ML for VLQ Searches USCMS — PURSUE

Johan Sebastian Bonilla Castro
(They/Them)
June 17, 2024
Assistant Professor, Northeastern University

What Do I Do in CMS?

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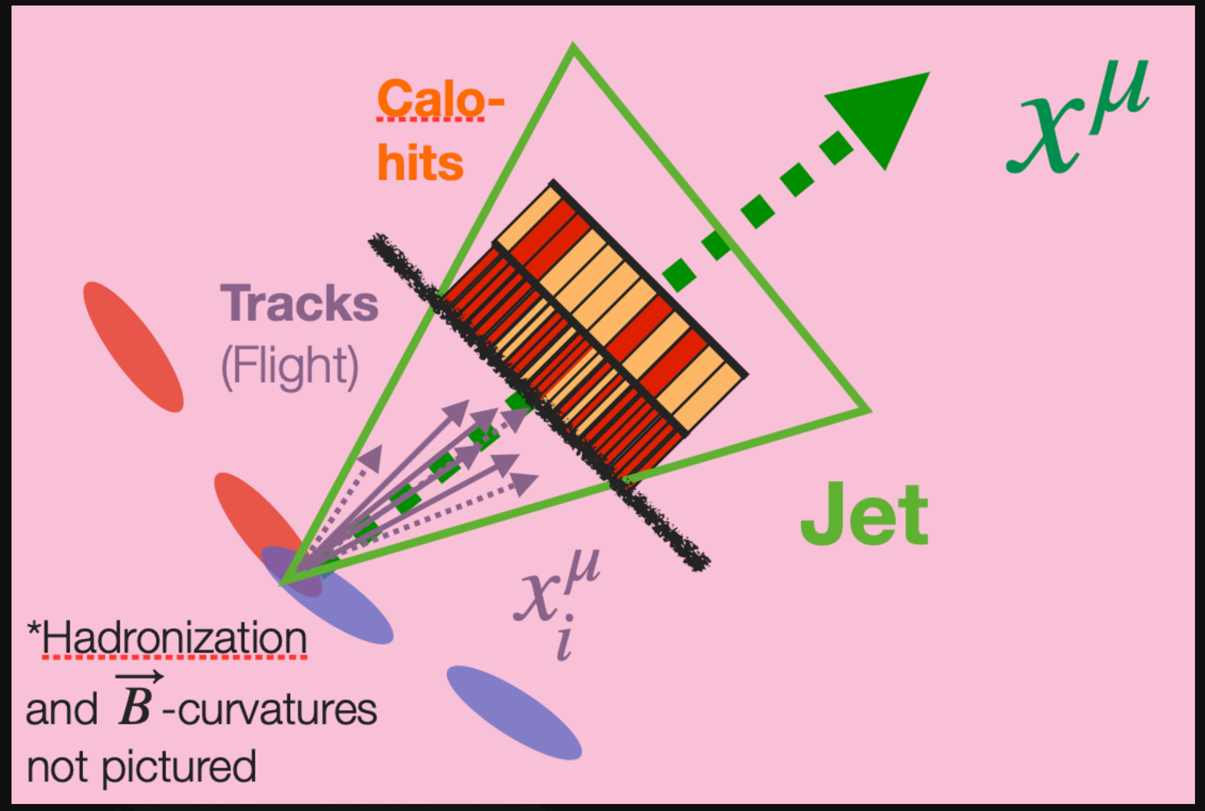

- Physics Analysis
  - Vector-Like Quarks: pair-production, all-hadronic
  - ttbar Resonances, all-hadronic

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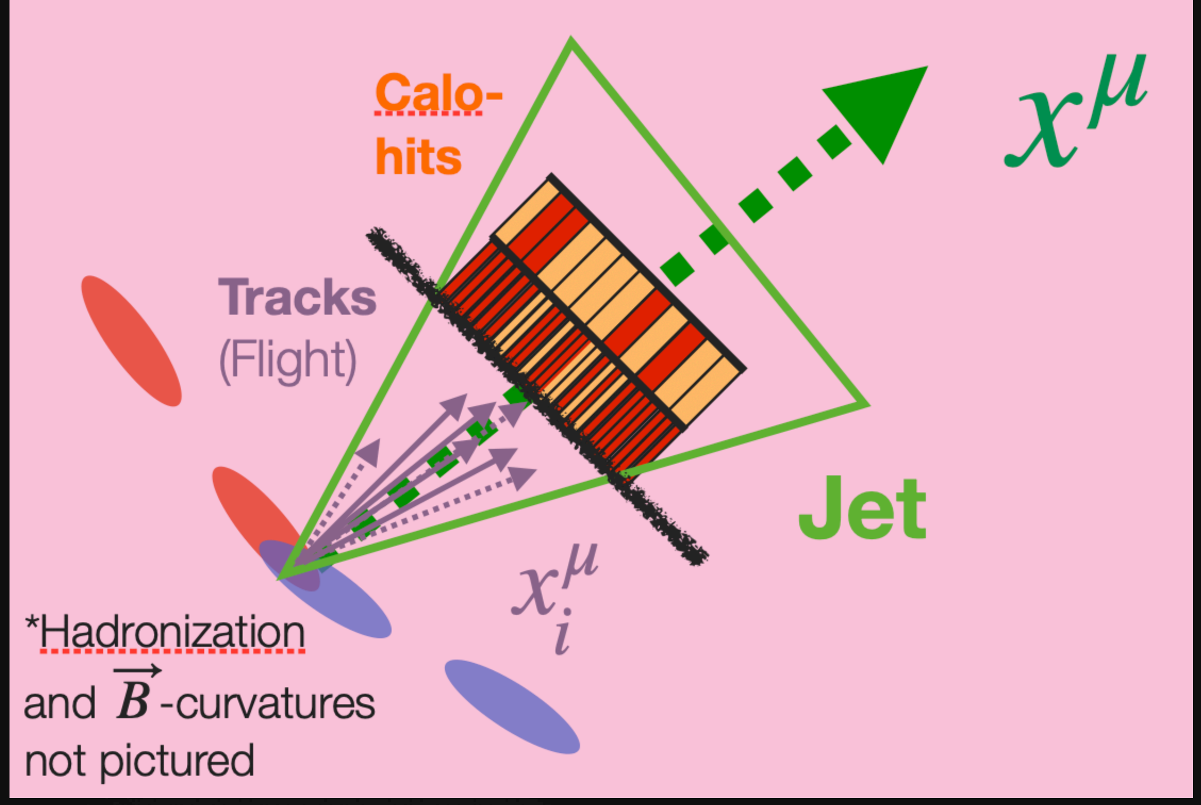
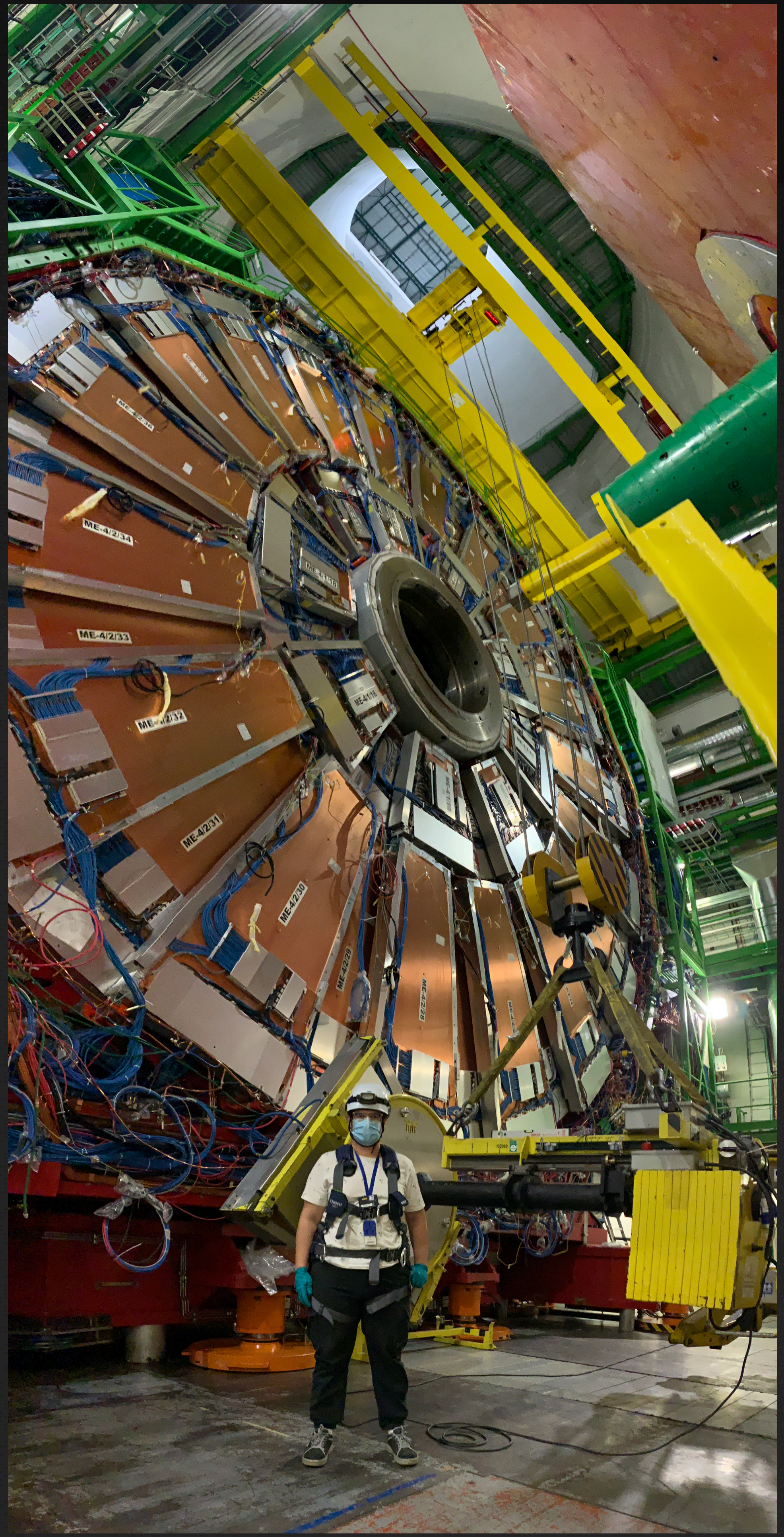
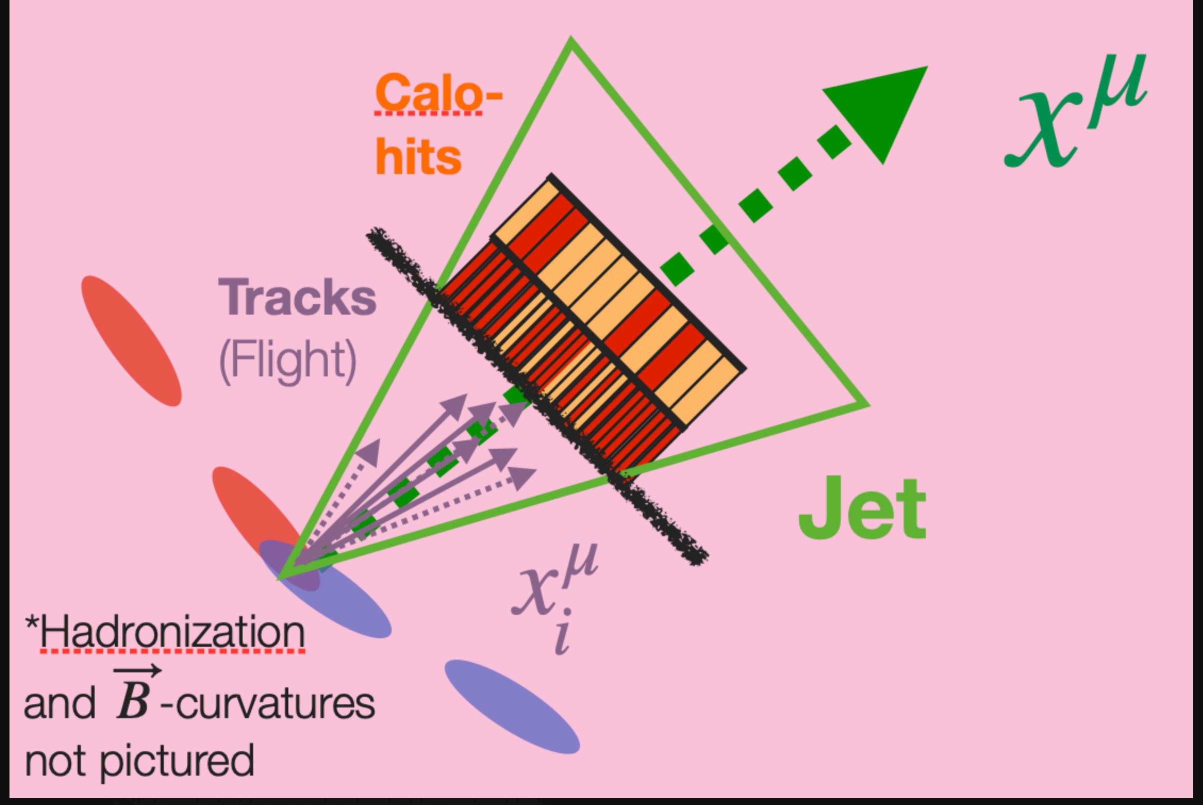
- Detector Operations
  - Cathode Strip Chambers: Operations Manager
  - CSC-GEM Trigger System

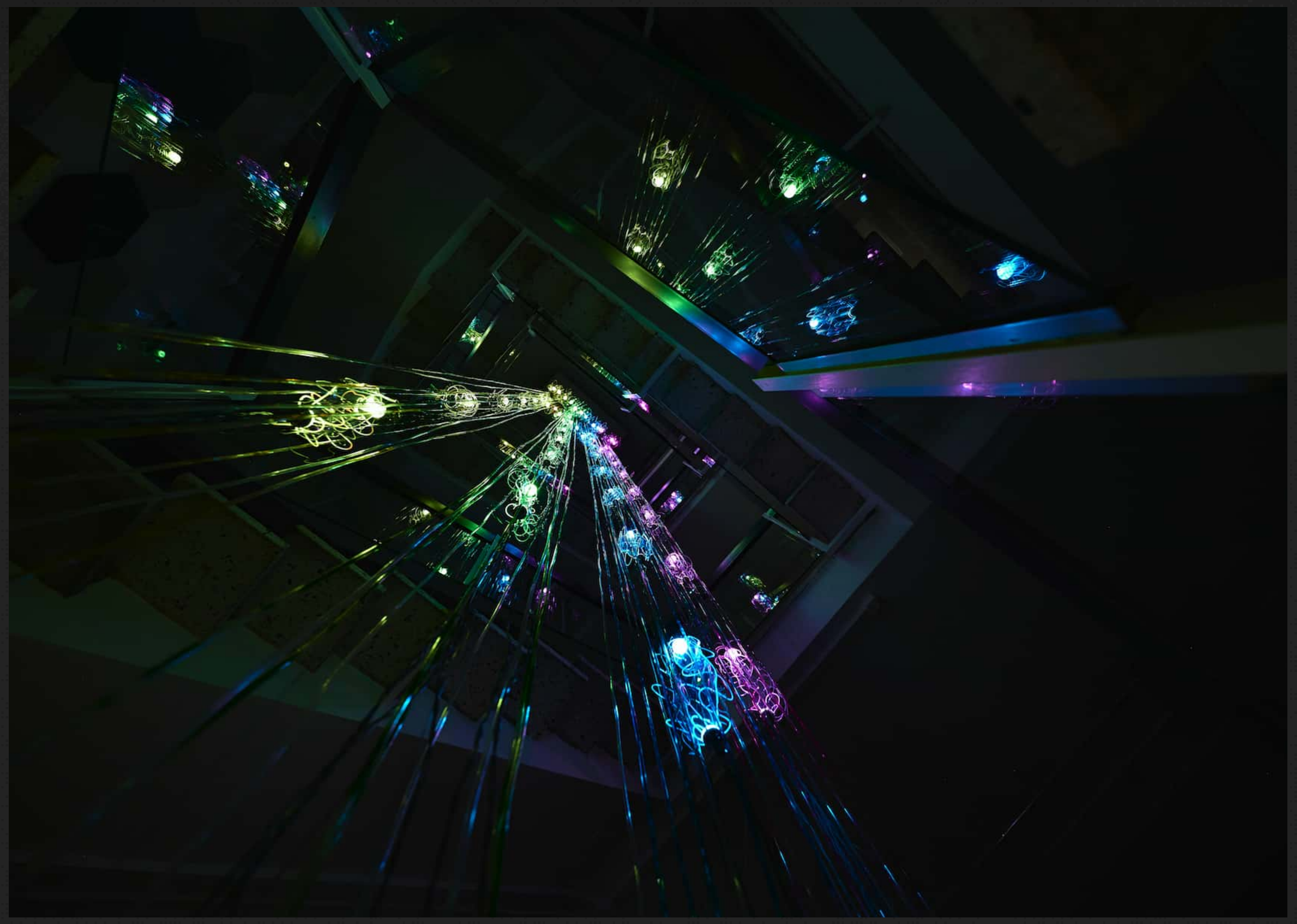


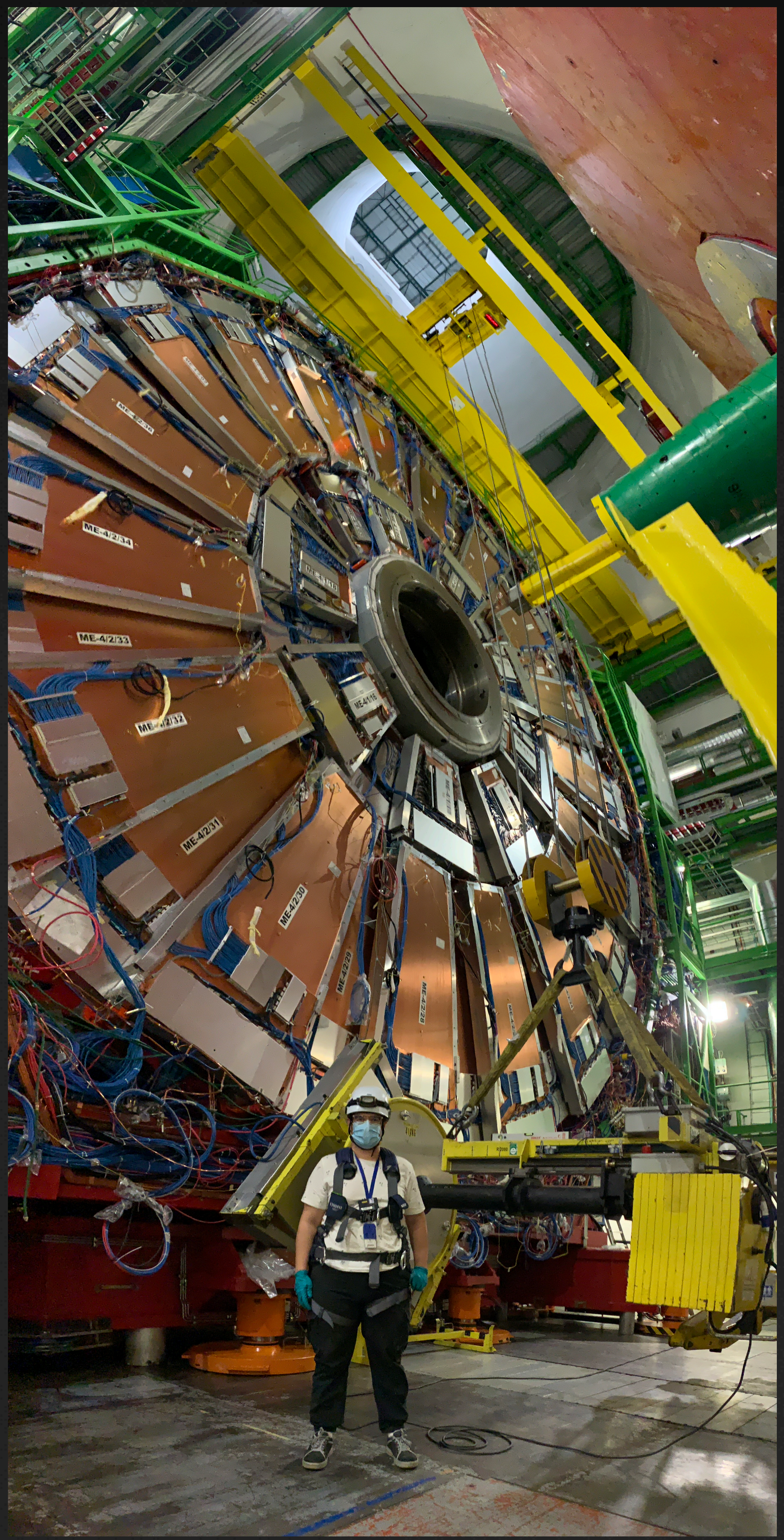


What Do I Do in CMS?

- Physics Analysis
  - Vector-Like Quarks: pair-production, all-hadronic
  - ttbar Resonances, all-hadronic
- Detector Operations
  - Cathode Strip Chambers: Operations Manager
  - CSC-GEM Trigger System
- Outreach/Inreach
  - STEAM (STEM+Arts)
  - CMS D&I Office, Co-Chair
  - Science Communication







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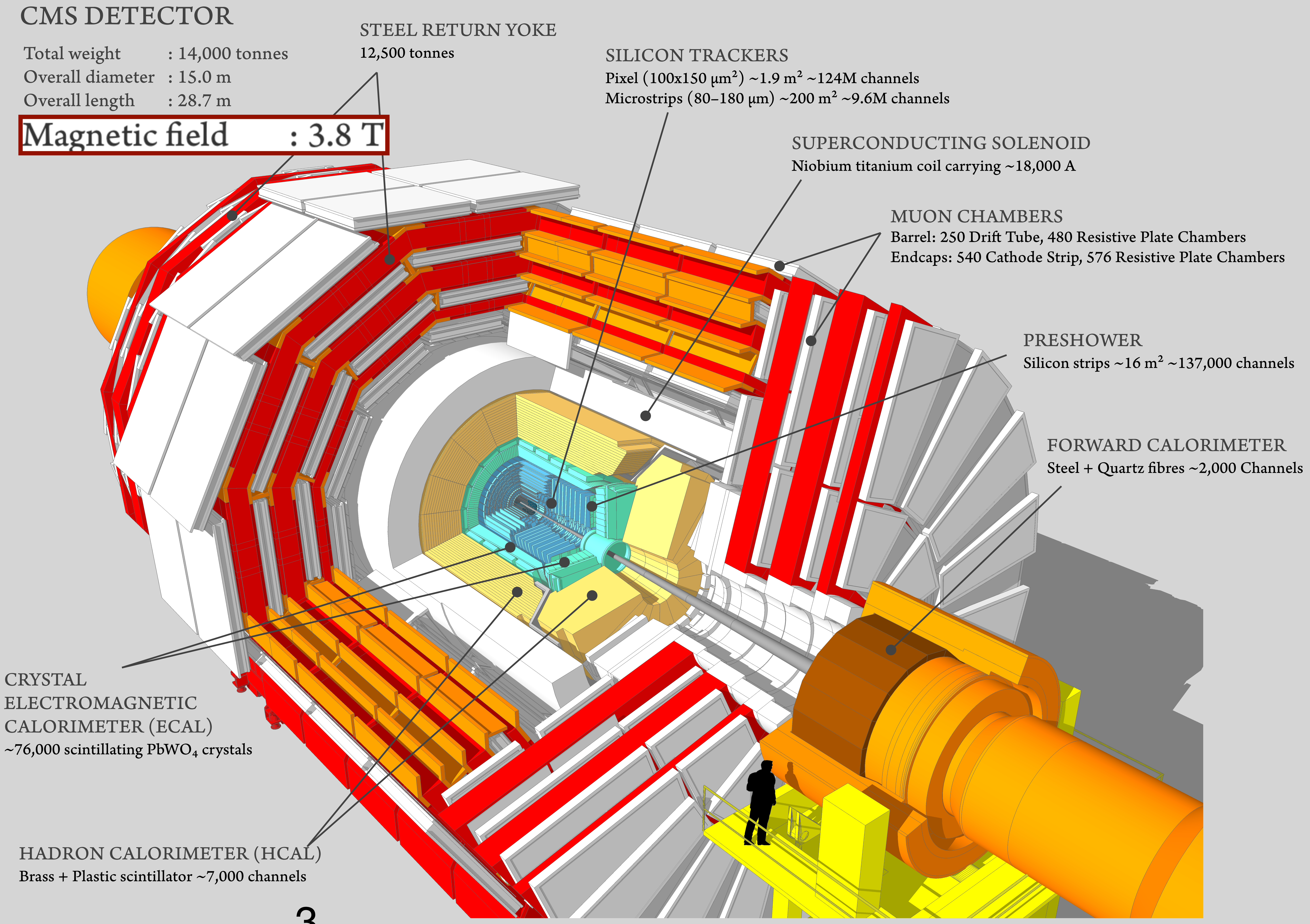
The Compact Muon Solenoid



J. Phys.: Conf. Ser. 513 022032

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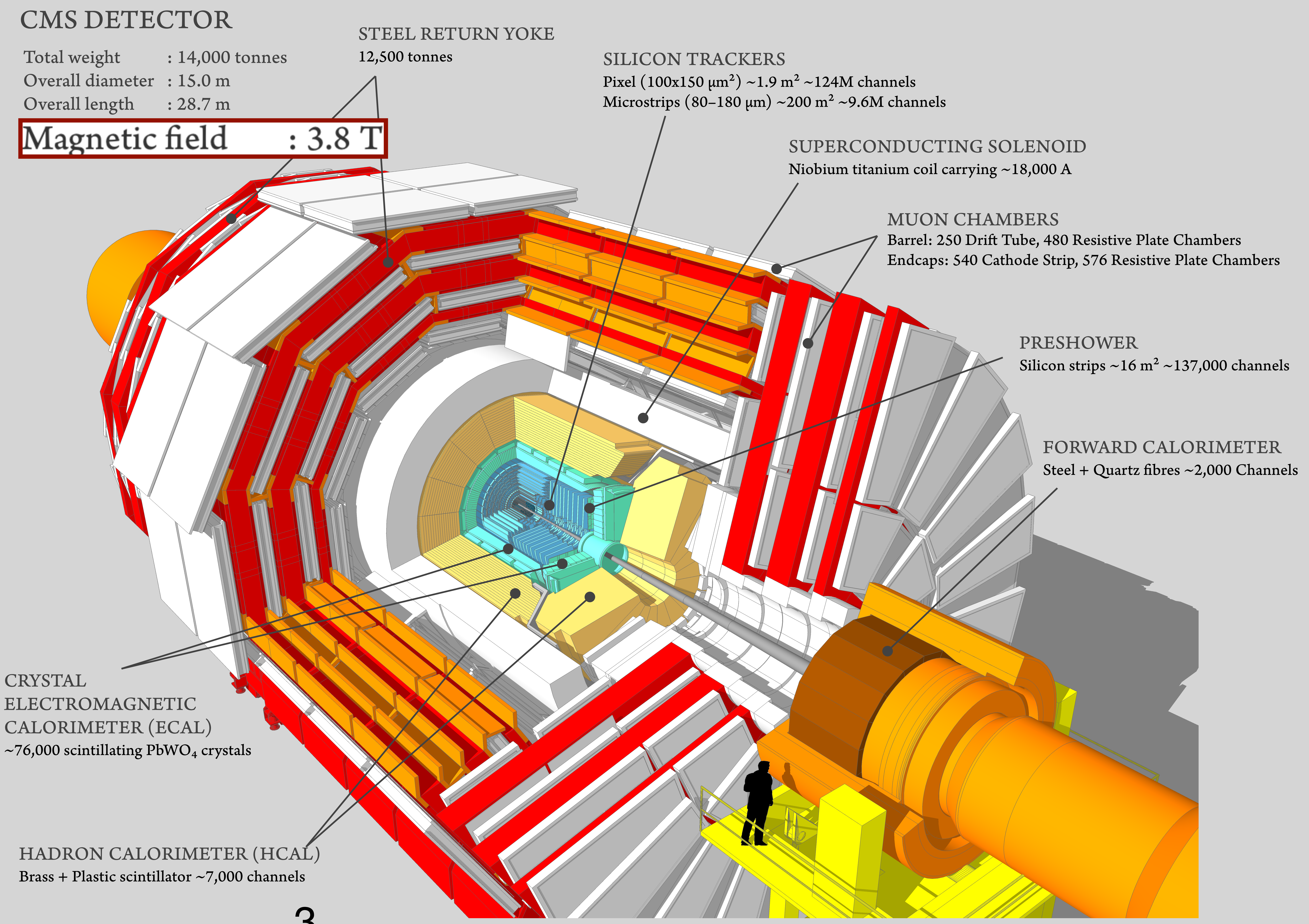

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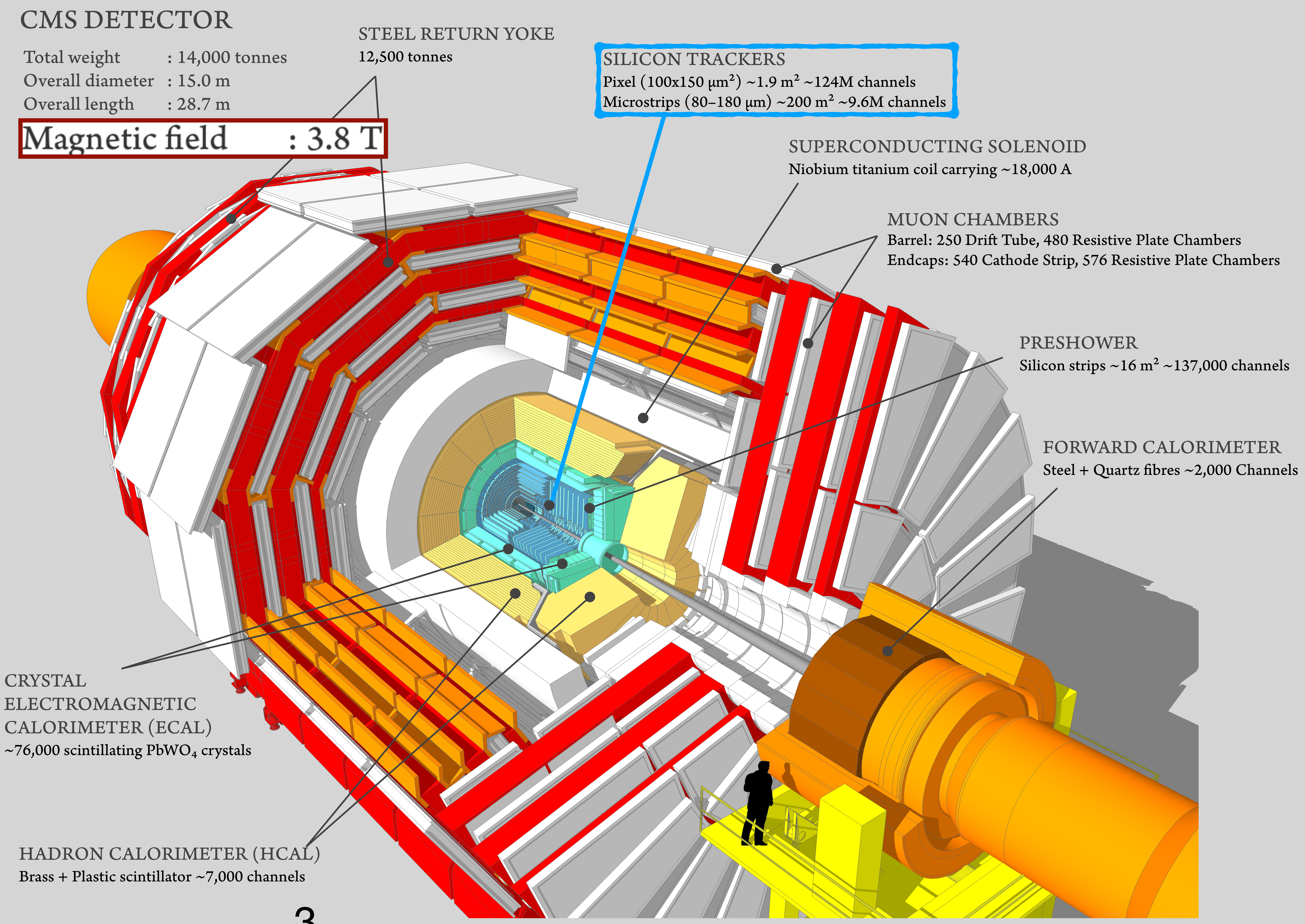
The Compact Muon Solenoid

- High resolution silicon tracking in $|\eta| < 2.4$



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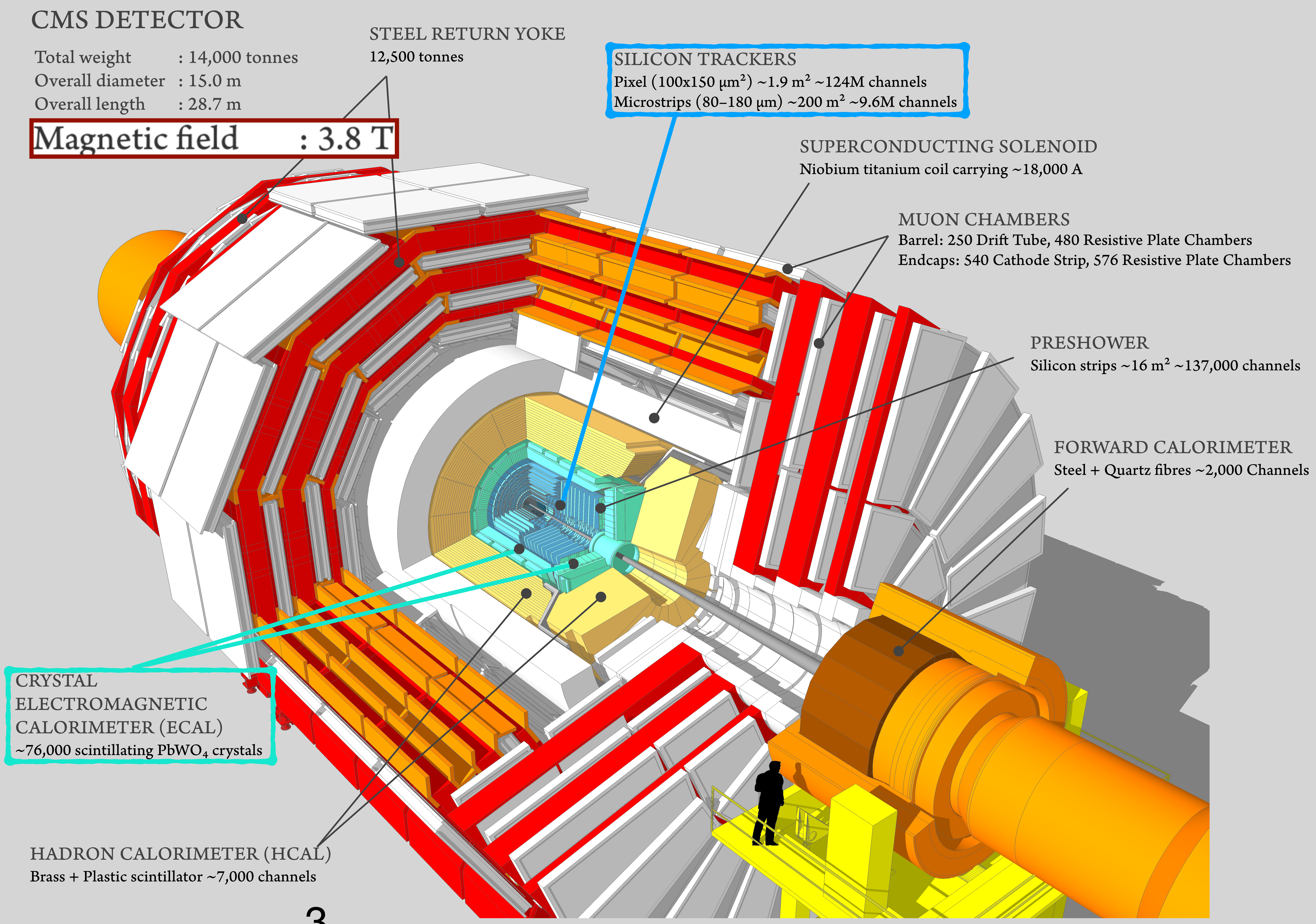
The Compact Muon Solenoid

- High resolution silicon tracking in $|\eta| < 2.4$
- $PbWO_4$ EM Calorimetry



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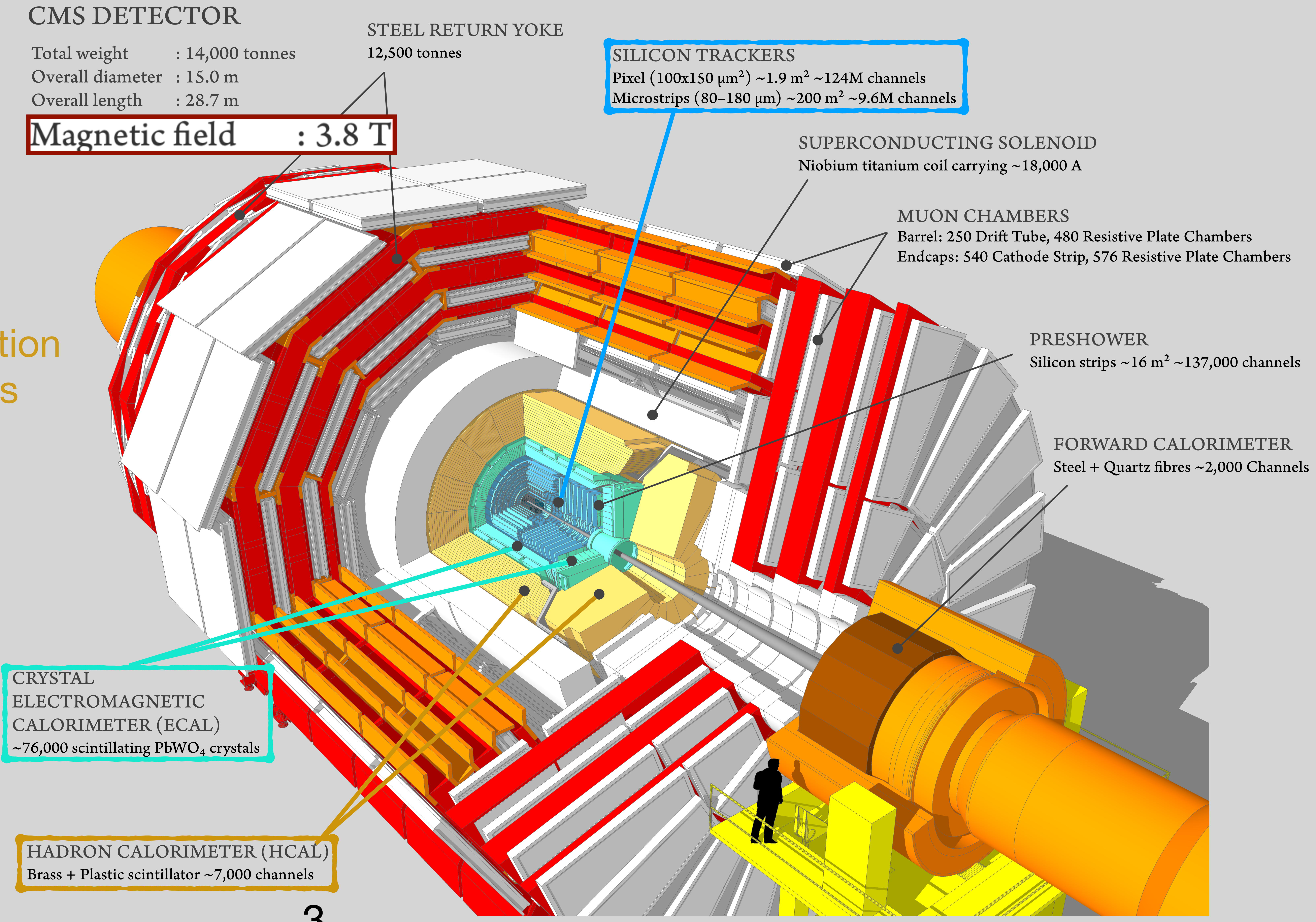
The Compact Muon Solenoid

- High resolution silicon tracking in $|\eta| < 2.4$
- $PbWO_4$ EM Calorimetry
- Brass Hadron Calorimeter
  — Provides excellent energy resolution for strongly-coupled parton showers



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The Compact Muon Solenoid

- High resolution silicon tracking in $|\eta| < 2.4$
- $PbWO_4$ EM Calorimetry
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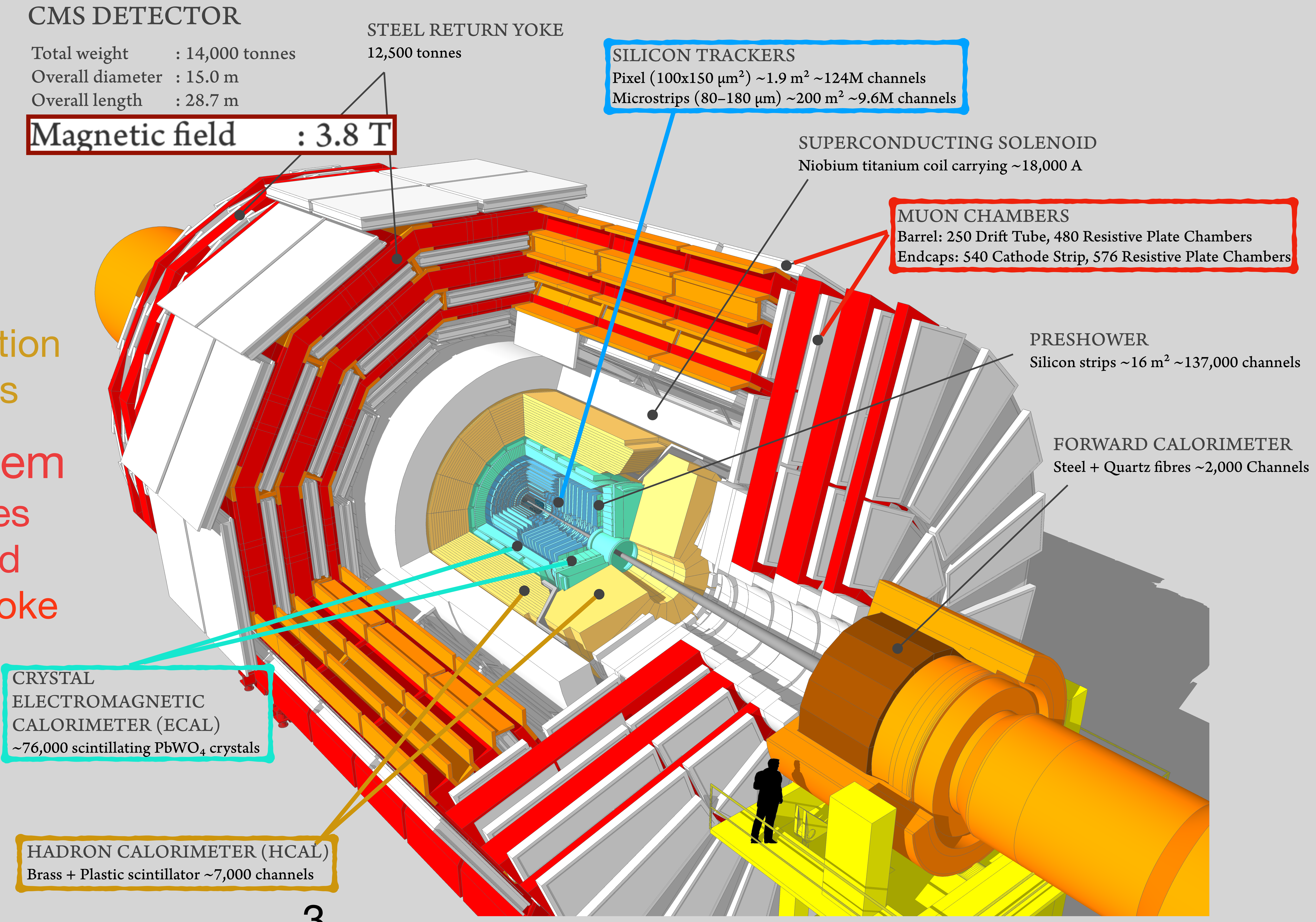
  - Provides excellent energy resolution for strongly-coupled parton showers
- Excellent, Robust Muon System
  - Superconducting solenoid creates 3.8*T* magnetic field in tracker and calorimeters, 2*T* is steel return yoke



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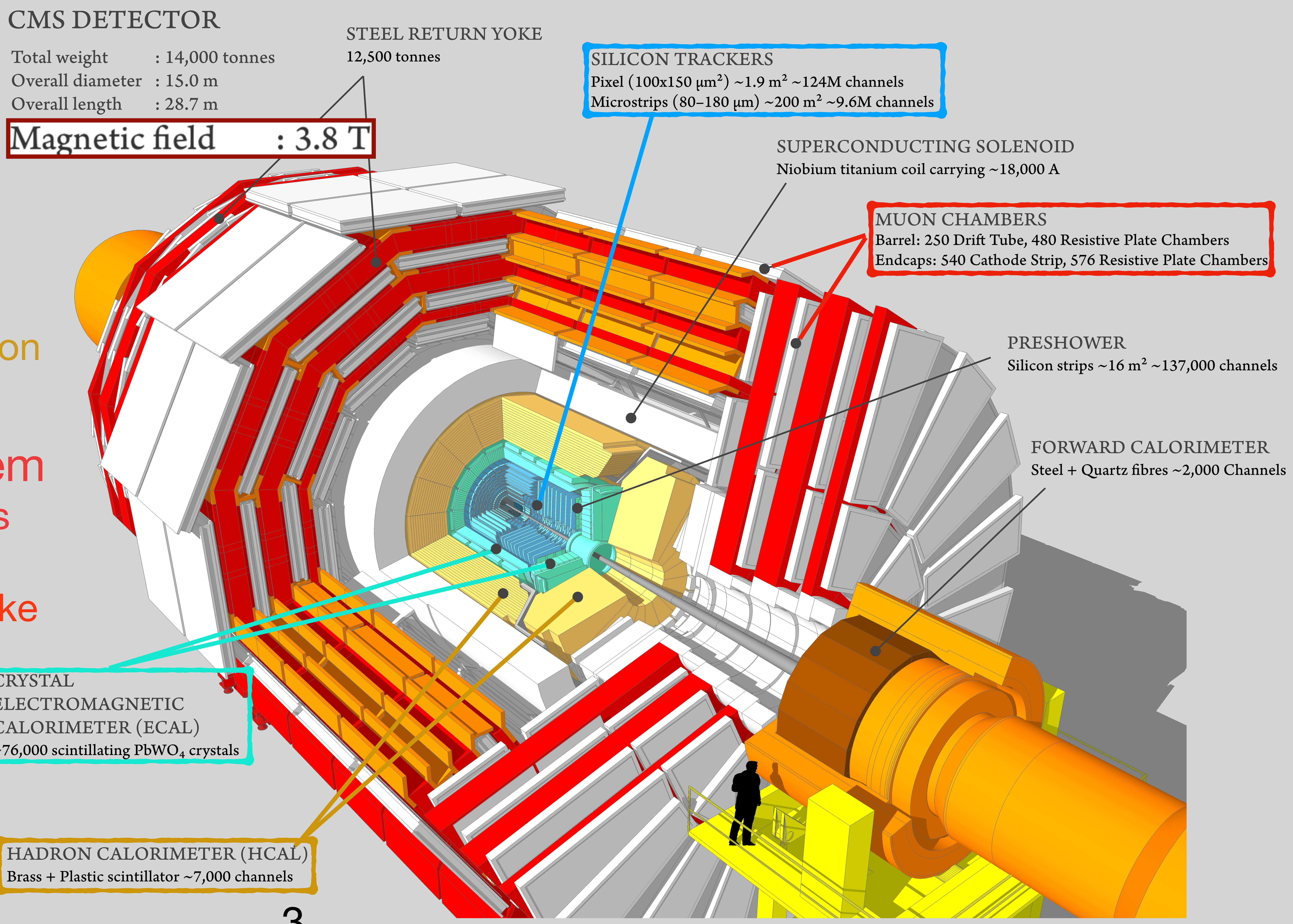
  — Provides excellent energy resolution for strongly-coupled parton showers
- Excellent, Robust Muon System
  — Superconducting solenoid creates 3.8*T* magnetic field in tracker and calorimeters, 2*T* is steel return yoke
- **Cost: ~500 MCHF**
  + ~200 MCHF (Upgrades)



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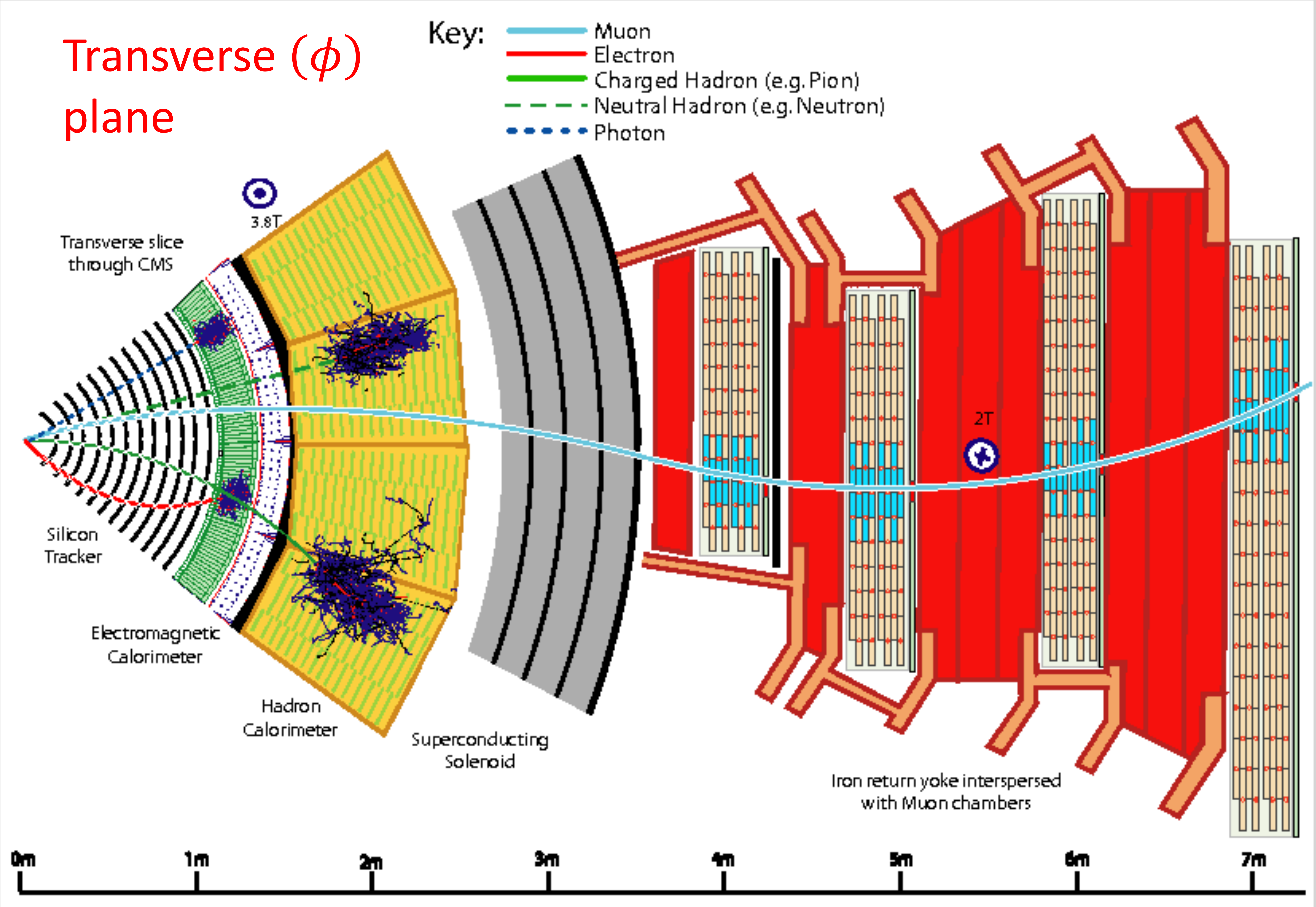
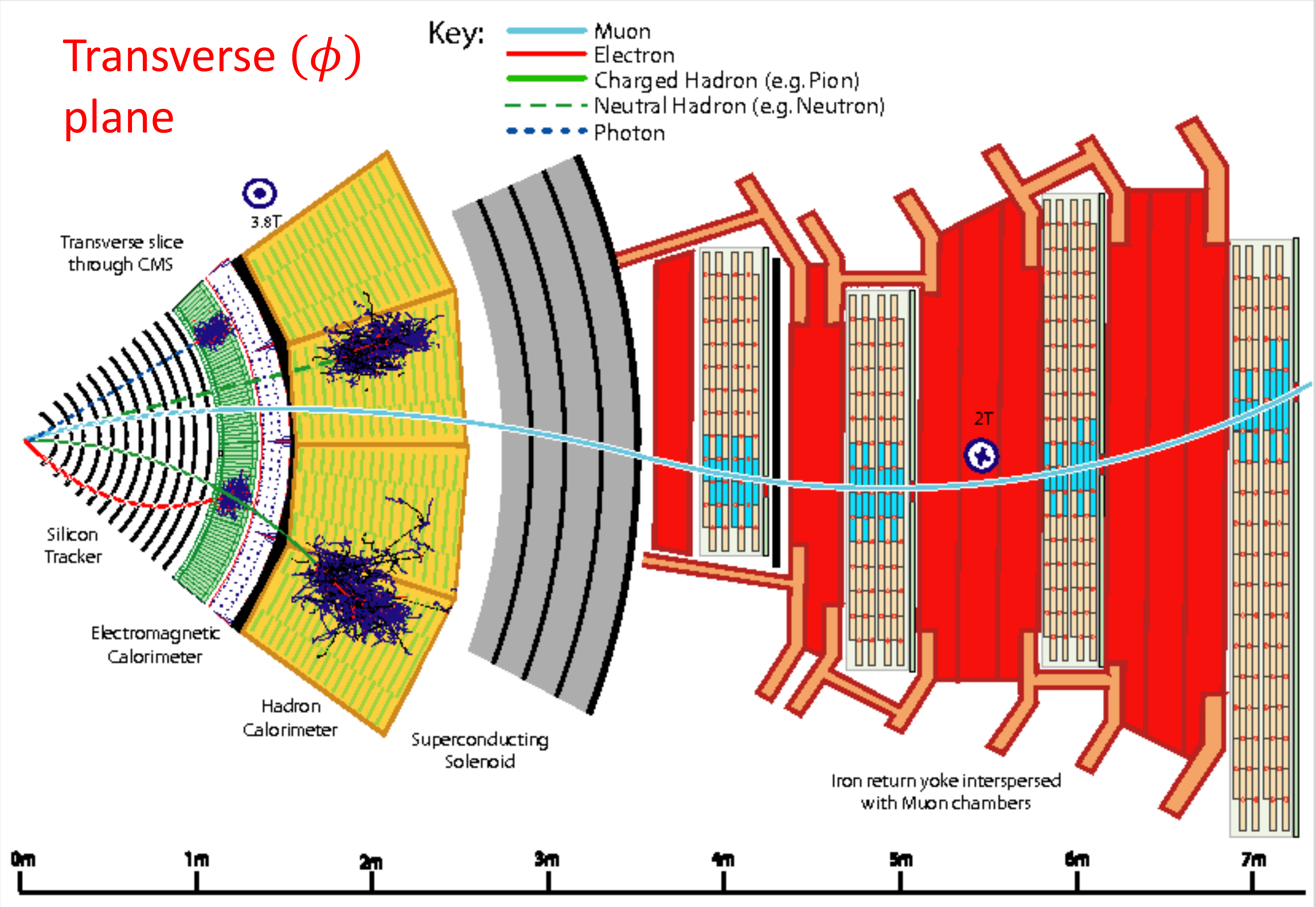
Detecting Particles in CMS



JINST 12 (2017) P10003

Detecting Particles in CMS

Tracker:
  Momentum of charged particles
  $(e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm})$



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Detecting Particles in CMS

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  Momentum of charged particles
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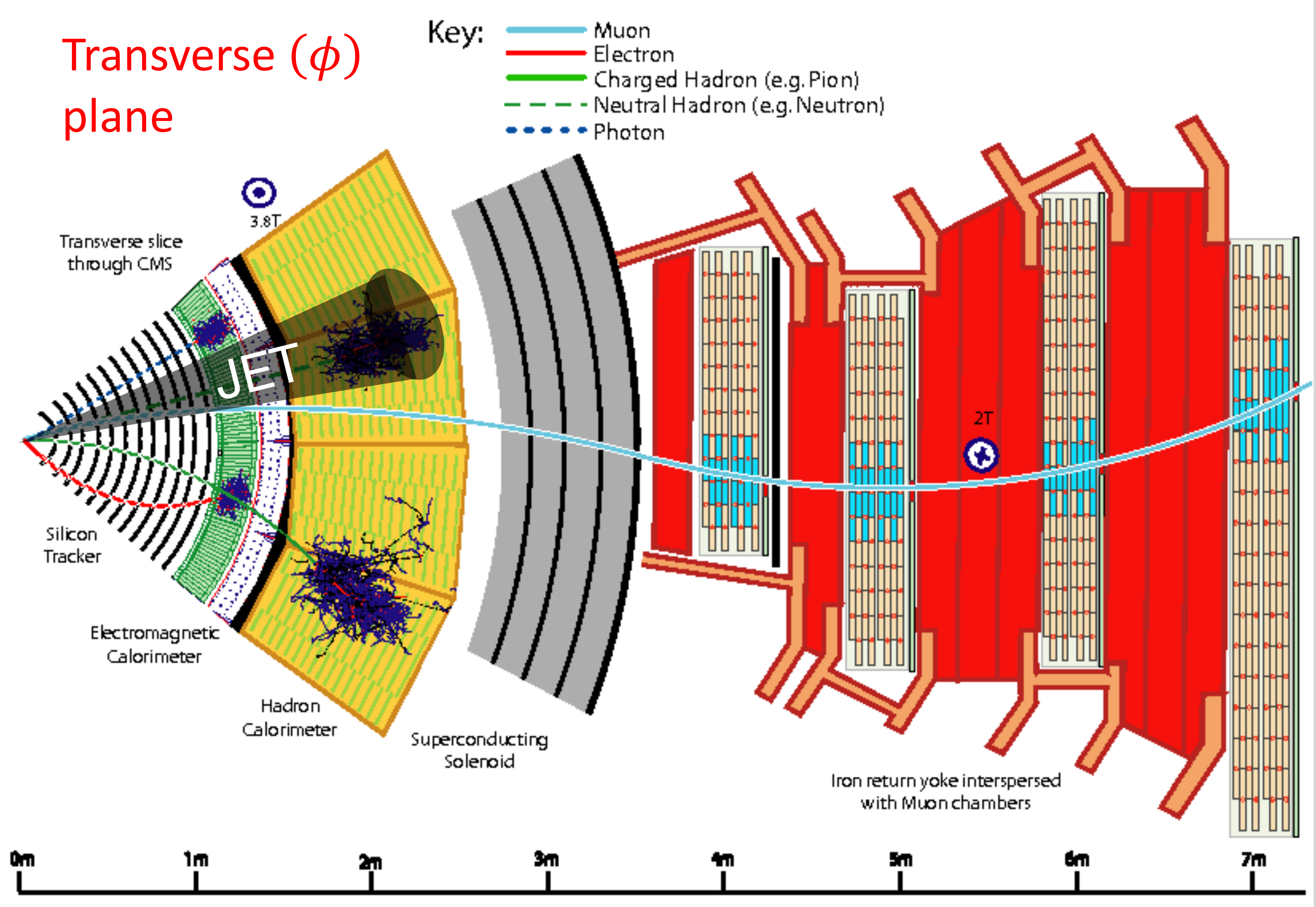
EM Calorimeter:
  Energy of EM showers
  $(\gamma, e^{\pm}, \pi^0 \rightarrow \gamma\gamma, K_S^0)$

Hadronic Calorimeter:
  Energy of hadronic showers
  $(\pi^{\pm}, K^{\pm}, K_L^0, p, n)$



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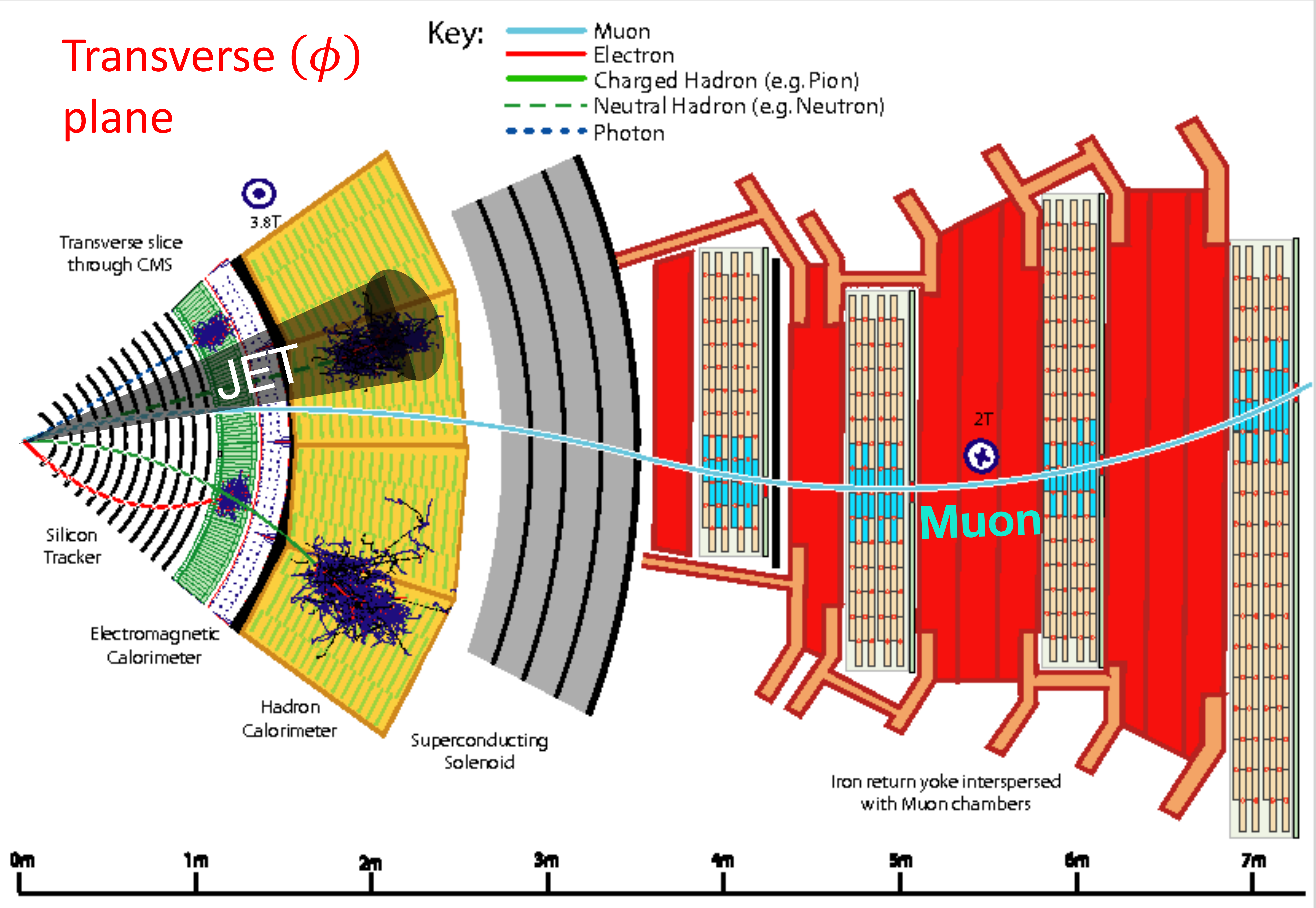
EM Calorimeter:
  Energy of EM showers
  $(\gamma, e^{\pm}, \pi^0 \rightarrow \gamma\gamma, K^0_S)$

Hadronic Calorimeter:
  Energy of hadronic showers
  $(\pi^{\pm}, K^{\pm}, K^0_L, p, n)$

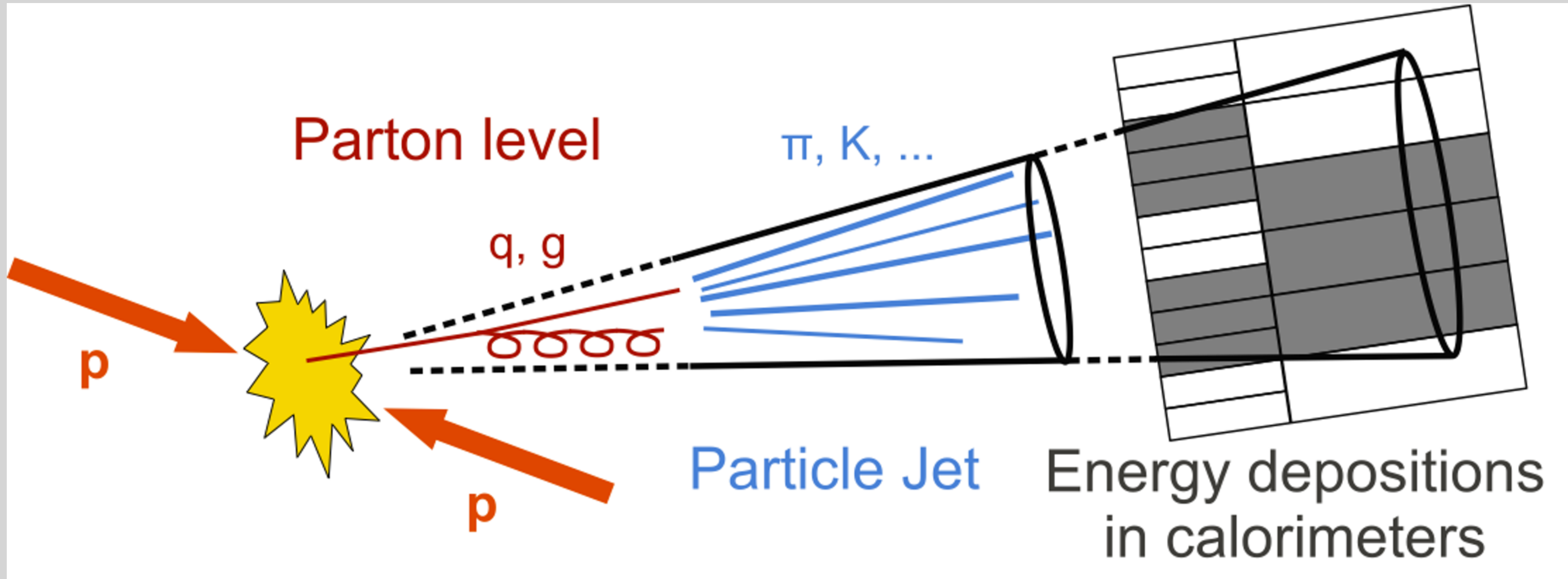
Muon Spectrometer
  Momentum of surviving minimal ionizing (charged) particles, i.e. muons



JINST 12 (2017) P10003

Jets, jets, jets!

Capturing Hadronic Showers



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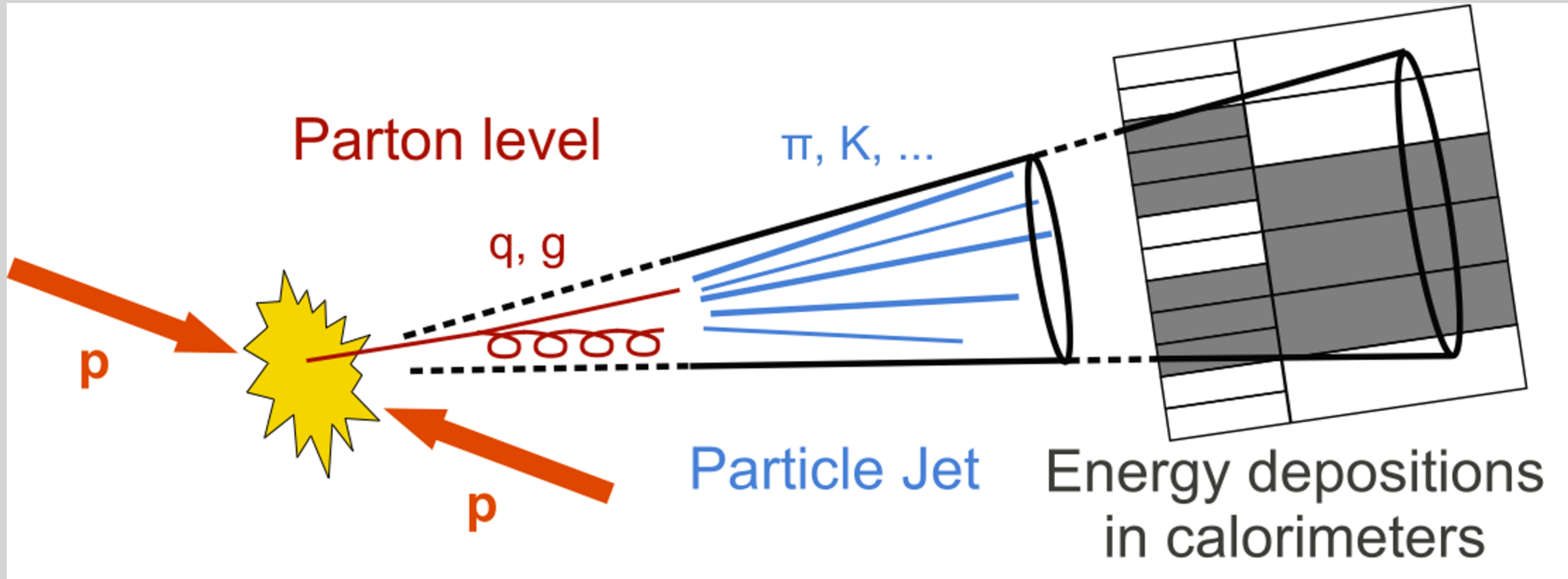

- Input: Calorimeter + Tracking info
  —> ParticleFlow: Individual final-state particles'
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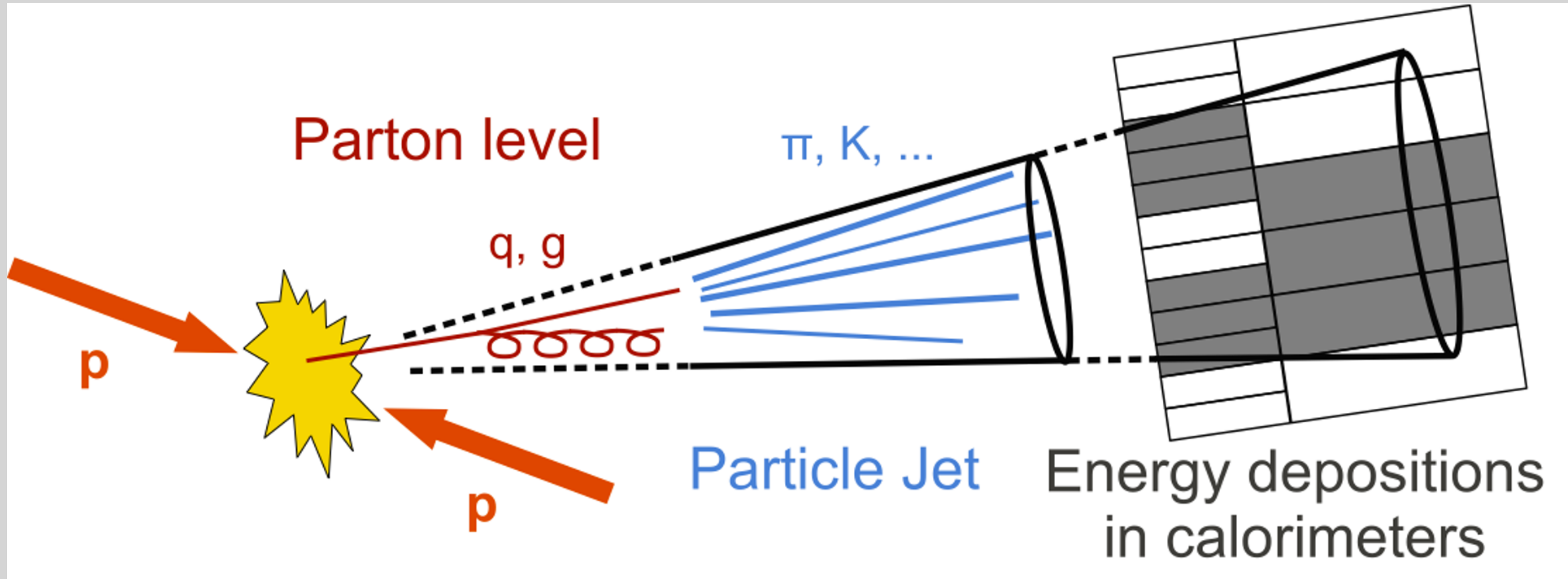
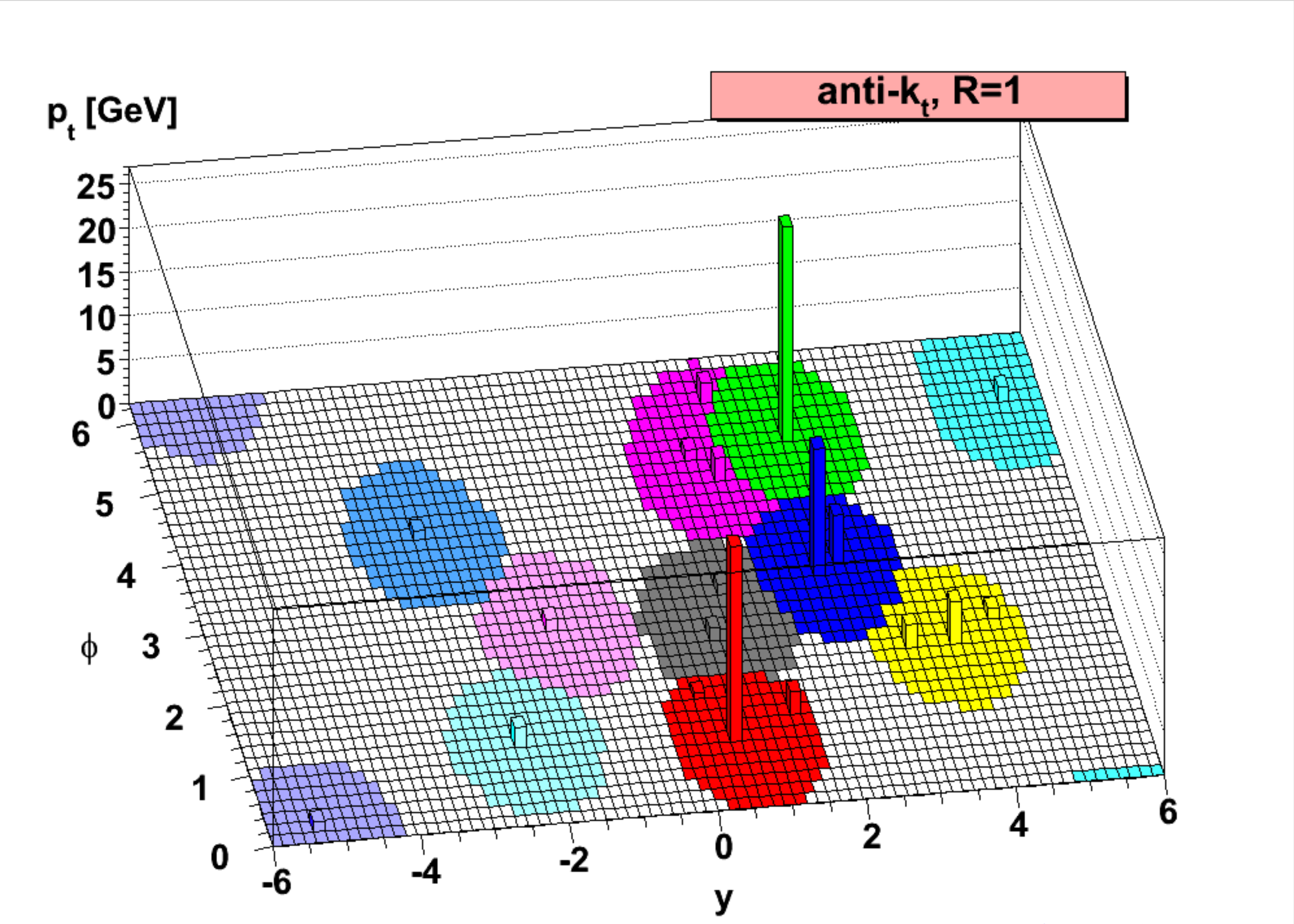
Capturing Hadronic Showers



- Input: Calorimeter + Tracking info
  —> ParticleFlow: Individual final-state particles' 4-vectors and other measured characteristics

- Clustering Algorithm of Choice: anti-kt
  —> Soft grouped onto hard objects
  —> Yields circular jets (simplifies calibrations)
  —> Greedy: Leading 'eats' all within R-param
  —> R-parameter: 0.4 (resolved partons)
  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ 1.2 (boosted decay)



M. Cacciari, G. Salam, and G. Soyez

Physics of a Top Quark Decay

Top quarks decay very quickly

t -> b+W   (W can decay to quarks or leptons)

$\tau_t \sim 10^{-25} sec, \tau_{b-hadron} \sim 10^{-12} sec$

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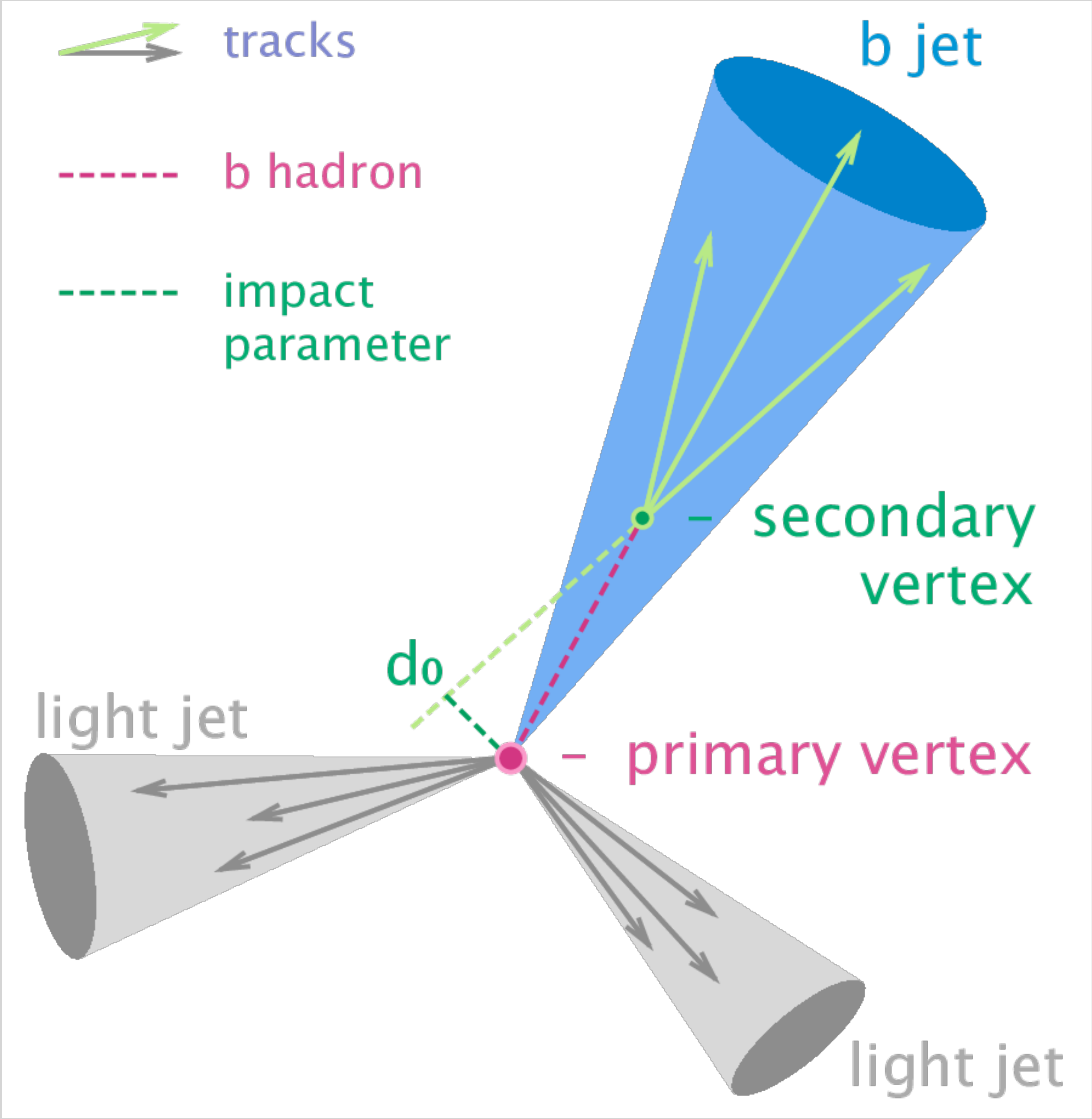

Figures from FNAL.gov

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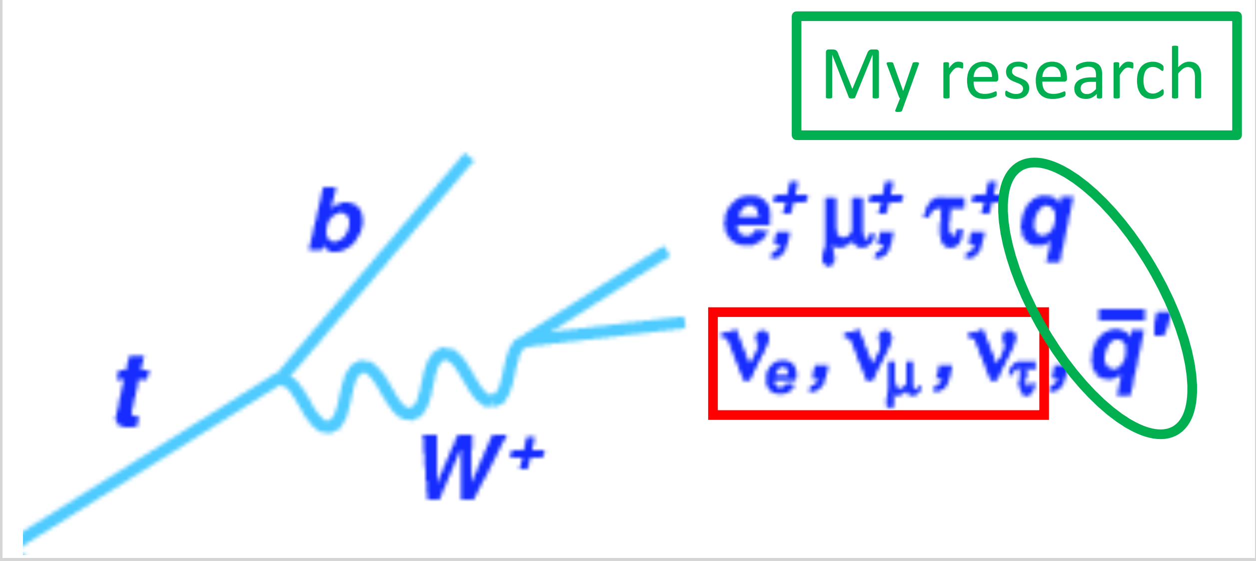
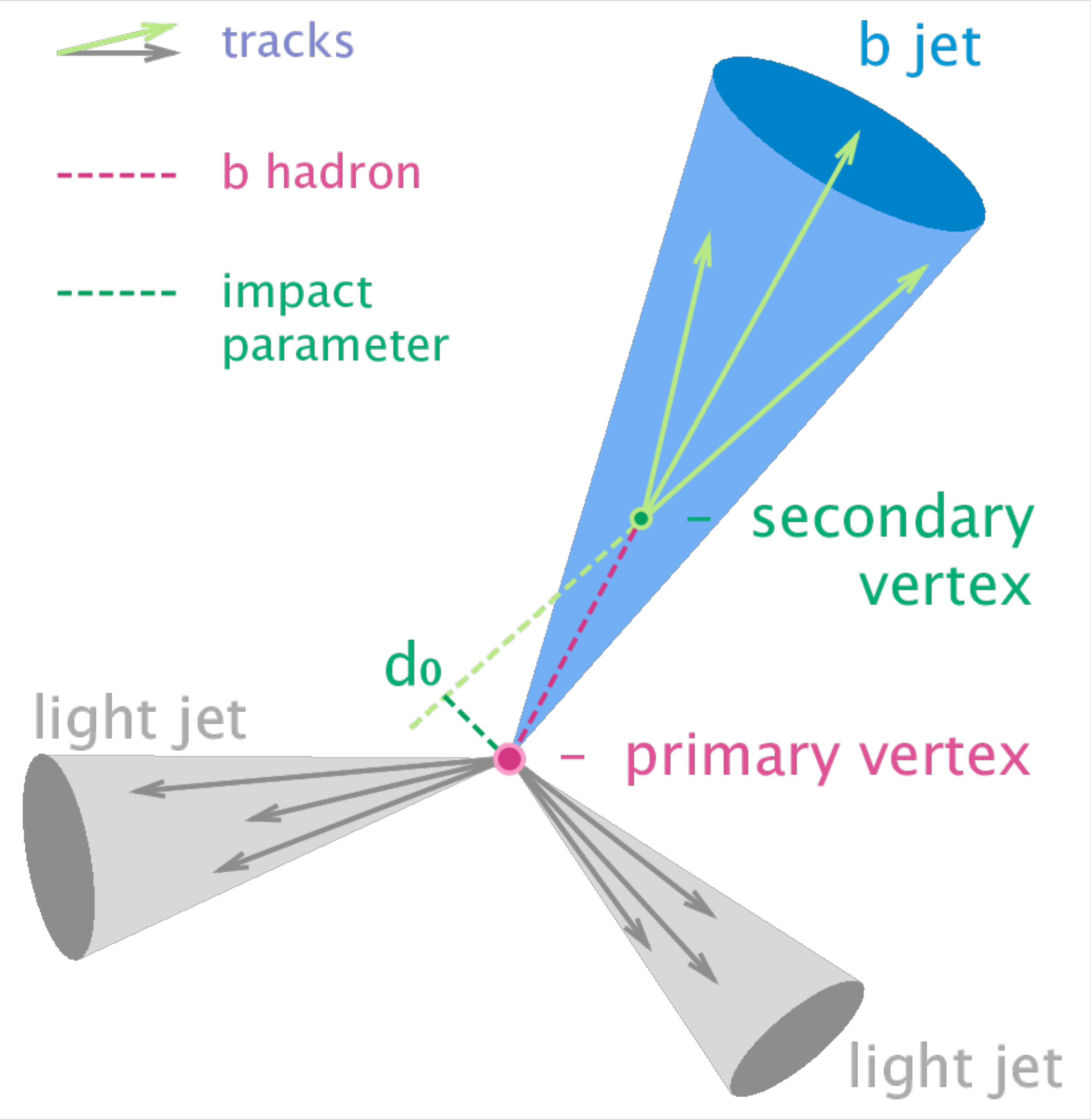
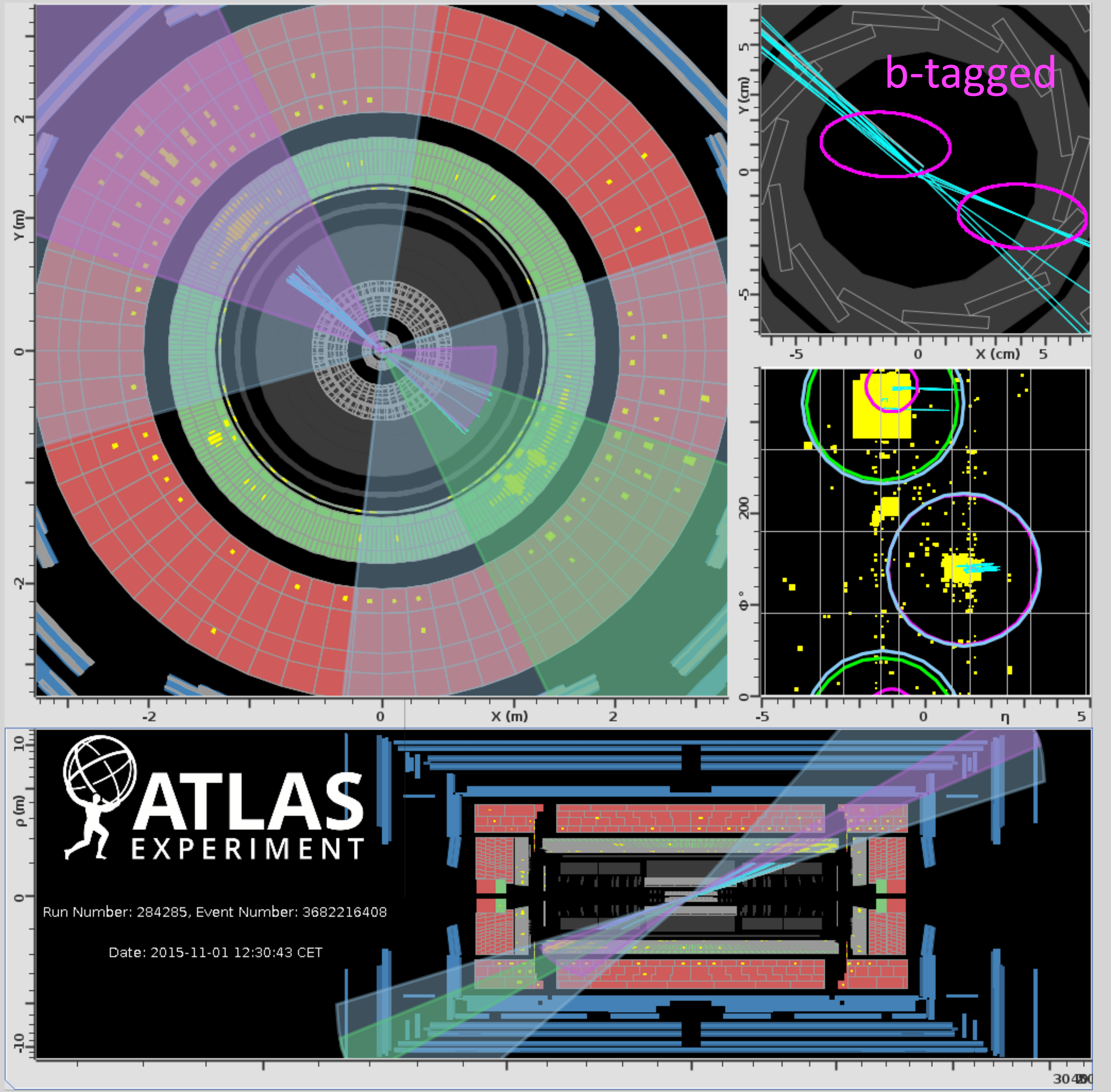


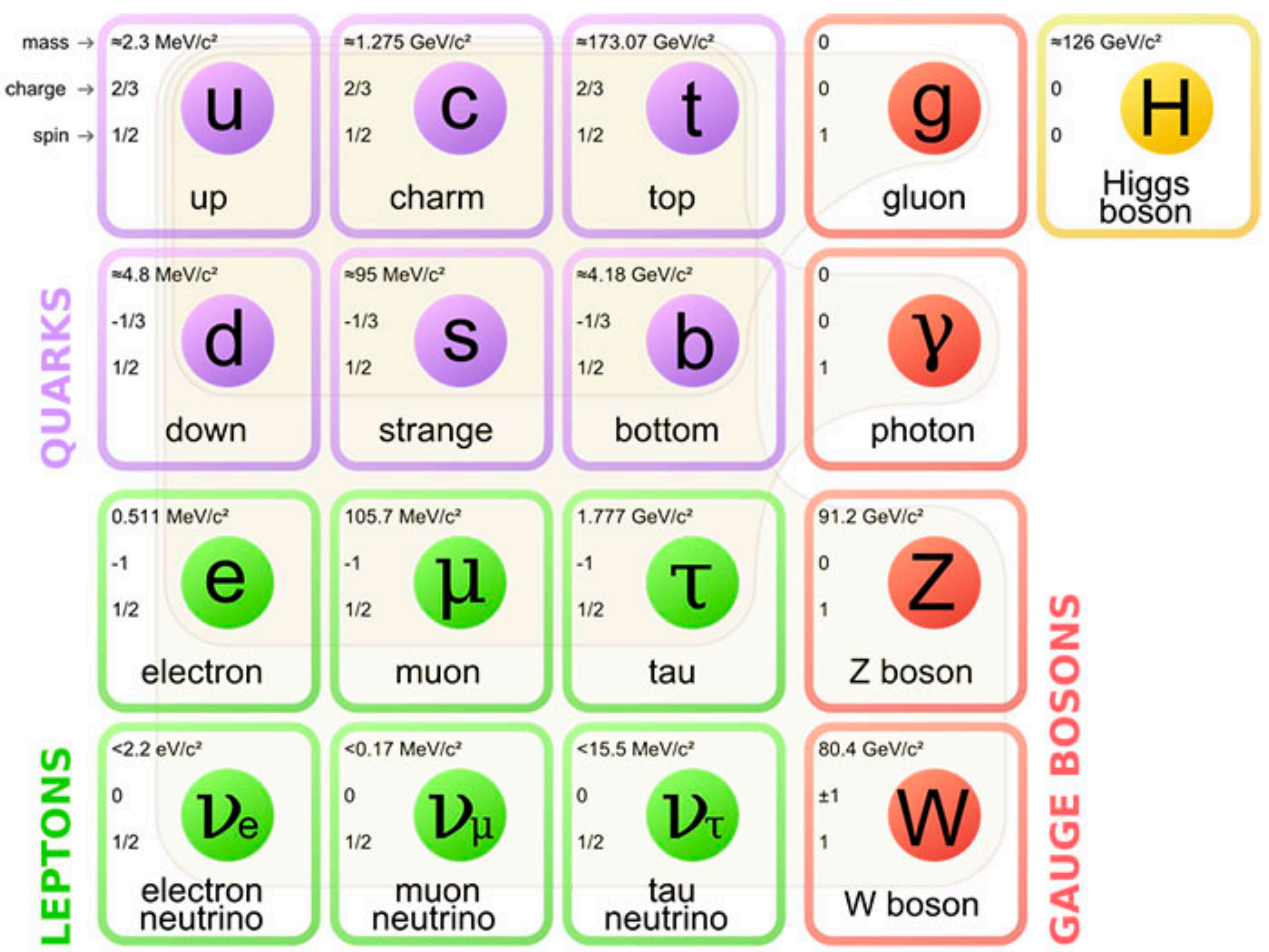




Figures from FNAL.gov

But Who Cares?

The Standard Model of Particle Physics



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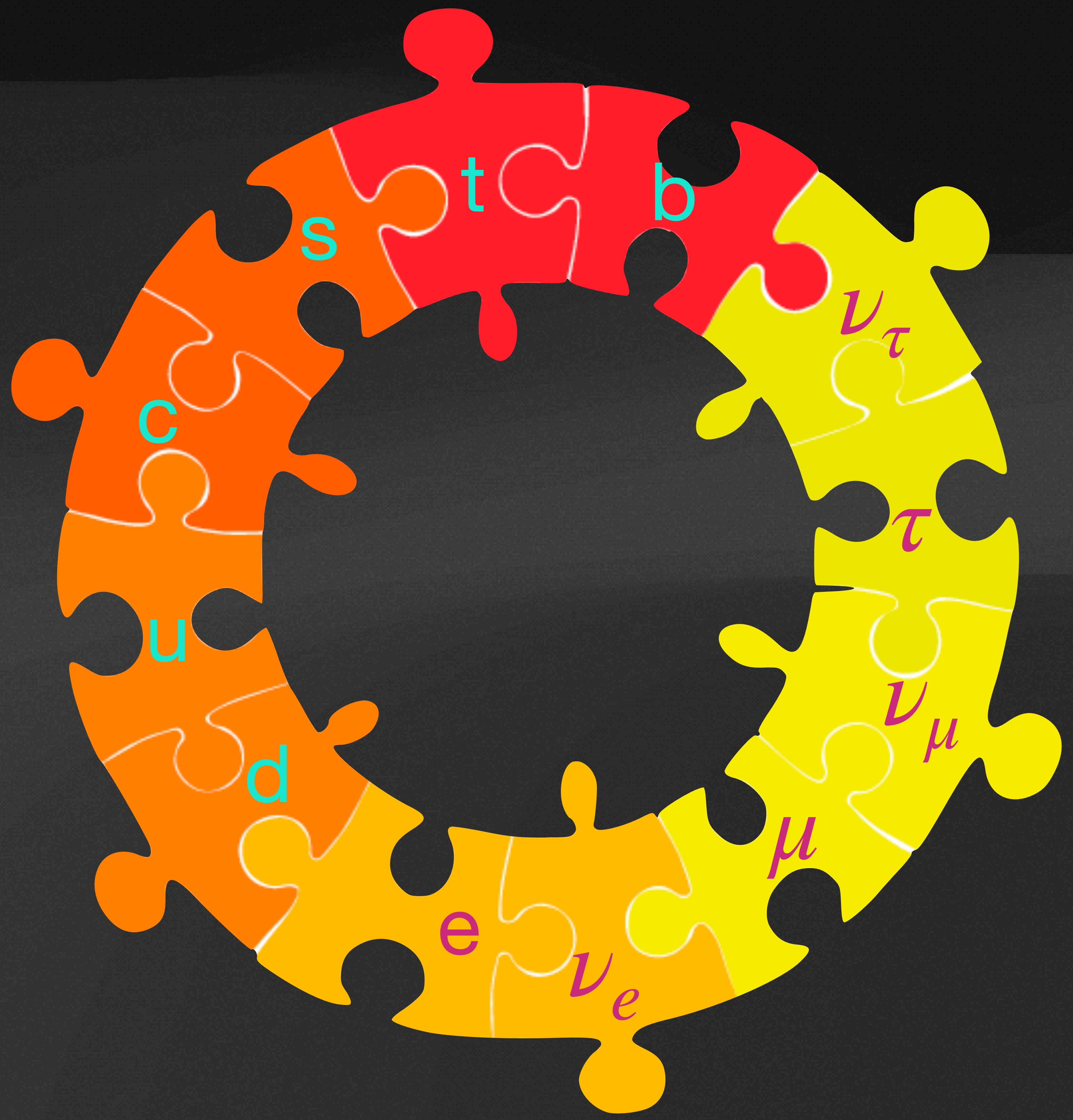

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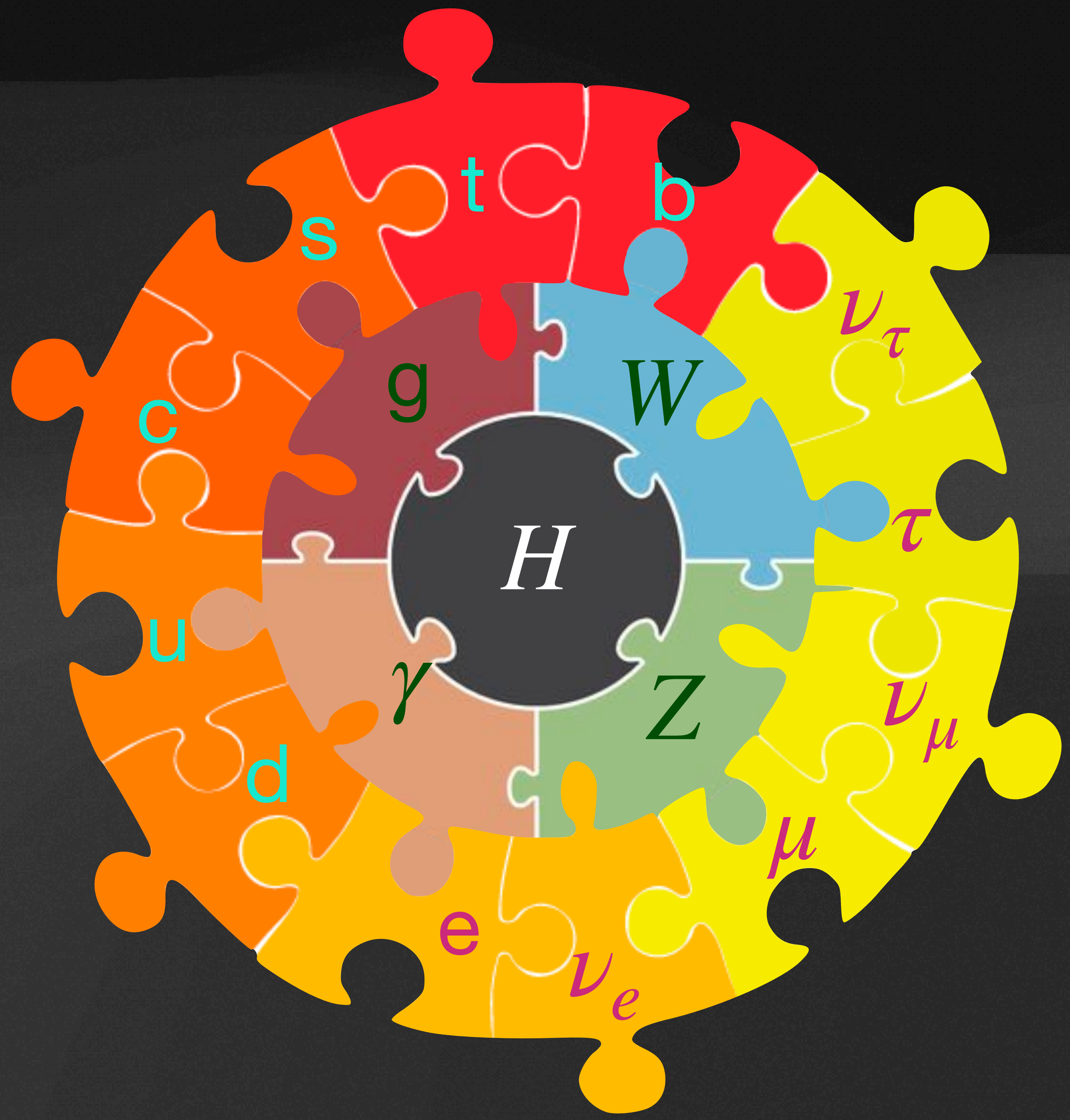

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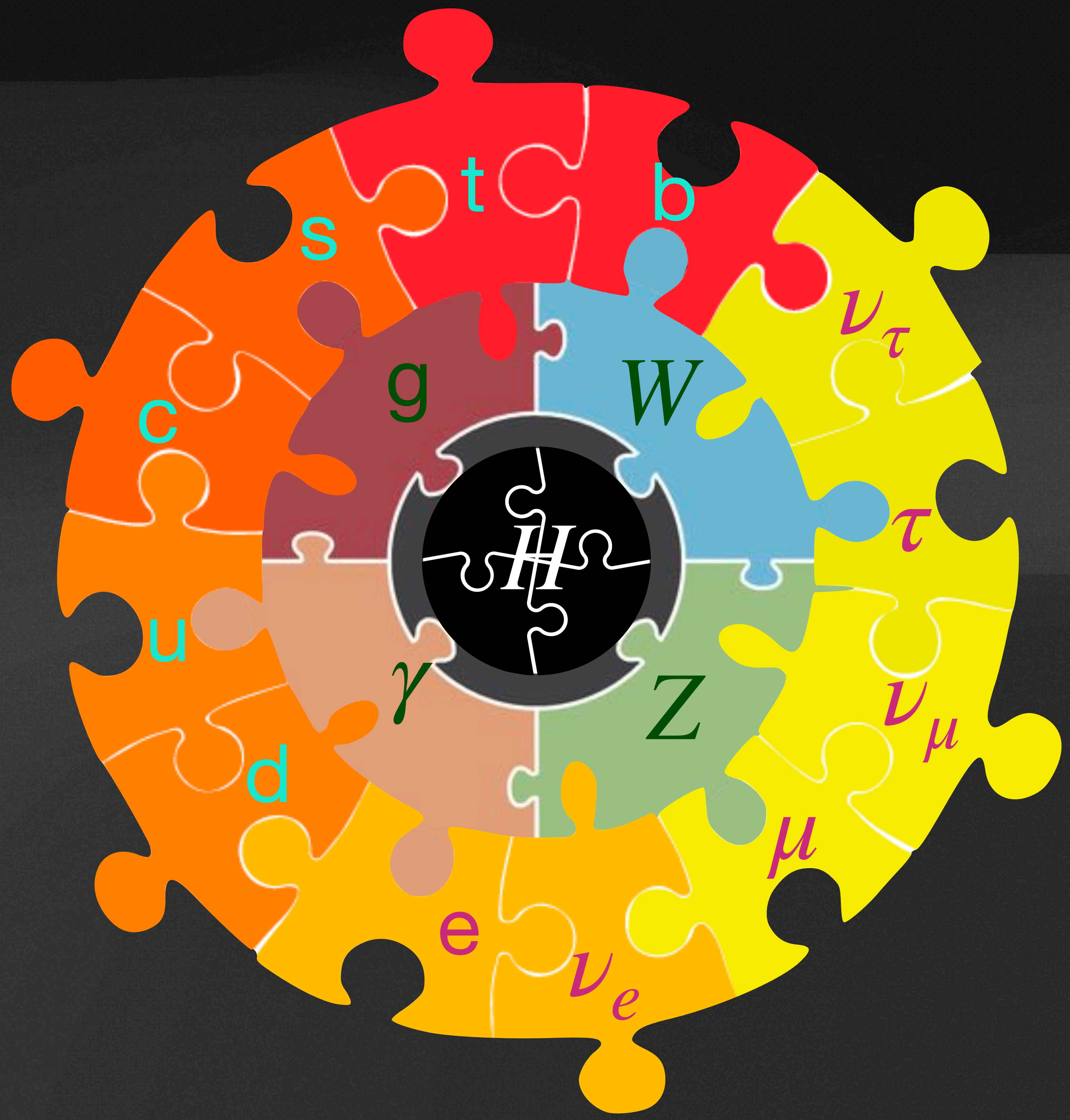

Lagrangian of the Standard Model

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Symmetry Magazine

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$

$$\frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$

$$\frac{1}{2}m^2_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$

$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$

$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$

$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$

$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$

$$g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$

$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$

$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$

$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$

$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$

$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$

$$\frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$

$$g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$

$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w -$$

$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$

$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$

$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

$$\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$

$$m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$

$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$

$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

$$\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$

$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$

$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] +$$

$$\frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$

$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Lagrangian of the Standard Model

Symmetry Magazine

1

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} +$$
$$\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

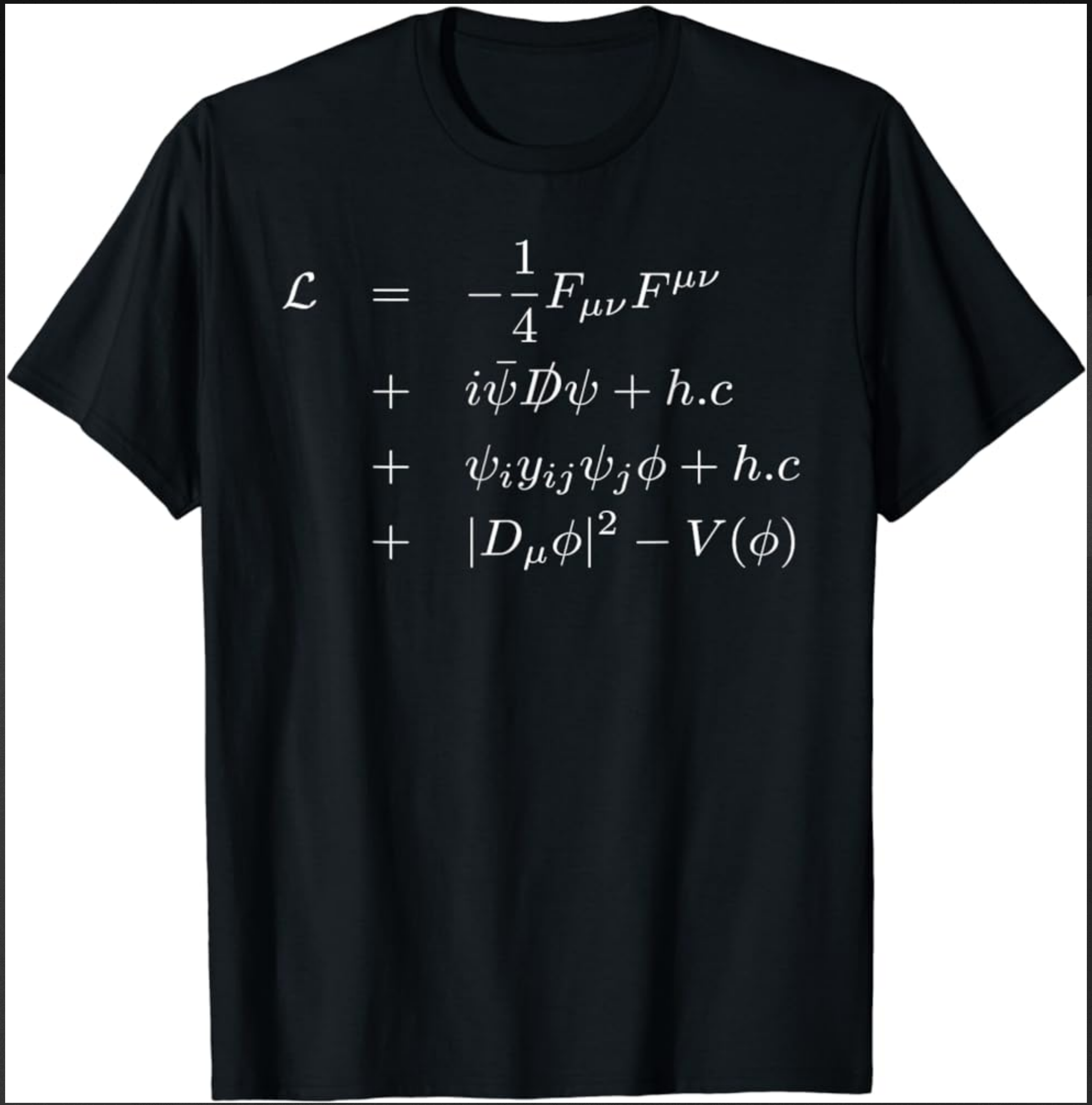
4

$$\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

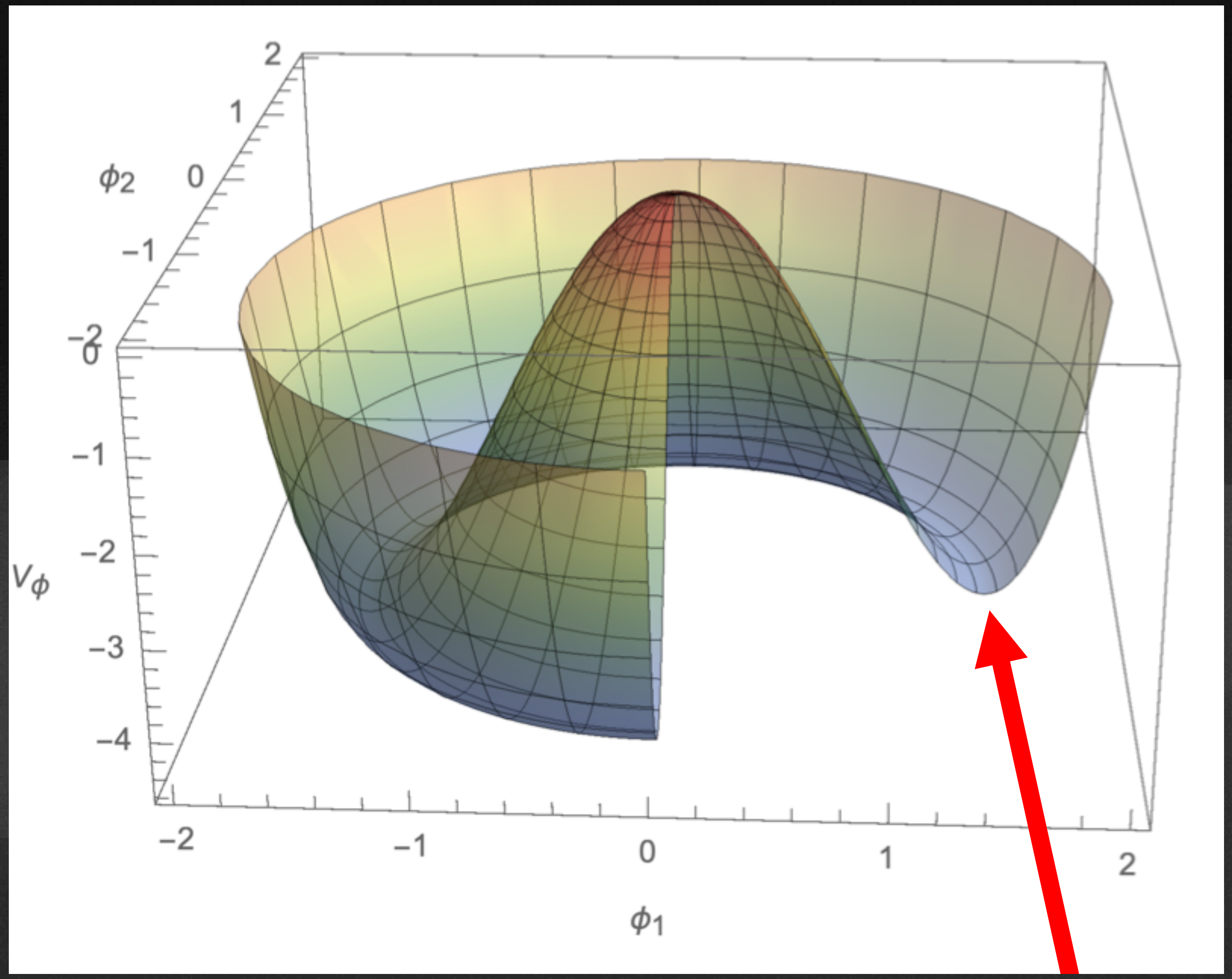
$$\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Lagrangian of the Standard Model



(Un-)Naturalness of the Standard Model

Motivation for BSM Physics



Can be measured from
Weak Interactions

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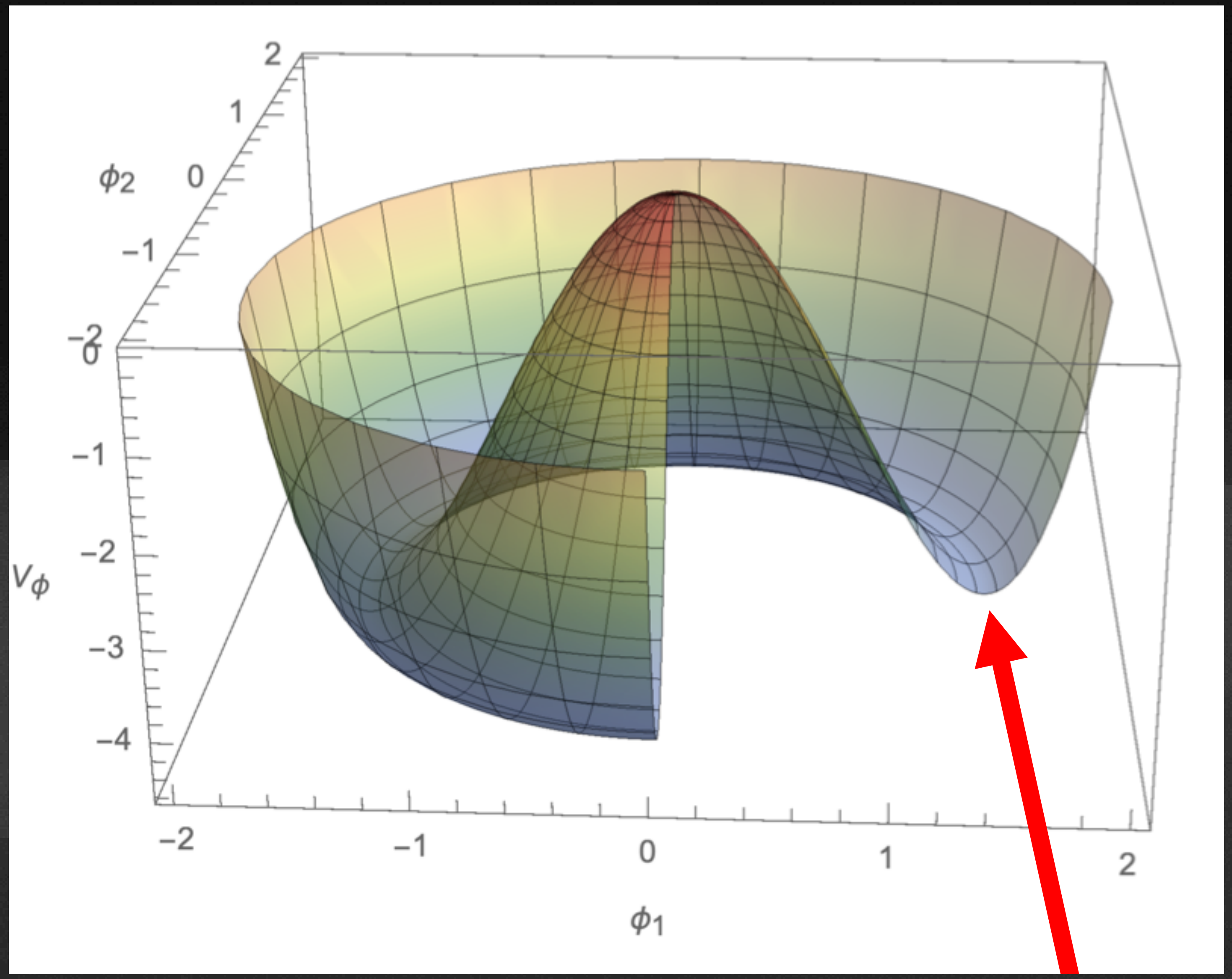
Motivation for BSM Physics

$$V(\phi_H) = \frac{1}{2}\mu^2 |\phi_H|^2 + \frac{1}{4}\lambda |\phi_H|^4$$

$$\langle \phi_H \rangle = \nu = \frac{\mu}{\sqrt{\lambda}} = 256\ \text{GeV}$$



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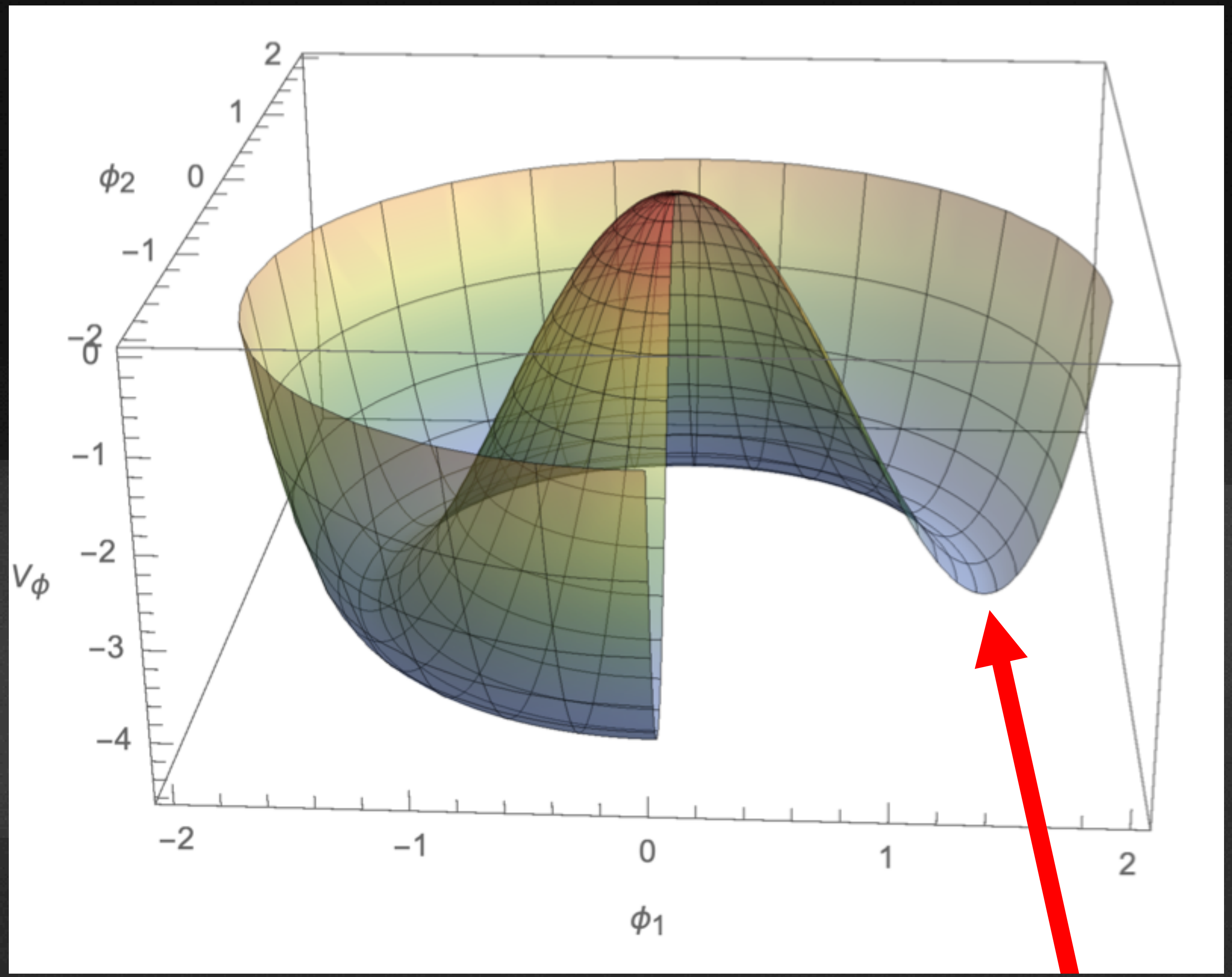

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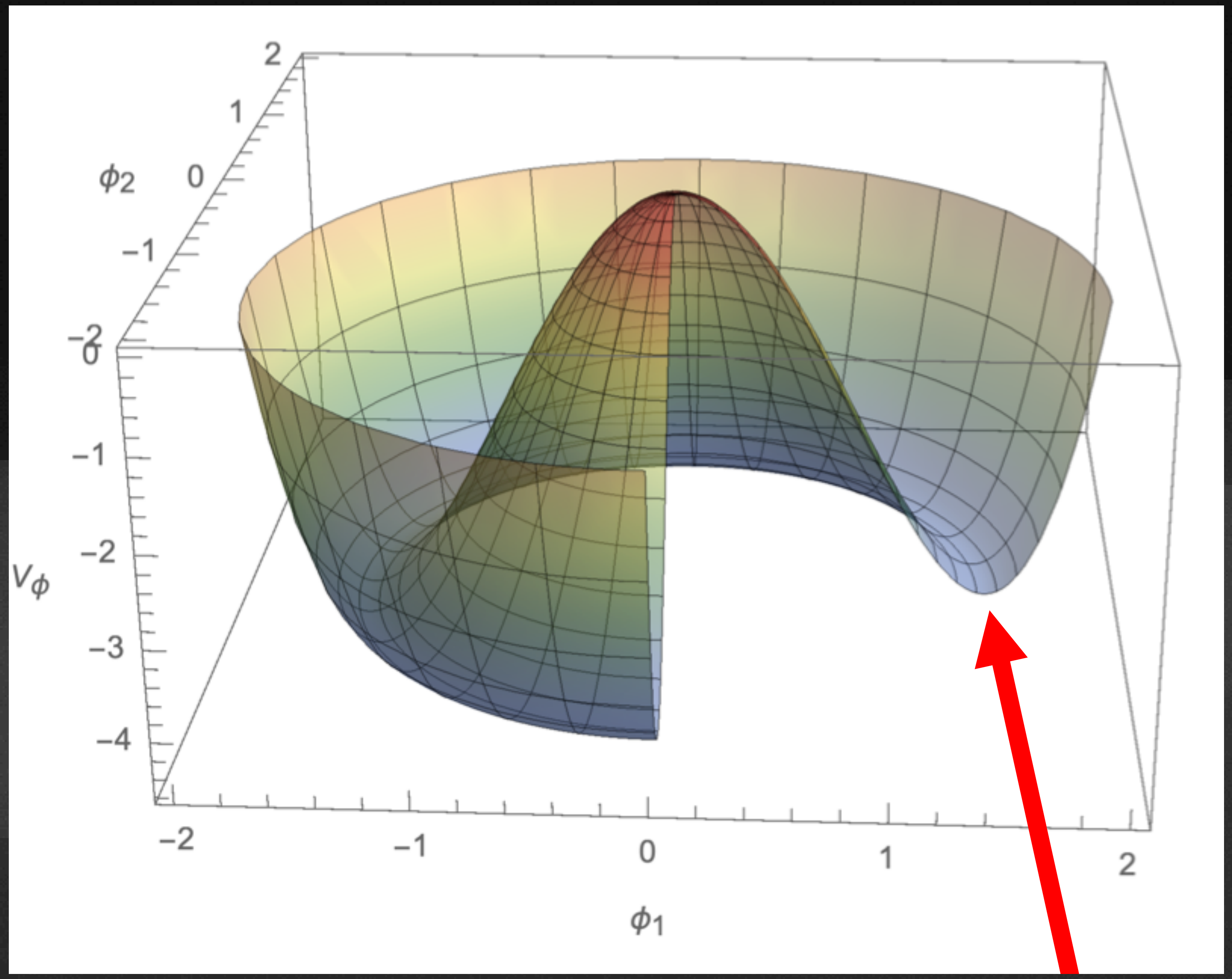
$\sim\text{GeV}^2$ = +



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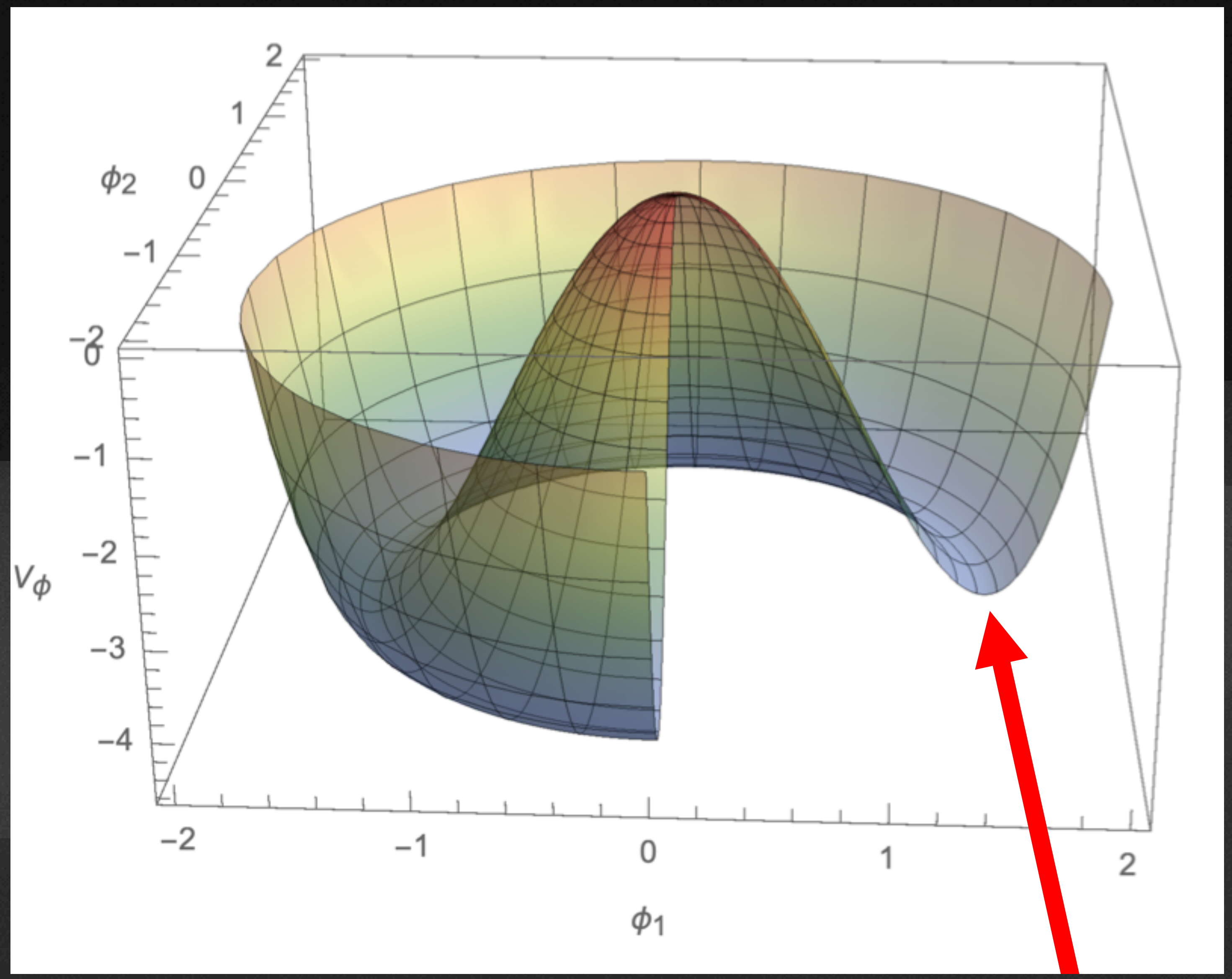

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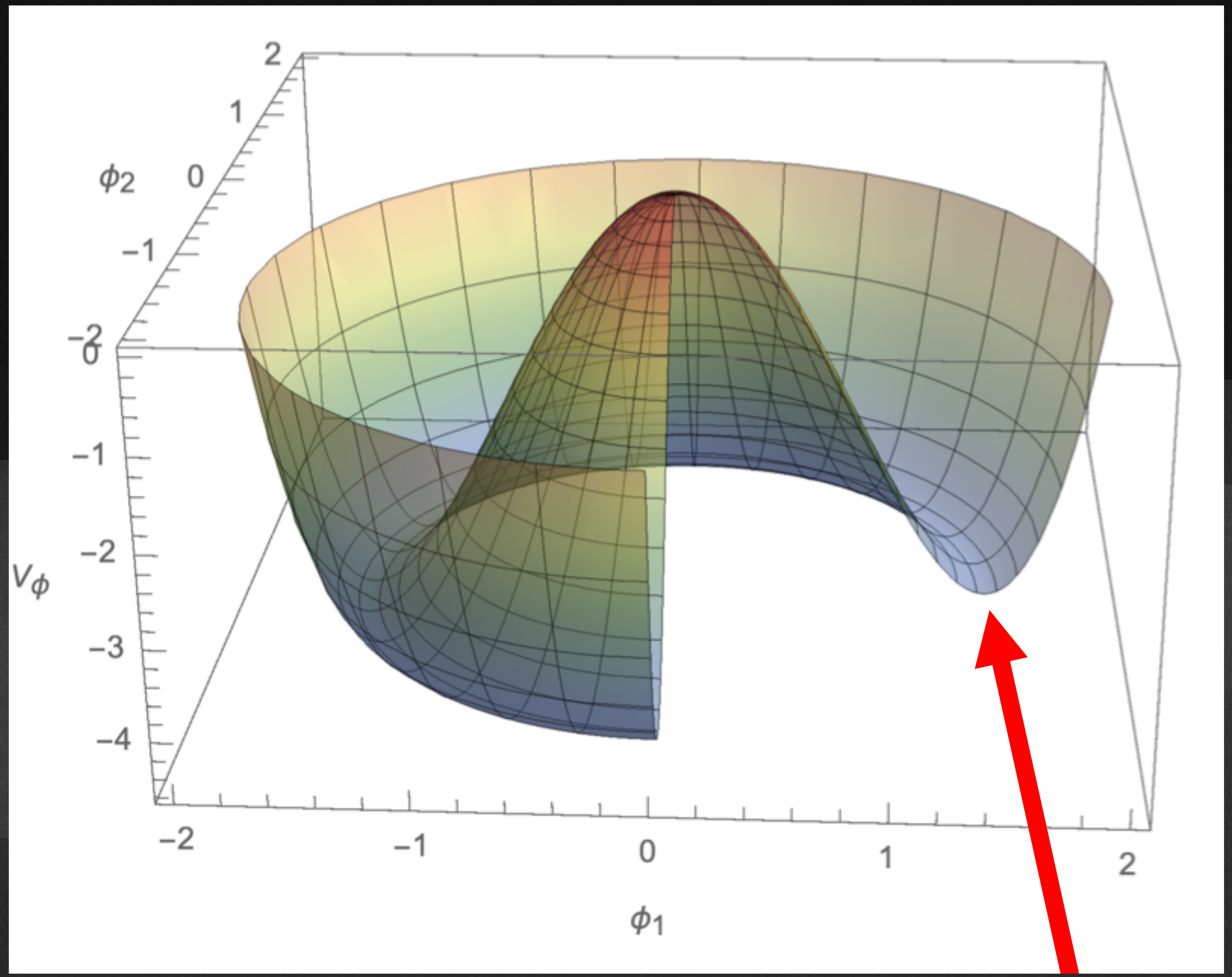

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For ANY choice of Λ_{UV}!

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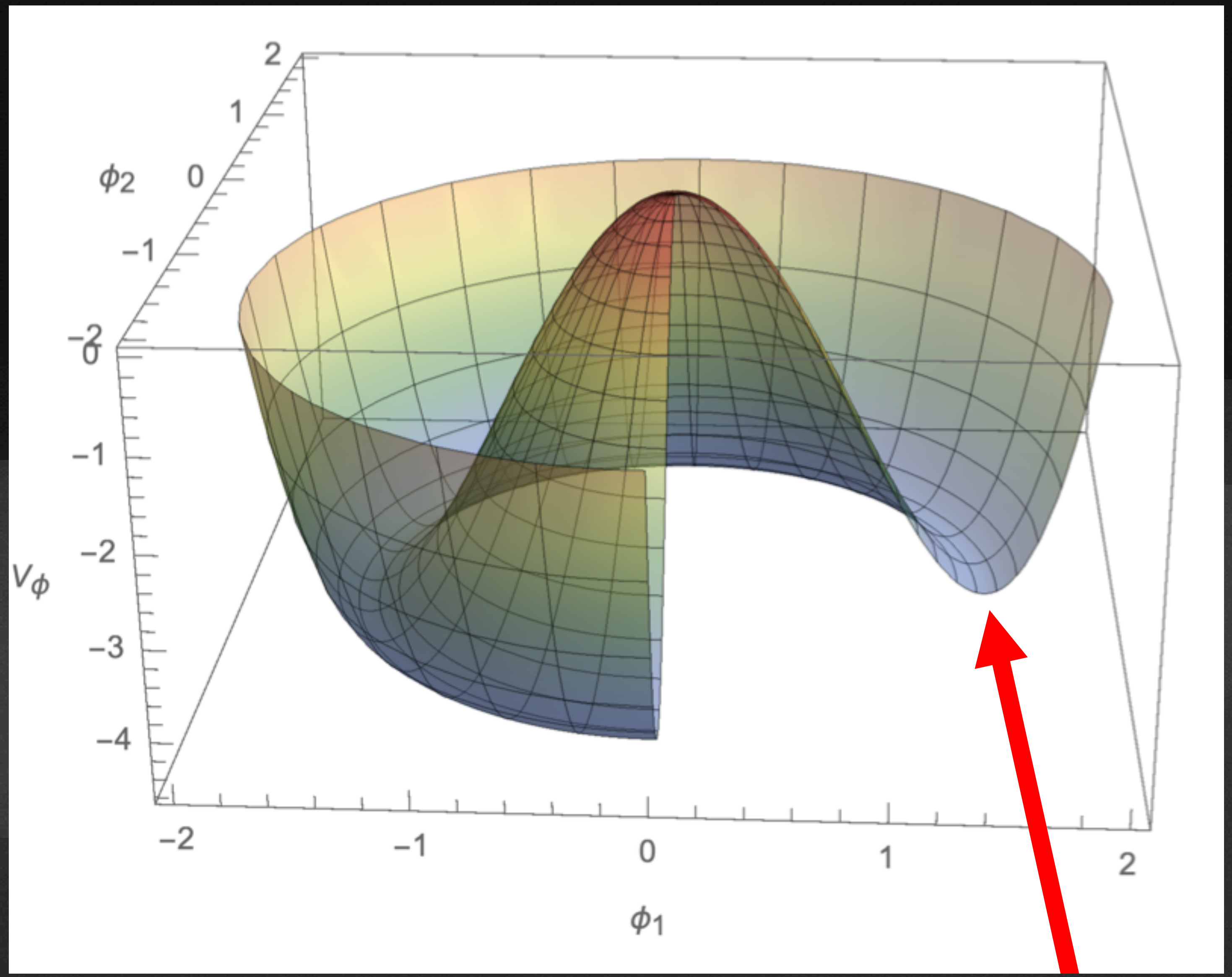

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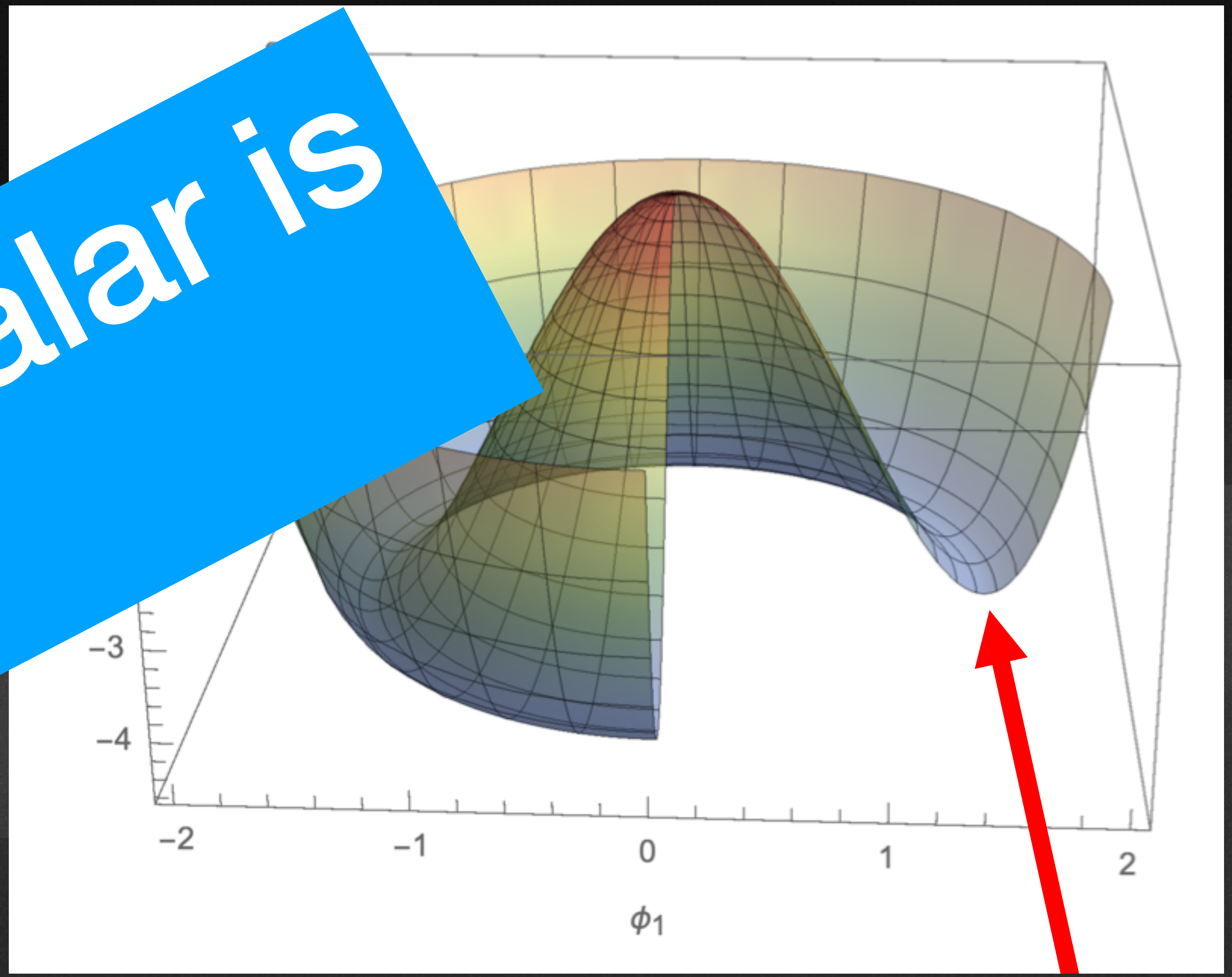
…rmions bosons

~GeV … une + $\sim \mathcal{O}(\Lambda^2_{UV})$ - $\sim \mathcal{O}(\Lambda^2_{UV})$

:(

But, what if this 125 GeV scalar is non-fundamental?



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Vector-Like Quarks

Overview of Theoretical and Experimental Motivations

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Many extensions of SM have VLQs

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$$Q_L^0 = \begin{pmatrix} T_{L,R}^0 \\ B_{L,R}^0 \end{pmatrix} \qquad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

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- Mechanism to stabilize Higgs mass

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$$\downarrow$$

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$$-\Delta_L \bar{q}_L Q_R - \Delta_R \bar{t}_R T_L + h.c$$

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$$m_t \simeq \frac{\Delta_L \Delta_R y^* v}{\sqrt{2}(M^2 - m^2)}$$

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- Possible explanation for BSM phenomena,
  => see Shi-Ping's talk on $(g-2)_\mu$ anomaly (Jul 7 2022)

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Production Modes of Vector Like Quarks

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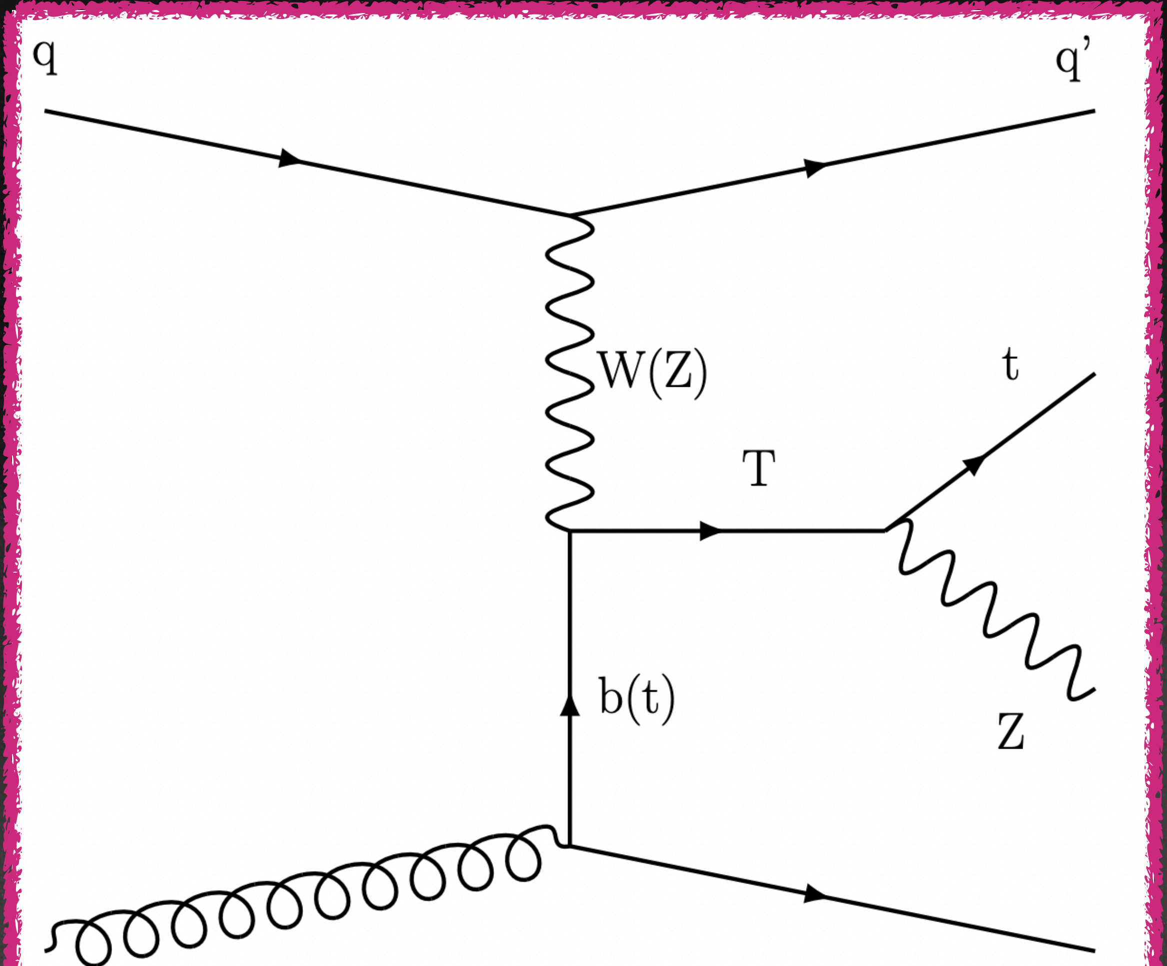
Single-Production: EW

— In association w/ t/b + quark



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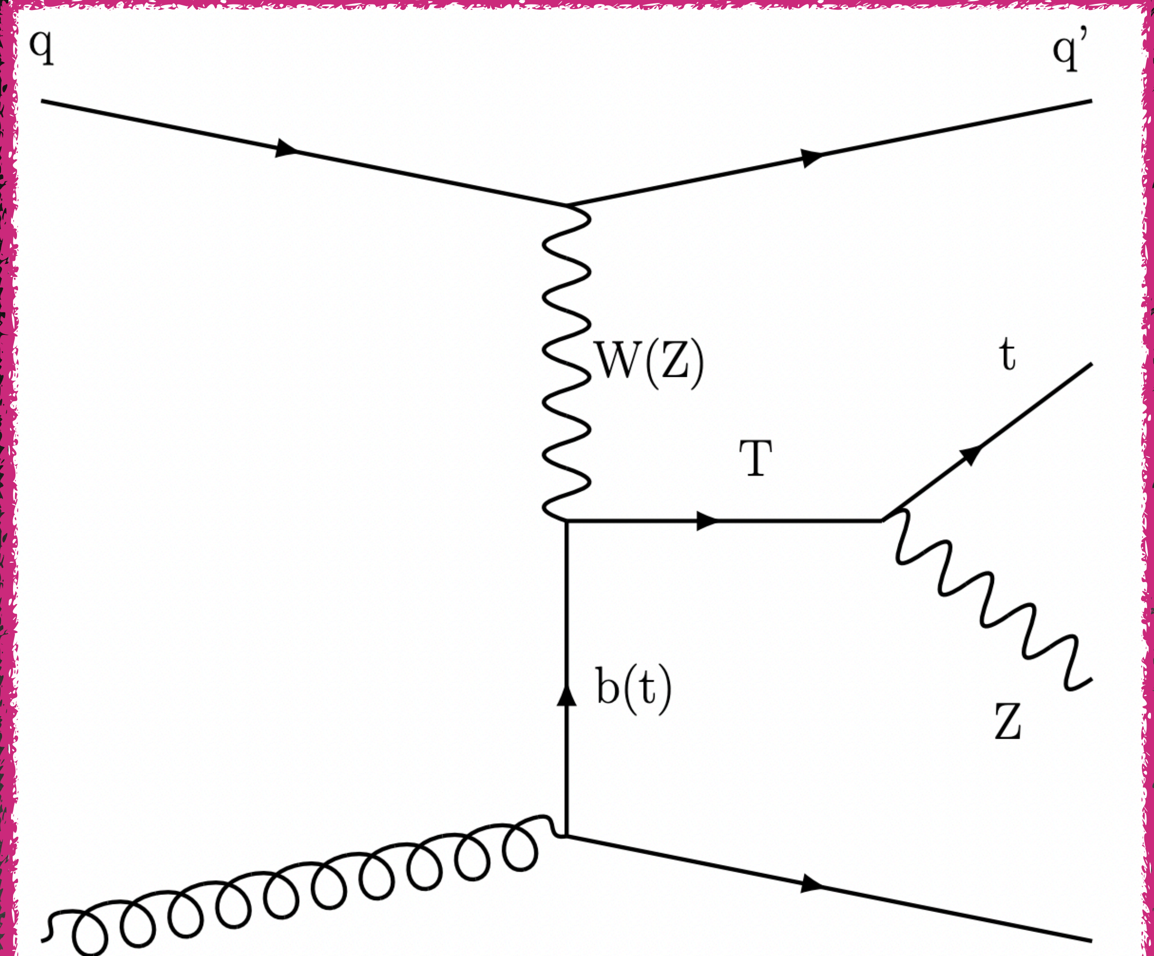

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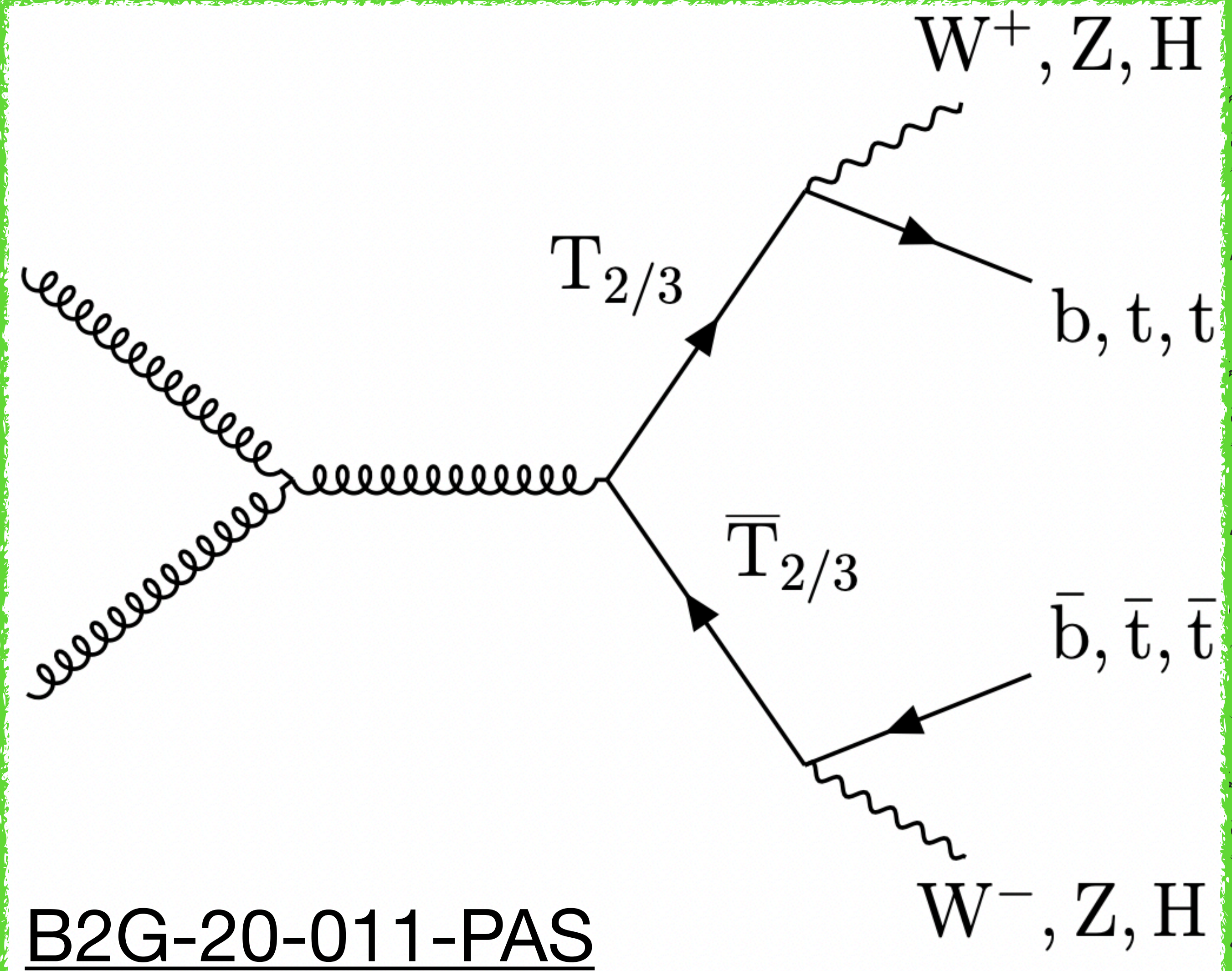
Pair-Production: Strong

— Four massive (boosted) bosons and 3rd generation quarks



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Production Modes of Vector Like Quarks

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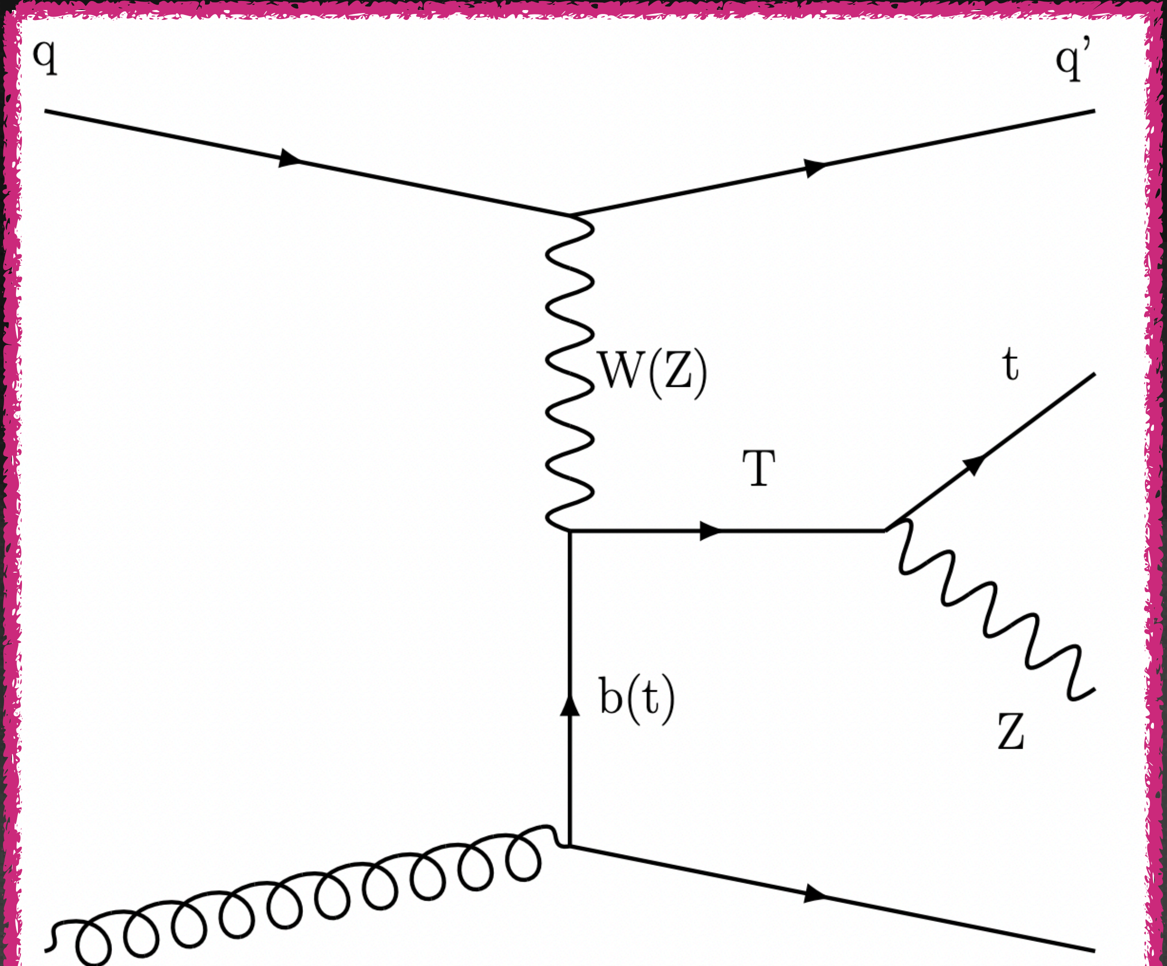
Recent non-minimal mechanisms

e.g. Chromo-magnetic moment

=> gluon-t/b-T/B vertex



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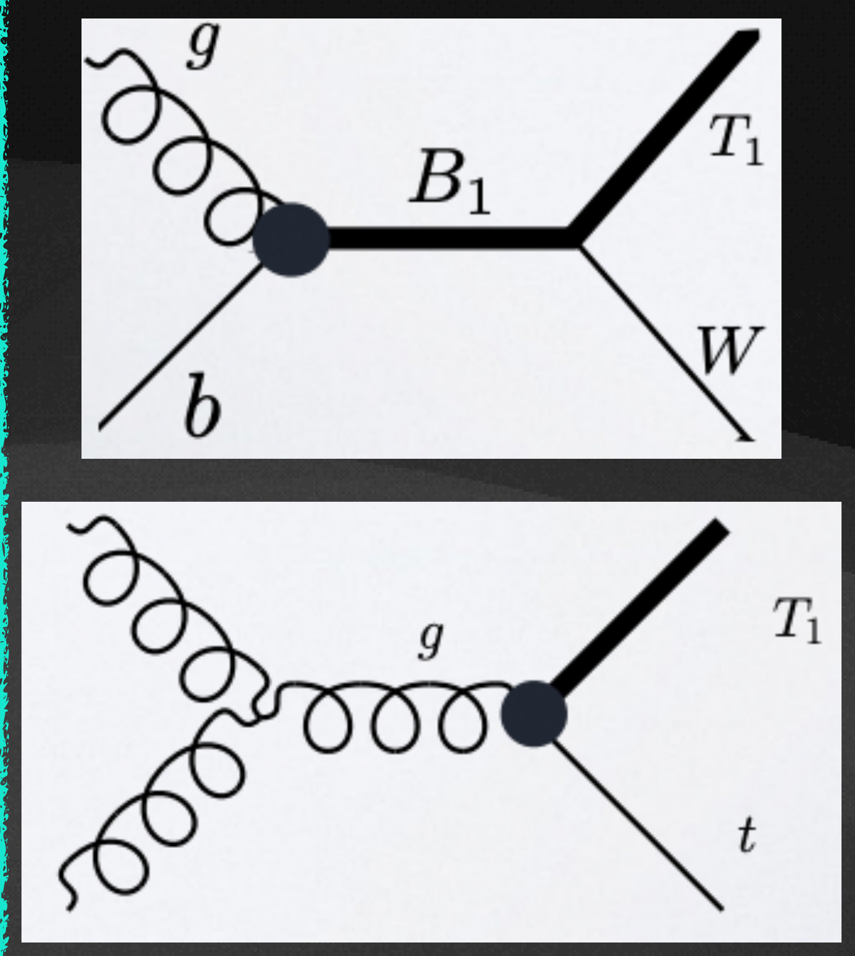
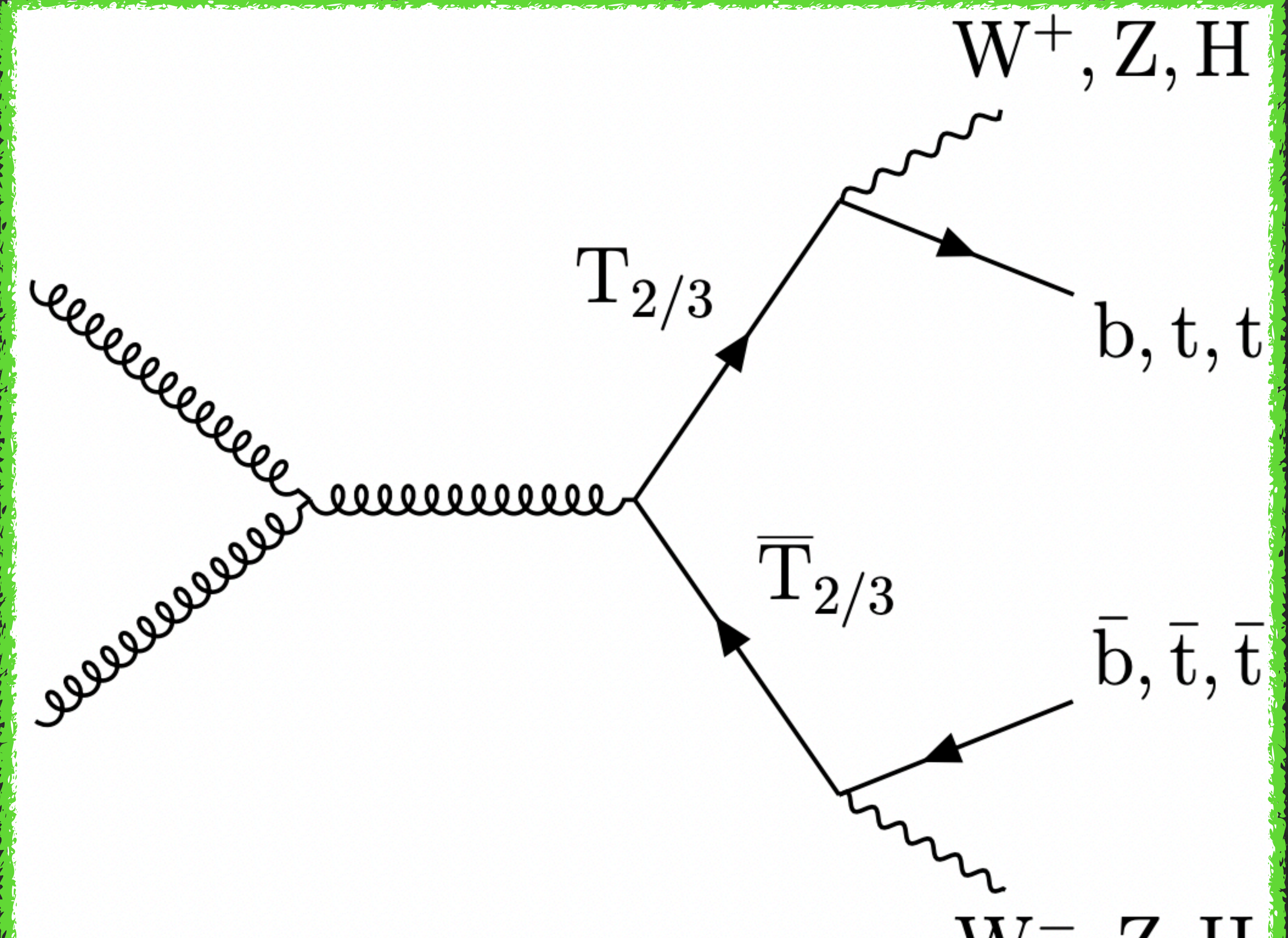


[arXiv:2107.12402]



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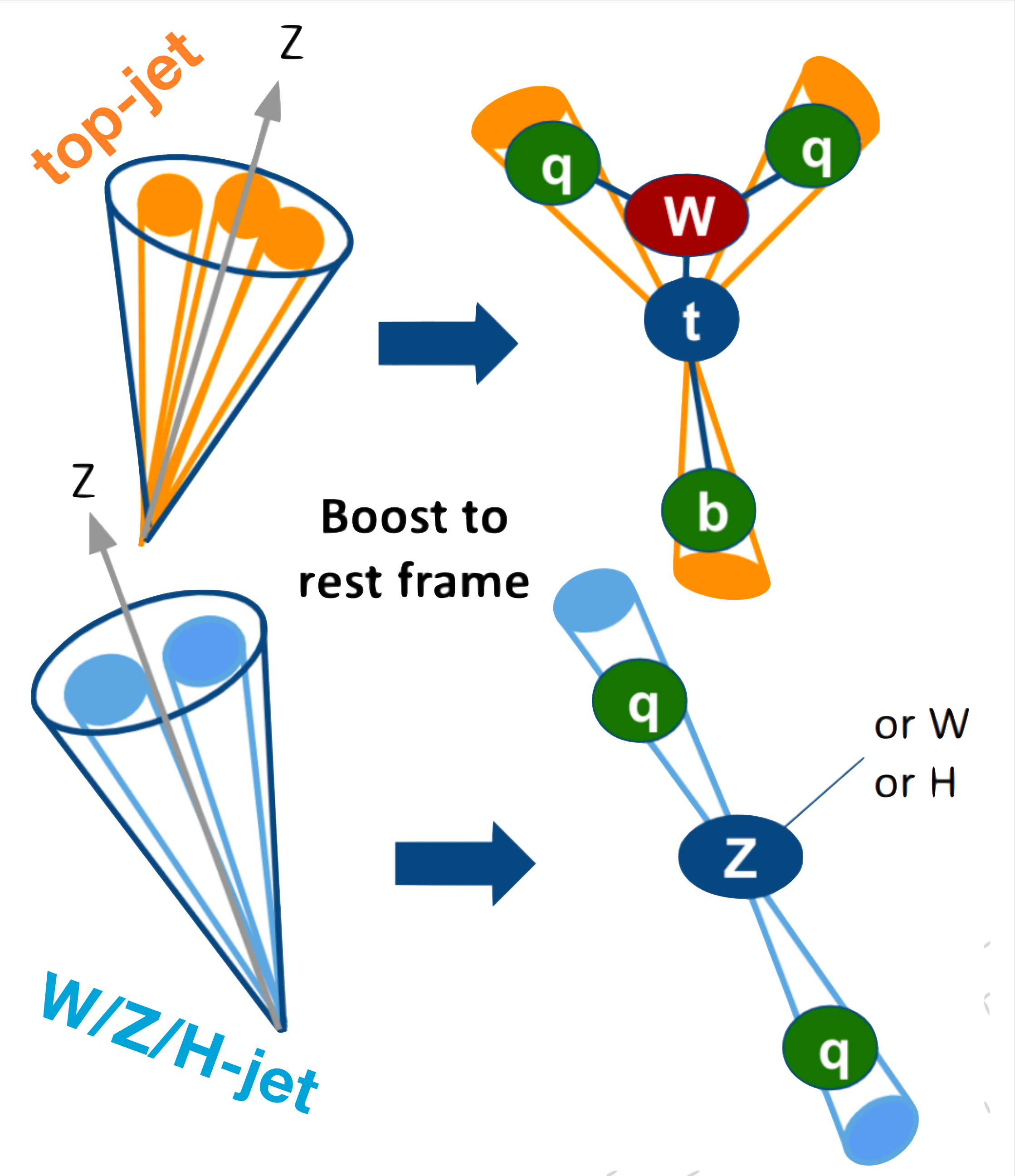
Remember those jets?



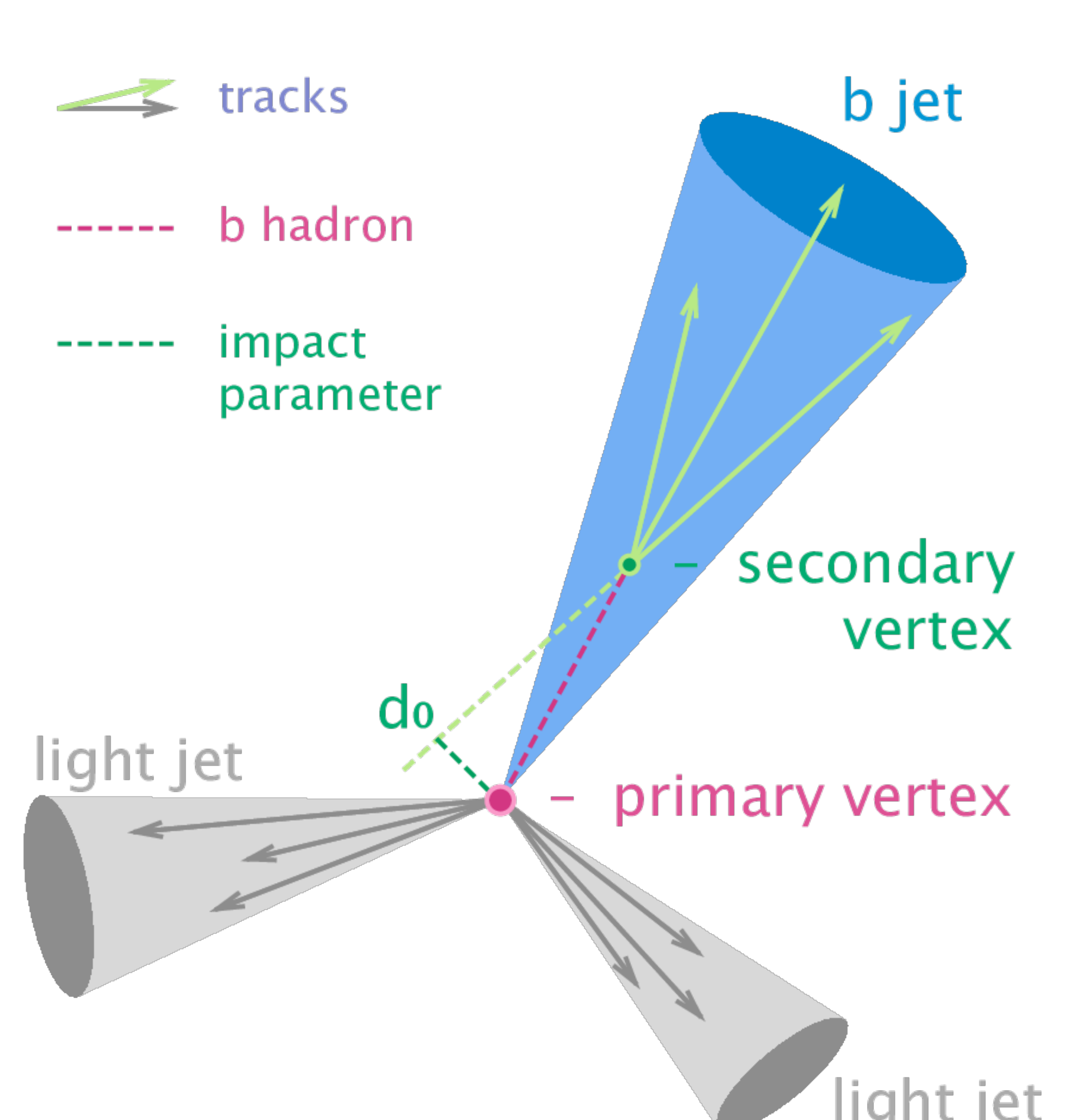
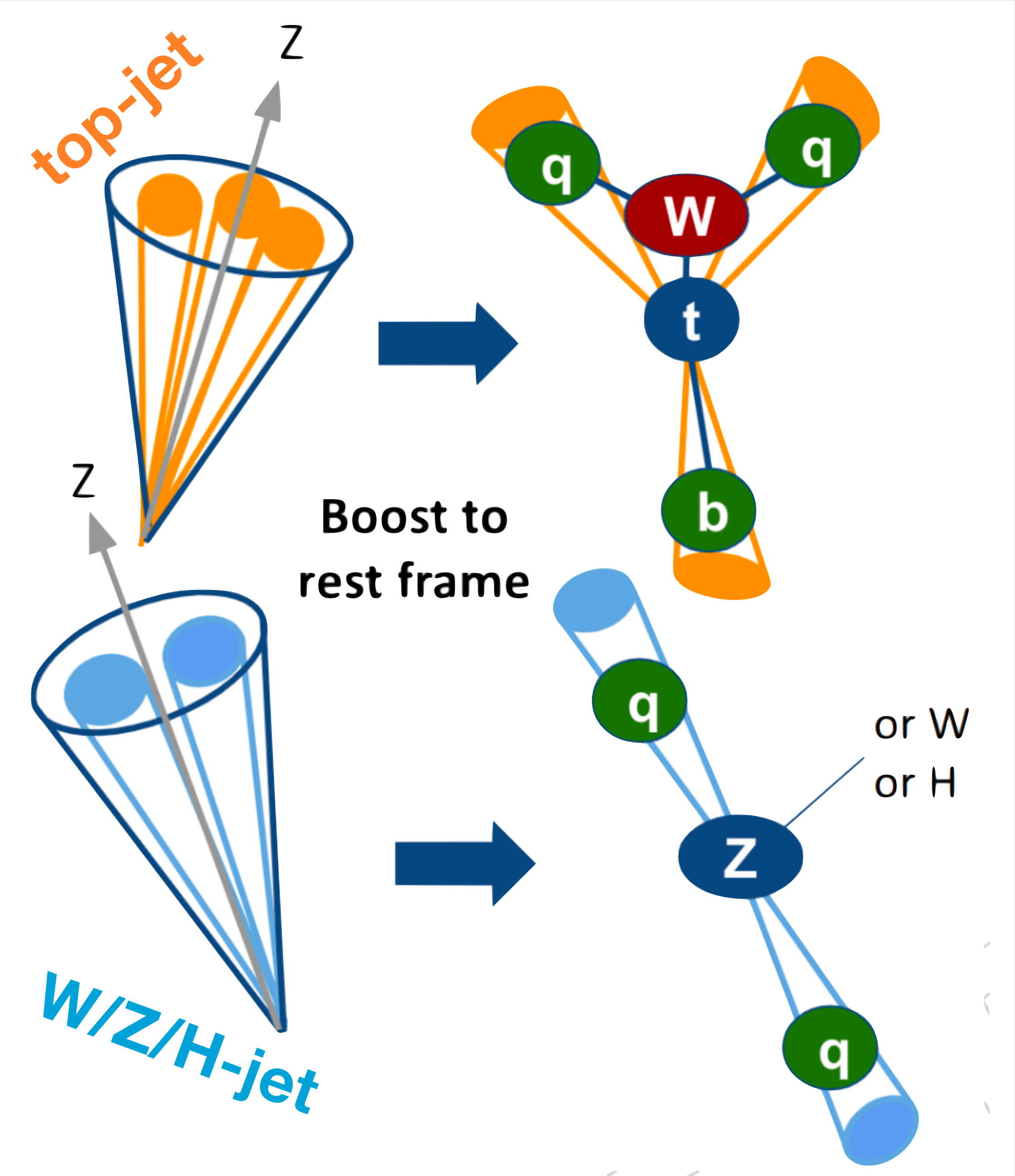


Figure from
FNAL.gov

Remember those jets?



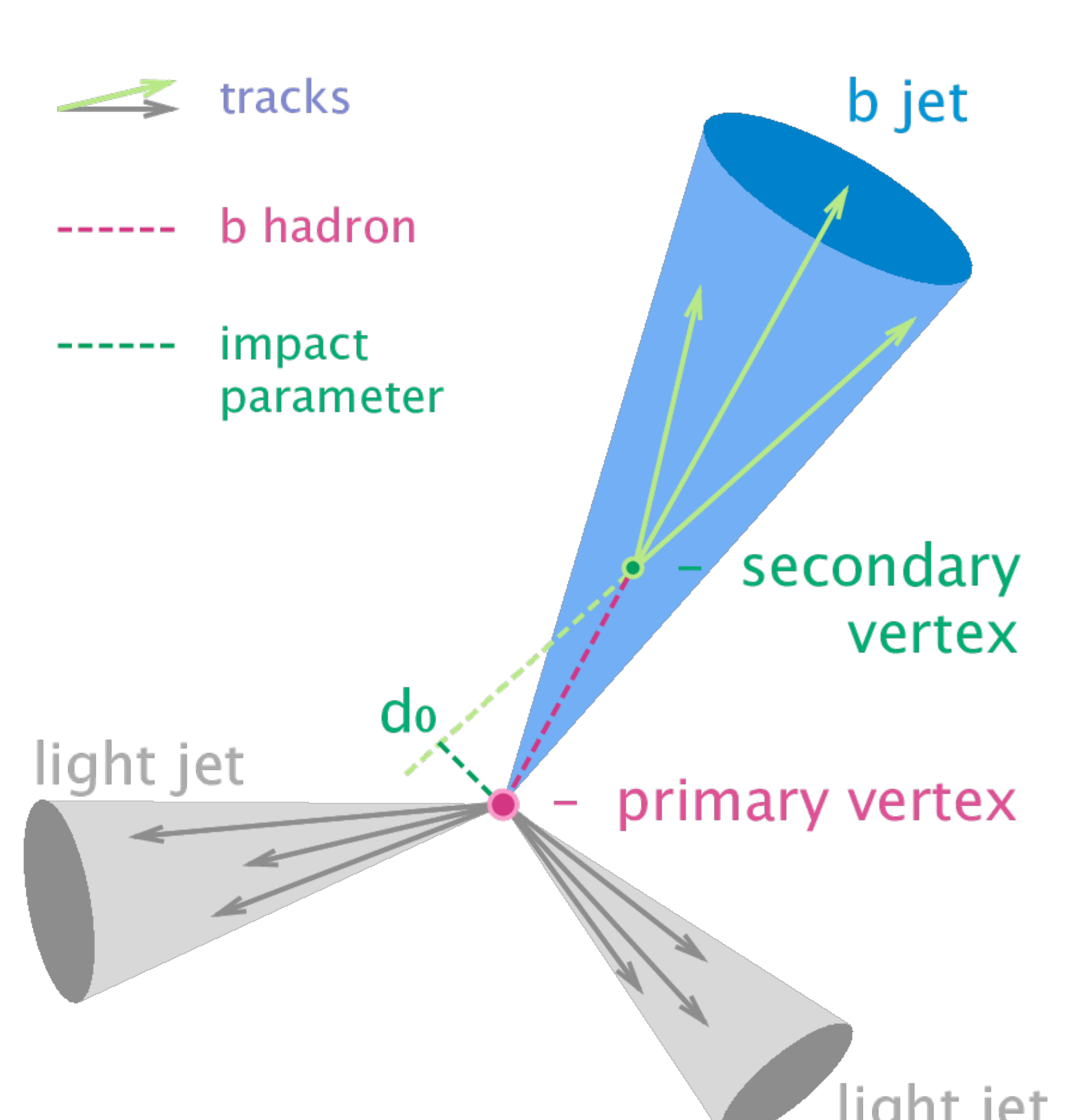


Figure from
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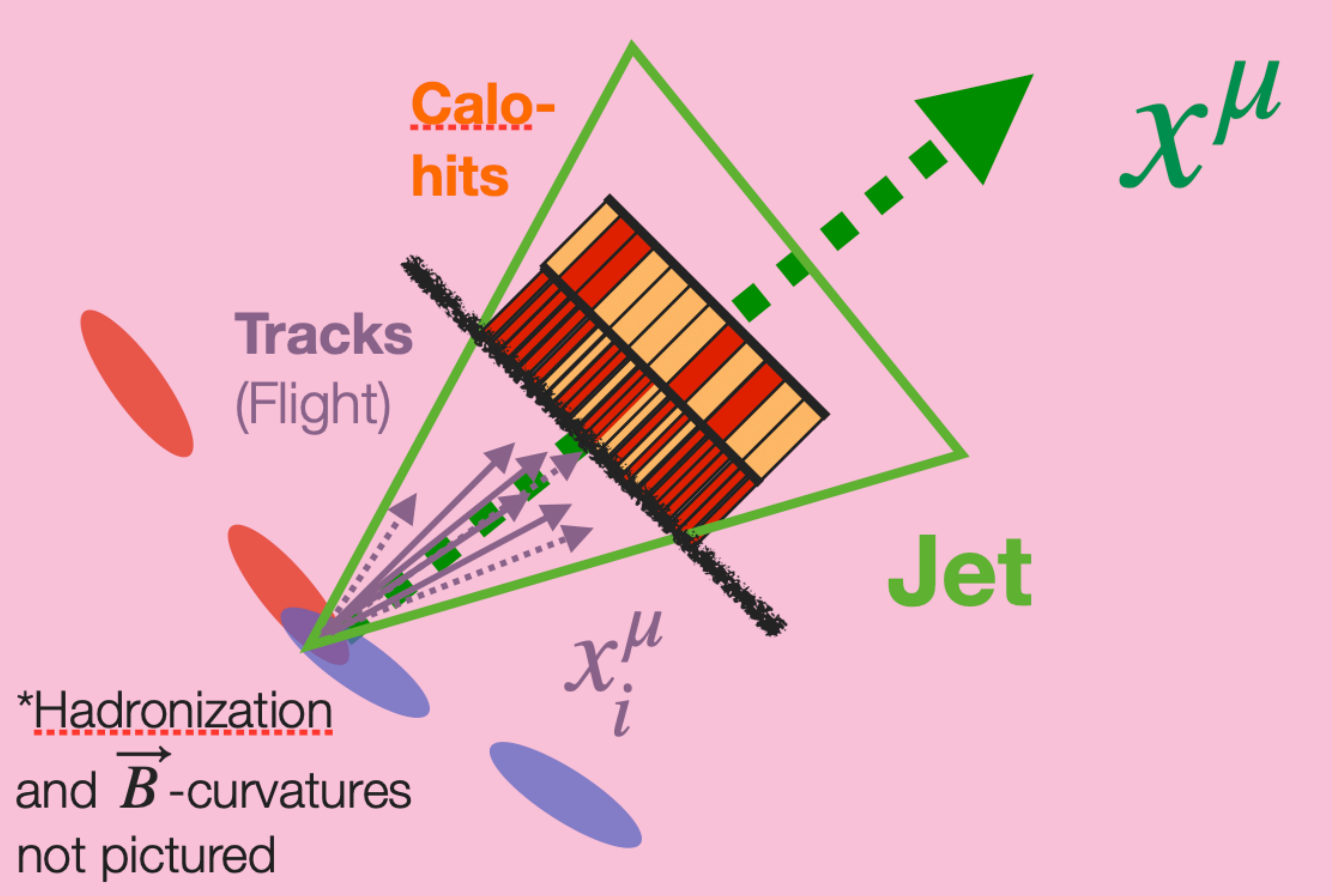

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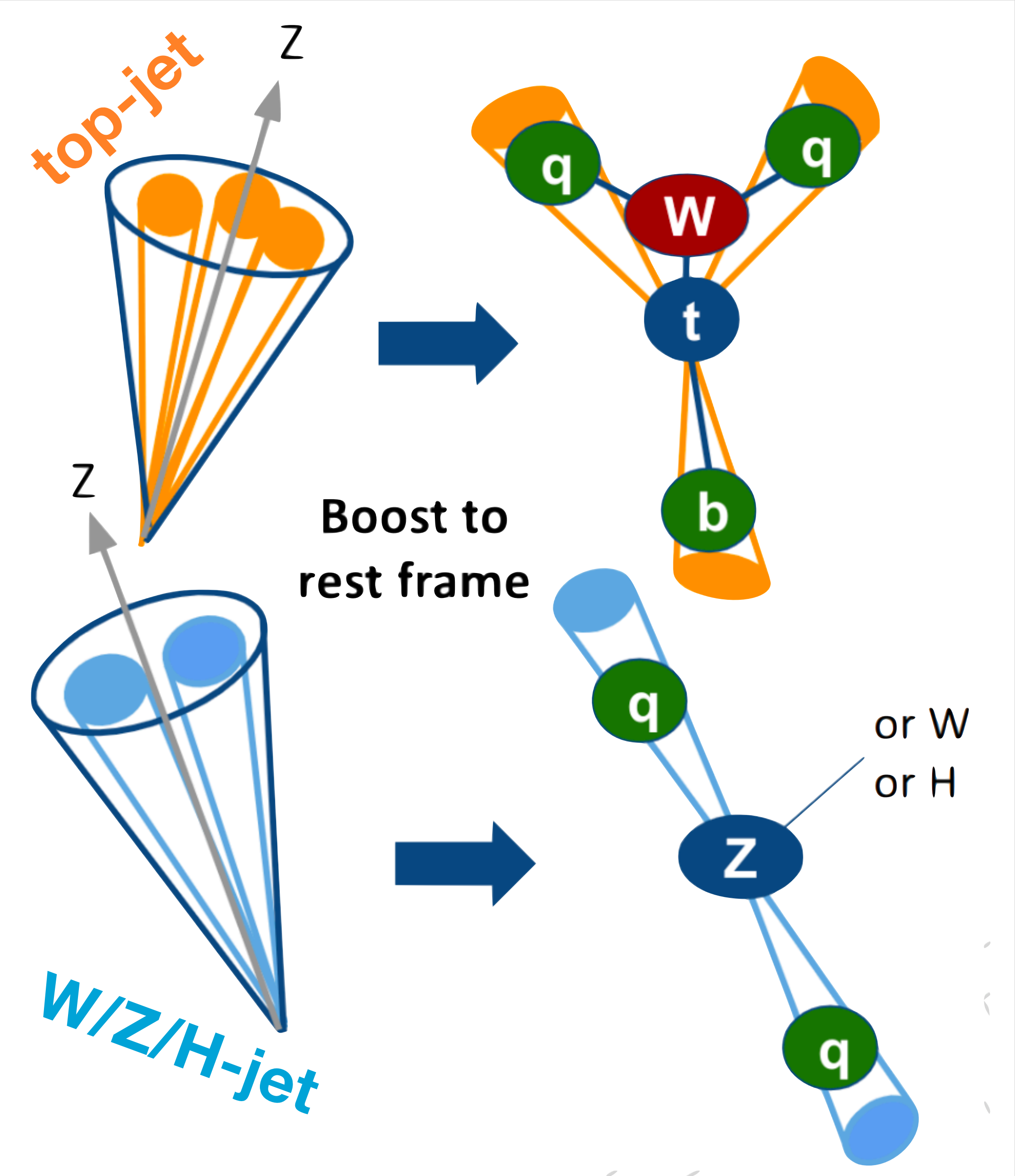

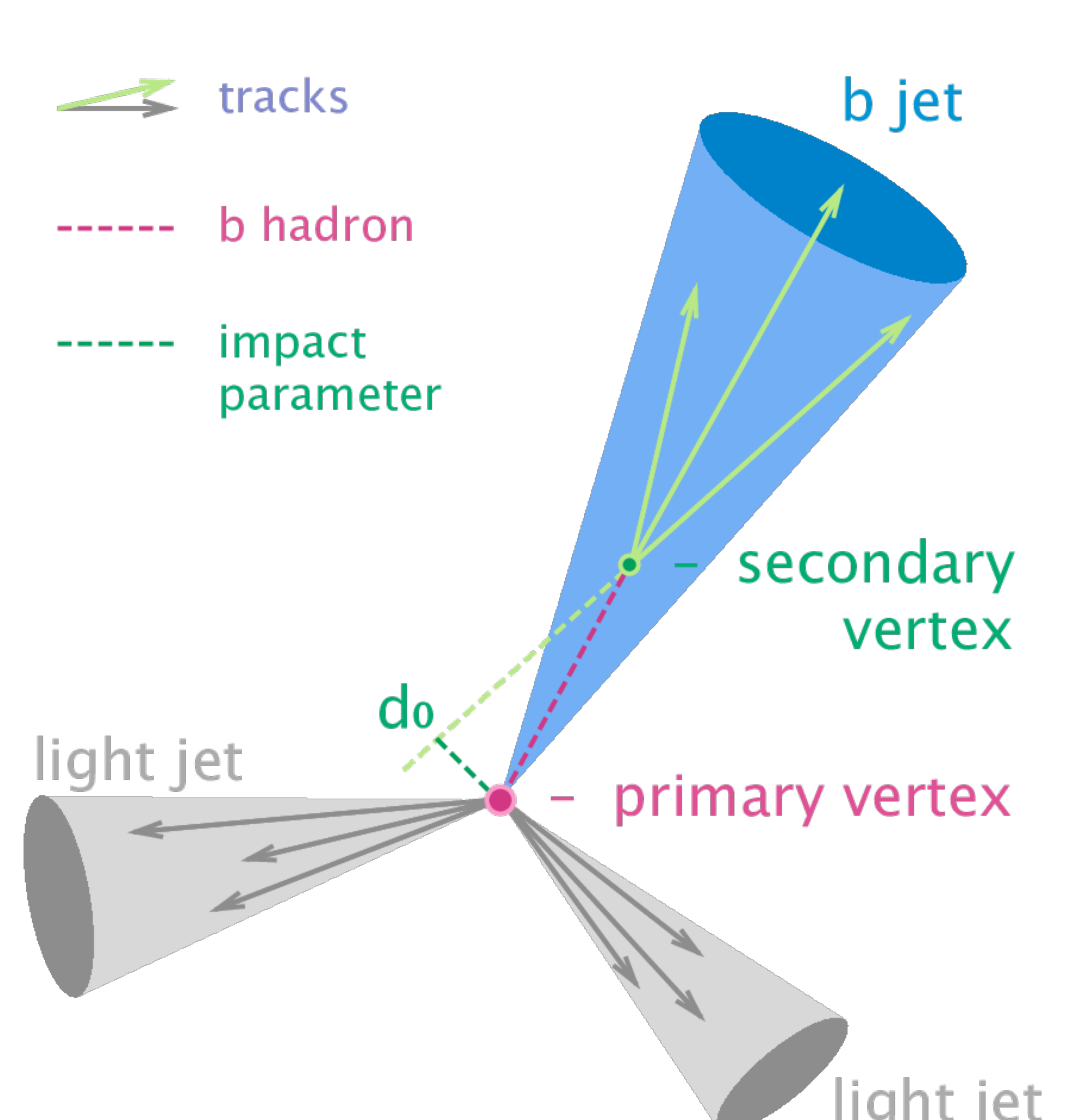

Figure from
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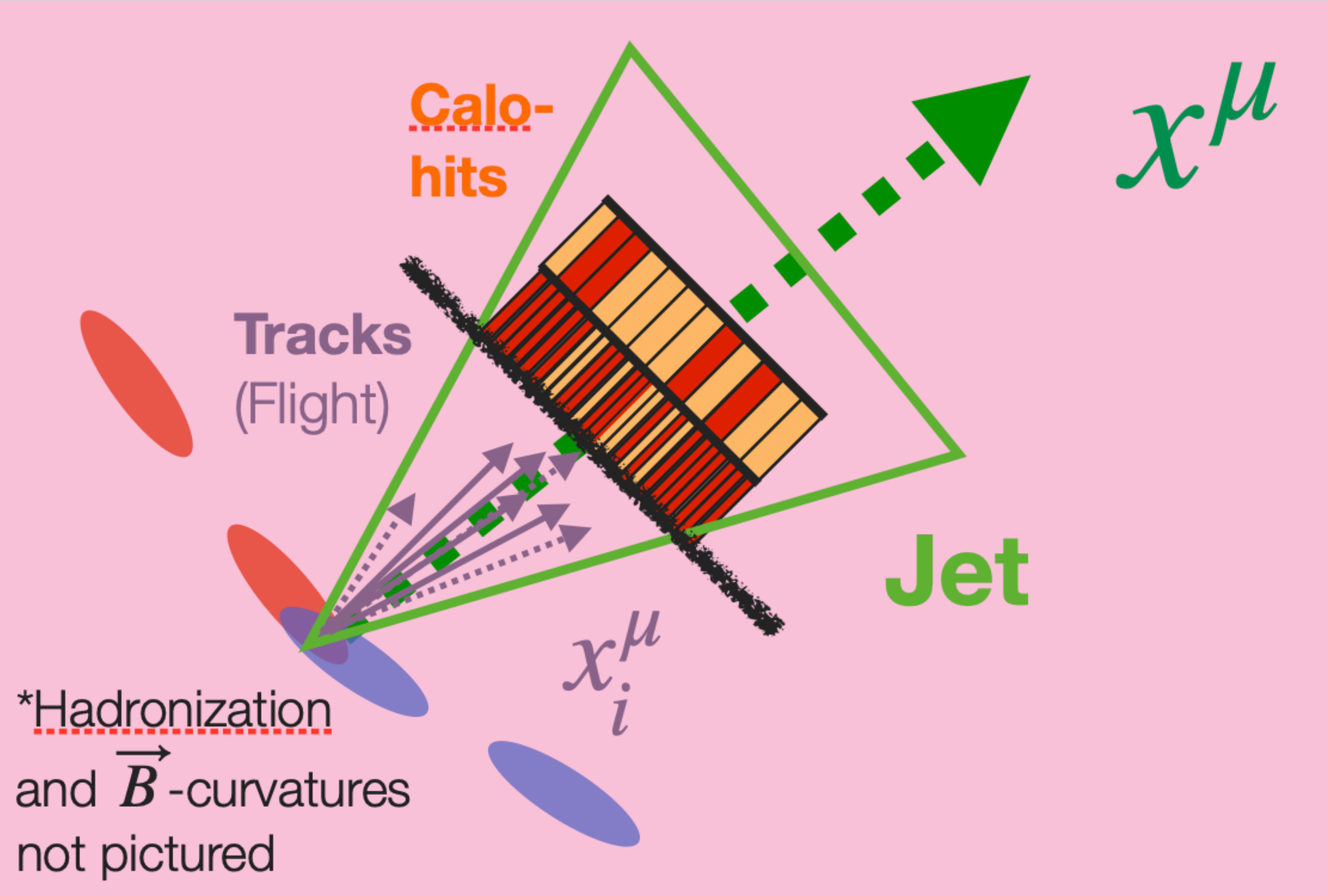
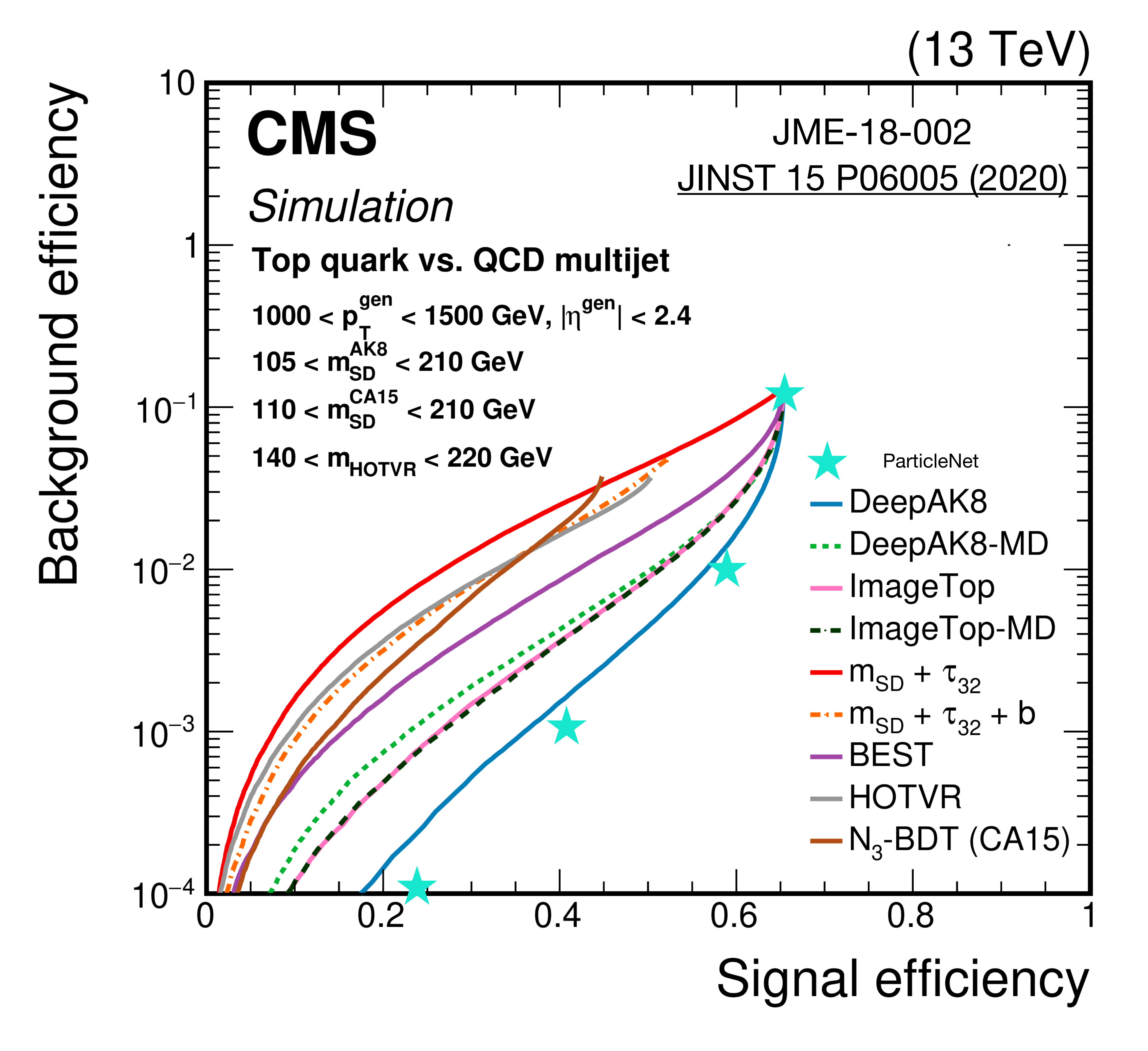
$$ECF(N,\beta) = \sum_{i \in Ntuples} \left(\prod_{a=1}^{N} p_{T_{i_a}} \right) * \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} d_{ij} \right)^{\beta}$$



$$\tau_N = \frac{1}{d_0} \sum_i p_{T,i} \bullet min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})$$

Jet Tagging in CMS

Evolving Architectures During Run 2



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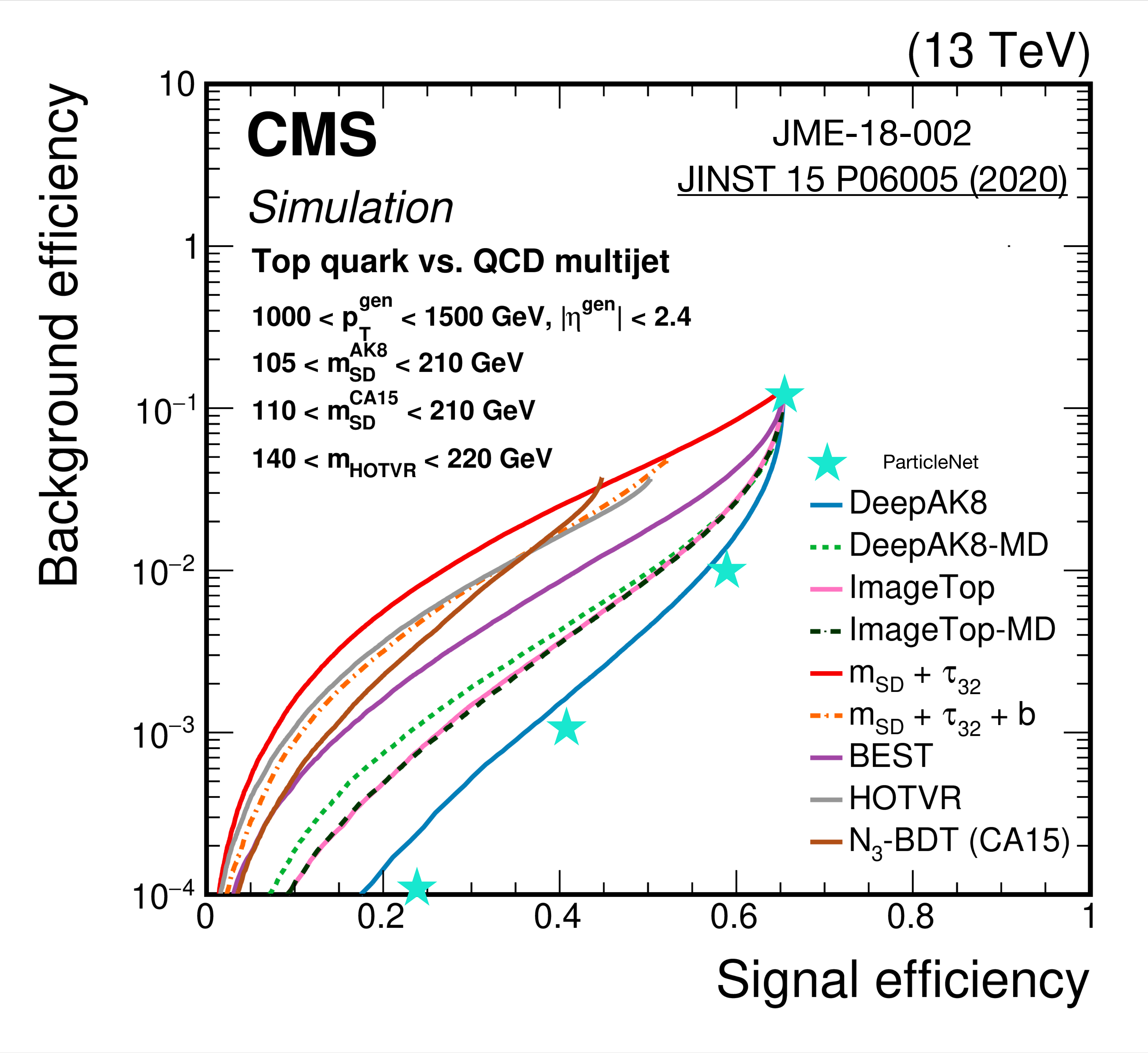
Jet Tagging in CMS

Evolving Architectures During Run 2

$m_{SD}, \tau_{32}, ECF, N_b$

Traditional JSS

HOTVR



Jet Tagging in CMS

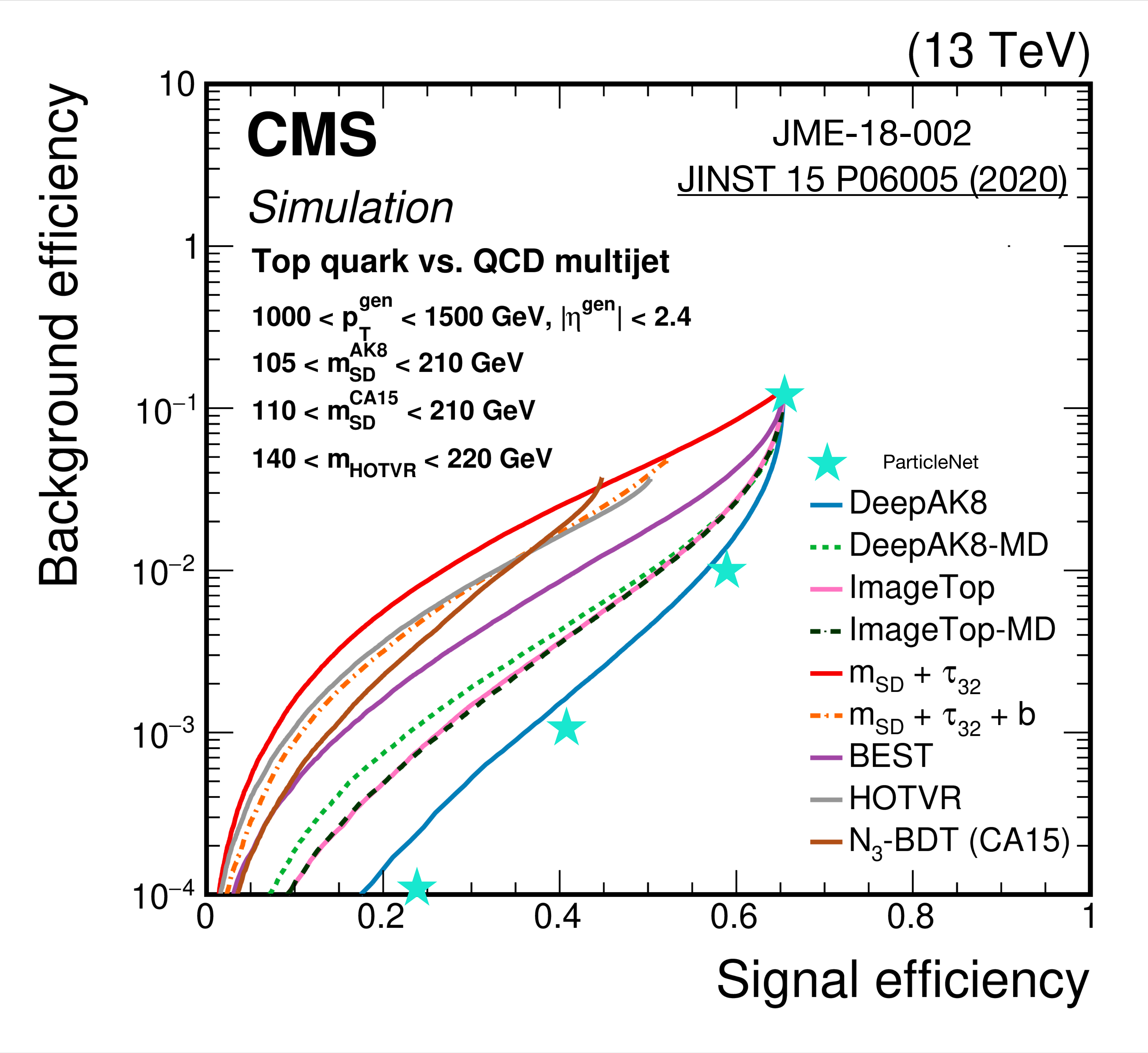
Evolving Architectures During Run 2

Increasing Sophistication

$m_{SD}, \tau_{32}, ECF, N_b$ — Traditional JSS

HOTVR

N_3 BDT — Boosted Decision Trees



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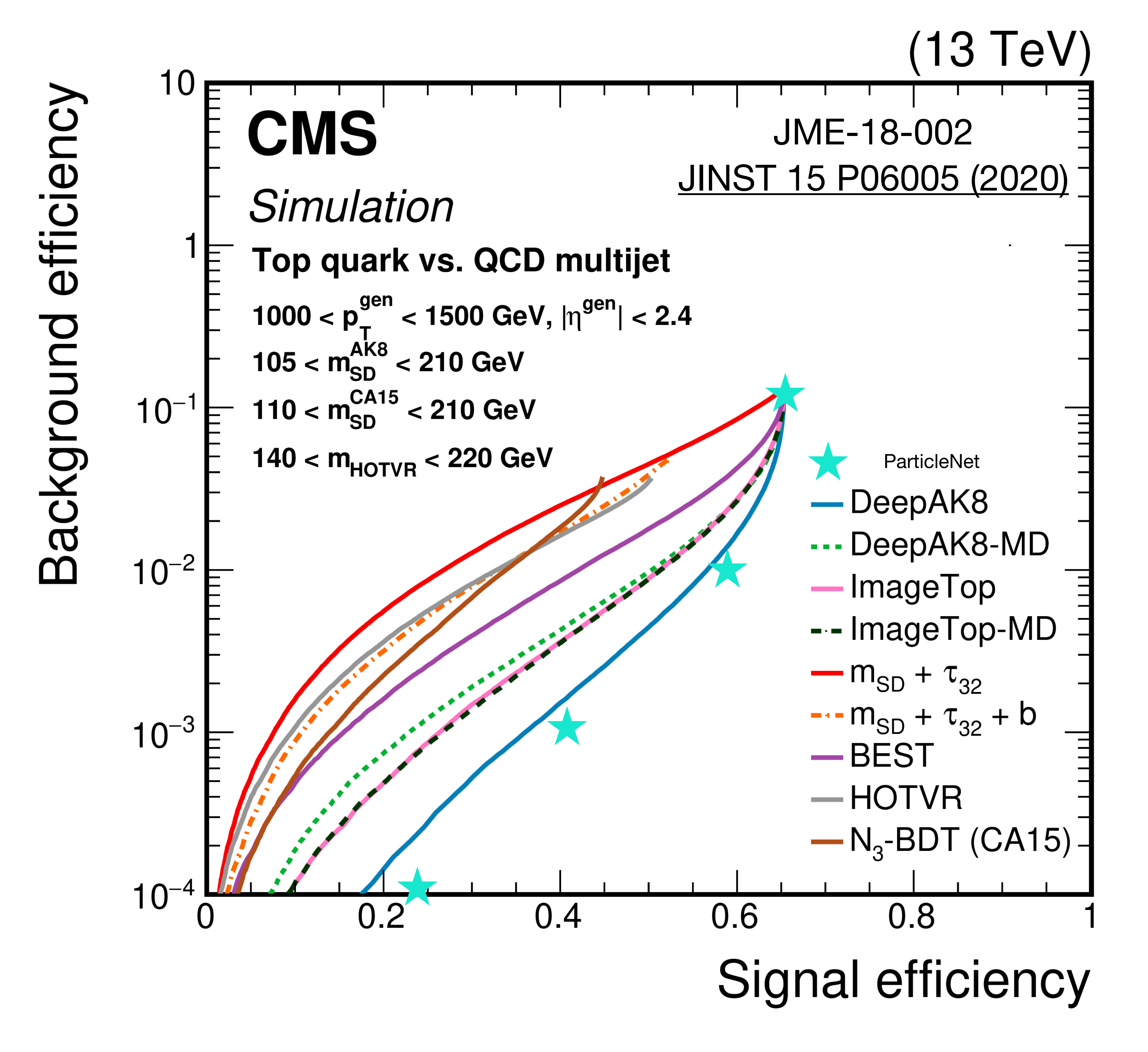
Boosted Event Shape Tagger	Deep Neural Net



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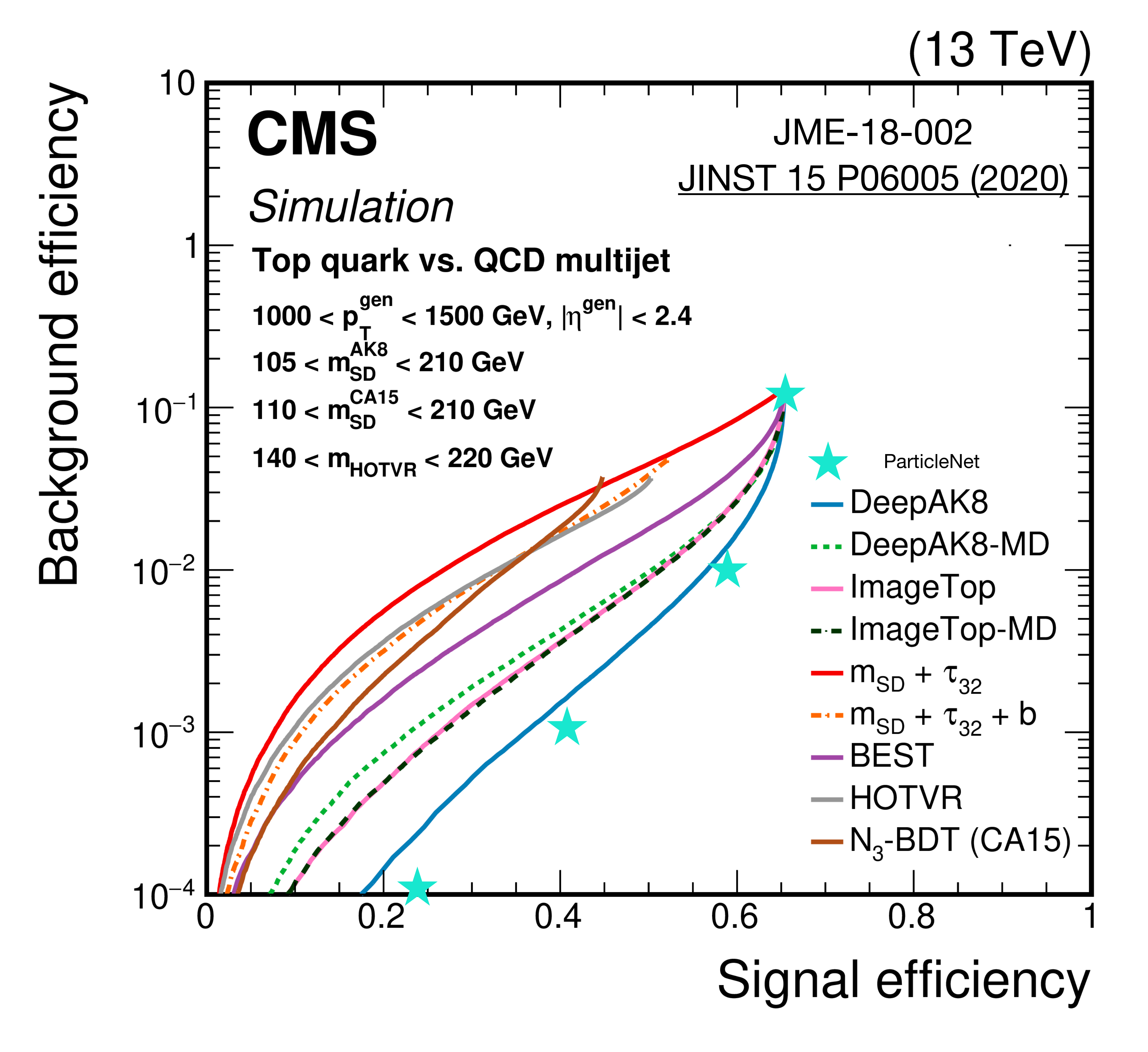

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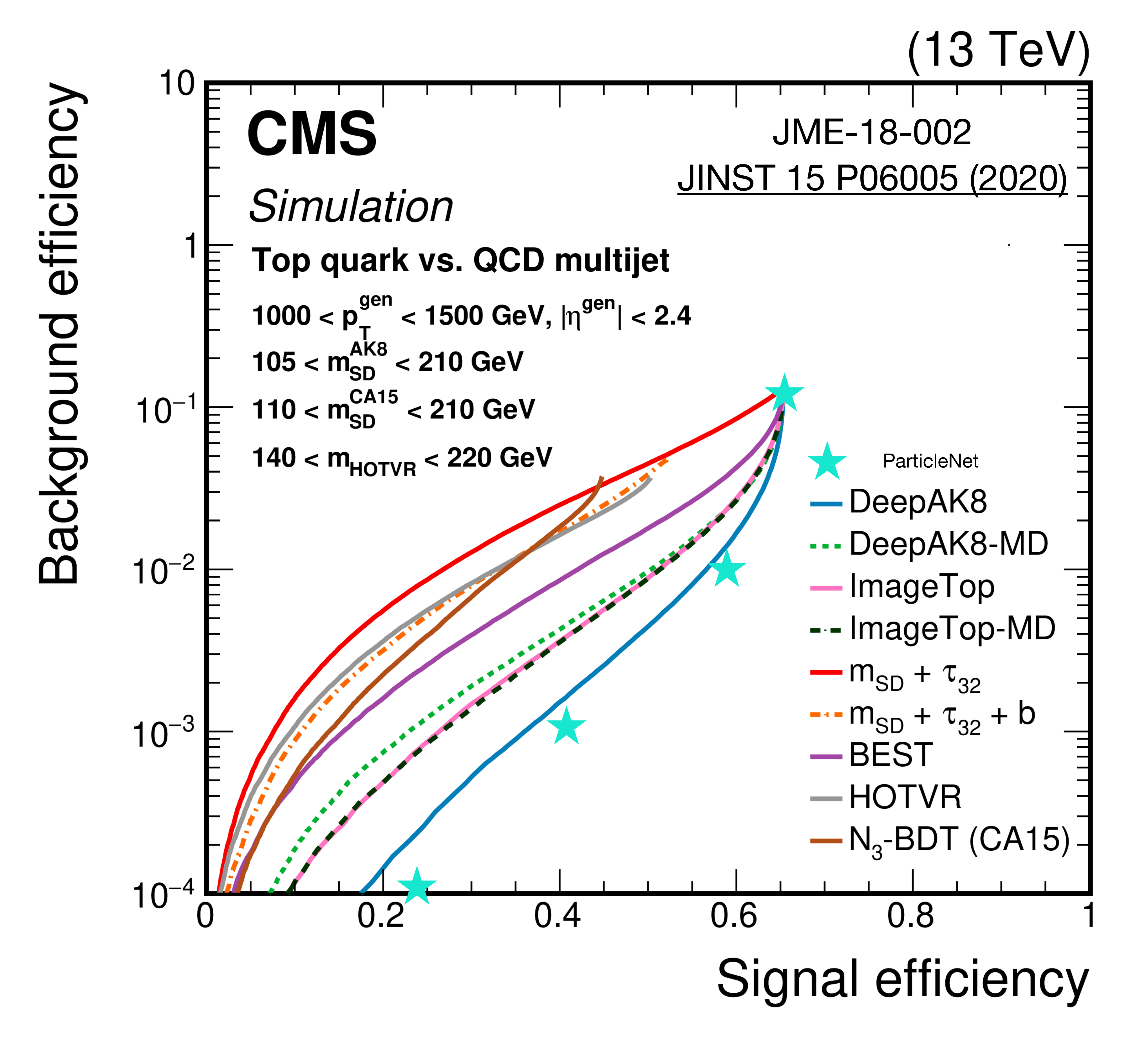
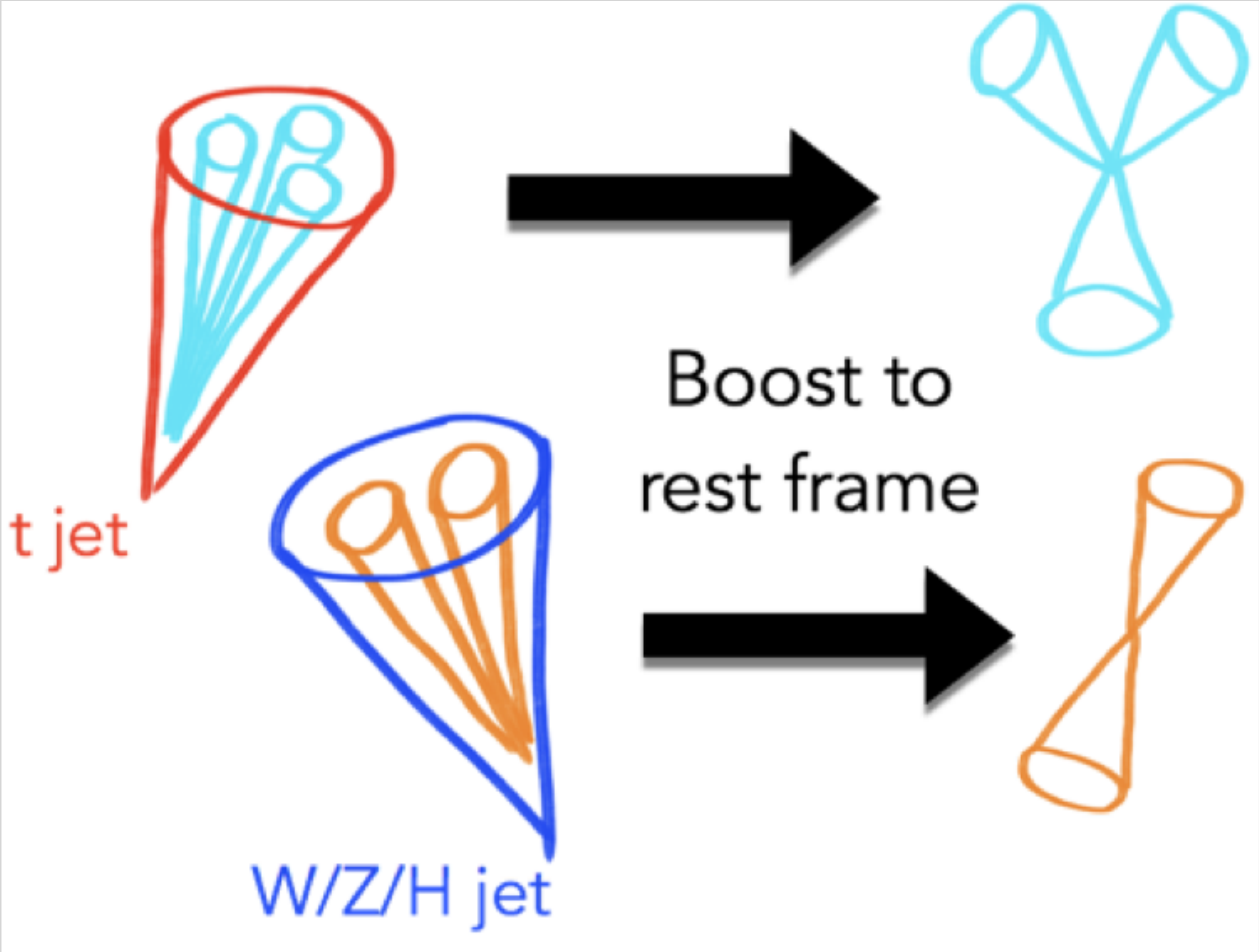


Search for Vector-Like Quarks using the Boosted Event Shape Tagger in the All-Hadronic Channel



Key Idea: Boost jet constituents into hypothetical rest frames

- Lab frame: jet constituents merged into fat-jet cone of R=0.8
- Boost into correct frame: jet constituents become isotropic
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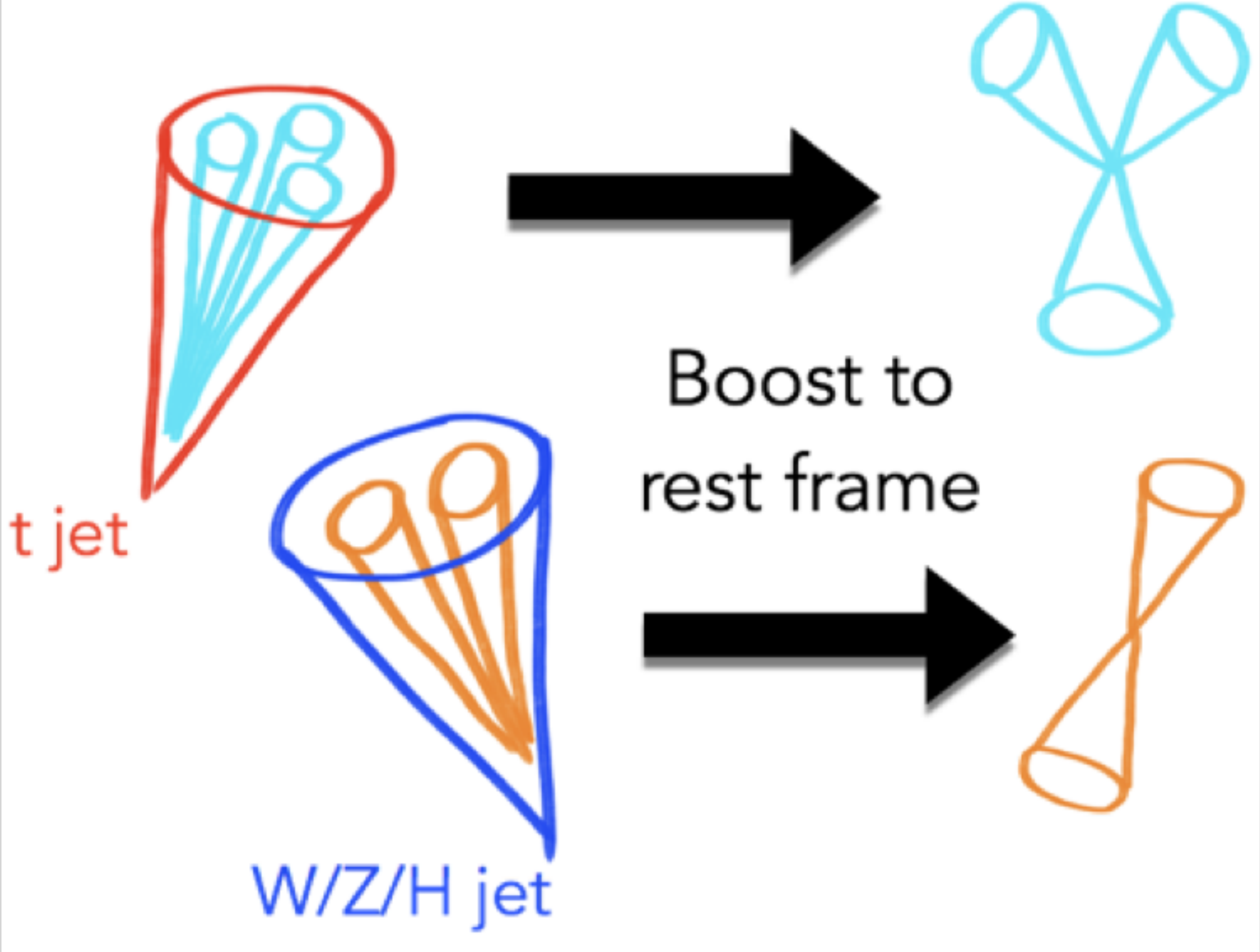

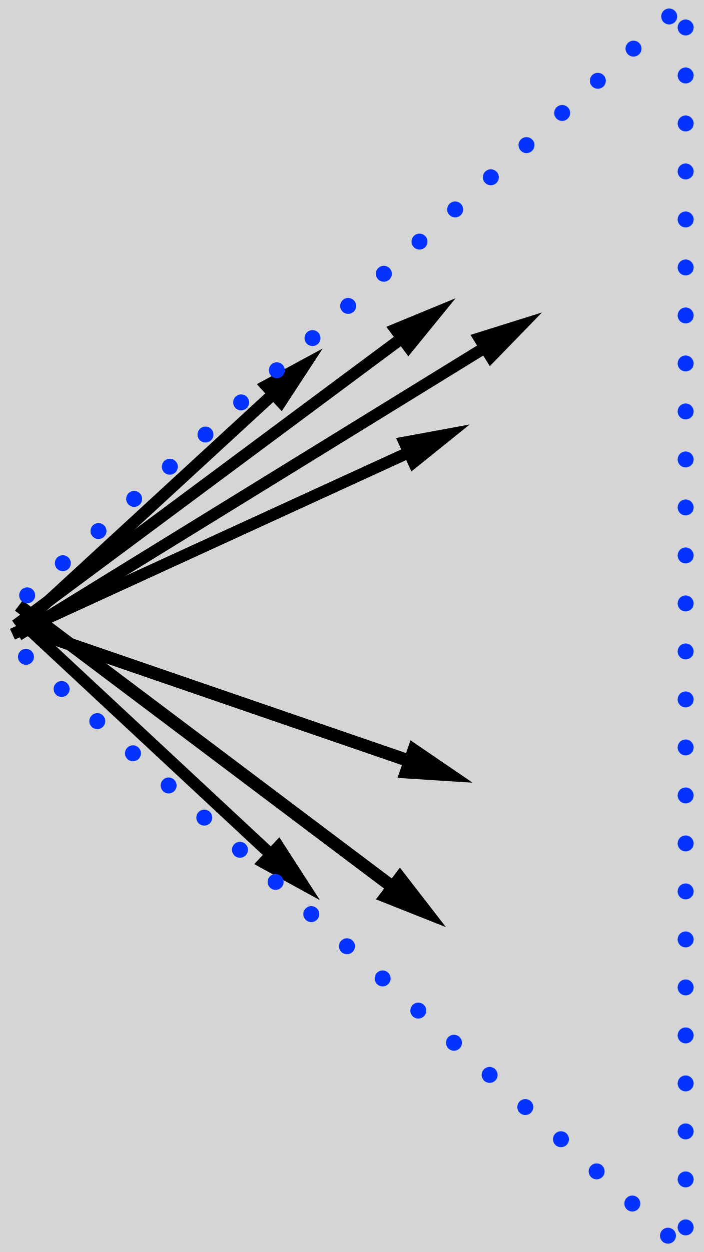

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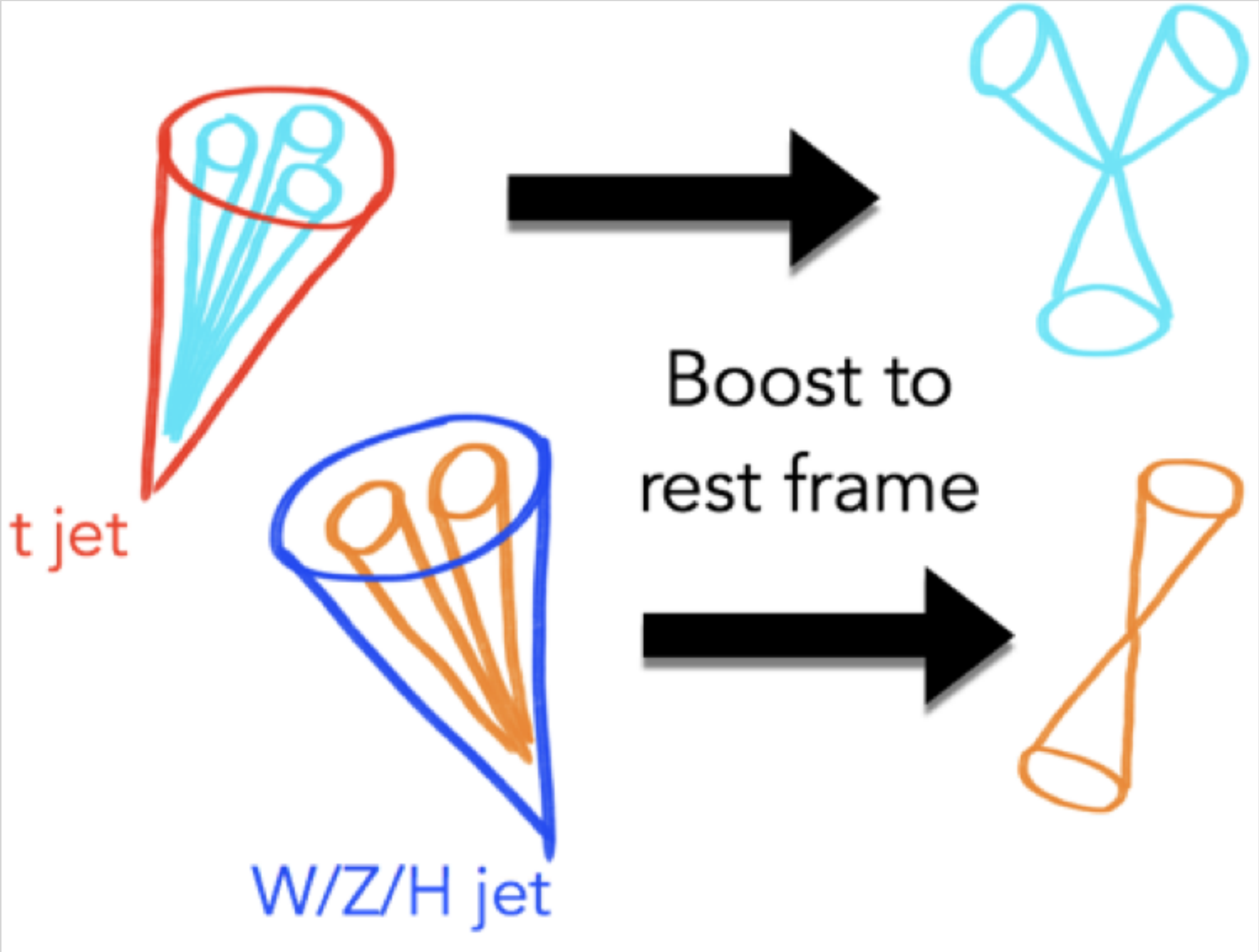

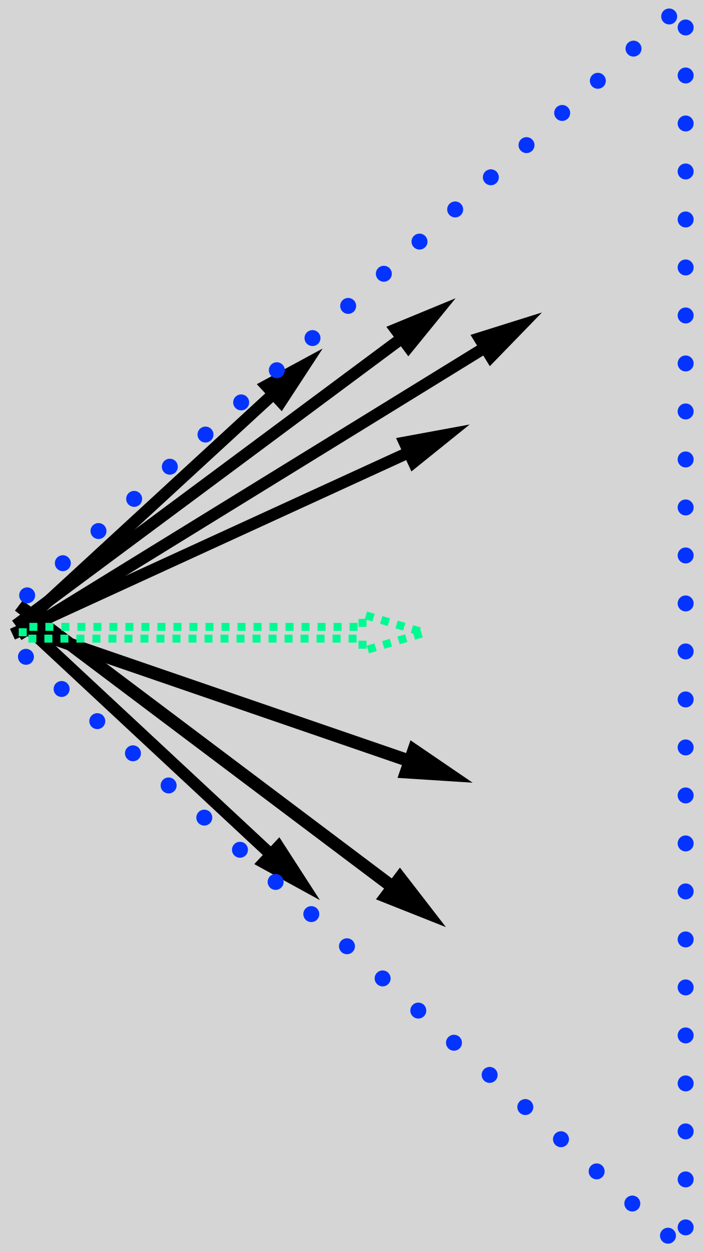

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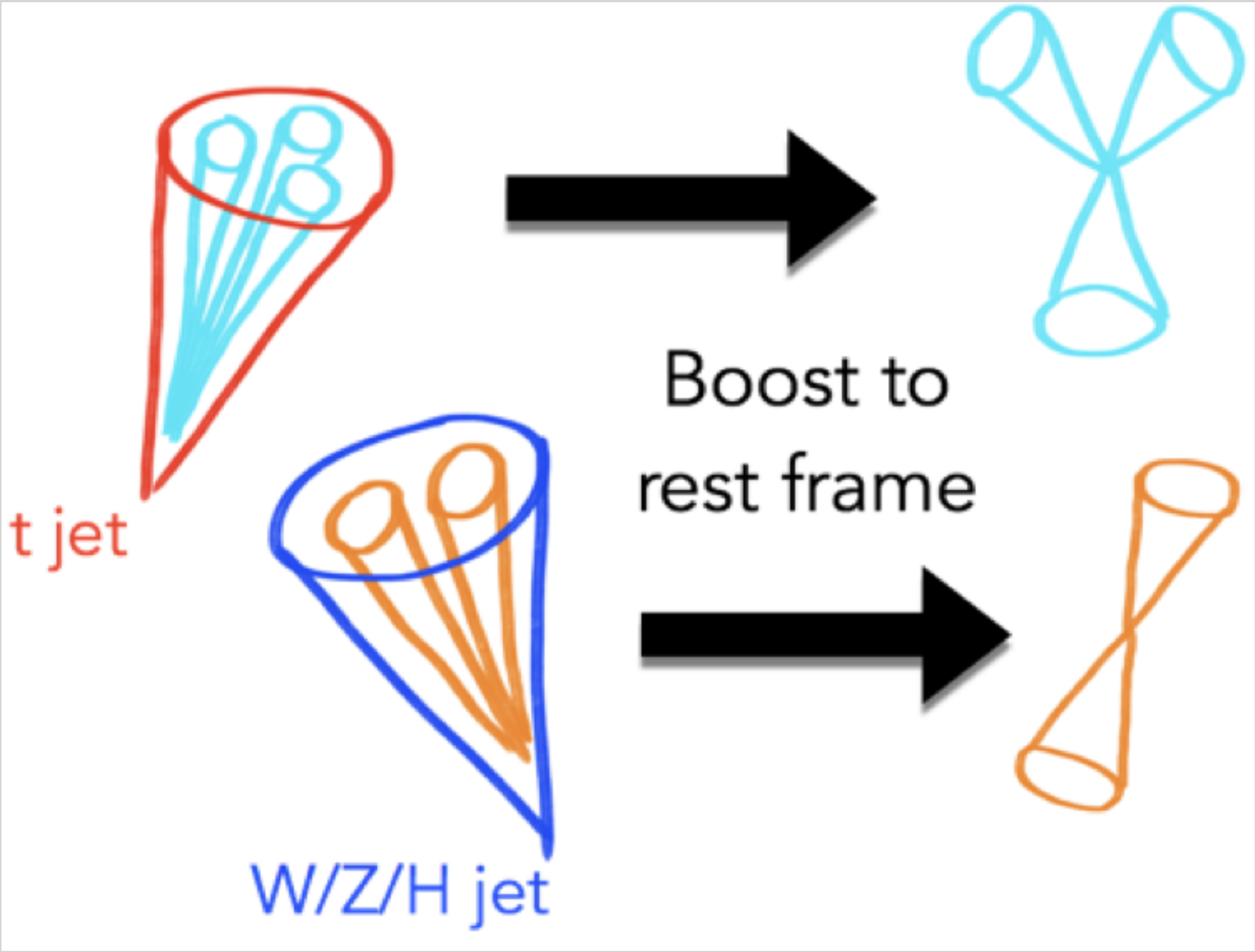

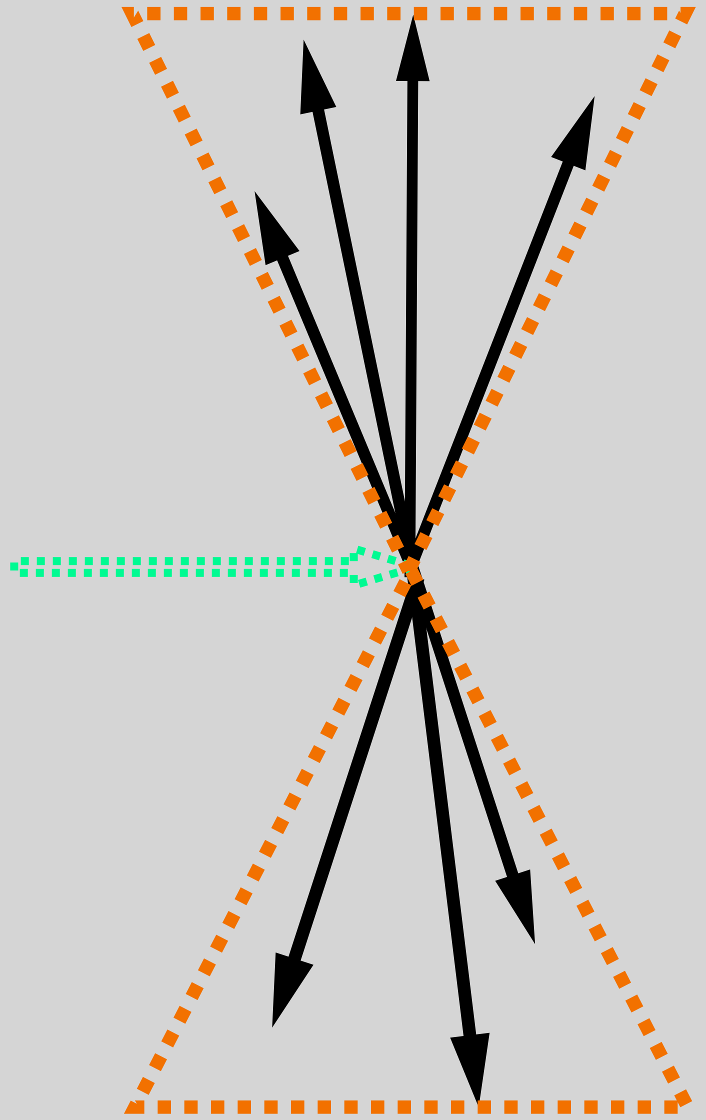

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BESTagger Architecture

Improvements wrt B2G-18-005

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Inputs

59

↓

264
BES vars

BESTagger Architecture

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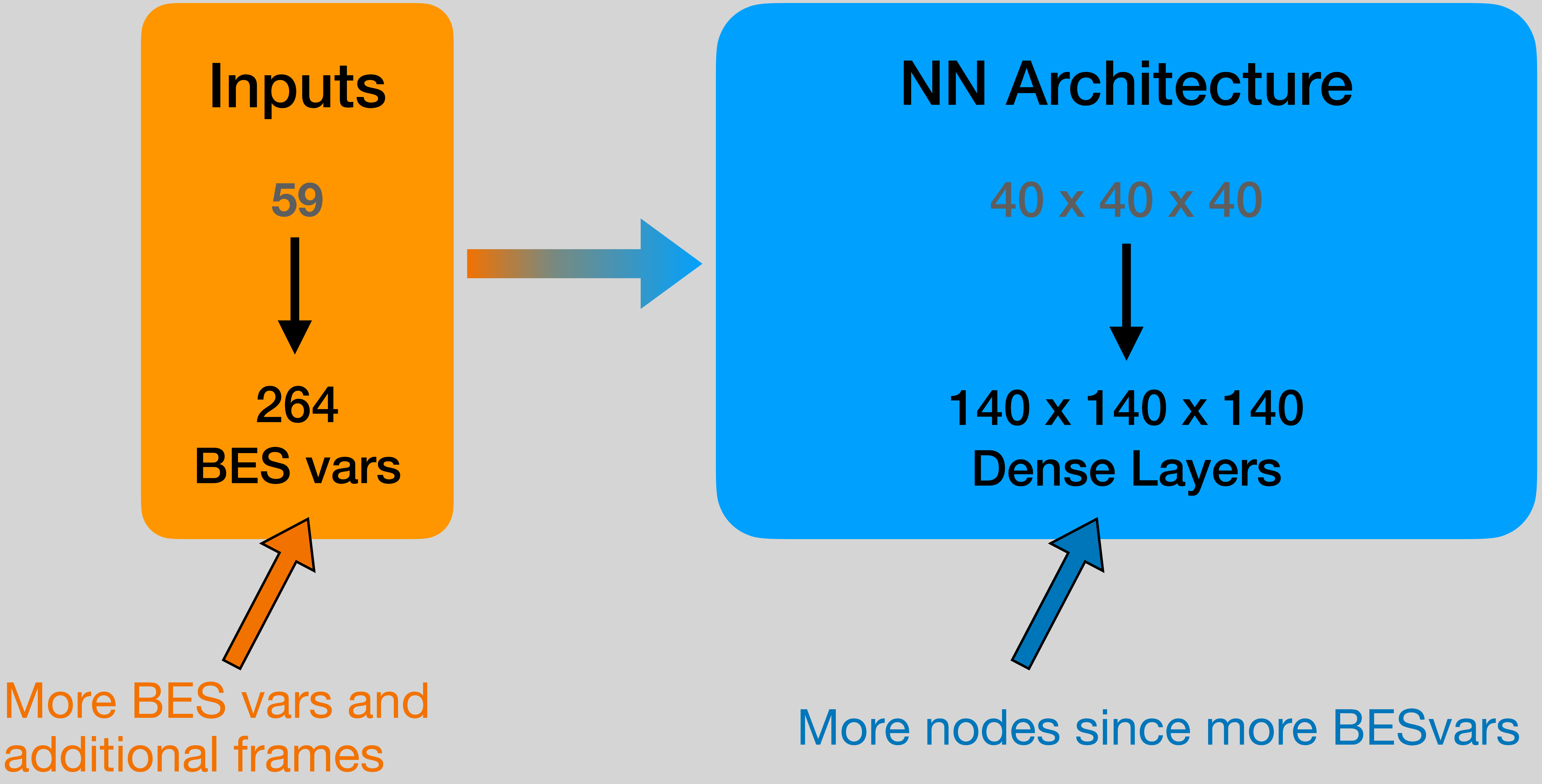
More BES vars and
additional frames

BESTagger Architecture
Improvements wrt B2G-18-005



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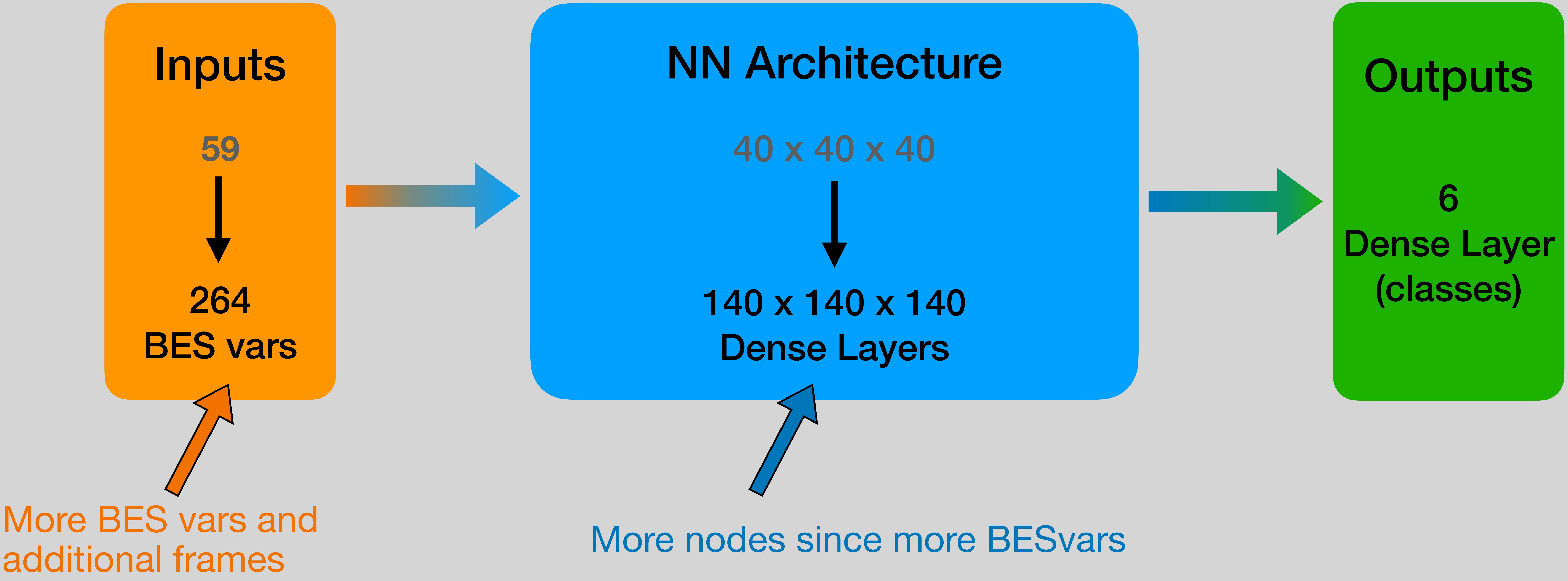

Jet Images

Representing 3D -> 2D

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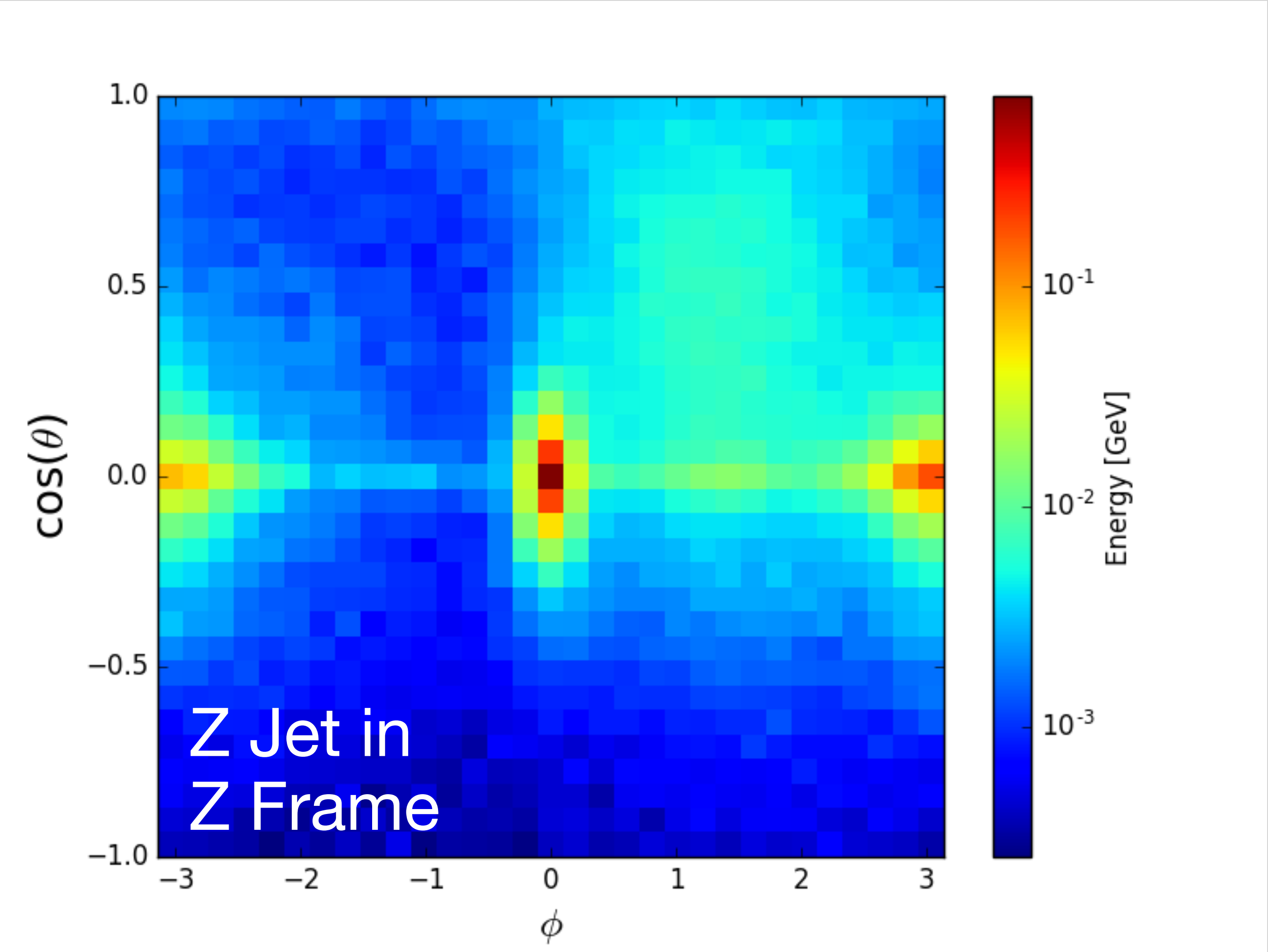
Cylindrical Projection



Johan S Bonilla Castro (Northeastern)

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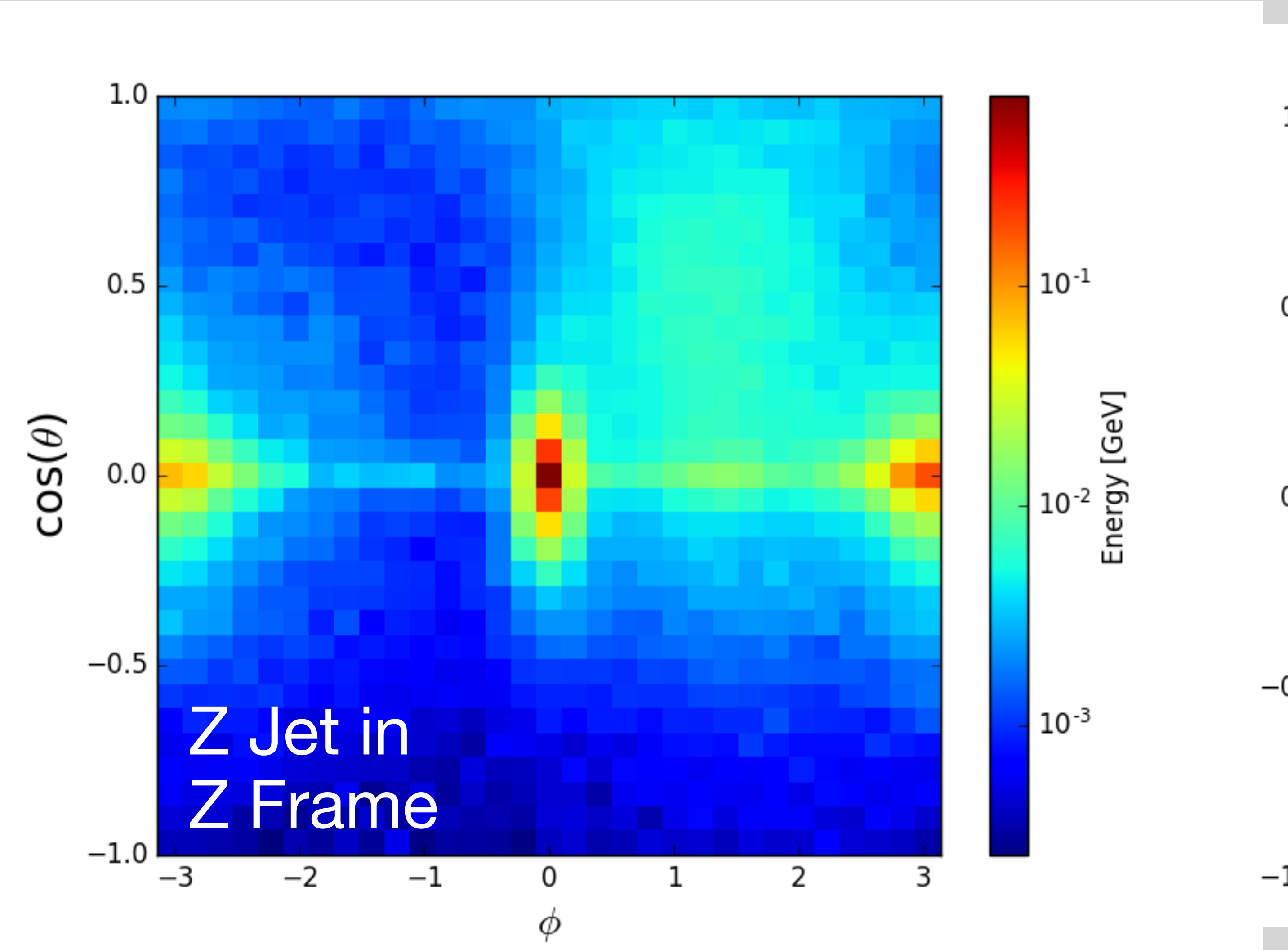
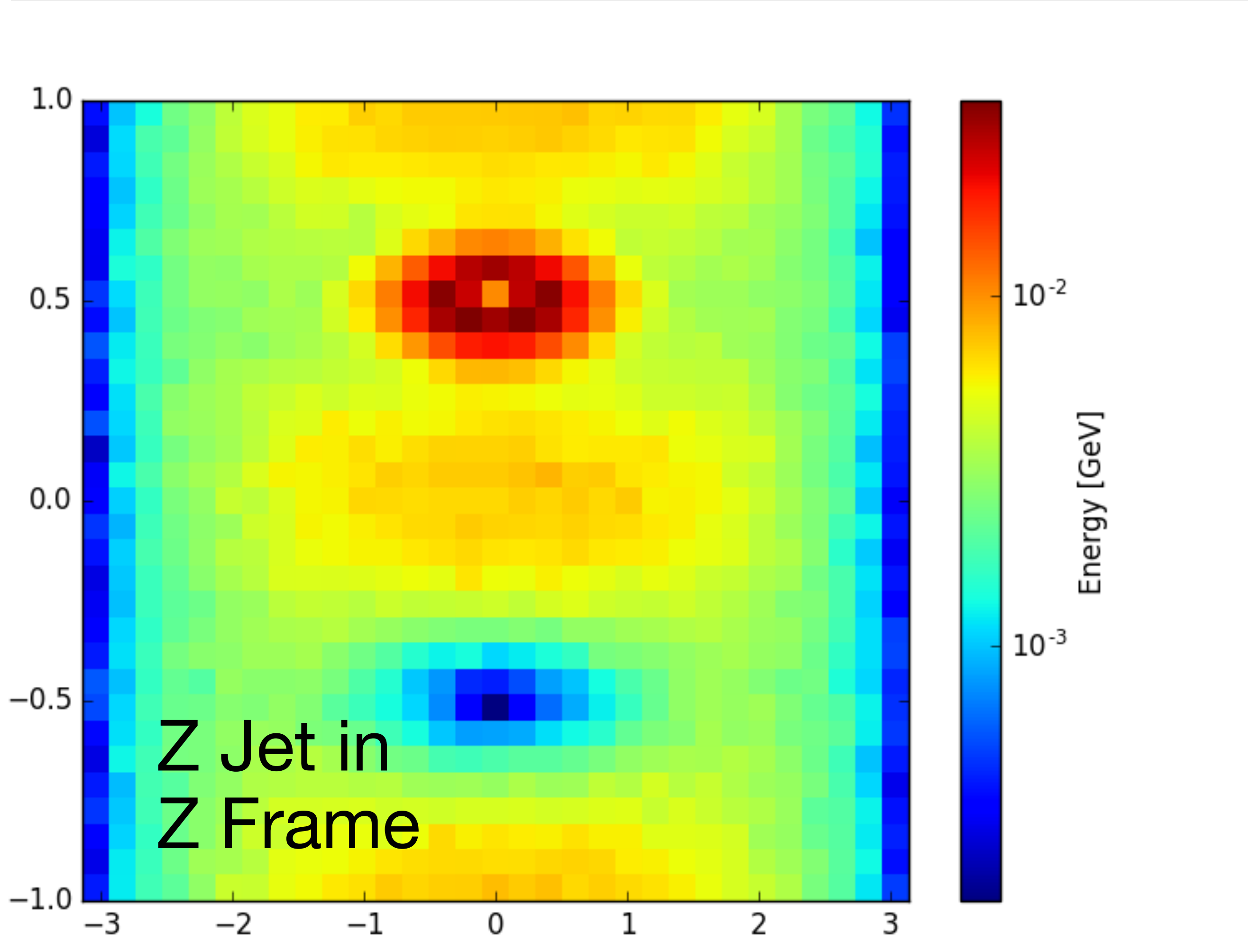


Cassini Projection



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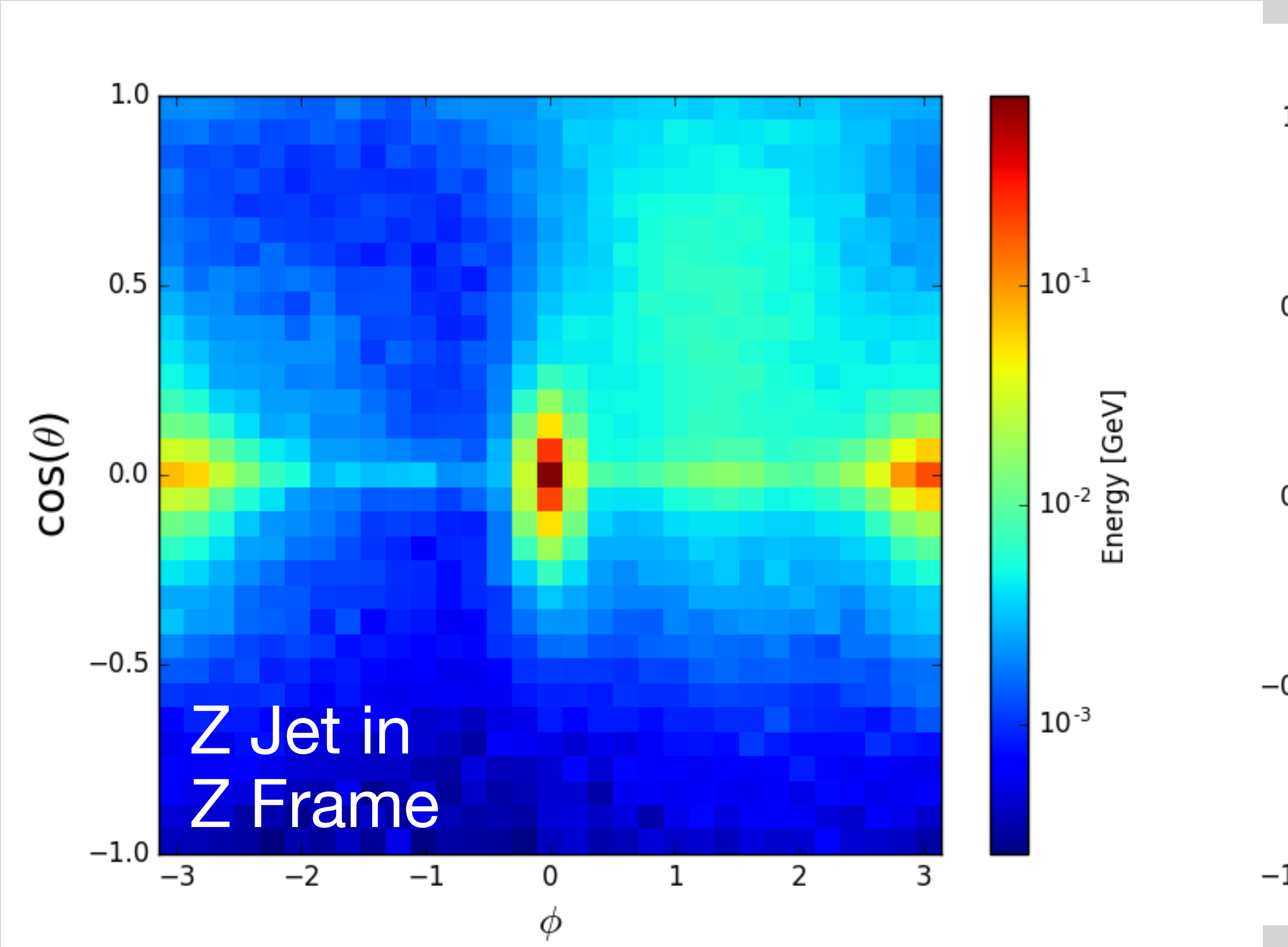

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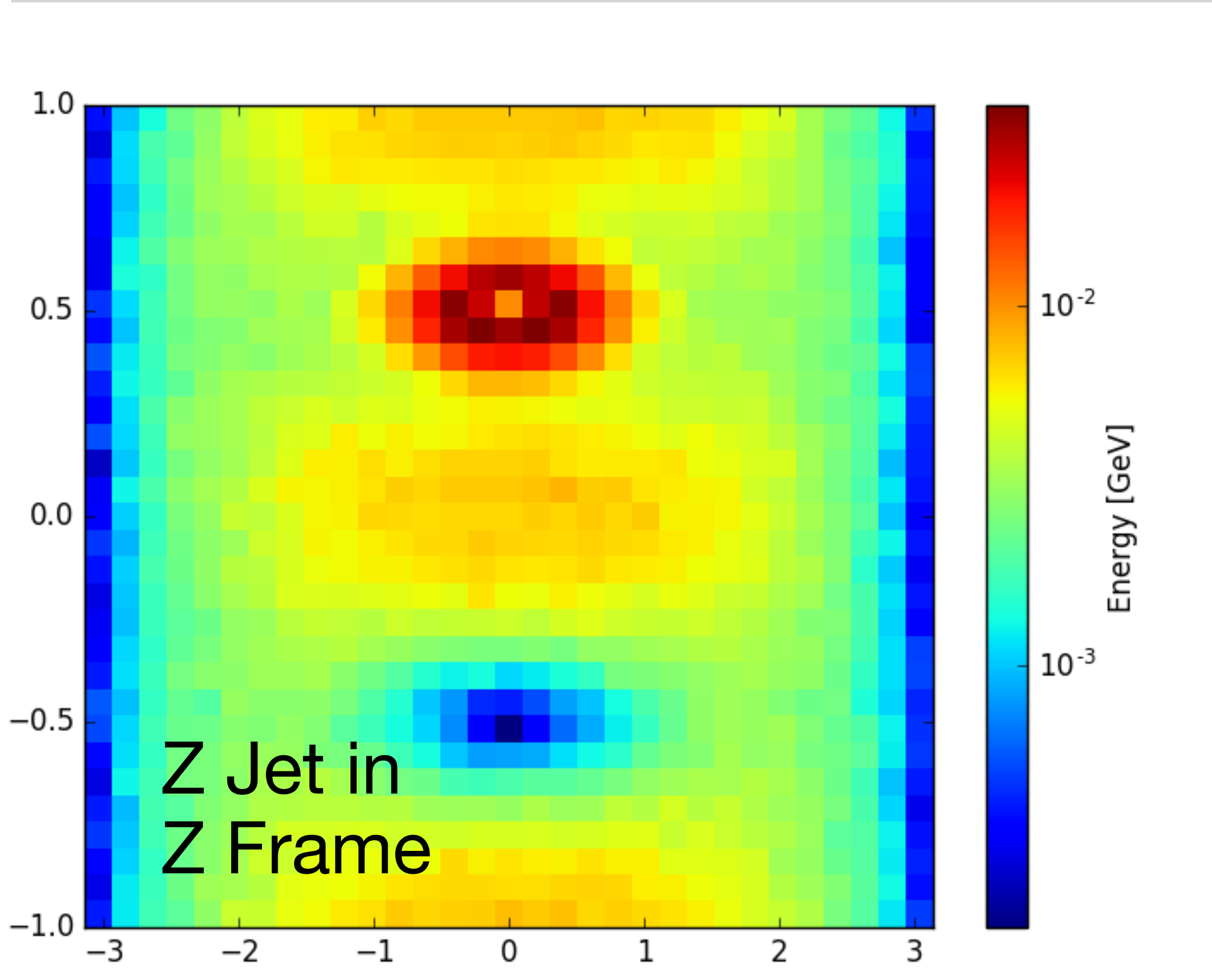

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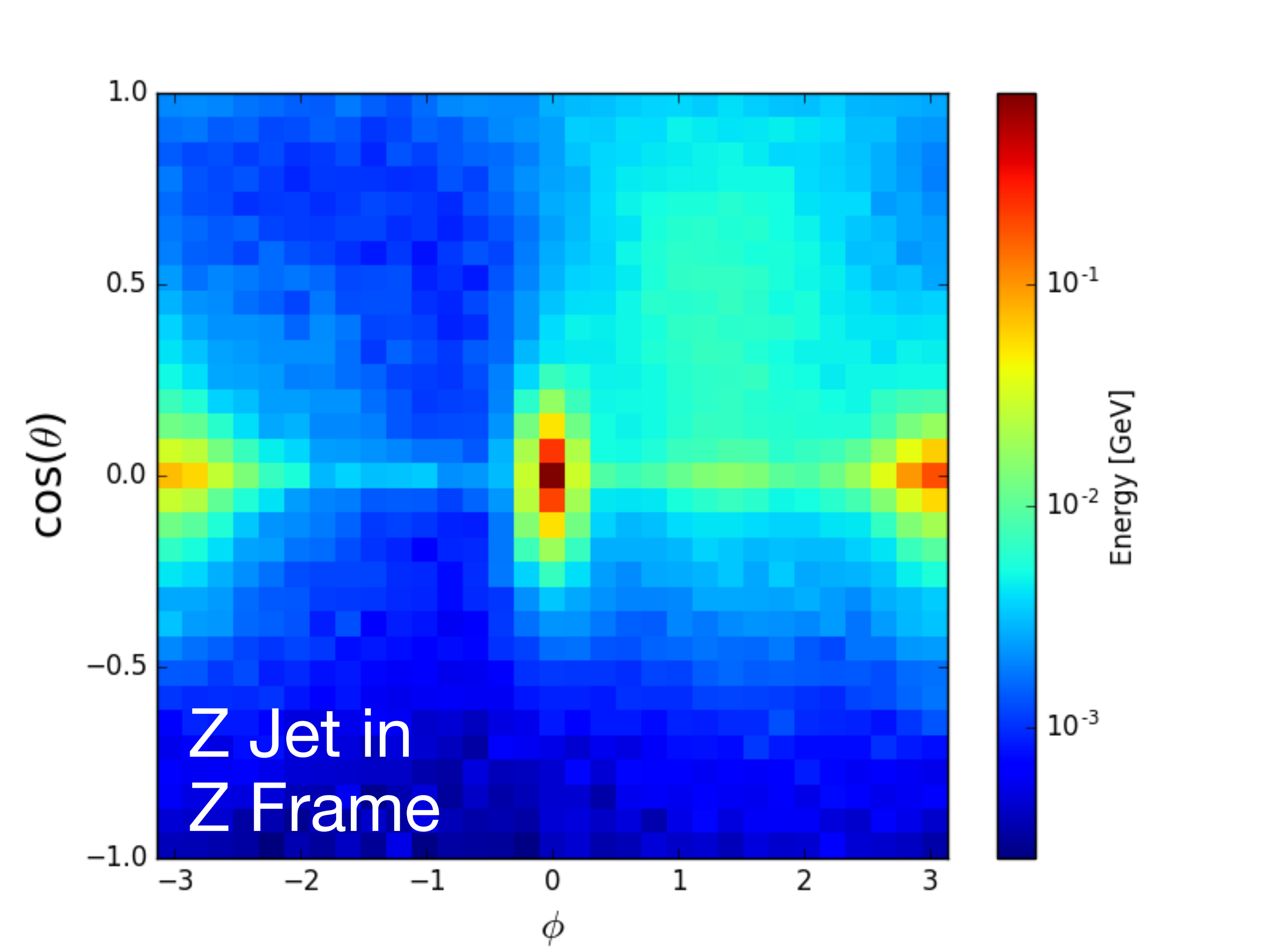

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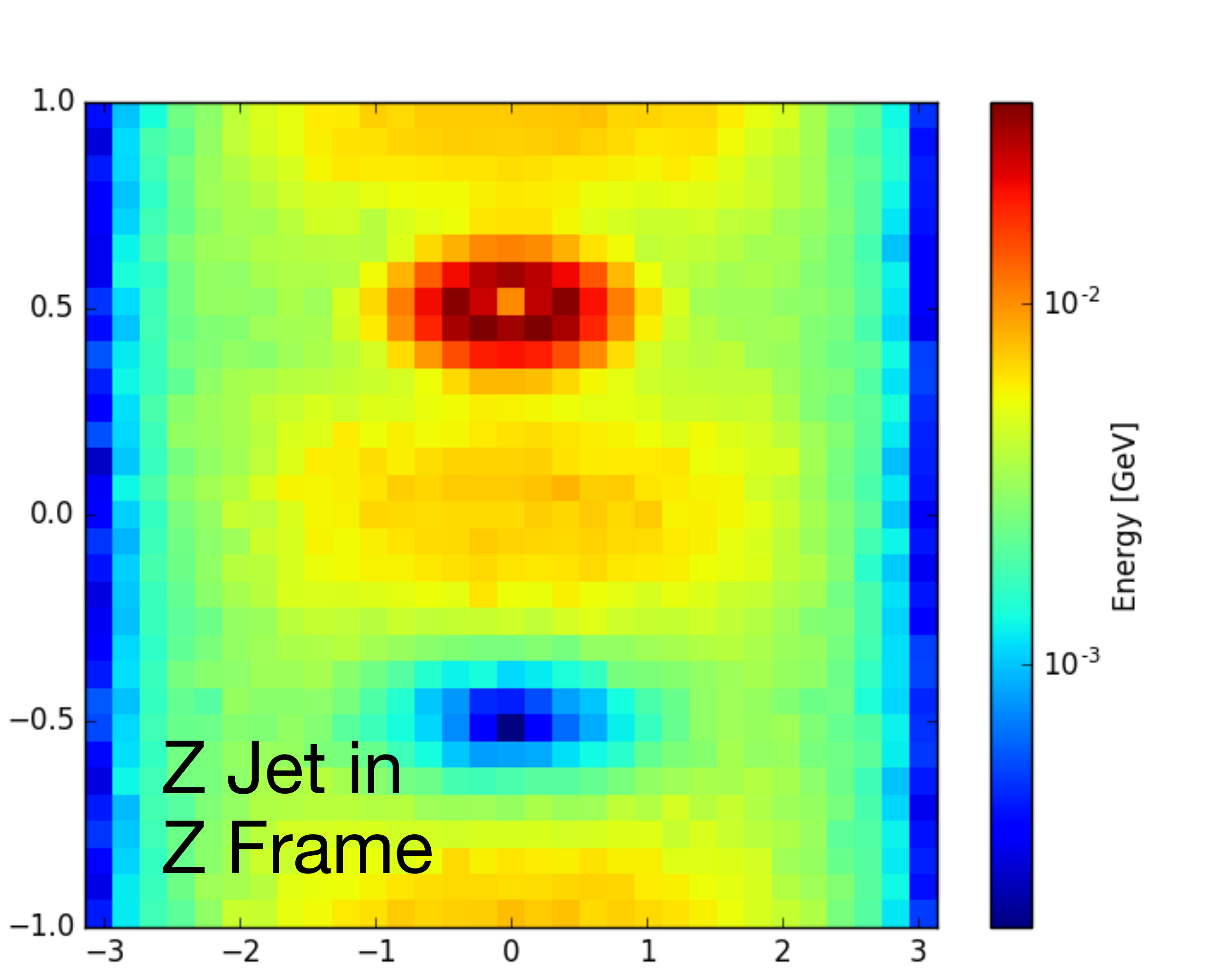

Projecting forces a choice of granularity and transformation

Note: 31x31 ~1k pixels for relatively small (~30) occupancy

More Flexible Data Representation

Application of Point Cloud Transformers[2]

[2]: arxiv:2102.05073

More Flexible Data Representation

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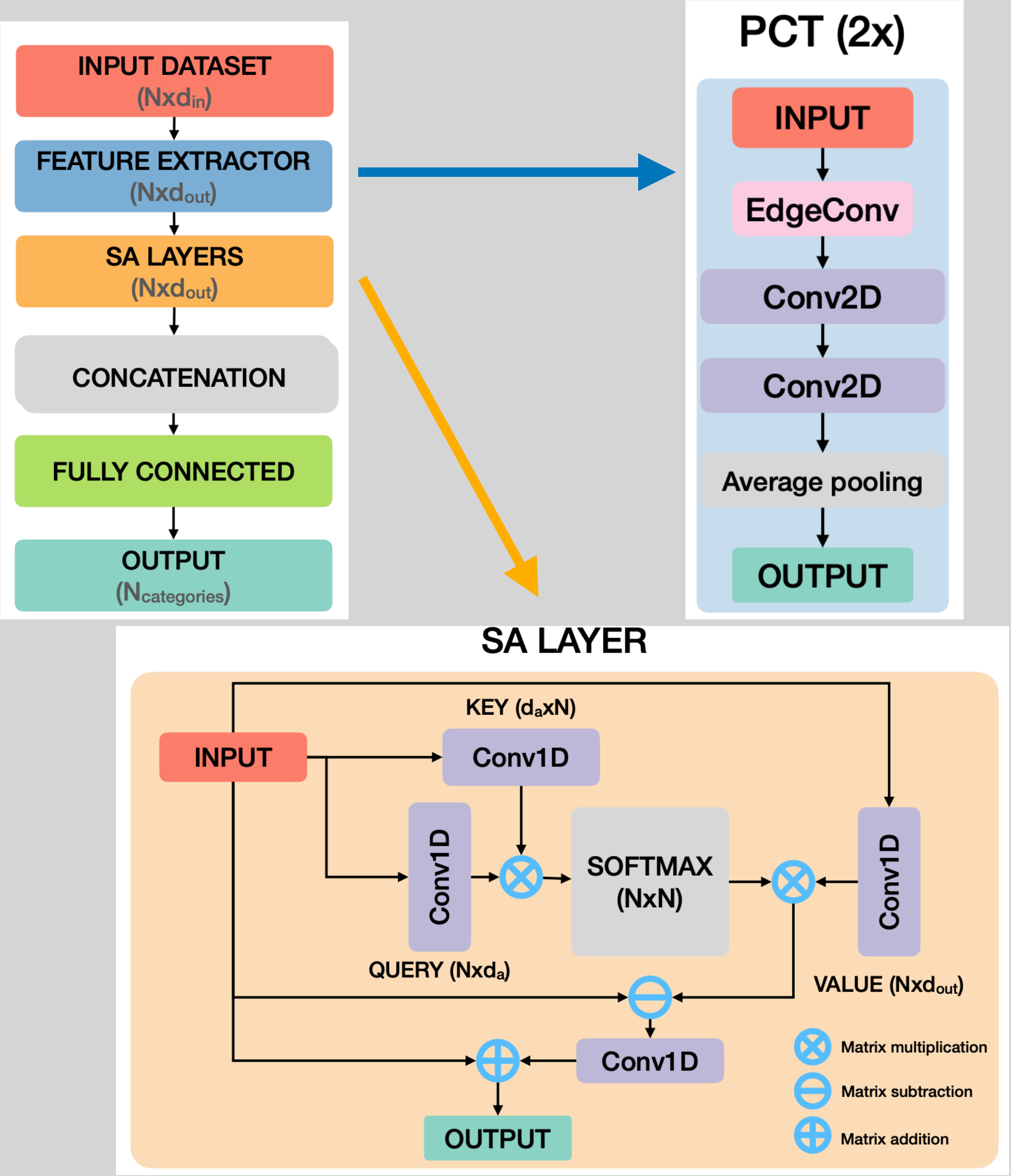

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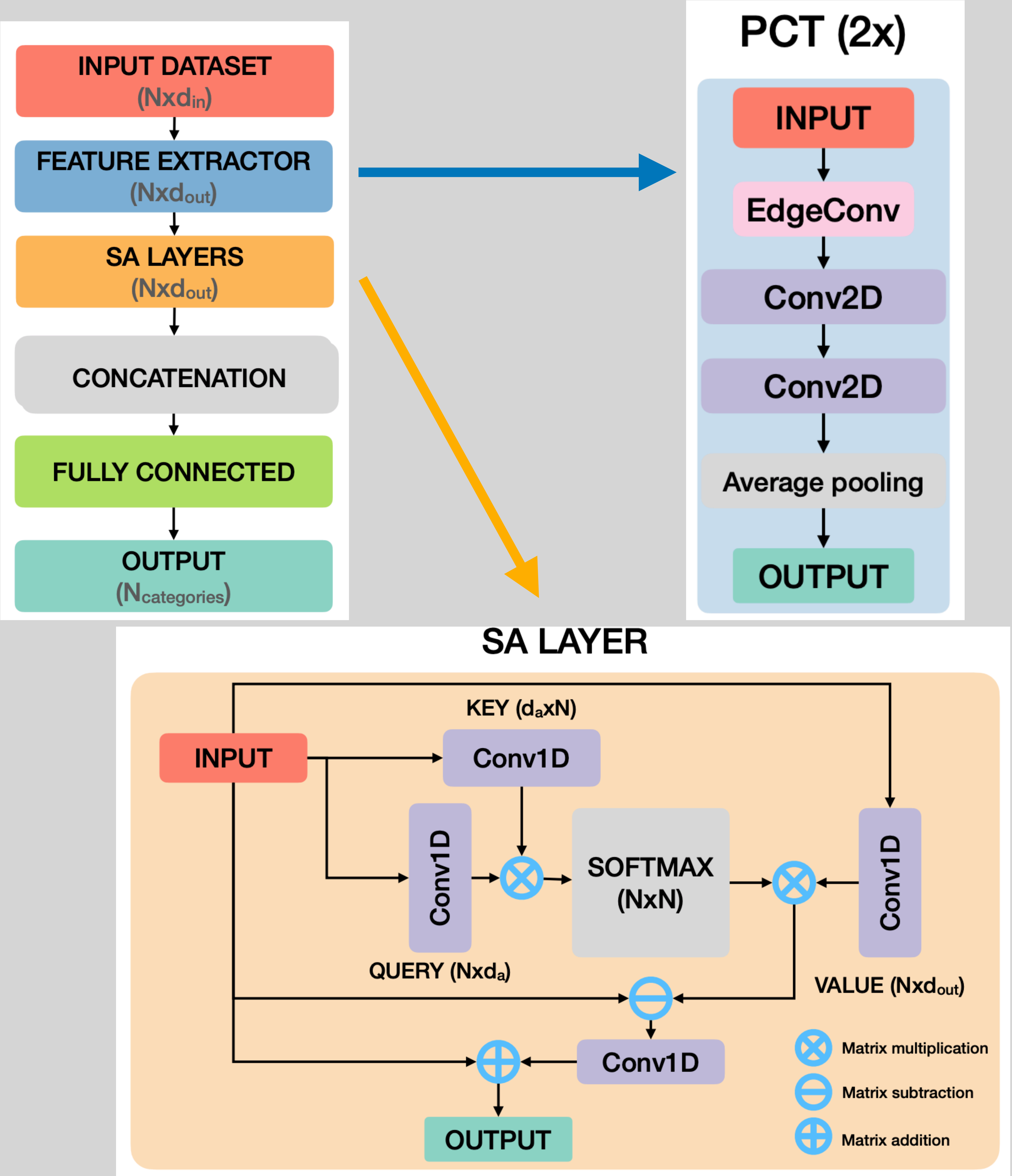
  - k-nearest-neighbors: $\Delta\eta, \Delta\phi$ with respect to jet
  - Further optimizations could be done



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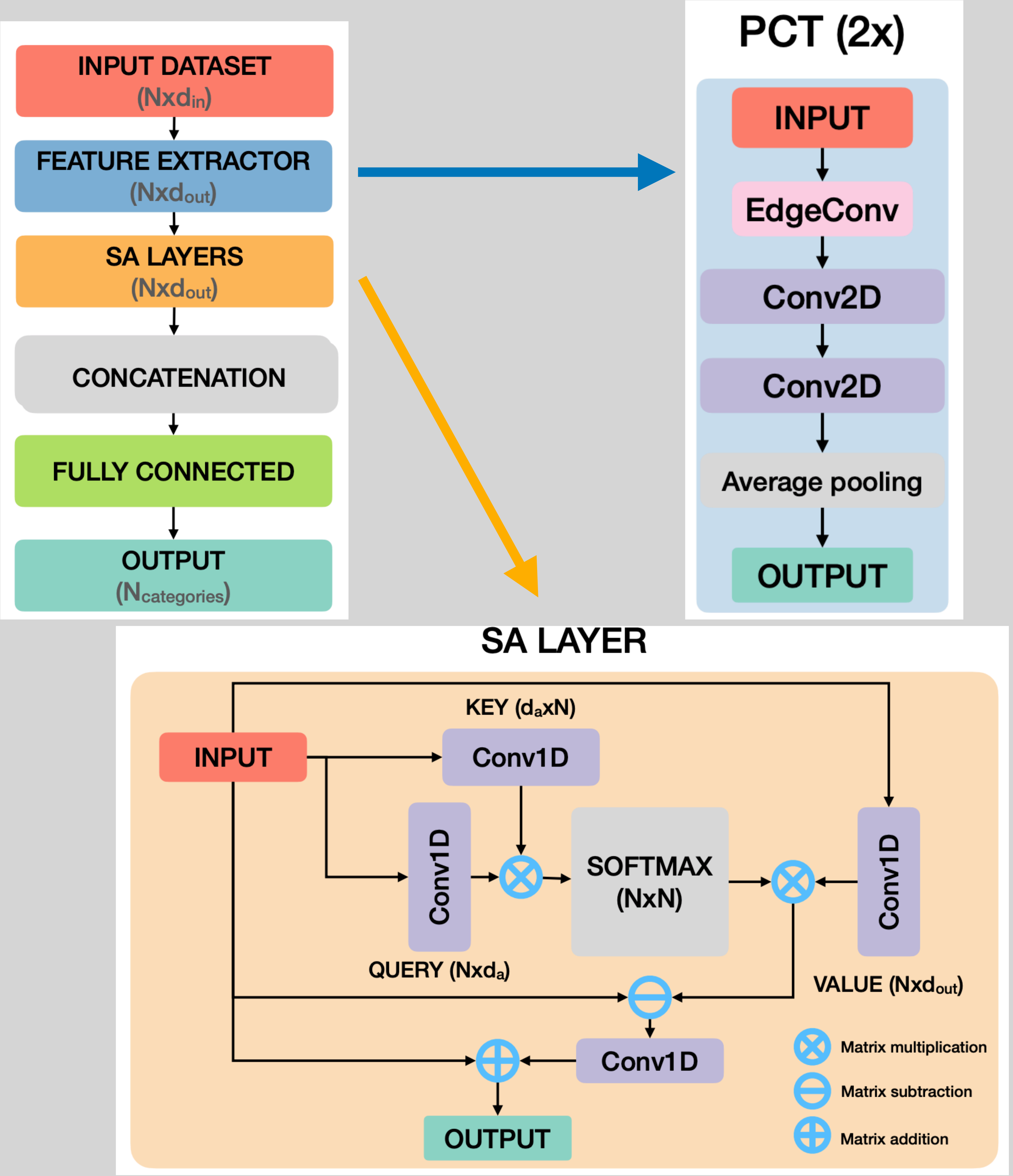
- Idea: Integrate BES vars into multi-frame PCT
  - Generalize ‘order’ of constituents for clustering
  - Take advantage of ‘order’ of frame boosts, i.e. $m_b < m_W < m_Z < m_H < m_t$



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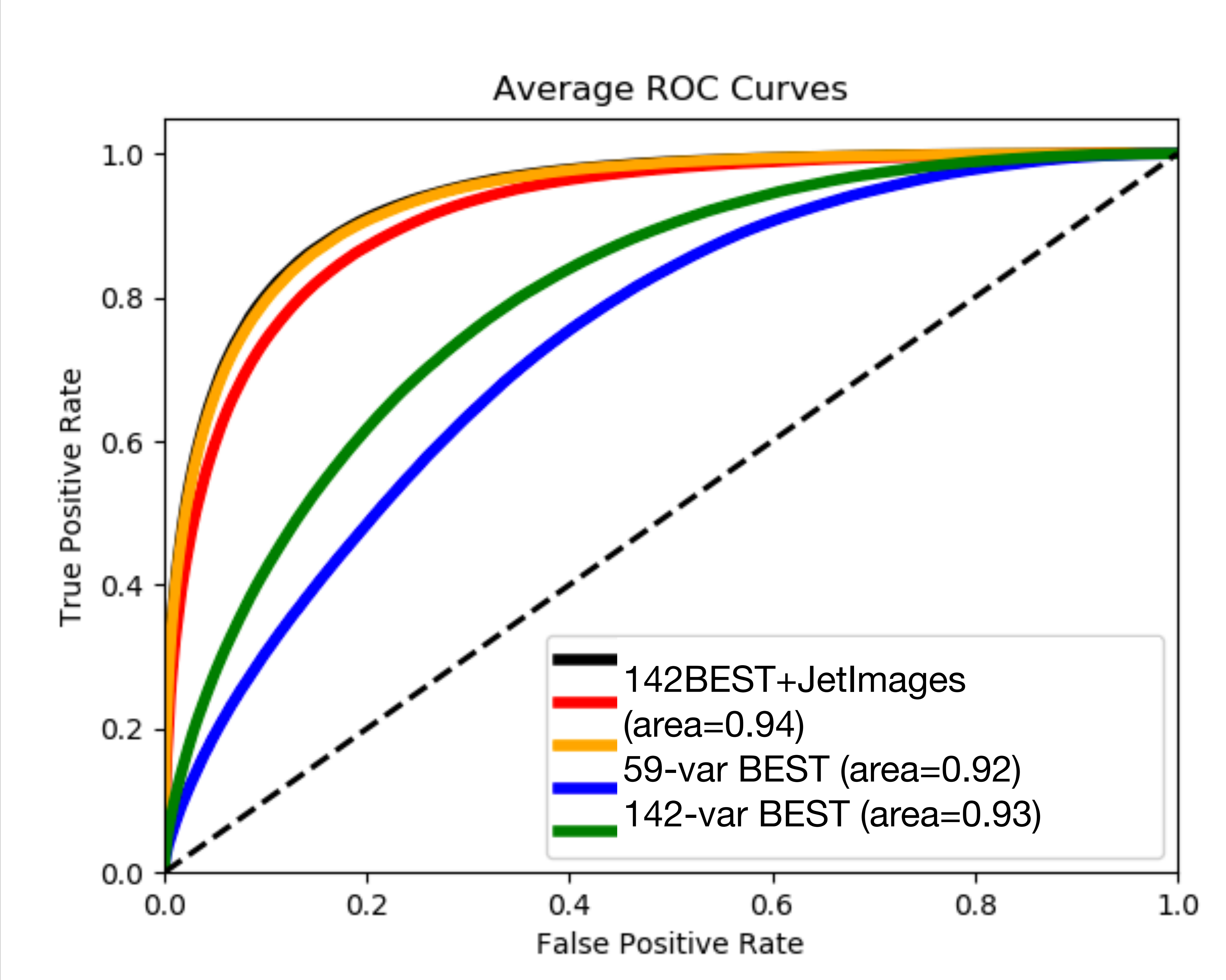
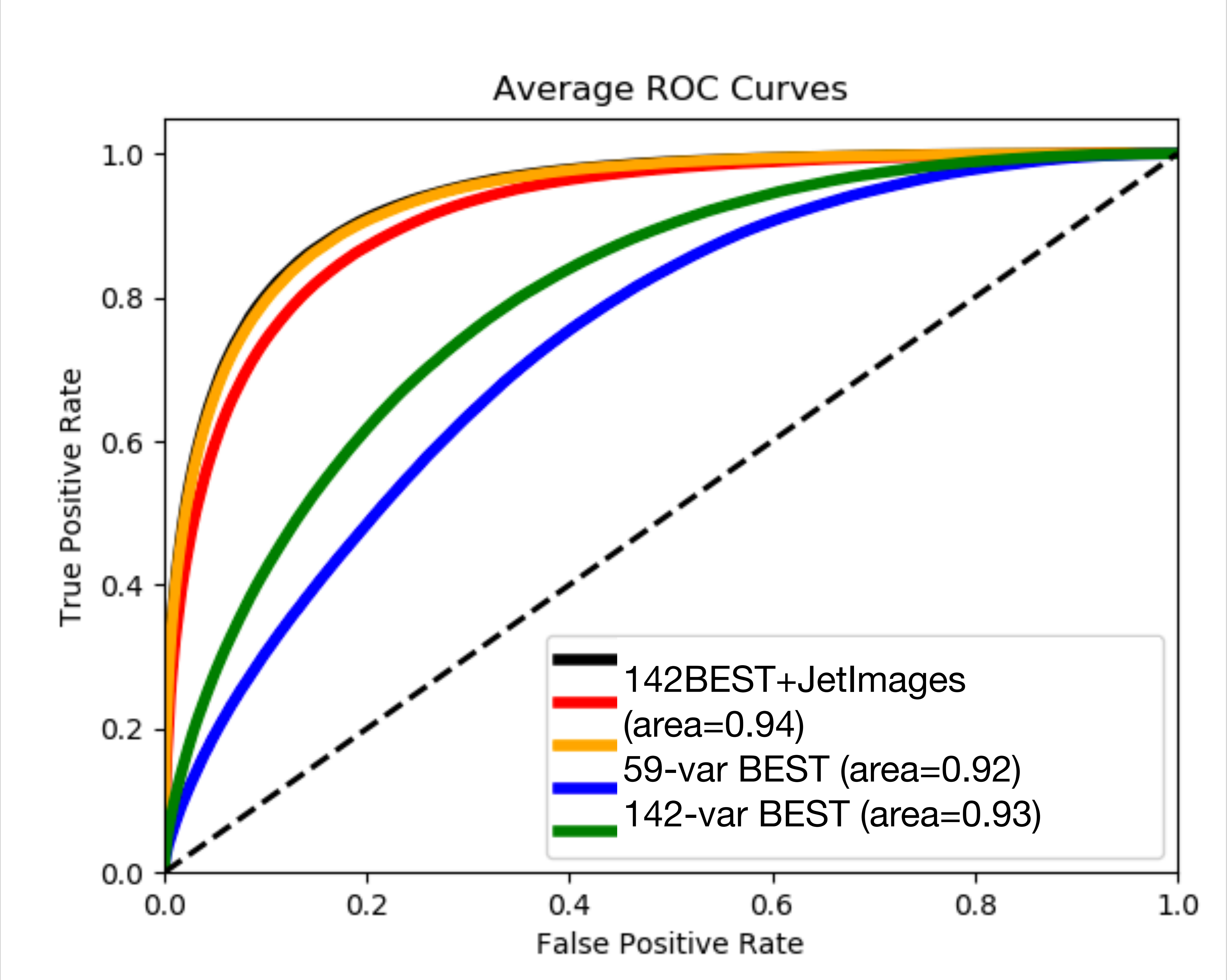
BEST Outlook



BEST Outlook

Full Run 2 data brings ~3.8x more data

- ~2x increase in sensitivity due to stats
- Further improvements with tagger



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- BES vars powerful, saturating learning on physics-driven high-level variables
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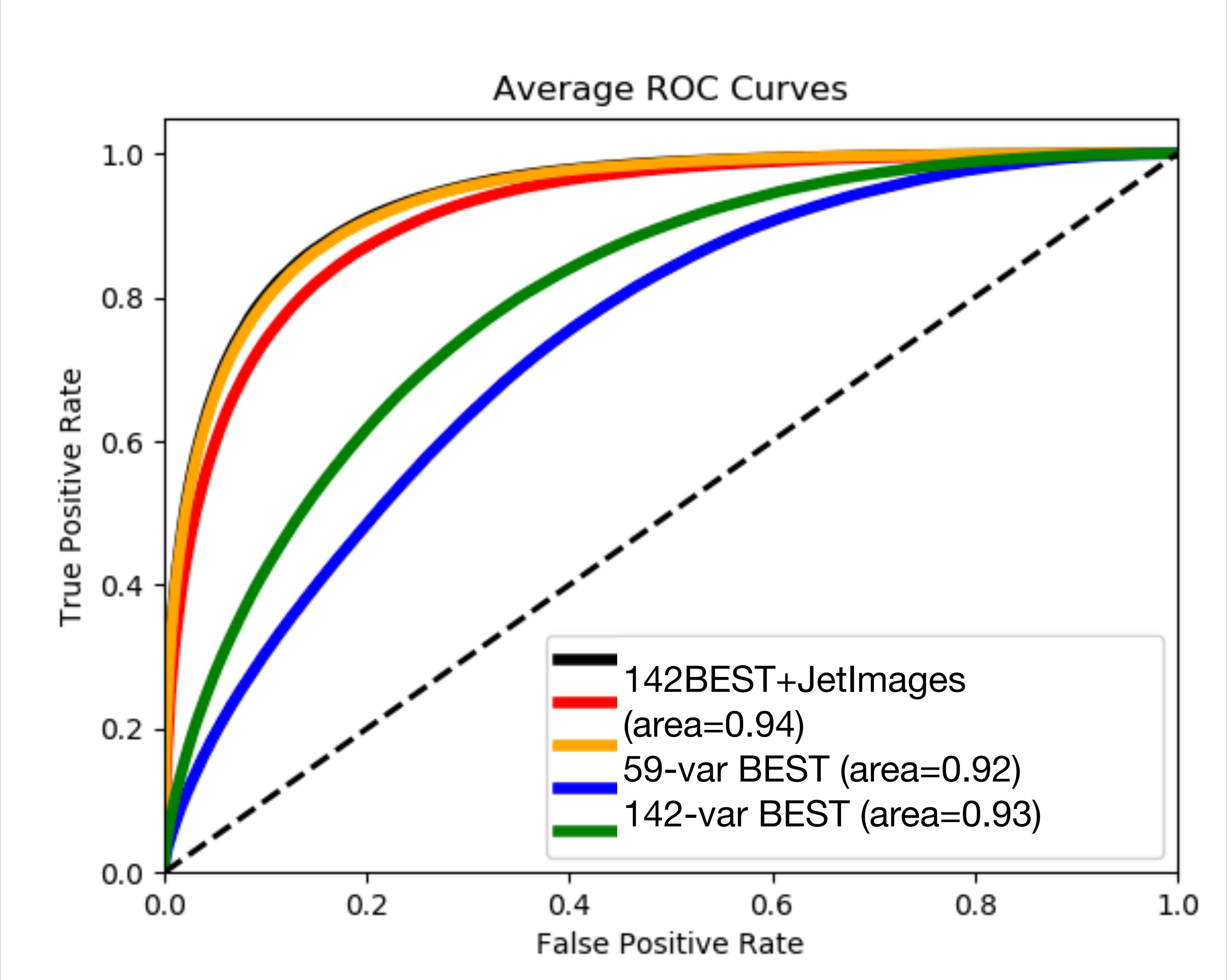

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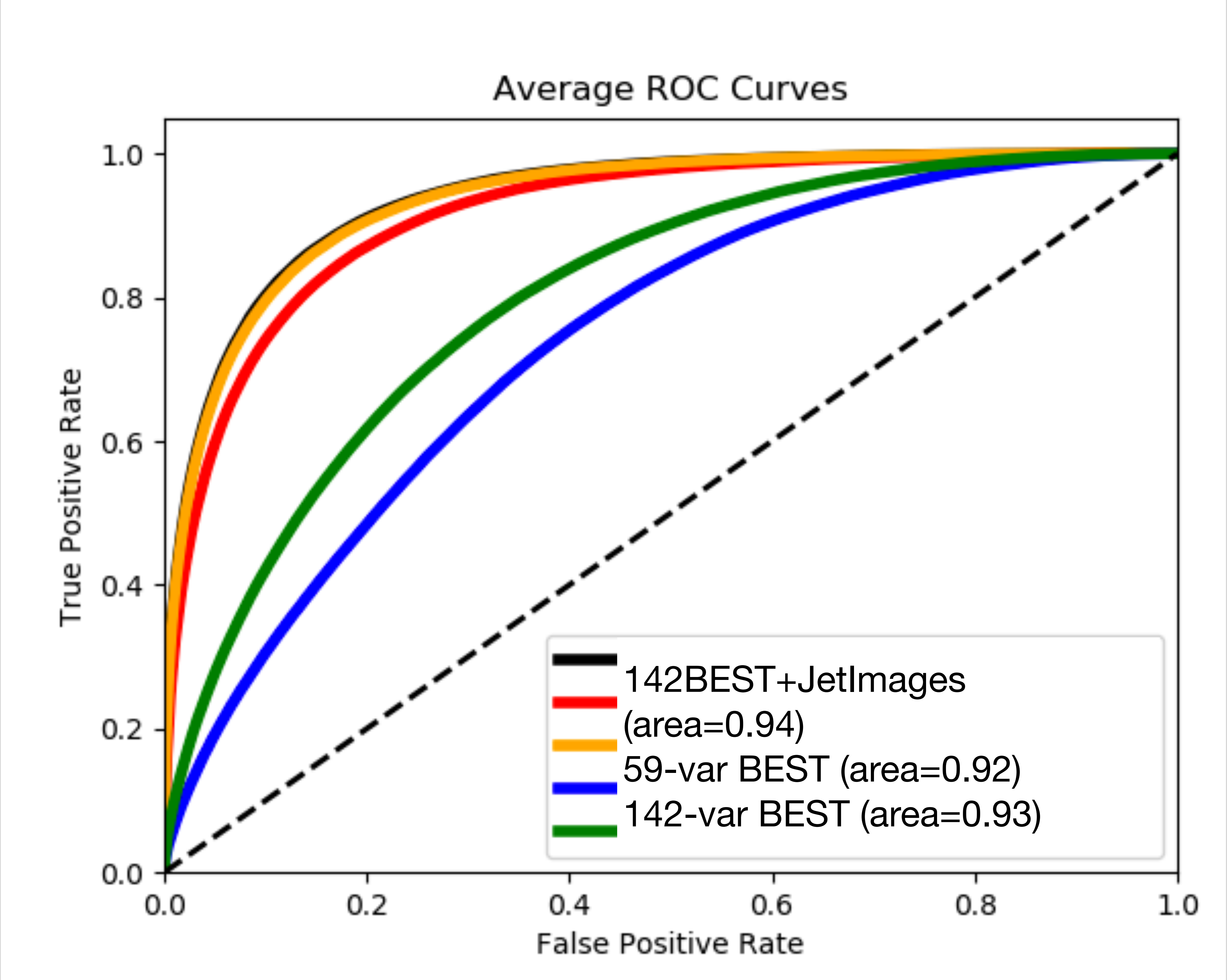
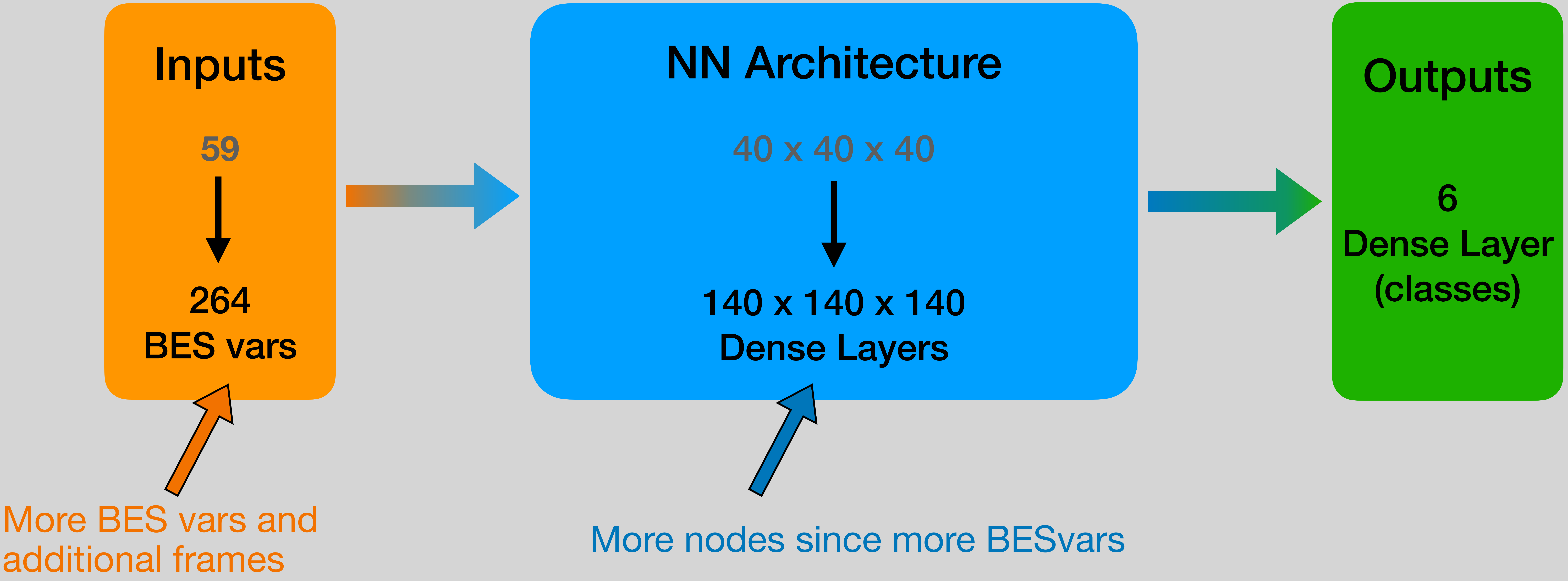


Aiming for publication by end of year

- Planned combination with semi-leptonic channels
- Possibly first LHC results for VLQs @ NLO

BESTagger Architecture

Improvements wrt B2G-18-005



Shape-Matching in p_T

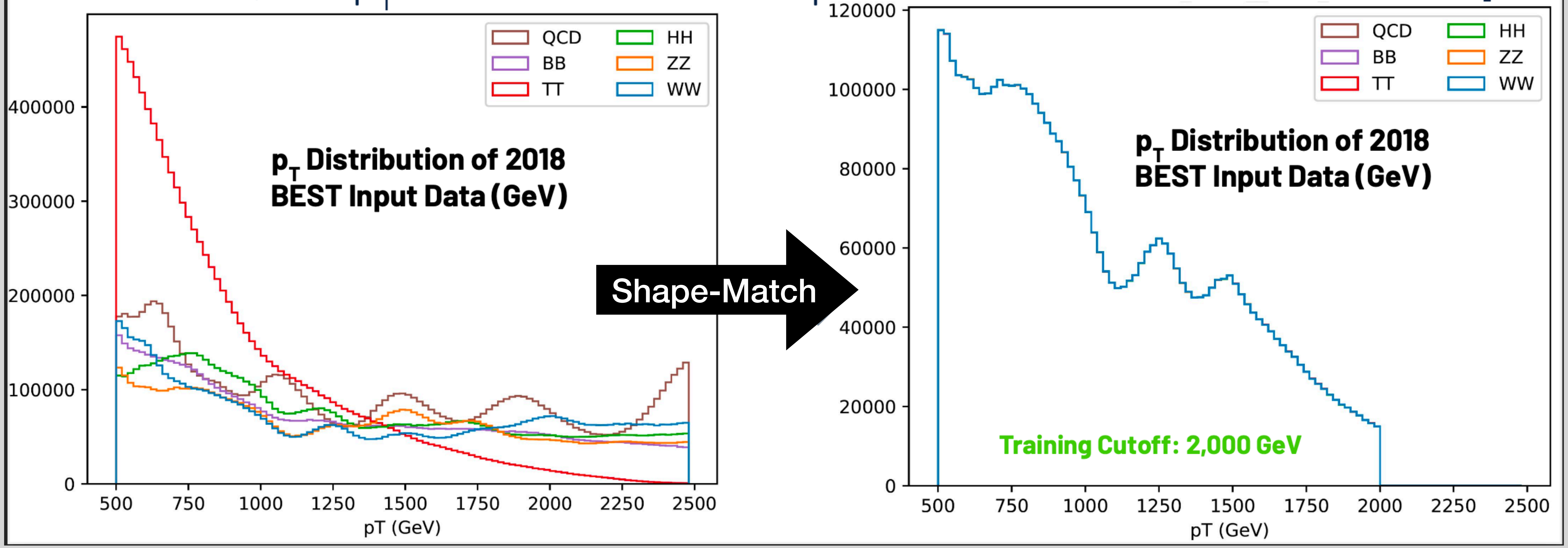
Samantha Abbott
JMAR 14 June 2022

12

The BEST Approach to Flattening

UCDAVIS

- For each **p_T bin** (**20 GeV**):
  - Identify **process** with the **fewest events**
  - For the other **5 processes**, begin **randomly dropping events**
    - Continue until they match the process with the **least events**
- Now, the p_T distribution for all 6 processes will have **identical shape**



Johan S Bonilla Castro (Northeastern)

Search for Vector-Like Quarks using the Boosted Event Shape Tagger in the All-Hadronic Channel

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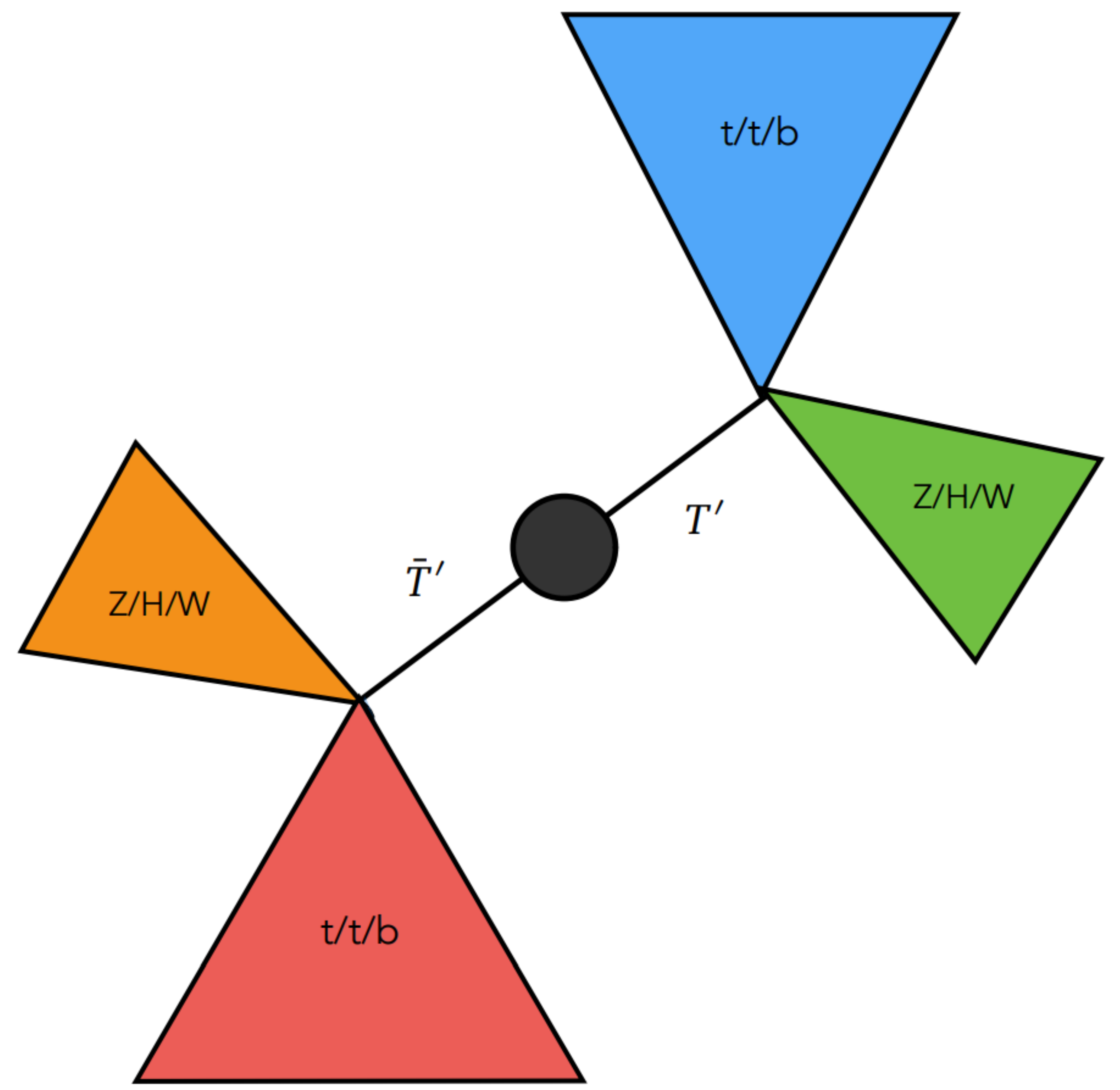

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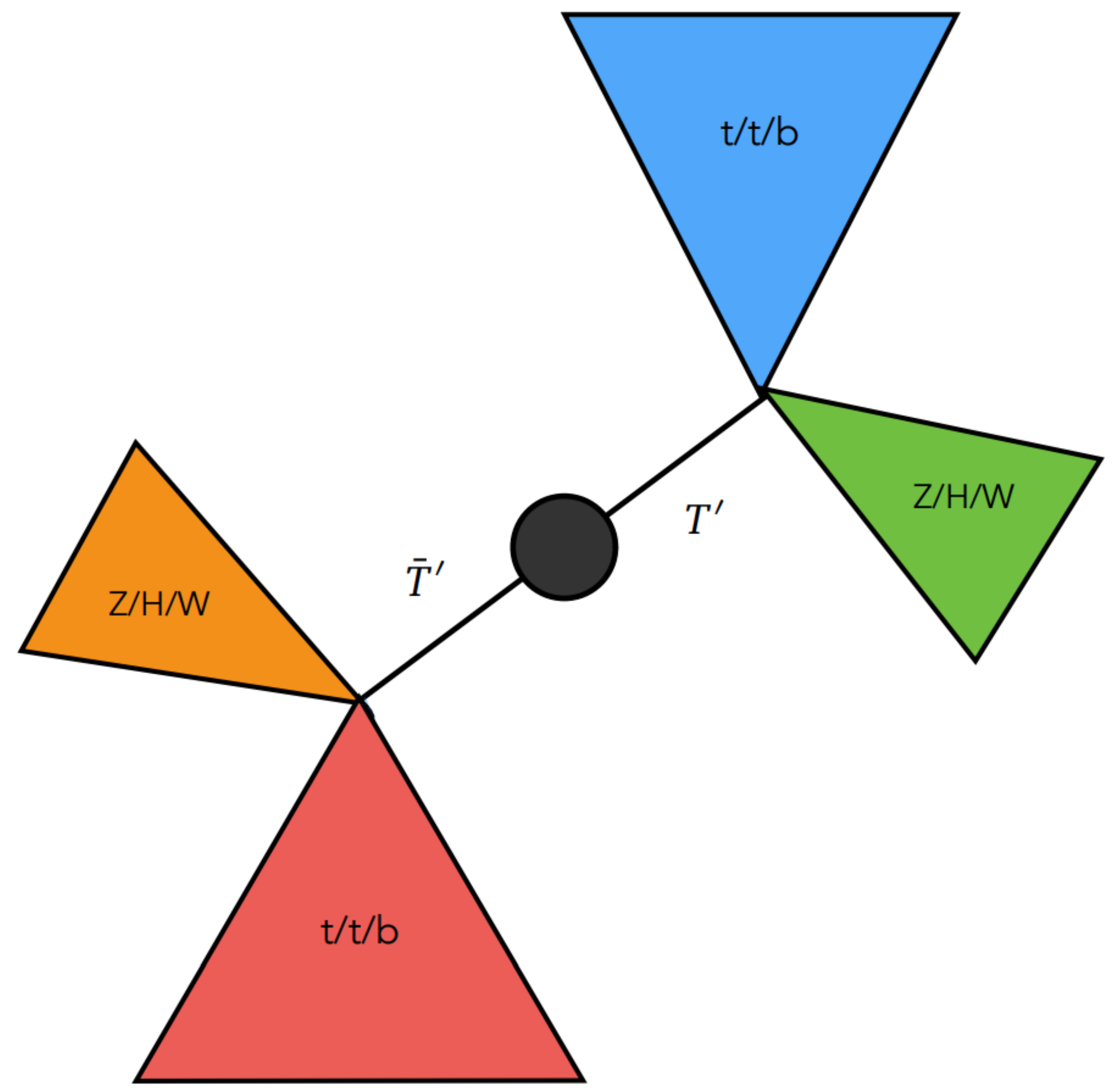

All-Hadronic Channel

- At-least 4 large-R Jets
- $p_T > 400$ GeV, $|\eta| < 2.4$

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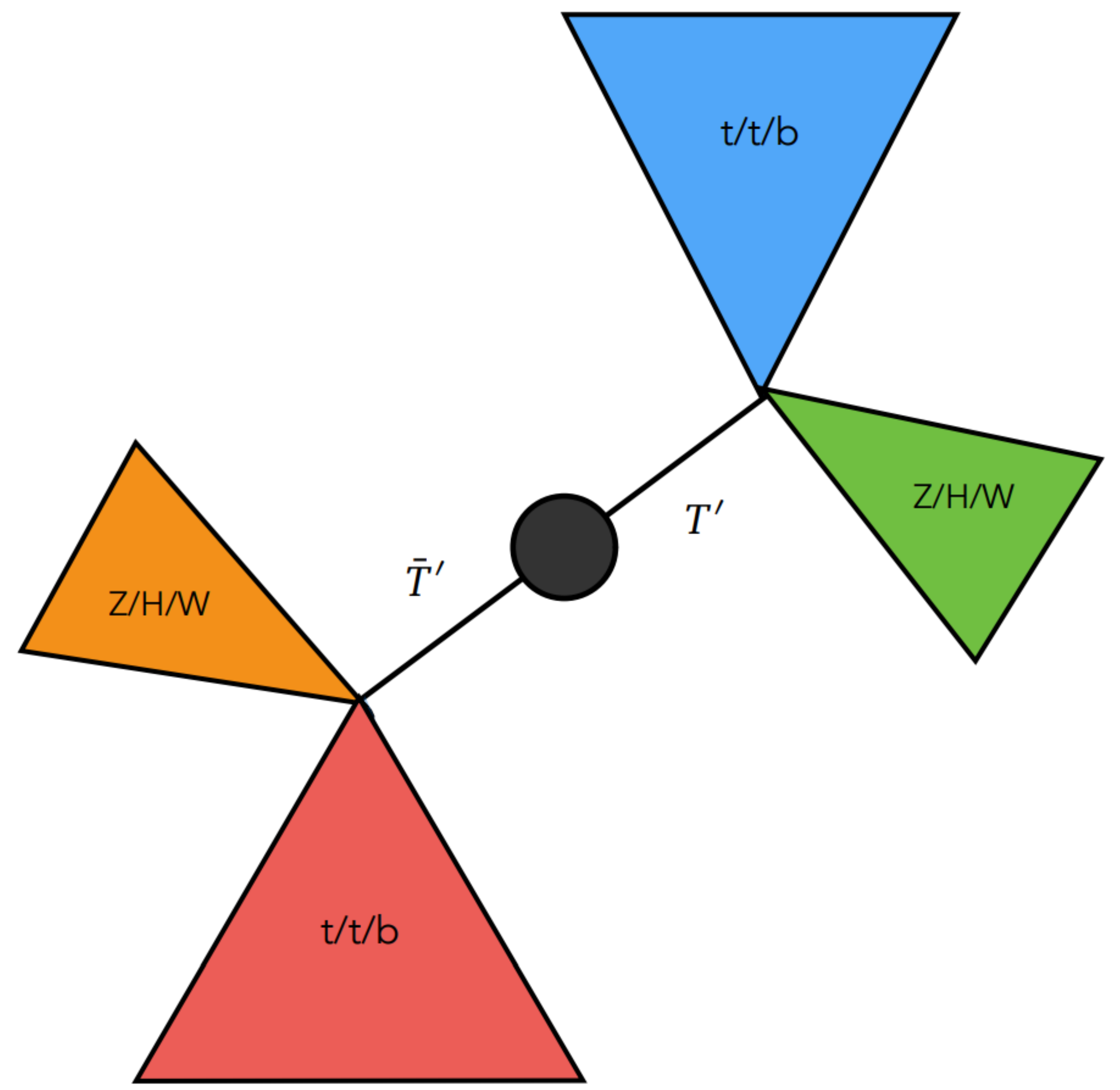

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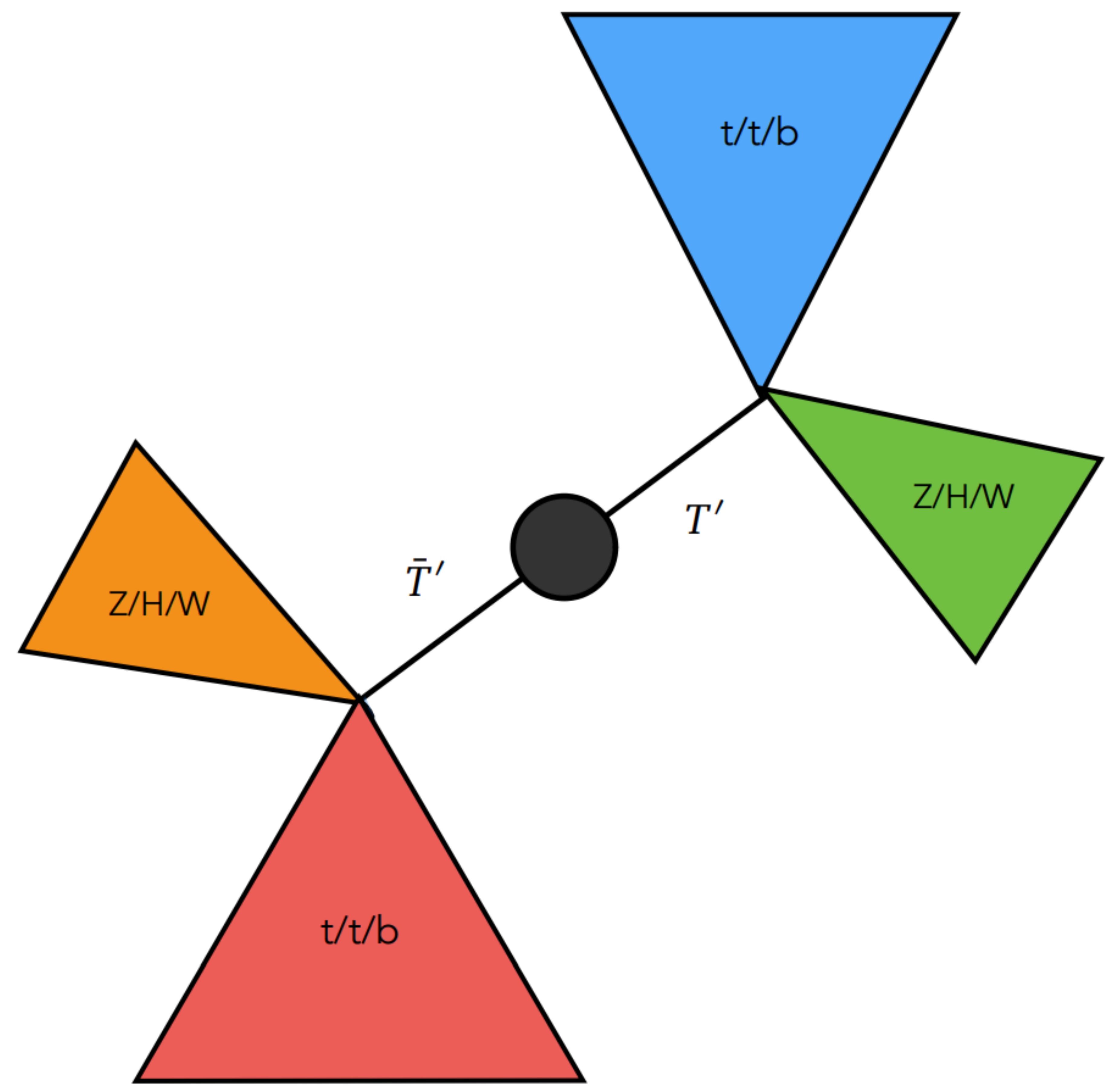

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Background Estimation

- QCD: Data-driven control region
- V+Jets, dibosons, ttbar, ttV, 4t shapes from simulation

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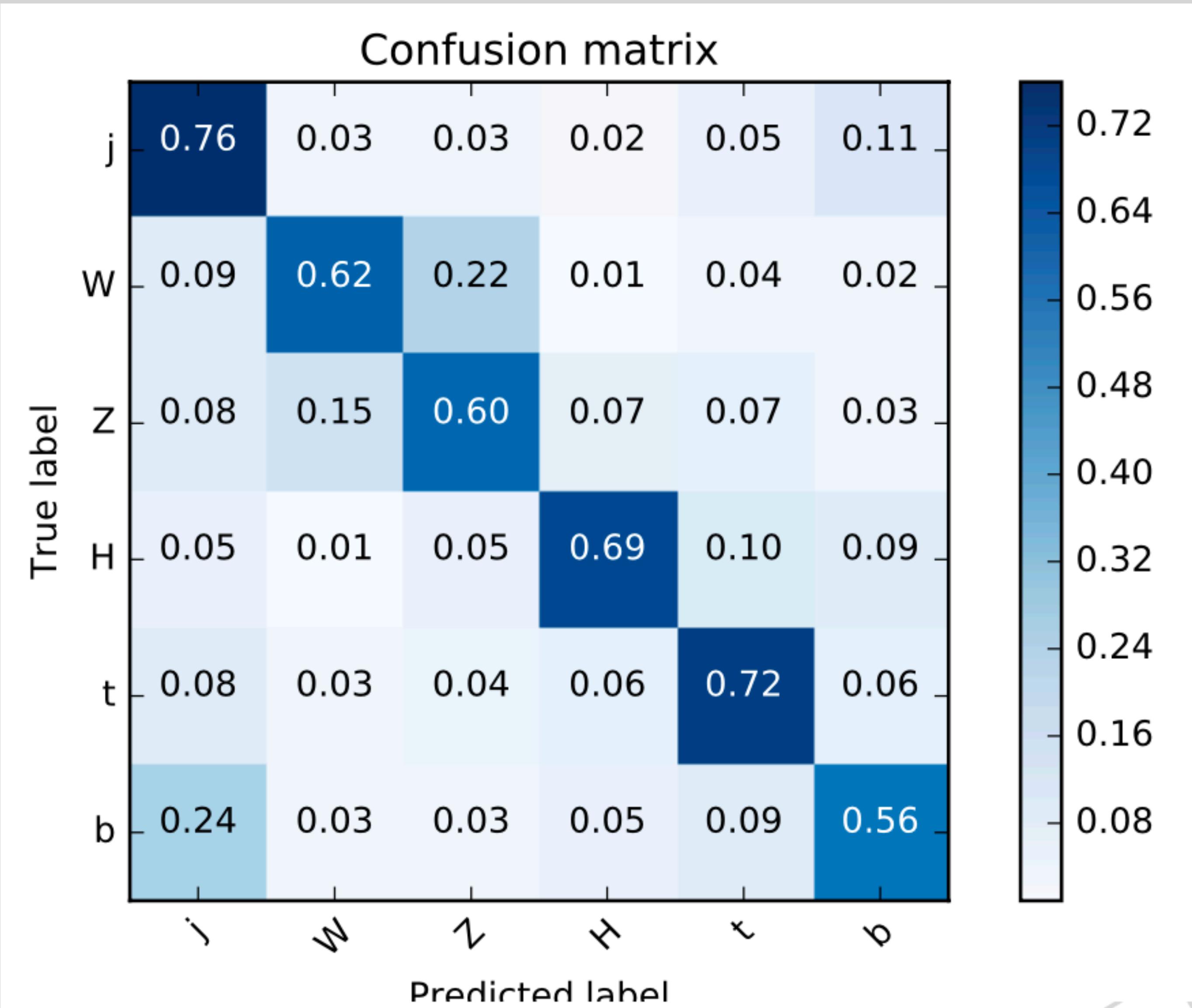
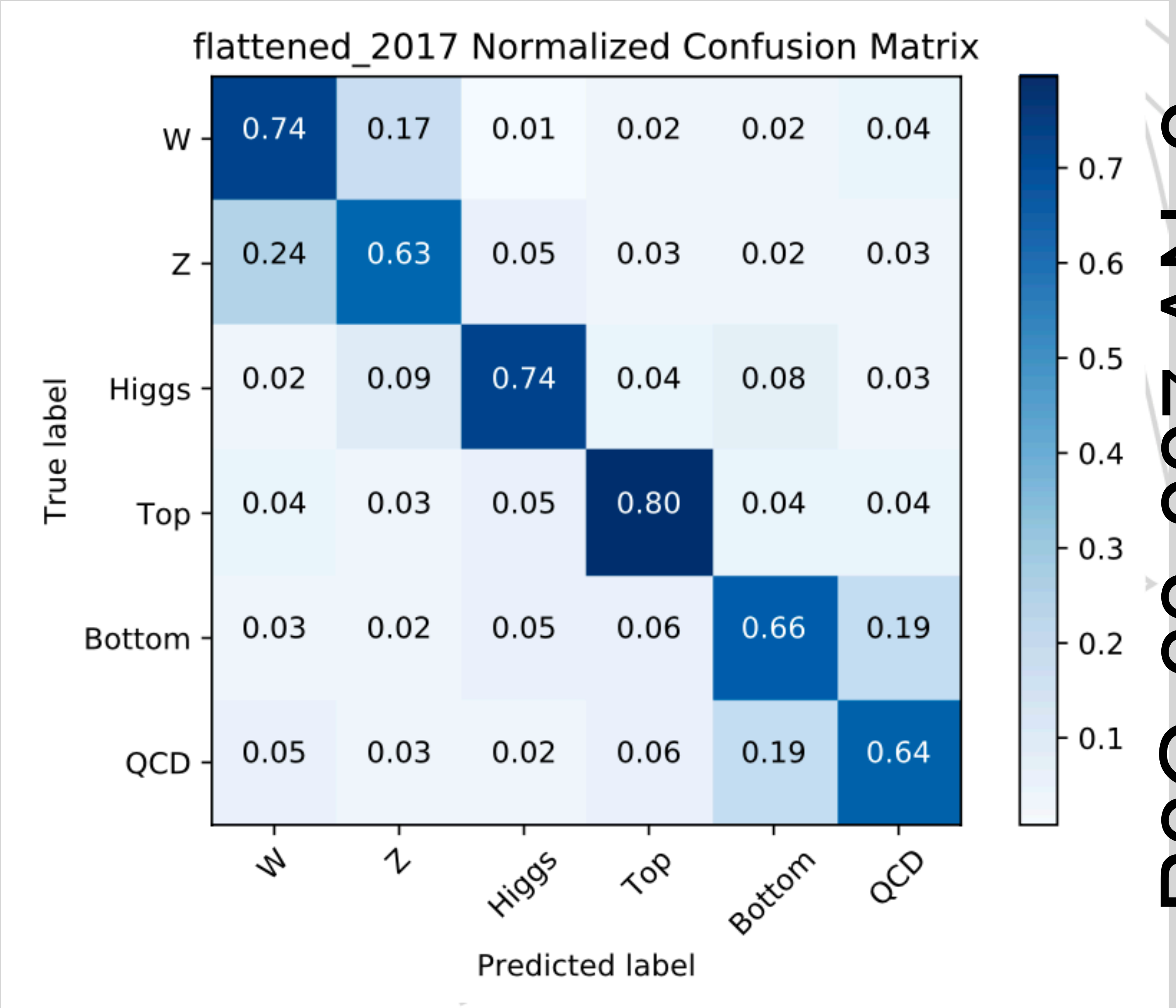
BEST Performance Improvements

B2G-18-005

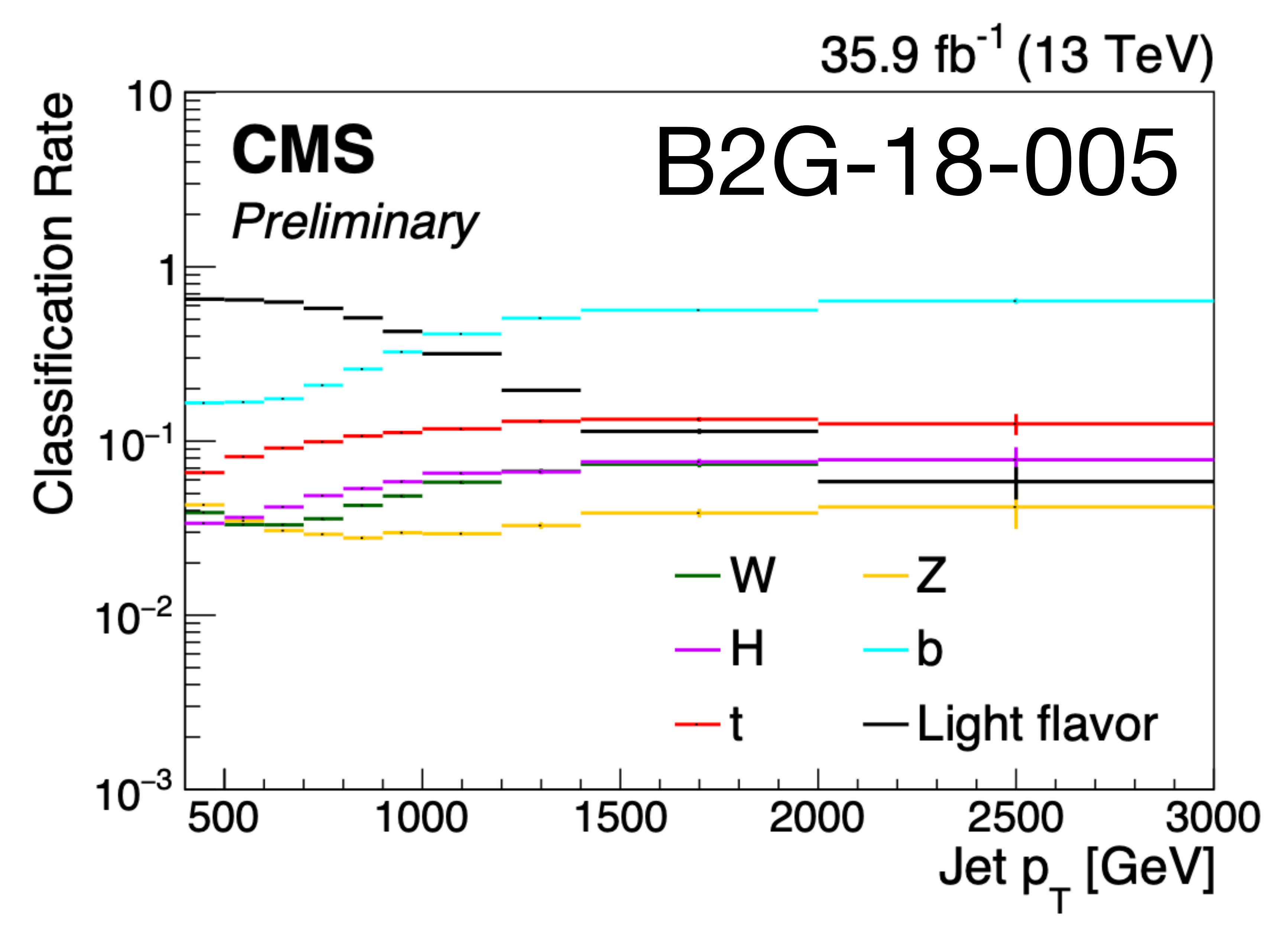


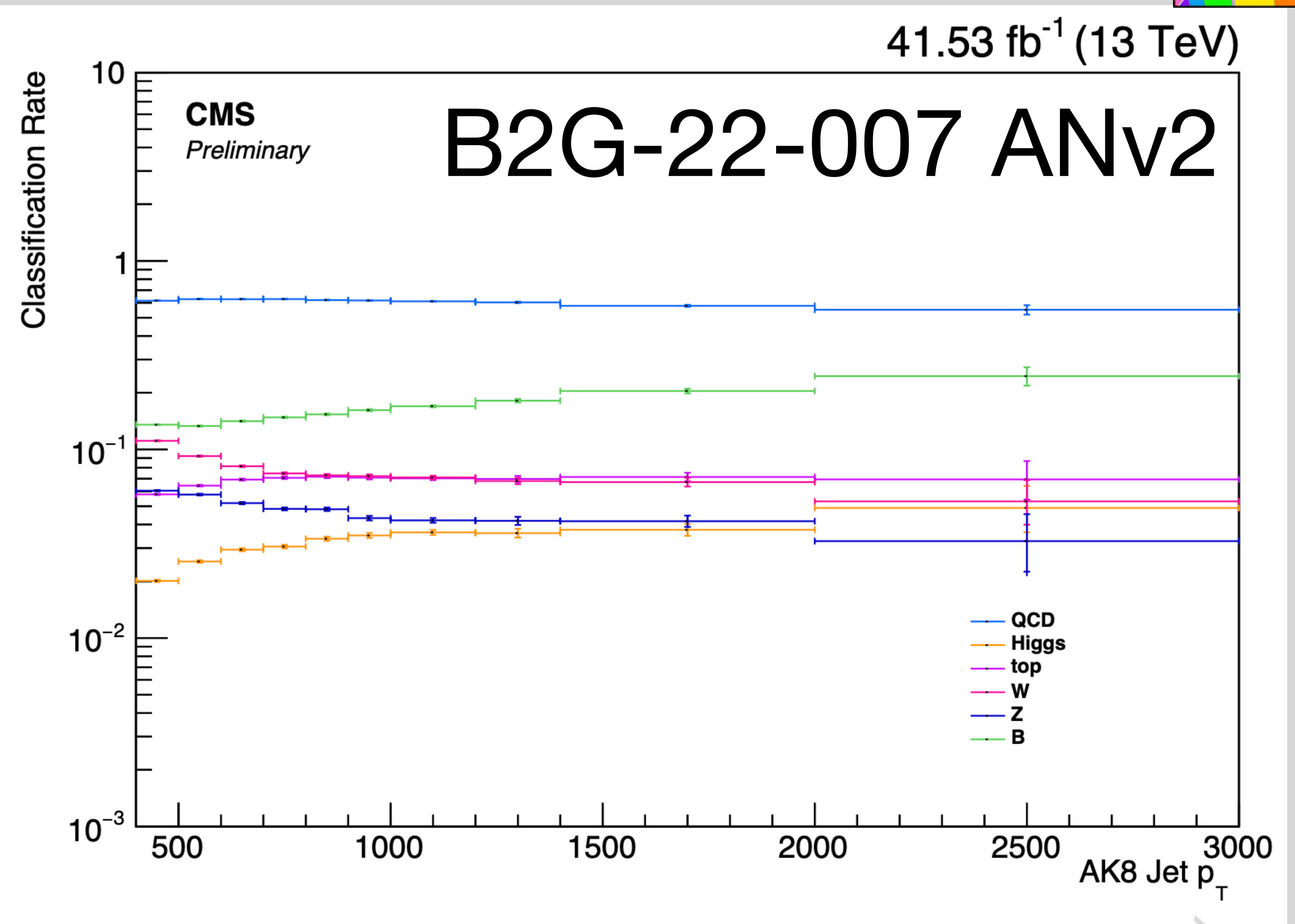
CAREFUL with classes!!



B2G-22-007 ANv2

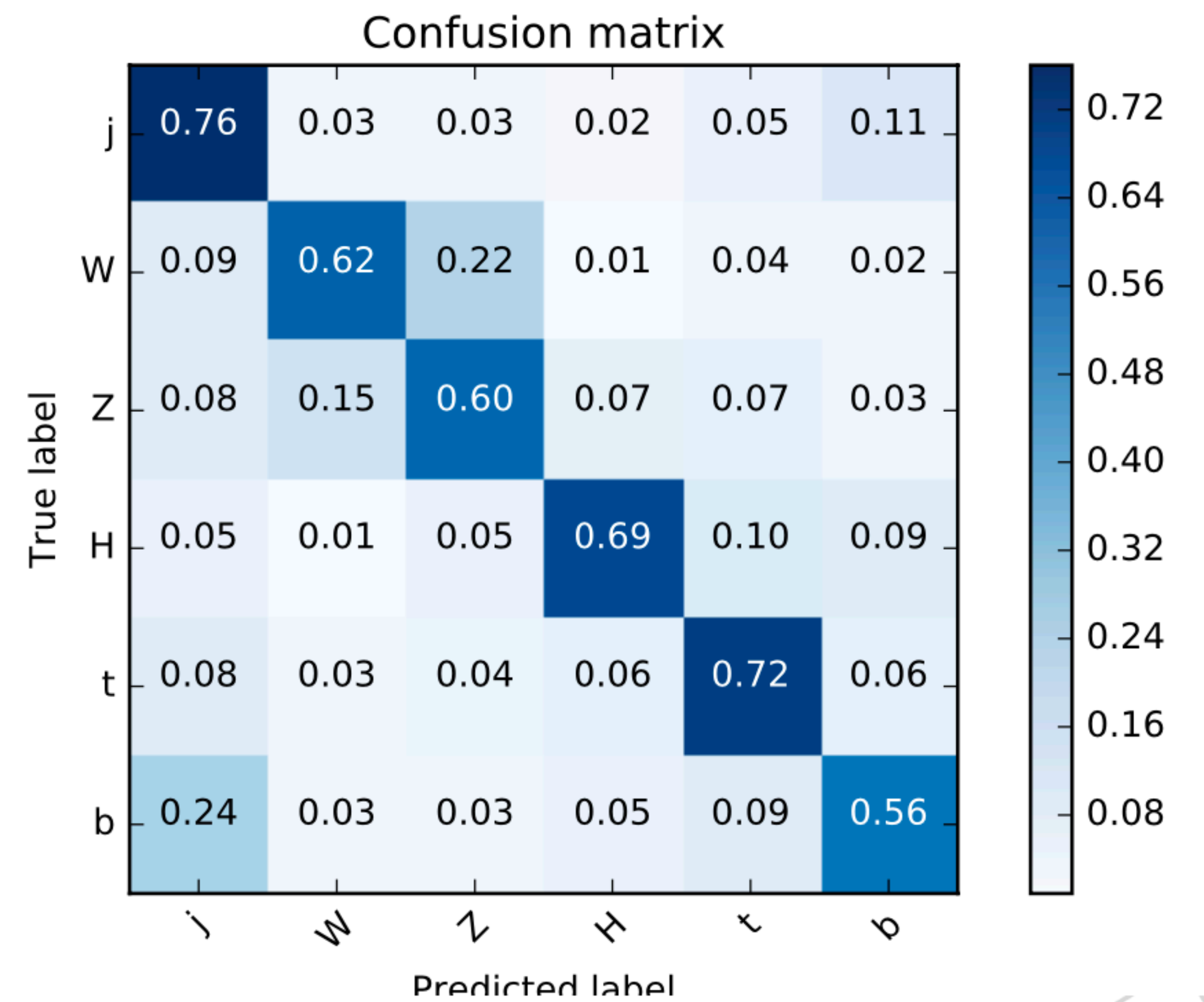
BEST Performance Improvements





CAREFUL with colors!!

B2G-18-005



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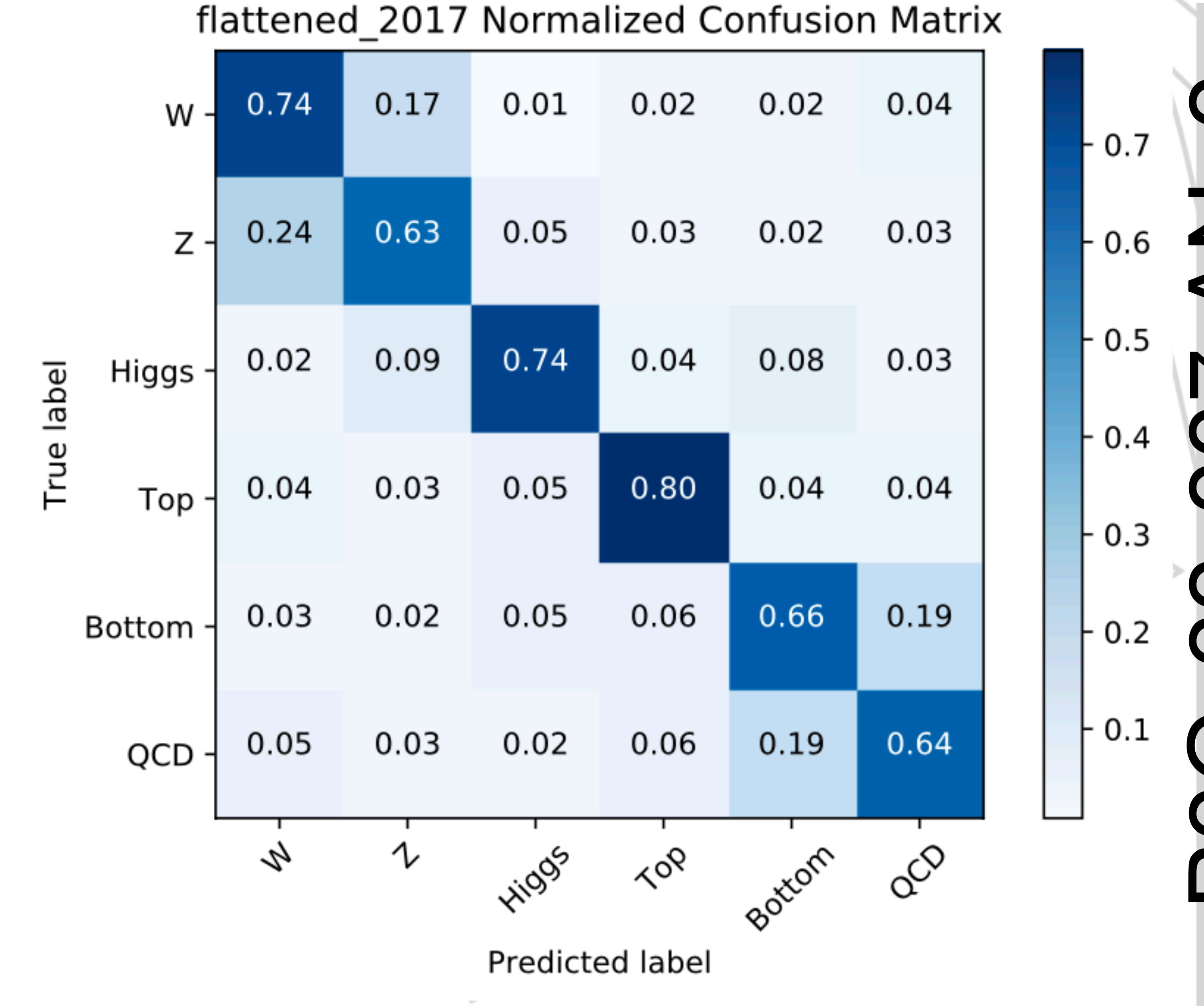
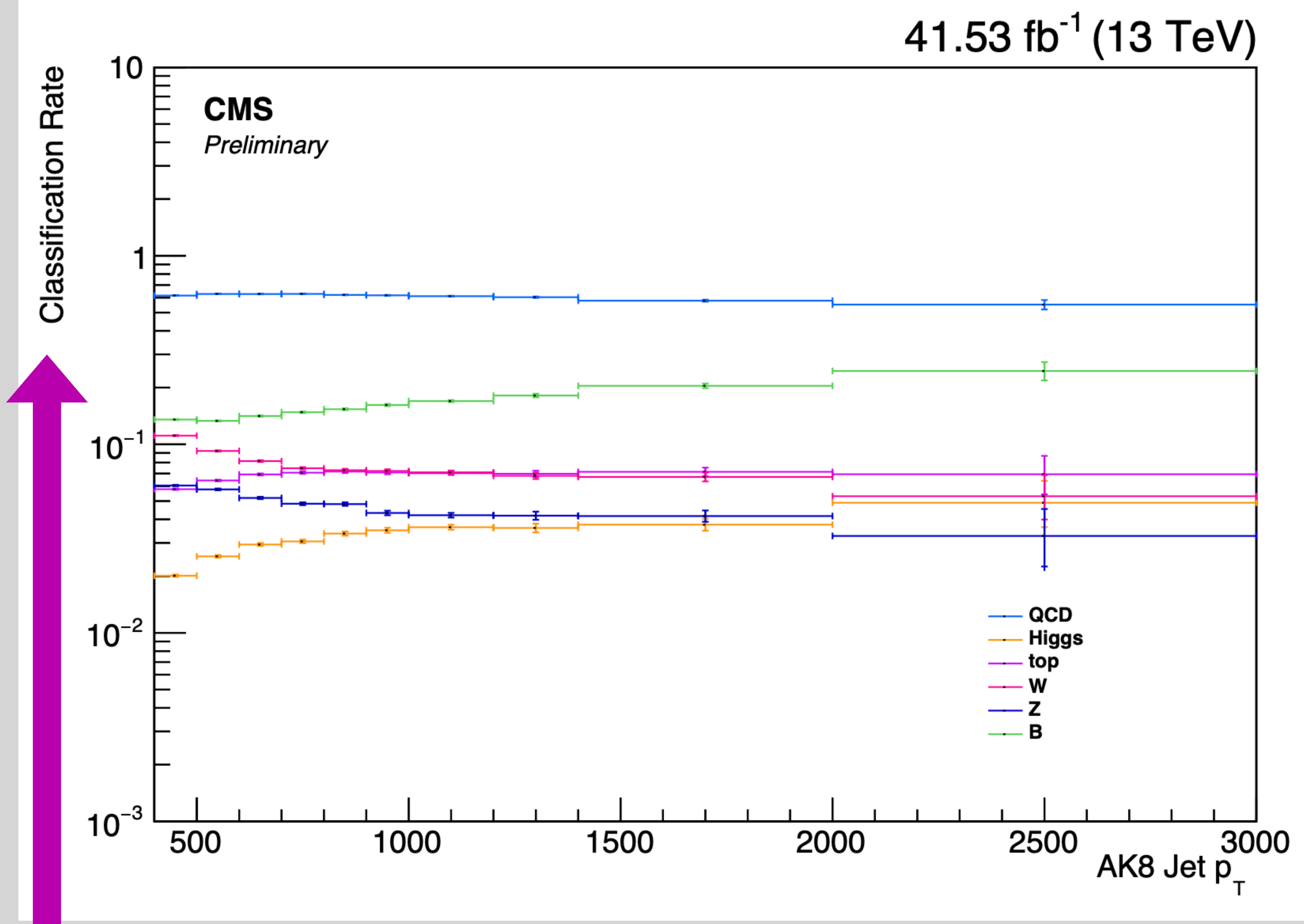
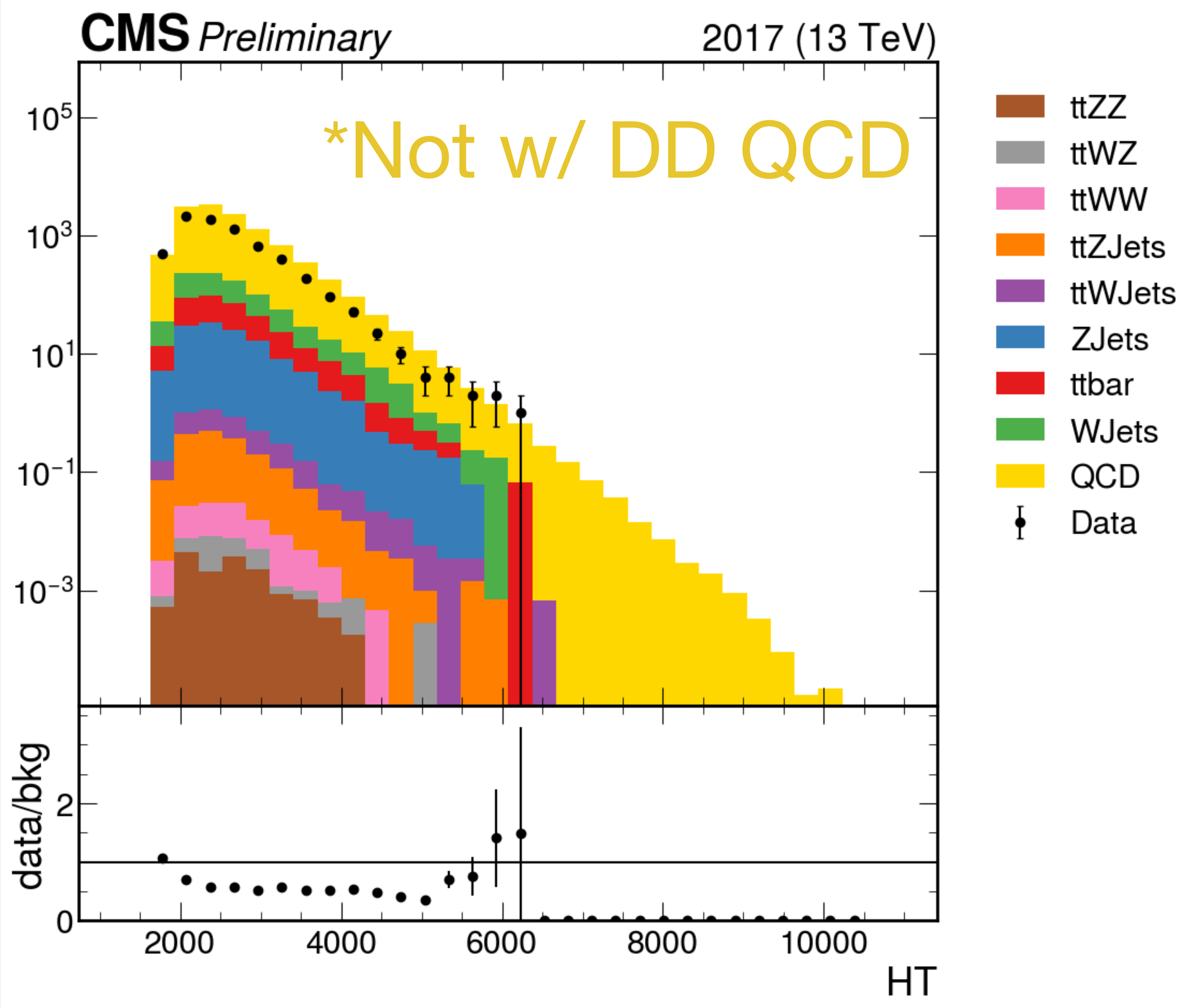


B2G-22-007 ANv2

Background Estimation

Tagging Rates in Data-MC for QCD





$$\epsilon_X(p_T) = \frac{N_X}{N_{tot}}$$ Measure tagging rate in QCD-rich region to obtain weights for multi-jet BG

[1]: PhysRevD 100, 072001

Illustrative Example of BG Estimate

- Goal: Estimate amount of QCD to expect, only with data
- Key Idea: Use QCD-dominant regions to 'turn mistag rate' into probability

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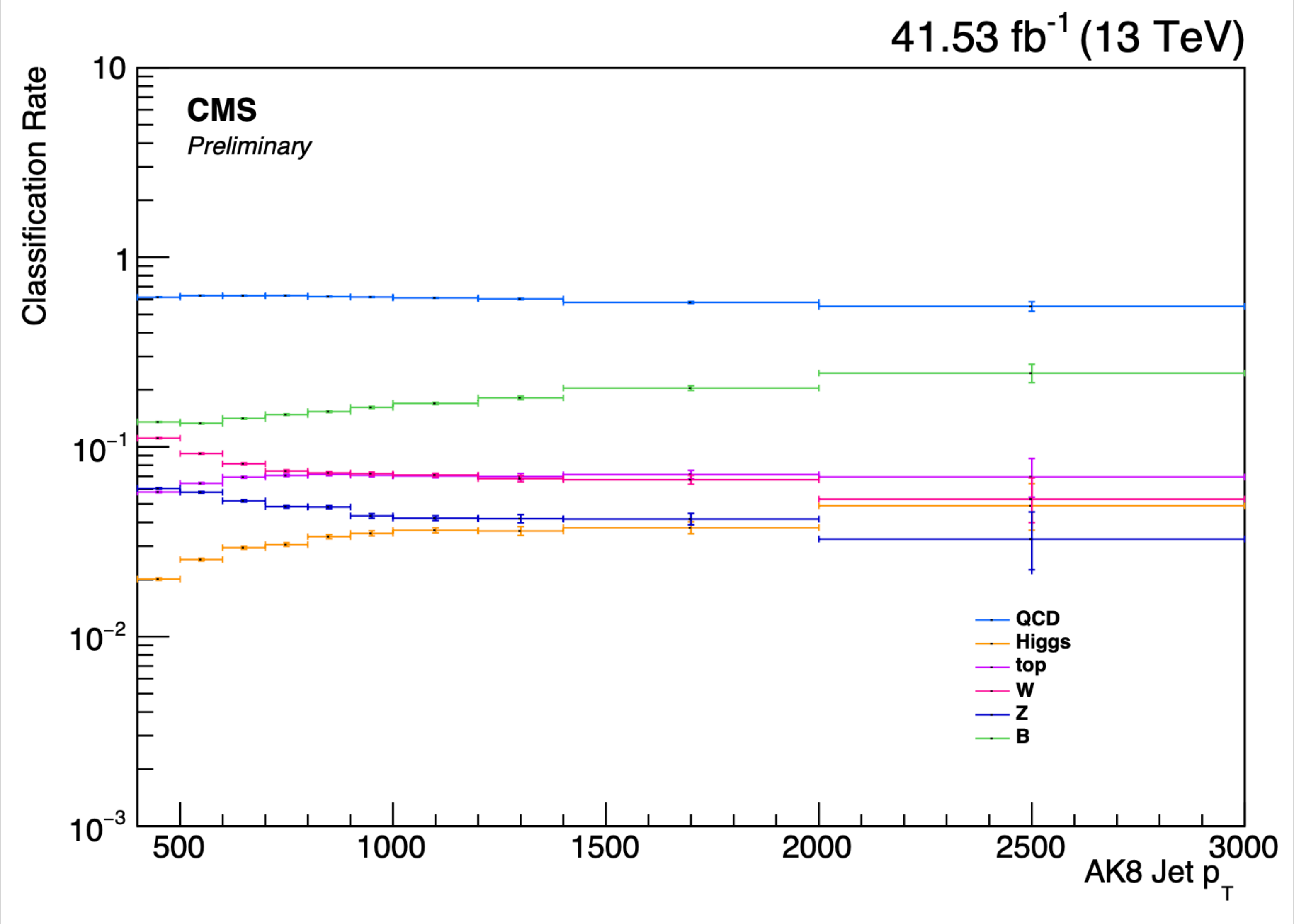

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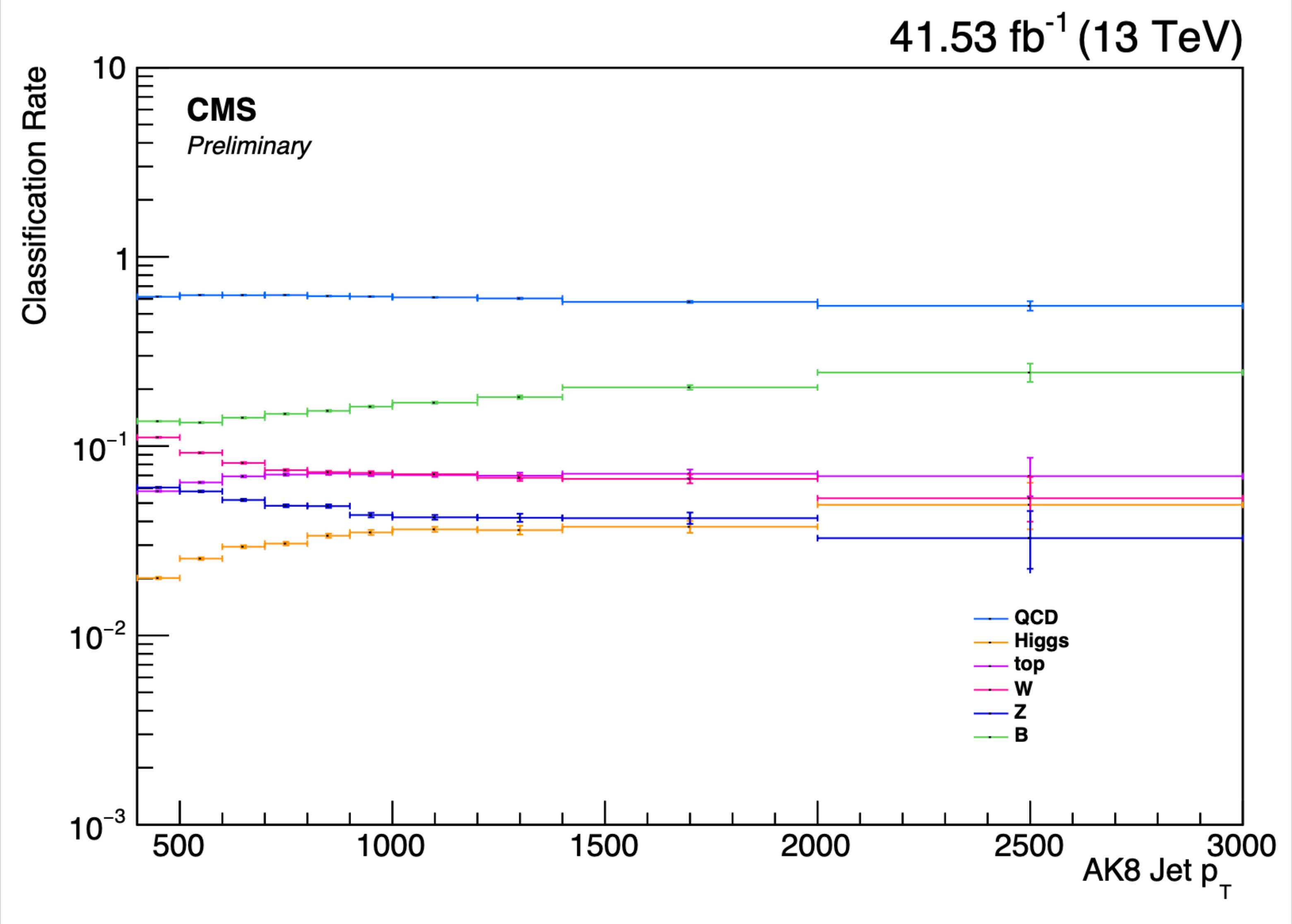

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$$r = \sum_{events} \sum_{permutaions} \prod_{i=1}^{4} \epsilon_X\left(p_{T,i}\right)$$

Johan S Bonilla Castro (Northeastern)

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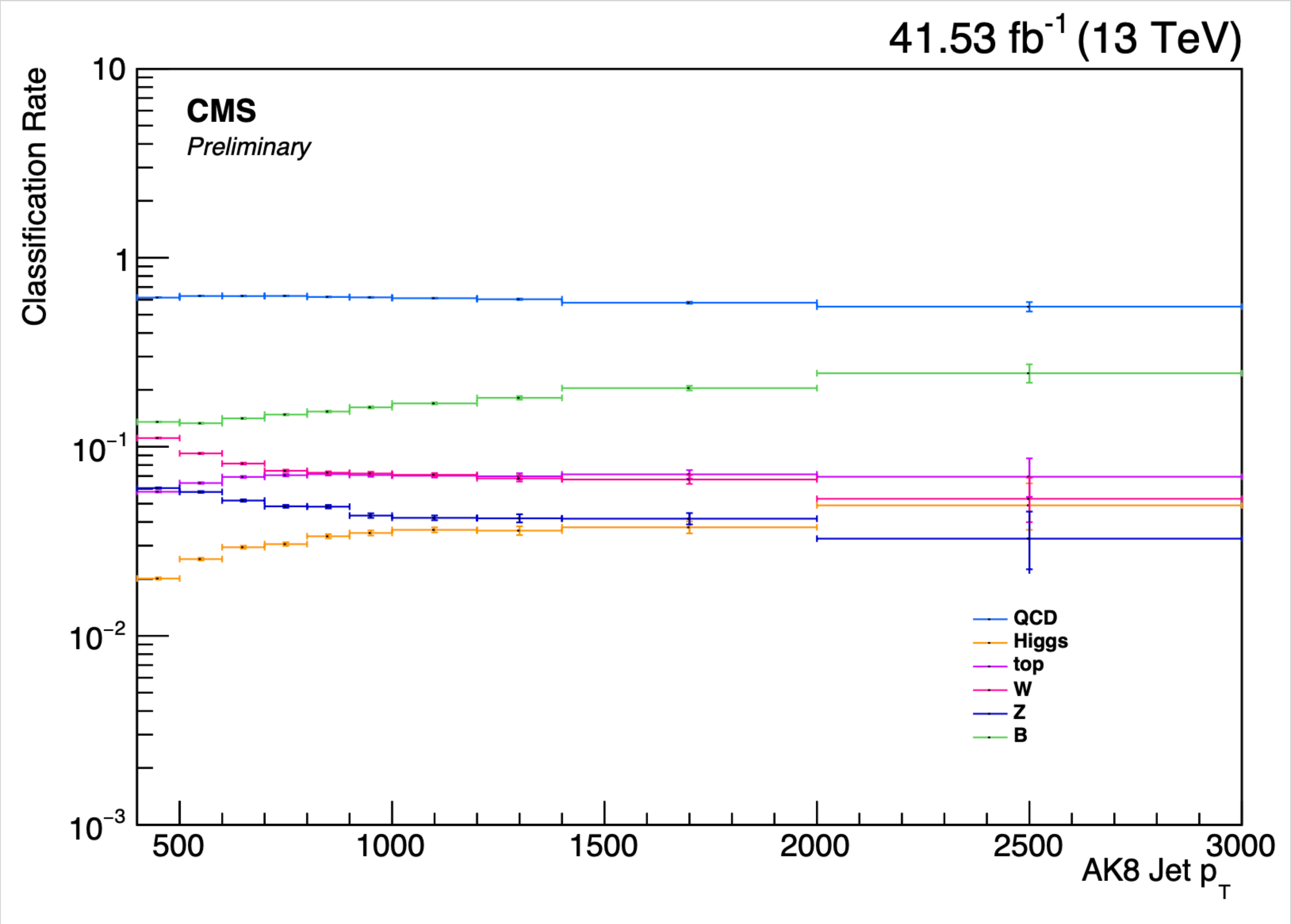


P(QCD->QQtW) =

P(Q->Q)*P(Q->Q)*P(Q->t)*P(Q->W)

$$= \epsilon(Q\,|\,p_{T,1})\epsilon(Q\,|\,p_{T,2})\epsilon(t\,|\,p_{T,3})\epsilon(W\,|\,p_{T,4})$$

$$r = \sum_{events} \sum_{permutaions} \prod_{i=1}^{4} \epsilon_X\left(p_{T,i}\right)$$

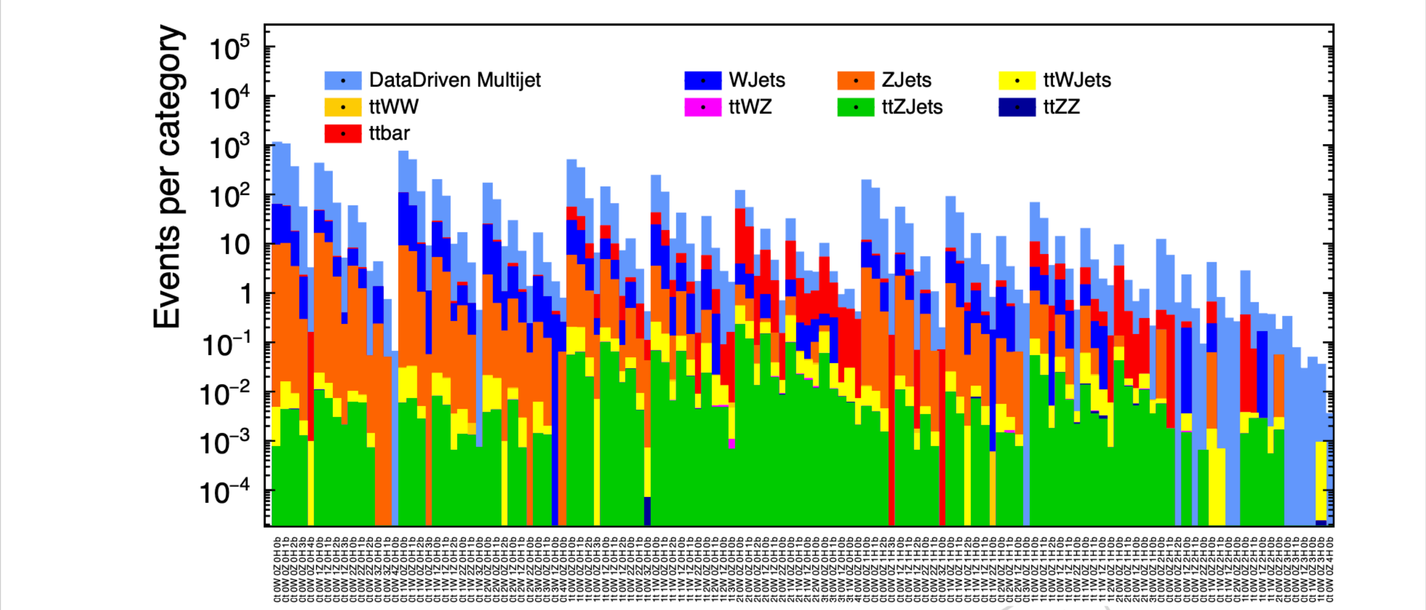


Figure 24: The estimated background in each of the 120 signal regions. Each bin represents one signal region labeled by the classification of the four jets (ex. WWWZ, WWHZ, etc.) for 2017

Signal Region Categorization

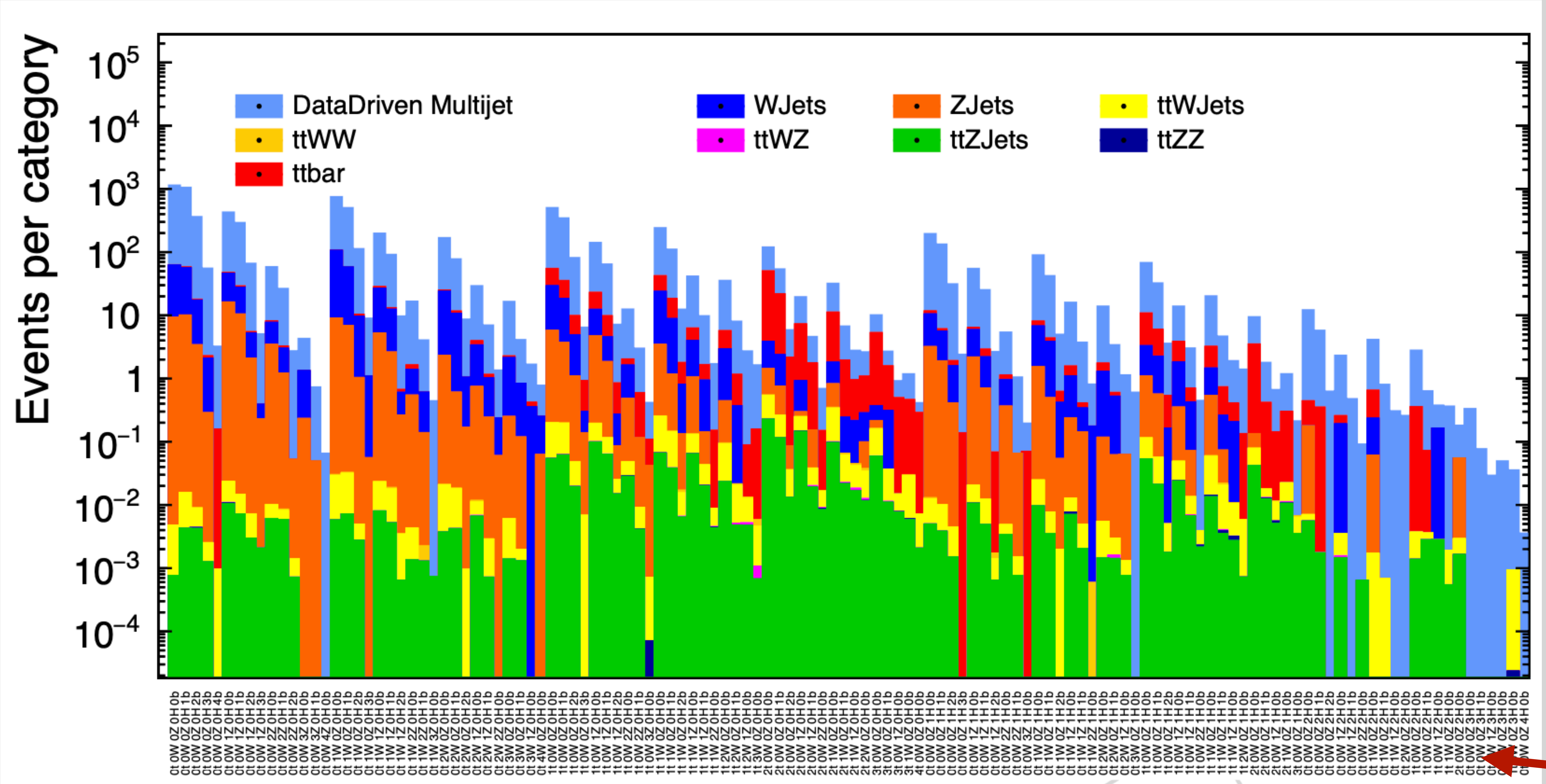
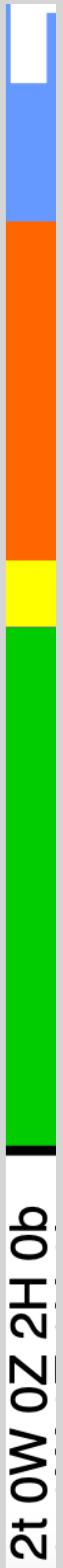


Figure 24: The estimated background in each of the 120 signal regions. Each bin represents one signal region labeled by the classification of the four jets (ex. WWWZ, WWHZ, etc.) for 2017

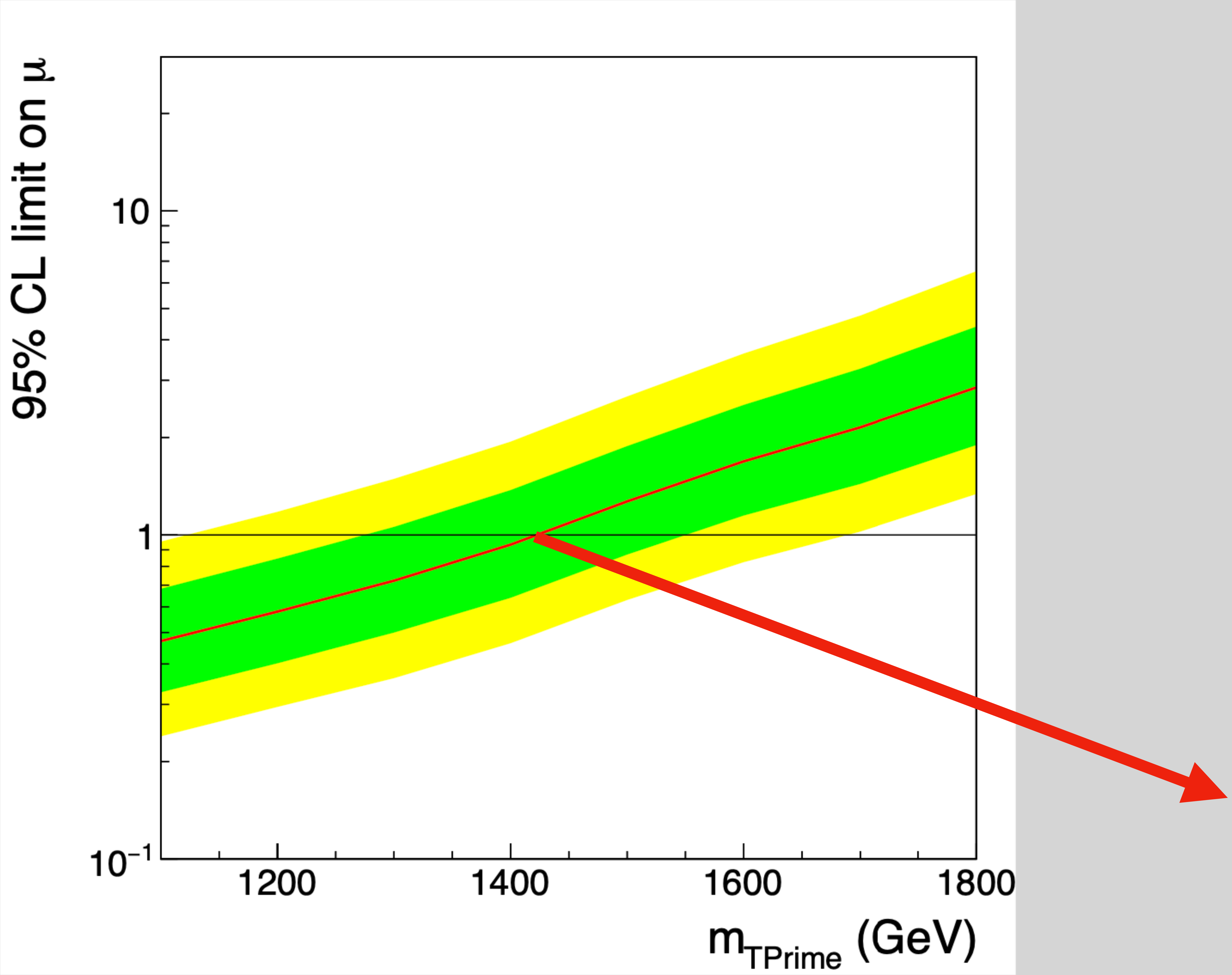
Four jets, six classes each, 126 possible combinations

Orthogonal SRs provide powerful combined result

Unlike 2016 analysis, six 4-jet regions now used as VRs to improve fitting



Work in Progress: Expectated Exclusions



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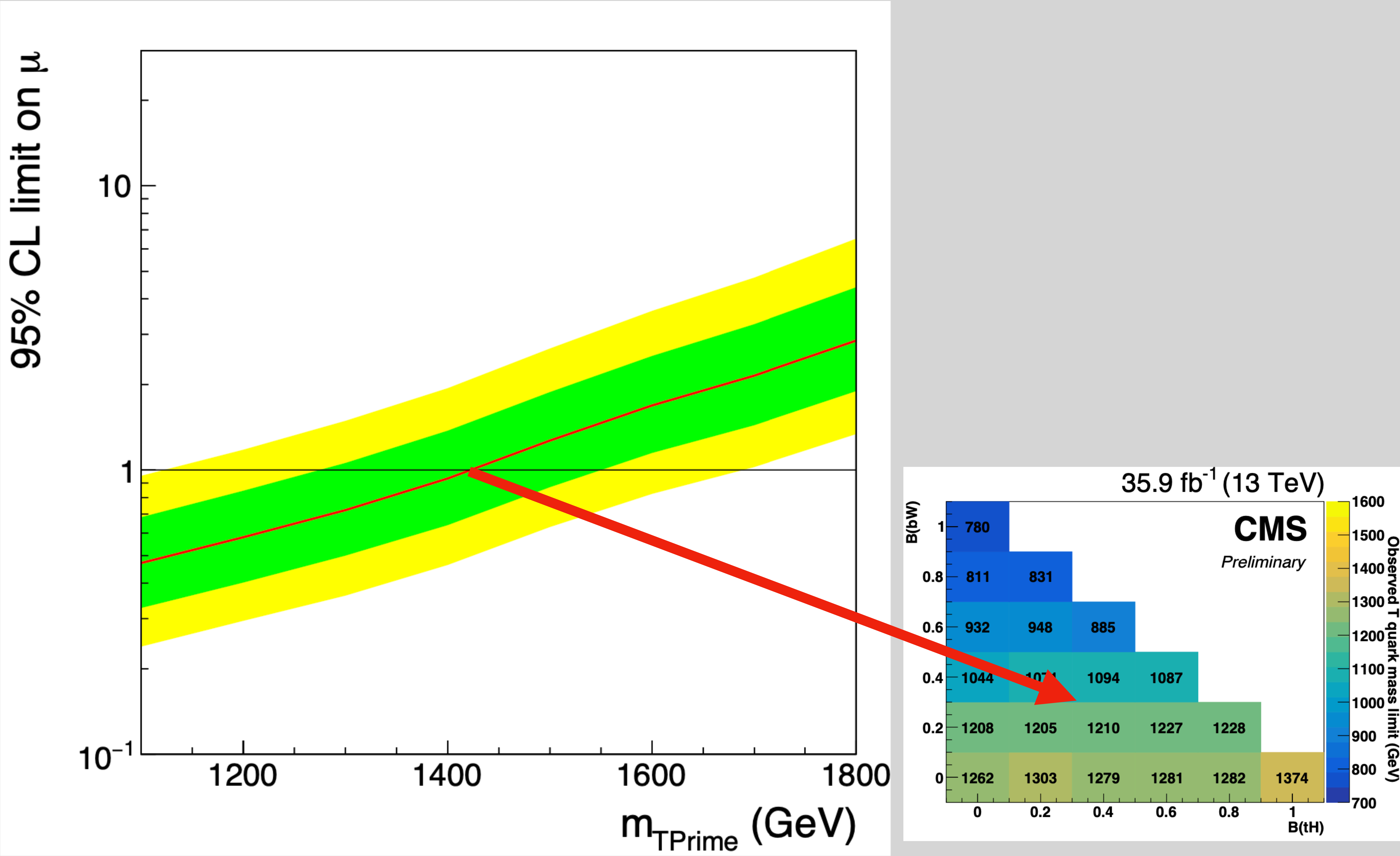
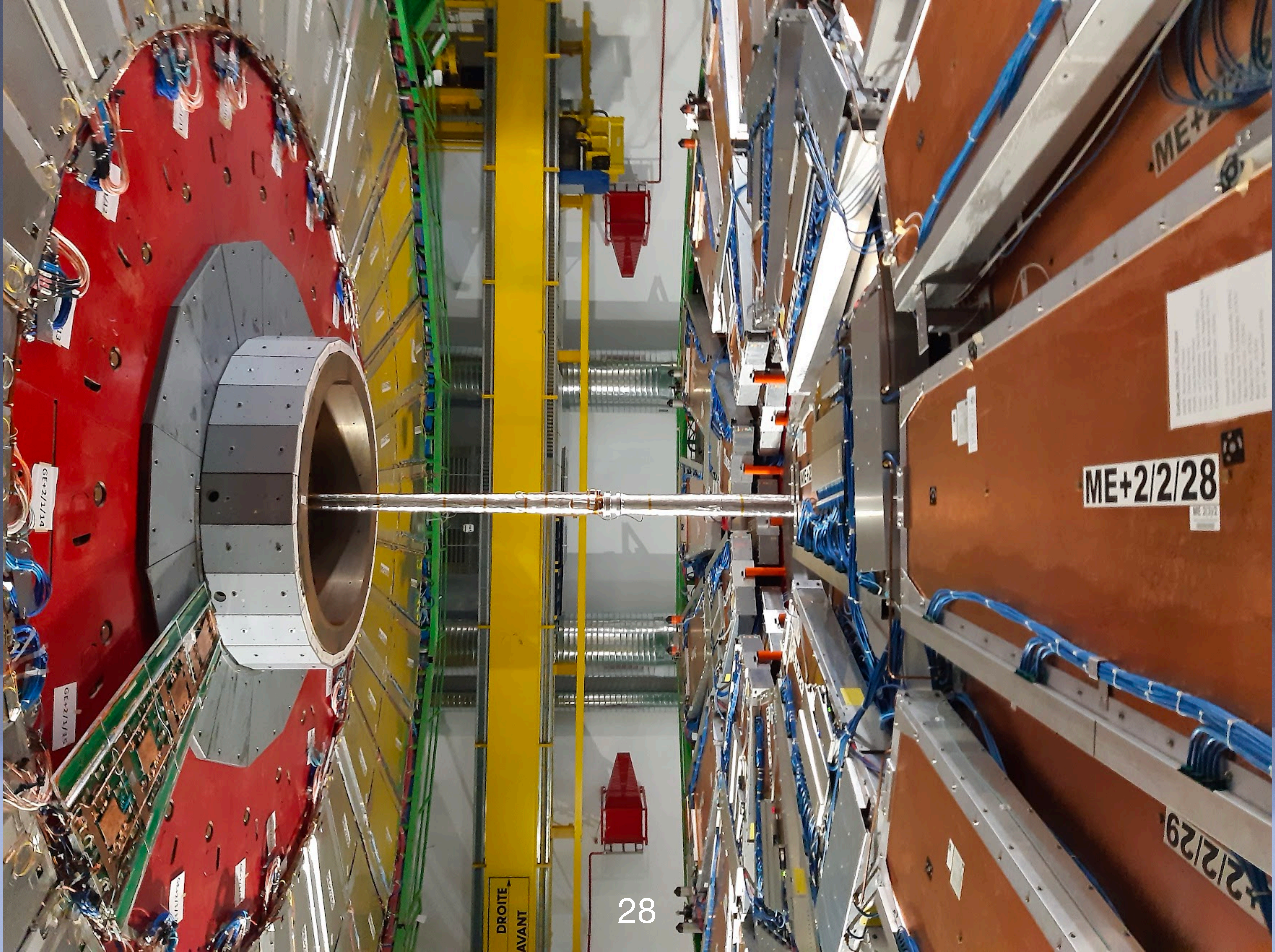
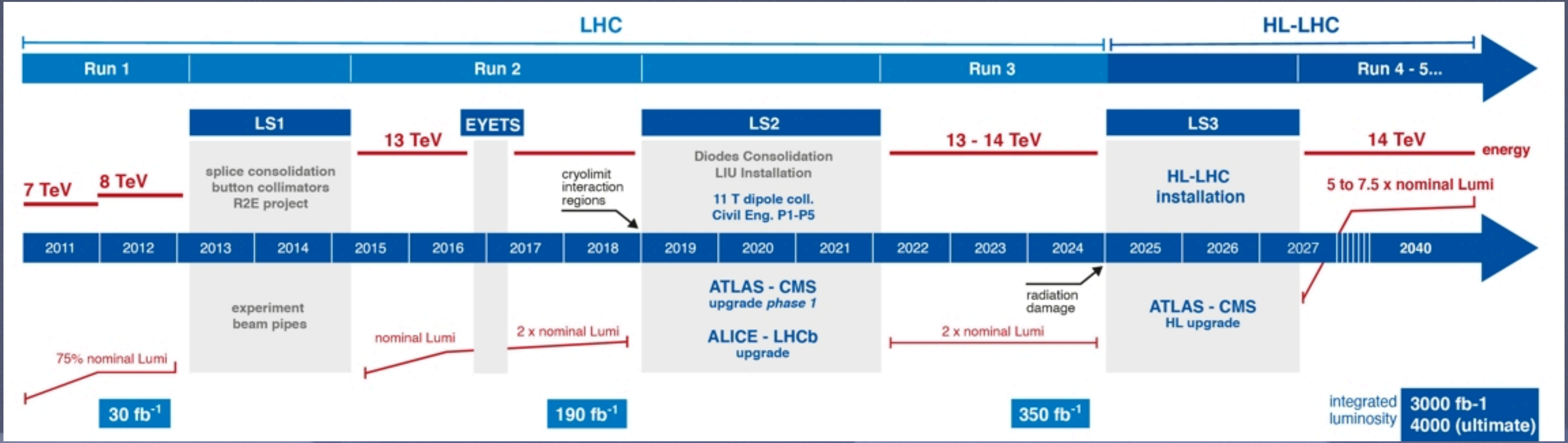
Work in Progress: Expectated Exclusions




ME+2/2/28
DROITE
AVANT

HL-LHC Timeline at a Glace



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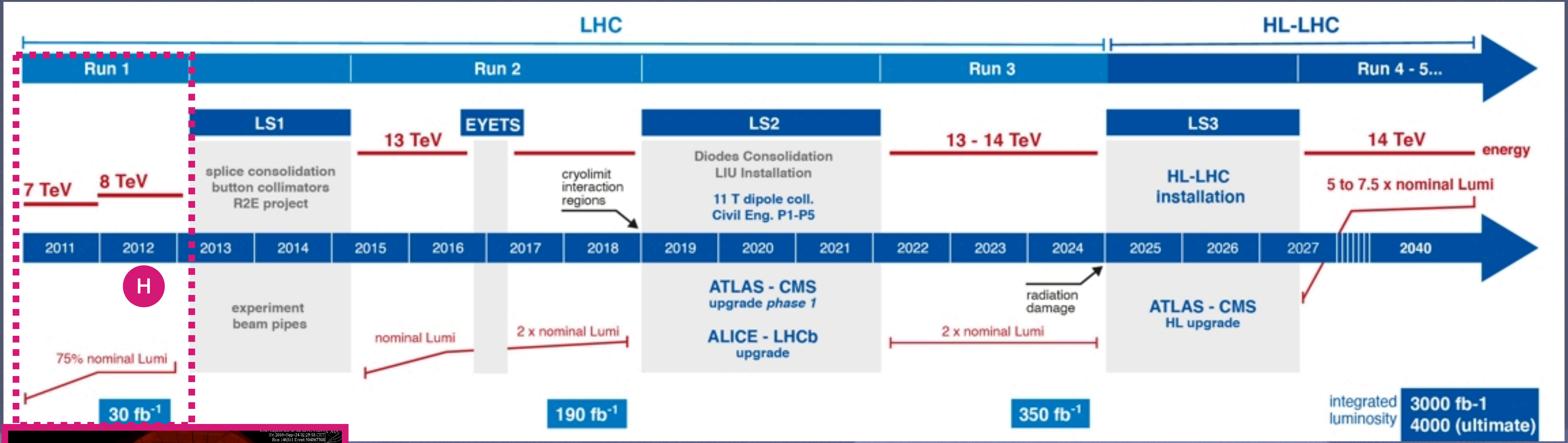
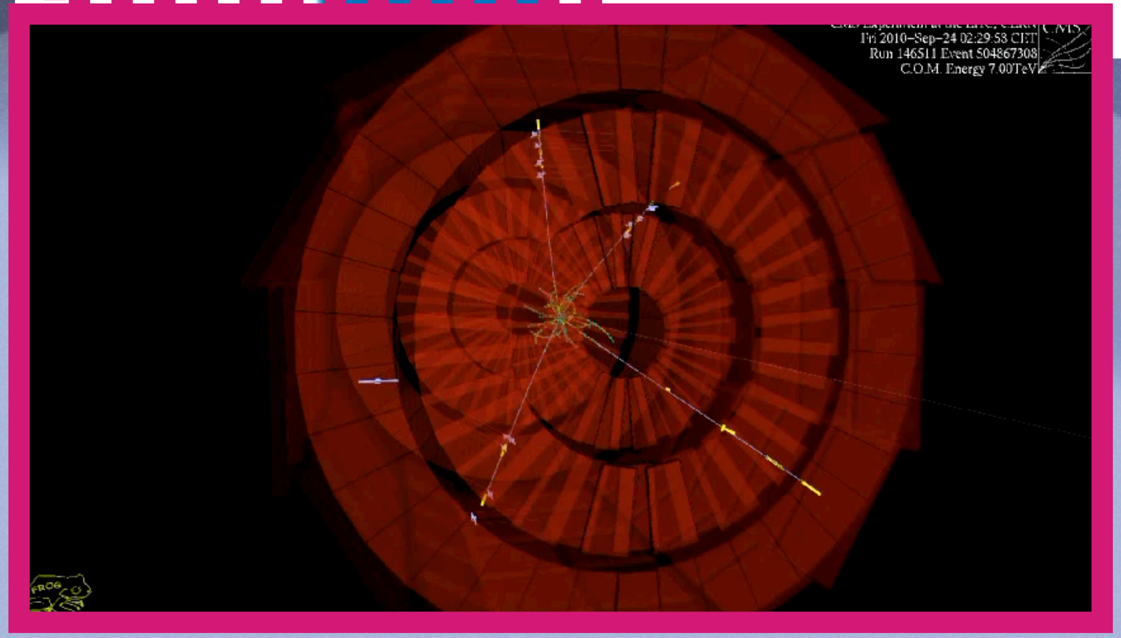
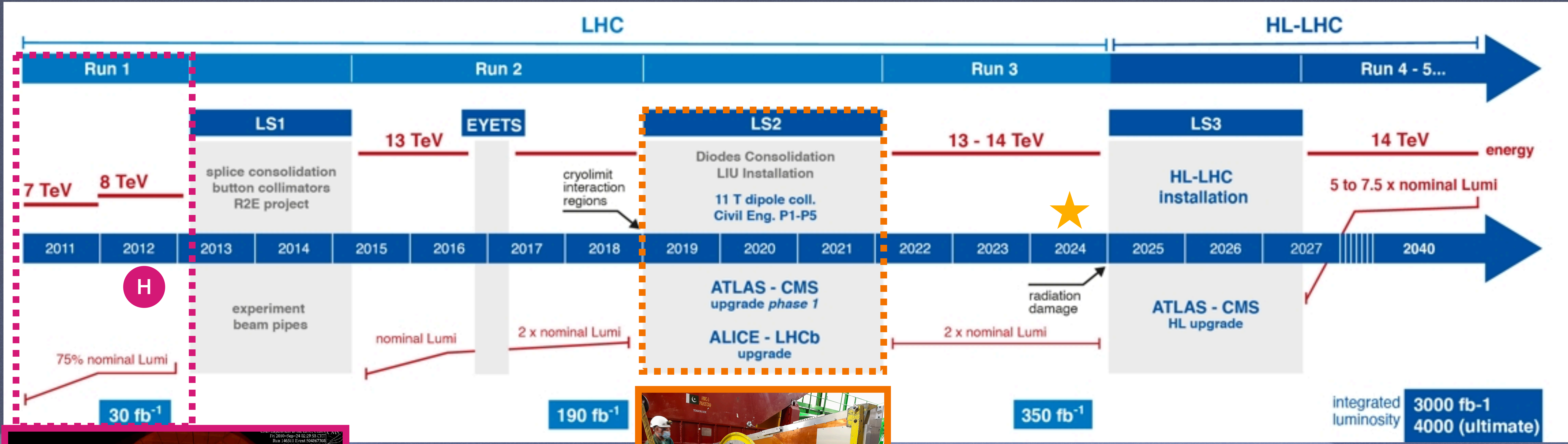
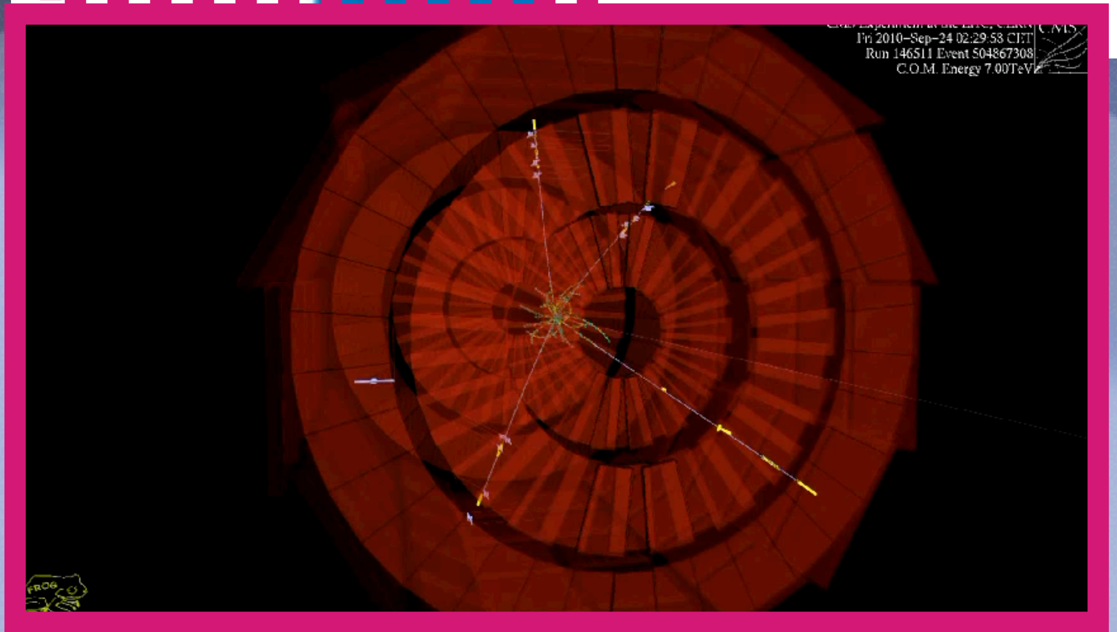




H = Jul 2012

HL-LHC Timeline at a Glace





H = Jul 2012

★ = June 2024

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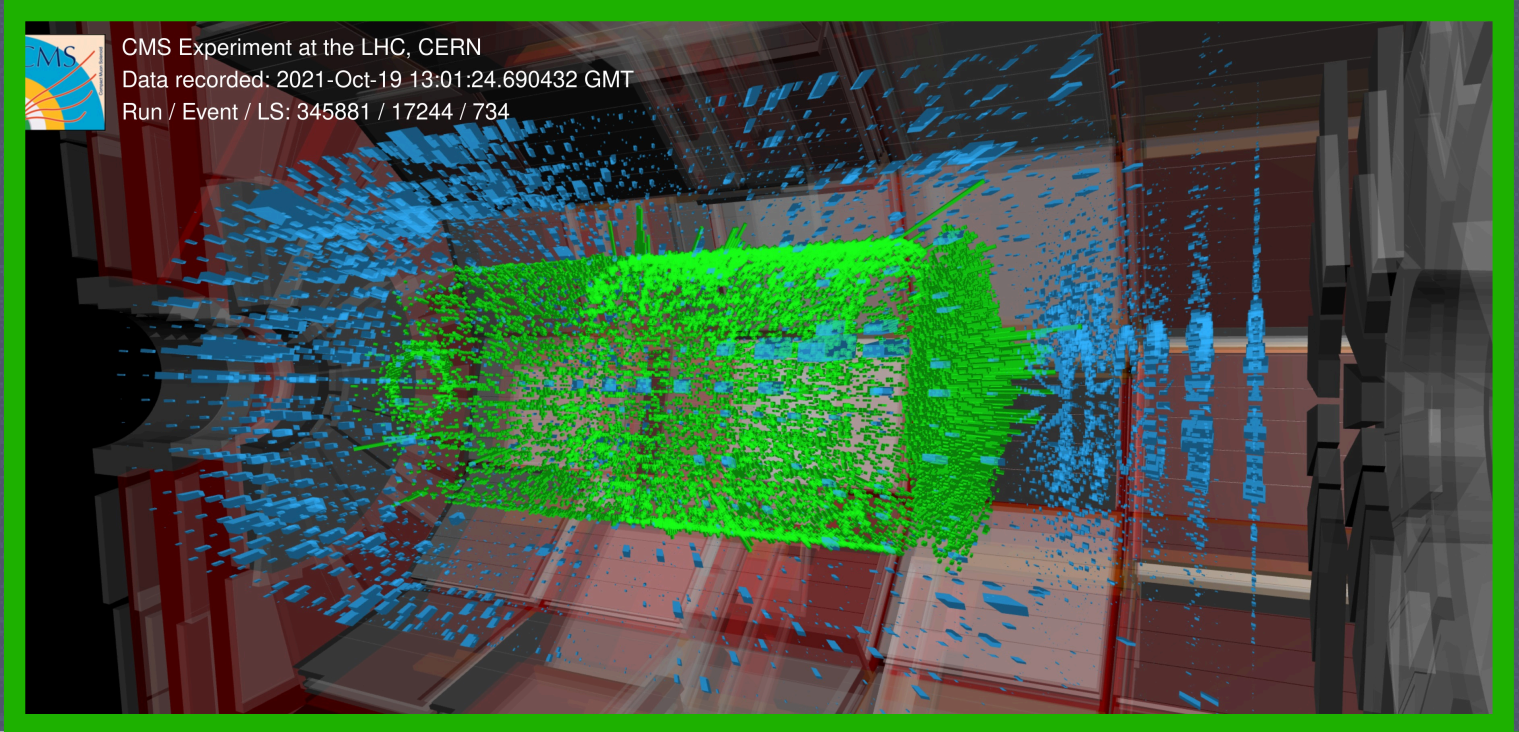

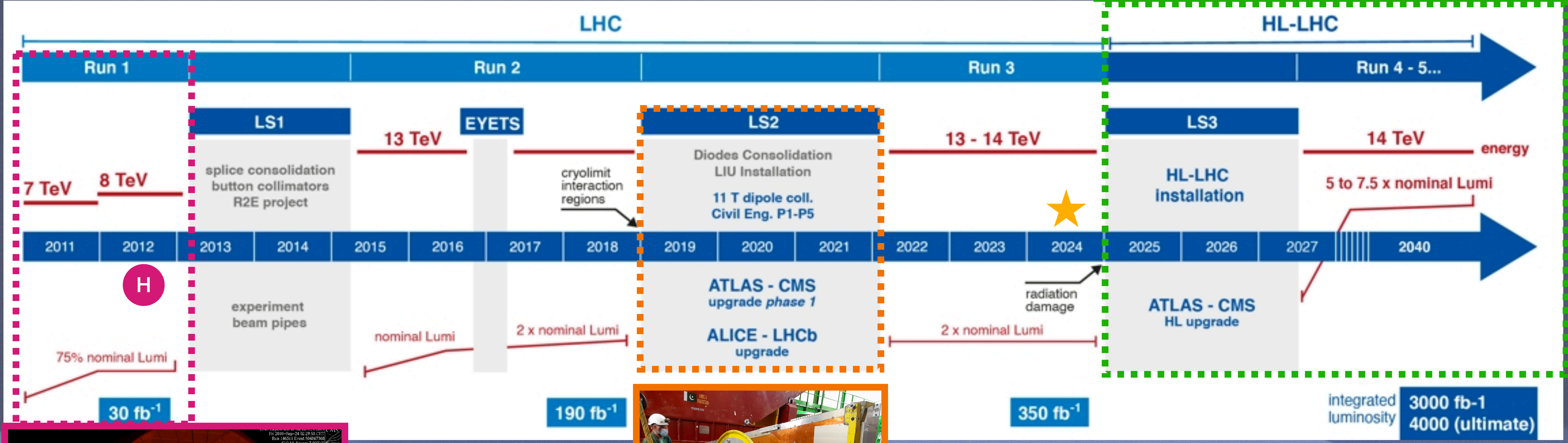

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What Are Cathode Strip Chambers (CSCs)?

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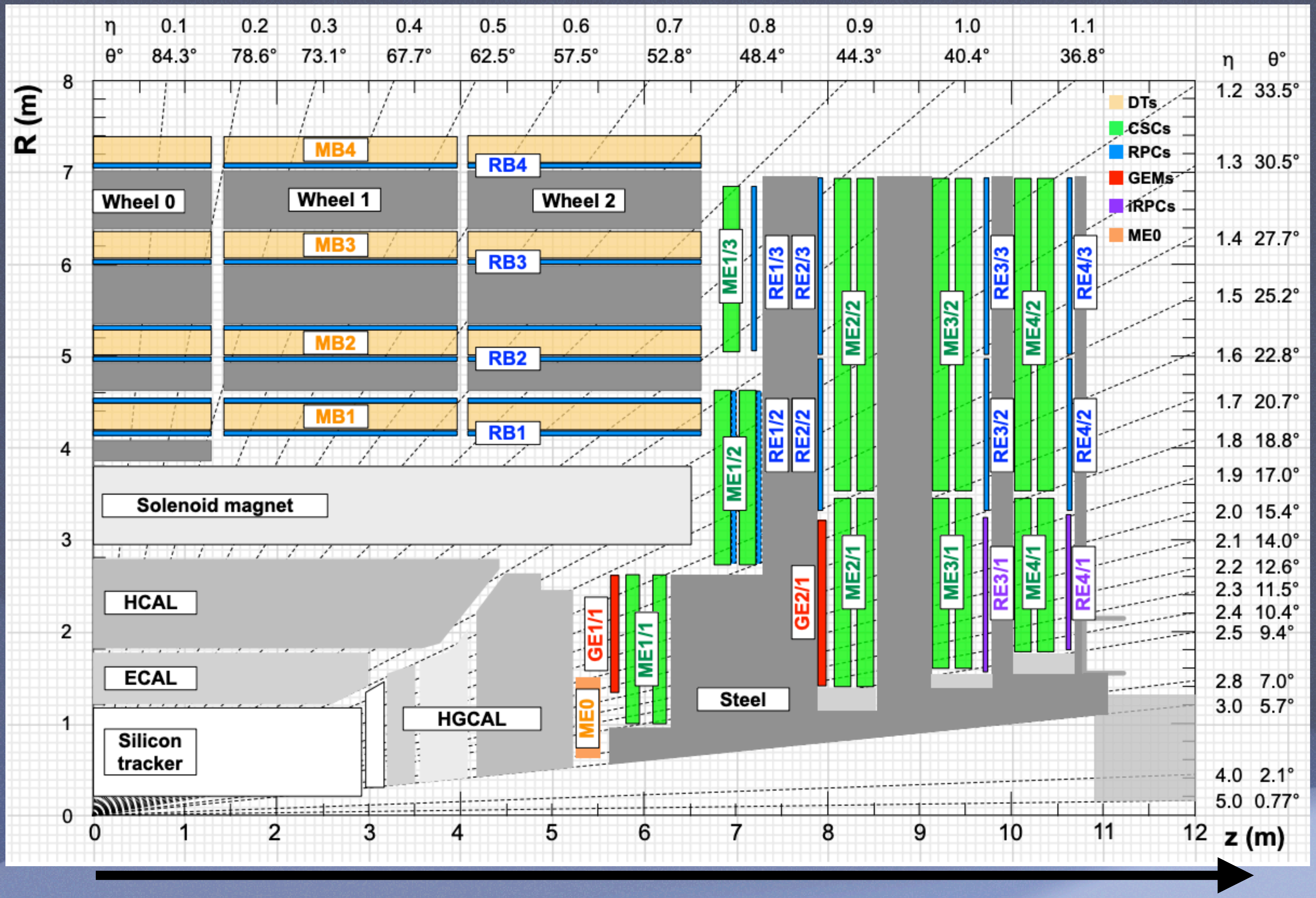
- Muon system employs different technologies
  - Barrel: Drift Tube + Resistive Plate Chamber (RPC)
  - End-Caps: CSC + RPC + Gas Electron Multipliers (GEM)



CMS-TDR-016

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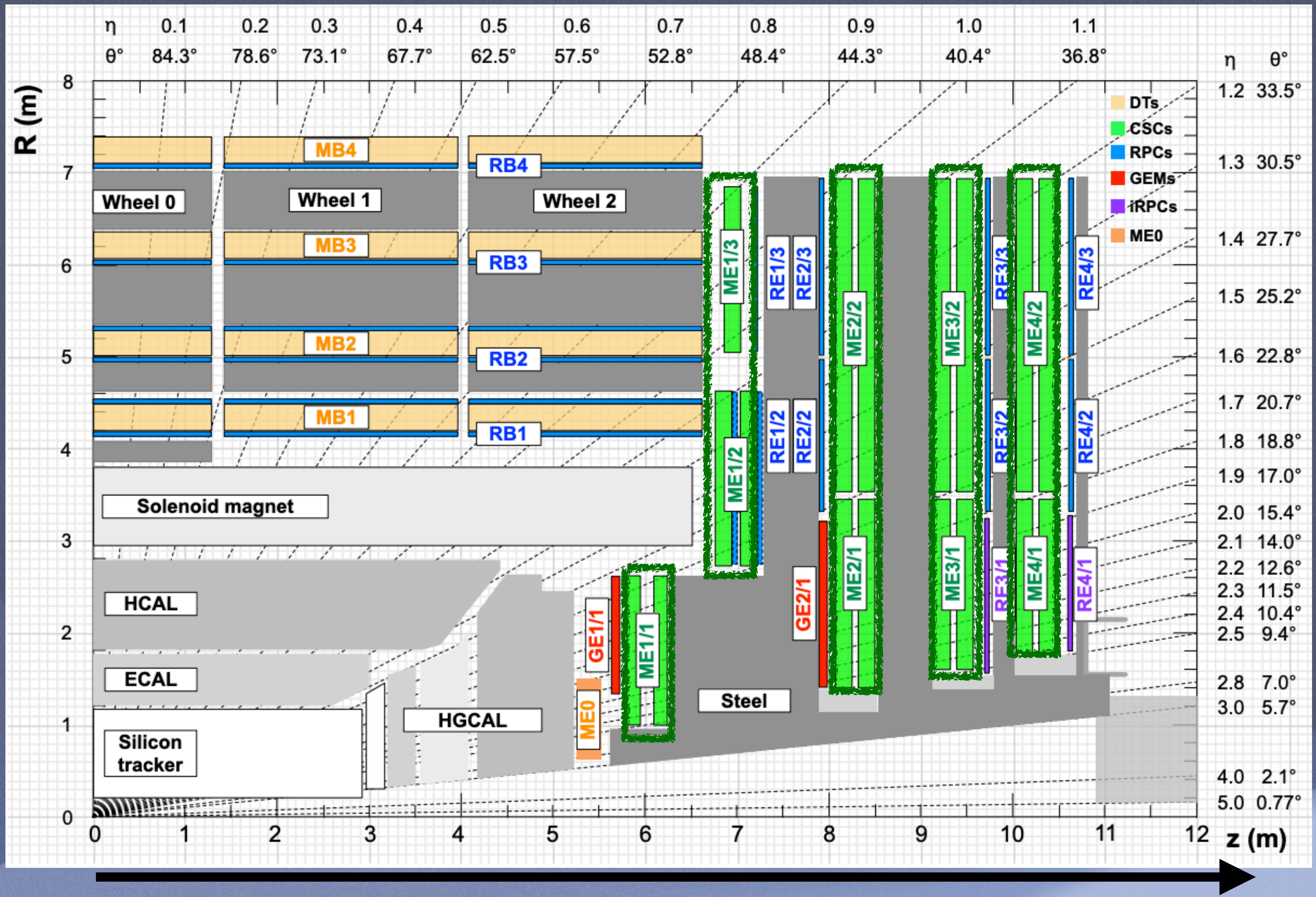

CMS-TDR-016

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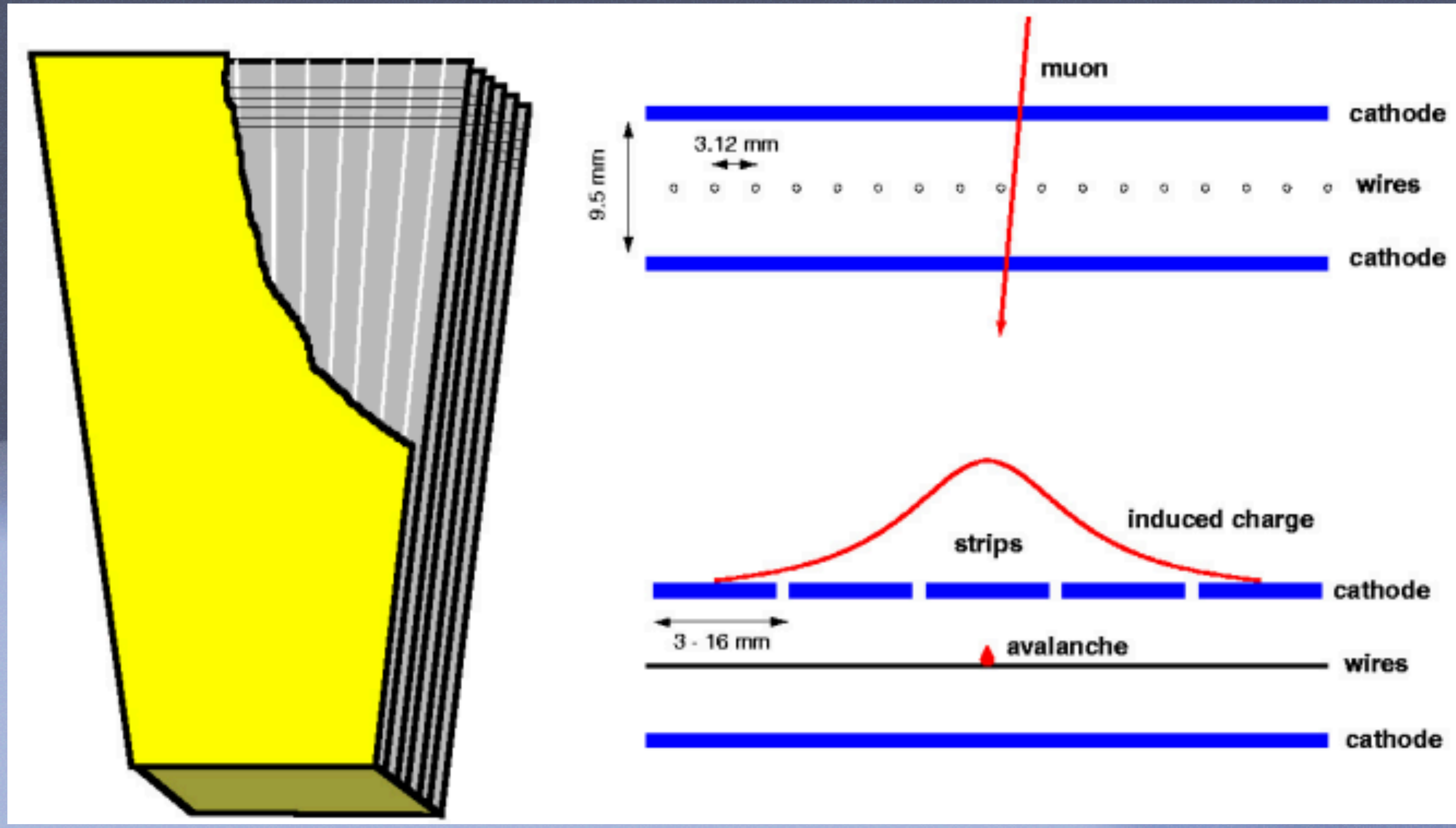
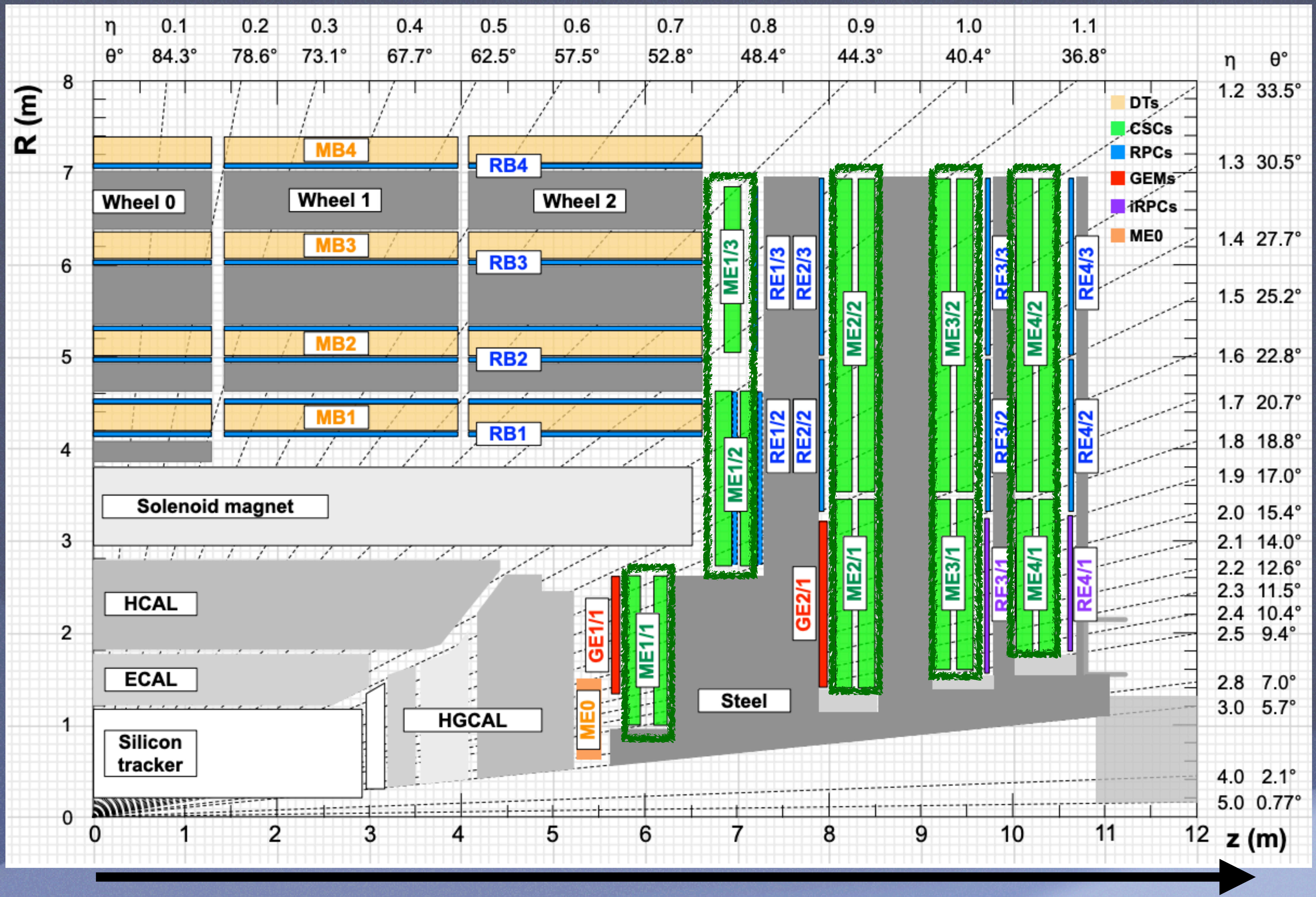
  - End-Caps: CSC + RPC + Gas Electron Multipliers (GEM)
- CSCs are 6-layers of wires (anodes) and strips (cathodes) in $Ar/CO_2/CF_4$ gas mixture
  - Traversing muons ionize gas at HV
  - Avalanche signal read by anode and cathode electronics





[CMS-TDR-016]

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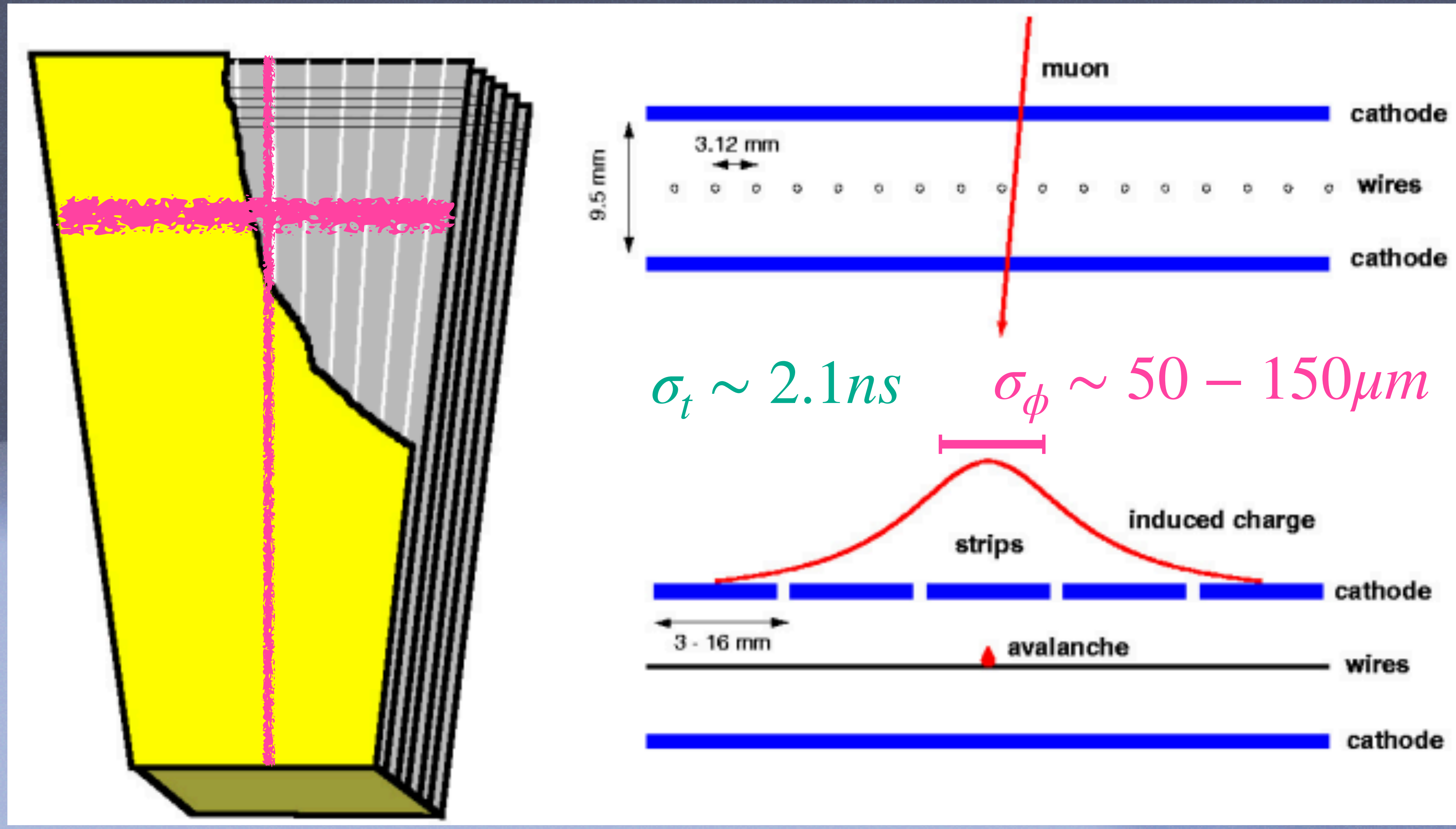
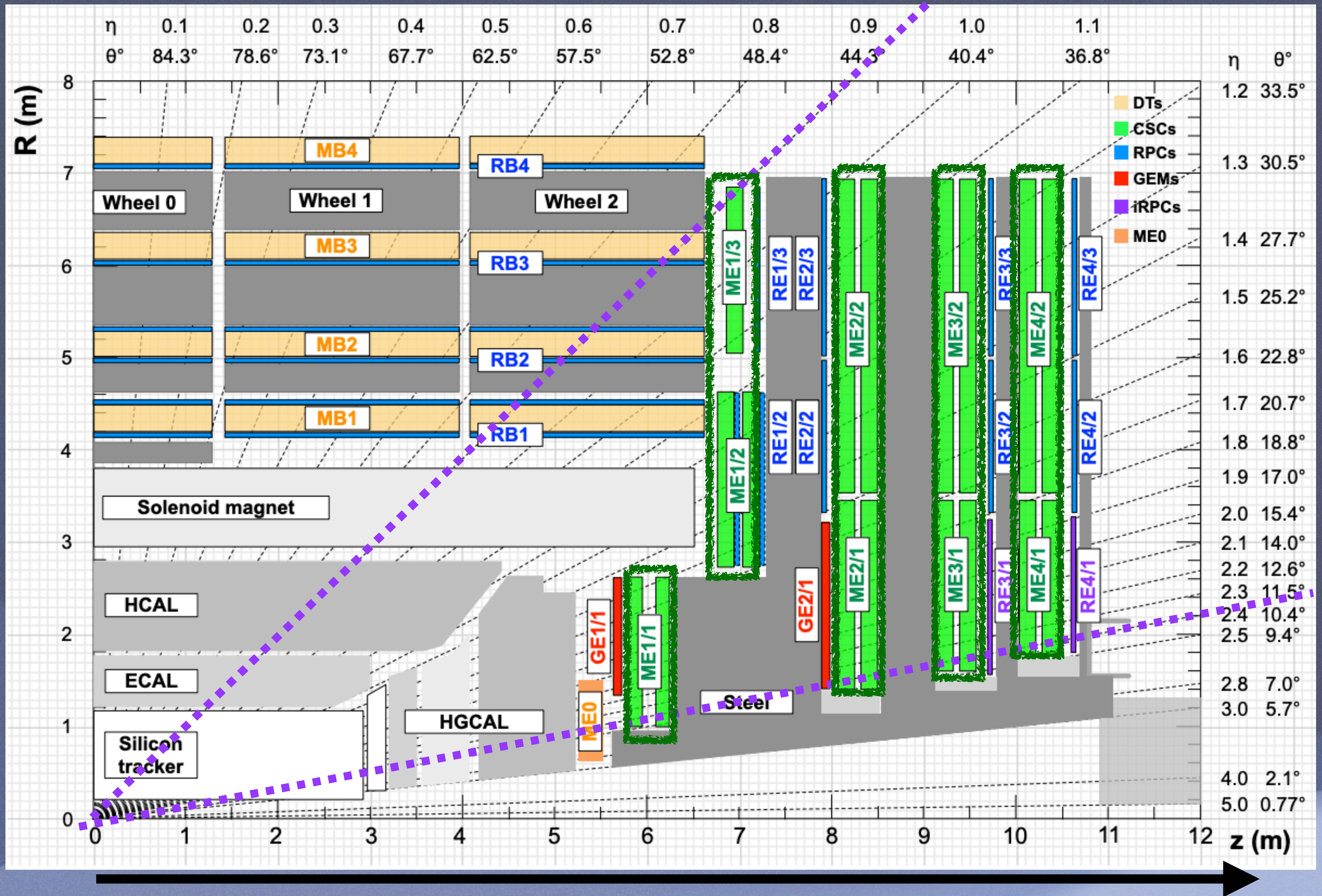
  - Traversing muons ionize gas at HV
  - Avalanche signal read by anode and cathode electronics
- CSCs measure <u>4D</u> position, $|\eta| \in [0.9, 2.4]$
  - Work great in intense, non-uniform magnetic fields





CMS-TDR-016

On-Detector Refurbishment of Electronics

ALCT Mezzanines and DCFEBs

On-Detector Refurbishment of Electronics

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- 108 ALCT-LX150T Mezzanine boards installed in all ME234/1
- 288 ALCT-LX100T Mezzanine boards installed in ME1/1,123/2

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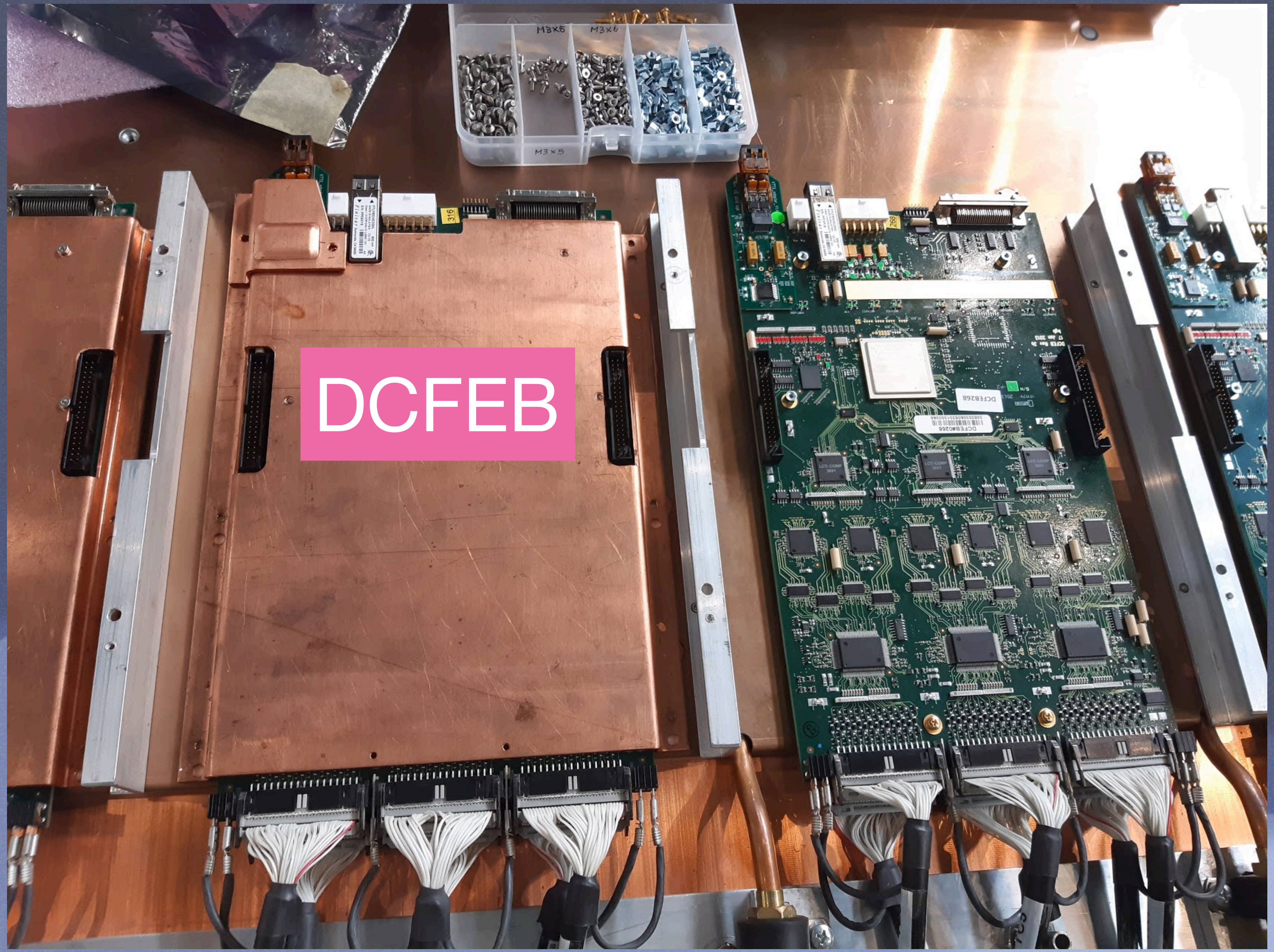
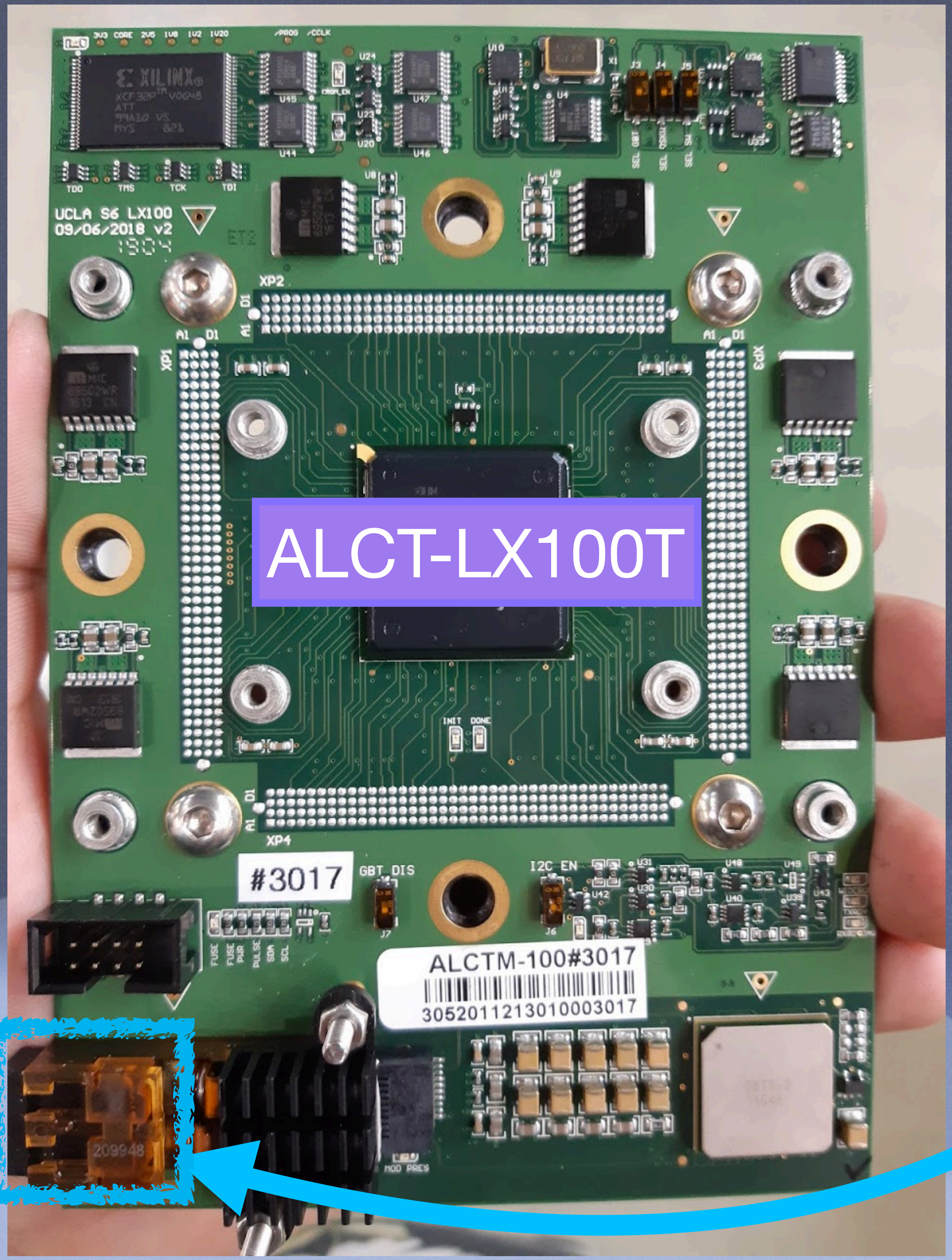
- 108 ALCT-LX150T Mezzanine boards installed in all ME234/1
- 288 ALCT-LX100T Mezzanine boards installed in ME1/1,123/2
- 504 DCFEBv2 installed in ME1/1 and 45 in ME+2/1, older DCFEB from ME1/1 → ME234/1



On-Detector Refurbishment of Electronics

ALCT Mezzanines and DCFEBs



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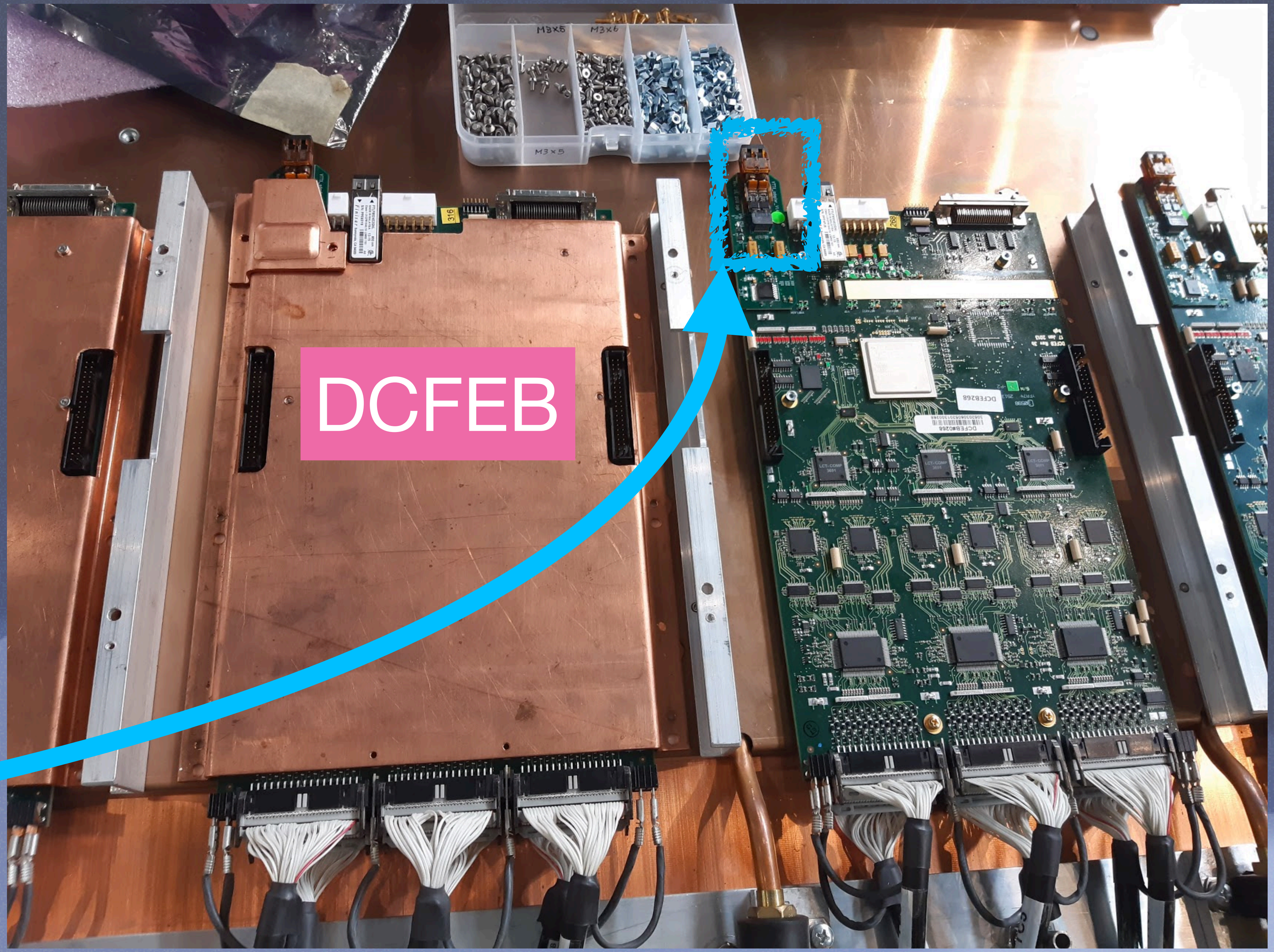
- 504 DCFEBv2 installed in ME1/1 and 45 in ME+2/1, older DCFEB from ME1/1 → ME234/1
- New boards capable of optical readout

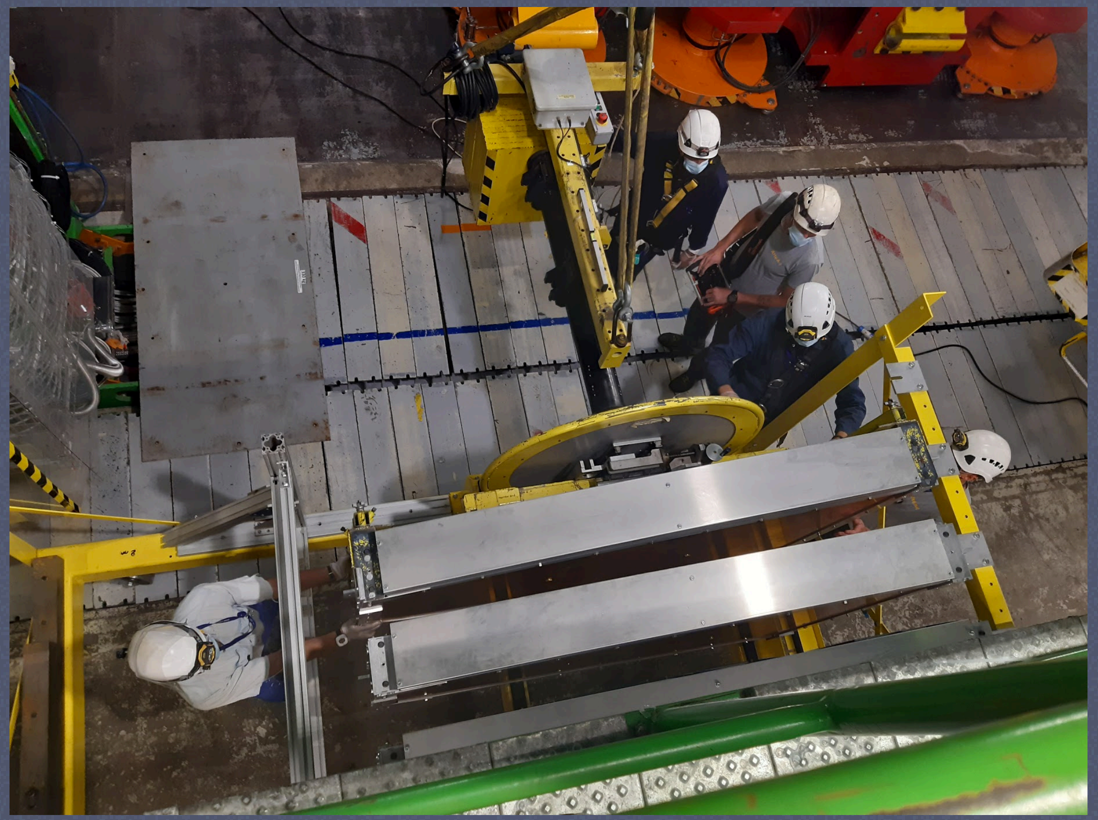


Chamber Re-Installation

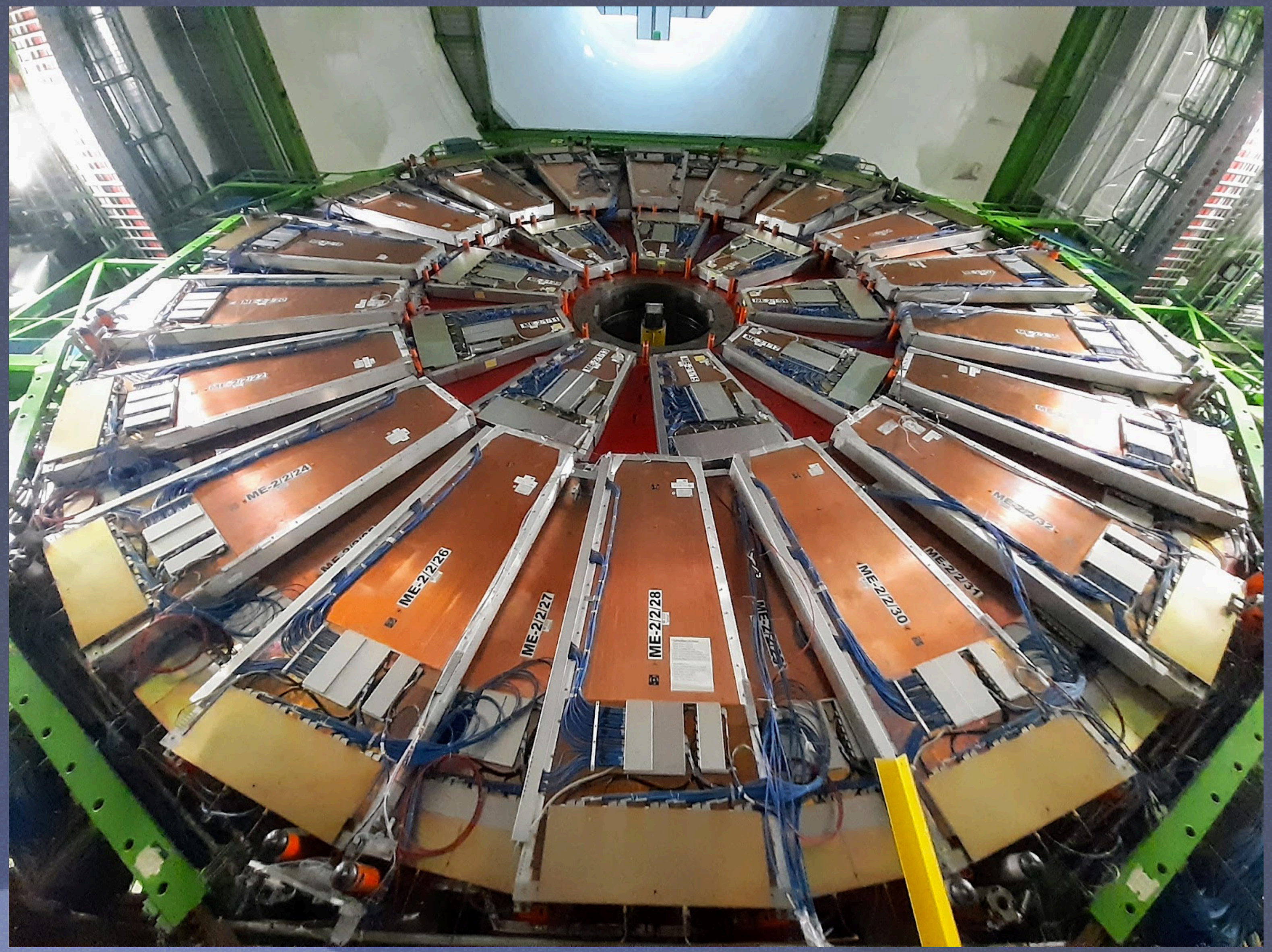
1: Refurbish+Test

2: Transport

3: Load on Fixture



4: Hoist with crane

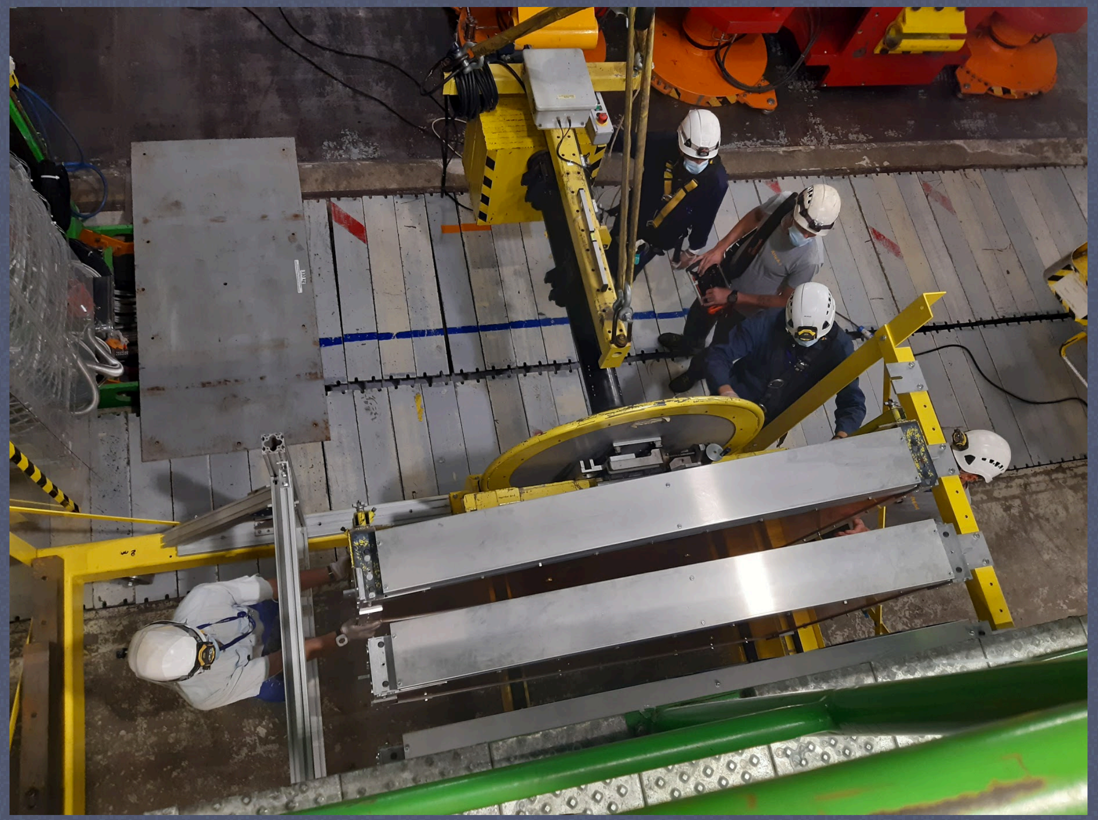


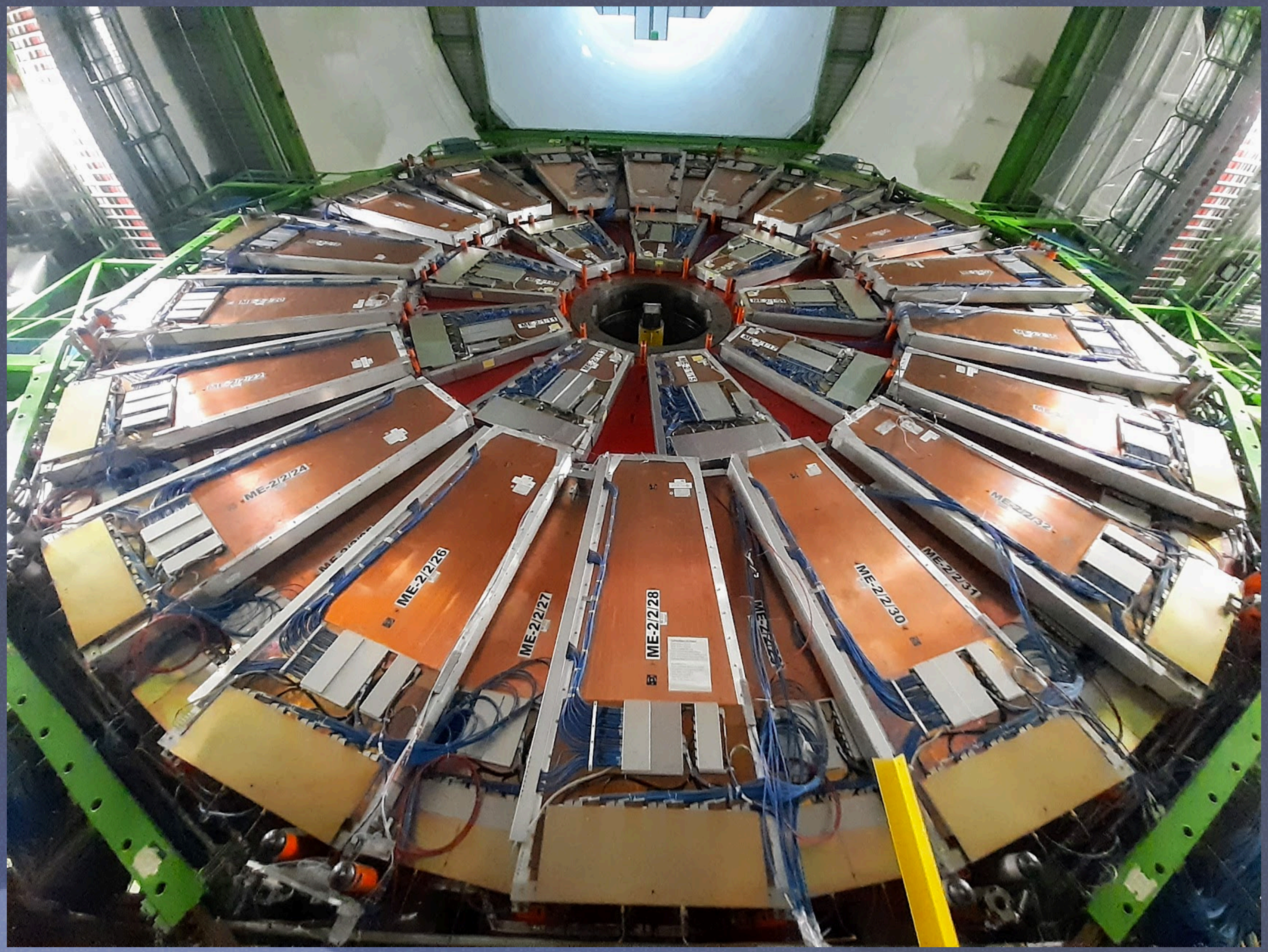
5: Install+Commission on CMS

Chamber Re-Installation

3: Load on Fixture

1: Refurbish+Test





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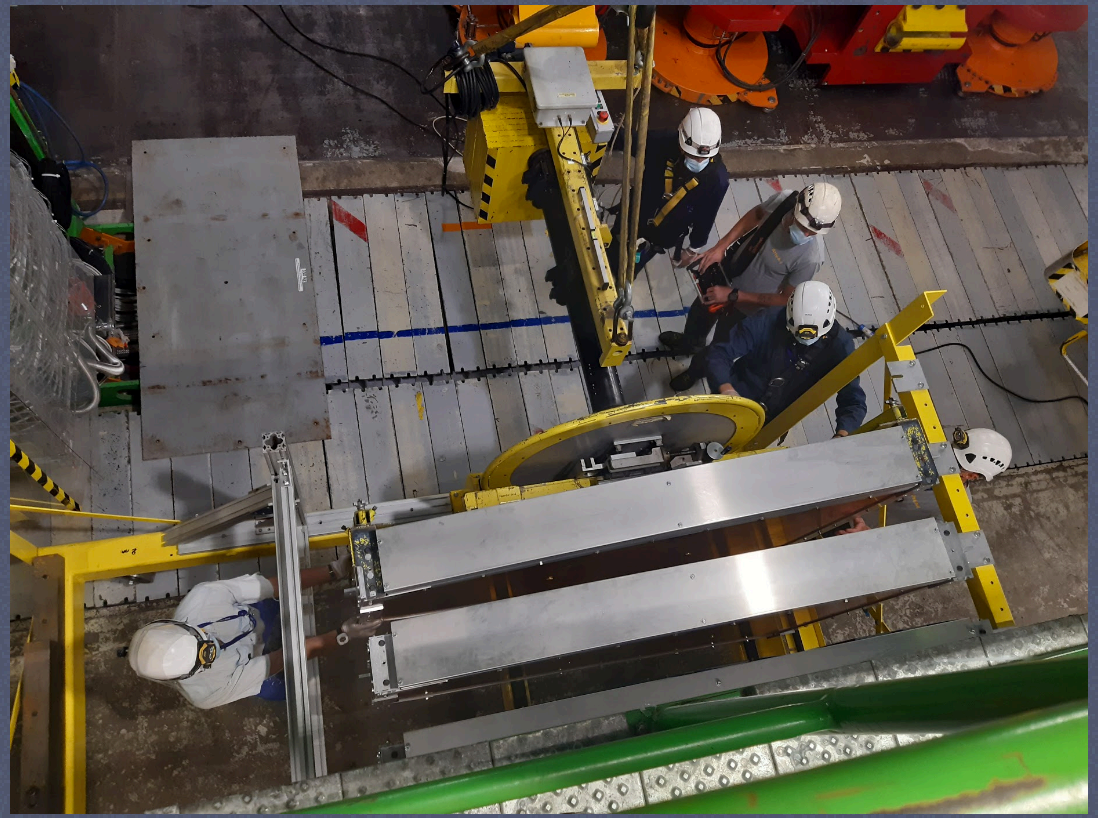

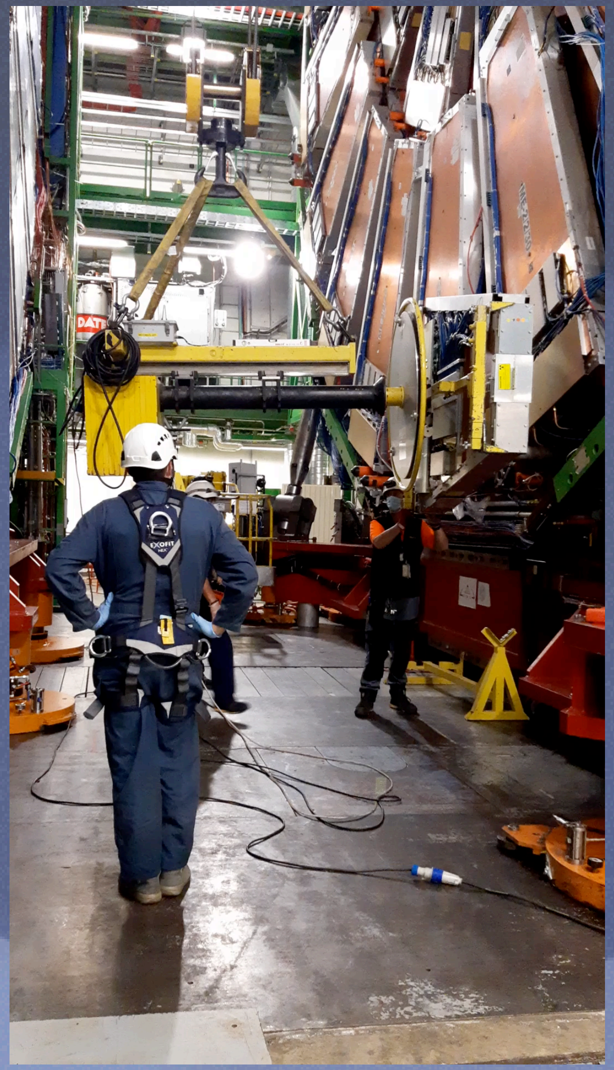
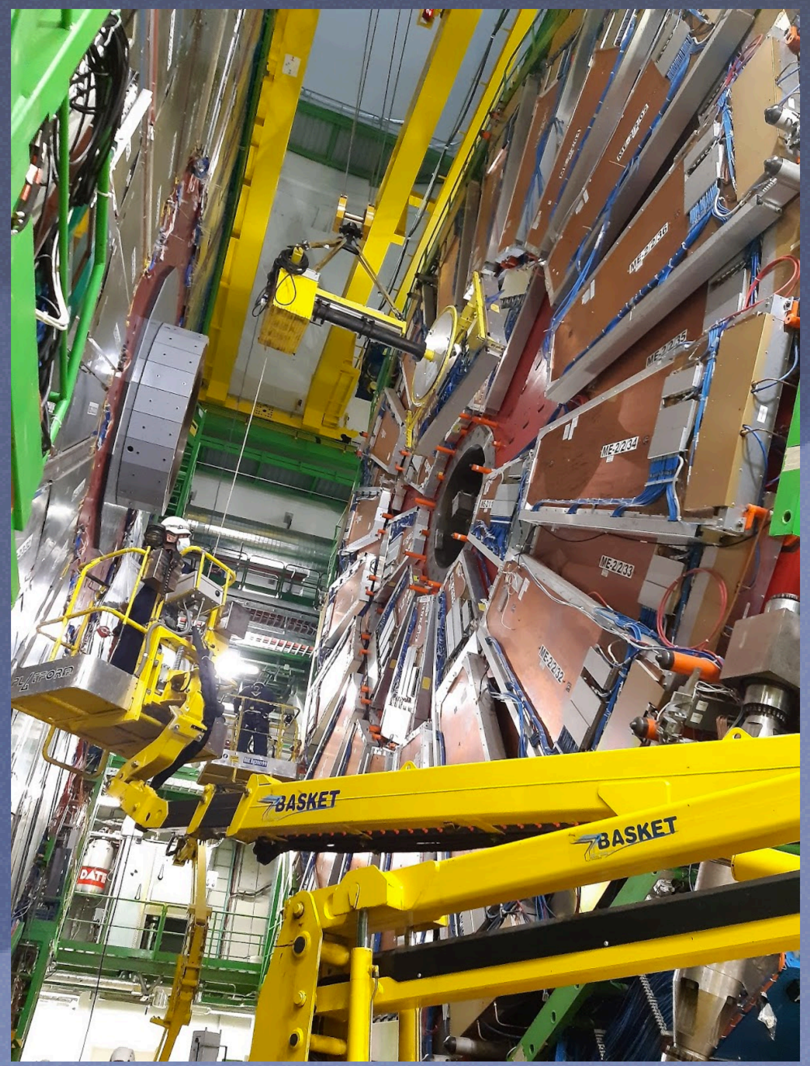

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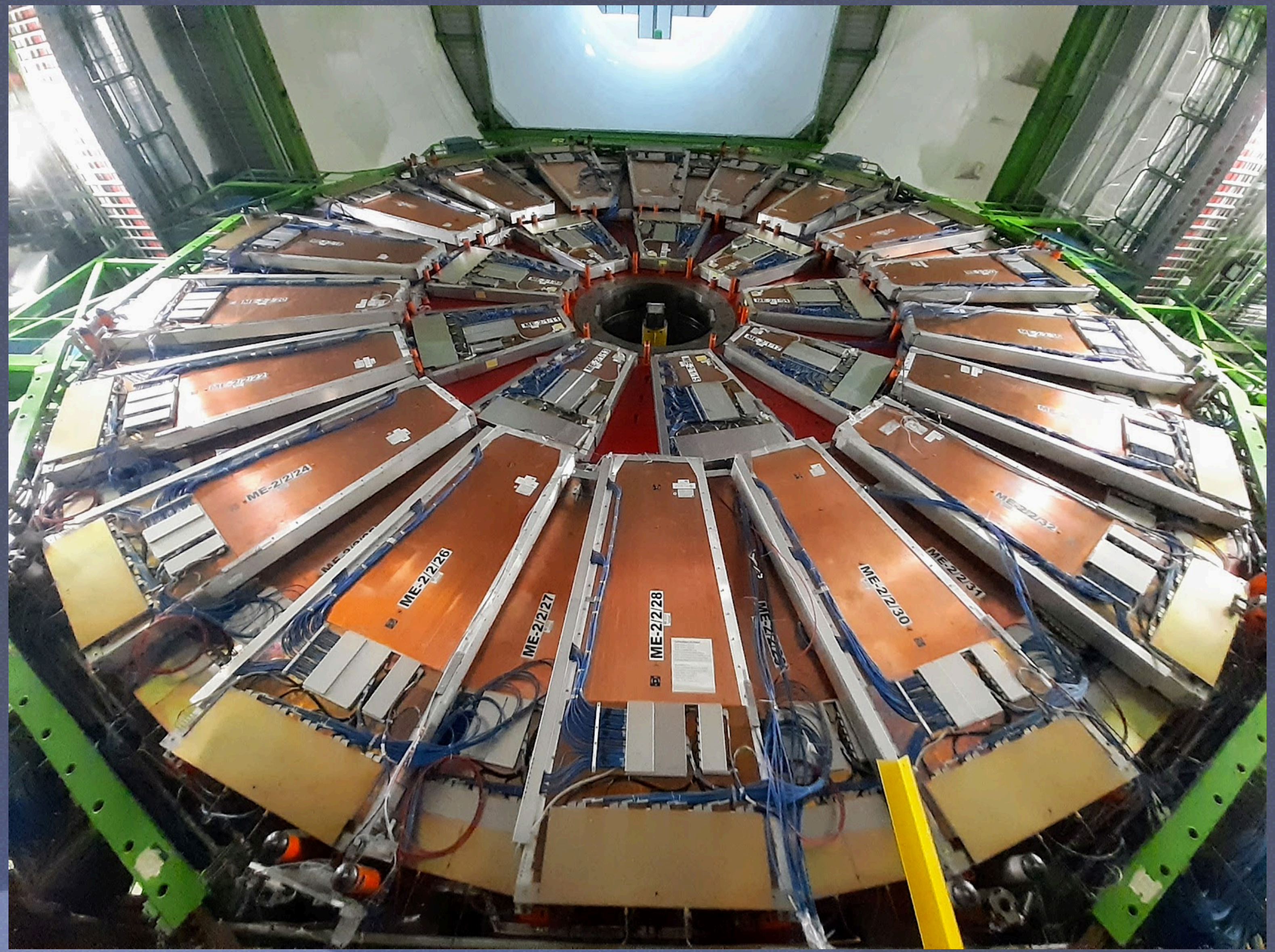
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Chamber Re-Installation

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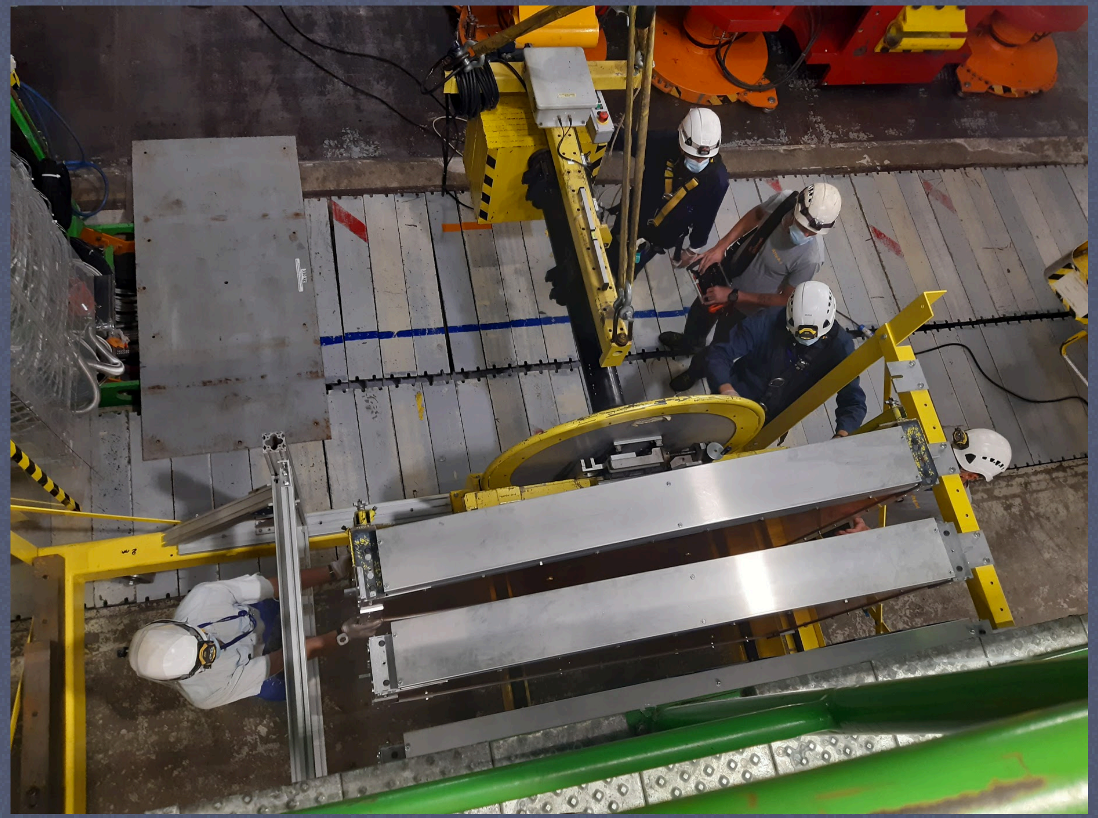

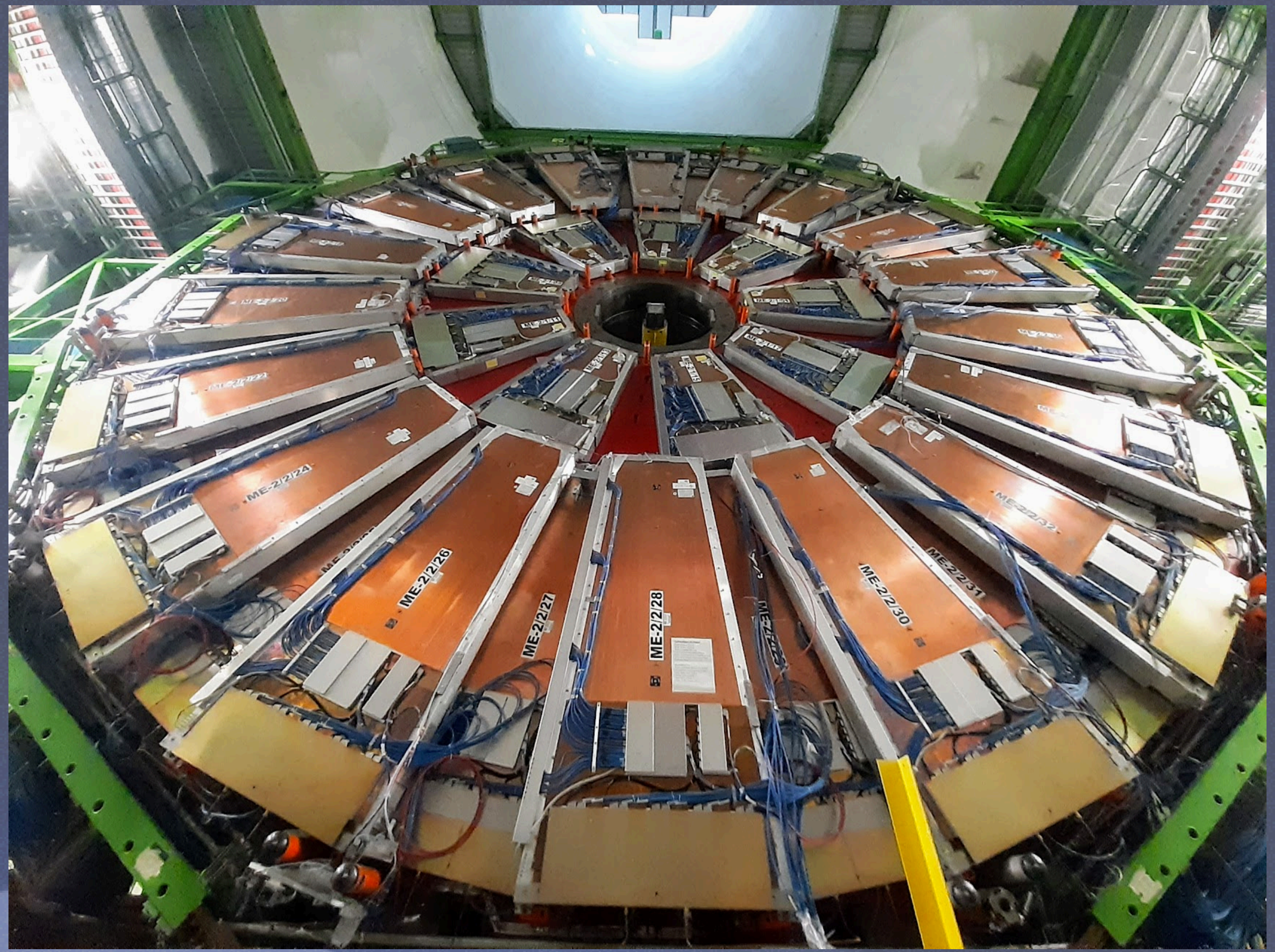

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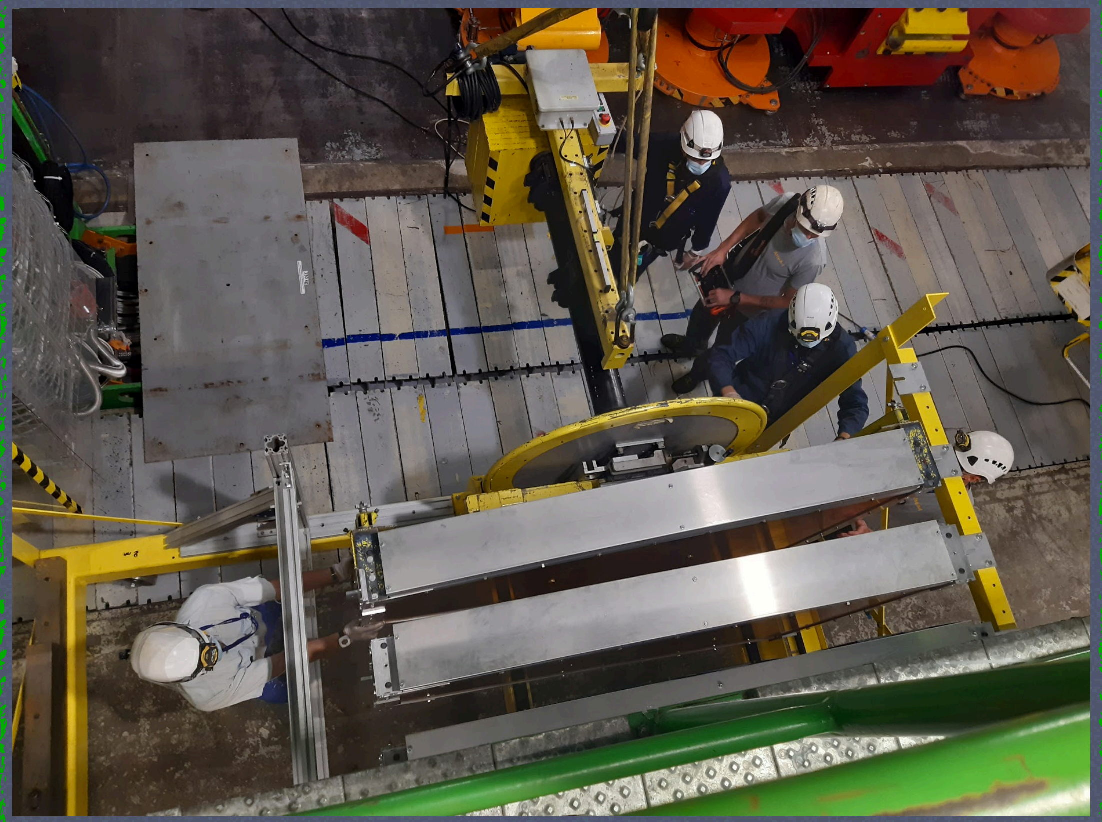

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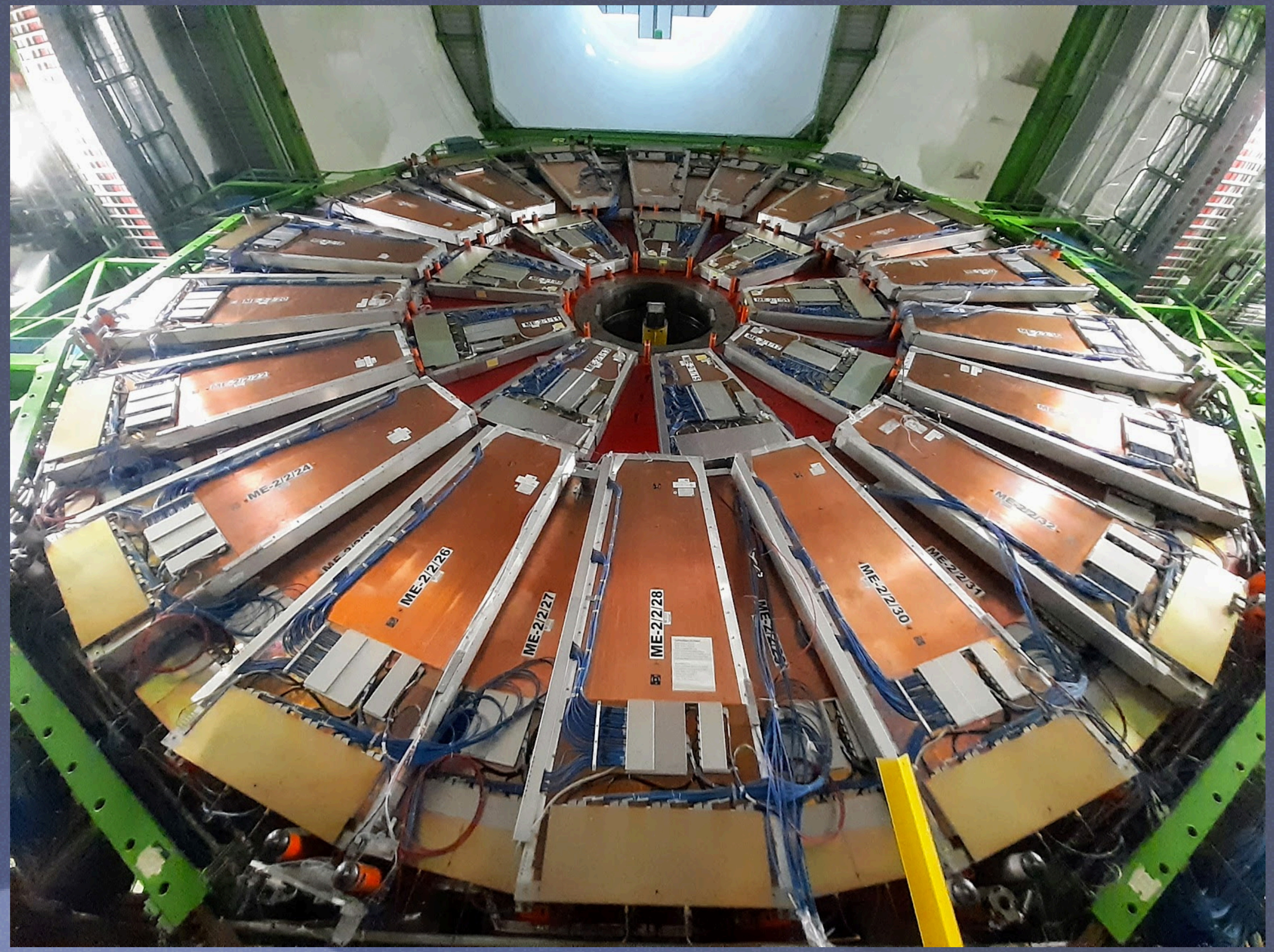

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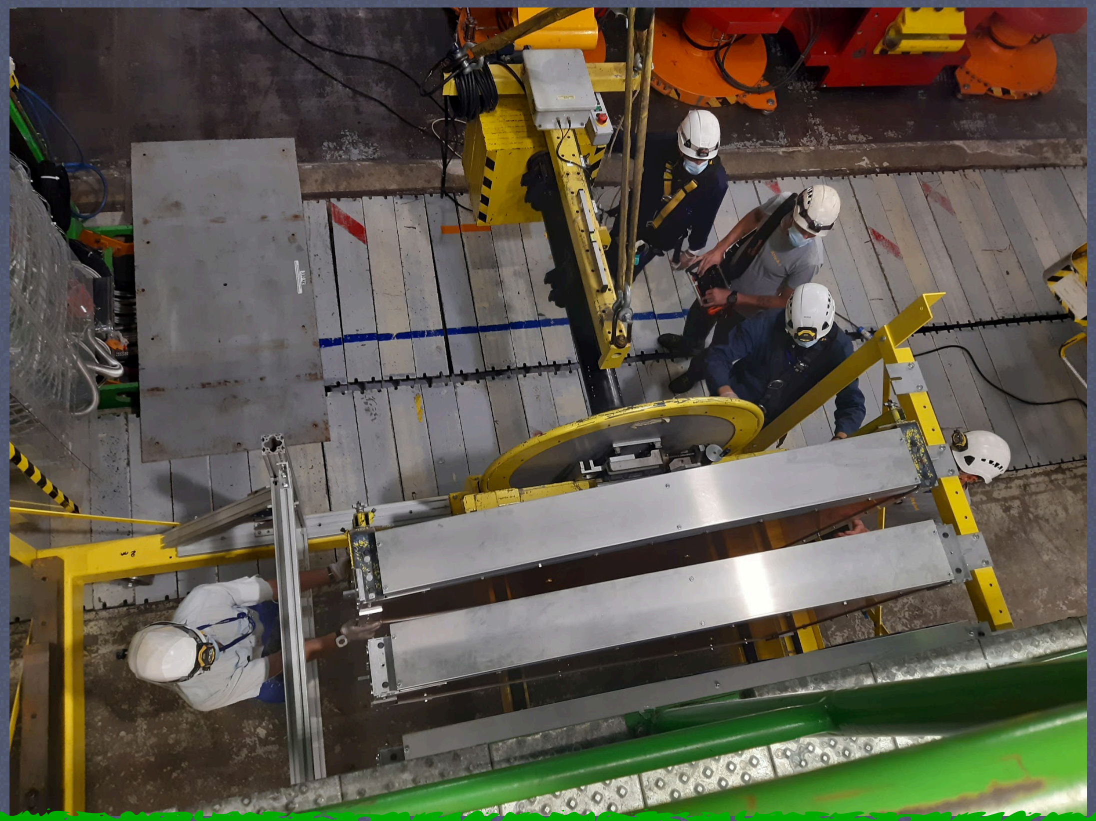

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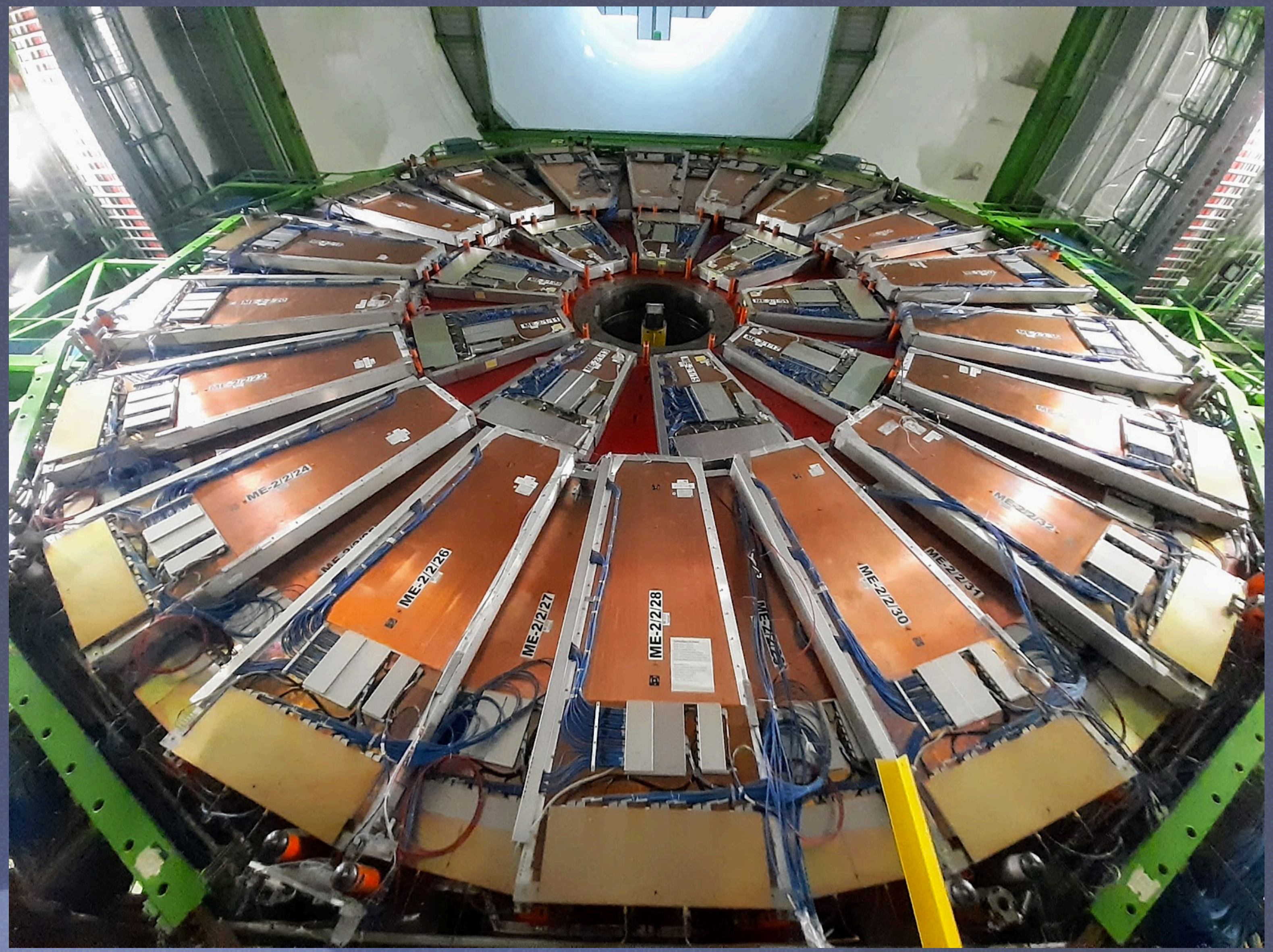

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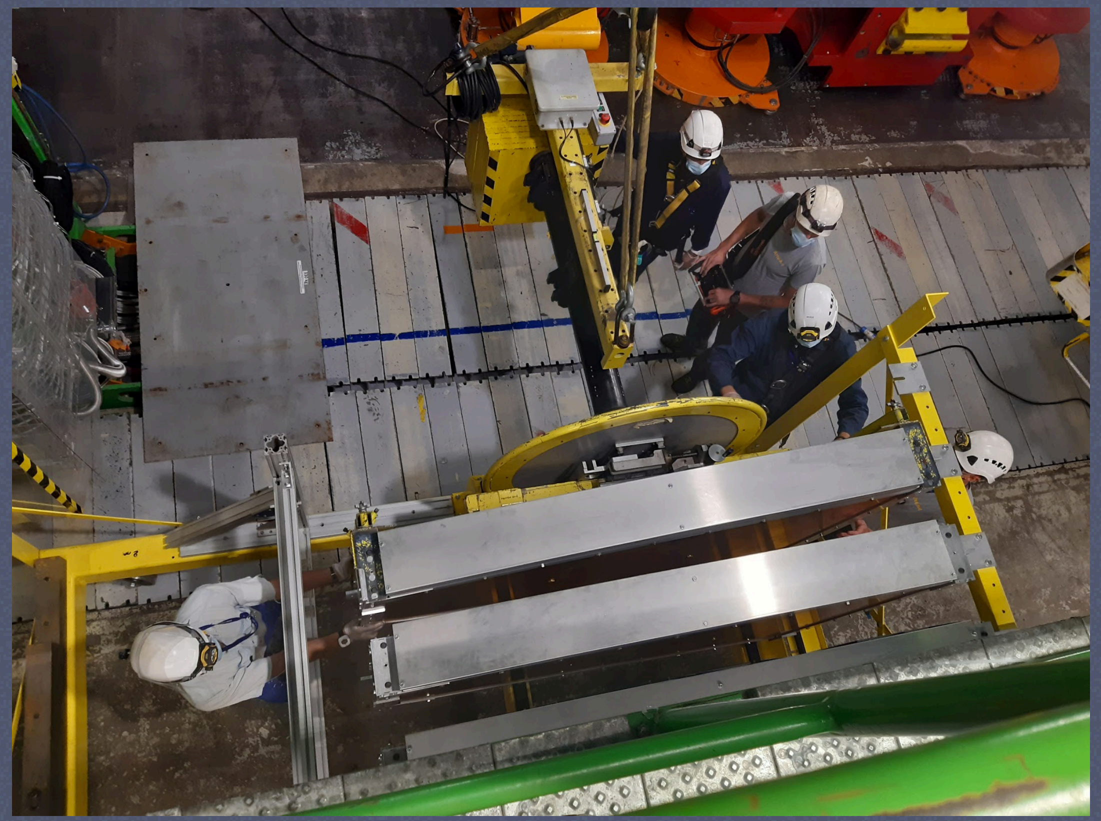

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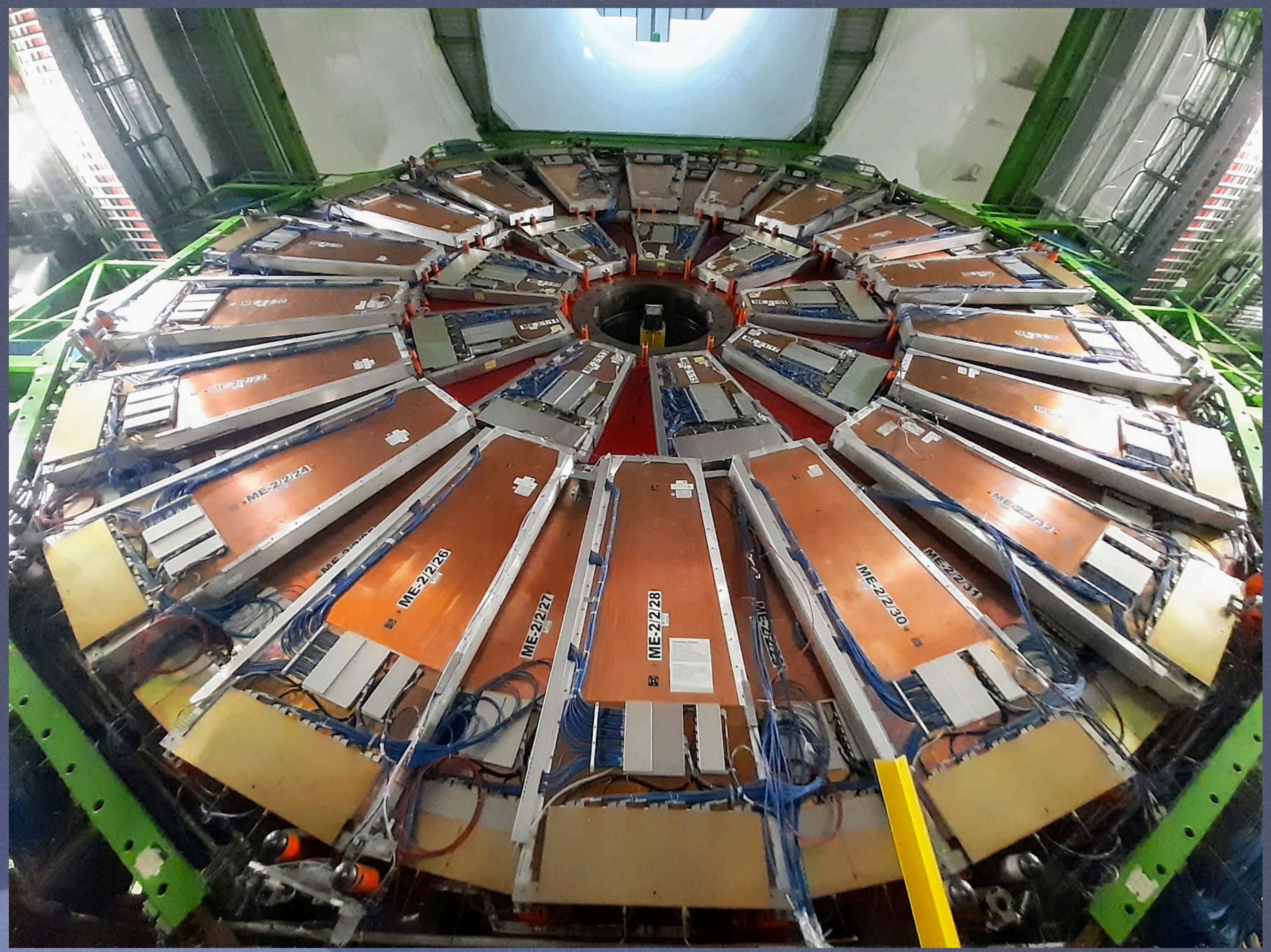

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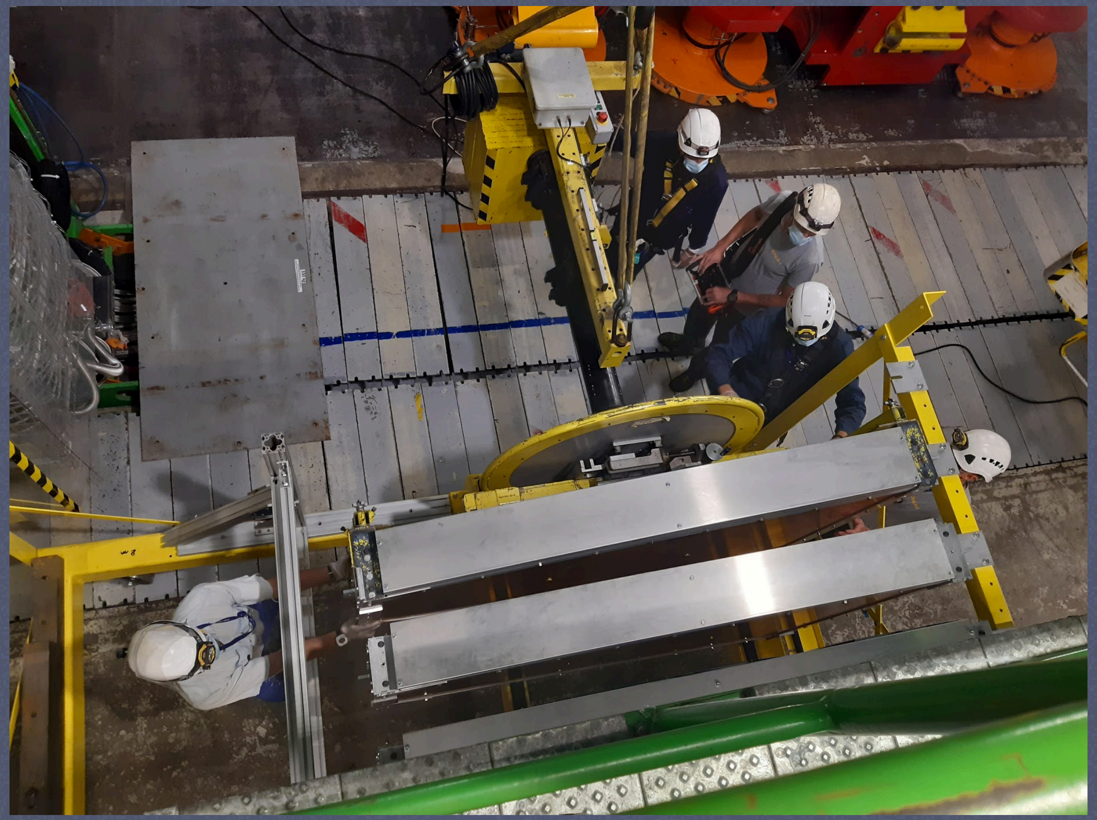

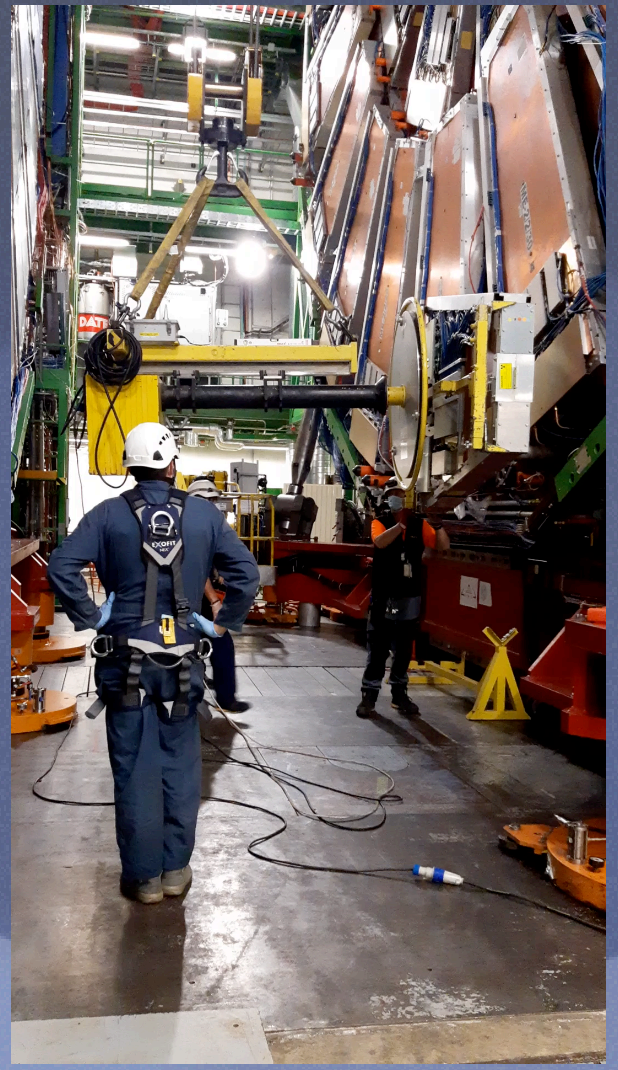

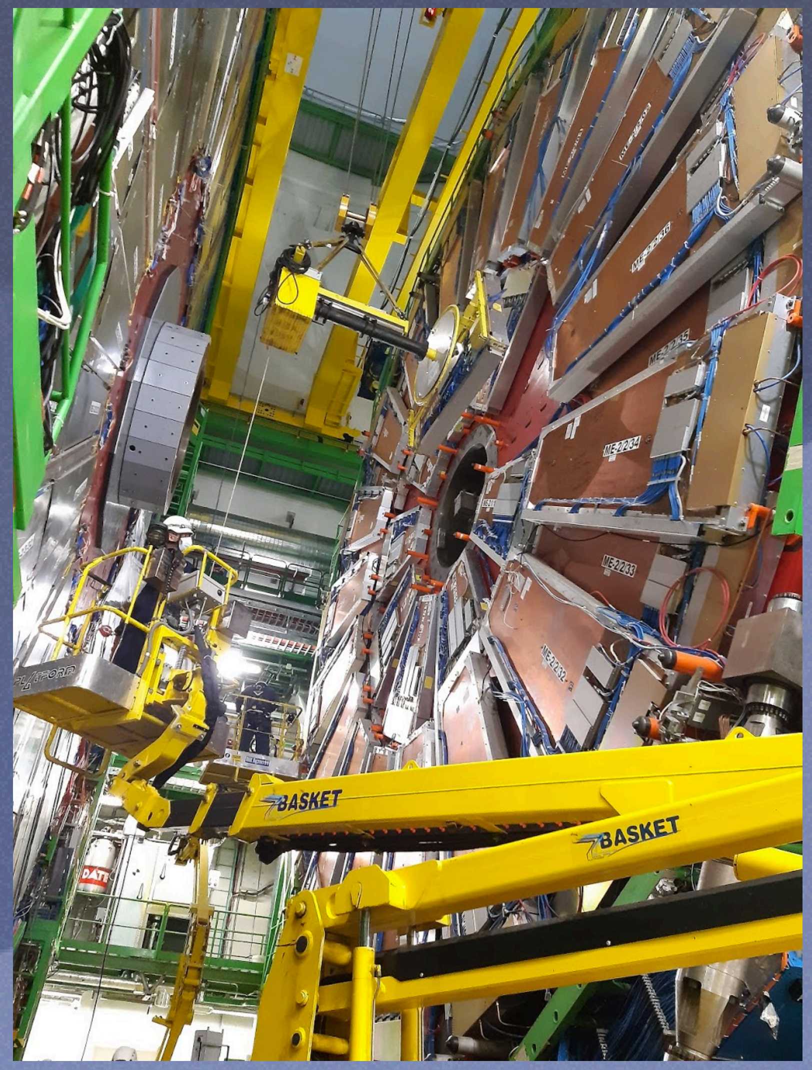

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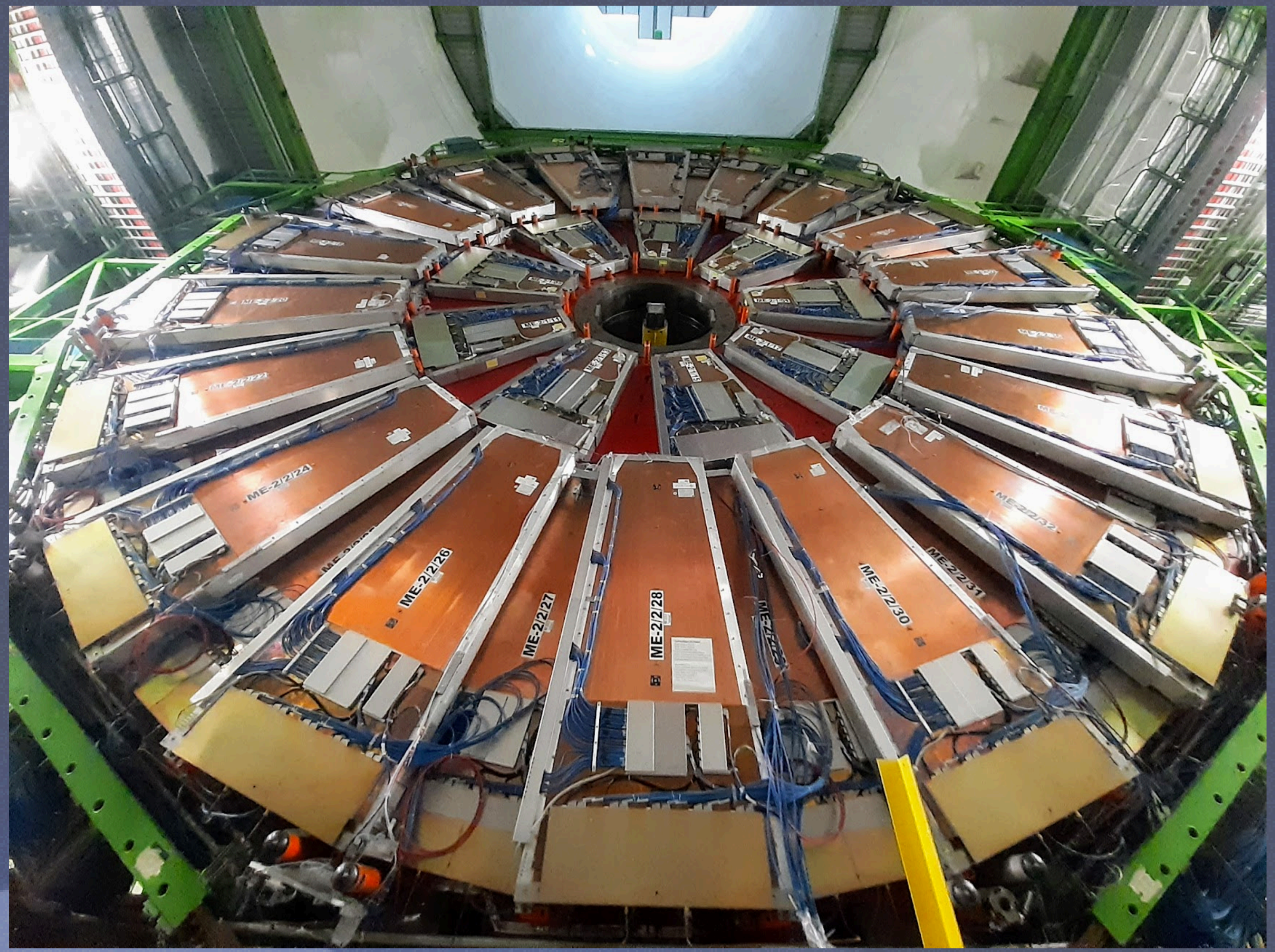


5: Install+Commission on CMS

x180 Chambers!

108 ME234/1
x72 ME1/1

Link to Artist Website

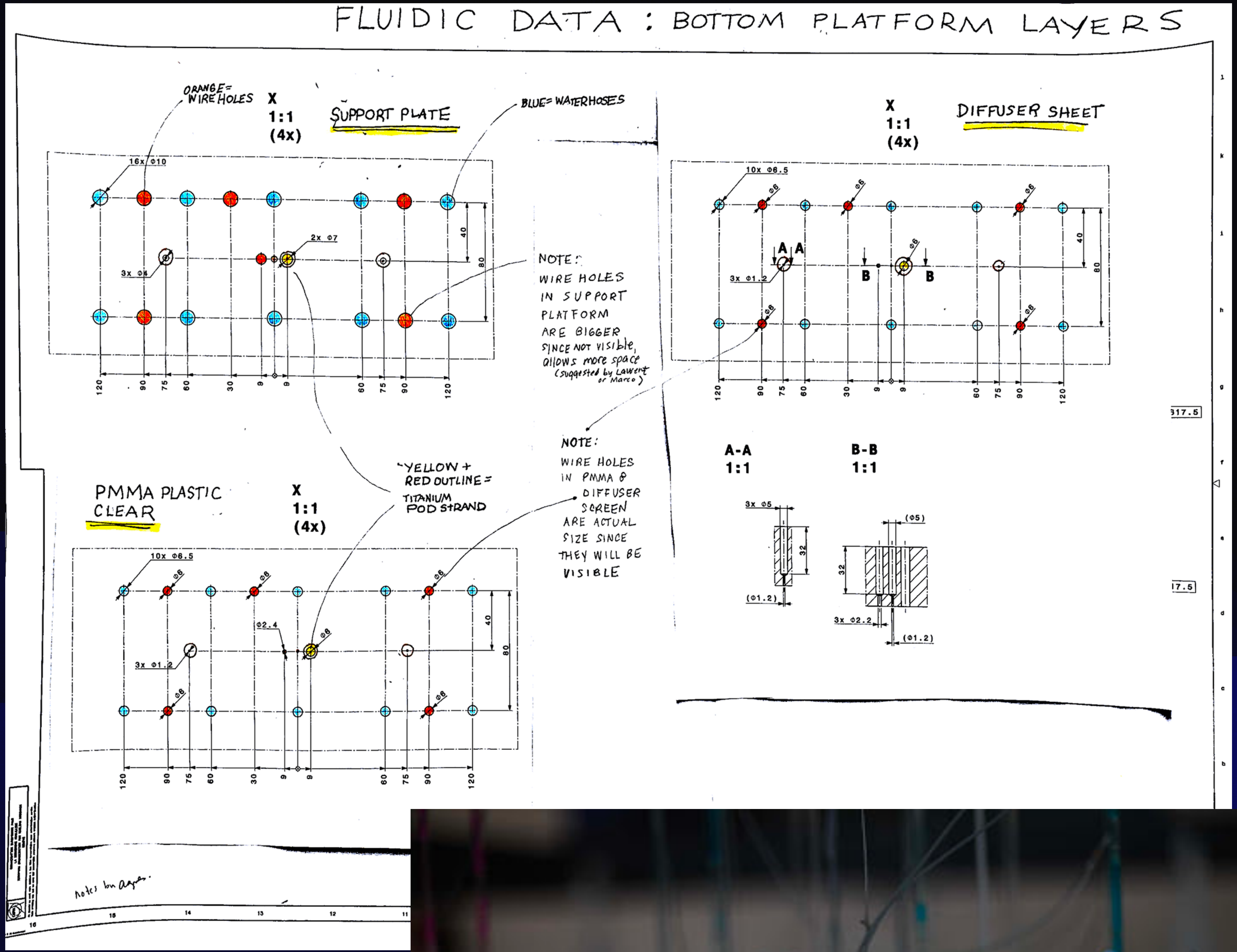
Fluidic Data: A Bit of Context

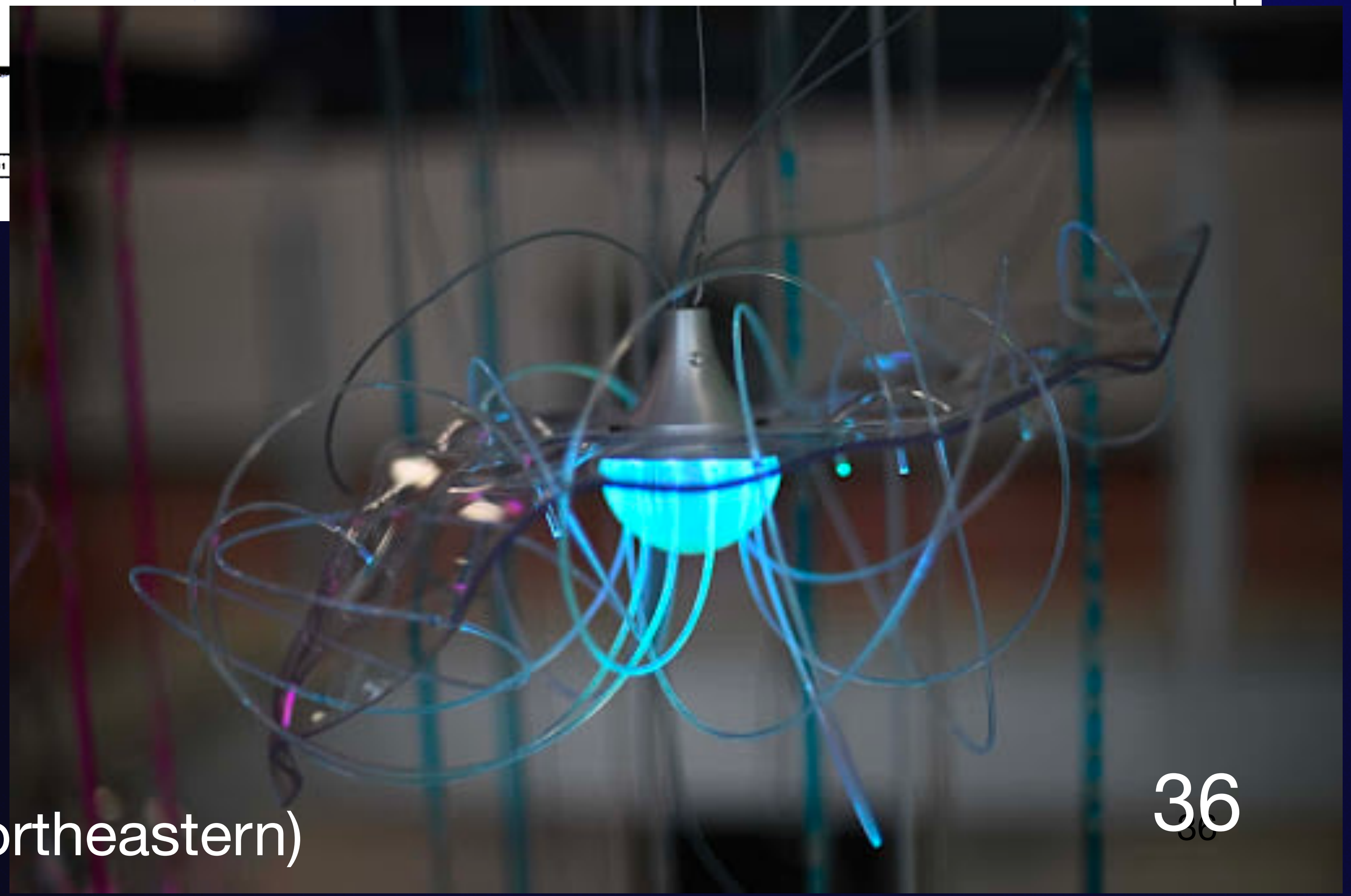
- Target: CERN Data Centre
  - Building 513 (adjacent to 33)
  - Visitor point for WWCG, Data Centre Control Room
- Sponsoring Department: CERN IT
  - Volunteer work from EN, EP, and IT
- Aim: Communicate the purpose and magnitude of data throughput
  - Provide a mental break (recovery) from information overload during visits
  - Balance industrial aesthetic of CERN
- Audience: CERN visitors, but also resident/working scientists and engineers
  - Visitors: Science communication w/o ‘lecturing’, self-discovery
  - Scientists: Intrigue experts, provide equal ground as visitor

Fluidic Data

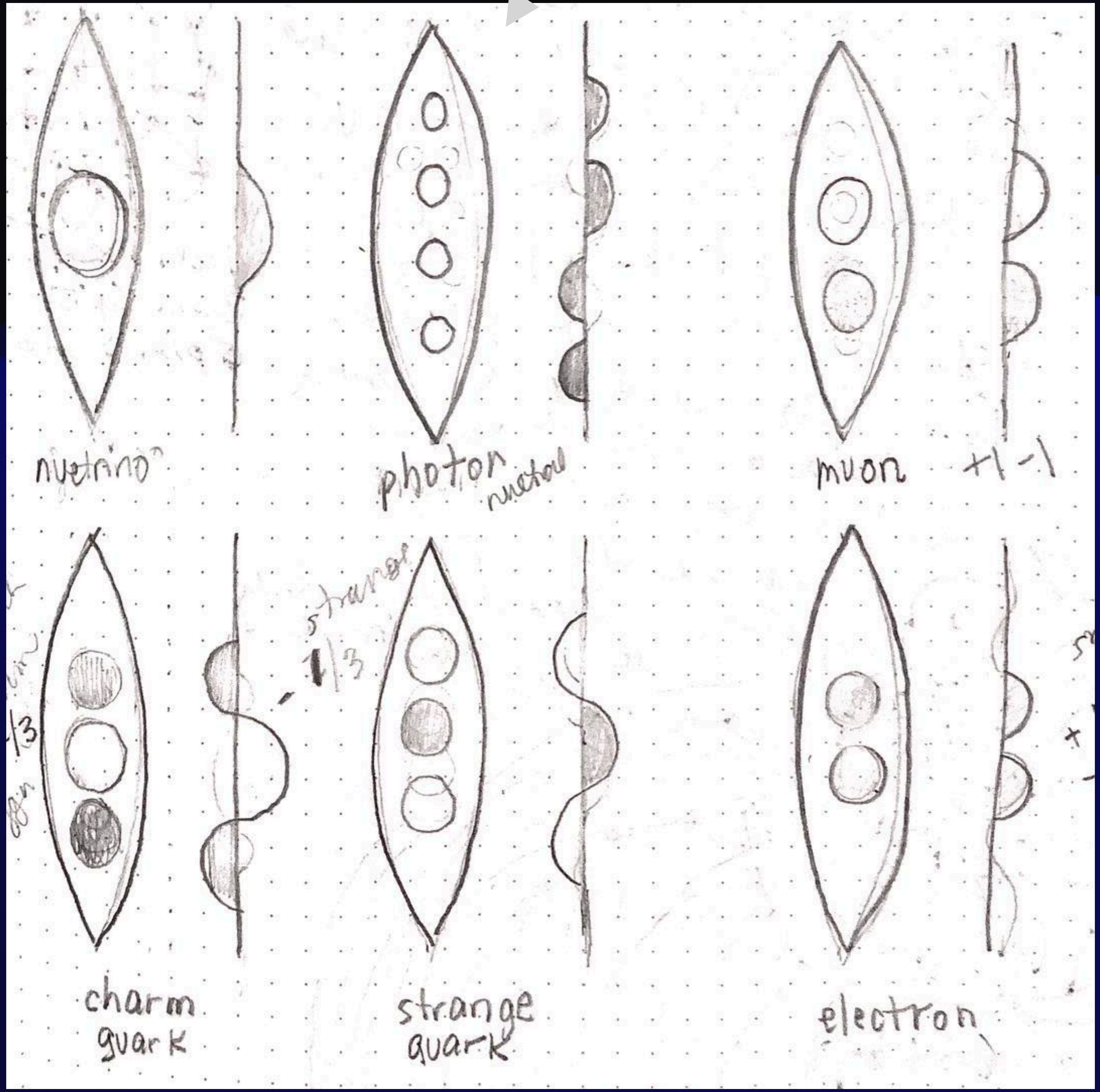
In a Nutshell

- Data (Fluid)
  - Linked in real-time through monitoring data from IT
  - Fluid-air ratio and flow rate symbolizes data throughput
- Particles (Pods/Flowers)
  - Pods: Detector interactions
  - Flowers: Reconstruction
  - Details correspond to differing observables (mass, charge, etc.)





Actually, we decided massless bosons have 0 ‘wells’



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