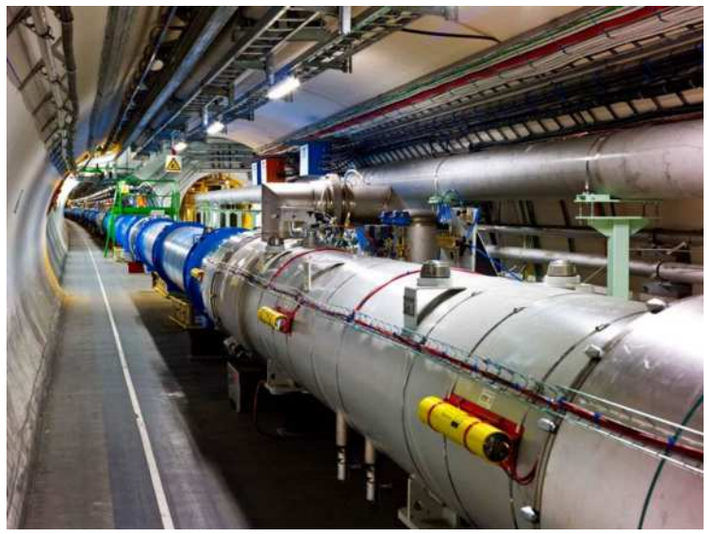
Physics Opportunities for Future Circular Colliders

Jesse Thaler

FCC Week 2015, Washington, DC — March 23, 2015

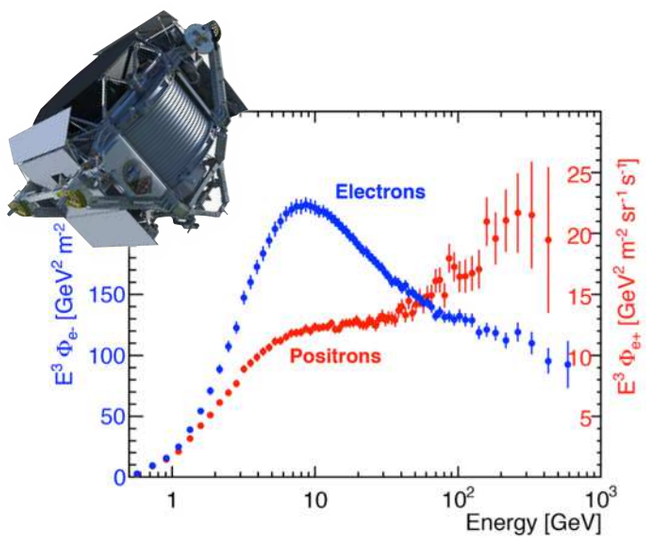
Present Excitement

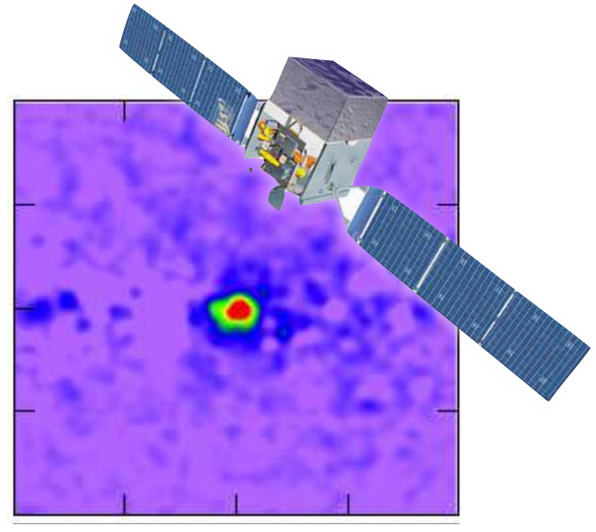
Afterglow of Higgs Discovery



Anticipation of LHC Run 2

Snowmass/P5

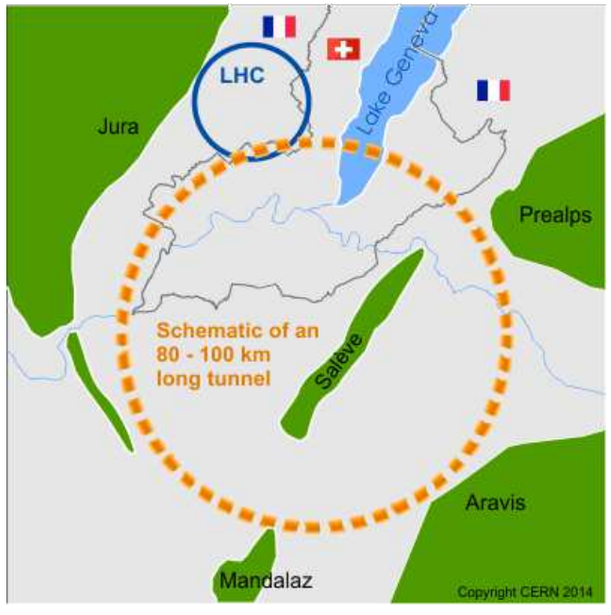




Dark matter hints in cosmic rays?

The Next Leap Forward?

FCC
hh ee he



This talk: personal perspective (not exhaustive)

The Next Leap Forward?

FCC
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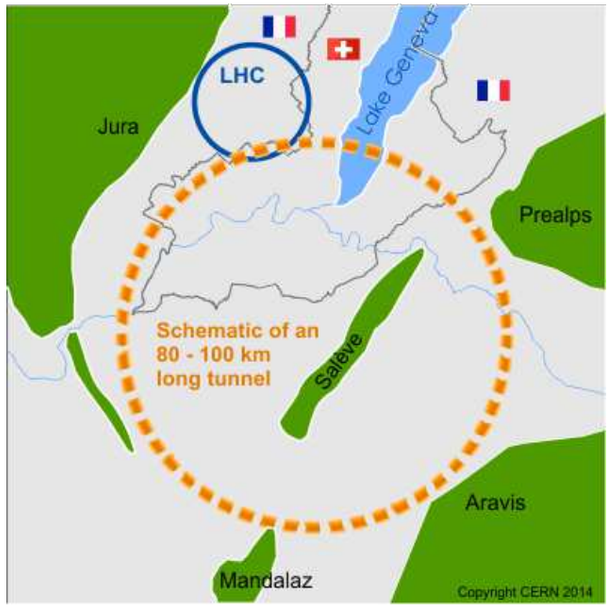
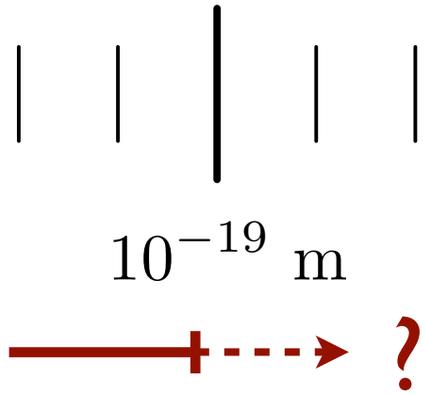


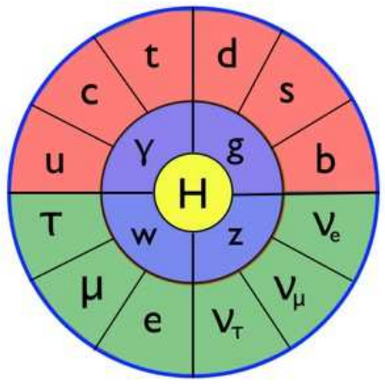
50 gauss magnet technology

This talk: personal perspective (not exhaustive)

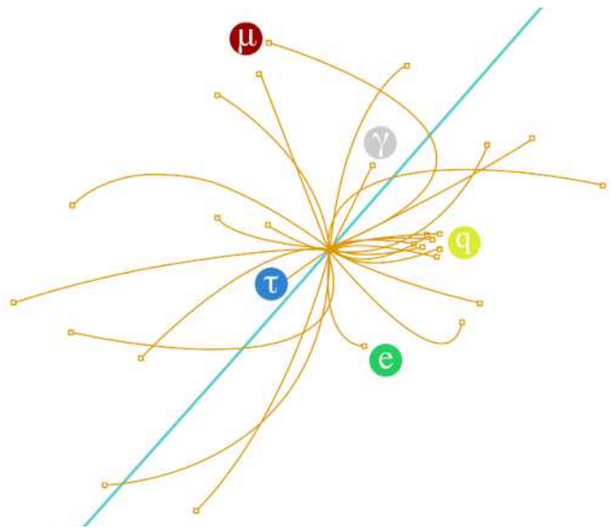
Outline



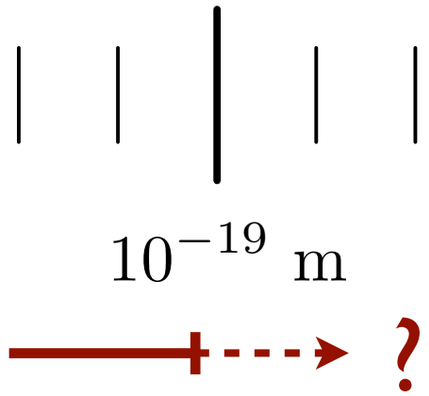
Discoveries Beyond the Standard Model



Revelations Within the Standard Model



New Opportunities for Data Analysis?



Discoveries Beyond the Standard Model

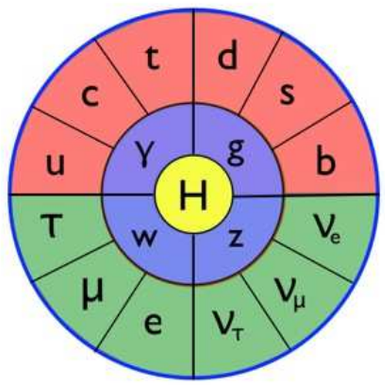
Revelations Within the Standard Model

New Opportunities for Data Analysis?

The Universe
Galaxy
Solar System
Planet
Us
Hairs
Cells
Molecules
Electrons
Protons
The TeV Scale
Grand Unification
Quantum Gravity

10^{26} m 10^{11} m 10^{-4} m 10^{-19} m 10^{-34} m

The Standard Model



The Universe
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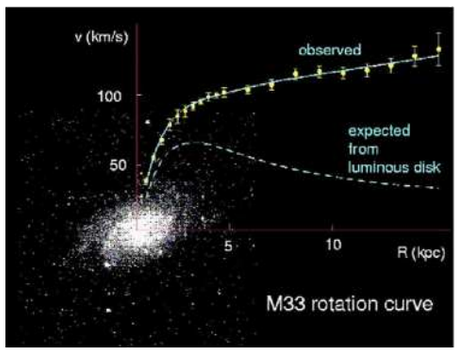
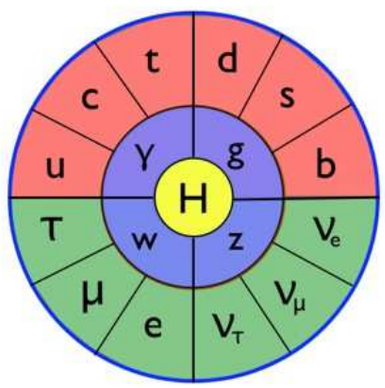
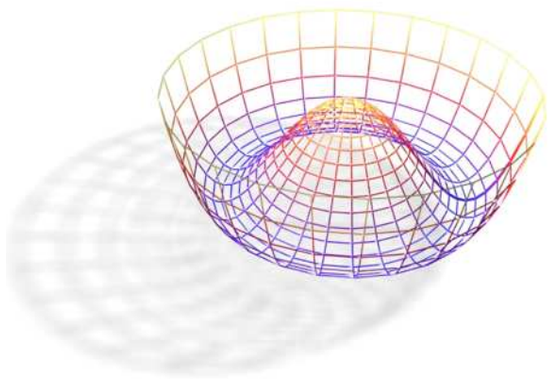






Matter/Anti-Matter?

Three Generations?

Neutrino Masses?

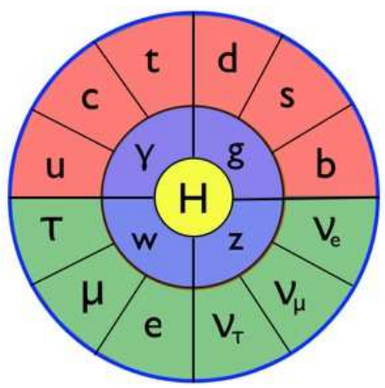
Strong CP?

10^{26} m 10^{11} m 10^{-4} m 10^{-19} m 10^{-34} m

The Standard Model ?

Grand Unification?

Dark Matter?



Origin of Mass? Higgs Boson!

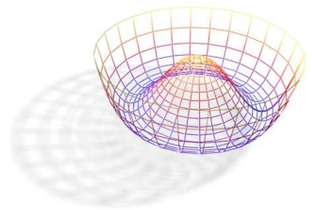
Quantum Gravity?

Dark Energy?

Hierarchy Problem?

Inflation?

Exploiting the Higgs



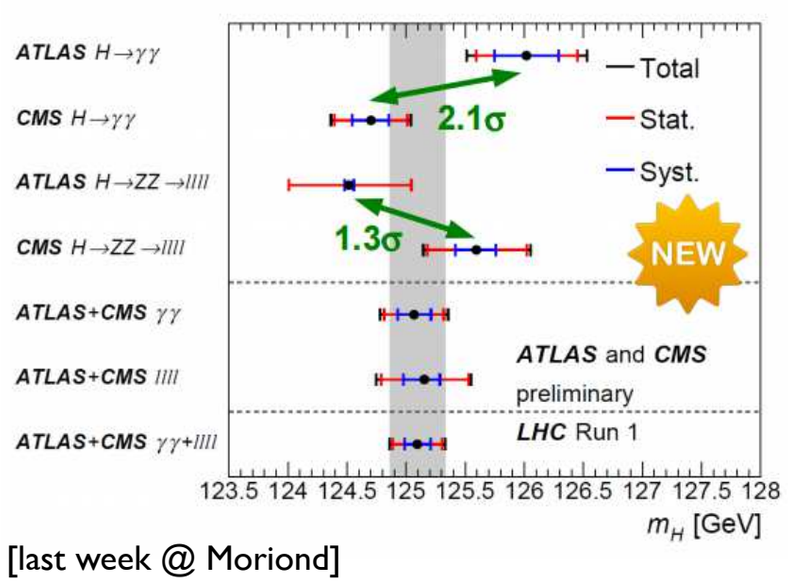
Key FCC-ee/hh/he Targets

$$V(h) = -m^2 h^\dagger h + \lambda_h (h^\dagger h)^2$$

Higgs self-coupling

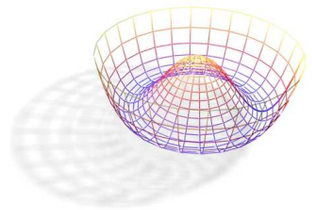
c. March 2015:
Barely scratched the surface

$$\mathcal{L} \supset y_\psi \psi h \psi^c$$



[last week @ Moriond]

Exploiting the Higgs



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Higgs self-coupling

+ $|h|^6$?

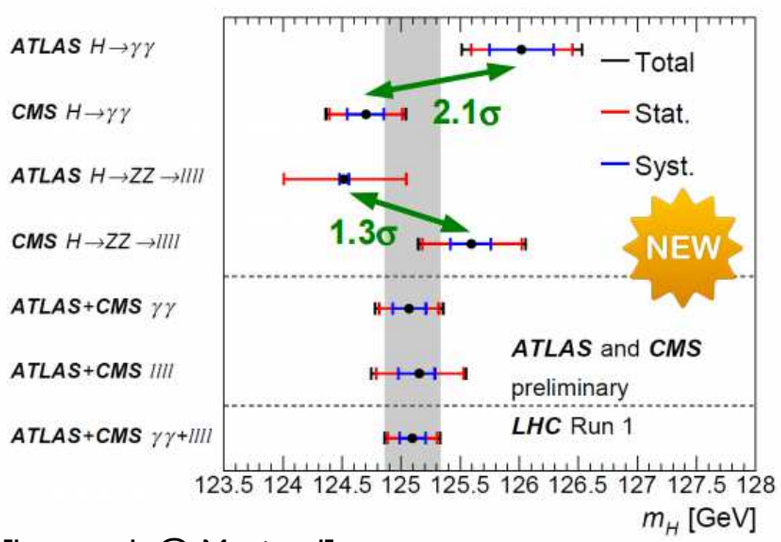
Higgs compositeness

x $|h|^2$?

mass/coupling relations

+ $|h^\dagger D_\mu h|^2$?

precision electroweak



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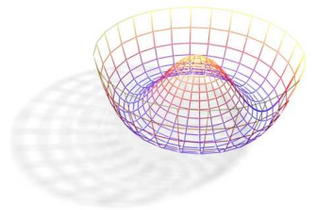

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+ $V(h_2,s,\ldots)$?

extended Higgs sectors

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mass/coupling relations

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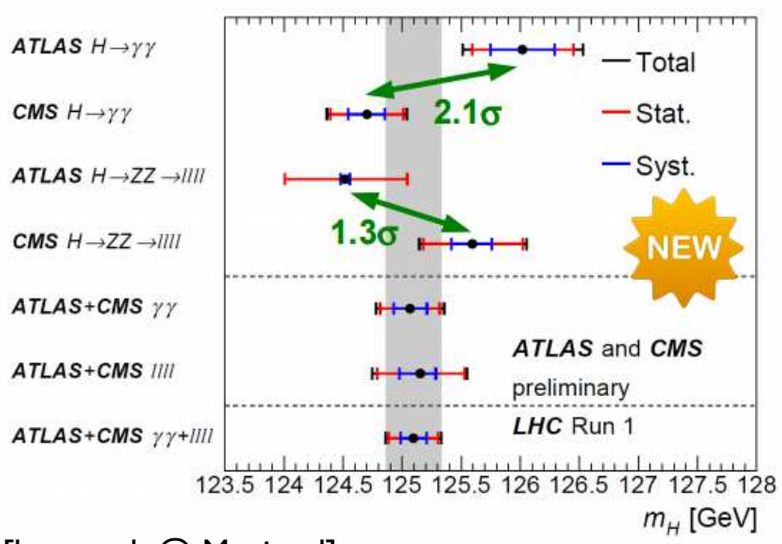
precision electroweak

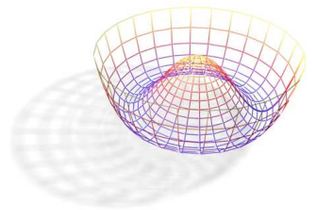
+ $|h|^2 O_{BSM}$?

Higgs portal to new physics



[last week @ Moriond]

Exploiting the Higgs



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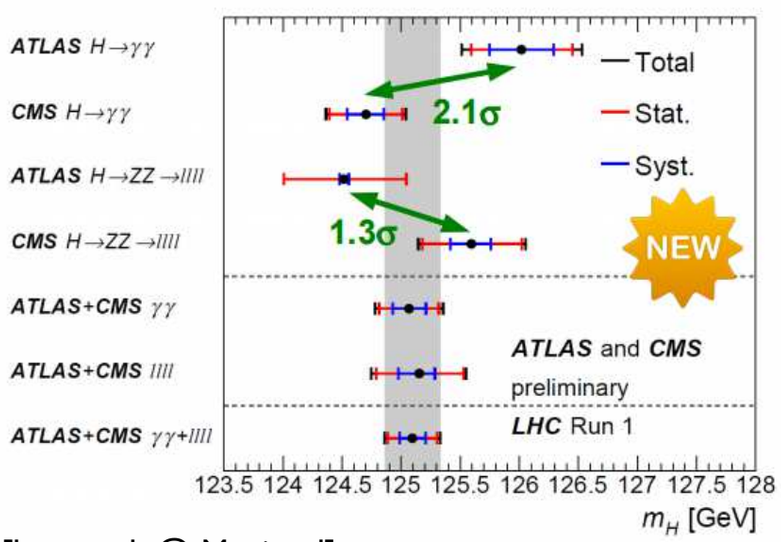
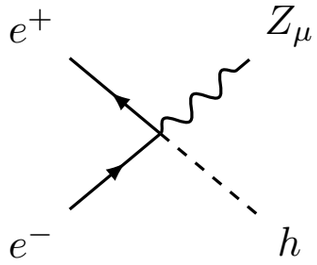


[last week @ Moriond]

& electroweak phase transition,
new physics in loops, neutral naturalness, …

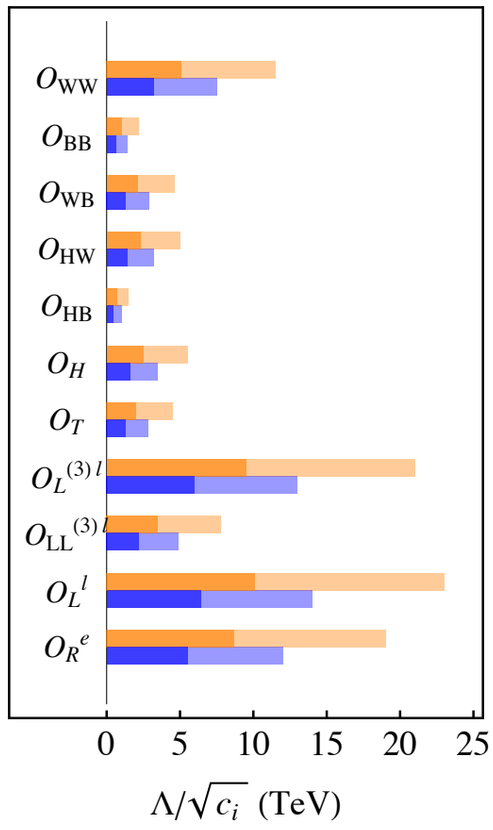
Higgs physics alone worth investment in FCC

Exploiting the Higgs

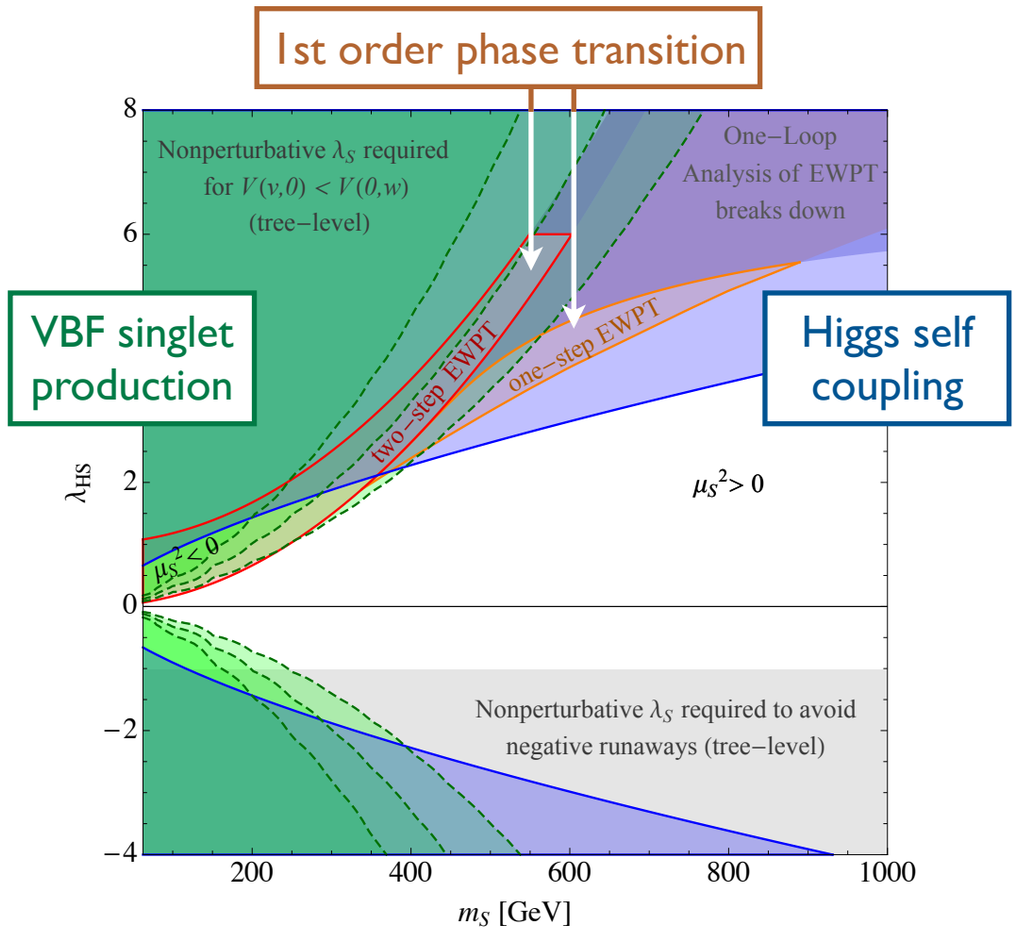


Dimension 6 Operators

$$\mathcal{O}_{WW} = g^2|H|^2 W^a_{\mu\nu} W^{a,\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_H = \tfrac{1}{2}(\partial_\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\mathcal{O}_L^{(3)\ell} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$$
$$\mathcal{O}_{LL}^{(3)\ell} = (\bar{L}_L \gamma_\mu \sigma^a L_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$$
$$\mathcal{O}_L^{\ell} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$$
$$\mathcal{O}_R^{e} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$



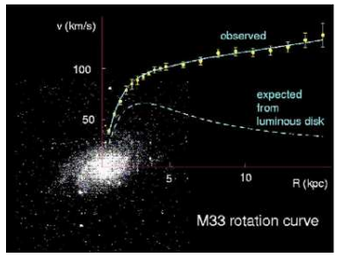
FCC-ee: Bounds from Higgsstrahlung Cross Section

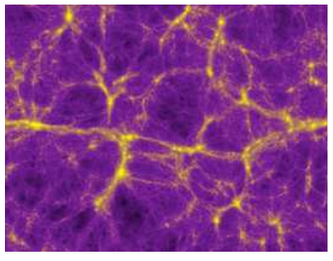


FCC-hh: Singlet-aided Electroweak Baryogenesis

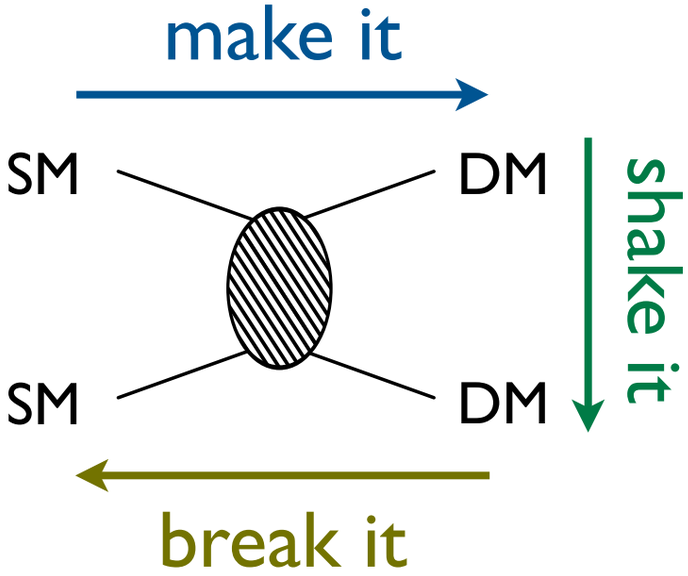
[Craig, Farina, McCullough, Perelstein, 2014]
[Curtin, Meade, Yu, 2014]

Dark Matter





WIMP Paradigm?



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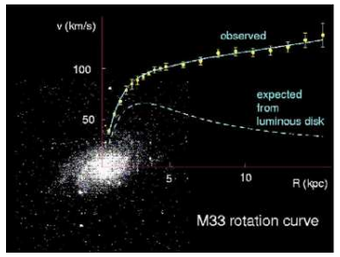
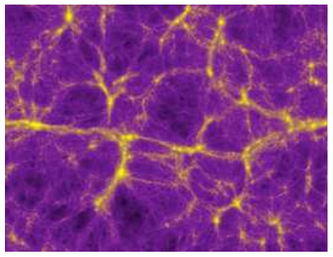


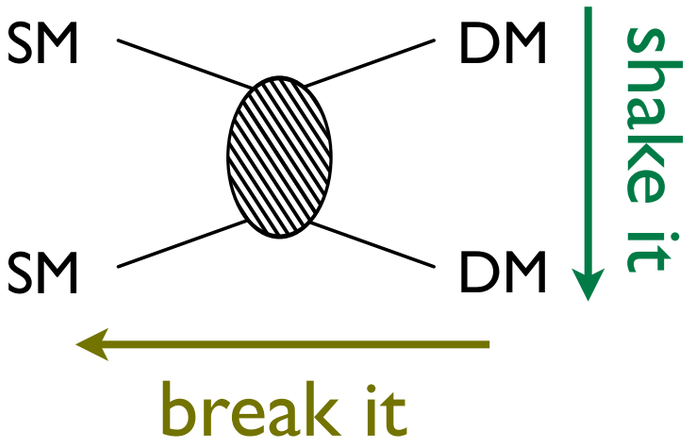


WIMP Paradigm?

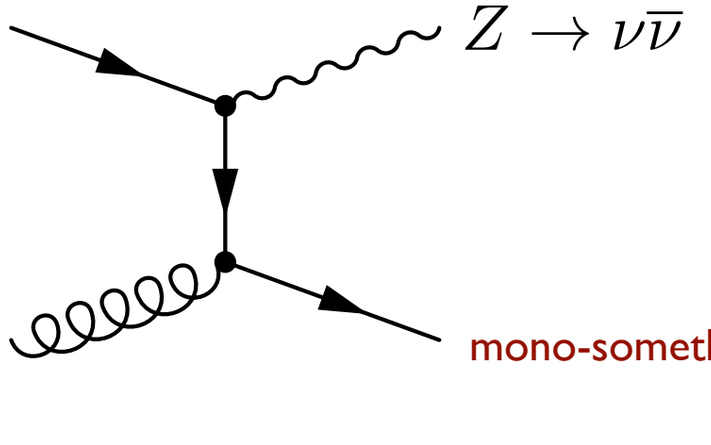
make it

shake it

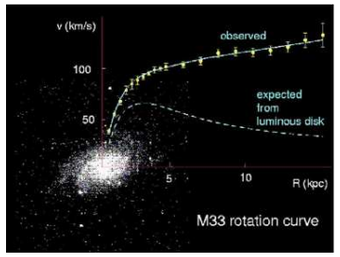
break it

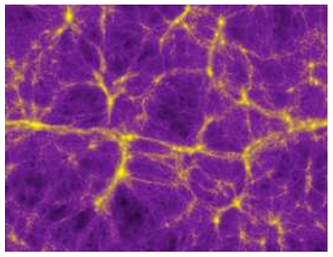


fake it



Dark Matter





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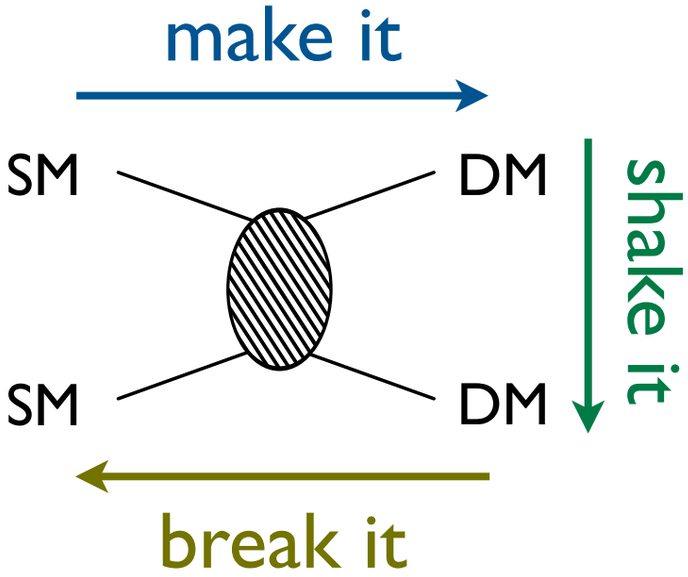
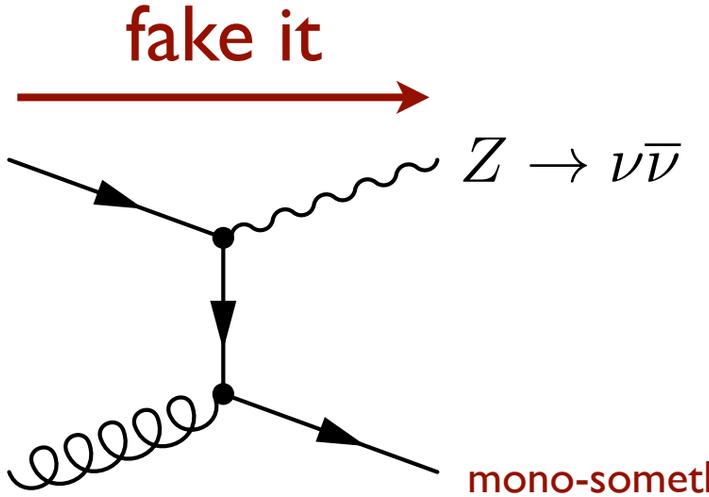
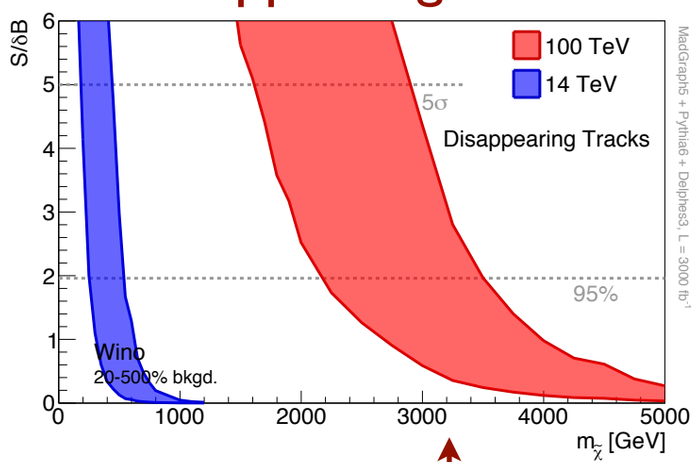




e.g. Pure Wino-like DM (electroweak triplet):

$\chi^{\pm}$, χ^{0} — $\Delta m \approx m_{\pi+}$

Disappearing Tracks



Thermal Relic Expectation

(non-thermal/partial DM equally plausible)

[Low, Wang, 2014]

Hierarchy Problem

Chiral Symmetry Breaking $\xrightarrow{\times 10^3}$ *Electroweak Breaking*

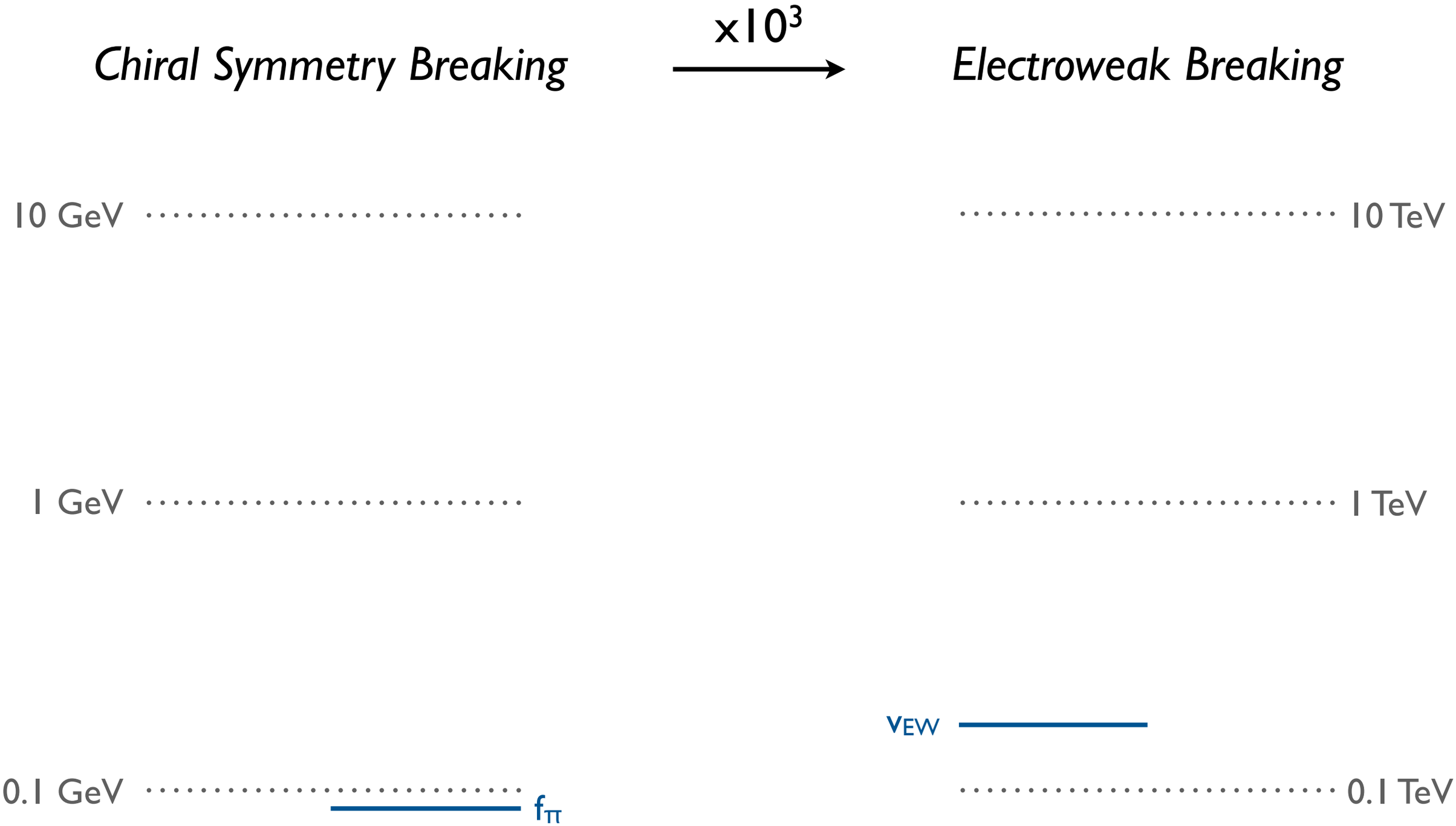
10 GeV ····· 10 TeV

1 GeV ····· 1 TeV

0.1 GeV ····· 0.1 TeV

Hierarchy Problem

Chiral Symmetry Breaking $\xrightarrow{\times 10^3}$ *Electroweak Breaking*



Hierarchy Problem

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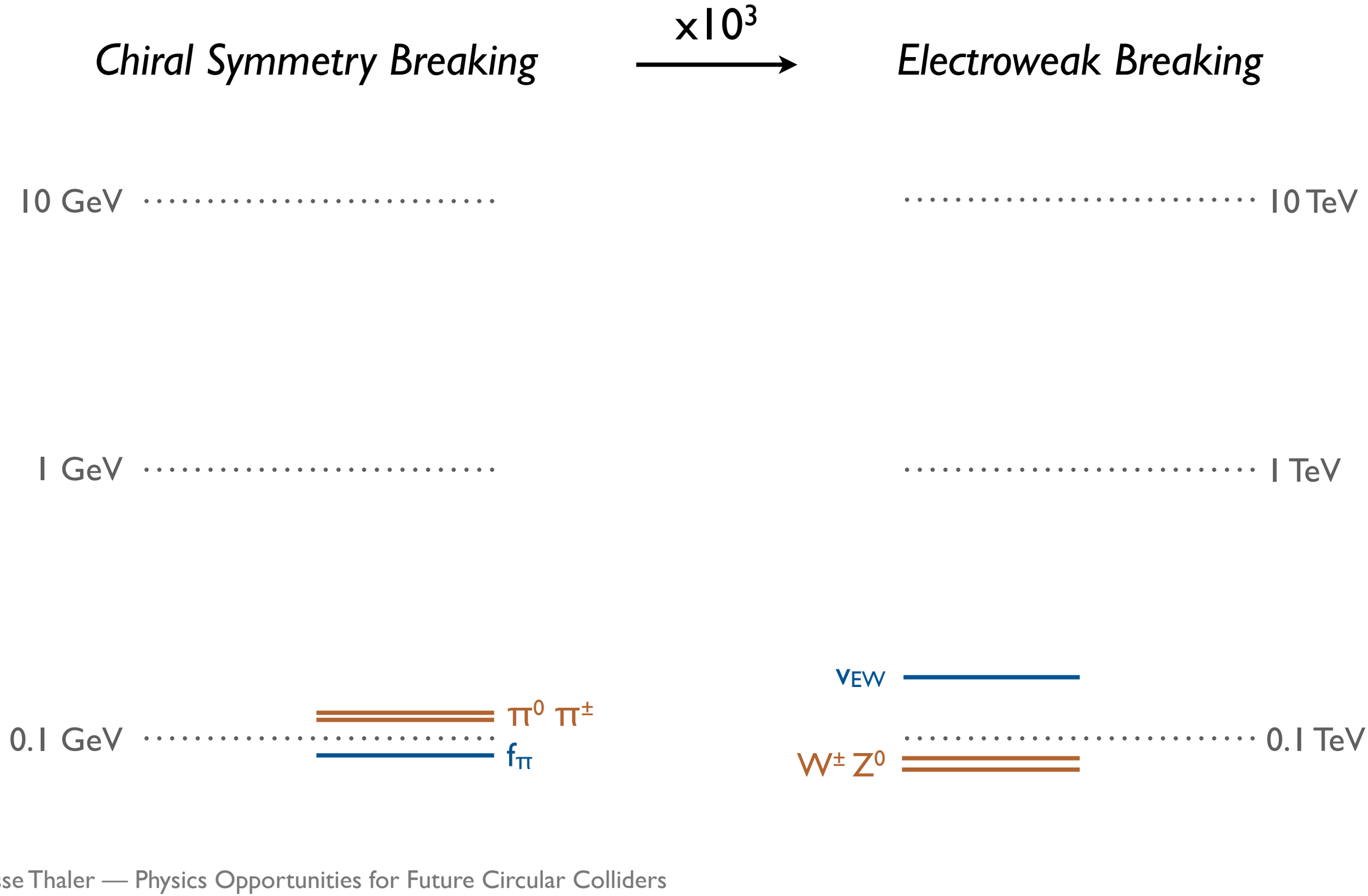

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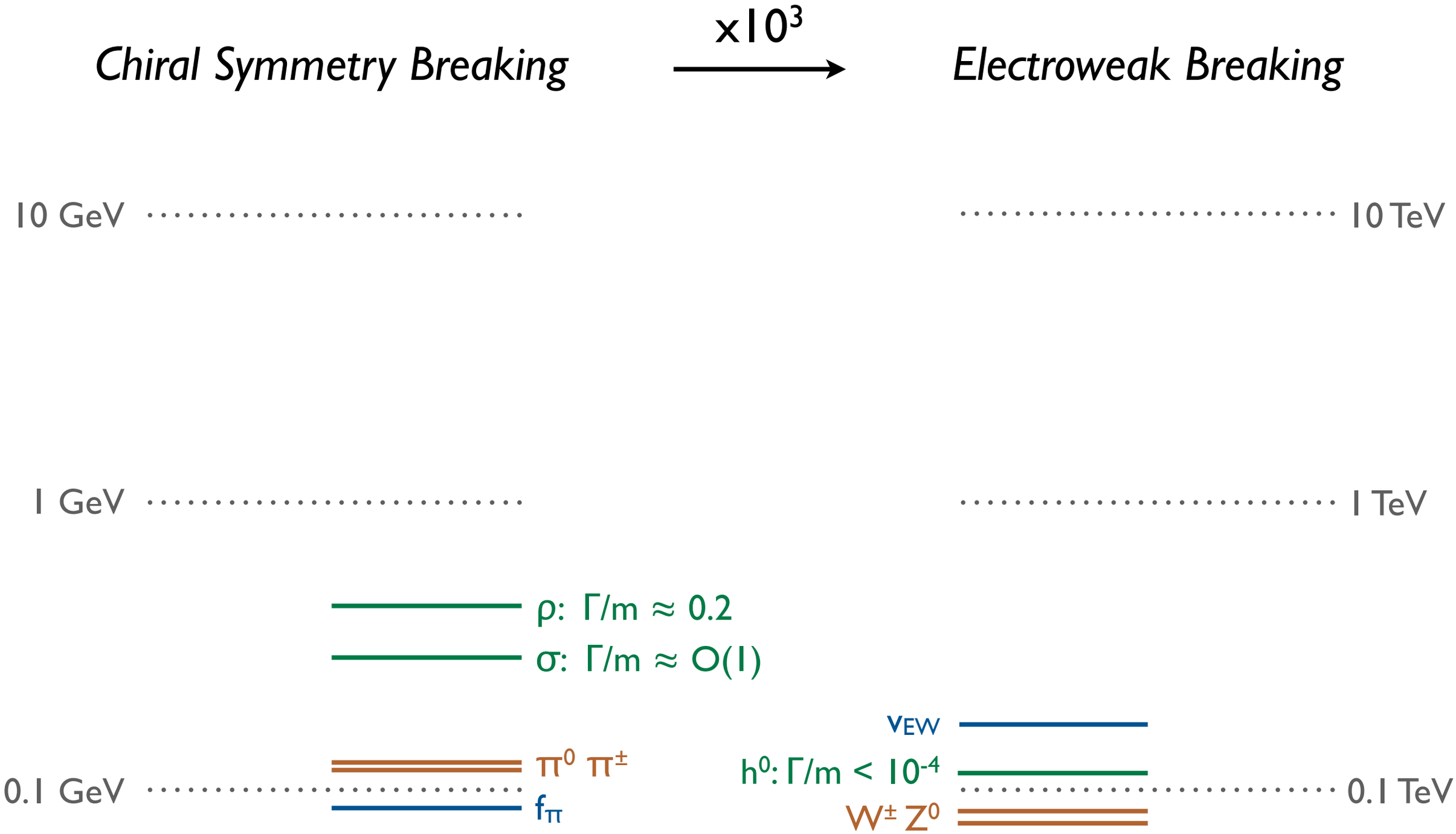

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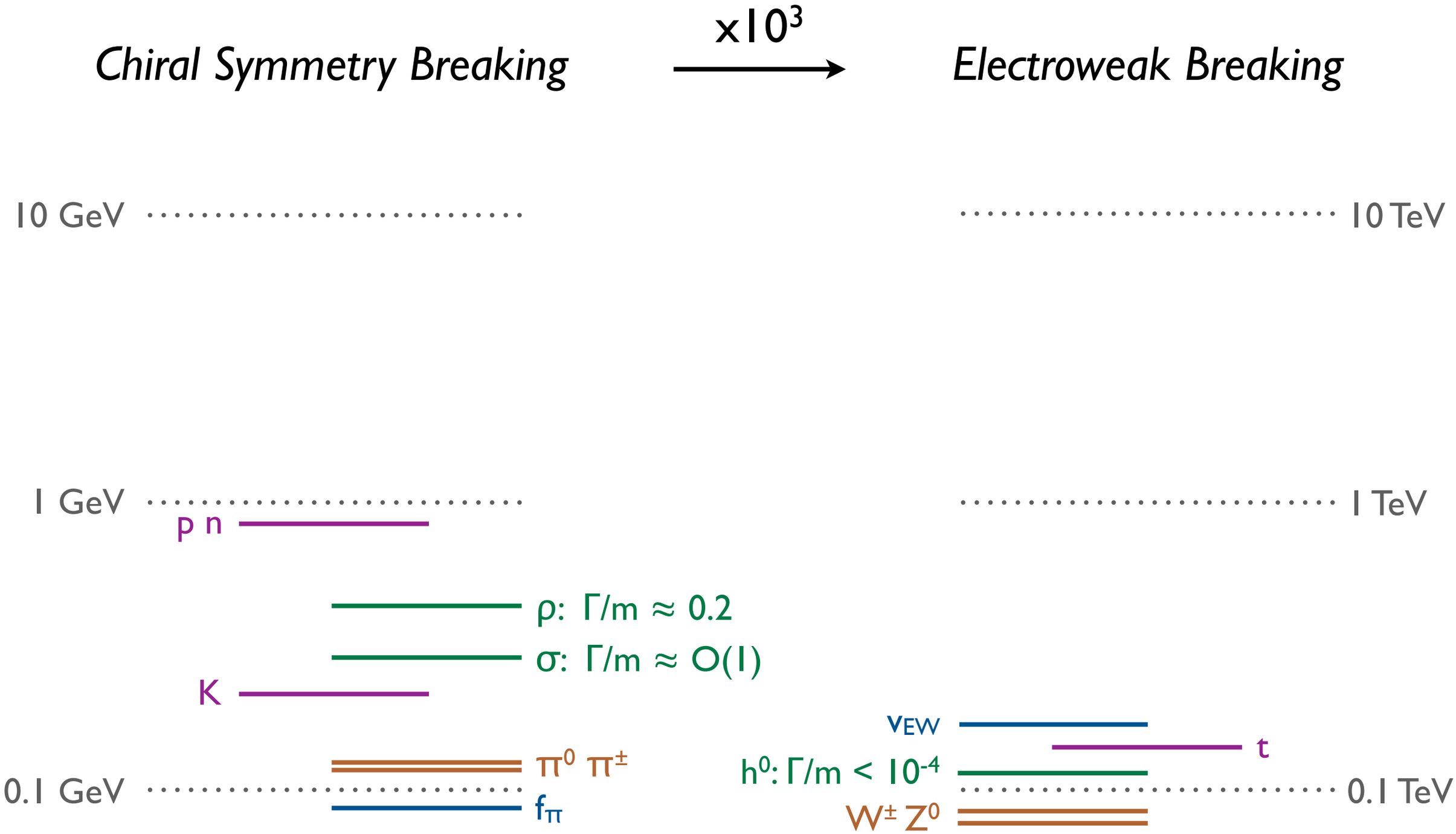


Hierarchy Problem

Chiral Symmetry Breaking $\xrightarrow{\times 10^3}$ *Electroweak Breaking*

10 GeV ····· 10 TeV

1 GeV ····· 1 TeV

p n

ρ: Γ/m ≈ 0.2

σ: Γ/m ≈ O(1)

K

v_{EW}

t

h^0: Γ/m < 10^{-4}

π^0 $\pi^\pm$

f_π

$W^\pm$ Z^0

0.1 GeV ····· 0.1 TeV

Hierarchy Problem

Chiral Symmetry Breaking $\xrightarrow{\times 10^3}$ *Electroweak Breaking*

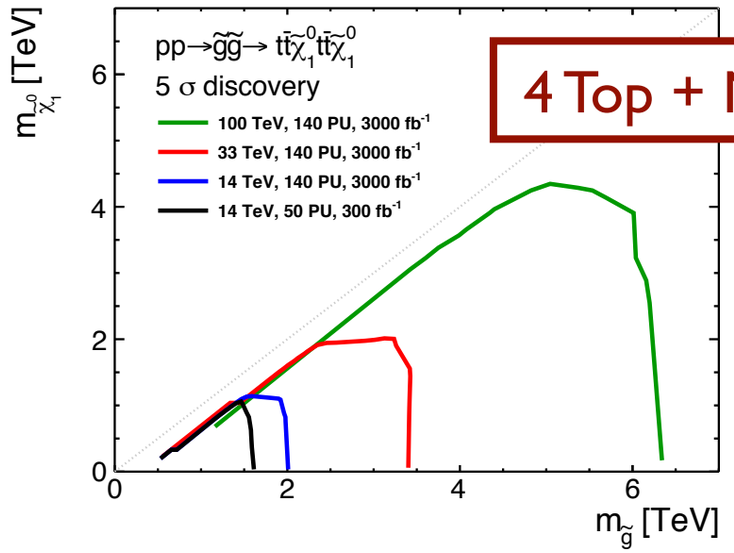
Hierarchy Problem

Chiral Symmetry Breaking $\xrightarrow{\times 10^3}$ *Electroweak Breaking*

Hierarchy Problem

Chiral Symmetry Breaking *king*

10 GeV ····· 10 TeV



4 Top + MET

[Cohen, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker, 2013]

1 GeV ····· 1 TeV

p n

ρ: Γ/m ≈ 0.2

σ: Γ/m ≈ O(1)

K

π^0 $\pi^\pm$

0.1 GeV ····· 0.1 TeV

f_π

compositeness?
supersymmetry?
extended space-time?
…

v_{EW}

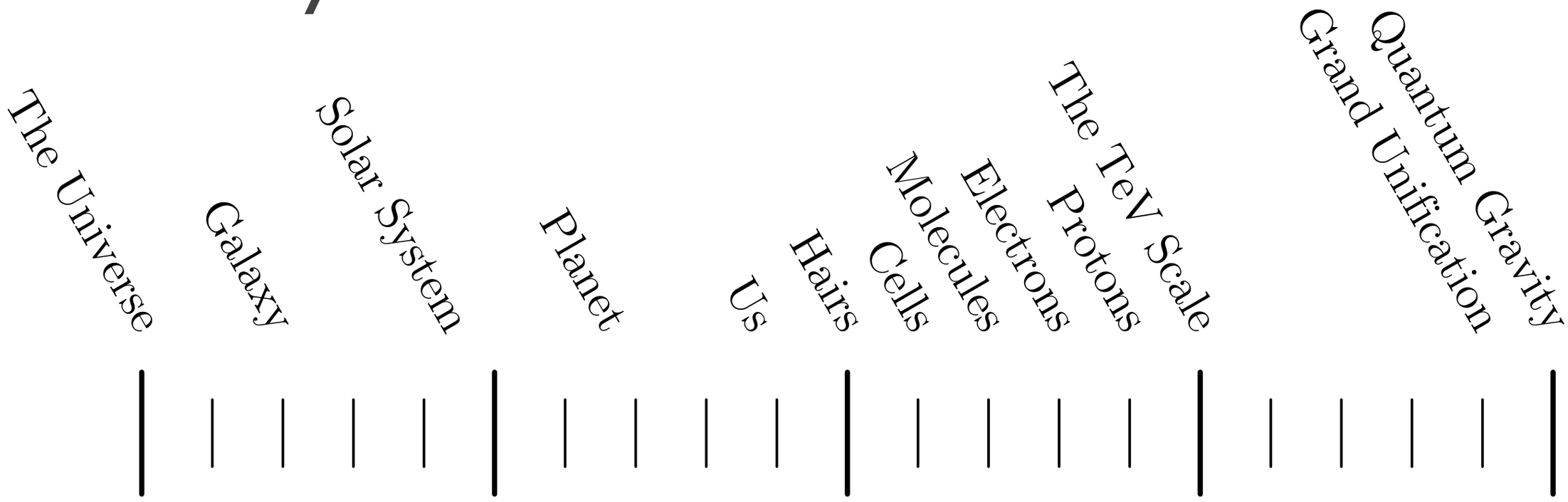
t

h^0: Γ/m < 10^{-4}

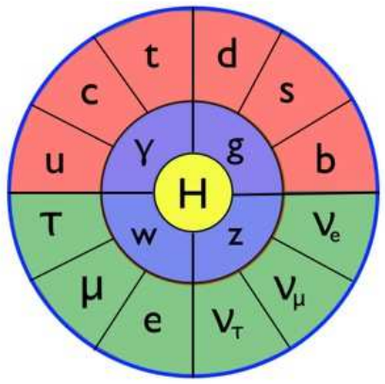
$W^\pm$ Z^0

LHC Reach

Core Physics Goals for FCC



Frontier exploration alone worth investment in FCC



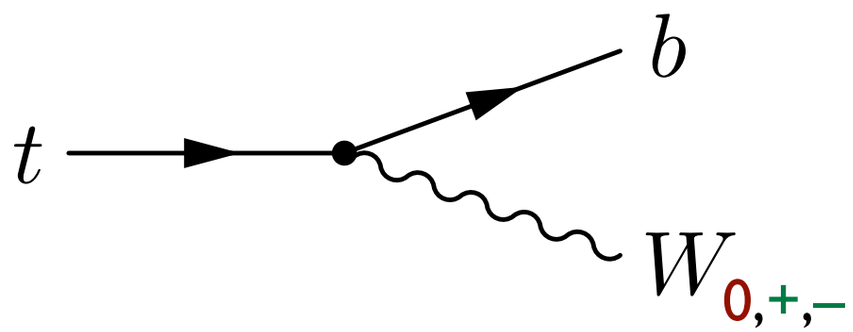
Discoveries Beyond the Standard Model

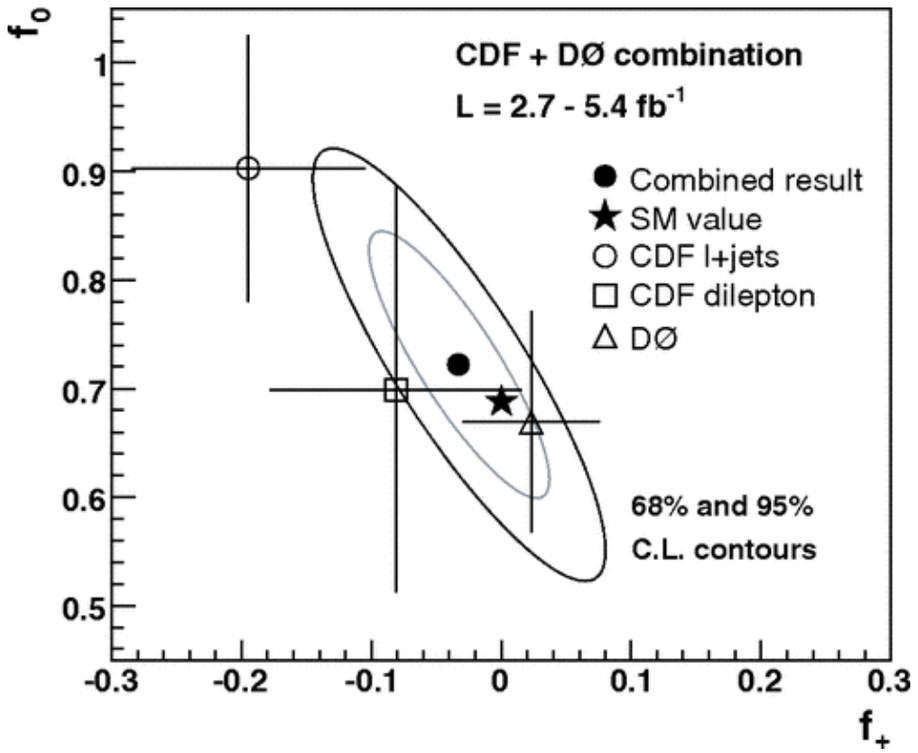
Revelations Within the Standard Model

New Opportunities for Data Analysis?

A Tevatron Example

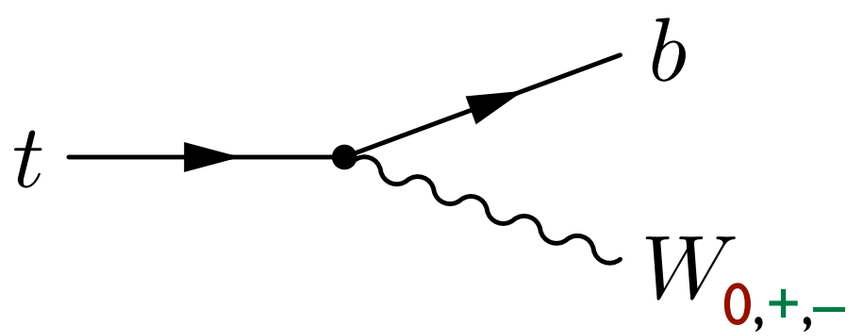
W Polarization in Top Decay





A Tevatron Example

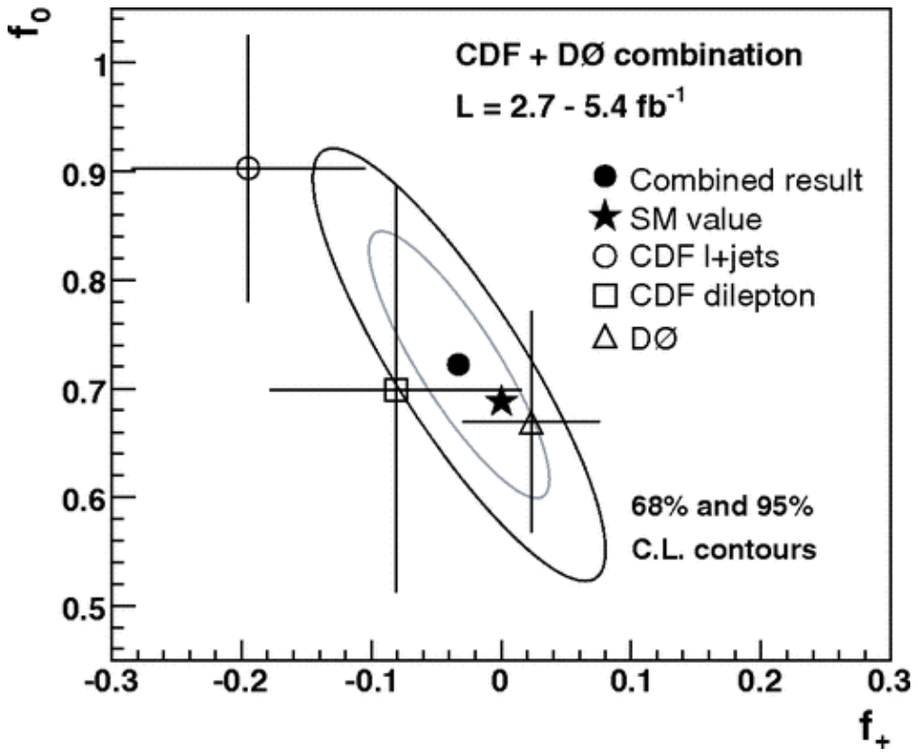
W Polarization in Top Decay ⇔ *Spontaneous Electroweak Breaking*



Longitudinal: $\mathcal{F}_0 \approx 70\% \propto m_t^2$

Transverse: $\mathcal{F}_- \approx 30\% \propto 2m_W^2$

$\mathcal{F}_+ \approx 0\%$



Goldstone Equivalence Theorem

$$\lambda_t\, q h t^c \;\Rightarrow\; m_t\, q\, e^{i\pi^a T^a/v}\, t^c$$

Not just "top property"
Deserving of celebration

Towards a Deeper Understanding

Measurements ⇔ *Core Principles of SM*

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \propto \sum_i \int \mathrm{d}\Phi_i \, |\mathcal{M}_i|^2 \, \delta\Big(\mathcal{O} - \hat{\mathcal{O}}(\Phi_i)\Big)$$

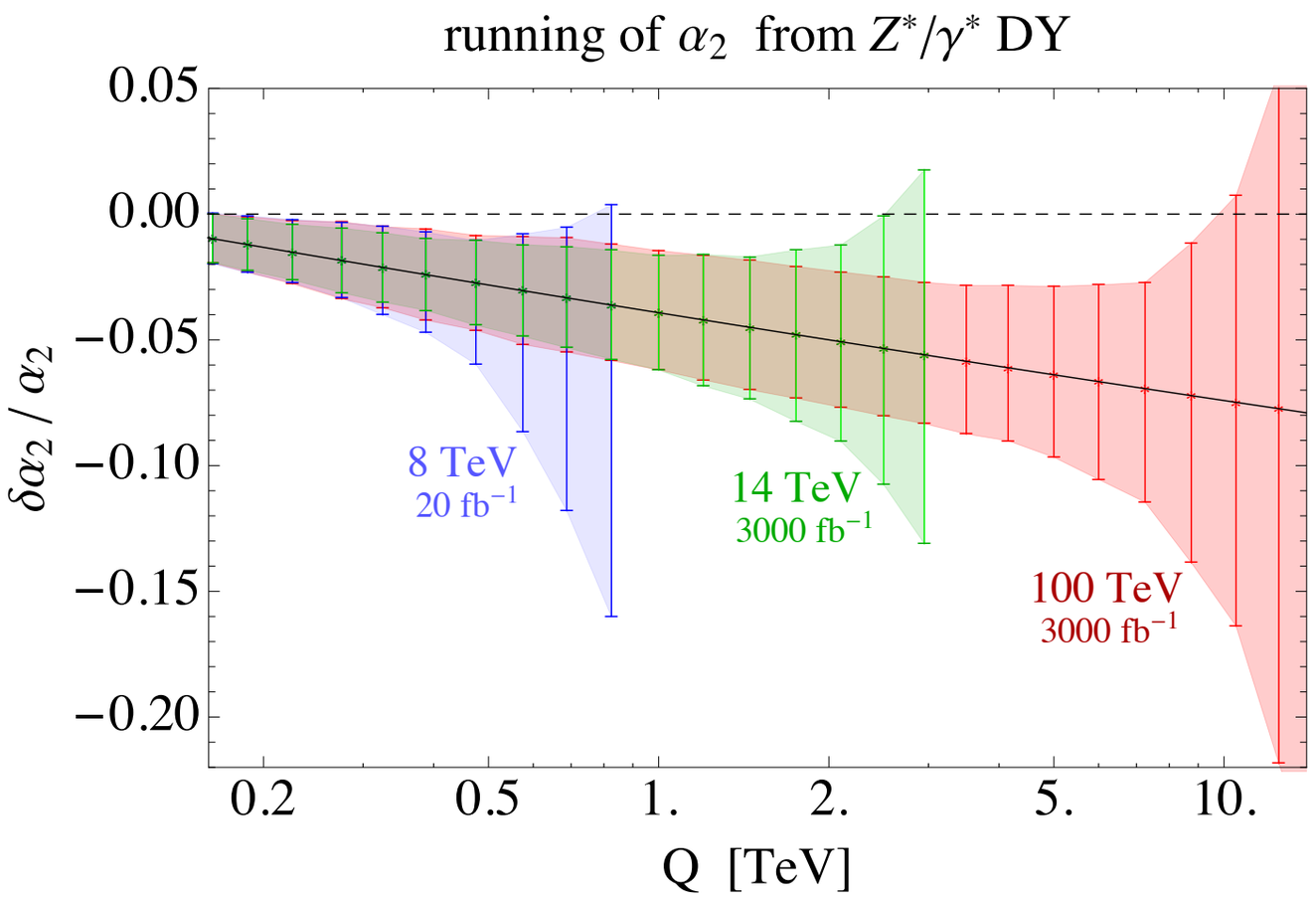
Precision Calculations

Clever Observables

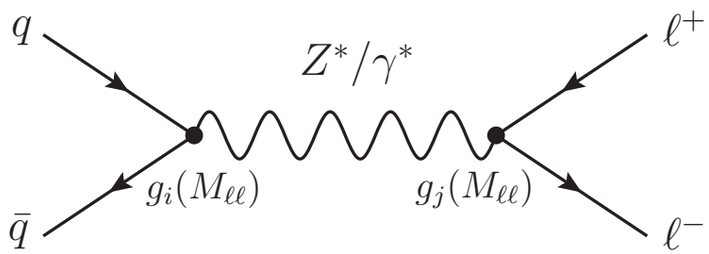
How can we exploit energy/luminosity/precision of FCC?

Electroweak Probes with FCC-hh

High Mass Drell-Yan ⇔ *Electroweak Coupling Running*



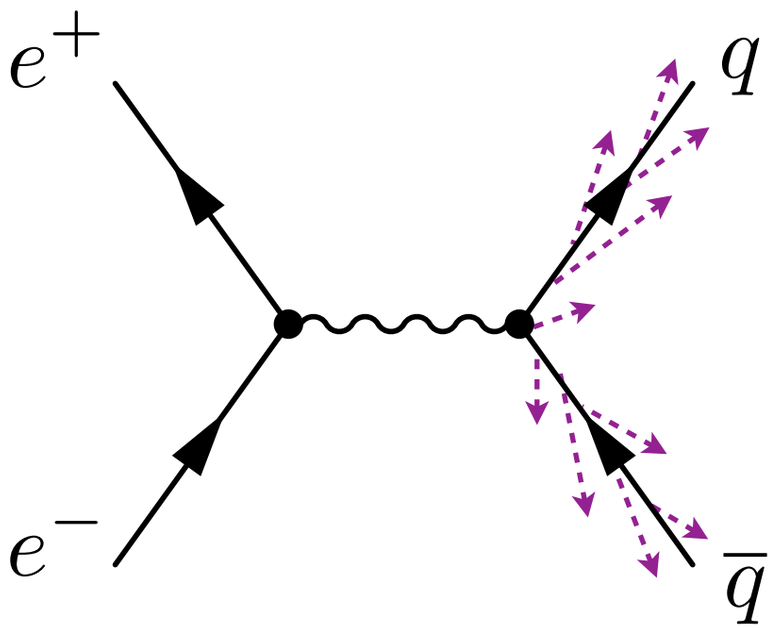
Asymptotic Freedom of $SU(2)_W$ in SM



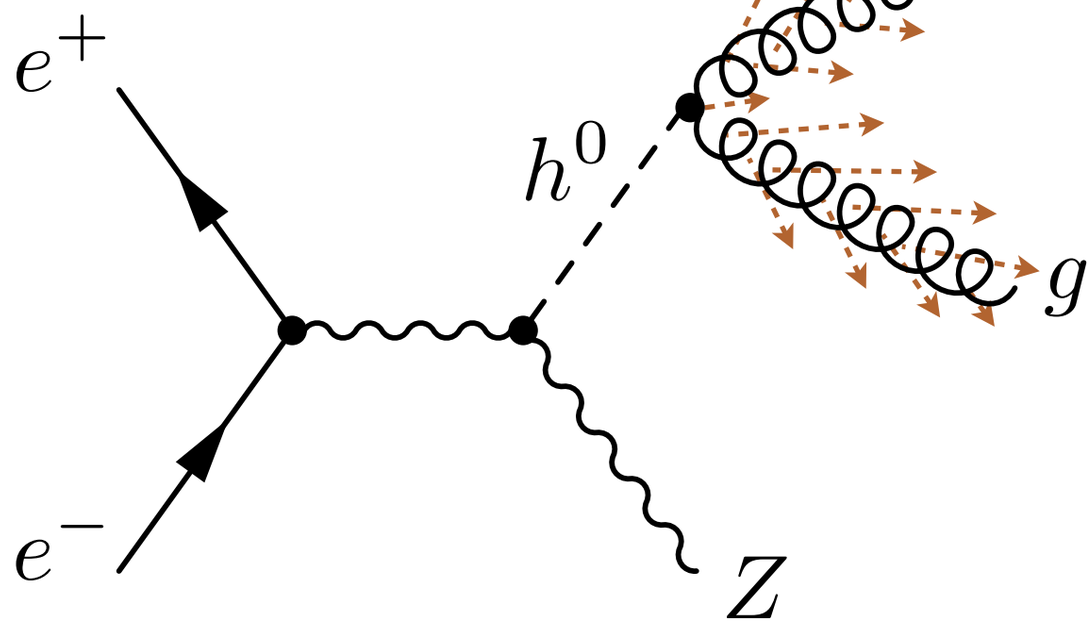
Model-independent test for new electroweak states

[Alves, Galloway, Ruderman, Walsh, 2014]

QCD Probes with FCC-ee



vs.

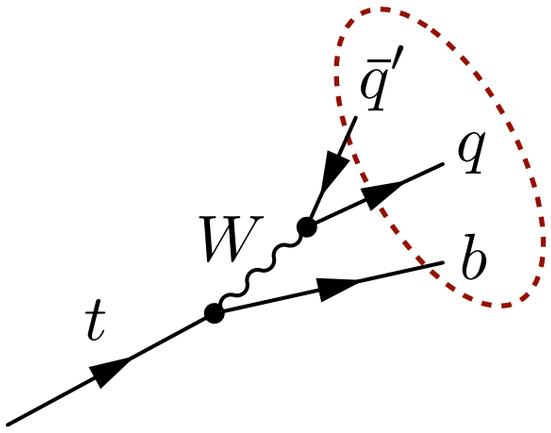


$C_F = 4/3$ (quark)

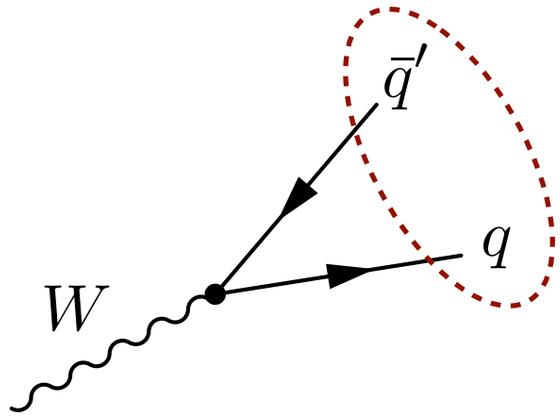
$C_A = 3$ (gluon)

Higgs Event Shapes ⇔ *Quark/Gluon Color Scaling*

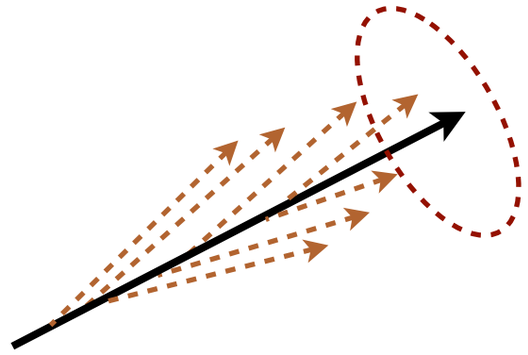
Detour: Jet Substructure



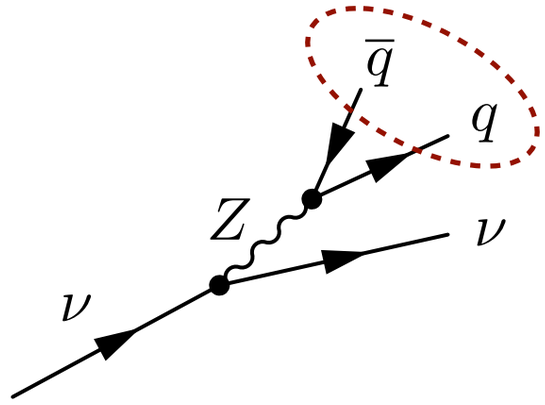
Boosted Top



Boosted W/Z/H

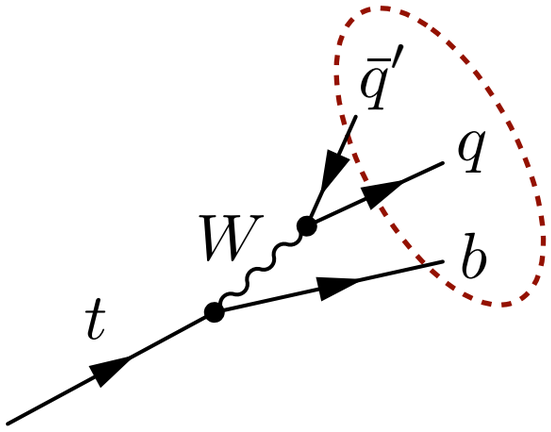


Quark/Gluon

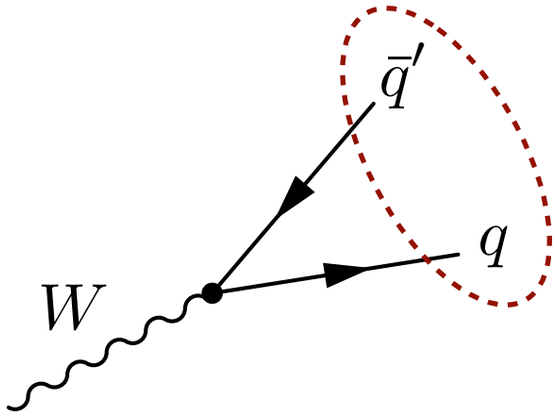


Neutrino (!)

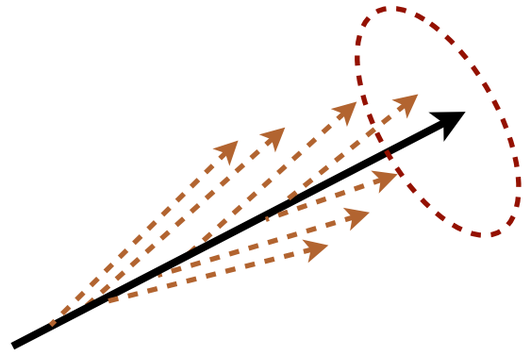
Detour: Jet Substructure



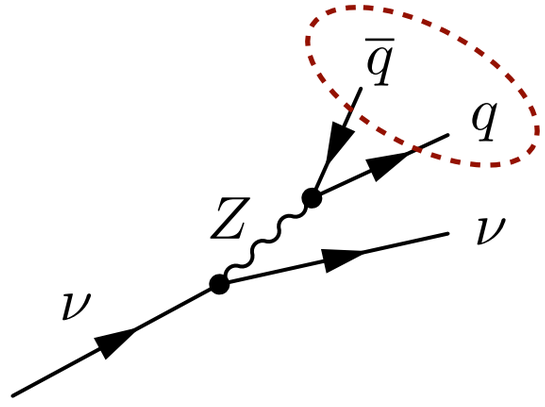
Boosted Top



Boosted W/Z/H

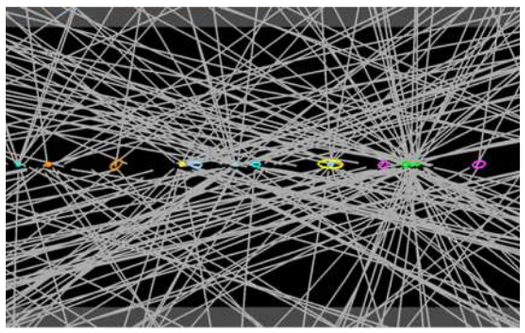


Quark/Gluon



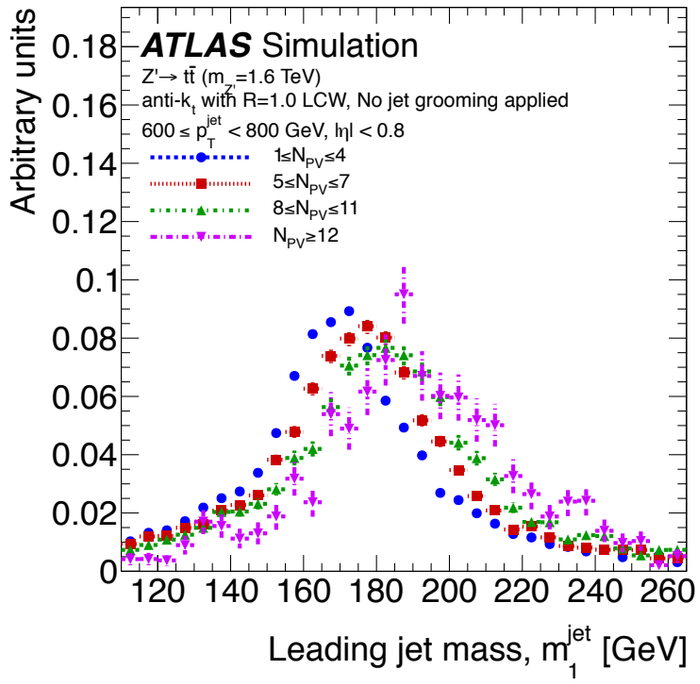
Neutrino (!)

\+

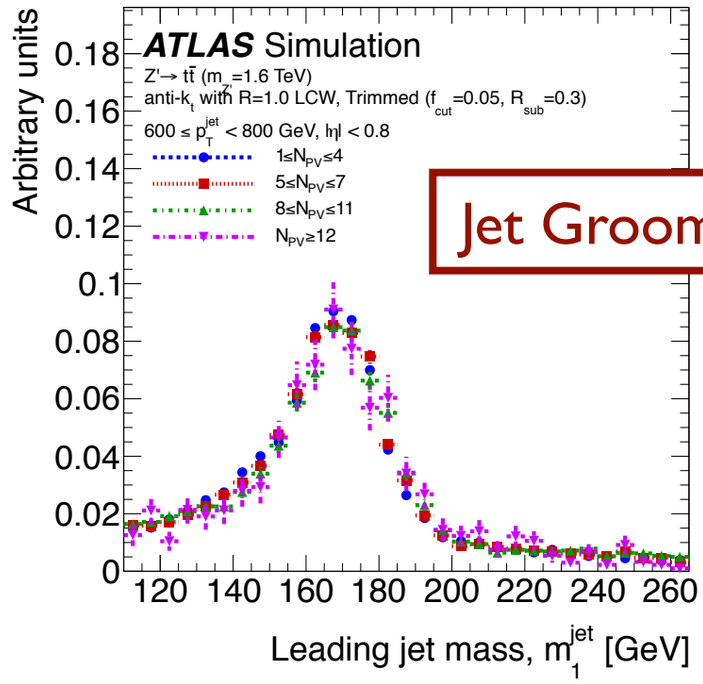


Pileup

=



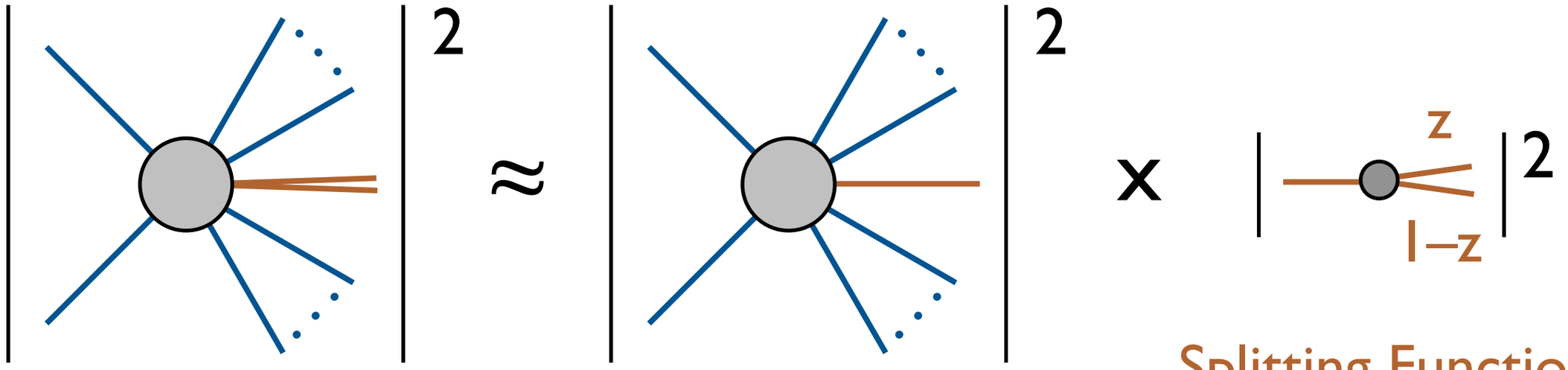
⇒



Jet Grooming

[ATLAS, 2012; using Krohn, JDT, Wang, 2009]

Textbook QCD with FCC-hh?



2→n 2→n–1 1→2

Basis of PDF evolution, FF evolution, parton showers, NLO subtractions, …

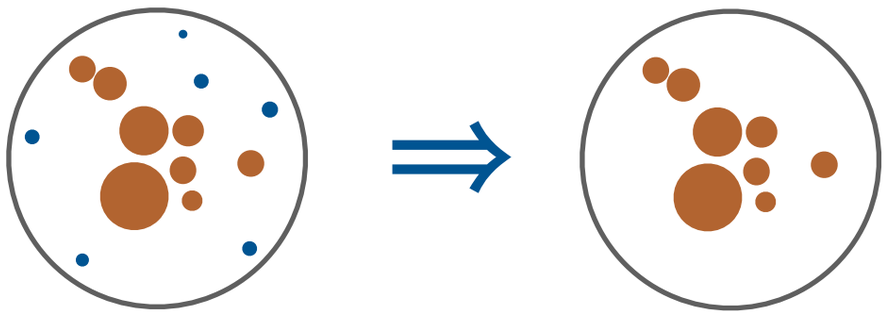
$$\int \frac{\mathrm{d}\theta}{\theta}\,\mathrm{d}z\,P(z)$$

Collinear singularity

Energy sharing ~1/z

Measurable?

Soft Drop Grooming

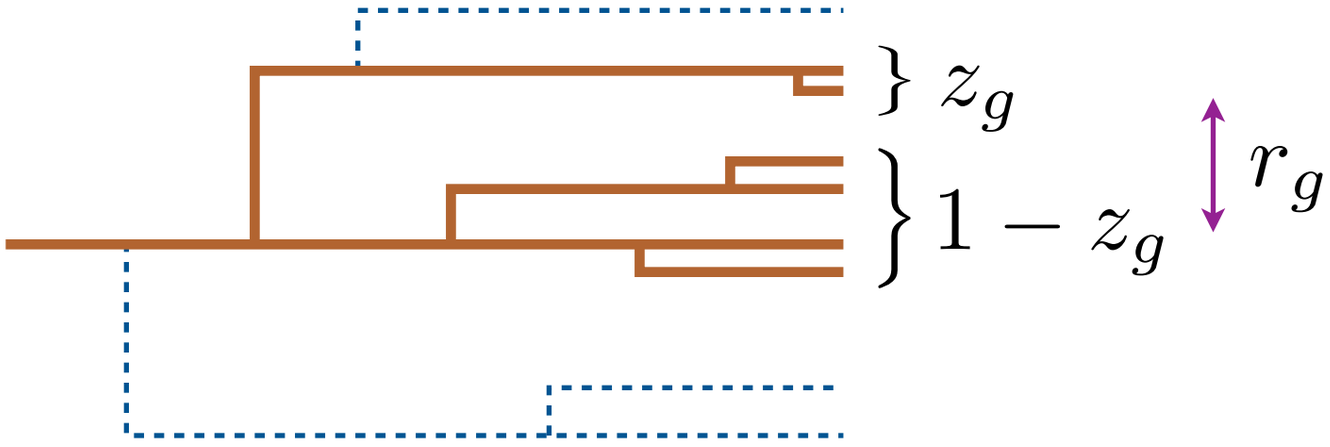


$$z > z_{\text{cut}}\,\theta^{\beta}$$

energy threshold

angular exponent

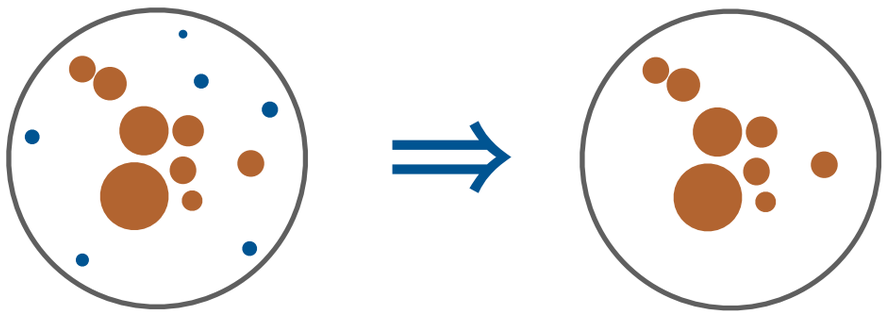
Recursively drop wide-angle soft radiation



Angular-ordered Tree

[Larkoski, Marzani, Soyez, JDT, 2014]
[see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam, 2013]

Soft Drop Grooming

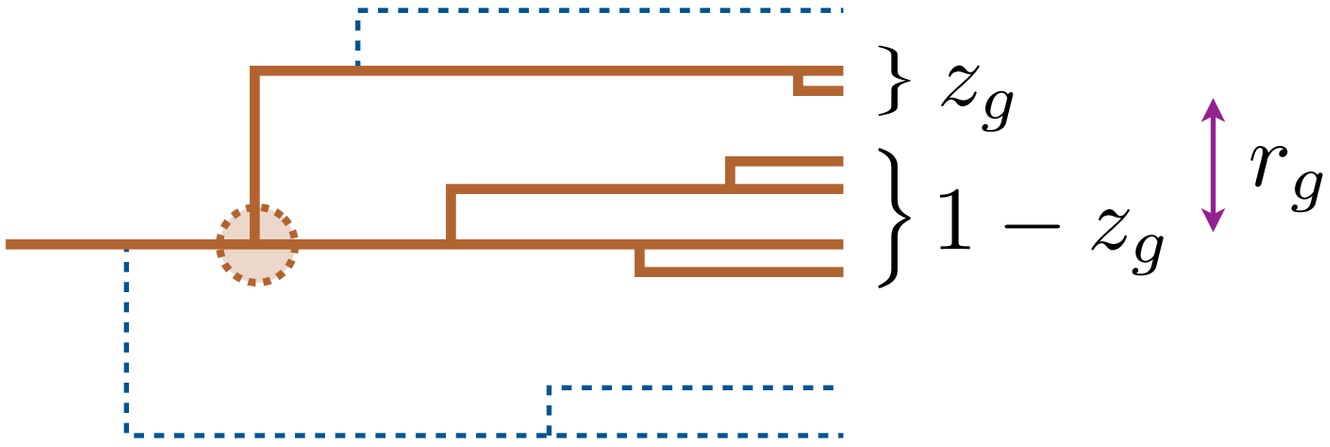


$$z > z_{\text{cut}}\,\theta^{\beta}$$

energy threshold

angular exponent

Recursively drop wide-angle soft radiation



Angular-ordered Tree

$$\int \frac{\mathrm{d}\theta}{\theta}\,\mathrm{d}z\,P(z)$$

Splitting Function?

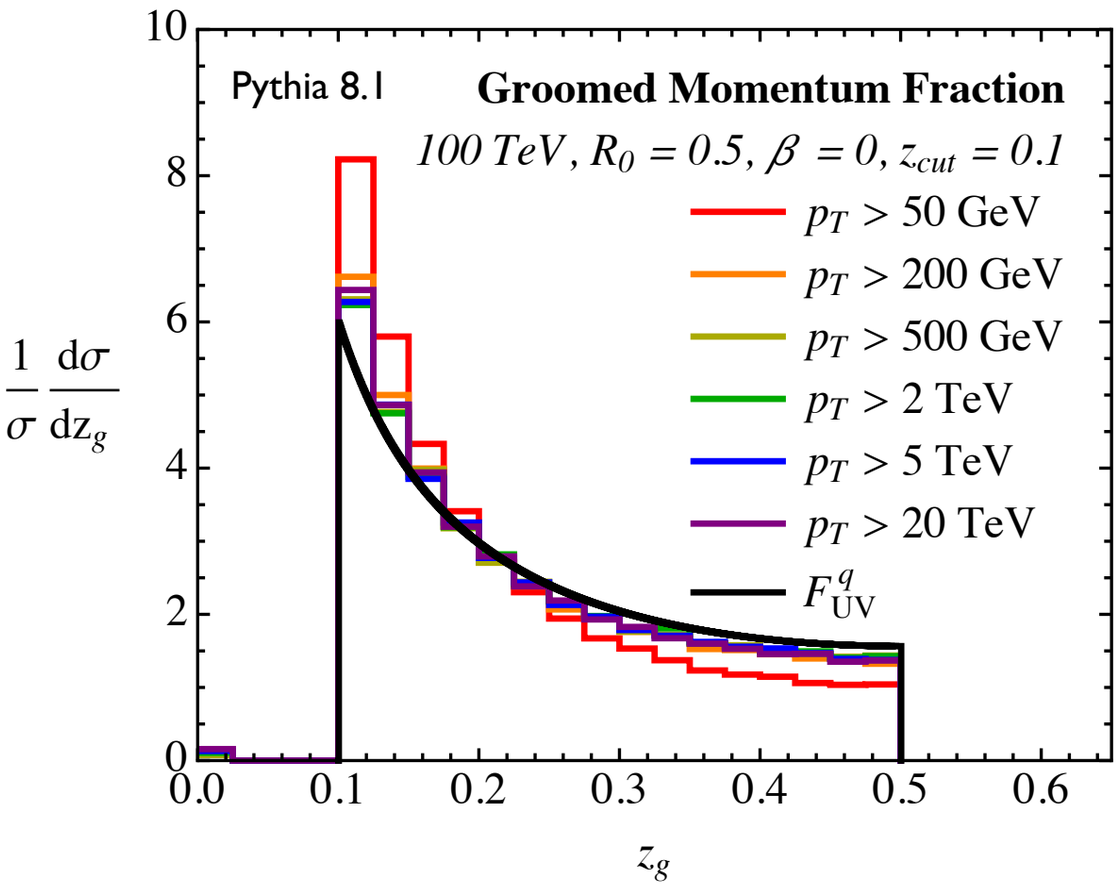
[Larkoski, Marzani, Soyez, JDT, 2014]
[see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam, 2013]

A Standard Candle for Jets

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \frac{\overline{P}_i(z_g)}{\int_{z_{\mathrm{cut}}}^{1/2} dz\, \overline{P}_i(z)} + \ldots$$

suppressed going from LHC to FCC

(β = 0)



≈ independent of α_s (!)
≈ independent of jet p_T and radius
≈ same for quarks and gluons

calculable deviations from universality

Soft Drop Grooming ⇔ *QCD Splitting Functions*

[Larkoski, Marzani, JDT, 2015; see also Larkoski, JDT, 2014]

Measurements ⇔ *Core Principles of SM*

W Polarization in Top Decay ⇔ *Spontaneous Electroweak Breaking*

Higgs Pair Production ⇔ *Nature of Higgs Potential*

High Mass Drell-Yan ⇔ *Electroweak Coupling Running*

Higgs Event Shapes ⇔ *Quark/Gluon Color Scaling*

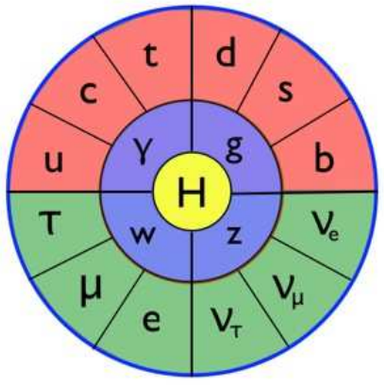
Neutrino Jets ⇔ *Electroweak Radiation*

Soft Drop Grooming ⇔ *QCD Splitting Functions*

… ⇔ …

Non-trivial, intrinsically interesting
Deviations are sure signs of new physics

Probing the Standard Model & Beyond



Principles

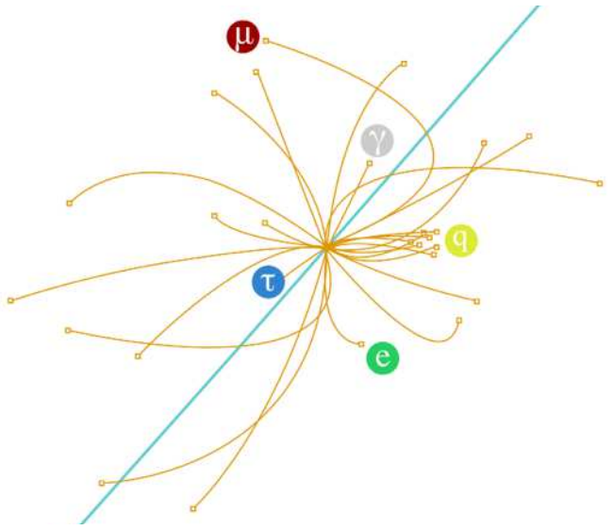
Quantum Mechanics
Lorentz/CPT Invariance
Spin/Statistics
Locality/Causality/Unitarity
Global Symmetries
Conservation Laws
Spontaneous Symmetry Breaking
Gauge Invariance
Anomaly Cancellation
Renormalization Group Evolution
Effective Field Theories
Naturalness (??)
…

Paradigms

Chiral Mass Generation
Quark Flavor Structure
P/CP Violation
Accidental B, L Conservation
Asymptotic Freedom
(?) Baryogenesis
(?) Dark Matter
(?) Unification
(?) Supersymmetry
(?) Extended Space-time
(?) Neutrino Mass Generation
(?) Strong CP
…

Discoveries Beyond the Standard Model

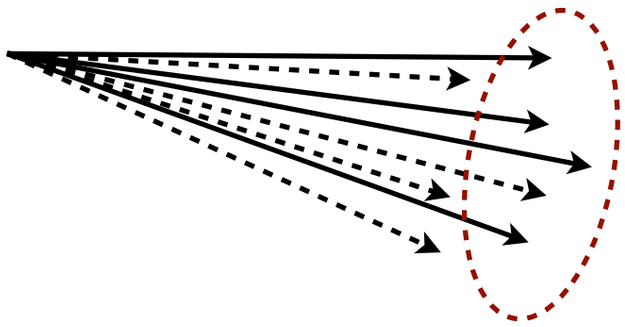
Revelations Within the Standard Model



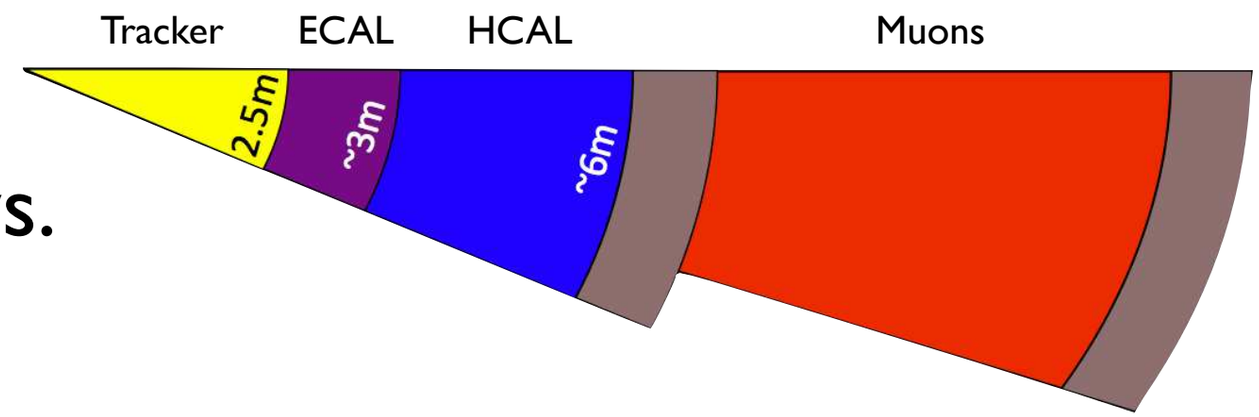
New Opportunities for Data Analysis?

Better Measurements through Theory?

FCC-hh Challenge: Calorimeter Angular Resolution



vs.

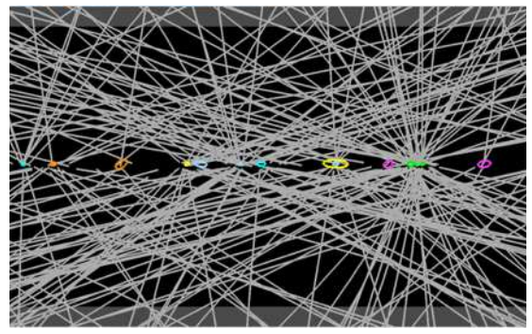


Track-Corrected Measurements?

$$m_{\text{approx}} = m_{\text{tracks}} \frac{p_T}{p_{T,\text{tracks}}}$$

Track-Only Measurements?

Pileup Mitigation



Theory Challenge: Track Fraction is Non-perturbative

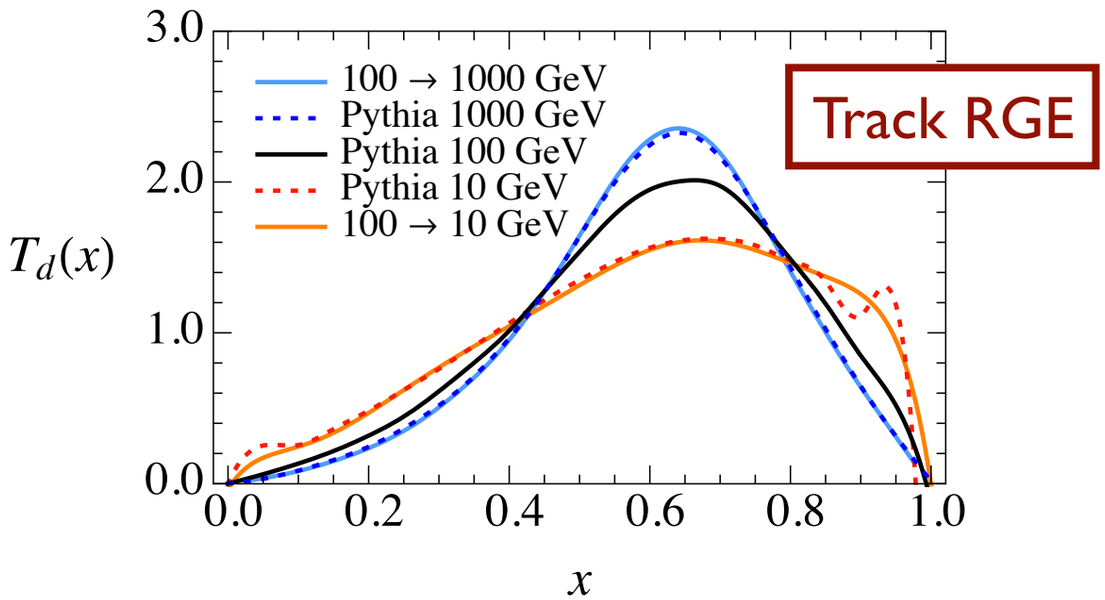
[see e.g. Larkoski, Maltoni, Selvaggi, 2015]

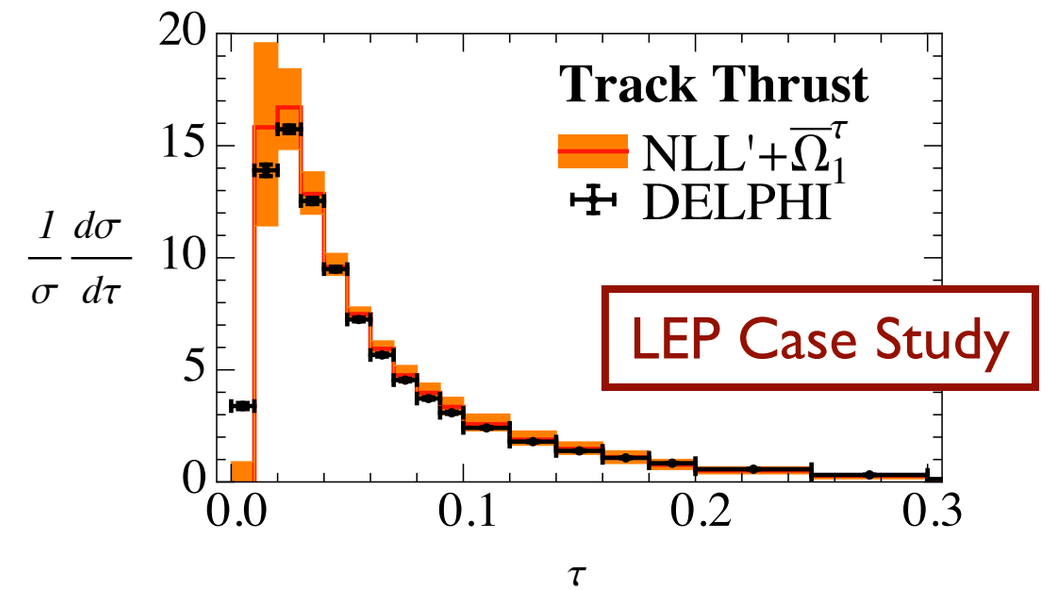
Better Measurements through Theory?

Introducing Track Functions: $T_i(x, \mu)$

(Generalizes to other non-perturbative effects)

track fraction — RGE, just like PDFs





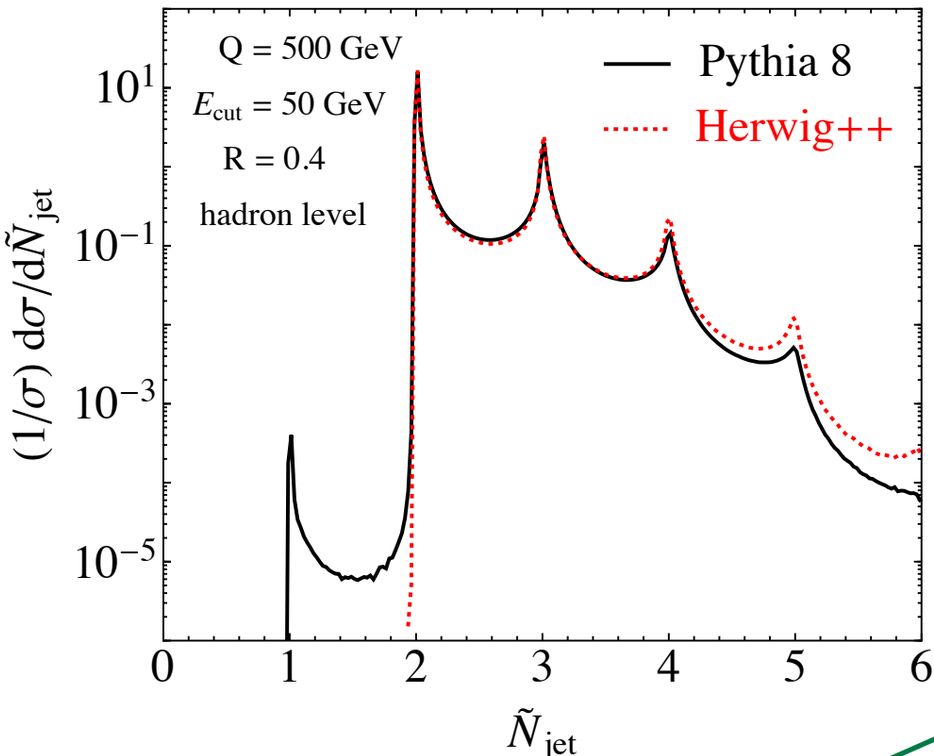
Measure at FCC-ee/he, extrapolate to FCC-hh?

[Chang, Procura, JDT, Waalewijn, 2013]
[see also Waalewijn, 2012; Krohn, Lin, Schwartz, Waalewijn, 2012; Larkoski, JDT, Waalewijn, 2014]

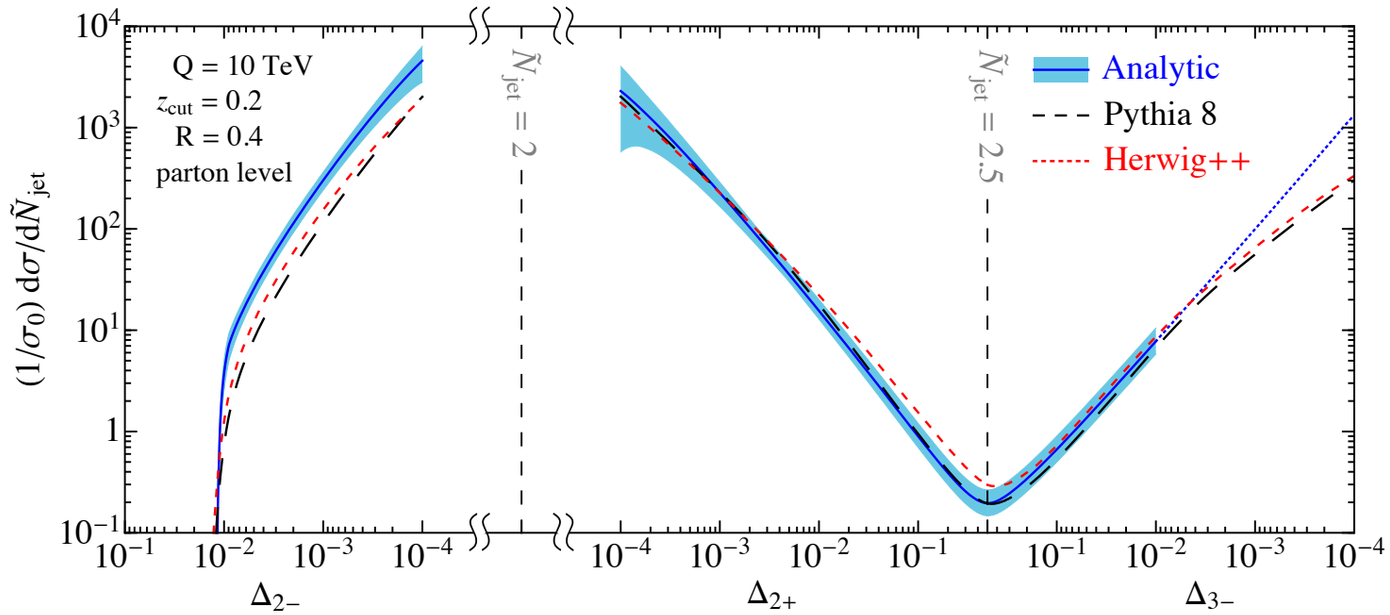
Planning for Archival Data Access?

"Jets Without Jets" $\widetilde{N}_{\text{jet}}(p_{T\text{cut}}, R) = \sum_{i \in \text{event}} \frac{p_{Ti}}{p_{Ti,R}} \Theta(p_{Ti,R} - p_{T\text{cut}})$

In Monte Carlo…



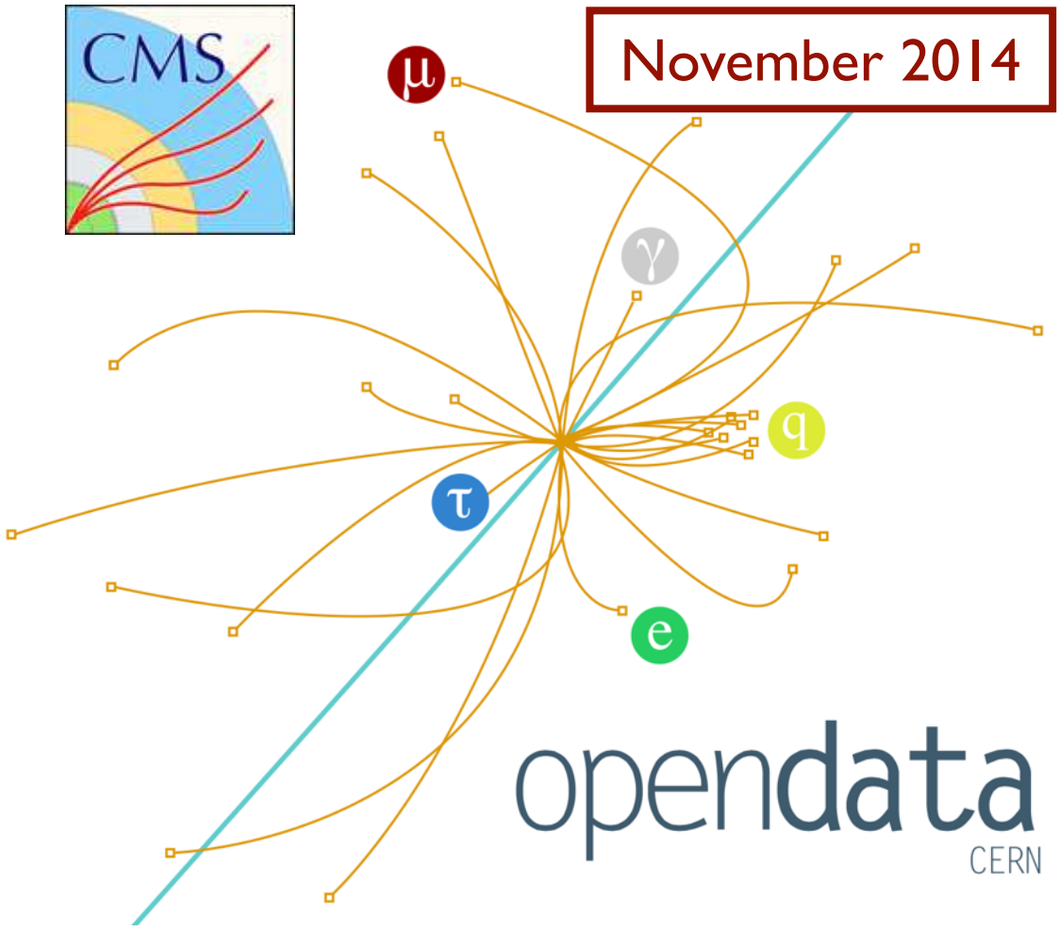
…in QCD at $O(\alpha_s^2)$…

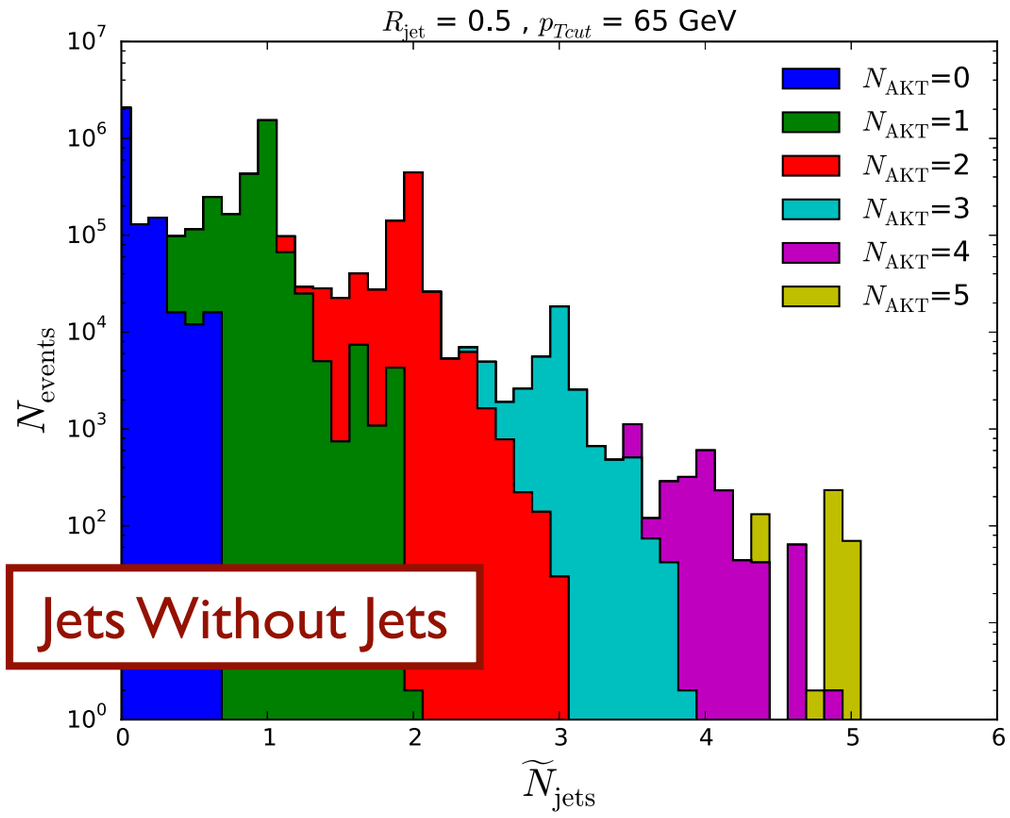


…in data?

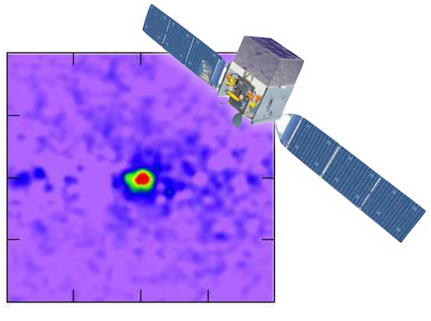
[Bertolini, Chan, JDT, 2013; Bertolini, JDT, Walsh, 2015]

Planning for Archival Data Access?



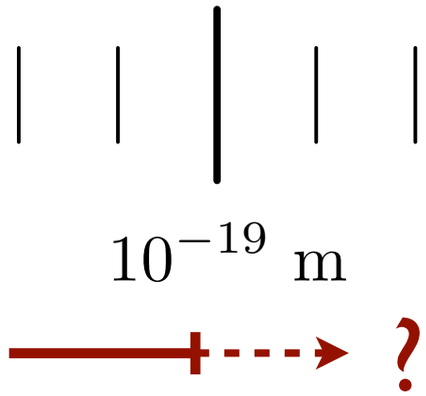


Extremely preliminary from Wei Xue
(limited sample size, missing MinBias, no JEC factors)

c.f. Fermi 

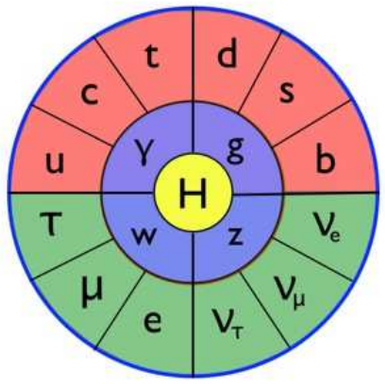
Can FCC accelerate scientific progress through judicious open data releases?

Summary



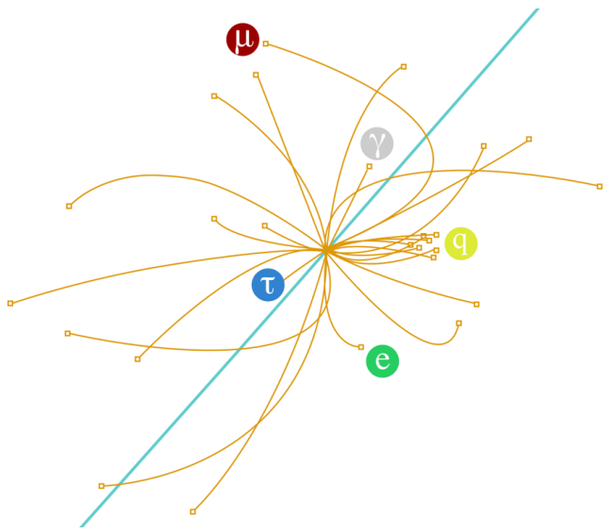
Discoveries Beyond the Standard Model

My Big 3: Exploiting the Higgs, Dark Matter, Hierarchy Problem
Ultimate reason: Pushing the frontiers, exploring the unknown



Revelations Within the Standard Model

Novel measurements to test deep principles of nature,
explore fundamental structures of quantum field theory

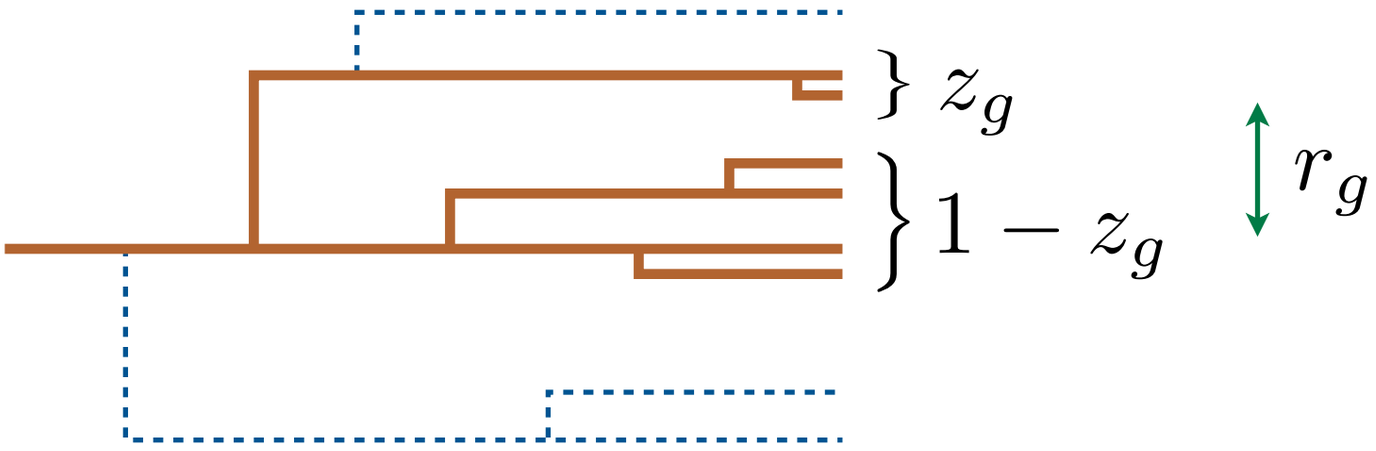


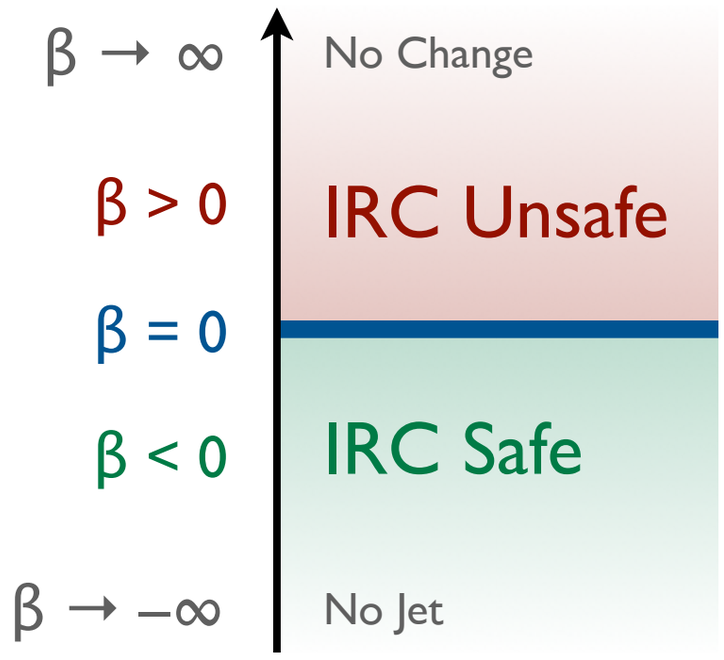
New Opportunities for Data Analysis?

Prospects for theory-aided measurements?
Archival data on day one (+N year offset)?

Backup Slides

Soft Drop Energy Sharing





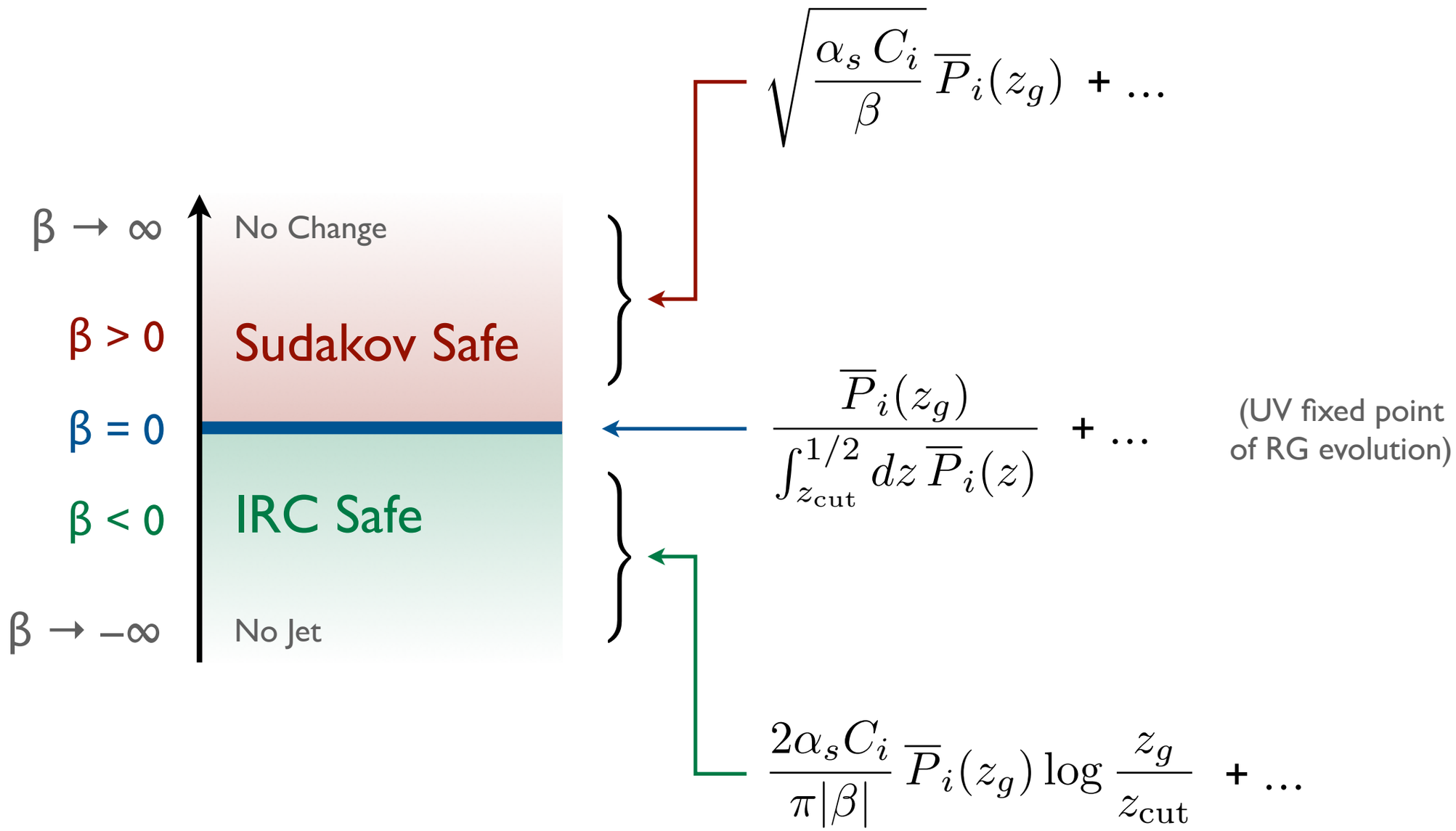
Want: $p(z_g)$ **Need:** r_g Dynamical jet radius (safe companion)

Insight: $$p(z_g) = \int \mathrm{d}r_g \, p(r_g) \, p(z_g|r_g)$$

Form factor regulates collinear singularity

[Larkoski, Marzani, JDT, 2015]

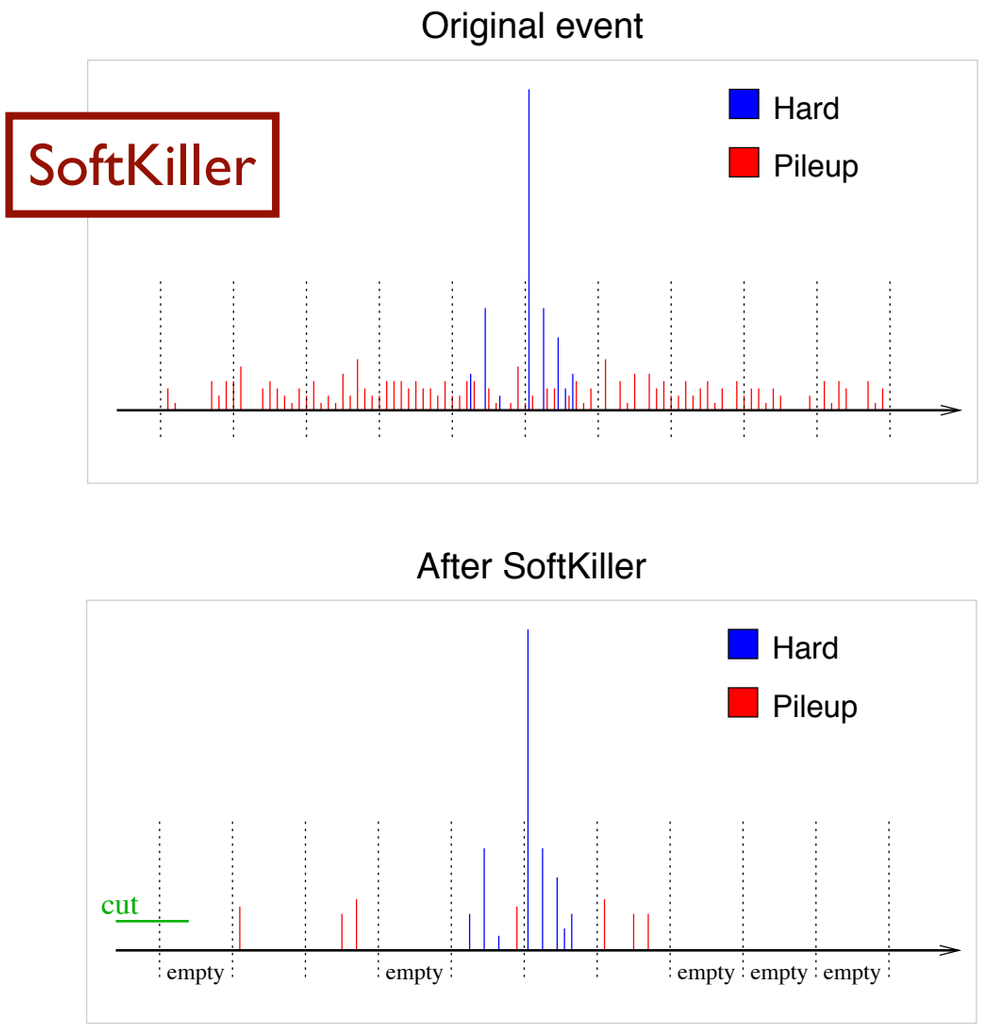
“Phase Diagram” for Observables



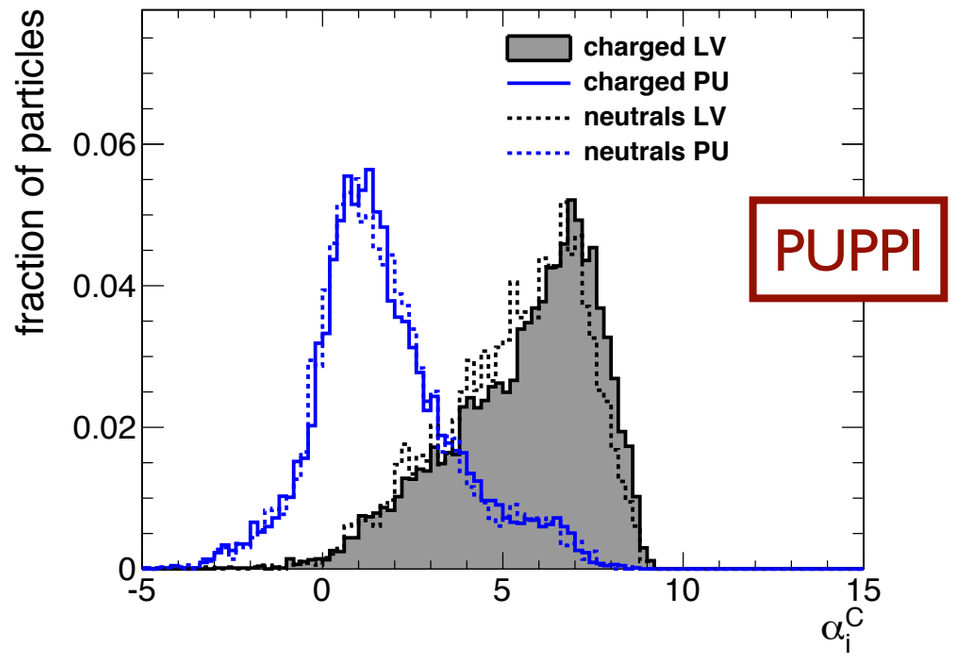
Rich structures within the standard model (and QFTs)

[Larkoski, Marzani, JDT, 2015; see also Larkoski, JDT, 2013]

Joint Detector/Pileup Mitigation Development?



Prioritizes Energy Resolution?



$$\alpha_i \simeq \log \sum_j \frac{p_{Tj}}{R_{ij}}$$

Energy/Angle Tradeoff?

[Cacciari, Salam, Soyez, 2014]
[Bertolini, Harris, Low, Tran, 2014]