Colliders, Higgs and the strong interaction

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European Research Council
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particle physics

“big unanswered questions”

about fundamental particles & their interactions

(dark matter, matter-antimatter asymmetry,
nature of dark energy, hierarchy of scales…)

v.

“big answerable questions”

and how we go about answering them

(nature of Higgs interactions, validity of SM up to high scales,
lepton flavour universality, pattern of neutrino mixing, …)

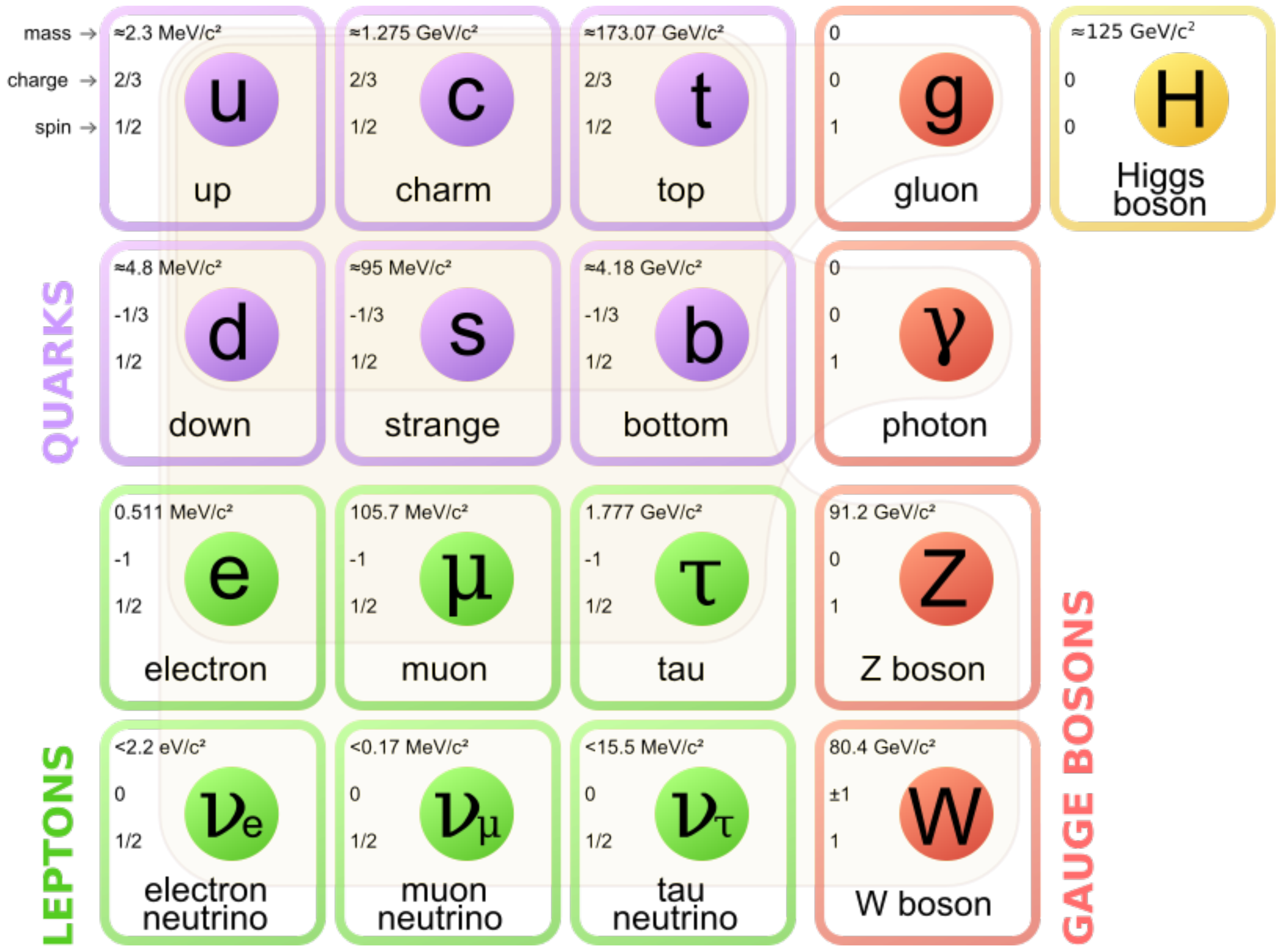
https://cerncourier.com/a/nobel-expectations-for-new-physics-at-the-lhc/

"

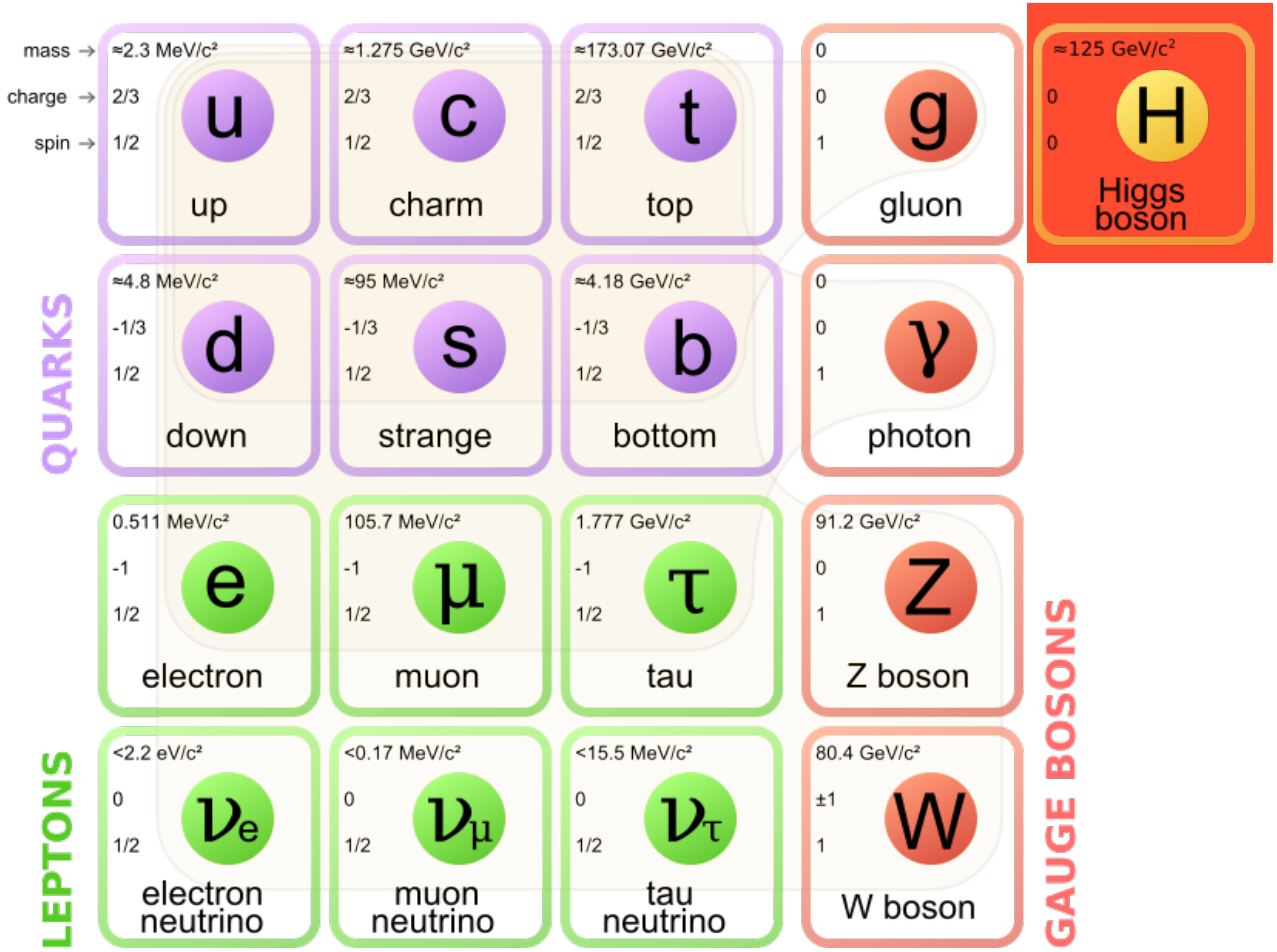
I personally expect supersymmetry to be discovered at the LHC

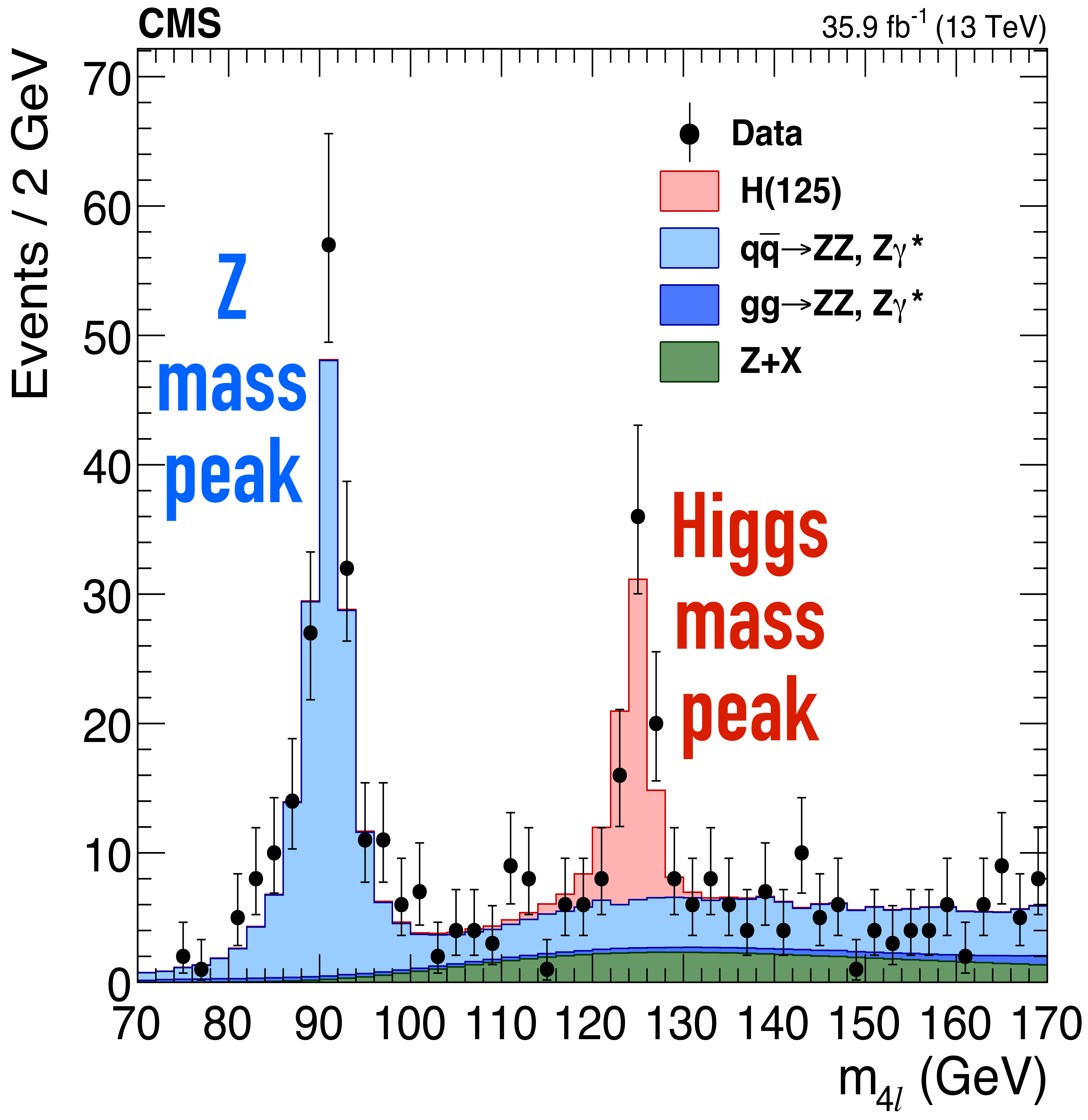
-a Nobel prize-winning theorist [2008]

The Higgs boson



The Higgs boson



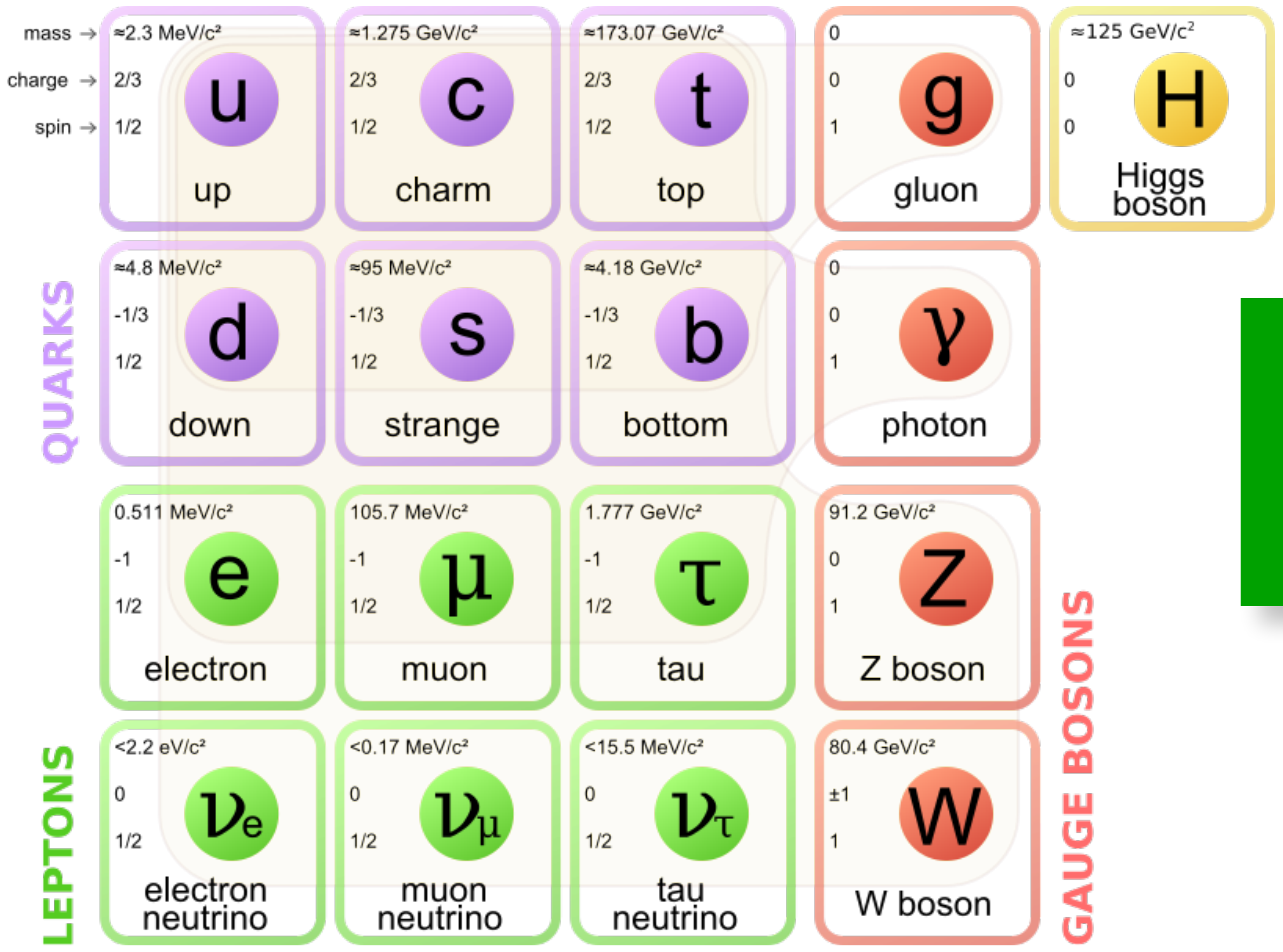


ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

2012 discovery of a Higgs-like boson

plot shows more recent data

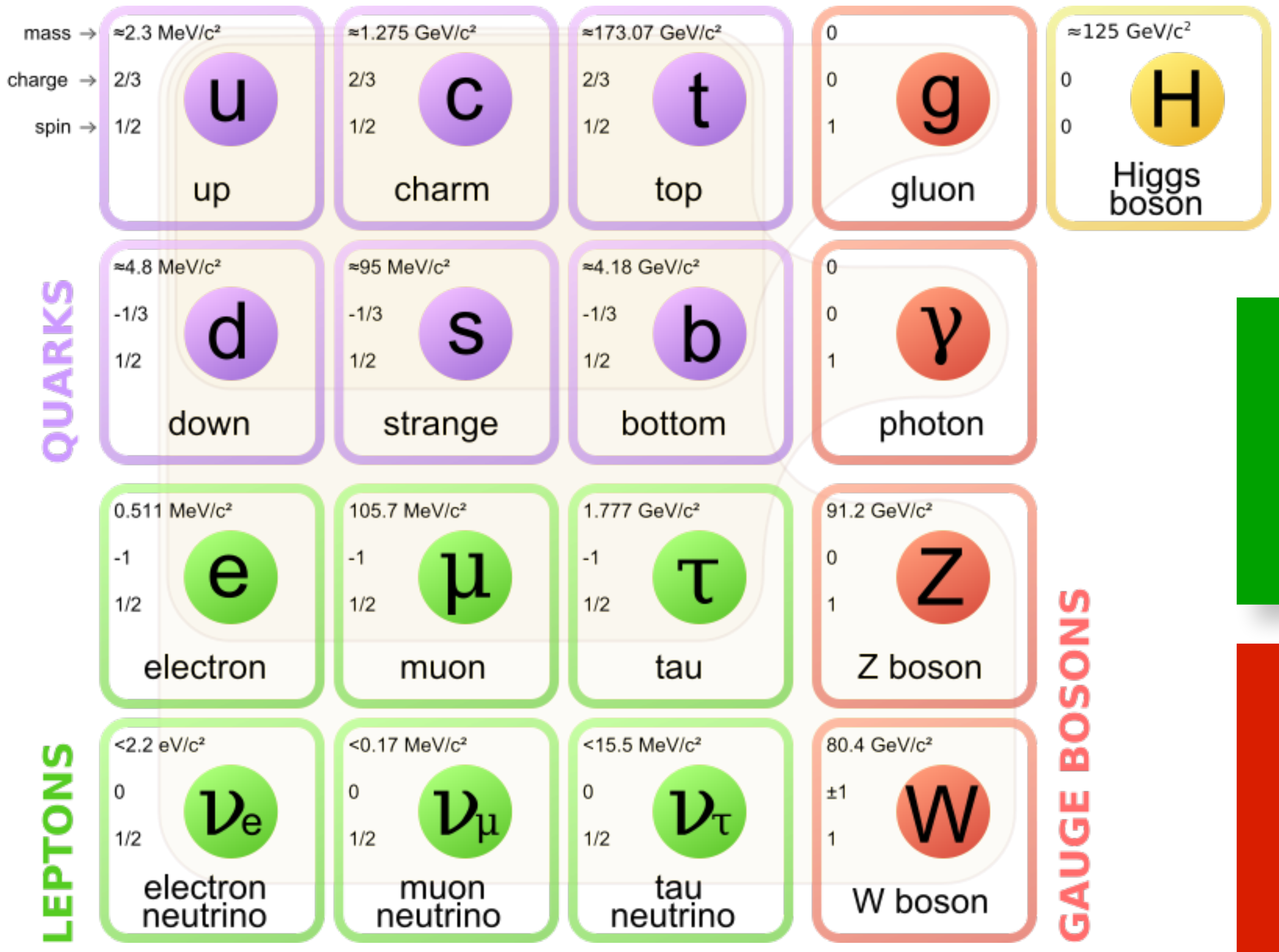
The Higgs boson (2012)



Success!

“The Standard Model is complete”

The Higgs boson (2012)



Success!

“The Standard Model is complete”

Crisis!

No supersymmetry, no extra dimensions, there’s nothing left for us to do . . .

The New York Times

By DENNIS OVERBYE JUNE 19, 2017

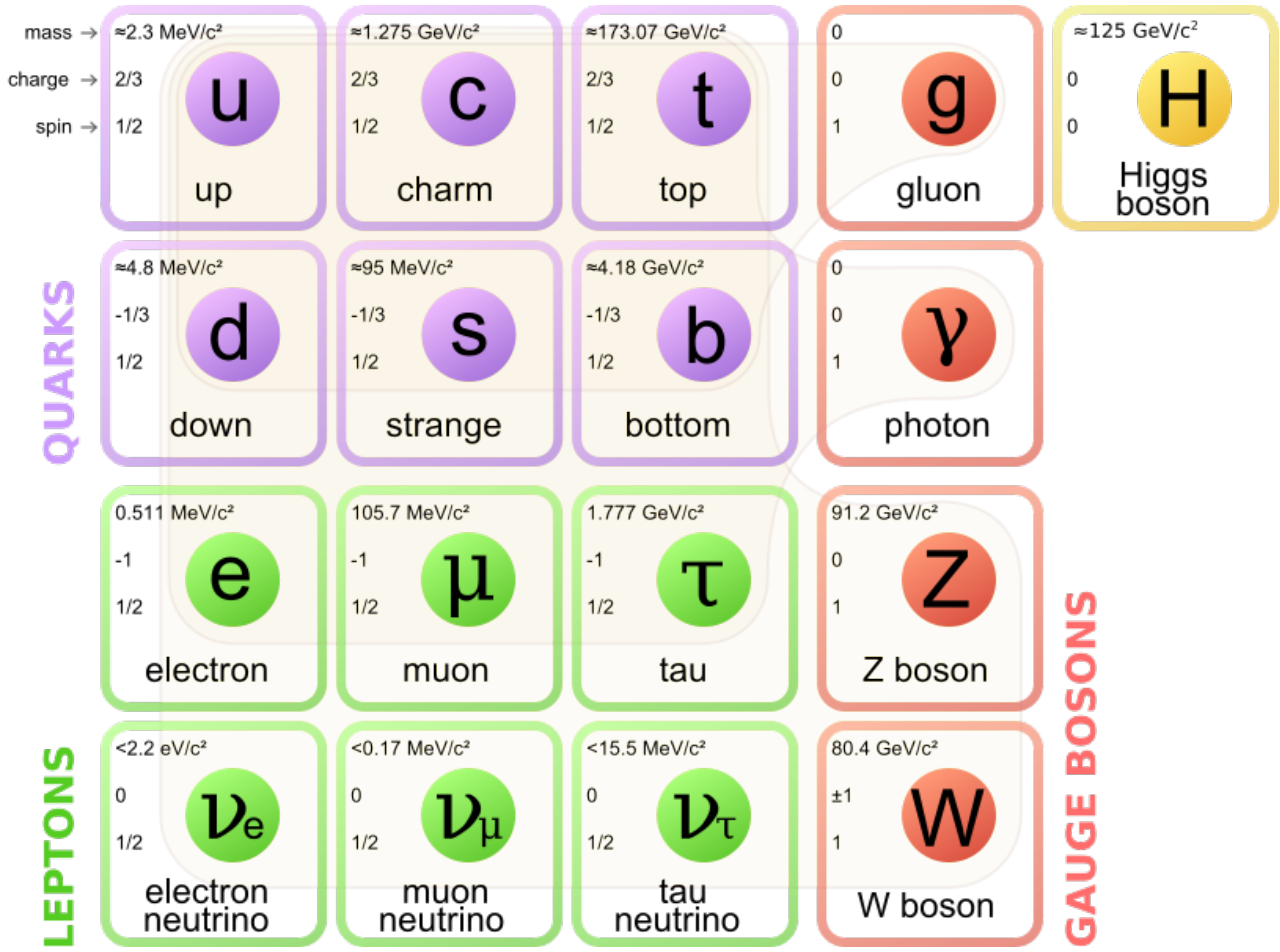
[…]

What if there is nothing new to discover? ***That prospect is now a cloud hanging over the physics community.***

https://www.nytimes.com/2017/06/19/science/cern-large-hadron-collider-higgs-physics.html

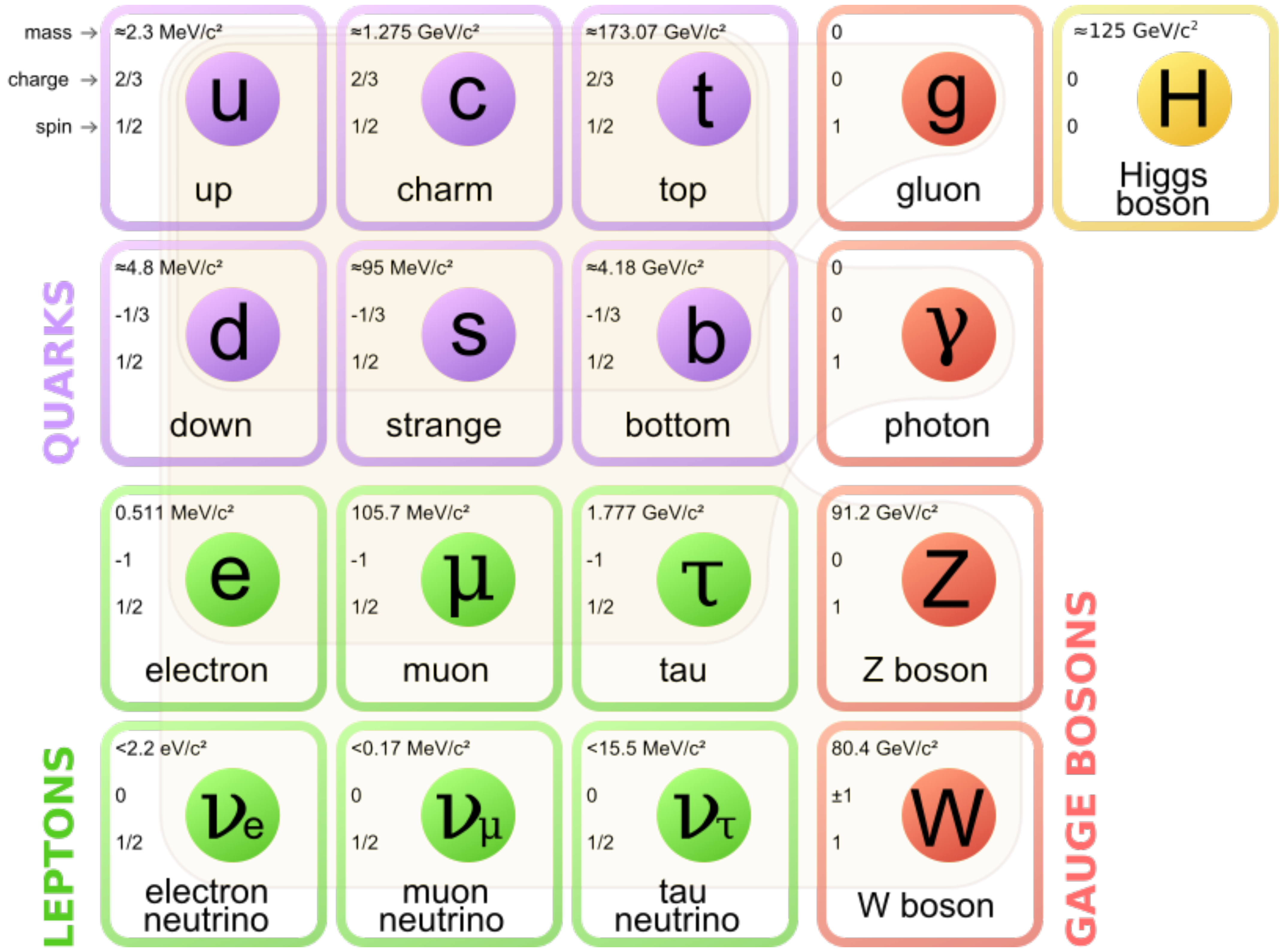
[…]

what is the Standard Model?



particles

what is the Standard Model?



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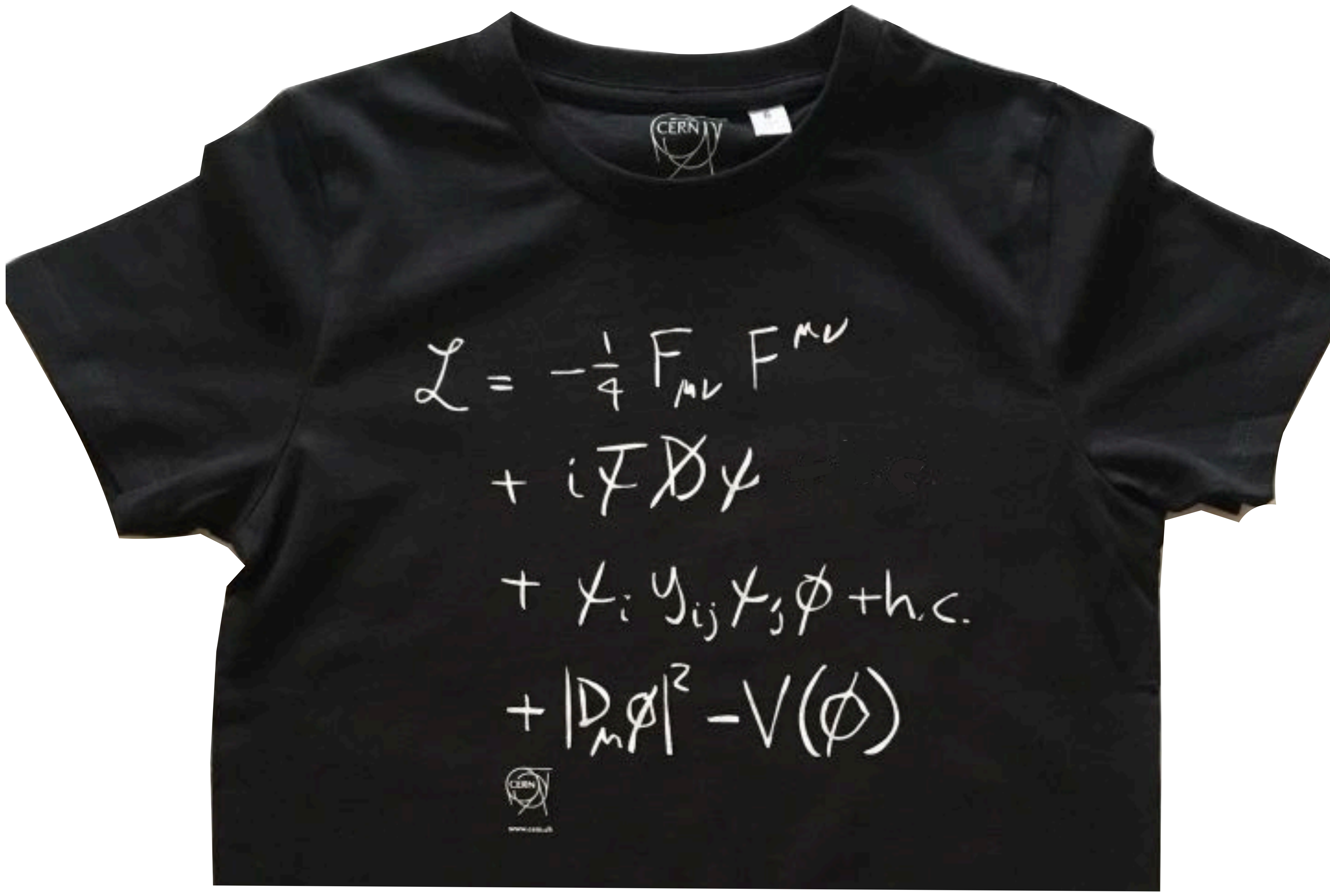
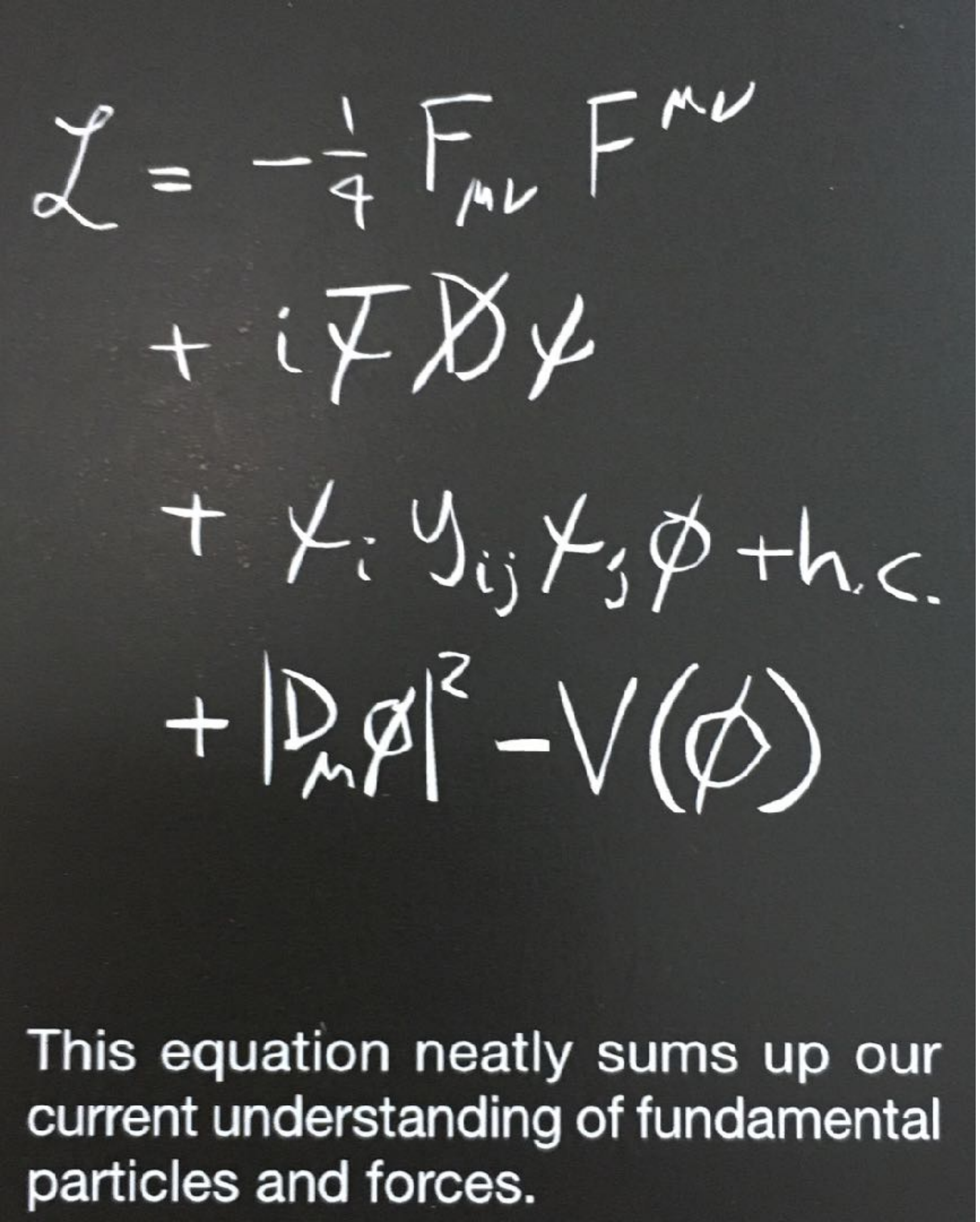


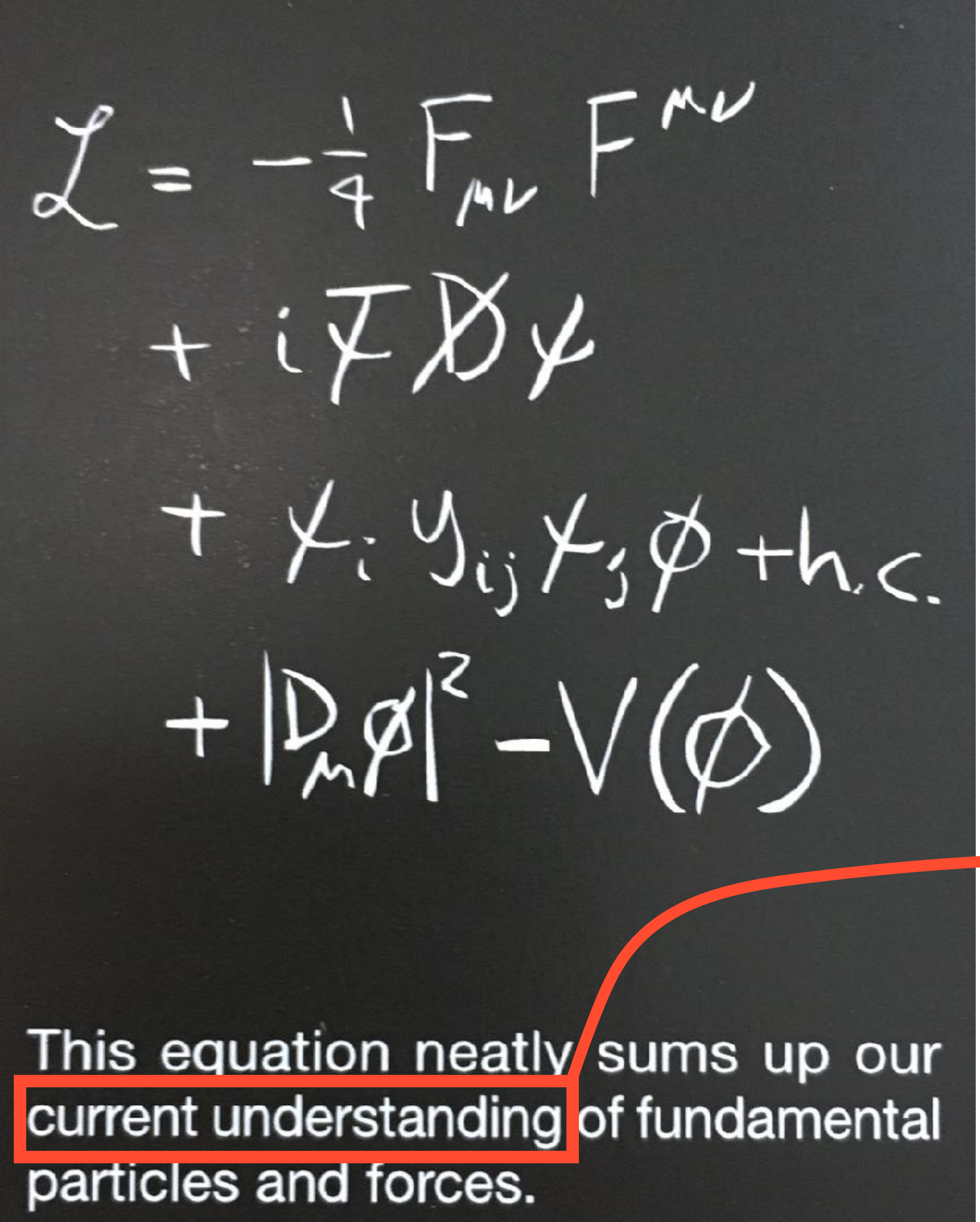
particles

interactions

STANDARD MODEL — KNOWABLE UNKNOWNS



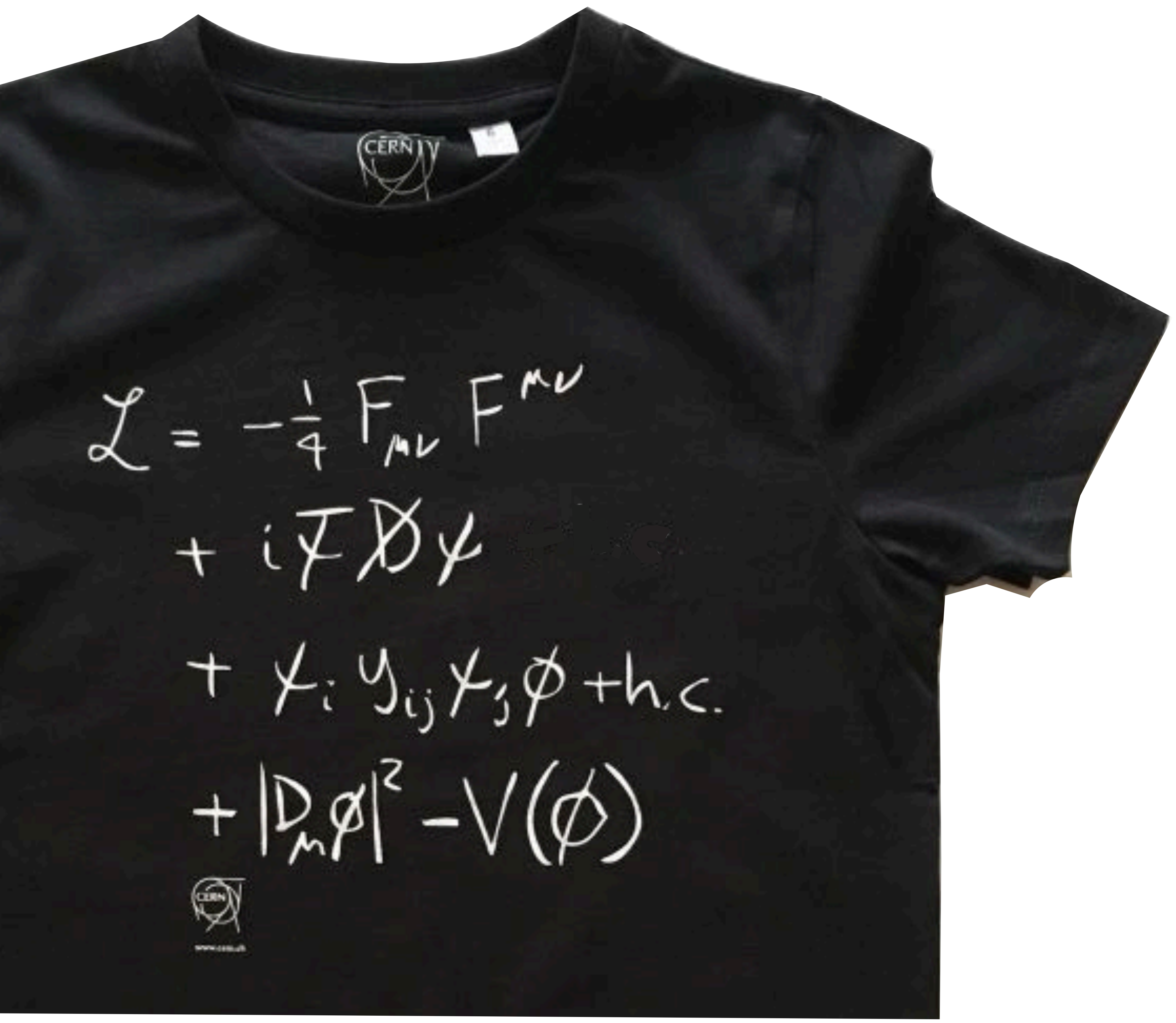
These T-shirts come with a little explanation



These T-shirts come with a little explanation

"understanding" = knowledge ?

"understanding" = assumption ?



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Standard Model Lagrangian (including neutrino mass terms)
From *An Introduction to the Standard Model of Particle Physics, 2nd Edition*,
W. N. Cottingham and D. A. Greenwood, Cambridge University Press, Cambridge, 2007,
Extracted by J.A. Shifflett, updated from Particle Data Group tables at pdg.lbl.gov, 2 Feb 2015.

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)}\\
& +(\bar\nu_L,\bar e_L)\,\tilde\sigma^\mu iD_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar e_R\sigma^\mu iD_\mu e_R + \bar\nu_R\sigma^\mu iD_\mu\nu_R + \text{(h.c.)} && \text{(lepton dynamical term)}\\
& -\frac{\sqrt2}{v}\left[(\bar\nu_L,\bar e_L)\,\phi M^e e_R + \bar e_R \bar M^e\bar\phi\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] && \text{(electron, muon, tauon mass term)}\\
& -\frac{\sqrt2}{v}\left[(-\bar e_L,\bar\nu_L)\,\phi^* M^\nu \nu_R + \bar\nu_R \bar M^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right] && \text{(neutrino mass term)}\\
& +(\bar u_L,\bar d_L)\,\tilde\sigma^\mu iD_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar u_R\sigma^\mu iD_\mu u_R + \bar d_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)}\\
& -\frac{\sqrt2}{v}\left[(\bar u_L,\bar d_L)\,\phi M^d d_R + \bar d_R \bar M^d\bar\phi\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] && \text{(down, strange, bottom mass term)}\\
& -\frac{\sqrt2}{v}\left[(-\bar d_L,\bar u_L)\,\phi^* M^u u_R + \bar u_R \bar M^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right] && \text{(up, charmed, top mass term)}\\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar\phi\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$

where (h.c.) means Hermitian conjugate of preceeding terms, $\bar\psi=\text{(h.c.)}\psi=\psi^\dagger=\psi^{*T}$, and the derivative operators are

$$D_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}=\left[\partial_\mu-\frac{ig_1}{2}B_\mu+\frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L\\ e_L\end{pmatrix},\quad D_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix}=\left[\partial_\mu+\frac{ig_1}{6}B_\mu+\frac{ig_2}{2}\mathbf{W}_\mu+ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \quad (2)$$

$$D_\mu\nu_R=\partial_\mu\nu_R,\quad D_\mu e_R=[\partial_\mu-ig_1B_\mu]\,e_R,\quad D_\mu u_R=\left[\partial_\mu+\frac{i2g_1}{3}B_\mu+ig\mathbf{G}_\mu\right]u_R,\quad D_\mu d_R=\left[\partial_\mu-\frac{ig_1}{3}B_\mu+ig\mathbf{G}_\mu\right]d_R, \quad (3)$$

$$D_\mu\phi=\left[\partial_\mu+\frac{ig_1}{2}B_\mu+\frac{ig_2}{2}\mathbf{W}_\mu\right]\phi. \quad (4)$$

ϕ is a 2-component complex Higgs field. Since $\mathcal{L}$ is $SU(2)$ gauge invariant, a gauge can be chosen so ϕ has the form

$$\phi^T=(0,v+h)/\sqrt2,\qquad <\phi>_0^T=\text{(expectation value of }\phi)=(0,v)/\sqrt2, \quad (5)$$

where v is a real constant such that $\mathcal{L}_\phi=\overline{(\partial_\mu\phi)}\partial^\mu\phi-m_h^2[\bar\phi\phi-v^2/2]^2/2v^2$ is minimized, and h is a residual Higgs field. B_μ, $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are the gauge boson vector potentials, and $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are composed of 2×2 and 3×3 traceless Hermitian matrices. Their associated field tensors are

$$B_{\mu\nu}=\partial_\mu B_\nu-\partial_\nu B_\mu,\quad \mathbf{W}_{\mu\nu}=\partial_\mu\mathbf{W}_\nu-\partial_\nu\mathbf{W}_\mu+ig_2(\mathbf{W}_\mu\mathbf{W}_\nu-\mathbf{W}_\nu\mathbf{W}_\mu)/2,\quad \mathbf{G}_{\mu\nu}=\partial_\mu\mathbf{G}_\nu-\partial_\nu\mathbf{G}_\mu+ig(\mathbf{G}_\mu\mathbf{G}_\nu-\mathbf{G}_\nu\mathbf{G}_\mu). \quad (6)$$

The non-matrix $A_\mu, Z_\mu, W_\mu^\pm$ bosons are mixtures of $\mathbf{W}_\mu$ and B_μ components, according to the weak mixing angle θ_w,

$$A_\mu=W_{11\mu}sin\theta_w+B_\mu cos\theta_w,\qquad Z_\mu=W_{11\mu}cos\theta_w-B_\mu sin\theta_w,\qquad W_\mu^+=W_\mu^{-*}=W_{12\mu}/\sqrt2, \quad (7)$$

$$B_\mu=A_\mu cos\theta_w-Z_\mu sin\theta_w,\quad W_{11\mu}=-W_{22\mu}=A_\mu sin\theta_w+Z_\mu cos\theta_w,\quad W_{12\mu}=W_{21\mu}^*=\sqrt2\,W_\mu^+,\quad sin^2\theta_w=.2315(4). \quad (8)$$

The fermions include the leptons e_R, e_L, ν_R, ν_L and quarks u_R, u_L, d_R, d_L. They all have implicit 3-component generation indices, $e_i=(e,\mu,\tau)$, $\nu_i=(\nu_e,\nu_\mu,\nu_\tau)$, $u_i=(u,c,t)$, $d_i=(d,s,b)$, which contract into the fermion mass matrices $M_{ij}^e, M_{ij}^\nu, M_{ij}^u, M_{ij}^d$, and implicit 2-component indices which contract into the Pauli matrices,

$$\sigma^\mu=\left[\begin{pmatrix}1&0\\0&1\end{pmatrix},\begin{pmatrix}0&1\\1&0\end{pmatrix},\begin{pmatrix}0&-i\\i&0\end{pmatrix},\begin{pmatrix}1&0\\0&-1\end{pmatrix}\right],\quad \tilde\sigma^\mu=[\sigma^0,-\sigma^1,-\sigma^2,-\sigma^3],\quad tr(\sigma^i)=0,\quad \sigma^{\mu\dagger}=\sigma^\mu,\quad tr(\sigma^\mu\sigma^\nu)=2\delta^{\mu\nu}. \quad (9)$$

The quarks also have implicit 3-component color indices which contract into $\mathbf{G}_\mu$. So $\mathcal{L}$ really has implicit sums over 3-component generation indices, 2-component Pauli indices, 3-component color indices in the quark terms, and 2-component $SU(2)$ indices in $(\bar\nu_L,\bar e_L)$, $(\bar u_L,\bar d_L)$, $(-\bar e_L,\bar\nu_L)$, $(-\bar d_L,\bar u_L)$, $\bar\phi$, $\mathbf{W}_\mu$, $\binom{\nu_L}{e_L}$, $\binom{u_L}{d_L}$, $\binom{-e_L}{\nu_L}$, $\binom{-d_L}{u_L}$, ϕ.

The electroweak and strong coupling constants, Higgs vacuum expectation value (VEV), and Higgs mass are,

$$g_1=e/cos\theta_w,\quad g_2=e/sin\theta_w,\quad g>6.5e=g(m_\tau^2),\quad v=246GeV(PDG)\approx\sqrt2\cdot180\,GeV(CG),\quad m_h=125.02(30)GeV \quad (10)$$

where $e=\sqrt{4\pi\alpha\hbar c}=\sqrt{4\pi/137}$ in natural units. Using (4,5) and rewriting some things gives the mass of $A_\mu, Z_\mu, W_\mu^\pm$,

$$-\frac14B_{\mu\nu}B^{\mu\nu}-\frac18tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu})=-\frac14A_{\mu\nu}A^{\mu\nu}-\frac14Z_{\mu\nu}Z^{\mu\nu}-\frac12\mathcal{W}_{\mu\nu}^-\mathcal{W}^{+\mu\nu}+\begin{pmatrix}\text{higher}\\ \text{order terms}\end{pmatrix}, \quad (11)$$

$$A_{\mu\nu}=\partial_\mu A_\nu-\partial_\nu A_\mu,\quad Z_{\mu\nu}=\partial_\mu Z_\nu-\partial_\nu Z_\mu,\quad \mathcal{W}_{\mu\nu}^\pm=D_\mu W_\nu^\pm-D_\nu W_\mu^\pm,\quad D_\mu W_\nu^\pm=[\partial_\mu\pm ieA_\mu]W_\nu^\pm, \quad (12)$$

$$D_\mu<\phi>_0=\frac{iv}{\sqrt2}\begin{pmatrix}g_2W_{12\mu}/2\\ g_1B_\mu/2+g_2W_{22\mu}/2\end{pmatrix}=\frac{ig_2v}{2}\begin{pmatrix}W_{12\mu}/\sqrt2\\ (B_\mu sin\theta_w/cos\theta_w+W_{22\mu})/\sqrt2\end{pmatrix}=\frac{ig_2v}{2}\begin{pmatrix}W_\mu^+\\ -Z_\mu/\sqrt2\,cos\theta_w\end{pmatrix}, \quad (13)$$

$$\Rightarrow\quad m_A=0,\qquad m_{W^\pm}=g_2v/2=80.425(38)GeV,\qquad m_Z=g_2v/2cos\theta_w=91.1876(21)GeV. \quad (14)$$

Ordinary 4-component Dirac fermions are composed of the left and right handed 2-component fields,

$$e=\begin{pmatrix}e_{L1}\\ e_{R1}\end{pmatrix},\ \nu_e=\begin{pmatrix}\nu_{L1}\\ \nu_{R1}\end{pmatrix},\ u=\begin{pmatrix}u_{L1}\\ u_{R1}\end{pmatrix},\ d=\begin{pmatrix}d_{L1}\\ d_{R1}\end{pmatrix},\quad \text{(electron, electron neutrino, up and down quark)} \quad (15)$$

$$\mu=\begin{pmatrix}e_{L2}\\ e_{R2}\end{pmatrix},\ \nu_\mu=\begin{pmatrix}\nu_{L2}\\ \nu_{R2}\end{pmatrix},\ c=\begin{pmatrix}u_{L2}\\ u_{R2}\end{pmatrix},\ s=\begin{pmatrix}d_{L2}\\ d_{R2}\end{pmatrix},\quad \text{(muon, muon neutrino, charmed and strange quark)} \quad (16)$$

$$\tau=\begin{pmatrix}e_{L3}\\ e_{R3}\end{pmatrix},\ \nu_\tau=\begin{pmatrix}\nu_{L3}\\ \nu_{R3}\end{pmatrix},\ t=\begin{pmatrix}u_{L3}\\ u_{R3}\end{pmatrix},\ b=\begin{pmatrix}d_{L3}\\ d_{R3}\end{pmatrix},\quad \text{(tauon, tauon neutrino, top and bottom quark)} \quad (17)$$

$$\gamma^\mu=\begin{pmatrix}0&\sigma^\mu\\ \tilde\sigma^\mu&0\end{pmatrix}\qquad \text{where }\ \gamma^\mu\gamma^\nu+\gamma^\nu\gamma^\mu=2Ig^{\mu\nu}.\quad \text{(Dirac gamma matrices in chiral representation)} \quad (18)$$

The corresponding antiparticles are related to the particles according to $\psi^c=-i\gamma^2\psi^*$ or $\psi_L^c=-i\sigma^2\psi_R^*$, $\psi_R^c=i\sigma^2\psi_L^*$. The fermion charges are the coefficients of A_μ when (8,10) are substituted into either the left or right handed derivative operators (2-4). The fermion masses are the singular values of the 3×3 fermion mass matrices M^ν, M^e, M^u, M^d,

$$M^e=\mathbf{U}_L^{e\dagger}\begin{pmatrix}m_e&0&0\\0&m_\mu&0\\0&0&m_\tau\end{pmatrix}\mathbf{U}_R^e,\quad M^\nu=\mathbf{U}_L^{\nu\dagger}\begin{pmatrix}m_{\nu_e}&0&0\\0&m_{\nu_\mu}&0\\0&0&m_{\nu_\tau}\end{pmatrix}\mathbf{U}_R^\nu,\quad M^u=\mathbf{U}_L^{u\dagger}\begin{pmatrix}m_u&0&0\\0&m_c&0\\0&0&m_t\end{pmatrix}\mathbf{U}_R^u,\quad M^d=\mathbf{U}_L^{d\dagger}\begin{pmatrix}m_d&0&0\\0&m_s&0\\0&0&m_b\end{pmatrix}\mathbf{U}_R^d, \quad (19)$$

$$m_e=.510998910(13)MeV,\quad m_{\nu_e}\sim.001-2eV,\qquad m_u=1.7-3.1MeV,\quad m_d=4.1-5.7MeV, \quad (20)$$

$$m_\mu=105.658367(4)MeV,\quad m_{\nu_\mu}\sim.001-2eV,\qquad m_c=1.18-1.34GeV,\quad m_s=80-130MeV, \quad (21)$$

$$m_\tau=1776.84(17)MeV,\quad m_{\nu_\tau}\sim.001-2eV,\qquad m_t=171.4-174.4GeV,\quad m_b=4.13-4.37GeV, \quad (22)$$

where the $\mathbf{U}$s are 3×3 unitary matrices ($\mathbf{U}^{-1}=\mathbf{U}^\dagger$). Consequently the "true fermions" with definite masses are actually linear combinations of those in $\mathcal{L}$, or conversely the fermions in $\mathcal{L}$ are linear combinations of the true fermions,

$$e'_L=\mathbf{U}_L^e e_L,\quad e'_R=\mathbf{U}_R^e e_R,\quad \nu'_L=\mathbf{U}_L^\nu\nu_L,\quad \nu'_R=\mathbf{U}_R^\nu\nu_R,\quad u'_L=\mathbf{U}_L^u u_L,\quad u'_R=\mathbf{U}_R^u u_R,\quad d'_L=\mathbf{U}_L^d d_L,\quad d'_R=\mathbf{U}_R^d d_R, \quad (23)$$

$$e_L=\mathbf{U}_L^{e\dagger}e'_L,\quad e_R=\mathbf{U}_R^{e\dagger}e'_R,\quad \nu_L=\mathbf{U}_L^{\nu\dagger}\nu'_L,\quad \nu_R=\mathbf{U}_R^{\nu\dagger}\nu'_R,\quad u_L=\mathbf{U}_L^{u\dagger}u'_L,\quad u_R=\mathbf{U}_R^{u\dagger}u'_R,\quad d_L=\mathbf{U}_L^{d\dagger}d'_L,\quad d_R=\mathbf{U}_R^{d\dagger}d'_R. \quad (24)$$

When $\mathcal{L}$ is written in terms of the true fermions, the $\mathbf{U}$s fall out except in $\bar u'_L\mathbf{U}_L^u\tilde\sigma^\mu W_\mu^\pm\mathbf{U}_L^{d\dagger}d'_L$ and $\bar\nu'_L\mathbf{U}_L^\nu\tilde\sigma^\mu W_\mu^\pm\mathbf{U}_L^{e\dagger}e'_L$. Because of this, and some absorption of constants into the fermion fields, all the parameters in the $\mathbf{U}$s are contained in only four components of the Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V}^q=\mathbf{U}_L^u\mathbf{U}_L^{d\dagger}$ and four components of the Pontecorvo-Maki-Nakagawa-Sakata matrix $\mathbf{V}^l=\mathbf{U}_L^\nu\mathbf{U}_L^{e\dagger}$. The unitary matrices $\mathbf{V}^q$ and $\mathbf{V}^l$ are often parameterized as

$$\mathbf{V}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}e^{-i\delta/2}&0&0\\0&1&0\\0&0&e^{i\delta/2}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}\\0&1&0\\-s_{13}&0&c_{13}\end{pmatrix}\begin{pmatrix}e^{i\delta/2}&0&0\\0&1&0\\0&0&e^{-i\delta/2}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix},\quad c_j=\sqrt{1-s_j^2}, \quad (25)$$

$$\delta^q=69(4)\,\text{deg},\quad s_{12}^q=0.2253(7),\quad s_{23}^q=0.041(1),\quad s_{13}^q=0.0035(2), \quad (26)$$

$$\delta^l=?,\quad s_{12}^l=0.560(16),\quad s_{23}^l=0.7(1),\quad s_{13}^l=0.153(28). \quad (27)$$

$\mathcal{L}$ is invariant under a $U(1)\otimes SU(2)$ gauge transformation with $U^{-1}=U^\dagger$, $detU=1$, θ real,

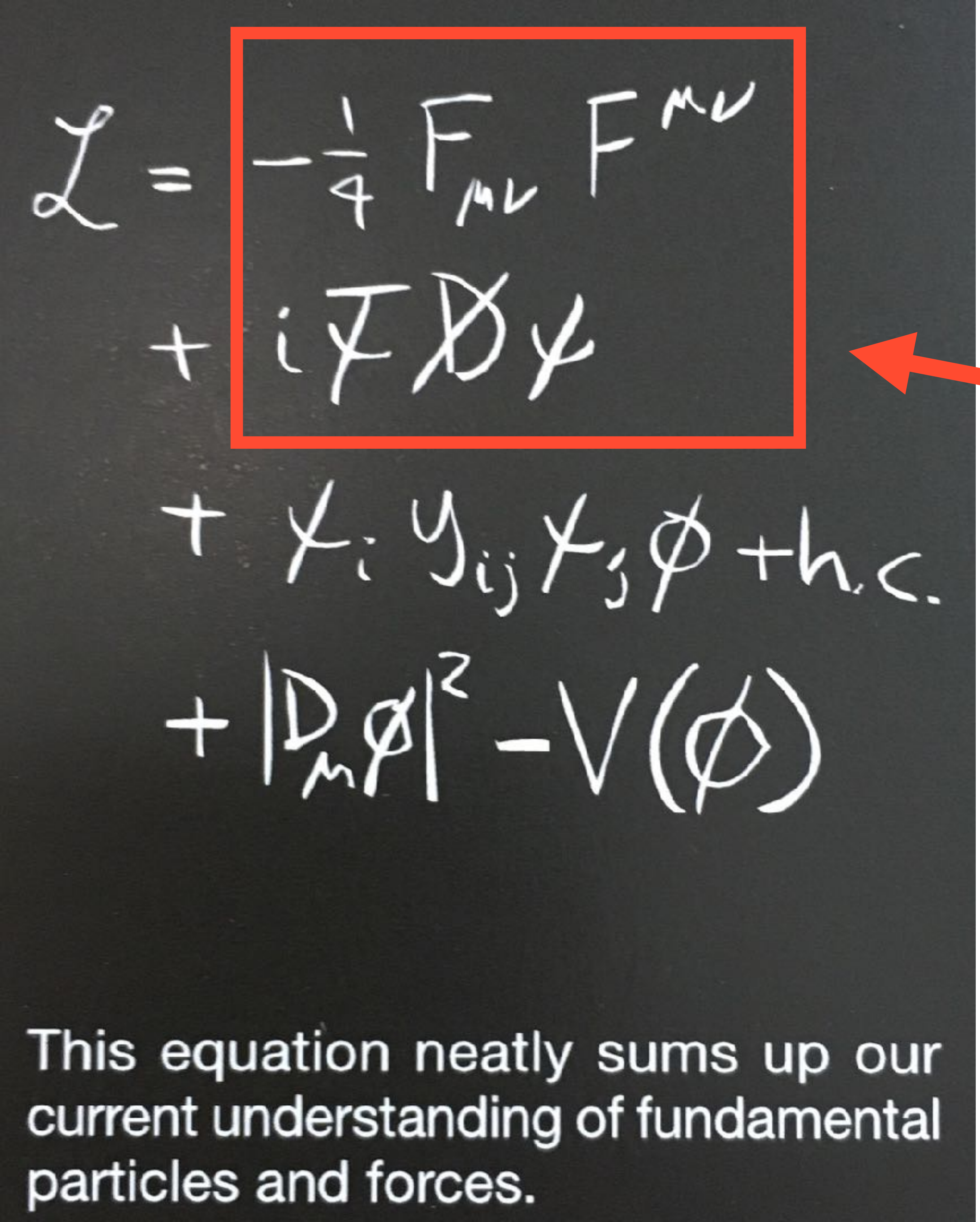
$$\mathbf{W}_\mu\to U\mathbf{W}_\mu U^\dagger-(2i/g_2)U\partial_\mu U^\dagger,\quad \mathbf{W}_{\mu\nu}\to U\mathbf{W}_{\mu\nu}U^\dagger,\quad B_\mu\to B_\mu+(2/g_1)\partial_\mu\theta,\quad B_{\mu\nu}\to B_{\mu\nu},\quad \phi\to e^{-i\theta}U\phi, \quad (28)$$

$$\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\to e^{i\theta}U\begin{pmatrix}\nu_L\\ e_L\end{pmatrix},\quad \begin{pmatrix}u_L\\ d_L\end{pmatrix}\to e^{-i\theta/3}U\begin{pmatrix}u_L\\ d_L\end{pmatrix},\quad \begin{matrix}\nu_R\to\nu_R, & u_R\to e^{-4i\theta/3}u_R,\\ e_R\to e^{2i\theta}e_R, & d_R\to e^{2i\theta/3}d_R,\end{matrix} \quad (29)$$

and under an $SU(3)$ gauge transformation with $V^{-1}=V^\dagger$, $detV=1$,

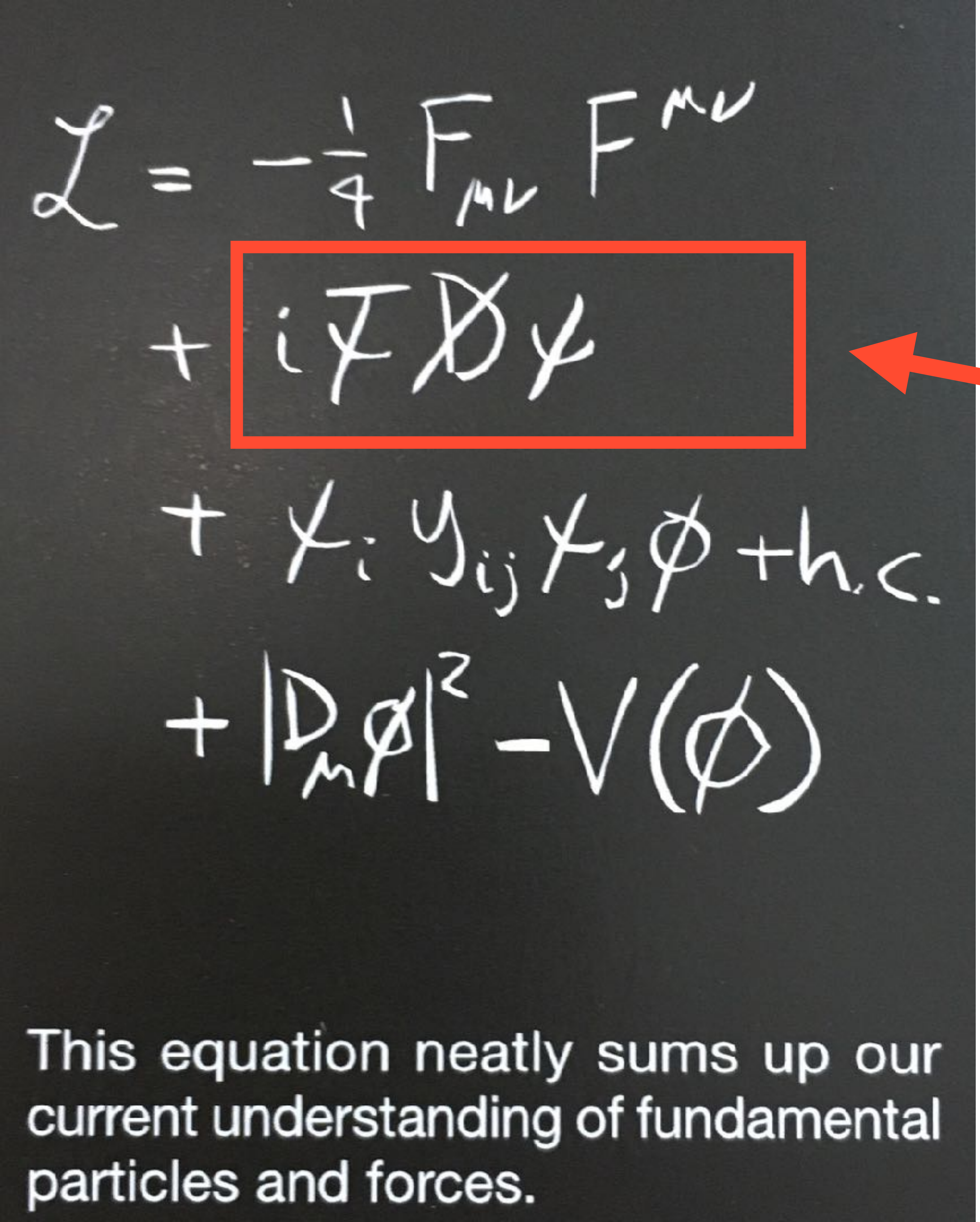
$$\mathbf{G}_\mu\to V\mathbf{G}_\mu V^\dagger-(i/g)V\partial_\mu V^\dagger,\quad \mathbf{G}_{\mu\nu}\to V\mathbf{G}_{\mu\nu}V^\dagger,\quad u_L\to Vu_L,\quad d_L\to Vd_L,\quad u_R\to Vu_R,\quad d_R\to Vd_R. \quad (30)$$

http://einstein-schrodinger.com/Standard_Model.pdf



What does it mean?

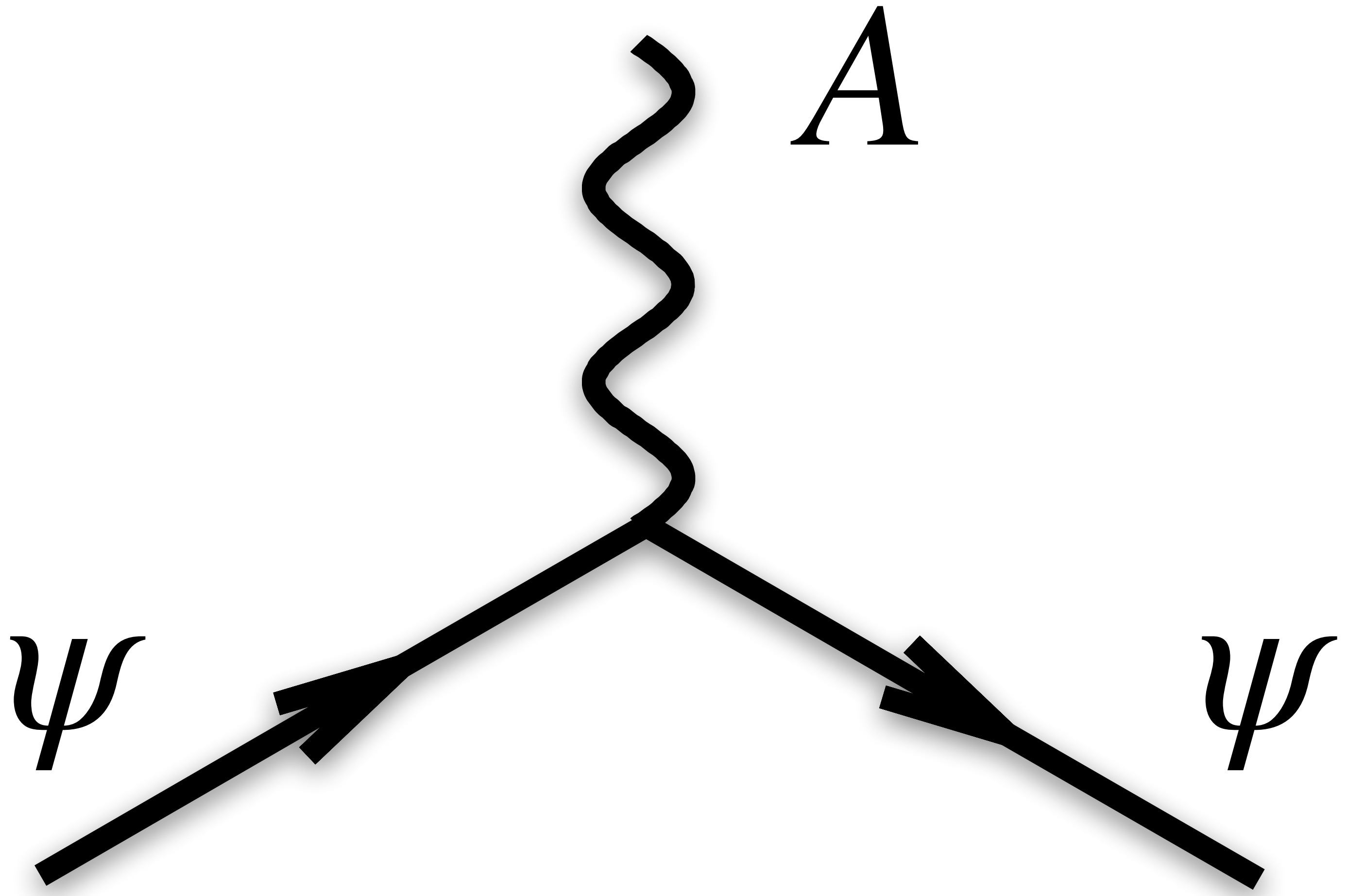
Quantum formulation of Maxwell's equations, (and their analogues for the weak and strong forces).



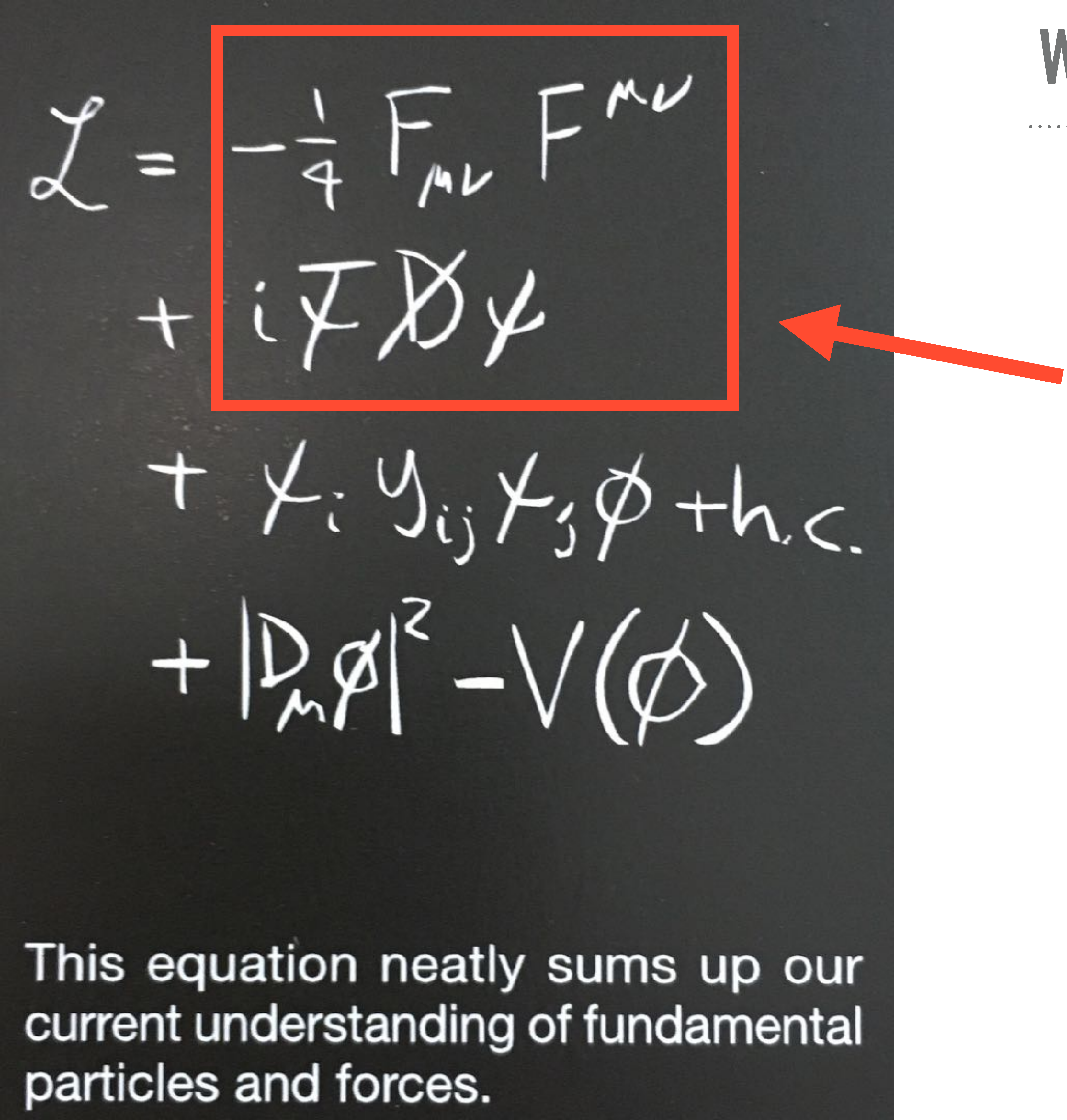
What does it mean?

ψ = *fermion (e.g. electron) field*

$D \sim eA(=\text{photon field}) + \cdots$



tells you there's an electron-photon interaction vertex



What does it mean?

many experiments have probed these so-called “gauge” interactions (in classical form, they date back to 1860s)

Describe electromagnetism, full electroweak theory & the strong force.

They work to high precision (best tests go up to 1 part in 10^8)

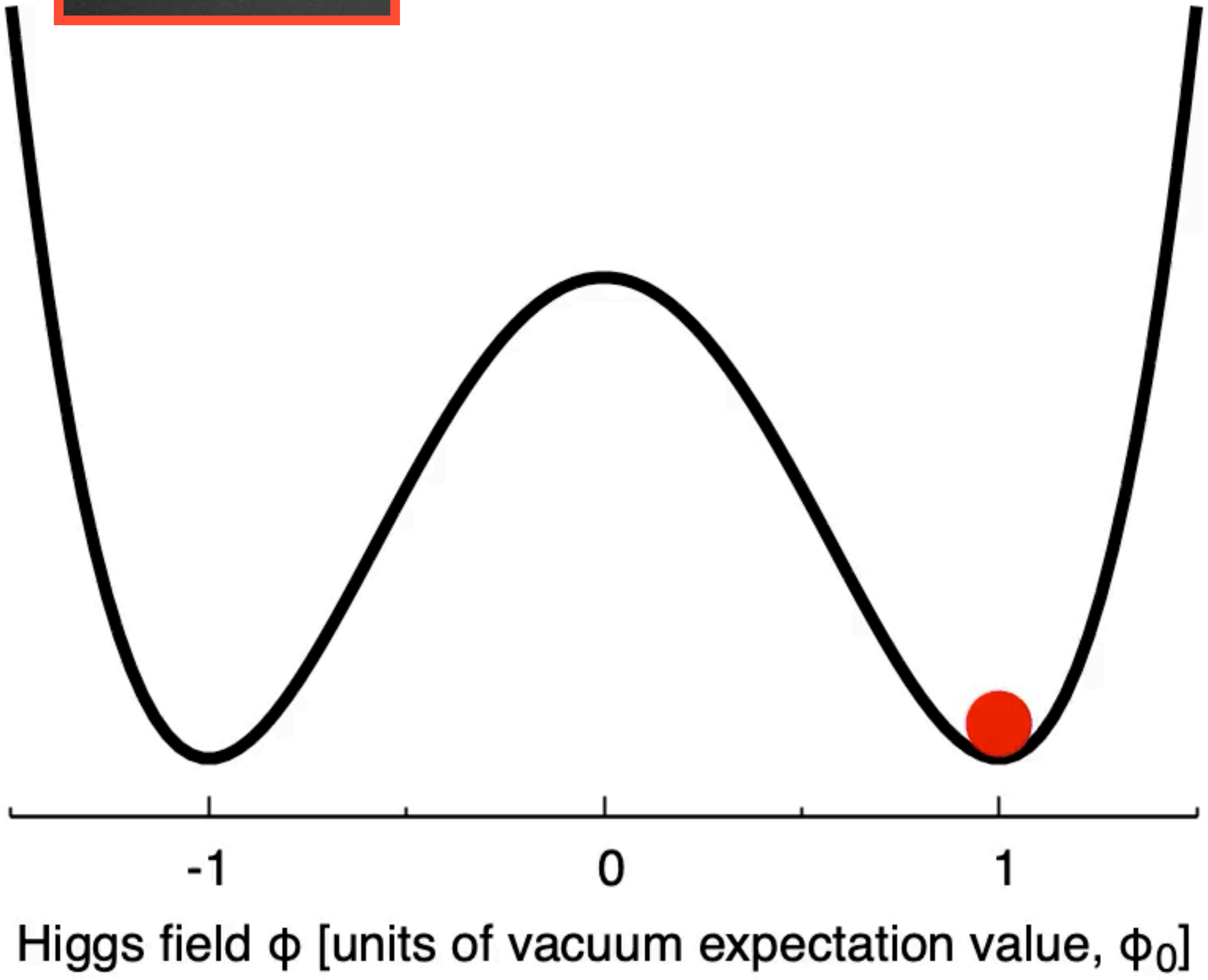
Higgs sector

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi$$
$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

This equation neatly sums up our current understanding of fundamental particles and forces.

until 7 years ago none of these terms had ever been directly observed.

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)

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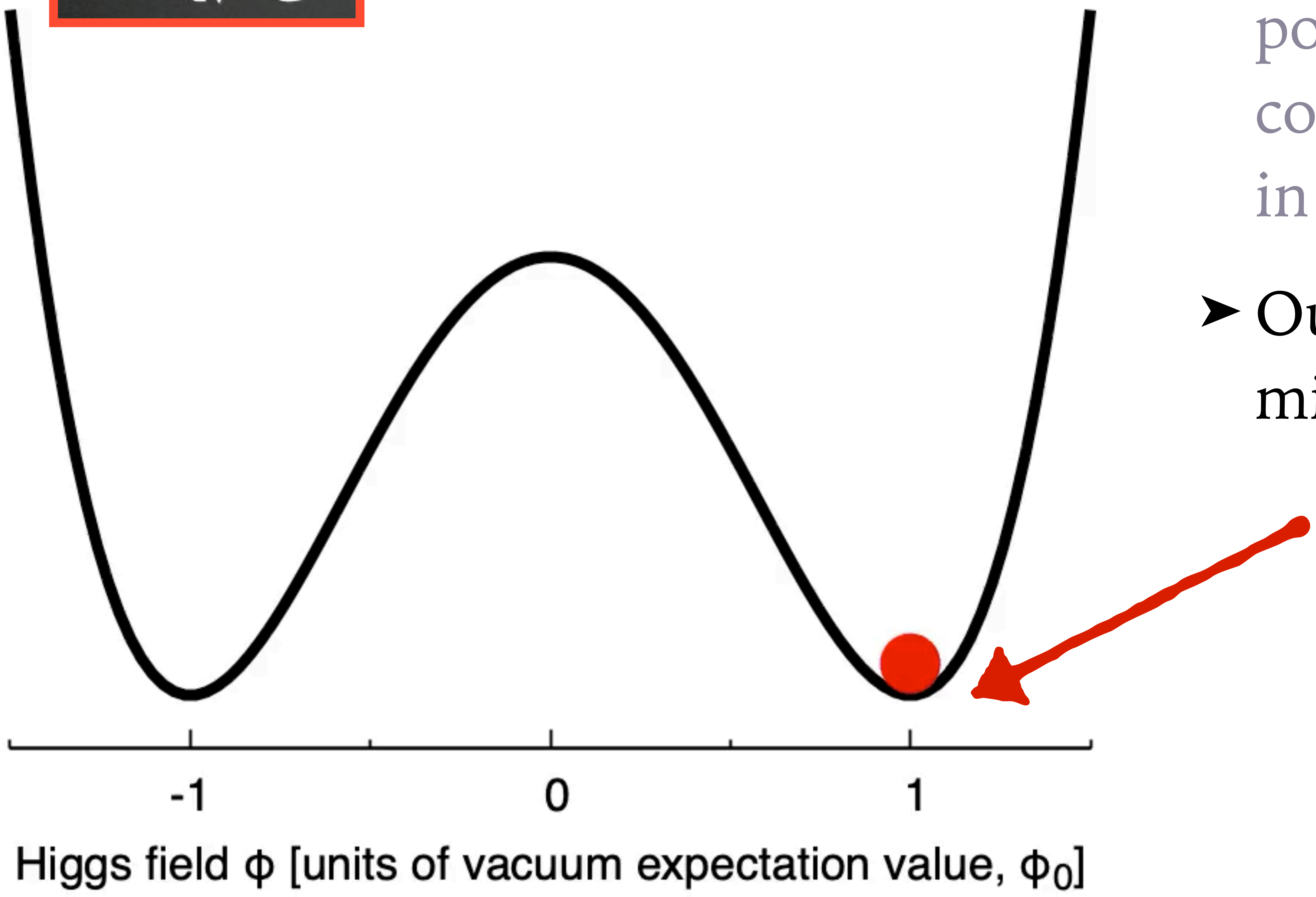
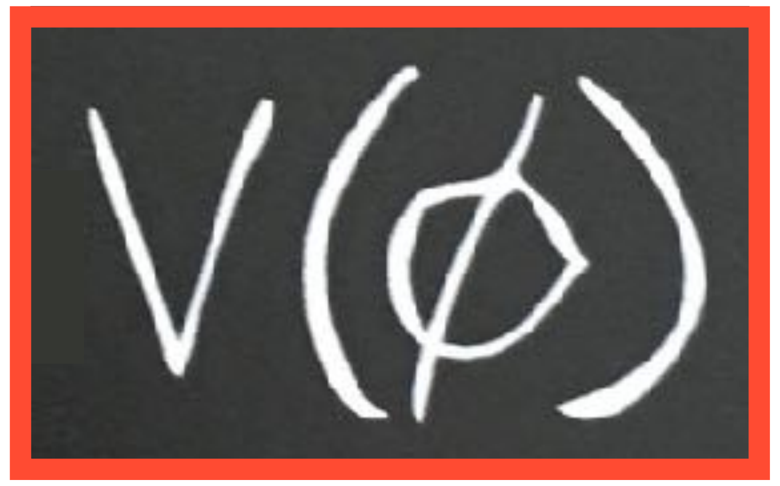
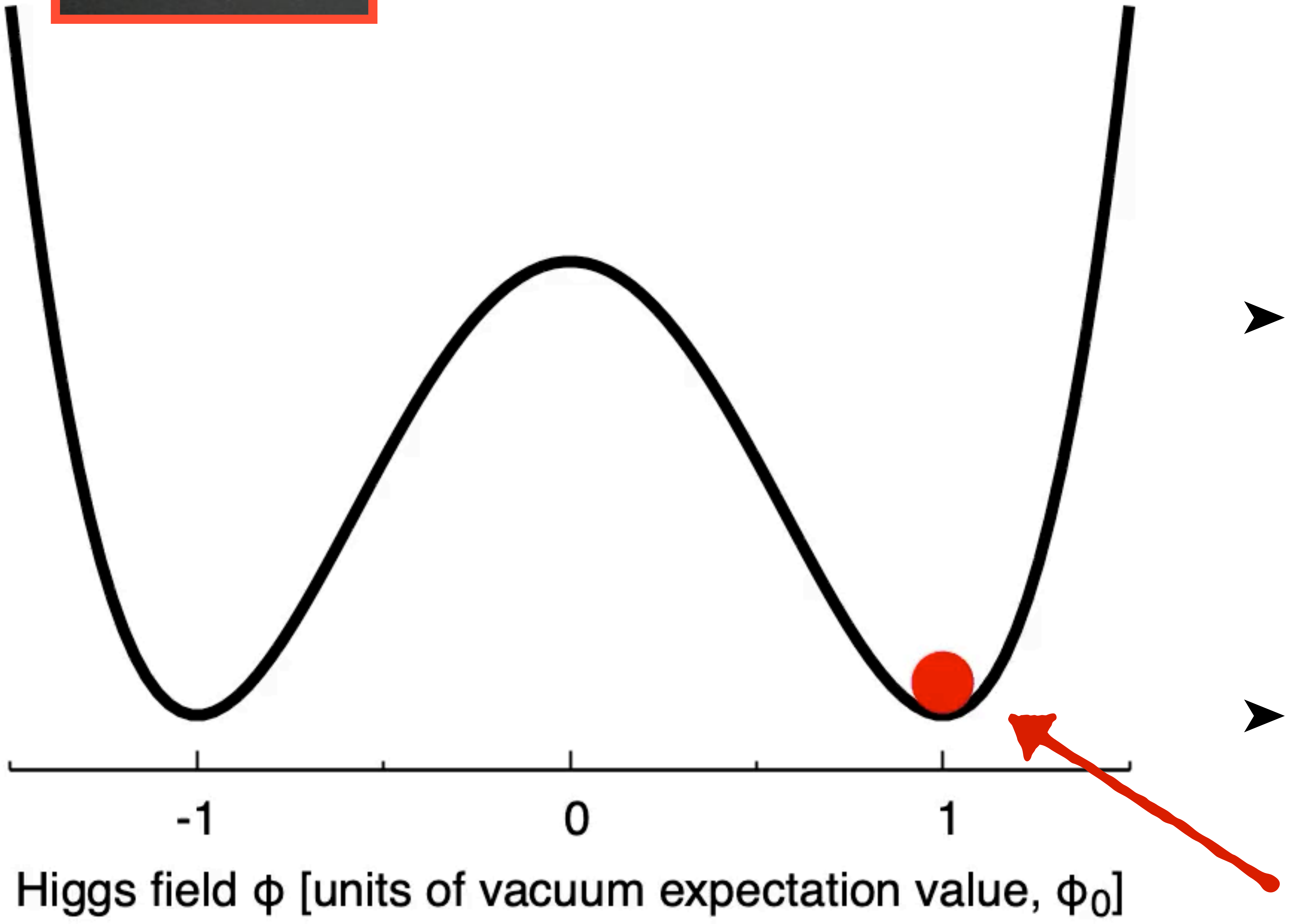


- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)
- Our universe sits at minimum of V(φ), at

$$\phi = \phi_0 = \frac{\mu}{\sqrt{2\lambda}}$$



$$= -\mu^2\phi^2 + \lambda\phi^4$$



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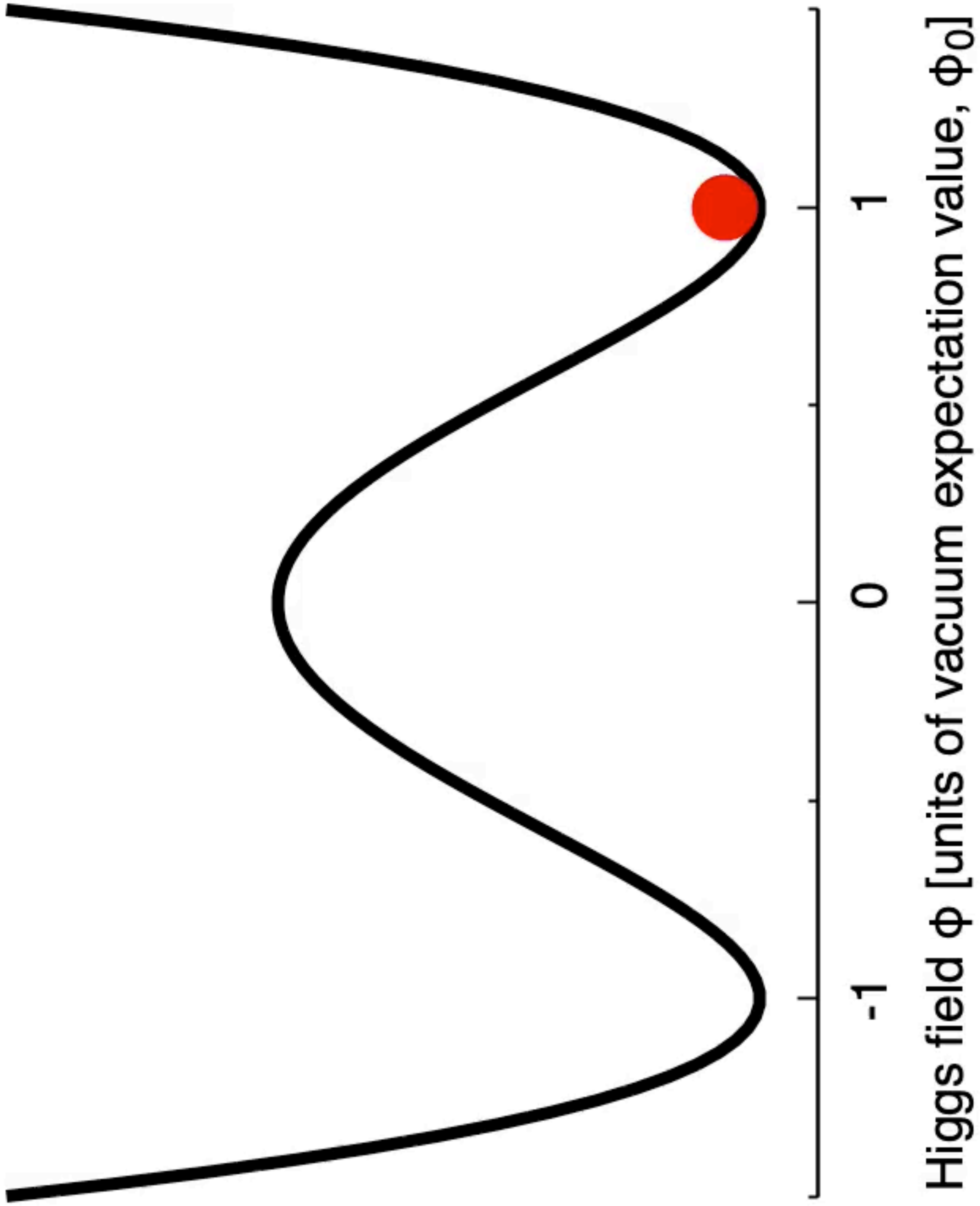
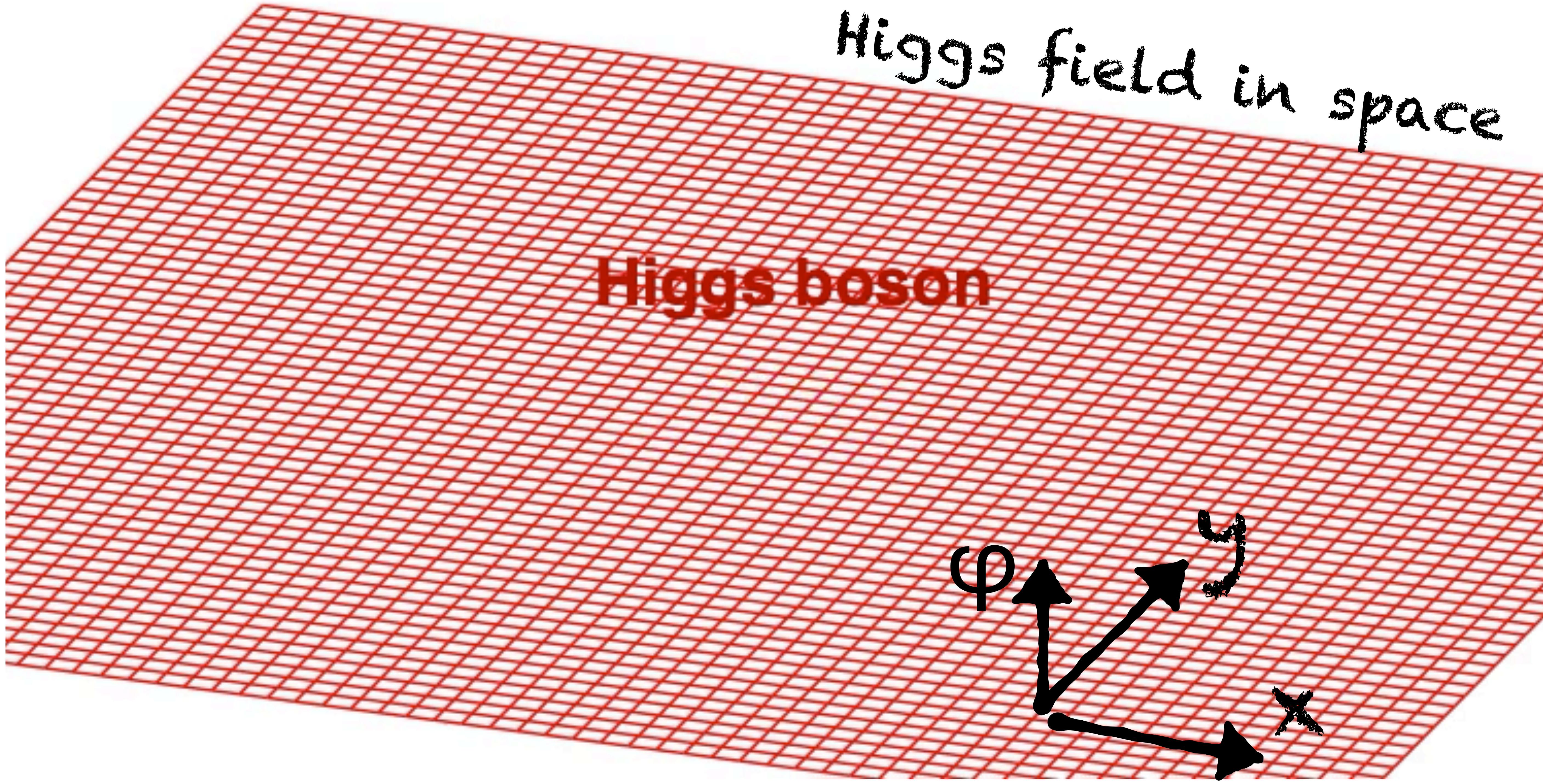
- Our universe sits at minimum of V(φ), at

$$\phi = \phi_0 = \frac{\mu}{\sqrt{2\lambda}}$$

- Excitation of the φ field around φ_0 is a Higgs boson ($\varphi = \varphi_0 + H$)

$$\varphi = \varphi_0 + H$$

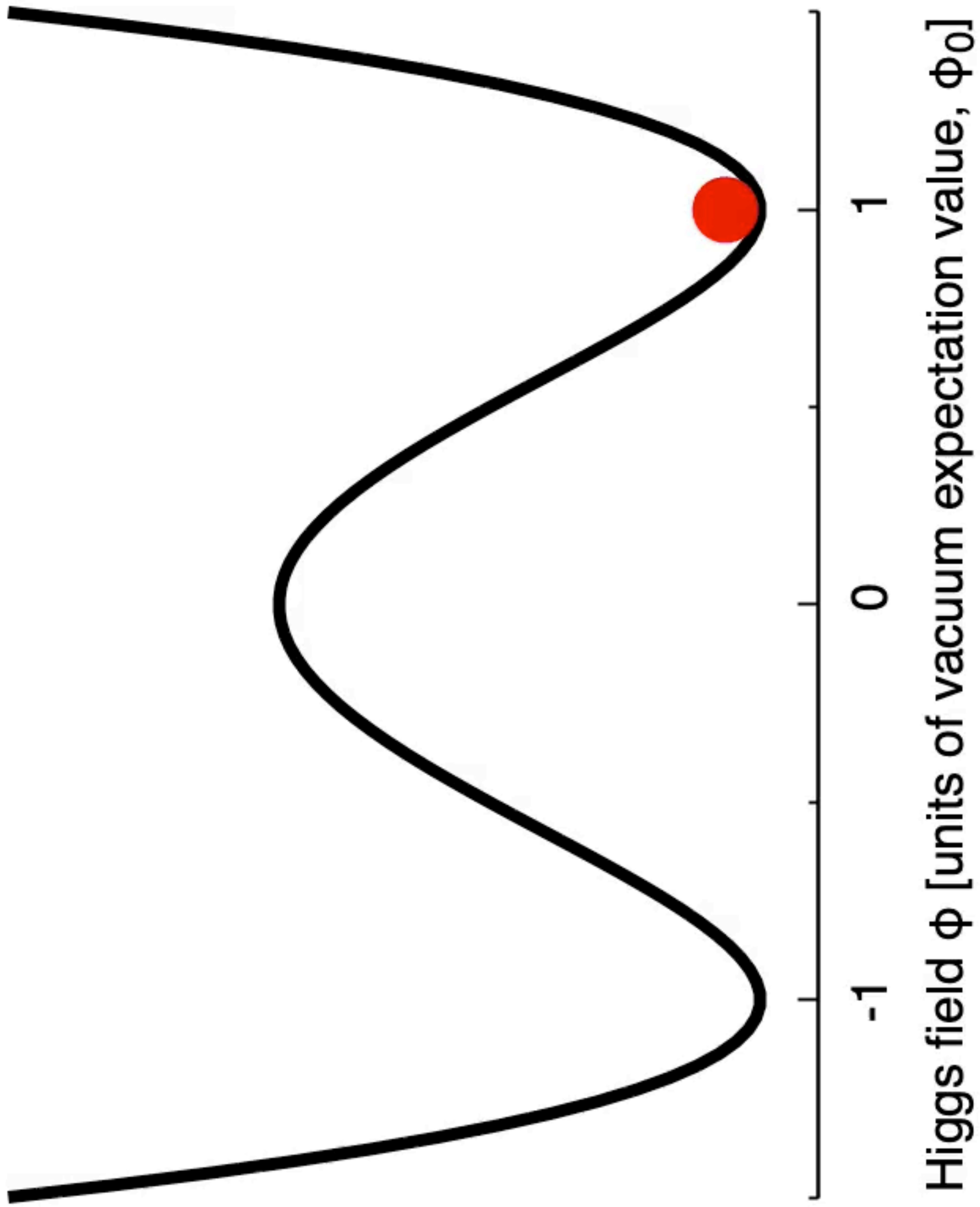


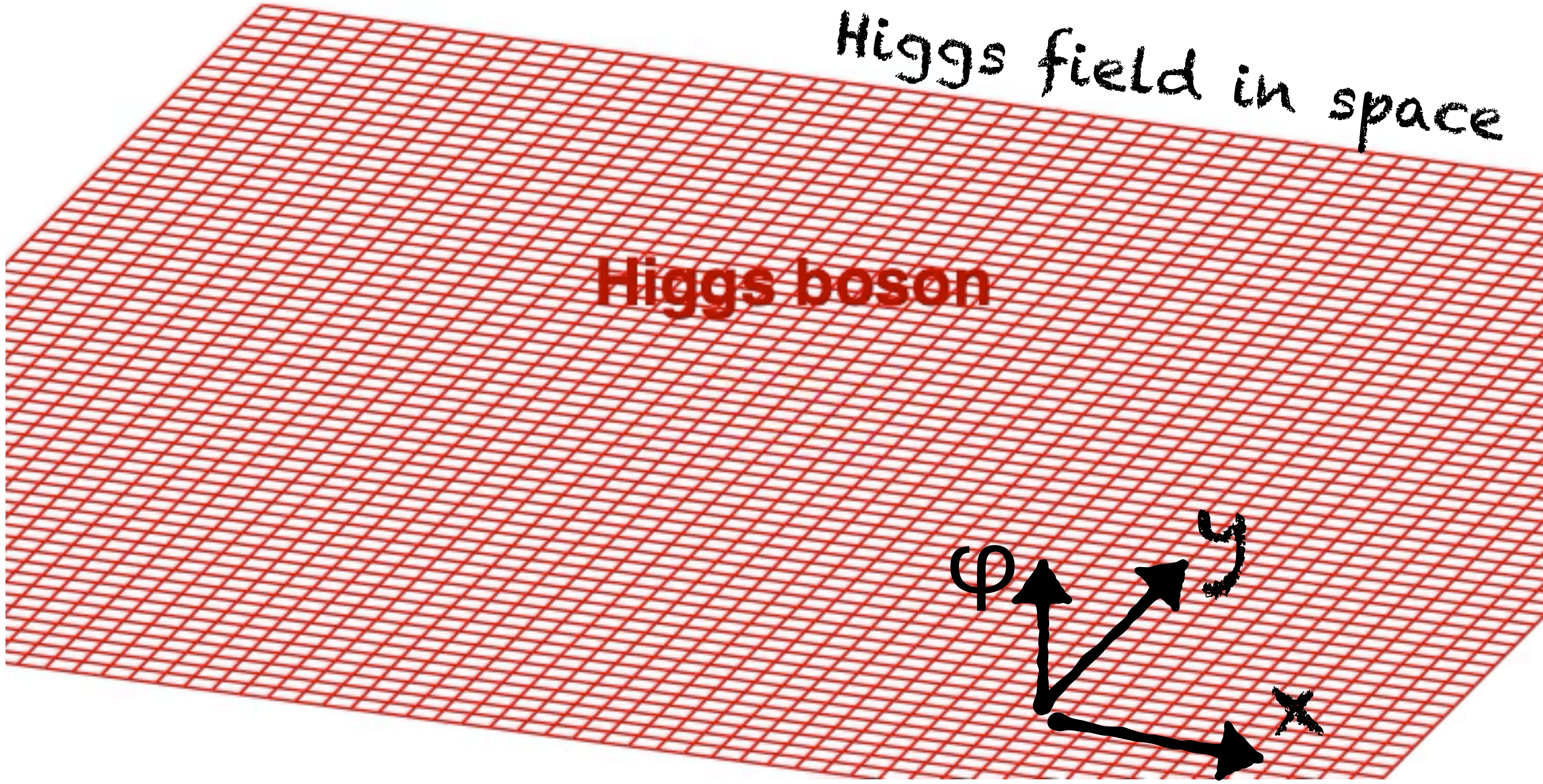


Higgs field can be different at each point in space

A Higgs boson at a given point in space is a localised fluctuation of the field

$$\varphi = \varphi_0 + H$$





Higgs field can be different at each point in space

A Higgs boson at a given point in space is a localised fluctuation of the field

$$\varphi = \varphi_0 + H$$

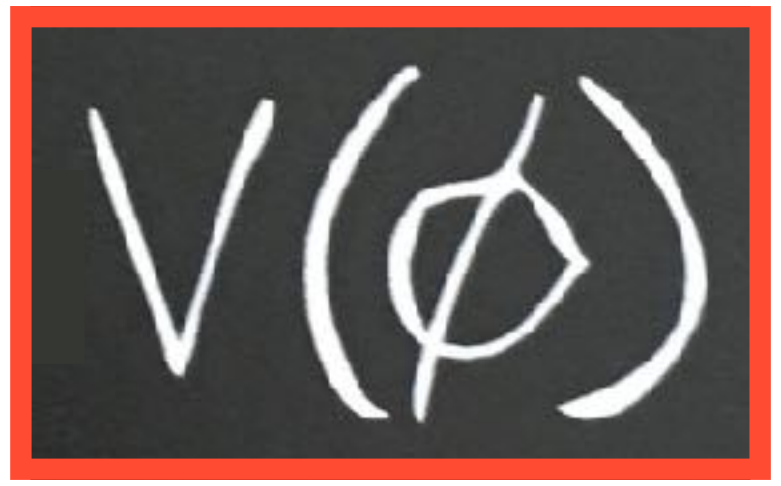
established

(2012 Higgs boson discovery)

$\varphi = \varphi_0 + H$

established

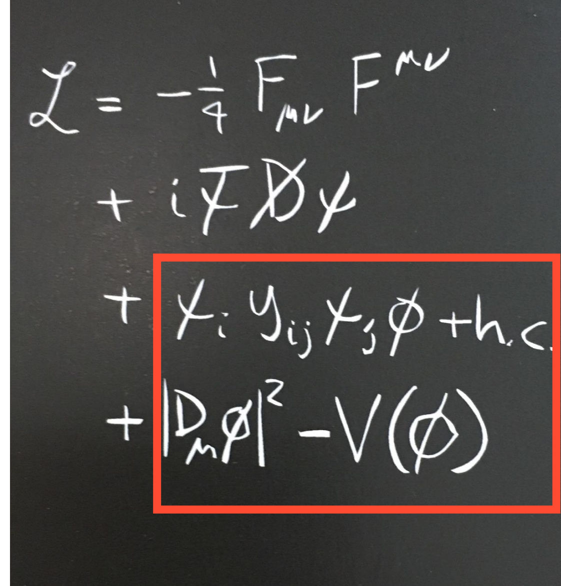
(2012 Higgs boson discovery)



$$= -\mu^2\phi^2 + \lambda\phi^4$$

hypothesis

what terms are there in the Higgs sector?
2. Gauge–Higgs term



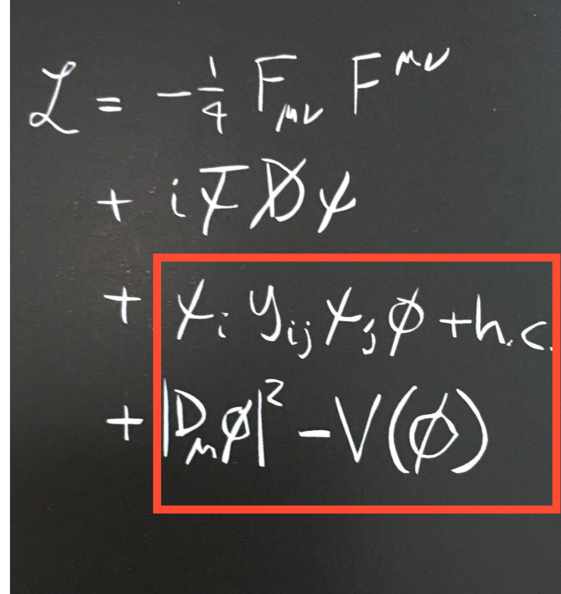
This equation neatly sums up our current understanding of fundamental particles and forces.

$$\rightarrow \underbrace{g^2\phi_0^2}_{\text{constants}}\ \underbrace{Z_\mu Z^\mu}_{\text{fields}} \quad + \quad \underbrace{2g^2\phi_0}_{\text{constants}}\ \underbrace{H\ Z_\mu Z^\mu}_{\text{fields}} \quad + \ldots$$

Z-boson mass term

HZZ interaction term

$$[\phi^2 = (\phi_0 + H)^2 = \phi_0^2 + 2\phi_0 H + \ldots]$$



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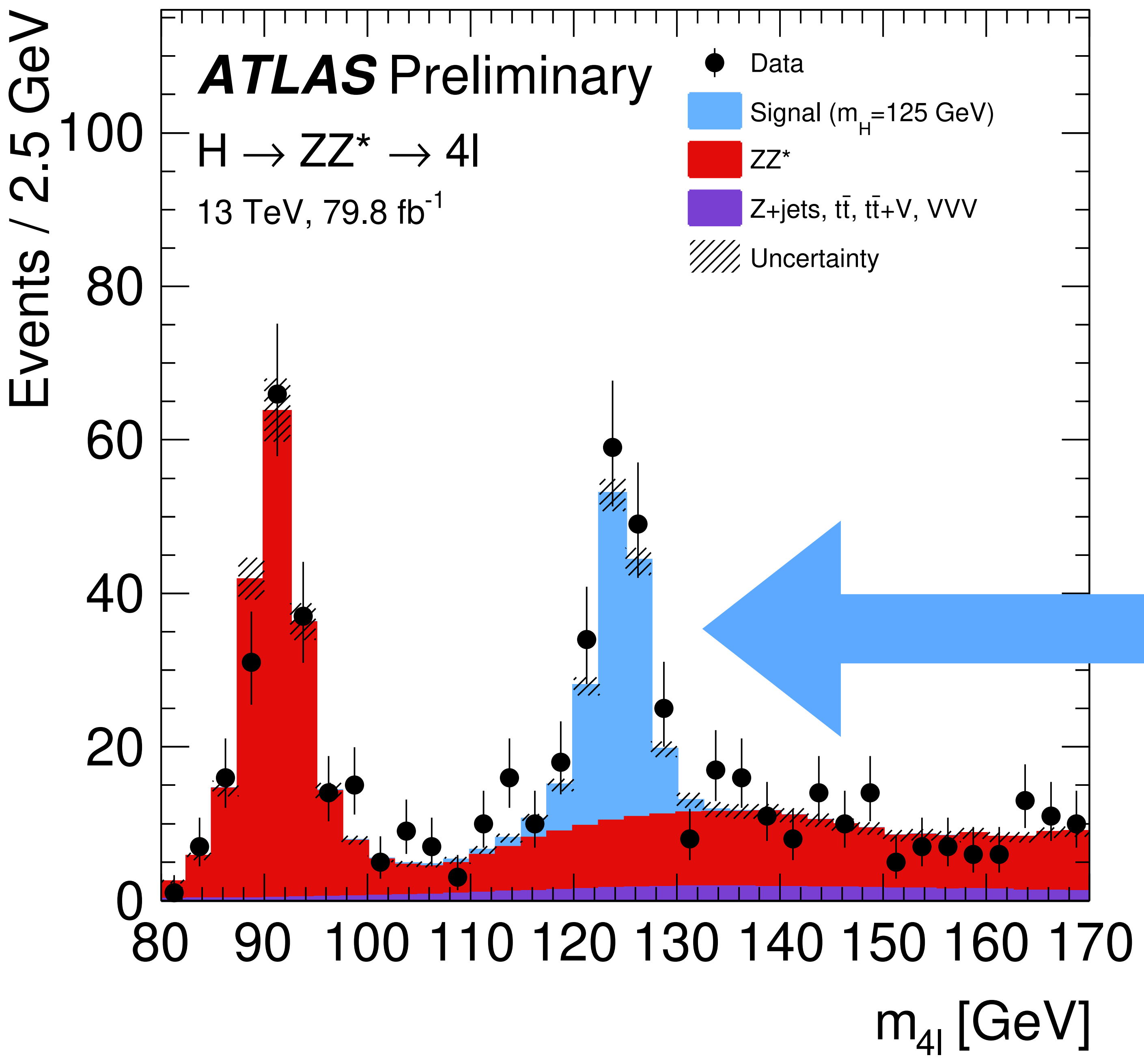
2. Gauge-Higgs term

$$\rightarrow g^2 \phi_0^2 Z_\mu Z^\mu + 2 g^2 \phi_0 H Z_\mu Z^\mu + \ldots$$

Z-boson mass term

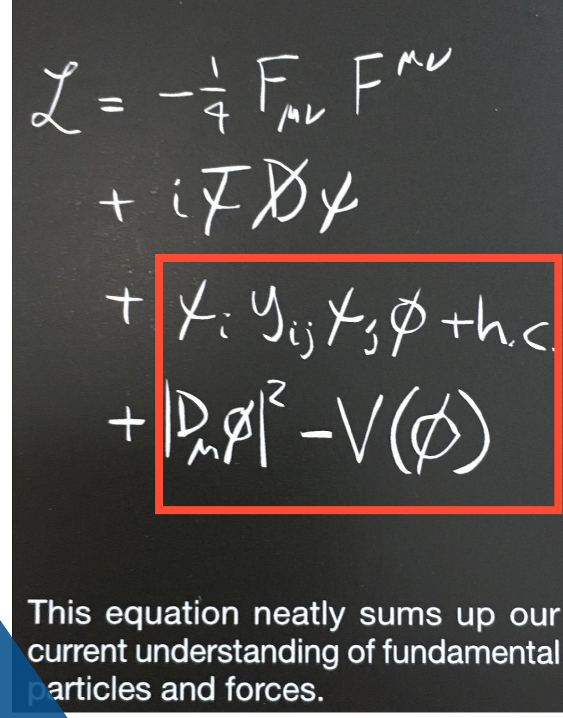
ZZH interaction term



H → ZZ*

Higgs mechanism predicts specific relation between Z-boson mass and HZZ interaction

what terms are there in the Higgs sector?
2. Gauge–Higgs term

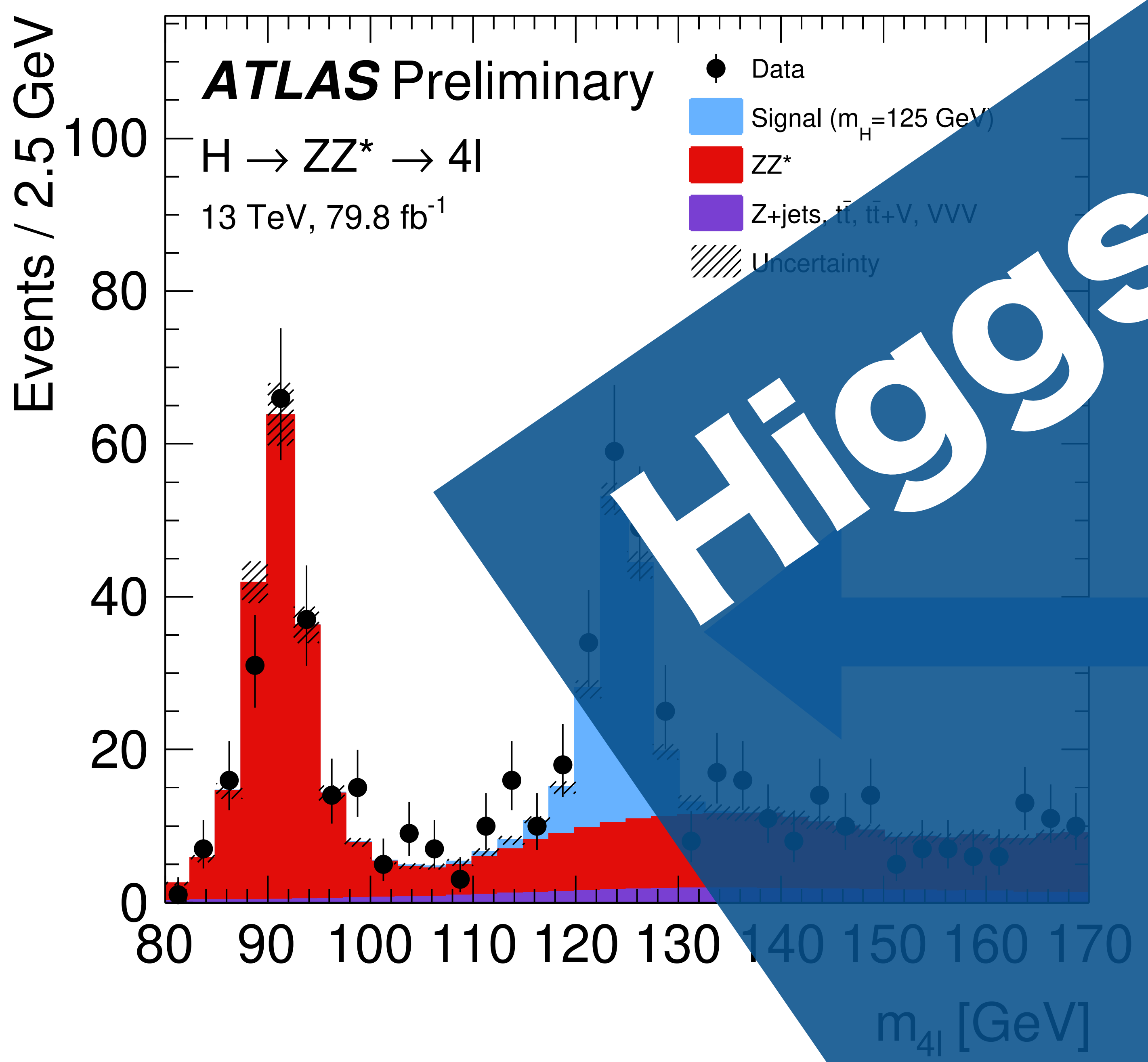


$$\rightarrow g^2\phi_0^2 Z_\mu Z^\mu + 2g^2\phi_0 H Z_\mu Z^\mu + \ldots$$

Z boson mass term

ZZH interaction term

Higgs (BEH) mechanism for vector boson mass = 2013 Nobel prize



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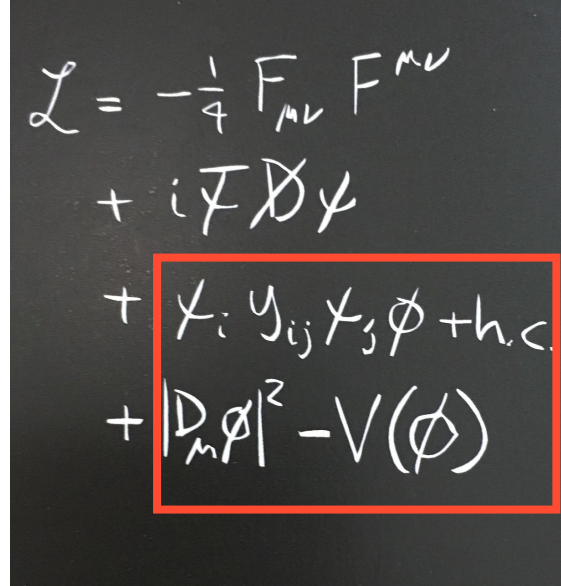
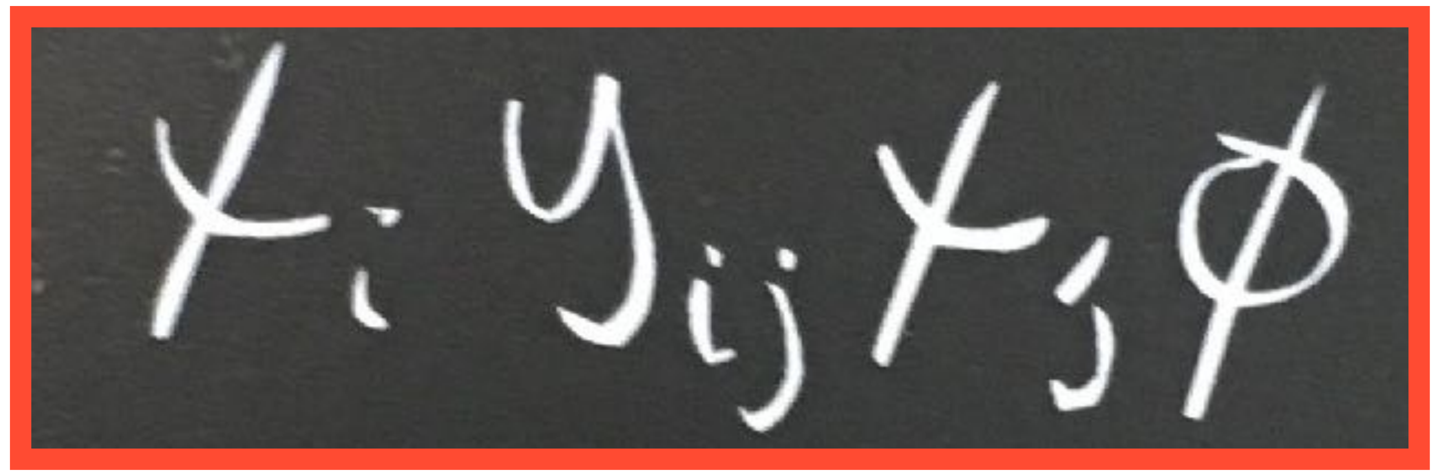


This equation neatly sums up our current understanding of fundamental particles and forces.

what terms are there in the Higgs sector?
3. Fermion–Higgs (Yukawa) term



$$\rightarrow \quad y_{ij}\, \phi_0\, \psi_i\, \psi_j \;+\; y_{ij}\, H\, \psi_i\, \psi_j$$

fermion mass term

$$m_i = y_{ii}\phi_0$$

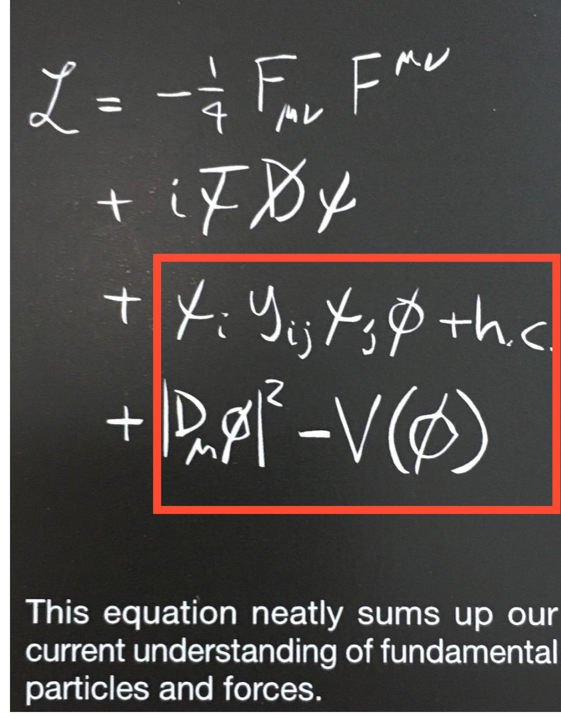
Higgs-fermion-fermion interaction term;

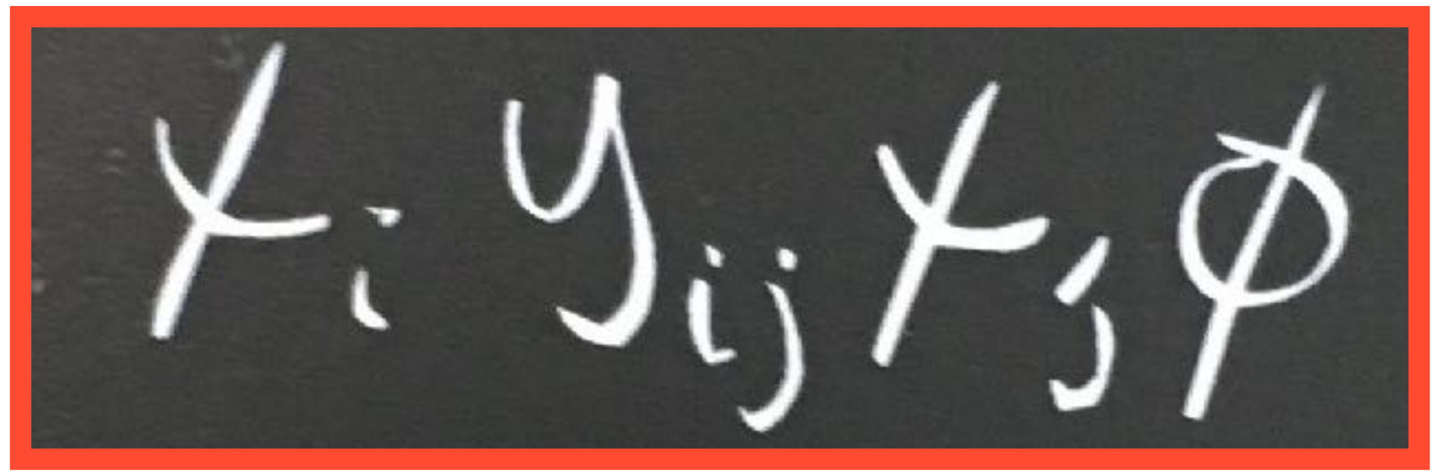
coupling $\sim y_{ii}$

i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$?	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10^{-4}$

$$\phi = \phi_0 + H$$

what terms are there in the Higgs sector?
3. Fermion–Higgs (Yukawa) term





$$\rightarrow \quad y_{ij}\,\phi_0\,\psi_i\,\psi_j \; + \; y_{ij}\,H\,\psi_i\,\psi_j$$

fermion mass term

$m_i = y_{ii}\phi_0$

Higgs-fermion-fermion interaction term; coupling $\sim y_{ii}$

i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	3 · 10[illegible]
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$?	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10^{-4}$

the subject of the next few slides

$$\phi = \phi_0 + H$$

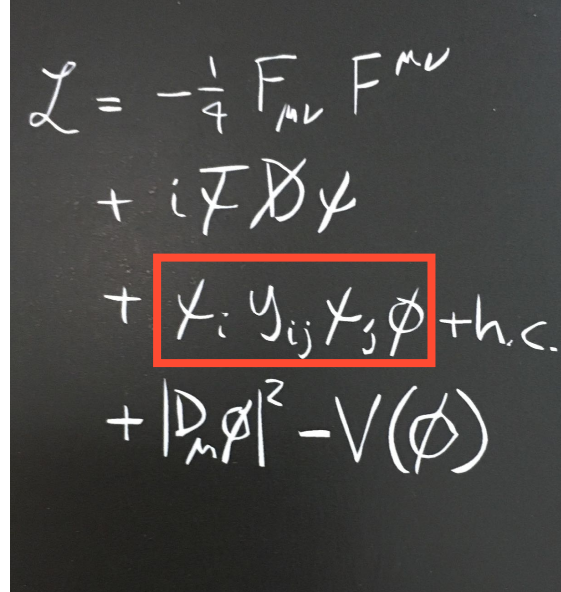
Yukawa interaction hypothesis

Yukawa couplings ~ fermion mass

first fundamental interaction that we probe at the quantum level where interaction strength (y_{ij}) not quantised

(i.e. no underlying unit of conserved charge across particles)

Why do Yukawa couplings matter?
(1) Because, within SM **conjecture**, they're what give masses to all **quarks**



This equation neatly sums up our current understanding of fundamental particles and forces.

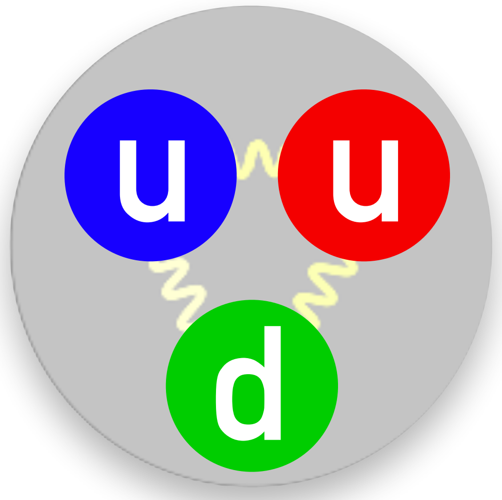
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

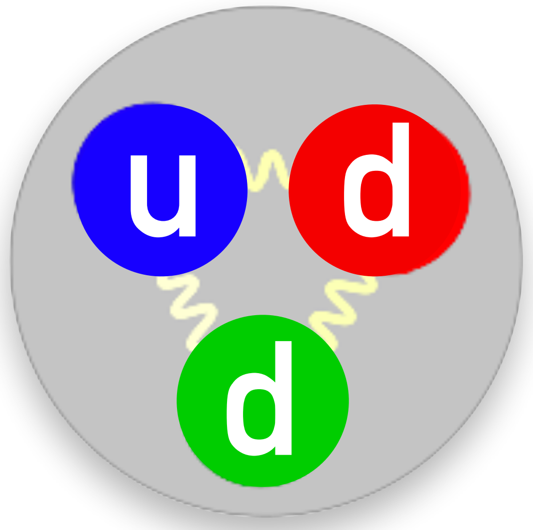
So protons are **lighter** than neutrons,
→ protons are stable.

Which gives us the hydrogen atom,
& chemistry and biology as we know it

proton
mass = 938.3MeV

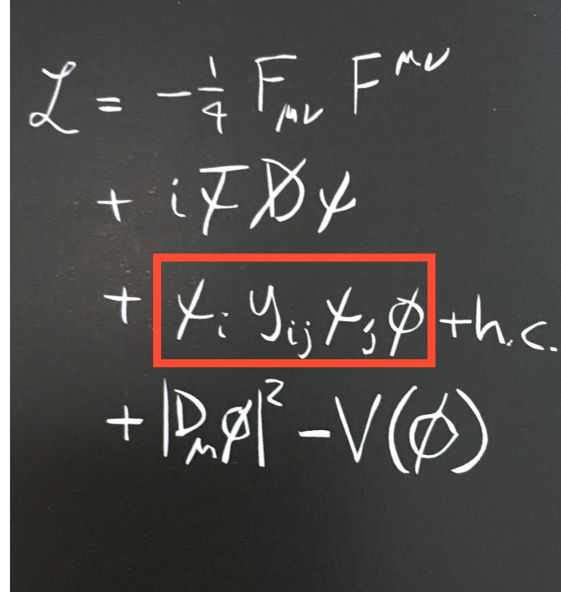


neutron
mass = 939.6MeV



Why do Yukawa couplings matter?

(2) Because, within SM **conjecture**, they're what give masses to all **leptons**



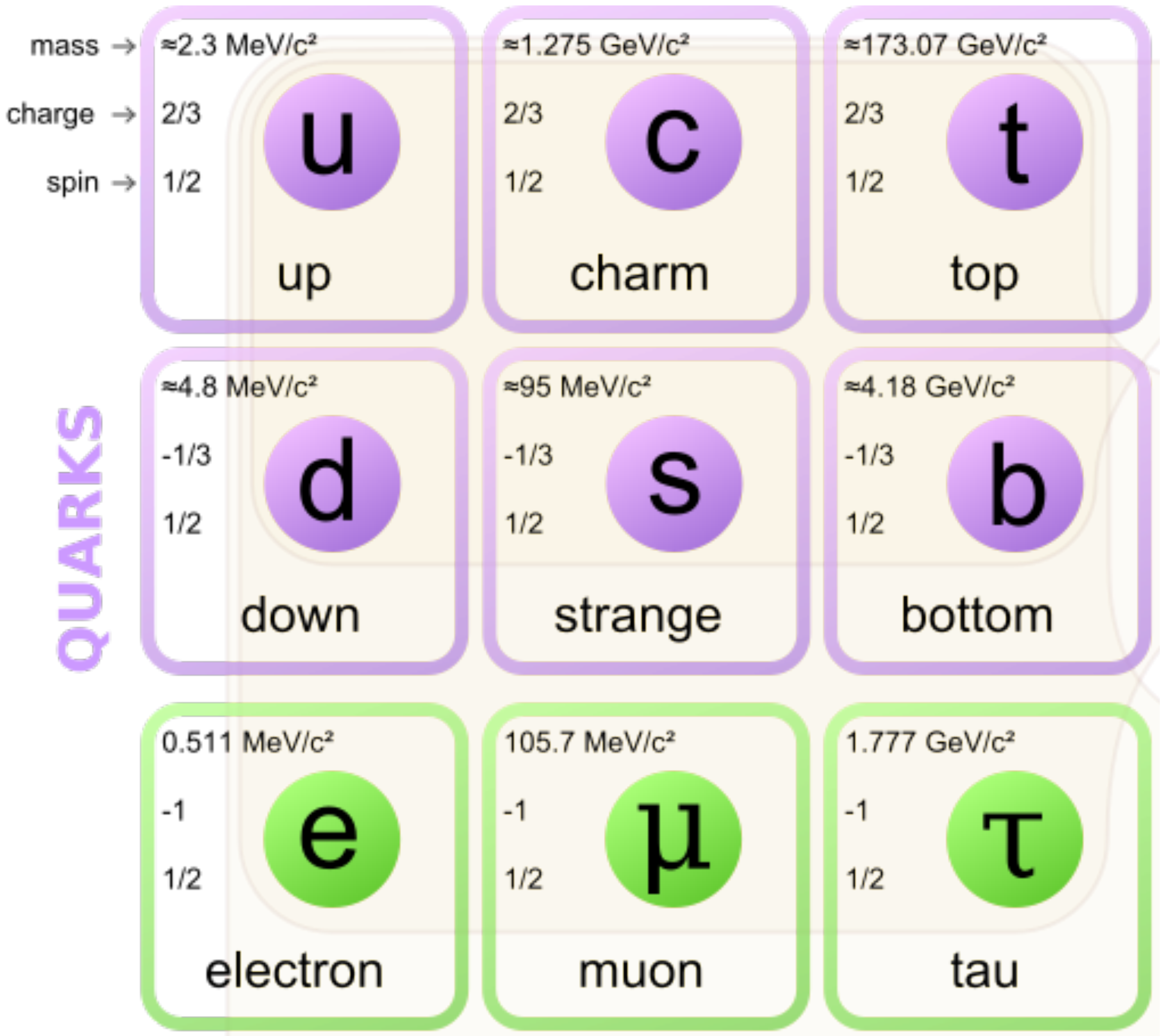
This equation neatly sums up our current understanding of fundamental particles and forces.

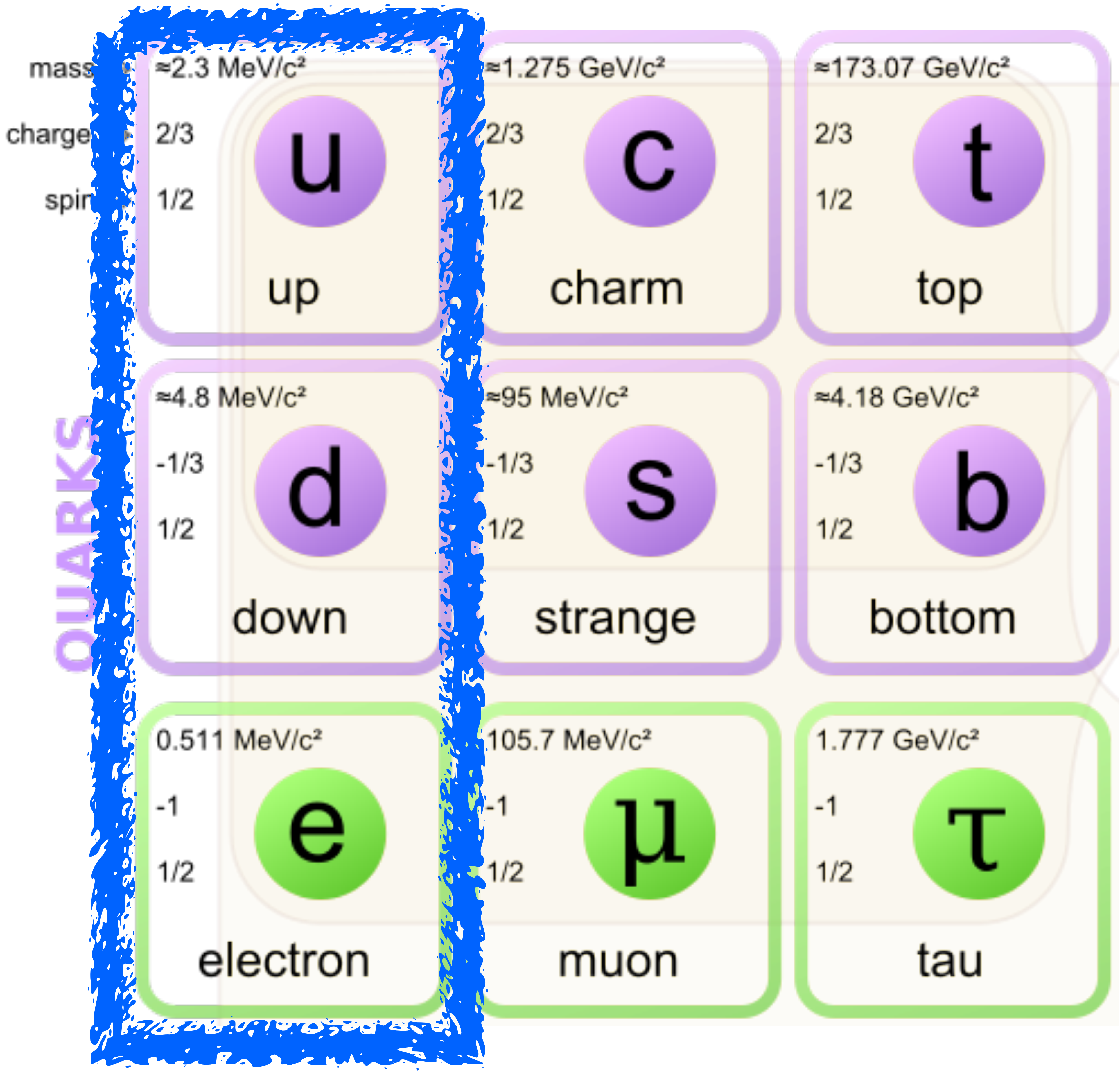
Bohr radius

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

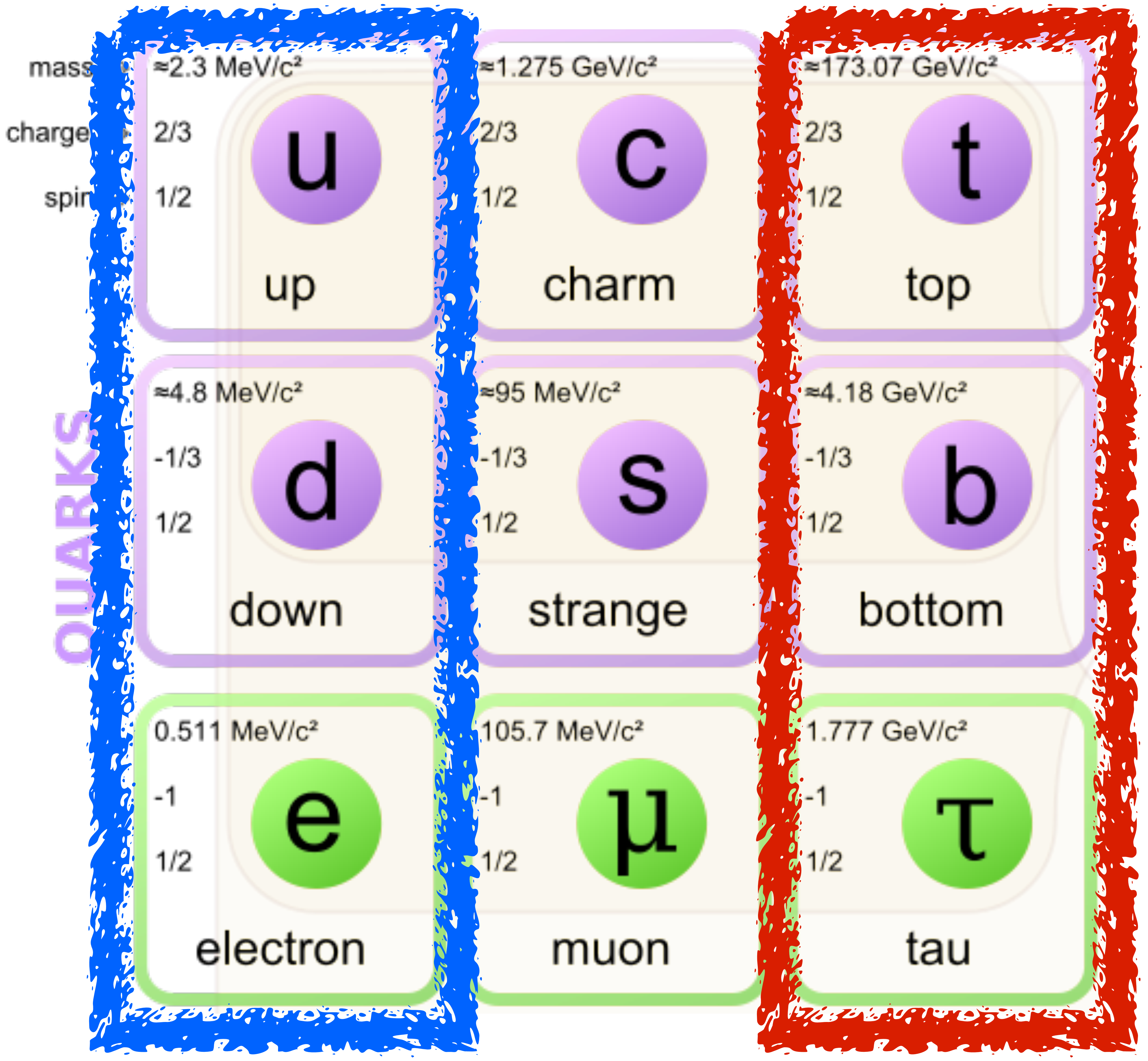
electron mass determines size of all atoms

it sets energy levels of all chemical reactions


mass →
charge →
spin →
QUARKS
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau

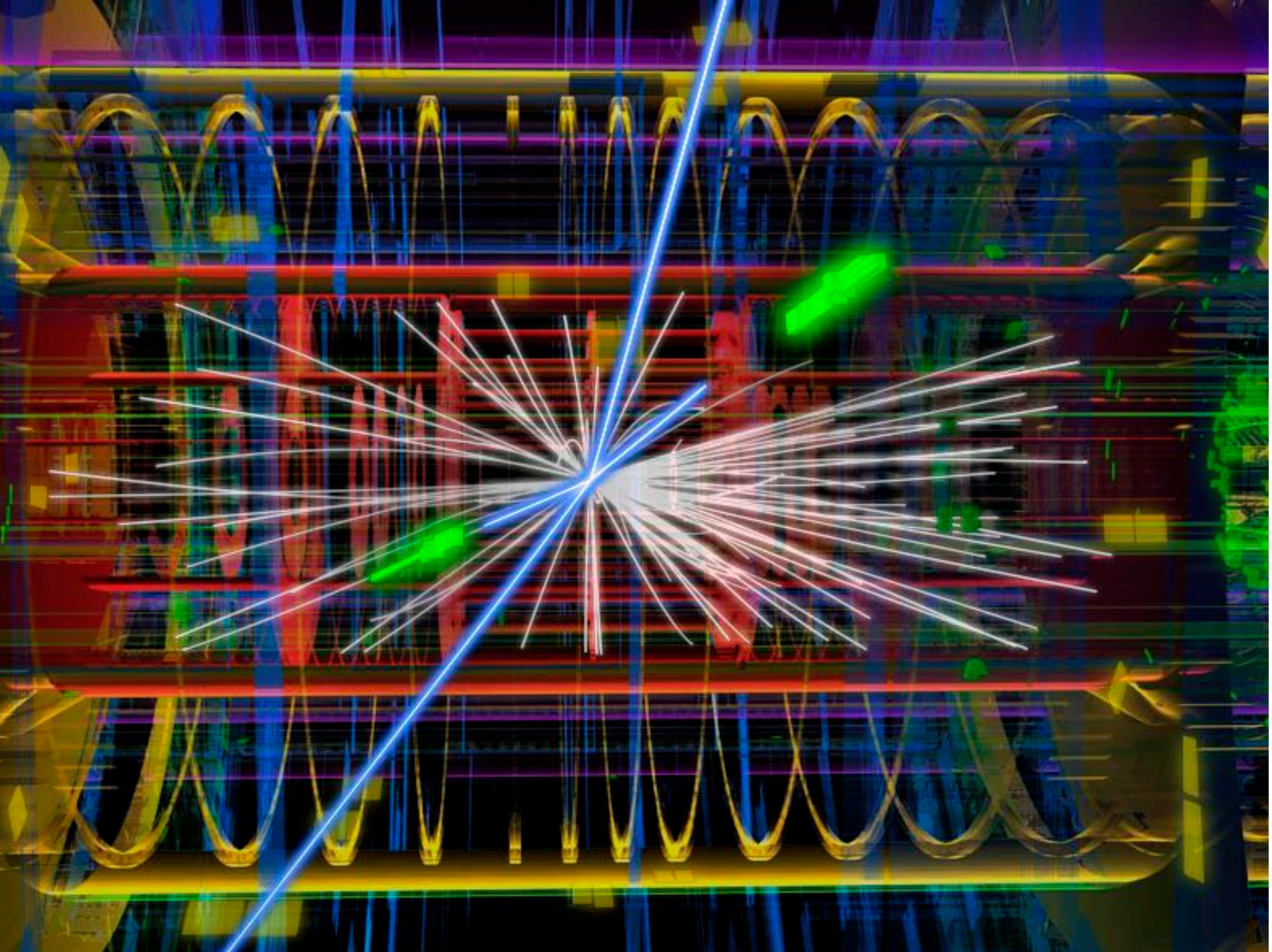


1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**



1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**

3rd generation (us) has high mass because of strong interactions with Higgs field (and so with Higgs bosons): **can potentially be tested**



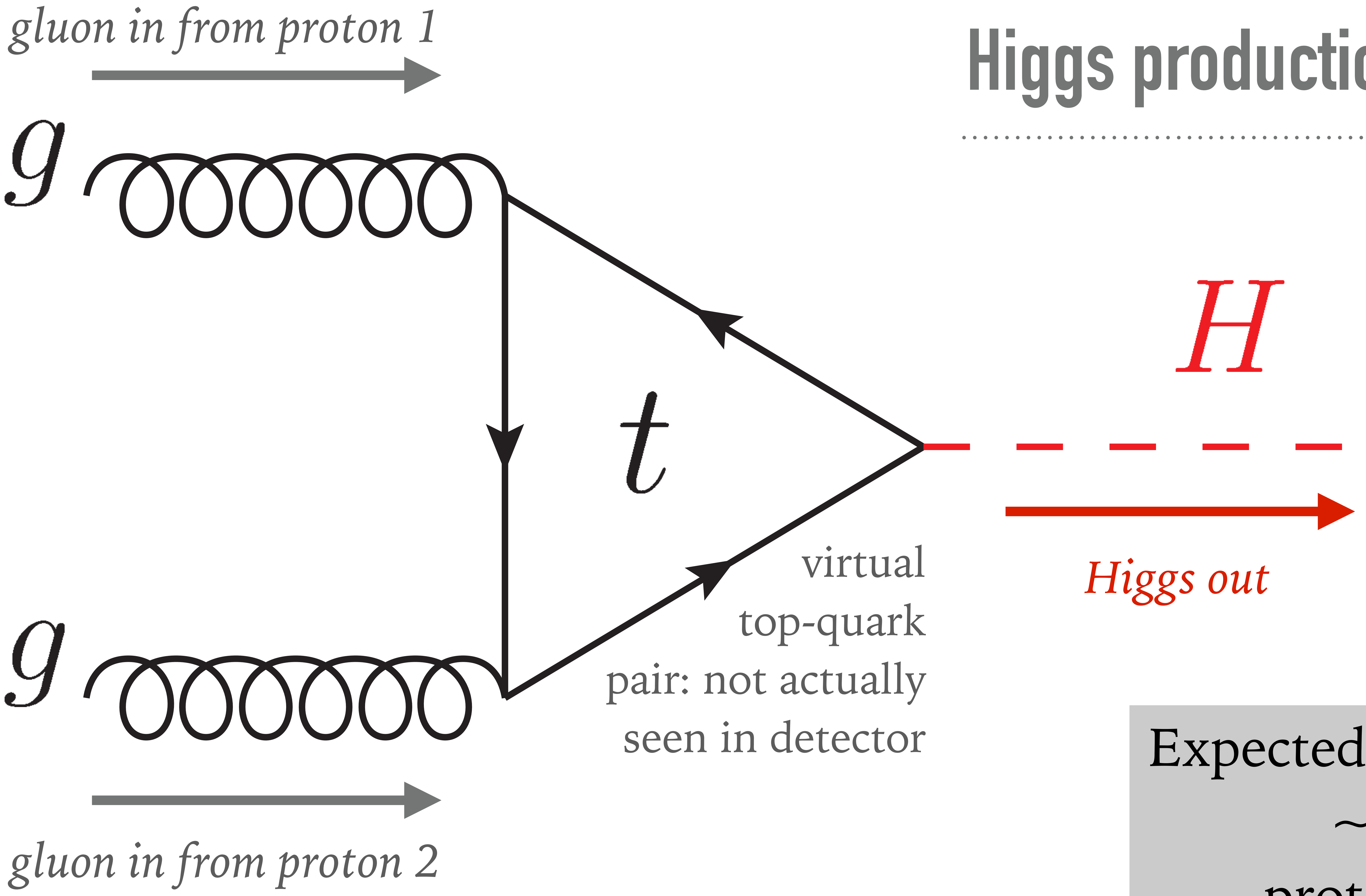
ATLAS & CMS
@LHC

~up to 2 billion collisions/second

(+ lower rates at LHCb and ALICE)

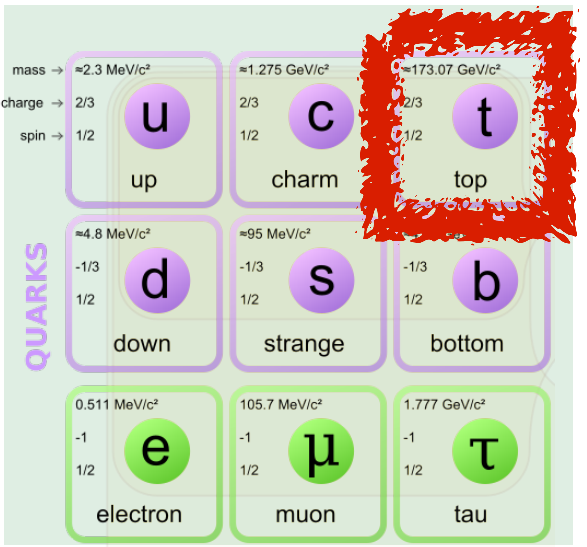
what underlying processes tell us about Yukawa interactions?

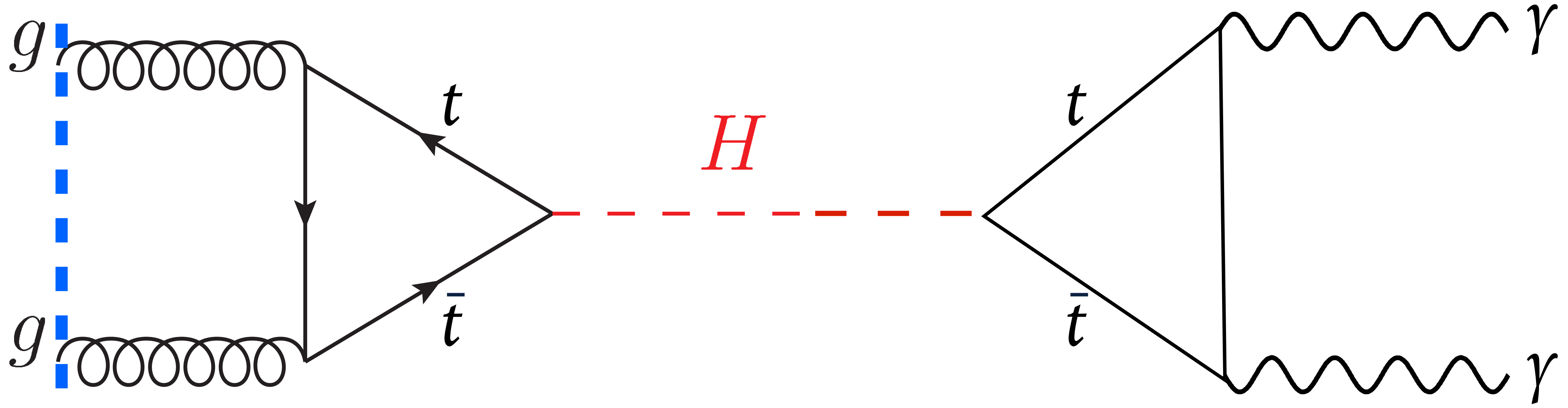
Higgs production: the dominant channel



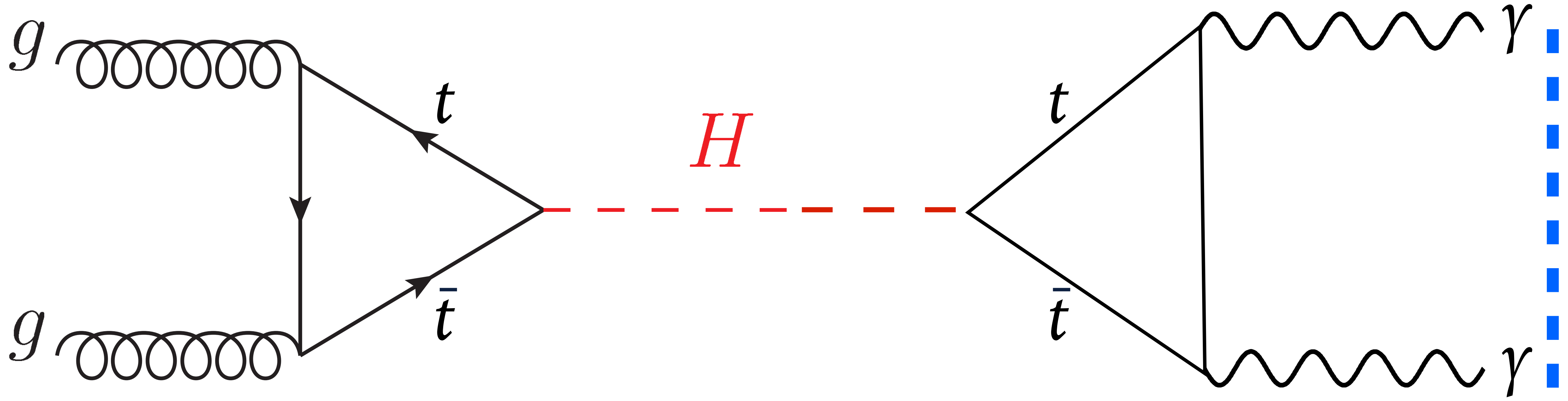
Expected to happen once for every ~2 billion inelastic proton–proton collisions

LHC data consistent with that already at discovery in 2012




g
g
t
t̄
H
t
t̄
γ
γ


luon
gluo
φ
y
x
Higgs field in space


g
g
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$\bar{t}$
H
t
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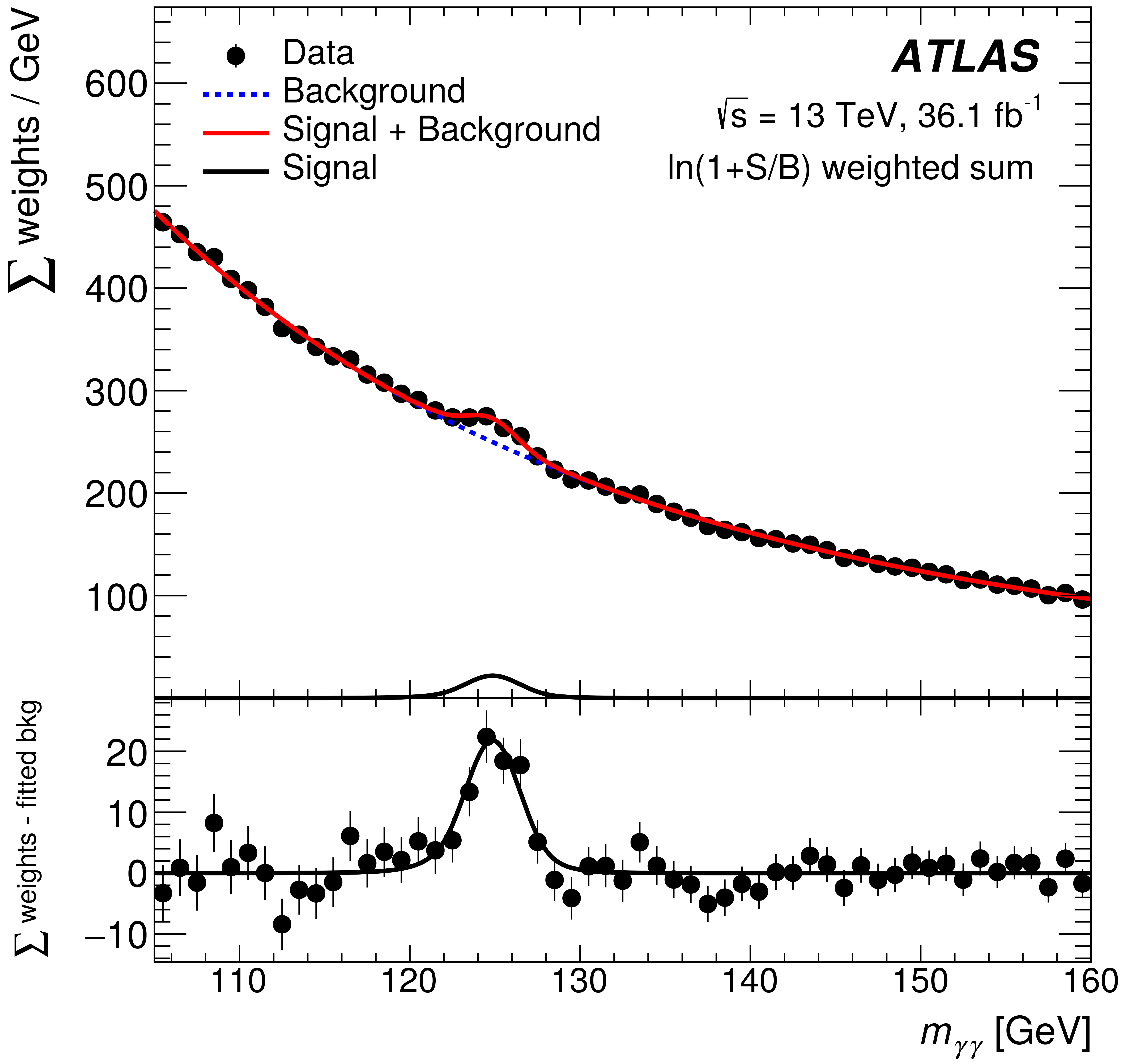
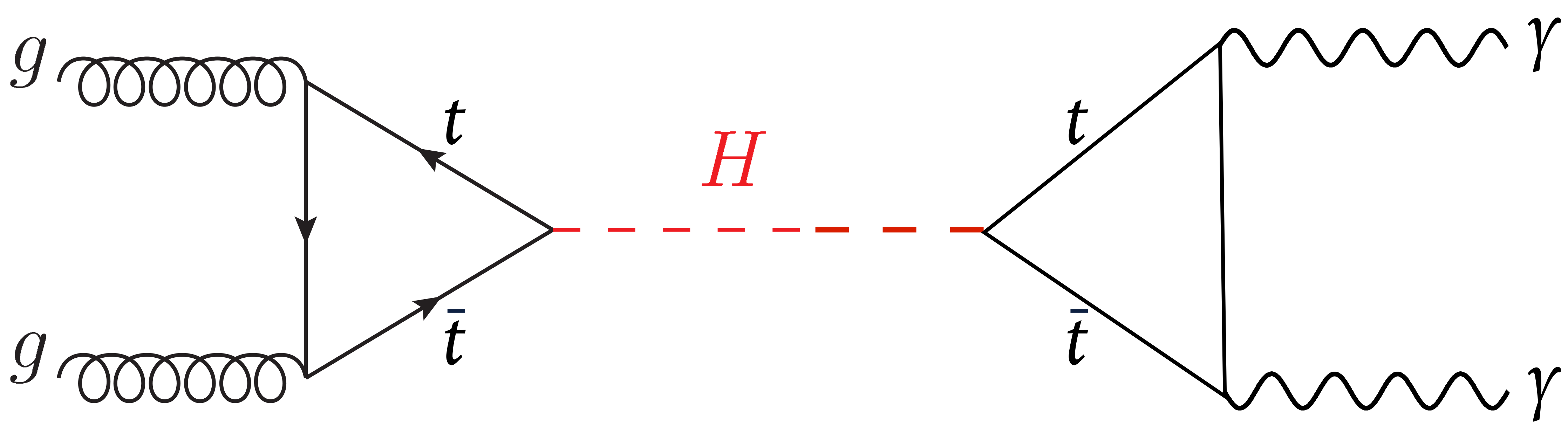
γ
γ

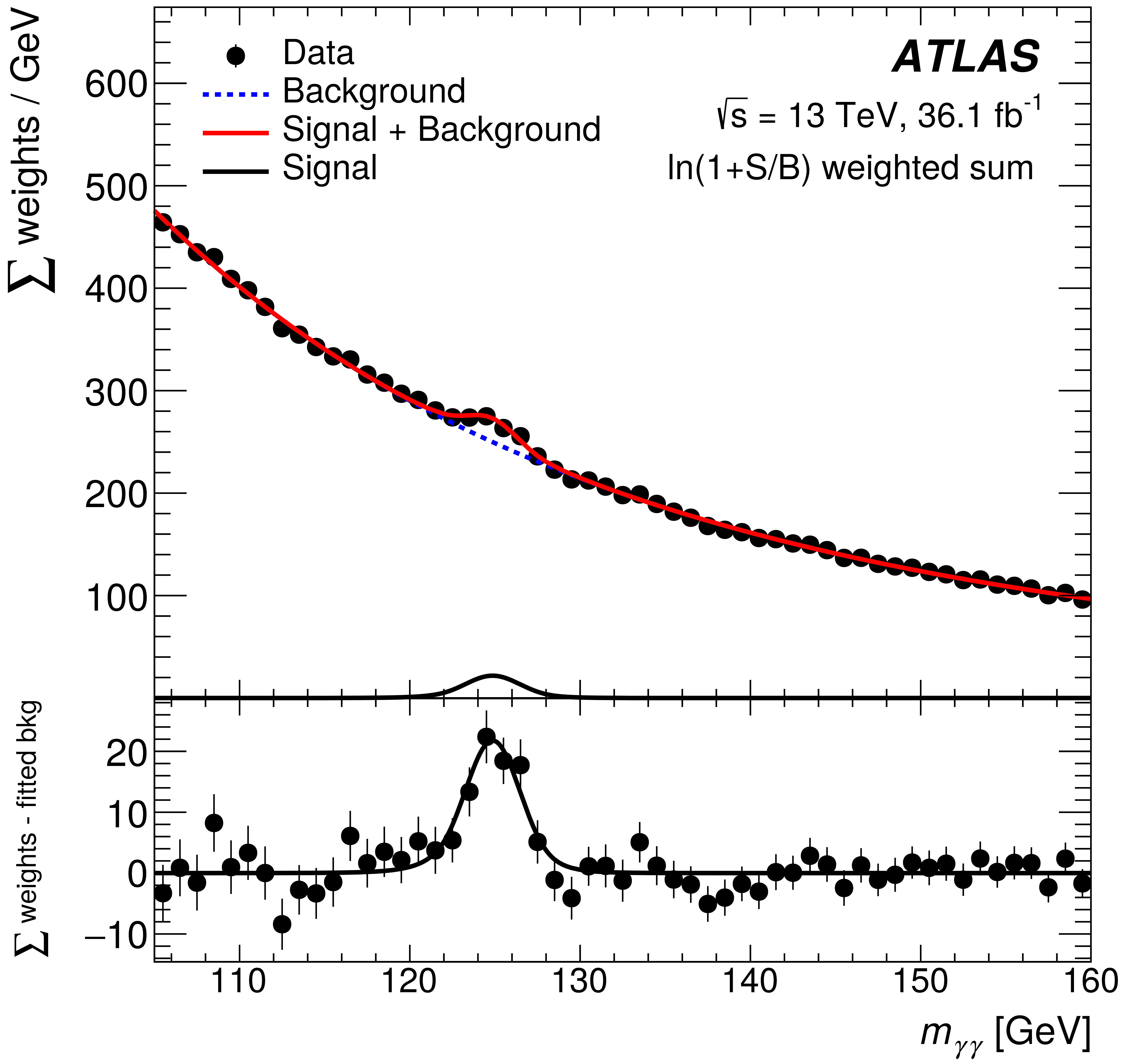

luon
gluo
φ
y
x
Higgs field in space

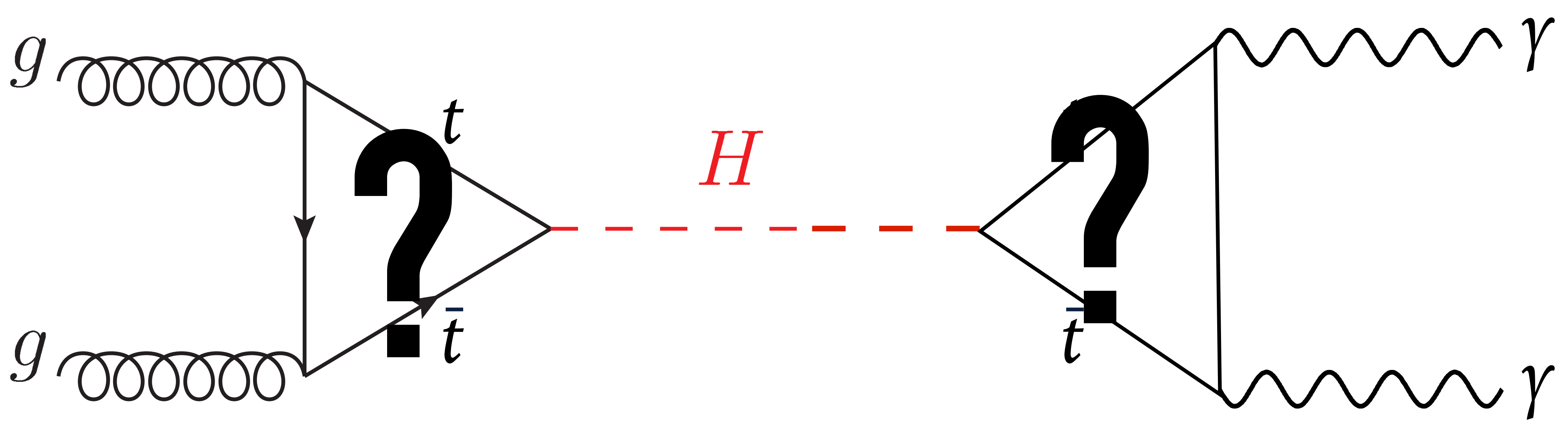


Data
Background
Signal + Background
Signal
ATLAS
√s = 13 TeV, 36.1 fb-1
ln(1+S/B) weighted sum
∑ weights / GeV
∑ weights - fitted bkg
m_γγ [GeV]



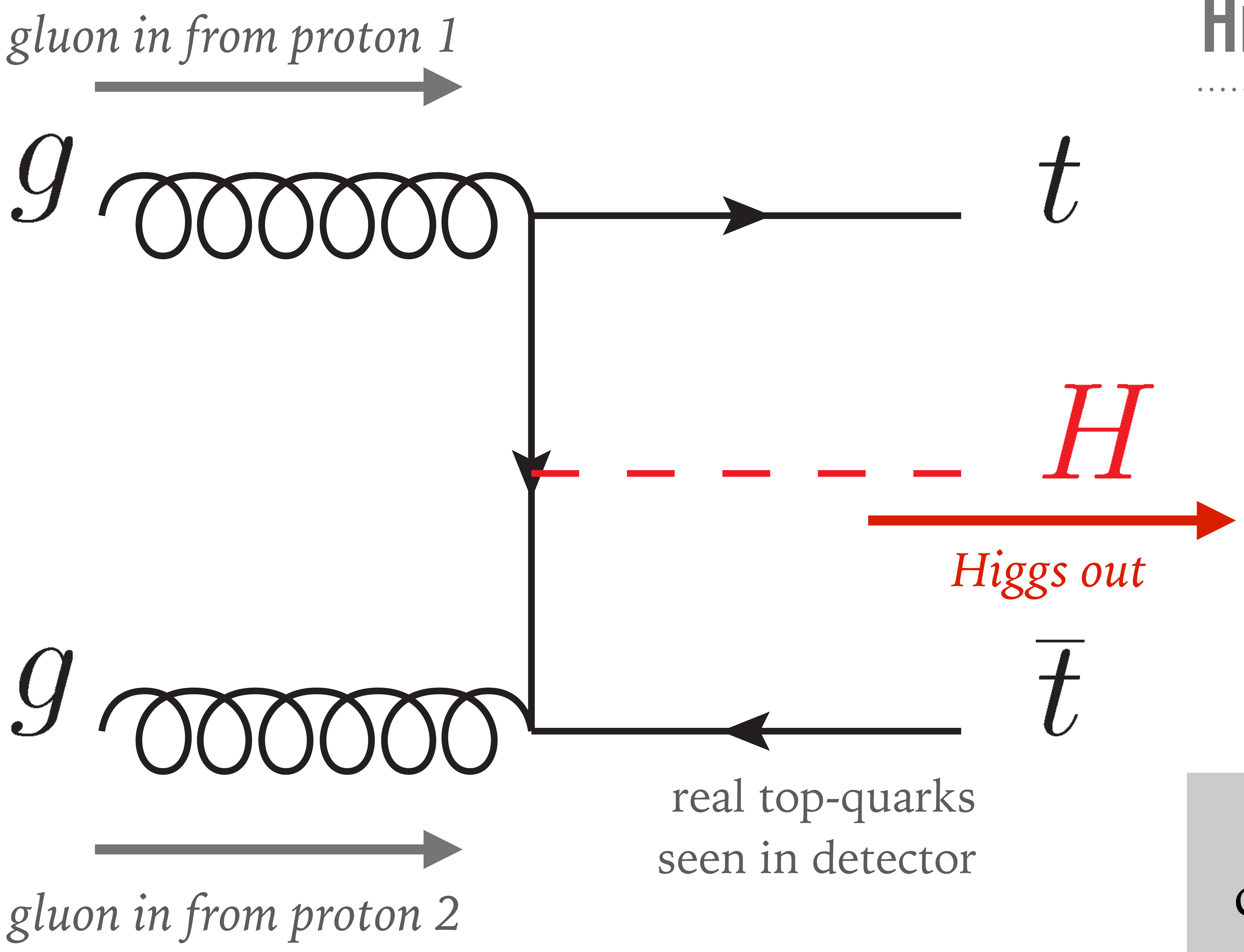
g
g
t
t̄
H
t
t̄
γ
γ





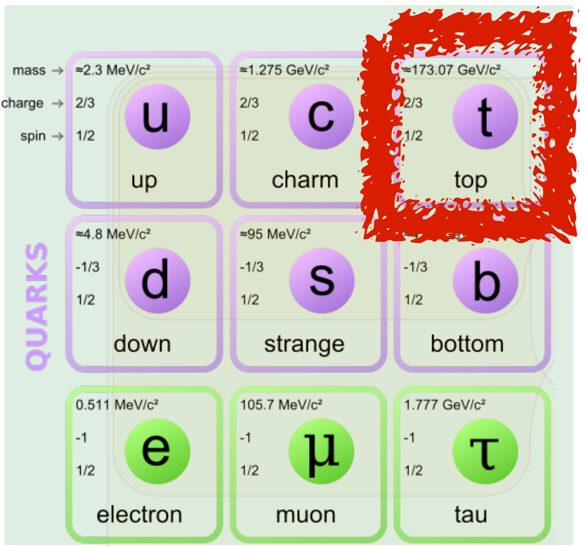
but how can you be sure the Higgs boson is really being radiated off a top-quark, i.e. that you're actually seeing a Yukawa coupling?

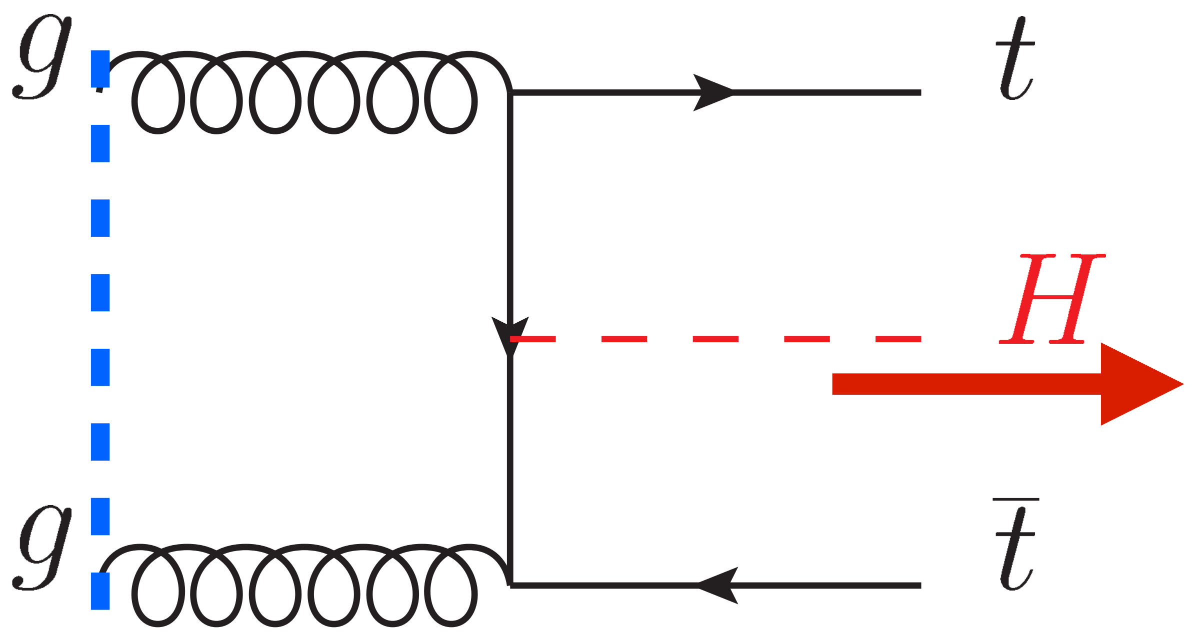
Higgs production: the ttH channel



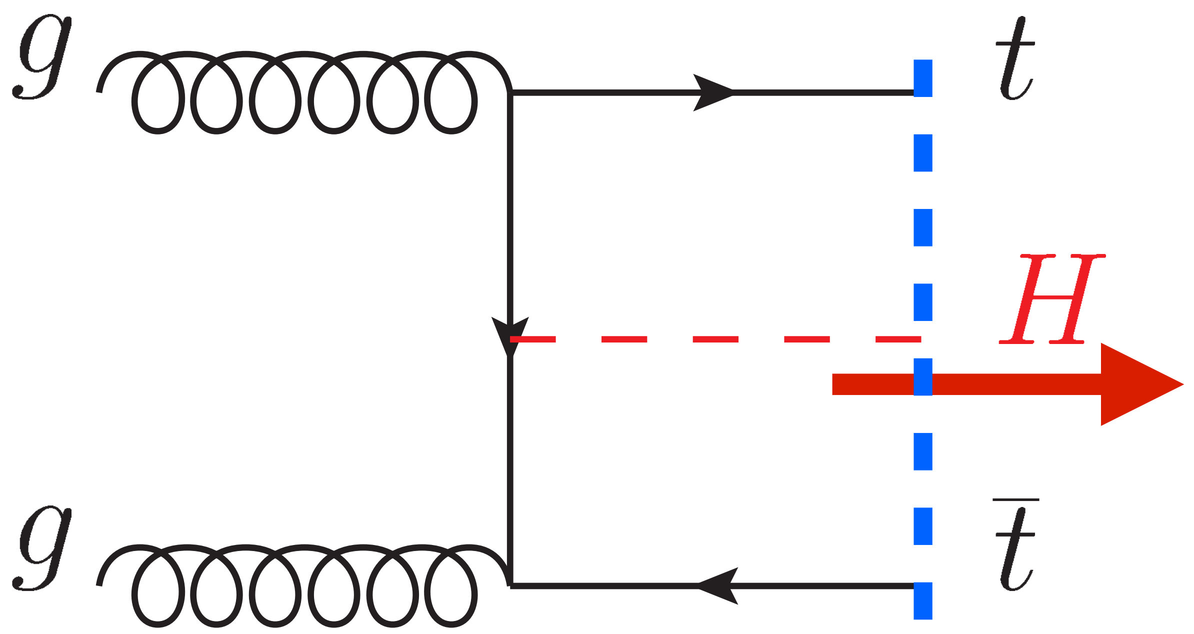
If SM top-Yukawa hypothesis is correct, expect 1 Higgs for every 1600 top-quark pairs.

(rather than 1 Higgs for every 2 billion pp collisions)




g
t
H
g
$\bar{t}$


luon
gluo
φ
y
x
Higgs field in space


g
t
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luon
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y
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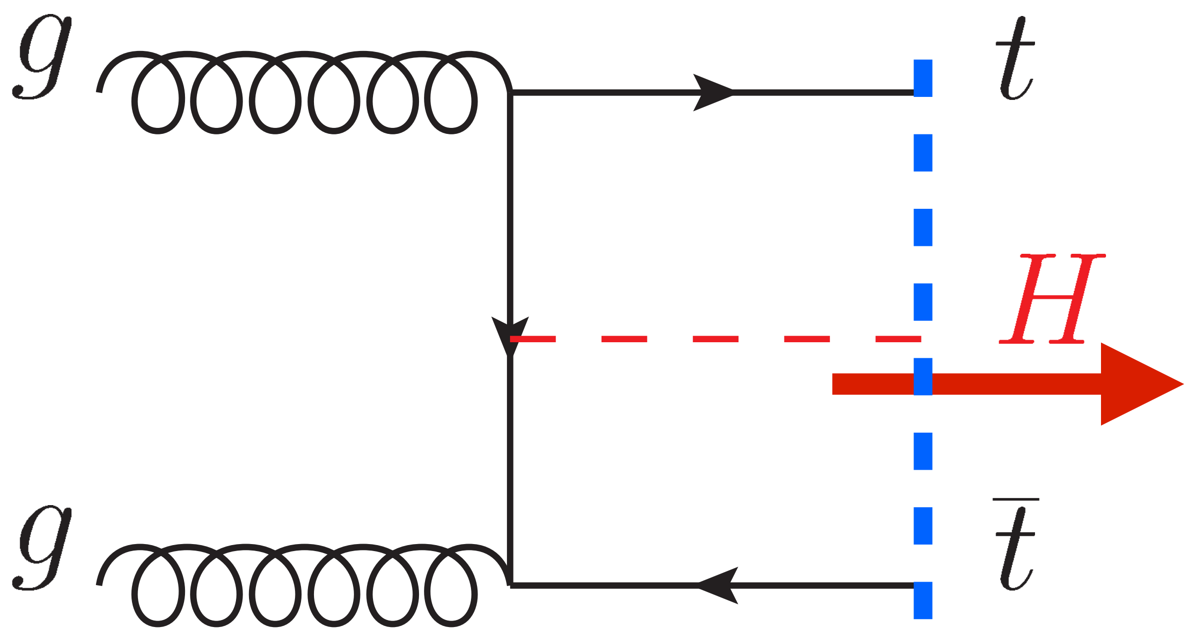
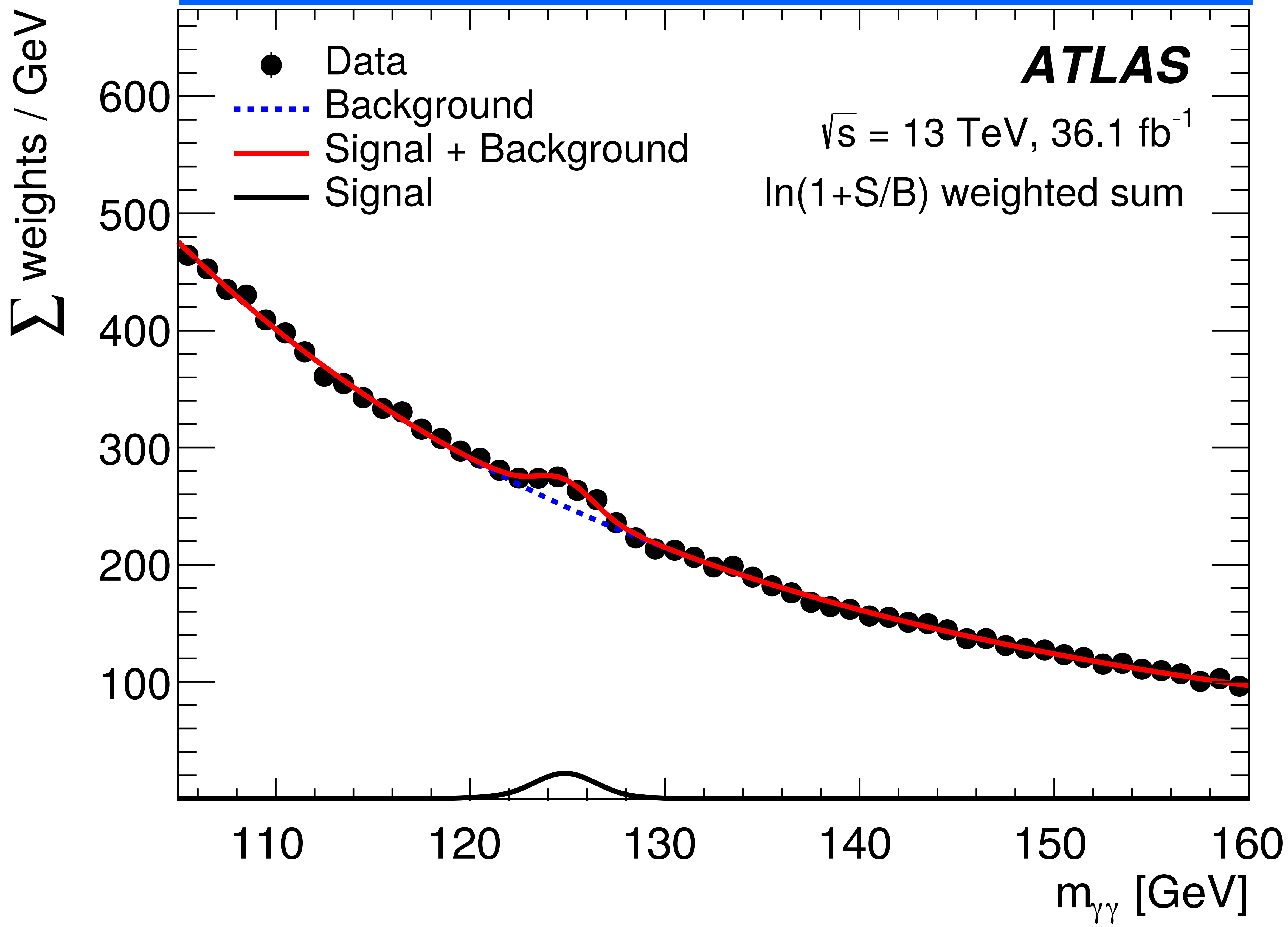
Higgs field in space


g
t
H
g
$\bar{t}$

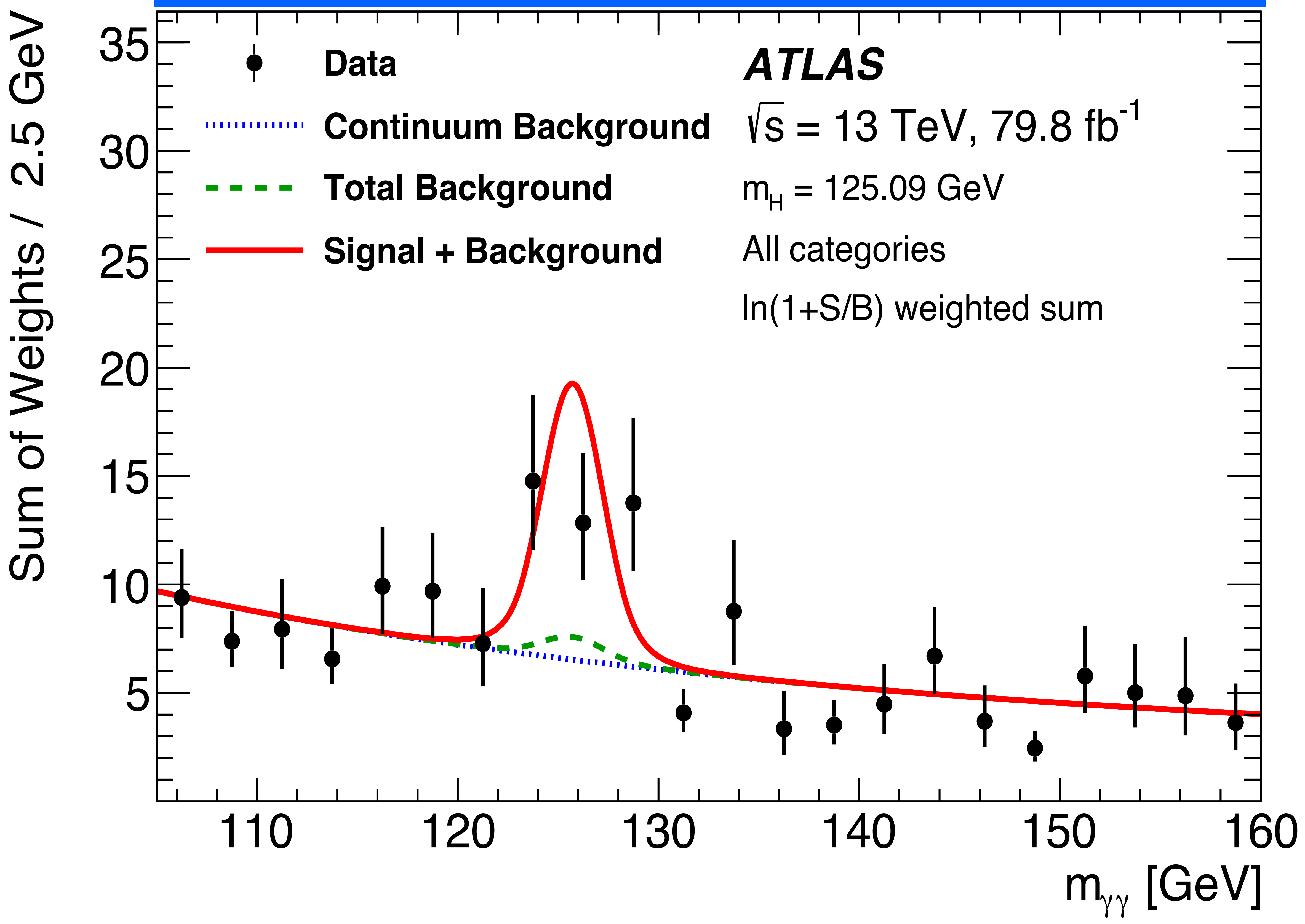

luon
gluo
φ
y
x
Higgs field in space

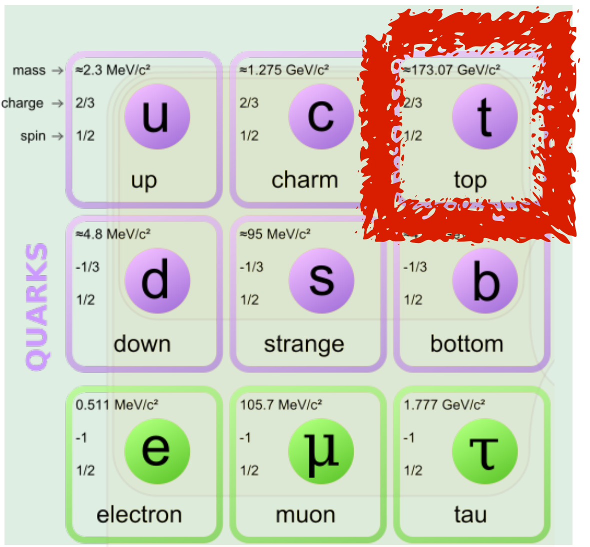
the news of the past 18 months: ATLAS & CMS see events with top-quarks & Higgs simultaneously

across all events



in events with top quarks



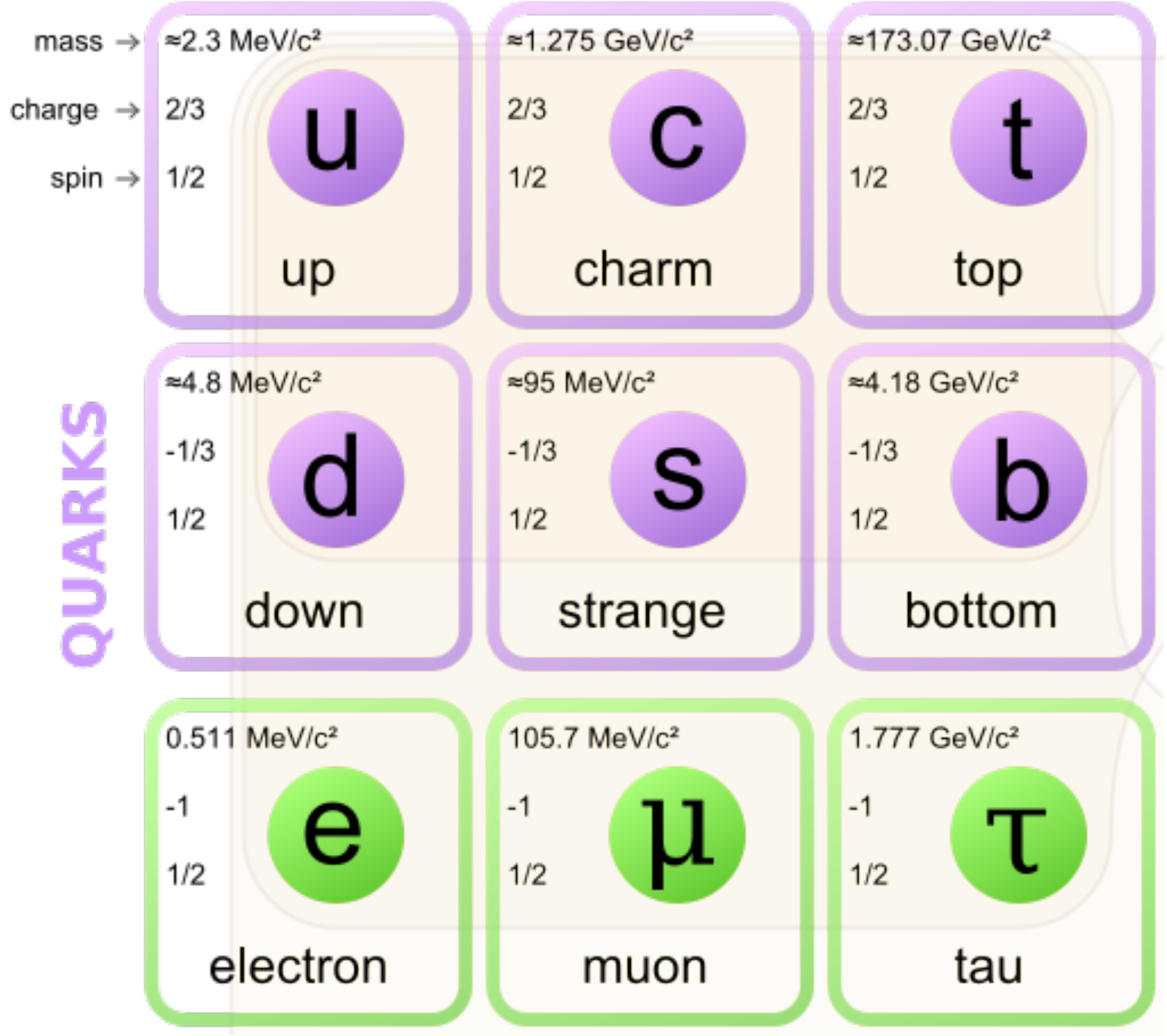


enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

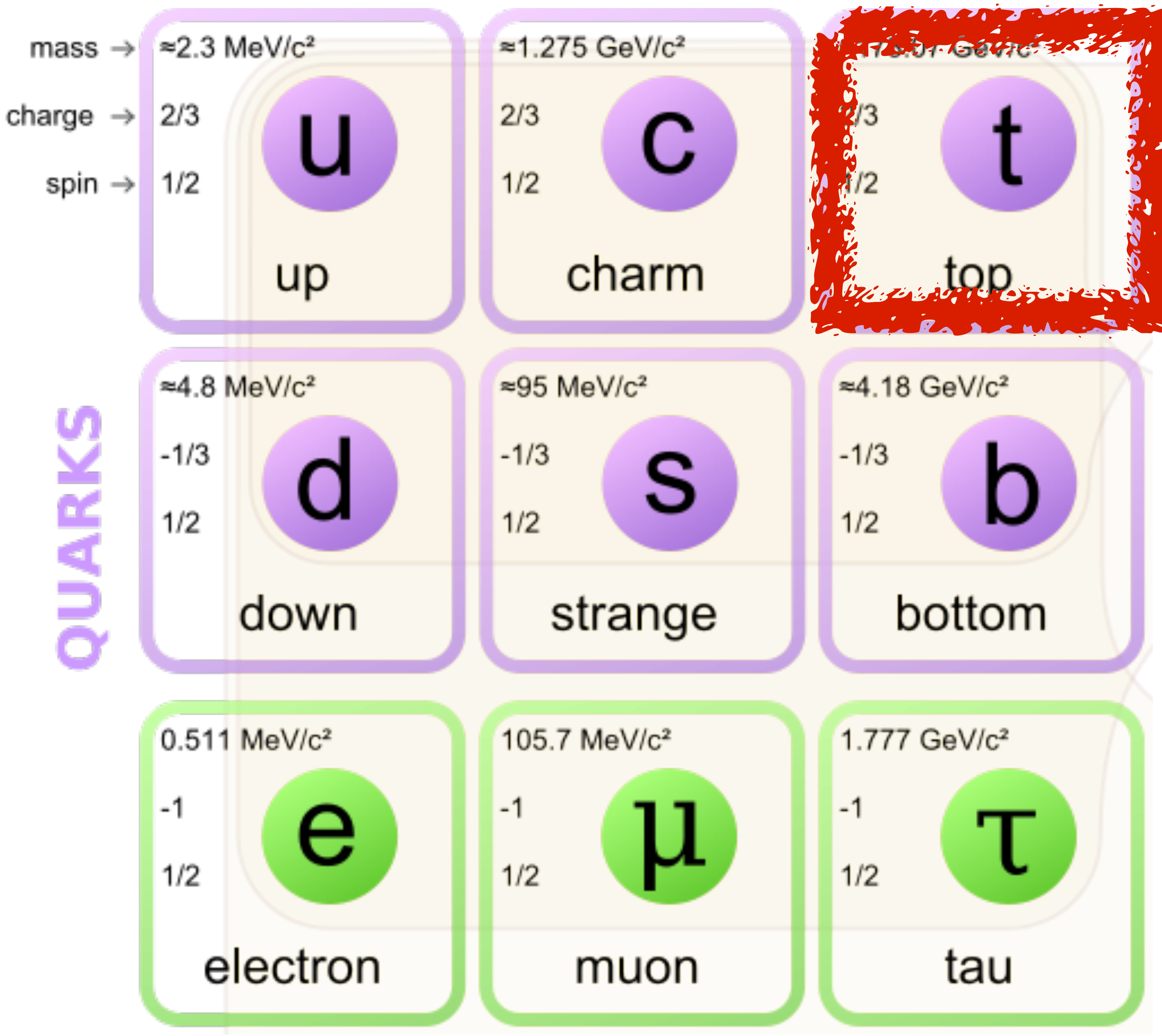
(consistent with SM to c. ±20%)

2017/18 discovery of 3rd generation Yukawa interactions by ATLAS & CMS



Discovery $\equiv 5\sigma \simeq \pm 20\,\%$

2017/18 discovery of 3rd generation Yukawa interactions by ATLAS & CMS



by observing H in association with top quarks

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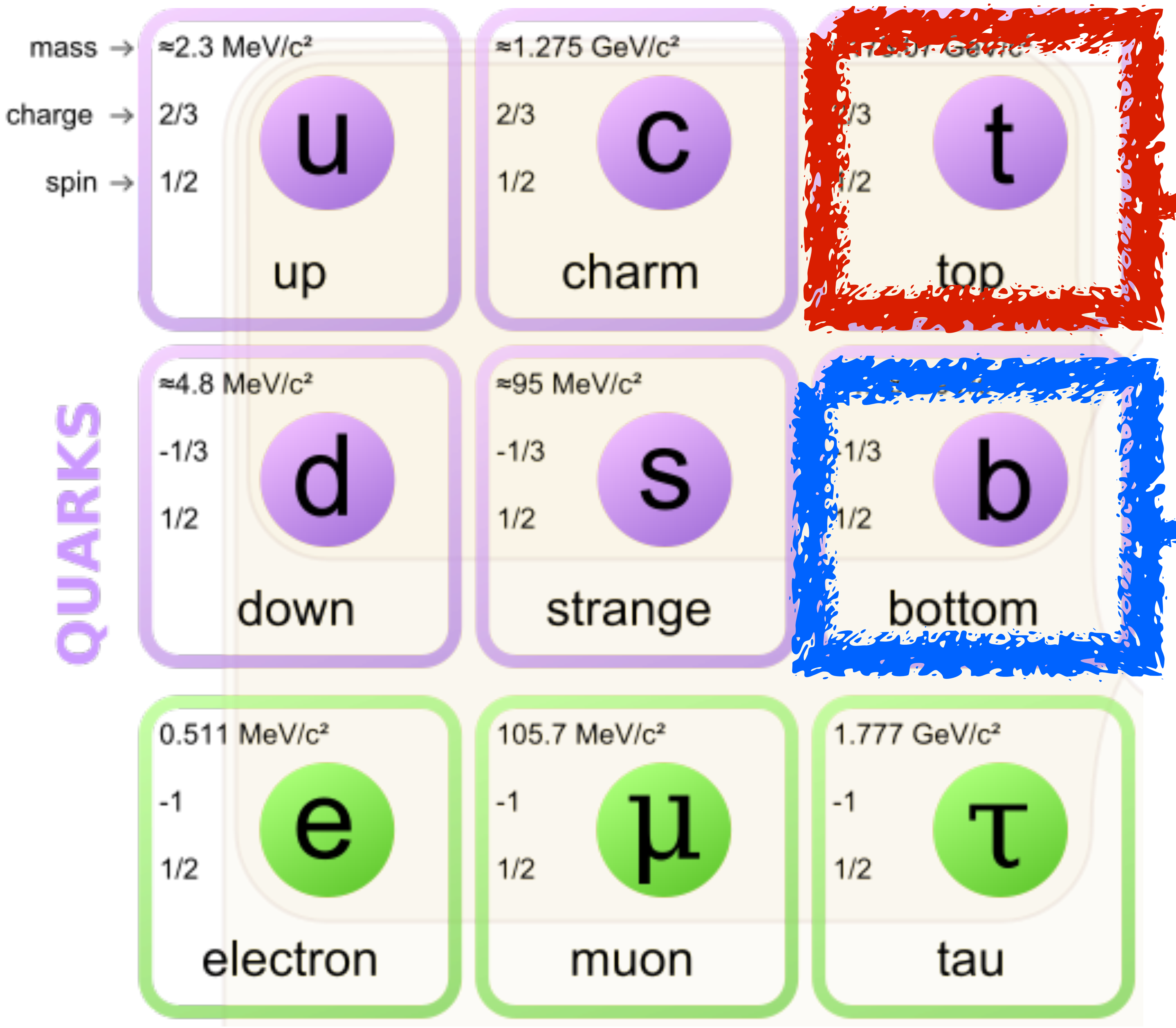

by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays

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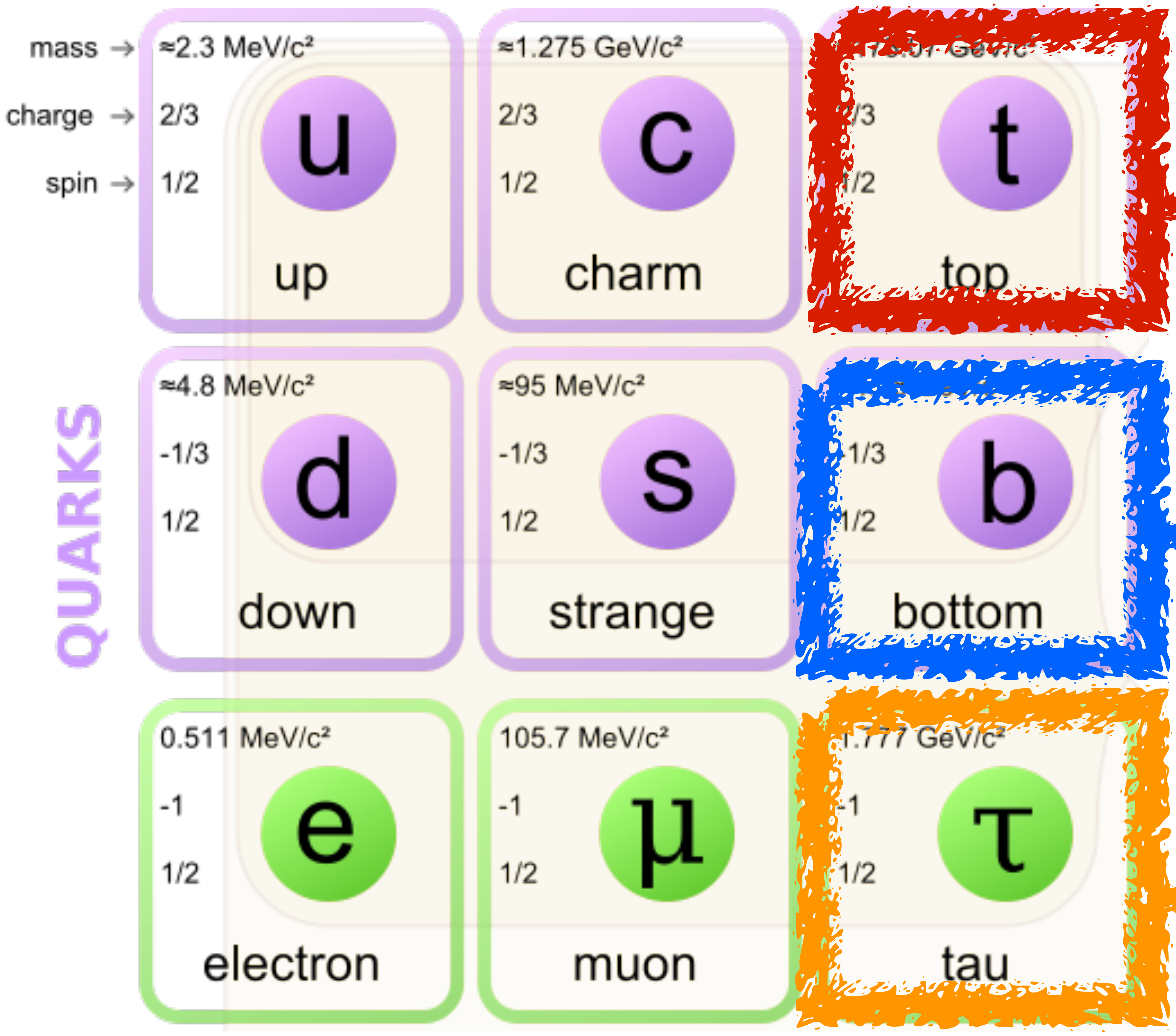
2017/18 discovery of 3rd generation Yukawa interactions by ATLAS & CMS



by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays

by observing $H \to \tau^+\tau^-$ decays

Discovery $\equiv 5\sigma \simeq \pm 20\,\%$

what's the message?

The >5σ observations of the ttH process and of H → ττ and H→ bb decays, independently by ATLAS and CMS, **firmly establish the existence of a new kind of fundamental interaction,** Yukawa interactions.

Yukawa interactions are important because they are:
(1) **qualitatively unlike any quantum interaction probed before** (effective charge not quantised),
(2) **hypothesized to be responsible for the stability of hydrogen,** and for determining the size of atoms and the energy scales of chemical reactions.

Establishing the pattern of Yukawa couplings across the full remaining set of quarks and charged leptons is one of the major challenges for particle physics today.

what's the message?

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Is this any less important than the discovery of the Higgs boson itself?

My opinion: no, because fundamental interactions are as important as fundamental particles

what could one be saying about it?

This is a **fifth force, the "Higgs force"**

(up to you to decide whether you prefer to talk about new interactions or new force)

Is this any less important than the discovery of the Higgs boson itself?

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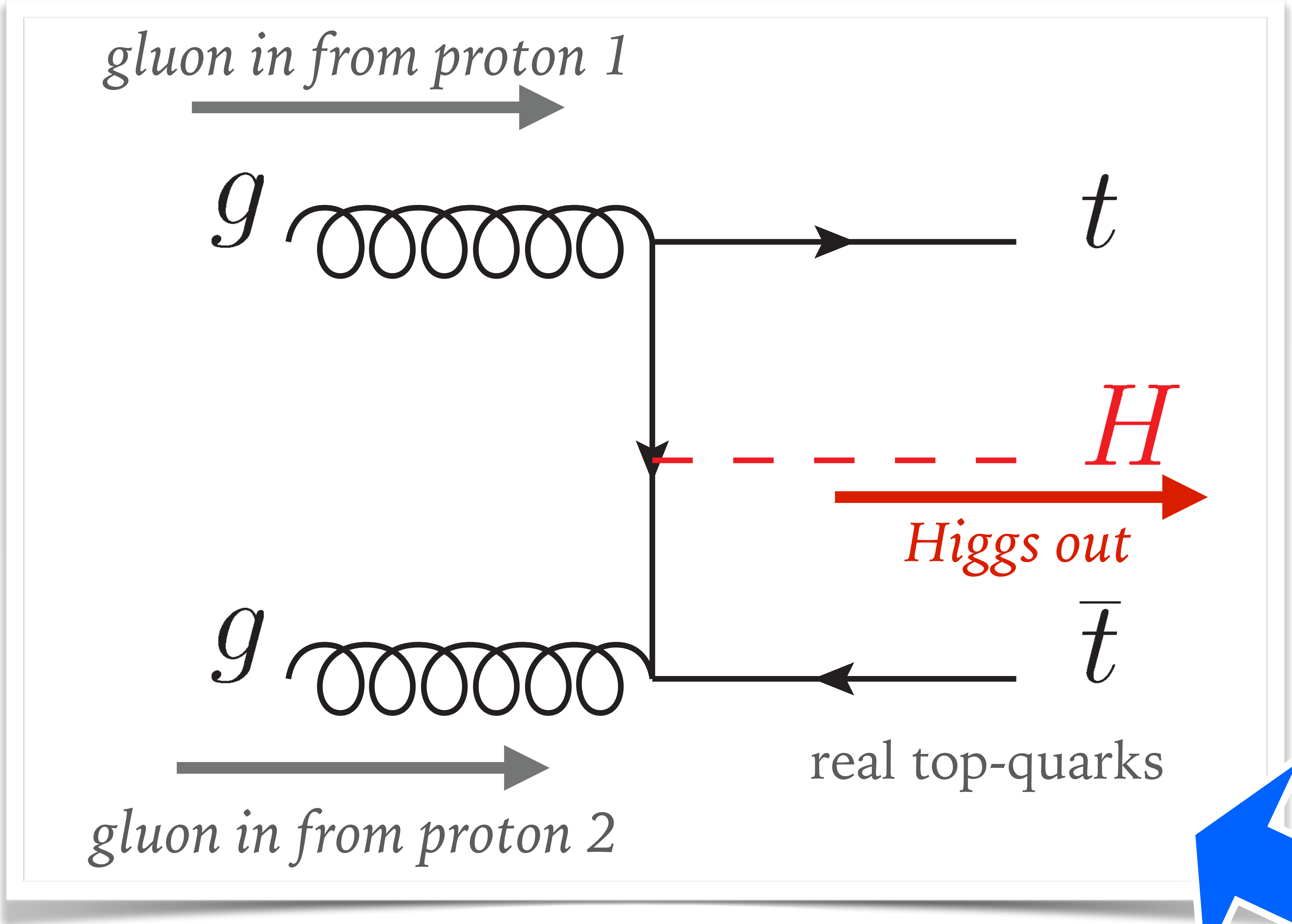
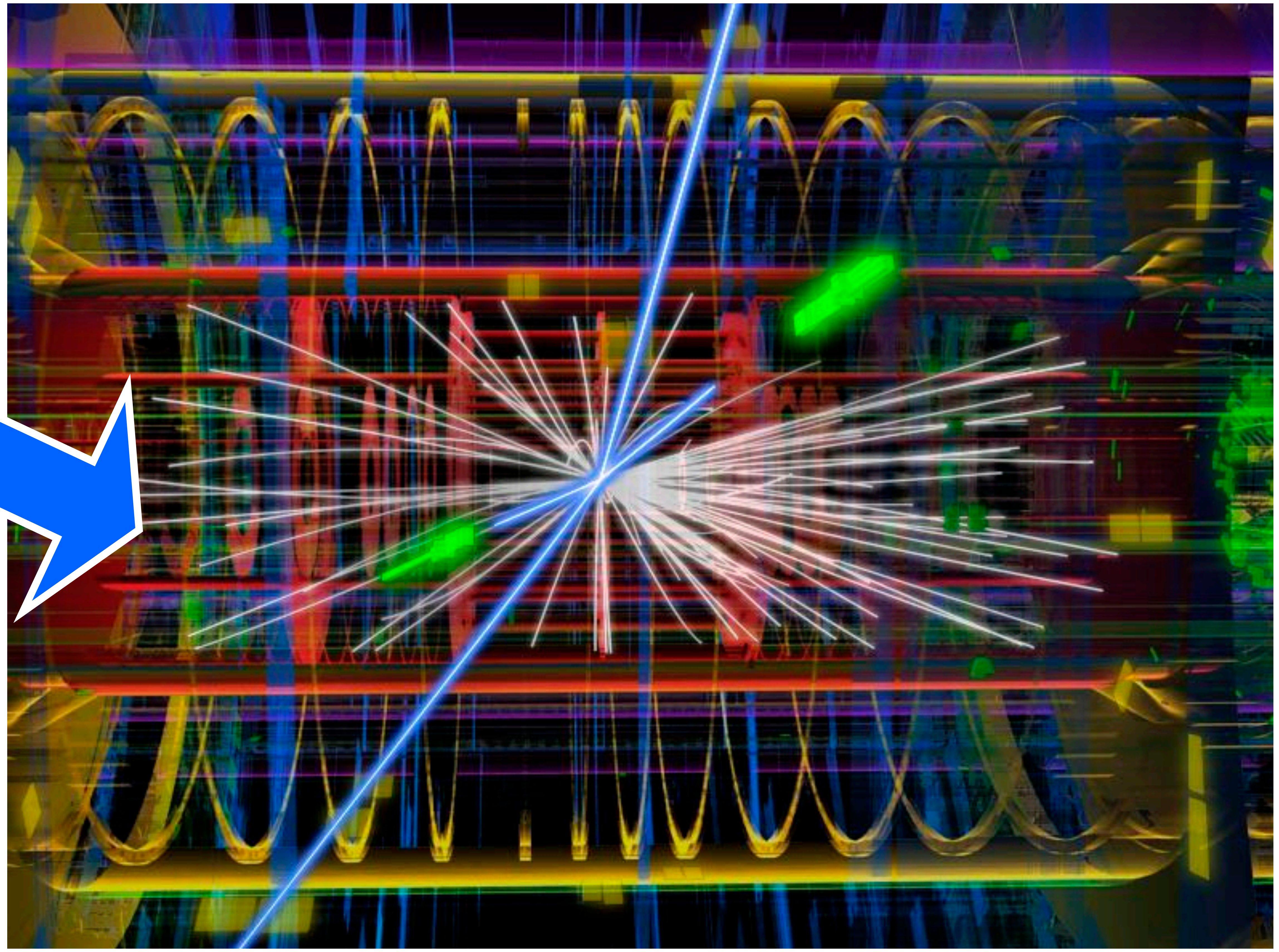
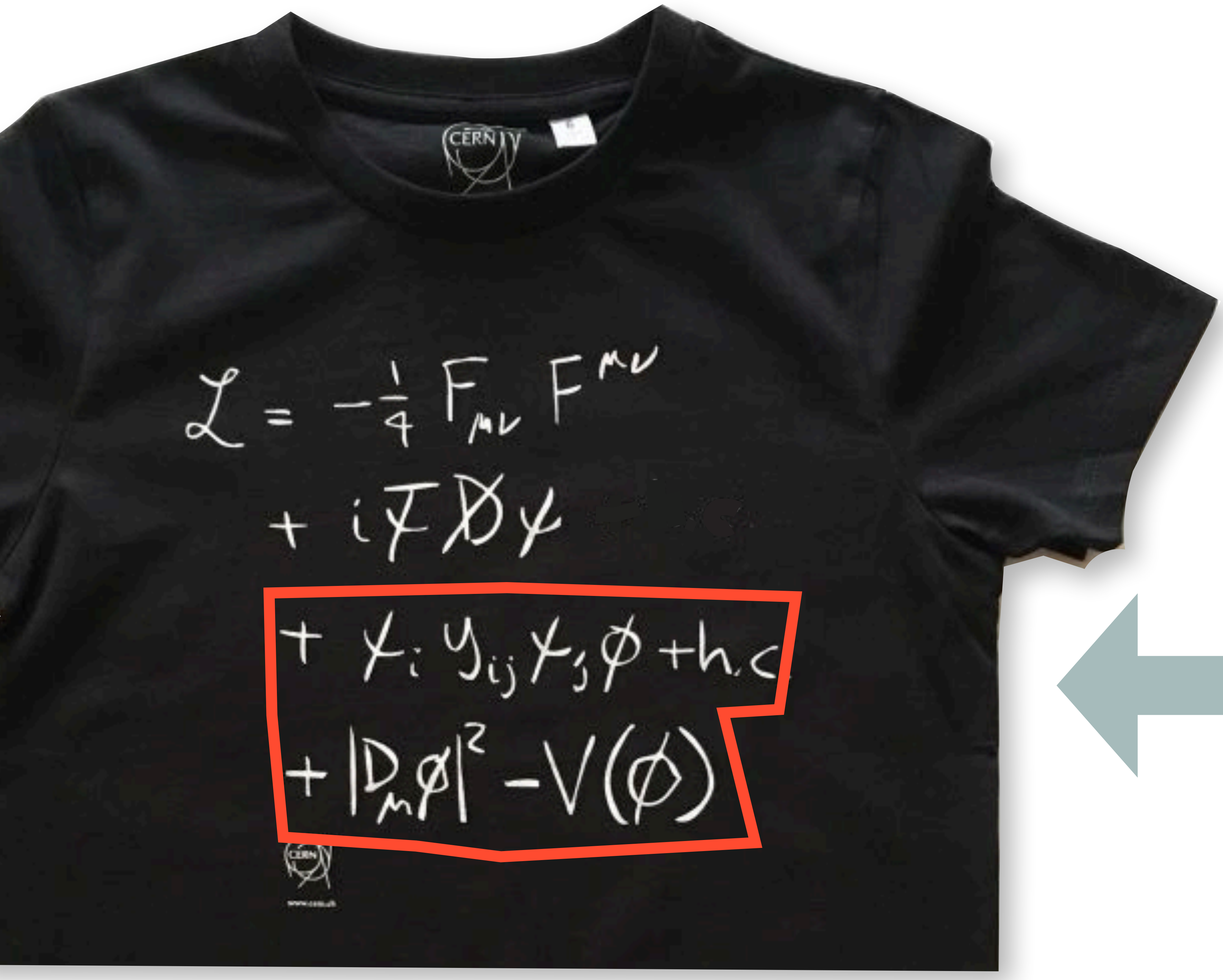




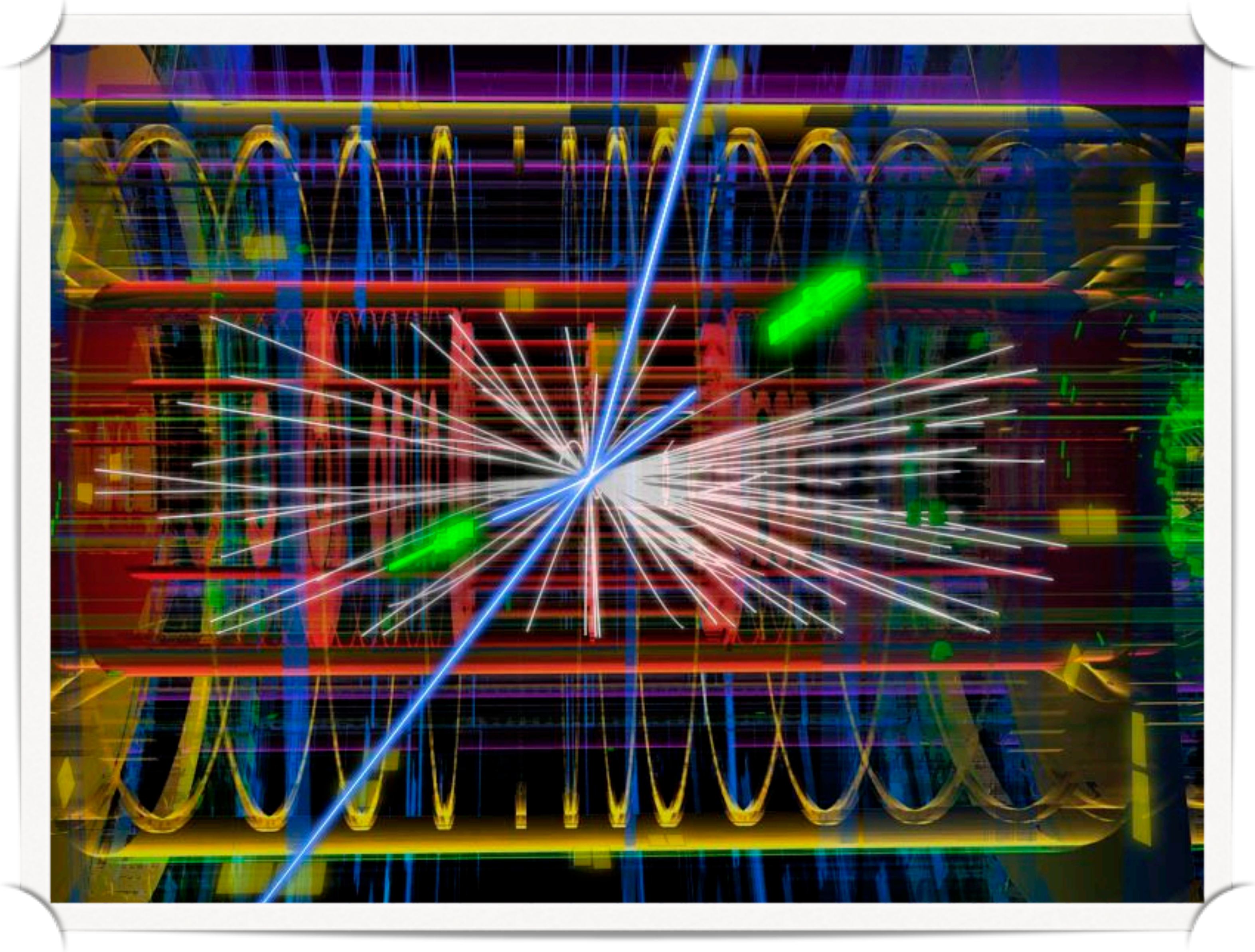
how can one claim a connection,
let alone a quantitative one?

UNDERLYING THEORY

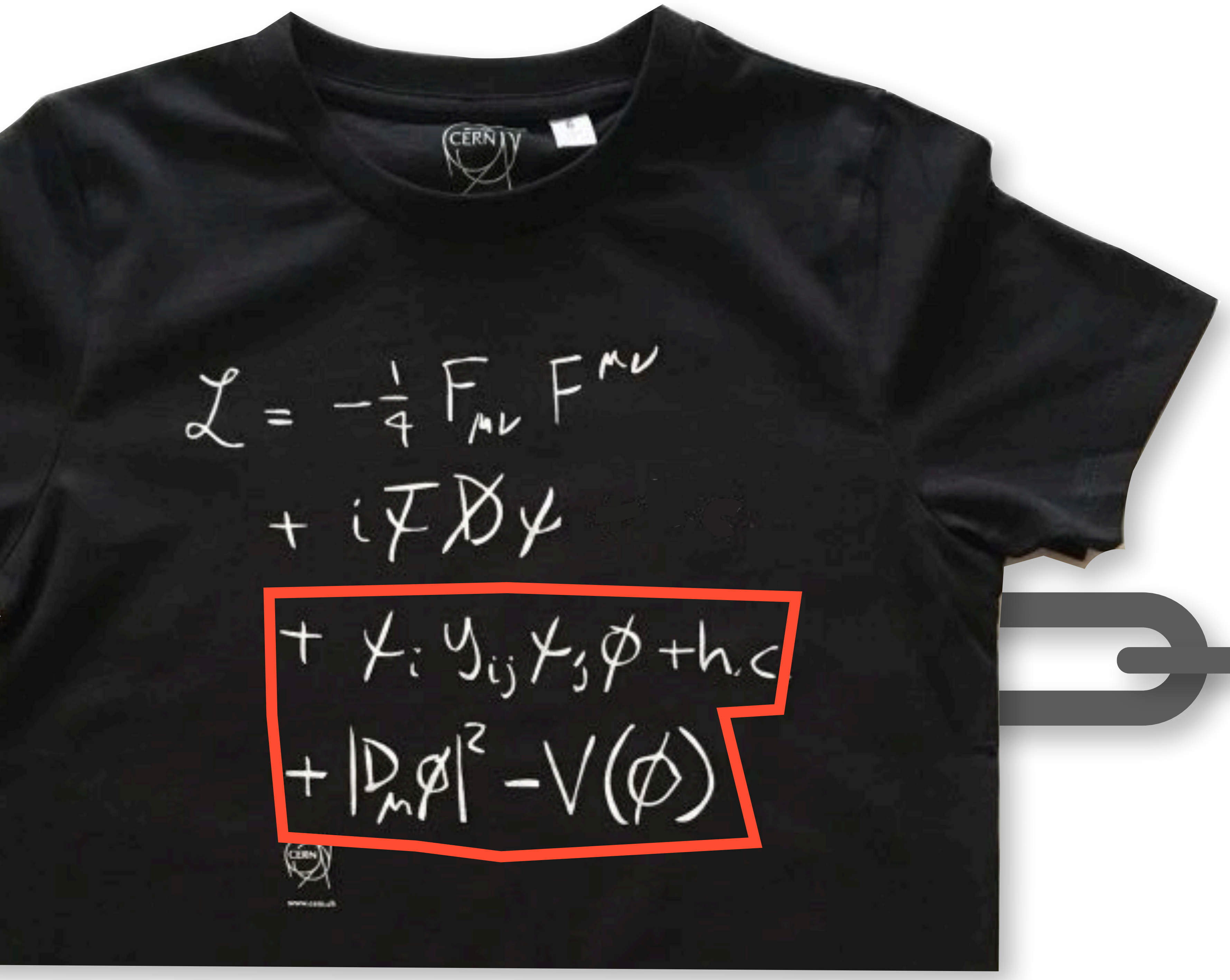
EXPERIMENTAL DATA



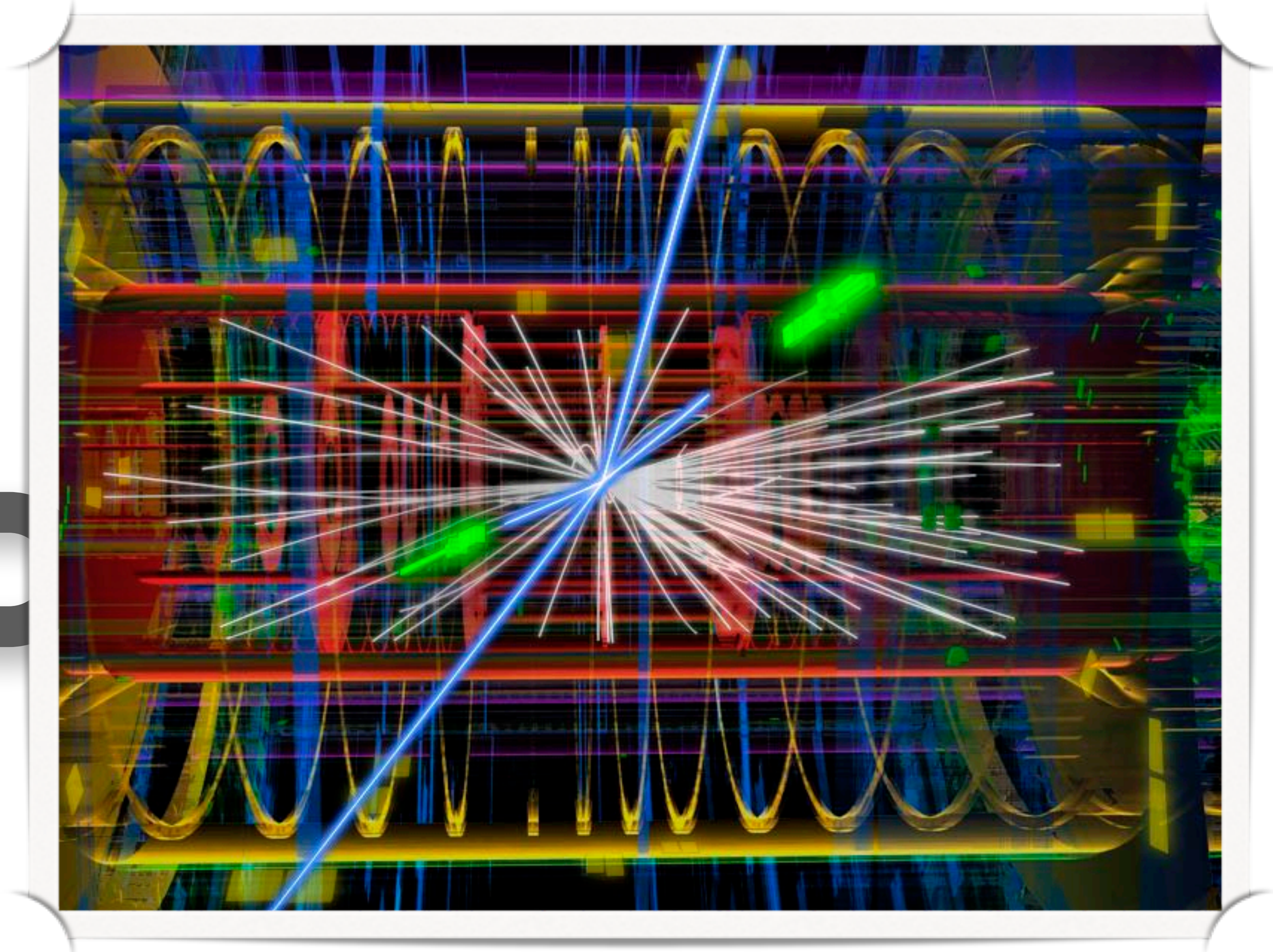
how do you make quantitative connection?



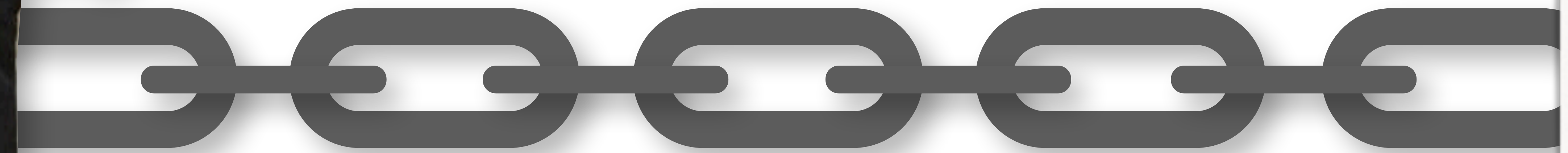
UNDERLYING THEORY



EXPERIMENTAL DATA



how do you make quantitative connection?

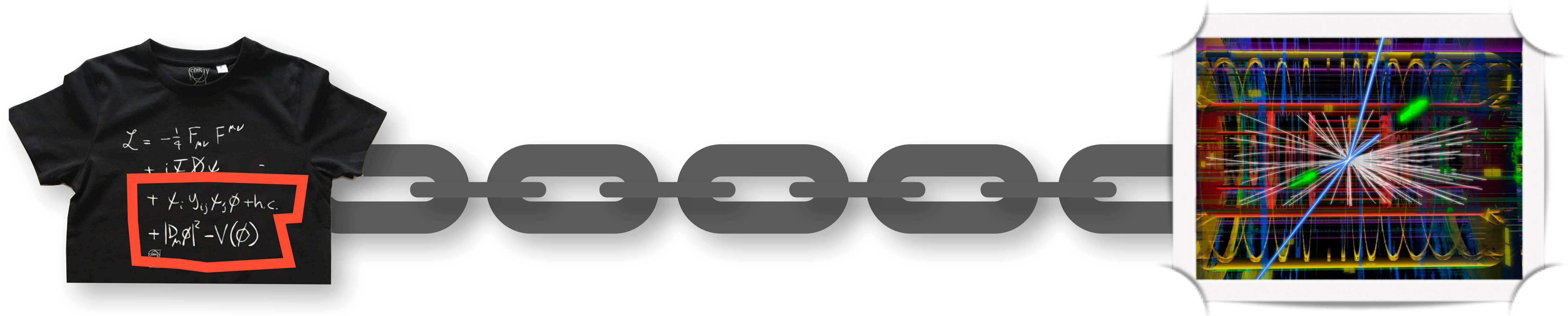


through a chain of experimental and theoretical links

QCD

quantum chromodynamics

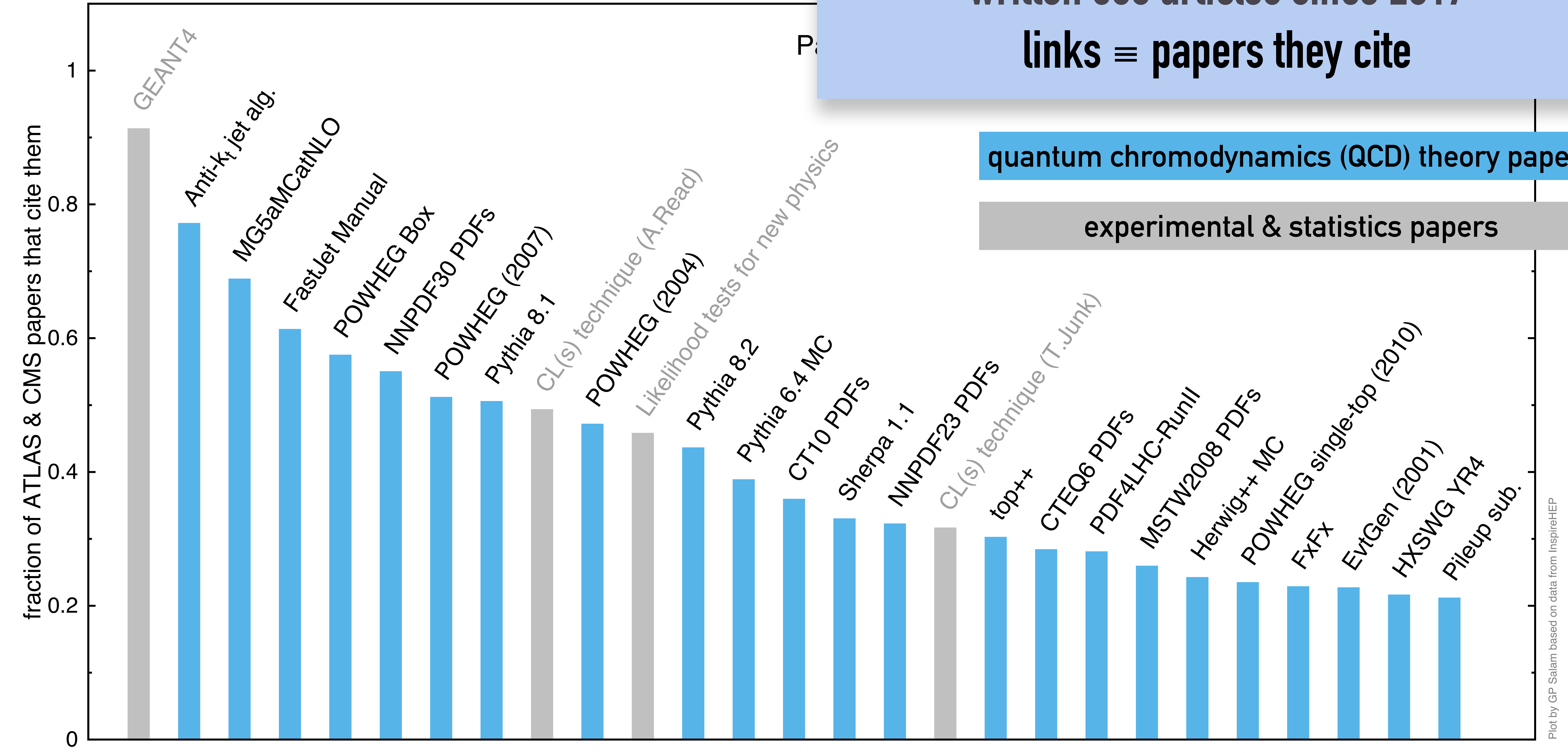
the theory of the strong interaction



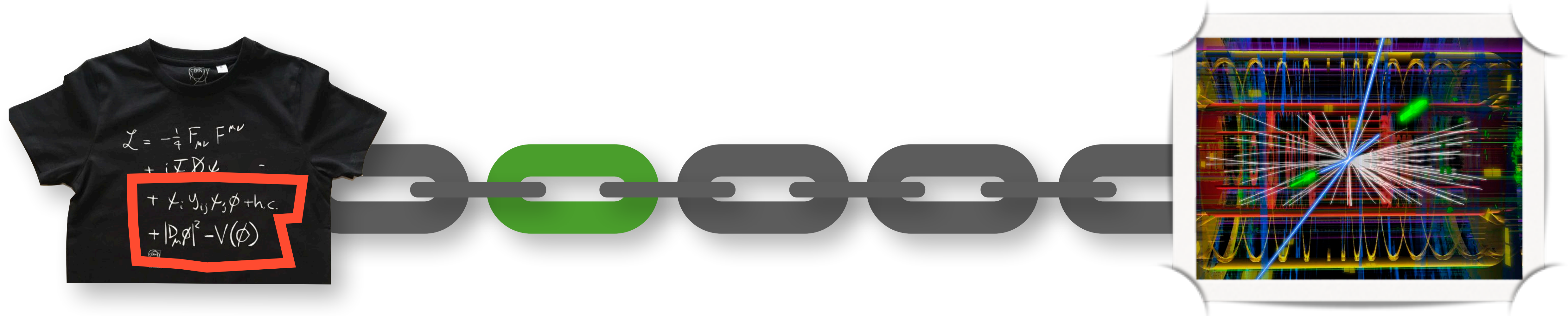
What are the links?

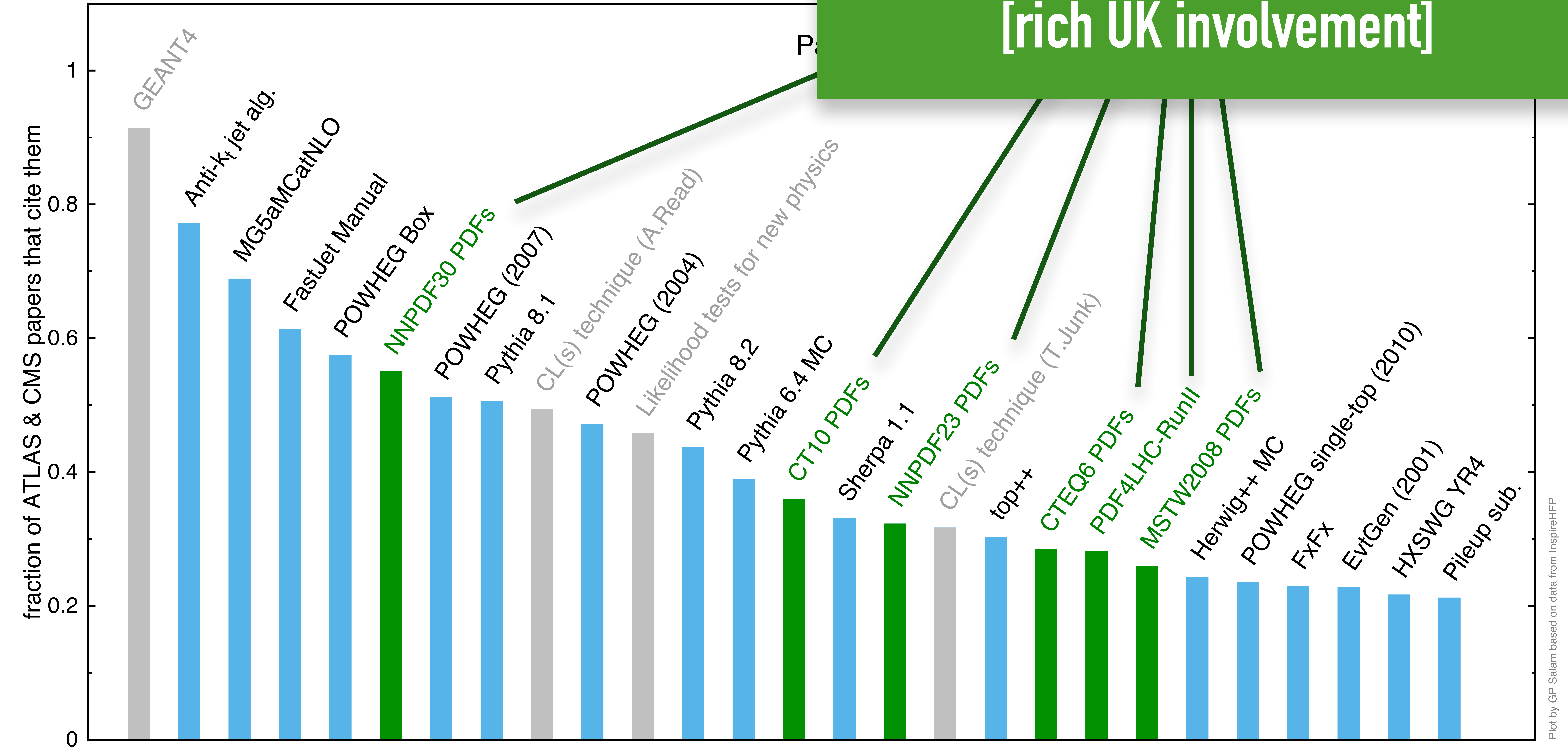
ATLAS and CMS (big LHC expts.) have written 650 articles since 2017

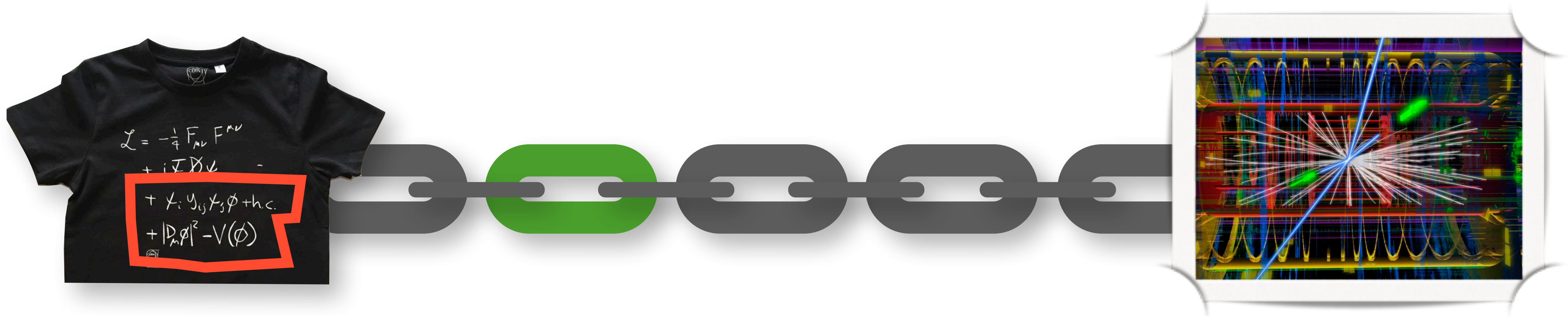
links ≡ papers they cite



knowing what goes into a collision
i.e. proton structure
[rich UK involvement]







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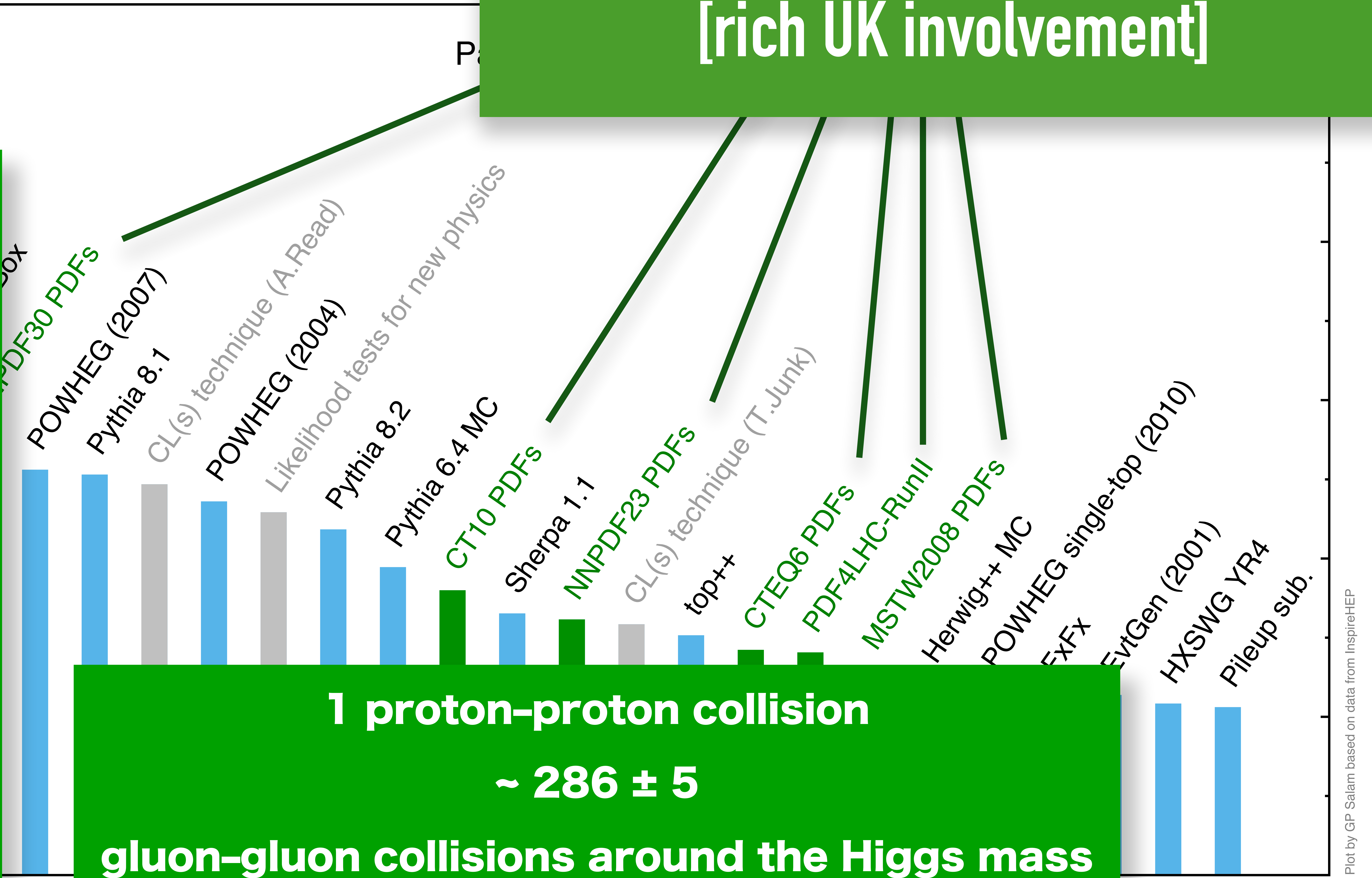
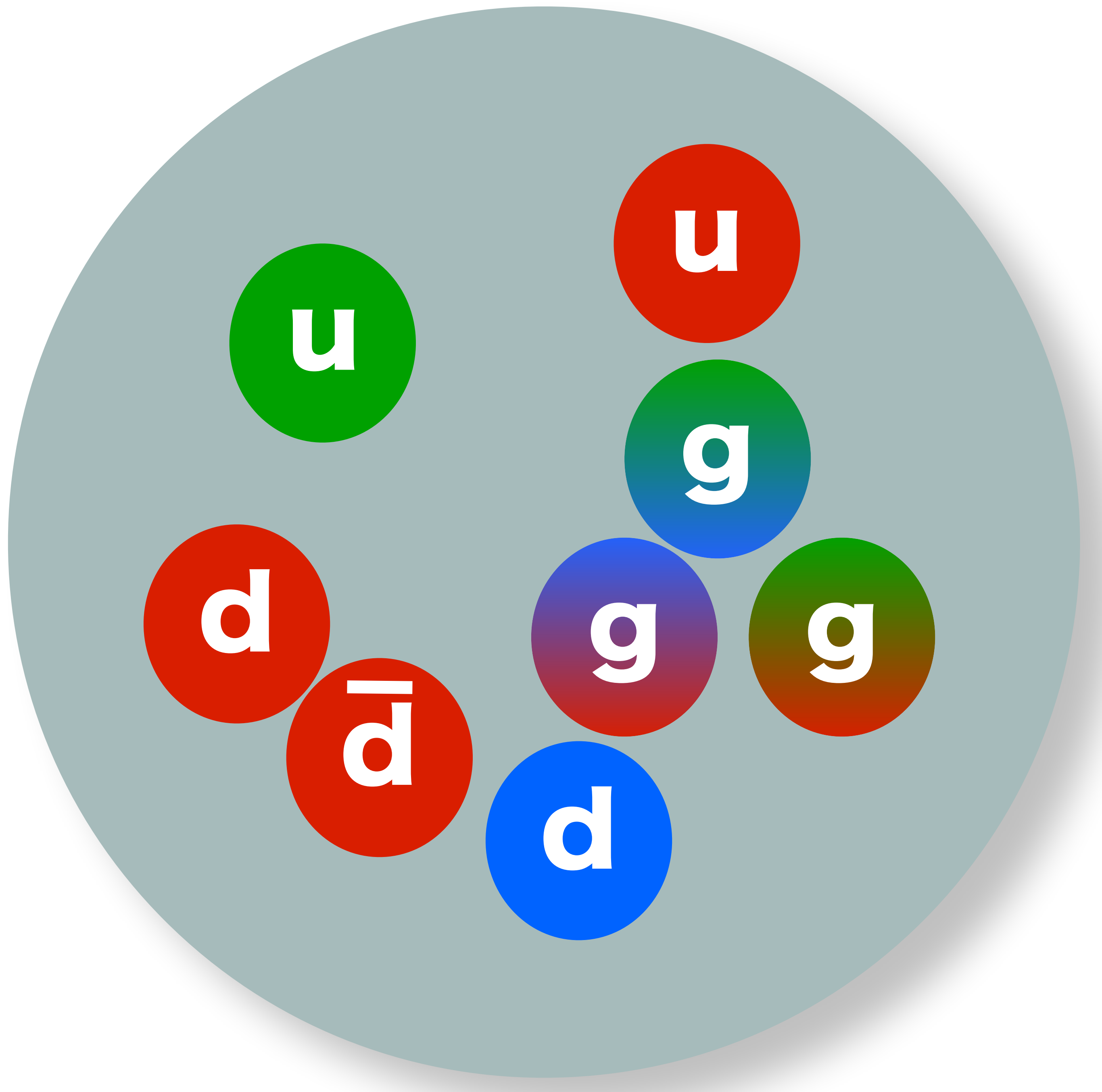


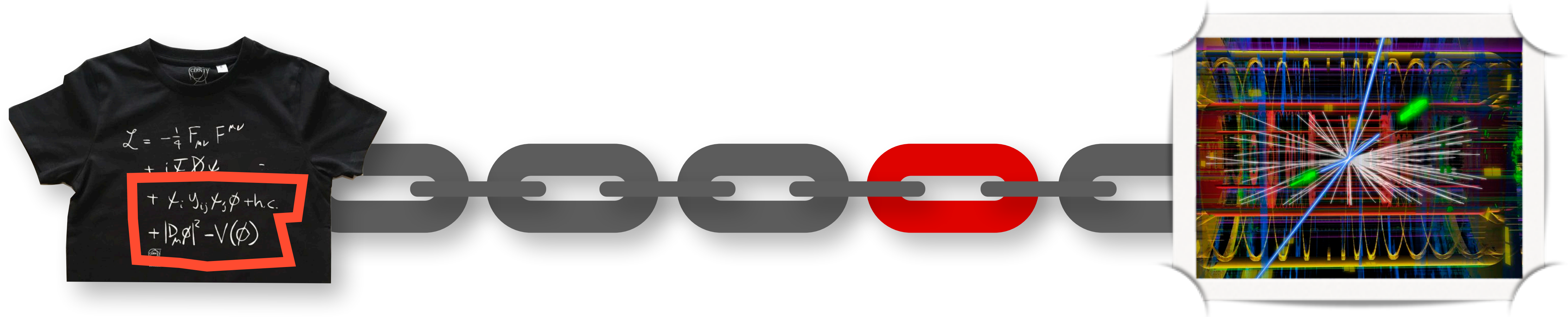
PROTON



1 proton-proton collision

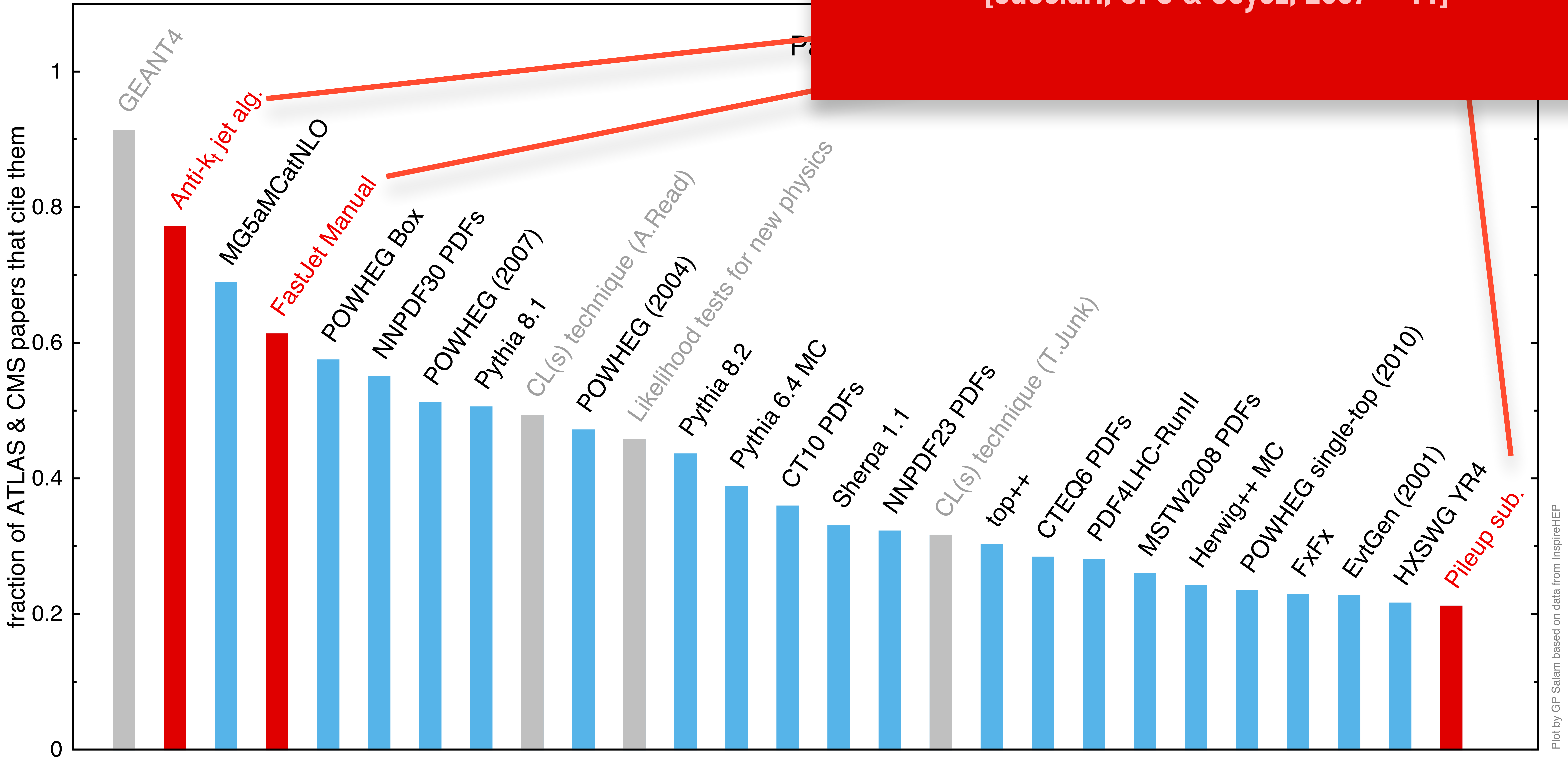
~ 286 ± 5

gluon-gluon collisions around the Higgs mass

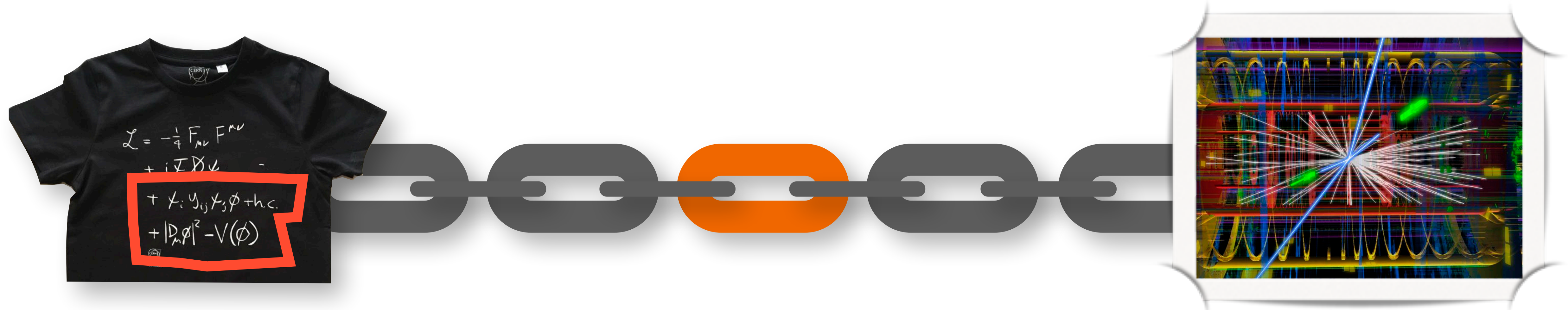


organising event information ("jets")

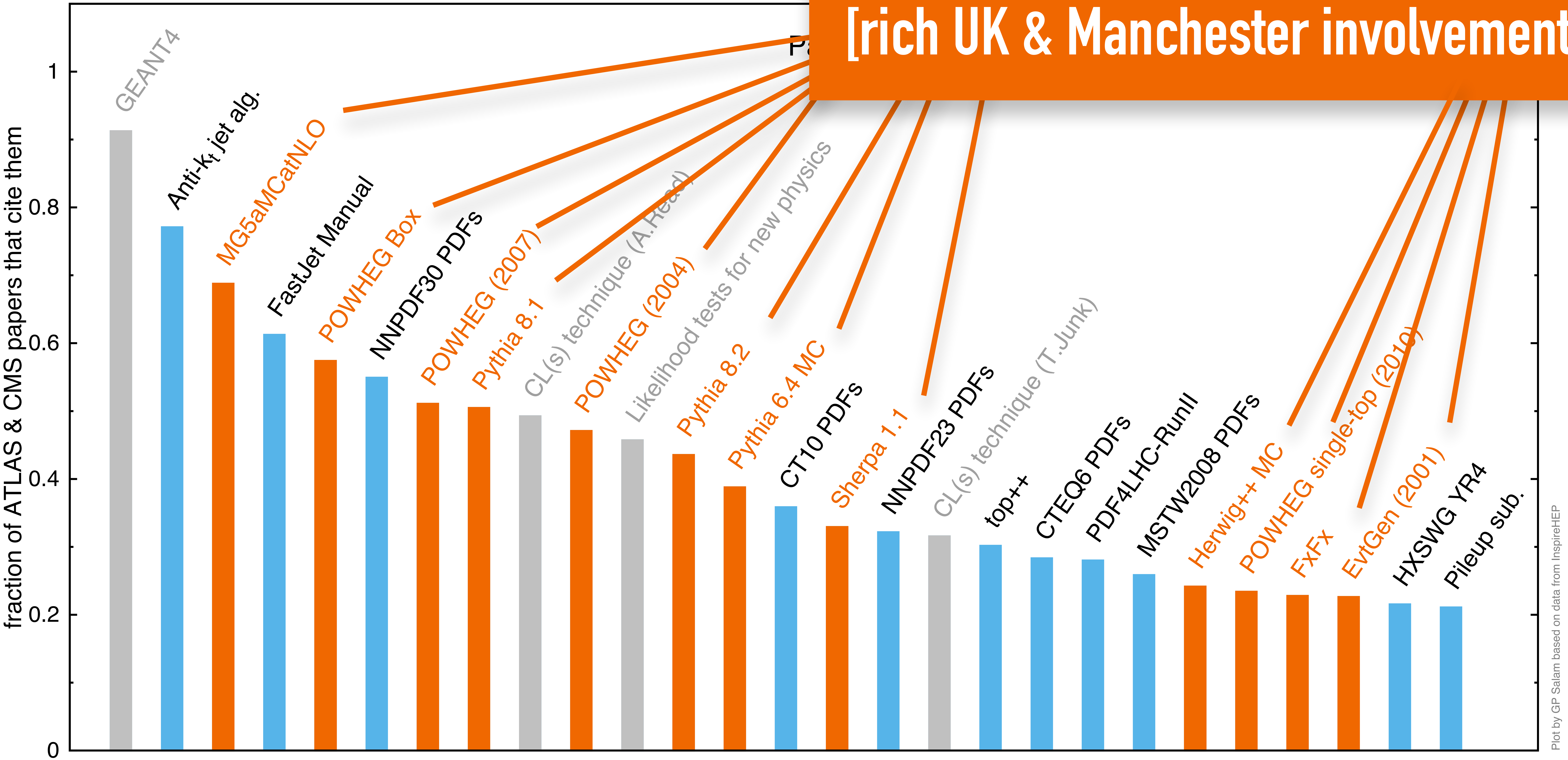
[Cacciari, GPS & Soyez, 2007 – 11]

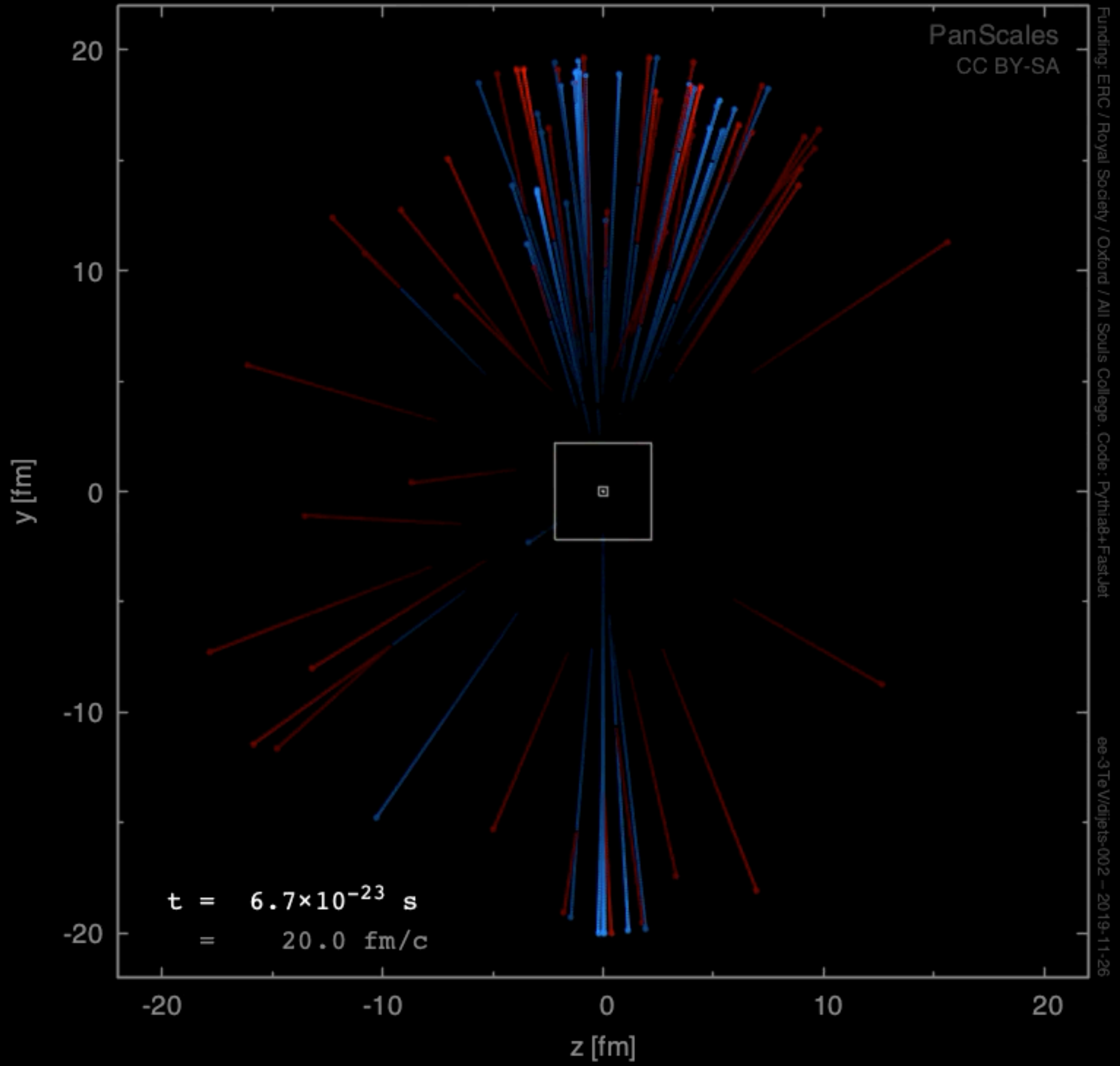


the question of organising information from hundreds of particles will come back later

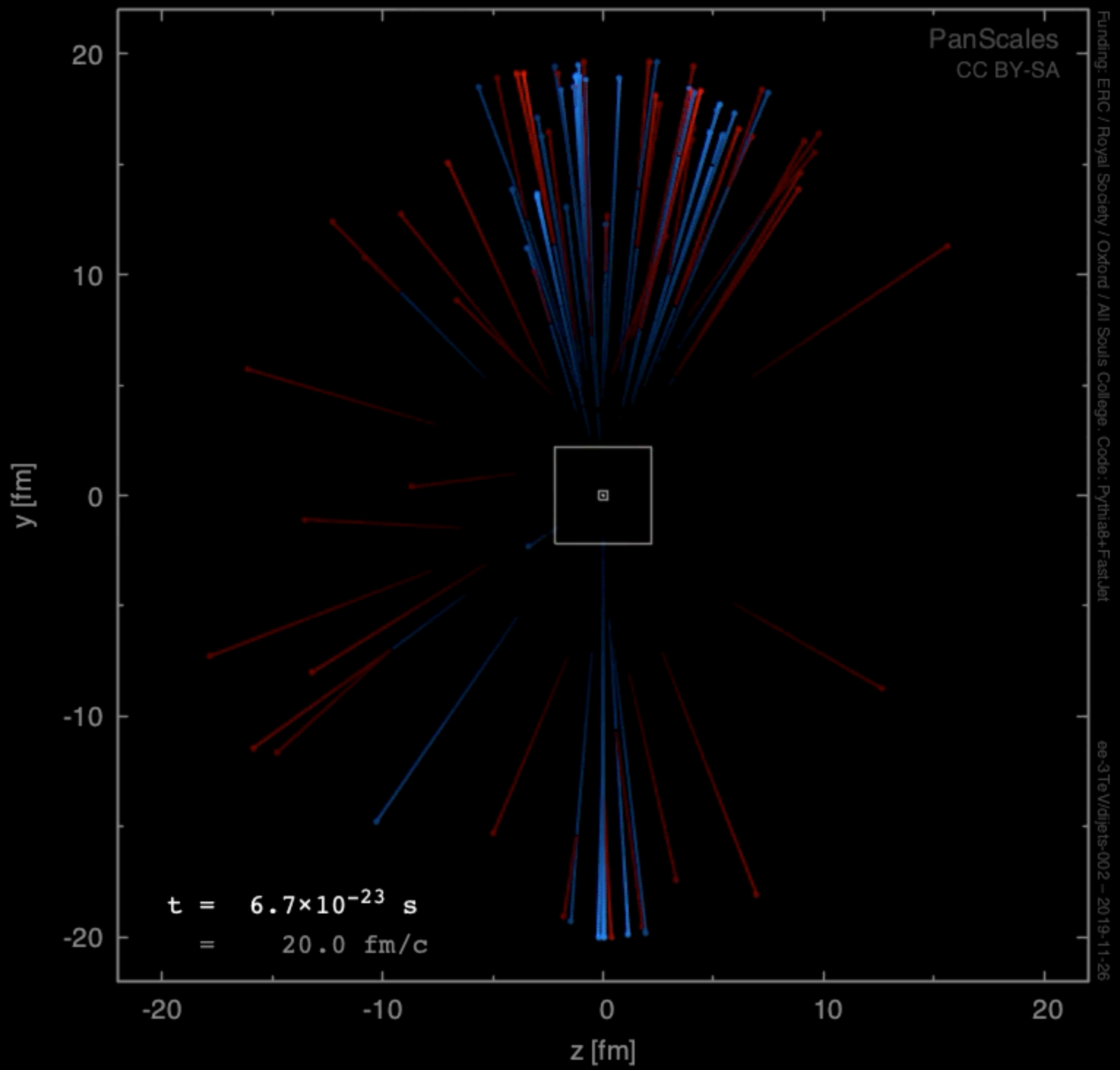


predicting full particle structure that comes out of a collision [rich UK & Manchester involvement]





Event evolution spans 7 orders of magnitude in space-time



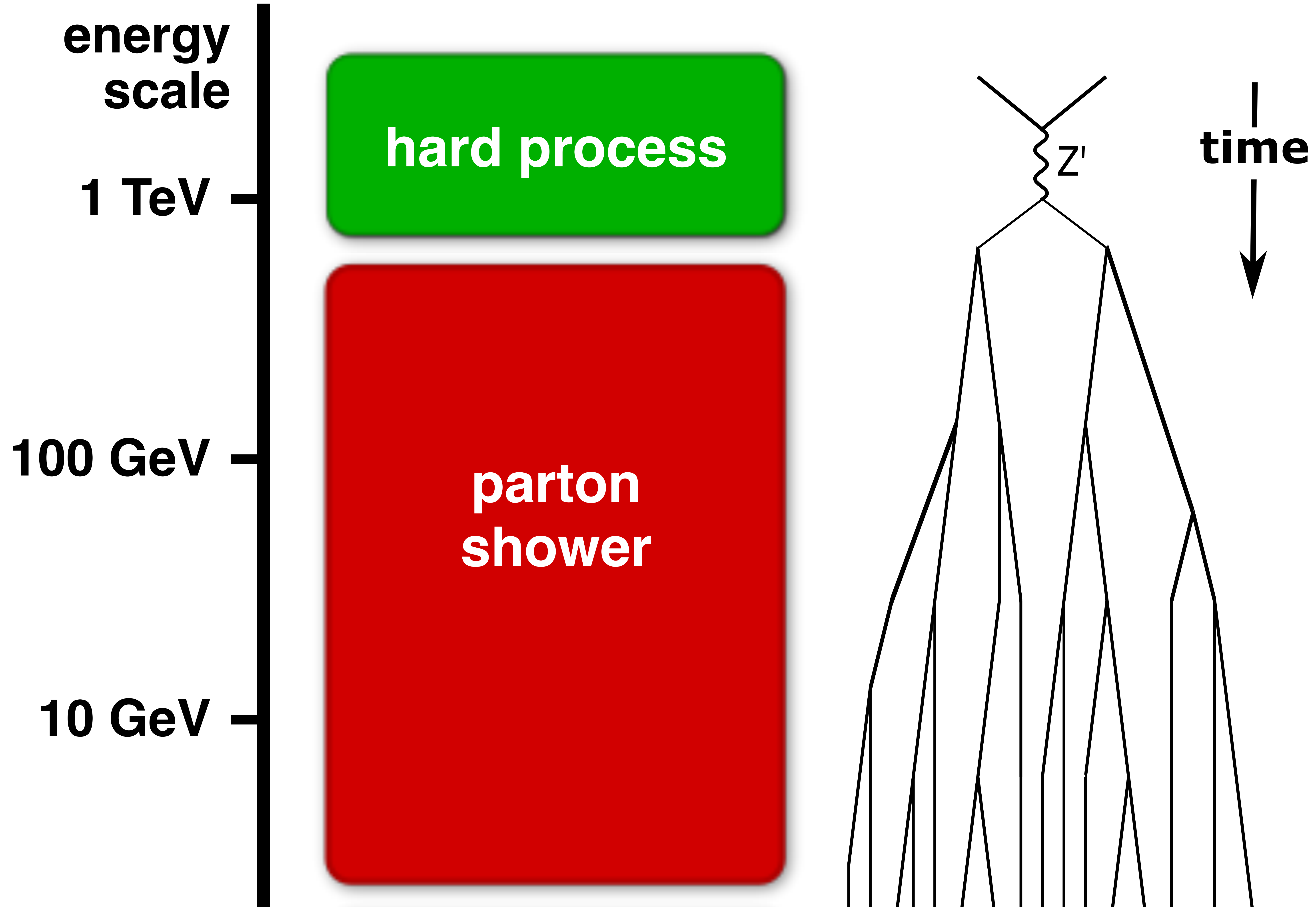
incoming beam particle

intermediate particle

final particle

Event evolution spans 7 orders of magnitude in space-time

schematic view of key components of QCD predictions and Monte Carlo event simulation



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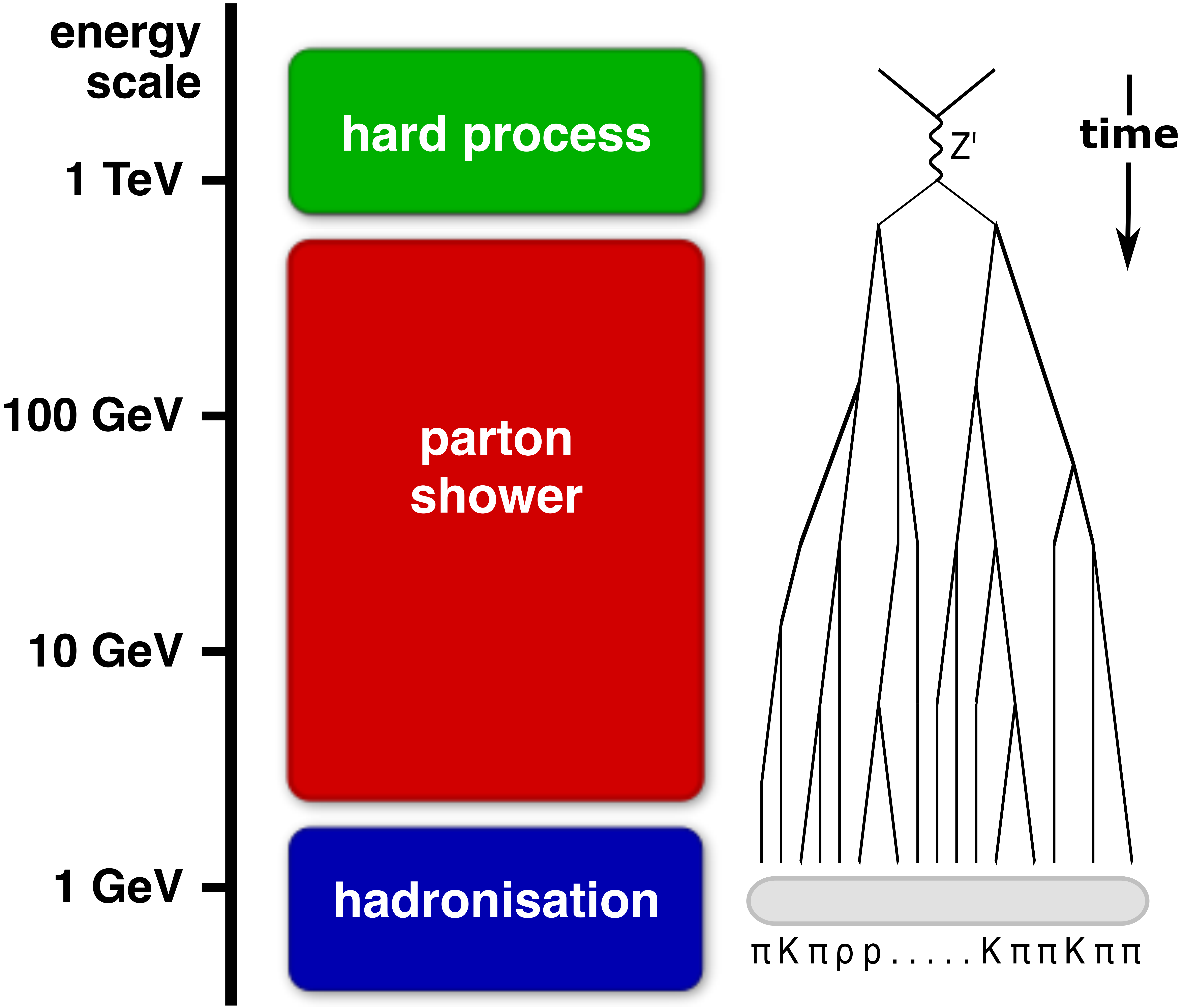
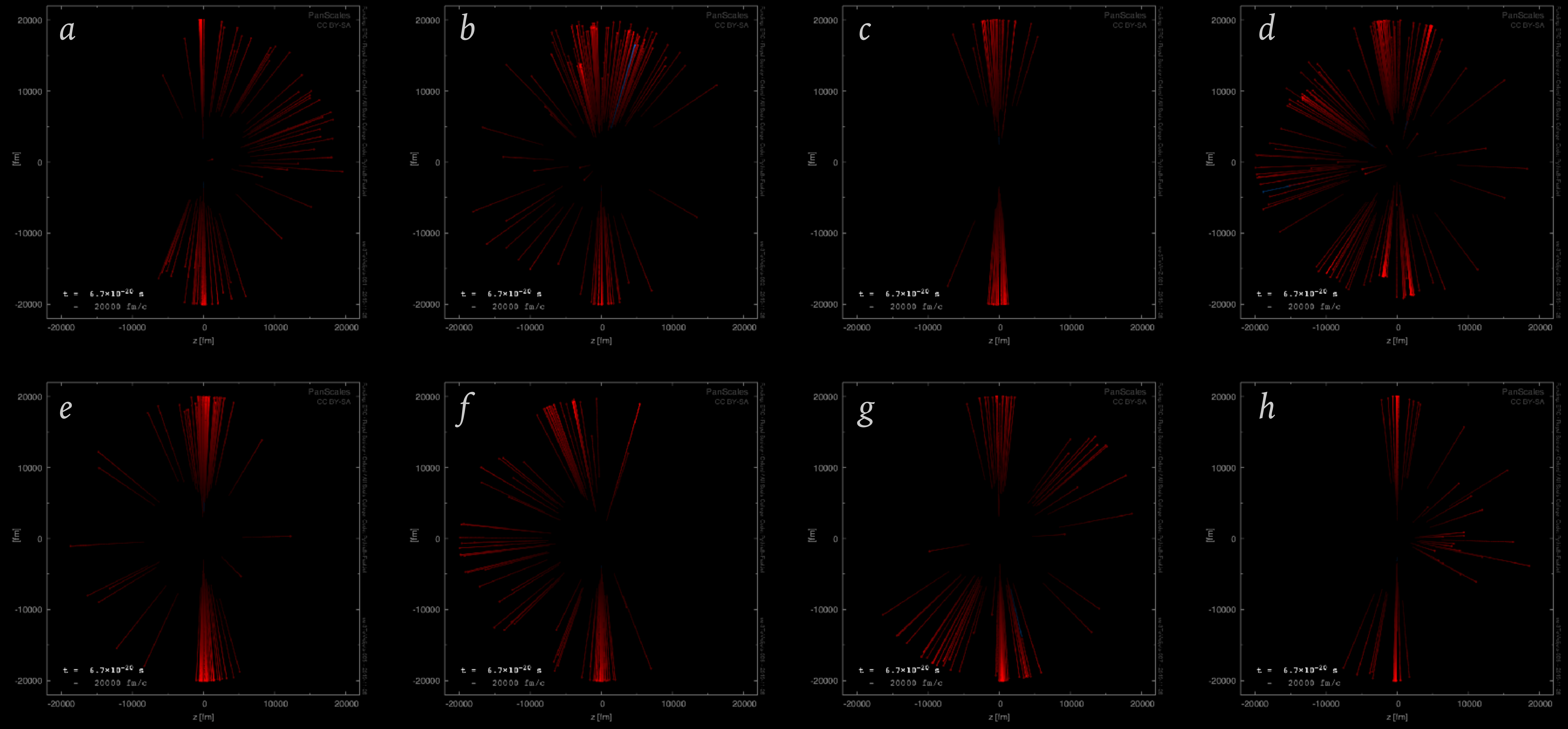


schematic view of key components of QCD predictions and Monte Carlo event simulation

pattern of particles in MC can be directly compared to pattern in experiment

(jet) substructure

how much information is hidden among
the hundreds of particles produced in a collisions?



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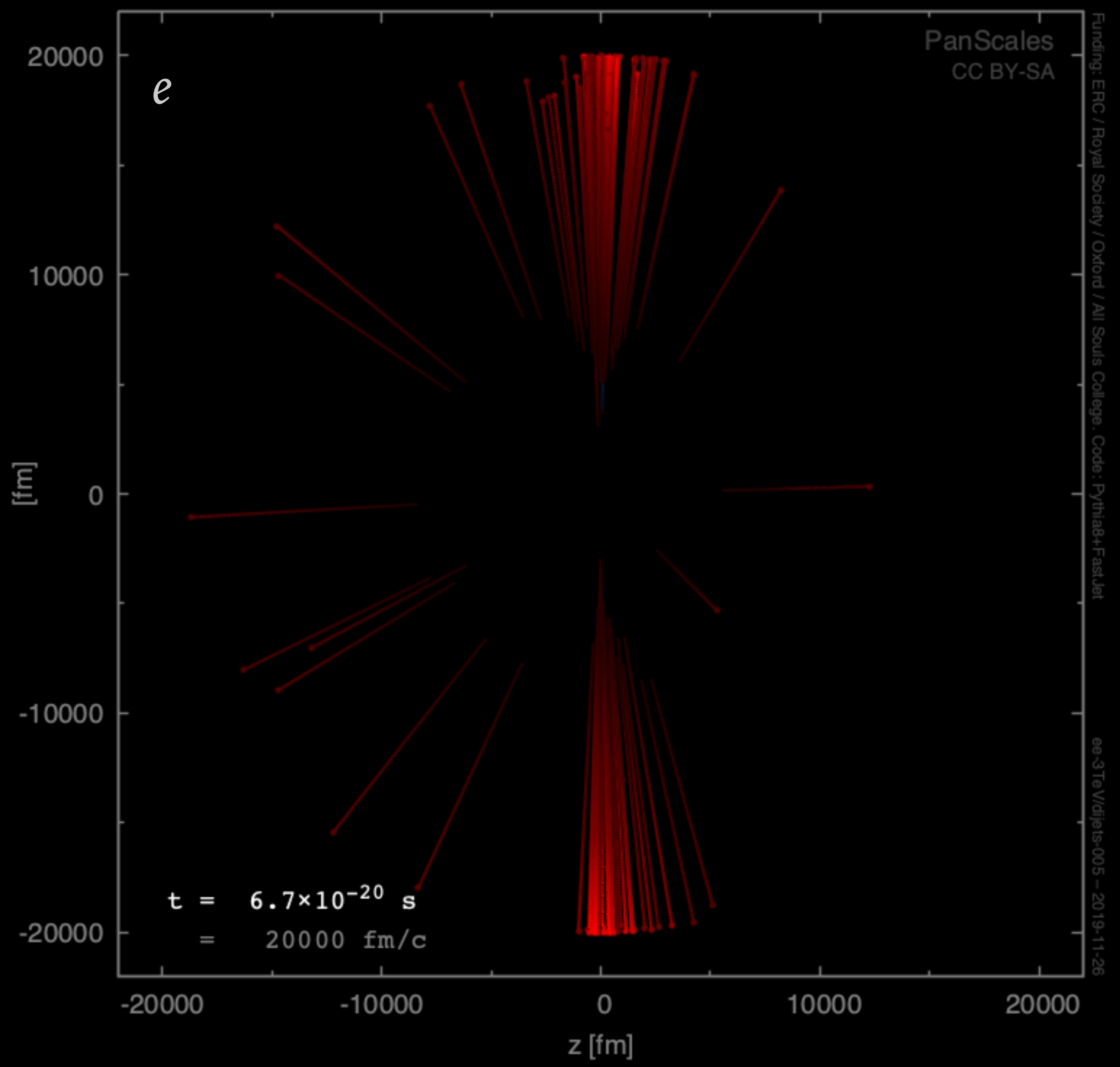
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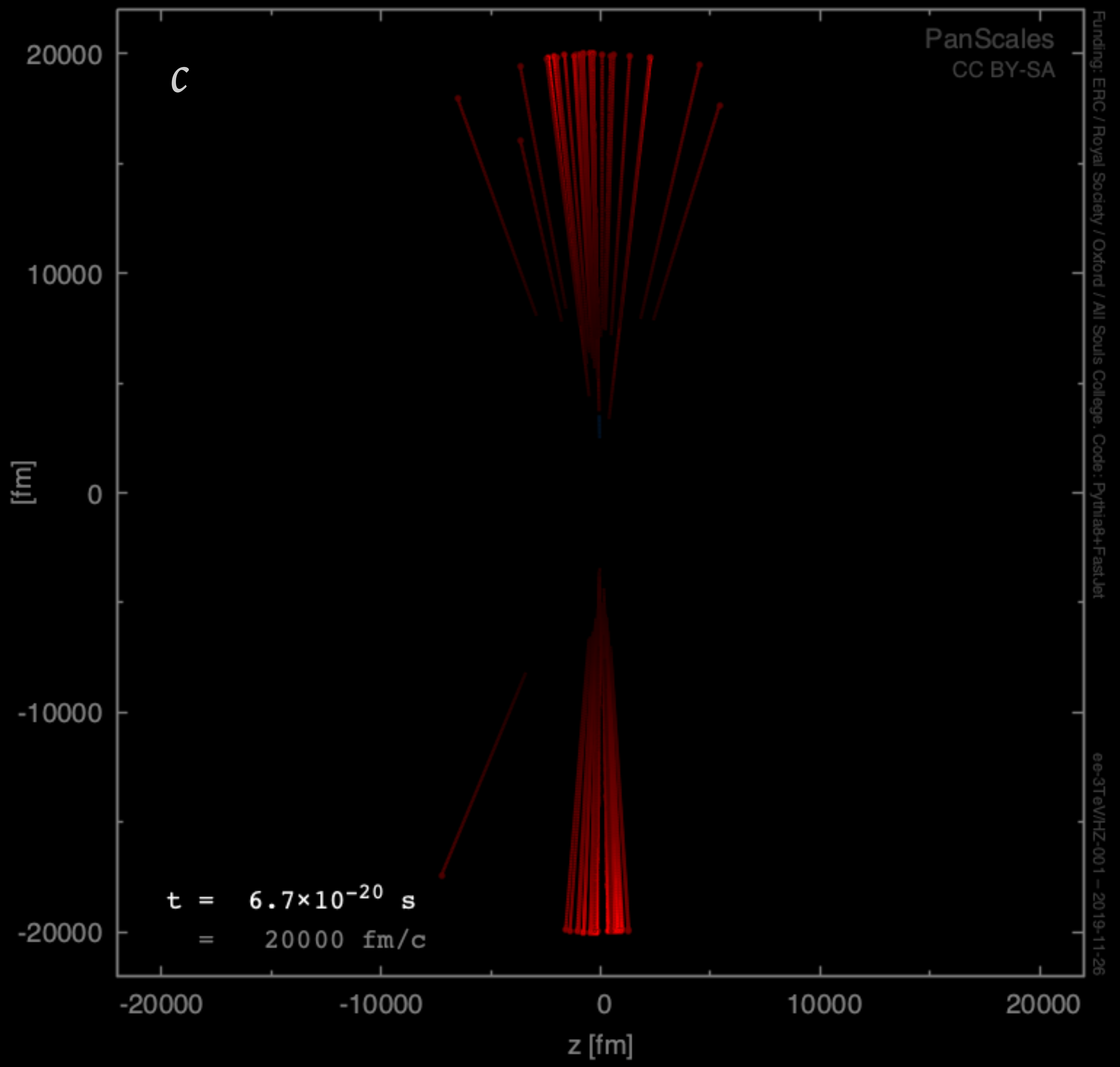
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV/dijets-005 – 2019-11-26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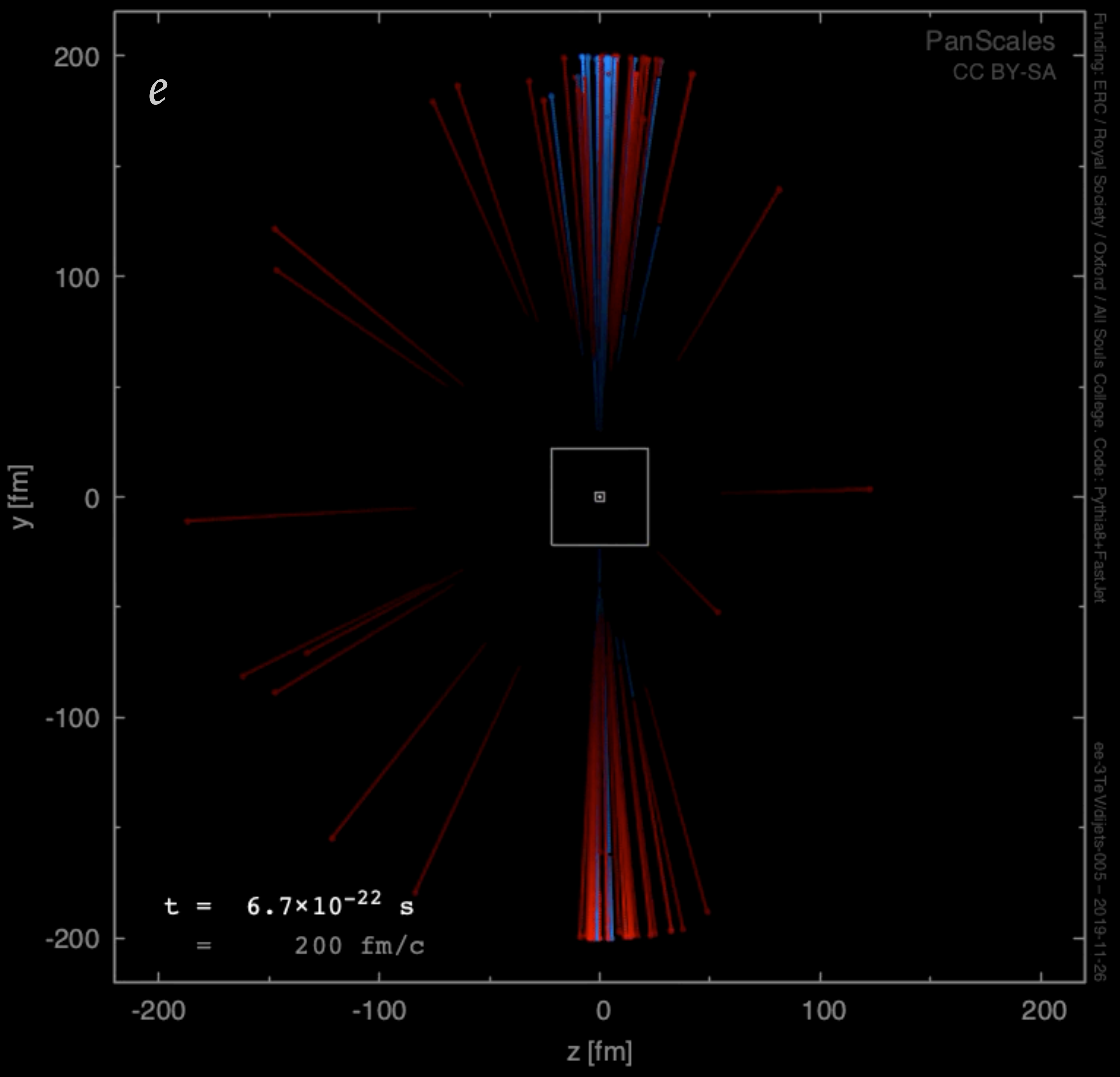
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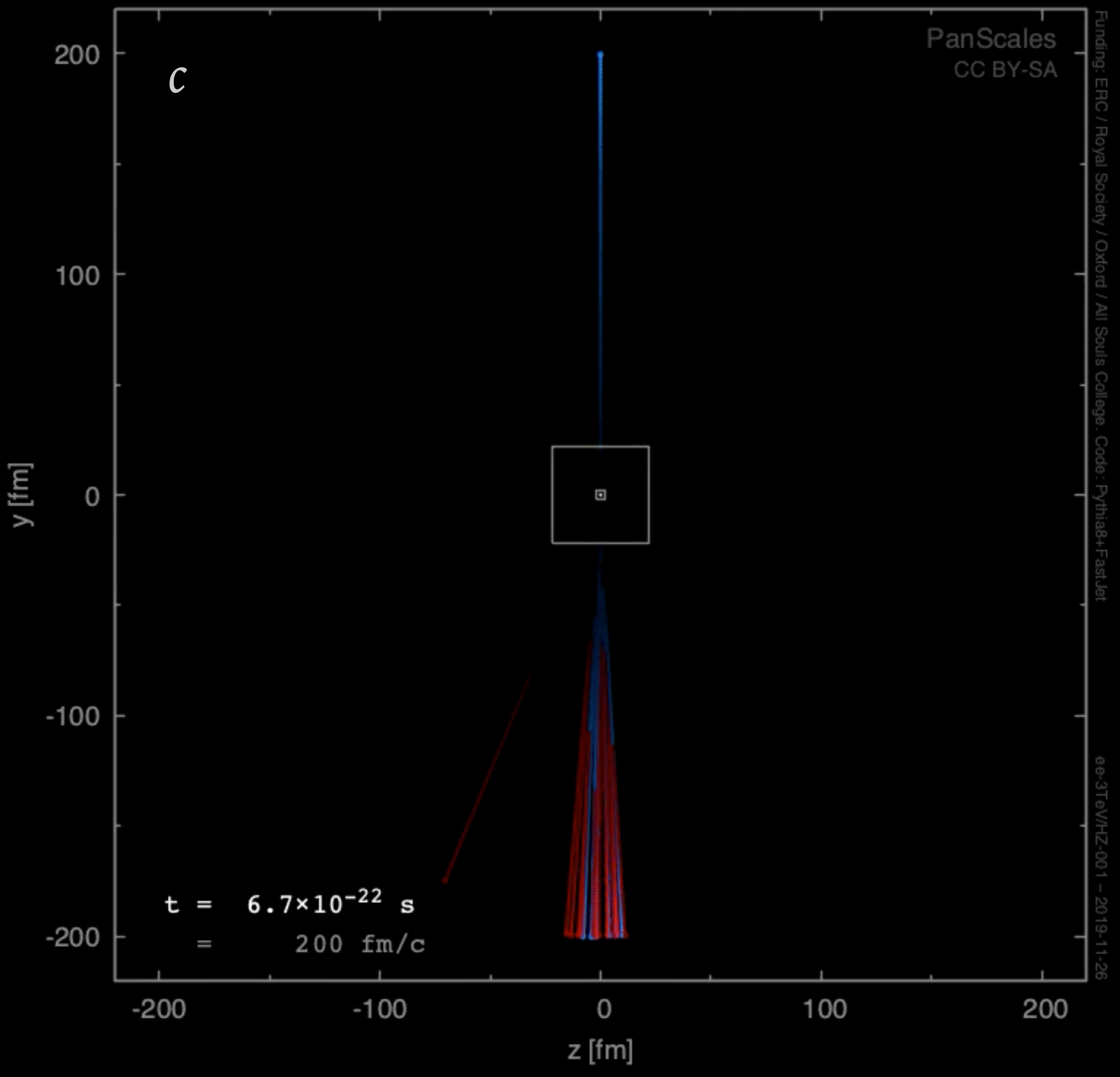
ee-3TeV/dijets-005 – 2019-11-26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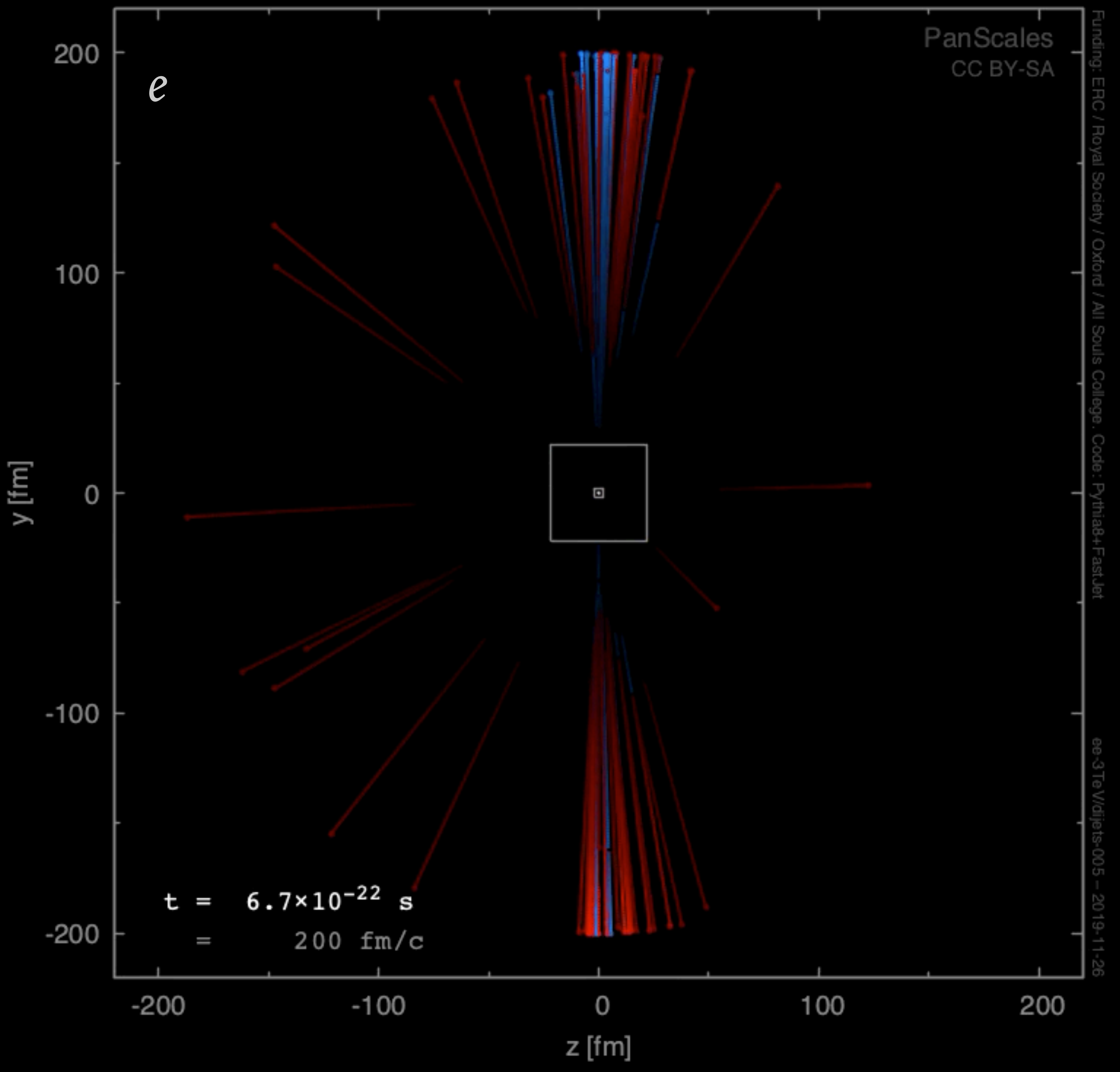
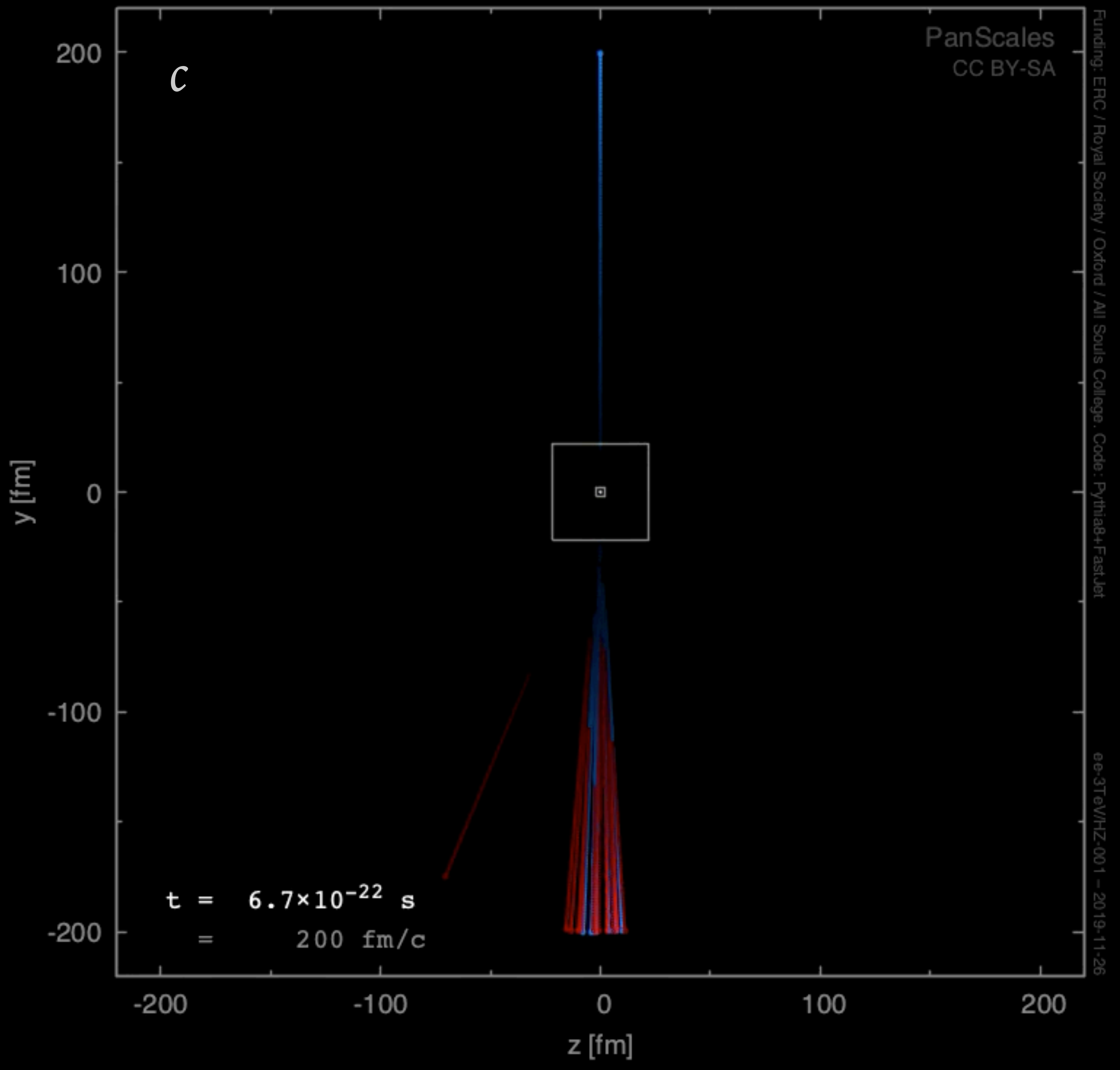
pure QCD event

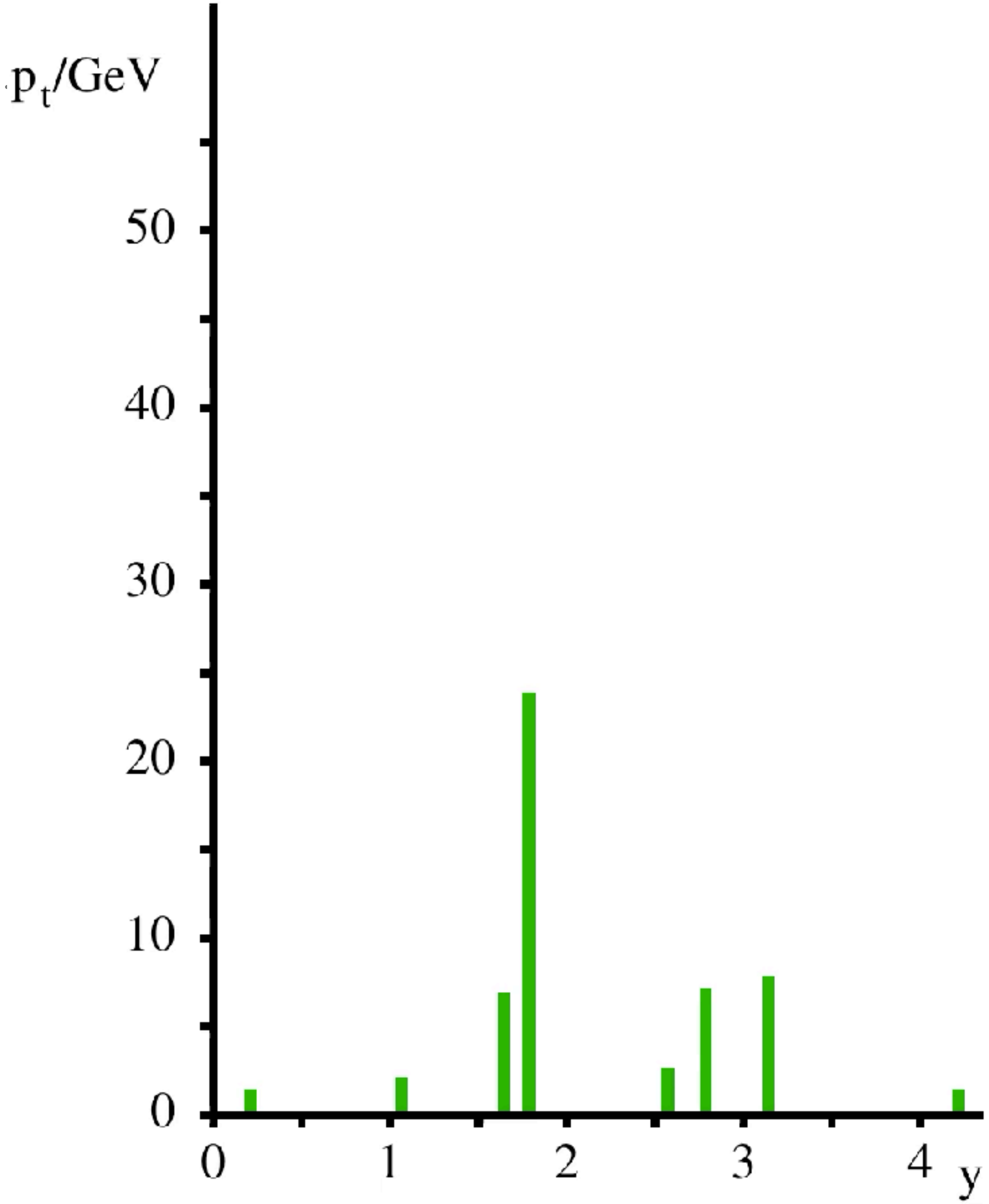


event with Higgs & Z boson decays



the Cambridge / Aachen (C/A) jet algorithm

1. Identify pair of particles, i & j, with smallest ΔR_{ij}
2. If $\Delta R_{ij} < R$ (jet radius parameter)
   A. recombine i & j into a single particle
   B. loop back to step 1
3. Otherwise, stop the clustering



Dokshitzer, Leder, Moretti & Webber '97
Wobisch & Wengler '98

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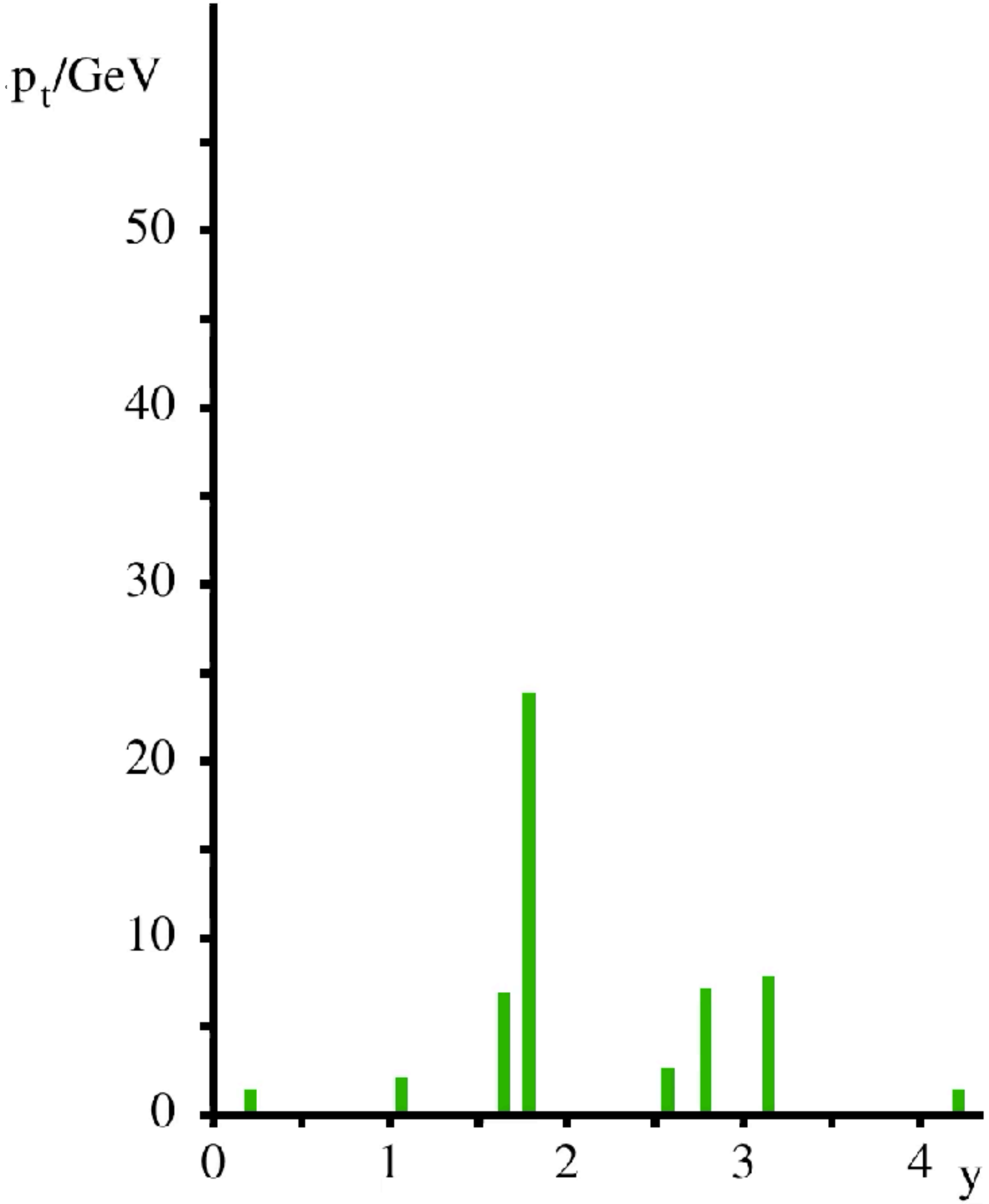

Dokshitzer, Leder, Moretti & Webber '97
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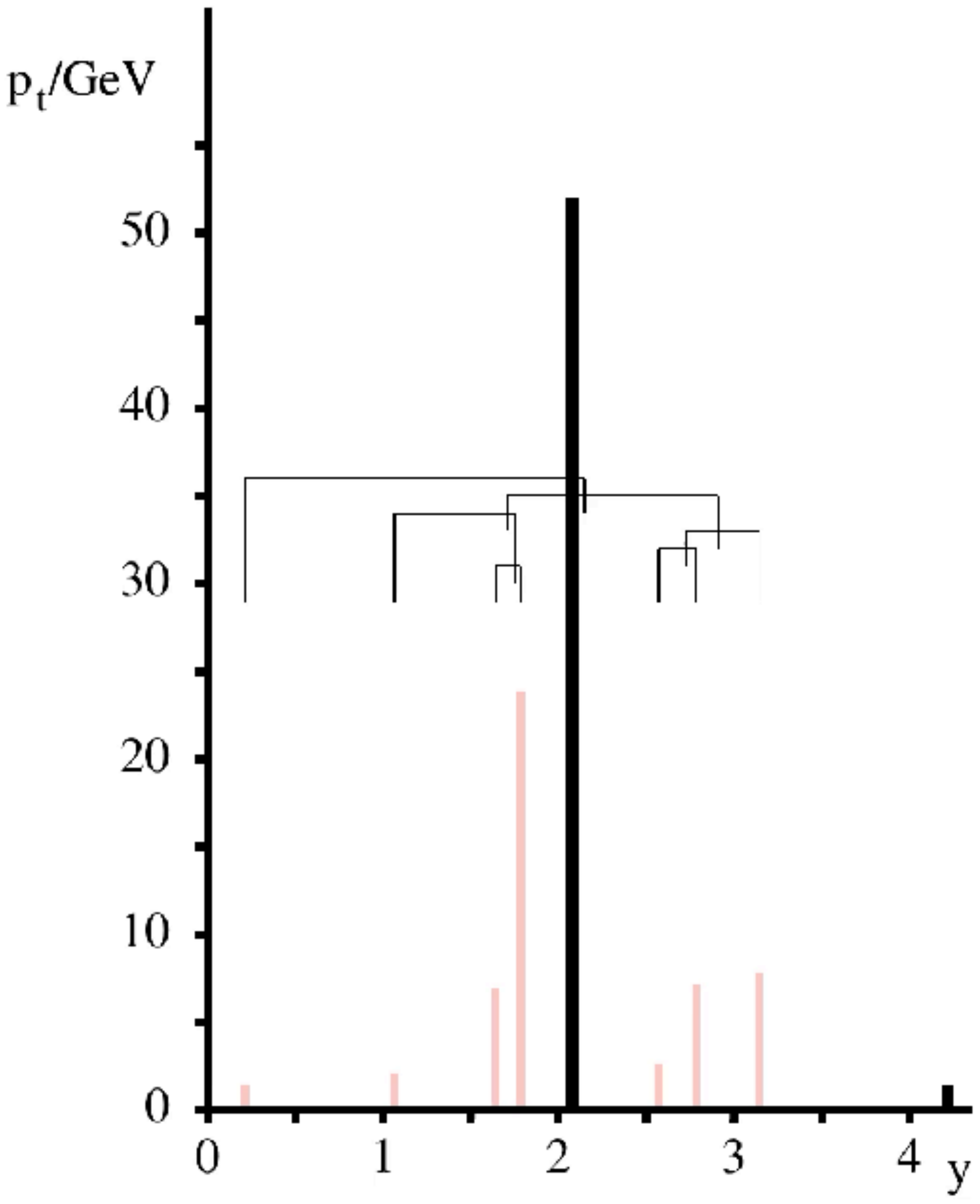
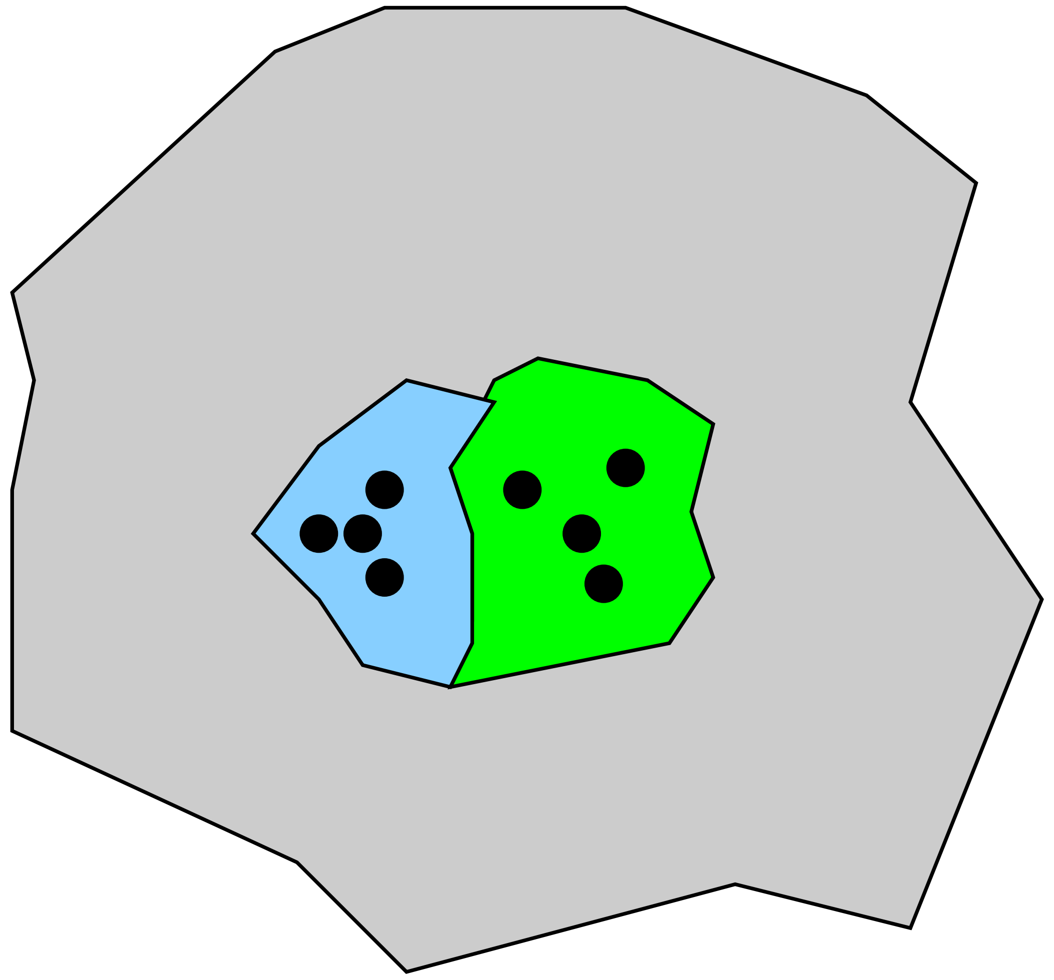
A sequence of jet substructure tools taggers

- 1993: k_t declustering for boosted W's: [Seymour]
- 2002: Y-Splitter (k_t declustering with a cut) [Butterworth. Cox, Forshaw]
- 2008: Mass-Drop Tagger (C/A declustering with a k_t/m cut) [Butterworth, Davison, Rubin, GPS]
- 2013: Soft Drop, $\beta=0$ [Dasgupta, Fregoso, Marzani, GPS]
- 2014: Soft Drop, $\beta\neq0$ [Larkoski, Marzani, Soyez, Thaler]

1. Undo last clustering of C/A jet into subjets 1, 2
2. Stop if $z = \frac{\min(p_{t1}, p_{t2})}{p_{t1}+p_{t2}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta} > z_{\text{cut}}$
3. Else discard softer branch, repeat step 1 with harder branch





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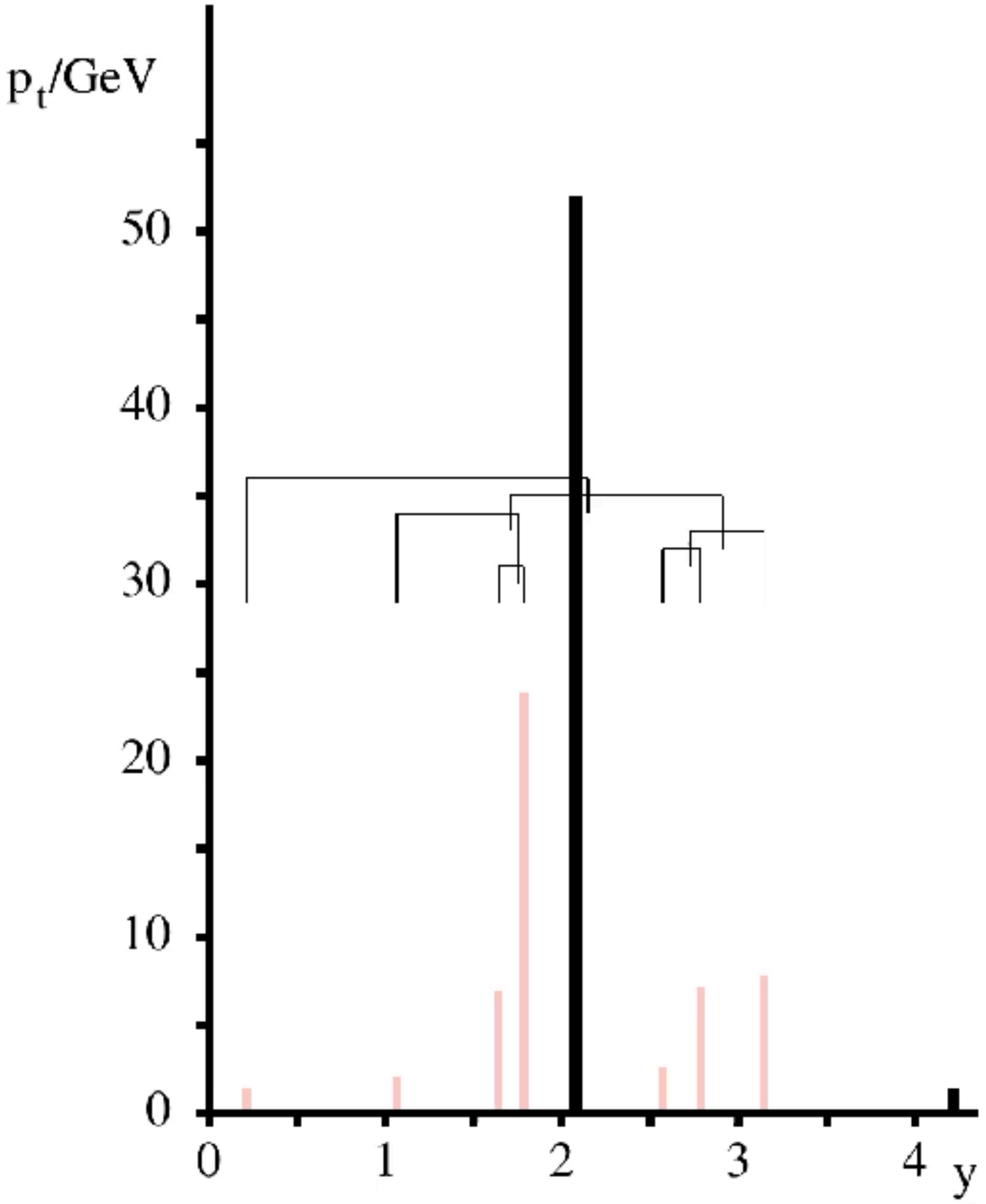
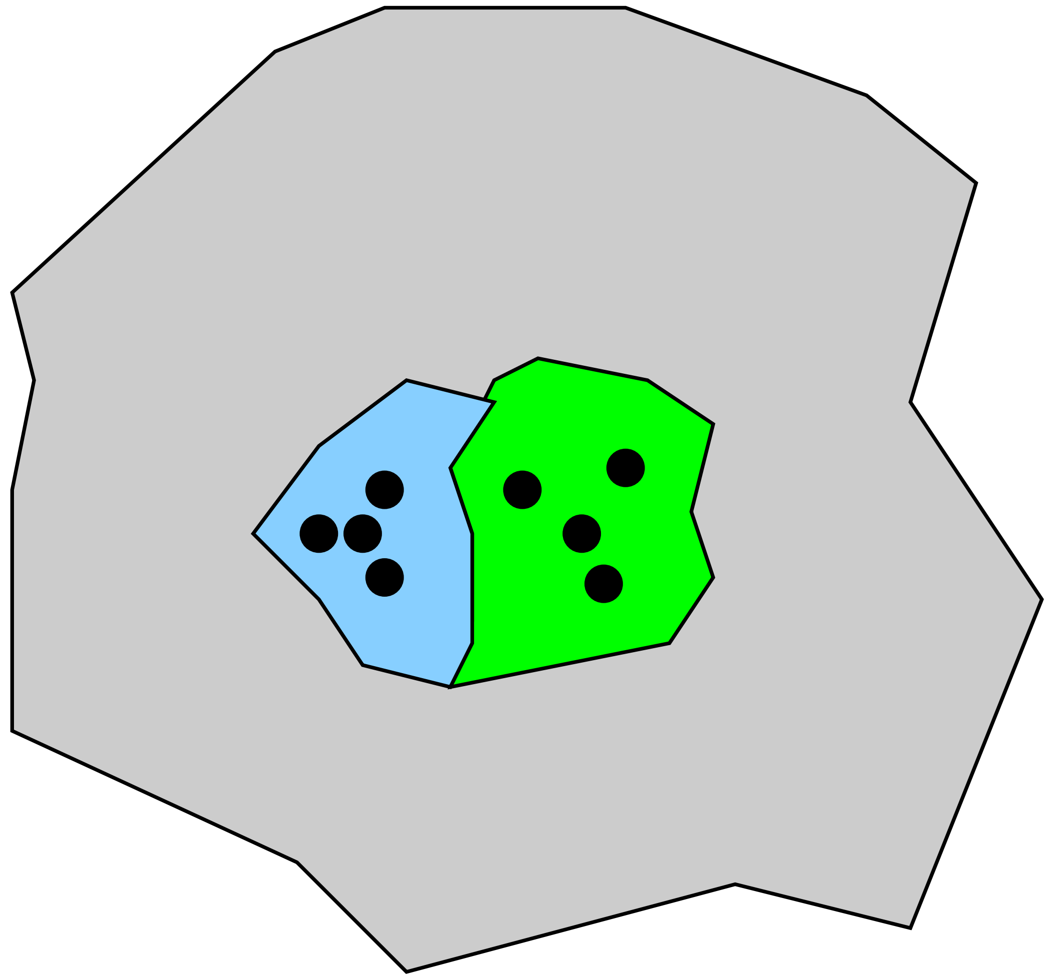




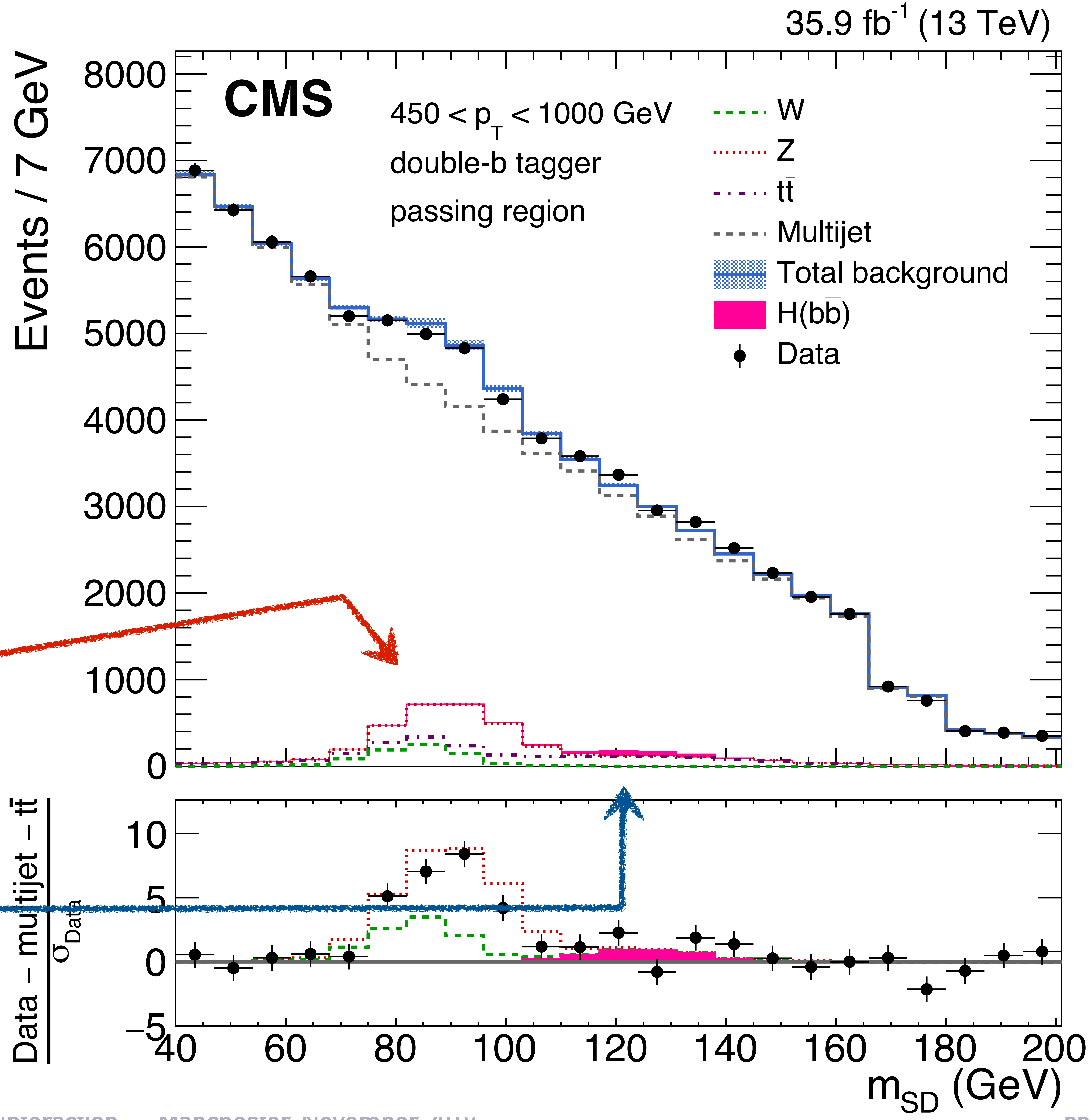
Soft Drop & high p_T Higgs

We wouldn't trust electromagnetism if we'd only tested at one length/ momentum scale.

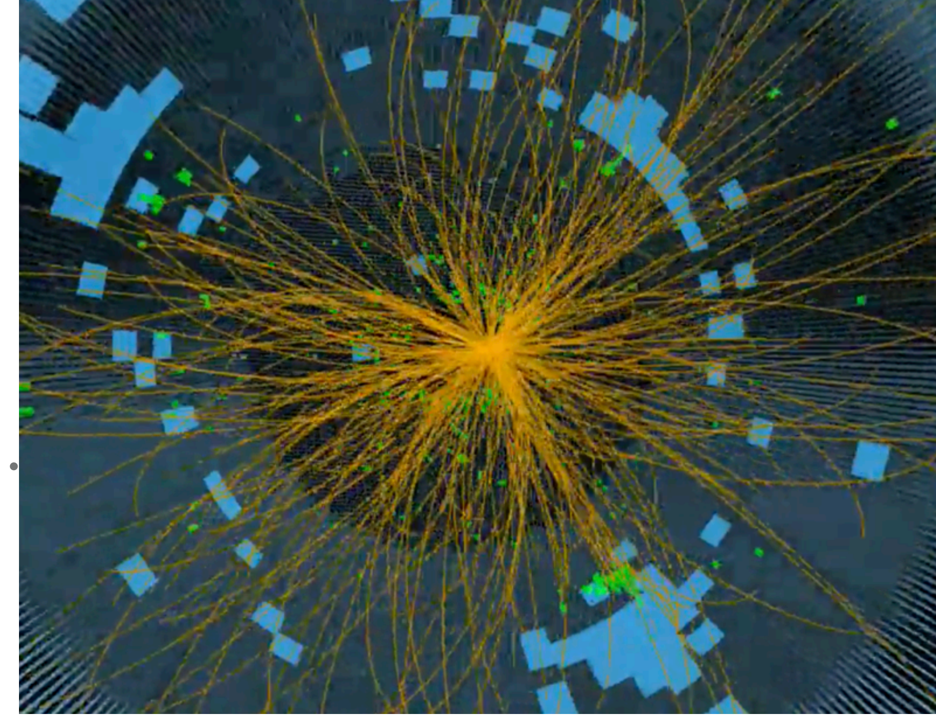
New Higgs interactions need testing at both low and (here) high momenta.

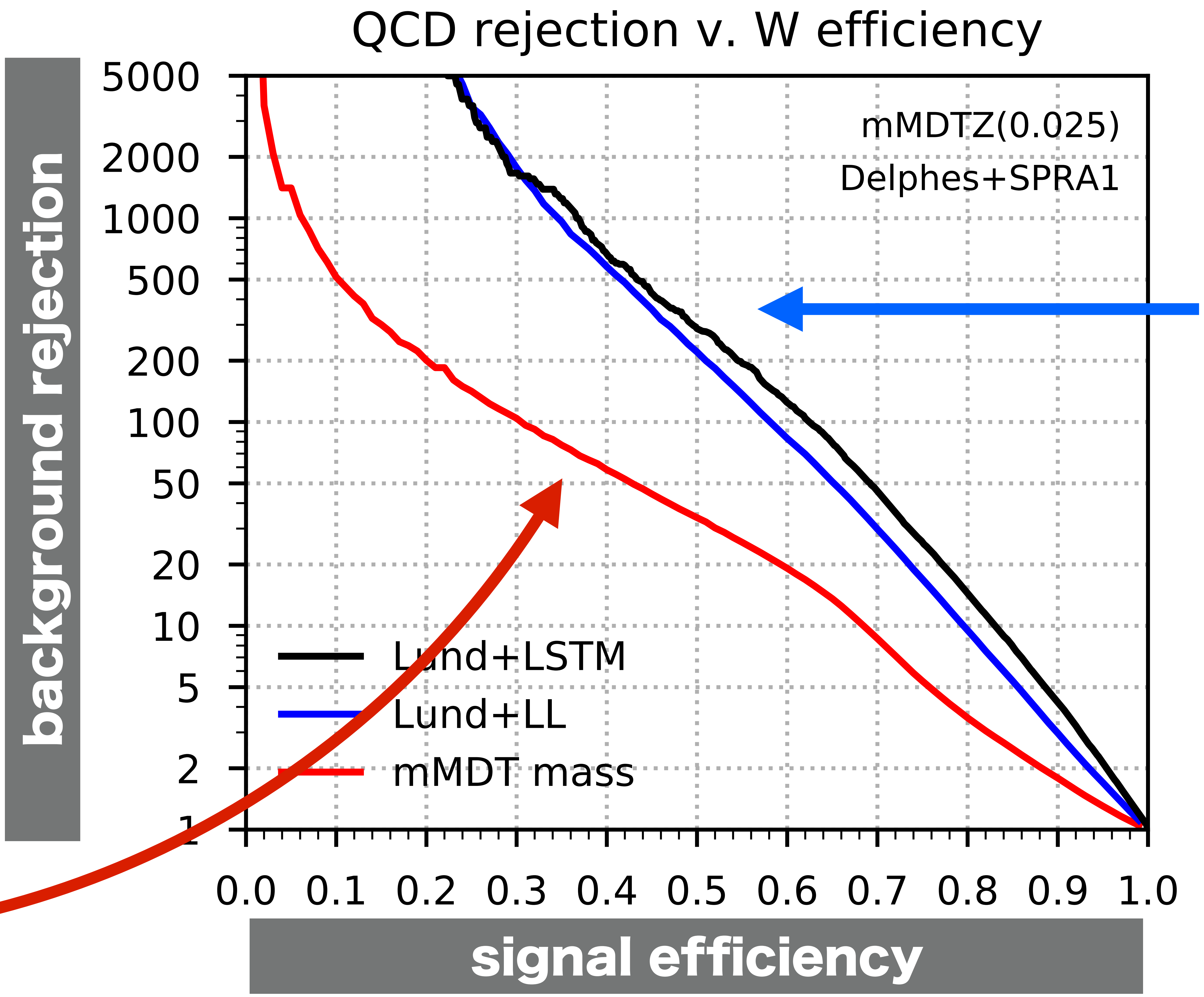
high-p_T Z → bb (5σ)

high-p_T H → bb (~ 1σ)



using full event information for H/etc. boson tagging





QCD rejection with use of full jet substructure (2018 tools)

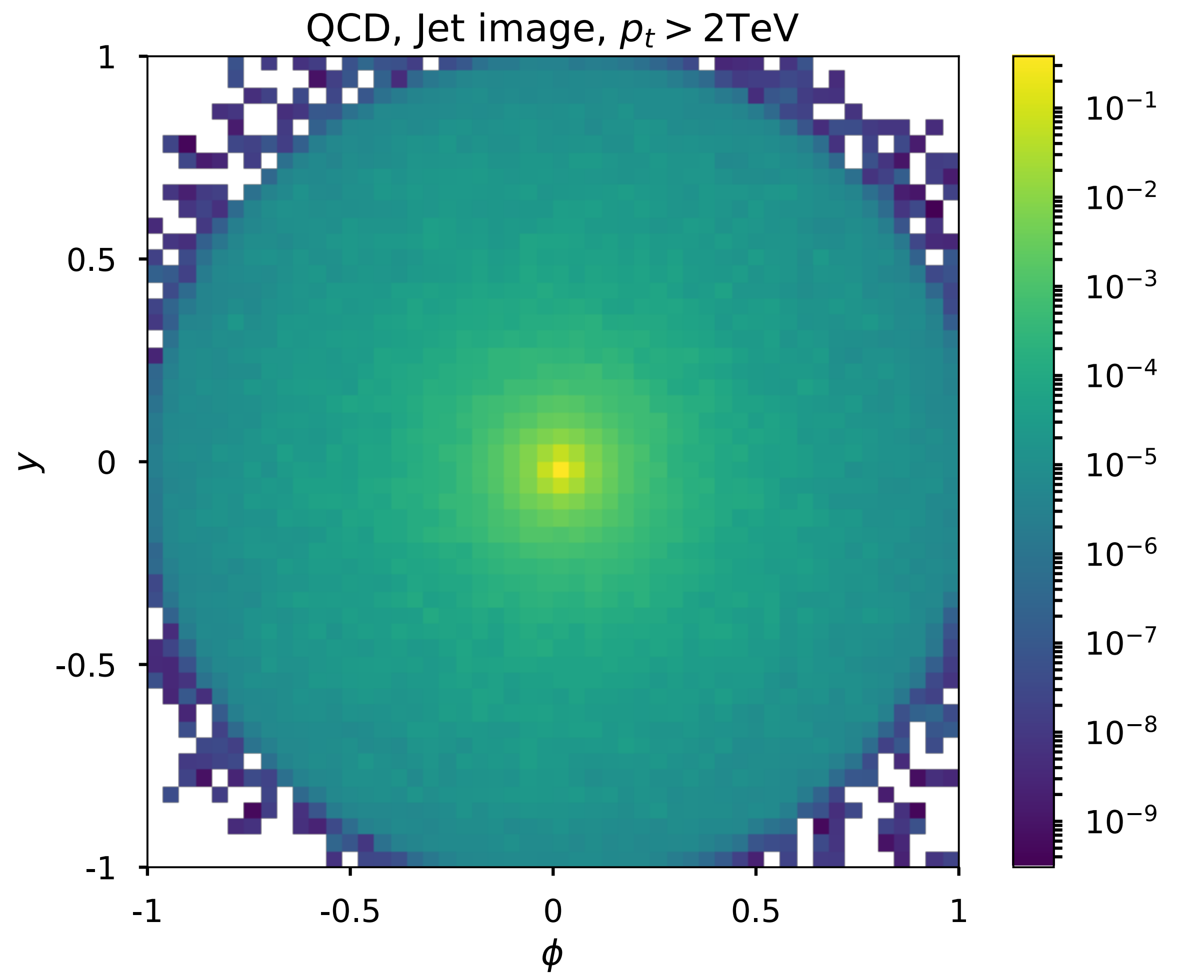
5–10x better

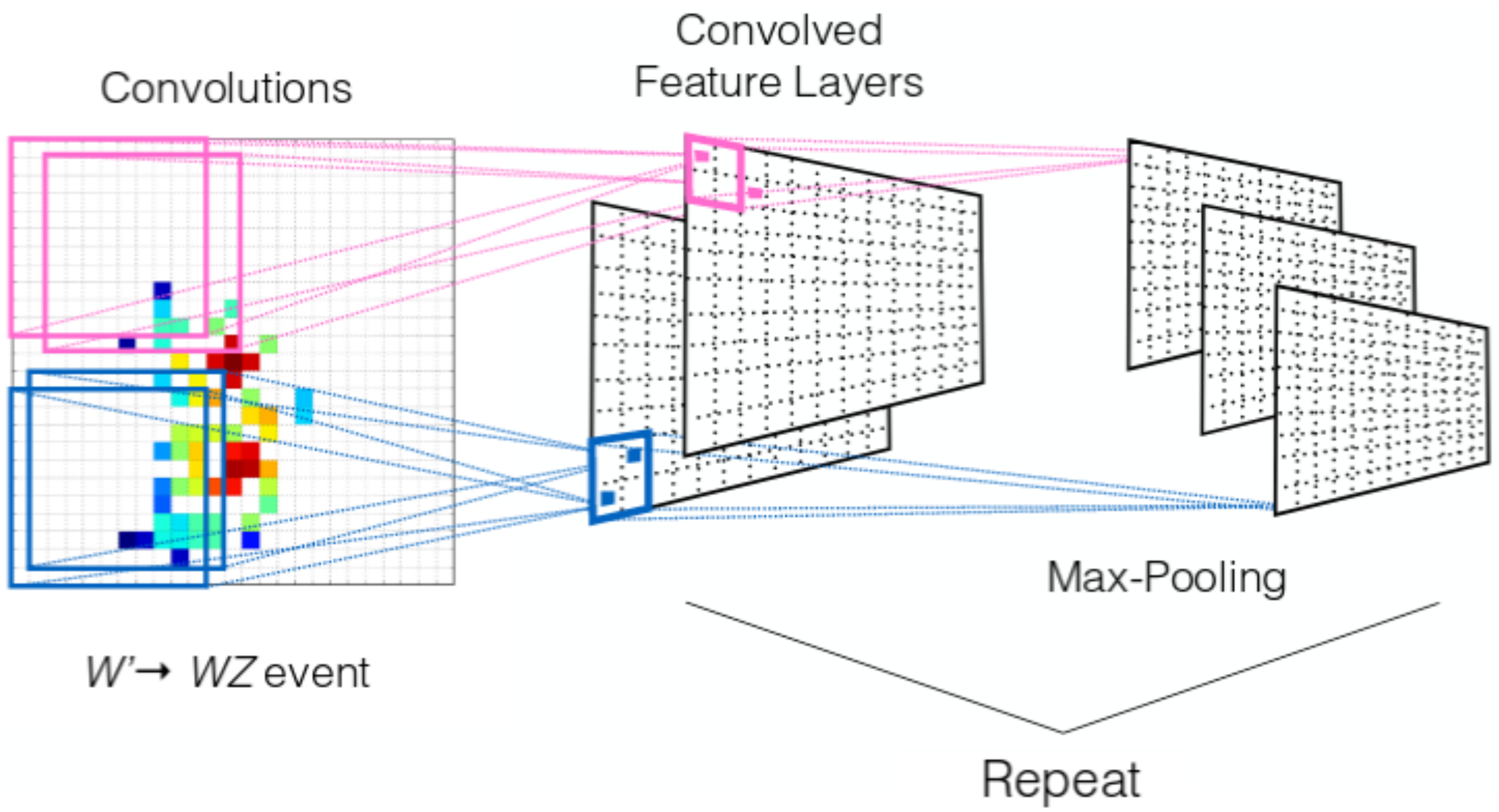
QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their decsendants

First started to be exploited by Thaler & Van Tilburg with "N-subjettiness" (2010/11)

Convolutional neural networks and jet images

- Project a jet onto a fixed $n \times n$ pixel image in rapidity-azimuth, where each pixel intensity corresponds to the momentum of particles in that cell.
- Can be used as input for classification methods used in computer vision, such as deep convolutional neural networks.





[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

powerful

but black box

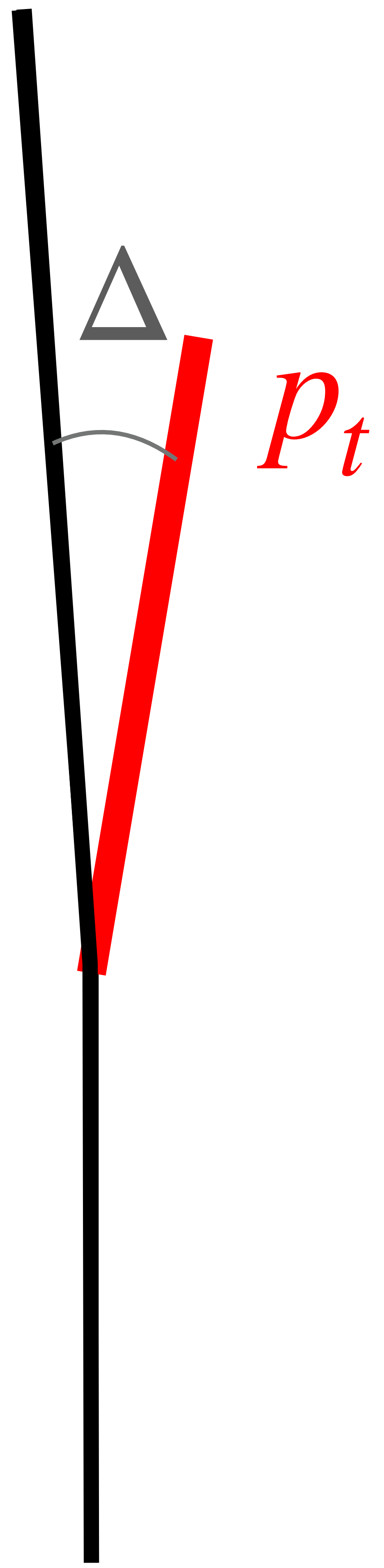
the "Lund plane"

can we construct observables that are

(a) ***transparent*** *in terms of the physical info they extract?*

(b) close to ***optimal*** *for multivariate techniques & machine-learning?*

Phase space: two key variables (+ azimuth)

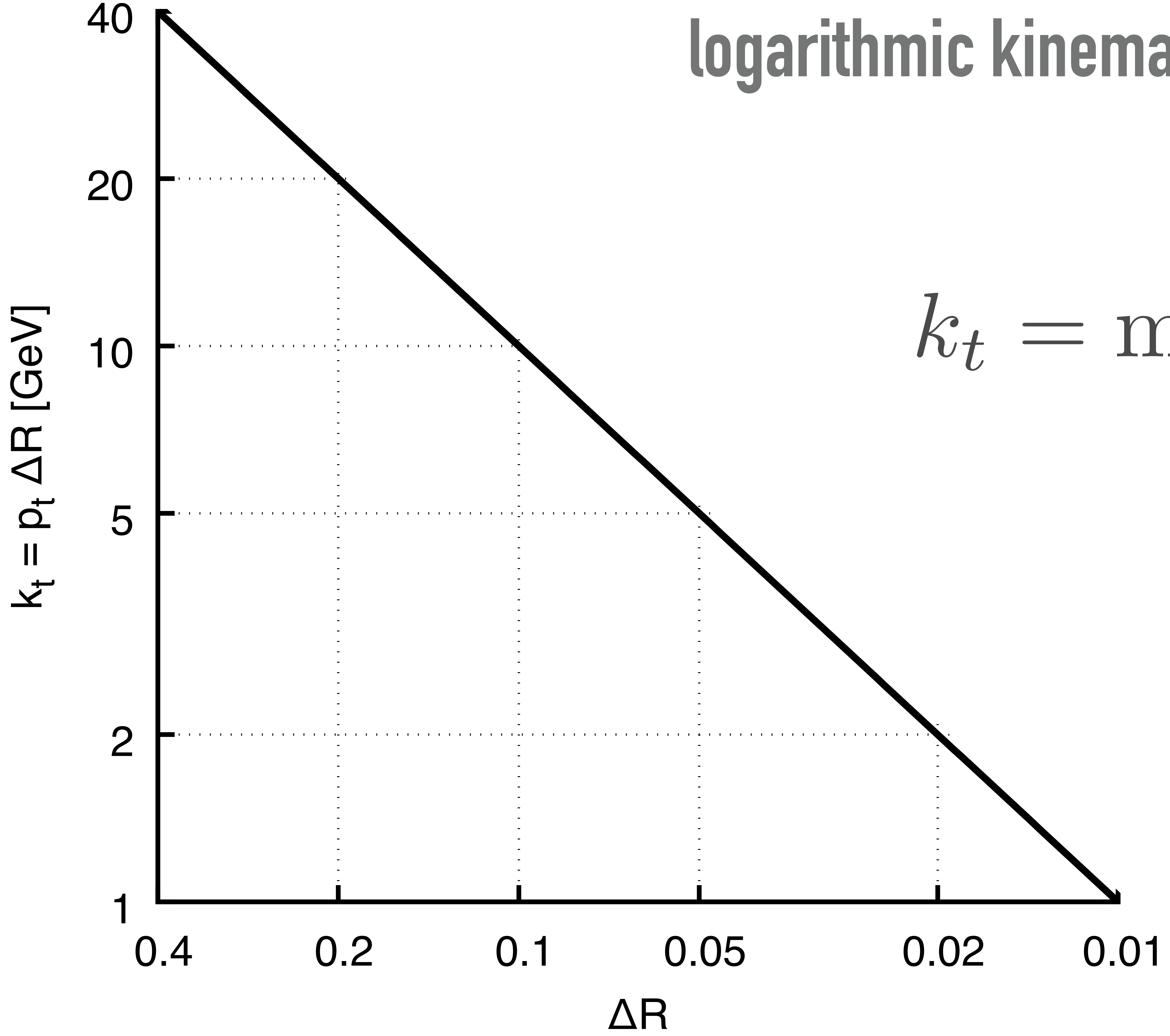


ΔR (or just Δ) — *opening angle of a splitting*

$k_t = p_t \Delta$ — *p_t (or $p_\perp$) is transverse momentum wrt beam*

k_t is $\sim$ transverse momentum wrt jet axis

jet with R = 0.4, p_t = 200 GeV



logarithmic kinematic plane whose two variables are

$$\Delta R_{ij}$$

$$k_t = \min(p_{ti}, p_{tj})\Delta R_{ij}$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson, 1989

The Lund Plane

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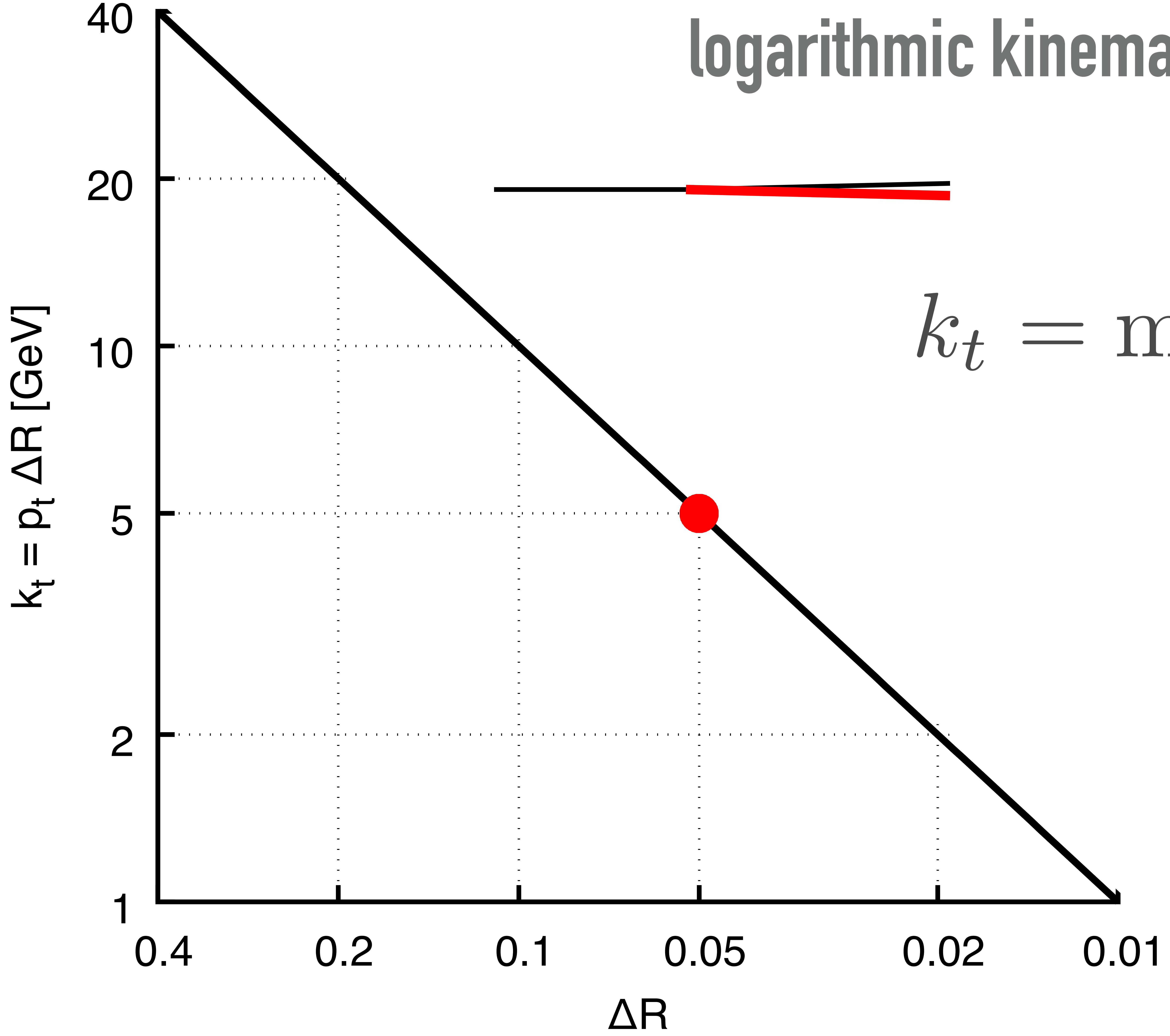

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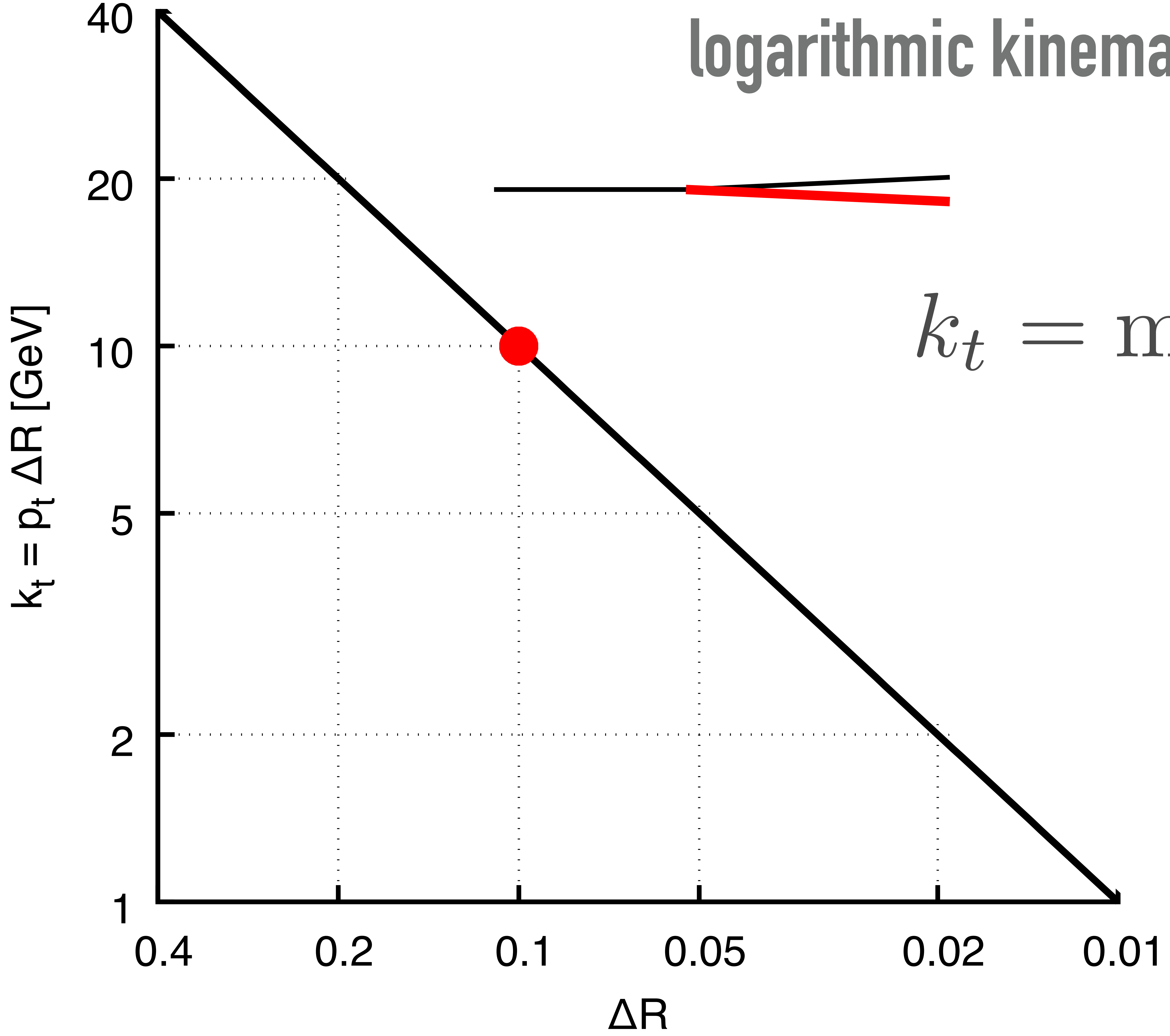

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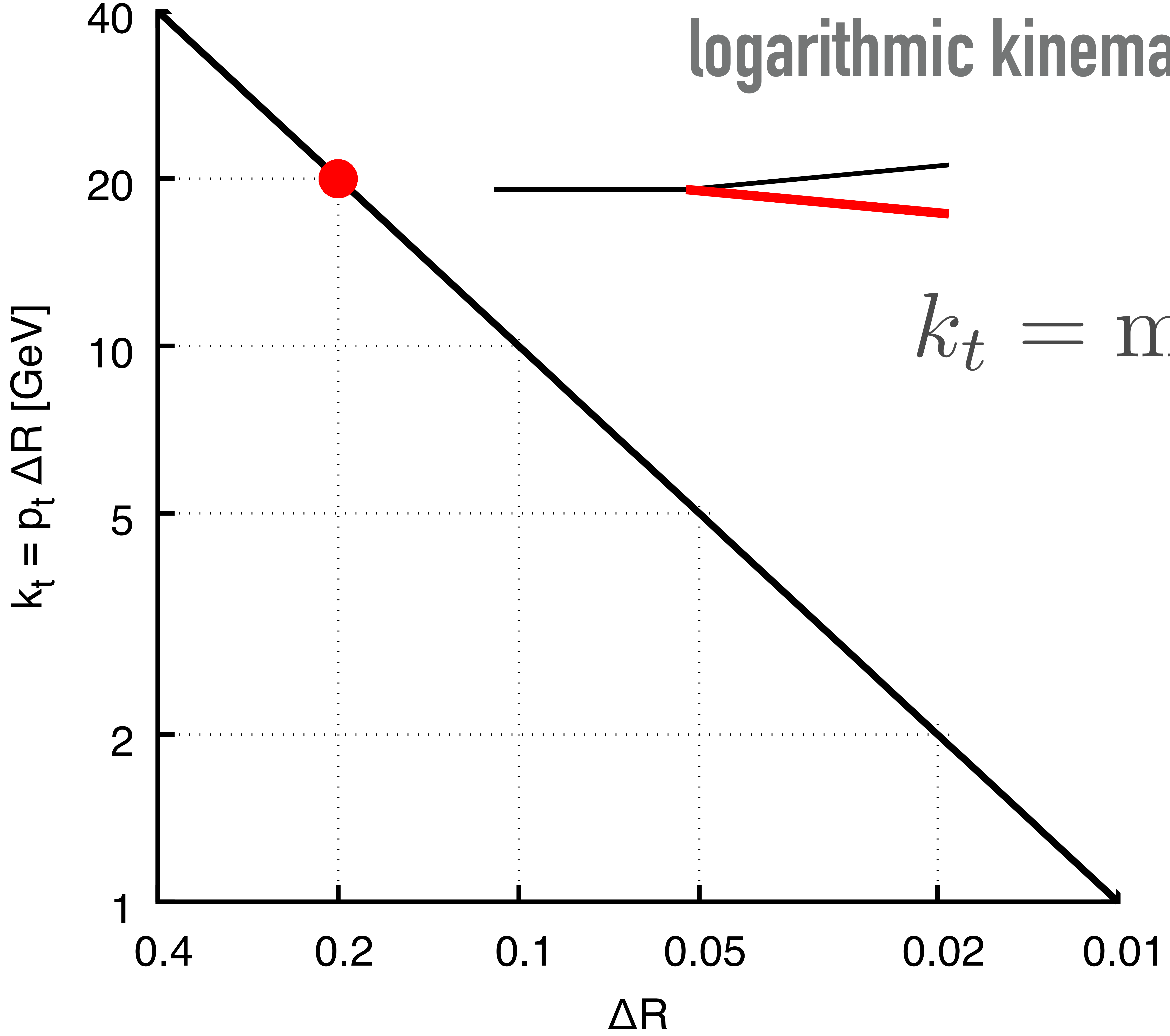

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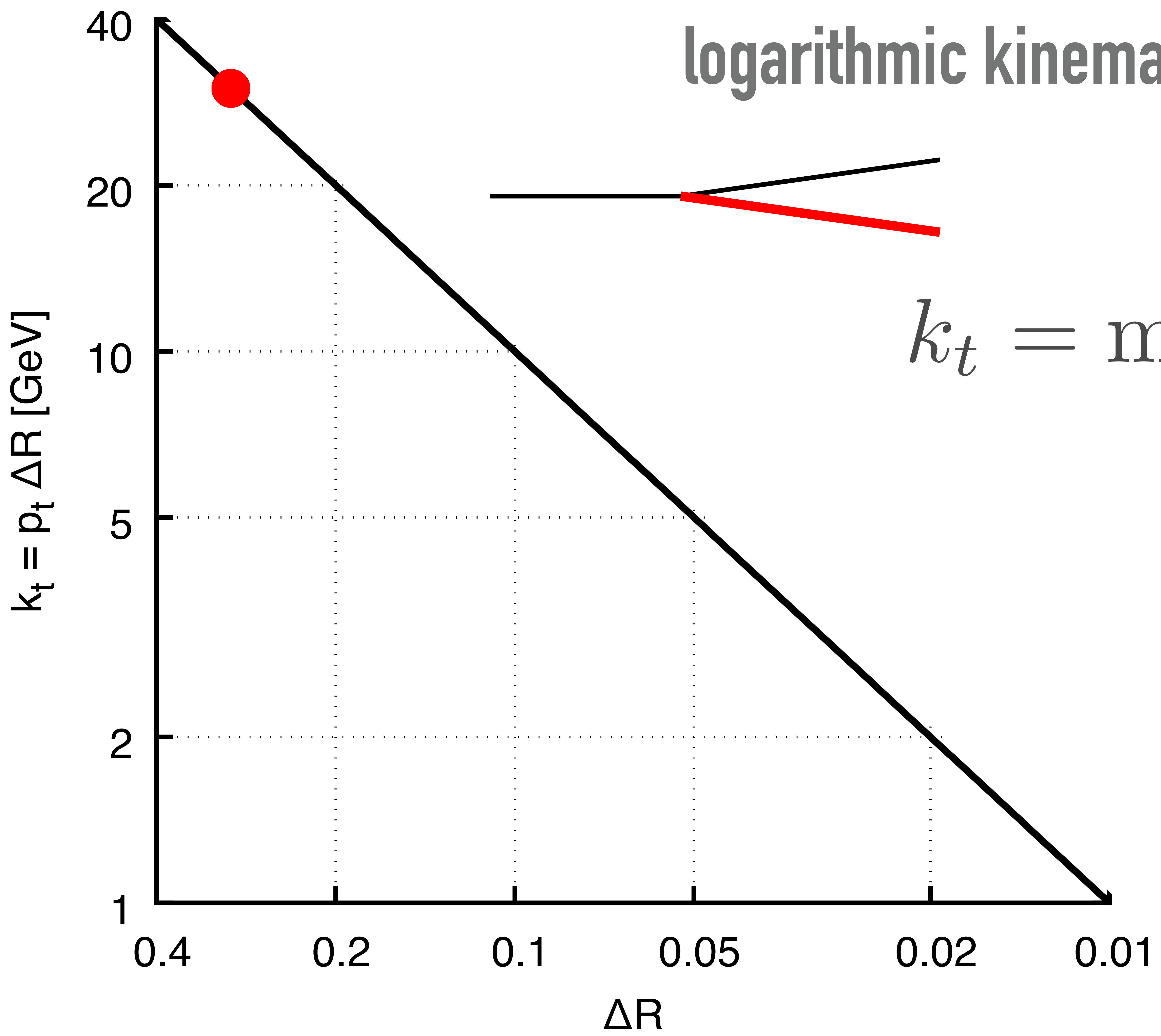

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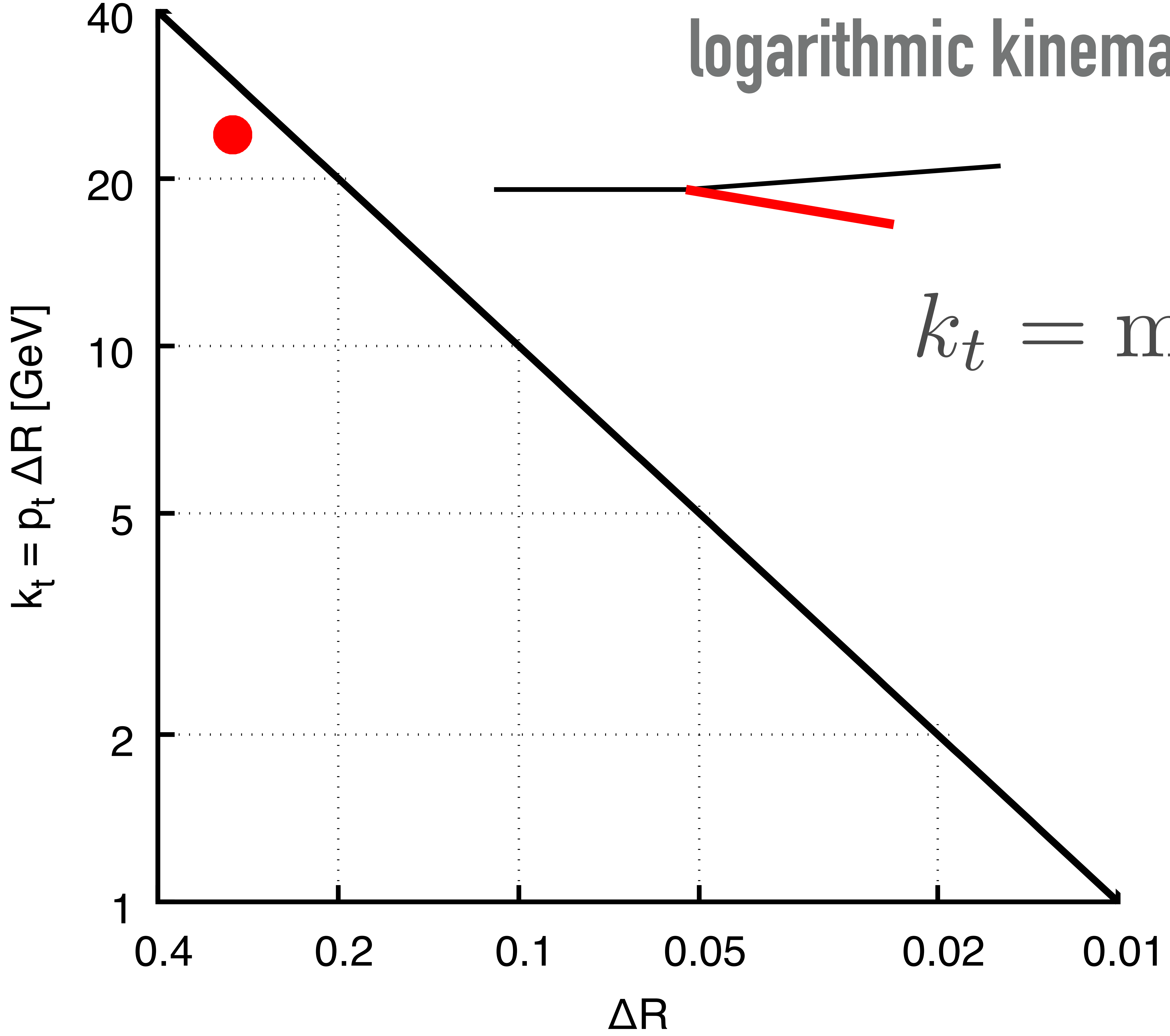

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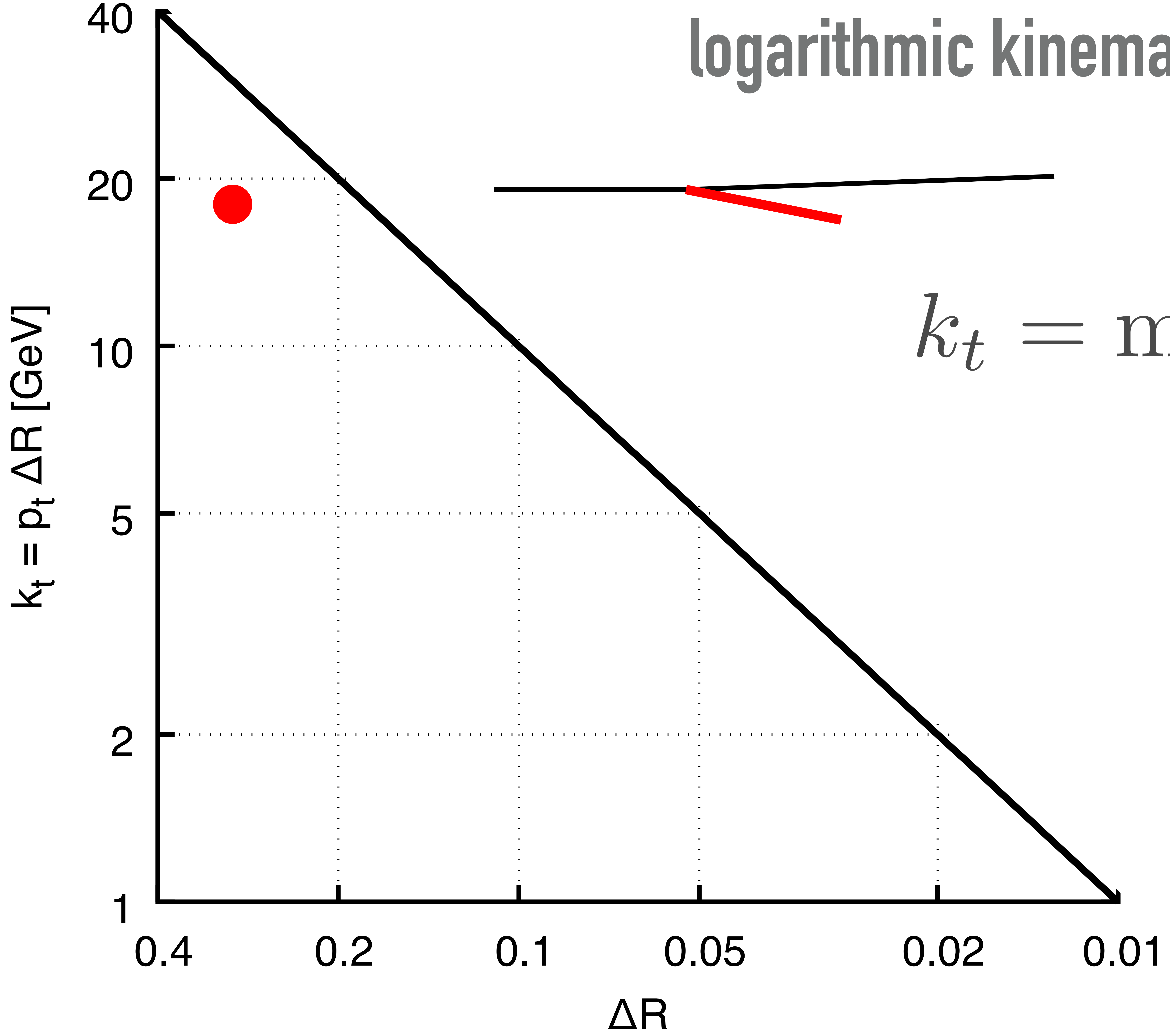

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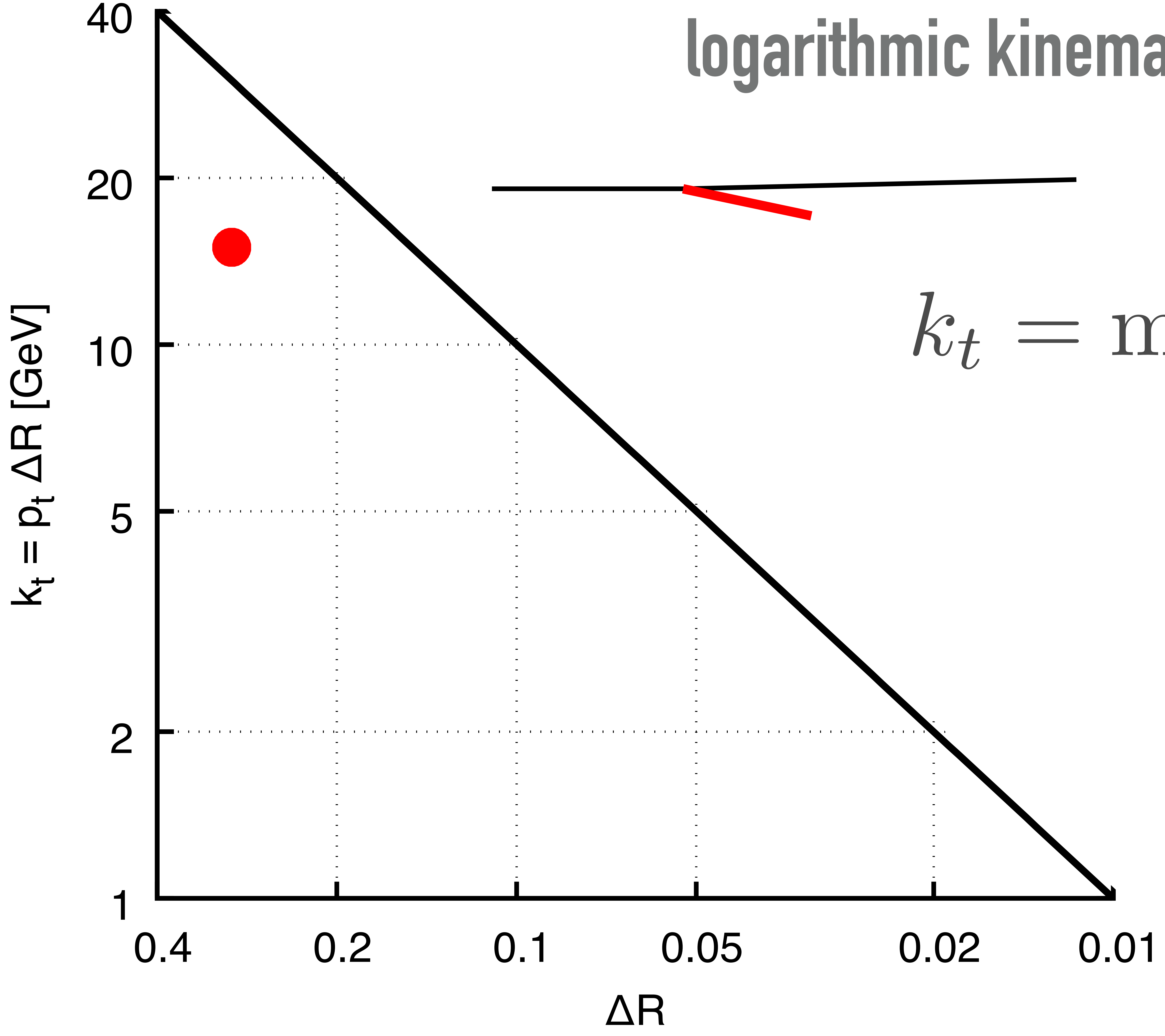

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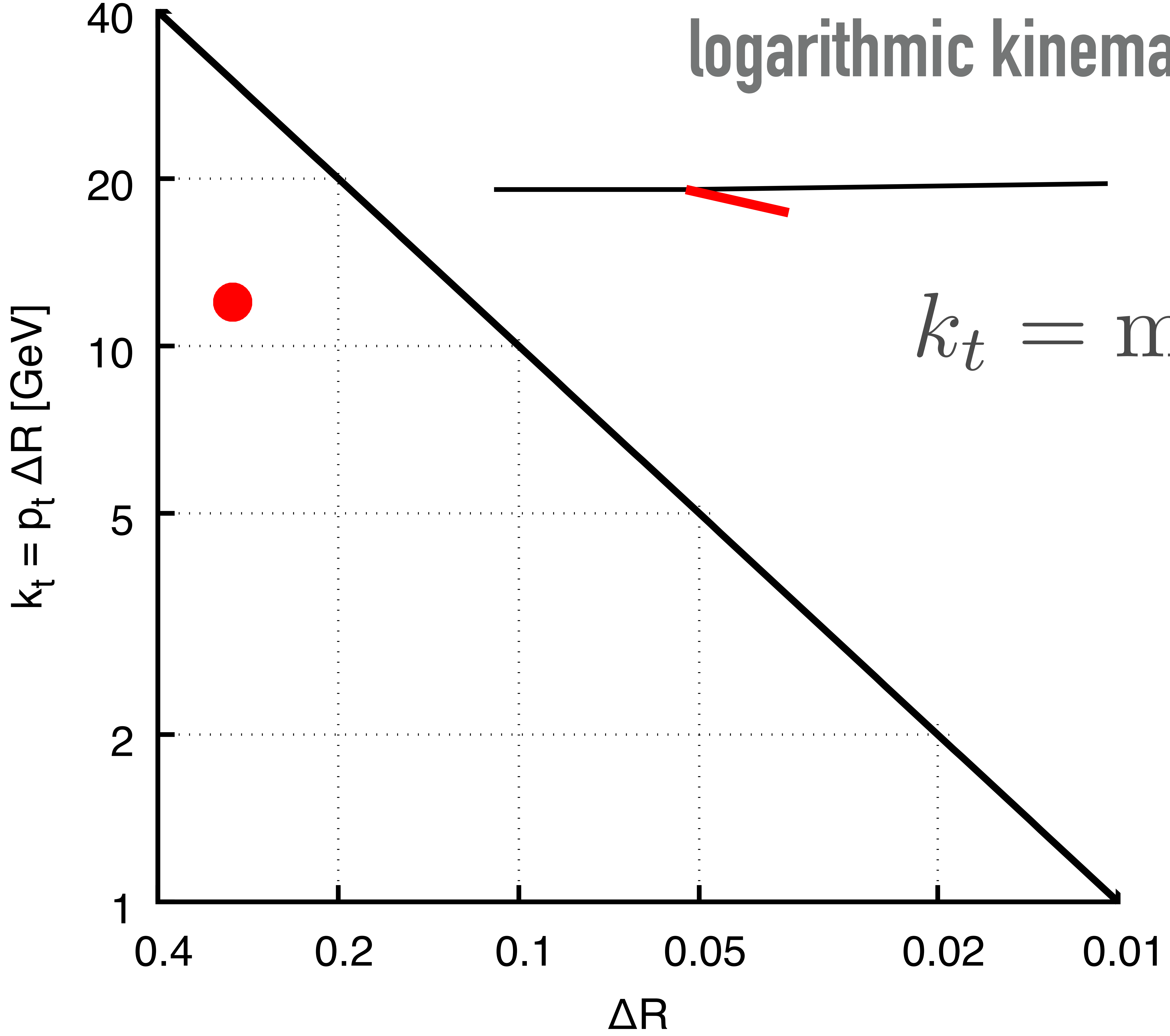

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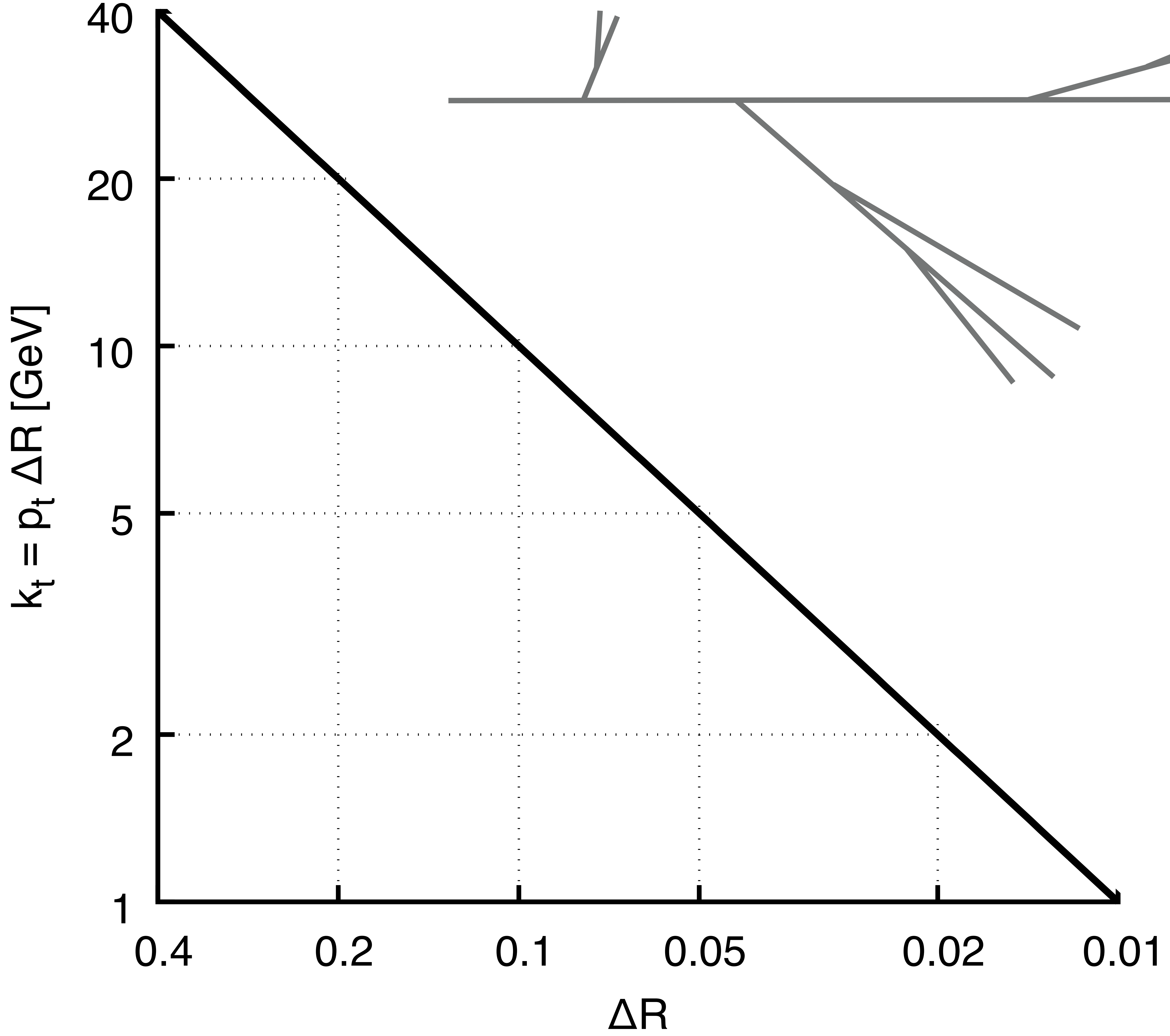
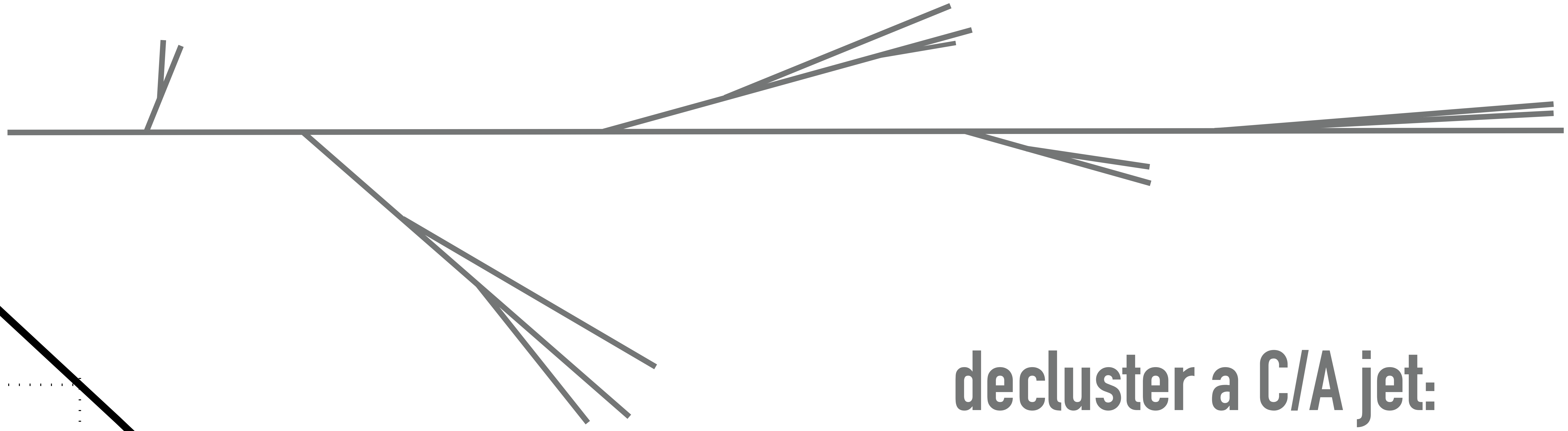


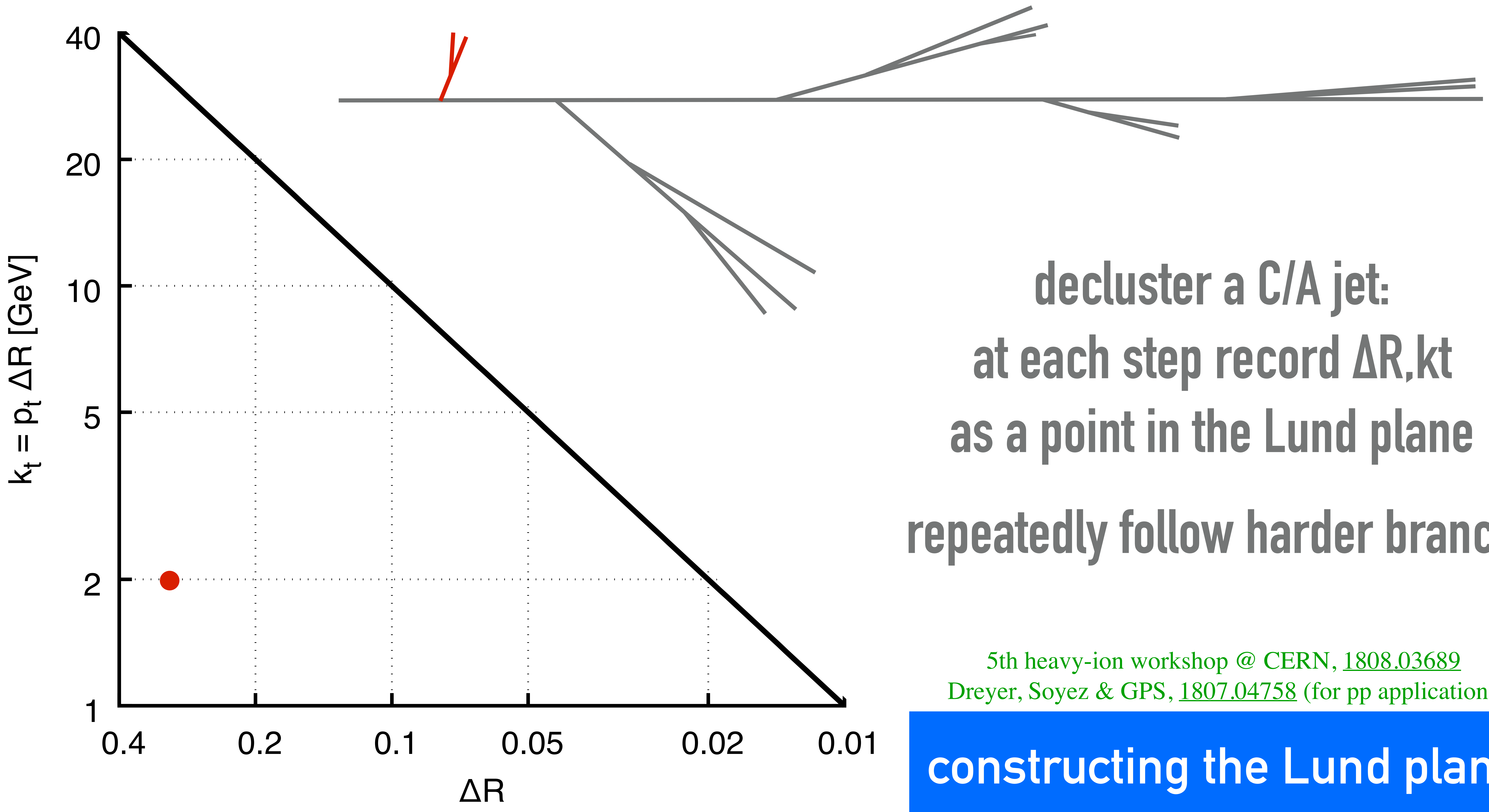


decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane



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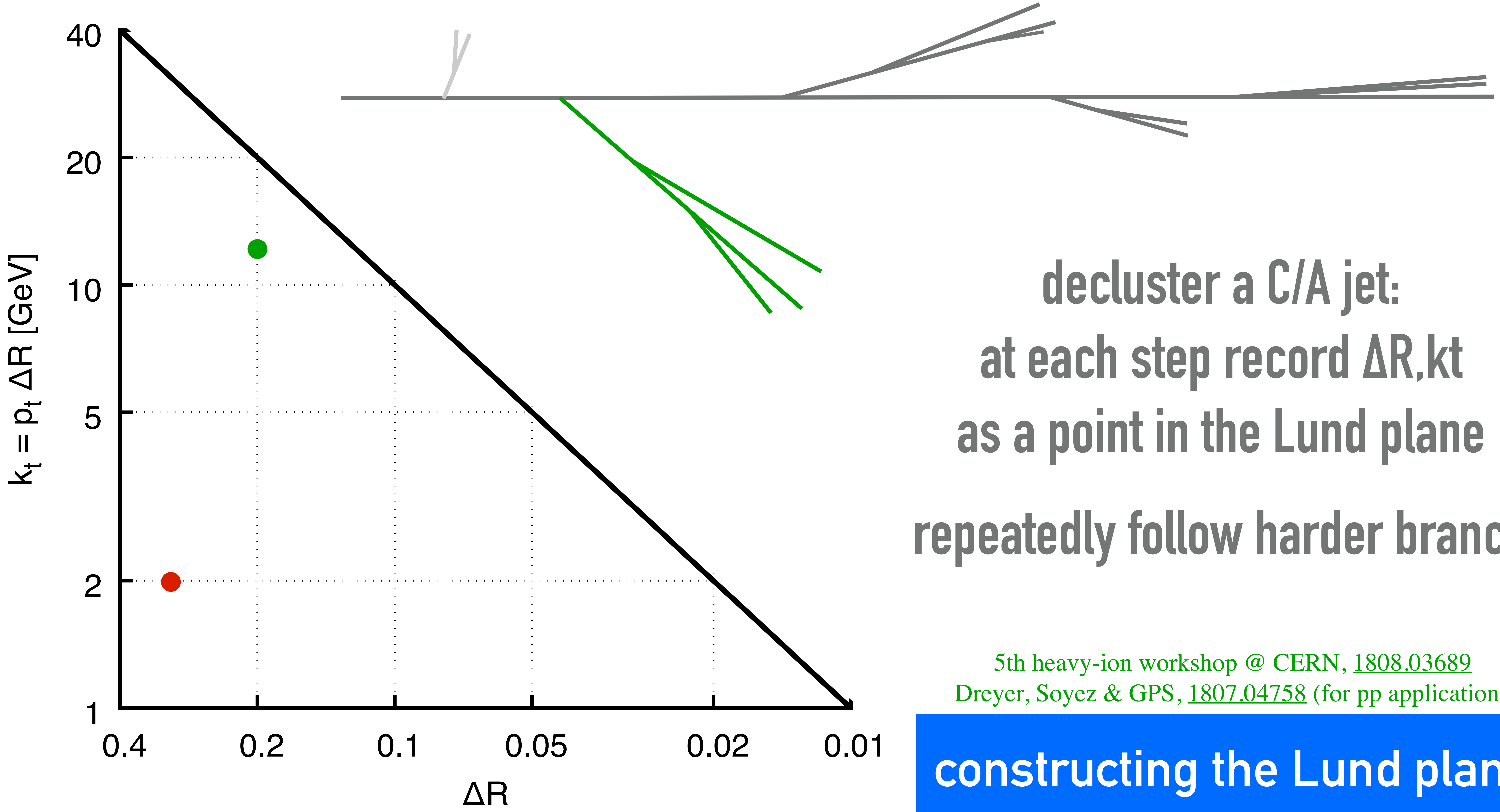

decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

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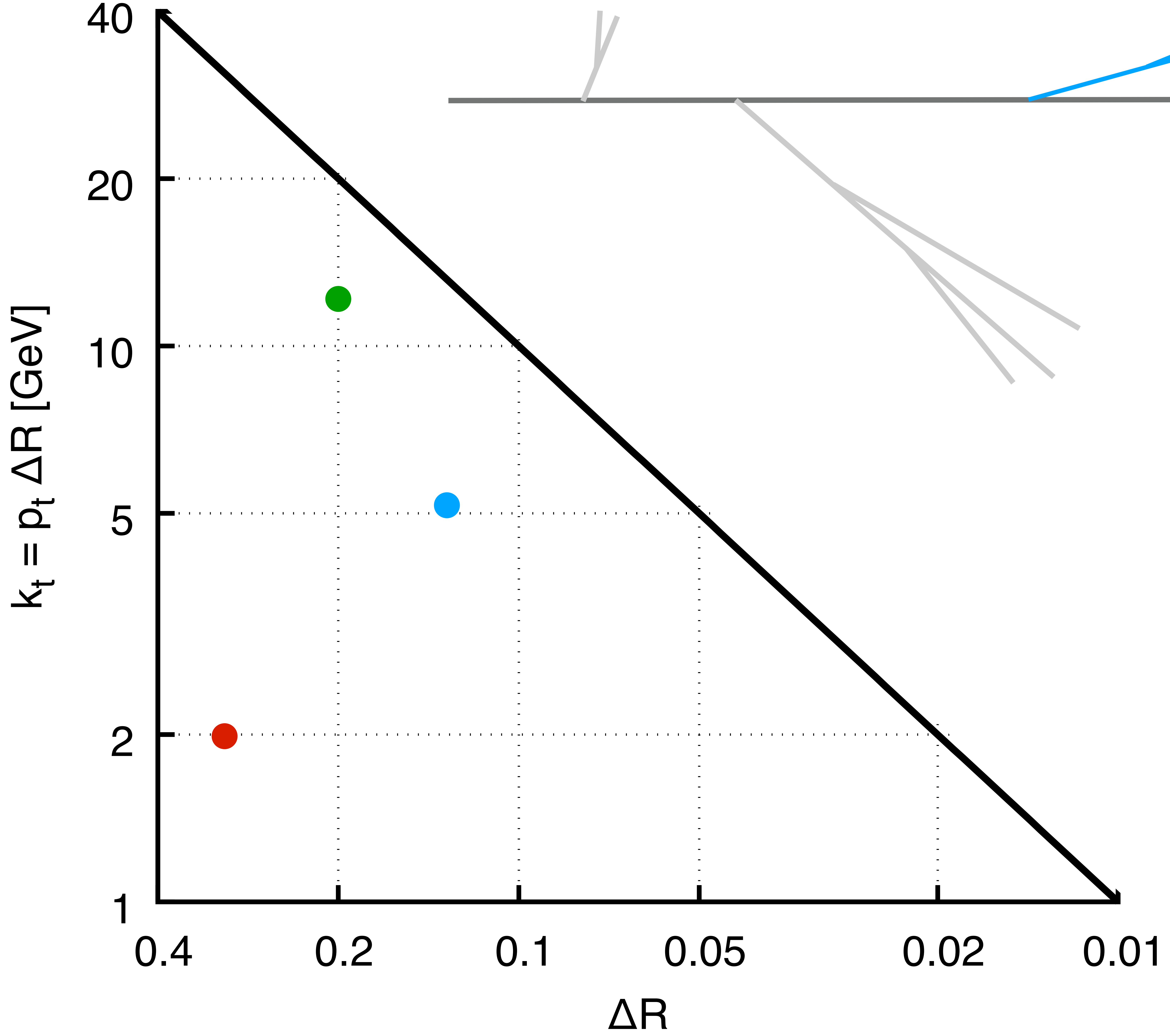

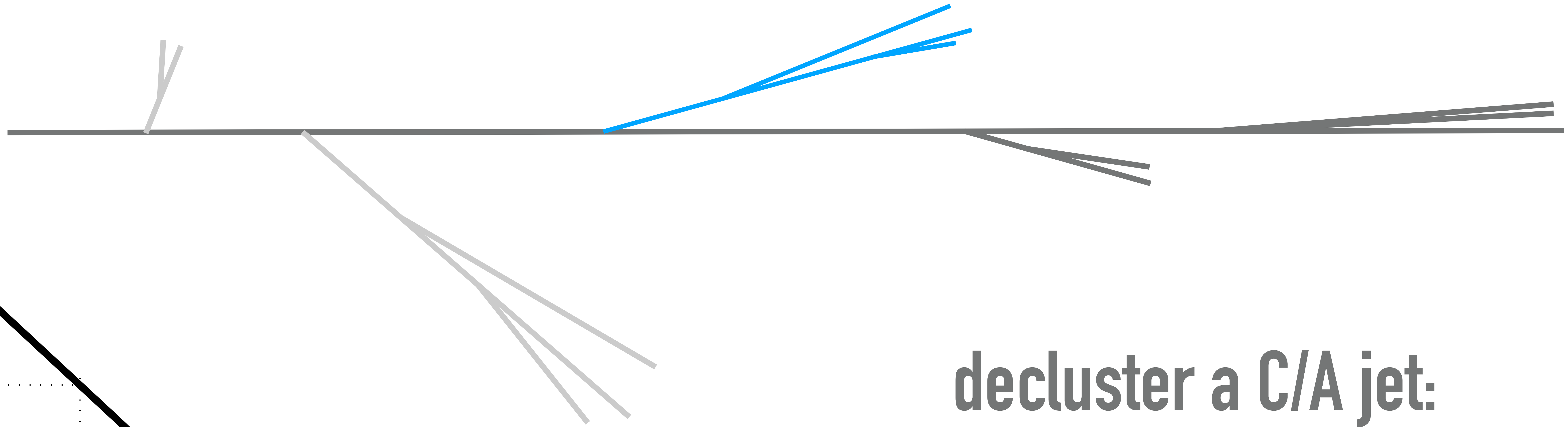

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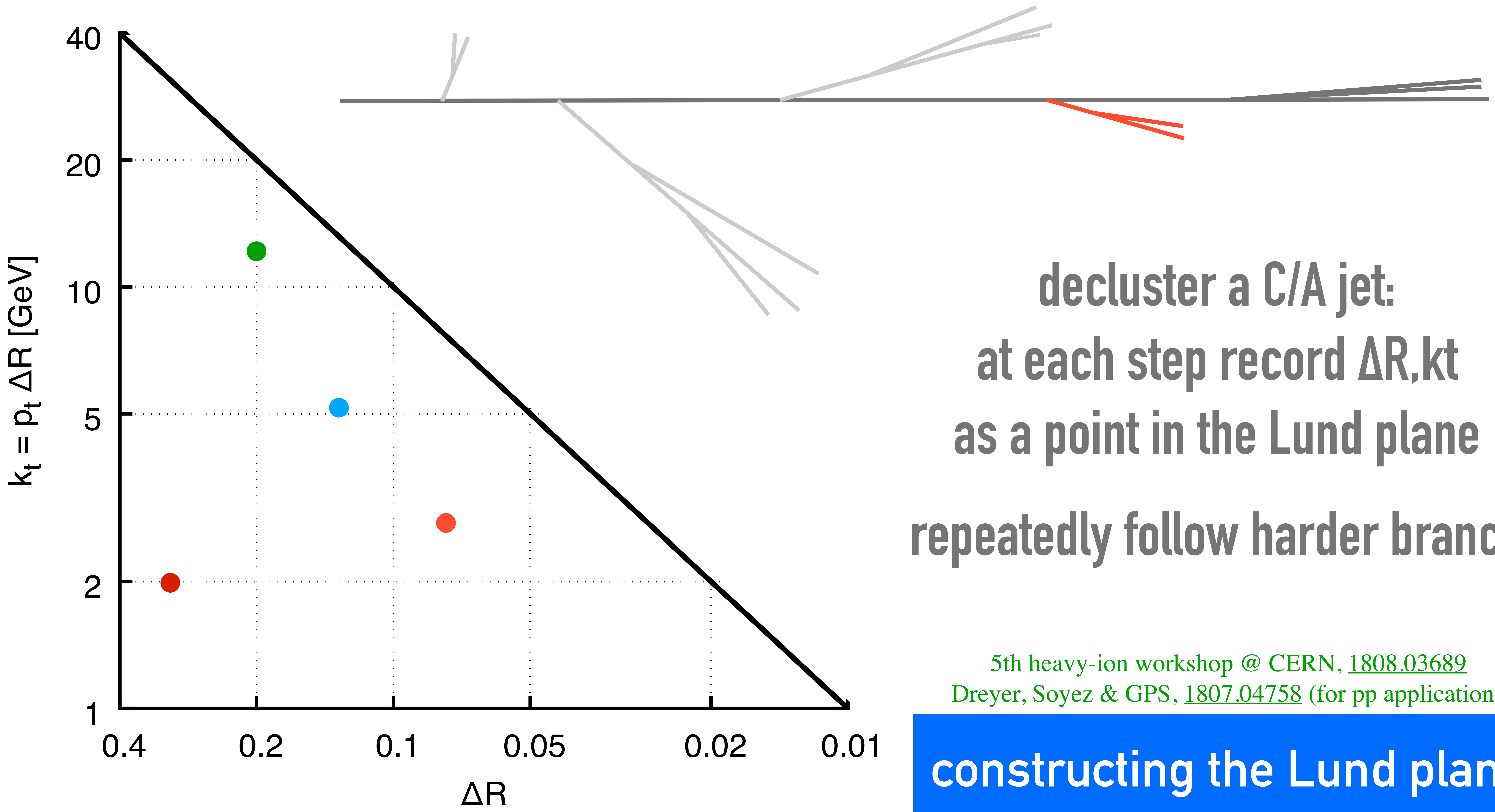

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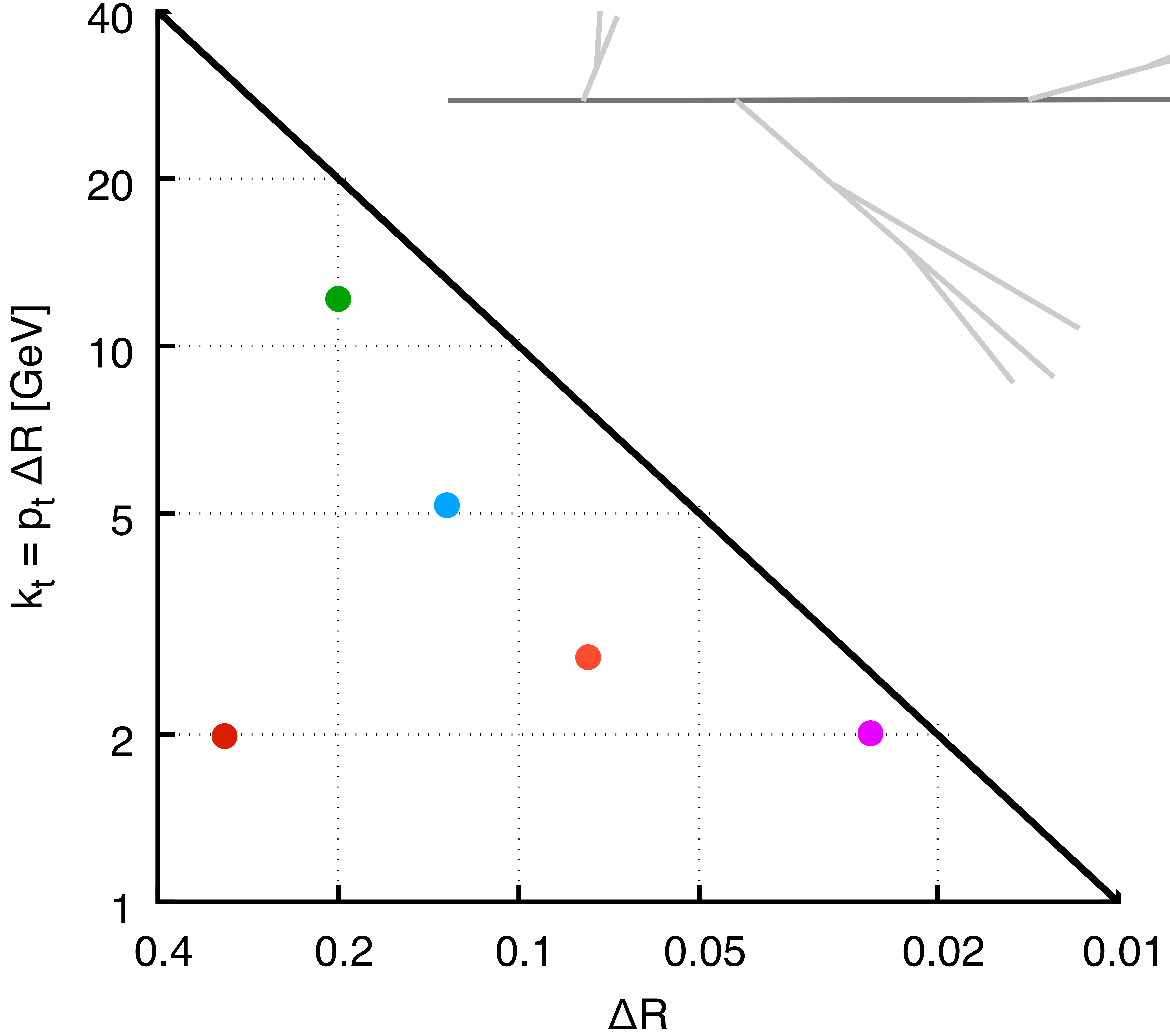

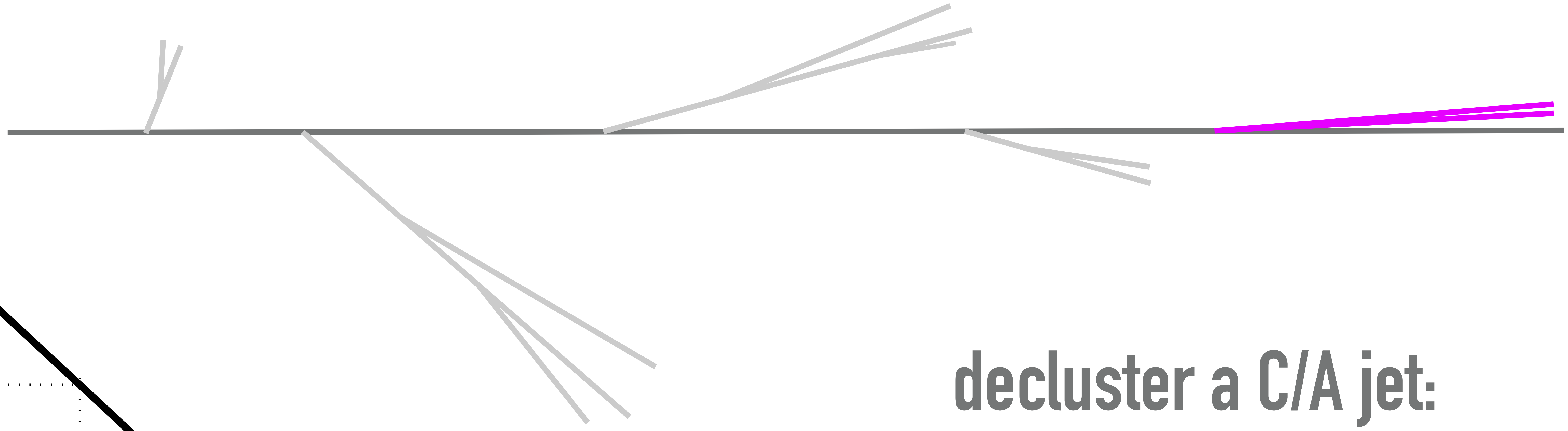

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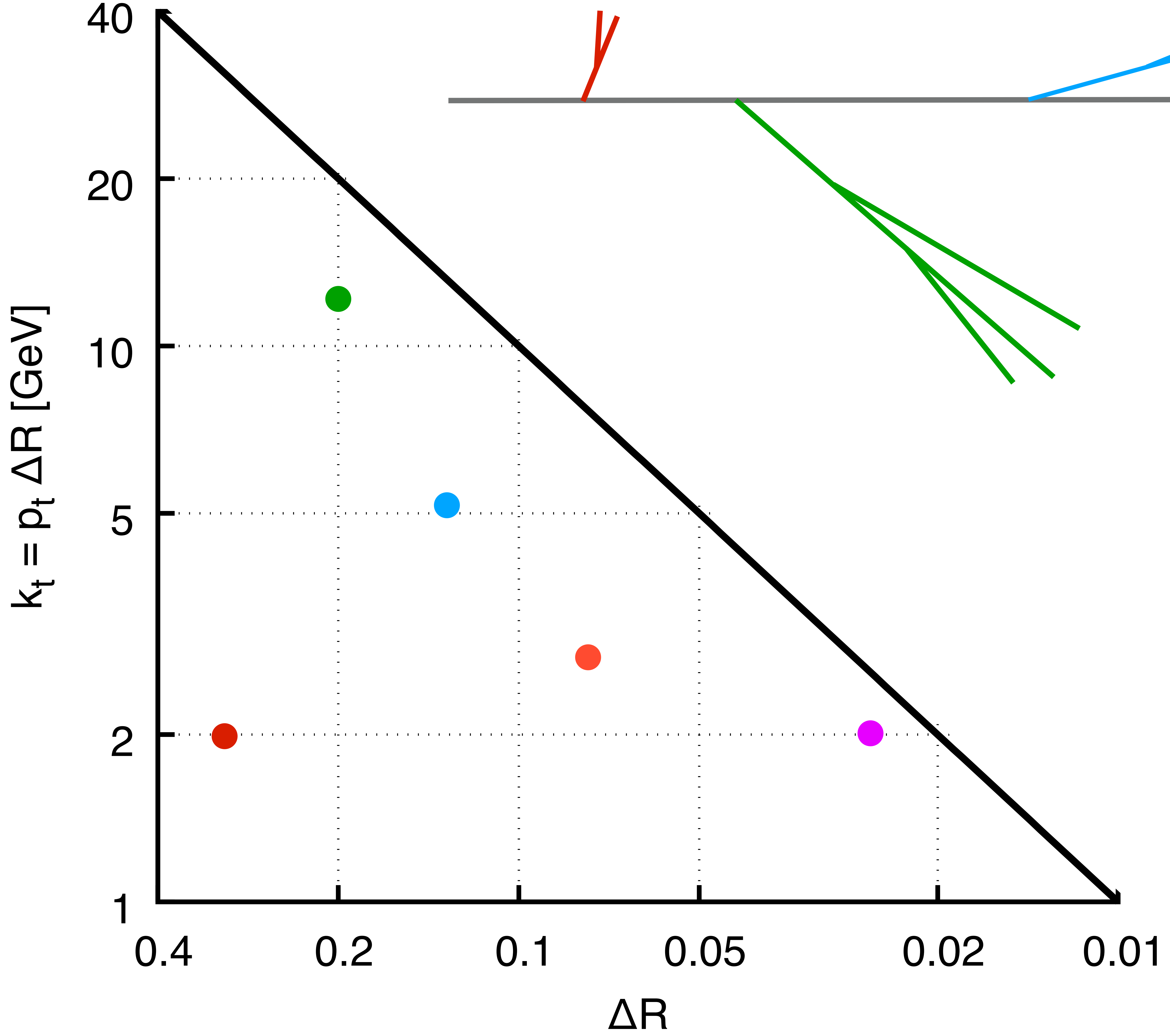

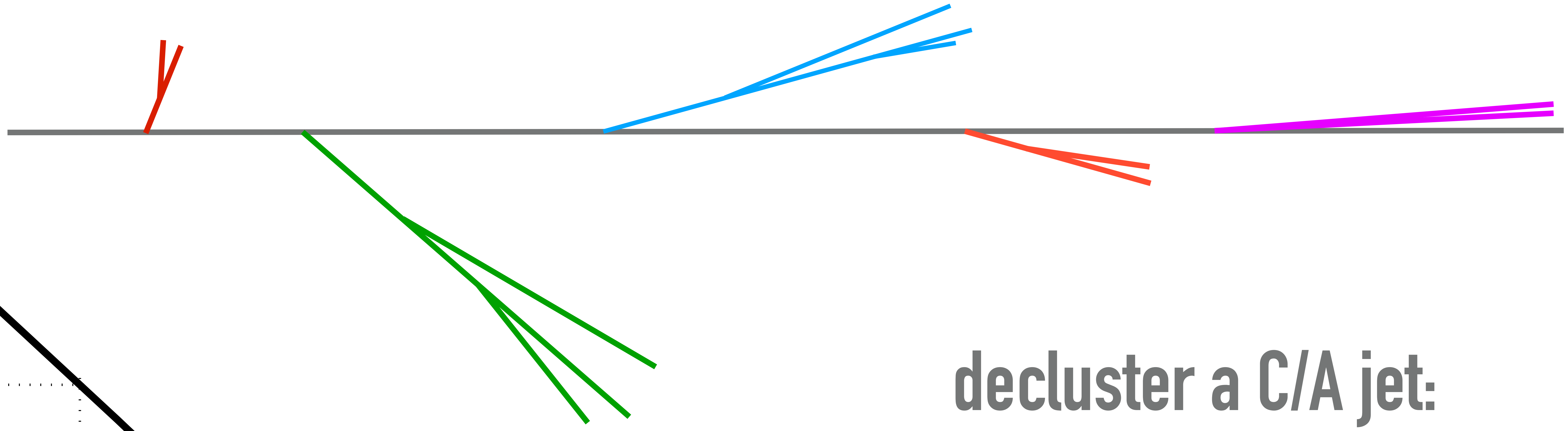

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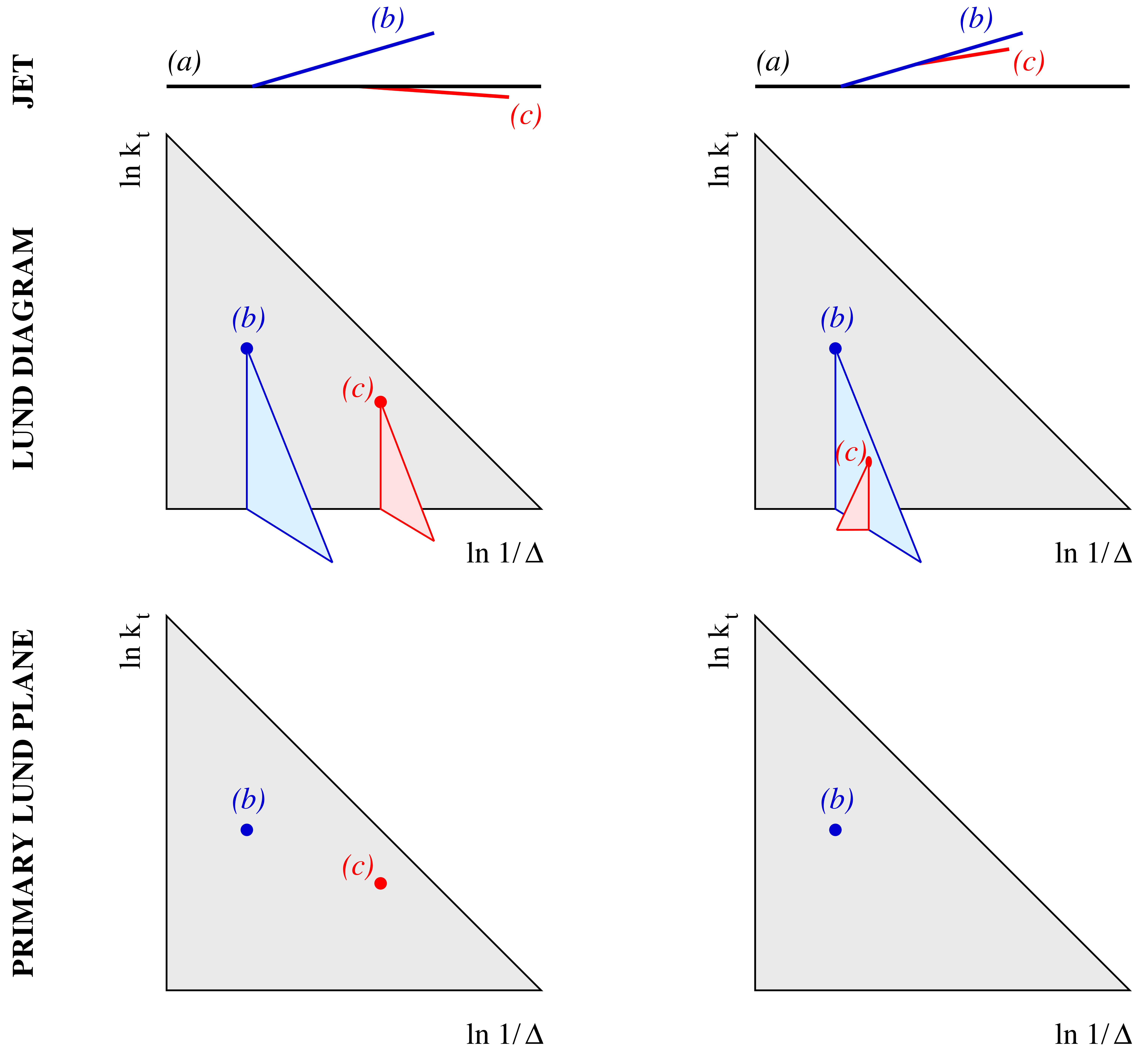
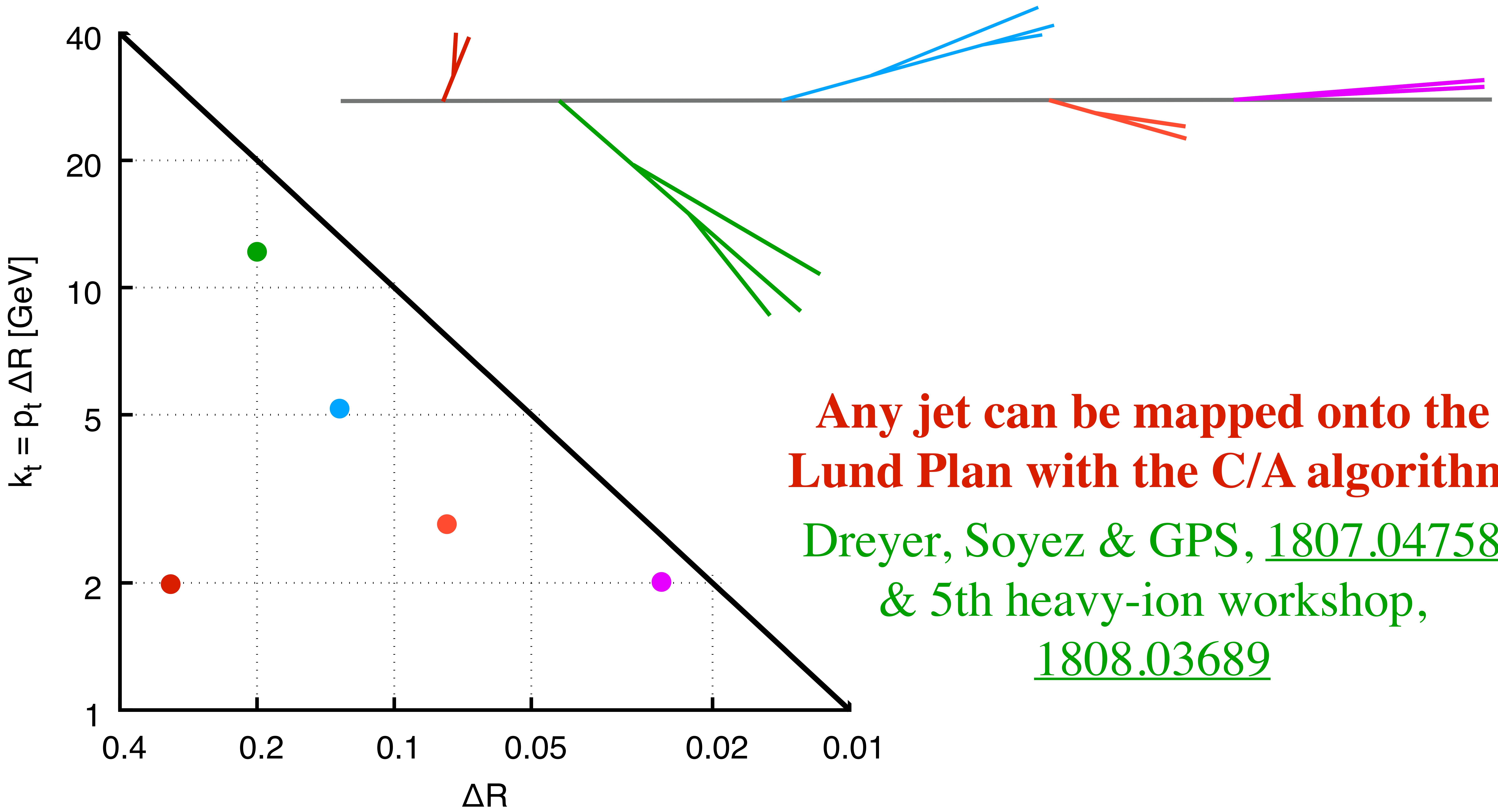
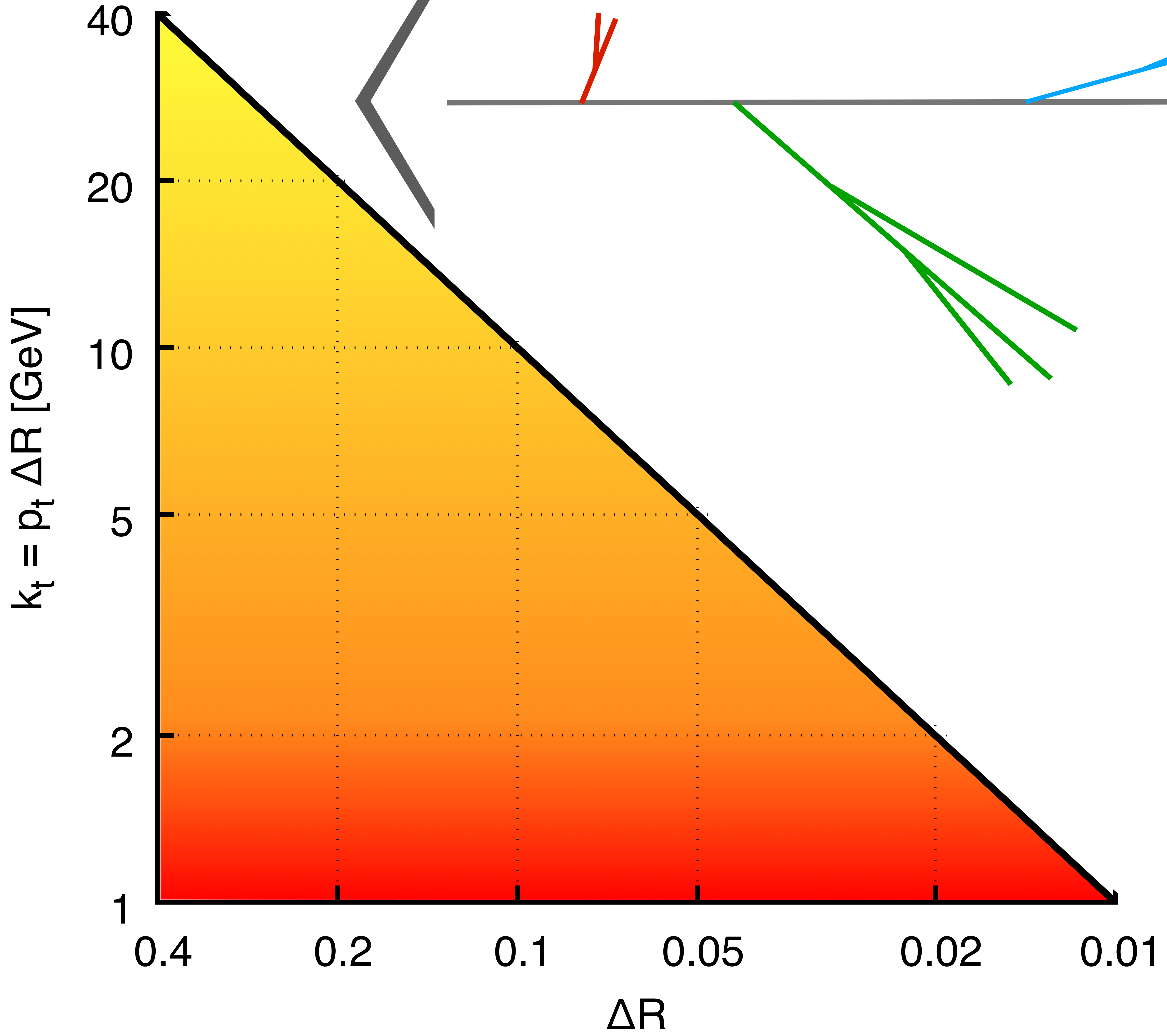
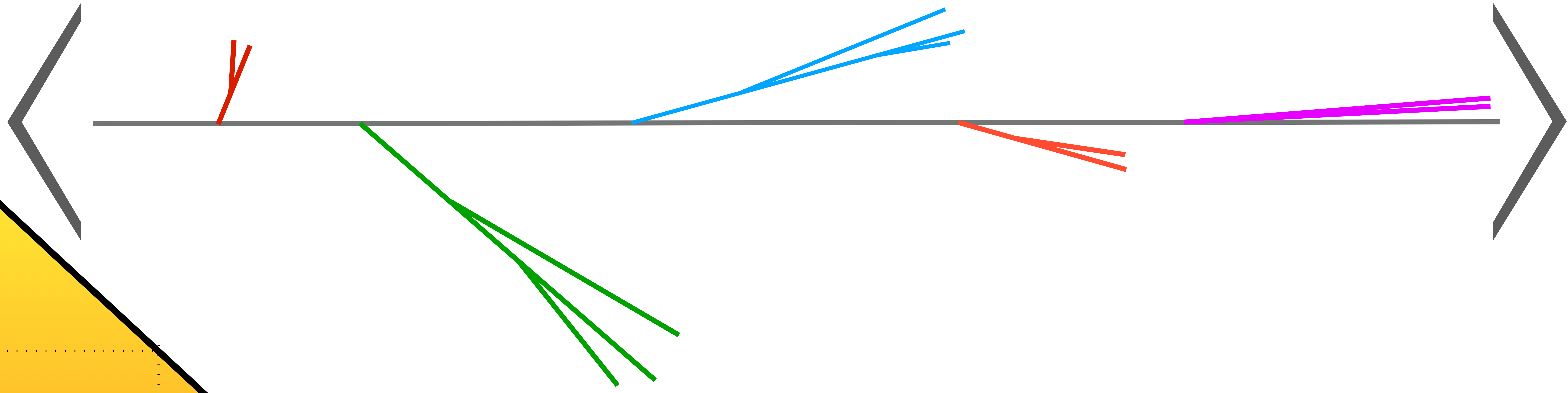

JET
LUND DIAGRAM
PRIMARY LUND PLANE
(a)
(b)
(c)
ln k_t
ln 1/Δ



Any jet can be mapped onto the Lund Plan with the C/A algorithm

Dreyer, Soyez & GPS, 1807.04758 & 5th heavy-ion workshop, 1808.03689 *jet with R = 0.4, p_t = 200 GeV*

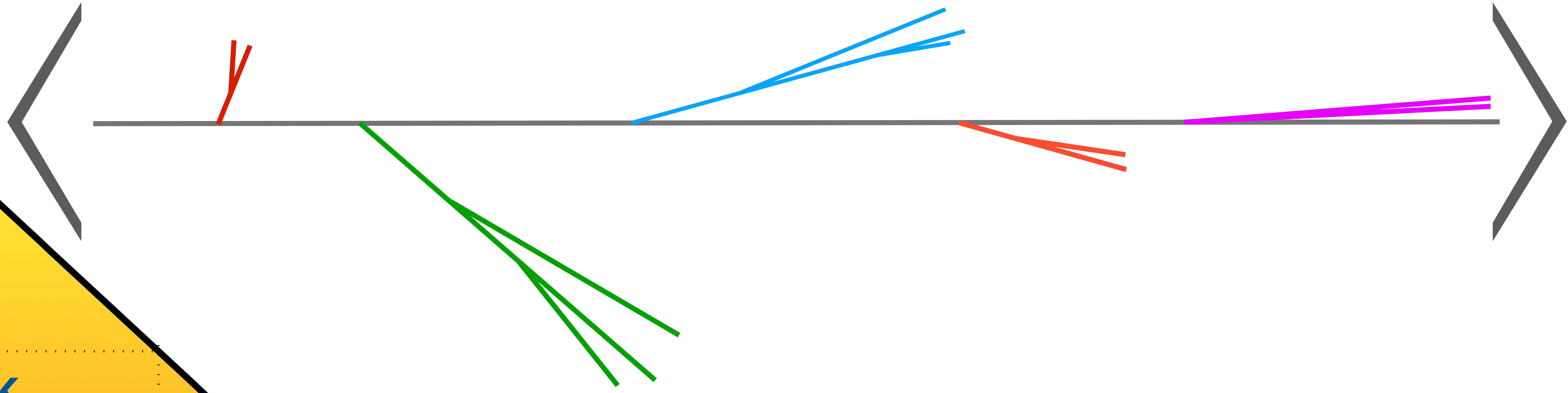


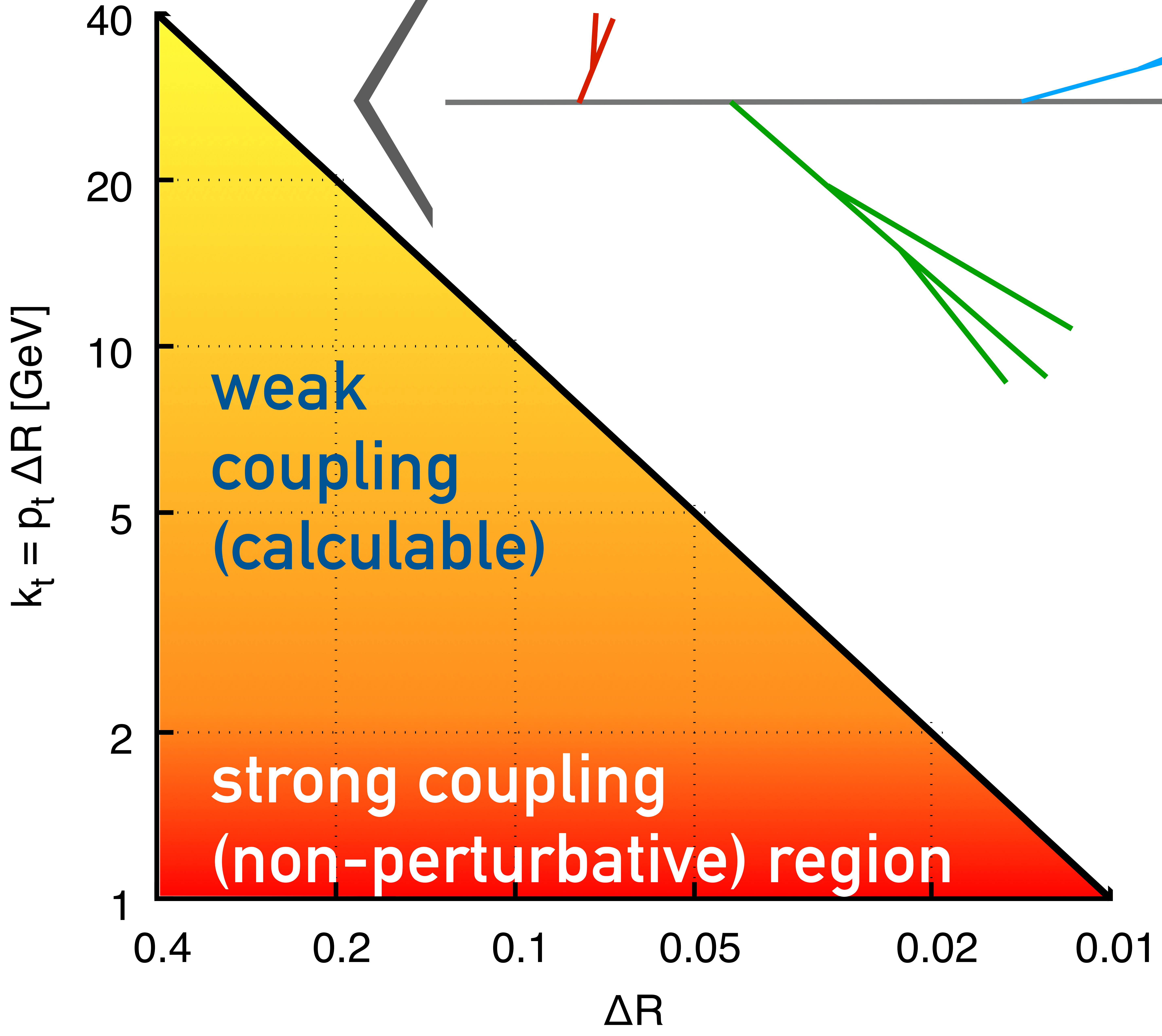


average over many jets:

Lund plane density

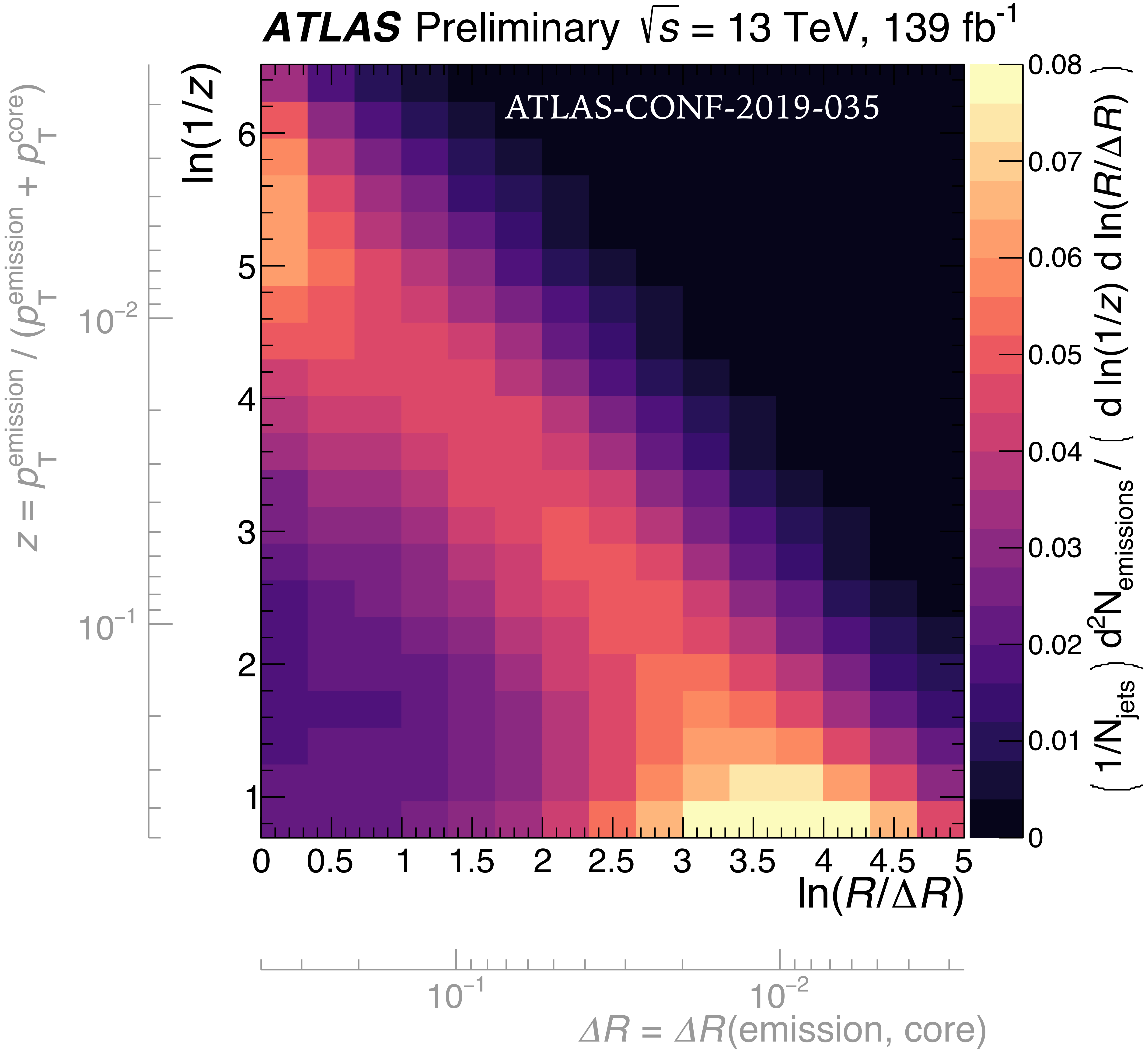
jet with $R = 0.4$, $p_t = 200$ GeV

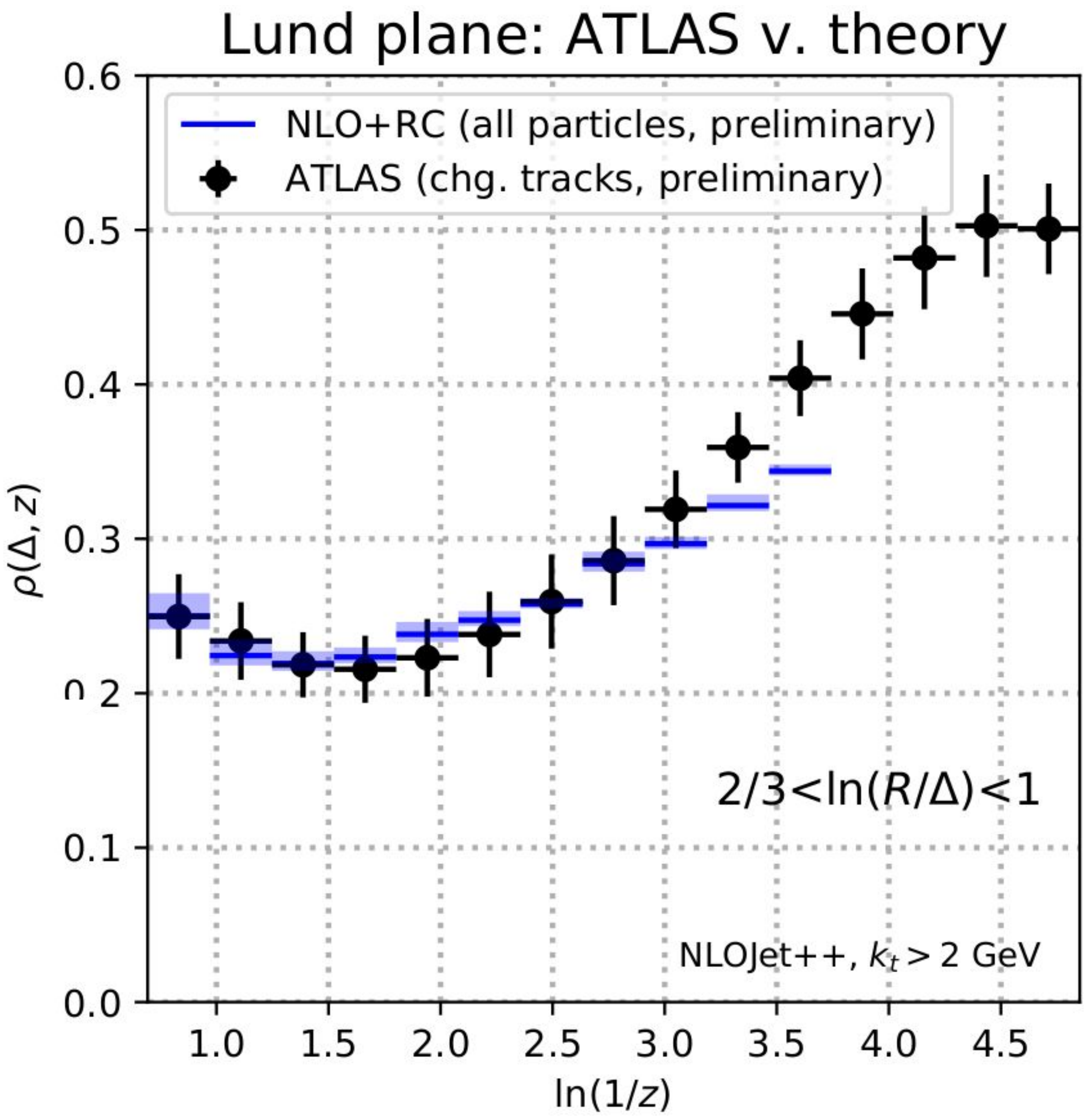




average over many jets:
Lund plane density

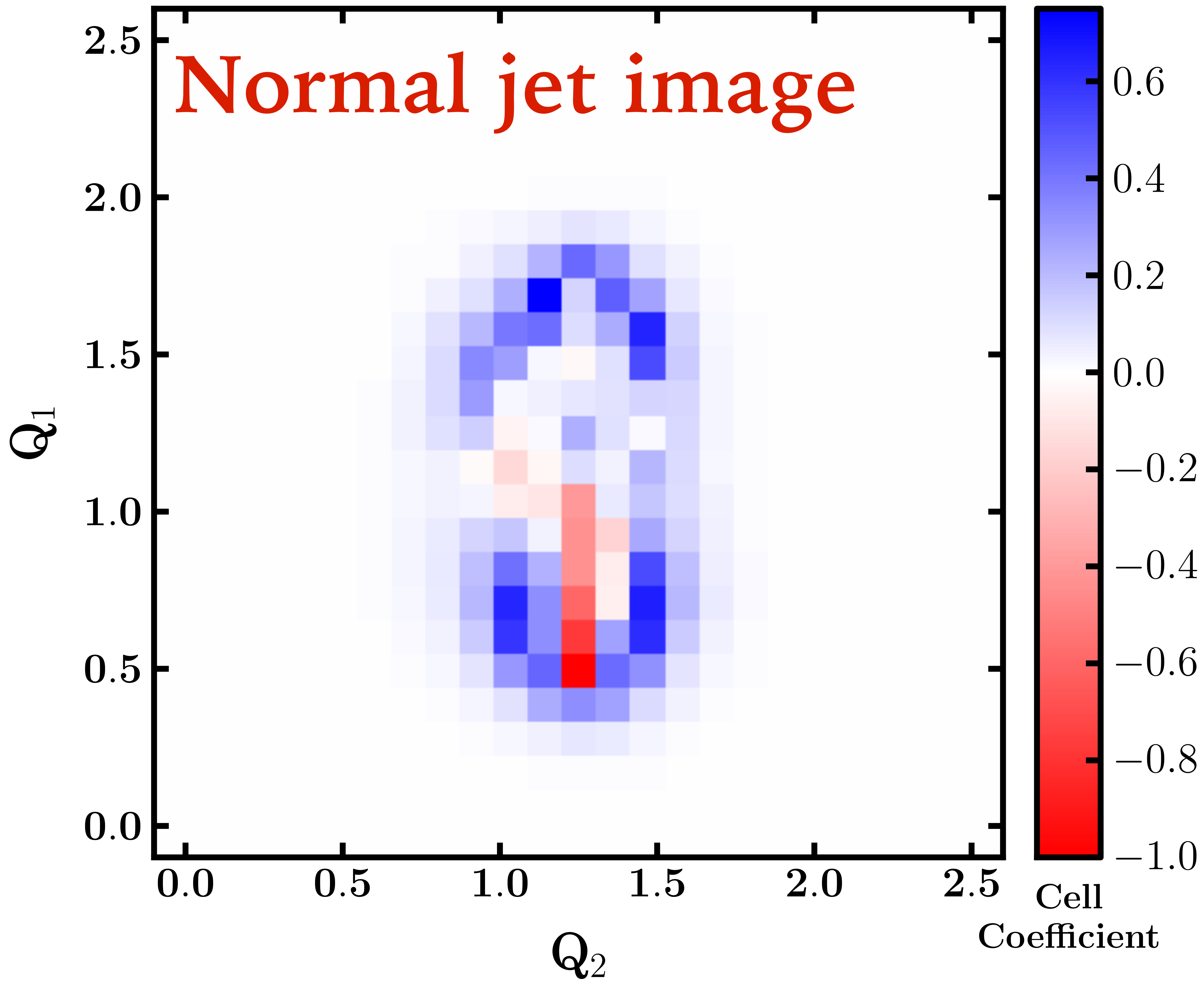
Lund plane measurement



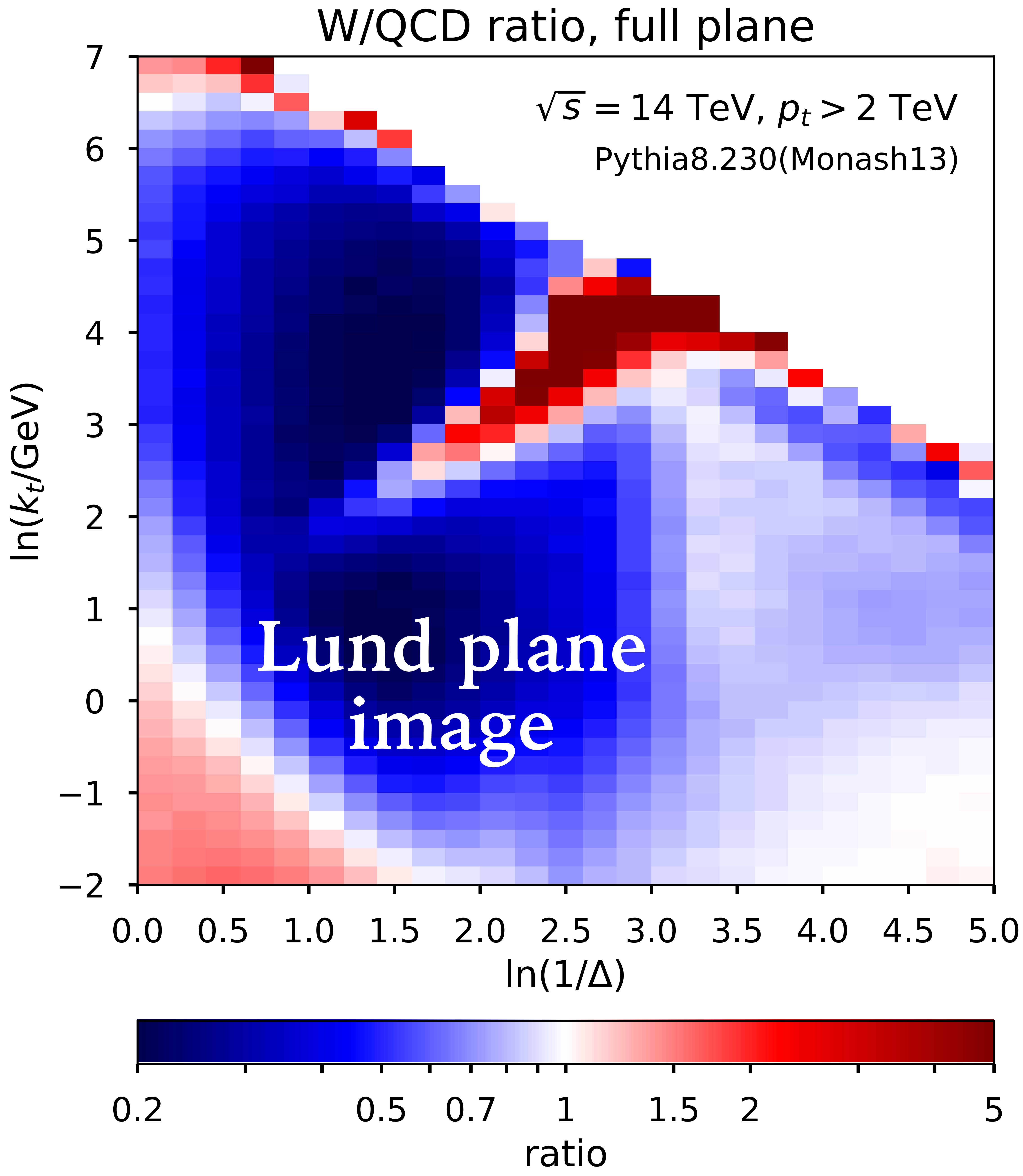


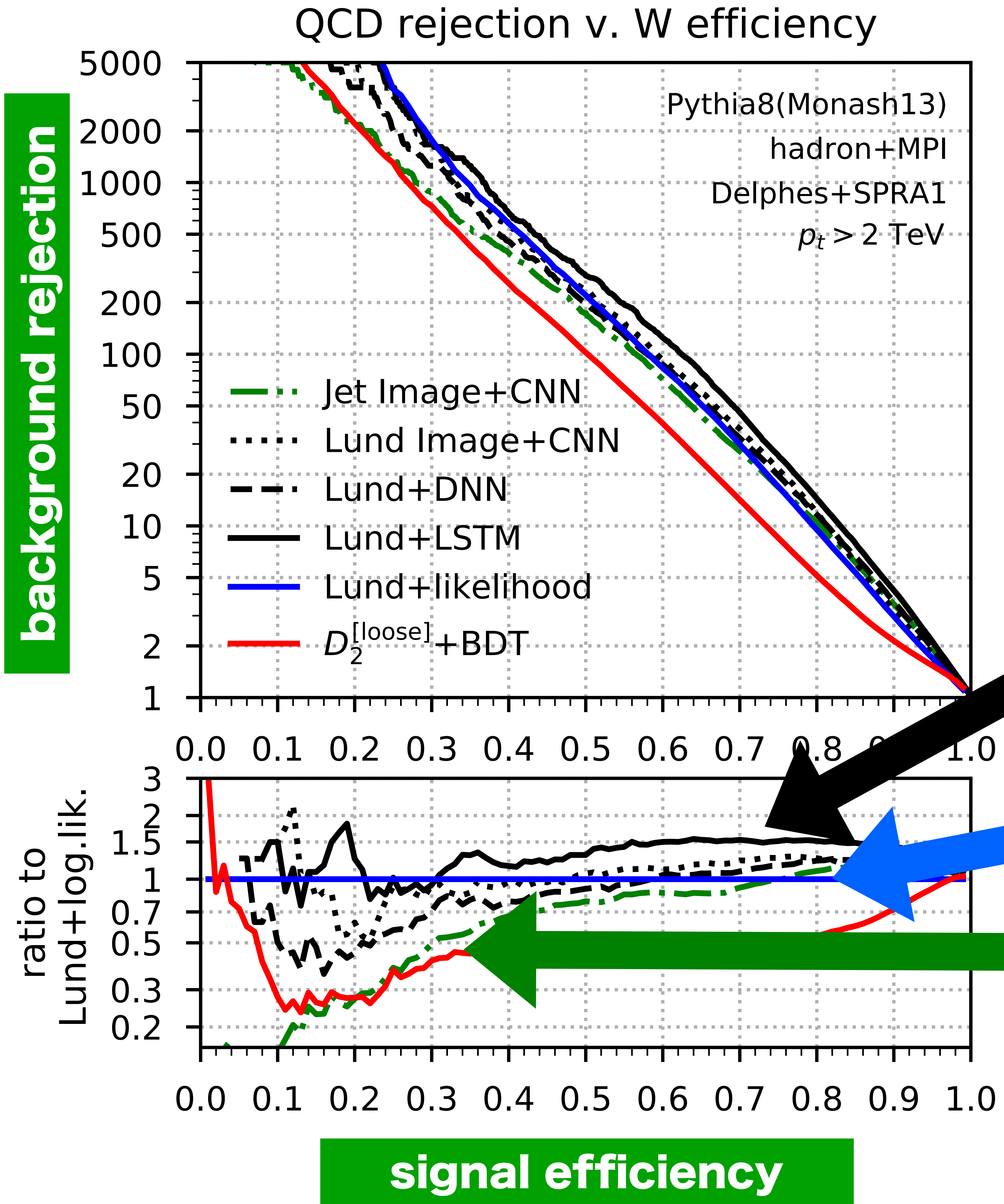
Dreyer & Soyez prelim @Boost 2019

W-boson (~H-boson) v. normal jets



Cogan, Kagan, Strauss, Schwartzman, 1407.5674





Performance: background rejection v. signal efficiency

Lund + machine-learning (LSTM)
up to twice the bkgd rejection compared to non-Lund methods

Lund info without machine learning

Jet image + CNN

can we trust machine learning? A question of confidence in the training…

“

Unless you are highly confident in the information you have about the markets, you may be better off ignoring it altogether

- Harry Markowitz (1990 Nobel Prize in Economics)

[via S Gukov]

understanding parton showers, the core simulation tool

(& machine-learning training tool)

illustrate with dipole / antenna showers

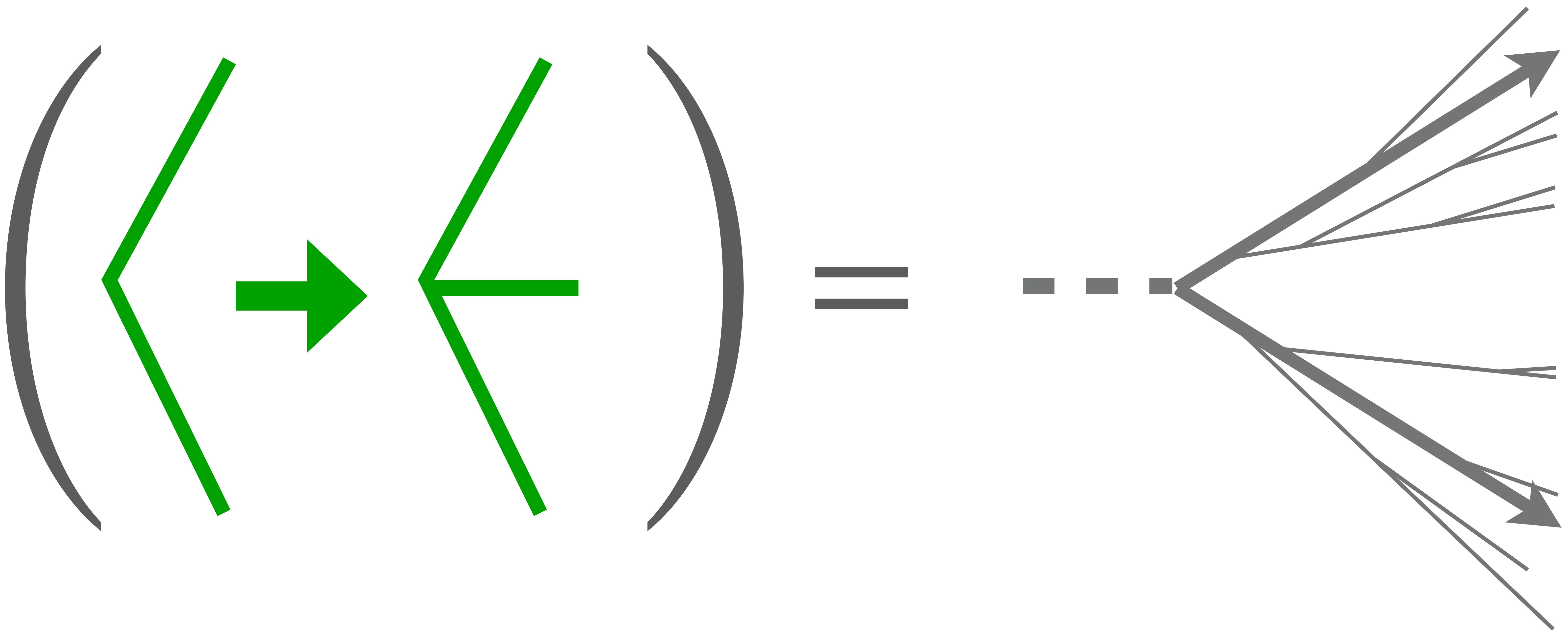
Gustafson & Pettersson 1988, Ariadne 1992, main Sherpa & Pythia8 showers, option in Herwig7, Vincia shower & (partially) Deductor shower

results from Dasgupta, Dreyer, Hamilton, Monni & GPS, 1805.09327

[using an approach pioneered by Banfi, Corcella, Dasgupta, hep-ph/0612282 for angular-ordered showers; *see also Bewick, Ravasio-Ferrario, Richardson & Seymour 1904.11866]*

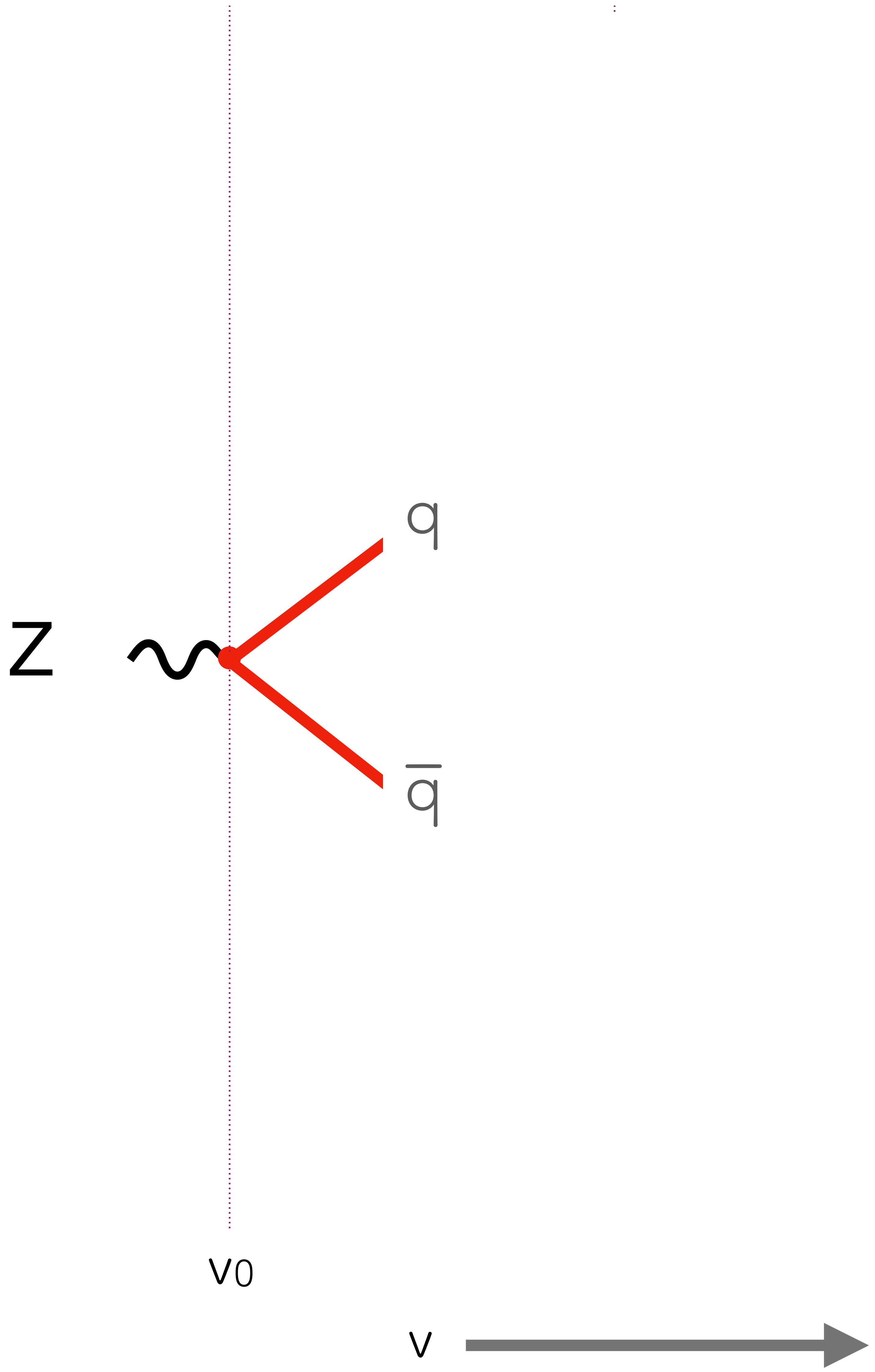
A parton shower, at its simplest

$$\sum_{n=0}^{\infty}\prod_{i=1}^{n}$$



iteration of 2→3 (or 1→2) splitting kernel

in practice: an evolution equation (in evolution scale v, e.g. 1/trans.mom.)

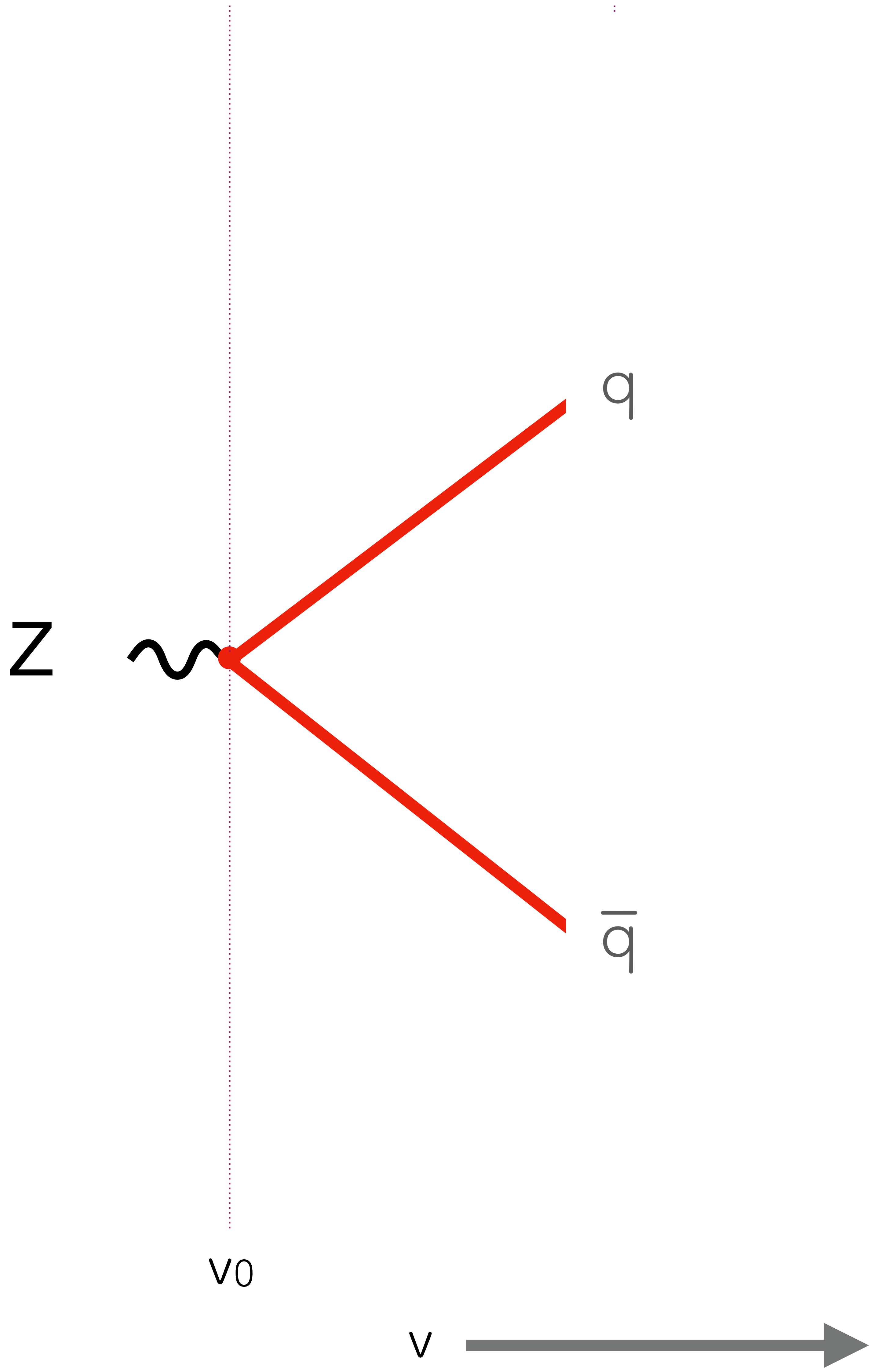


Start with q-qbar state.

Evolve a step in v and throw a random number to decide if state remains unchanged

$$\frac{dP_2(v)}{dv} = -f^{q\bar{q}}_{2\to 3}(v)\, P_2(v)$$

in practice: an evolution equation (in evolution scale v, e.g. 1/trans.mom.)



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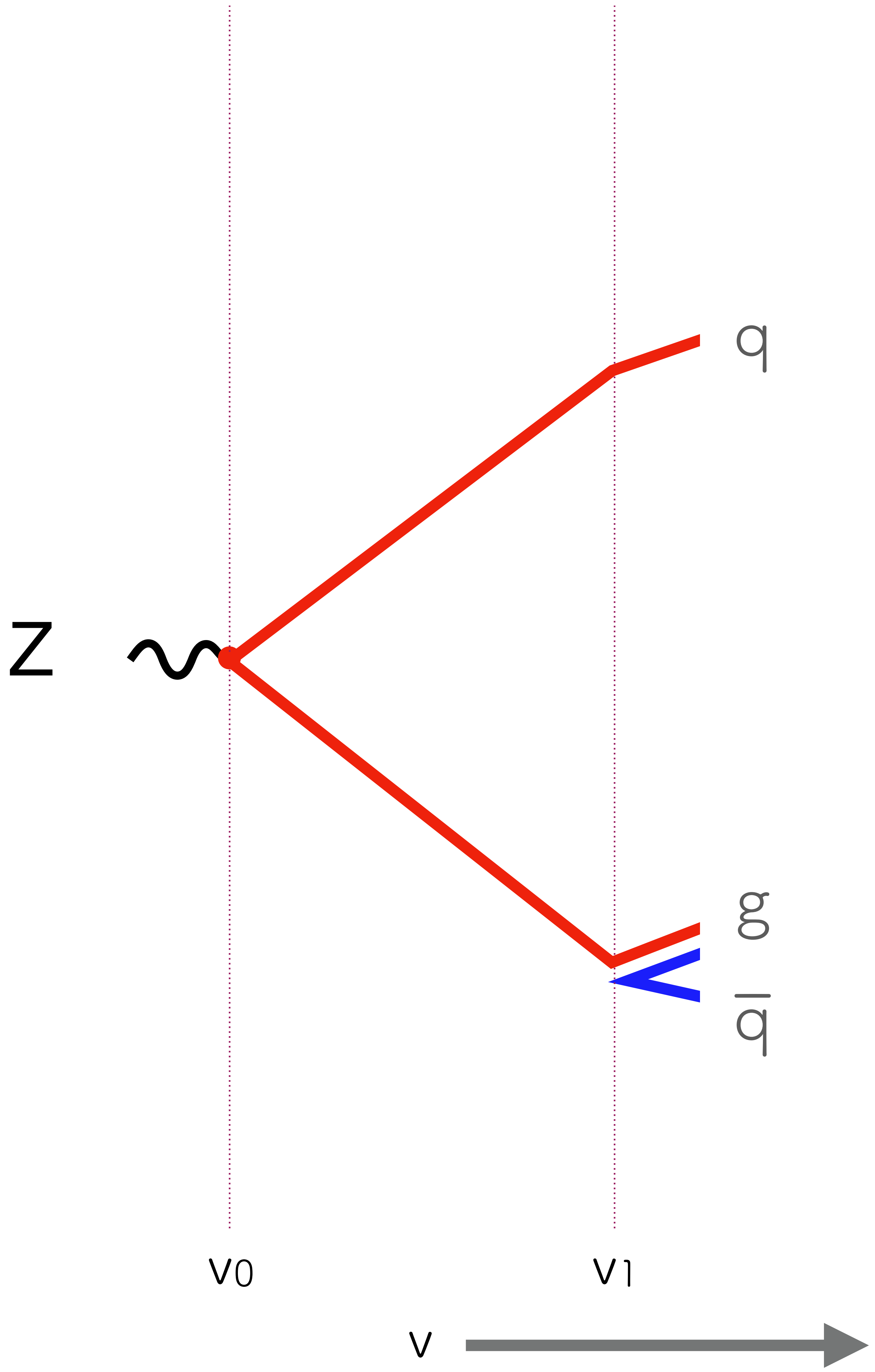


Start with q-qbar state.

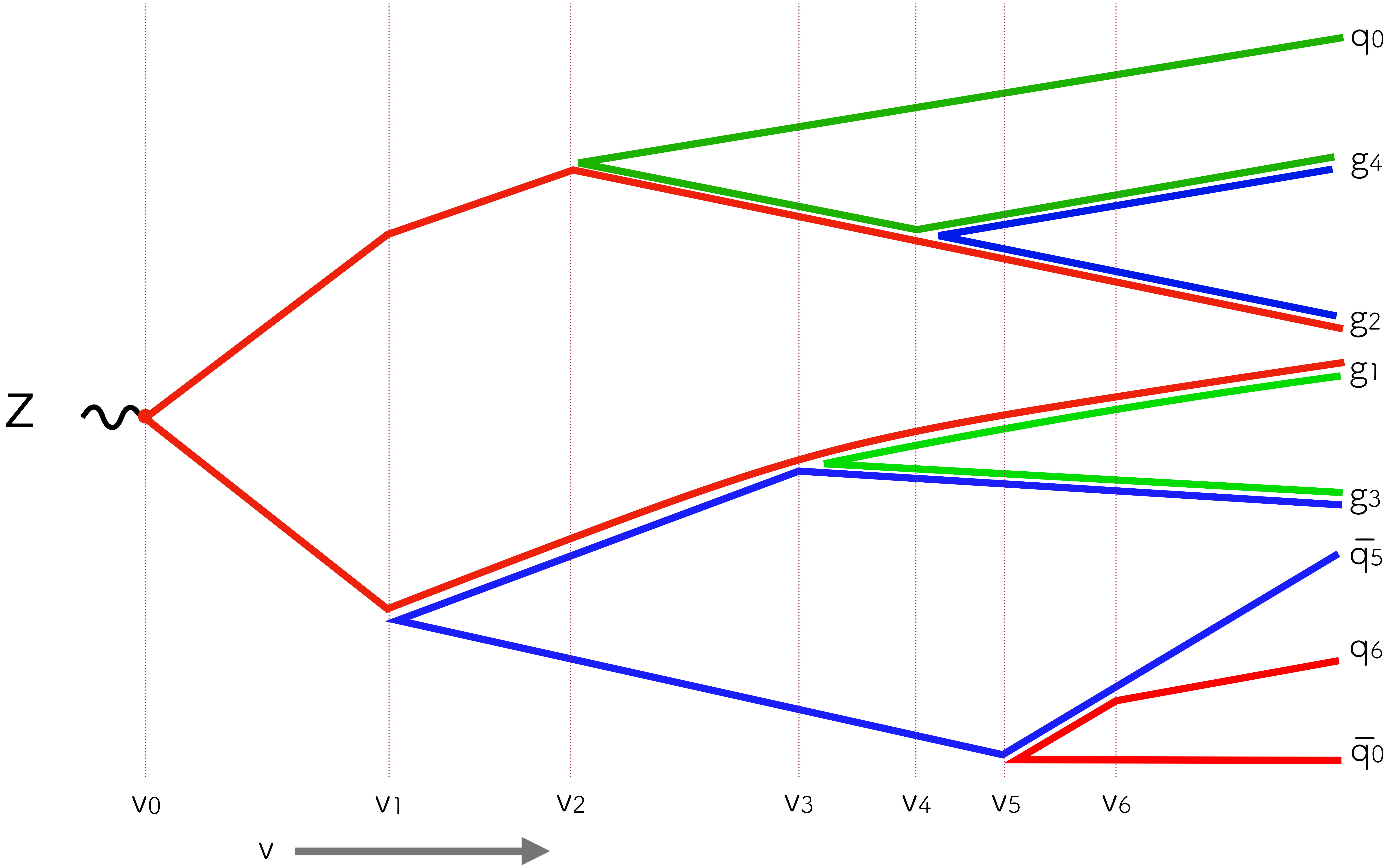
Evolve a step in v and throw a random number to decide if state remains unchanged

At some point, rand.numb. is such that **state splits** (2→3, i.e. emits gluon). Evolution equation changes

$$\frac{dP_3(v)}{dv} = -\left[f^{qg}_{2\to 3}(v) + f^{g\bar{q}}_{2\to 3}(v)\right] P_3(v)$$

gluon is part of two dipoles $(qg, \bar{q}g)$

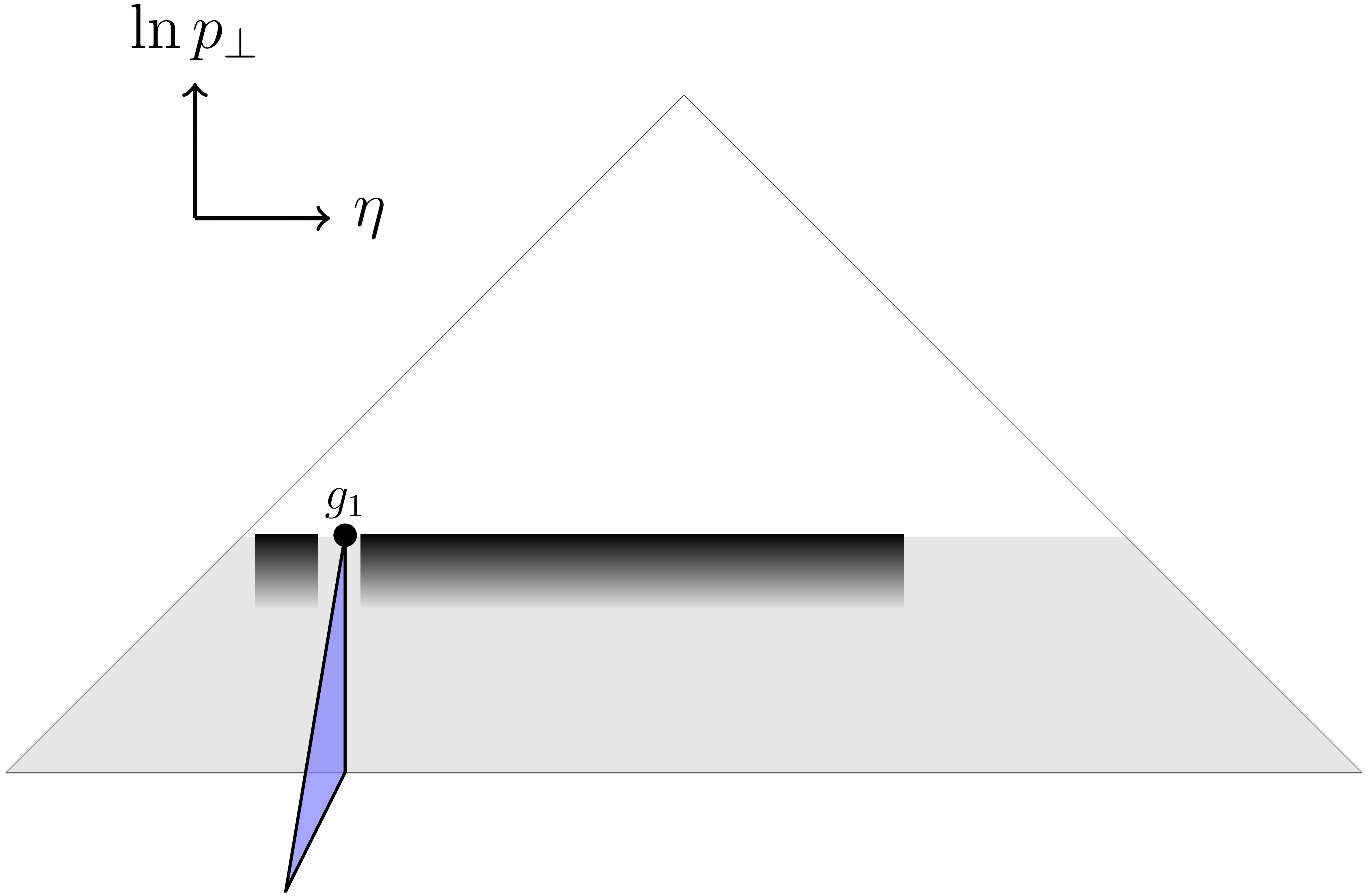
in practice: an evolution equation (in evolution scale v, e.g. 1/trans.mom.)



self-similar evolution continues until it reaches a non-perturbative scale

Does such a procedure produce the right pattern for two emissions?

Lund phasespace map



analogous effect commented on by Nagy & Soper for Drell-Yan recoil, but wider relevance not appreciated?

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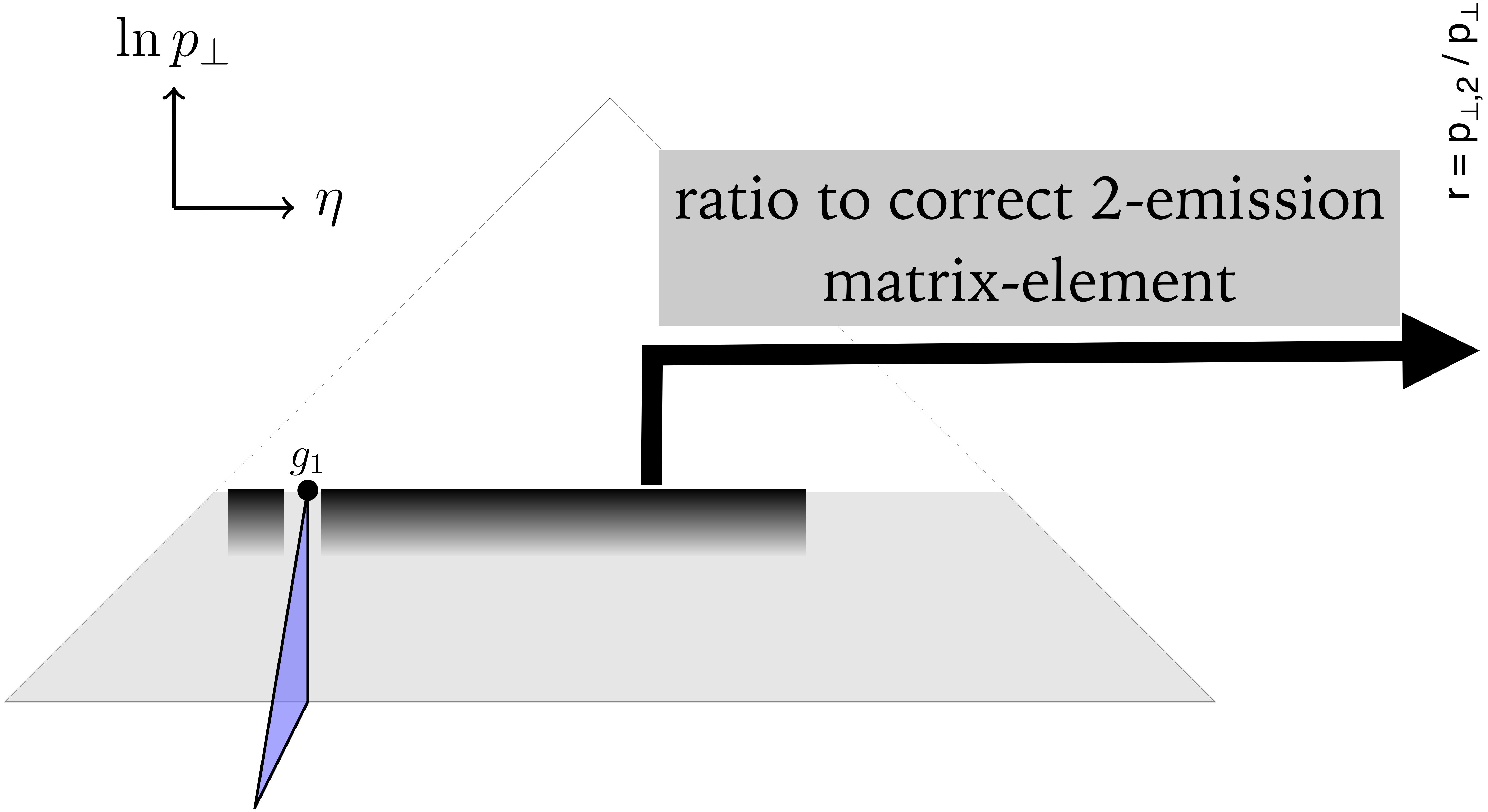

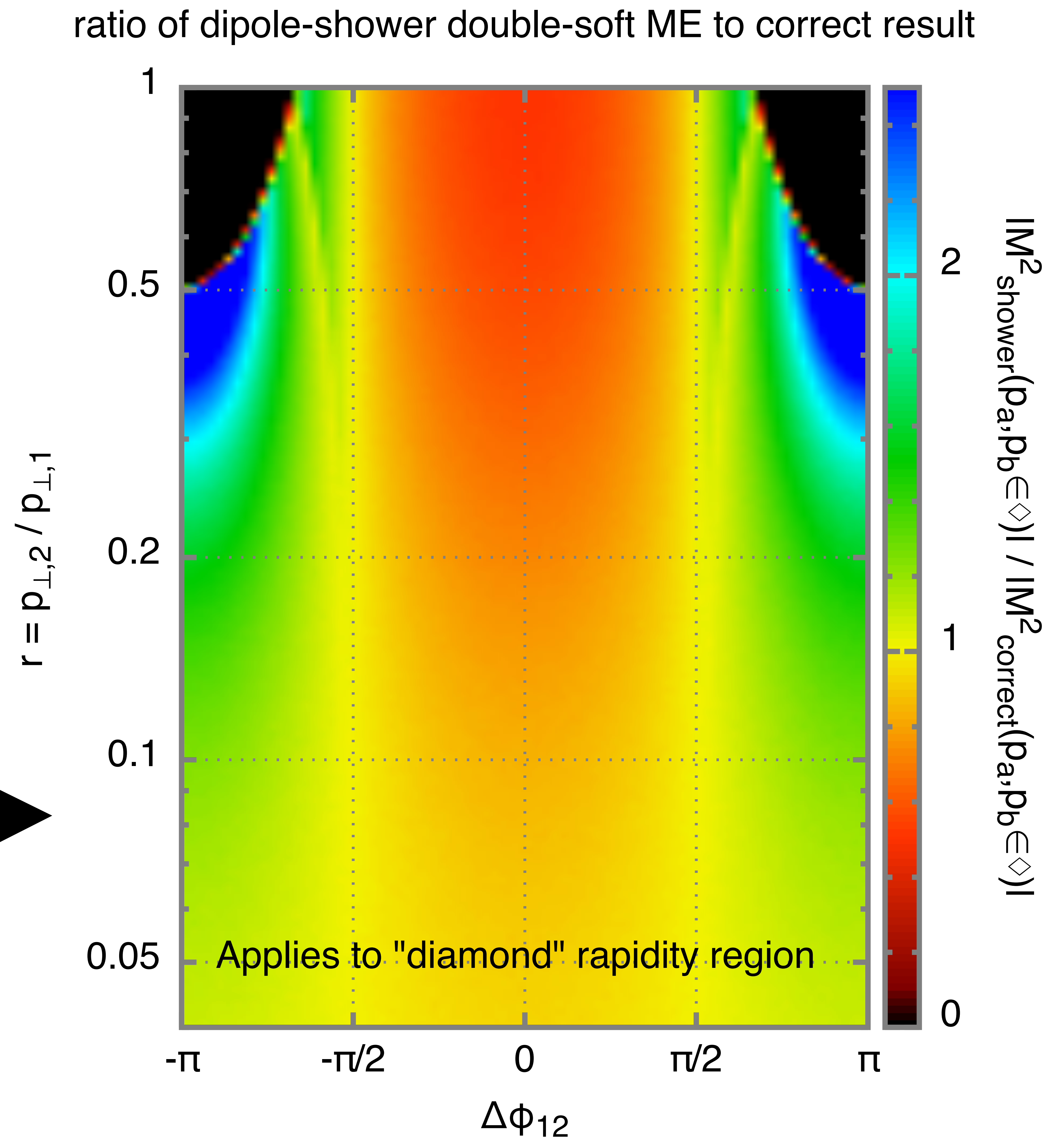

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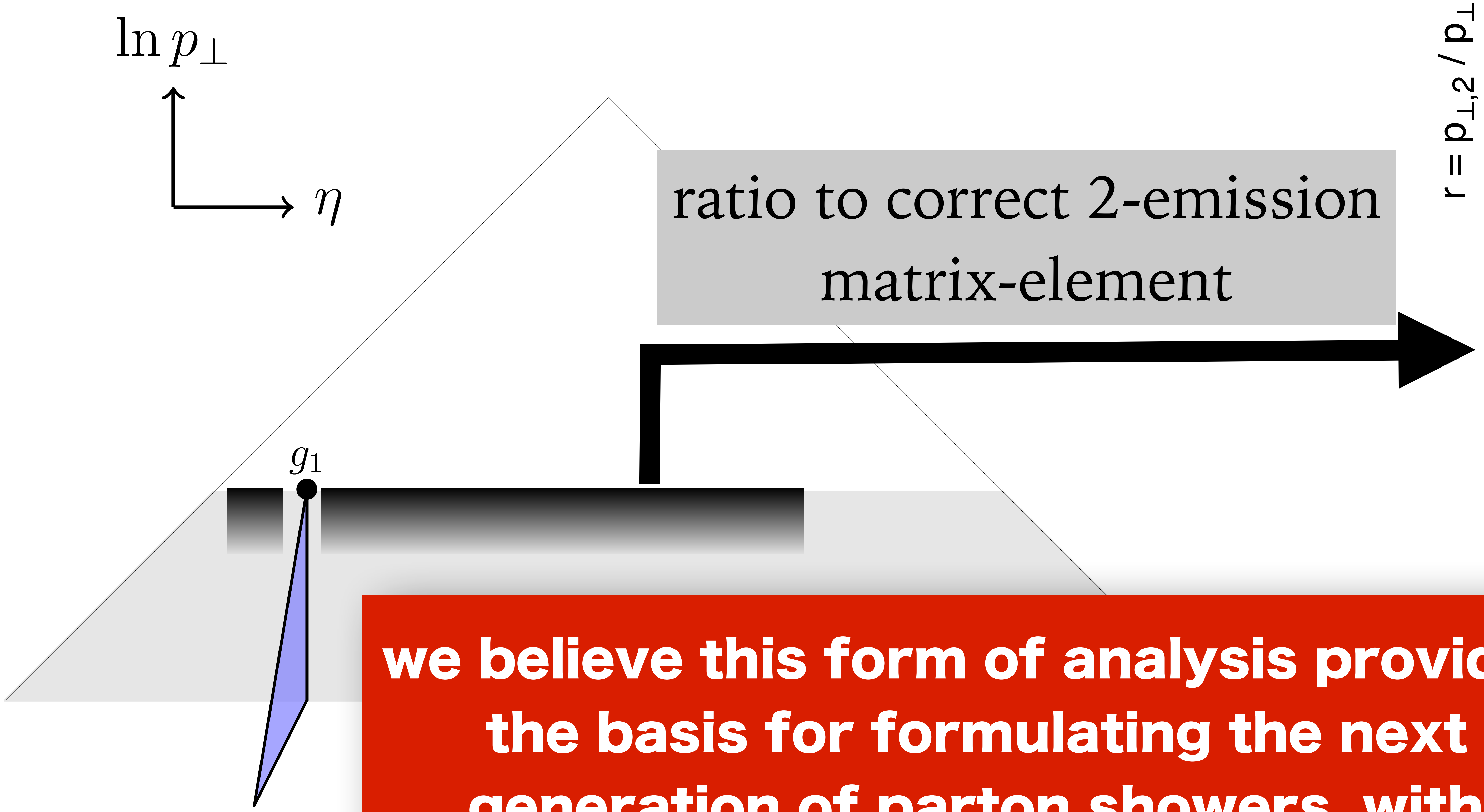

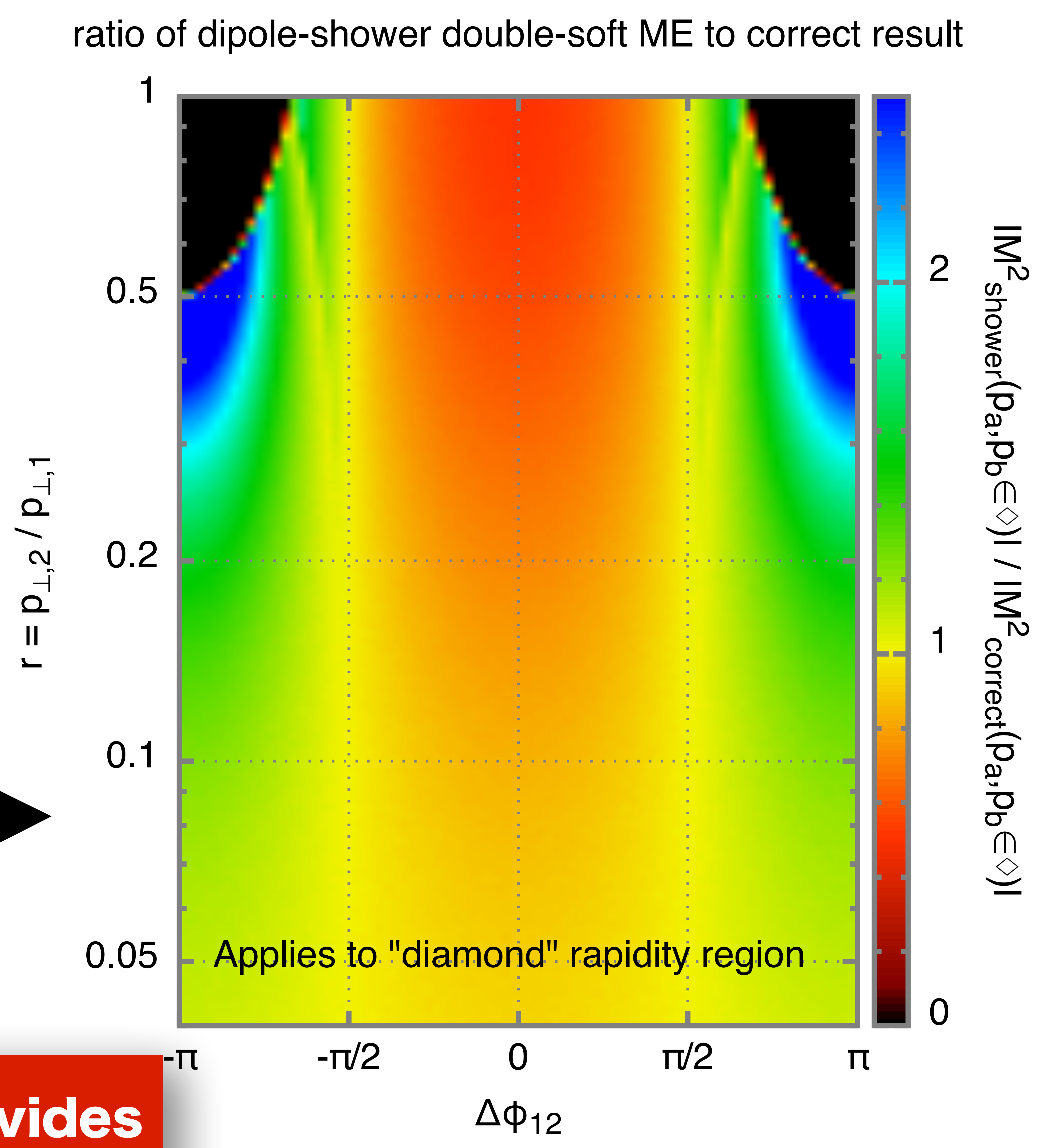

we believe this form of analysis provides the basis for formulating the next generation of parton showers, with quantifiable accuracy

analogous effect commented on by Nagy & Soper for Drell-Yan recoil, but wider relevance not appreciated?

outlook

Where is collider particle physics going?

- Higgs discovery opened a new chapter in particle physics
- **Qualitatively new kind of interaction — Yukawa interactions ("fifth force")**
  - critical to the world as we know it
  - so far probed only to 20%
  - and in only a corned of phase space
- **The biggest [accessible] challenge for the future is to see what we can learn, experimentally, about the Higgs potential, V(φ)** (one of strongest drivers for a new collider)
- Many other challenges remain (e.g. dark matter), but much as we should search for them, we should be wary of promising breakthroughs

“

I think Nature is smarter than physicists. We should have the courage to say: "Let Nature tell us what is going on."

-Carlo Rubbia [2008]

http://cerncourier.com/cws/article/cern/35456

How can we get there?

- Collider physics relies crucially on understanding QCD
- **Two big frontiers**
  - learning to use all the information contained in events, each with 100s of particles
  - accurate quantitative connection between events and fundamental Lagrangian
- Even with machine-learning, we seem to **benefit from physics-driven understanding of how to structure event information**
- Structuring event information likely **crucial also in understanding what to ask of a key QCD tool, the parton shower**