Unparticles and QCD Jets

John Terning
UC Davis

Outline

* Motivation
* Unparticles
* LHC signals
* QCD Jets
* Conclusions

Hierarchy Problem Now

SUSY

Technicolor

Hierarchy Problem Now

SUSY

Extra Dimensions

Technicolor

Hierarchy Problem Now

SUSY

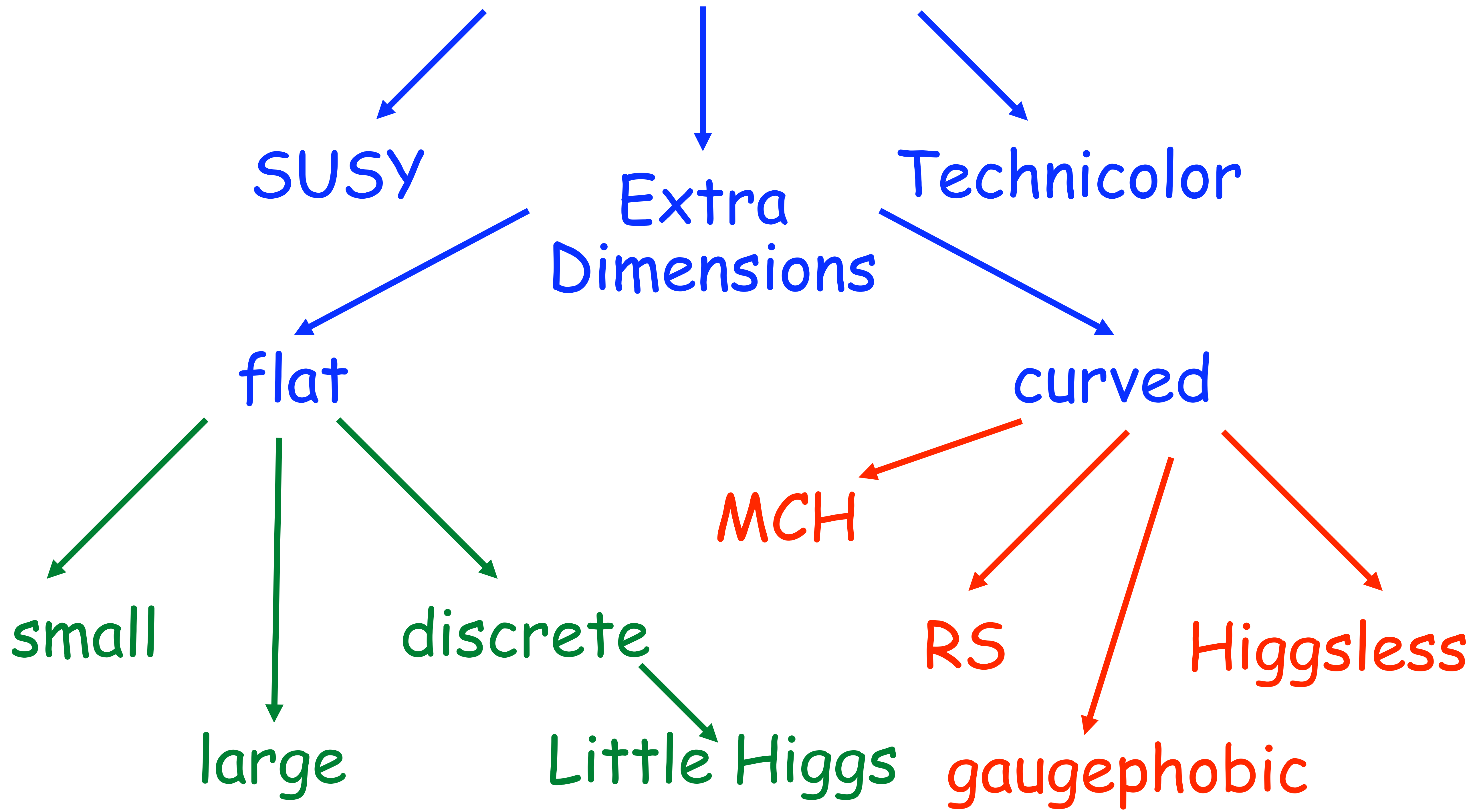
Extra Dimensions

Technicolor

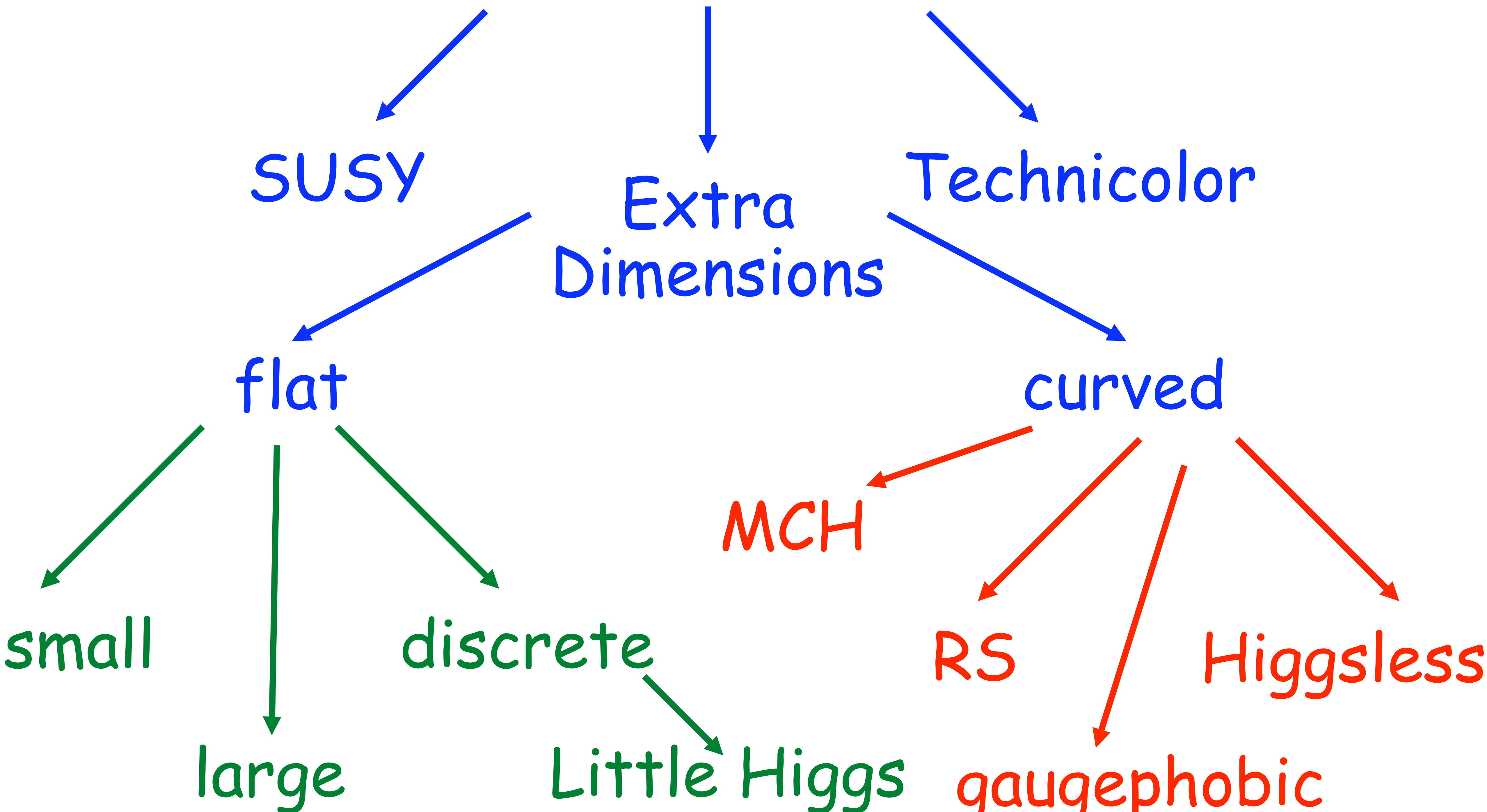
flat

curved

Hierarchy Problem Now



Hierarchy Problem Now



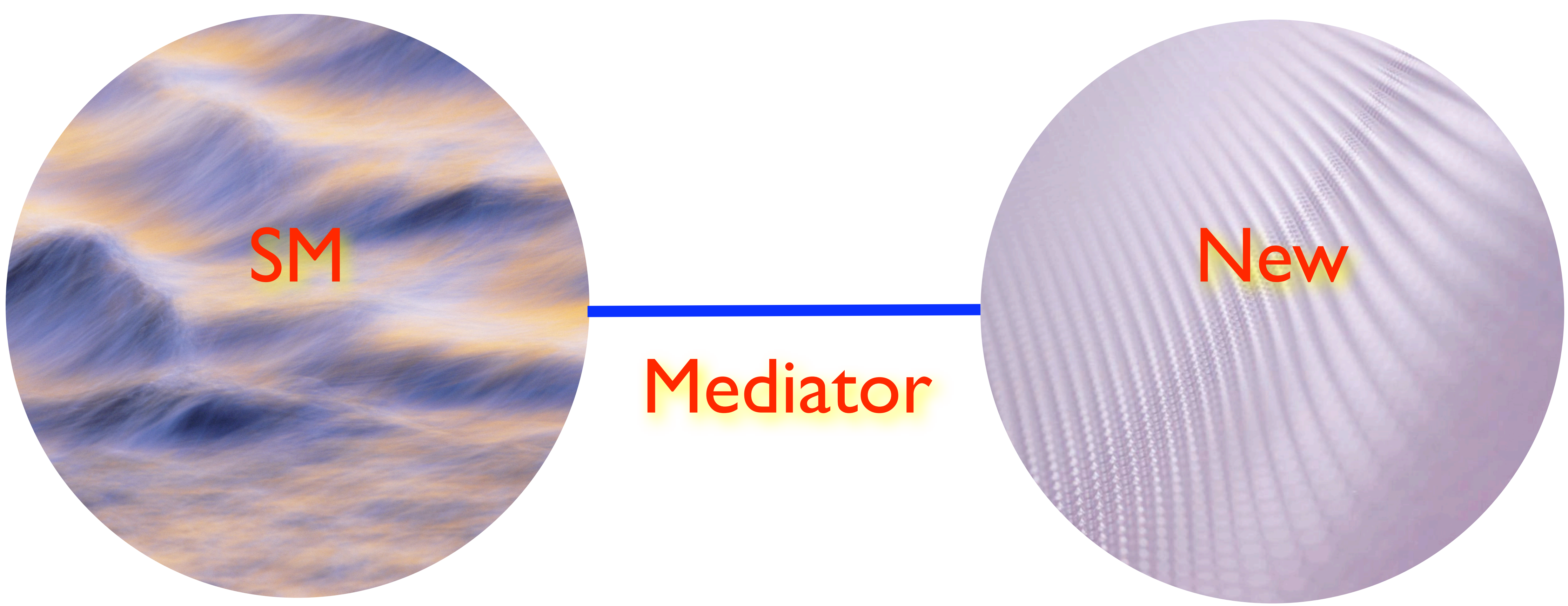
All of these are fine-tuned!

Looking Under the Lamppost

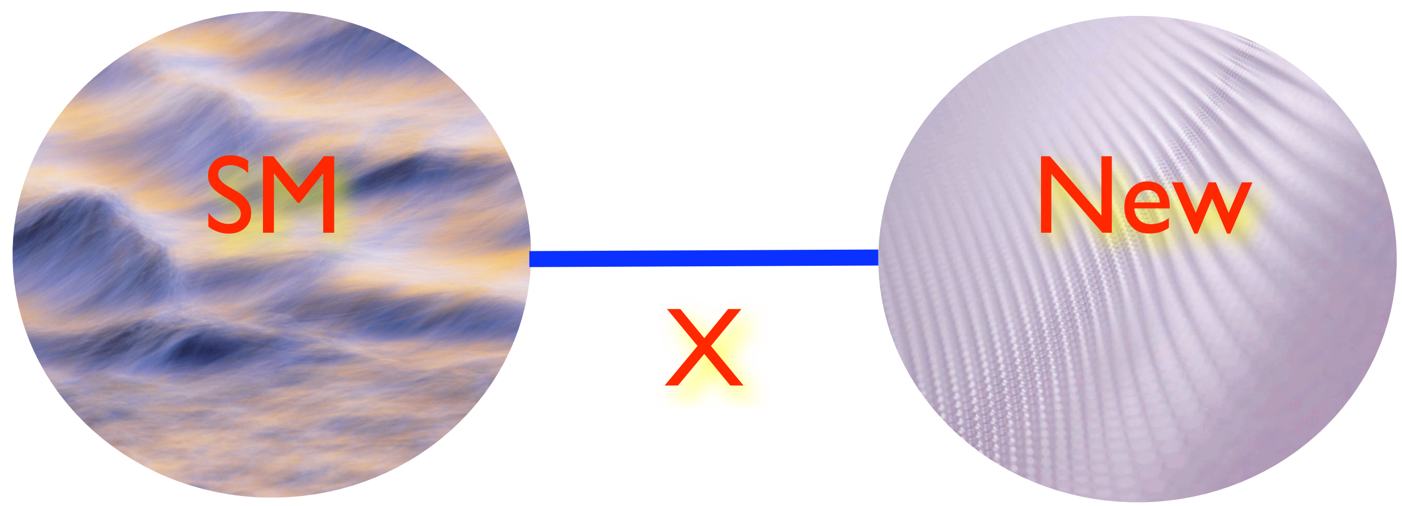
Looking Under the Lamppost

quirks/hidden valleys/unparticles

New Sector



New Sector

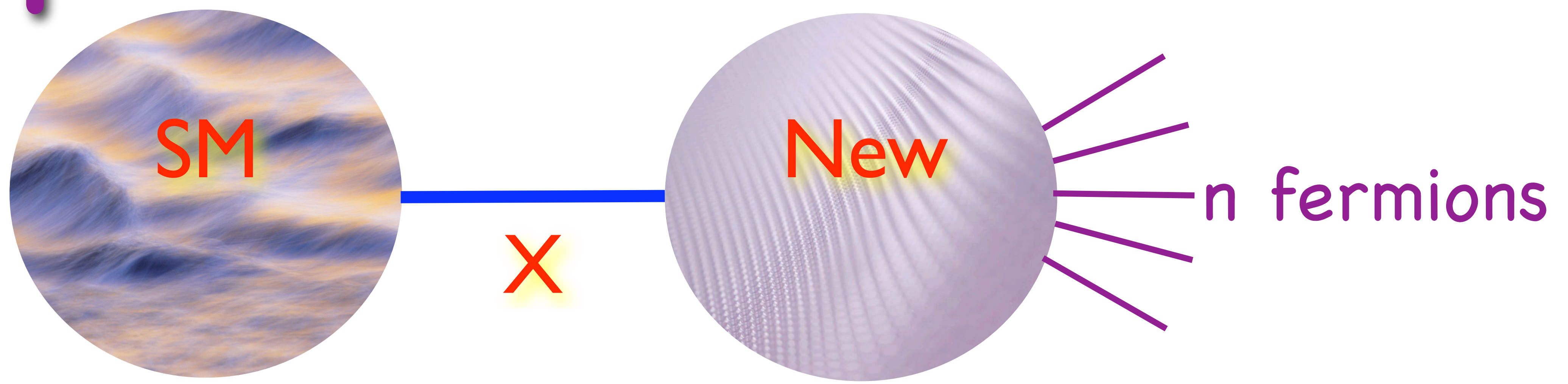


$$M_X \gg \mathrm{TeV} \qquad \frac{\mathcal{O}_{SM}\mathcal{O}_{new}}{M_X^n}$$

$$M_X \sim \mathrm{TeV} \qquad gg \to X + \ldots$$

$$X \to Y_{new} + \ldots$$

Quirk/Hidden Valley/ Unparticle Model



X is a heavy fermion with both SM and New gauge couplings

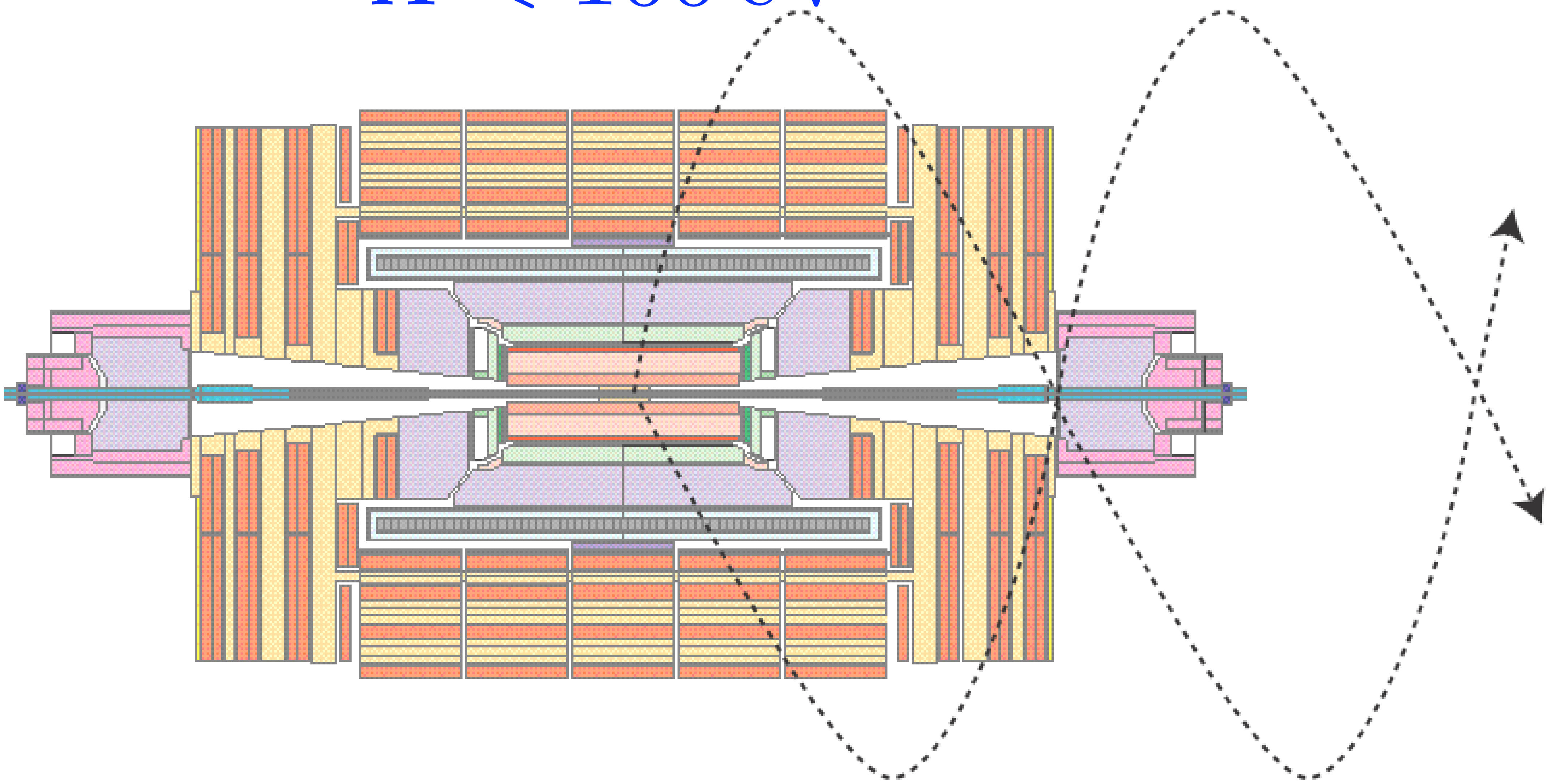
stringy confinement ⟶ quirks n=0

QCD-like confinement ⟶ hidden valley n=few

CFT, no confinement ⟶ unparticles n=many

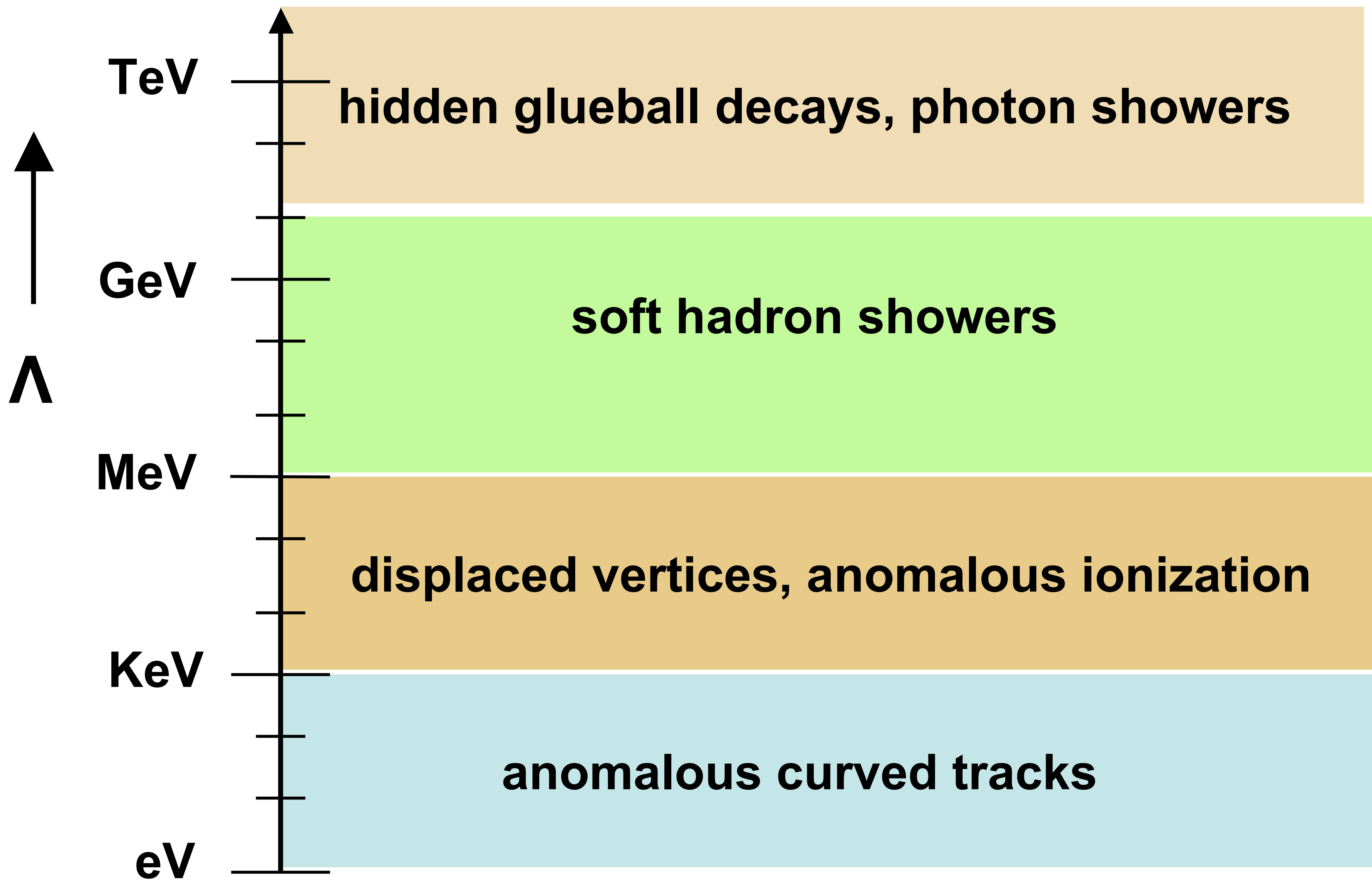
Quirks

$$\Lambda < 100\,\mathrm{eV}$$



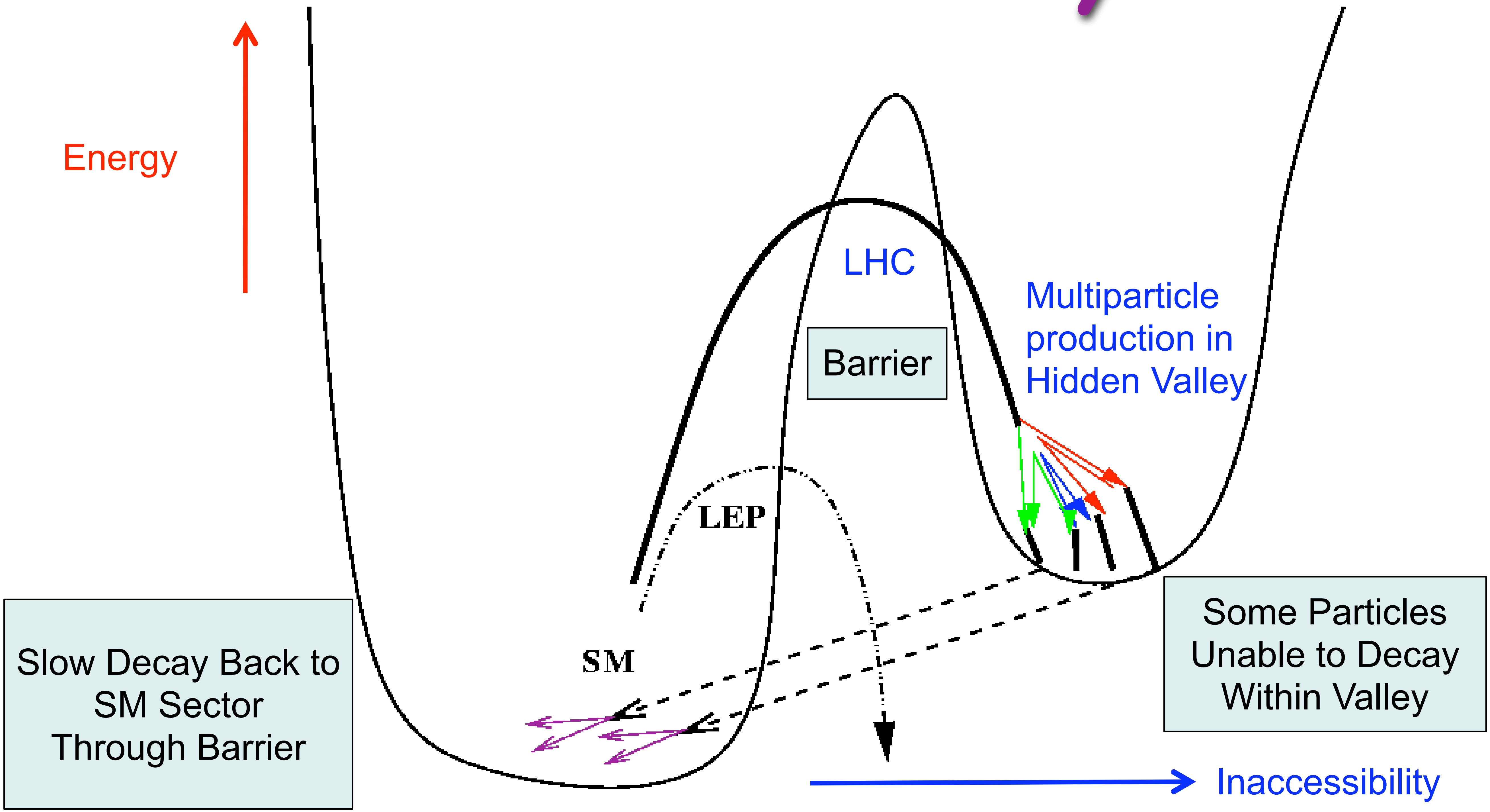
Luty, Kang, Nasri in preparation

Quirks



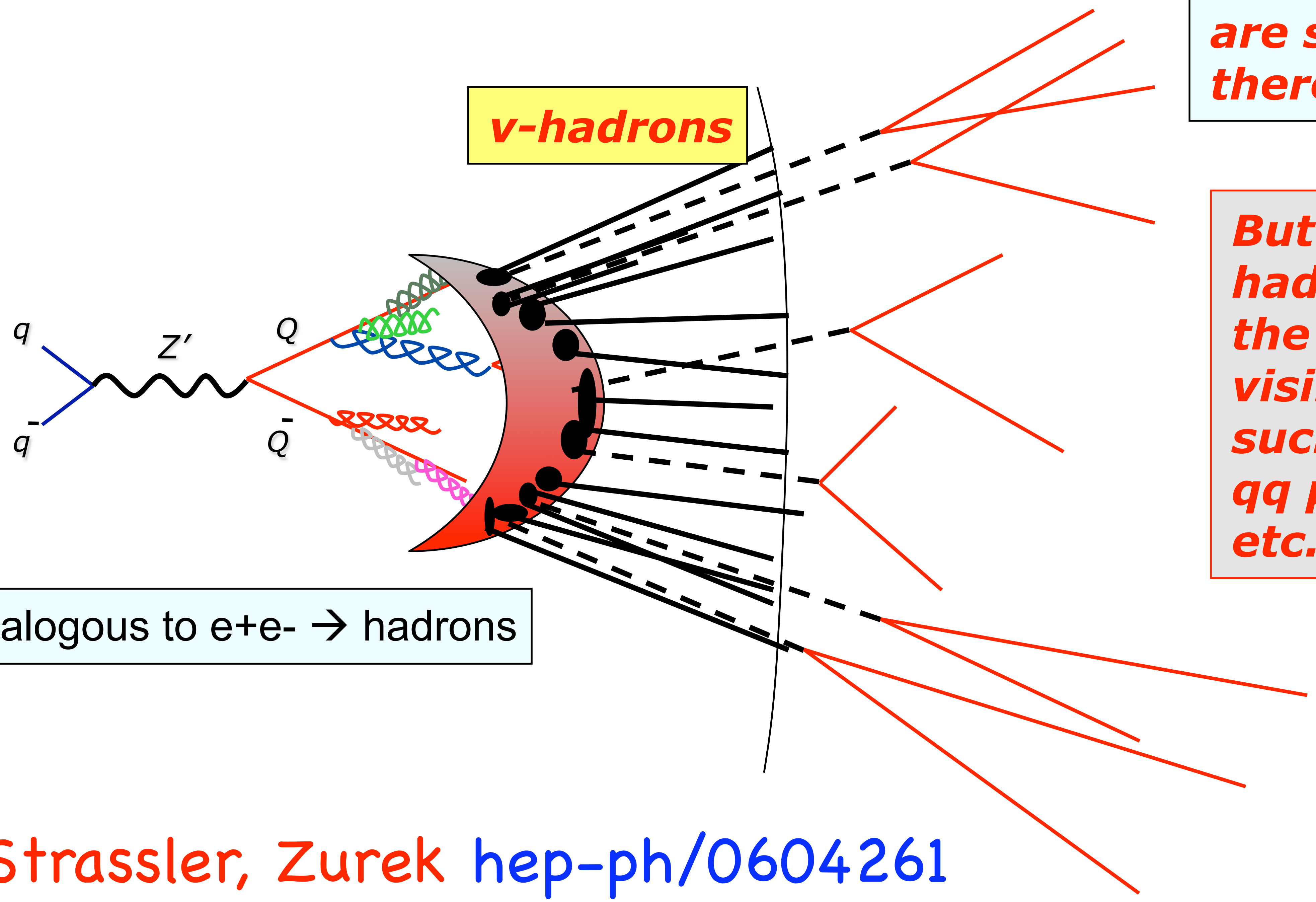
Chacko, Harnik in preparation

Hidden Valleys



Strassler, Zurek hep-ph/0604261, 0605193

Hidden Valleys



Some v-hadrons are stable and therefore invisible

But some v-hadrons decay in the detector to visible particles, such as bb pairs, qq pairs, leptons etc.

Analogous to e+e- → hadrons

Strassler, Zurek hep-ph/0604261

Unparticles

$$
\begin{aligned}
\Delta(p,d) &\equiv \int d^4x\, e^{ipx} \langle 0|T\mathcal{O}(x)\mathcal{O}^\dagger(0)|0\rangle \\
&= \frac{A_d}{2\pi}\int_0^\infty (M^2)^{d-2}\frac{i}{p^2-M^2+i\epsilon}dM^2 \\
&= i\frac{A_d}{2}\frac{\left(-p^2-i\epsilon\right)^{d-2}}{\sin d\pi}
\end{aligned}
$$

$$
A_d = \frac{16\pi^{5/2}}{(2\pi)^{2d}}\frac{\Gamma(d+1/2)}{\Gamma(d-1)\,\Gamma(2d)}
$$

Georgi hep-ph/0703260, 0704.2457

Unparticles

$$\Delta(p) \propto (-p^2 - i\epsilon)^{d-2}$$

$$d\Phi(p) \propto \frac{1}{\Gamma(d-1)}\theta(p^0)\theta(p^2)(p^2)^{d-2}$$

* must be equivalent to RS2

Georgi hep-ph/0703260, 0704.2457

Broken CFT's are Interesting

* IR cutoff at TeV turns RS2 to RS1
* address the hierarchy problem
* new phenomenology for LHC

Quarks are Unparticles

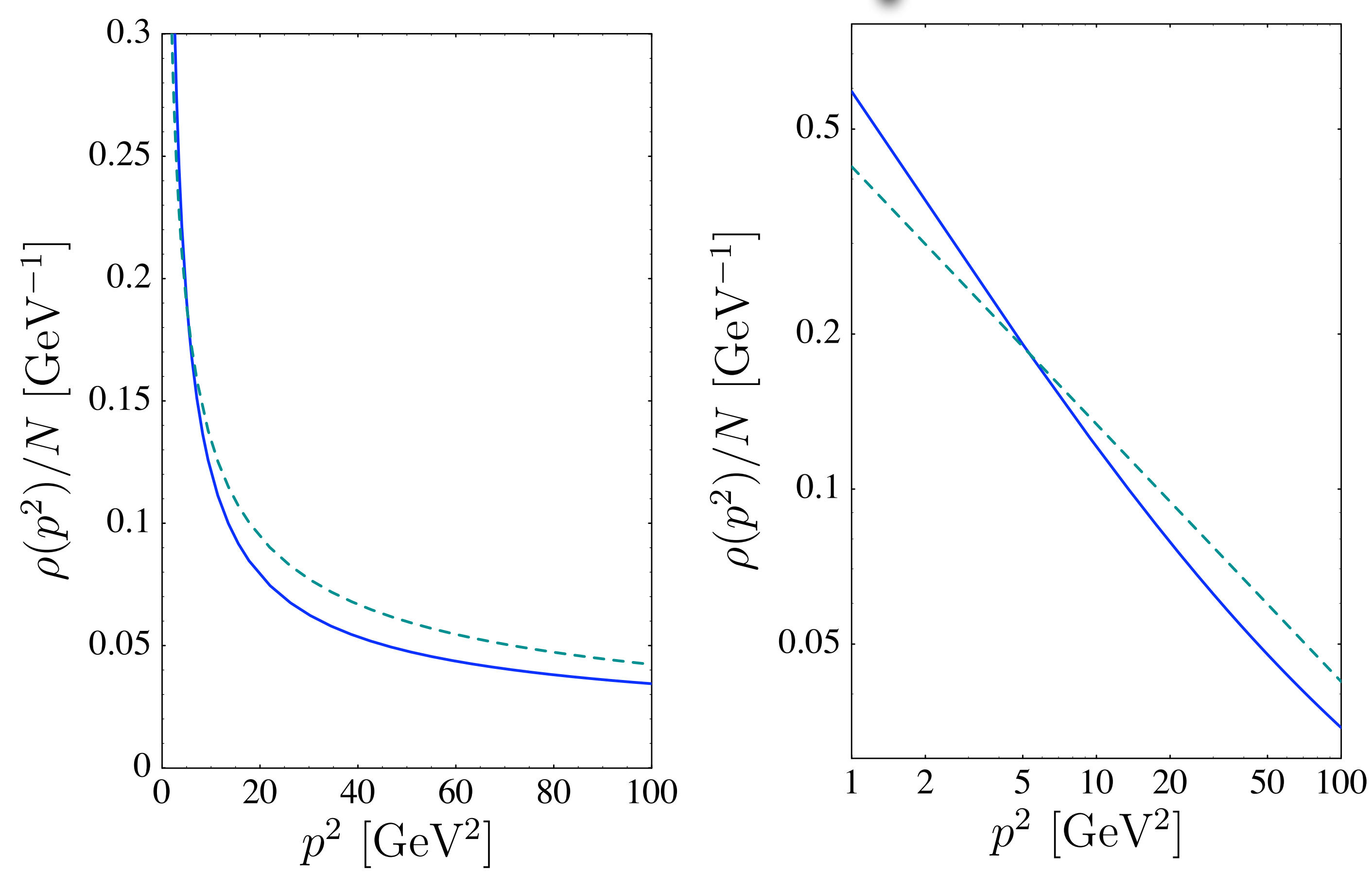
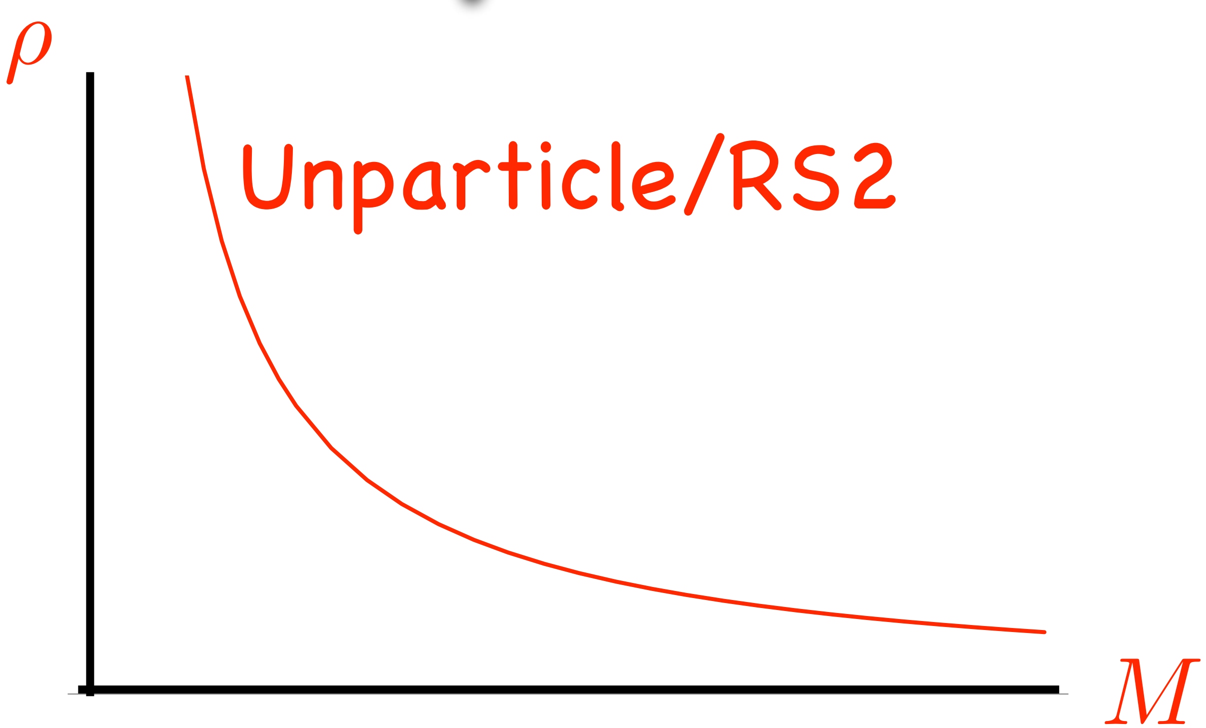
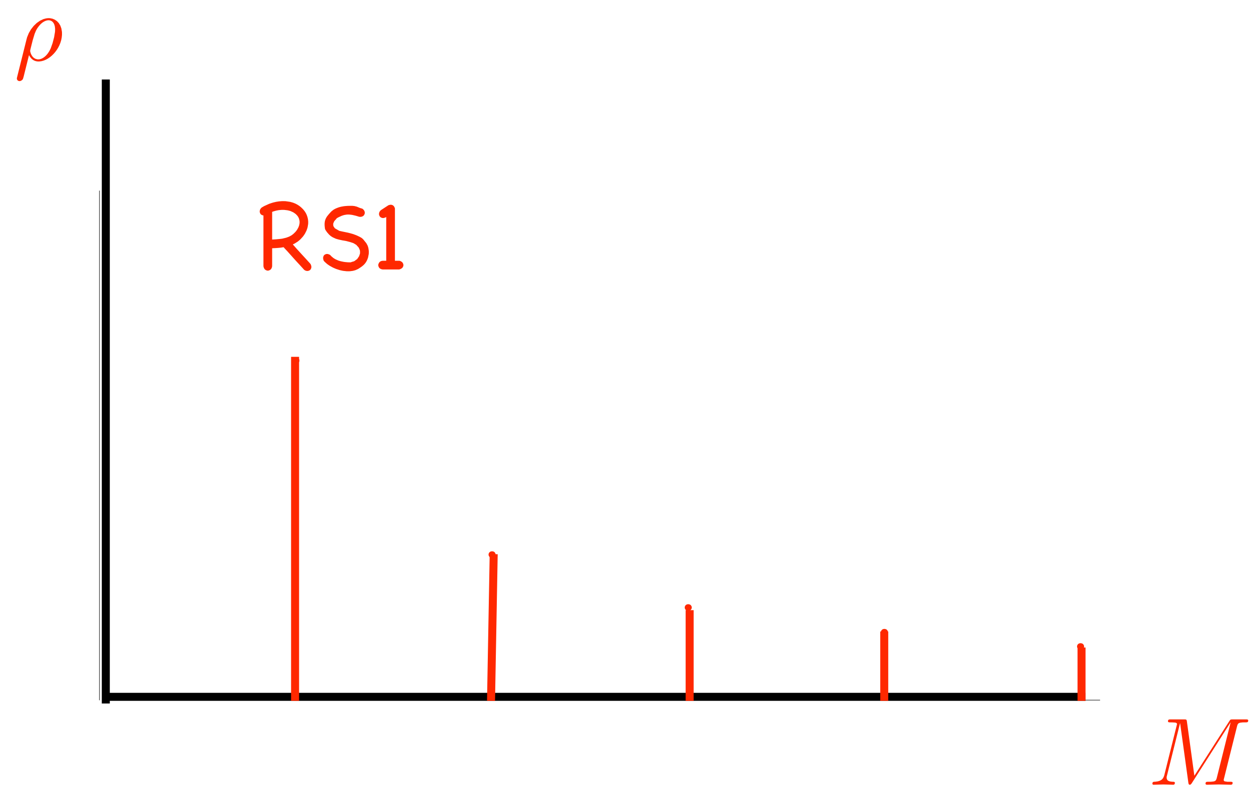


FIG. 1. Comparison of the unparticle spectral density (2) (dashed) and the spectral density (9) of a massless quark jet at next-to-leading order in QCD (solid). We use parameters $M = 10\,\mathrm{GeV}$ and $\eta = 0.5$. The right plot shows the same results on logarithmic scales.

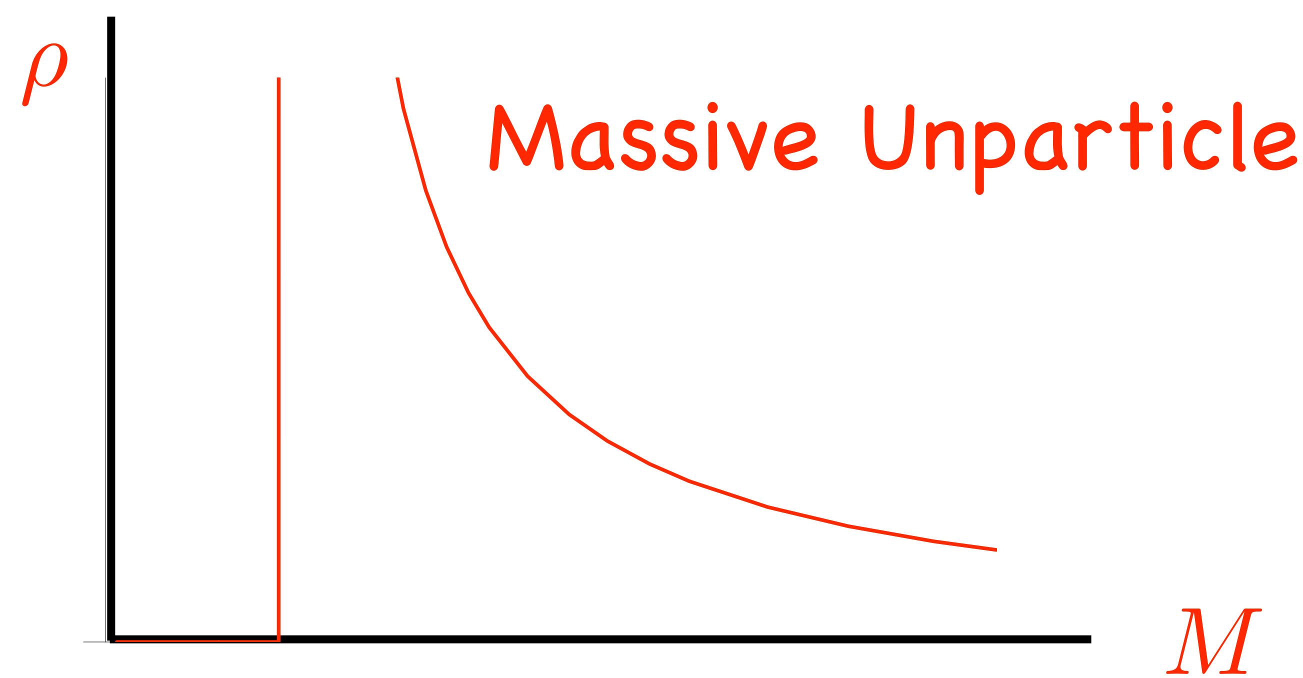
Neubert hep-ph/0708.0036

Spectral Densities





$$\Delta(p) \sim (\mu^2 - p^2 - i\epsilon)^{d-2}$$



Fox, Rajaraman, Shirman hep-ph/0705.3092

Effective Action

$$S = \int \frac{d^4p}{(2\pi)^4}\, \phi^\dagger(p) \left[\mu^2 - p^2\right]^{2-d} \phi(p)$$

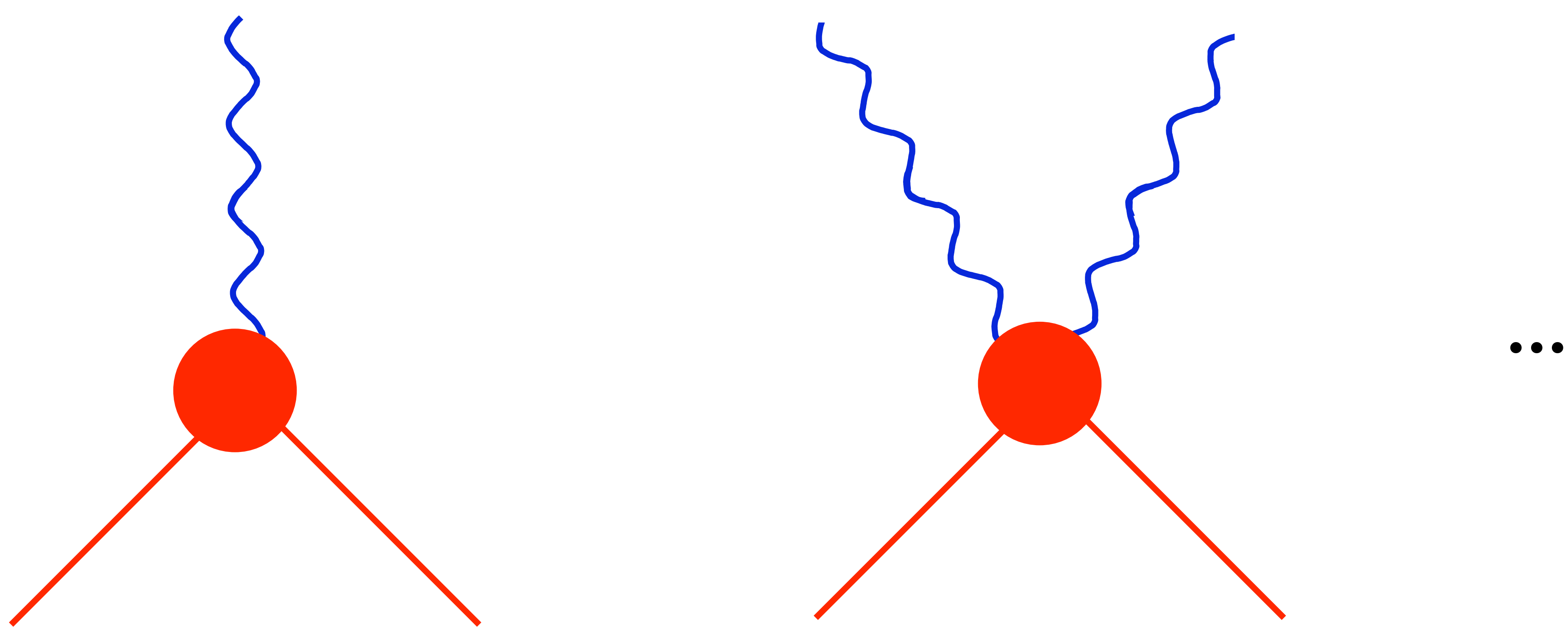
$$S = \int d^4x d^4y\, \phi^\dagger(x) F(x-y) \phi(y)$$

$$F(x-y) = \left[\partial^2 - \mu^2\right]^{2-d} \delta(x-y)$$

Minimal Gauge Coupling

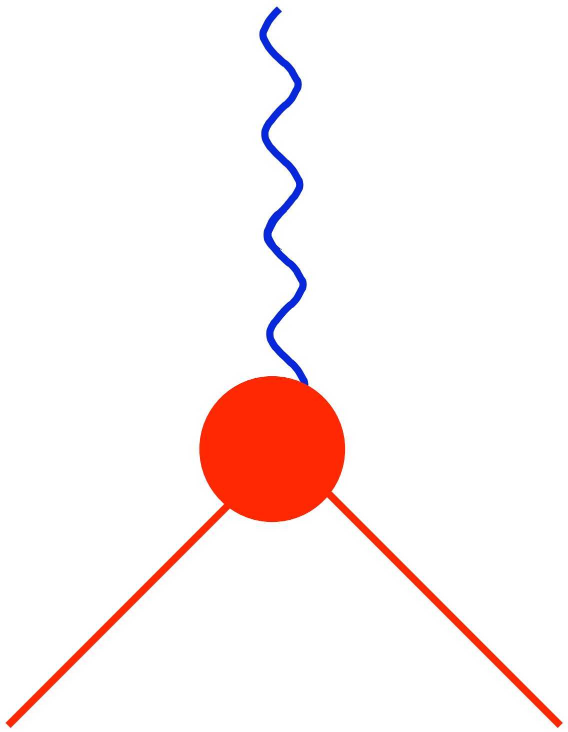
$$F(x-y) \to F(x-y)W(x,y)$$

$$W(x,y) = P\exp\left[-igT^a \int_x^y A_\mu^a dw^\mu\right]$$



cf Mandelstam Ann Phys **19** (1962) 1

Gauge Vertex



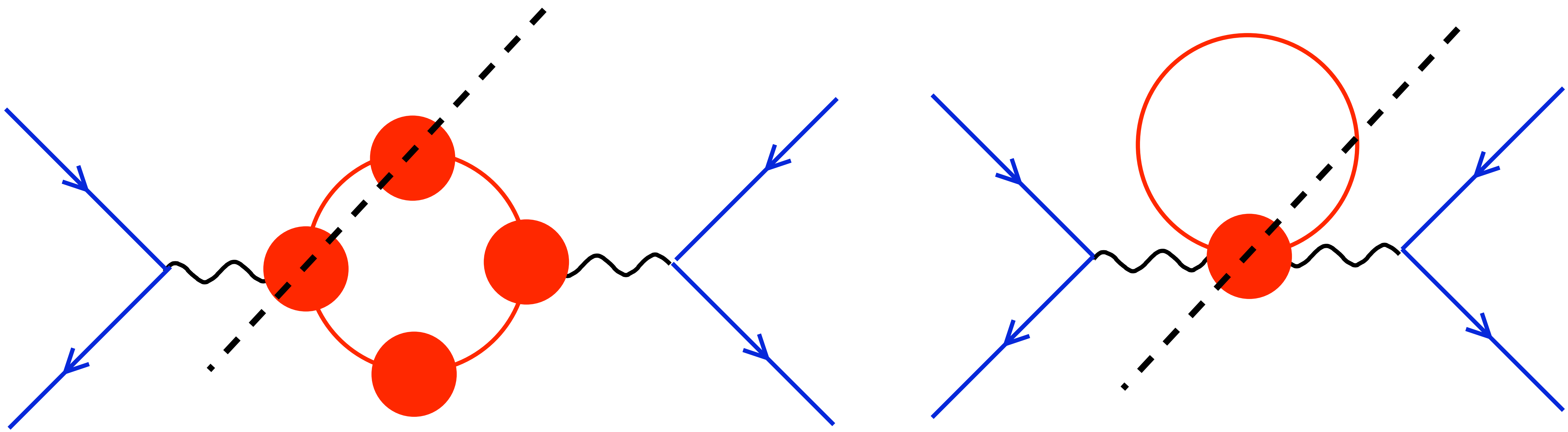
$$= -igT^a \frac{2p^\alpha + q^\alpha}{2p \cdot q + q^2} \left[\left(\mu^2 - (p+q)^2\right)^{2-d} - \left(\mu^2 - p^2\right)^{2-d} \right]$$

Ward-Takahashi Identity

$$ig\Gamma^{a\alpha}(p,q) \quad \propto \quad \frac{2p^\alpha + q^\alpha}{2p\cdot q + q^2}\left[\left(\mu^2 - (p+q)^2\right)^{2-d} - \left(\mu^2 - p^2\right)^{2-d}\right]$$

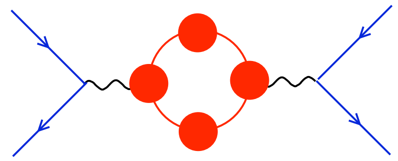
$$iq_\mu \Gamma^{a\mu} = \Delta^{-1}(p+q,m,d)T^a - T^a\Delta^{-1}(p,m,d)$$

unquark production

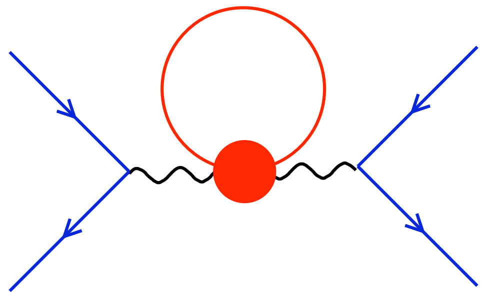


unquark production

$$\left.\frac{\sigma_d}{\sigma_1}\right|_{\text{diag. }1} = \frac{d(2-d)^2(4-d)}{3}$$



$$\left.\frac{\sigma_d}{\sigma_1}\right|_{\text{diag. }2} = \frac{(d-1)(d-2)(d^2-5d+3)}{3}$$



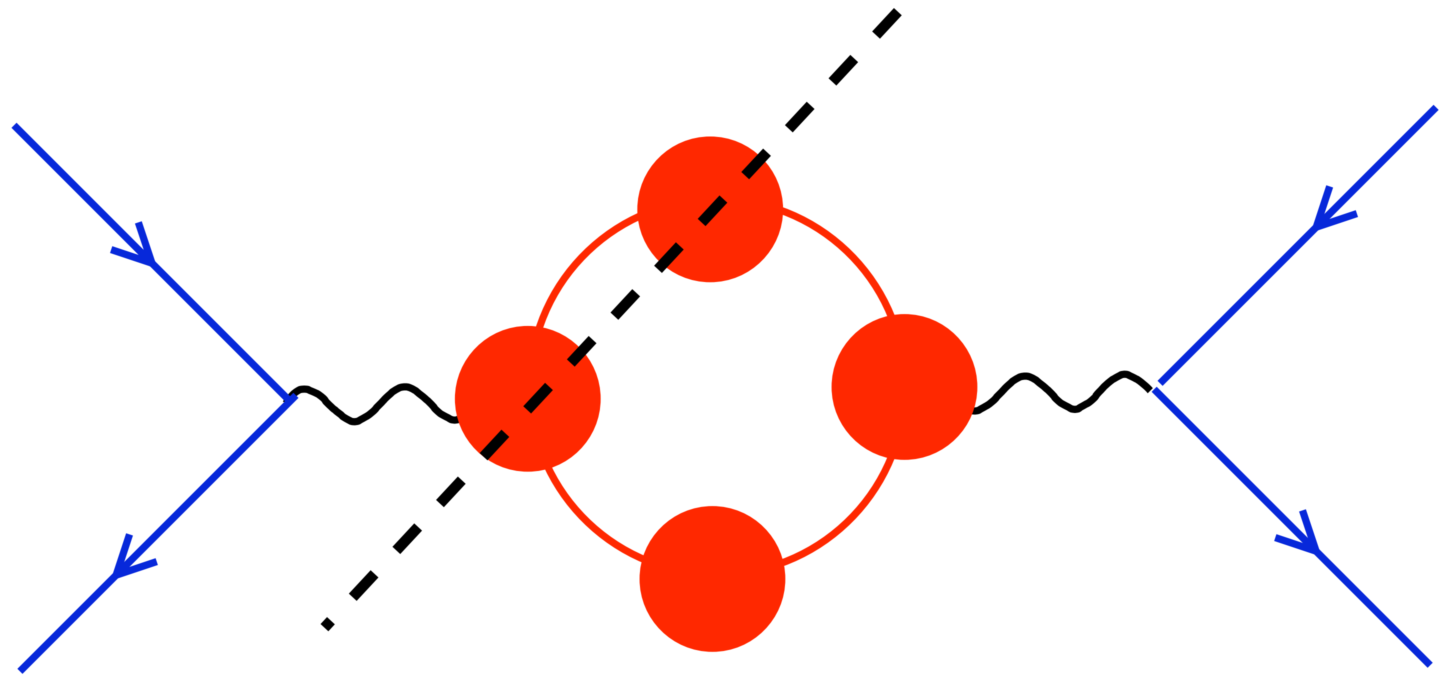
$$\sigma_d(m) = (2-d)\left(\sqrt{1-\frac{4m^2}{q^2}}\right)^3 \sigma_1(m=0) \qquad d<2$$

Cacciapaglia, Marandella, JT hep-ph/0708.0005

In General

$$
\begin{aligned}
\ln Z &= -\frac{1}{2}\ln \mathrm{Det}(D^2+m^2)^{2-d} \\
&= -\frac{1}{2}\mathrm{Tr}\ln(D^2+m^2)^{2-d} \\
&= -\frac{1}{2}(2-d)\mathrm{Tr}\ln(D^2+m^2)
\end{aligned}
$$

Colored Unproduction



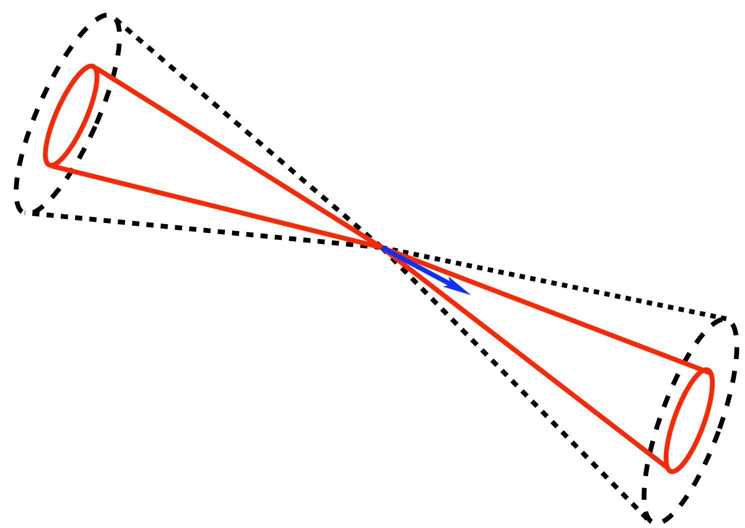
$$\sigma_{unparticle} = (2-d)\sigma_{particle} \qquad d < 2$$

R-Hadrons, anomalous jets/E loss

Cacciapaglia, Marandella, JT hep-ph/0708.0005

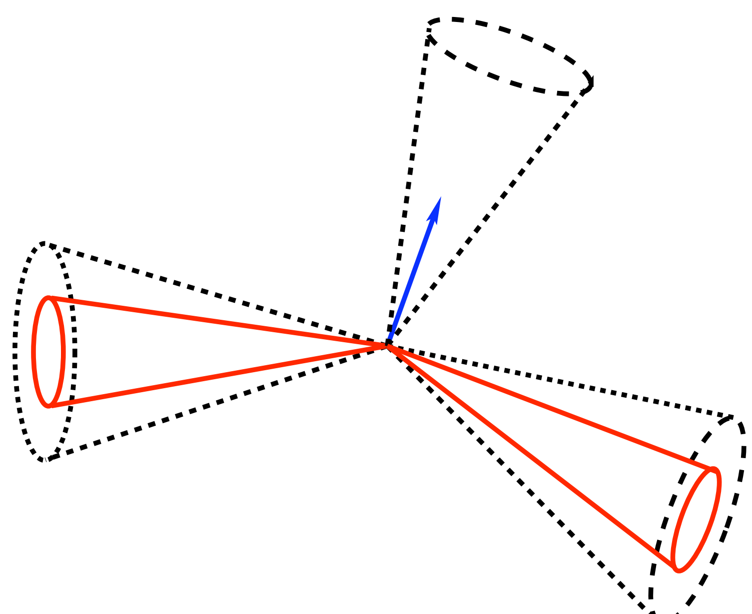
Anomalous Jets

2 jets + $\not{p}_T$



Pair production

$\not{p}_T$ is aligned to visible p_T

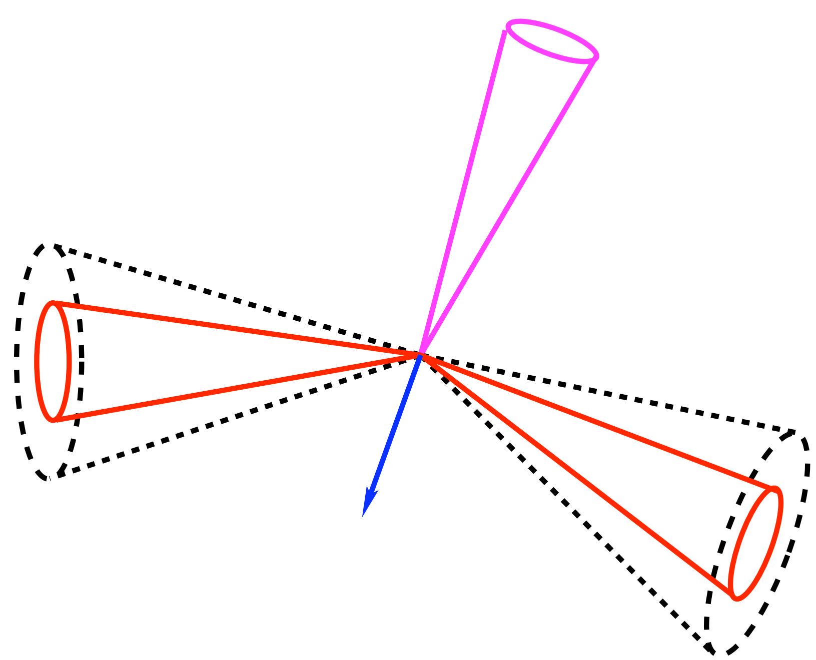


CFT stuff radiation

$\not{p}_T$ not aligned

Anomalous Jets

QCD radiation

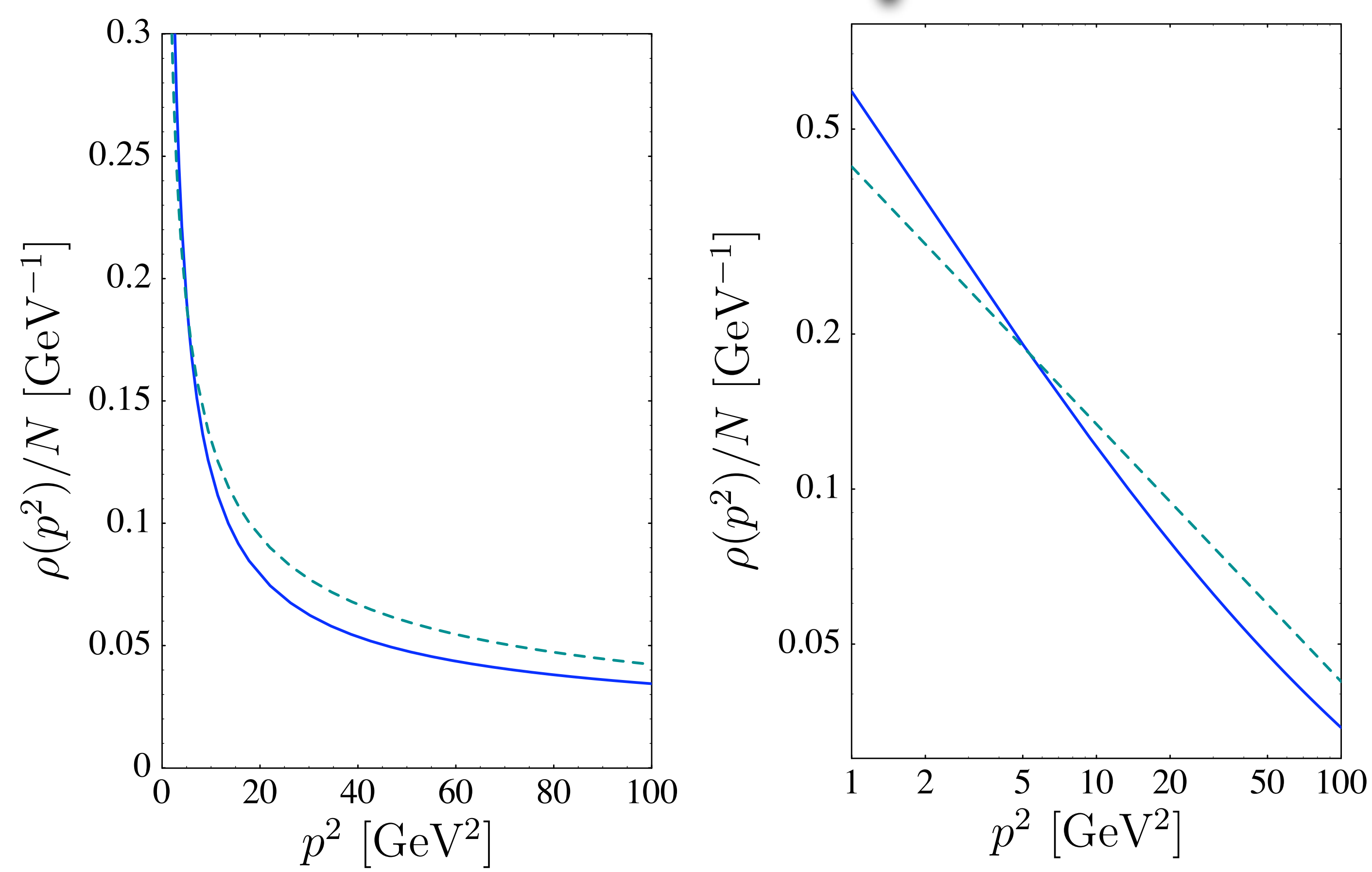


Hard jet + 2 jets + $\not{p}_T$

$\not{p}_T$ in opposite direction to the hard jet

Detailed calculation and simulation needed (background)

Quarks are Unparticles



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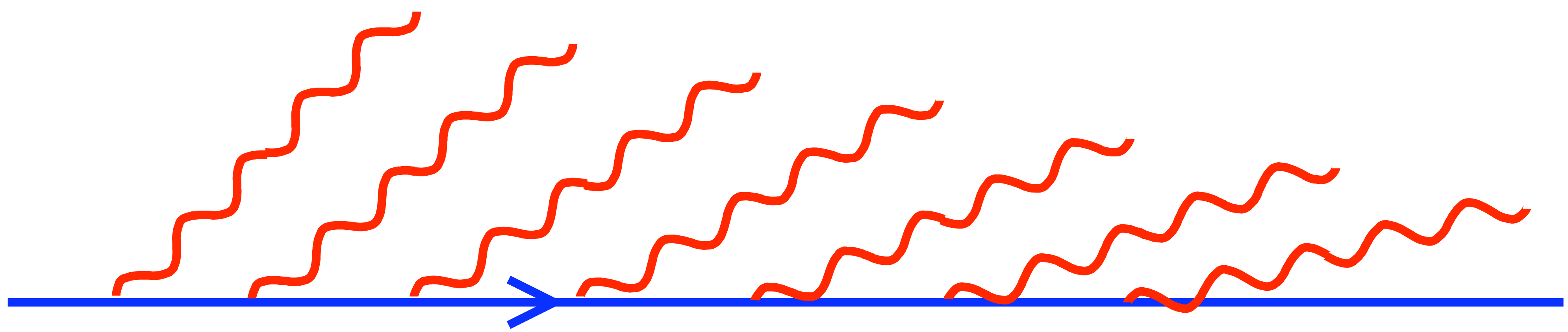
Neubert hep-ph/0708.0036

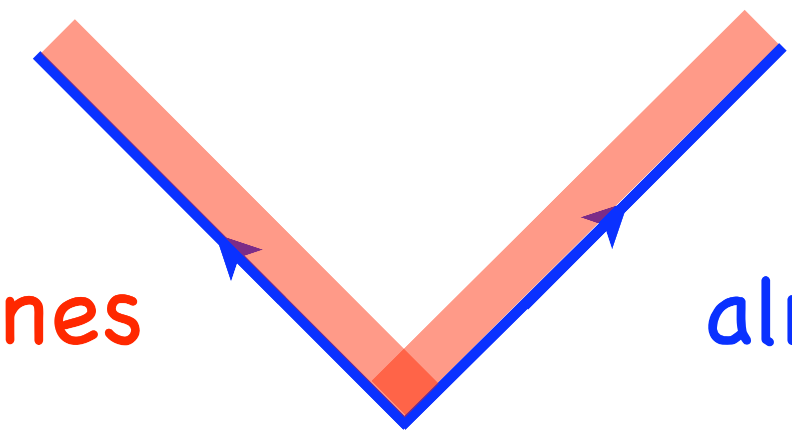
Pythia Jets



resum large logs in tree-level amplitudes
from soft and collinear gluons

SCET Jets

collinear Wilson lines

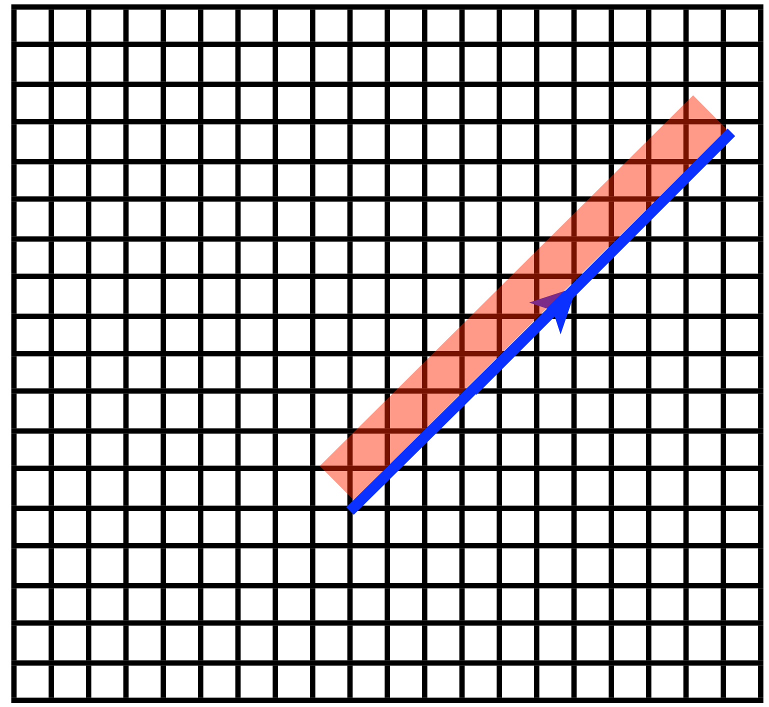


almost light-like quarks

resum enhanced tree-level amplitudes:
soft and collinear gluons

some one-loop corrections

Lattice Jets



quark with Wilson line

is gauge invariant

non-perturbative two point function

Conclusions

to understand unparticle
signals at the LHC we need a
non-perturbative understanding of
jets

it wouldn't hurt to get a better
understanding of QCD jets either

AdS/CFT

$$\phi(p,\epsilon) = \phi_0(p)$$

$$S = \frac{1}{2}\int d^4x dz\, \partial_5 \left(\frac{R^3}{z^3}\phi\partial_5\phi\right) = \frac{1}{2}\int d^4x \left(\frac{R^3}{z^3}\phi\partial_5\phi\right)|_{z=\epsilon}$$

$$\phi_0(p) \to \epsilon^{-\nu} R^{-3/2}\phi_0(p)$$

$$S = \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\phi_0(-p)\phi_0(p)\left[\Delta_{\mathrm{local}}(p) + \Delta_{\mathrm{non-local}}(p)\right]$$

AdS/CFT

$$d = 2 - \nu$$

$$S_{\mathrm{UV}} = \int \frac{d^4p}{(2\pi)^4} \frac{\nu - 2}{\epsilon} \phi_0(-p)\phi_0(p)$$

$$S' = \frac{1}{2} \int \frac{d^4p}{(2\pi)^4} \phi_0(-p)\Delta(p)\phi_0(p) + c \int \frac{d^4p}{(2\pi)^4} \phi_0(-p)A(p)$$

$$S' = -\frac{c^2}{2} \int \frac{d^4p}{(2\pi)^4} A(-p)\Delta^{-1}(p)A(p)$$

Klebanov, Witten hep-th/9905104