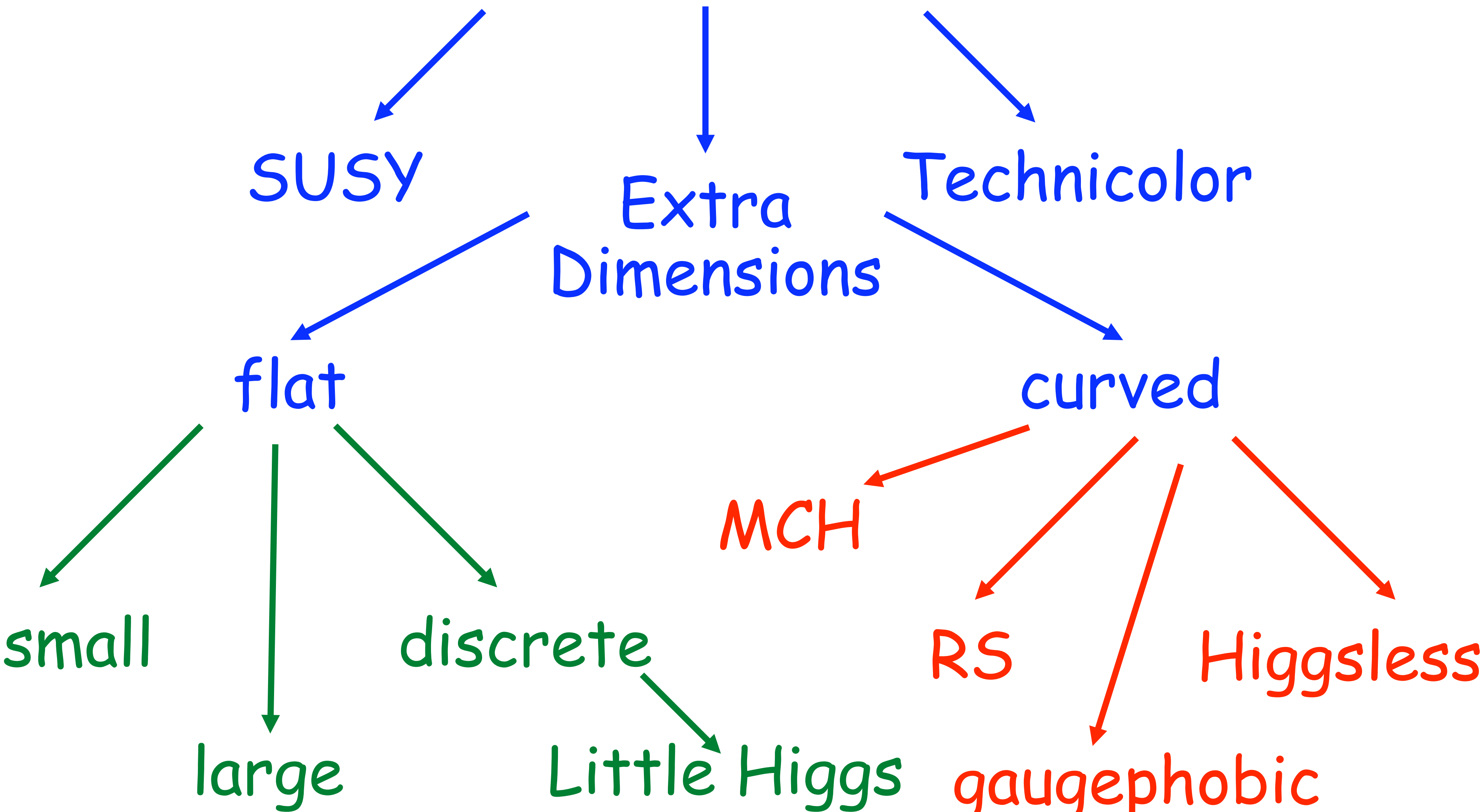
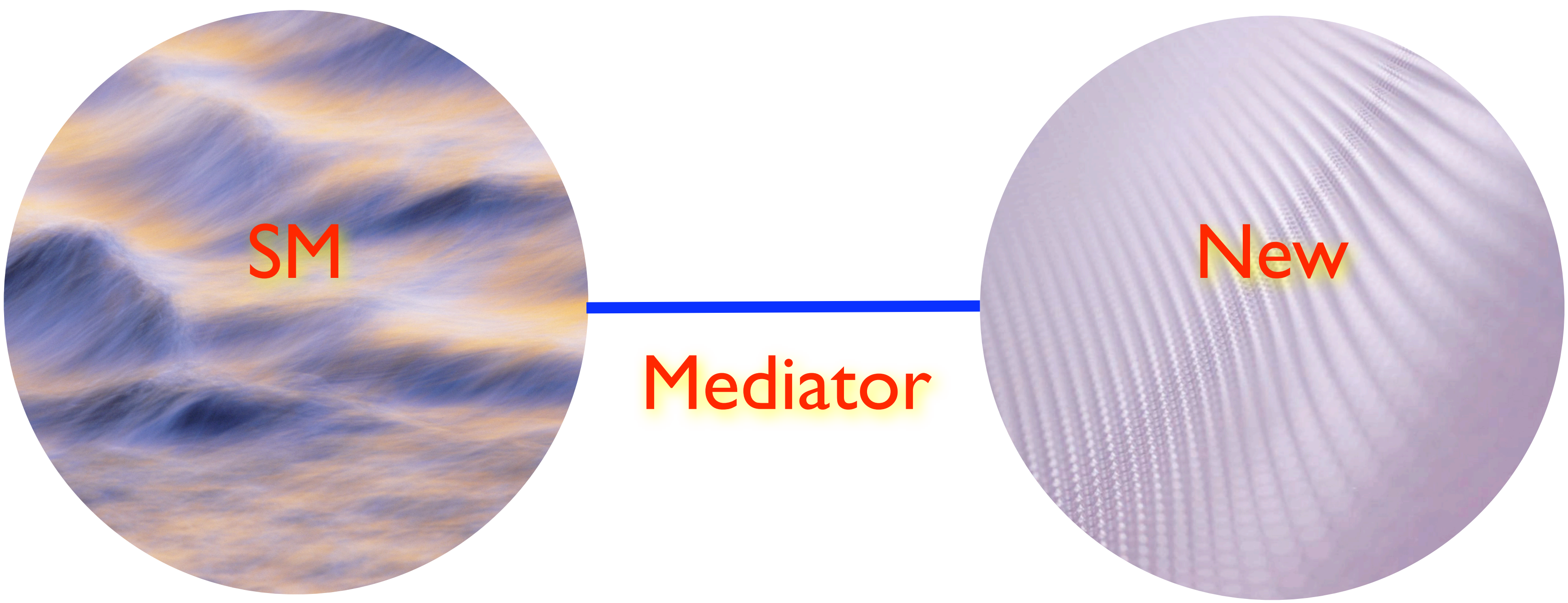
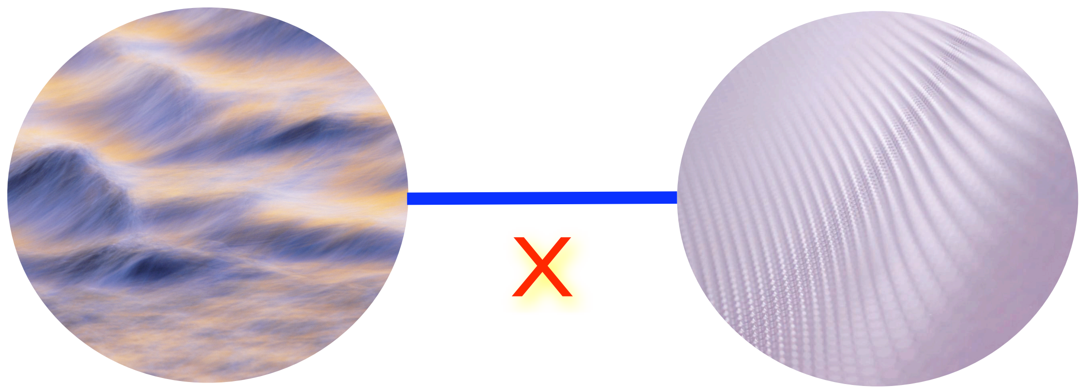
Hierarchy Problem Now



New Sector



New Sector

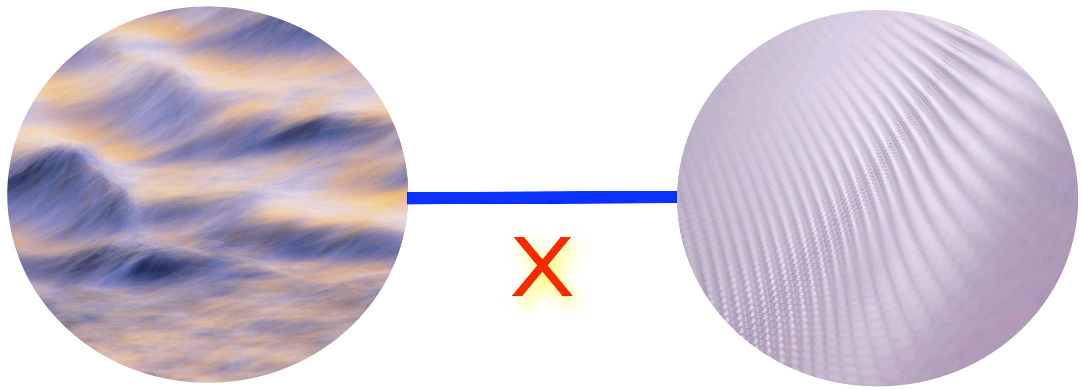


$$M_X \gg \text{TeV} \qquad \frac{\mathcal{O}_{SM}\mathcal{O}_{new}}{M_X^n}$$

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

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

Hidden Un/Valley Quirk Model



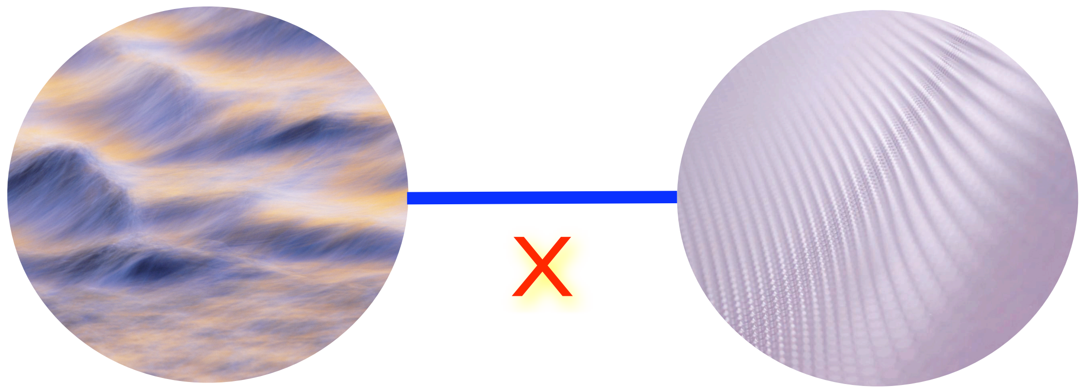
X is a heavy colored fermion

QCD-like confinement → hidden valley

stringy confinement → quirks

no confinement → unparticles

Hidden Un/Valley Quirk Model



X is a heavy colored fermion

stringy confinement	→	quirks	n=0
QCD-like confinement	→	hidden valley	n=few
no confinement	→	unparticles	n=many

Unparticles

Georgi:

* a different way to calculate in CFT's

* phase space looks like a fractional number of particles

Georgi hep-ph/0703260, 0704.2457

unparticle propagator

$$\Delta(p,d) \equiv \int d^4x\, e^{ipx} \langle 0|T\mathcal{O}(x)\mathcal{O}^\dagger(0)|0\rangle$$

$$= \frac{A_d}{2\pi}\int_0^\infty (M^2)^{d-2}\frac{i}{p^2-M^2+i\epsilon}dM^2$$

$$= i\frac{A_d}{2}\frac{\left(-p^2-i\epsilon\right)^{d-2}}{\sin d\pi}$$

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

unparticle phase space

$$d\Phi(p,d) = A_d\,\theta\left(p^0\right)\,\theta\left(p^2\right)\,\left(p^2\right)^{d-2}$$

$$d\Phi(p,1) = 2\pi\,\theta\left(p^0\right)\,\delta(p^2)$$

IR cutoff propagator

$$\Delta(p,\mu,d) \equiv \int d^4x\, e^{ipx} \langle 0|T\mathcal{O}(x)\mathcal{O}^\dagger(0)|0\rangle|_\mu$$

$$= \frac{A_d}{2\pi}\int_{\mu^2}^{\infty}(M^2-\mu^2)^{d-2}\frac{i}{p^2-M^2+i\epsilon}dM^2$$

$$= i\frac{A_d}{2}\frac{\left(\mu^2-p^2-i\epsilon\right)^{d-2}}{\sin d\pi}$$

$$\Delta(p,\mu,1) = \frac{i}{p^2-\mu^2+i\epsilon}$$

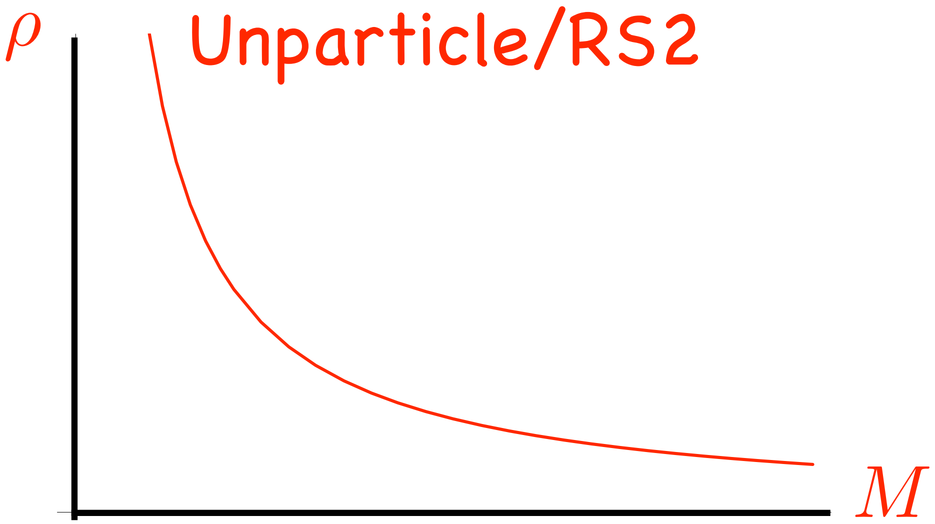
Fox, Rajaraman, Shirman hep-ph/0705.3092

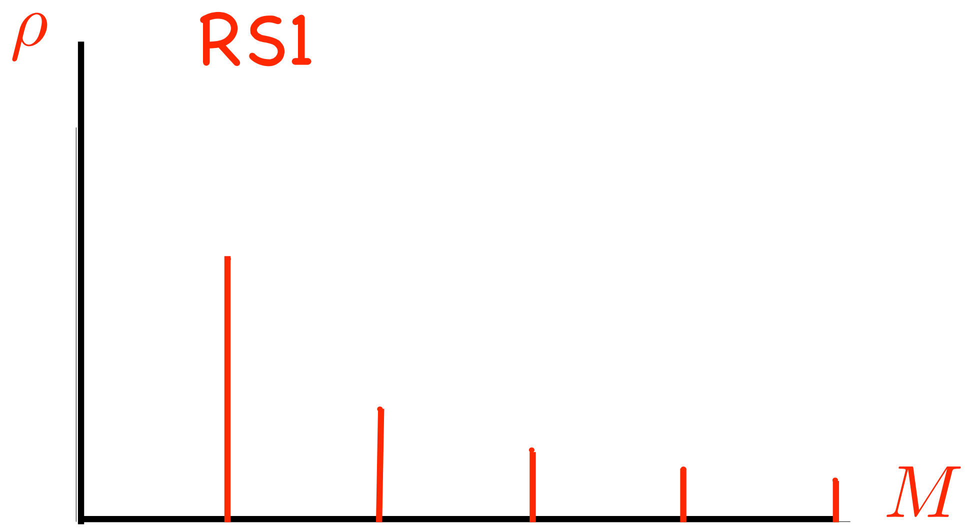
unparticle phase space

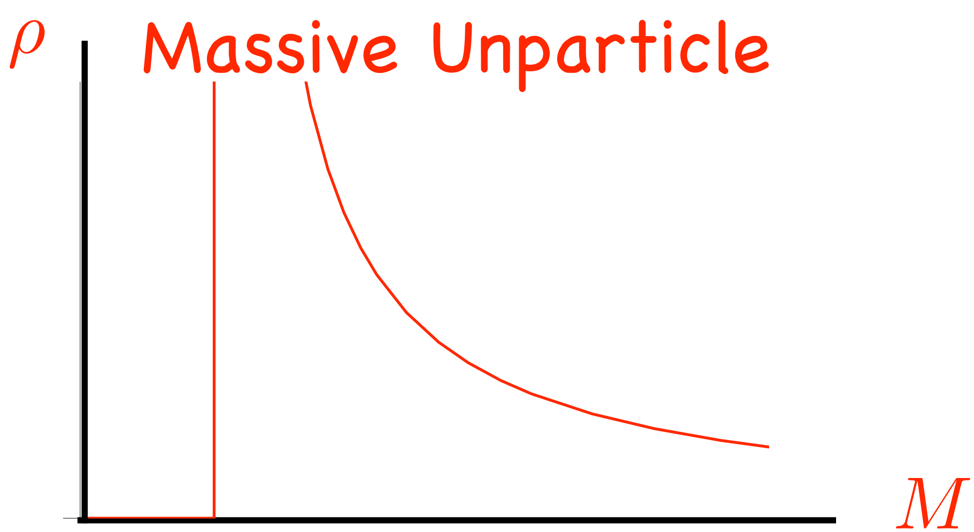
$$d\Phi(p,\mu,d) = A_d\,\theta\left(p^0\right)\,\theta\left(p^2-\mu^2\right)\,\left(p^2-\mu^2\right)^{d-2}$$

$$d\Phi(p,\mu,1) = 2\pi\,\theta\left(p^0\right)\,\delta(p^2-\mu^2)$$

Spectral Densities







Quarks are Unparticles

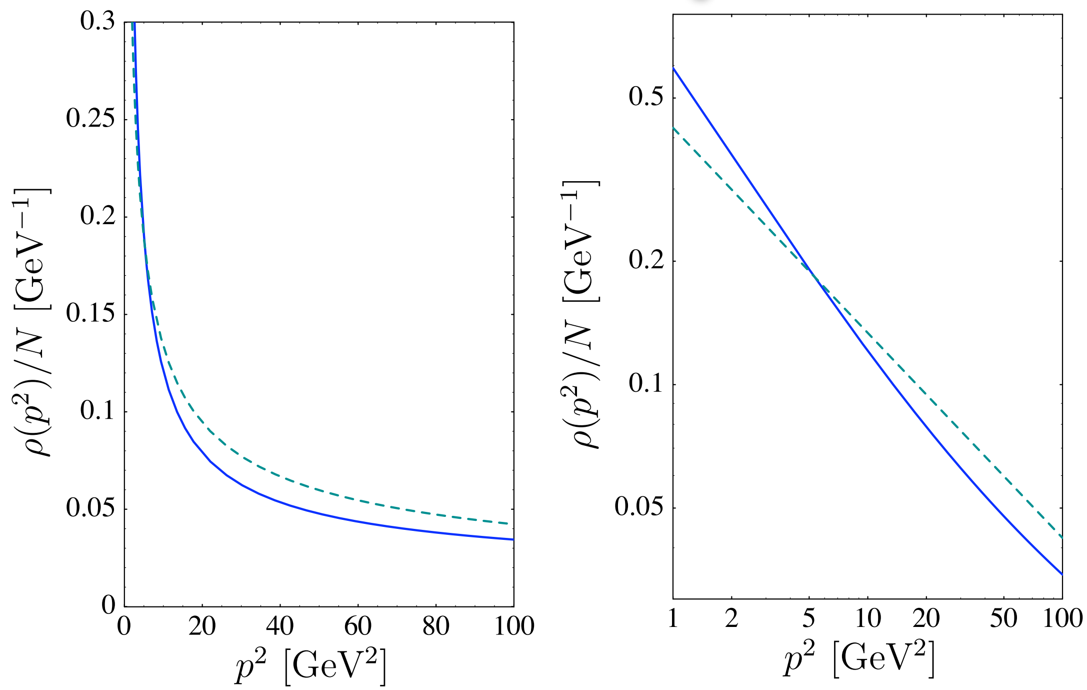


FIG. 1. Comparison of the unparticle spectral density (2) (dashed) and the spectral density (9) of a massless quark jet at next-to-leading order in QCD (solid). We use parameters $M = 10\,\mathrm{GeV}$ and $\eta = 0.5$. The right plot shows the same results on logarithmic scales.

Neubert hep-ph/0708.0036

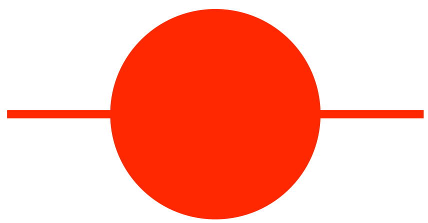
electrons are Unparticles

resummed electron propagator

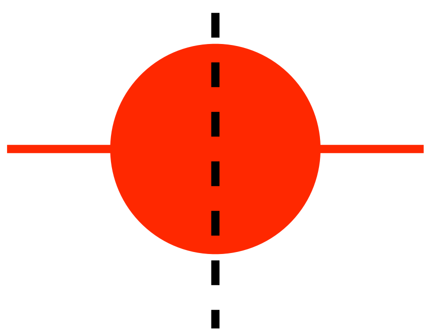
$$\Delta_e(p) = \frac{i}{\not{p} - m}(p^2 - m^2)^\gamma$$

cf Yennie Gauge

unparticle propagator



$$= i\,\frac{A_d}{2}\,\frac{\left(\mu^2 - p^2 - i\epsilon\right)^{d-2}}{\sin d\pi}$$



$$= A_d\,\theta\left(p^0\right)\,\theta\left(p^2 - \mu^2\right)\,\left(p^2 - \mu^2\right)^{d-2}$$

Heavy Mediator

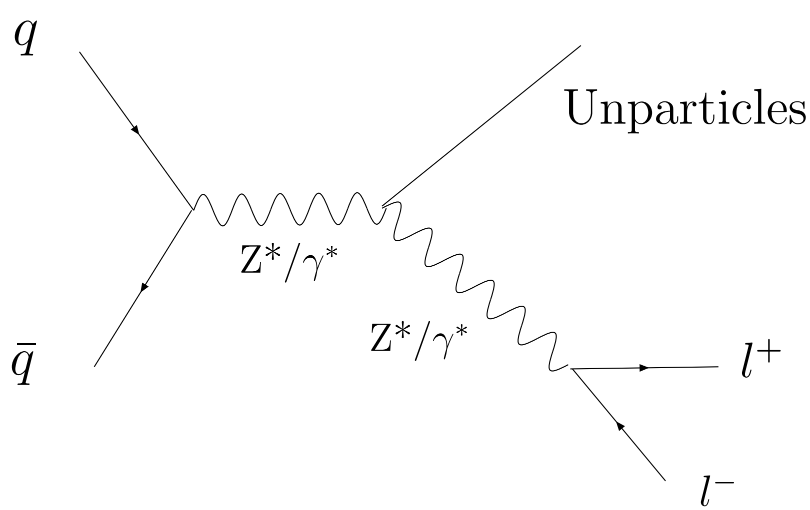
- Important Operators

$$\mathcal{O}_1 = \frac{\mathcal{C}_\mathcal{U}\,\Lambda_\mathcal{U}^{d_{\mathcal{BZ}}-d_\mathcal{U}}}{\mathcal{M}^k} Z^{\mu\nu} Z_{\mu\nu}\,\mathcal{O}_\mathcal{U}$$

$$\mathcal{O}_2 = \frac{\mathcal{C}'_\mathcal{U}\,\Lambda_\mathcal{U}^{d_{\mathcal{BZ}}-d_\mathcal{U}}}{\mathcal{M}^k} A^{\mu\nu} A_{\mu\nu}\,\mathcal{O}_\mathcal{U}$$

$$\mathcal{O}_3 = \frac{\mathcal{C}''_\mathcal{U}\,\Lambda_\mathcal{U}^{d_{\mathcal{BZ}}-d_\mathcal{U}}}{\mathcal{M}^k} m_Z^2\, Z^{\mu} Z_{\mu}\,\mathcal{O}_\mathcal{U}$$

- Representative Feynman Graph



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Lineshape Bounds from LEP

$$d_{\mathcal{U}} = 1 \qquad {\mathcal{C}_{\mathcal{U}}}^2 \left(\frac{\Lambda_{\mathcal{U}}}{\mathcal{M}}\right)^{2\mathcal{B}\mathcal{Z}} \frac{1}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}\Bigg|_{d_{\mathcal{U}}=1} \geq 5 \times 10^{-12} \ \text{GeV}^{-2}$$

$$d_{\mathcal{U}} = 1.5 \qquad {\mathcal{C}_{\mathcal{U}}}^2 \left(\frac{\Lambda_{\mathcal{U}}}{\mathcal{M}}\right)^{2\mathcal{B}\mathcal{Z}} \frac{1}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}\Bigg|_{d_{\mathcal{U}}=1.5} \geq 6.4 \times 10^{-13} \ \text{GeV}^{-3}$$

$$d_{\mathcal{U}} = 2.0 \qquad {\mathcal{C}_{\mathcal{U}}}^2 \left(\frac{\Lambda_{\mathcal{U}}}{\mathcal{M}}\right)^{2\mathcal{B}\mathcal{Z}} \frac{1}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}\Bigg|_{d_{\mathcal{U}}=2} \geq 1.3 \times 10^{-13} \ \text{GeV}^{-4}$$

$$d_{\mathcal{U}} = 2.5 \qquad {\mathcal{C}_{\mathcal{U}}}^2 \left(\frac{\Lambda_{\mathcal{U}}}{\mathcal{M}}\right)^{2\mathcal{B}\mathcal{Z}} \frac{1}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}\Bigg|_{d_{\mathcal{U}}=2.5} \geq 2.8 \times 10^{-14} \ \text{GeV}^{-5}$$

$$d_{\mathcal{U}} = 3.0 \qquad {\mathcal{C}_{\mathcal{U}}}^2 \left(\frac{\Lambda_{\mathcal{U}}}{\mathcal{M}}\right)^{2\mathcal{B}\mathcal{Z}} \frac{1}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}\Bigg|_{d_{\mathcal{U}}=3} \geq 3.2 \times 10^{-15} \ \text{GeV}^{-6}$$

$$d_{\mathcal{U}} = 3.5 \qquad {\mathcal{C}_{\mathcal{U}}}^2 \left(\frac{\Lambda_{\mathcal{U}}}{\mathcal{M}}\right)^{2\mathcal{B}\mathcal{Z}} \frac{1}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}\Bigg|_{d_{\mathcal{U}}=3.5} \geq 5.3 \times 10^{-17} \ \text{GeV}^{-7}$$

The bounds are derived assuming final state electrons.
They are more stringent than the literature.
Use these values in the following analysis.

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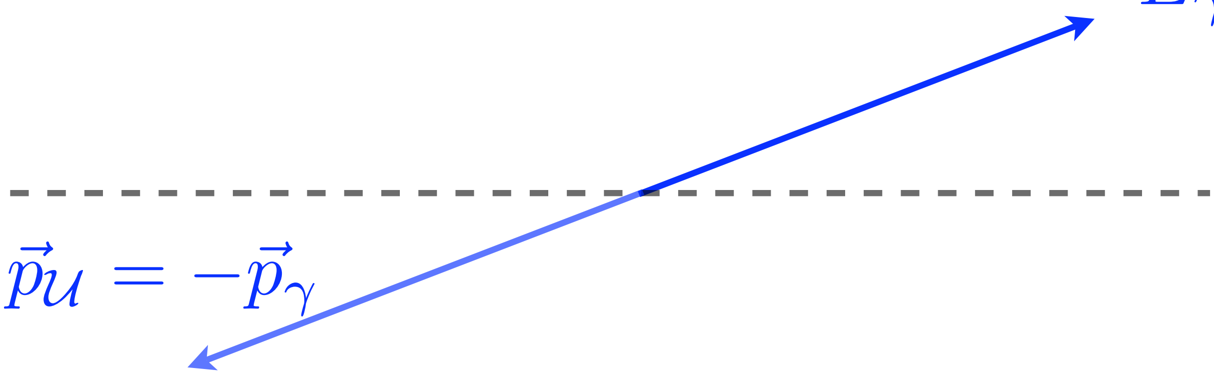
MonoPhotons

$$F^{\mu\nu} F_{\mu\nu} \frac{\mathcal{O}_{\mathcal{U}}}{\Lambda^d}$$

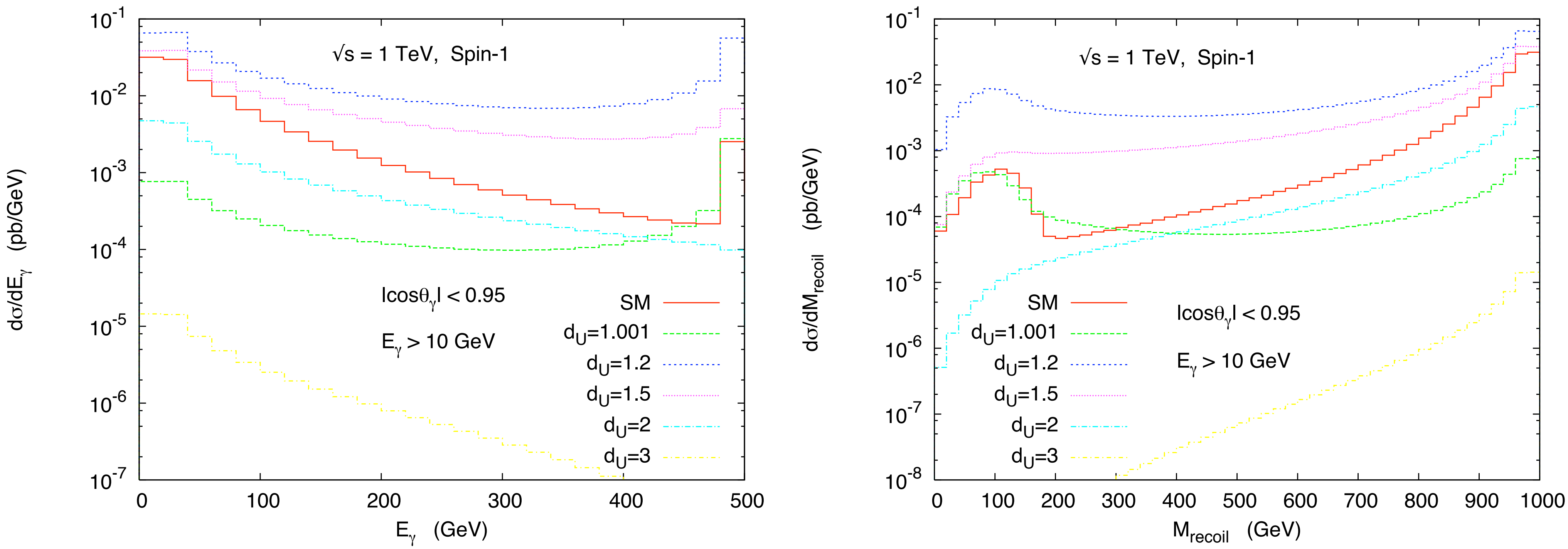
$$E_\gamma = |p_\gamma|$$



$$\vec{p}_{\mathcal{U}} = -\vec{p}_\gamma$$

$$E_{\mathcal{U}} = E_{beam} - E_\gamma$$

MonoPhotons



K. Cheung et. al. hep-ph/0706.3155

Monojets

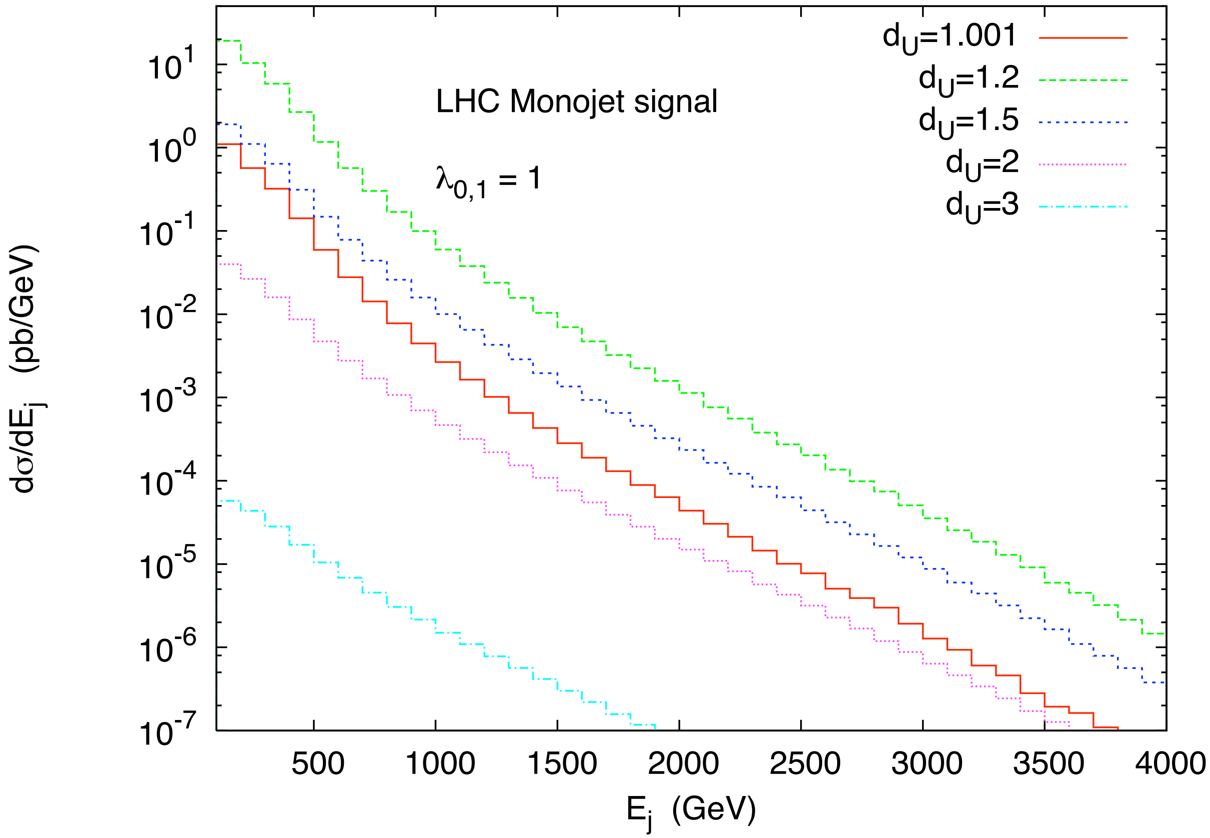
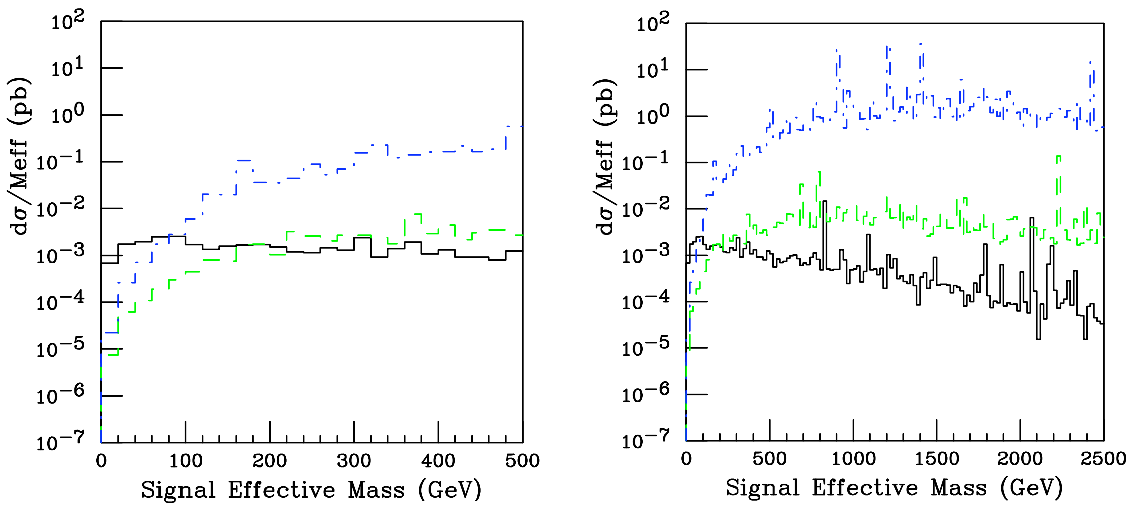


FIG. 8: Differential cross section $d\sigma/dE_j$ versus E_j for the monojet signal at the LHC, with various $d_{\mathcal{U}}$. We have set $\Lambda_{\mathcal{U}} = 1$ TeV and $\lambda_0 = \lambda_1 = 1$.

K. Cheung et. al. hep-ph/0706.3155

LHC:Z->U+e$^+$e$^-$



$$M_{\text{eff}} = \sum_{\text{visible particles}} p_T + \not{E}_T$$

- Again, no associated mass scale for the effective mass. (No cuts applied.)
- Left/right panels = 1 (black solid), 2 (green solid), 3 (blue dot-dashed)
- Distribution is clearly different from background.
- Electron final states.

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Higgs Mediator

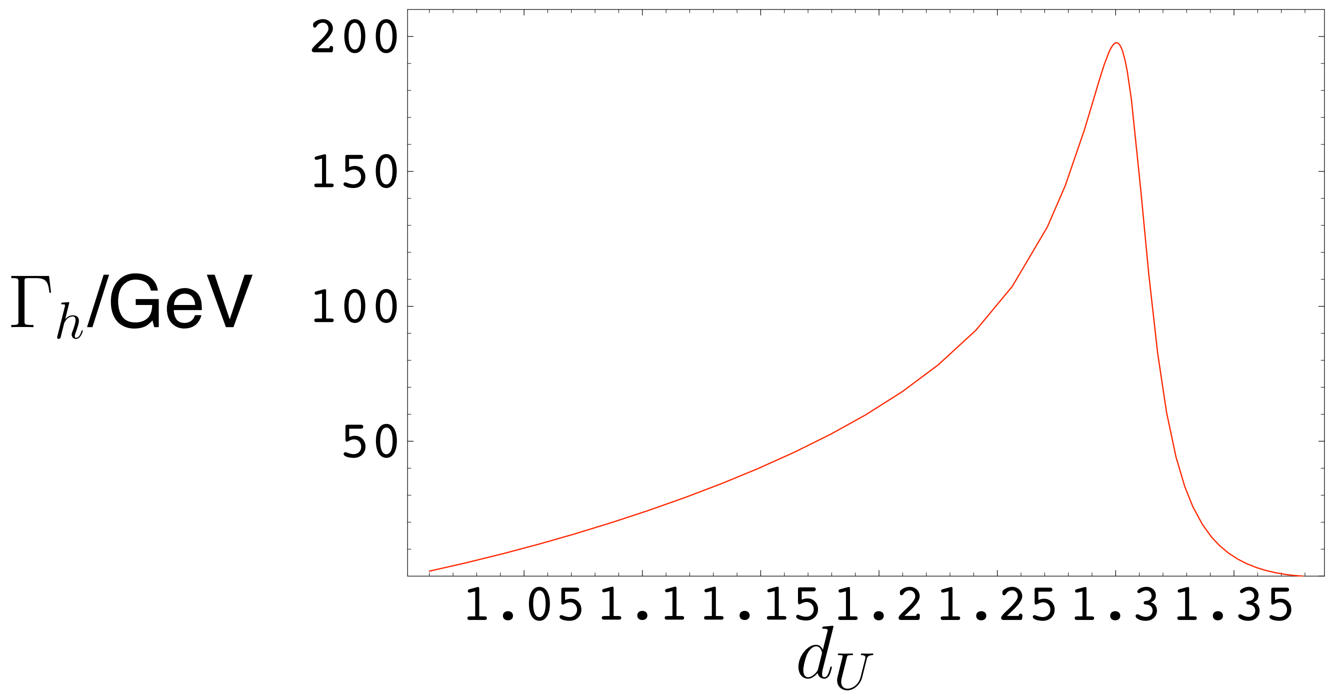
- We will use the Higgs portal to unparticles [a]

$$\mathcal{L} = -\kappa_U |H|^2 \mathcal{O}_U$$

Mariano Quiros

[a] P.J. Fox, A. Rajaraman and Y. Shirman, arXiv:0705.3092

Broad Higgs



Width of the Higgs boson from unparticle merging

Mariano Quiros

Colored Mediator

Strong production rate, similar to heavy colored particles

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

Hadronization: they form heavy (stable) meson-like states (charged, neutral...)

Unjets: containing SM hadrons + CFT stuff

R-Hadrons, anomalous jets/E loss

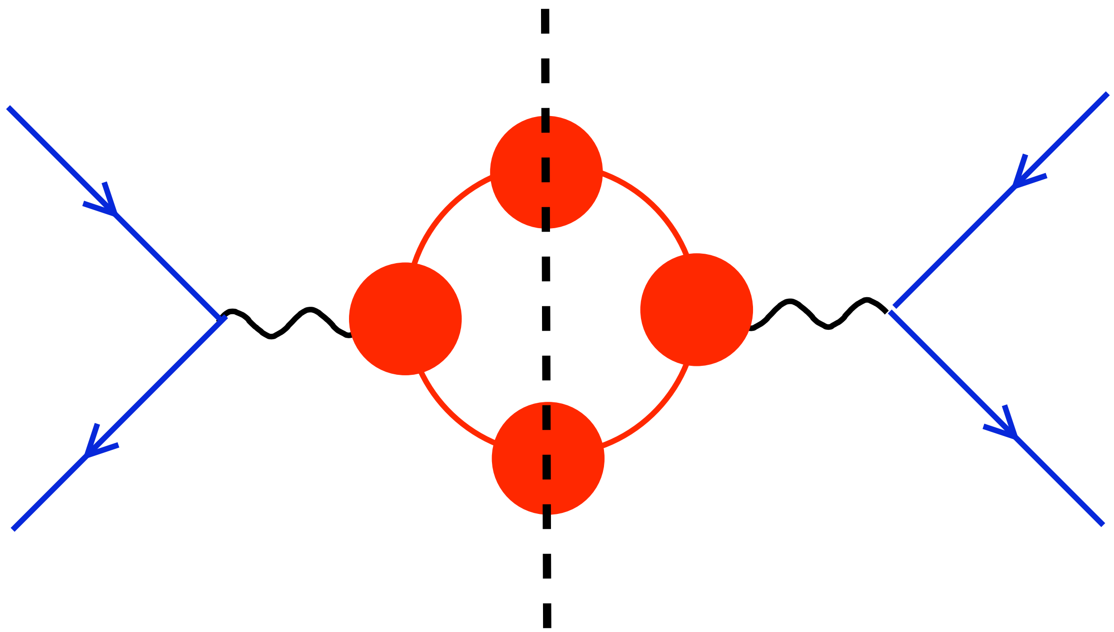
Only a small fraction of the energy is in hadrons (visible)

Look like (maybe broader) QCD jets + $\not{p}_T$

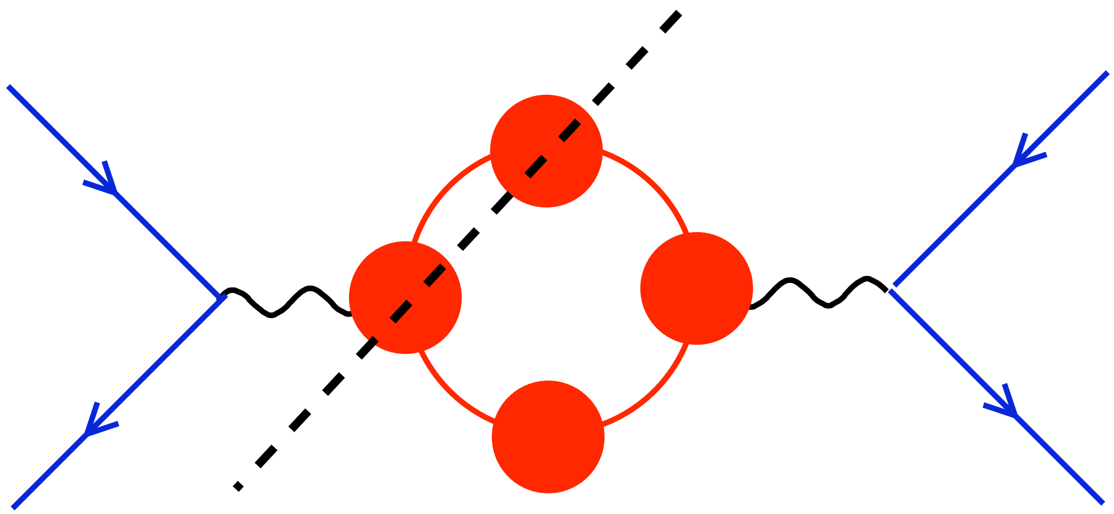
Guido Marandella,

Giacomo Cacciapaglia

unquark production



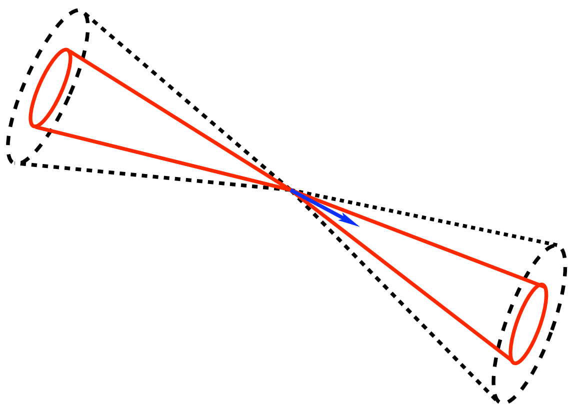
unquark production



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

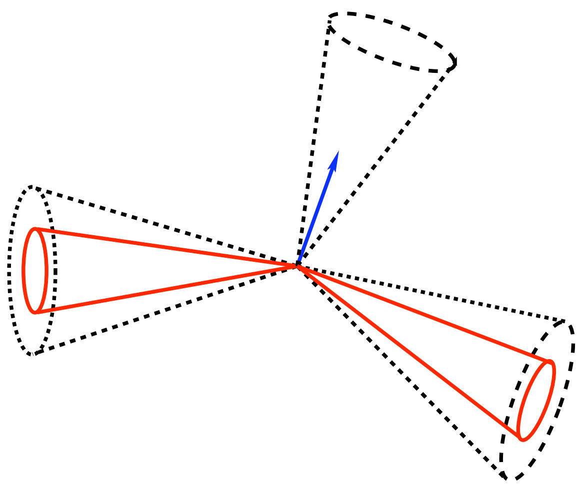
Colored Mediator

2 jets + $\not{p}_T$



Pair production

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



CFT stuff radiation

$\not{p}_T$ not aligned