Limits on Electroweak Instanton-induced Processes

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In collaboration with

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- In pure SU(2) YM theory, there are infinitely many gauge equivalent vacua.

$$A^a_\mu T^a = 0 \xrightarrow{\text{gauge trans.}} \frac{i}{g} U \partial_\mu U^\dagger$$

They are as many as $U_{ij}(\mathbf{x})$

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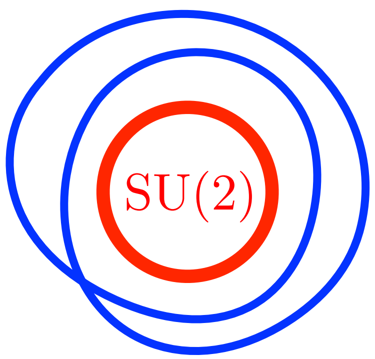

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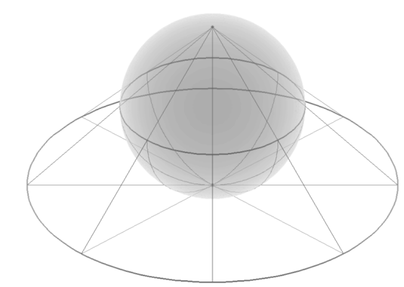
topological gauge

$$U(\infty) \to \mathbf{1}$$



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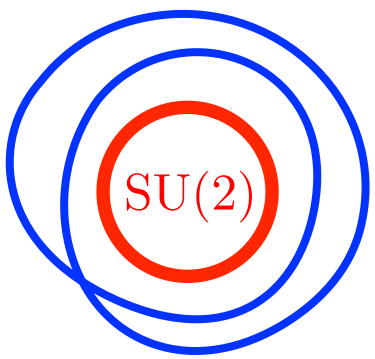

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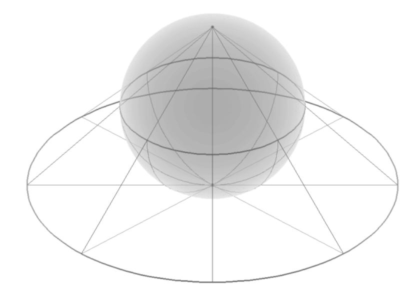
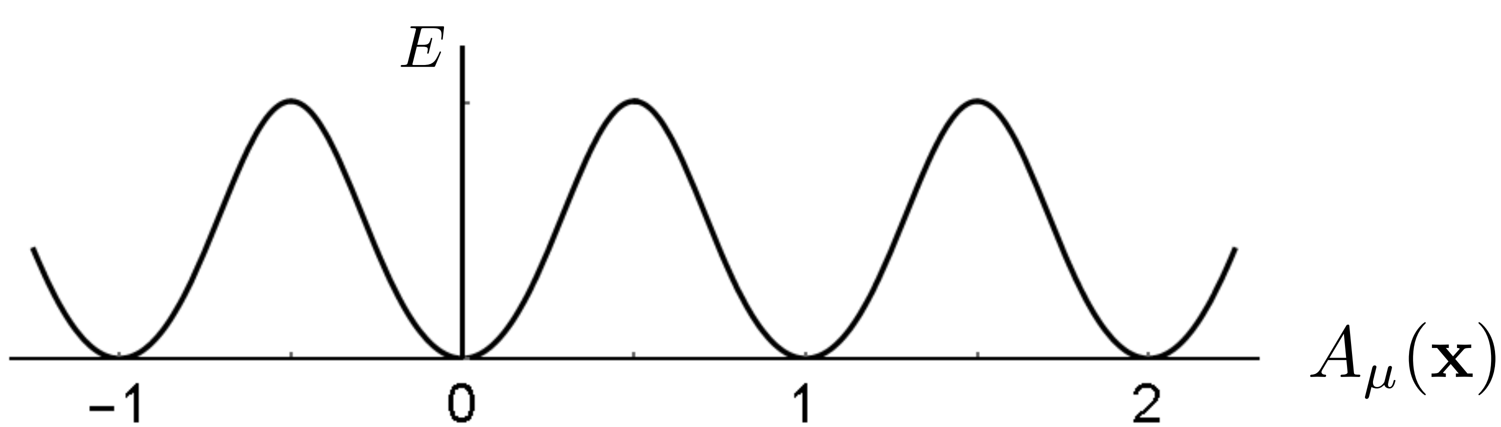


- These disconnected vacua are characterised by the integer N_{CS}.



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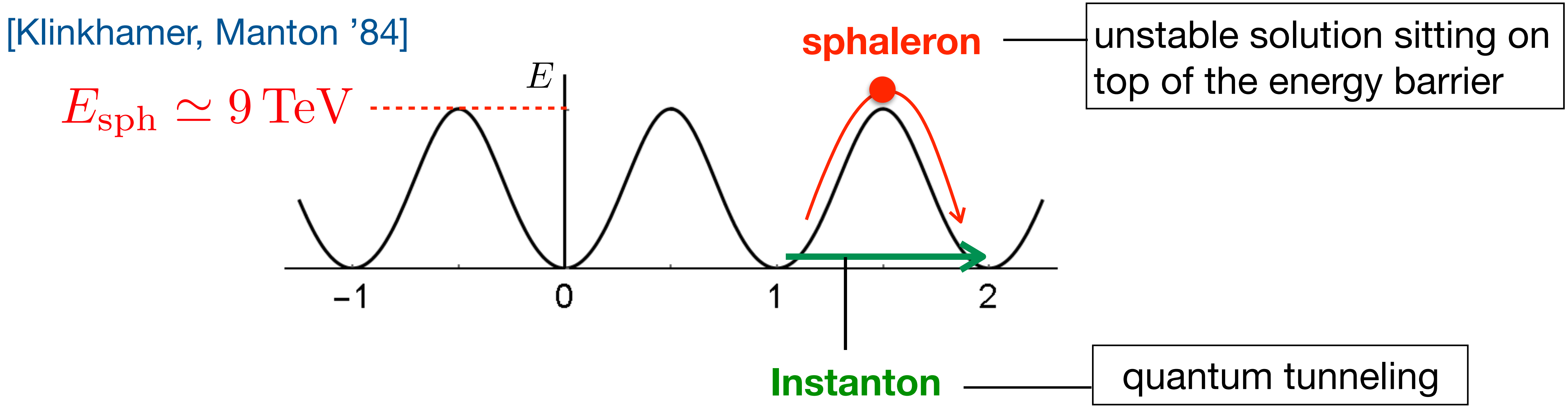

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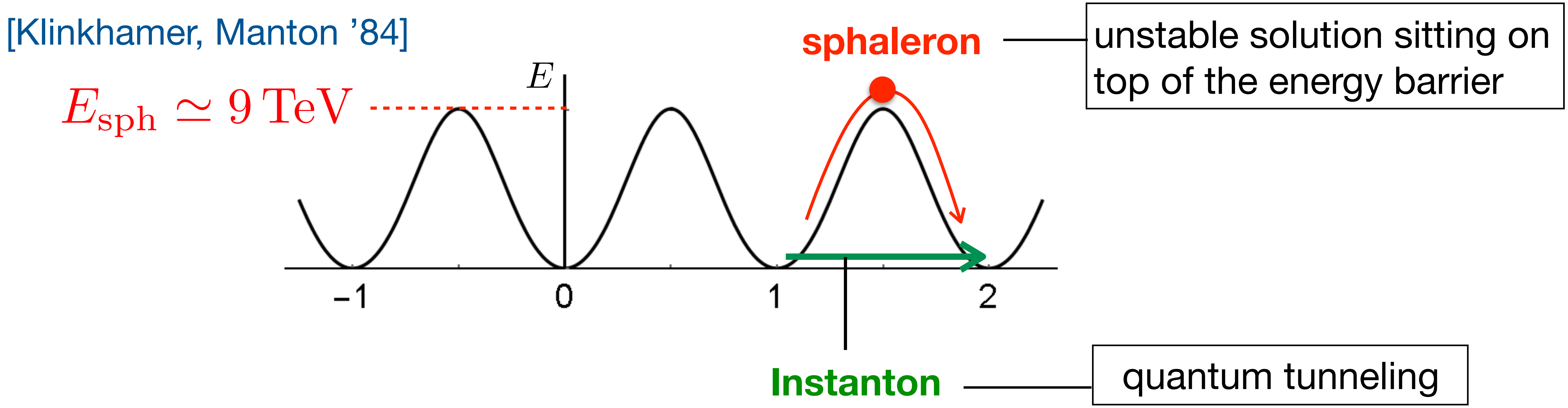

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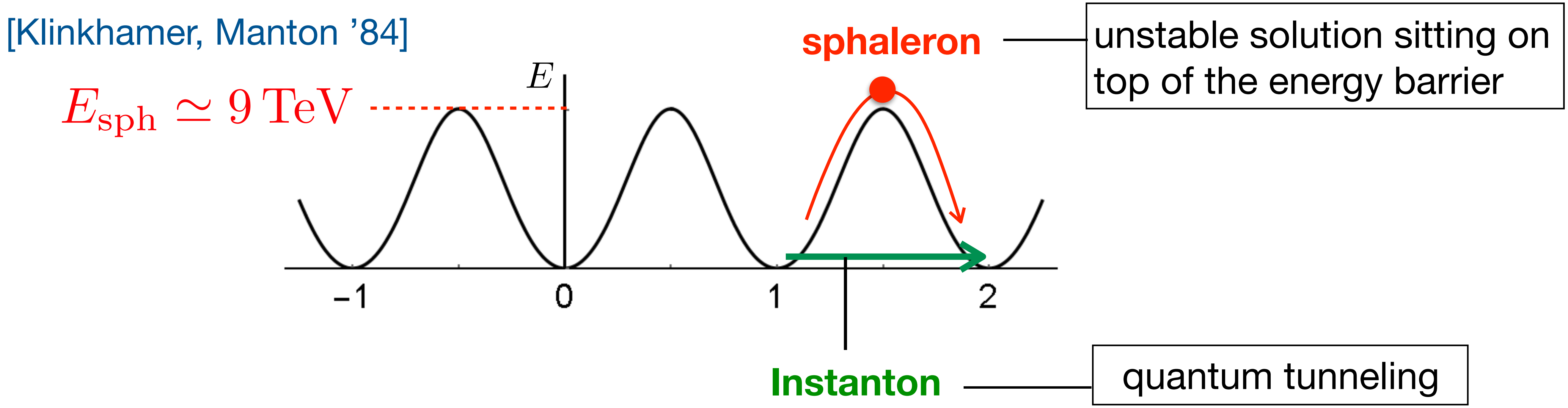

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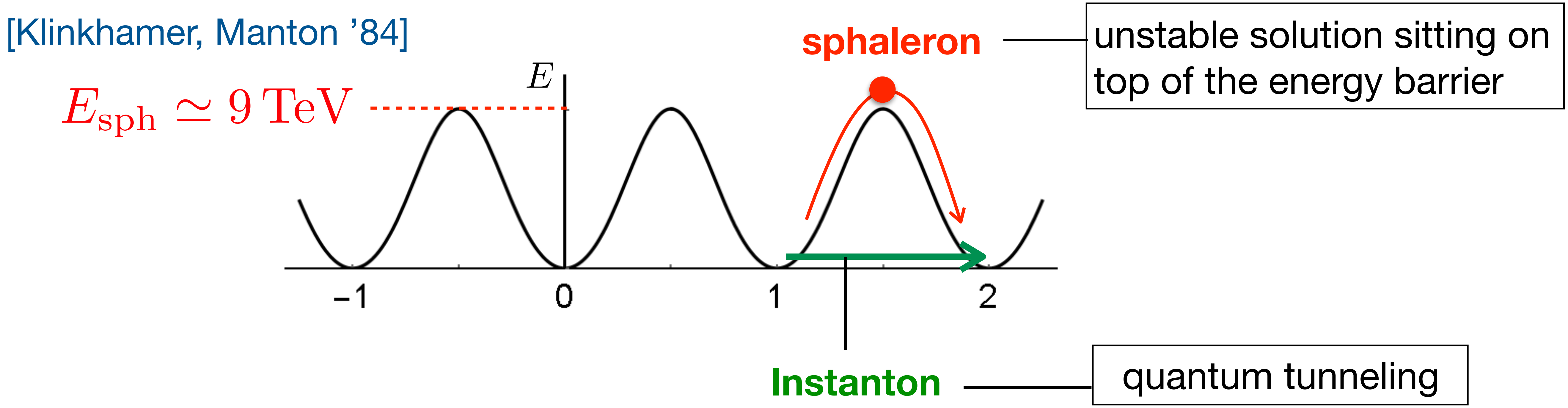

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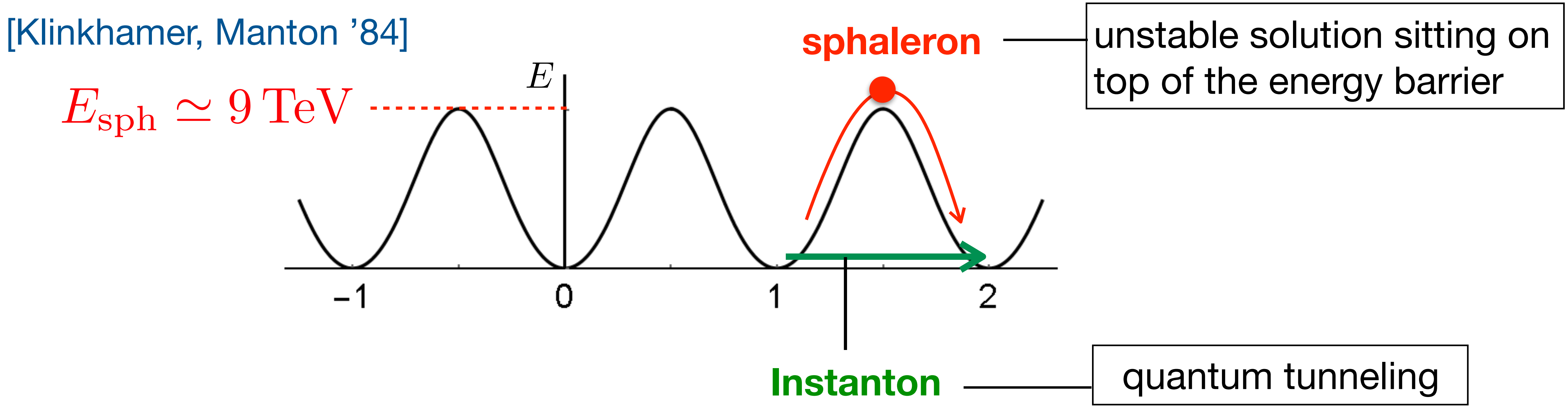

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Setting limits on vacuum transitions from the LHC ← **This talk**

- The change of N_{CS} is related to the following quantity:

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ΔN_F: **SU(2) charged fermion**

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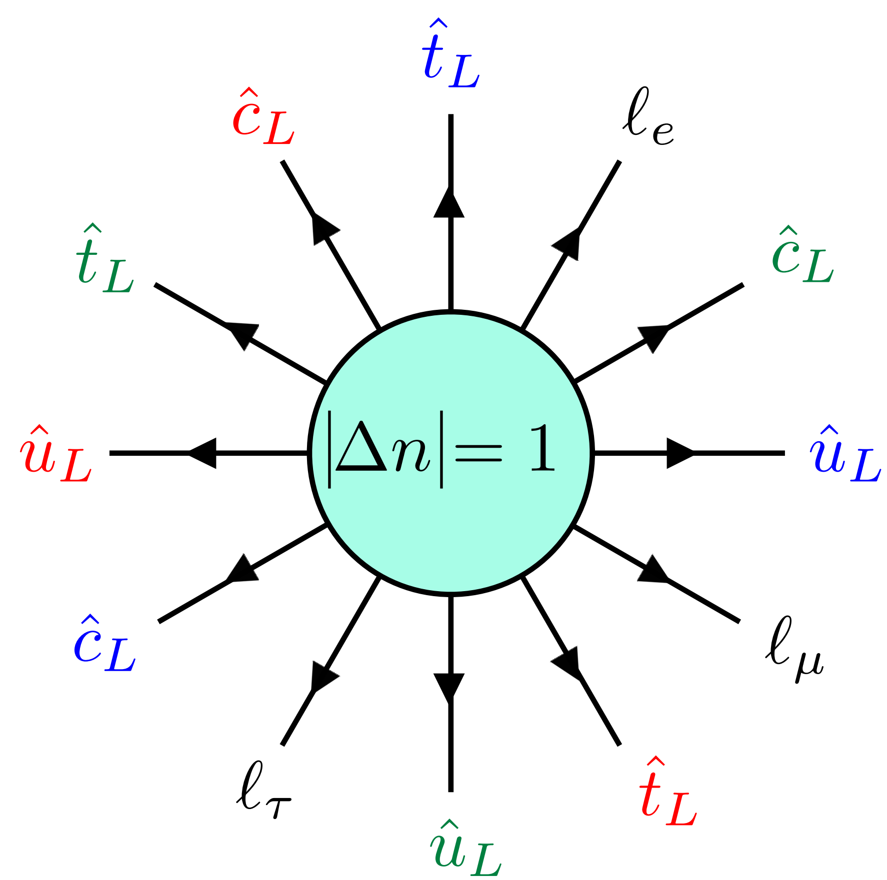
- ΔN_{CS} is related to the change of SU(2) charged fermion numbers.



$|\Delta N_{CS}| = 1$ transition creates 12 fermions altogether!

Party at collider!

- The LO Matrix Element in the ***instanton*** **background**

$$i\mathcal{M} \sim \int \mathcal{D}q\mathcal{D}W\mathcal{D}\phi \, q(x_1)\cdots q(x_{12})W(y_1)\cdots W(y_{n_W})\phi(z_1)\cdots\phi(z_{n_h}) \exp(-S_E)\Big|_{\mathrm{LSZ}}$$

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$$W^{\mu a}_{\rm inst} \simeq \frac{2\rho^2}{g} U_{ab} \frac{\bar\eta_{b\mu\nu}(x-x_0)_\nu}{(x-x_0)^2[(x-x_0)^2+\rho^2]} \qquad \phi_{\rm inst}(x) \simeq v\left[\frac{(x-x_0)^2}{(x-x_0)^2+\rho^2}\right]^{1/2}$$

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orientation position size

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- Result

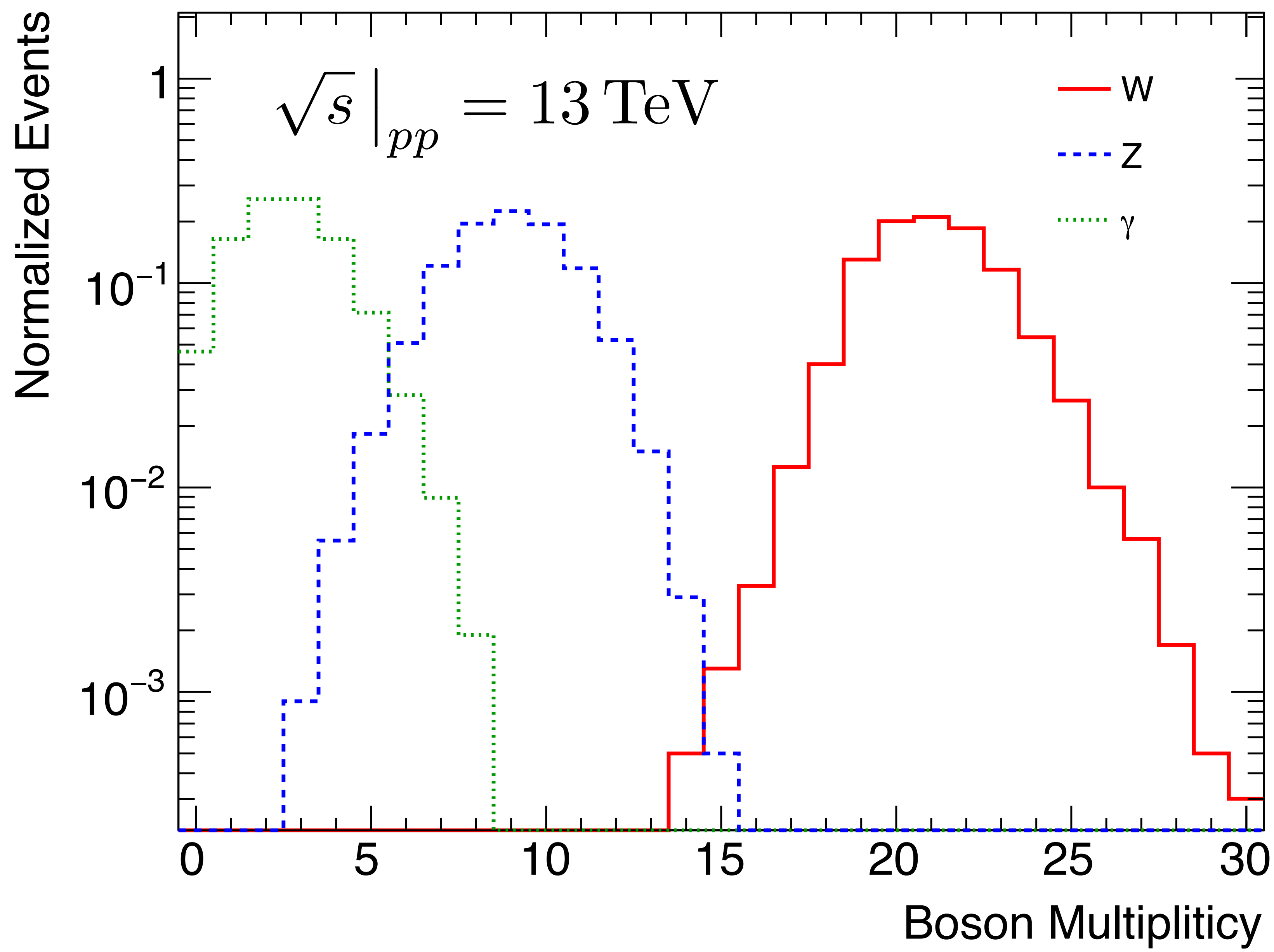
[Ringwald '90, Espinosa '90]

$$\sigma_{\mathrm{LO}}(n_W, n_h) \sim \mathscr{G}^2 2^n v^{-2n}\left[\frac{\Gamma(n+103/12)}{\Gamma(103/12)}\right]^2 \frac{1}{n_B!\,n_H!} \qquad \mathscr{G} = 1.6\times 10^{-101}\ \mathrm{GeV}^{-14}$$

$$\times \int \prod_{i=1}^{10} \frac{d^3p_i}{(2\pi)^3 2E_i} E_i \prod_{j=1}^{n_B} \frac{d^3p_j}{(2\pi)^3 2E_j} \frac{2(4E_j^2 - m_W^2)}{m_W^2} \prod_{k=1}^{n_H} \frac{d^3p_k}{(2\pi)^3 2E_k} (2\pi)^4 \delta^{(4)}\left(P_{\mathrm{in}} - \sum_{i=1}^{10} p_i - \sum_{j=1}^{n_B} p_j - \sum_{k=1}^{n_H} p_k\right)$$

The cross-section becomes very large for large n_W and n_h!

- The MC Event Generator (**HERBVI**) was developed by Gibbs and Webber based on the LO ME formula:

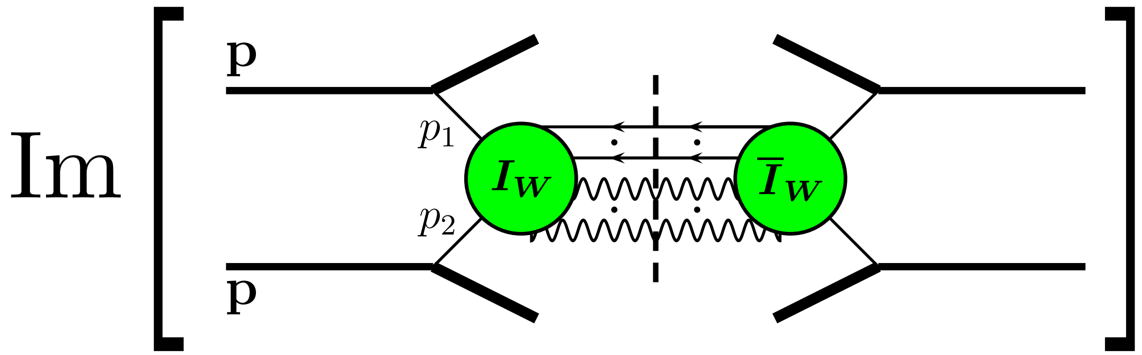


O(30) EW gauge bosons are produced!

Festival at collider!

- The inclusive cross-section can be estimated using the dispersion relations (optical theorem).

[Khoze, Ringwald '91]



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$$\epsilon \equiv \frac{\sqrt{\hat{s}}}{M_0} \qquad M_0 \equiv \sqrt{6}\pi \frac{m_W}{\alpha_W} \simeq 18.3 \text{ TeV}$$

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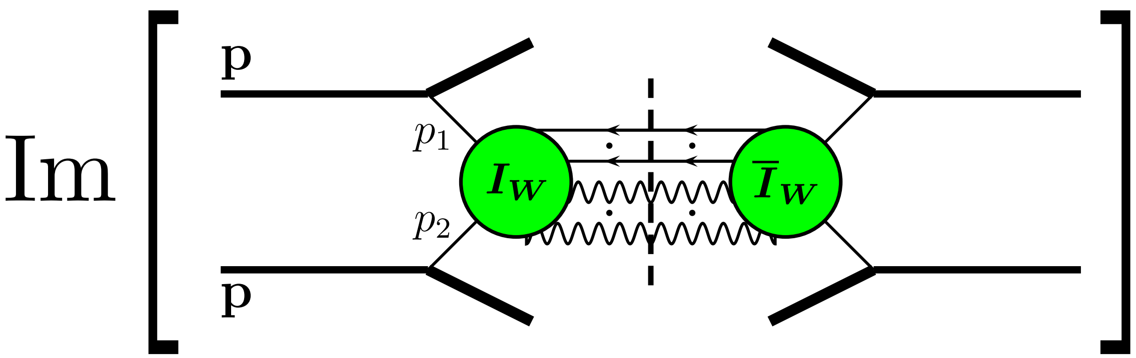

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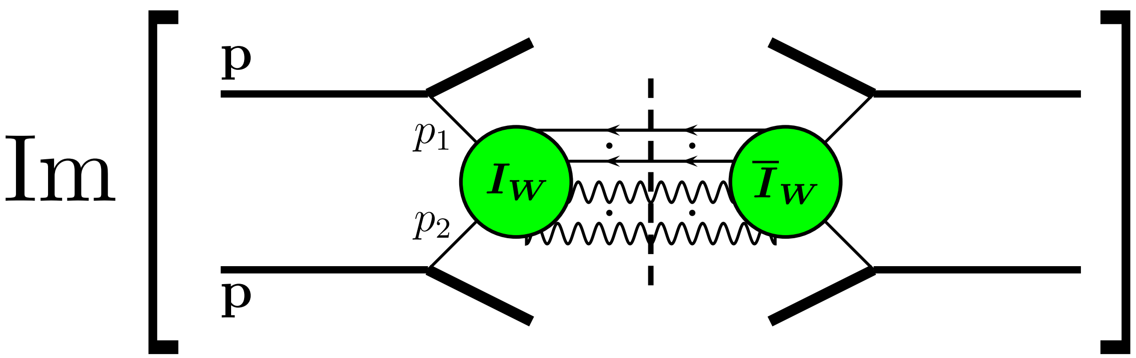

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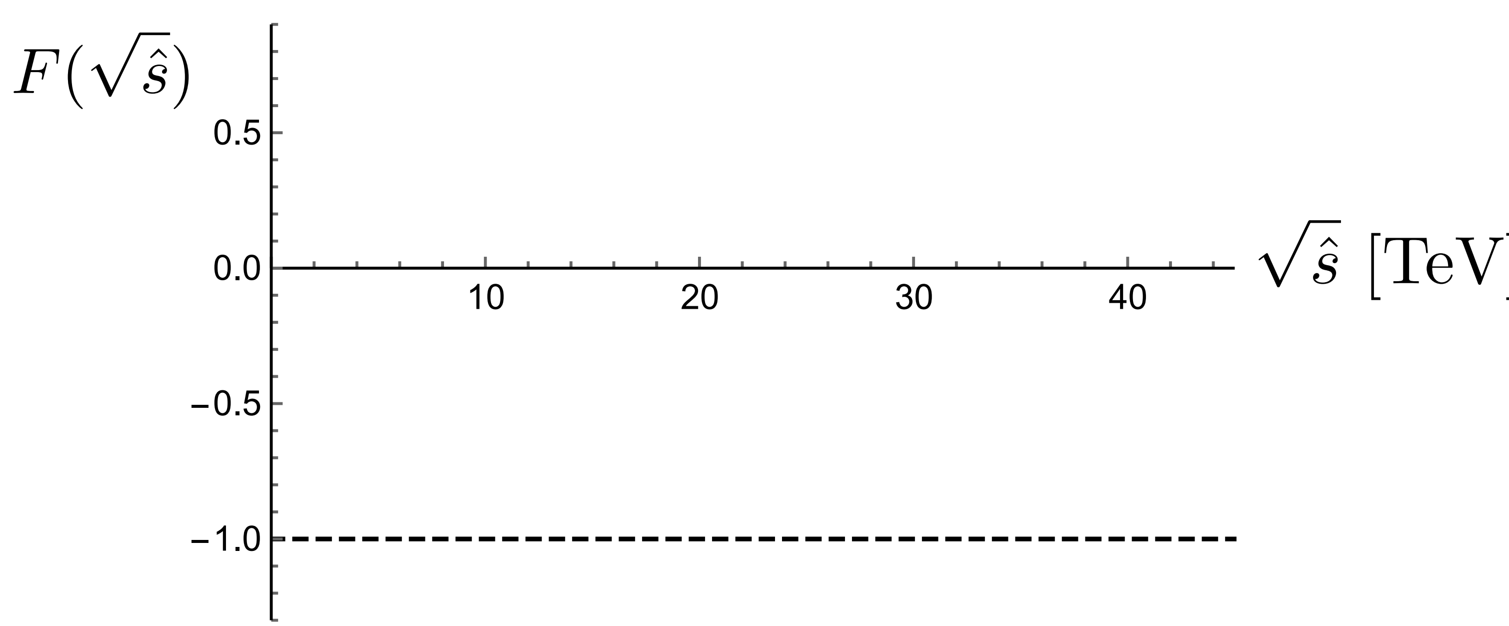

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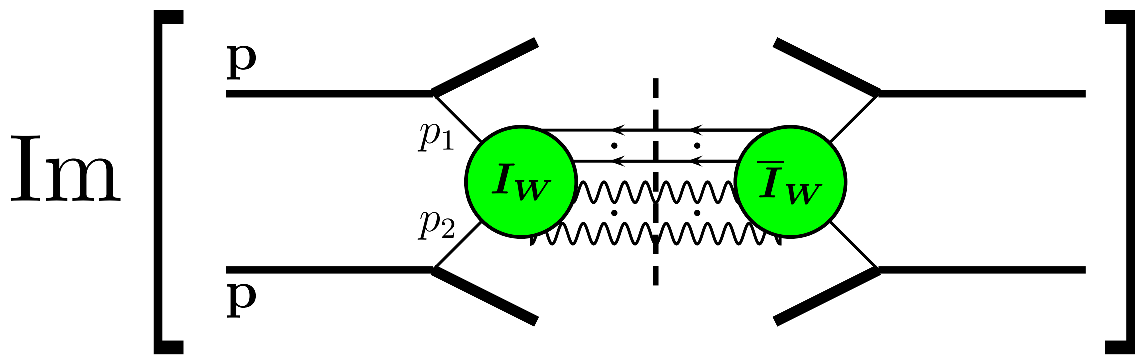

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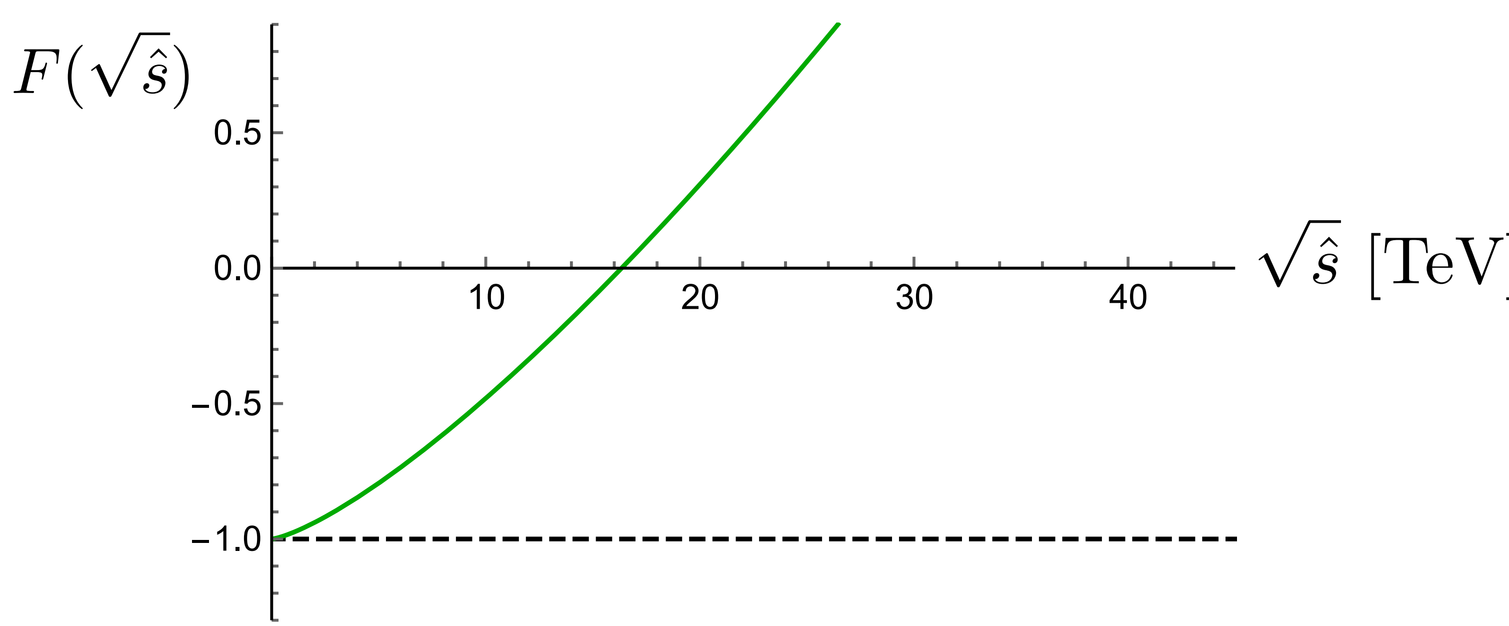

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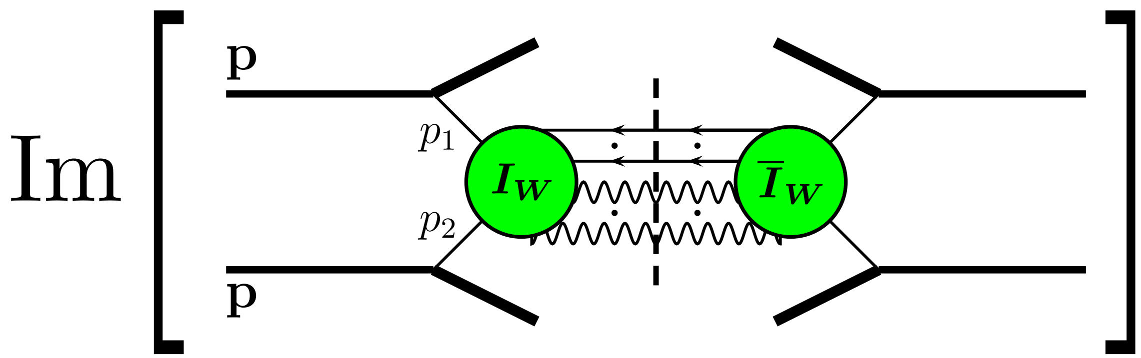

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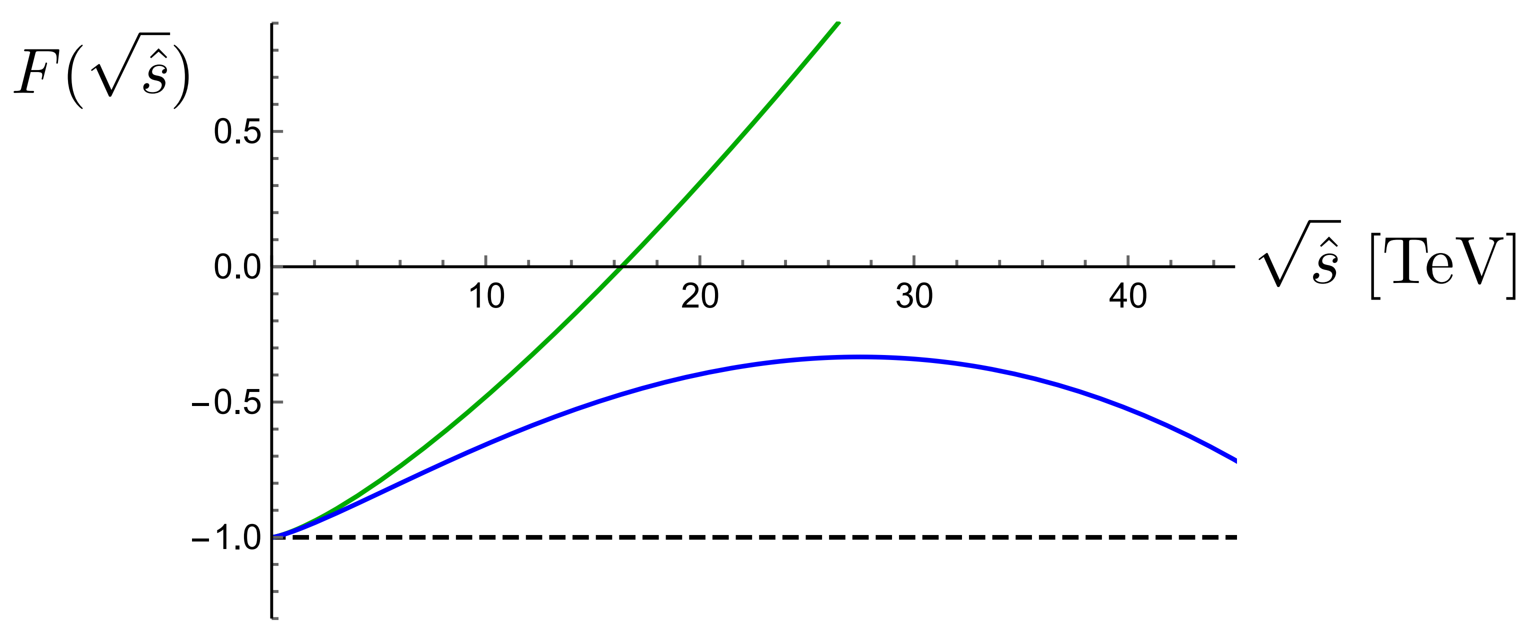

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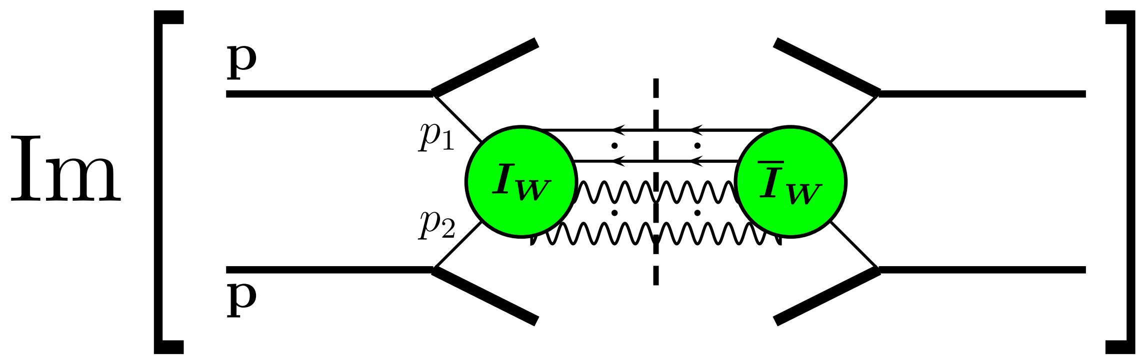

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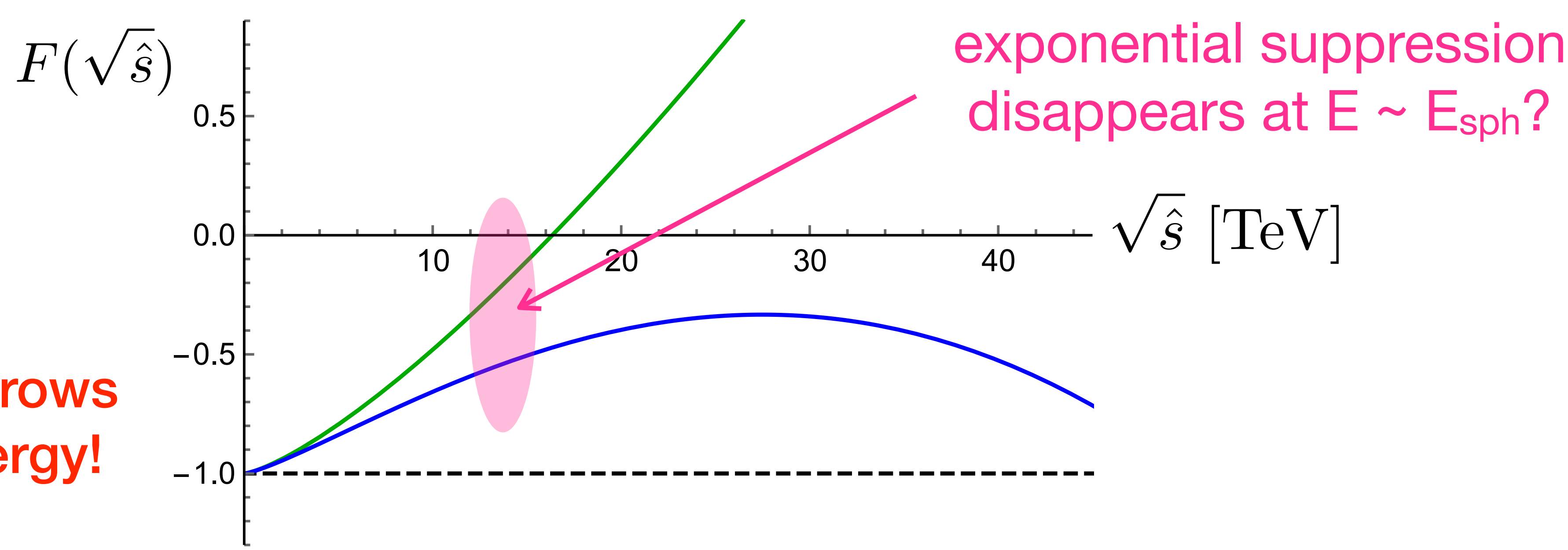


Cross-section grows rapidly with energy!

- The time evolution of the sphaleron field configuration has been simulated numerically, and it found O(30) gauge bosons in the final state.

[Hellmund, Kripfganz '91]

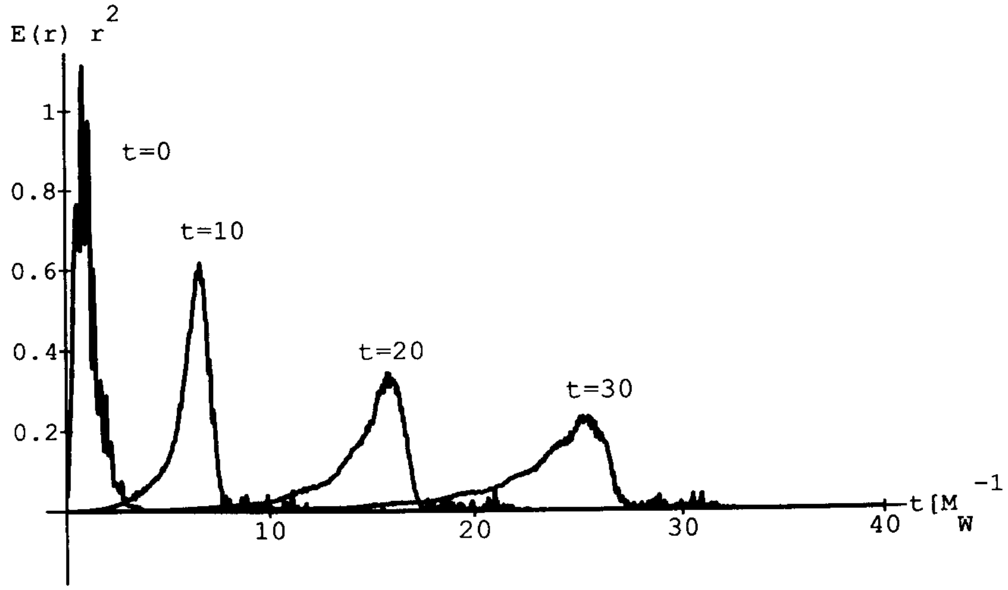
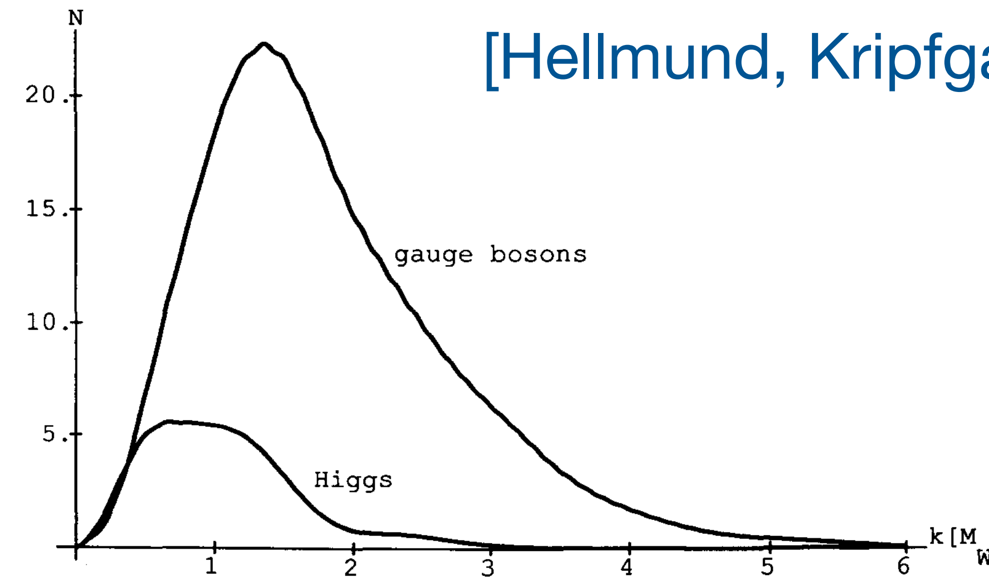


Fig. 1. Radial energy distribution (in units of M_W) of the decaying sphaleron at different times (in units of M_W^{-1}).



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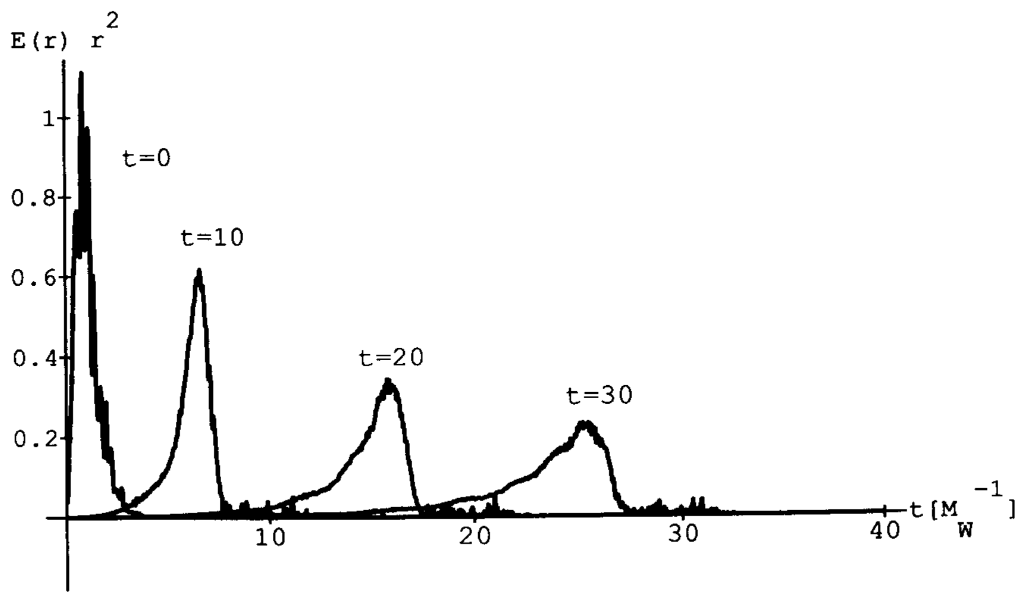

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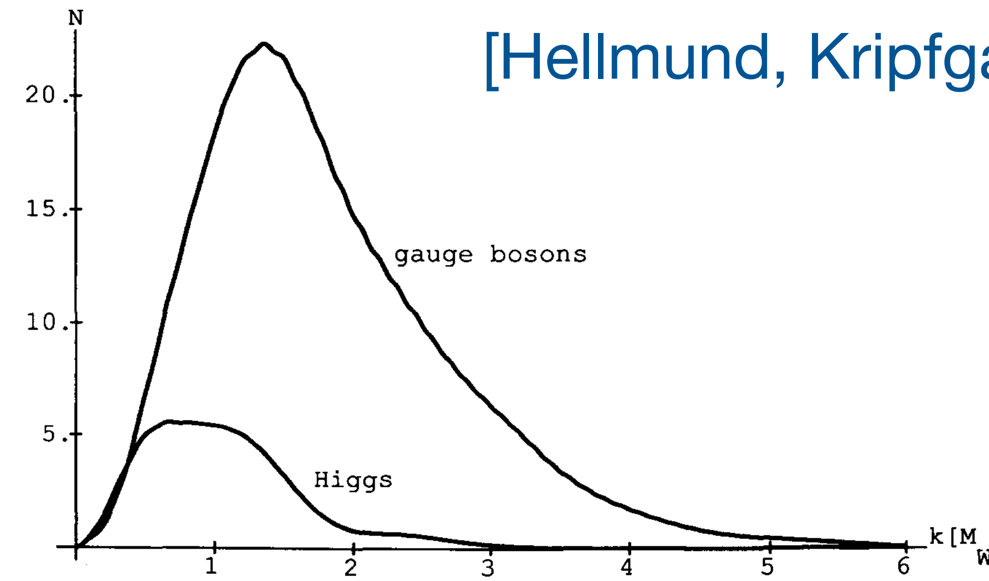
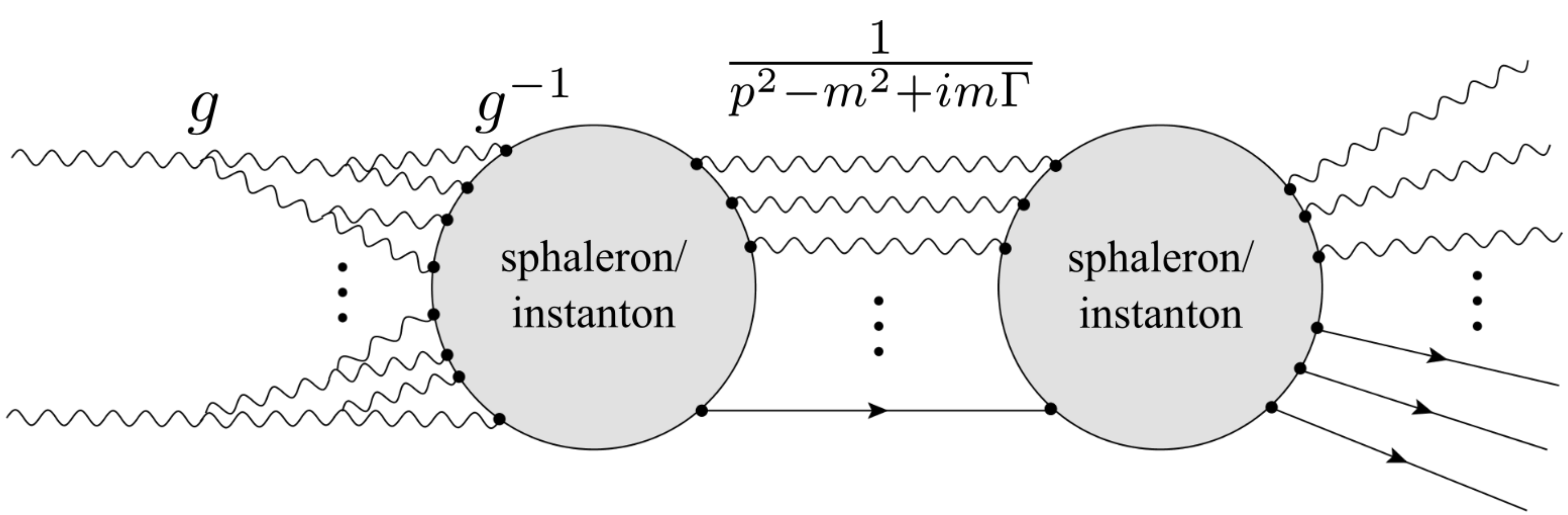


Fig. 4. Multiplicity distribution $4\pi k^2 N(k)$ of the final-state particles over the momentum k in units of M_W.

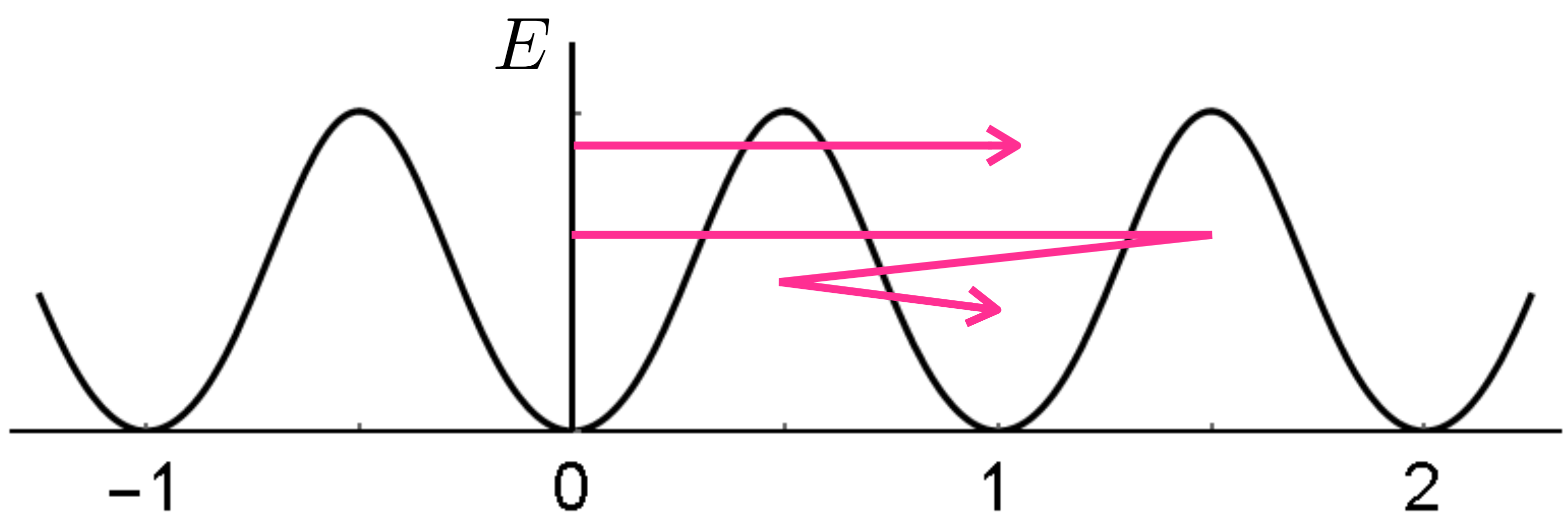
- These studies seem to suggest that many W-bosons are produced in the instanton BG, which produces a sphaleron-like field configuration at E ~ E_{sph}, and vacuum transitions occur semi-classically in some sense.



- More recently (2015), Tye and Wong claims that at zero temperature instanton rate overcomes the exponential suppression for $E > E_{sph}$ ~ 9 TeV, if the periodicity of the EW potential is taken into account, due to *resonant tunnelling*.

Resonant tunneling:

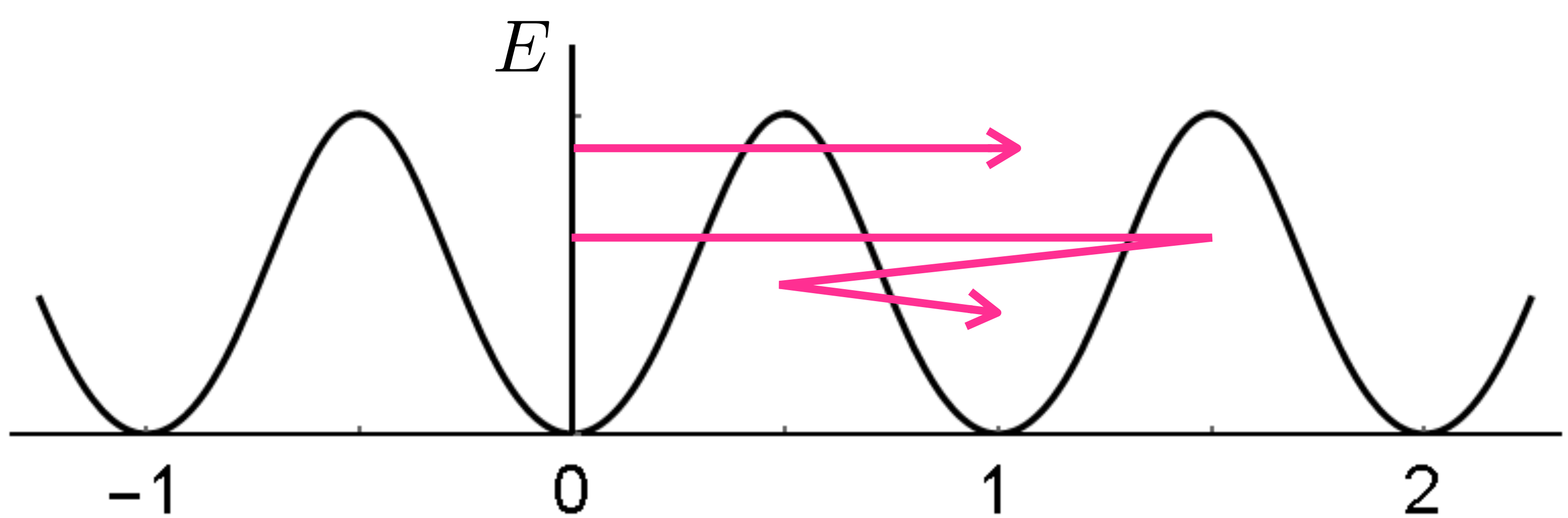
Different paths coherently interfere at particular energies, forming a conducing band structure



- More recently (2015), Tye and Wong claims that at zero temperature instanton rate overcomes the exponential suppression for $E > E_{sph} \sim 9$ TeV, if the periodicity of the EW potential is taken into account, due to *resonant tunnelling*.

Resonant tunneling:

Different paths coherently interfere at particular energies, forming a conducing band structure



- This triggers many theoretical and phenomenological studies:

[Ellis, KS '16], [Brooijmans, Schichtel, Spannowsky '16], [Ellis, KS, Spannowsky '16], [Spannowsky, Tamarit '17], [Cerdeno, Reimitz, KS, Tamarit '18], [Y.Jho, S.C.Park '18], …

- CMS has published their search for sphaleron-like events. [CMS-EXO-17-023]

- However, they consider zero-boson final state.

$$qq \to n_q q + 3\ell \qquad n_q = 7,\ 9 \text{ or } 11$$

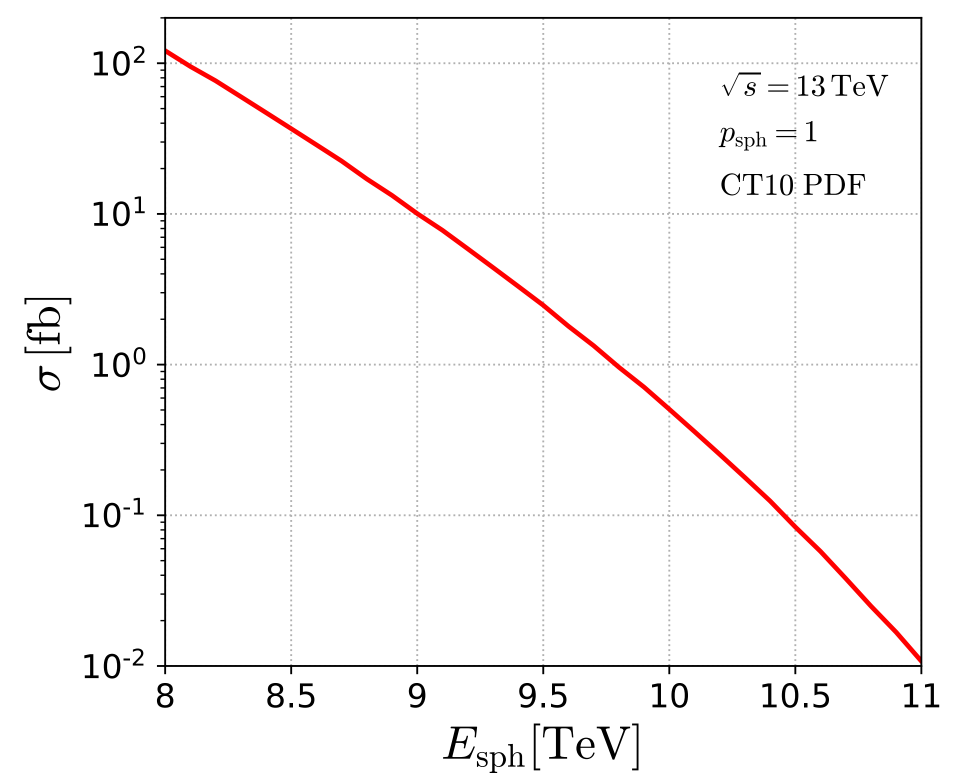
- How does their simulation compare with (more realistic) multi-boson events?

$$qq \to \begin{cases} n_q q + 3\ell & (\texttt{BaryoGEN}) \\ 7q + 3\ell + \sum n_B B & (\texttt{HERBVI}) \end{cases}$$

We use *Delphes* to simulate CMS detector.

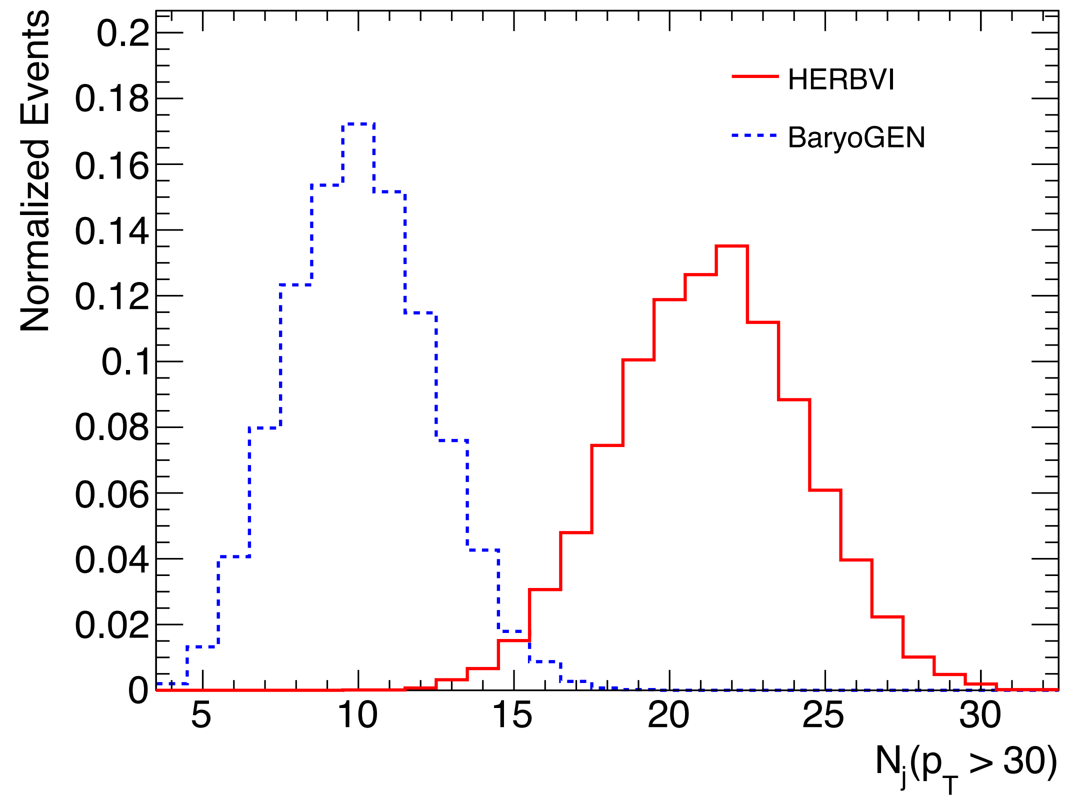
- We model the partonic cross-section as:

$$\hat{\sigma}(\sqrt{\hat{s}}) = \frac{p_{\rm sph}}{m_W^2}\Theta(\sqrt{\hat{s}} - E_{\rm sph})$$



[Ringwald, KS, Webber 1809.10833]

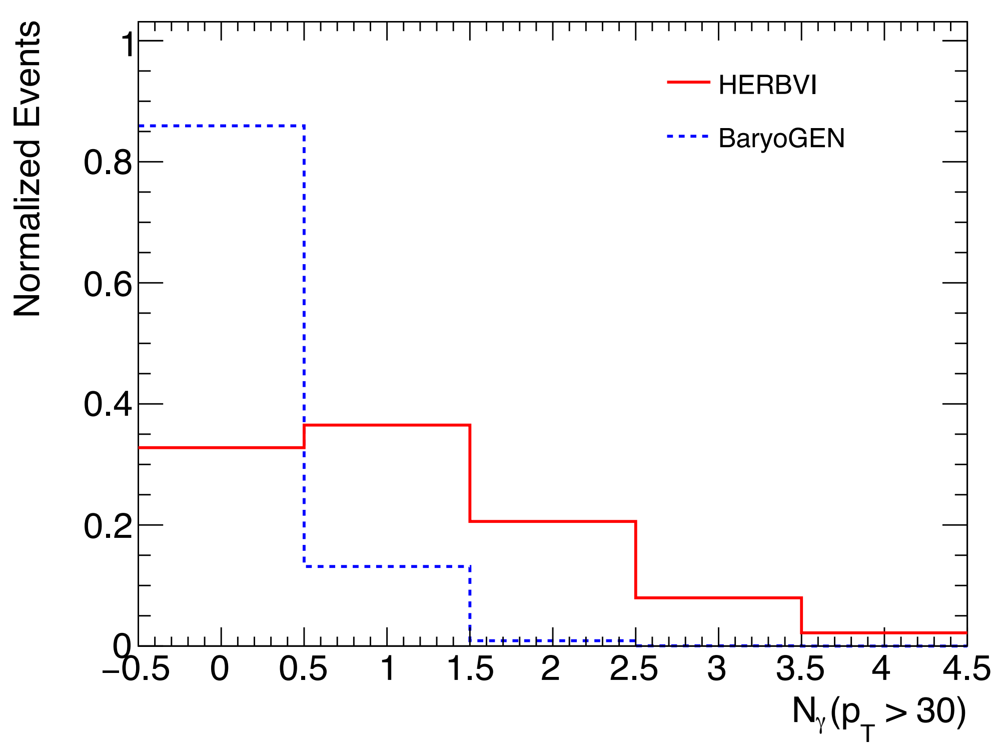
jet multiplicity



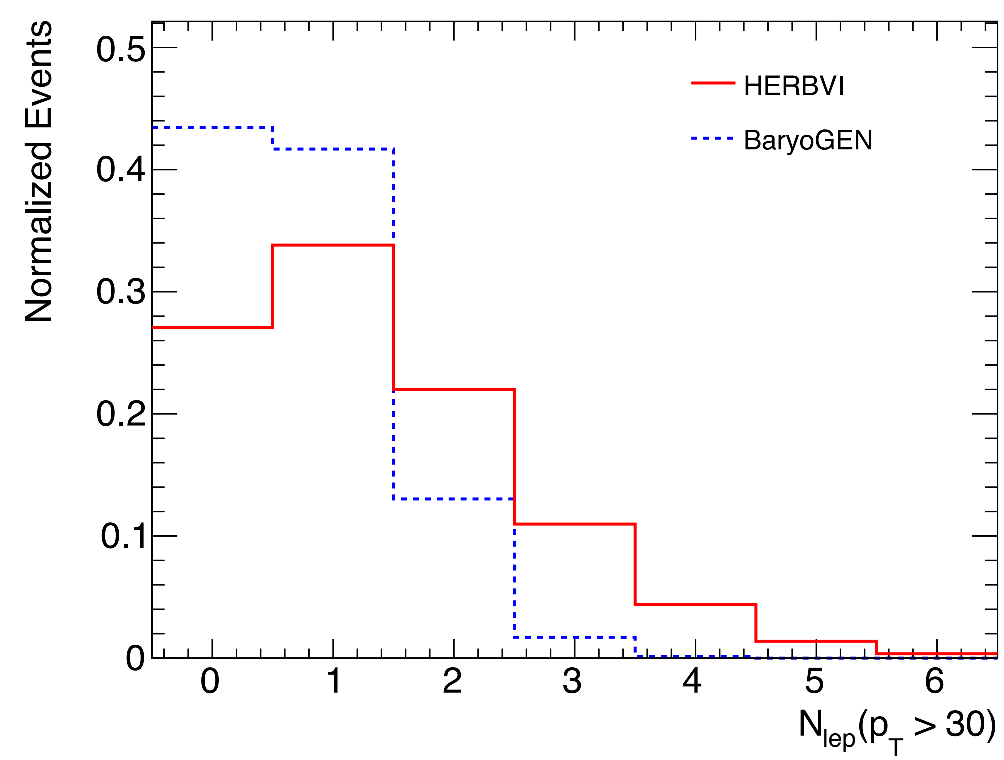
multi-boson

zero-boson

lepton multiplicity



photon multiplicity



- In the CMS analysis the cuts impose on S_T and multiplicity.

$$S_T \equiv E_T^{\text{miss}} + \sum_i^{p_T > 70\text{GeV}} p_T^{(i)} \quad > S_T^{\min} \qquad 3.8 < S_T^{\min}/\text{TeV} < 8$$

$$N(p_T > 70\,\text{GeV}) \quad \geq N_{\min} \qquad N_{\min} = 3, \ldots, 11$$

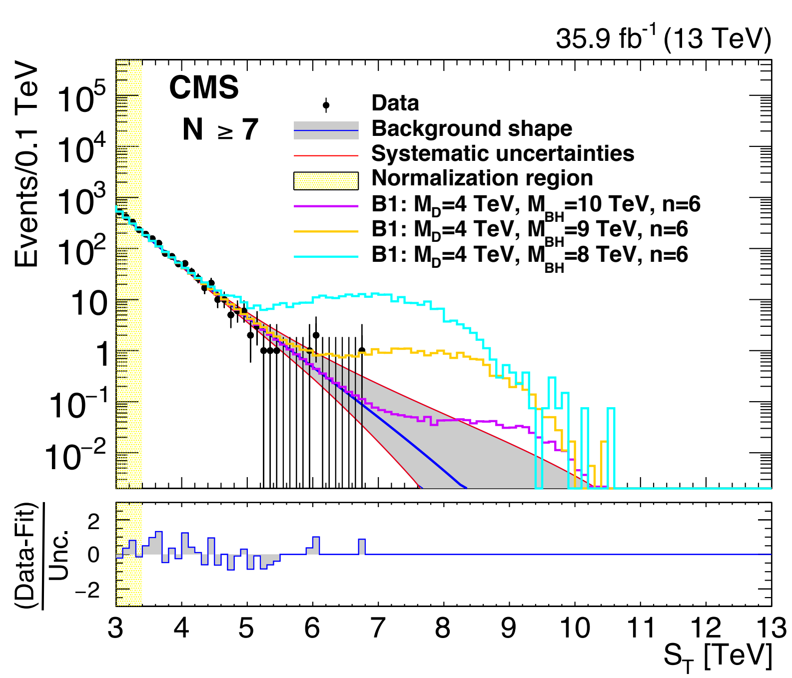
[Ringwald, KS, Webber 1809.10833]

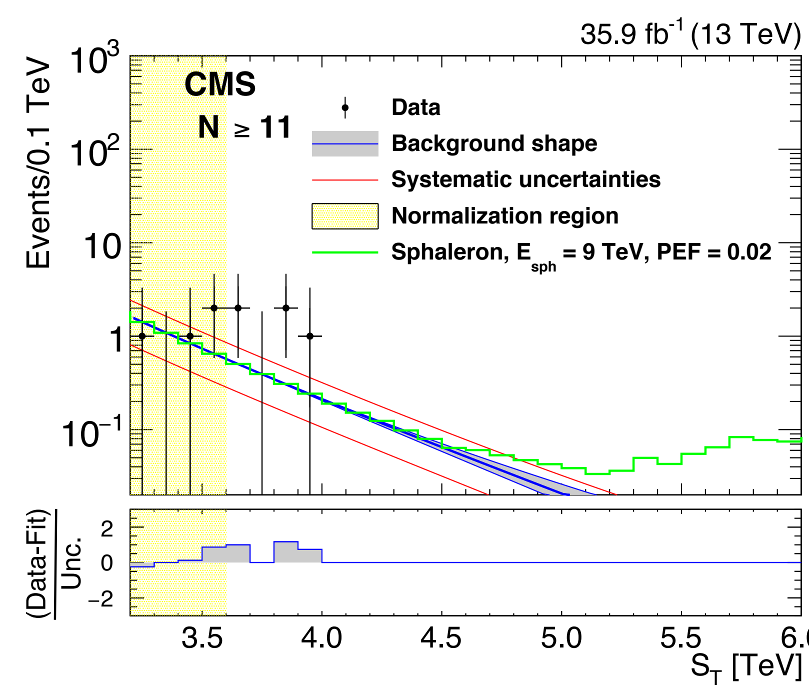
E_{sph} [TeV]		8	8.5	9	9.5	10
multi-boson	$(N_{\min}, S_T^{\min}\,[\text{TeV}])^*$	(11, 4.2)	(11, 4.2)	(11, 4.2)	(11, 4.2)	(11, 4.2)
	$\epsilon^{(a^*)}$ [%]	94.8	97.5	99.2	99.6	99.9
	$N_{\text{obs}}^{\max(a^*)}$	3.0	3.0	3.0	3.0	3.0
Zero Boson	$(N_{\min}, S_T^{\min}\,[\text{TeV}])^*$	(9, 5.4)	(9, 5.6)	(9, 5.6)	(8, 6.2)	(8, 6.2)
	$\epsilon^{(a^*)}$ [%]	37.7	40.5	45.3	50.5	57.5
	$N_{\text{obs}}^{\max(a^*)}$	6.9	5.8	5.8	3.0	3.0

most sensitive SR

signal efficiency

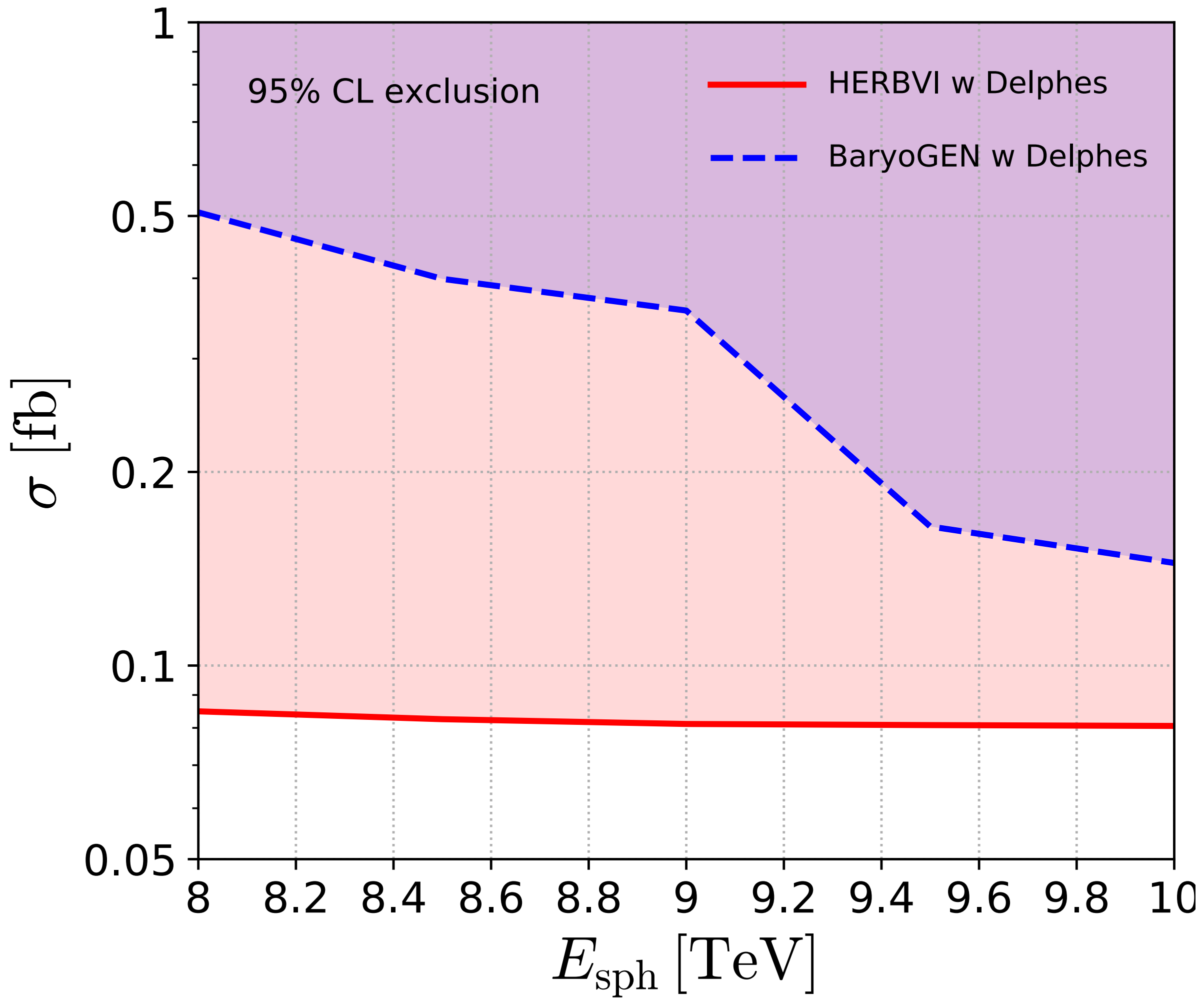
limit on signal events

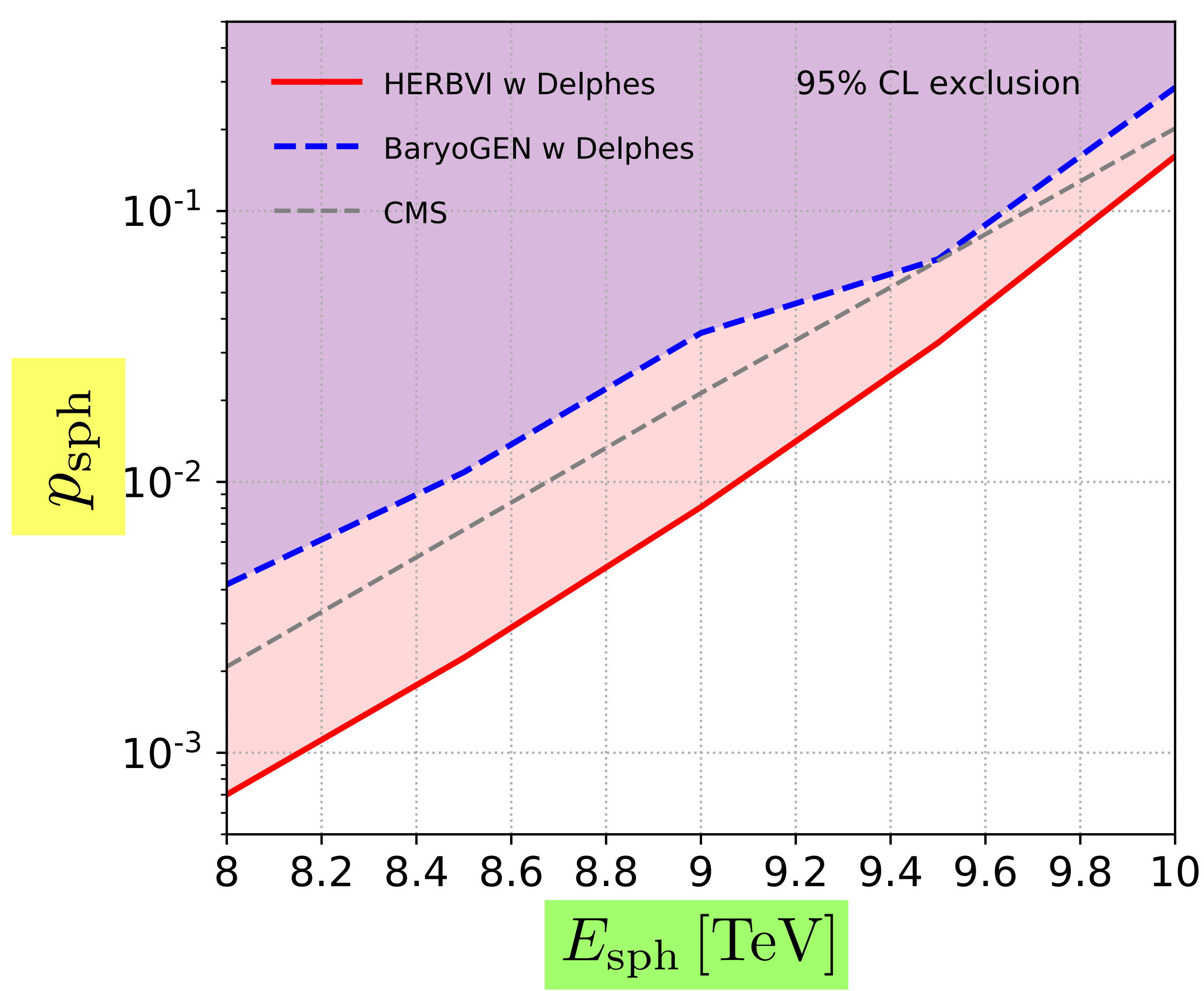




Limits on Sphaleron-like process

$$\hat{\sigma}(\sqrt{\hat{s}}) = \frac{p_{\rm sph}}{m_W^2}\Theta(\sqrt{\hat{s}} - E_{\rm sph})$$





- The limit on the multi-boson cross-section: $\sigma_{\rm sph} < 0.8\,{\rm fb}^{-1}$
- We found that their analysis can be more tuned for multi-boson analysis by extending their range of N_{min} cut for higher energy or luminosity options.

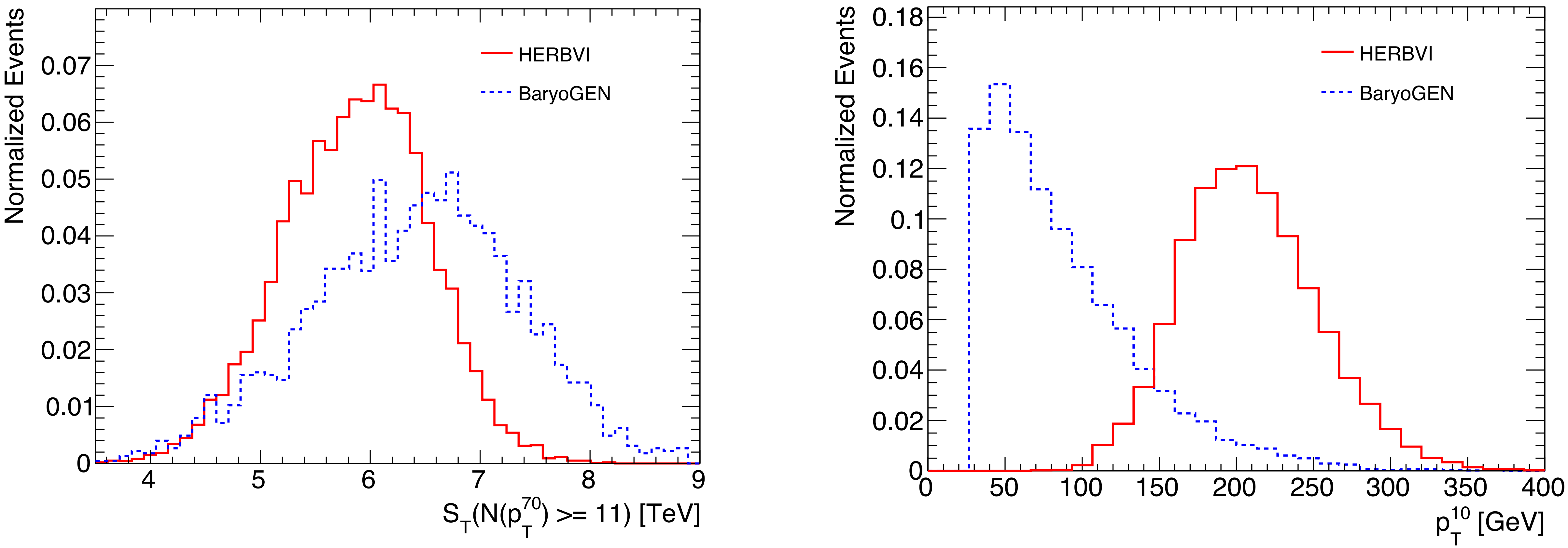
Conclusions

- The rate of zero temperature, high energy instanton-induced process is still an open question.

- Many studies suggest that such process may have observably large rate at collider if multiple gauge bosons are produced together with fermions.

- We recast CMS analysis and found the limit, 0.8 fb^{-1}

- Their analysis can be more tuned for multi-boson final state by extending the range of N_{min} cut for higher energy or lumi options.



Normalized Events
HERBVI
BaryoGEN
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
4
5
6
7
8
9
$S_T(N(p_T^{70}) >= 11)$ [TeV]
Normalized Events
HERBVI
BaryoGEN
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0
50
100
150
200
250
300
350
400
p_T^{10} [GeV]