Colliders, Higgs and the strong interaction

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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…)

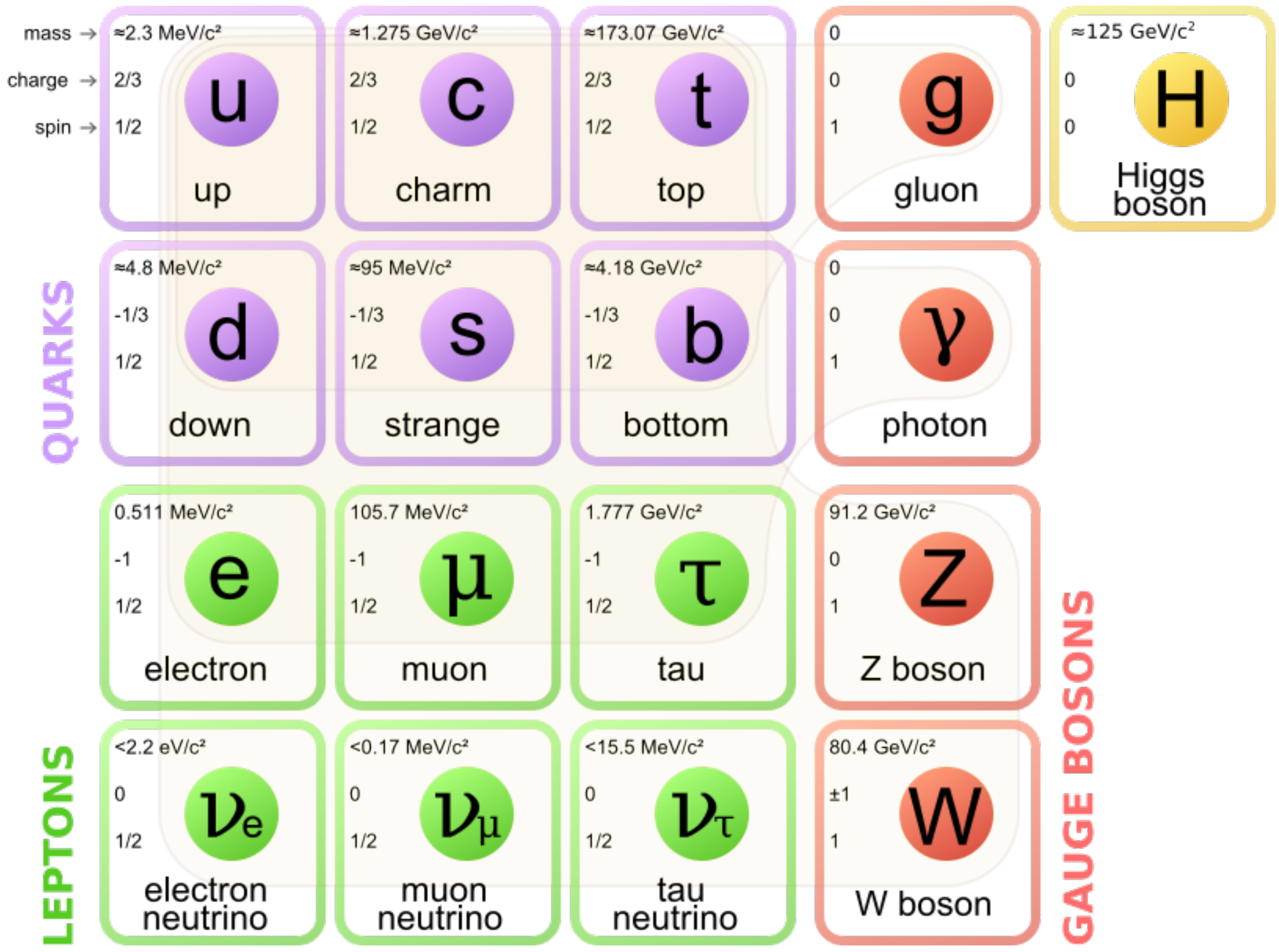
v.

“big answerable questions”

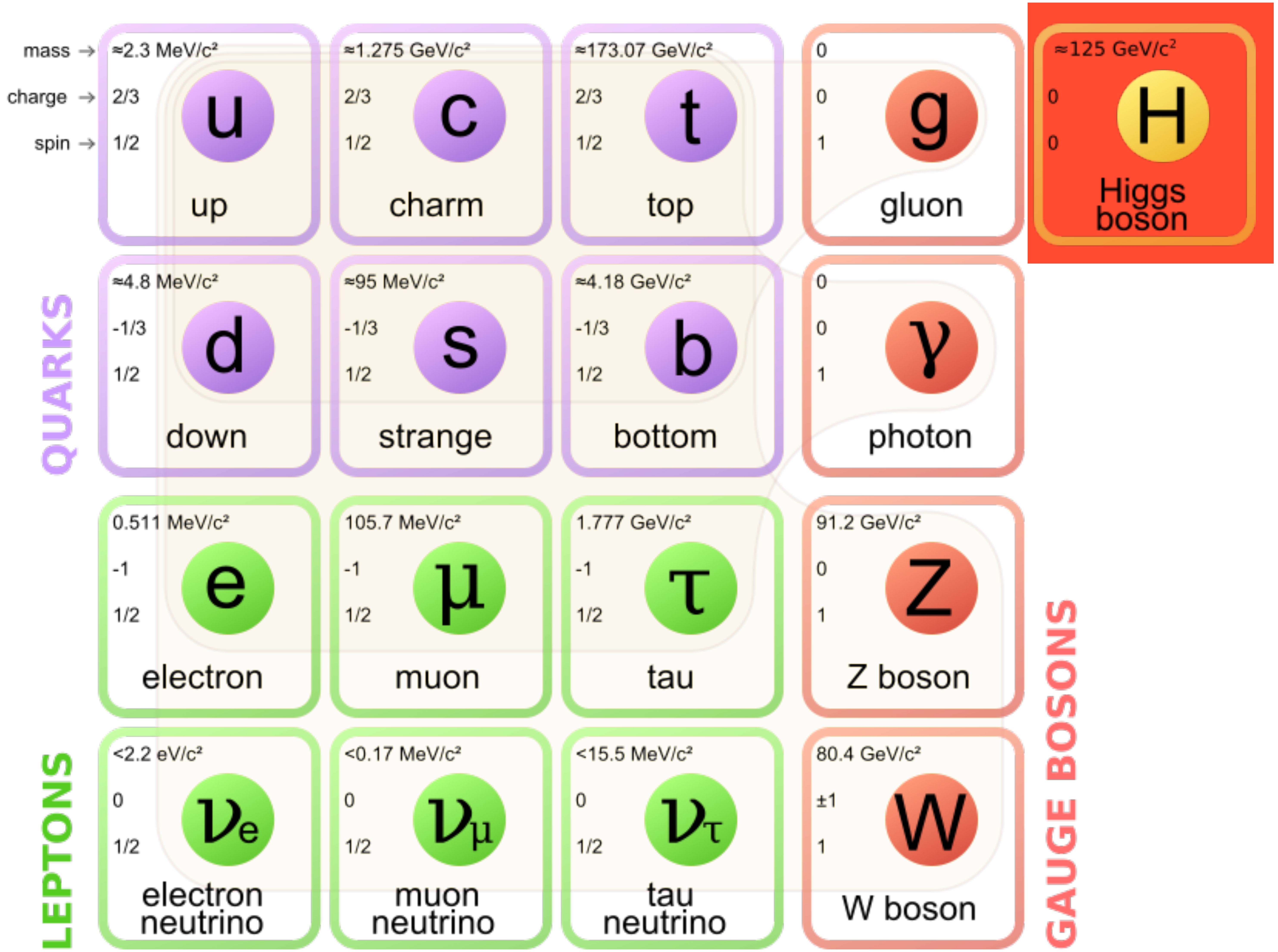
and how we go about answering them

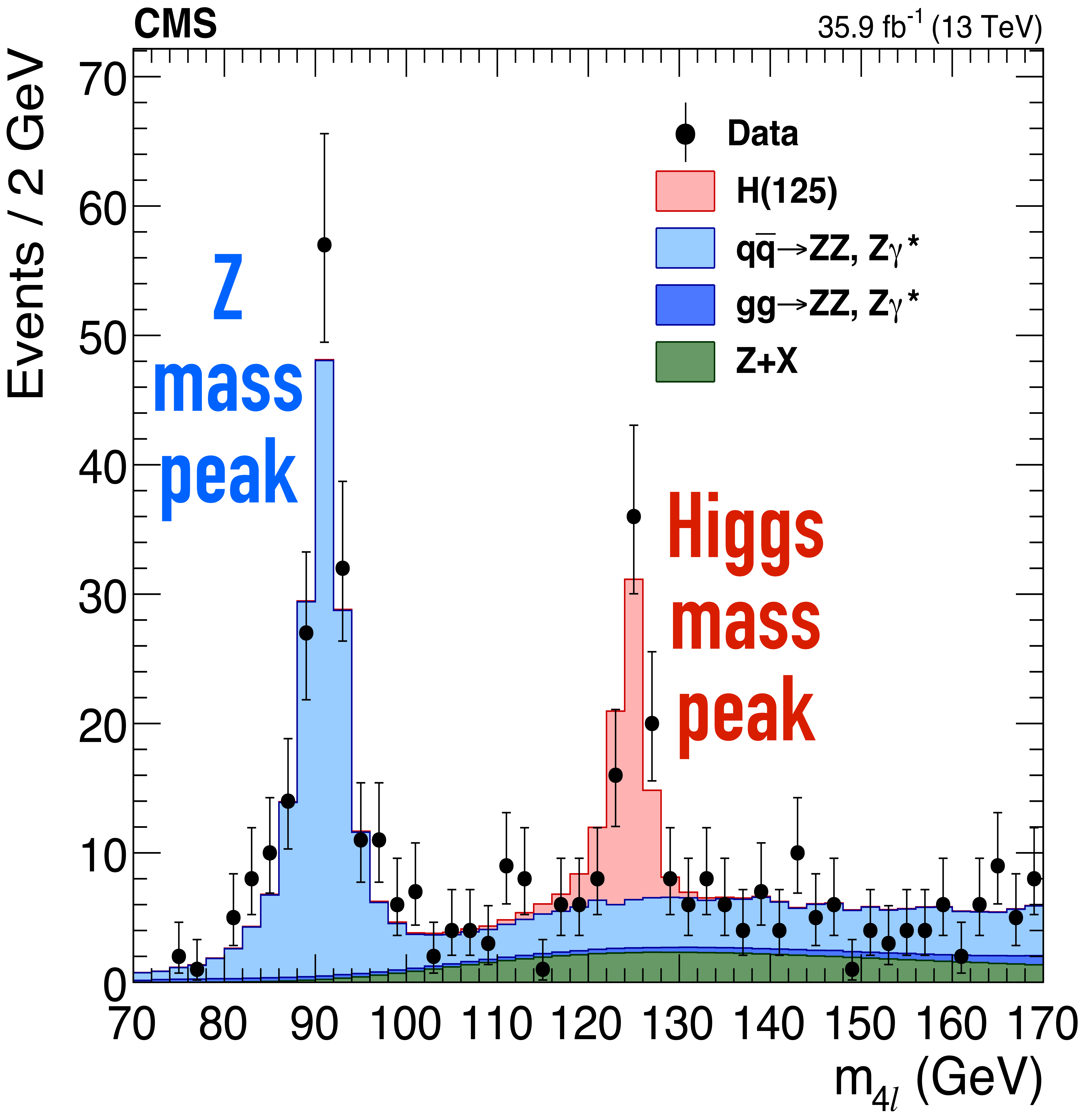
(nature of Higgs interactions, validity of SM up to high scales,
lepton flavour universality, pattern of neutrino mixing, …)

The Higgs boson



The Higgs boson



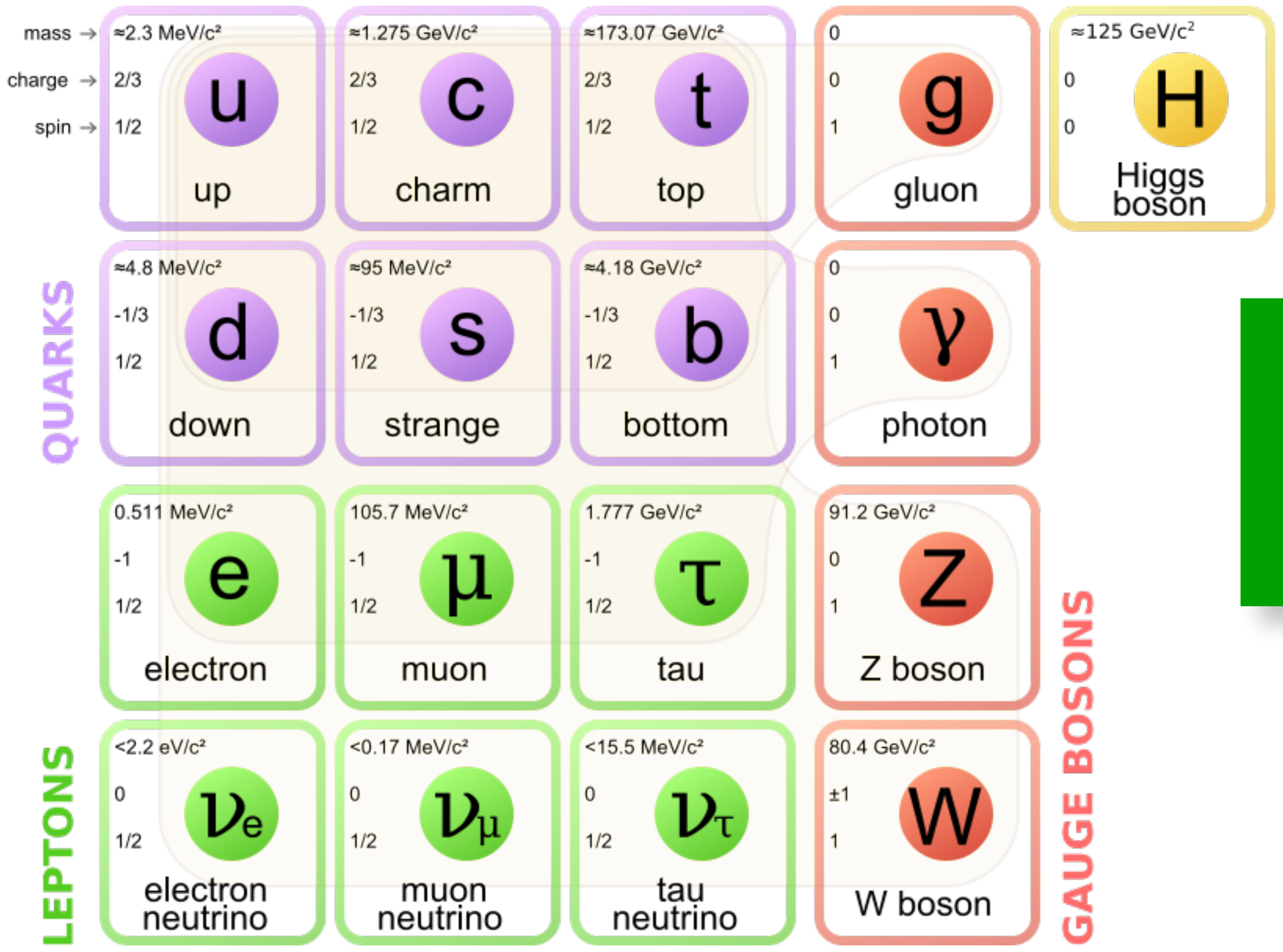


ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

2012 discovery of a Higgs-like boson

plot shows more recent data

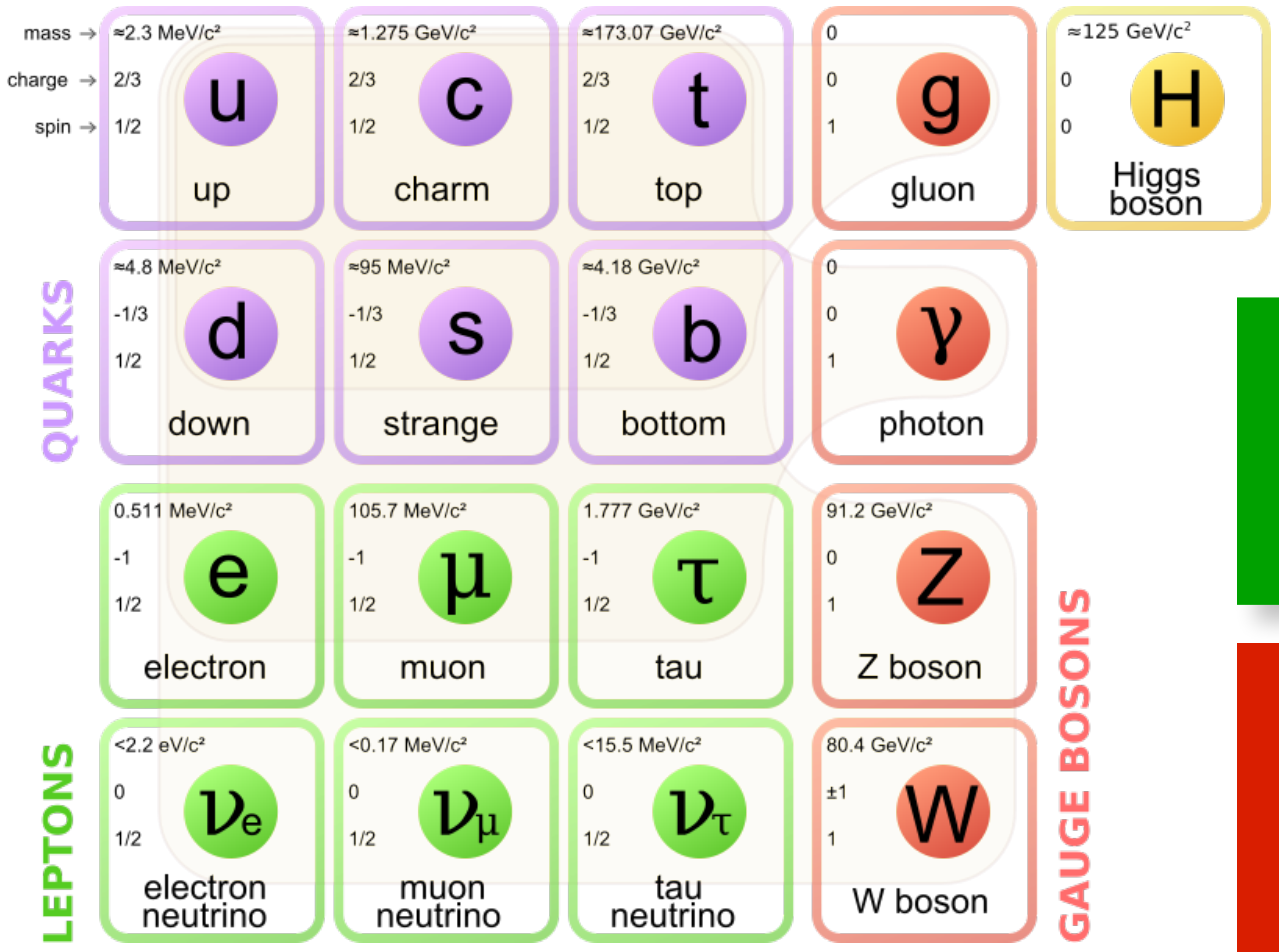
The Higgs boson (2012)



Success!

“The Standard Model is complete”

The Higgs boson (2012)



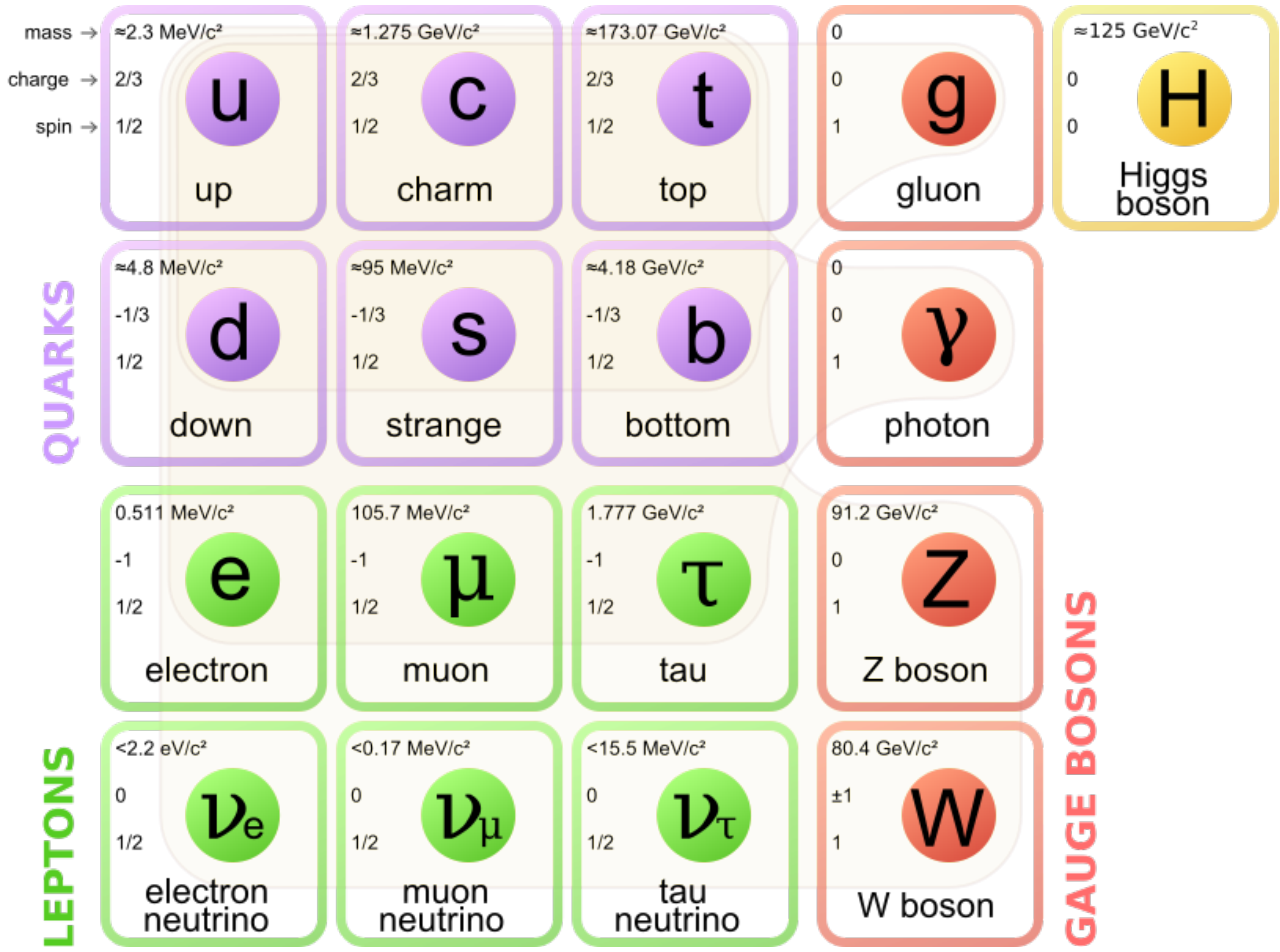
Success!

“The Standard Model is complete”

Crisis!

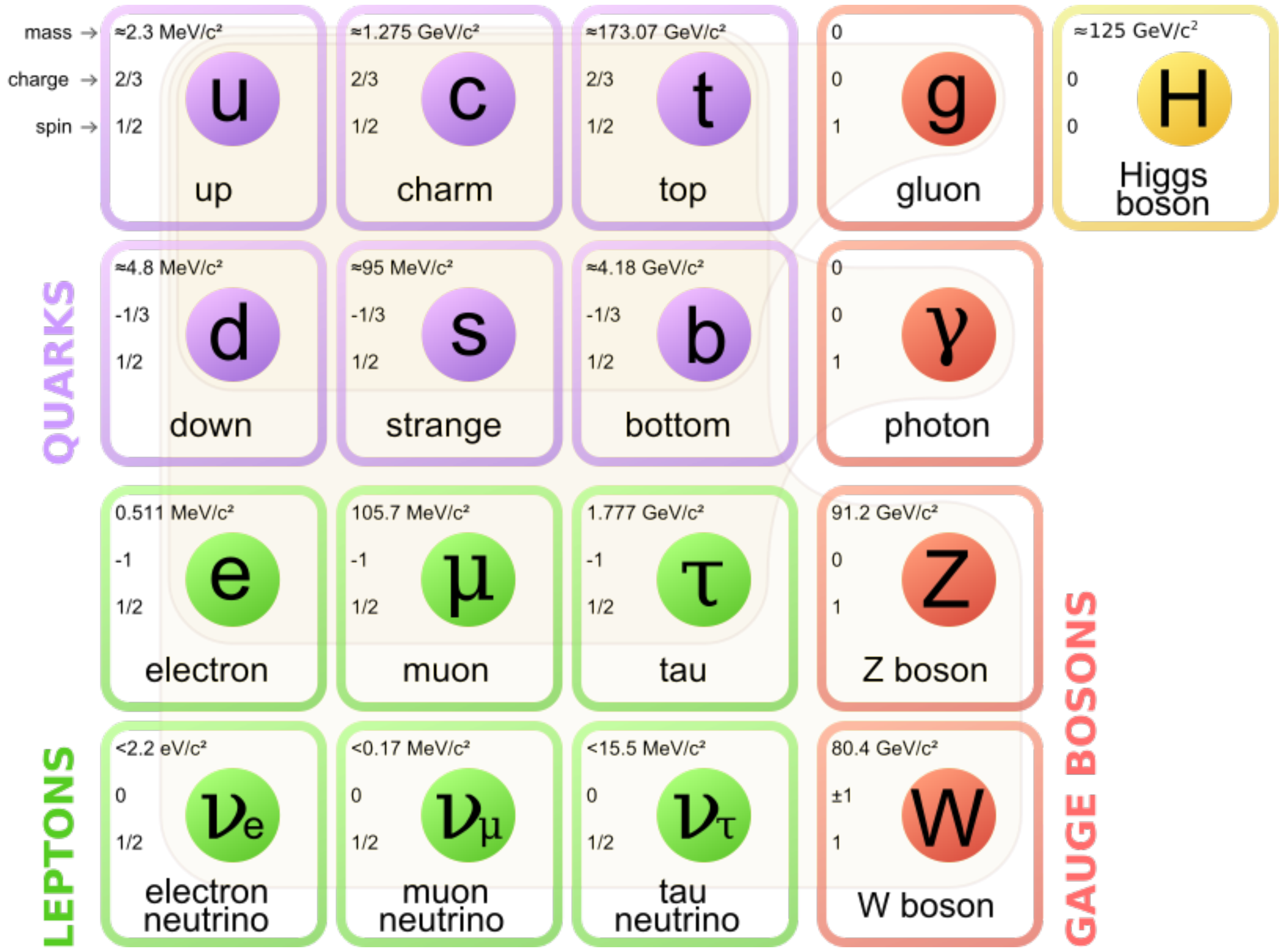
No supersymmetry, no extra dimensions, there’s nothing left for us to do . . .

what is the Standard Model?



particles

what is the Standard Model?



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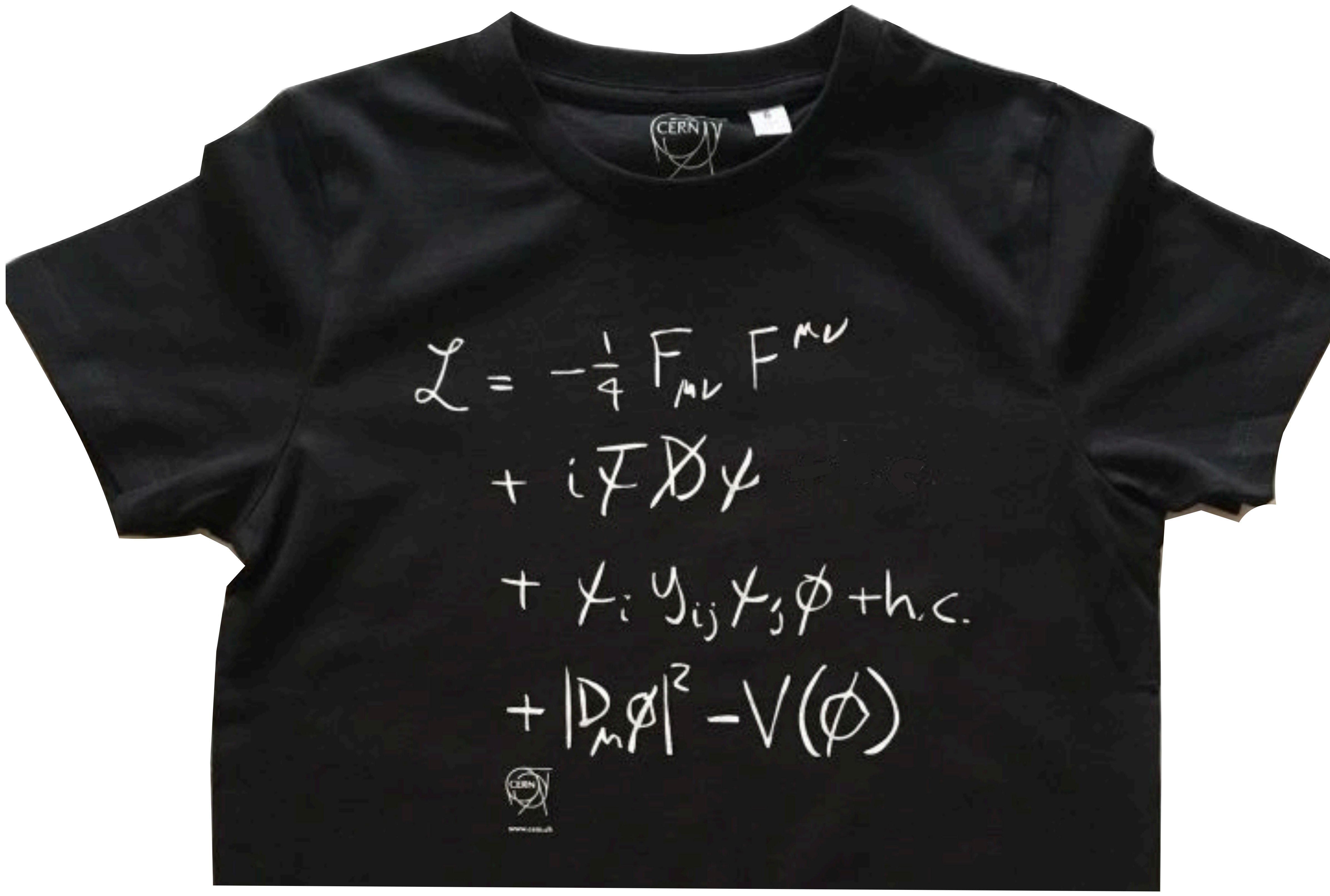
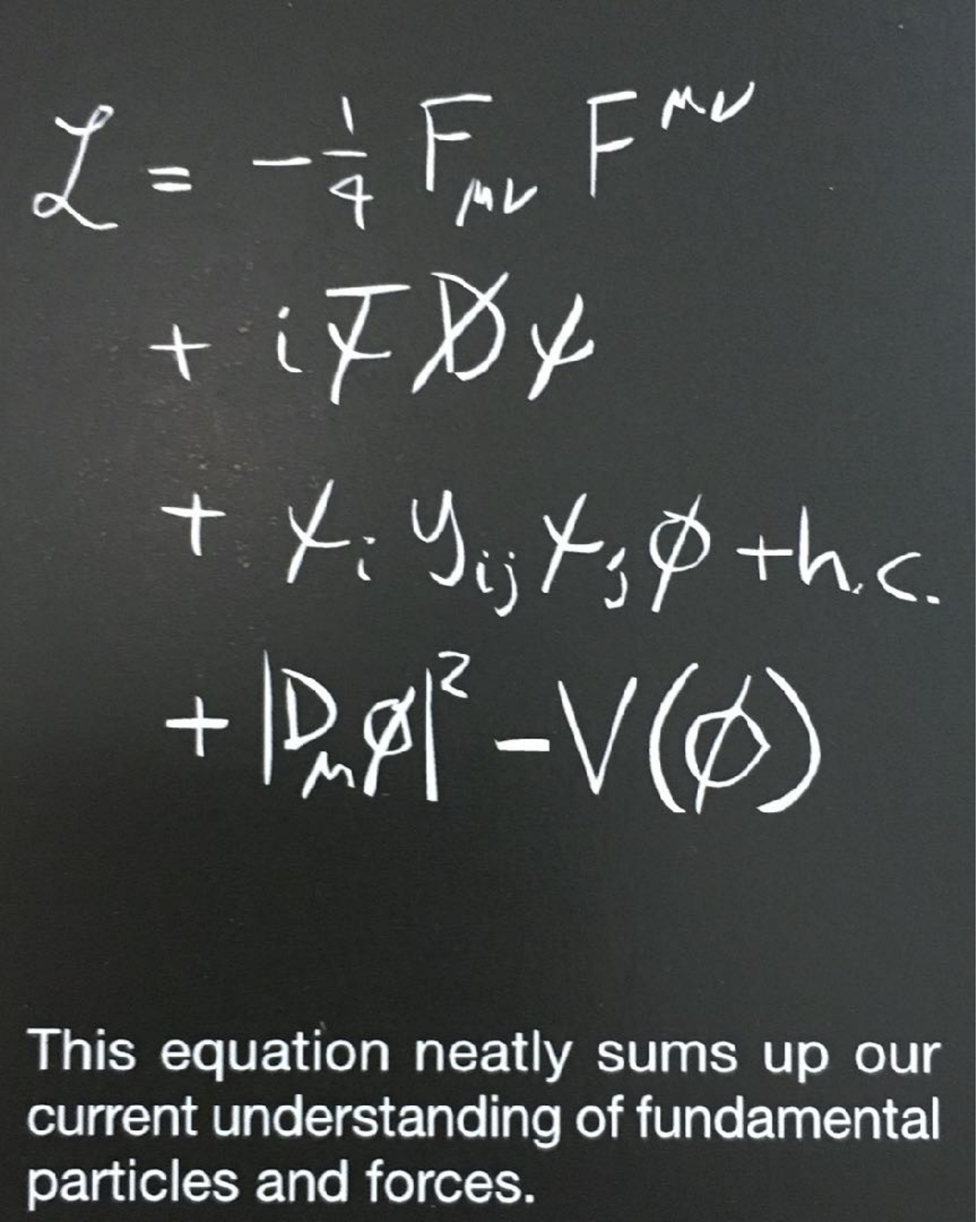


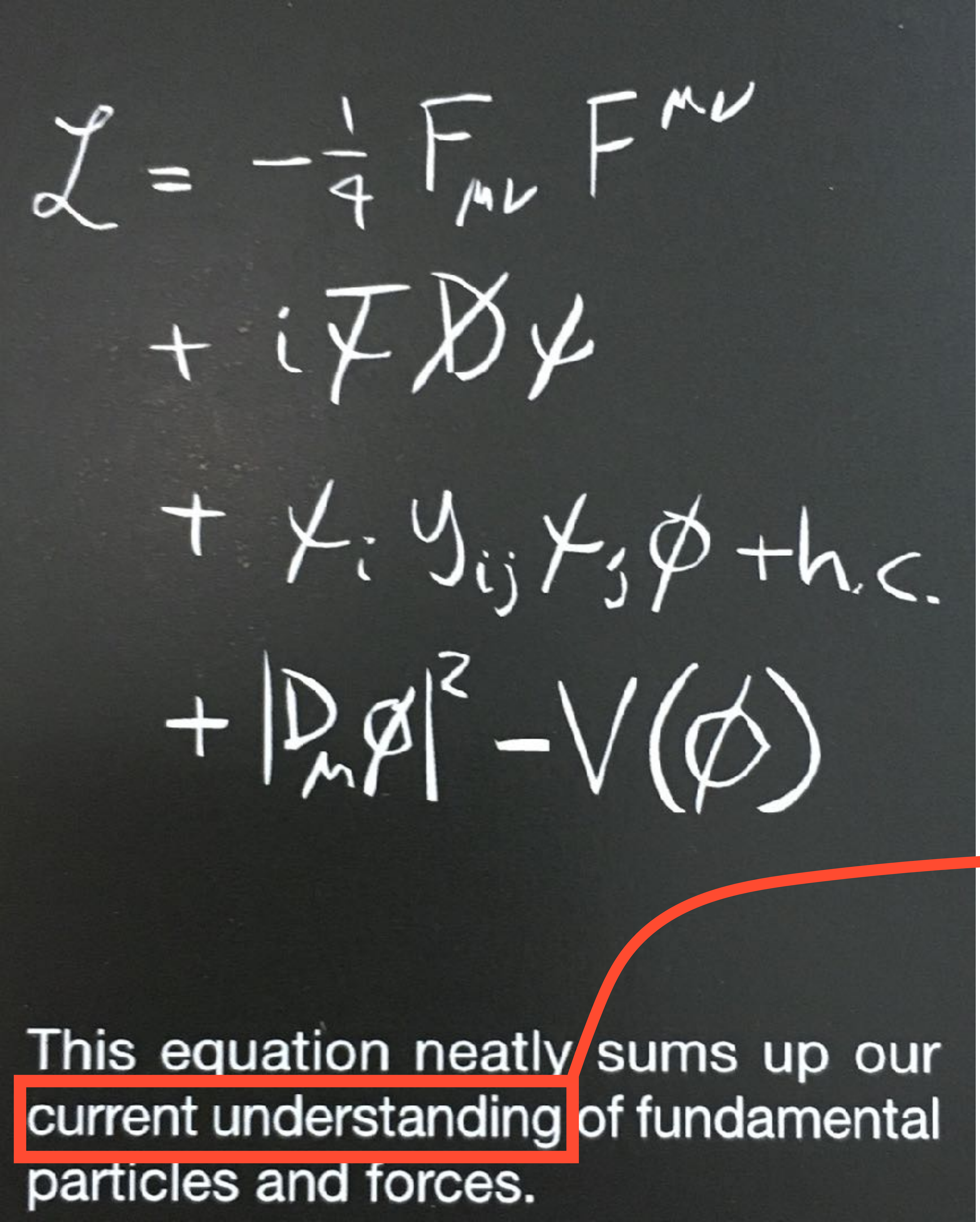
particles

interactions



STANDARD MODEL — KNOWABLE UNKNOWNS

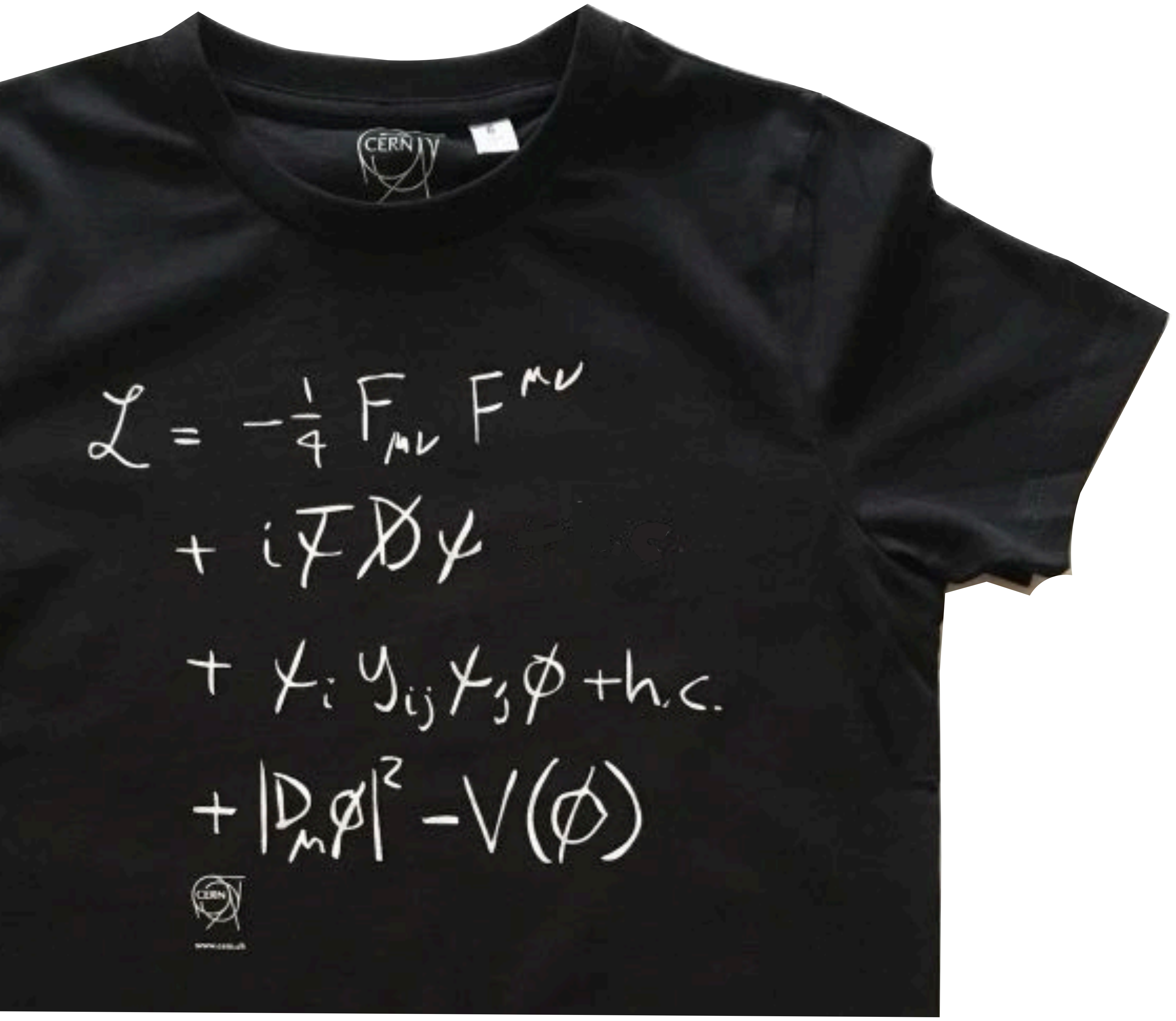
These T-shirts come with a little explanation



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.

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

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

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

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

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

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

$$\phi^T = (0, v+h)/\sqrt{2}\,, \qquad <\phi>_0^T = \text{(expectation value of } \phi) = (0, v)/\sqrt{2}\,, \tag{5}$$

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

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

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

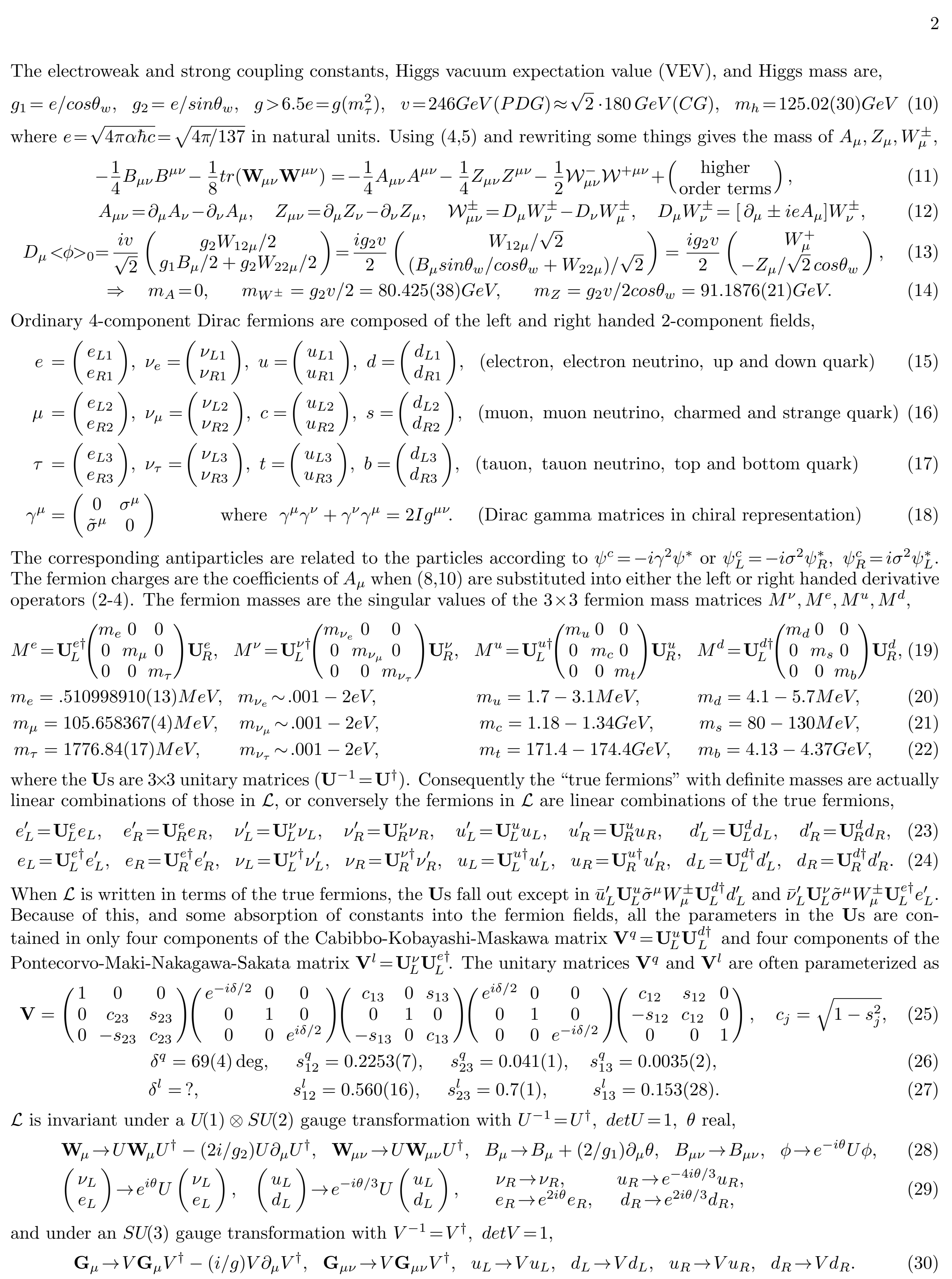
$$A_\mu = W_{11\mu}sin\theta_w + B_\mu cos\theta_w, \qquad Z_\mu = W_{11\mu}cos\theta_w - B_\mu sin\theta_w, \quad W^+_\mu = W^{-*}_\mu = W_{12\mu}/\sqrt{2}, \tag{7}$$

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

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 $M^e_{ij}, M^\nu_{ij}, M^u_{ij}, M^d_{ij}$, and implicit 2-component indices which contract into the Pauli matrices,

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

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



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

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

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 $A_\mu, Z_\mu, W^\pm_\mu$,

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) = -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}\mathcal{W}^-_{\mu\nu}\mathcal{W}^{+\mu\nu} + \begin{pmatrix}\text{higher}\\ \text{order terms}\end{pmatrix}, \tag{11}$$

$$A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu, \quad \mathcal{W}^\pm_{\mu\nu} = D_\mu W^\pm_\nu - D_\nu W^\pm_\mu, \quad D_\mu W^\pm_\nu = [\partial_\mu \pm ieA_\mu]W^\pm_\nu, \tag{12}$$

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

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

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

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

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

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

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

The corresponding antiparticles are related to the particles according to $\psi^c = -i\gamma^2\psi^*$ or $\psi^c_L = -i\sigma^2\psi^*_R$, $\psi^c_R = i\sigma^2\psi^*_L$. 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,

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

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

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

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

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,

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

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

When $\mathcal{L}$ is written in terms of the true fermions, the $\mathbf{U}$s fall out except in $\bar{u}'_L\mathbf{U}^u_L\tilde{\sigma}^\mu W^\pm_\mu\mathbf{U}^{d\dagger}_L d'_L$ and $\bar{\nu}'_L\mathbf{U}^\nu_L\tilde{\sigma}^\mu W^\pm_\mu\mathbf{U}^{e\dagger}_L e'_L$. 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 $\mathbf{V}^q = \mathbf{U}^u_L\mathbf{U}^{d\dagger}_L$ and four components of the Pontecorvo-Maki-Nakagawa-Sakata matrix $\mathbf{V}^l = \mathbf{U}^\nu_L\mathbf{U}^{e\dagger}_L$. The unitary matrices $\mathbf{V}^q$ and $\mathbf{V}^l$ are often parameterized as

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

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

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

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

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

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

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

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

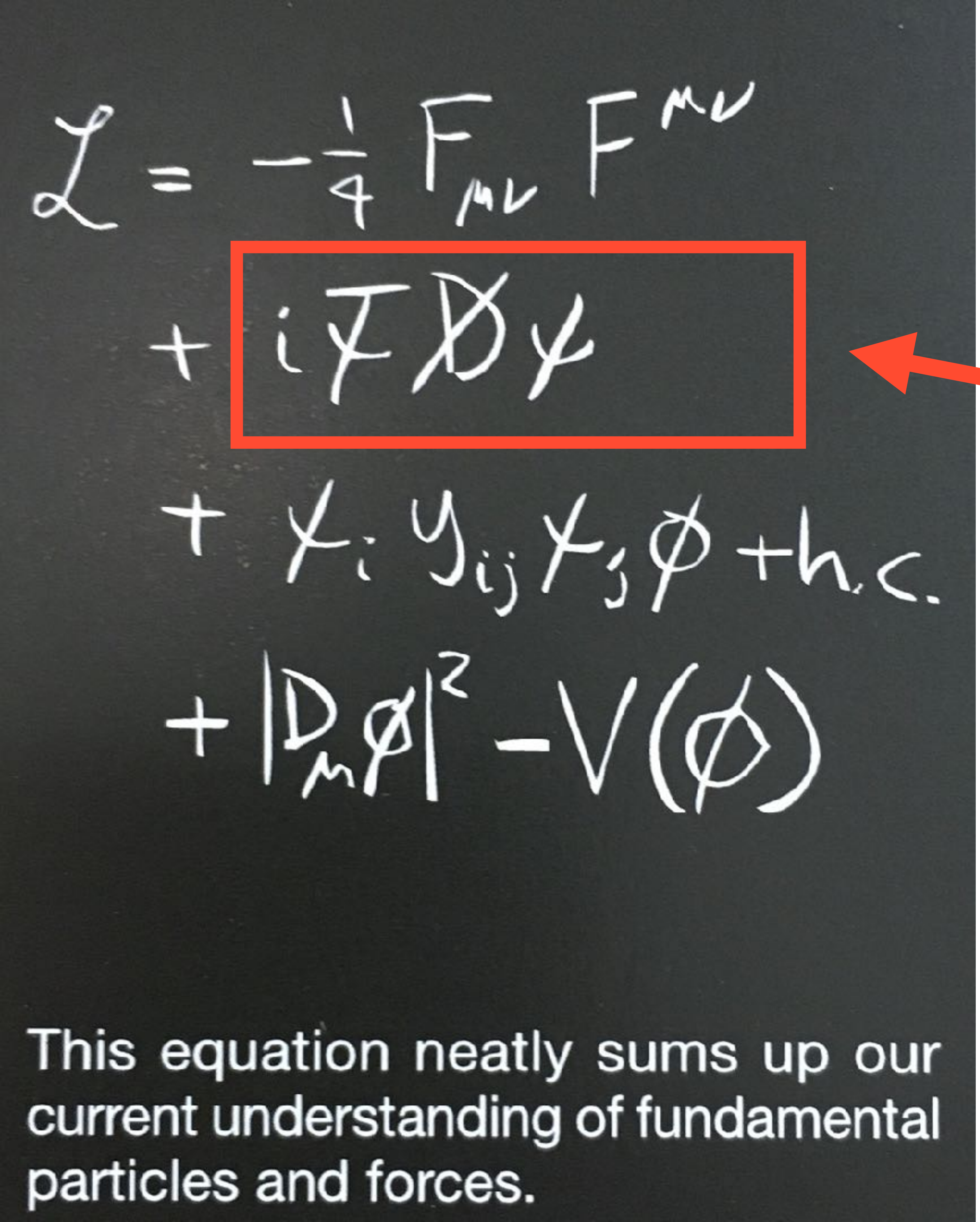
http://einstein-schrodinger.com/Standard_Model.pdf

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

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

What does it mean?

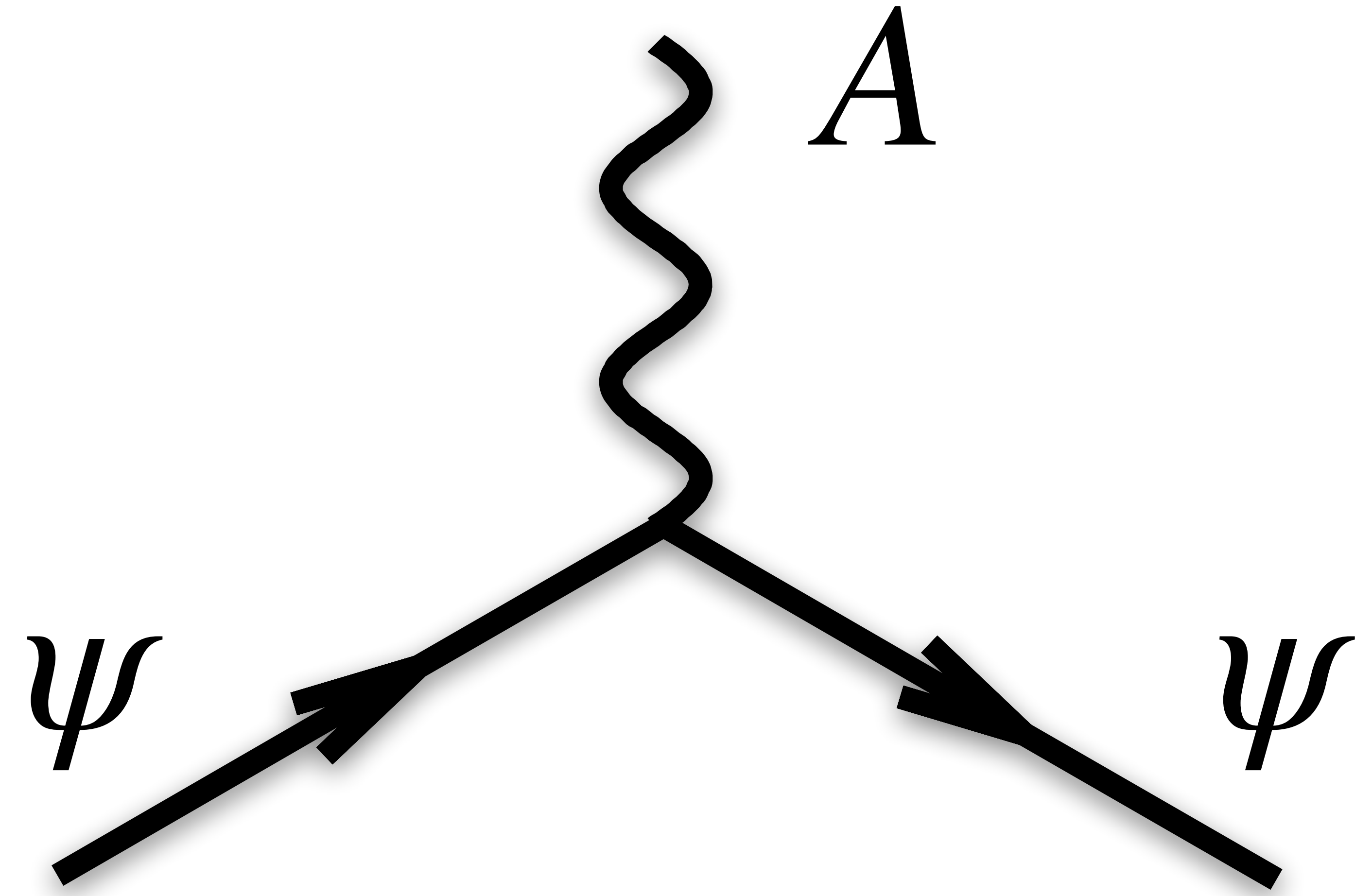
Quantum formulation of Maxwell's equations, (and their analogues for the weak and strong forces).



What does it mean?

$$\psi = \textit{fermion (e.g. electron) field}$$

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



tells you there's an electron-photon interaction vertex

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

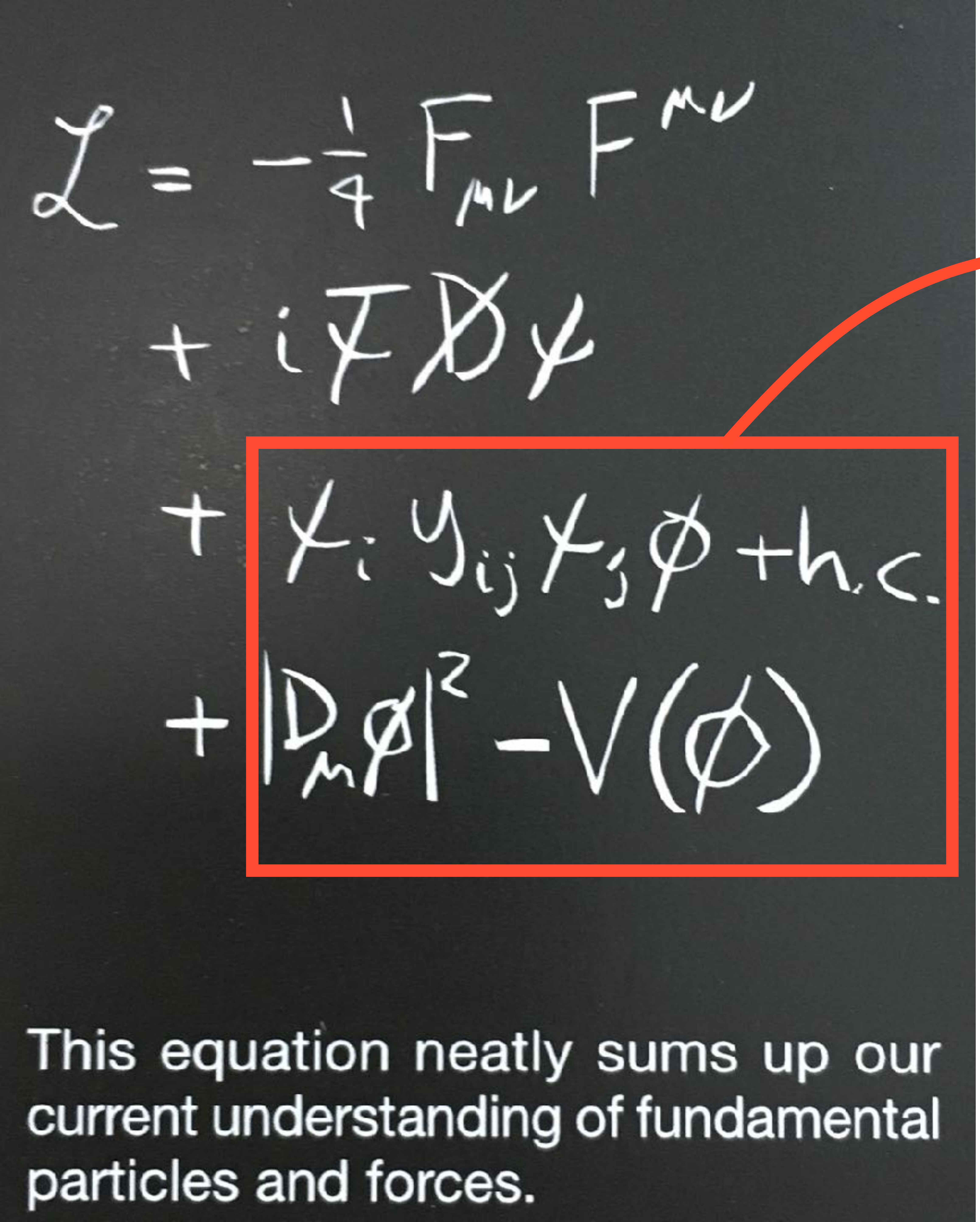
This equation neatly sums up our current understanding of fundamental particles and forces.

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.

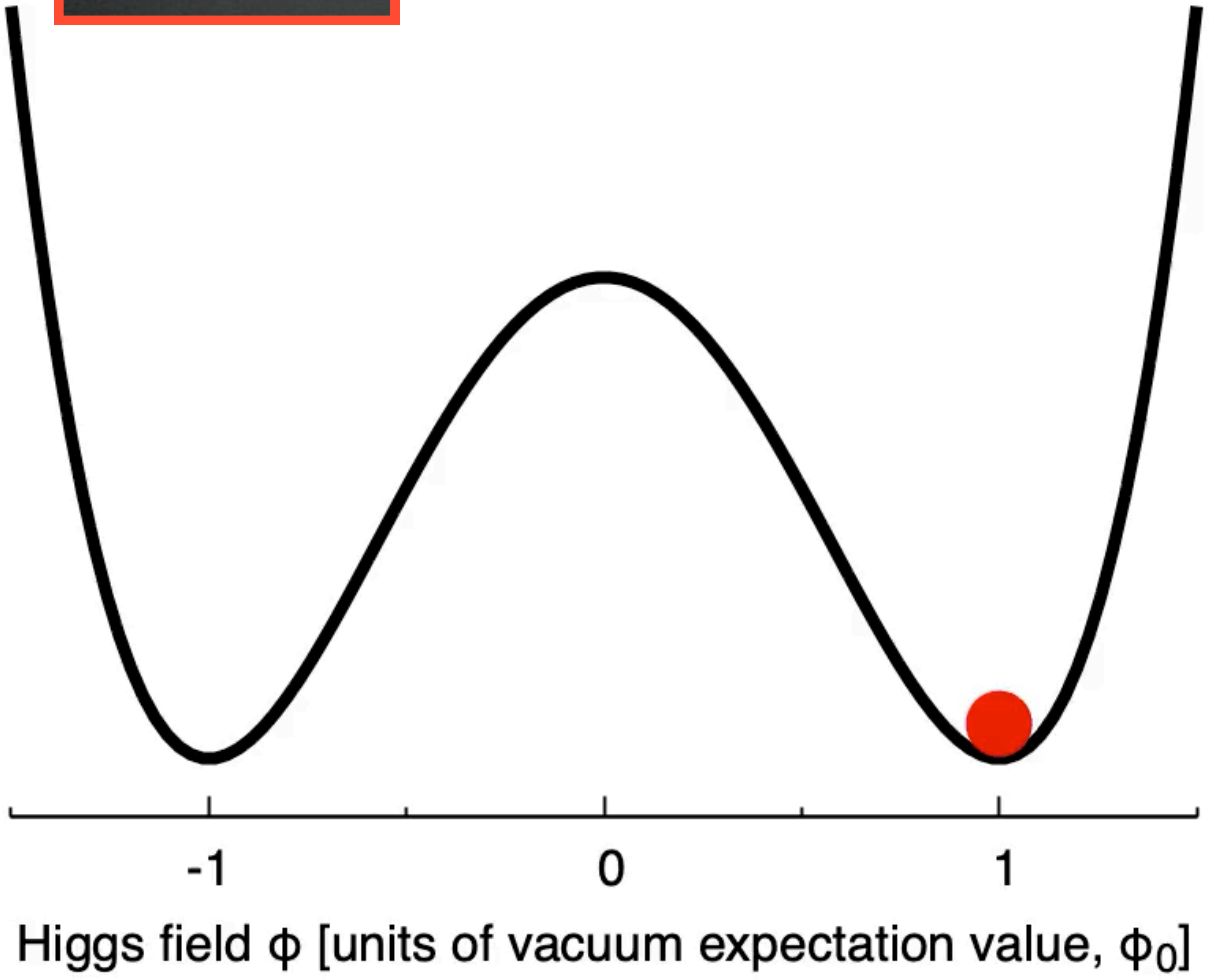
They work to high precision (best tests go up to 1 part in 10^8)



Higgs sector

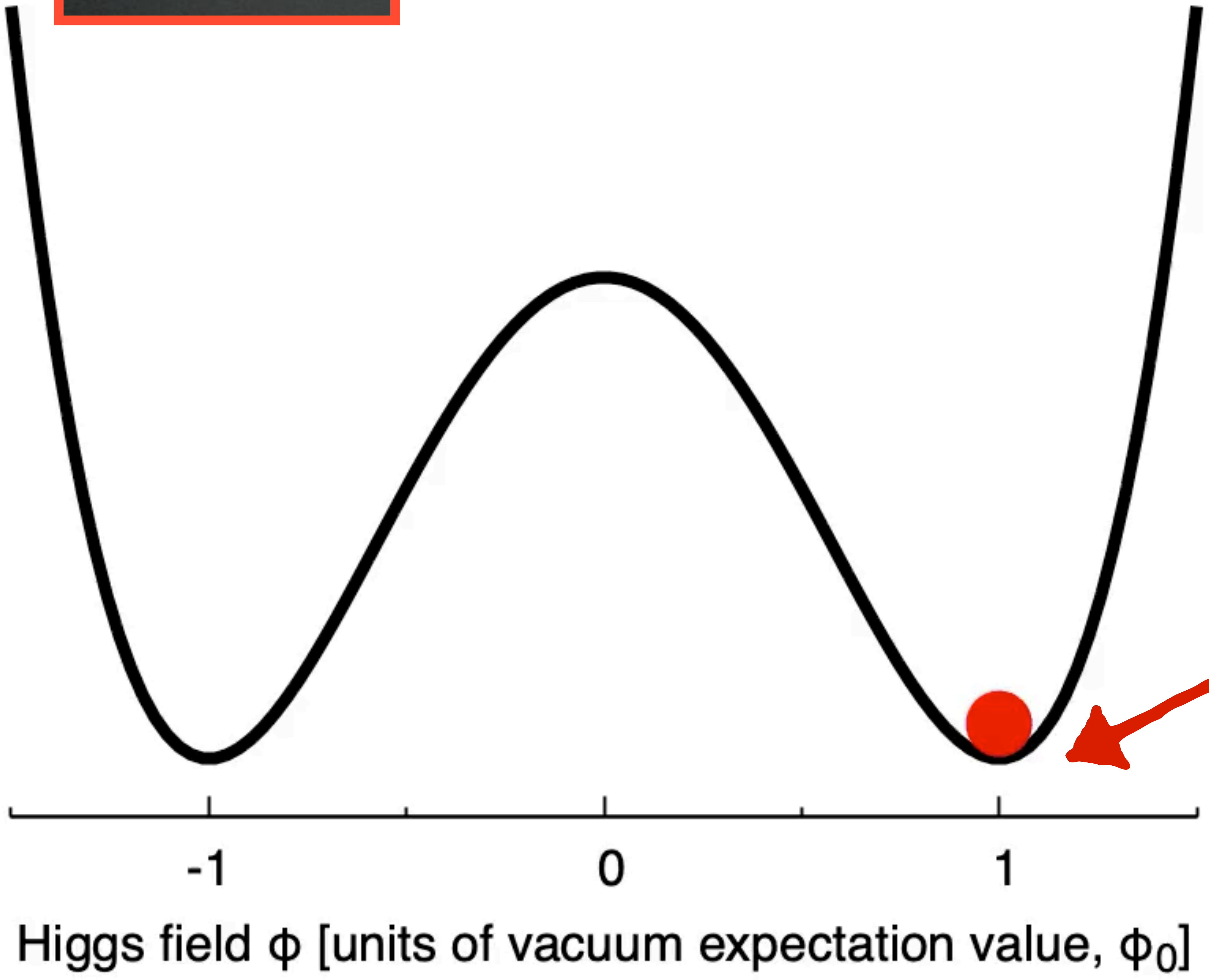
until 7 years ago none of these terms had ever been directly observed.

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



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

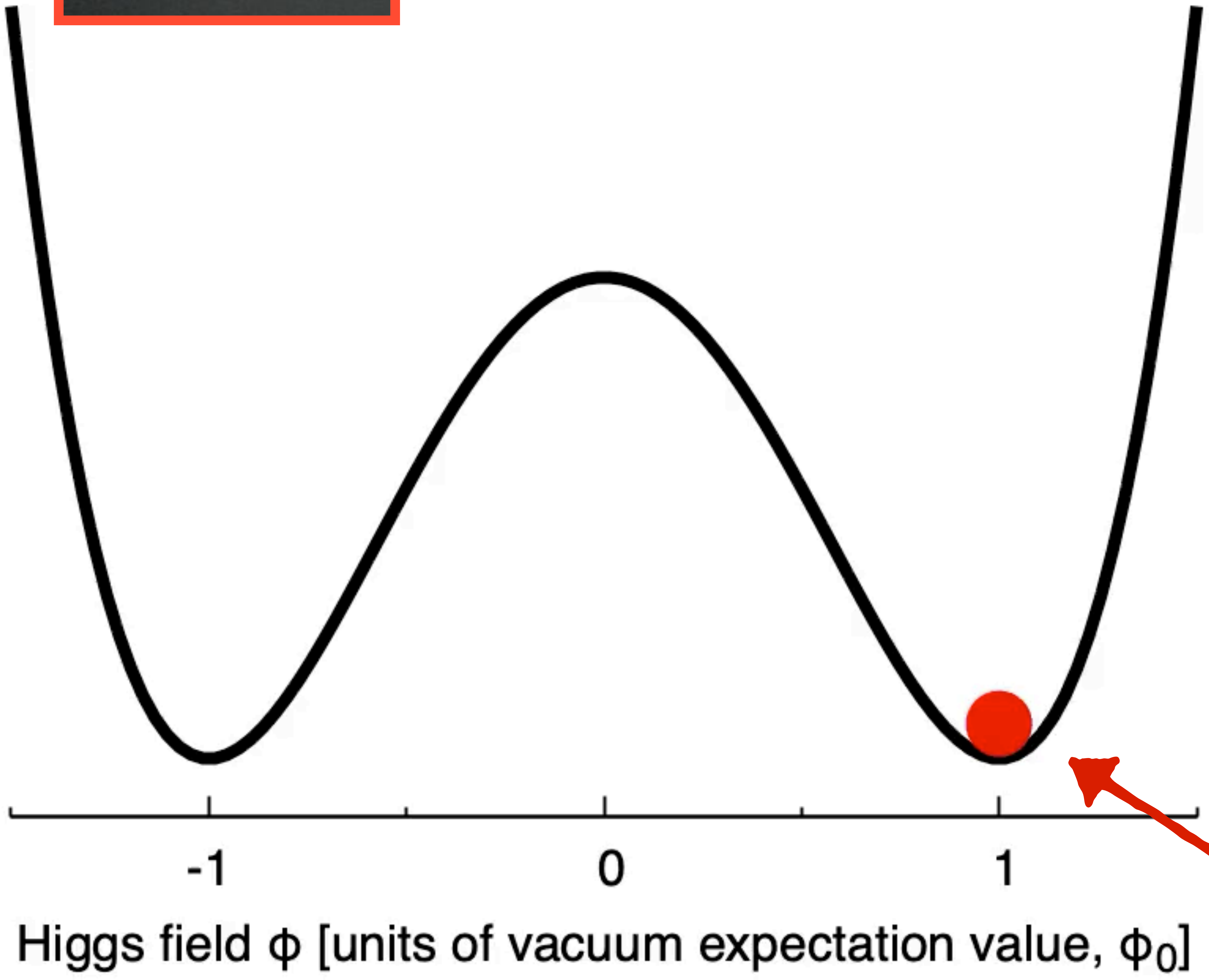
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



- 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

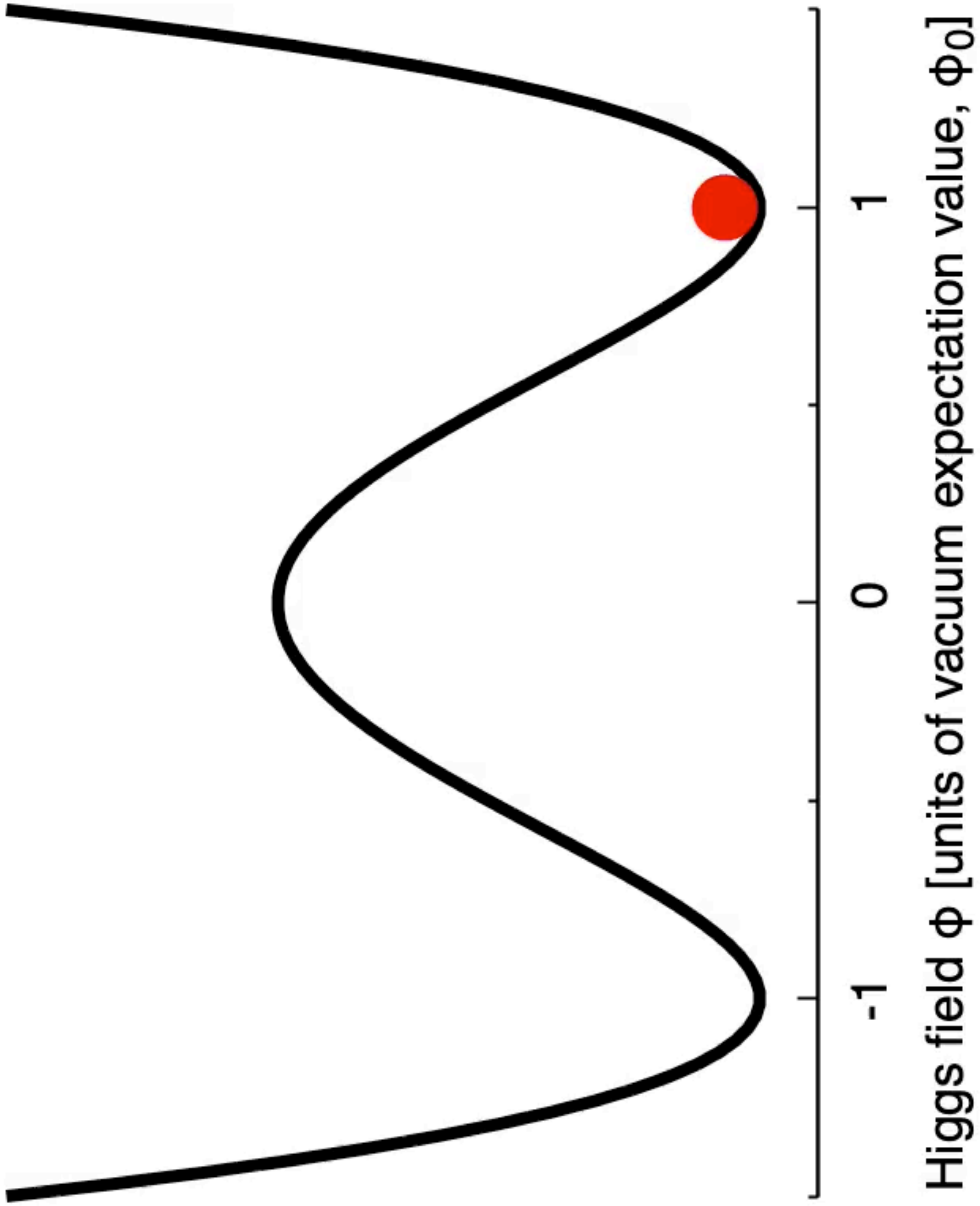
$$\phi = \phi_0 = \frac{\mu}{\sqrt{2\lambda}}$$

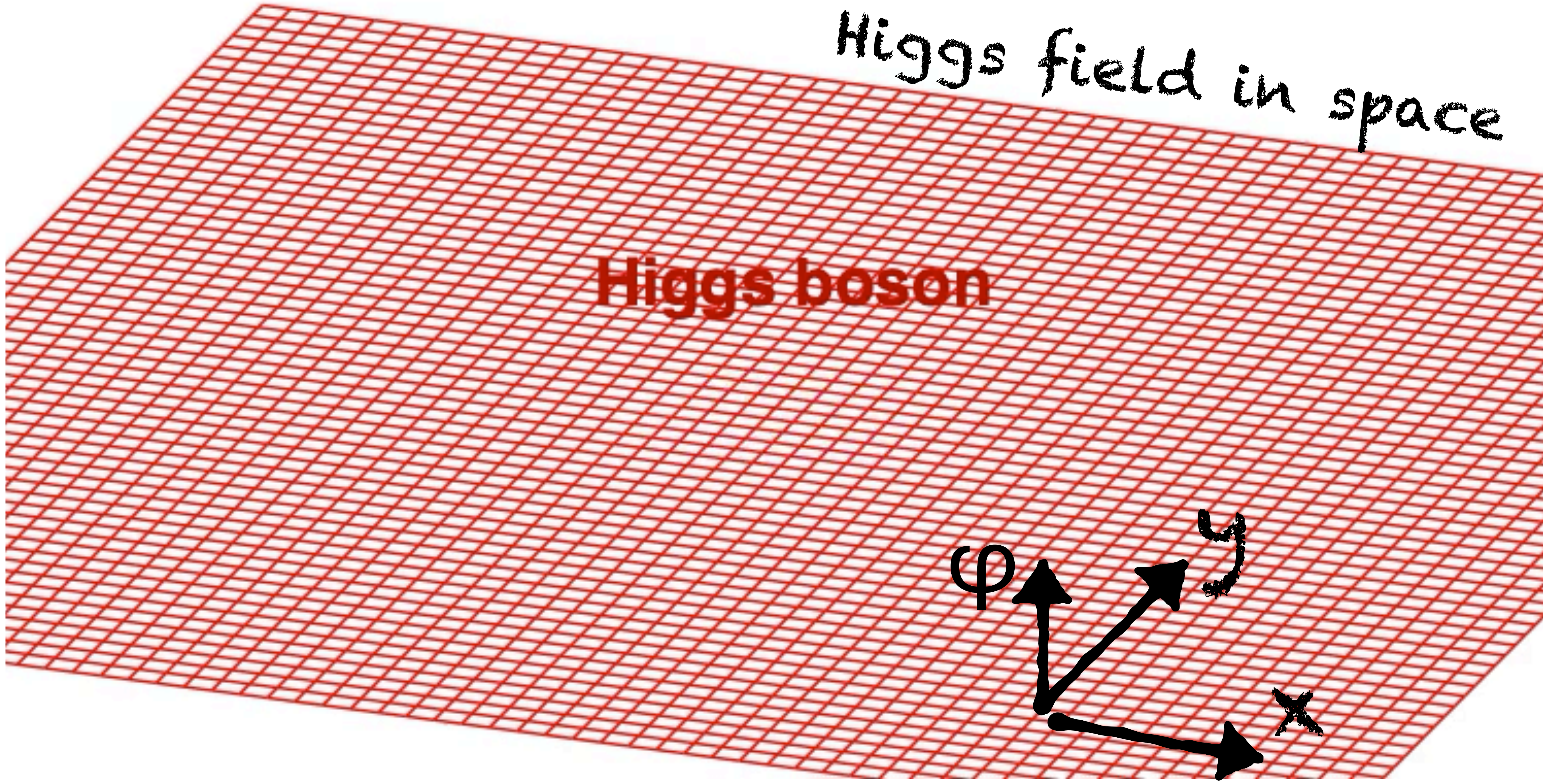
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



- 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 ($\varphi = \varphi_0 + H$)

$$\varphi = \varphi_0 + H$$

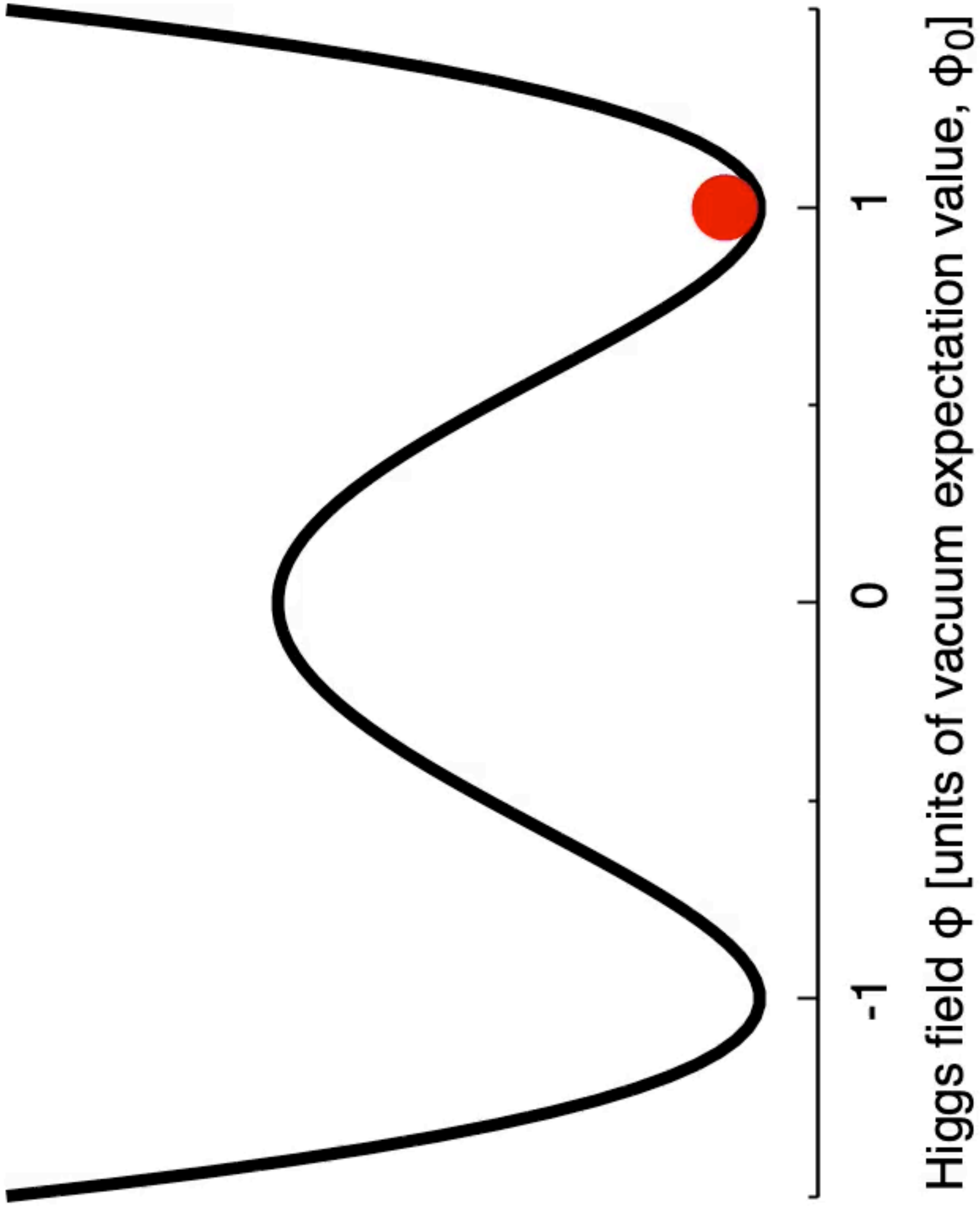


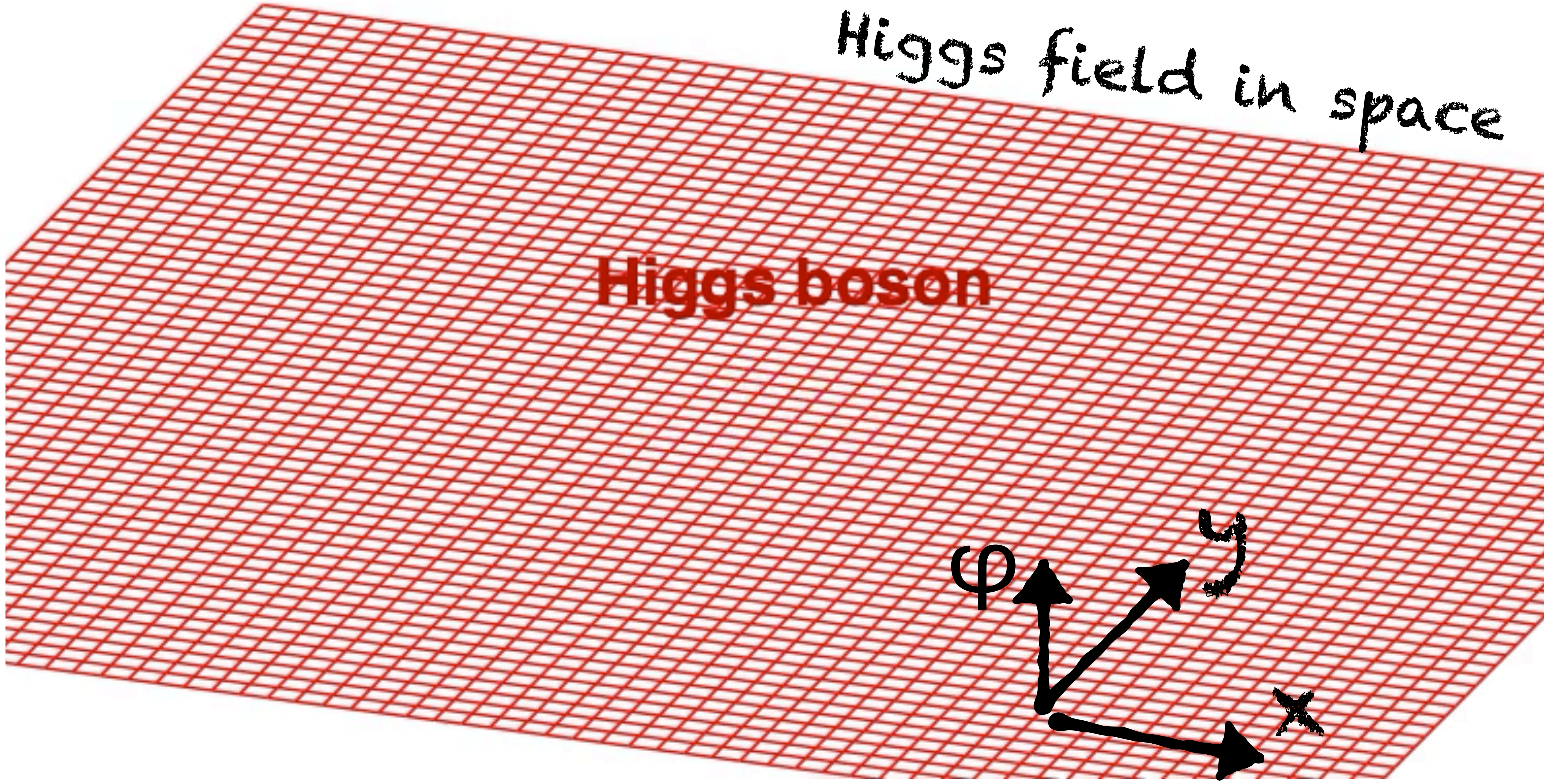


Higgs field can be different at each point in space

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)

$$\varphi = \varphi_0 + H$$

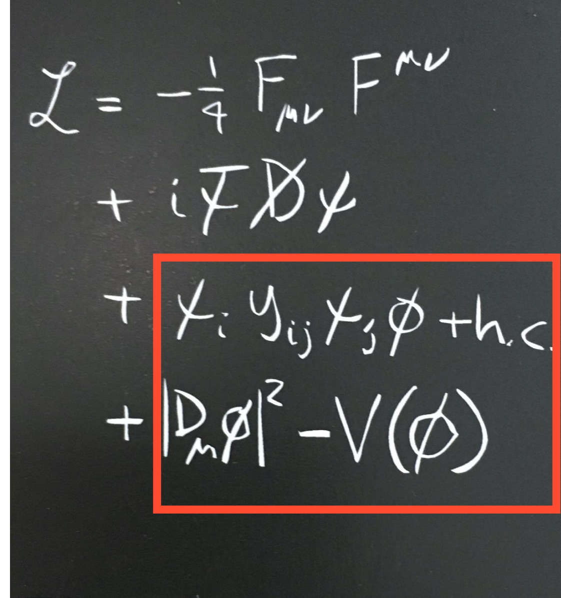
established

(2012 Higgs boson discovery)

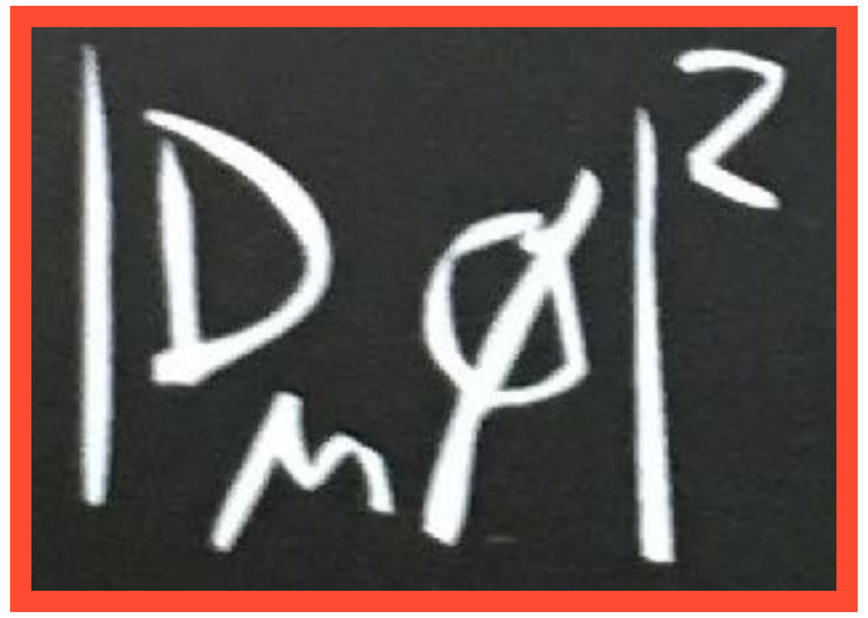
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

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.



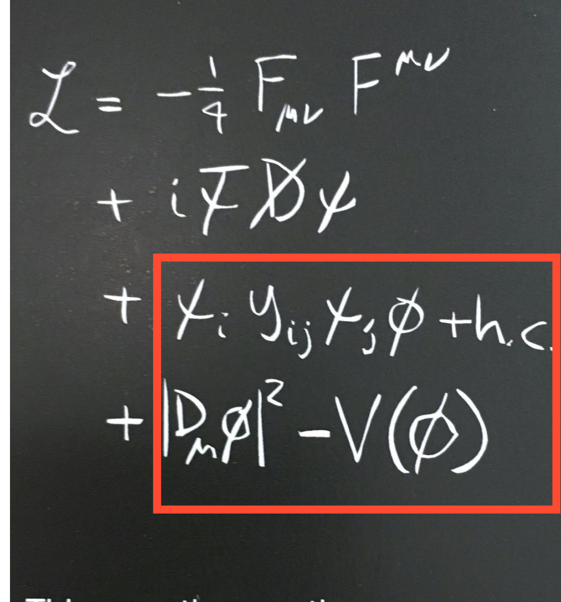
$$\rightarrow \overbrace{g^2\phi_0^2}^{constants}\,\overbrace{Z_\mu Z^\mu}^{fields} + \overbrace{2g^2\phi_0}^{constants}\,\overbrace{H\,Z_\mu Z^\mu}^{fields} + \ldots$$

Z-boson mass term

HZZ interaction term

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

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



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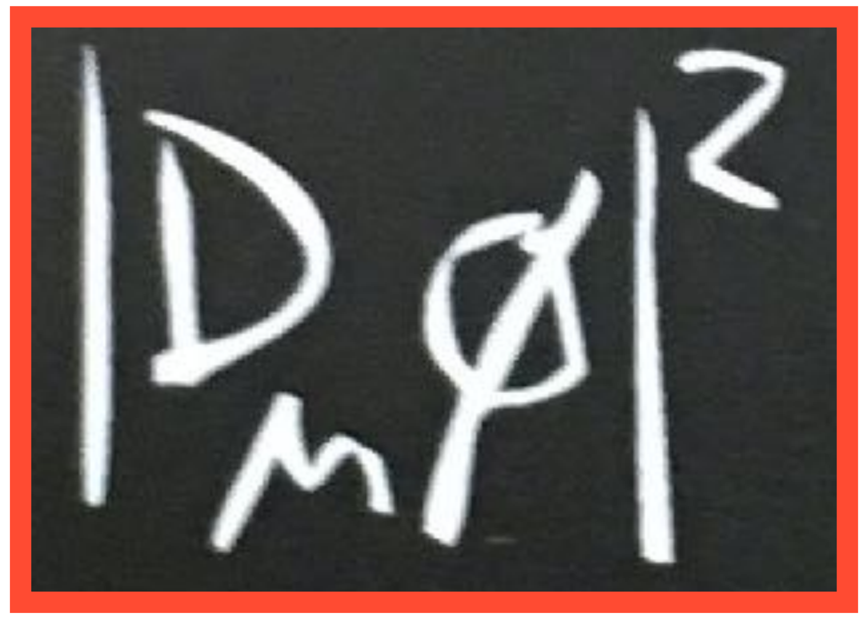
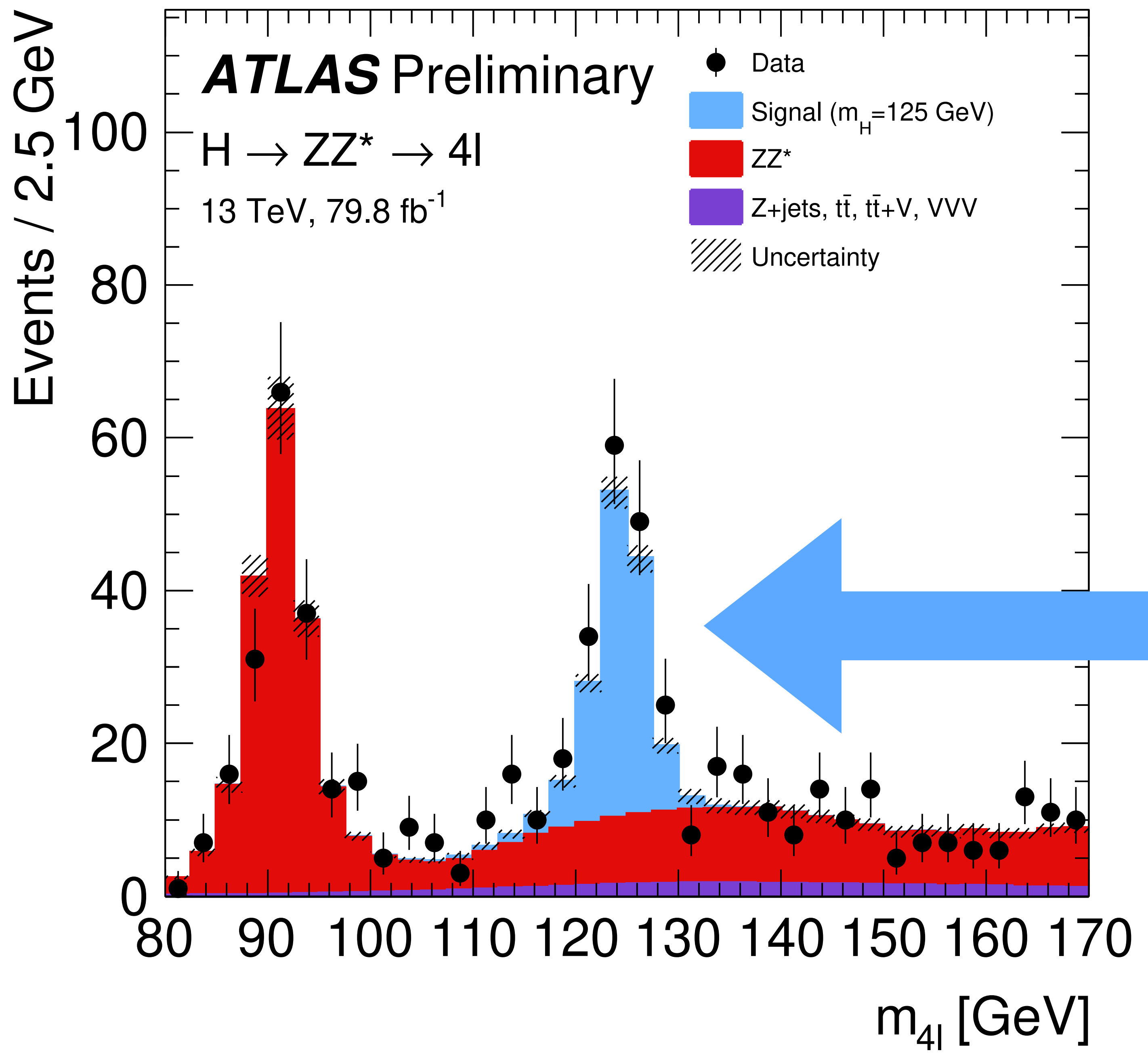


$$\rightarrow g^2 \phi_0^2 Z_\mu Z^\mu + 2g^2 \phi_0 H Z_\mu Z^\mu + \ldots$$

Z-boson mass term

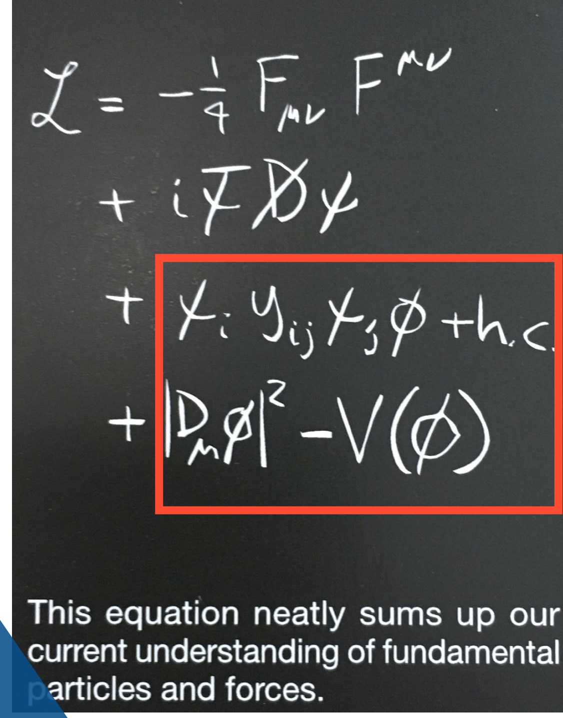
ZZH interaction term

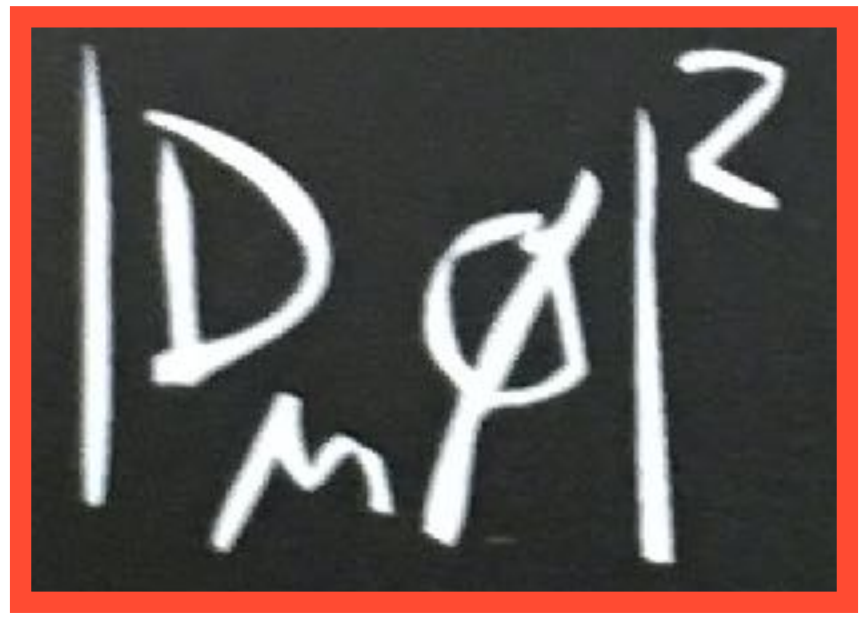


$H \rightarrow ZZ^*$

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

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

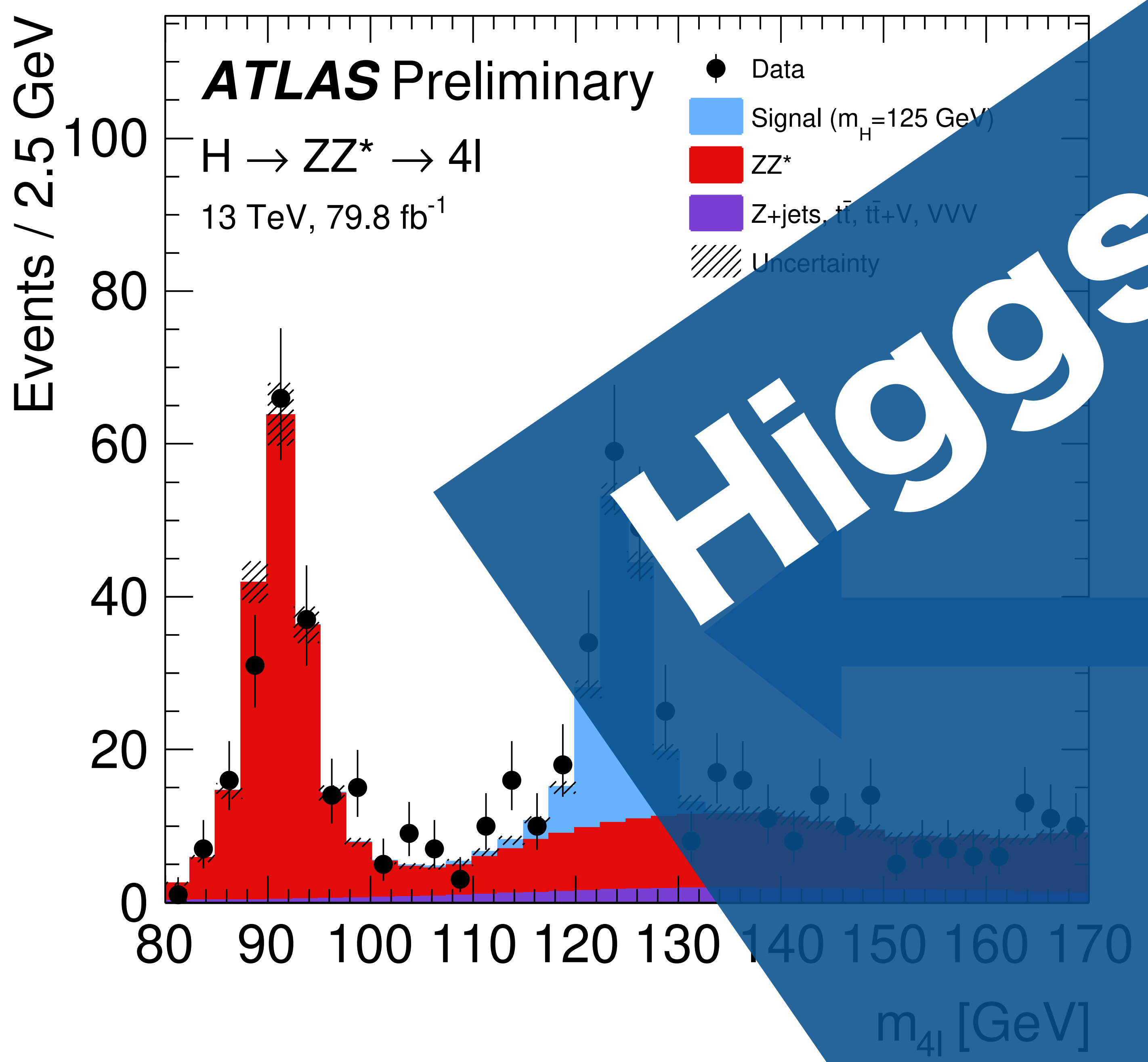




$$\rightarrow g^2\phi_0^2 Z_\mu Z^\mu + 2g^2\phi_0 H Z_\mu Z^\mu + \ldots$$

Z boson mass term

ZZH interaction term

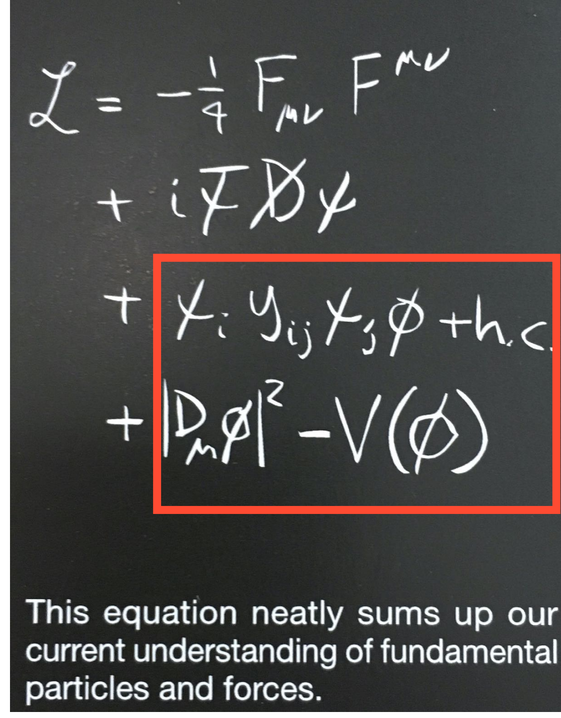


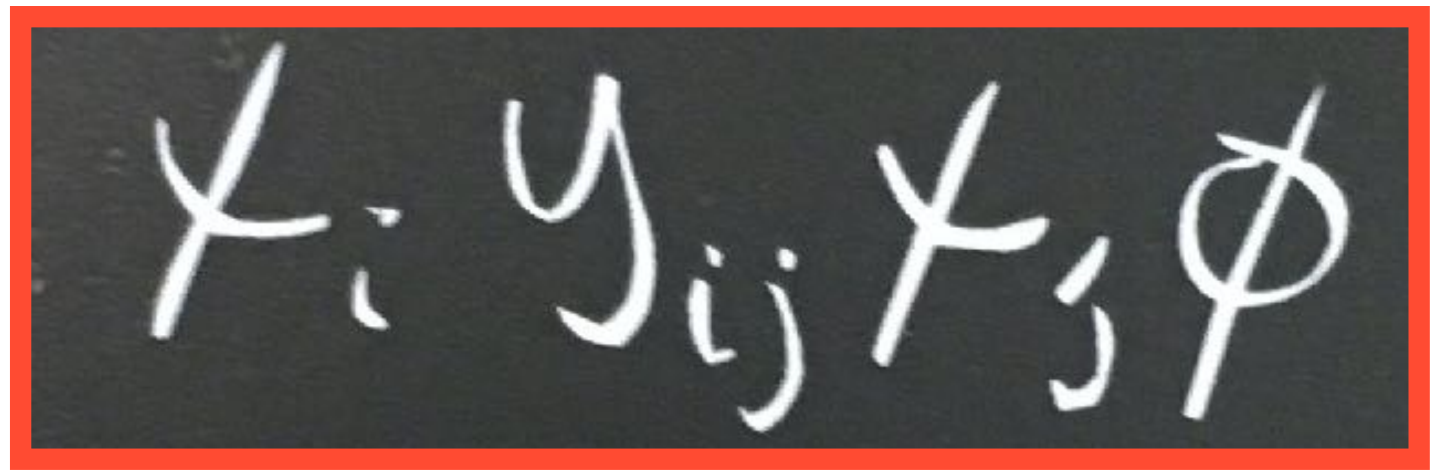
H → ZZ*

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





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

fermion mass term

$m_i = y_{ii}\phi_0$

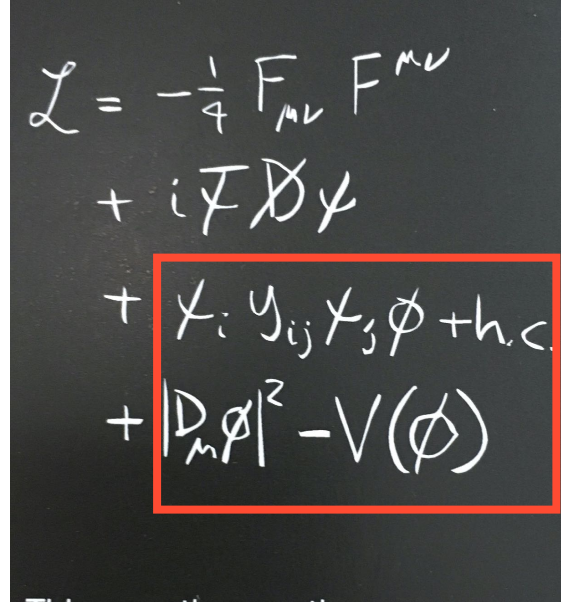
Higgs-fermion-fermion interaction term;

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	$1 \cdot 10^{-4}$

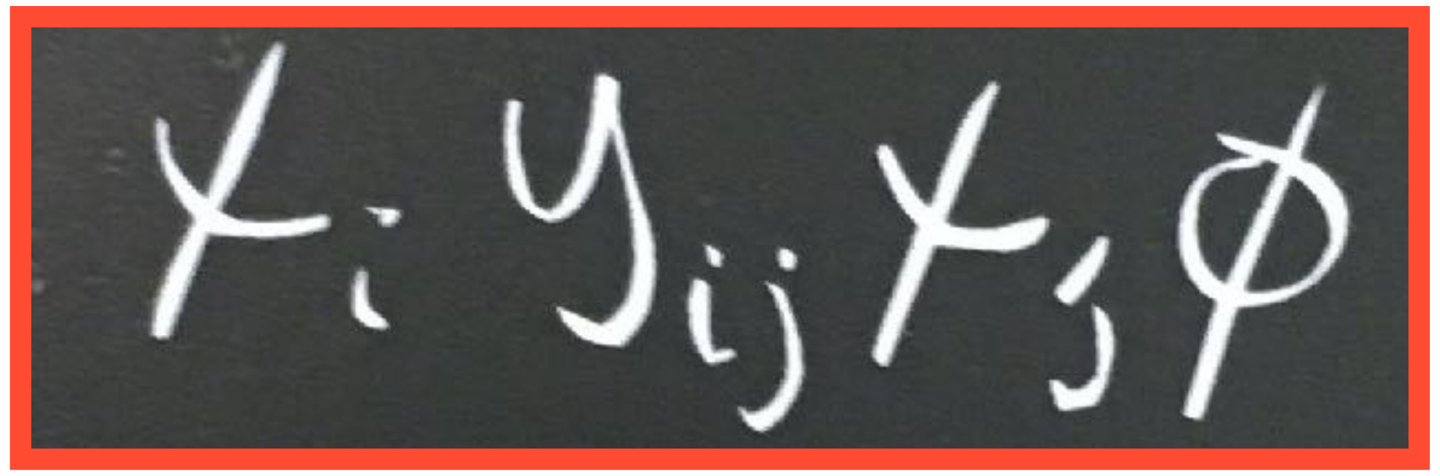
$$\phi = \phi_0 + H$$

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



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

the subject of the next few slides



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

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	$2\cdot10^{-5}$	d	$3\cdot10^{-5}$
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ν_e	$\sim 10^{-13}$?	e	$3\cdot10^{-6}$
ν_μ		μ	$6\cdot10^{-4}$
ν_τ		τ	$1\cdot10^{-4}$

$$\phi = \phi_0 + H$$

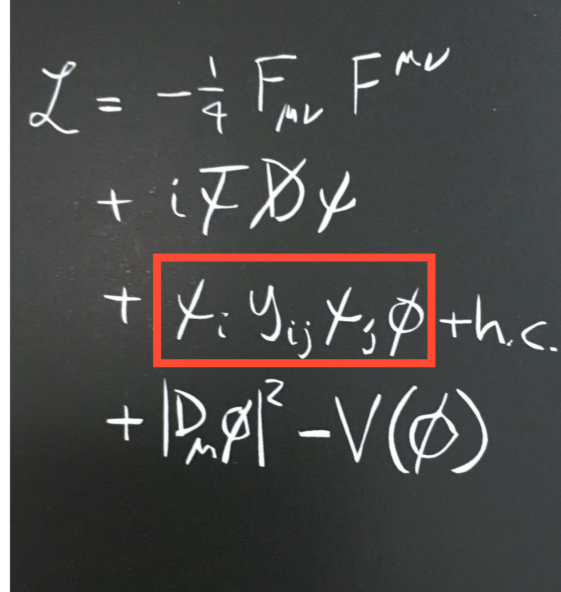
Yukawa interaction hypothesis

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.

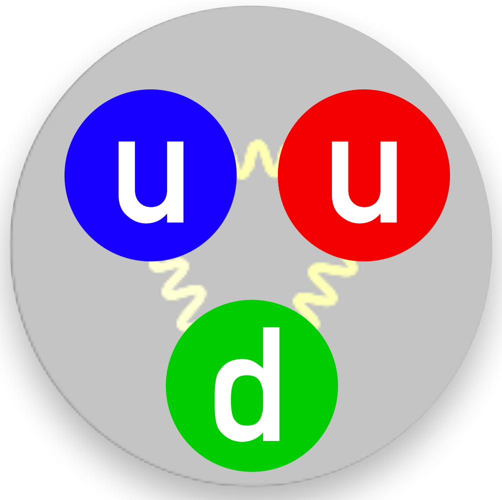
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

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

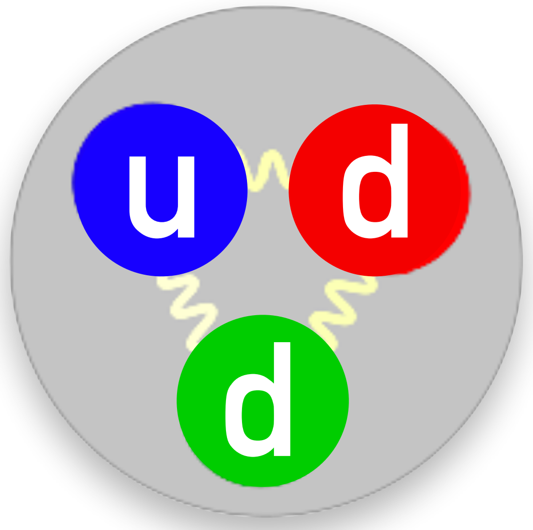
So protons are **lighter** than neutrons,
→ protons are stable.

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

proton
mass = 938.3MeV

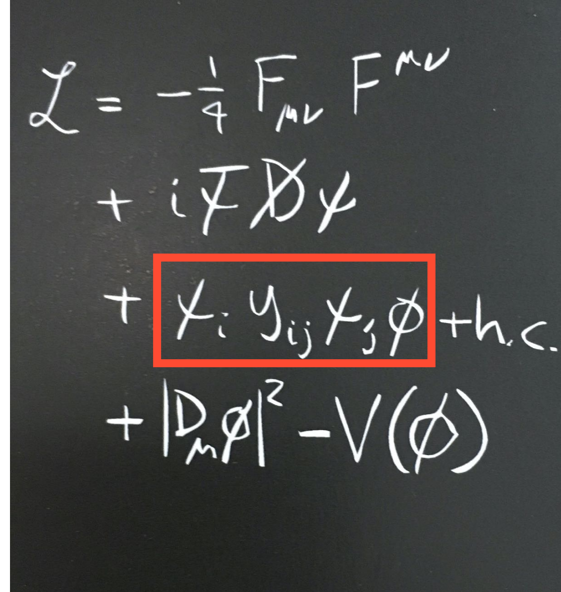


neutron
mass = 939.6MeV



Why do Yukawa couplings matter?

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



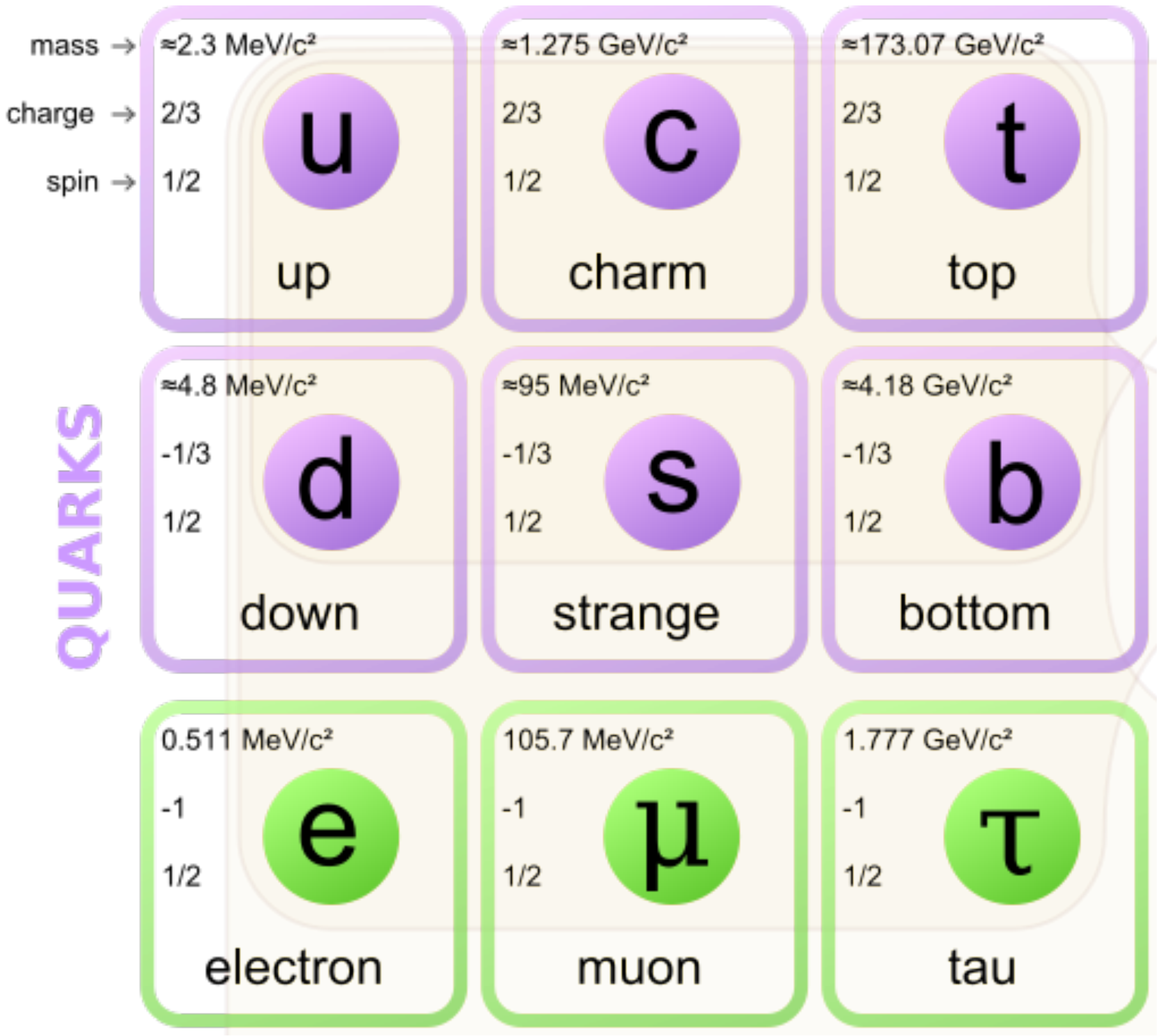
This equation neatly sums up our current understanding of fundamental particles and forces.

Bohr radius

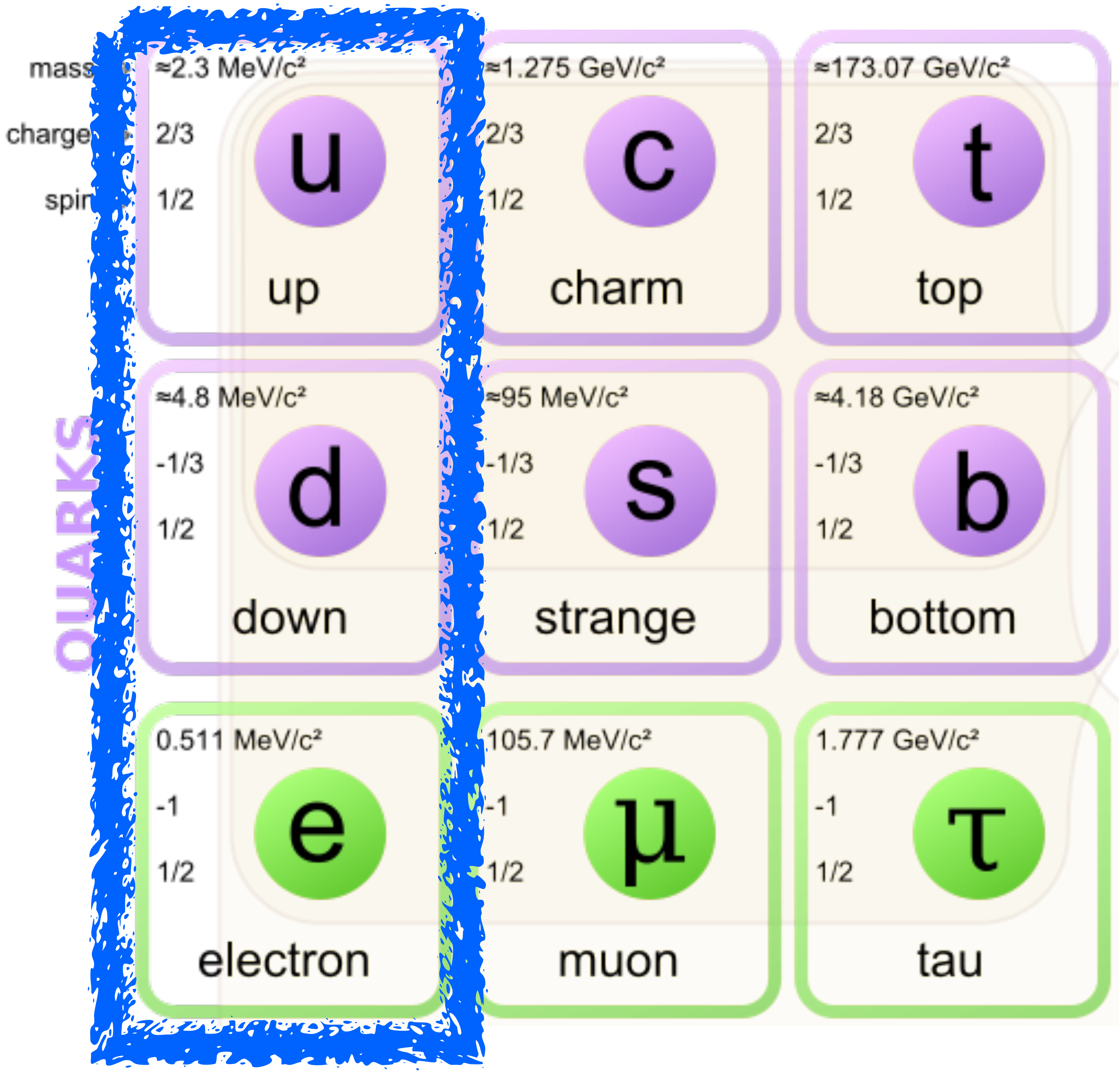
$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c \alpha} \propto \frac{1}{y_e}$$

electron mass determines size of all atoms

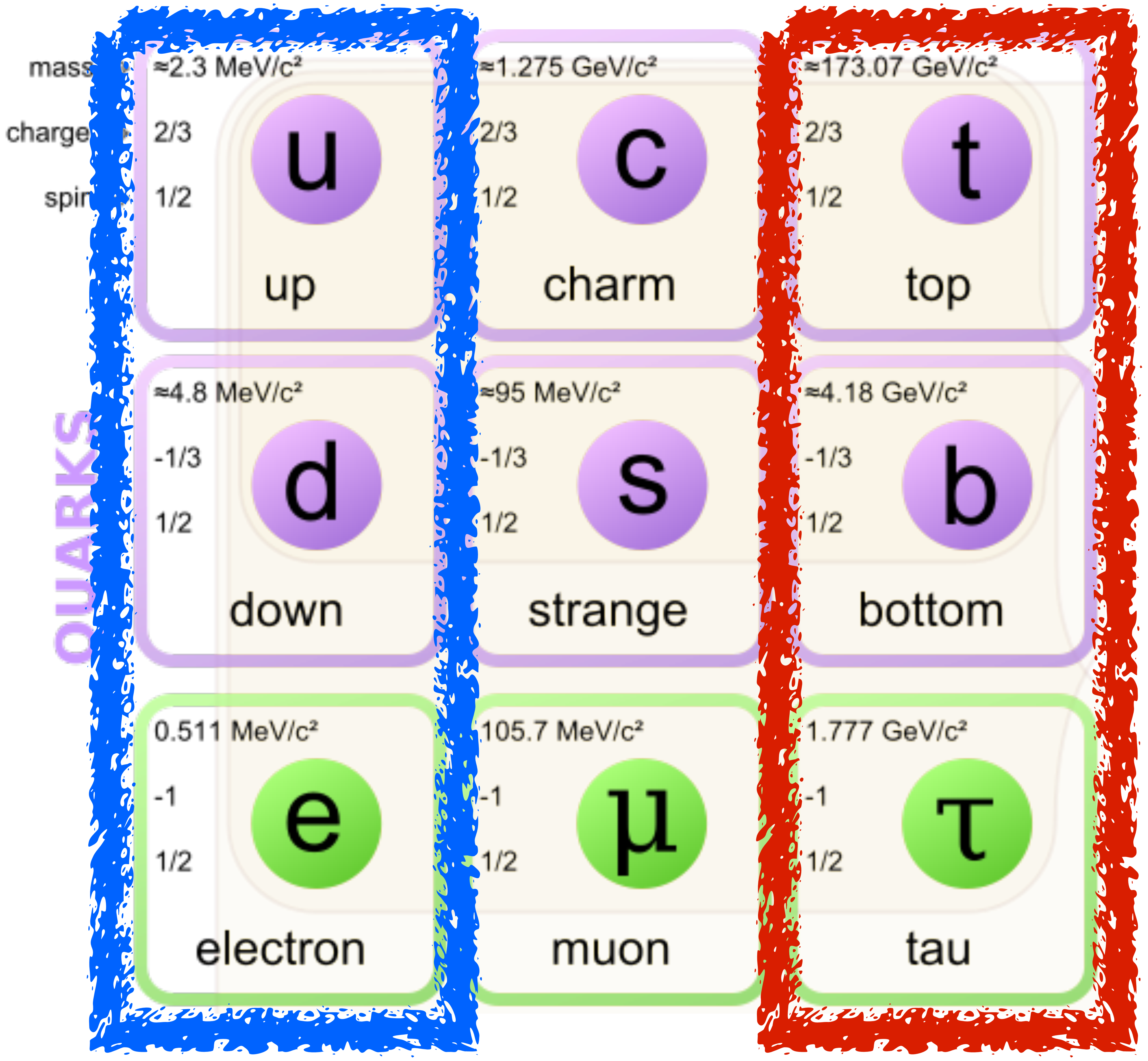
it sets energy levels of all chemical reactions



mass →
charge →
spin →
≈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
QUARKS
≈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

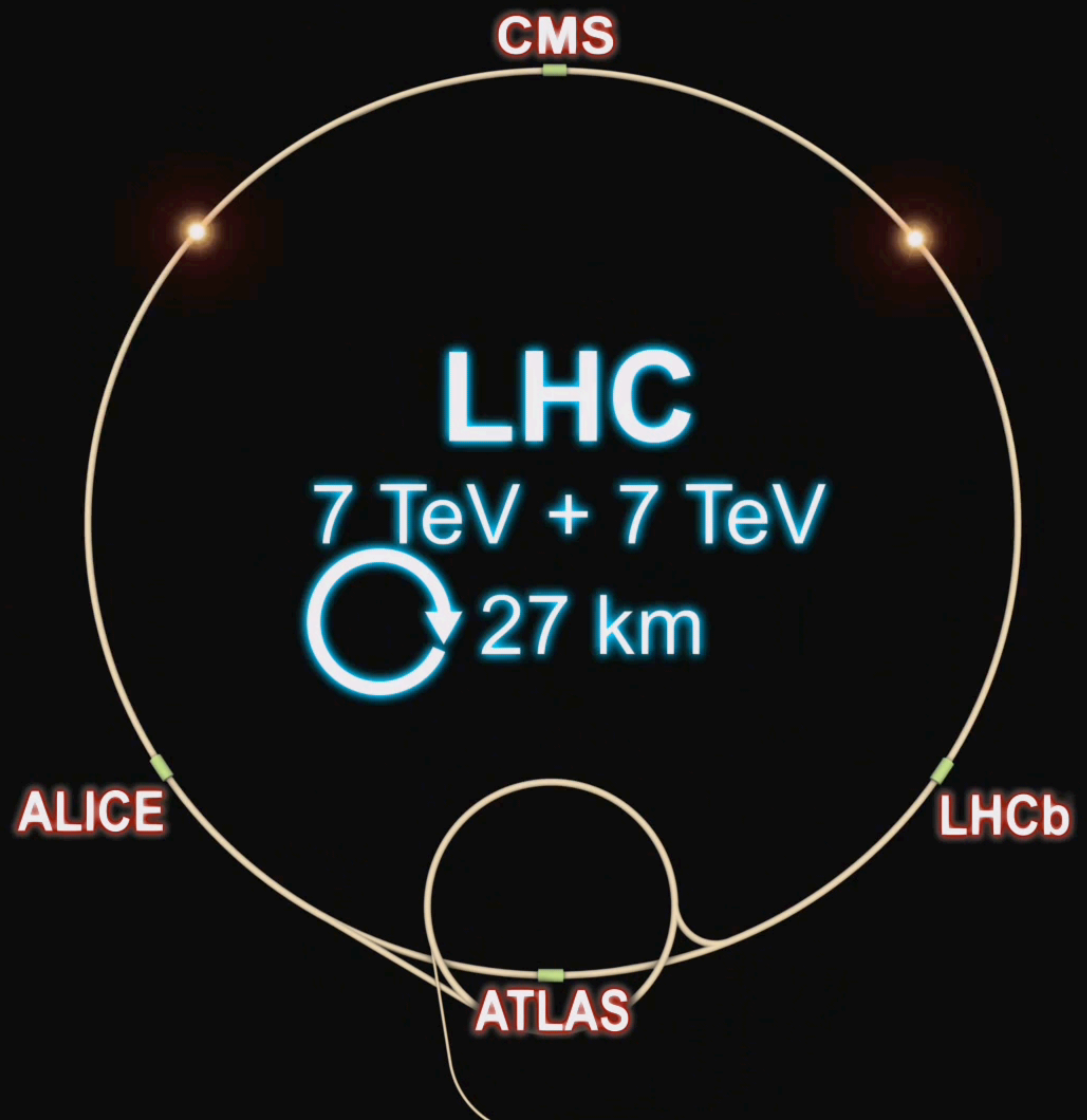


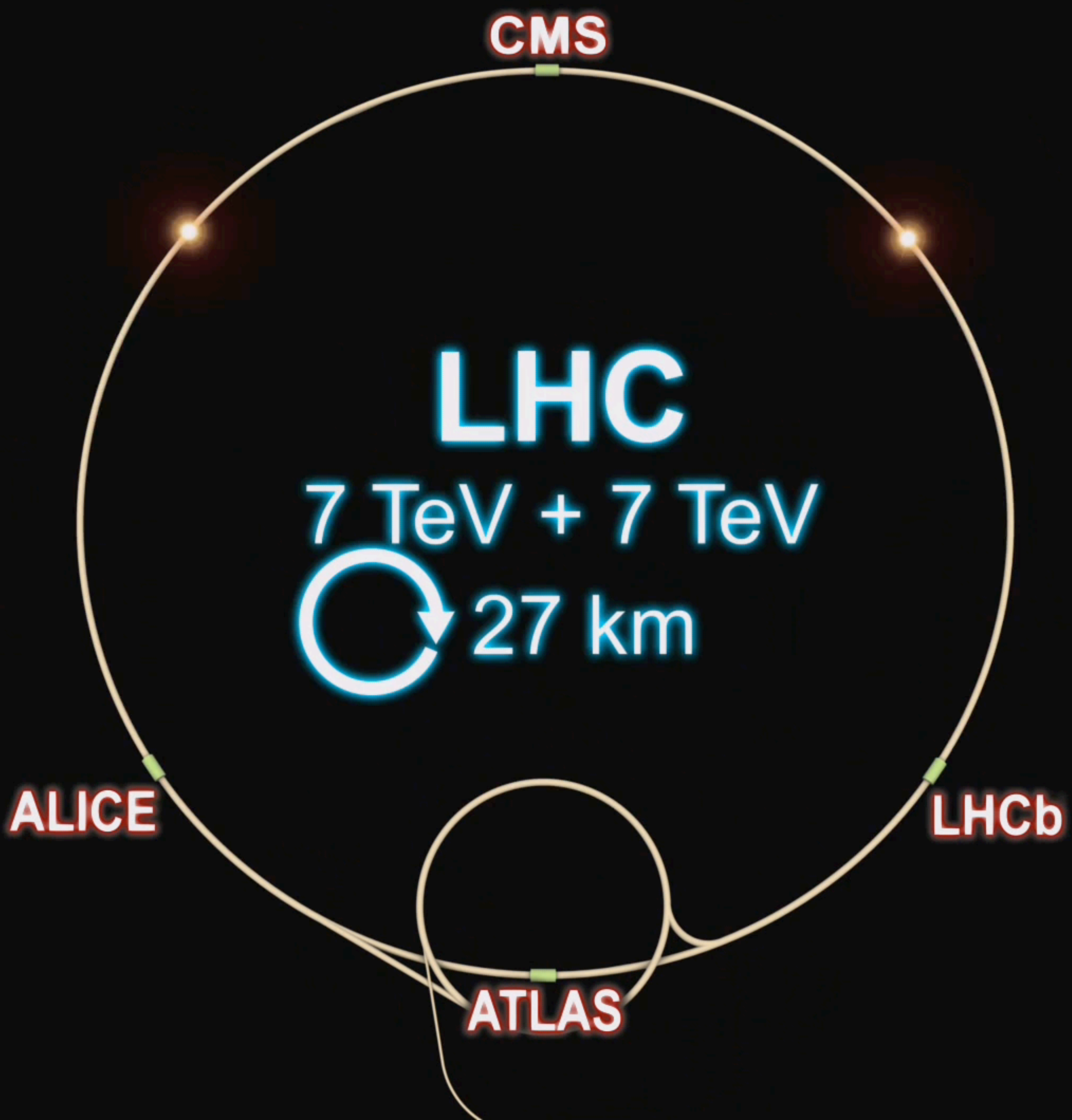
1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**



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**


CMS
LHC
7 TeV + 7 TeV
27 km
ALICE
LHCb
ATLAS


CMS
LHC
7 TeV + 7 TeV
27 km
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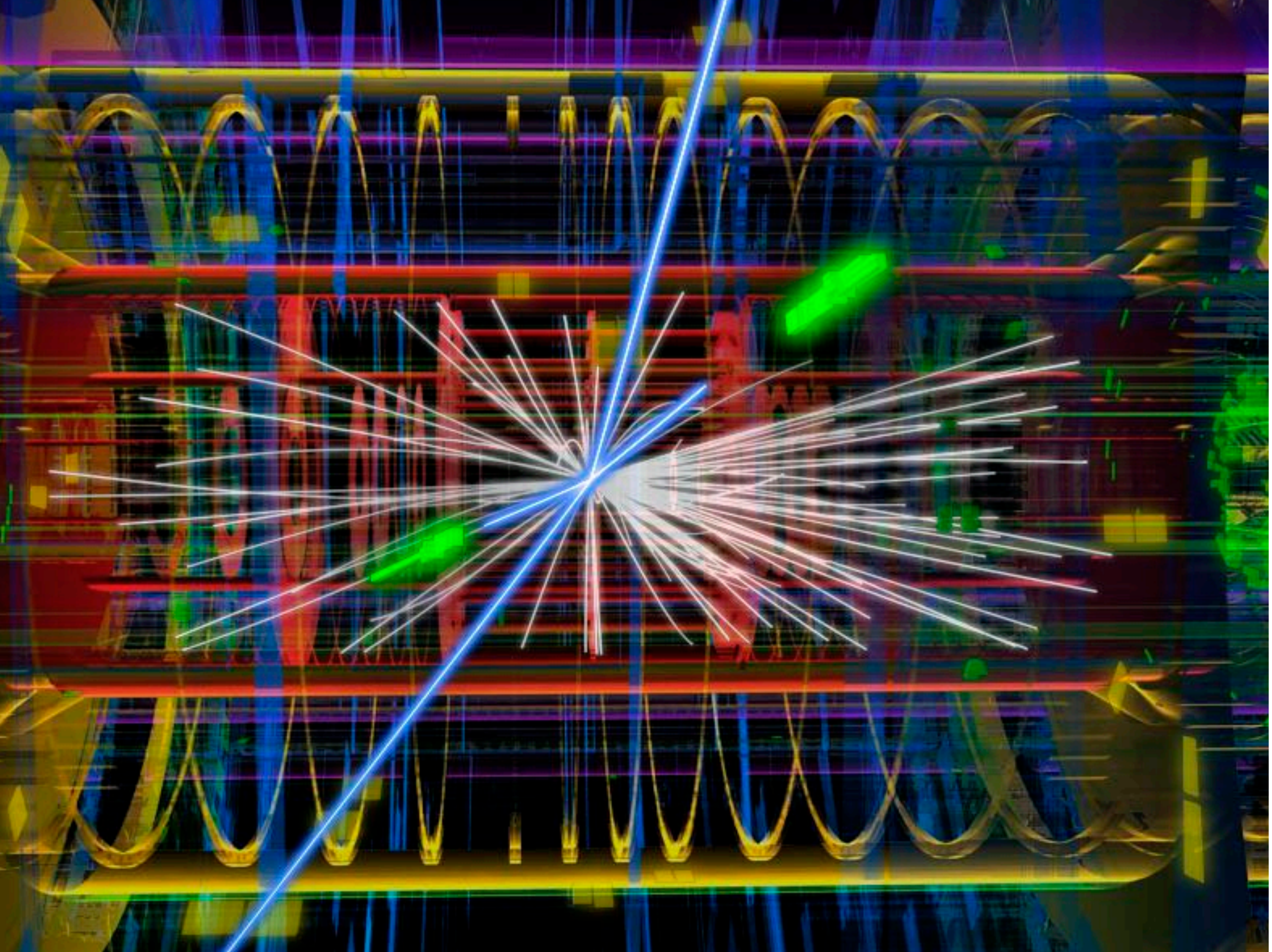
LHCb
ATLAS



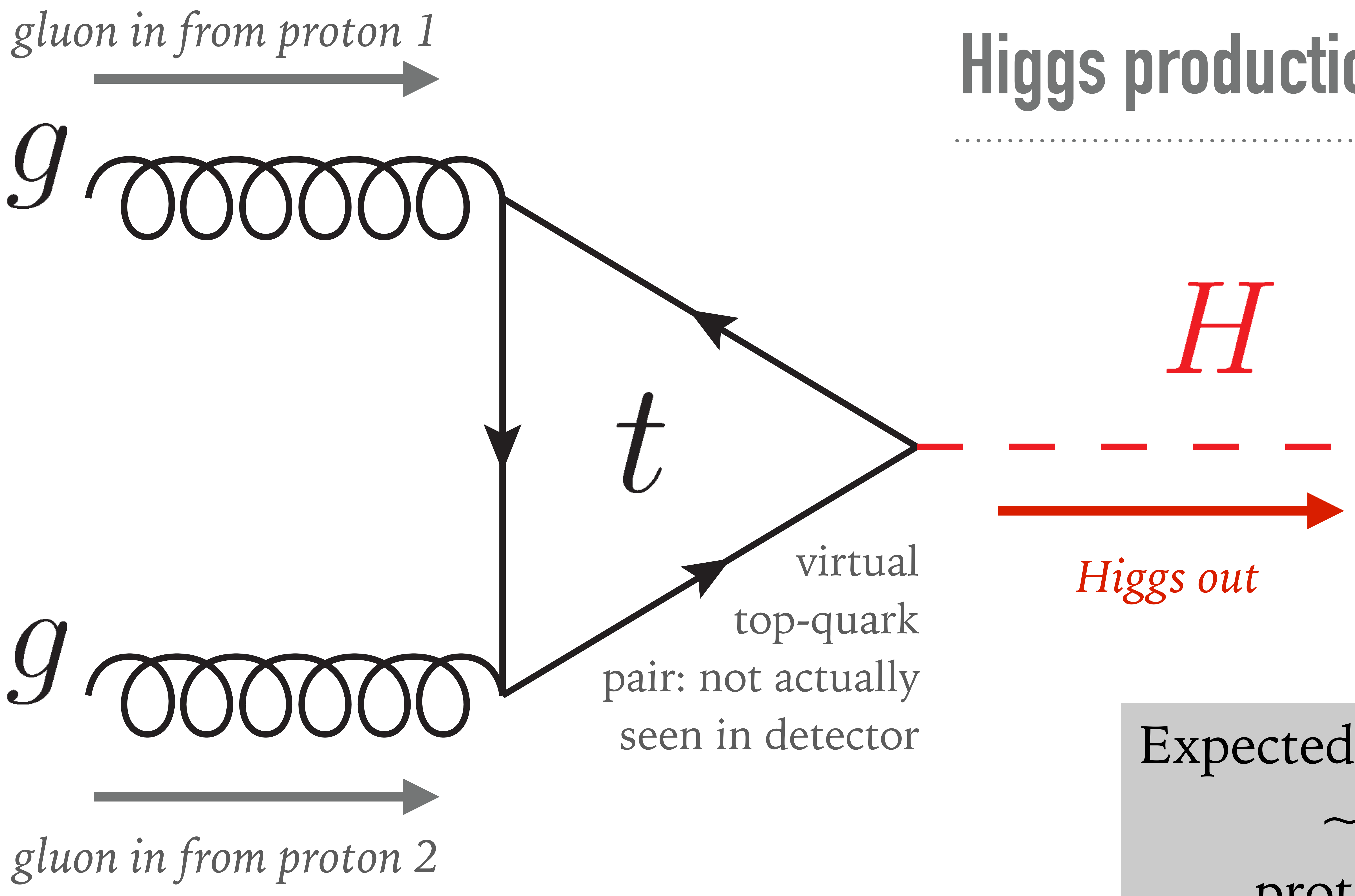
ATLAS & CMS
@LHC

~up to 2 billion collisions/second

(+ lower rates at LHCb and ALICE)

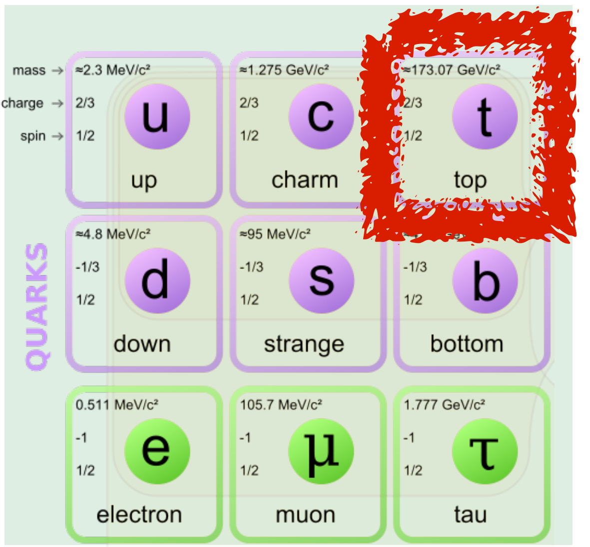
what underlying processes tell us about Yukawa interactions?

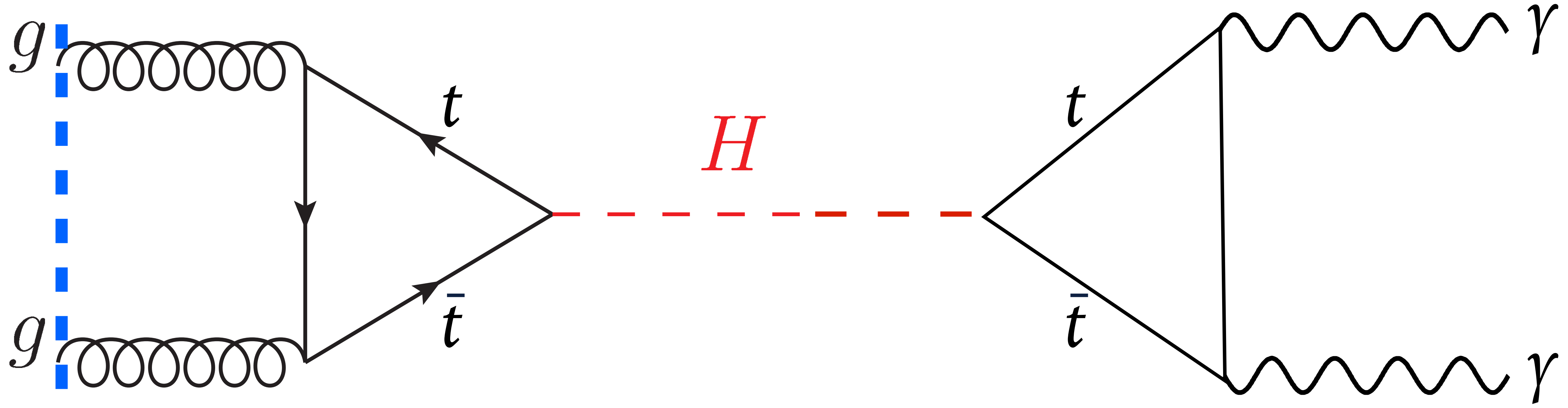
Higgs production: the dominant channel



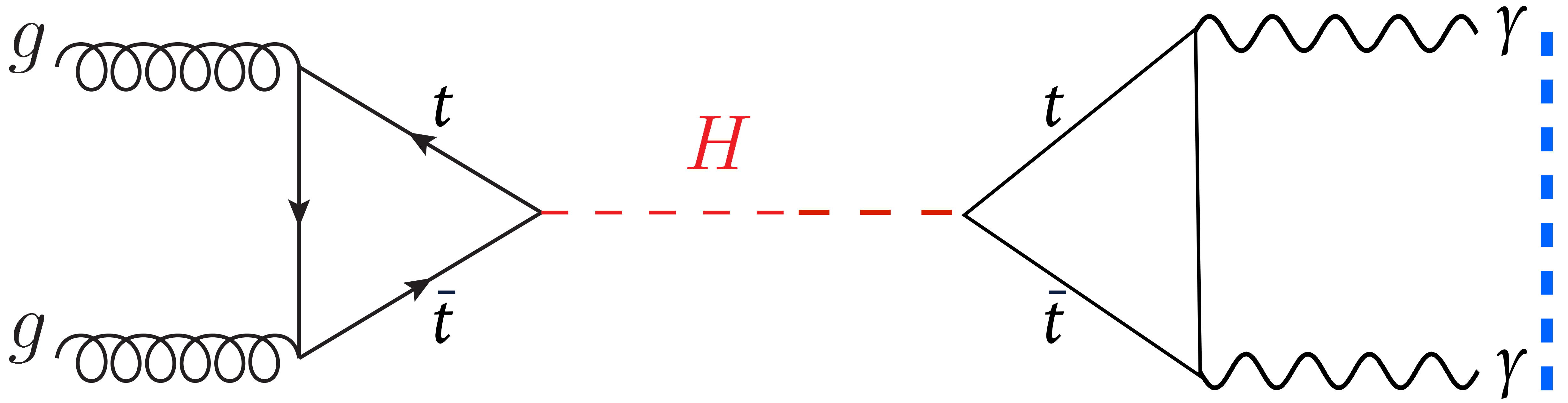
Expected to happen once for every ~2 billion inelastic proton–proton collisions

LHC data consistent with that already at discovery in 2012

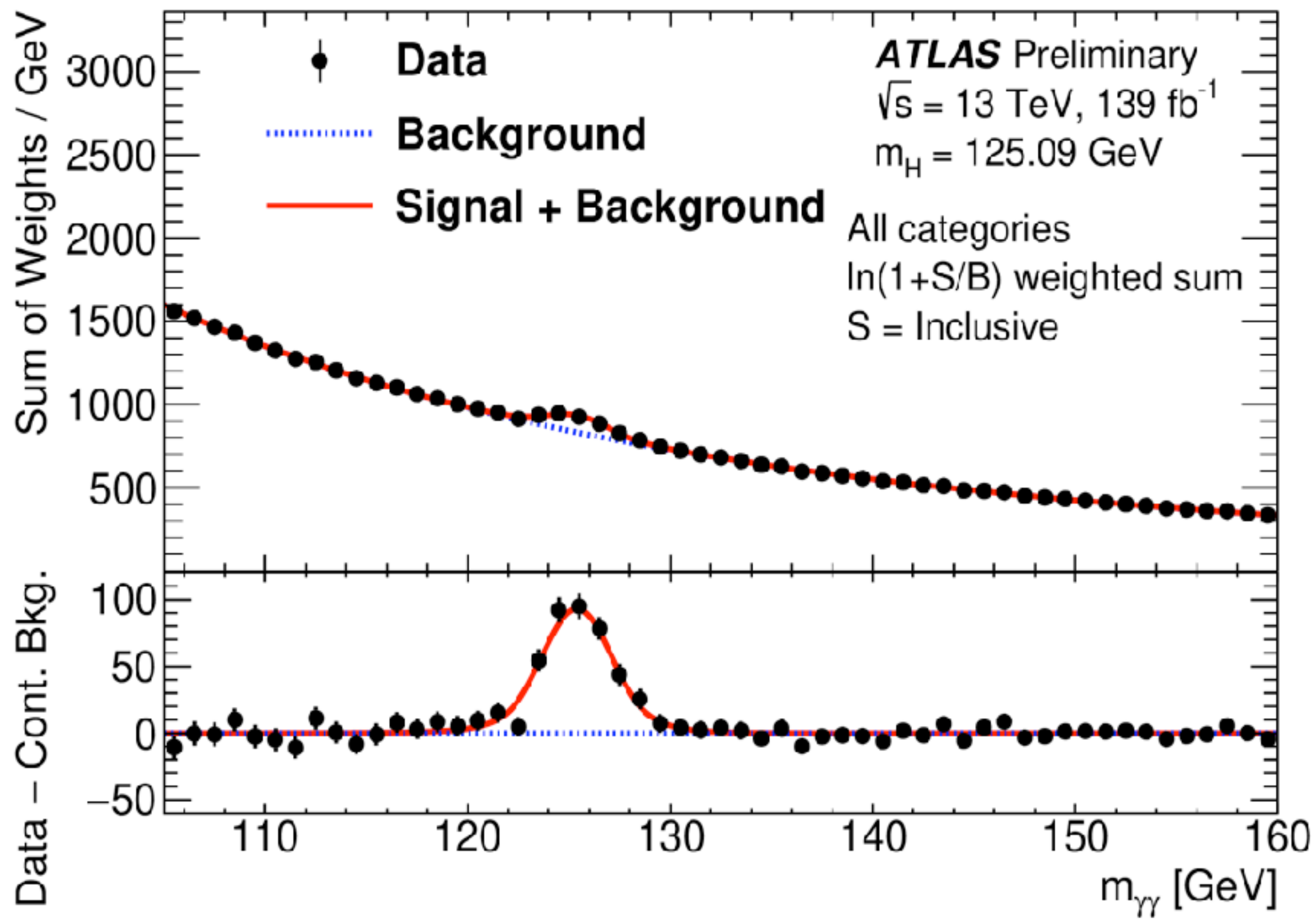


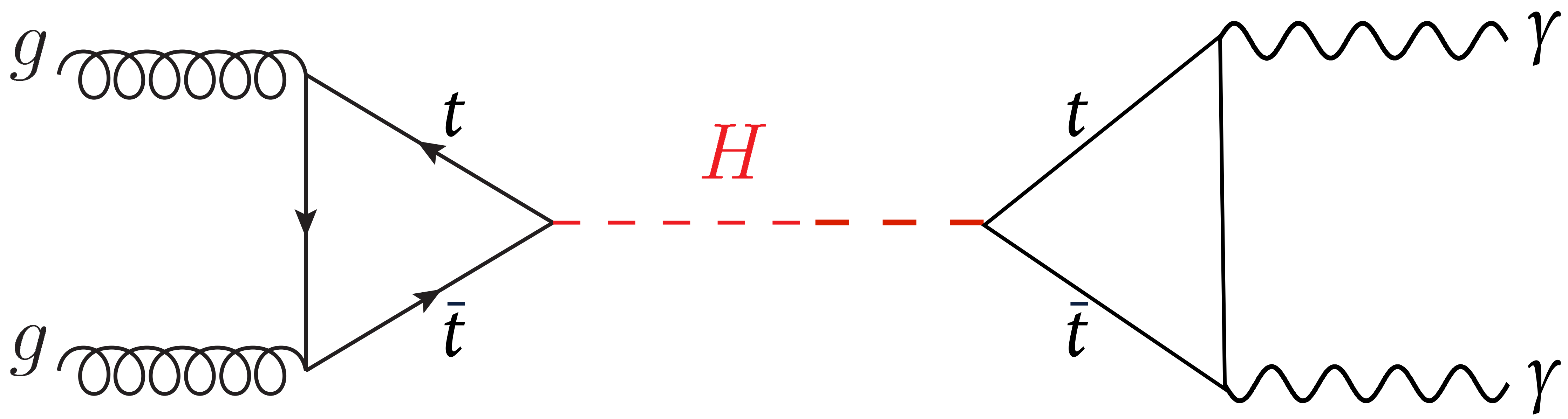

g
g
t
$\bar{t}$
H
t
$\bar{t}$
γ
γ


luon
gluo
φ
y
x
Higgs field in space


g
g
t
$\bar{t}$
H
t
$\bar{t}$
γ
γ


luon
gluo
φ
y
x
Higgs field in space


Data
Background
Signal + Background
ATLAS Preliminary
√s = 13 TeV, 139 fb-1
mH = 125.09 GeV
All categories
ln(1+S/B) weighted sum
S = Inclusive
Sum of Weights / GeV
Data − Cont. Bkg.
mγγ [GeV]


g
g
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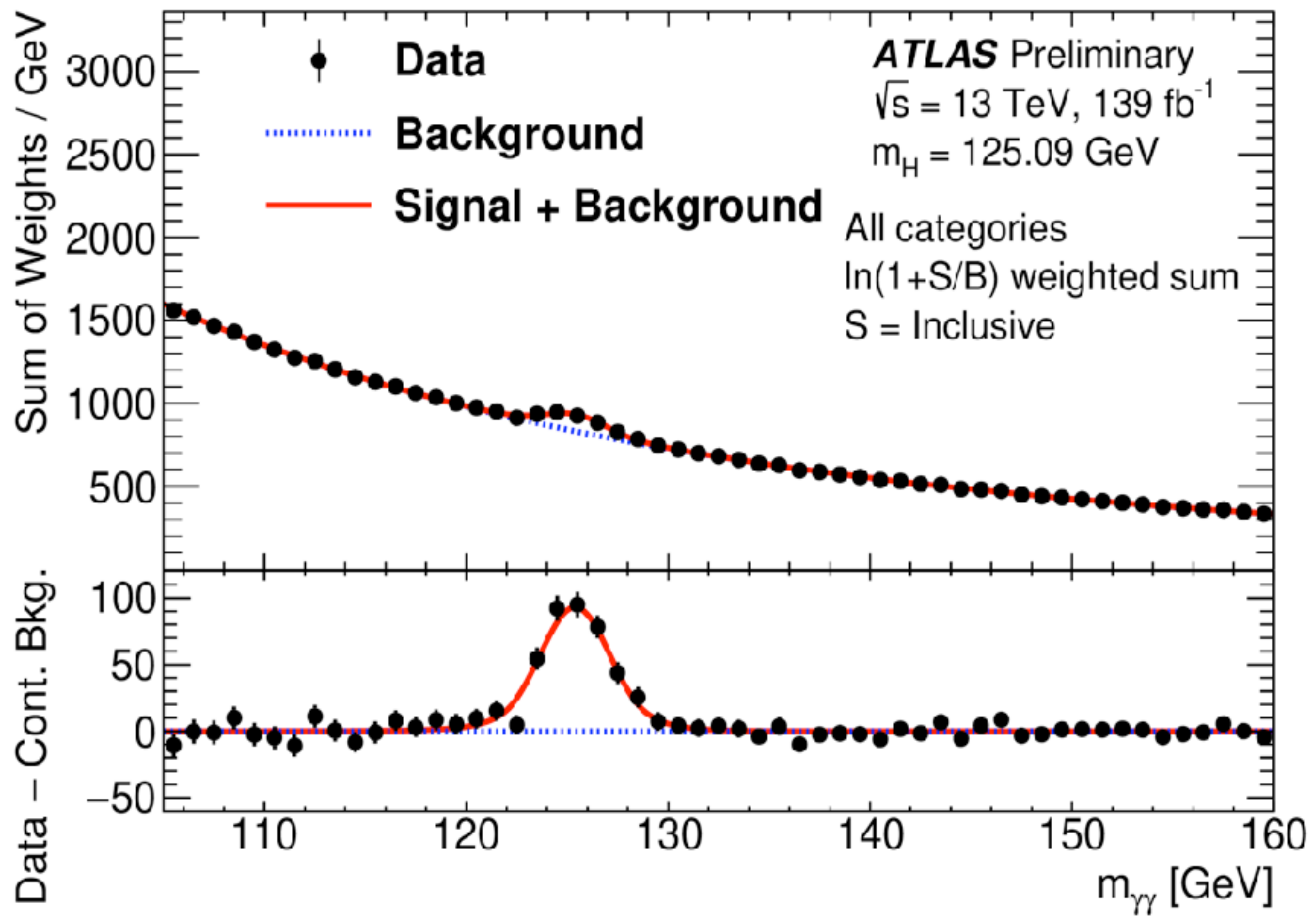
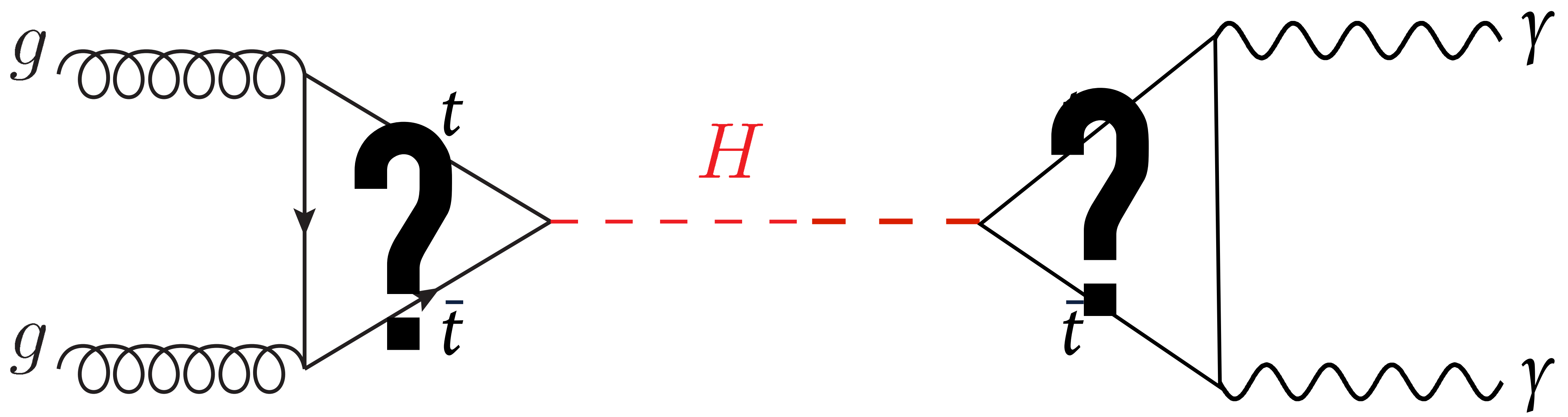
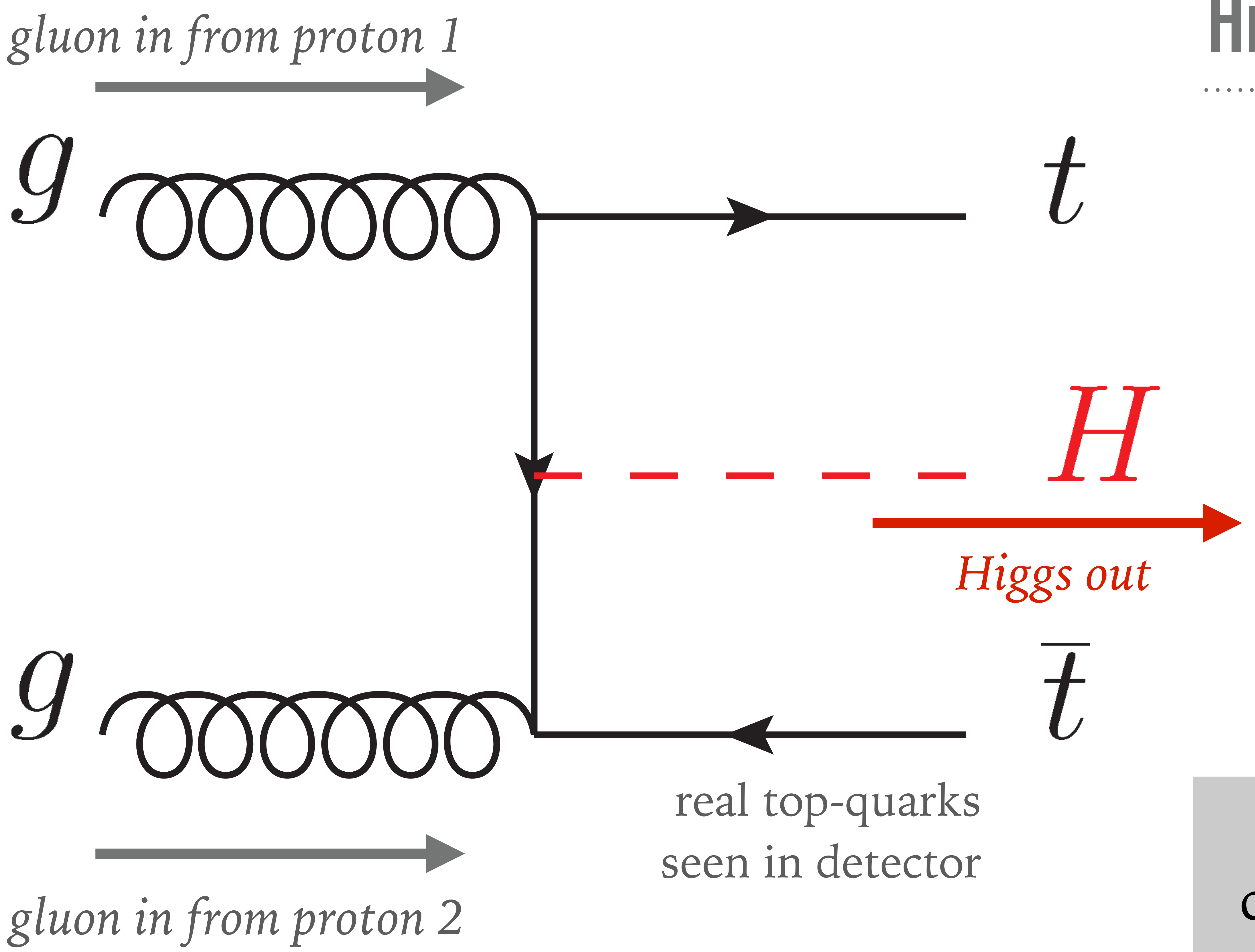




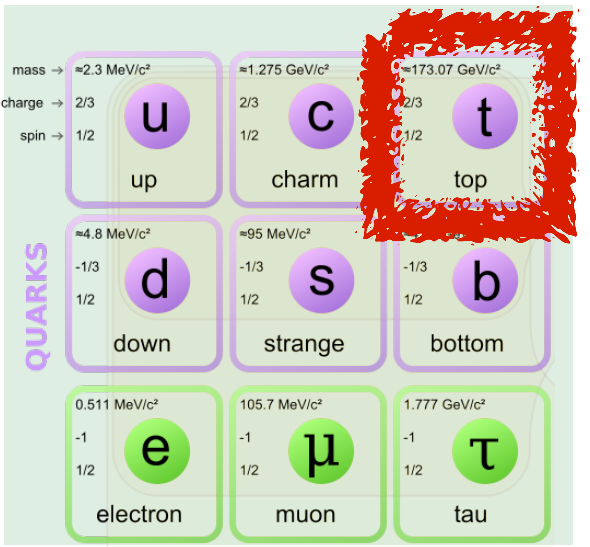
but how can you be sure the Higgs boson is really being radiated off a top-quark, i.e. that you're actually seeing a Yukawa coupling?

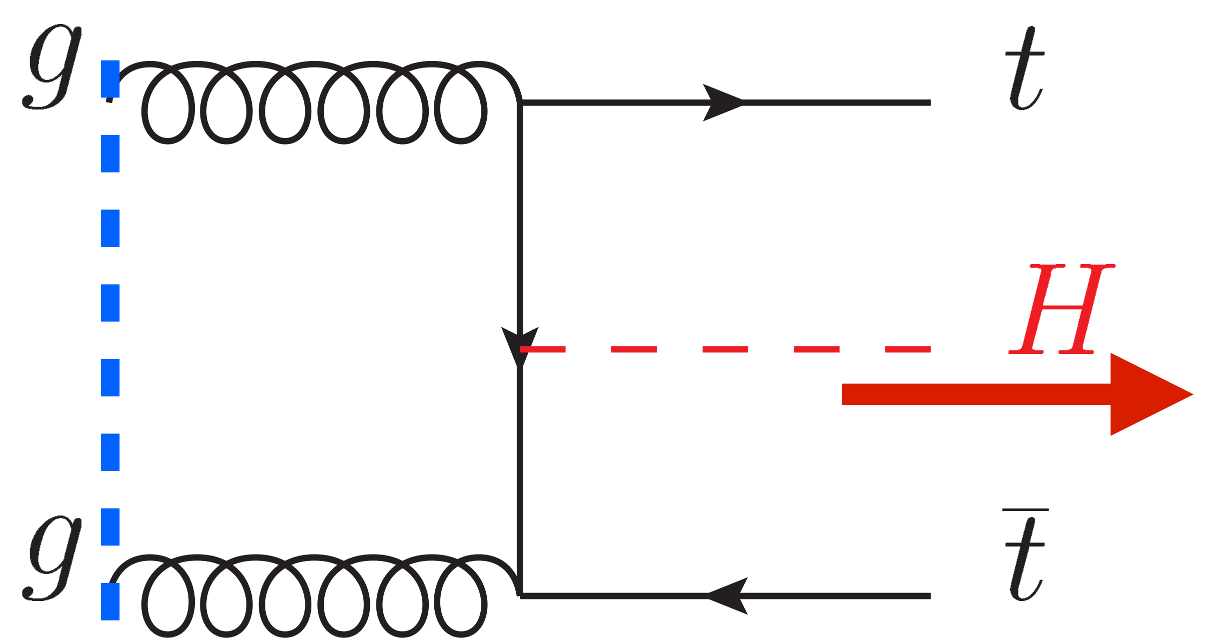
Higgs production: the ttH channel



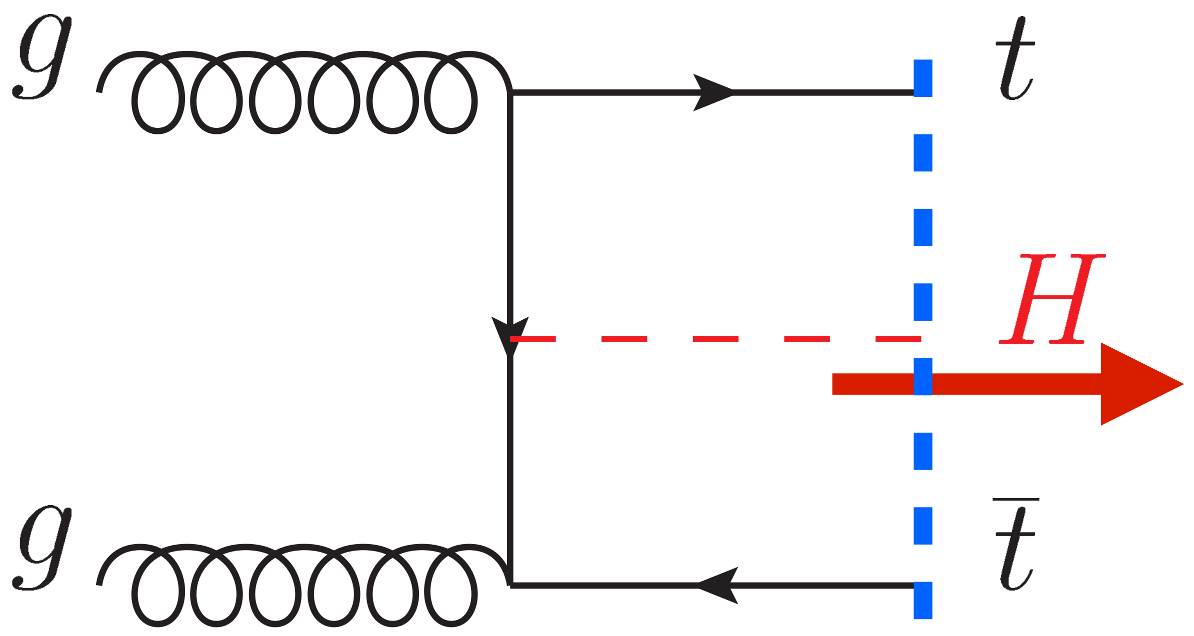
If SM top-Yukawa hypothesis is correct, expect 1 Higgs for every 1600 top-quark pairs.

(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
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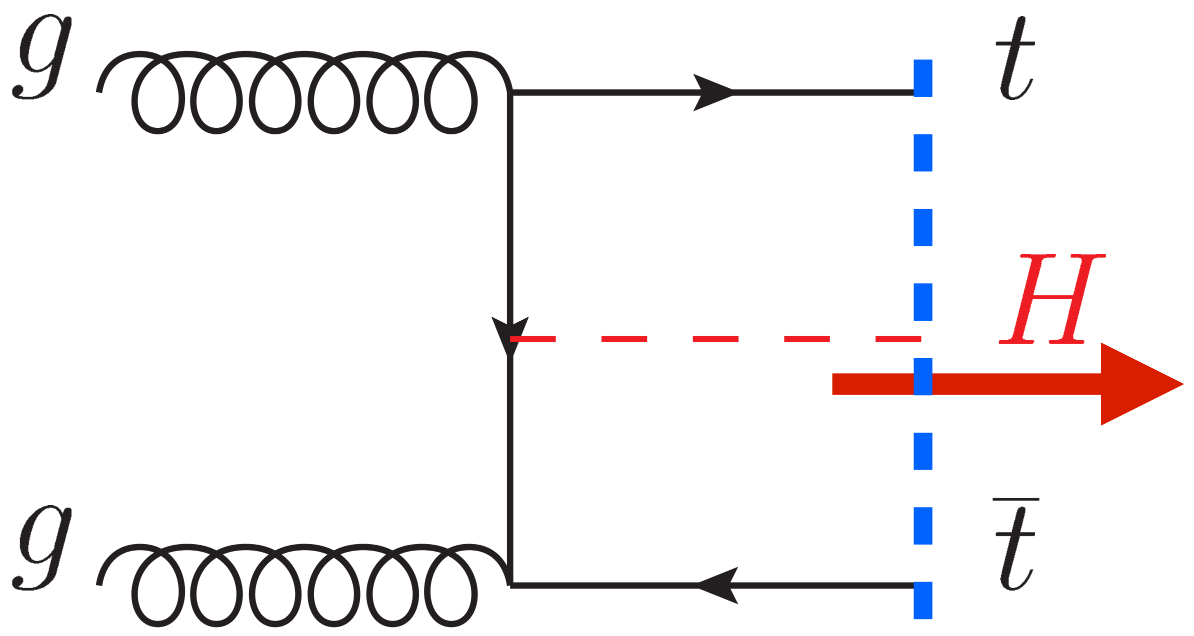
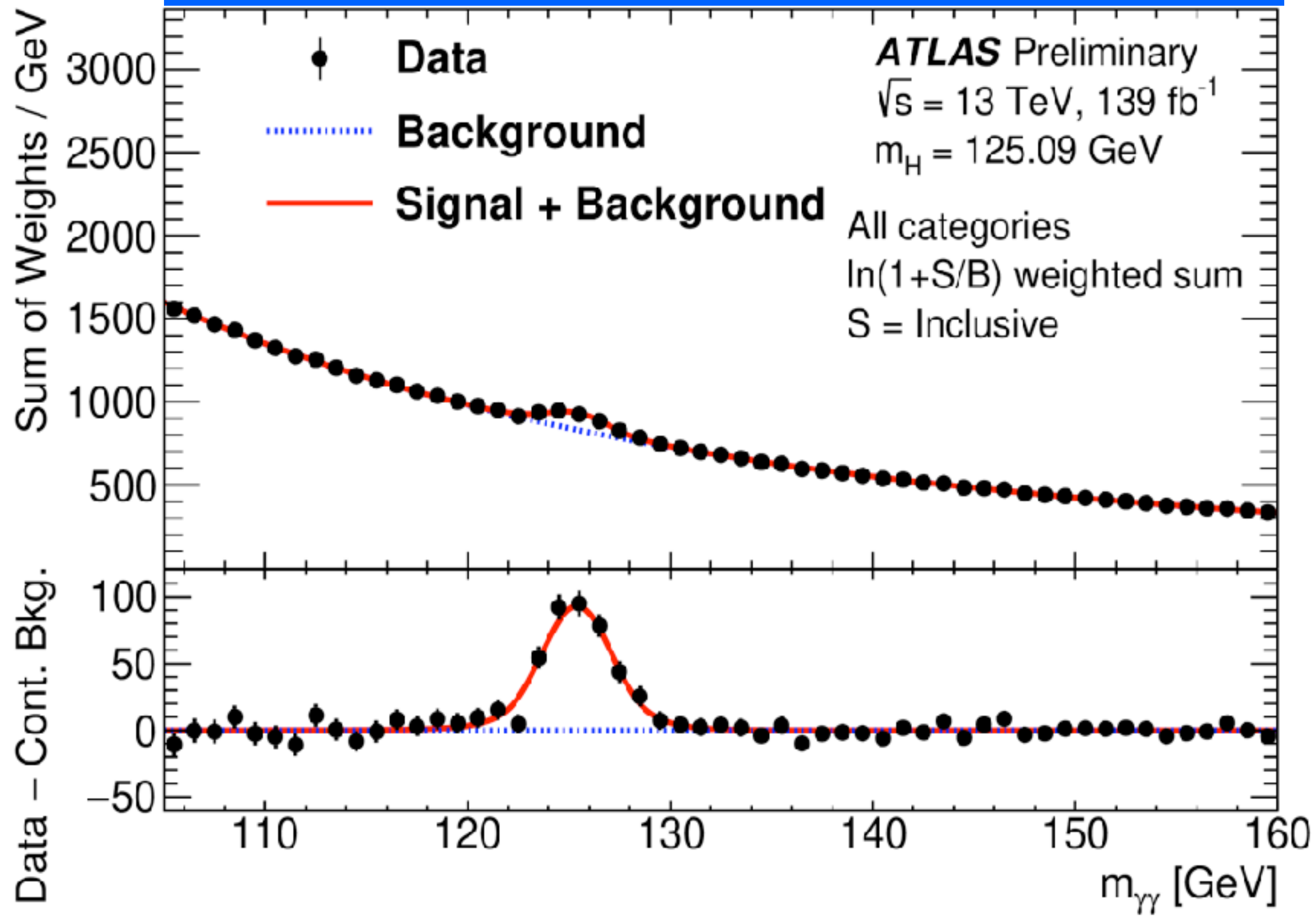
luon
gluo
φ
y
x
Higgs field in space


g
t
H
g
$\bar{t}$

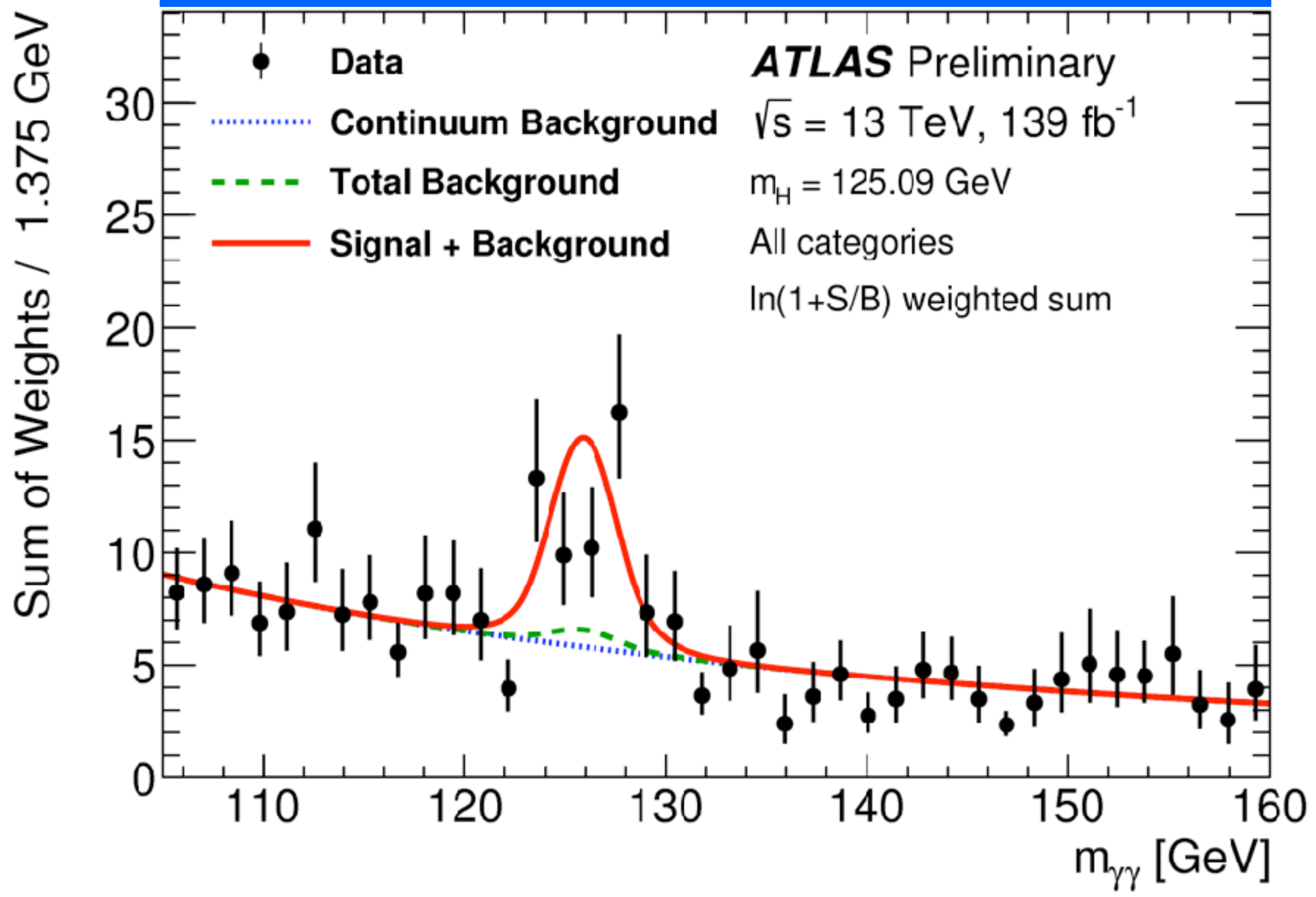

luon
gluo
φ
y
x
Higgs field in space

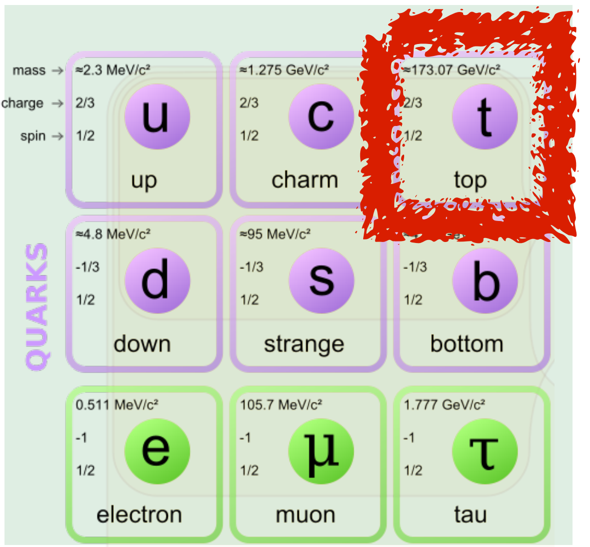
since 2018: ATLAS & CMS see events with top-quarks & Higgs simultaneously

across all events



in events with top quarks



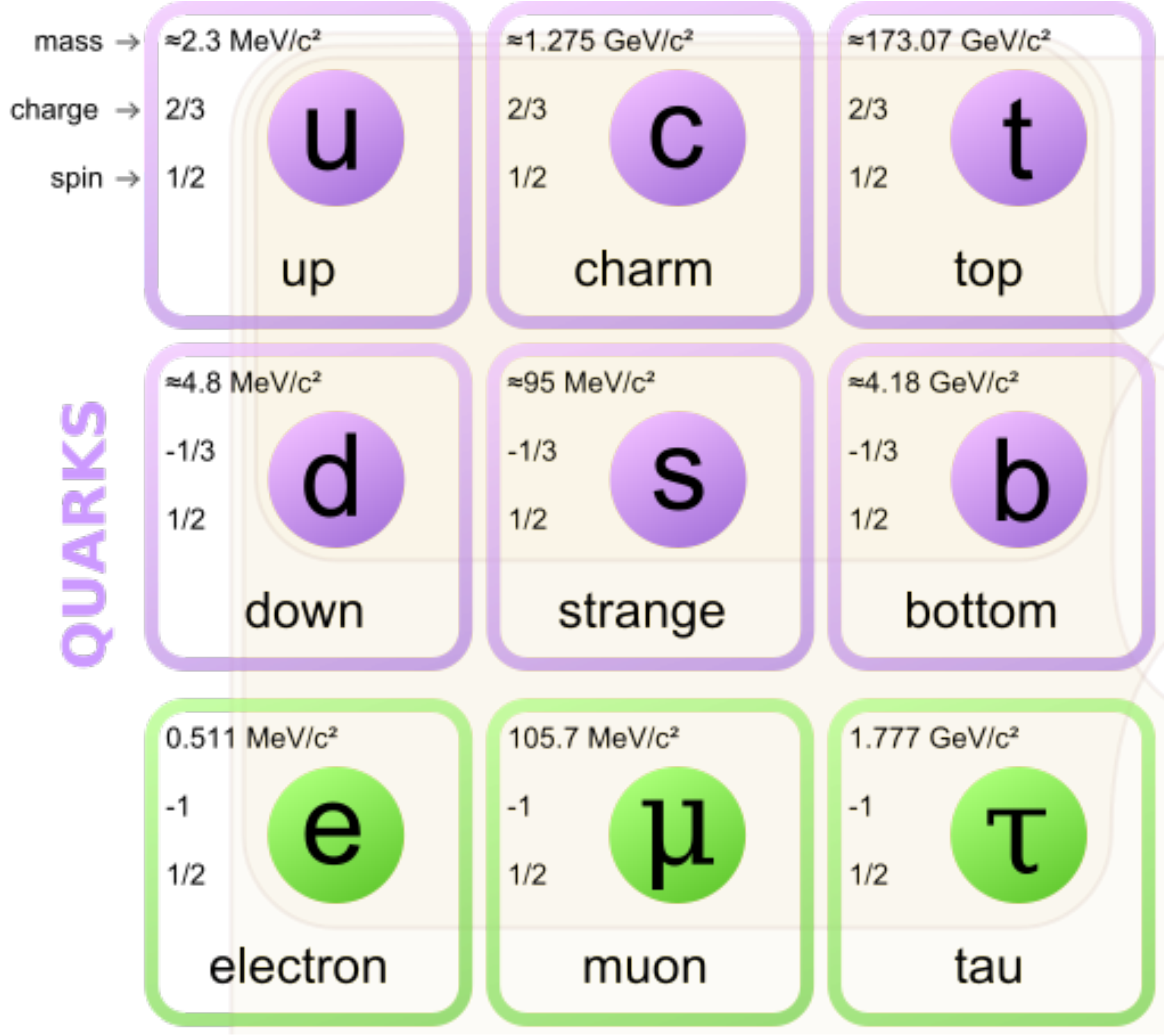


enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

(consistent with SM to c. ±20 – 40%)

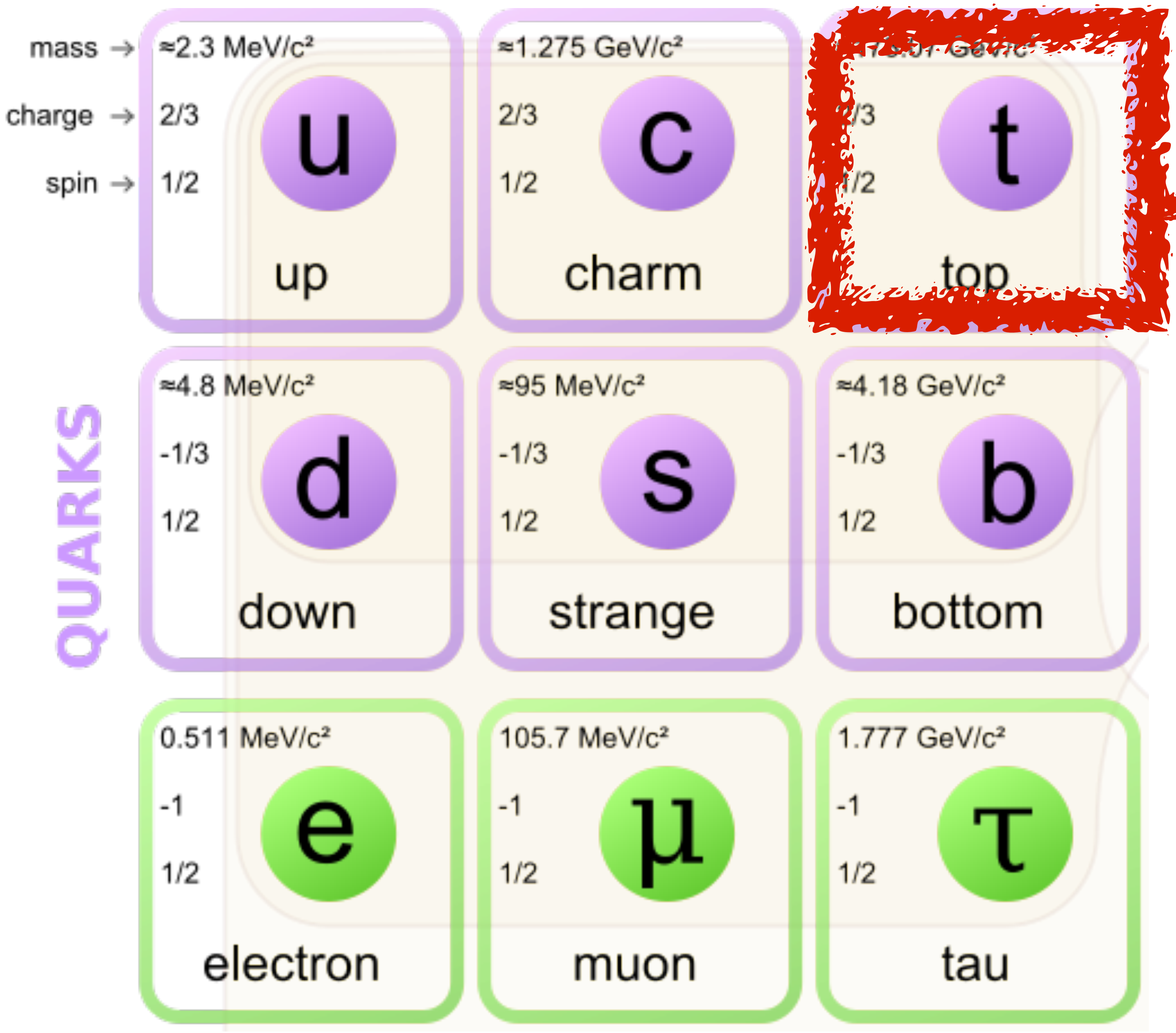
2017/18 discovery of 3rd generation Yukawa interactions by ATLAS & CMS



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

†in part with approach from Butterworth, Davison, Rubin & GPS '08

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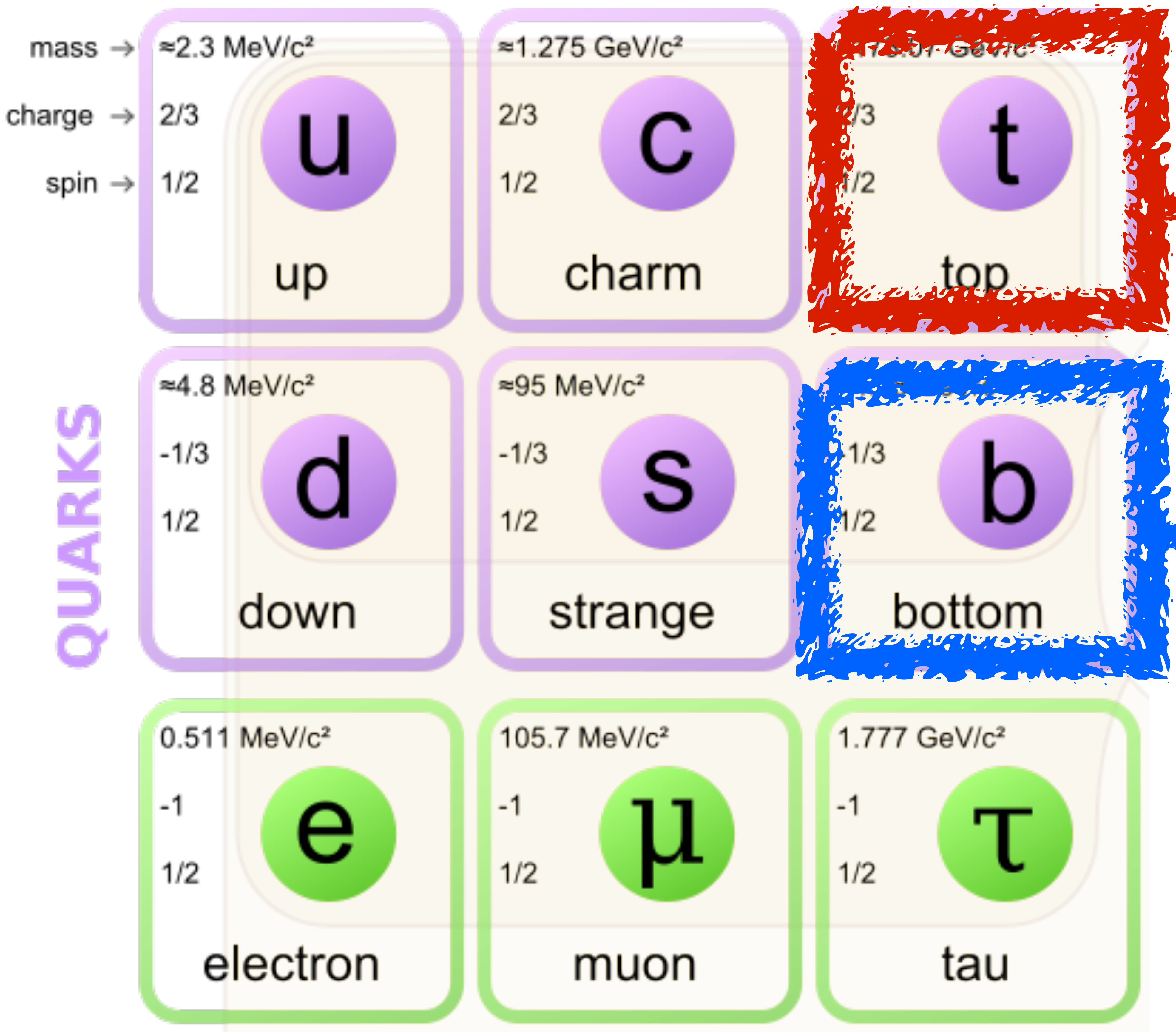
2017/18 discovery of 3rd generation Yukawa interactions by ATLAS & CMS



by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays†

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

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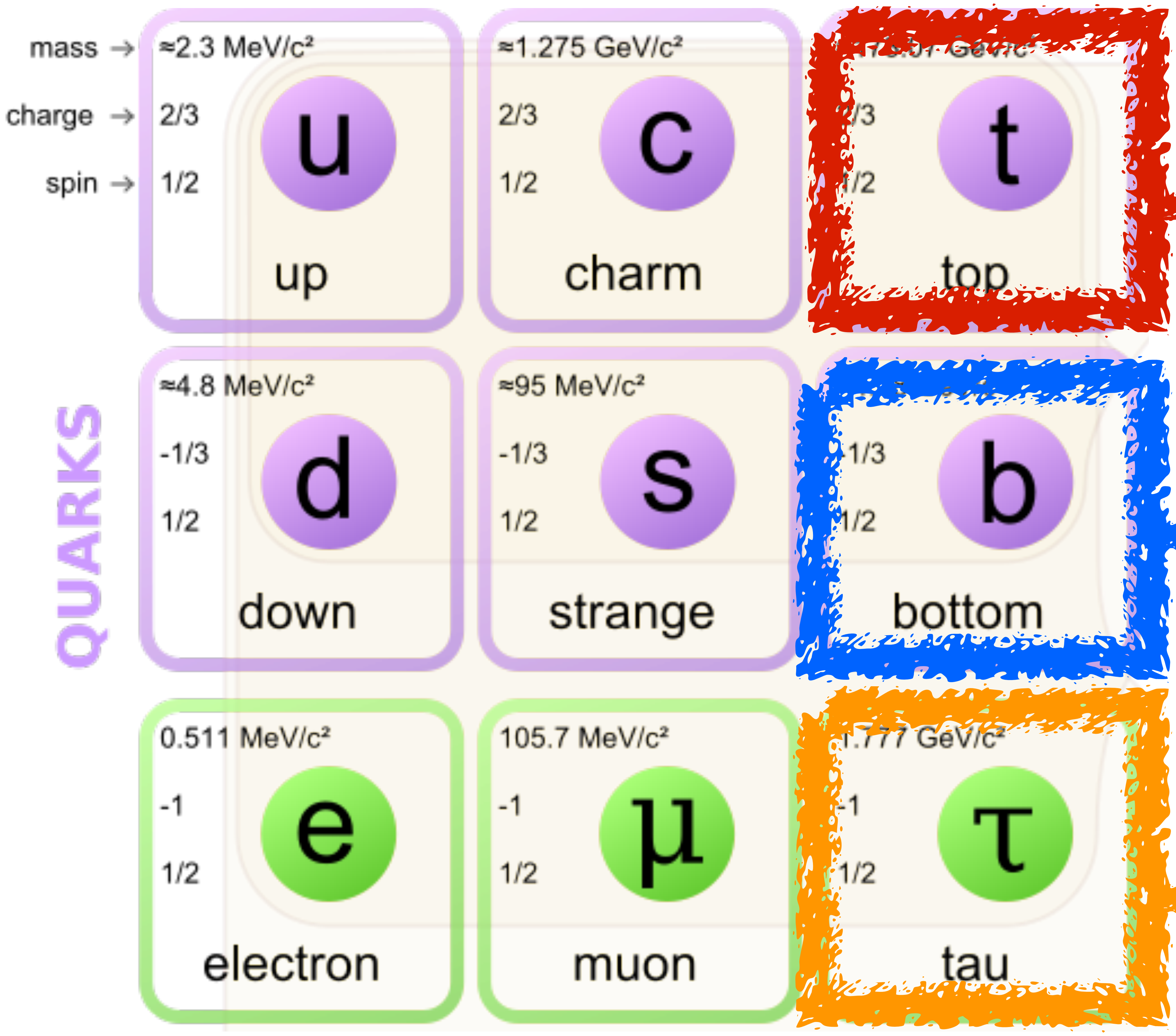
2017/18 discovery of 3rd generation Yukawa interactions by ATLAS & CMS



by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays†

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

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

†in part with approach from Butterworth, Davison, Rubin & GPS '08

what's the message?

The $>5\sigma$ observations of the ttH process and of $H \to \tau\tau$ and $H \to bb$ decays, independently by ATLAS and CMS, **firmly establish the existence of a new kind of fundamental interaction,** Yukawa interactions.

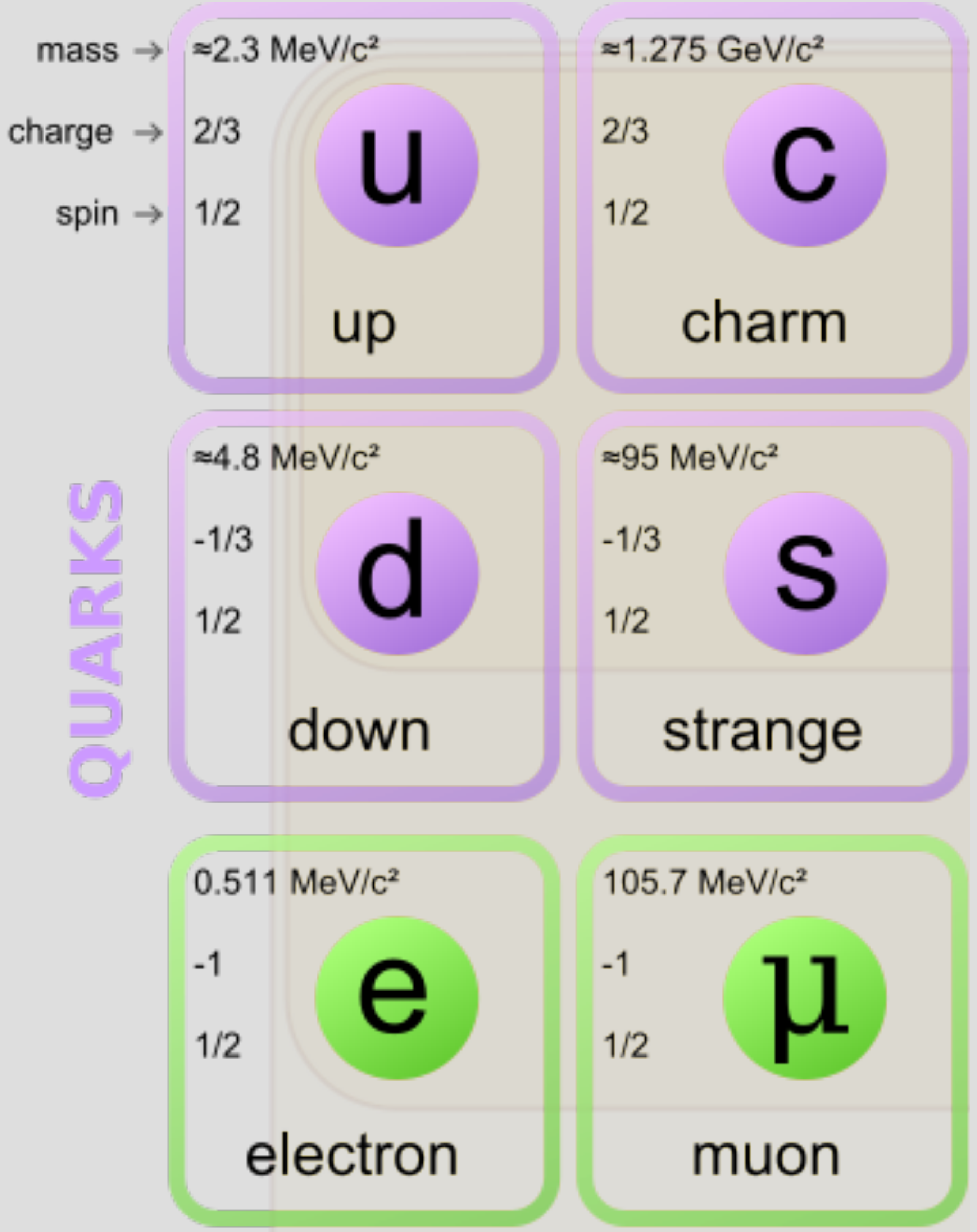
Yukawa interactions are important because they are:

(1) **qualitatively unlike any quantum interaction probed before**
(effective charge not quantised, not conserved)

(2) hypothesized to be responsible for the **stability of hydrogen,** and for determining the **size of atoms** and the energy scales of chemical reactions.

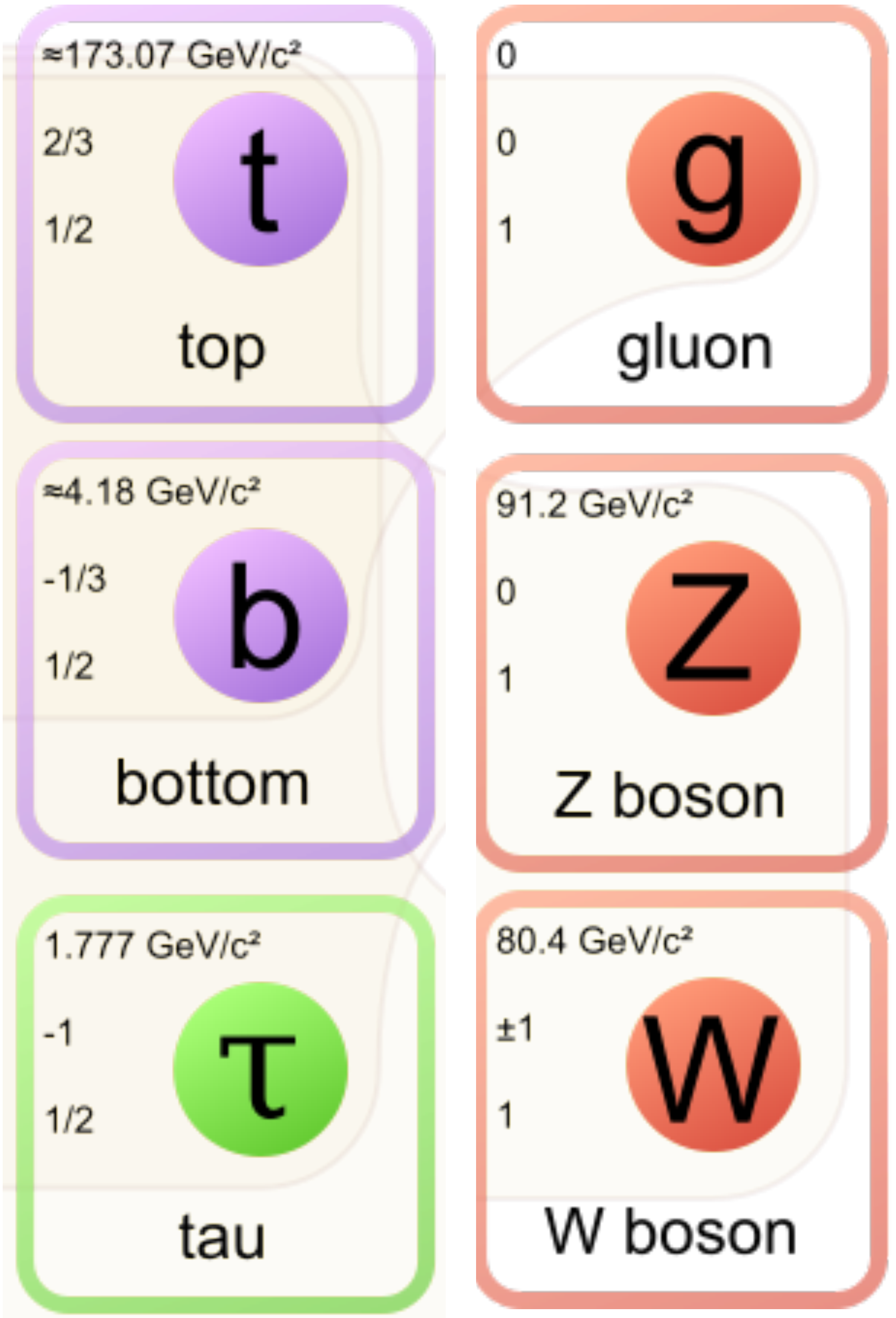
Equivalently this is a **fifth force, the "Higgs force"**

H interaction not yet seen



Are Yukawa interactions responsible for all fermion masses?

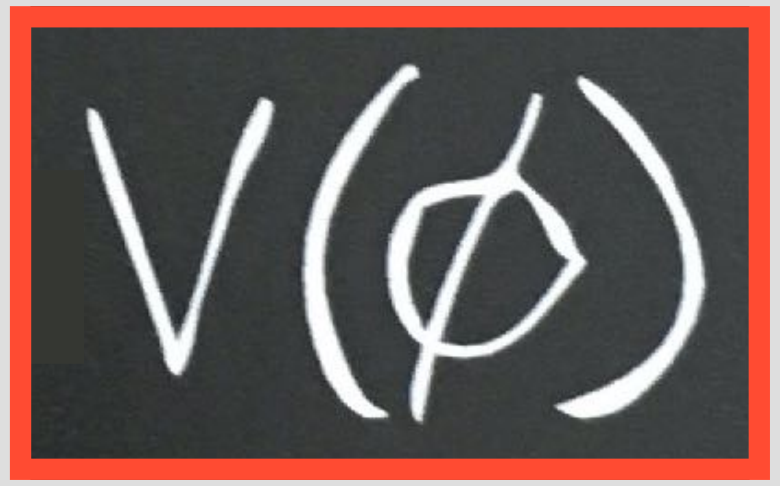
H interaction seen



Do these interactions follow the Standard Model to better than current 10-40% accuracy?

Does the Higgs behave as a pointlike (fundamental) particle?

Higgs potential not yet seen



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

Is this "toy-model" potential Nature's choice?

H interaction not yet seen

H interaction seen

Higgs potential not yet seen

$V(\phi)$

Some answers will come with more data

LHC has delivered only 5% of its collisions

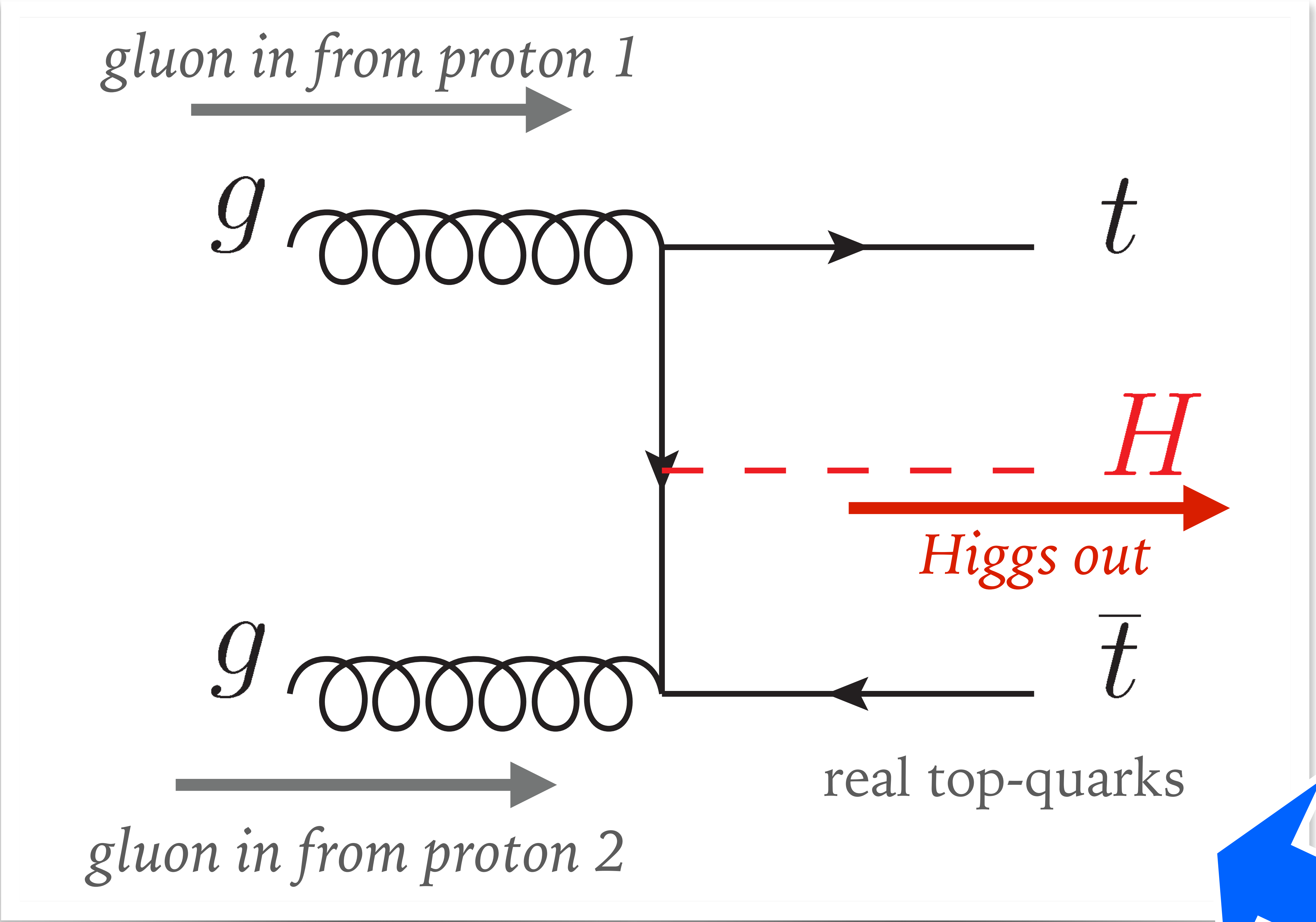
Future colliders could produce ~ 200x more Higgses than the LHC

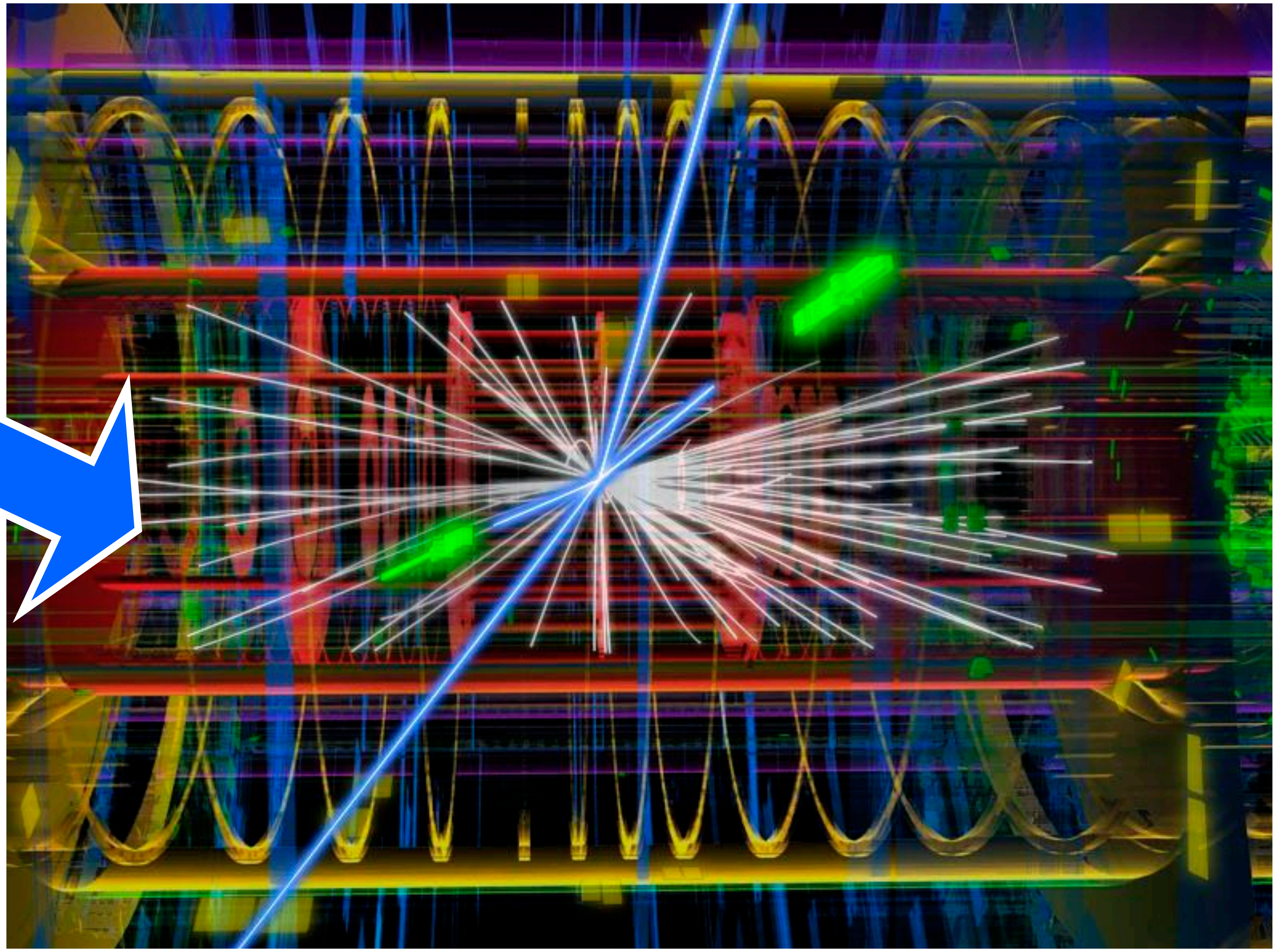
But nothing will be learnt without QCD . . .

Are Yukawa interactions responsible for all fermion masses?

Do these interactions follow the Standard Model to better than current 10-40% accuracy?

Does the Higgs behave as a pointlike (fundamental) particle?

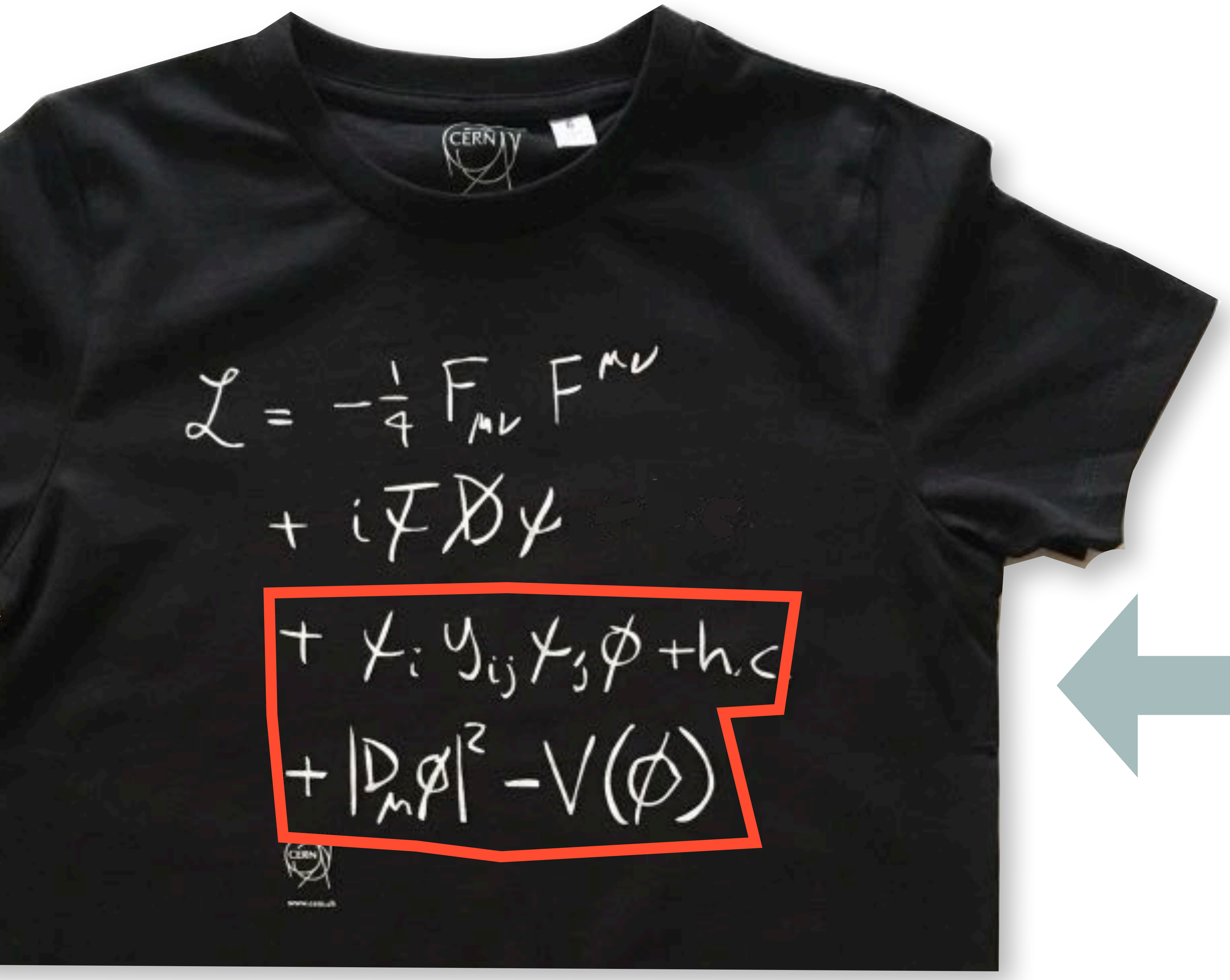




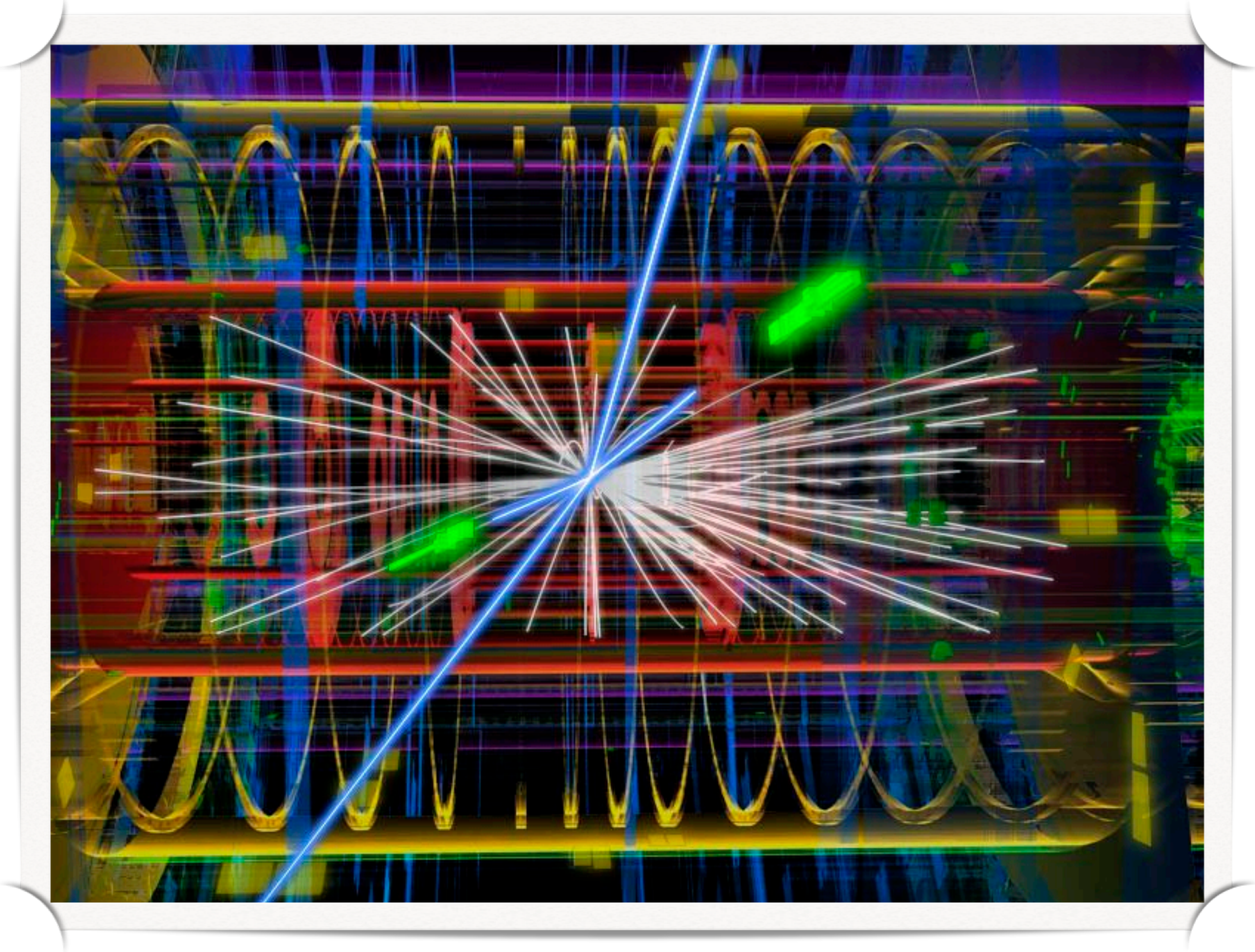
how can one claim a connection,
let alone a quantitative one?

UNDERLYING THEORY

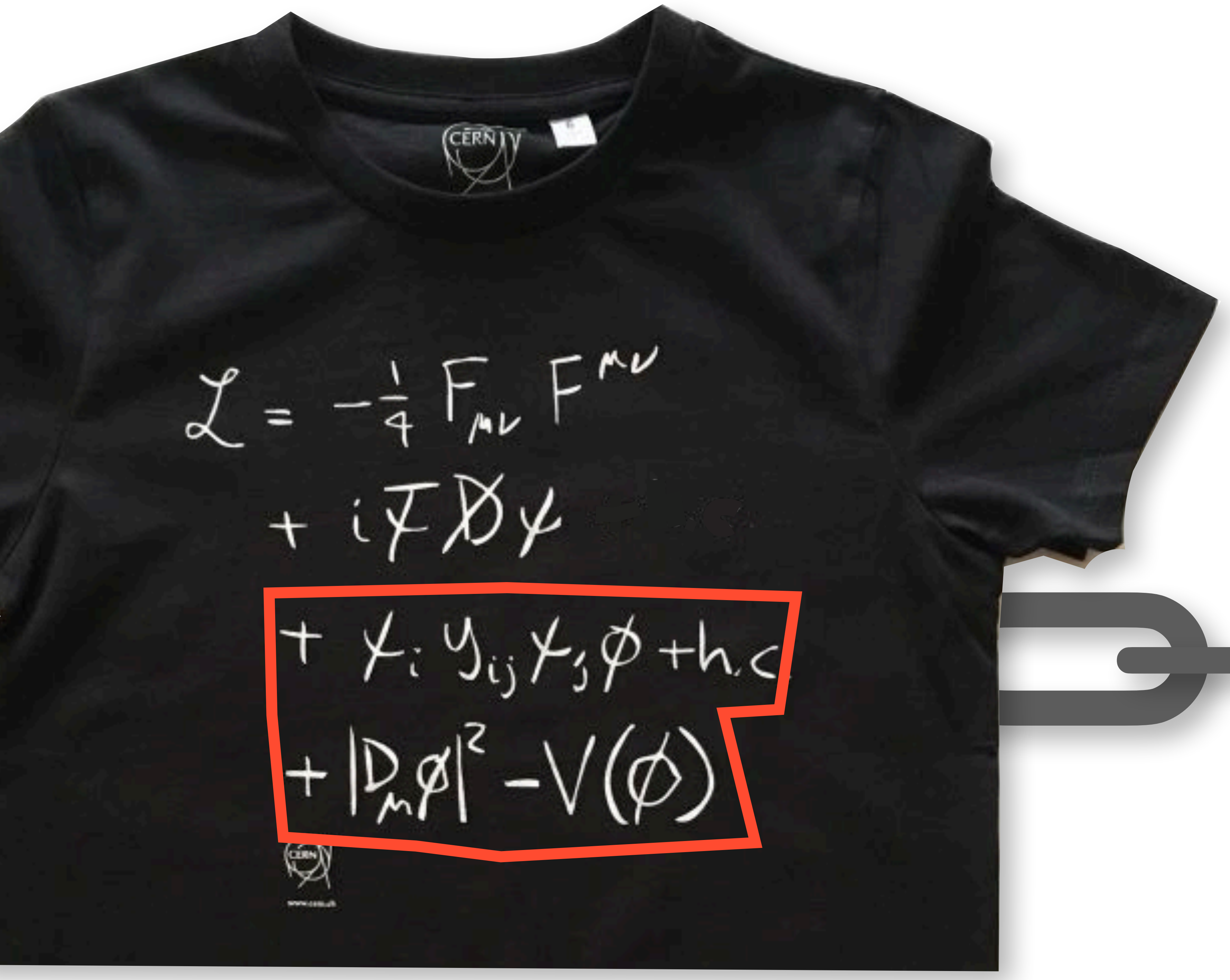
EXPERIMENTAL DATA



how do you make quantitative connection?

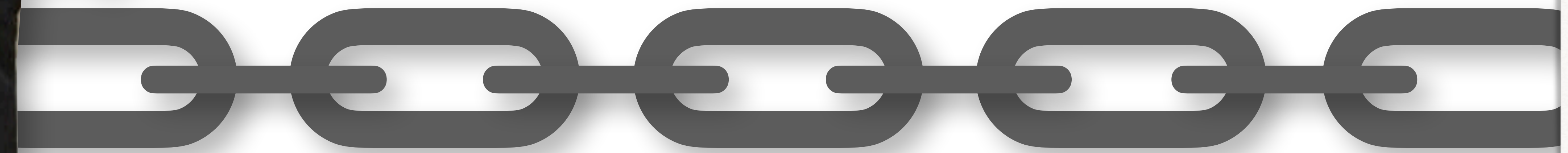


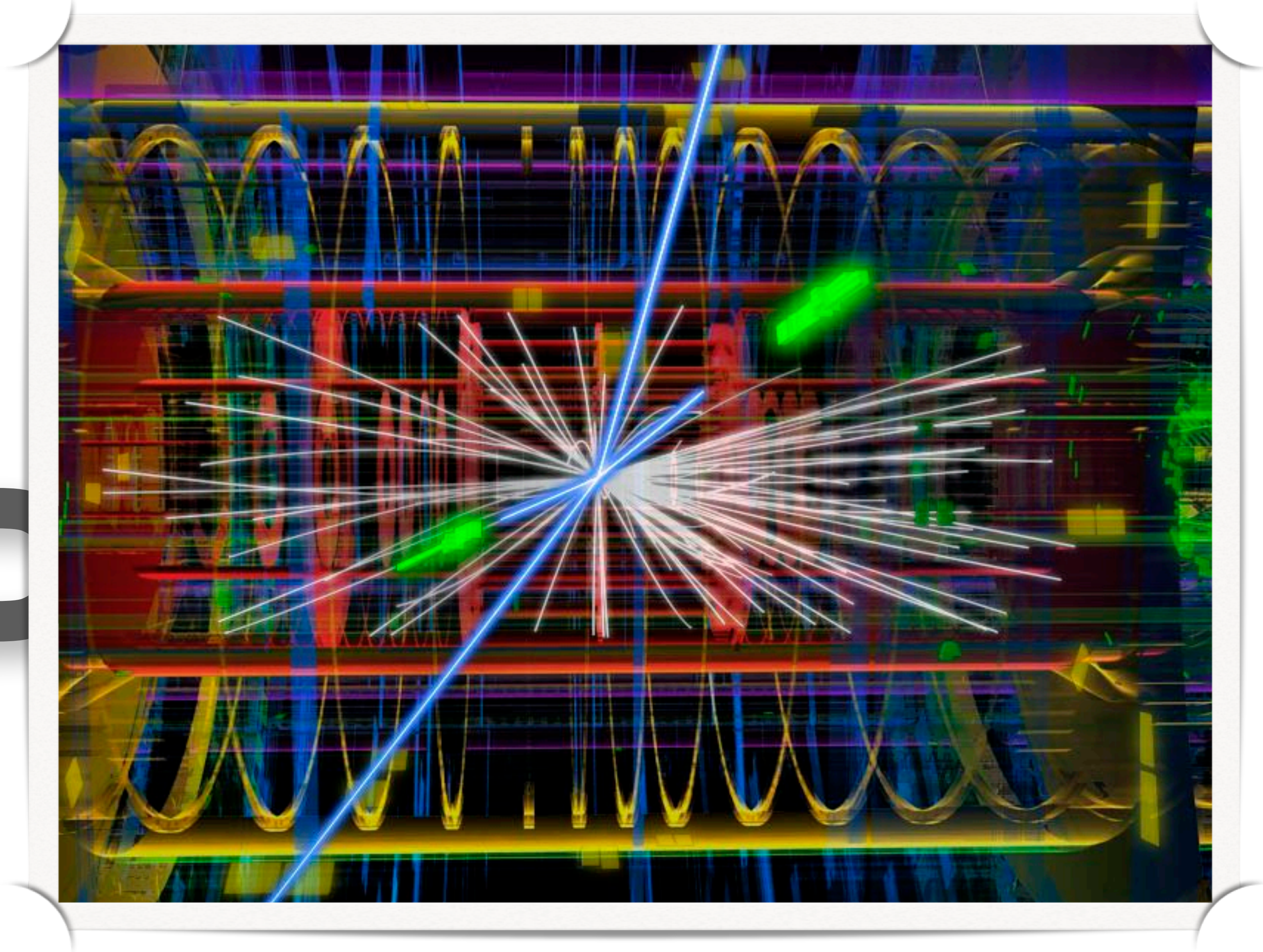
UNDERLYING THEORY



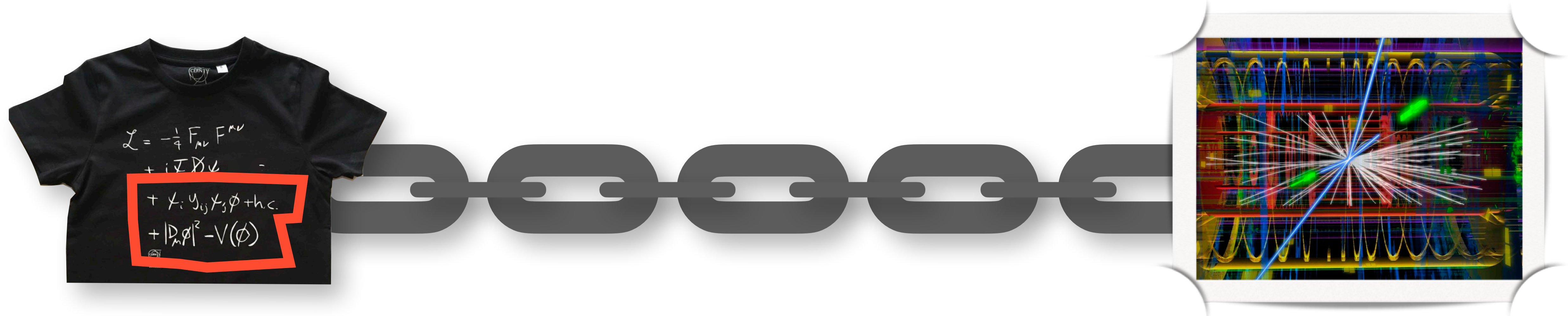
EXPERIMENTAL DATA

how do you make quantitative connection?





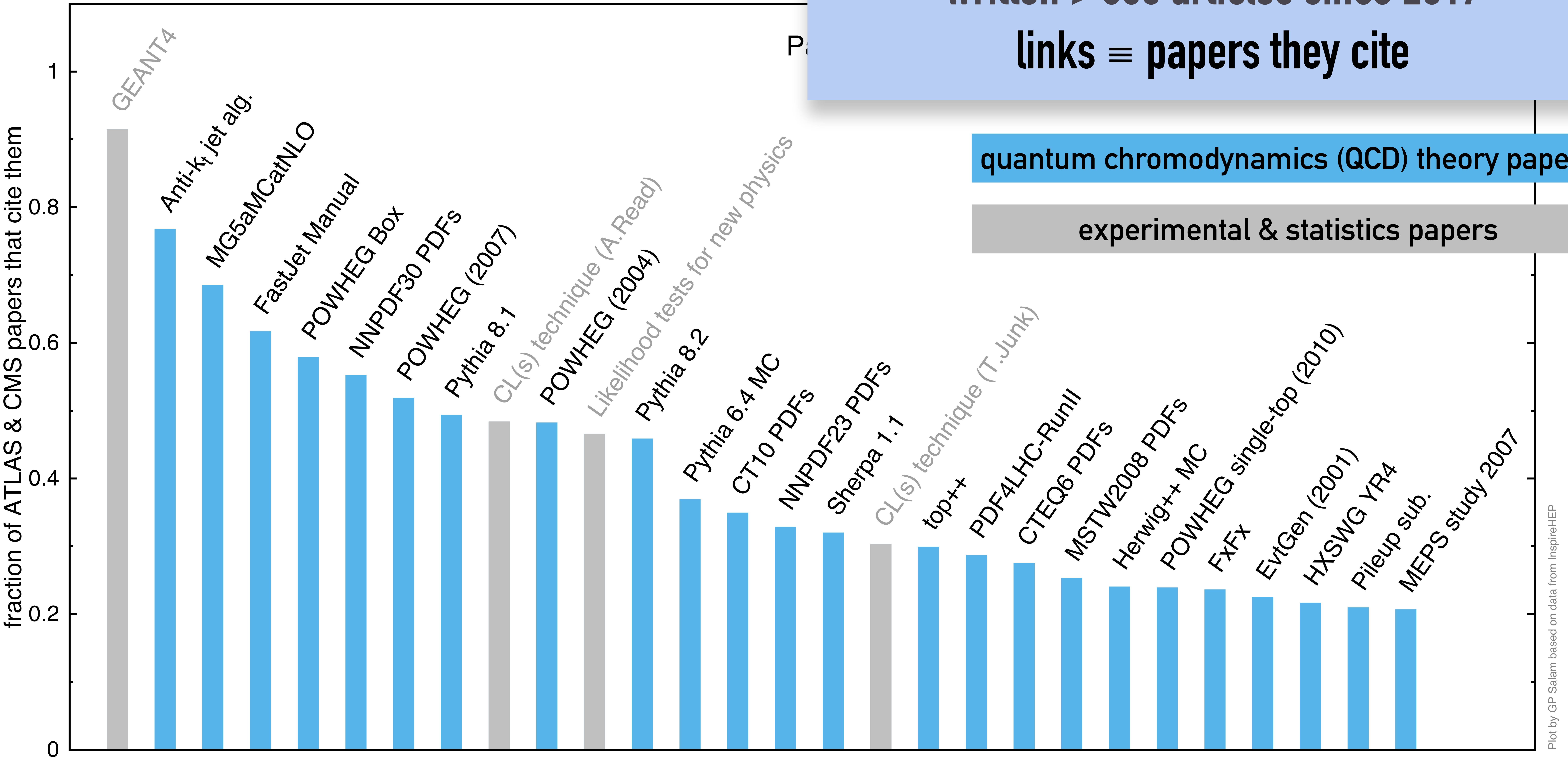
through a chain of experimental and theoretical links



What are the links?

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

links ≡ papers they cite



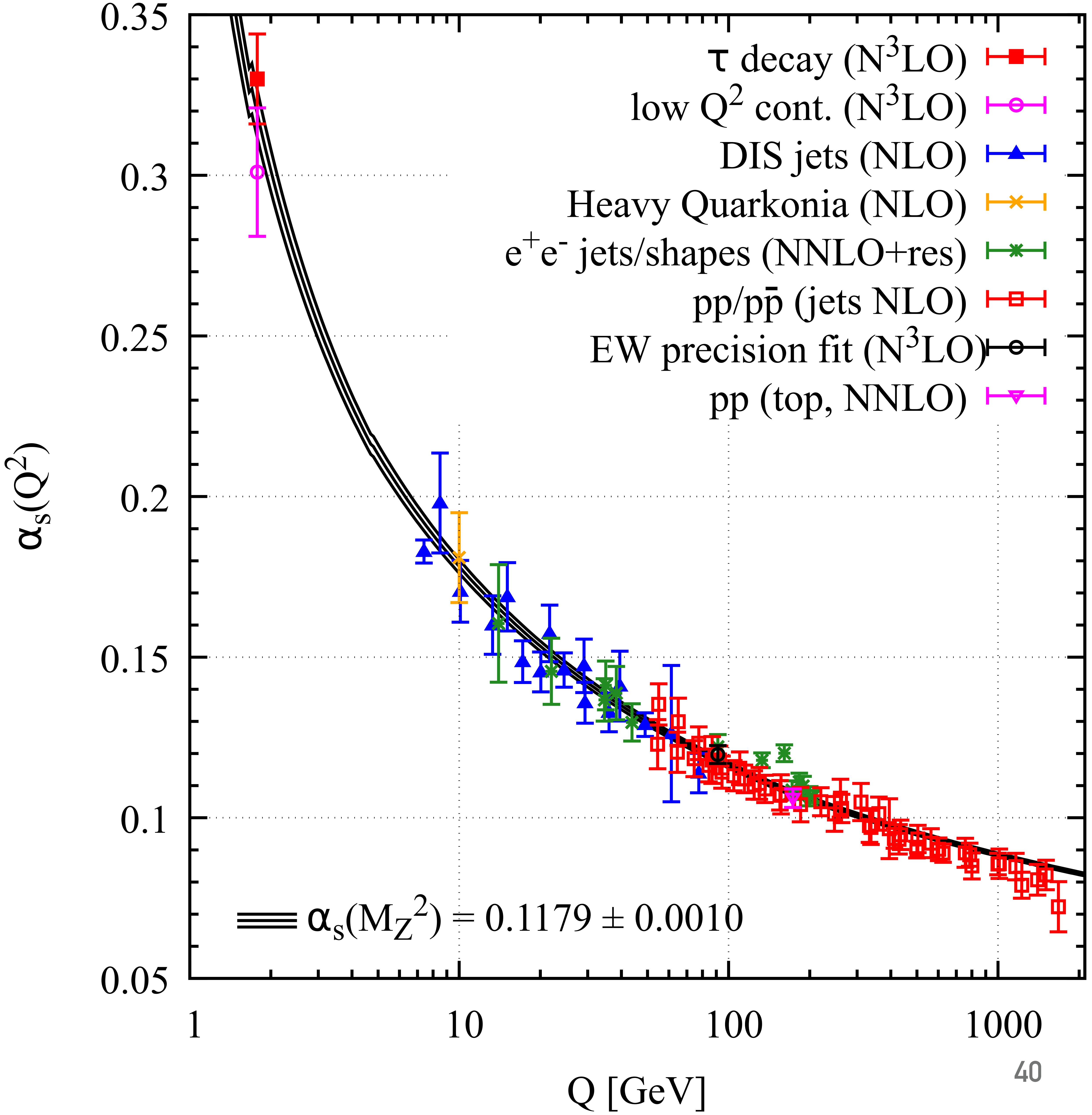
QCD

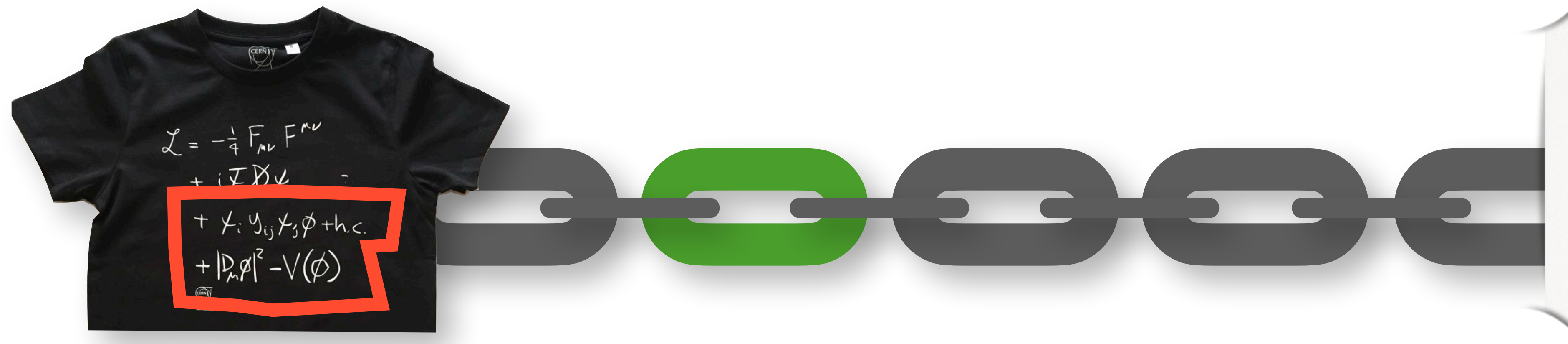
quantum chromodynamics
the theory of the strong interaction

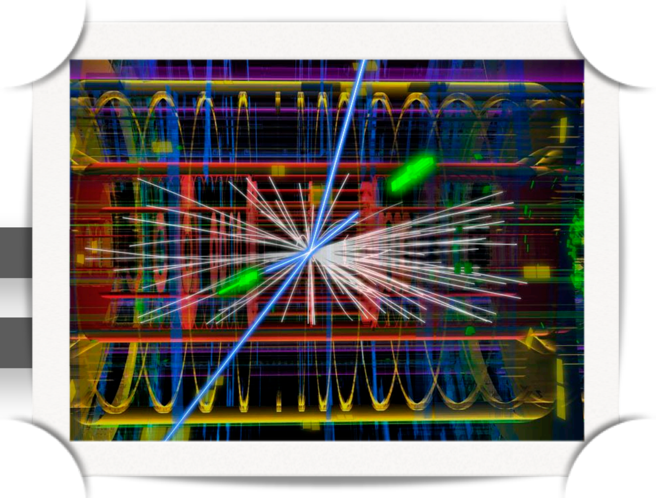
Like QED, with key differences

- Charge comes in three variants (red, green, blue)
- Force carrier (gluon), is charged
- Coupling is larger (and non-perturbative at small momenta)

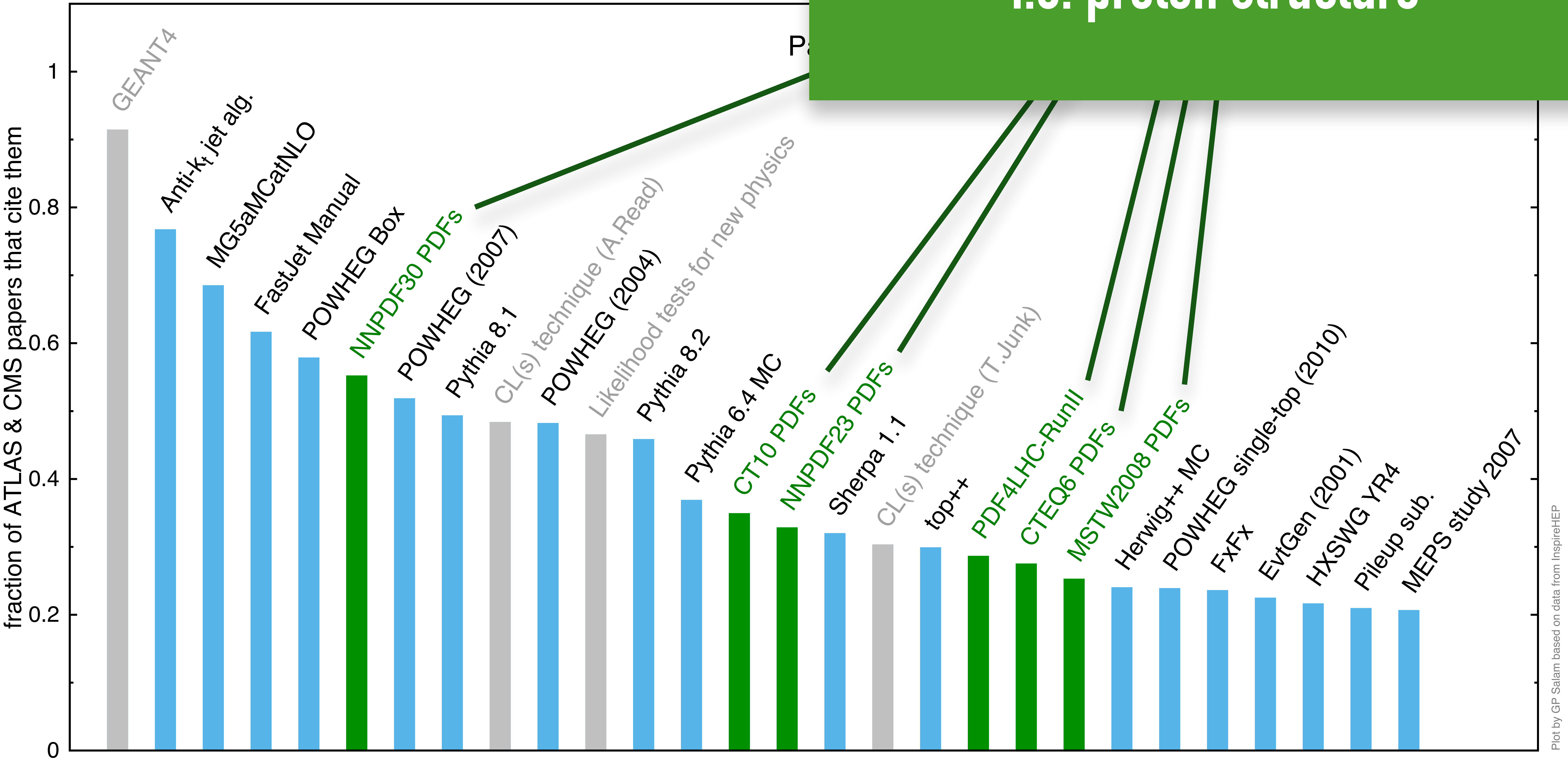
strong coupling v. momentum scale

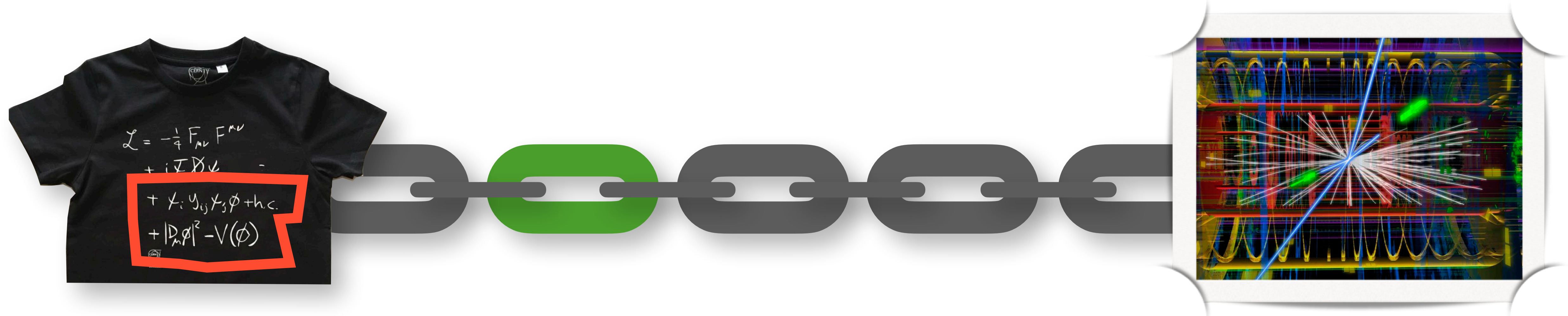




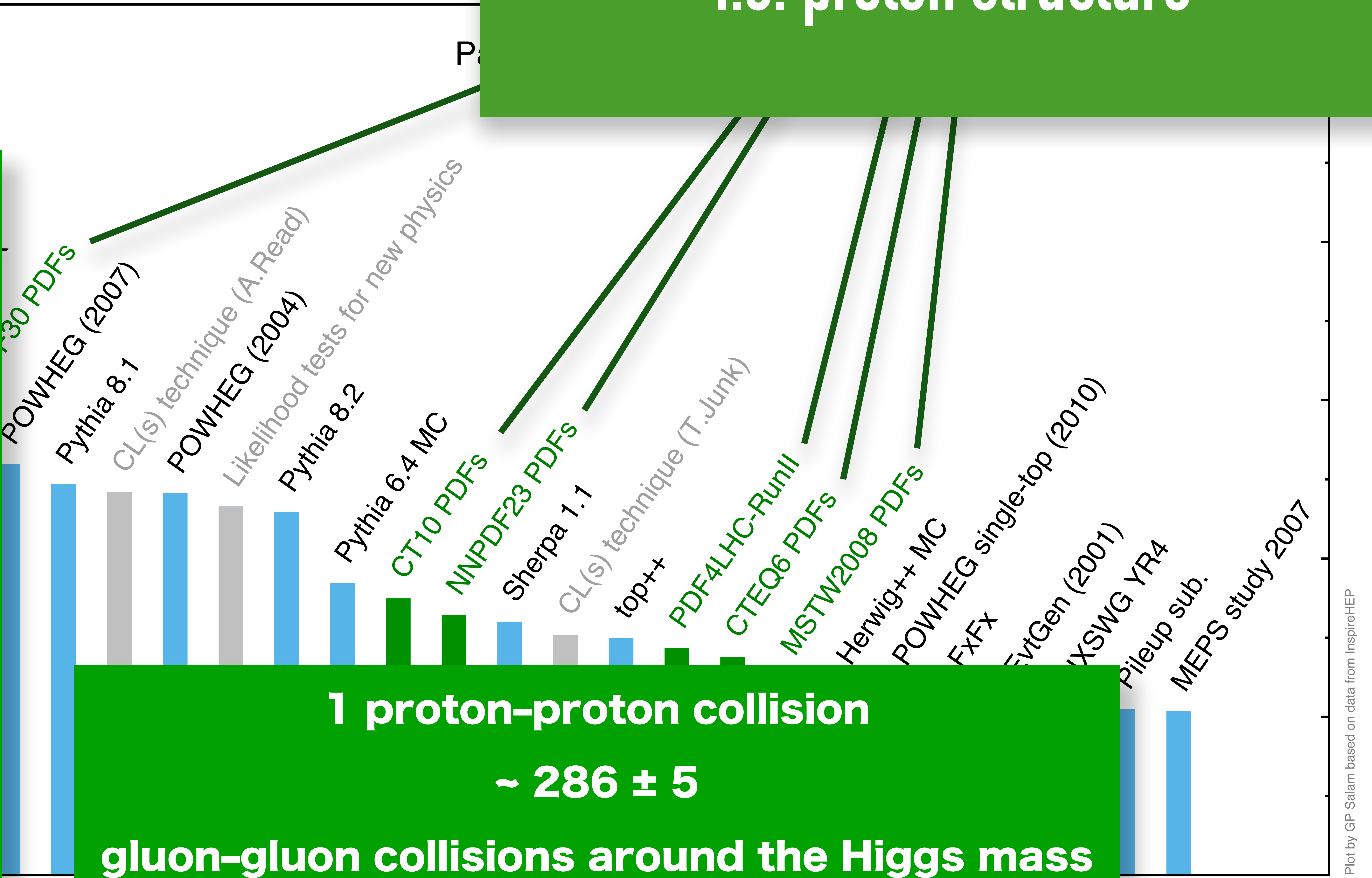


knowing what goes into a collision
i.e. proton structure

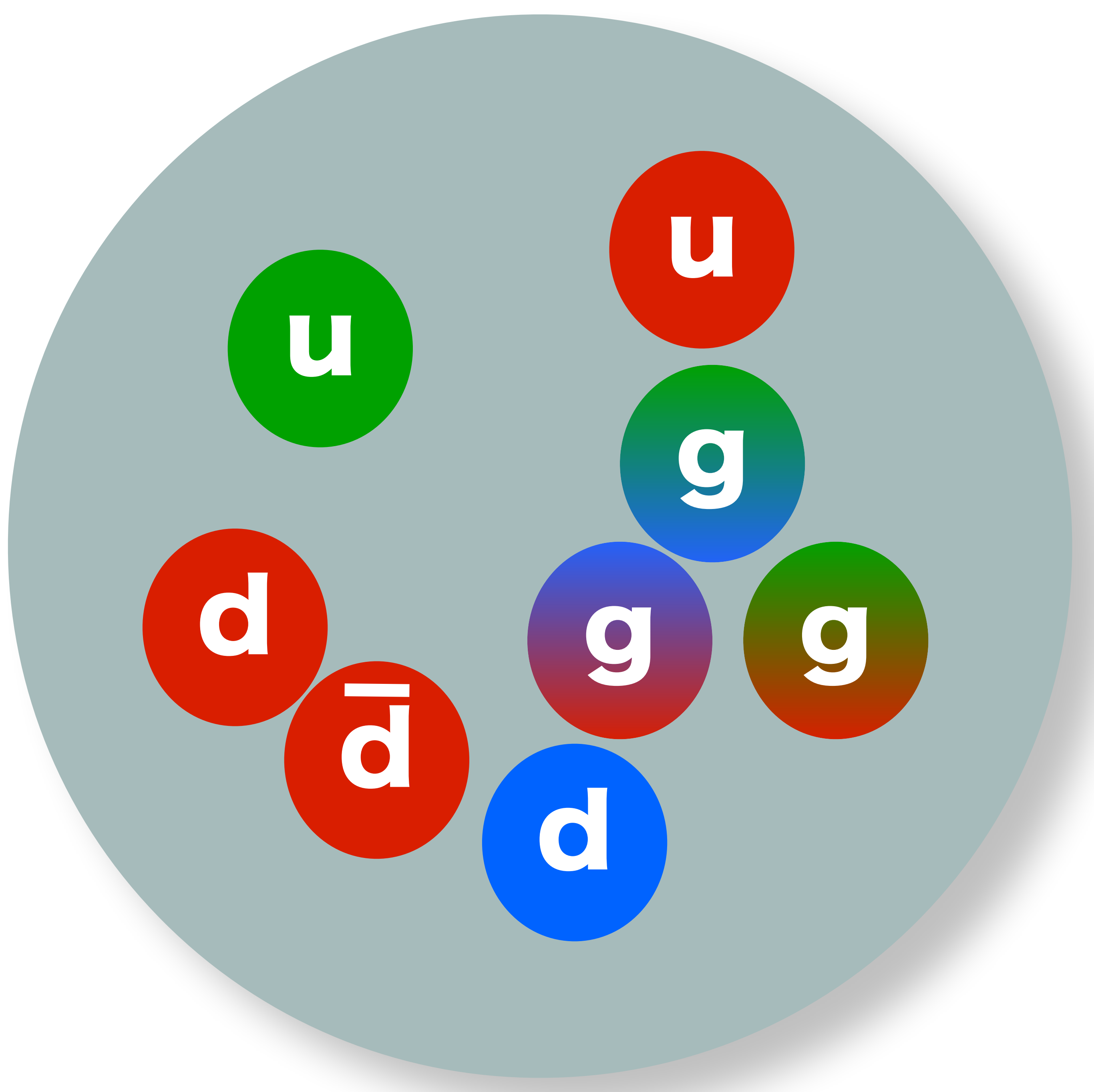




knowing what goes into a collision i.e. proton structure



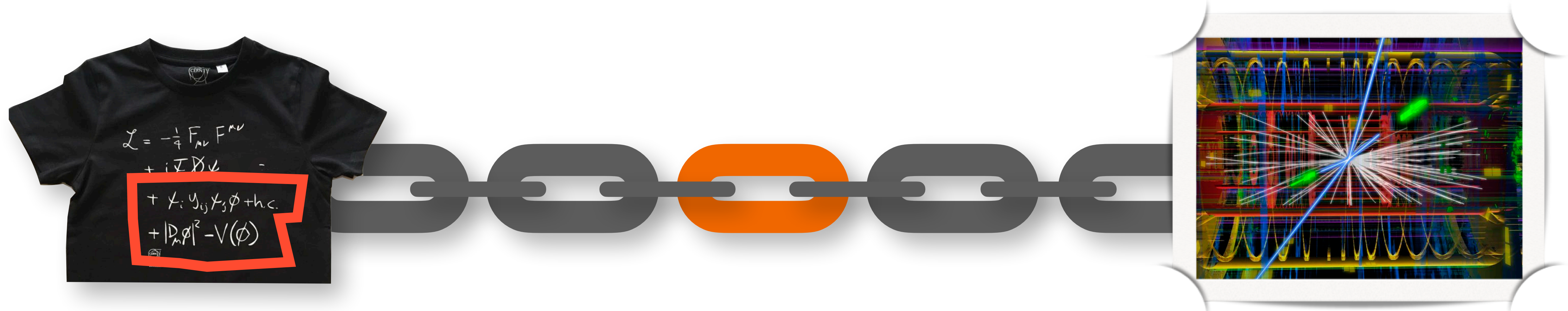
PROTON



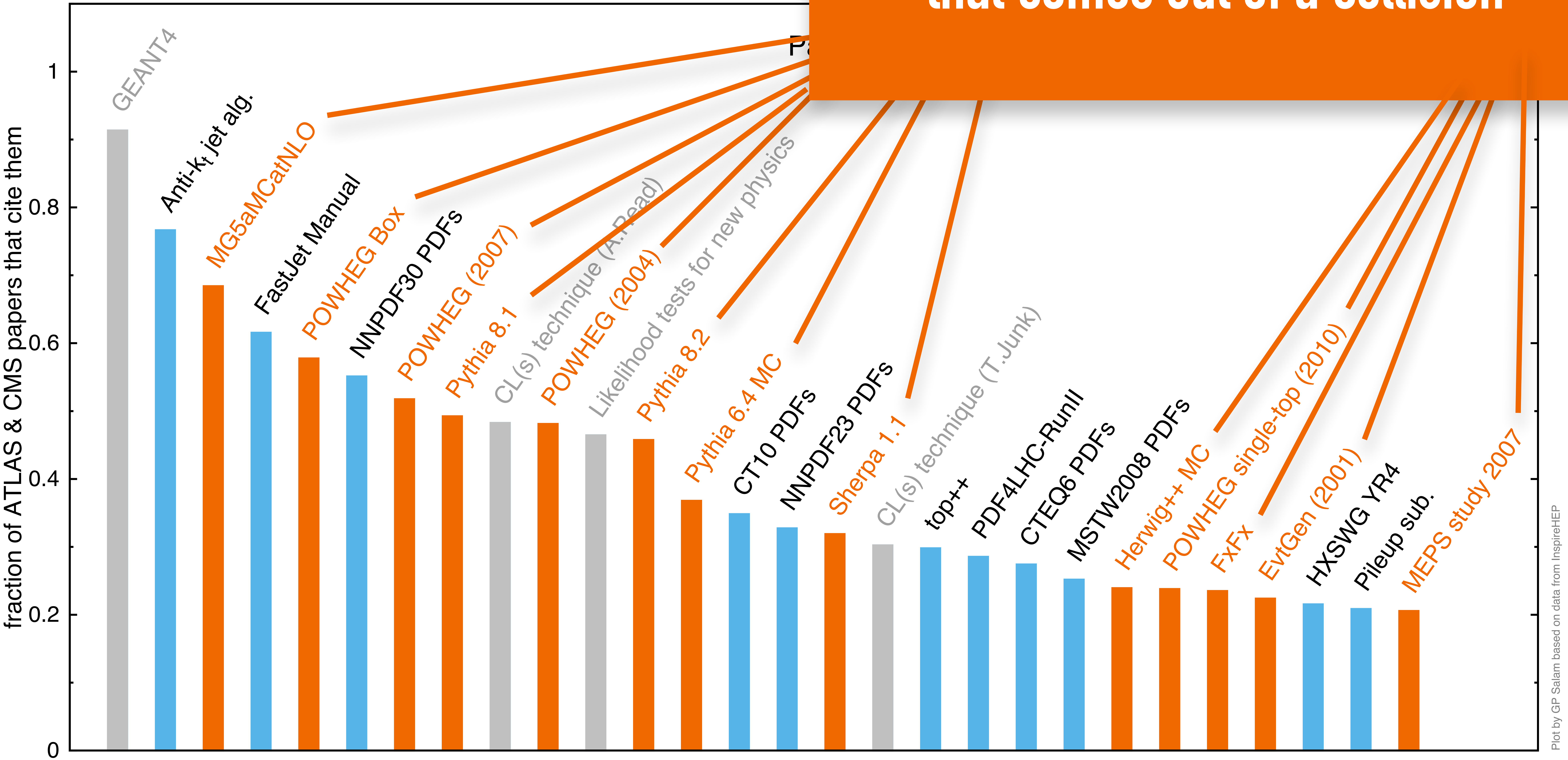
1 proton-proton collision

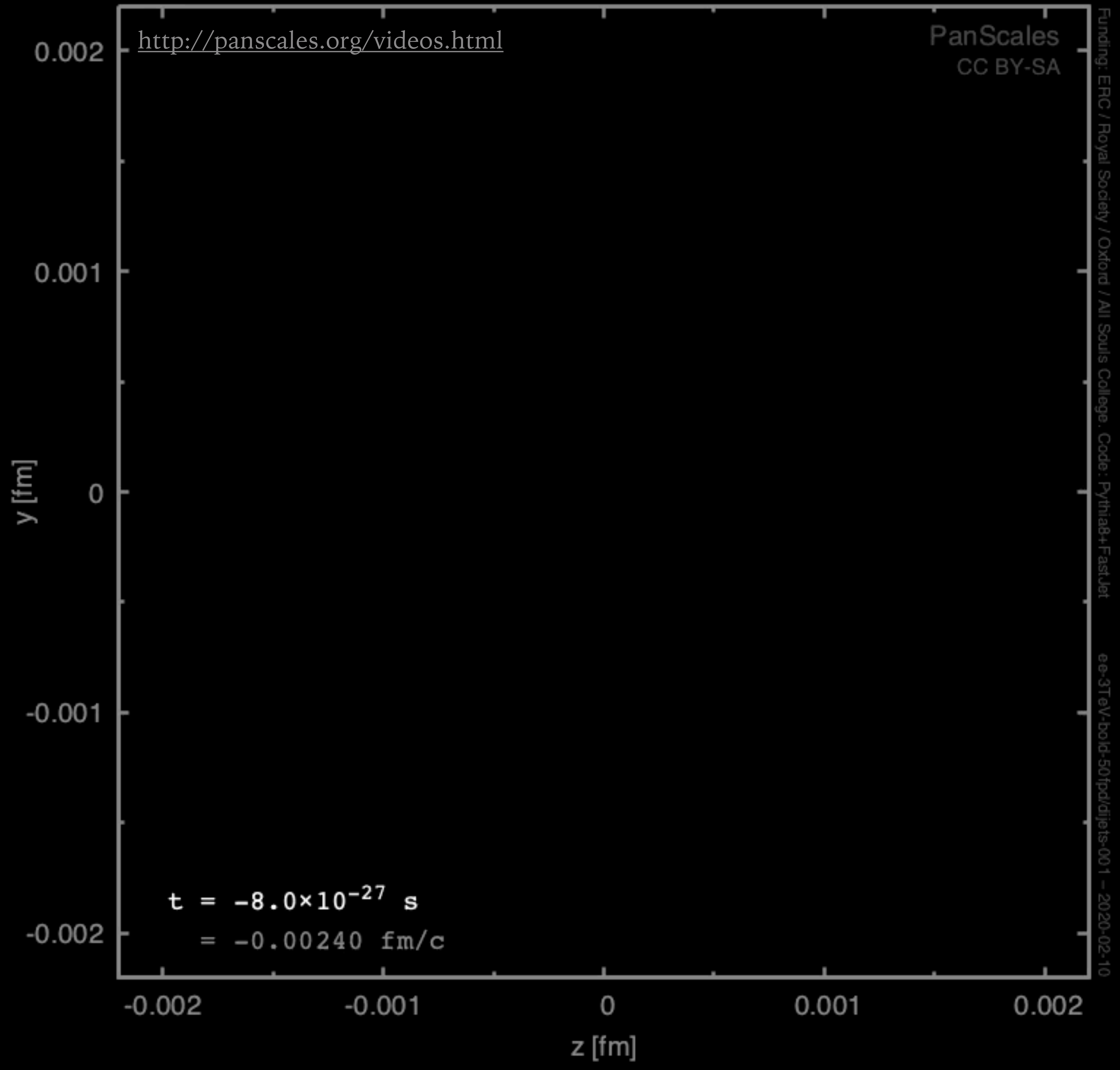
~ 286 ± 5

gluon-gluon collisions around the Higgs mass



predicting full particle structure that comes out of a collision



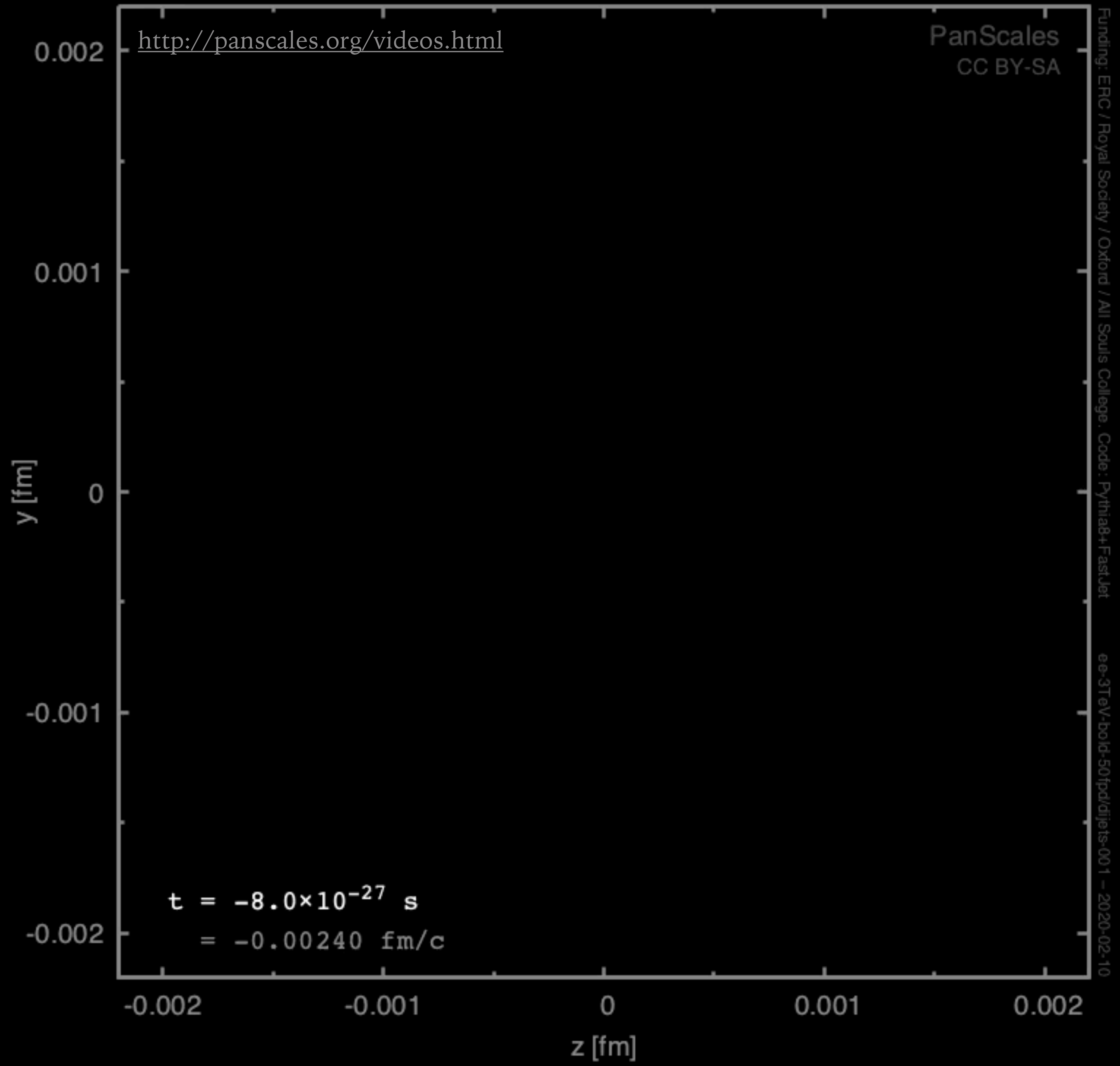


incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time



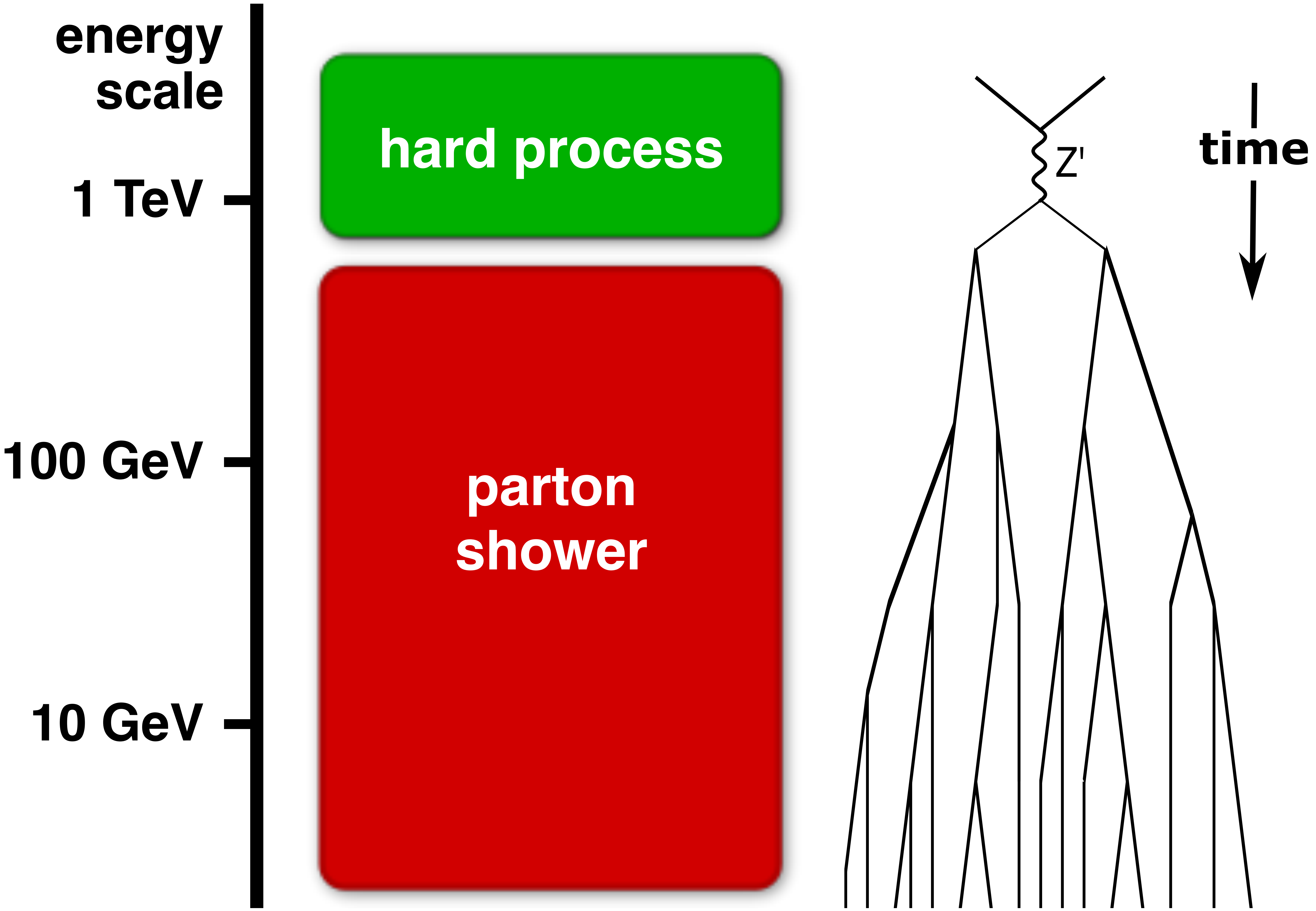
incoming beam particle

intermediate particle (quark or gluon)

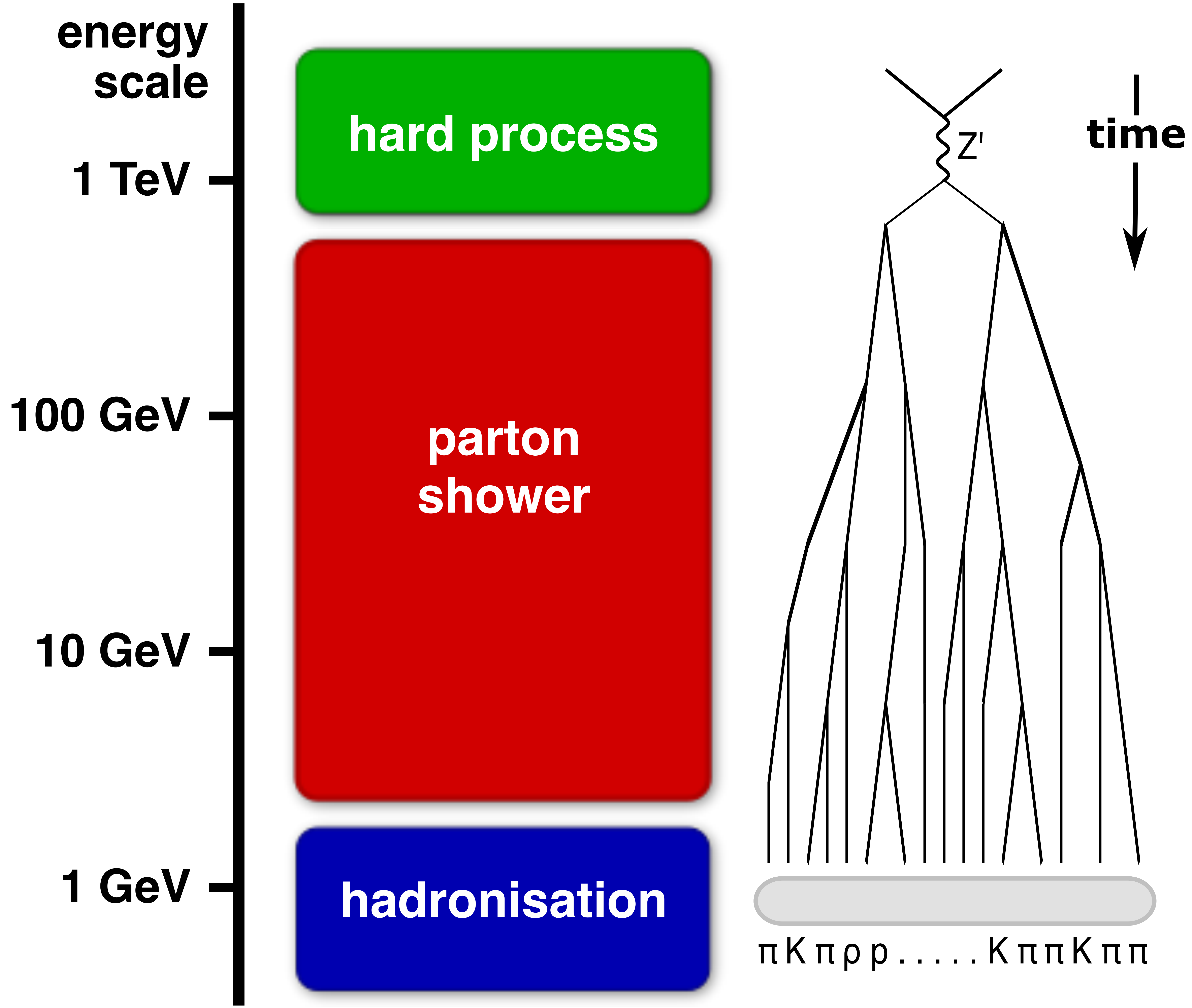
final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time

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

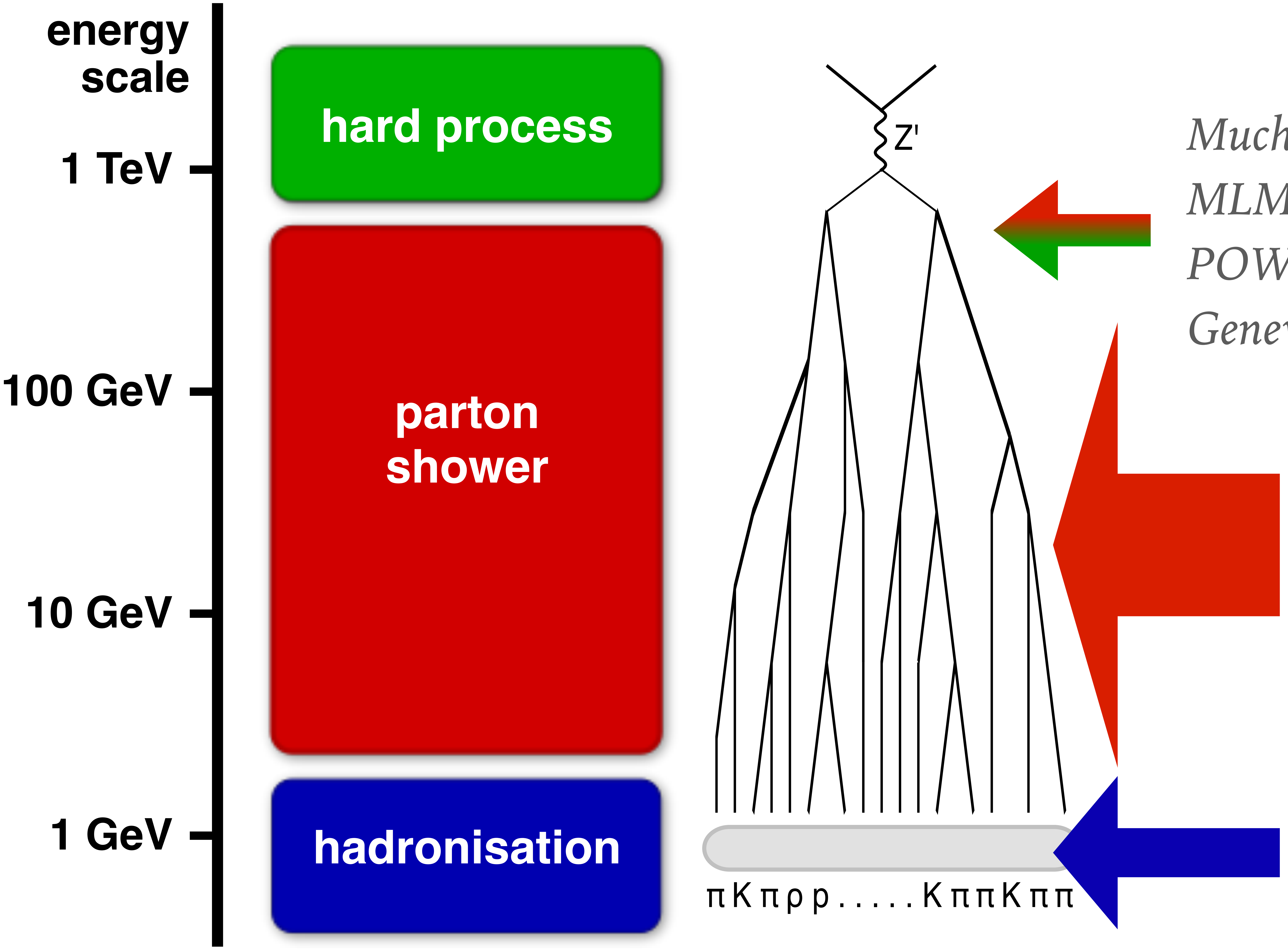


schematic view of key components of QCD predictions and Monte Carlo event simulation



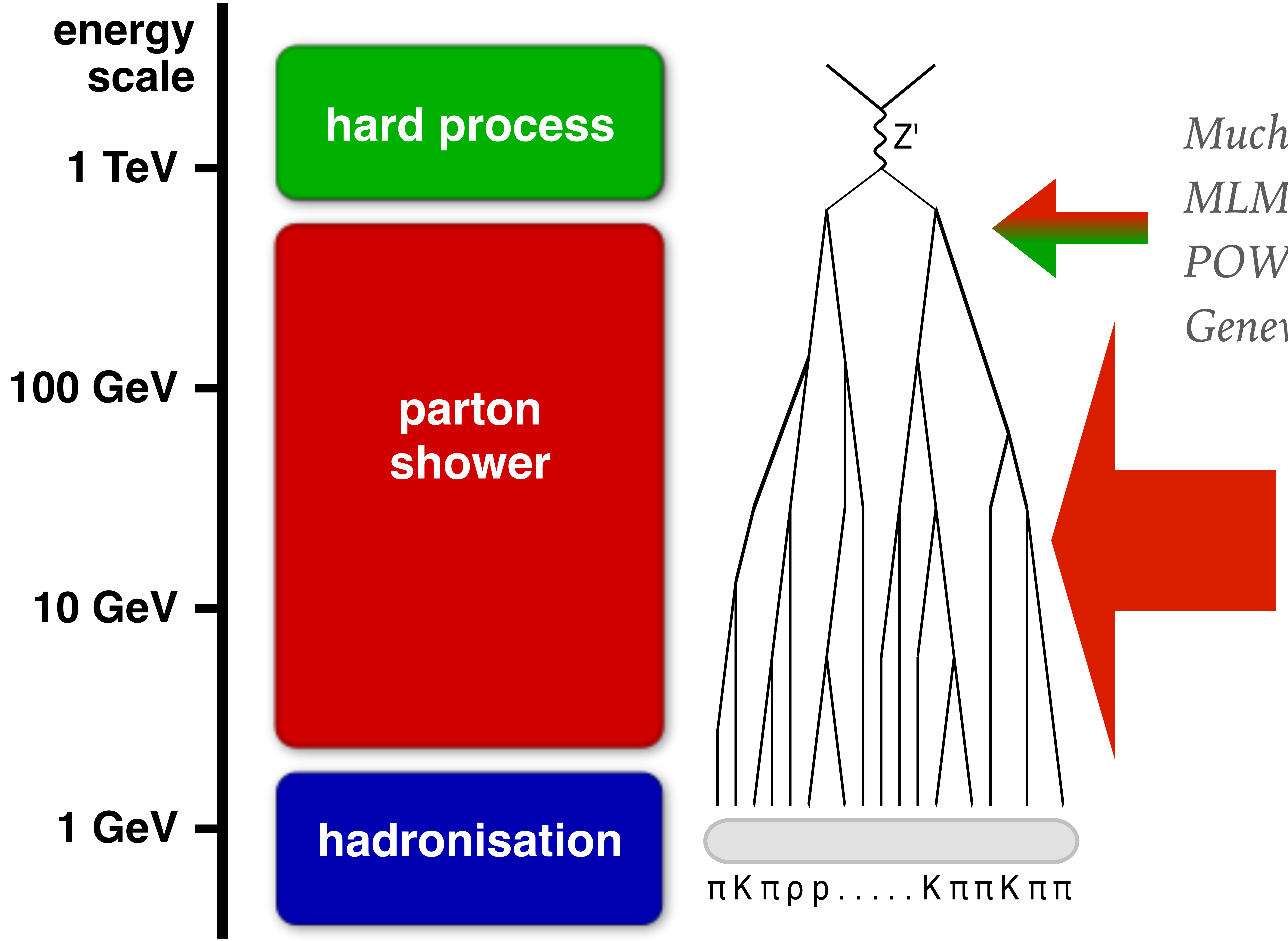
schematic view of key components of QCD predictions and Monte Carlo event simulation

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



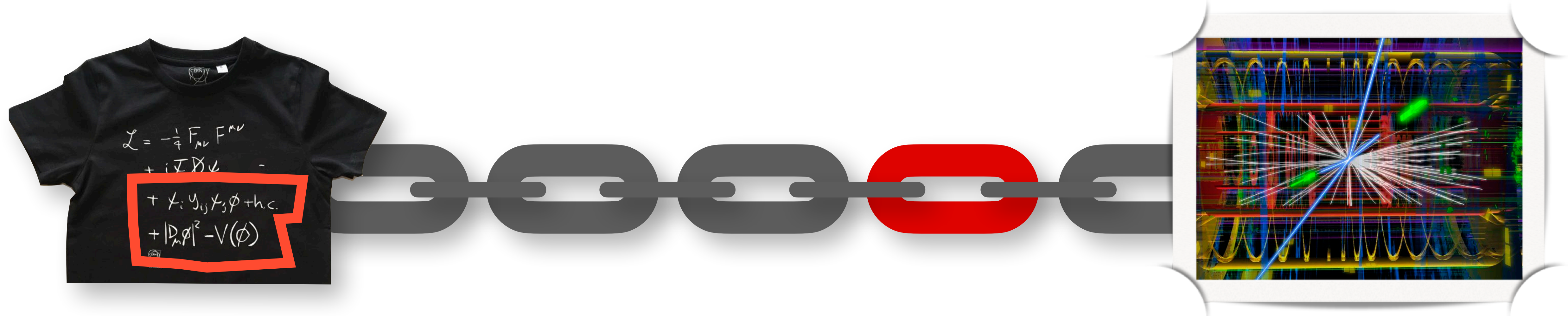
Much of past 20 years' work: MLM, CKKW, MC@NLO, POWHEG, MIN(N)LO, FxFx, Geneva, UNNLOPS, Vincia, etc.

Largely based on principles from 20-30 years ago



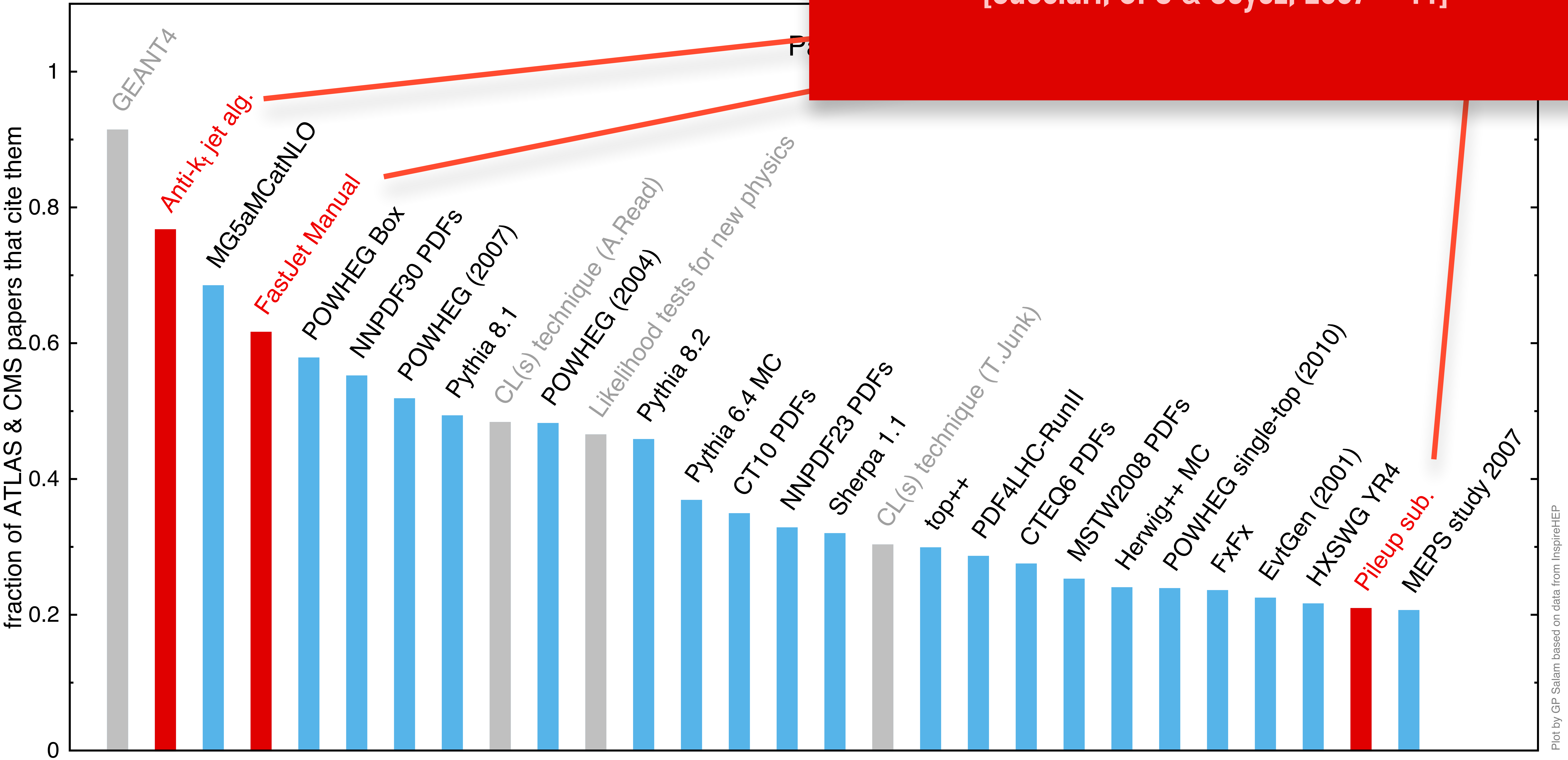
Much of past 20 years' work: MLM, CKKW, MC@NLO, POWHEG, MINLO, FxFx, Geneva, UNNLOPS, Vincia, etc.

We'll return to this part at the end



organising event information (“jets”)

[Cacciari, GPS & Soyez, 2007 – 11]




CMS Experiment at the LHC, CERN
Simulated event at 13 TeV centre-of-mass energy

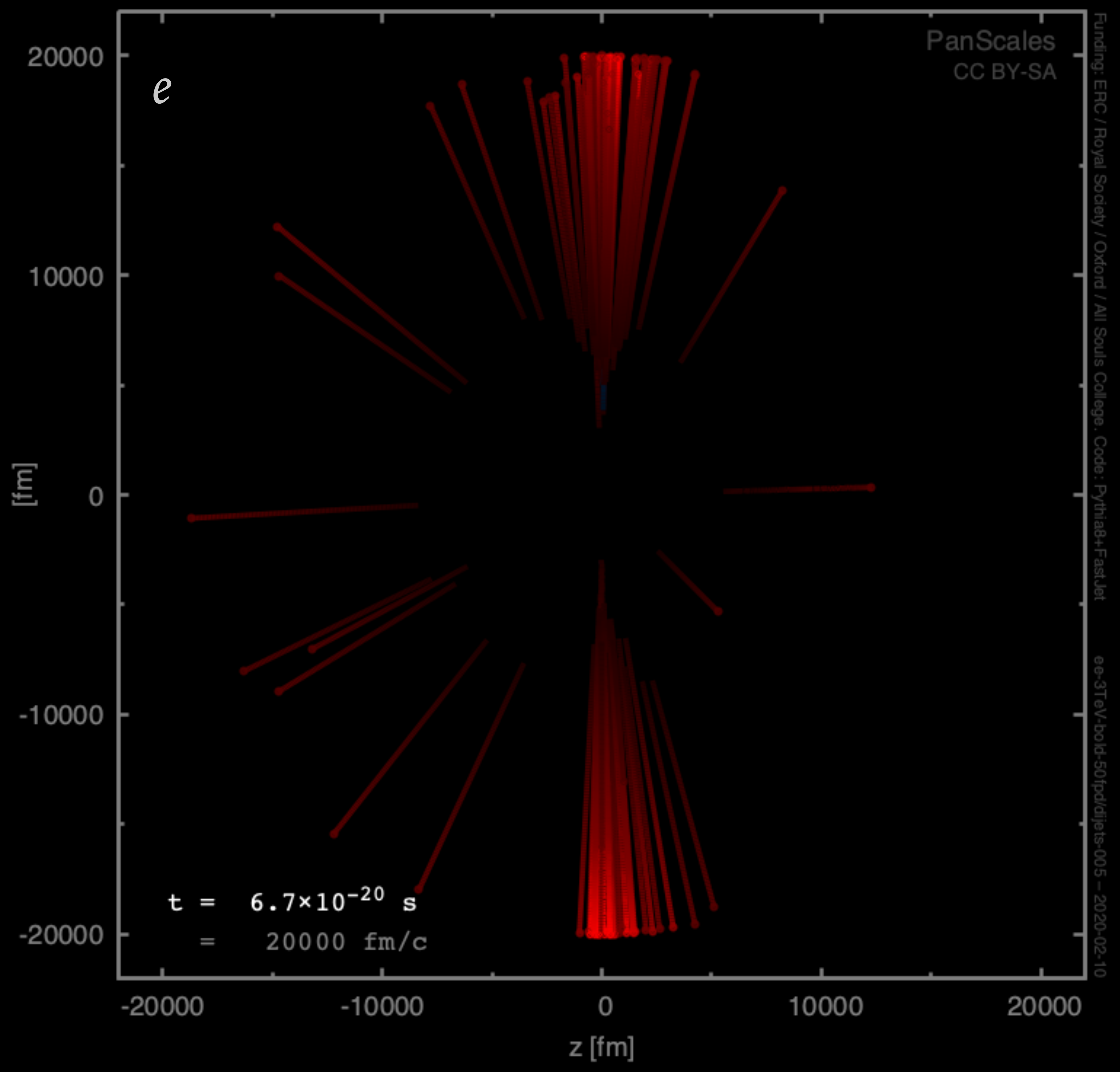

CMS
CMS Experiment at the LHC, CERN
Simulated event at 13 TeV centre-of-mass energy
Y

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

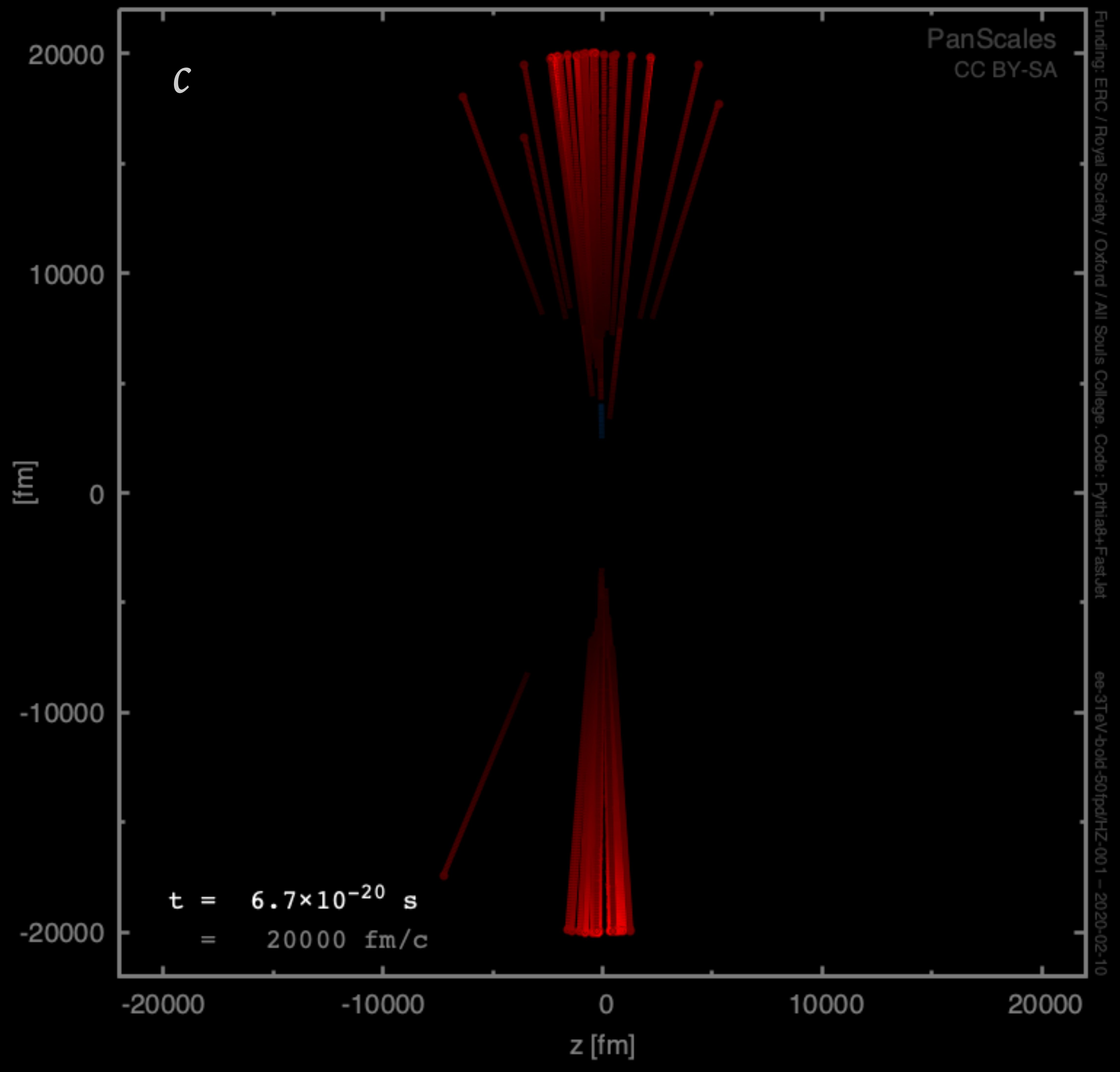
(jet) substructure

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

pure QCD event

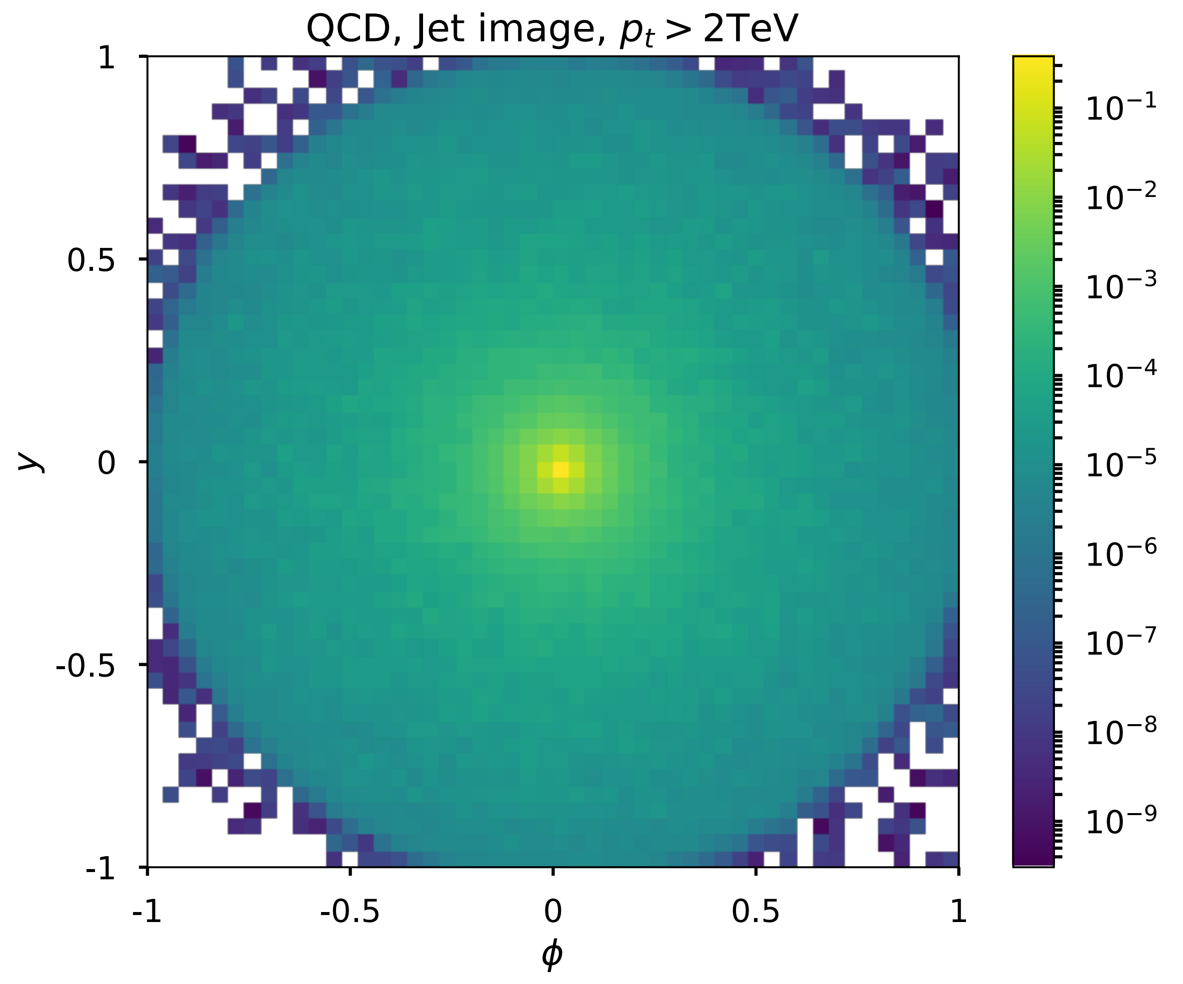


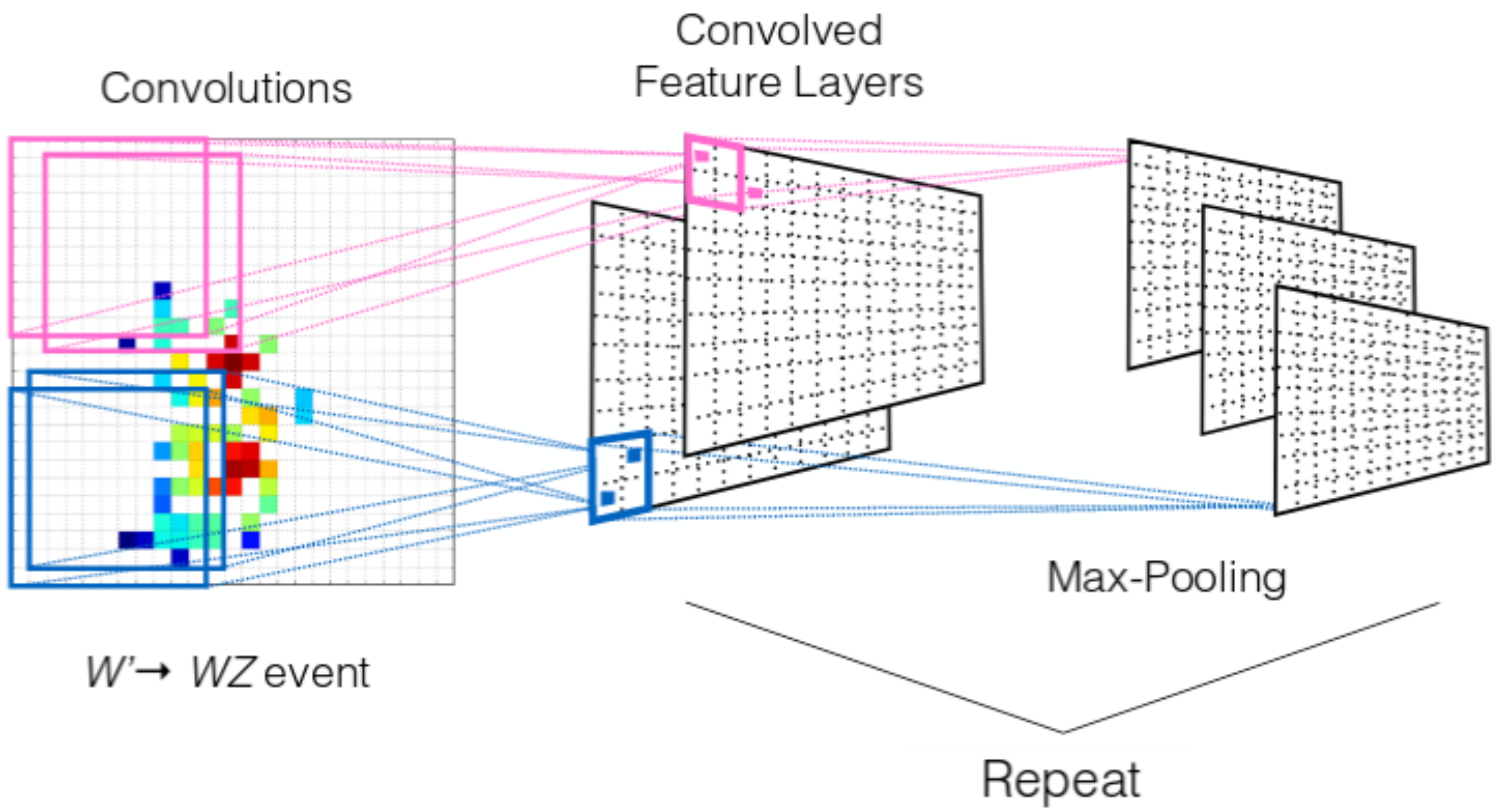
event with Higgs & Z boson decays

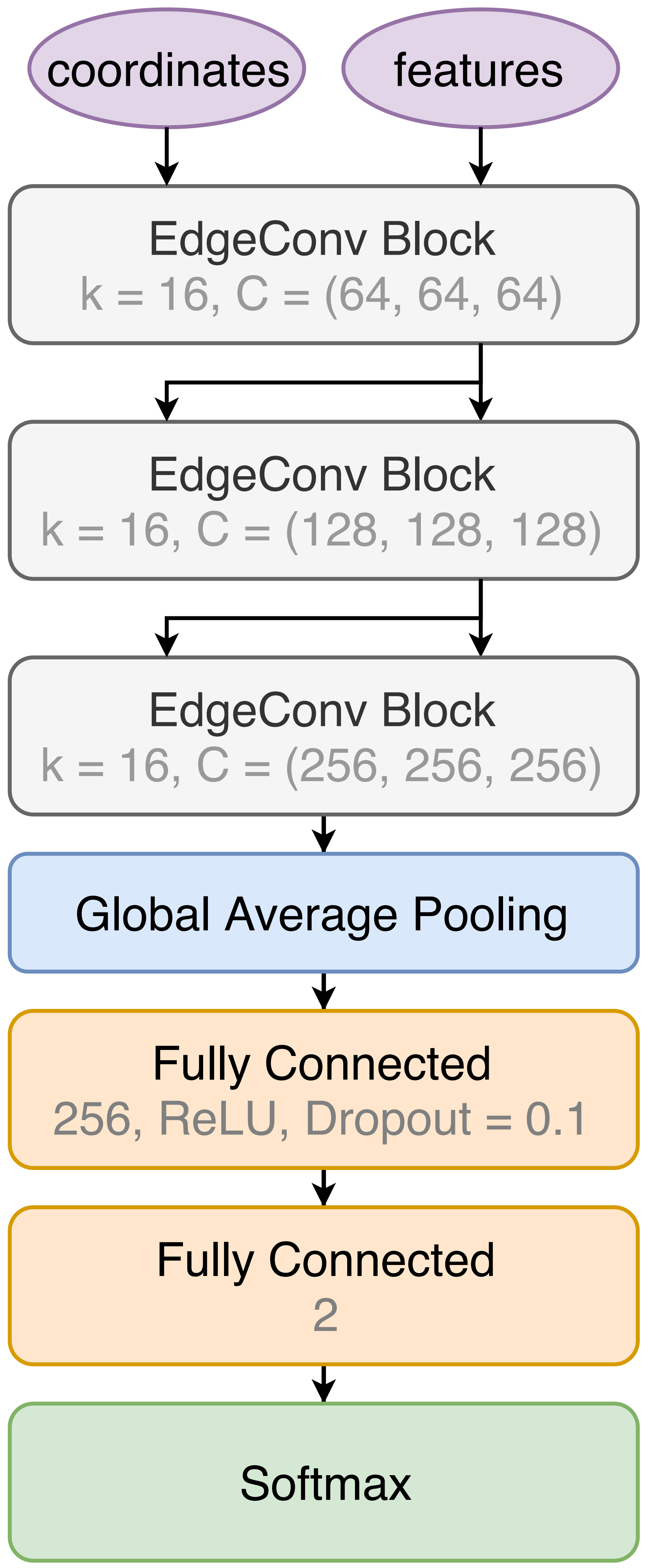


Machine learning and jet/event structure

- 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.







(a) ParticleNet

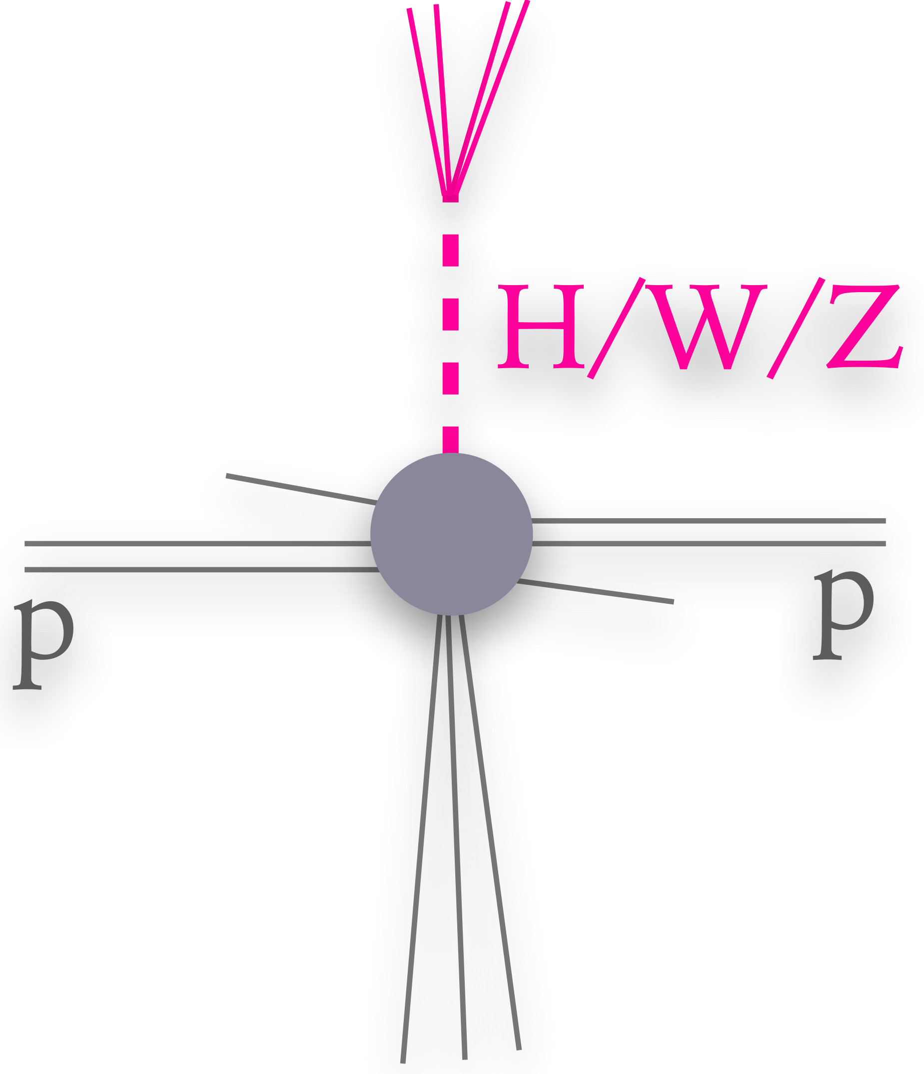
[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

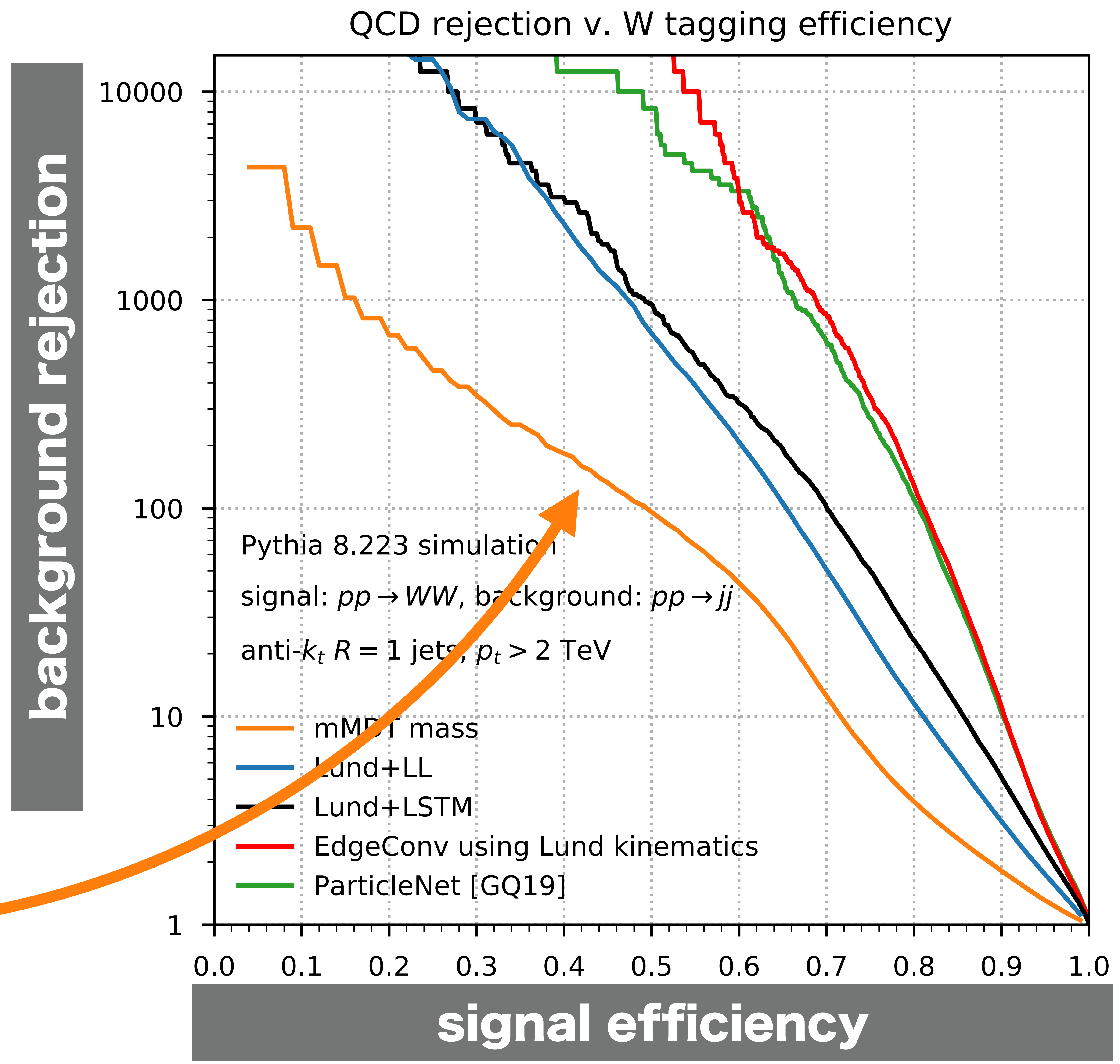
[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

2021 Young Experimental Physicist Prize EPS HEPP prize

Qu & Guskos, arXiv:1902.08570

using full jet/event information for H/W/Z-boson tagging



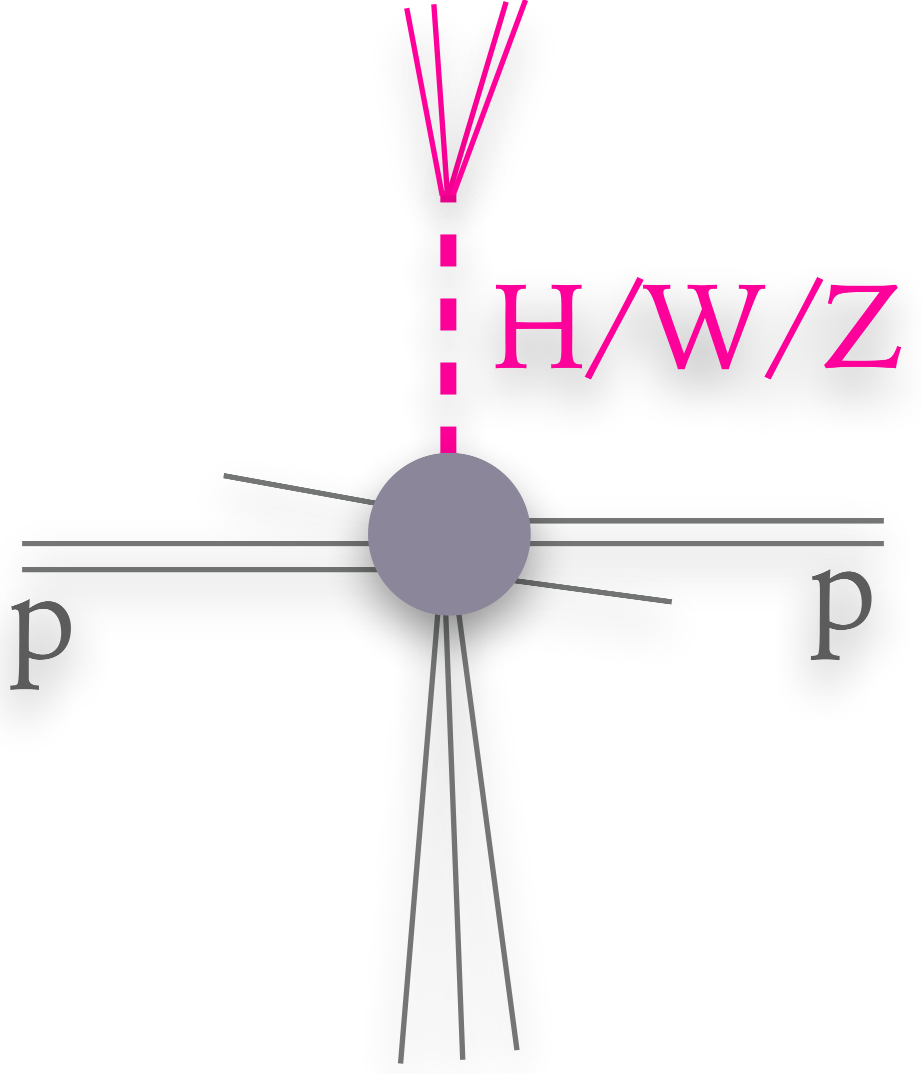


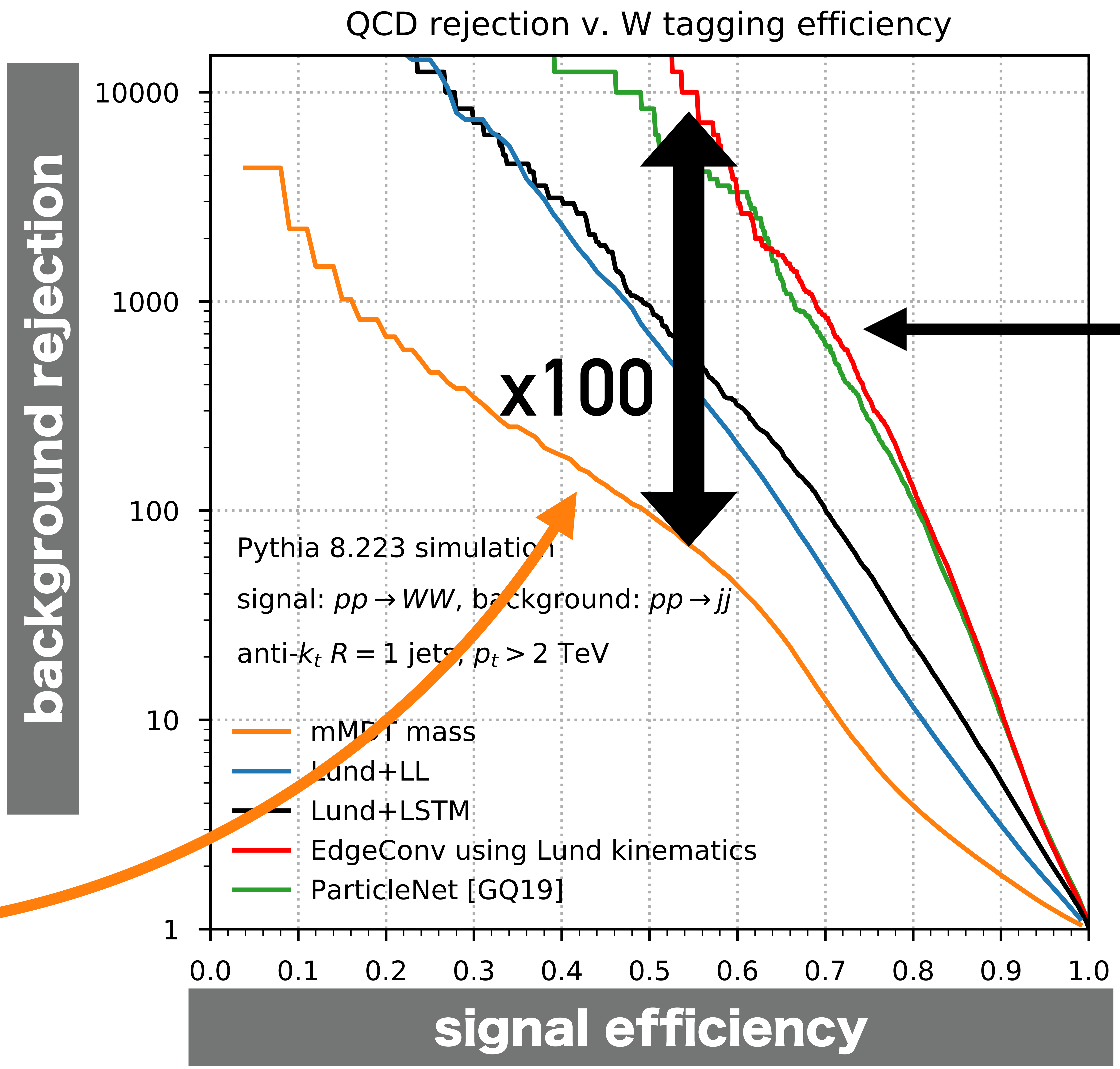
QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

adapted from Dreyer & Qu 2012.08526

incl. techniques from Dreyer, GPS & Soyez, 1807.04758 +Qu & Guskos, 1902.08570

using full jet/event information for H/W/Z-boson tagging





QCD rejection with use of full jet substructure (2021 tools)

100x better

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

adapted from Dreyer & Qu 2012.08526

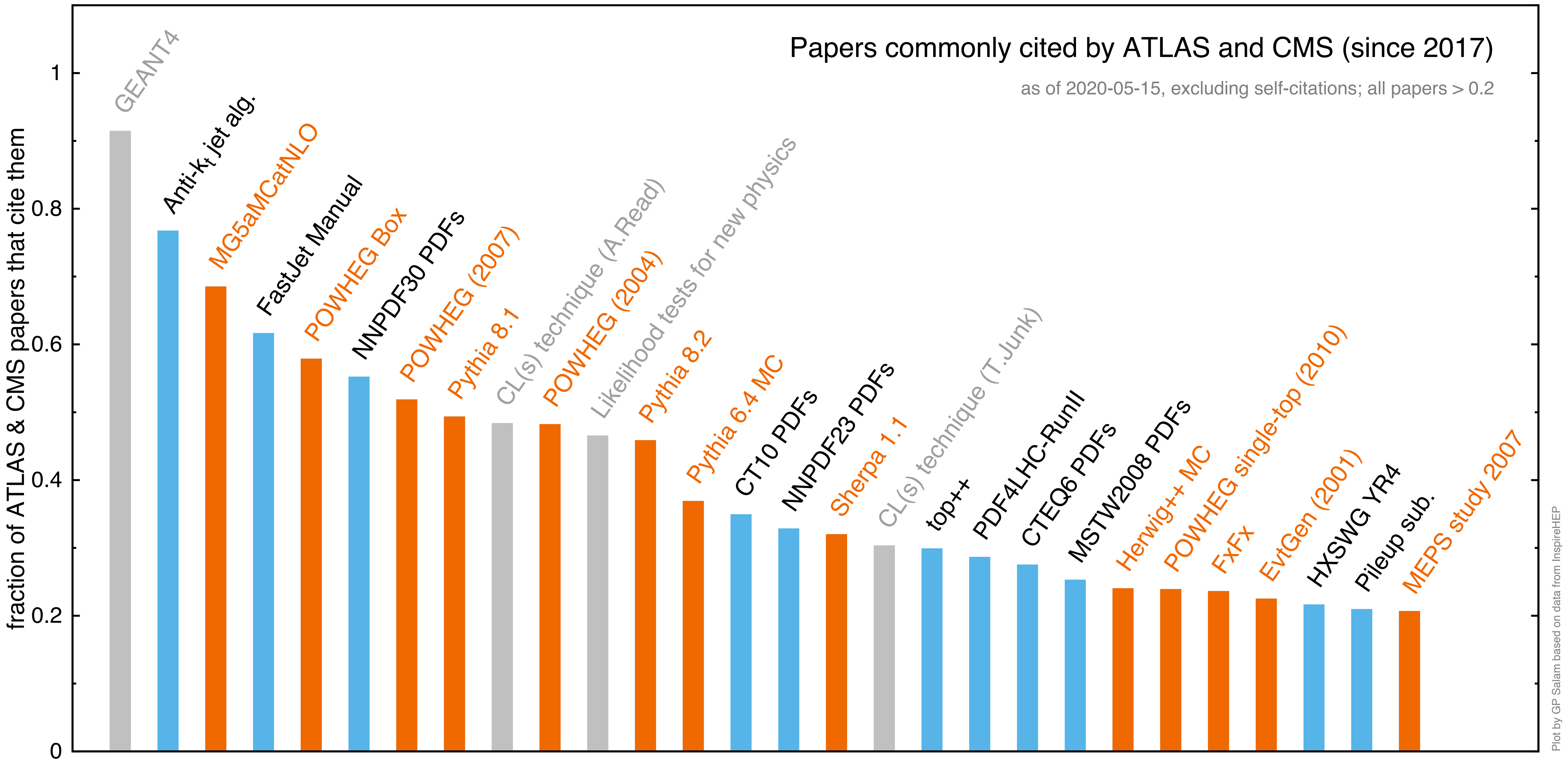
incl. techniques from Dreyer, GPS & Soyez, 1807.04758 +Qu & Guskos, 1902.08570

All of this is impossible without simulations

Herwig 7

Pythia 8

Sherpa founded in Dresden (now F. Siegert)



used in ~95% of ATLAS/CMS publications

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

```
 |  *------------------------------------------------------------------------------*  |
 |  |                                                                              |  |
 |  |                                                                              |  |
 |  |   PPP   Y   Y  TTTTT  H   H  III    A      Welcome to the Lund Monte Carlo!  |  |
 |  |   P  P   Y Y     T    H   H   I    A A     This is PYTHIA version 8.303      |  |
 |  |   PPP     Y      T    HHHHH   I   AAAAA    Last date of change:  1 Sep 2020  |  |
 |  |   P       Y      T    H   H   I   A   A                                      |  |
 |  |   P       Y      T    H   H  III  A   A    Now is 19 Jul 2021 at 11:41:40    |  |
 |  |                                                                              |  |
 *-------  PYTHIA Process Initialization  --------------------------*
 | We collide p+ with p+ at a CM energy of 1.400e+04 GeV             |
 |-------------------------------------------------------------------|
 | Subprocess                                    Code |   Estimated |
 |                                                    |    max (mb) |
 |-------------------------------------------------------------------|
 |                                                    |             |
 | g g -> H (SM)                                  902 |   3.065e-07 |
 --------  PYTHIA Event Listing  (complete event)  ---------------------------------------------------------------------------------

    no         id  name            status     mothers   daughters     colours      p_x        p_y        p_z         e          m
     0         90  (system)           -11     0     0     0     0     0     0      0.000      0.000      0.000  14000.000  14000.000
     1       2212  (p+)               -12     0     0   649     0     0     0      0.000      0.000   7000.000   7000.000      0.938
     2       2212  (p+)               -12     0     0   650     0     0     0      0.000      0.000  -7000.000   7000.000      0.938
     3         21  (g)                -21    19     0     5     0   101   102      0.000      0.000     10.638     10.638      0.000
     4         21  (g)                -21    20    20     5     0   102   101      0.000      0.000   -373.110    373.110      0.000
     5         25  (h0)               -22     3     4    21    21     0     0      0.000      0.000   -362.472    383.747    126.000
     6         21  (g)                -31    75    75     8     9   104   105      0.000      0.000    162.462    162.462      0.000
     7         21  (g)                -31    76     0     8     9   106   104      0.000      0.000     -8.450      8.450      0.000
     8         21  (g)                -33     6     7    42    43   106   107      2.904     -9.848     -5.104     11.466      0.000
     9         21  (g)                -33     6     7    44    44   107   105     -2.904      9.848    159.116    159.447      0.000
    10         21  (g)                -31    14     0    12    13   108   109      0.000      0.000     14.037     14.037      0.000
 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
  1624        111  pi0                 91  1516     0     0     0     0     0      0.081      0.097     -0.757      0.779      0.135
  1625        111  pi0                 91  1516     0     0     0     0     0     -0.082     -0.156     -0.614      0.653      0.135
  1626        130  K_L0                91  1522  1522     0     0     0     0     -2.188      0.152     13.925     14.106      0.498
                                   Charge sum:  2.000           Momentum sum:     -0.000      0.000     -0.000  14000.000  14000.000
 --------  End PYTHIA Event Listing  -----------------------------------------------------------------------------------------------
```

European Physical Society
High Energy and Particle Physics Division

The **2021 High Energy and Particle Physics Prize of the EPS** for an outstanding contribution to High Energy Physics is awarded to **Torbjörn Sjöstrand and Bryan Webber** for the conception, development and realisation of parton shower Monte Carlo simulations, yielding an accurate description of particle collisions in terms of quantum chromodynamics and electroweak interactions, and thereby enabling the experimental validation of the Standard Model, particle discoveries and searches for new physics.

Torbjörn Sjöstrand: founding author of Pythia
Byran Webber: founding author of Herwig (with Marchesini†)

Mrinal Dasgupta
Manchester

Frédéric Dreyer
Oxford

Keith Hamilton
Univ. Coll. London

Pier Monni
CERN

Gavin Salam
Oxford

Grégory Soyez
IPhT, Saclay

since 2017

Emma Slade
Oxford (PhD) → GSK.ai

2018-20

Basem El-Menoufi
Manchester

Alexander Karlberg
Oxford

Rok Medves
Oxford (PhD)

Ludovic Scyboz
Oxford

Rob Verheyen
Univ. Coll. London

since 2019

Melissa van Beekveld
Oxford

Silvia Ferrario Ravasio
Oxford

Alba Soto Ontoso
IPhT, Saclay

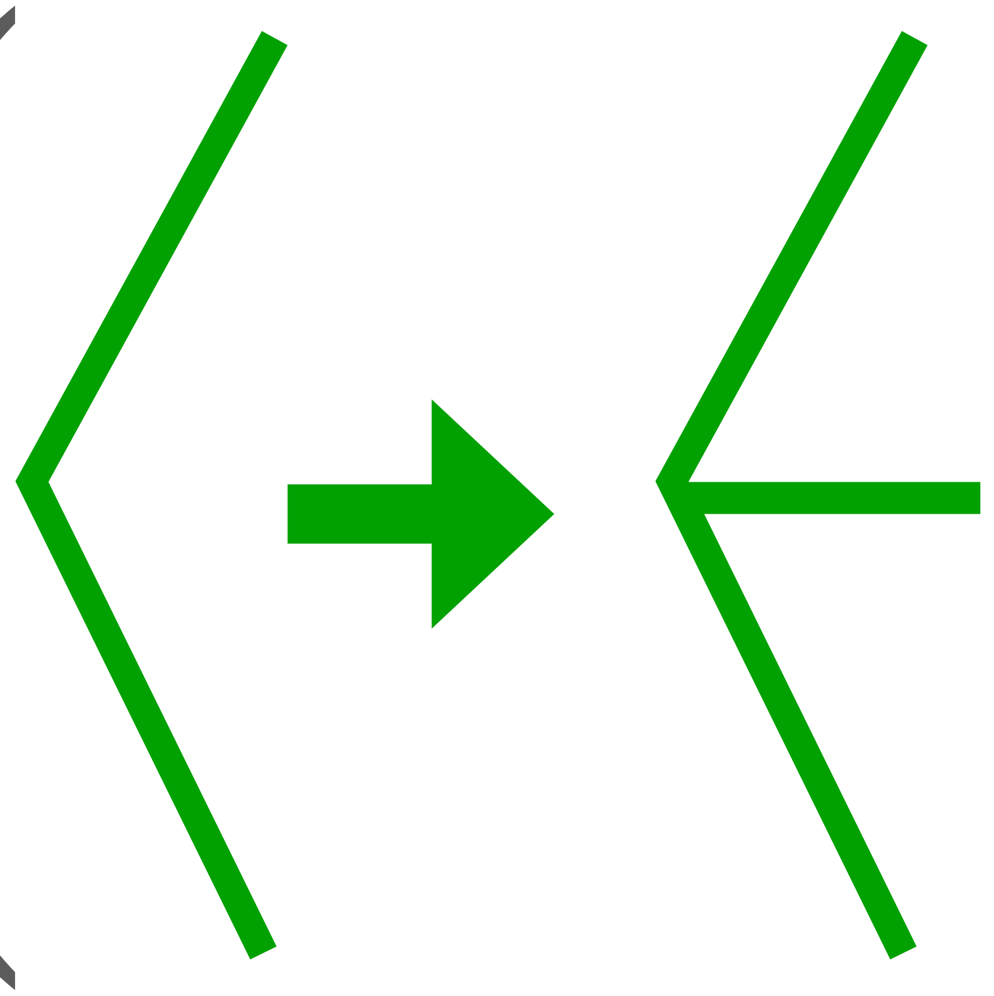
since 2020

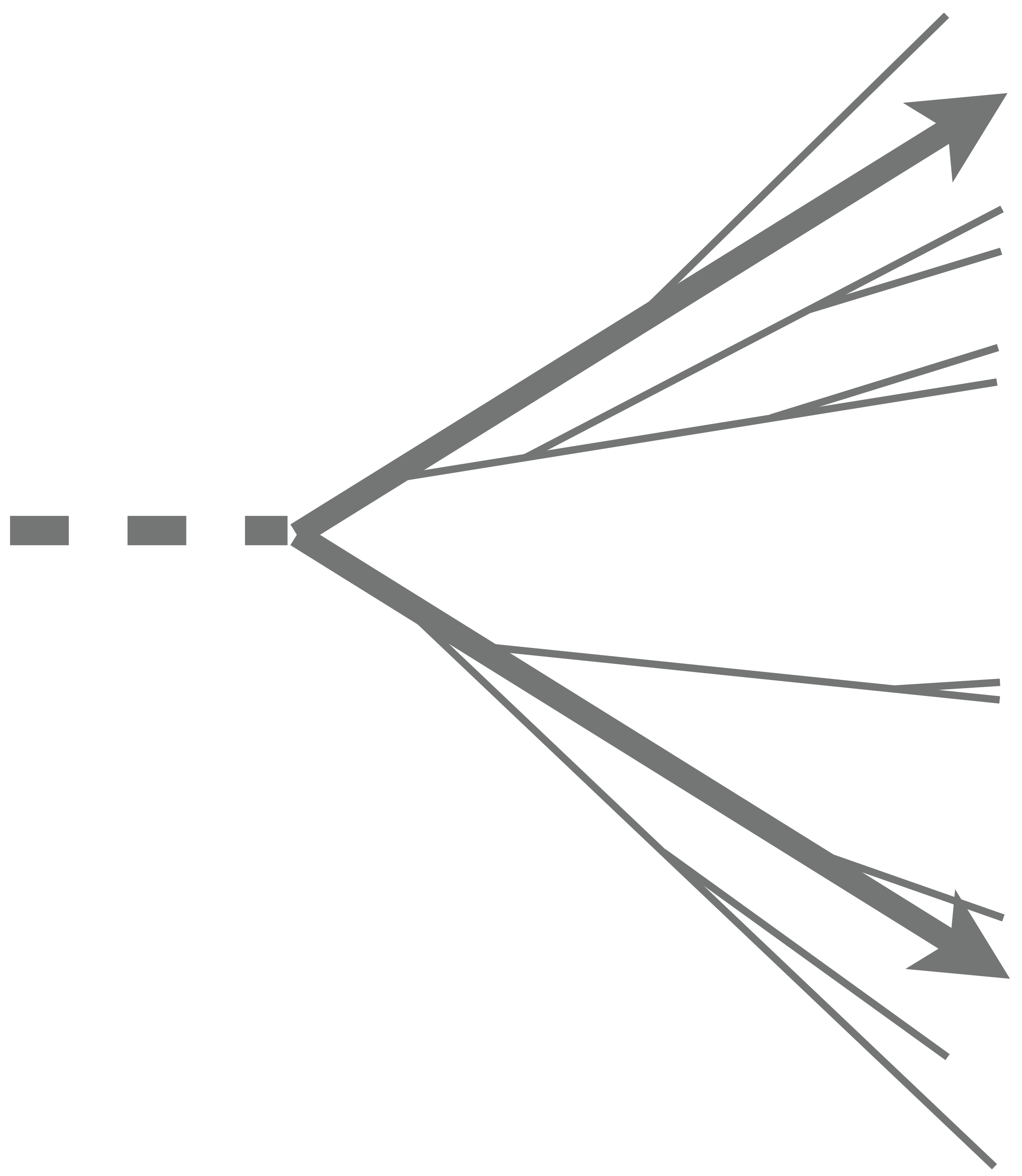
PanScales

A new project to bring logarithmic understanding and accuracy to parton showers

A parton shower, at its simplest

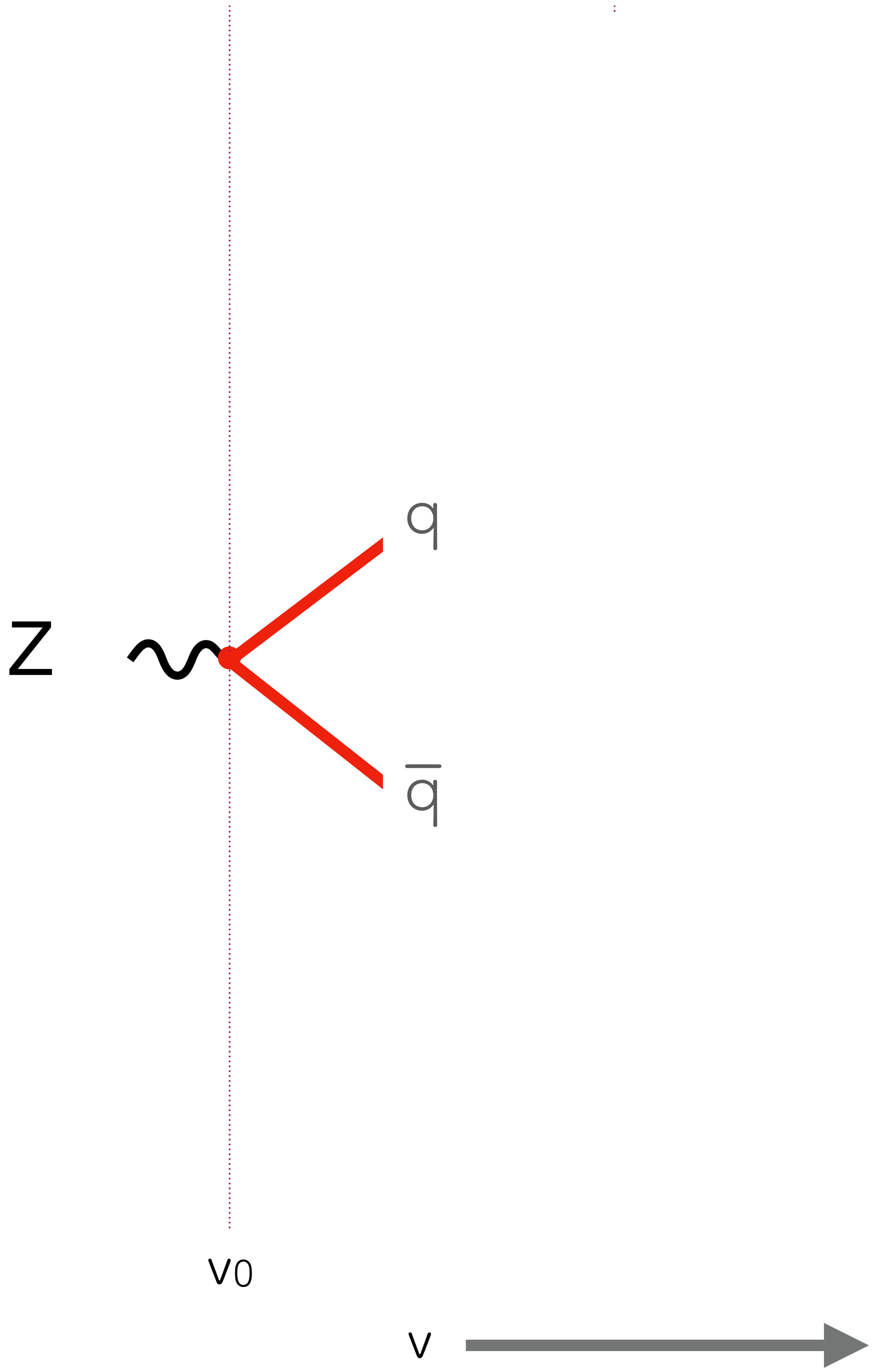
$$\sum_{n=0}^{\infty}\prod_{i=1}^{n}\Bigg(\quad \Bigg) =$$





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

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

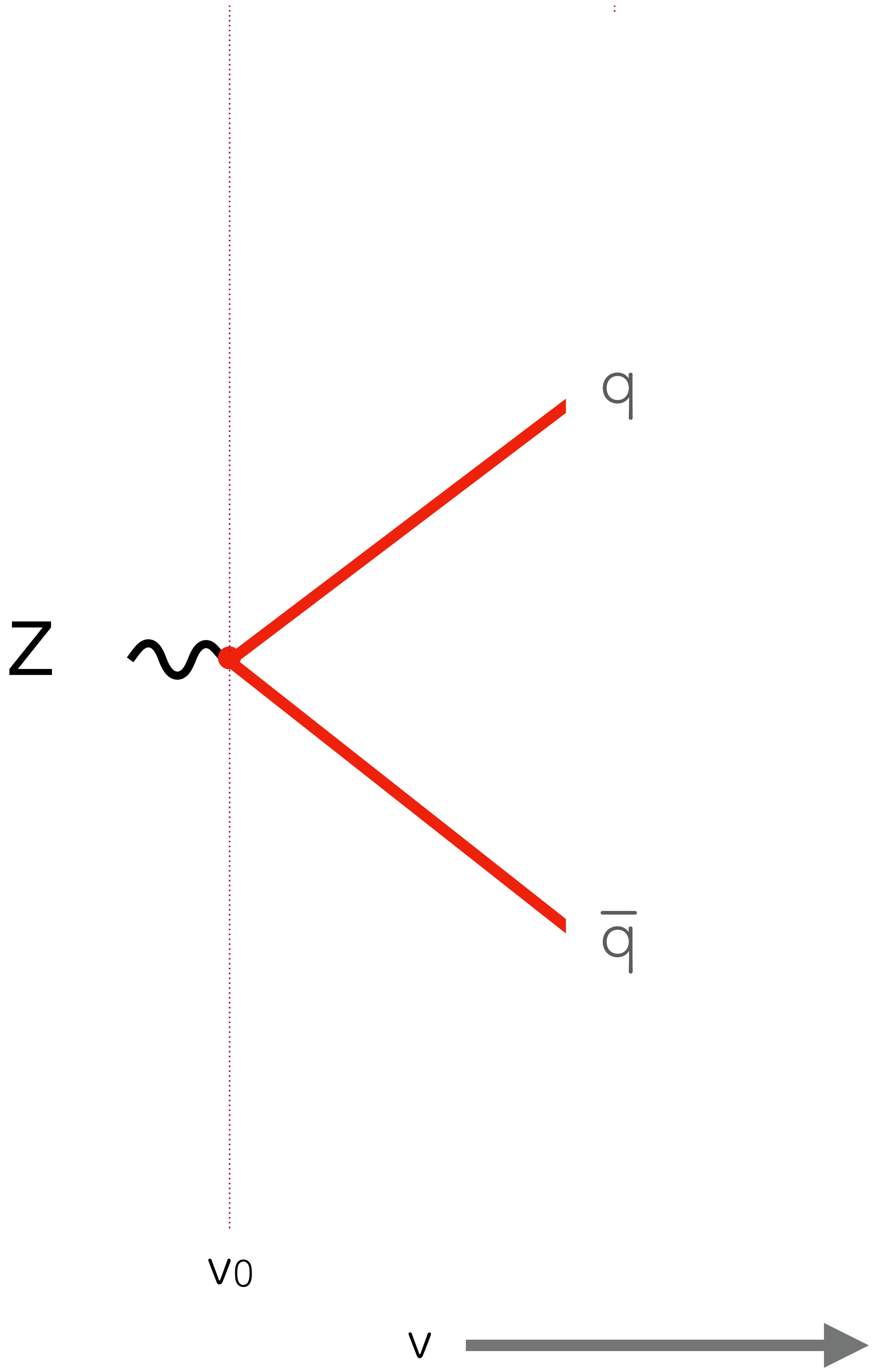


Start with q-qbar state.

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

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

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

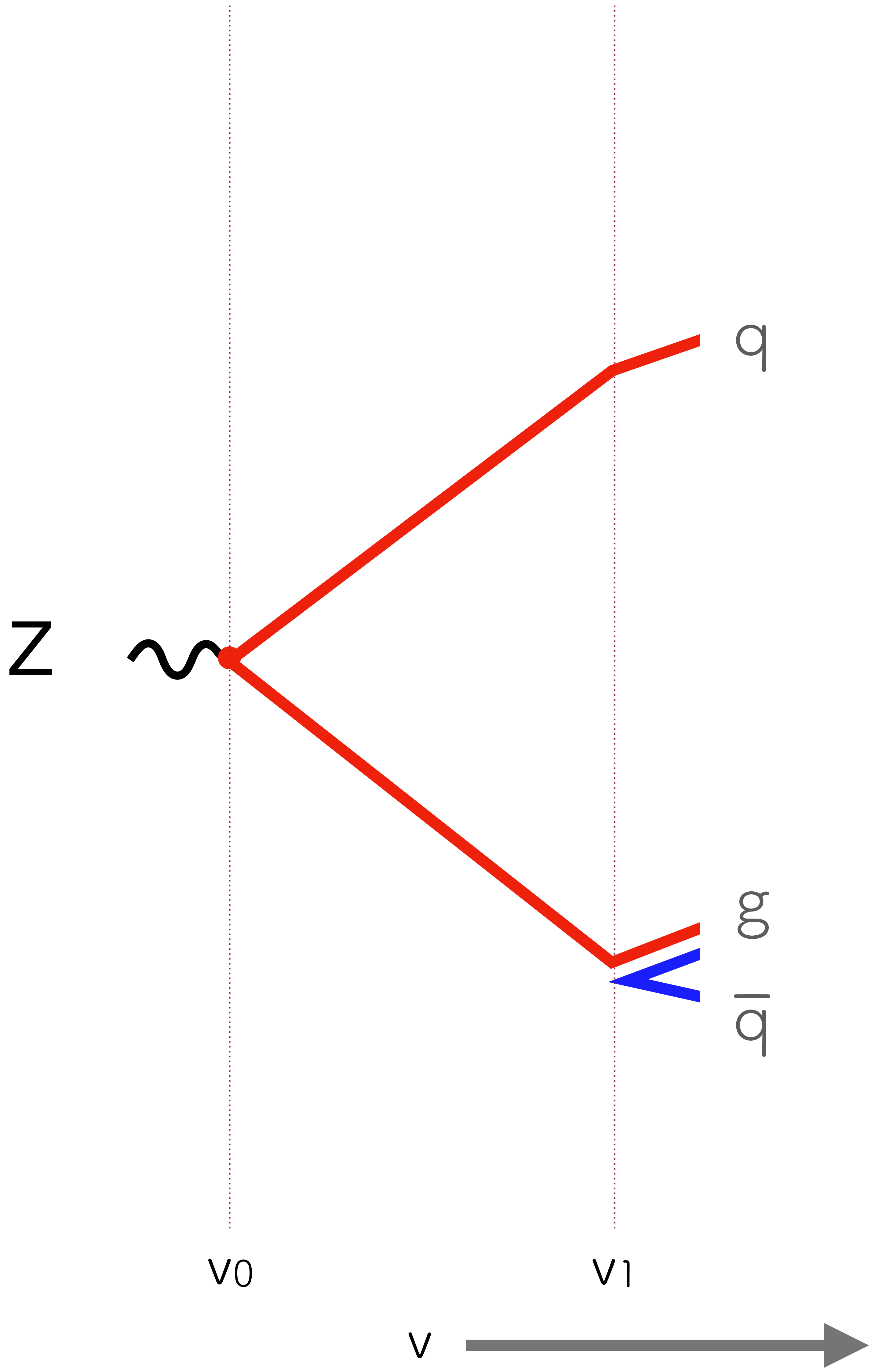


Start with q-qbar state.

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

$$\frac{dP_2(v)}{dv} = -f_{2\to3}^{q\bar{q}}(v)\,P_2(v)$$

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



Start with q-qbar state.

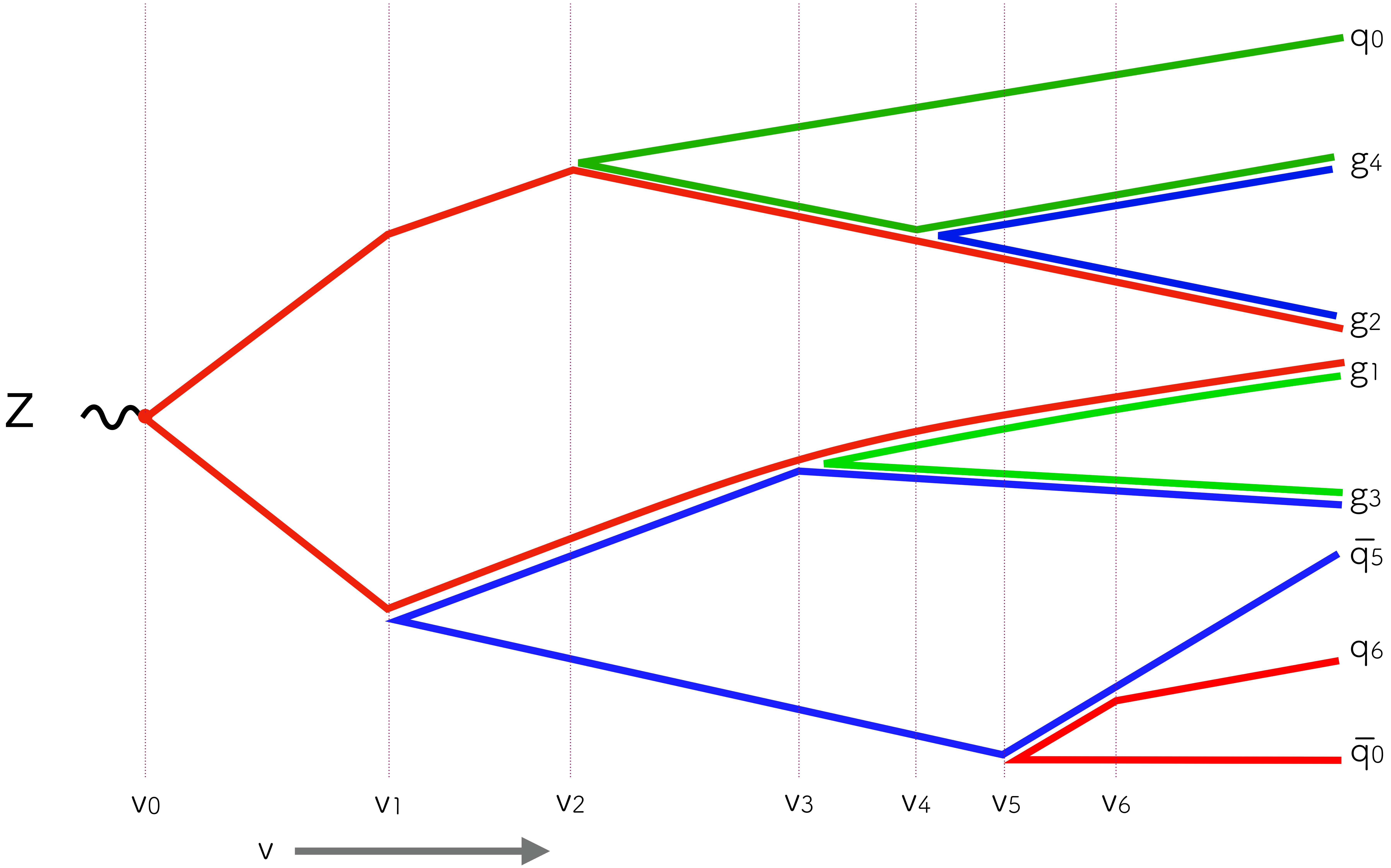
Evolve a step in v and throw a random number to decide if state remains unchanged

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

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

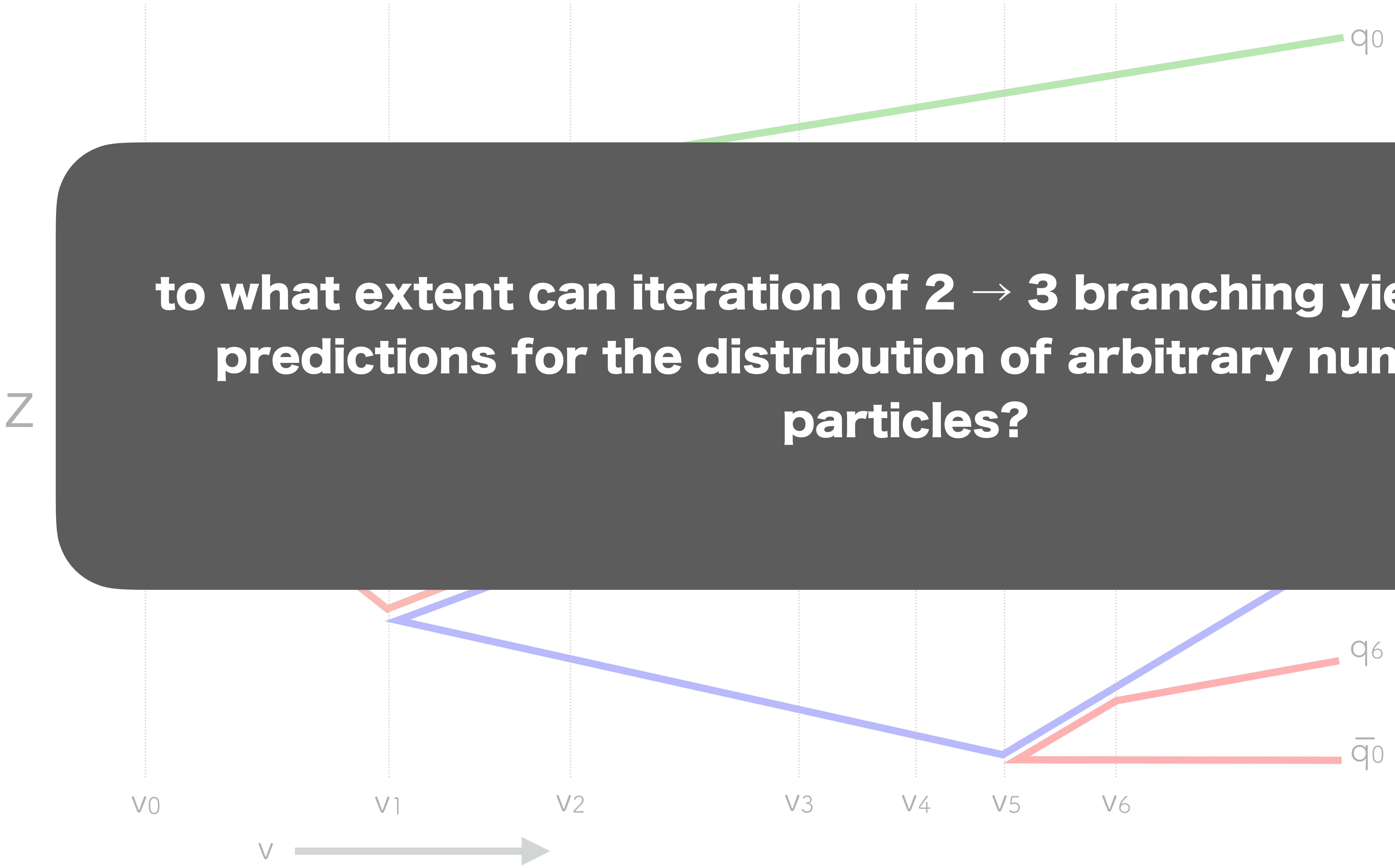
gluon is part of two dipoles $(qg, \bar{q}g)$

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

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



to what extent can iteration of 2 → 3 branching yield correct predictions for the distribution of arbitrary numbers of particles?

Our proposal for investigating shower accuracy

Resummation

Establish logarithmic accuracy for main classes of resummation:

- global event shapes (thrust, broadening, angularities, jet rates, energy-energy correlations, …)
- non-global observables (cf. Banfi, Corcella & Dasgupta, hep-ph/0612282)
- fragmentation / parton-distribution functions
- multiplicity, cf. original Herwig angular-ordered shower from 1980's

Matrix elements

Establish in what sense iteration of (e.g. 2→3) splitting kernel reproduces *N*-particle tree-level matrix elements *for any N*.
Because this kind of info is exploited by machine-learning algorithms.

Our proposal for investigating shower accuracy

Resummation

Establish logarithmic accuracy for main classes of resummation:

- global event shapes (thrust, broadening, angularities, jet rates, energy-energy correlations, …)
- non-global observables (cf. Banfi, Corcella & Dasgupta, hep-ph/0612282)
- fragmentation / parton-distribution functions
- multiplicity, cf. original Herwig angular-ordered shower from 1980's

Matrix elements

Establish in what sense iteration of (e.g. 2→3) splitting kernel reproduces *N*-particle tree-level matrix elements *for any N.* Because this kind of info is exploited by machine-learning algorithms.

Baseline "NLL" requirements

Aim for NLL, control of $\alpha_s^n L^n$

Aim for NDL, i.e. $\alpha_s^n L^{2n-1}$

Aim for correctness when all particles well separated in Lund diagram

Core principles for NLL showers

1. for a new emission k, when it is generated far in the Lund diagram from any other emission ($|d_{ki}^{Lund}| \gg 1$), **it should not modify the kinematics (Lund coordinates) of any preceding emission** by more than an amount $\exp(-p|d_{ki}^{Lund}|)$, where $p = \mathcal{O}(1)$

2. when k is distant from other emissions, generate it with matrix element and phasespace (and associated Sudakov)

$$\frac{d\Phi_k}{d\Phi_{k-1}} \frac{|M_{1\ldots k}|^2}{|M_{1\ldots(k-1)}|^2}$$

[simple forms known from factorisation properties of matrix-elements]

3. emission k **should not impact $d\Phi \times |M|^2$ ratio for subsequent distant emissions *unless***

    a. they are at commensurate angle (or on k's Lund "leaf"), or

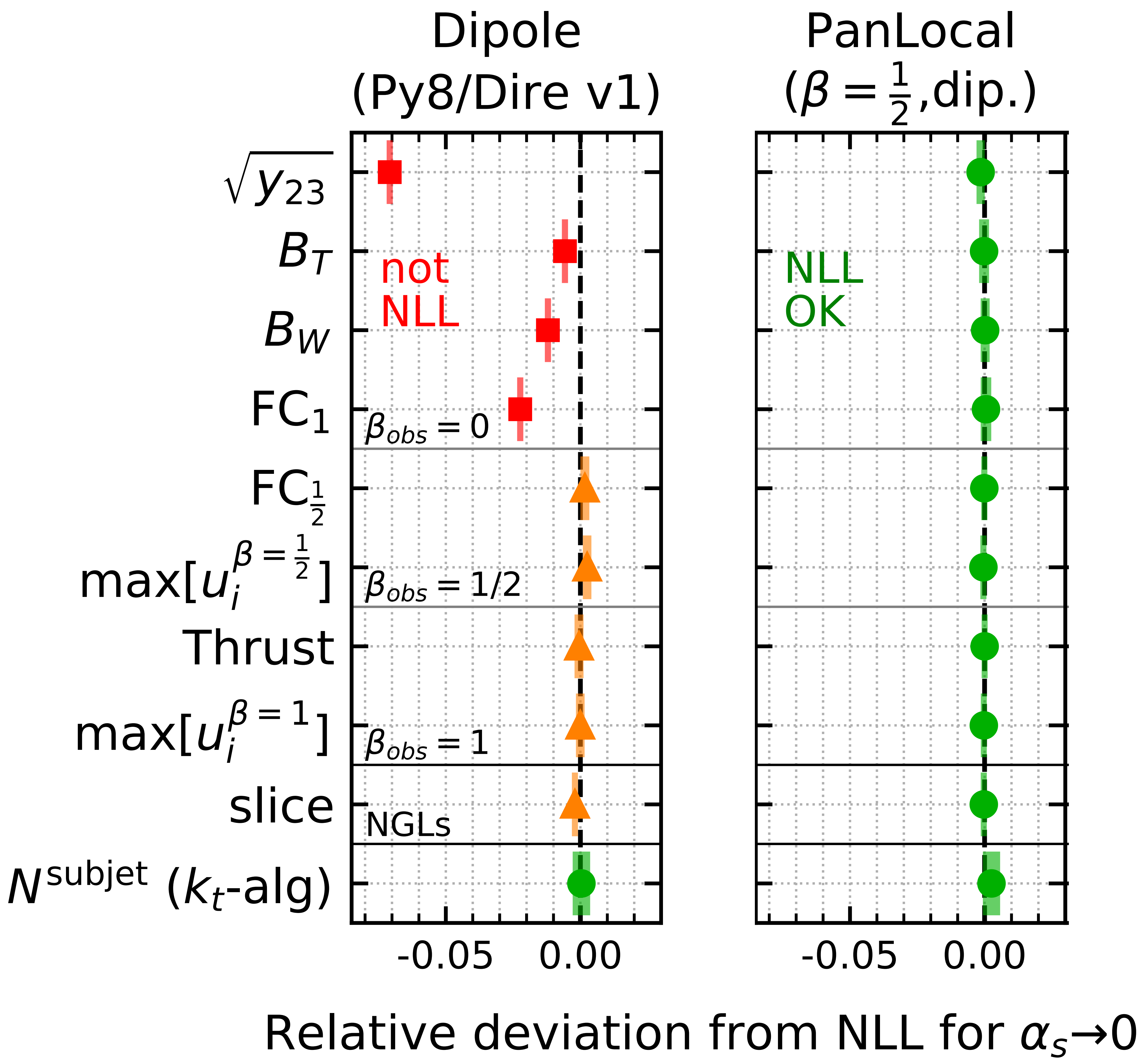
    b. k was a hard collinear splitting, which can affect other hard collinear splittings (cross-talk on same leaf ≡ DGLAP, cross-talk on other leaves ≡ spin correlations)

Step 3c: test new showers against NLL calculations — for many observables

standard parton showers

new "PanScales" parton showers, designed specifically to achieve NLL accuracy

Dasgupta, Dreyer, Hamilton, Monni, GPS, Soyez, [2002.11114](https://arxiv.org/abs/2002.11114) (Phys.Rev.Lett.)



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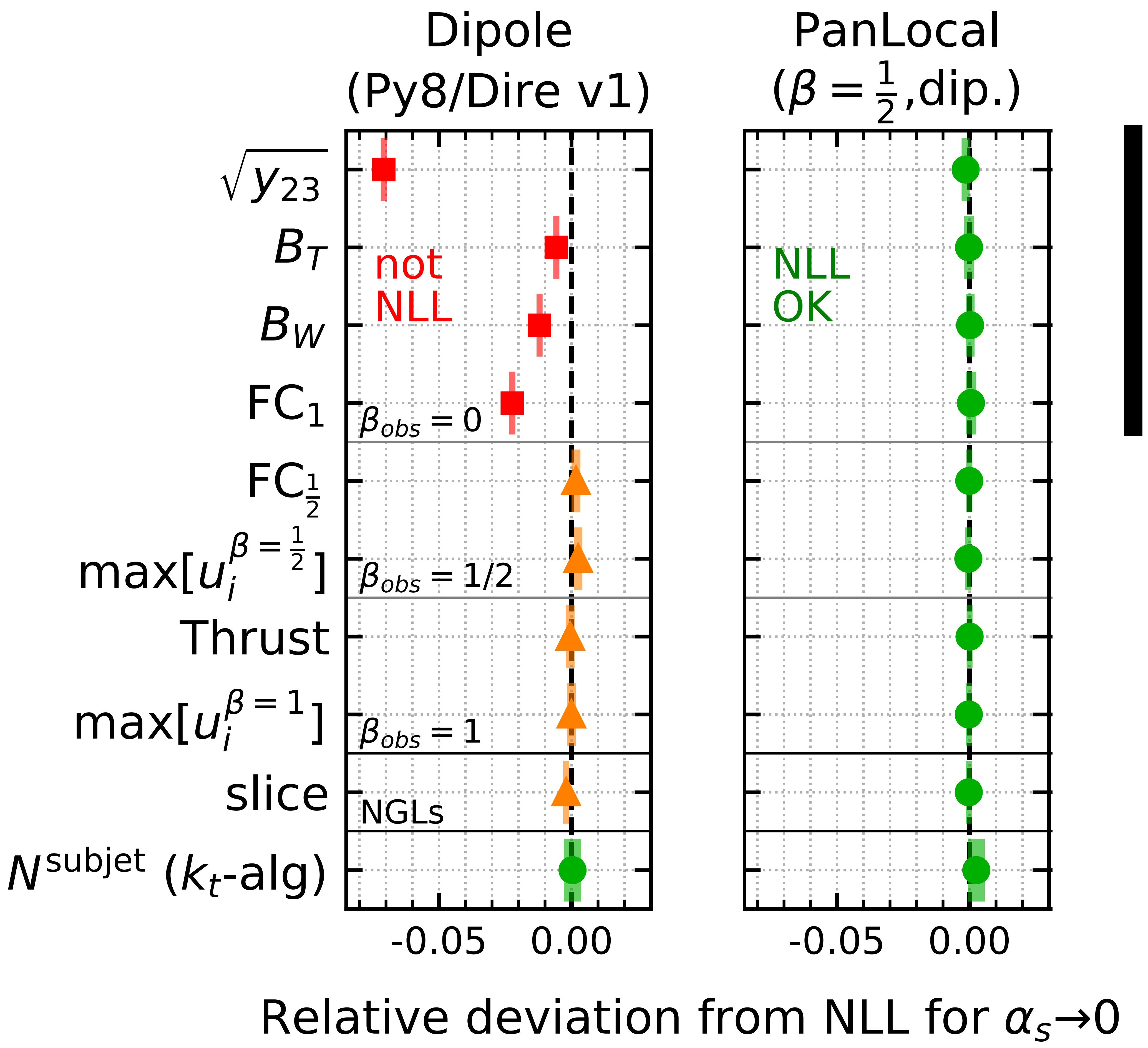

Event shapes sensitive to transverse momentum (jet broadenings, jet clustering transitions)

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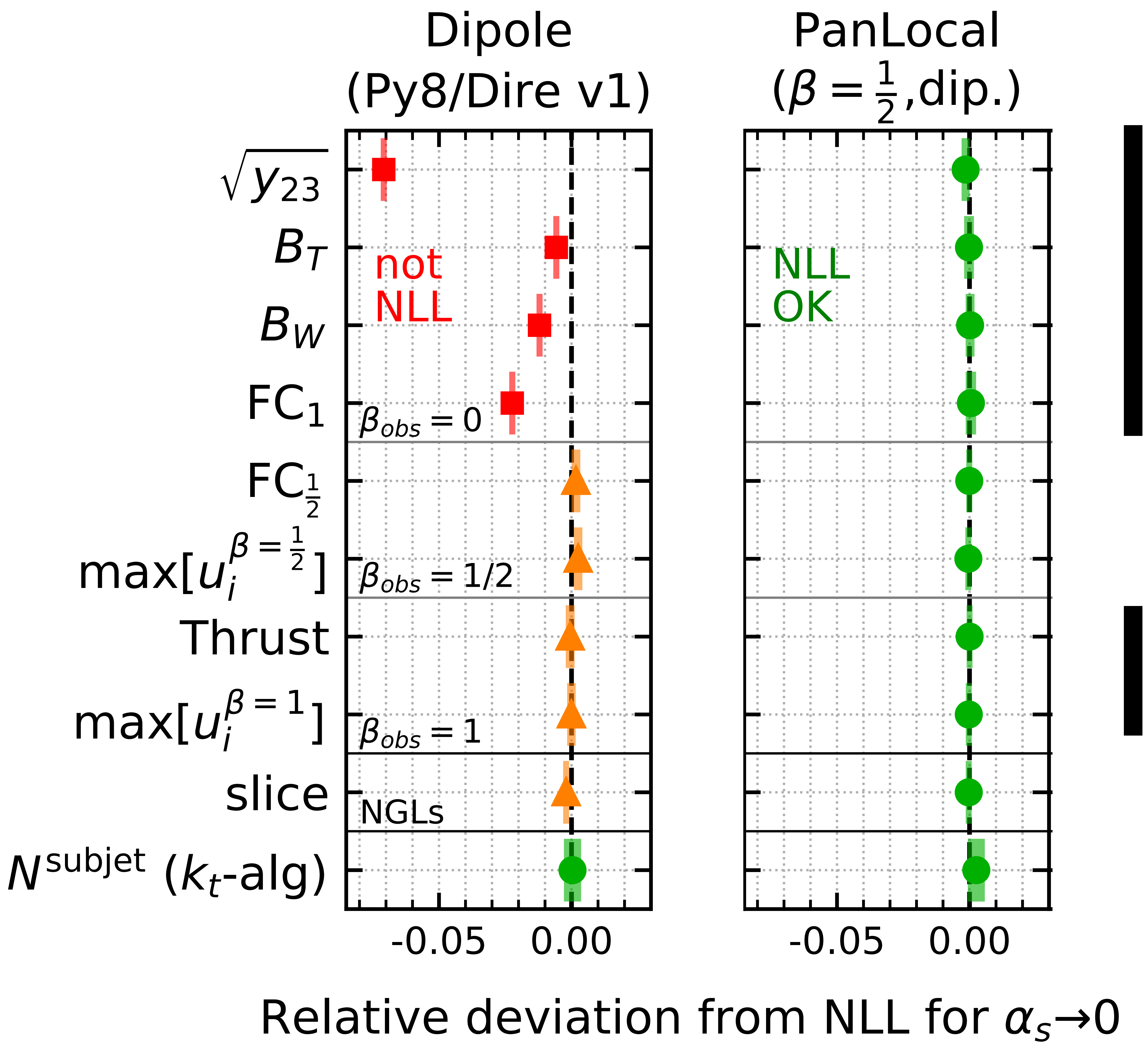

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Event shapes like thrust

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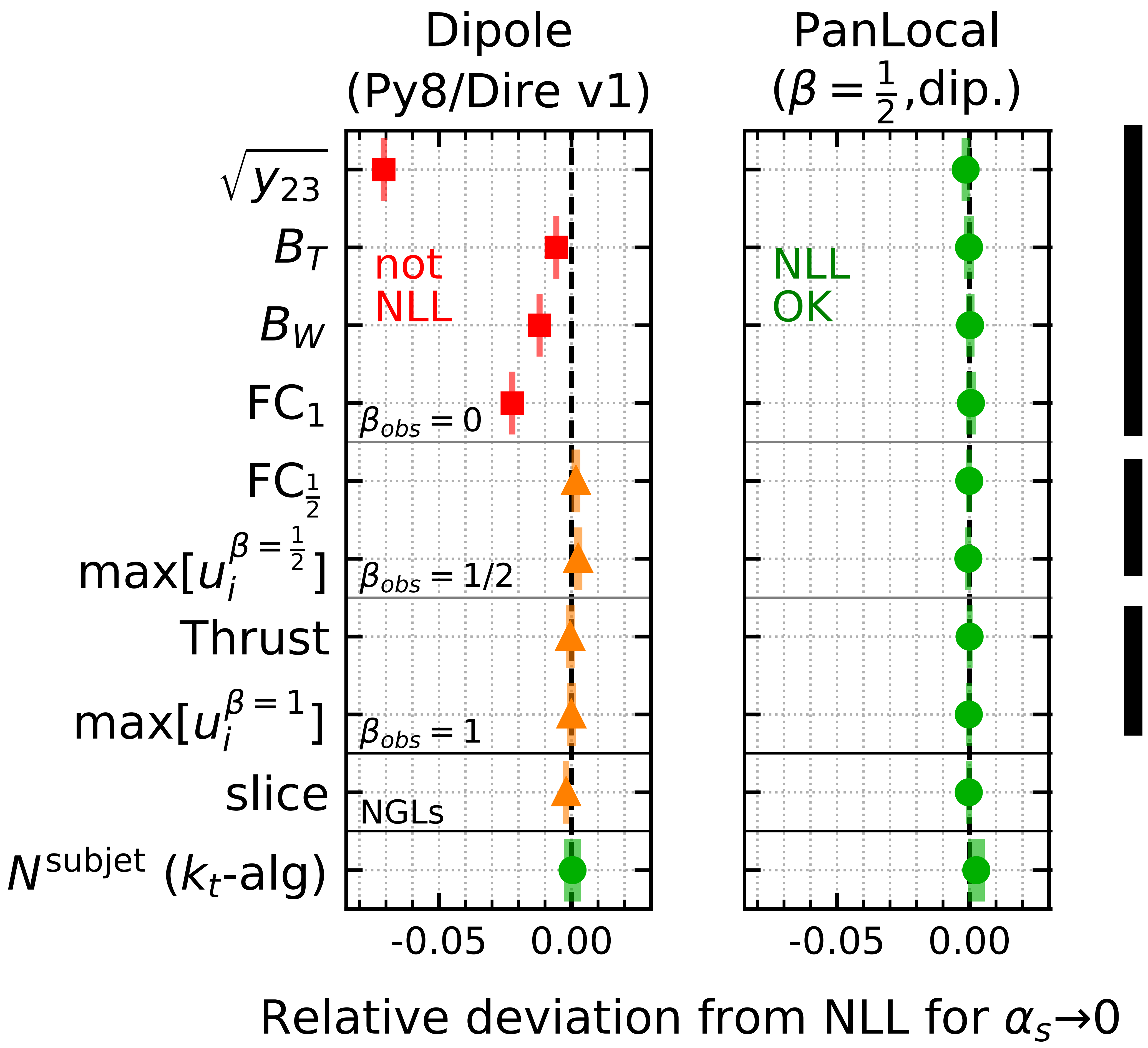

Event shapes sensitive to transverse momentum (jet broadenings, jet clustering transitions)

Event shapes that probe $p_t e^{-0.5|\eta|}$ (like $\beta = 0.5$ ordering variable)

Event shapes like thrust

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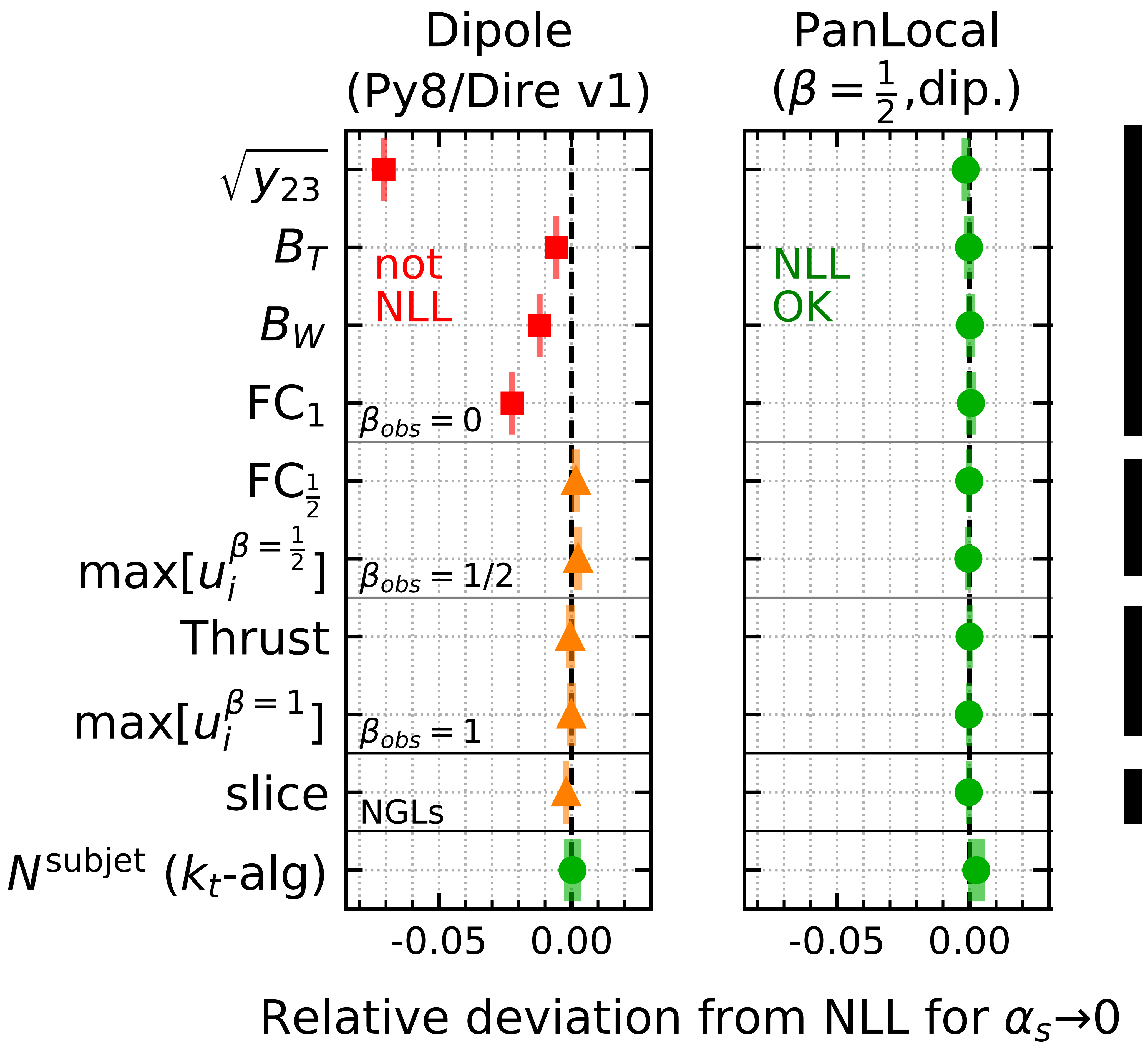

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probe of non-global logarithms

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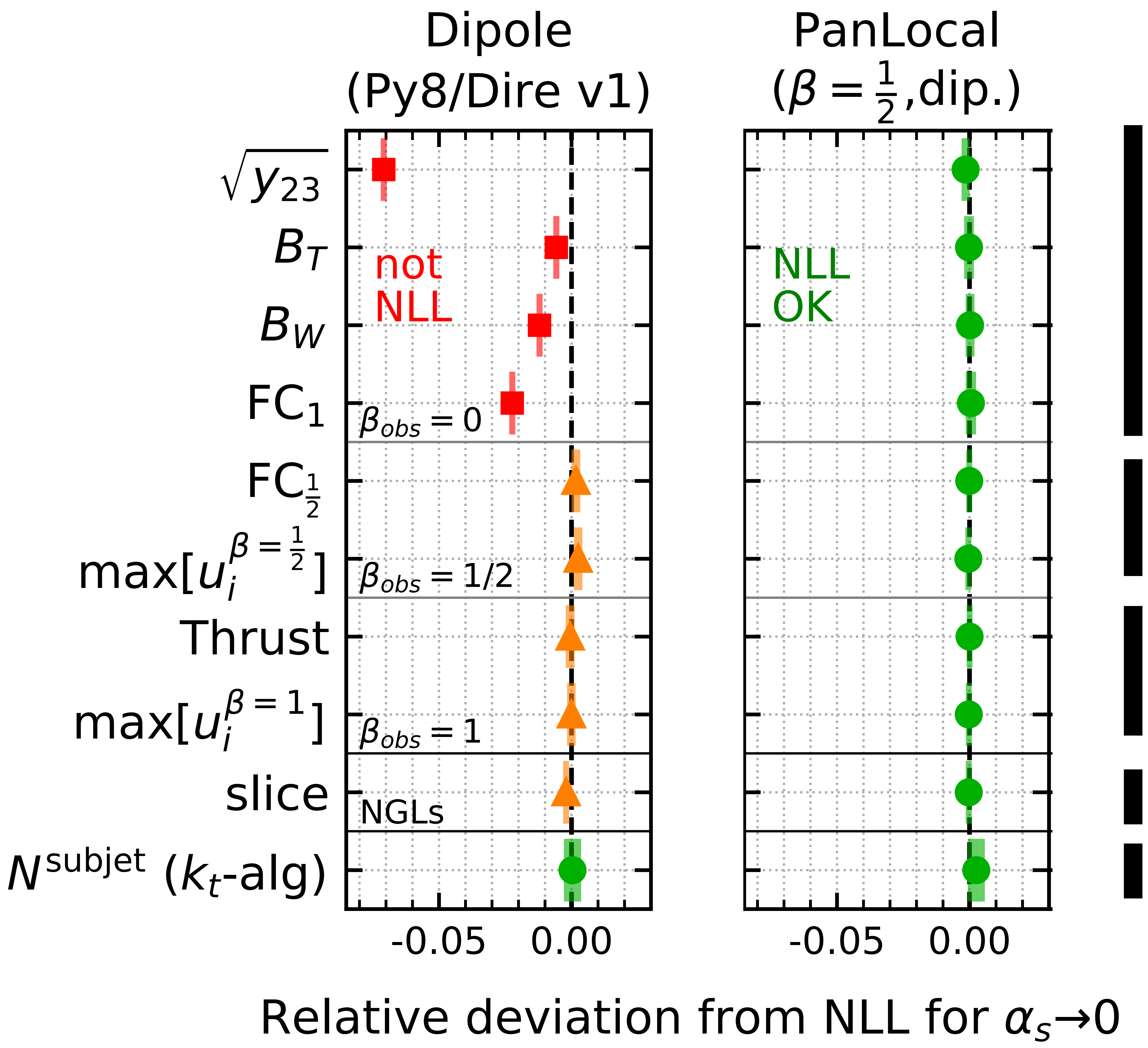

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Event shapes like thrust

probe of non-global logarithms

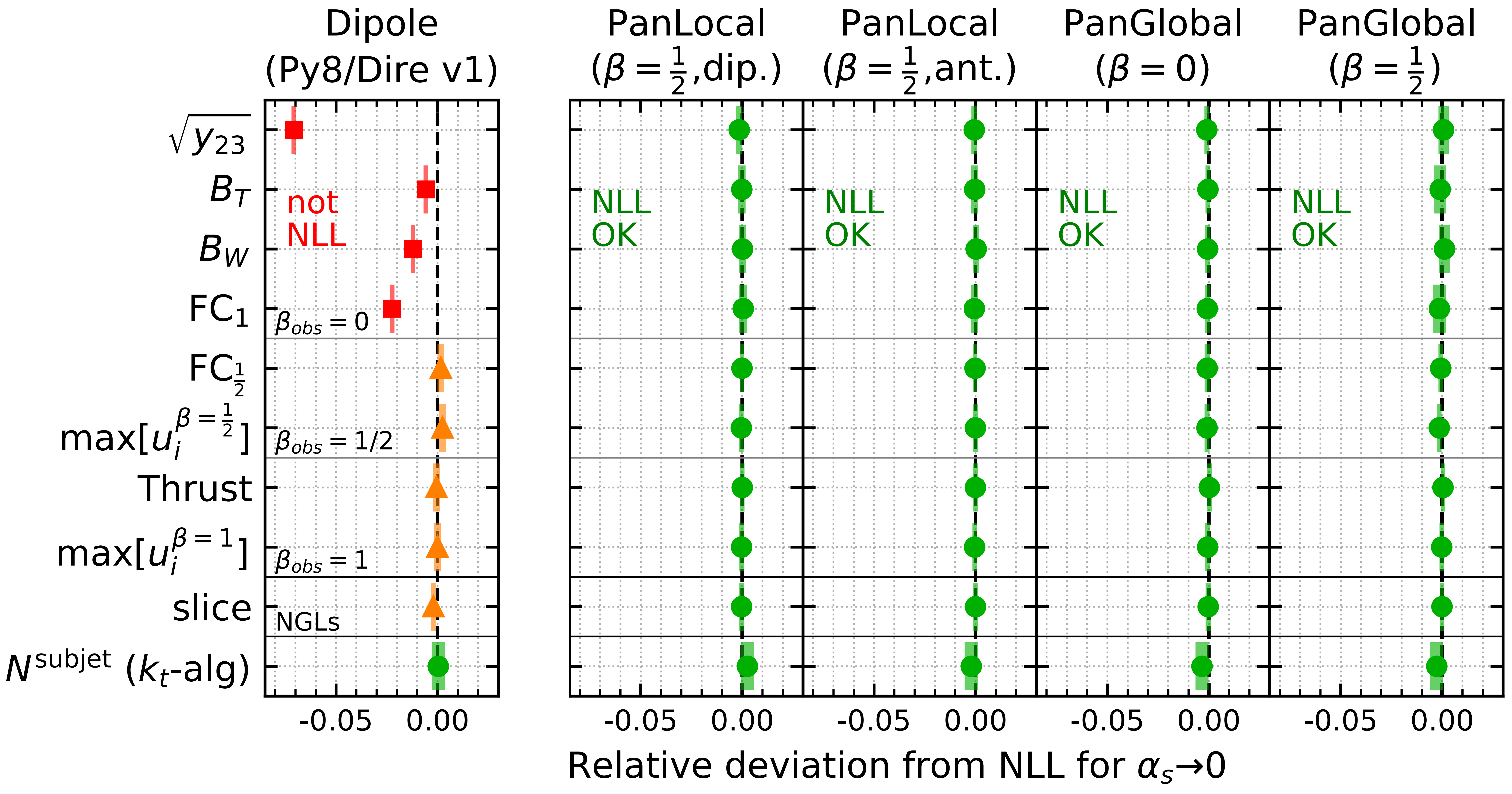
standard jet multiplicity (probe of full recursive shower structure)

Step 3c: test new showers against NLL calculations — for many observables

Dasgupta, Dreyer, Hamilton, Monni, GPS, Soyez, 2002.11114 (Phys.Rev.Lett.)

standard parton showers

new "PanScales" parton showers, designed specifically to achieve NLL accuracy

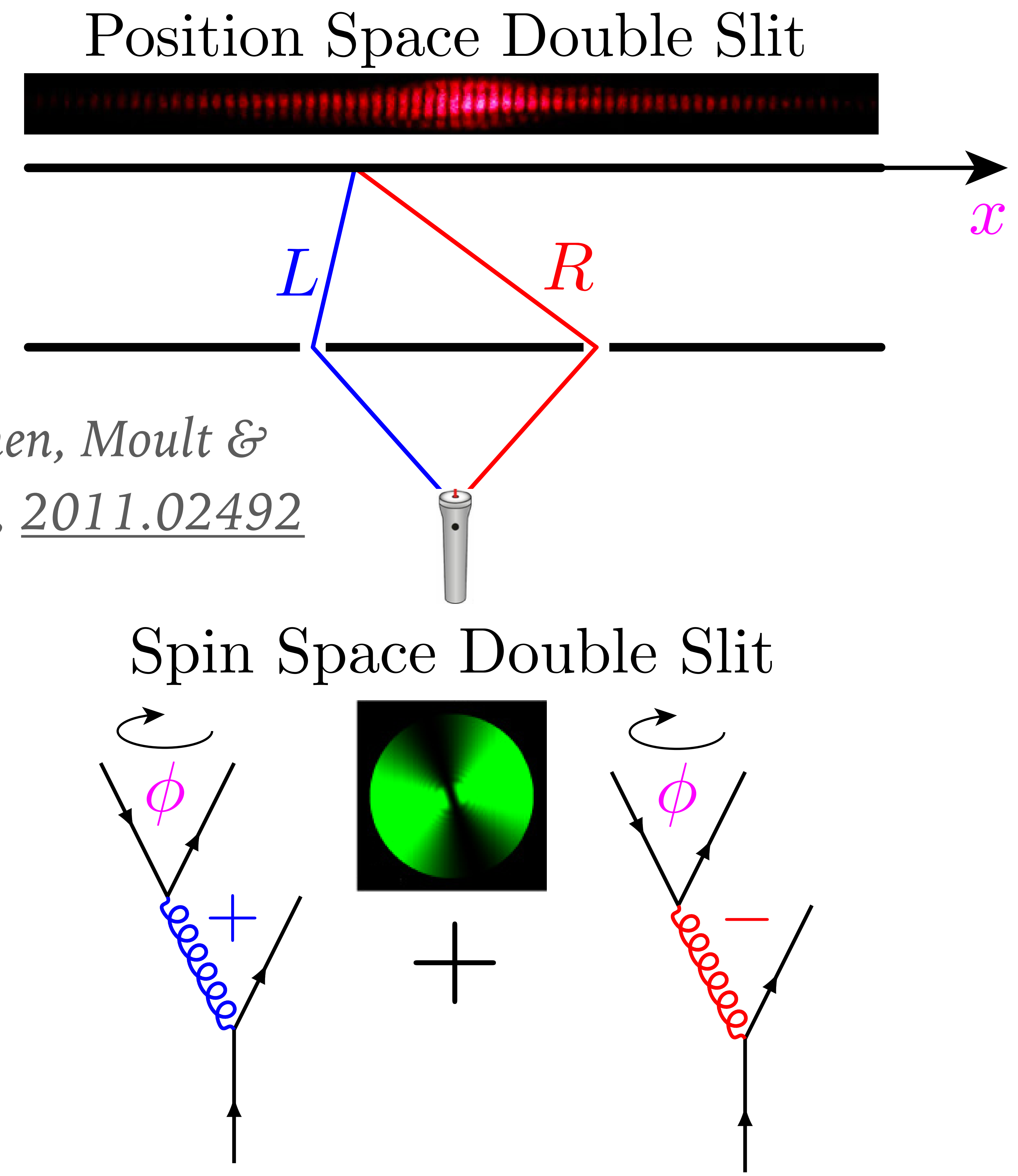


All PanScales shower that are expected to agree with NLL pass these tests

(Standard dipole showers don't)

see also Bewick, Ferrario Ravasio, Richardson and Seymour 1904.11866, Forshaw, Holguin & Plätzer, 2003.06400 and Nagy & Soper, 2011.04777

Collinear spin in parton showers (last but one of NLL ingredients)



Chen, Moult & Zhu, 2011.02492

Quantum mechanical interference in otherwise quasi-classical regime

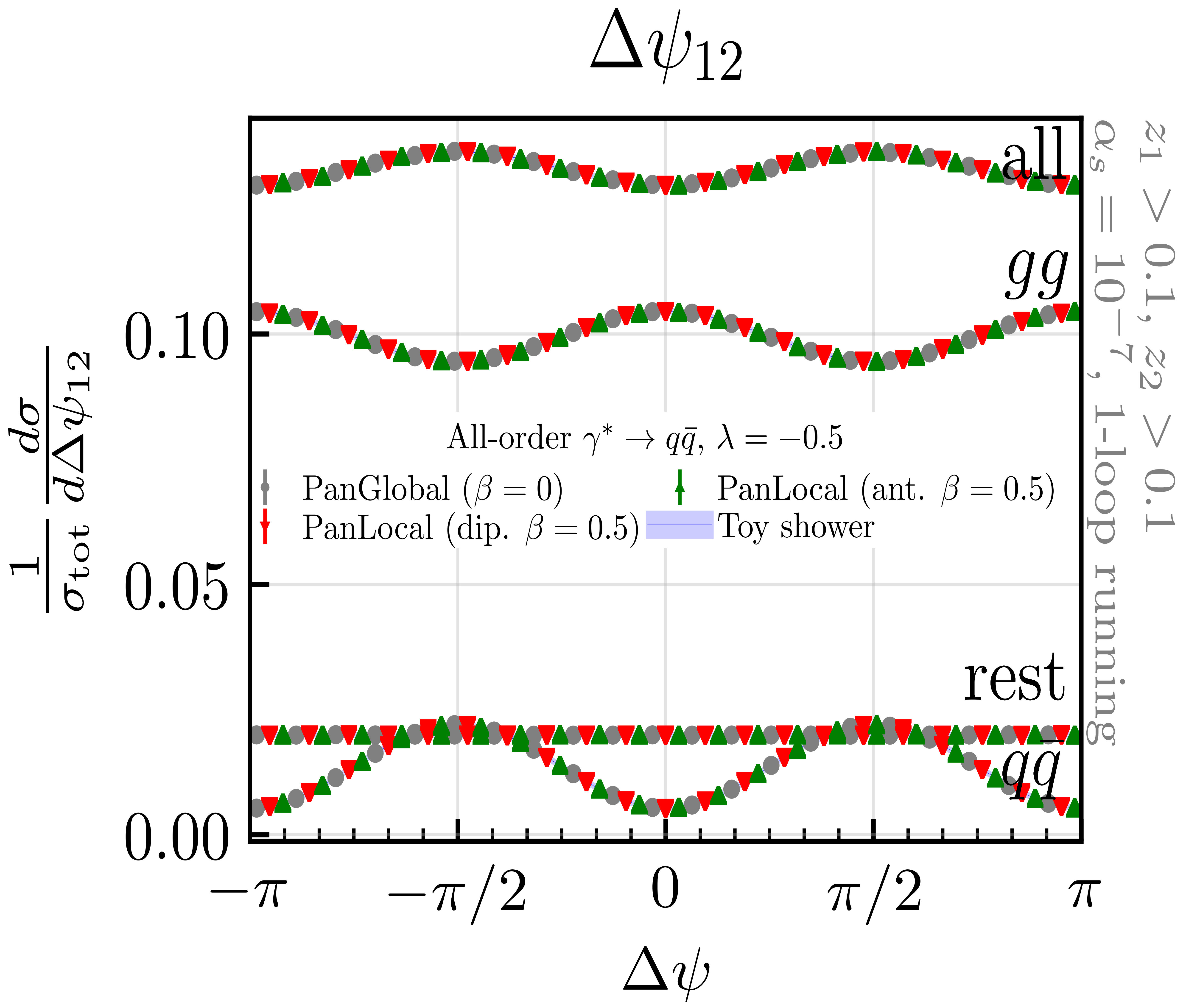
Algorithm for spin interference in collinear part of parton showers introduced long ago by Collins (1988)

A standard part of Herwig angular ordered showers, which are excellent for collinear regime, but can't do soft sector at NLL (cf. Banfi, Corcella & Dasgupta hep-ph/0612282)

Recoil in normal dipole showers may break the spin correlations (cf. Richardson and Webster, 1807.01955)

But Collins algorithm and PanScales showers should be compatible.

Spin correlations in full shower



magnitude of spin correlation effects	
EEEC	-0.008
$\Delta\psi_{12},\ z_1, z_2 > 0.1$	-0.025
$\Delta\psi_{12},\ z_1 > 0.1,\ z_2 > 0.3$	-0.042

In learning how to test shower accuracy, we also discovered observables that make it easier to observe these quantum mechanical effects experimentally

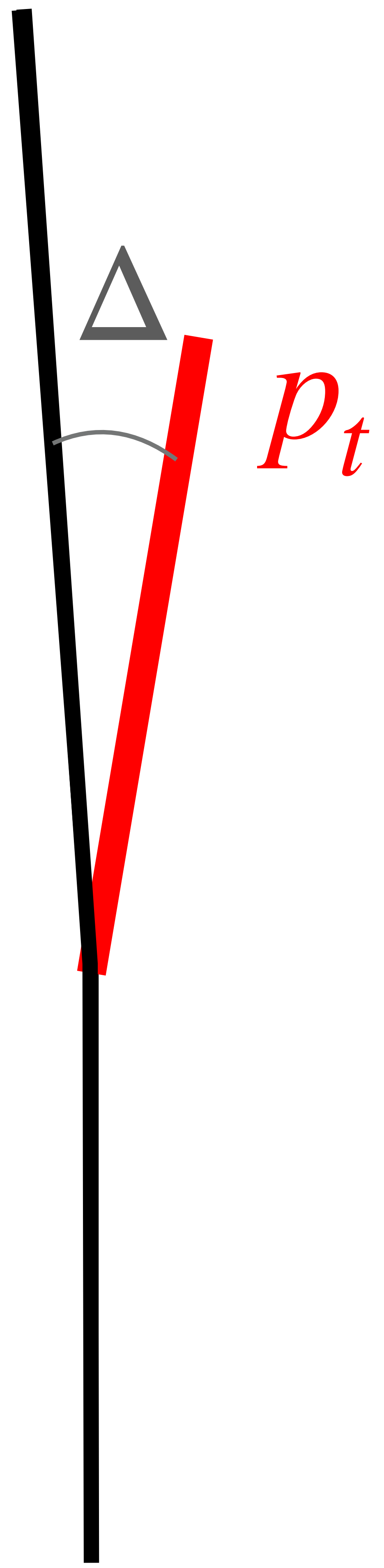
Karlberg, GPS, Scyboz & Verheyen, 2103.16526

outlook

Outlook

- Higgs discovery has 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 10–30%, for a subset of its interactions
  - and in only a corner of phase space
- **Future progress will come in many forms:**
  - More data from LHC, and possible new colliders (e.g. Future Circular Collider)
  - More powerful methods to extract the information (cf. machine learning)
  - Accurate quantitative connection between events and fundamental Lagrangian (e.g. parton showers and PanScales project, and much other in QCD)

Phase space: two key variables (+ azimuth)

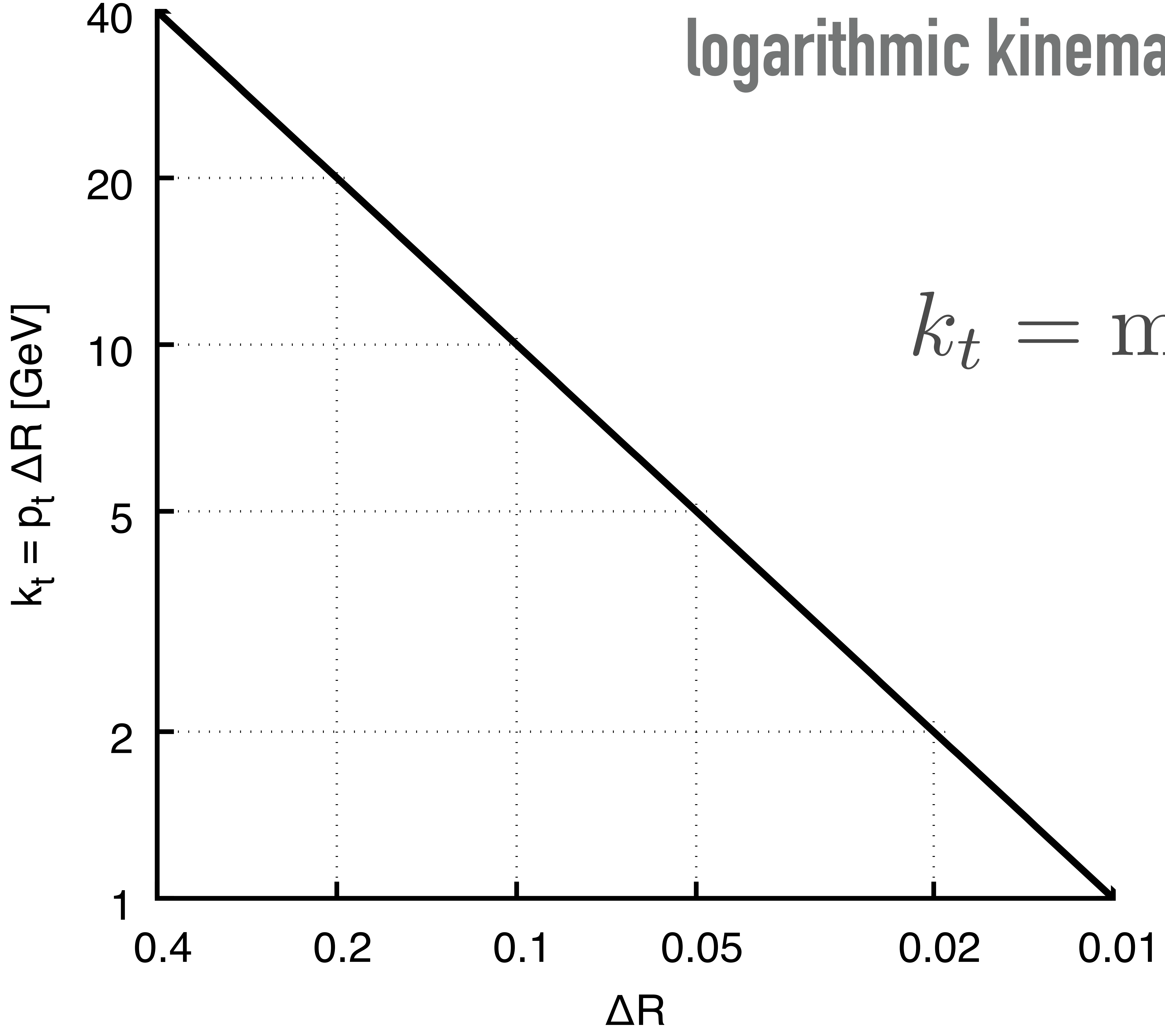


ΔR (or just Δ) — *opening angle of a splitting*

$k_t = p_t \Delta$ — 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



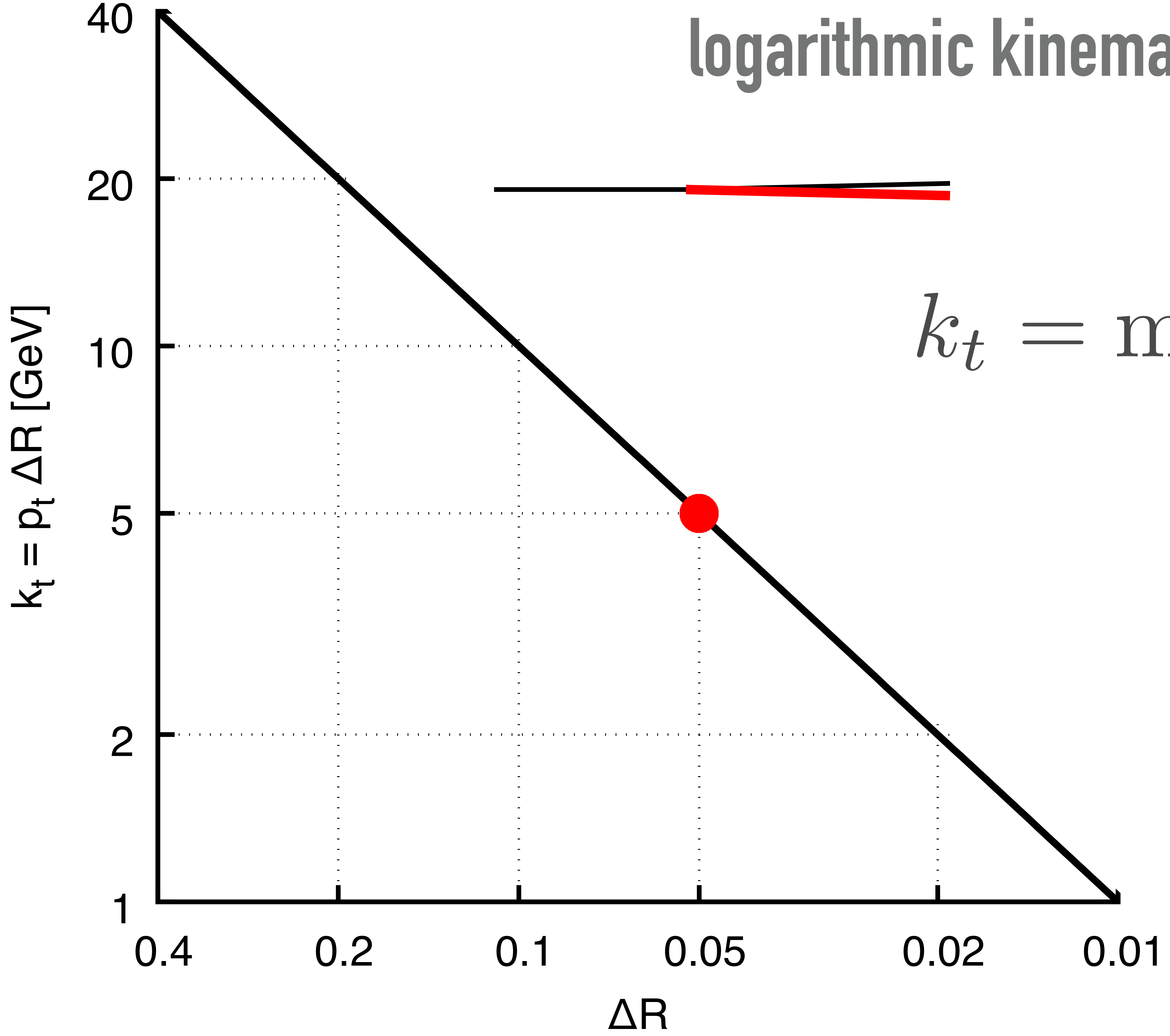
logarithmic kinematic plane whose two variables are

$$\Delta R_{ij}$$

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

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

The Lund Plane



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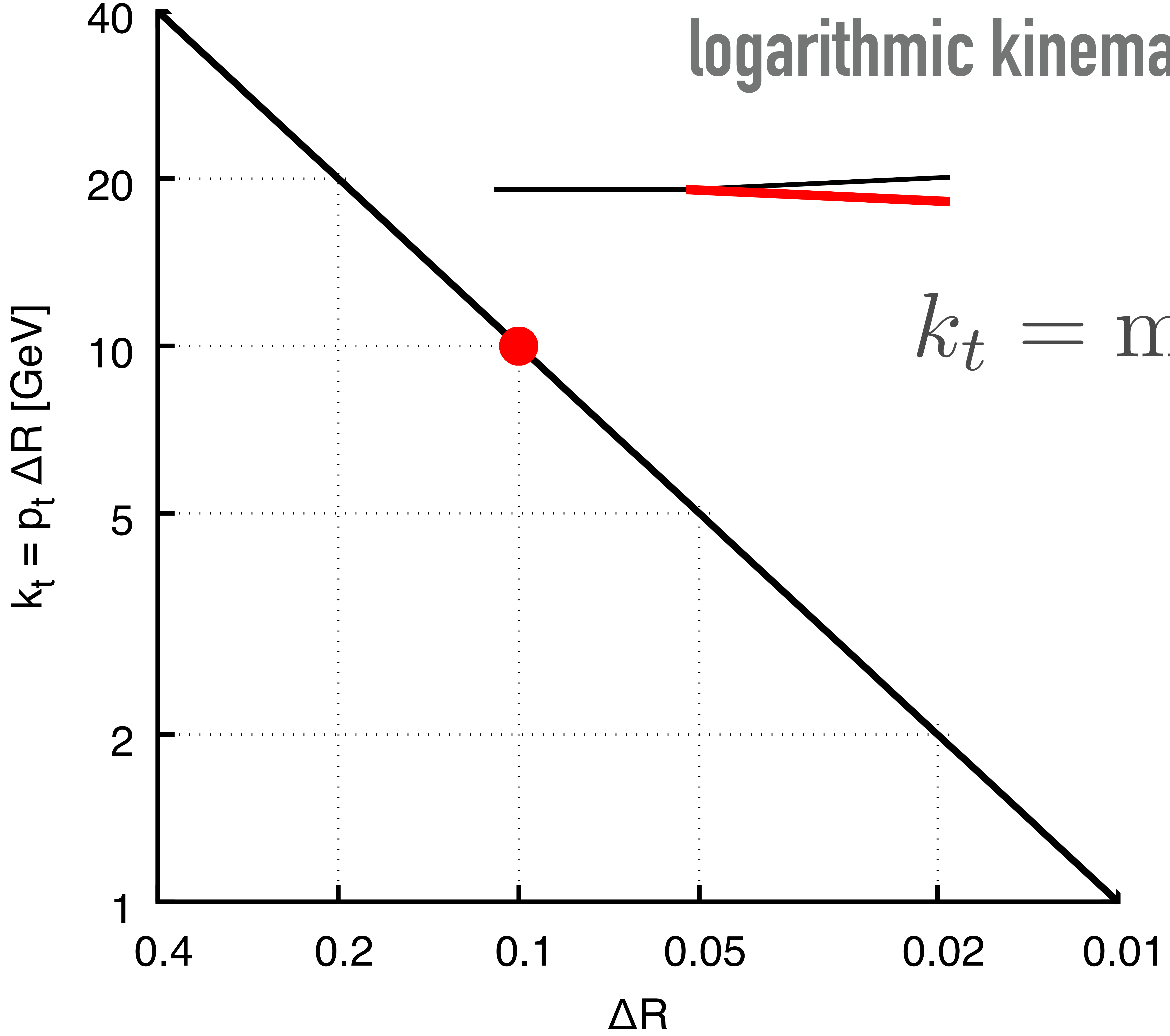

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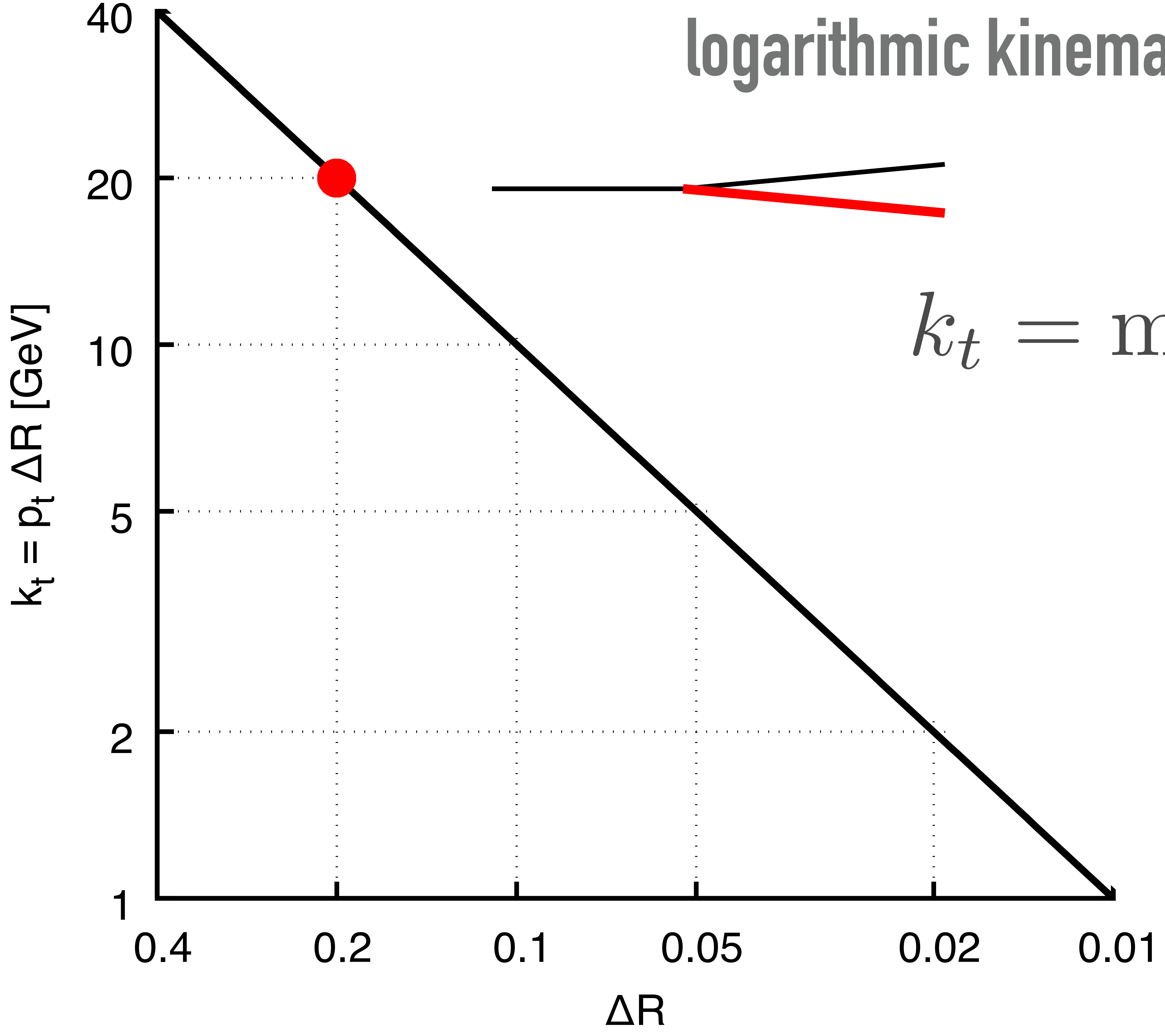

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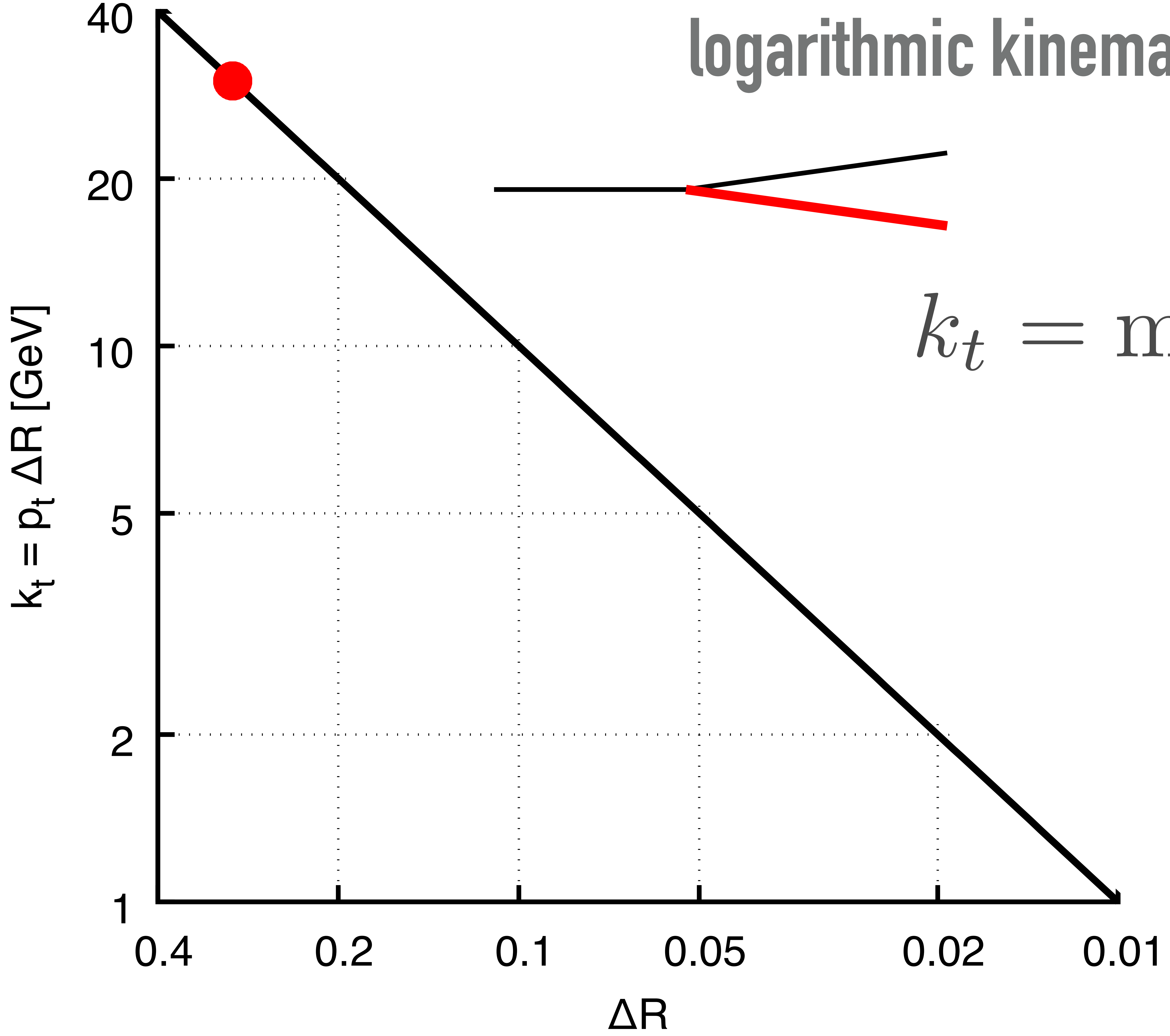

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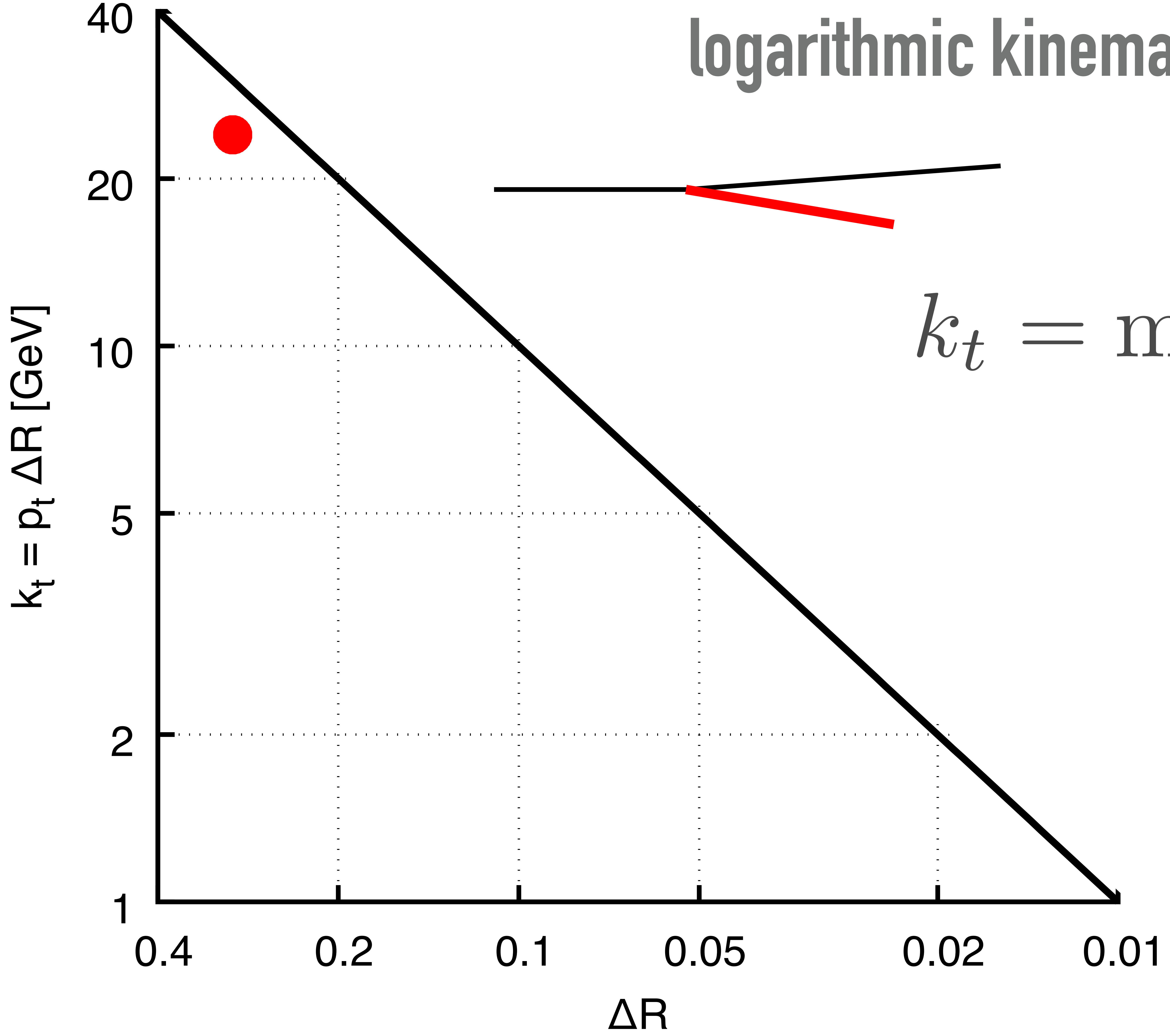

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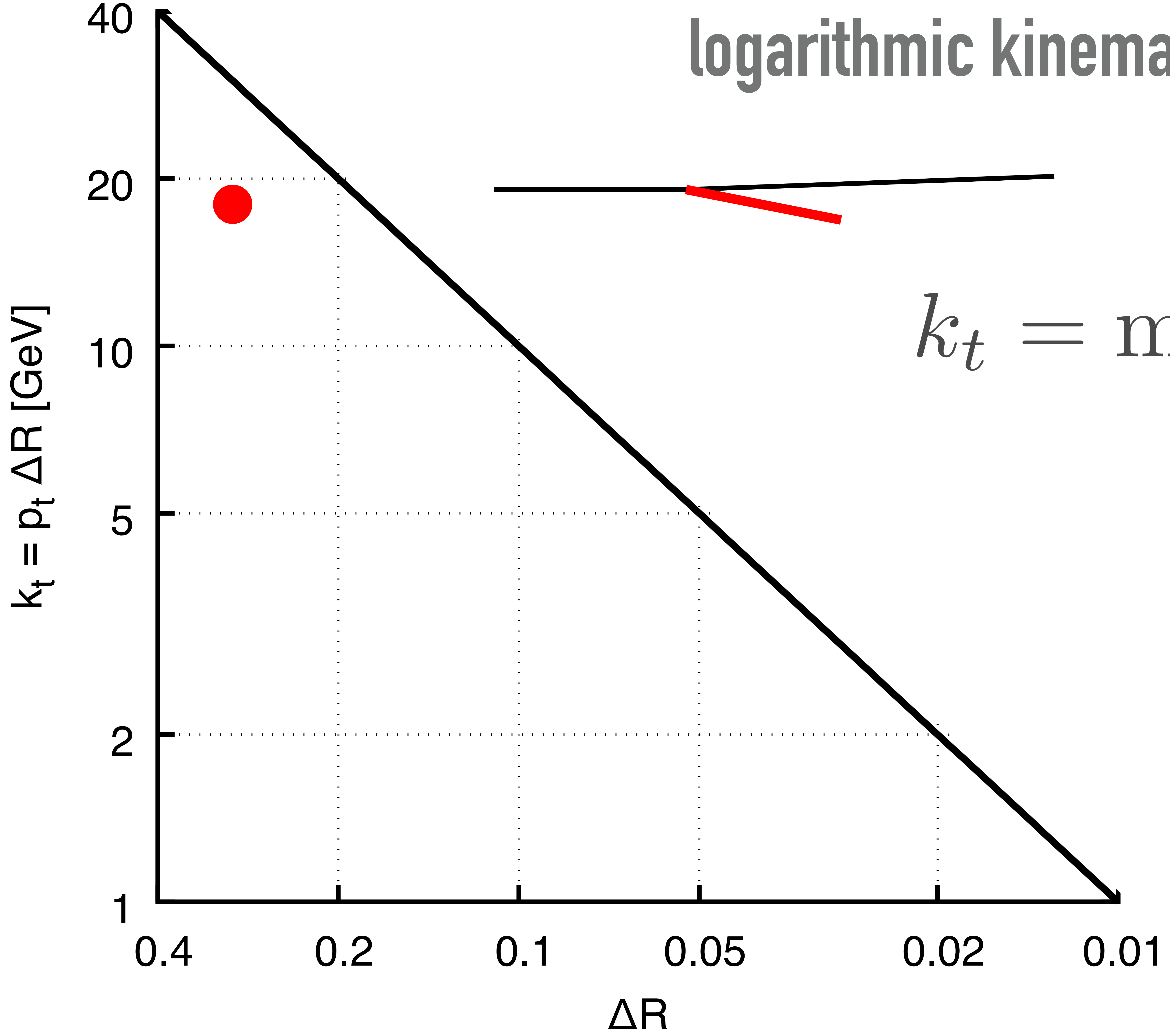

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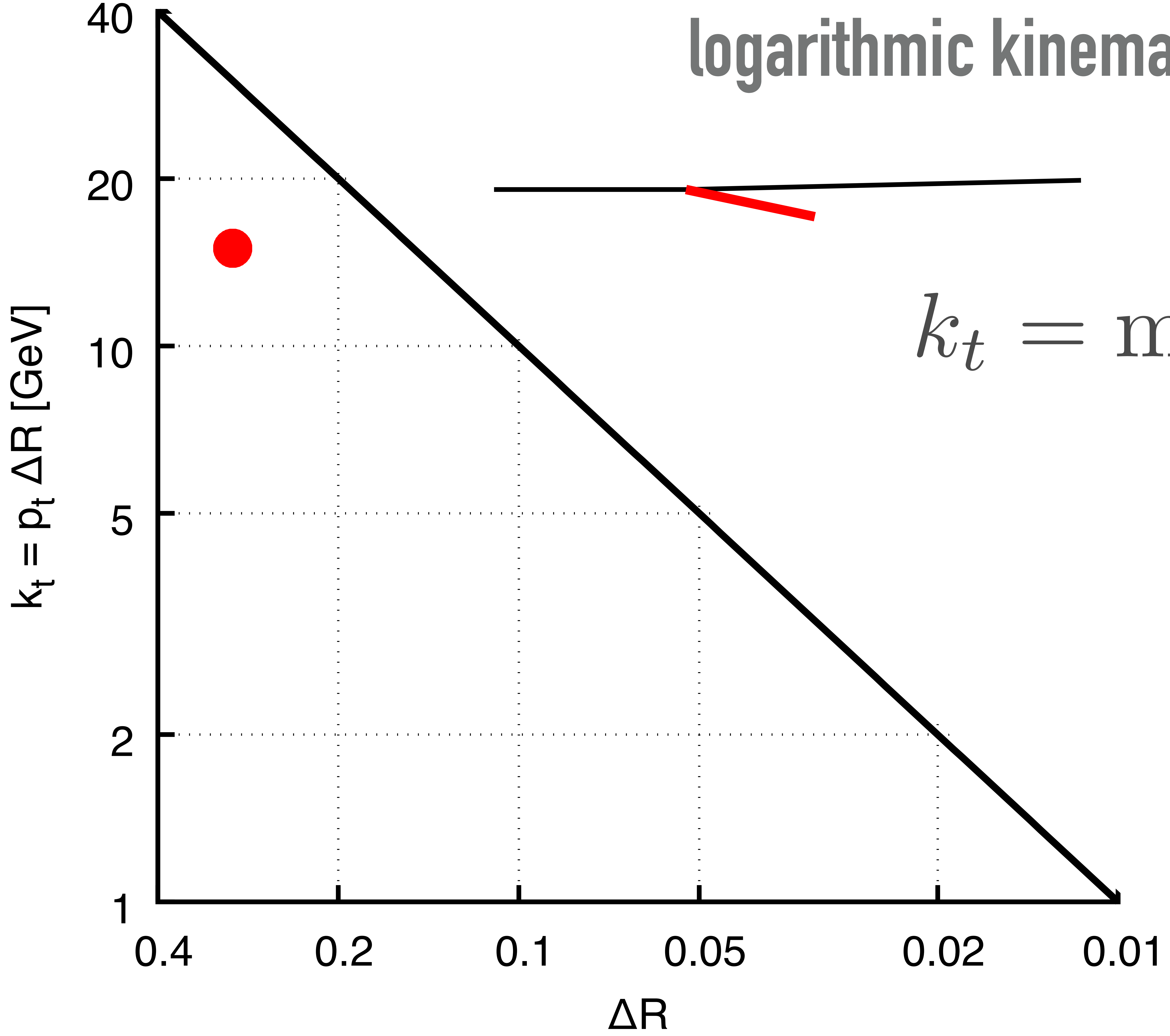

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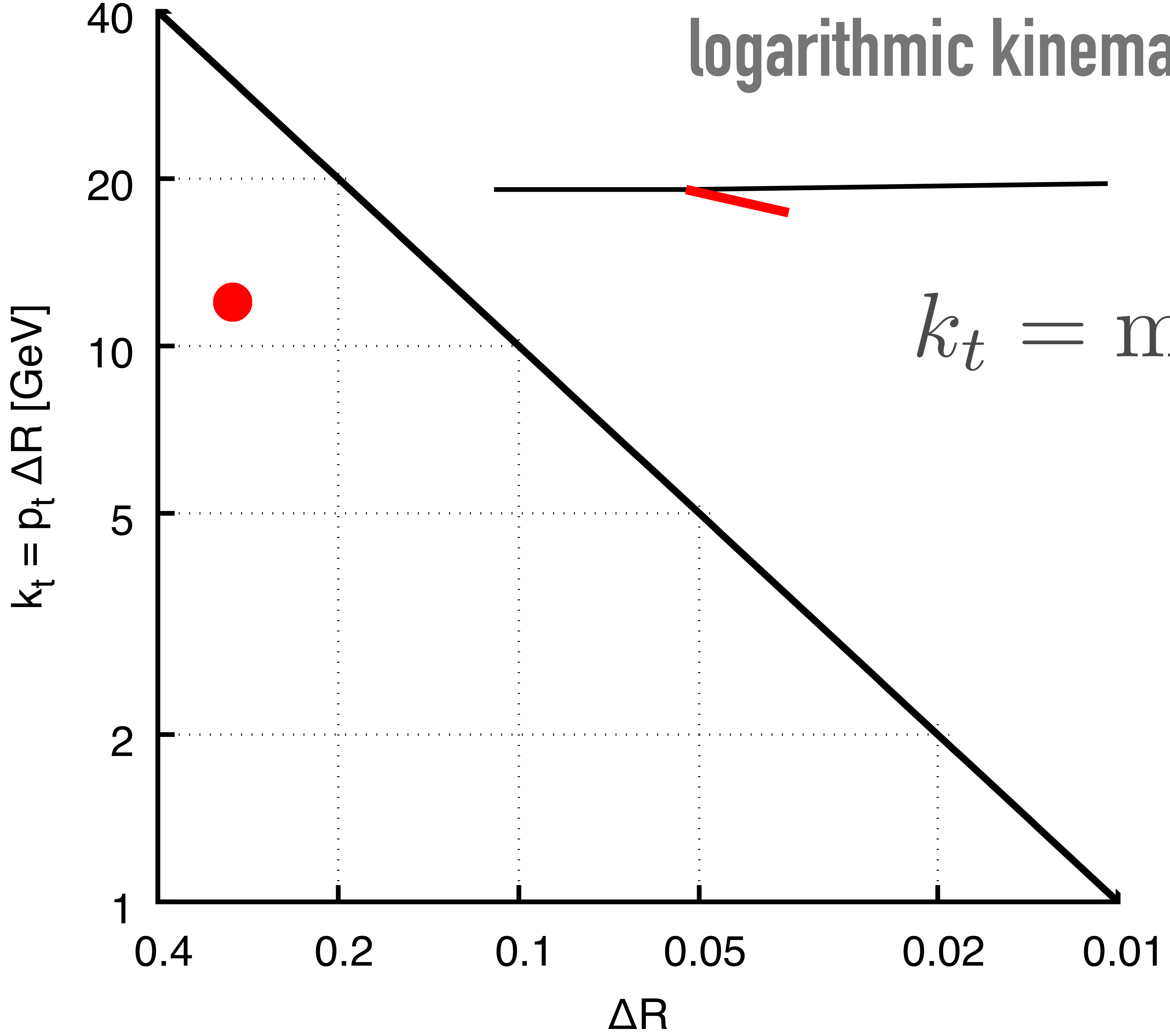

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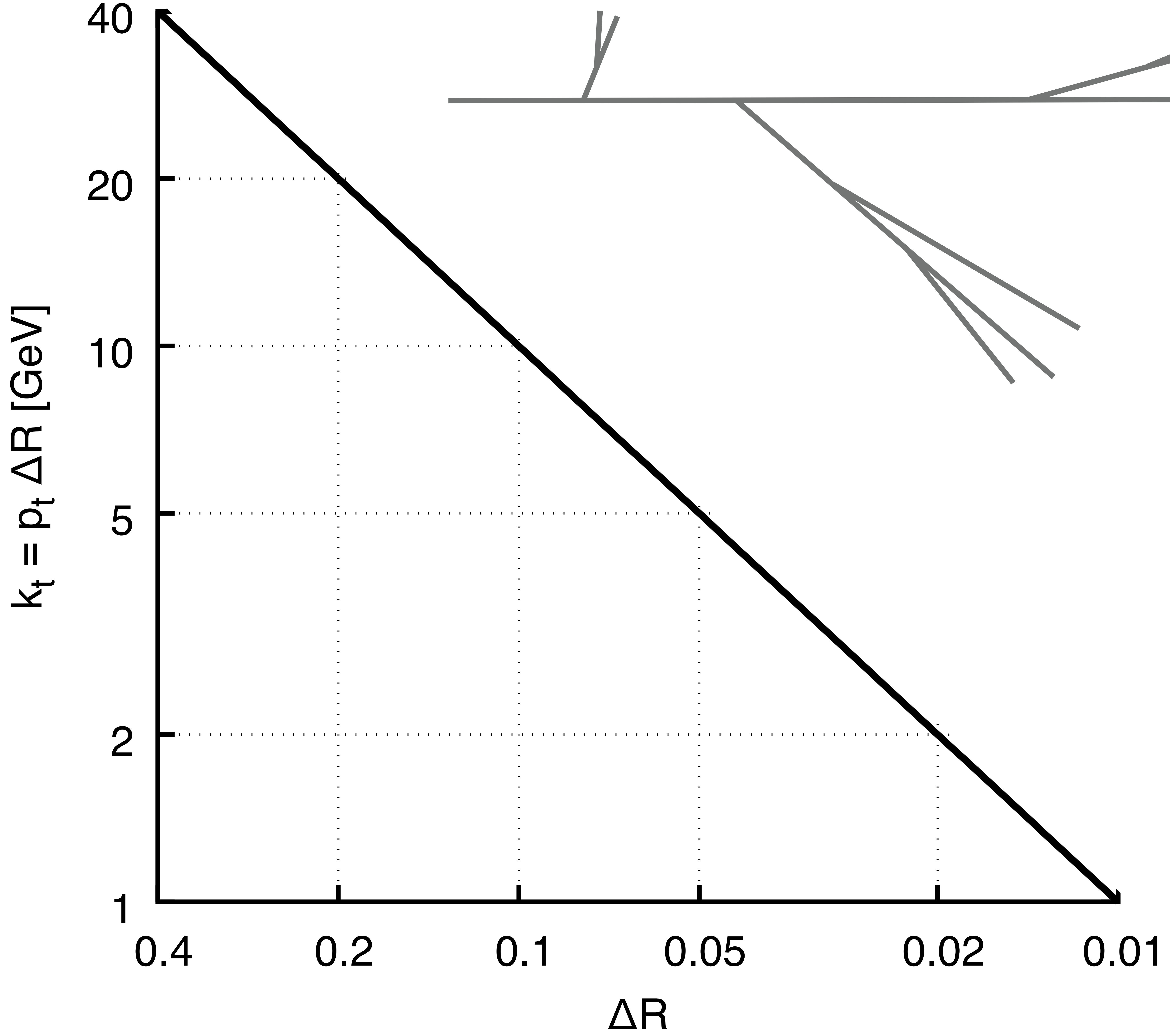
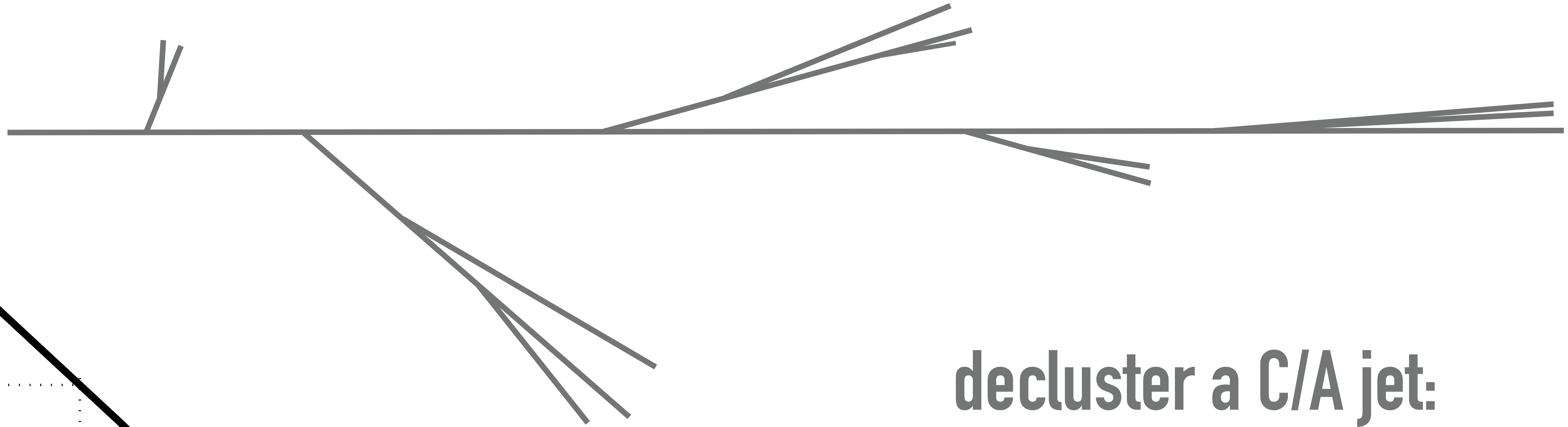


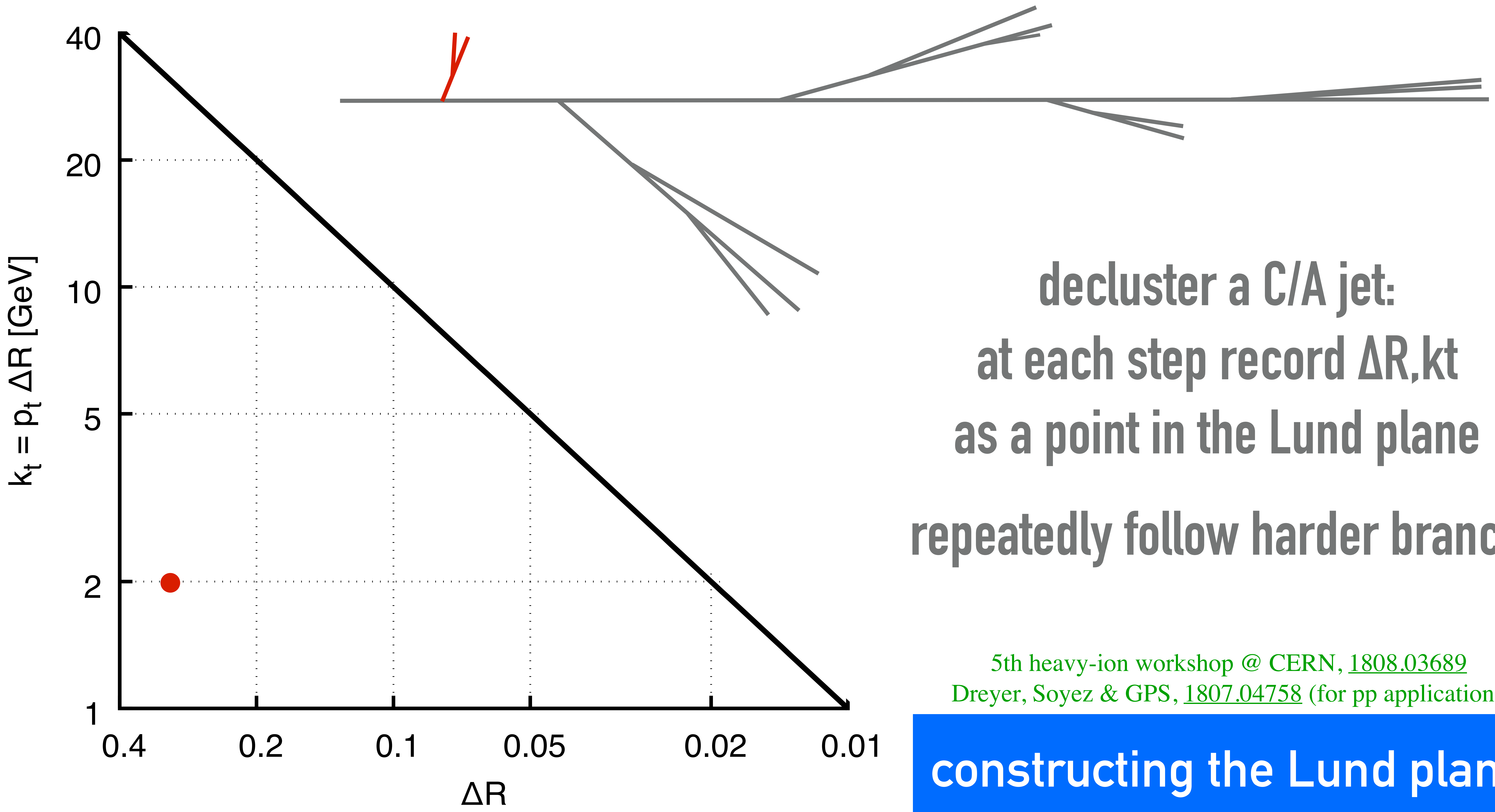


decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

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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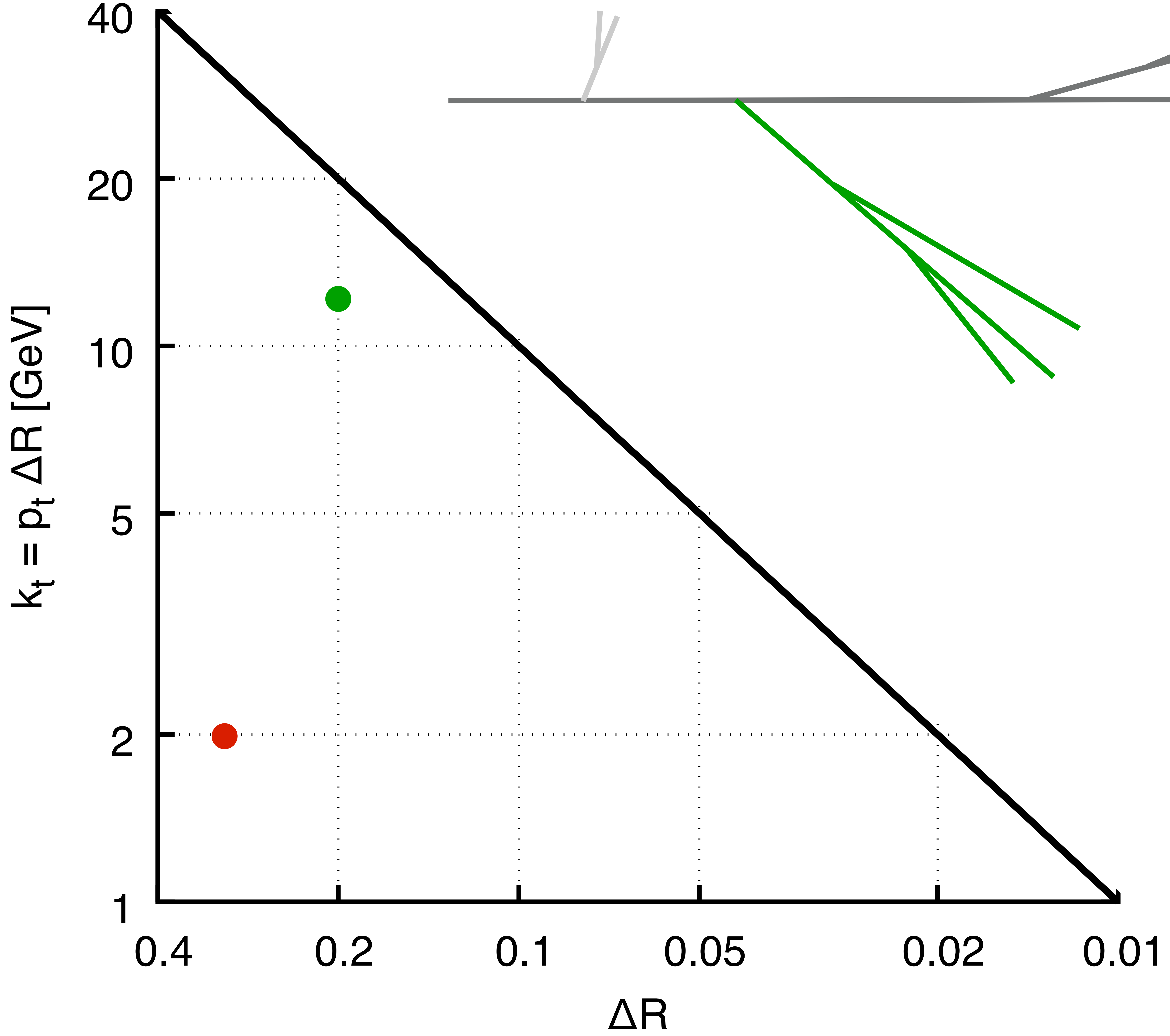

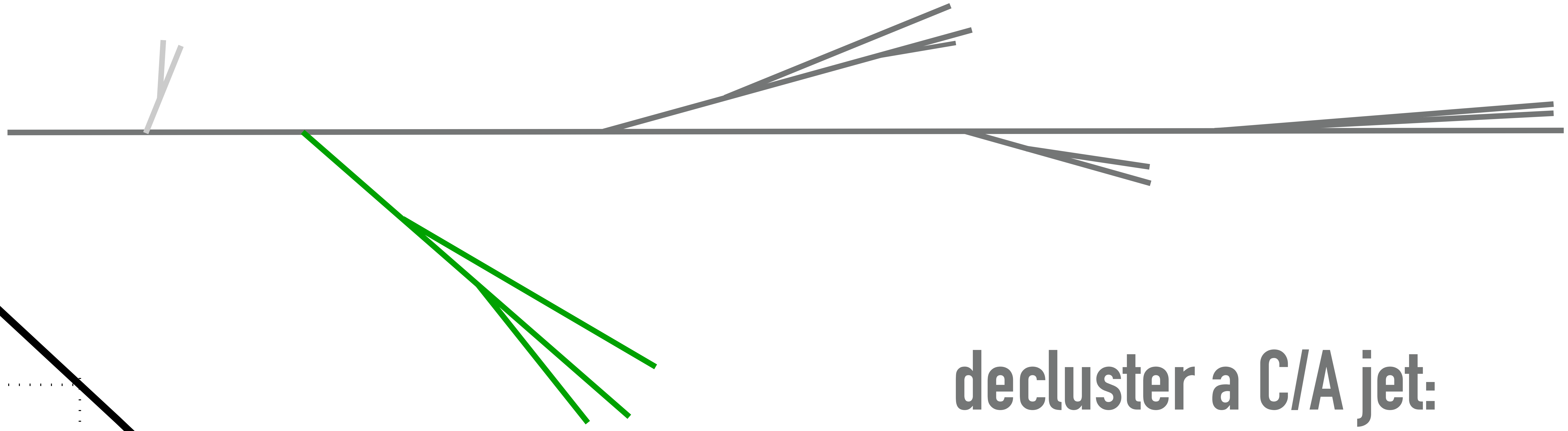

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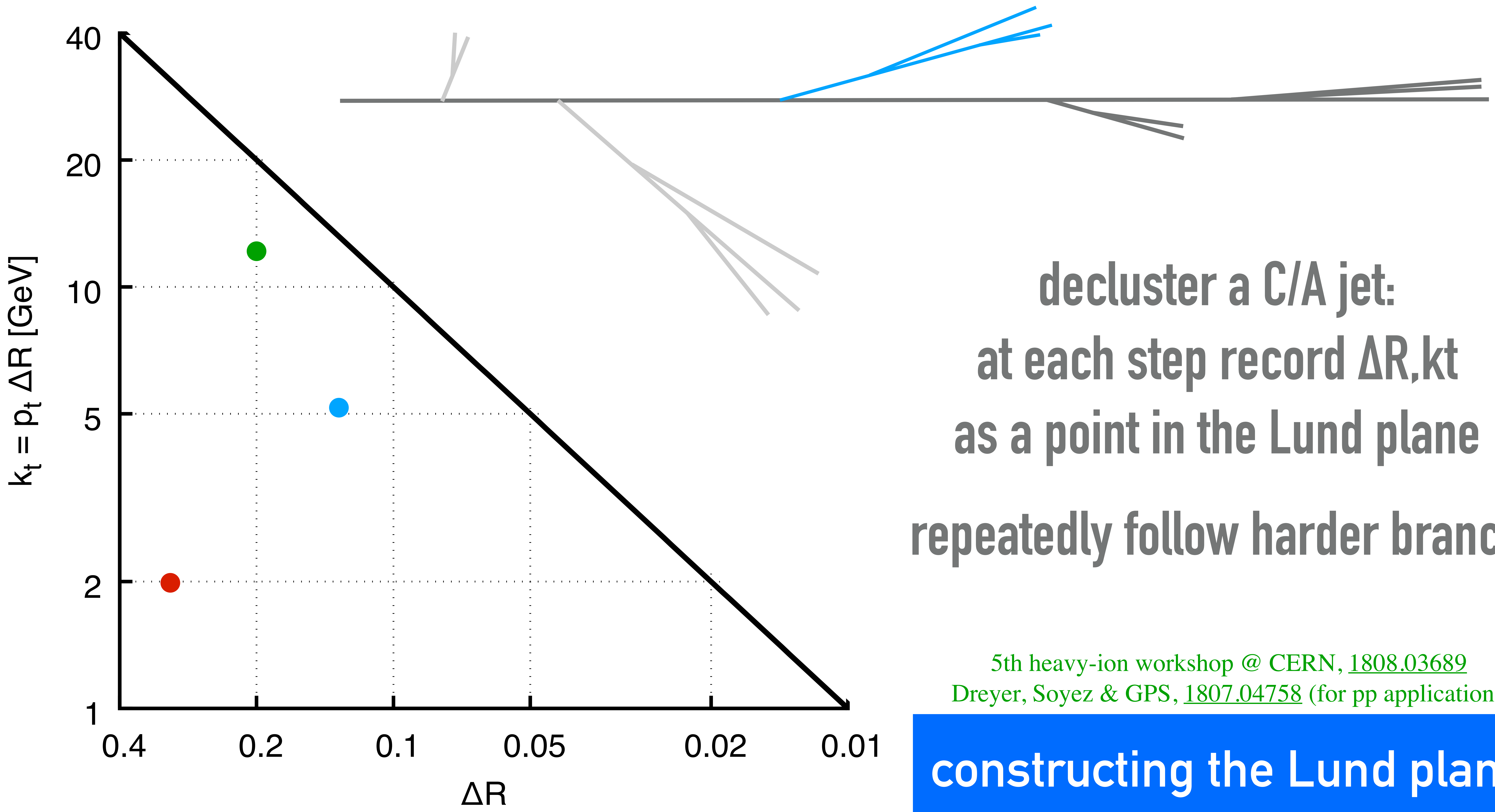

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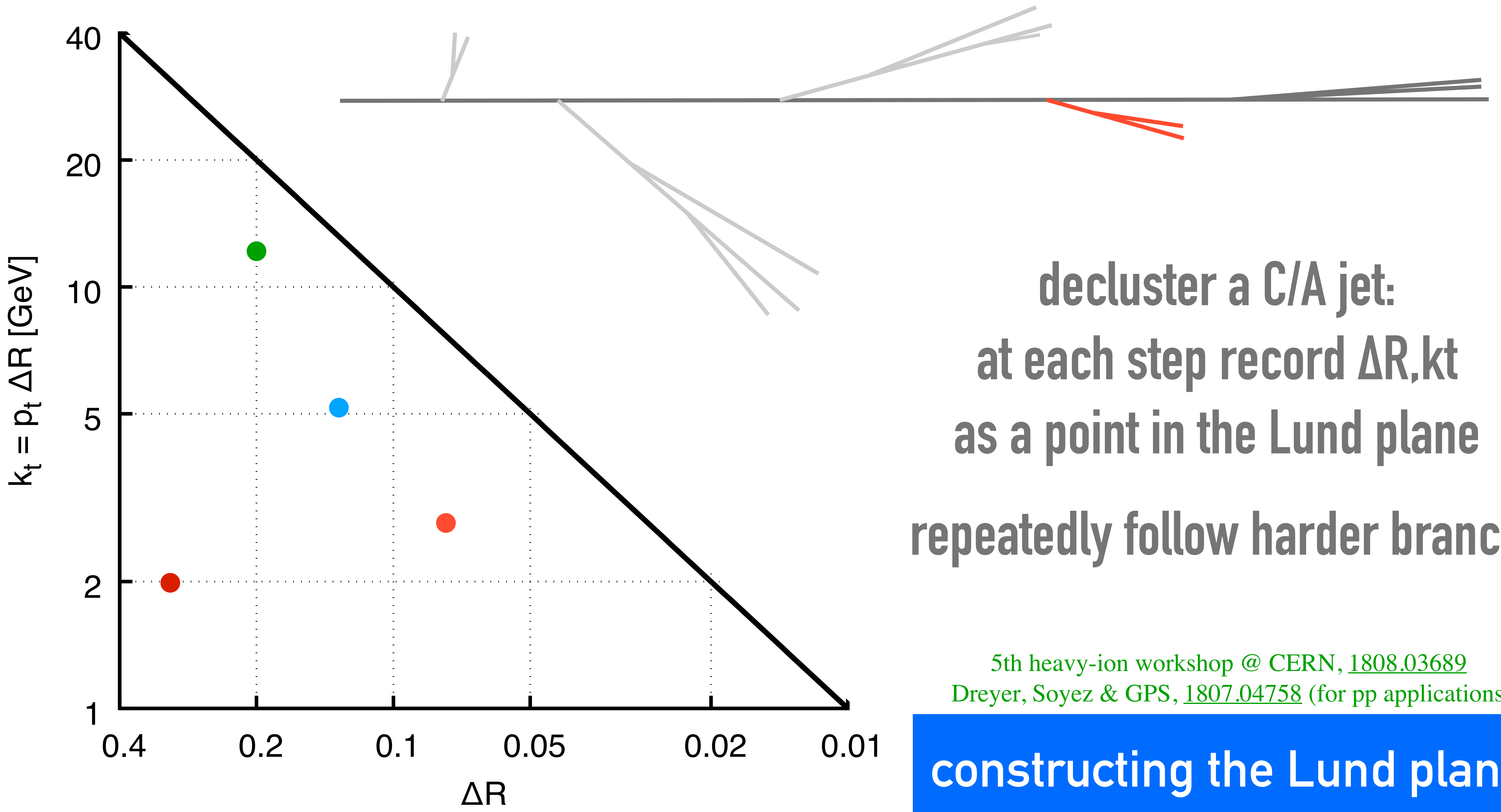

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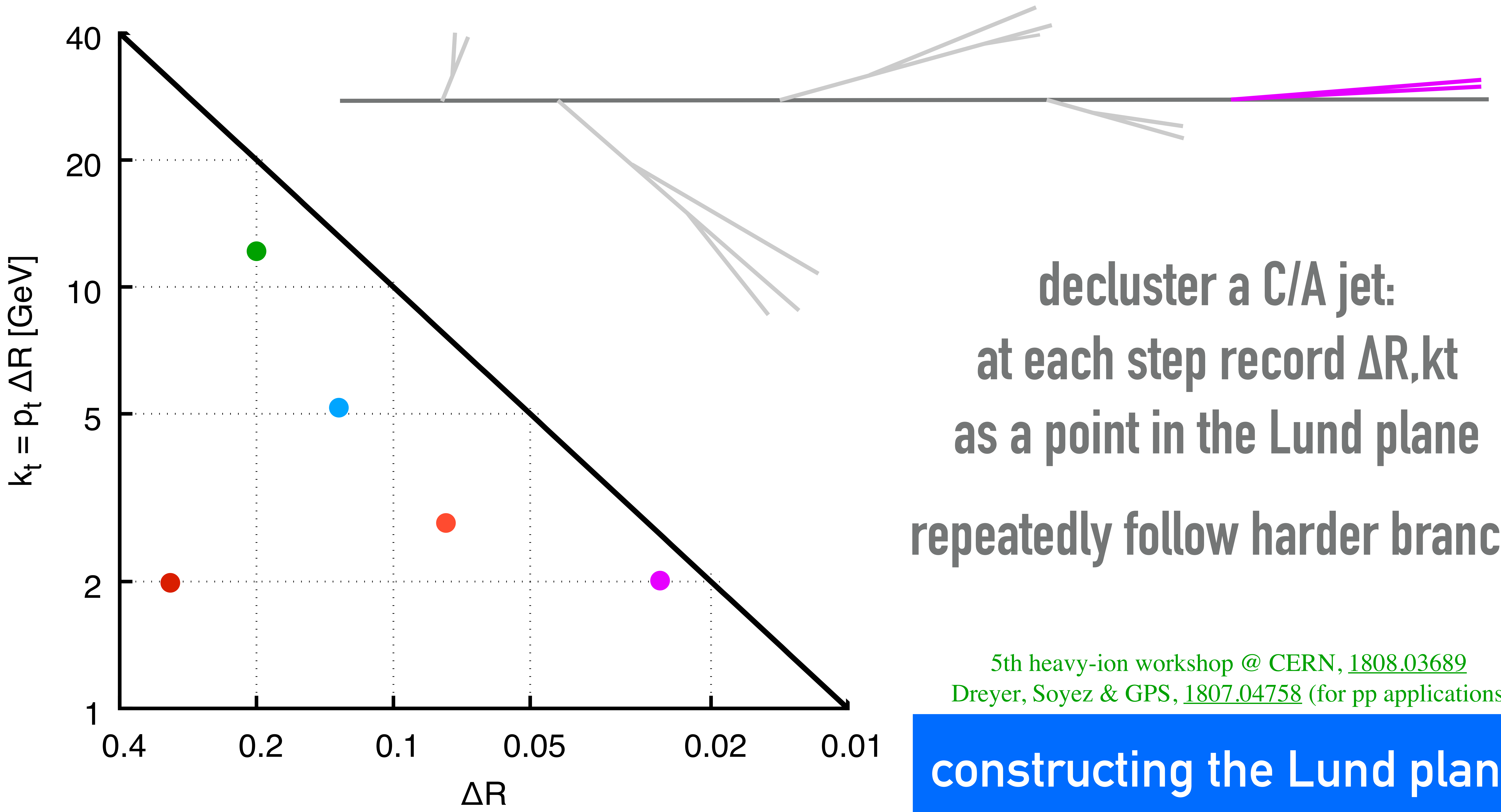

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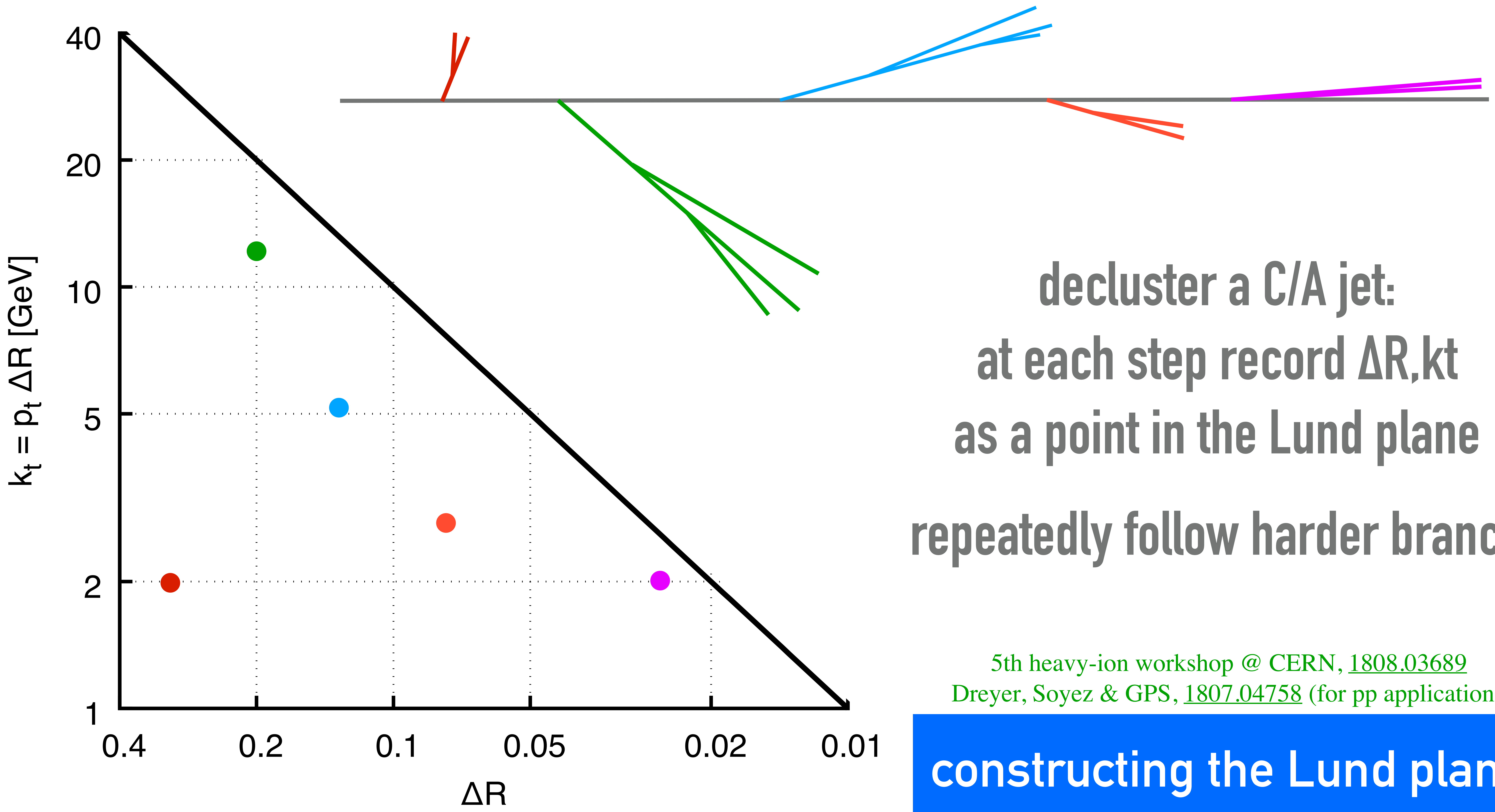

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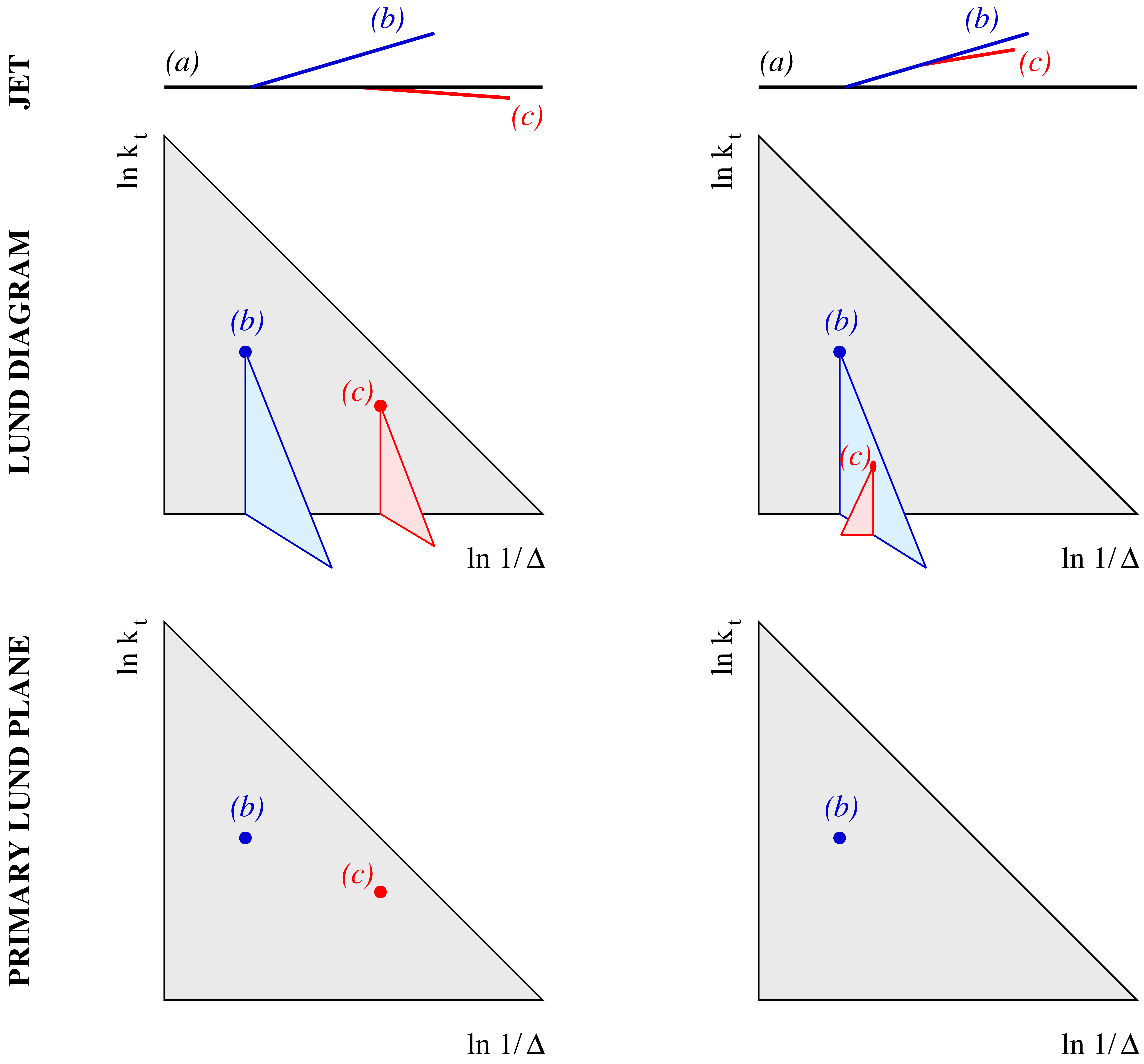
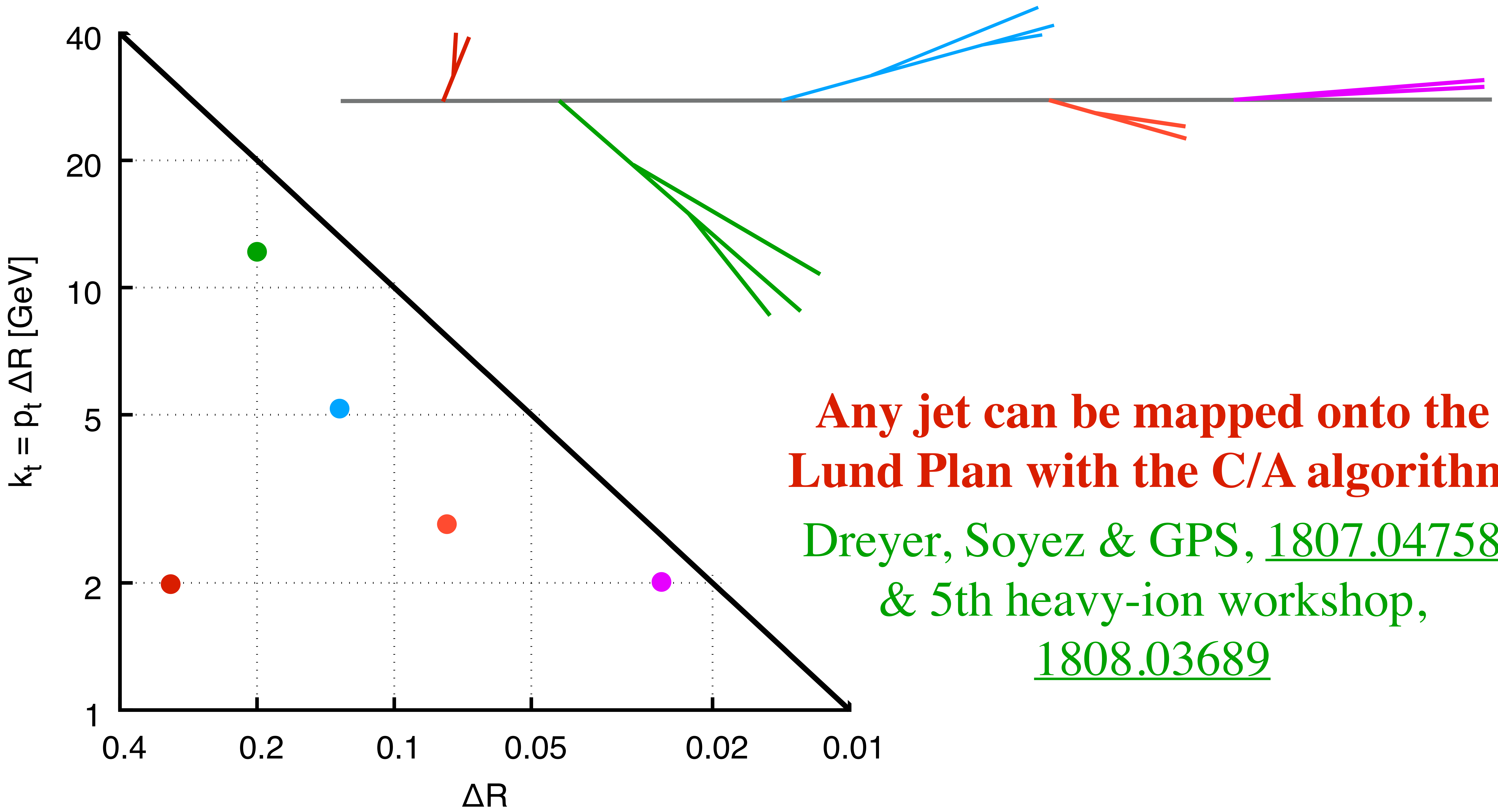
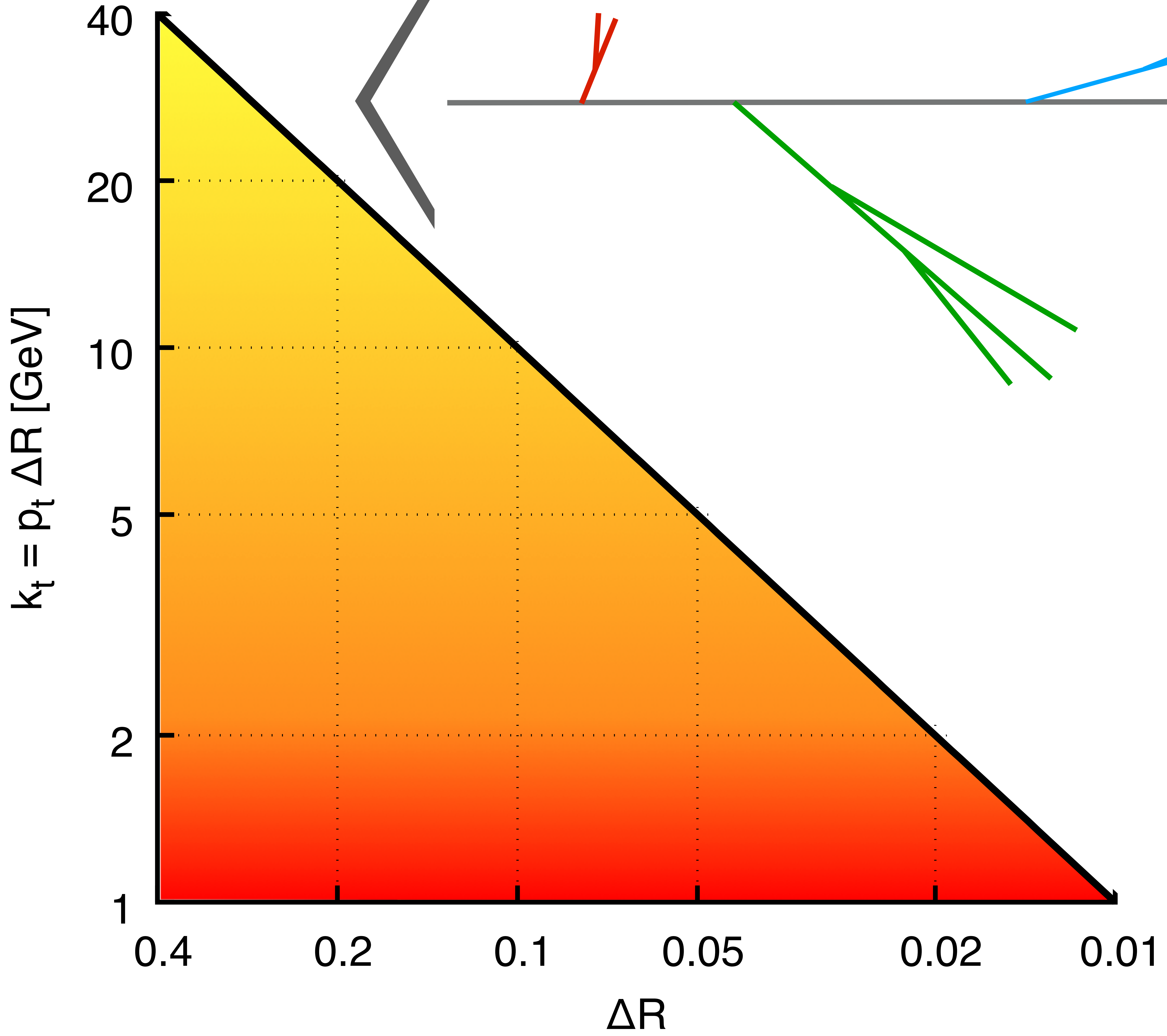

JET
LUND DIAGRAM
PRIMARY LUND PLANE
(a)
(b)
(c)
ln k_t
ln $1/\Delta$

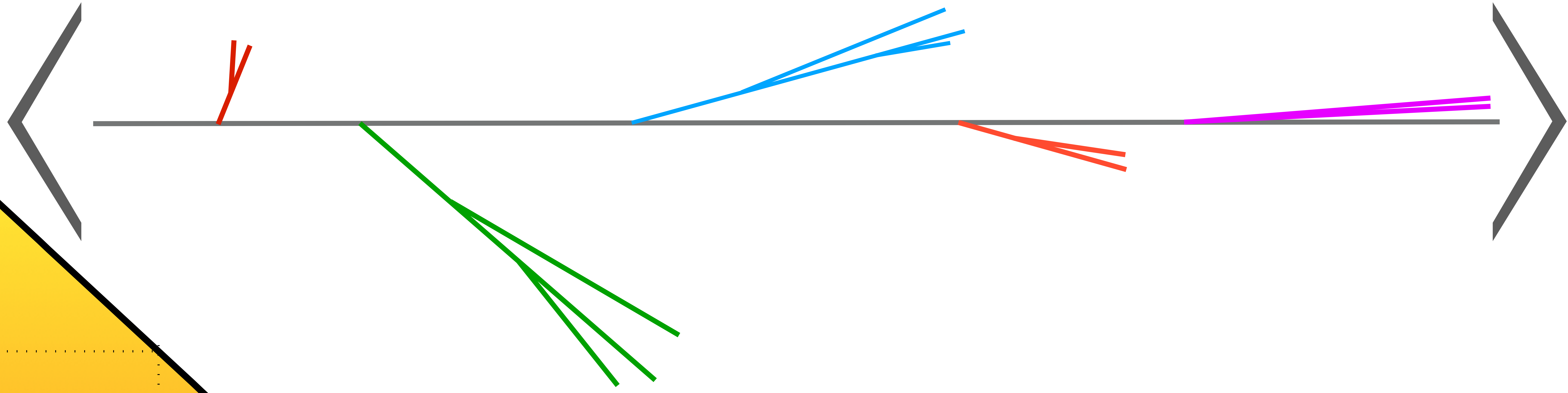


Any jet can be mapped onto the Lund Plan with the C/A algorithm

Dreyer, Soyez & GPS, 1807.04758 & 5th heavy-ion workshop, 1808.03689

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

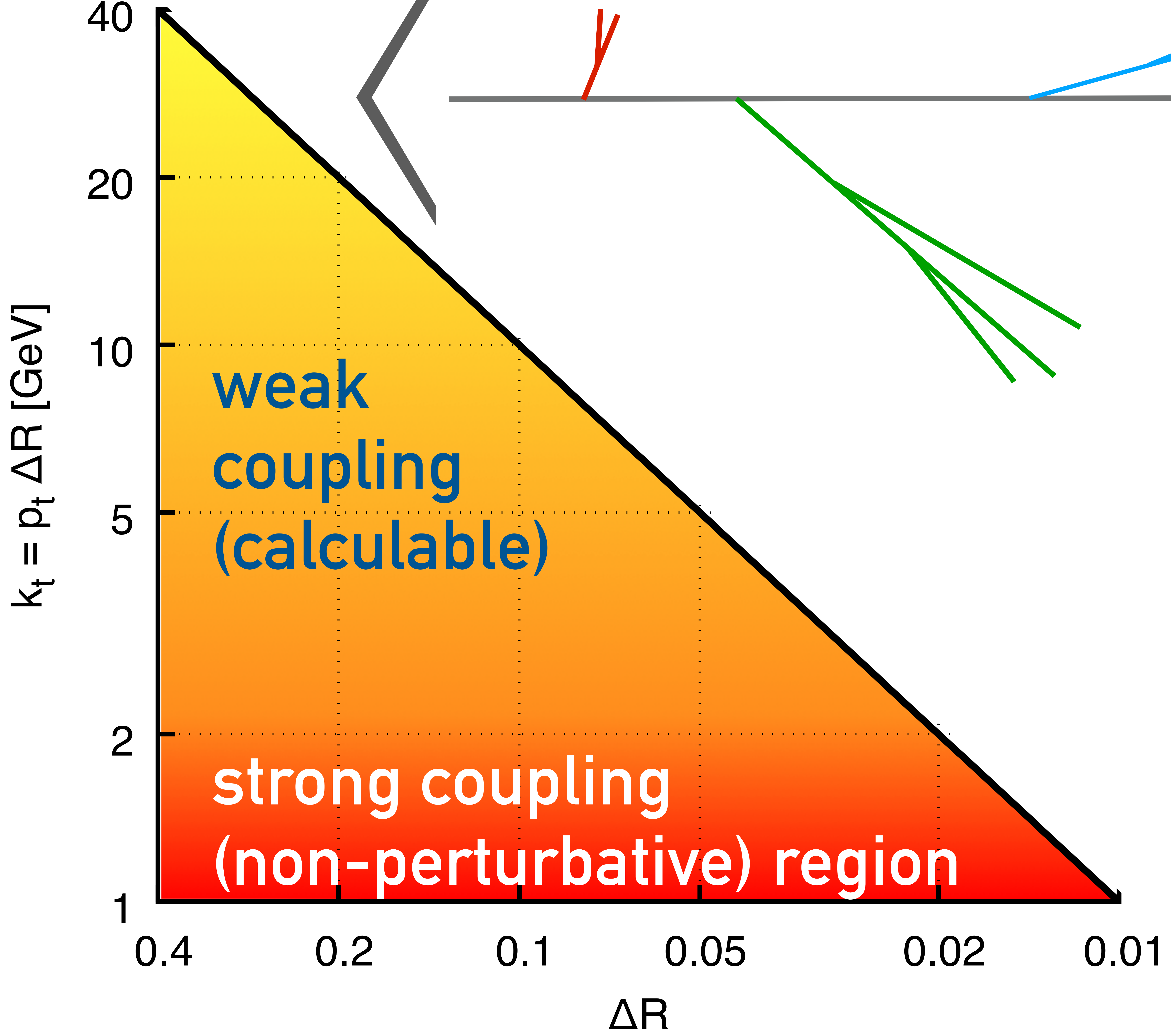


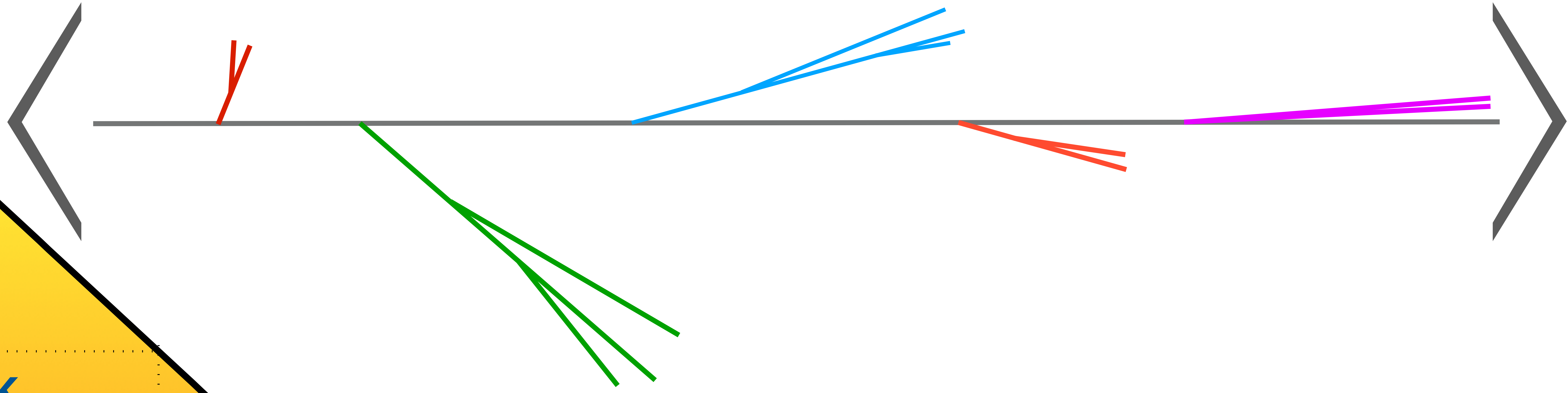


average over many jets:

Lund plane density

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

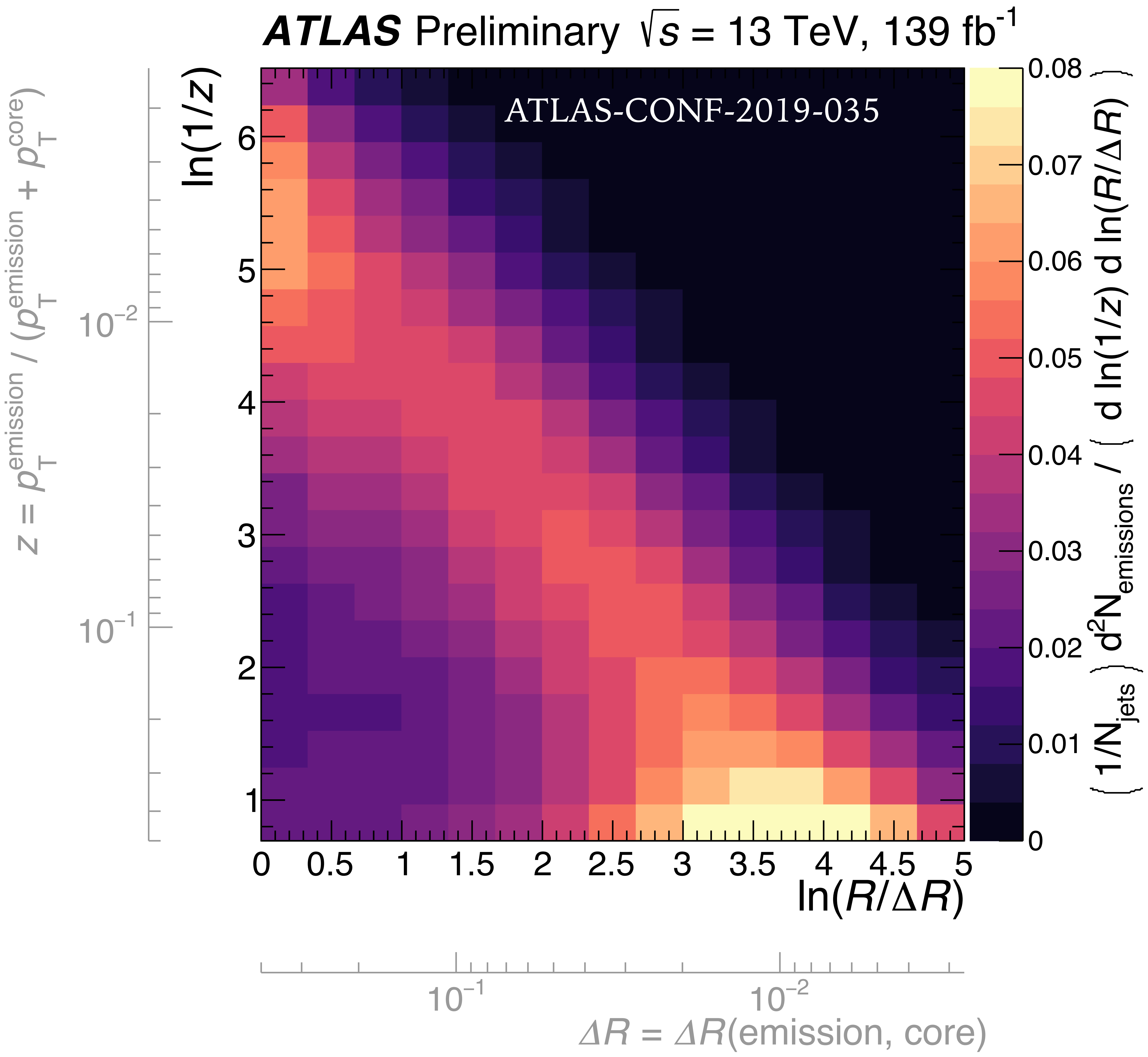


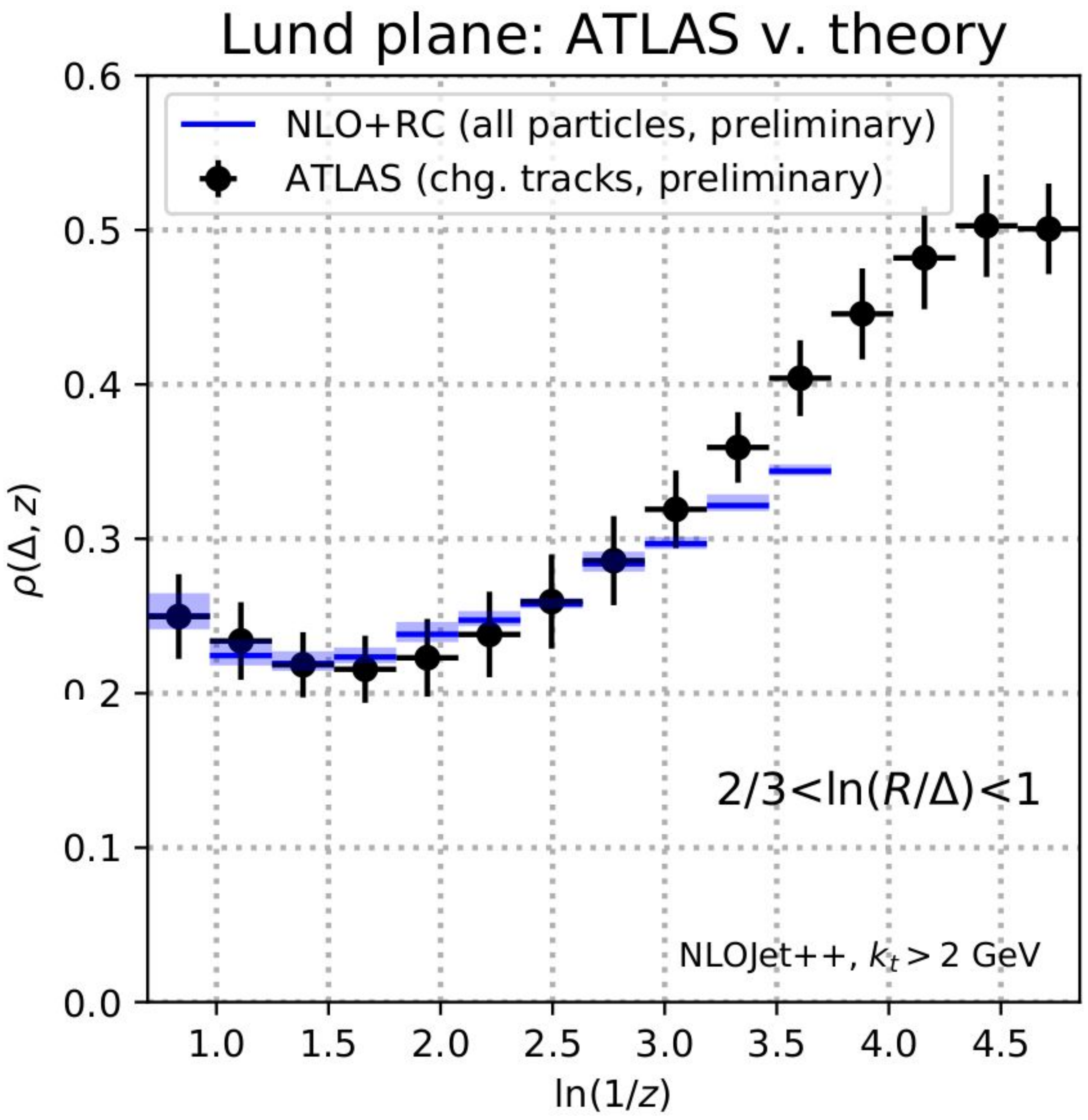


average over many jets:

Lund plane density

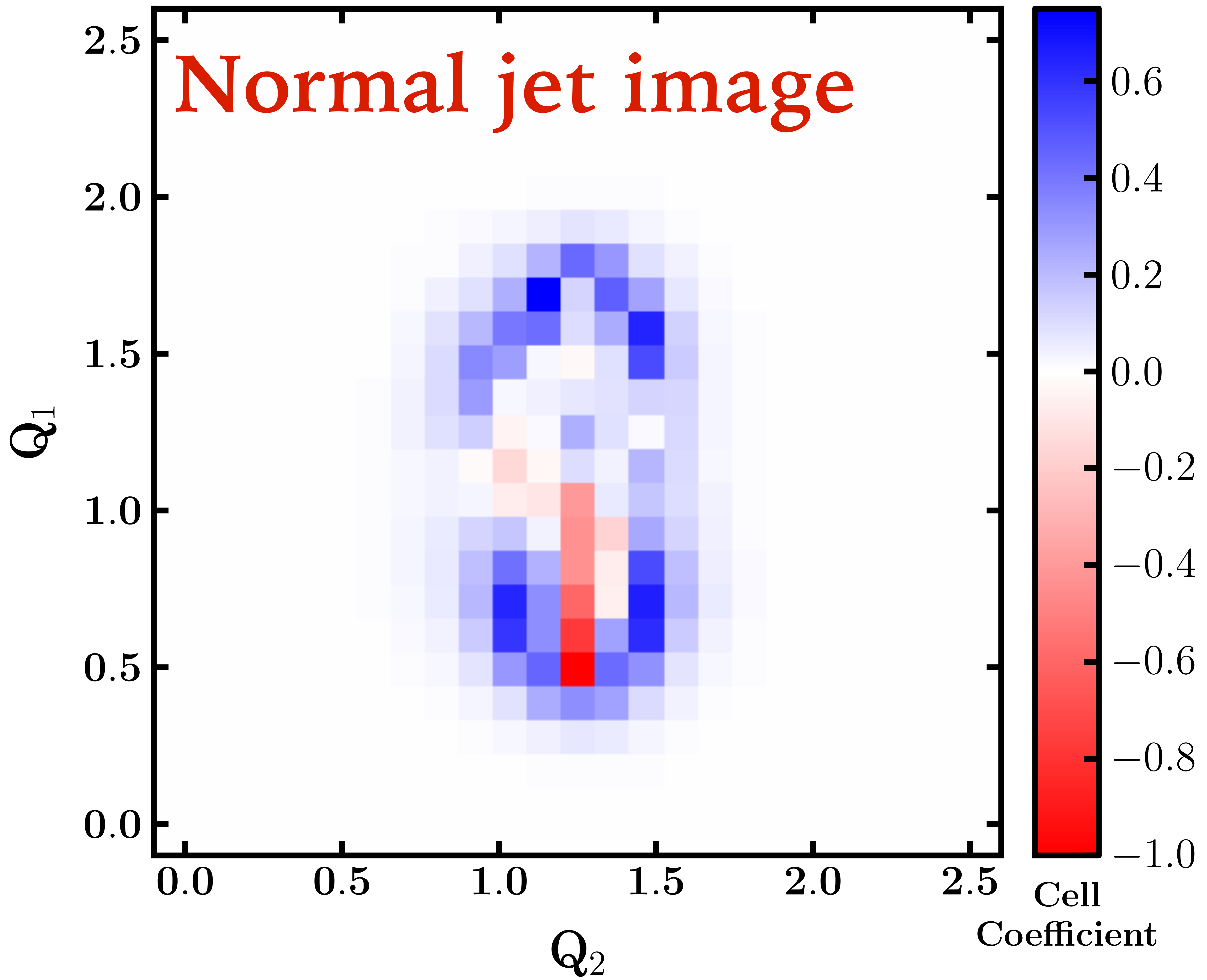
Lund plane measurement



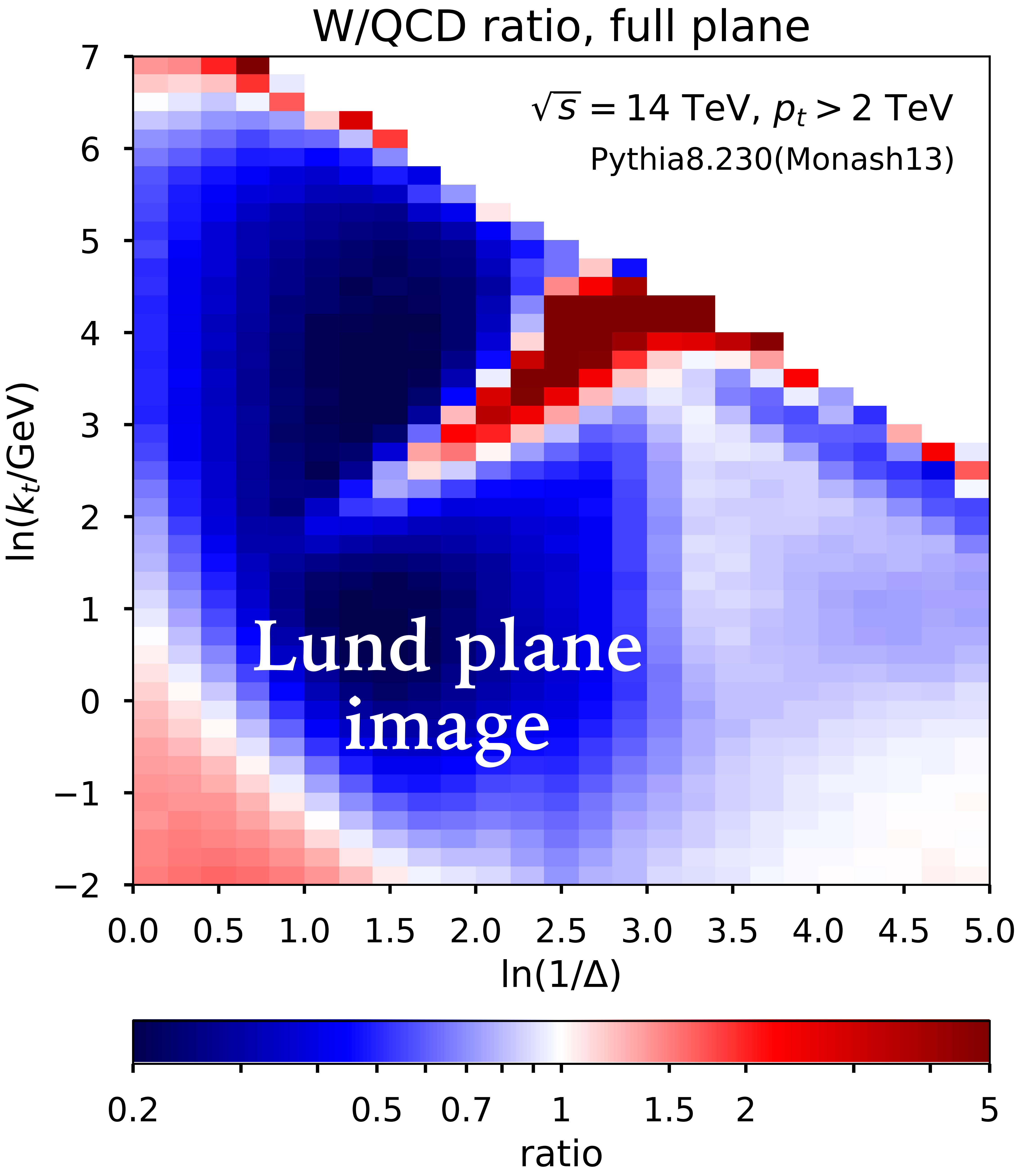


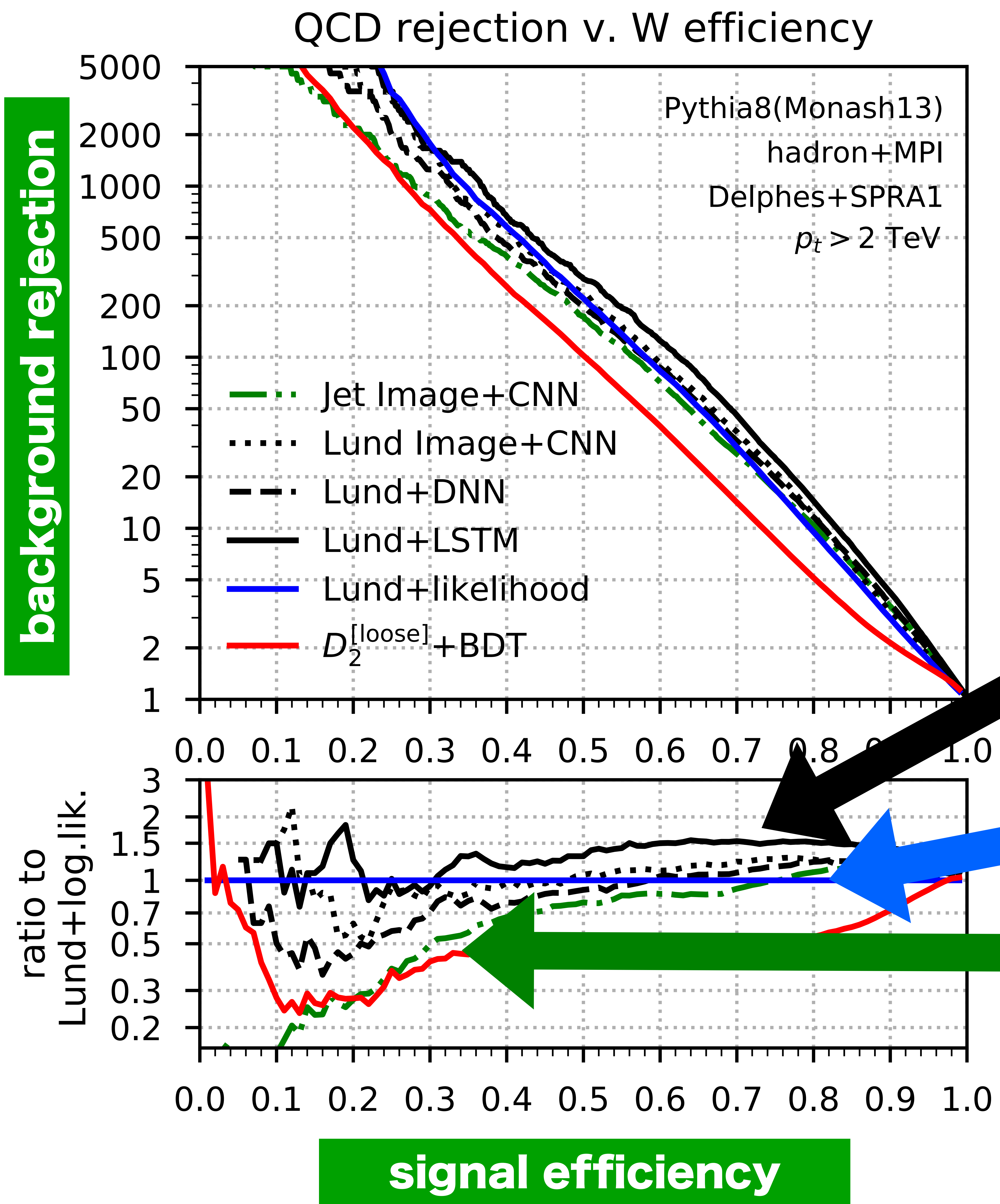
Dreyer & Soyez prelim @Boost 2019

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…

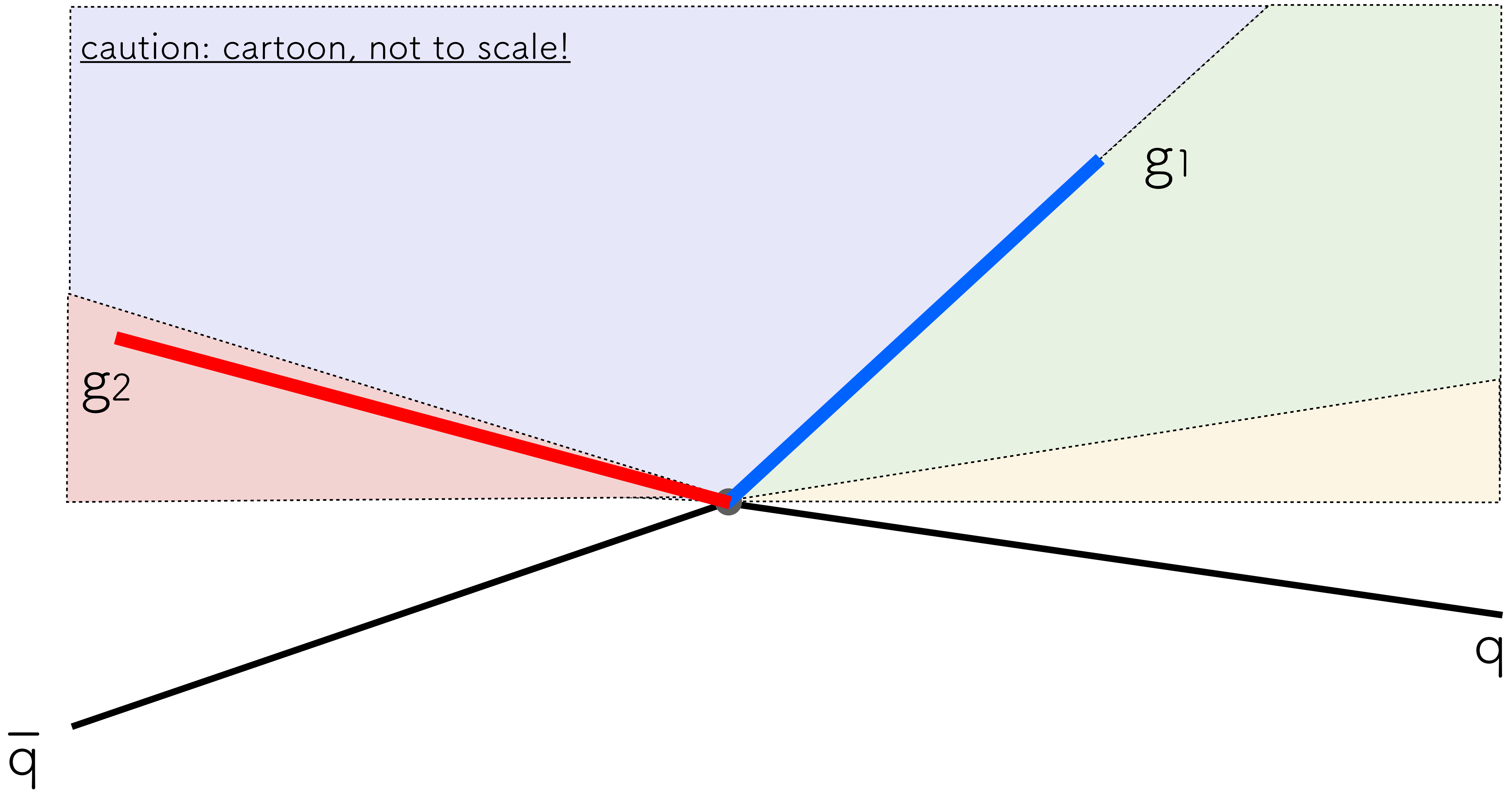
"

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

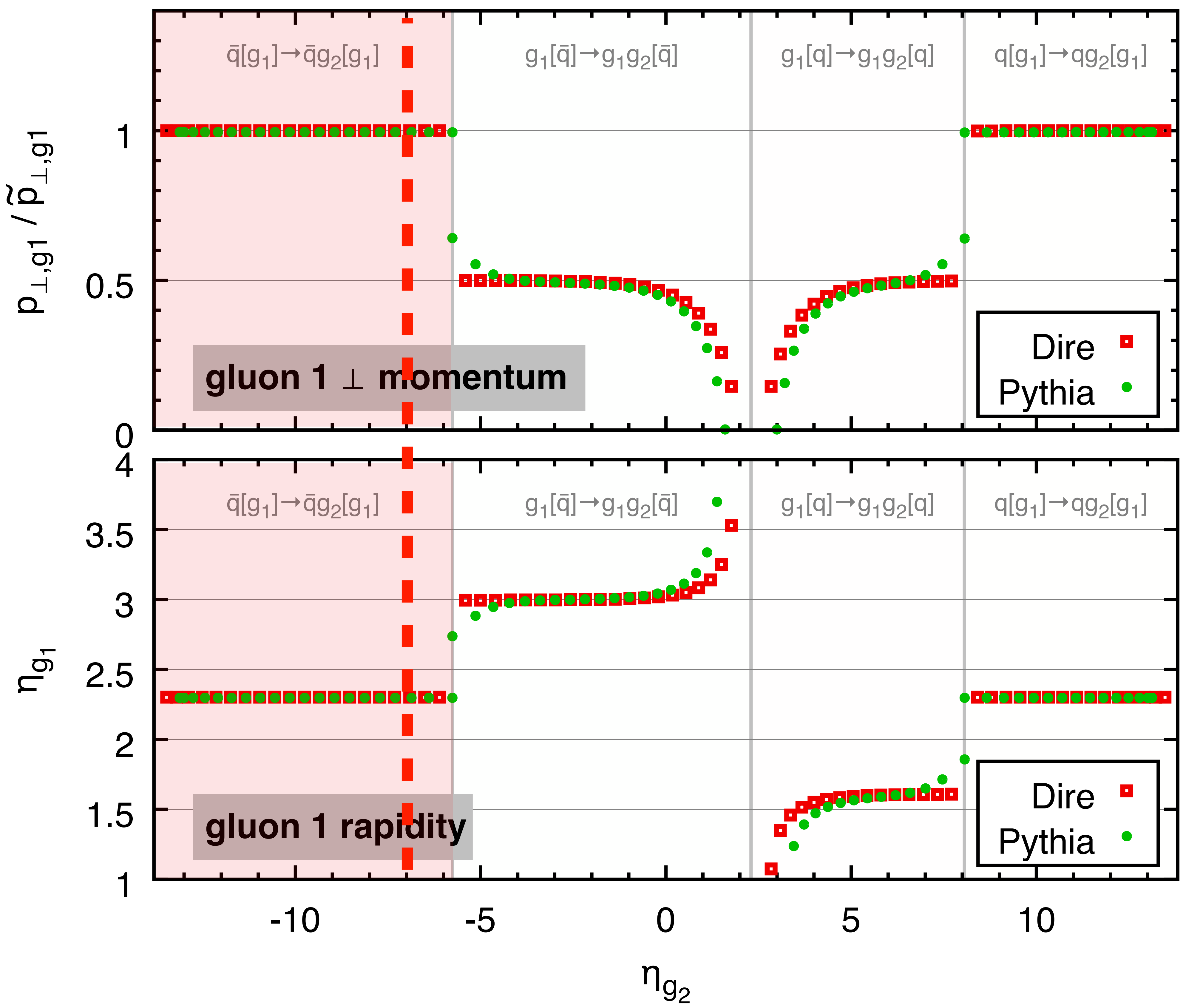
- Harry Markowitz (1990 Nobel Prize in Economics)

[via S Gukov]

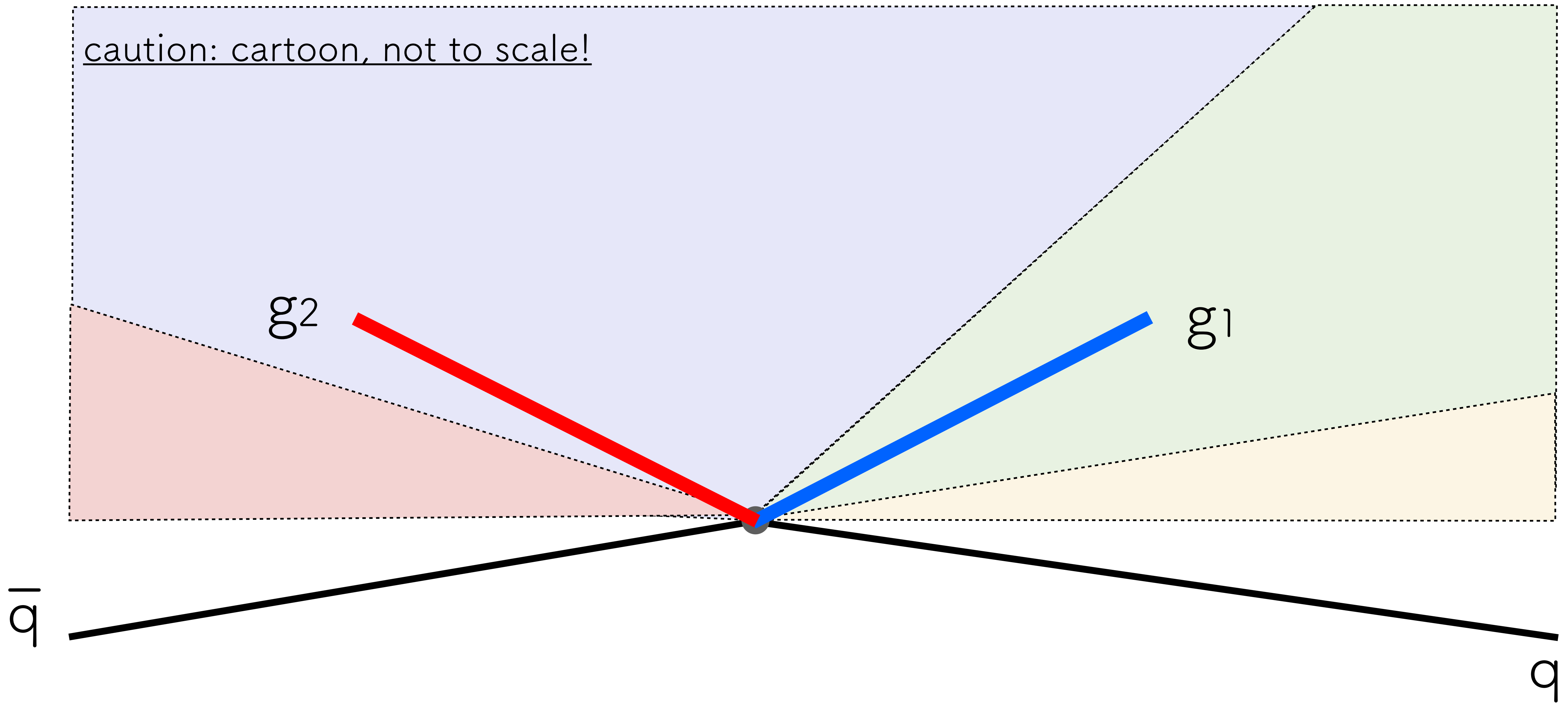
Two emissions in dipole showers (Dire / Pythia8)



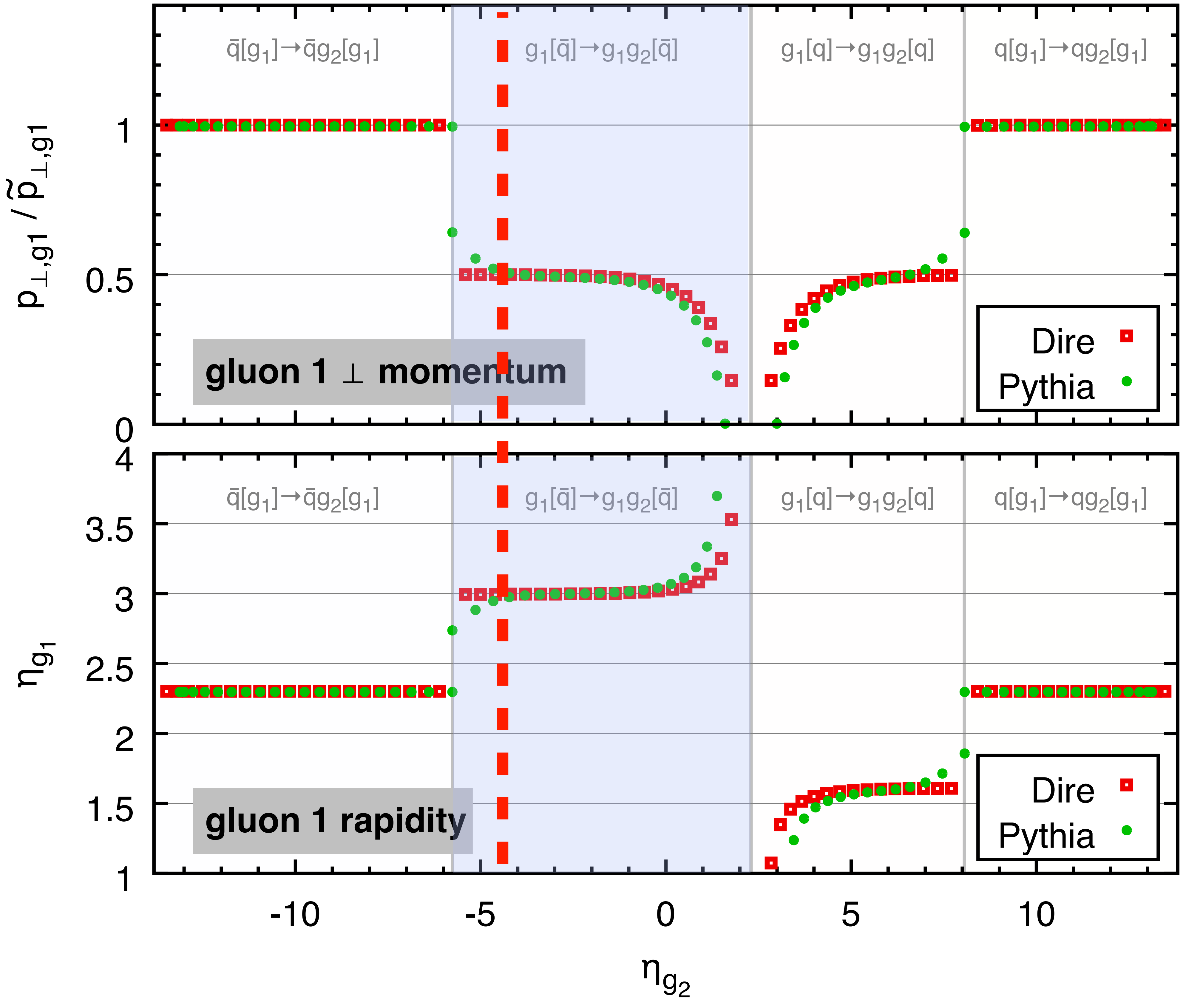
impact of gluon-2 emission on gluon-1 momentum



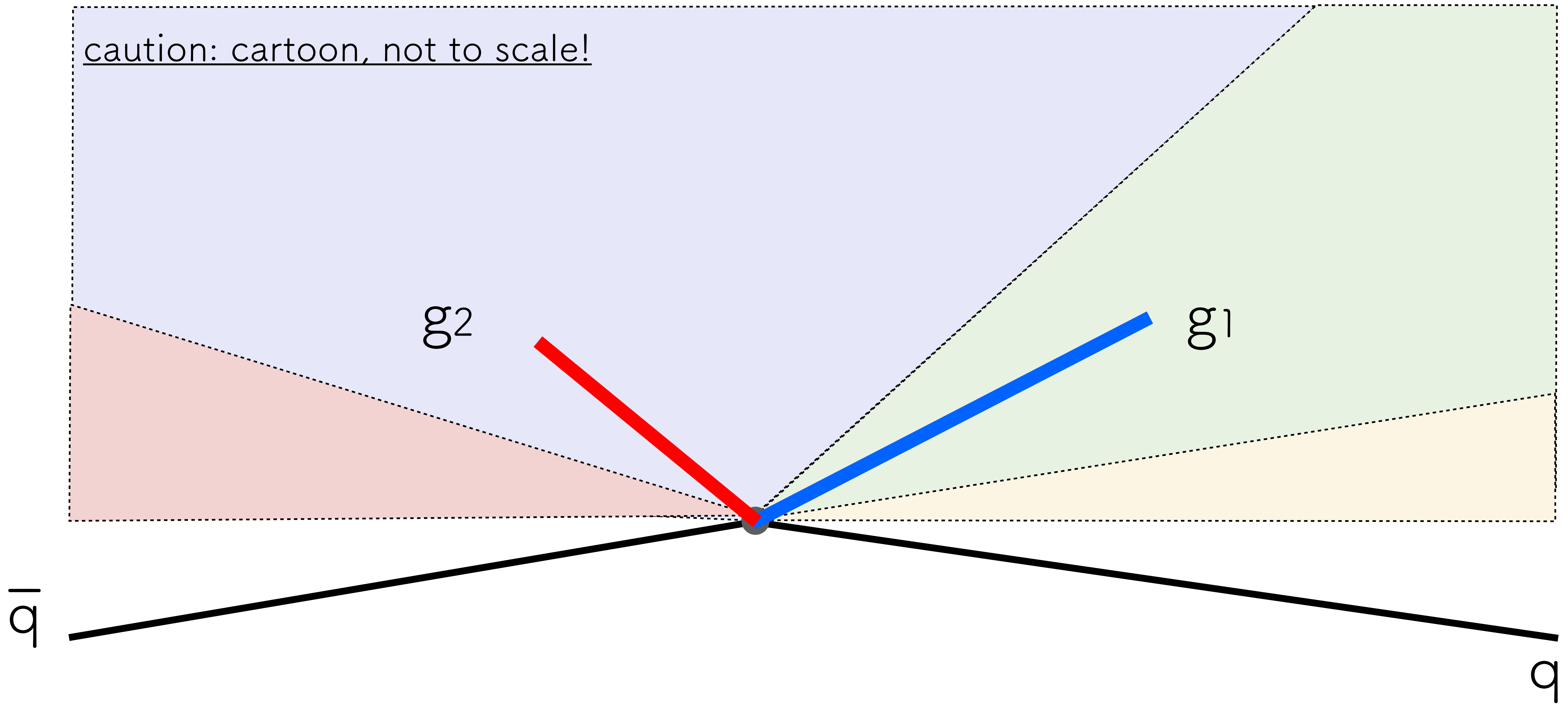
Two emissions in dipole showers (Dire / Pythia8)



impact of gluon-2 emission on gluon-1 momentum



Two emissions in dipole showers (Dire / Pythia8)



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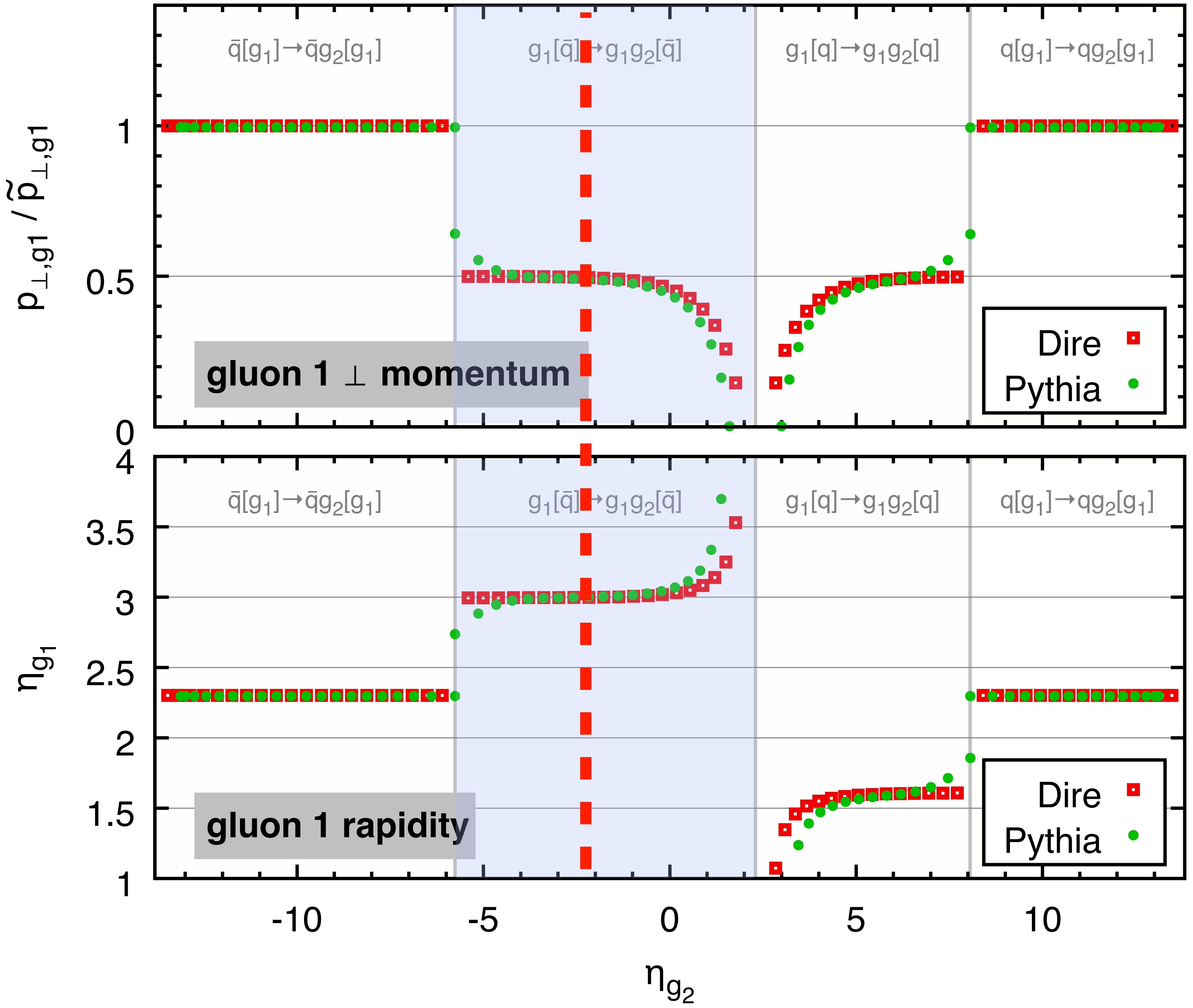

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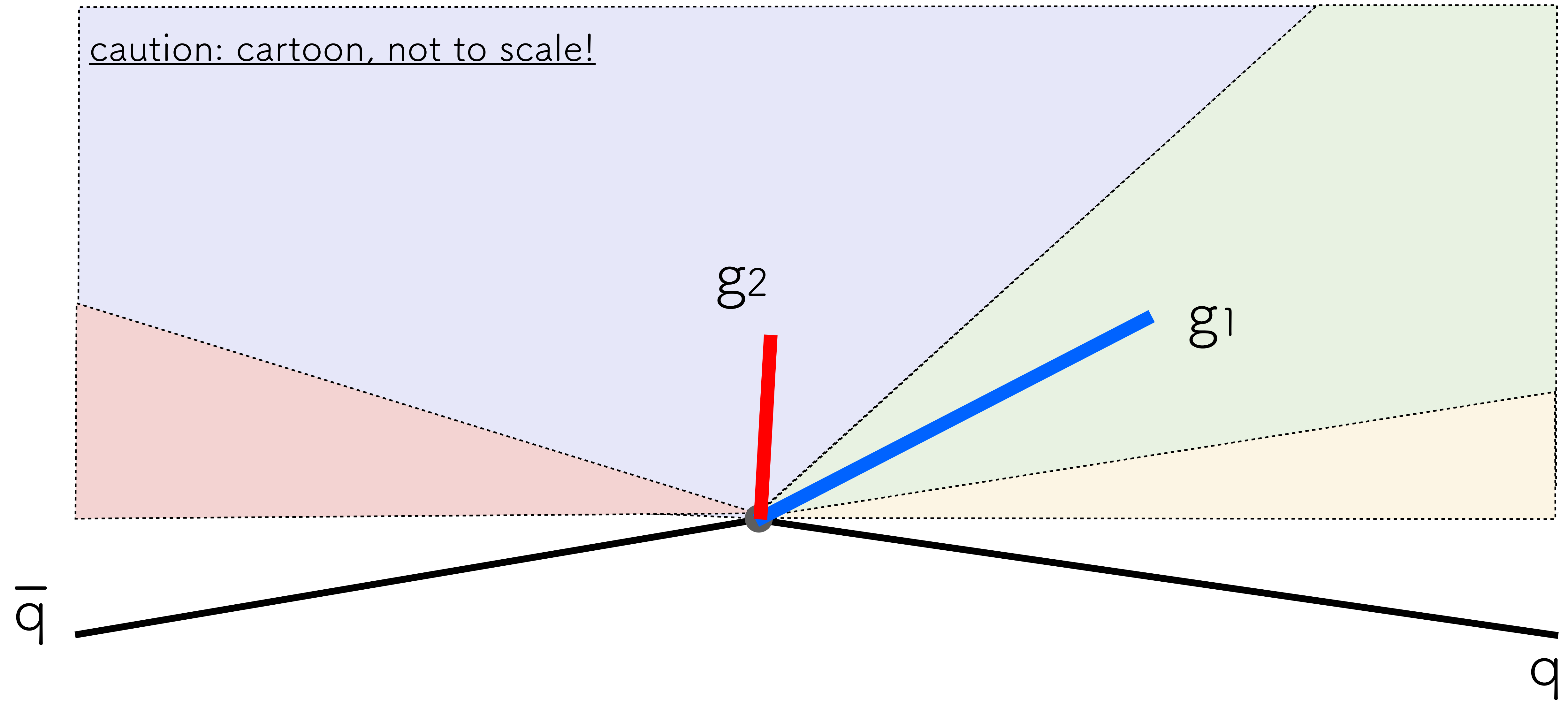

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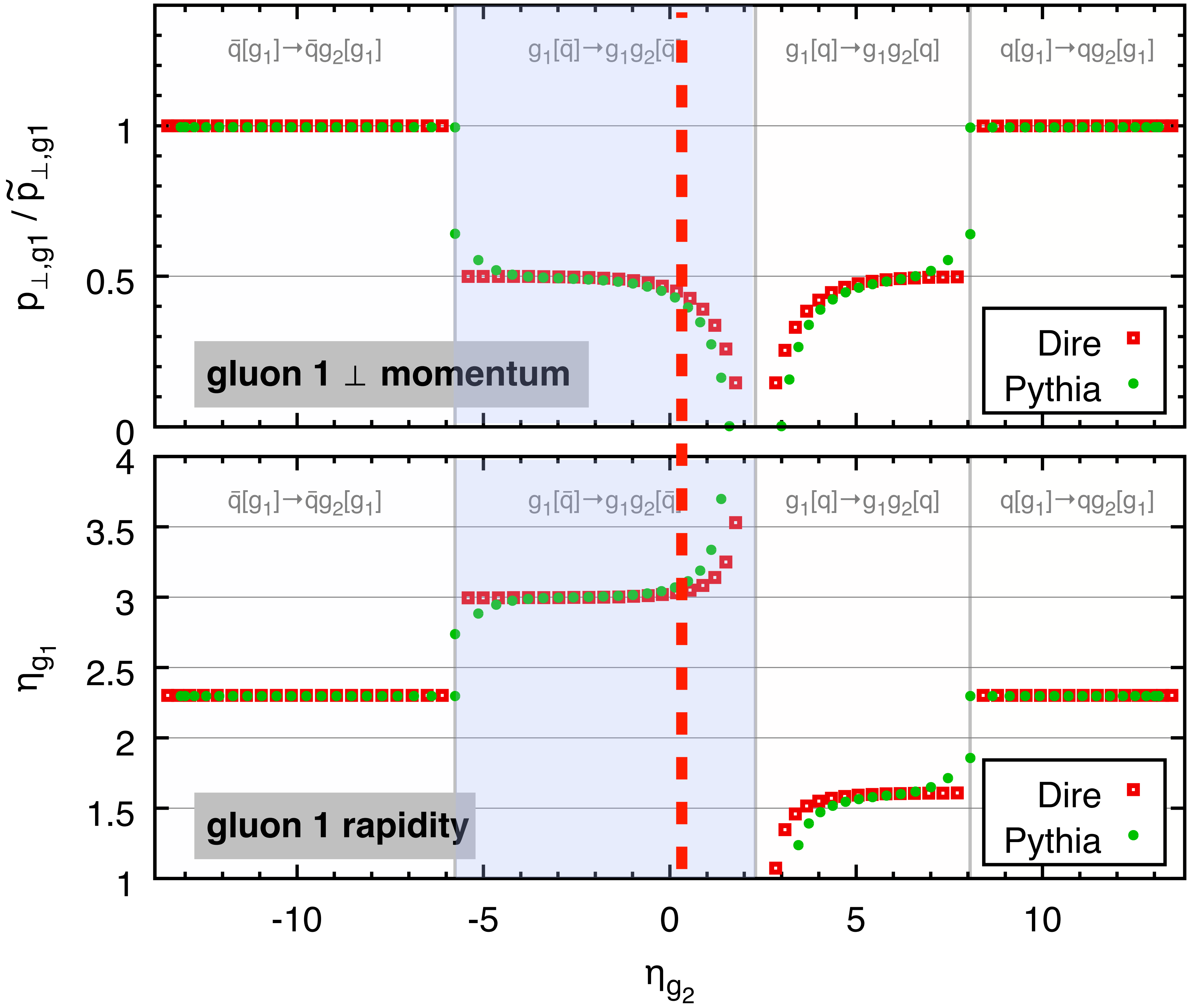

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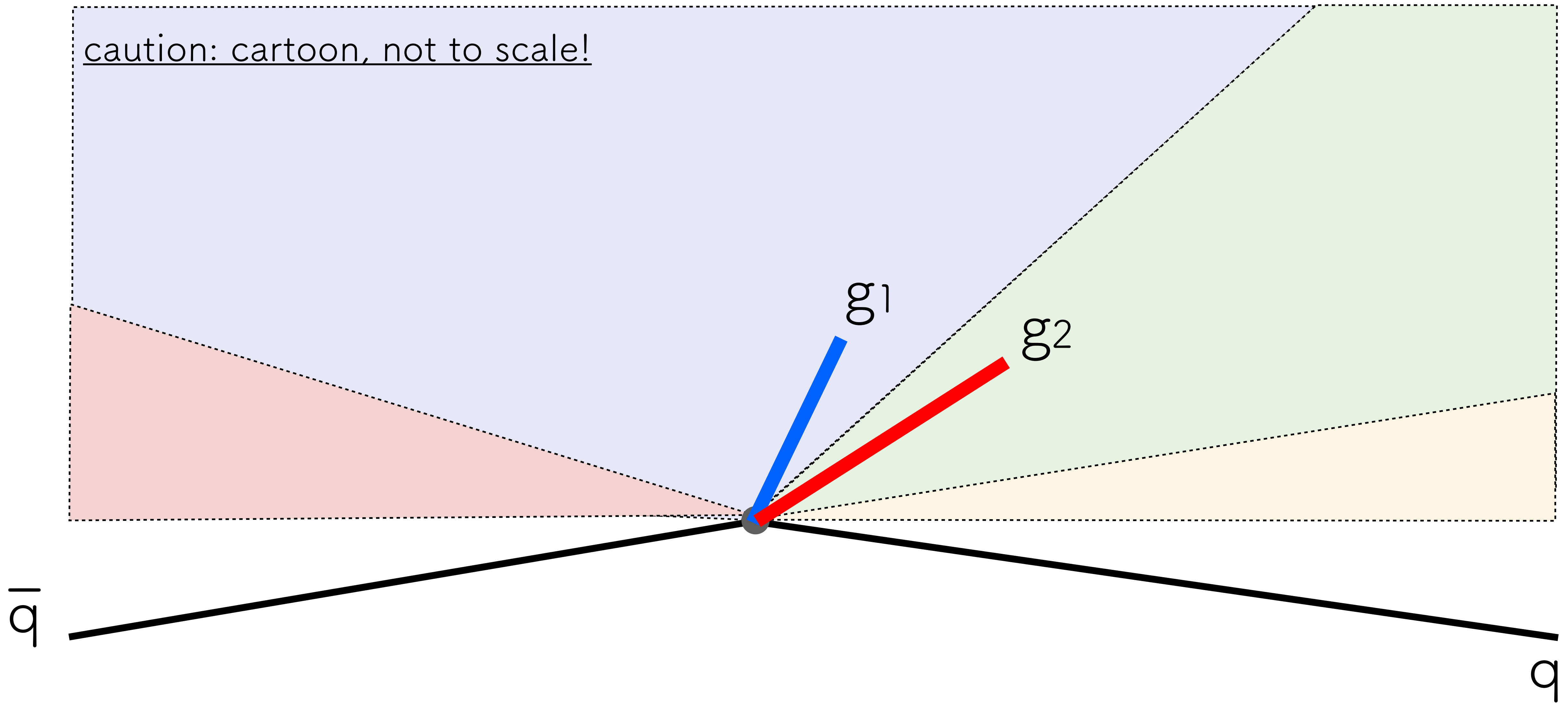

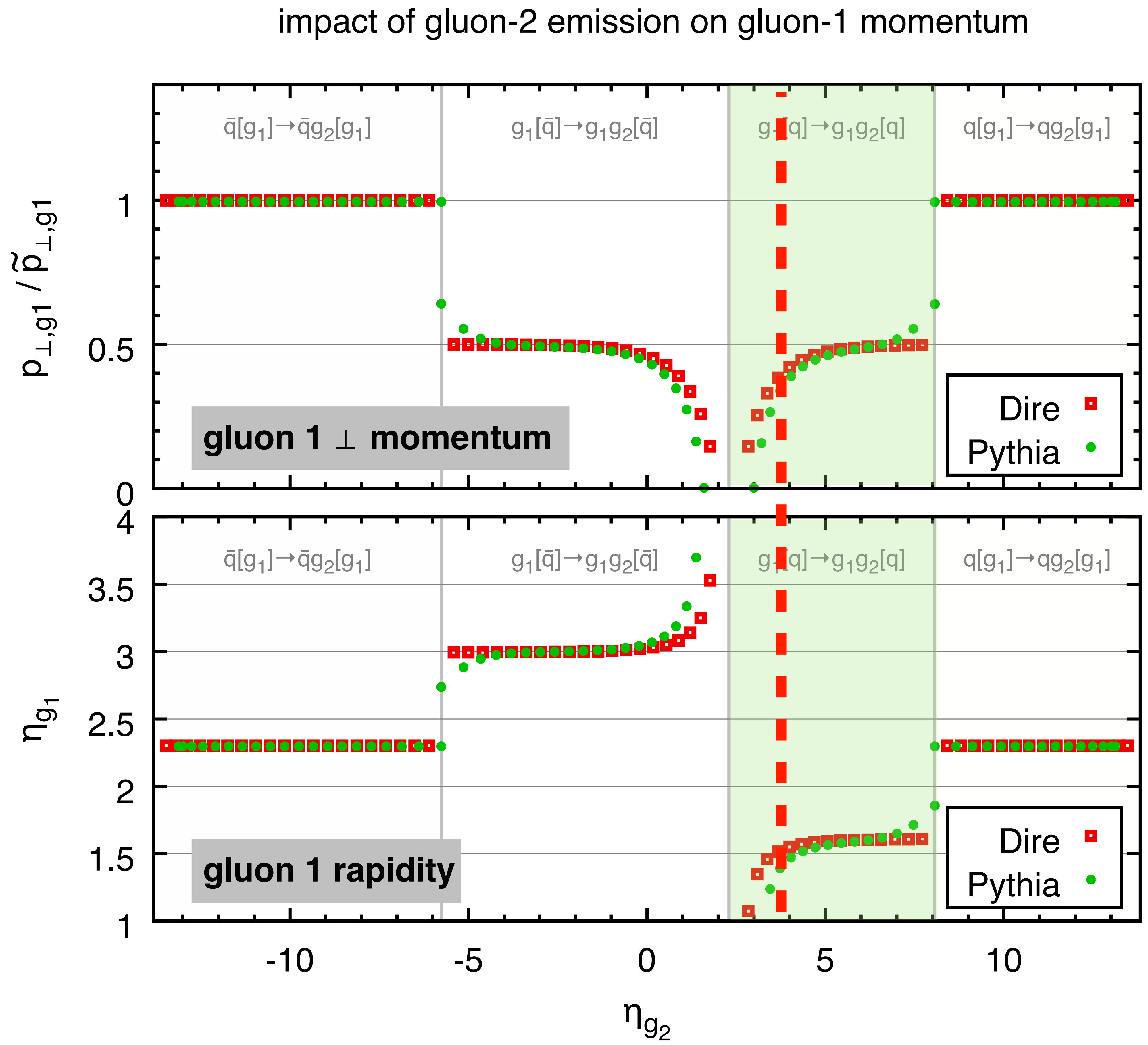

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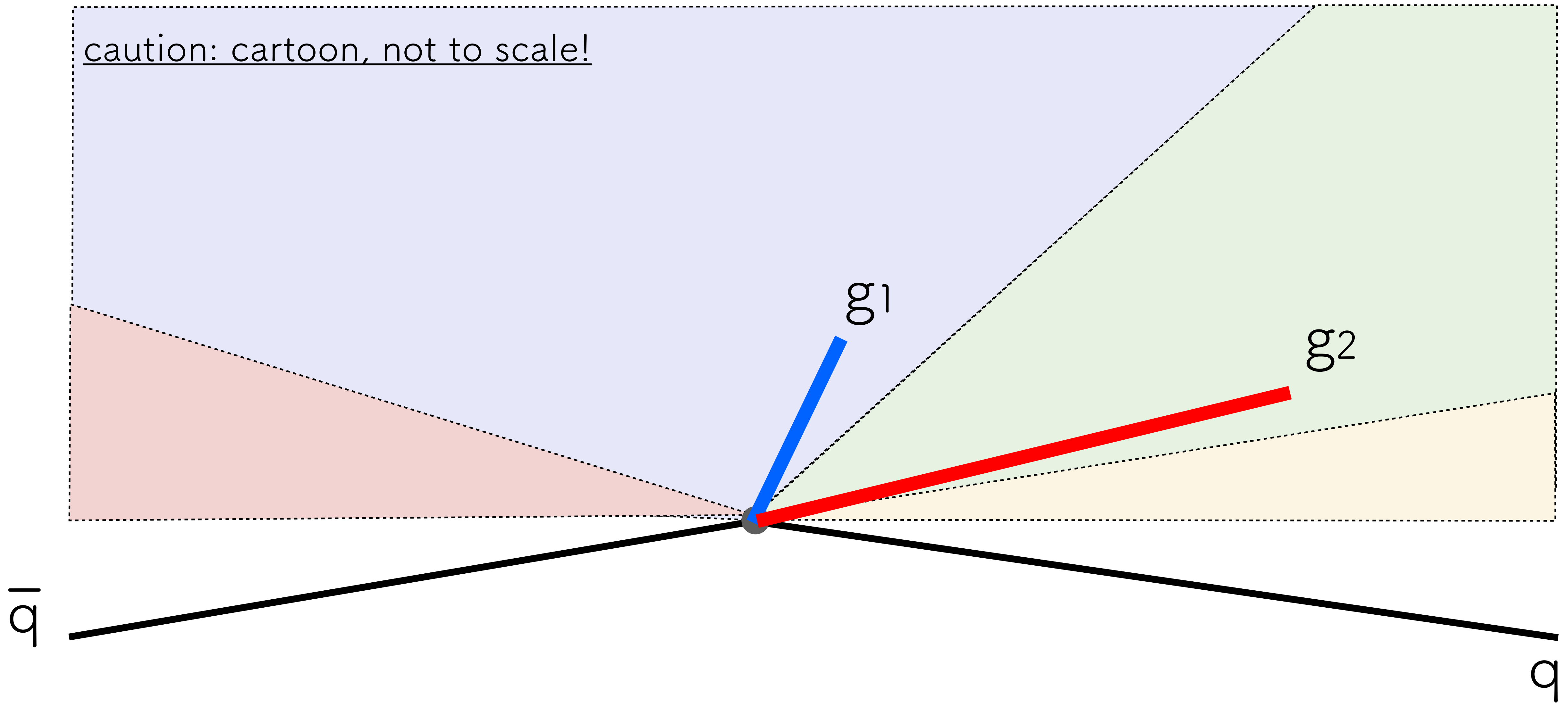
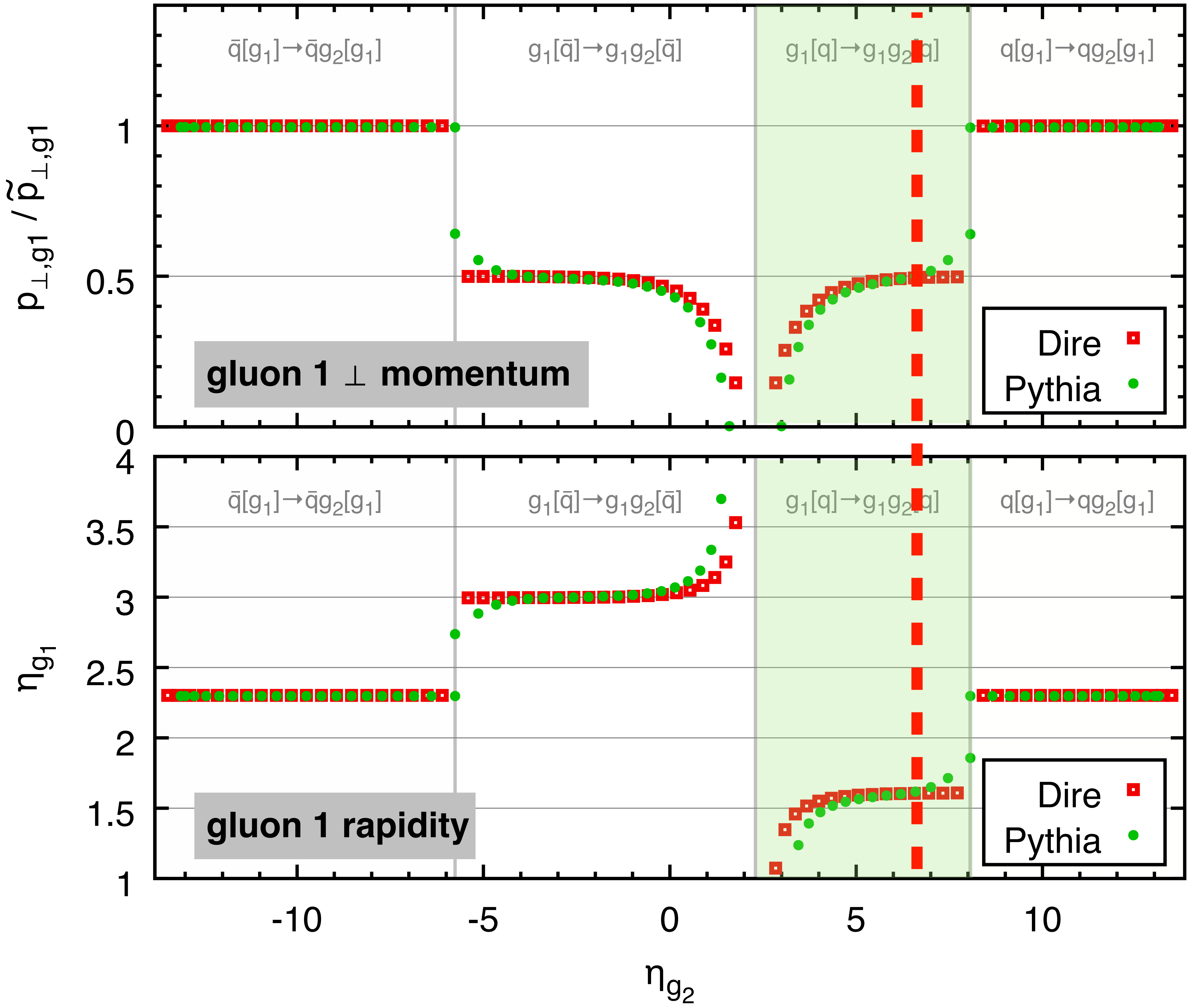
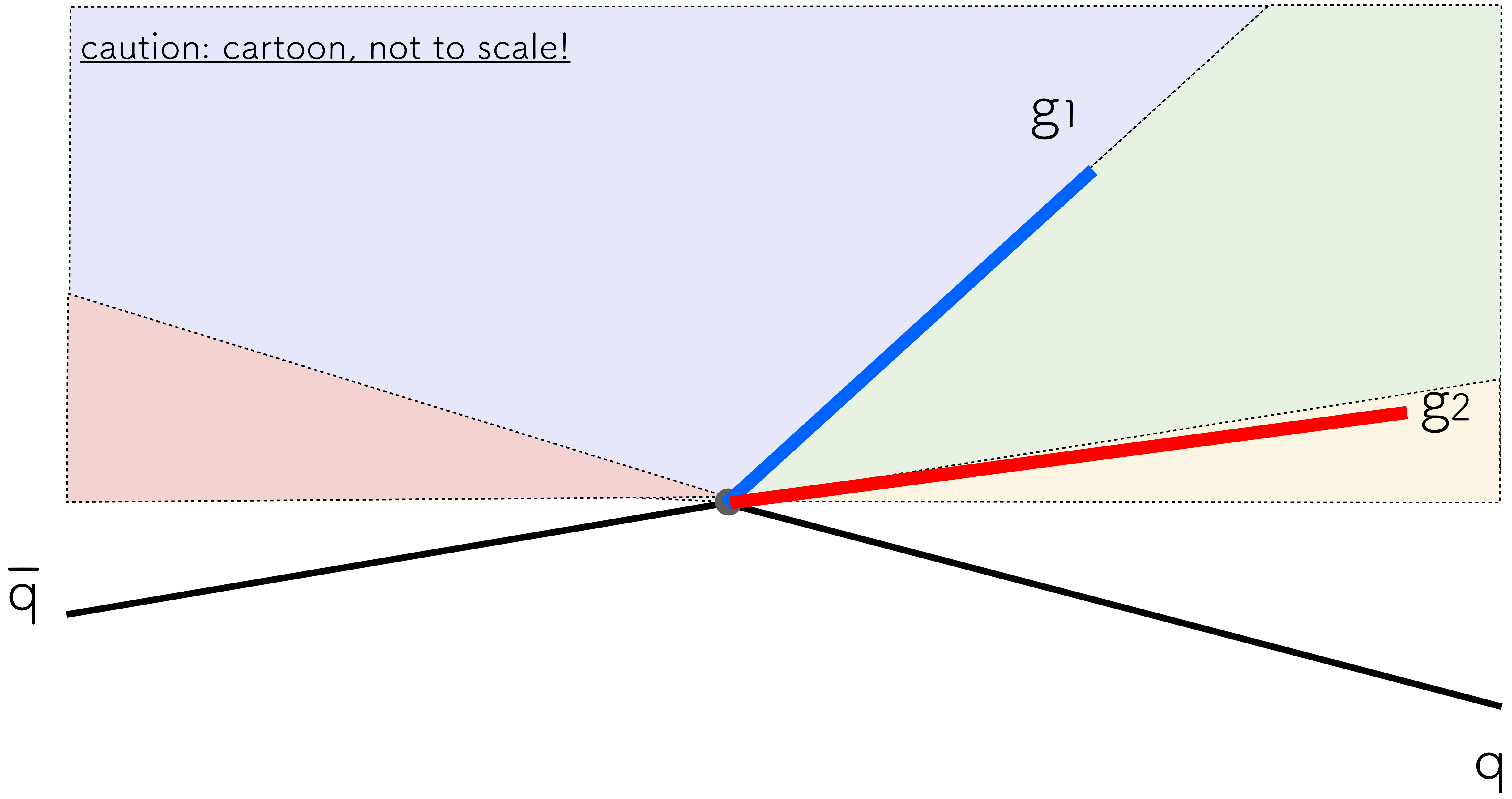


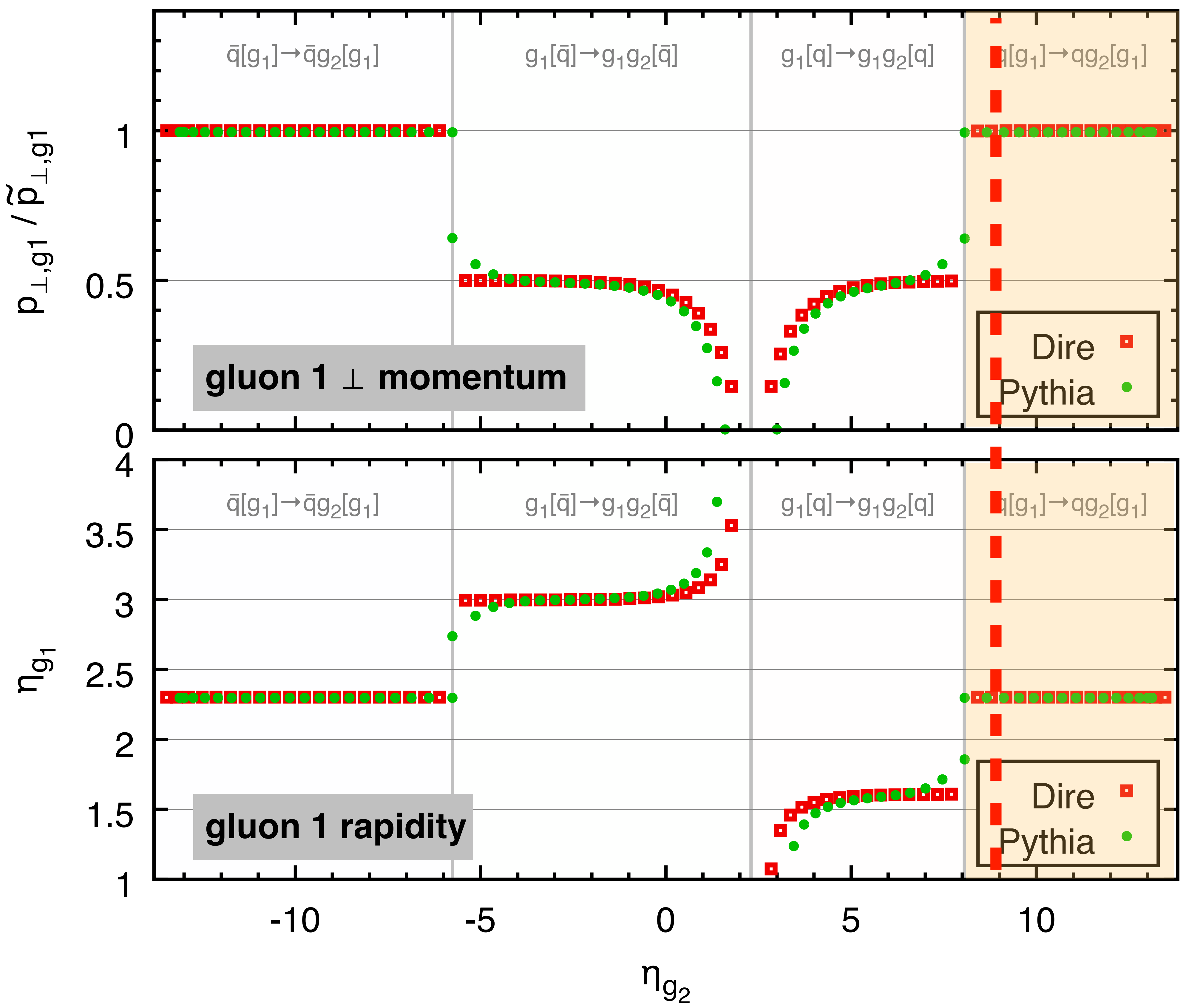
impact of gluon-2 emission on gluon-1 momentum



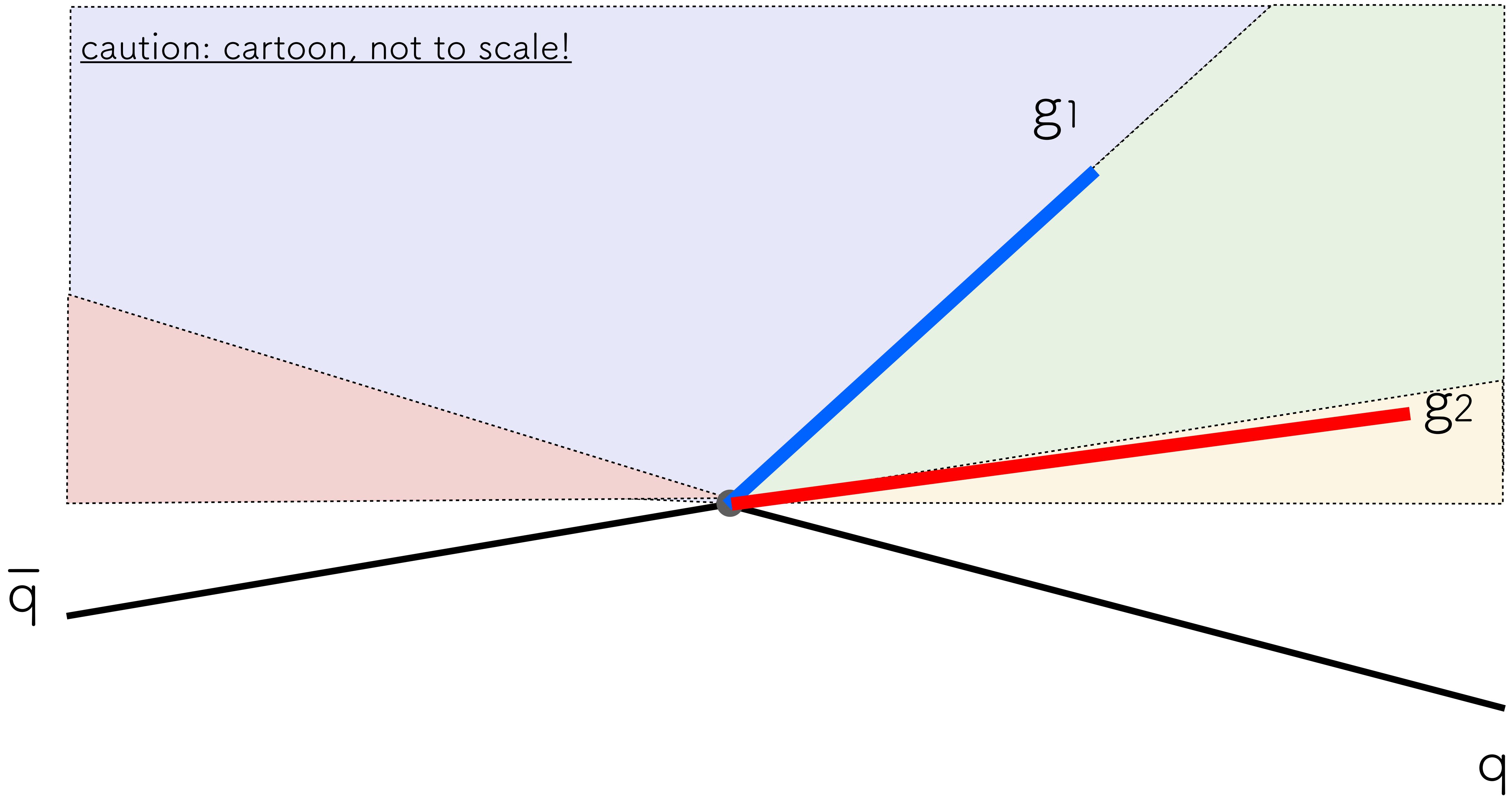
Two emissions in dipole showers (Dire / Pythia8)



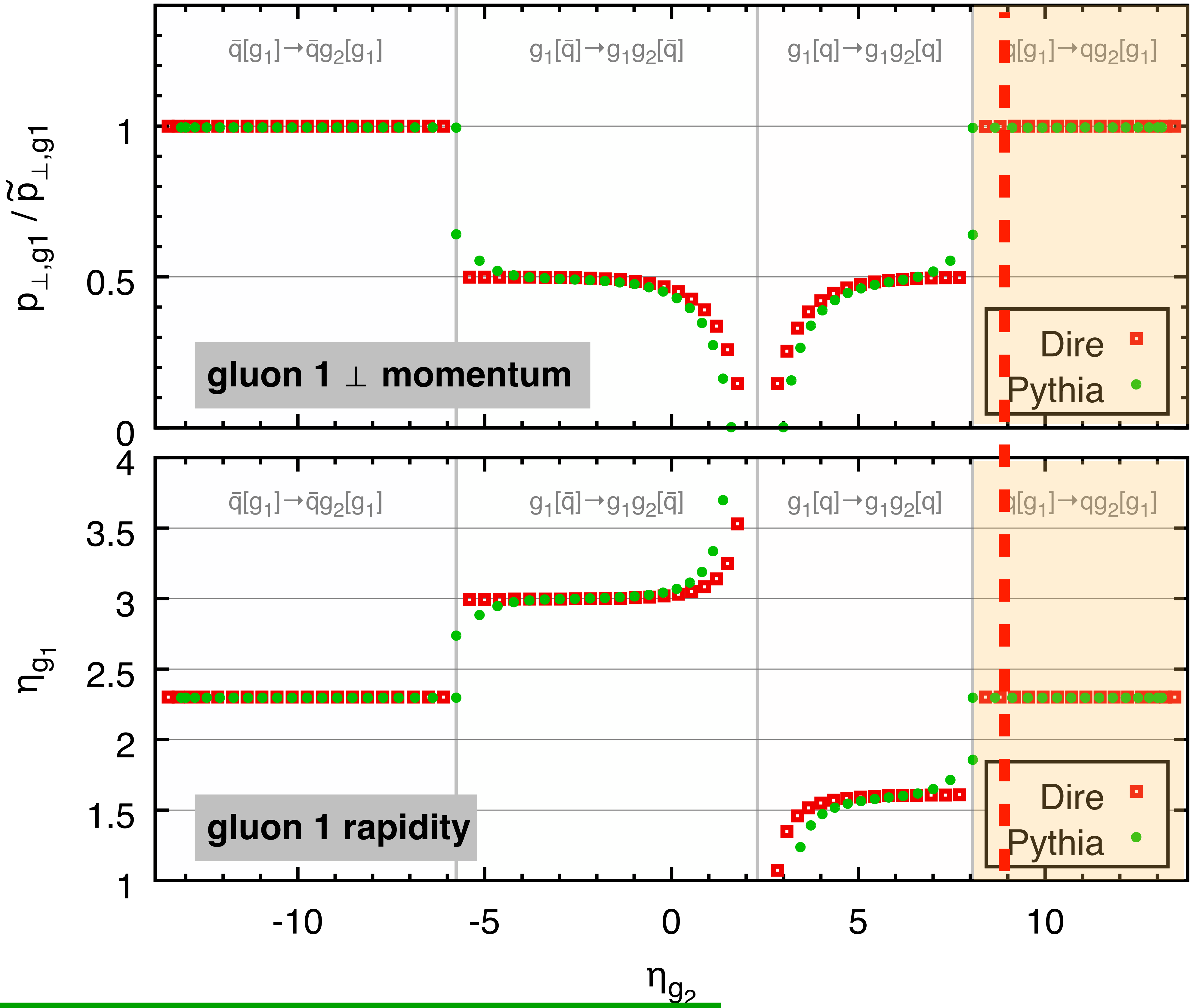
impact of gluon-2 emission on gluon-1 momentum



Two emissions in dipole showers (Dire / Pythia8)



impact of gluon-2 emission on gluon-1 momentum



Key observation #1

highly non-trivial cross talk between emissions

also noticed in 1992 by Andersson, Gustafson & Sjogren → special "fudge" in Ariadne

in equations

$$
\begin{array}{lllll}
1. & \bar{q}[g_1] \to \bar{q}g_2[g_1]: & \boldsymbol{p}_{\perp,g_1} = \widetilde{\boldsymbol{p}}_{\perp,g_1}\,, & & \eta_{g_1} = \widetilde{\eta}_{g_1}\,, \\
2. & g_1[\bar{q}] \to g_1 g_2[\bar{q}]: & \boldsymbol{p}_{\perp,g_1} = \widetilde{\boldsymbol{p}}_{\perp,g_1} - \boldsymbol{p}_{\perp,g_2}\,, & & \eta_{g_1} = \widetilde{\eta}_{g_1} - \ln \frac{|\boldsymbol{p}_{\perp,g_1}|}{|\widetilde{\boldsymbol{p}}_{\perp,g_1}|}\,, \\
3. & g_1[q] \to g_1 g_2[q]: & \boldsymbol{p}_{\perp,g_1} = \widetilde{\boldsymbol{p}}_{\perp,g_1} - \boldsymbol{p}_{\perp,g_2}\,, & & \eta_{g_1} = \widetilde{\eta}_{g_1} + \ln \frac{|\boldsymbol{p}_{\perp,g_1}|}{|\widetilde{\boldsymbol{p}}_{\perp,g_1}|}\,, \\
4. & q[g_1] \to q g_2[g_1]: & \boldsymbol{p}_{\perp,g_1} = \widetilde{\boldsymbol{p}}_{\perp,g_1}\,, & & \eta_{g_1} = \widetilde{\eta}_{g_1}
\end{array}
$$

With/without tilde: momentum before/after emission of gluon 2