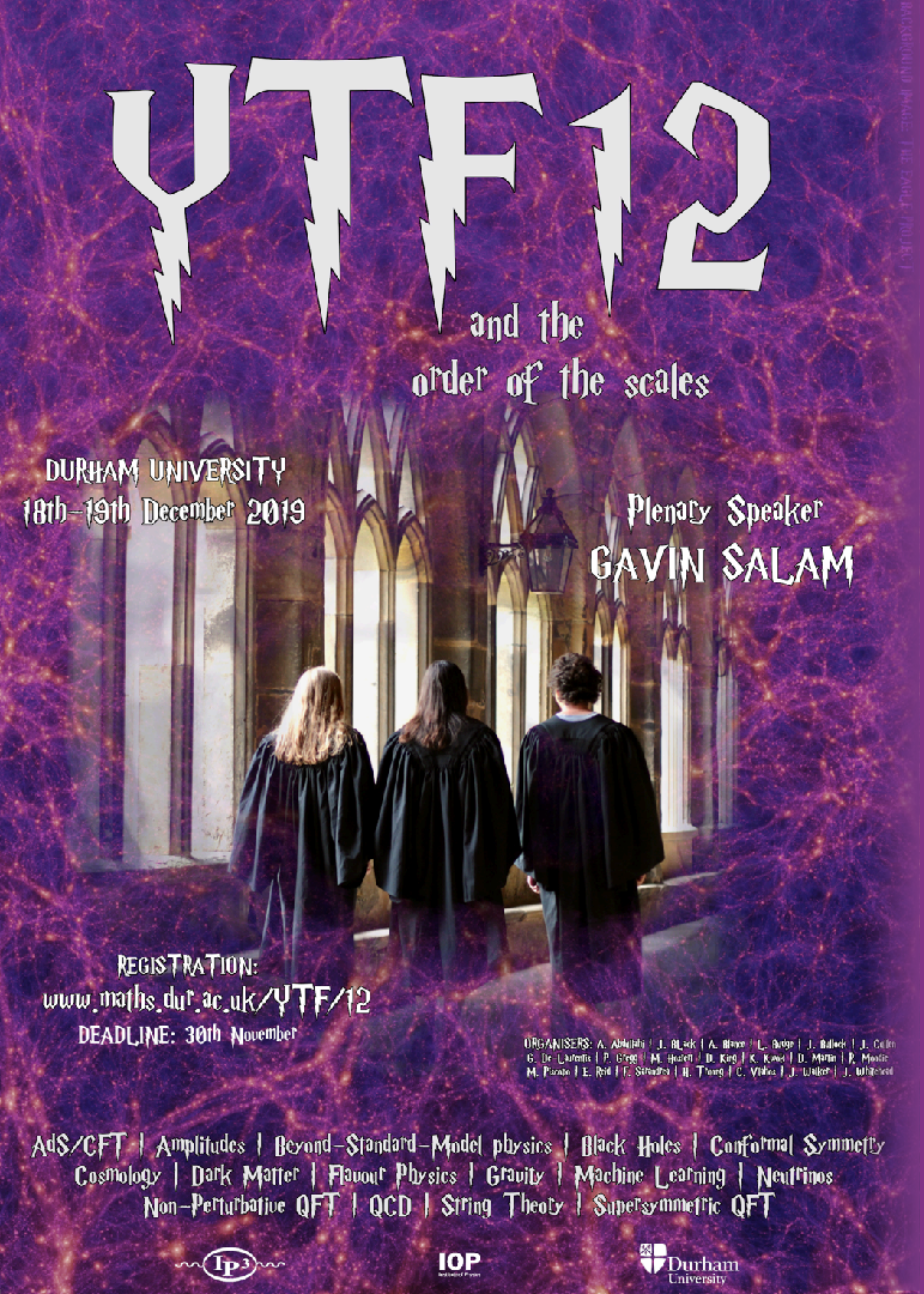


Colliders, Higgs and the strong interaction

Gavin Salam
University of Oxford & All Souls College*

*on leave from CERN and CNRS

European Research Council
Established by the European Commission
THE ROYAL SOCIETY
UNIVERSITY OF OXFORD

invitation for this talk:

"engage and inspire young researchers in [your] field, whilst also straddling the boundary of both Mathematics and Physics"

AdS/CFT | Amplitudes | Beyond-Standard-Model physics | Black Holes | Conformal Symmetry
Cosmology | Dark Matter | Flavour Physics | Gravity | Machine Learning | Neutrinos
Non-Perturbative QFT | QCD | String Theory | Supersymmetric QFT

invitation for this talk:

"engage and inspire young researchers in [your] field, whilst also straddling the boundary of both Mathematics and Physics"

Mission Impossible?

(at least for me!)

a thread through this talk

what are our metrics for progress and/or success?

for progress on the big picture of particle physics
and the more specific problems that we work on daily

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]

particle physics

"big unanswered questions"

about fundamental particles & their interactions

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

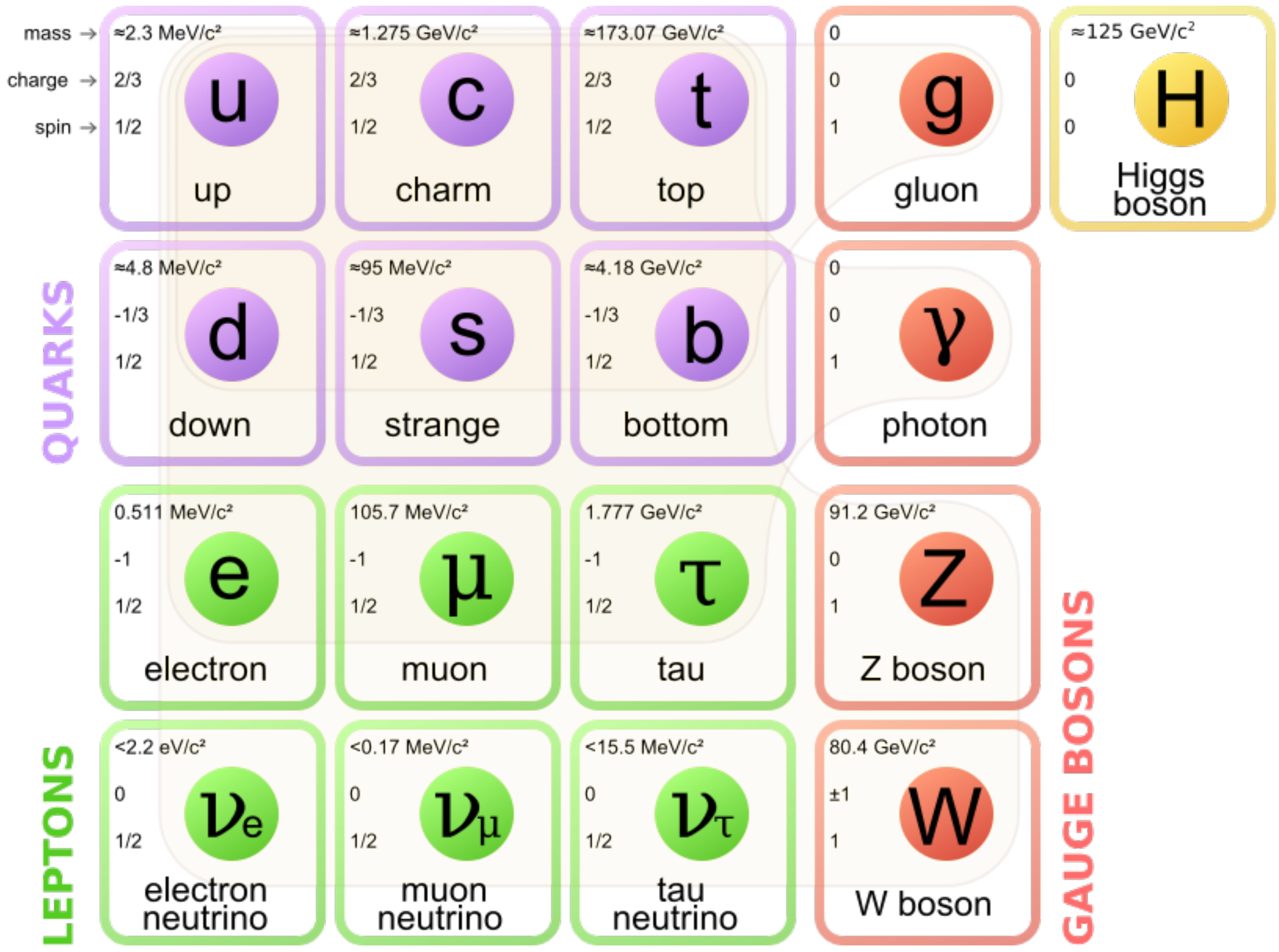
v.

"big answerable questions"

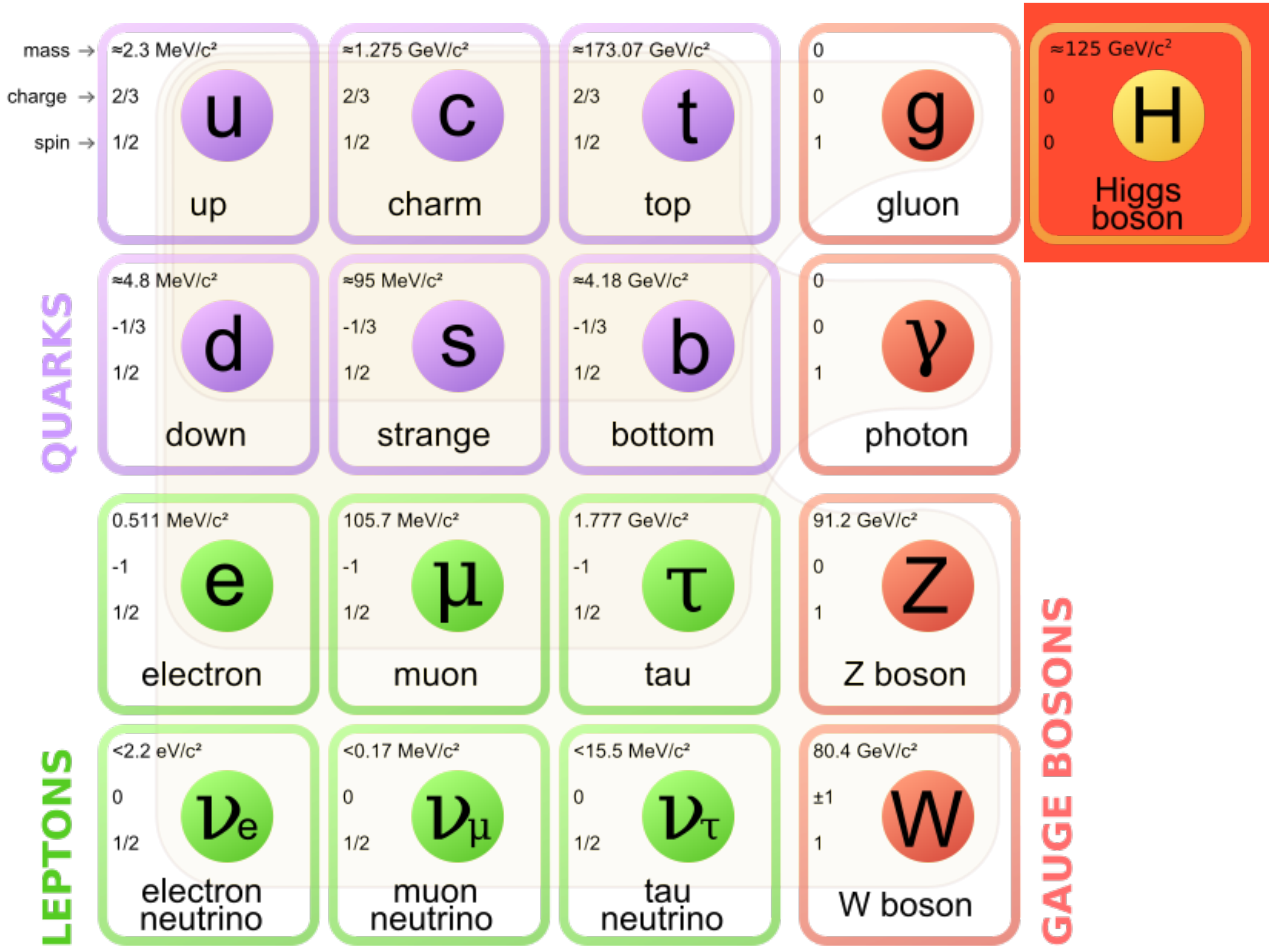
and how we go about answering them

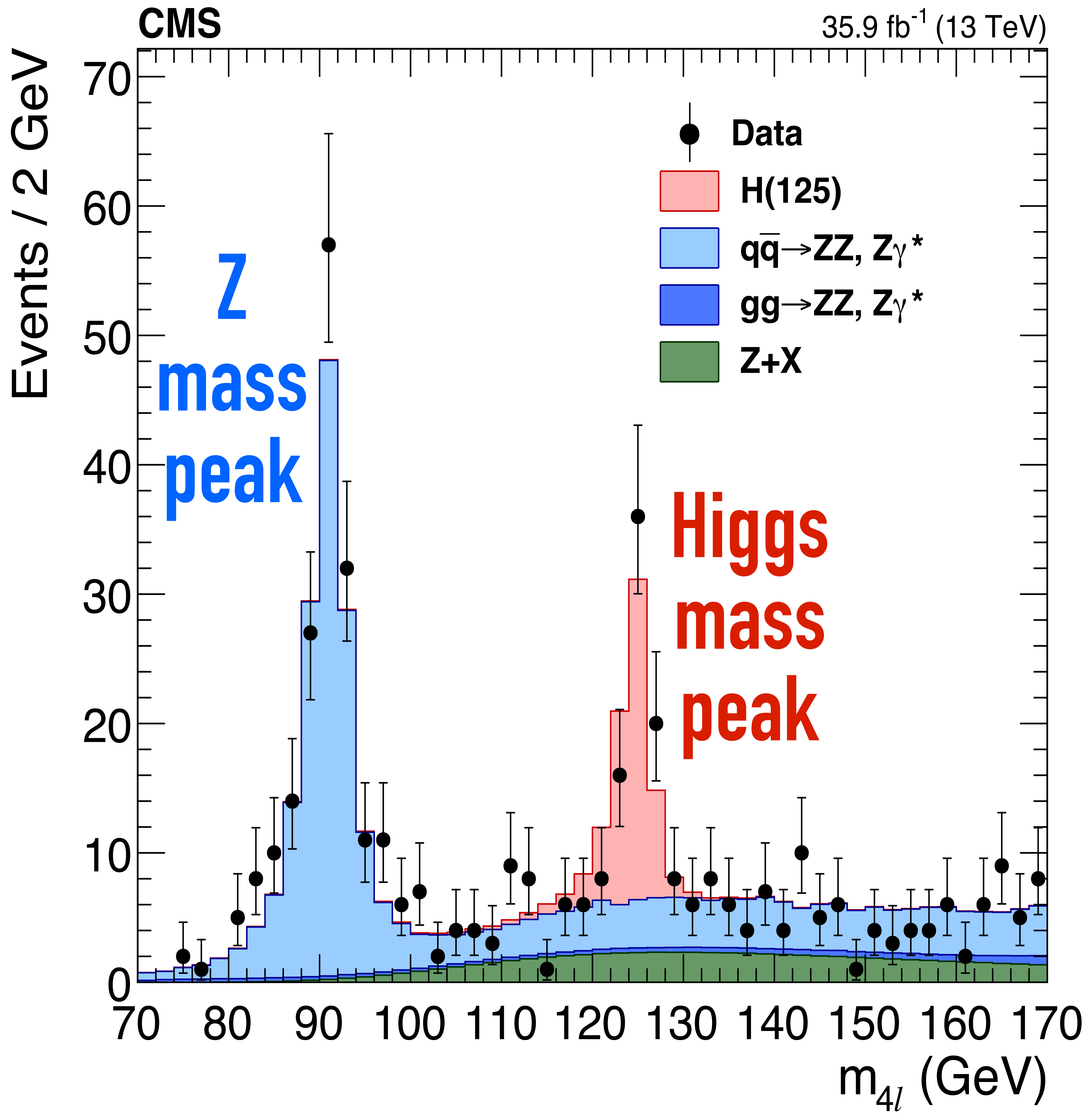
(nature of Higgs interactions, validity of SM up to high scales,
lepton flavour universality, pattern of neutrino mixing, …)

The Higgs boson



The Higgs boson



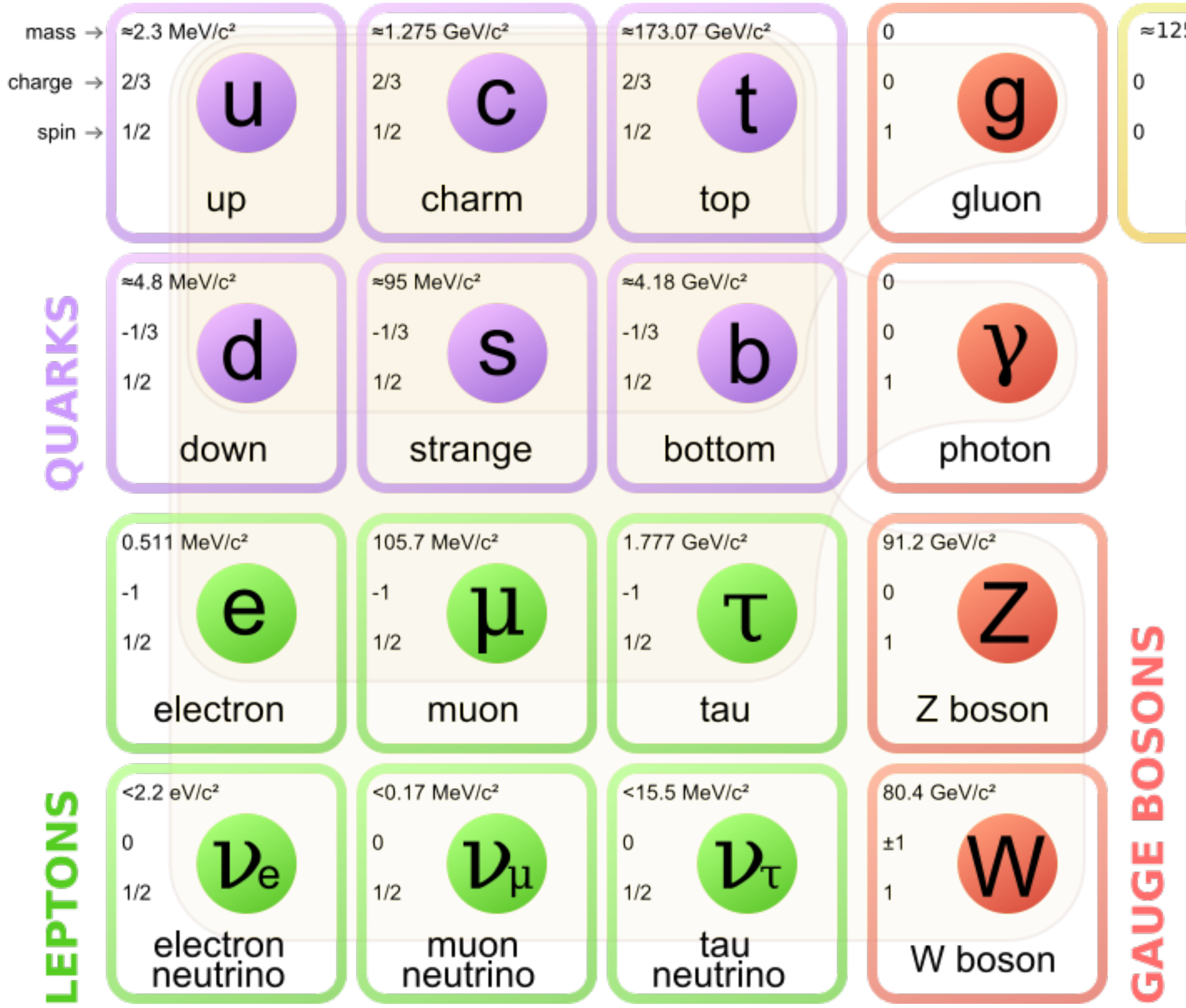


ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

2012 discovery of a Higgs-like boson

plot shows more recent data

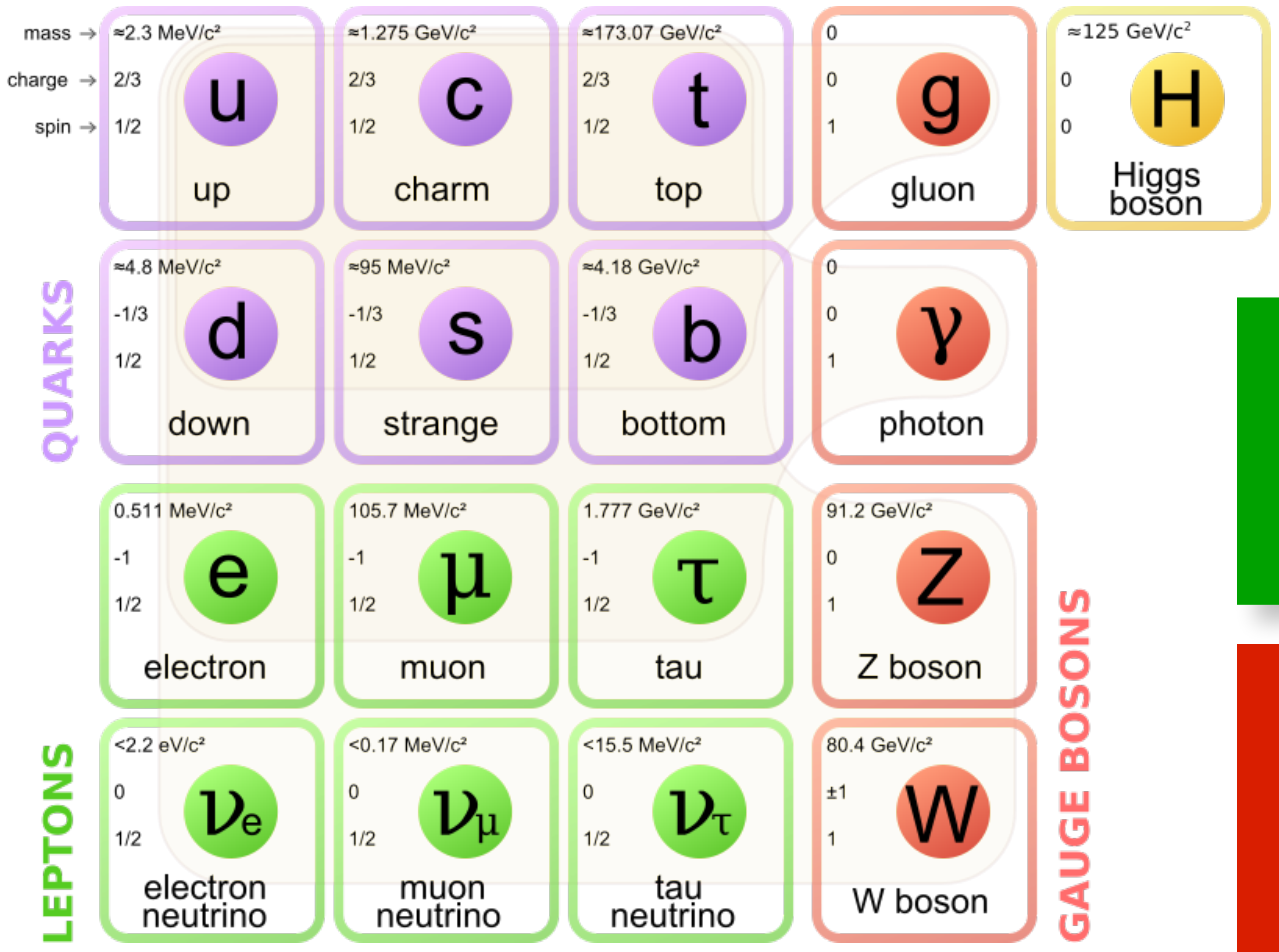
The Higgs boson (2012)



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

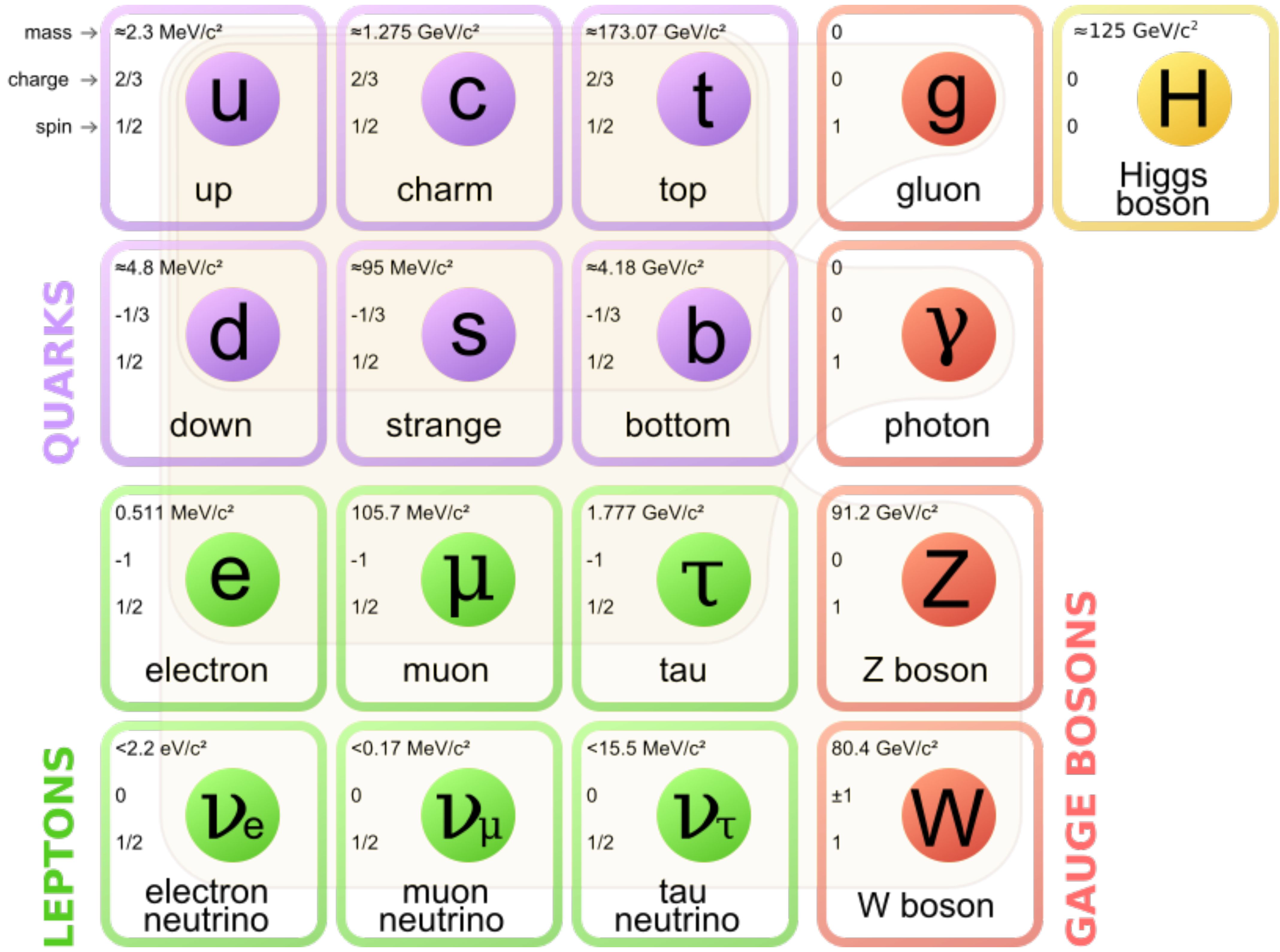
[…]

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

[…]

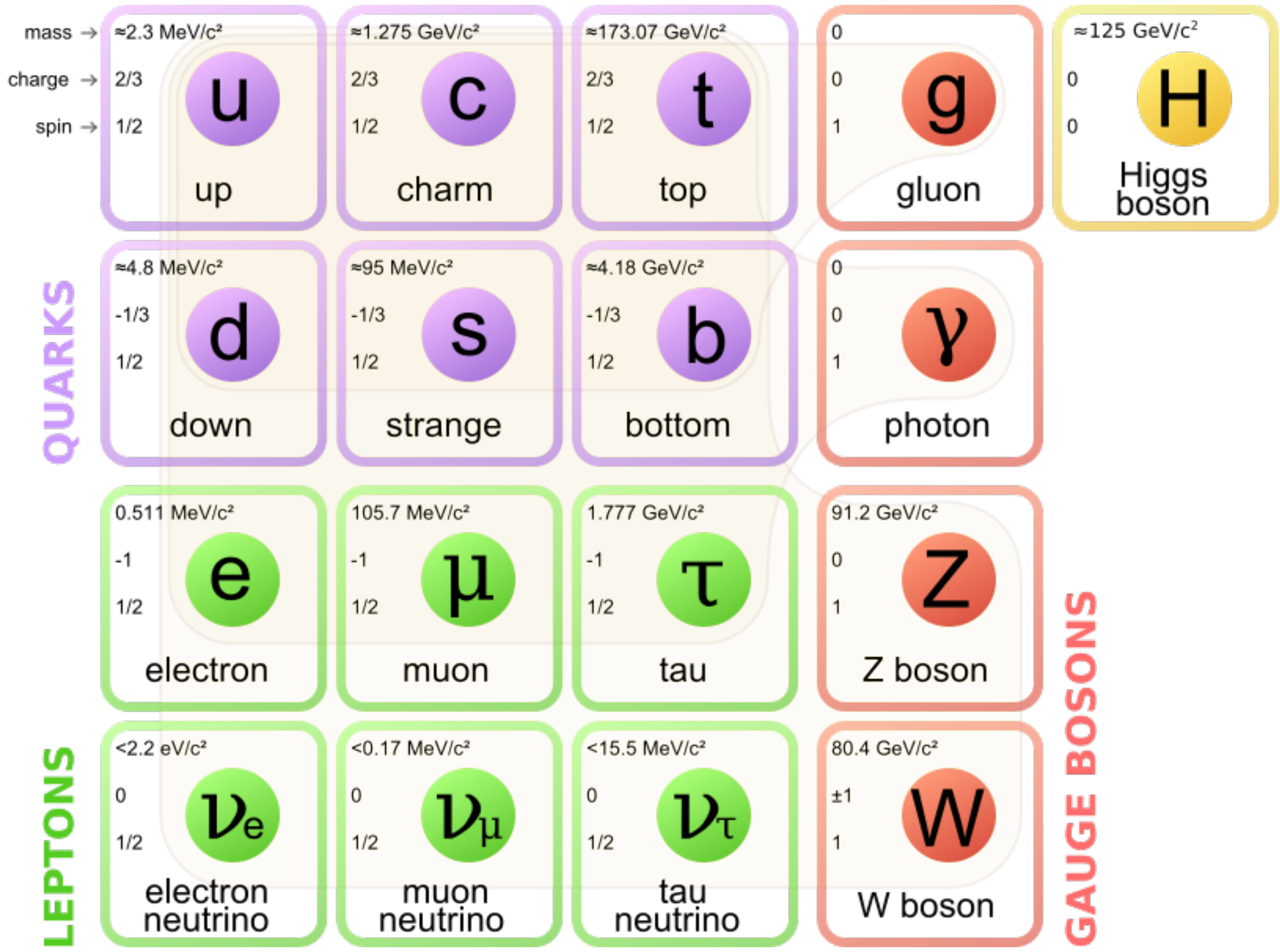
https://www.nytimes.com/2017/06/19/science/cern-large-hadron-collider-higgs-physics.html

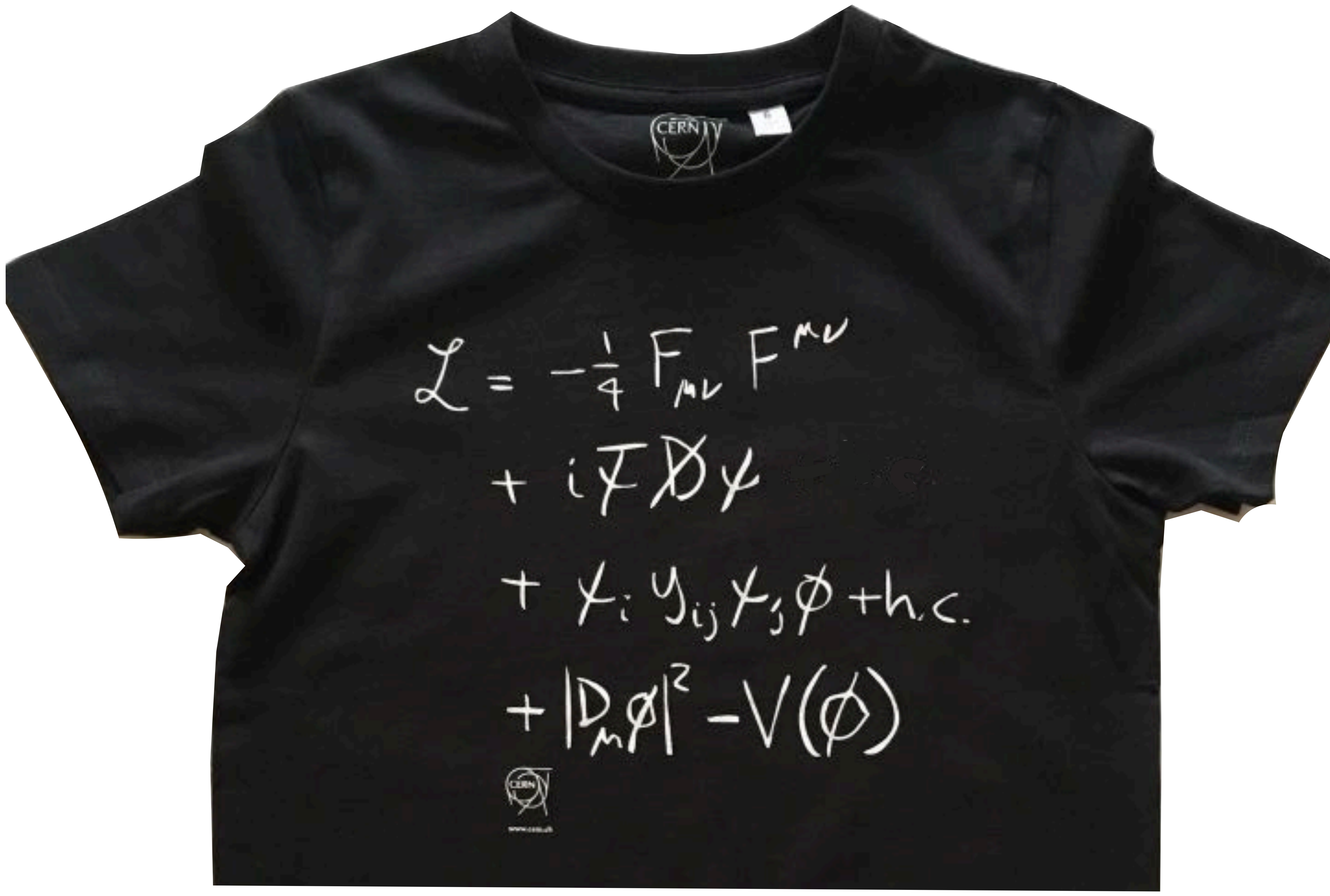
what is the Standard Model?



particles

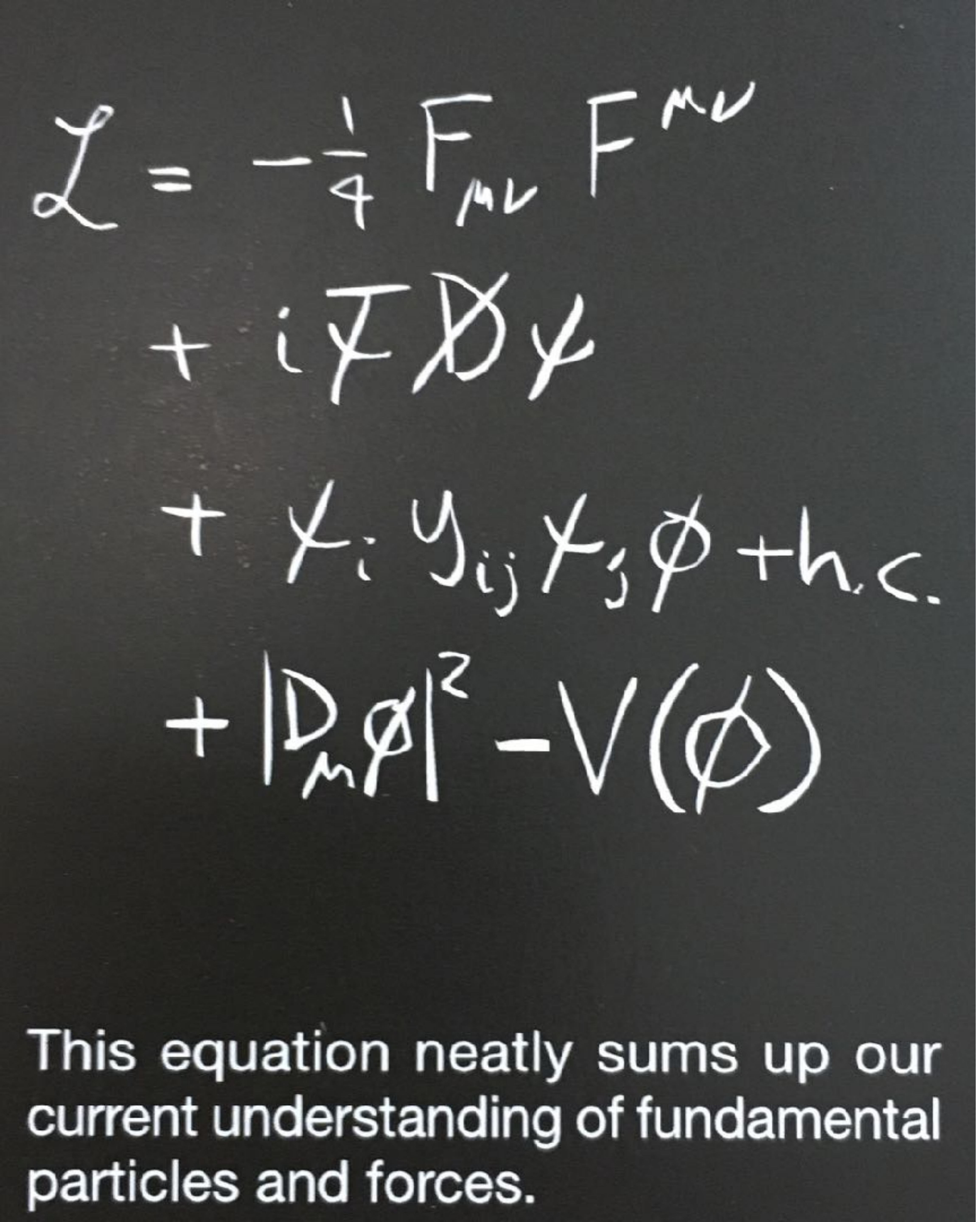
what is the Standard Model?





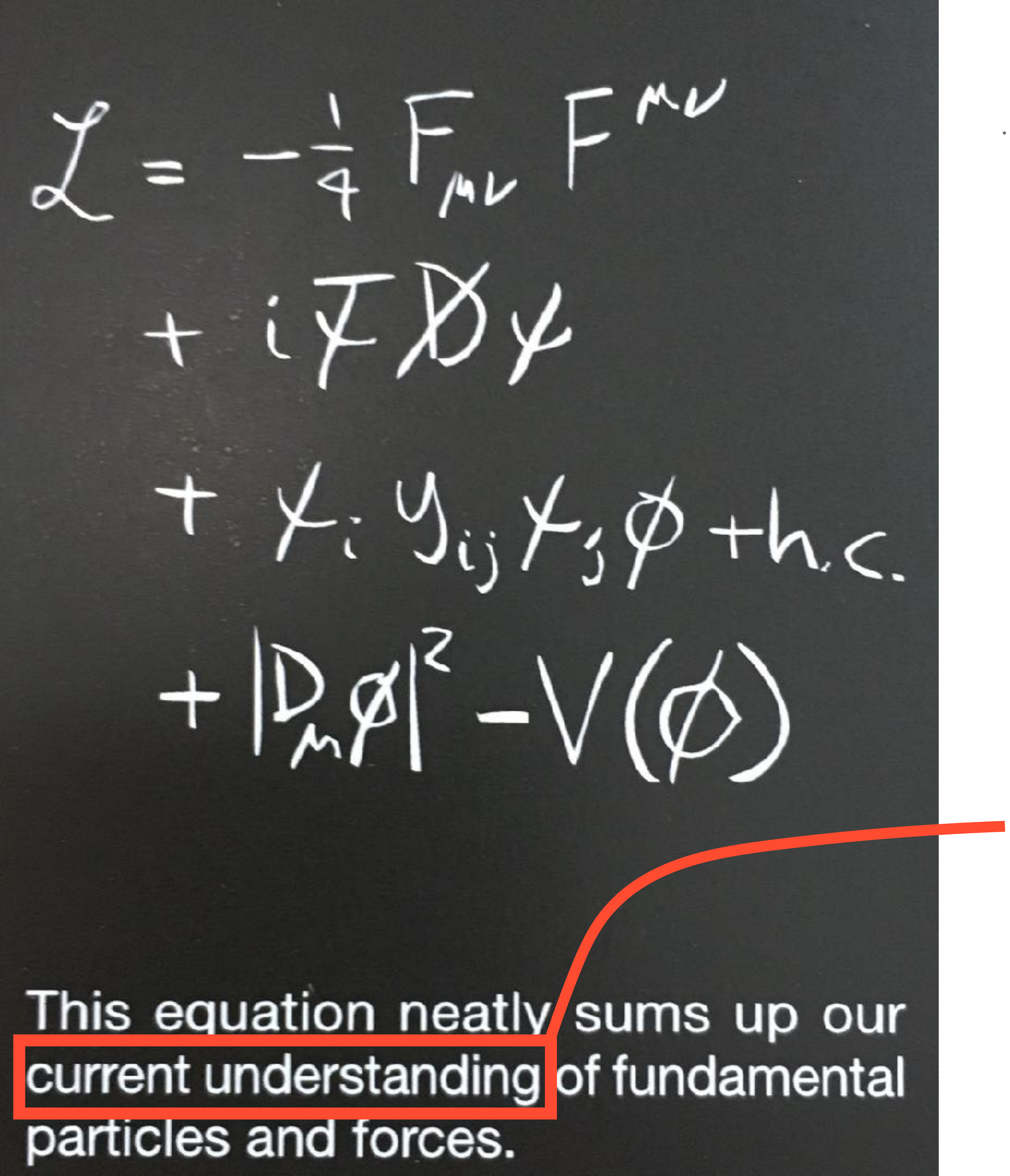
particles *interactions*

Standard Model —— knowable unknowns



These T-shirts come with a little explanation

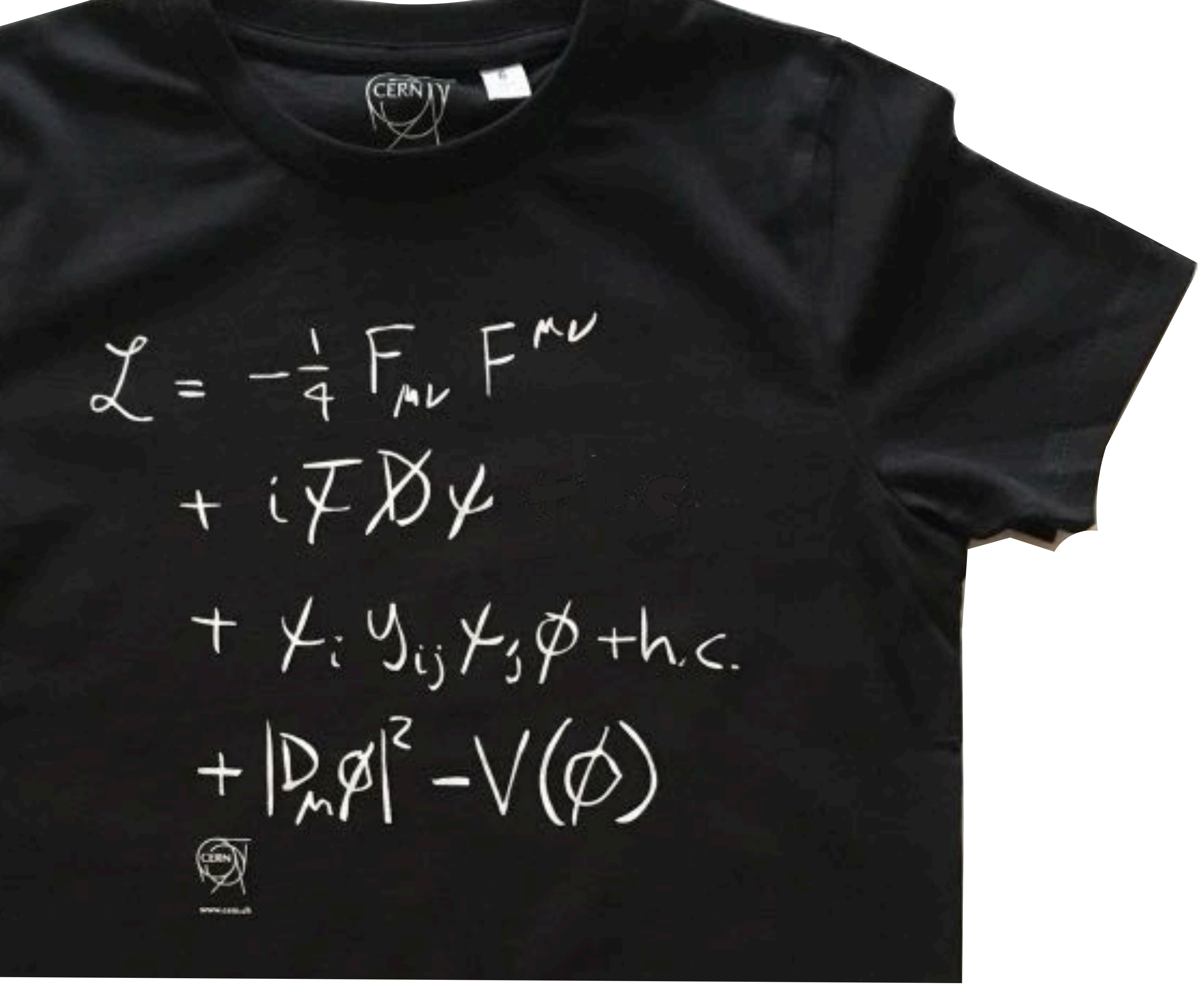
Standard Model — knowable unknowns



These T-shirts come with a little explanation

"understanding" = knowledge ?

"understanding" = assumption ?



=

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 $(\bar\nu_L,\bar e_L),(\bar u_L,\bar d_L),(-\bar e_L,\bar\nu_L),(-\bar d_L,\bar u_L),\bar\phi,\ \mathbf{W}_\mu,\ \binom{\nu_L}{e_L},\binom{u_L}{d_L},\binom{-e_L}{\nu_L},\binom{-d_L}{u_L},\phi$.

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,

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

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

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

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

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,

$$e'_L=\mathbf{U}_L^ee_L,\quad e'_R=\mathbf{U}_R^ee_R,\quad \nu'_L=\mathbf{U}_L^\nu\nu_L,\quad \nu'_R=\mathbf{U}_R^\nu\nu_R,\quad u'_L=\mathbf{U}_L^uu_L,\quad u'_R=\mathbf{U}_R^uu_R,\quad d'_L=\mathbf{U}_L^dd_L,\quad d'_R=\mathbf{U}_R^dd_R, \quad (23)$$

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

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,

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

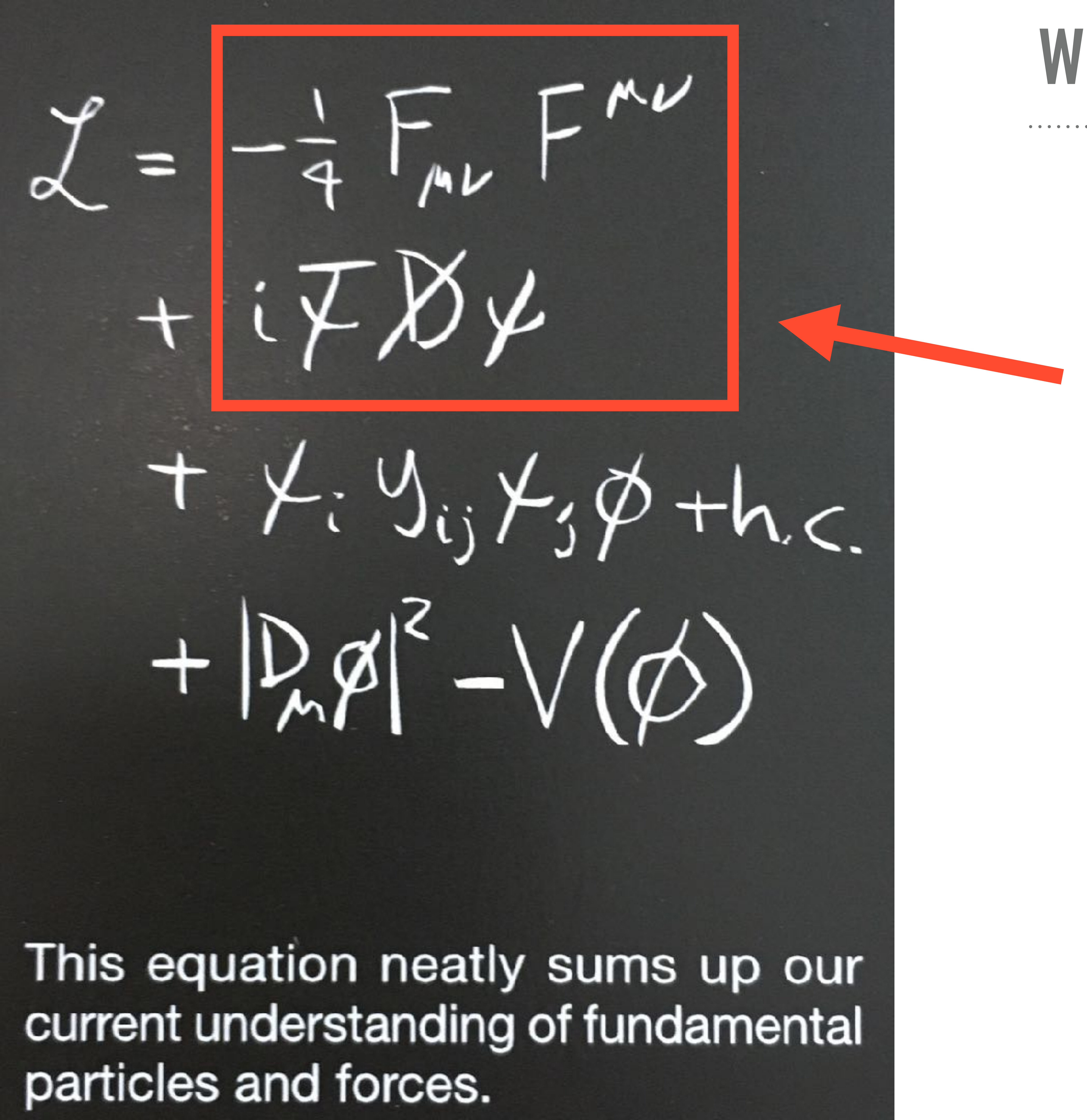
$$\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\to e^{i\theta}U\begin{pmatrix}\nu_L\\ e_L\end{pmatrix},\quad \begin{pmatrix}u_L\\ d_L\end{pmatrix}\to e^{-i\theta/3}U\begin{pmatrix}u_L\\ d_L\end{pmatrix},\quad \begin{matrix}\nu_R\to\nu_R, & u_R\to e^{-4i\theta/3}u_R,\\ e_R\to e^{2i\theta}e_R, & d_R\to e^{2i\theta/3}d_R,\end{matrix}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

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

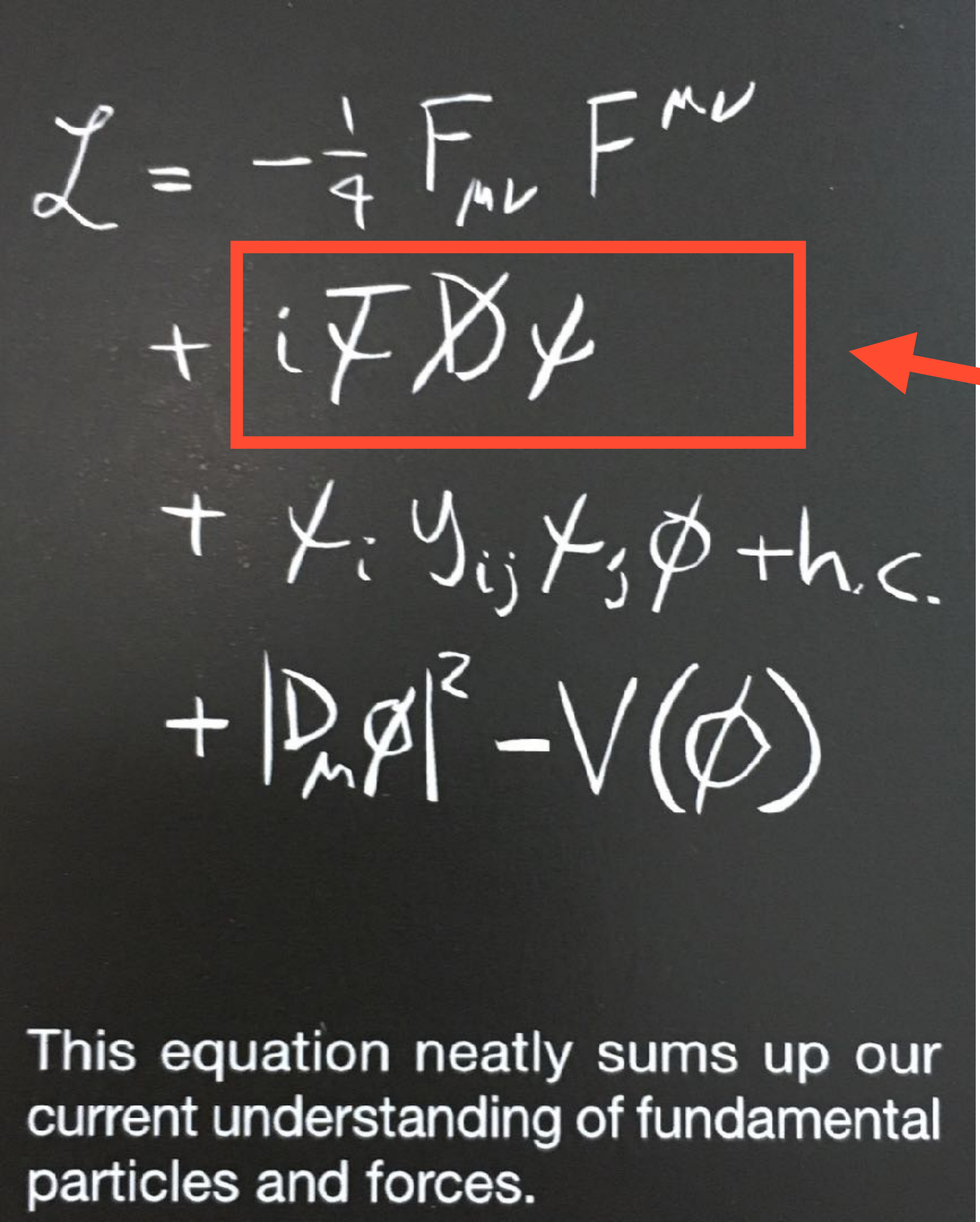
$$\mathbf{G}_\mu\to V\mathbf{G}_\mu V^\dagger-(i/g)V\partial_\mu V^\dagger,\quad \mathbf{G}_{\mu\nu}\to V\mathbf{G}_{\mu\nu}V^\dagger,\quad u_L\to Vu_L,\quad d_L\to Vd_L,\quad u_R\to Vu_R,\quad d_R\to Vd_R. \quad (30)$$

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

What does it mean?



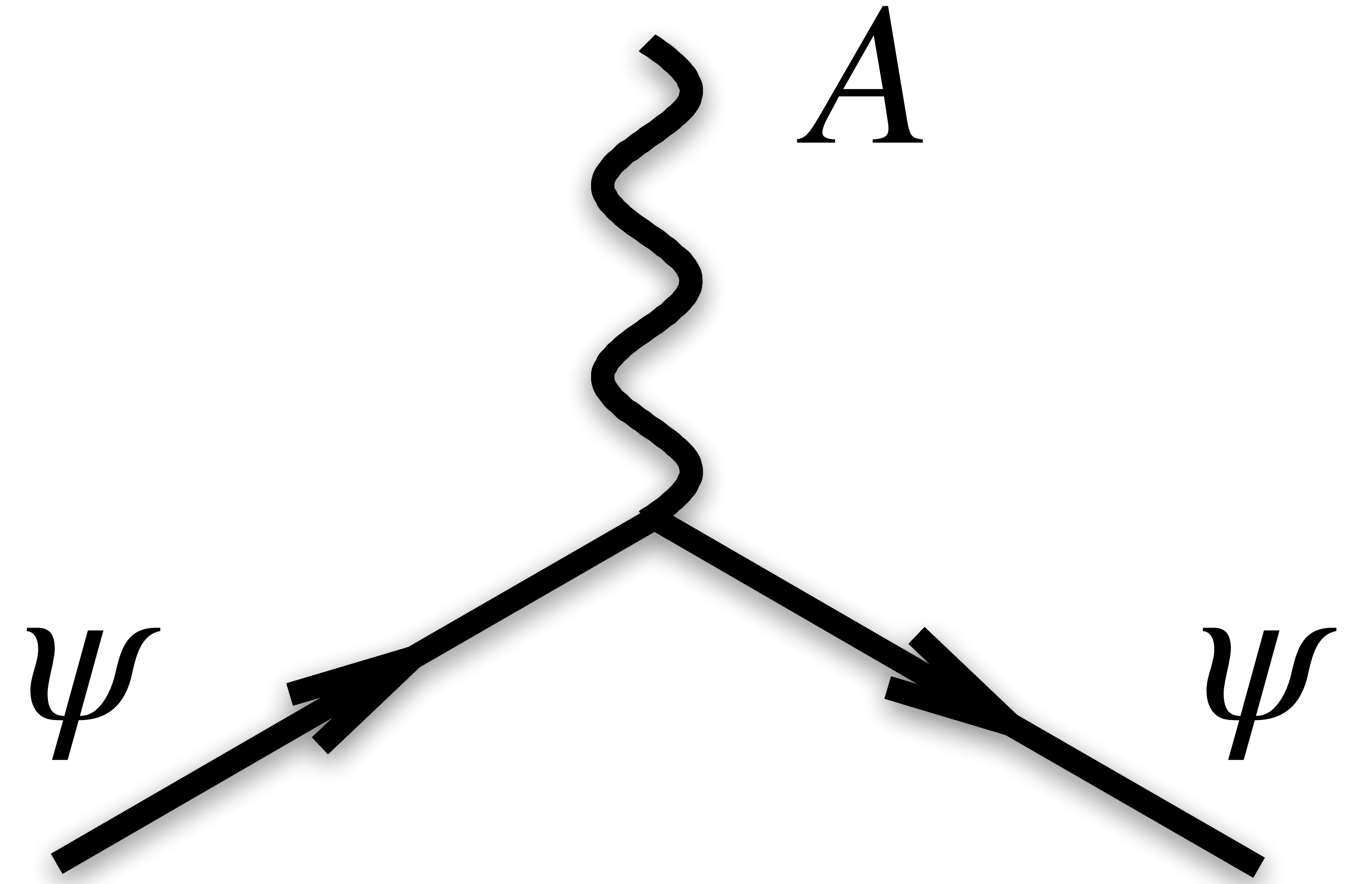
Quantum formulation of Maxwell’s equations, (and their analogues for the weak and strong forces).



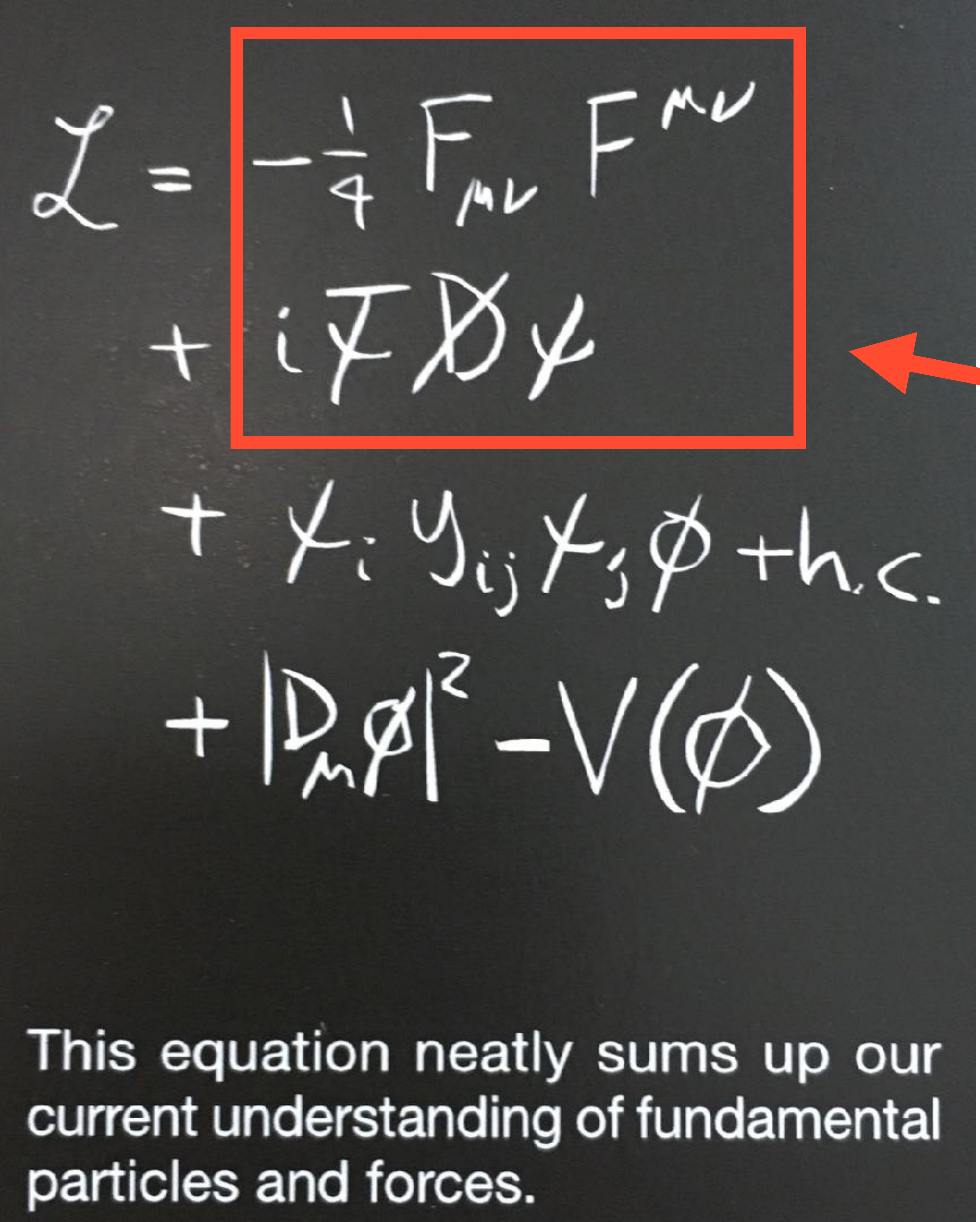
What does it mean?

ψ = *fermion (e.g. electron) field*

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



tells you there's an
electron-photon interaction vertex



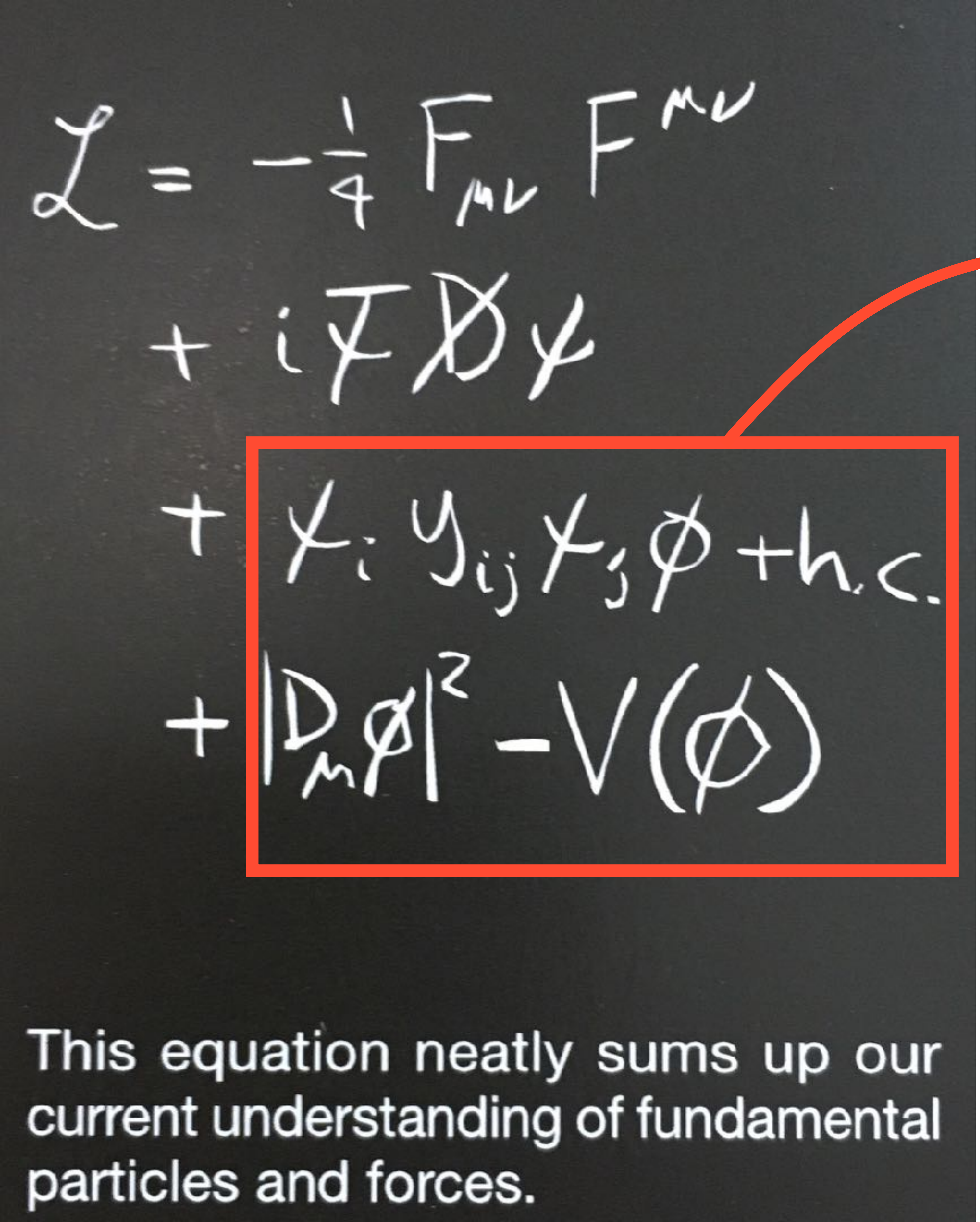
What does it mean?

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.

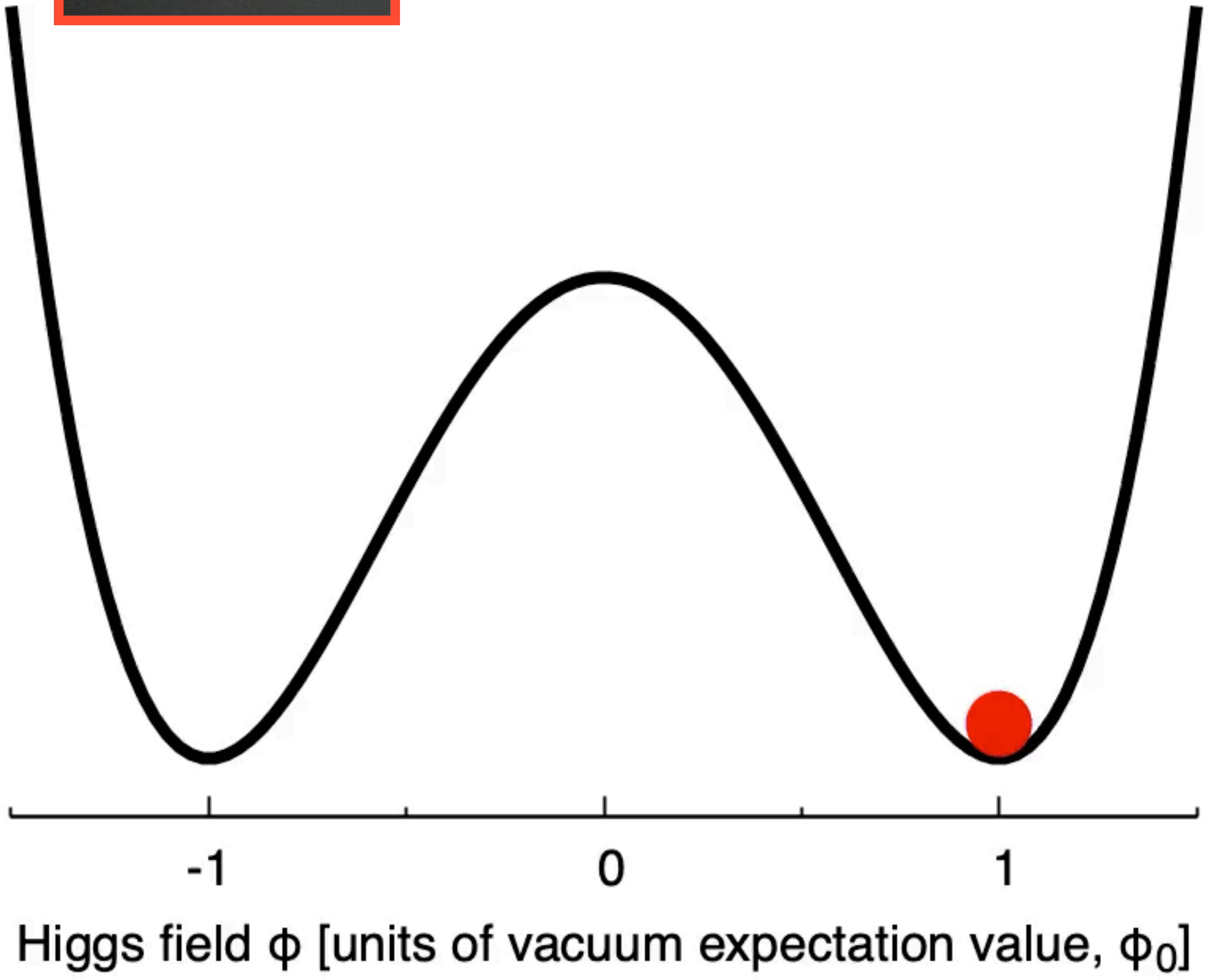
They work to high precision (best tests go up to 1 part in 10^8)

Higgs sector



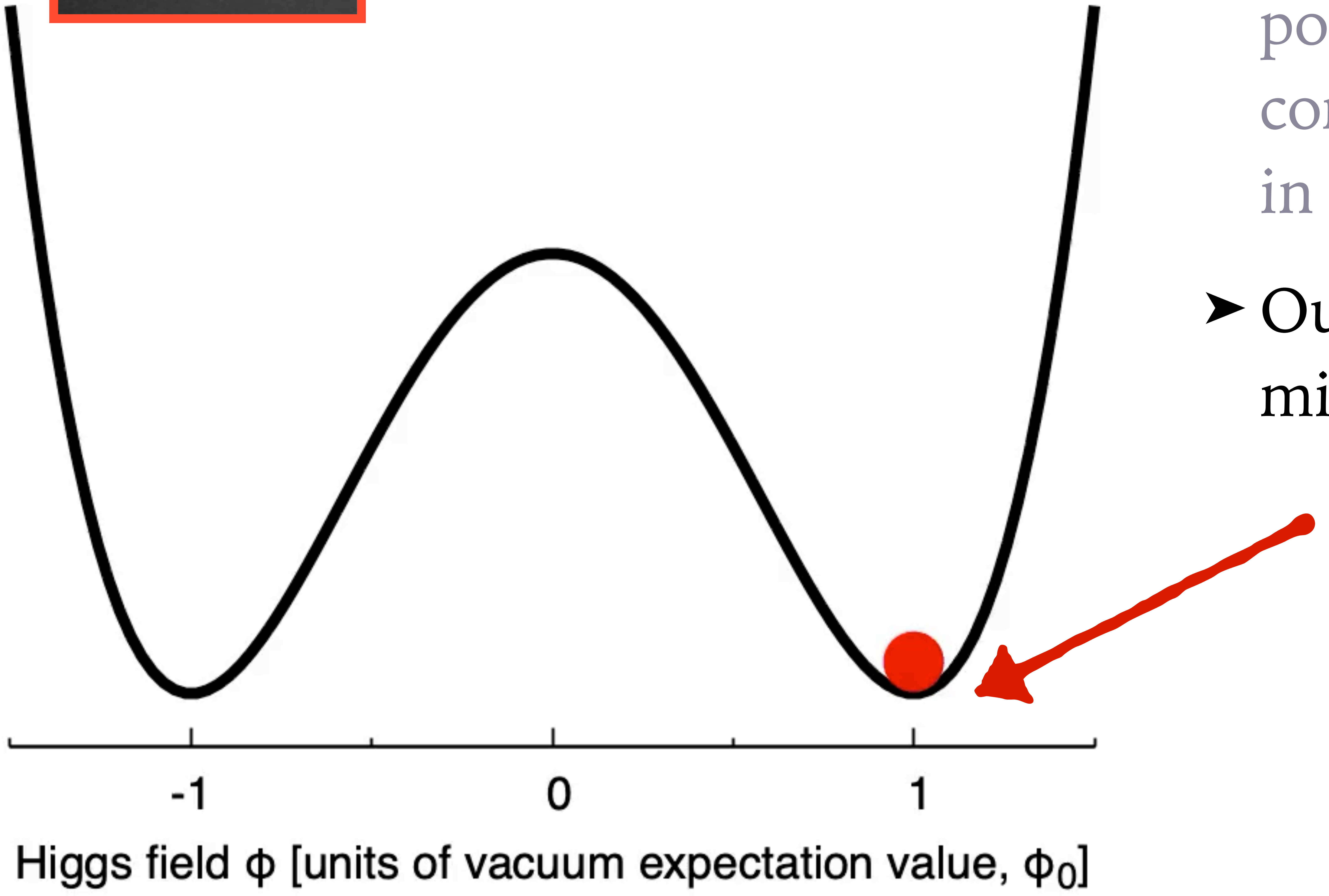
until 7 years ago none of these terms had ever been directly observed.

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



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

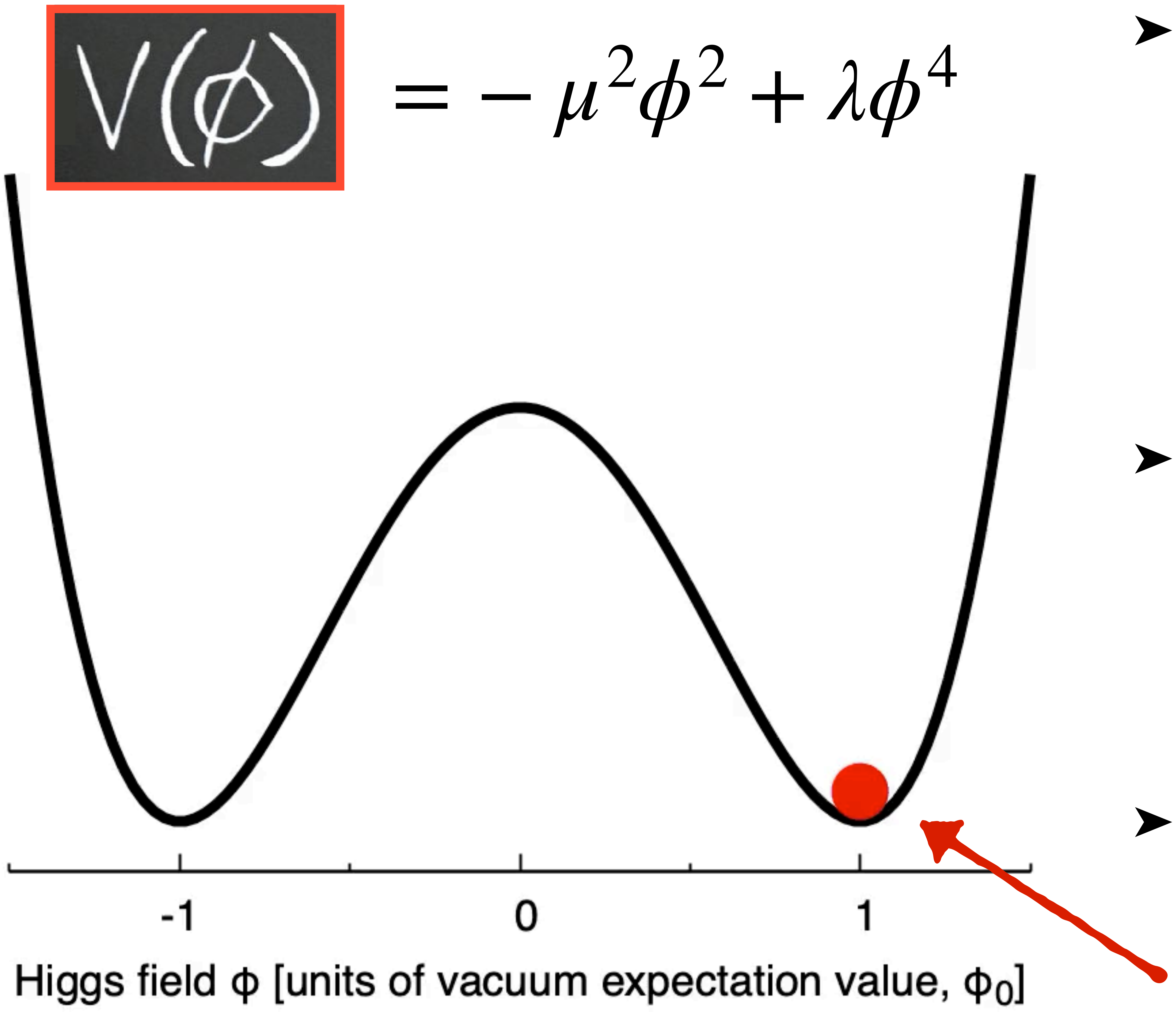
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



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

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

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

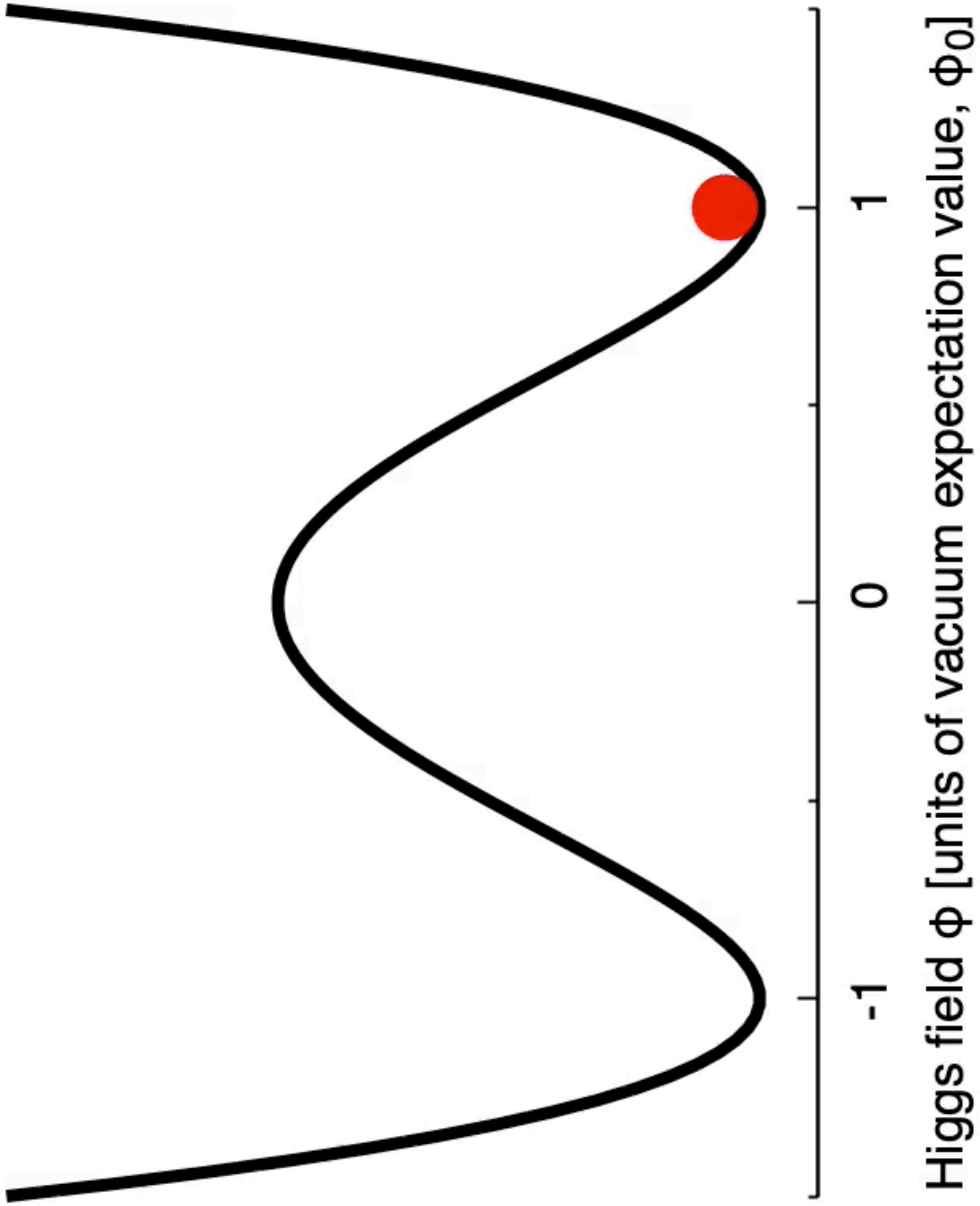


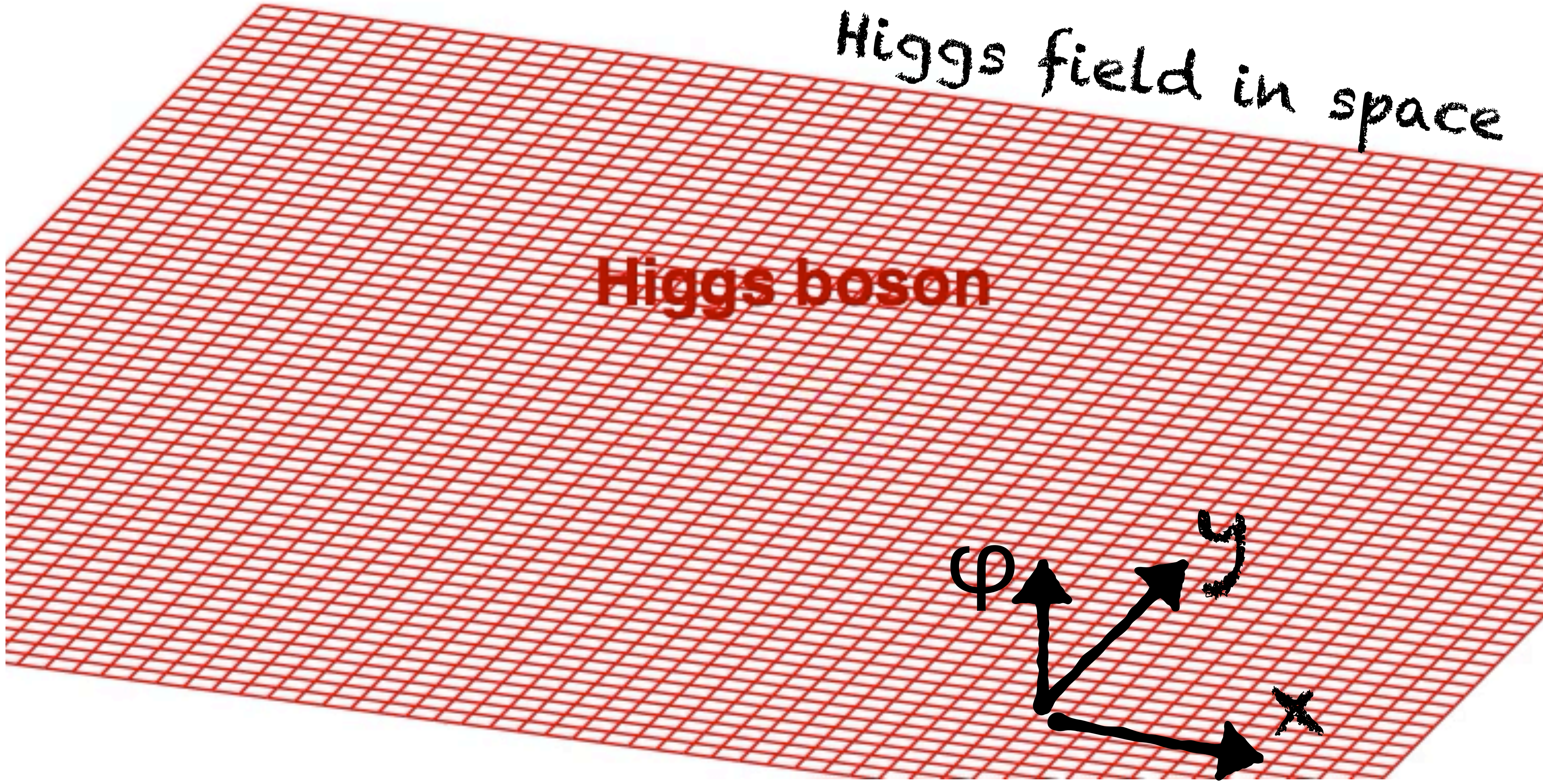
- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)
- Our universe sits at minimum of V(φ), at

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

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

$$\varphi = \varphi_0 + H$$

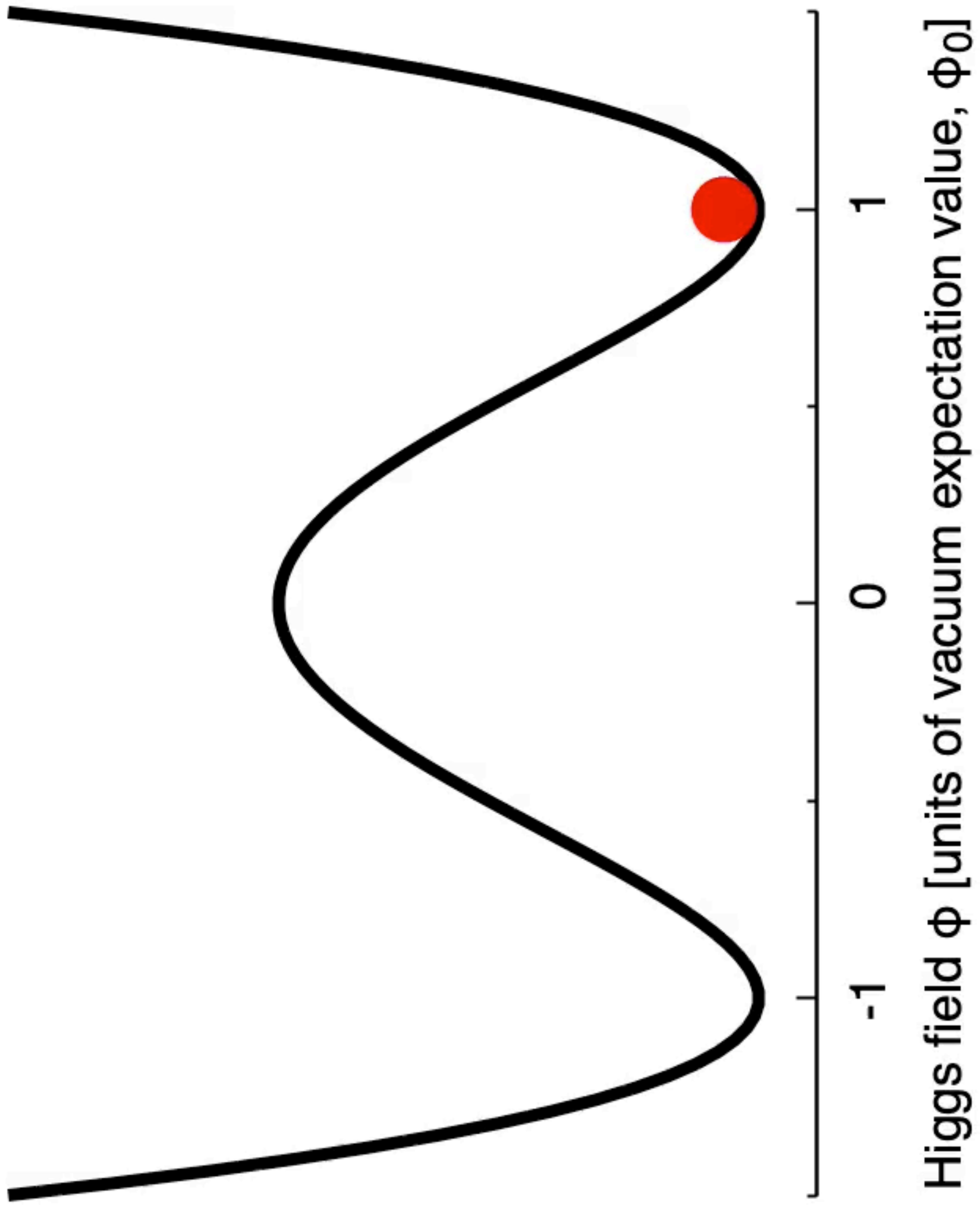


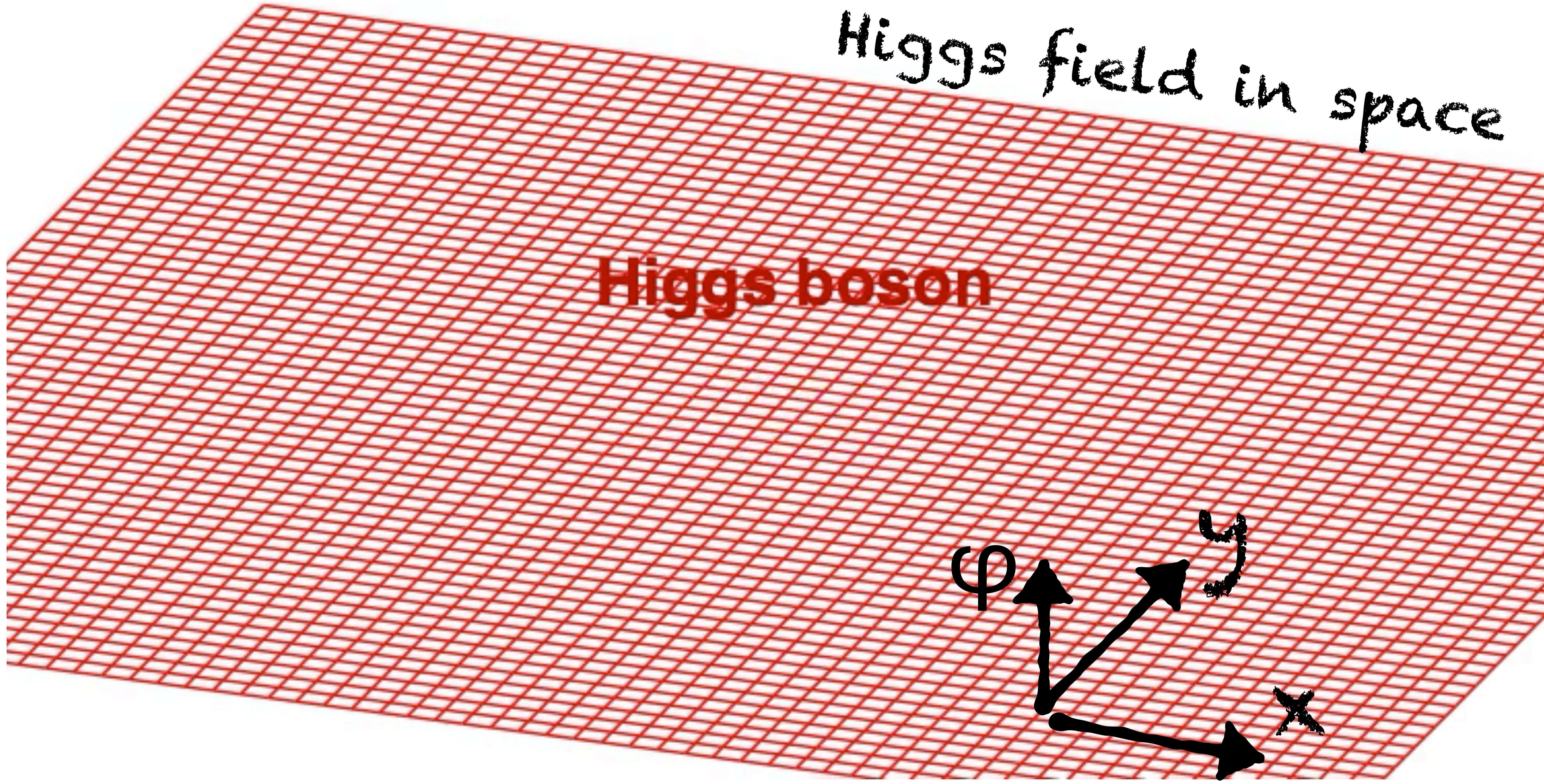


Higgs field can be different at each point in space

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)

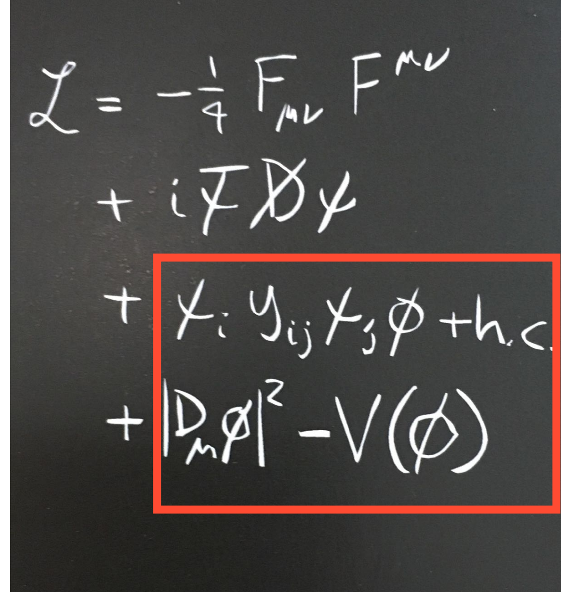
$$\varphi = \varphi_0 + H$$

established
(2012 Higgs boson discovery)

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

hypothesis

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



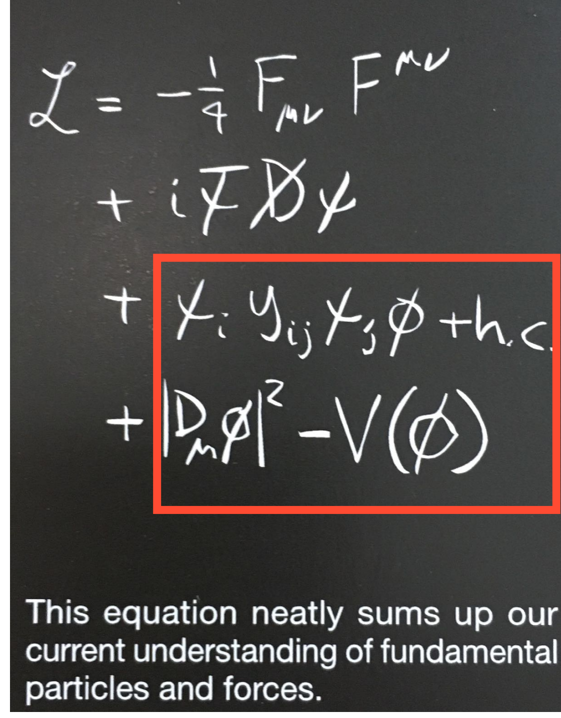
This equation neatly sums up our current understanding of fundamental particles and forces.

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

Z-boson mass term — *HZZ interaction term*

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

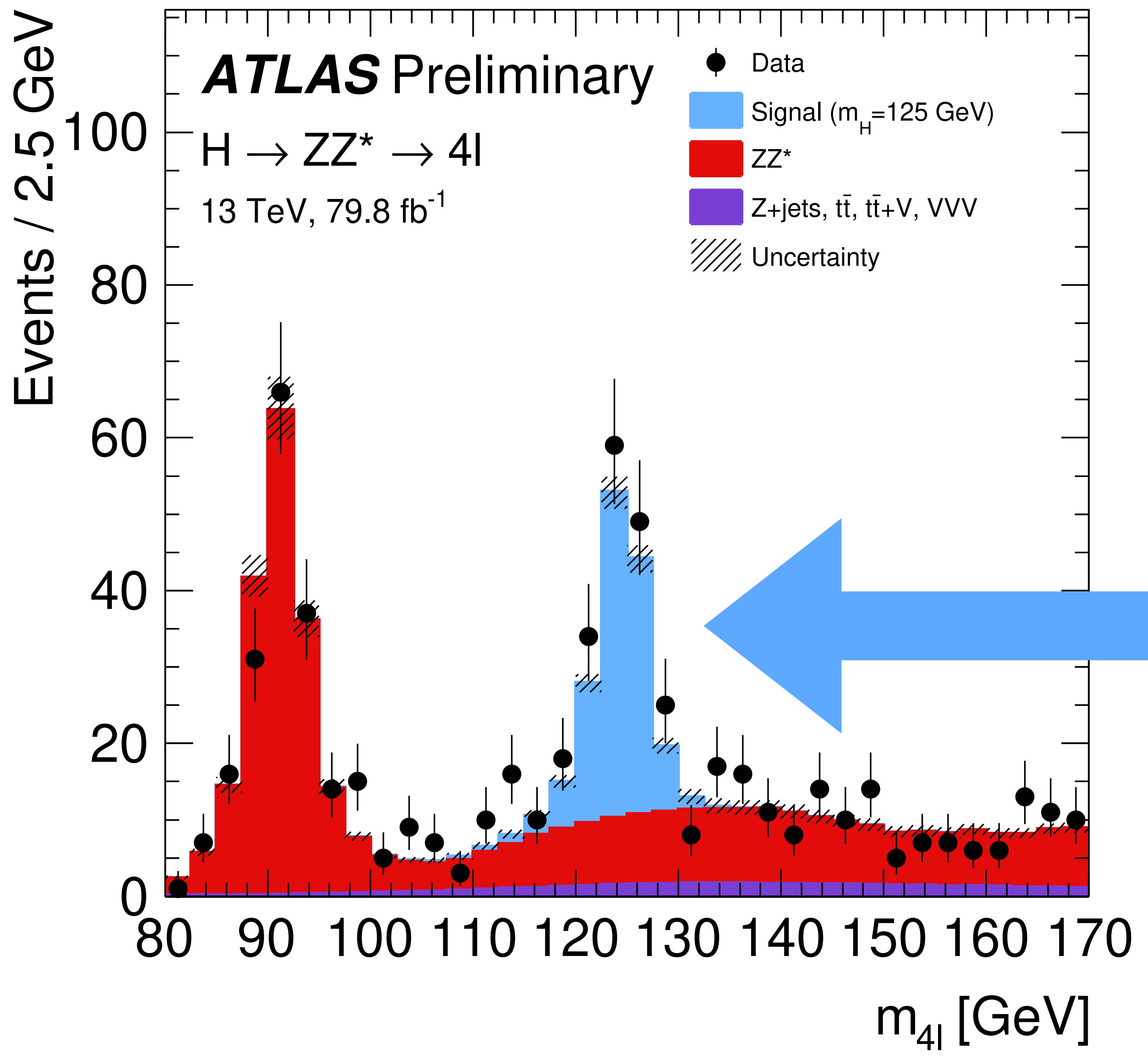
what terms are there in the Higgs sector?
2. Gauge–Higgs term



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

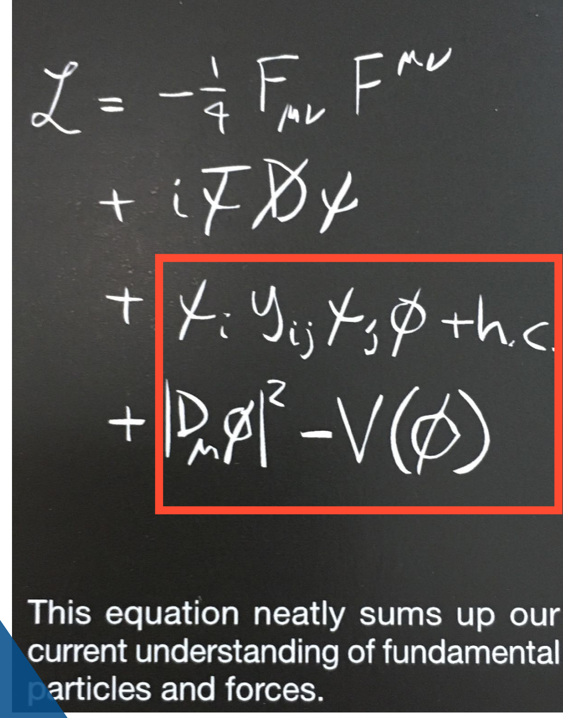
Z-boson mass term

ZZH interaction term



H → ZZ*

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

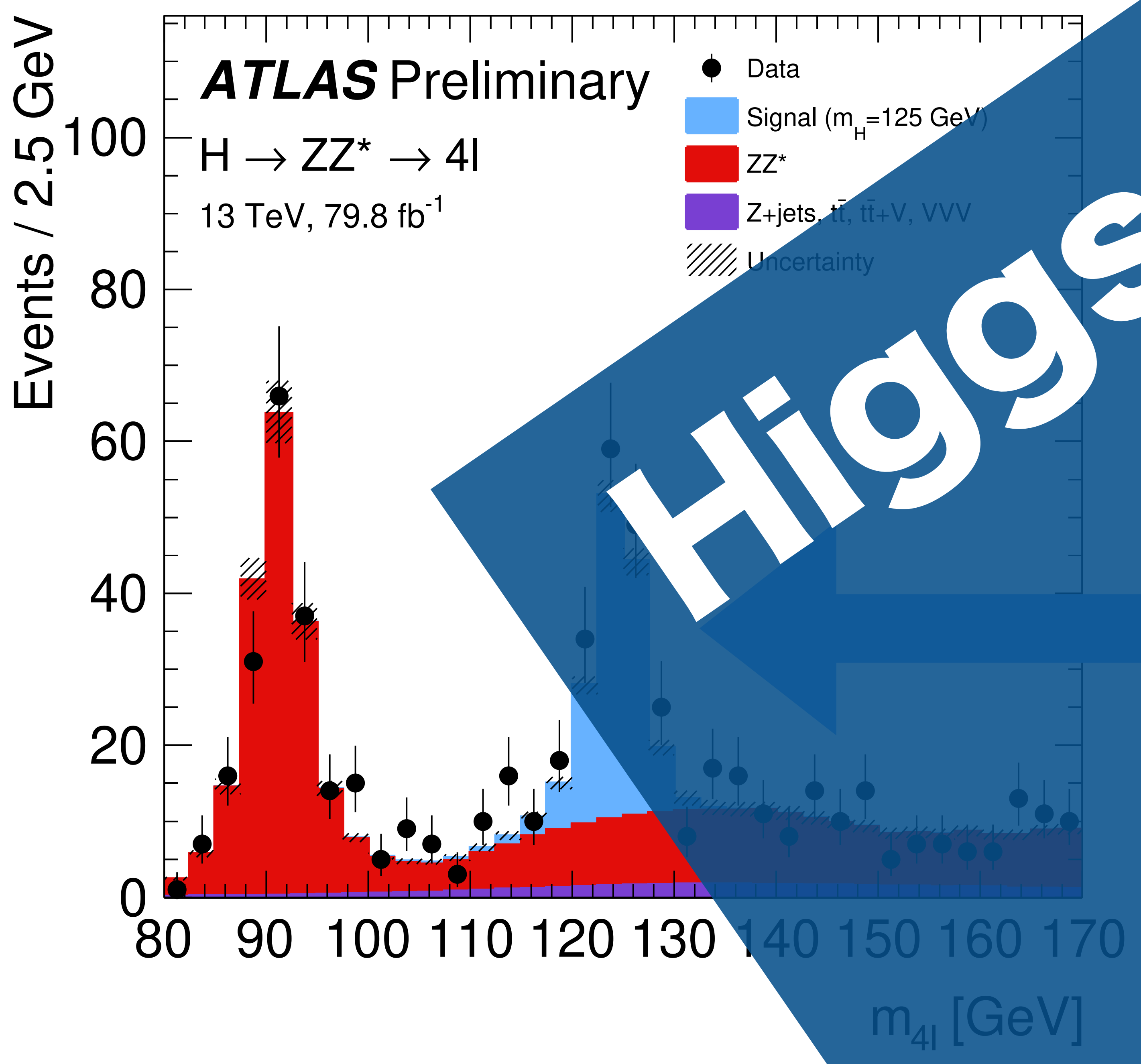


what terms are there in the Higgs sector?
2. Gauge–Higgs term

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

Z boson mass term

ZZH interaction term

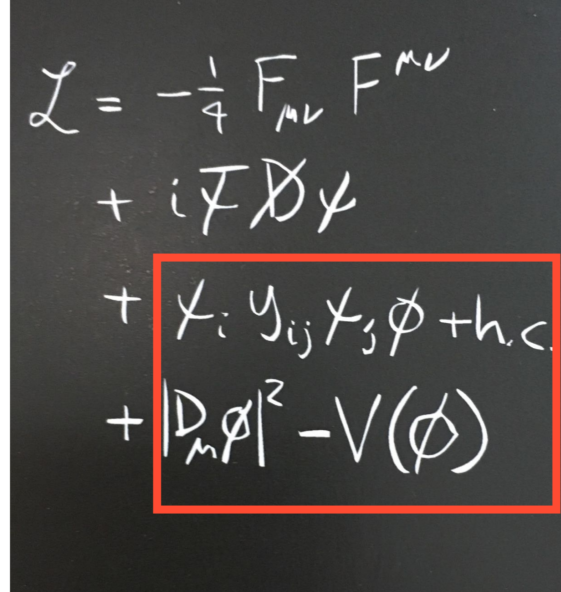


H → ZZ*

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

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

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



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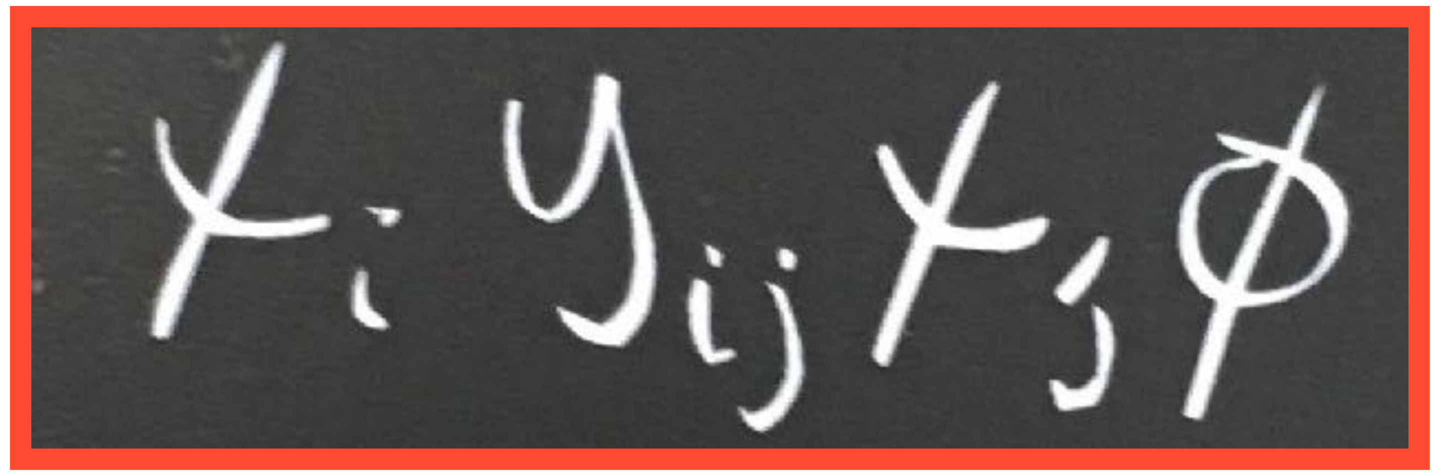

$$\rightarrow \; y_{ij}\, \phi_0\, \psi_i\, \psi_j \; + \; y_{ij}\, H\, \psi_i\, \psi_j$$

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?
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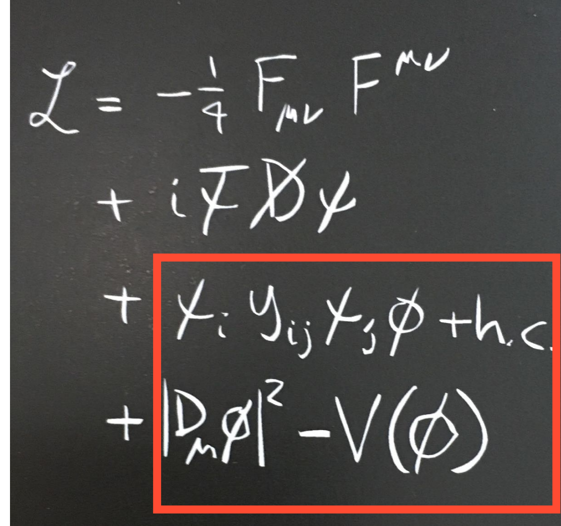

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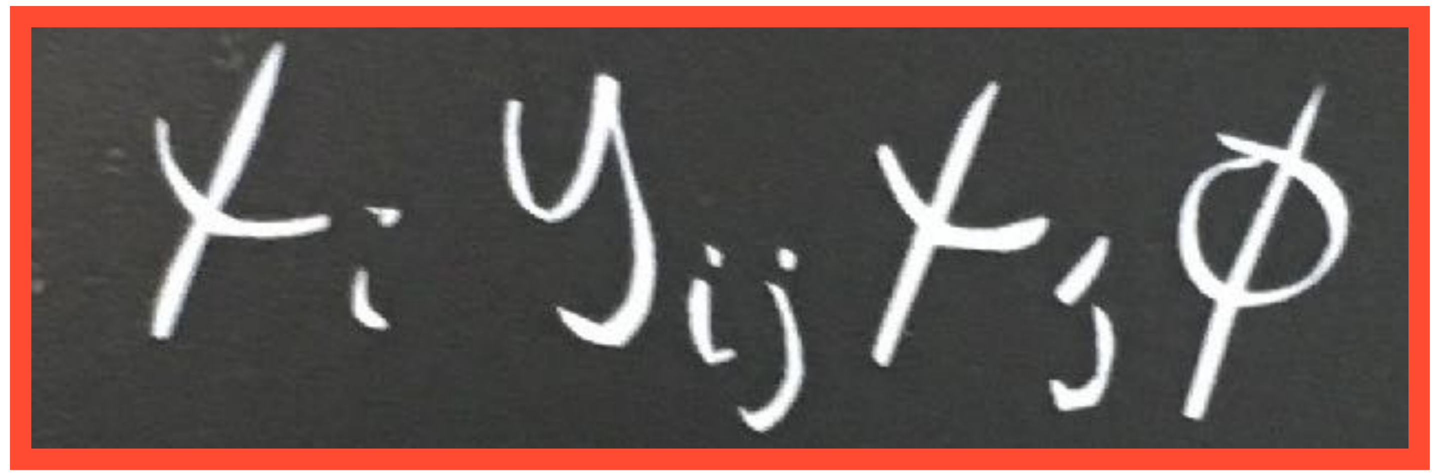


$\rightarrow \; y_{ij}\,\phi_0\,\psi_i\,\psi_j + y_{ij}\,H\,\psi_i\,\psi_j$

fermion mass term

$m_i = y_{ii}\phi_0$

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

the subject of the next few slides

i	y_i	i	y_i
u	$2\cdot 10^{-5}$	d	$3\cdot 10^{-}$[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	$1\cdot 10^{-4}$

$\phi = \phi_0 + H$

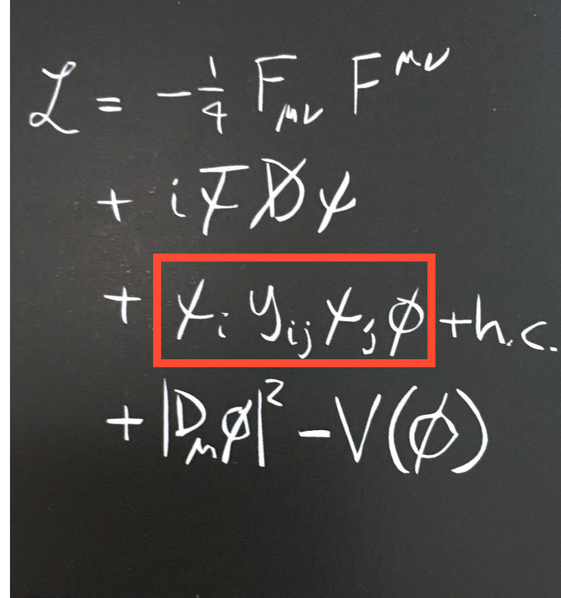
Yukawa interaction hypothesis

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**

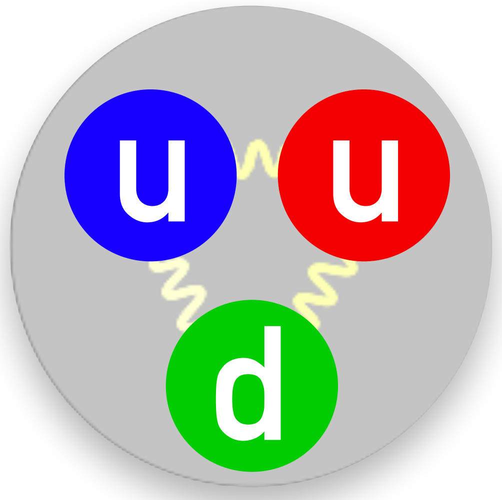


This equation neatly sums up our current understanding of fundamental particles and forces.

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

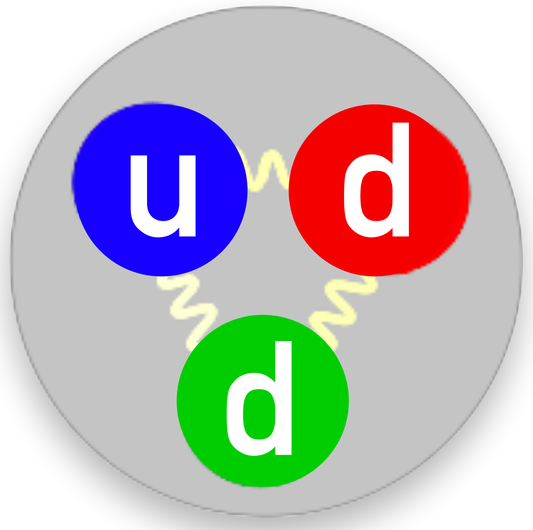
proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

proton
mass = 938.3MeV



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

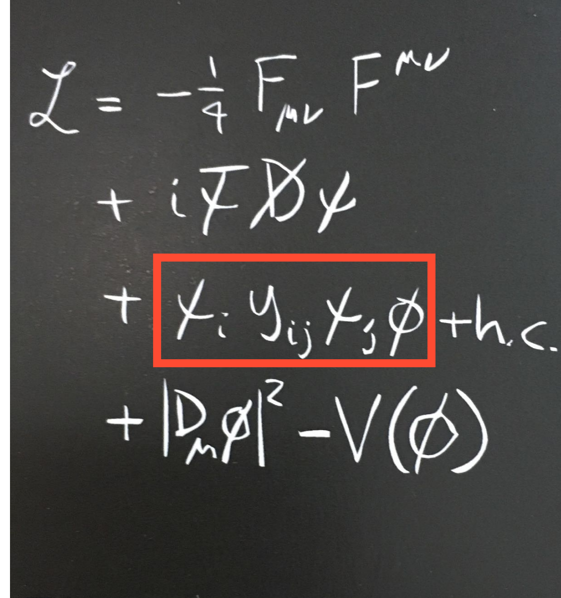
neutron
mass = 939.6MeV



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

Why do Yukawa couplings matter?

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



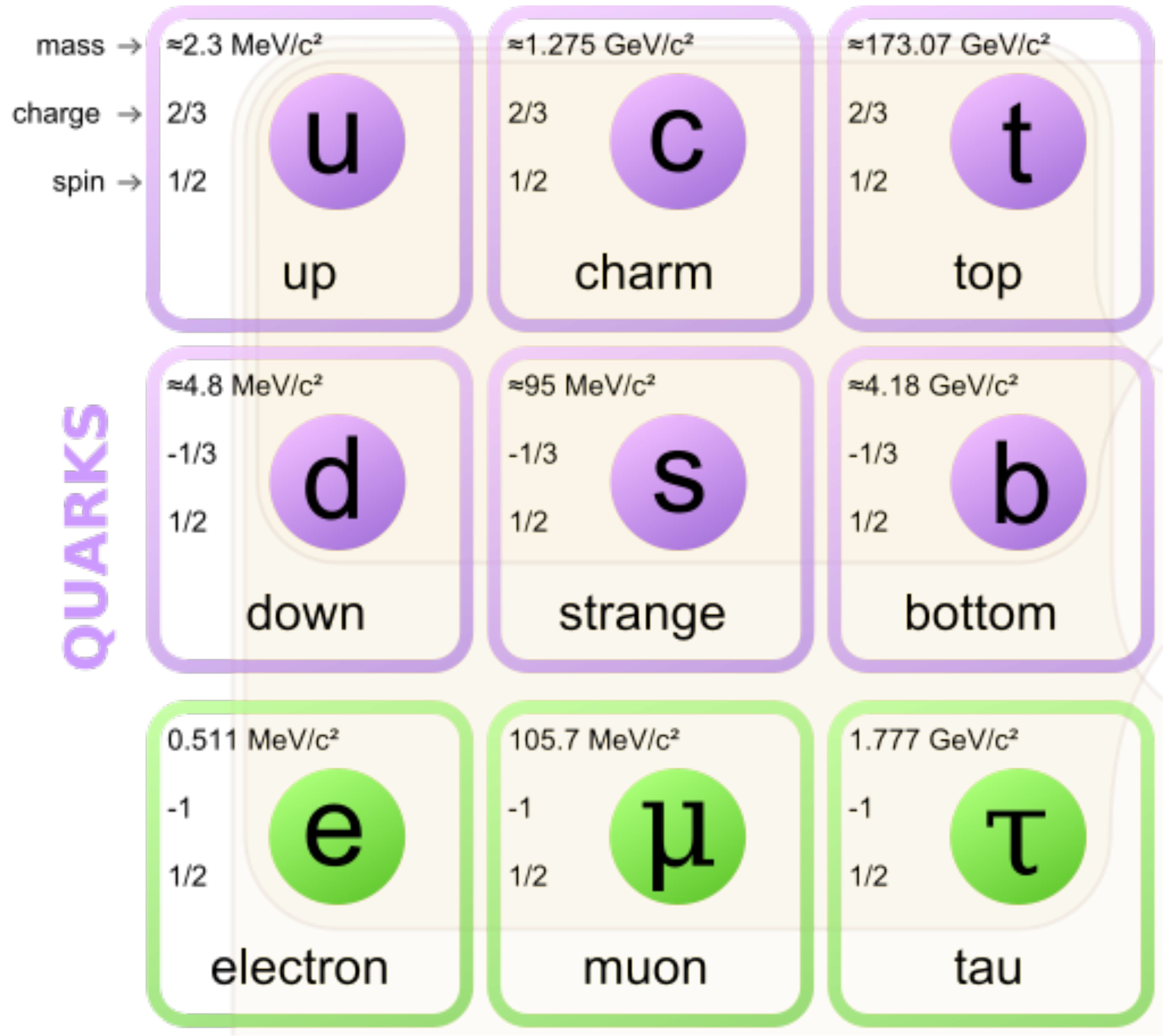
This equation neatly sums up our current understanding of fundamental particles and forces.

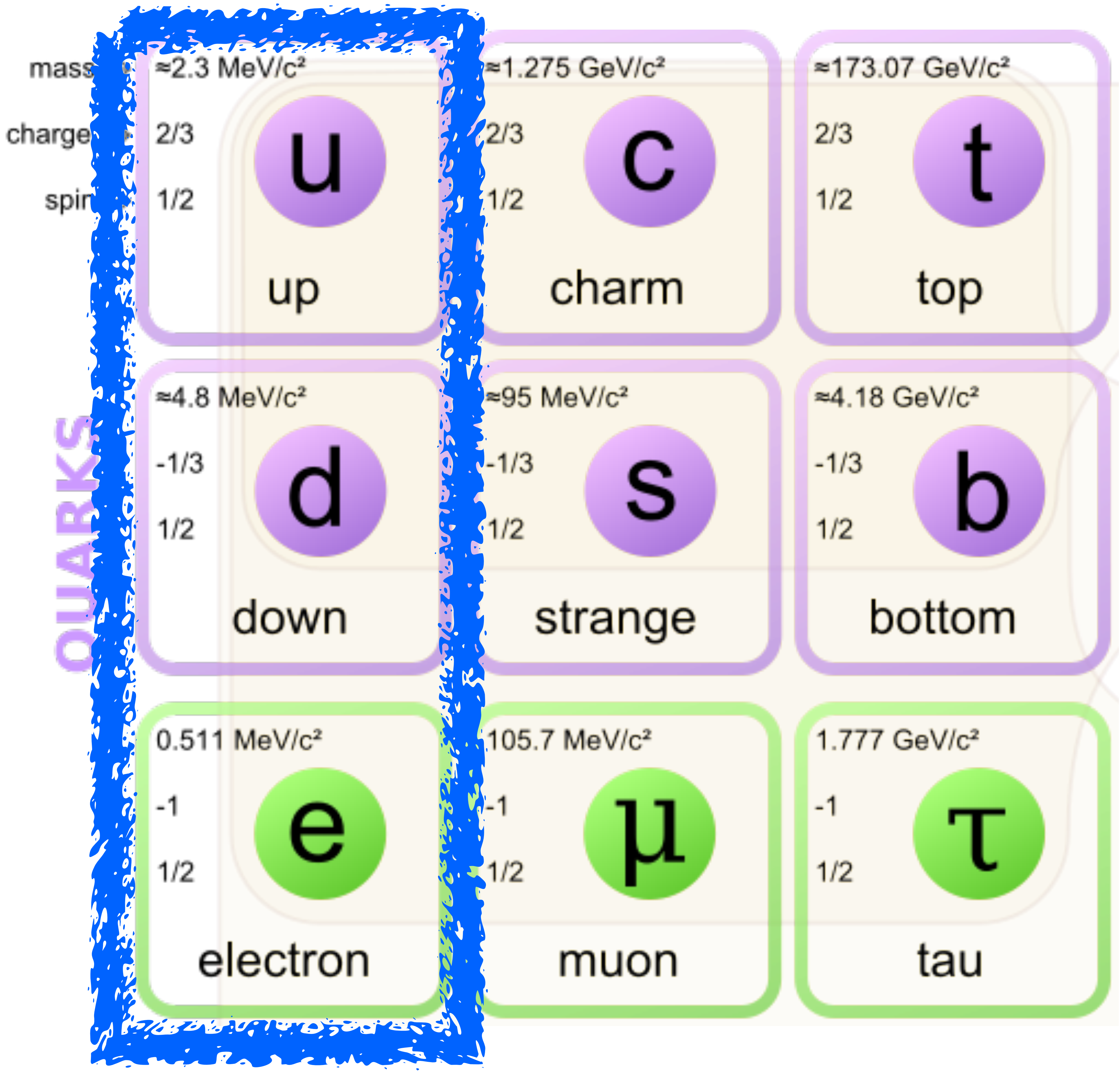
Bohr radius

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

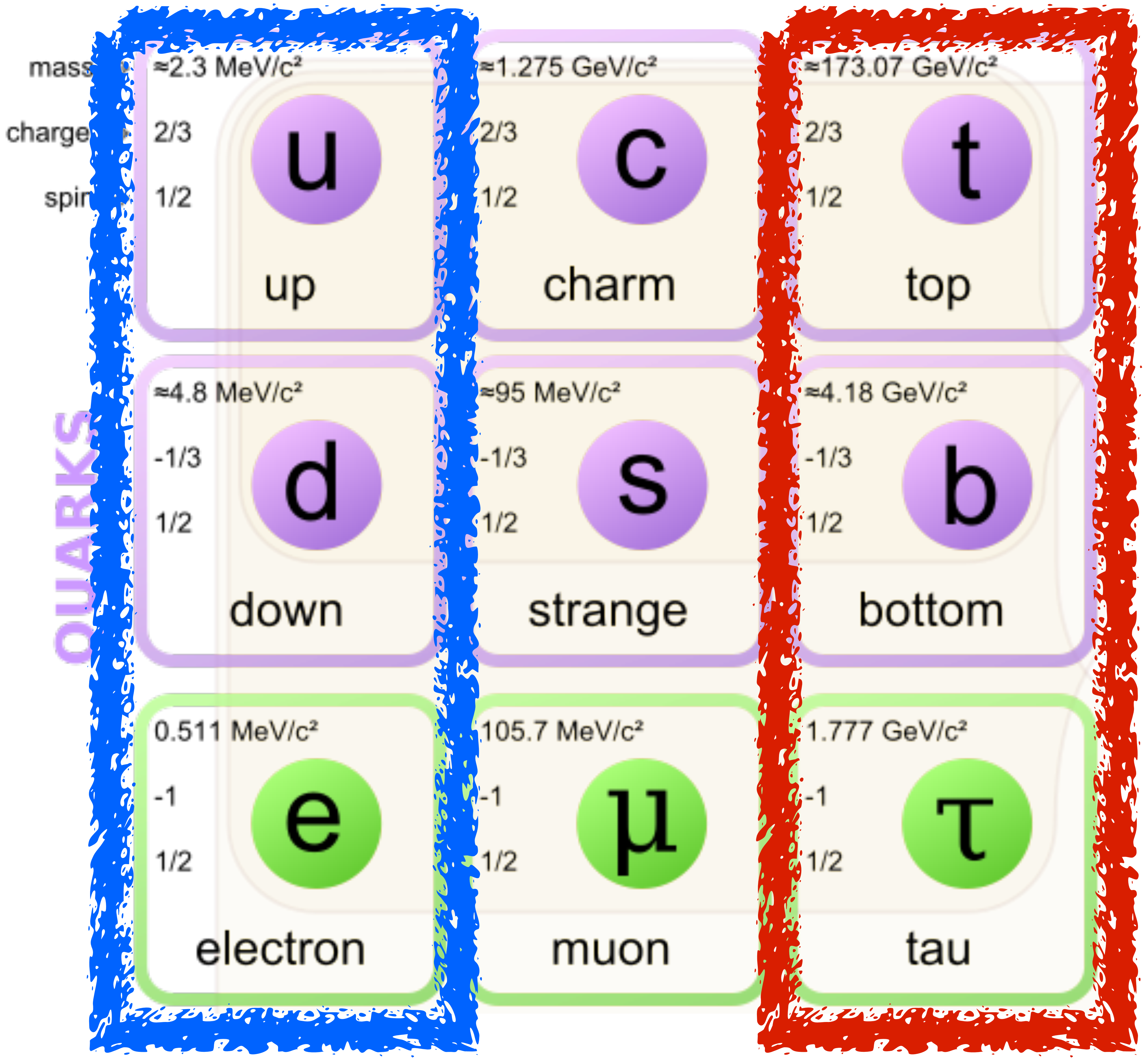
electron mass determines size of all atoms

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

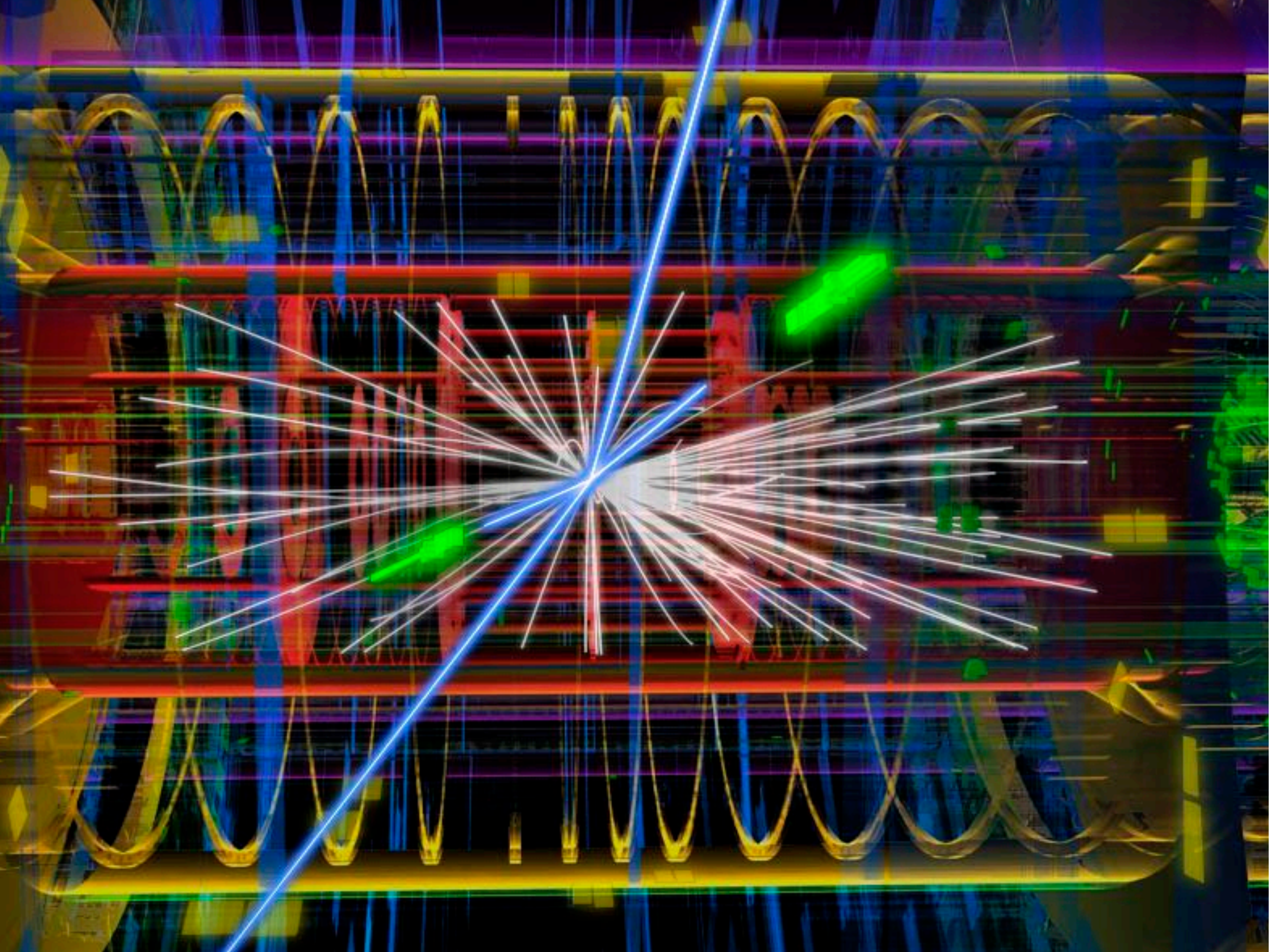


1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**



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



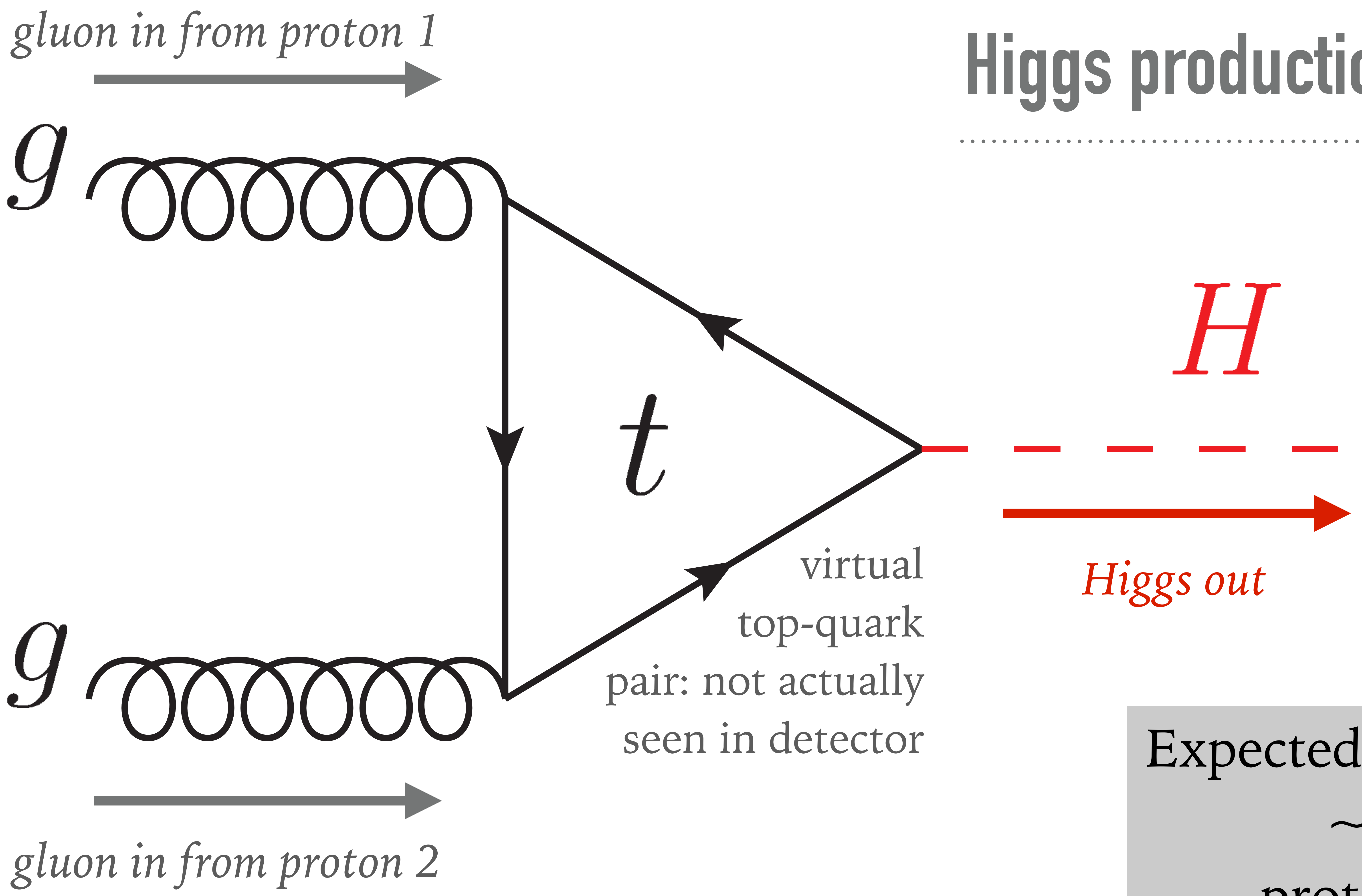
ATLAS & CMS
@LHC

~up to 2 billion collisions/second

(+ lower rates at LHCb and ALICE)

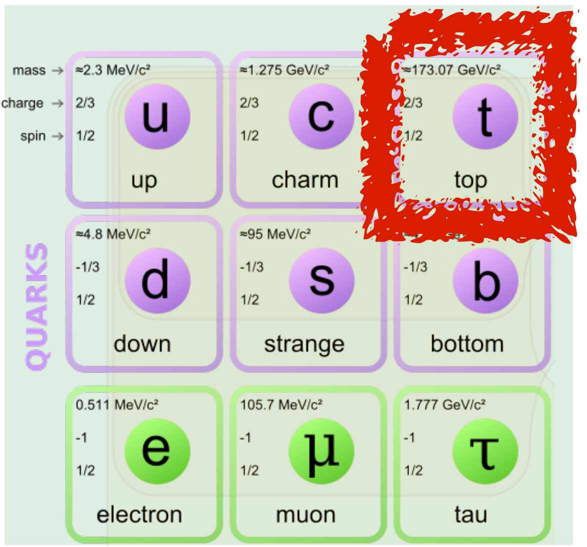
what underlying processes tell us about Yukawa interactions?

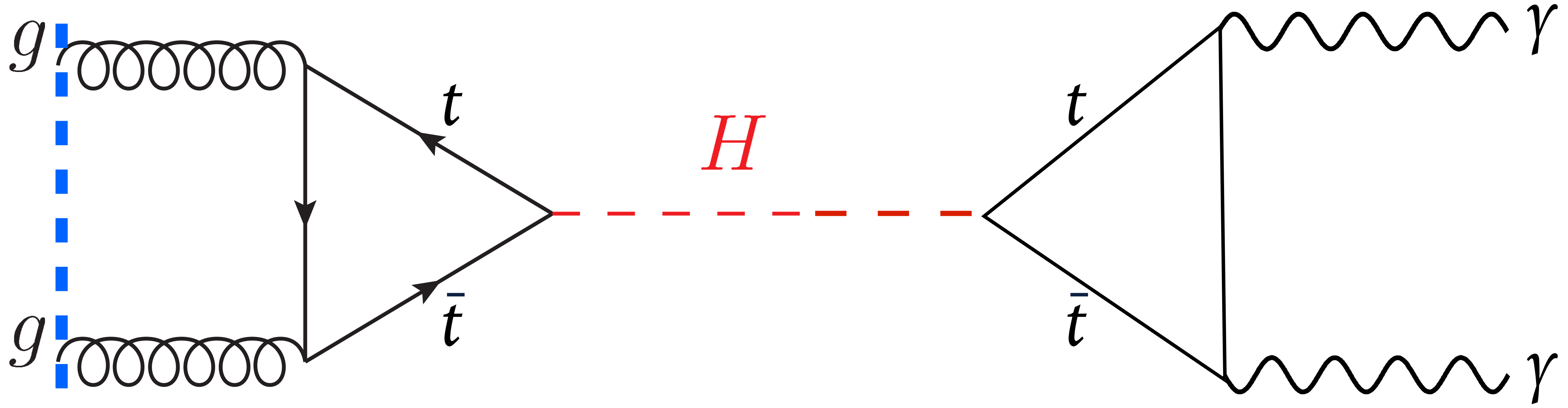
Higgs production: the dominant channel



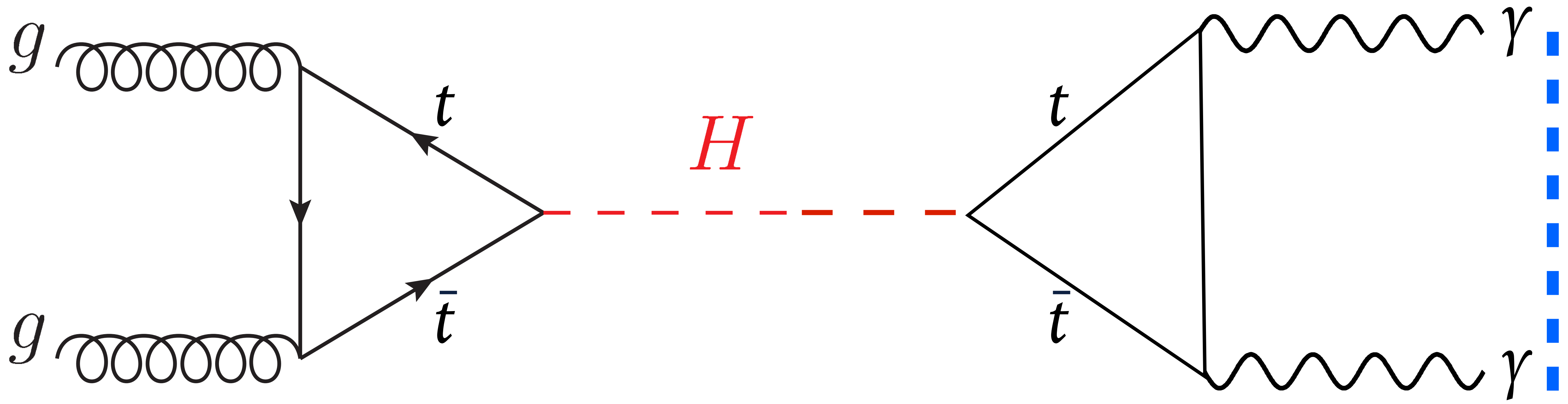
Expected to happen once for every ~2 billion inelastic proton–proton collisions

LHC data consistent with that already at discovery in 2012




g
g
t
$\bar{t}$
H
t
$\bar{t}$
γ
γ


luon
gluo
φ
y
x
Higgs field in space


g
g
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H
t
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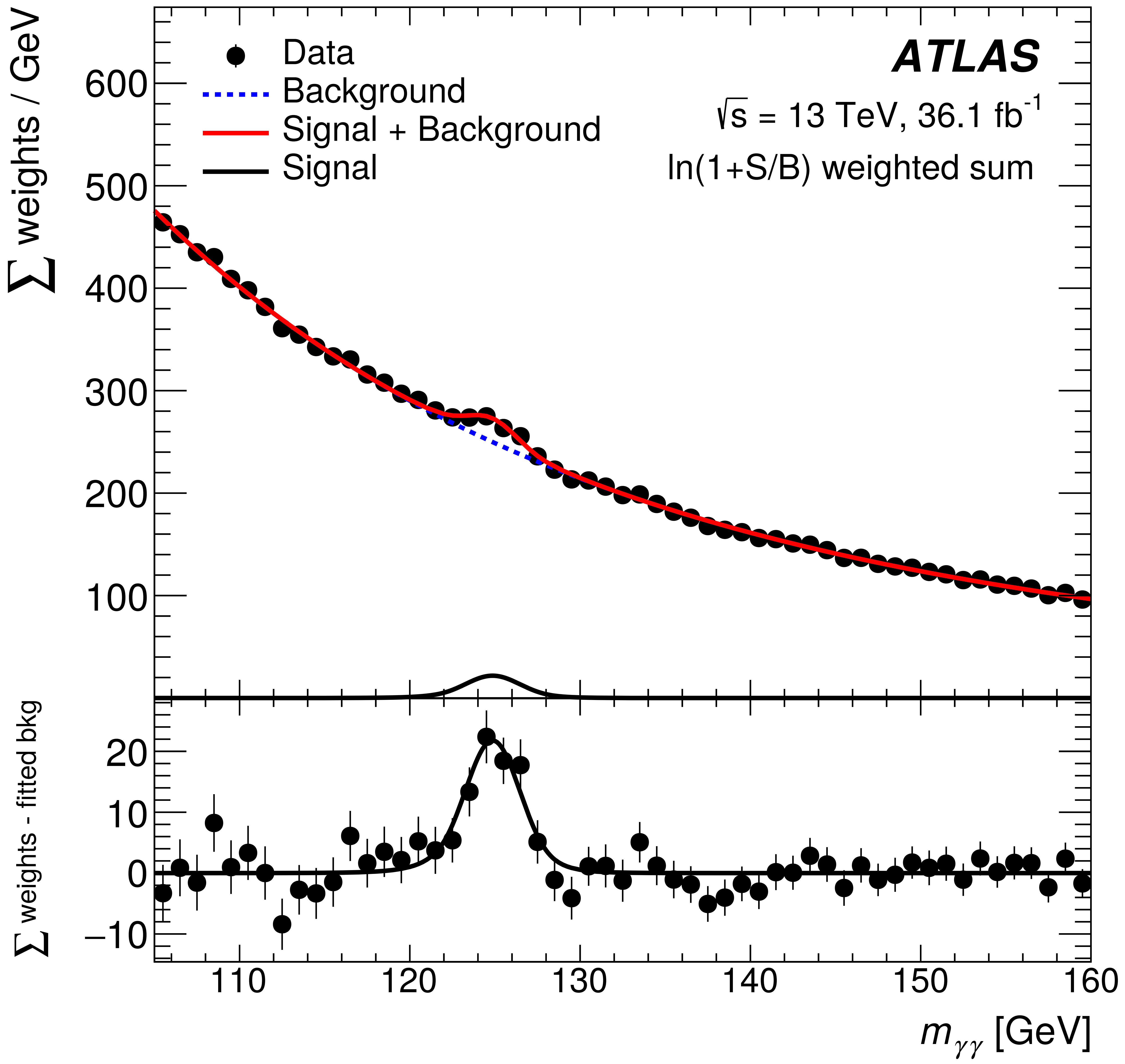
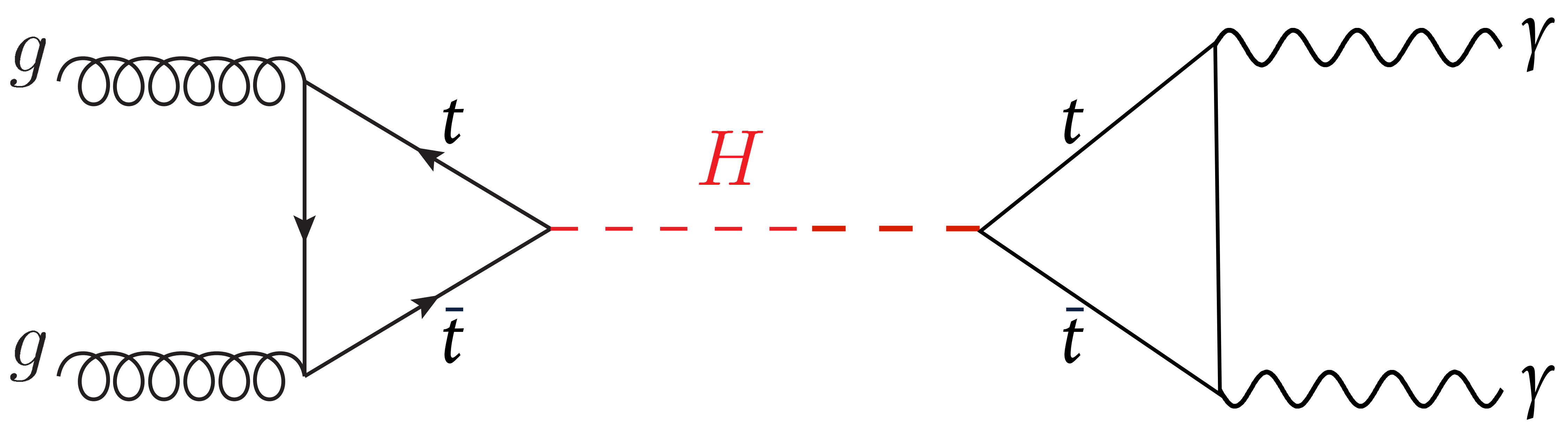
γ
γ

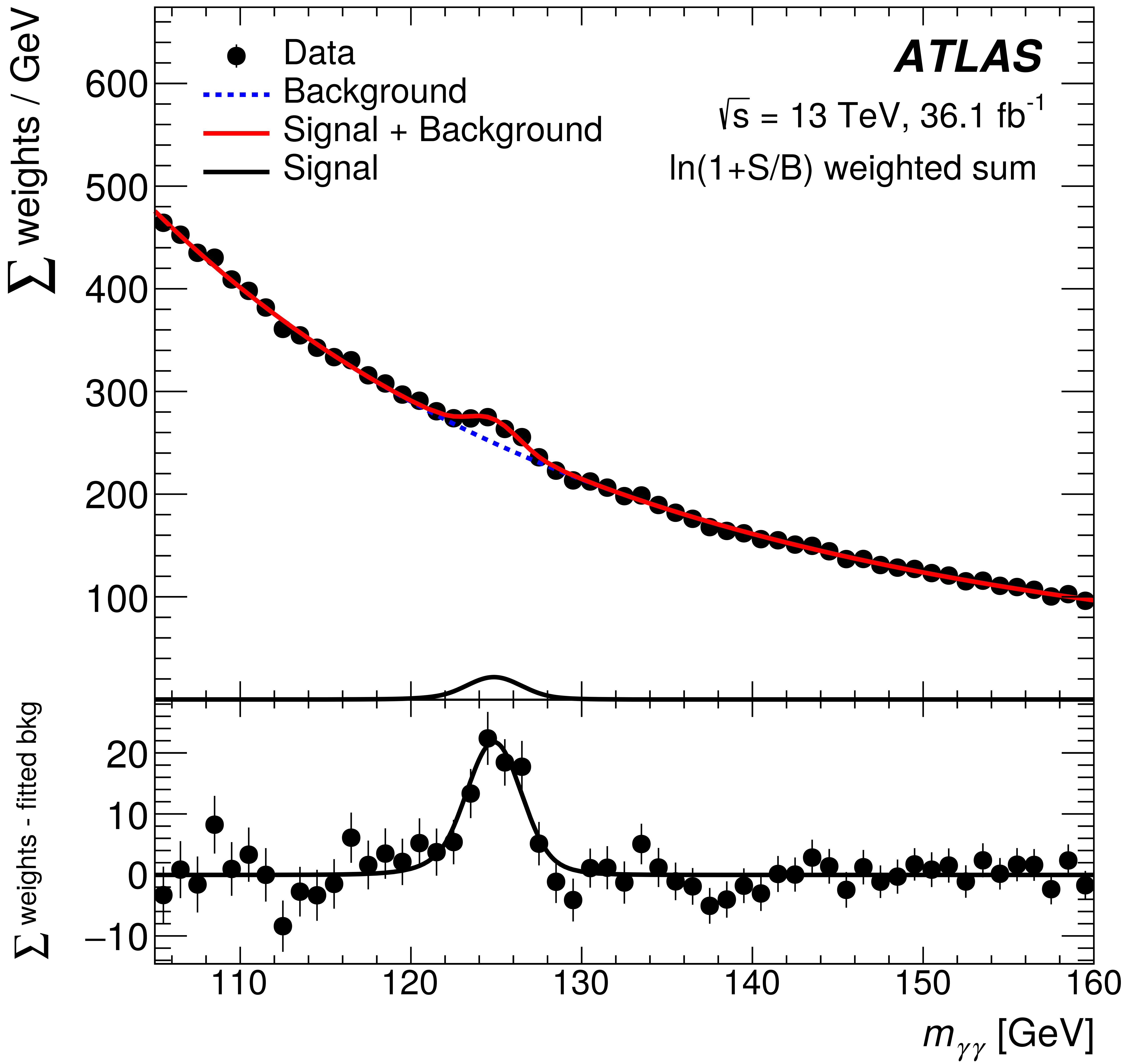

luon
gluo
φ
y
x
Higgs field in space

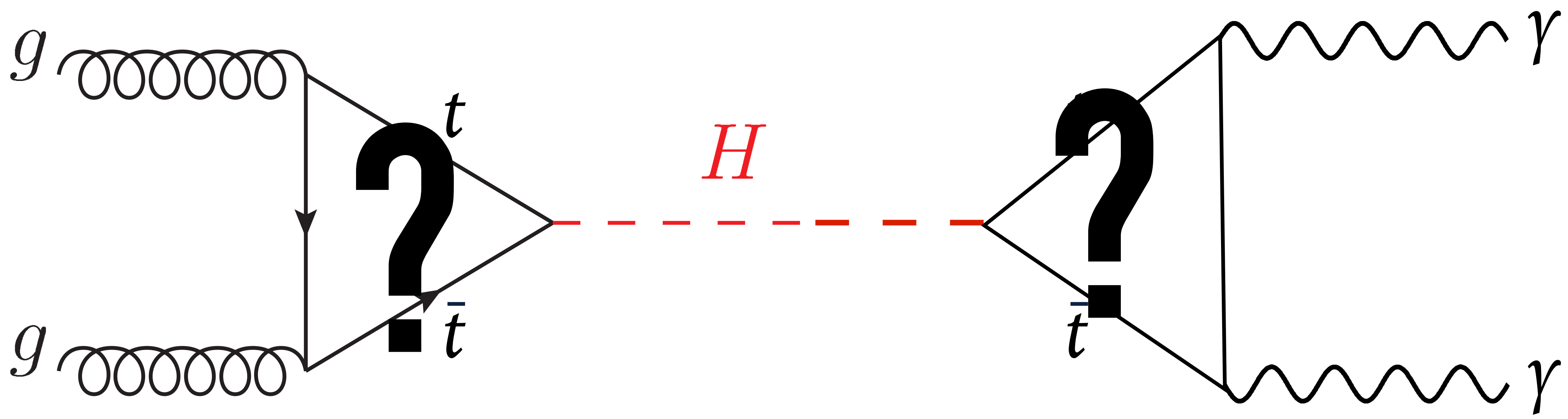


Data
Background
Signal + Background
Signal
ATLAS
√s = 13 TeV, 36.1 fb-1
ln(1+S/B) weighted sum
∑ weights / GeV
∑ weights - fitted bkg
m_γγ [GeV]



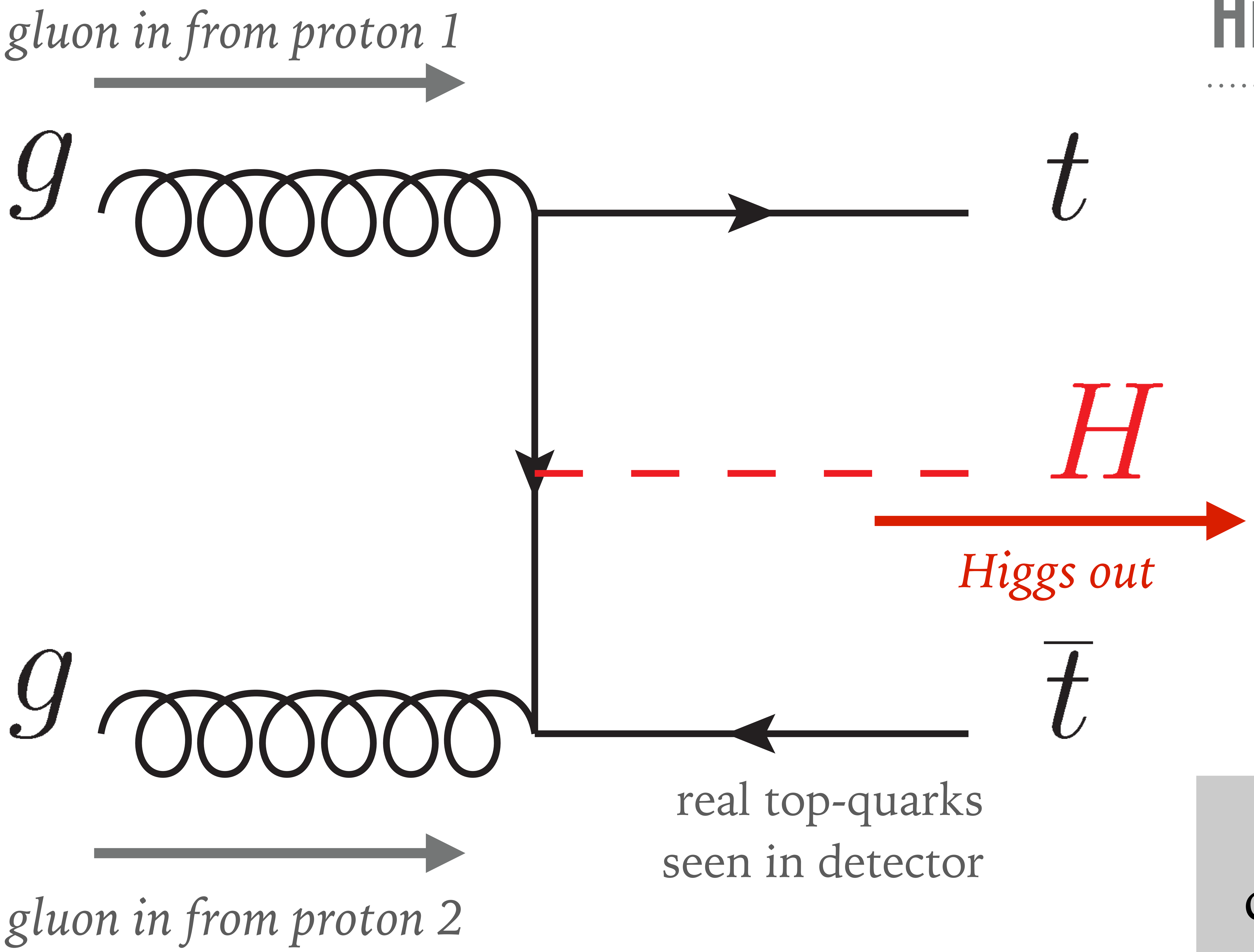
g
g
t
t̄
H
t
t̄
γ
γ





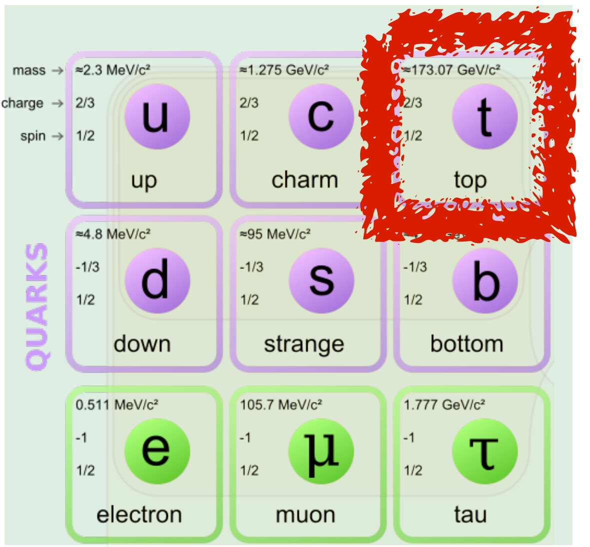
but how can you be sure the Higgs boson is really being radiated off a top-quark, i.e. that you're actually seeing a Yukawa coupling?

Higgs production: the ttH channel

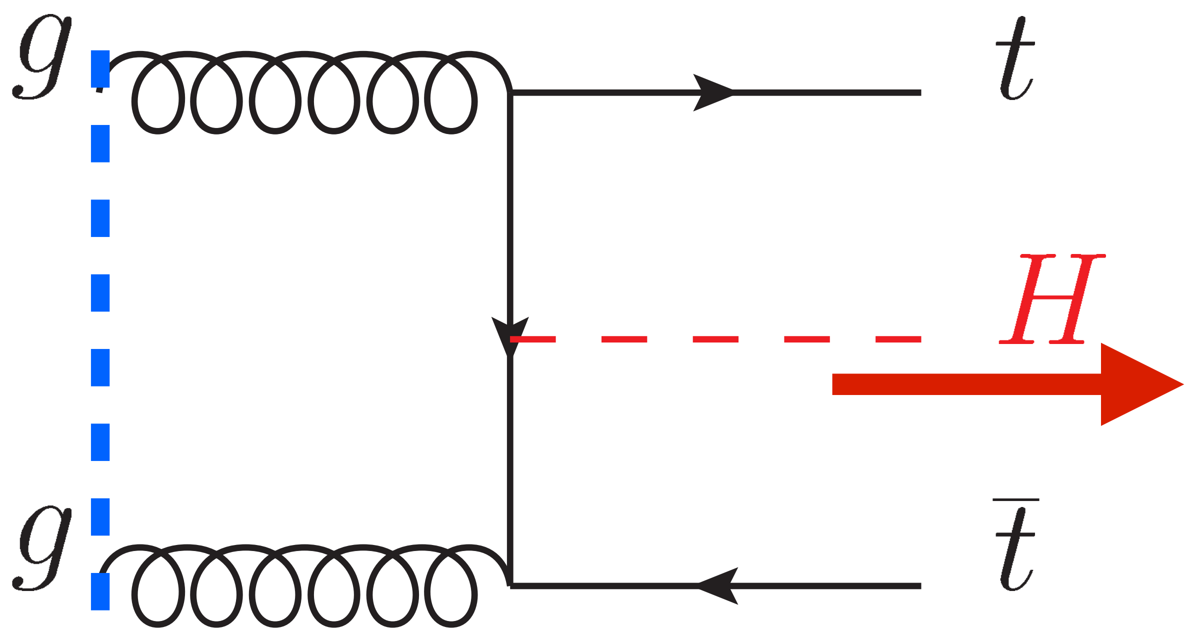


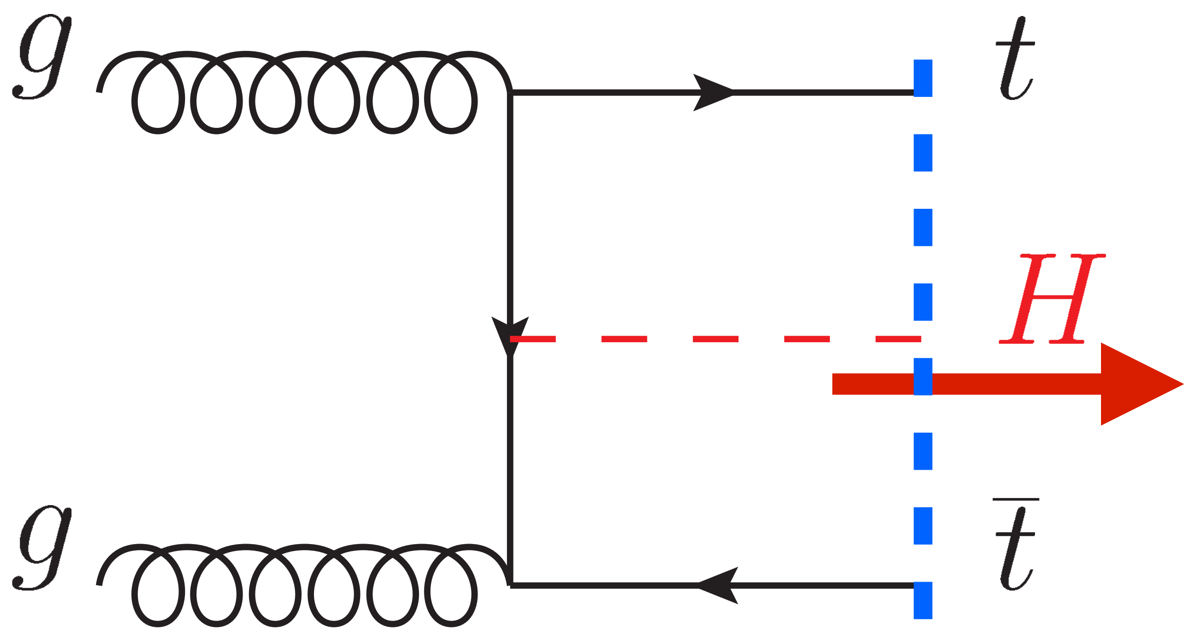
If SM top-Yukawa hypothesis is correct, expect 1 Higgs for every 1600 top-quark pairs.

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

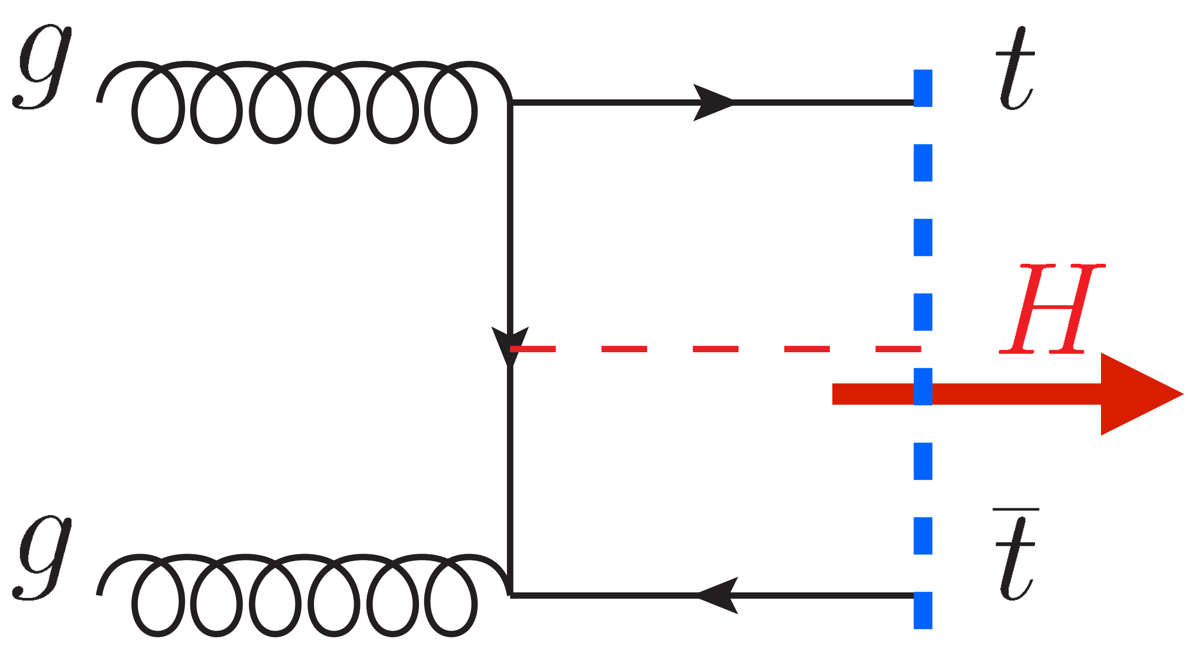


https://cern.ch/gsalam/higgs




g
g
t
H
$\bar{t}$

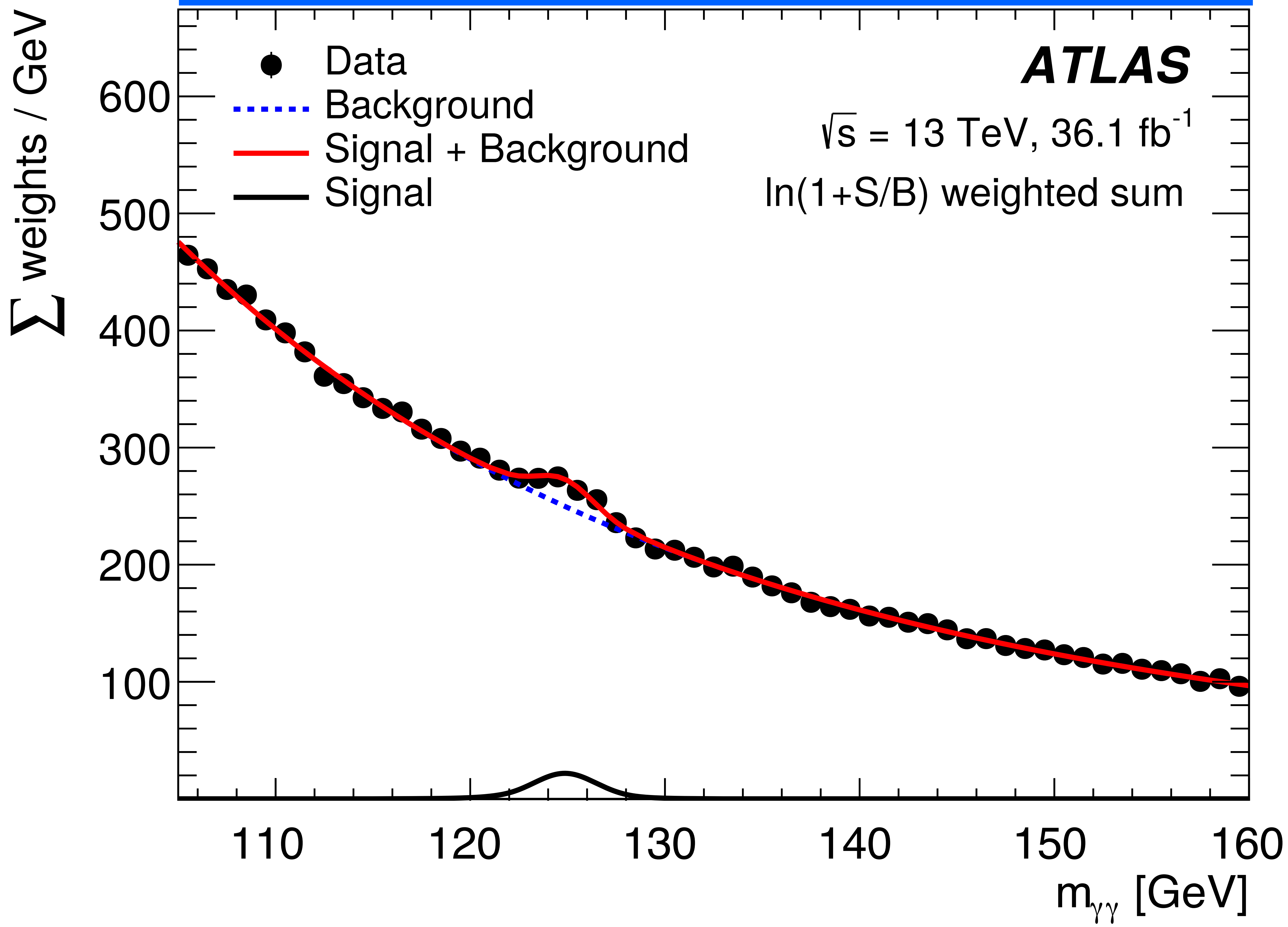

luon
gluo
φ
y
x
Higgs field in space


g
t
H
g
t̄

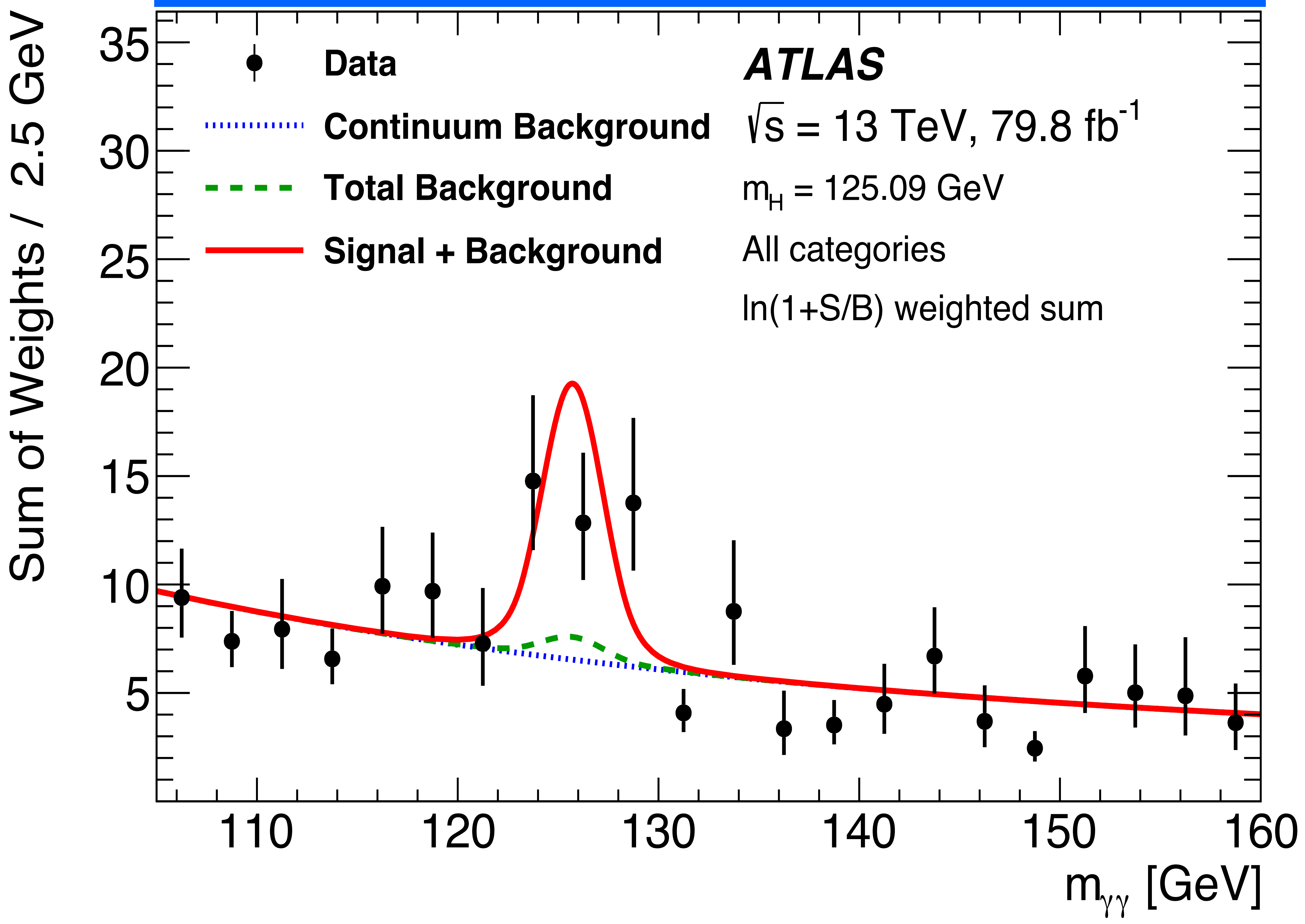

luon
gluo
φ
y
x
Higgs field in space

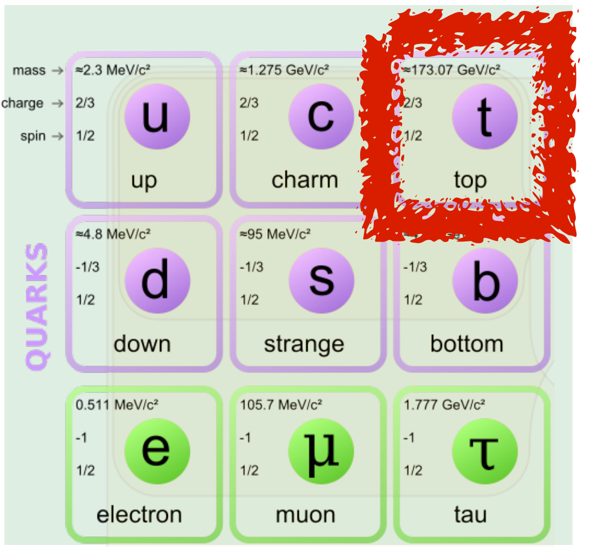
the news of the past 18 months: ATLAS & CMS see events with top-quarks & Higgs simultaneously

across all events



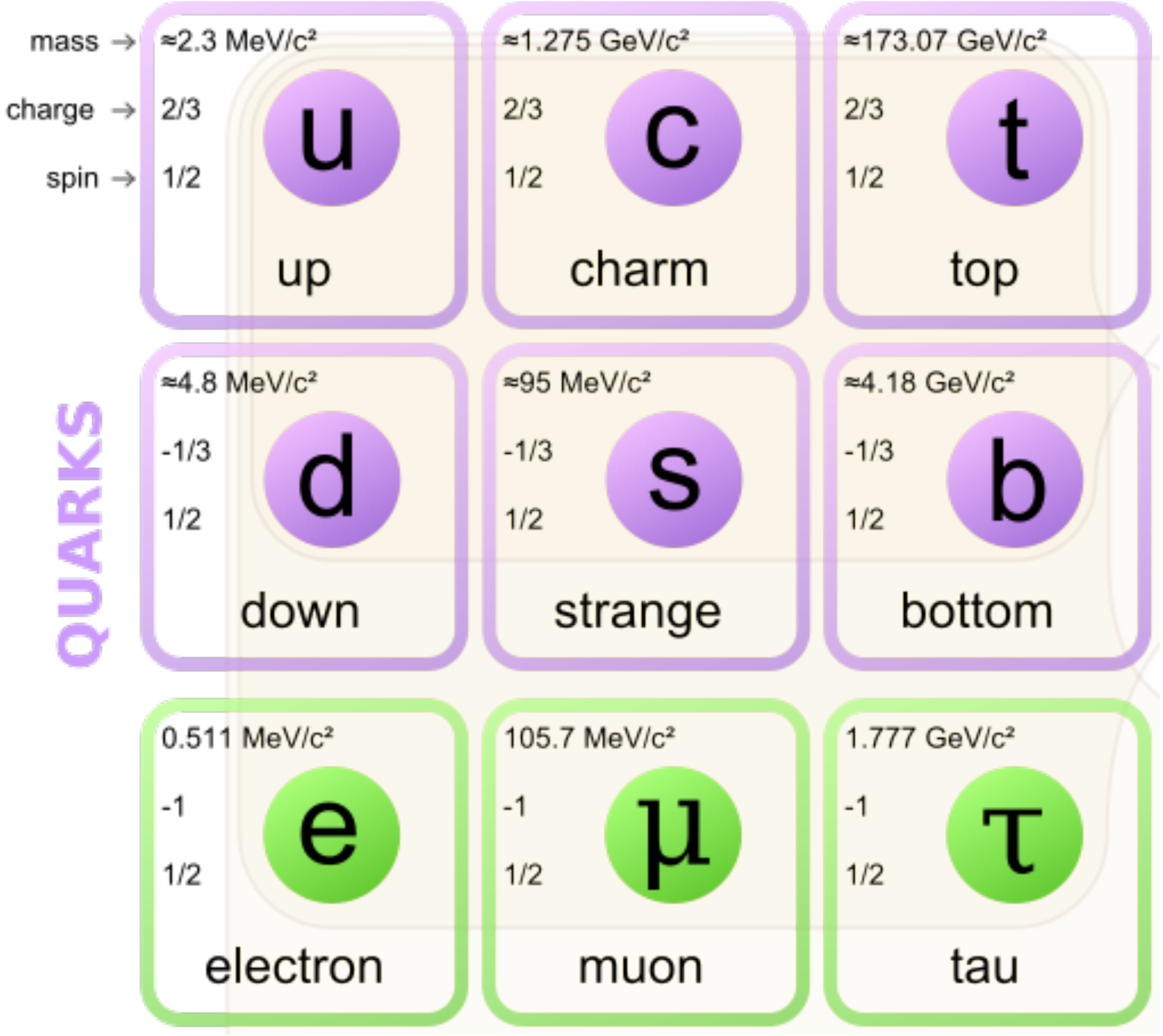
in events with top quarks





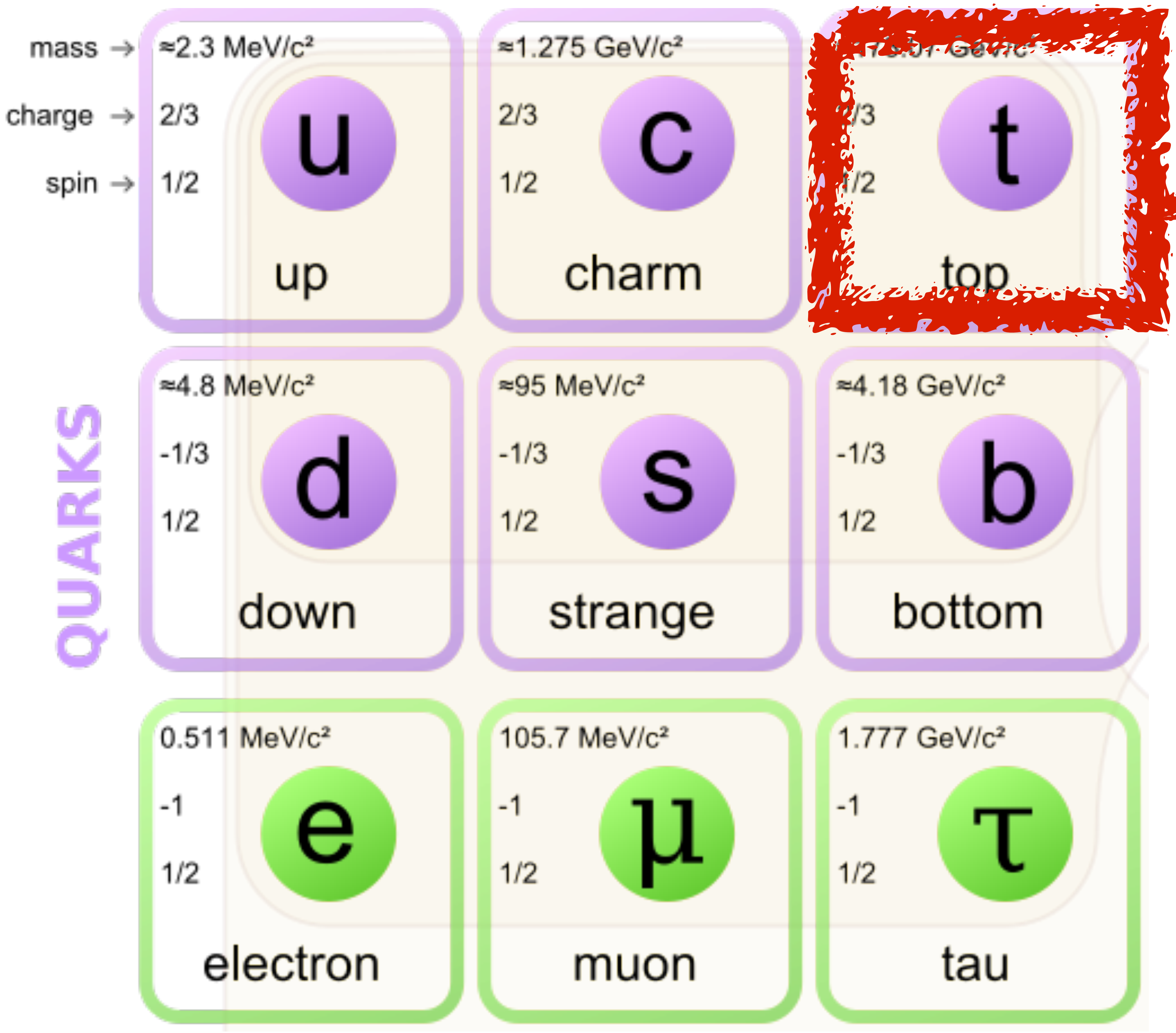
enhanced fraction of Higgs bosons in events with top quarks
→ direct observation of Higgs interaction with tops
(consistent with SM to c. ±20%)

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



$$\text{Discovery} \equiv 5\sigma \simeq \pm 20\,\%$$

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



by observing *H* in association with top quarks

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

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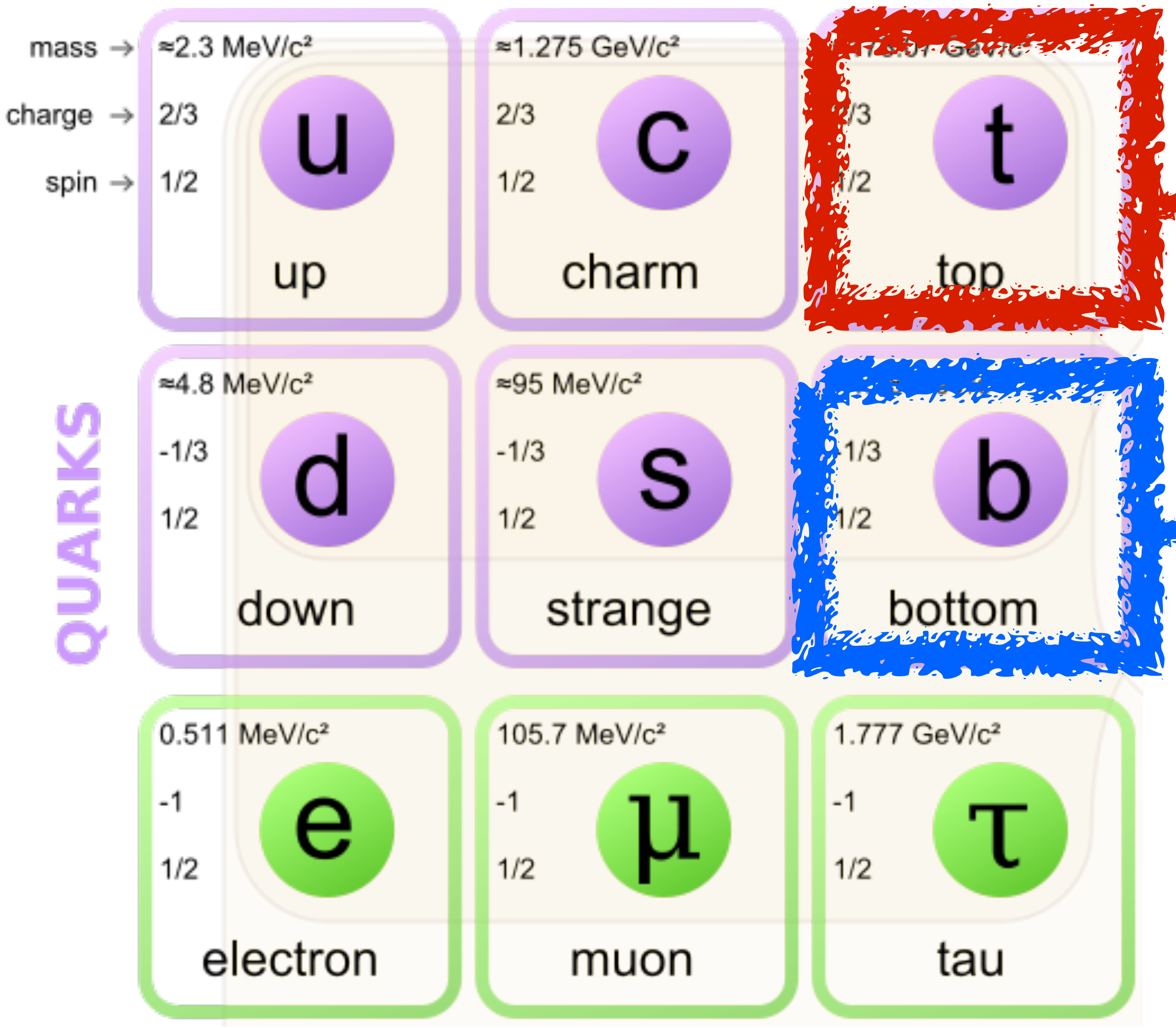

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by observing $H \to b\bar{b}$ decays

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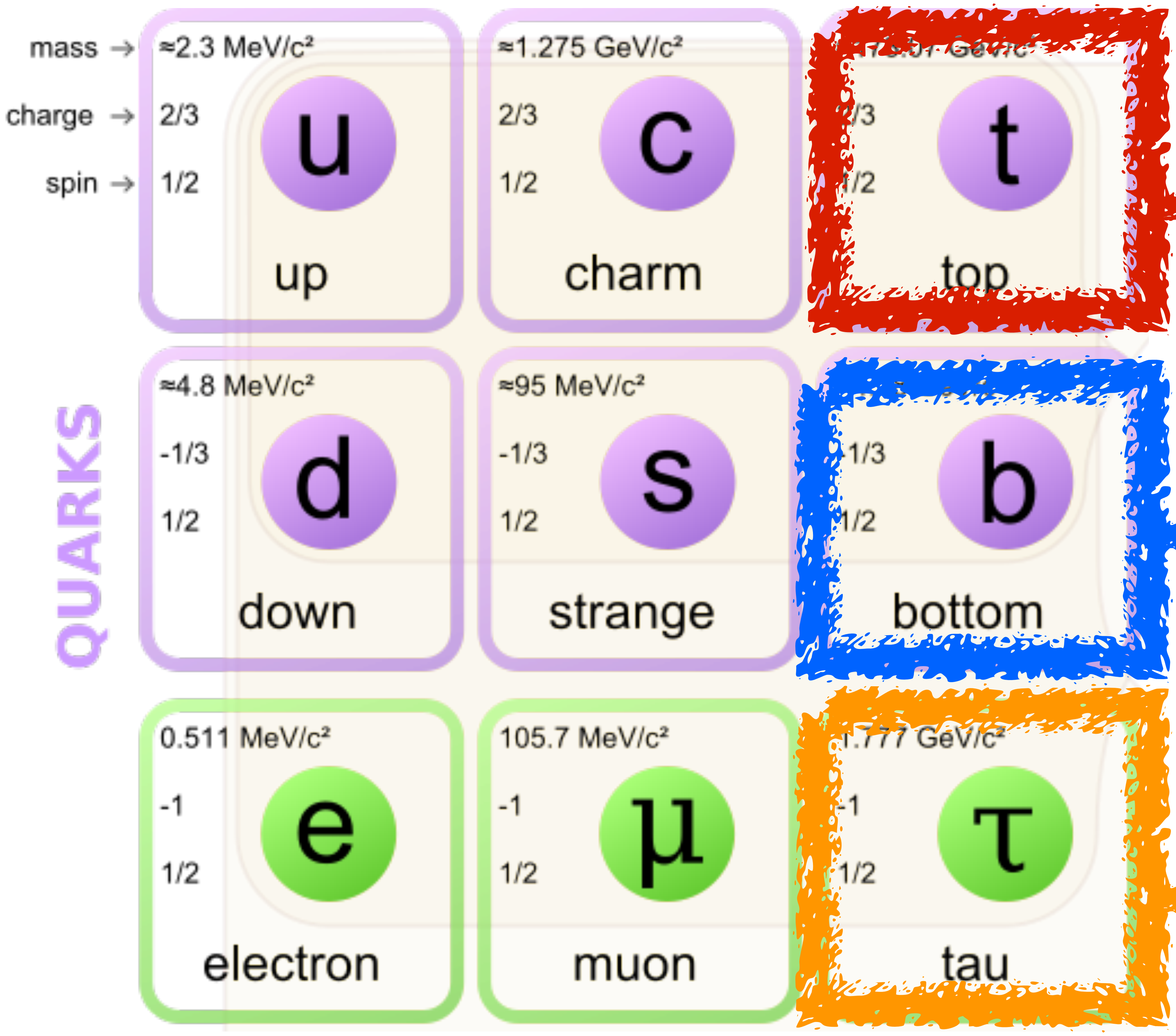

by observing H in association with top quarks

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.

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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?

LHC discovers fifth force, the "Higgs force"

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

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metric for success going forwards [one possible view]

- **Long term:**
  can we observe Higgs self coupling?
  I.e. get an experimental window on the Higgs potential, which underpins the rest of the SM

- **Medium term:**
  evolve today's c. 10-20% constraints on Higgs sector towards accuracy
  (we wouldn't consider QED established if it had only been tested to 10%)

- **Bonuses:**
  maximise our sensitivity to new physics at colliders and smaller experiments,
  (what form it takes and whether it's even accessible is in Nature's hands, not ours)

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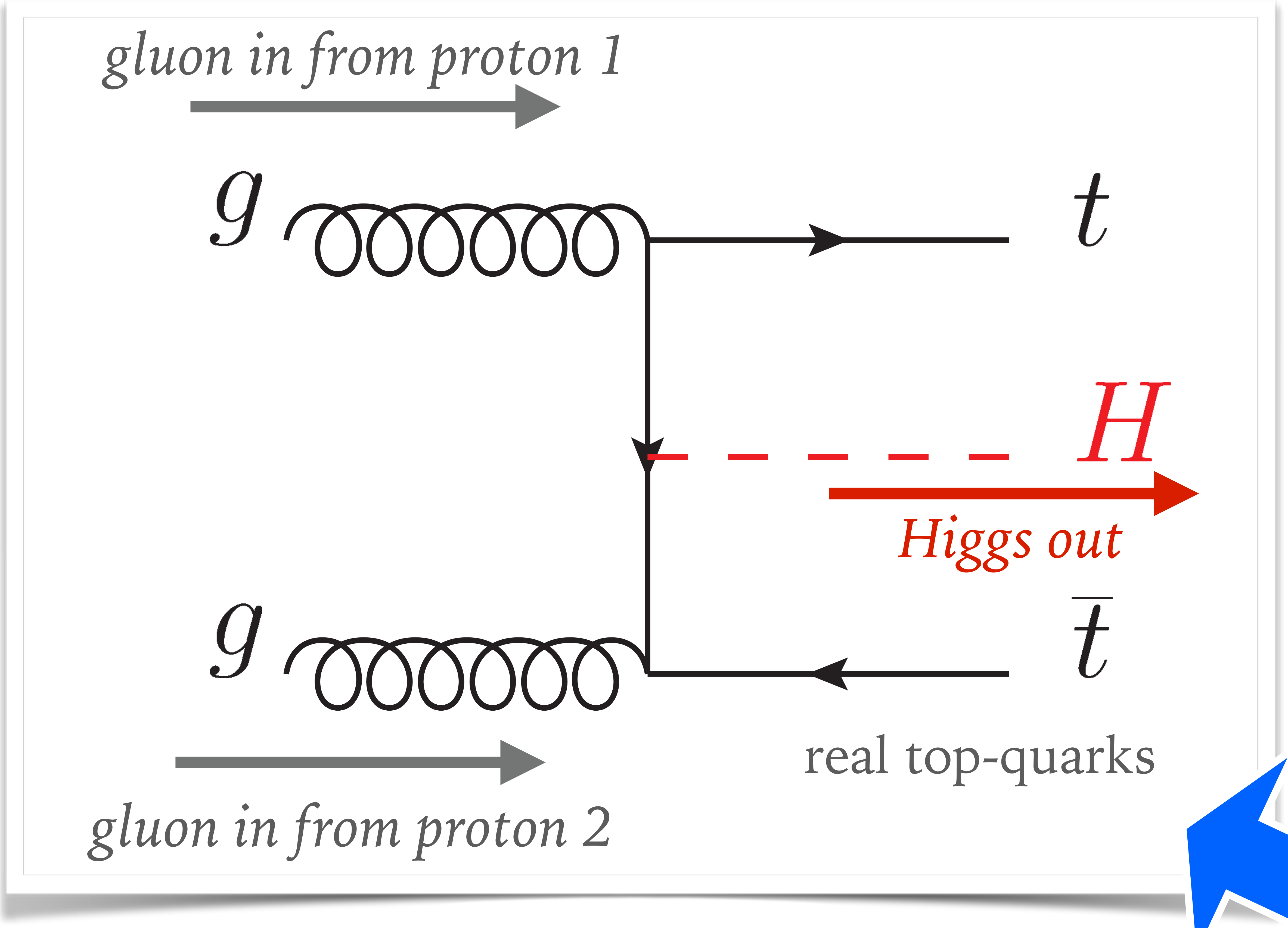
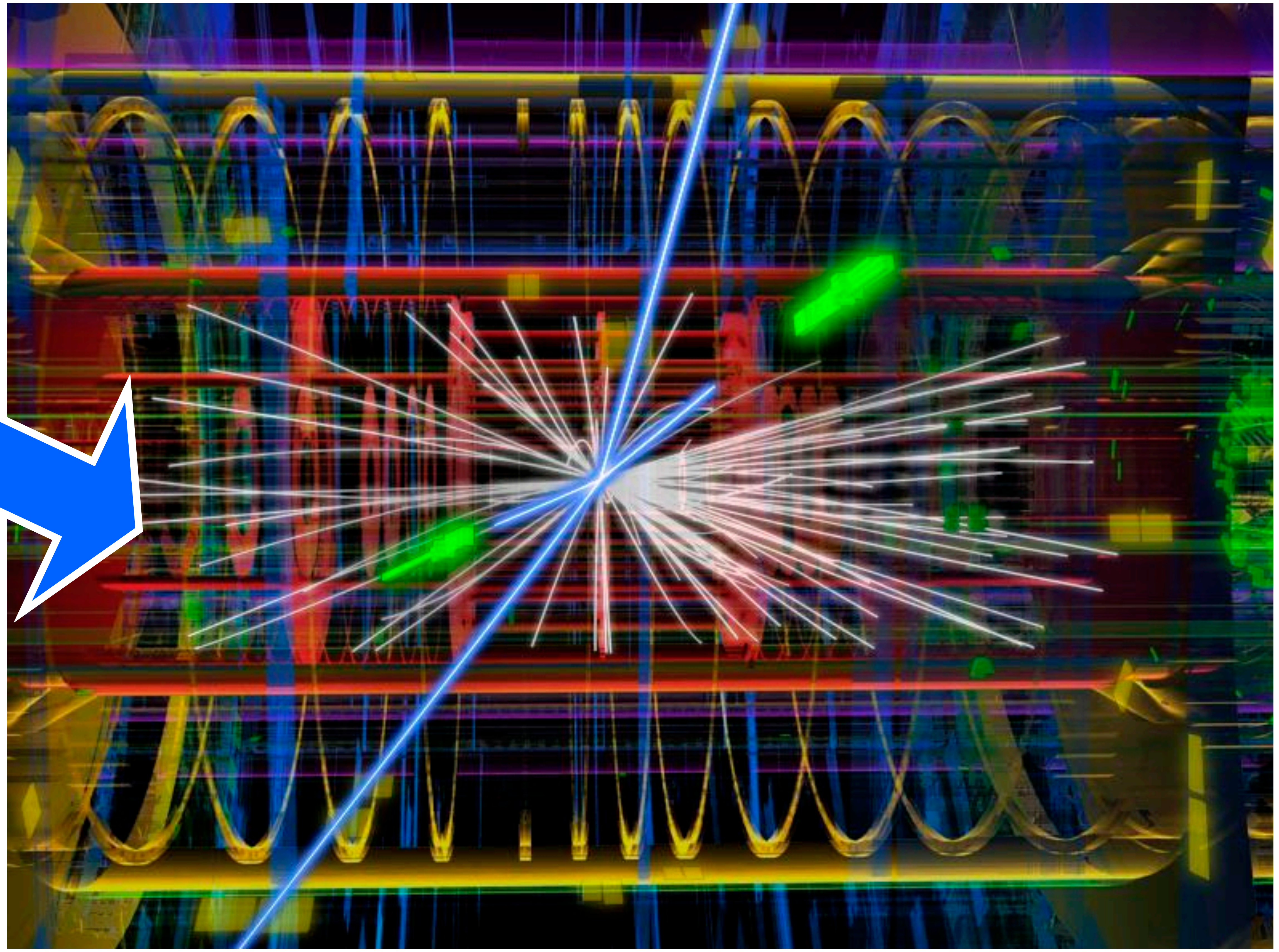
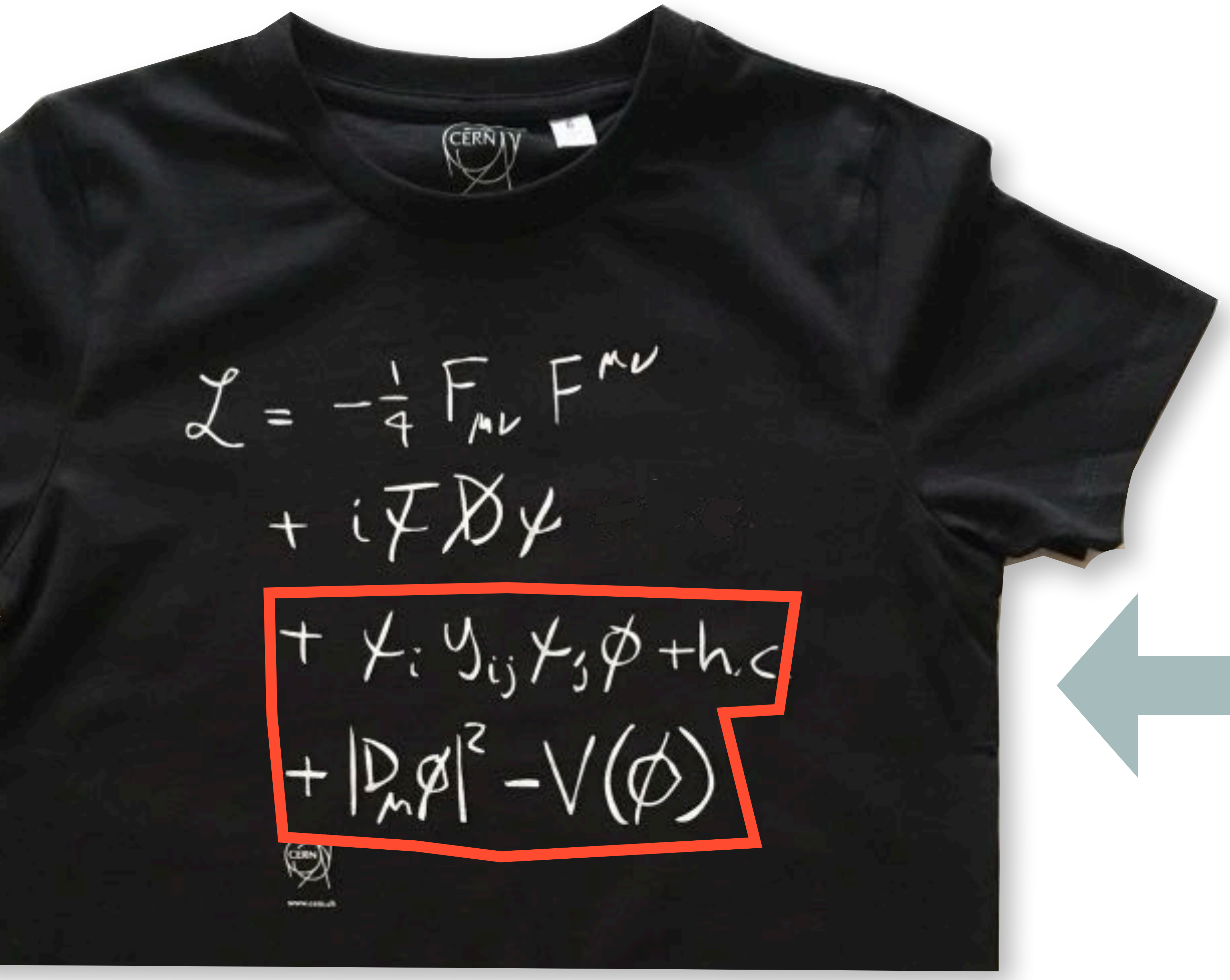




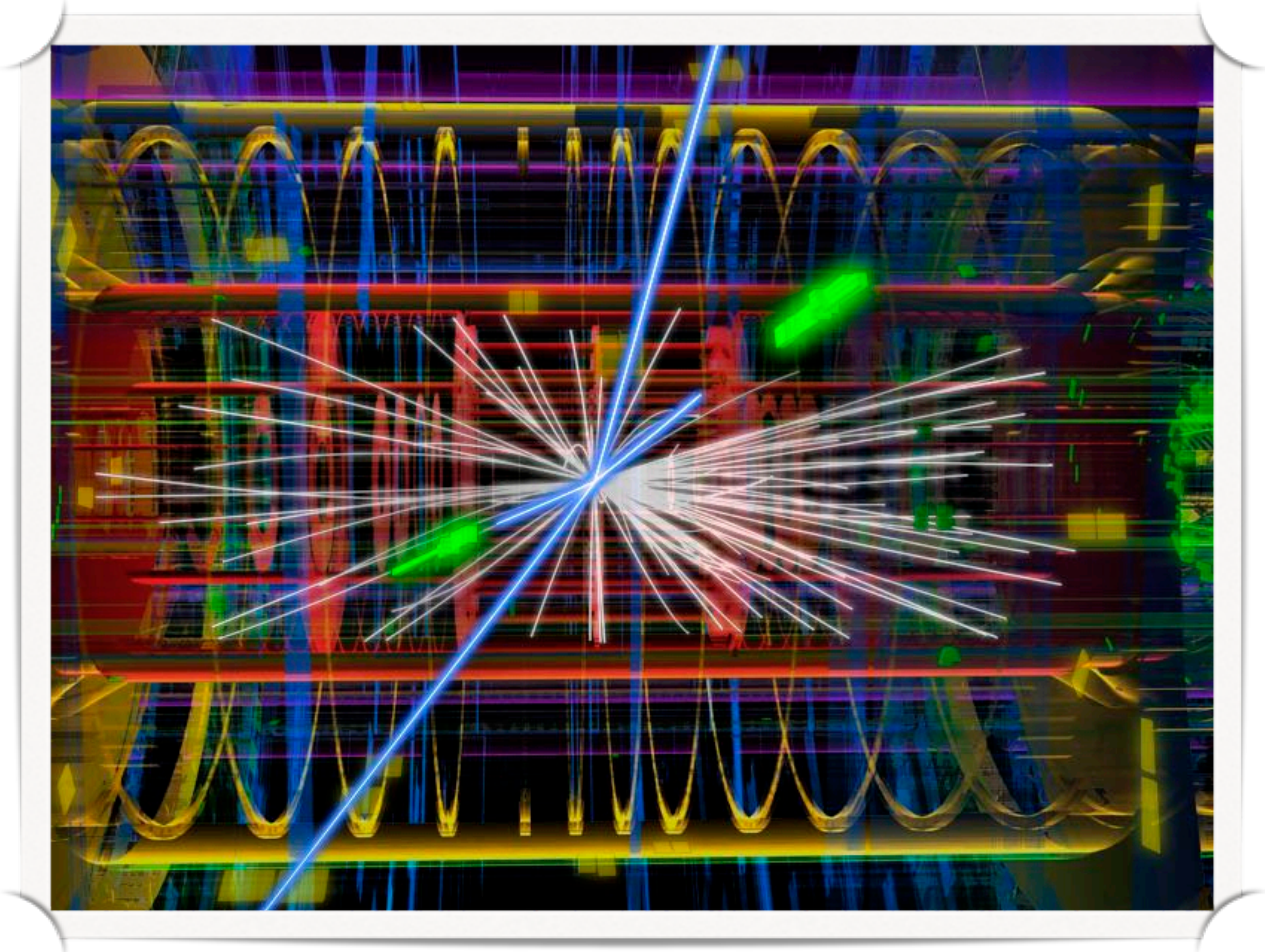
how can one claim a connection, let alone a quantitative one?

UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?



UNDERLYING THEORY

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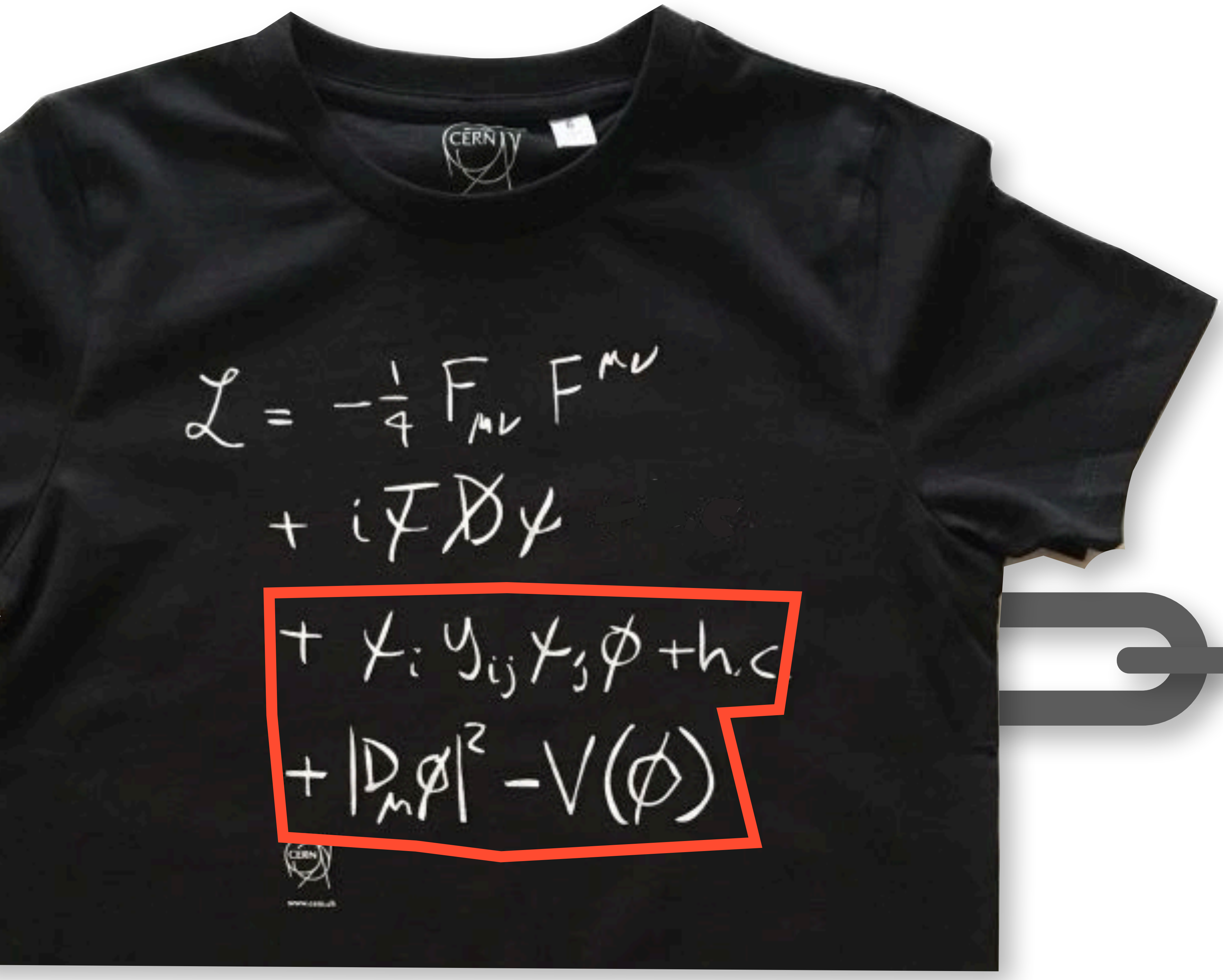

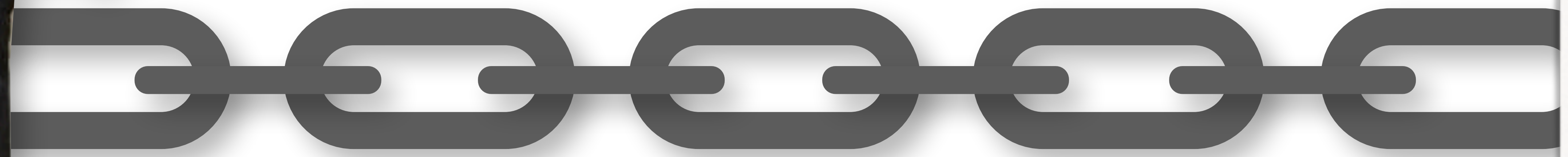

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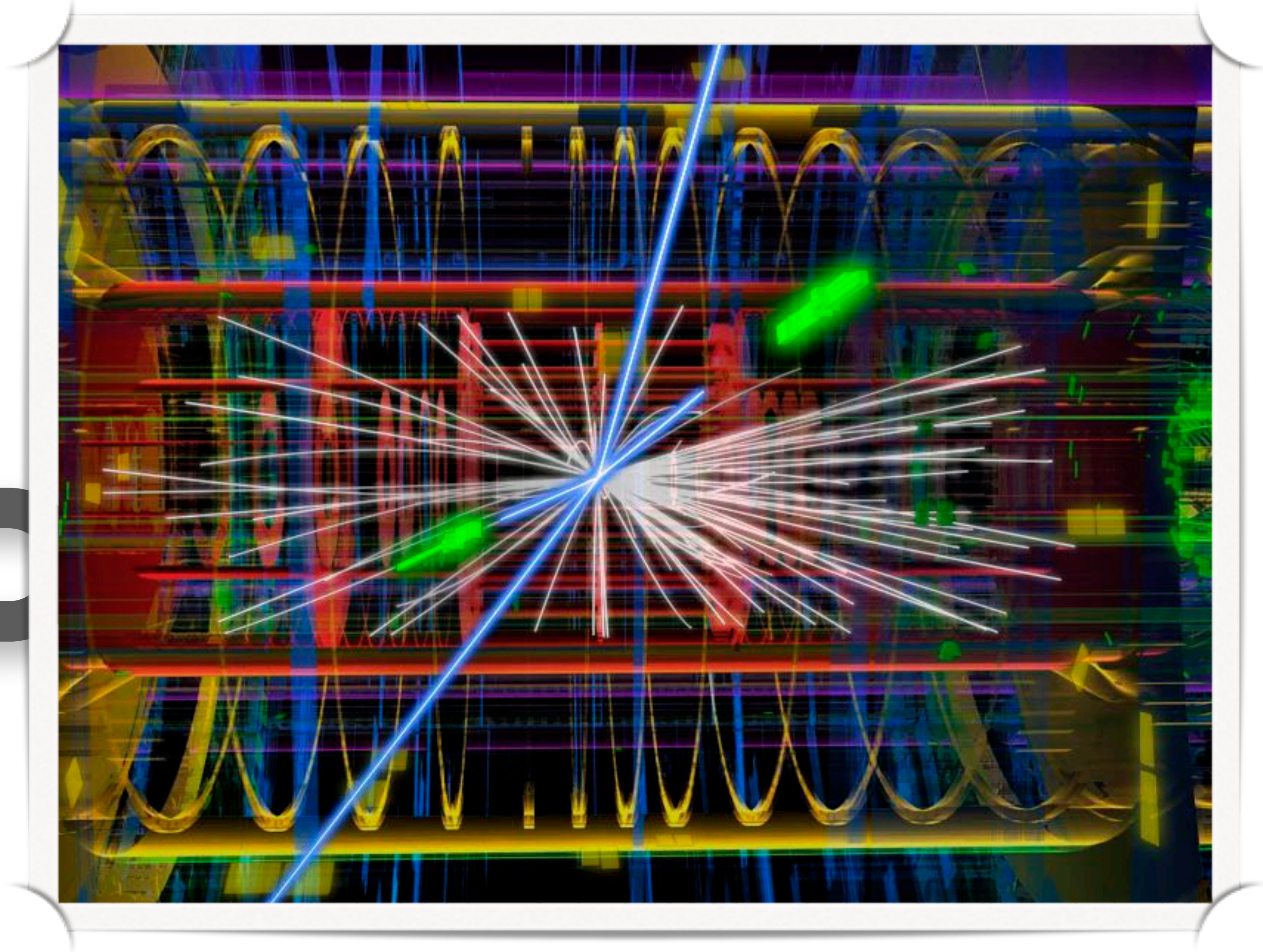
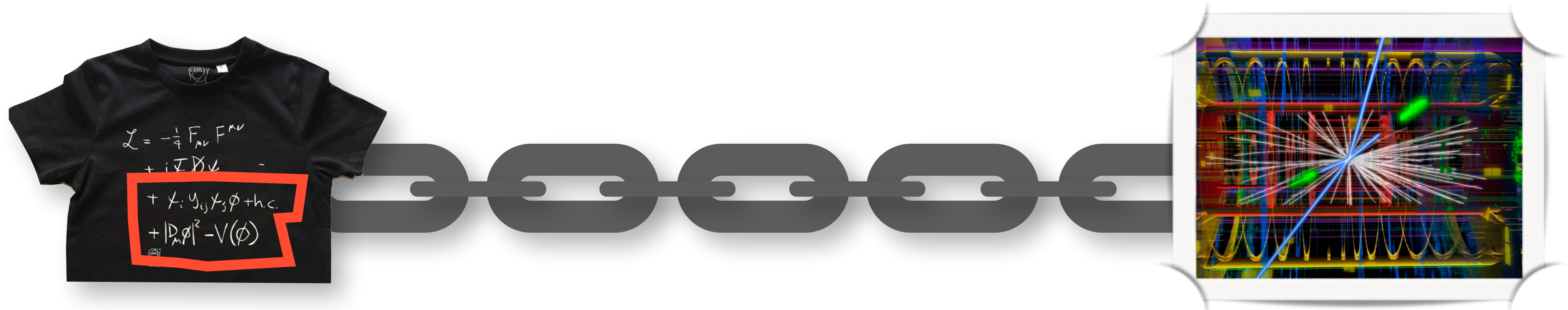


through a chain of experimental and theoretical links

QCD

quantum chromodynamics

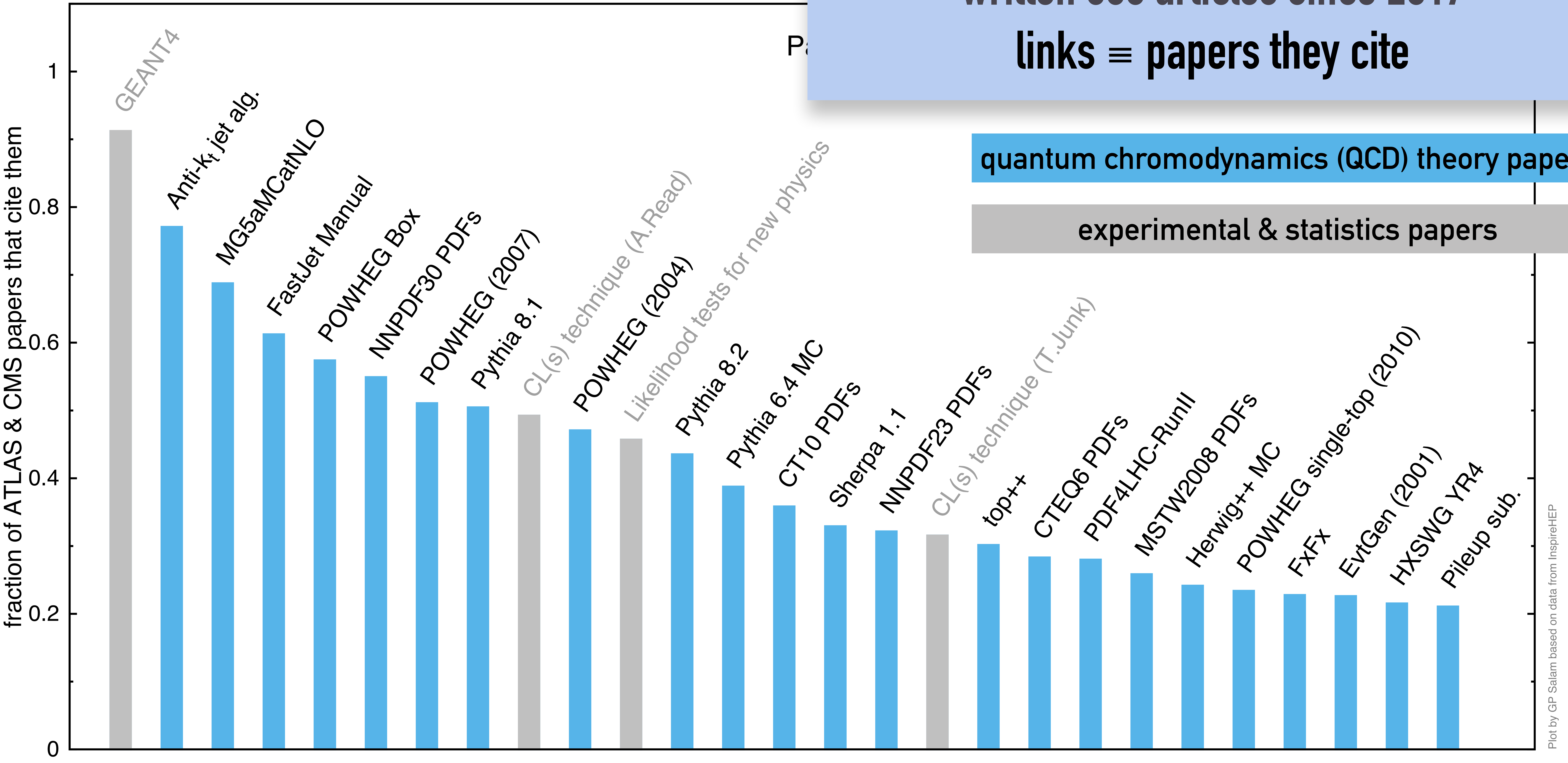
the theory of the strong interaction



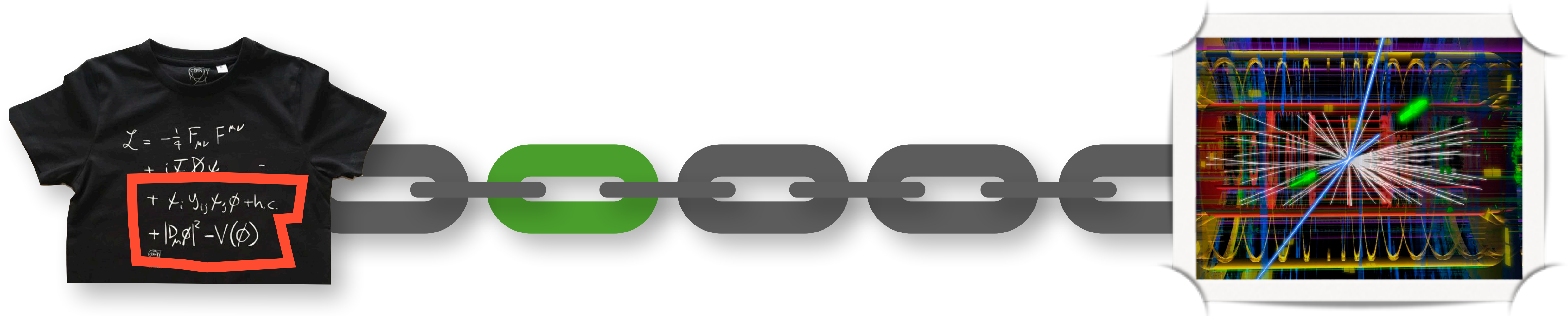
What are the links?

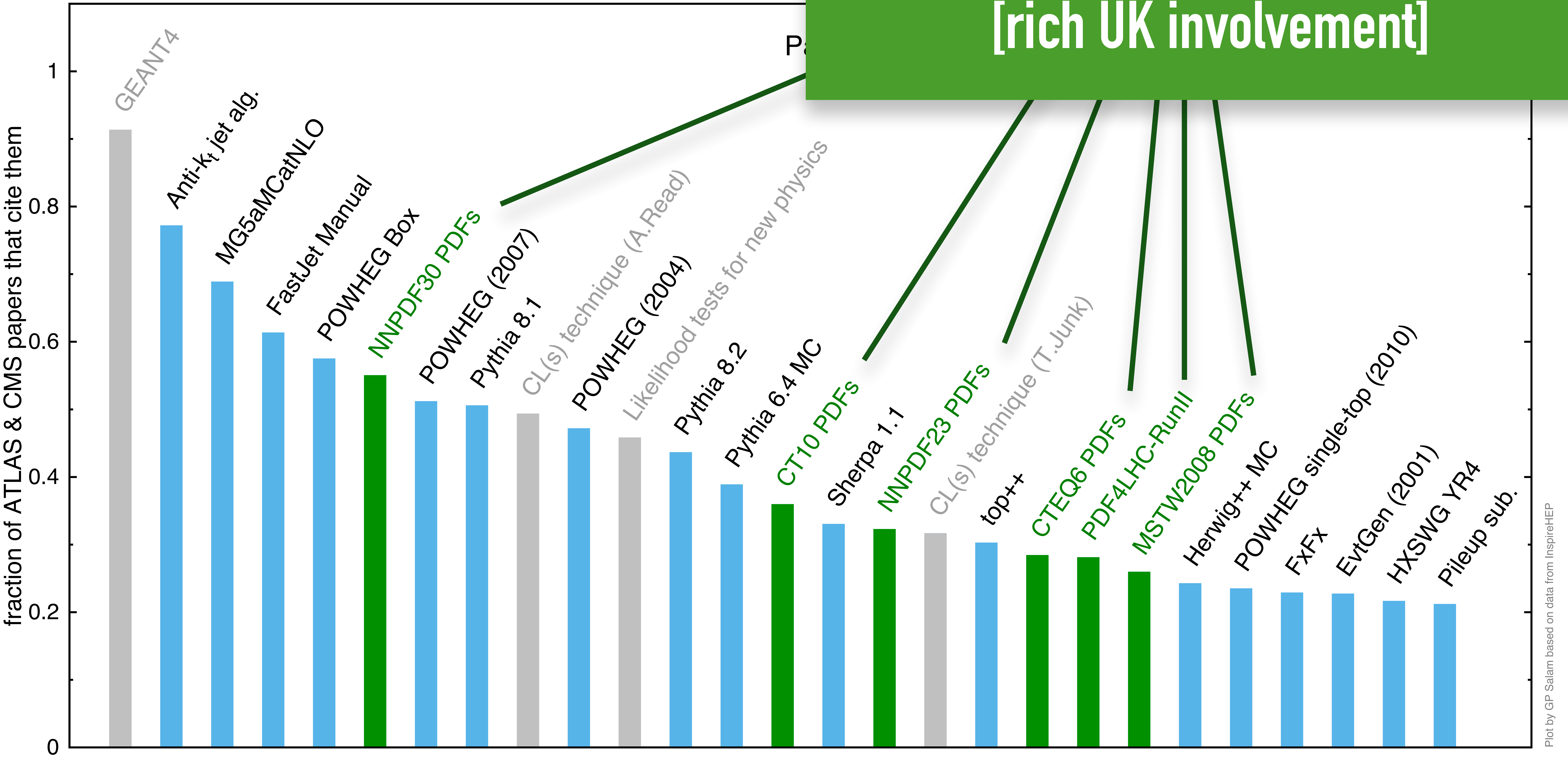
ATLAS and CMS (big LHC expts.) have written 650 articles since 2017

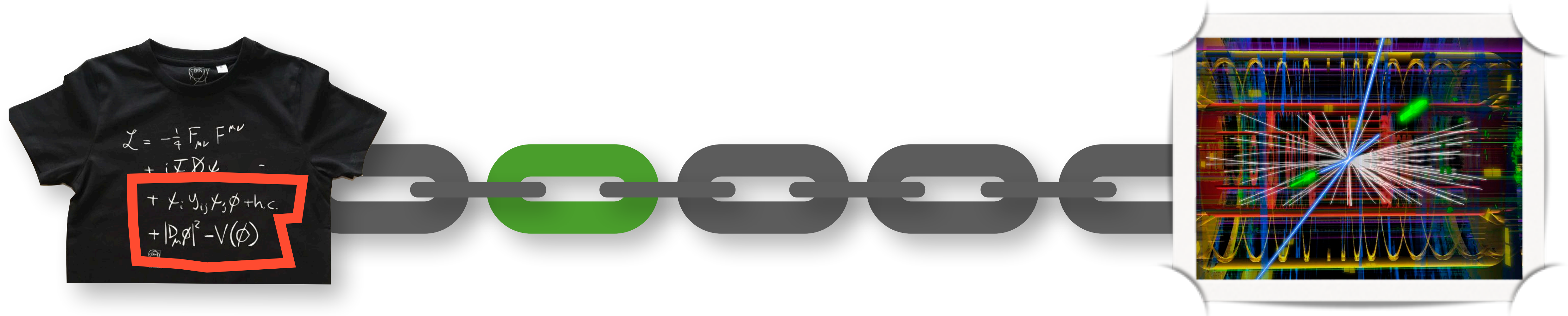
links ≡ papers they cite



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







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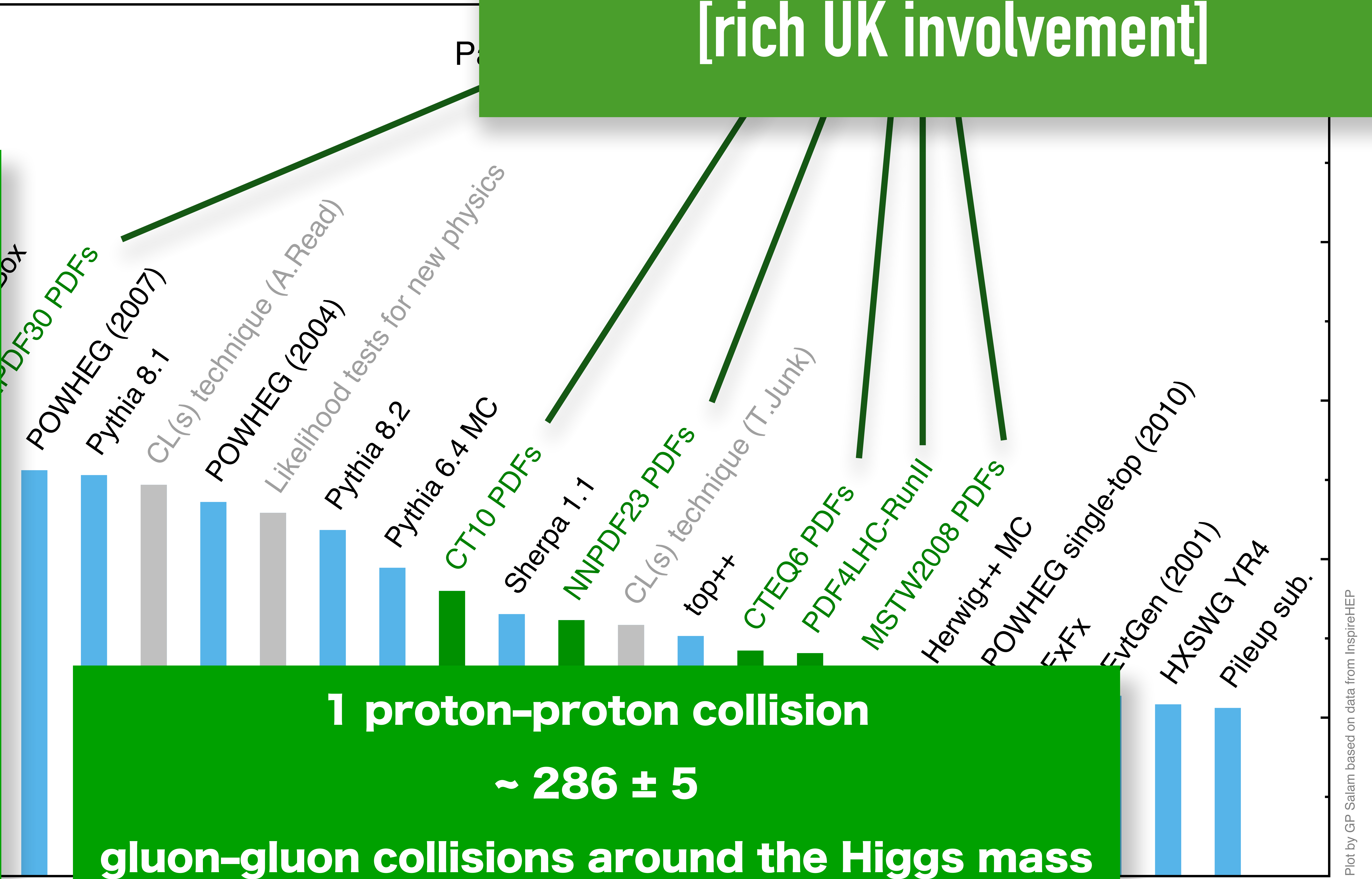
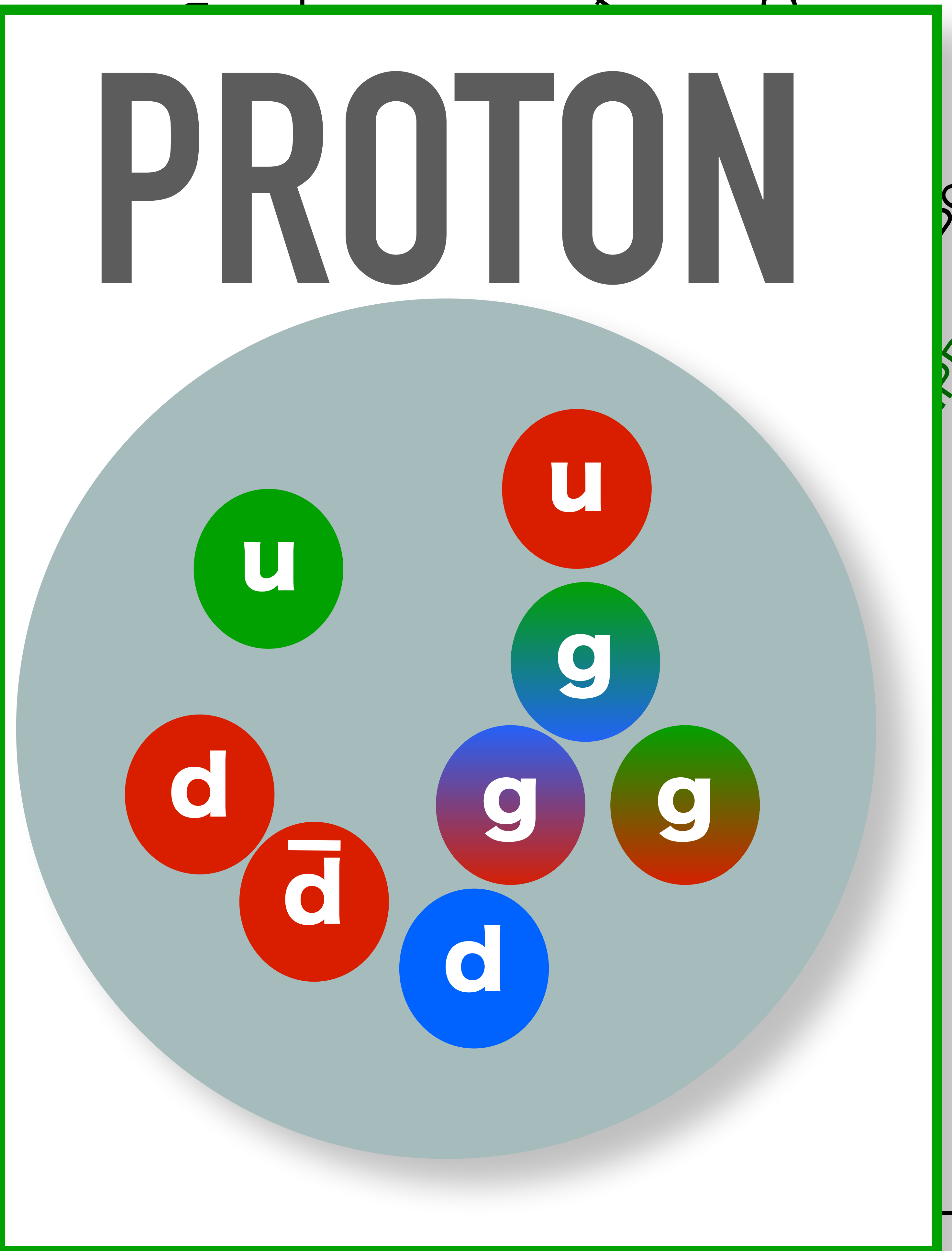
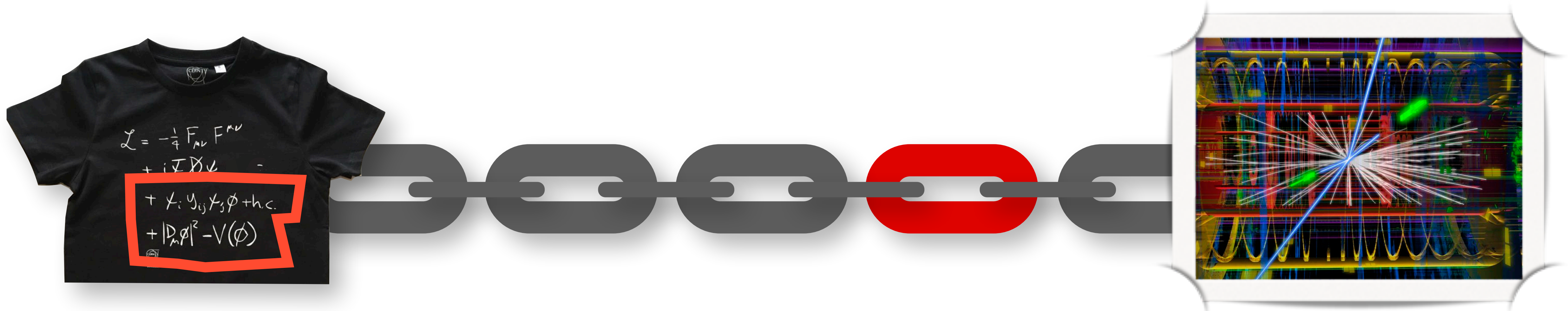




1 proton-proton collision

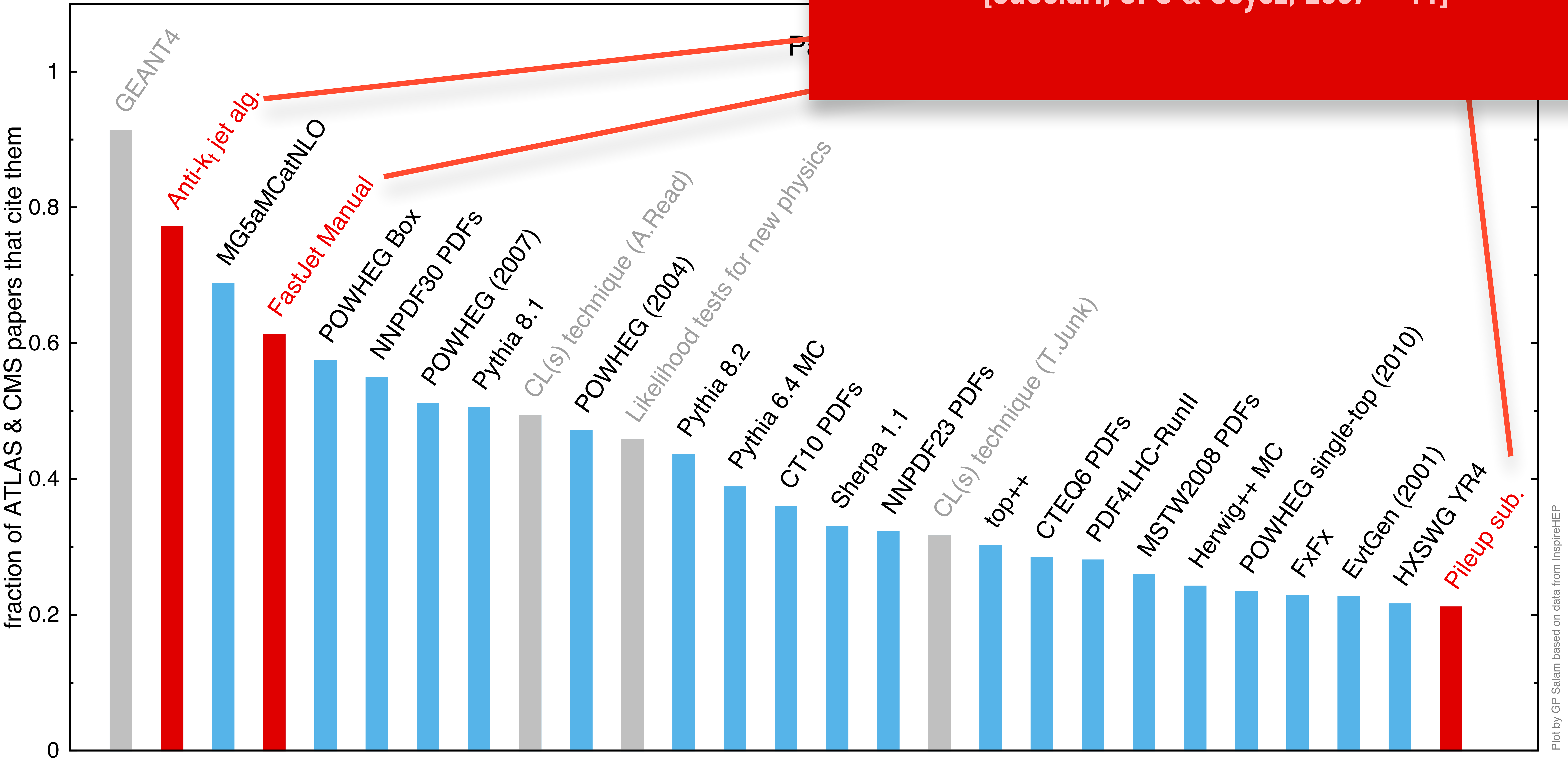
~ 286 ± 5

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 nature > scientific reports > articles > article

SCIENTIFIC REPORTS

Article | Open Access | Published: 09 May 2018

qSR: a quantitative super-resolution analysis tool reveals the cell-cycle dependent organization of RNA Polymerase I in live human cells

J. O. Andrews, W. Conway, W -K. Cho, A. Narayanan, J -H. Spille, N. Jayanth, T. Inoue, S. Mullen, J. Thaler & I. I. Cissé

Scientific Reports 8, Article number: 7424 (2018) | Cite this article

Abstract

We present qSR, an analytical tool for the quantitative analysis of single molecule based super-resolution data. The software is created as an

"For identifying spatial clusters, we have implemented both centroid-linkage hierarchical clustering using FastJet [...]"

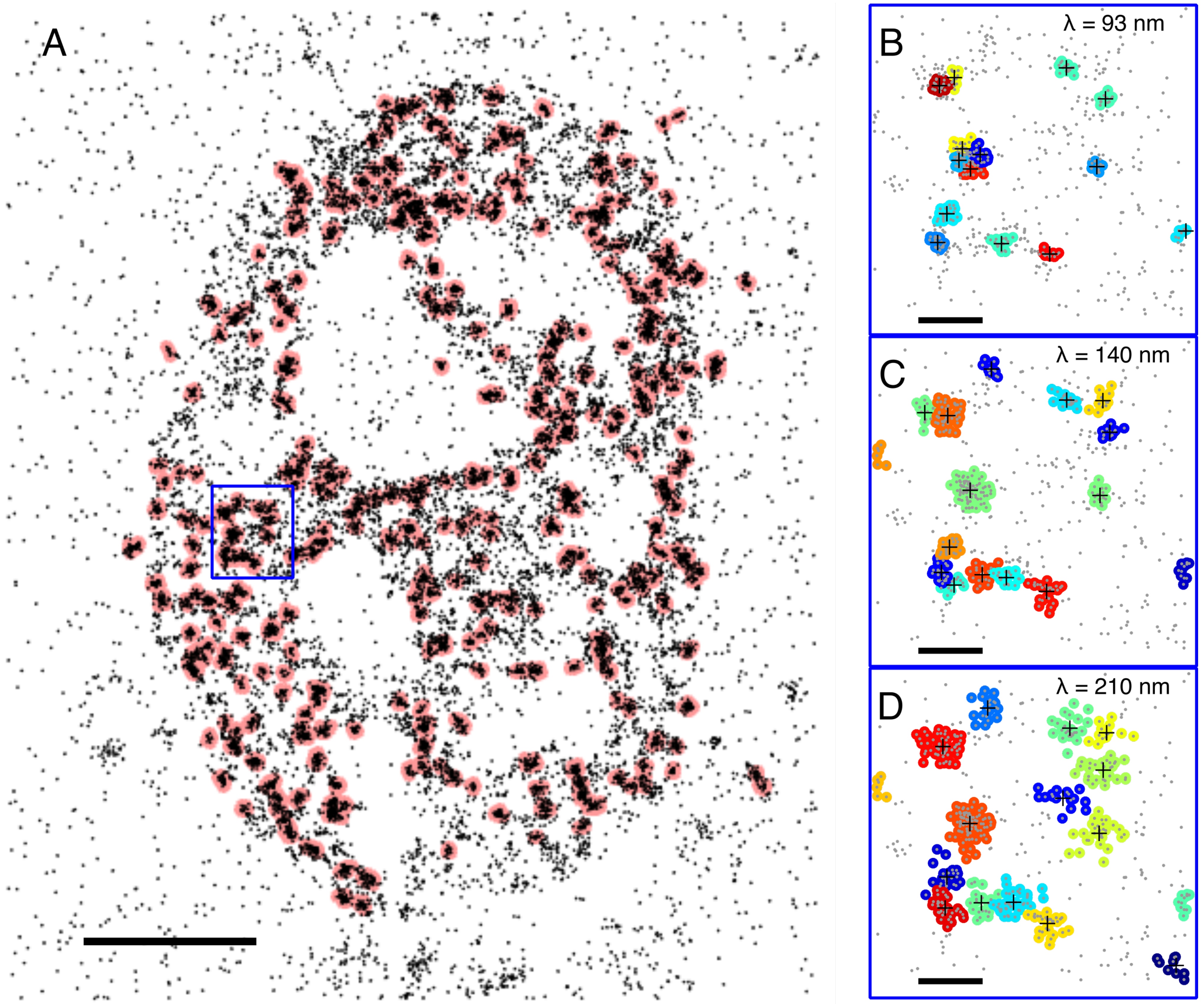
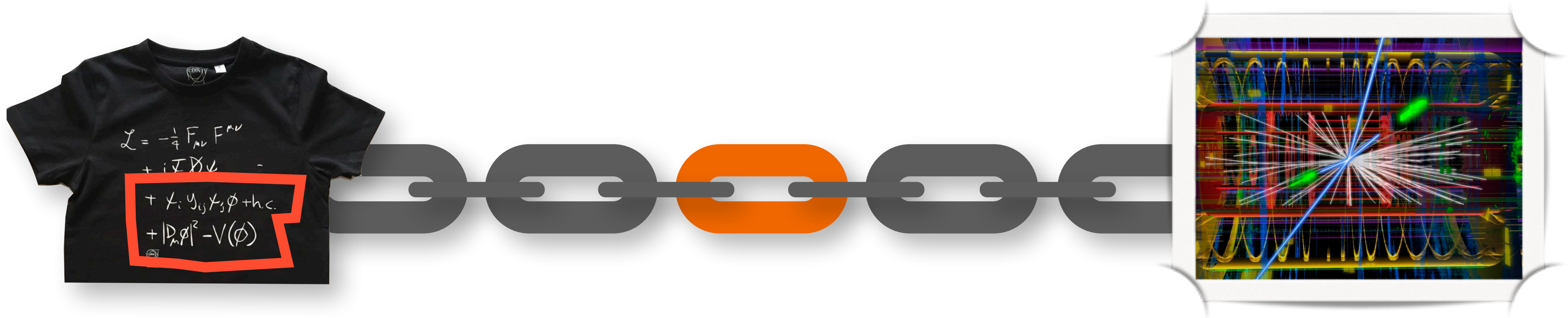
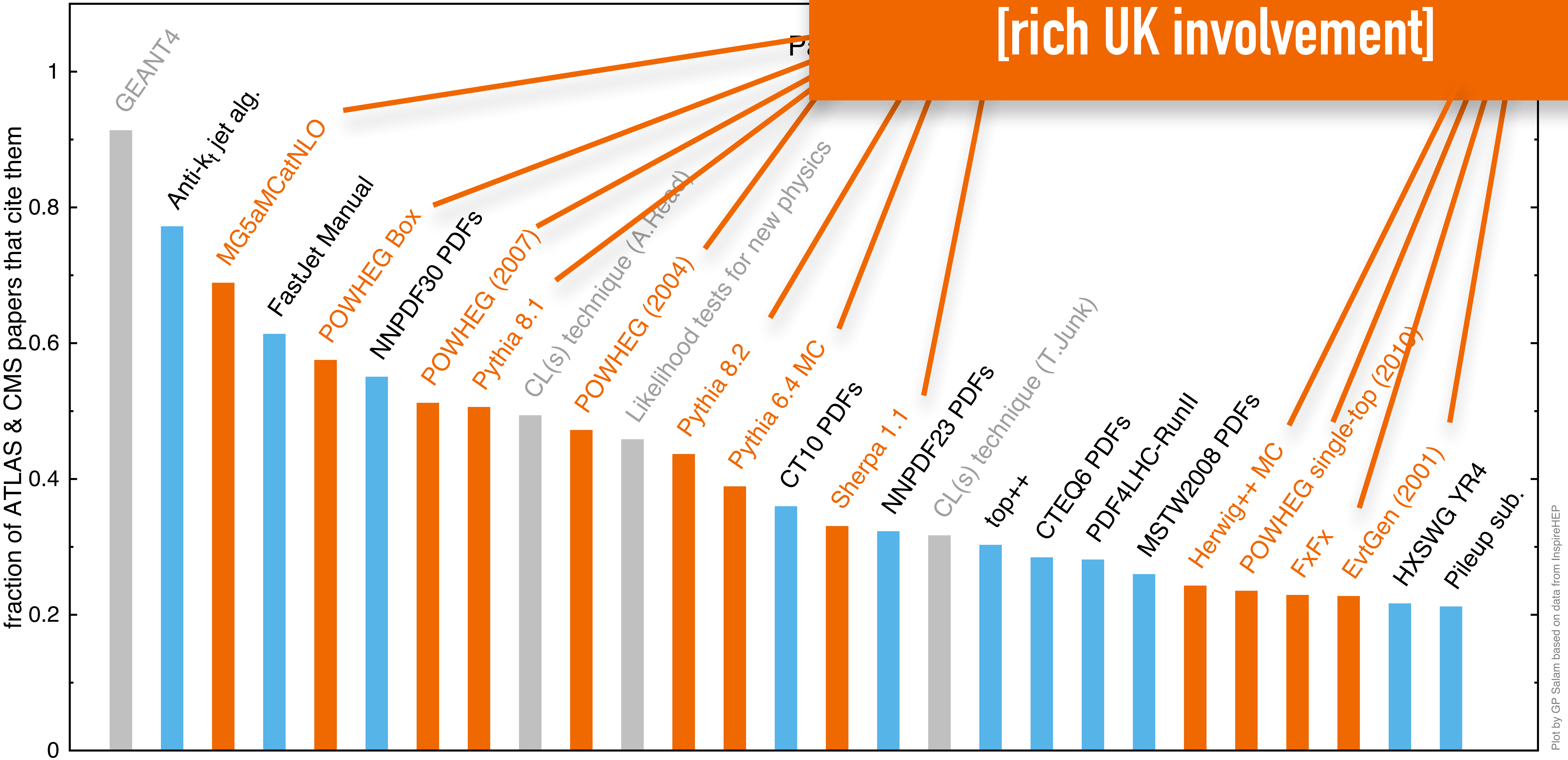
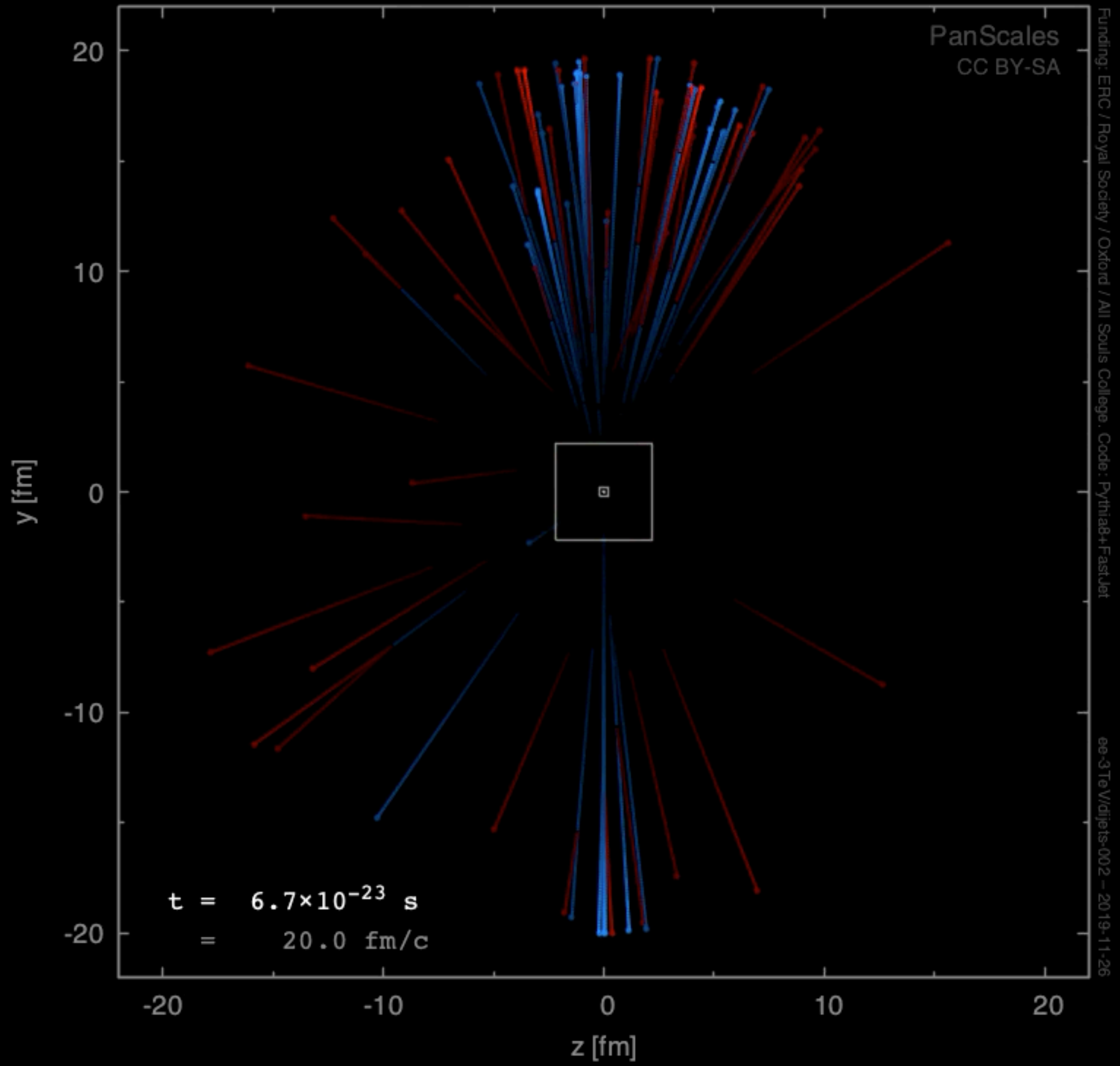


Figure S6: FastJet hierarchical clustering. (A) FastJet clusters found with a length scale of 140nm. (B-D) Zoomed in view of the region in the blue box from A. The clusters were generated by cutting the tree with a length scale of 93 nm, 140 nm, and 210 nm respectively. The black + signs mark the centroids of each cluster. Scale Bars – A: 5 μm B - D: 500 nm



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



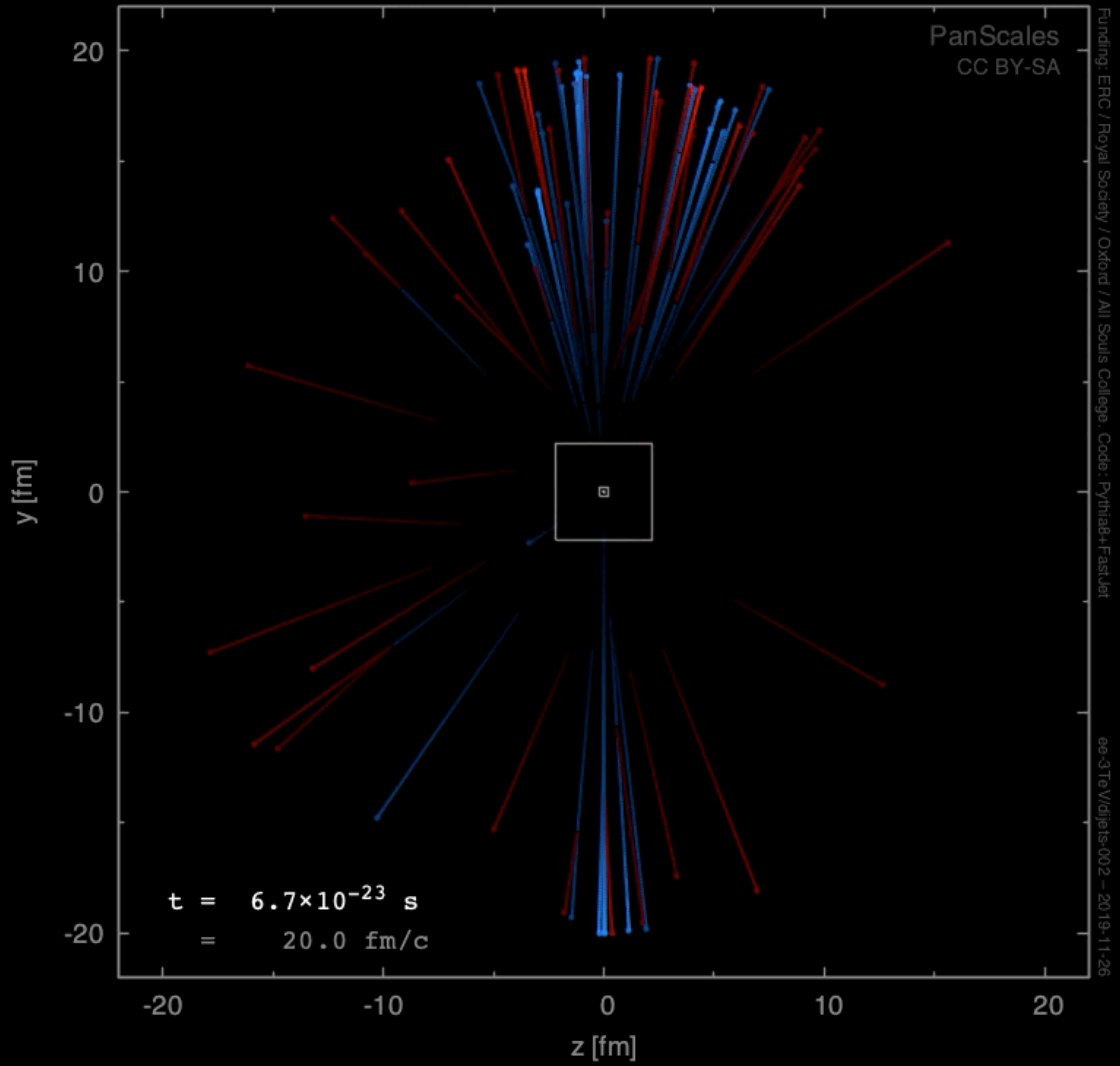


incoming beam particle

intermediate particle

final particle

Event evolution spans 7 orders of magnitude in space-time



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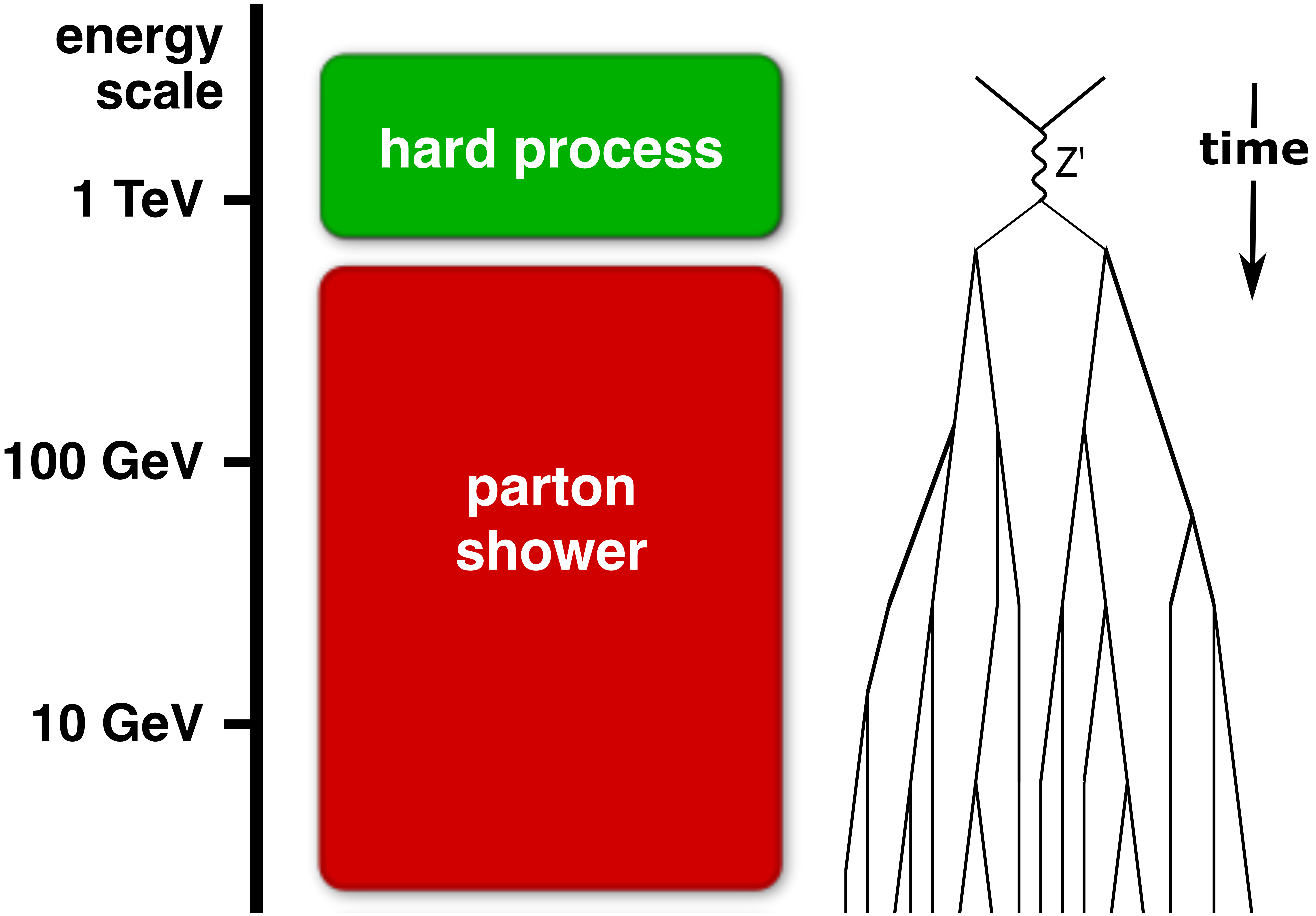
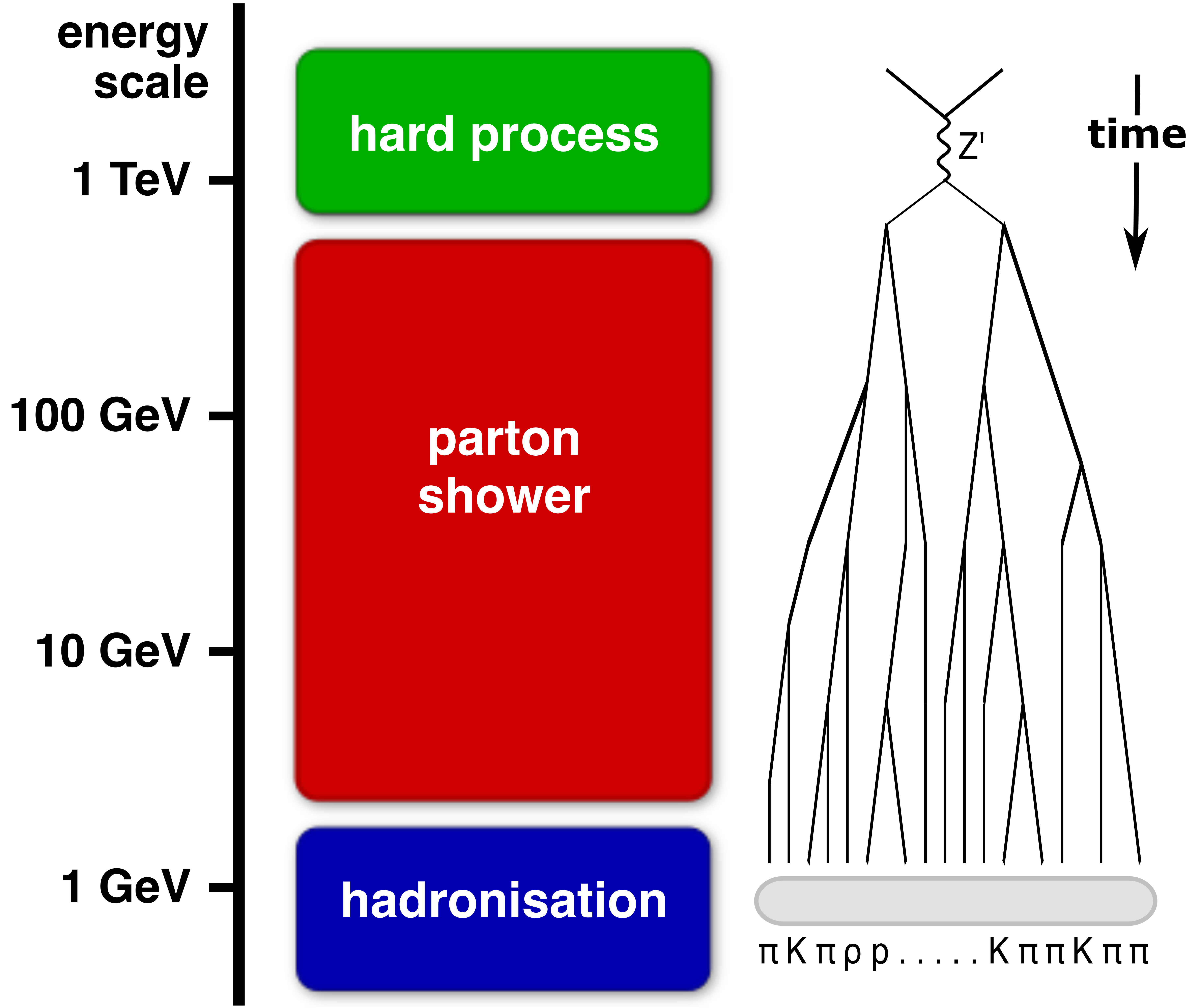
Event evolution spans 7 orders of magnitude in space-time

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



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



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

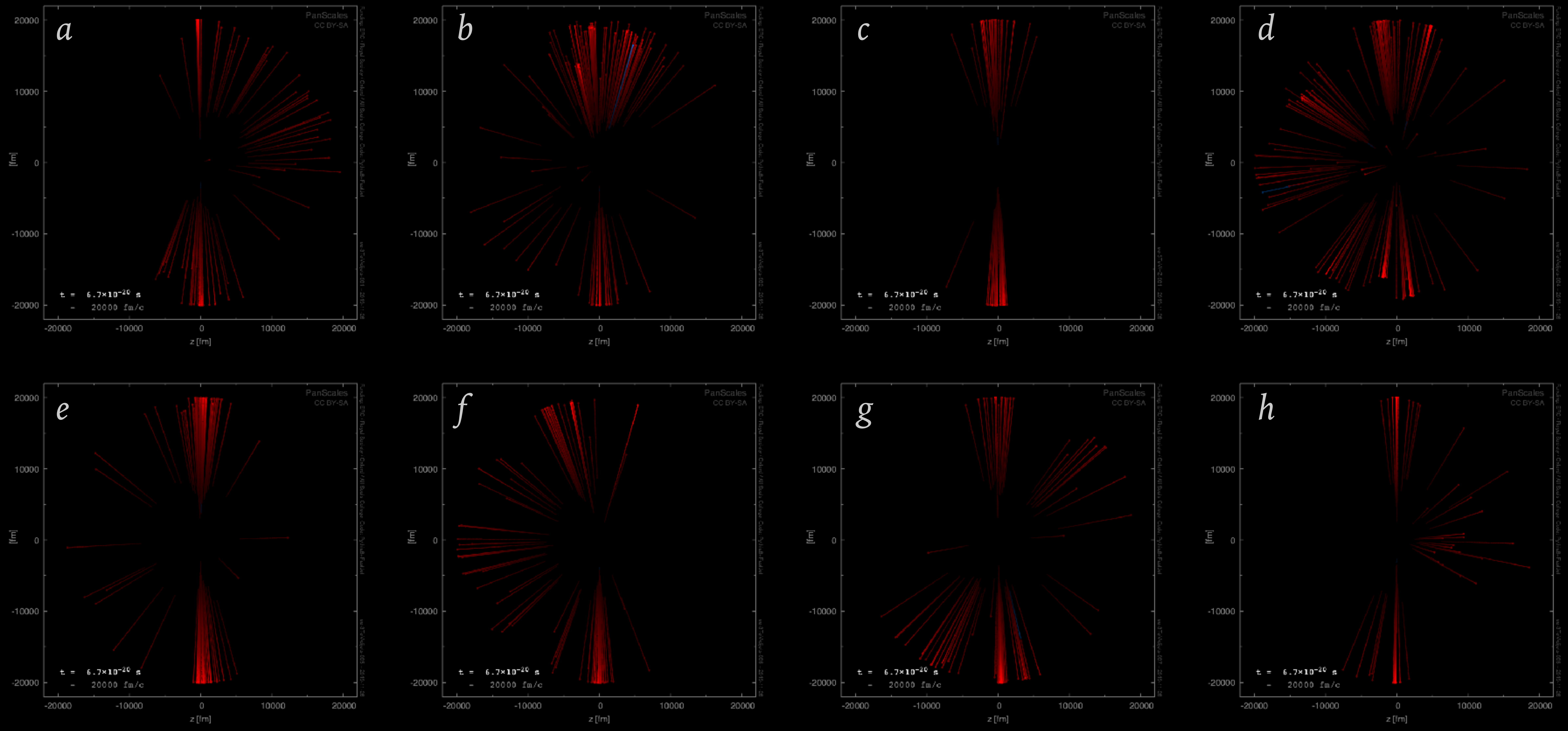
general purpose Monte Carlo event generators:
THE BIG 3

Herwig 7 | Pythia 8 | Sherpa 2

they do an amazing job of simulation vast swathes of data; collider physics would be unrecognisable without them

using full event information

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


a
b
c
d
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g
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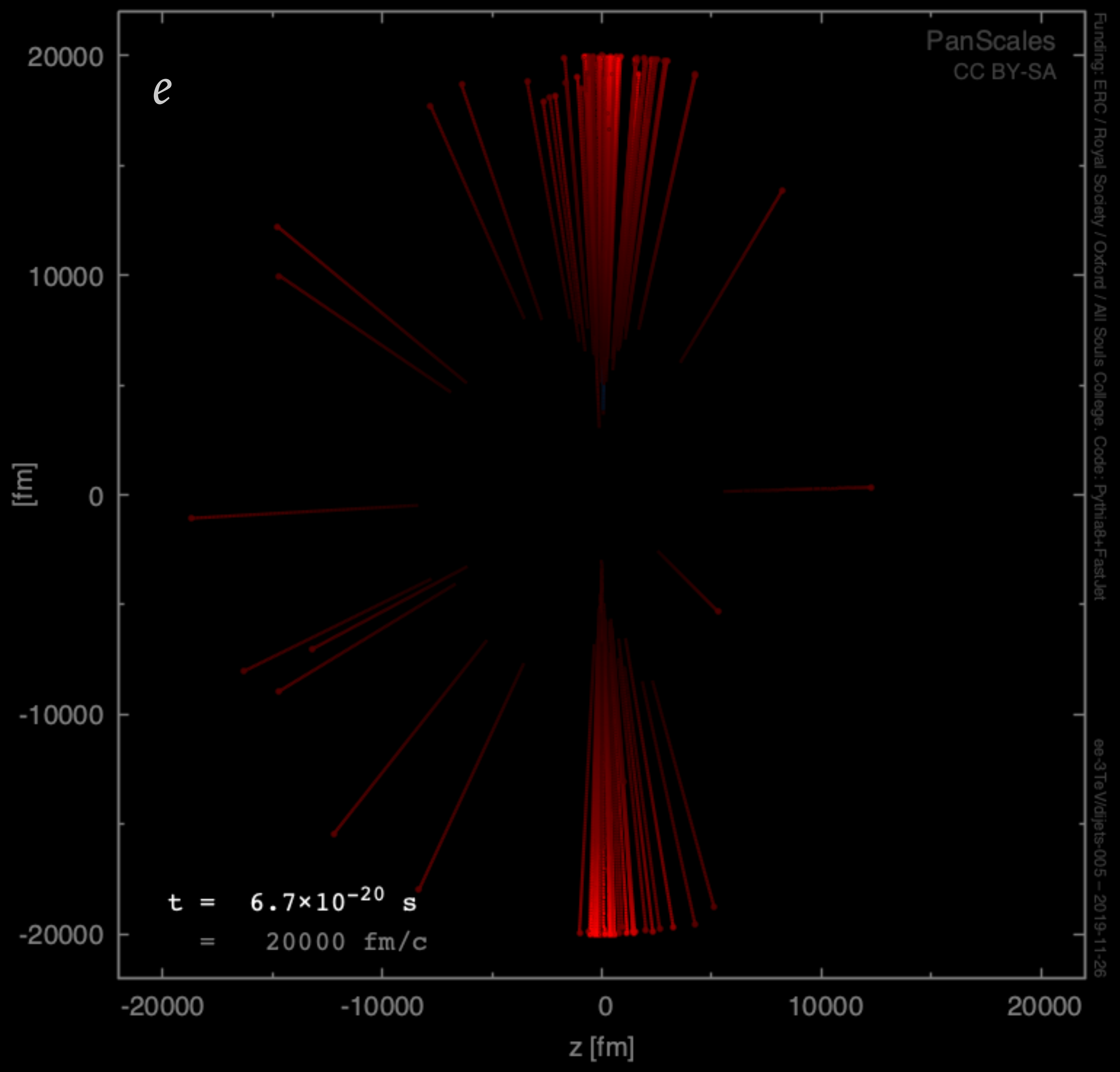
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
z [fm]
[fm]
-20000
-10000
0
10000
20000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CC BY-SA
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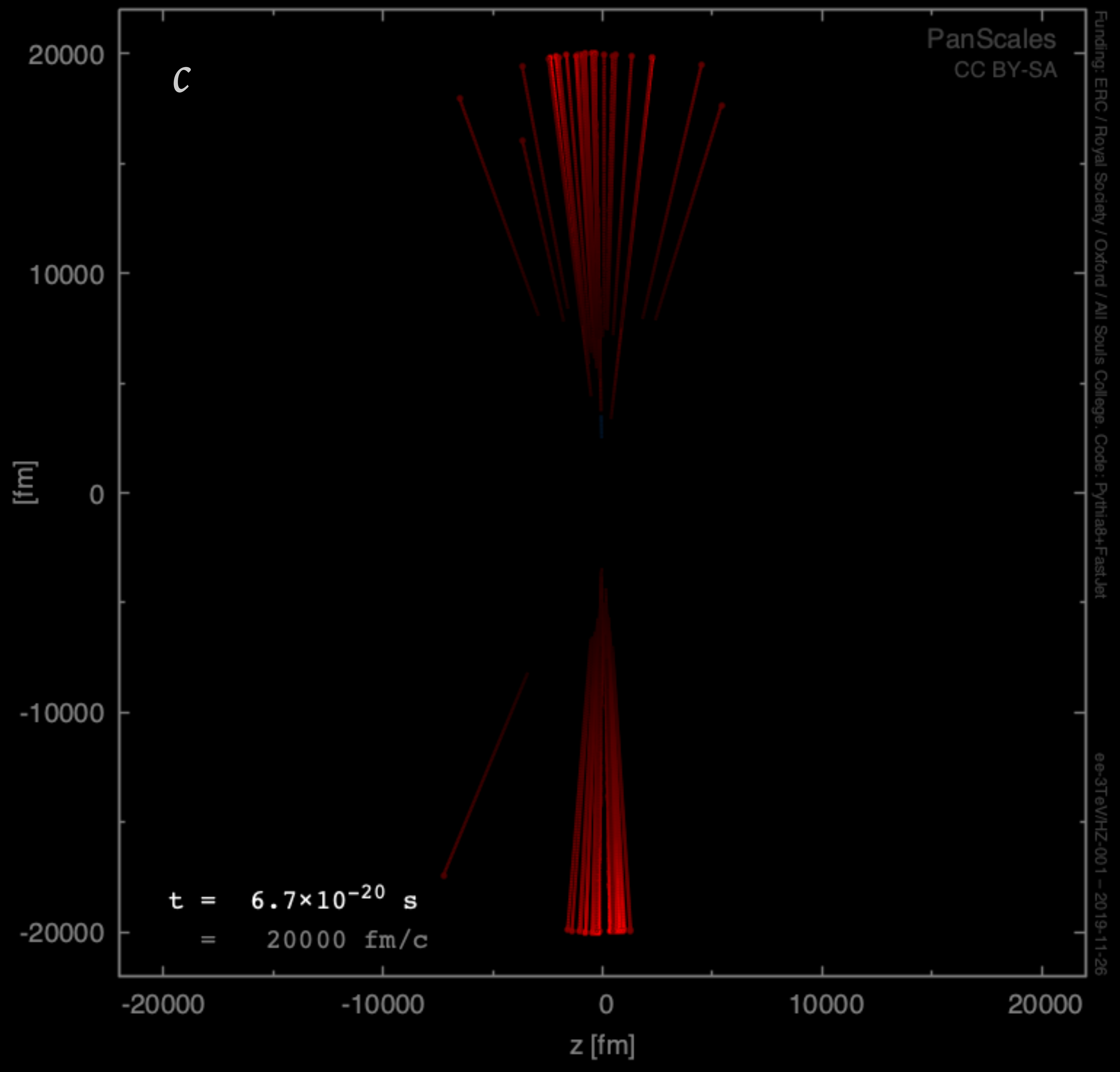
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t = 6.7×10^-20 s
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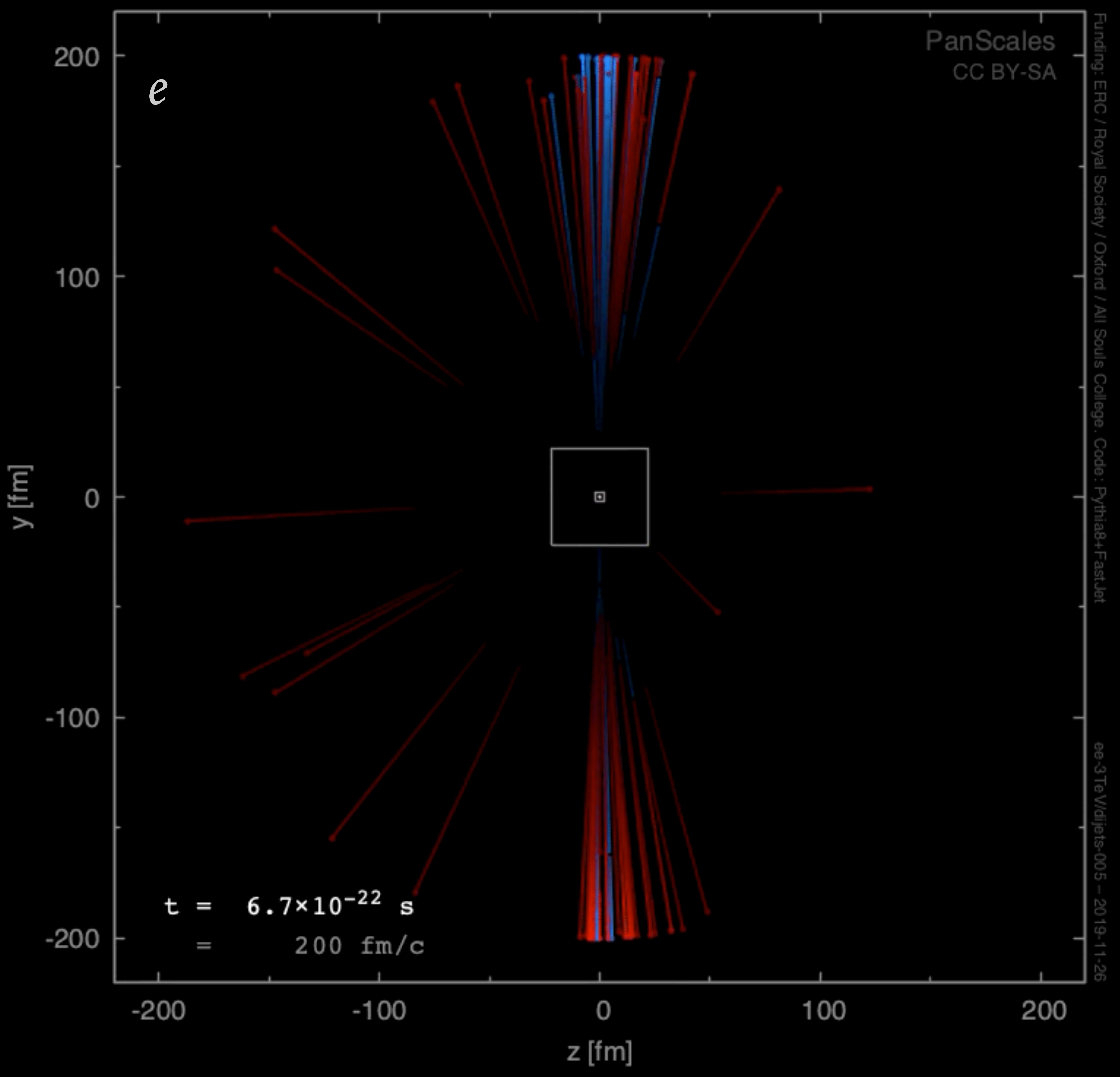
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CC BY-SA
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV/dijets-005 – 2019-11-26
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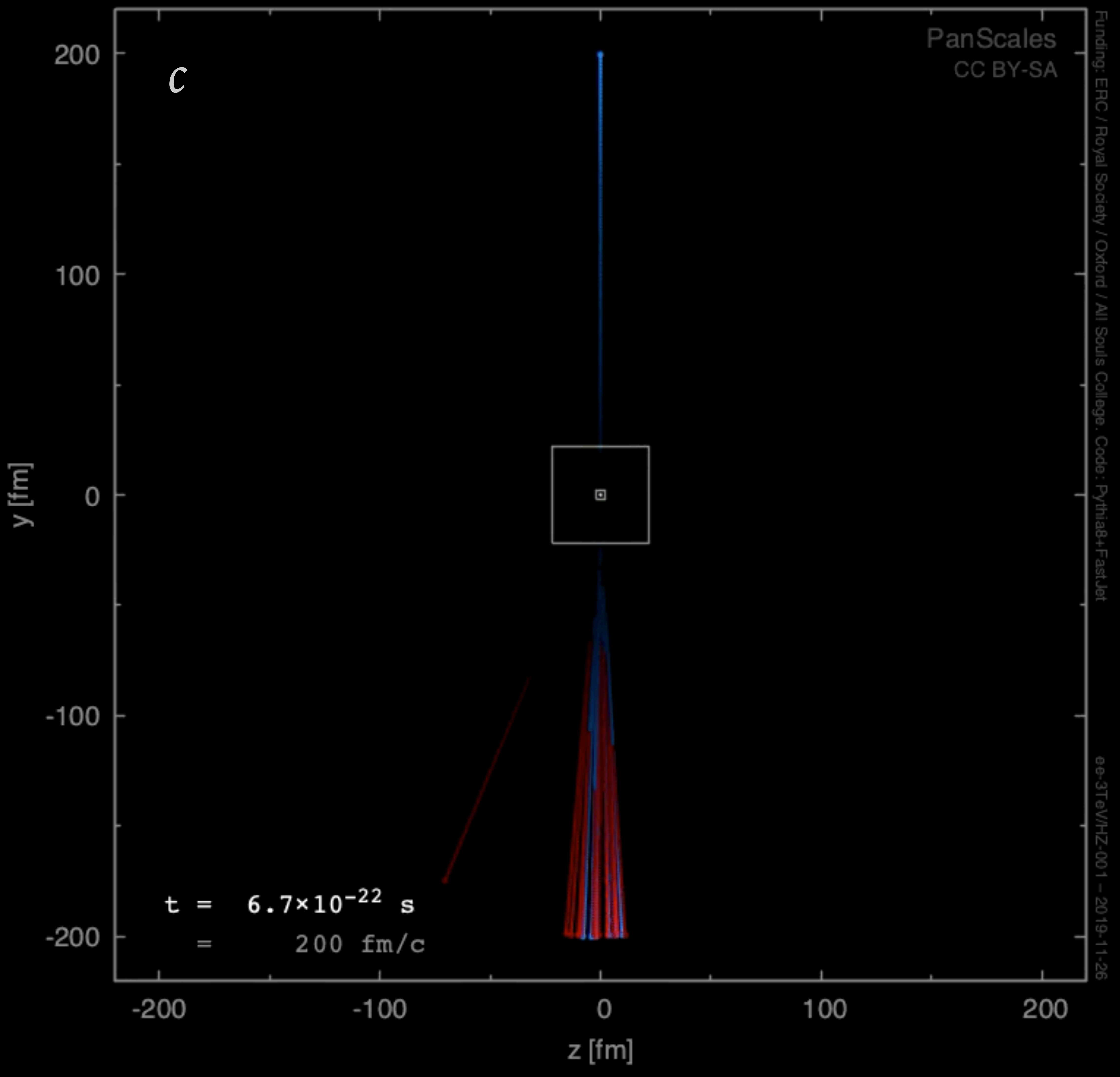
c
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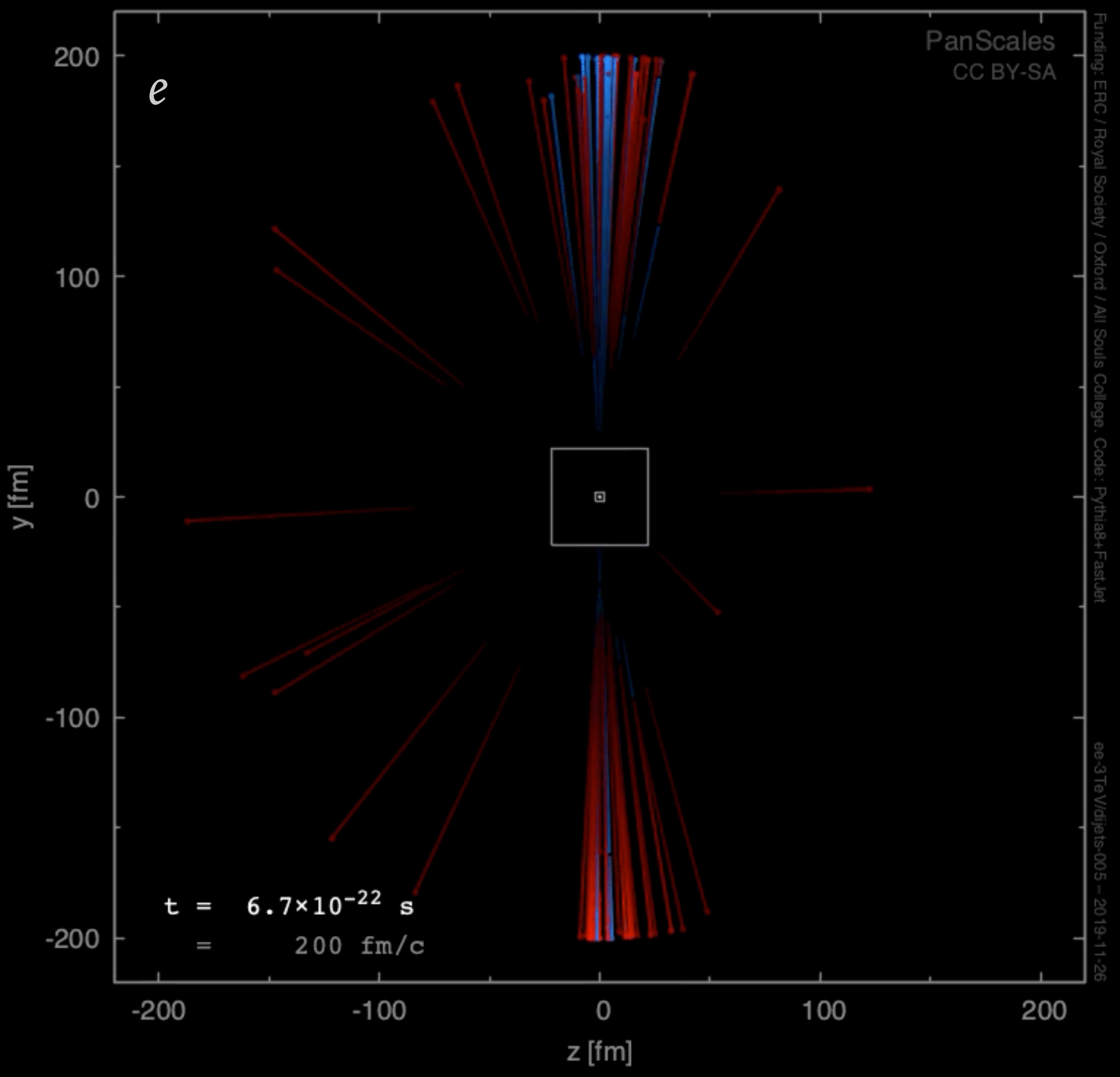
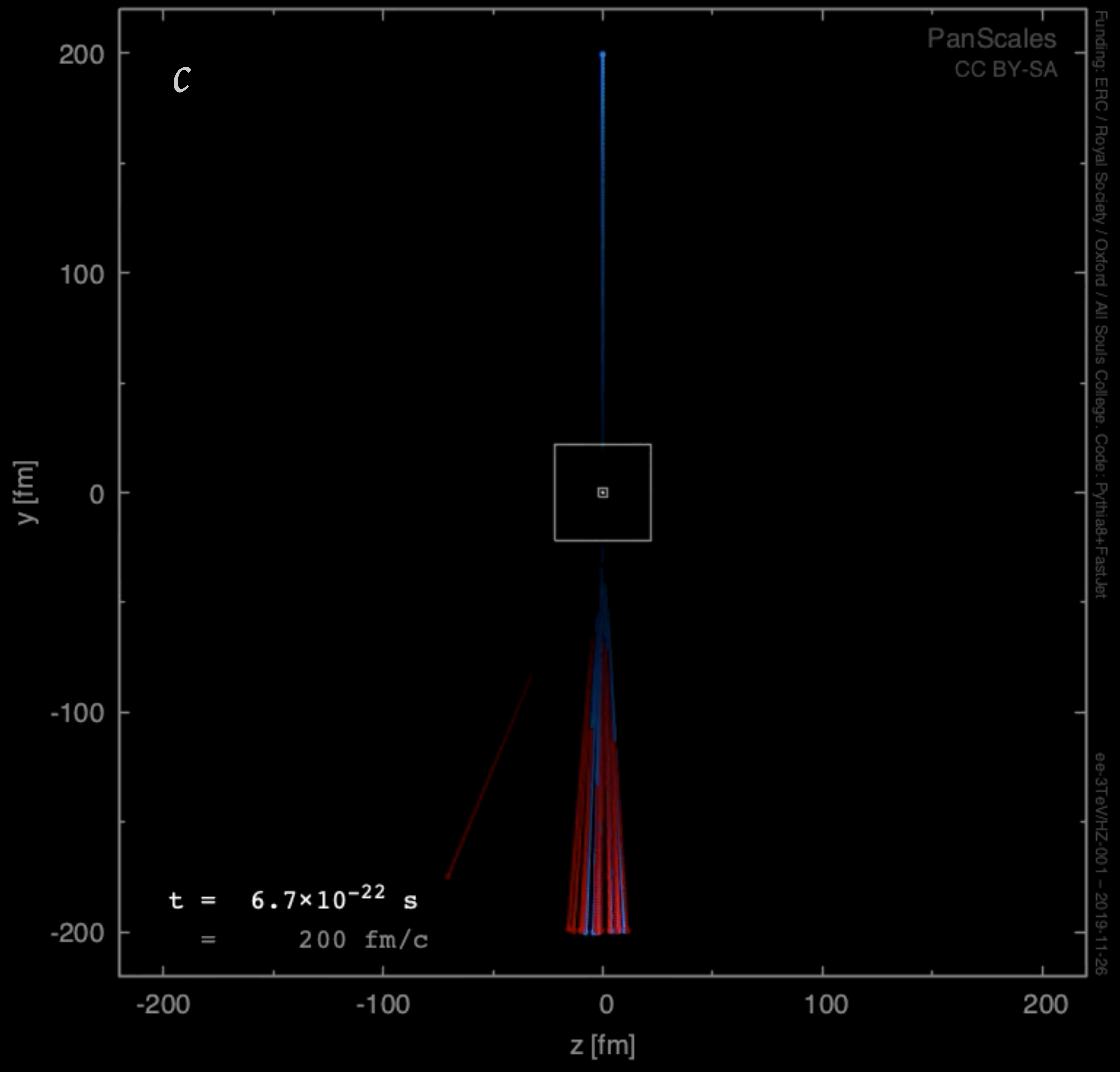
CC BY-SA
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV/HZ-001 – 2019-11-26
t = 6.7×10^-22 s
= 200 fm/c
y [fm]
z [fm]

pure QCD event



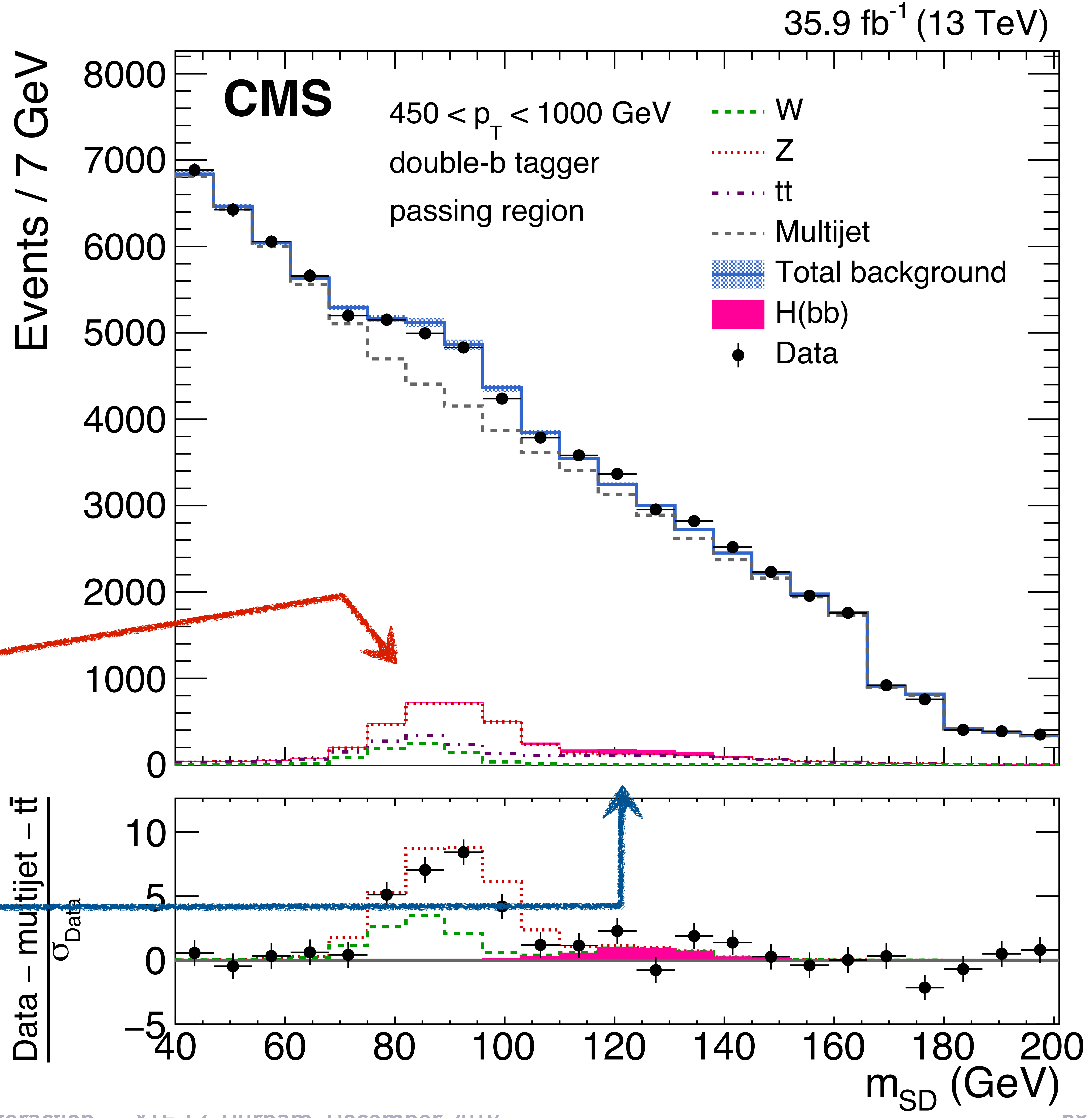
event with Higgs & Z boson decays



high p_T Higgs & [SD] jet mass

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.**

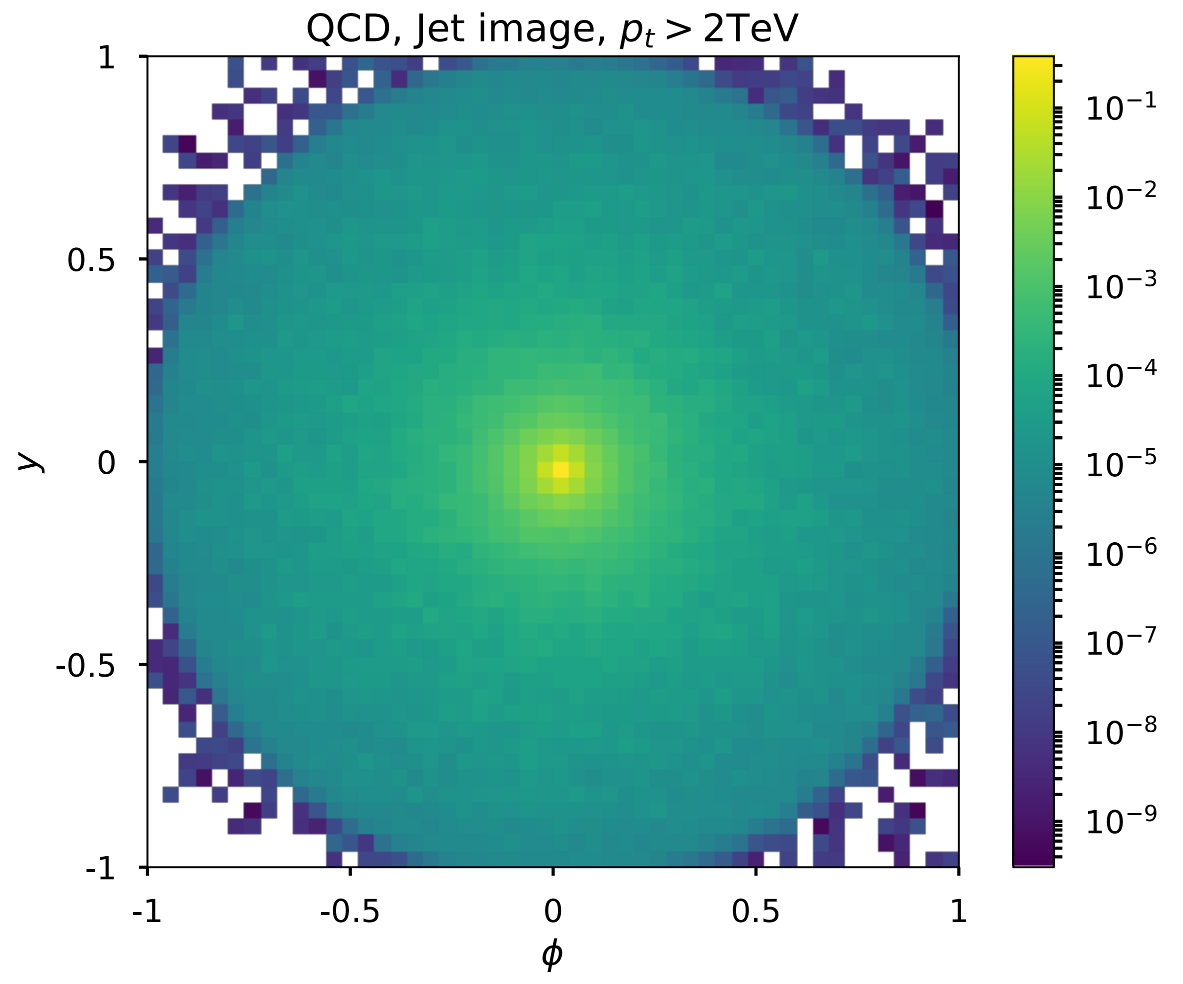


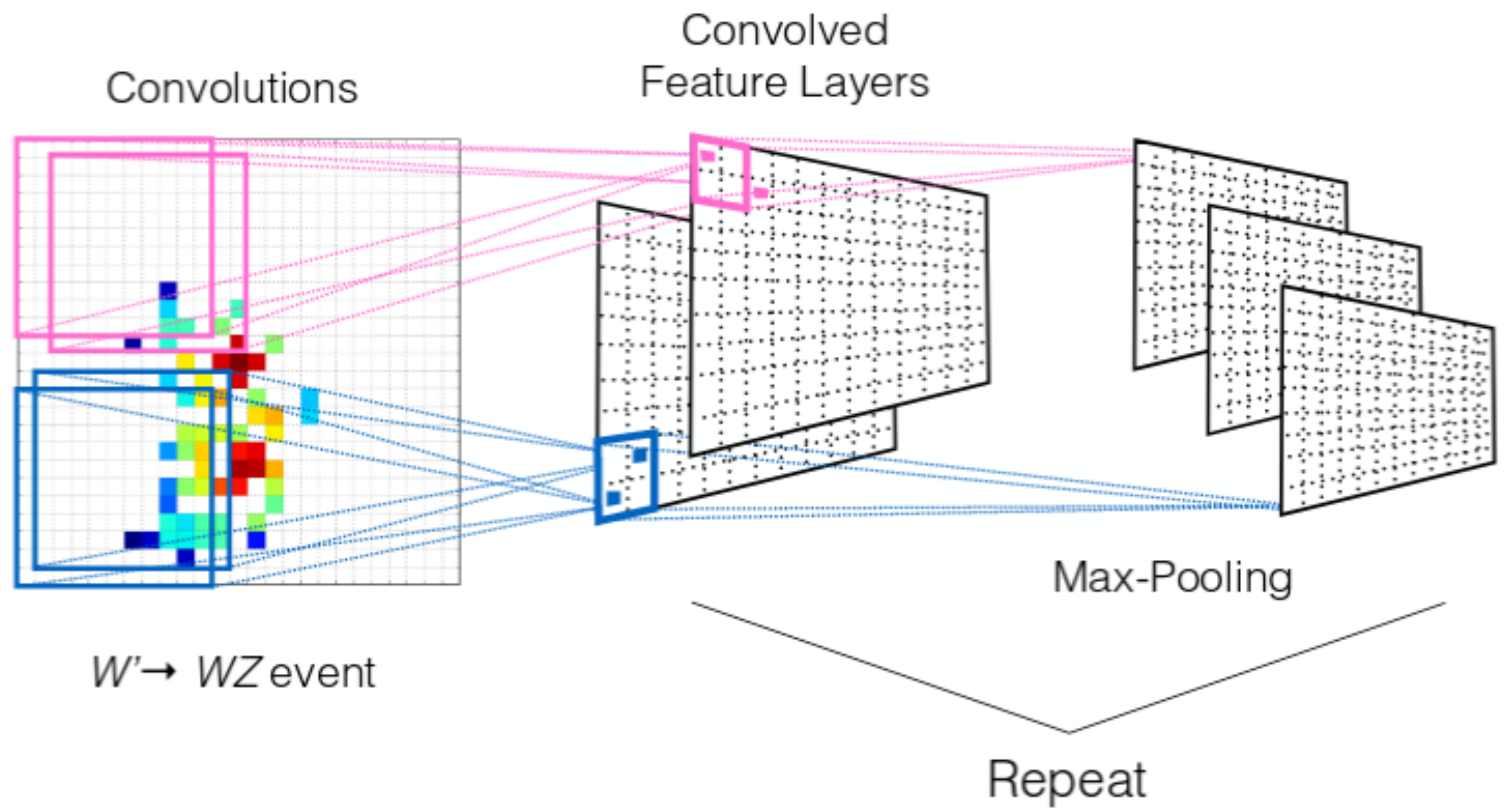
high-p_T Z → bb (5σ)

high-p_T H → bb (~ 1σ)

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.





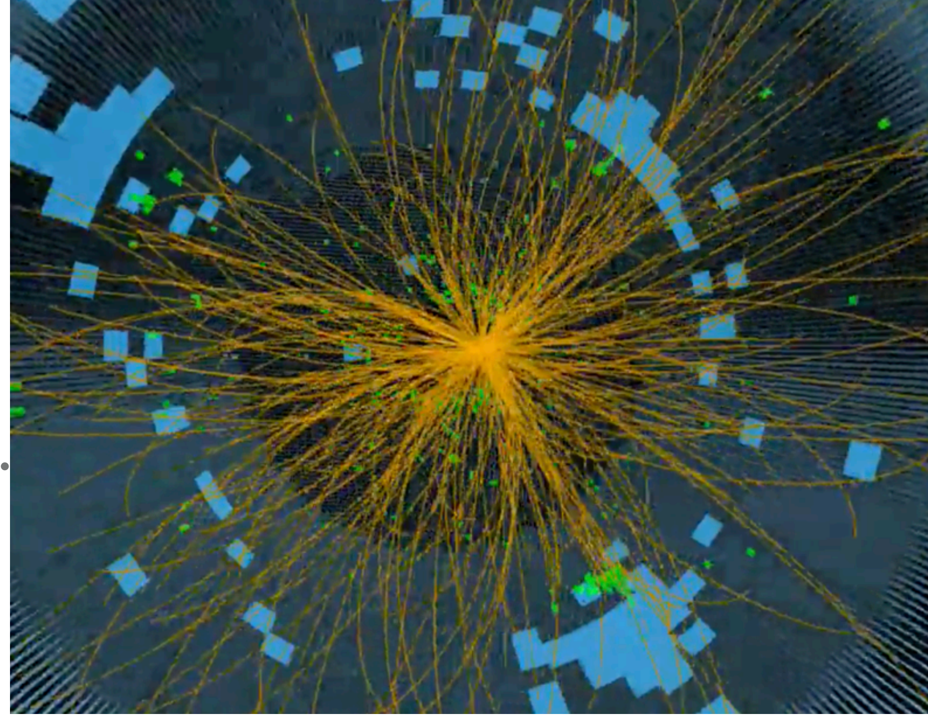
powerful

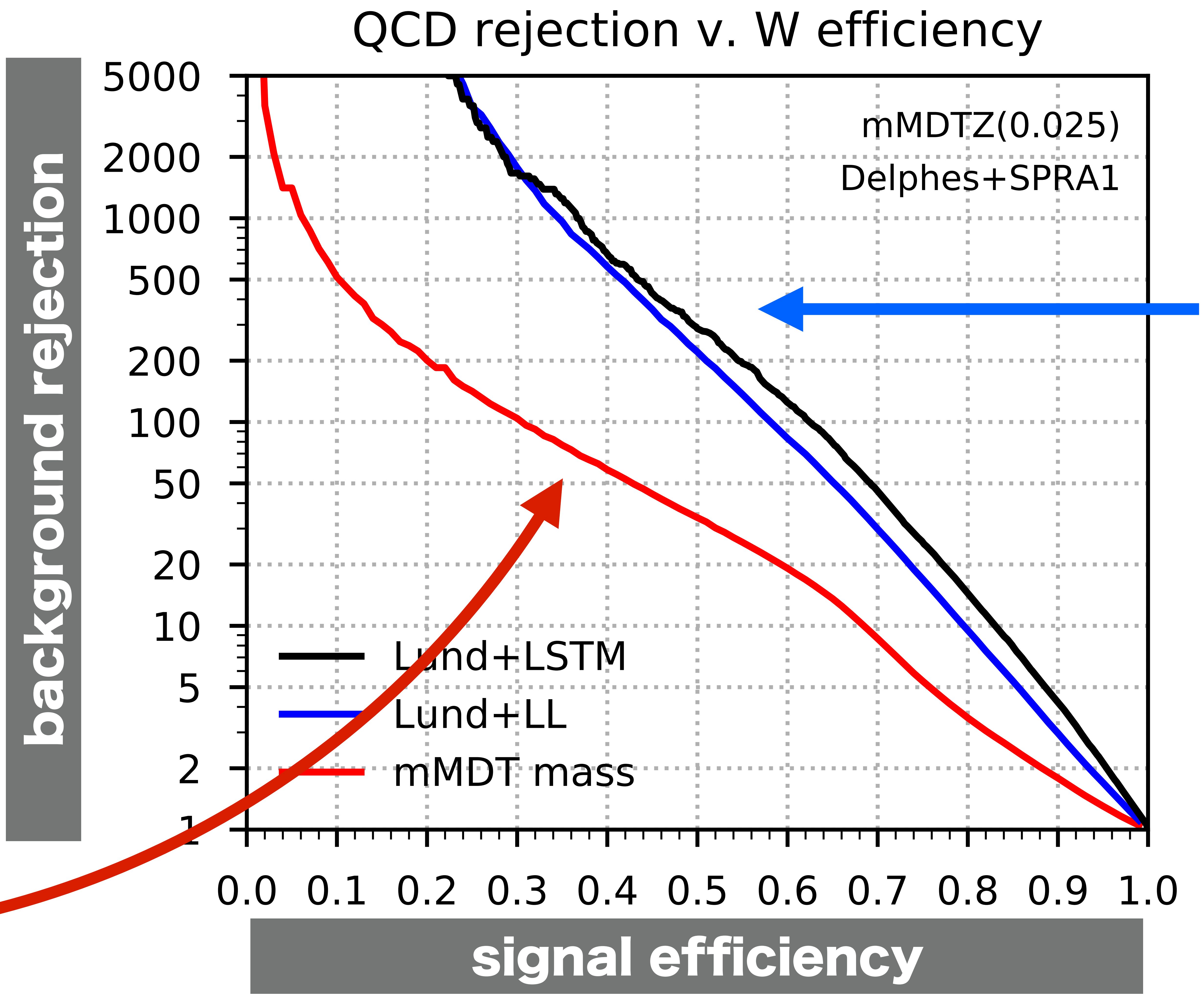
but black box

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

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

using full event information for H/etc. boson tagging





QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

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

5–10x better

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

from Dreyer, GPS & Soyez 2018

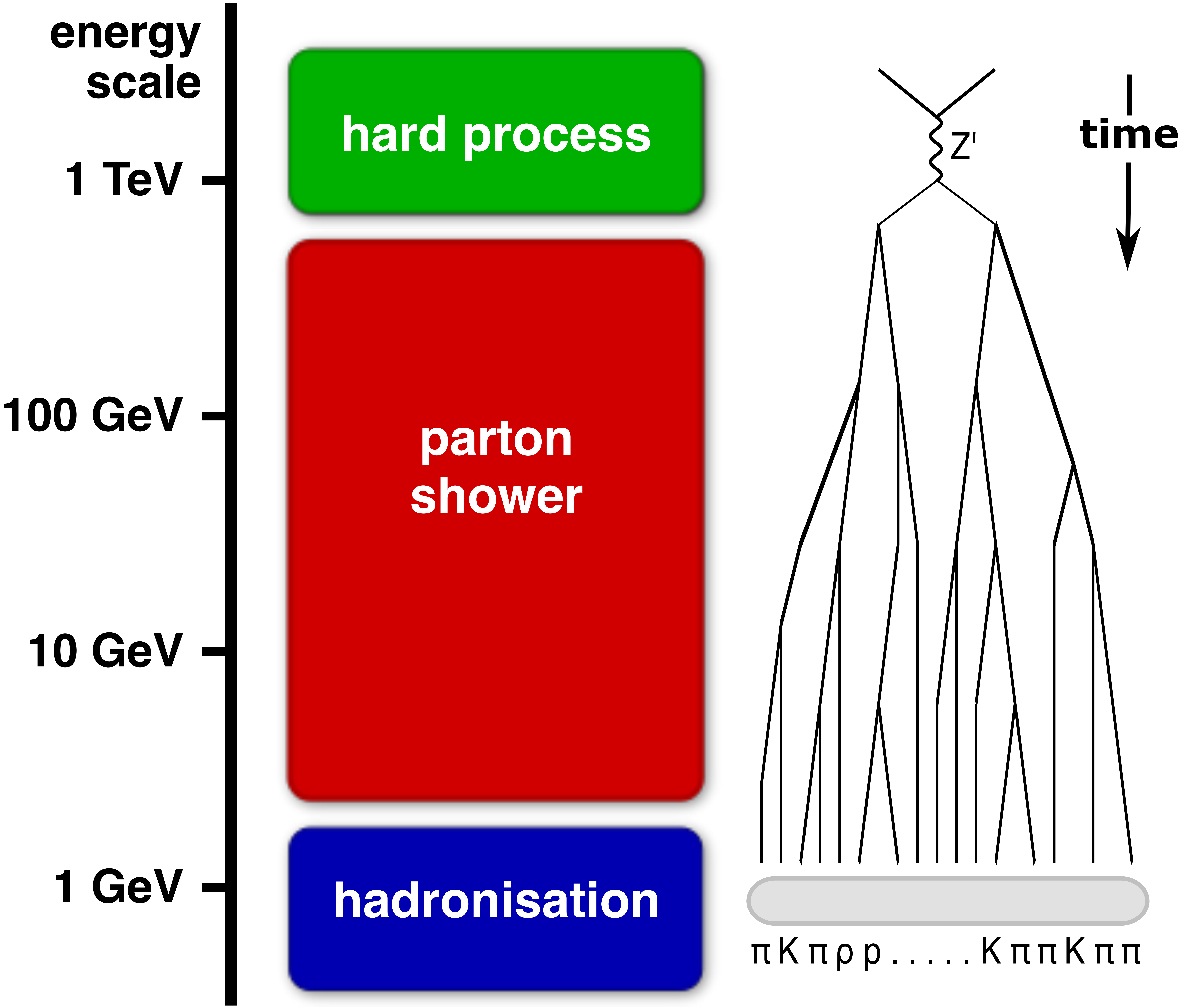
can we trust machine learning? A question of confidence in the training…

"

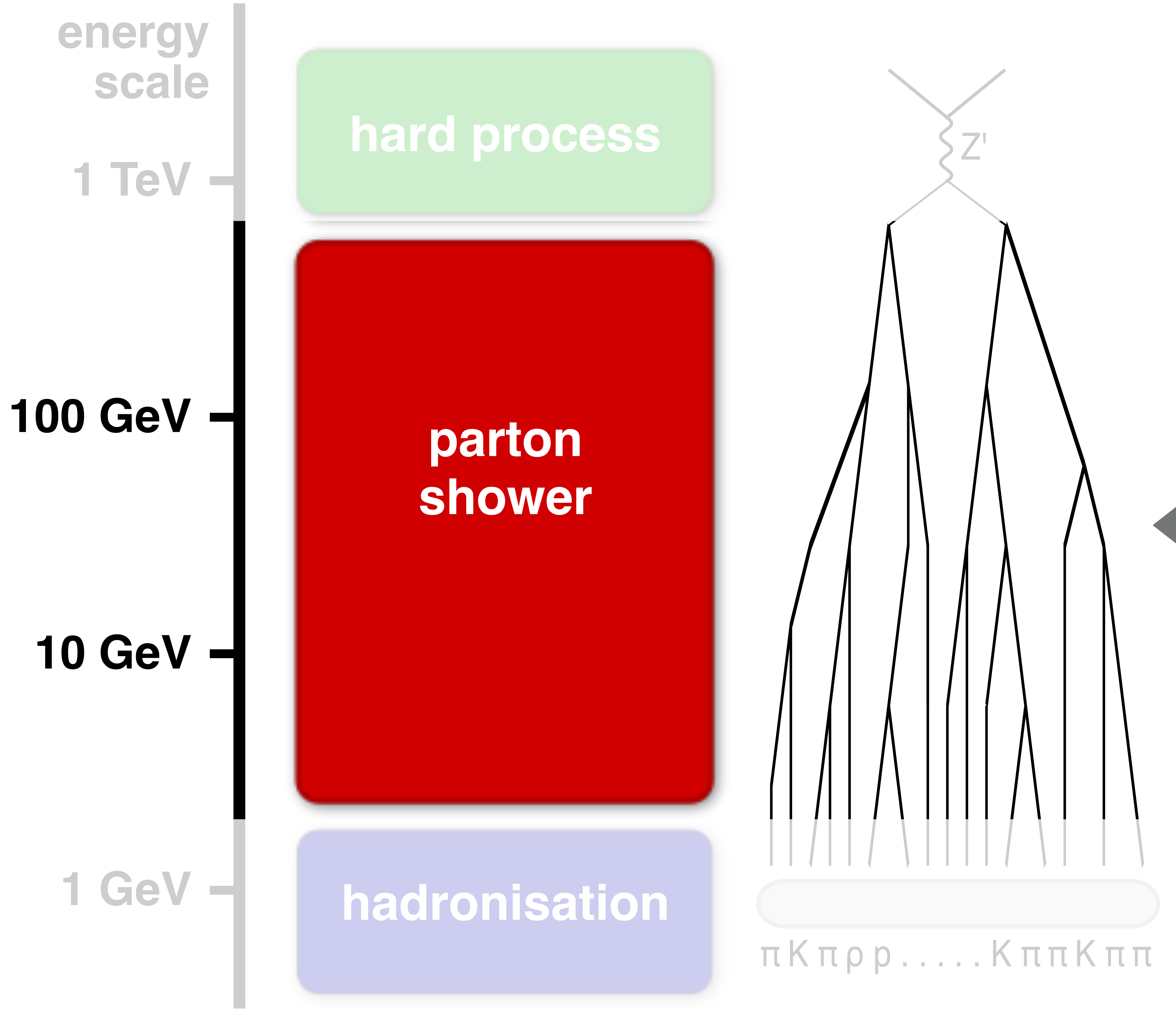
Unless you are highly confident in the information you have about the markets, you may be better off ignoring it altogether

- Harry Markowitz (1990 Nobel Prize in Economics)

[via S Gukov]

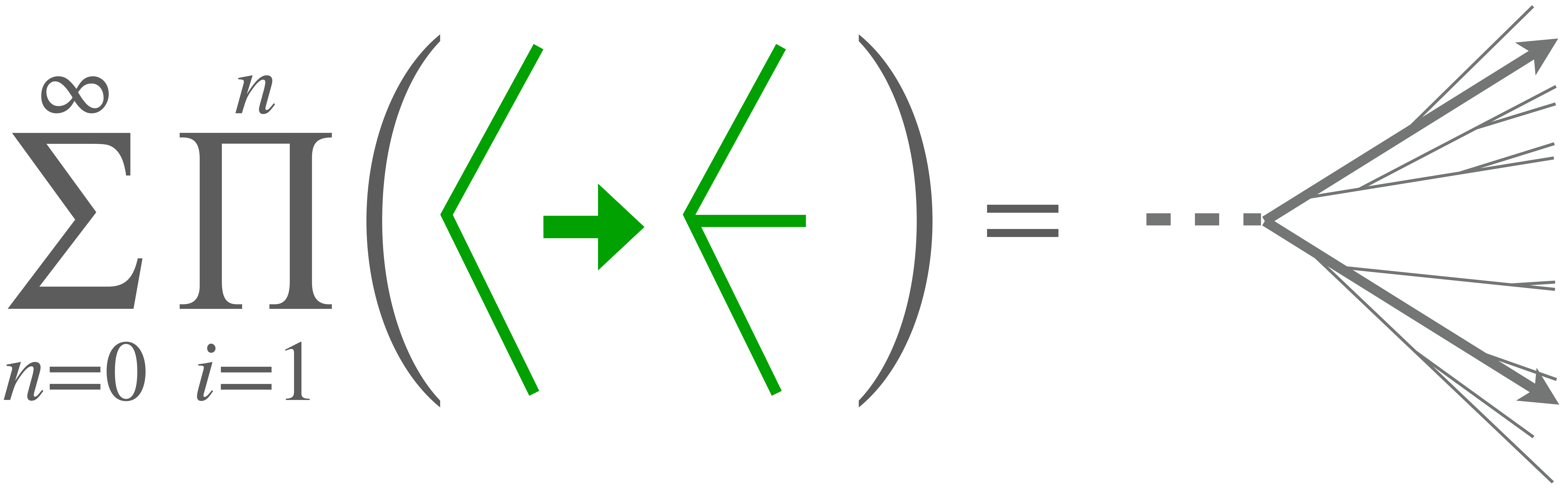


machine-learning gets trained on QCD simulations



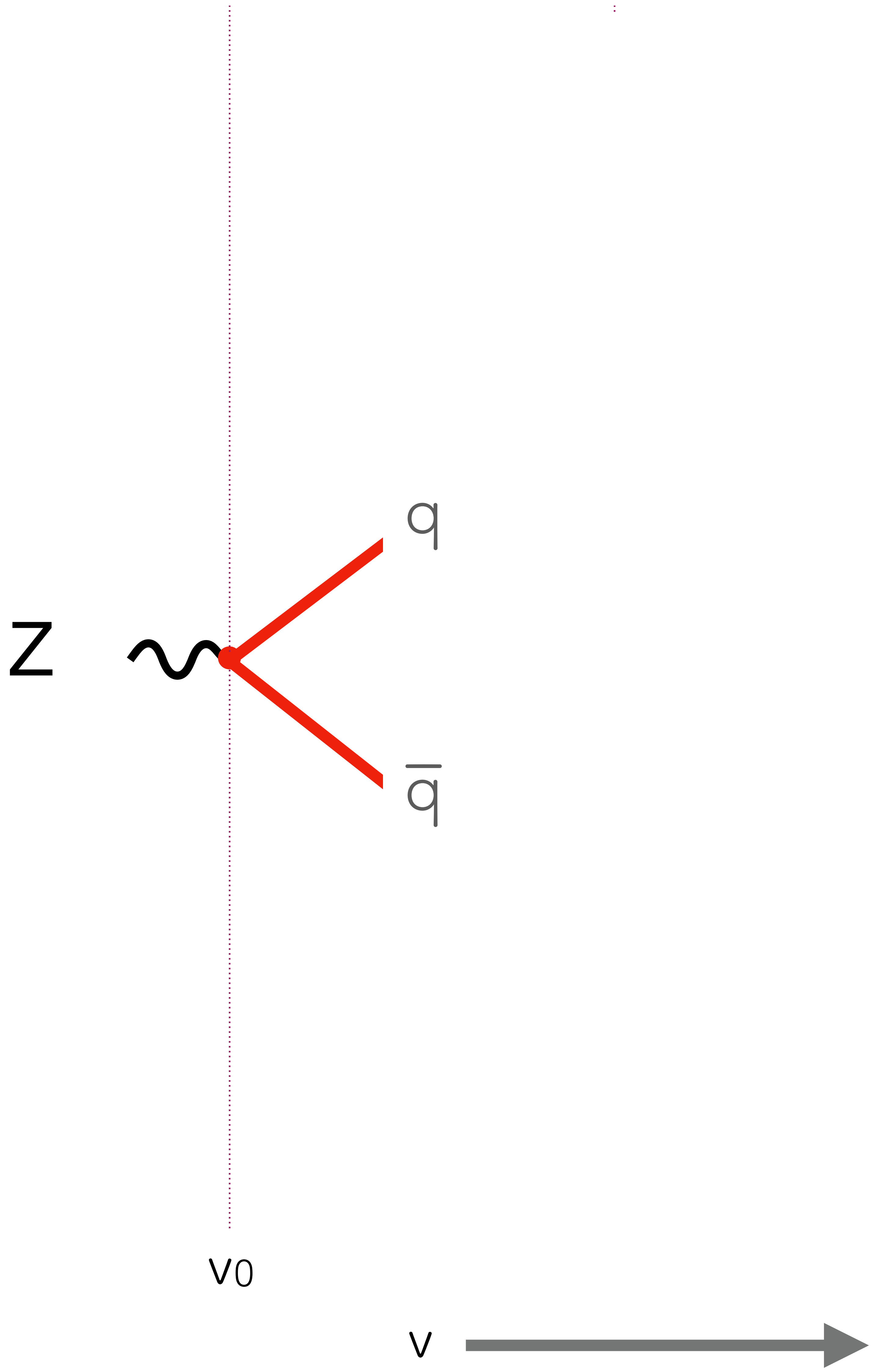
concentrate on this part

A parton shower, at its simplest



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

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

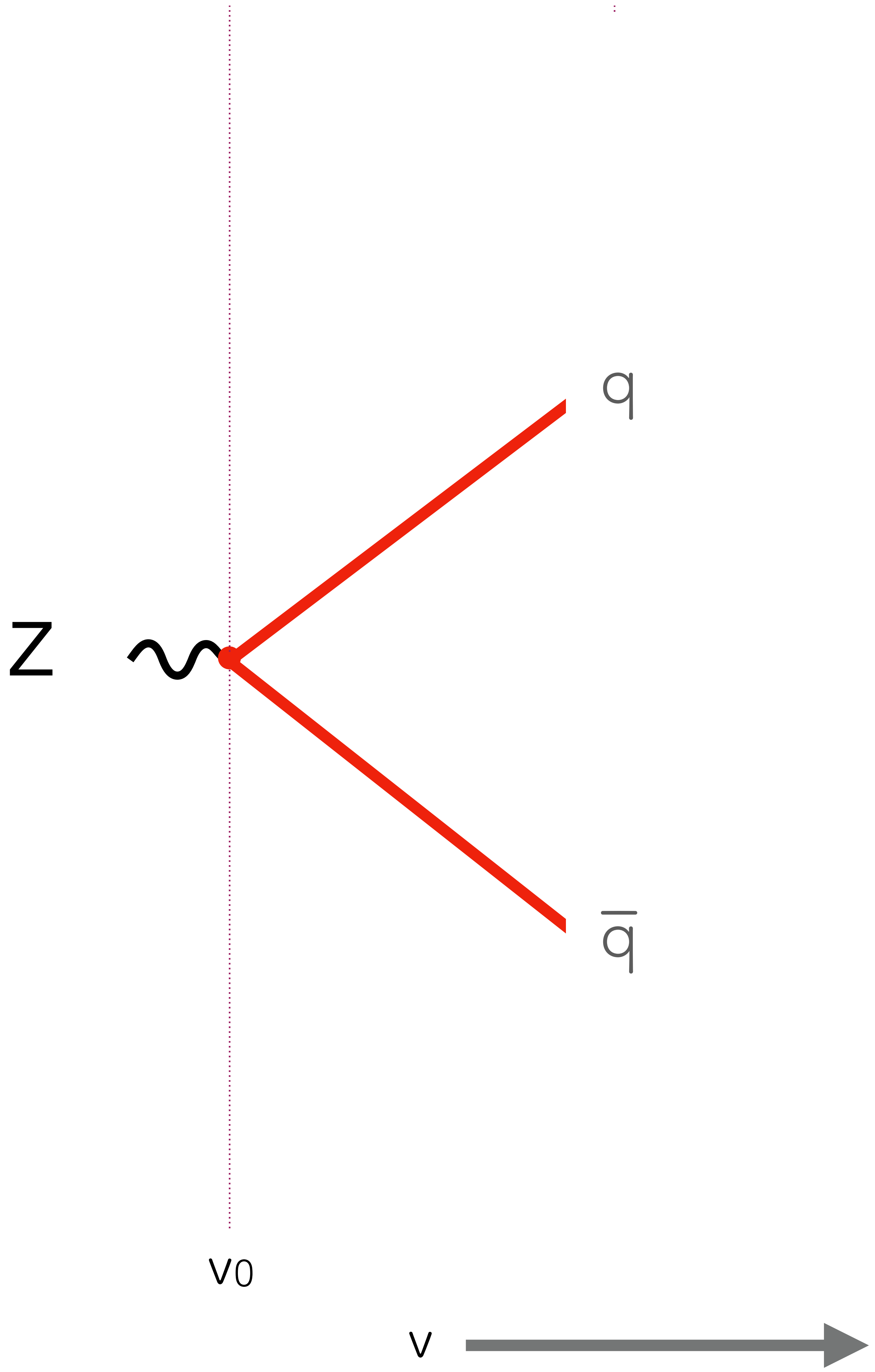


Start with q-qbar state.

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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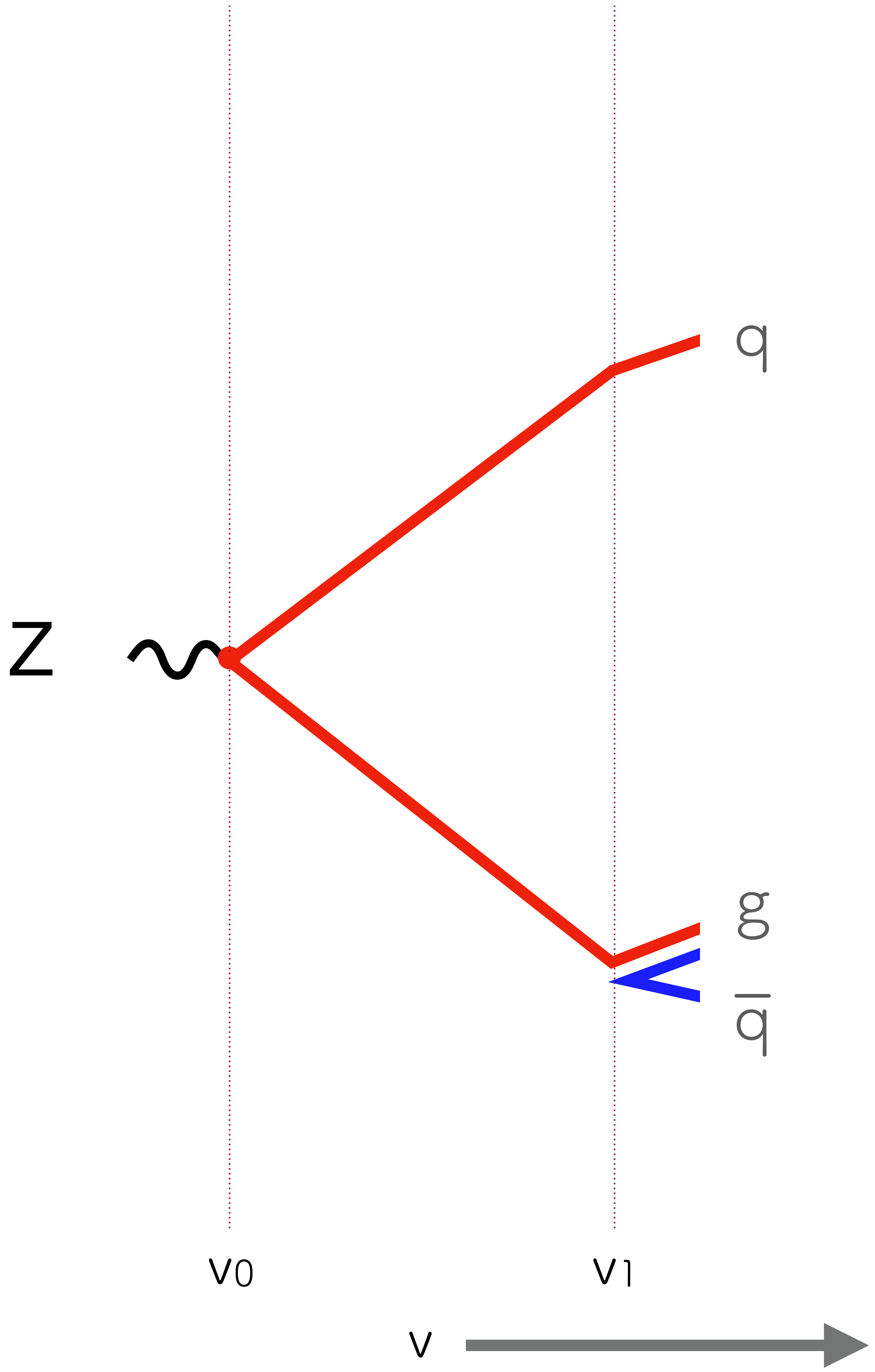


Start with q-qbar state.

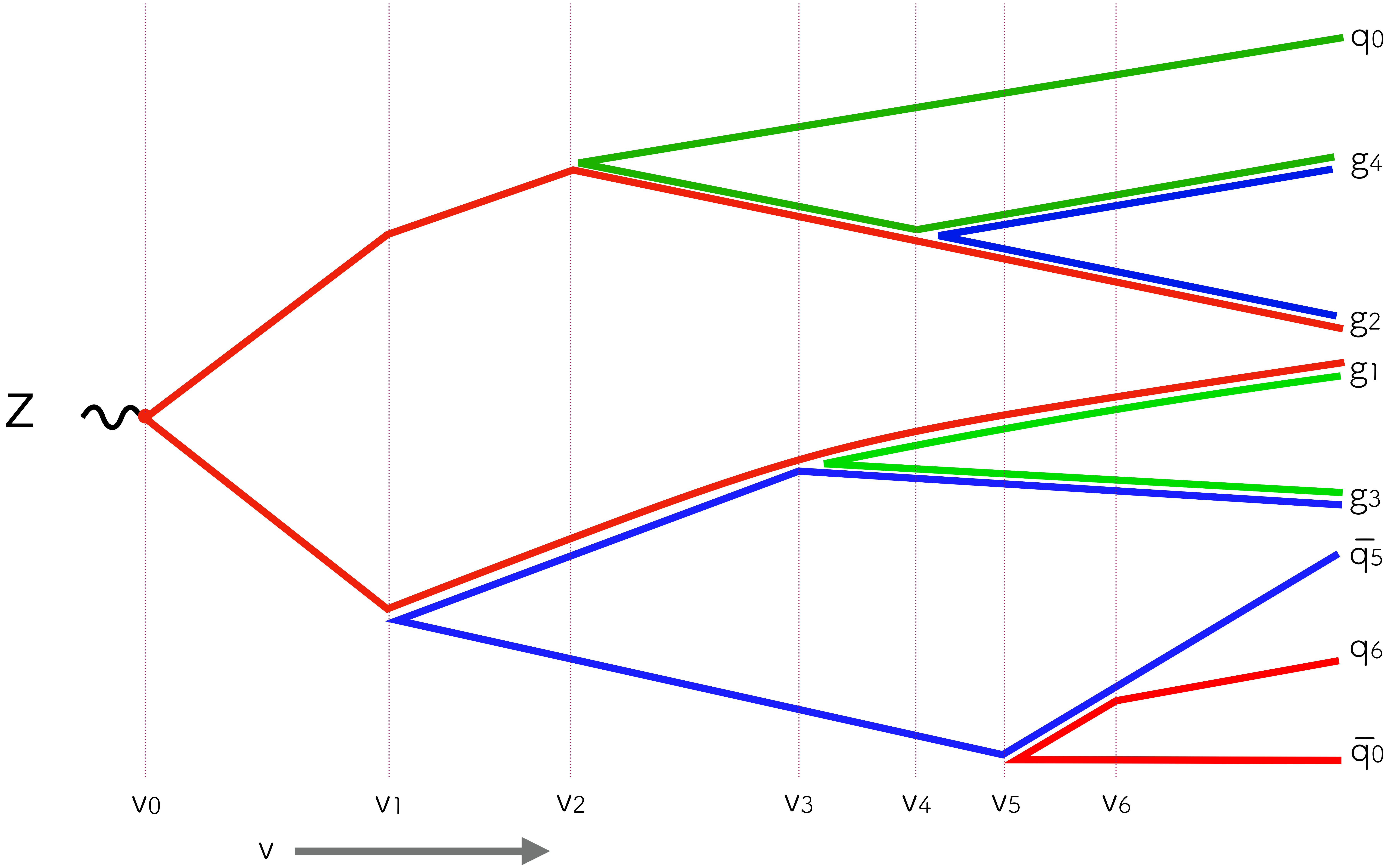
Evolve a step in v and throw a random number to decide if state remains unchanged

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

metric for "success" for parton showers?

- **you can use it to predict anything:**
  i.e. pattern of N-particle production for any N,
  there's no way of getting this right all the time
- **we need to identify a criterion for "success" that is within reach**
  lack of criterion → lack of clear guideline for parton shower development

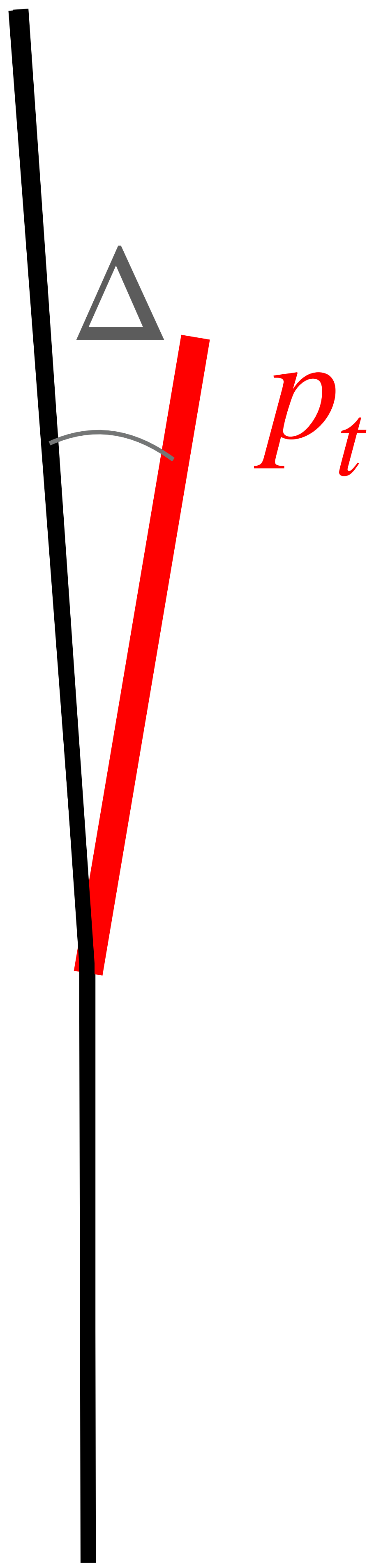
Dipole showers
Dasgupta, Dreyer, Hamilton, Monni & GPS, 1805.09327
Dasgupta, Dreyer, Hamilton, Monni, GPS & Soyez (in progress)
Nagy & Soper (a series of article since ~ 2008)

Angular-ordered showers:
Banfi, Corcella, Dasgupta, hep-ph/0612282
Bewick, Ravasio-Ferrario, Richardson & Seymour 1904.11866

the “Lund plane”

one crucial element to build a metric of success for parton showers

Phase space: two key variables (+ azimuth)

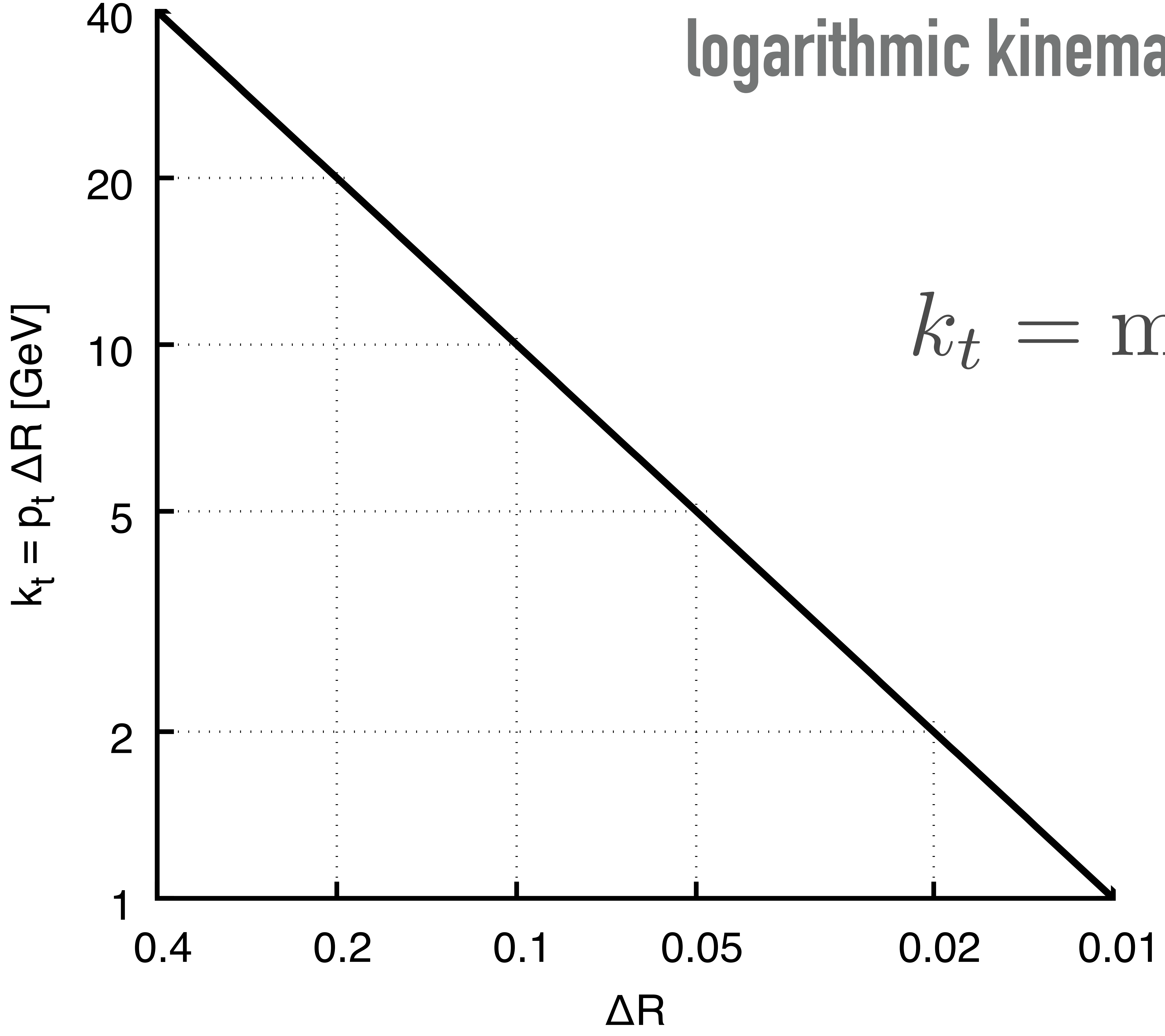


ΔR (or just Δ) — *opening angle of a splitting*

$k_t = p_t \Delta$ — 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



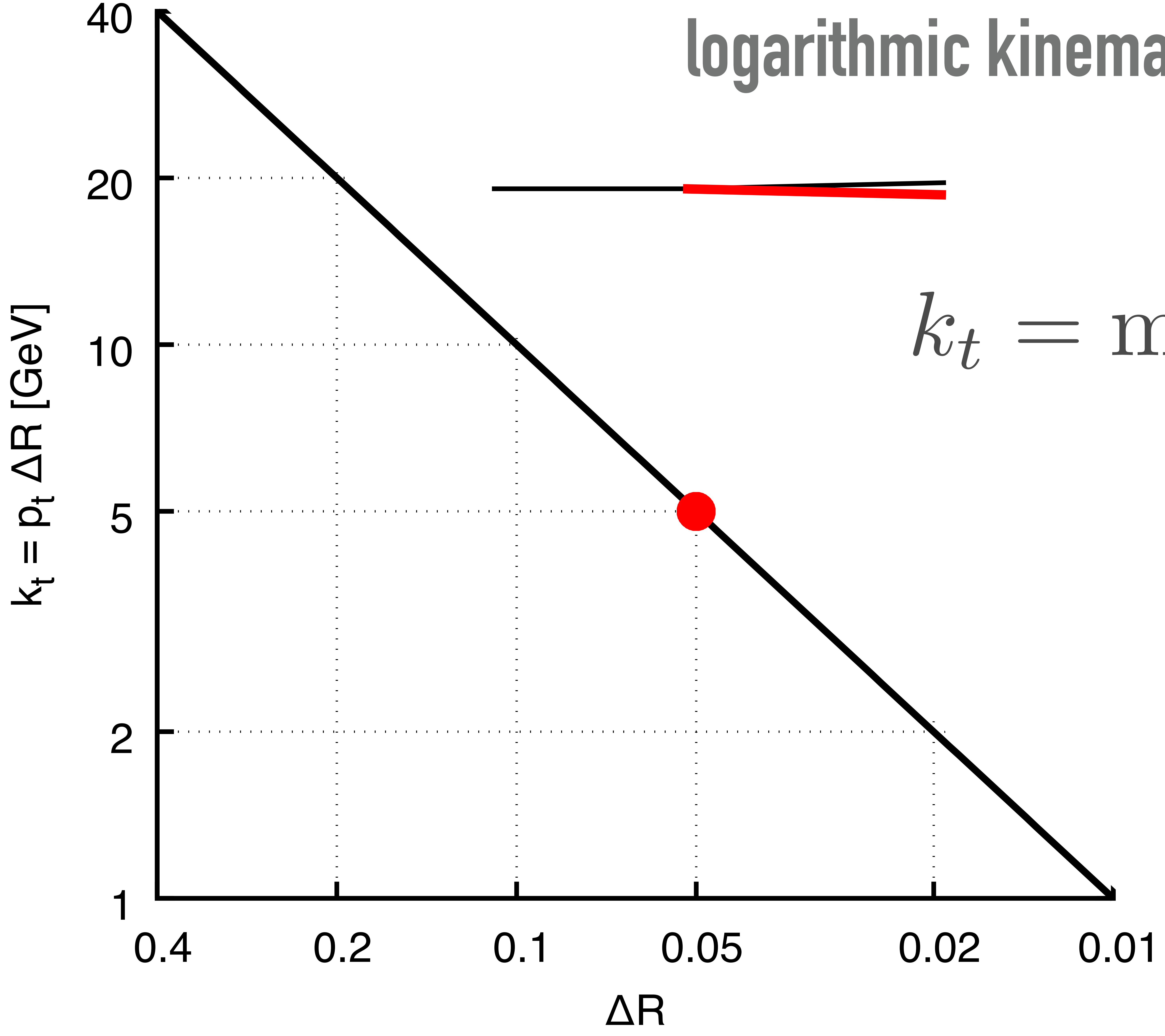
logarithmic kinematic plane whose two variables are

$$\Delta R_{ij}$$

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

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

The Lund Plane



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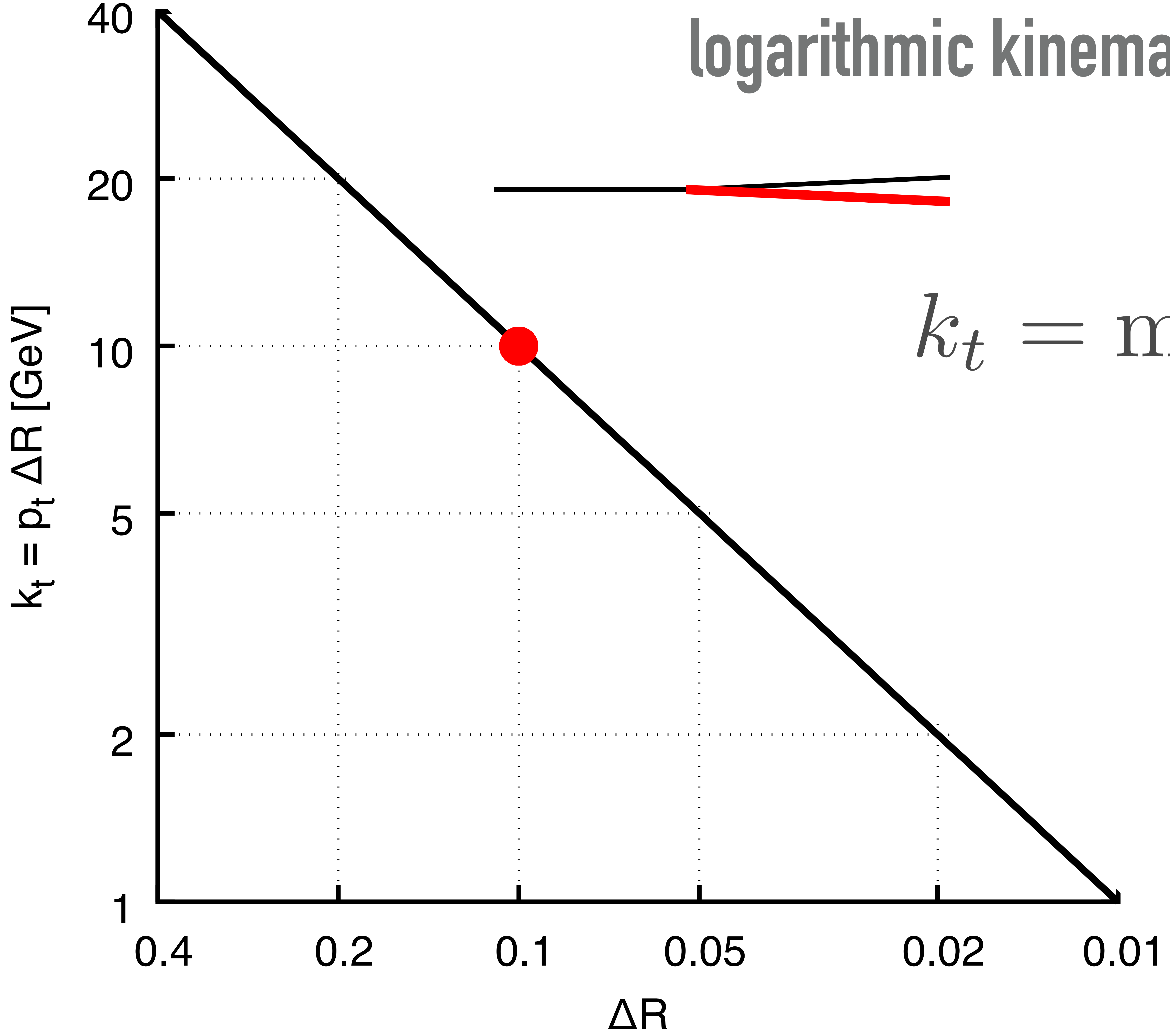

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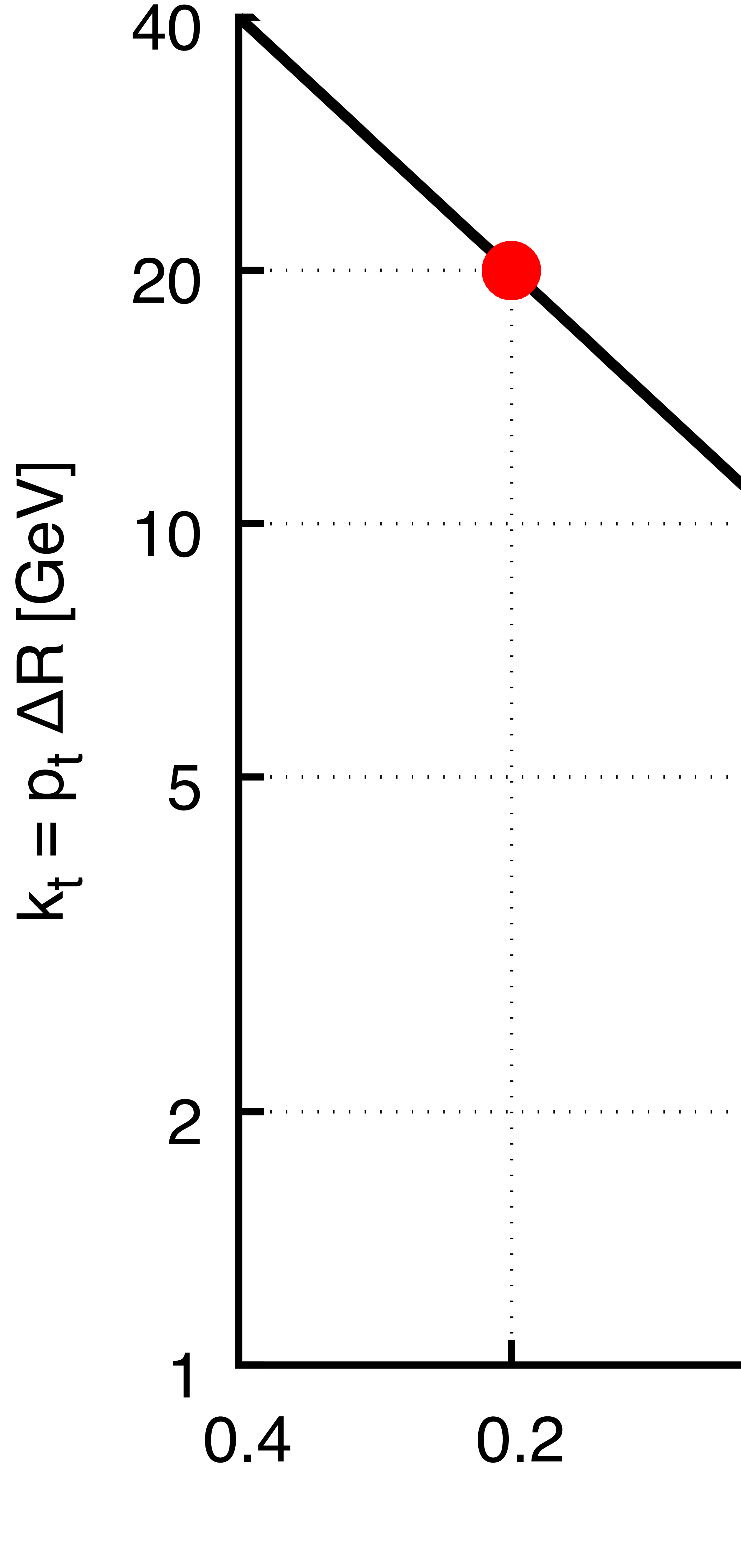

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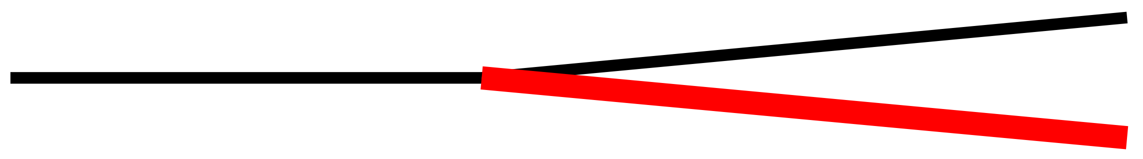

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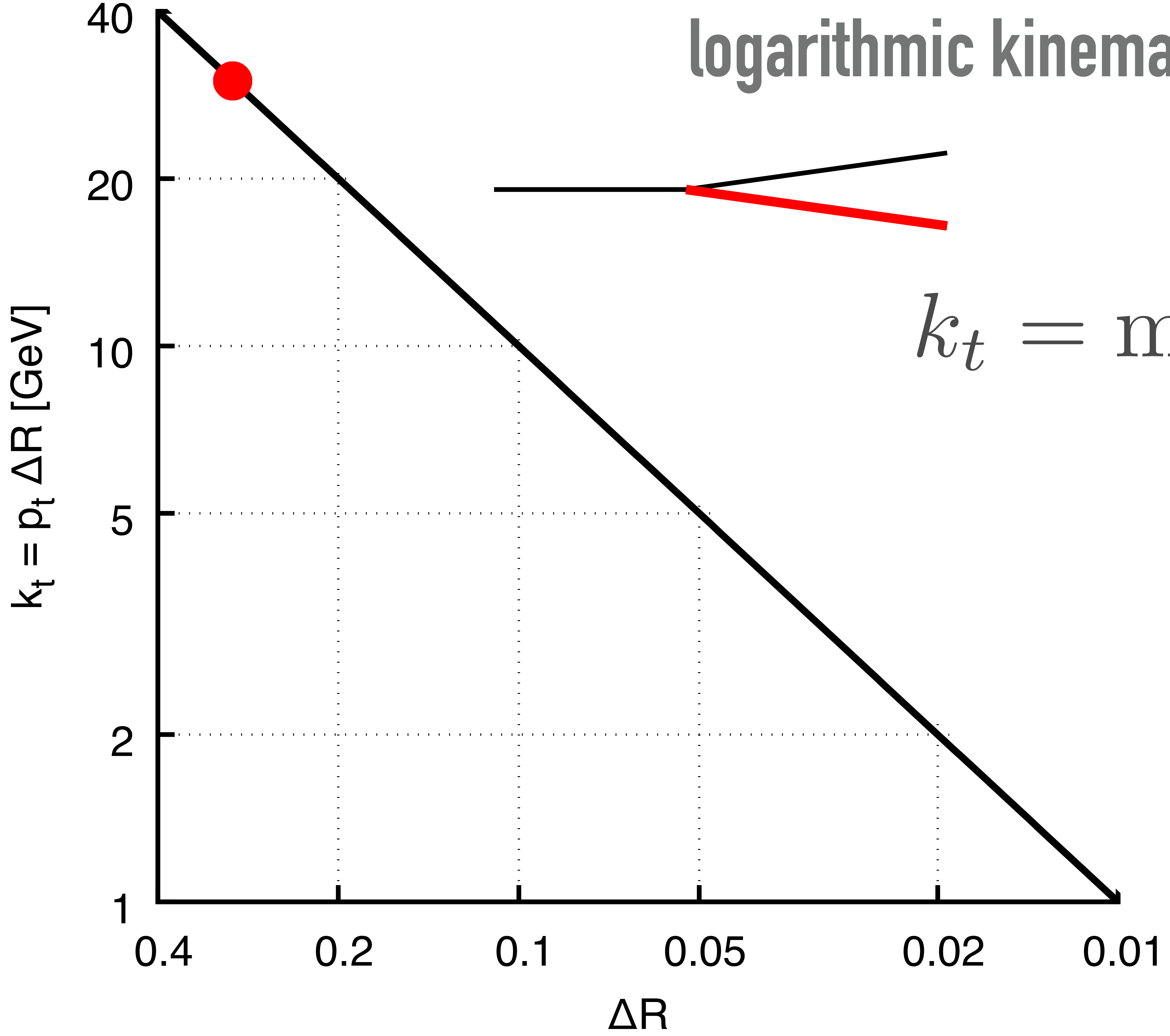

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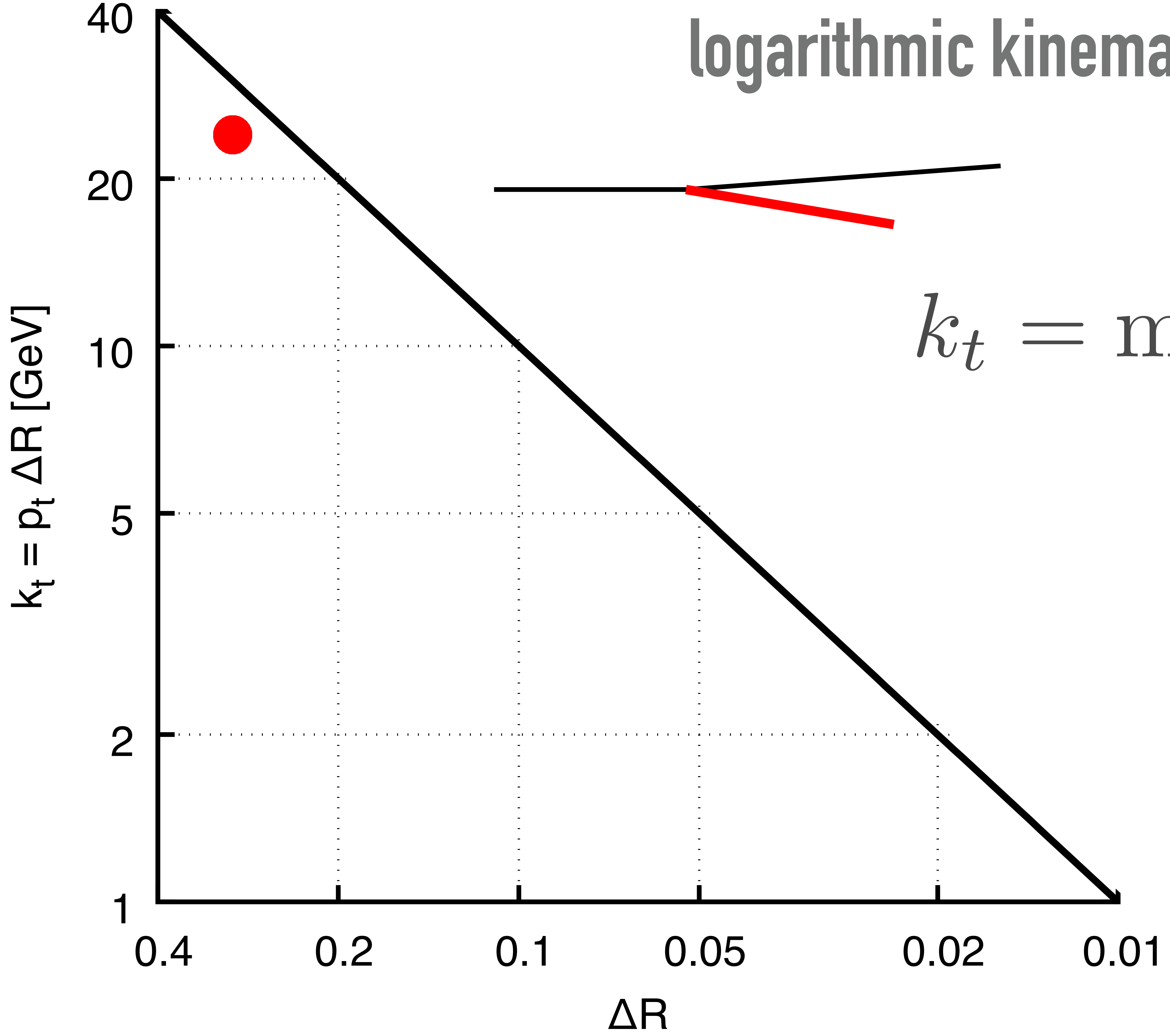

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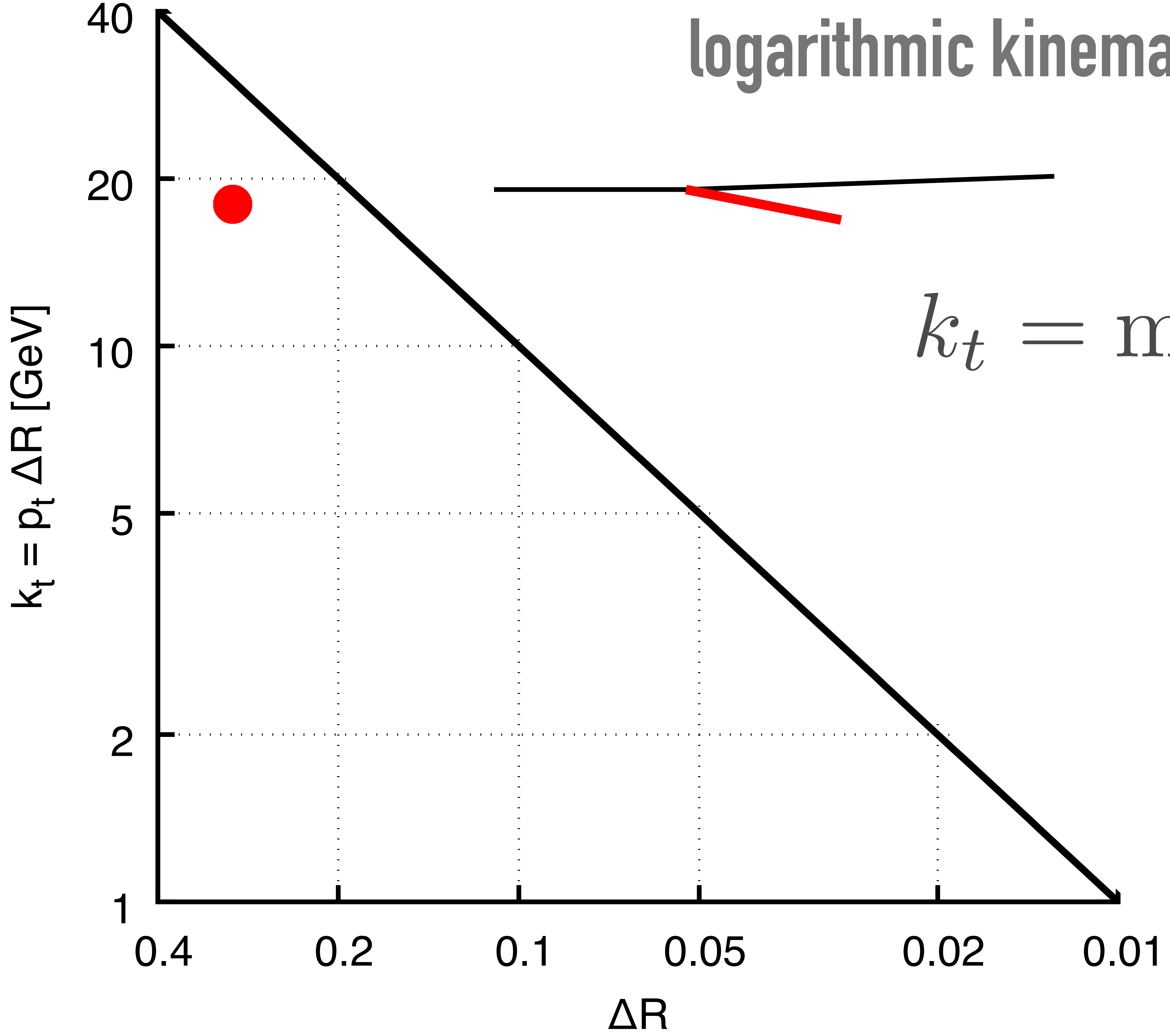

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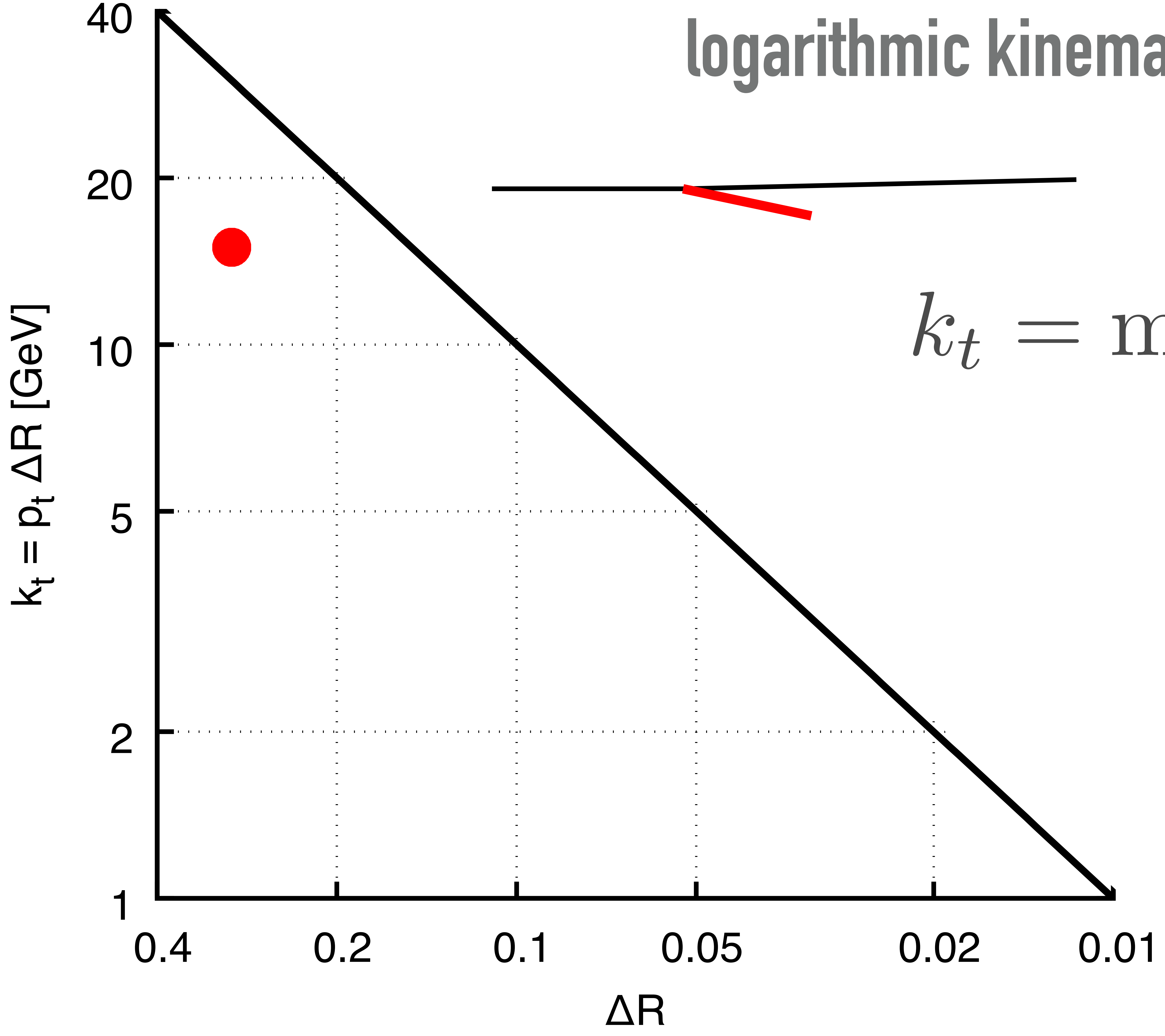

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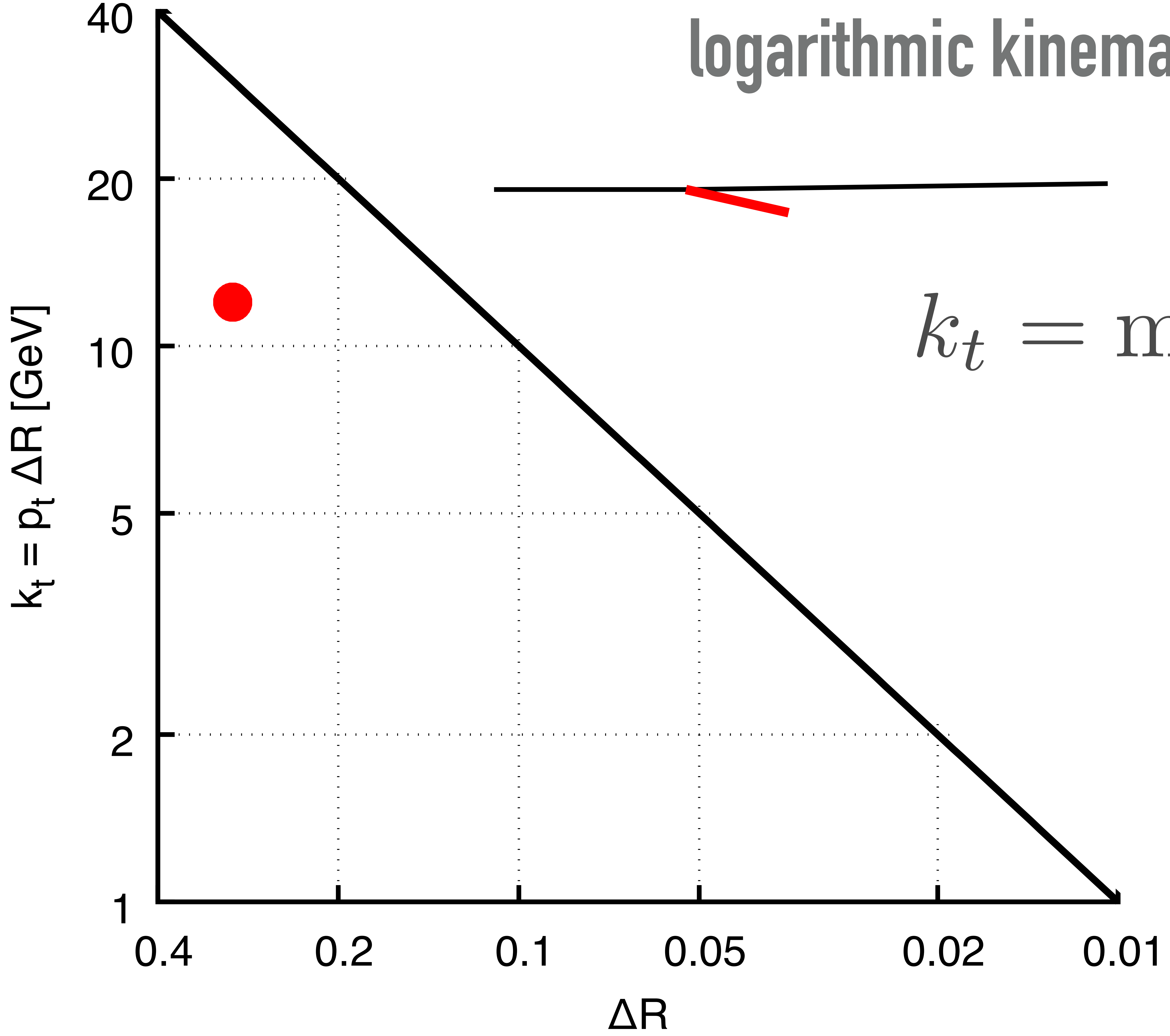
Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson, 1989

The Lund Plane

jet with R= 0.4, p_t = 200 GeV



logarithmic kinematic plane whose two variables are

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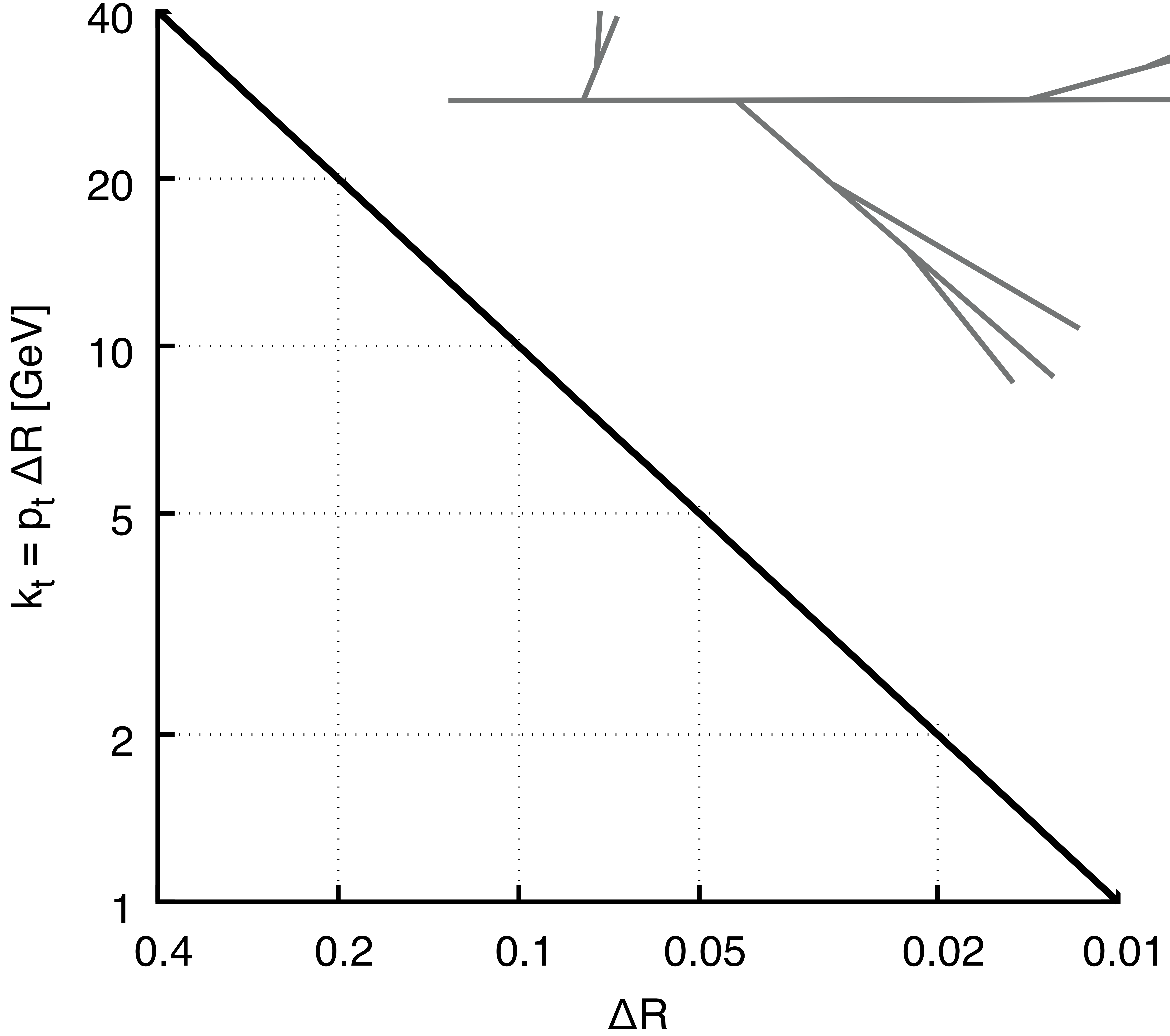
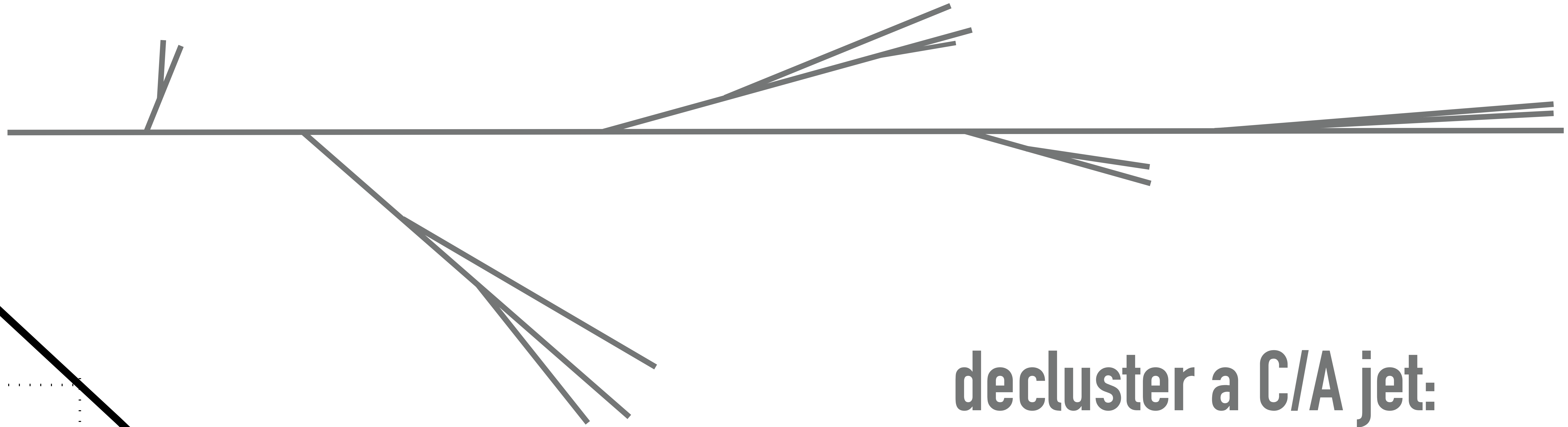


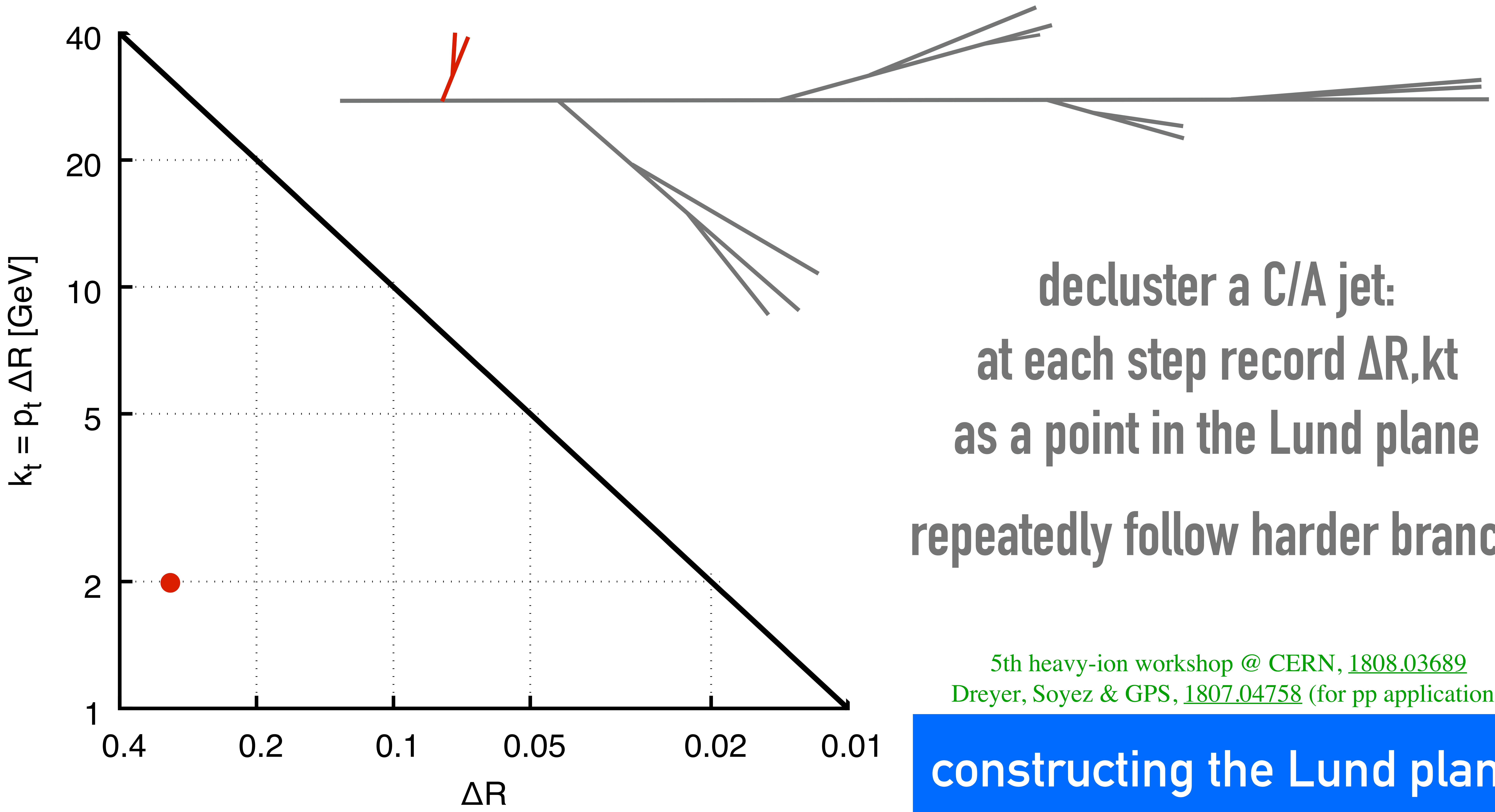


decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

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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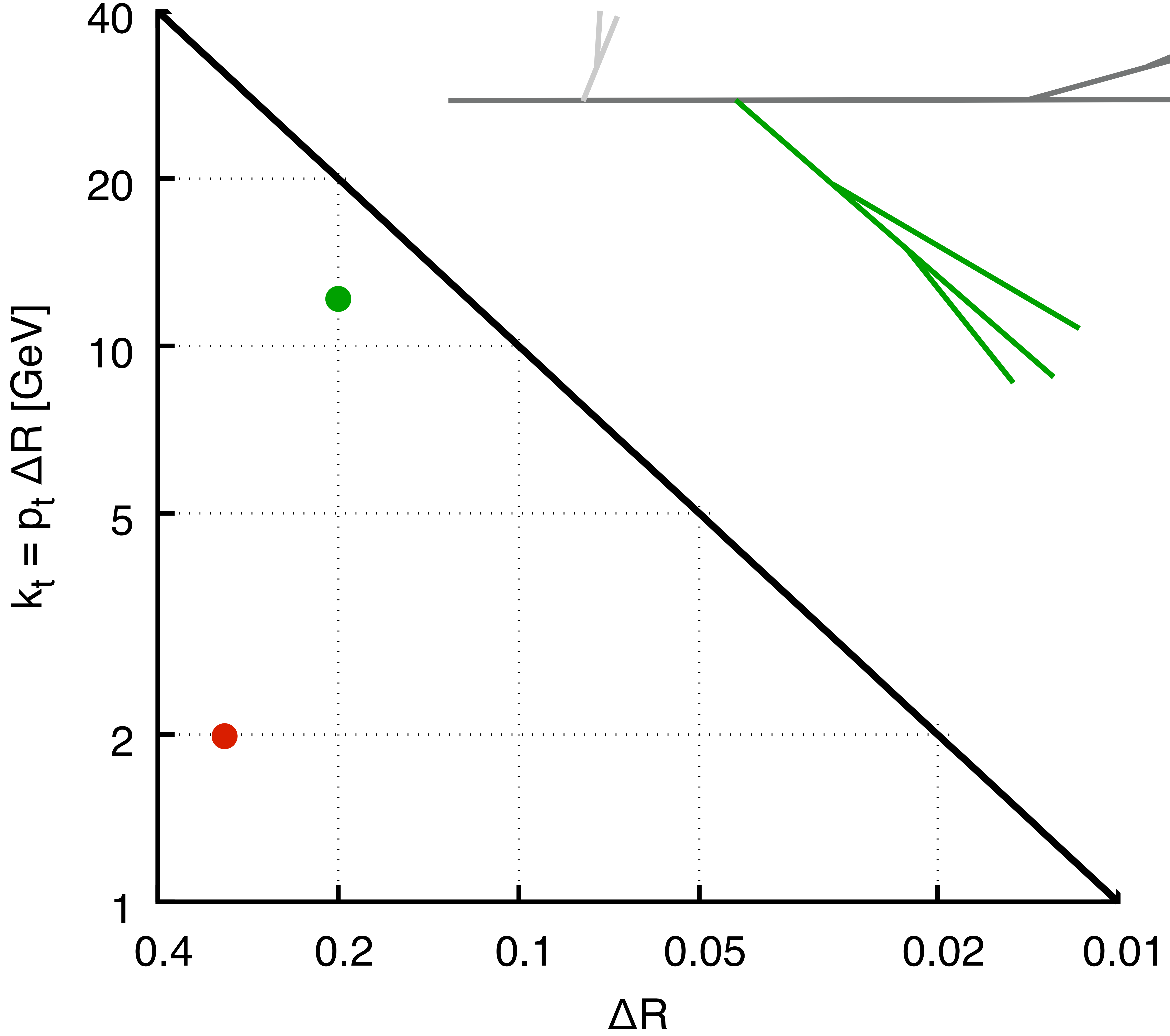

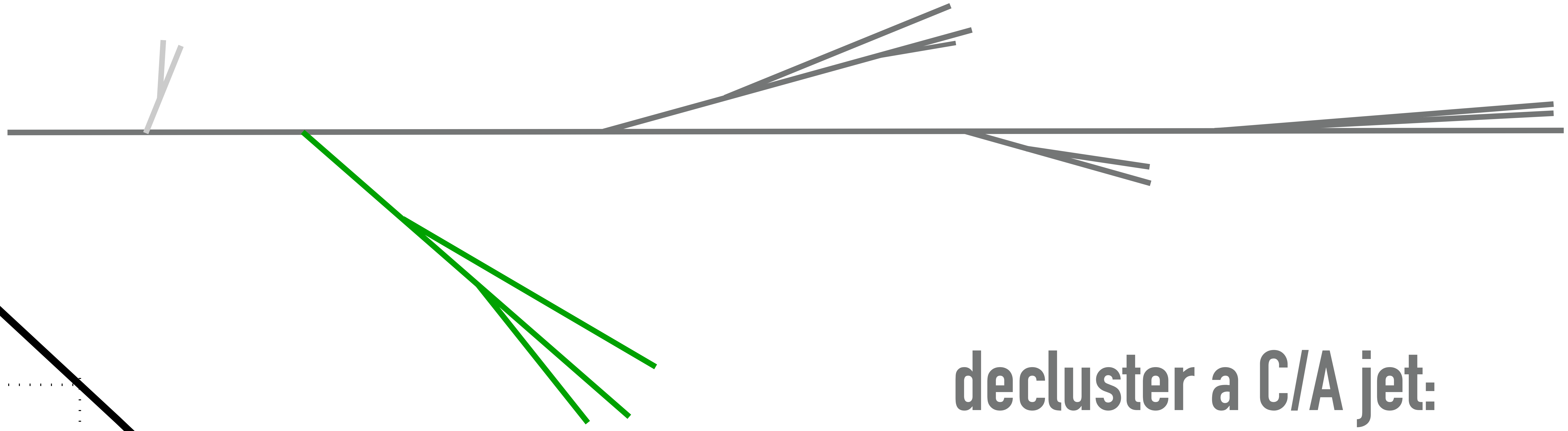

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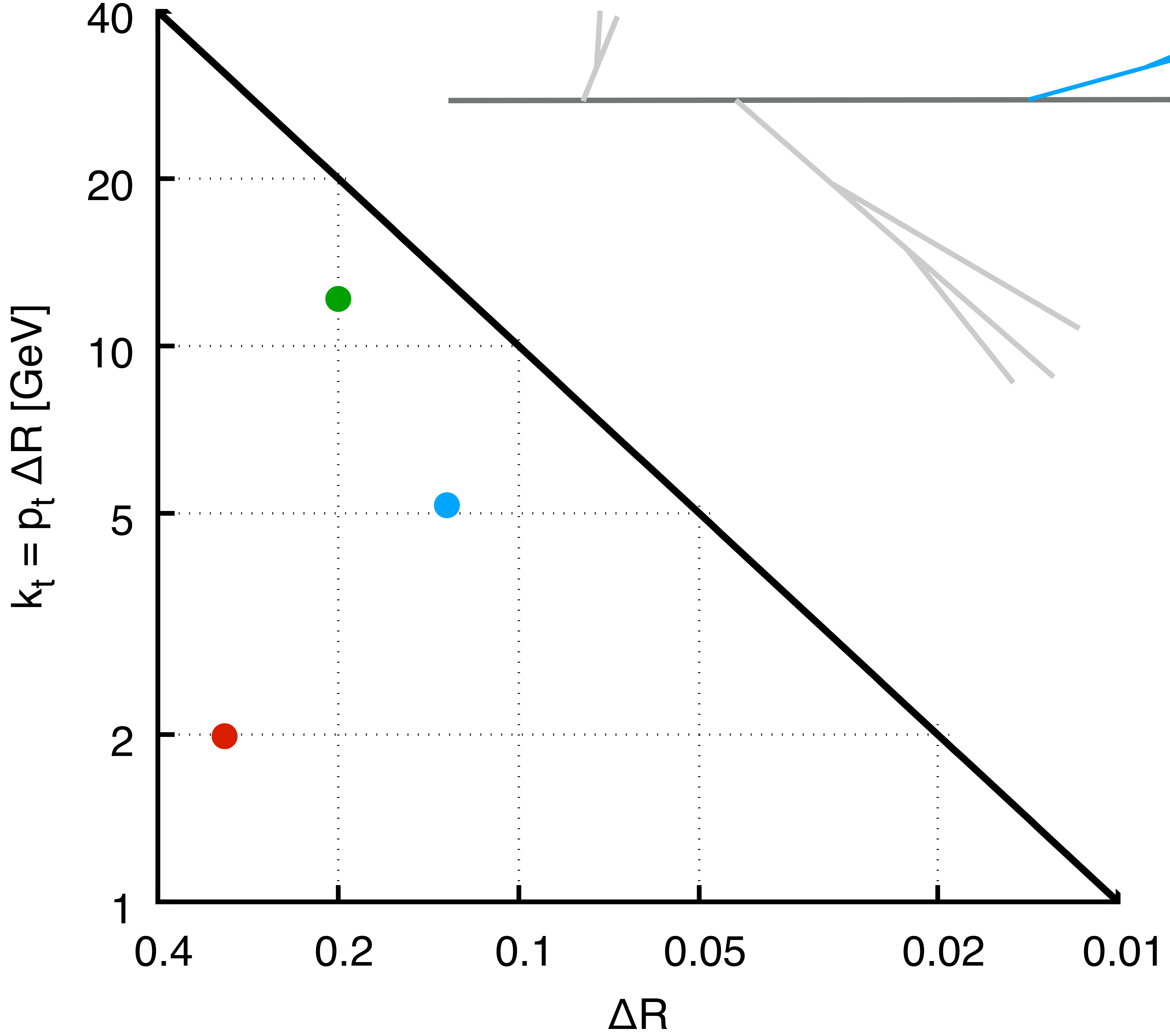

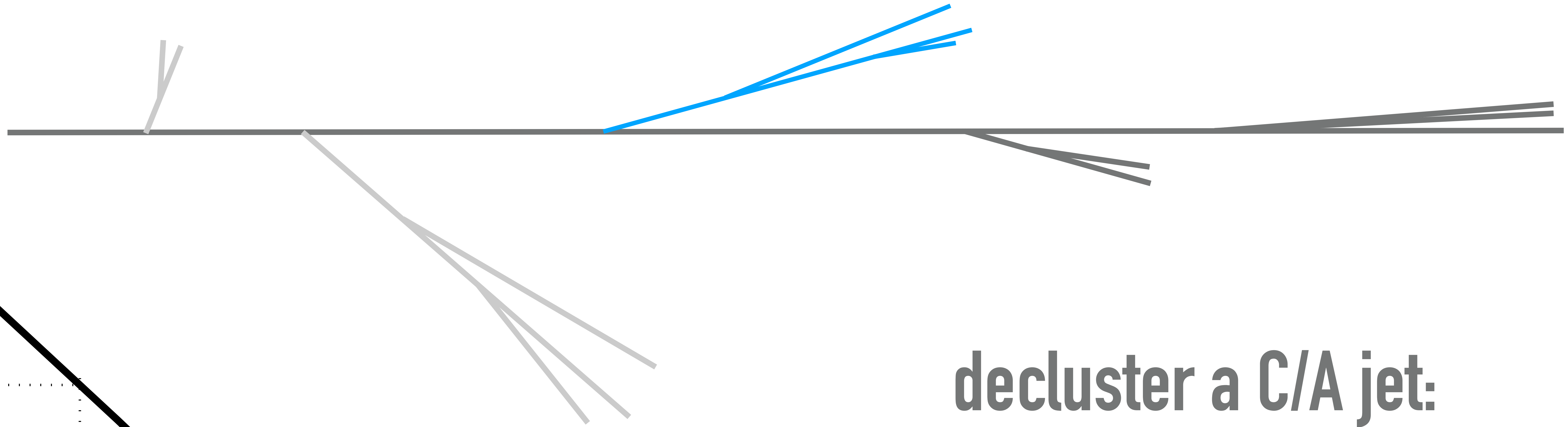

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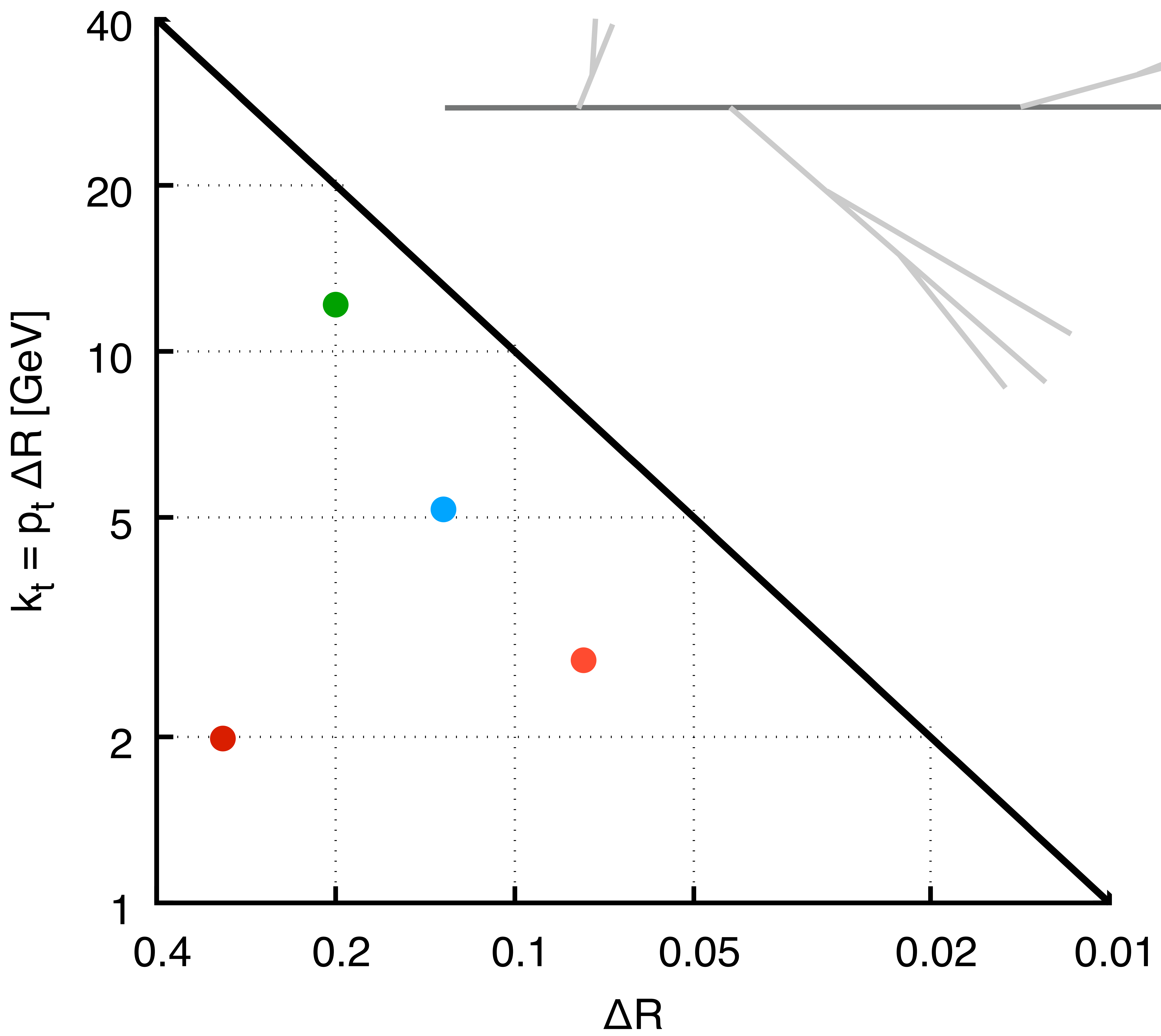

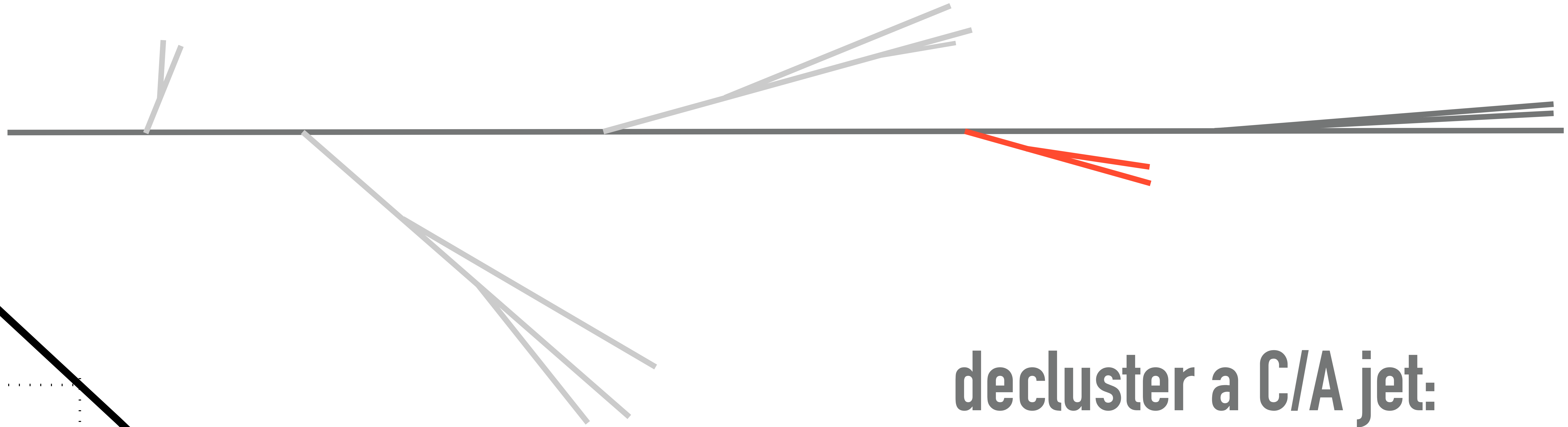

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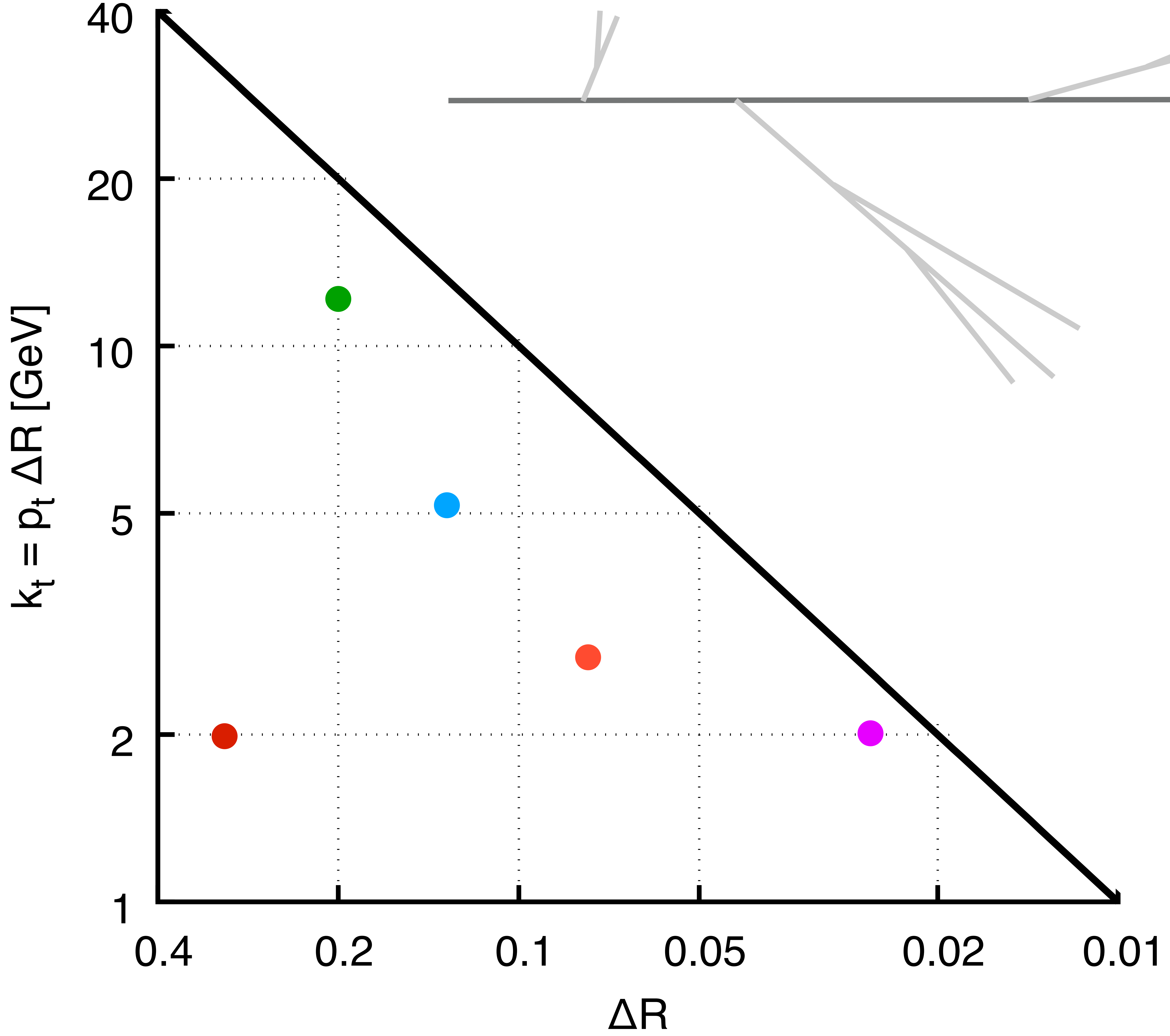

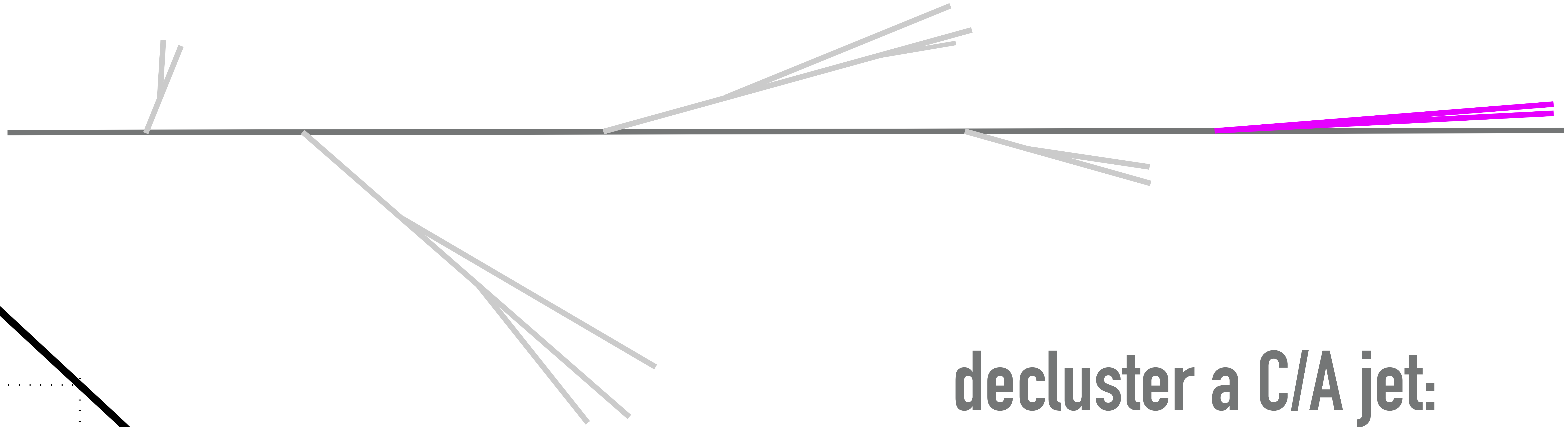

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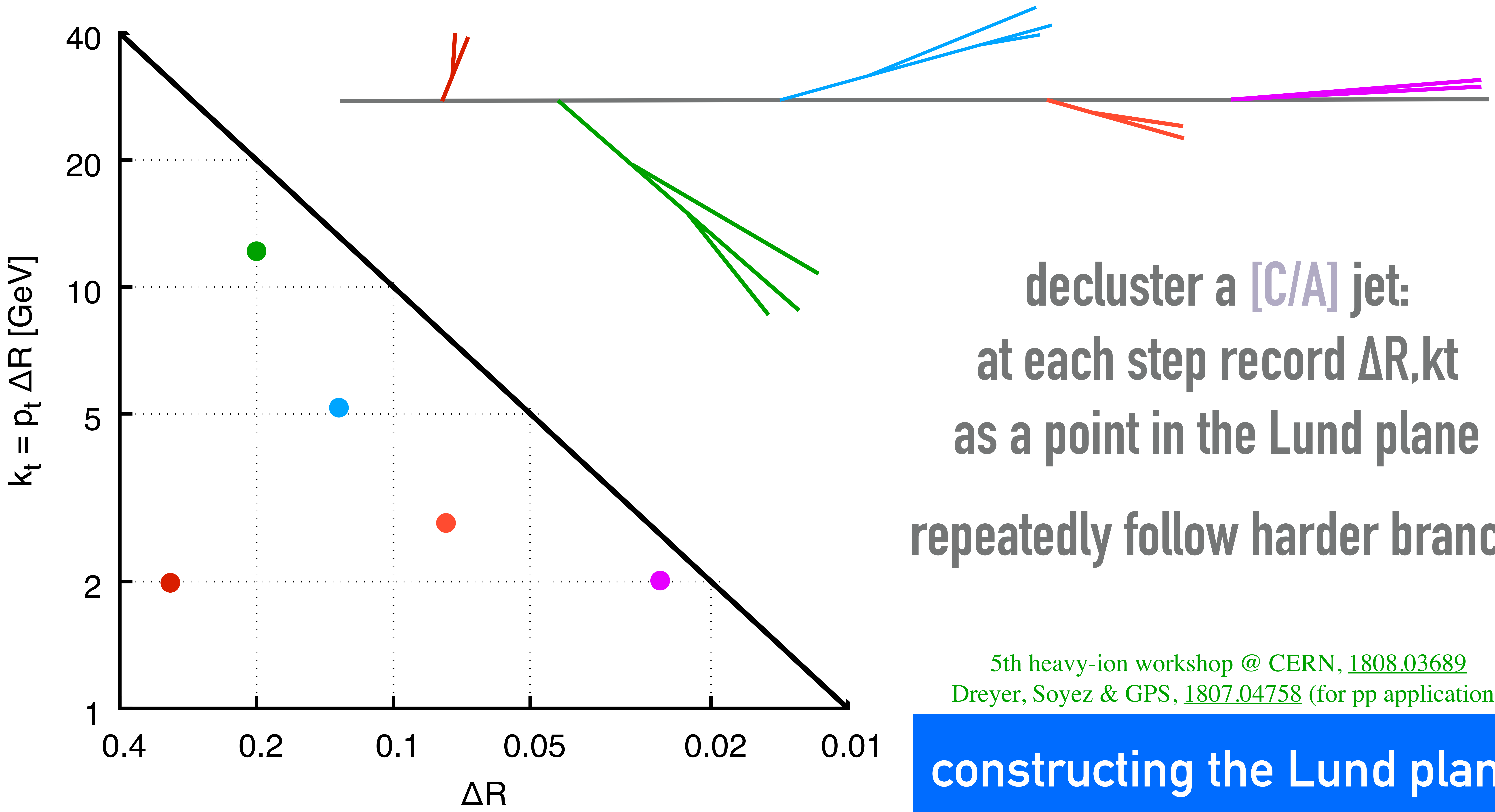

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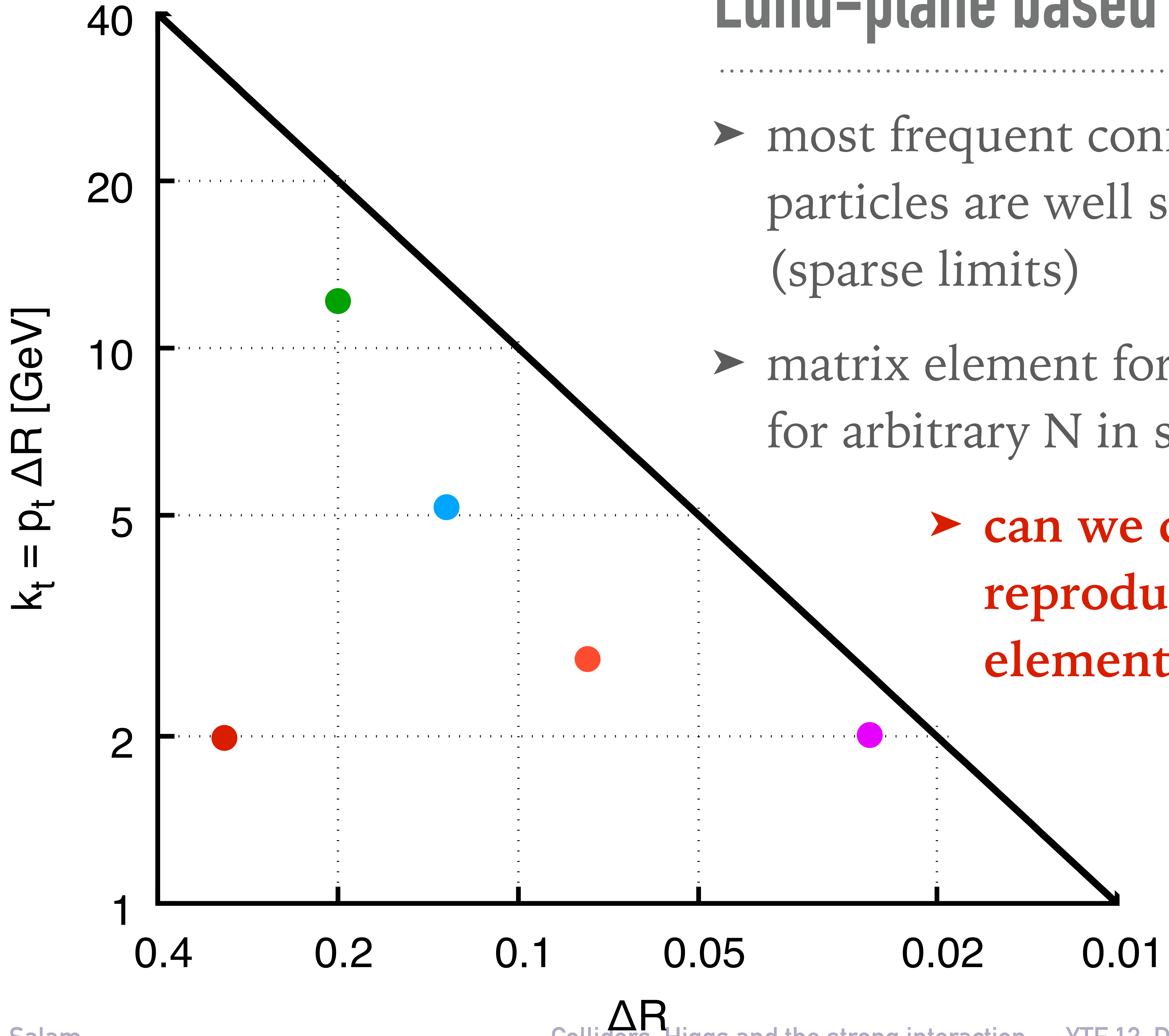
constructing the Lund plane

Lund-plane based requirement for parton showers



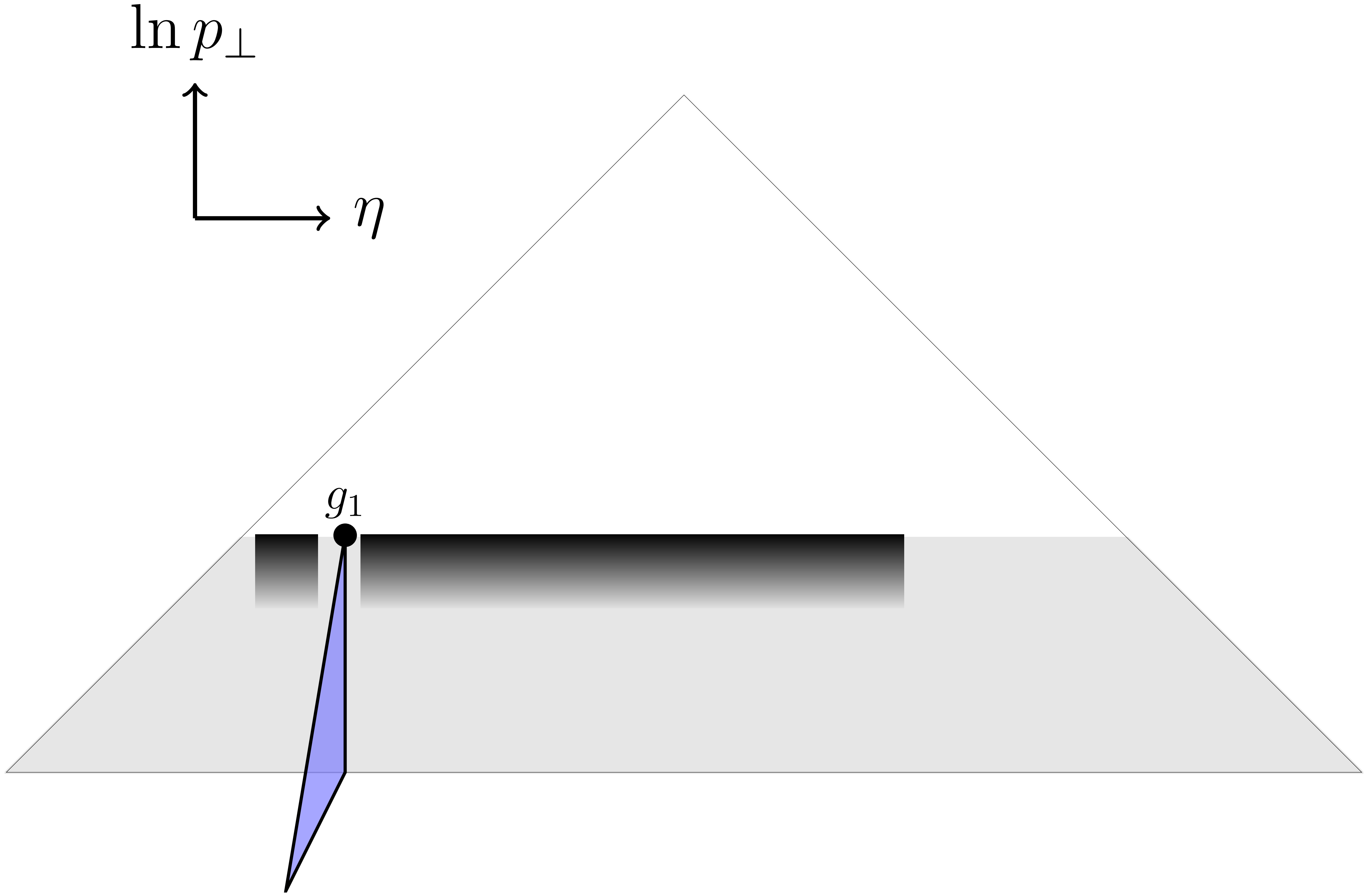
- most frequent configurations are those where particles are well separated in the Lund plane (sparse limits)
- matrix element for N-particle production is known for arbitrary N in sparse limit (at large N_C)
  - **can we construct a parton shower that reproduces all N-particle matrix elements in the sparse limit?**

[only part of the story]

Dasgupta, Dreyer, Hamilton, Monni & GPS, 1805.09327, idem + Soyez (in progress)

Check whether common ("dipole") showers already satisfy this condition

Lund phasespace map



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

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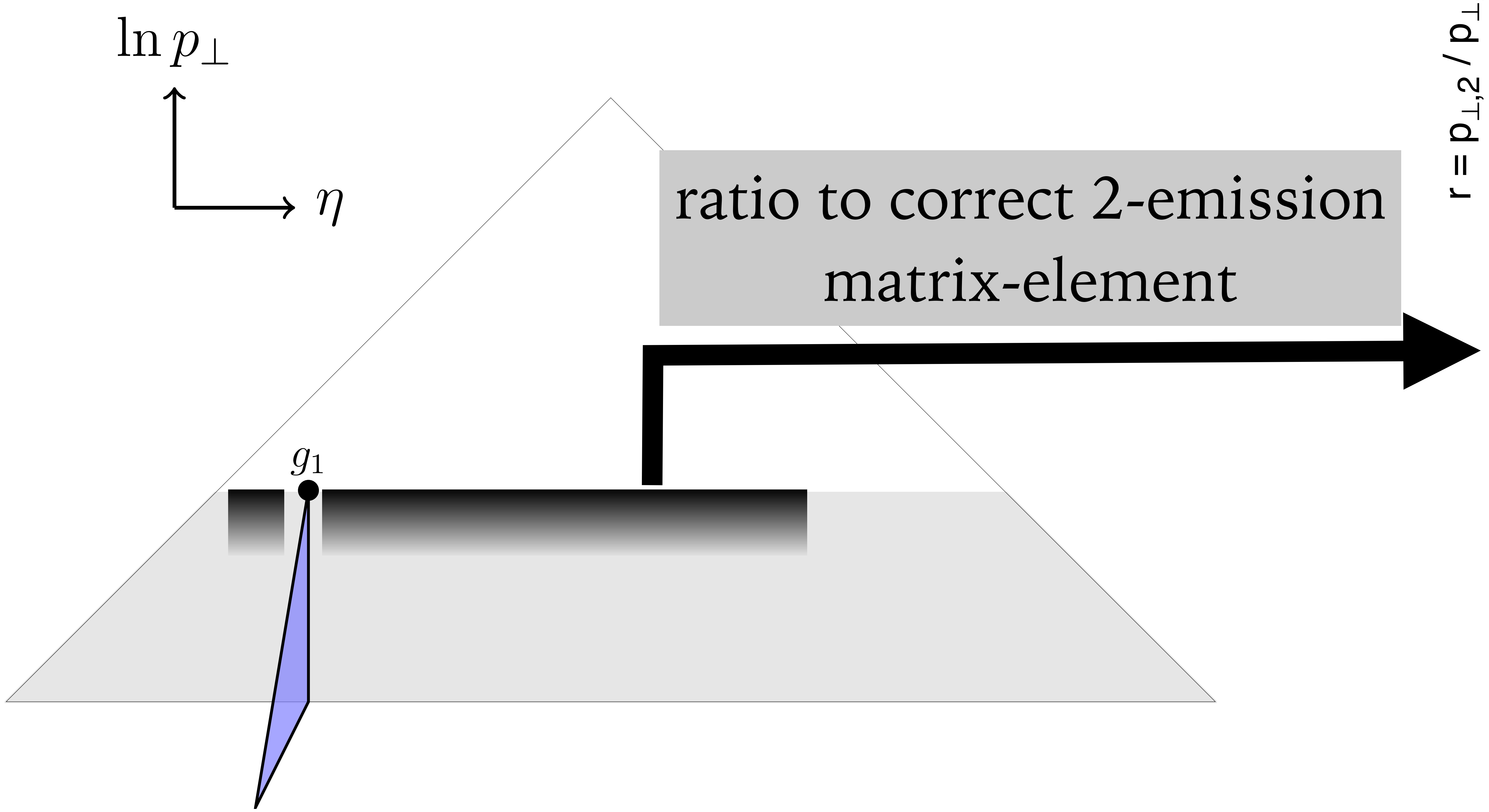

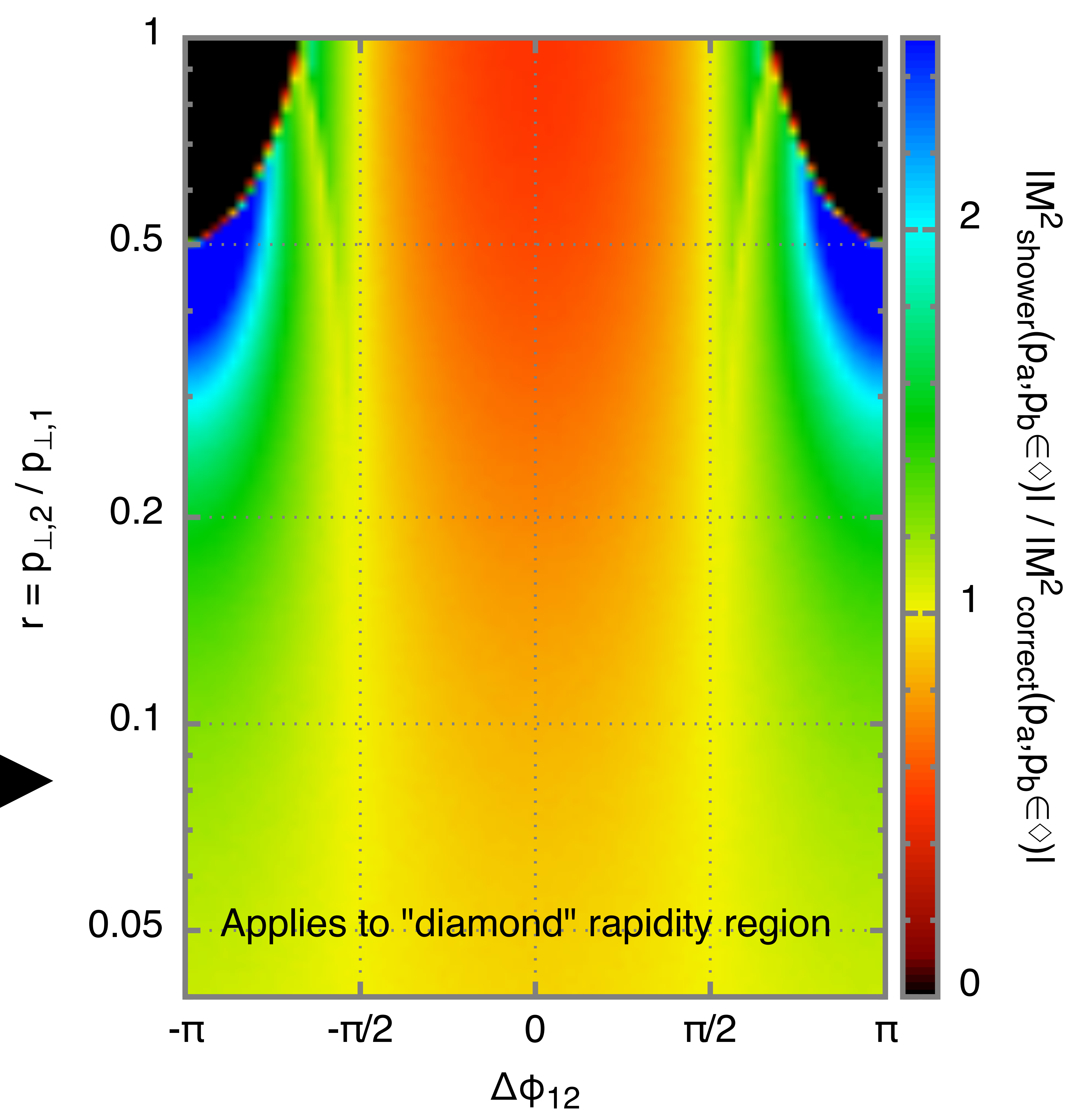

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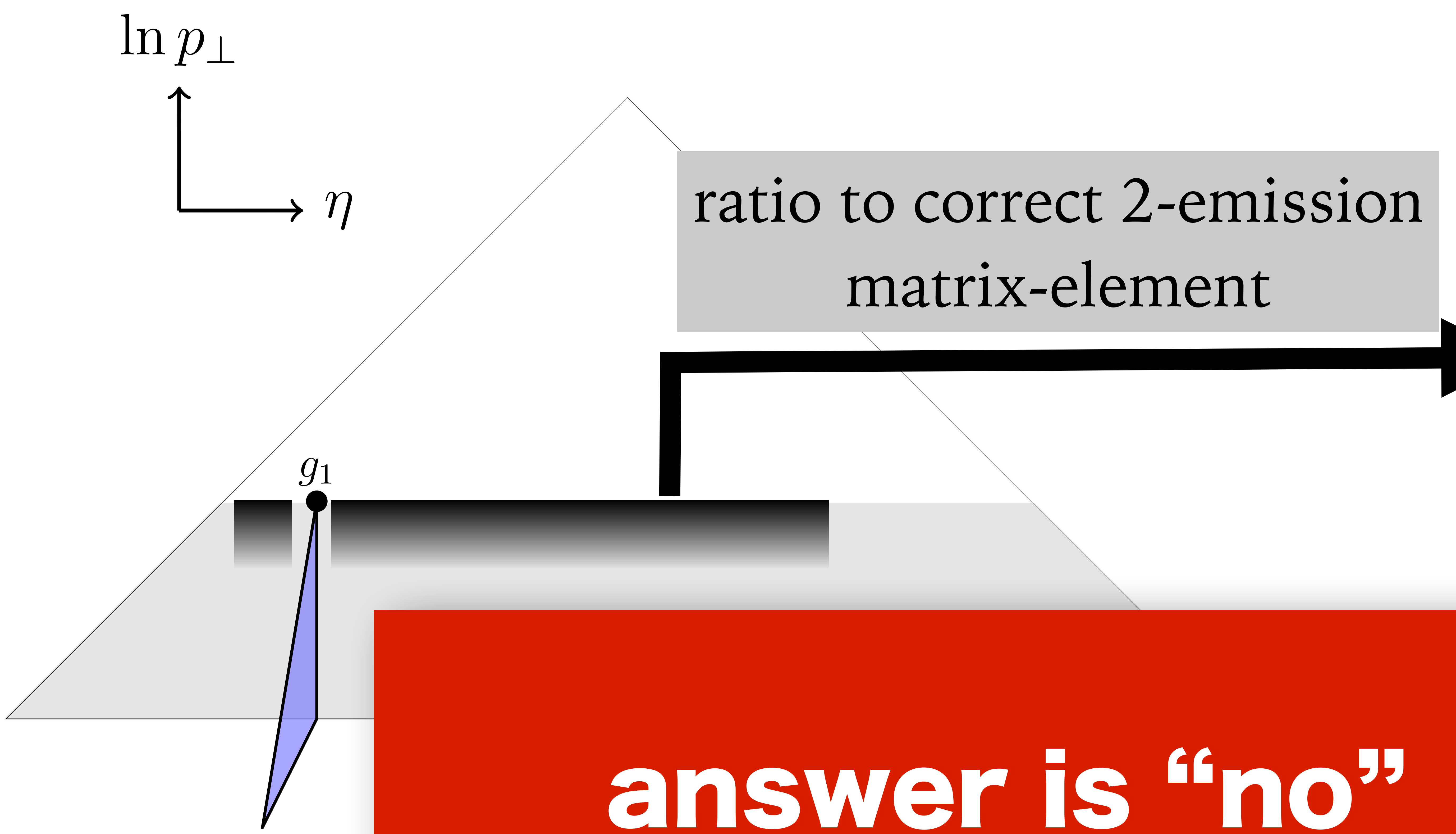

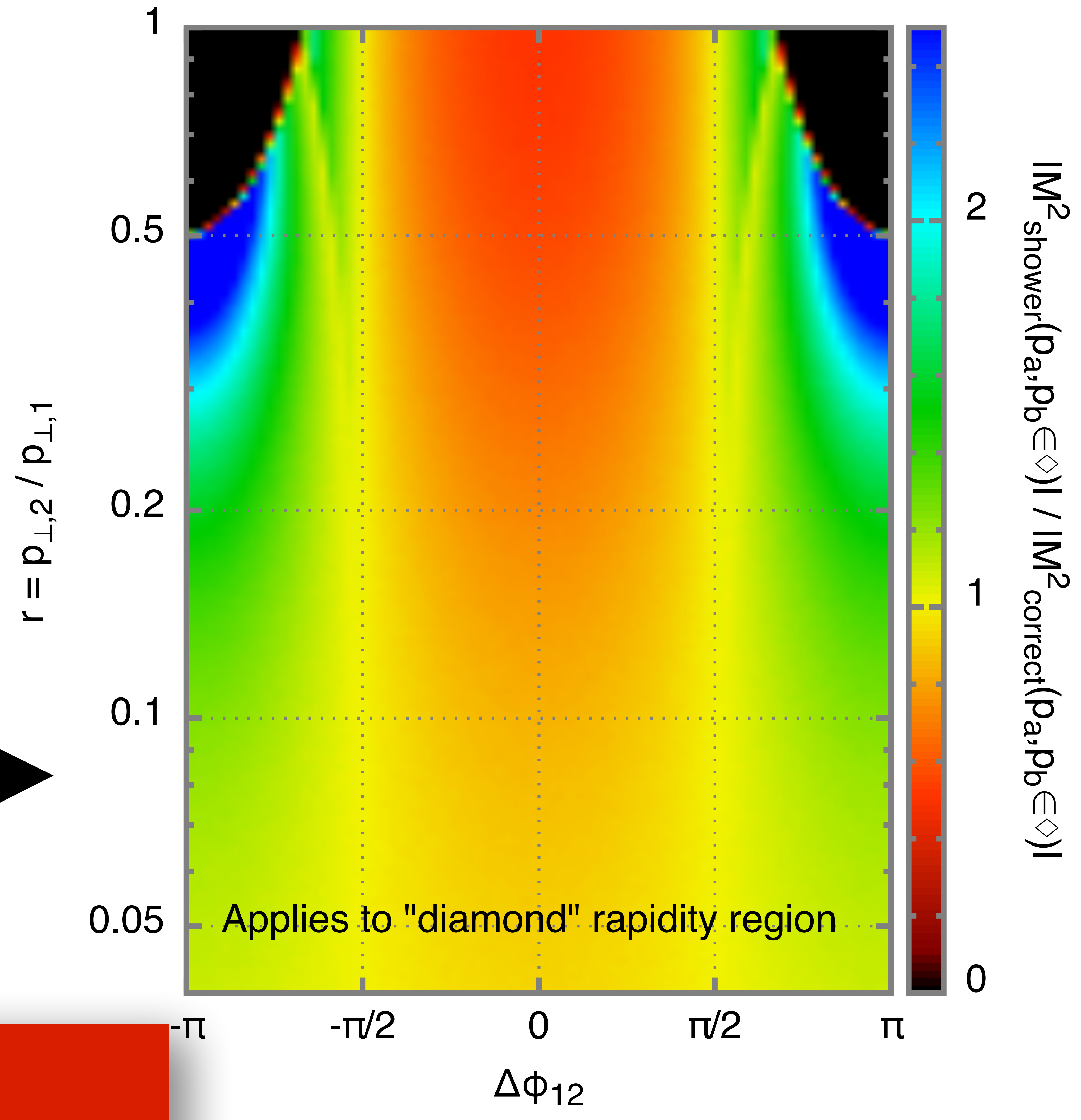

answer is "no"

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

Parton showering as an inverse problem

parton shower branching operator → B

n particle momenta → $k_1, \ldots, k_n$

state info → s

n updated particle momenta → $k'_1, \ldots, k'_n$

new particle momentum → k'_{n+1}

updated state info → s'

$$B(\{r\}) : \{k_1, \ldots, k_n; s\} \to \{k'_1, \ldots, k'_n, k'_{n+1}; s'\}$$

random numbers → $\{r\}$

- Repeated application of operator B generates an event
- What classes of B reproduces correct matrix element for N emissions (sparse in the Lund plane)?

outlook

"

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

What should particle physics expect of itself?

- Many fascinating challenges (e.g. dark matter, hierarchy of scales). We should think about solutions & search for them experimentally, but be wary of promising breakthroughs
- **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)
- Don't stop thinking about how to come up with the "right" questions to ask
  - whether for the big picture
  - or smaller problems that might, one day, help with that big picture