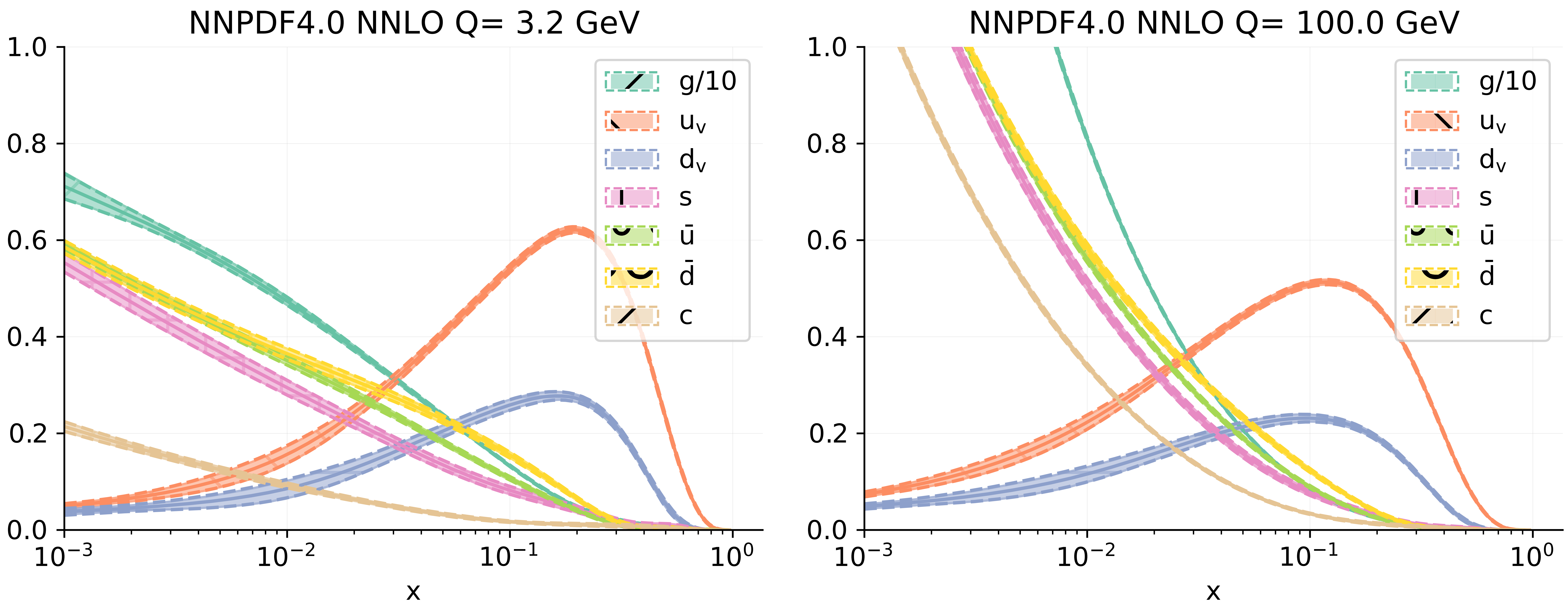
[Fit I.C. with experimental data]



One of the most standardised methods in HEP

NNPDF4.0 set

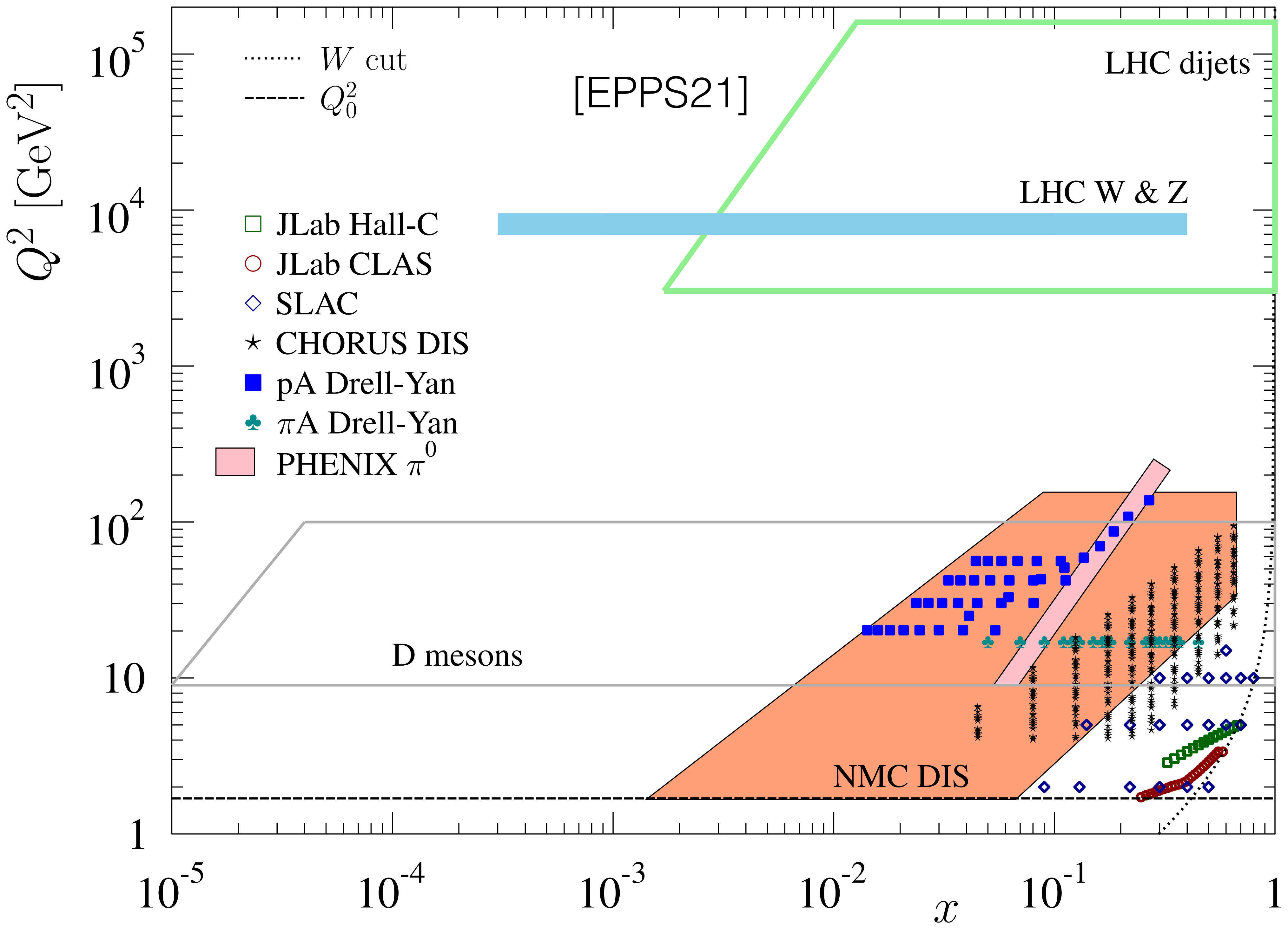
Parton Distribution Functions for the proton from NNPDF global analysis



Huge number of data needed to achieve this degree of precision

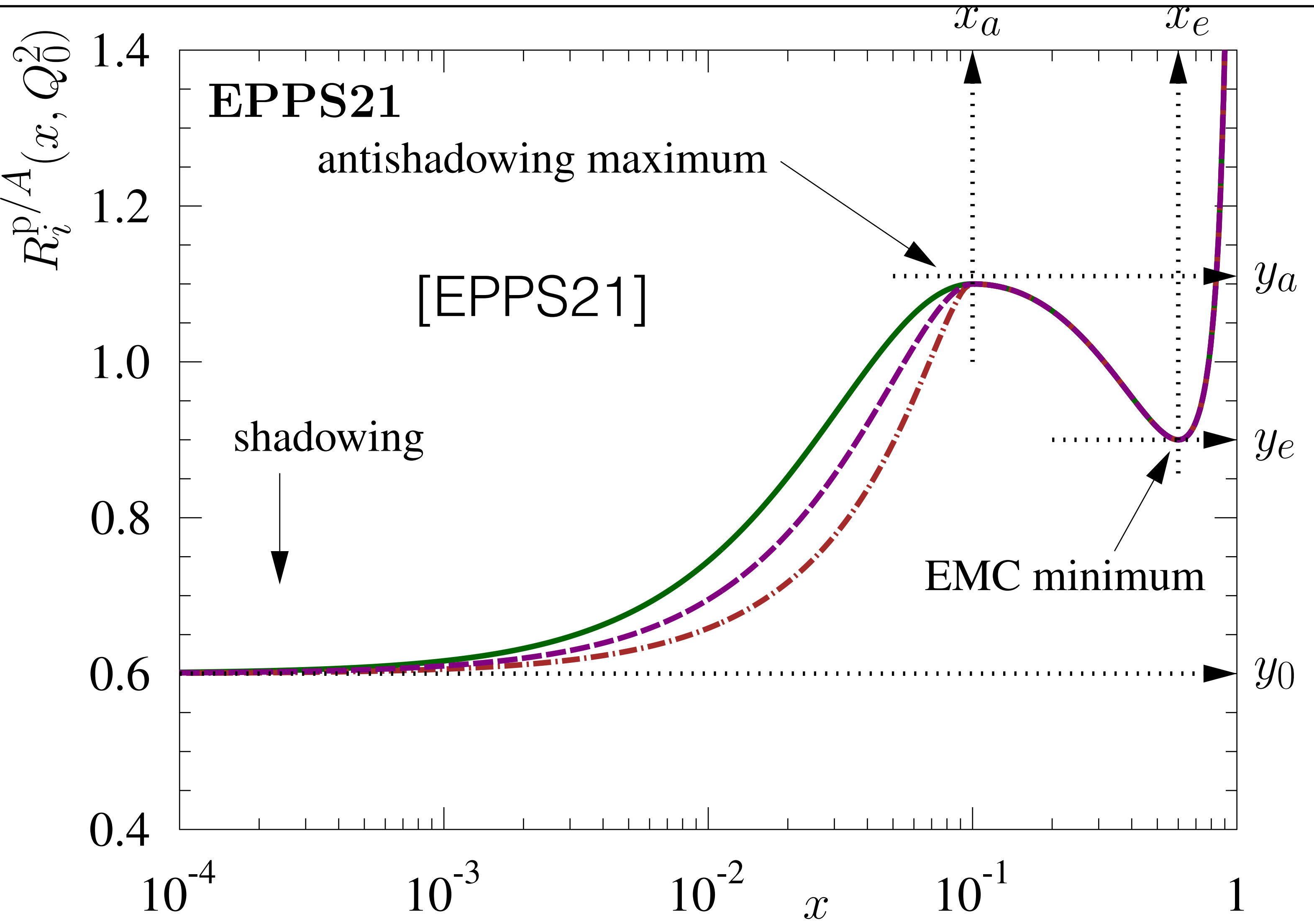
Nuclear Parton Distribution Functions I

Nuclear PDF analyses have remarkably improved with LHC proton-lead data - new sets



Ratios with a free proton PDF set

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



[Several different teams: EPPS, nNNPDF, nCTEQ, TUJU, DSSZ, HKN, KA]

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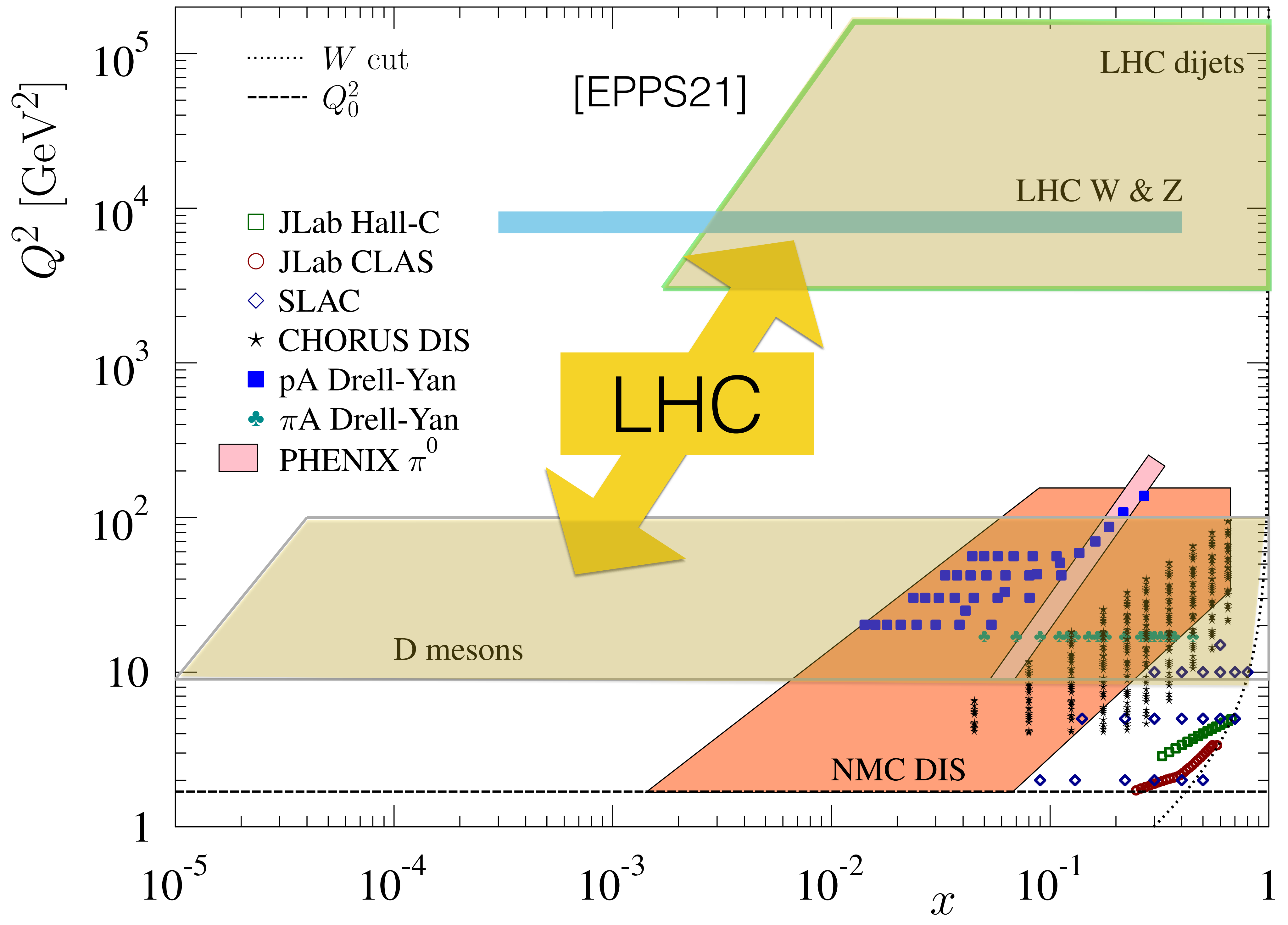

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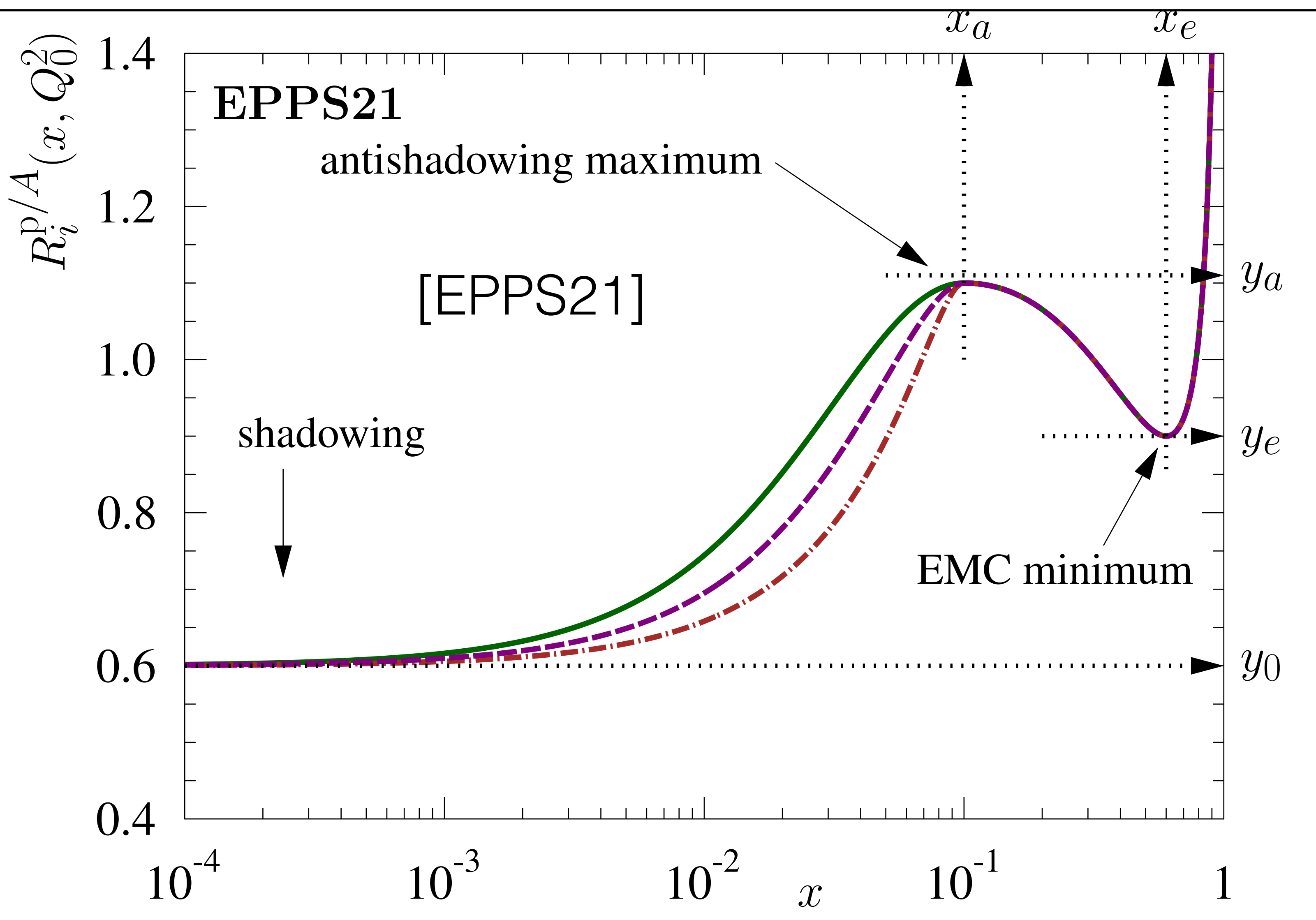

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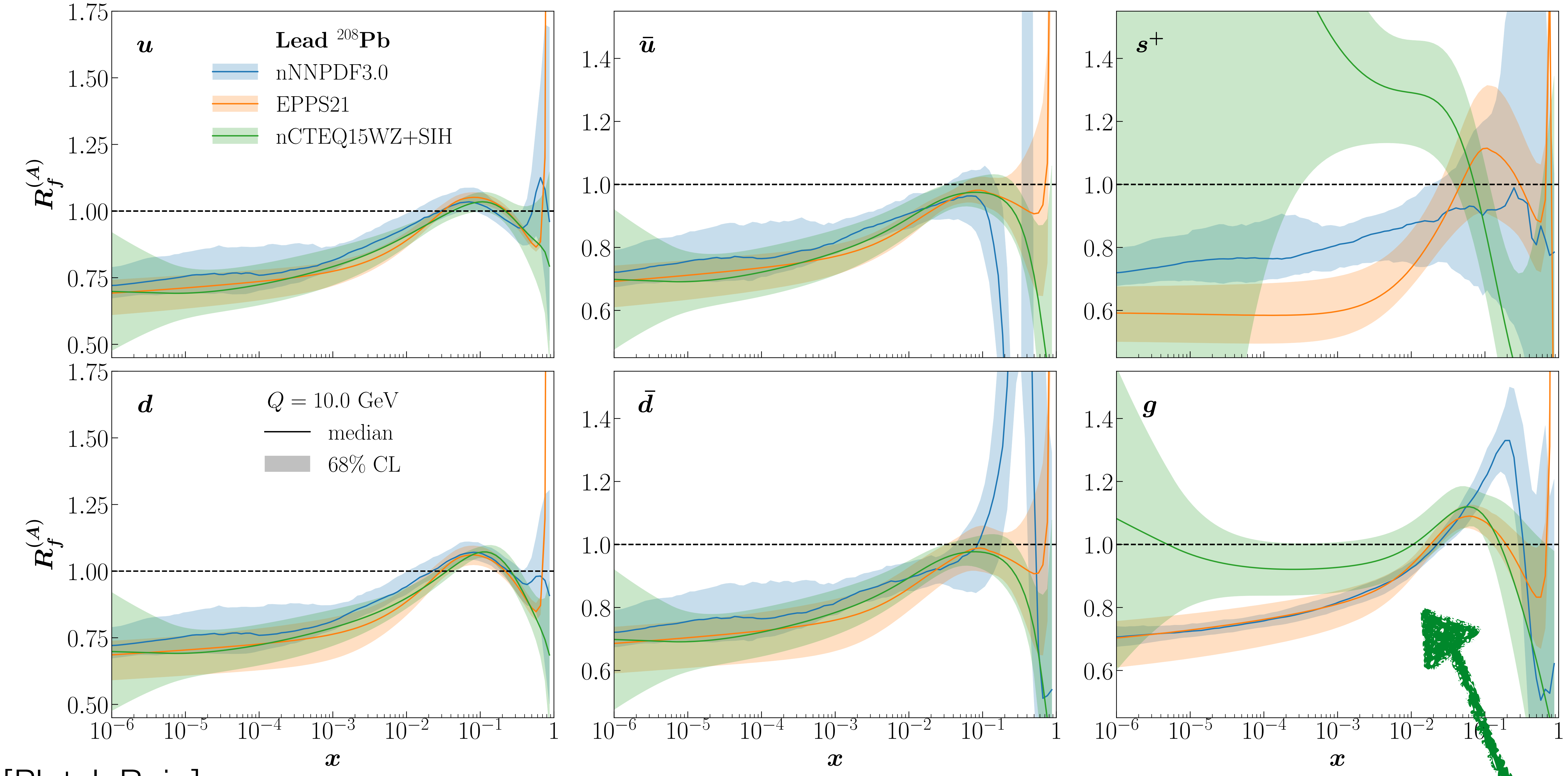
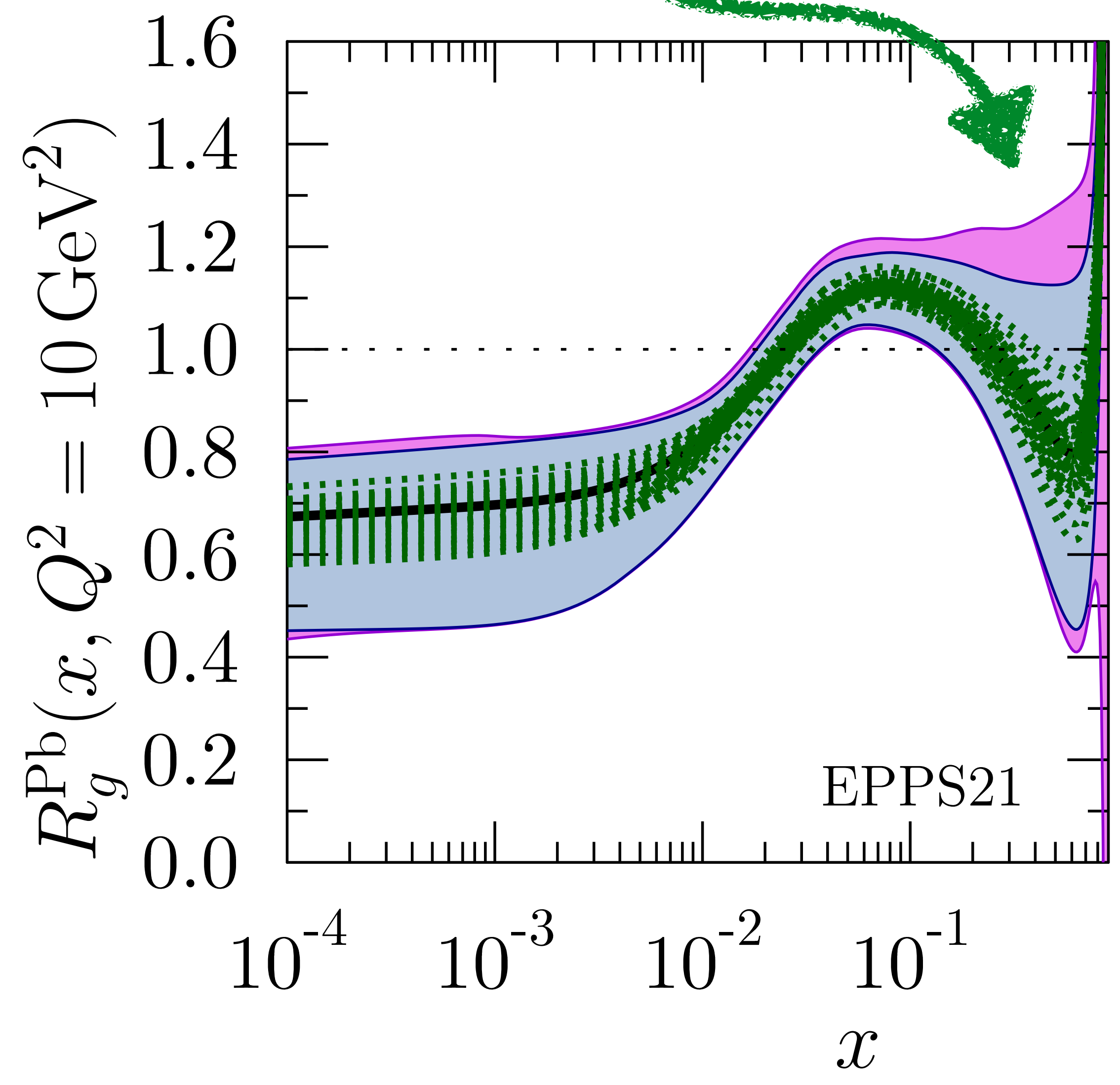
Nuclear Parton Distribution Functions II

Two new analyses EPPS21, nNNPDF3.0 **Proton PDF uncertainties**



[Plot J. Rojo]

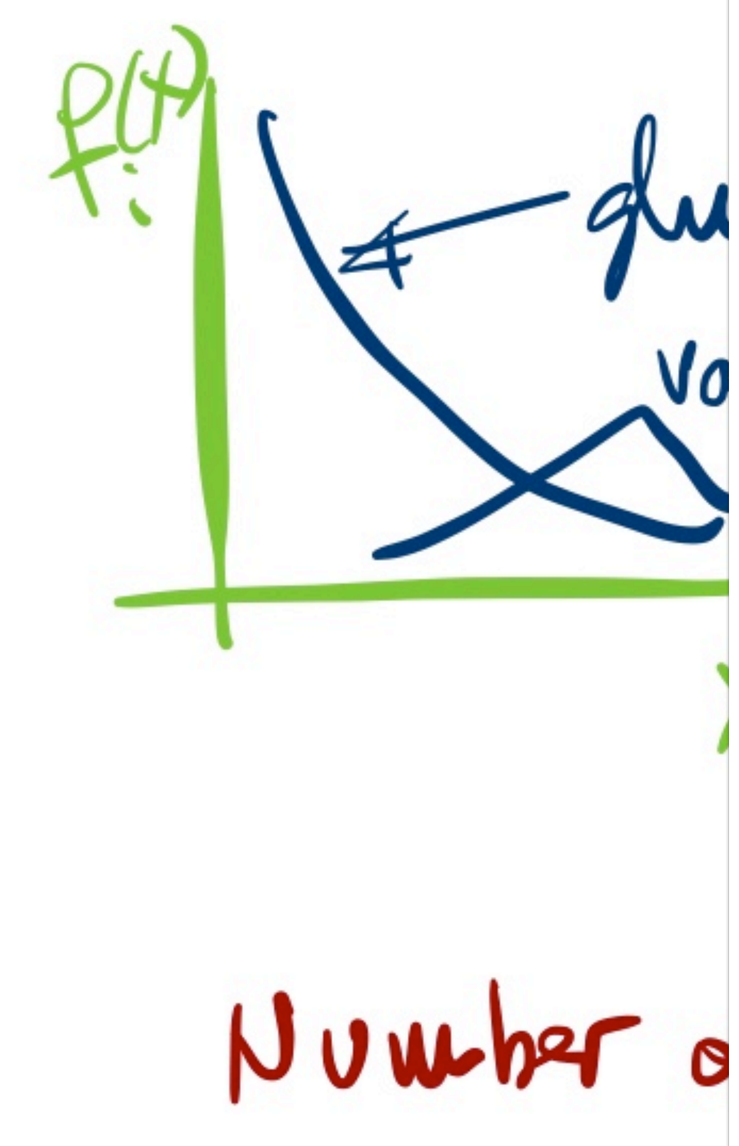


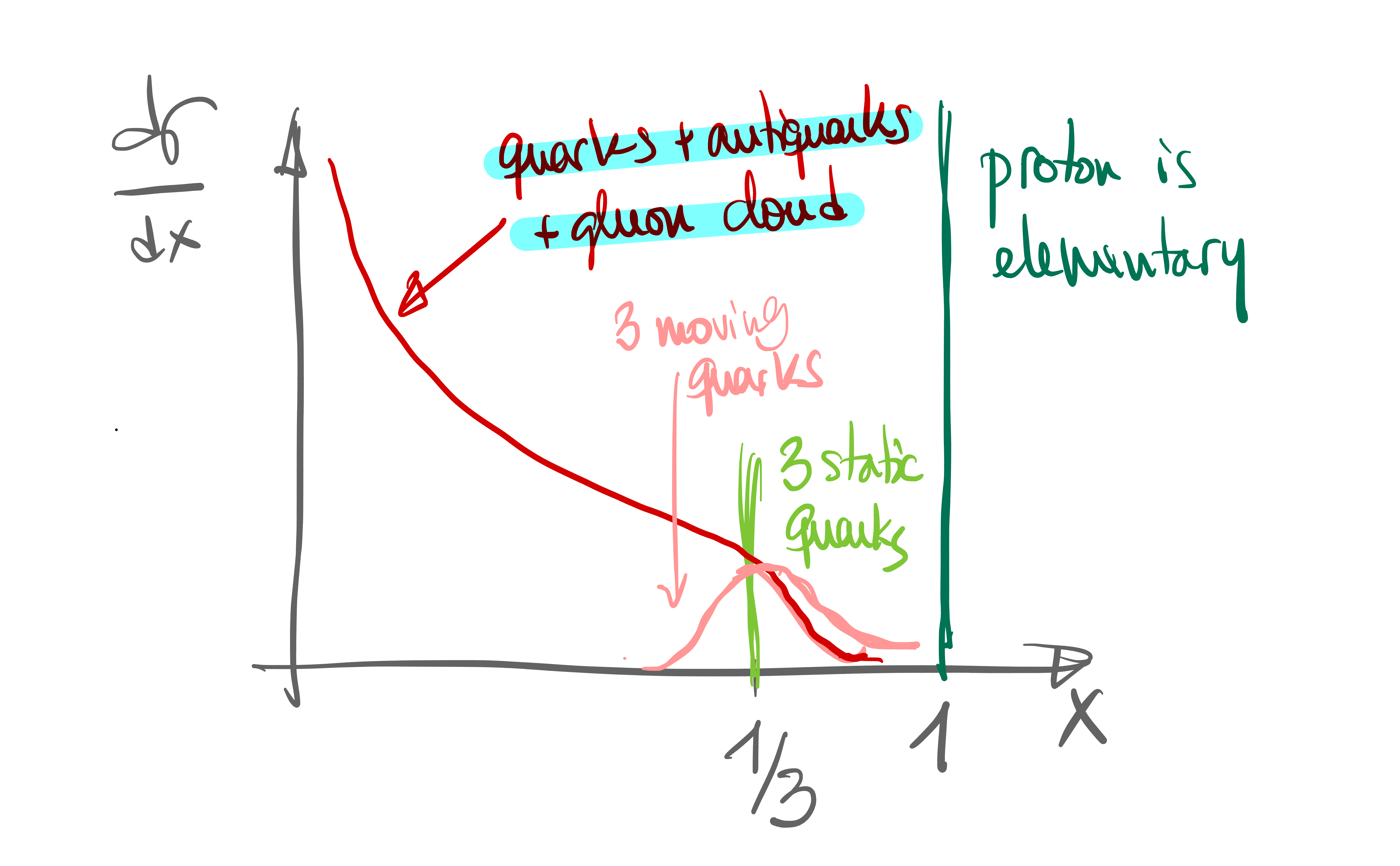
D's LHCb
dijets CMS
pPb

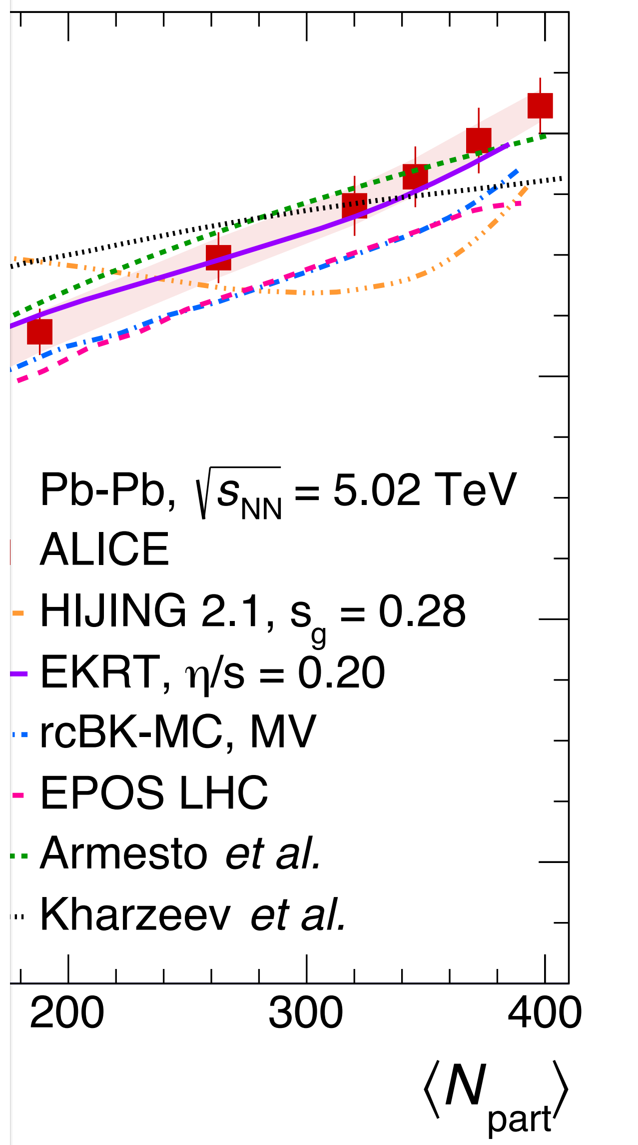
More on nPDFs: Thomas Jezo Plenary Thursday

Saturation of partonic densities [small-x]

More on Saturation: Paul Caucal Plenary Thursday





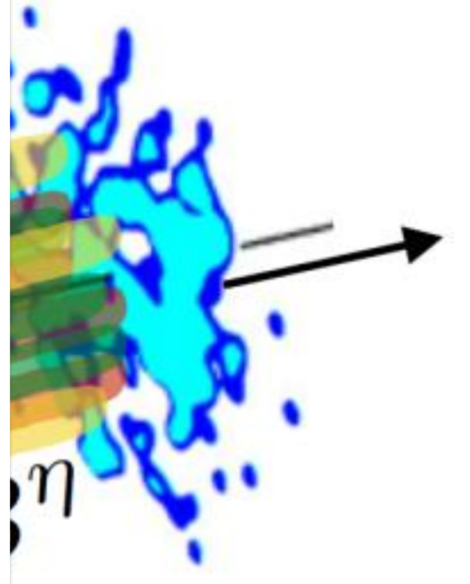


Color Glass

Large occupati

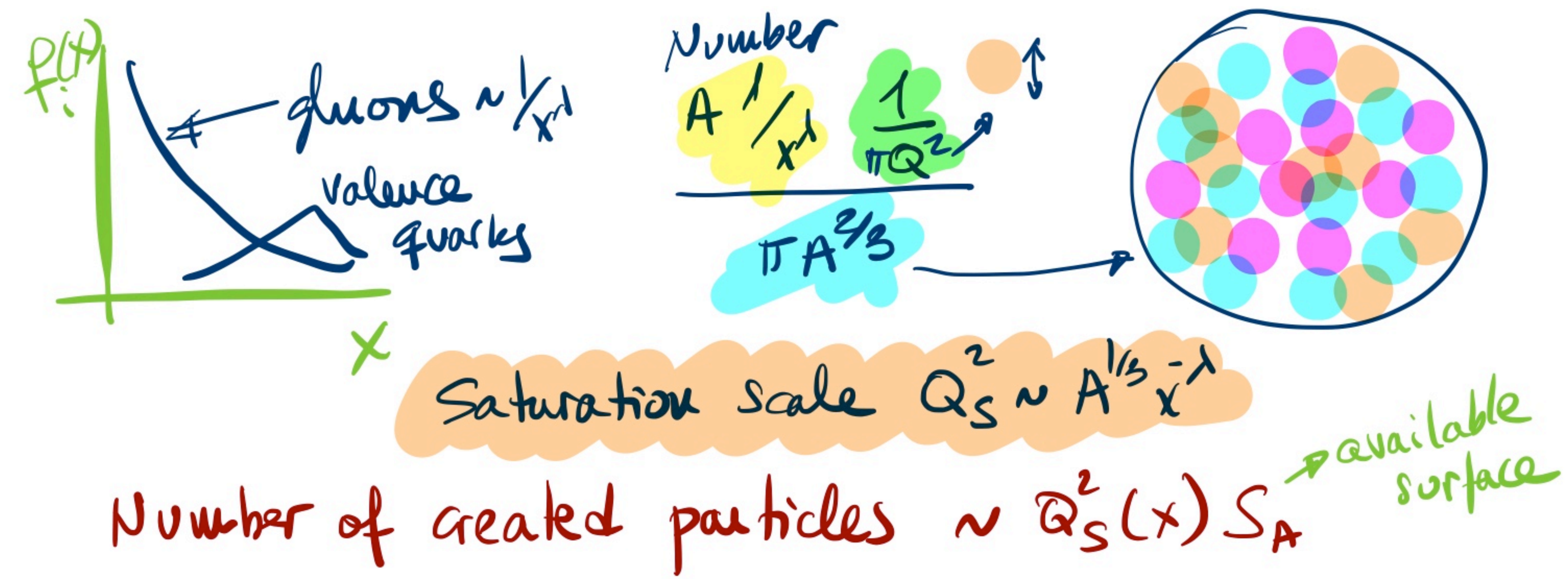
Quantum C

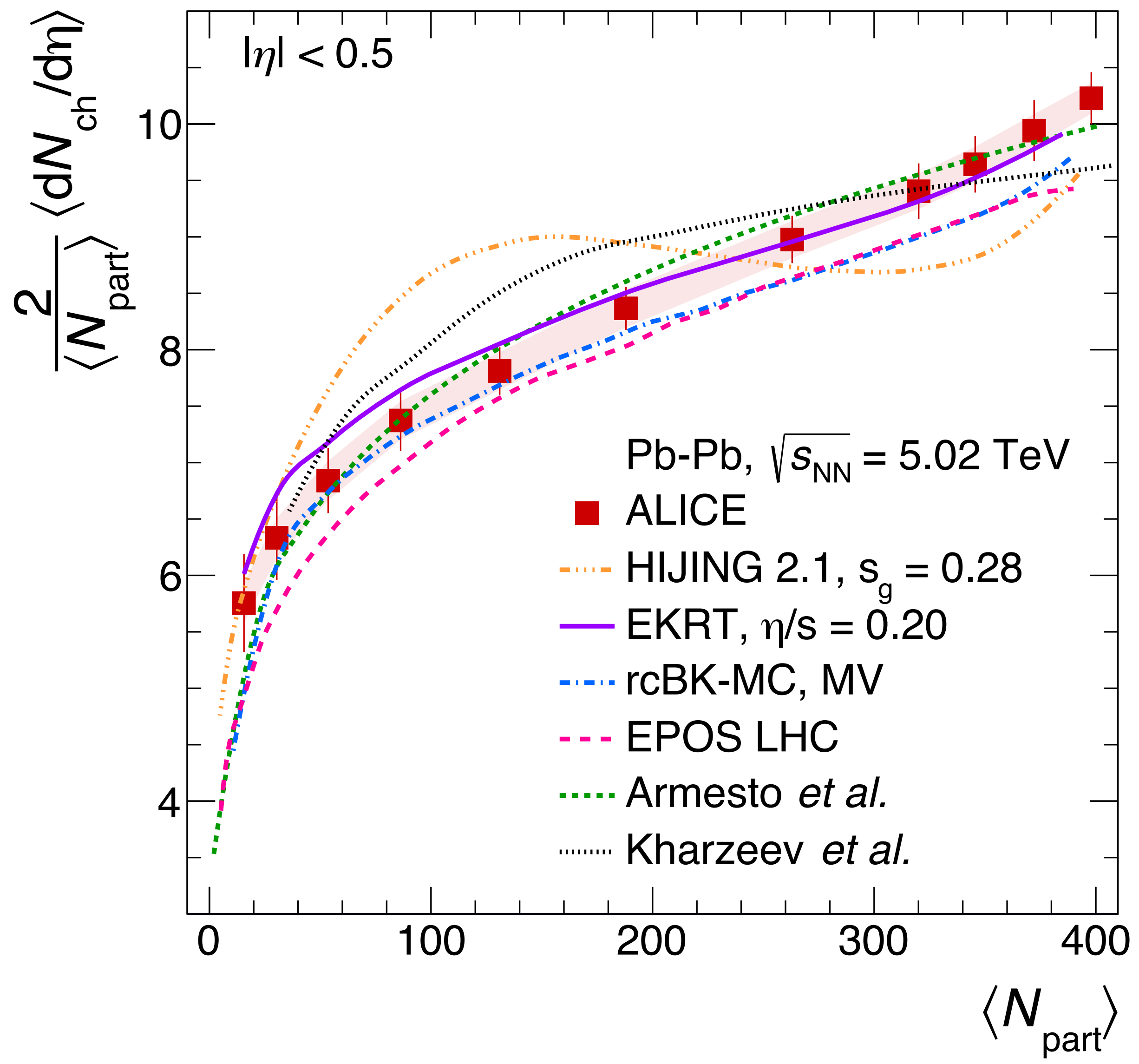
Color Glass C
framework to compute initial stages



Saturation of partonic densities [small-x]

More on Saturation: Paul Caucal Plenary Thursday



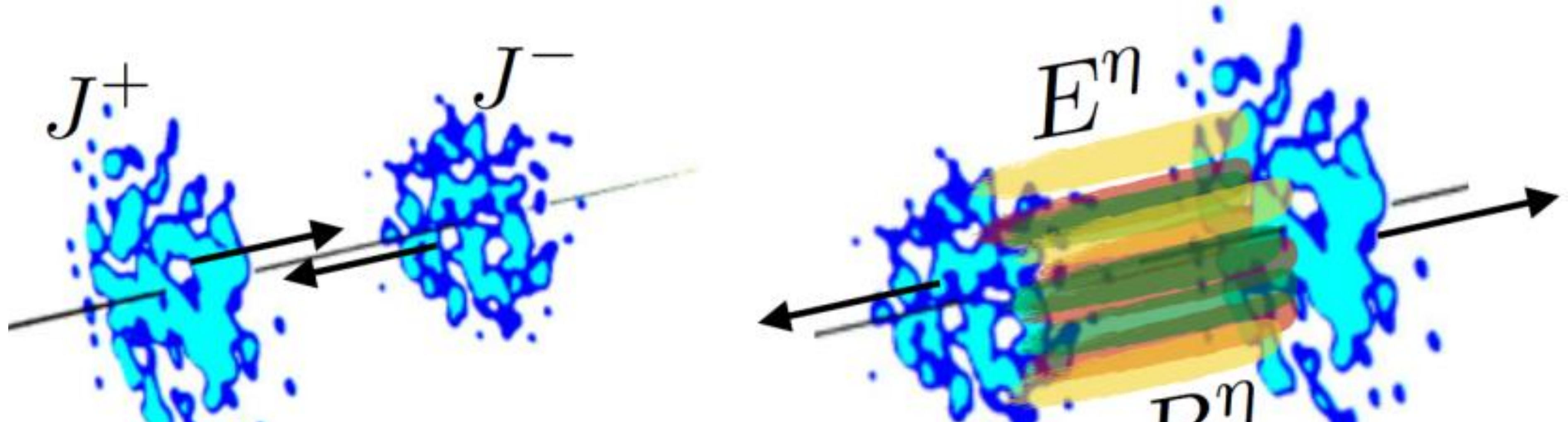


Color Glass Condensate

Large occupation numbers - classical fields

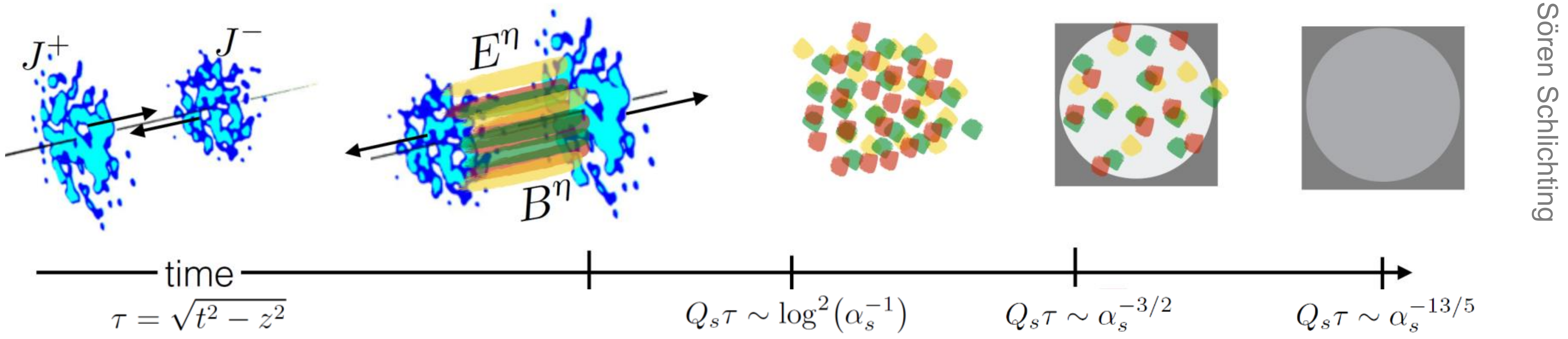
Quantum Corrections - evolution eqs.

Color Glass Condensate provides a general framework to compute initial stages



$$D_\mu F^{\mu\nu} = J^\nu$$

A picture for equilibration



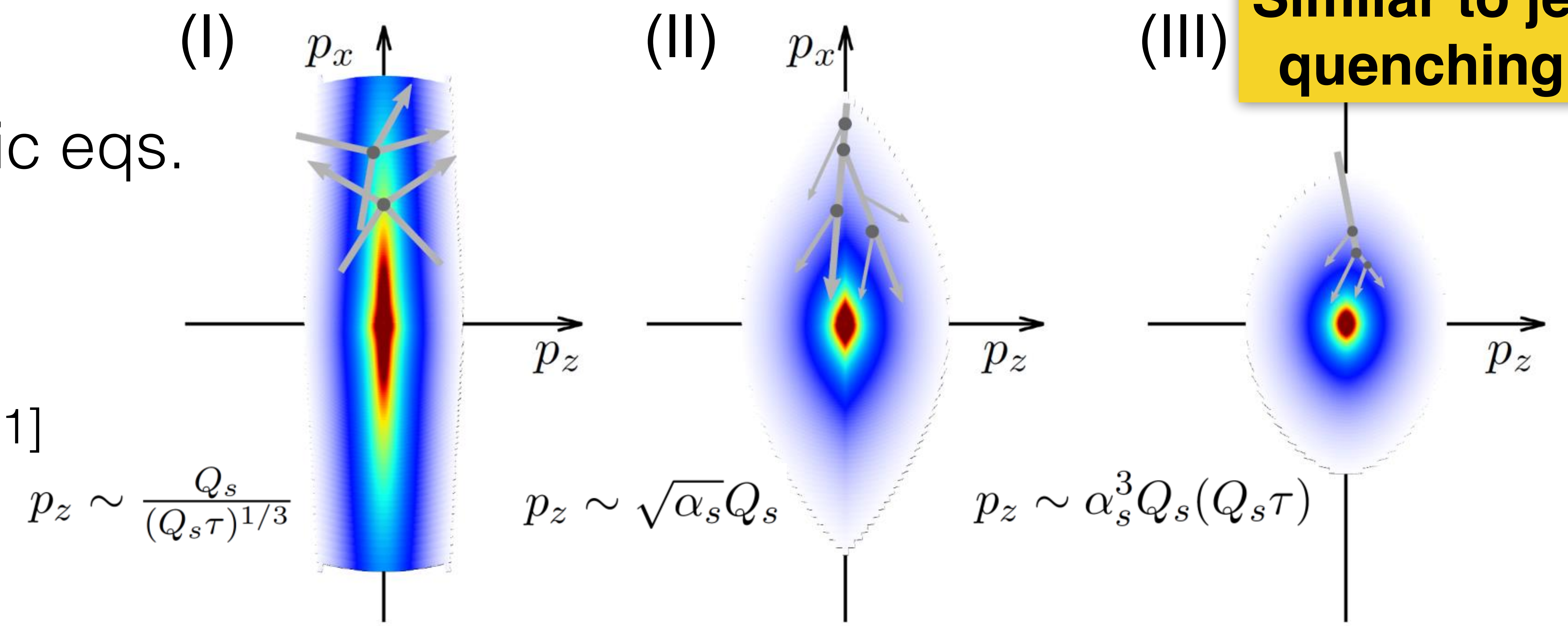
[Classical statistical/lattice gauge theory…]

Evolution of boost-invariant system with kinetic eqs.

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

[Bottom-up thermalization — Baier, Mueller, Schiff, Son 2001]

[Arnold, Moore, Yaffe 2001; Kurkela, Zhu 2015; Keegan, Kurkela, Mazeliauskas, Teaney 2016; Kurkela Mazeliauskas, Paquet, Schlichting, Teaney 2019…]



Similar to jet quenching

A picture for equilibration

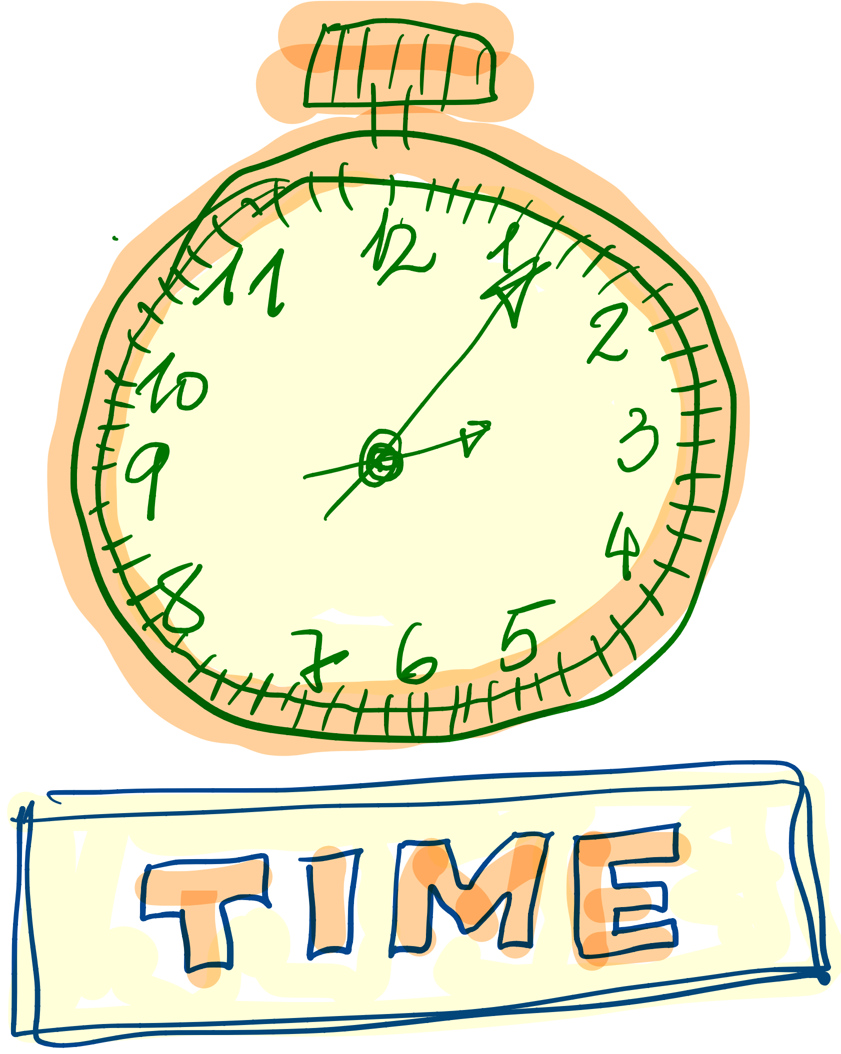
[Classi

Evolution of bo

$p^\mu \partial_\mu f(x,p)$

[Bottom-up therma

[Arnold, Moore, Yaffe
Mazeliauskas, Tea
Schlichting, Teaney 2019…]

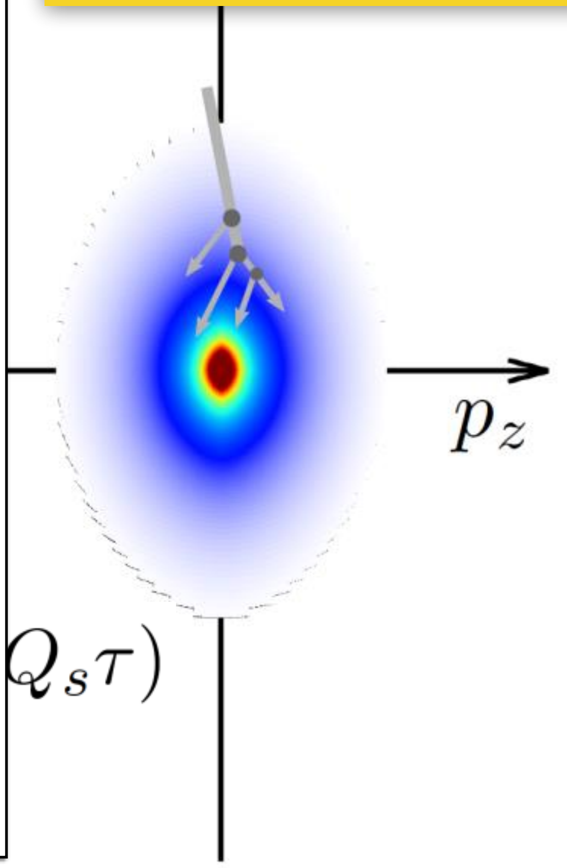


Can hard processes measure this (or other) time evolution and check the initial stages; how is equilibrium reached; and the later stages when QGP is equilibrated…?

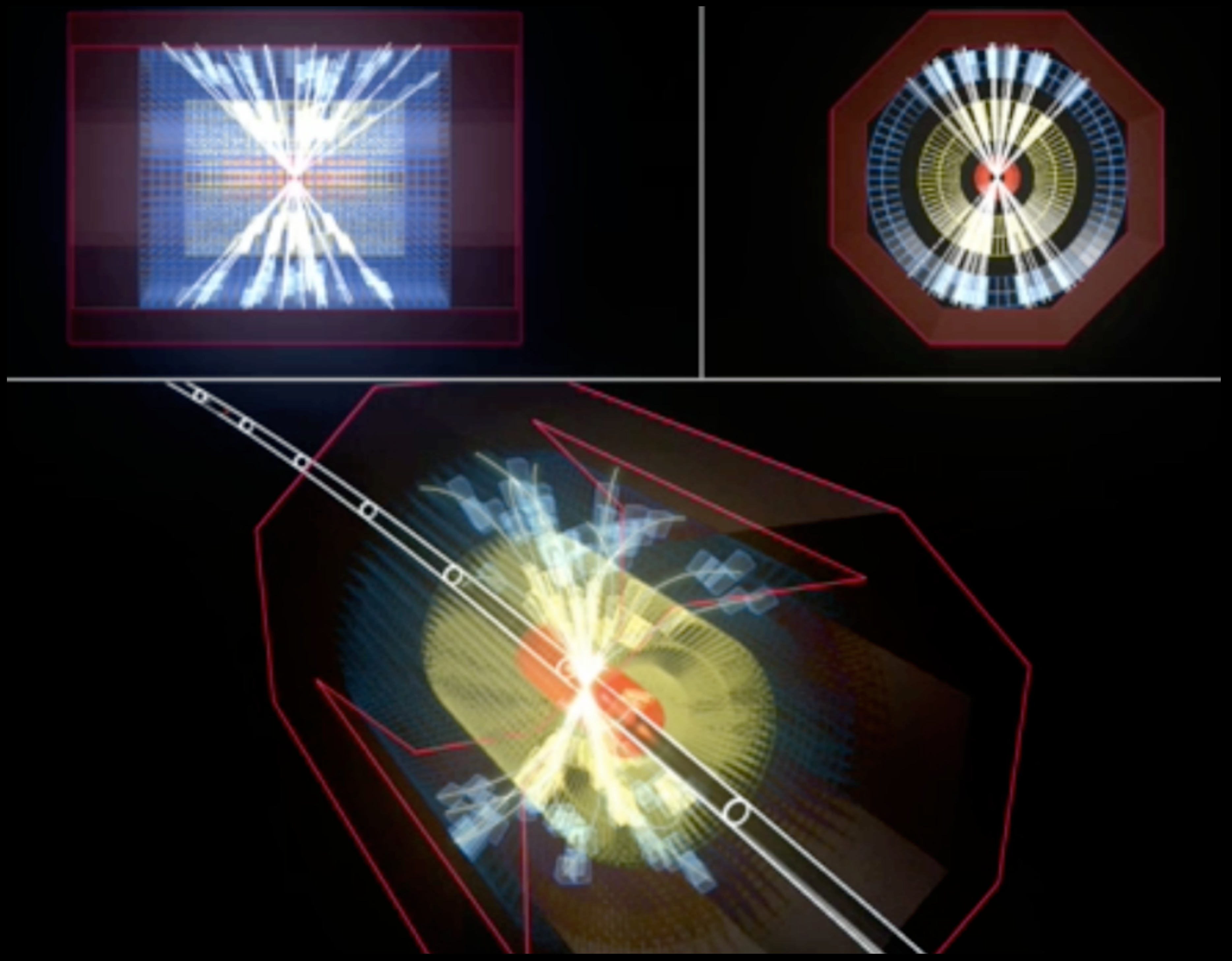
More on early time dynamics
Kirill Boguslavski plenary Monday

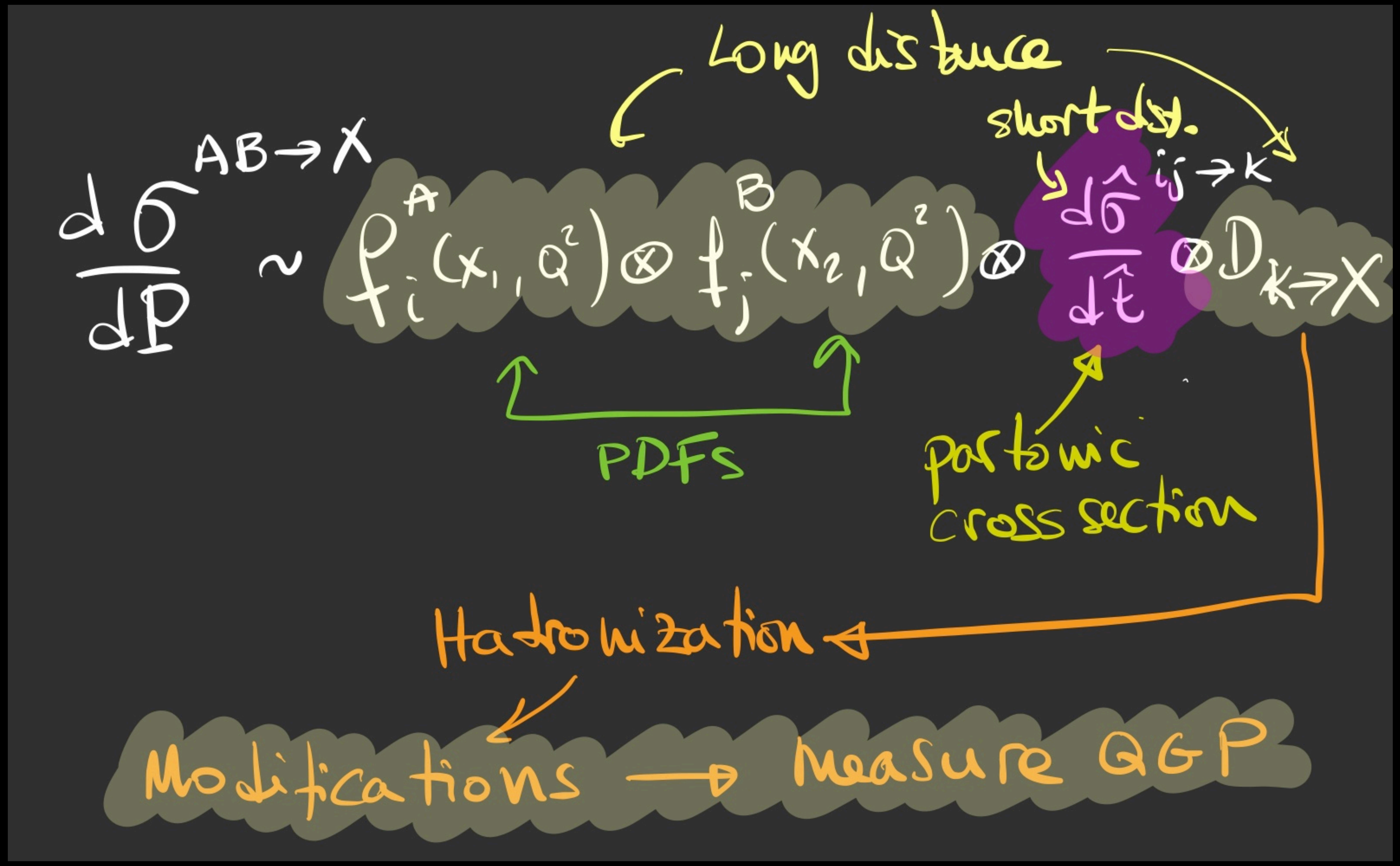
Sören Schlichting

Similar to jet quenching



HARD **PROBES**





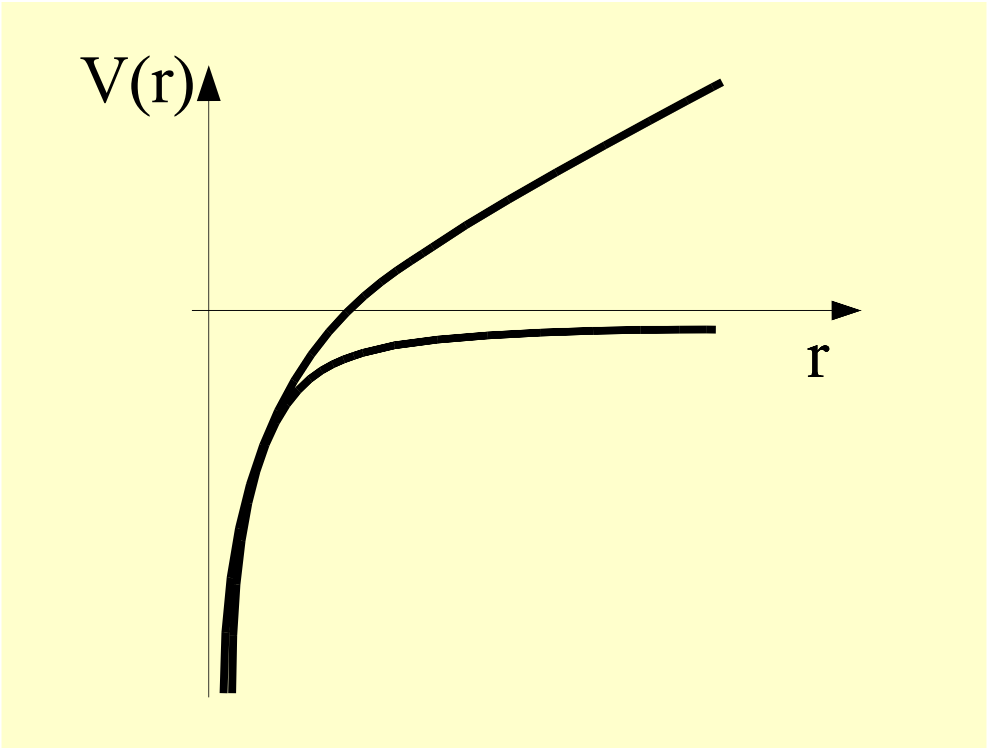
- ☐ Jet quenching
- ☐ Quarkonia suppression
- ☐ Open heavy flavor
- ☐ Electroweak probes

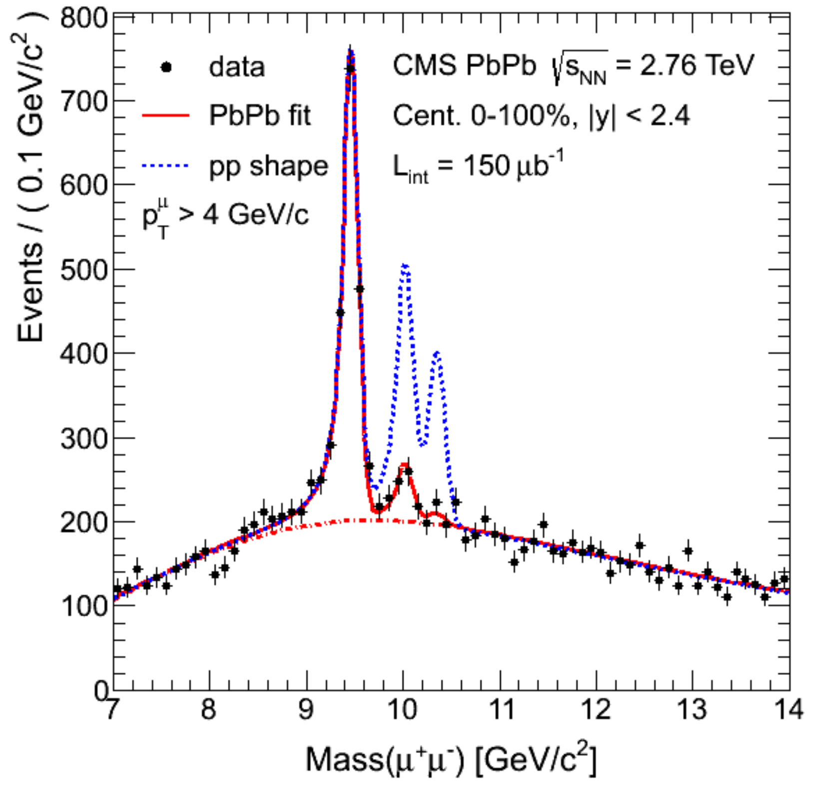
Quarkonia suppression

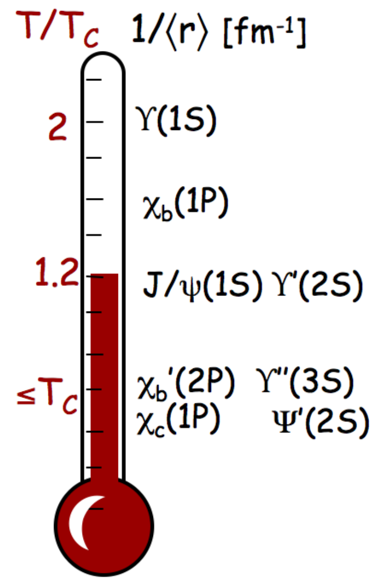
More on quarkonia: M.A. Escobedo Plenary Thursday

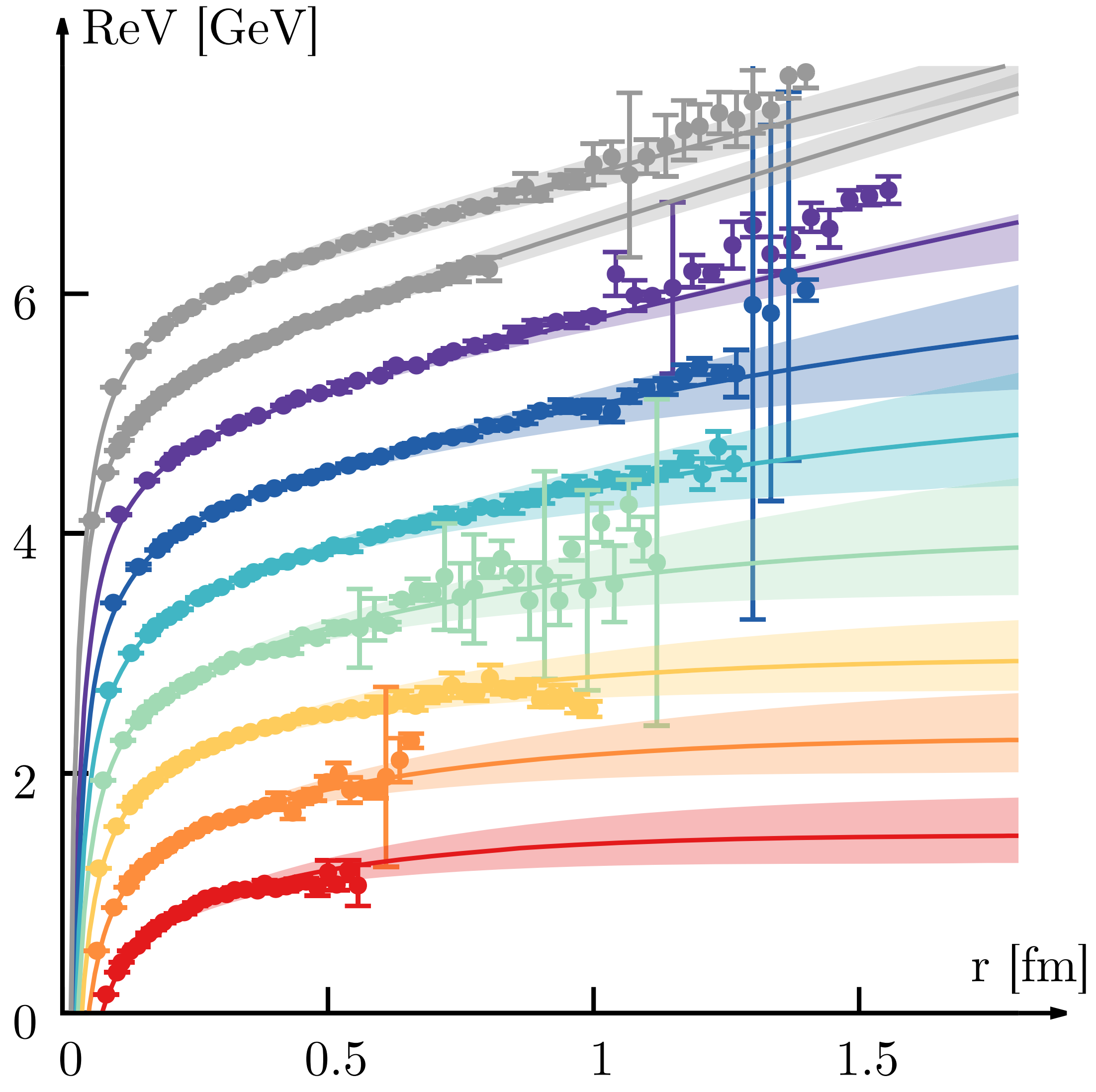
Simple **intuitive picture** [Matsui & Satz 1986]

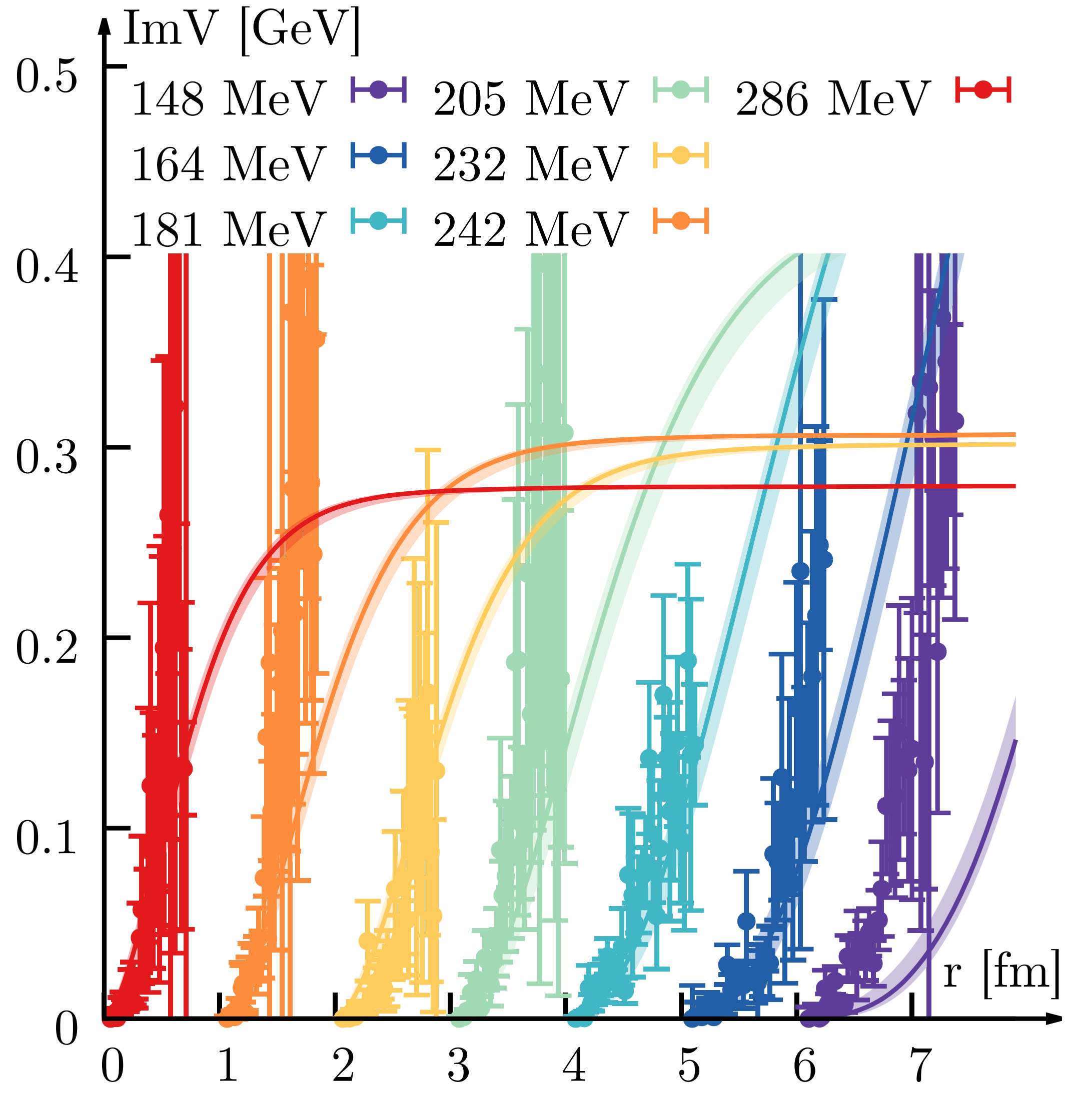
- Potential screened at high-T
- Quarkonia suppressed
- Sequential suppression of excited states
- **Quarkonia as a thermometer**











[Lafferty, Rothkopf 2020]

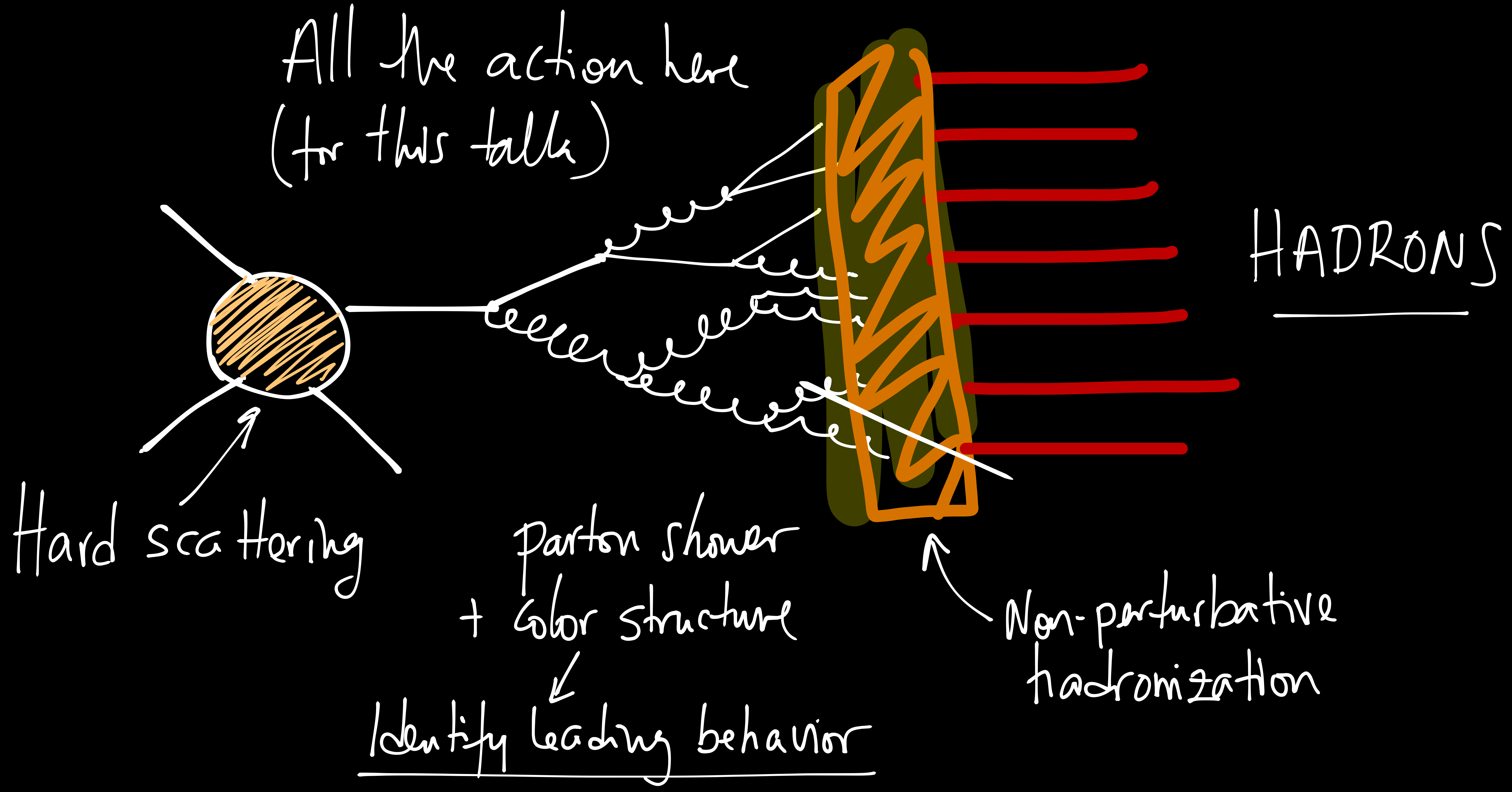
Dynamical picture:

- different effects: screening / rescattering / recombination
- Induced transition between quarkonia states

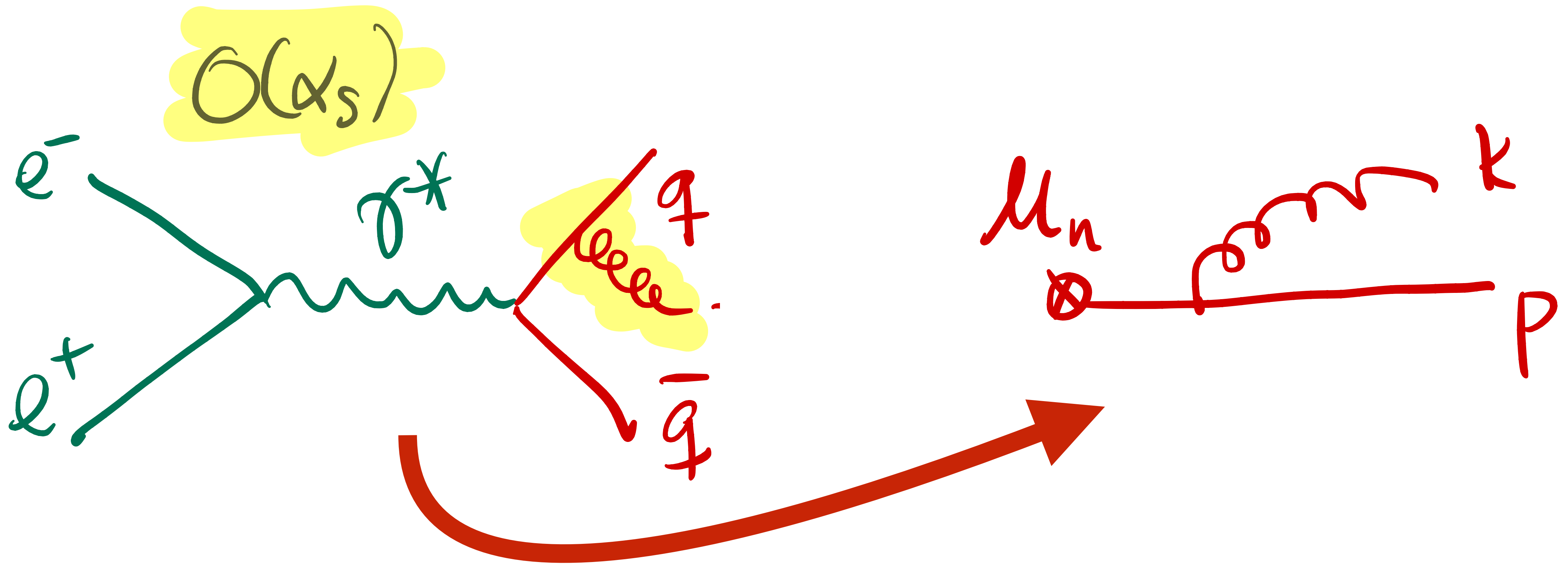
Quarkonia as an open quantum system

[Bambrilla, Soto, Escobedo, Vairo, Ghiglieri, Petreczky, Strickland, Blaizot, Rothkopf, Kaczmarek, Asakawa, Katz, Gossiaux, Kajimoto, Akamatsu, Borghini …]

QCD JETS [No medium for the moment]



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

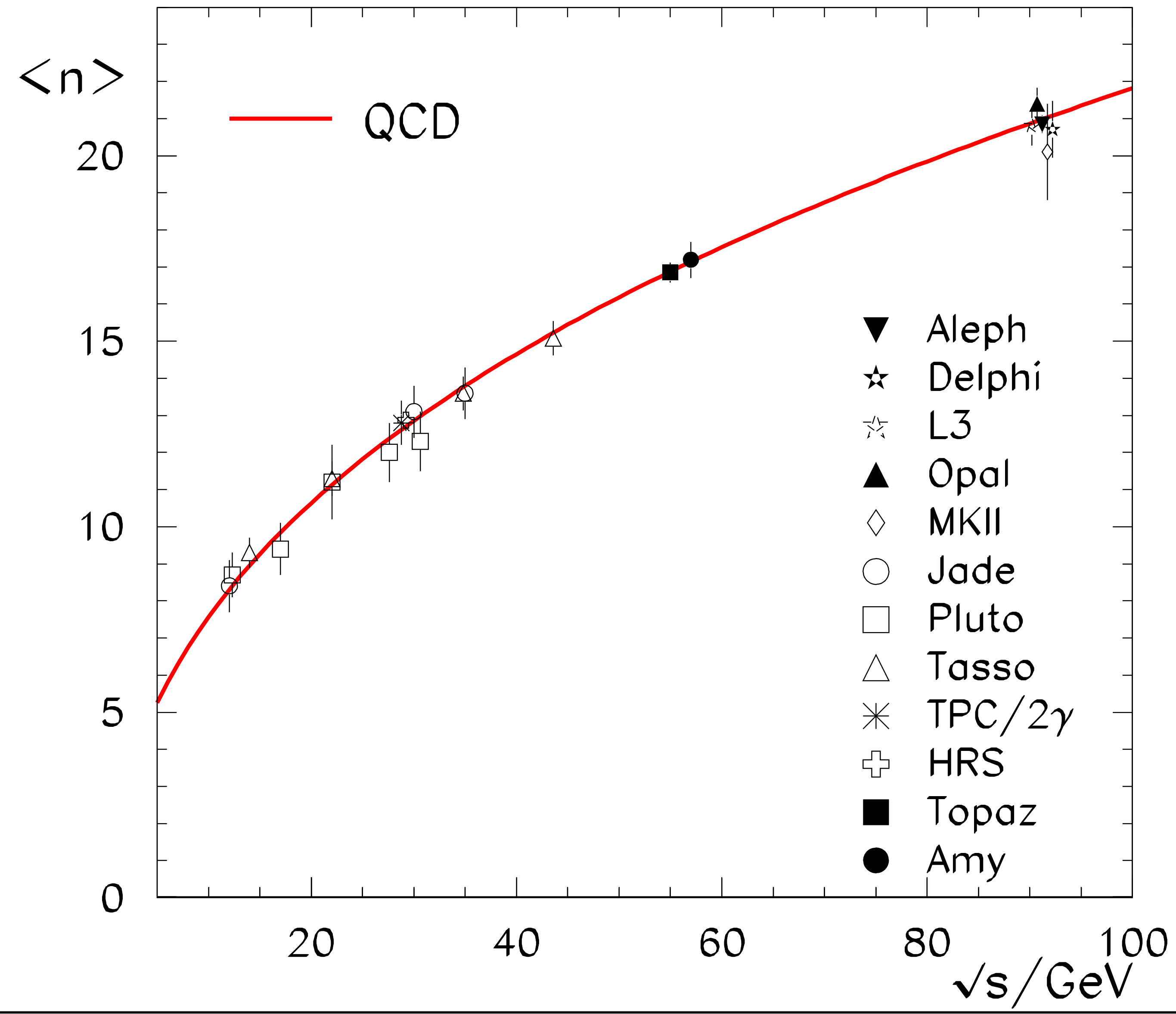
Gluon (and quark) multiplication

→ 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



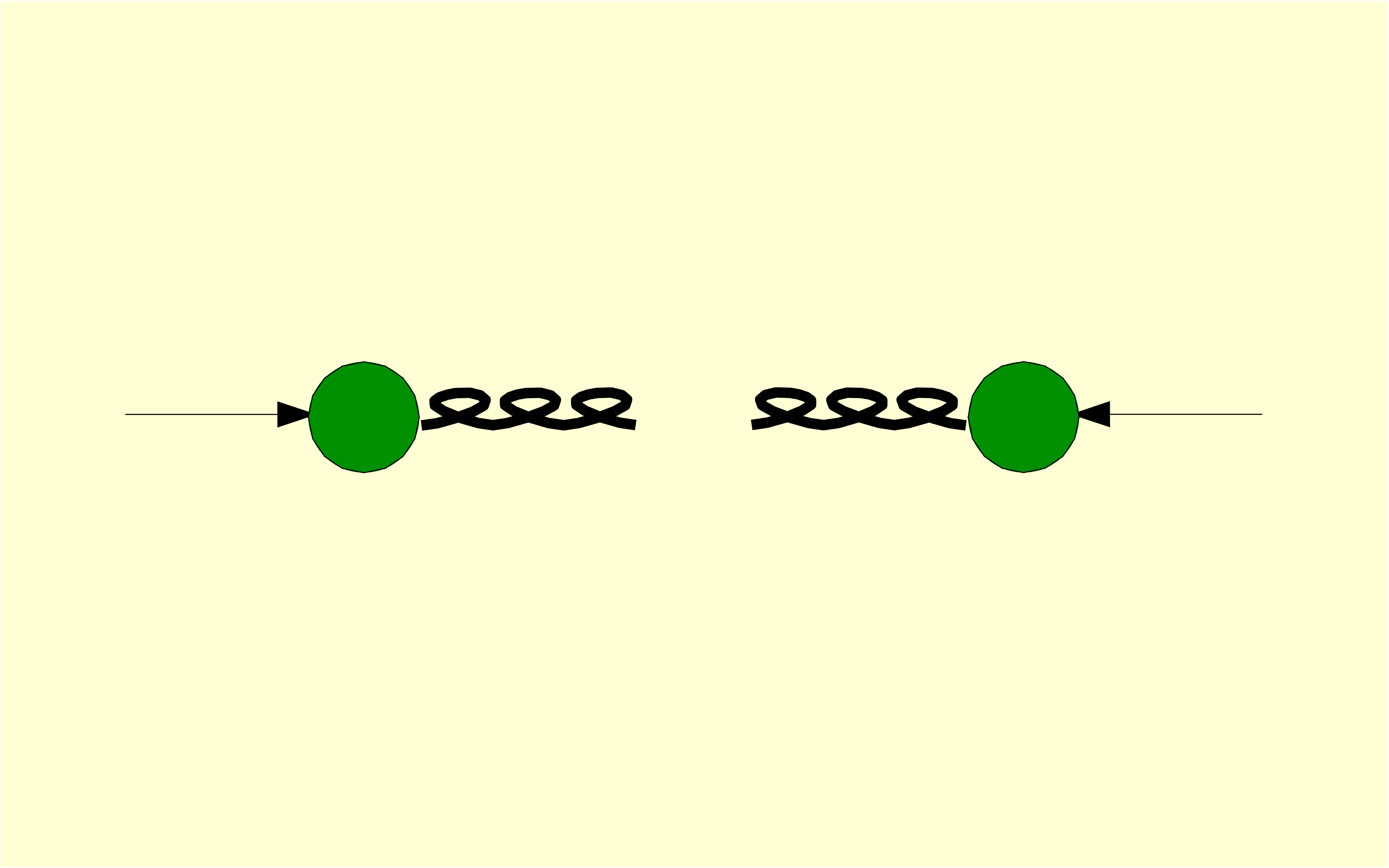
Resummation needed - **gluon multiplication**

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

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

Jets: simple [perhaps too naive] picture

Monte Carlos: Liliana Apolinario Plenary on Monday



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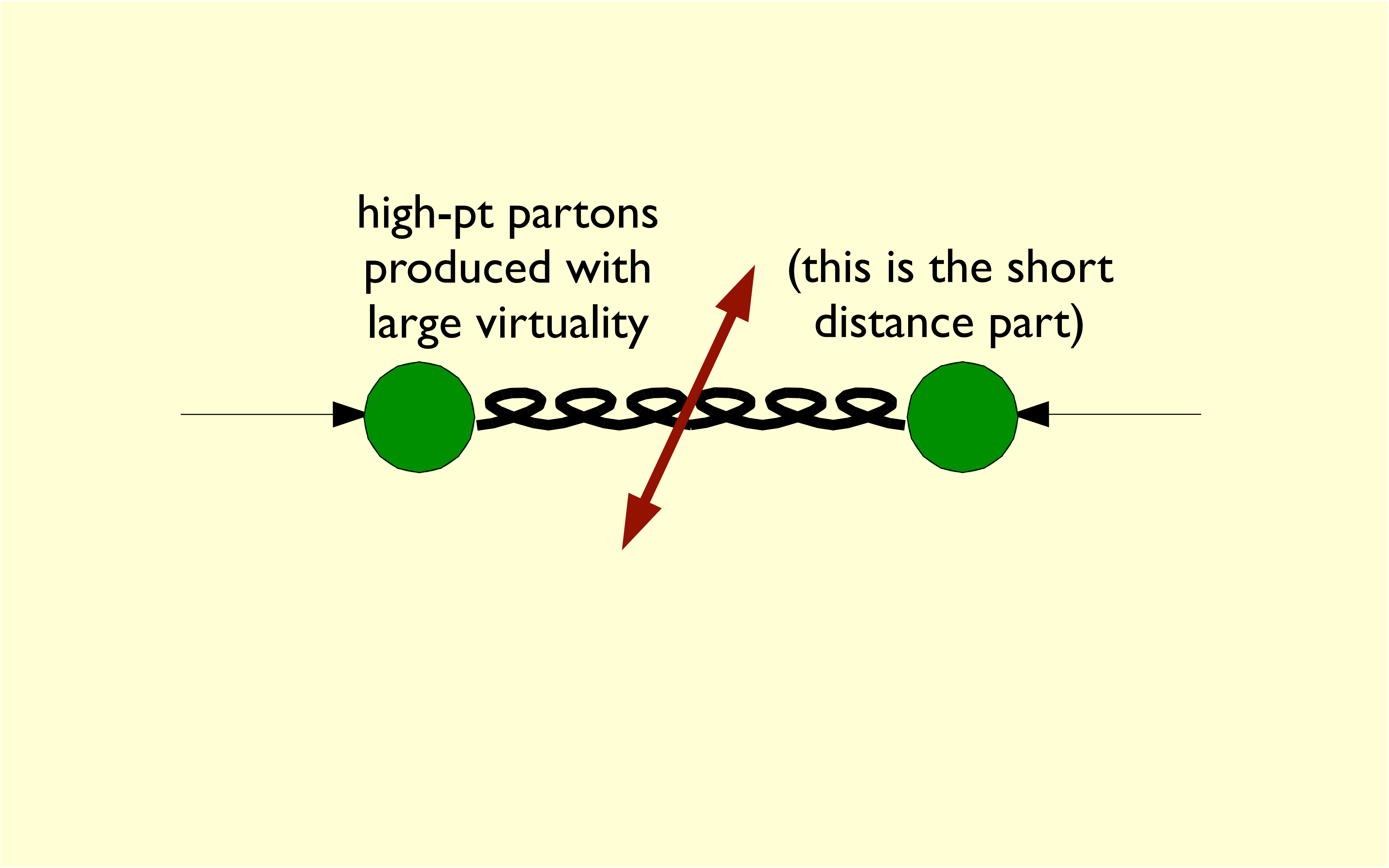

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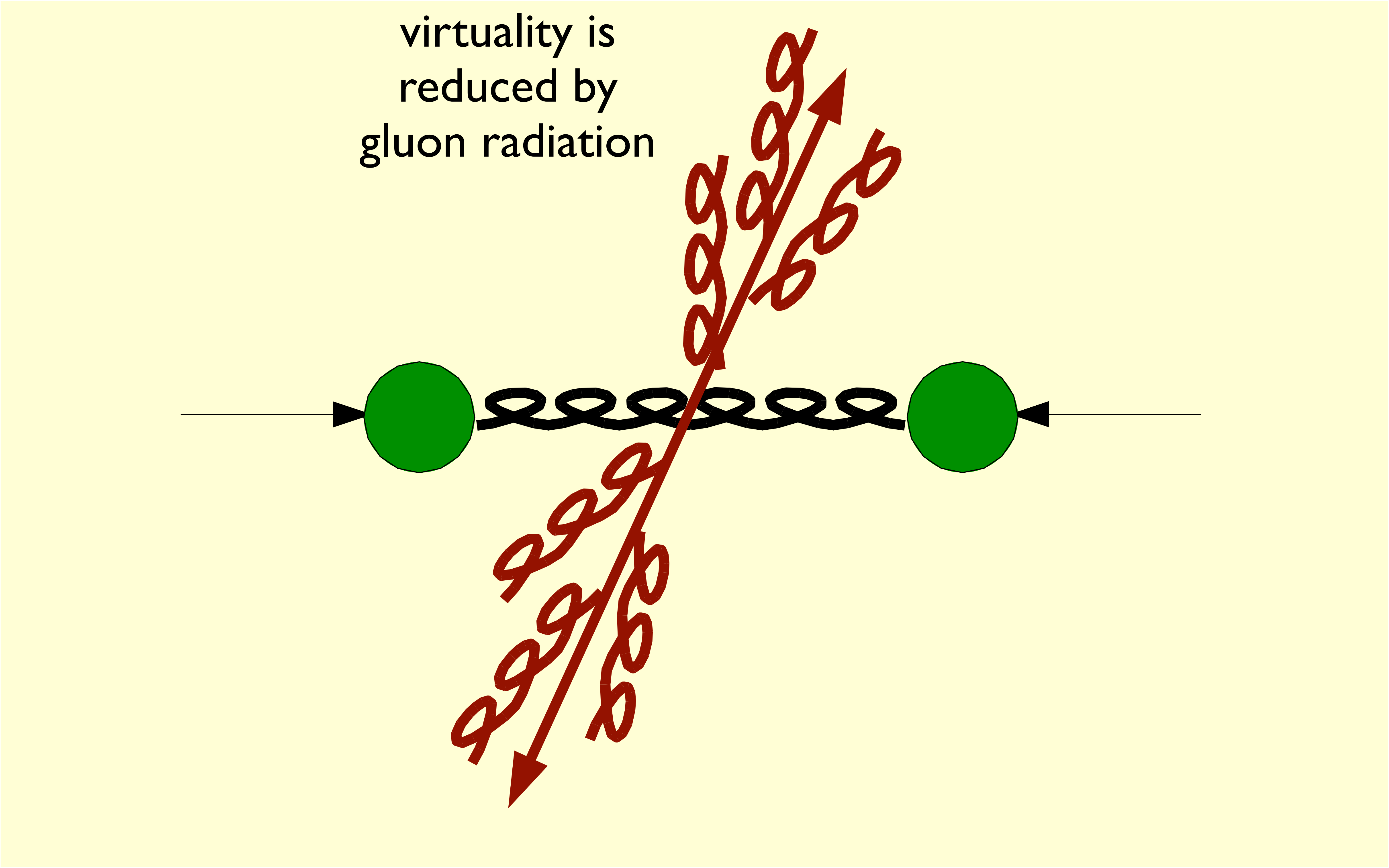

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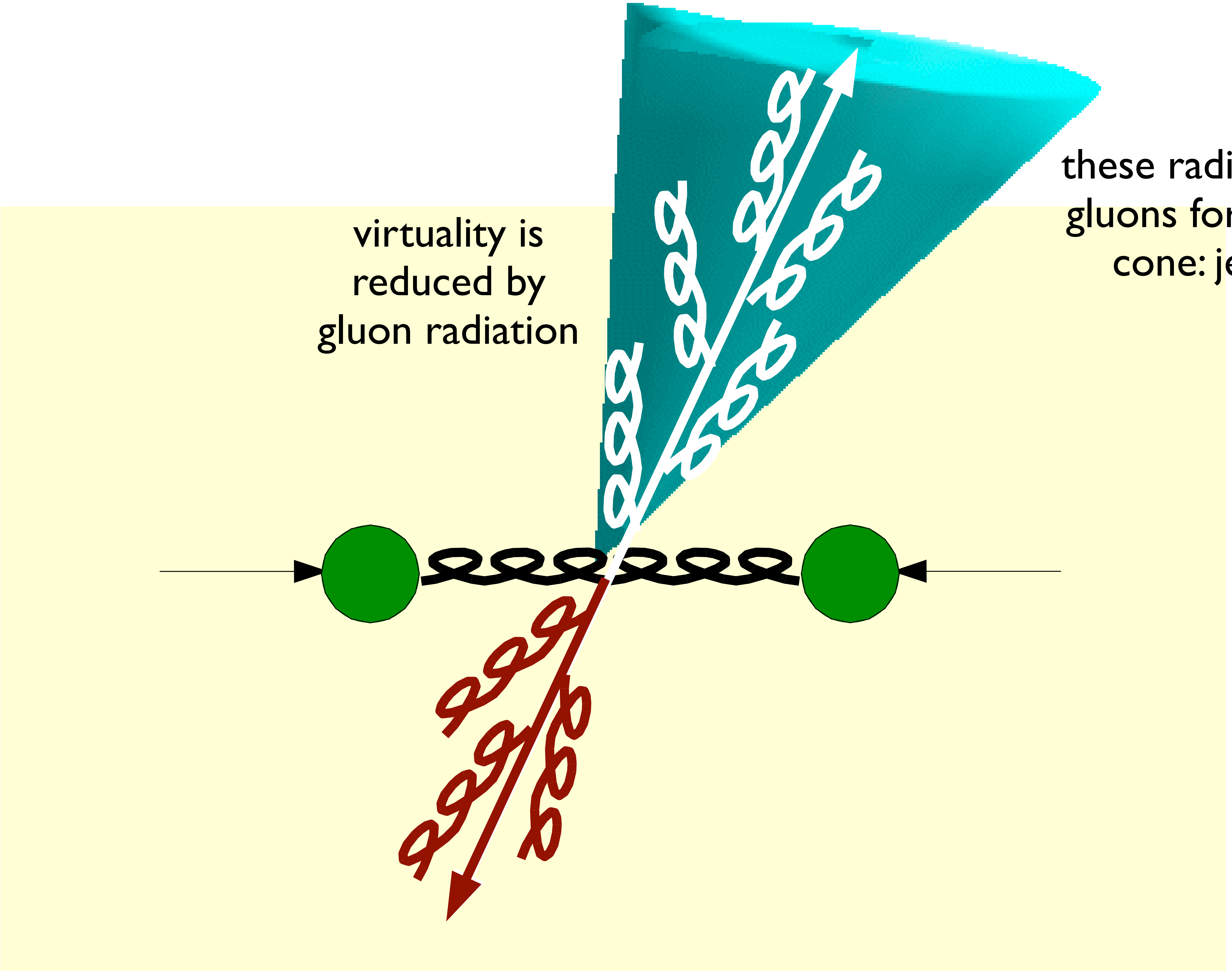

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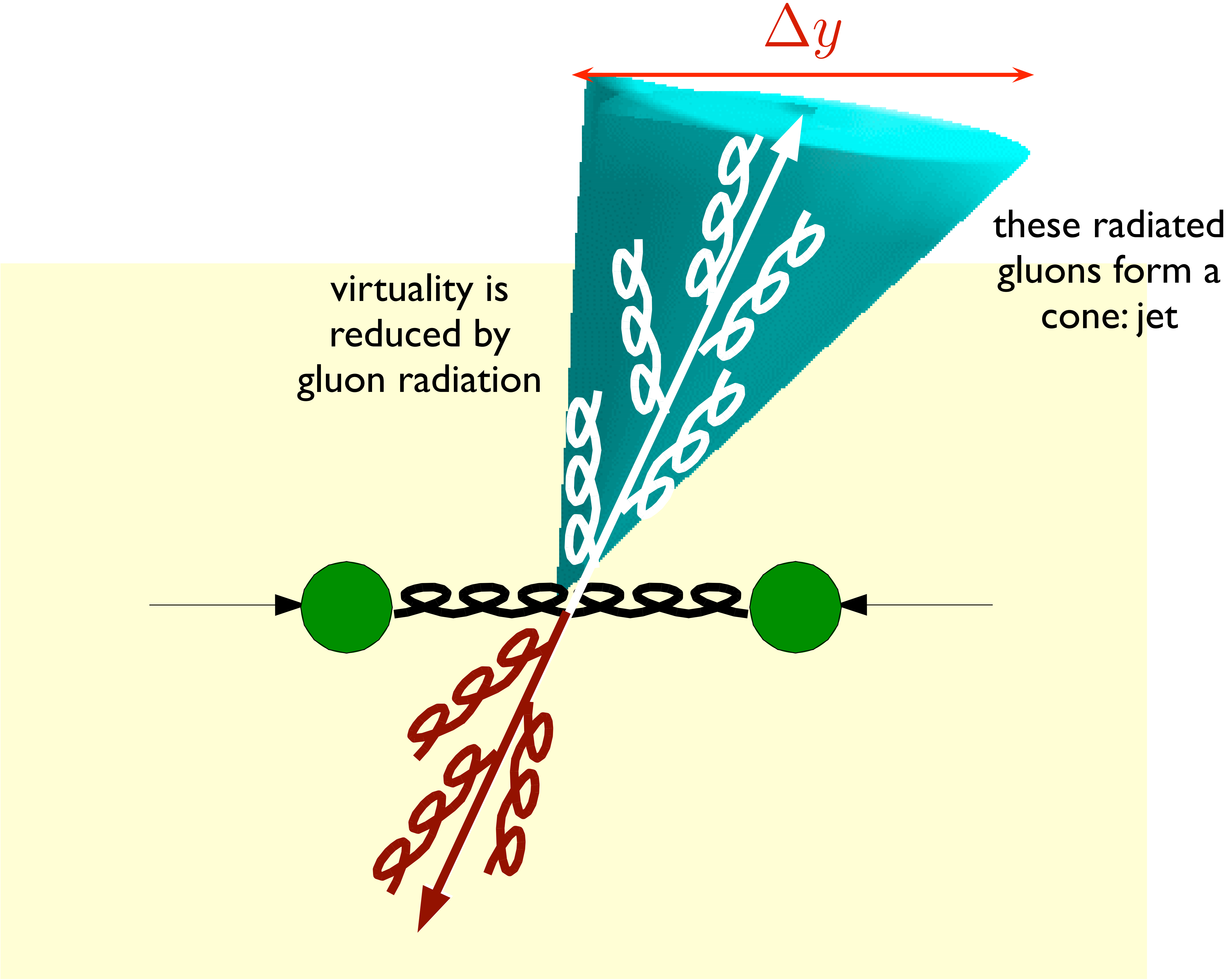

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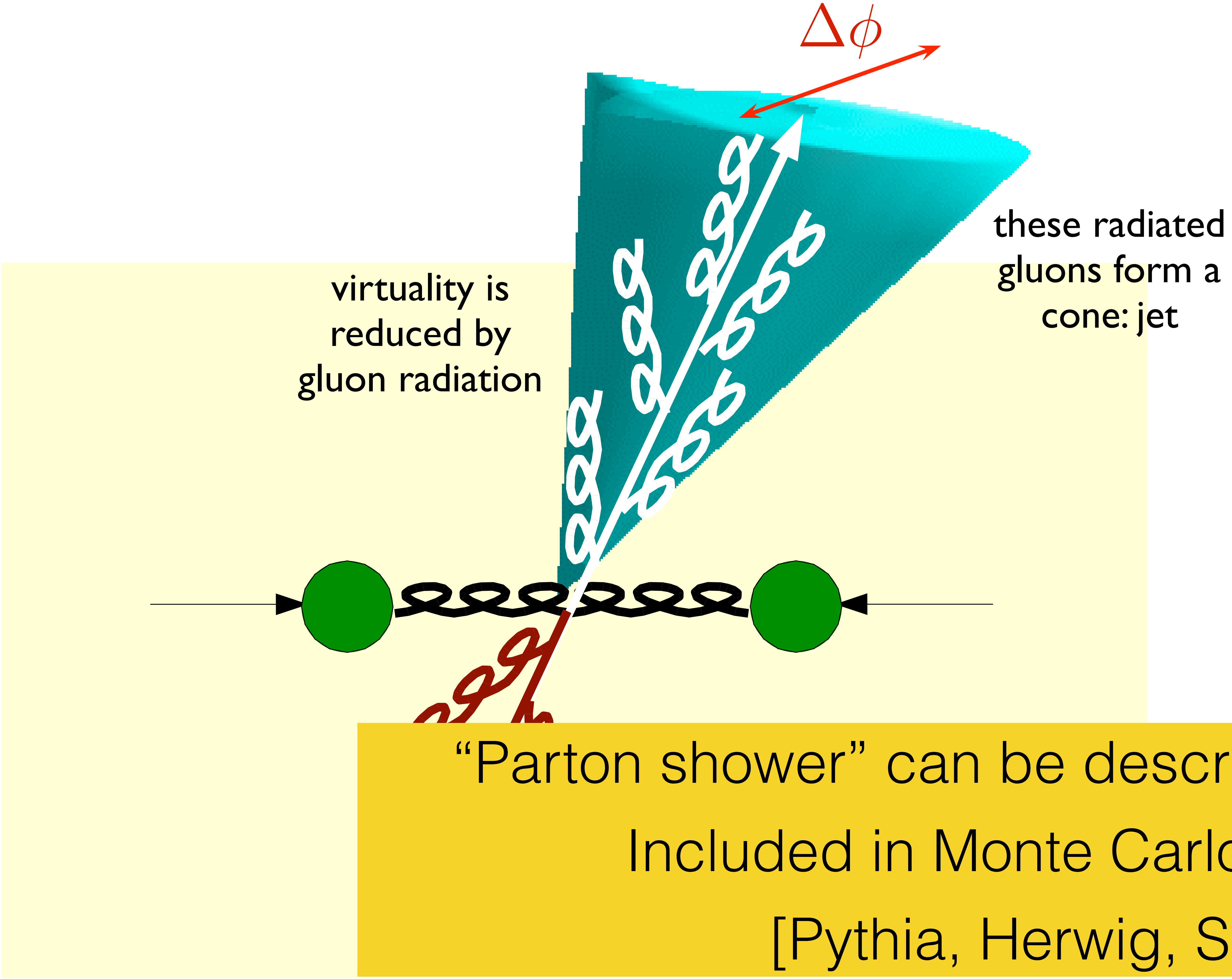
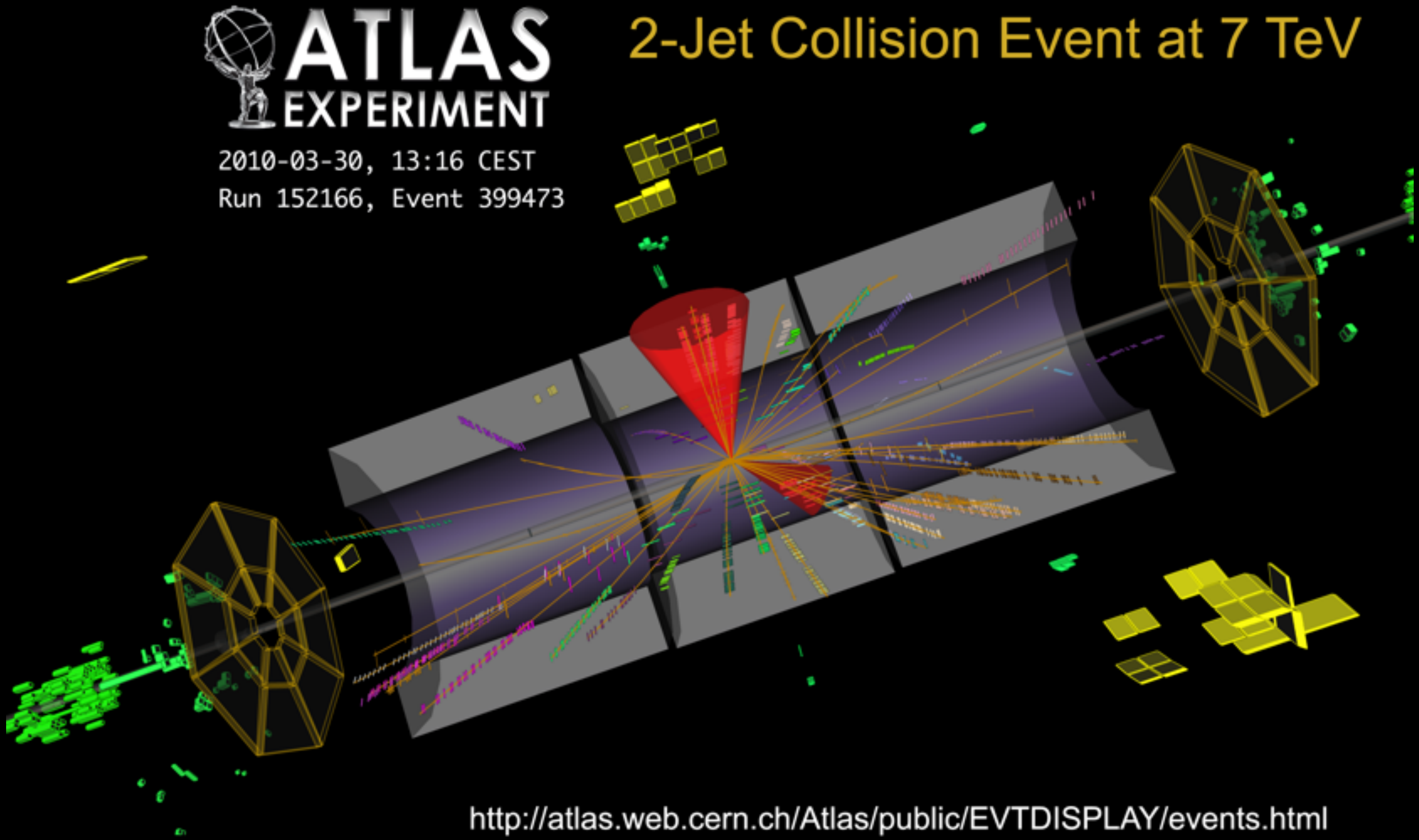


"Parton shower" can be described perturbatively

Included in Monte Carlo generators

[Pythia, Herwig, Sherpa]

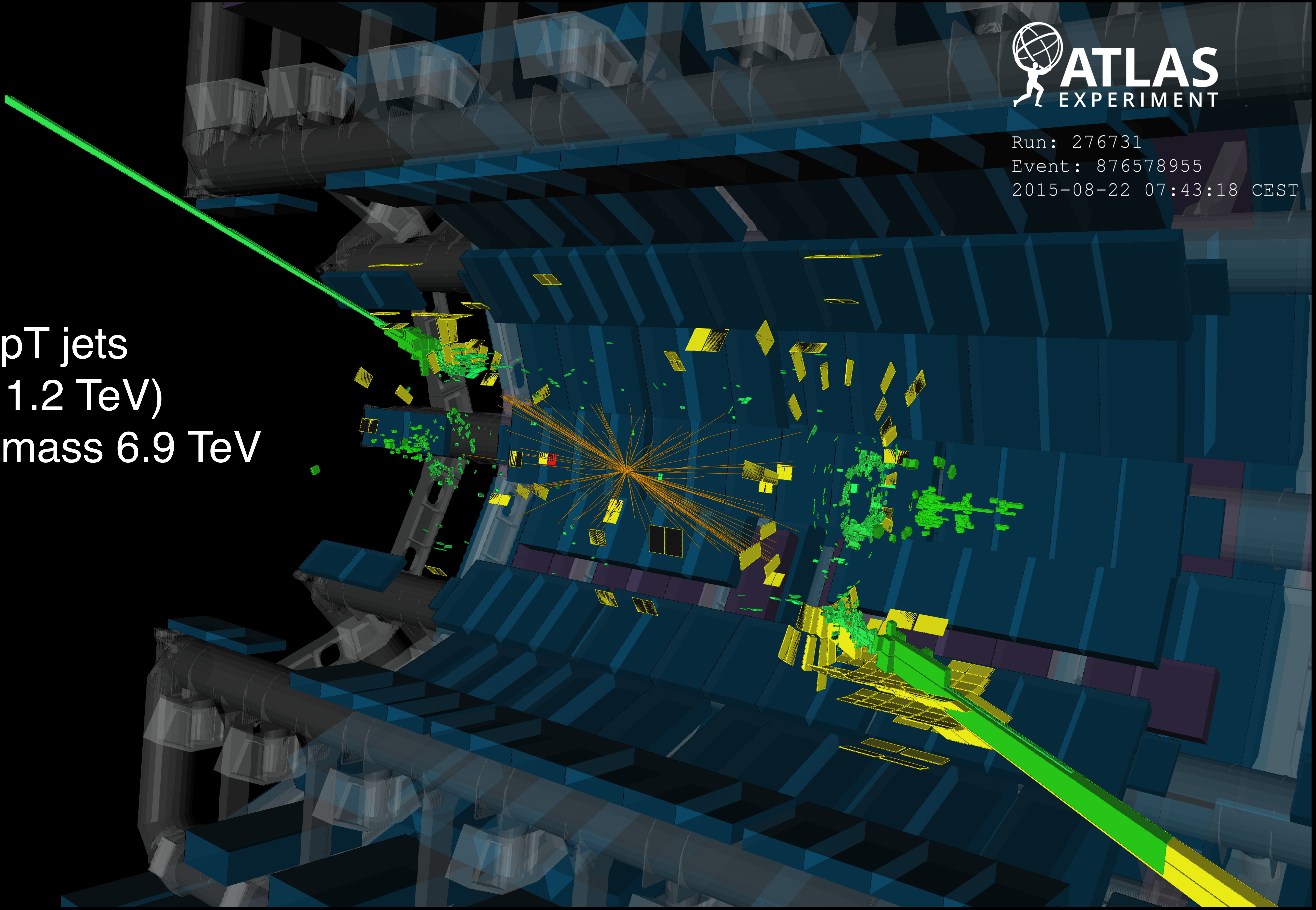
Jets in hadronic colliders



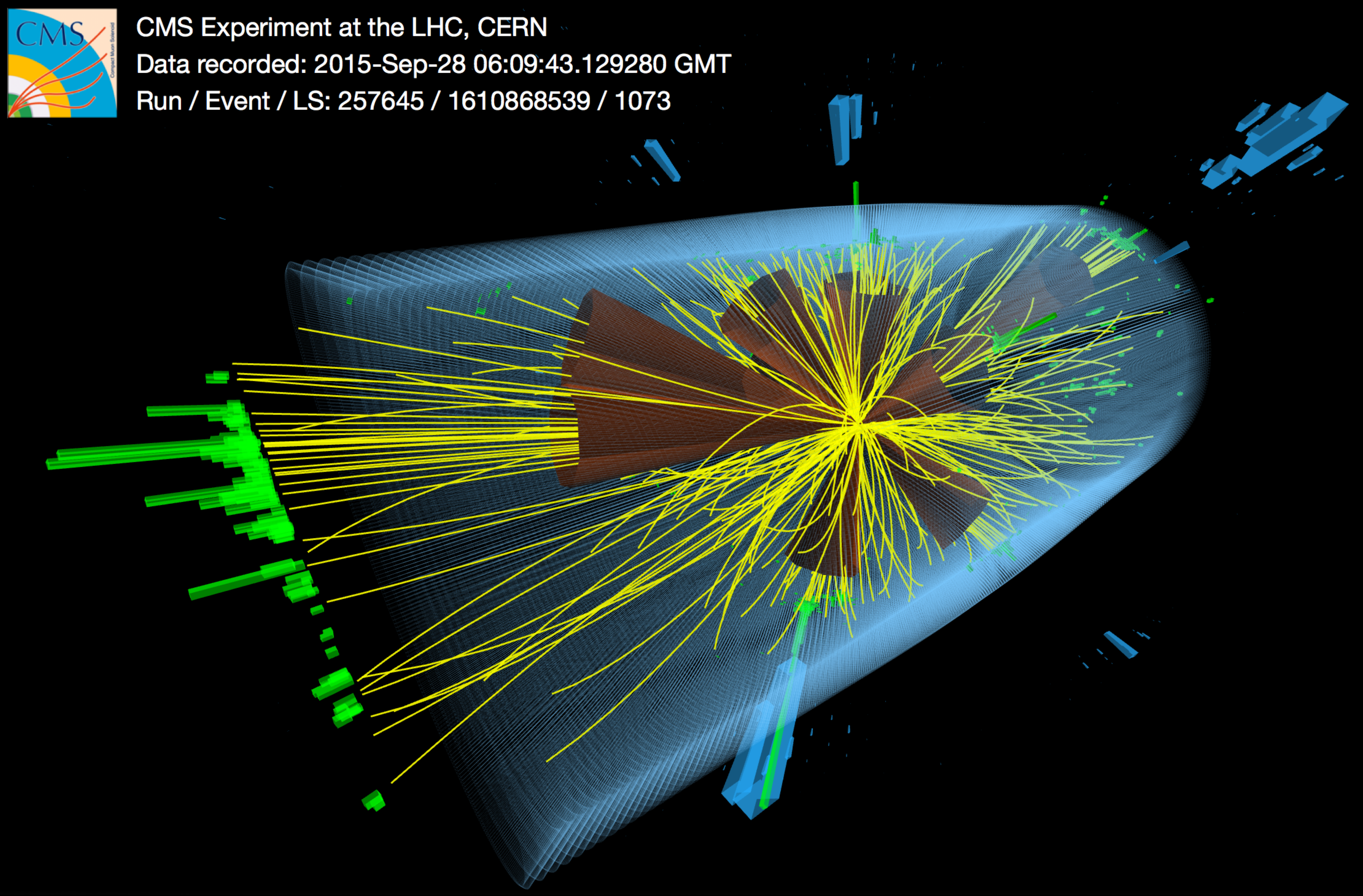
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Jets in hadronic colliders

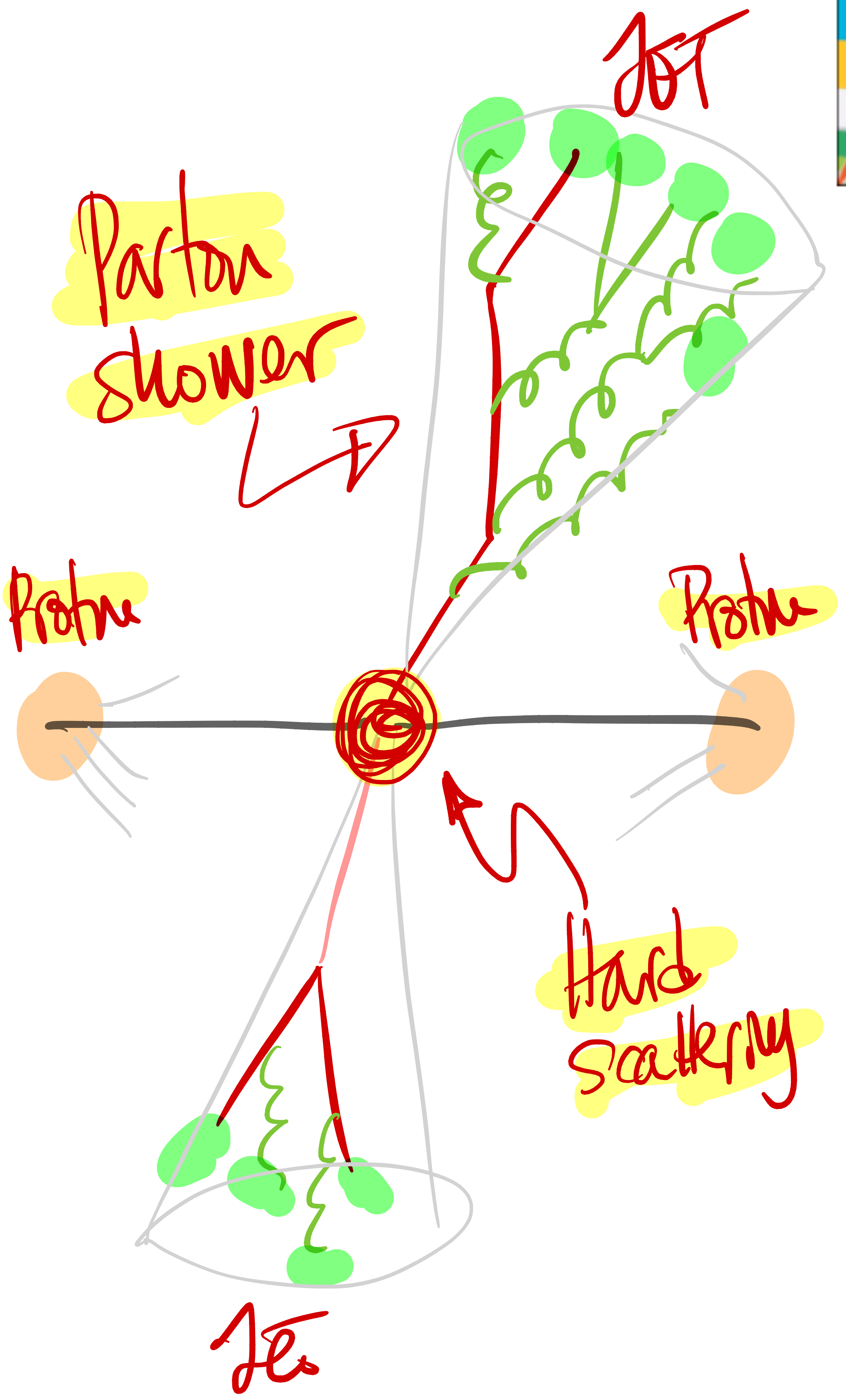
2 high pT jets
(1.3 and 1.2 TeV)
with invariant mass 6.9 TeV

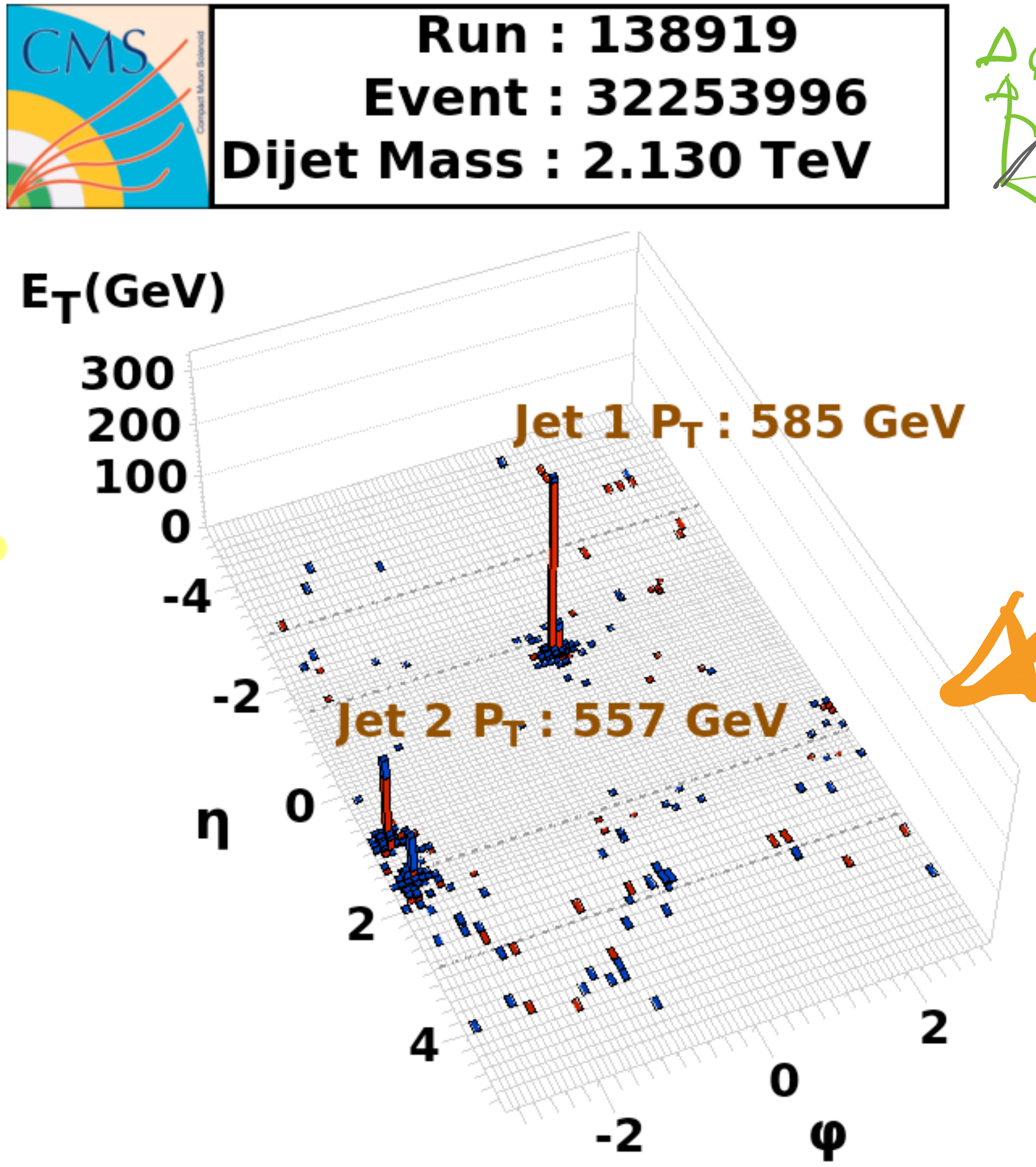


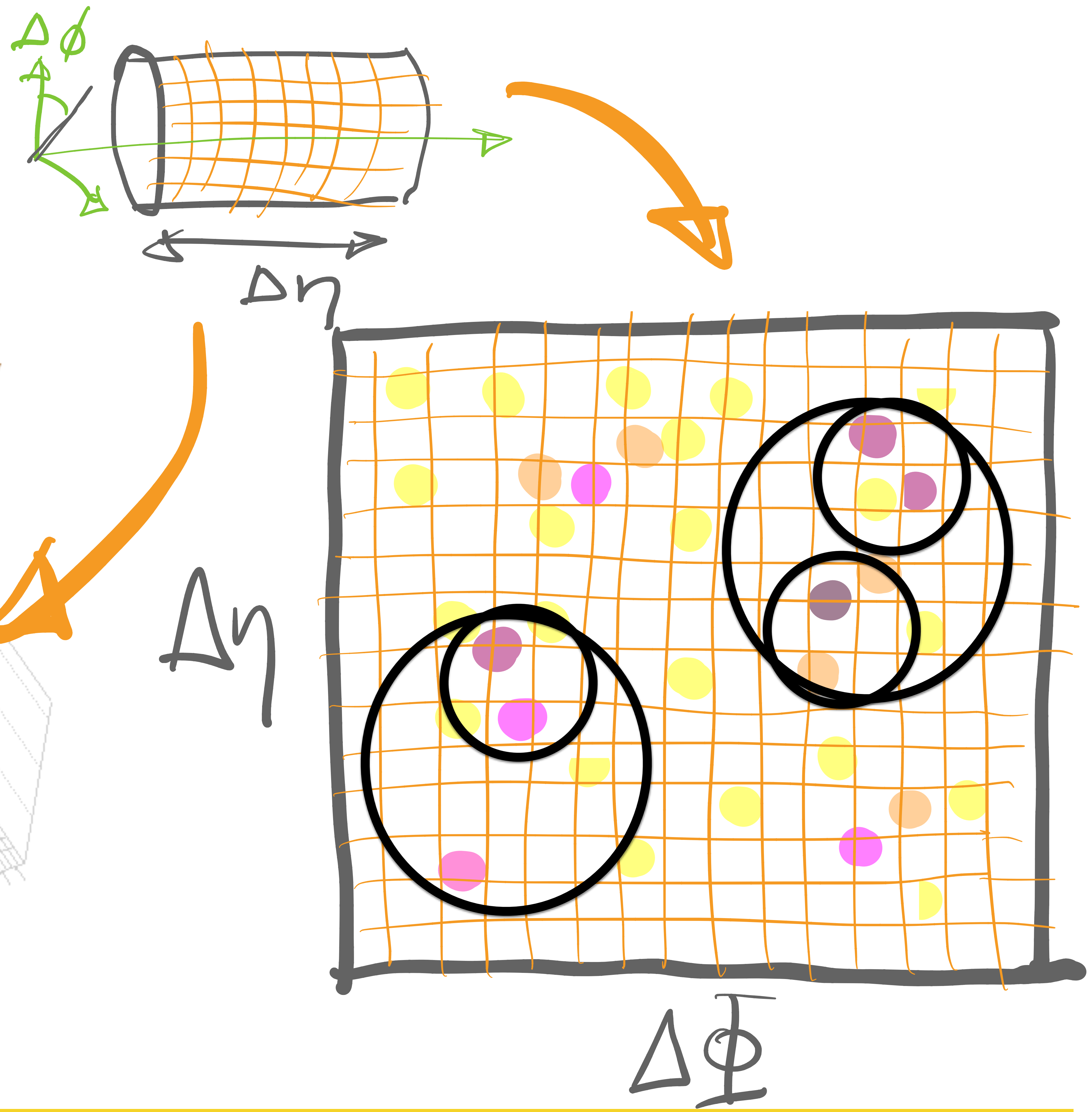
A multijet event at the LHC@13TeV



How to identify jets?

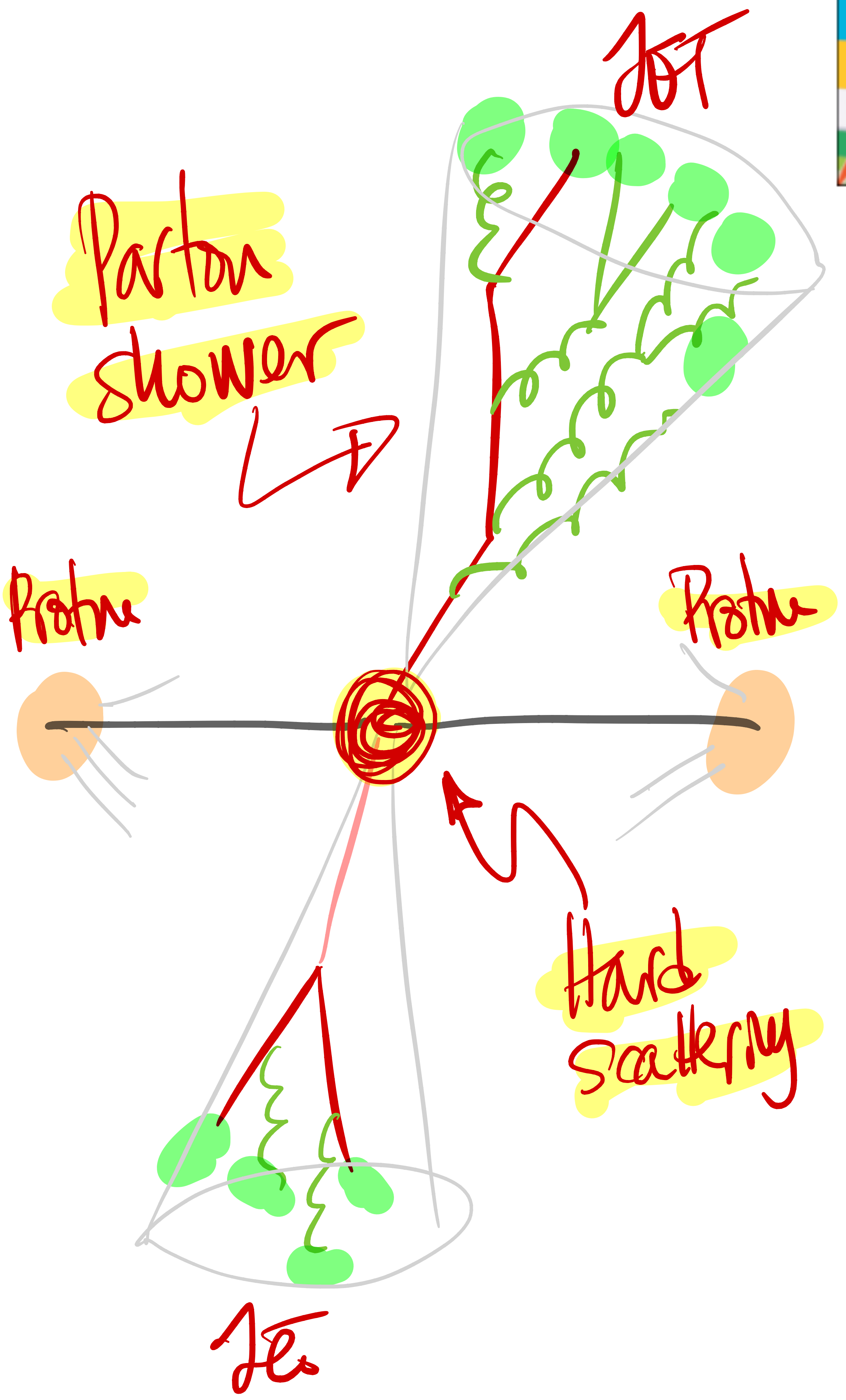


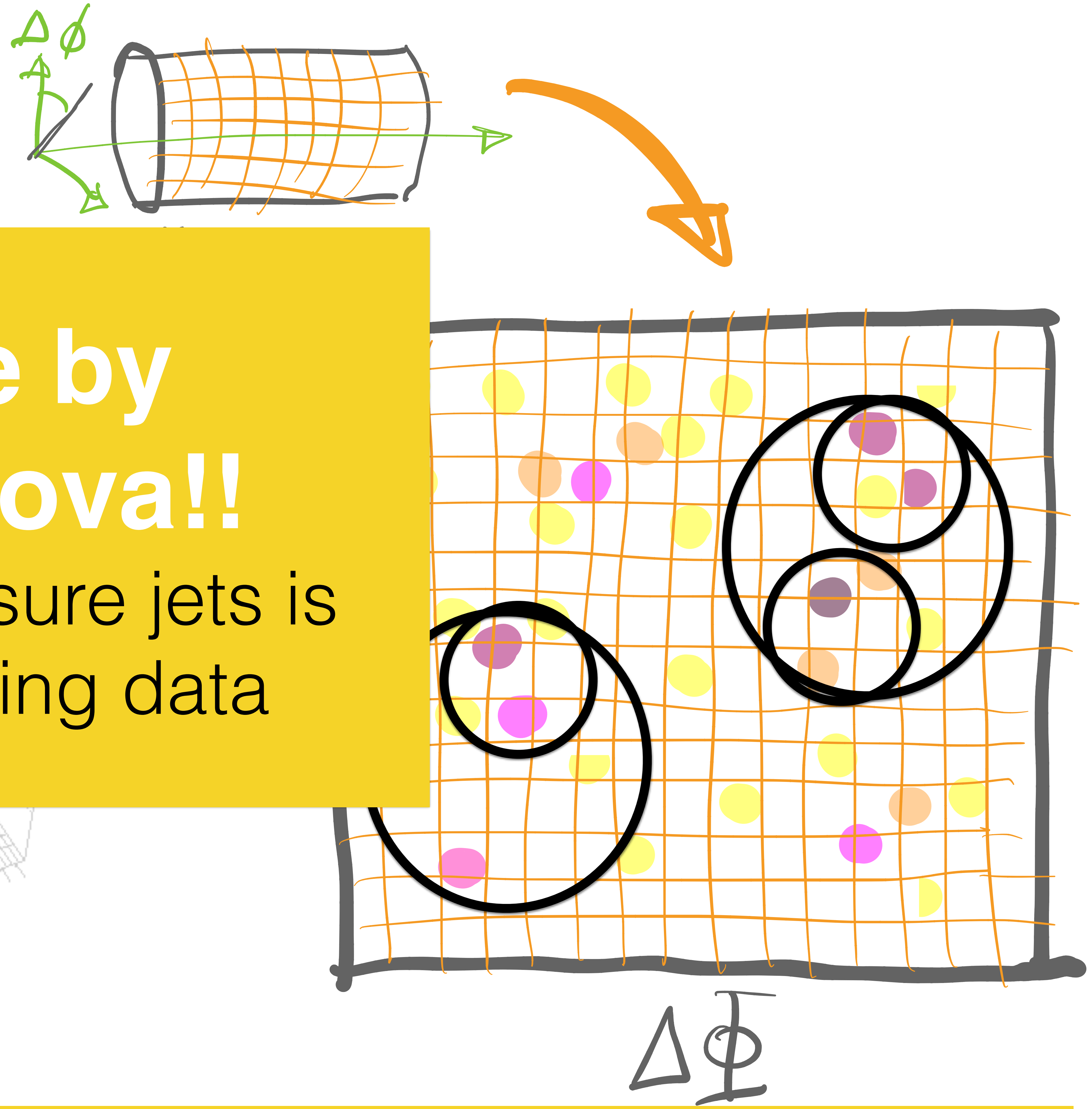




Jets are **proxies** to quarks and gluons produced in elementary QCD processes

How to identify jets?





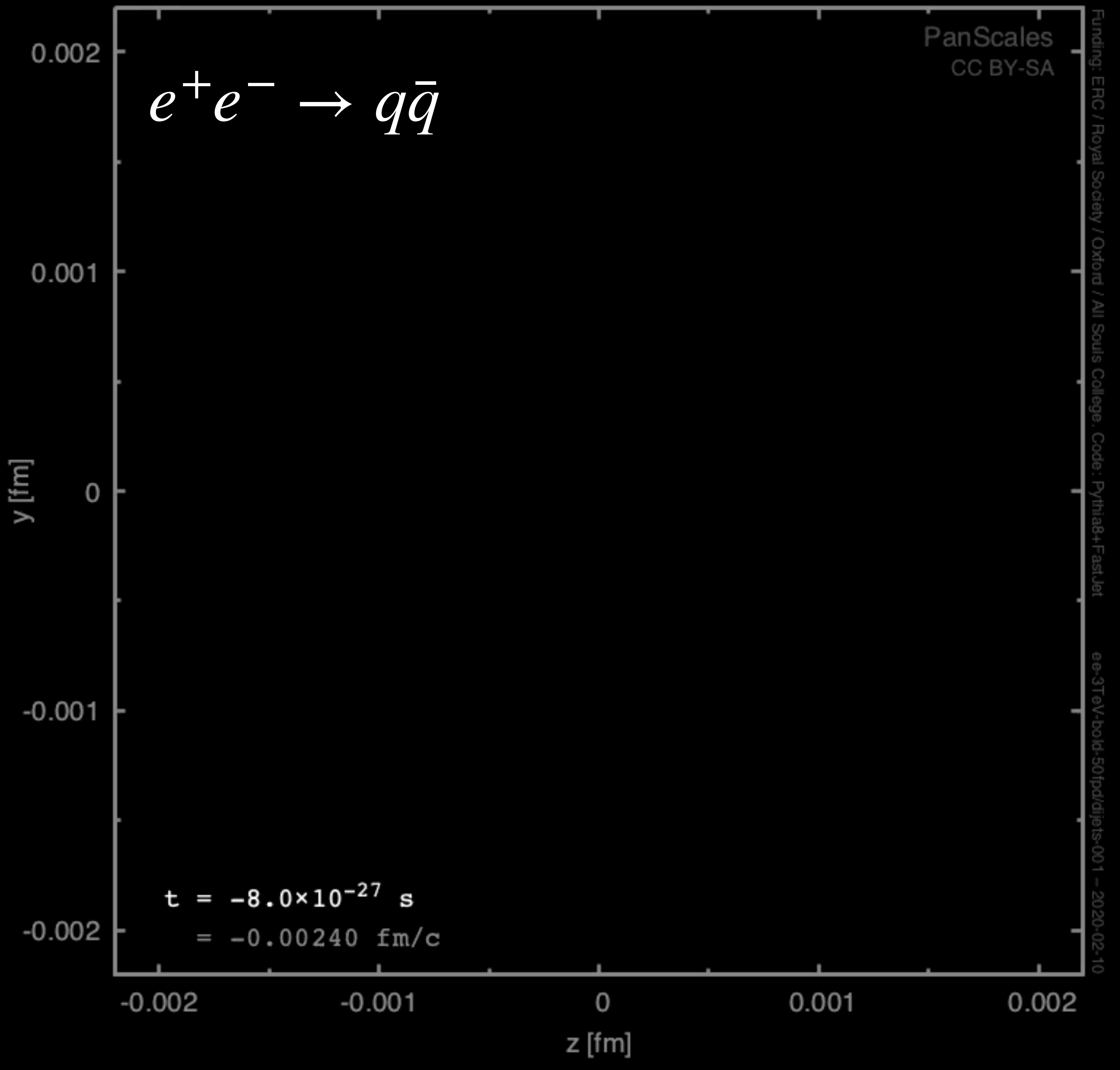
See lecture by Jana Bielcikova!!

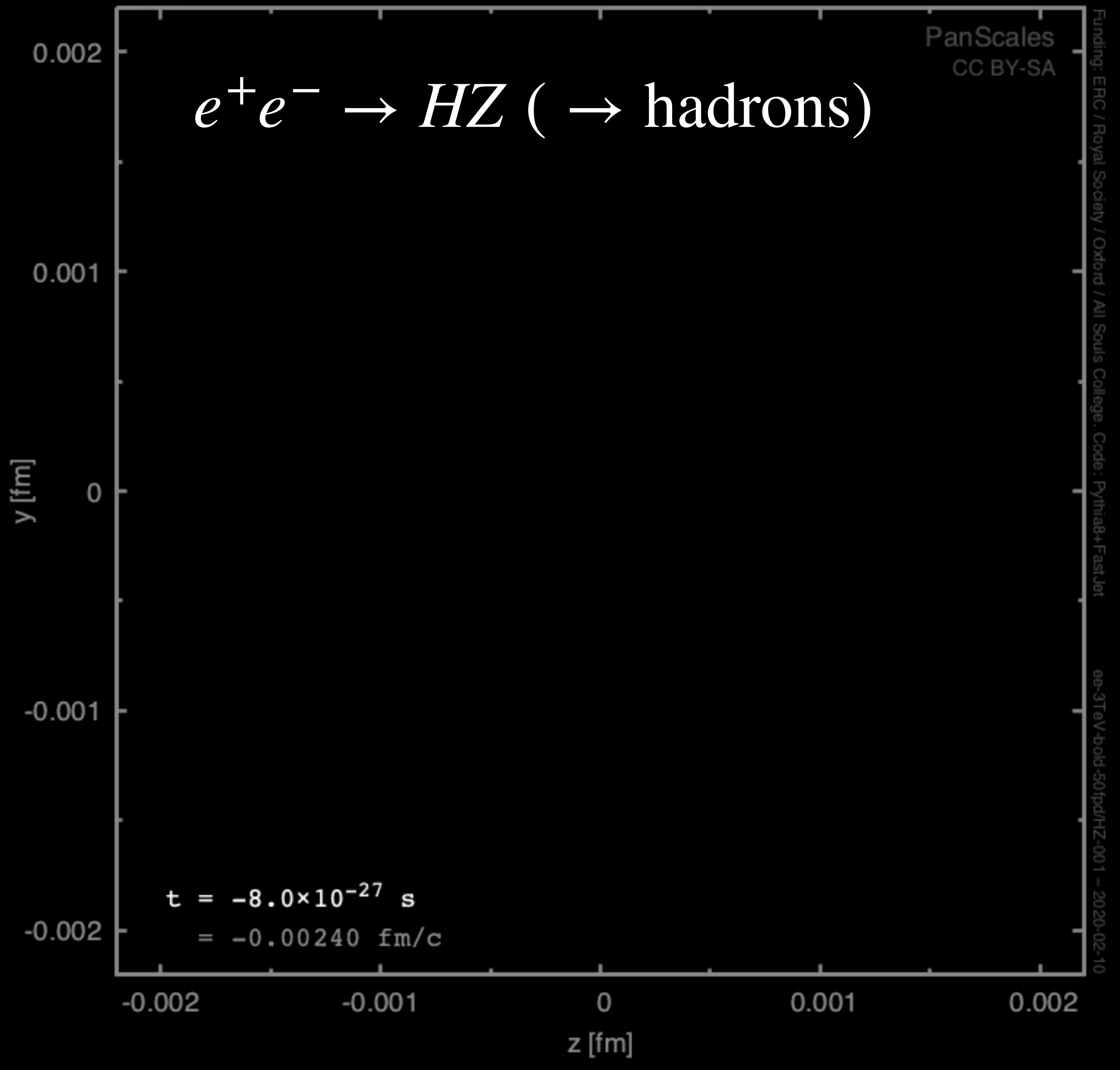
How you define/measure jets is crucial for interpreting data

Jets are **proxies** to quarks and gluons produced in elementary QCD processes

QCD jets are fundamental tools at the LHC

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



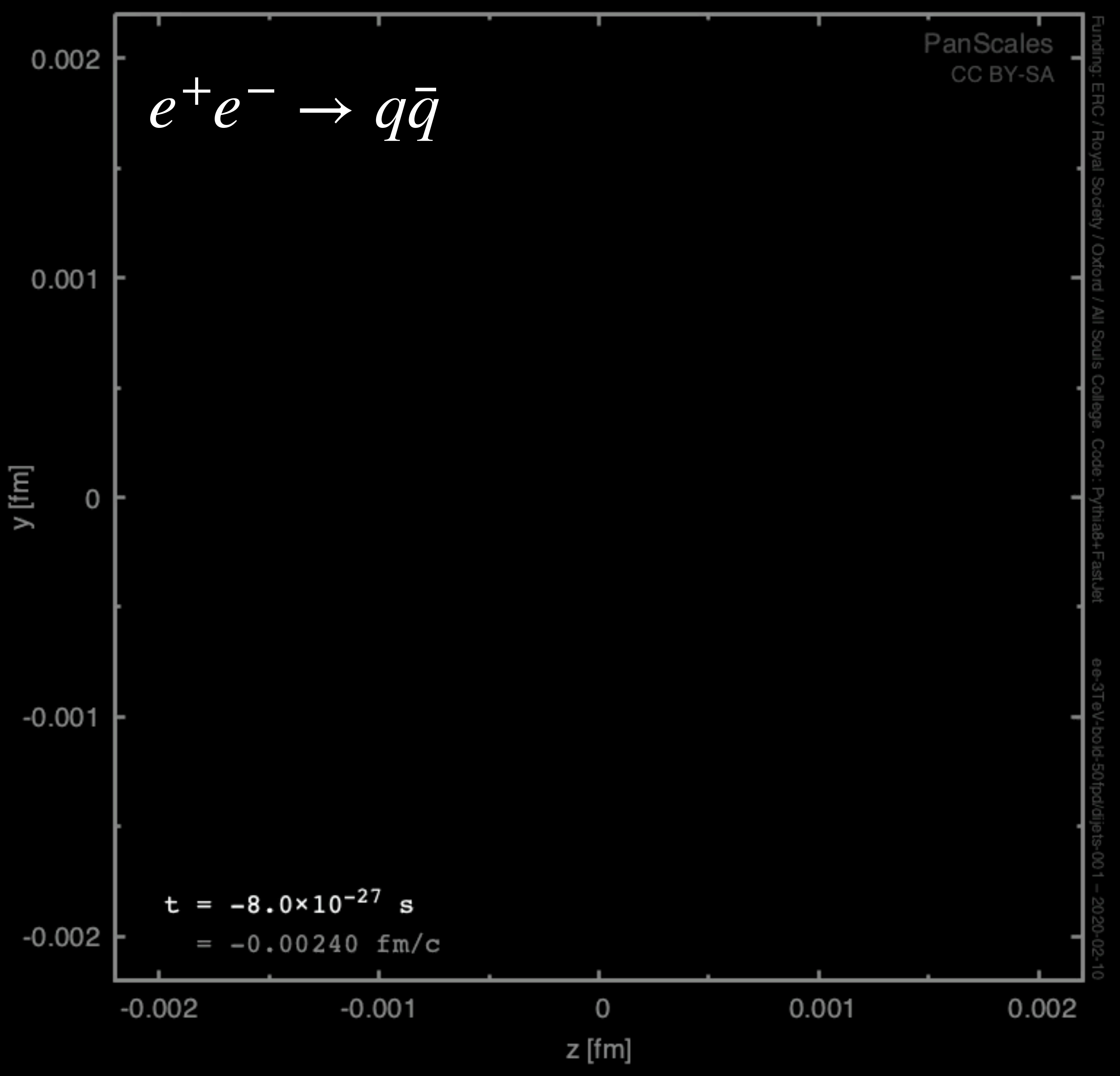


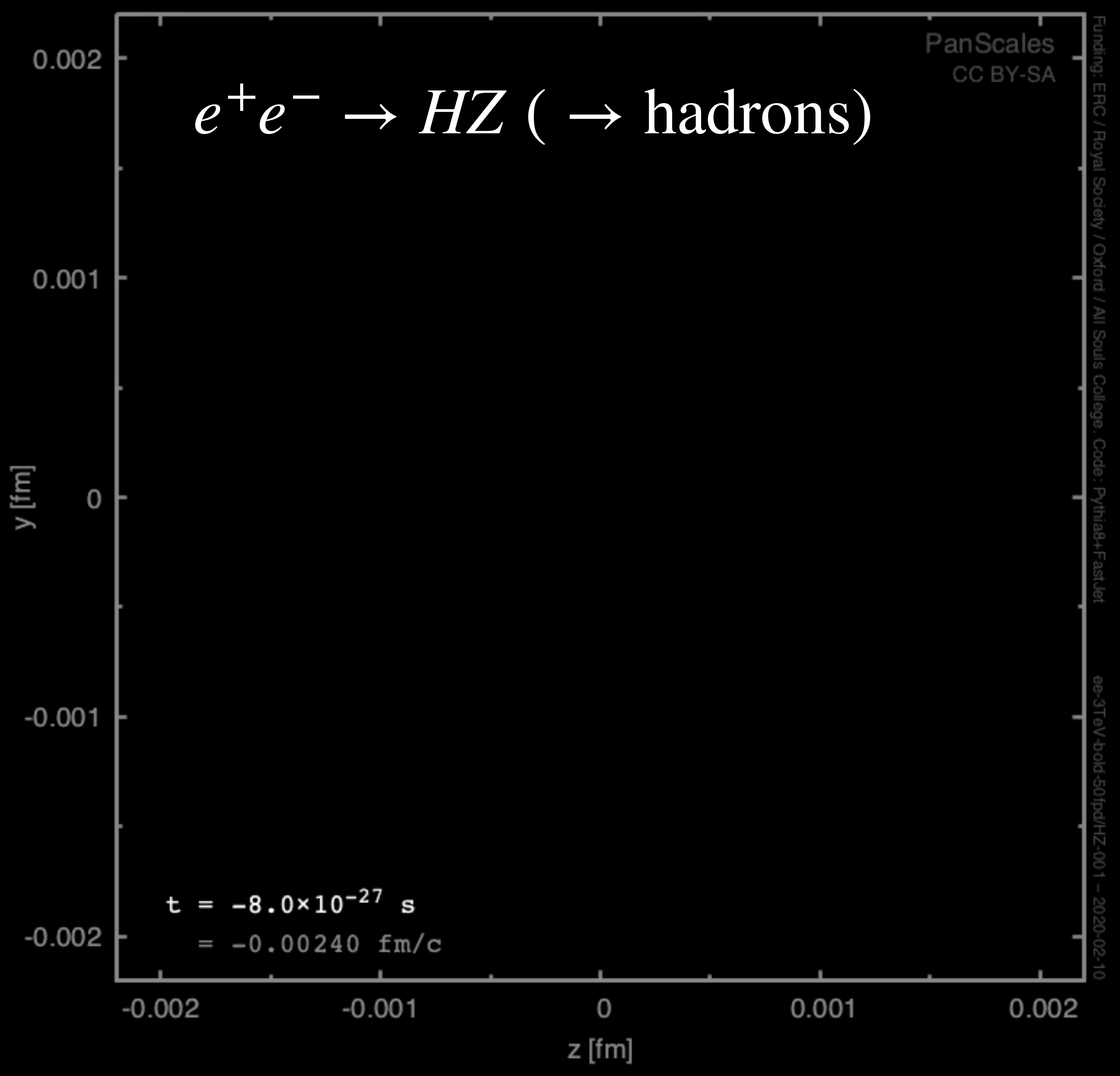
Initial particles in yellow
Intermediate particles in blue
Final particles in red

[PANSCALES - G. Salam et al - Simulation of the events are produced with Pythia 8 times estimated by clustering algorith - see details in the web page]

QCD jets are fundamental tools at the LHC

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





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

[PANSCALES - G. Salam et al - Simulation of the events are produced with Pythia 8 times estimated by clustering algorith - see details in the web page]

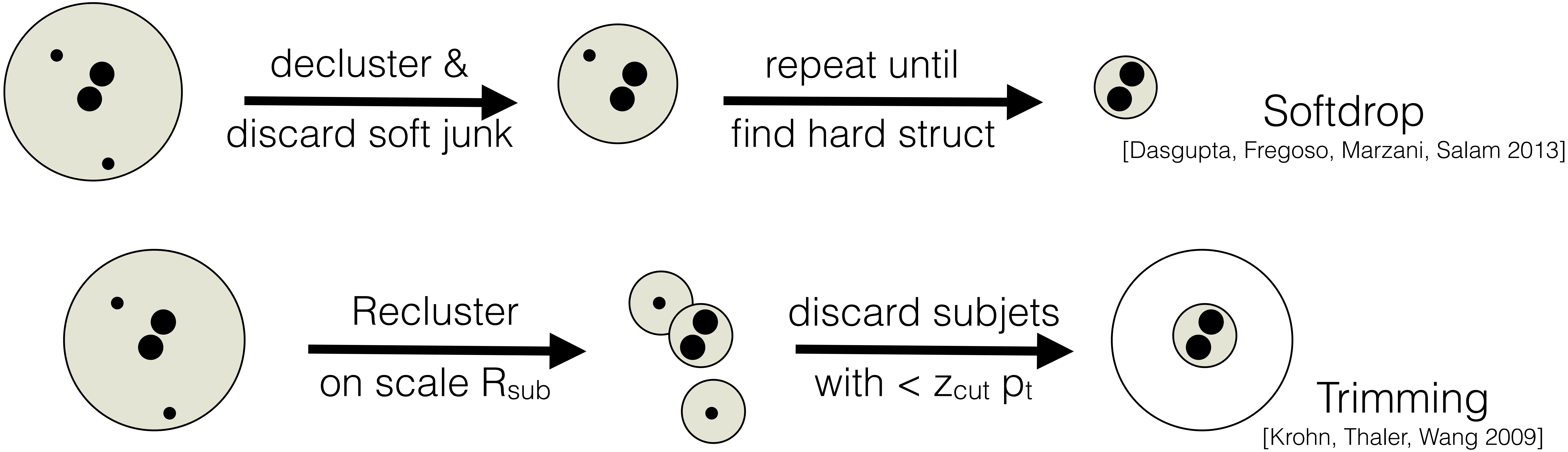
Jet substructure

More in Alba Soto Ontoso Plenary on Monday

Find different substructures in identified jets

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

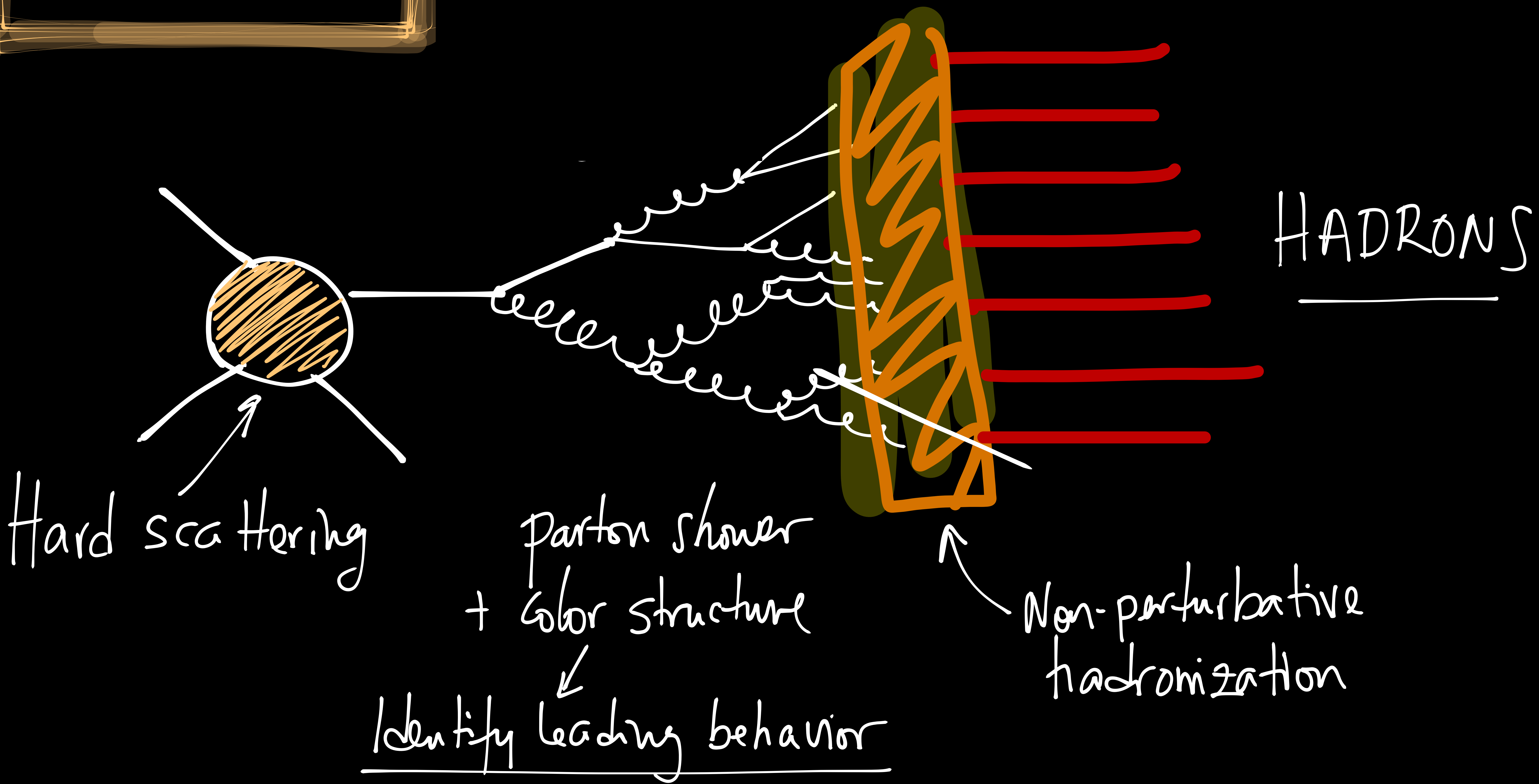
[Figs from G Salam]



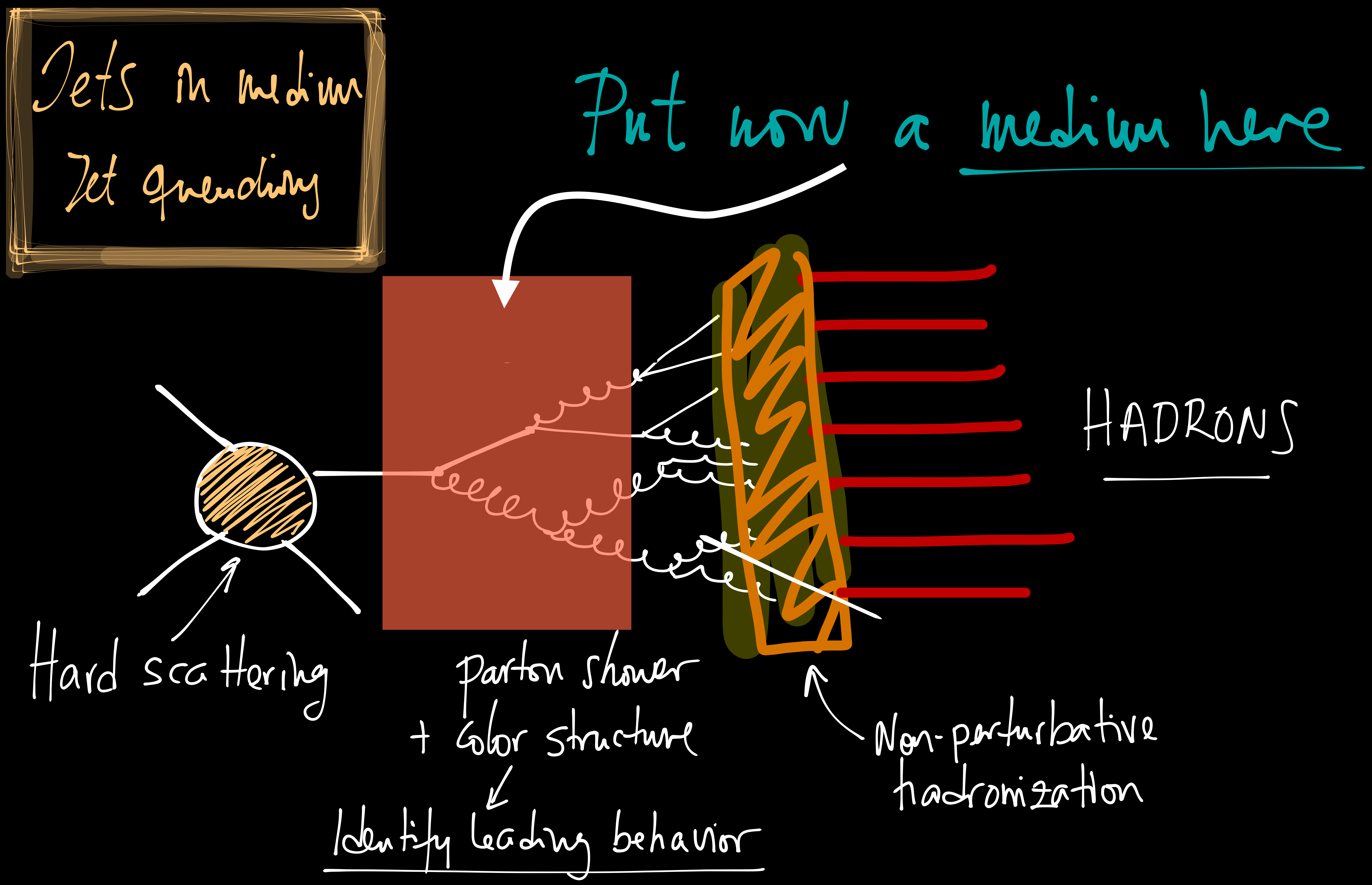
E.g. to identify two-pronged jet structures - boosted H/W/Z

Jets in medium

Jet quenching



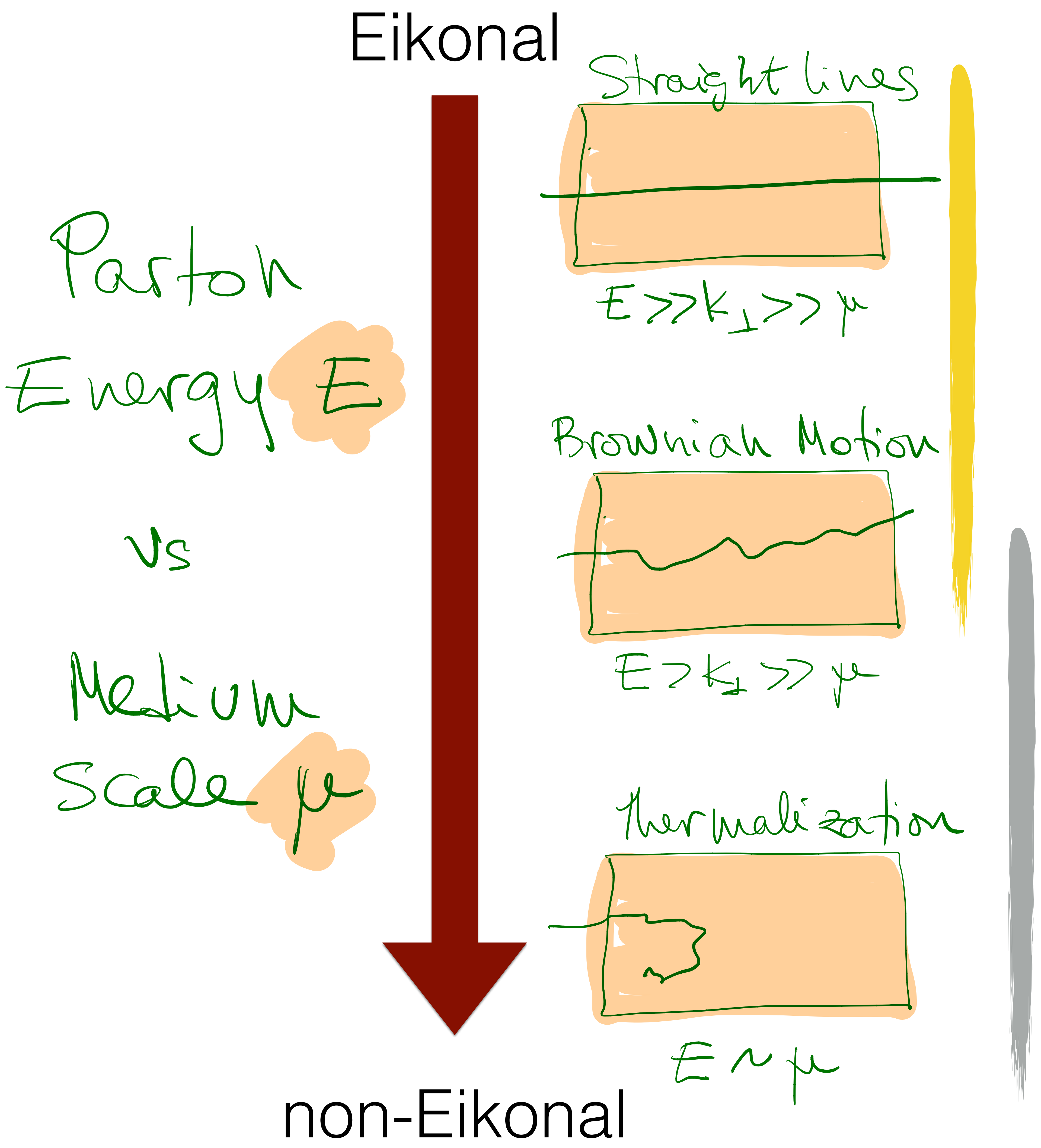
Jets are extended objects - ideal to probe different times and scales



Jets are extended objects - ideal to probe different times and scales

In-medium parton propagation

Medium response: Yeonju Go Plenary on Monday

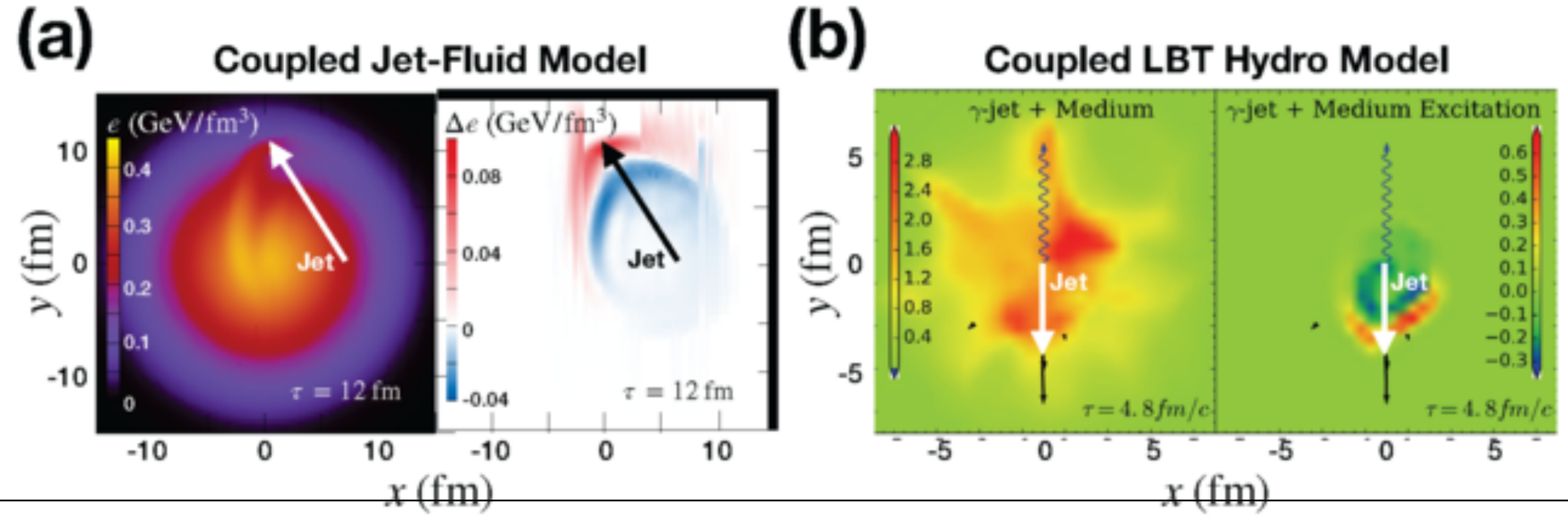


Medium is a background field: **color rotation**
[Energy of the parton unmodified]

$$W(x_\perp) = \mathcal{P} \exp\left\{ig\int d\xi\, n\cdot A(\xi, x_\perp)\right\}$$

$$G(x_\perp; y_\perp) = \mathcal{P}\int \mathcal{D}\mathbf{r} \exp\left\{i\frac{E}{2}\int d\xi \left[\frac{d\mathbf{r}}{d\xi}\right]^2 + ig\int d\xi\, n\cdot A(\xi, \mathbf{r})\right\}$$

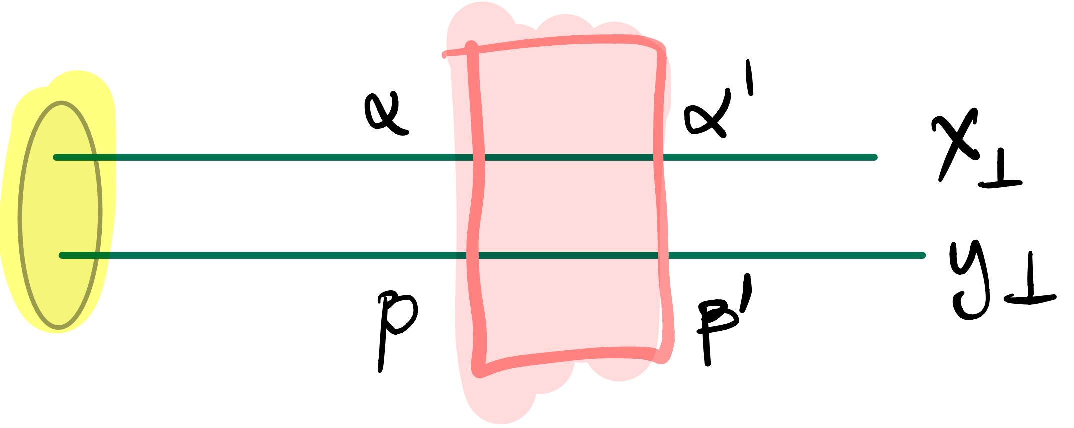
Medium is **dynamical**
[Energy exchanged with the medium]



[Tachibana 2019]

Scattering amplitudes

Color dipole - The simplest configuration



Background field
Color Rotation

S-Matrix

$$|\alpha'\beta'\rangle = S_{\alpha'\beta'\alpha\beta}|\alpha\beta\rangle = W_{\alpha'\alpha}(x_\perp)\,W^\dagger_{\beta'\beta}(y_\perp)|\alpha\beta\rangle$$

Survival Probability

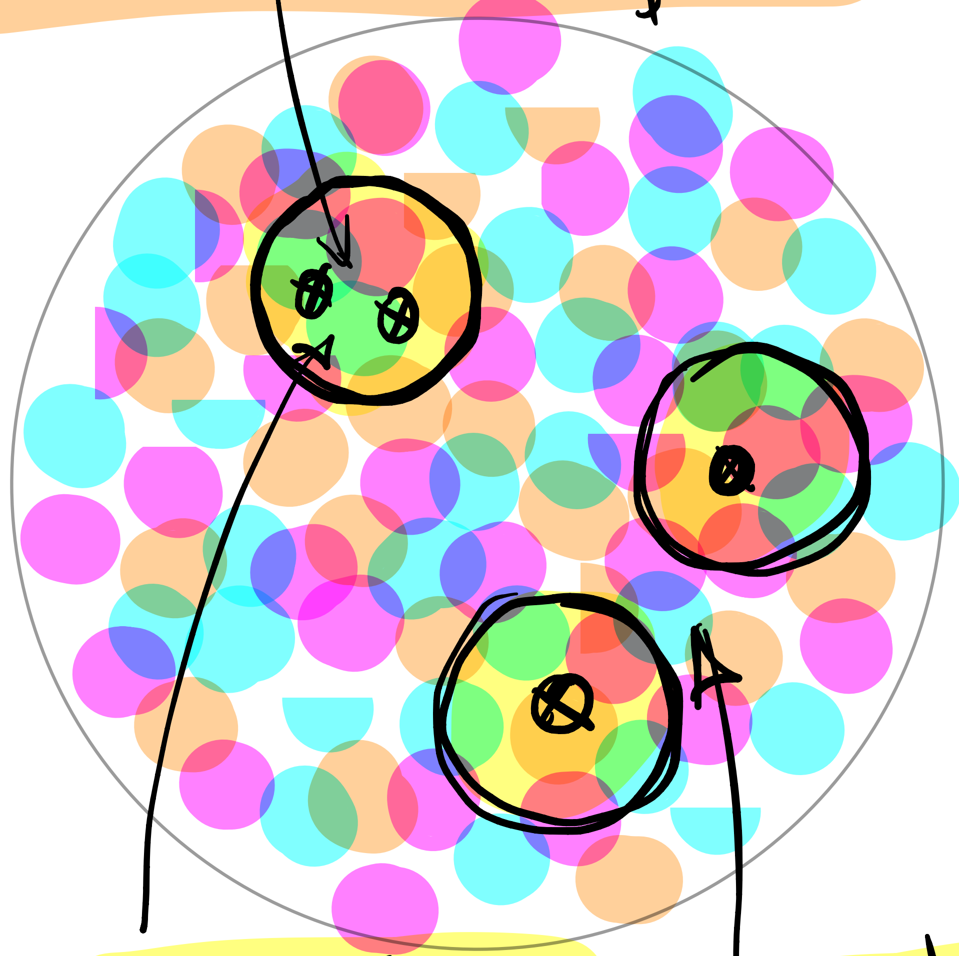
$$S(x_\perp, y_\perp) = \frac{1}{N_c}\,\mathrm{tr}\left[W(x_\perp)\,W^\dagger(y_\perp)\right]$$

Average over Configurations $\frac{1}{N_c}\langle \mathrm{tr}\left(W(x_\perp)W^\dagger(y_\perp)\right)\rangle_{med}$

A useful picture: color domains in transverse plane

Correlation length

$1/Q_s \sim \frac{1}{\sqrt{\hat{q}t}}$

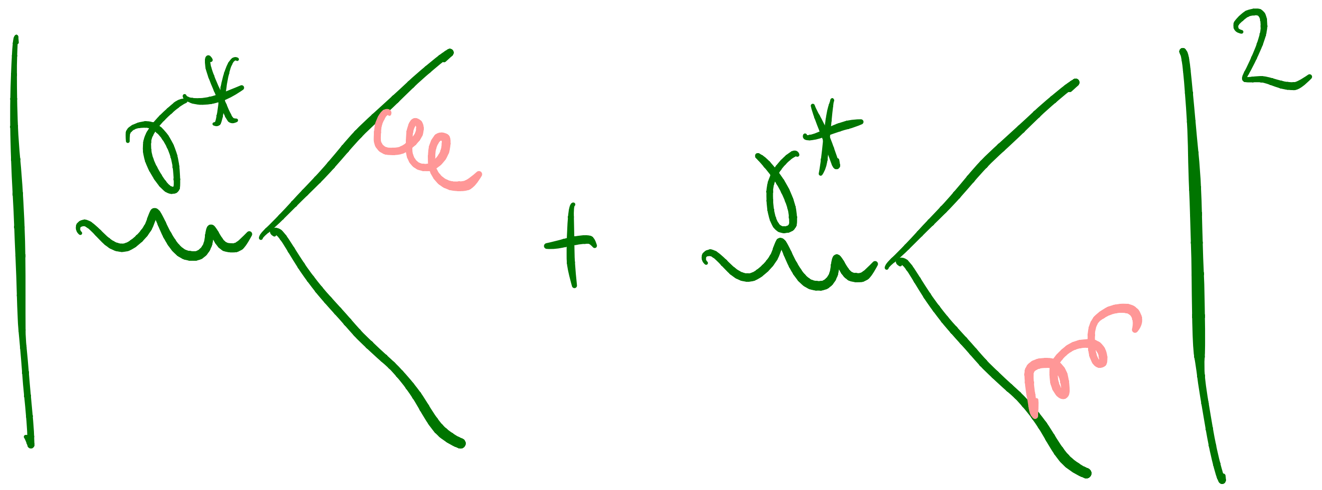


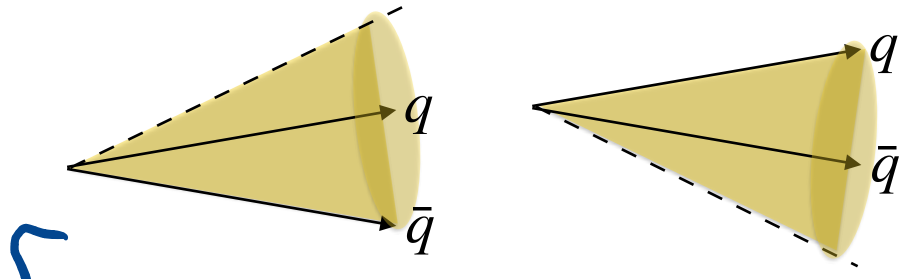
correlated uncorrelated

Intra-jet color coherence

[Mehtar-Tani, Salgado, Tywoniuk; Iancu, Casalderrey-Solana, … 2010-]

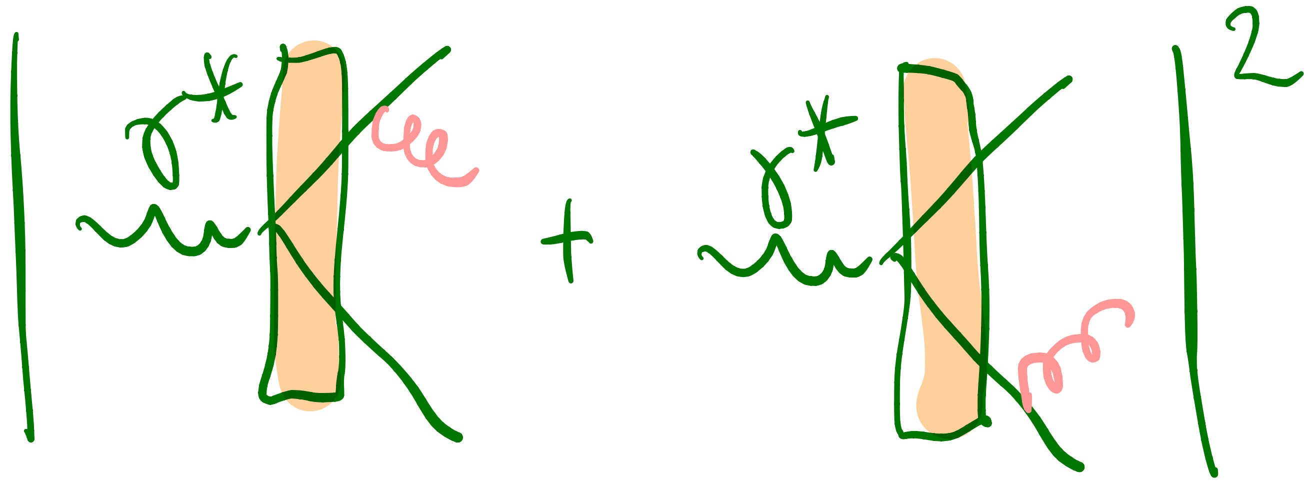
QCD antenna - classical calculation including color coherence *[angular ordering]*





$$\omega \frac{dN}{d\omega\, d\theta} \sim \alpha_s C_F \left[R_q - J + R_{\bar{q}} - J \right]$$

The QCD medium can break color coherence - independent color rotation of q and qbar



$$\omega \frac{dN}{d\omega\, d\theta} \sim \alpha_s C_F \left[R_q - S_{q\bar{q}} J + R_{\bar{q}} - S_{\bar{q}q} J \right]$$

$$S(x_\perp, y_\perp) \equiv \frac{1}{N_c^2 - 1} \mathrm{Tr} \left\langle W(x_\perp) W^\dagger(y_\perp) \right\rangle_{\mathrm{med}} \simeq \exp\left\{ -\frac{1}{4} \hat{q}\, \theta_{q\bar{q}}^2\, L^3 \right\}$$

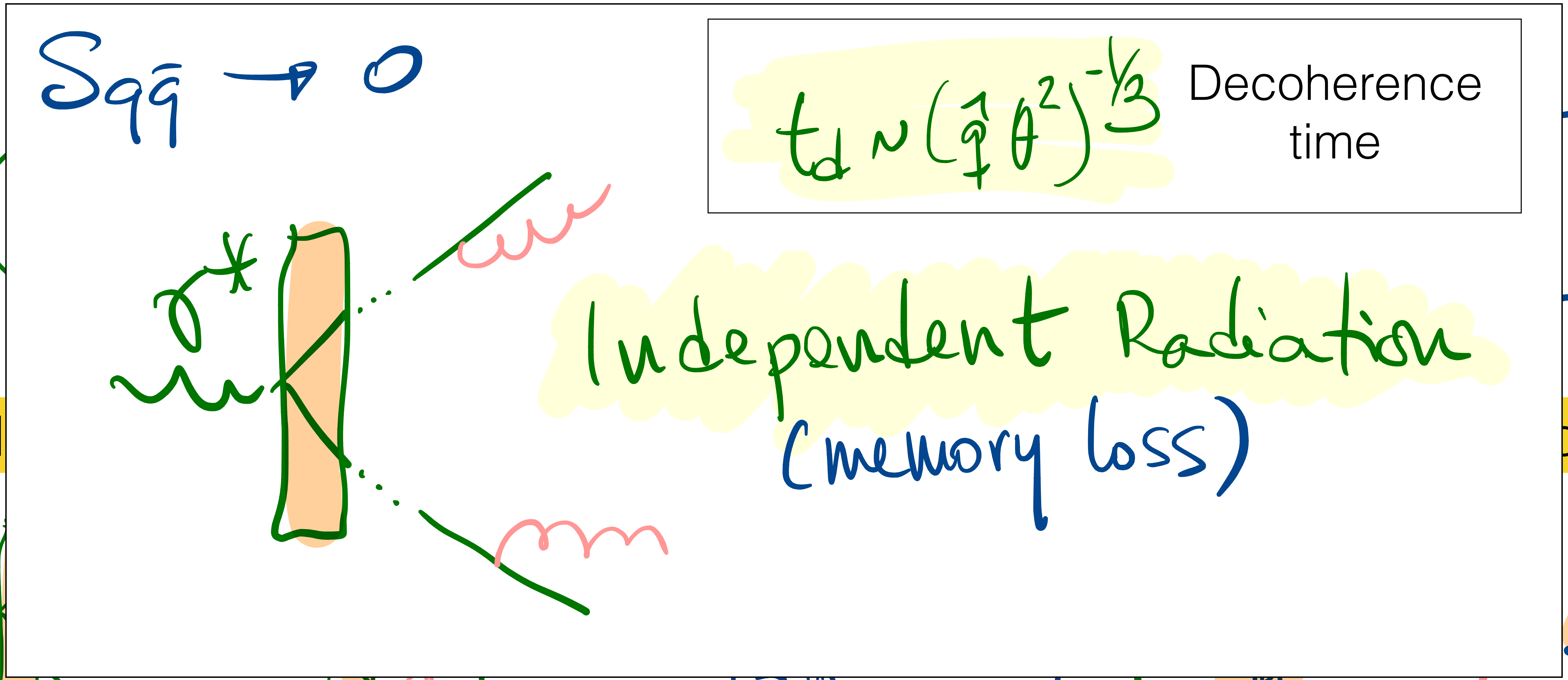
Survival probability

$\hat{q}$ - jet quenching parameter

Intra-jet color coherence

[Mehtar-Tani, Salgado, Tywoniuk; Iancu, Casalderrey-Solana, … 2010-]

QCD antenna - classical calculation including color coherence *[angular ordering]*



The QCD med … of q and qbar

$$S(x_\perp,y_\perp) \equiv \frac{1}{N_c^2-1}\mathrm{Tr}\left\langle W(x_\perp)W^\dagger(y_\perp)\right\rangle_{\mathrm{med}} \simeq \exp\left\{-\frac{1}{4}\hat{q}\,\theta_{q\bar{q}}^2\,L^3\right\}$$

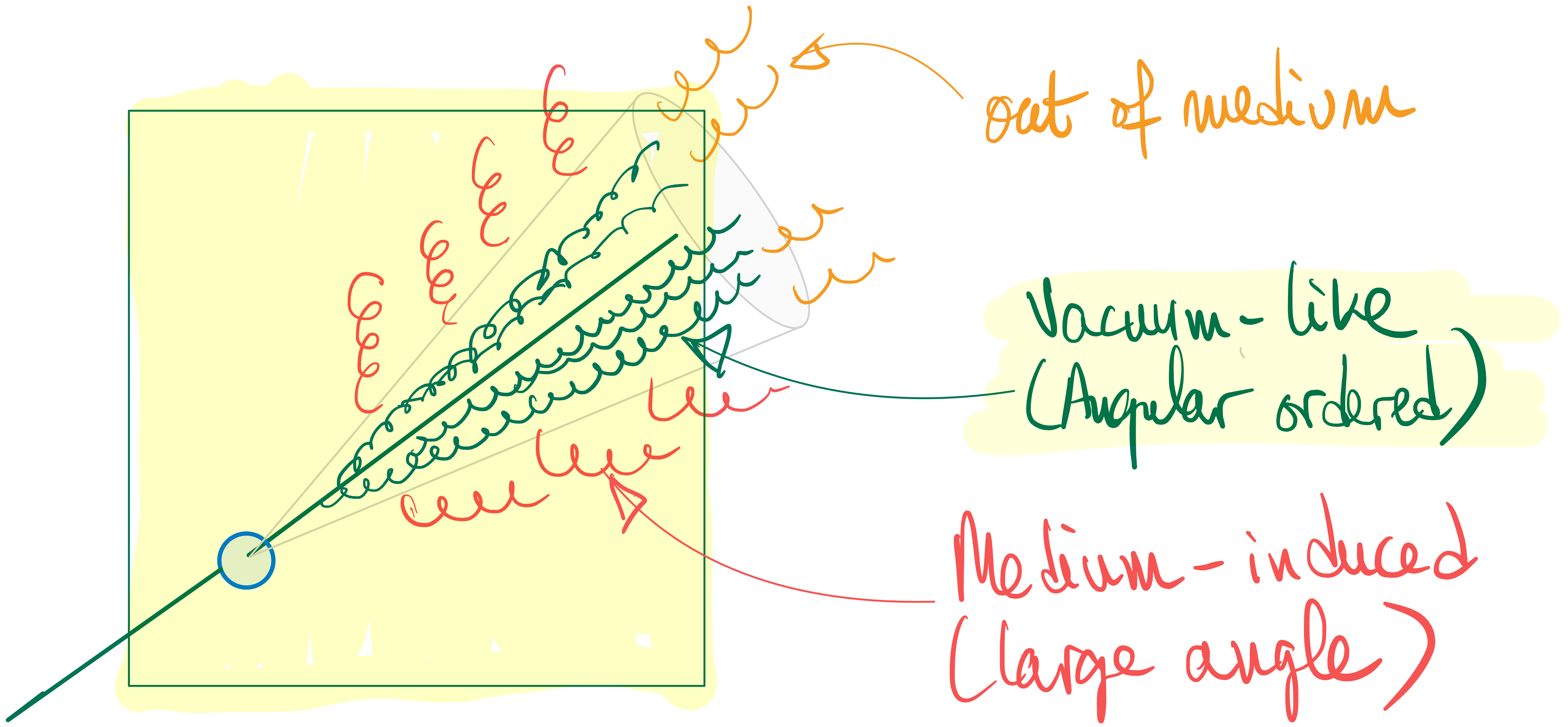
Survival probability

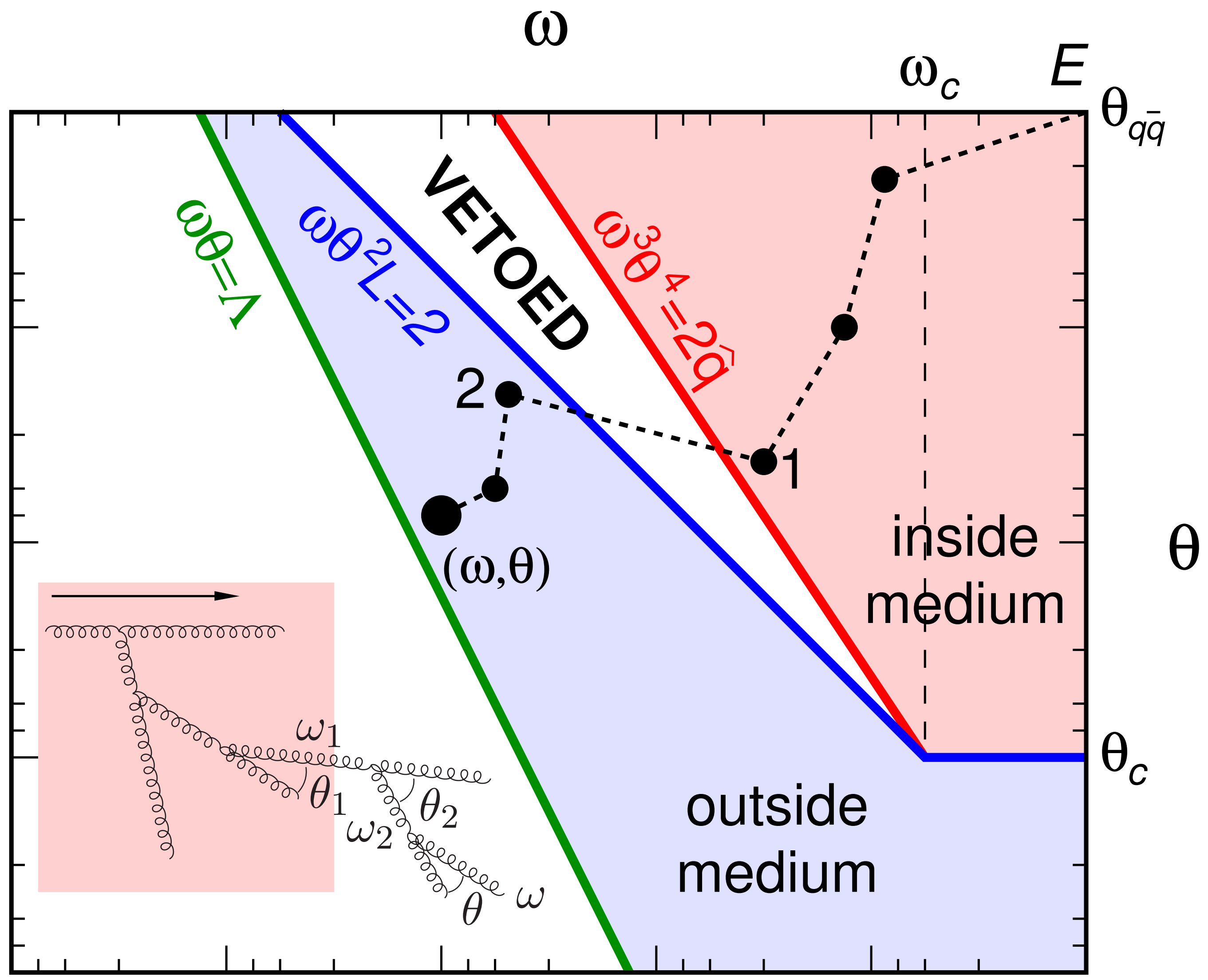
$\hat{q}$ - jet quenching parameter

Vacuum-like emissions

Hard splittings with small formation time $t_f \ll t_d$ cannot be resolved by the medium

First hard splitting + DLA — **most of the cascade is vacuum-like** (with energy loss on top)





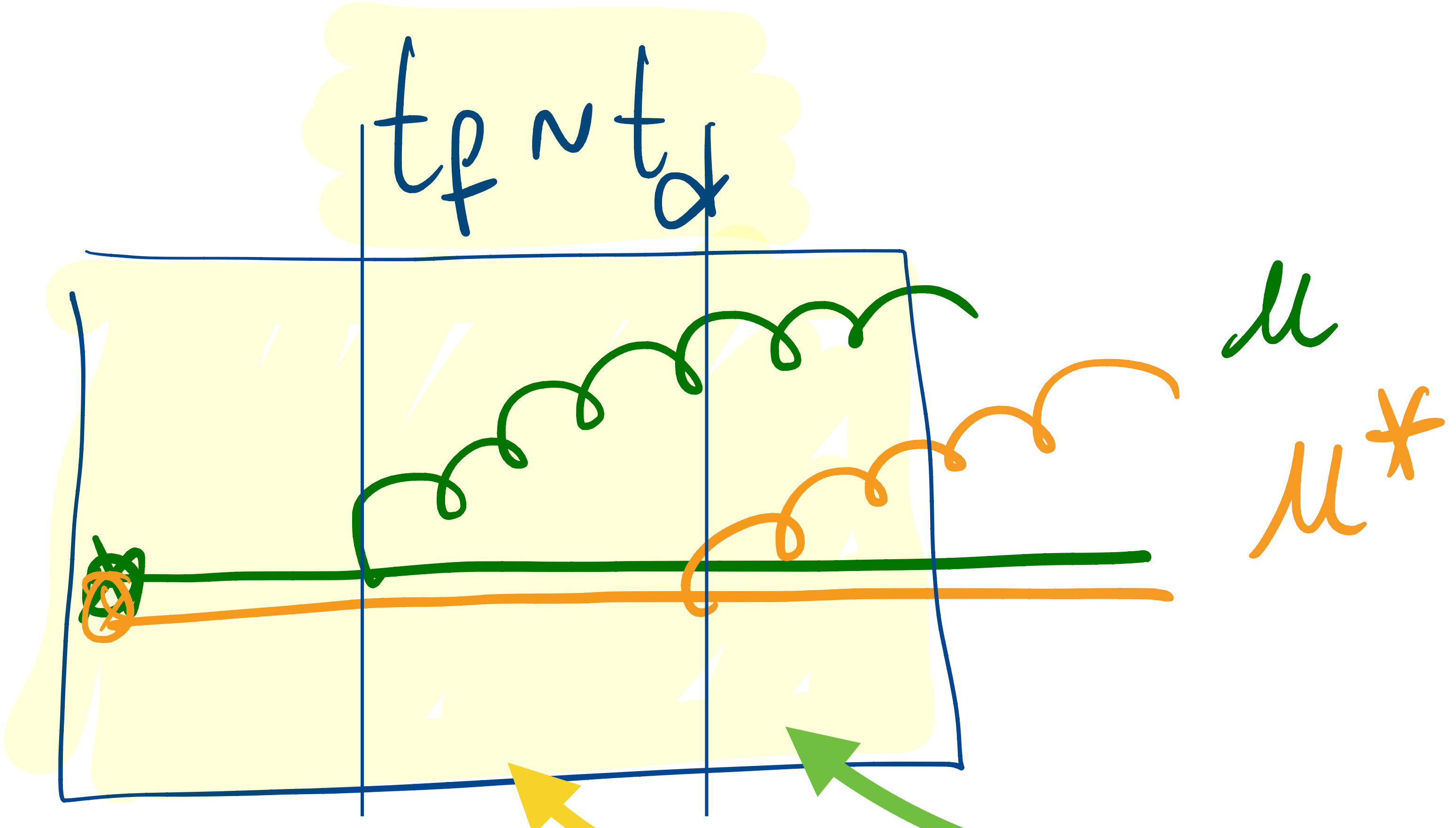
[Caucal, Iancu, Mueller, Soyez 2018]

In the DLA approach, the relevant jet structure is formed very early in the cascade

Medium-induced radiation

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others… starting in the mid-90's]

For fluctuation with $t_f \sim t_d$ the gluon is resolved: **medium-induced radiation**



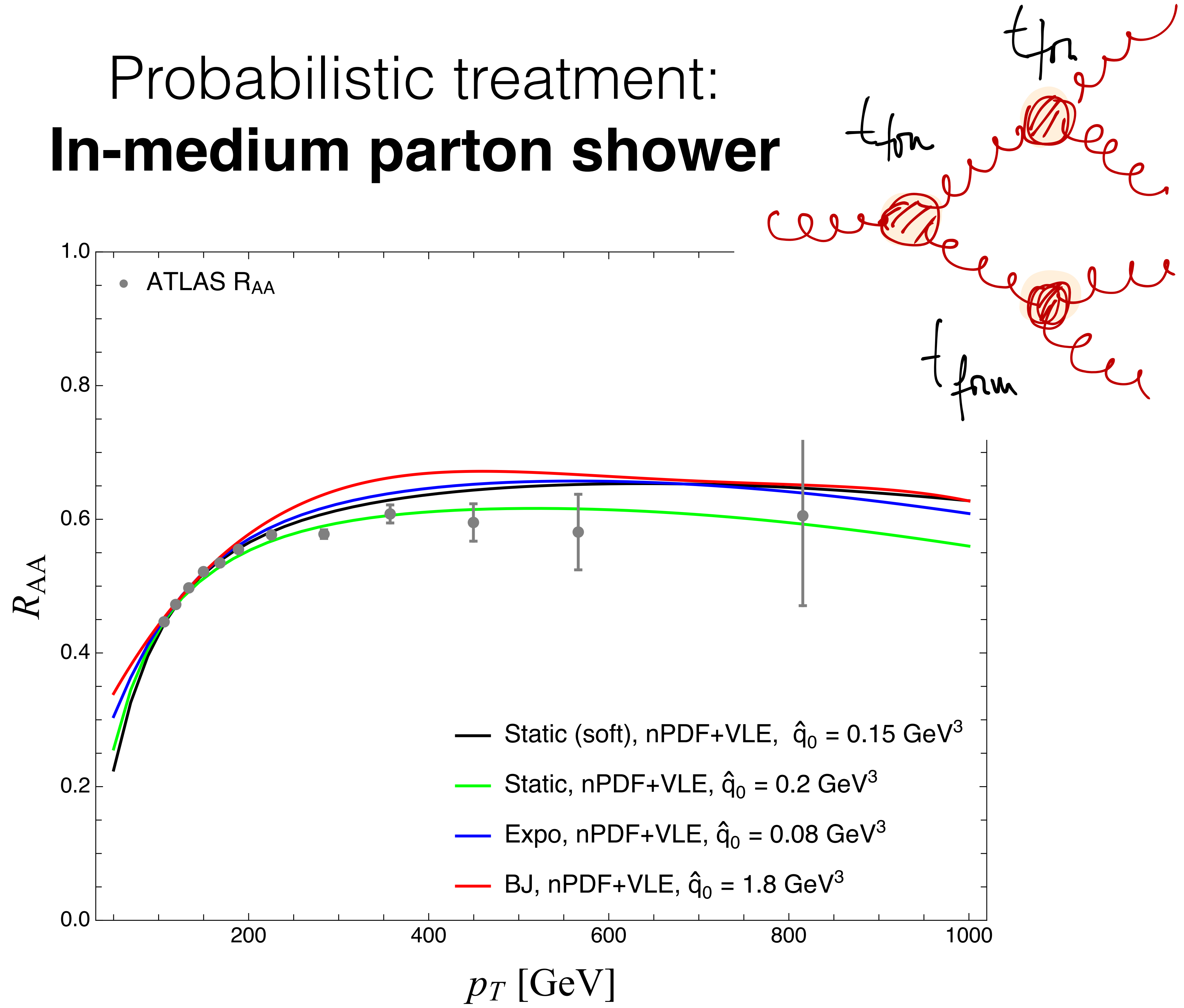
$$\omega \frac{dN}{d\omega d^2\mathbf{k}} \sim \frac{\alpha_s C_R}{\omega^2} \mathrm{Re} \int_{t',t} \int_{\mathbf{p},\mathbf{q}} \mathbf{p}\cdot\mathbf{q}\,\tilde{\mathcal{K}}(t',\mathbf{q};t,\mathbf{p})\,\mathcal{P}(L,\mathbf{k};t',\mathbf{q})$$

$$\mathcal{K}(t',\mathbf{z};t,\mathbf{y}) = \int \mathcal{D}\mathbf{r}\, \exp\left[\int_t^{t'} ds \left(\frac{i\omega}{2}\dot{\mathbf{r}}^2 - \frac{1}{2}n(s)\sigma(\mathbf{r})\right)\right]$$

$t_f \sim t_d \ll L$: democratic branching

[Balizot, Dominguez, Iancu, Mehtar-Tani 2013; Jeon, Moore 2005]

Probabilistic treatment:
In-medium parton shower



[Adhya, Salgado, Spousta, Tywoniuk 2022]

Medium-induced radiation

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others… starting in the mid-90's]

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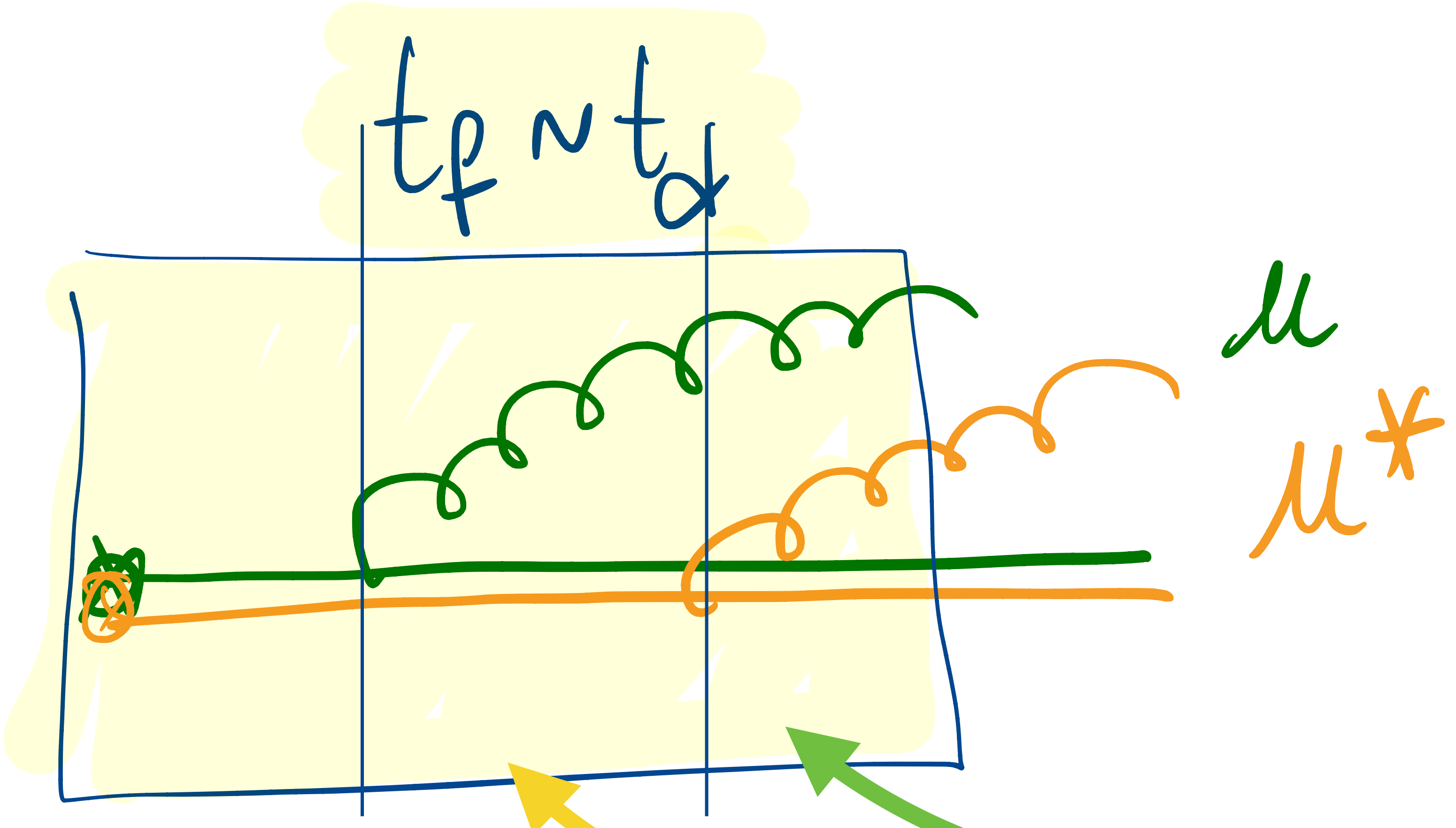

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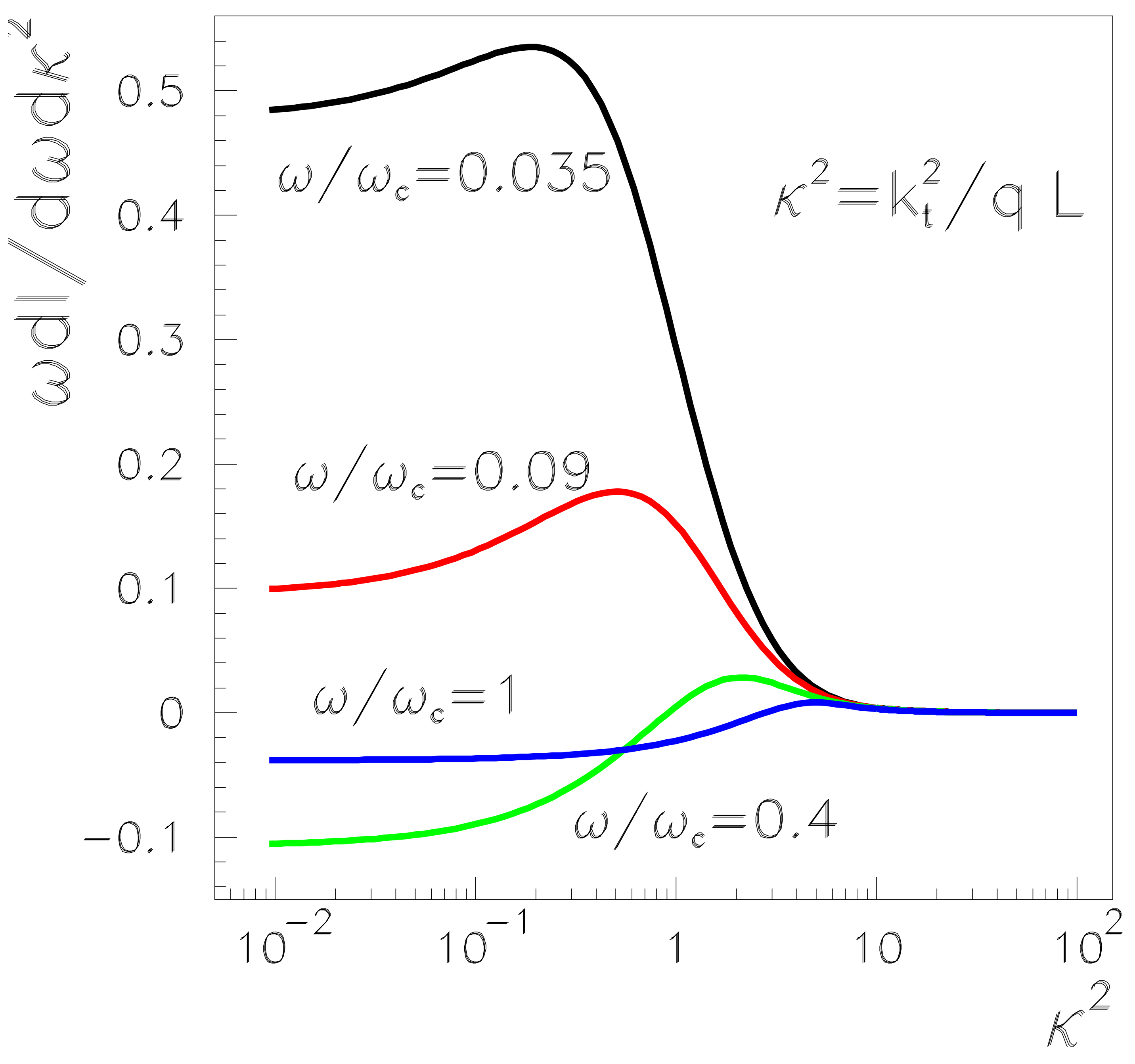
$$\mathcal{K}(t',\mathbf{z};t,\mathbf{y}) = \int \mathcal{D}\mathbf{r}\,\exp\left[\int_t^{t'} ds\left(\frac{i\omega}{2}\dot{\mathbf{r}}^2 - \frac{1}{2}n(s)\sigma(\mathbf{r})\right)\right]$$

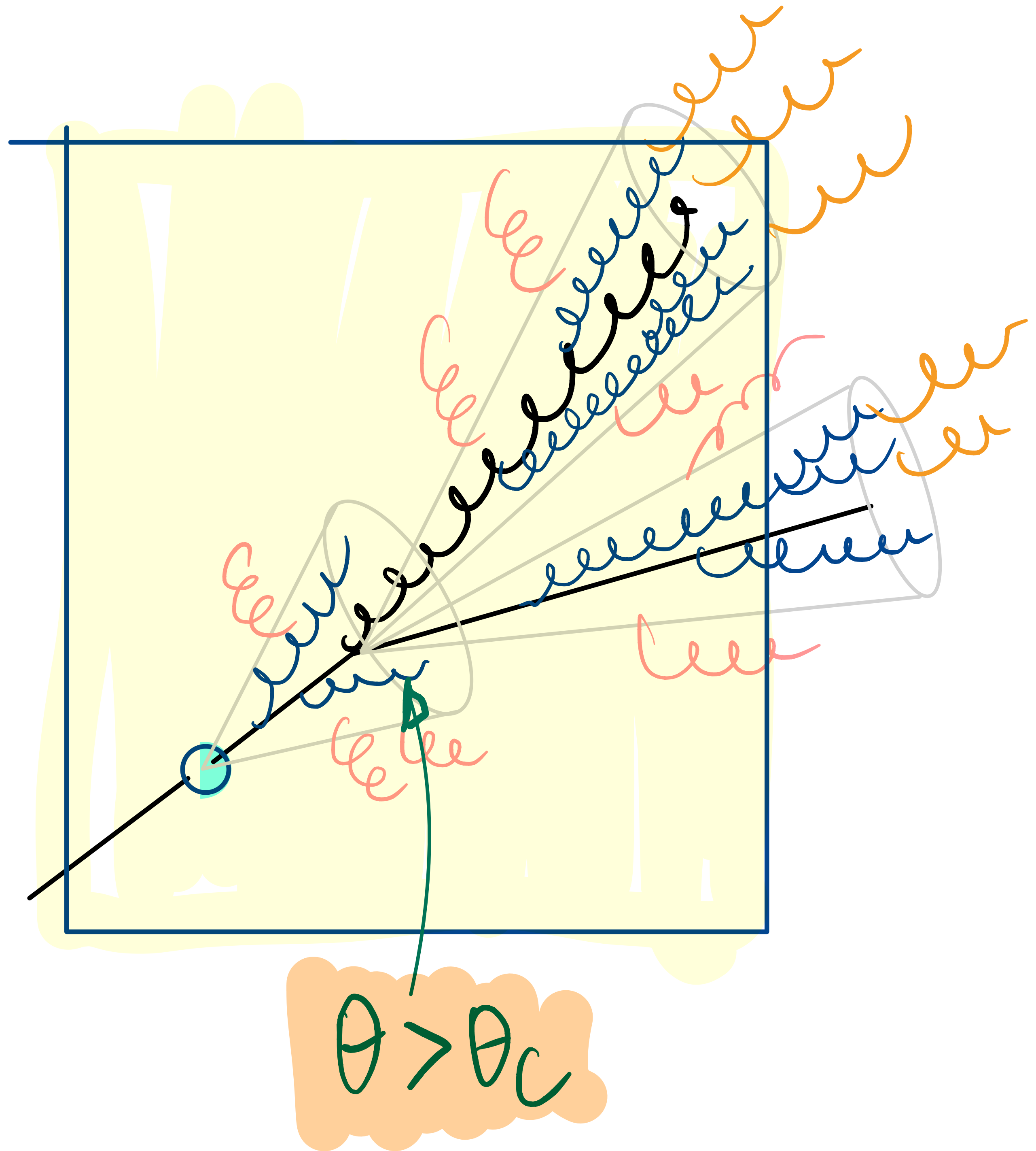
For fluctuation with $t_f > t_d$
LPM suppression



A picture of in-medium jets

[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2012]

Color coherence provides a clean picture of parton shower in medium
Medium induced radiation by **subjets** defined by **<u>resolution scale</u>** of the medium



$$S(r_\perp) = e^{-\frac{1}{4}\int dt\, \hat{q}\, r^2(t)}$$

$$r(t) = \theta t \Rightarrow \theta_c \sim \frac{1}{\sqrt{\hat{q} t^3}}$$

Resolution power

$$\Lambda_\perp \sim \frac{1}{\sqrt{\hat{q} t}} \equiv \frac{1}{Q_s}$$

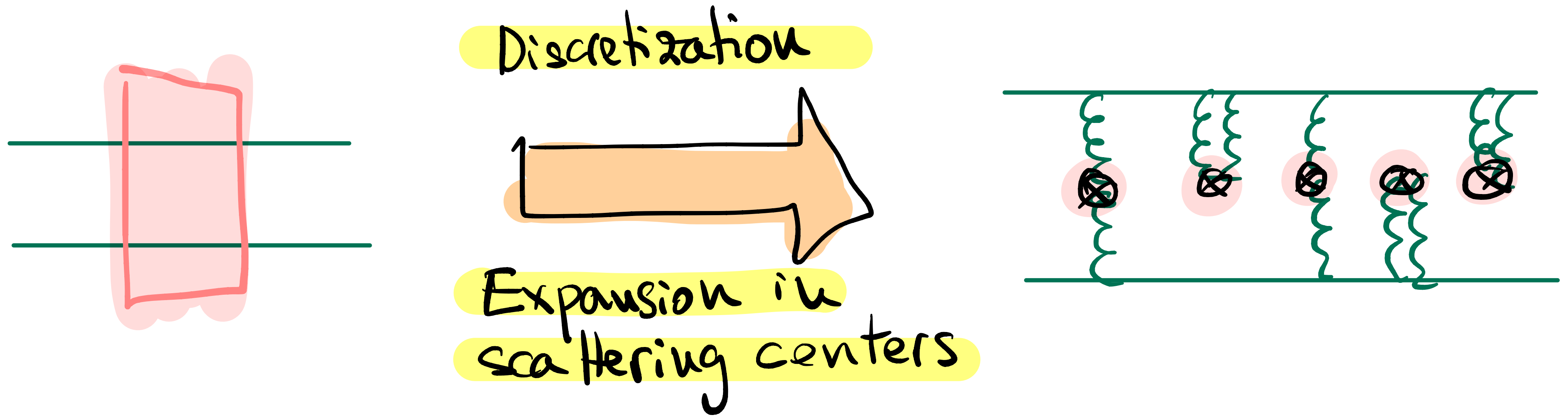
Inner core of the jet (subjet) is mildly modified

Medium-induced radiation at **large angles**

Subjets are effective emitters

Medium averages

A recoil-less medium $\sim$ a collection of static scattering centers



$$\frac{1}{N^2-1}\mathrm{Tr}\left\langle W_A(\mathbf{x})W_A(\mathbf{y})\right\rangle = \exp\left\{-\frac{1}{2}\int_{t_0}^{t} ds\, n(s)\,\sigma(\mathbf{x}-\mathbf{y})\right\}$$

$$S(x_\perp, y_\perp) \equiv \frac{1}{N_c^2-1}\mathrm{Tr}\left\langle W(x_\perp)W^\dagger(y_\perp)\right\rangle_{\rm med} \simeq \exp\left\{-\frac{1}{4}\hat{q}\,\theta_{q\bar{q}}^2\,L^3\right\}$$

$$n(s)\sigma(r) \simeq \frac{1}{2}\hat{q}\, r^2$$

harmonic oscillator

…Valid for (very)many soft scatterings - but QCD potential has **perturbative tails**

$$\sigma(\mathbf{r}) = \int_{\mathbf{q}} V(\mathbf{q})\left(1 - e^{i\mathbf{q}\mathbf{r}}\right) \qquad V(\mathbf{q}) \sim \frac{m_D^2}{\mathbf{q}^2(\mathbf{q}^2+m_D^2)}$$

New resummation needed - with both perturbative tails **and** multiple scattering

Improving the resummation

[Caron-Huot, Gale; Feal, Vazquez; Andres, Apolinario, Dominguez, Gonzalez-Martinez; Barata, Mehtar-Tani, Ontoso, Tywoniuk, Salgado]

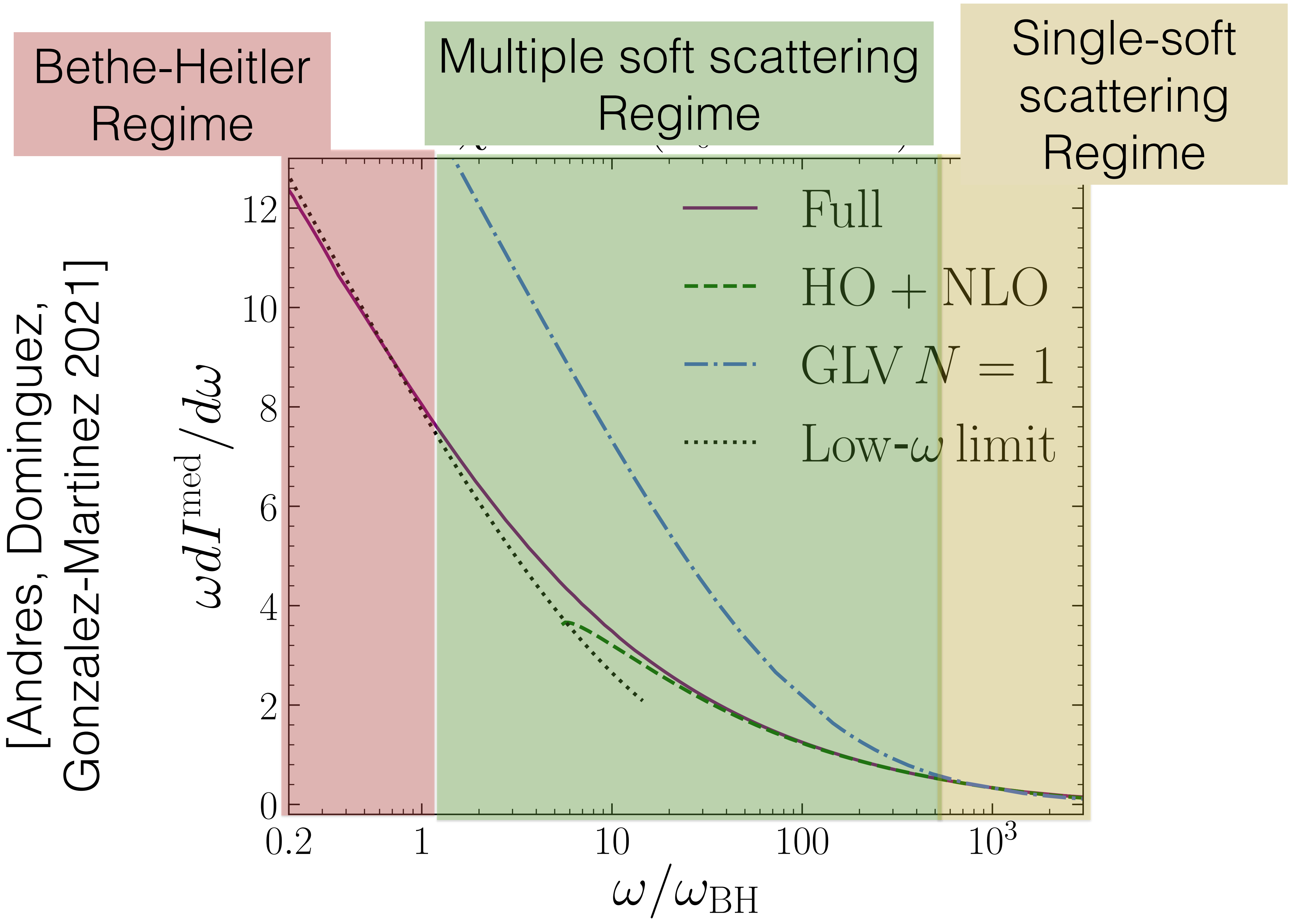
More in Carlota Andres Plenary Monday

A lot of activity in the last 3-4 years to compute the gluon spectrum with a **correct resummation**

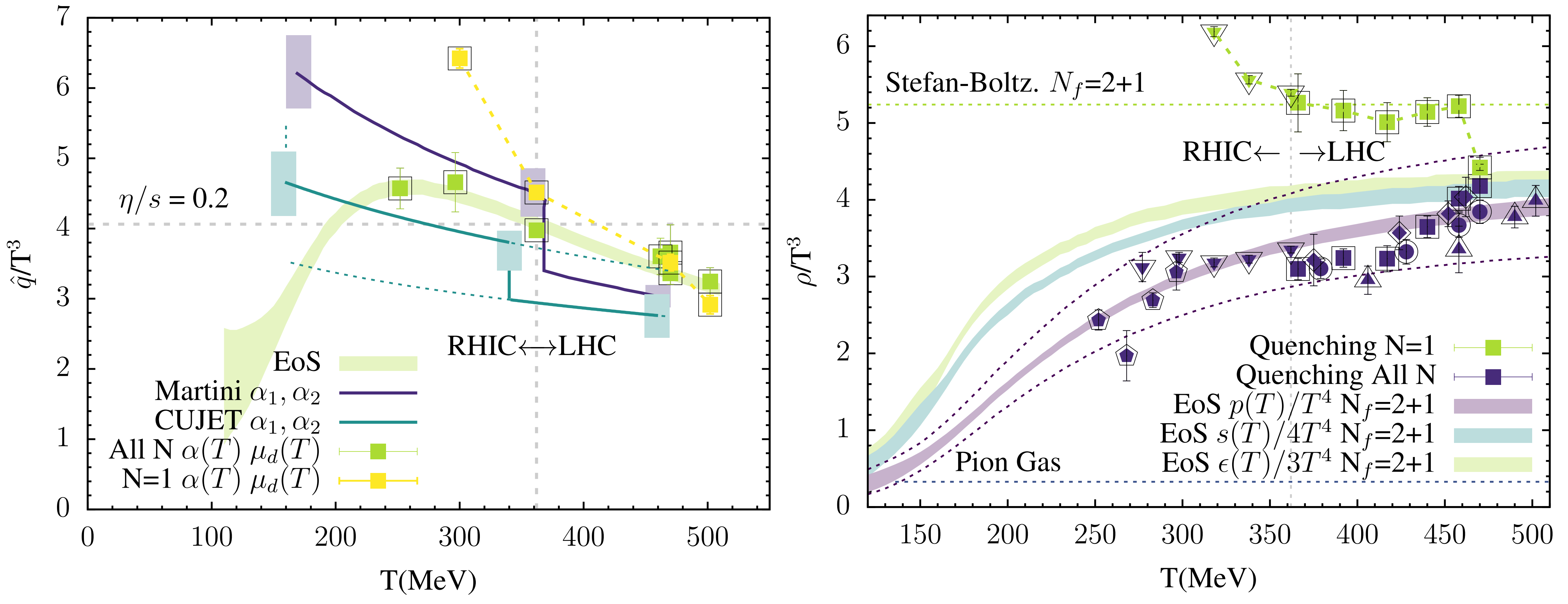
- **Perturbative tails**
- **Arbitrary number of scatterings**

$$\mathcal{P}(t'',\boldsymbol{k};t',\boldsymbol{q}) = (2\pi)^2\,\delta^{(2)}(\boldsymbol{k}-\boldsymbol{q}) - \frac{1}{2}\int_{t'}^{t''} ds\, n(s)\int_{\boldsymbol{k}'} \sigma(\boldsymbol{k}'-\boldsymbol{q})\mathcal{P}(t'',\boldsymbol{k};s,\boldsymbol{k}')\,,$$

$$\widetilde{\mathcal{K}}(t',\boldsymbol{q};t,\boldsymbol{p}) = (2\pi)^2\,\delta^{(2)}(\boldsymbol{q}-\boldsymbol{p})\,e^{-i\frac{p^2}{2\omega}(t'-t)} - \frac{1}{2}\int_{t}^{t'} ds\, n(s)\int_{\boldsymbol{k}'} \sigma(\boldsymbol{q}-\boldsymbol{k}')e^{-i\frac{q^2}{2\omega}(t'-s)}\widetilde{\mathcal{K}}(s,\boldsymbol{k}';t,\boldsymbol{p})\,.$$



[Andres, Dominguez, Gonzalez-Martinez 2021]



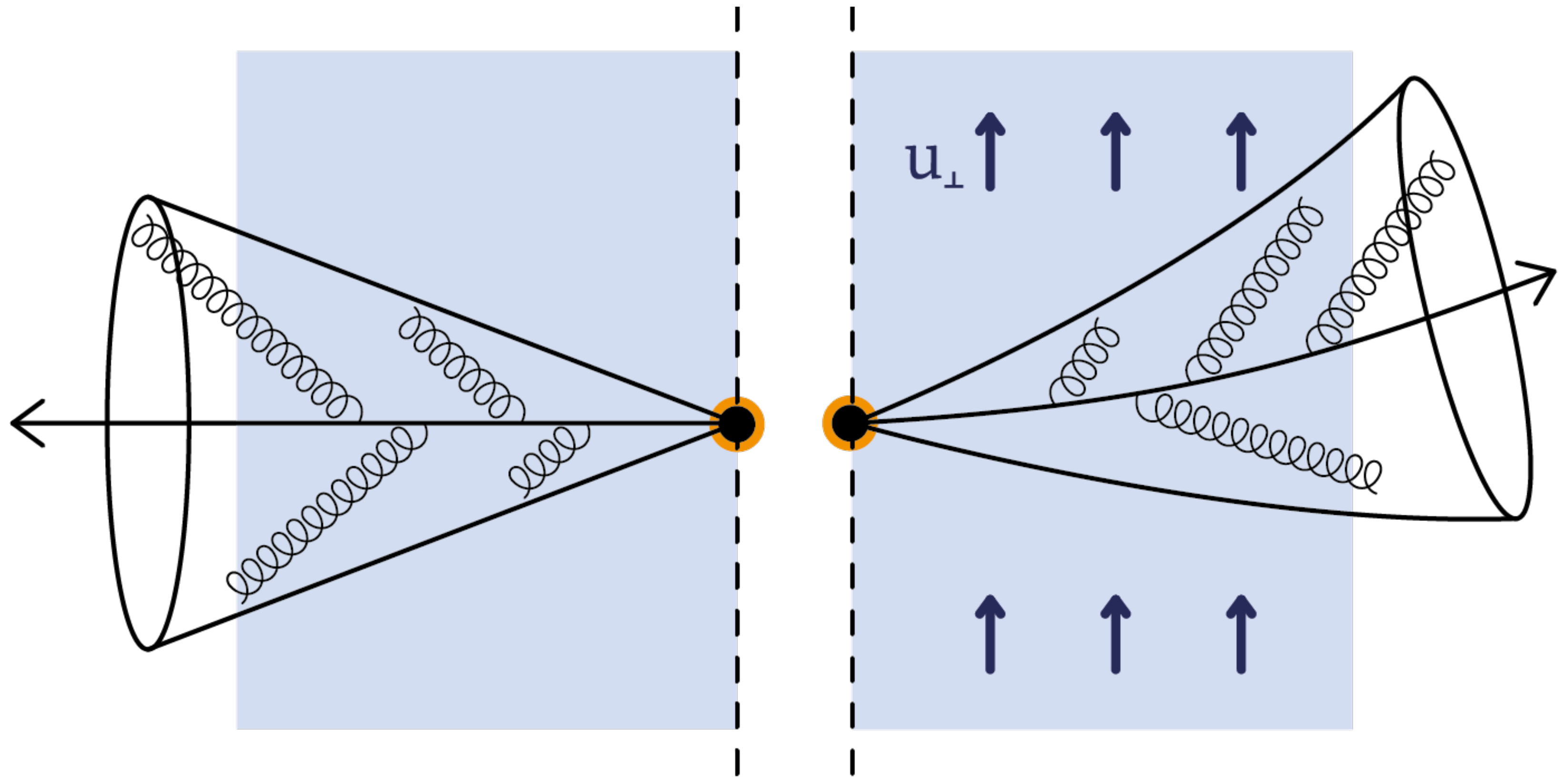
[Feal, Salgado, Vazquez 2019]

Essential for a consistent extraction of medium parameters - $N_{\rm scatt}$ depends on $\sqrt{s}$ and centrality

Improving the averages

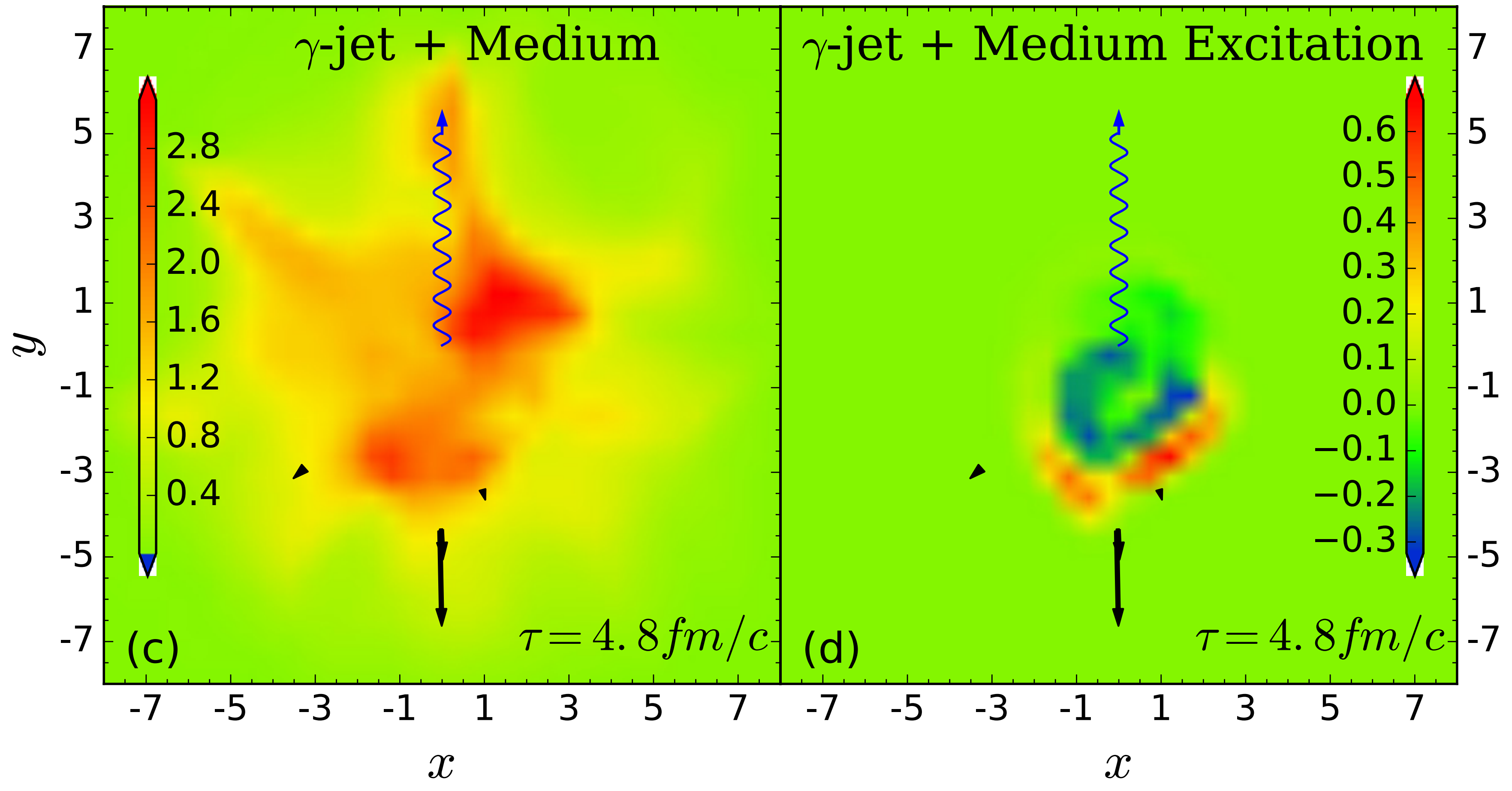
See also Andrey Sadofyev Parallel Wednesday

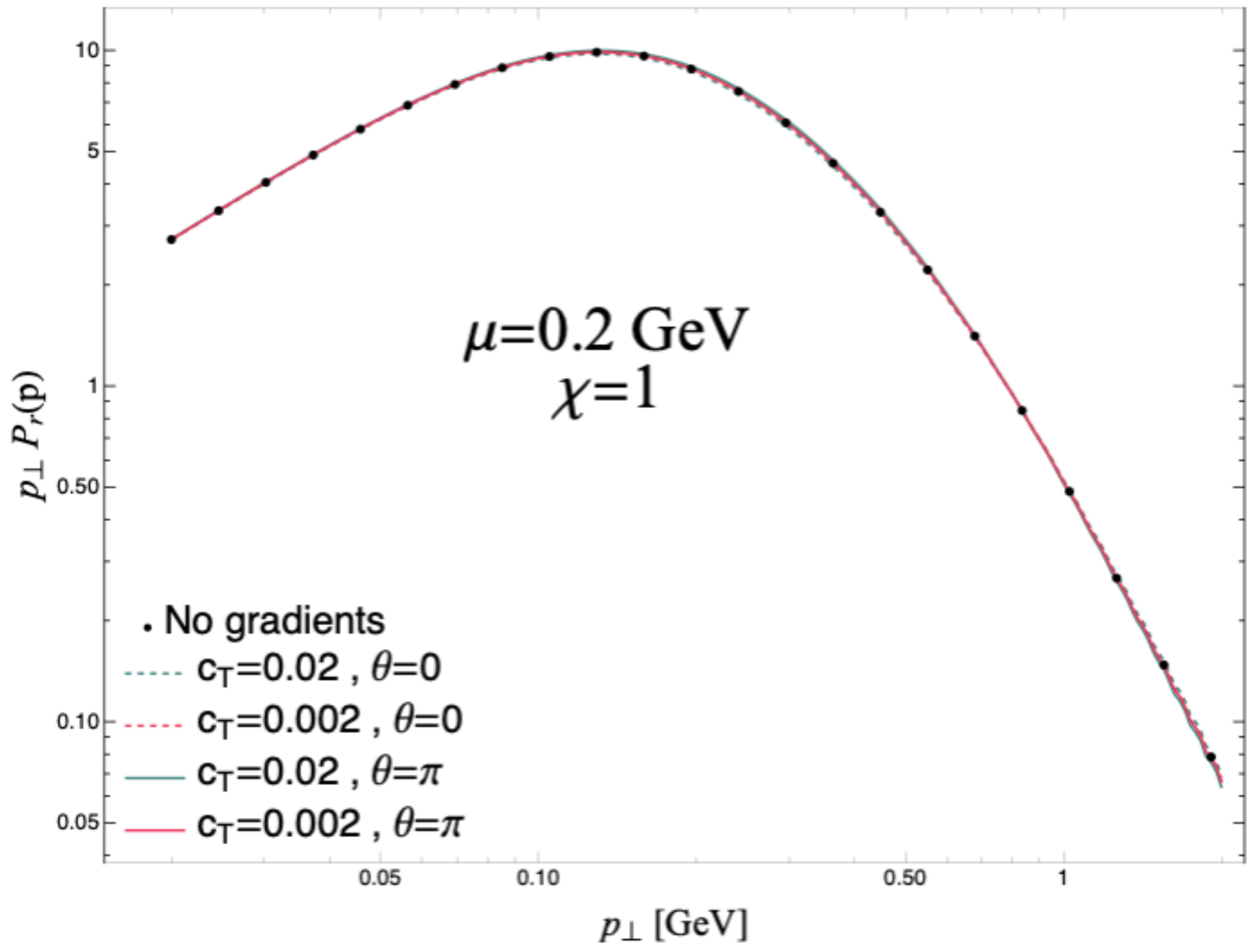
Jet-medium coupling can be implemented for more realistic profiles - gradients/flow fields

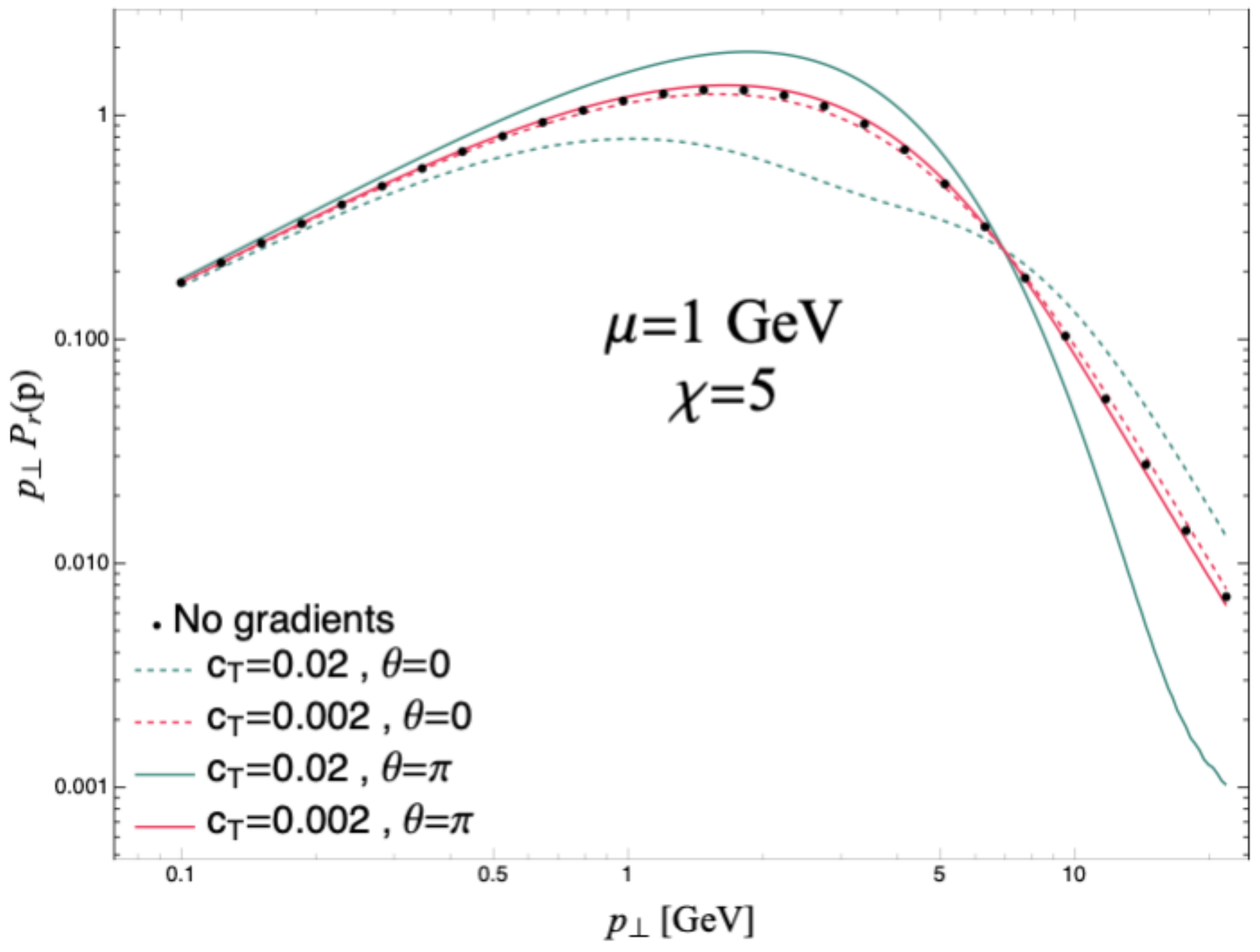


[Sadofyev, Sievert, Vitev 2021; Antiporda, Bahder, Rahman, Sievert 2022; Barata, Sadofyev, Salgado 2022; Fu, Casalderrey, Wang 2022; Andres, Dominguez, Sadofyev, Salgado 2022; Ipp, Muller, Schuh 2022 — Previous: Armesto, Salgado, Wiedemann 2004]

$$gA^{a\lambda}(q) = u^\lambda\, v(q)\,\left[\int d^2\boldsymbol{x}\, dz\, e^{-i(\boldsymbol{q}\cdot\boldsymbol{x}+q_z z)}\,\hat{\rho}^a(\boldsymbol{x}, z)\right]\,(2\pi)\,\delta(q^0 - \boldsymbol{u}\cdot\boldsymbol{q})$$







Instead of conclusions..

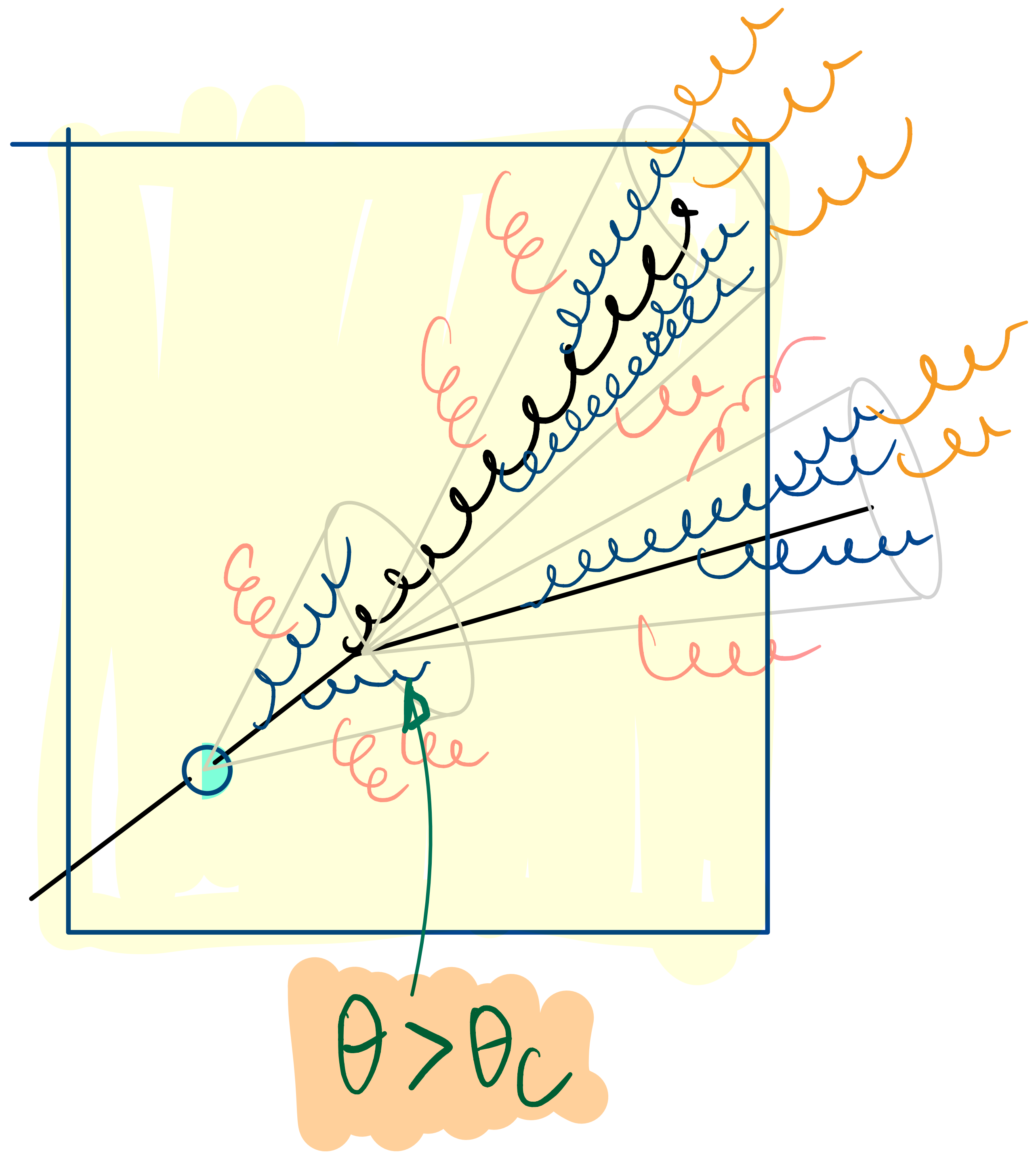
PHENO

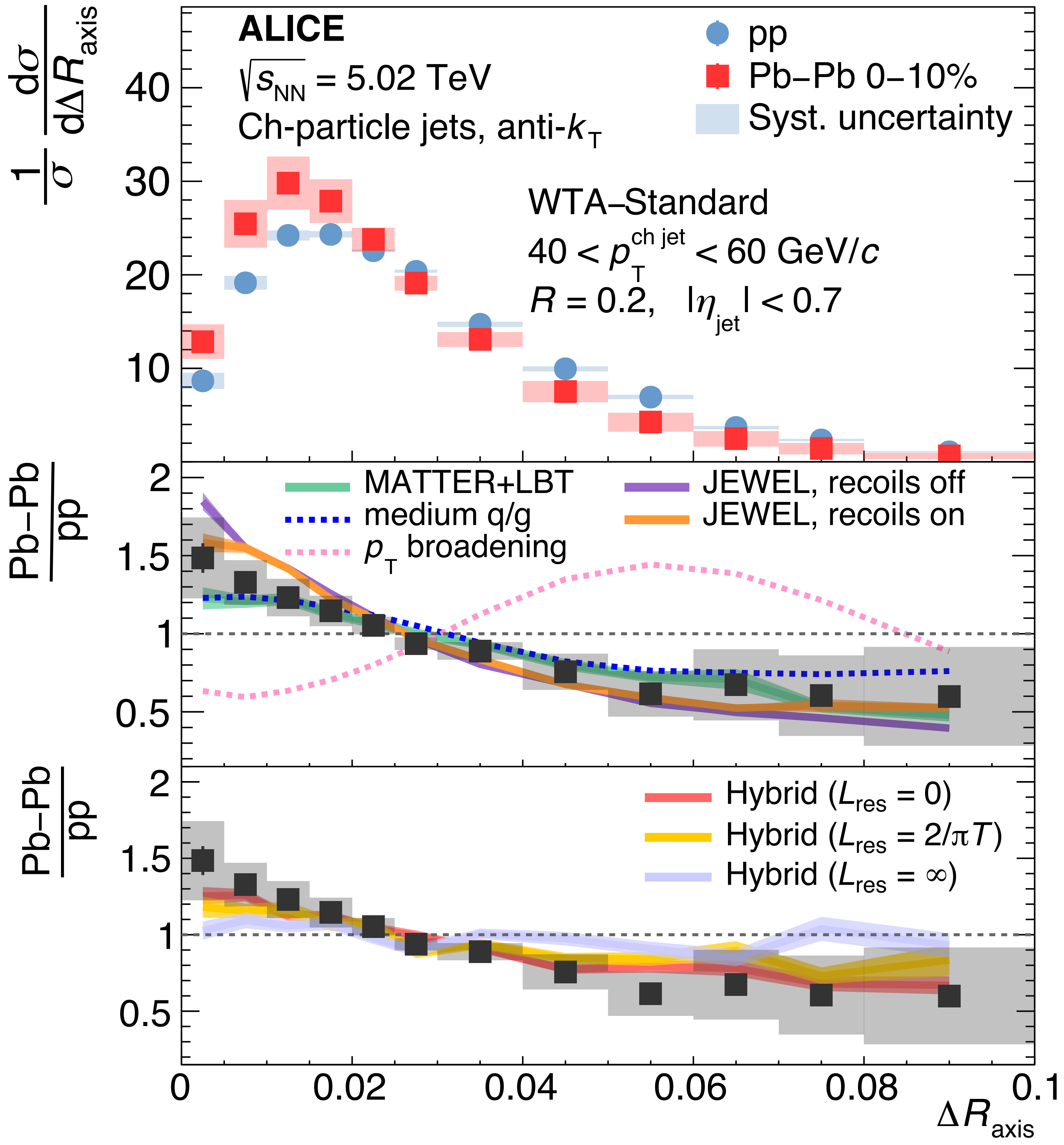
WARNING

[… with two simple examples as illustration]

Measurements ≠ modifying one “theory” jet

E.g.: Energy loss and p_T– broadening are generic for medium parton propagation and splitting





Narrowing??? 😱

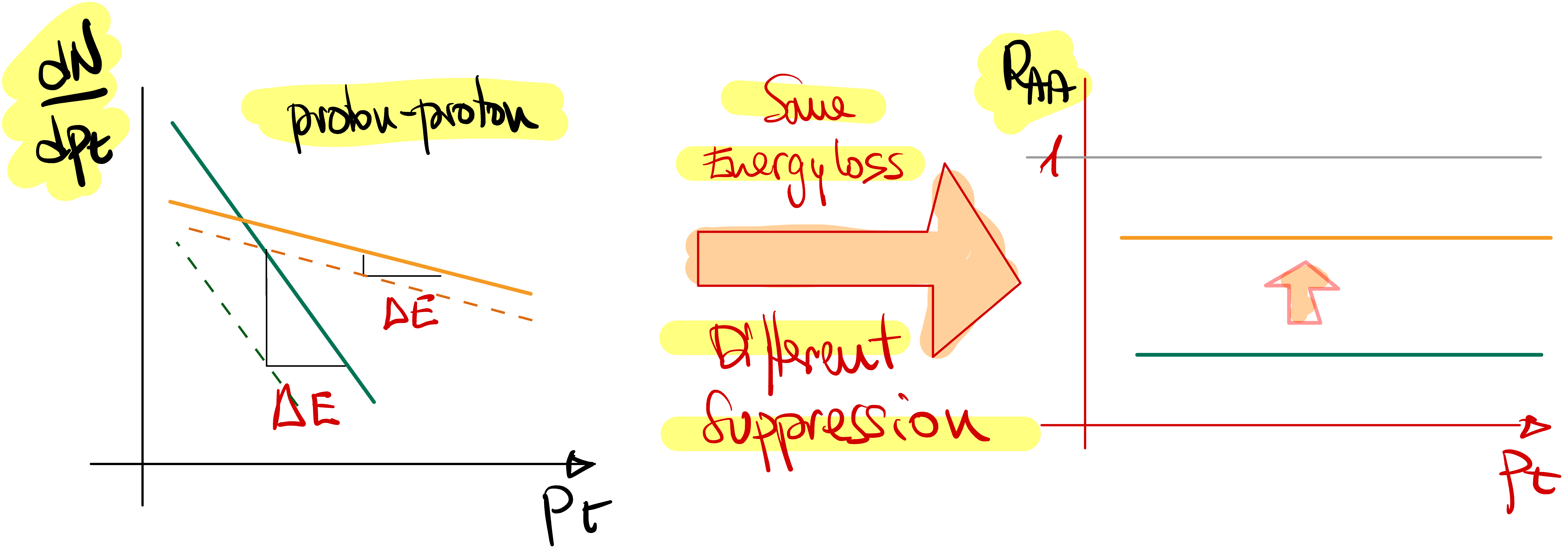
Reconstructed jets:

You are not comparing here **the same** quark/gluon evolution w/ and wo/ medium

[but the result of an analysis on an ensemble of jets]

Other [sometimes trivial] effects

E.g.: The slope of the proton-proton spectrum very relevant for suppression



Also:

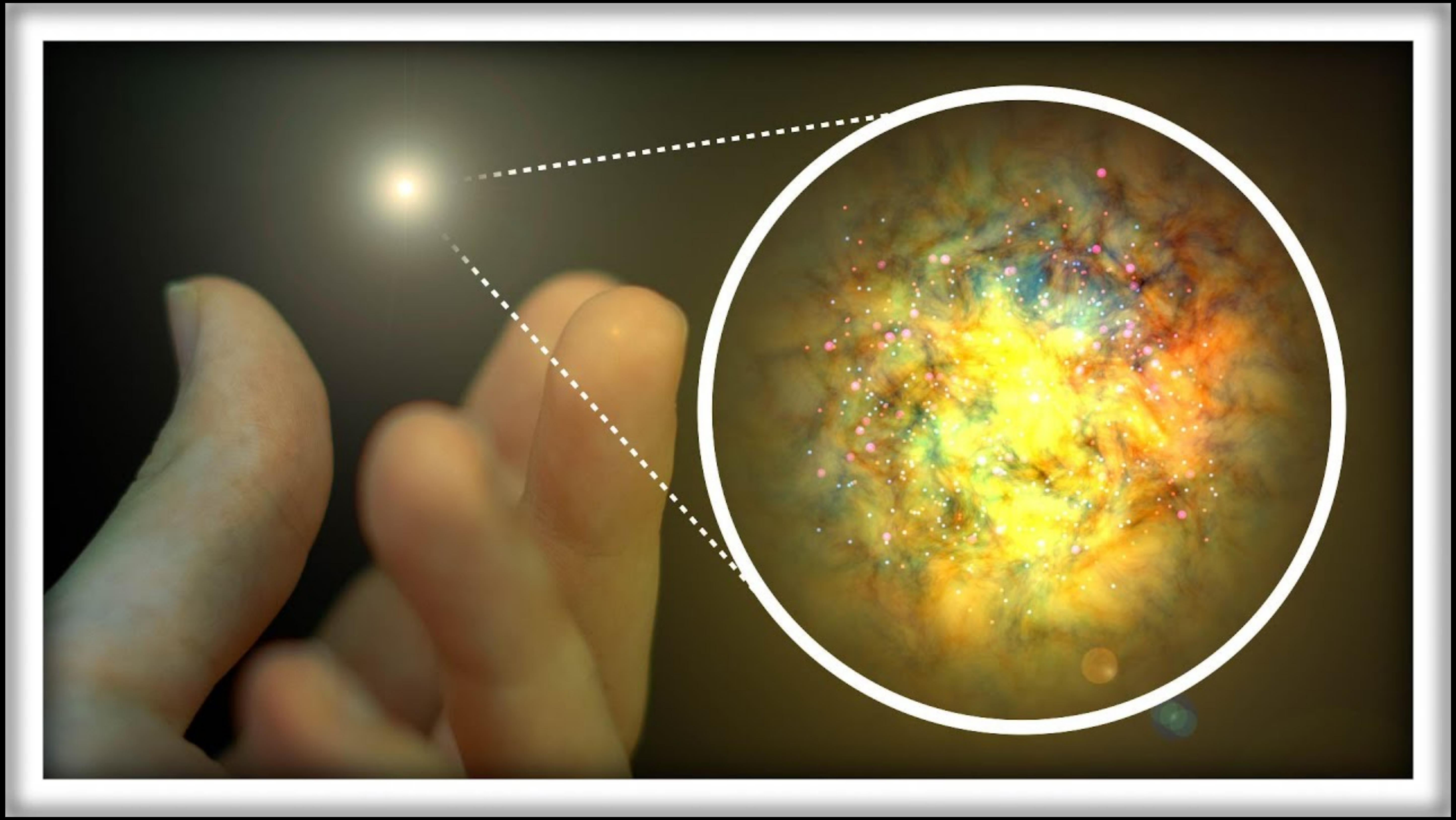
- ☐ Nuclear PDFs
- ☐ Jet definition, reconstruction, etc
- ☐ Quark/gluon content…

These effects need to be taken into account for a correct interpretation of the data

Have fun at HP2023!
THANKS!

For Fun

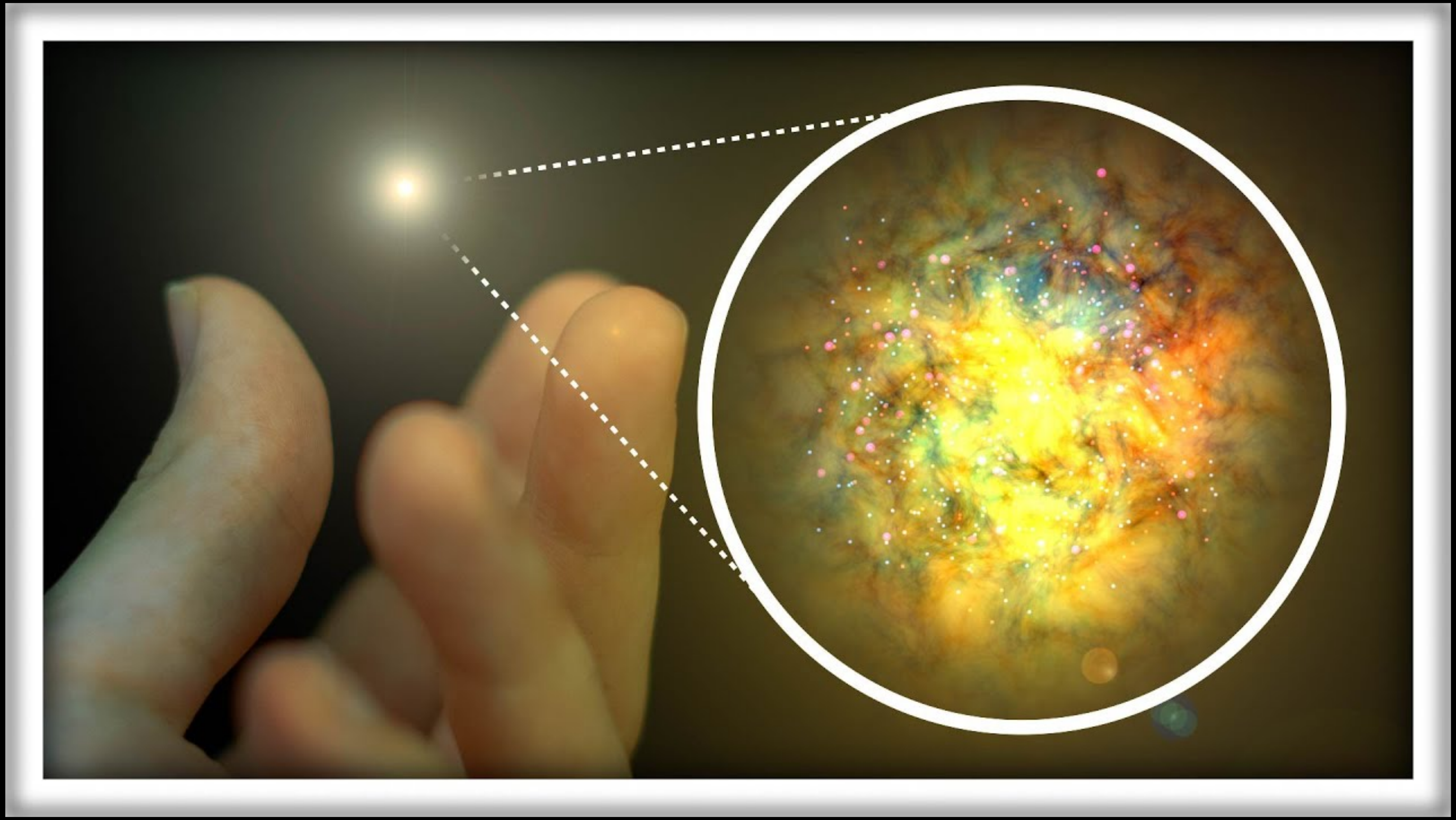
Youtube video - QGP (in Spanish)



https://youtube.com/watch?v=JdahywF2_D4

For Fun

Youtube video - QGP (in Spanish)



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