Mass Scales and Unparticle Physics at the LHC

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with
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(to appear soon on the arXiV!)

Why Unparticles?

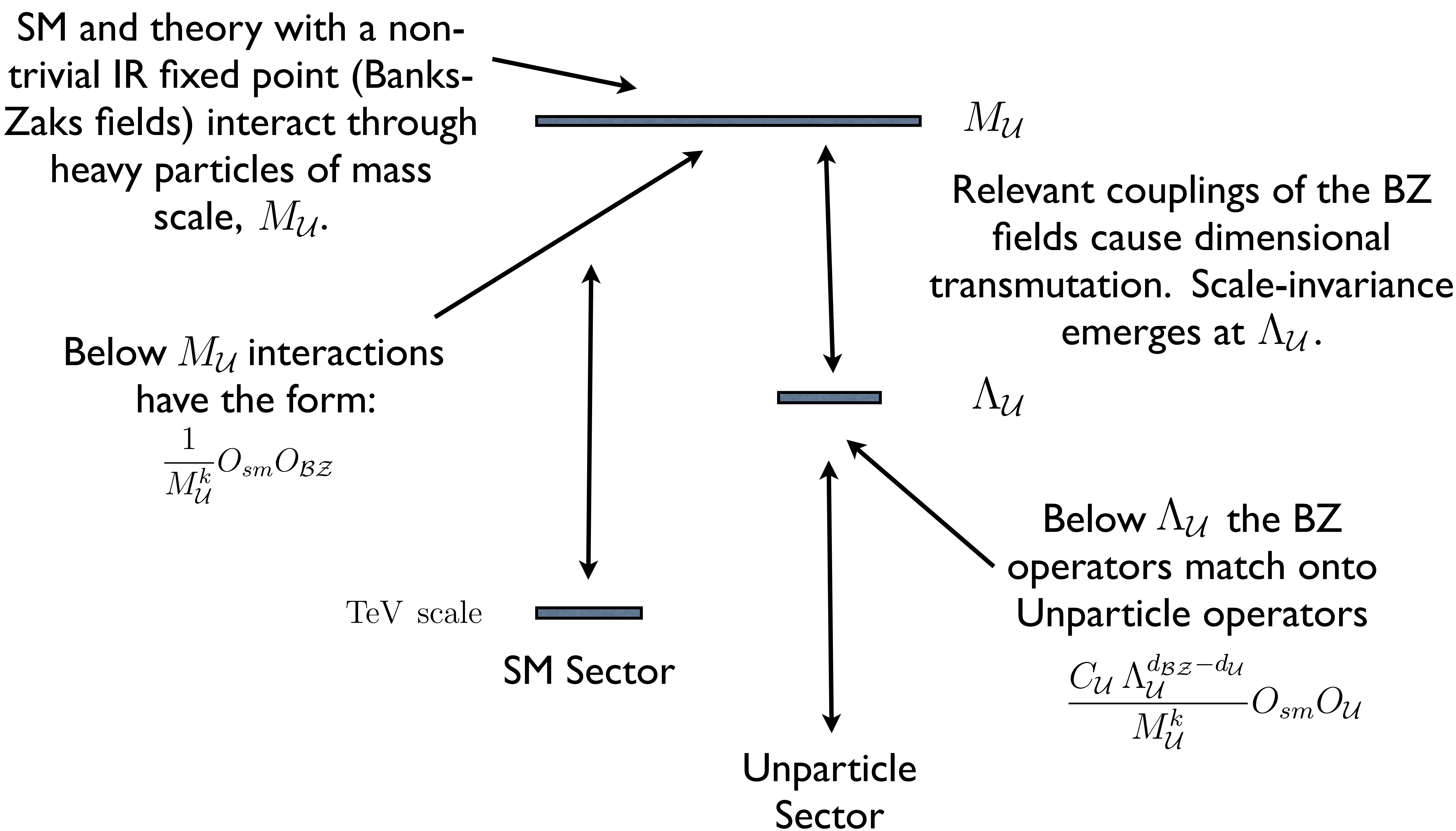
- Be prepared for all signatures at the LHC!
  - A scheme discussed by Georgi* to motivate unusual collider signatures at the LHC.
    - Centerpiece of the scheme involves a decoupled scale invariant sector.
- Our work centers on distinguishing Unparticle collider signatures from the SM and beyond.

*Georgi: hep-ph/0703260 and 0704.2457

The Gist

- In this talk we will present kinematic variables and cuts to distinguish scale invariance in $l^+l^-\not{E}_T$ signals at the LHC.
  - Key point: Unparticles do not have a mass scale associated with the missing energy. The SM and BSMs do. We exploit this to provide clean signatures.
- First a quick review on the theory behind Unparticles.

Scale Invariant Scheme



Additional Points:

- Because the BZ fields are decoupled from the SM, the IR scale invariance of the Unparticles should not be effected. (For a large enough $M_{\mathcal{U}}$ the Unparticles should be suppressed enough not to be seen in experiment.)
- Unparticle effects on the SM can given with a single insertion of $\frac{C_{\mathcal{U}}\,\Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}}-d_{\mathcal{U}}}}{M_{\mathcal{U}}^{k}}$.

Unique Unparticle Effects

- The Unparticle phase space is formally defined as:

$$d\sigma = \frac{1}{2\lambda^{1/2}(s, m_1^2, m_2^2)\,(2\pi)^{3n-4}} \sum |\mathcal{M}|^2 \delta^4(p_1 + p_2 - P_{\mathcal{U}} - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2E_i)}$$

$$\times \quad A_{d_{\mathcal{U}}}\, \theta(P_{\mathcal{U}}^2)\theta(P_{\mathcal{U}}^0)(P_{\mathcal{U}}^2)^{d_{\mathcal{U}}-2}\, \frac{d^4 P_{\mathcal{U}}}{(2\pi)^4}$$

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

Unparticle stuff with scale dimension $d_{\mathcal{U}}$ looks like a non-integral number $d_{\mathcal{U}}$ of invisible particles.

The Plan

- To suggest kinematic variables and cuts useful in elucidating scale invariance at the LHC.
- Searching for Unparticles:
  - Constrain Unparticles with LEP. Will find highly suppressed couplings to the SM.
  - Because of this, consider only Unparticles in the final state. Searching for Unparticles is similar to searching for $d_{\mathcal{U}}$ massless, invisible particles.
  - Emphasize: Unparticles do not have a mass scale associated with the missing energy. All SM/BSM processes have such a scale. This will provide clean Unparticle signatures.

More Plans...

- We only consider only $l^+l^-\not{E}_T$ final states. Why?
  - $d_{\mathcal{U}}$ Unparticles + n jets is potentially problematic. Assume a reasonable 10% jet mismeasurement. The scale invariant nature for $d_{\mathcal{U}} \sim 1$ (single massless Unparticle) can be potentially obscured.
  - Processes are suppressed by electroweak couplings. (Not a problem... coming soon.)
  - Generate $l^+l^-\not{E}_T$ final states by coupling to the virtual photon/Z.

More Plans

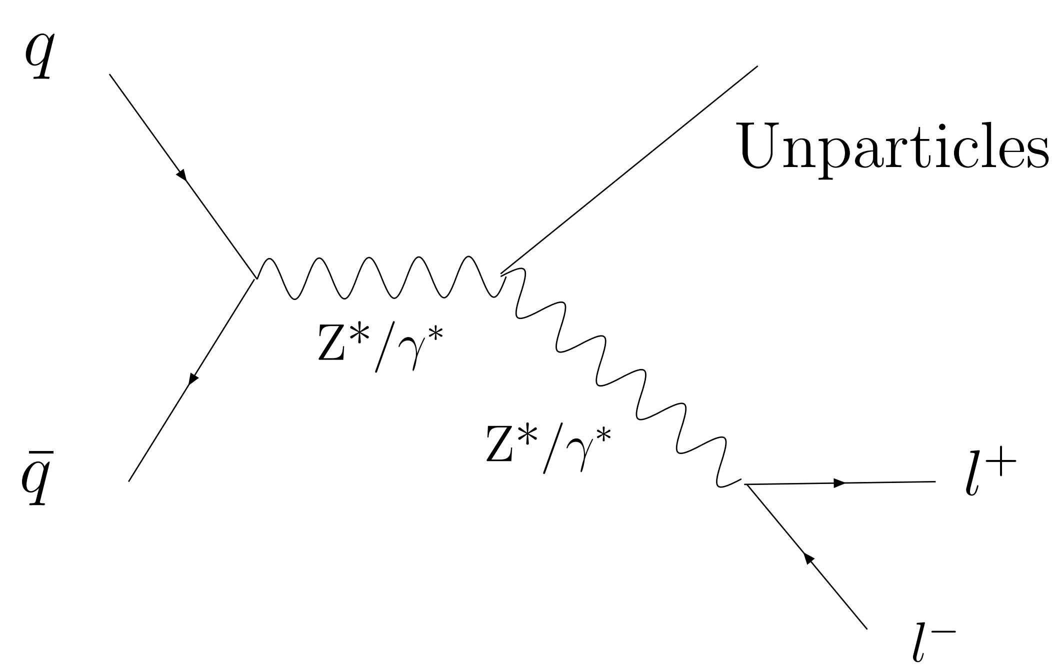
- Important Operators

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

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

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

- Representative Feynman Graph



Remainder of the Talk

Part I: LEP and TeVatron Constraints
(more on the special kinematics)

Part II: Distinguishing Unparticles from the SM backgrounds.

Part III: Distinguishing Unparticles from the BSMs.
(Here, without loss of generality, BSM means the canonical MSSM.)

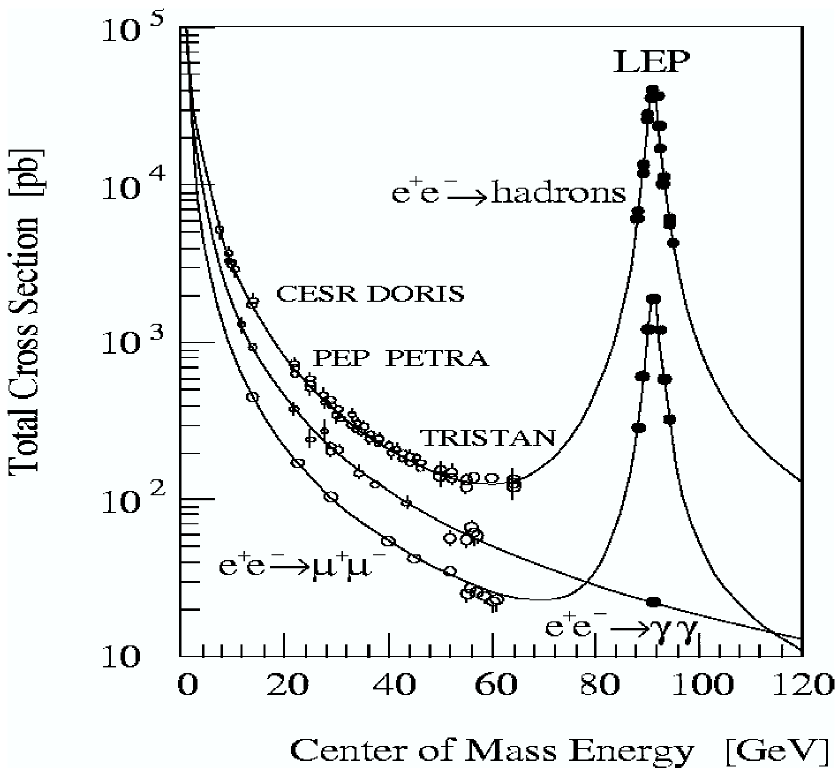
Part IV: Potential to discover Unparticles early in the LHC's run. (Time permitting.)

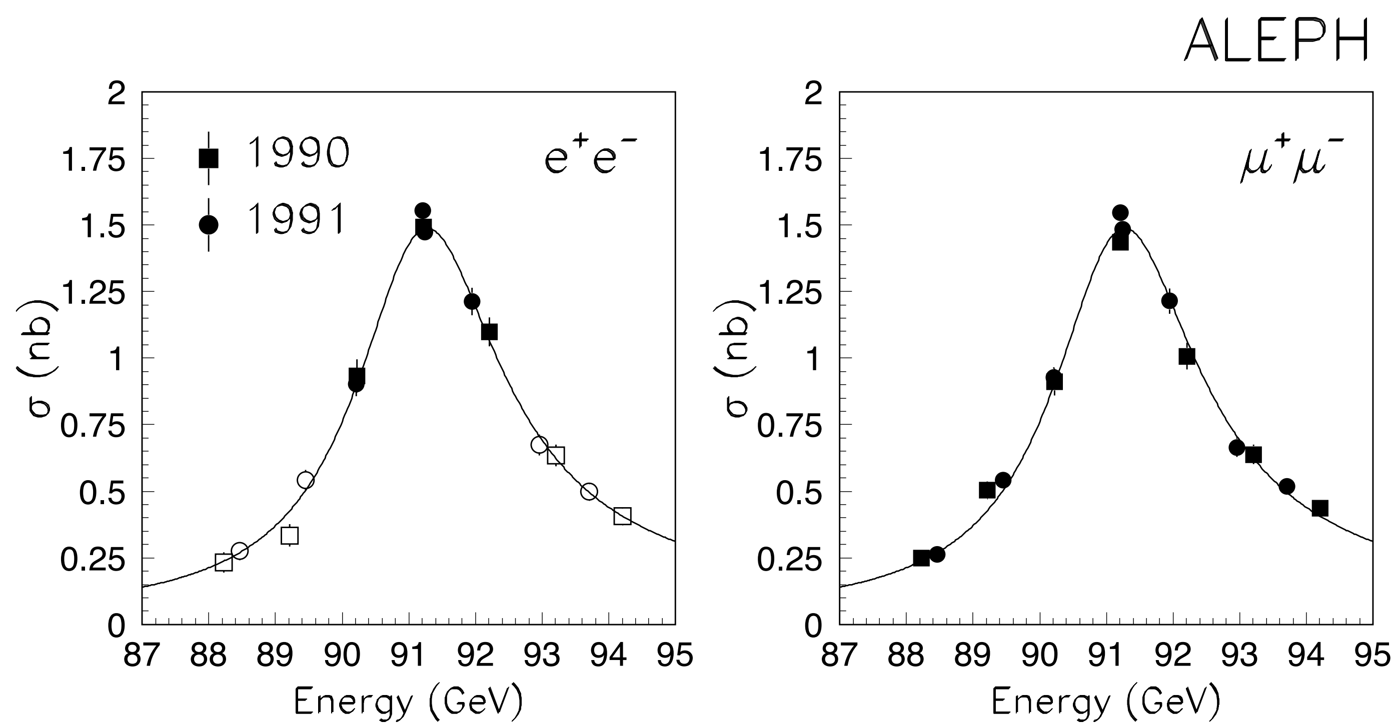
Conclusions follow.

LEP and TeVatron Constraints

Lineshape Bounds from LEP

- Z lineshape is extremely well measured.





- Number of Z events precisely known
- Tune Unparticle coupling so S + B reproduces the lineshape.

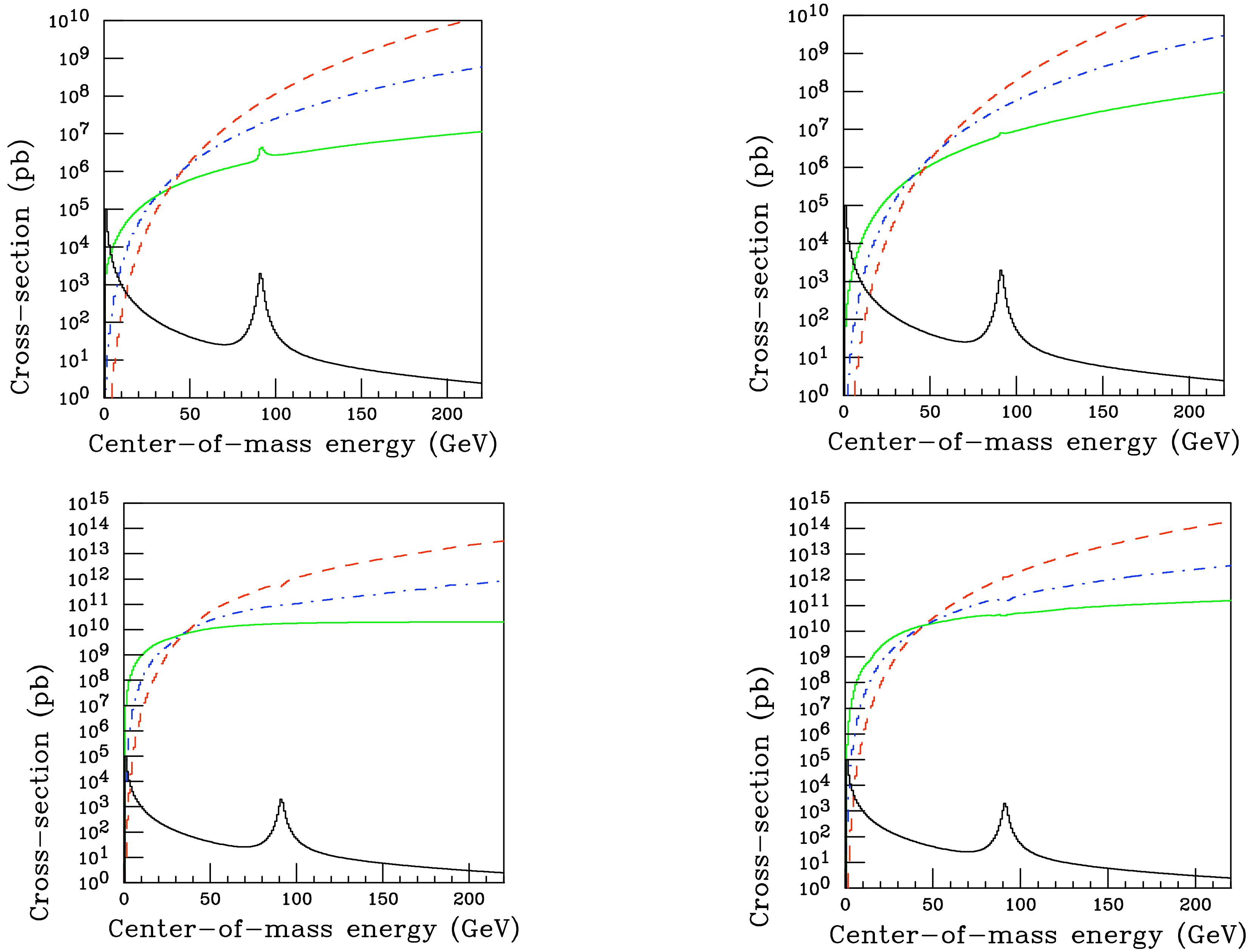
LEP Unparticle Signal

- Just to illustrate the Unparticle signal, set the Unparticle coefficients to

$$\frac{\mathcal{C}_{\mathcal{U}}\,\Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}}-d_{\mathcal{U}}}}{\mathcal{M}^k} = \frac{\mathcal{C}_{\mathcal{U}}\,\Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}}}}{\mathcal{M}^{d_{\mathcal{SM}}+d_{\mathcal{BZ}}-4}}\,\frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \to \mathcal{C}_{\mathcal{U}}\left(\frac{\Lambda_{\mathcal{U}}}{\mathcal{M}}\right)^{\mathcal{BZ}}\frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}}$$

$$\mathcal{C}_{\mathcal{U}}\left(\frac{\Lambda_{\mathcal{U}}}{\mathcal{M}}\right)^{\mathcal{BZ}} \to 1 \qquad\qquad \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \to \frac{1}{(1\ \mathrm{GeV})^{d_{\mathcal{U}}}}$$

LEP Unparticle Signal



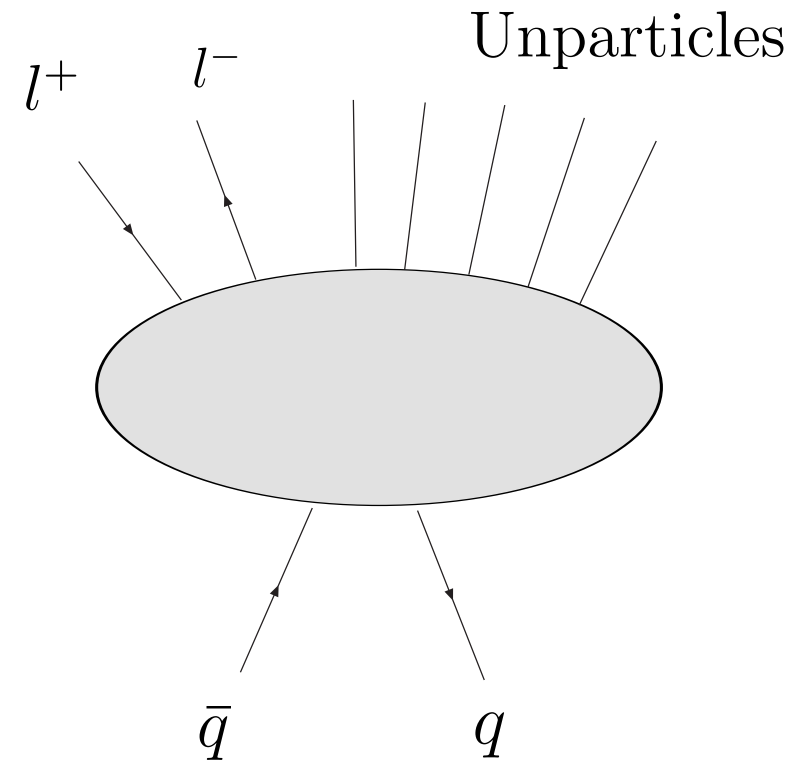
- Upper panels - muon final states
- Lower panels - electron final states
(left panels $d_{\mathcal{U}}$ = 1, 2, 3; right panels $d_{\mathcal{U}}$ = 1.5, 2.5, 3.5)

Special Kinematics

- The diagrams with virtual photons dominate. More Unparticle phase space.
- Besides the chosen Unparticle coupling, the signal is large because
  - The Unparticles can force the virtual photon that decay to the final state leptons (almost) on shell. This enhancement is key to seeing LHC signatures.
  - The final state lepton mass prevents this photon from going exactly on shell. (Hence the diagrams with final state electrons dominate.) The order of magnitude difference in the muon and electron signals is a key effect.

Special Kinematics Cont'd...

- Even though the Unparticles force the second virtual photon on shell, the final state leptons are still highly boosted. (all of the final states are massless)



- Unparticles simply force a scan over the virtual photon momentum. Recall theta function in the phase space:

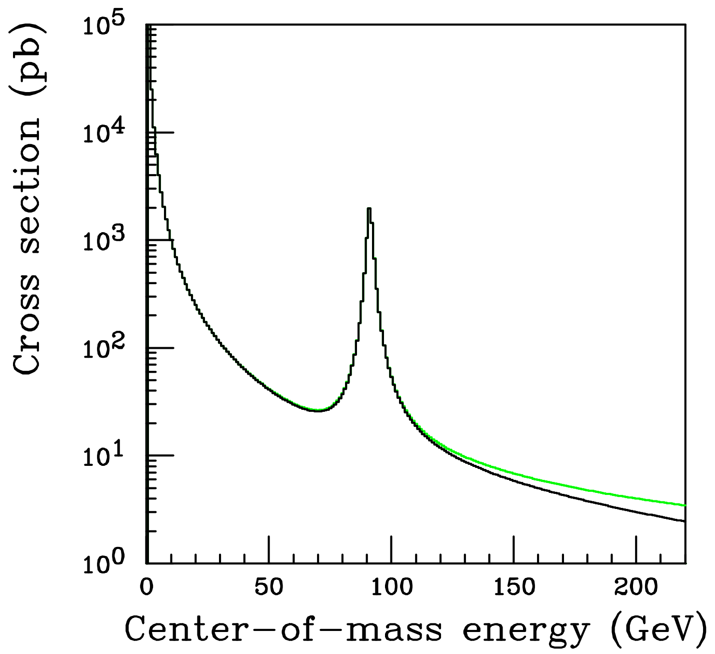
$$
\begin{aligned}
d\sigma &= \frac{1}{2\lambda^{1/2}(s, m_1^2, m_2^2)\,(2\pi)^{3n-4}} \sum |\mathcal{M}|^2 \delta^4(p_1 + p_2 - P_{\mathcal{U}} - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2E_i)} \\
&\times \; A_{d_{\mathcal{U}}}\, \theta(P_{\mathcal{U}}^2)\theta(P_{\mathcal{U}}^0)(P_{\mathcal{U}}^2)^{d_{\mathcal{U}}-2} \frac{d^4 P_{\mathcal{U}}}{(2\pi)^4}
\end{aligned}
$$

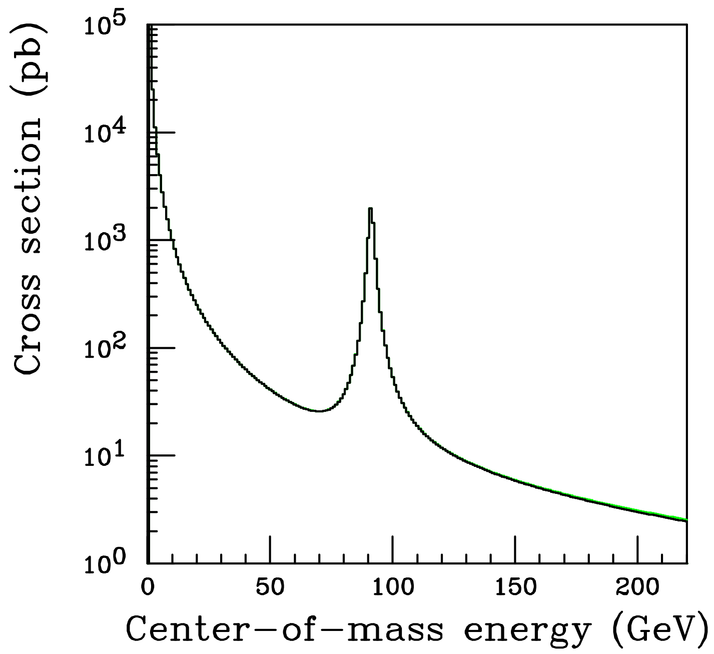
Special Kinematics Cont'd...

- Final point: Cross section scales like $\sigma \sim E^{2n-6}$. Scaling is dominated by the unique phase space. This is similar to Fermi theory where the cross section scales like powers of E.
- This enhancement is also key for seeing the Unparticle signal the LHC.

Lineshape Bounds from LEP

- Can tune the Unparticle coefficients. Graphically, for $d_{\mathcal{U}} = 1$ with final state electrons:





- The Unparticle coefficient is 5×10^{-11} and $5 \times 10^{-12}\ \mathrm{GeV}^{-2}$, respectively.

Lineshape Bounds from LEP

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

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

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

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

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

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

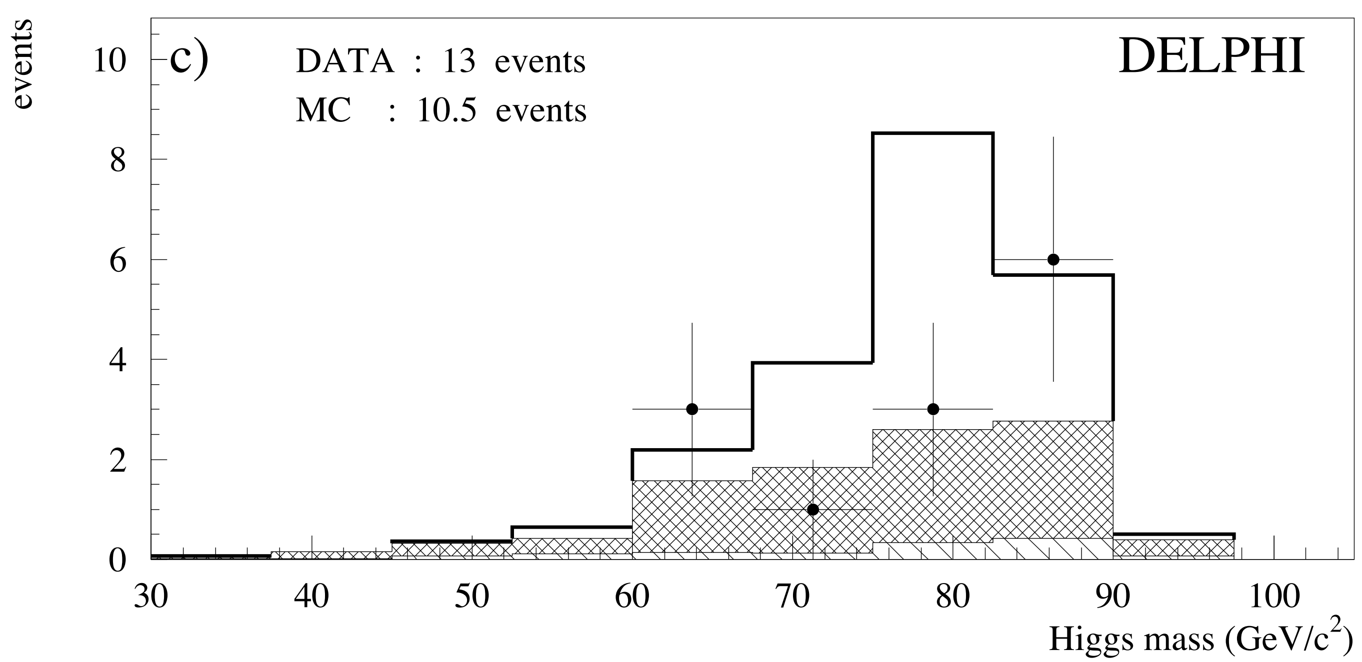
The bounds are derived assuming final state electrons.
They are more stringent than the literature.
Use these values in the following analysis.

Invisible Higgs Constraints

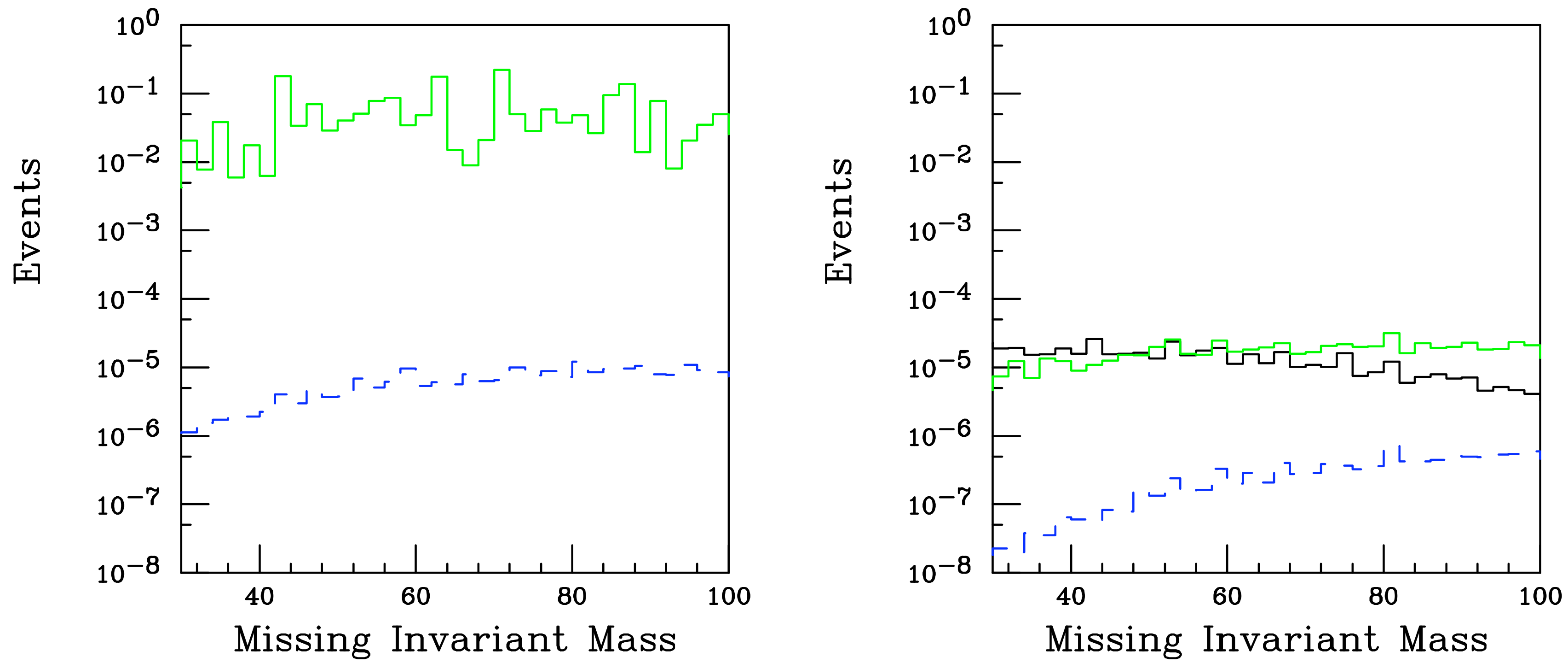
- Kinematically our signal is similar to LEP invisible higgs searches.
  - Process: $e^+e^- \longrightarrow Z^*\ \text{higgs}$

$$\begin{cases} \text{higgs} \longrightarrow \text{LSP LSP} \\ Z^* \longrightarrow \mu^+\mu^- \end{cases}$$

- Delphi results for the invisible recoil mass:



Invisible Higgs Constraints

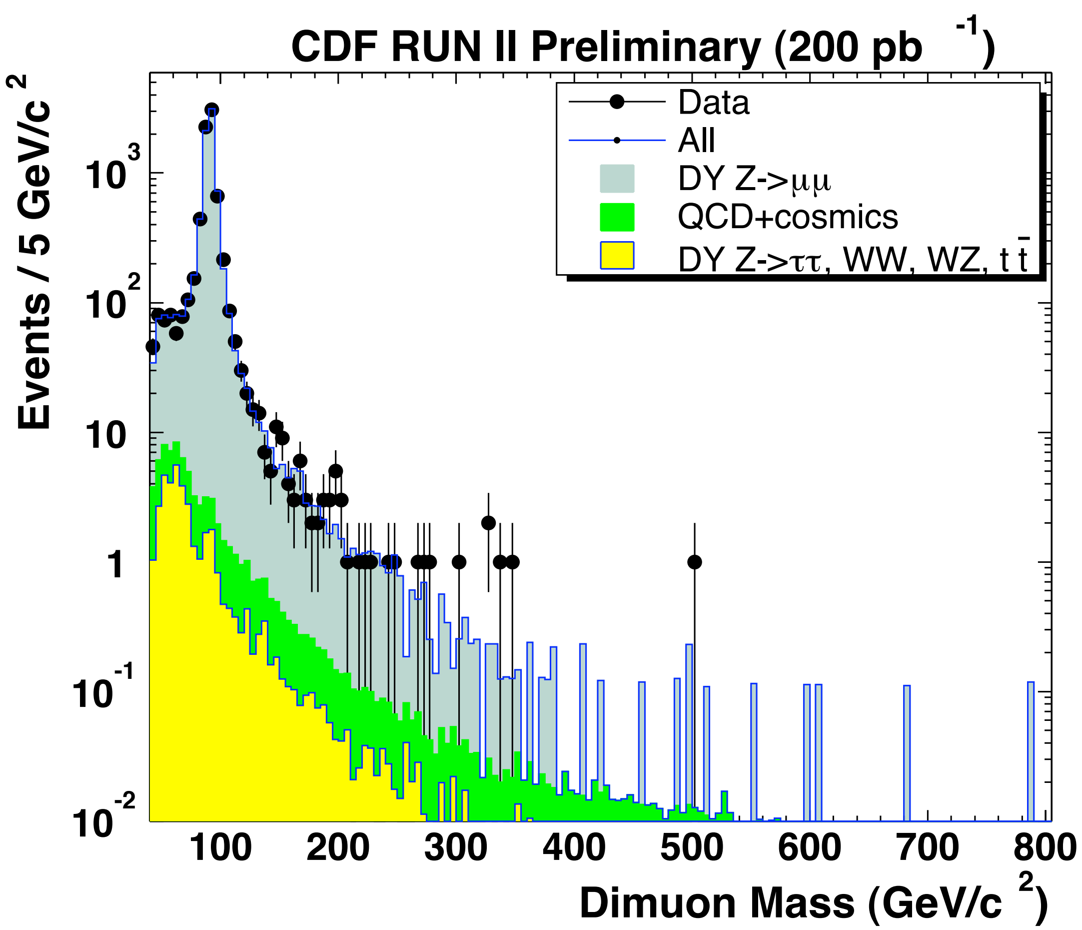


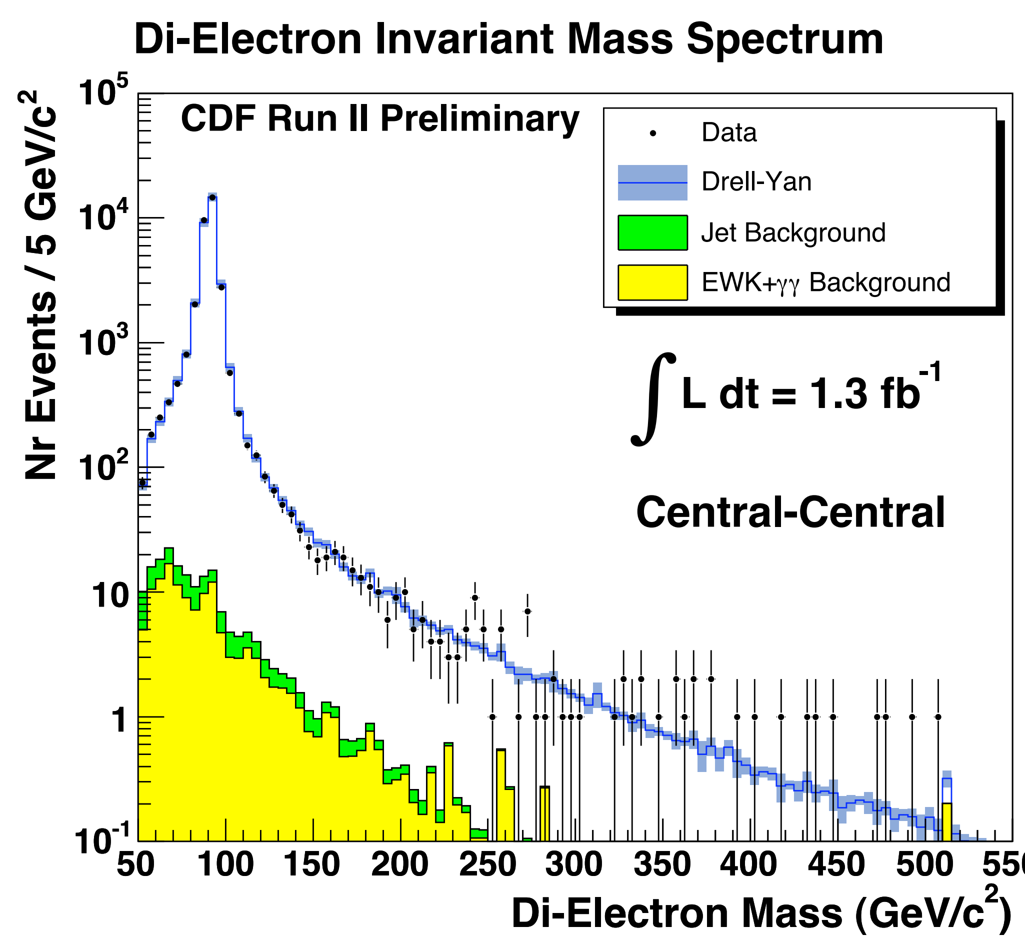
- Compare the Unparticle invisible recoil mass. (189 GeV COM energy. 50.6 pb^{-1} of luminosity. Same as Delphi.)
- Left panel $d_{\mathcal{U}}$ = 1 (black solid), 2 (green solid), 3 (blue dashed); Right panel $d_{\mathcal{U}}$ = 1.5 (black solid), 2.5 (green solid), 3.5 (blue dashed)

TeVatron Constraints

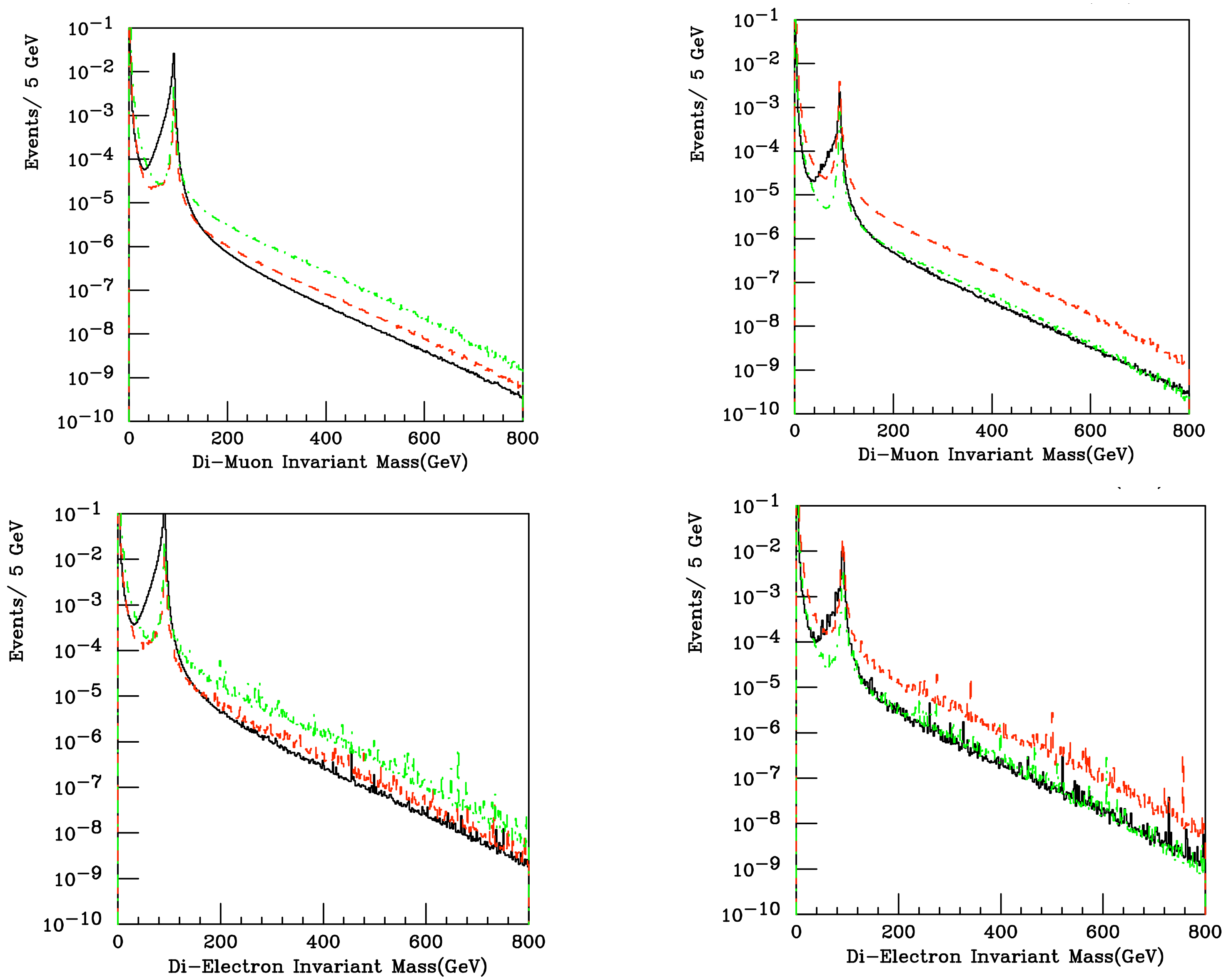
- Want to ensure Unparticle bounds will not conflict with TeVatron measurements. Look for excesses in the di-electron and muon invariant mass spectrum.

- CDF results:





TeVatron Constraints



- Compare Unparticle di-muon (upper)/electron (lower) invariant masses. (Strictly for comparison. No acceptance/detector cuts.)
- Left panels $d_{\mathcal{U}}$ = 1 (black solid), 2 (green solid), 3 (blue dashed); Right panels $d_{\mathcal{U}}$ = 1.5 (black solid), 2.5 (green solid), 3.5 (blue dashed)

Search for Unparticle Physics at the LHC

A Note on Kinematic Variables

- Kinematic variables are needed to maximize signal-to-background ratio.

- Not all kinematic variables, however, are useful in uncovering Unparticle kinematics. Consider the (cluster) transverse mass variable used to reconstruct $pp \to ZZ$ ($pp \to WW$)

$$M_T^2 = \left(\sqrt{p_{T,l^+l^-}^2 + m_{l^+l^-}^2} + \sqrt{\not{p}_{T,l^+l^-}^2 + M_{Z(W)}^2} \right)^2$$

Artificial mass bias at $M_{Z(W)}^2$. The effective mass

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

and the $\not{E}_T$ are suitable non-baised variables.

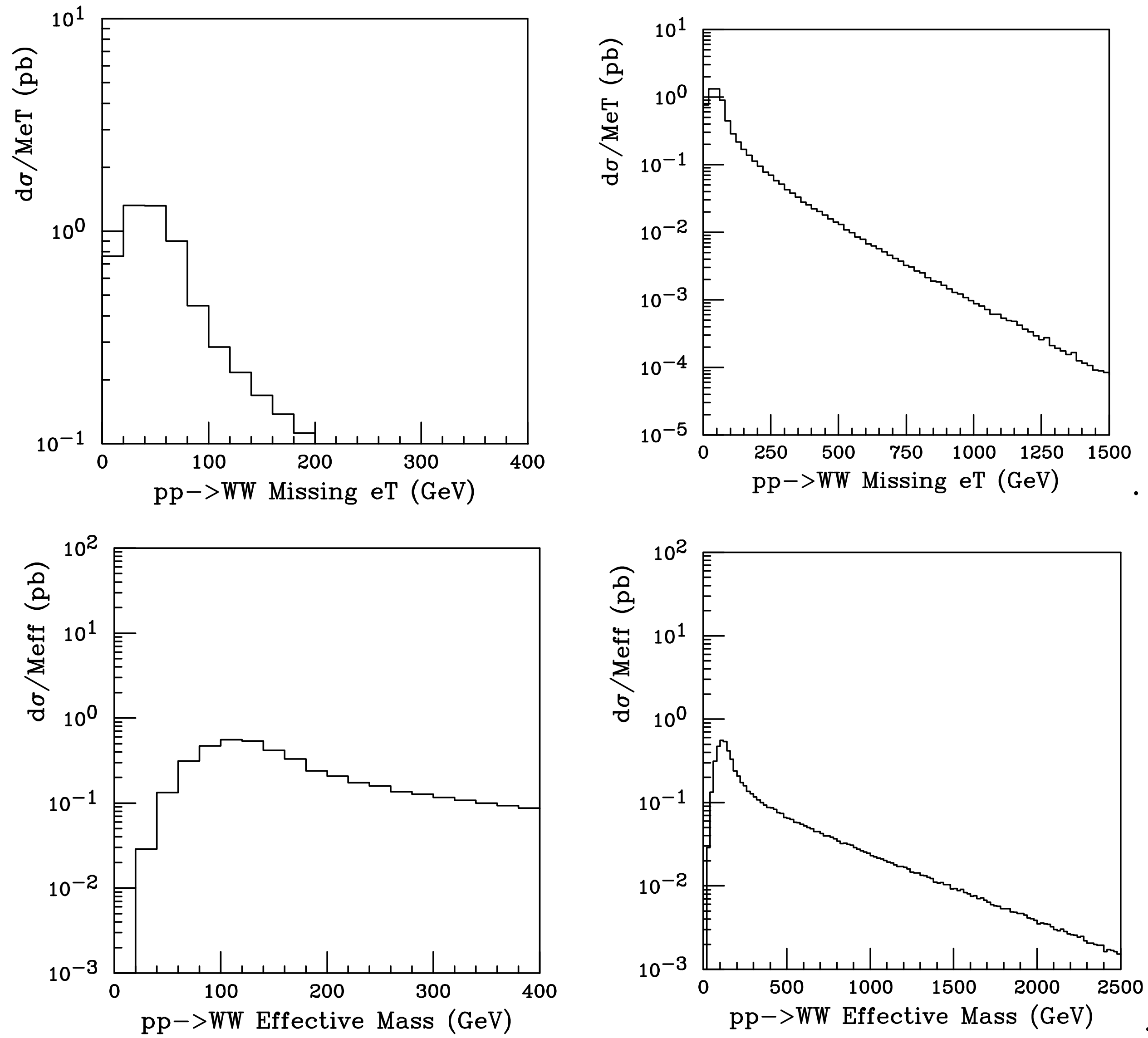
SM Backgrounds

- SM backgrounds for $l^+l^-\not{E}_T$ final state:

$$pp \to WW \to l^+\nu\ l^-\bar{\nu}$$
$$pp \to ZZ \to l^+l^-\bar{\nu}\nu$$
$$pp \to hZ \ \text{ with } \begin{cases} h \to l^+l^- \\ Z \to \bar{\nu}\nu \end{cases}$$

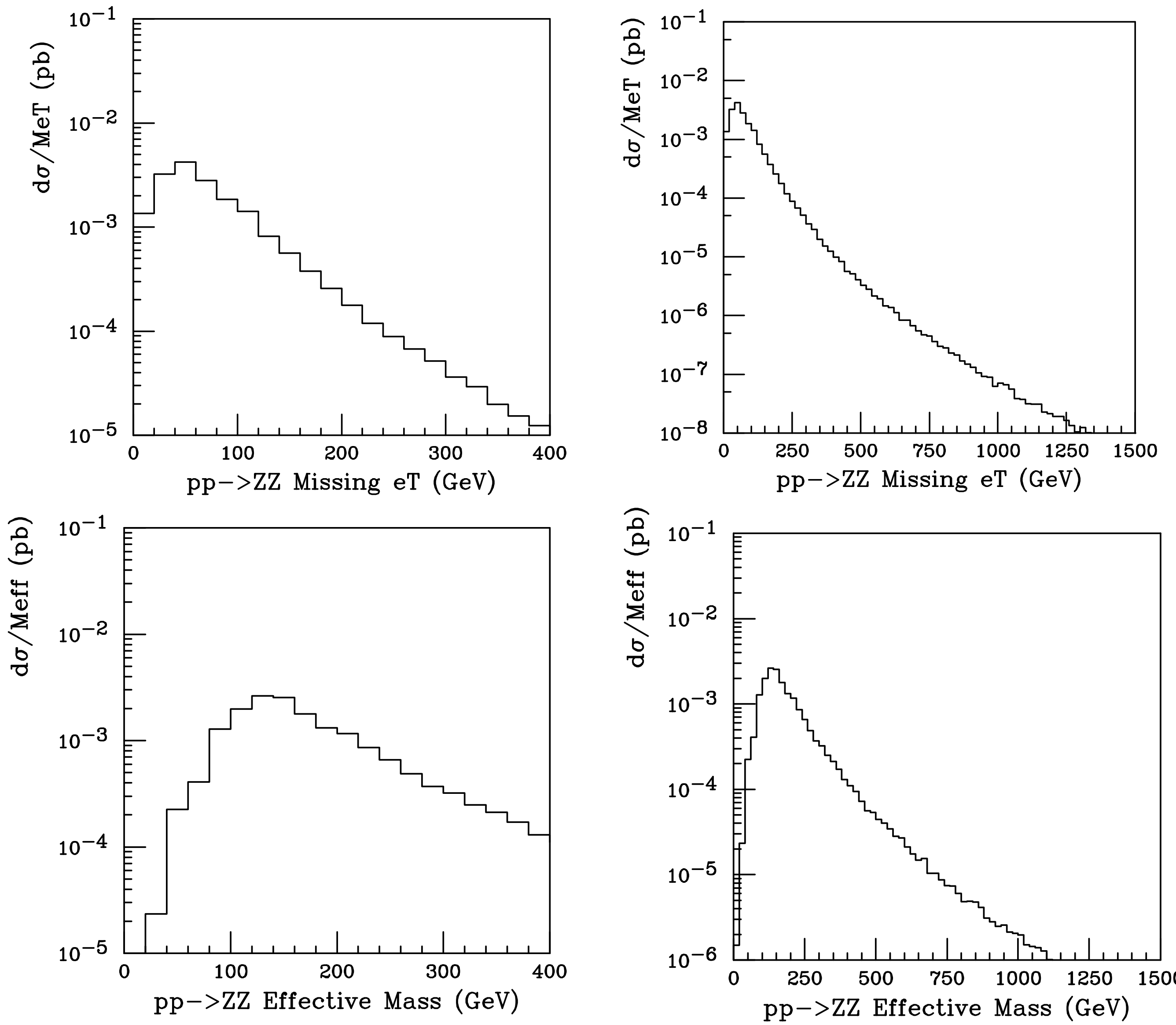
- The hZ background is sub-dominant. Not discussed
- In analysis, higgs mass in ZZ (hZ) decays is taken to be 350 (120) GeV.

WW Background



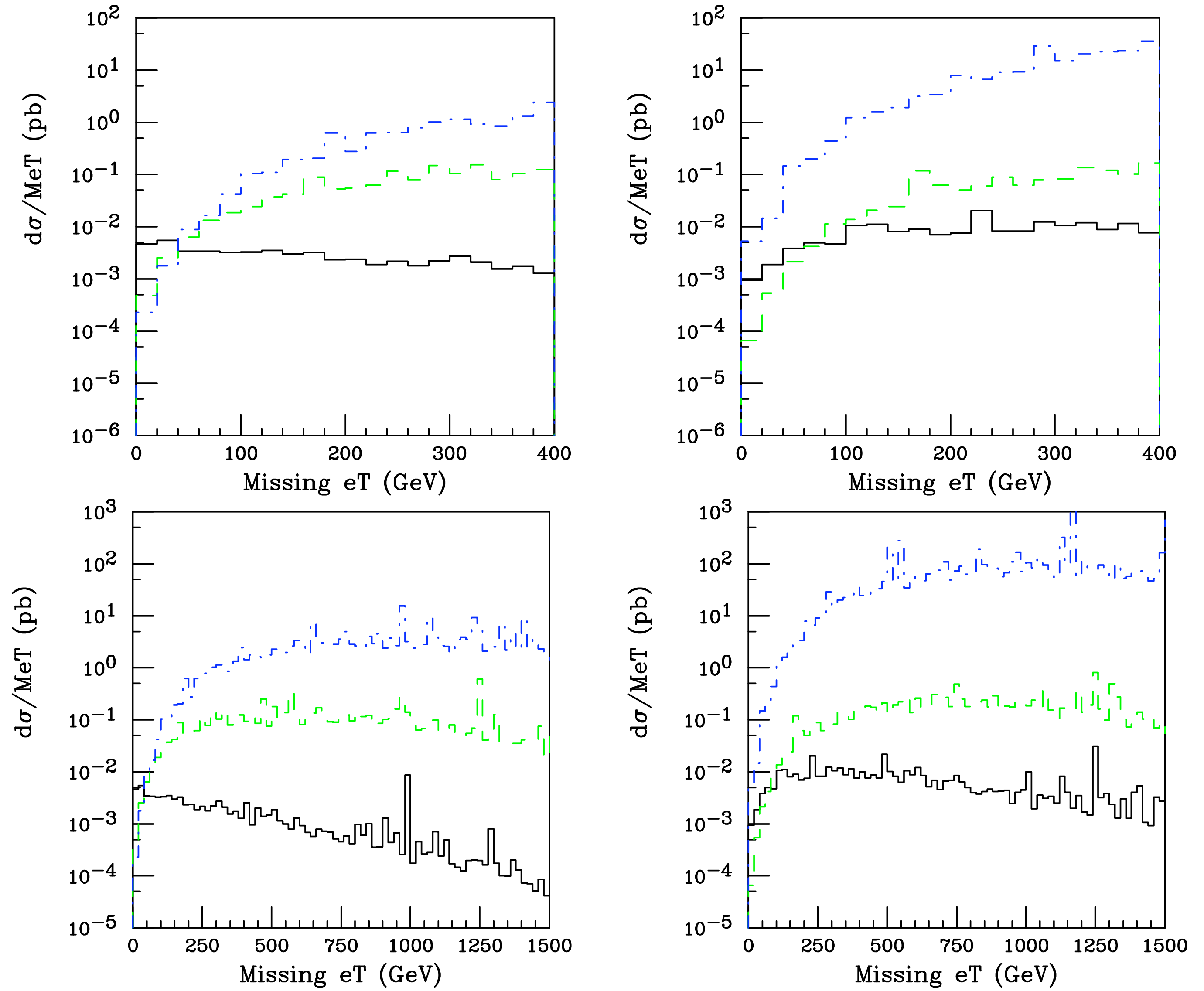
- Definitive missing energy/effective mass peak.
- W mass sets the missing energy mass scale.
- No cuts applied to see physics.

ZZ Background



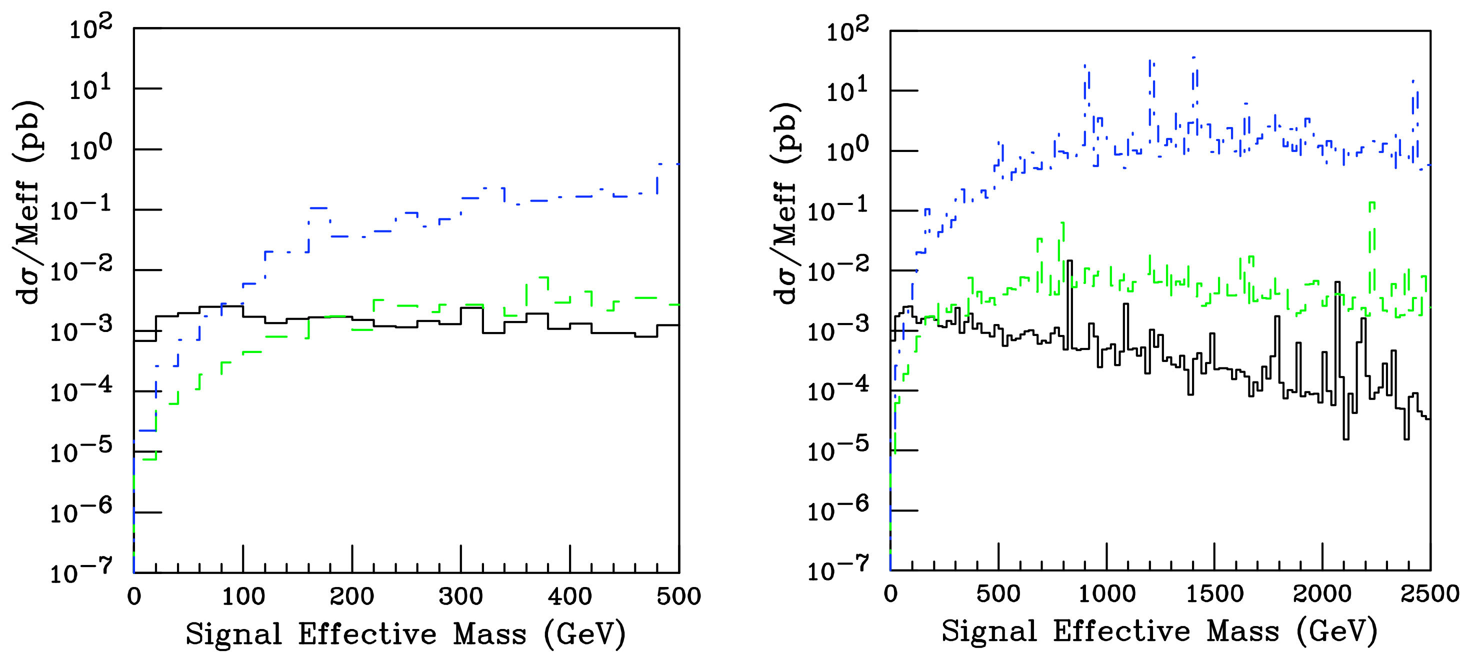
- Definitive missing energy mass scale set by the Z mass.
- No cuts applied to see the physics.

Unparticle Signal at LHC



- No associated mass scale or cuts applied. Distribution is clearly different from background. For electron final states.
- Left panels $d_{\mathcal{U}}$ = 1 (black solid), 2 (green solid), 3 (blue dot-dashed); Right panels $d_{\mathcal{U}}$ = 1.5 (black solid), 2.5 (green solid), 3.5 (blue dot-dashed)
- Signal for muon final state is orders of magnitude smaller.

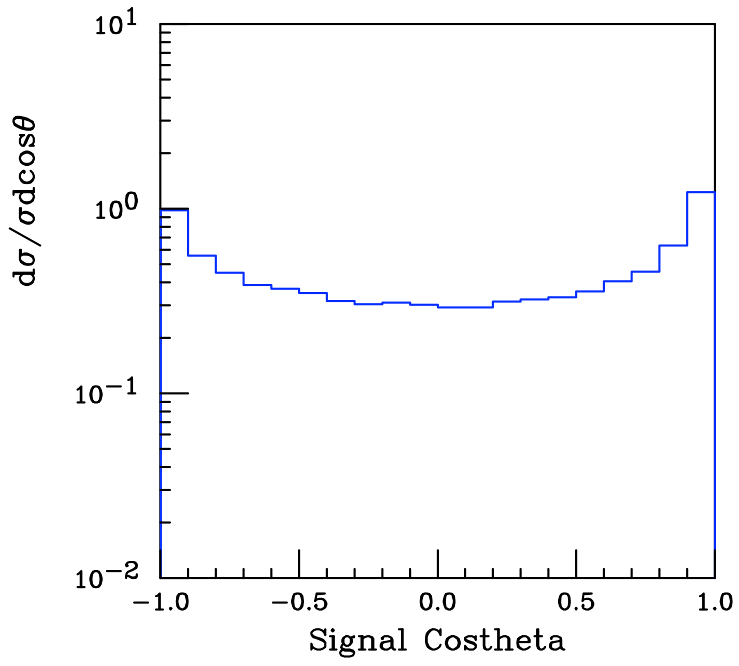
Unparticle Signal at LHC

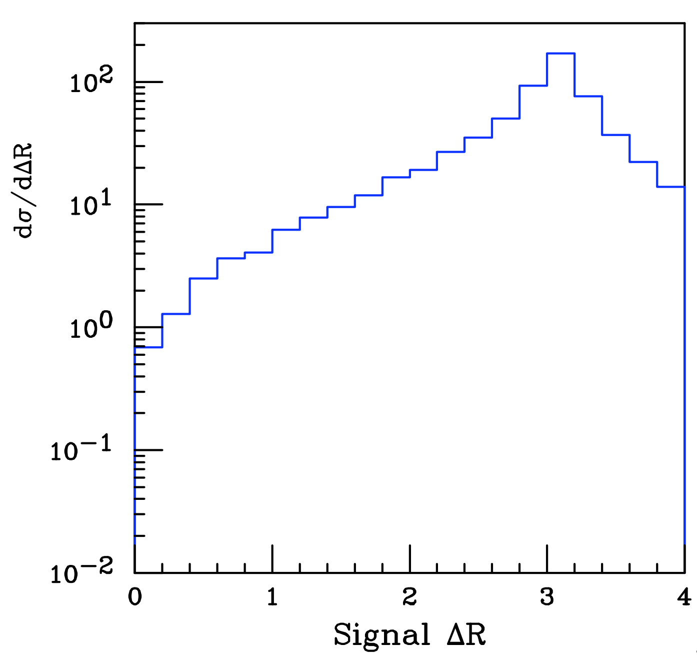


- Again, no associated mass scale for the effective mass. (No cuts applied.)
- Left/right panels = 1 (black solid), 2 (green solid), 3 (blue dot-dashed)
- Distribution is clearly different from background.
- Electron final states.

Clarify Signal

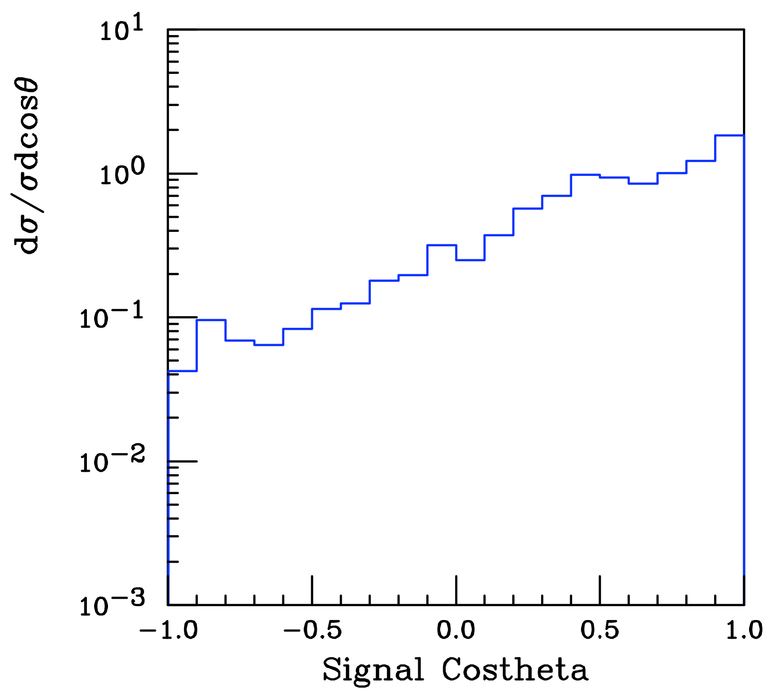
- We can clarify the signal by looking at the angle between the leptons. Di-lepton $cos\theta$ and $\Delta R_{l^+l^-}$ for WW background.

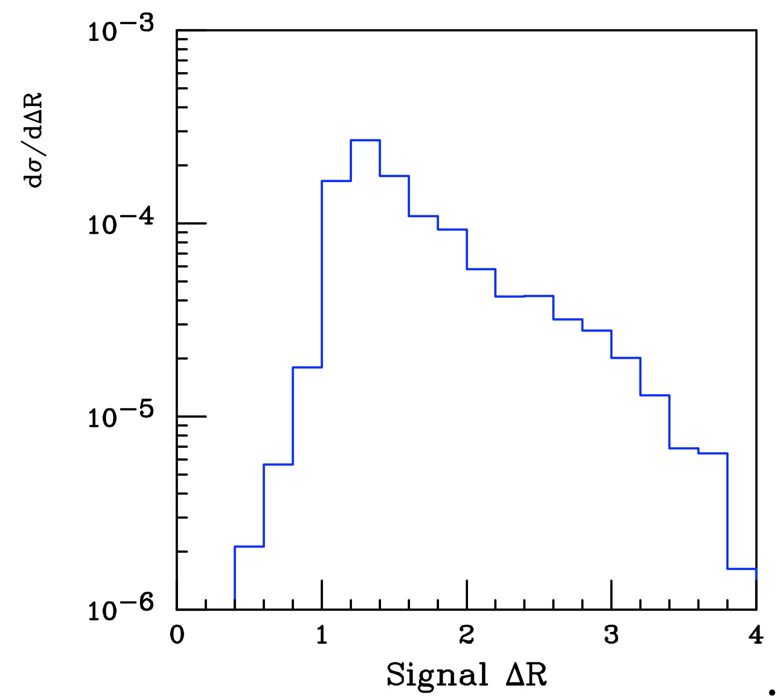




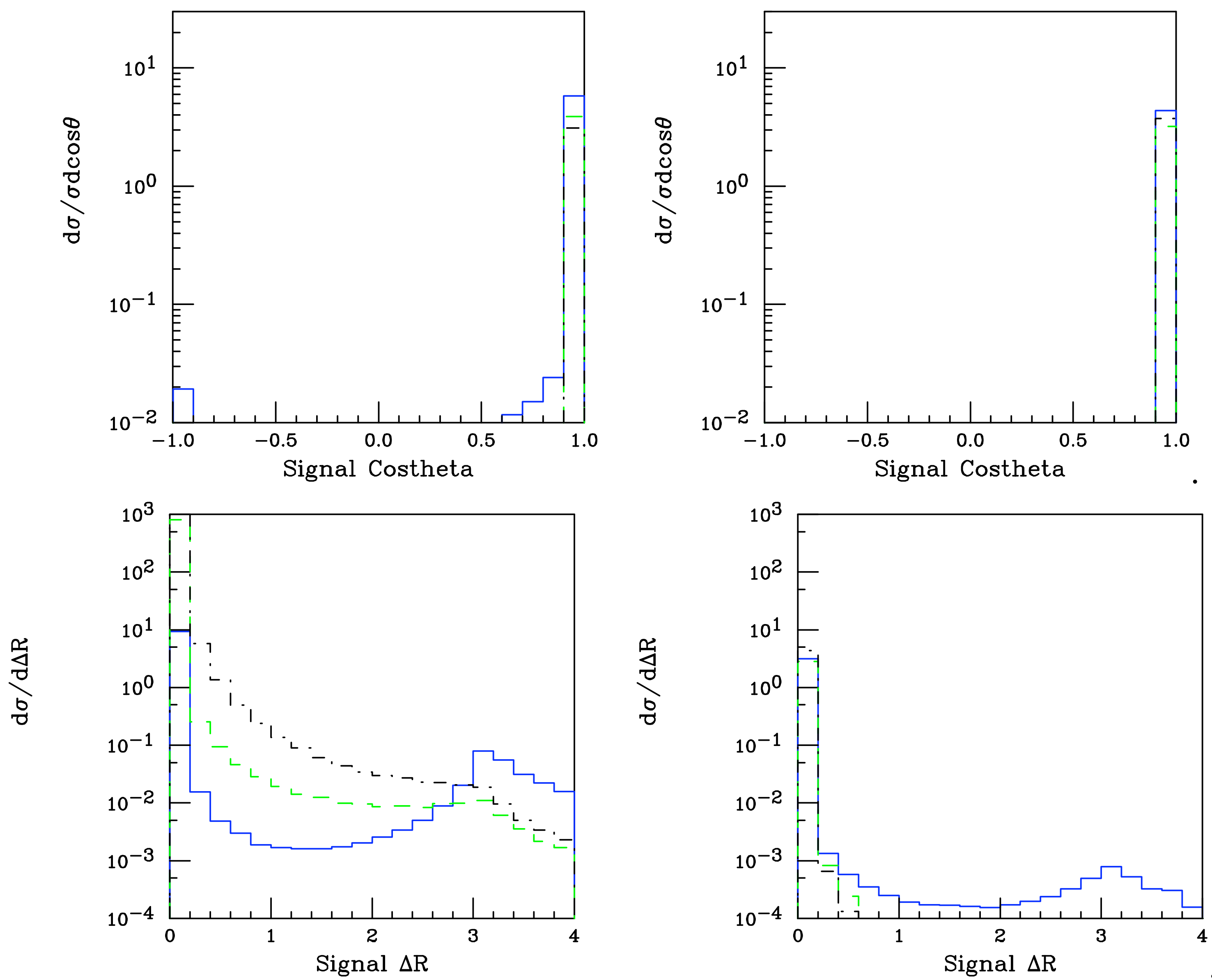
Clarify Signal

- Di-lepton $cos\theta$ and ΔR_{l+l-} for ZZ background.



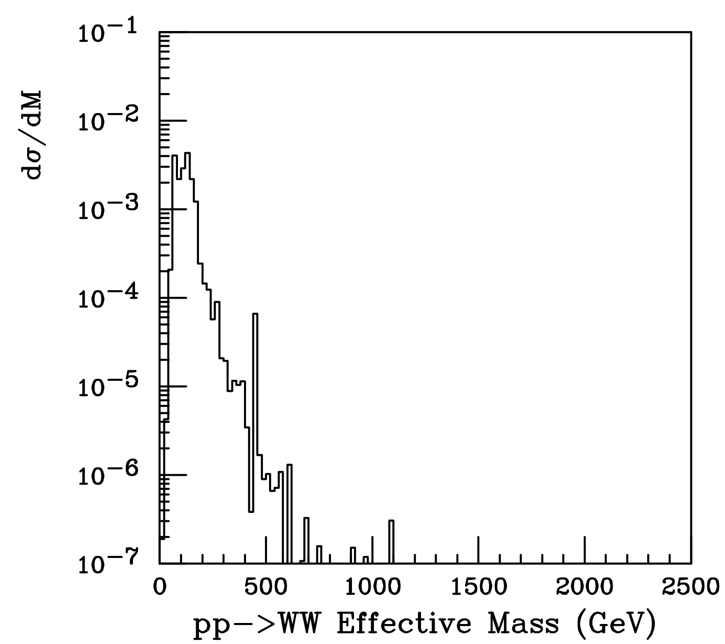


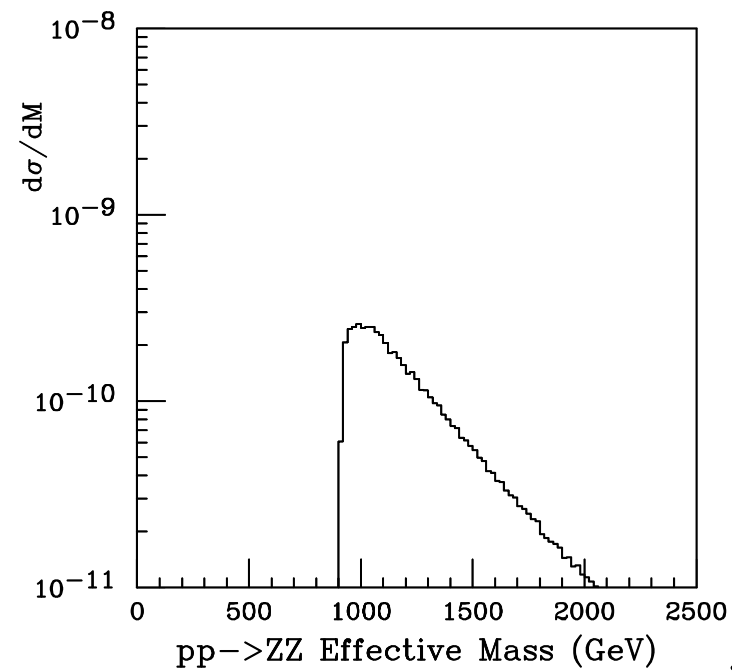
Clarify Signal



- Di-lepton $cos\theta$ and $\Delta R_{l^+l^-}$ for signal.
  - Left panels $d_{\mathcal{U}}$ = 1 (blue solid), 2 (green dashed), 3 (black dot-dashed); Right panels $d_{\mathcal{U}}$= 1.5 (blue solid), 2.5 (green dashed), 3.5 (black dot-dashed)

Effect on Background





- Effectively a cut on the missing energy. We could do a simple missing energy cut. This cut will prove more useful when we look for early signatures of Unparticles at the LHC.

- WWs are produced in separate hemispheres. $\Delta R_{l^+l^-}$ cut reduces the signal to W pairs that are nearly on shell. The daughter leptons will not be as boosted. Note: Restricting to the central detector region will eliminate the rest of this background. No cuts are applied on the plots to see the physics.

- The $\Delta R_{l^+l^-}$ cut eliminates the ZZ pairs when they are produced nearly on shell.

Kinematic Cuts

- Apply di-lepton cut: $\Delta R_{\text{dilepton}} < 0.4$
- Apply also the detector cuts:

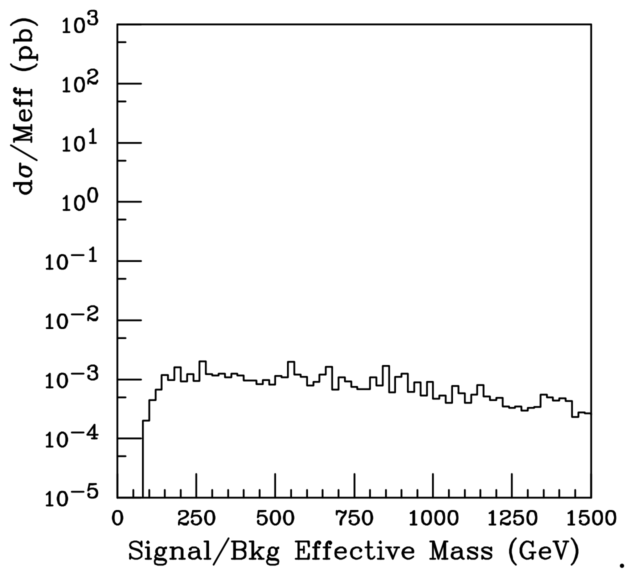
Minimum Lepton p_T cut	$p_T > 20$ GeV
Minimum Lepton Rapidity cut	$\lvert\eta_{\text{lepton}}\rvert \leq 2.5$

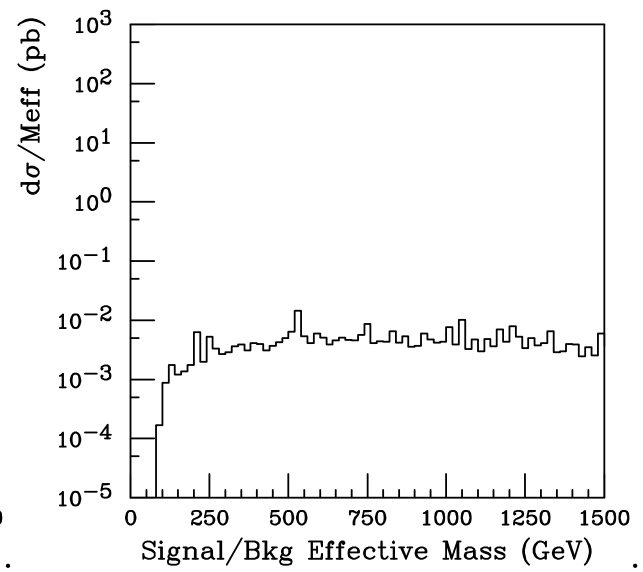
- Smearing parameters:

p_T ATLAS Resolution	$a = 3.6 \times 10^{-4}$, $b = 0.013$
ATLAS ECAL Resolution	$a = 0.1$, $b = 0.007$
p_T CMS Resolution	$a = 1.5 \times 10^{-4}$, $b = 0.05$
CMS ECAL Resolution	$a = 0.03$, $b = 0.005$

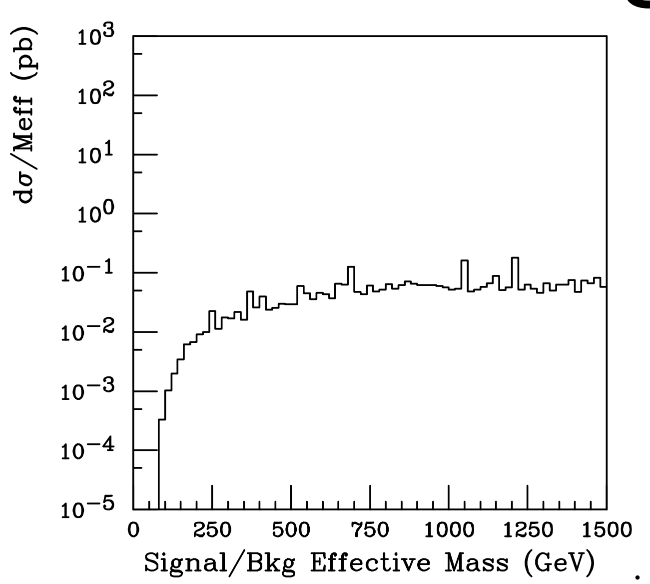
Signal + Background

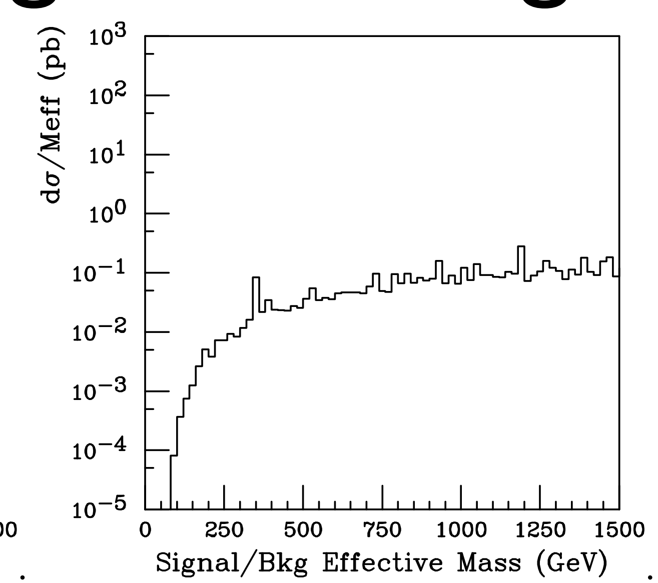
- $d_{\mathcal{U}}$ = 1 and 1.5 signal + background





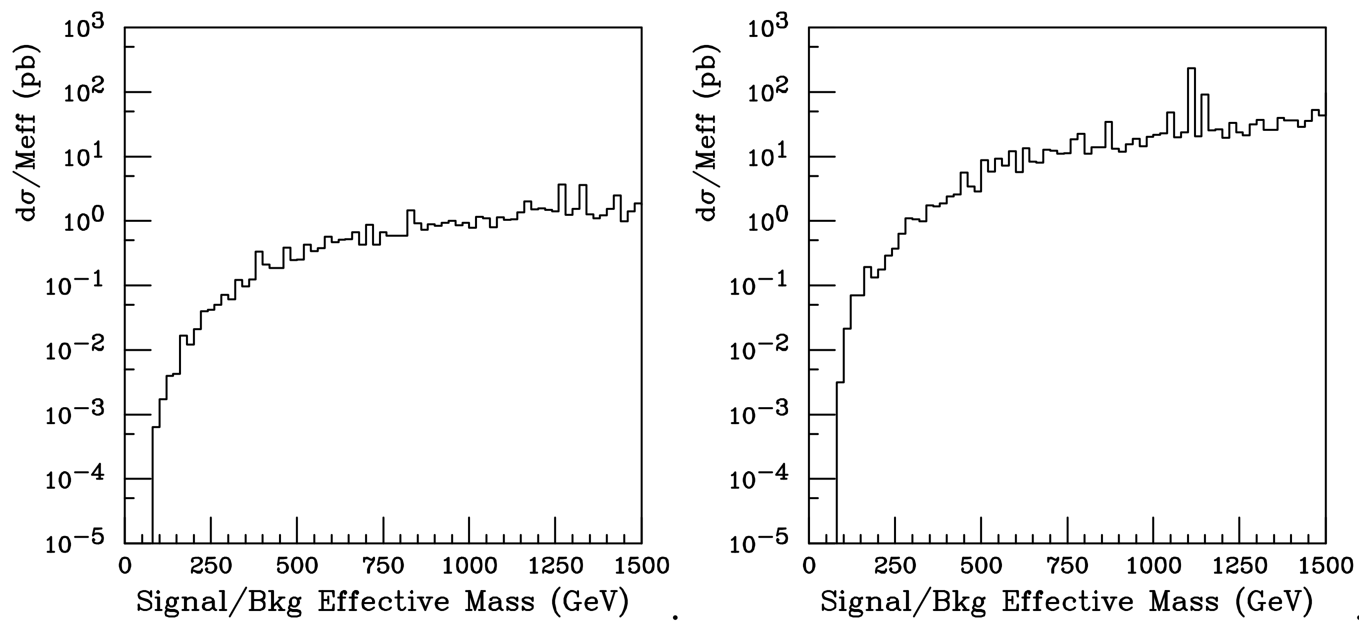
- $d_{\mathcal{U}}$ = 2 and 2.5 signal + background





Signal + Background

- $d_{\mathcal{U}}$ = 3 and 3.5 signal + background



- All plots have electron final states. Plots with muon final states have the same structure but are down an order of magnitude.

Final Tally

- Muons:

	Process	All cuts (pb cross section)
signal	$d = 1$	2.37
	$d = 1.5$	0.3×10^{-2}
	$d = 2$	0.06
	$d = 2.5$	0.4
	$d = 3$	2.6
	$d = 3.5$	2.9
background	$pp \to WW$	0.0
	$pp \to ZZ$	0.15×10^{-3}
Total background		0.15×10^{-3}

$10\ \mathrm{fb}^{-1}$	$S/\sqrt{B+S}$	S/B
$d = 1$	5+	10+
$d = 2$	1.7 (5.8 $S/\sqrt{B}$)	10+
$d = 3$	5+	10+
$d = 1.5$	5+	10+
$d = 2.5$	5+	10+
$d = 3$	5+	10+

Final Tally

- Electrons:

	Process	All cuts (pb cross section)
signal	$d = 1$	2.37
	$d = 1.5$	3.1
	$d = 2$	16.2
	$d = 2.5$	38.1
	$d = 3$	100
	$d = 3.5$	163
background	$pp \to WW$	0.0
	$pp \to ZZ$	0.15×10^{-3}
Total background		0.15×10^{-3}

10 fb^{-1}	$S/\sqrt{B+S}$	S/B
$d = 1$	5+	10+
$d = 2$	5+	10+
$d = 3$	5+	10+
$d = 1.5$	5+	10+
$d = 2.5$	5+	10+
$d = 3$	5+	10+

Distinguishing Unparticles from other BSM Scenarios

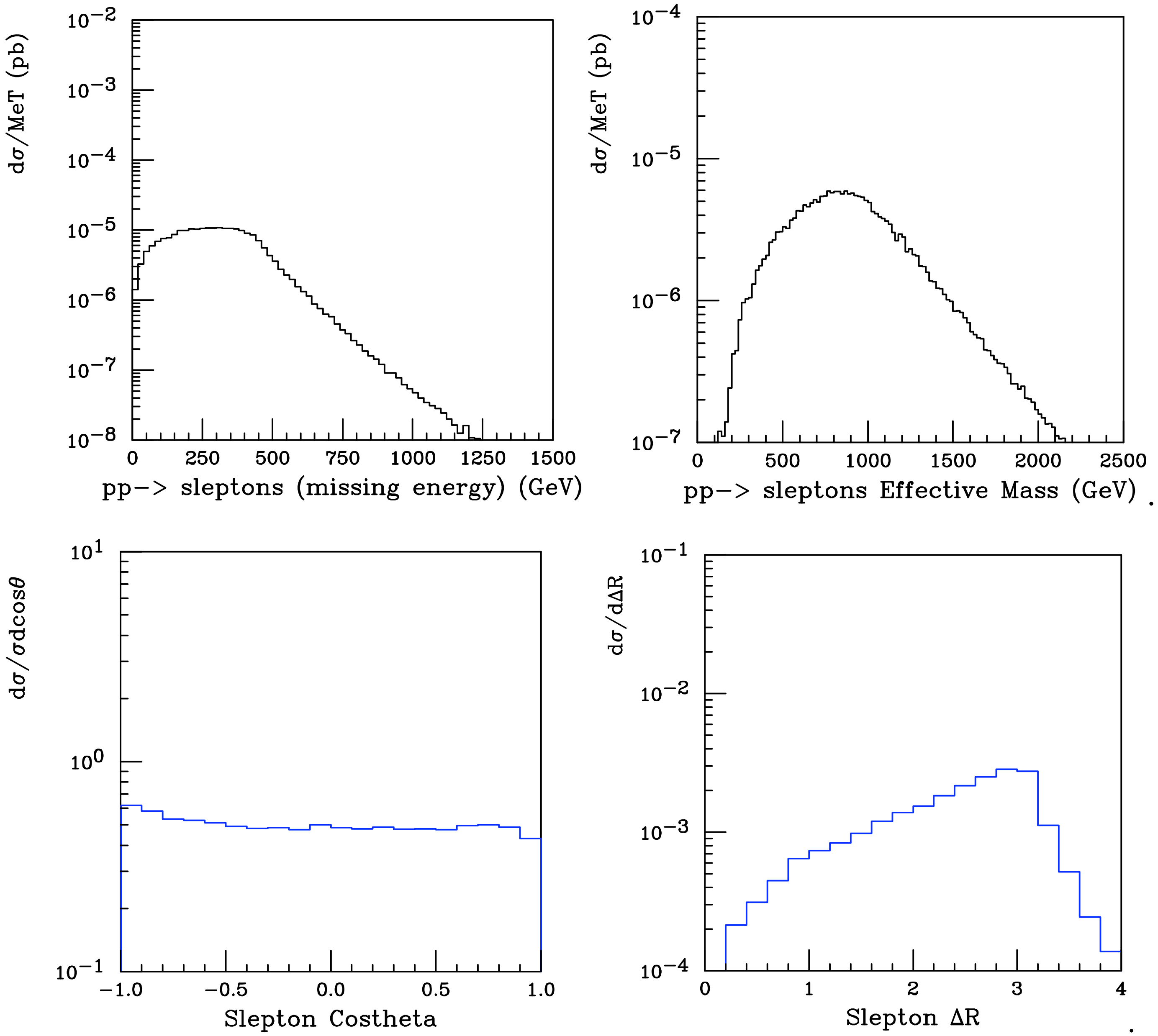
Slepton Decays

- Choose the distinguish Unparticles from the MSSM. All BSMs have the same features:
  - Large missing energy with a mass scale defined by the LSP.
  - Mass difference between parent parity odd particle and LSP most important kinematic parameter.*
- Consider slepton decay: $pp \to \tilde{l}\tilde{l} \to l^+ l^- \bar{\tilde{Z}}\tilde{Z}$
  With difference parameter $\Delta M_{\tilde{l}\tilde{Z}} = M_{\tilde{l}} - M_{\tilde{Z}}$

* Han, Mahbubani, Walker, and Wang to appear.

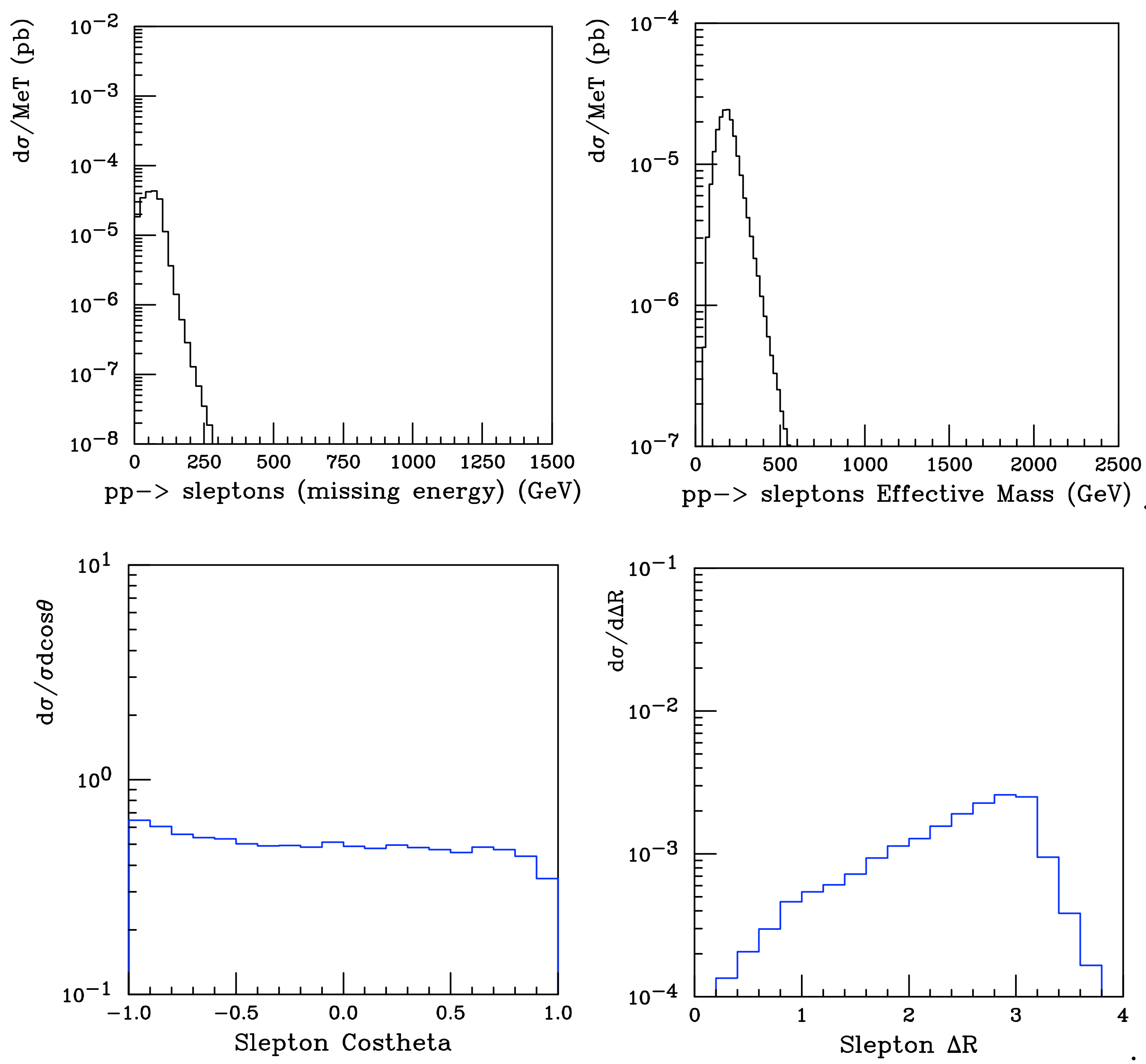
Slepton Decays

- When $\Delta M_{\tilde{l}\tilde{Z}}$ is large, the effective mass gives a general estimate of the neutralino mass scale.
  - Consider 150 GeV neutralino mass with 500 GeV slepton mass.



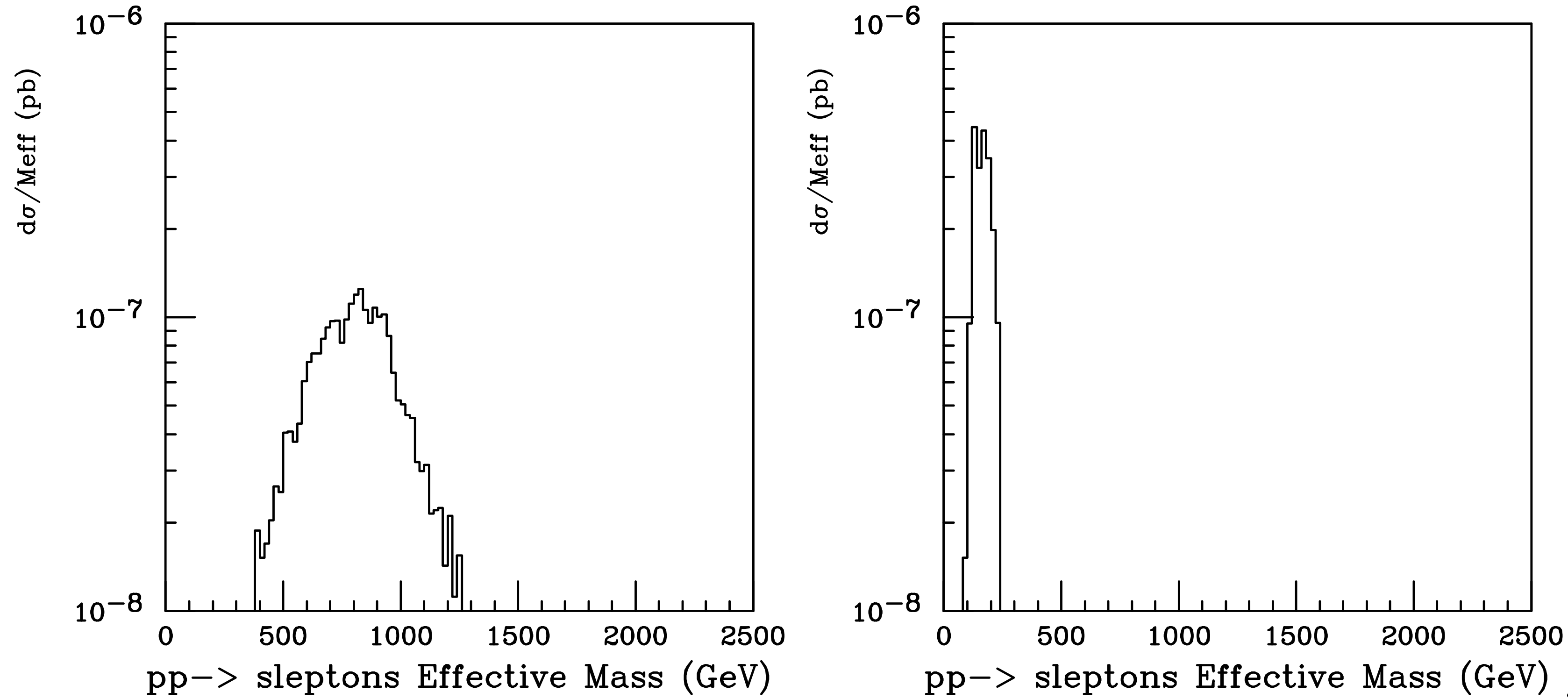
Slepton Decays

- Consider 450 GeV neutralino mass with 500 GeV slepton mass.
  - The effective mass does not give the correct mass scale.



Slepton Decays

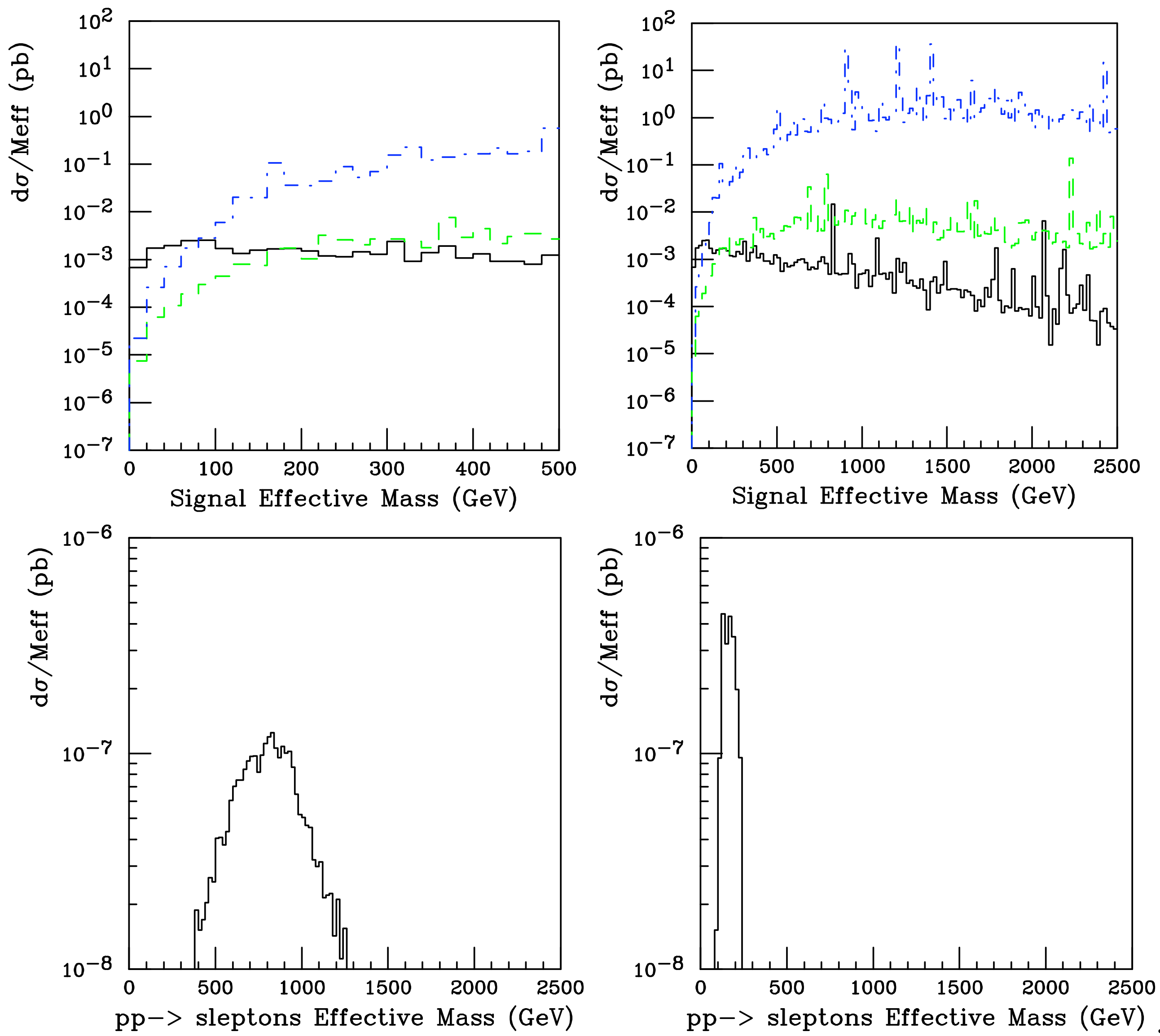
- Apply $\Delta R_{\text{dilepton}} < 0.4$ cut. The effective mass for large $\Delta M_{\tilde{l}\tilde{Z}}$ (left panel) and small $\Delta M_{\tilde{l}\tilde{Z}}$ (right panel):



- Rate is noticeably down. Signal distribution is distinct from Unparticles.

Distribution Comparison

- Unparticle and Slepton signals + bkg



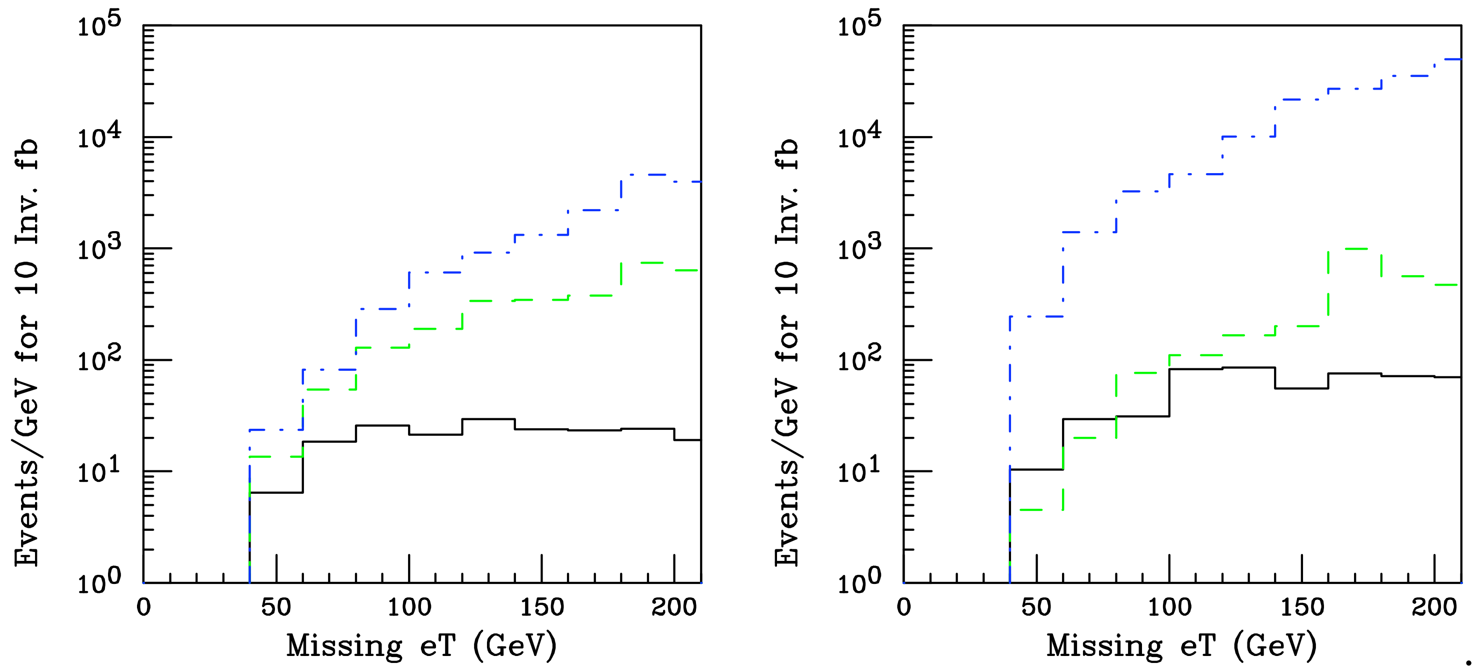
Early Indications of Unparticles at the LHC

Z Lineshape Measurement

- An early benchmark for experimentalists to measure when the LHC turns on is the Z resonance.
- Reminder: Unparticle signal grows like powers of E.
  - LEP ruled out an invisible higgs at these energy scales.
  - Unlikely a LSP will give a $l^+ l^- \not{E}_T$ signature for dilepton invariant masses ~ 100 GeV.
- Look for missing energy in this invariant mass range.

Missing Energy

- Electron final states with all cuts.
    - Left panel $d_{\mathcal{U}}$ = 1 (black solid), 2 (green dashed), 3 (blue dot-dashed); Right panels $d_{\mathcal{U}}$ = 1.5 (black solid), 2.5 (green dashed), 3.5 (blue dot-dashed)



- Muon final states give a similar signature as well.

Summary:

- We showed how to distinguish signatures of Unparticle physics at the LHC from the Standard Model and beyond.
- The key point is models with Unparticle physics do not have a definitive mass scale associated with the missing energy. The Standard Model and models of new physics (such as SUSY, LH, etc.) each have such a scale.
- To clarify the collider signatures, we provided a set of kinematic variables and cuts useful in distinguishing scale invariance at the LHC.
- We showed how Unparticle physics can potentially be seen with as little as $10\ \mathrm{fb}^{-1}$ of data at the LHC.
- We provided stringent bounds on Unparticles from LEP and the TeVatron.

Backup Slides

Unique Unparticle Effects

- Can calculate density of final states for Unparticles:

$$\langle 0|\, O_{\mathcal{U}}(x)\, O_{\mathcal{U}}^{\dagger}(0)\, |0\rangle = \int e^{-ipx}\, |\langle 0|\, O_{\mathcal{U}}(0)\, |P\,\rangle|^2\, \rho\left(P^2\right)\, \frac{d^4P}{(2\pi)^4}$$

- By scale invariance the matrix element is:

$$|\langle 0|\, O_{\mathcal{U}}(0)\, |P\,\rangle|^2\, \rho\left(P^2\right) = A_{d_{\mathcal{U}}}\, \theta\left(P^0\right)\, \theta\left(P^2\right)\, \left(P^2\right)^{d_{\mathcal{U}}-2}$$

- This is the appropriate phase space for Unparticles.