Unusual bound states in Higgs theories

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  - Bound states, phase transitions,...
- Are there (relevant) non-perturbative effects in the weak interactions and the Higgs?
  - Bound states?

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    - Gauge theory
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- Next stop: Higgs+W sector
  [Lang et al., Münster et al., ALPHA collaboration, Wittig et al., Jansen et al., Rummukainen et al.,...]
  - Also investigations of Higgs+Yukawa
    [Gerhold et al. PLB'11,...]

The Higgs sector as a gauge theory

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$$L = -\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a$$

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- Ws W^a_μ

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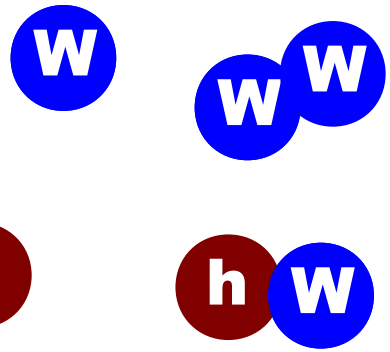

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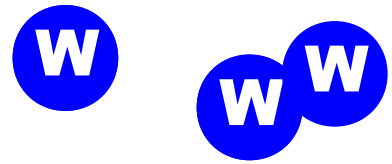

- Ws W^a_μ
- Higgs h_i

- No QED: Ws and Zs are degenerate
- Couplings g, v, λ and some numbers f^{abc} and t^{ij}_a

Symmetries

$$L = -\frac{1}{4} W^{a}_{\mu\nu} W^{\mu\nu}_{a} + \left(D^{ij}_{\mu} h^{j} \right)^{+} D^{\mu}_{ik} h_{k} + \lambda \left(h^{a} h_{a}^{+} - v^{2} \right)^{2}$$

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- Local SU(2) gauge symmetry
  - Invariant under arbitrary gauge transformations $\phi^a(x)$

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- Global SU(2) Higgs flavor symmetry
  - Acts as right-transformation on the Higgs field only

$$W^a_\mu \to W^a_\mu \qquad h_i \to h_i + a^{ij} h_j + b^{ij} h_j{}^*$$

Parameters

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- Tree-level setup Higgs+W
  - v=246 GeV
  - λ=0.125 (4!λ=3)
  - g=0.325 (α=0.00815)

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    - Tree-level Higgs mass: 123 GeV, Higgs vev: 246 GeV

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- Non-perturbative: Simulate Higgs+W [Maas EPJC'11, PR'13]

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  - λ=0.125 (4!λ=3)
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    - Tree-level Higgs mass: 87.0i GeV, Higgs vev: 0 GeV
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W boson

[Maas, EPJC 2011
Maas unpublished
24^4, β=2.3, κ=0.32 λ=1]

- Renormalization scheme with
  $D(\mu)=1/(\mu^2+(80.375\,GeV)^2)\wedge\mu=80.375\,GeV$

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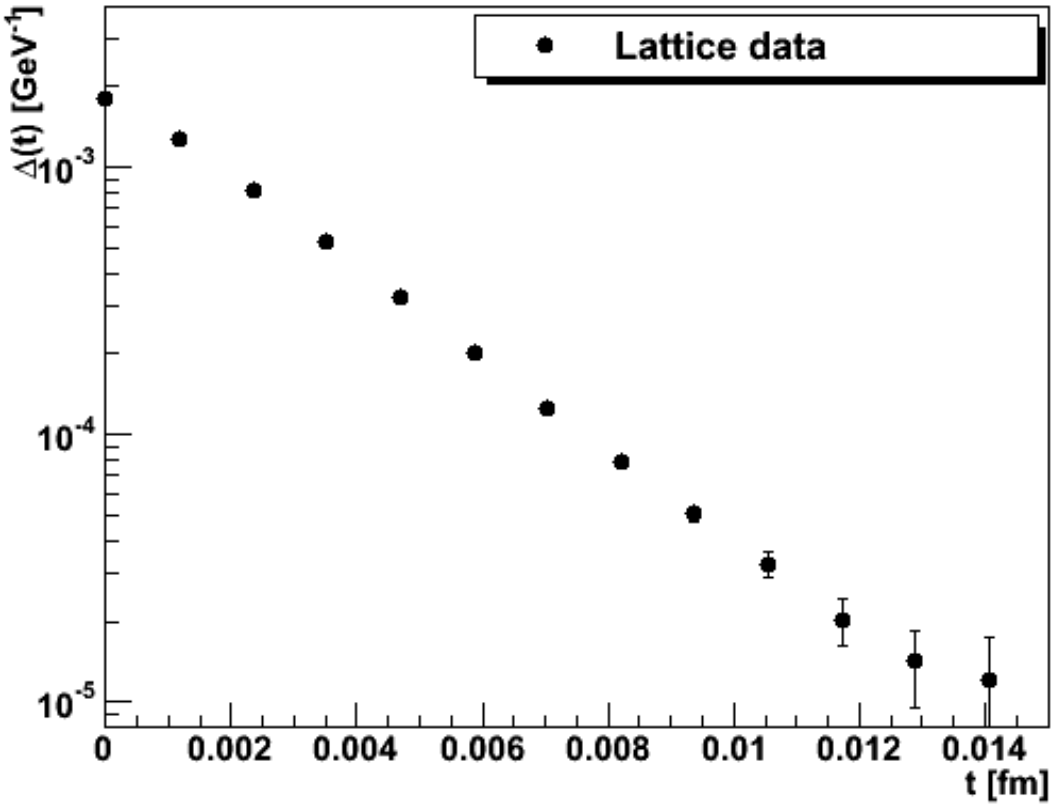
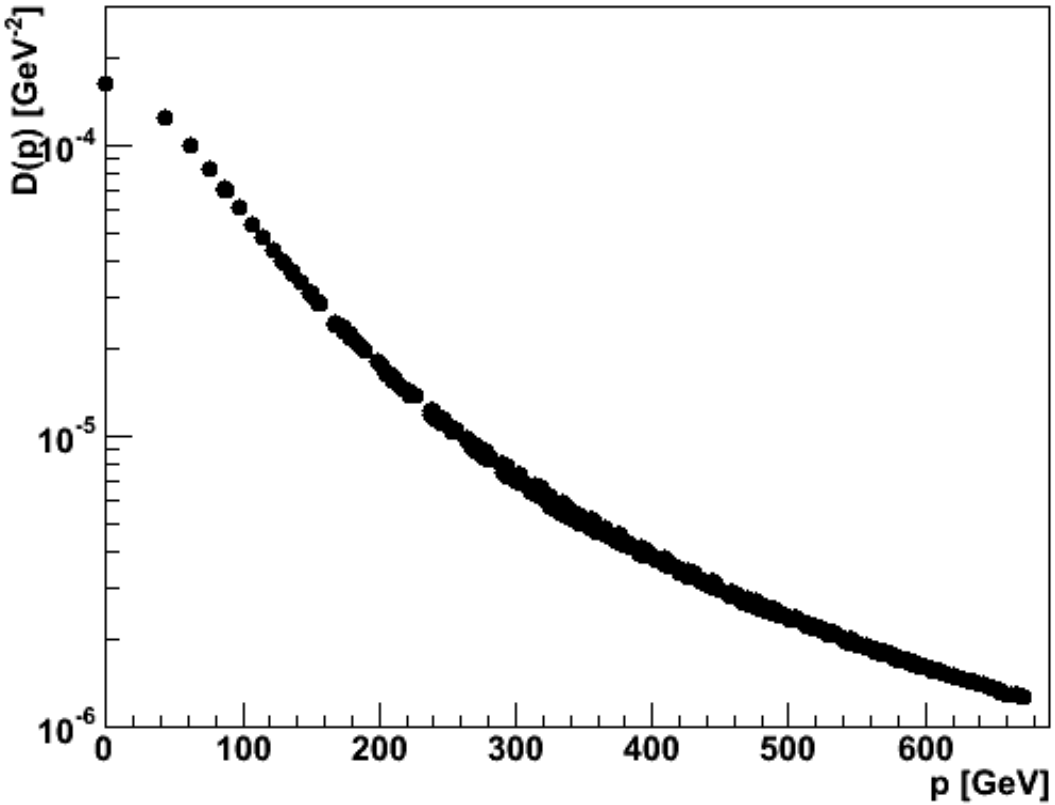
Schwinger function



W propagator



- Renormalization scheme with
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- Massive-like propagator
- Dynamical mass generation

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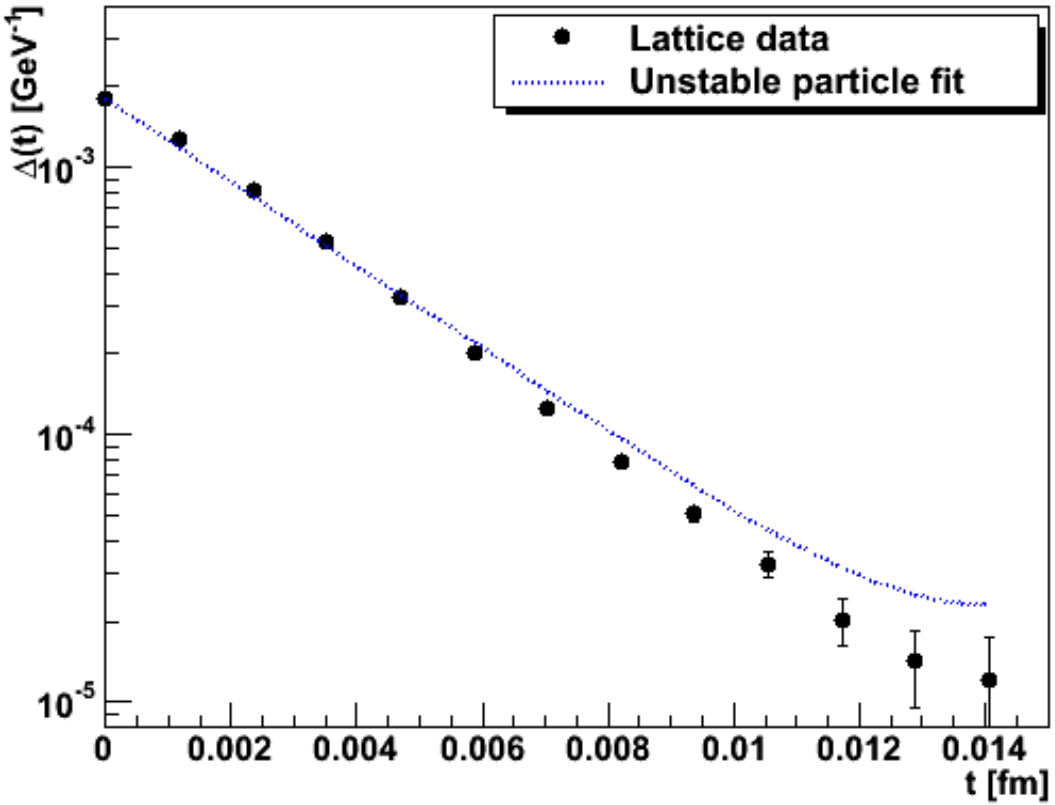

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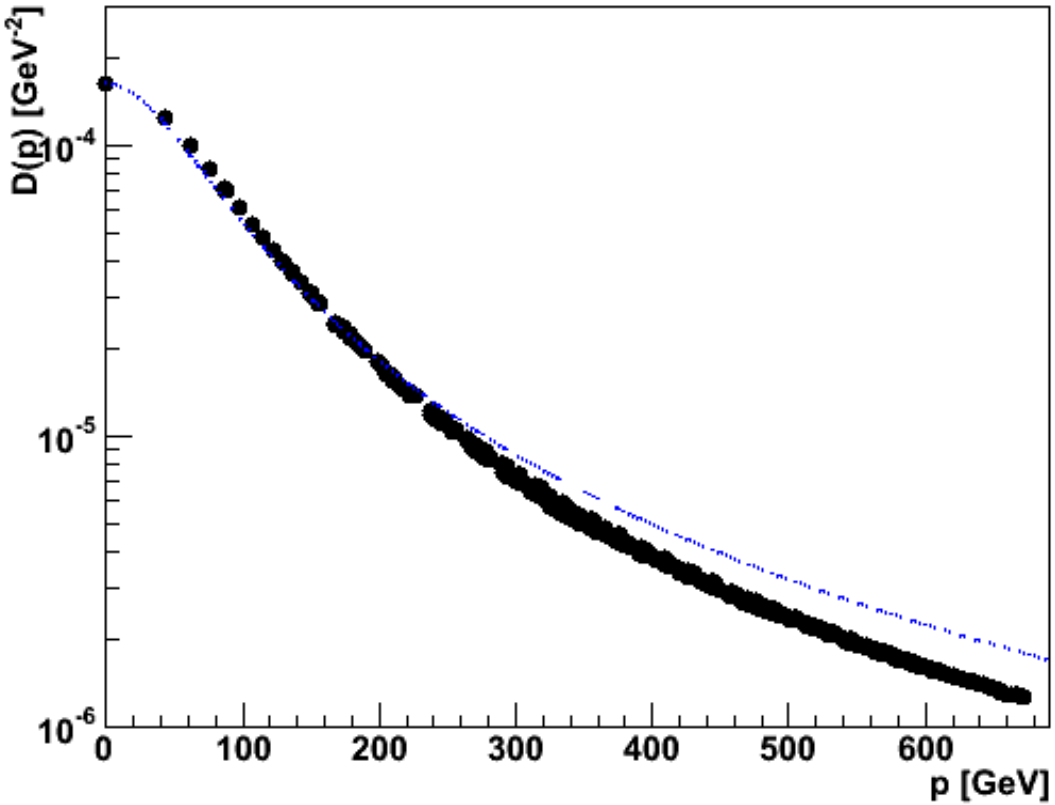

Fit type	Mass	Remark
Unstable	71.8(1) GeV	Width: 2.1(4) GeV

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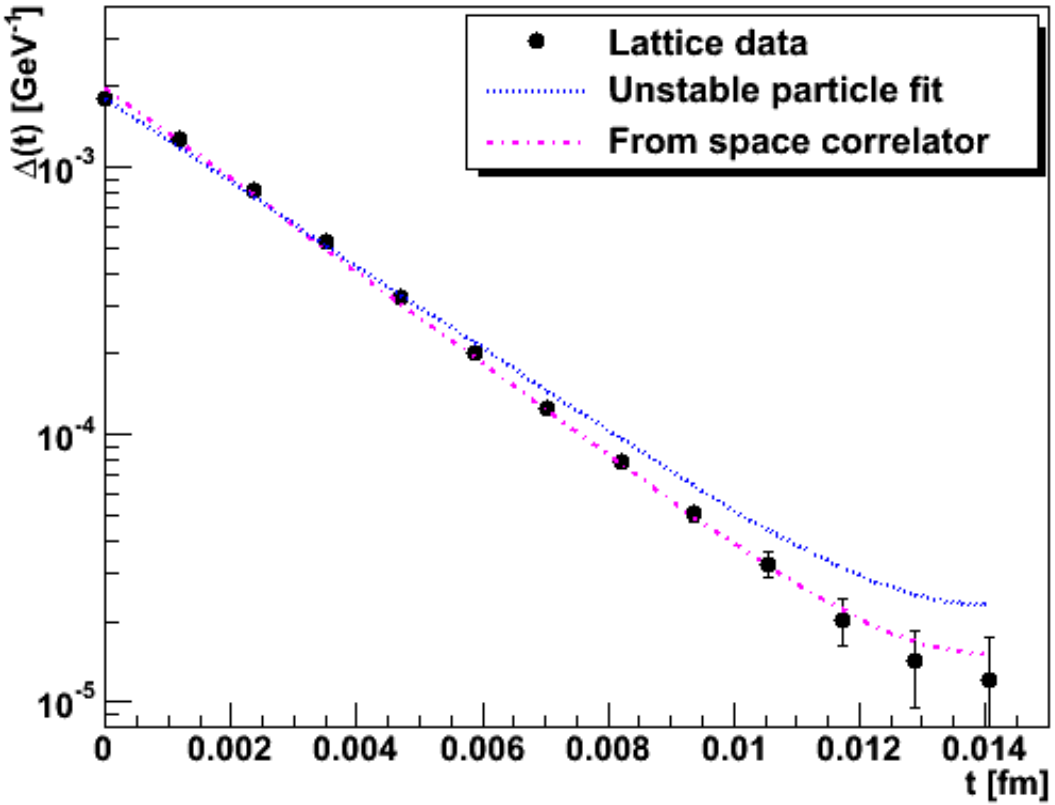

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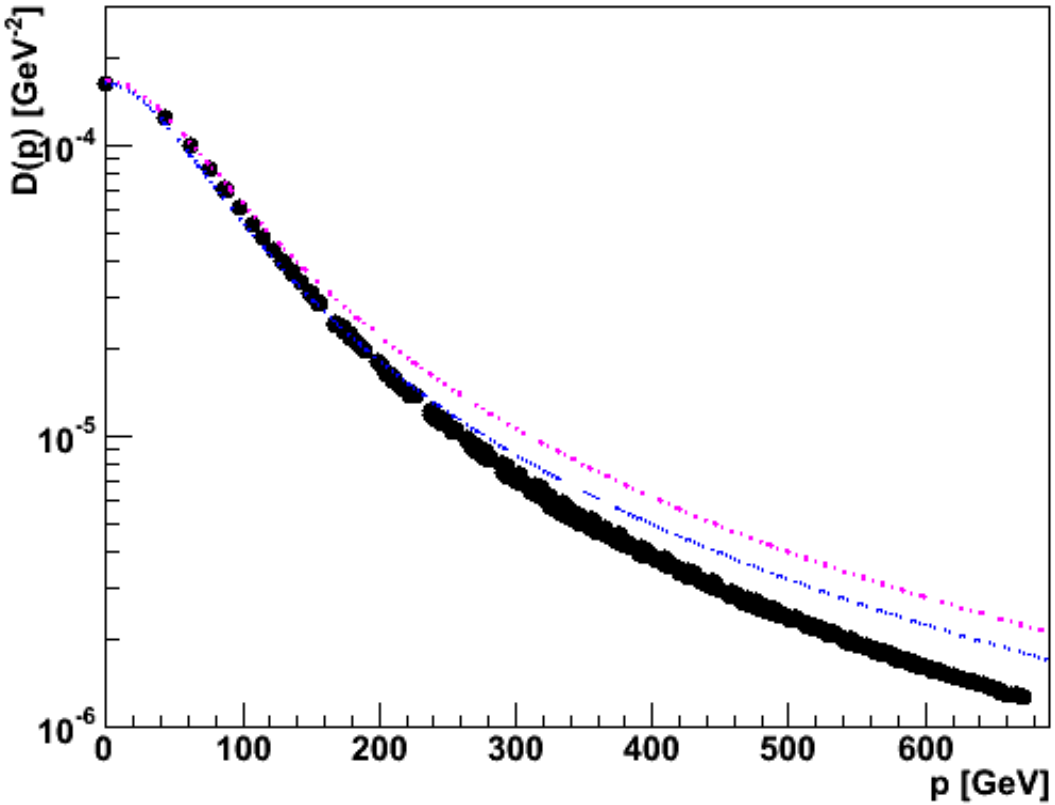

Fit type	Mass	Remark
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Configuration space	79(4) GeV	

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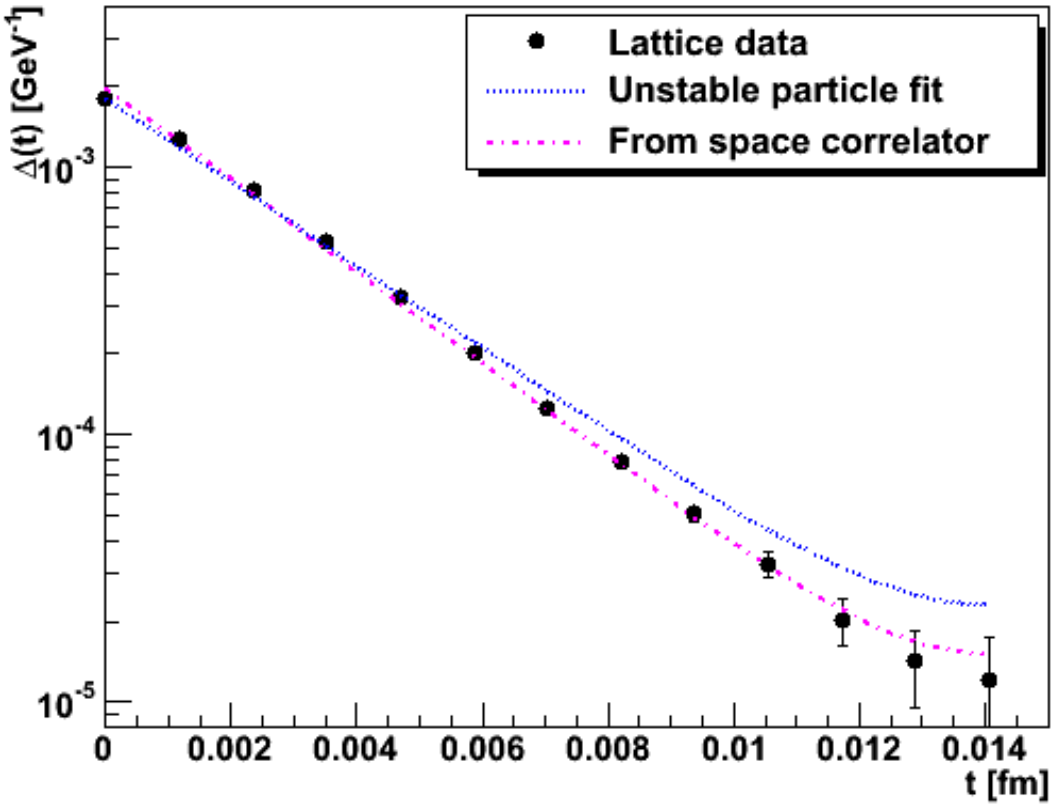

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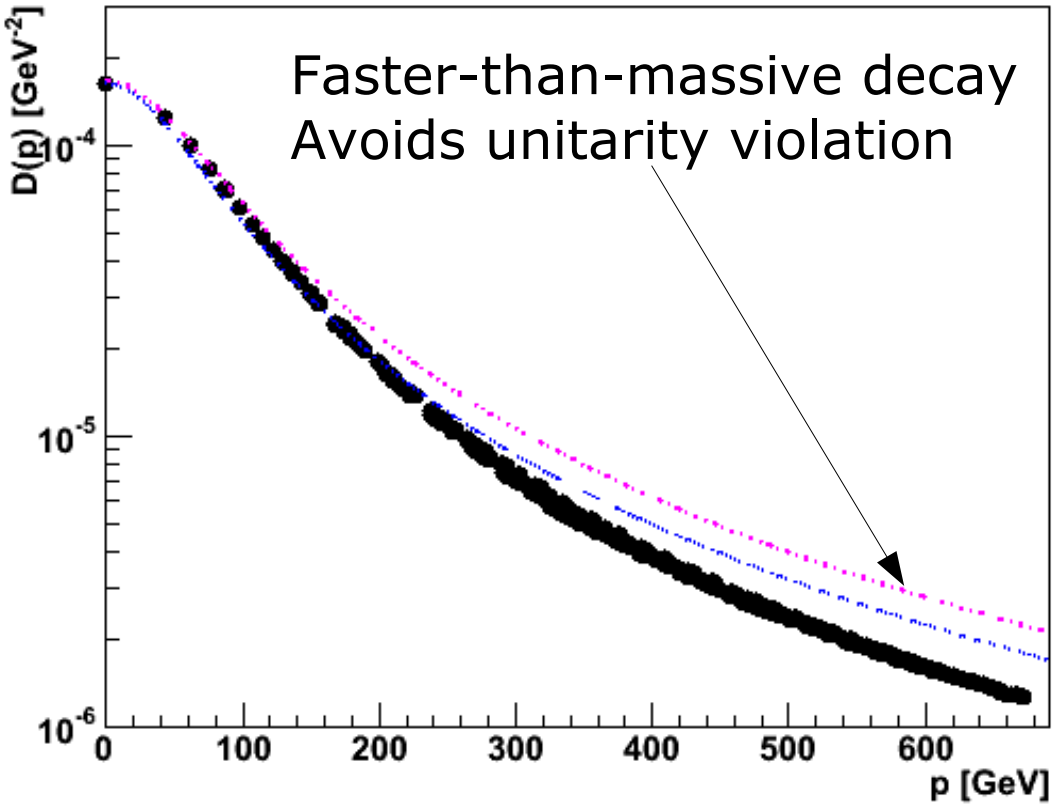

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Higgs boson

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- Renormalization scheme with

$$D(\mu)=D^{tl}(\mu)$$
$$D(\mu)'=D^{tl}(\mu)'$$
$$D^{tl}(p)=1/(p^2+(123\,GeV)^2)$$
$$\mu=123\,GeV$$

Higgs boson

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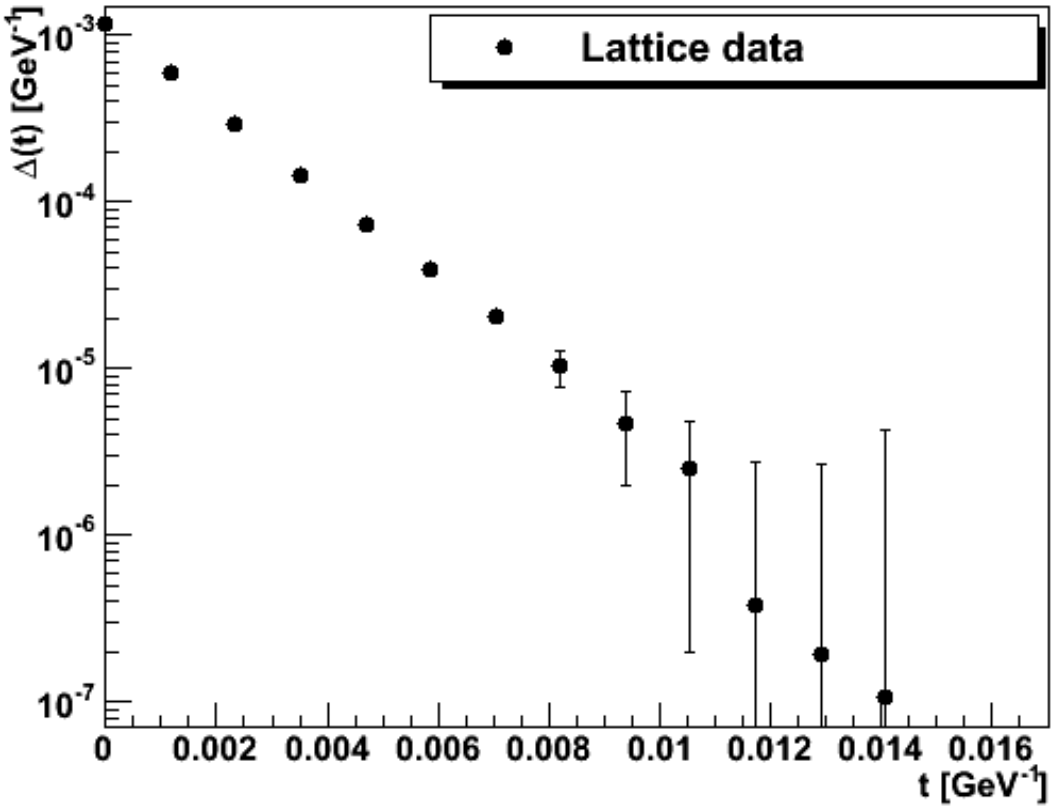

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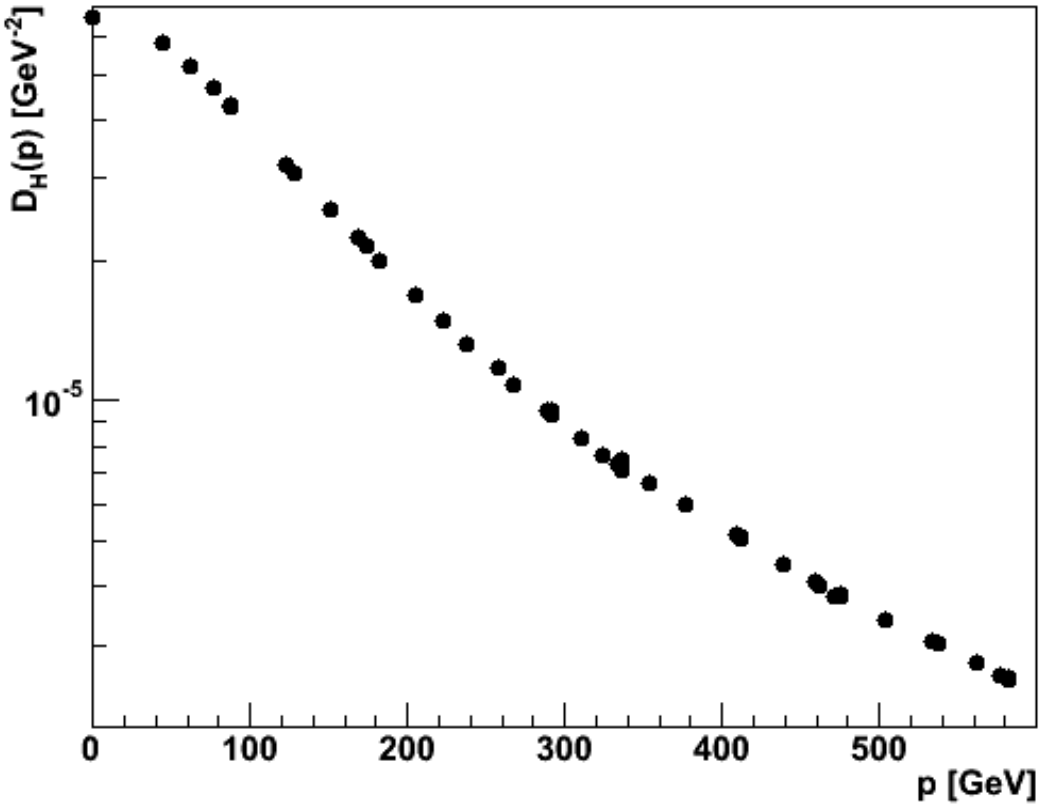

- Normal propagator – normal mass

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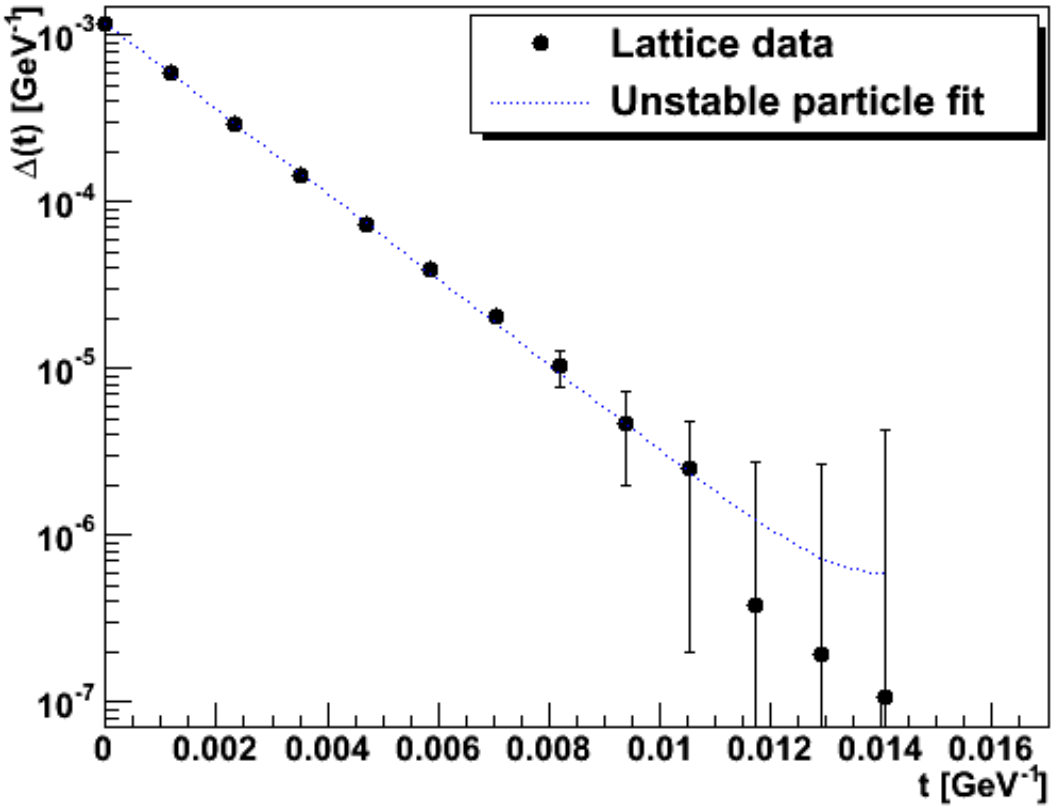
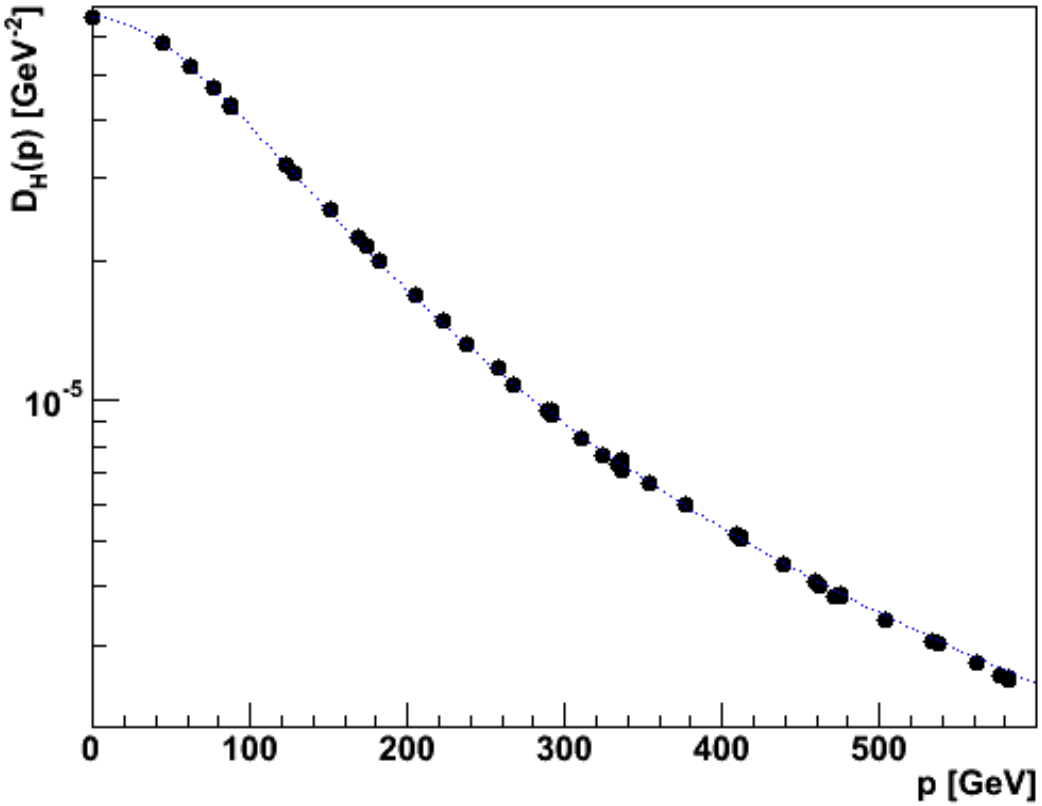


Higgs propagator



Fit type	Pole mass	Remark
Unstable	119(2) GeV	Width 1(1) GeV

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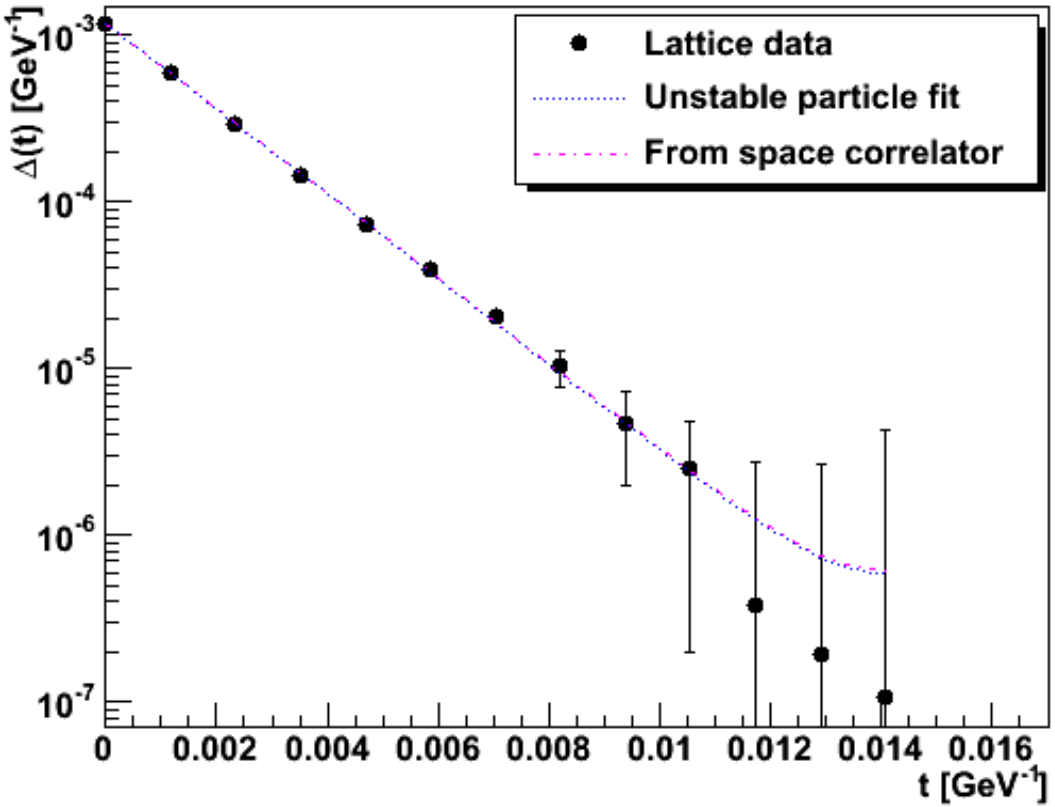
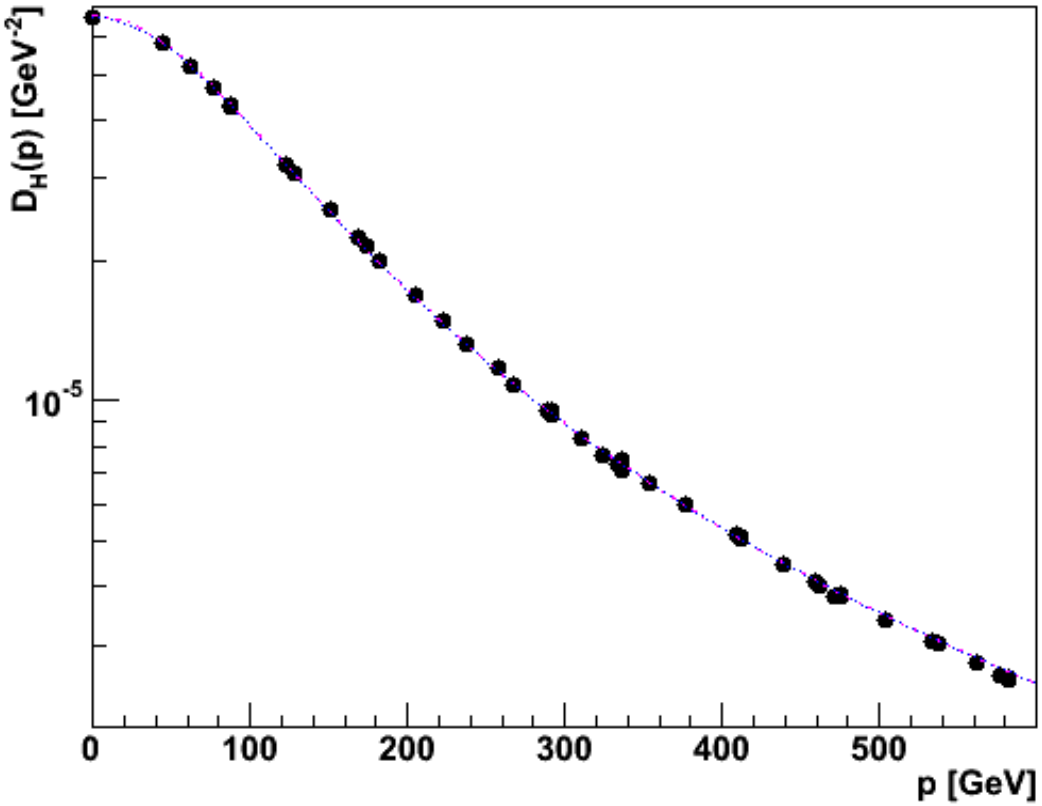


Higgs propagator



Fit type	Pole mass	Remark
Unstable	119(2) GeV	Width 1(1) GeV
Configuration space	118(1) GeV	

Scheme dependent!

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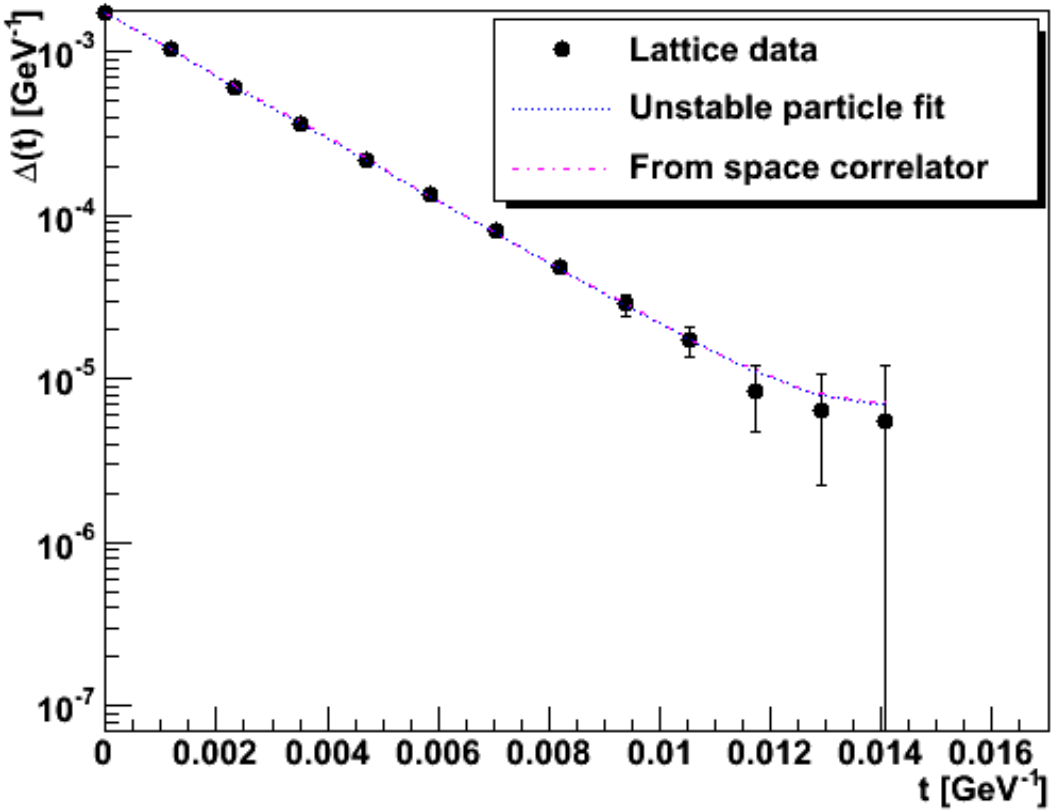
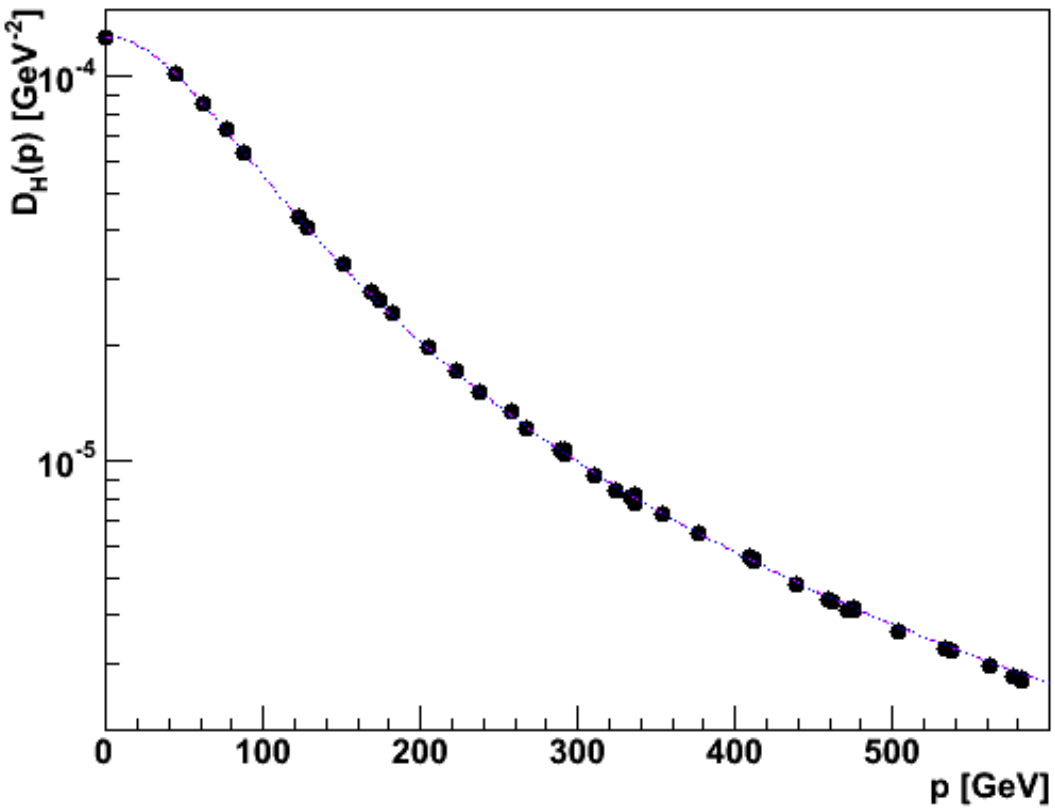


Higgs propagator



Fit type	Pole mass	Remark
Unstable	86(1) GeV	Width 1(1) GeV
Configuration space	87(1) GeV	

- Different renormalization scheme with mass 90 GeV

Physical states

[Fröhlich et al. PLB 80,
't Hooft ASIB 80,
Bank et al. NPB 79]

- Elementary particles depend on scheme, gauge, scale

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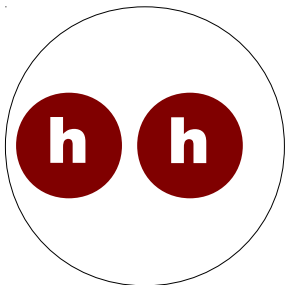

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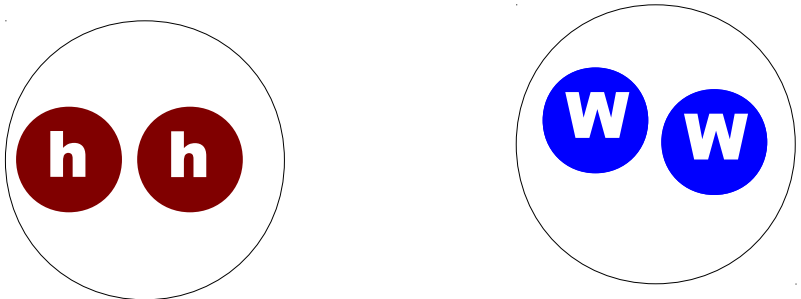
  - Higgs-Higgs, W-W



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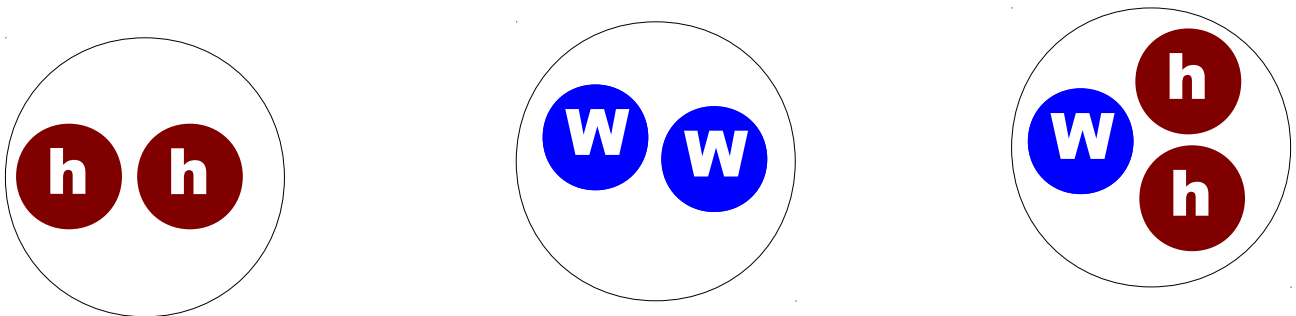
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.



Phase diagram

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[Fradkin & Shenker PRD'79
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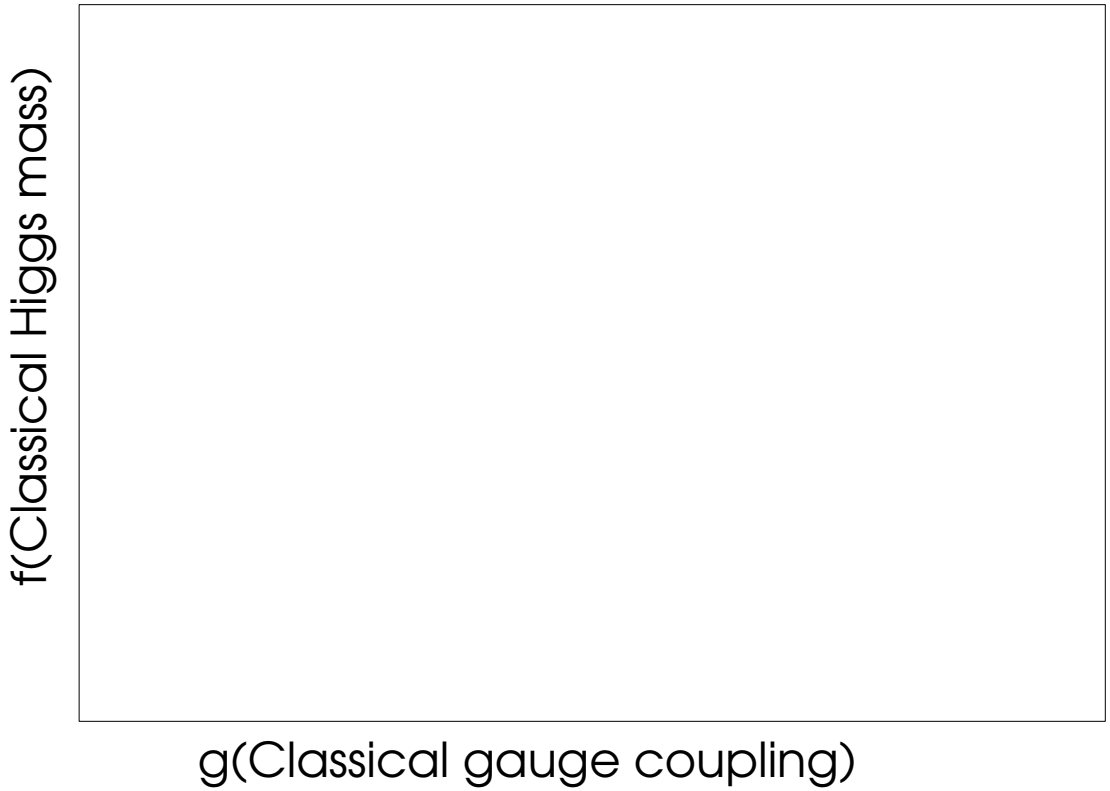

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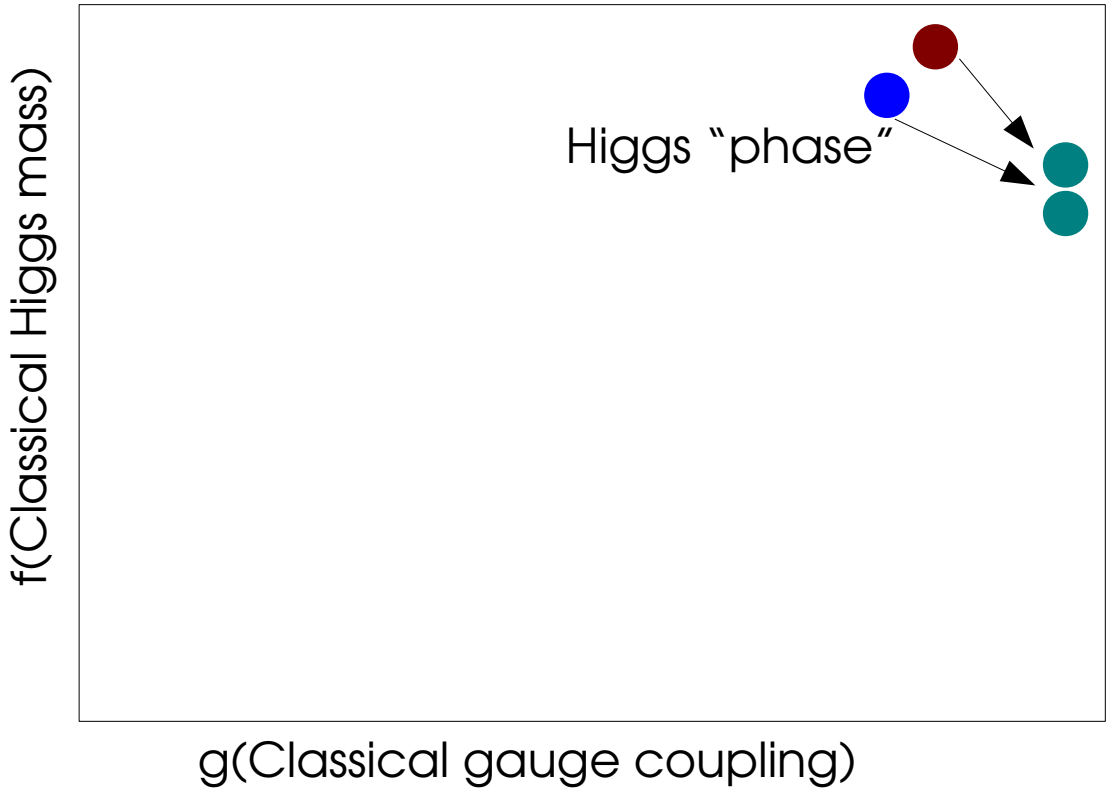

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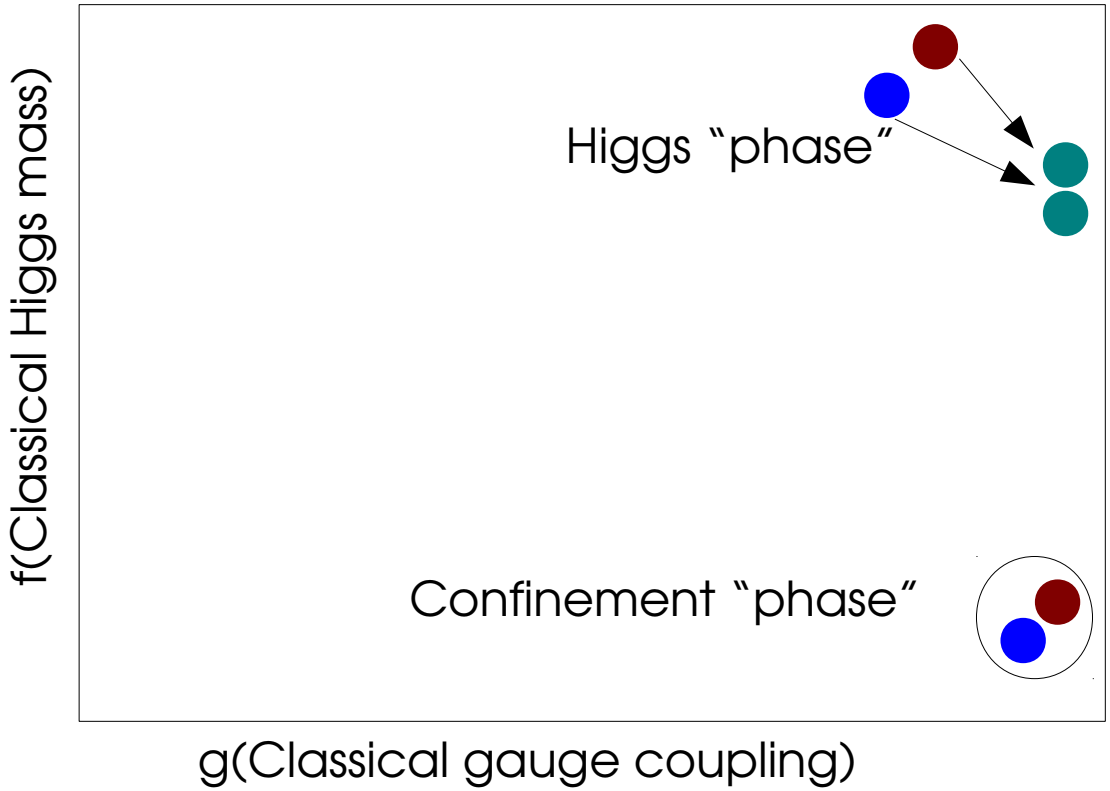

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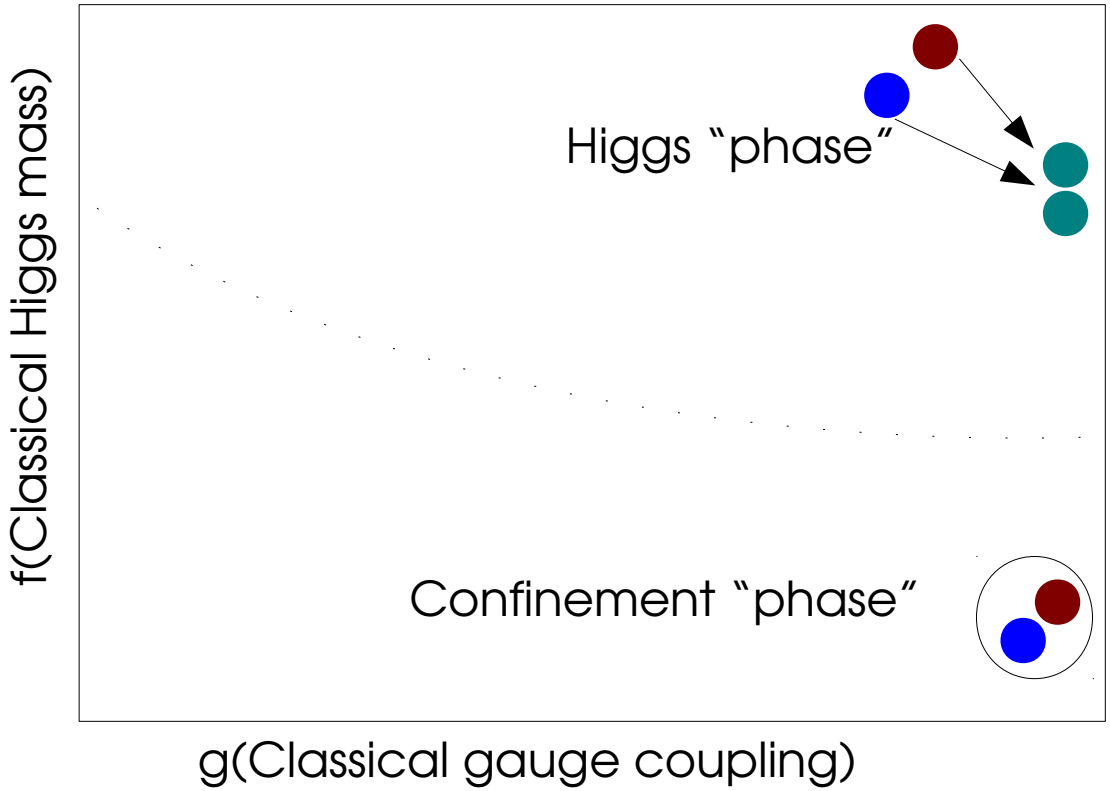

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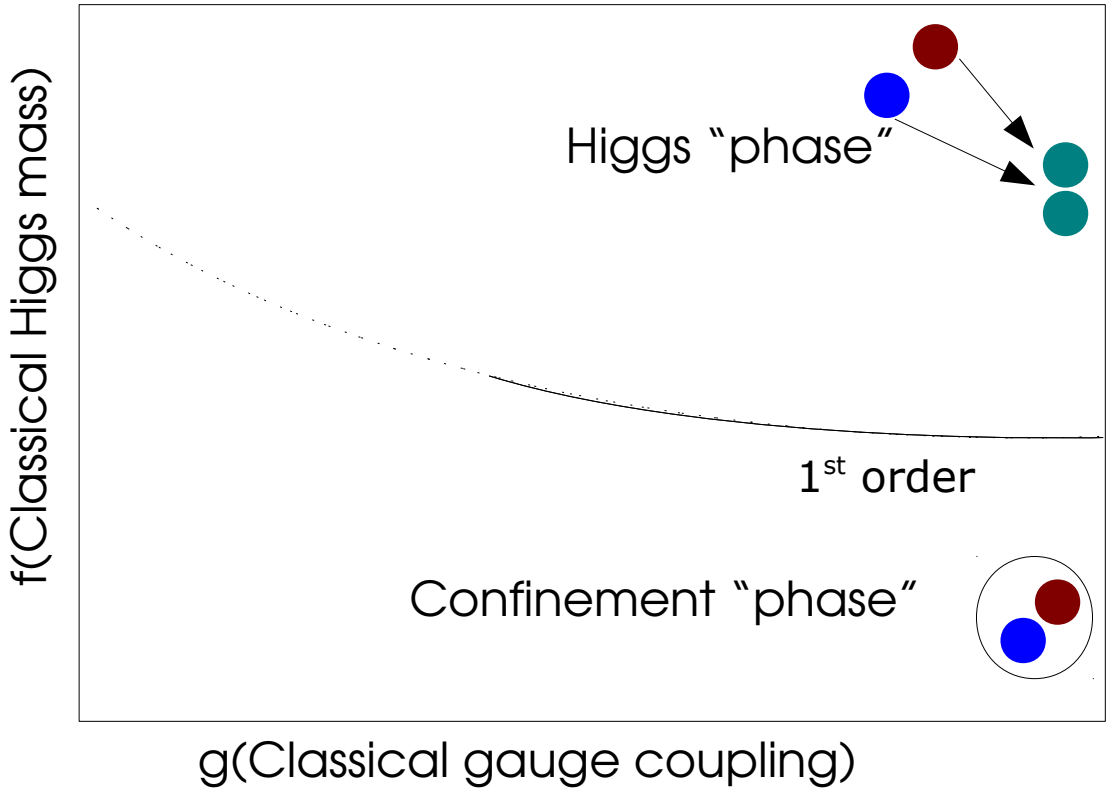

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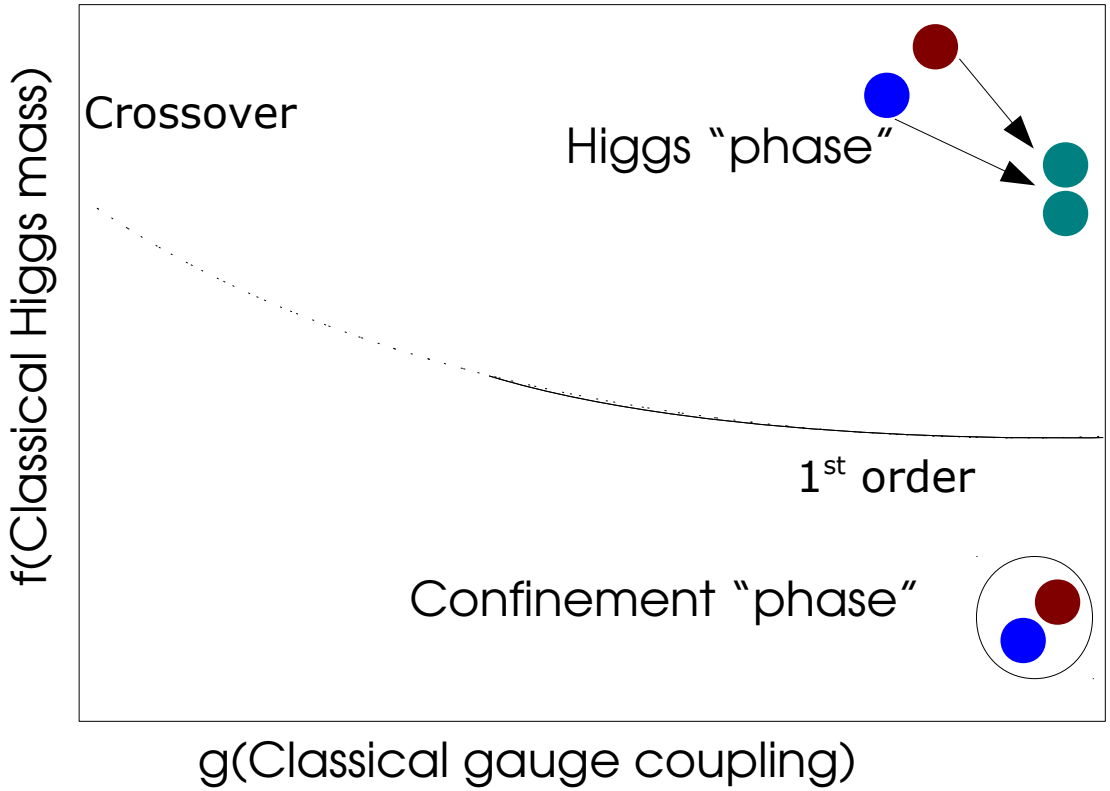

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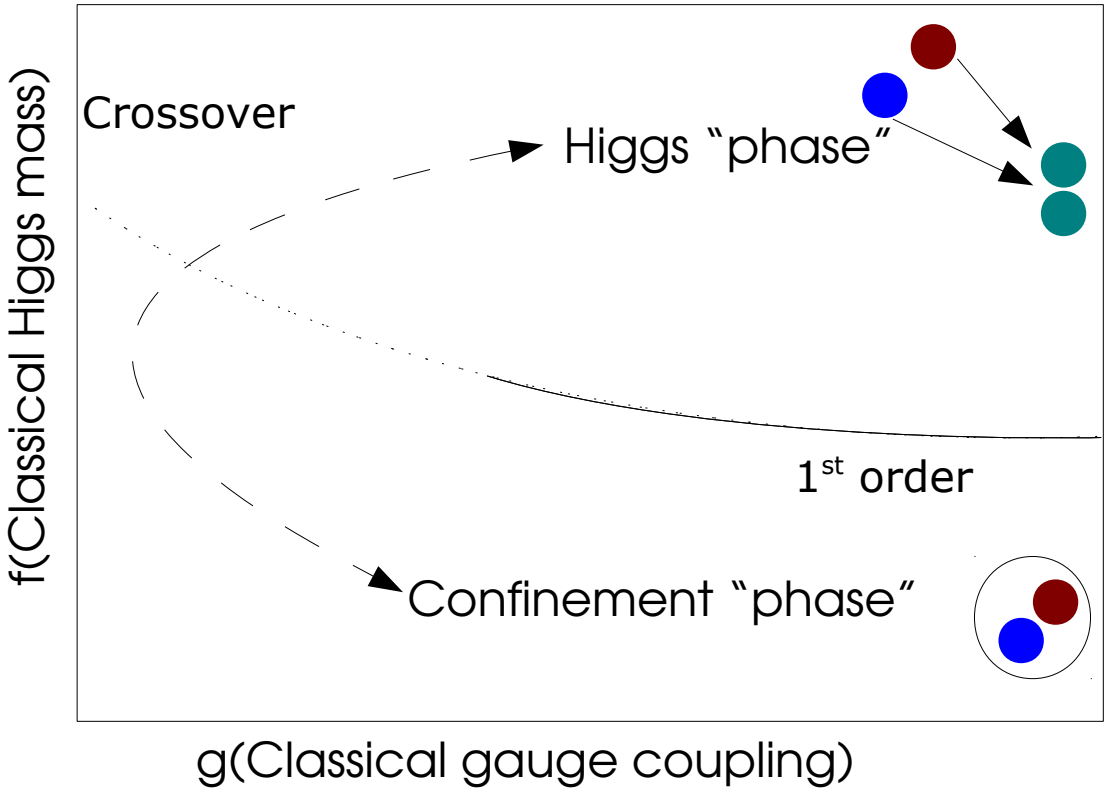

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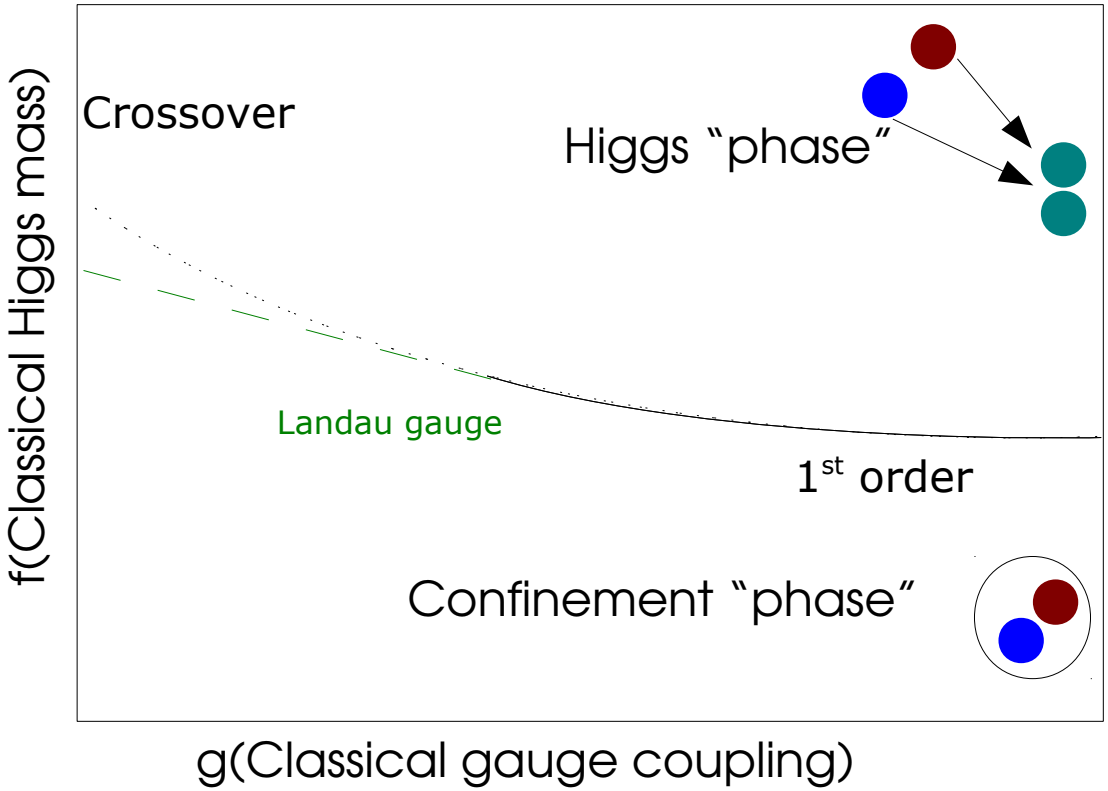

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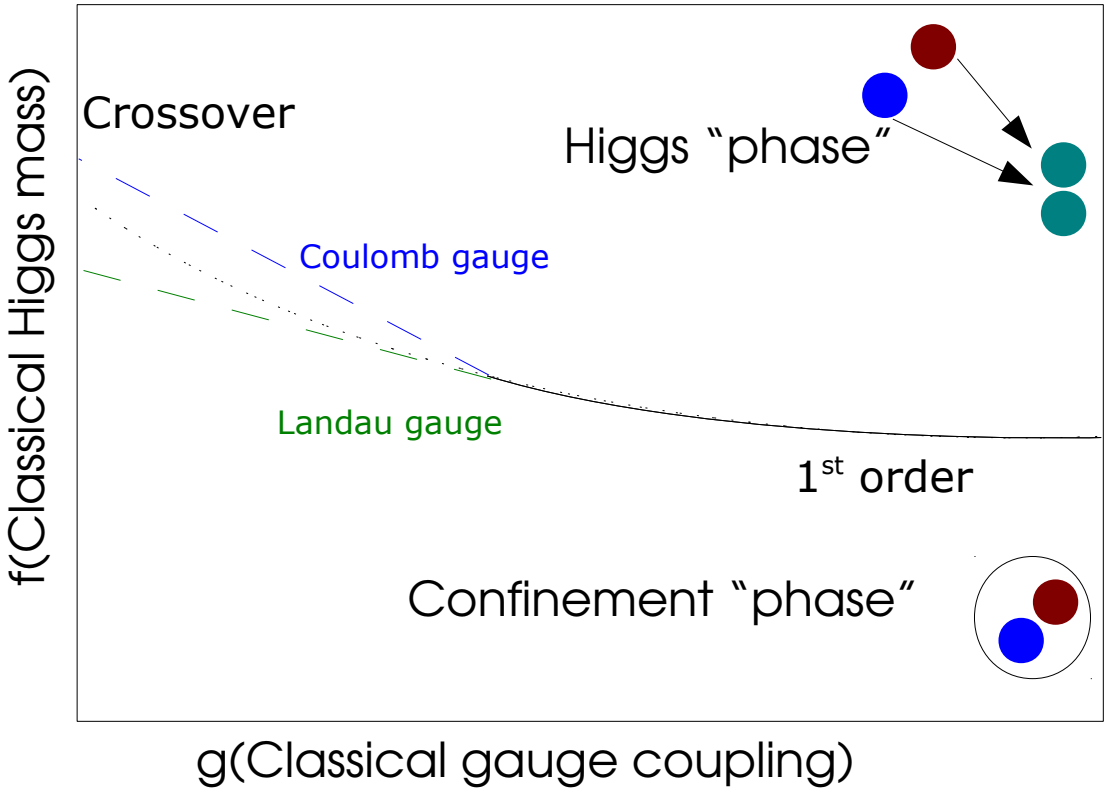

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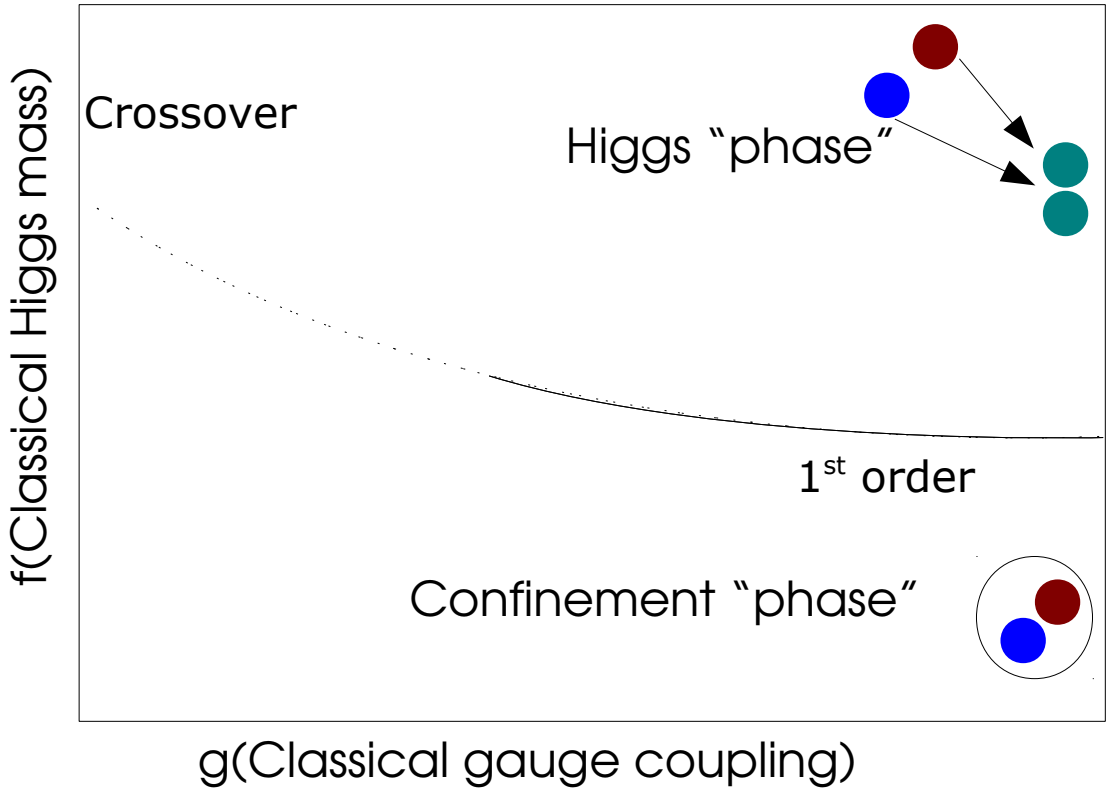

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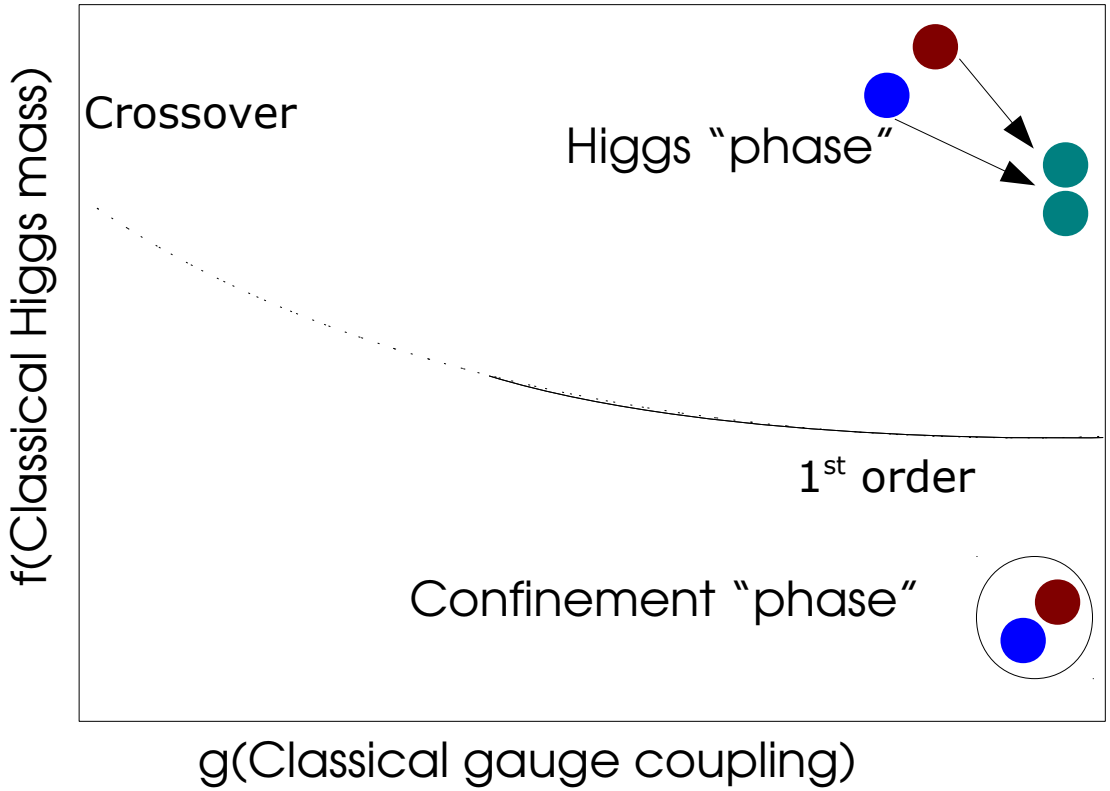

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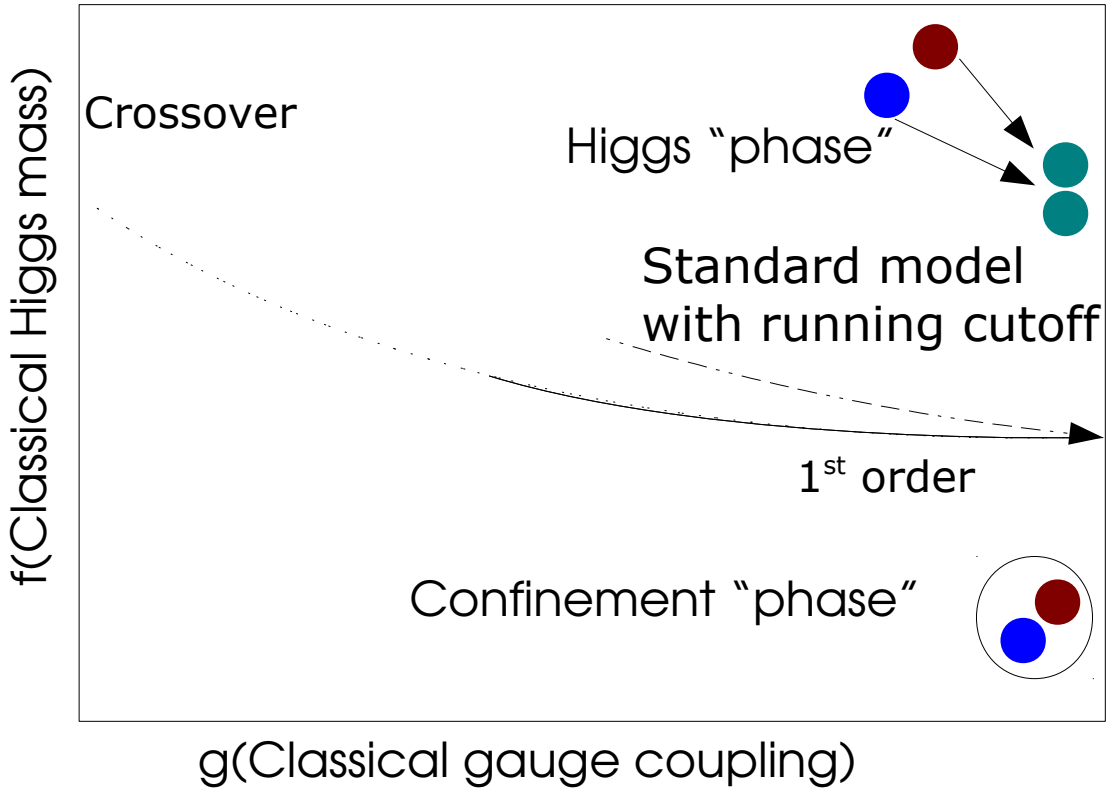

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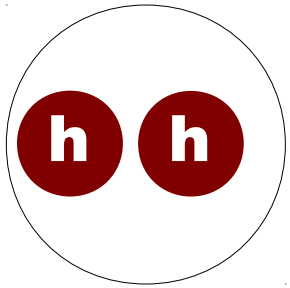
[Maas unpublished, PoS'11
24^4, β=2.3, κ=0.32 λ=1]



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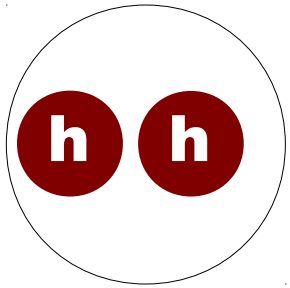

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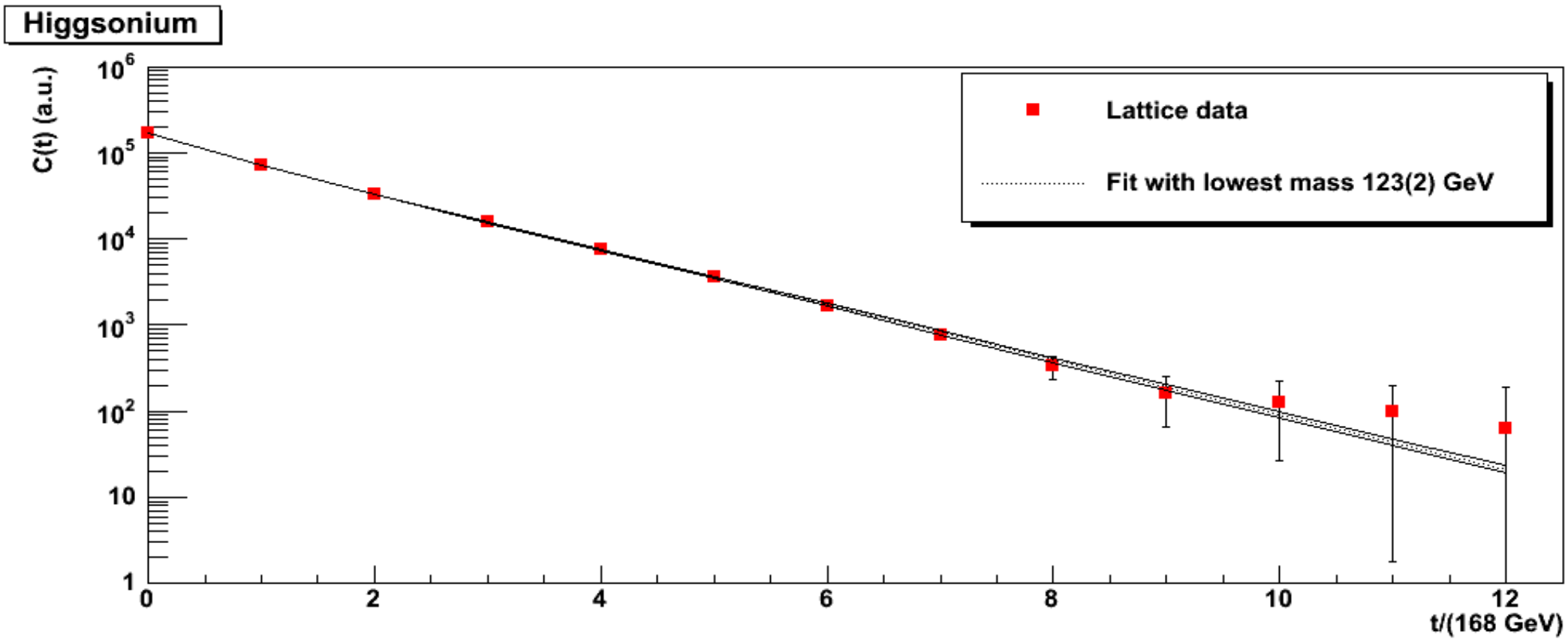

- Simpelst 0^{++} bound state $h^+(x)h(x)$
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  - Mass is about 123 GeV

Mass relation - Higgs

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  - Very different from QCD bound states

Isovector-vector state

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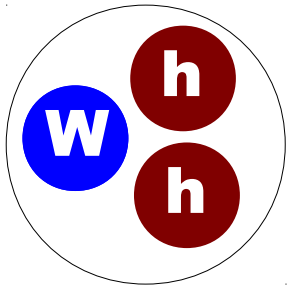

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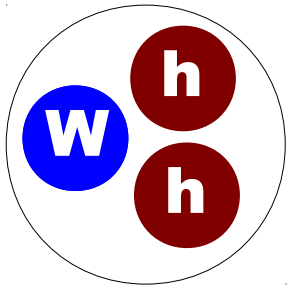

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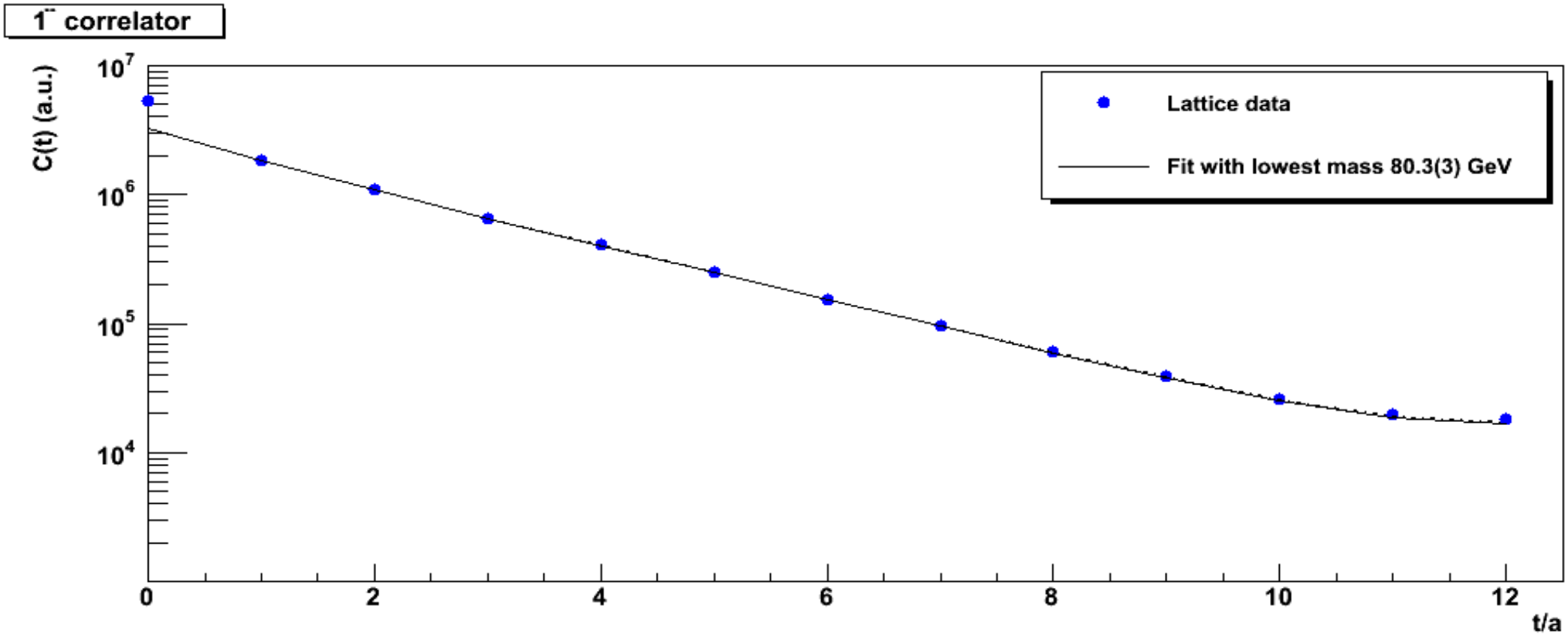

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  - At least for a light Higgs

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[Fröhlich et al. PLB 80 Maas'12]

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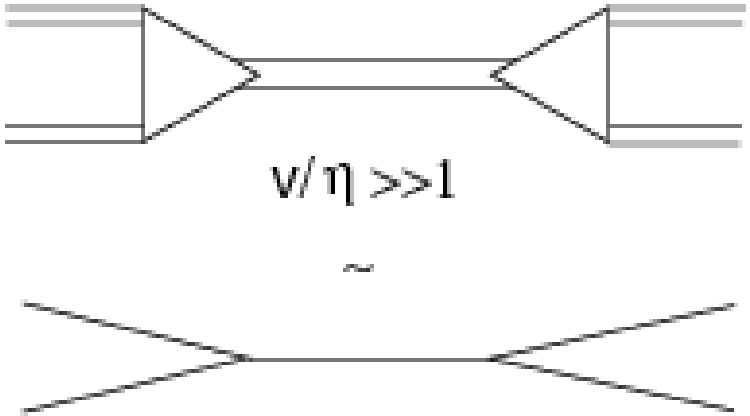

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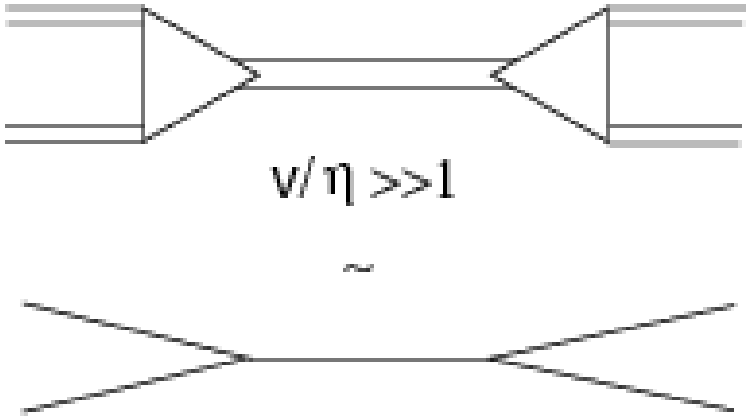
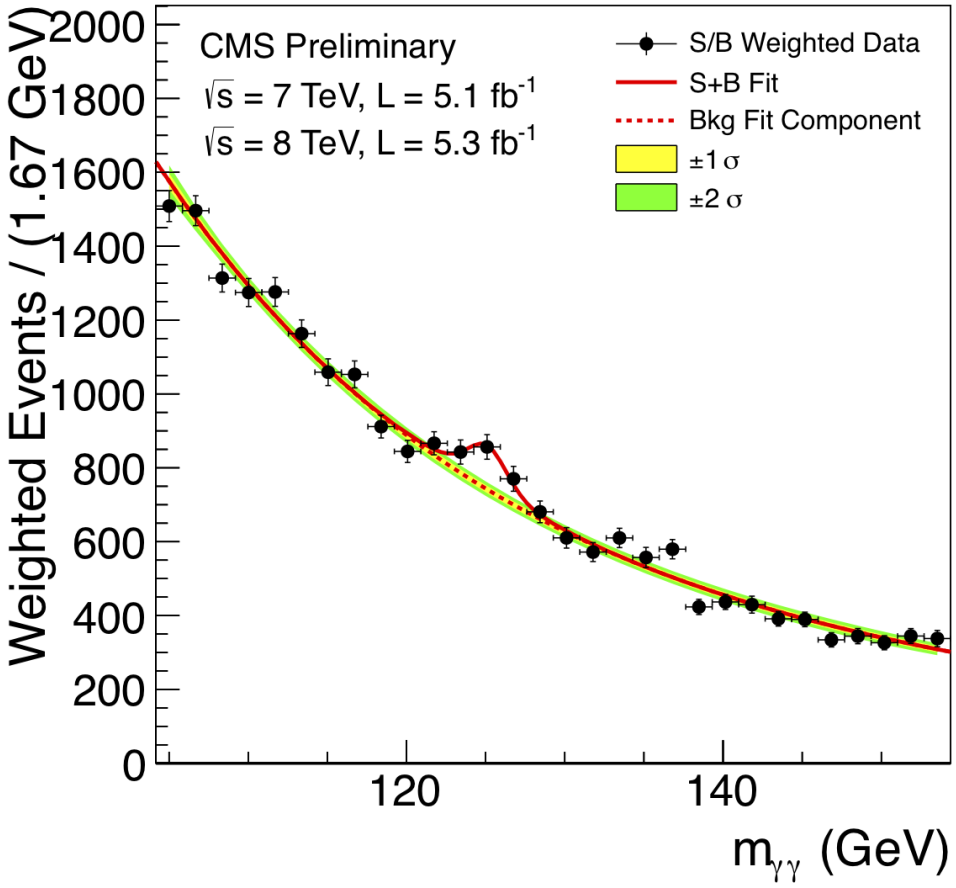
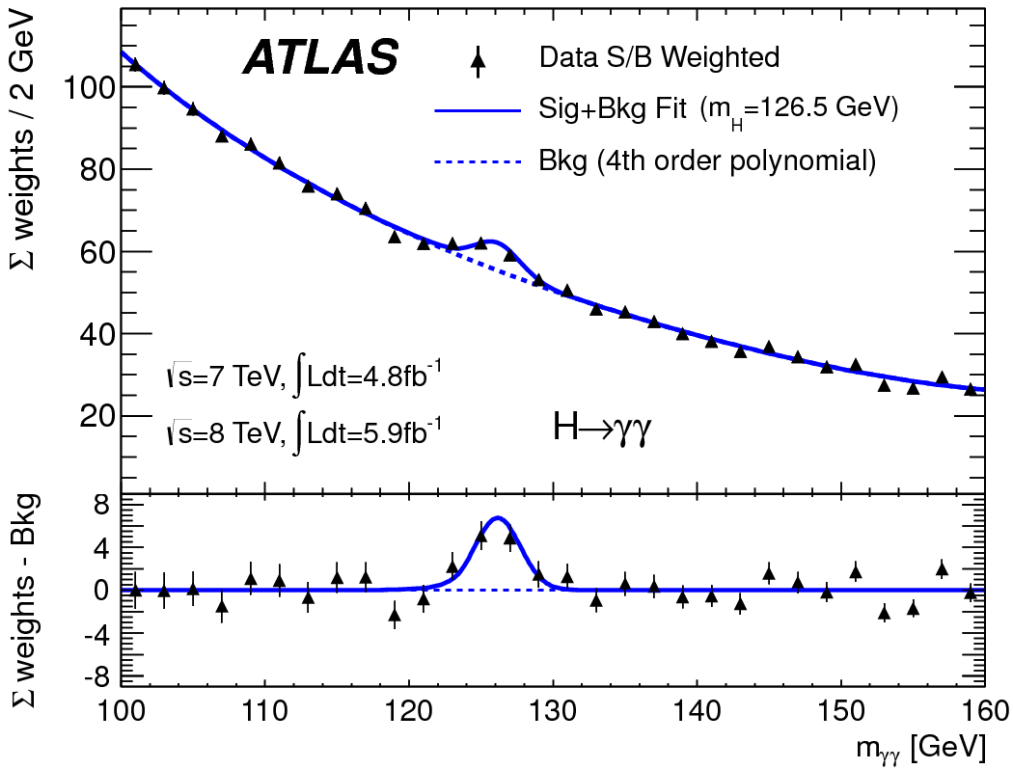


- Beyond tree-level: Resonances in cross sections remain scheme, scale, and gauge invariant
  - At least Higgs mass is not

Observation

[ATLAS & CMS, '11+'12 data, 10 fb^{-1}]





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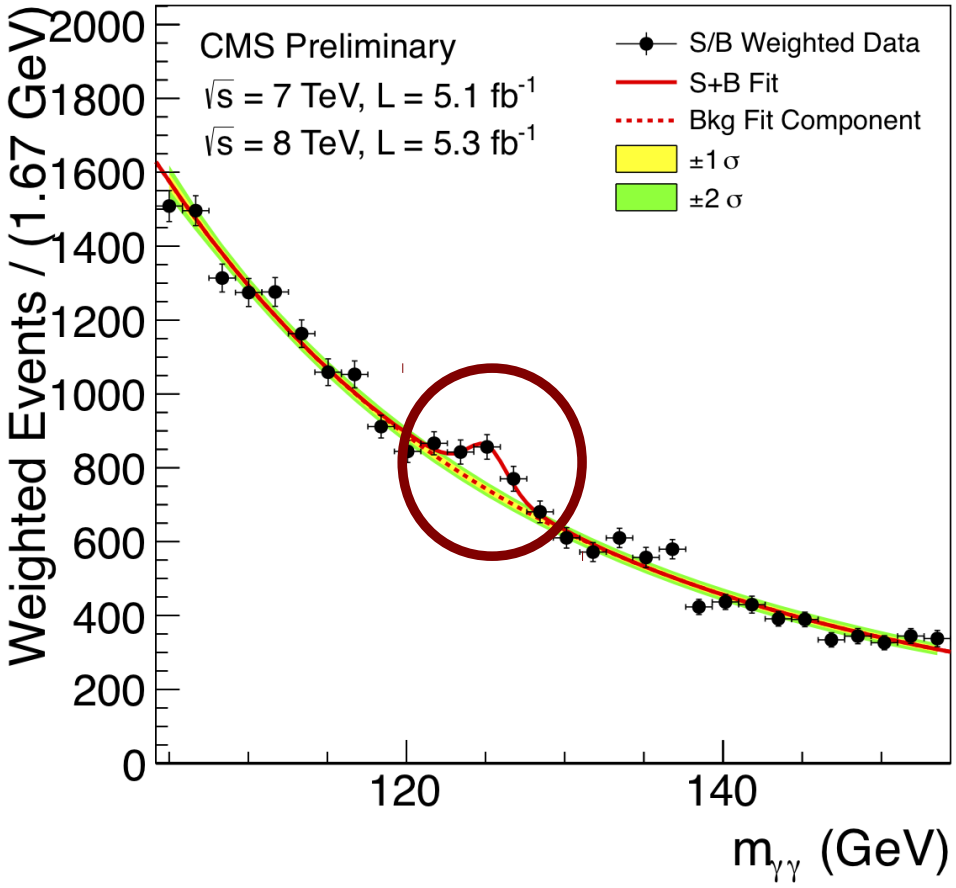

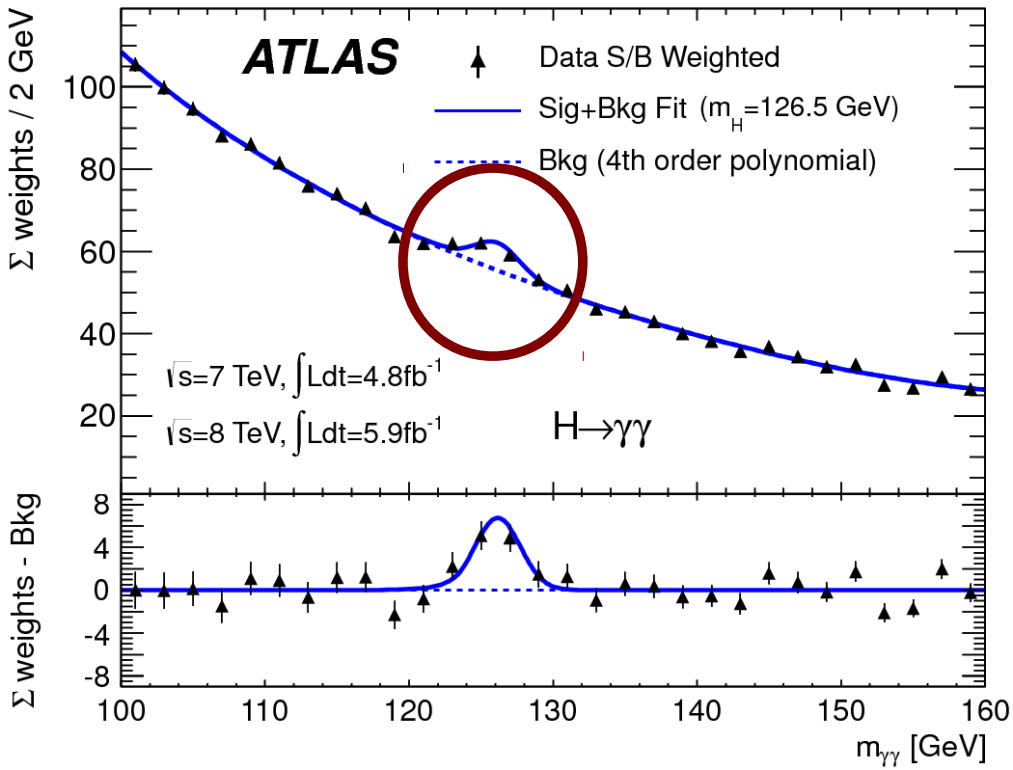

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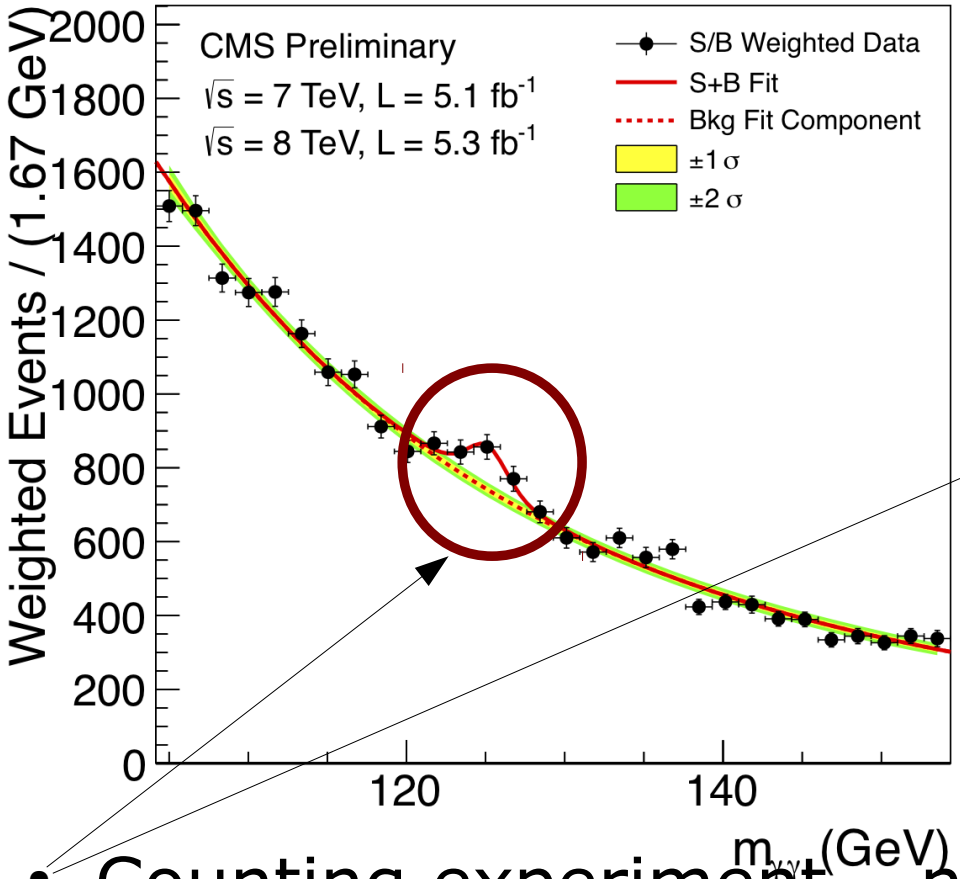

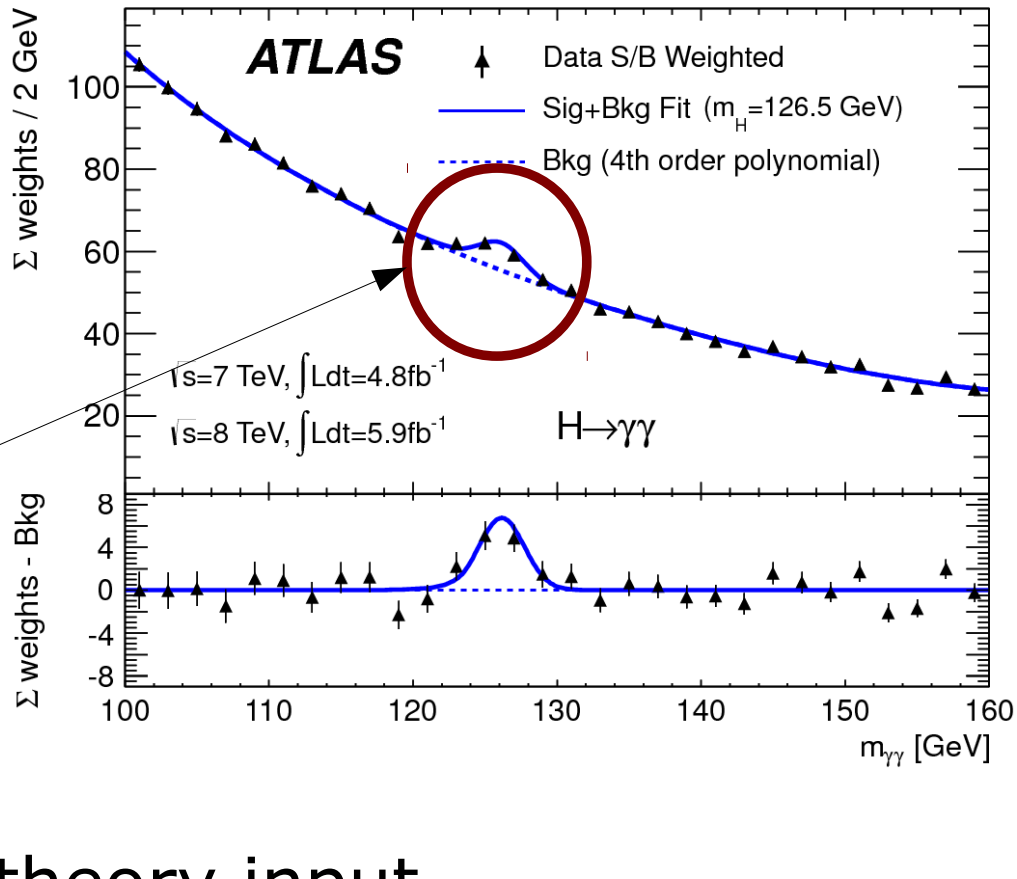

- Counting experiment – no theory input

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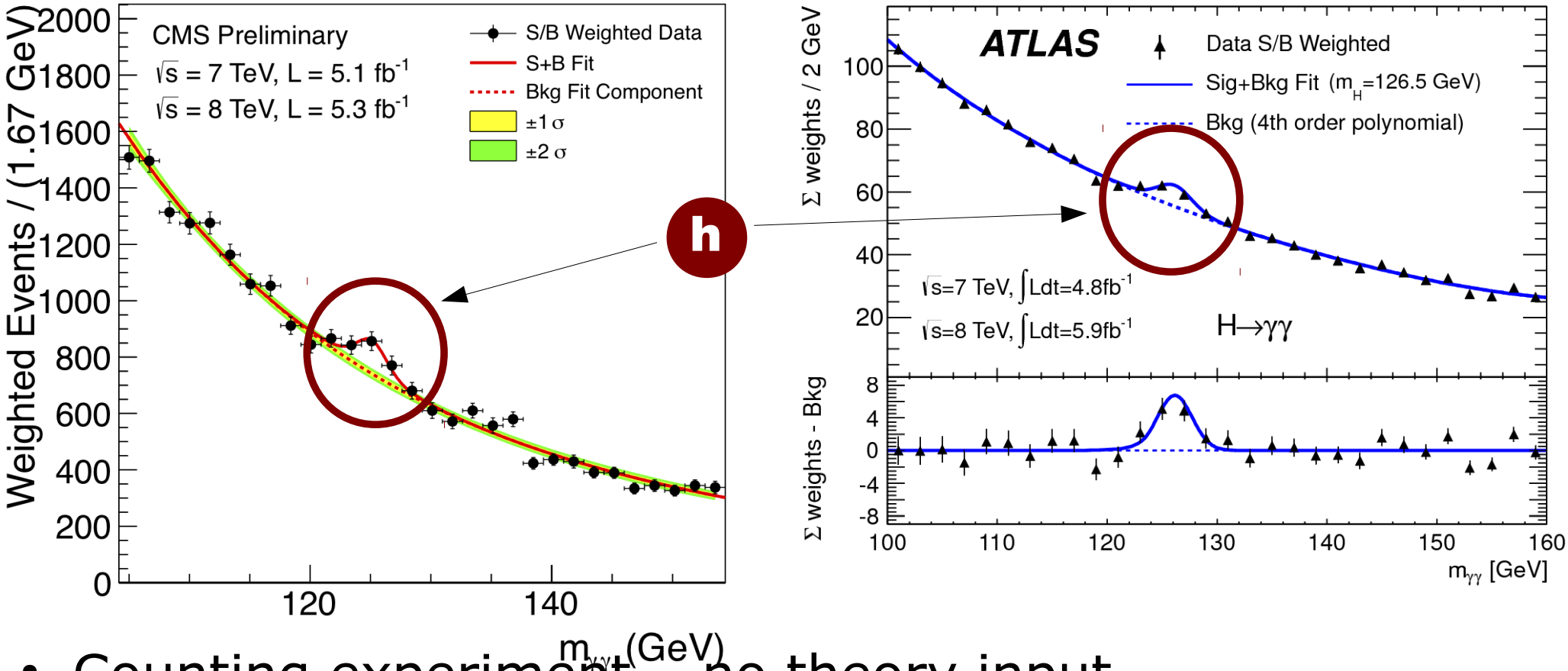

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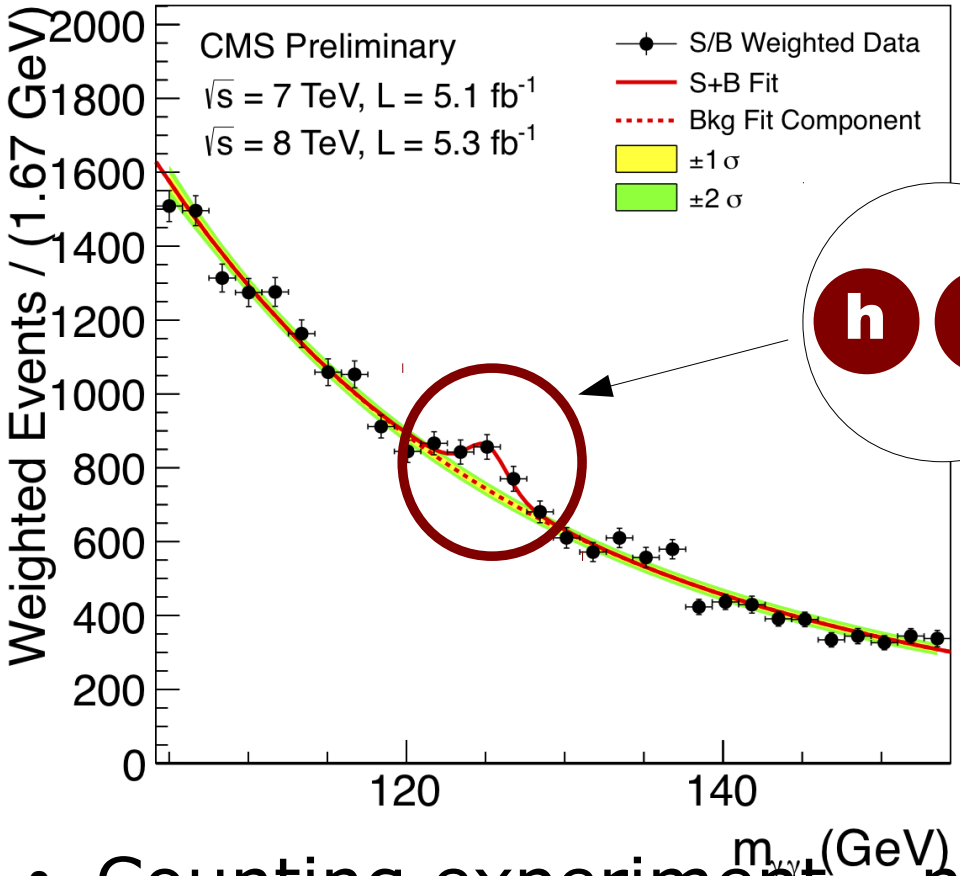

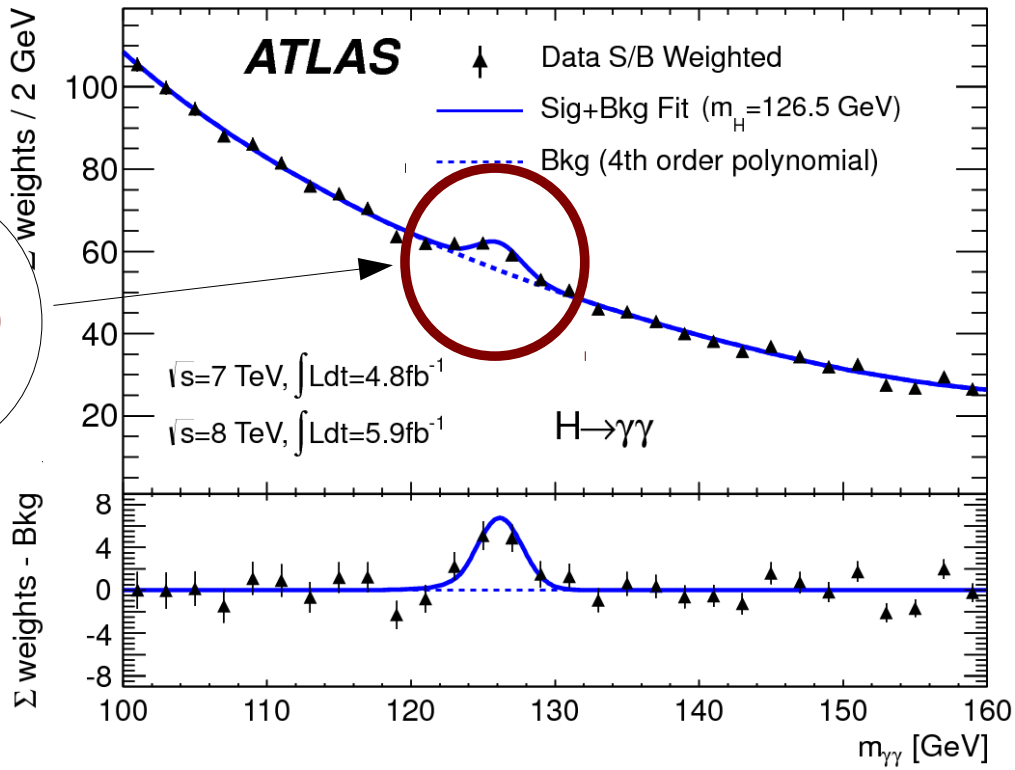

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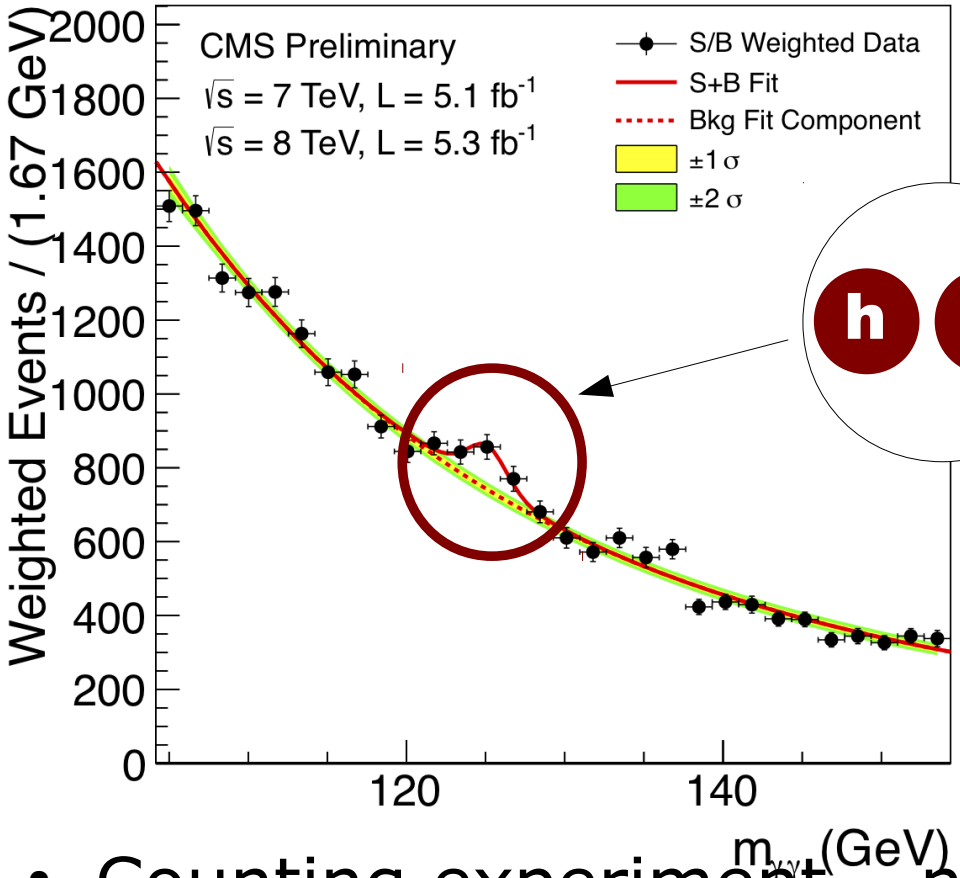
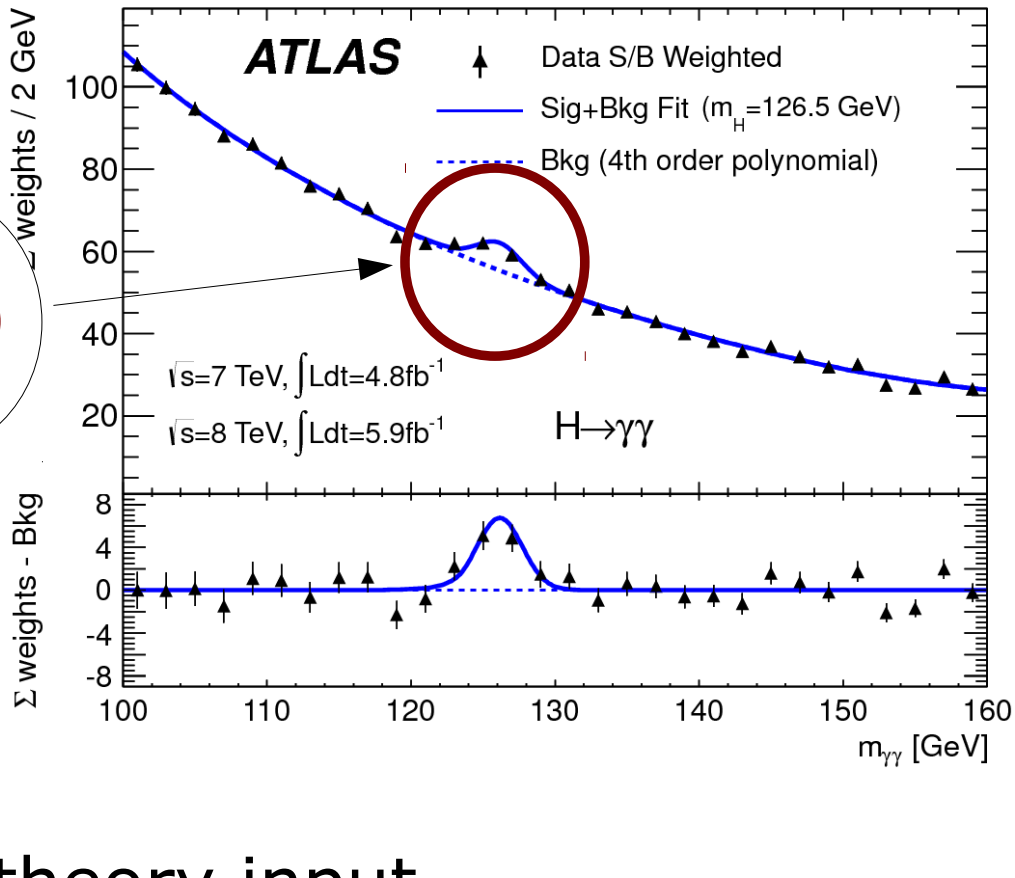
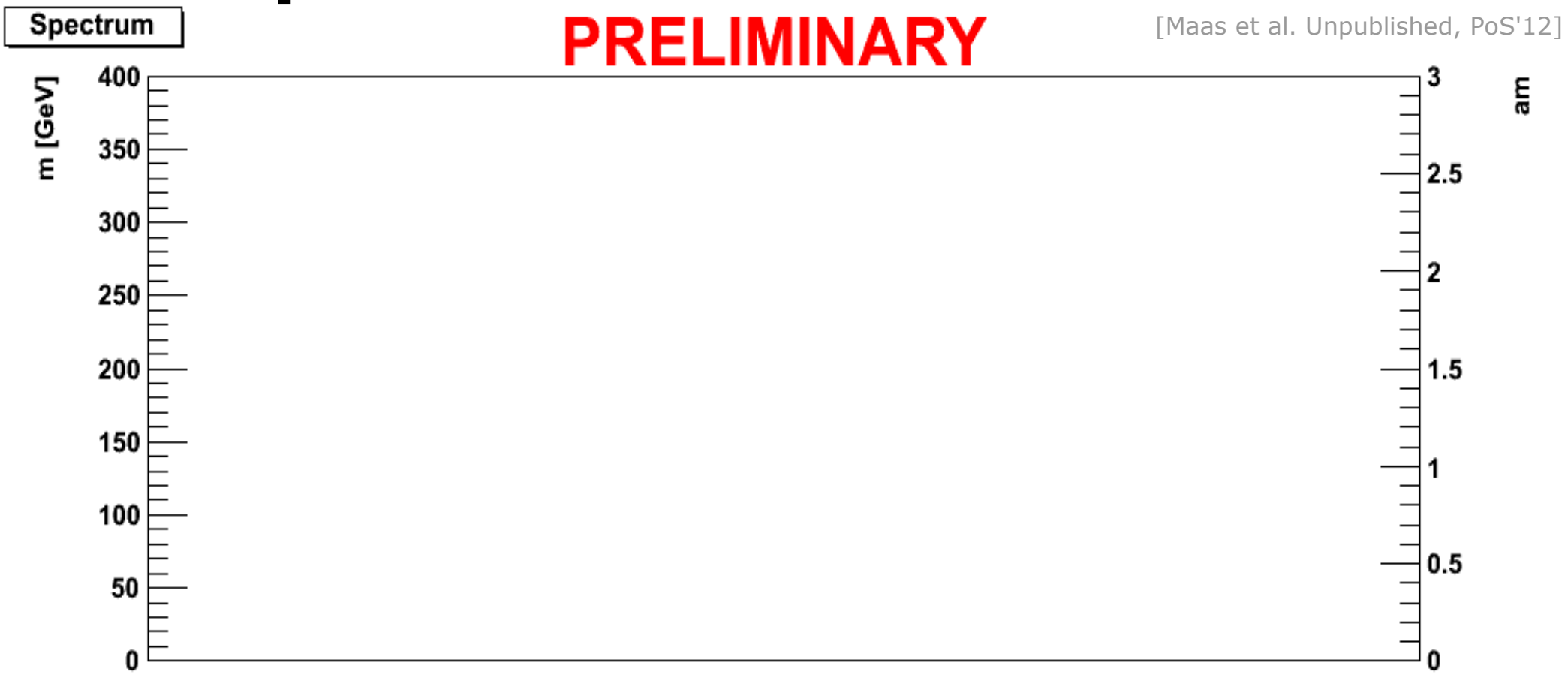




- Counting experiment – no theory input
- Cross section resonances associated with physical particles: Bound states
  - Similar to quarkonium resonances
  - No large differences for light Higgs

Consequences II – Excited states



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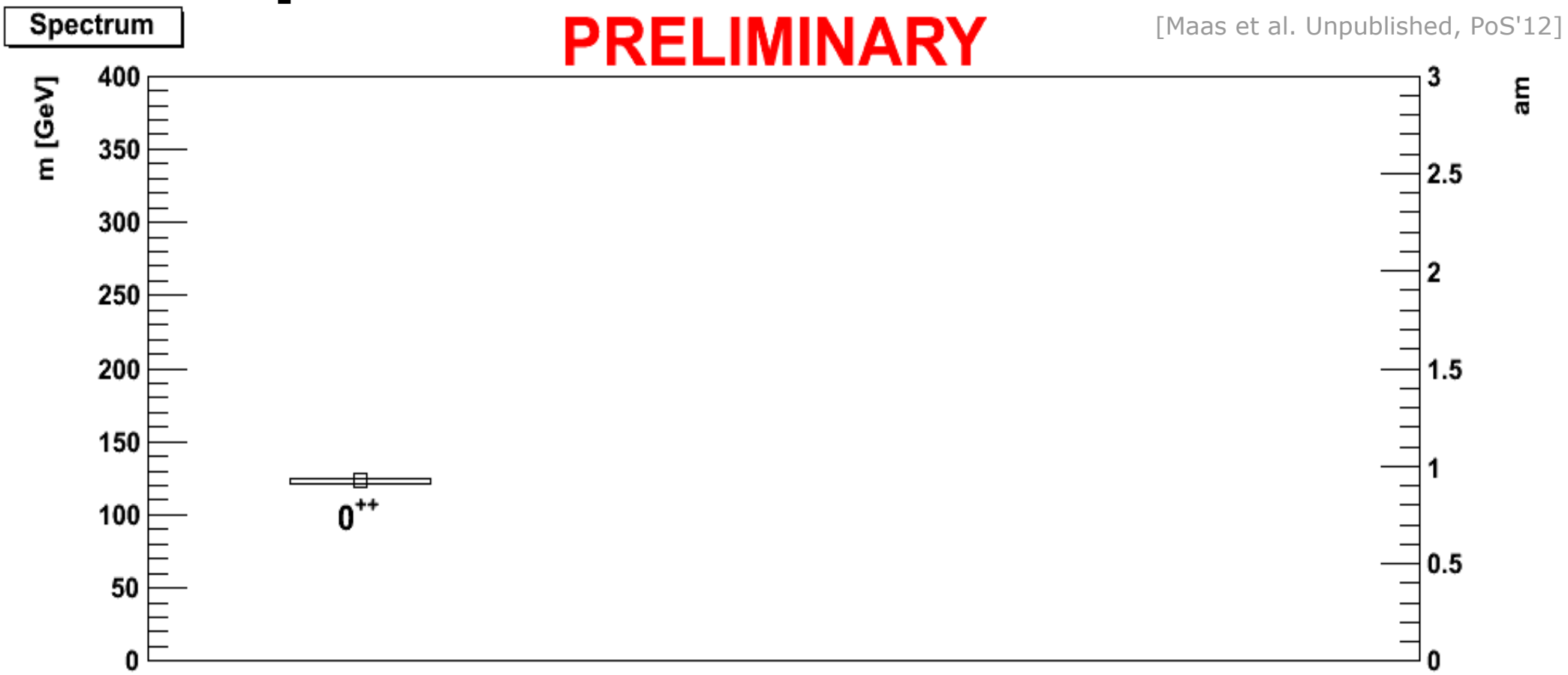

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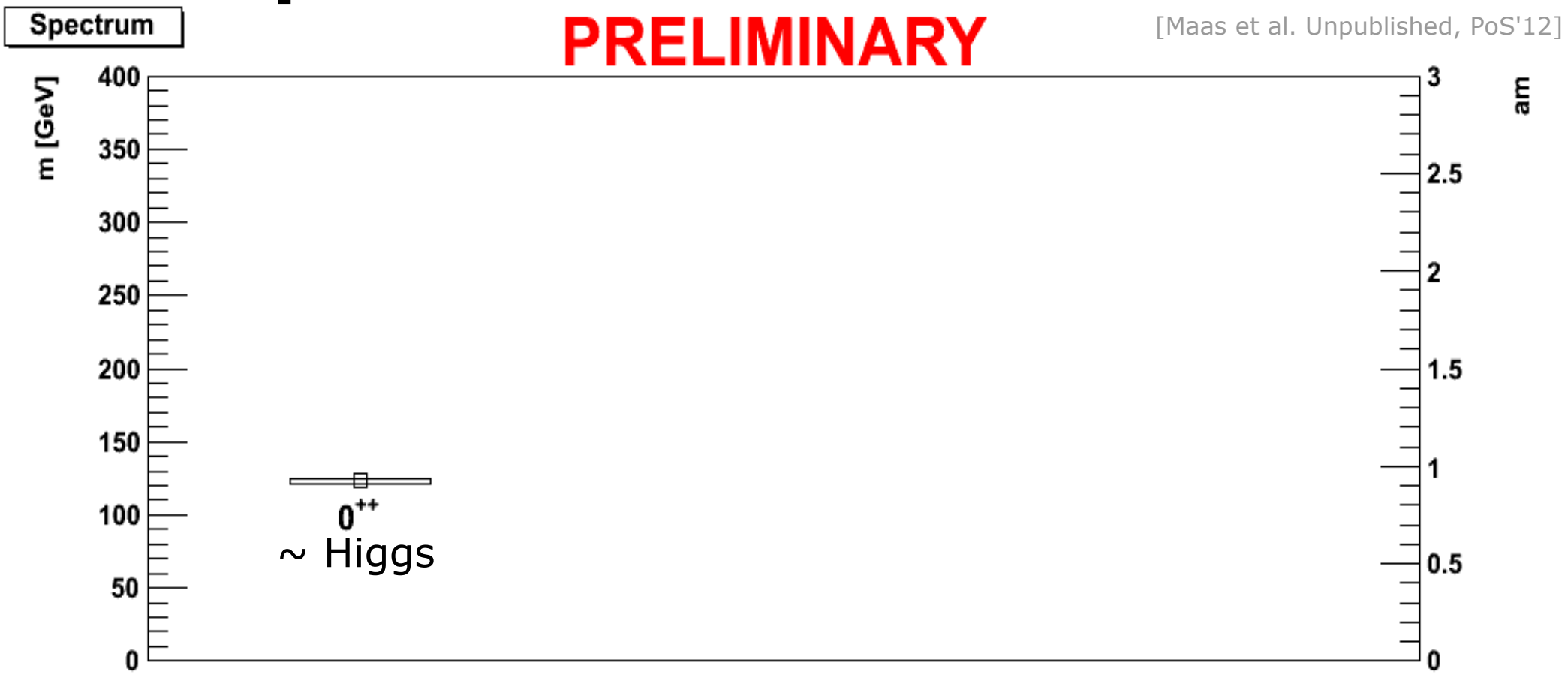

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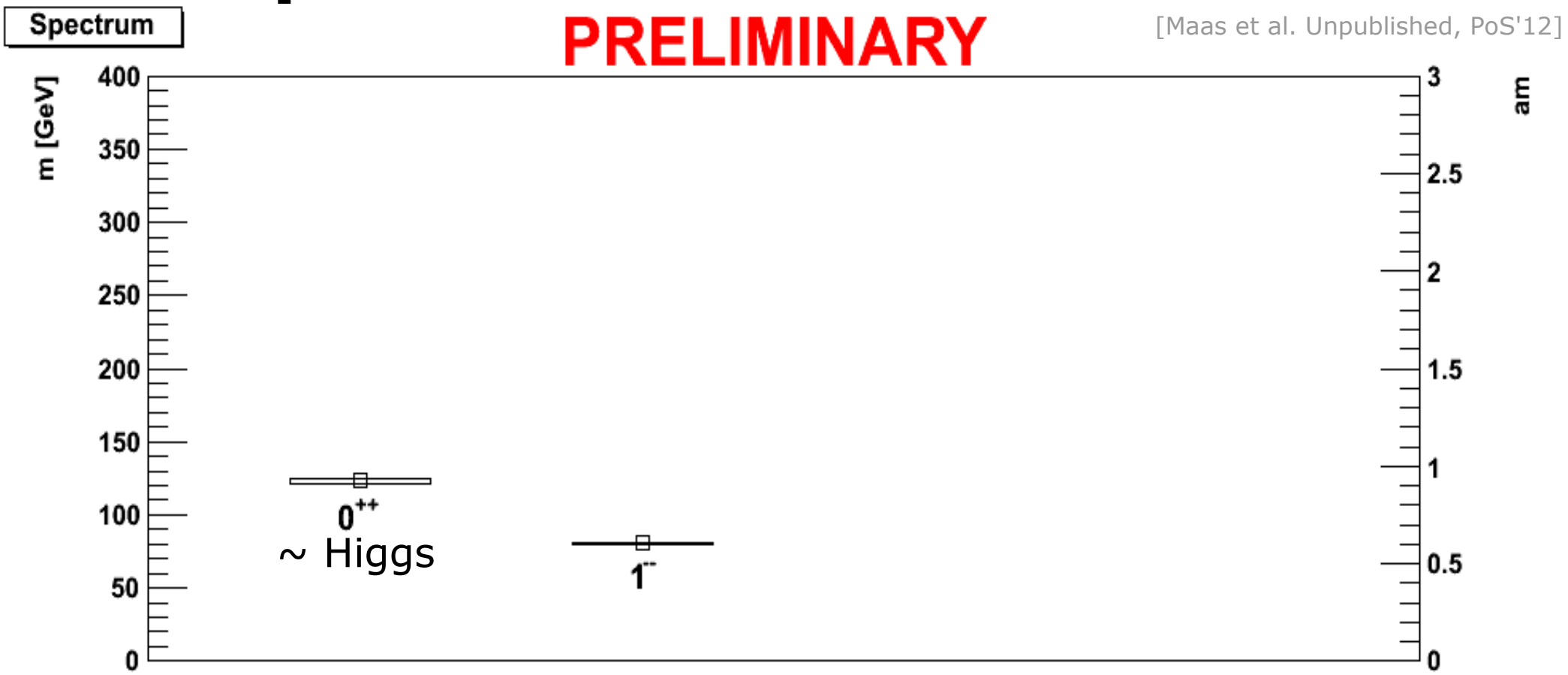

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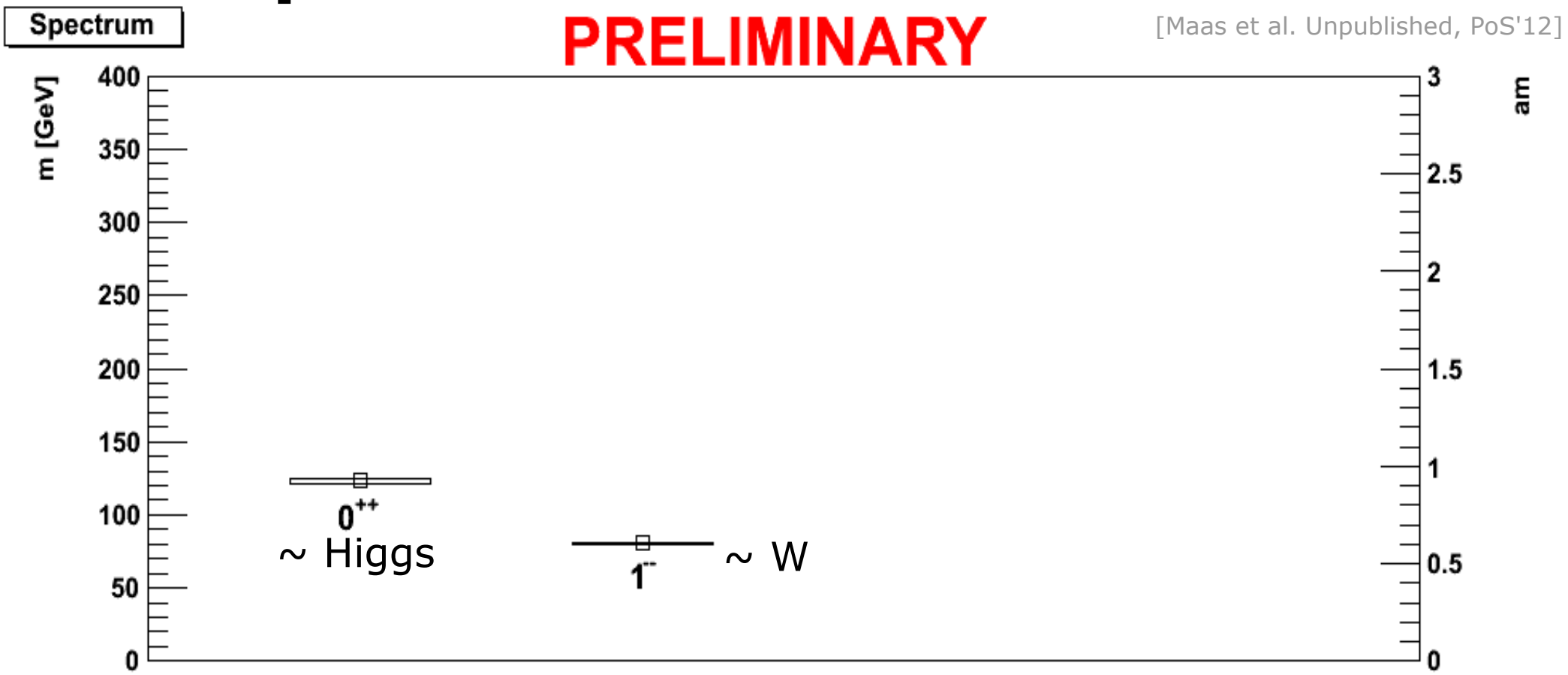

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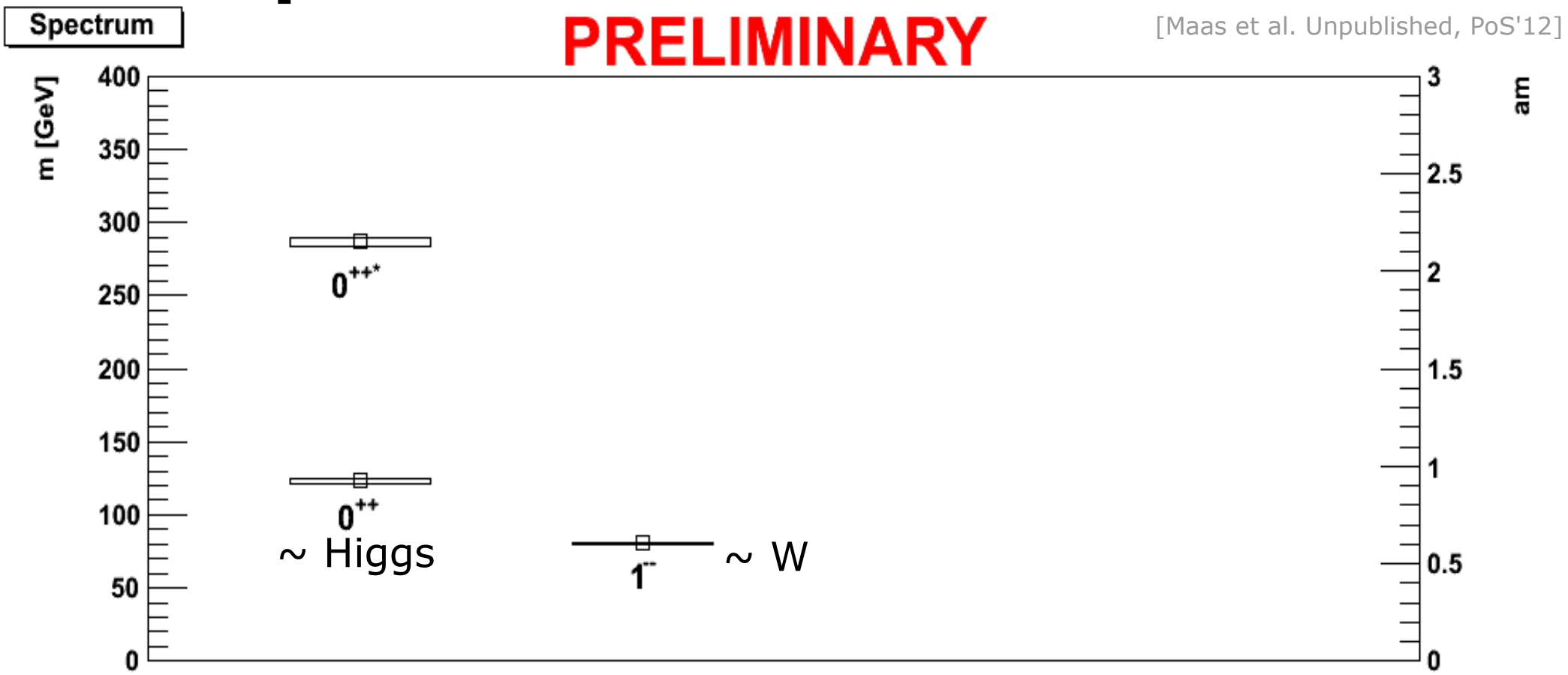

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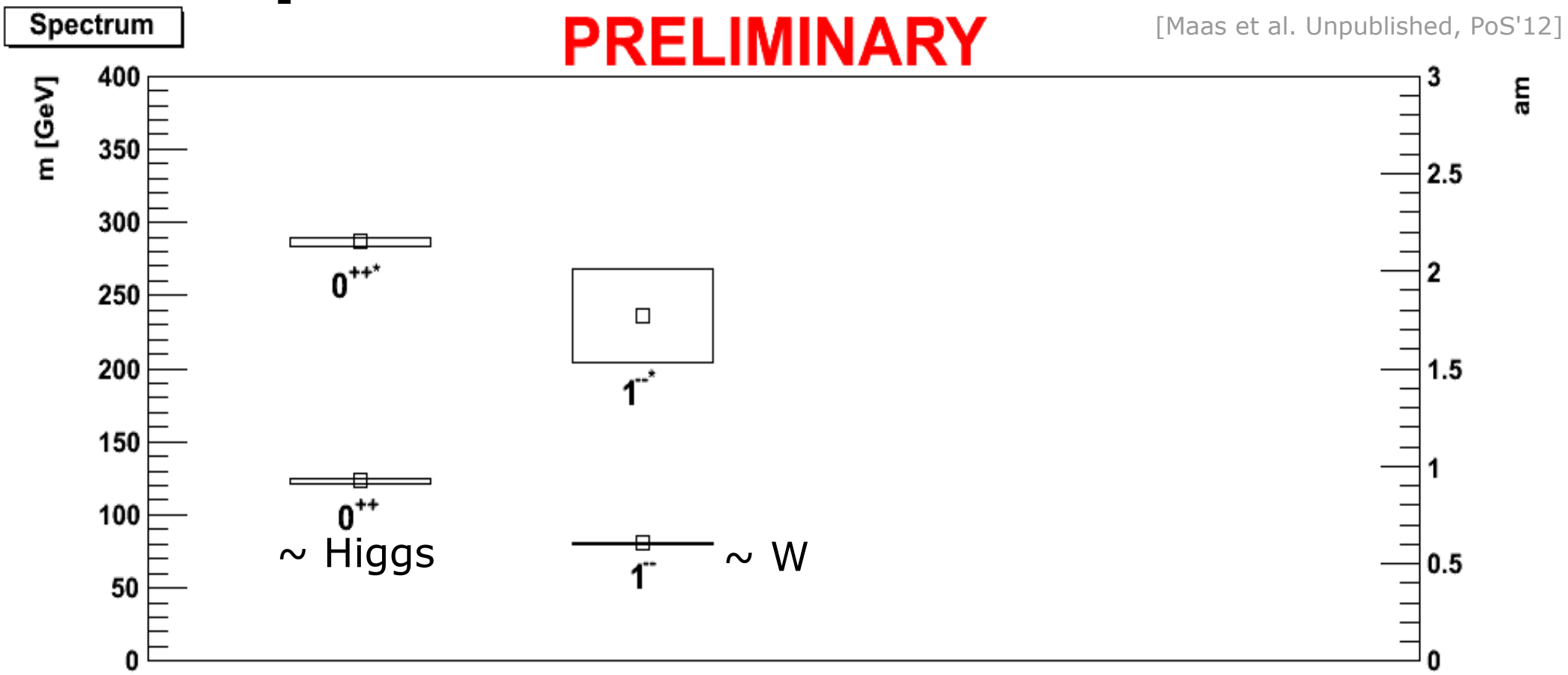

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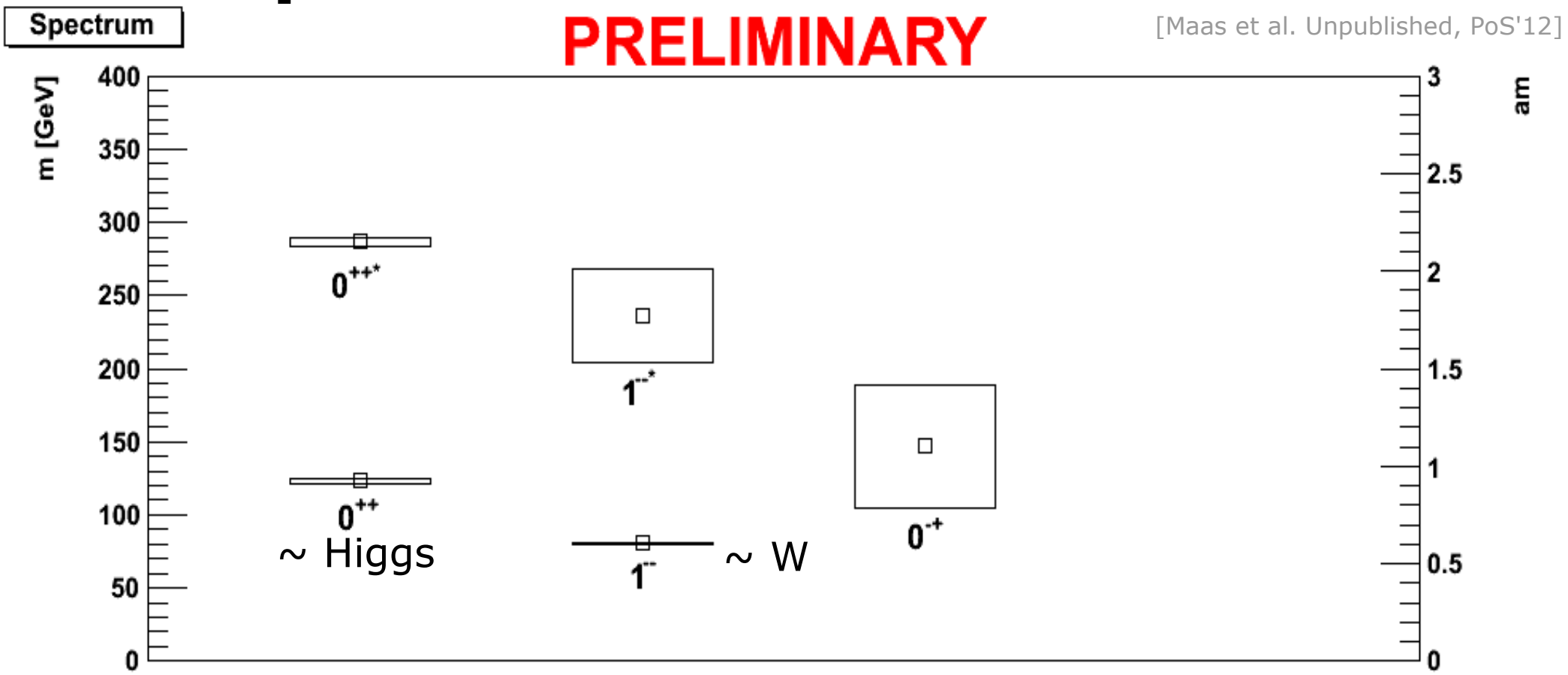

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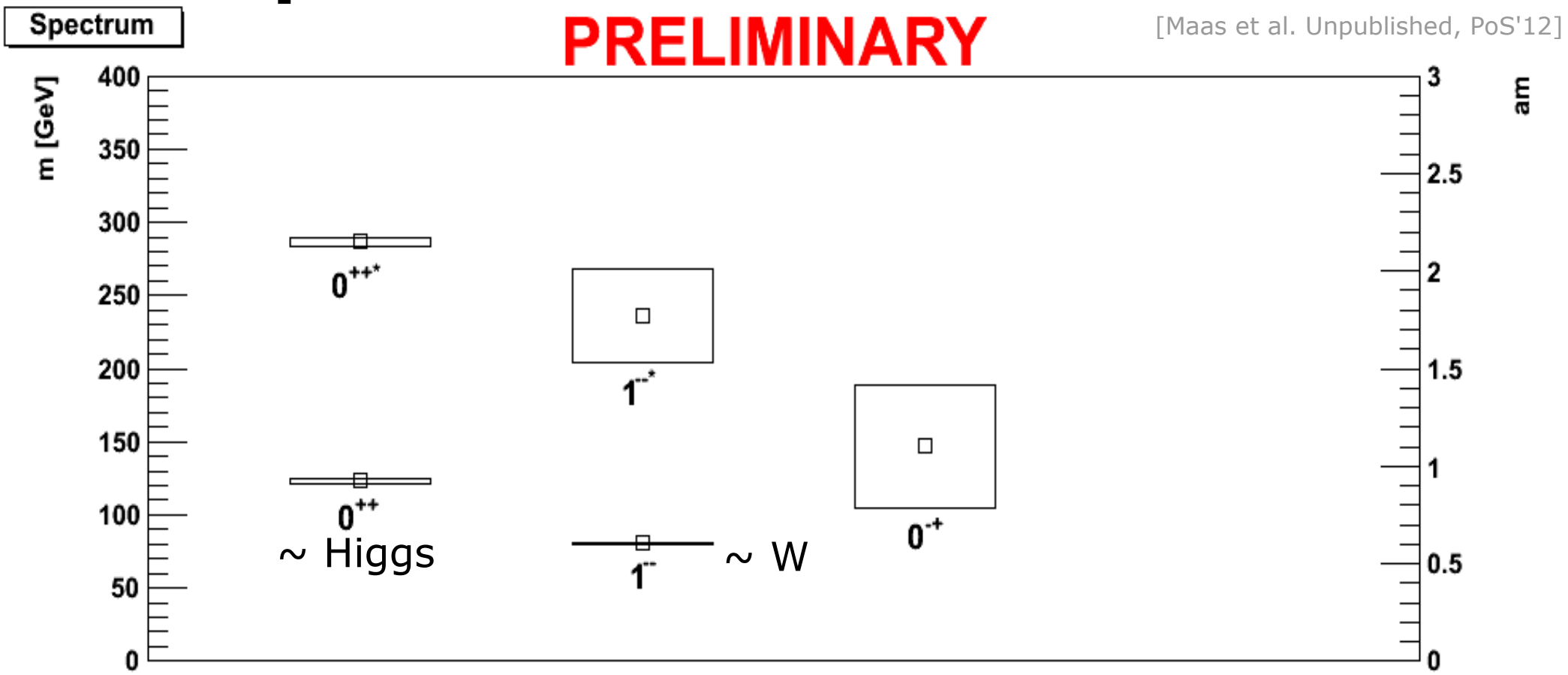

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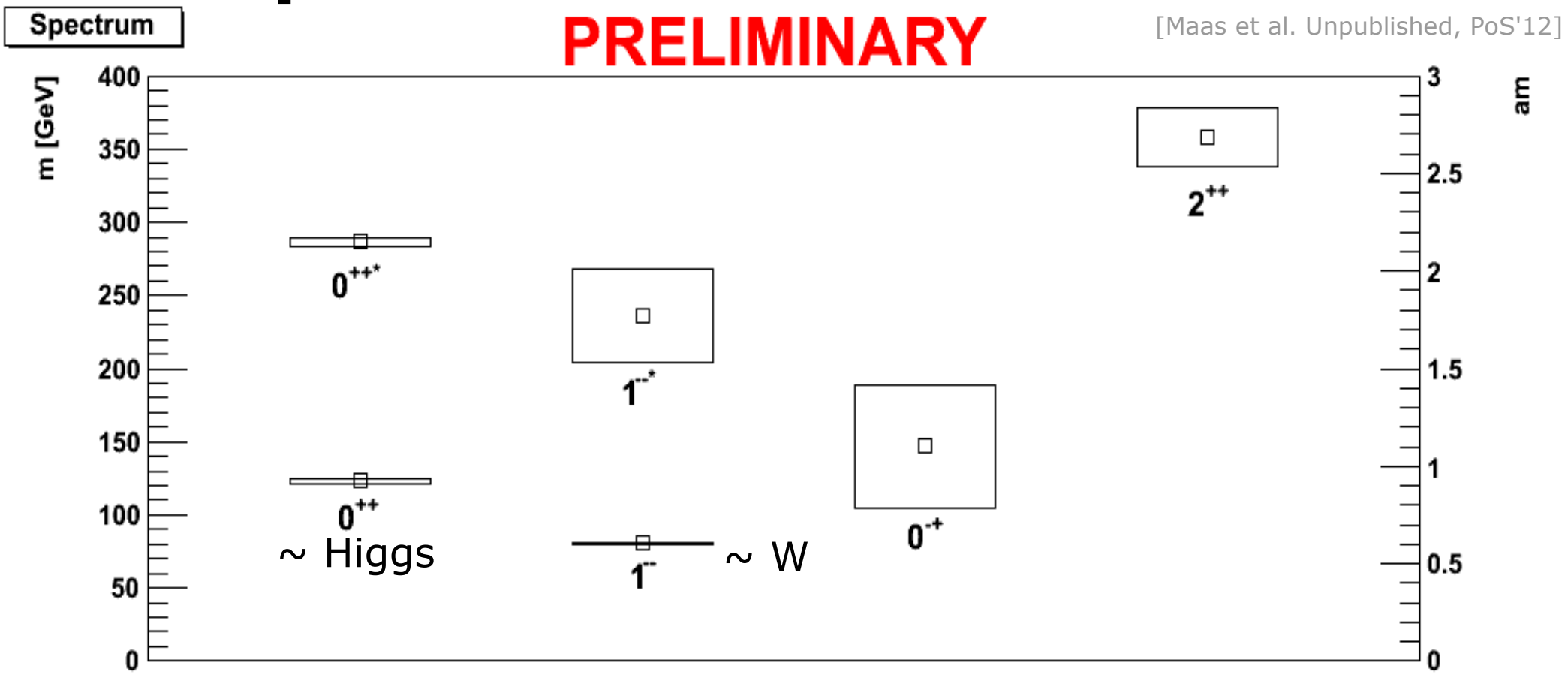

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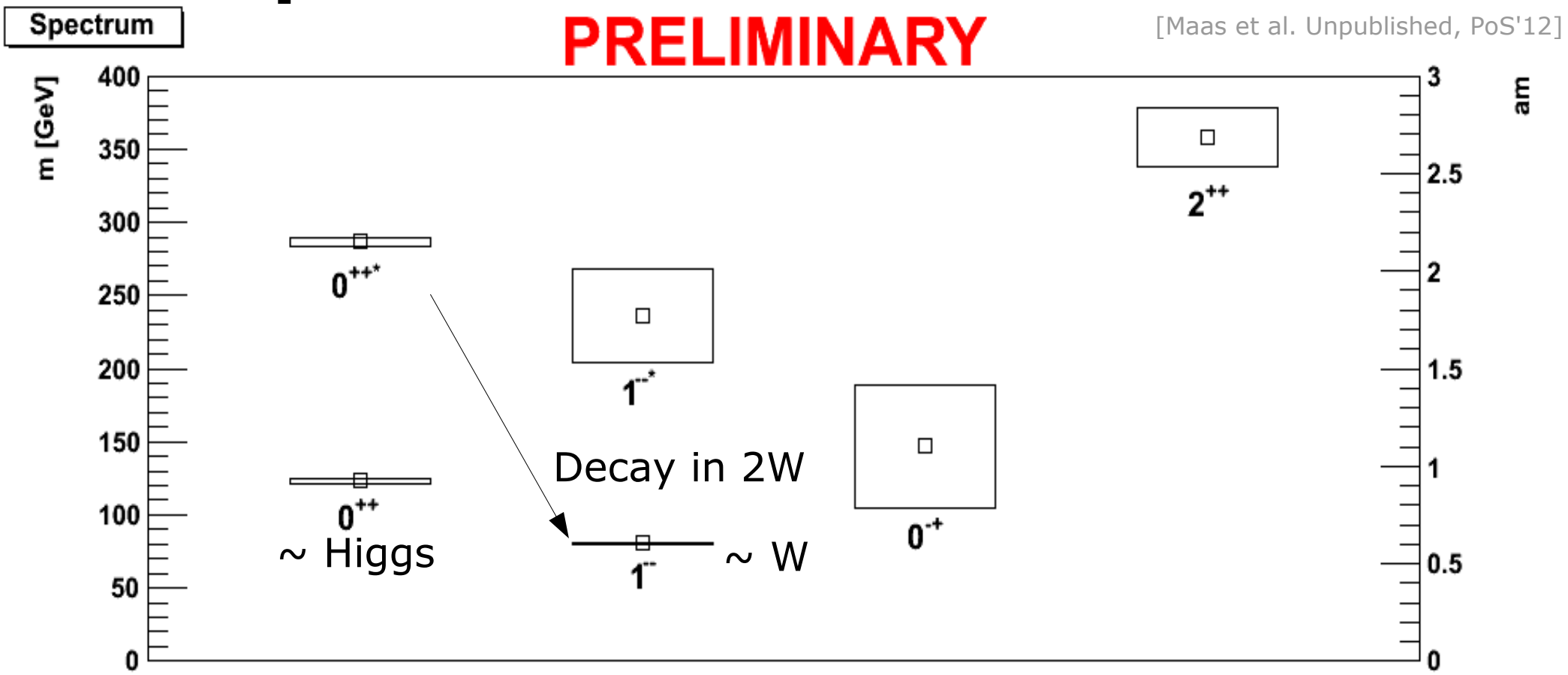

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[Maas et al. Unpublished]

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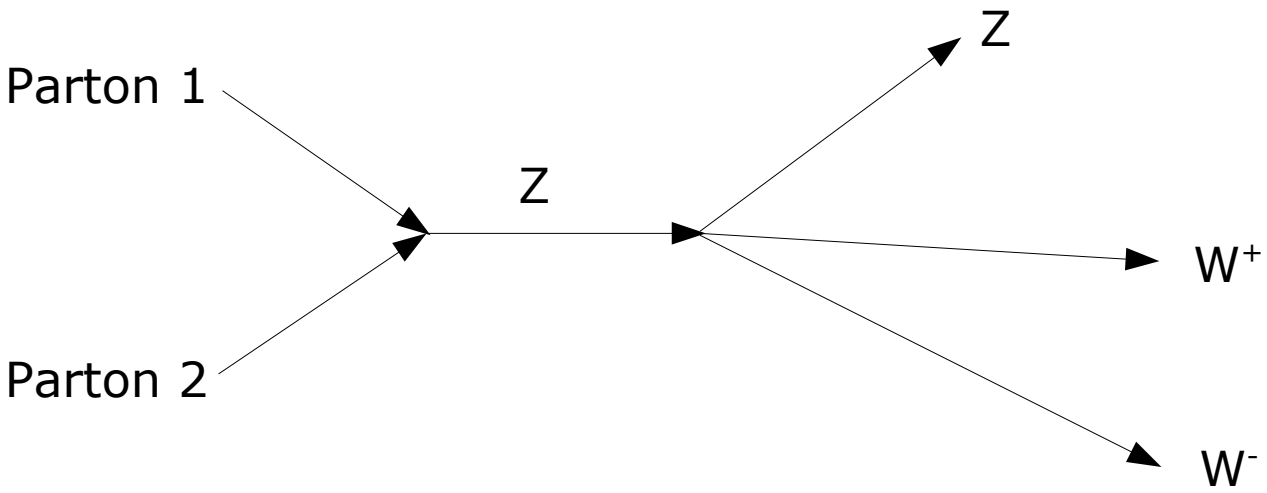

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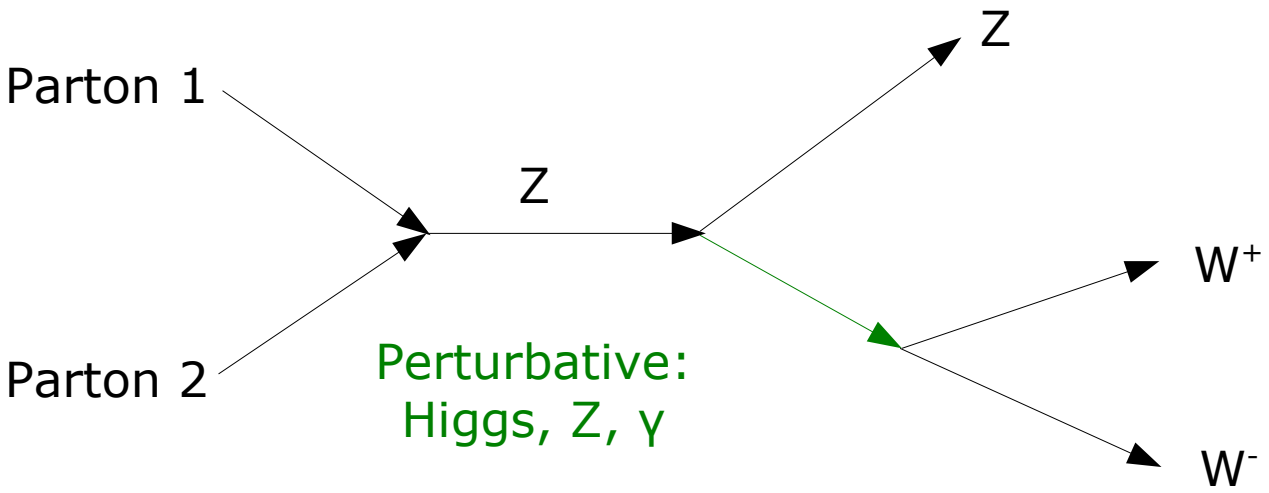

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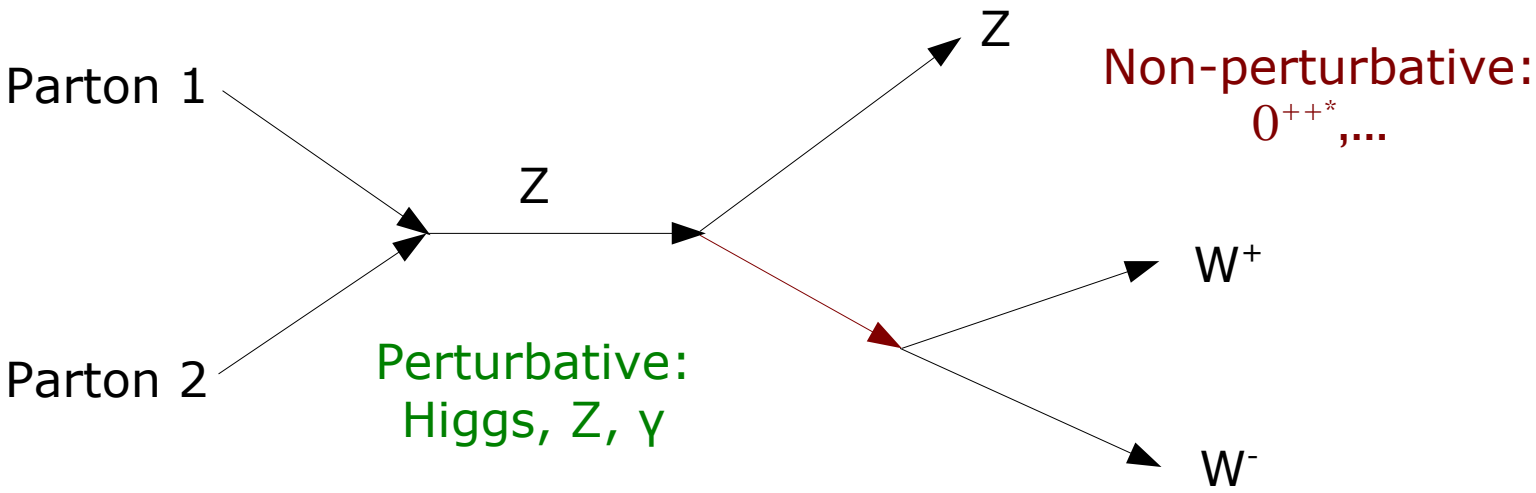

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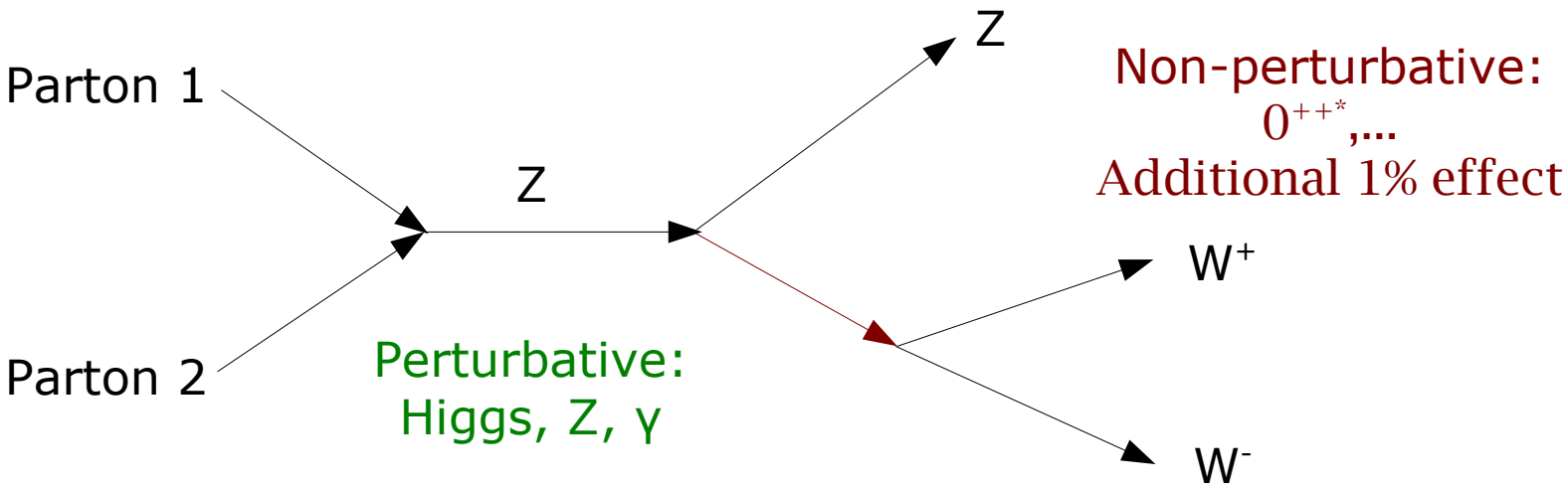

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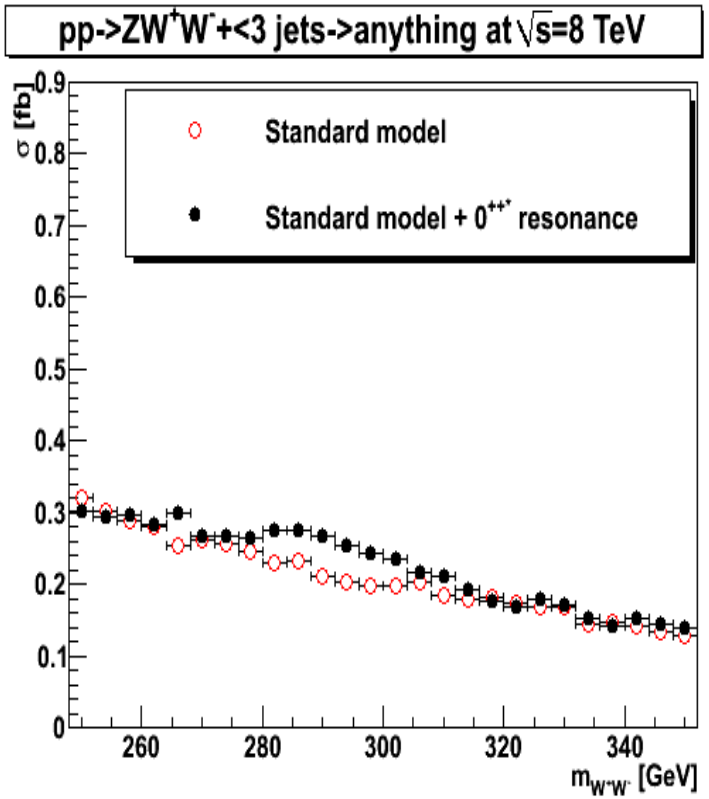

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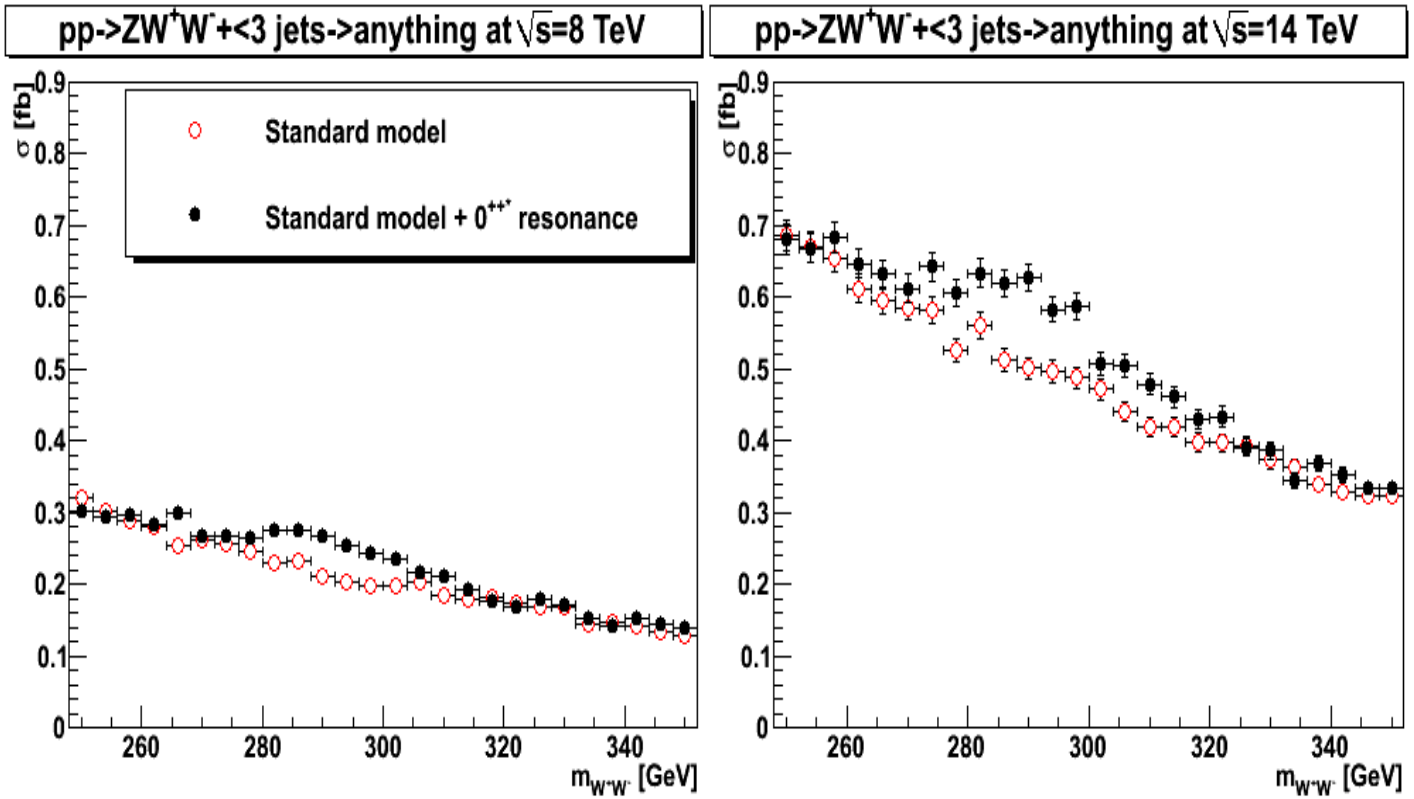

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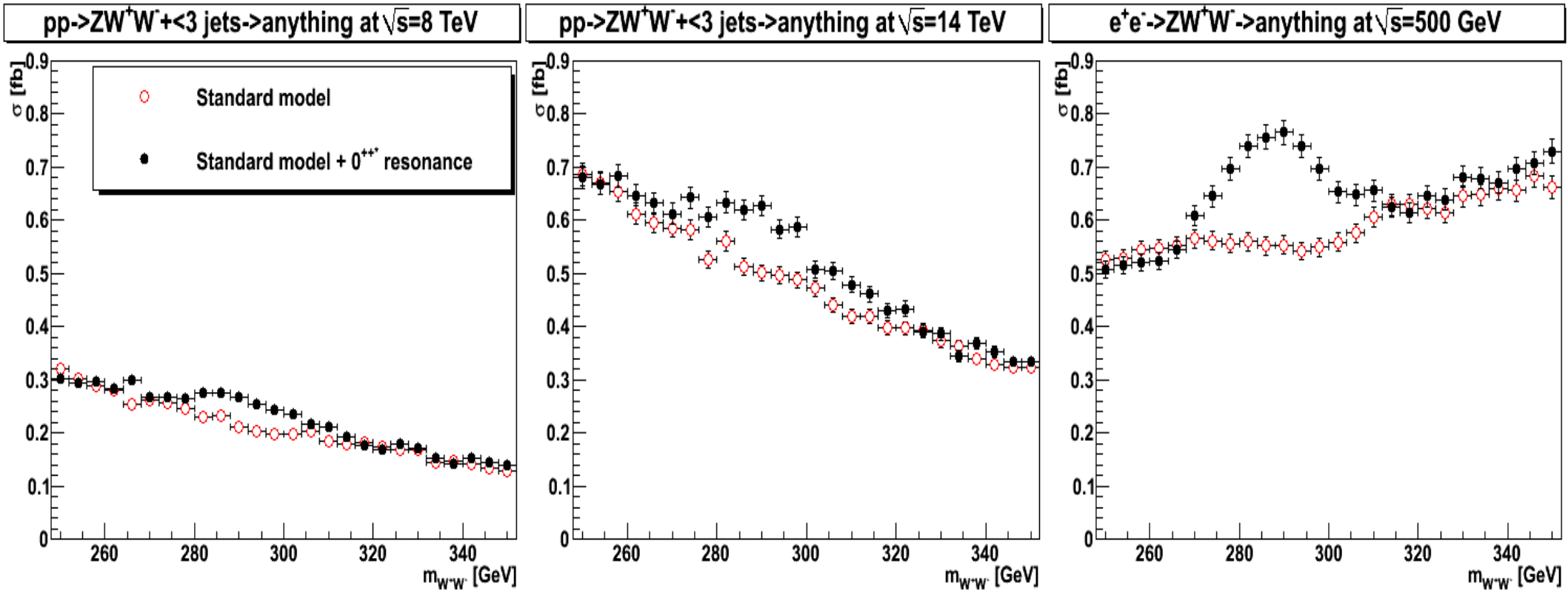

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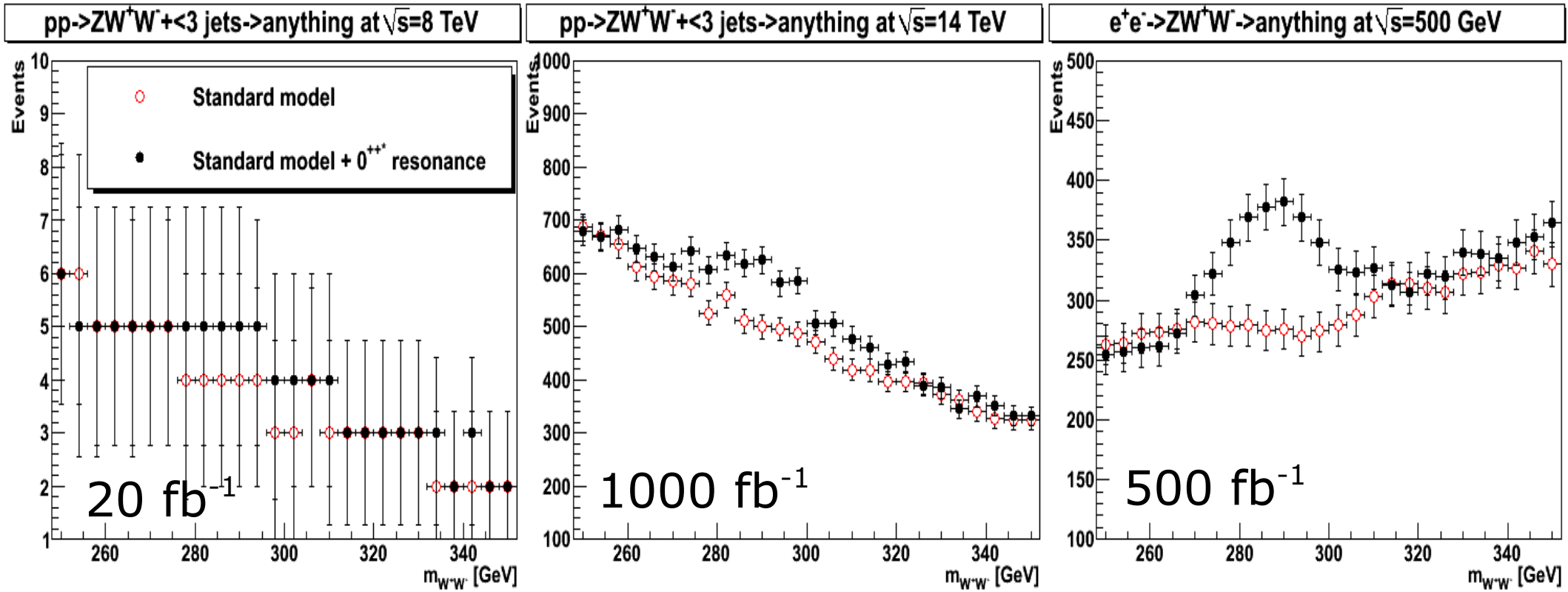

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