

The Higgsploding Universe

Michael Spannowsky

IPPP, Durham University

In collaboration with Valya Khoze

Due to absence of signs of new physics

HEP has 'Big Mac' blues,

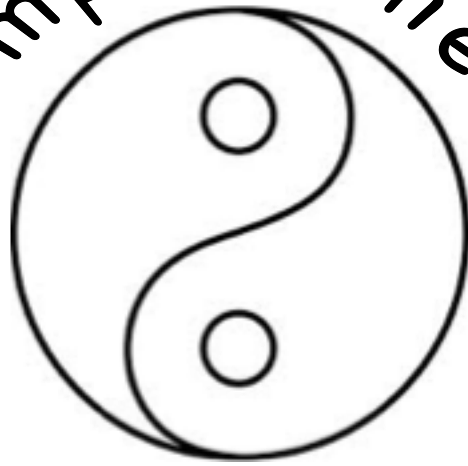
i.e. why nature not like (as natural as) advertised?

Commercial Reality

Sure, Higgs boson does the job, but...

The Higgs boson, a window to new physics

Compositeness



Effective Theory

$$\mathcal{L}_{\text{eff}} = \sum C_i \mathcal{O}_i$$

Symmetry

SUSY, CW, ...

Naturalness

fermionic top partners

simplified models

scalar top partners

simplified models

Leptons width Measurements Jets

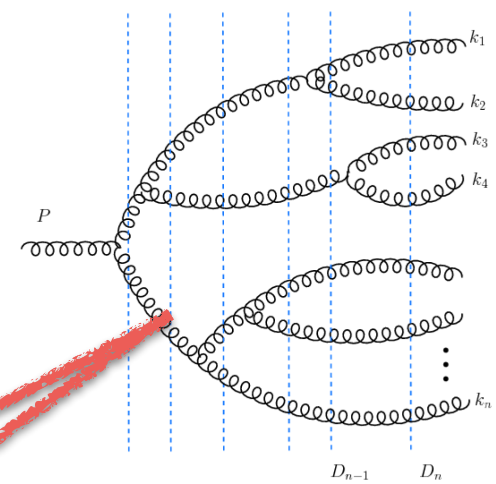
mass MET boost Photons interference

A Standard Model Tale

Before the discovery of the Higgs boson - (**Yang-Mills theories**)

Situation at tree-level

Multiplicity



Gluon amplitudes for

n x gluon -> m x gluon

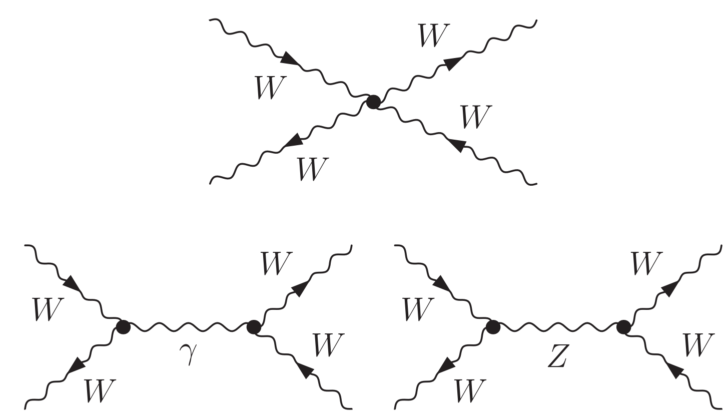
for given helicity and color structure strong cancellations between Feynman diagrams

[Parke, Taylor ’86]

[Berends, Giele ’87]

m gluon -> m! Feyn. diags

but not m! growth for Amplitude value



Kinetic Energy

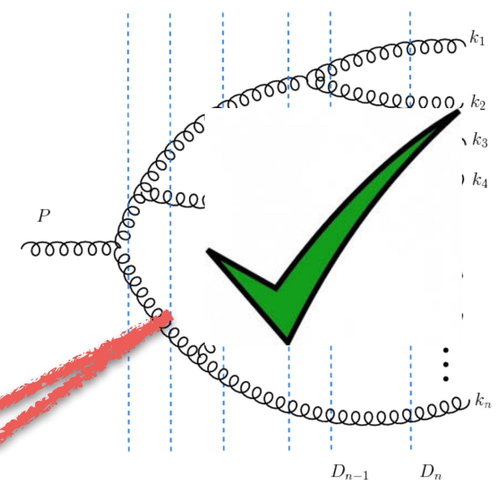
Perturbative unitarity violated at high energies → model inconsistent (at high energies)

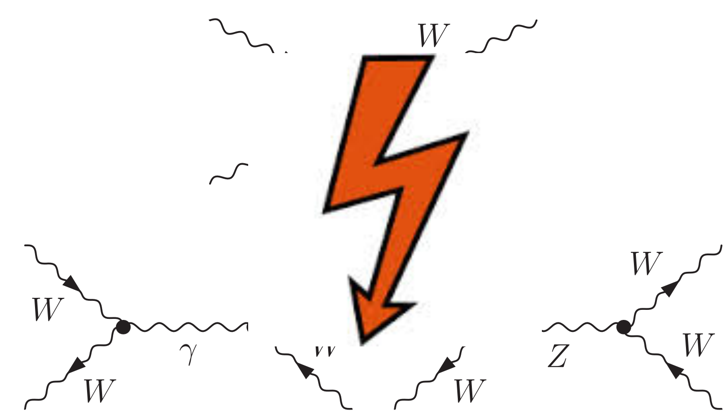
A Standard Model Tale

Before the discovery of the Higgs boson - (**Yang-Mills theories**)

Situation at tree-level

Multiplicity





Kinetic Energy

Gluon amplitudes for

n x gluon -> m x gluon

for given helicity and color structure strong cancellations between Feynman diagrams

[Parke, Taylor '86]
[Berends, Giele '87]

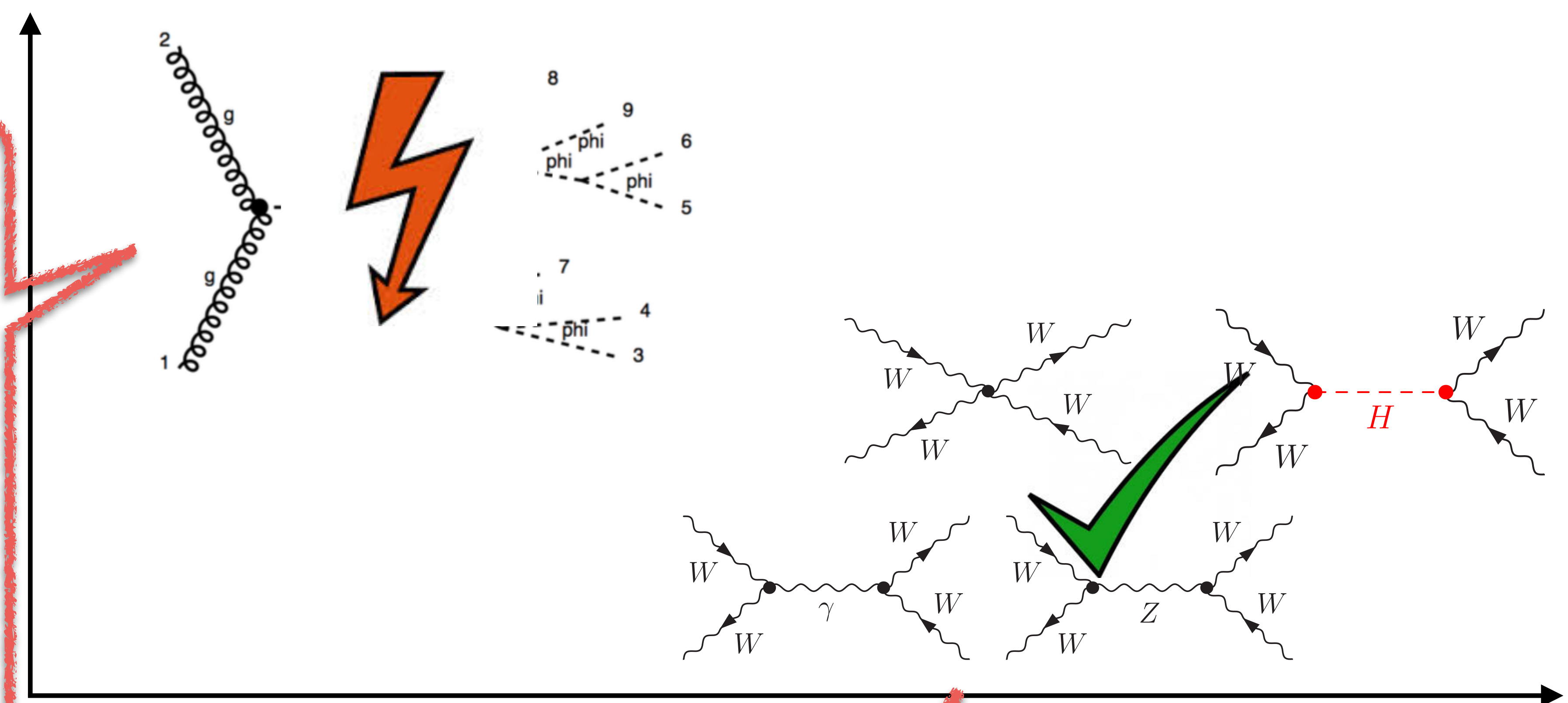
m gluon -> m! Feyn. diags but not m! growth for Amplitude value

Perturbative unitarity violated at high energies → model inconsistent (at high energies)

After the discovery of the Higgs boson - **complete Standard Model**

Situation at tree-level

Multiplicity



Kinetic Energy

Lack of symmetry for elementary scalar particle

h* -> n x h

n Higgs -> n! Feyn. diags

and not n! growth for Amplitude value

[Brown '92] [Voloshin '92]

Perturbative unitarity restored at high energies → model consistent (at high energies)

\+ Hierarchy problem (Loop level)

Calculation of 1* -> n amplitudes

Assume Lagrangian

$$\mathcal{L}_\rho(\phi) \,=\, \frac{1}{2}\,(\partial\phi)^2 - \frac{1}{2}M^2\phi^2 - \frac{1}{4}\lambda\phi^4 + \,\rho\,\phi$$

The amplitude is calculated using the LSZ reduction technique [Brown '92]

$$\langle n|\phi(x)|0\rangle \,=\lim_{\rho\to 0}\left[\prod_{j=1}^{n}\lim_{p_j^2\to M^2}\int d^4x_j e^{ip_j\cdot x_j}(M^2-p_j^2)\frac{\delta}{\delta\rho(x_j)}\right]\langle 0_{\rm out}|\phi(x)|0_{\rm in}\rangle_\rho$$

where the tree-level approximation is obtained via $\langle 0_{\rm out}|\phi(x)|0_{\rm in}\rangle_\rho \longrightarrow \phi_{\rm cl}(x)$

and $\phi_{\rm cl}(x)$ is a solution to the classical field equation

IDEA: Fill whole phase-space with particles, i.e. produce all particles at mass threshold

with $\vec{p}_j = 0$ $\quad p_j^\mu = (\omega,\vec{0})$ $\quad$ and $\quad \rho(x) = \rho(t) = \rho_0(\omega)\,e^{i\omega t}$

Here QFT -> time-dep QM:

$$(M^2-p_j^2)\frac{\delta}{\delta\rho(x_j)} \longrightarrow (M^2-\omega^2)\frac{\delta}{\delta\rho(t_j)} = \frac{\delta}{\delta z(t_j)}$$

$$z(t) \,:=\, \frac{\rho_0(\omega)\,e^{i\omega t}}{M^2-\omega^2-i\epsilon} \,:=\, z_0\;e^{i\omega t}\,, \quad z_0 = \text{finite}\,\text{const}$$

Hence, the generating function of tree amplitudes on multi-particle thresholds is a classical solution to the Euler-Lagrange equation. It solves an ordinary differential equation with no source term

$$d_t^2\phi + M^2\phi + \lambda\phi^3 \;=\; 0$$

h*->nh relies on outgoing particles
thus, only positive freq. modes present

(initial condition)

with $$\phi_{\rm cl}(t) \;=\; z(t) \;+\; \sum_{n=2}^{\infty} d_n\, z(t)^n\,, \qquad z := z_0\, e^{iMt}$$

The coefficients d_n determine the actual amplitudes by differentiation w.r.t. z

$$\mathcal{A}_{h^*\to n\times h} \;=\; \left(\frac{\partial}{\partial z}\right)^n \phi_{\rm cl}\Big|_{z=0} \;=\; n!\, d_n \;=\; n!\,(2v)^{1-n}$$

Factorial growth!

$$\phi_{\rm cl}(t) \;=\; \frac{z(t)}{1-\frac{\lambda}{8M^2}\,z(t)^2}$$

$$\boxed{\mathcal{A}_{1\to n} \;=\; n!\,\left(\frac{\lambda}{8M^2}\right)^{\frac{n-1}{2}}}$$

Same findings by [Voloshin '92] [Argyes, Kleiss, Papadopoulos '92] [Libanov, Rubakov, Son, Troitski '94]

Several generalisations of this approach:

- Higgs like, ie. phi^4 with vev: [Brown '92]

$$\mathcal{L}(h) = \frac{1}{2}(\partial h)^2 - \frac{\lambda}{4}\left(h^2 - v^2\right)^2 \quad \longrightarrow \quad \mathcal{A}_{1\to n} = \left(\frac{\partial}{\partial z}\right)^n h_{\rm cl}\Big|_{z=0} = n!\,(2v)^{1-n}$$

- Gauge-Higgs theory: [Khoze '14]

Higgs process $$\mathcal{A}(h \to n \times h + m \times Z_L) = (2v)^{1-n-m}\, n!\, m!\, d(n,m)$$

Z process $$\mathcal{A}(Z_L \to n \times h + (m+1) \times Z_L) = \frac{1}{(2v)^{n+m}}\, n!\,(m+1)!\, a(n,m)$$

- Go beyond mass threshold (needs space-dep sol.):

DGL: $$-(\partial^\mu \partial_\mu + M_h^2)\,\varphi = 3\lambda v\,\varphi^2 + \lambda\,\varphi^3$$

$$\varepsilon = \frac{1}{n\,M_h} E_n^{\rm kin} = \frac{1}{n}\frac{1}{2M_h^2}\sum_{i=1}^n \vec{p}_i^{\,2}$$

$$\downarrow$$

$$\mathcal{A}_n(p_1 \ldots p_n) = n!\,(2v)^{1-n}\left(1 - \frac{7}{6}n\,\varepsilon - \frac{1}{6}\frac{n}{n-1}\varepsilon + \mathcal{O}(\varepsilon^2)\right)$$

[Argyres, Kleiss, Papadopoulos '92] [Libanov, Rubakov, Son, Troitski '94]

How about loops?

Usual criticism: need to include loops to render cross section finite.

Keep in mind, we calculate exclusive rate of massive internal and outgoing particles -> **no mass-divergencies and observable IR-safe**

Loop corrections calculated by expanding around classical field $\phi(x) = \phi_0(x) + \phi_q(x)$

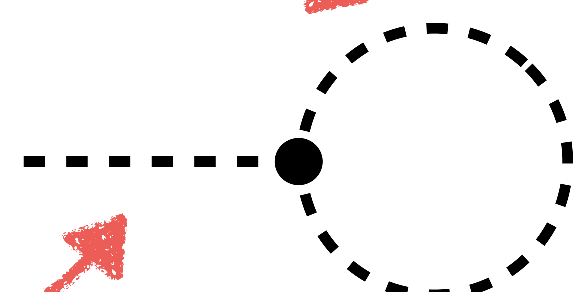
Euclidean Lagrangian becomes $\mathcal{L} = \frac{1}{2}(\partial_\mu \phi_q)^2 + \frac{1}{2}\left(m^2 + 3\lambda\phi_0^2\right)\phi_q^2 + \lambda\phi_0\phi_q^3 + \frac{\lambda}{4}\phi_q^4 .$

After promoting classical solution ϕ_0 to quantum expectation value $\langle\phi\rangle = \phi_0 + \langle\phi_q\rangle$

Individual amplitudes calculated via gen. functional $\langle n|\phi|0\rangle = \left(\frac{\partial}{\partial z_0}\right)^n (\phi_0 + \langle\phi_q\rangle)\,|_{z_0=0}$

Use Feynman rules of Eucl. Lagrangian and calculate

$$\langle\phi_q(y)\rangle_{1-\mathrm{loop}} = (-3\lambda)\int d^4x\, G(y,x)\,\phi_0(x)\,G(x,x)$$

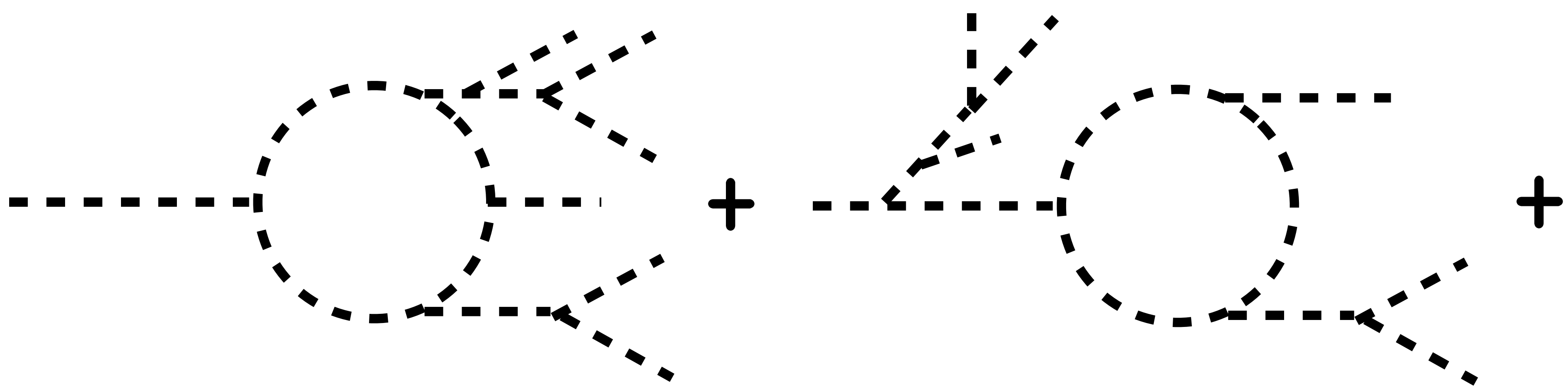


You will find for the combined tree + 1-loop generating functional

[Smith '92]
[Voloshin '92]

$$\phi_{0+1}(t) = \frac{z(t)}{1-(\bar{\lambda}/8\bar{m}^2)z(t)^2}\left(1-\frac{3\lambda}{4}F\frac{(\lambda/8m^2)^2 z(t)^4}{(1-(\lambda/8m^2)z(t)^2)^2}\right)$$

Now follow Brown's program to build



all possible combinations

One obtains for scalar loops

$$A_n = n!\,(2v)^{1-n}\left[1+n(n-1)\,\frac{\sqrt{3}\,\lambda}{8\pi}+O(\lambda^2)\right] \quad \text{for} \quad \lambda n \ll 1$$

and including fermion loops it is argued cancellations can occur [Voloshin '17]

$$A_n \to A_n \times \left[1+(-1)^{2r}\,C(r)\,n^{4r-4}\,\lambda\right] \quad \text{with} \quad r = m_t/\sqrt{2\lambda v^2}$$

(exponentiate for $n\lambda > 1$)? in SM subleading to scalar loops

In non-rel. limit the LO cross section for n-Higgs production scales like:

$$\sigma_n \propto \exp\left[\frac{1}{\lambda} F_{\mathrm{h.g.}}(\lambda n, \varepsilon)\right] \quad \text{with} \quad \frac{1}{\lambda} F_{\mathrm{h.g.}}(\lambda n, \varepsilon) = \frac{\lambda n}{\lambda}\left(f_0(\lambda n) + f(\varepsilon)\right)$$

for a scalar theory with SSB: $f_0(\lambda n) = \log \frac{\lambda n}{4} - 1$ at tree level

[Libanov, Rubakov, Son, Troitsky '94] $f(\varepsilon) \to \frac{3}{2}\left(\log \frac{\varepsilon}{3\pi} + 1\right) - \frac{25}{12}\varepsilon$ for $\varepsilon \ll 1$

However, leading loop contributions can be resummed (only valid when $n\lambda < 1$):

Resummed 1-loop contribution:

$$\mathcal{A}_{1\to n} = \mathcal{A}^{\mathrm{tree}}_{1\to n} \times \exp\left[B\,\lambda n^2 + \mathcal{O}(\lambda n)\right] \quad \text{with} \quad B = \frac{\sqrt{3}}{4\pi}$$

$$f_0(\lambda n) = \underbrace{\log \frac{\lambda n}{4} - 1}_{\text{tree}} + \underbrace{\lambda n \frac{\sqrt{3}}{4\pi}}_{\text{loop}}$$

significant loop enhancement

Higher loops expected to scale $\left(\frac{n\lambda}{4\pi}\right)^{\#\mathrm{Loop}}$

$$f(\varepsilon) \to \underbrace{\frac{3}{2}\left(\log \frac{\varepsilon}{3\pi} + 1\right) - \frac{23}{12}\varepsilon}_{\text{kinematics}} \quad \text{for} \quad \varepsilon \ll 1$$

[Smith '92, Voloshin '92]

[Voloshin '17]

From amplitudes to cross sections

$$\sigma_{n,m} = \int d\Phi_{n,m} \frac{1}{n!\, m!} \left|\mathcal{A}_{h^* \to n\times h + m \times Z_L}\right|^2 \quad \text{x} \quad \text{flux factor}$$

$$\int d\Phi_n = (2\pi)^4 \delta^{(4)}(P_{\rm in} - \sum_{j=1}^{n} p_j) \prod_{j=1}^{n} \int \frac{d^3 p_j}{(2\pi)^3\, 2p_j^0}$$

Bose statistics factors for n identical Higgs and m identical long. Vec.

Integration with $n\varepsilon_h$ fixed $\Phi_n \simeq \frac{1}{\sqrt{n}} \left(\frac{M_h^2}{2}\right)^n \exp\left[\frac{3n}{2}\left(\log\frac{\varepsilon_h}{3\pi} + 1\right) + \frac{n\varepsilon_h}{4} + \mathcal{O}(n\varepsilon_h^2)\right]$

factorial growth (Stirling formula)

$$\sigma_{n,m} \sim \exp\left[2\log(\kappa^m d(n,m)) + n\log\frac{\lambda n}{4} + m\log\frac{\lambda m}{4}\right.$$
$$\left. + \frac{n}{2}\left(3\log\frac{\varepsilon_h}{3\pi} + 1\right) + \frac{m}{2}\left(3\log\frac{\varepsilon_V}{3\pi} + 1\right) - \frac{25}{12} n\,\varepsilon_h - 3.15\, m\,\varepsilon_V + \mathcal{O}(n\varepsilon_h^2 + m\varepsilon_V^2)\right]$$

kinematic (phase space) suppression

For $n\lambda > 1$ loops overpower tree result, how about semi-classical approach?

[Son '95]

- Multiparticle decay rates Γ_n can be calculated using semi-classical method

  → intrinsically non-perturbative method

  → no reference to perturbation theory

- Path-integral calculated in deepest descend method, where

$$\lambda \to 0\,, \quad n \to \infty\,, \quad \text{with} \quad \lambda n = \text{fixed}\,, \quad \varepsilon = \text{fixed}\,.$$

- Semi-classical calculation in regime where $\lambda n = \text{fixed} \ll 1\,, \quad \varepsilon = \text{fixed} \ll 1\,,$

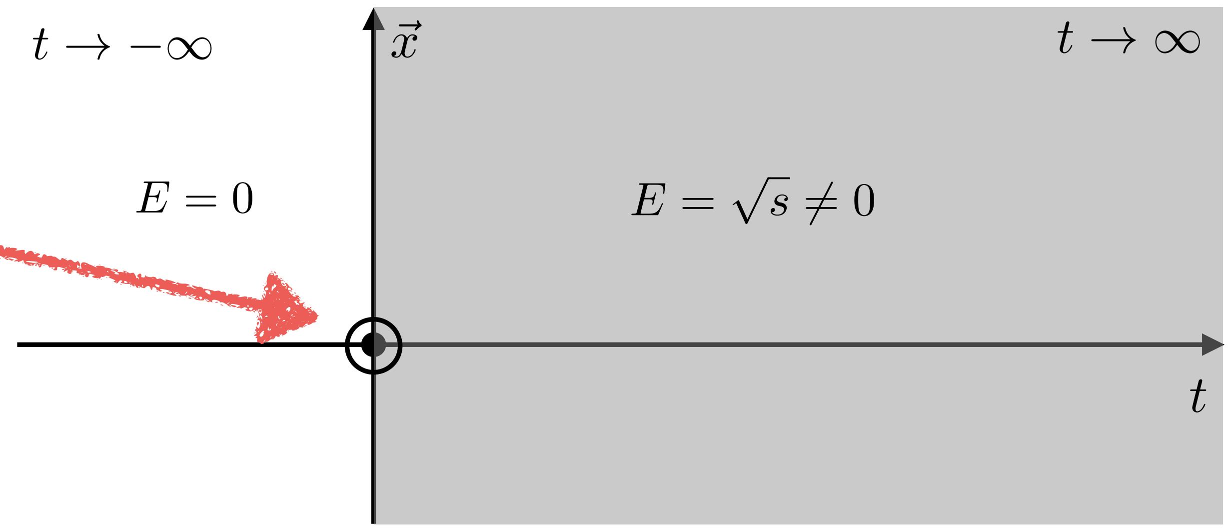
  reproduces tree-level perturbative result for non-relativistic final states

  Remarkably this semi-classical calculation also reproduces the 1-loop resummed calculation in this limit

Just like in the case of Brown's solution for diagrams in perturbation theory, is the self-energy $\hat{\Sigma}(p^2)$ calculated semi-classically

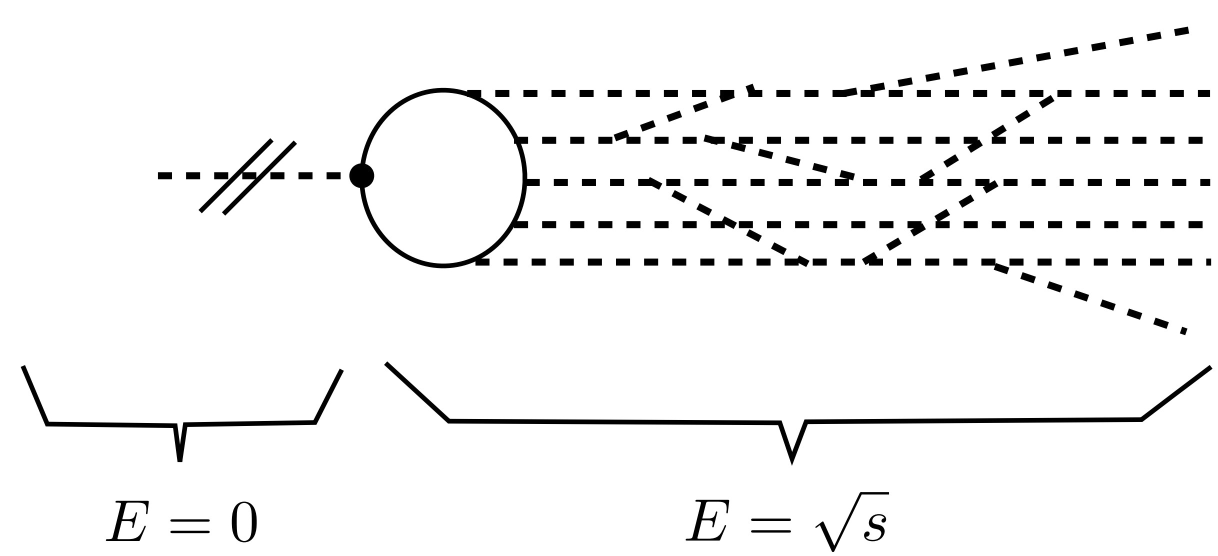
$$\Gamma_n(s) \;\propto\; \mathcal{R}_n^{\rm semicl}(\sqrt{s}) \;=\; \int d\Phi_n(s)\;\langle 0|\mathcal{O}^\dagger(0)\,\mathcal{S}^\dagger|n\rangle_{\rm 1PI}\,\langle n|\mathcal{S}\,\mathcal{O}(0)|0\rangle_{\rm 1PI}$$

configuration with single jump in energy corresponds to 1-PI contribution



Saddle-point solutions considered in semi-classical approach approximate the matrix element

$$\mathcal{M}^\dagger_{1^*\to n} \;=\; {}^{\rm in}\langle X|n\rangle^{\rm out}{}_{\rm 1PI} \;=\; \langle 0|\mathcal{O}^\dagger(0)\,\mathcal{S}^\dagger|n\rangle_{\rm 1PI}$$



Semi-classical calculation for rate R(1->nh, E)

[Son '95]
[Khoze '17]

- Semi-classical calculation is applicable and more relevant for non-perturbative regime of Higgsplosion, where

$$\lambda n = \text{fixed} \gg 1\,, \quad \varepsilon = \text{fixed} \ll 1\,.$$

- This calculation was carried out with result given by [Khoze '17]

$$\mathcal{R}^{\text{semiclassical}}_{\text{1-loop}} = \exp\left[n\left(\log\frac{\lambda n}{4} - 1\right) + 3.02n\sqrt{\frac{\lambda n}{4\pi}} + \frac{3n}{2}\left(1 + \log\frac{\varepsilon}{3\pi}\right) - \frac{25}{12}n\varepsilon\right]$$

higher orders are suppressed by powers of $\mathcal{O}(1/\sqrt{\lambda n})$ and powers of ε

Recovers structure of 1-loop resummed result:

$$\mathcal{R}^{\text{resummed}}_{\text{1-loop}} = \exp\left[n\left(\log\frac{\lambda n}{4} - 1\right) + \sqrt{3}\frac{\lambda n^2}{4\pi} + \frac{3n}{2}\left(1 + \log\frac{\varepsilon}{3\pi}\right) - \frac{25}{12}n\varepsilon\right]$$

Thus we have computed the rate R in the large lambda n limit:

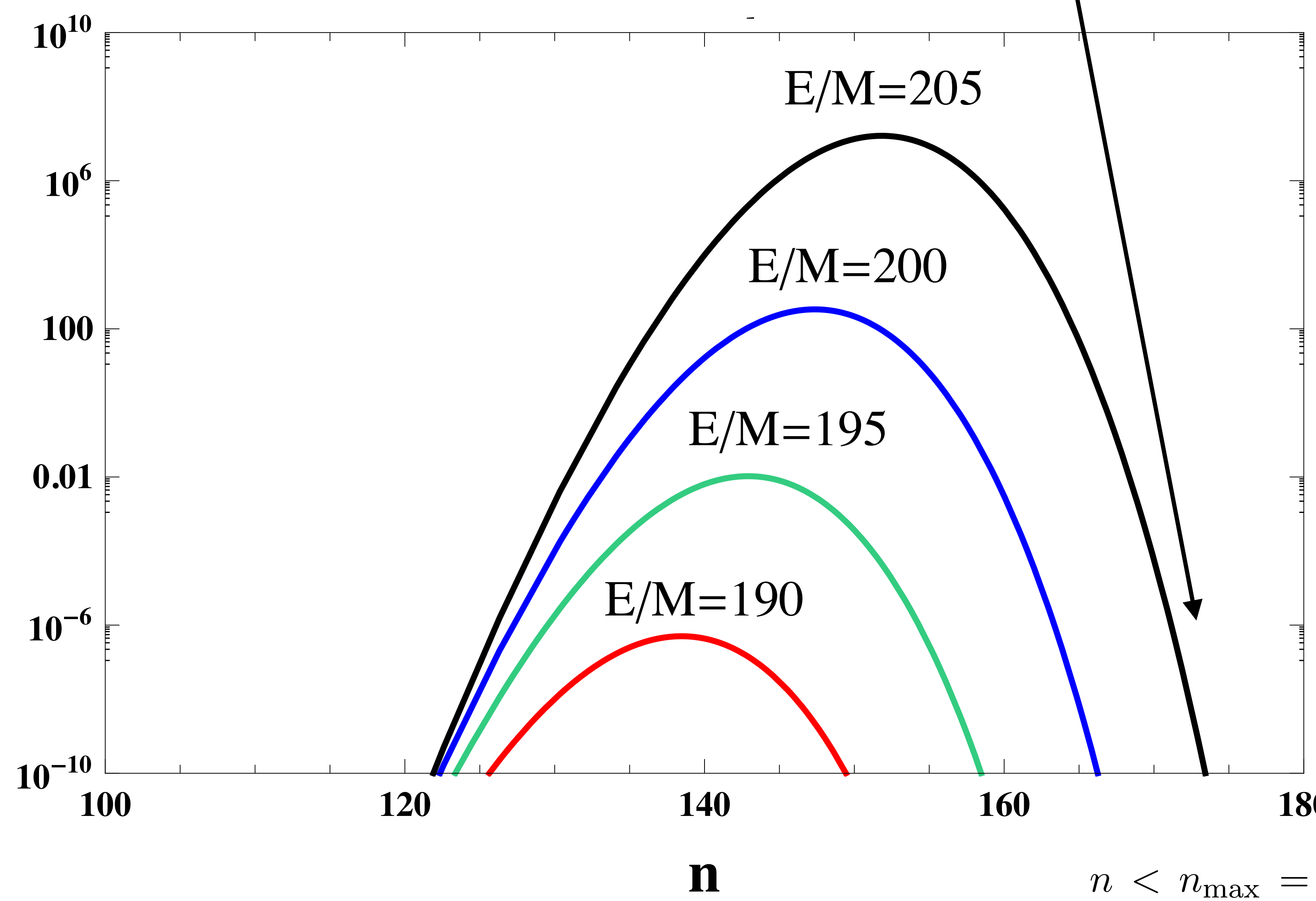
using the semi-classical approach and the thin-wall approximation

Explosive growth of 1->n process $\mathcal{R}_n(s) := \frac{1}{2M_h^2}\int d\Pi_n |\mathcal{M}(1\to n)|^2$ $\quad \varepsilon = \frac{\sqrt{s}-nM_h}{nM_h}$

where $\mathcal{R} = \exp\left[\frac{\lambda n}{\lambda}\left(\log\frac{\lambda n}{4} \boxed{+ 3.02\sqrt{\frac{\lambda n}{4\pi}}} - 1 \boxed{+ \frac{3}{2}\left(\log\frac{\varepsilon}{3\pi}+1\right)} - \frac{25}{12}\varepsilon\right)\right]$

$\lambda n \gg 1 \quad$ small ε $\qquad n \to n_{\max} \Rightarrow \varepsilon \to 0$

- Massive energy dependence
- Very narrow - resonance-like - peak in n



$n < n_{\max} = E/M_h$

Thus we have computed the rate R in the large lambda n limit:

using the semi-classical approach and the thin-wall approximation

Explosive growth of 1->n process $$\mathcal{R}_n(s) := \frac{1}{2M_h^2} \int d\Pi_n |\mathcal{M}(1 \to n)|^2$$

where $$\mathcal{R} = \exp\left[\frac{\lambda n}{\lambda}\left(\log\frac{\lambda n}{4} + \boxed{3.02\sqrt{\frac{\lambda n}{4\pi}}} - 1 + \frac{3}{2}\left(\log\frac{\varepsilon}{3\pi} + 1\right) - \frac{25}{12}\varepsilon\right)\right]$$

energy low

energy beyond threshold

Schwinger-Dyson-propagator and optical theorem

SD propagator, valid in perturbative and non-perturbative QFT

$$\Delta(p) = \int d^4x\, e^{ip\cdot x} \langle 0| T\left(\phi(x)\,\phi(0)\right)|0\rangle = \frac{i}{p^2 - m_0^2 - \Sigma(p^2) + i\epsilon}$$

where $-\,i\,\Sigma(p^2) = \sum -(1\mathrm{PI})-$ and the physical (pole) mass is $m^2 = m_0^2 + \Sigma(m^2)$

with the renormalisation constant $Z_\phi = \left(1 - \left.\frac{d\Sigma}{dp^2}\right|_{p^2=m^2}\right)^{-1}$ we define the renorm. quantities

$$\begin{aligned} \Delta_R(p) &= Z_\phi^{(-1)}\,\Delta(p)\,, \\ \Sigma_R(p) &= Z_\phi\left(\Sigma(p^2) - \Sigma(m^2) - \Sigma'(m^2)(p^2 - m^2)\right) \end{aligned}$$

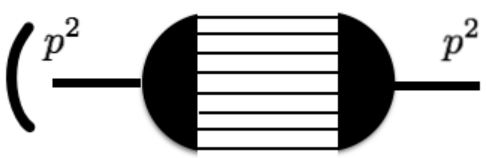
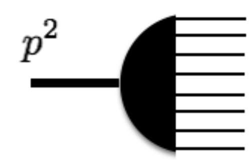
$\rightarrow$ renormalised propagator $\Delta_R(p) = \dfrac{i}{p^2 - m^2 - \Sigma_R(p^2) + i\epsilon}$

Schwinger-Dyson-propagator and optical theorem

[Khoze, MS '17]

The optical theorem now relates the 1* -> nh amplitudes with the imaginary part of the self-energy (valid to all orders)

$$-\,\mathrm{Im}\,\Sigma_R(p^2) \;=\; m\,\Gamma(p^2)$$

- Im () = m 

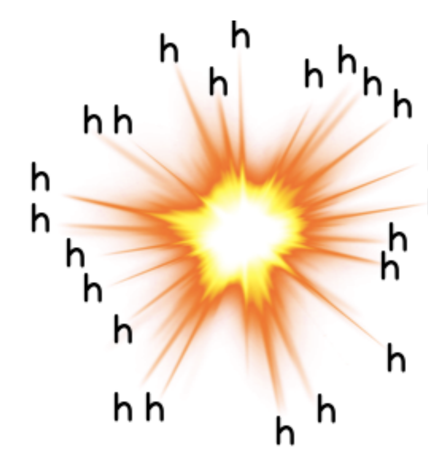
where $\Gamma(s) \;=\; \sum_{n=2}^{\infty} \Gamma_n(s)$ and $\Gamma_n(s) \;=\; \frac{1}{2m}\int \frac{d\Phi_n}{n!}\,|\mathcal{M}(1\to n)|^2$

and thus

$$\Delta_R(p) \;=\; \frac{i}{p^2 - m^2 \;-\; \mathrm{Re}\,\Sigma_R(p^2) \;+\; im\Gamma(p^2) \;+ i\epsilon}$$

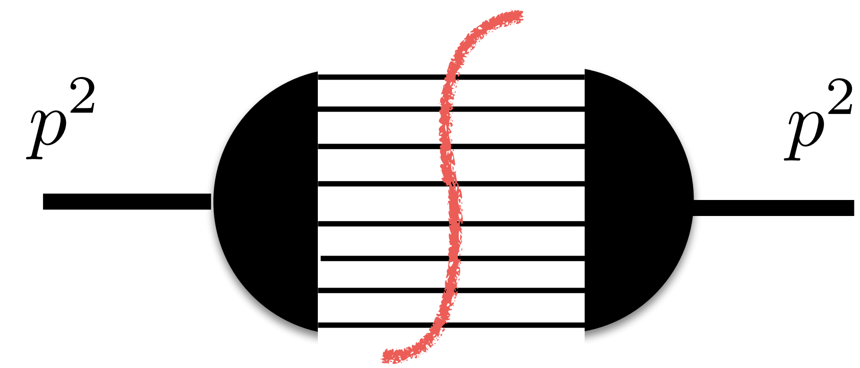
No information as perturbation theory breaks down for many loops, but no physical reason to explode or cancel imaginary part

Higgsplodes

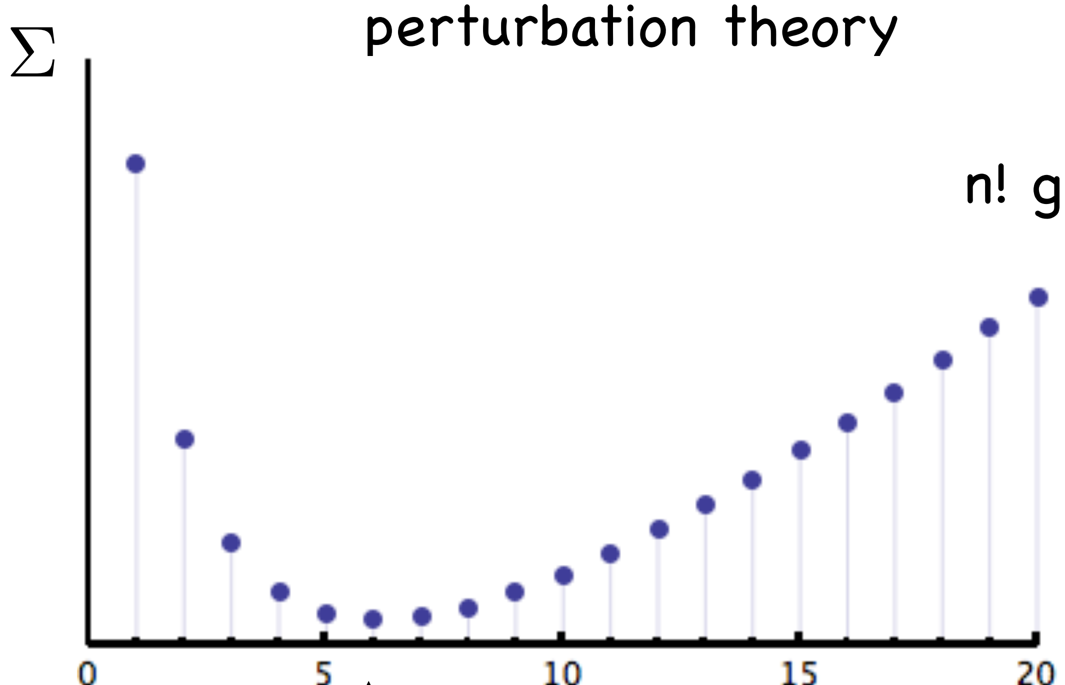


"It is just like asymptotic perturbative series!
We always expected it to break down!"

Except, its not…



Asymptotic behaviour of large order in perturbation theory



n! growth

order of pert. series

divergent tail

stop here

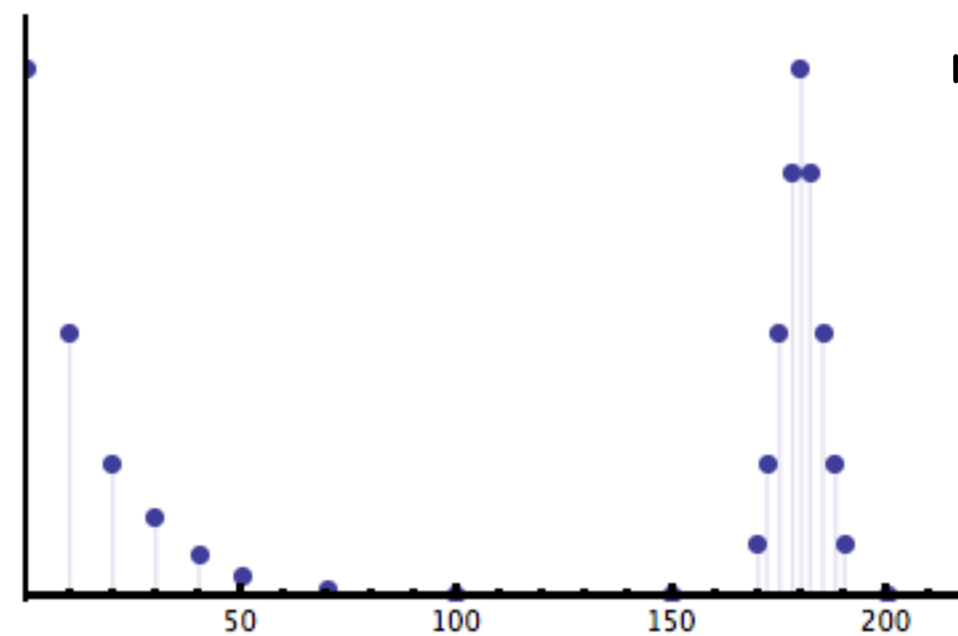
$$\Sigma = \sum_{n=1}^{\infty} \Sigma_n \to \infty$$

[Dyson '52]

e.g. [Broadhurst, Kreimer '99]

Higgsplosion

$\Gamma(p^2) \sim \mathrm{Im}\ \Sigma(p^2)$



n=number of cuts of internal propagators

$$n_{\max} = \frac{\sqrt{p^2}}{M}$$

$$\mathrm{Im}\ \Sigma(p^2) \simeq \sum_{n=1}^{n_{\max}} \Gamma_n = \text{finite sum}$$

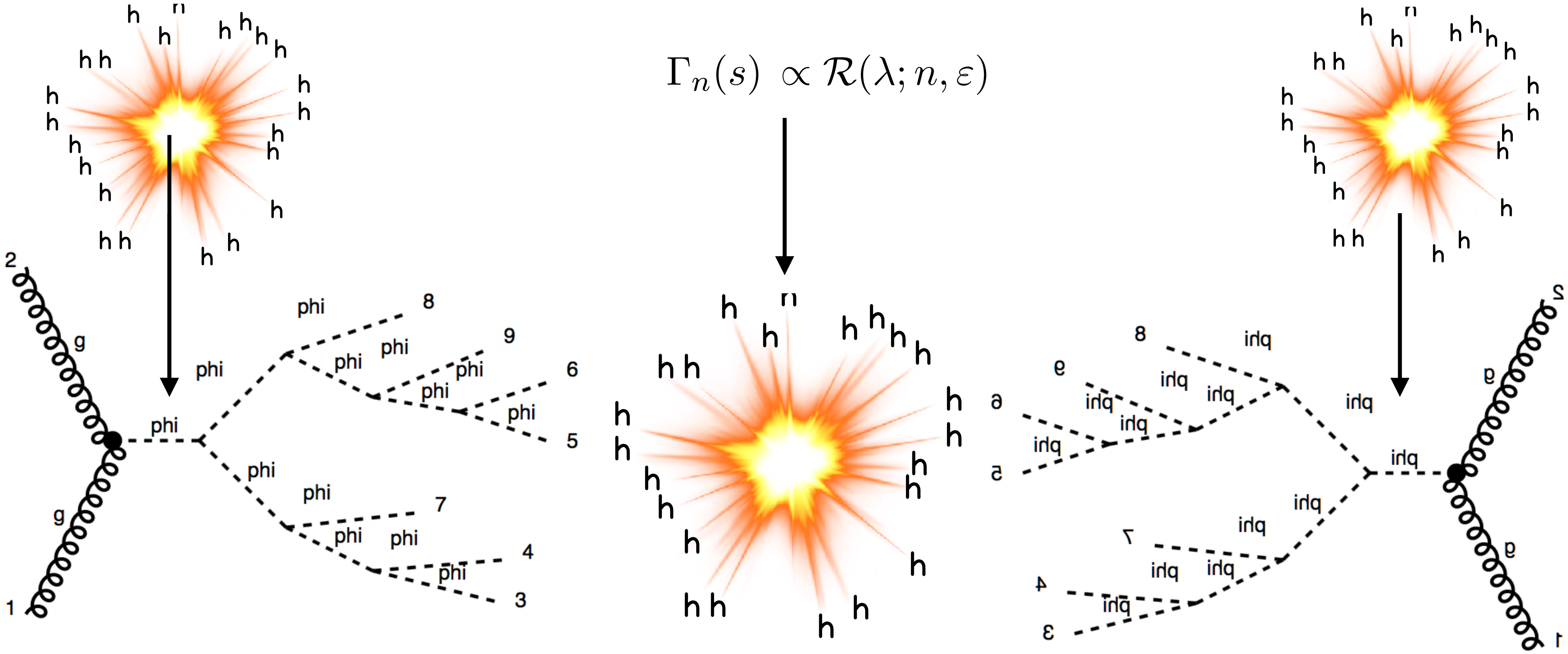
Not the same types of beasts

Higgspersion

[Khoze, MS '17]

Previous calculations neglected 'width'/self-energy contribution to scalar propagator

$$\mathcal{M}_{gg\to h^*} \times \frac{i}{p^2 - m_h^2 - Re\tilde{\Sigma}(p^2) + i m_h \Gamma(p^2)} \times \mathcal{M}_{h^*\to n\times h}$$



$$\sigma^{\Delta}_{gg\to n\times h} \sim y_t^2 \frac{m_t^2}{m_h} \log^4\left(\frac{m_t}{\sqrt{s}}\right) \times \frac{1}{(s - Re\Sigma(s))^2 + m_h^2 \Gamma^2(s)} \times \Gamma_n(s)$$

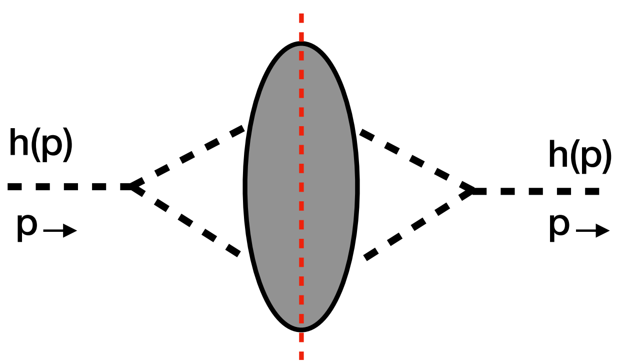
-> no violation of perturbative unitarity for large multiplicities

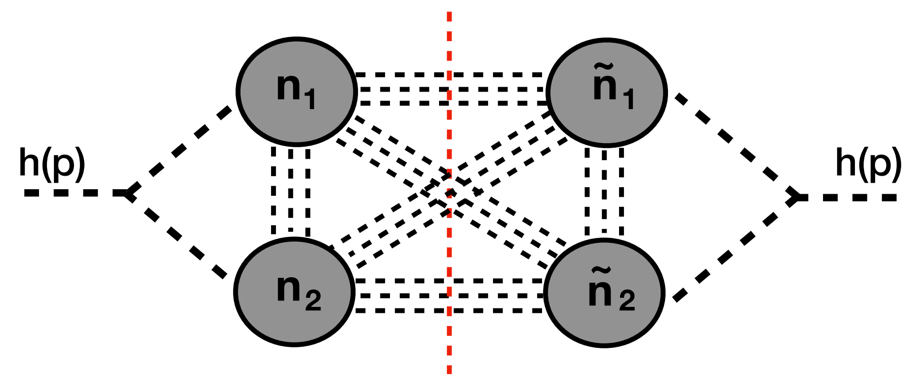
Higgspersion in loops

Continuous resummation of the SD propagator does not shut down imaginary part. You need to consider the self-energy as one object.

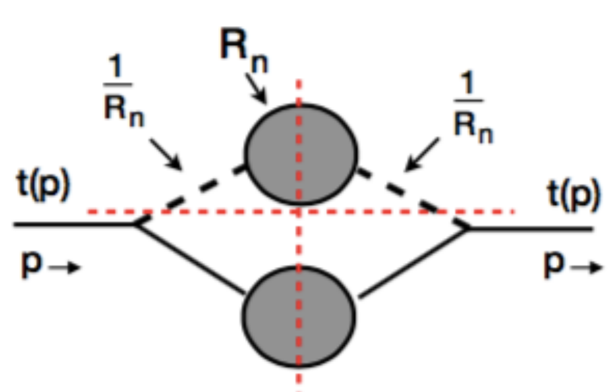
$$\mathrm{Im}\,\Sigma_n \sim \frac{1}{n!}\,(\mathcal{A}_n)^2 \sim \begin{cases} \frac{1}{n!} \times n! \times n! \;\sim n! & : \;\text{all terms included} \\ \frac{1}{n!} \times n! \;\sim 1 & : \;\text{no interference terms}\,. \end{cases}$$

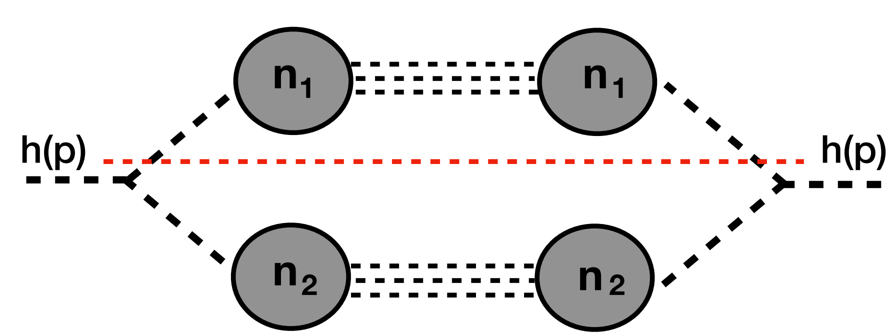
dominant contributions:





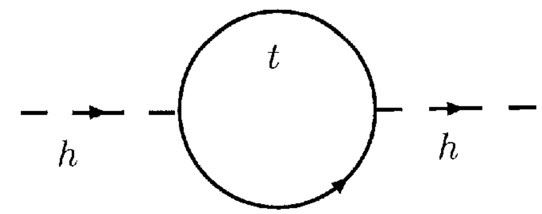
subleading contributions:

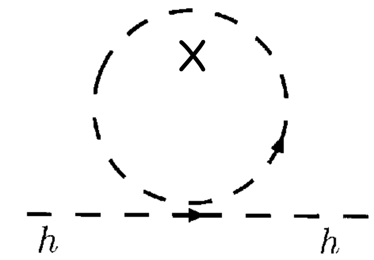




Higgsploding the Hierarchy Problem [Khoze, MS '17]

$$\Delta M_h^2 \sim \lambda_P \int \frac{d^4p}{16\pi^4} \frac{1}{M_X^2 - p^2 + i\,\mathrm{Im}\,\Sigma_X(p^2)}$$





$$= \lambda_P \int \frac{d^4p}{16\pi^4} \left(\frac{M_X^2 - p^2}{(M_X^2 - p^2)^2 + (\mathrm{Im}\,\Sigma_X(p^2))^2} - \frac{i\,\mathrm{Im}\,\Sigma_X(p^2)}{(M_X^2 - p^2)^2 + (\mathrm{Im}\,\Sigma_X(p^2))^2} \right)$$

Due to Higgsplosion the multi-particle contribution to the width of X explode at $p^2 = s_\star$ where $\sqrt{s_\star} \simeq \mathcal{O}(25)\mathrm{TeV}$

→ It provides a sharp UV cut-off in the integral, possibly at $s_\star \ll M_X^2$

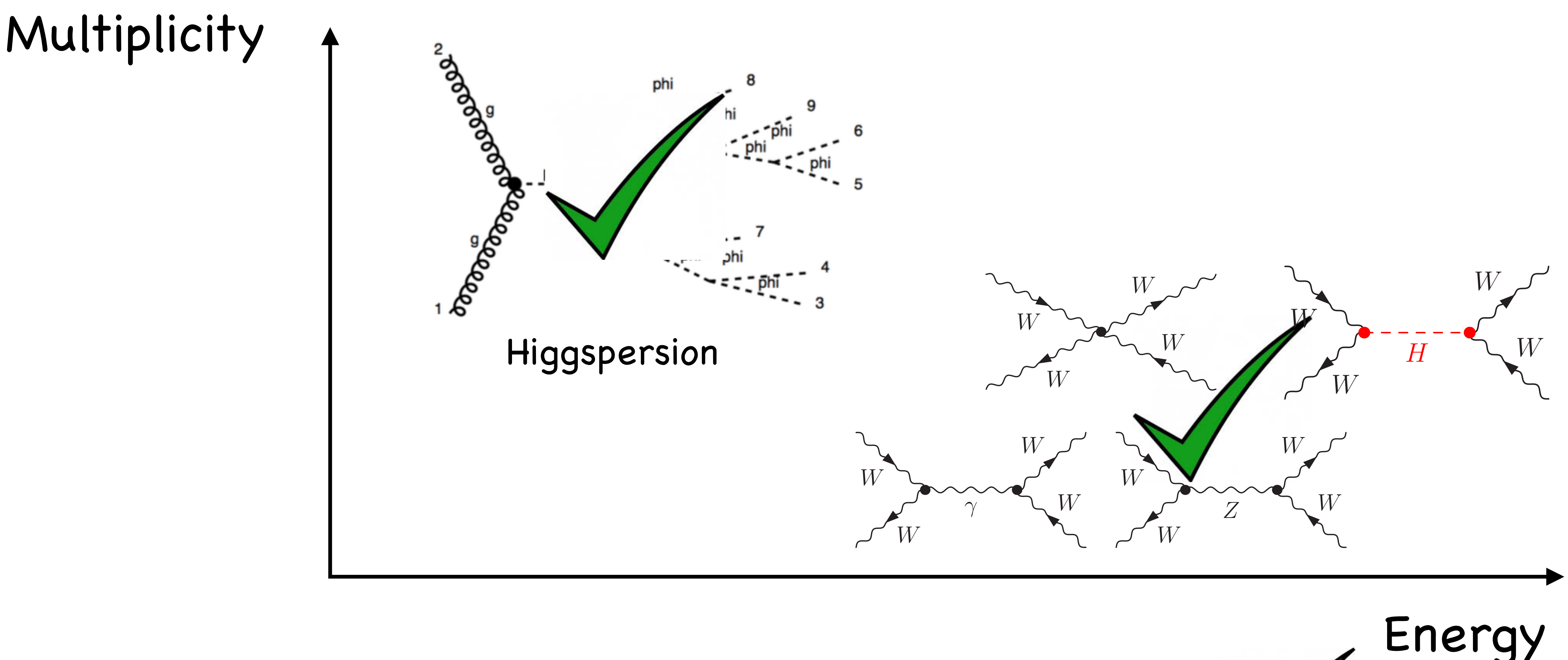
Hence, the contribution to the Higgs mass amounts to

$$\Delta M_h^2 \propto \lambda_P \frac{s_\star}{M_X^2} s_\star \ll \lambda_P M_X^2$$

and thus mends the Hierarchy problem by $\left(\frac{\sqrt{s_\star}}{M_X}\right)^4 \simeq \left(\frac{25\,\mathrm{TeV}}{M_X}\right)^4$

If Higgsplosion is not a mathematical artefact but realised in nature:

Situation at tree-level



\+ Hierarchy problem (Loop level)

Higgsplosion

SM heals itself, retains self-consistency to very high energies and multiplicities

Higgsplosion ⟷ constructive interference between amplitudes for h*-> nh elementary scalars in a spontaneously broken QFT

[Khoze, MS '17]

Why not observed somewhere else before?

Higgs lacks symmetry to prevent Higgsplosion:

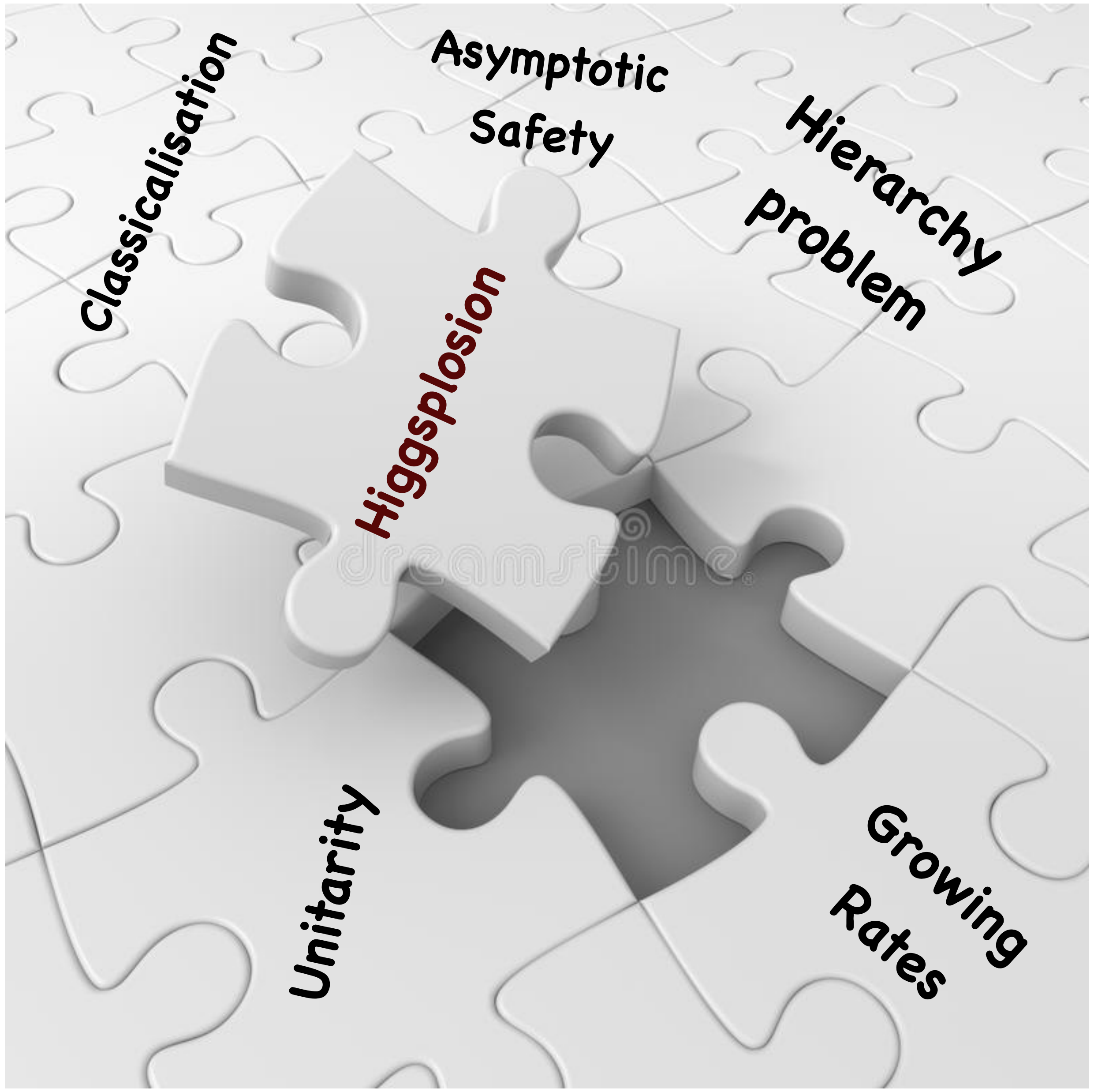
- Gauge fields (gauge symmetry)
  see [Parke, Taylor '86]
- Fermions (Pauli principle)   zero at threshold

Quantum Mechanics:

- Energy levels not equidistantly spaced

Integrable systems in 1+1 and 2+1 dim:

- Scalar loop integrals near mass threshold IR divergent   [Libanov, Rubakov, Son, Troitski '94]



Might need spontaneously broken scalar QFT in at least 3+1 dim

Consequences of Higgsplosion

[Khoze, MS '17]

- SM has new physical scale

(close analogy to Sphaleron)

$$E_* = C\,\frac{m_h}{\lambda} \quad \text{with} \quad C = \text{const.} \qquad\qquad M_{\rm sph} = \text{const}\,\frac{m_W}{\alpha_w}$$

Scaling behaviour of propagator:

$$\Delta(x) := \langle 0|T(\phi(x)\,\phi(0))|0\rangle \sim \begin{cases} m^2\,e^{-m|x|} & : \text{ for } |x| \gg 1/m \\ 1/|x|^2 & : \text{ for } 1/E_* \ll |x| \ll 1/m \\ E_*^2 & : \text{ for } |x| \lesssim 1/E_* \end{cases},$$

for $|x| \lesssim 1/E_*$ one enters the Higgsplosion regime

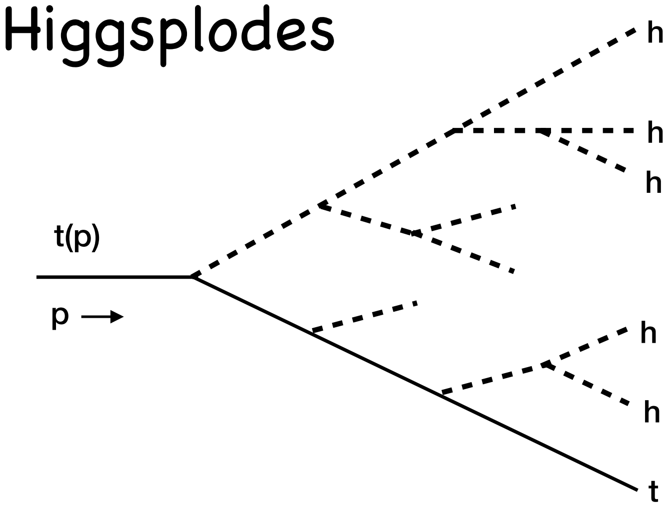
Effect calculable on the lattice?

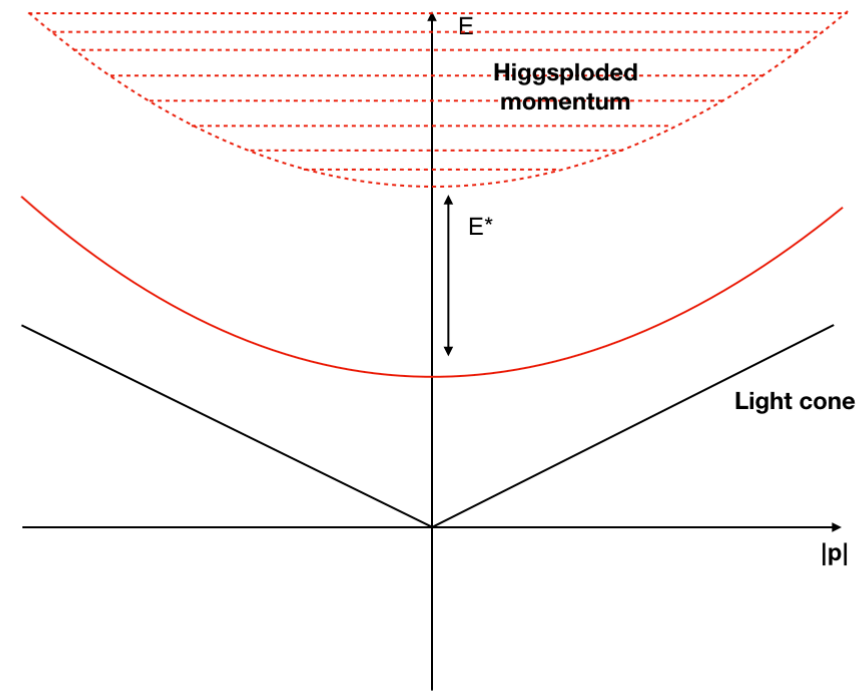
Consequences of Higgsplosion

[Khoze, MS '17]

- All particles Higgsplode if **virtual** enough

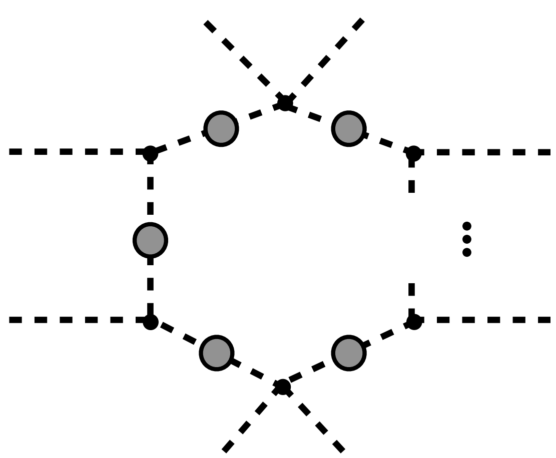
  e.g. top quark Higgsplodes





- As all virtual particles Higgsplode, all virtual corrections are regulated

  In full analogy to [Polchinski '84]



Consequences of Higgsplosion

- As all loop-diagrams are regulated, i.e. quantum fluctuations are exponentially suppressed, the Standard Model develops an asymptotic fix point.

  → Classical/Deterministic theory

  → From high scale, quantum fluctuations are emergent phenomenon

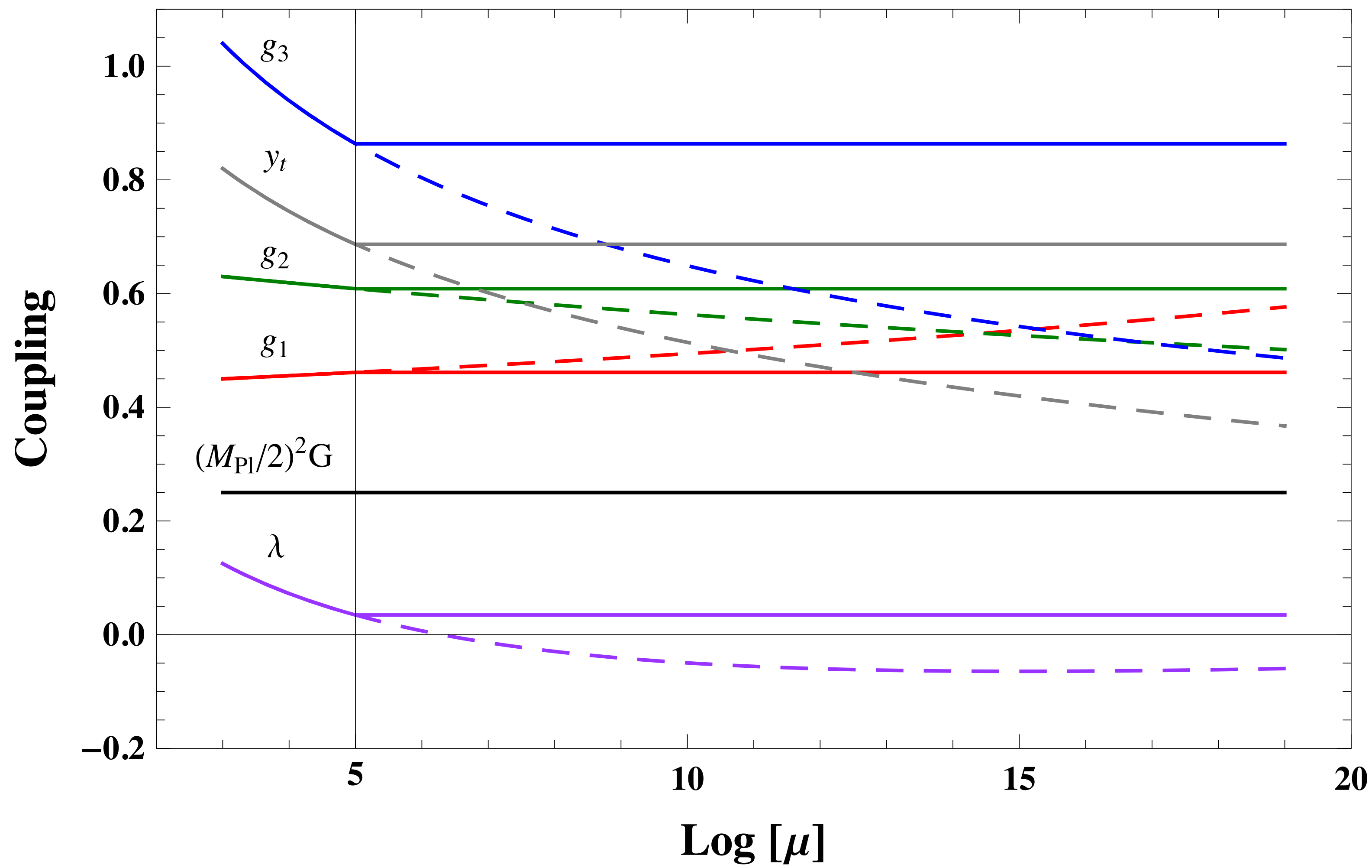
- SM is embedded into asymptotically safe theory

  → Graviton Higgsplodes as well, as do all quantum corrections

  → Allows to combine QFT and Gravity

Consequences of Higgsplosion

Running of couplings in presence of Higgsplosion



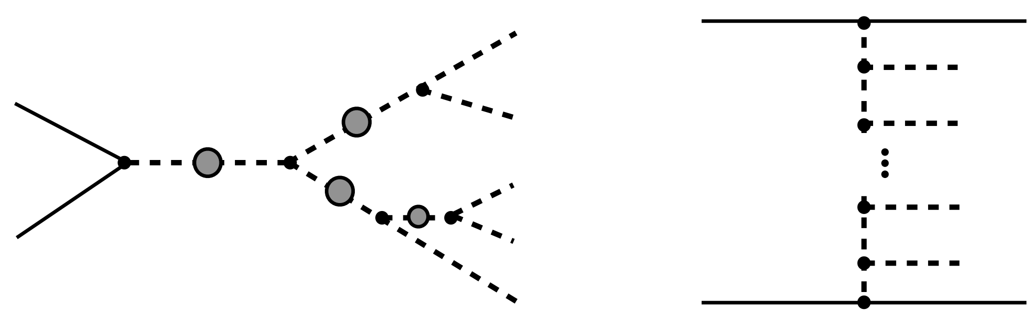
→ Higgs self-coupling doesnt turn negative

→ Electroweak potential remains stable

→ No Landau poles for U(1) and Yukawas

Consequences of Higgsplosion

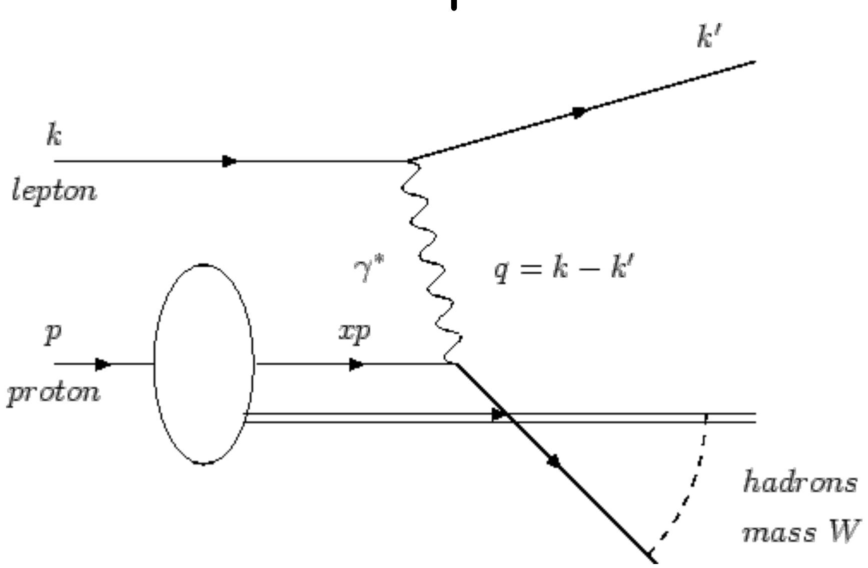
- High-energy scatterings are significantly modified, i.e. virtual s-channel particles are Higgspersed



At high energies only ladder diagrams important

In analogy to Reggeon picture

example DIS



To probe smaller and smaller structure the photon needs to be more and more virtual

Higgsplosion sets cut-off

theory with 'minimal-length'

dynamical mechanism for classicalization

Questions on implications:

[Khoze, MS '17]

Is Inflation excluded/affected by Higgsplosion?

Not necessarily... for example singlet field S non-minimally coupled to gravity

Take Lagrangian in Jordan frame

$$\mathcal{L} = \sqrt{-g}\left[-\frac{M_{Pl} + \xi_s S^2}{2} R + \partial_\mu H^\dagger \partial^\mu H + (\partial_\mu S)^2 - V(H,S)\right]$$

the scalar potential is $V(H,S) = -\mu_h H^\dagger H + \lambda_h (H^\dagger H)^2 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\lambda_{Sh} H^\dagger H S^2$

During Inflation Higgs mass in Inflaton background large $M_h \simeq \sqrt{\frac{\lambda_{Sh}}{2}} S(x) \simeq \frac{M_{Pl}}{\sqrt{\xi_s}}$

→ No phase space for S to Higgsplode

→ Picture changes fundamentally during reheating

Questions on implications:

Is the existence of Axions (light scalars) irreconcilable with Higgsplosion?

QCD-Axion provides predictive framework to address this question

$$m_a \simeq \frac{5.7 \cdot 10^{15}\mathrm{eV}}{f_a} \qquad \text{and} \qquad \lambda_a \equiv \left.\frac{\partial^4 V(a)}{\partial a^4}\right|_{a=0} \simeq -0.346\frac{m_a^2}{f_a^2}$$

→ Axionplosion scale $E_*^{\mathrm{Axion}} \simeq 60\frac{f_a^2}{m_a}$ → limit $f_a \gtrsim 2.1\ \mathrm{GeV}$

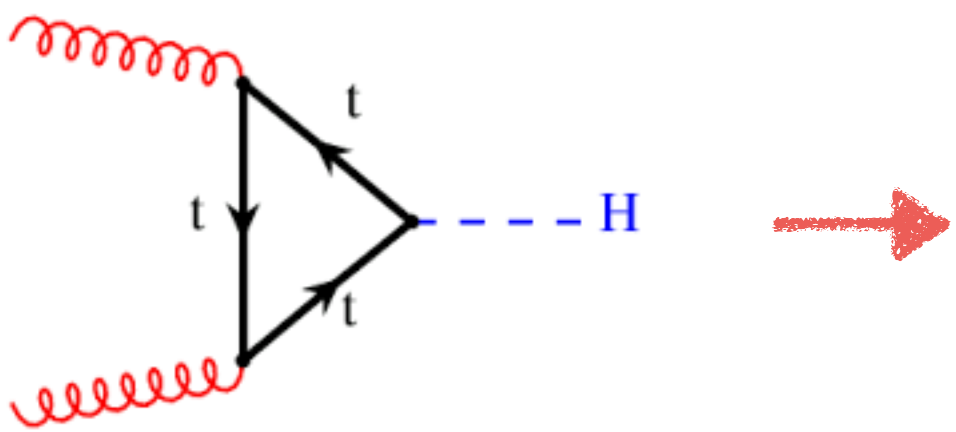
current experimental limit $f_a \gtrsim 10^8 - 10^{17}\ \mathrm{GeV}$

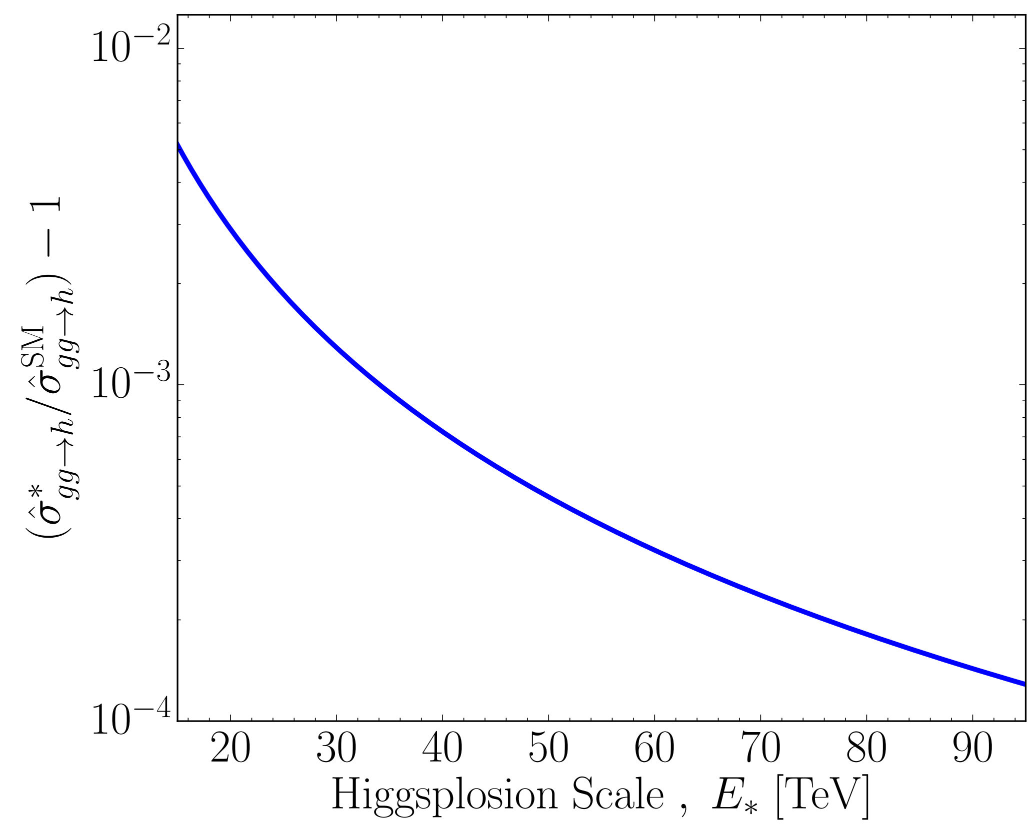
→ If scalars are very weakly coupled they will not trigger X-plosion

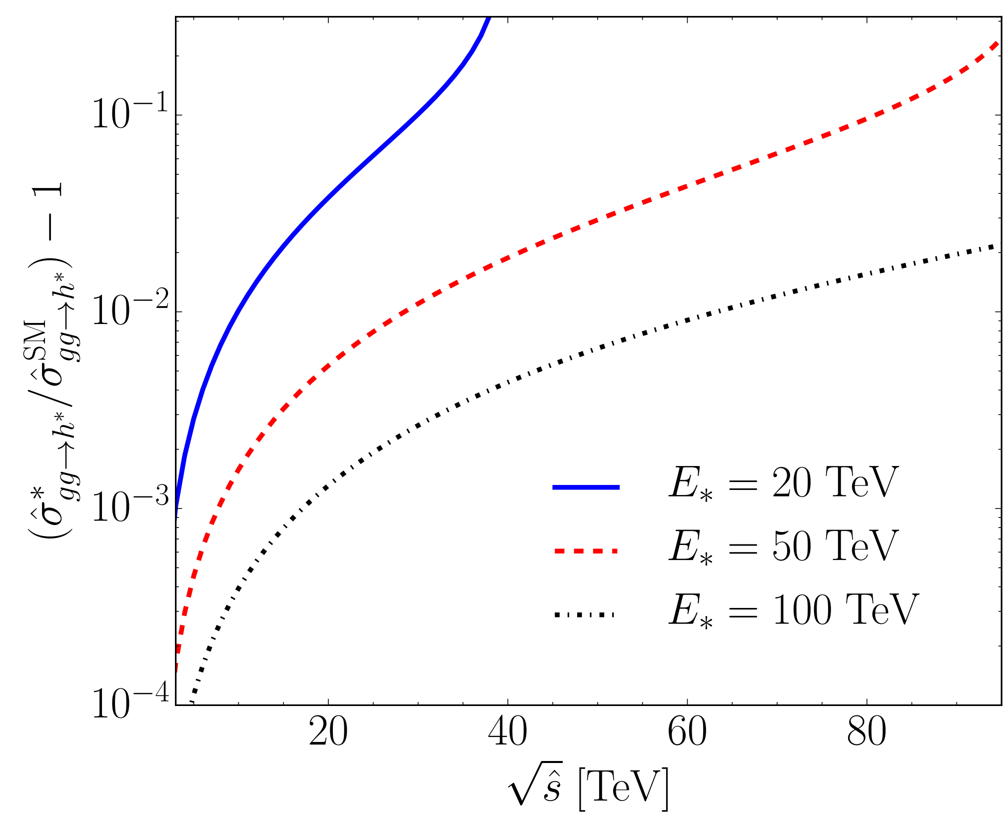
Can we discover Higgsplosion?

Modification in loop corrections:

Gluon fusion







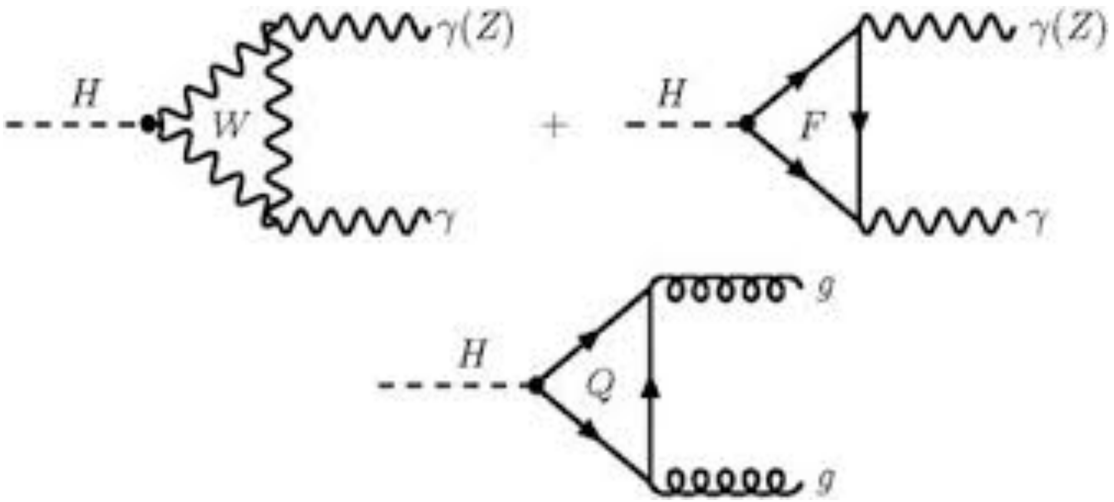
Gluon-fusion for different shat or mH

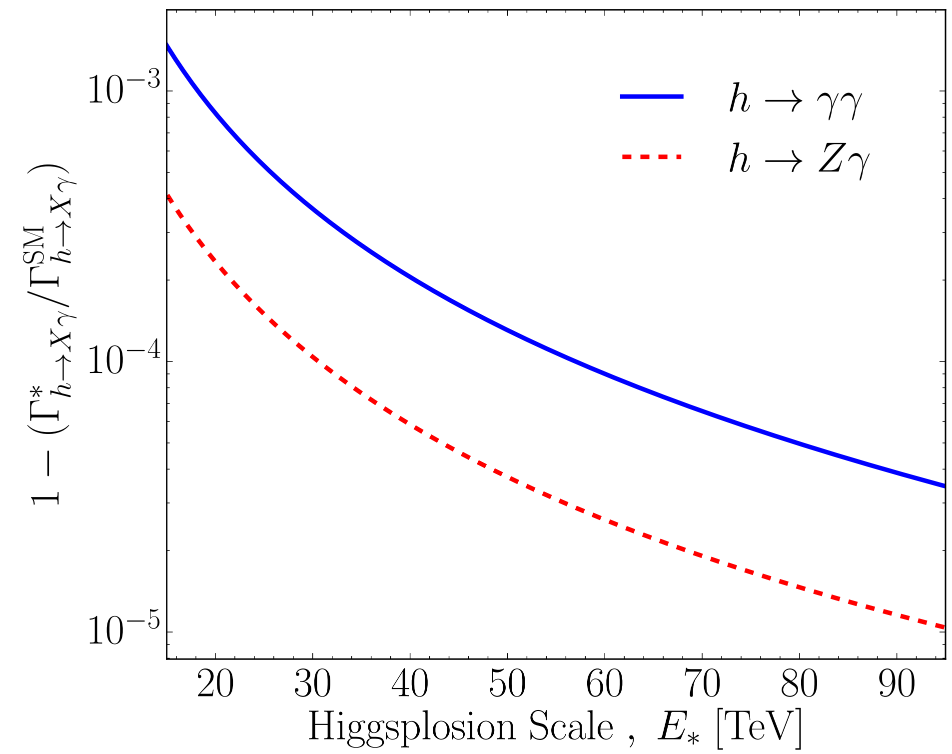
O(1) effects when $\sqrt{\hat{s}} \sim 2E_*$

[Khoze, Reiness, MS, Waite '17]

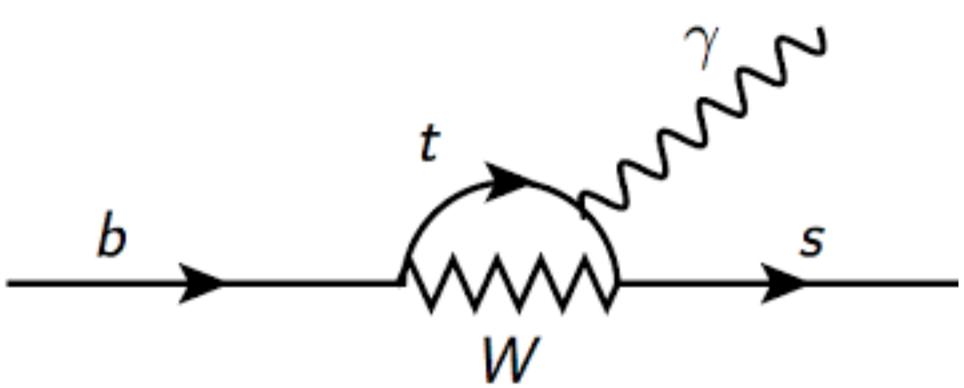
Can we discover Higgsplosion?

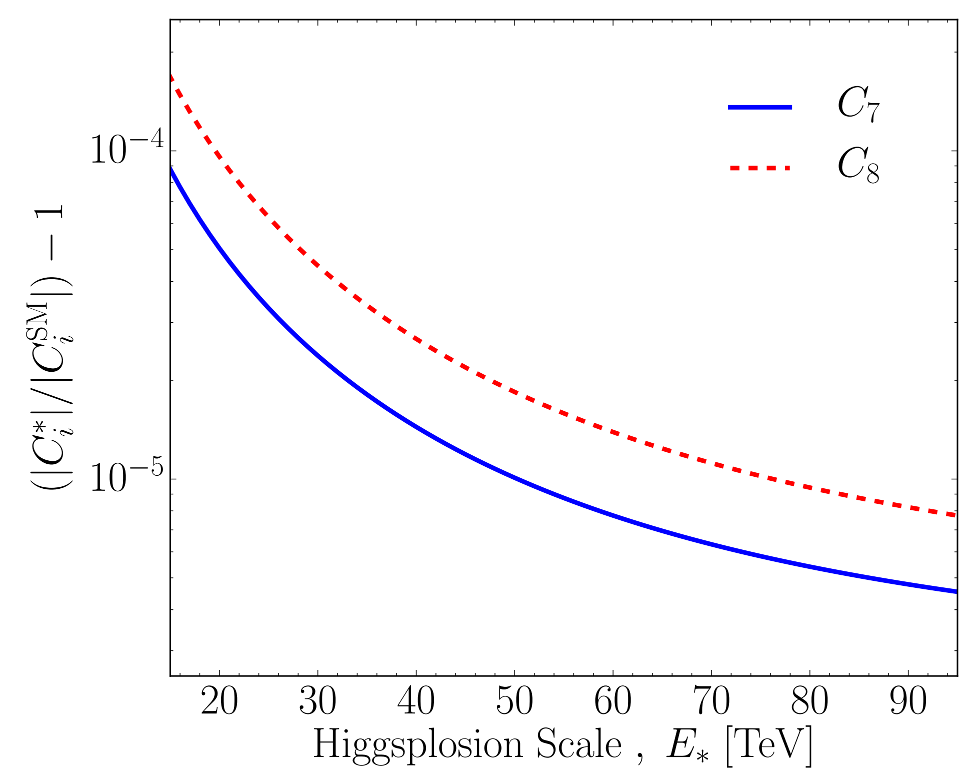
Loop-induced Higgs decays





b -> s gamma





Can we discover Higgsplosion?

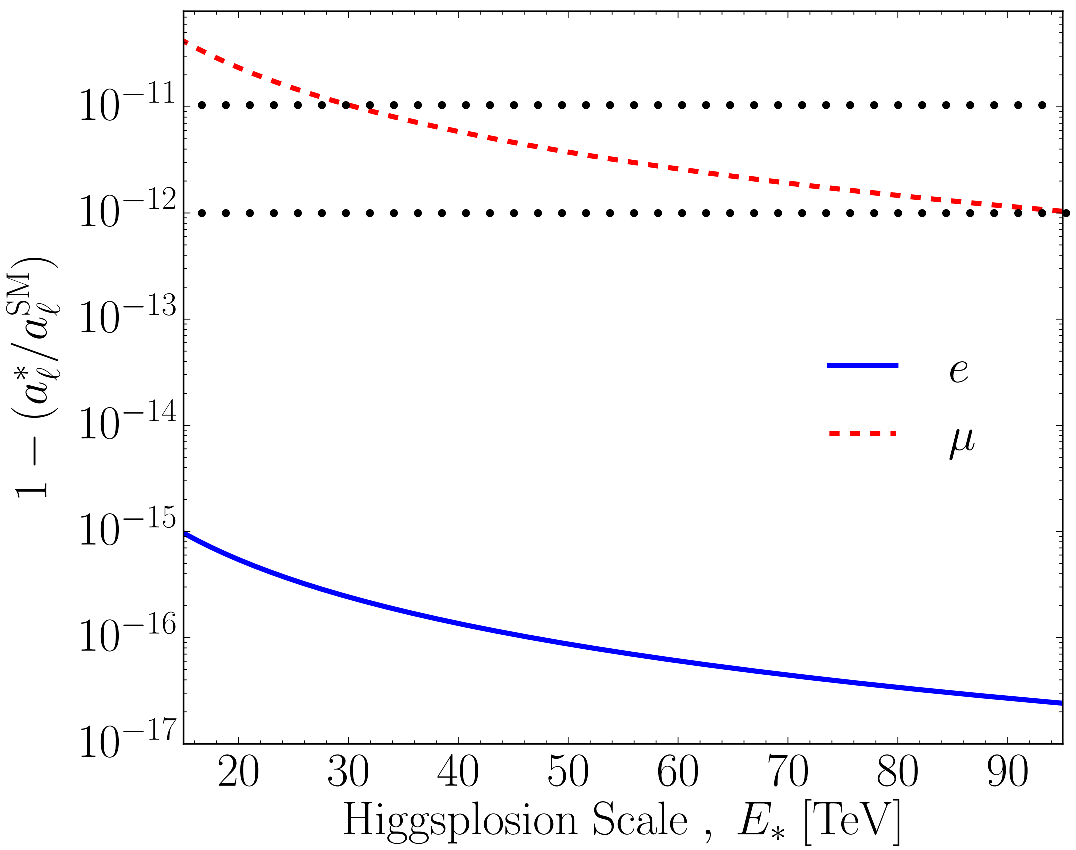
Anomalous magnetic moment of the muon and electron

$$\Gamma^\mu = F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m}$$

anomalous magnetic moment given by $F_2(0)$

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{theory}} \simeq 2.90 \cdot 10^{-9}$$

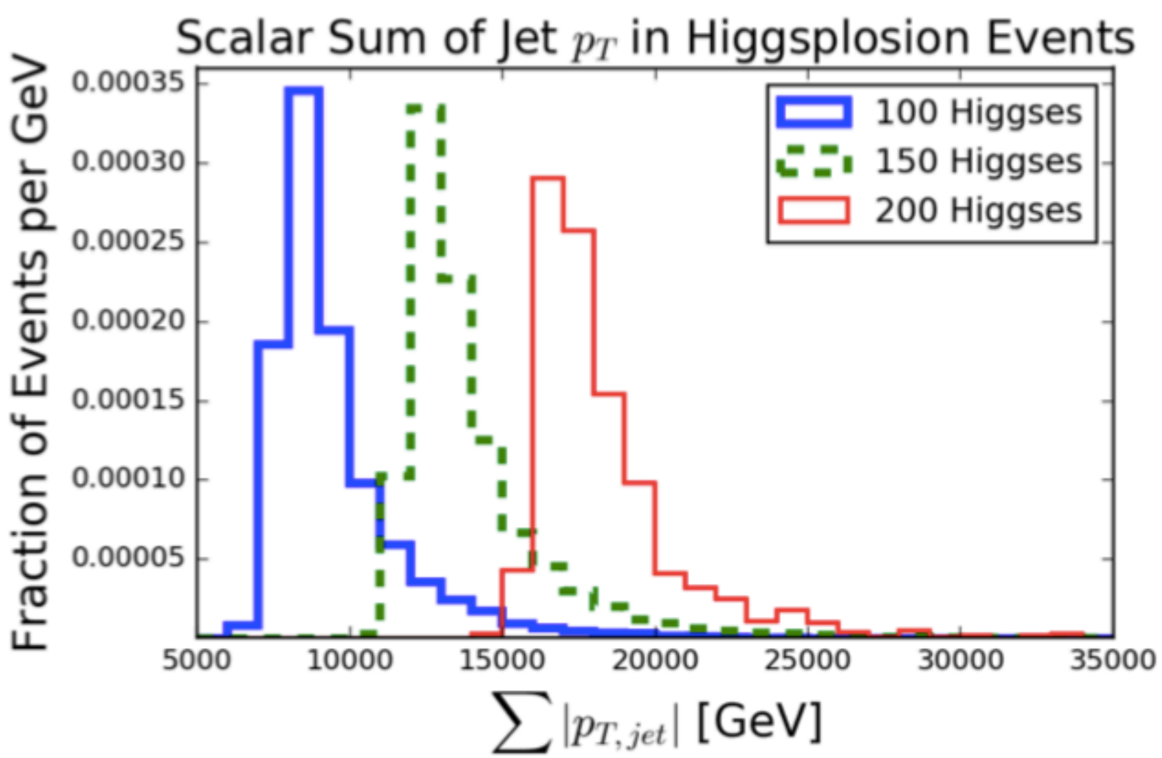
$$a_e^{\text{exp}} = 11596521807.3(2.8) \cdot 10^{-13}$$

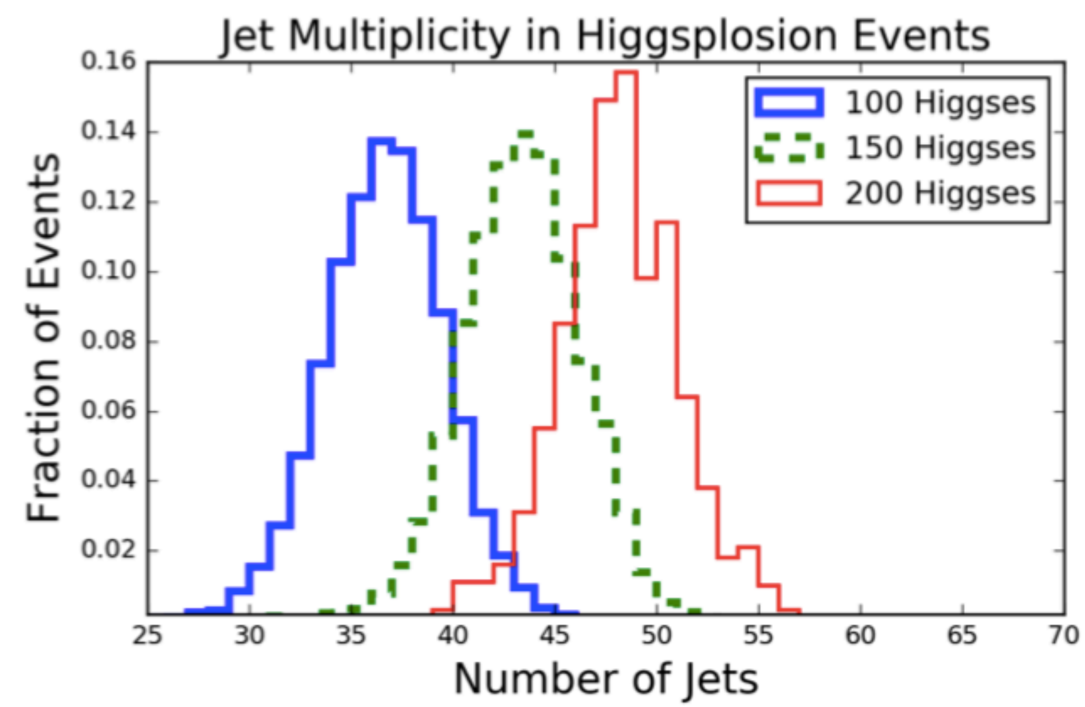


Problem: all corrections scale like $\hat{s}/E_*^2$

Prospects of direct observation of Higgslposion

Collider observables for Higgsplosion production

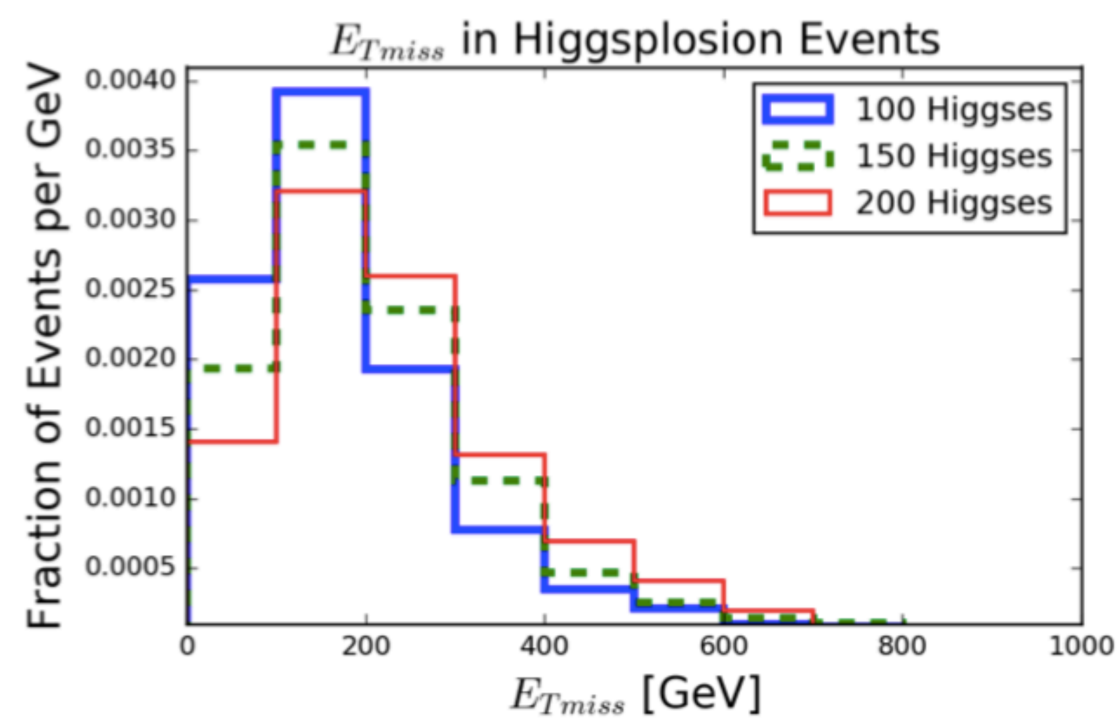




see [Gainer '17]

If Higgsplosion is realised, the detector lights up like a Christmas tree

-> discovery with few events possible



Prospects of direct observation of Higgsplosion

Partonic gluon-fusion cross section:

$$\sigma^{\Delta}_{gg\to n\times h} \sim y_t^2 m_t^2 \log^4\left(\frac{m_t}{\sqrt{s}}\right) \times \frac{\mathcal{R}_n(s)}{\left(1-\frac{m_h^2}{s}\right)^2 + \mathcal{R}^2(s)}$$

$$\sigma_{gg\to n\times h} \sim \begin{cases} \mathcal{R} & : \text{ for } \sqrt{s} \le E_* \text{ where } \mathcal{R} \lesssim 1 \\ 1/\mathcal{R} \to 0 & : \text{ for } \sqrt{s} \ge E_* \text{ where } \mathcal{R} \gg 1 \end{cases}$$

asymptotic large energy behaviour

there is smooth-spot for energy into hard process, or subsequent emissions of jets

$$\sigma_{gg\to n\times h} \sim \begin{cases} \mathcal{R} & : \text{ for } \sqrt{s} \ll E_* \text{ where } \mathcal{R} \ll 1 \\ 1 & : \text{ for } \sqrt{s} \ge E_* \text{ where } \mathcal{R} \sim 1 \end{cases}$$

maximum probability for hard process

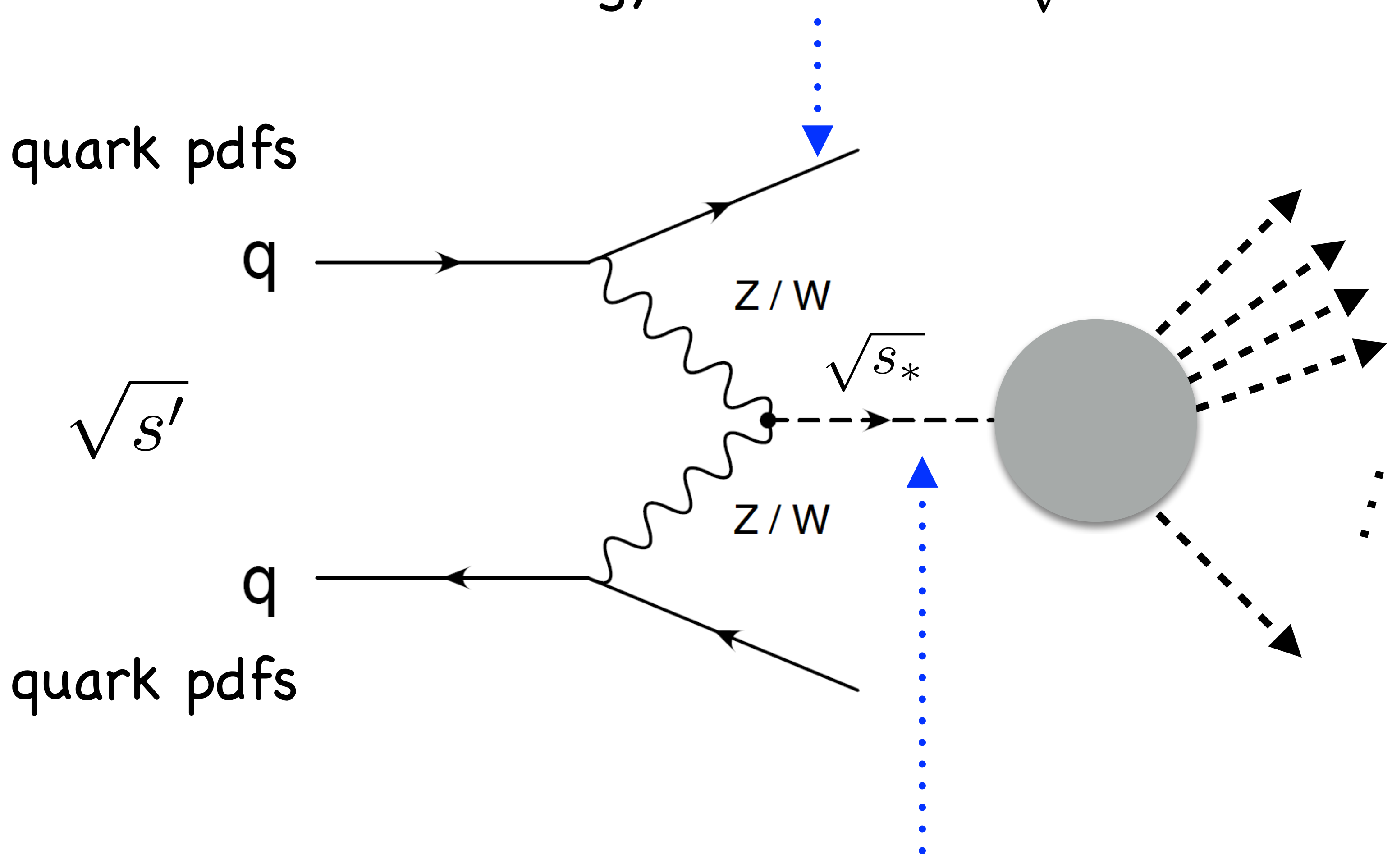
Partonic process want to stay 'on resonance', where $\sum_n \mathcal{R}_n(s) = \mathcal{R}(s) \sim 1$

→ adjust x in hadron collision or emit excessive energy via jets

Prospects of direct observation of Higgslposion

Vector boson fusion at high-energy pp colliders (FCC)

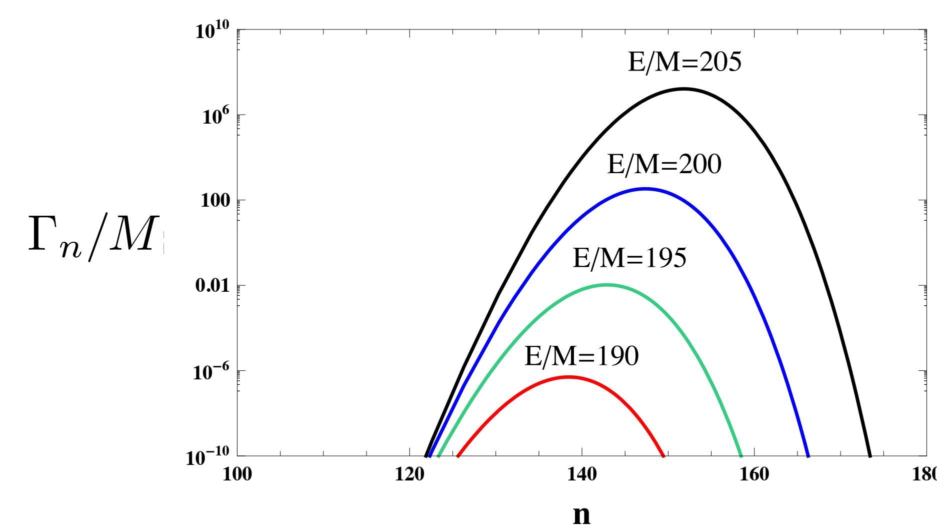
energy excess over $\sqrt{s_*}$ carried away by jets



$$\frac{i}{s_* - m_h^2 - Re\tilde{\Sigma}(s_*) + i m_h \Gamma(s_*)}$$

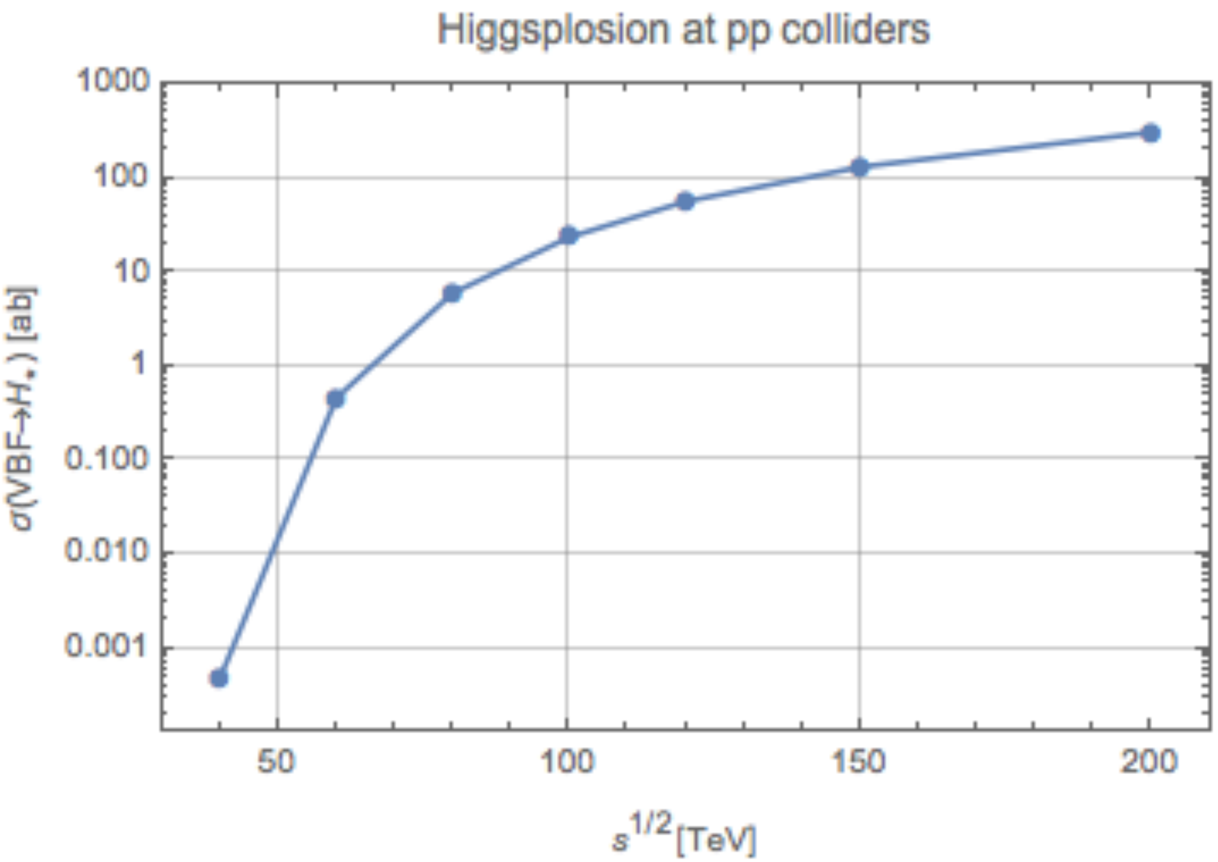
n non-relativistic Higgses

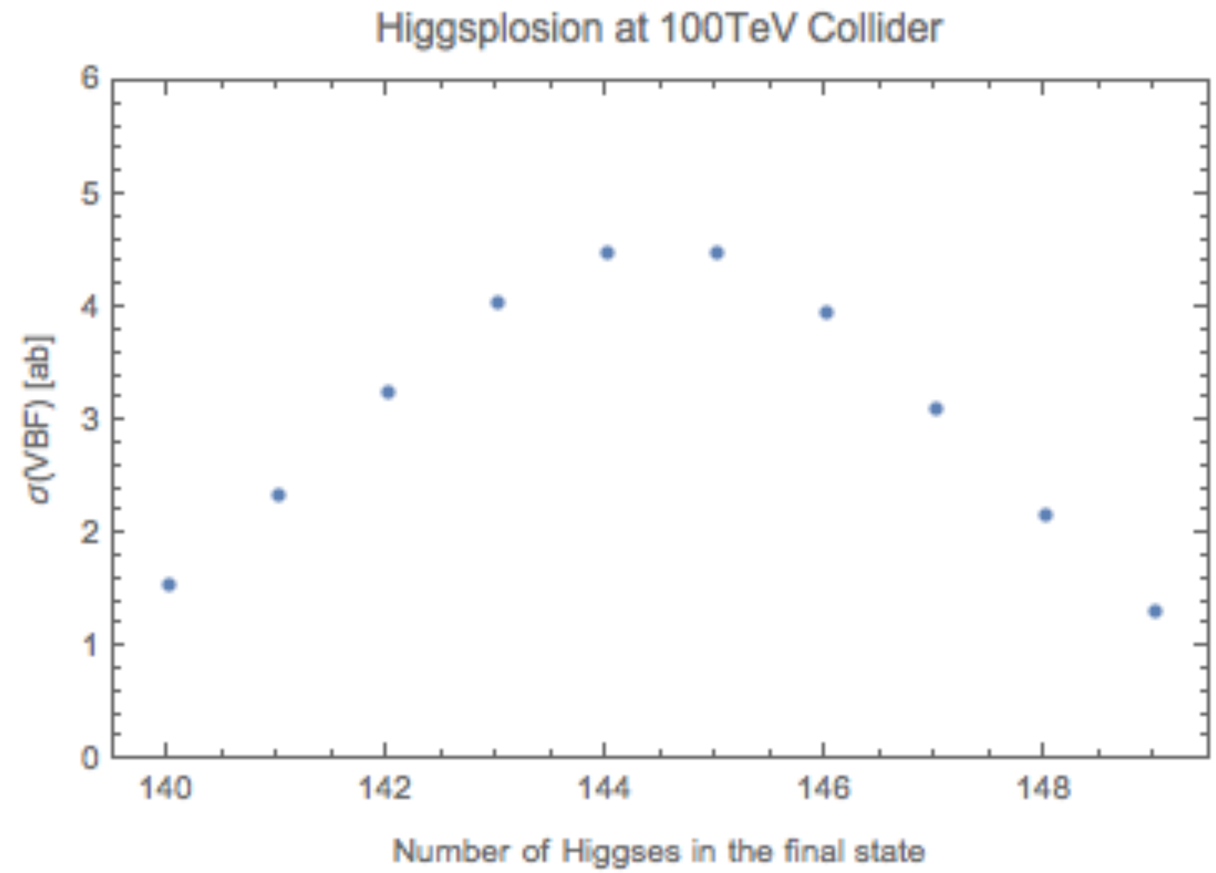
Higgsplosion at $\sqrt{s_*}$



Propagator with Higgspersion at $\sqrt{s_*}$

Vector boson fusion at high-energy pp colliders (FCC)



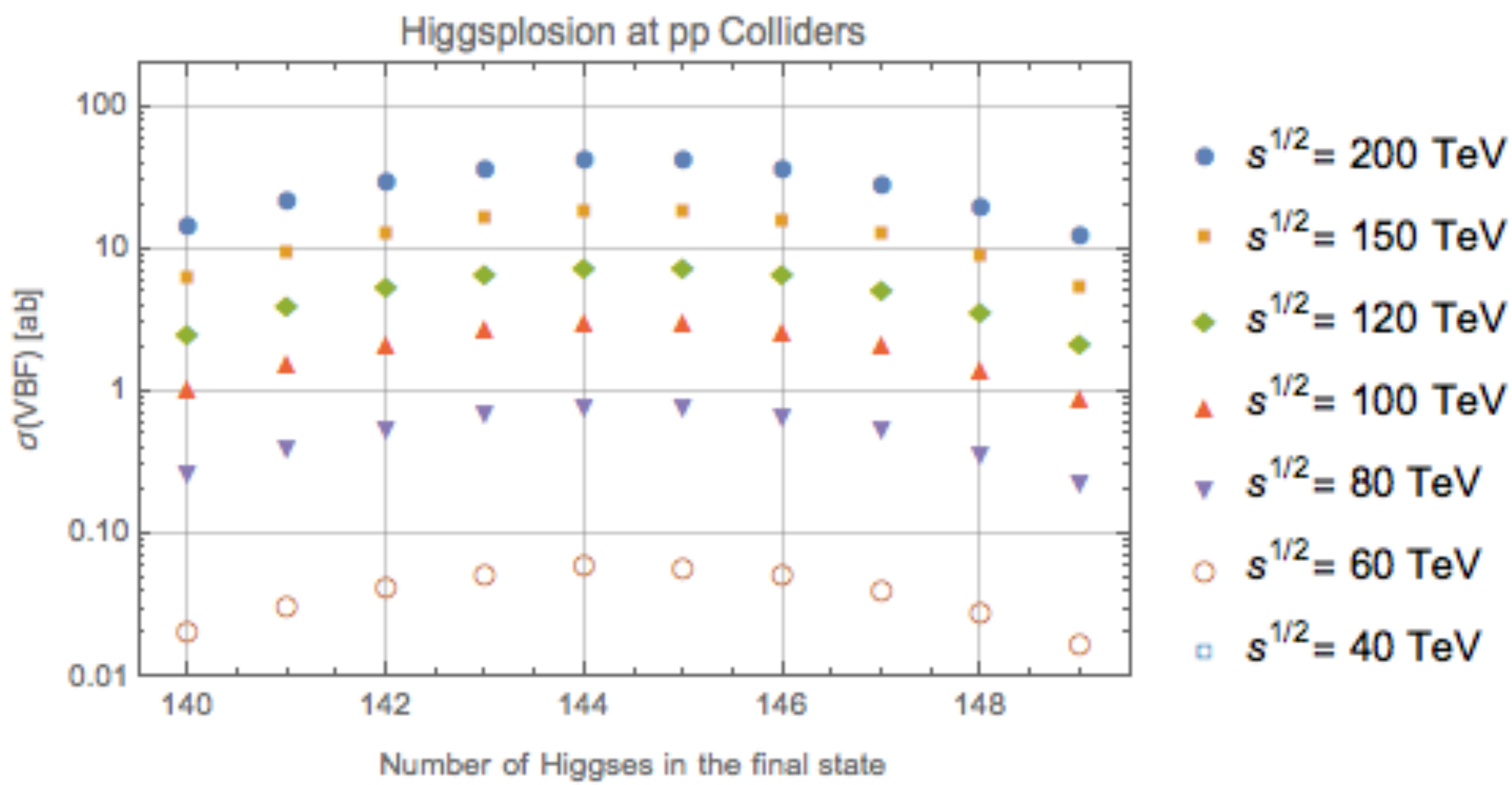


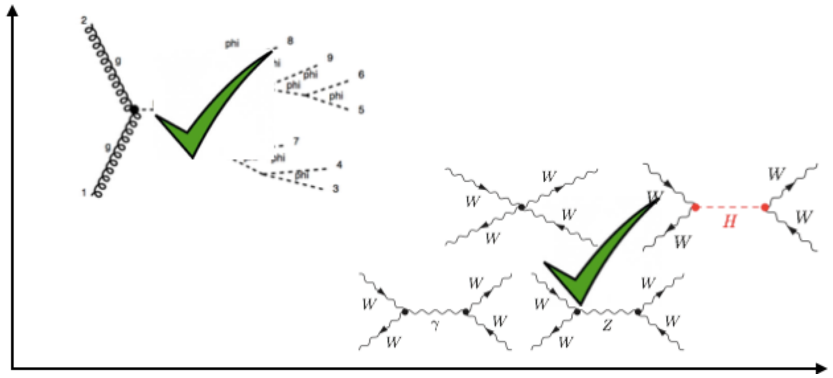
using $p_{t\,\mathrm{jet}} > 40$ GeV

[Khoze, Scholtz, MS in prep]

preliminary: no Higgs decays into SM dofs included;
& no vector bosons in final states yet

see also [Gainer '17]





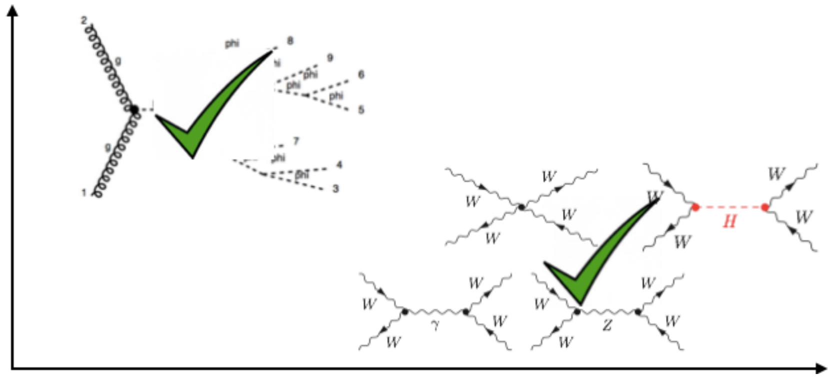
Train of thought:

h* -> n h shows factorial growth in classical, 1-loop resummed and semi-classical calculations

- If $\Gamma_n(p^2)$ for any n explodes $\Gamma_{\mathrm{tot}}(p^2)$ explodes

optical theorem (all orders)

- Imaginary part of self-energies explode
- Real part can't cancel imaginary part of self-energy
- All 2-point and n-point functions shut down beyond Higgsplosion scale
- New physical scale in SM, no Unitarity violation, no Hierarchy problem, asymptotically safe theory, stable vacuum, minimal-length theory



Summary

If Higgsplosion realised it will have spectacular consequences, i.e. many pieces fall into place

The SM has a new energy scale one can test

➔ No-loose theorem for future collider
(either Higgsplosion or NP, e.g. composite Higgs)

Currently, idea relies on 20th century QFT

Experimental tests	Theoretical tests
-> build O(100) TeV collider	-> Lattice calculation
-> much improved low energy measurements, e.g. g-2	-> Improved semi-classical approach?