Search for *Sphalerons* at LHC and IceCube

Kazuki Sakurai

IPPP, Durham

In collaboration with:

John Ellis and **Michael Spannowsky**

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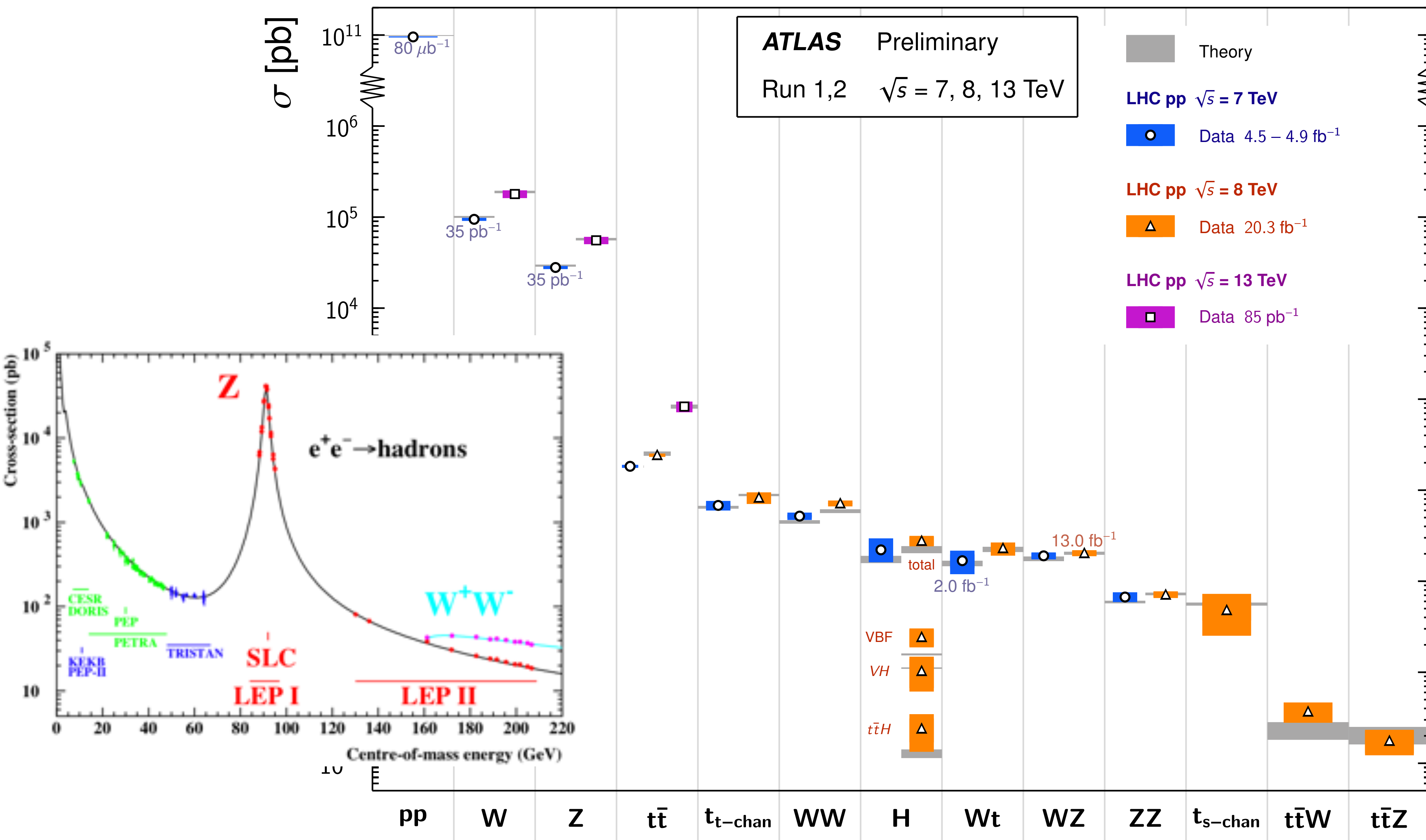
Plan

- Introduction
- Review of Sphalerons
- Sphalerons at the LHC
- Sphalerons at IceCube
- Summary

How well do we know about EW theory?

- Remarkable agreement between experimental results and perturbative calculations.
- How about non-perturbative part of EW theory?



Vacua of EW theory

action: $S_{EW} = \frac{1}{2g^2}\int d^4x F_{\mu\nu}F^{\mu\nu}$ $\quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + [A_\mu, A_\nu]$

gauge trans.: $A_\mu \to U^\dagger A_\mu U + U^\dagger \partial_\mu U$ $\quad U \in SU(2) \quad U = a + i(\mathbf{b}\cdot\sigma)$

$S_{EW} \to S_{EW}$ $\quad a^2 + \mathbf{b}^2 = 1$

a vacuum: $A_\mu = 0 \quad \leftrightarrow \quad A = U^\dagger \partial_\mu U$

At a given t, $U(\mathbf{x})$ is a function that maps from $\mathbf{x} \in \mathbb{R}^3$ to $U \in SU(2)$.

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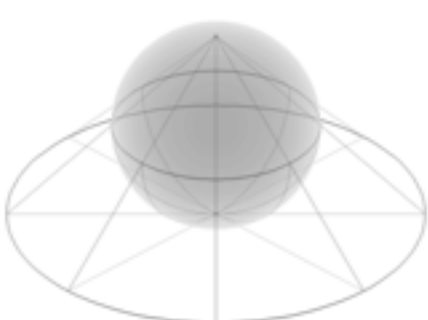
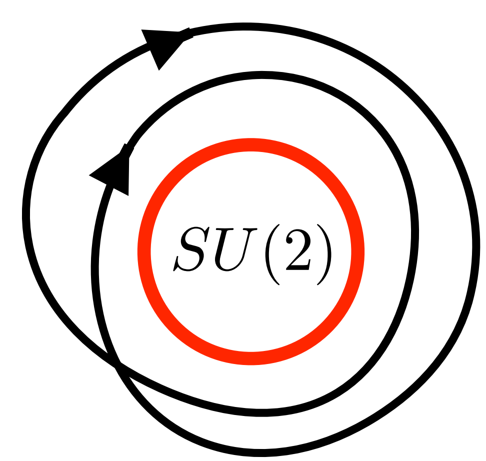
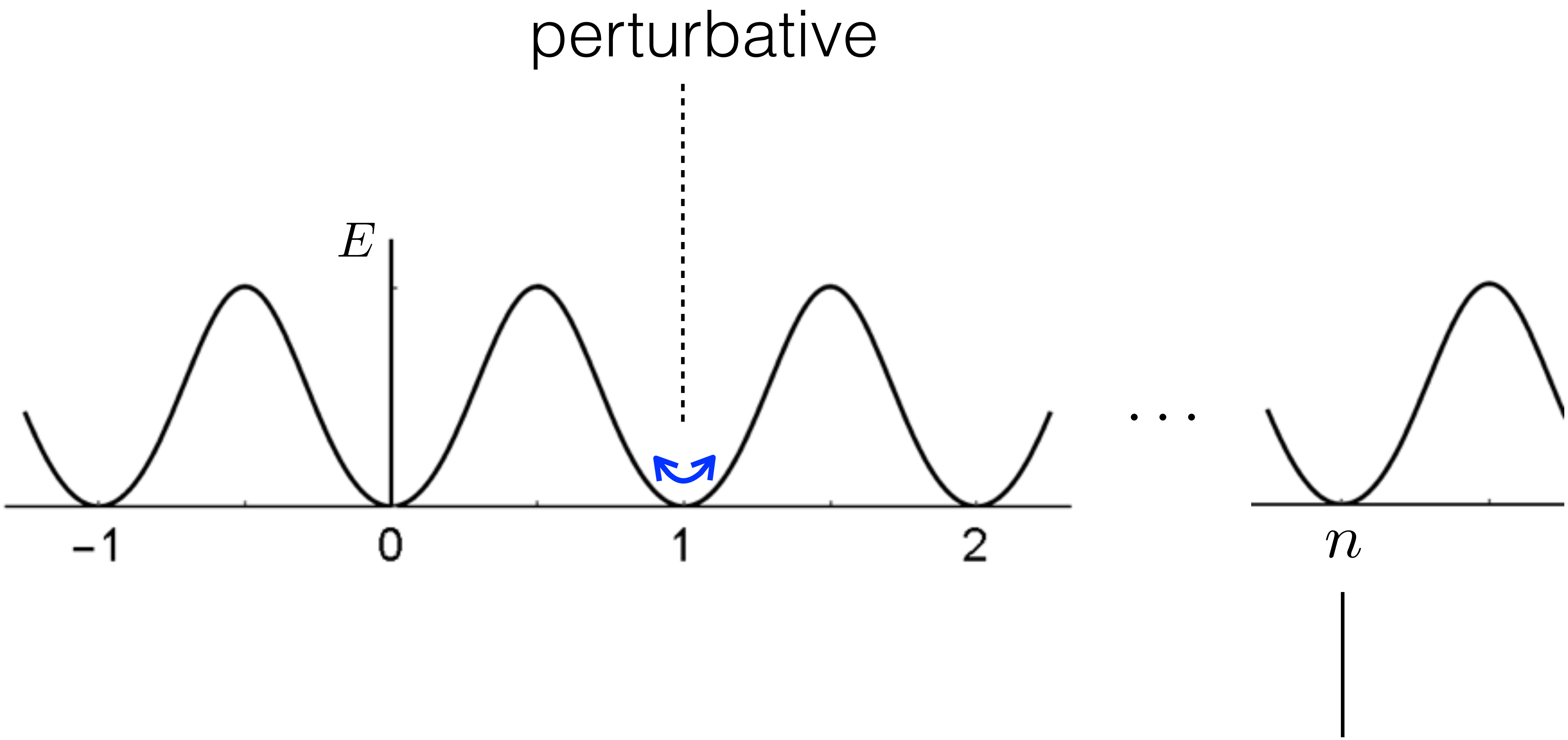


$$\mathbb{R}^3 = S^3 + (\cdot),\ SU(2) = S^3$$

$$\pi_3(S^3) = \mathbb{Z}$$

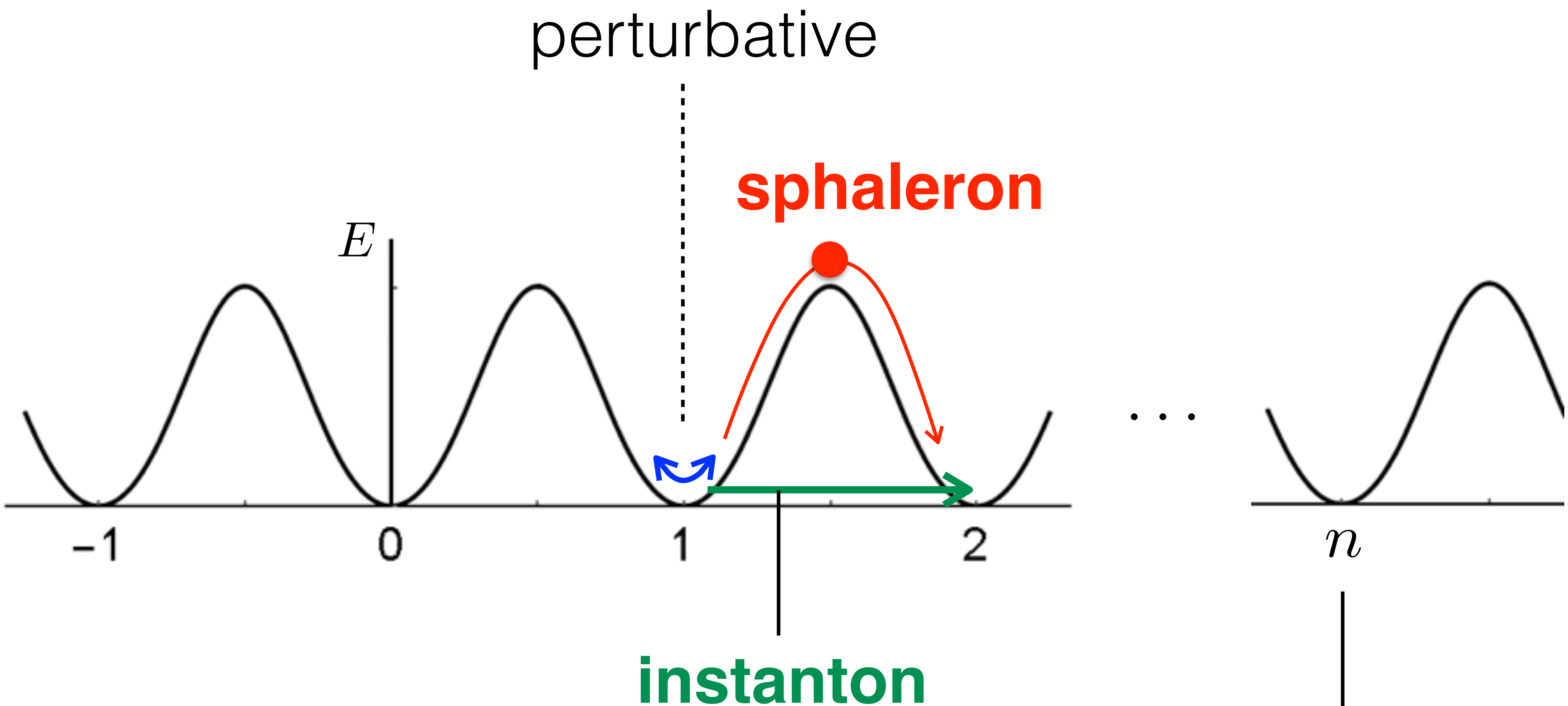


The map has distinctive sectors classified by the winding number!



$$A_{n,\mu}(\mathbf{x}) = U_n(\mathbf{x})^\dagger \partial_\mu U_n(\mathbf{x})$$

$$U_n(\mathbf{x}) = \exp\left(in\pi \frac{\mathbf{x}\cdot\sigma}{\sqrt{\mathbf{x}^2 - \rho^2}} \right)$$



$$A_{n,\mu}(\mathbf{x}) = U_n(\mathbf{x})^\dagger \partial_\mu U_n(\mathbf{x})$$

$$U_n(\mathbf{x}) = \exp\left(i n \pi \frac{\mathbf{x} \cdot \sigma}{\sqrt{\mathbf{x}^2 - \rho^2}} \right)$$

Instantons

finite energy condition:

$F_{\mu\nu}(\mathbf{x}) \to 0 \text{ for } \mathbf{x} \to \infty$

Define a current K as

$$K_\mu = \frac{1}{8\pi^2}\epsilon_{\mu\nu\rho\sigma}\mathrm{tr}A^\nu(\partial^\rho A^\sigma + \frac{2}{3}A^\rho A^\sigma)$$

Then it follows

$$\int K_0(A_n(\mathbf{x}))d^3x = n\,, \qquad \frac{1}{16\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} = \partial^\mu K_\mu\,, \qquad \tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}\,,$$

therefore

$$\int \frac{1}{16\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}d^4x = \int \partial^\mu K_\mu d^3x dt = \left[\int K_0(t,\mathbf{x})d^3x\right]_{t=-\infty}^{t=\infty}$$

$$= n(t=\infty) - n(t=-\infty) = \Delta n$$

There exist evolutions of field configuration that change the winding number.

- What do such processes look like?
- How large is the event rate?

The triangle anomaly gives

$$\partial^\mu J_\mu^{(i)} = \frac{1}{16\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \text{with} \quad J_\mu^{(i)} = \bar{\psi}_L^{(i)} \gamma_\mu \psi_L^{(i)}$$

$$\psi_L^{(i)} = \{\hat{u}_L^\alpha, \hat{c}_L^\alpha, \hat{t}_L^\alpha, \ell_e, \ell_\mu, \ell_\tau\}$$

$$\hat{u}_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; \ell_e = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix}, \cdots$$

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We find 12 related equalities

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The event looks like a fire ball!

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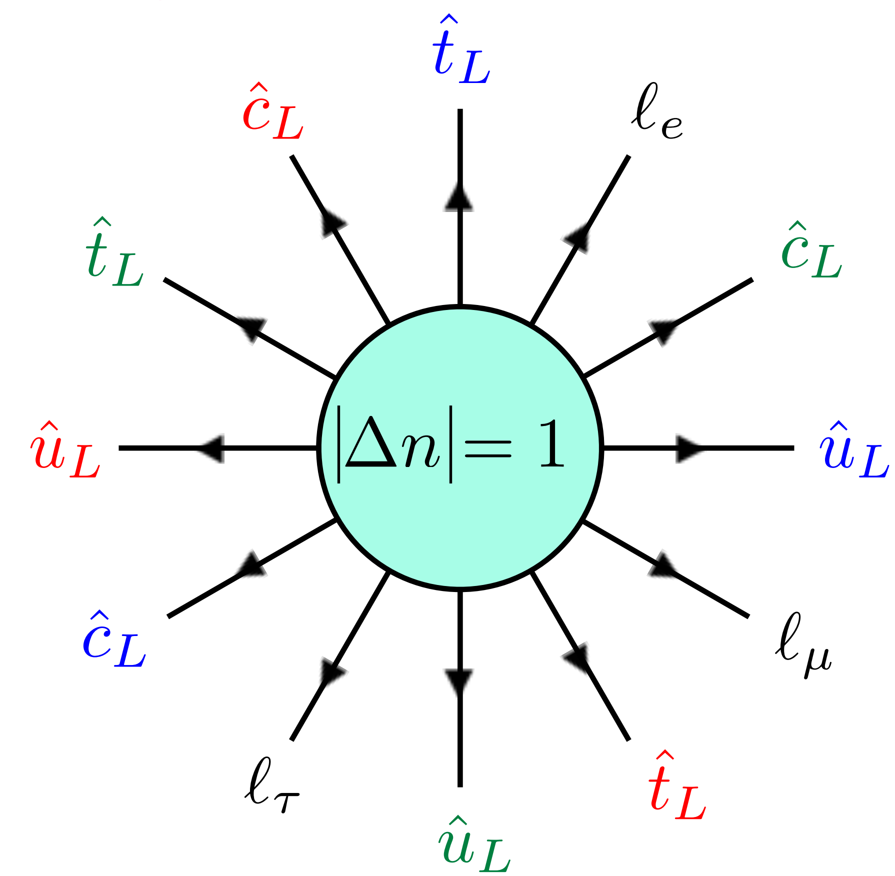

The tunnelling rate can be estimated using the WKB approximation as

$$\langle n | n + \Delta n \rangle \sim e^{-\hat{S}_E}$$

S_E is the Euclidean action at the stationary point, which is given by

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&= \frac{8\pi^2}{g^2} |\Delta n|
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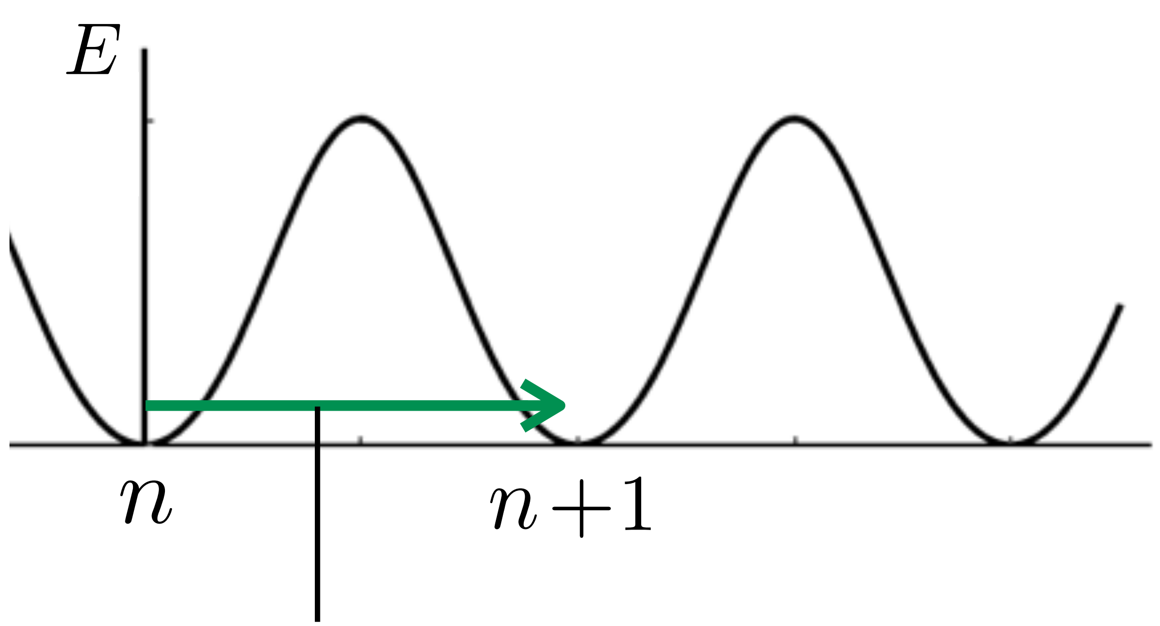
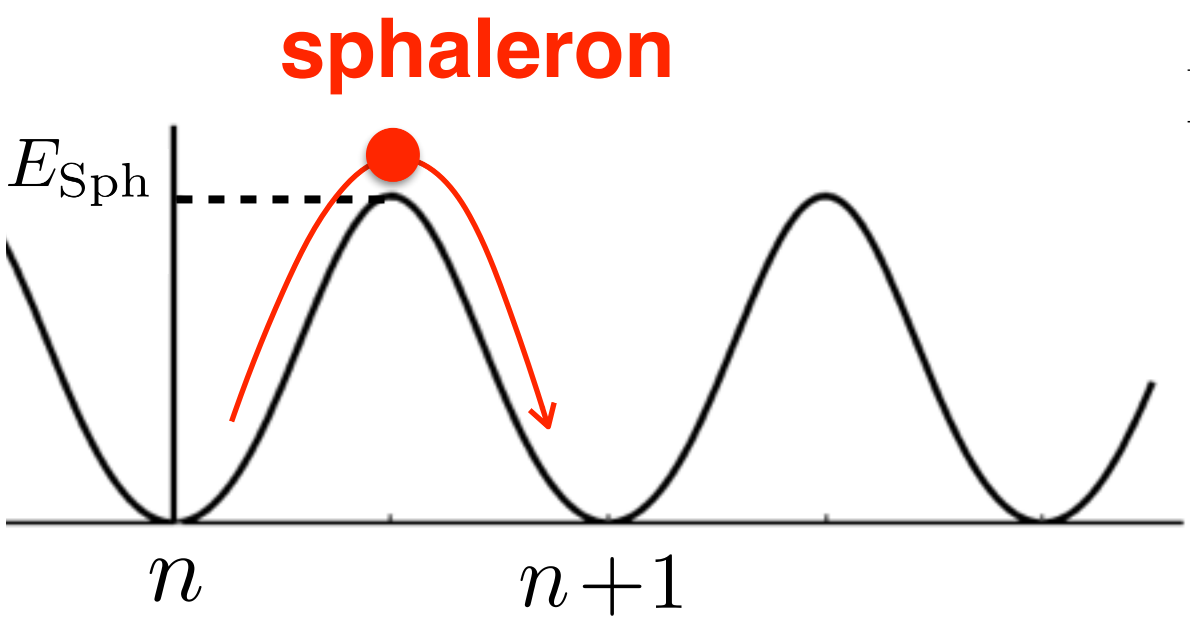


$$e^{-\frac{4\pi}{\alpha_W}} \sim 10^{-170}$$

The tunnelling rate is unobservably small



The barrier hight was calculated by F.R.Klinkhamer and N.S.Manton (1984)

$$E_{\rm Sph} = \frac{2m_W}{\alpha_W} B\left(\frac{m_H}{m_W}\right)$$

$$\simeq 9\,\text{TeV} \quad (\text{for } m_H = 125\text{GeV})$$

- At high temperature, the sphaleron rate may be unsuppressed.

$$\Gamma \propto \exp\left(-\frac{E_{\rm Sph}}{T}\right)$$

It plays an important role in baryo(lepto)genesis.

- At high energy, the tunnelling exponent was calculated by a semi-classical approach (perturbation in the instanton background).

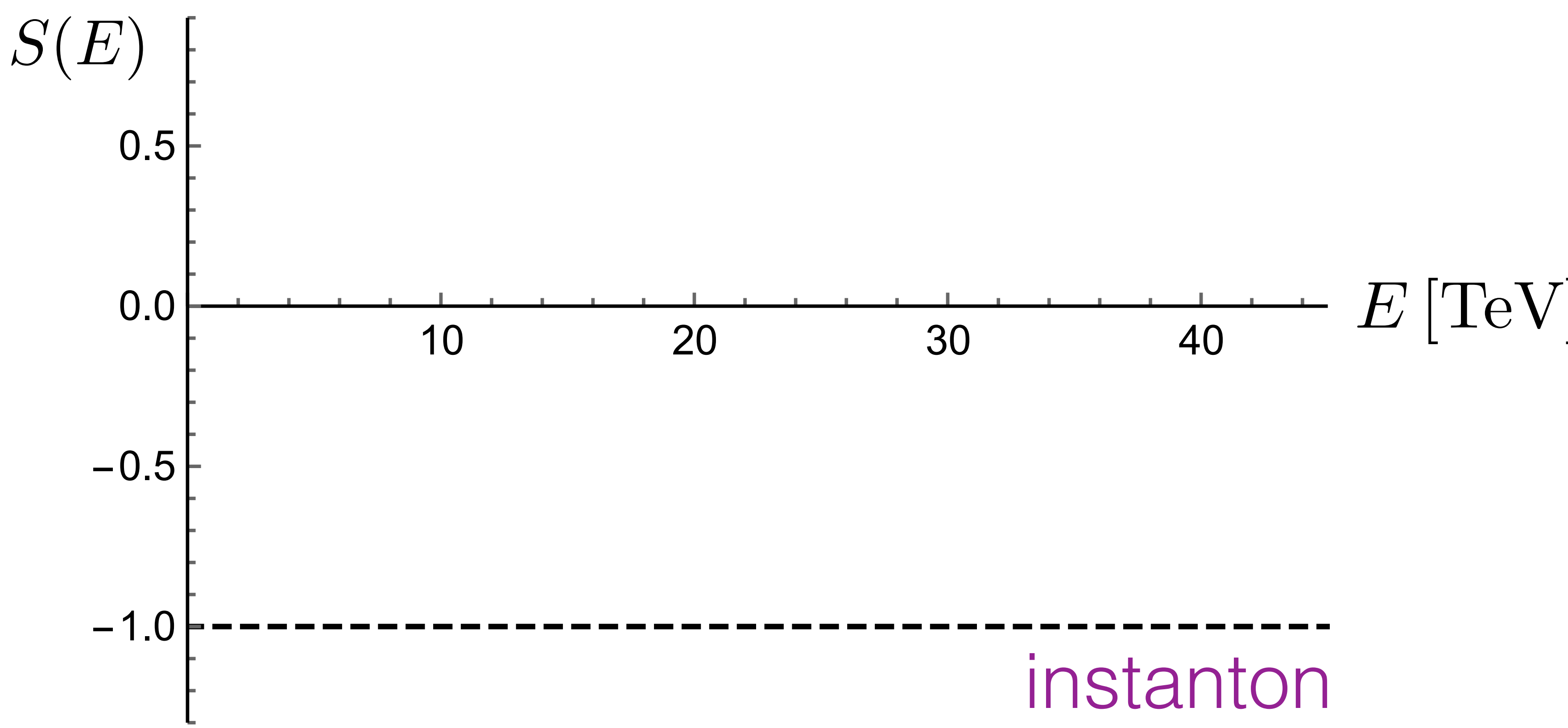
$$\sigma(\Delta n = \pm 1) \propto \exp\left[c\frac{4\pi}{\alpha_W} S(E)\right] \qquad (c \simeq 2)$$

$$S(E) = -1 \ + \cdots$$

$\uparrow$

instanton

$$E_0 = \sqrt{6}\pi m_W/\alpha_W \simeq 18\,\mathrm{TeV}$$



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$$S(E) = -1 + \frac{9}{8}\left(\frac{E}{E_0}\right)^{\frac{4}{3}} + \cdots$$

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S.Khlebnikov, V.Rubakov, P.Tinyakov 1991,
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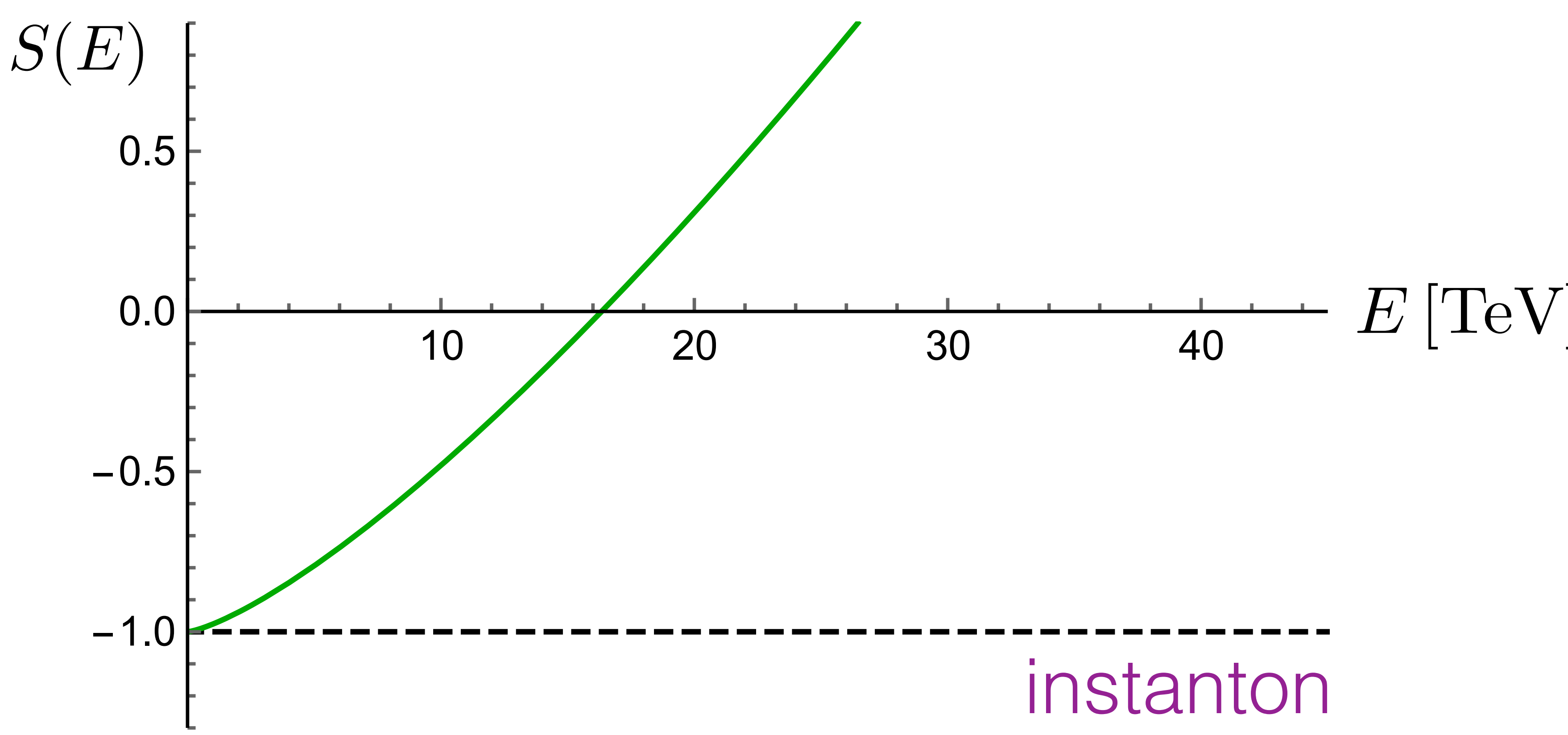

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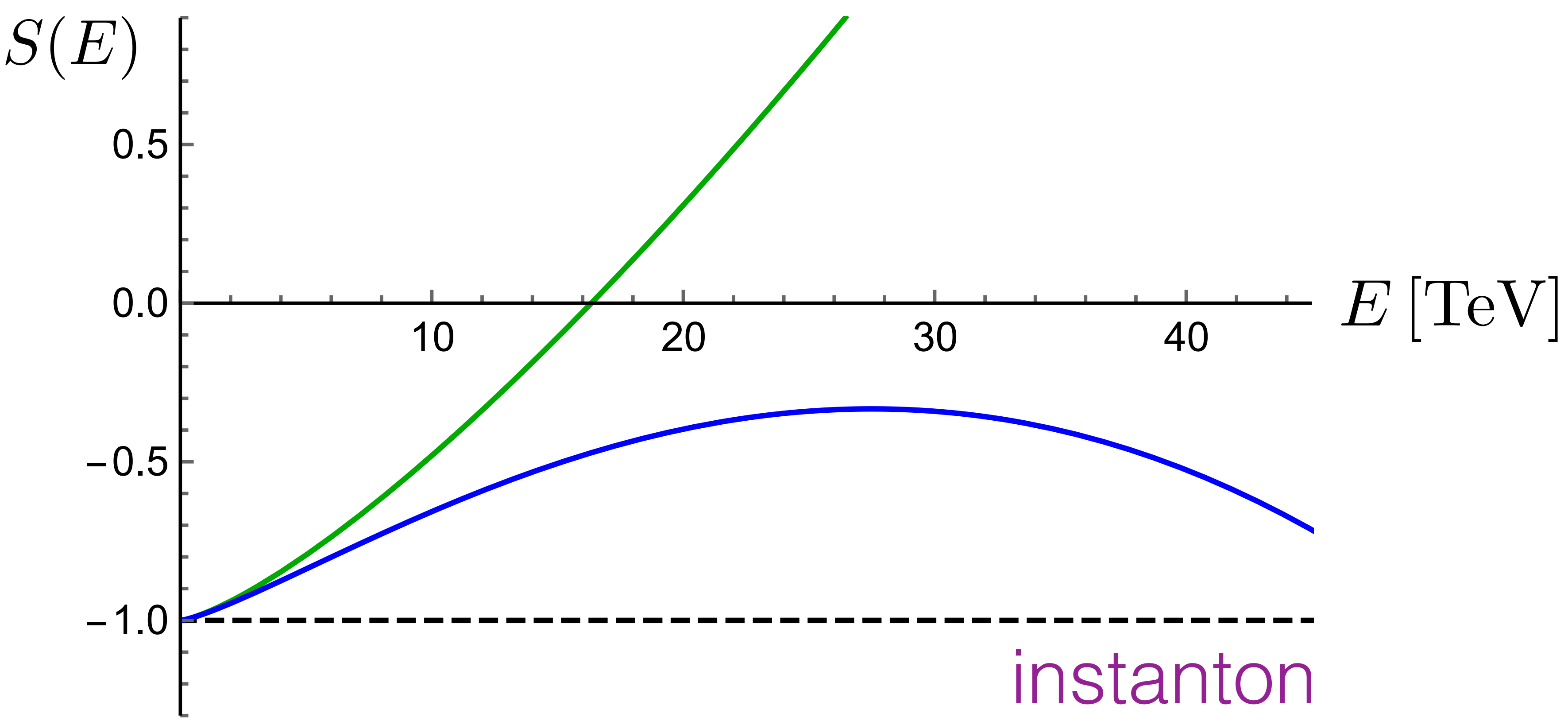
S.Khlebnikov, V.Rubakov, P.Tinyakov 1991, M.Porrati 1990, V.Zakharov 1992, …

P.Arnold, M.Mattis 1991, A.Mueller 1991, D.Diakonov, V.Petrov 1991, …



Recently Tye and Wong (TW) have pointed out that the periodic nature of the EW potential is important and this effect was not taken into account in the previous calculations. They evaluated the sphaleron rate by constructing a 1D quantum mechanical system [1505.03690].

$$\left(-\frac{1}{2m}\frac{\partial^2}{\partial Q^2} + V(Q) \right)\Psi(Q) = E\Psi(Q)$$

where Q is related to the winding number n as

$$Q = \mu/m_W, \quad n\pi = \mu - \sin(2\mu)/2$$

By following a sphaleron trajectory in the original YM Lagrangian, they found:

$$\tilde{\Phi} = v\,(1-h(r))\,U \begin{pmatrix} 0 \\ \cos\mu \end{pmatrix} + h(r) \begin{pmatrix} 0 \\ v \end{pmatrix},$$

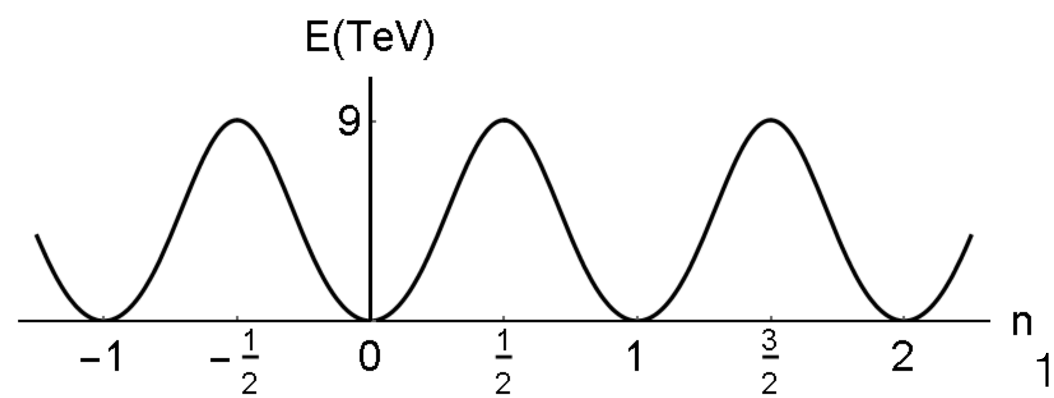
$$A_i = \frac{i}{g}(1-f(r))U\partial_i U^\dagger,$$

$$U = \begin{pmatrix} \cos\mu + i\sin\mu\cos\theta & -\sin\mu\sin\theta e^{i\varphi} \\ \sin\mu\sin\theta e^{-i\varphi} & \cos\mu - i\sin\mu\cos\theta \end{pmatrix}$$

$$\lim_{r\to 0}\frac{f(r)}{r} = h(0) = 0, \quad f(\infty) = h(\infty) = 1,$$

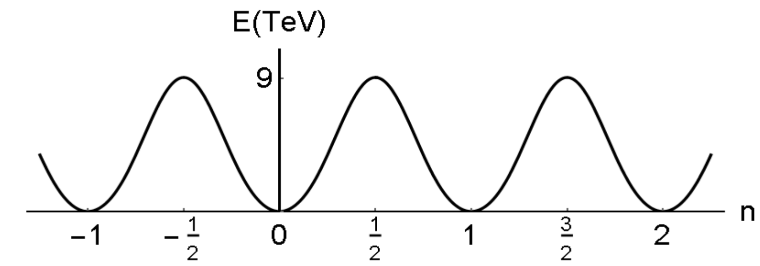
$$V(Q) \simeq 4.75\ \text{TeV}\left(1.31\sin^2(m_W Q) + 0.60\sin^4(m_W Q)\right)$$

$$m = 17.1\ \text{TeV}$$

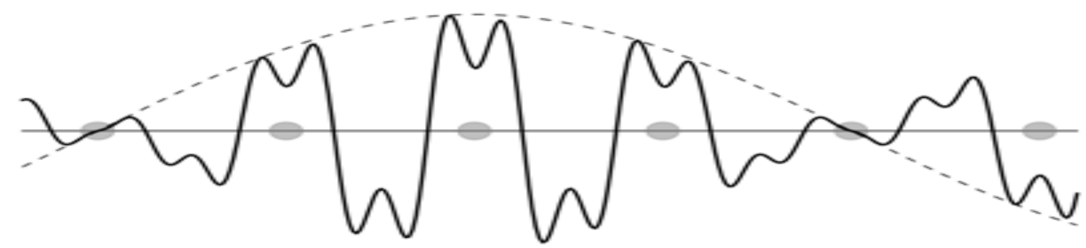


The wave functions in periodic potentials are given by Bloch waves.

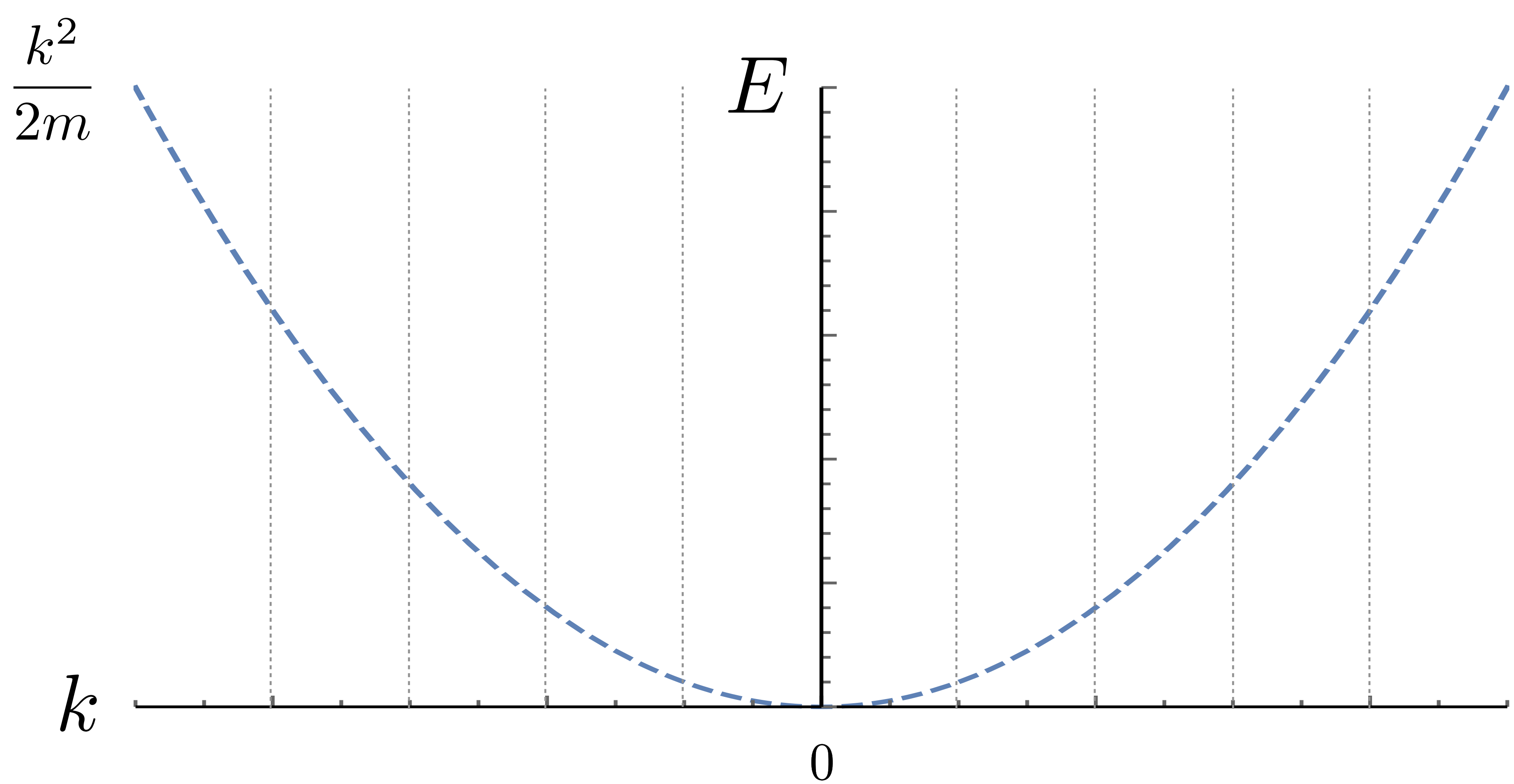
$$\Psi(Q) = e^{ikQ}\, u_k(Q), \quad u_k(Q) = u_k(Q + \tfrac{\pi}{m_W})$$



$$\Longrightarrow \; |\Psi(Q)|^2 = |\Psi(Q + \tfrac{\pi}{m_W})|^2$$



The spectrum exhibits a band structure.



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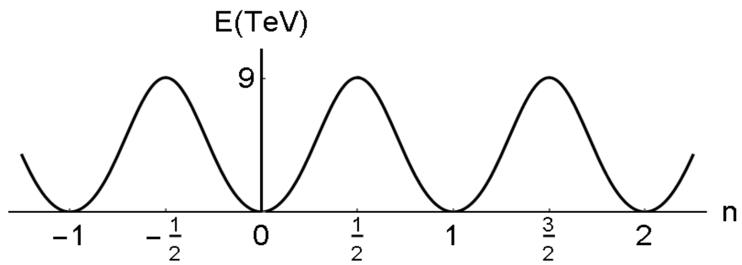
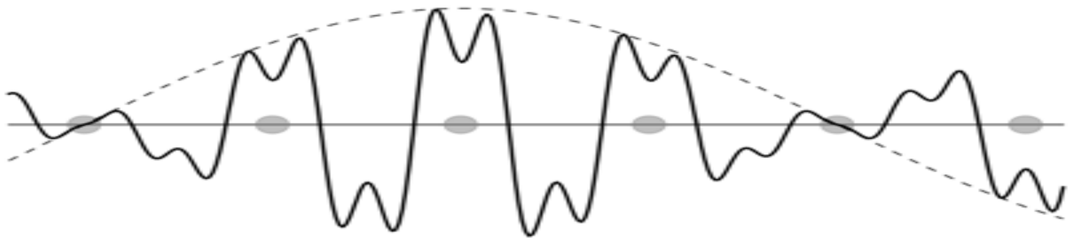


$$\Rightarrow \ |\Psi(Q)|^2 = |\Psi(Q + \frac{\pi}{m_W})|^2$$



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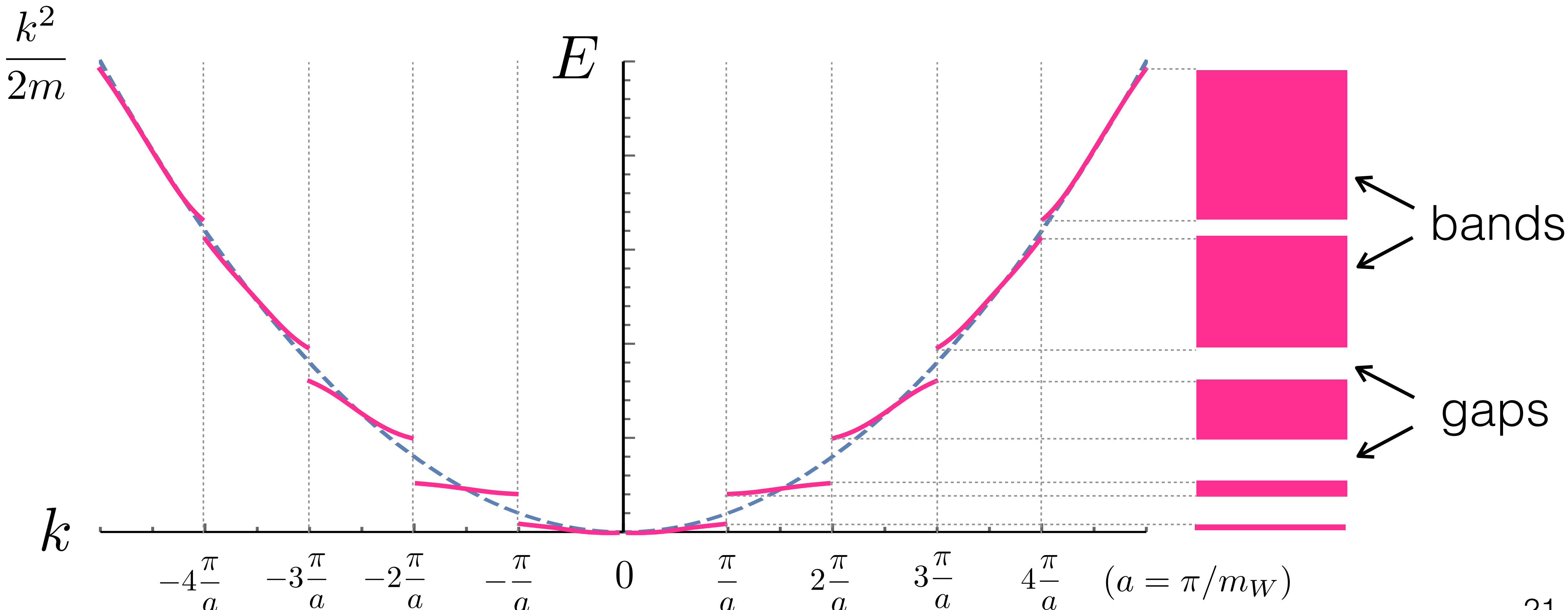
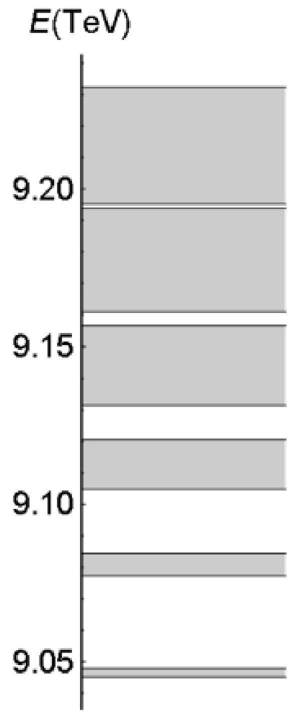
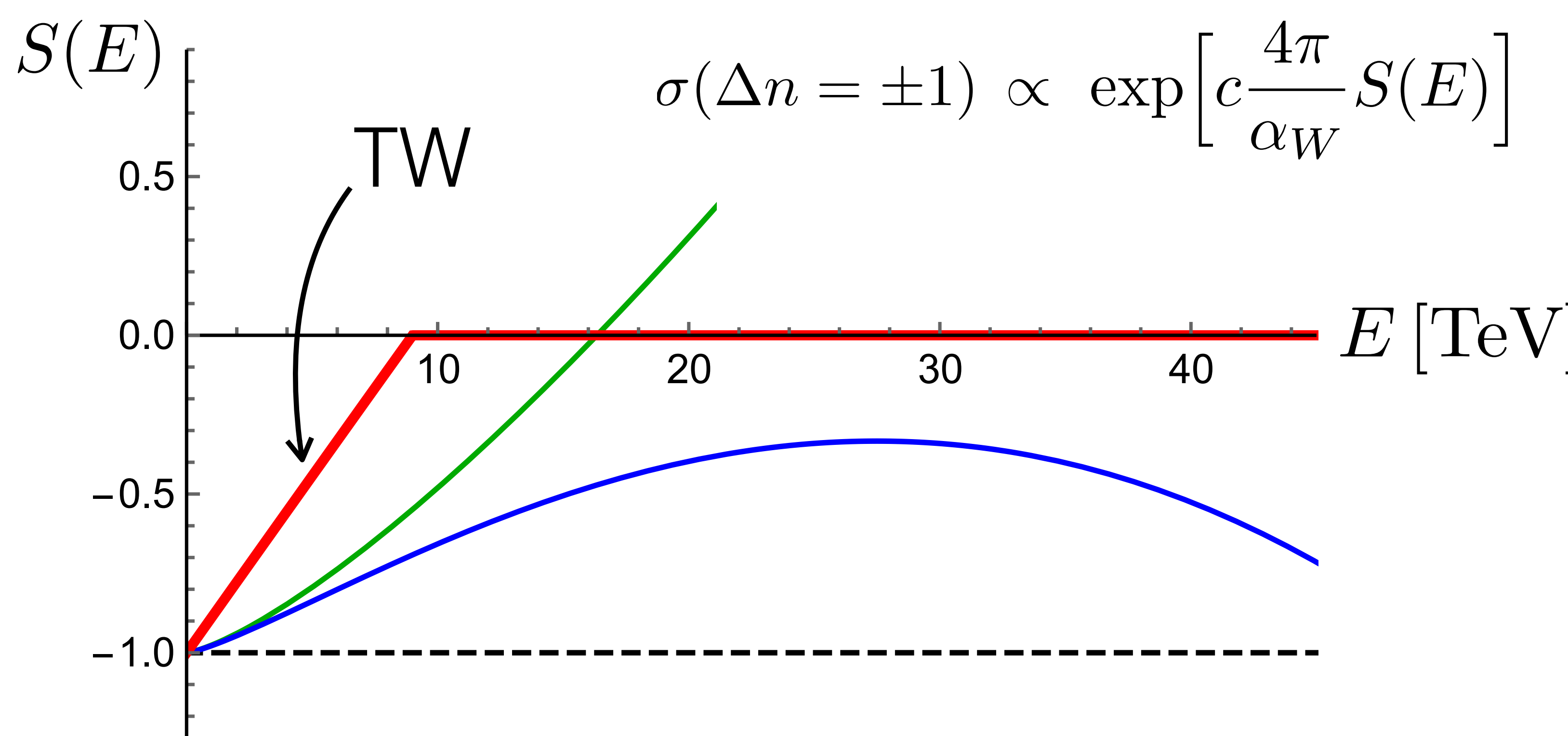




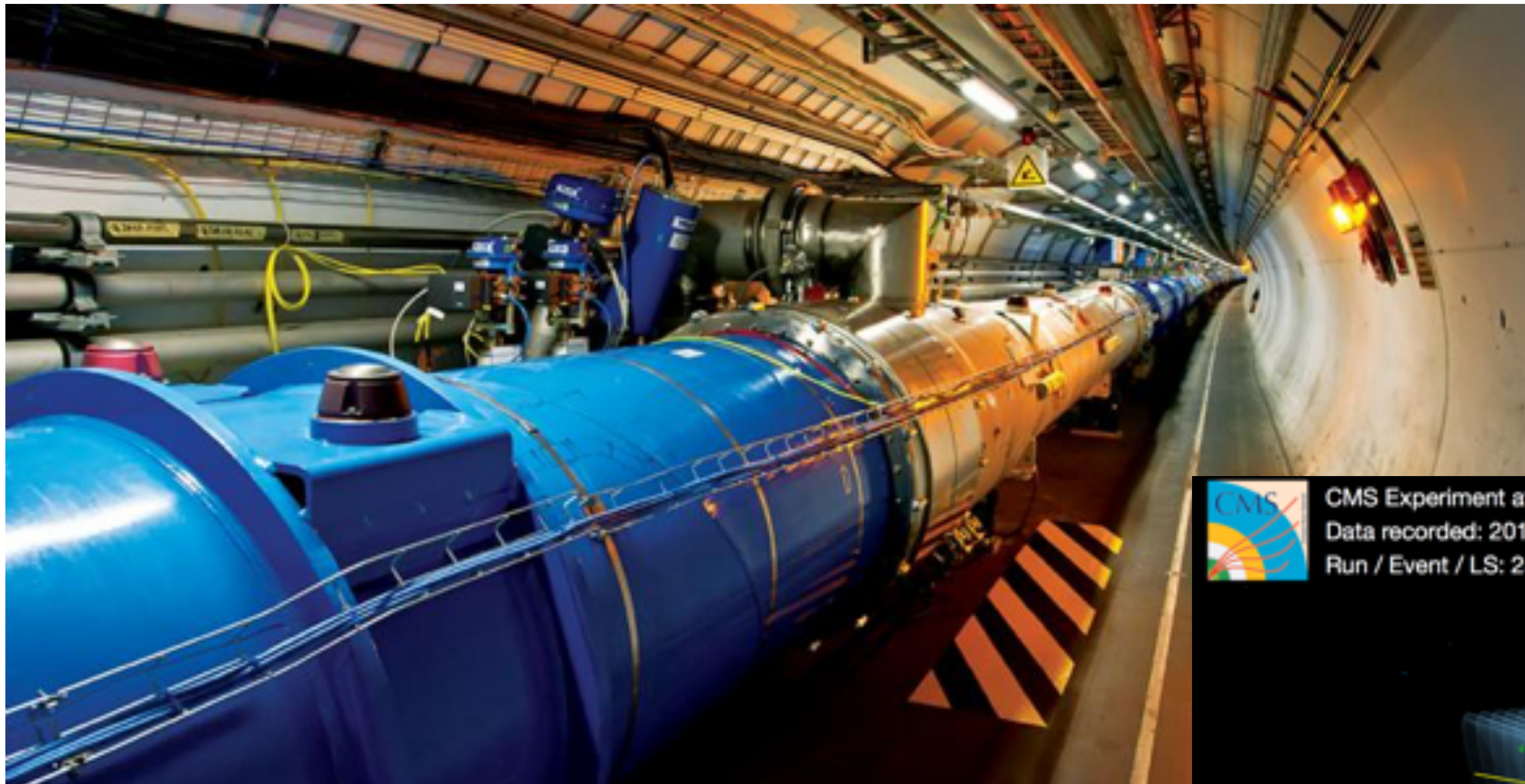
Manton		AKY	
Band center energy(TeV)	Width (TeV)	Band center energy(TeV)	Width (TeV)
9.113	0.01555	9.110	0.01134
9.081	7.192×10^{-3}	9.084	4.957×10^{-3}
9.047	2.621×10^{-3}	9.056	1.718×10^{-3}
9.010	8.255×10^{-4}	9.026	5.186×10^{-4}
8.971	2.382×10^{-4}	8.994	1.438×10^{-4}
8.931	6.460×10^{-5}	8.961	3.747×10^{-5}
8.890	1.666×10^{-5}	8.927	9.279×10^{-6}
8.847	4.114×10^{-6}	8.892	2.198×10^{-6}
8.804	9.779×10^{-7}	8.857	5.008×10^{-7}
8.759	2.245×10^{-7}	8.802	1.101×10^{-7}
8.714	4.993×10^{-8}	8.783	2.341×10^{-8}
8.668	1.078×10^{-8}	8.745	4.828×10^{-9}
8.621	2.262×10^{-9}	8.707	9.673×10^{-10}
8.574	4.622×10^{-10}	8.668	1.886×10^{-10}
8.526	9.210×10^{-11}	8.628	3.580×10^{-11}
8.477	1.792×10^{-11}	8.588	6.622×10^{-12}
8.428	3.411×10^{-12}	8.548	1.211×10^{-12}
8.379	6.395×10^{-13}	8.506	2.167×10^{-13}
8.328	1.208×10^{-13}	8.465	3.553×10^{-14}
⋮	⋮	⋮	⋮
0.3084	$\sim 10^{-169}$	0.3146	$\sim 10^{-204}$
0.2398	$\sim 10^{-171}$	0.2454	$\sim 10^{-207}$
0.1712	$\sim 10^{-174}$	0.1759	$\sim 10^{-209}$
0.1027	$\sim 10^{-177}$	0.1061	$\sim 10^{-212}$
0.03421	$\sim 10^{-180}$	0.03574	$\sim 10^{-216}$

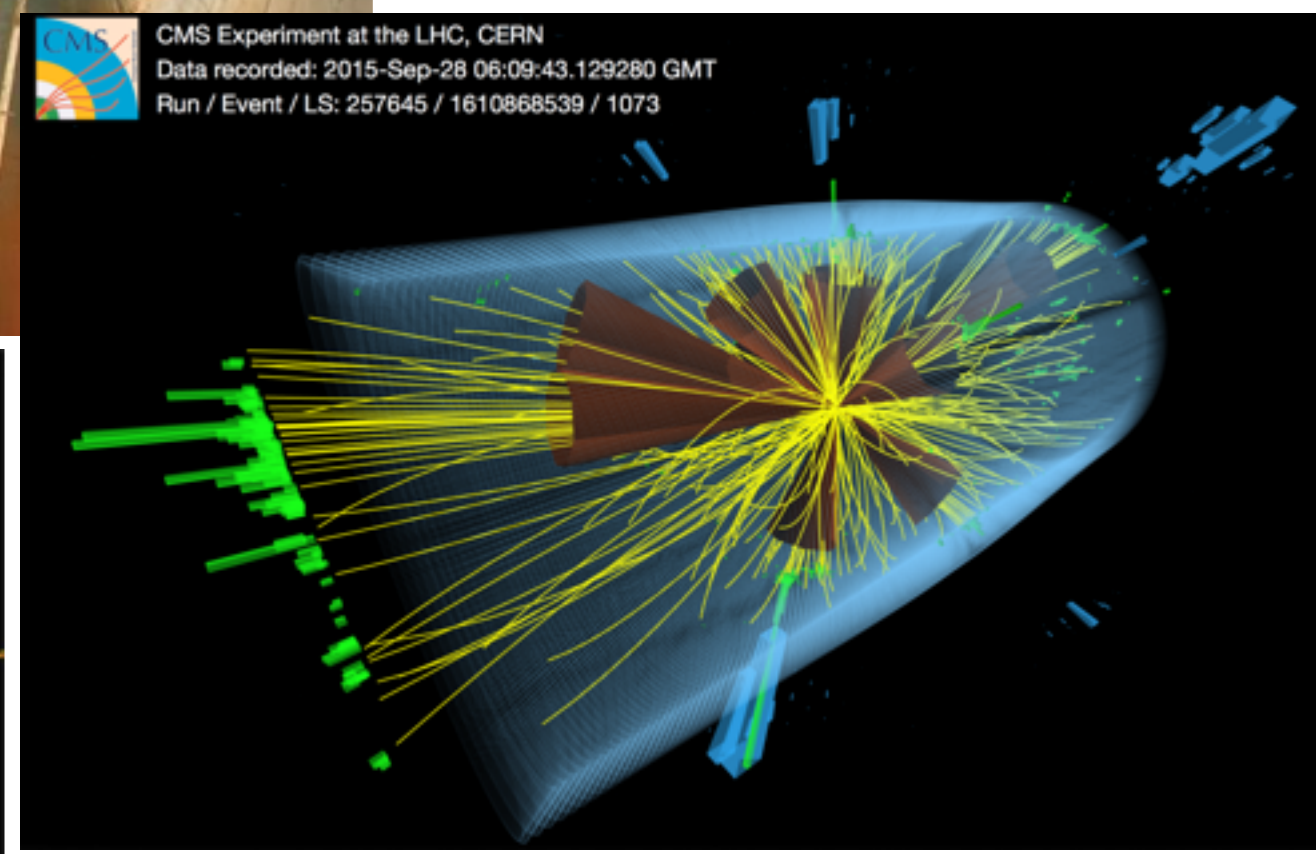
For $E \ll E_{Sph}$, TW found the band width is exponentially small compared to the gap, corresponding to the small tunnelling rate found in the previous calculations.

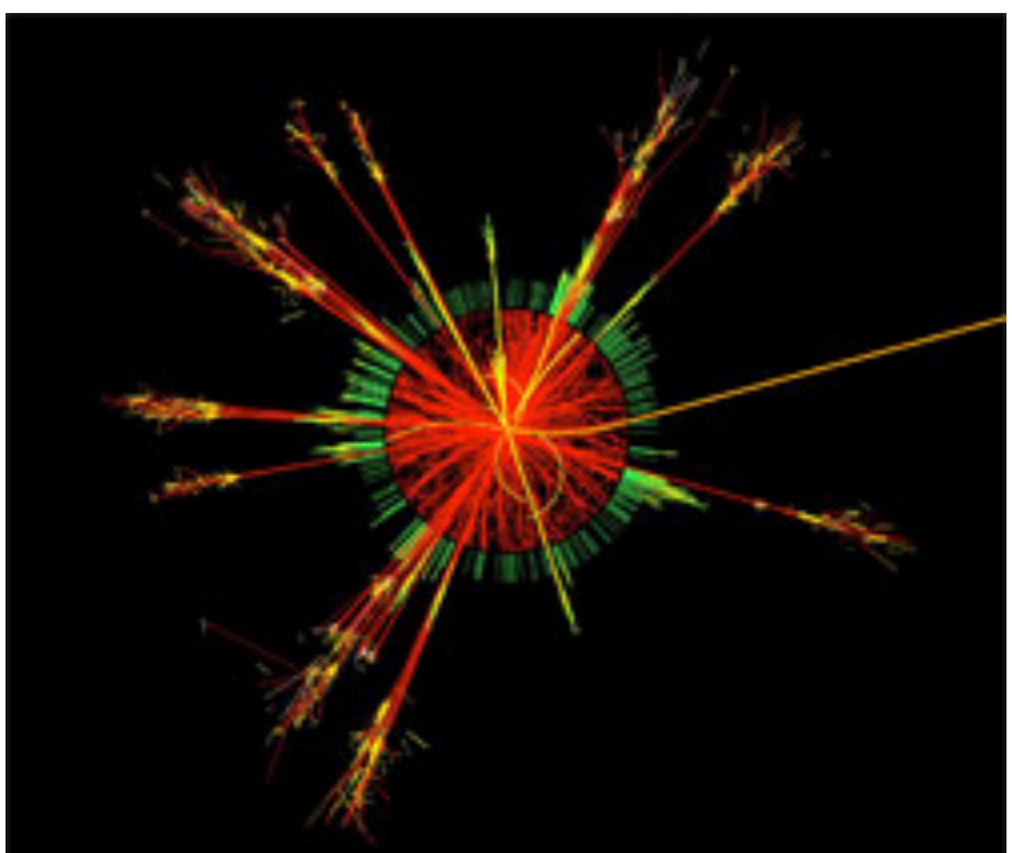
For $E > E_{Sph}$, the wave functions are approximately plane waves with their momentum larger than the potential barrier, implying the exponential suppression disappears!



Sphalerons @ LHC





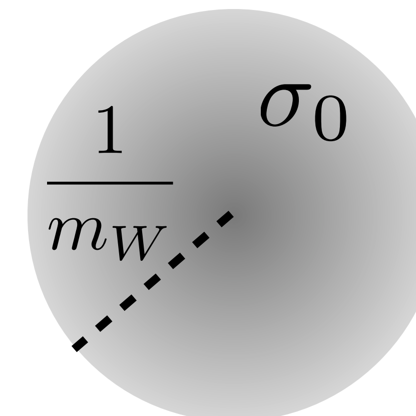


$(c \simeq 2)$

We parametrise the sphaleron production rate as:

$$\sigma(\Delta n = \pm 1) \; = \; \frac{p(E)}{m_W^2} \sum_{ab} \int dE \frac{d\mathcal{L}_{ab}}{dE} \exp\left(c \frac{4\pi}{\alpha_W} S(E) \right)$$

The typical scale is given by $1/m_W$, and the unknown pre-factor is given by $p(E)$, which we assume a constant $p = p(E_{\rm Sph})$, because $\sigma(E)$ very sharply peaks at $E{=}E_{\rm Sph}$.

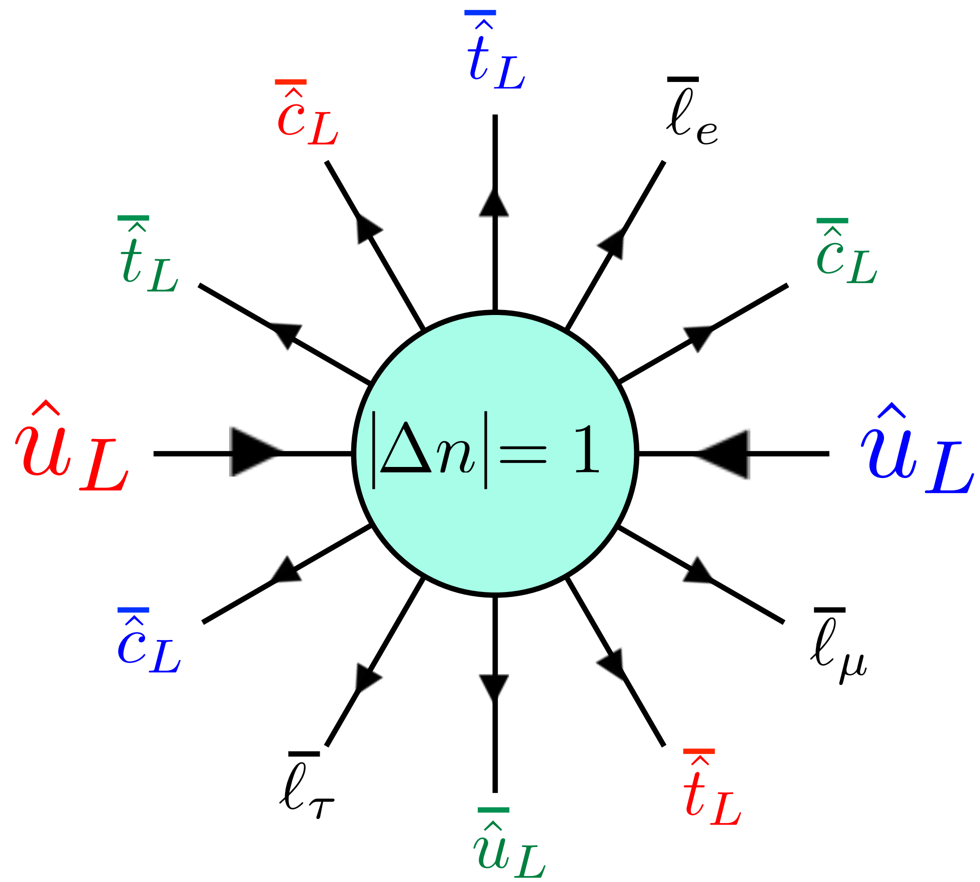


We parametrise and use the TW's exponent as

$$S(E) = \begin{cases} (1-a)\hat{E} + a\hat{E}^2 - 1 & \text{for } \hat{E} < 1 \\ 0 & \text{for } \hat{E} \geq 1 \end{cases} \qquad \hat{E} = E/E_{\rm Sph}$$

The parton luminosity function is given as usual as

$$\frac{d\mathcal{L}_{ab}}{dE} = \frac{2E}{E_{\rm CM}^2} \int_{\ln\sqrt{\tau}}^{-\ln\sqrt{\tau}} dy f_a(\sqrt{\tau} e^y) f_b(\sqrt{\tau} e^{-y}) \qquad (\tau = E^2/E_{\rm Sph}^2)$$



- Only left-handed particles interact.

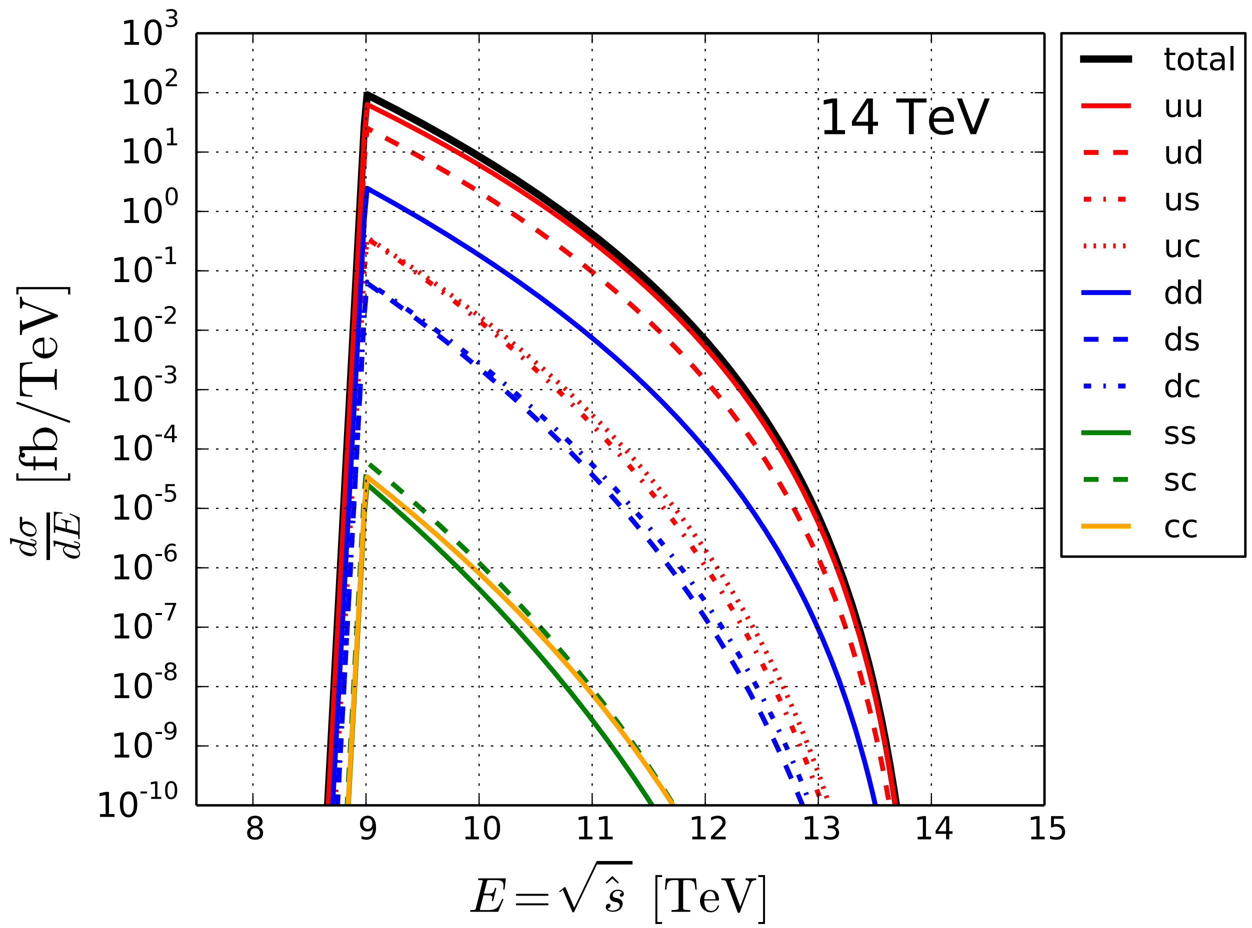
$$f_a(x) \to \frac{1}{2} f_a(x)$$

- For collisions of the same generation particles, their colour charges have to differ.

$$f_a(x) f_b(x) \to \frac{1}{3} f_a(x) f_b(x)$$

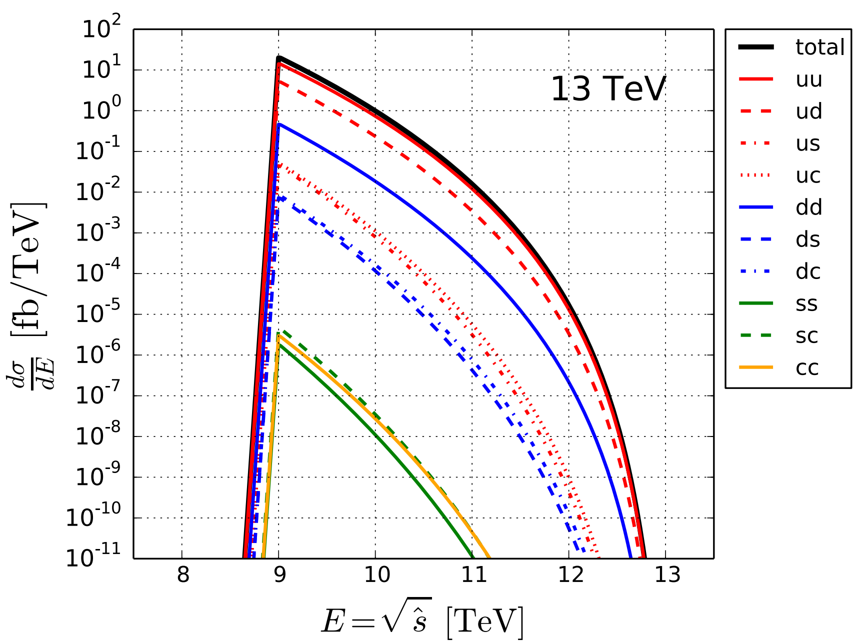
(if a, b are the same generation)

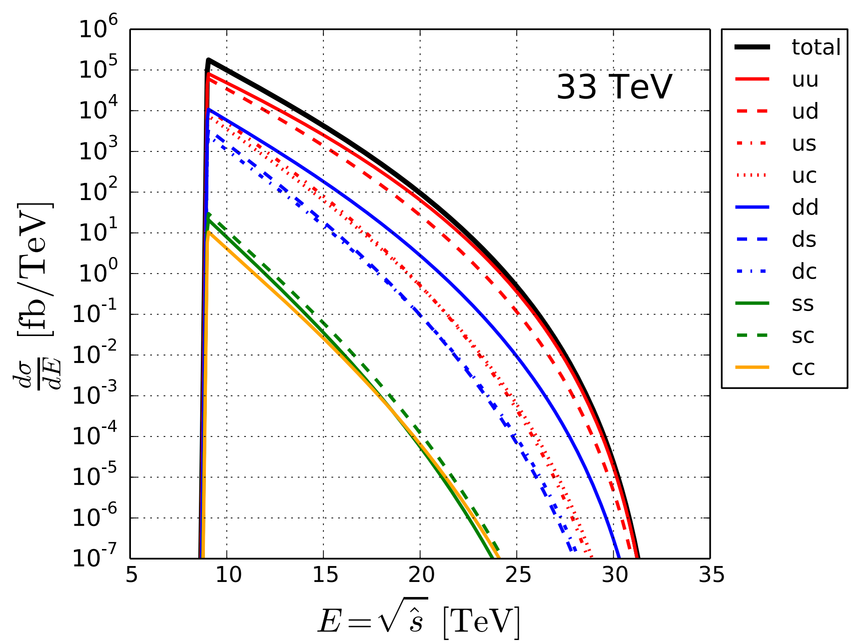
Differential Cross Section

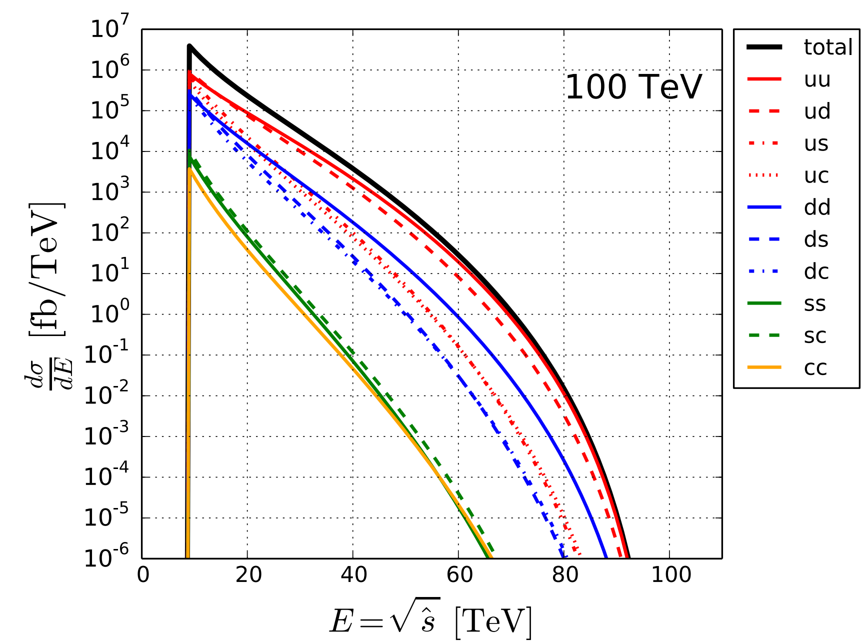


$$p(E) = p = 1$$

$$E_{\rm Sph} = 9\,\text{TeV}$$

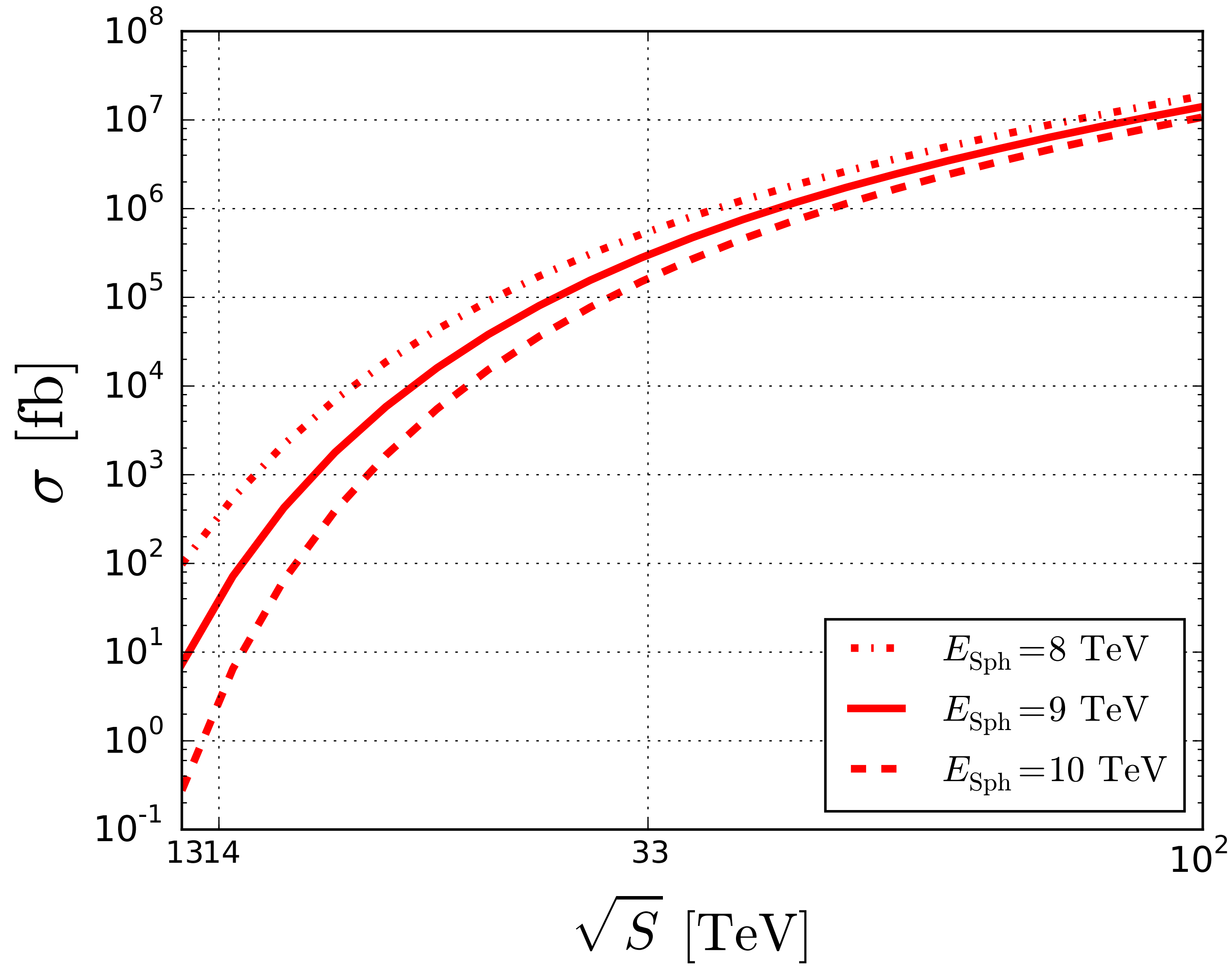






J. Ellis, KS [1601.03654]

Cross Section



$p = 1$

$E_{\rm Sph} = 9\,\rm TeV$

	Sphaleron	gg->H
13 TeV	7.3 fb	44 x 10^3 fb
14 TeV	41 fb	50 x 10^3 fb
33 TeV	0.3 x 10^6 fb	0.2 x 10^6 fb
100 TeV	141 x 10^6 fb	0.7 x 10^6 fb

J. Ellis, KS
[1601.03654]

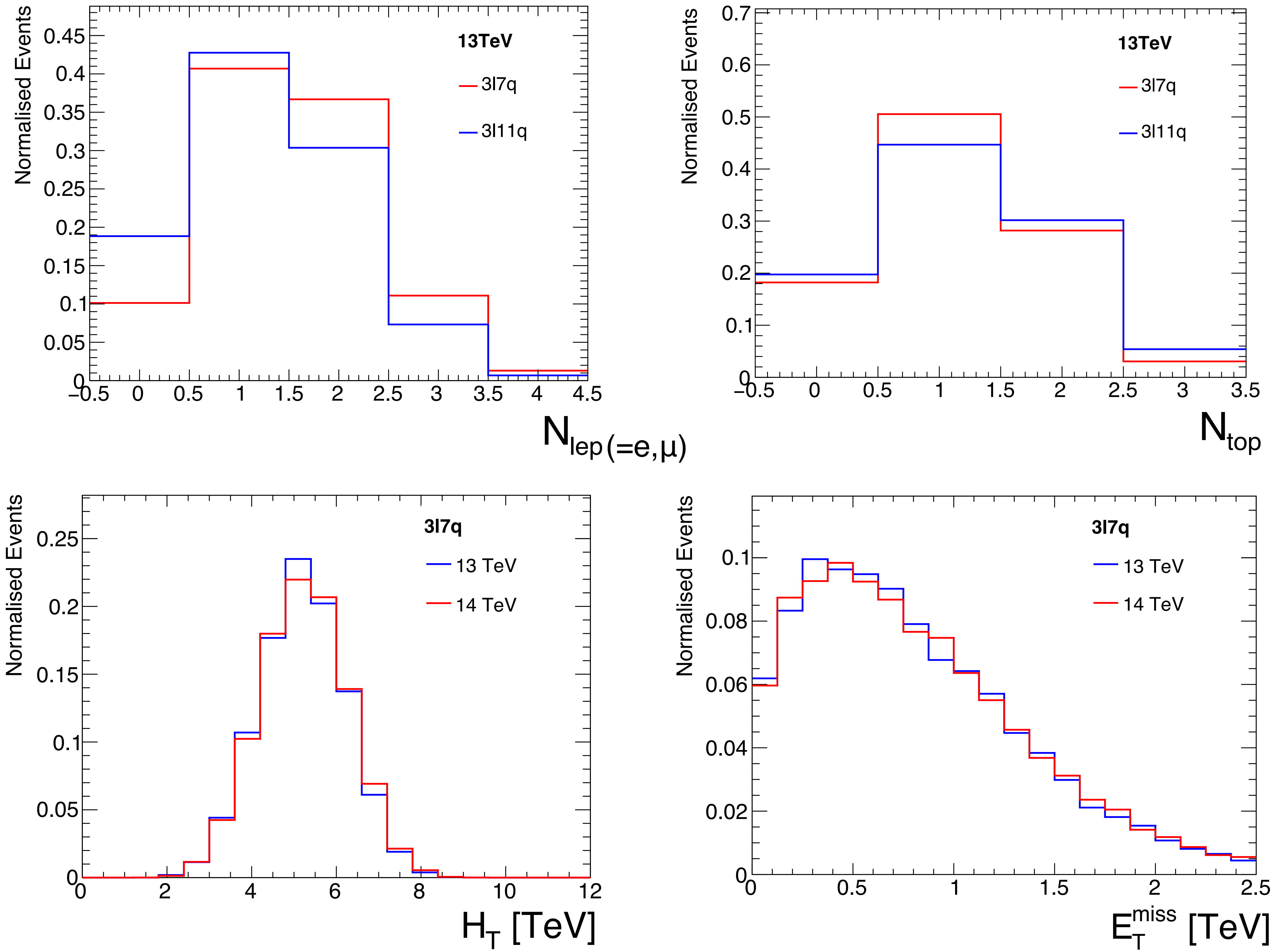
Event generation

- We use our own toy MC code. There is a public code **HERBVI** (by M.Gibbs, B.Webber).
- We generate a quanta with its mass √s and decay it to fermions according to the phase space.

$$\langle \mathsf{F} | \underbrace{(\bar\ell_e \bar\ell_\mu \bar\ell_\tau)(\bar q \bar q \bar q)(\bar q \bar q \bar q)(\bar q \bar q \bar q)}_{\Delta n = -1} | \mathsf{I} \rangle \quad \Longrightarrow \quad qq \to 3\bar\ell + 7\bar q$$

$$\langle \mathsf{F} | \underbrace{(\ell_e \ell_\mu \ell_\tau)(qqq)(qqq)(qqq)}_{\Delta n = +1} \cdot (\bar q q) \cdot (\bar q q) | \mathsf{I} \rangle \quad \Longrightarrow \quad qq \to 3\ell + 11q$$

- We randomly picks SU(2) component but takes it only if the net EM charge is conserved.
- We decay *t*, *W* and *τ* in our simulation.

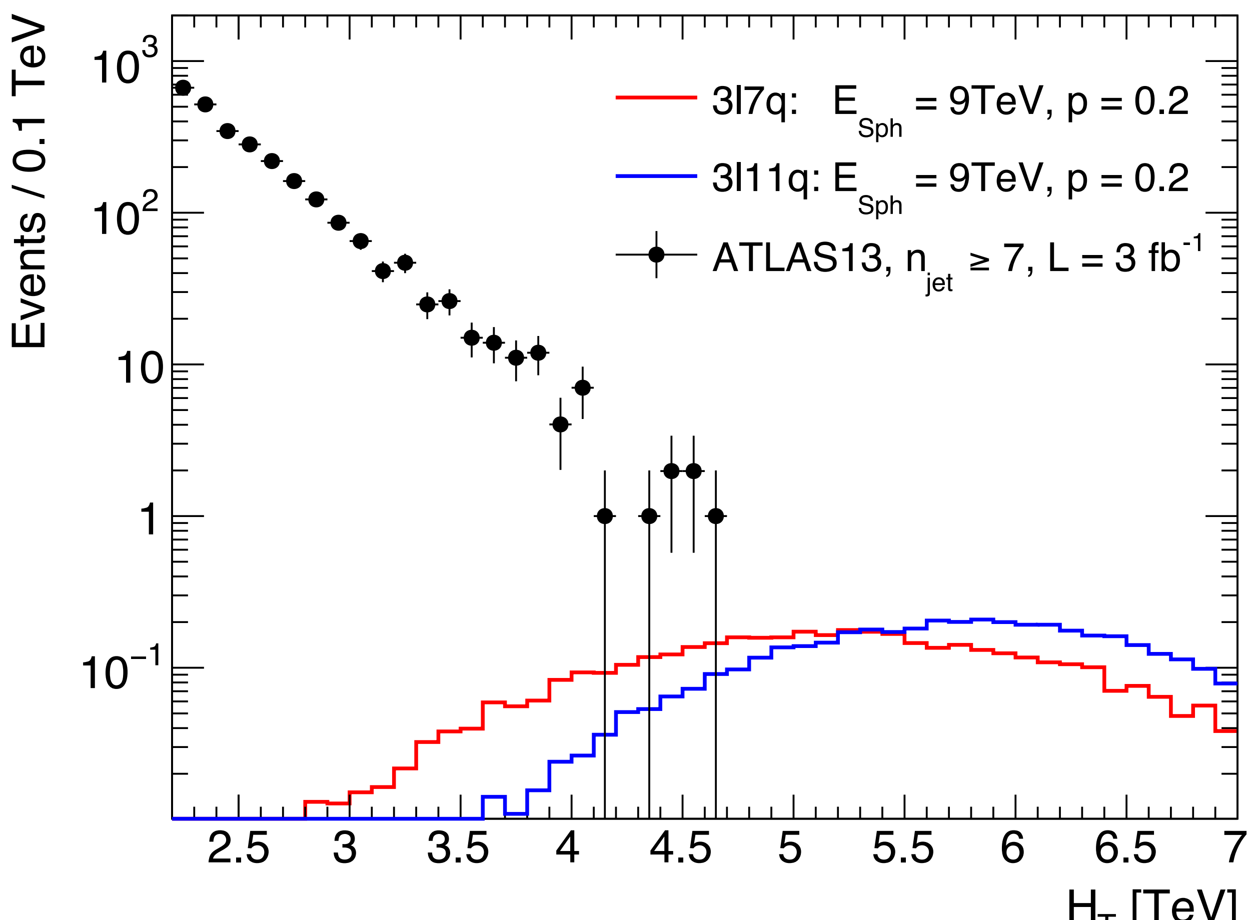


$$H_T = \sum_i p_T^{\mathrm{jet},i}$$

J.Ellis, KS [1601.03654]

We confront our sphaleron events with the ATLAS mini black hole search results @ 13TeV with 3.6/fb [1512.02586], where the signal regions are defined for different # of jets and H_T.

$n_{\rm jet} \geq$	$H_{\rm T} > H_{\rm T}^{\rm min}$ (TeV)	Expected limit (fb)	Observed limit (fb)
3	5.8	$1.63^{+0.70}_{-0.57}$	1.33
4	5.6	$1.77^{+0.70}_{-0.57}$	1.77
5	5.5	$1.56^{+0.73}_{-0.50}$	1.75
6	5.3	$1.52^{+0.69}_{-0.50}$	2.15
7	5.4	$1.02^{+0.36}_{-0.0}$	1.02
8	5.1	$1.01^{+0.29}_{-0.0}$	1.01



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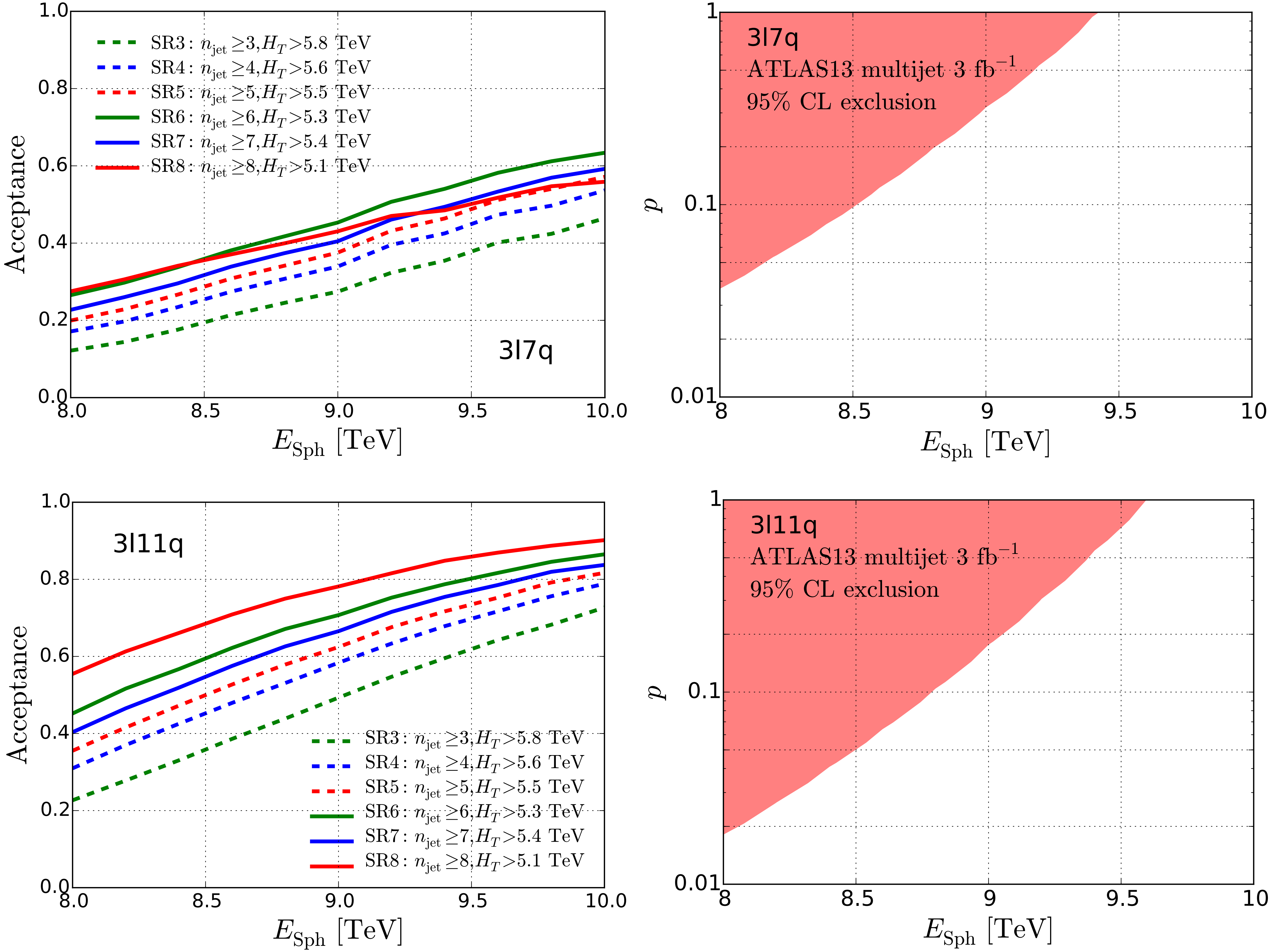
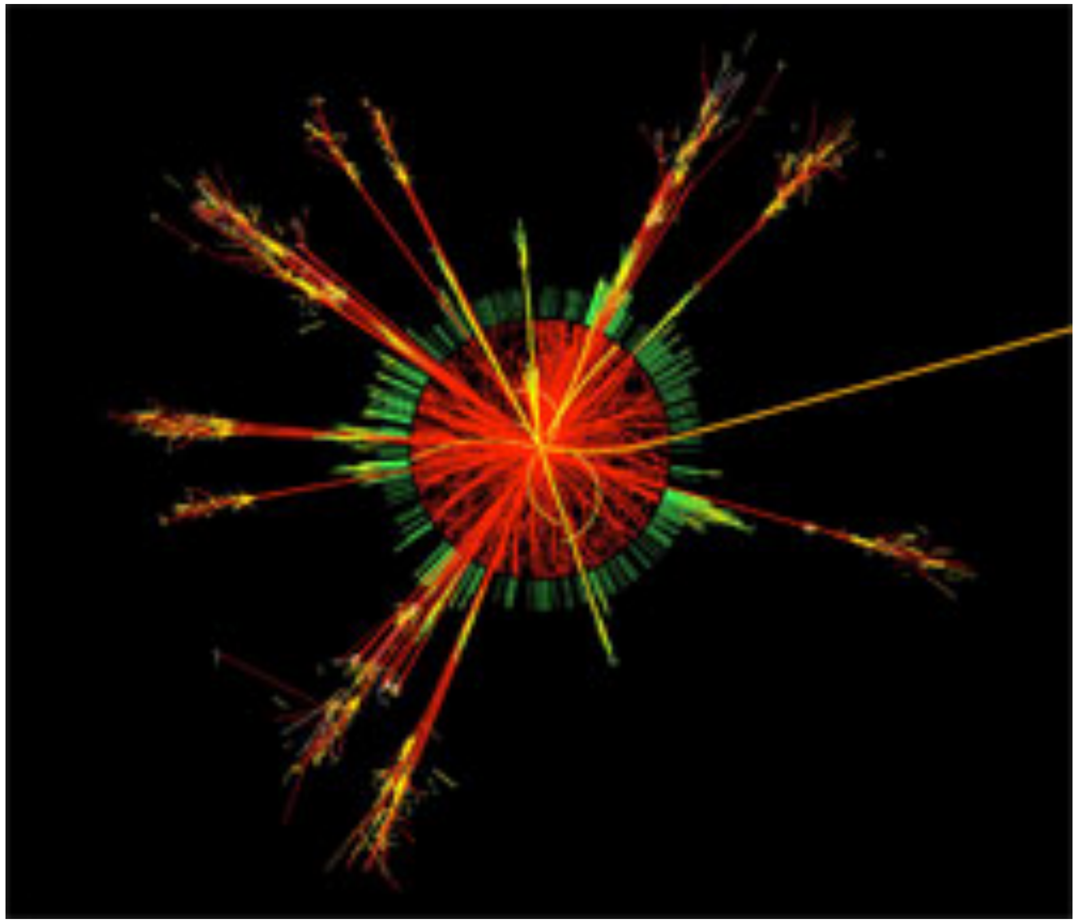
J.Ellis, KS [1601.03654]



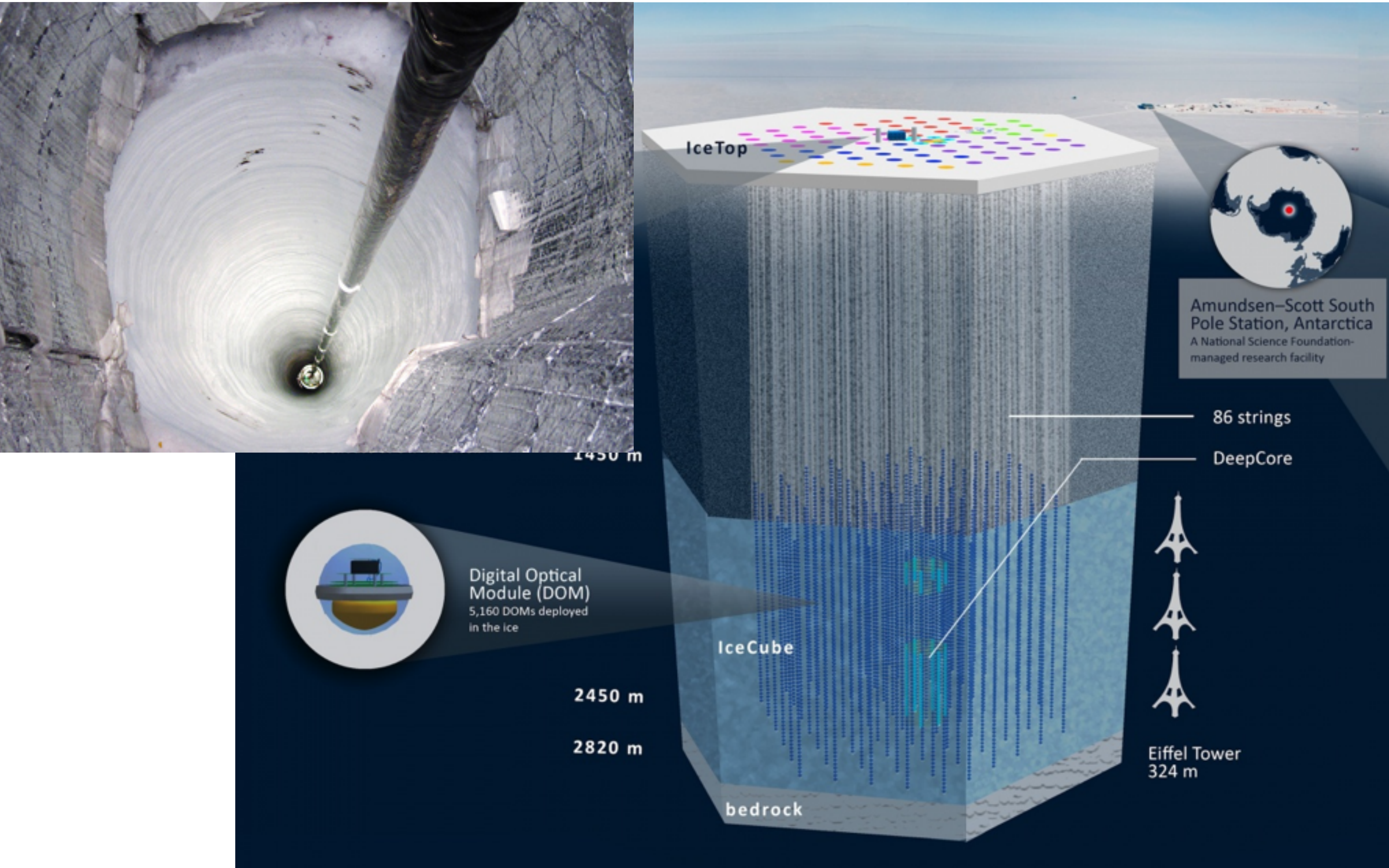
The best expected SR is SR8 for $E_{\rm Sph}$ < 9.3TeV, SR7 otherwise.

J.Ellis, KS [1601.03654]

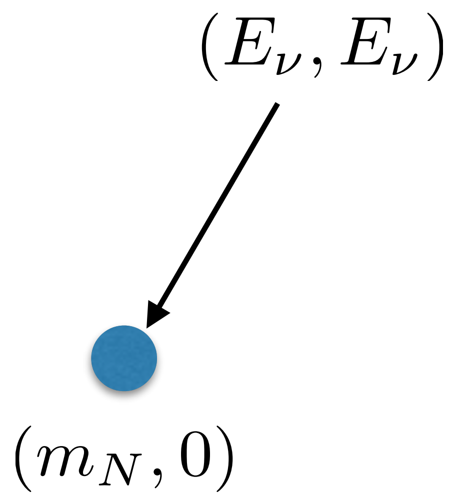


If LHC finds an excess in a black hole signature, can we distinguish it from sphaleron signature?

Sphalerons @ IceCube



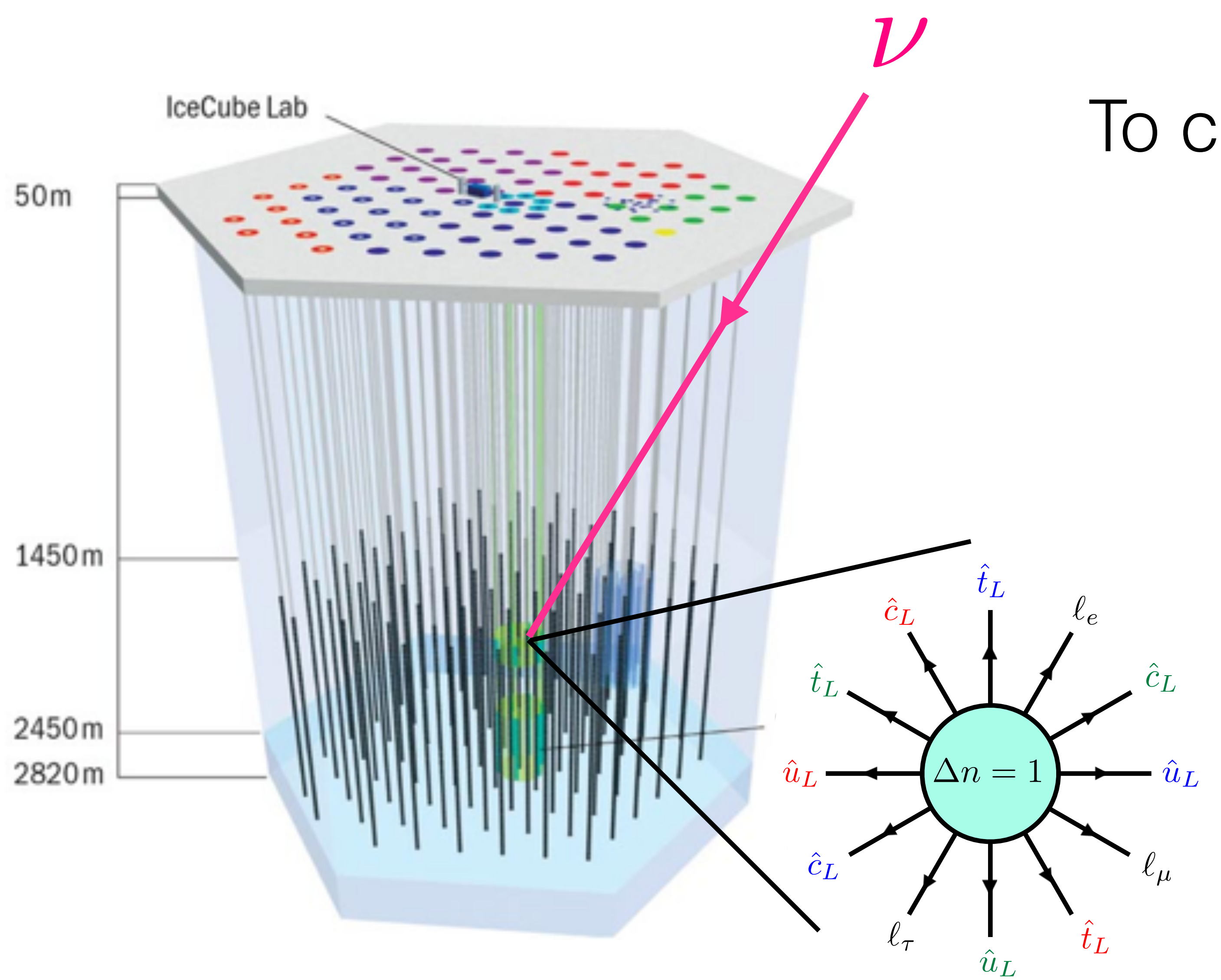
What neutrino energy is required to create a sphaleron?



$$s_{N\nu} = E^2 - p^2 = (m_N + E_N)^2 - E_N^2 \simeq 2 m_N E_\nu$$

$$s_{q\nu} \simeq 2 x m_N E_\nu \quad (x = E_q / E_N)$$

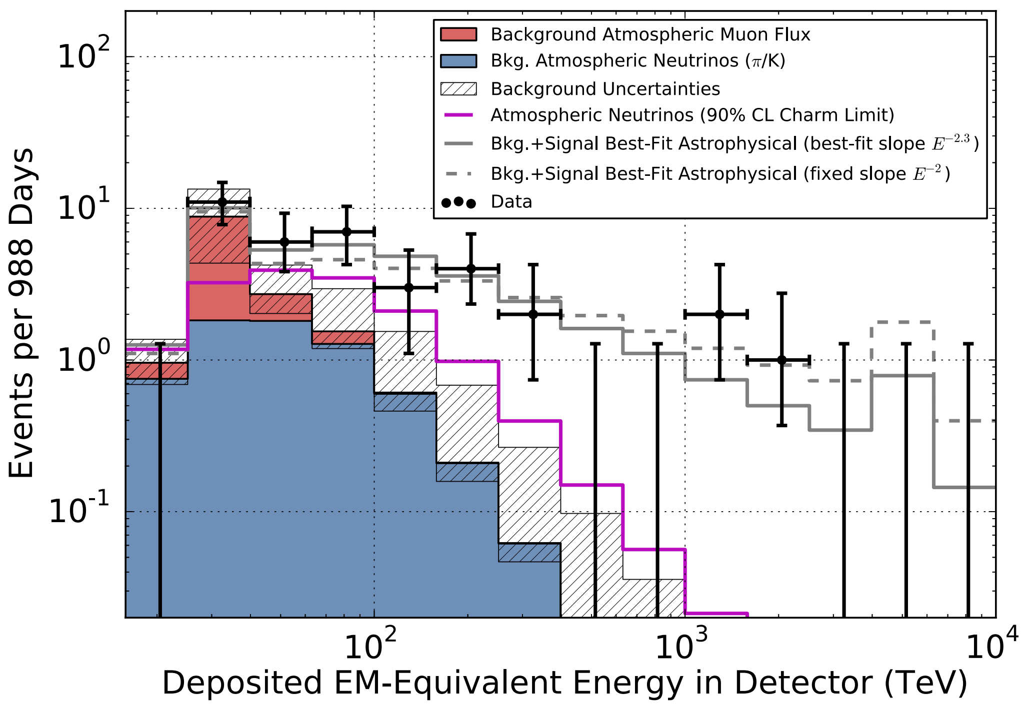
$$E_\nu \geq \frac{E_{\rm Sph}^2}{2 x m_N} \simeq \frac{(9\,{\rm TeV})^2}{2x(0.94\,{\rm GeV})} \simeq \frac{4 \cdot 10^7}{x}\,{\rm GeV}$$



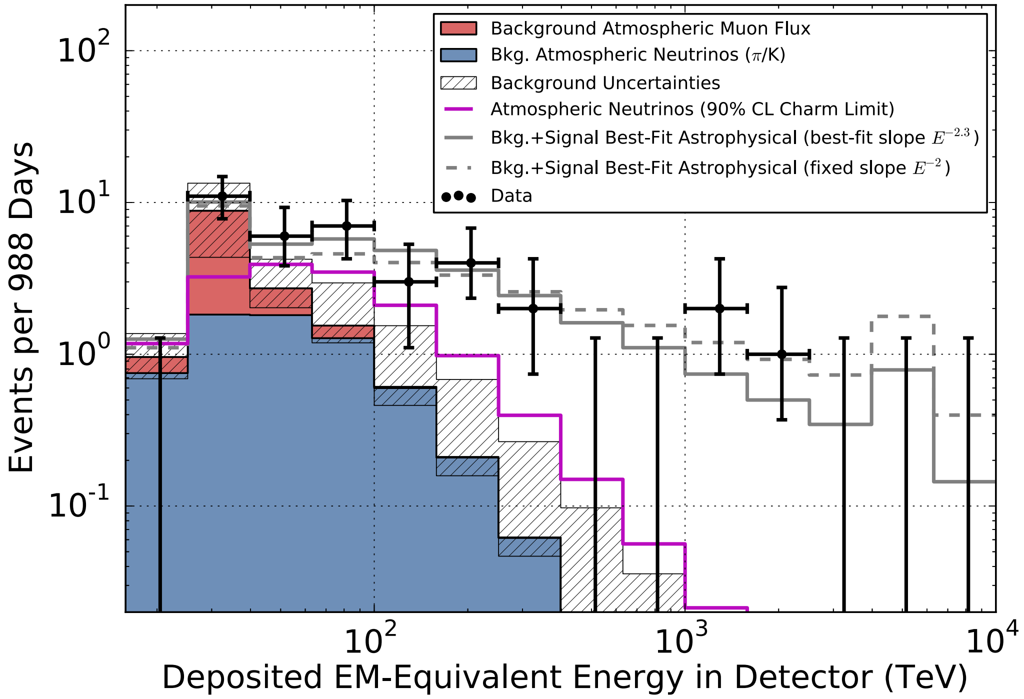
To create a sphaleron, one needs

$$E_\nu \gtrsim 10^{8-10}\,{\rm GeV}$$

$$({\rm for}\ 10^{-3} \lesssim x \lesssim 10^{-1})$$



~10^6 GeV neutrinos have been observed.



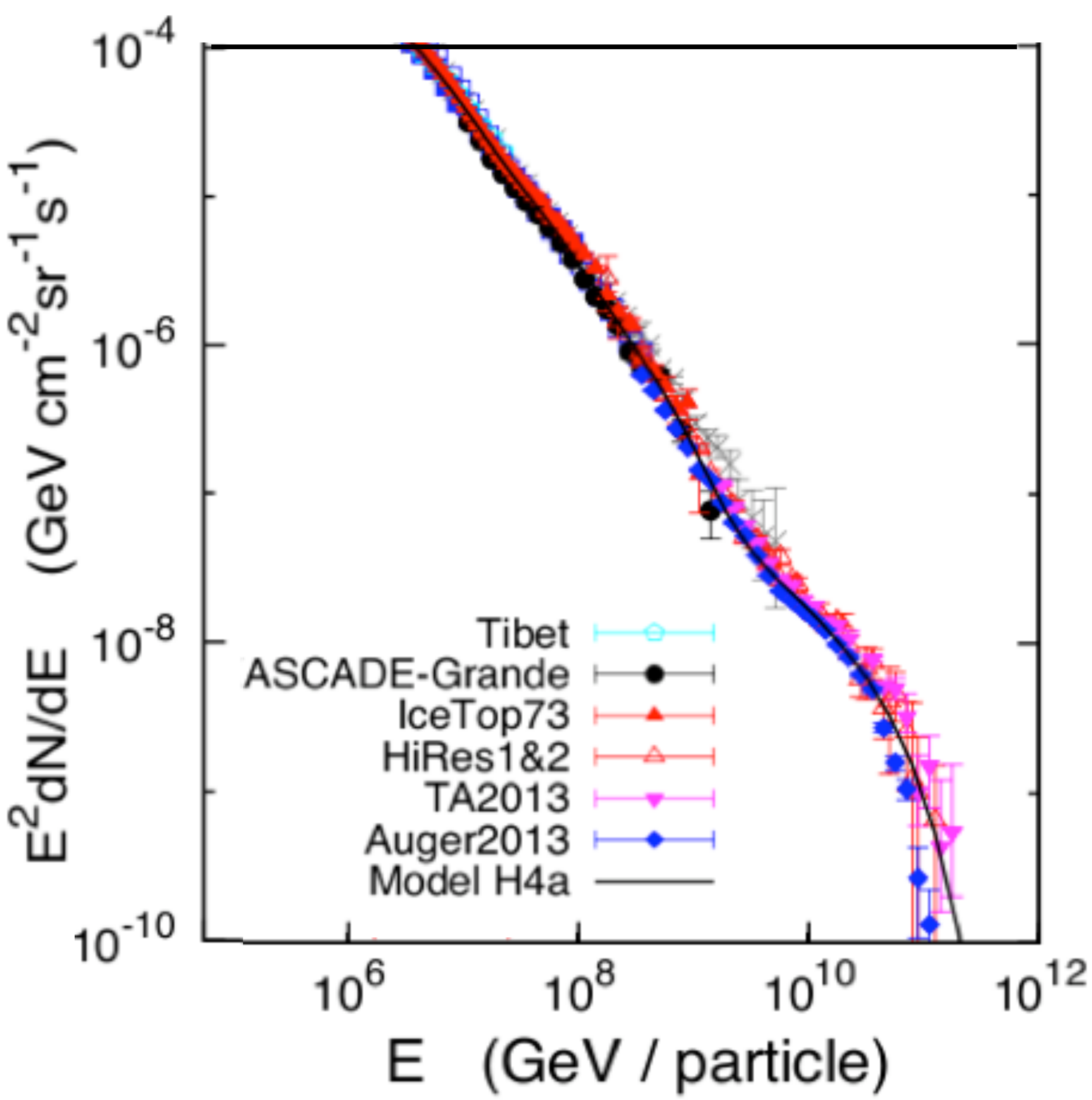
~10^6 GeV neutrinos have been observed.

Cosmic ray spectrum falling sharply above 10^{11} GeV has been observed.

Greisen–Zatsepin–Kuzmin (GZK) process:

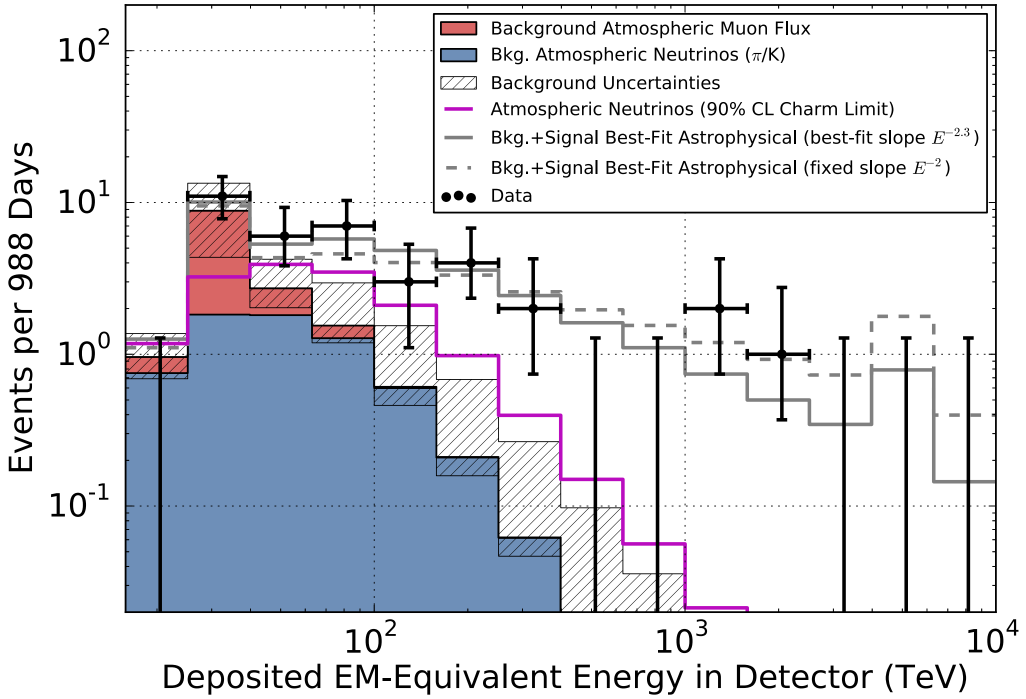
$$p + \gamma_{\rm CMB} \to p + \pi^0$$

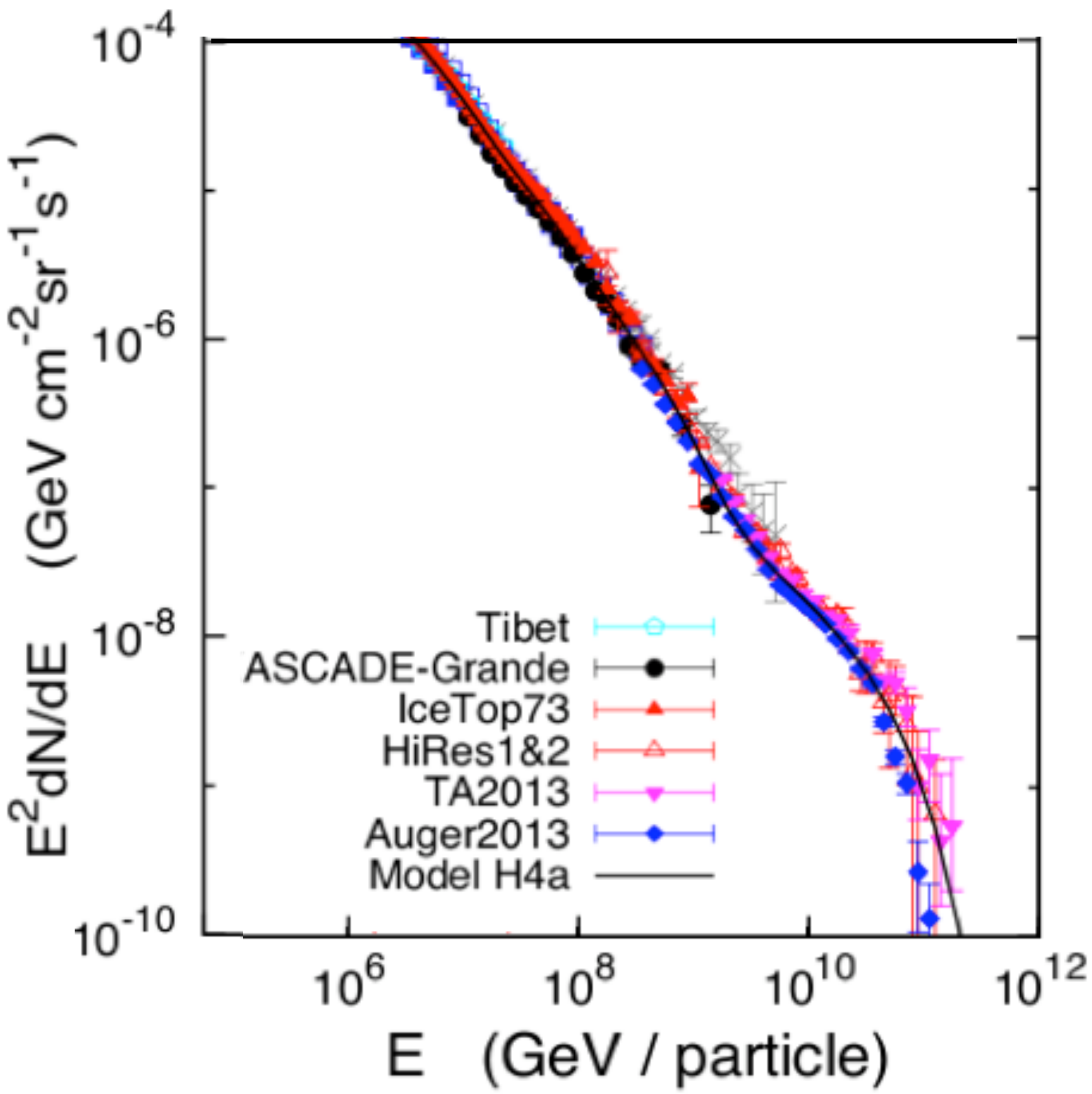
$$p + \gamma_{\rm CMB} \to n + \pi^+$$



$$(p_p + p_{\gamma_{\rm CMB}})^2 \geq (m_N + m_\pi)^2 \quad (E_{\gamma_{\rm CMB}} \sim 2.6 \cdot 10^{-13}\,{\rm GeV})$$

$$\Rightarrow \quad E_p \geq \frac{(m_N + m_\pi)^2 - m_p^2}{4E_{\gamma_{\rm CMB}}} \sim 3 \cdot 10^{11}\,{\rm GeV}$$





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$$p + \gamma_{\rm CMB} \to p + \pi^0 \ : \pi^0 \to \gamma\gamma$$

$$p + \gamma_{\rm CMB} \to n + \pi^+ : \pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$$

These high energy neutrinos and photons should reach the earth.

$$(p_p + p_{\gamma_{\rm CMB}})^2 \geq (m_N + m_\pi)^2 \quad (E_{\gamma_{\rm CMB}} \sim 2.6 \cdot 10^{-13}\,{\rm GeV})$$

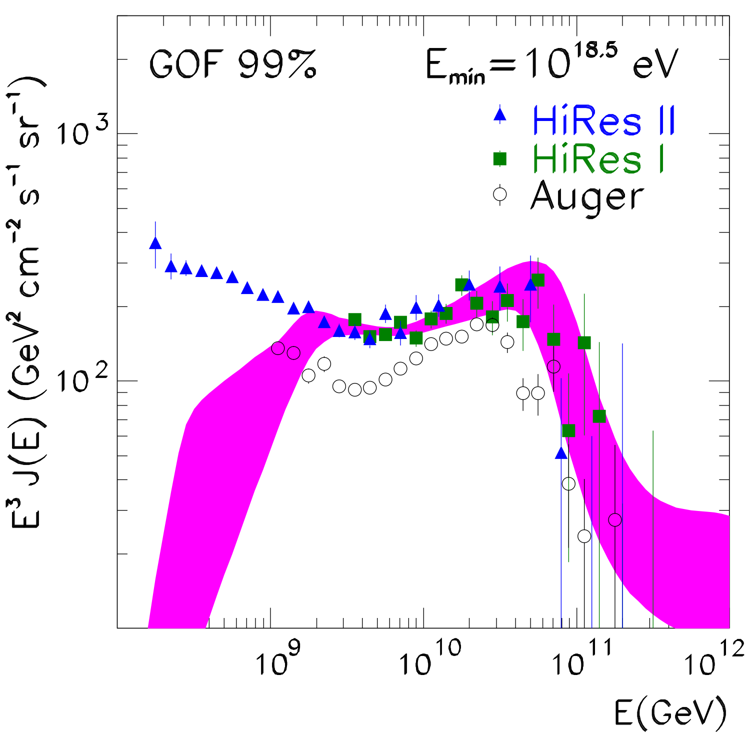
$$\Rightarrow \quad E_p \geq \frac{(m_N + m_\pi)^2 - m_p^2}{4E_{\gamma_{\rm CMB}}} \sim 3 \cdot 10^{11}\,{\rm GeV}$$

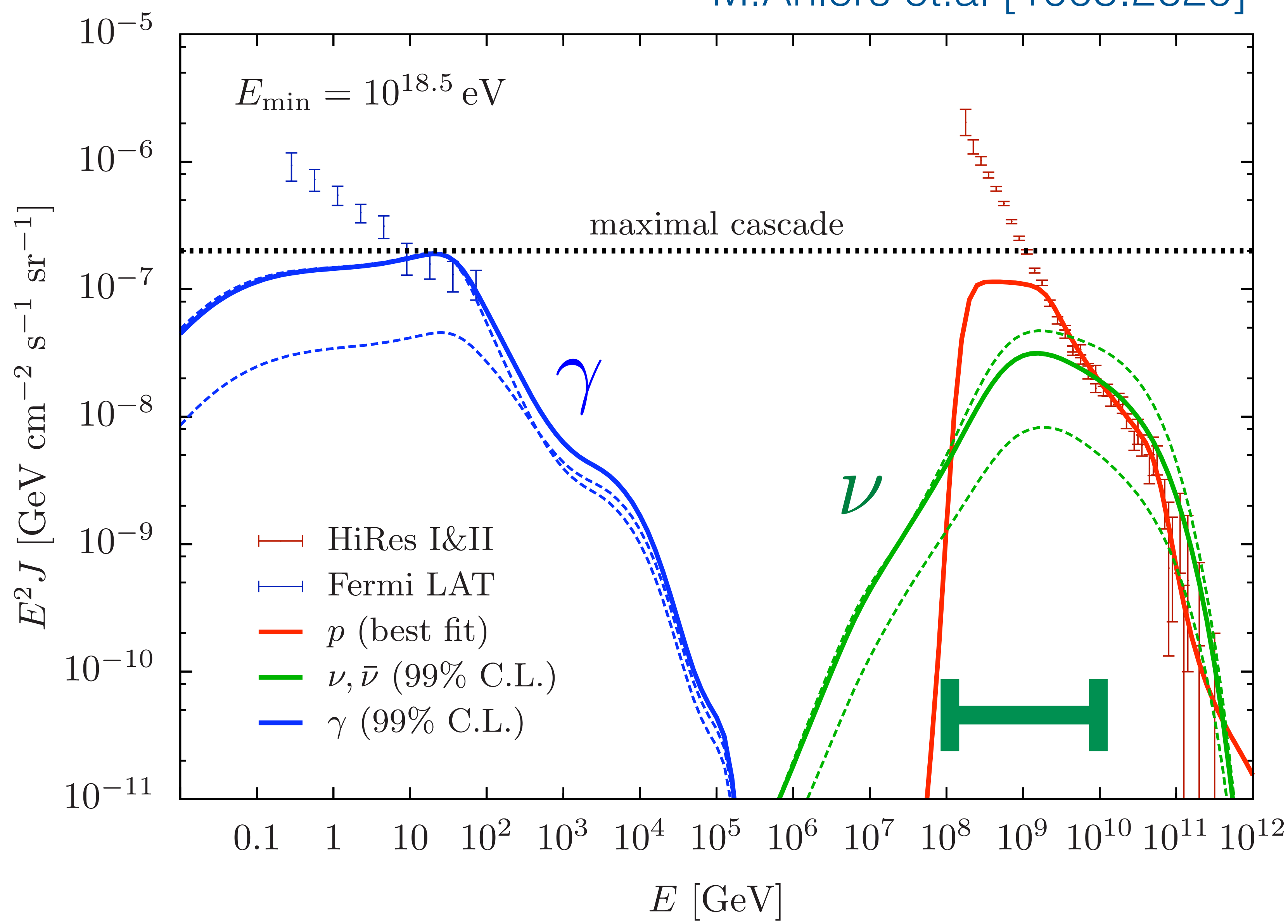
One could predict GZK neutrino and gamma ray fluxes by modelling the cosmic ray spectrum and fit it to the observed spectrum.

While neutrino energy is unchanged apart from redshift, the photons loose their energy by interacting with the intergalactic radiation fields.

$$\gamma_{\rm GZK} + \gamma \to e^+ e^-$$

M.Ahlers et.al [1005.2620]



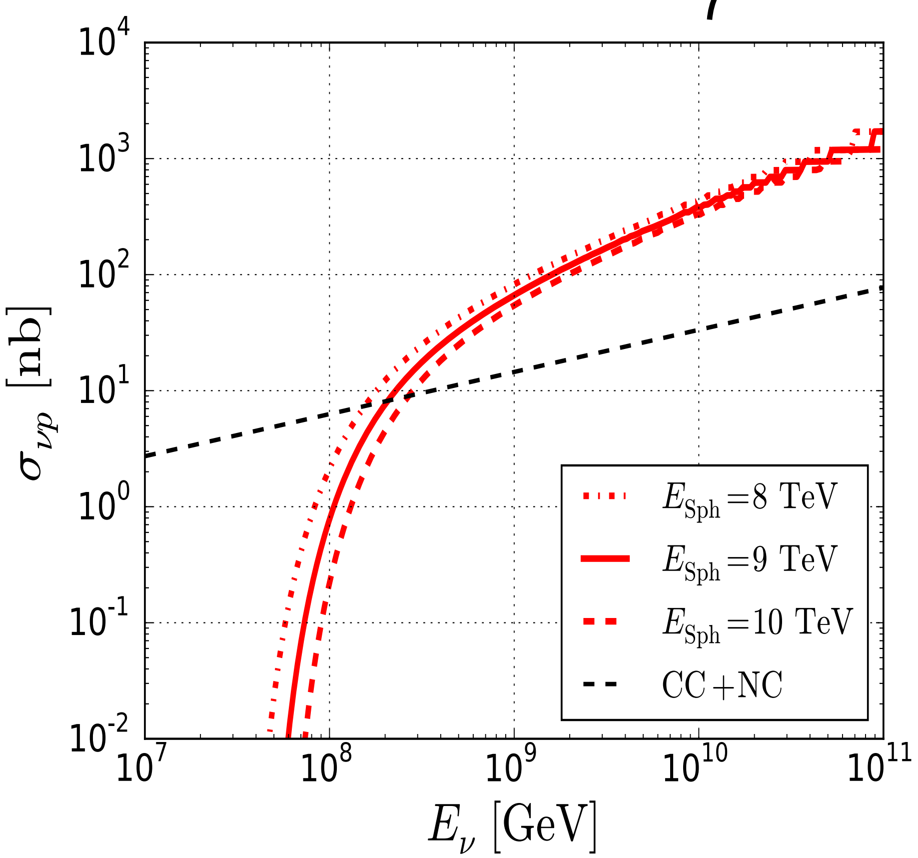


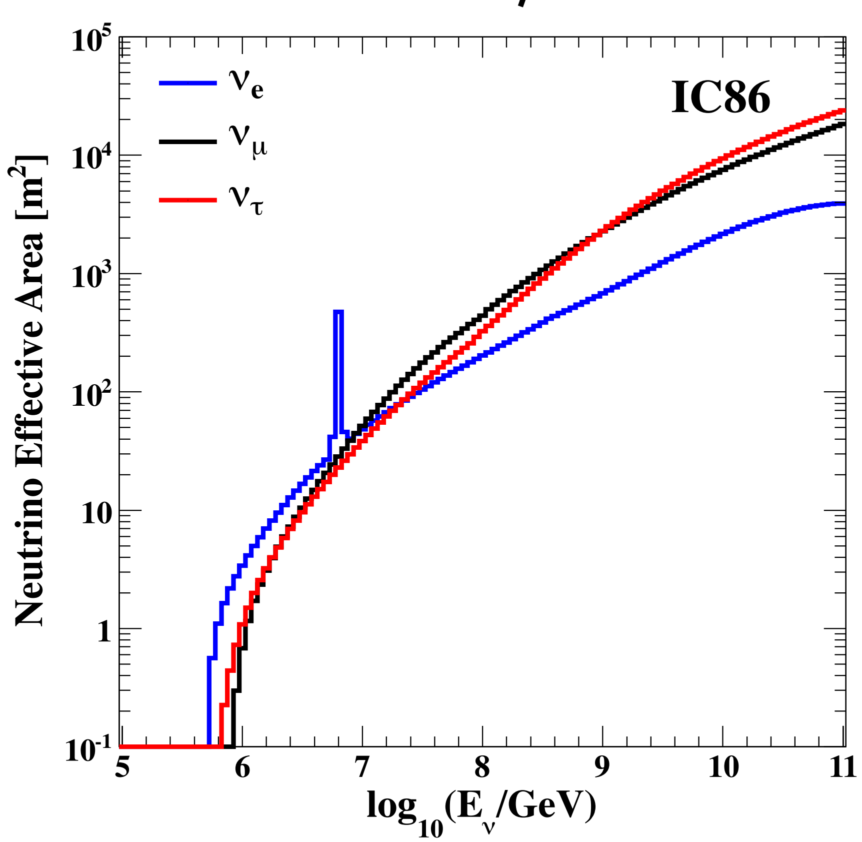
$$E_\nu^{\rm Sph} \gtrsim 10^{8-10}\,{\rm GeV}$$

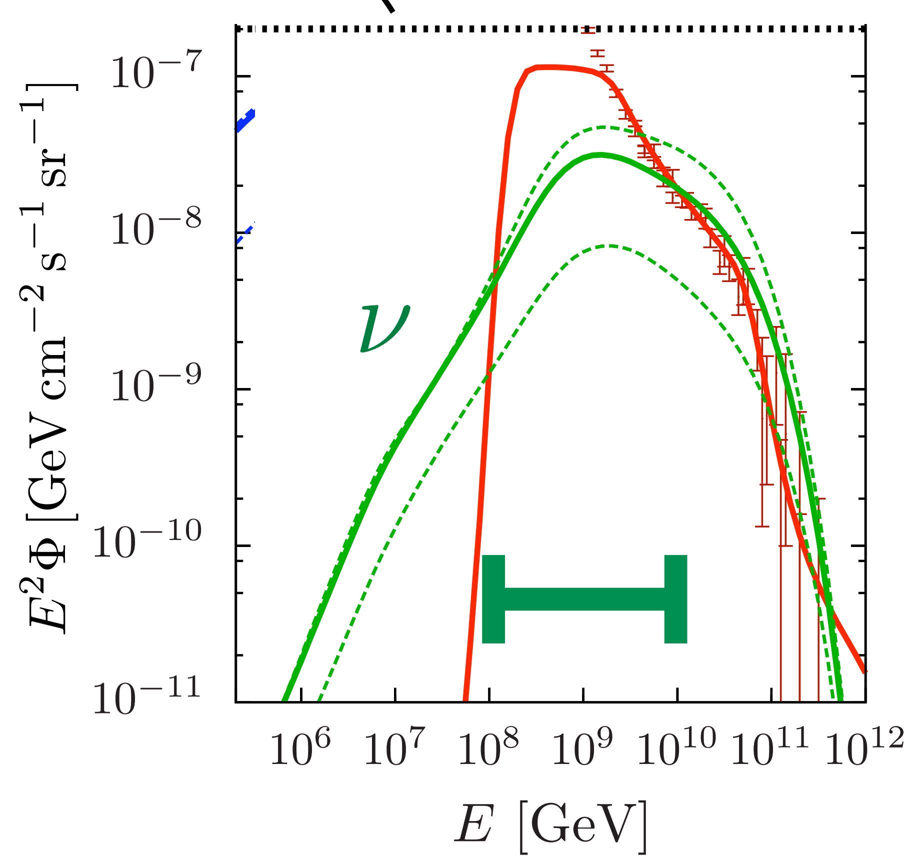
Event rate can be calculated using the energy dependent effective neutrino detection area.

$$\frac{dN_{CC/NC}}{dt} = \int_{E_{\rm three}} dE_\nu A_{\rm eff}(E_\nu) \frac{d^2\Phi}{dE_\nu dt}$$

$$\frac{dN_{\rm Sph}}{dt} = \int_{E_{\rm three}} dE_\nu \frac{\sigma^{\rm Sph}_{\nu N}(E_\nu)}{\sigma^{CC/NC}_{\nu N}(E_\nu)} A_{\rm eff}(E_\nu) \frac{d^2\Phi}{dE_\nu dt}$$







J.Ellis, KS, M.Spannowsky [1603.06573]

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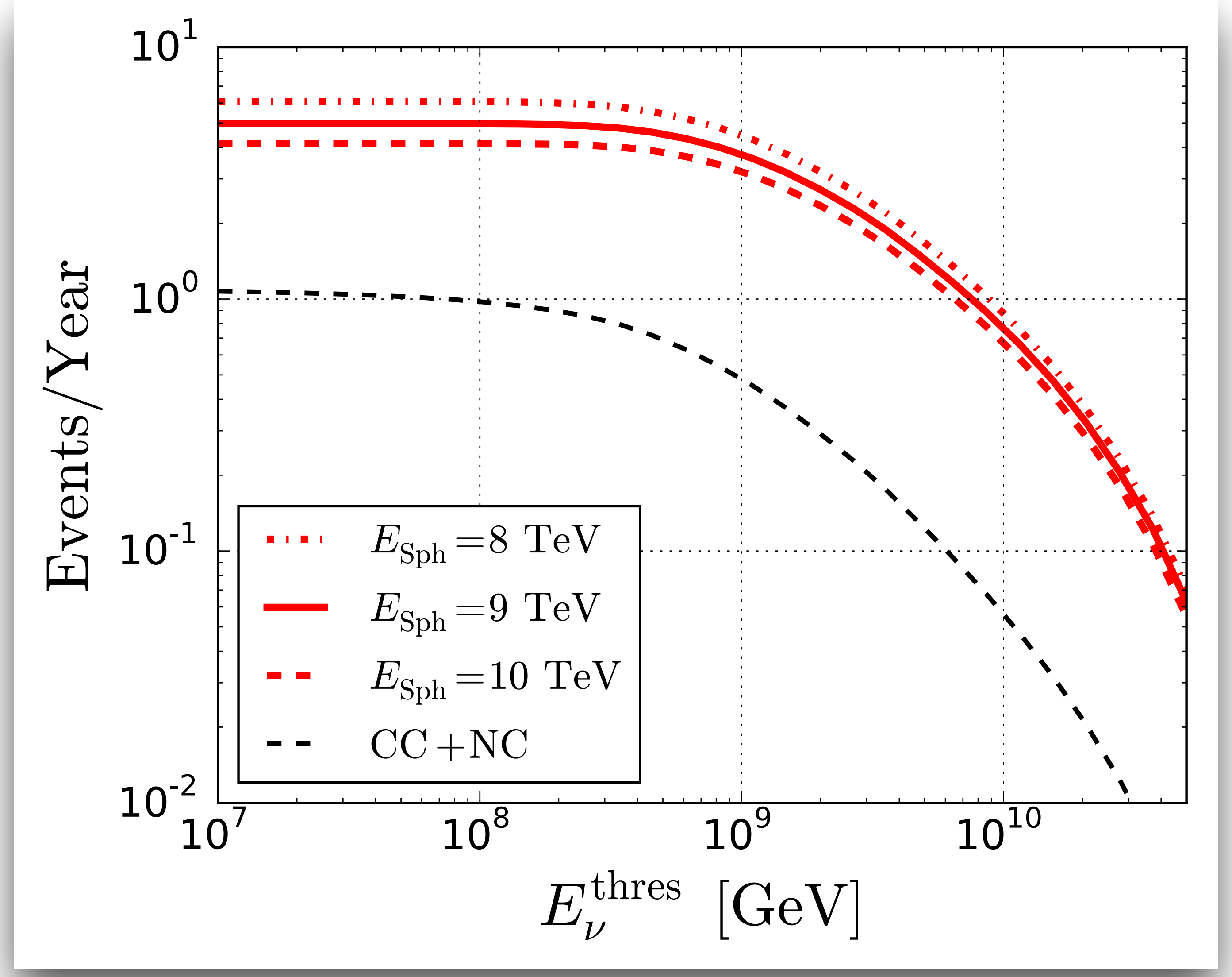
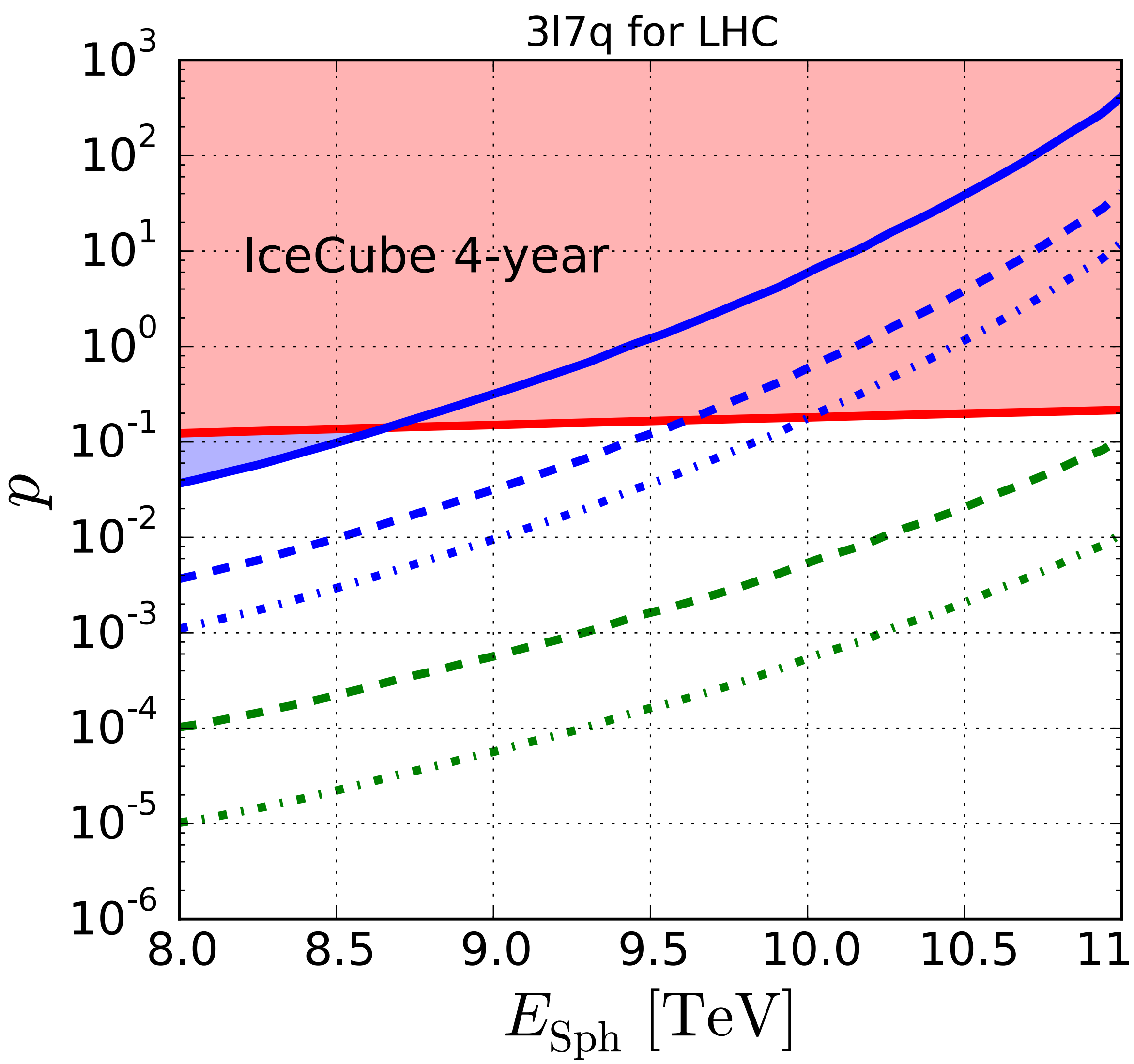
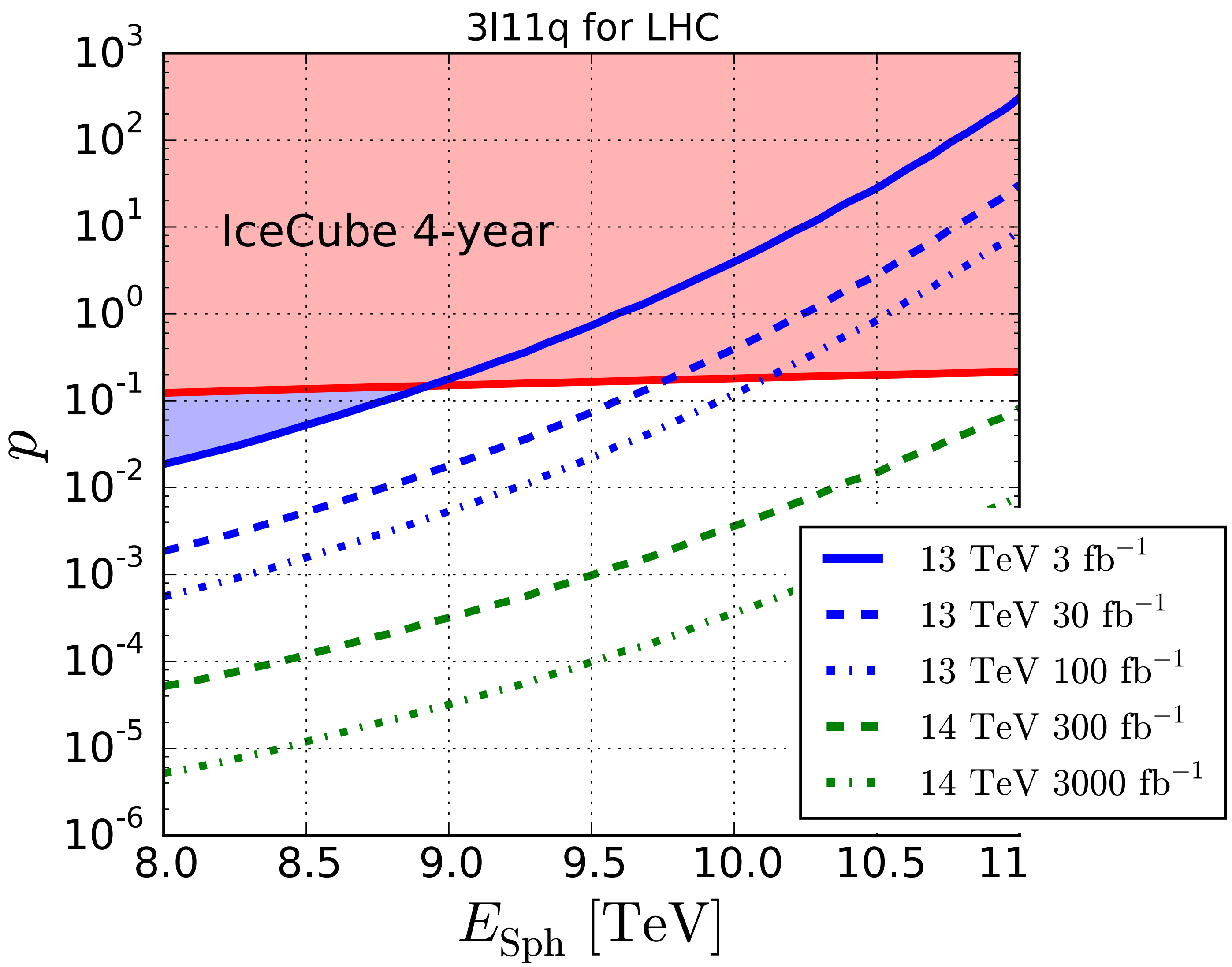


Sensitivity

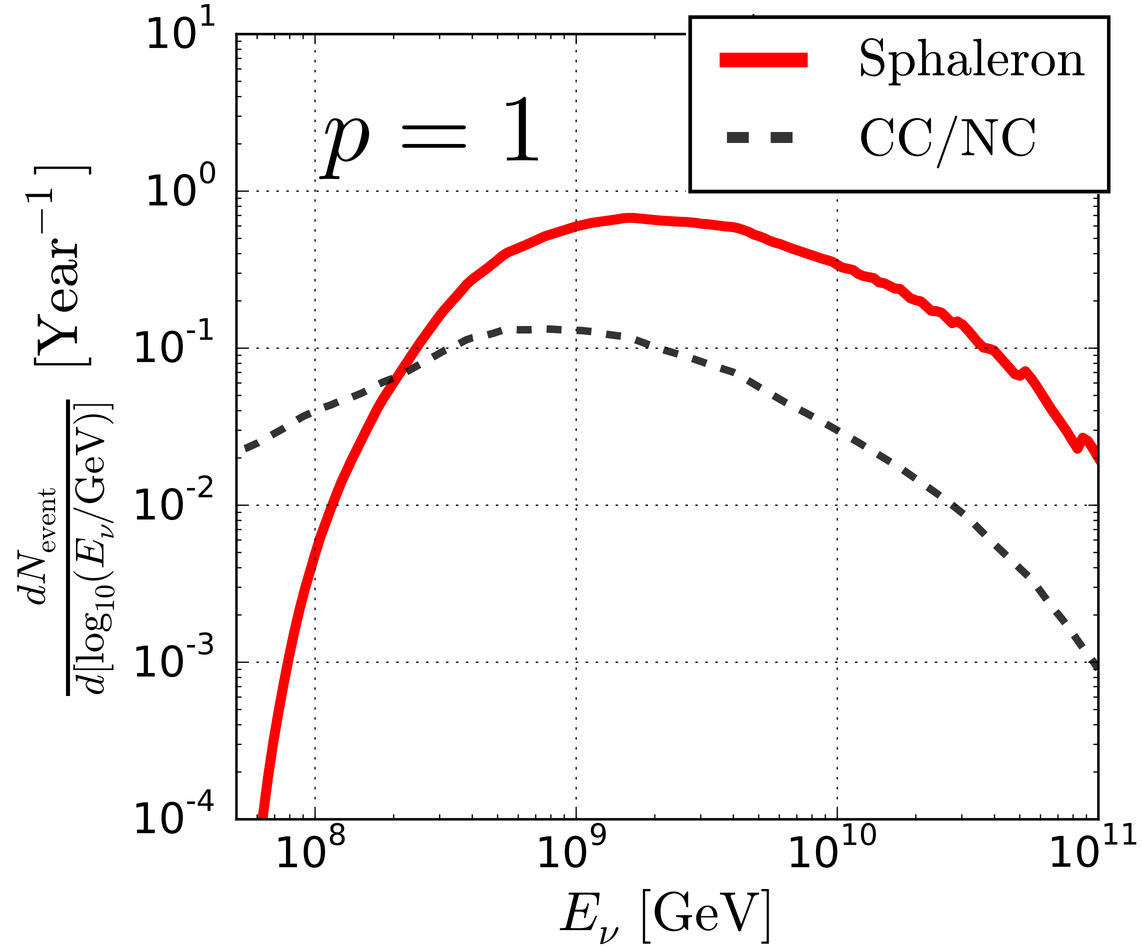


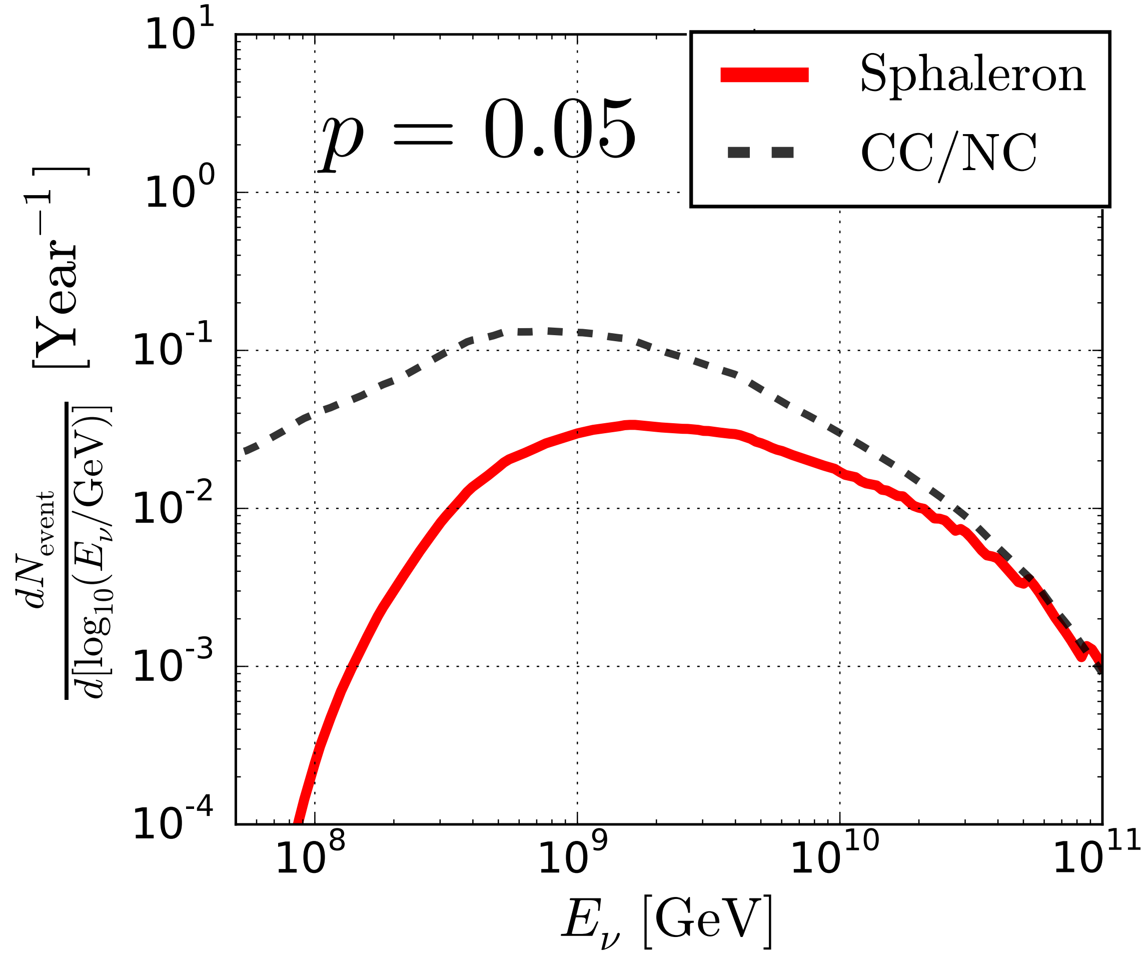


- For $E_{\rm Sph}$ ~ 9TeV, IceCube and LHC sensitivities are comparable.
- Good IceCube sensitivity persists for $E > E_{\rm Sph}$.

(because the fall of PDF is faster than that of GZK neutrino spectrum)

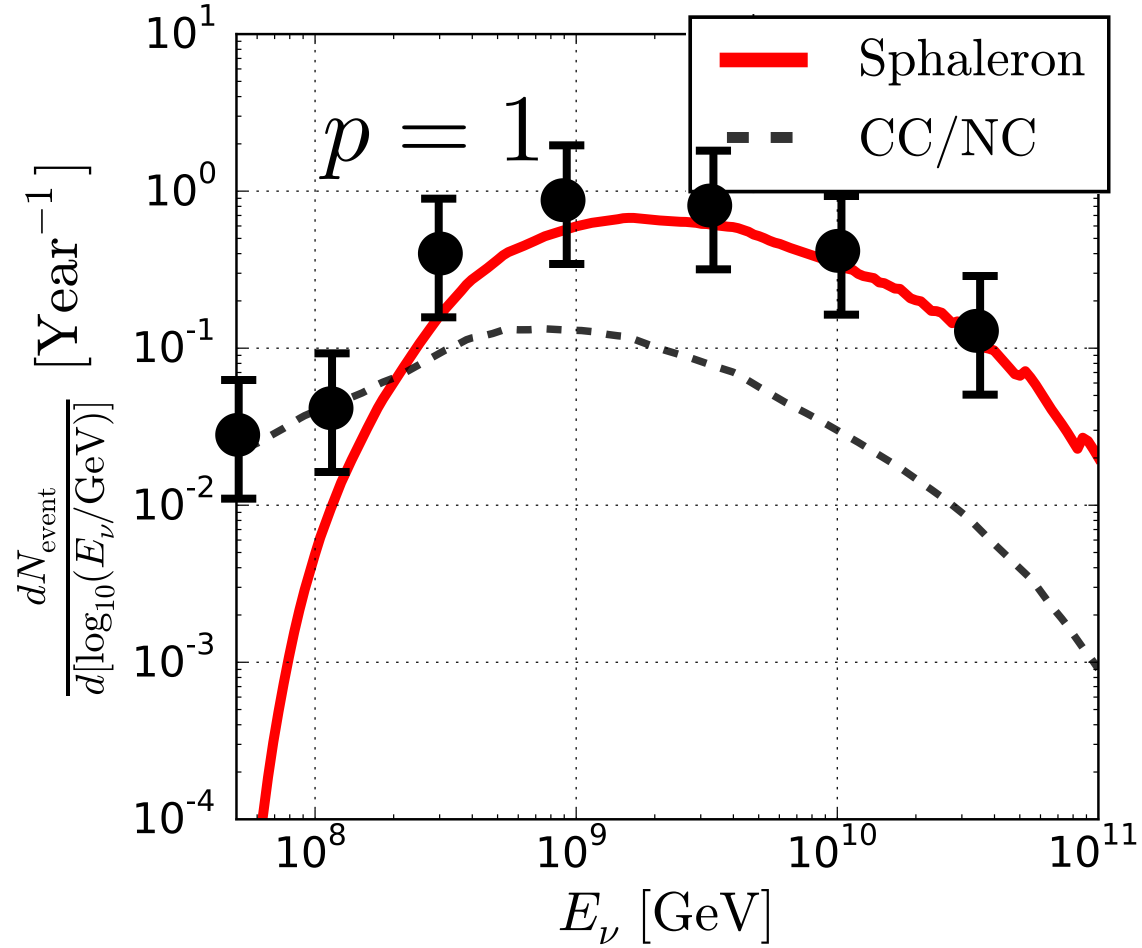
J.Ellis, KS, M.Spannowsky [1603.06573]

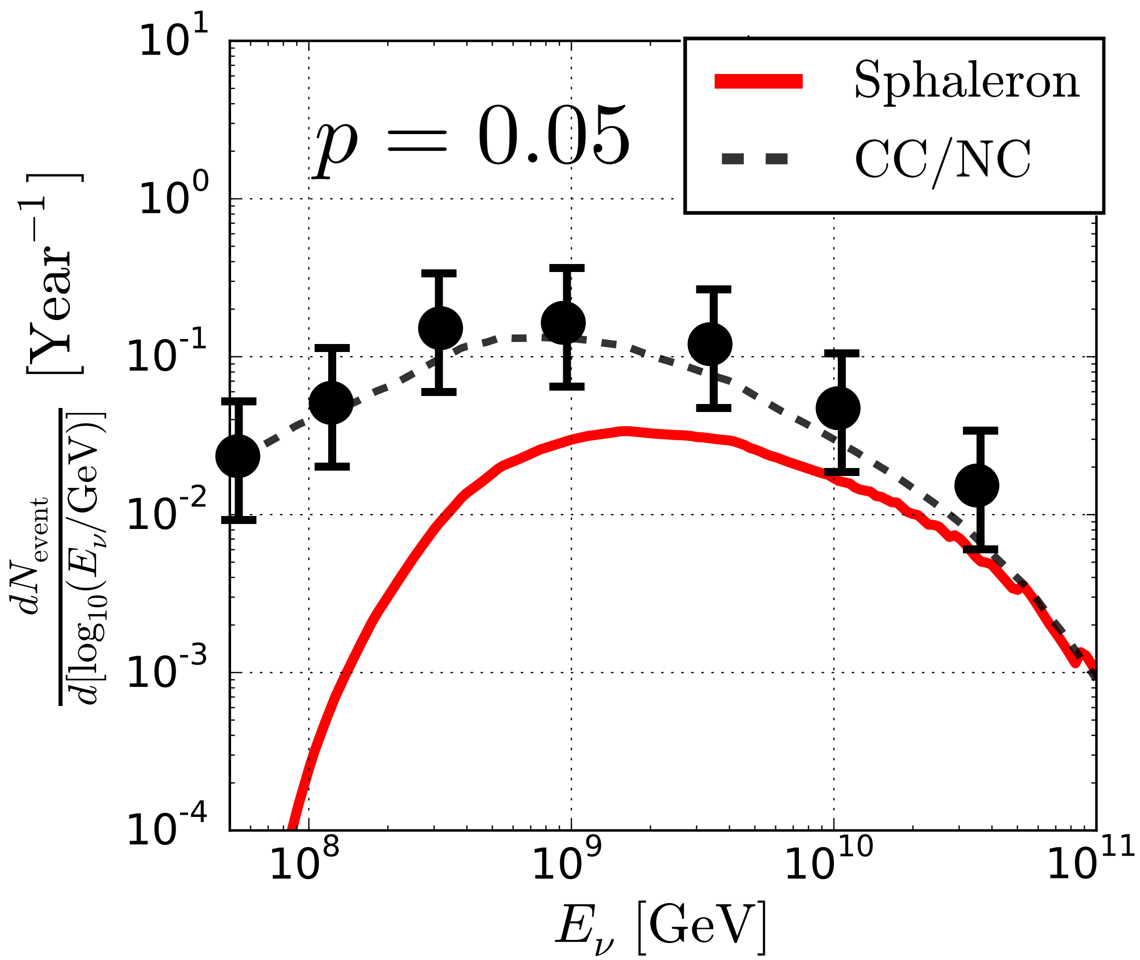




- If unknown pre-factor p is small, the sphaleron events may be hidden in the GZK neutrino events via the ordinary EW interaction.
- In this case, discrimination using the event shape is important.

How do sphaleron events look different from the ordinary neutrino events at IceCube?





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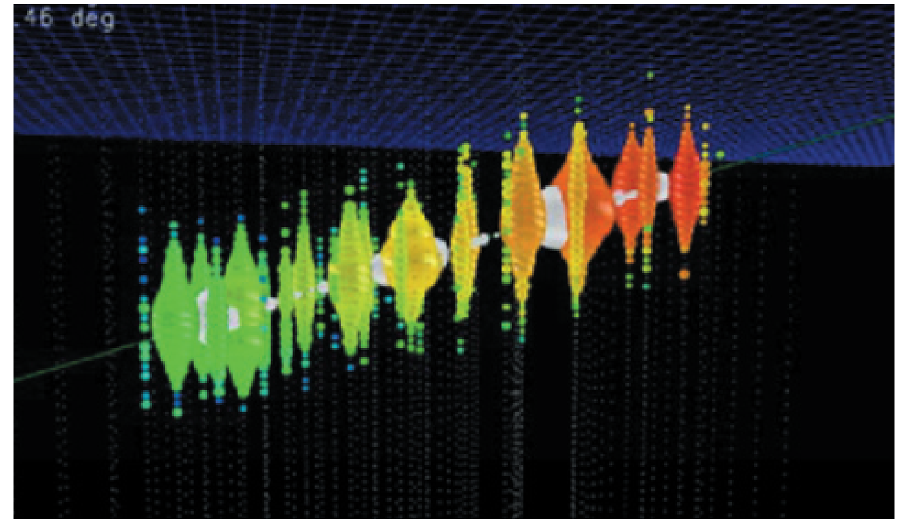
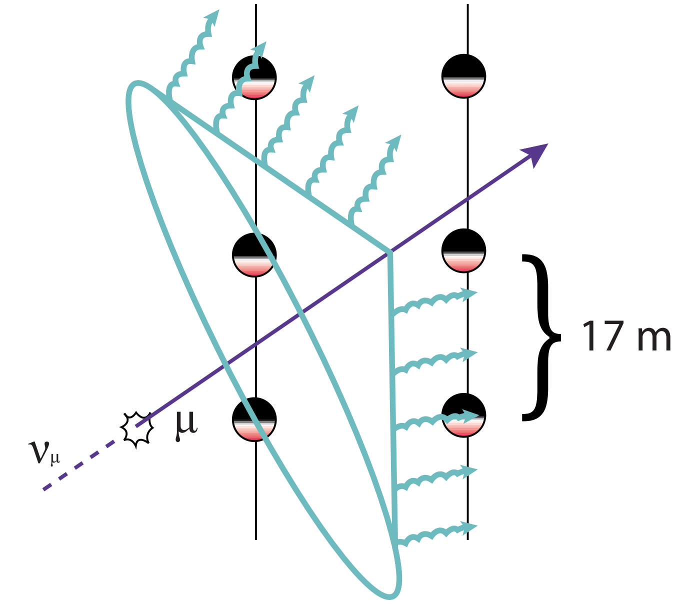
IceCube Events:

"muon bundle"

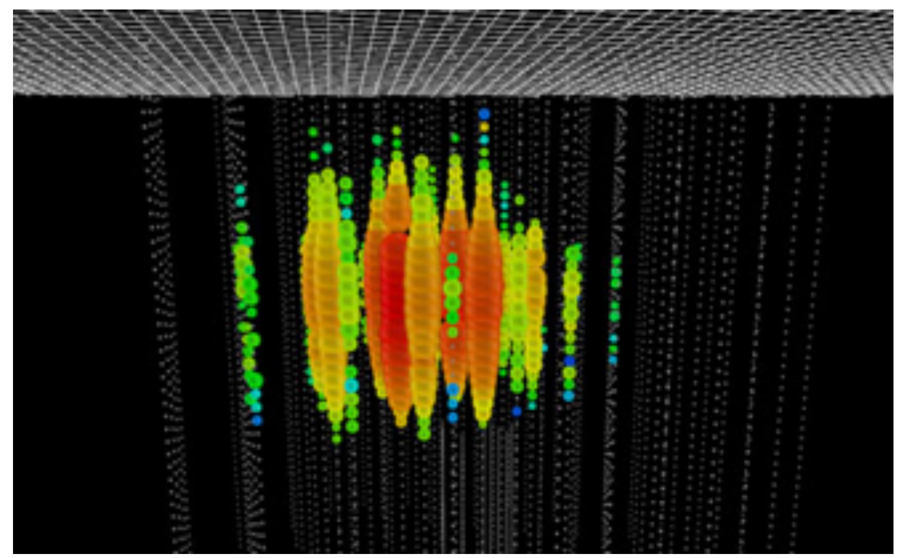
$$\nu_\mu N \to \mu X$$

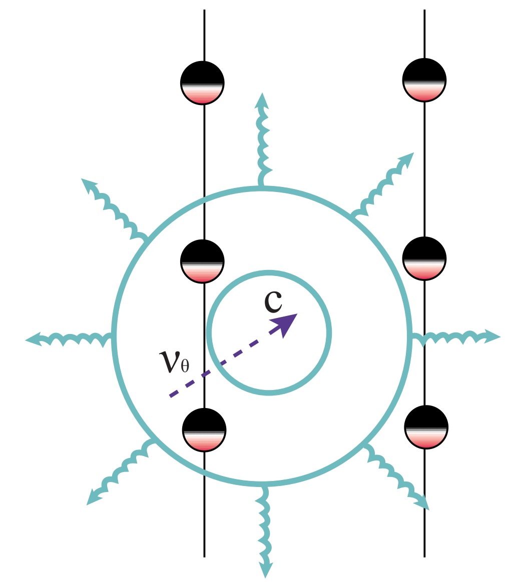




"shower"

$$\nu_e N \to e X$$
$$\nu_\tau N \to \tau X$$
$$\nu_i N \to \nu_i X$$

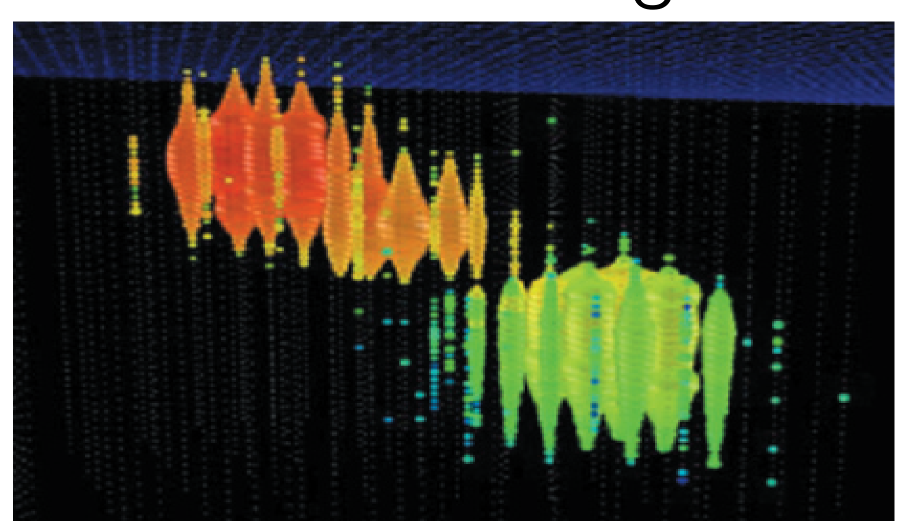




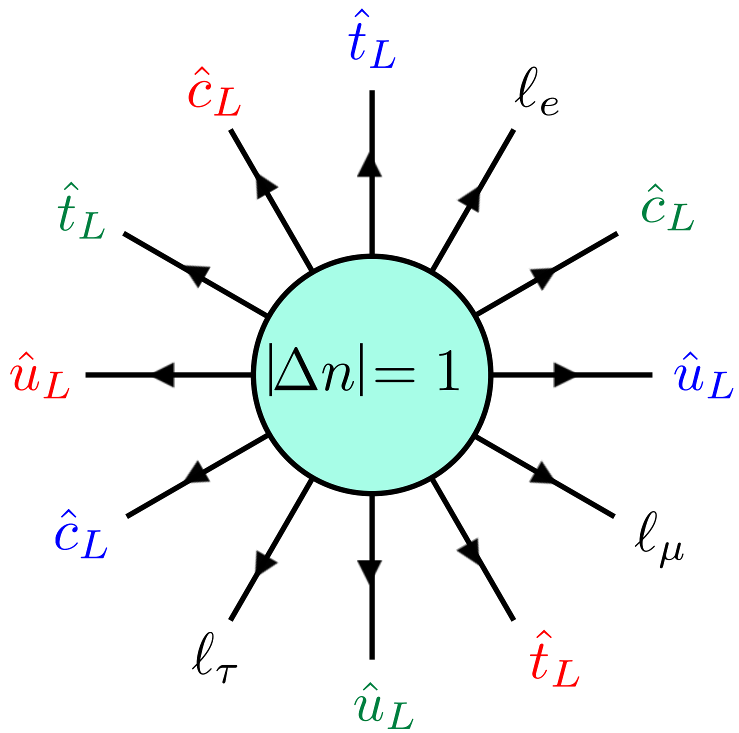
"double bang"

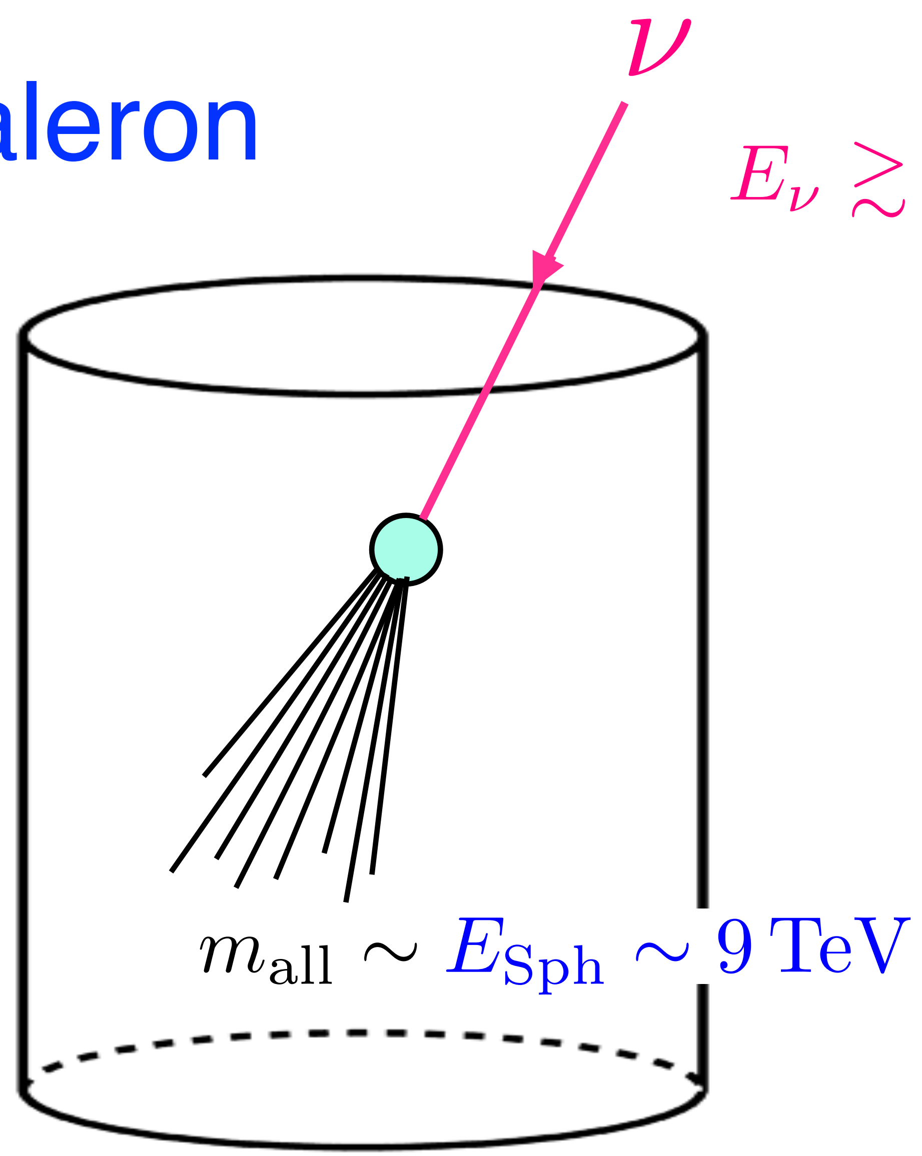
$$\nu_\tau N \to \tau X_1 \to X_1 \nu_\tau X_2$$

$$E_\tau \in [10^6, 10^7]\,\mathrm{GeV}$$

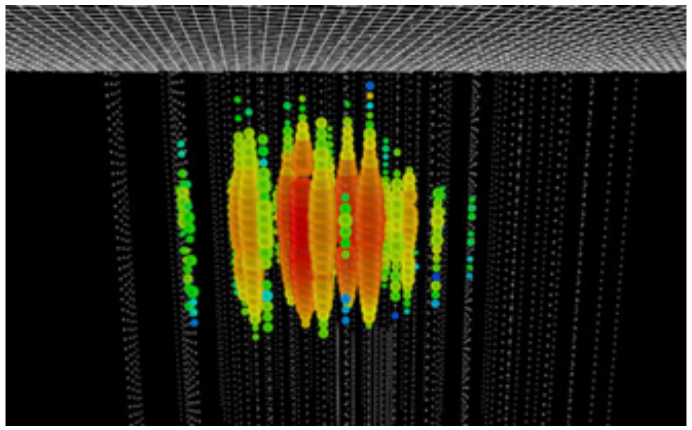


What does the sphaleron event look like?

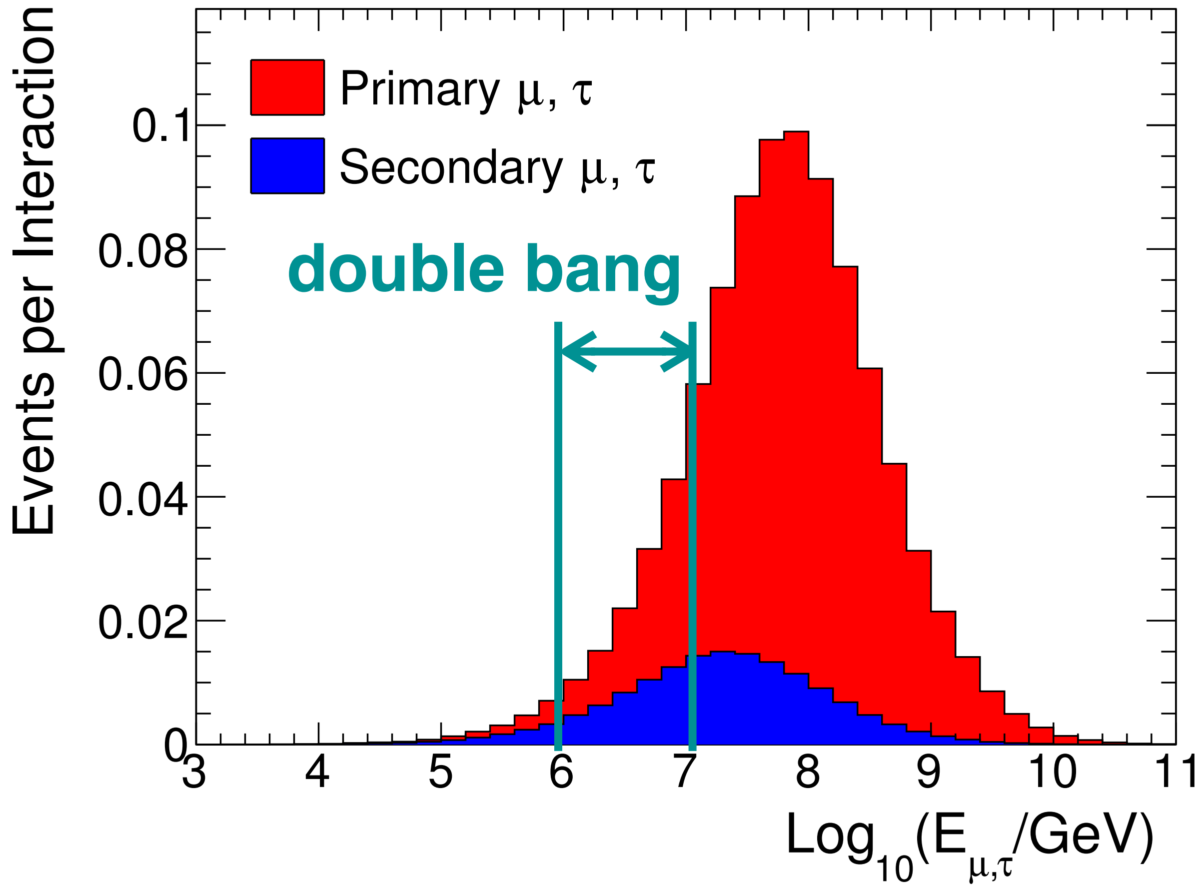




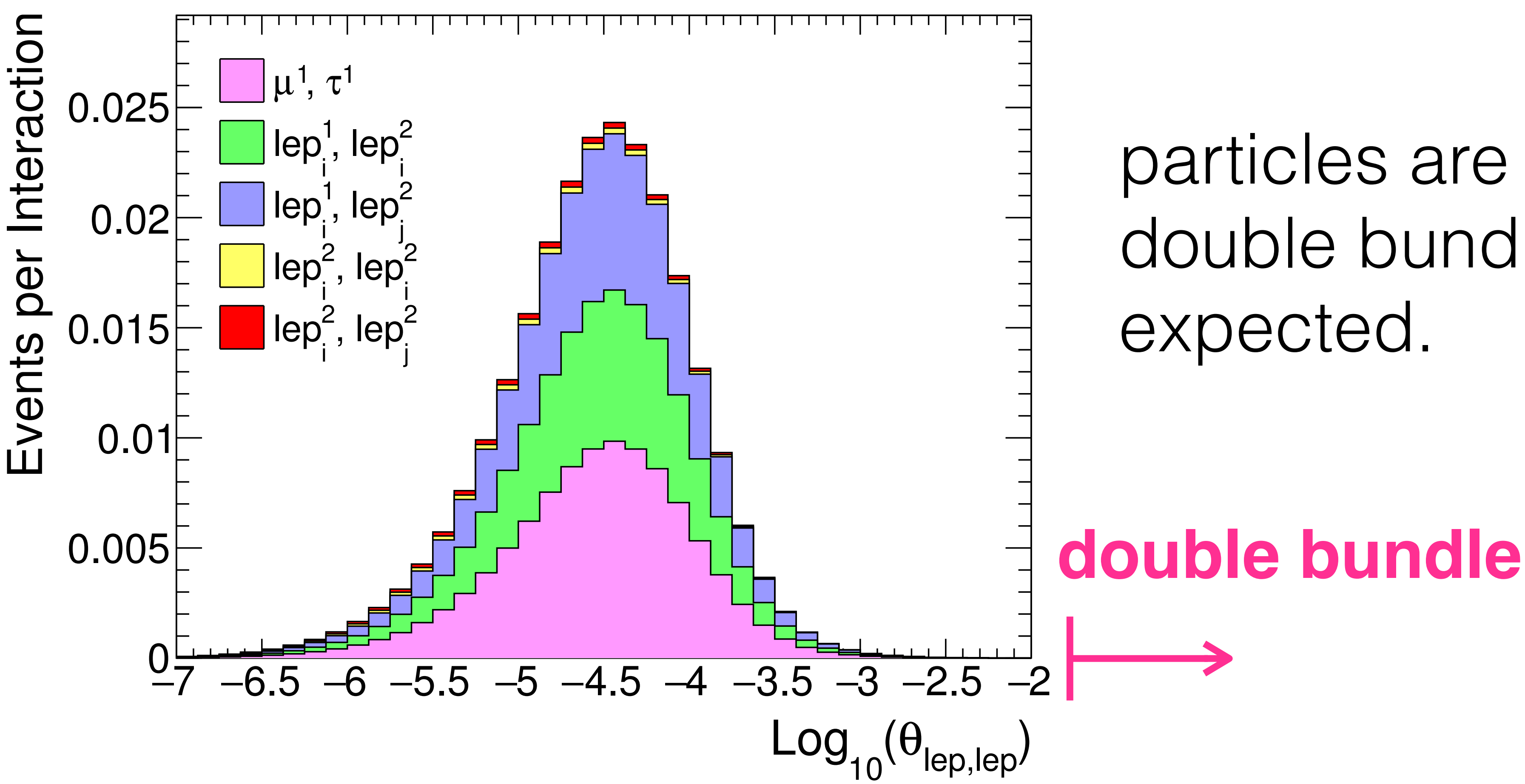
"shower"



- quarks and leptons are stopped in the ice (except for μ). ⇒ "shower"
- If μ is produced. ⇒ "bundle"
- If τ is produced with $E_\tau \in [10^6, 10^7]$ GeV. ⇒ "double bang"
- If primary μ and a μ from a top-quark decay has an opening angle with $\theta > 10^{-2}$ rad ⇒ "double bundle"??



Only 5% of the sphaleron-induced events have double bang taus.



particles are highly collimated and double bundles cannot be expected.

Summary

- EW theory has an interesting non-perturbative aspect, but it has not been observed experimentally.
- Inspired by the recent work by Tye and Wong, we have studied the sensitivity of observing sphaleron-induced processes at the LHC and IceCube.
- The event rate can be quite large at 13 TeV LHC. The 13 TeV BH analysis already excludes some parameter region.
- The event rage grows rapidly as the collision energy. A future 100TeV hadron collider can explore up to $p \sim 10^{-11}$.
- Sphaleron can be produced by high energy GZK neutrinos colliding with nucleus in the ice at IceCube. For $E_{\rm Sph}$ = 9TeV, the sensitivity is compatible with the 13TeV LHC with 3/fb.