Particle Physics at the Highest Energies

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Several Projects

- My completed projects:

Integral dispersion relations to extend the reach of the LHC.

Reconstructing quadrupole anisotropies with partial sky exposure.

- Papers collaborated on:

Quantum black holes: detecting low scale gravity using extensive air showers.

Higgs portal $\to \Delta N_{\mathrm{eff}}$ and dark matter.

- Projects in progress:

UHECR anisotropy study with spherical harmonics.

Neutrino energy cutoff $\Rightarrow \pi^{\pm}$ stability.

Nuetrino anisotropy at IceCube.

Extending the Reach of the LHC with Integral Dispersion Relations

and

Stability of Charged Pions

New Physics at the LHC

Nobel prize in 2013 for "old" physics found at the LHC.

Nothing "new" (BSM) at the LHC yet.

New physics is constrained to $\mathcal{O}$(few) TeV.

Suppose there is new physics near (above or below) 14 TeV...

About Integral Dispersion Relations: Key Formulas

Cauchy's integral formula:

$$f(z) = \frac{1}{2\pi i} \oint_{\partial A} \frac{f(z')}{z' - z} dz'$$

The optical theorem:

$$\sigma_{\mathrm{tot}} = \frac{4\pi}{p} \Im f(\theta = 0)$$

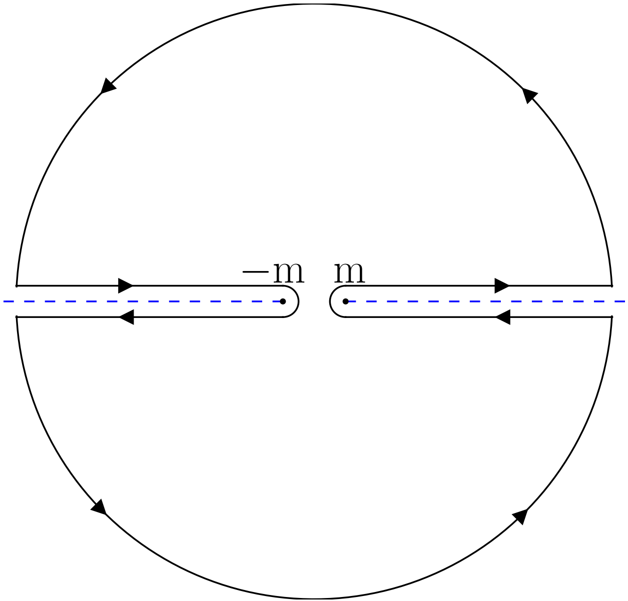
Froissart bound:

$$\sigma_{\mathrm{tot}}(E) \leq C \log^2(E/E_0)$$

Definitions:

$$\rho(E) \equiv \frac{\Re f(E, t=0)}{\Im f(E, t=0)} \qquad E \equiv \frac{s-u}{4m} \qquad f_\pm = \frac{1}{2}(f_{p\bar{p}} \pm f_{pp})$$

About Integral Dispersion Relations: Integration Contour



Integral Dispersion Relations

Subtraction + optical theorem:

$$\rho_{pp}(E)\sigma_{pp}(E) = \frac{4\pi}{p}\Re f(0) + \frac{E}{p\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \frac{p'}{E'}\left[\frac{\sigma_{pp}(E')}{E'-E} - \frac{\sigma_{p\bar{p}}(E')}{E'+E}\right]$$

Since $\lim_{E'\to\infty}\sigma(E')/E' \to 0$, outer circle $\to 0$.

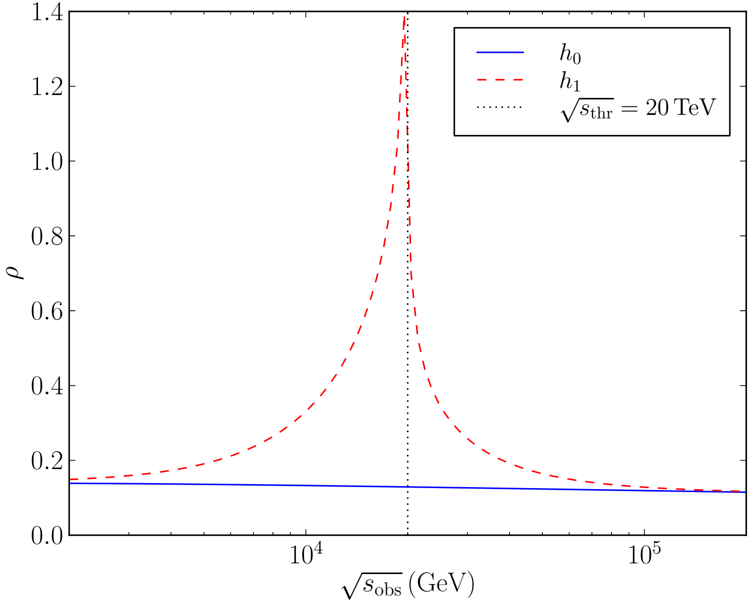
For integral to converge need $|\sigma_{pp} - \sigma_{p\bar{p}}| \to 0$.

Experimentally $|\sigma_{pp} - \sigma_{p\bar{p}}| \propto s^{-0.5}$: fast enough (Pomeranchuk).

From data, $f(0)$ is small (contributes < 1 part in 10^5 to ρ).

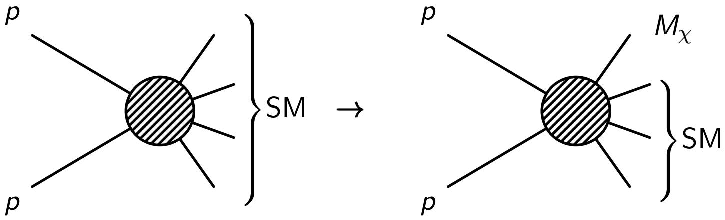
IDRs allow for the calculation of ρ in a model dependent way.

Step Function Doubling the Cross Section



More Physical Modifications

RPV SUSY: Replace one final state particle with a heavier partner.



More Physical Modifications: Parton Approach

We reduce the cross section by a phase space ratio given by

$$\sqrt{\frac{\lambda(\hat{s}, M_\chi^2, 0)}{\lambda(\hat{s}, 0, 0)}} = 1 - \frac{M_\chi^2}{\hat{s}}$$

We integrate this in terms of the pdfs

$$h_2(s, M_\chi) = z \sum_{i,j} \int_{x_1 x_2 > M_\chi^2/s} dx_1 dx_2$$

$$\times f_i(x_1, M_\chi) f_j(x_2, M_\chi) x_1 x_2 \left(1 - \frac{M_\chi^2}{\hat{s}}\right)$$

where $z = \sigma_{inel}/\sigma_{tot} \sim 0.7$.

More Physical Modifications: Diffractive Approach

Cut final states into two blocks by pseudorapidity and we let M_X be the mass of the more massive one. Let $\xi \equiv M_X^2/s$.

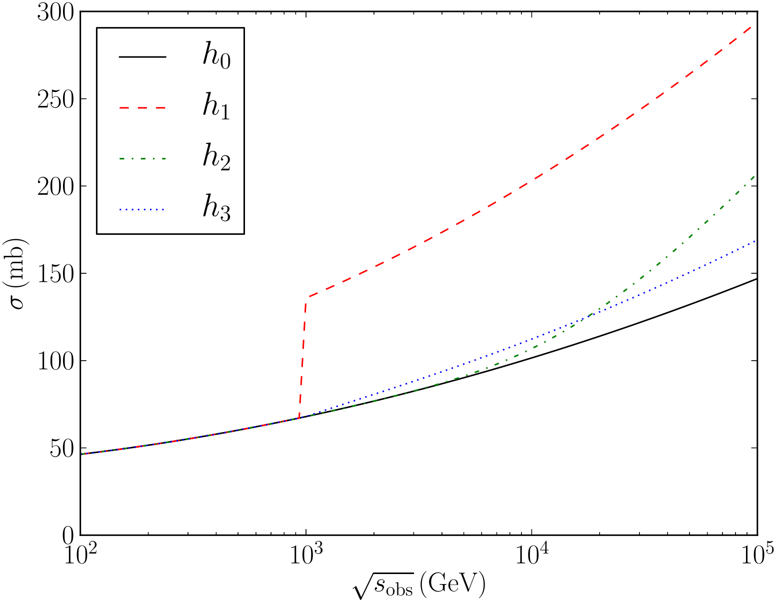
$$\frac{d\sigma}{d\xi} = \frac{1+\xi}{\xi^{1+\epsilon}} \qquad \epsilon \sim 0.08$$

The bounds on the above integral change from SM $\to$ new physics,

$$h_3(s) = z\frac{1-2\epsilon+(\epsilon-1)\xi_\chi^{-\epsilon}+\epsilon\xi_\chi^{1-\epsilon}}{1-2\epsilon+(\epsilon-1)\xi_p^{-\epsilon}+\epsilon\xi_p^{1-\epsilon}}\Theta(1-\xi_\chi)$$

$$\lim_{s\to\infty} h_3(s) = z\left(\frac{m_p}{M_\chi}\right)^{2\epsilon} \approx 0.23\left(\frac{1\,\mathrm{TeV}}{M_\chi}\right)^{2\epsilon}$$

Total Cross Section Modifications



Measuring ρ at the LHC

Most cited values of ρ are calculated from IDRs.

$$\frac{d\sigma}{dt} = \frac{\pi}{k^2}|f|^2 \qquad\qquad \frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

B is the measured slope parameter, valid at low $|t|$.

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\pi}{k^2}\left|(\rho+i)\Im f(t=0)\right|^2 = \frac{\rho^2+1}{16\pi}\sigma_{\rm tot}^2$$

Measuring $\sigma_{\rm tot}$ without ρ is difficult.

Requires an accurate luminosity measurement.

Moreover $\sigma_{\rm tot}$ only weakly depends on ρ.

Experimental Status

TOTEM: $\rho = 0.145$ at $\sqrt{s} = 7$ TeV (large errors).

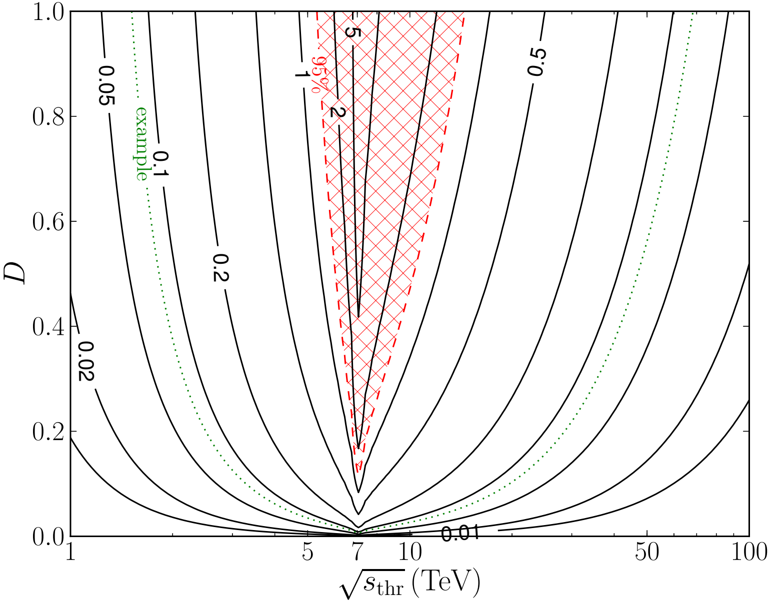
TOTEM measures ρ in a model independent fashion.

SM Prediction: $\rho = 0.1345$ at $\sqrt{s} = 7$ TeV.

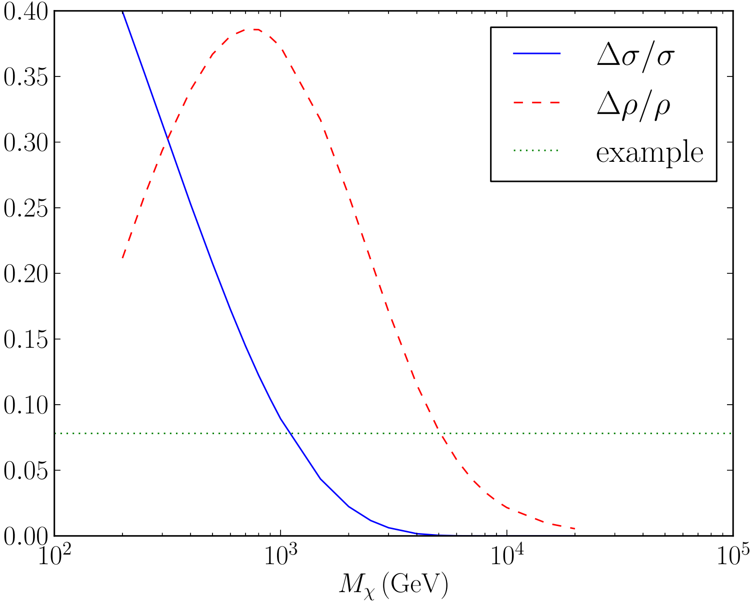
"Signal": $(\rho - \rho_{\rm SM})/\rho_{\rm SM} = 0.0781$ (a 0.1σ "signal").

Excluded: $\rho > 0.32$ at 95%.

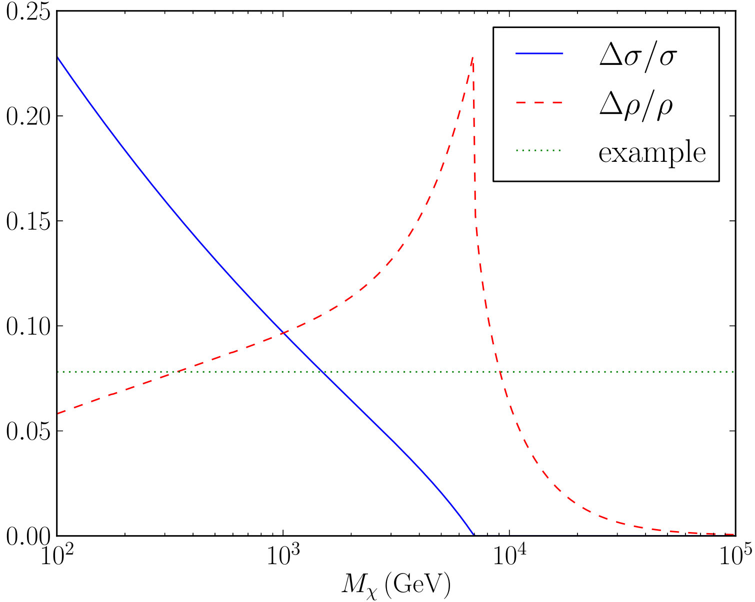
IDR Response at $\sqrt{s} = 7$ TeV for Step Function (h_1)



IDR Response at $\sqrt{s} = 7$ TeV for Parton Approach (h_2)



IDR Response at $\sqrt{s} = 7$ TeV for Diffractive Approach (h_3)



Integral Dispersion Relations: Conclusions

IDRs can probe new physics in a largely model independent fashion.

Most effective for new physics turning on near the machine energy.

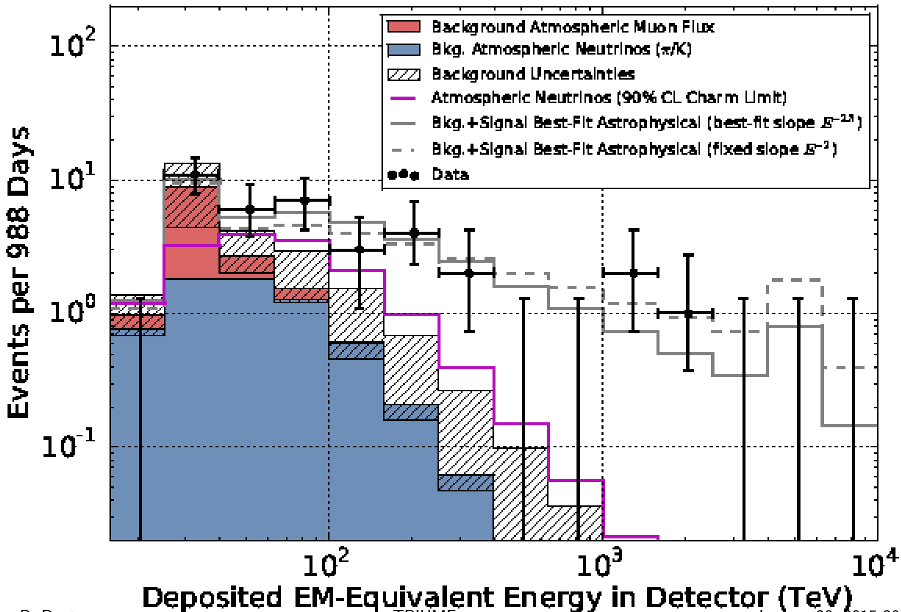
Await new data from the 14 TeV run as TOTEM will be upgraded.

Extending the Reach of the LHC with Integral Dispersion Relations

and

Stability of Charged Pions

Astrophysical Neutrinos



Glashow Resonance

At $E_\nu = 6.3$ PeV $\bar{\nu}_e$ resonantly creates a W.

Several events should have been seen at $E_\nu \sim 6.3$ PeV.

The spectrum appears to cut off around 2 PeV.

An absolute maximum energy of the neutrino has been proposed.

We extend the cutoff to the charged lepton sector as well.

The GZK process produces π^0, π^+ with $E_\pi \gtrsim 10$ EeV.

Pion Decay: Observed Processes

Main decays are two body,

$$\mu + \nu, \qquad e + \nu\,.$$

There is one very rare four body decay,

$$3e + \nu\,.$$

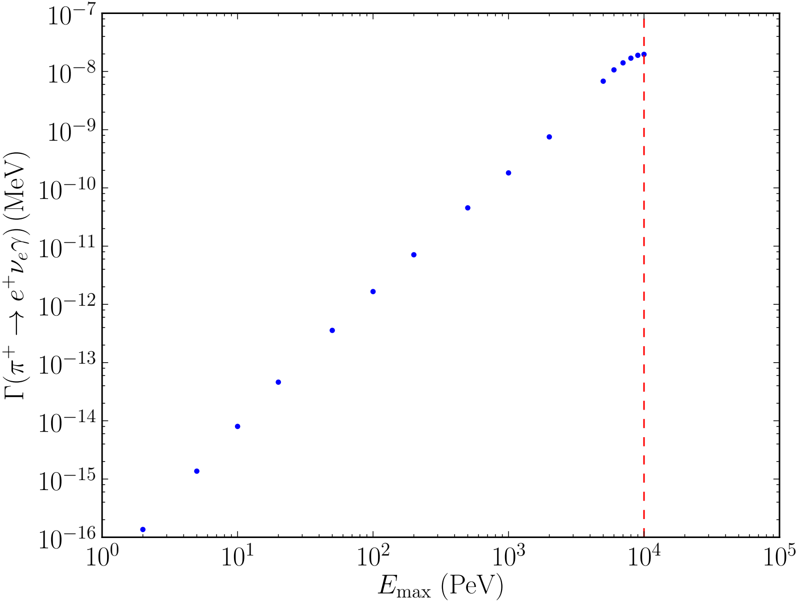
Charged pions decay to three three body processes,

$$\mu + \nu + \gamma, \qquad e + \nu + \pi^0, \qquad e + \nu + \gamma\,.$$

At $E_{\pi^\pm} = 10$ EeV and $E^\ell_{\text{max}} = E^\nu_{\text{max}} = 2$ PeV,

all but the last two are forbidden.

Pion Decay: $e + \nu + \gamma$



Pion Horizon

At $E_{\pi^\pm} = 10$ EeV and $E_{\mathsf{max}} = 2$ PeV, $c\tau > 3$ Gpc.

Photopion production could limit this horizon.

The process is $\pi^\pm + \gamma_{\rm CMB} \to \rho^\pm \to \pi^\pm + \pi^0$.

This process happens at $\sim E_{\rm GZK} \sim 50$ EeV.

Pion: Conclusions and Future Work

Lack of Glashow events suggests an end to the neutrino spectrum.

A maximum energy in the lepton sector effectively stabilizes a $\pi^{\pm}$.

Determine $\pi^{\pm} + \gamma$ cross section.

Determine relative spectrum of $\pi^{\pm}, p$.

...

Bibliography

References

- PDG, Chin.Phys. C38 (2014) 090001 (2014).
- PBD, T. Weiler, Phys.Rev. D89 (2014) 035013.
- IceCube Collaboration, Phys.Rev.Lett. 113 (2014) 101101.
- S. Glashow, Phys.Rev. 118 (1960) 316-317.
- L. Anchordoqui, et. al., Phys.Lett. B739 (2014) 99-101.

About Integral Dispersion Relations: Subtraction

Cauchy + Integration Contour + Reflection Identities:

$$\Re f_+(E) = \frac{1}{\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \Im f_+(E') \frac{2E'}{E'^2 - E^2}$$

$$\Re f_-(E) = \frac{1}{\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \Im f_-(E') \frac{2E}{E'^2 - E^2}$$

The first integrand scales like $\sigma_{\rm tot}(E')$.

Integral won't converge and the outer circle $\not\to 0$.

Need a subtraction to reduce the power: add a pole.

$$\Re f_+(E) = \Re f_+(0) + \frac{1}{\pi}\mathcal{P}\int_{m_p}^{\infty} dE' \Im f_+(E') \frac{2E^2}{E'(E'^2 - E^2)}$$

New constant $f(0)$ - not physical.

Integral Dispersion Relations: Simple Cross Section

An analytic calculation requires several simplifications:

$$\sigma_{pp}(E) \to \sigma_0 \leftarrow \sigma_{p\bar{p}}(E)$$

$$m_p \to 0$$

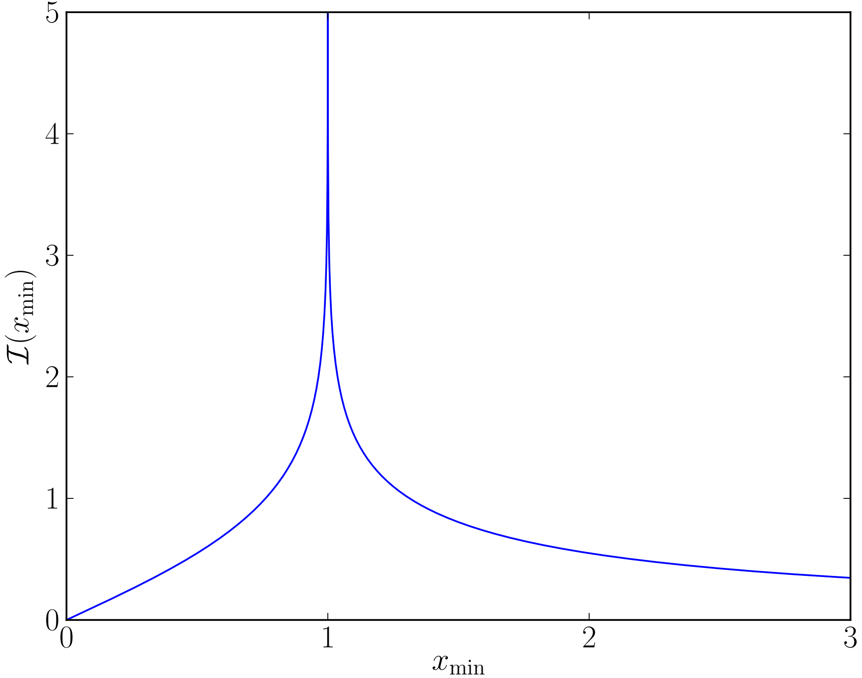
Then,

$$\rho = \frac{2}{\pi}\mathcal{P}\int_0^\infty \frac{dx}{x^2-1} = 0$$

$$x \equiv E'/E.$$

Modifying the cross section with a step increase at $E'_{\text{min}}, x_{\text{min}}$,

$$\mathcal{I}(x_{\text{min}}) \equiv \int_{x_{\text{min}}}^\infty \frac{dx}{x^2-1} > 0$$



5
4
3
2
1
0
$\mathcal{I}(x_{\rm min})$
0
1
2
3
$x_{\rm min}$

General Cross Section Modifications

Return $\sigma_{\rm tot} \propto \log^2 E$ and $m_p \neq 0$.

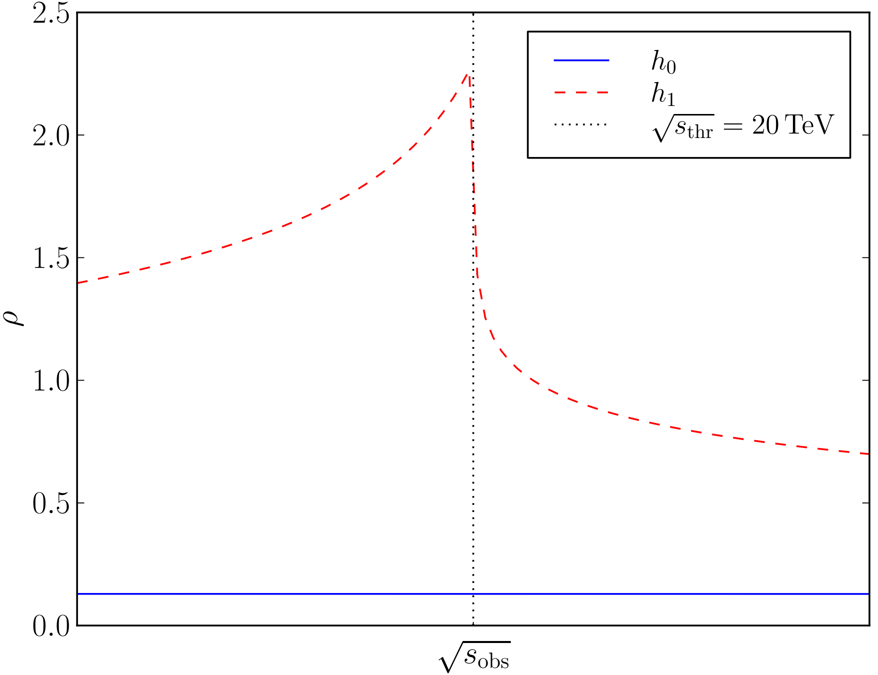
Consider modification of the general form,

$$\sigma(E) = \sigma_{\rm SM}(E)[1 + h(E)]$$

where $h(E) = 0$ for $E < E_{\rm thr}$.

The simplest such modification is $h(E) = D\Theta(E - E_{\rm thr})$.

That is, the cross section doubles at $E = E_{\rm thr}$ for $D = 1$.


2.5
2.0
1.5
1.0
0.5
0.0
ρ
h_0
h_1
$\sqrt{s_{\rm thr}} = 20\,{\rm TeV}$
$\sqrt{s_{\rm obs}}$

Diffractive Cross Section Reproduces Froissart Bound

The cross section function that goes into the modification h_3 rises like $\log^2 s$ in the appropriate limit:

$$\sigma \propto 1 - \xi_p - \log \xi_p + \left(1 - \xi_p + \xi_p \log \xi_p + \frac{1}{2} \log^2 \xi_p\right) \epsilon + \mathcal{O}(\epsilon^2)$$

with higher order ϵ terms resulting in higher orders of $\log s$ following the above pattern.