Particle Physics

Dr Victoria Martin, Spring Semester 2013

Lecture 19: Physics at the Large Hadron Collider

- ★Higgs couplings to Fermions
- ★Higgs branching ratios
- ★Hadron Collider physics
- ★Higgs boson discovery

Electroweak & Higgs Mechanism

- Three parameters are needed to describe all electroweak and Higgs physics phenomena.
  - e.g. Coupling constants: g_W, g'_W and the vacuum expectation value $\mathbf{v}$
- The Higgs mechanism gives mass to the W and Z bosons through their couplings with the Higgs field

$$m_W = \frac{v\, g_W}{2} \qquad m_Z = \frac{1}{2} v \sqrt{g_W^2 + g_W'^2} \qquad e = g'_W \cos\theta_W = g_W \sin\theta_W$$

- Other useful combinations:

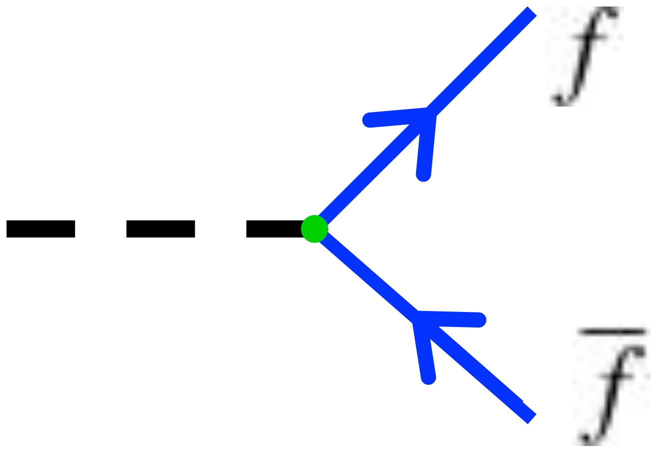
$$\cos\theta_W = \frac{g_W}{\sqrt{g_W^2 + g_W'^2}} = \frac{m_W}{m_Z} \qquad G_F = \frac{\sqrt{2}}{8}\frac{g_W^2}{m_W^2} = \frac{1}{\sqrt{2}\, v^2}$$

Higgs Couplings to Fermions

- The Higgs field also couples to all of the fermions, ***f***. Induces a term coupling incoming and outgoing fermions spinors to **v = 246 GeV**.

$$g_f(\bar{f}f)v = g_f(\bar{f}_{\mathrm{L}}f_{\mathrm{R}} + \bar{f}_{\mathrm{R}}f_{\mathrm{L}})v$$

- g_f is a unknown coupling constant, and can be different for each fermion.

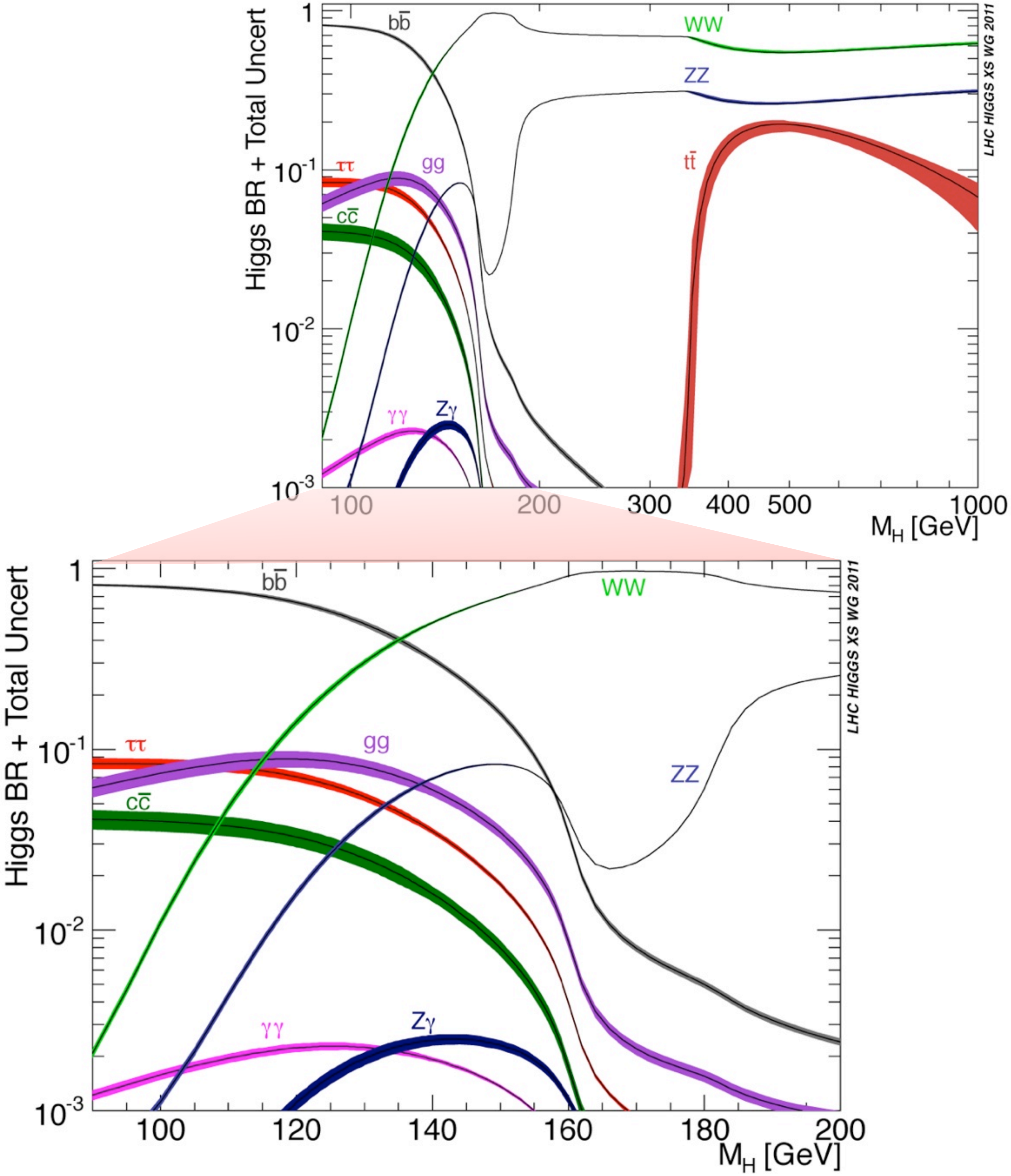


- Fermion wavefunctions are coupled to **v**, a quantity with mass dimension.
- We interpret (g_f **v**) as the mass of the fermion.
- The Higgs mechanism explains the masses of all the quarks and charged leptons! (Maybe neutrinos too!?)

Higgs Boson Decay

- In the Standard Model the Higgs boson decays preferentially to the heaviest thing it can.
- (Factor of ½ if the final state particles are identical e.g. ZZ)

- for $m_H = 125$ GeV/c^2
  - BR($H \to b\bar{b}$) = 57.7%
  - BR($H \to W^+W^-$) = 22.3%
  - BR($H \to \tau^+\tau^-$) = 6.3%
  - BR($H \to c\bar{c}$) = 2.9 %
  - BR($H \to ZZ$) = 2.6%
  - BR($H \to \gamma\gamma$) = 0.23%
  - BR($H \to Z\gamma$) = 0.15%
  - BR($H \to \mu^+\mu^-$) = 0.022%



Hadron Colliders

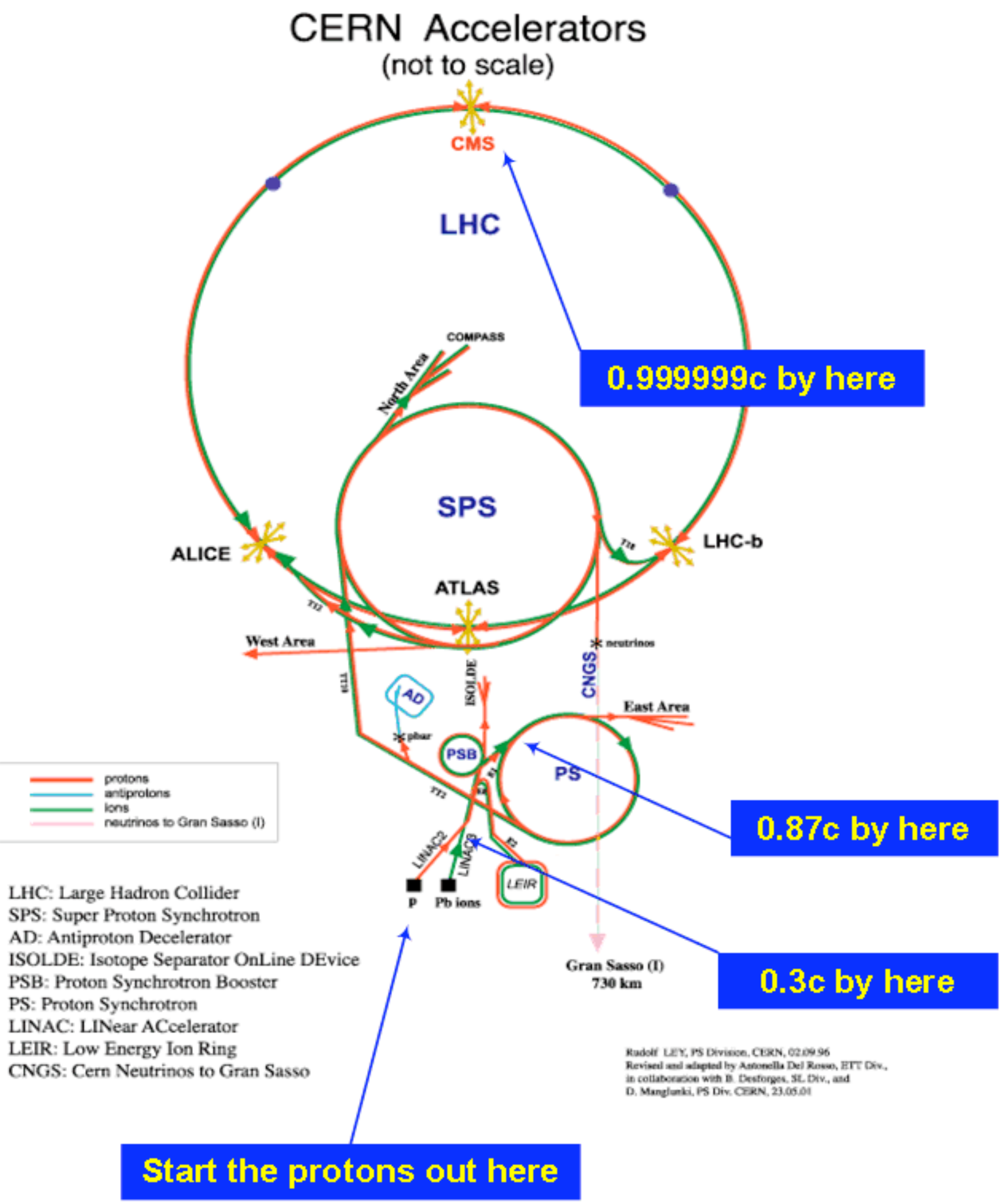
- **Sp$\bar{p}$S**: Super Proton anti-Proton Synchrotron at CERN
- 1981 - 1984, 6.9 km, $\sqrt{s} = 400$ GeV
- Two experiments: UA1 and UA2
- Tunnel now used for pre-acceleration for LHC

Nobel Prize for Physics 1984
Carlo Rubbia and Simon van der Meer, from CERN
"For their decisive contributions to large projects, which led to the discovery of the field particles W and Z, communicators of the weak interaction."

- **TeVatron** at Fermilab, near Chicago
- Proton anti-proton collider, 6.3 km
- Run 1: 1987 - 1995 $\sqrt{s} = 1.80$ TeV
- Run 2: 2000 - 2011 $\sqrt{s} = 1.96$ TeV
- Two experiments: CDF and DØ
- Highlight: discovery of the top quark!

The Large Hadron Collider (LHC)

- At CERN
- Proton-proton collider, $\sqrt{s} = 7 \text{ to } 14$ TeV
- 2009 – 202X
- Relies on network of accelerators
- Four collision points: ATLAS, CMS, LHCb, ALICE
- CMS & ATLAS: general purpose detectors: observation of highest energy collisions
- LHCb: specialist experiment looking at b-hadrons
- ALICE: specialist experiment looking at Pb ion collisions



0.999999c by here

0.87c by here

0.3c by here

Start the protons out here

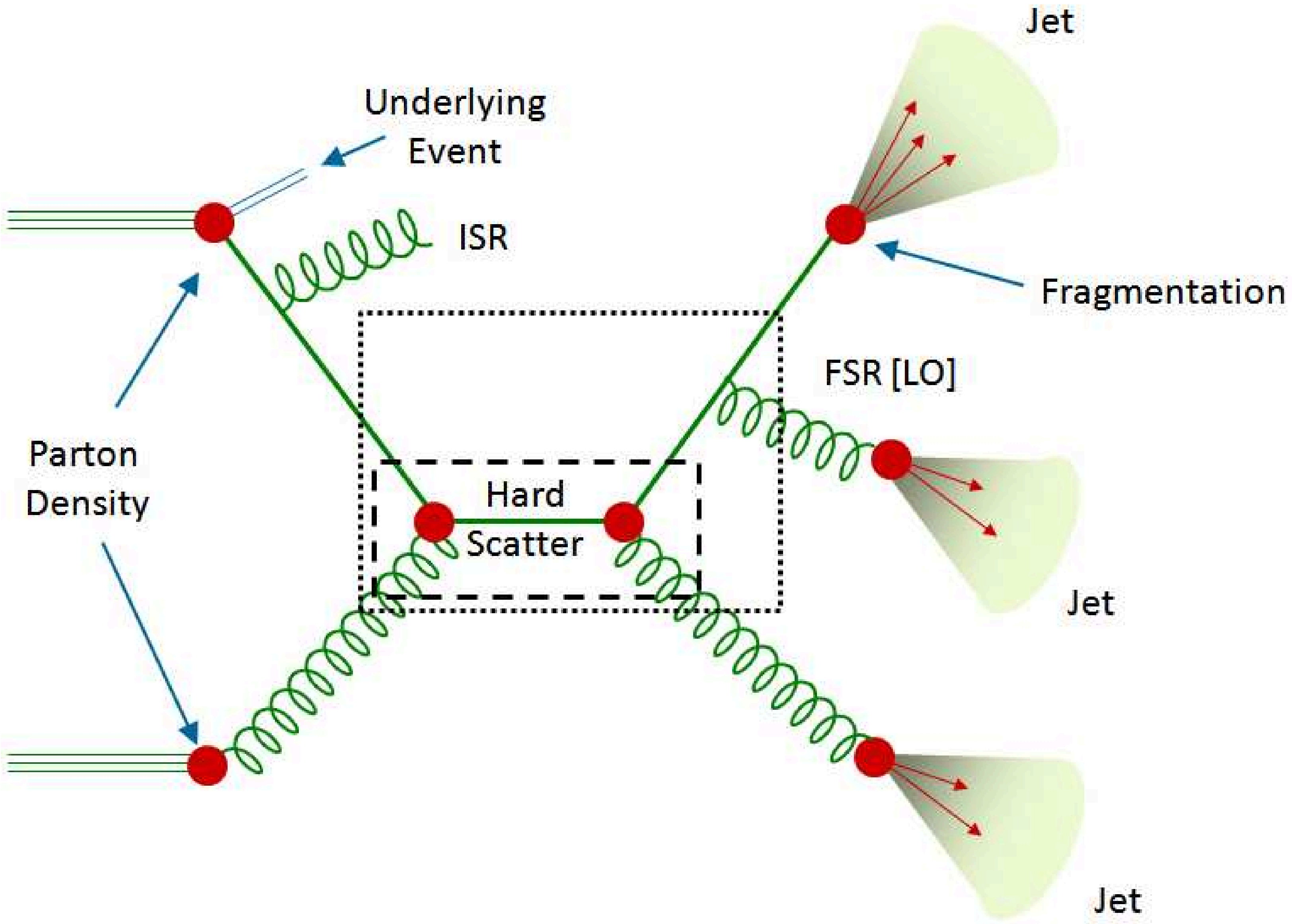
LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

The Large Hadron Collider: Facts

- 27km circumference
- 50 to 175 m underground
- 9300 magnets used to keep the beam in orbit
- 1232 dipole magnets
- Ultra-high vacuum of 10^{-10} Torr, equivalent to 1,000 km above earth
- Each dipole magnet: 14.3 m long, runs at 1.9 K, provides 8.3 Tesla, cost 500 kCHF
- four 400 MHz power supplies accelerate the beams from 450 GeV to collision energy
- Design energy: 7 TeV per beam
- Currently running at 4 TeV per beam

QCD production at Hadron Colliders



- Much more complicated due initial state hadrons not being fundamental particles
- Every object is colour charged: all object can interact with each other.
- QCD is very strong
- Not able to use perturbation theory to describe the interactions with low four momentum transfer q.

Hadron Collider Dictionary

- The **hard scatter** is an initial scattering at high q^2 between partons (gluons, quarks, antiquarks).
- The **underlying event** is the interactions of what is left of the protons after parton scattering.
- **Initial and final state radiation** (ISR and FSR) are high energy gluon emissions from the scattering partons.
- A hadronic **jet** is a collimated cone of particles associated with a final state parton, produced through fragmentation.
- Transverse quantities are measured transverse to the beam direction.

- An event with high **transverse momentum** (p_T) jets or isolated leptons, is a signature for the production of high mass particles (W,Z,H,t).
- An event with **missing transverse energy** (E_T) is a signature for neutrinos, or other missing neutral particles.

Measuring Jets

- A jet has a four-momentum $E = \sum_i E_i \quad \vec{p} = \sum_i \vec{p}_i$
  - ➡ Where the constituents (*i*) are hadrons detected as charged tracks and neutral energy deposits.

- Transverse momentum of jet:

$$p_T^{\text{JET}} = \sqrt{p_x^2 + p_y^2}$$

- Position in the detector in two coordinates:
  - ➡ ***Pseudorapidity*** of jet (η)

$$\eta^{\text{JET}} = -\ln\left(\tan\frac{\theta}{2}\right)$$

with polar angle, θ $\cos\theta = \frac{\sqrt{p_x^2+p_y^2}}{p_z}$

  - ➡ **Azimuthal angle** of jet (ϕ)

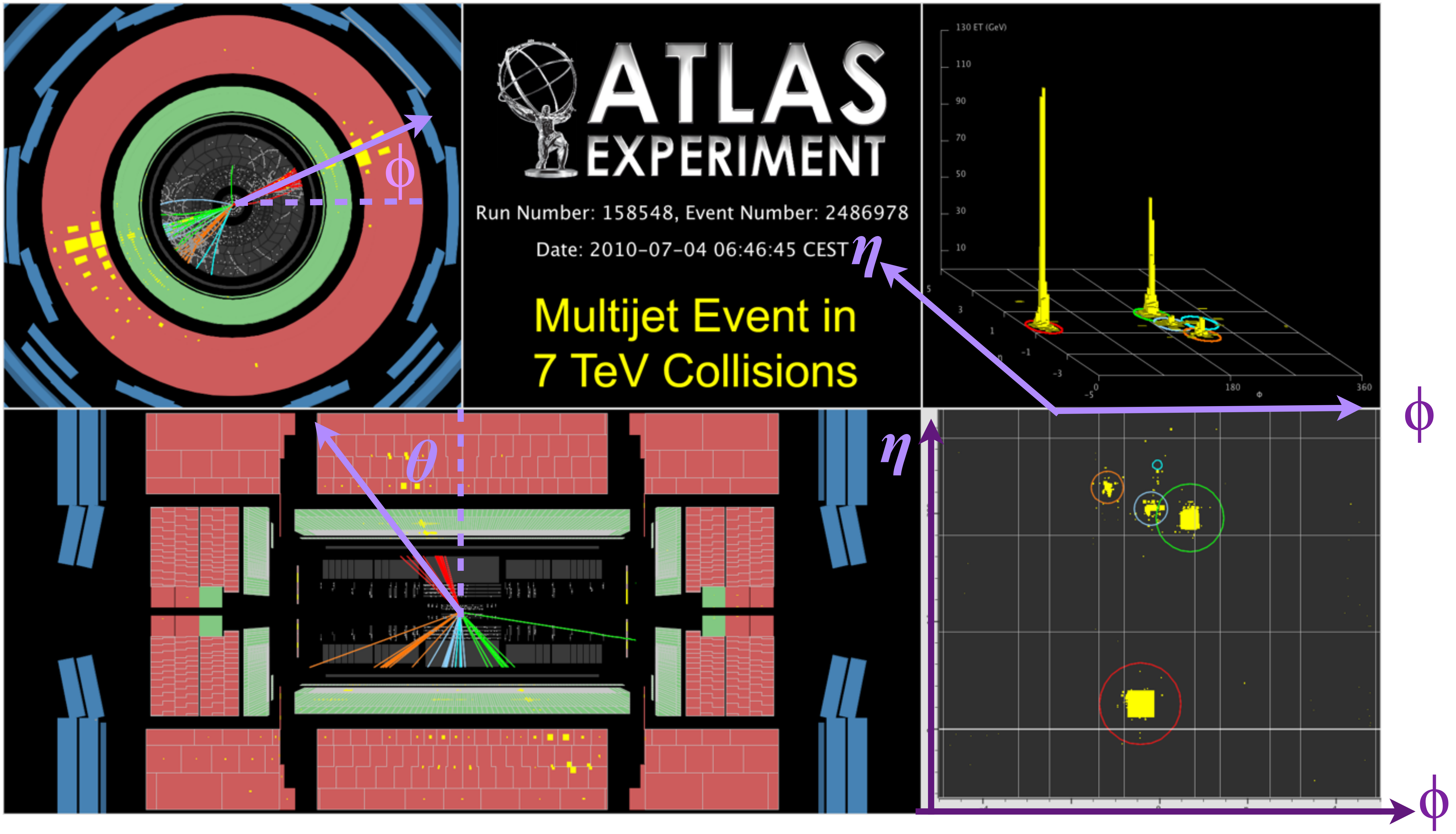
$$\phi^{\text{JET}} = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

- To assign individual constituents to the jet, simplest algorithm is to define a **cone** around a central value: η^{JET}, ϕ^{JET}.

$$R^2 = (\eta_i - \eta^{\text{JET}})^2 + (\phi_i - \phi^{\text{JET}})^2$$

- All objects with R less than a given value (typically 0.4 or 0.7) are assigned to the jet
- Many sophisticated jet clustering algorithms exist which take into account QCD effects.

ATLAS Multijet Event



ATLAS EXPERIMENT

Run Number: 158548, Event Number: 2486978

Date: 2010-07-04 06:46:45 CEST

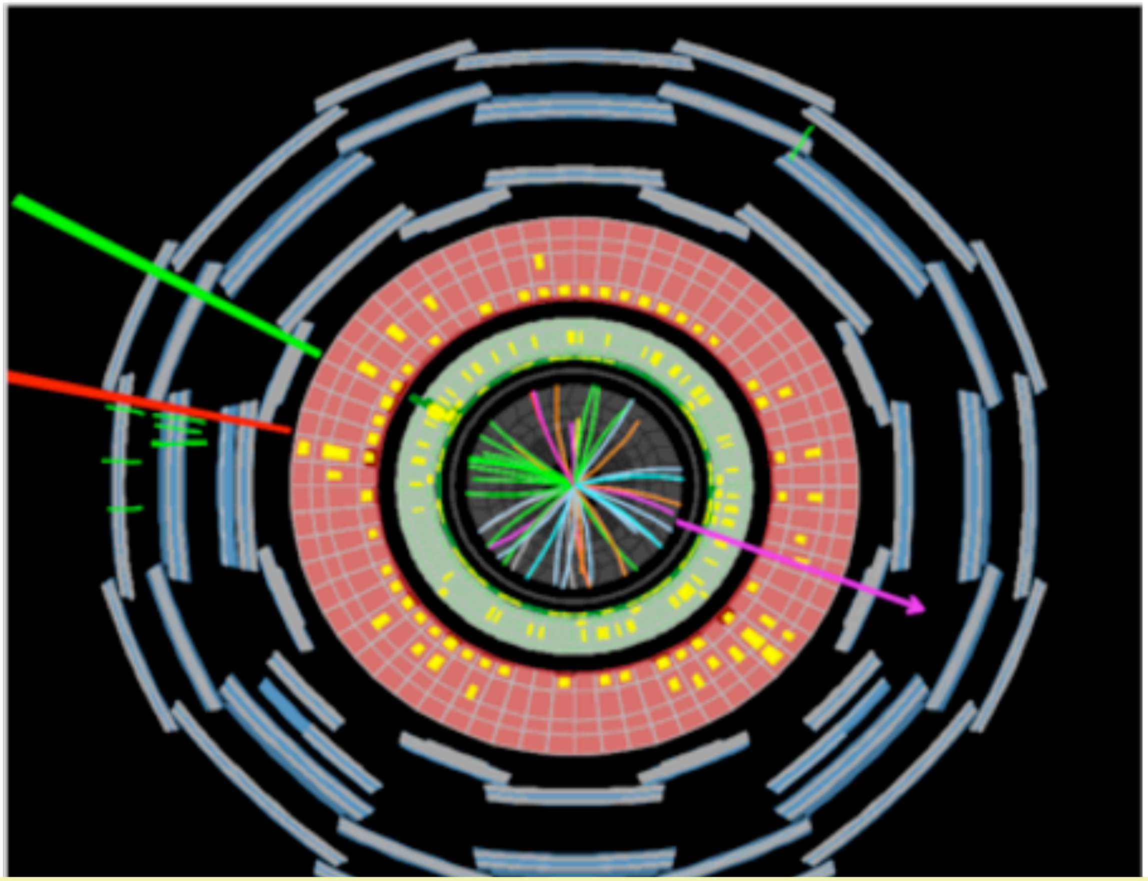
Multijet Event in
7 TeV Collisions

- η and ϕ act as map of activity in the detector

Detecting Neutrinos

- Neutrinos do not interact with any of the detector material.
- Their presence in the detector can be inferred from the lack of momentum balance transverse to the beam, known as **missing transverse energy** (E_T).

$$\sum_{\text{initial}} p_x = \sum_{\text{final}} p_x = 0 \qquad \sum_{\text{initial}} p_y = \sum_{\text{final}} p_y = 0$$



Red and green are reconstructed electron and muon

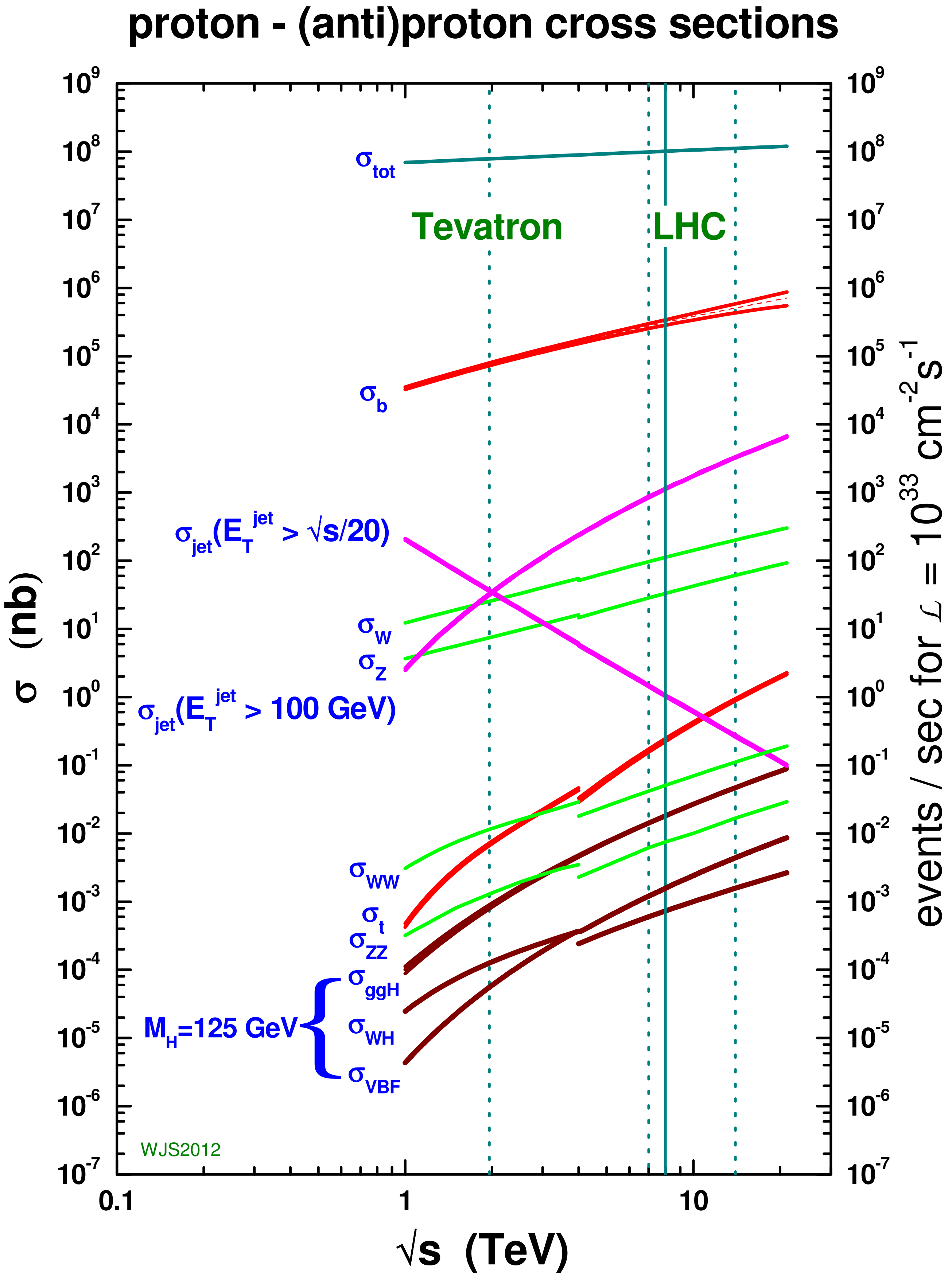
Pink is the inferred direction of the ν_e and ν_μ

- In an LHC collision, the momentum of the interacting partons is along the beam direction (e.g. the z-direction)
- If measured p_x and p_y don't sum to zero, the presence of a neutrino is inferred.
- The Σp_x and Σp_y of the total number of neutrinos in an event is measured.
  - Very sensitive to measurements effects, such as detector inefficiency.
- This doesn't work in the beam direction, as the momentum of the individual partons colliding is not known for each event.

LHC Collisions

- In 2012 the LHC run at **4 TeV** per beam
- 10^{11} protons in each bunch
- two bunches collide every **50 ns**

- Large backgrounds from non-Higgs processes



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