Searching for Smoking Guns for Light Resonances

(and LHC no lose theorems)

IZR with Chris Arnesen, R Porto and J Zupan

Prejudices for New Physics at TeV Scale

- Hierarchy Problem (Dirac/t'Hooft)
- Dark Matter candidate $\Omega_m \sim .3$

$$\Omega_m \sim \frac{F(g_\star, M_{pl})}{\int_{x_f}^{\infty} \langle v\sigma_{ann} \rangle (x)/x^2}$$

Choosing mass scales near TeV naturally gives necessary mass density

No compelling reason why we must see some resonance below TeV:

We do know that SOMETHING must unitarize the theory near the TeV scale

If we assume that possible new physics does not give significant a contribution to the T parameter then it seems that Higgs is light:

$$m_H \approx 120\ GeV$$

1) Will we know if light resonances are there and we're just missing them?

2) Is it possible that we dont see that Higgs or anything else?

Hadronic machines are blunt instruments when you dont know what you're looking for.

It could very well be that there are new "light" particles in the data, but were missing them.

HOW CAN WE DETERMINE IF WE'RE MISSING SOMETHING?

Studying properties of the higgs (or longitudinal gauge bosons) will allow us to sort this question out.

EFT Approach

$$L = L_0 + \sum_n C_n \frac{O_d}{\Lambda^{d-4}}$$

- Naturalness: Given scale of new physics, C's should be order one.
- Can they take on arbitrary values?
- Model independent analysis

If we have deviation from SM:

- If properties are consistent with EFT predictions, then we know where the new physics lies.
- If inconsistent: We know there are light resonances somewhere, we just gotta find them.

Inconsistency with EFT predictions follows from

Violating Bounds Wilson Coefficients

- First principles (QFT axioms)
- Experimentally (multiple observables)

Constraints from Axiomatic Bounds

(Case of Heavy Higgs)

- If the symmetry is non-linearly realized then the proper EFT is just the Gauged Non-Linear Sigma model.

$$\mathcal{L} = \mathcal{L}_{gauge} - \frac{1}{4}v^2 Tr(V_\mu V^\mu) + \frac{1}{2}\alpha_1 g g' Tr\left(B_{\mu\nu} T W^{\mu\nu}\right) + \frac{1}{2} i\alpha_2 g' Tr\left(T[V^\mu, V^\nu]\right) B_{\mu\nu}$$

$$+ i\alpha_3 g Tr\left(W_{\mu\nu}[V^\mu, V^\nu]\right) + \alpha_4 \left(Tr(V_\mu V_\nu)\right)^2 + \alpha_5 \left(Tr(V_\mu V^\mu)\right)^2$$

$$T \equiv 2\Sigma T^3 \Sigma^\dagger$$

$$V_\mu \equiv (D_\mu \Sigma)\Sigma^\dagger$$

$$D_\mu \Sigma = \partial_\mu \Sigma + \frac{1}{2} i g W_\mu^a \tau^a \Sigma - \frac{1}{2} i g' B_\mu \Sigma \tau^3$$

Assuming new physics respects custodial symmetry

α_1 Constrained by Precision EW data

α_2, α_3 Strongly constrained by lack of anomalous 3GB couplings

We can bound the coefficients

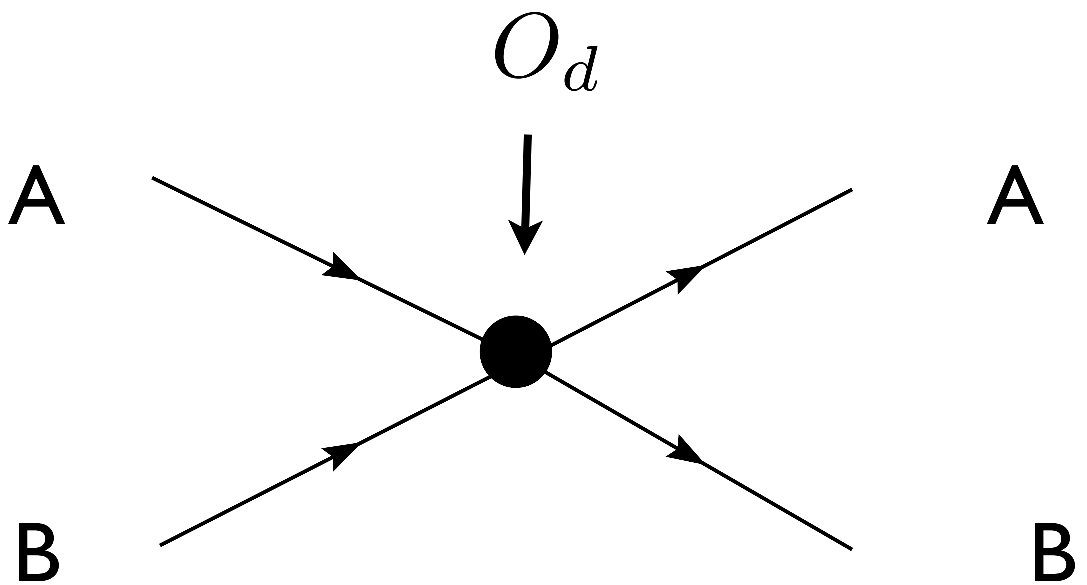
α_4, α_5

if we assume the underlying theory obeys the following assumptions

- Unitarity
- Analyticity
- Lorentz Invariance

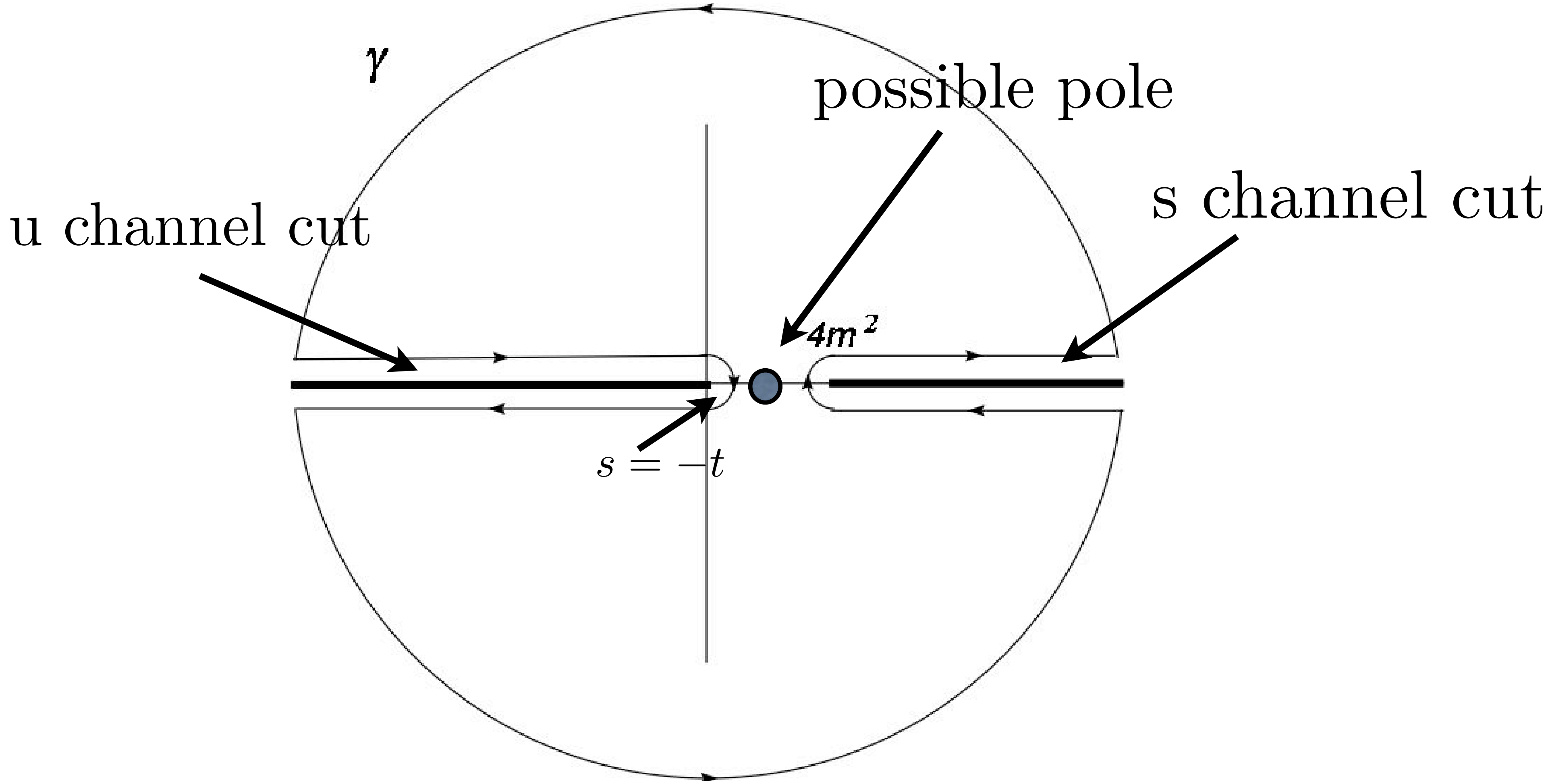
Consider first the non-gauged case (QCD) Expansion in s/v^2

Consider an elastic scattering process to which the operator of interest contributes Defining the s-channel as:



$$iM \propto C_o \frac{F(s,t,u)}{\Lambda^a}$$

Fixed t:Dispersion Relation



- Assuming cut structure dictated by unitarity

Assumes unitarity and Lorentz invariance at all scales

$$\frac{\partial^2 T(s,t)}{\partial s^2} = \frac{2}{\pi}\int_t^\infty \frac{dx\ ImT(-x+i\epsilon,t)}{(x+s)^3} + \frac{2}{\pi}\int_{4M_\pi^2}^\infty \frac{dx\ ImT(x+i\epsilon,t)}{(x-s)^3}$$

$$+\sum_{s_0^i} \frac{res(s_0^i)}{(s-s_0^i)^2}$$

- Twice subtracted for convergence at infinity.
- Froissart Bound follows from unitarity

$$\lim_{s\to\infty} \sigma(s) < s\ln^2 s$$

Also no long range forces

$$\frac{\partial^2 T(s,t)}{\partial s^2} = \frac{2}{\pi}\int_t^\infty \frac{dx\ ImT(-x+i\epsilon,t)}{(x+s)^3} + \frac{2}{\pi}\int_{4M_\pi^2}^\infty \frac{dx\ ImT(x+i\epsilon,t)}{(x-s)^3}$$

$$+\sum_{s_0^i} \frac{res(s_0^i)}{(s-s_0^i)^2}$$

If residue contribution is pos. def. and if we choose

$$s < 4m^2 \quad t=0$$

Then RHS is positive definite:

LHS= $iM \propto C_o \frac{F(s,t,u)}{\Lambda^a} + \text{low energy known physics cont.}$

Leads to a bound on the coupling

Poles are not an obstruction:

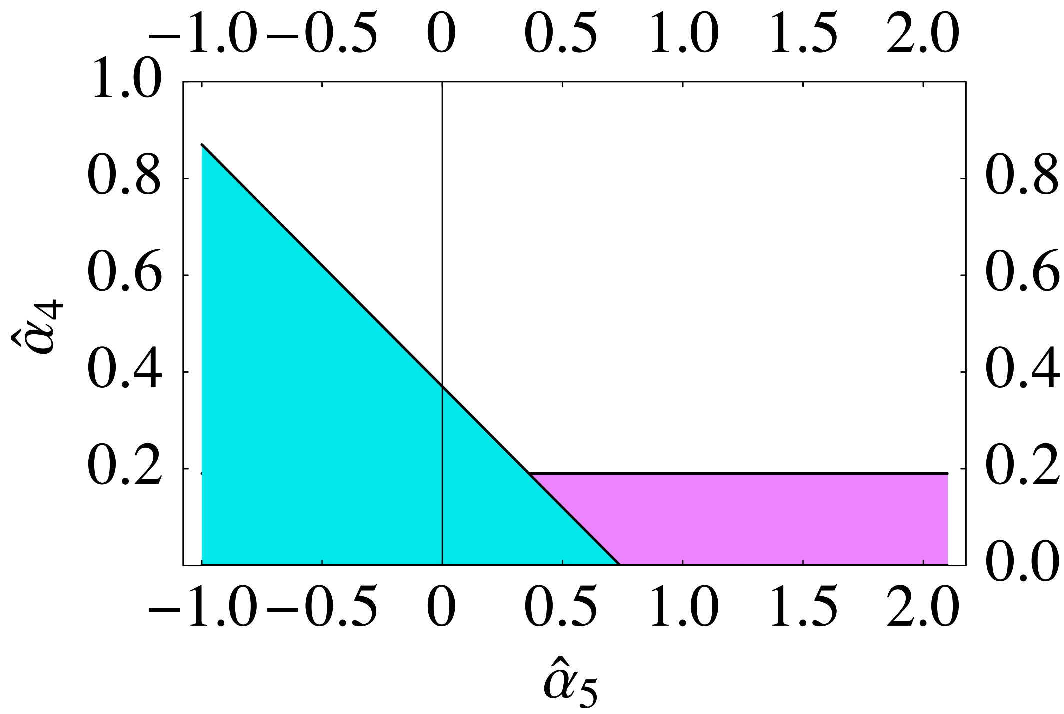
General structure:

$$\frac{(s, m^2, s^2/m^2)}{s - m^2}$$

$$\frac{\partial^2 T(s,t)}{\partial s^2} = \frac{2}{\pi}\int_t^\infty \frac{dx\ ImT(-x+i\epsilon,t)}{(x+s)^3} + \frac{2}{\pi}\int_{4M_\pi^2}^\infty \frac{dx\ ImT(x+i\epsilon,t)}{(x-s)^3}$$

$$+\sum_{s_0^i} \frac{res(s_0^i)}{(s-s_0^i)^2}$$

Pole contributions cancel:
Would not be true for s^3
terms.



Distler/Grinstein/
IZR PRL 07

Dominant source of errors on bound come from LHS

$$\delta l \sim \frac{g^2}{k} \sim \%20$$

Suppose bounds were violated:

1) Underlying theory does not obey usual axioms of QFT. NOT string theory (at least in form we build models with).

2) There exists light resonances below $4\pi v$

e.g. 5-d theory in Ads dual to large N

Bounding Coefficients experimentally

- Look for operators which contribute to more than one accessible observable. In particular concentrate on observables which have small rates in the SM, so the new physics can be expected to strongly compete.
- This will occur if: SM has an unaturally small coupling, the SM starts at one loop or if there is a PDF suppression in the SM relative to NP contribution

Case I: (Anomalously small coupling)

- E.G $bb \to h \quad \sigma_{bb} \approx 1 \; p_b$

What operators can enhance this rate?

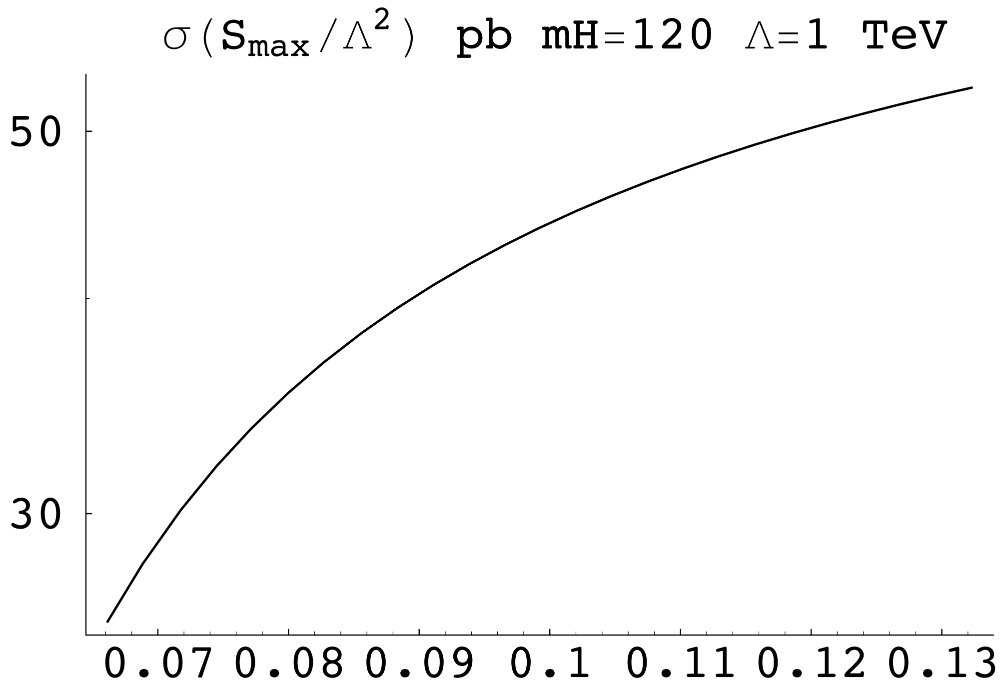
$$O_b = H^\dagger D^\mu H \bar{b}_R \gamma_\mu b_R$$

$$O_Q = H^\dagger D^\mu H \bar{Q}_L \gamma_\mu Q_L$$

$$O_{Q\sigma} = H^\dagger \sigma^a D^\mu H \bar{Q}_L \sigma^a \gamma_\mu Q_L$$

Only contribute to $bb \to Z + H$

(clean!)



Much cleaner experimentally, but there are constraints on these operators from

$$Z \rightarrow bb$$

$$\Lambda \geq 7\ TeV$$

(Skiba and Han)

- However, since the produciton is always in association with a Z, the SM will dominate by bremming a Higgs at no cost of a small Yukawa.
- A better possibility would be to look for the effects of the operator

$$GGB$$

This operator will contribute to Higgs+Z and could be enhanced by the gluonic PDF relative to the SM. However, the size of its coefficient is bounded by the width of the Z. So to large of a rate would imply the existence of light resonances. (have not done the analysis yet)

Case II: Or the set of operators are those contribute at tree level to process which start at one loop in the SM

$$\frac{g^2}{16\pi^2} \sim C\frac{s}{\Lambda^2}$$

$$O_{gg} = G^a_{\mu\nu}G^{a\mu\nu}H^\dagger H$$

$$O_{\gamma\gamma} = F_{\mu\nu}F^{\mu\nu}H^\dagger H$$

For light Higgs $m_H \leq 130\ GeV$

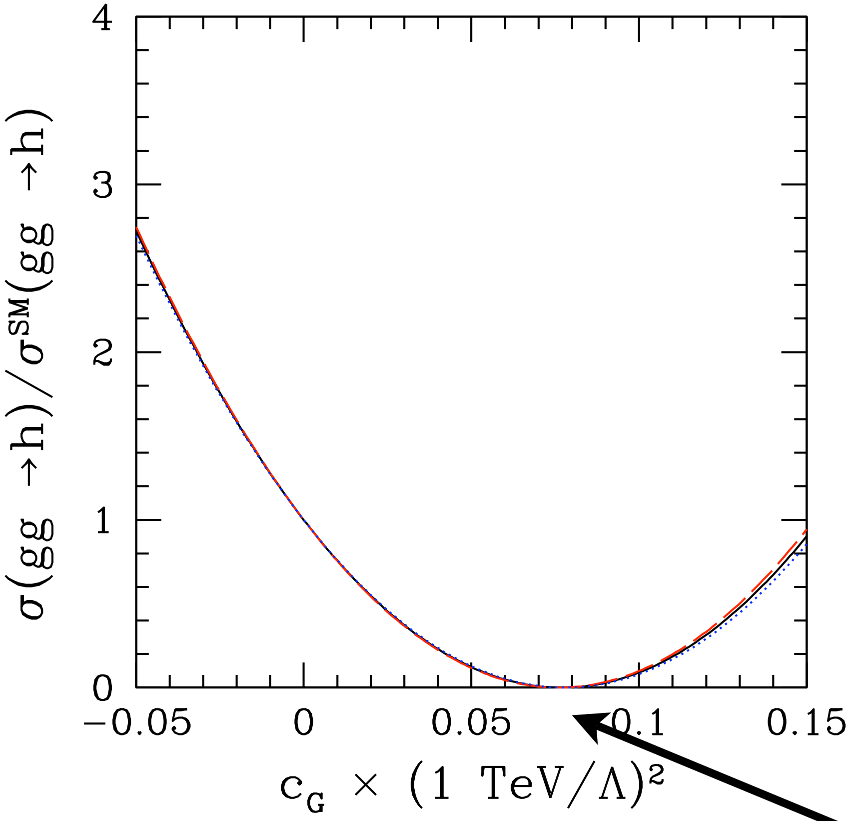
$H \to \gamma\gamma$ 3000 events/year (design lum.)

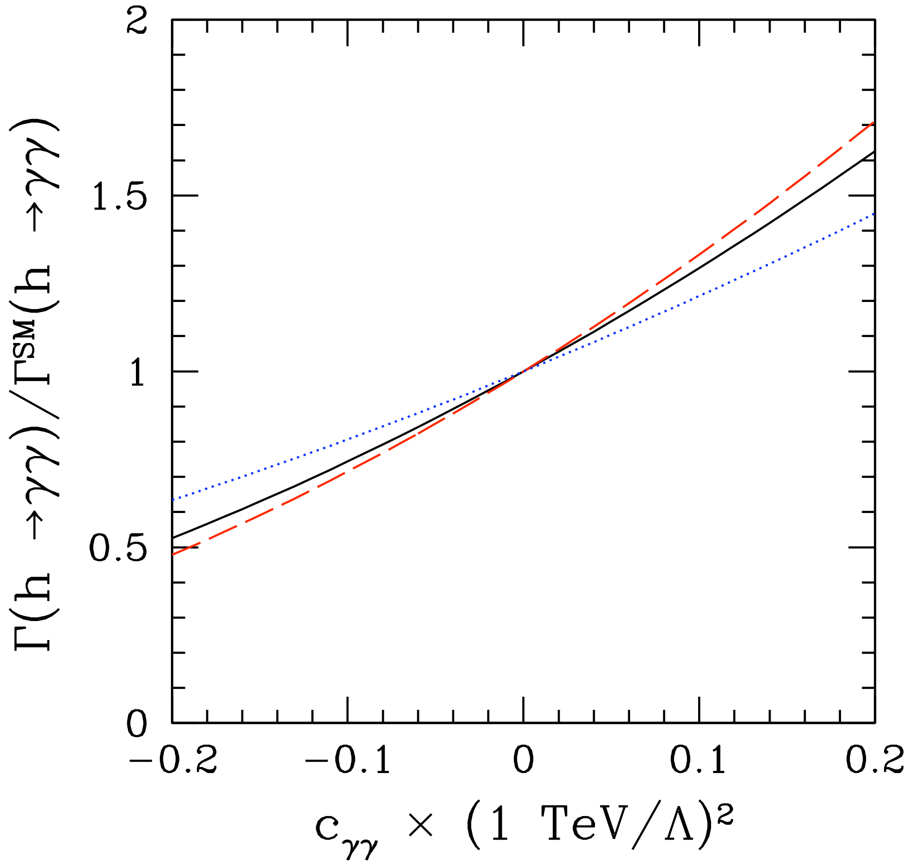
Note that

$$NP/SM \sim \frac{C_R \lambda m_t^2}{m_s^2}$$

Resonances with masses of order TeV can still compete quite easily

Effect of operators interfering with SM





(Manohar / Wise)

"Apologize to Public Region"

What can we learn from an anomalous measurement?

C_{gg} $\qquad$ $C_{\gamma\gamma}$

$$\sigma(gg \to h)\frac{\Gamma_{\gamma\gamma}}{\Gamma}$$

Is what we really measure, how can we disentangle these effects?

Di-Higgs Production

$$O_{gg} = G^{a}_{\mu\nu} G^{a\mu\nu} H^{\dagger} H$$

$$\sigma_{SM} \approx 10\ f_b \qquad \sigma_{NP} \approx 1\ p_b \quad (C_{gg} \sim O(1))$$

If new physics does not break EW sym, then Di-Higgs and Higgs production should be related, if there are no light resonances

$$O = CG^2\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)$$

If ratio is not obeyed, implies the existence of light resonances

Pipe Dream?

On the other hand just studying single Higgs production does not serve our purpose, as the data can be fit with one number, and the Wilson coefficient is not constrained by any other process

- Instead let us consider the process

$$g + g \rightarrow g + H$$

Discovery potential with 30 1/fb
(integrated over pt>40 GeV)

(Abdullin et al PLB 1998)

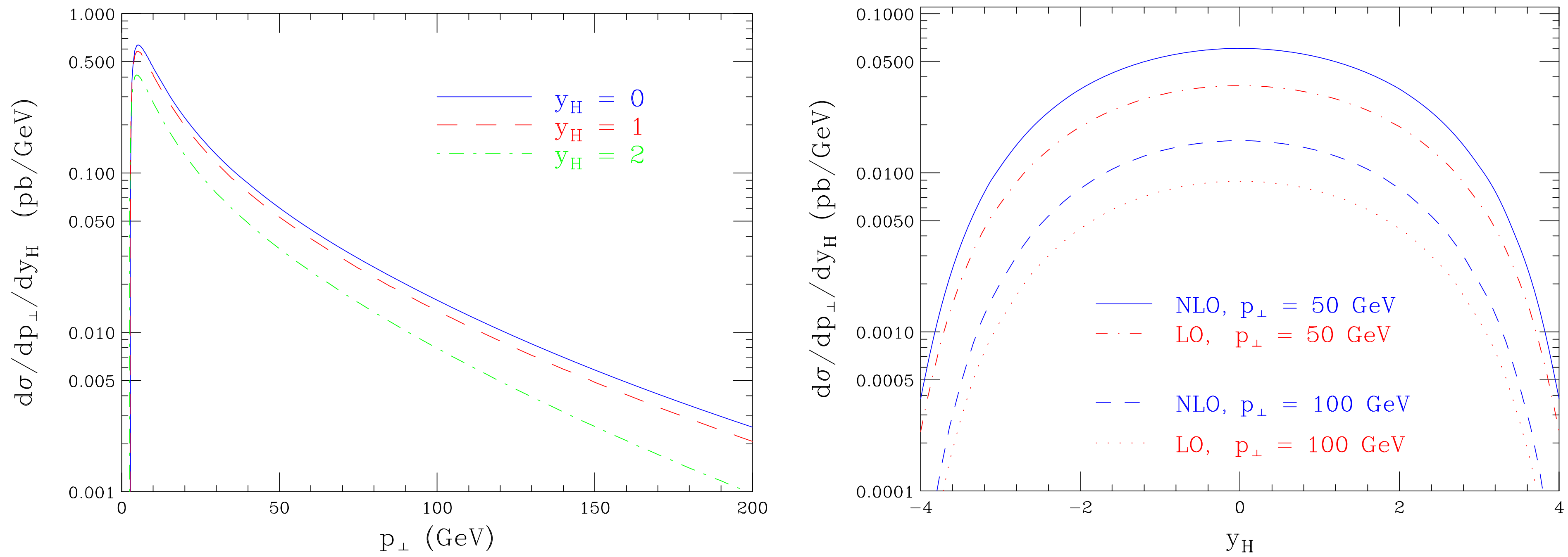
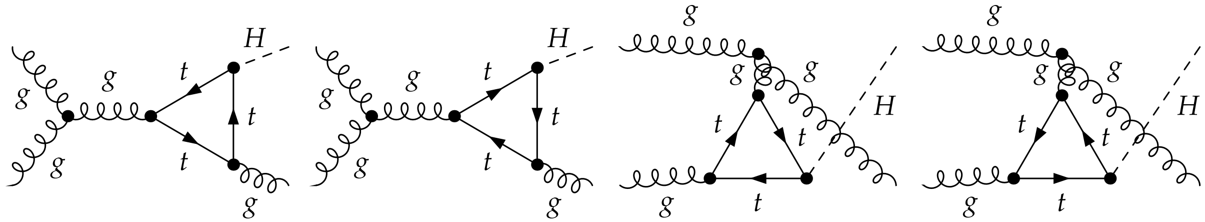
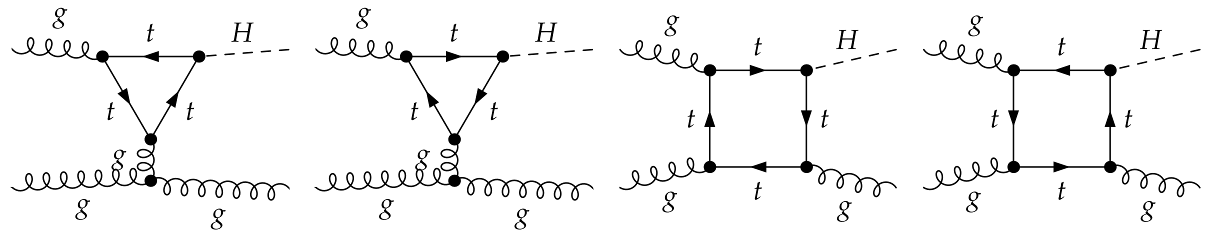


Figure 3.26: The Higgs transverse momentum dependence at NLO for three values of the rapidity $y_H = 0, 1, 2$ (left) and the rapidity dependence for two different transverse momenta $p_T = 50$ and 100 GeV at both LO and NLO (right). The CTEQ5 set of PDFs has been used while $M_H = 120$ GeV and the scales are set to $\mu_R = \mu_F = m_T$; from Ref. [294].

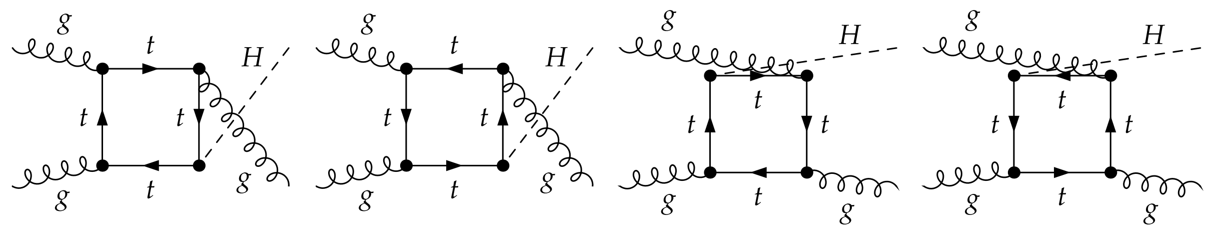
(Djoudi review)



T1 P1 N1 T1 P2 N2 T2 P1 N3 T2 P2 N4

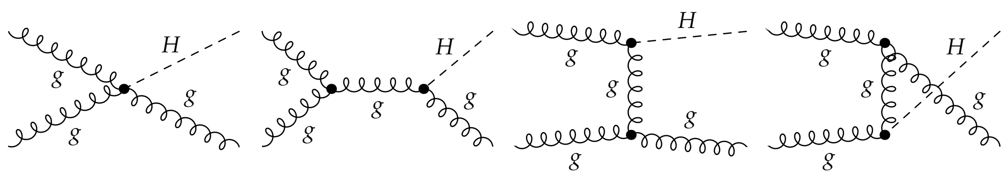


T3 P1 N5 T3 P2 N6 T4 P1 N7 T4 P2 N8



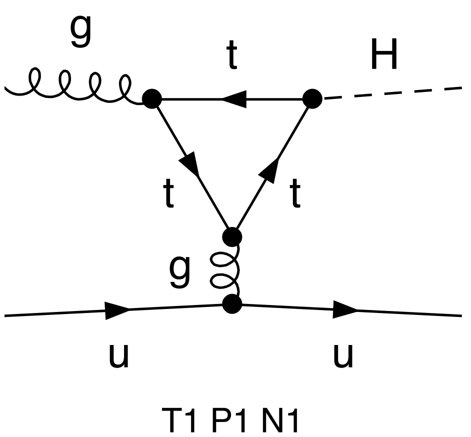
T5 P1 N9 T5 P2 N10 T6 P1 N11 T6 P2 N12

$g \quad g \;\rightarrow\; H \quad g$



T1 P1 N1 T2 P1 N2 T3 P1 N3 T4 P1 N4

g u → H u



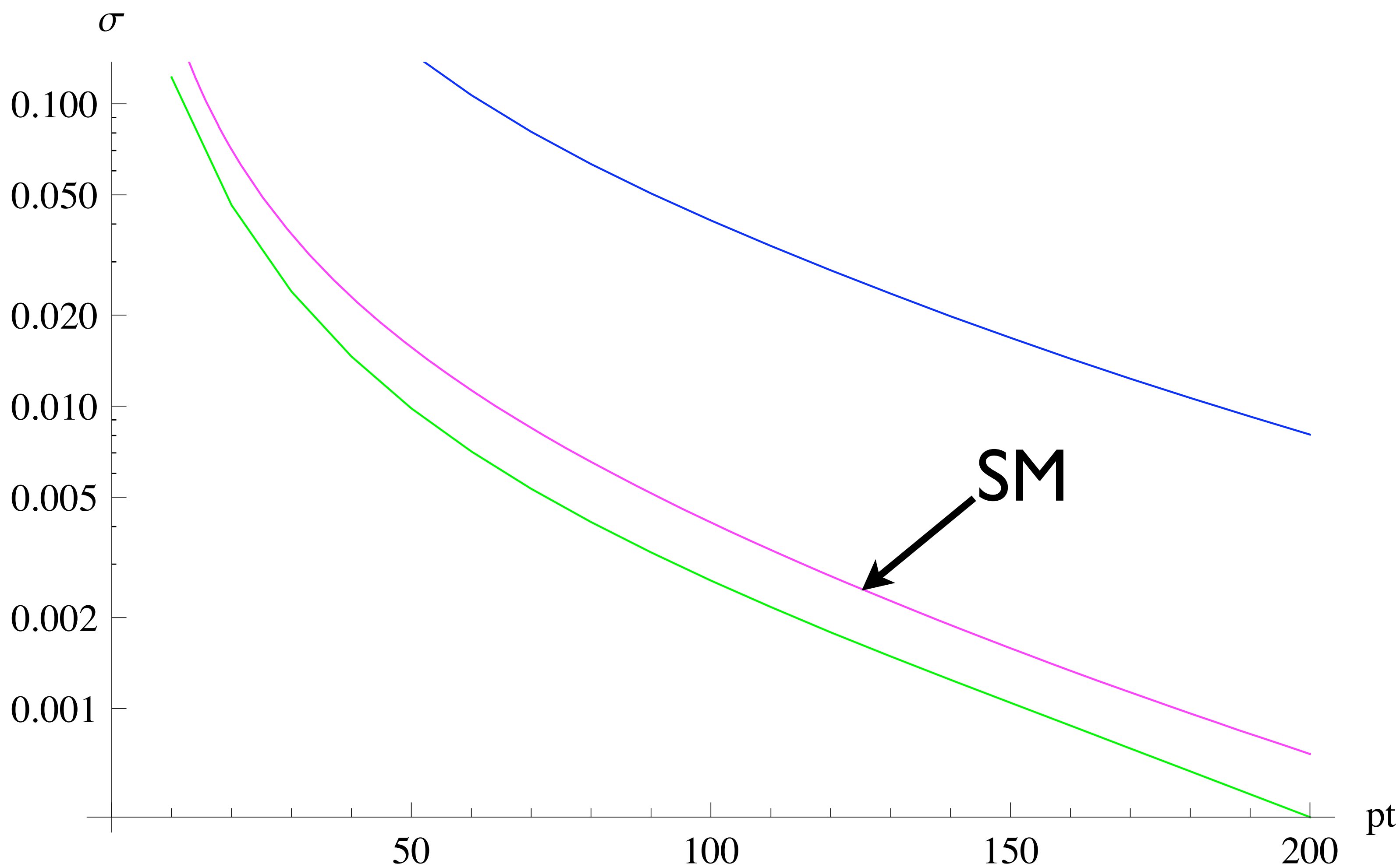
Relevant at high pt

$$\sigma(s, \theta) = F(C_O, s, m_t, m_h, \theta)$$

Functional form is model independent, fixed by one unknown parameter.

Higgs Plus Jet (y=1)

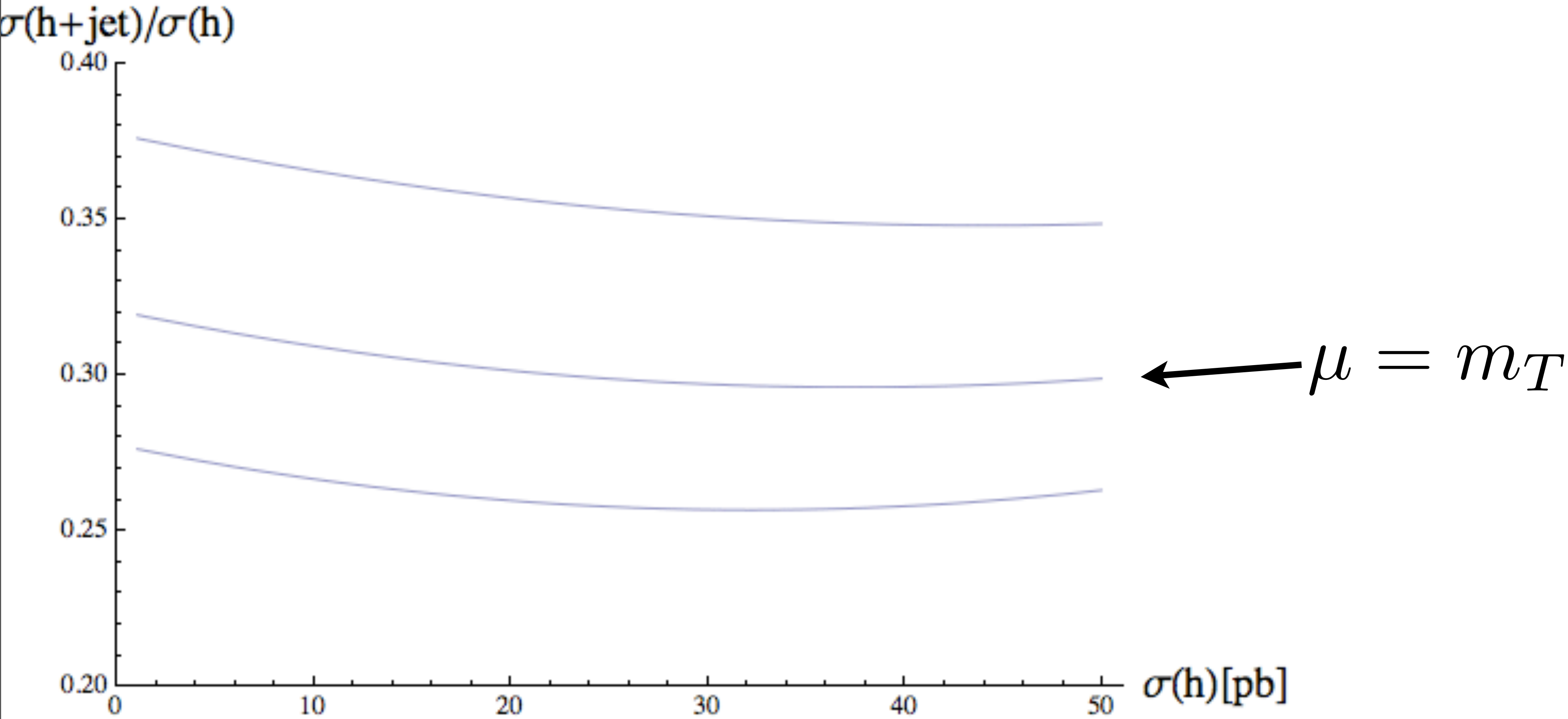
Out[200]=



- Deviations from this shape imply light resonances. But we would probably see the bump anyway if we had real spectral information.
- Instead we note that if EFT is valid, Higgs plus jet is fixed by inclusive Higgs production rate!

$$\frac{\frac{d\sigma}{dp_T}}{\sigma_T} \sim \frac{\mid C_{NP} + C_{SM} + \delta_1 \mid^2}{\mid C_{NP} + C_{SM} + \delta_2 \mid^2}$$

Deviations from infinite top quark limit


σ(h+jet)/σ(h)
0.40
0.35
0.30
0.25
0.20
0
10
20
30
40
50
σ(h)[pb]
$\mu = m_T$

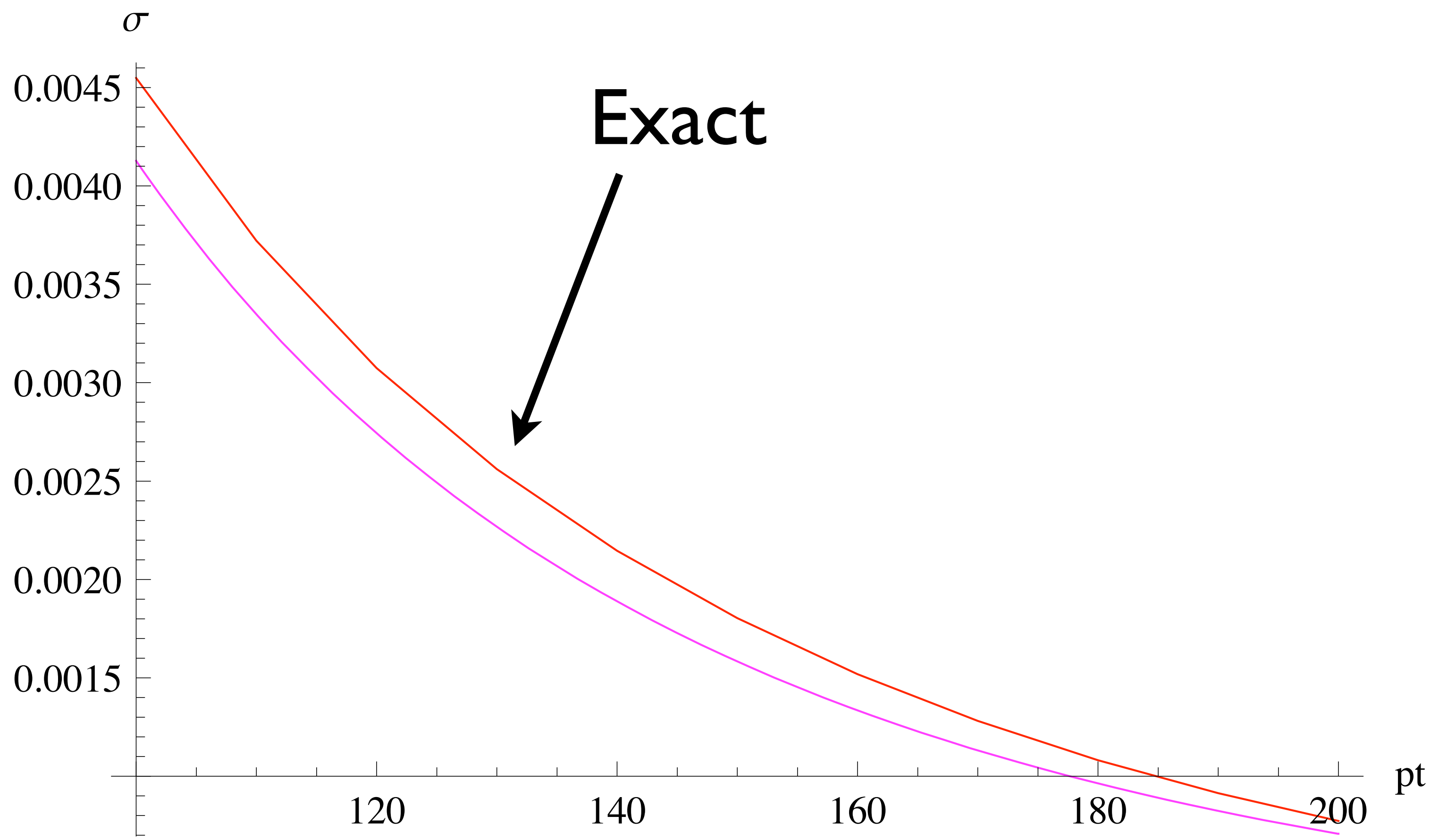
No Lose Theorems

The infinite top mass limit is nice for theorists but it leaves a whole in No Lose Theorems.

$$\sigma_T \sim | C_{NP} + C_{SM} + \delta_1 |^2$$

$$\frac{d\sigma}{dp_T} \sim | C_{NP} + C_{SM} + \delta_2 |^2$$

Out[76]=


σ
0.0045
0.0040
0.0035
0.0030
0.0025
0.0020
0.0015
120
140
160
180
200
pt
Exact

- Smallness of deltas imply that if we kill one we kill the other!
- Also true for other signales e.g. H+Z.
- Same reasoning applies to DI-Higgs production.
- Need to go to Dimension 8 operators. (R. Porto)

How Long would we have to run to DEFINATELY SEE A NEW PARTICLE AT THE LHC?

Conclusions

- Experimental bounds on Wilson coefficients can tell us if light resonances are there.

- Axiomatic bounds could be useful (depends upon how the data shakes out).

- Kinematic study in Higgs +Jet is a very useful tool as smoking gun for light resonance. Measure Higgs production rate predict Higgs plus jet, deviations imply MUST BE something in the data!

- Do we really have a no ``lose” theorem?