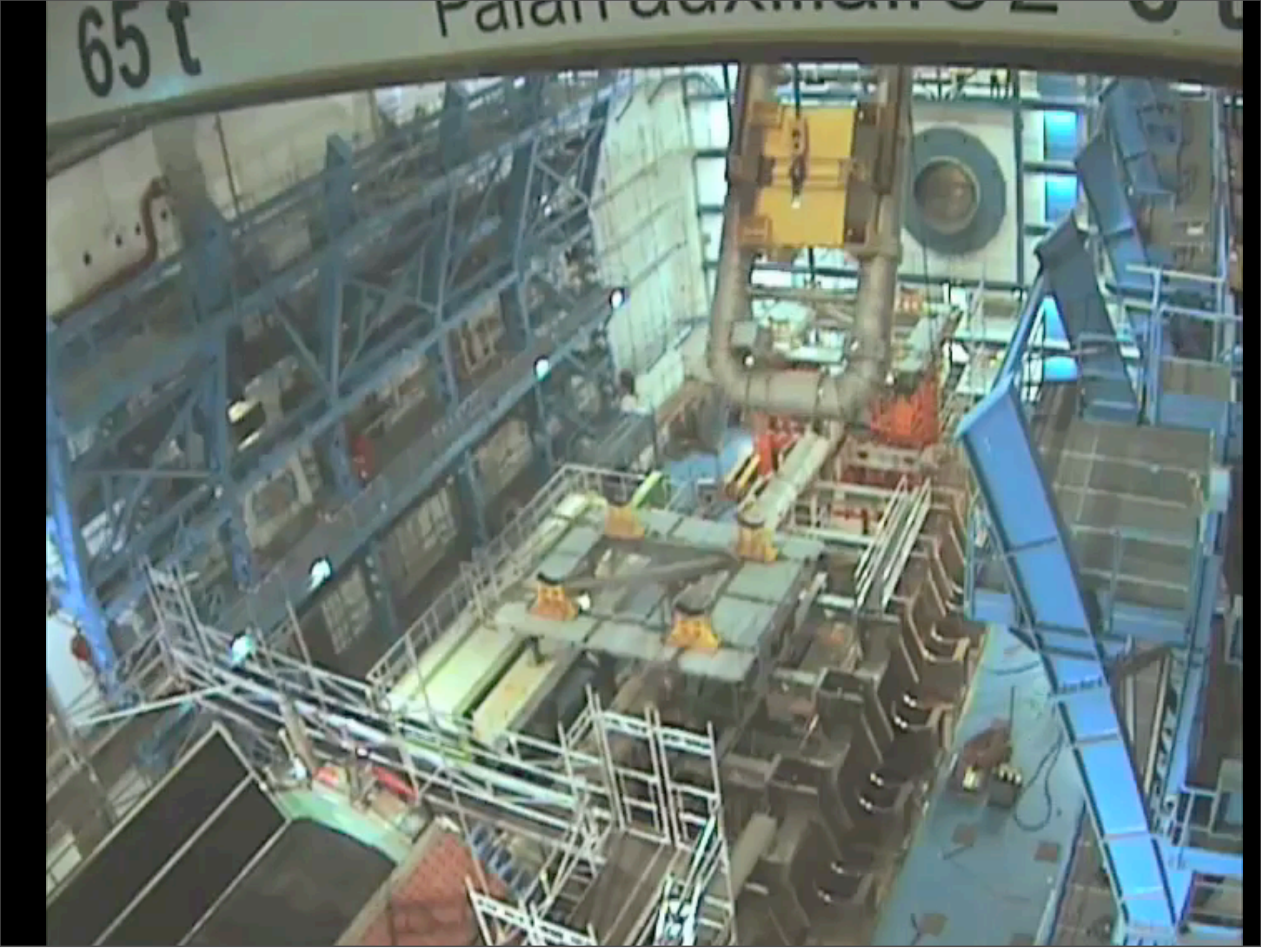
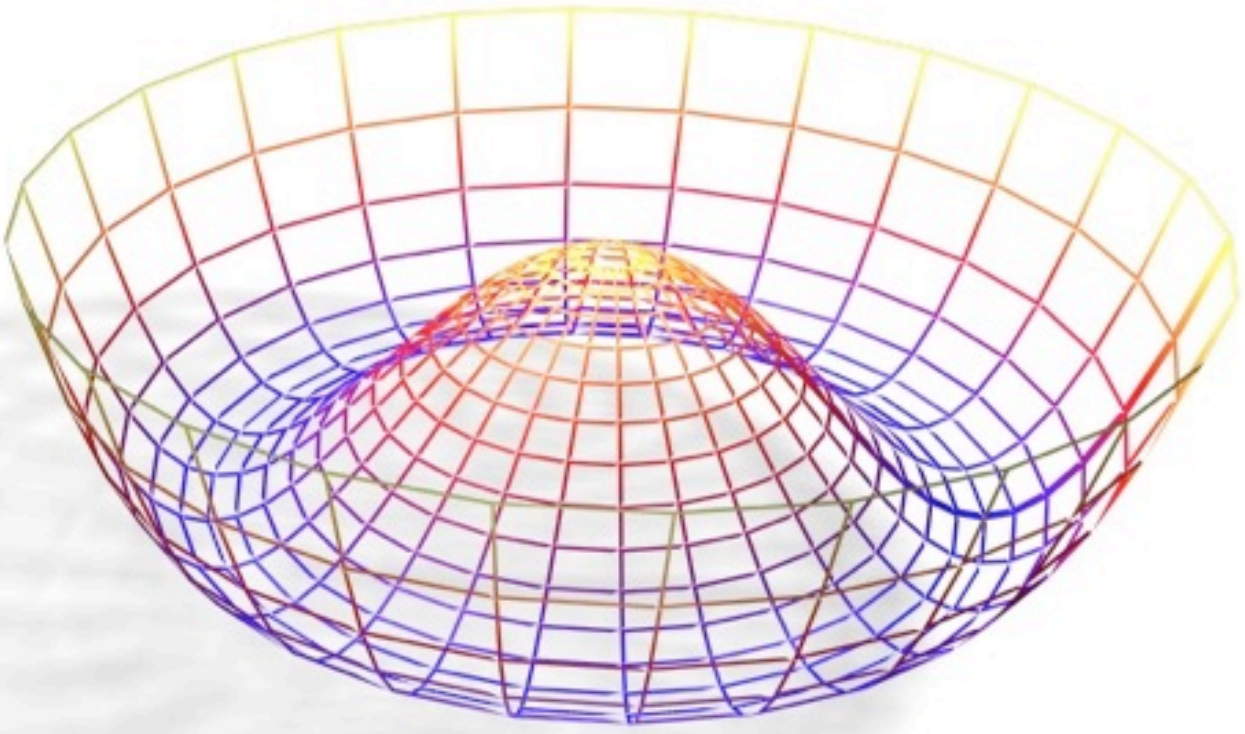


Tuesday, July 10, 12

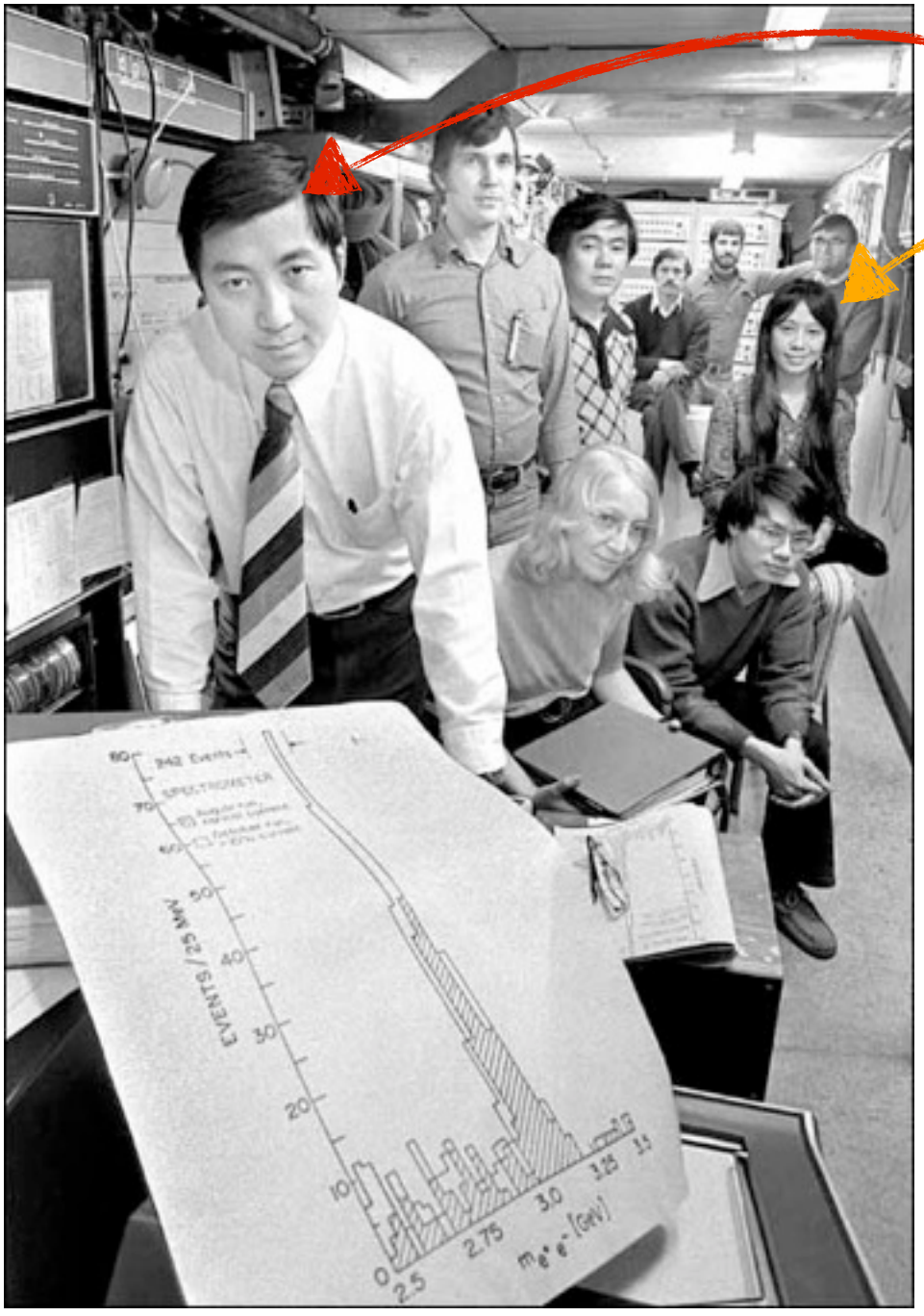
Center for
Cosmology and
Particle Physics

Discovery!
How we did it and what we know so far



Kyle Cranmer,
New York University

Last Really Exciting Discoveries

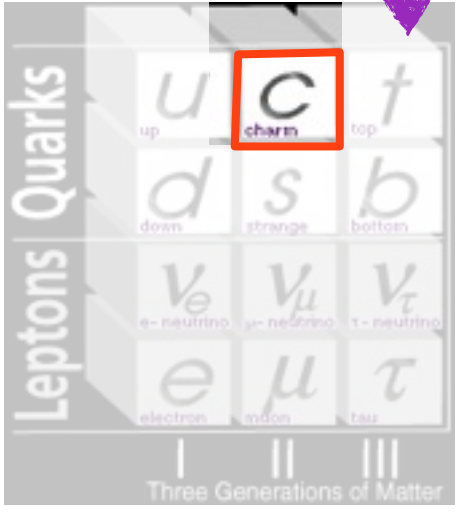


Sam Ting, Nobel Prize 1976

My Ph.D. advisor, Sau Lan Wu
co-discoverer of gluon (1979)

Top Quark discovery in
1995, exciting, but expected

(as heavy as a gold atom)



Fundamental Particles & Interactions

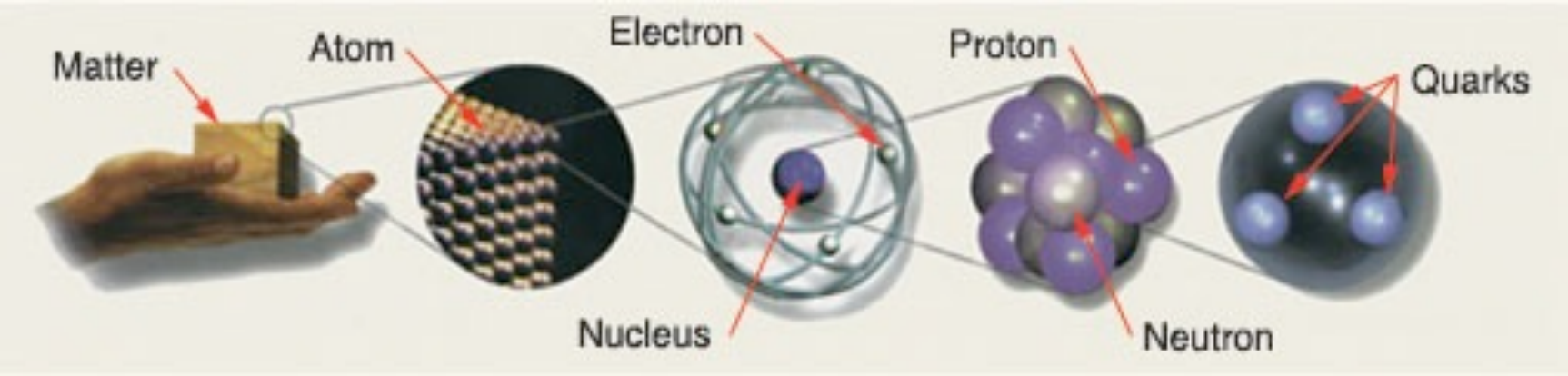
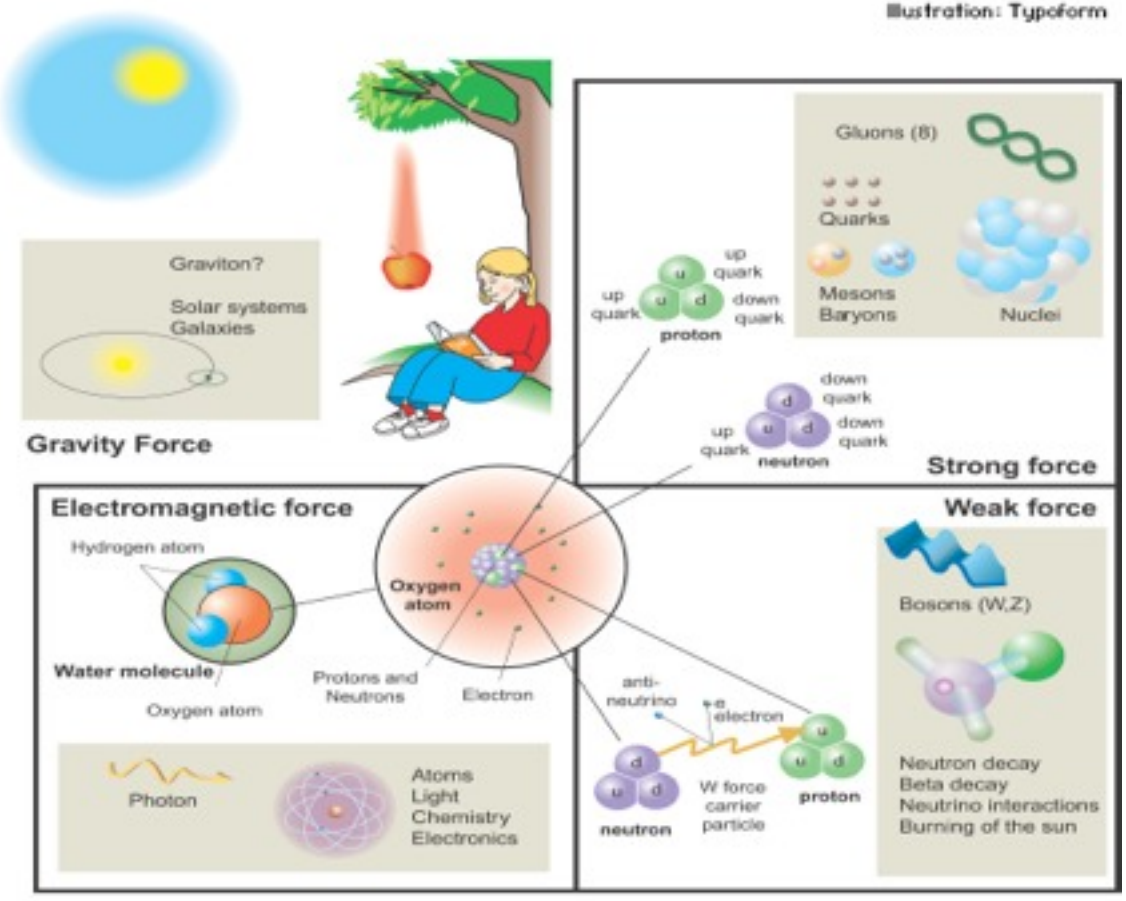
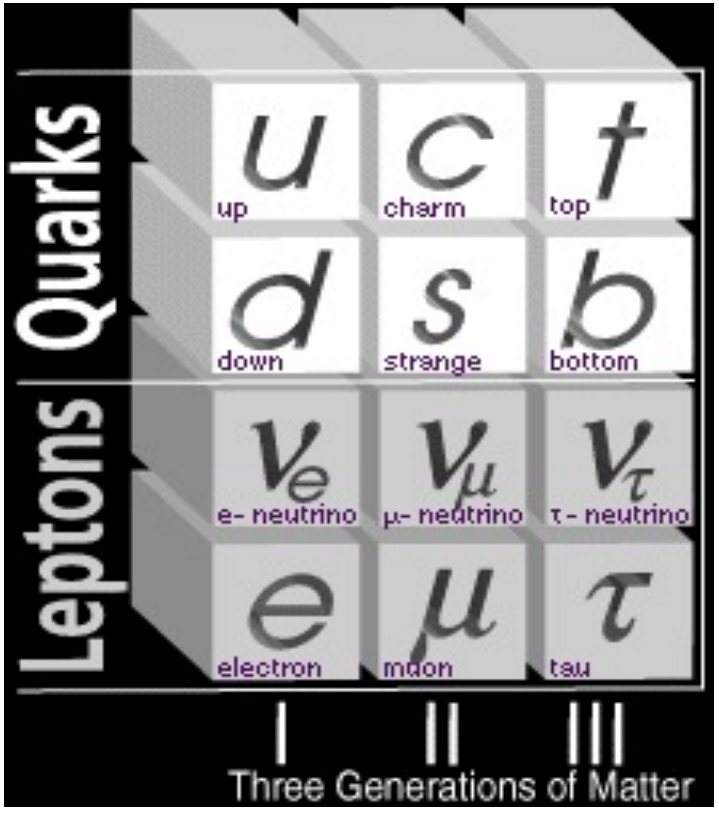
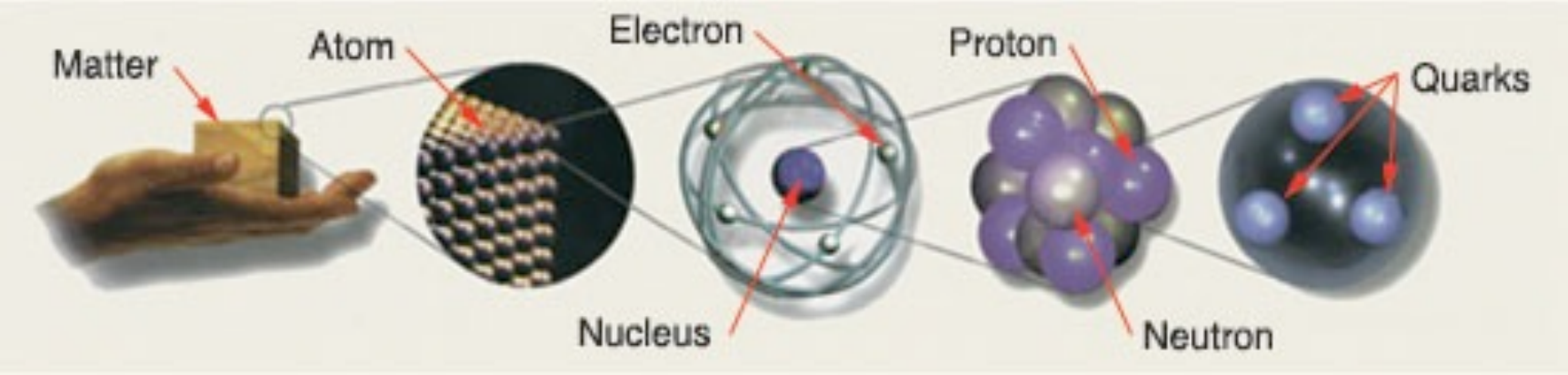


Illustration: Typoform





Fundamental Particles & Interactions

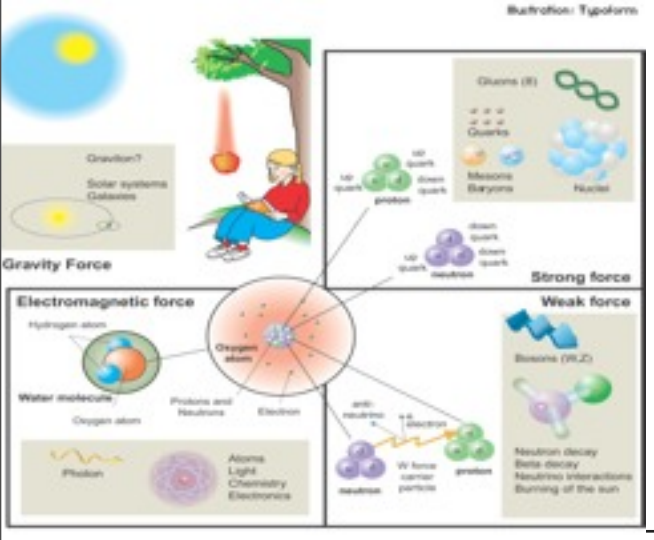


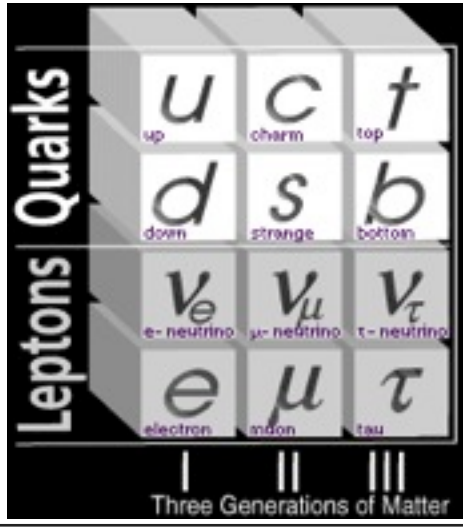
$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^\mu(i\partial_\mu - \frac{1}{2}g\tau\cdot\mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)L + \bar{R}\gamma^\mu(i\partial_\mu - \frac{1}{2}g'YB_\mu)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

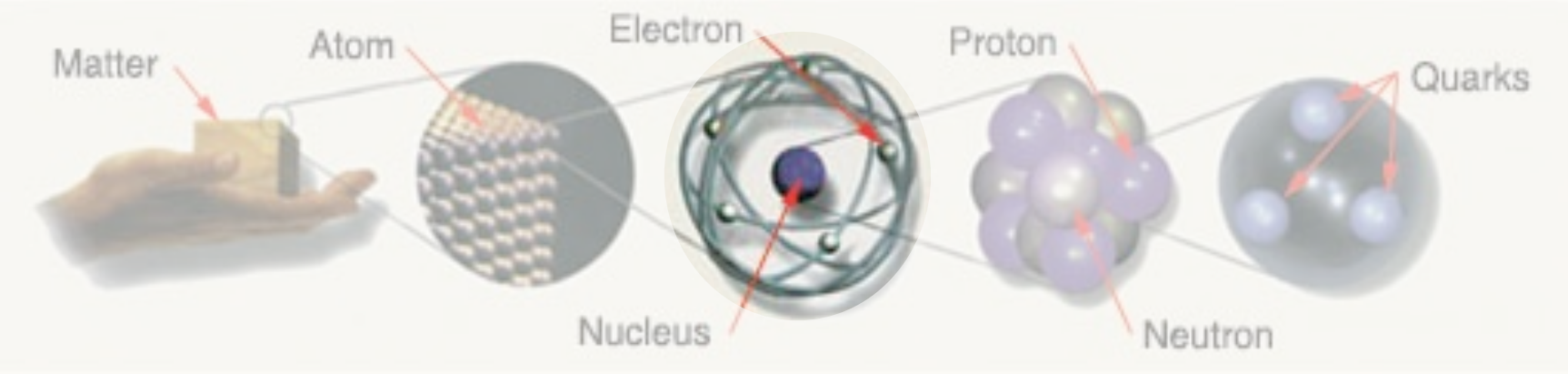
$$+ \underbrace{\frac{1}{2}\left|(i\partial_\mu - \frac{1}{2}g\tau\cdot\mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)\,\phi\right|^2 - V(\phi)}_{W^\pm,Z,\gamma,\text{and Higgs masses and couplings}}$$

$$+ \underbrace{g''(\bar{q}\gamma^\mu T_a q)\,G^a_\mu}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1\bar{L}\phi R + G_2\bar{R}\bar{\phi}_c L + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$





The mass of the electron



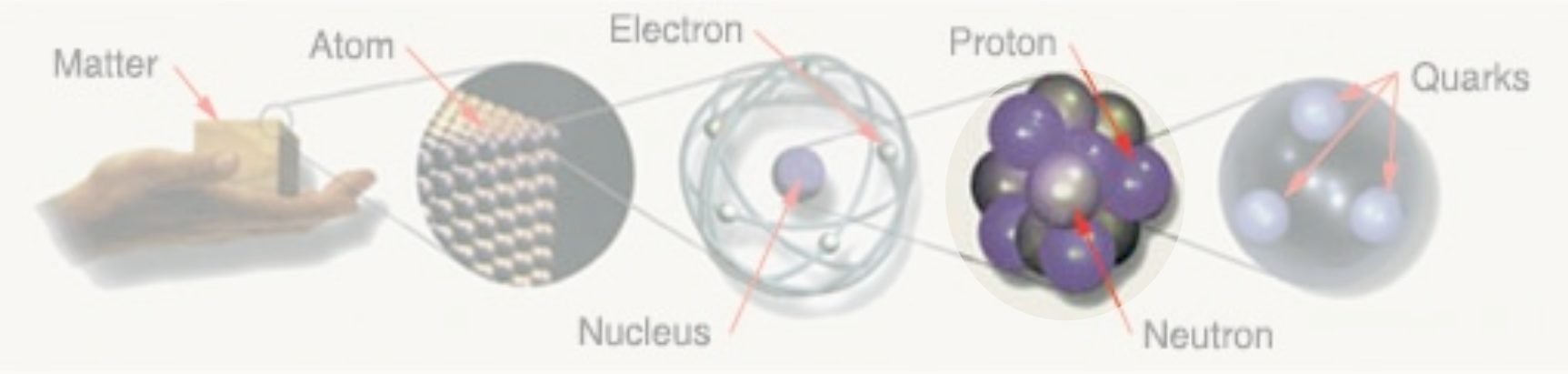
The electron is a fundamental particle deriving its mass from interactions with the Higgs field

The mass of the electron sets the scale of the atom

- without the Higgs, the universe would be a very different place

$$a_0 = \frac{\hbar^2}{m_e e^2}$$

The origin of mass

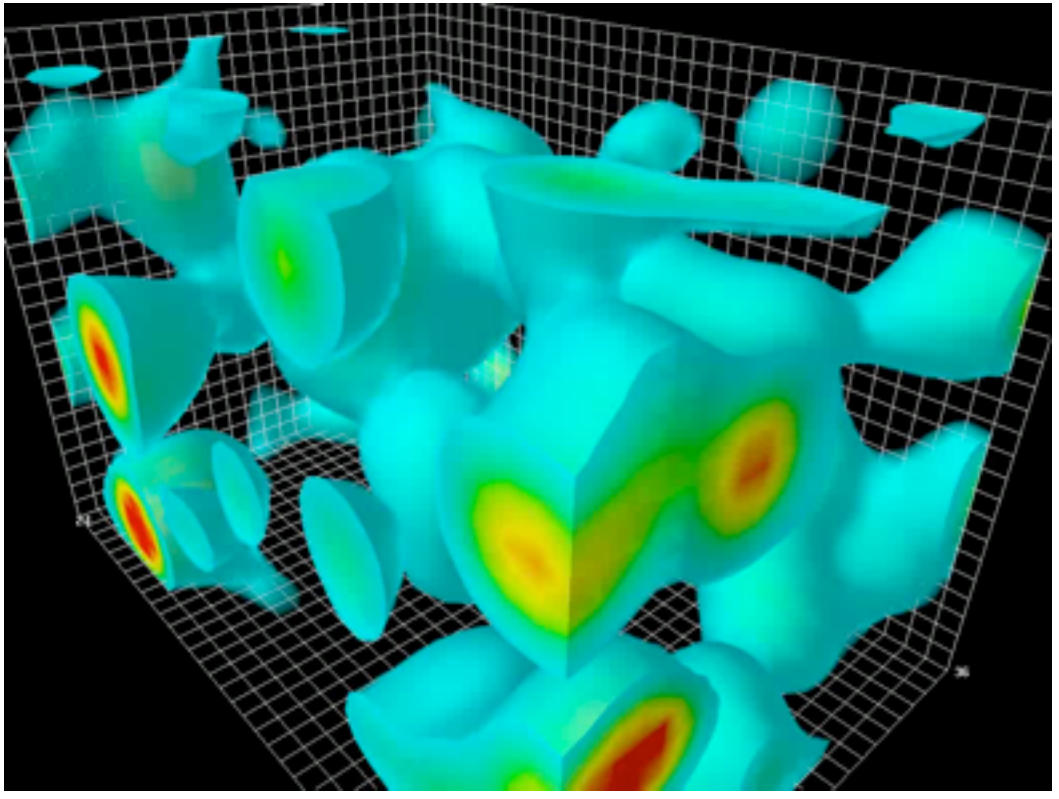


When you step on the scale, most of your mass comes from the nuclei of atoms.

Quark masses only contribute ~1%

Most mass comes from energy in the quarks and gluons inside very dynamic protons and neutrons

$$E = mc^2$$



Fermi's theory of beta decay

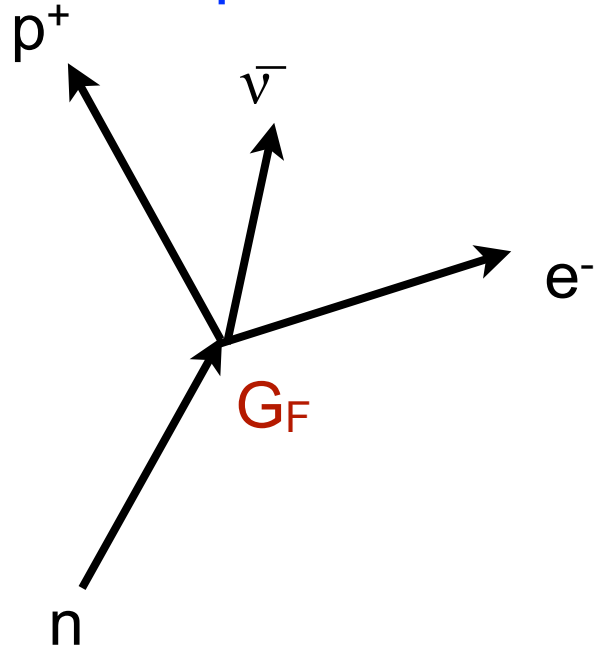
In 1933 Fermi proposed a theory of beta decay

- four-fermion vertex with coupling constant G_F

The theory has a serious sickness

- **unitarity violation:** interaction probability grows with energy until probabilities are greater than 1.
- The theory is non-renormalizable.

Now we see Fermi theory as an "effective theory" valid to energy scales comparable with the mass of the W-boson.



Fermi's theory of beta decay

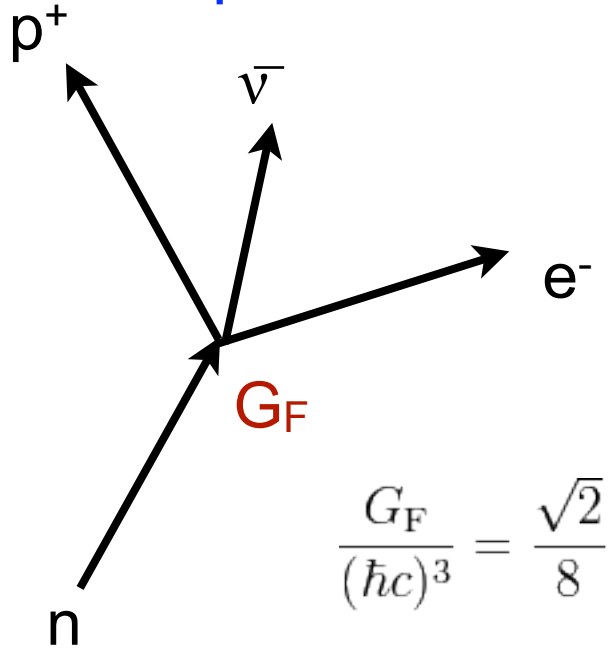
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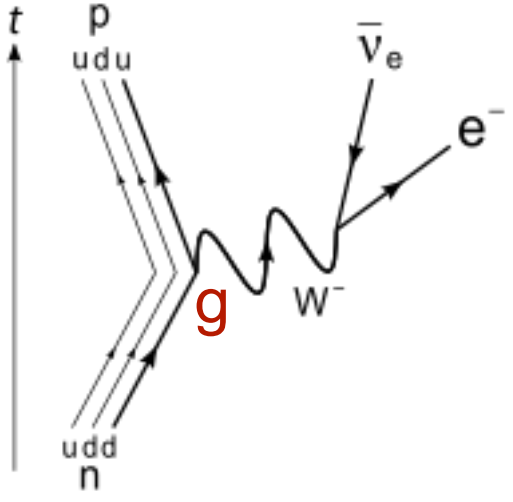
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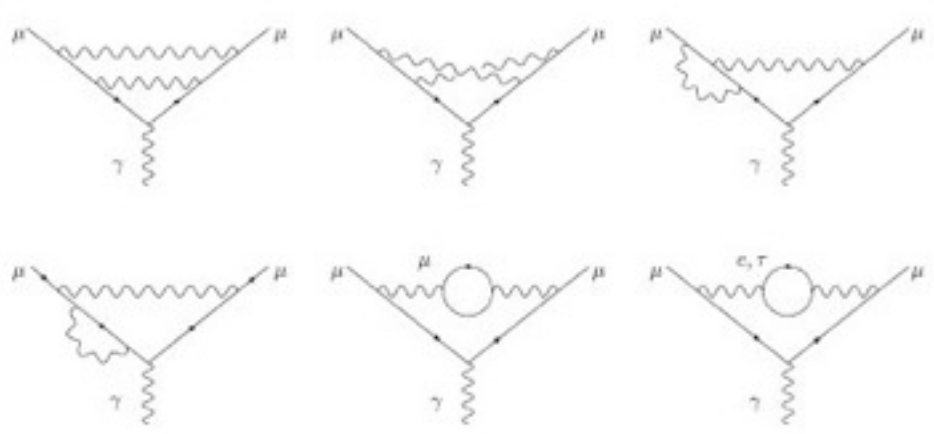
$$\frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2} = 1.16637(1) \times 10^{-5}\mathrm{GeV}^{-2} .$$



The Success of the Standard Model & QFT

Non-trivial aspects of the theory have been tested to < 1 ppm

- These results give us confidence QFT's concept of renormalization

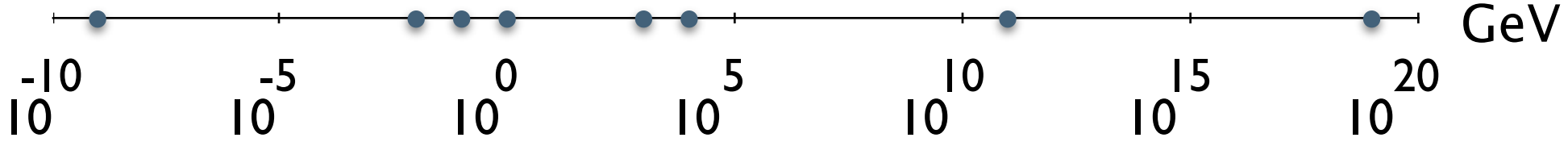


$$a_\mu\ (exp) = 11\ 659\ 208\ (6) \times 10^{-10}\ (0.5\ ppm)$$

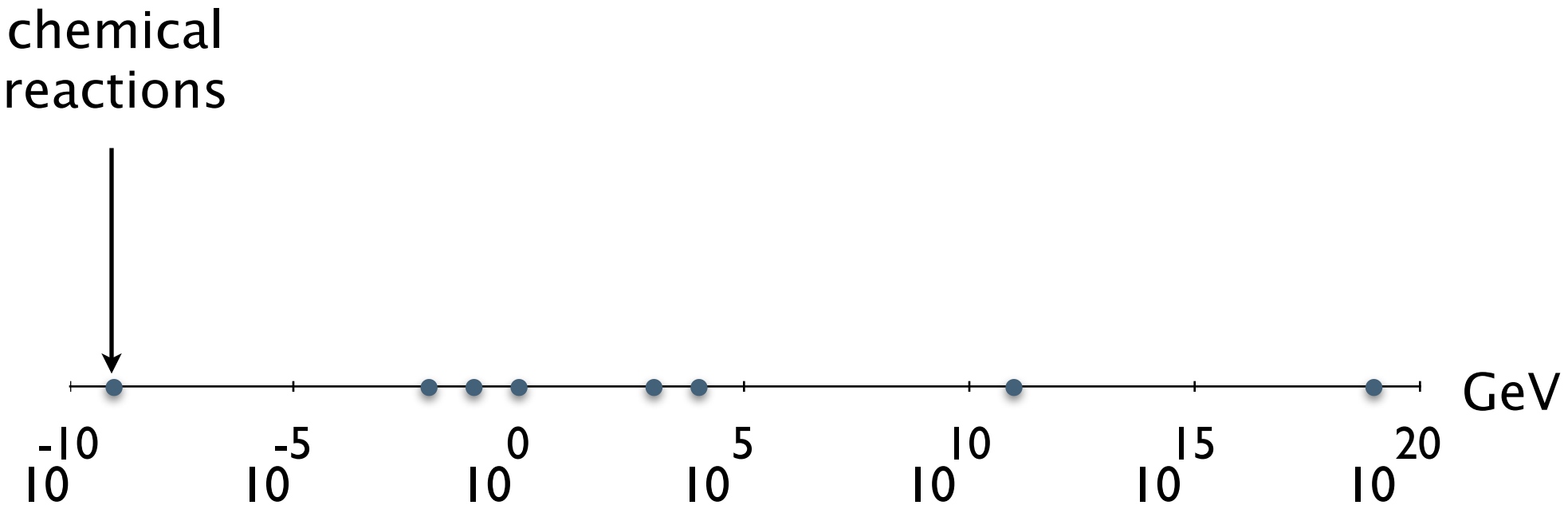




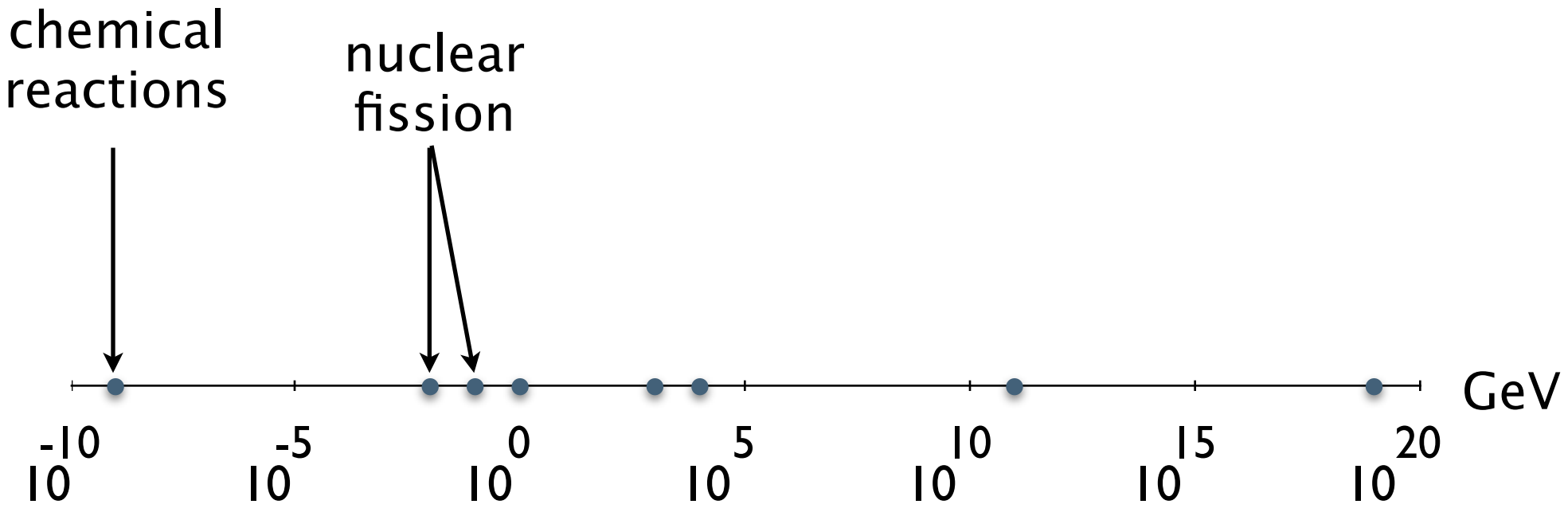
Energy scales in context



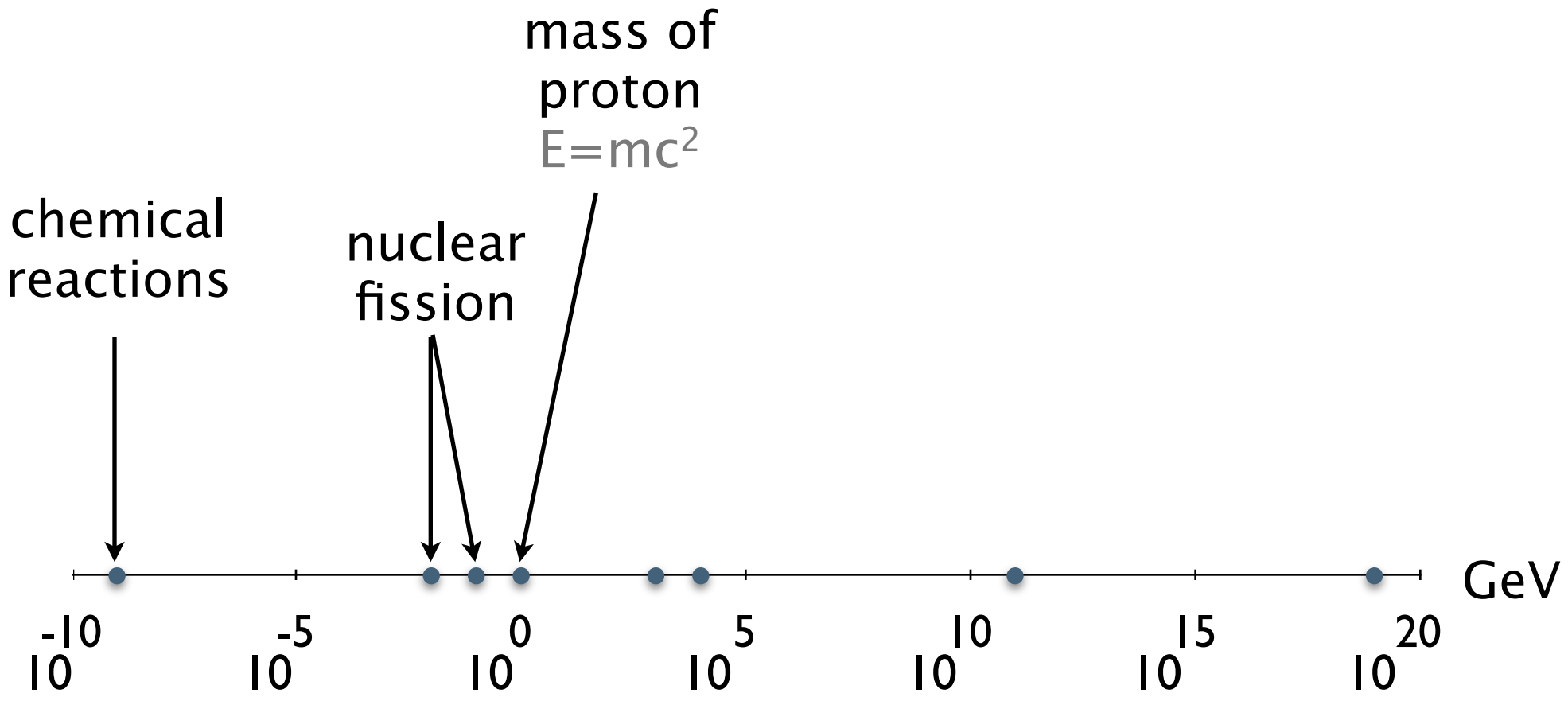
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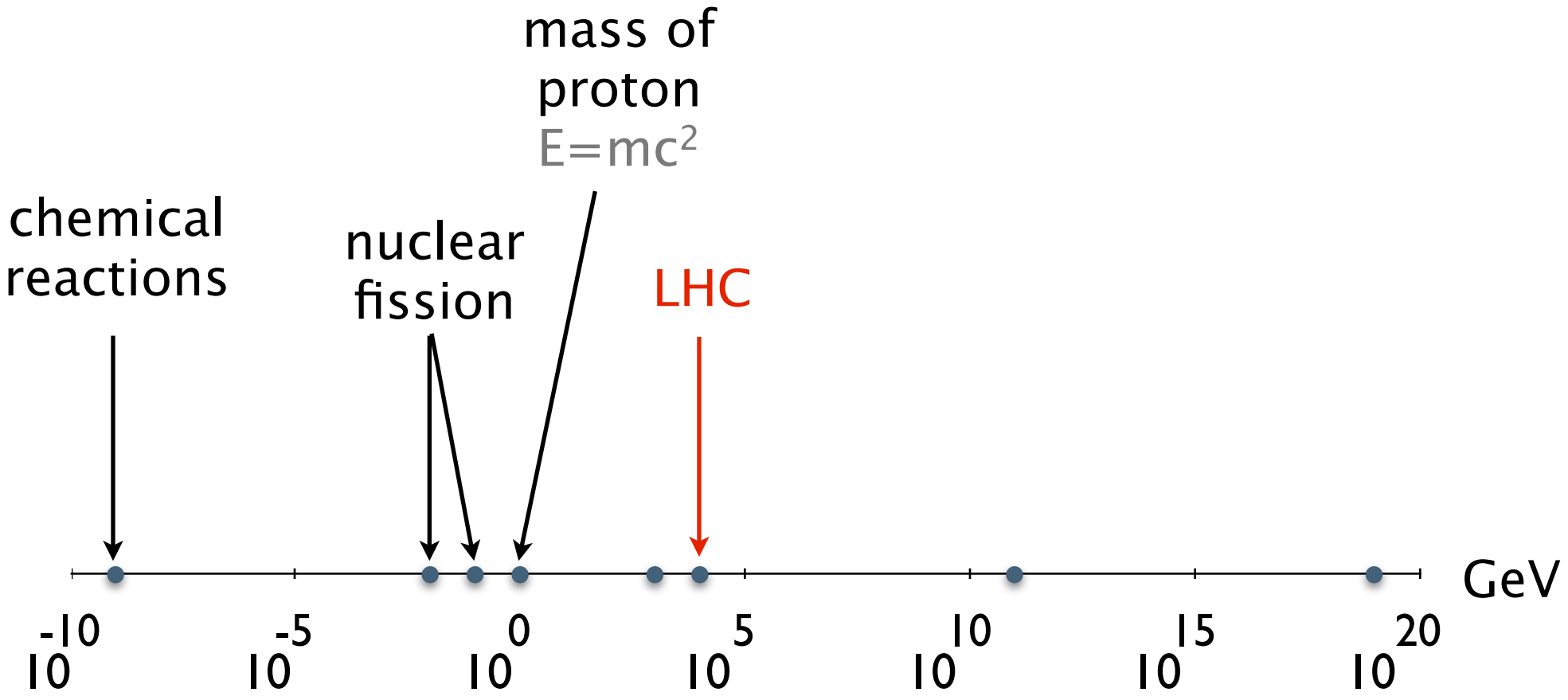
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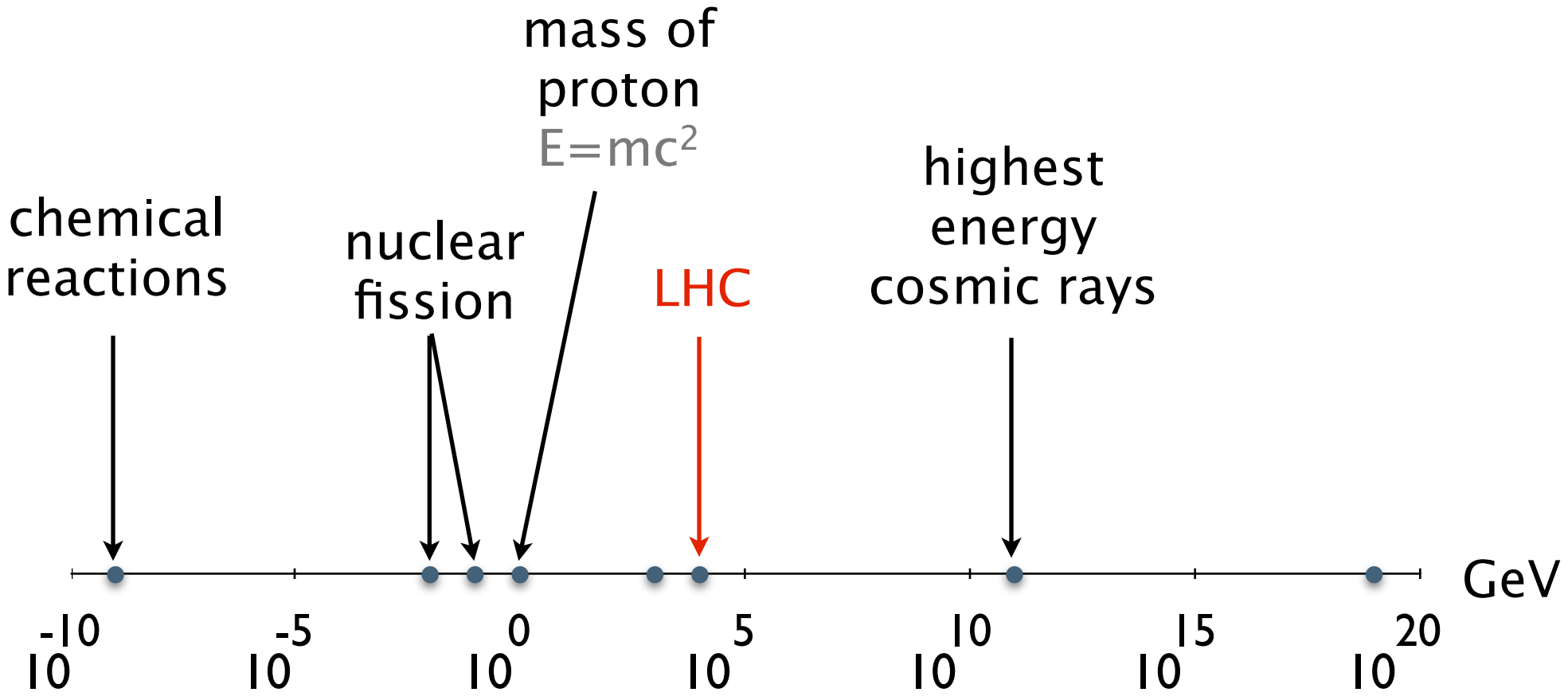
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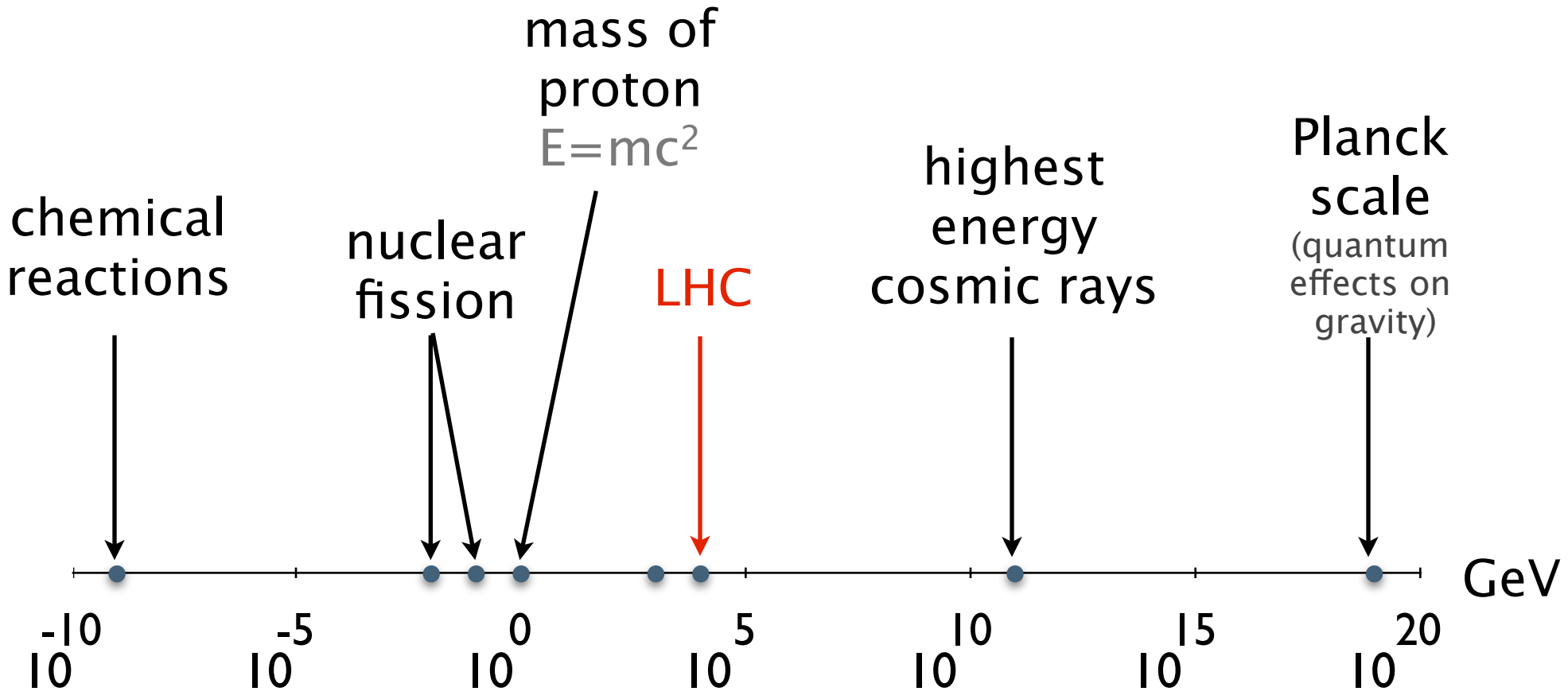
Energy scales in context



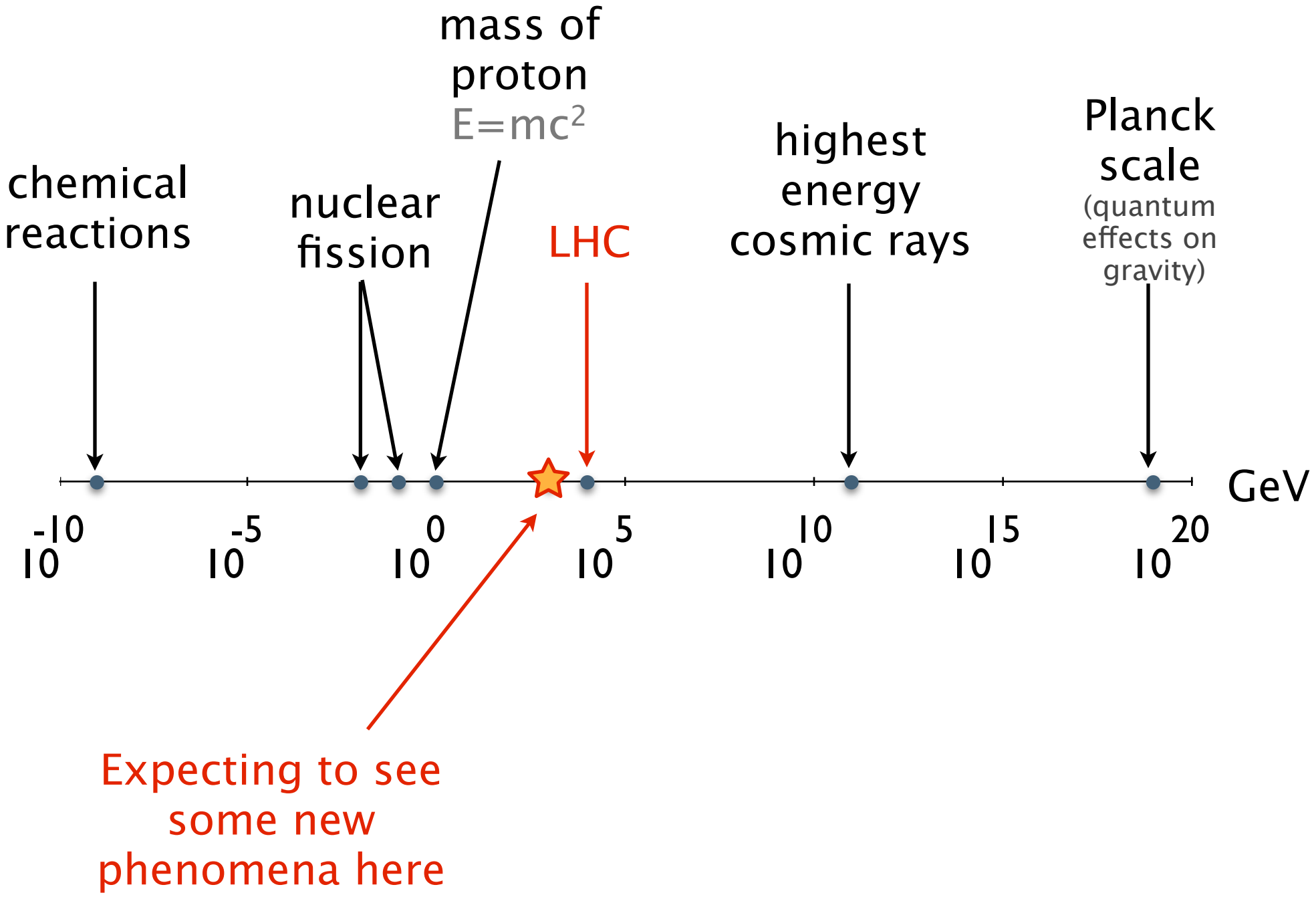
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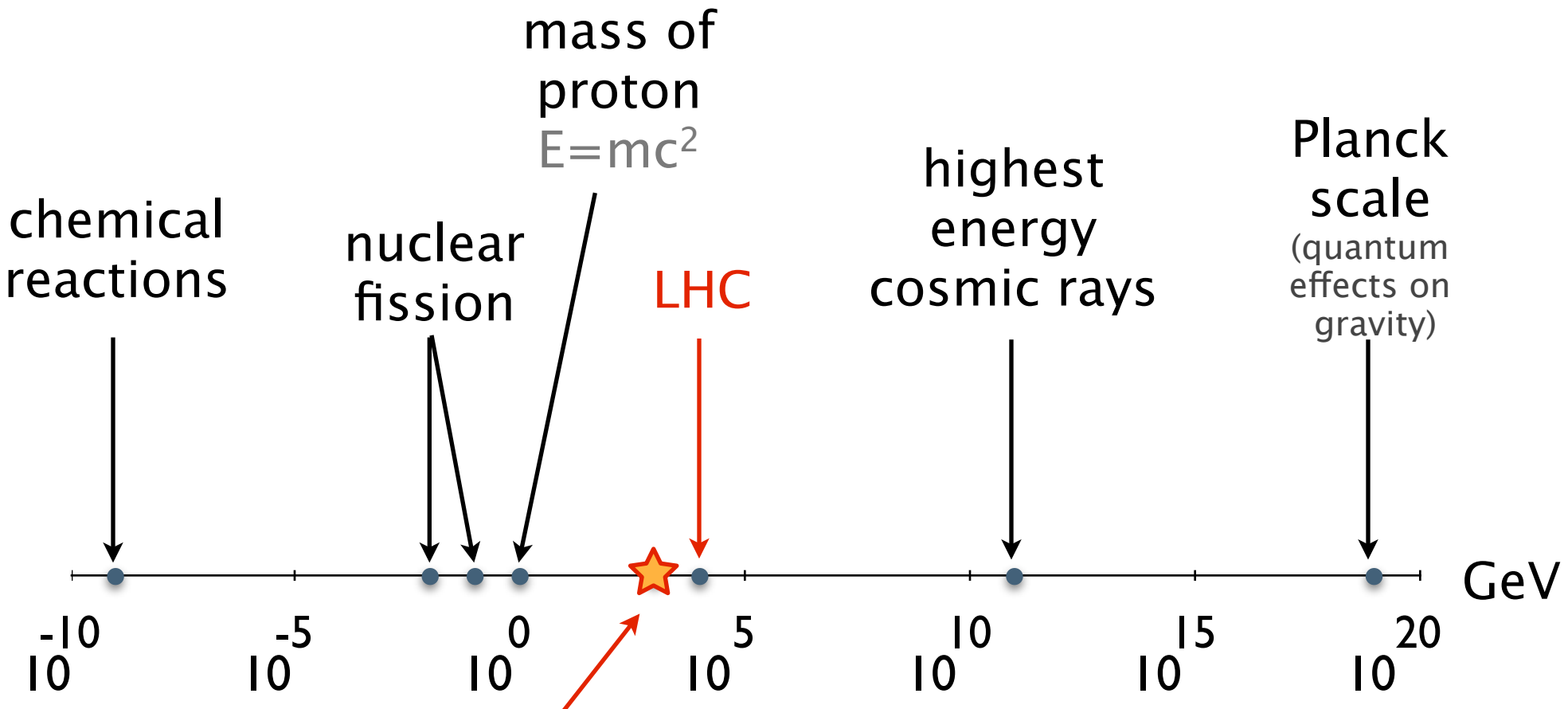
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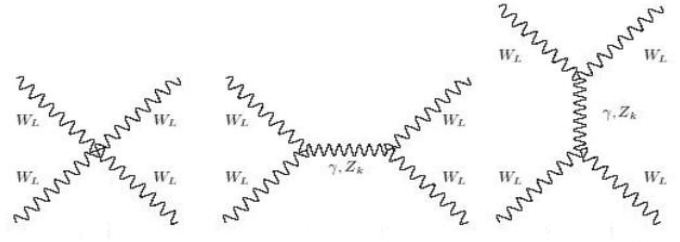
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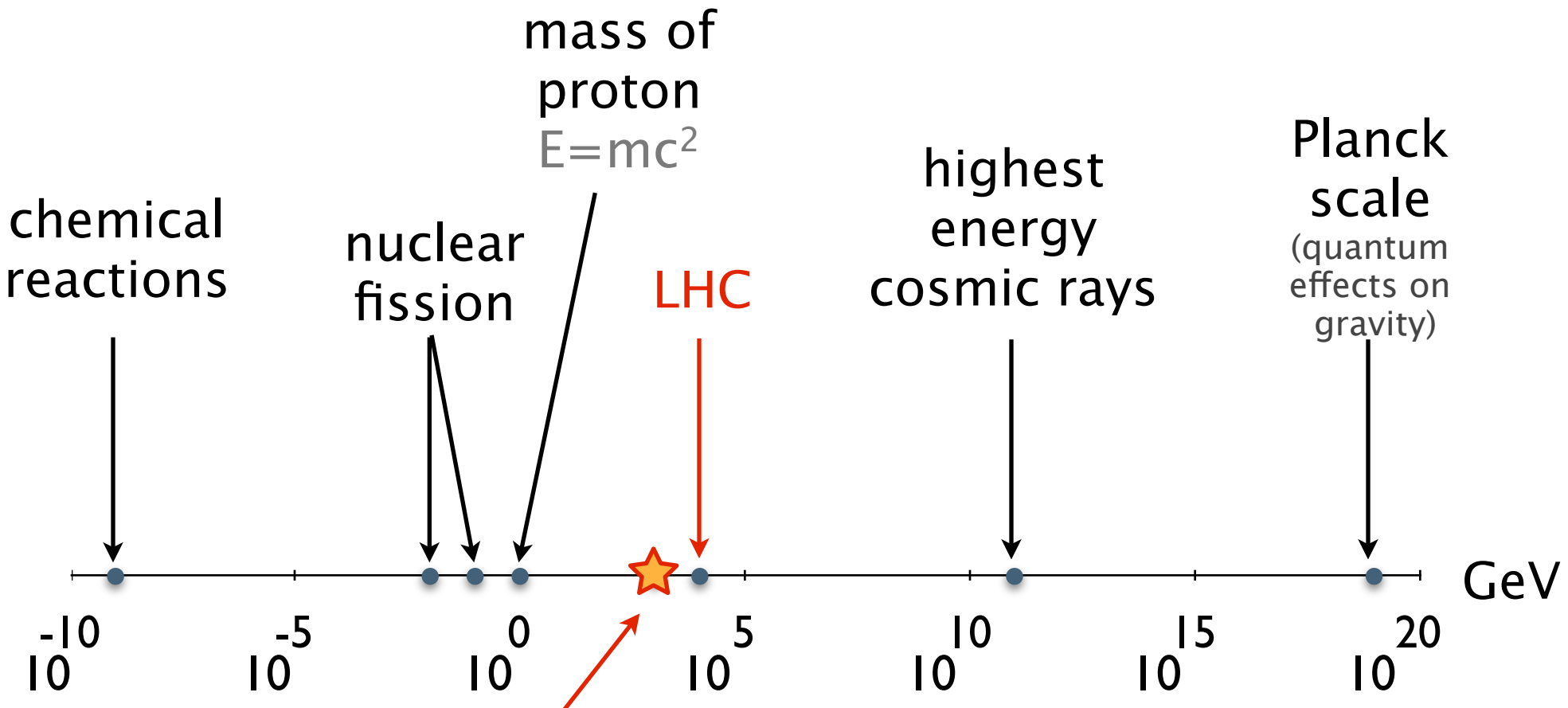


Expecting to see some new phenomena here

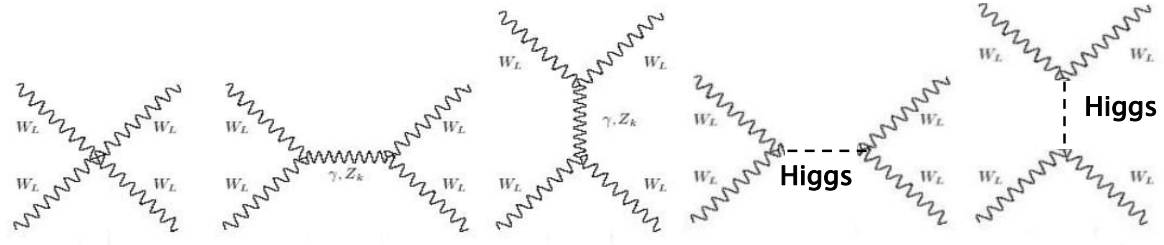


Violation of unitarity @ $\sqrt{s} \geq 1.7$ TeV

Energy scales in context

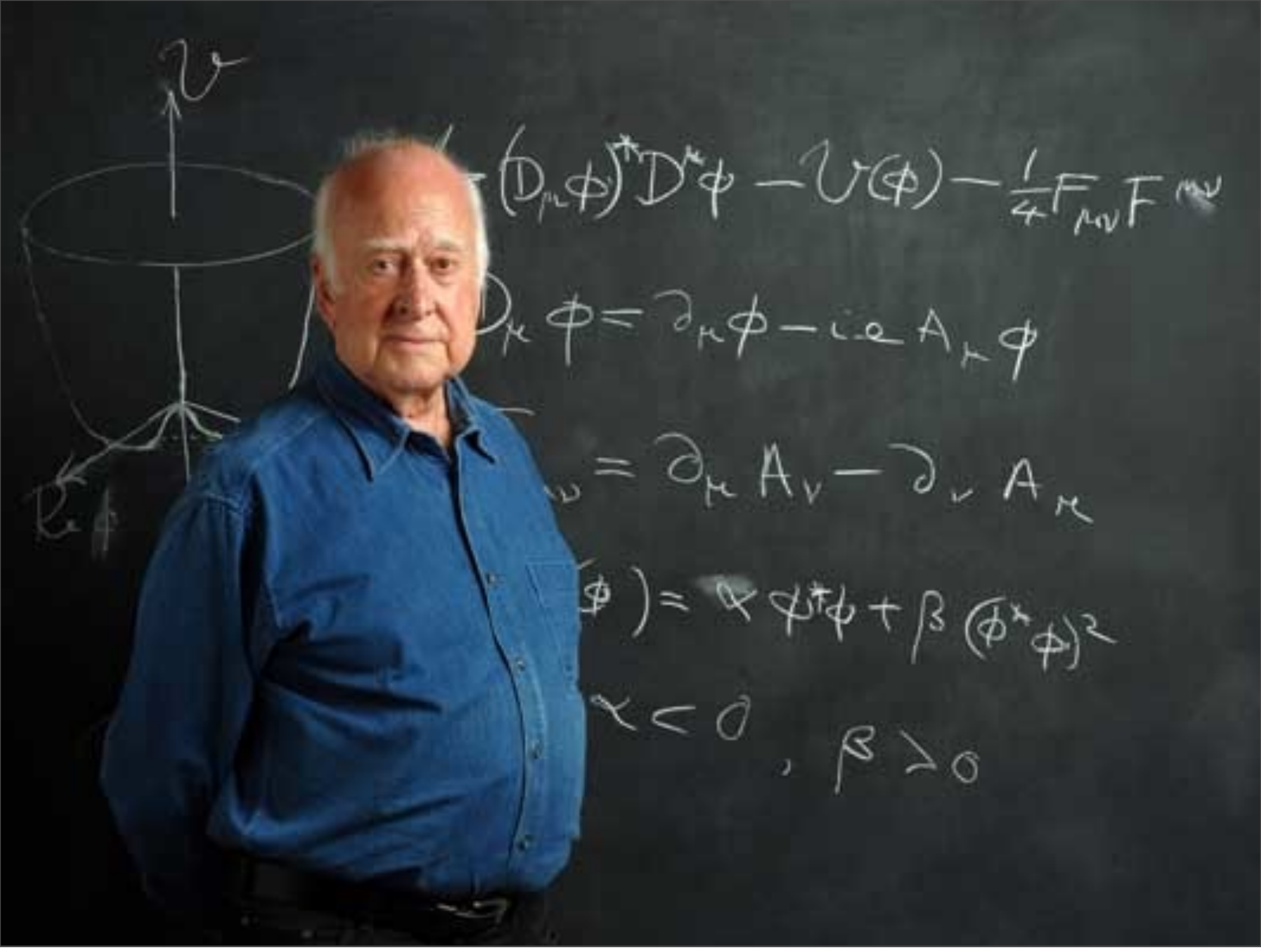


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Violation of unitarity @ $\sqrt{s} \geq 1.7$ TeV

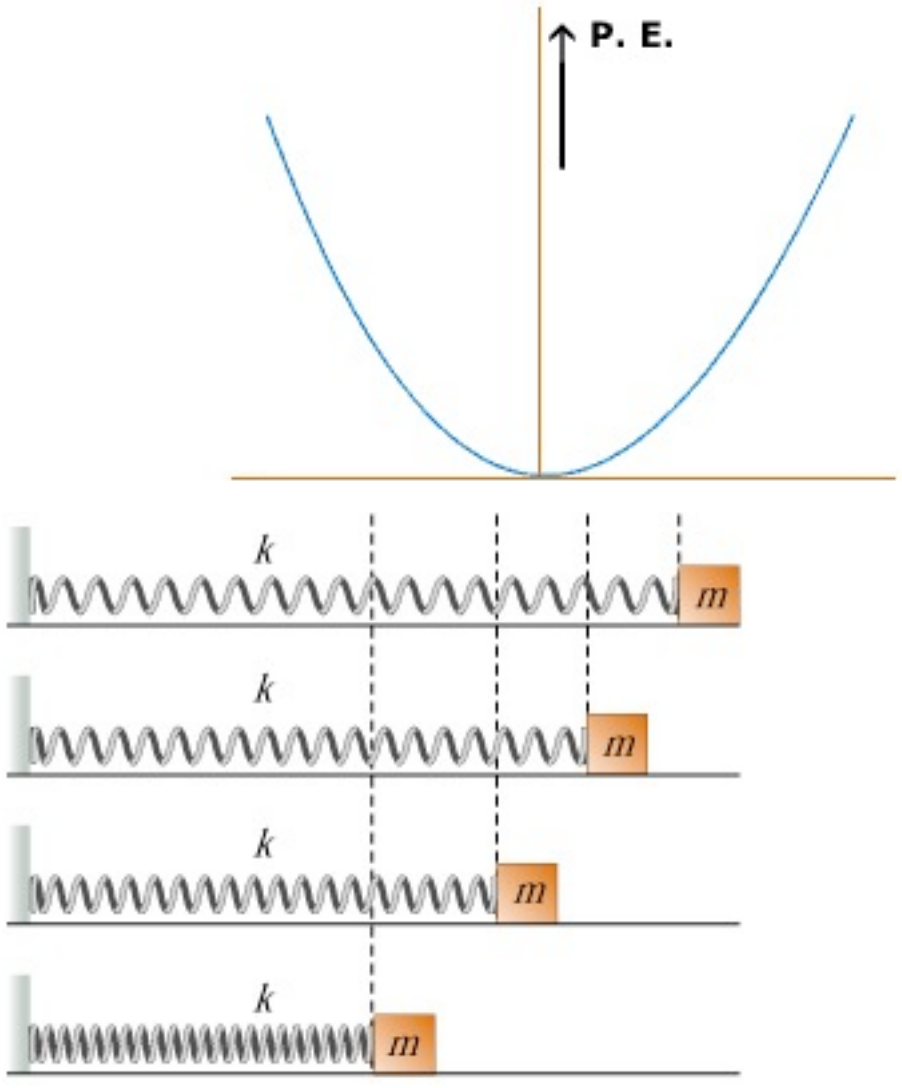
Restores unitarity if $m_H \lesssim 0.8$–1 TeV

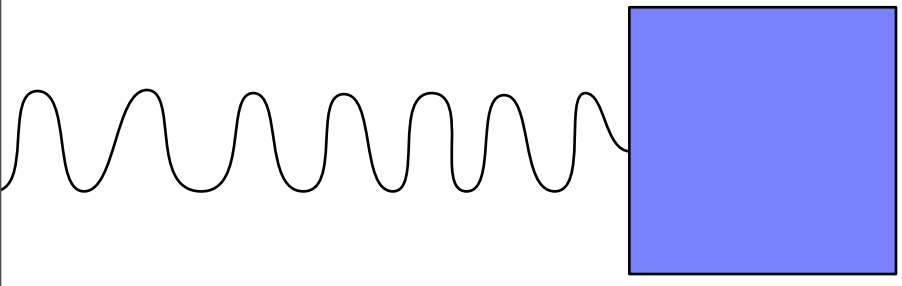

$(D_\mu\phi)^* D^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$D_\mu\phi = \partial_\mu\phi - ieA_\mu\phi$
$= \partial_\mu A_\nu - \partial_\nu A_\mu$
$\phi) = \alpha\phi^*\phi + \beta(\phi^*\phi)^2$
$\alpha < 0$
$\beta > 0$

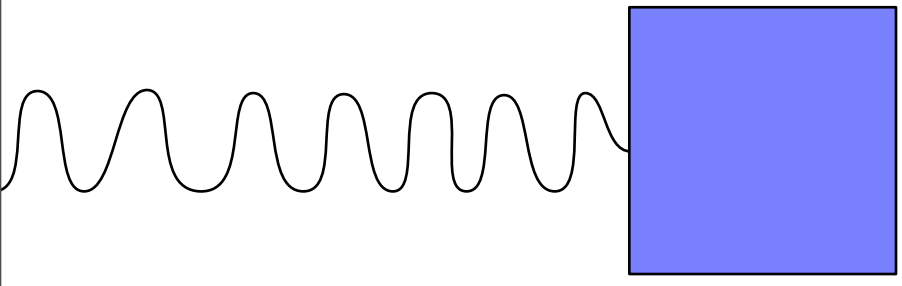
Physics of a spring

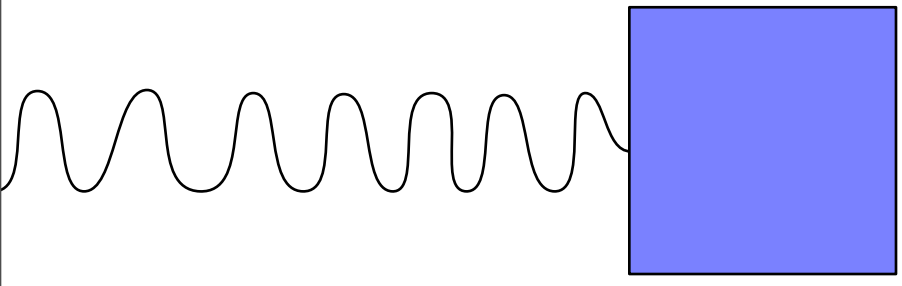
The potential energy depends on stiffness of spring

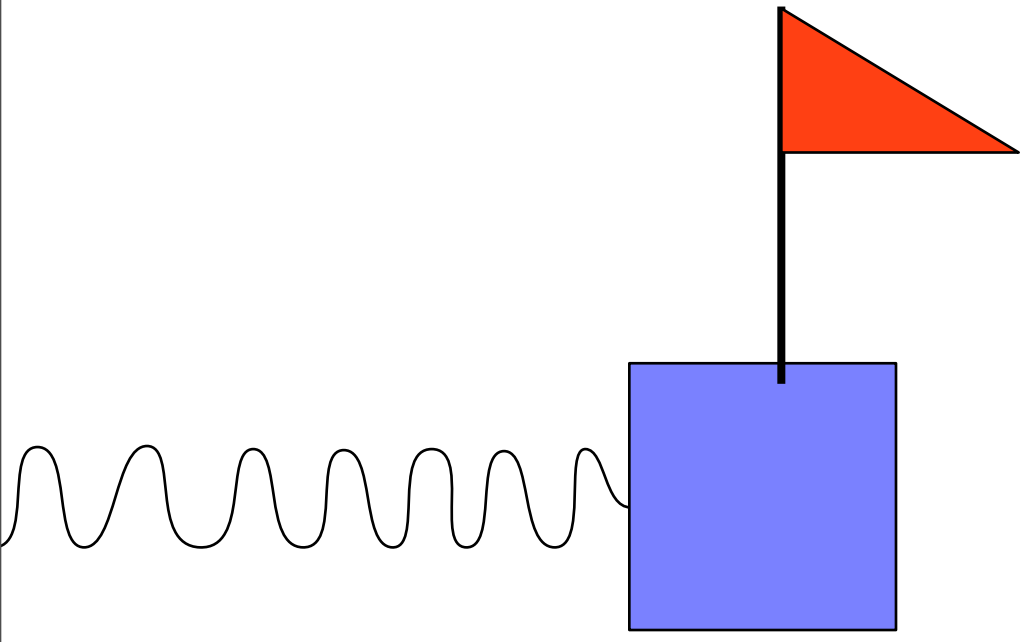
Period of oscillation depends on stiffness of spring and mass of block.

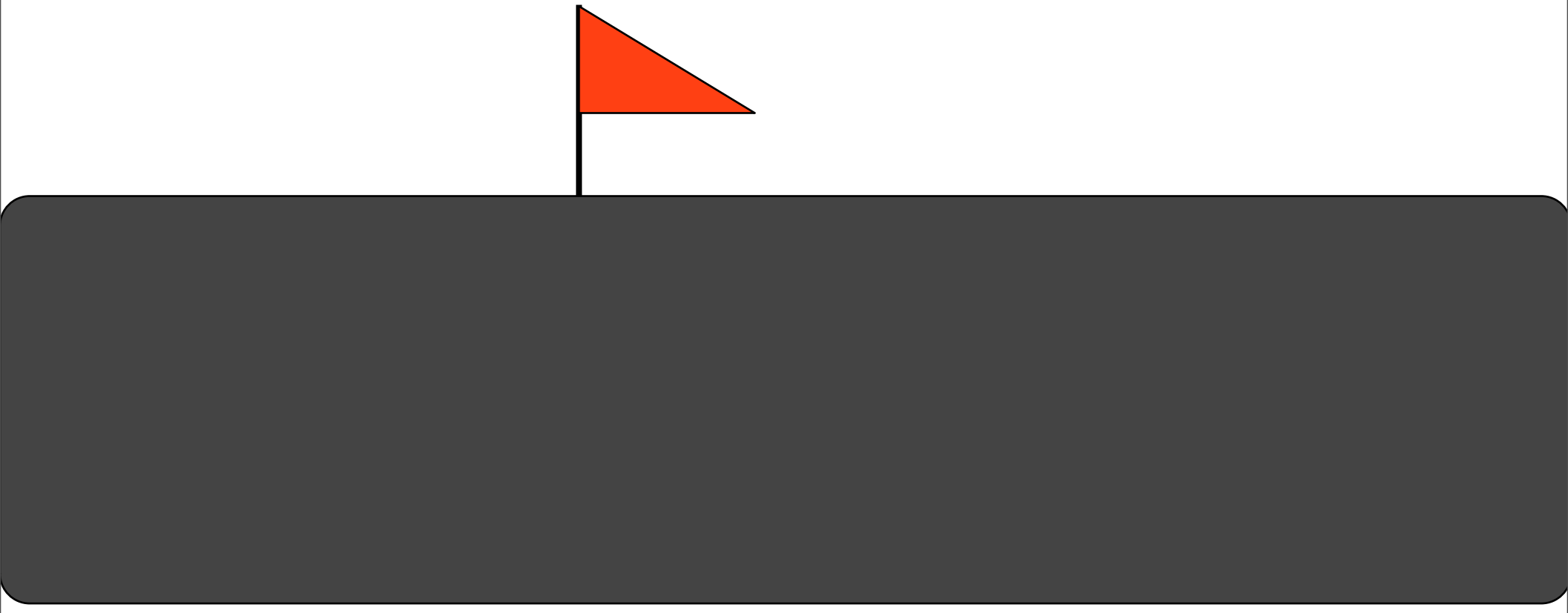


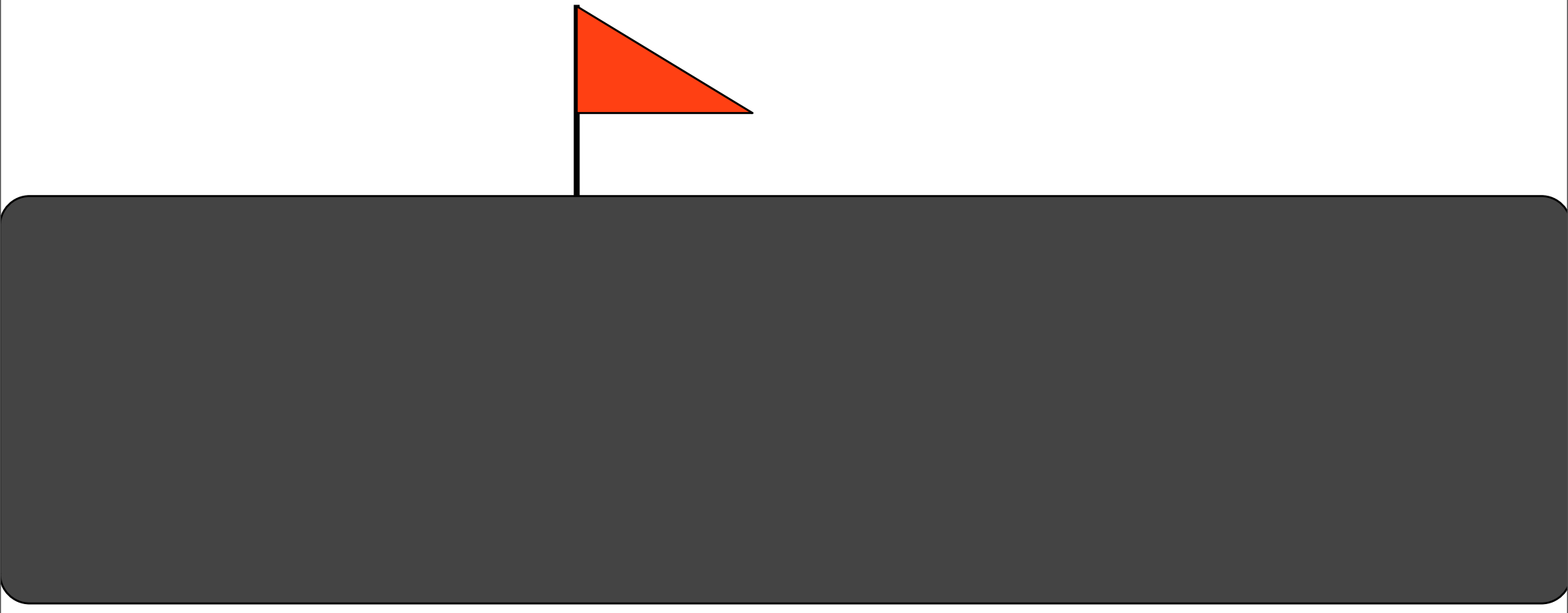


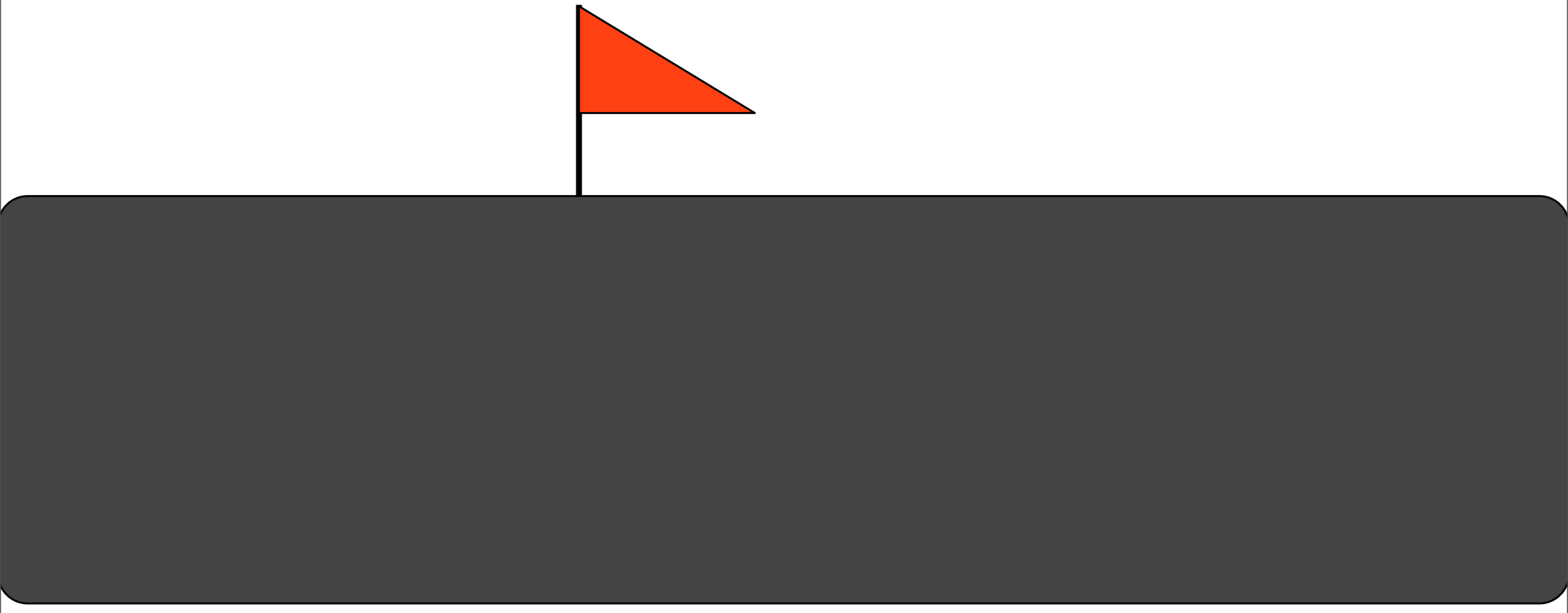


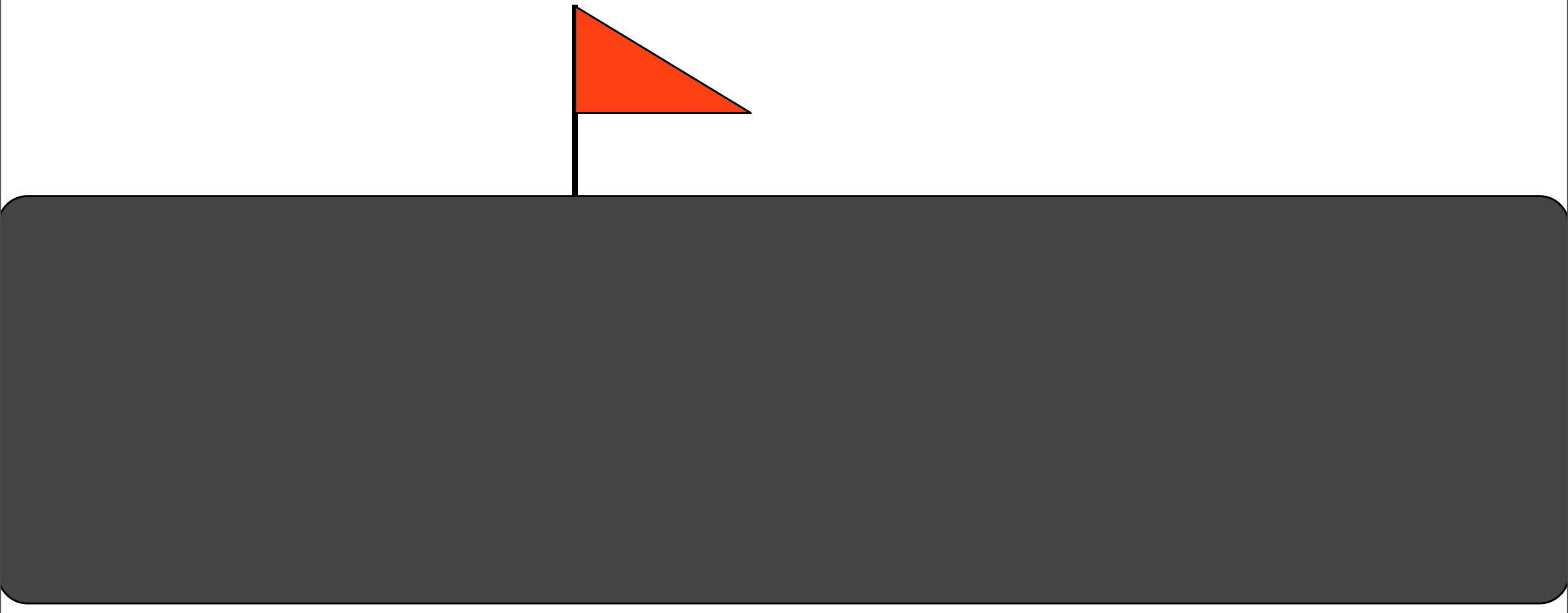


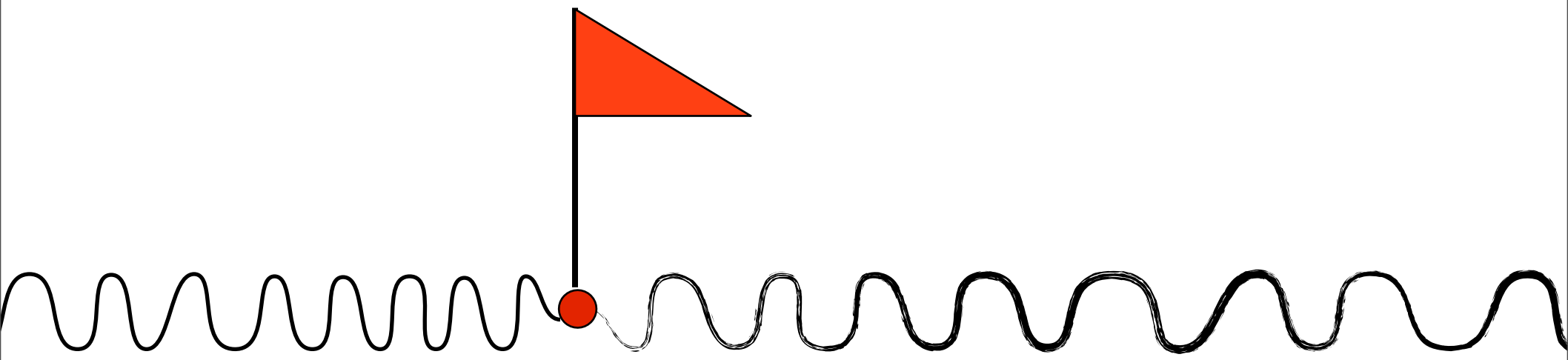








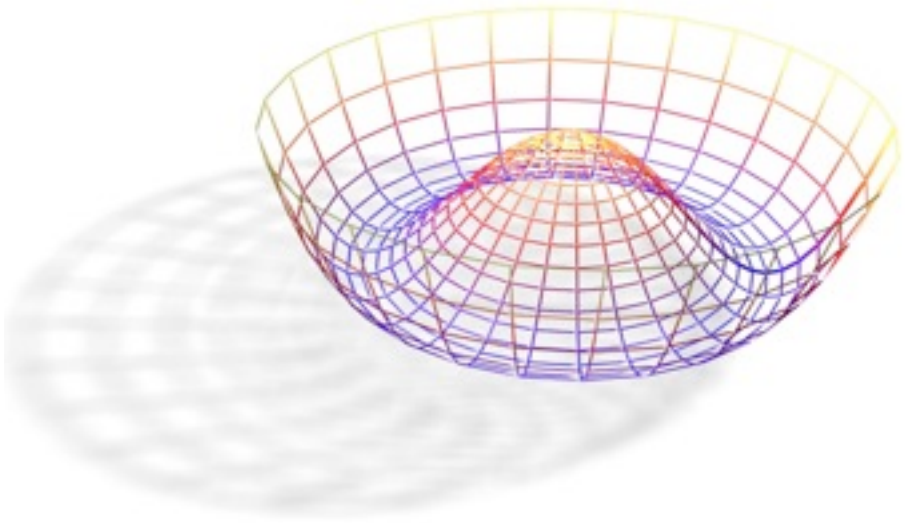




The Standard Model Higgs

We know that the W, Z bosons are massive, but explicit mass terms for the W,Z break the electroweak gauge symmetry.

- massless W,Z only have transverse polarizations



The Standard Model Higgs

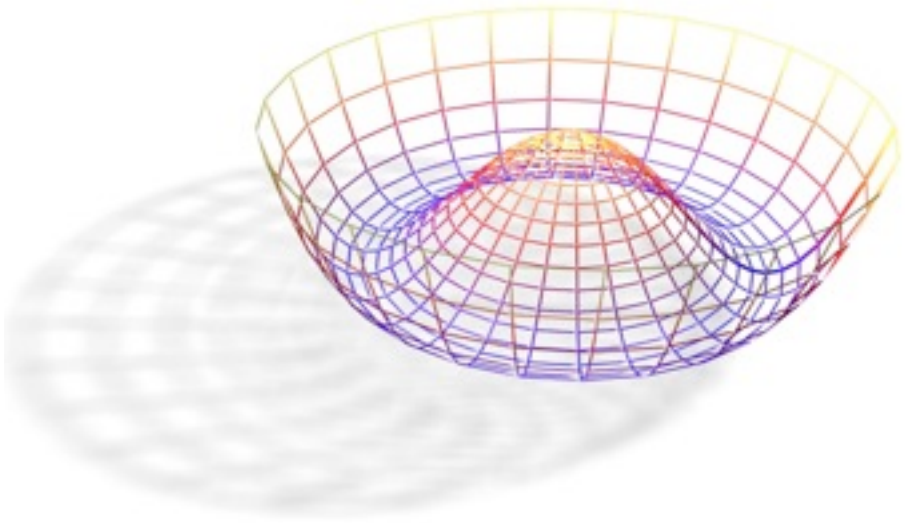
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Higgs mechanism:

- Add ϕ, a new [complex doublet of] scalar field[s] with specific potential $V(\phi)$ and interactions with W,Z
  - generates masses for W,Z

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$



The Standard Model Higgs

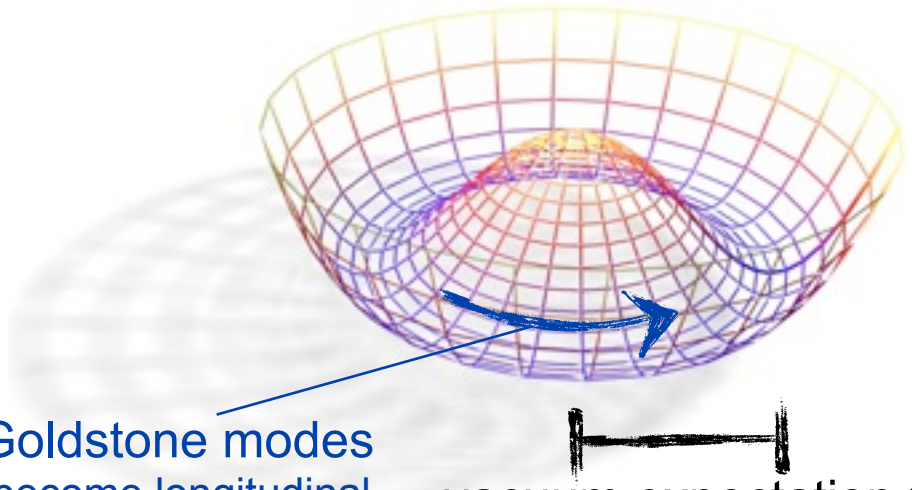
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$$\phi = \frac{1}{\sqrt{2}}(v + h)$$

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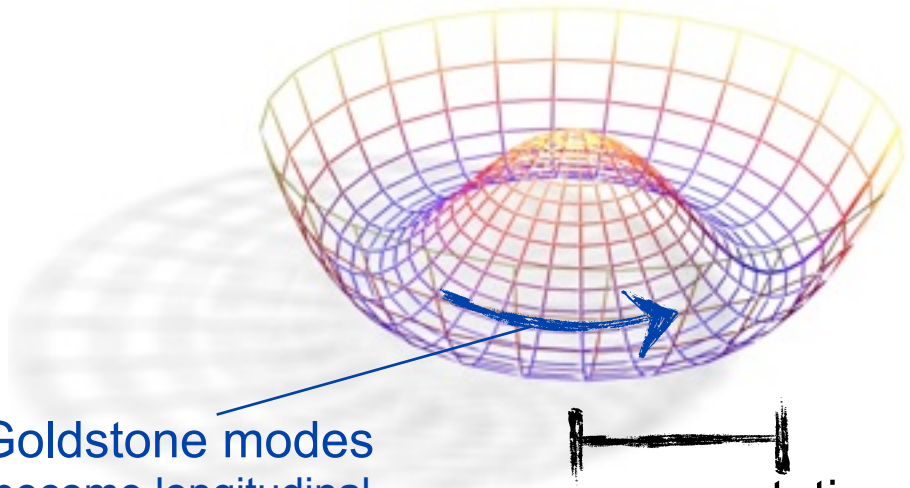
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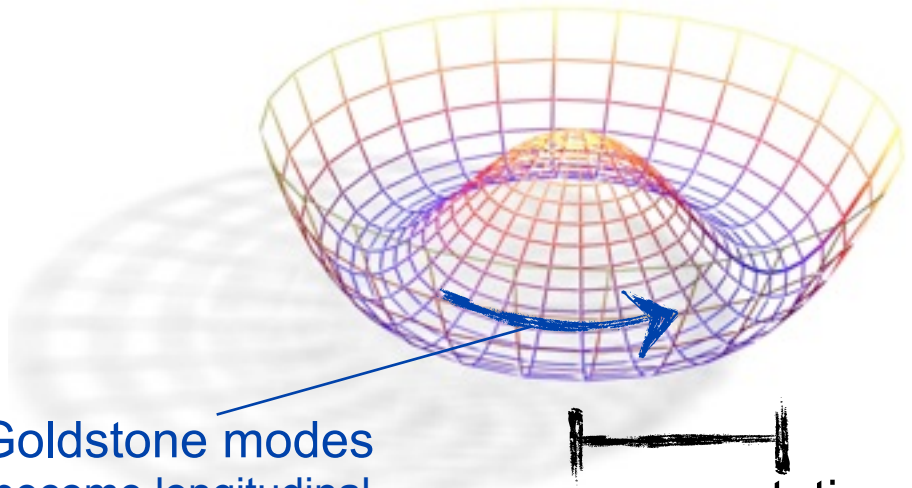
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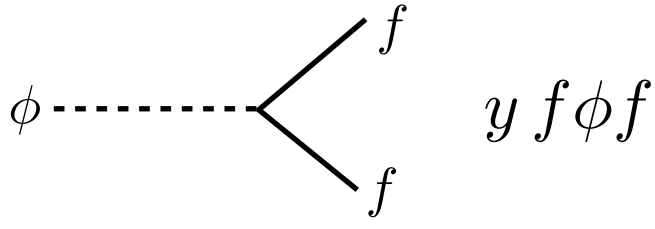
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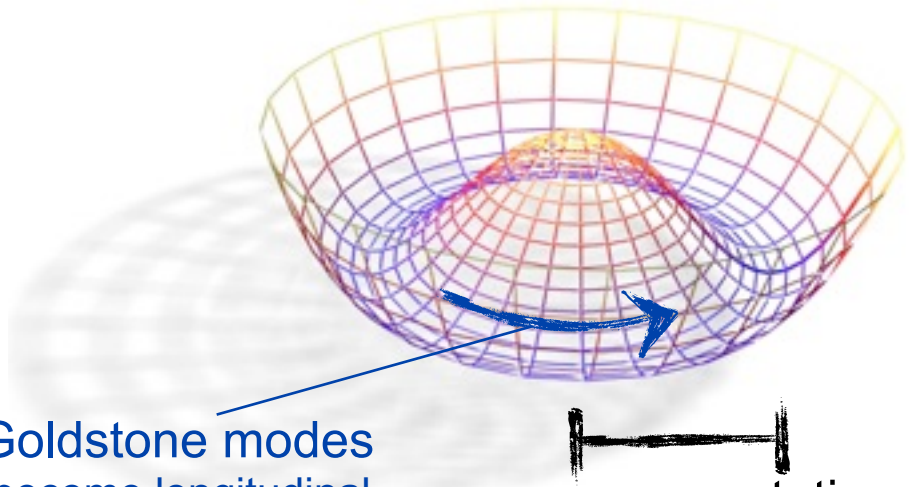
$$y\, f \phi f$$

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- massless W,Z only have transverse polarizations

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

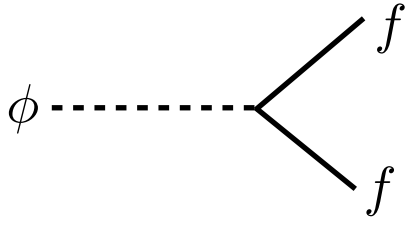


Higgs mechanism:

- Add ϕ, a new [complex doublet of] scalar field[s] with specific potential $V(\phi)$ and interactions with W,Z
  - generates masses for W,Z

$$\phi = \frac{1}{\sqrt{2}}(v + h)$$

Interactions with fermions:



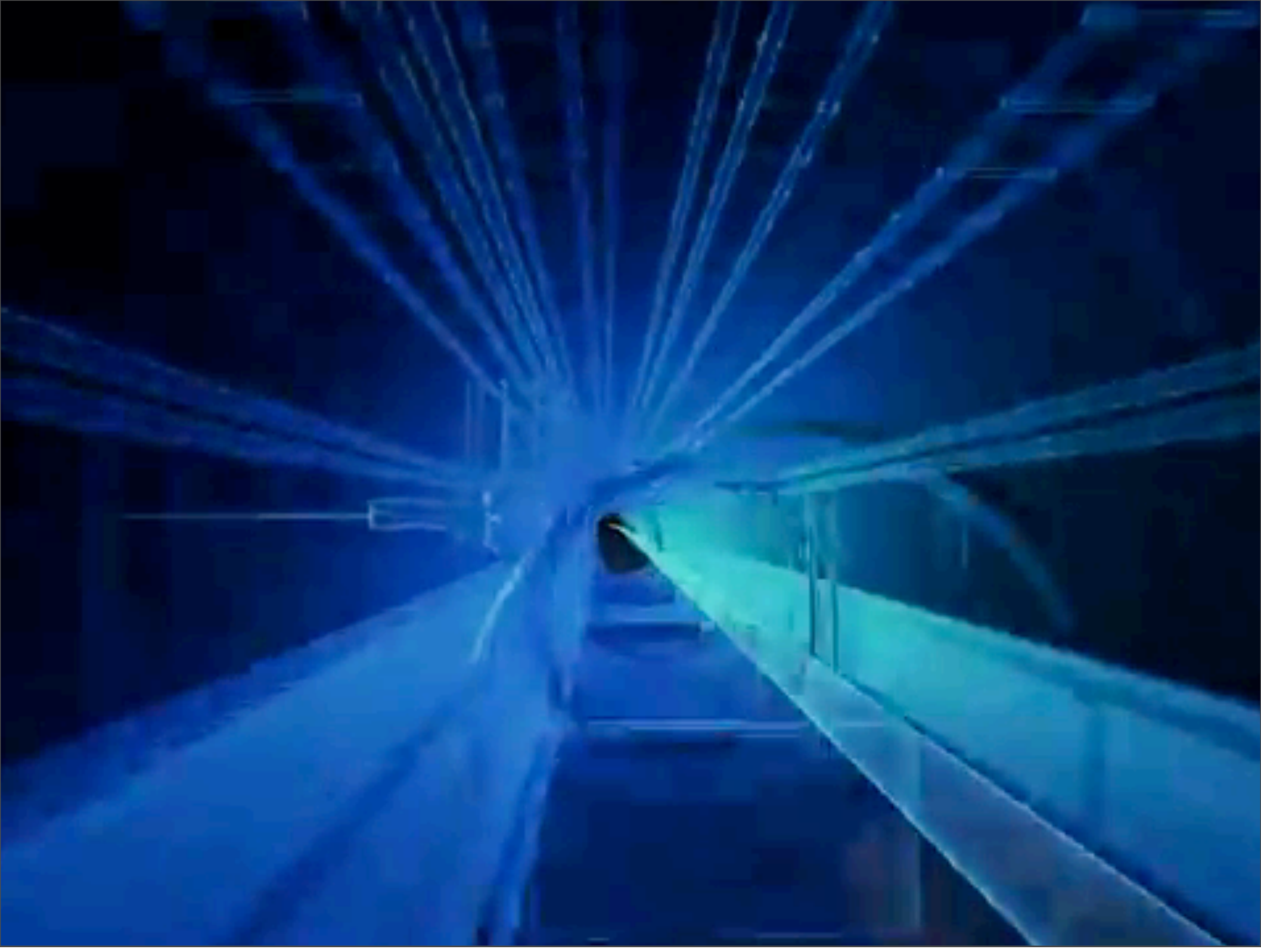
$$y\, f \phi f \longrightarrow \underbrace{\frac{yv}{\sqrt{2}}}_{m_f} f f + \underbrace{\frac{y}{\sqrt{2}} f h f}_{\text{interaction}}$$

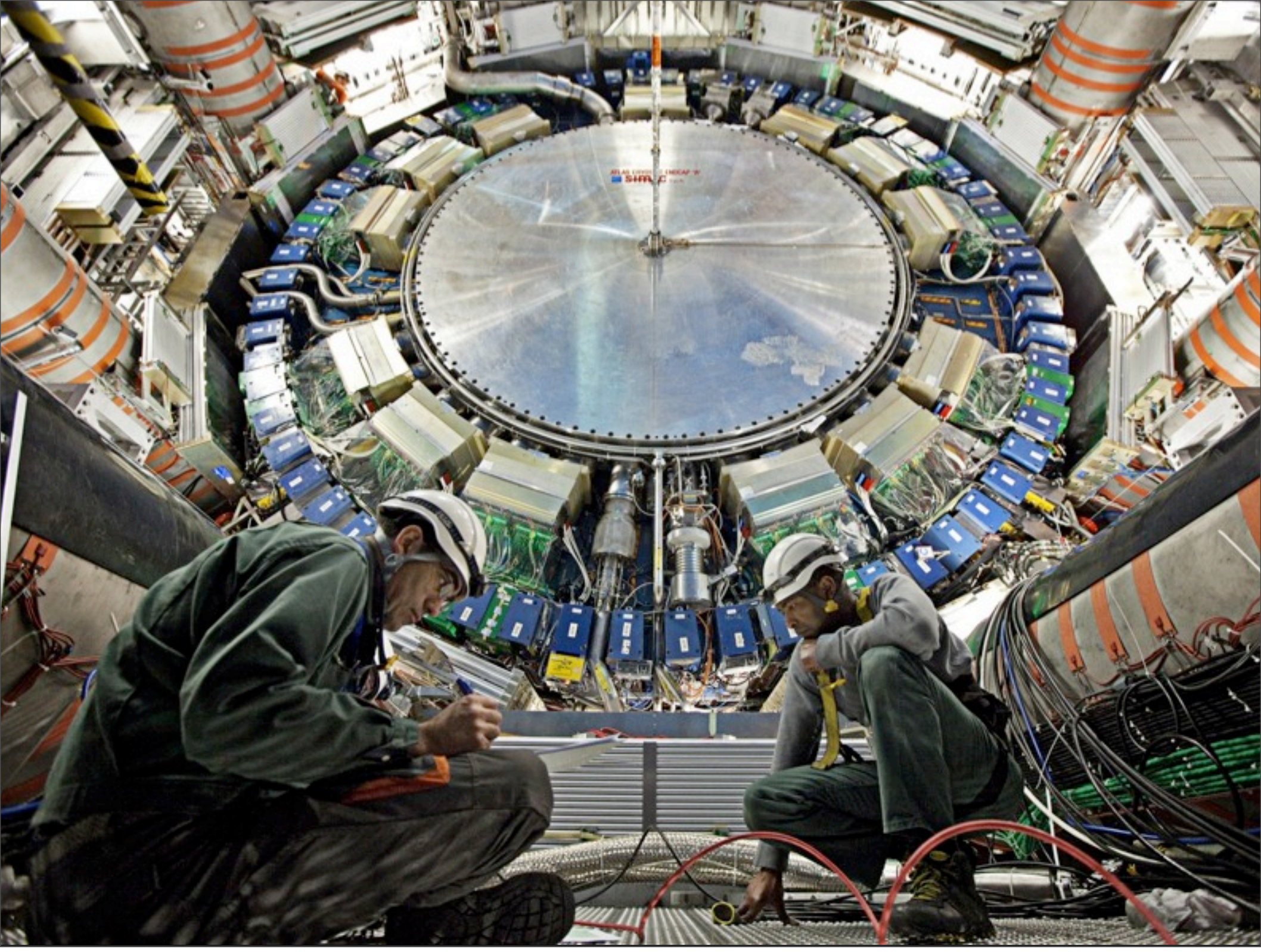
- coupling arbitrary, but proportional to mass

Quick guide to the LHC

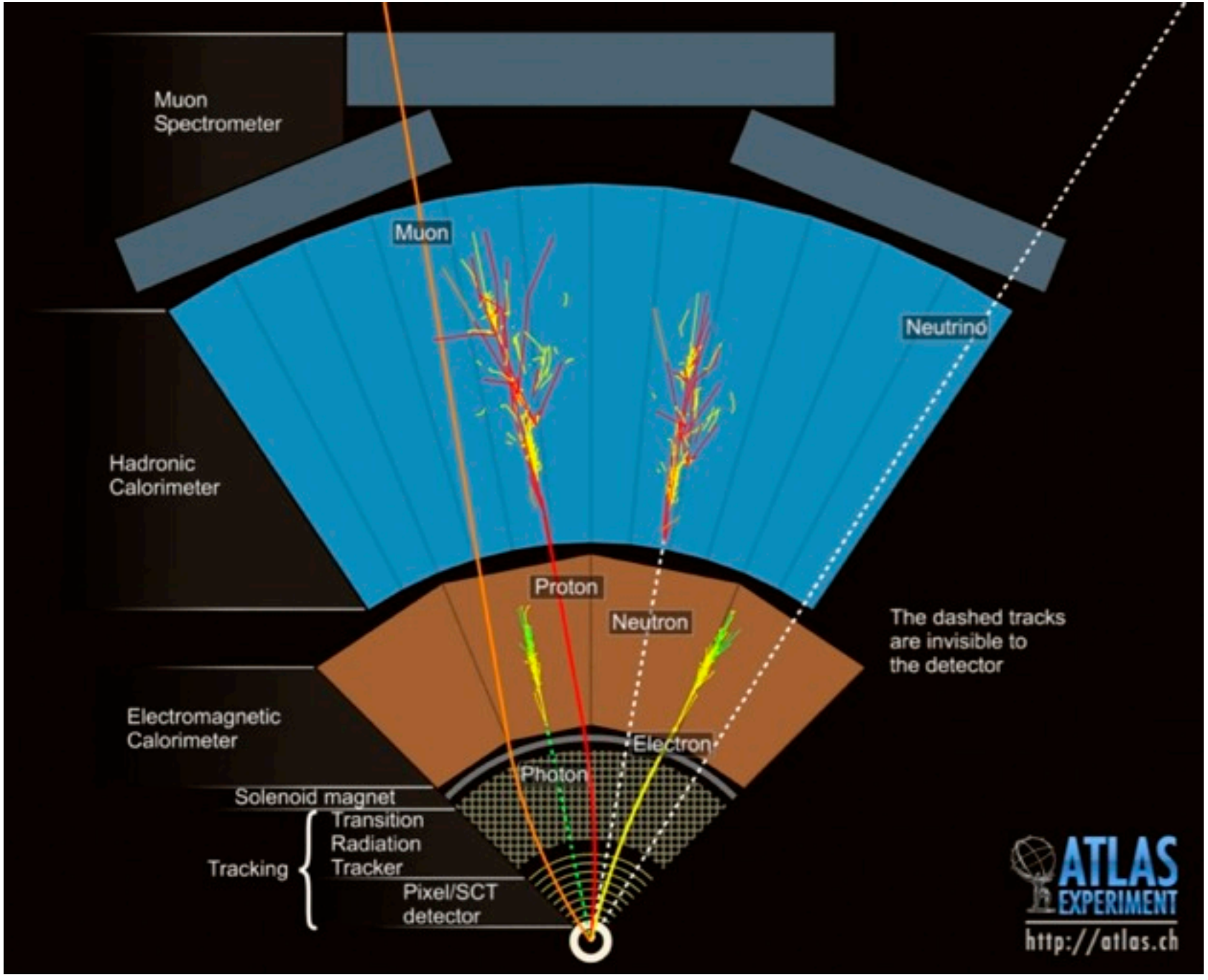






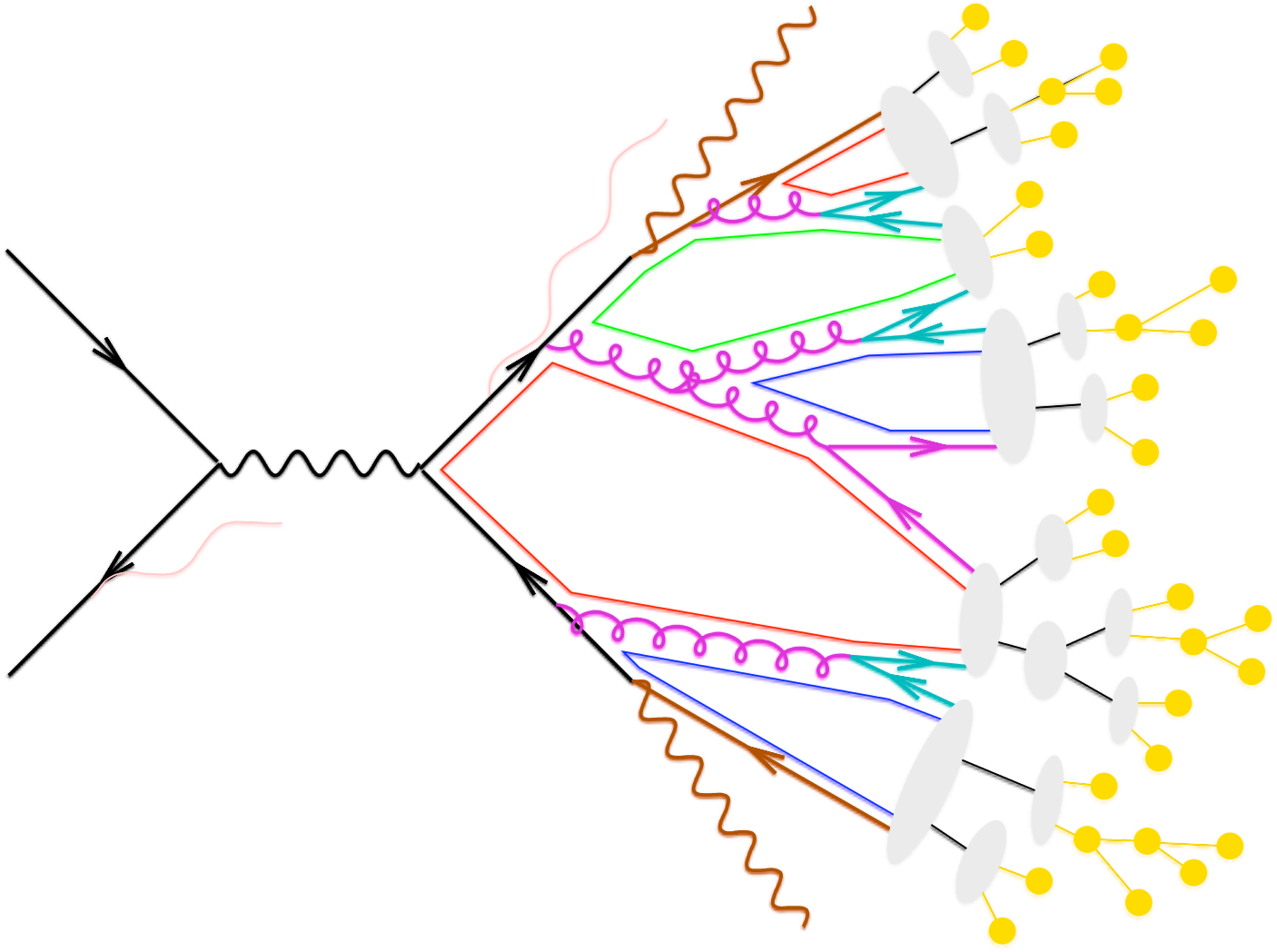


Particle identification



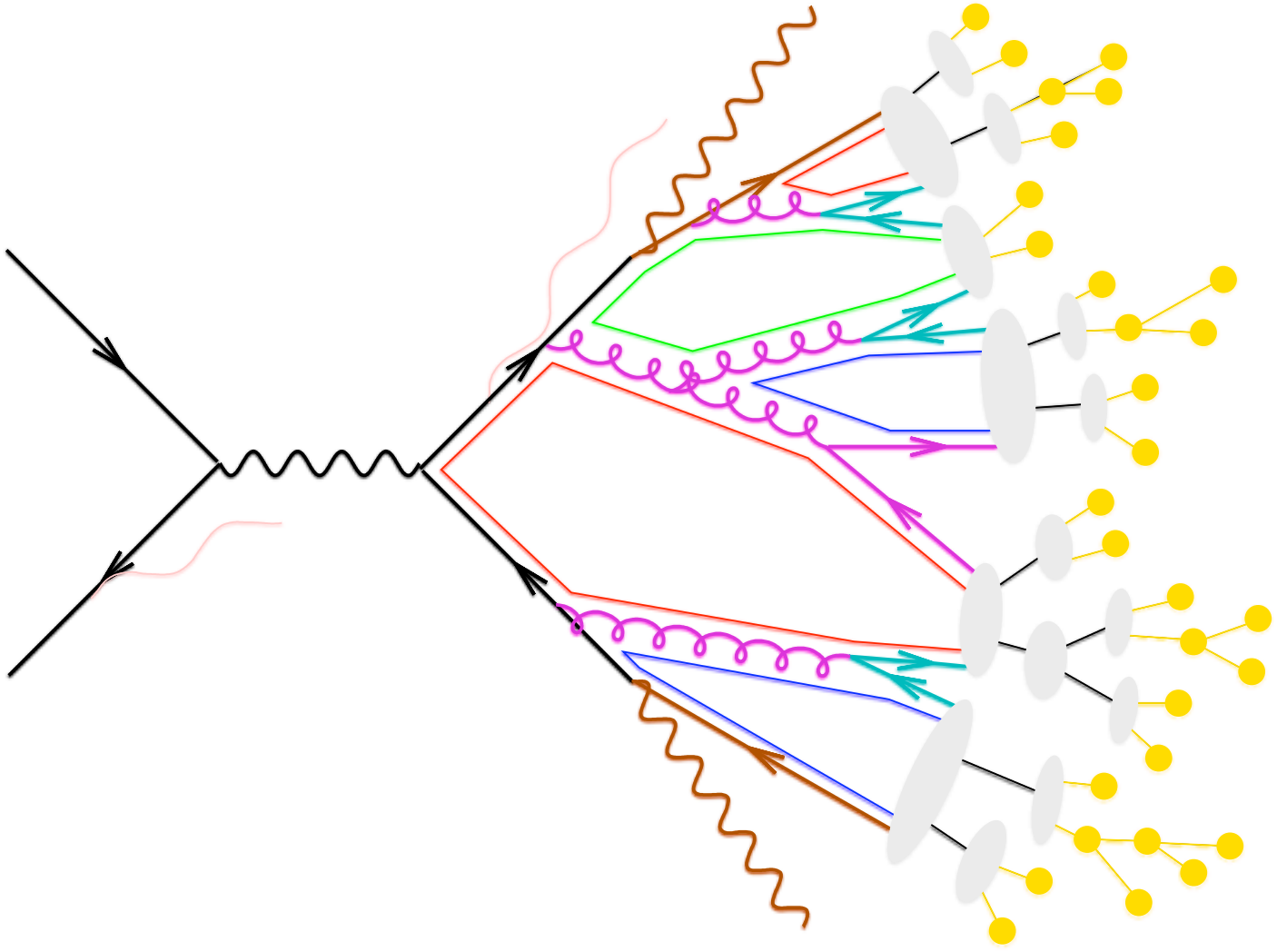
Anatomy of a collision

Anatomy of a collision



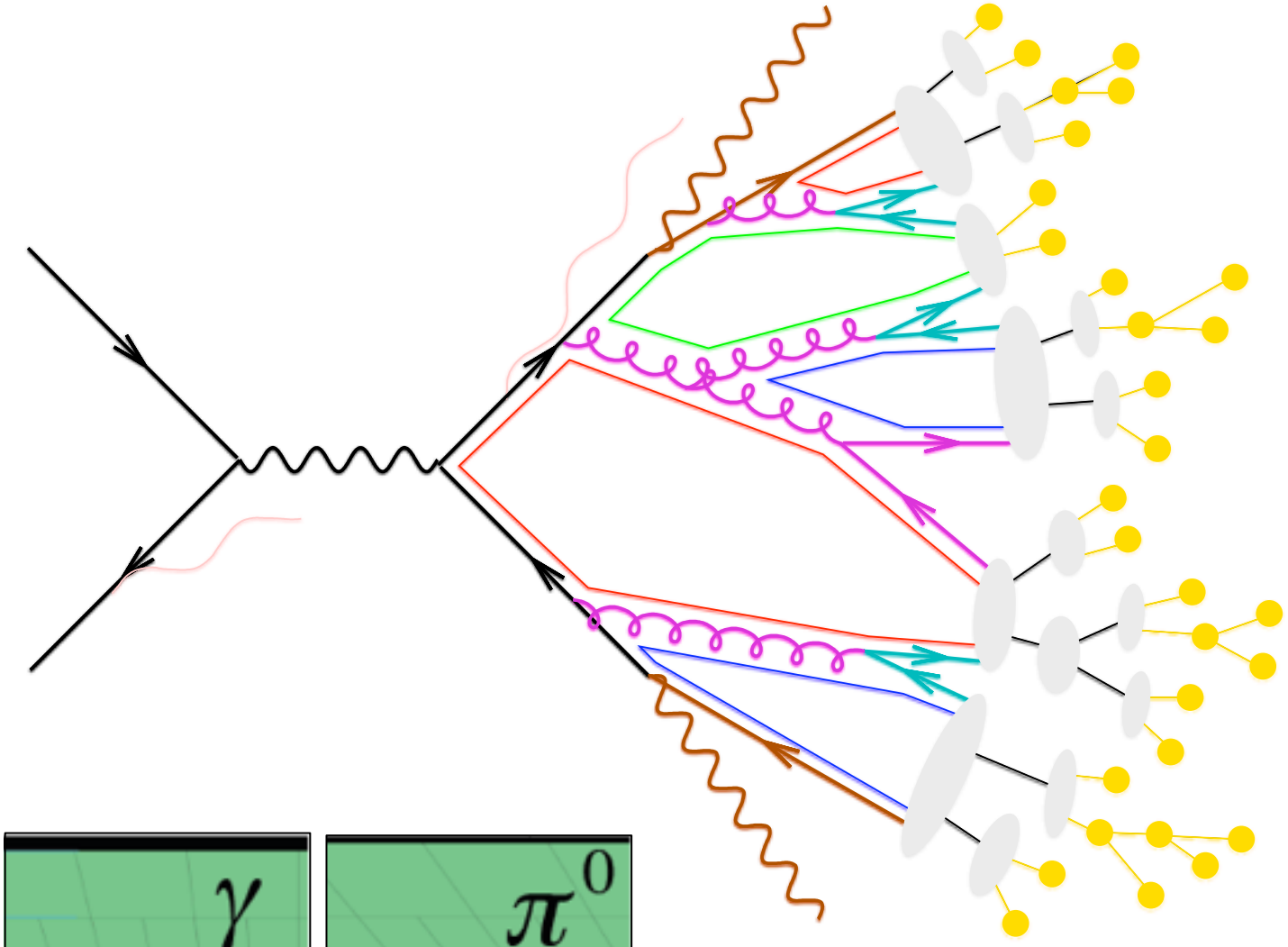
- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \to bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\longrightarrow$ hadrons
- hadronic decays

Anatomy of a collision

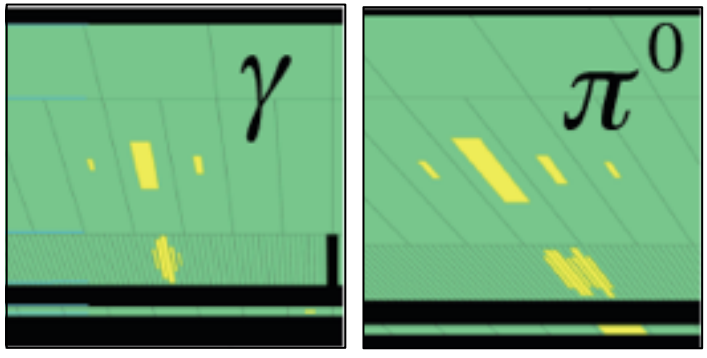


- hard scattering
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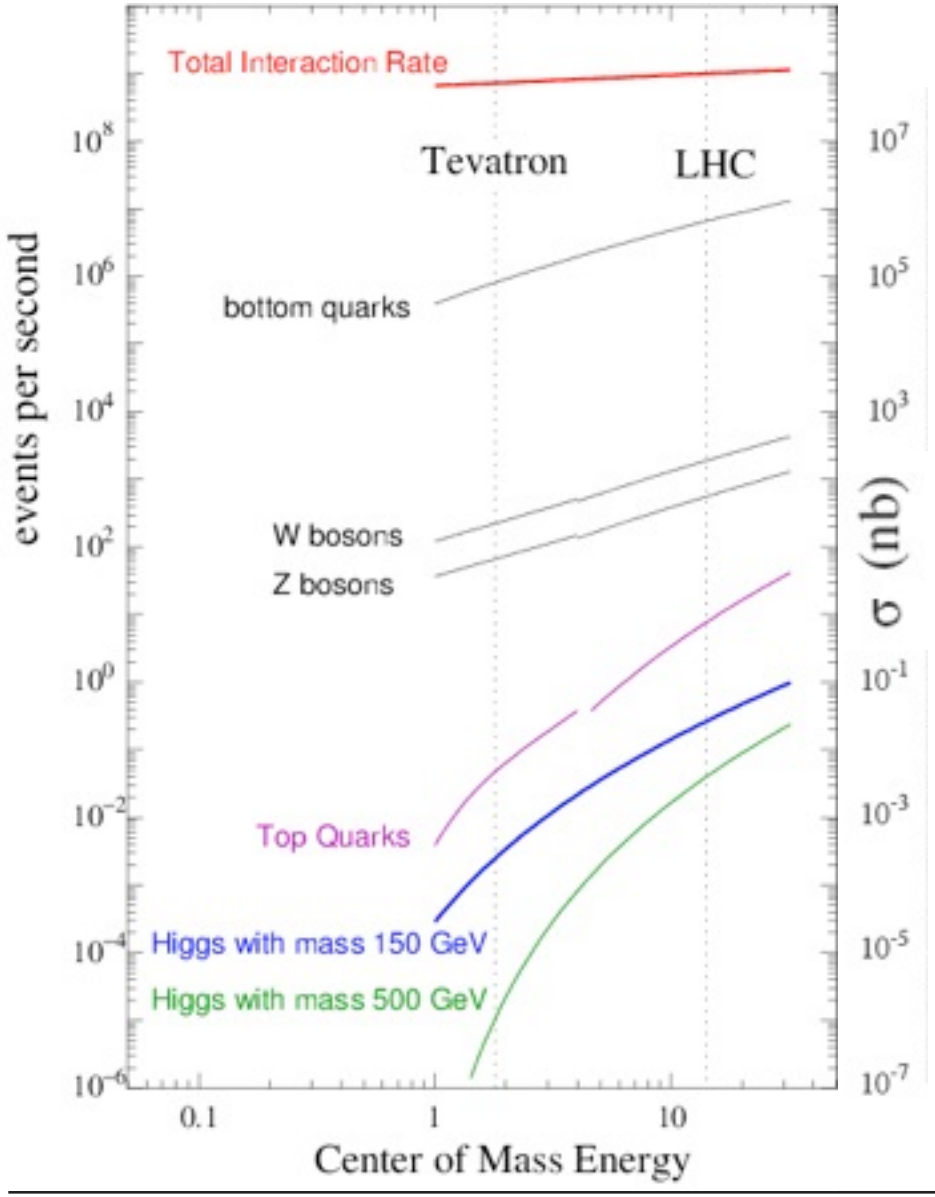


We don't always get it right, sometimes one particle "fakes" another

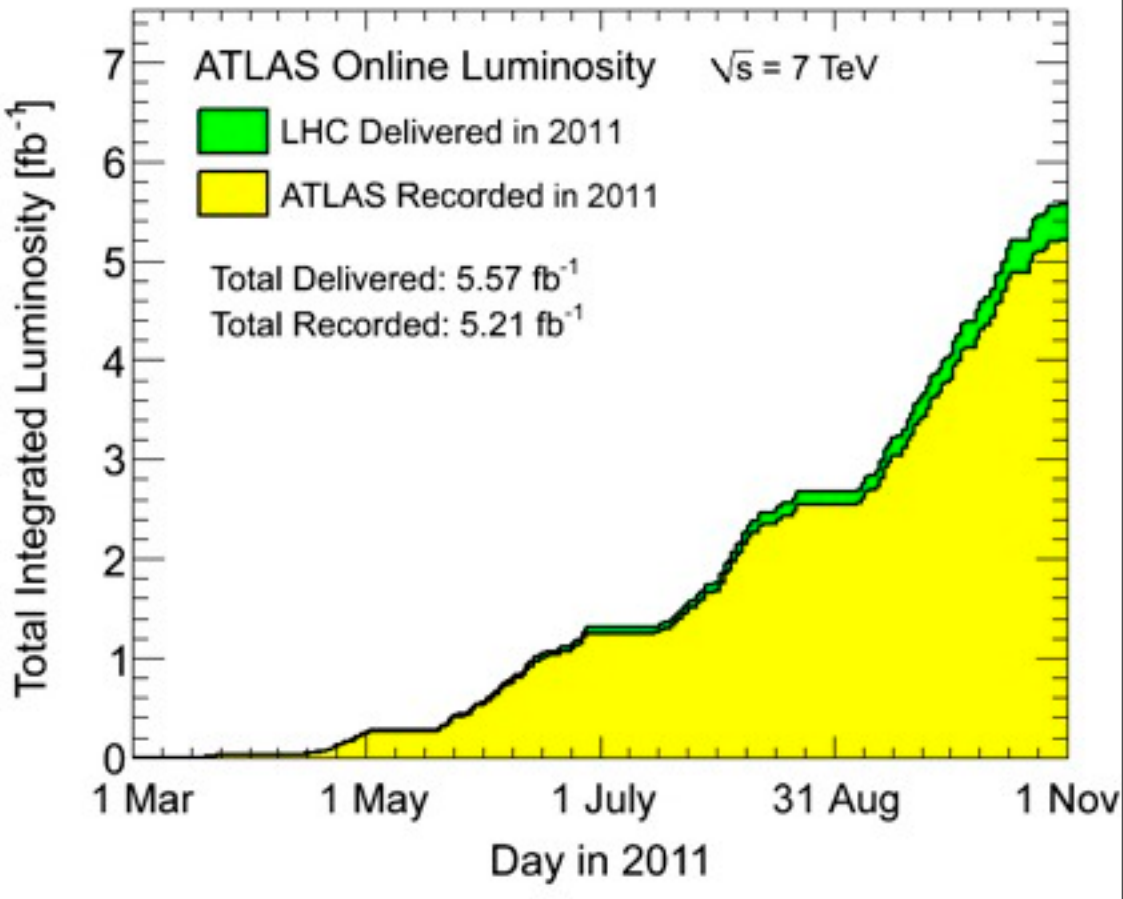
Number of collisions in 2011

expected number of scatterings = cross section [cm^2] x Luminosity [1/cm^2]

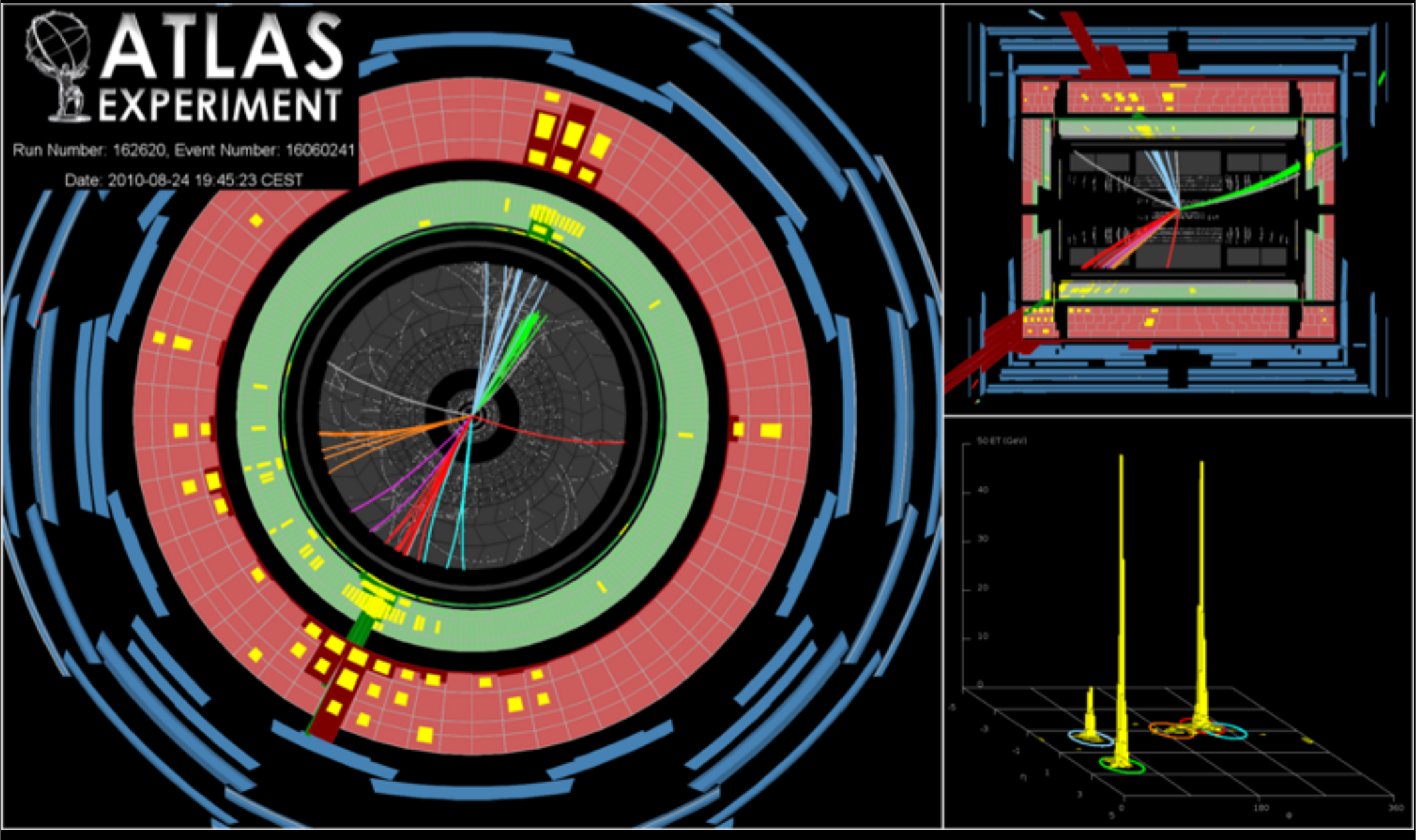
$$\langle N \rangle = \sigma L$$



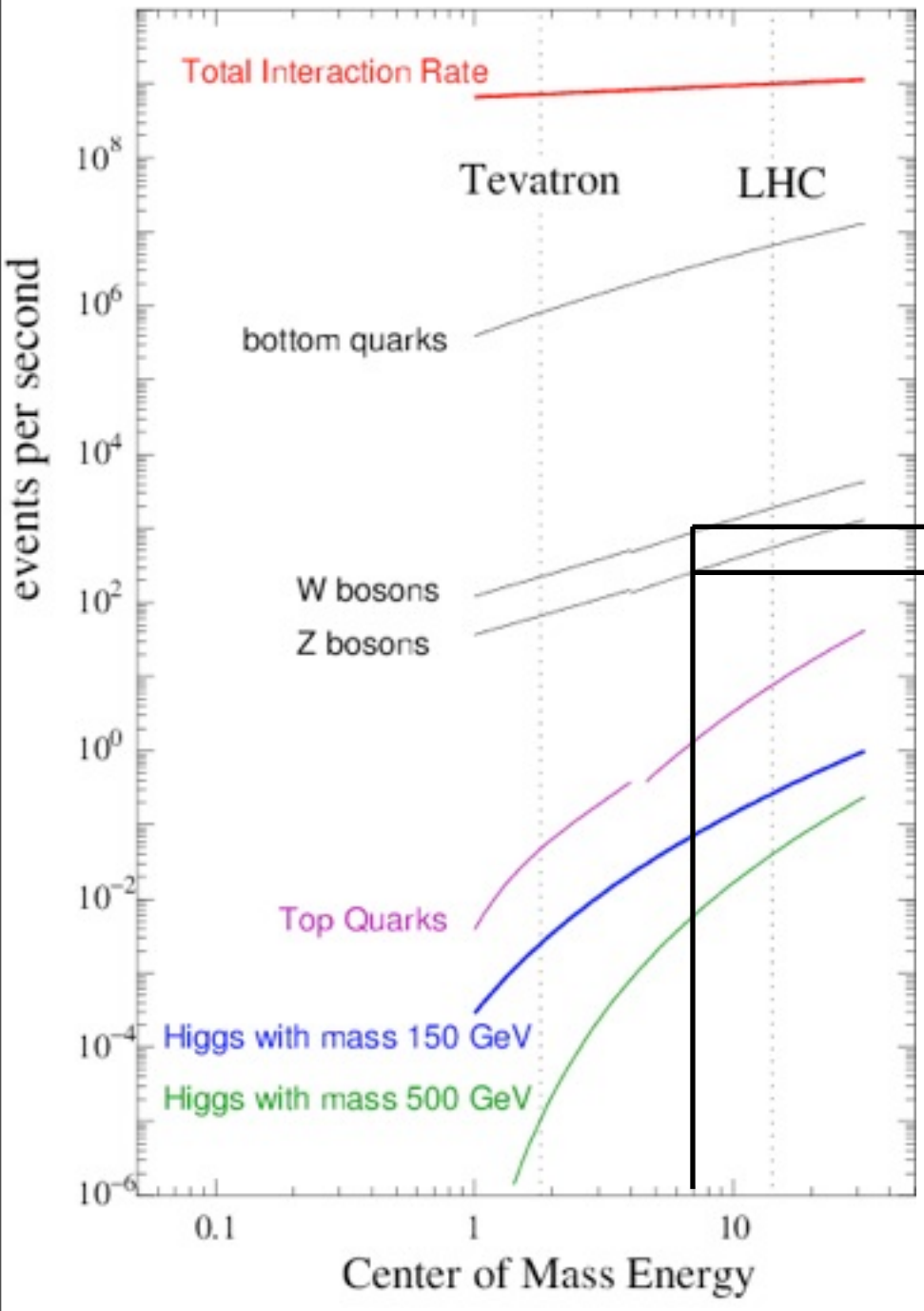
$80\ \text{mb} \cdot 5\ \text{fb}^{-1} = 4 \cdot 10^{14}$ collisions

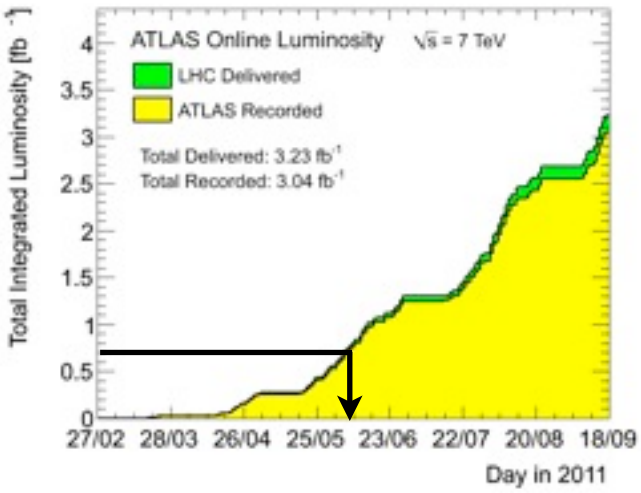


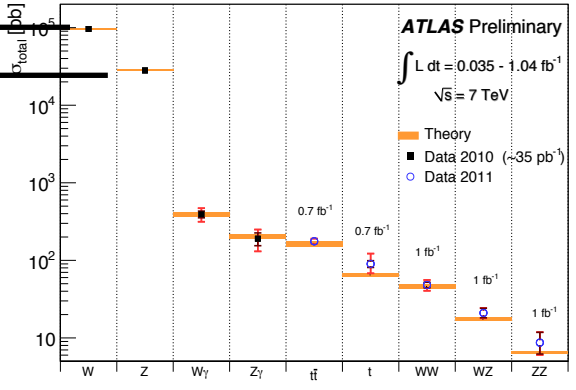
1 nb = 10^{-33} cm^2

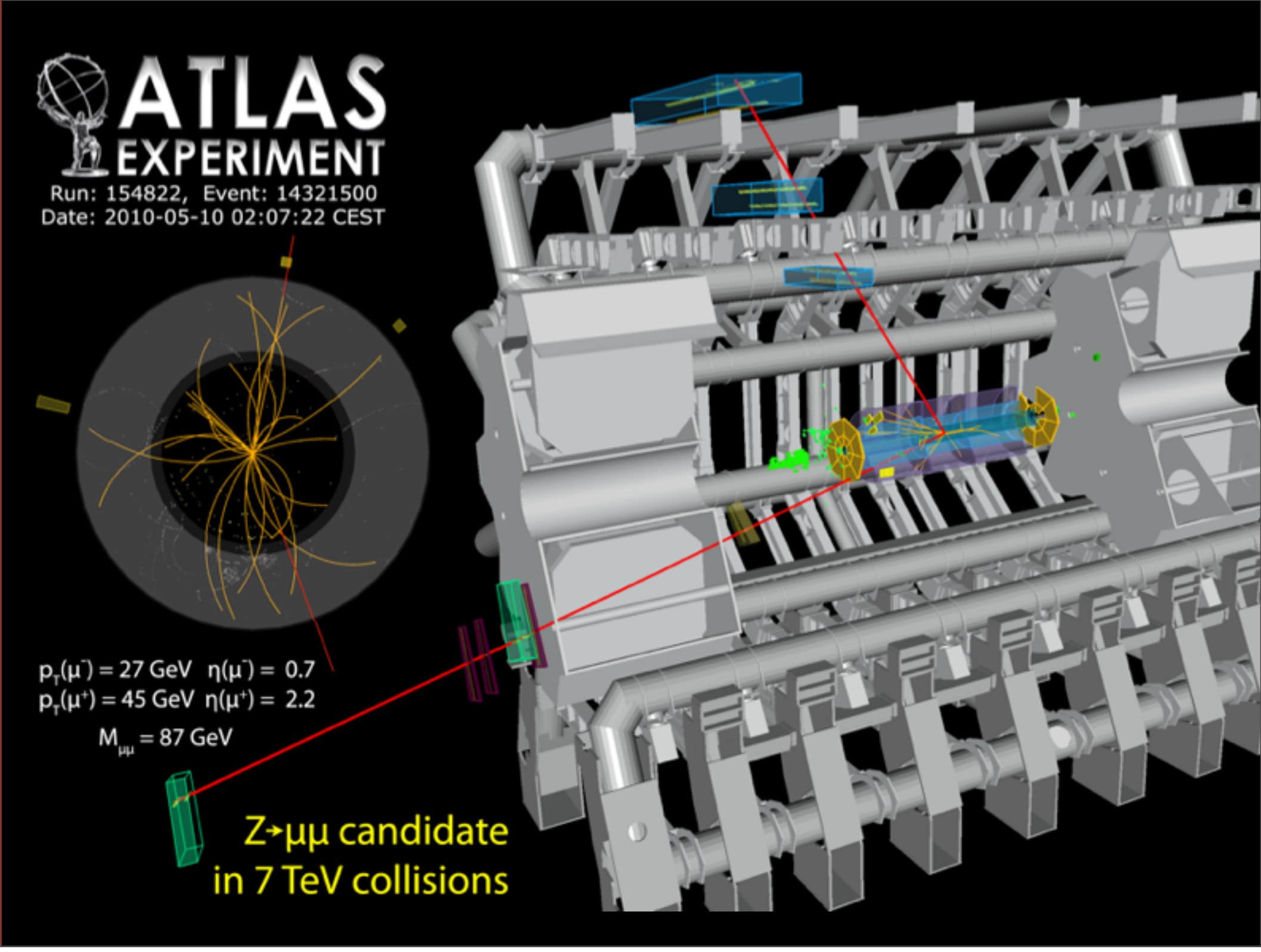

ATLAS
EXPERIMENT
Run Number: 162620, Event Number: 16060241
Date: 2010-08-24 19:45:23 CEST

The steady march of progress

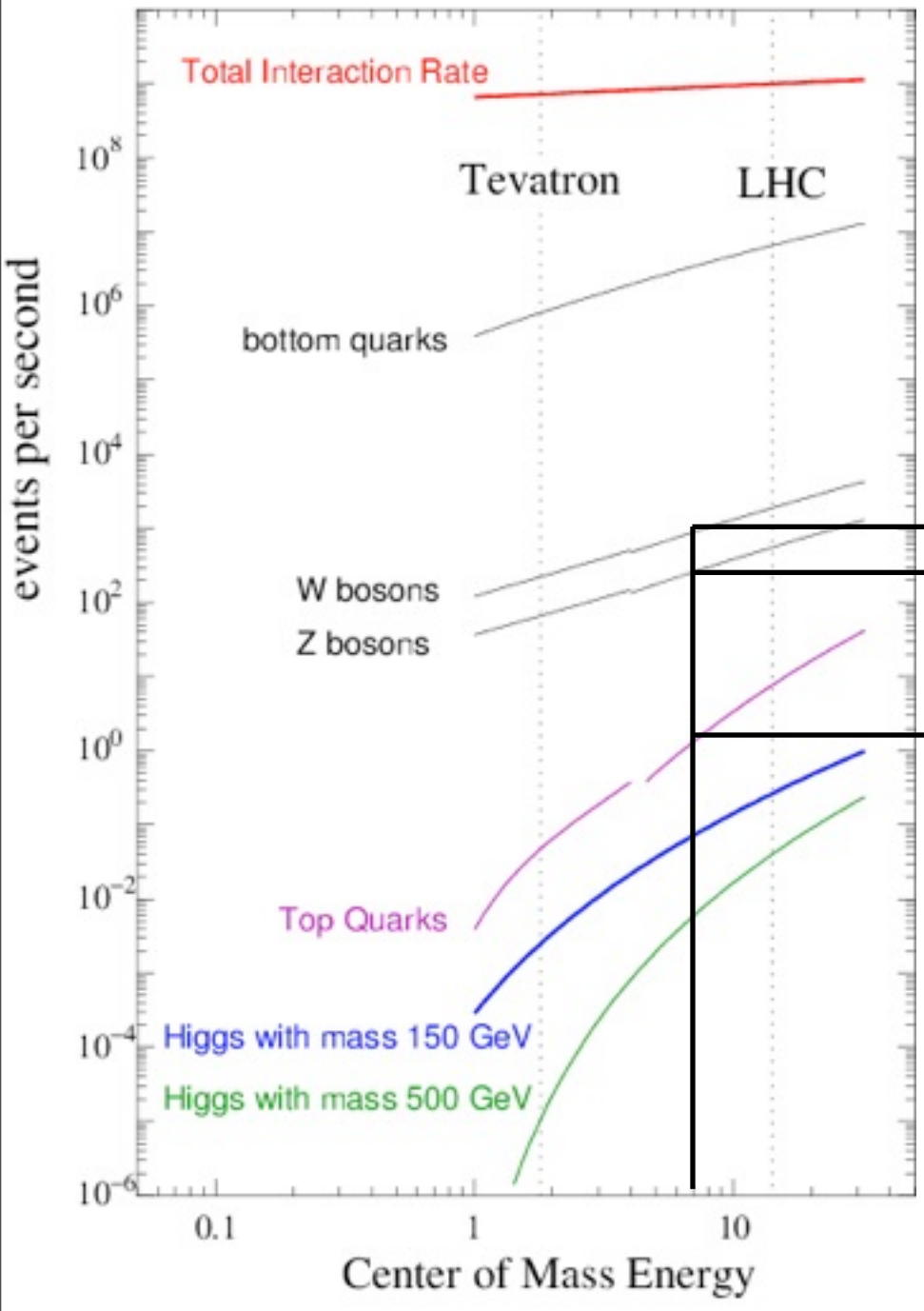


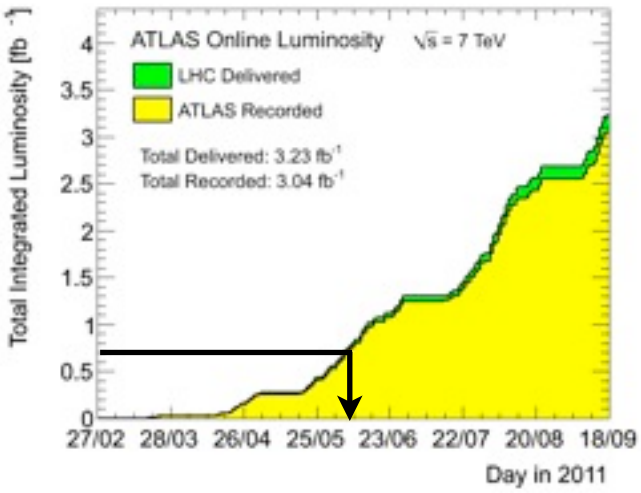


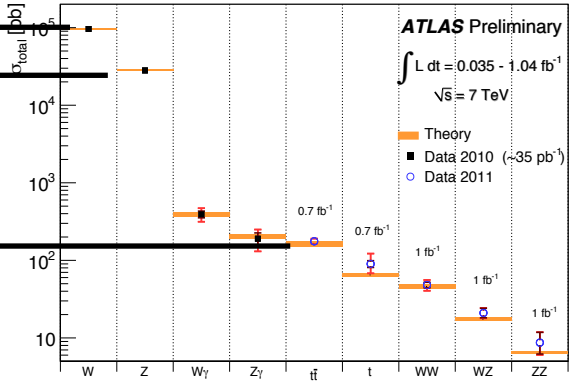



ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

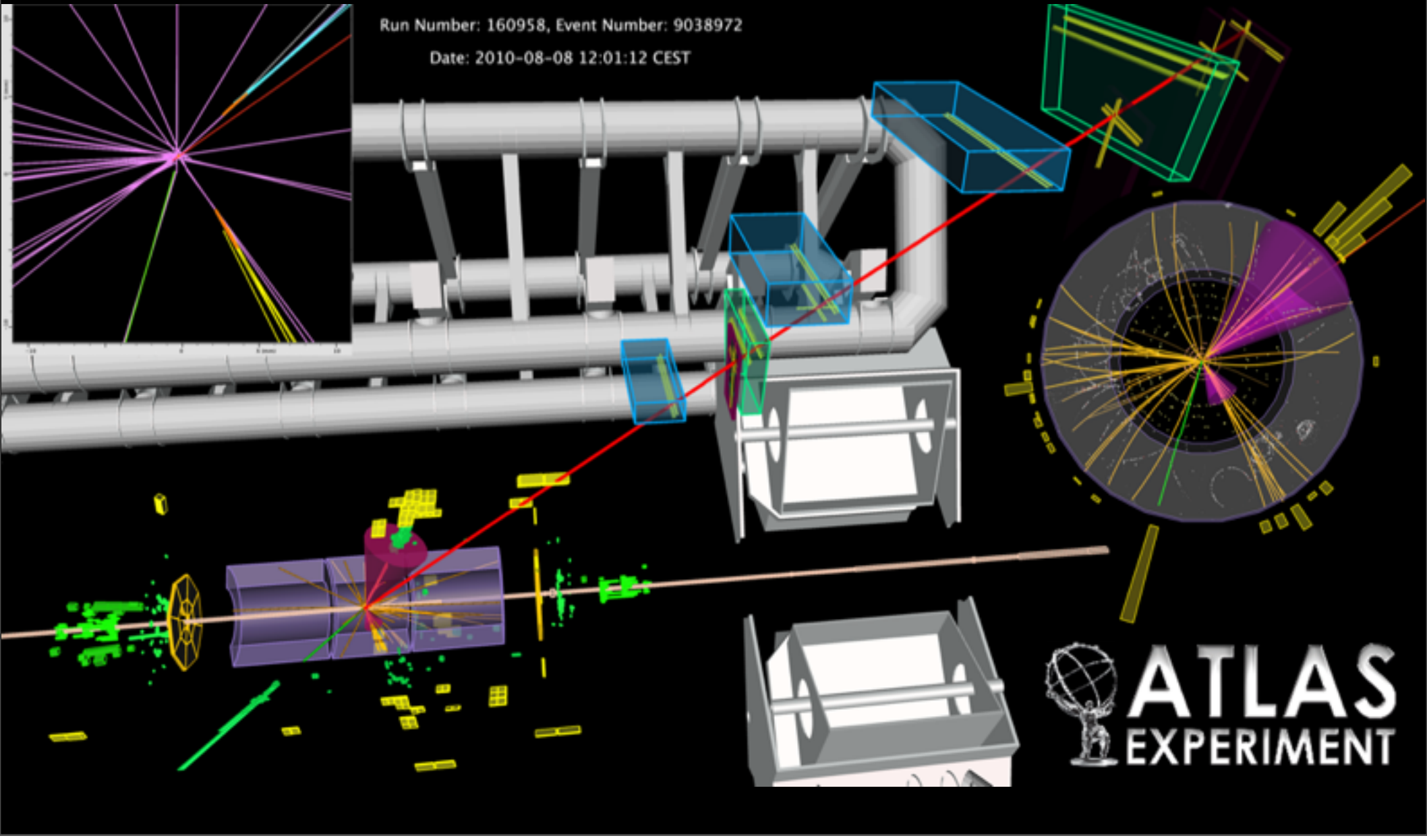
The steady march of progress



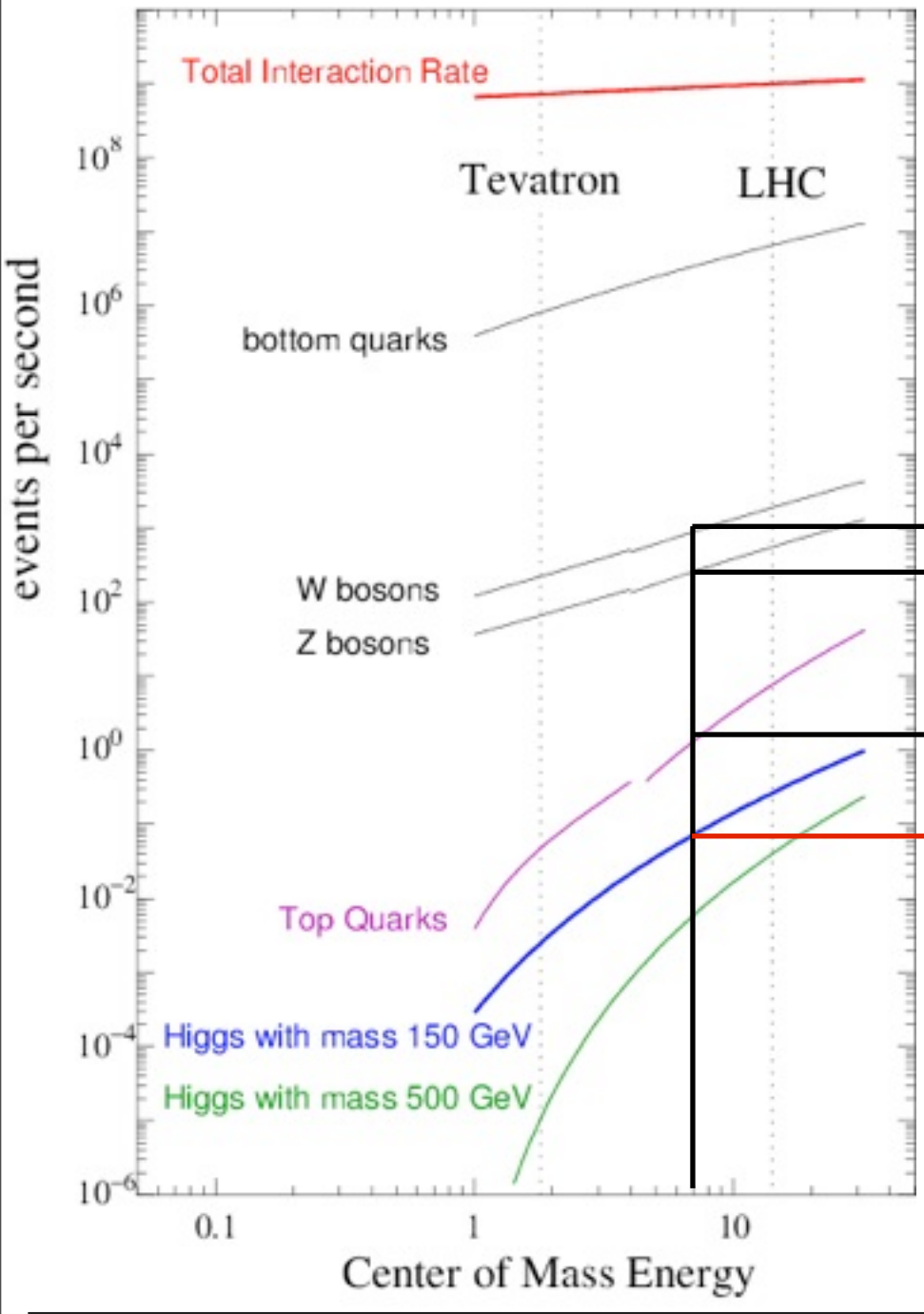


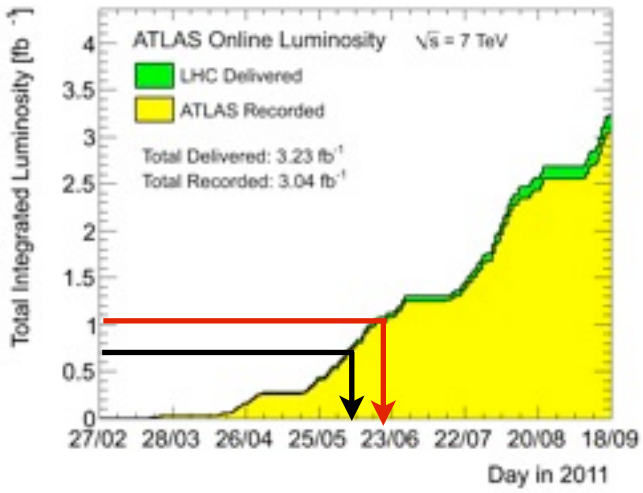


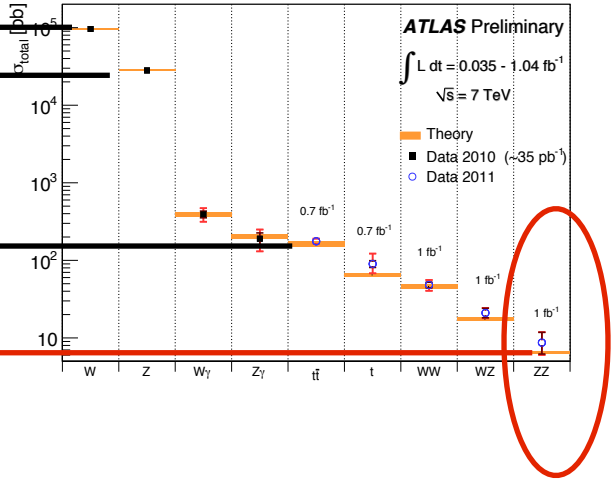
Top quark pair decaying to bb eμ $E_{T,miss}$

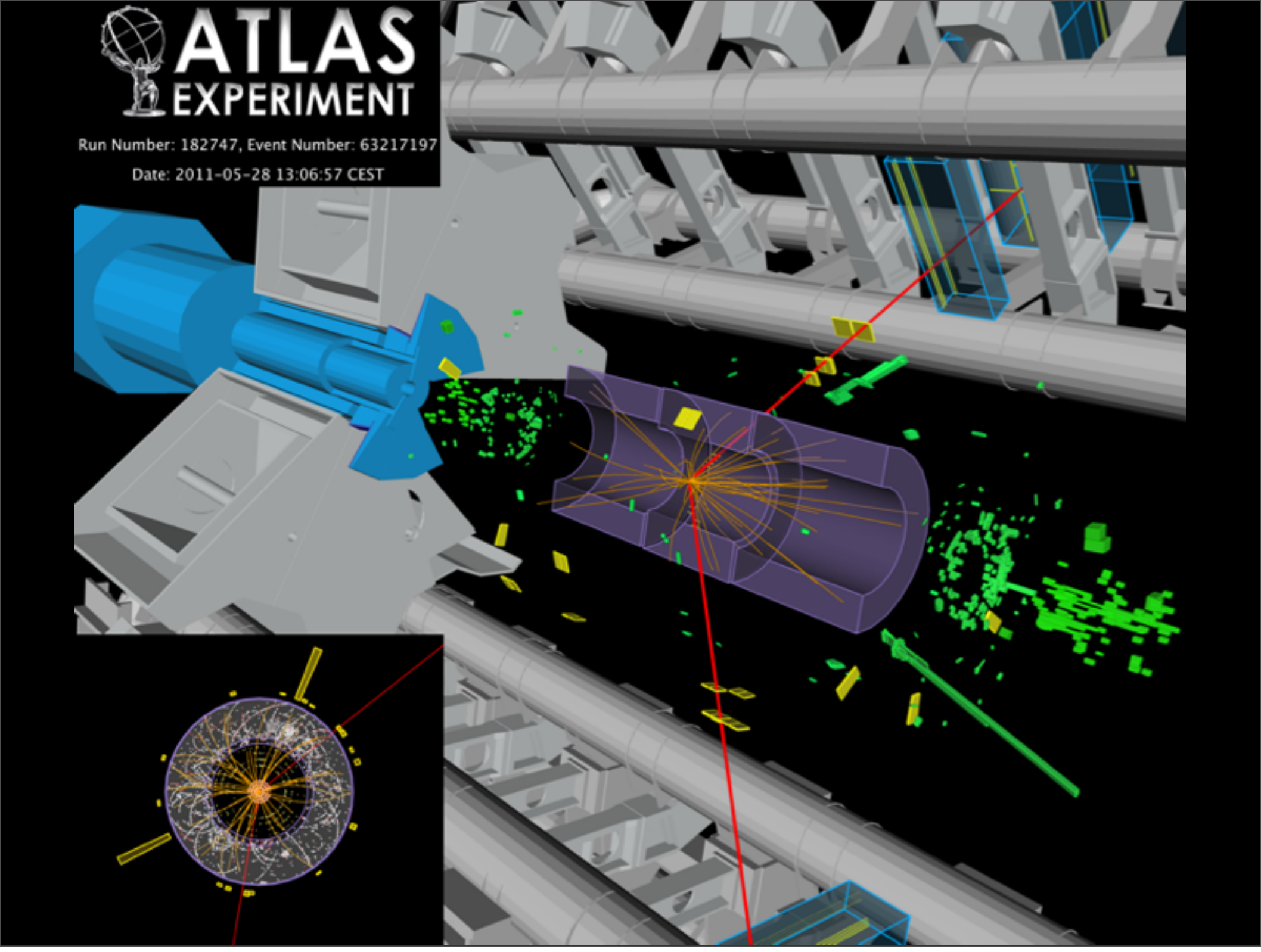


The steady march of progress





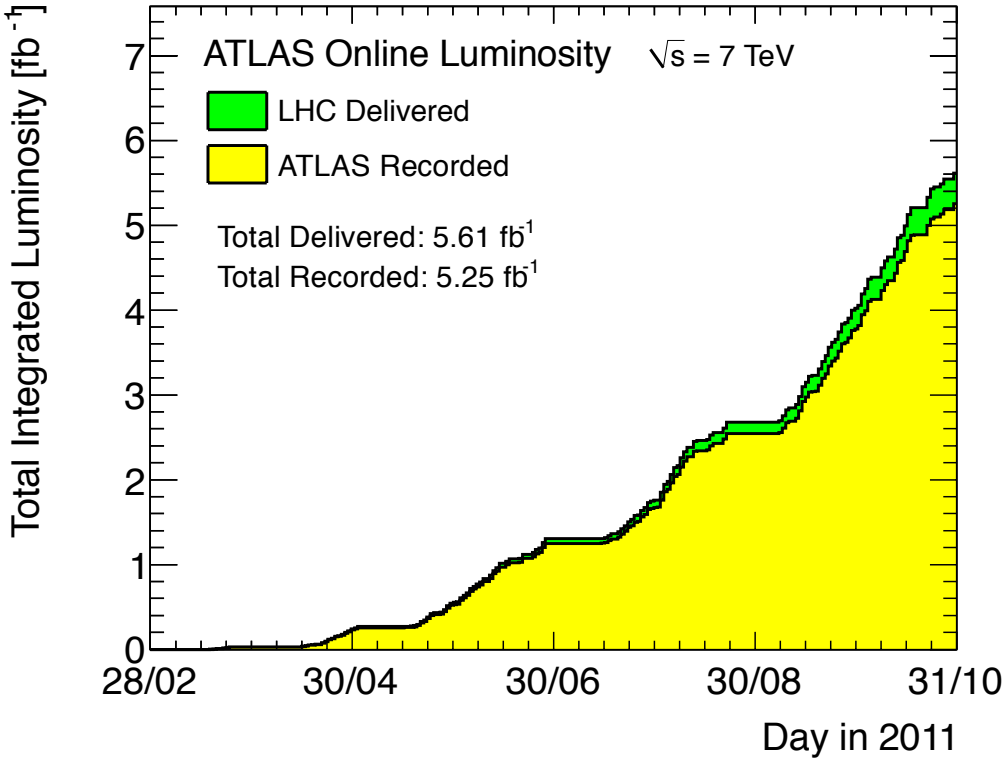


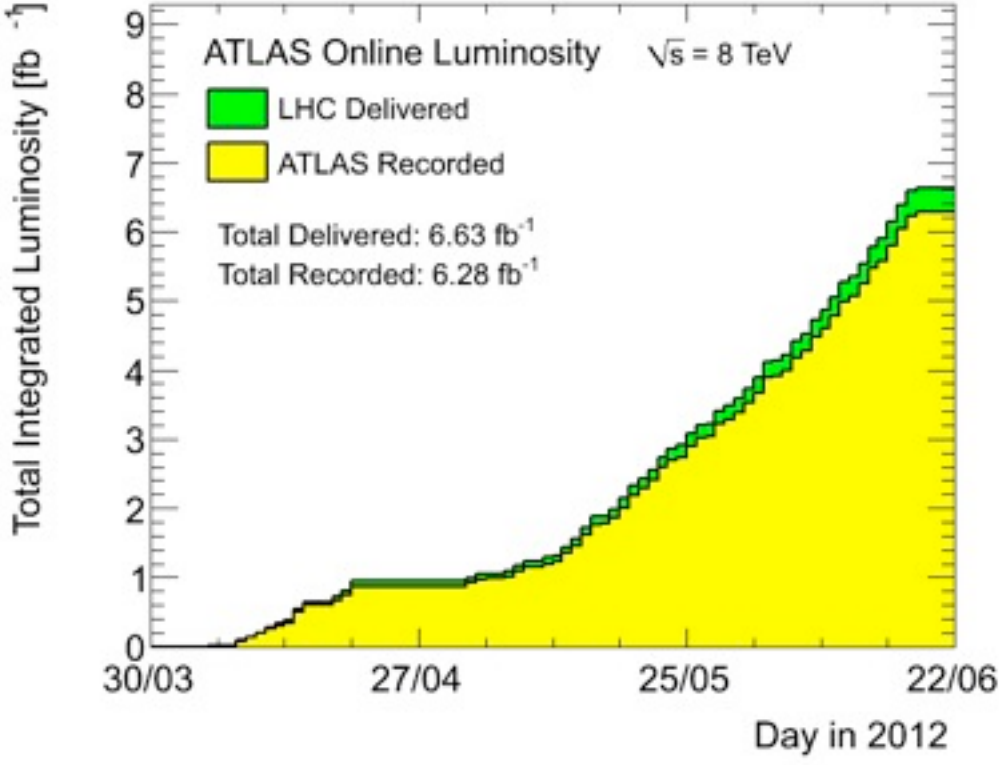

ATLAS
EXPERIMENT
Run Number: 182747, Event Number: 63217197
Date: 2011-05-28 13:06:57 CEST

The LHC has been performing very well

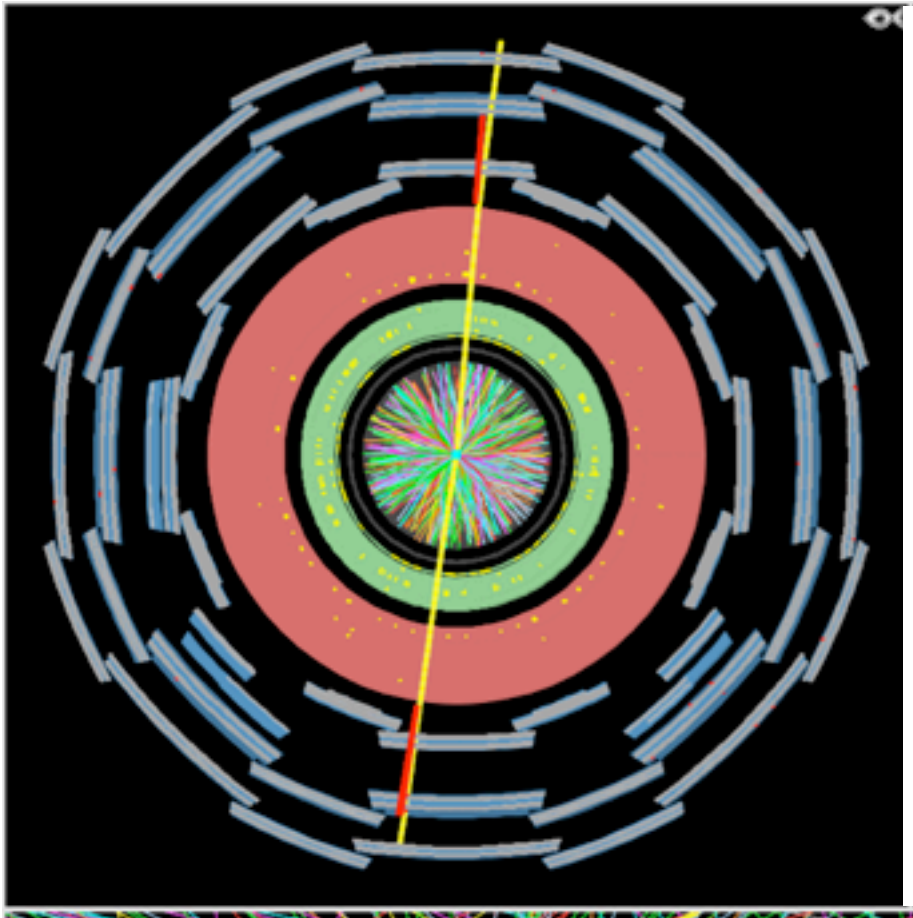
- >5 fb^{-1} delivered in 2011 at 7 TeV
- already >6 fb^{-1} delivered in 2012, running at 8 TeV
- peak luminosity ~$7 \cdot 10^{33}$ $cm^{-2}s^{-1}$ (high pile-up environment)

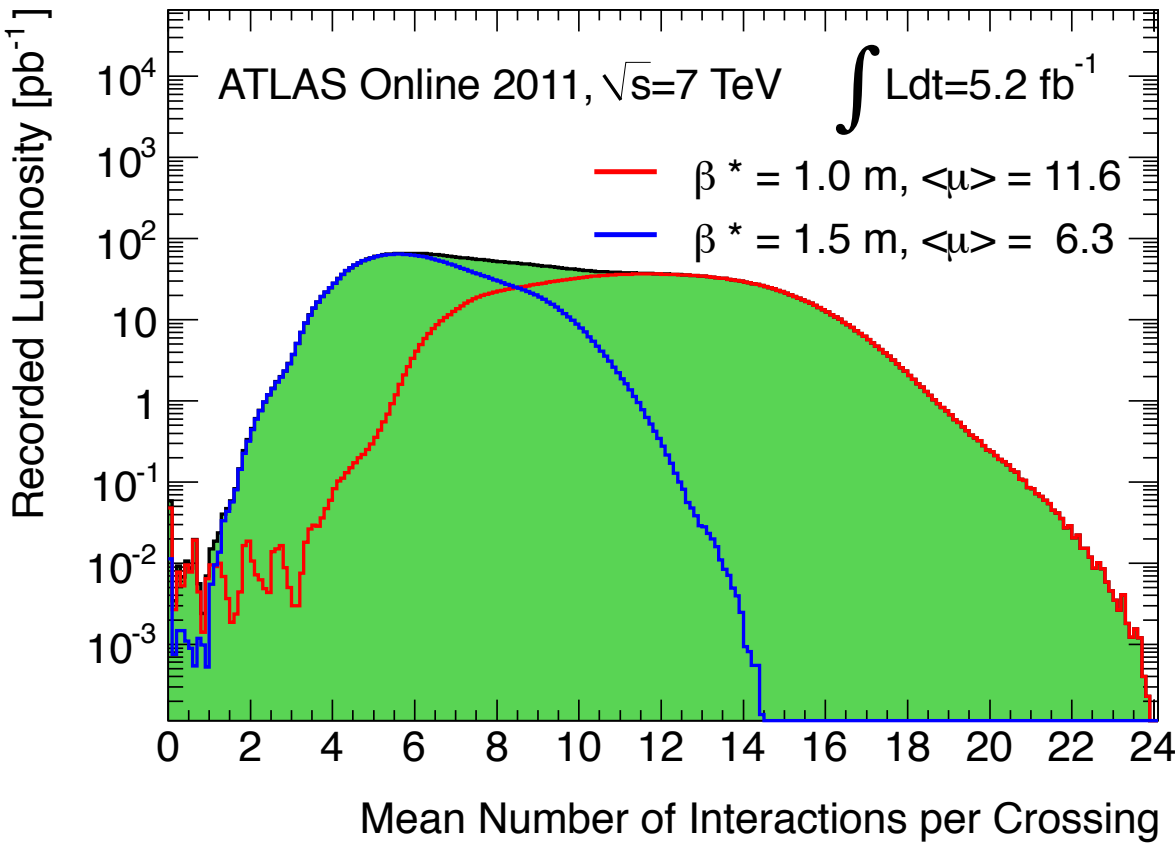
ATLAS data taking efficiency >93%

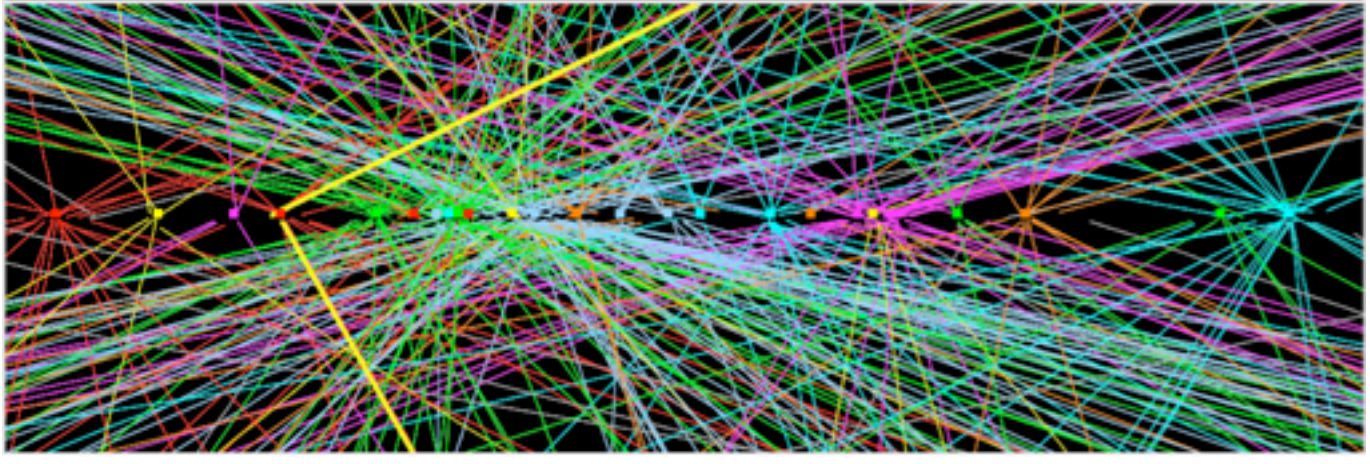




Pile-up

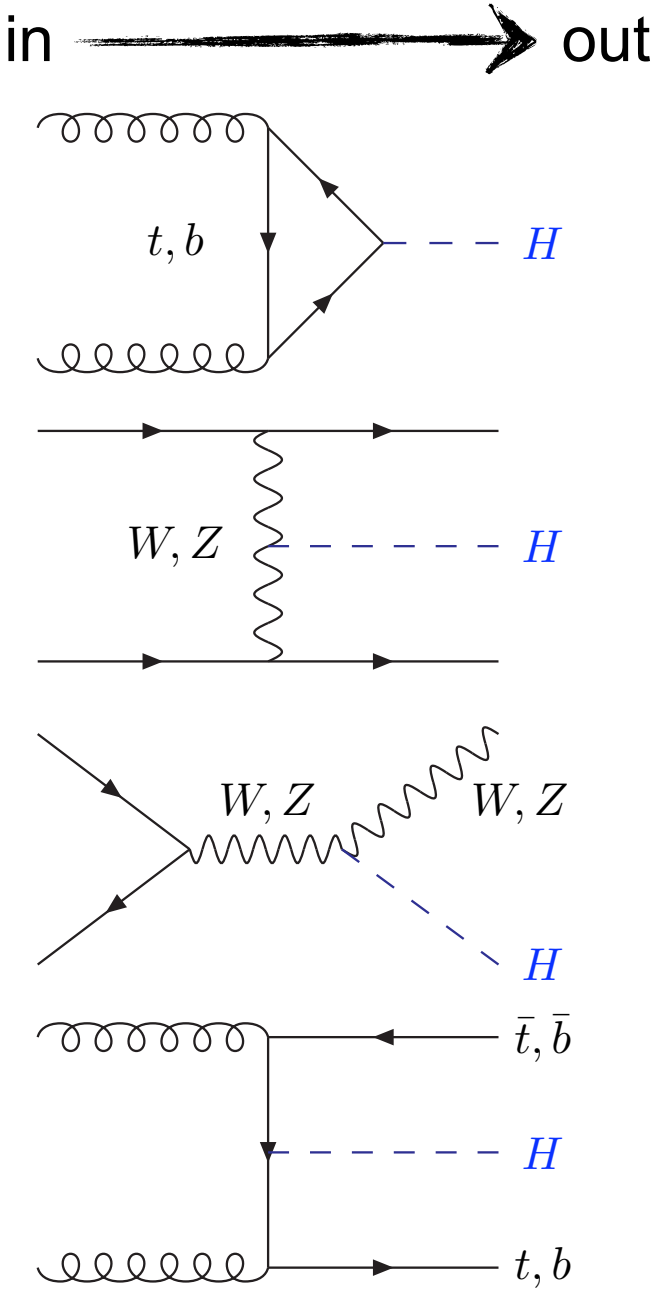


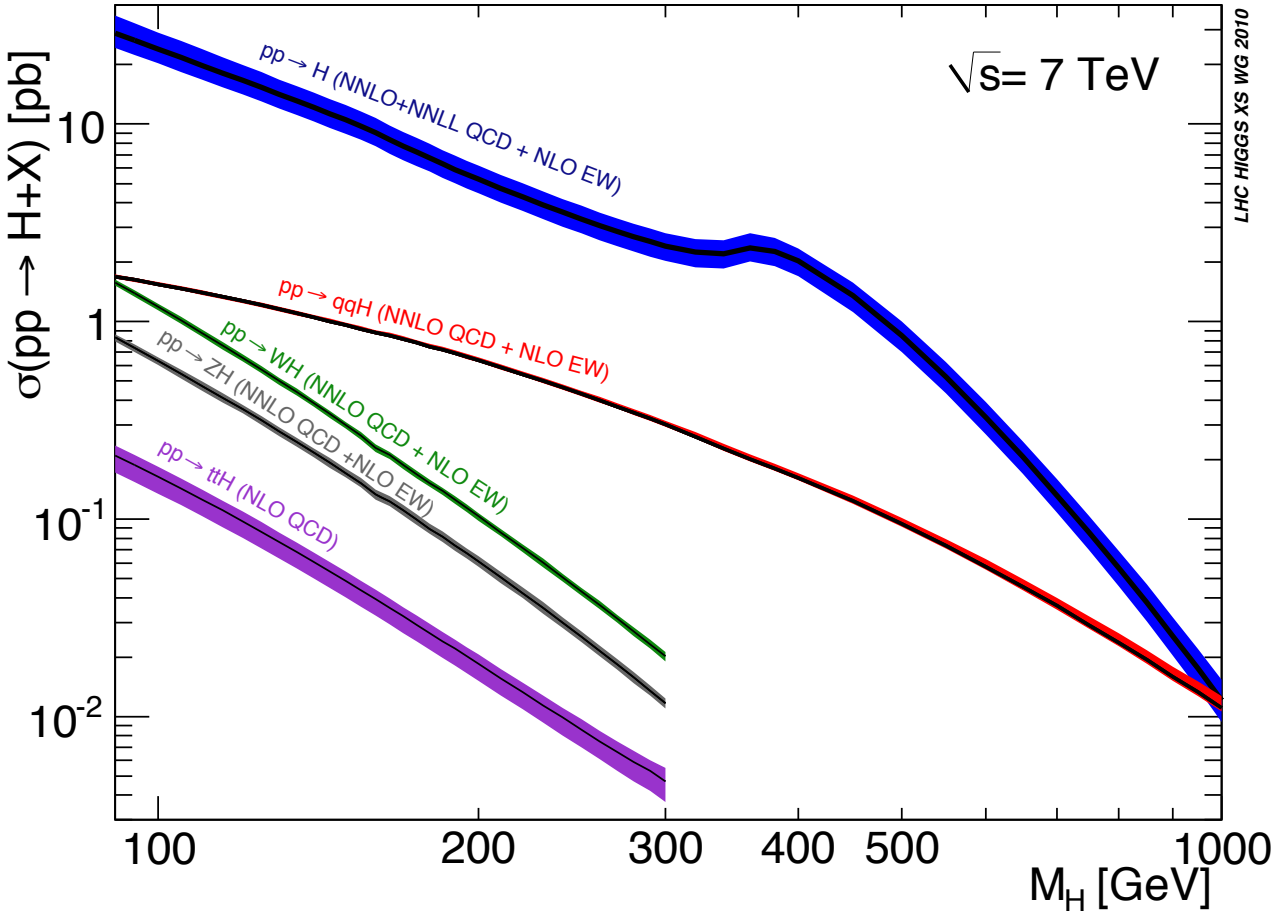




Z→μμ with 25 pile-up interactions in 2012

Standard Model Higgs Properties

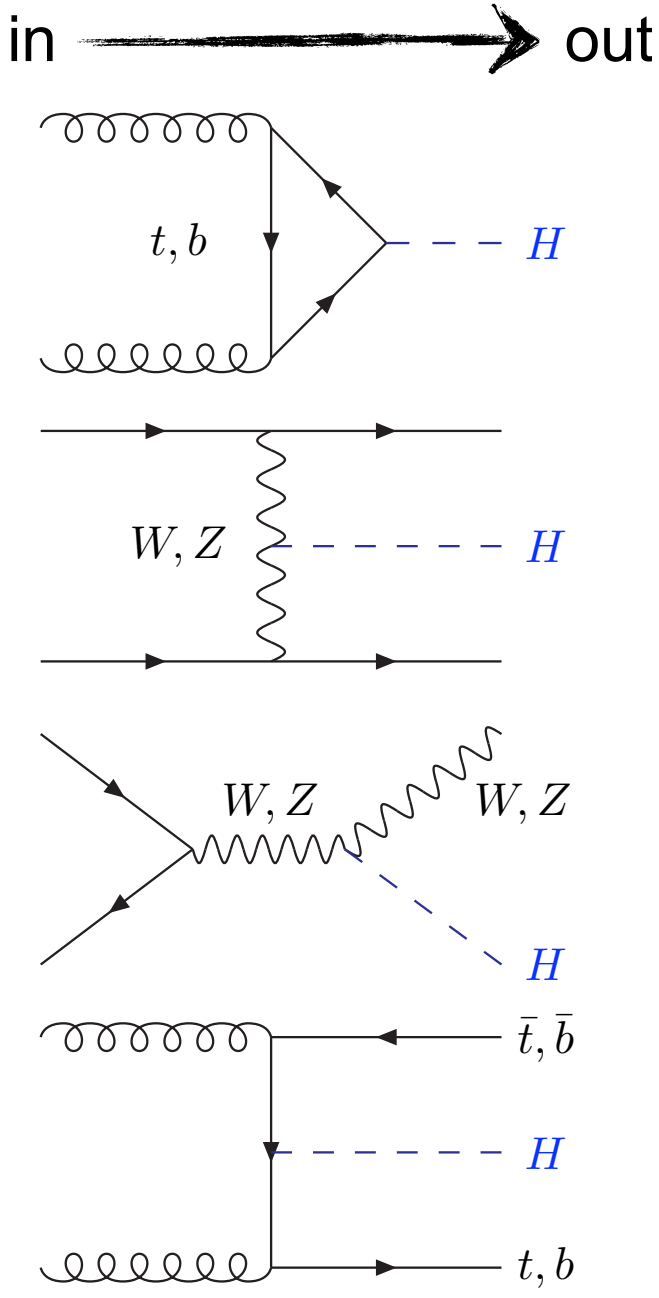


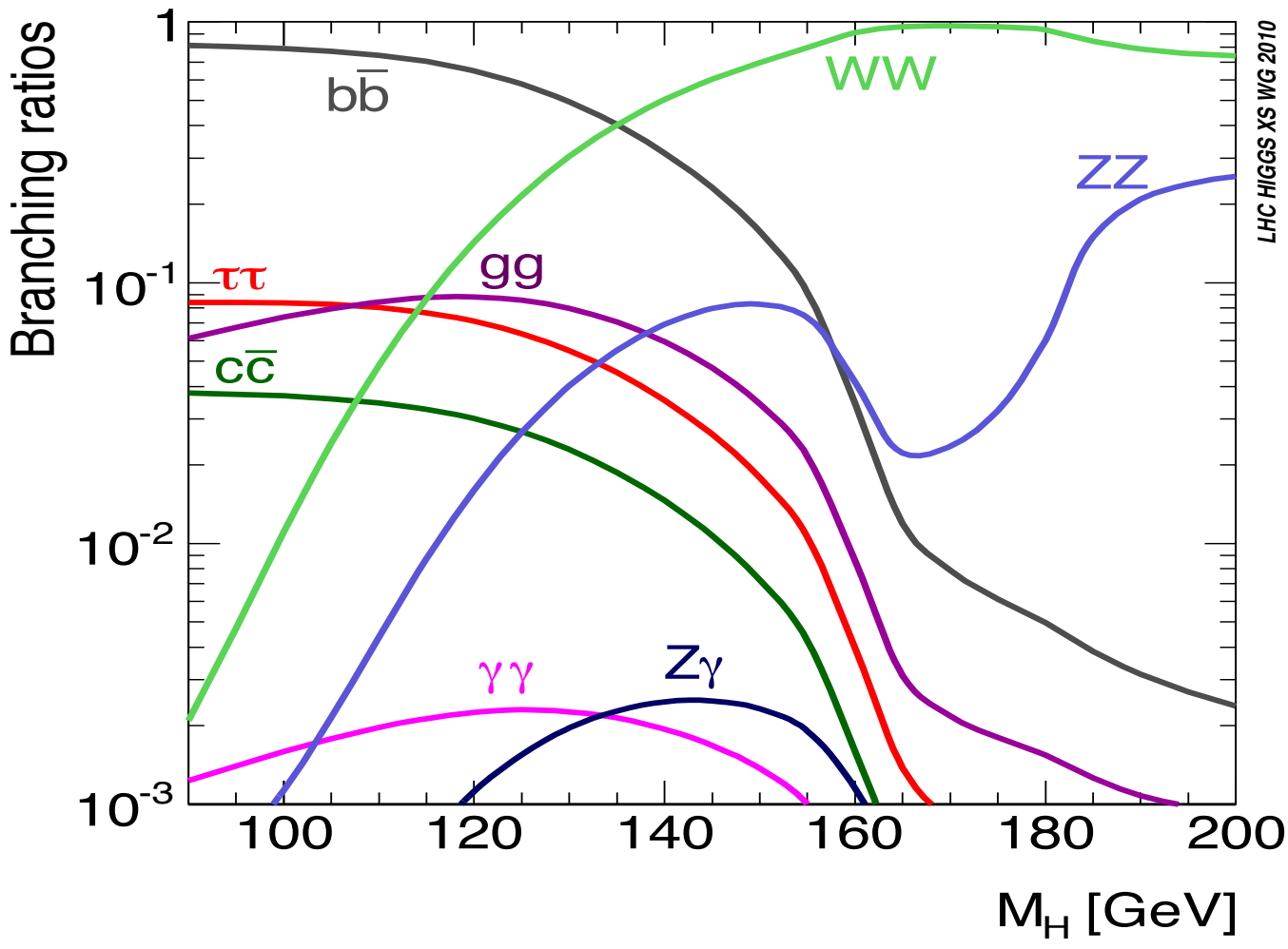


The Higgs boson can be produced via different interactions.

Production cross section σ depends on the unknown Higgs mass

Standard Model Higgs Properties





The Higgs boson then decays in one of several possible final states

The fraction of each decay mode also depends on the unknown Higgs mass

Putting the Higgs back together again



Don't believe the media: $E \neq mc^2$

Putting the Higgs back together again

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What Einstein really said:

$$E^2 = (mc^2)^2 + (|\vec{p}|c)^2$$

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Every Physics I student knows energy and momentum are conserved

$$E_{\text{Higgs}} = E_{\text{before}} = E_{\text{after}} = \sum_i E_i$$

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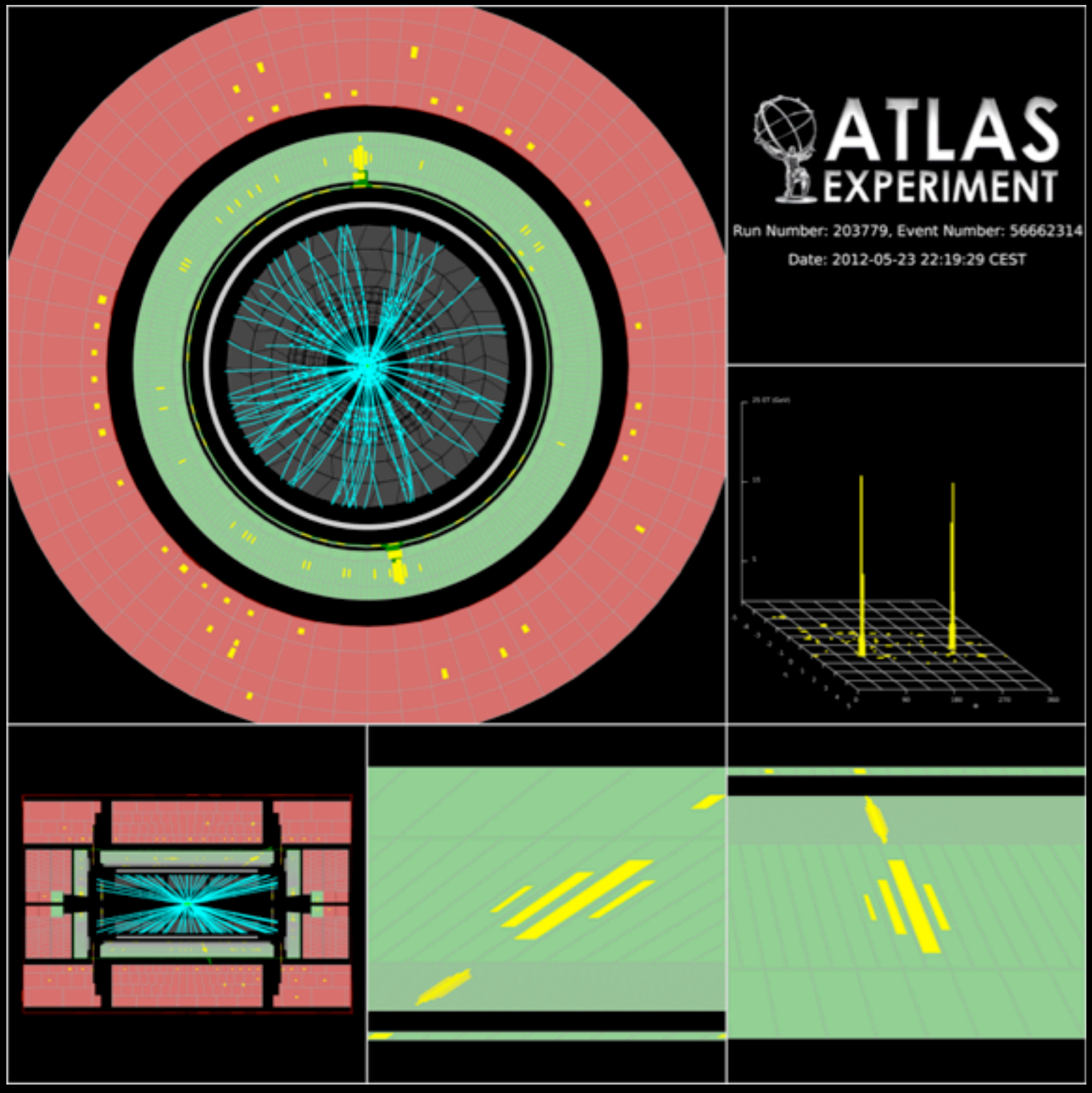
$$E_{\text{Higgs}} = E_{\text{before}} = E_{\text{after}} = \sum_i E_i$$

$$\vec{p}_{\text{Higgs}} = \vec{p}_{\text{before}} = \vec{p}_{\text{after}} = \sum_i \vec{p}_i$$

Thus, we can estimate the mass of the Higgs with

$$m_H = \sqrt{E^2_{\text{after}}/c^4 - |\vec{p}_{\text{after}}|^2/c^2}$$

$H \to \gamma\gamma$

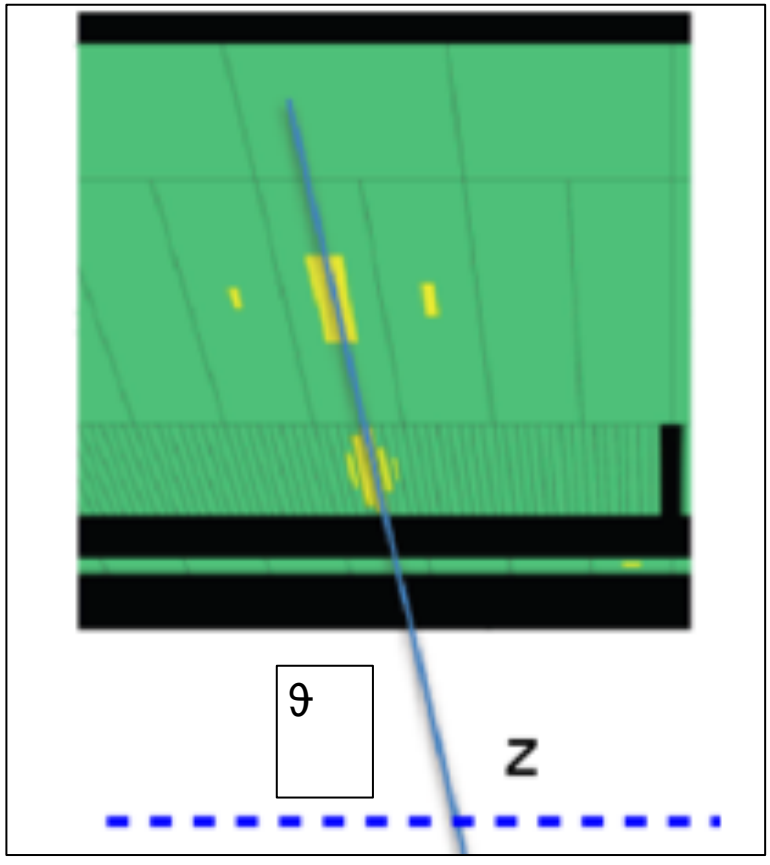


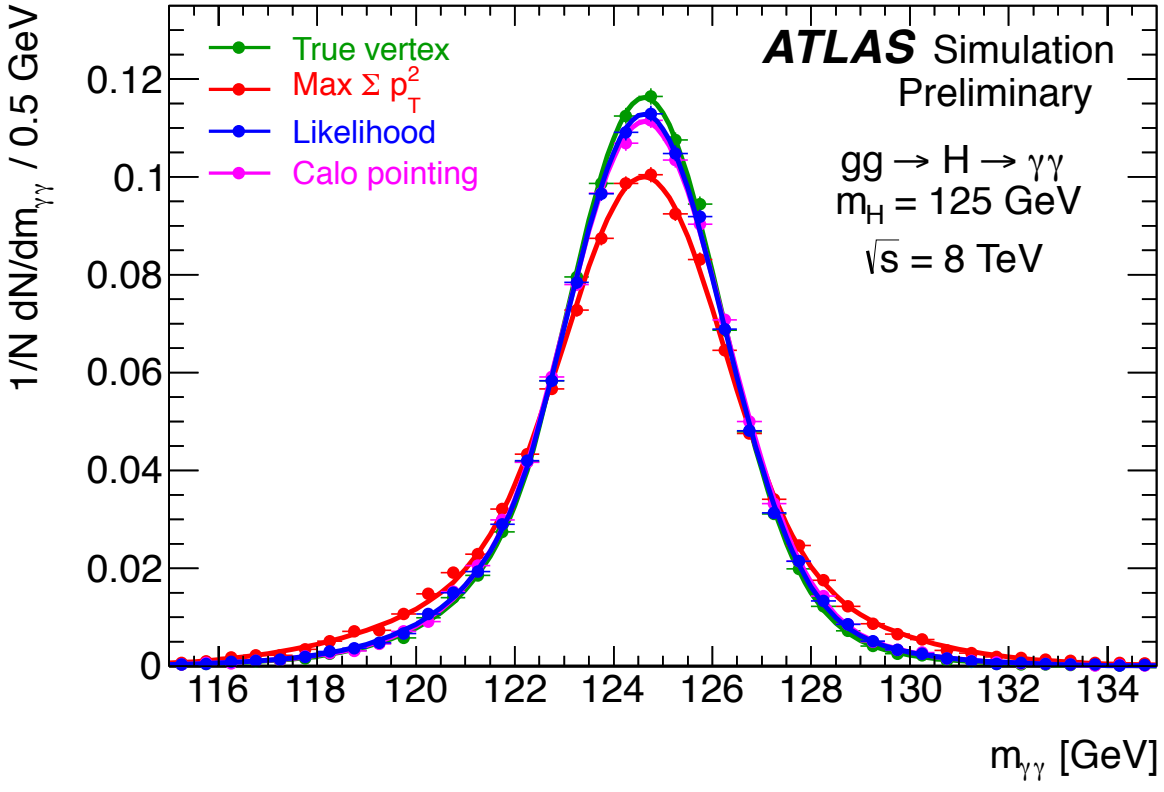
The 2-photon invariant mass

The invariant mass of the 2 photons will peak at the Higgs boson mass

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$$

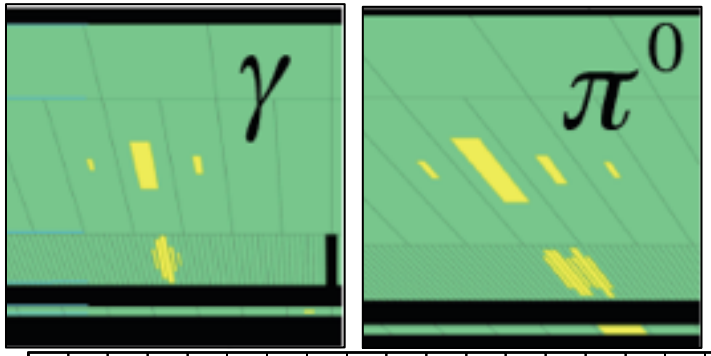
Measure γ direction with calorimeter to find location of primary vertex

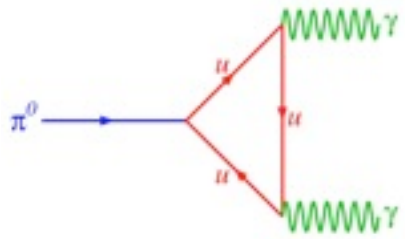


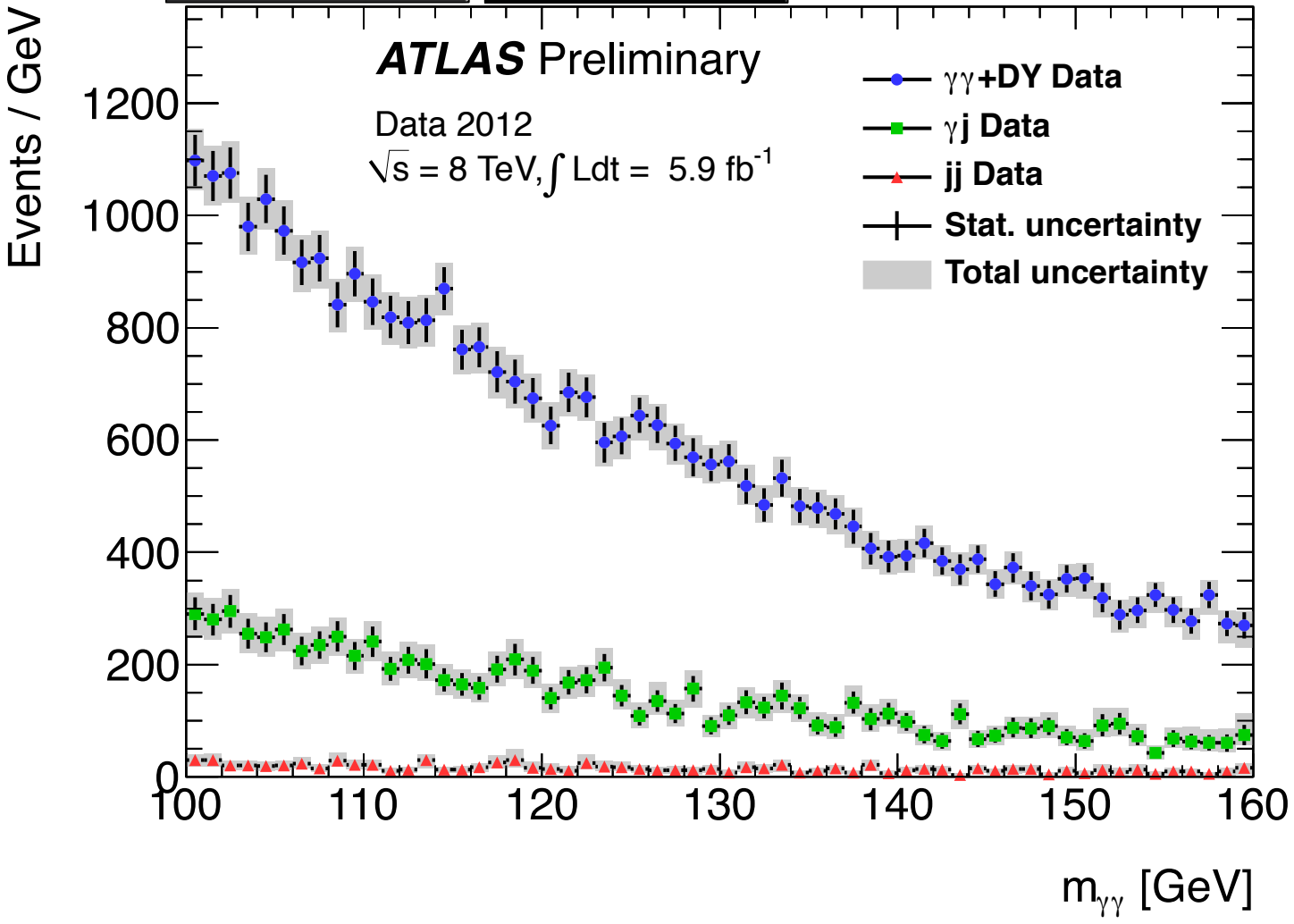


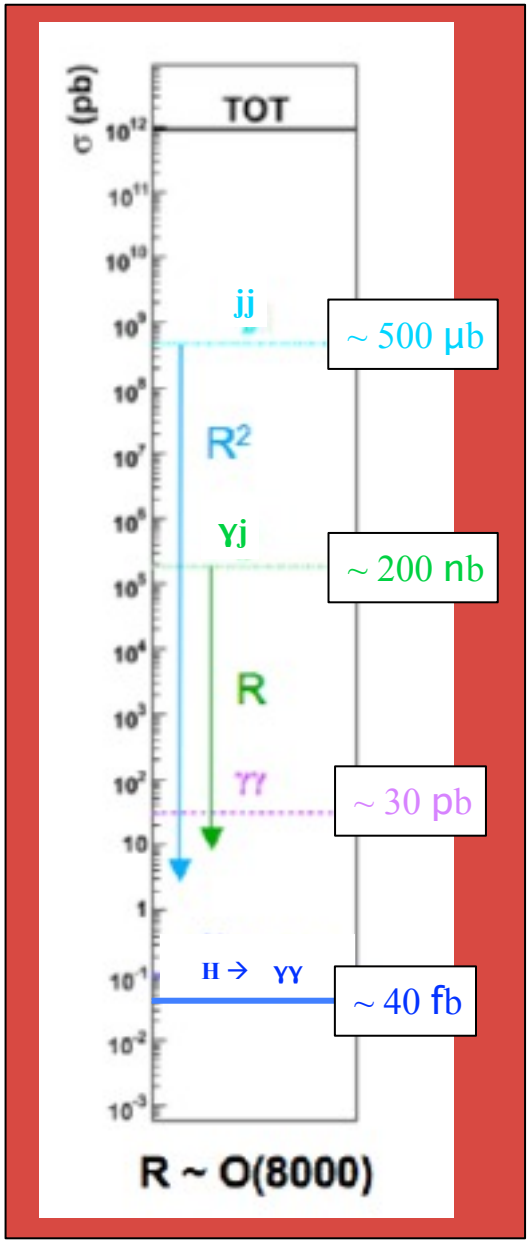
Measure γ direction with calorimeter to find location of primary vertex

Background composition

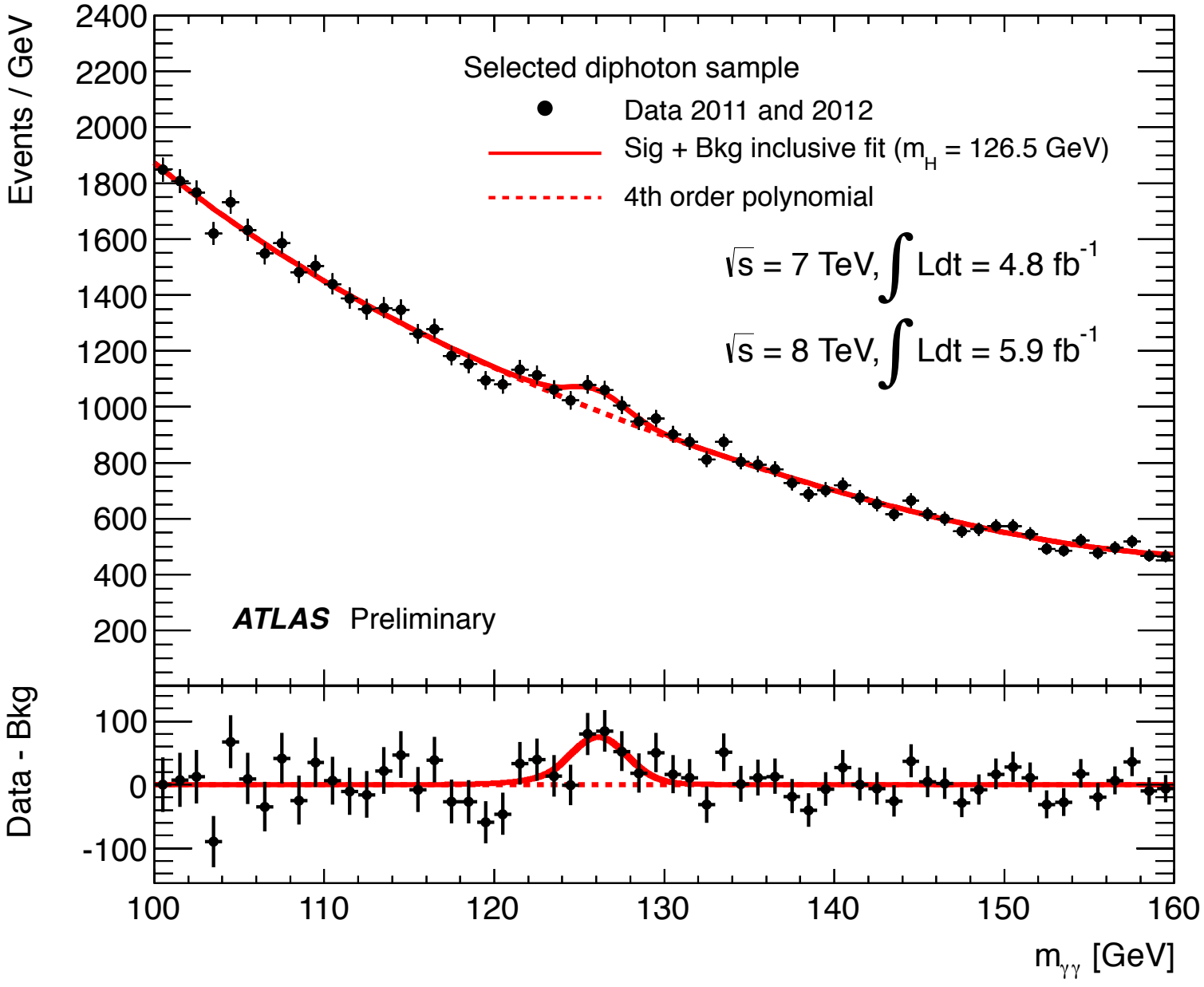








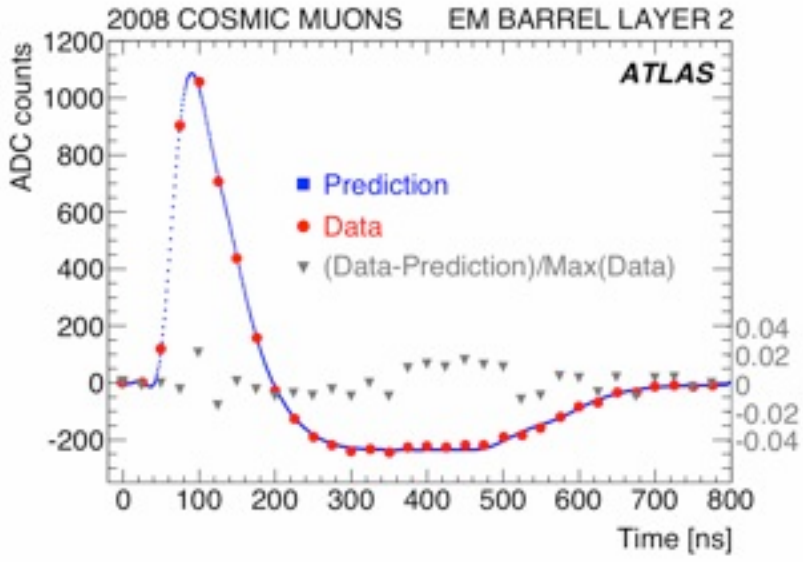
Peak!


Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
√s = 7 TeV, ∫ Ldt = 4.8 fb^-1
√s = 8 TeV, ∫ Ldt = 5.9 fb^-1
ATLAS Preliminary
Events / GeV
Data - Bkg
m_γγ [GeV]

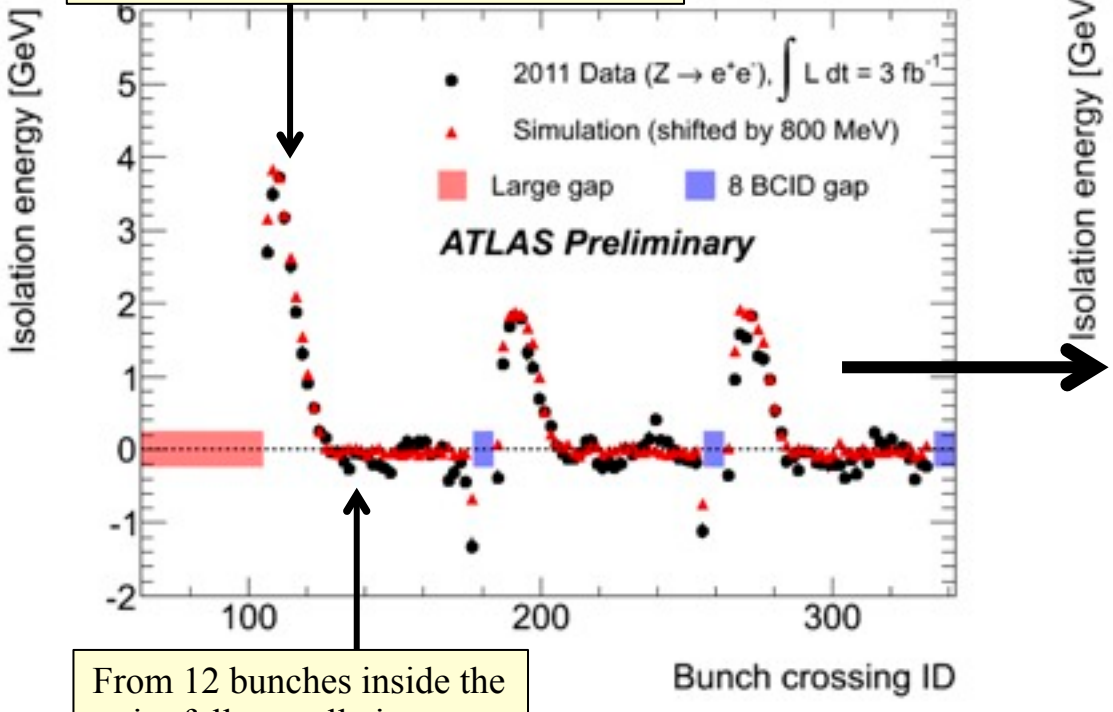
Photon Isolation and Pileup

Photon are required to be isolated

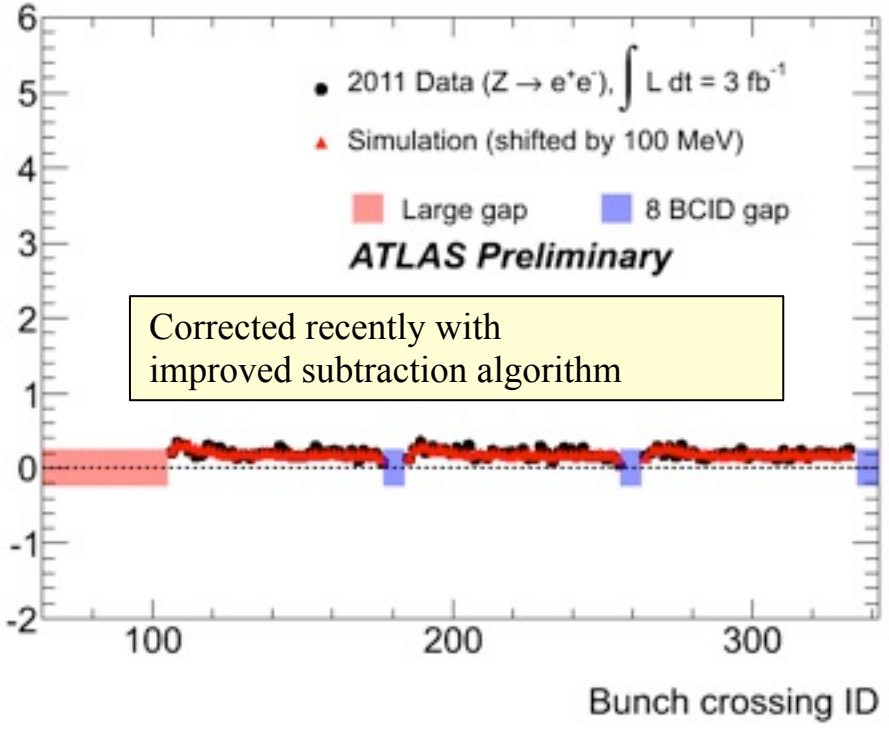
"Pile-up" contribution subtracted. If subtraction is not perfect, residual dependence of the isolation energy on the location along the beam



Beginning of the train: no cancellation from previous bunches



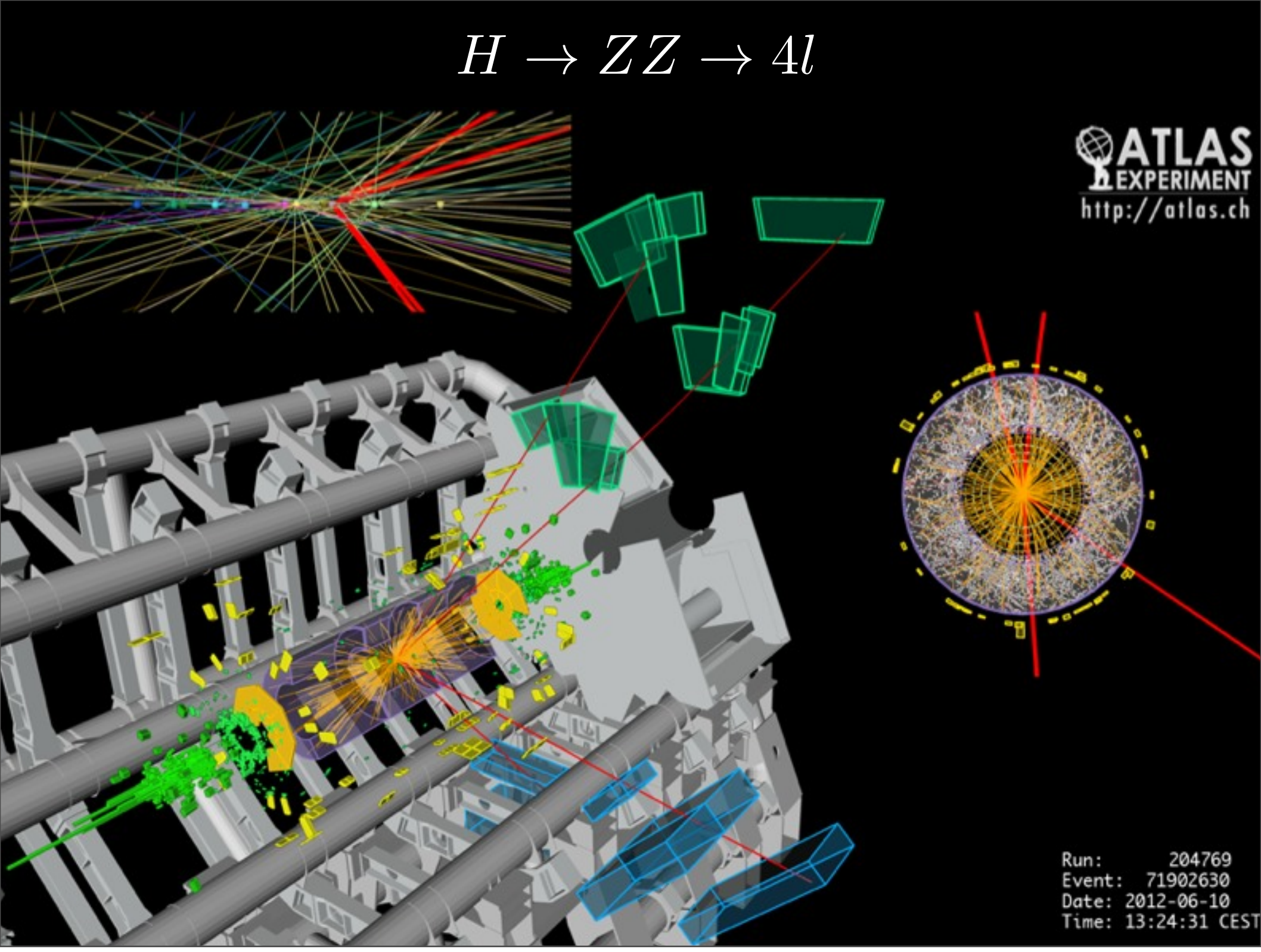
From 12 bunches inside the train: full cancellation



Corrected recently with improved subtraction algorithm

Effect well described by (detailed !) ATLAS simulation

$H \to ZZ \to 4l$

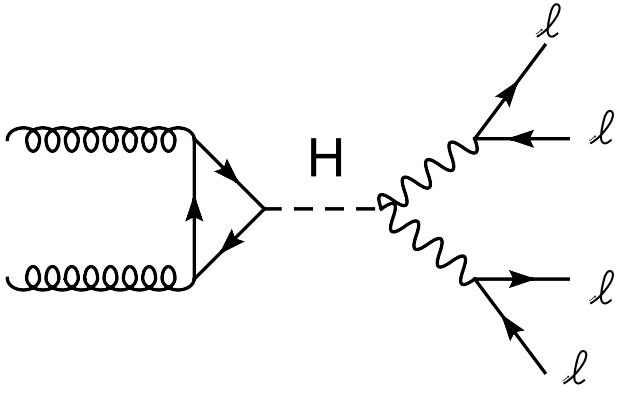

ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

The H→ ZZ*→ 4l signal

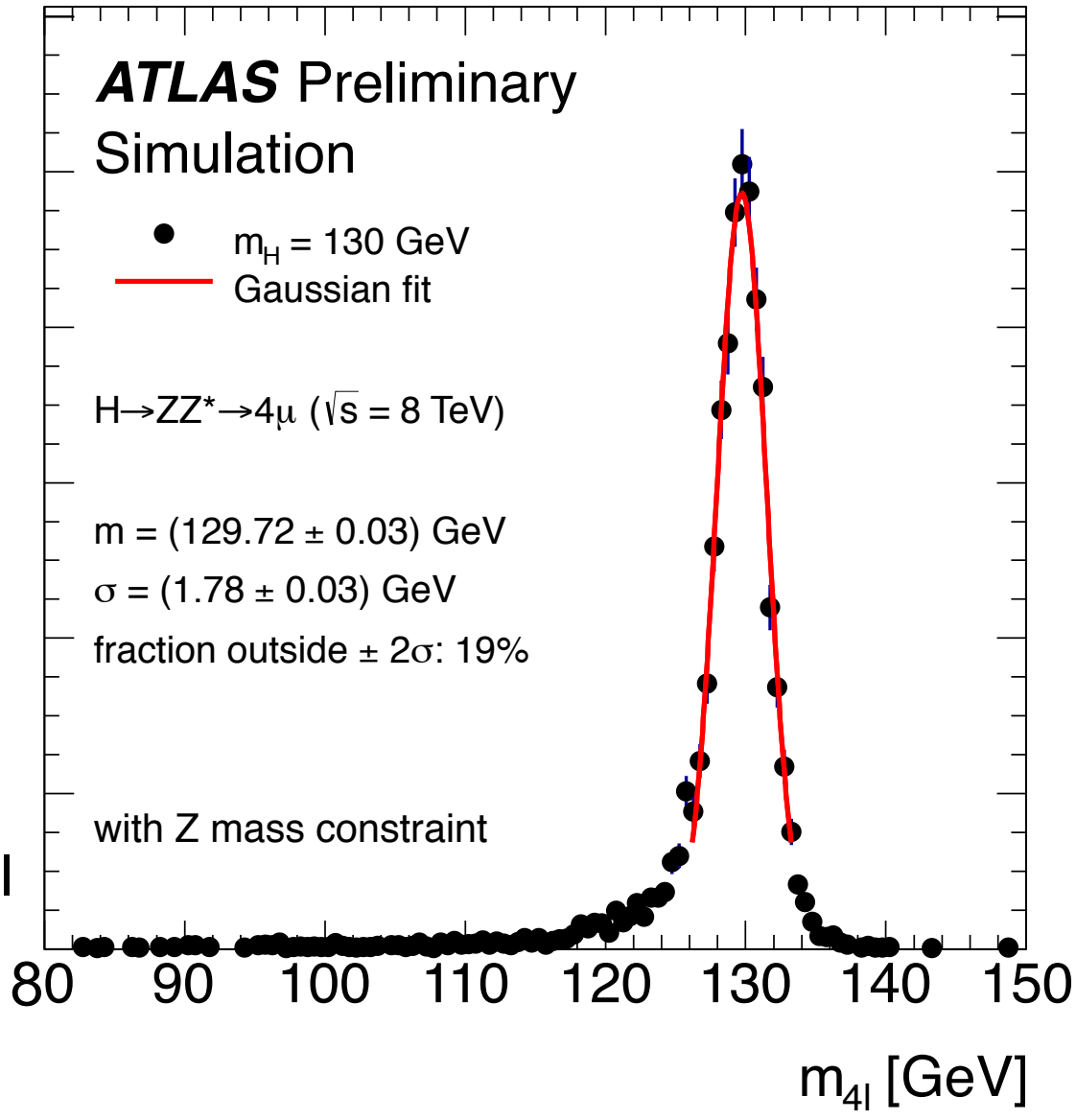
The 4-lepton channel is called the 'golden' channel because it has very little background and a very sharp peak

For a light Higgs boson, one of the Z-bosons must be "off shell"

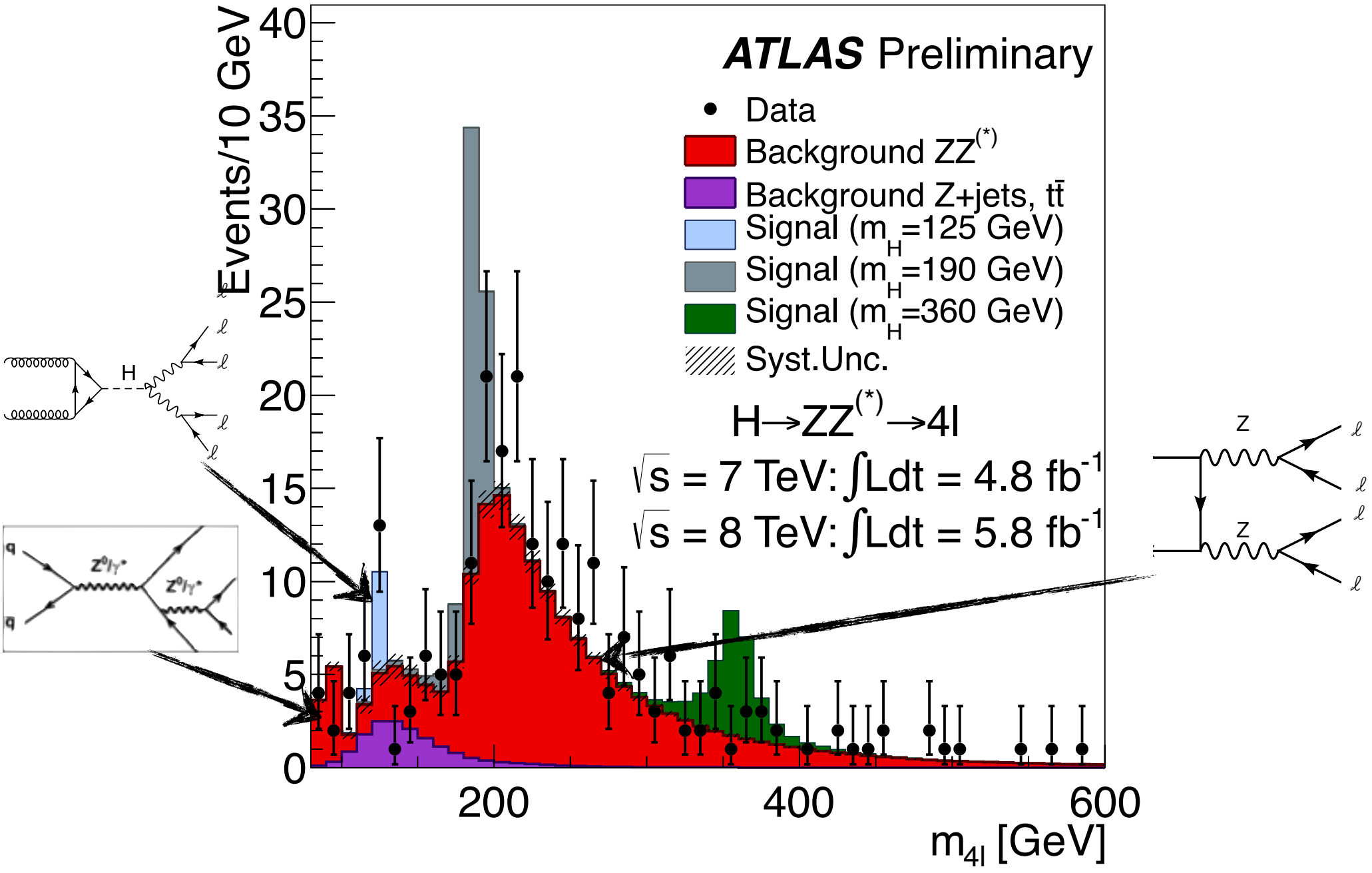
Crucial to efficiently find each lepton
$(90\%)^4 = 65\%$



Peak sharpest in the 4-muon channel



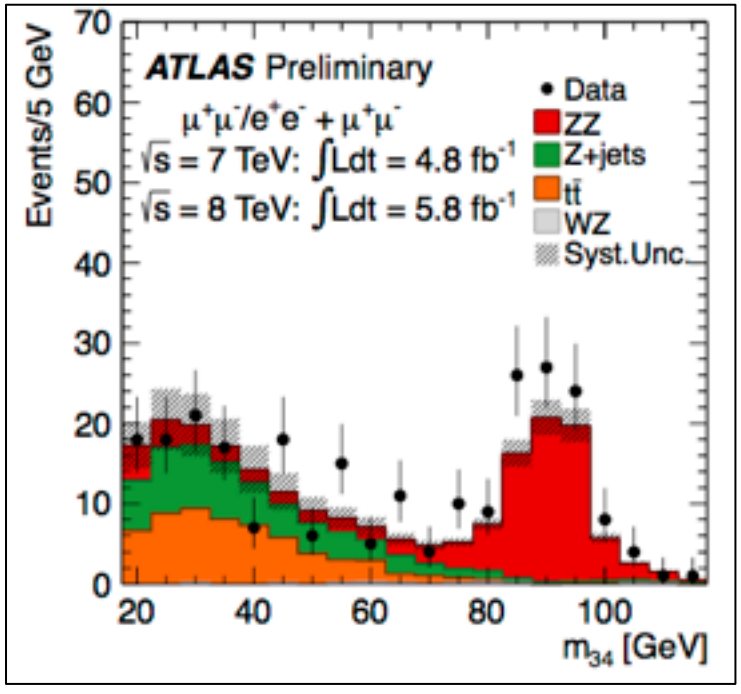
The observation in the 4l channel



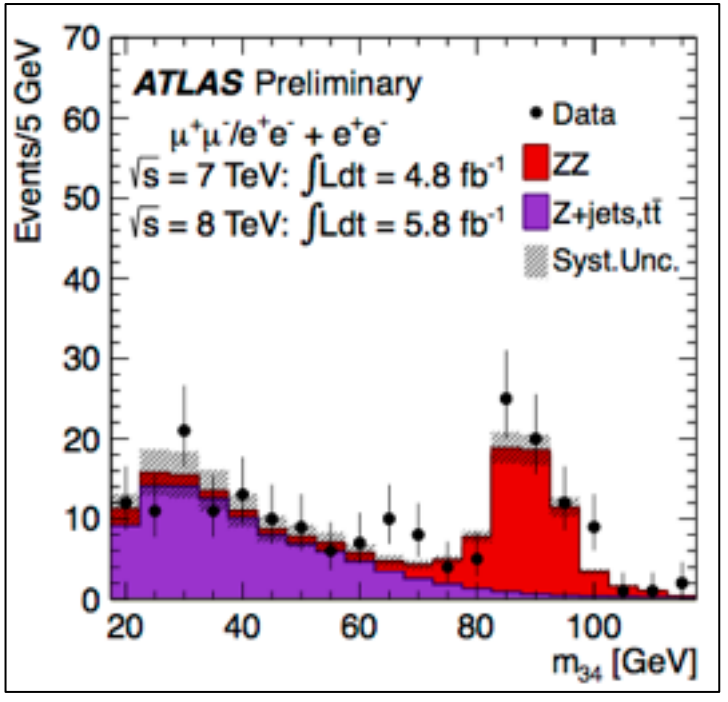
Background composition

Details of the background are different for electrons and muons

$l_3l_4 = \mu\mu \rightarrow$ background dominated by tt and Zbb in low mass region



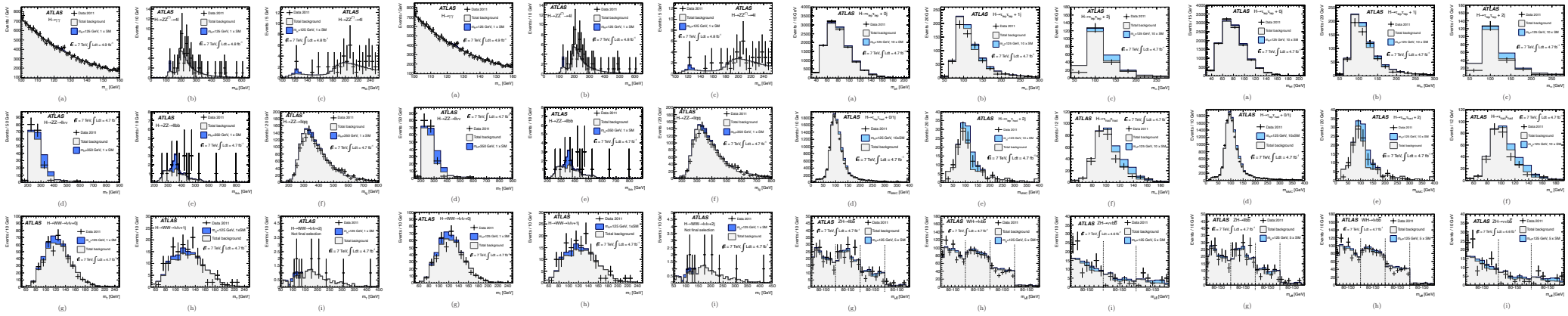
$l_3l_4 = ee \rightarrow$ background dominated by Z+jets in low mass region



Data well described by simulation within uncertainties

Samples of Z+"μ" and Z+"e" used to compare efficiencies of isolation and impact parameter requirements between data and simulation: good agreement

The rest of the story



Higgs Decay	Subsequent Decay	Sub-Channels	m_H Range [GeV]	$\int L\,dt$ [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV		
$H \to \gamma\gamma$	–	9 sub-channels $\{p_{T_t} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jets}\}$	110–150	4.8
$H \to ZZ^{(*)}$	$\ell\ell\ell'\ell'$	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	4.8
	$\ell\ell\nu\bar{\nu}$	$\{ee, \mu\mu\} \otimes \{\text{low, high pile-up}\}$	200–280–600	4.7
	$\ell\ell q\bar{q}$	$\{b\text{-tagged, untagged}\}$	200–300–600	4.7
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu\mu\} \otimes \{\text{0-jets, 1-jet, 2-jets}\} \otimes \{\text{low, high pile-up}\}$	110–200–300–600	4.7
	$\ell\nu q\bar{q}'$	$\{e, \mu\} \otimes \{\text{0-jets, 1-jet, 2-jets}\}$	300–600	4.7
$H \to \tau^+\tau^-$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\{e\mu\} \otimes \{\text{0-jets}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jets, } VH\}$	110–150	4.7
	$\tau_{\text{lep}}\tau_{\text{had}}$	$\{e, \mu\} \otimes \{\text{0-jets}\} \otimes \{E_{\text{T}}^{\text{miss}} < 20 \text{ GeV}, E_{\text{T}}^{\text{miss}} \geq 20 \text{ GeV}\}$ $\oplus \{e, \mu\} \otimes \{\text{1-jet}\} \oplus \{\ell\} \otimes \{\text{2-jets}\}$	110–150	4.7
	$\tau_{\text{had}}\tau_{\text{had}}$	$\{\text{1-jet}\}$	110–150	4.7
$VH \to b\bar{b}$	$Z \to \nu\bar{\nu}$	$E_{\text{T}}^{\text{miss}} \in \{120-160, 160-200, \geq 200 \text{ GeV}\}$	110-130	4.6
	$W \to \ell\nu$	$p_{\text{T}}^W \in \{< 50, 50-100, 100-200, \geq 200 \text{ GeV}\}$	110-130	4.7
	$Z \to \ell\ell$	$p_{\text{T}}^Z \in \{< 50, 50-100, 100-200, \geq 200 \text{ GeV}\}$	110-130	4.7
		2012 $\sqrt{s}$ =8 TeV		
$H \to \gamma\gamma$	–	9 sub-channels $\{p_{T_t} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jets}\}$	110–150	5.9
$H \to ZZ^{(*)}$	$\ell\ell\ell'\ell'$	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	5.8

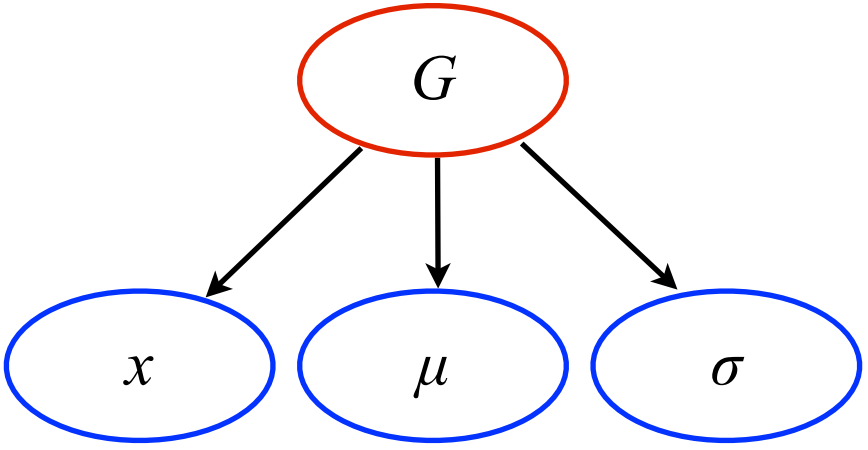


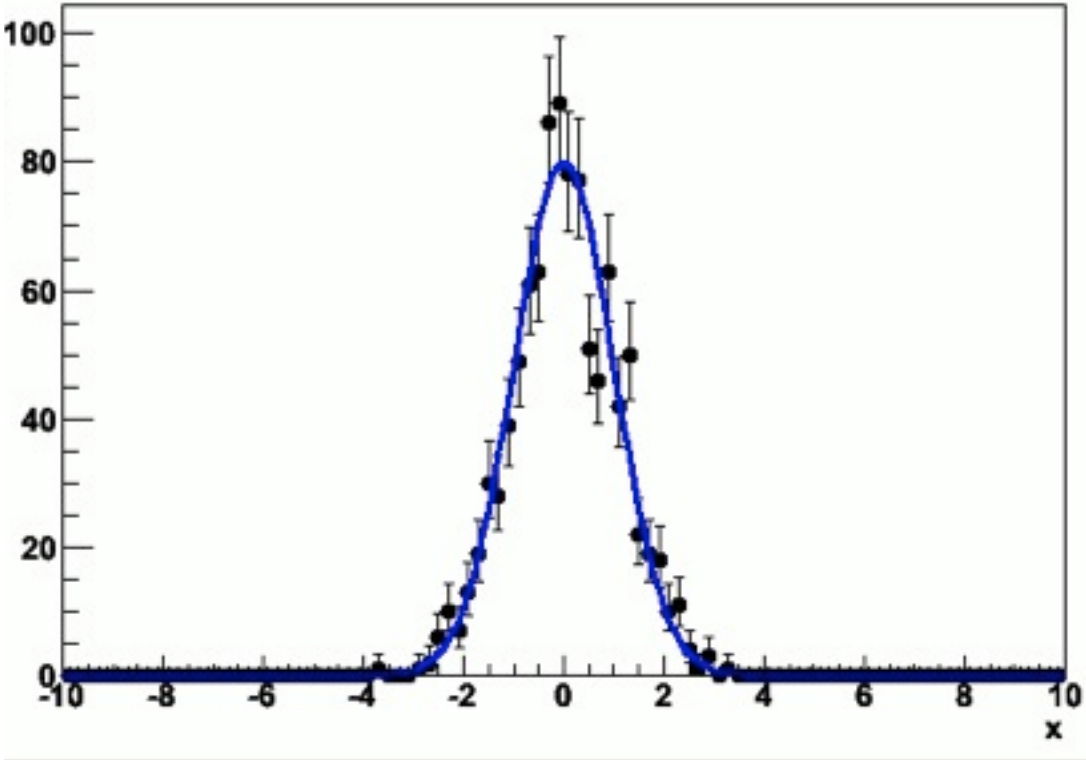
Modeling

Visualizing probability models

I will represent PDFs graphically as below (directed acyclic graph)

- eg. a Gaussian $G(x|\mu,\sigma)$ is parametrized by (μ,σ)
- every node is a real-valued function of the nodes below





Marked Poisson Process

Channel: a subset of the data defined by some selection requirements.

- eg. all events with 4 electrons with energy > 10 GeV
- n: number of events observed in the channel
- ν: number of events expected in the channel

Discriminating variable: a property of those events that can be measured and which helps discriminate the signal from background

- eg. the invariant mass of two particles
- $f(x)$: the p.d.f. of the discriminating variable x

$$\mathcal{D} = \{x_1, \ldots, x_n\}$$

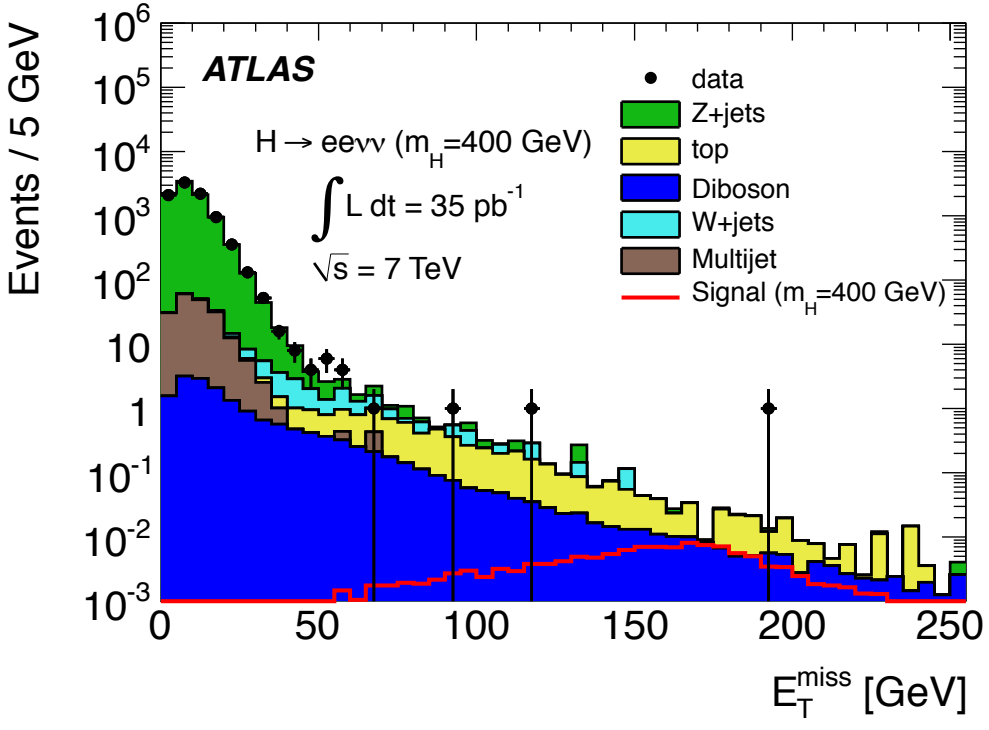
Marked Poisson Process:

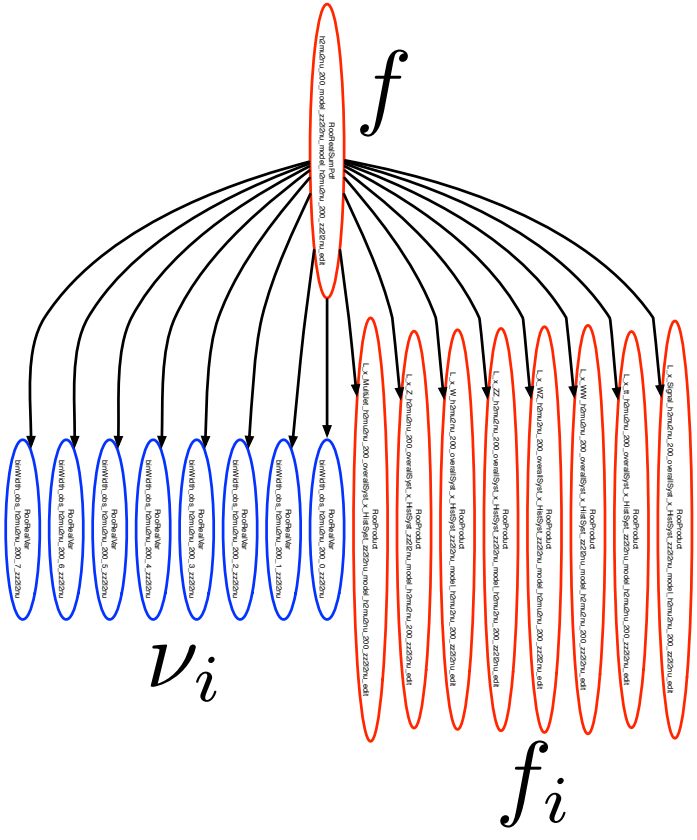
$$\mathbf{f}(\mathcal{D}|\nu) = \mathrm{Pois}(n|\nu) \prod_{e=1}^{n} f(x_e)$$

Mixture model

Total distribution is a mixture model with components corresponding to various signal and background interactions

$$f(x) = \frac{1}{\nu} \sum_{i \in \text{interactions}} \nu_i \, f_i(x) \,, \quad \nu = \sum_{i \in \text{interactions}} \nu_k$$





Parametrizing the model $\boldsymbol{\alpha} = (\mu, \boldsymbol{\theta})$

Parameters of interest (μ): parameters of the theory that modify the rates and shapes of the distributions, eg.

- the mass of the Higgs boson m_H
- the "signal strength" μ=0 no signal, μ=1 predicted signal rate

Nuisance parameters ($\boldsymbol{\theta}$): associated to uncertainty in:

- response of the detector (calibration)
- phenomenological model of interaction in non-perturbative regime

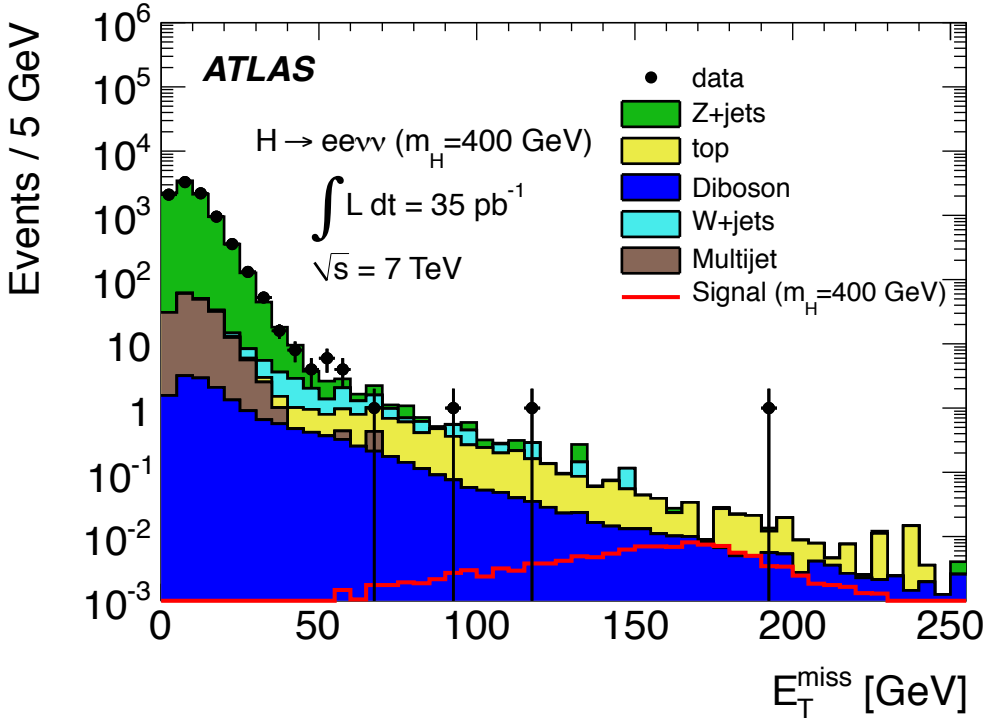
Lead to a parametrized model: $\nu \to \nu(\boldsymbol{\alpha}), f(x) \to f(x|\boldsymbol{\alpha})$

$$\mathbf{f}(\mathcal{D}|\boldsymbol{\alpha}) = \mathrm{Pois}(n|\boldsymbol{\alpha}) \prod_{e=1}^{n} f(x_e|\boldsymbol{\alpha})$$

Incorporating Systematic Effects

Tabulate effect of individual variations of sources of systematic uncertainty

- typically one at a time evaluated at nominal and "± 1 σ"
- use some form of interpolation to parametrize p^{th} variation in terms of **nuisance parameter** α_p



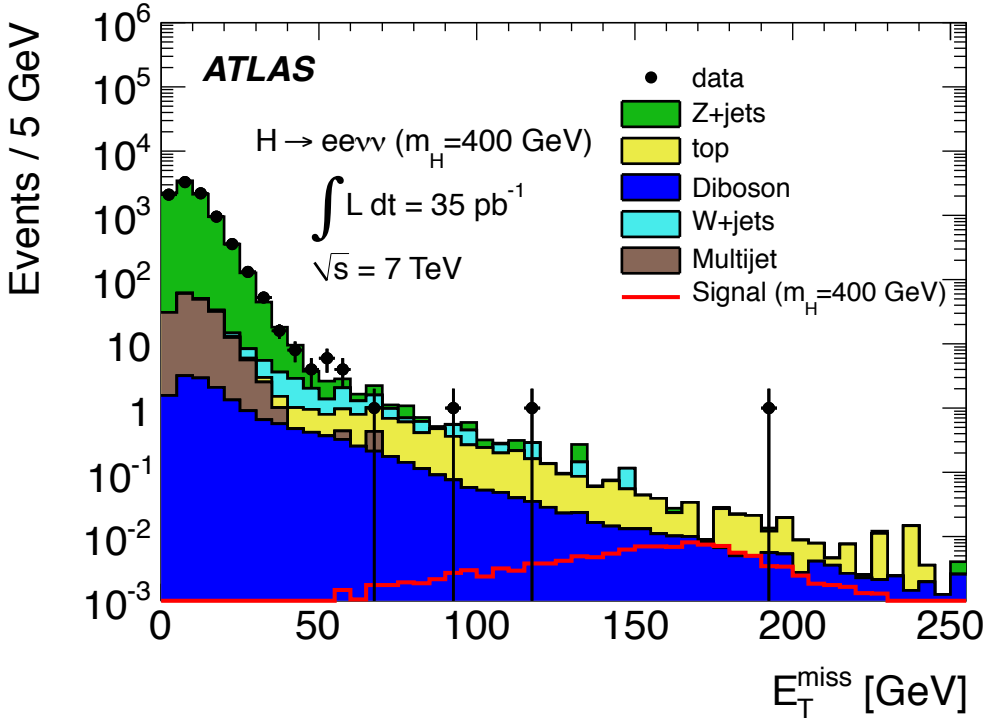
	Z+jets	top	Diboson	...
syst 1				
syst 2				
...				

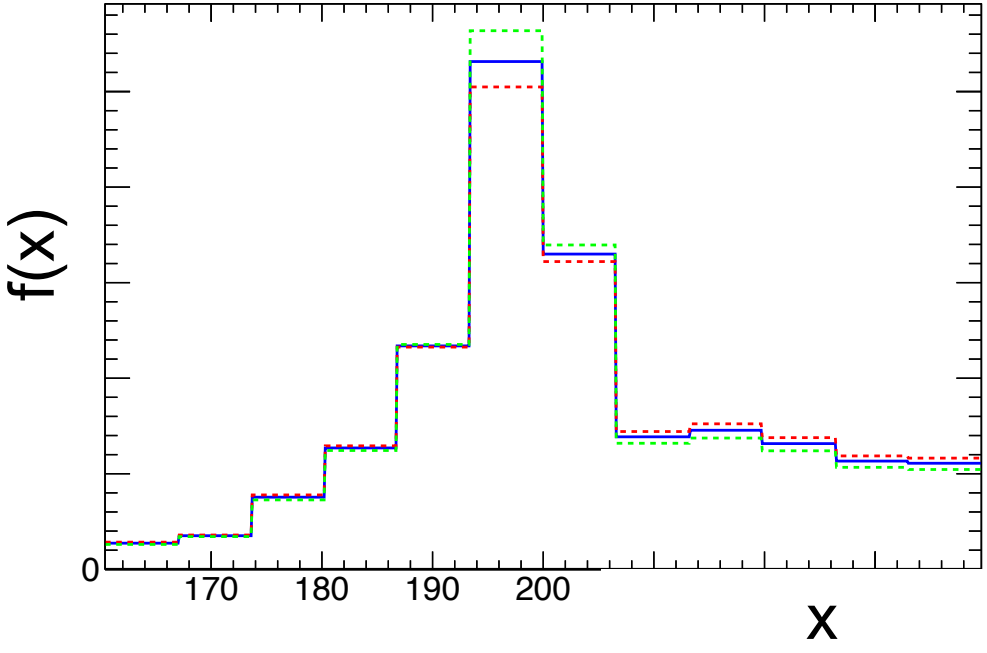
$$\mathbf{f}(\mathcal{D}|\boldsymbol{\alpha}) = \mathrm{Pois}(n|\boldsymbol{\alpha}) \prod_{e=1}^{n} f(x_e|\boldsymbol{\alpha})$$

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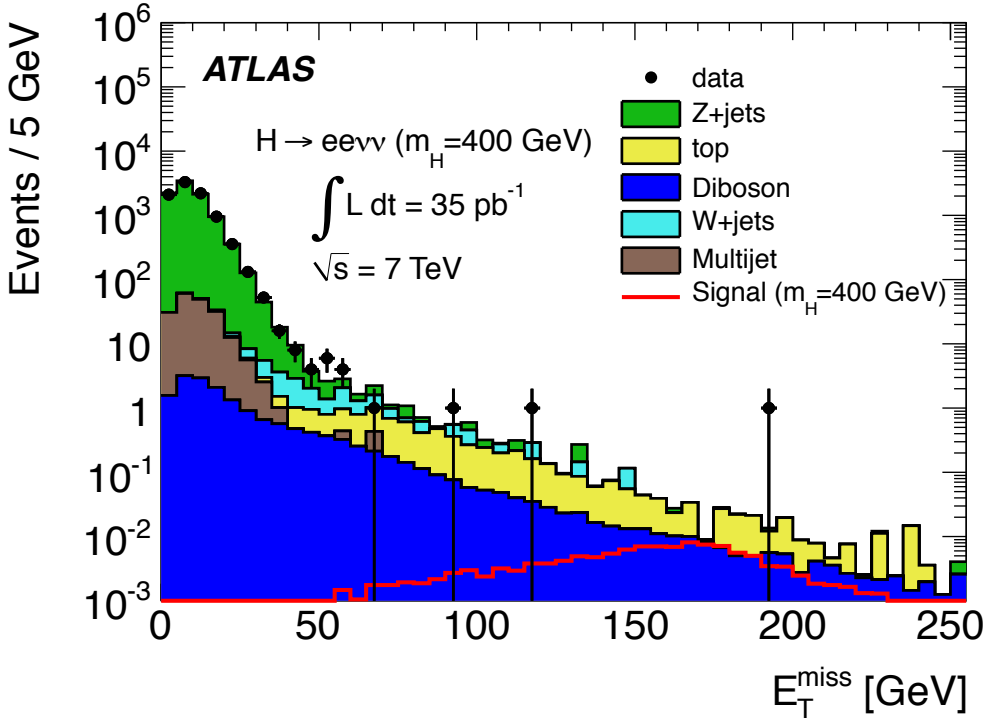


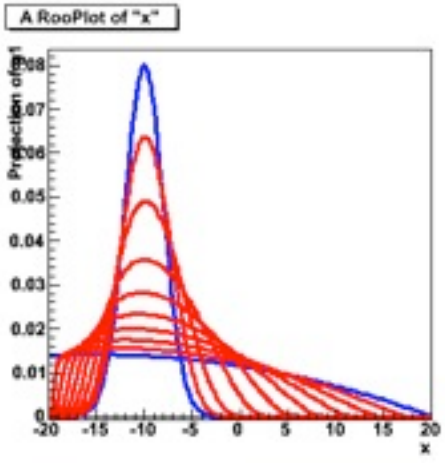
$$\mathbf{f}(\mathcal{D}|\boldsymbol{\alpha}) = \mathrm{Pois}(n|\boldsymbol{\alpha}) \prod_{e=1}^{n} f(x_e|\boldsymbol{\alpha})$$

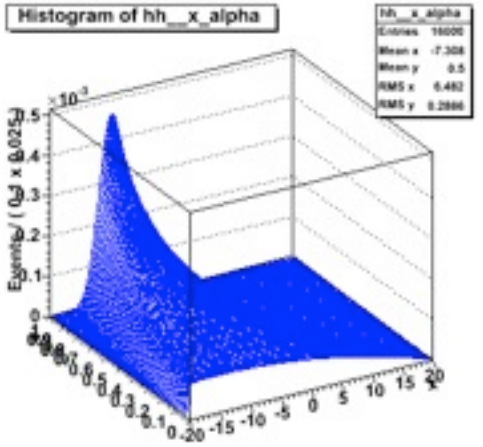
Incorporating Systematic Effects

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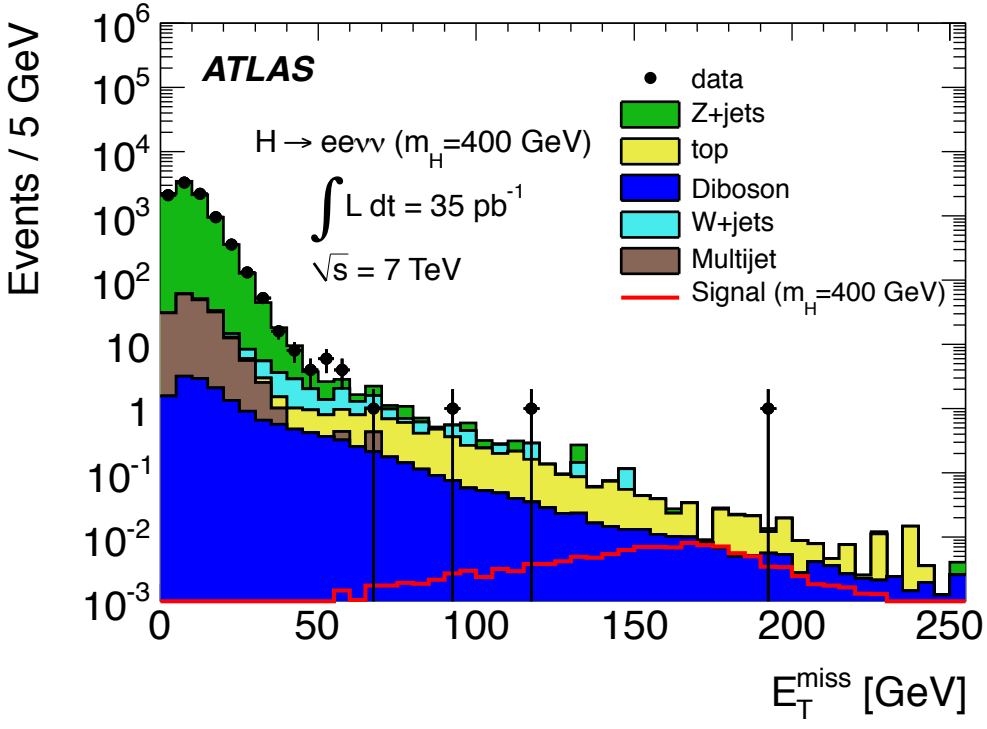


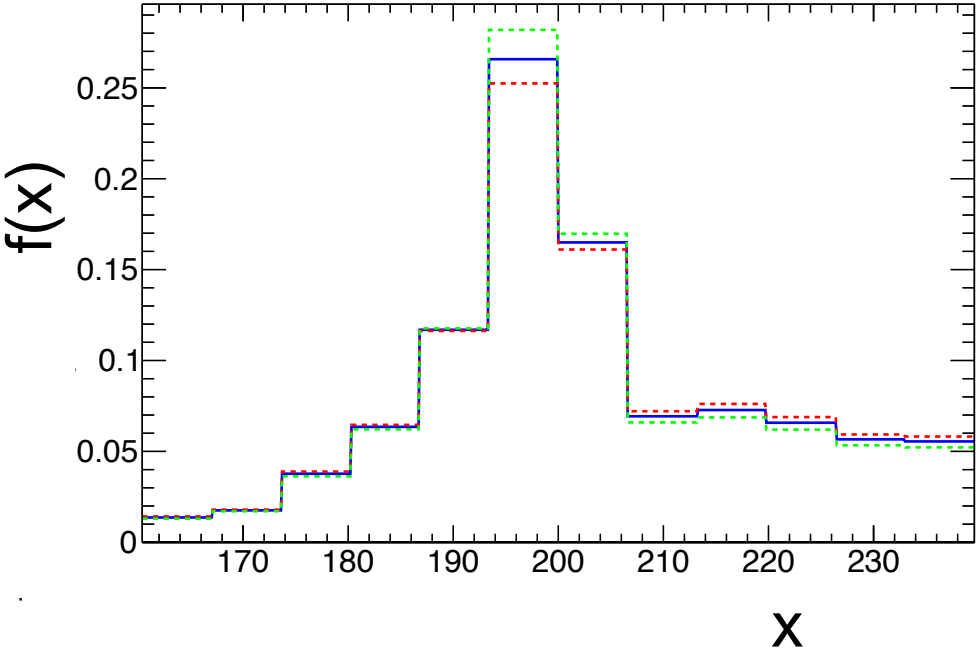


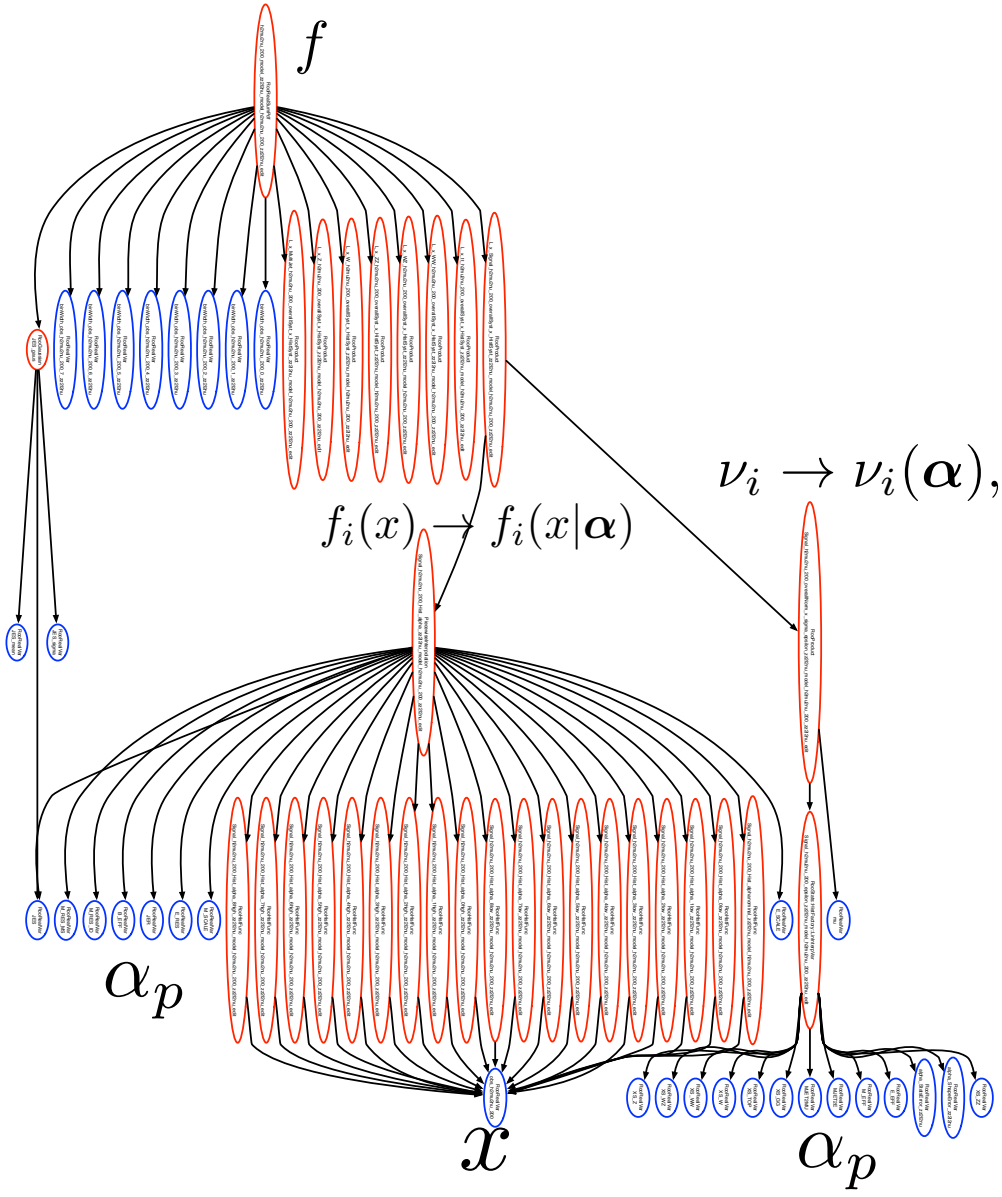


$$\mathbf{f}(\mathcal{D}|\boldsymbol{\alpha}) = \mathrm{Pois}(n|\boldsymbol{\alpha}) \prod_{e=1}^{n} f(x_e|\boldsymbol{\alpha})$$

Visualizing the model for one channel

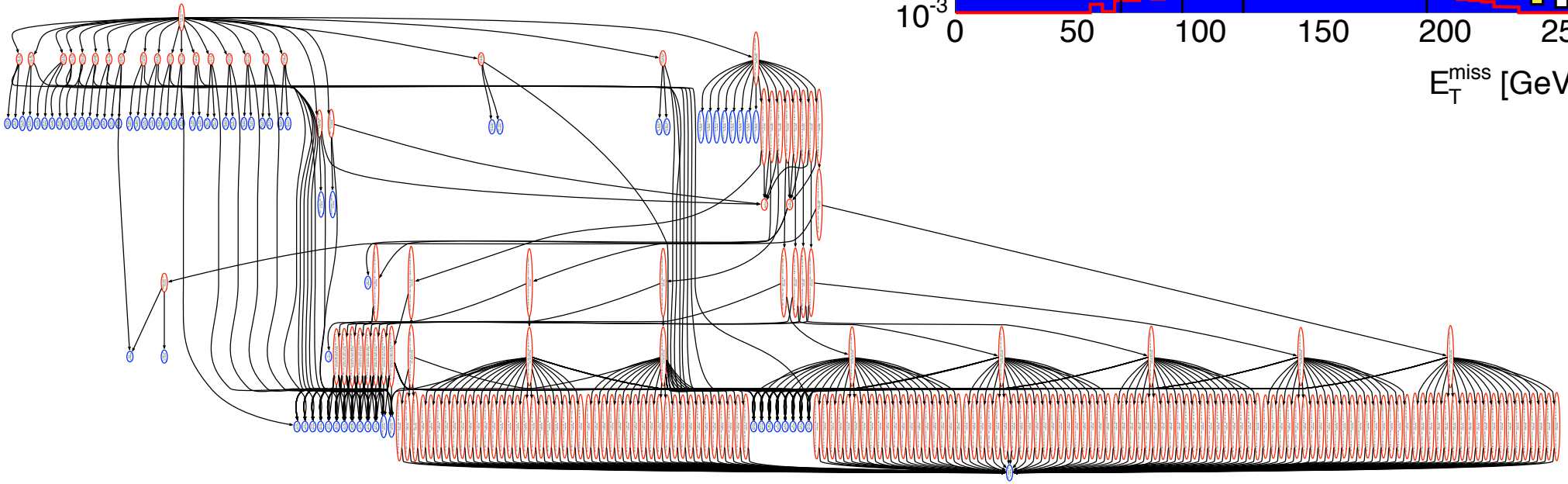






Visualizing the model for one channel

After parametrizing each component of the mixture model, the pdf for a single channel might look like this



Simultaneous multi-channel model

Simultaneous Multi-Channel Model: Several disjoint regions of the data are modeled simultaneously. Identification of common parameters across many channels requires coordination between groups such that meaning of the parameters are really the same.

$$\mathbf{f}_{\text{sim}}(\mathcal{D}_{\text{sim}}|\boldsymbol{\alpha}) = \prod_{c\in\text{channels}} \left[\text{Pois}(n_c|\nu_c(\boldsymbol{\alpha})) \prod_{e=1}^{n_c} f_c(x_{ce}|\boldsymbol{\alpha}) \right]$$

where $\mathcal{D}_{\text{sim}} = \{\mathcal{D}_1, \ldots, \mathcal{D}_{c_{\max}}\}$

Control Regions: Some channels are not populated by signal processes, but are used to constrain the nuisance parameters

Combined ATLAS Higgs Search for 2011

State of the art: Our most recent combined Higgs search includes 100 disjoint channels and >100 nuisance parameters

- Models for individual channels come from about 11 sub-groups performing dedicated searches for specific Higgs decay modes
- In addition low-level performance groups provide tools for evaluating systematic effects and corresponding constraint terms

Higgs Decay	Subsequent Decay	Sub-Channels	m_H Range [GeV]	$\int L\,dt$ [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV		
$H \to \gamma\gamma$	–	9 sub-channels $\{p_{T_t} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jets}\}$	110–150	4.8
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	$\ell\ell\nu\bar{\nu}$	$\{ee, \mu\mu\} \otimes \{\text{low, high pile-up}\}$	200–280–600	4.7
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	$\ell\nu q\bar{q}'$	$\{e, \mu\} \otimes \{\text{0-jets, 1-jet, 2-jets}\}$	300–600	4.7
$H \to \tau^+\tau^-$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\{e\mu\} \otimes \{\text{0-jets}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jets, } VH\}$	110–150	4.7
	$\tau_{\text{lep}}\tau_{\text{had}}$	$\{e, \mu\} \otimes \{\text{0-jets}\} \otimes \{E_{\text{T}}^{\text{miss}} < 20 \text{ GeV}, E_{\text{T}}^{\text{miss}} \geq 20 \text{ GeV}\}$ $\oplus \{e, \mu\} \otimes \{\text{1-jet}\} \oplus \{\ell\} \otimes \{\text{2-jets}\}$	110–150	4.7
	$\tau_{\text{had}}\tau_{\text{had}}$	$\{\text{1-jet}\}$	110–150	4.7
$VH \to b\bar{b}$	$Z \to \nu\bar{\nu}$	$E_{\text{T}}^{\text{miss}} \in \{120-160, 160-200, \geq 200 \text{ GeV}\}$	110-130	4.6
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$H \to \gamma\gamma$	–	9 sub-channels $\{p_{T_t} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jets}\}$	110–150	5.9
$H \to ZZ^{(*)}$	$\ell\ell\ell'\ell'$	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	5.8

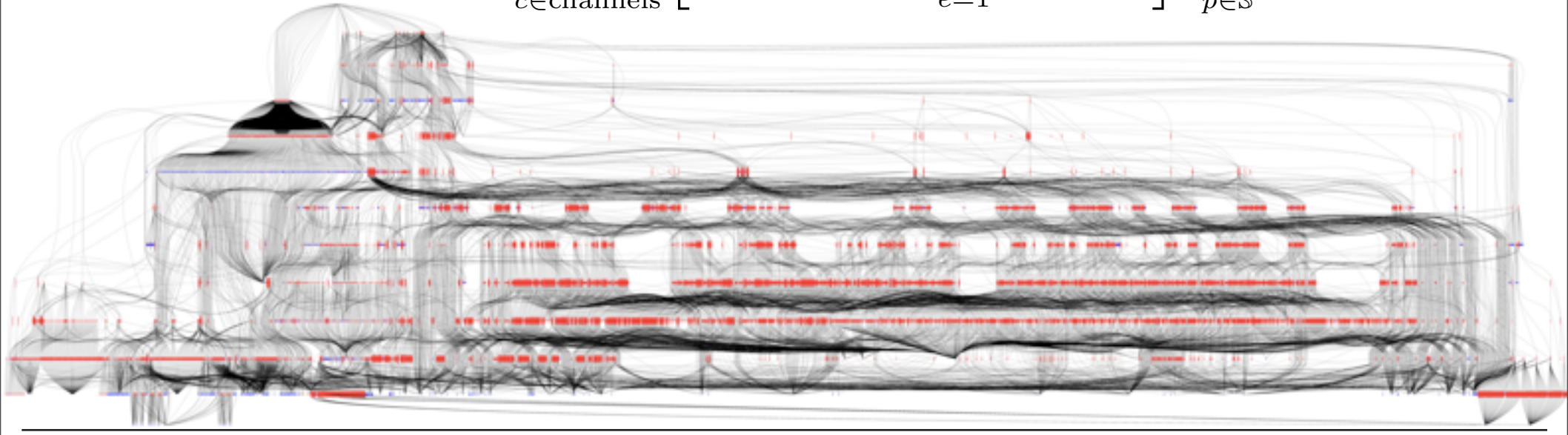
Visualizing the combined model

State of the art: Our most recent combined Higgs search includes 70 disjoint channels and >100 nuisance parameters

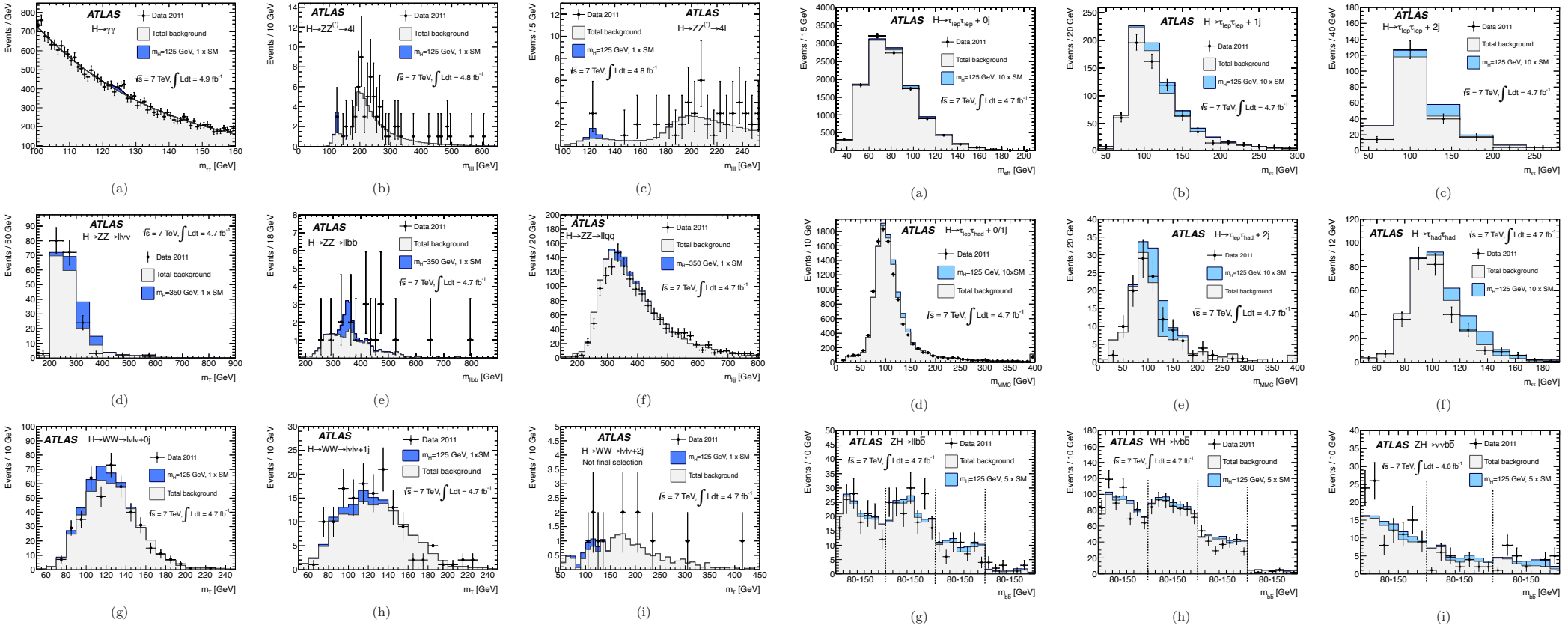
RooFit / RooStats: is the modeling language (C++) which provides technologies for collaborative modeling

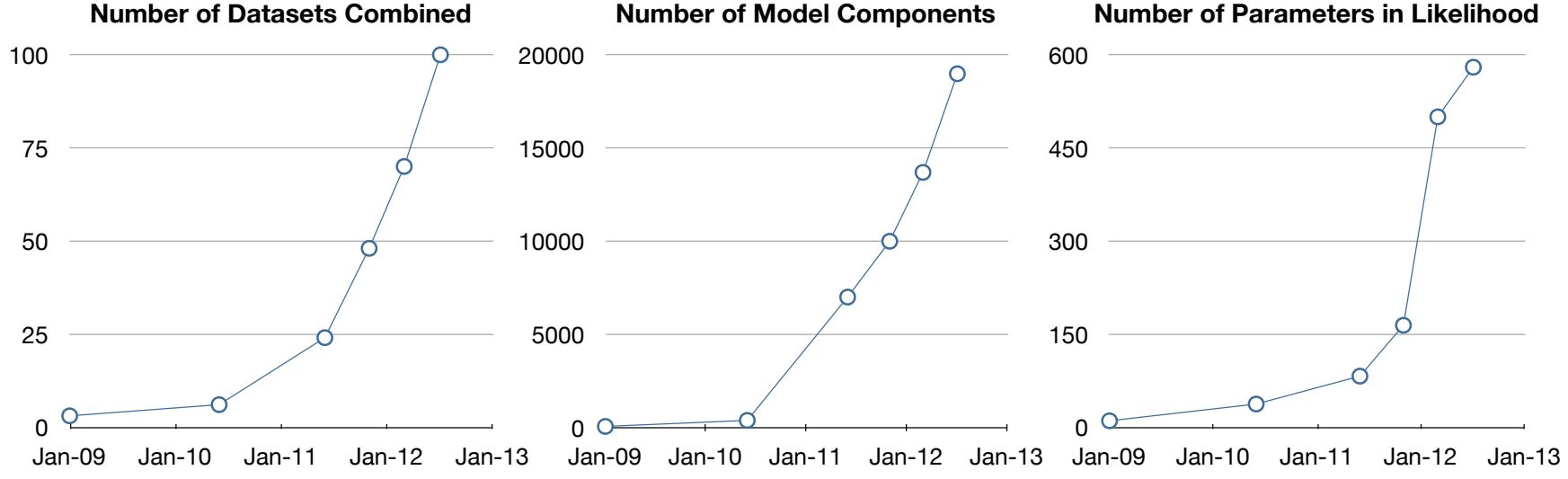
- provides technology to publish likelihood functions digitally
- and more, it's the full model so we can also generate pseudo-data

$$\mathbf{f}_{\text{tot}}(\mathcal{D}_{\text{sim}}, \mathcal{G}|\boldsymbol{\alpha}) = \prod_{c\in\text{channels}} \left[\text{Pois}(n_c|\nu_c(\boldsymbol{\alpha})) \prod_{e=1}^{n_c} f_c(x_{ce}|\boldsymbol{\alpha})\right] \cdot \prod_{p\in\mathbb{S}} f_p(a_p|\alpha_p)$$



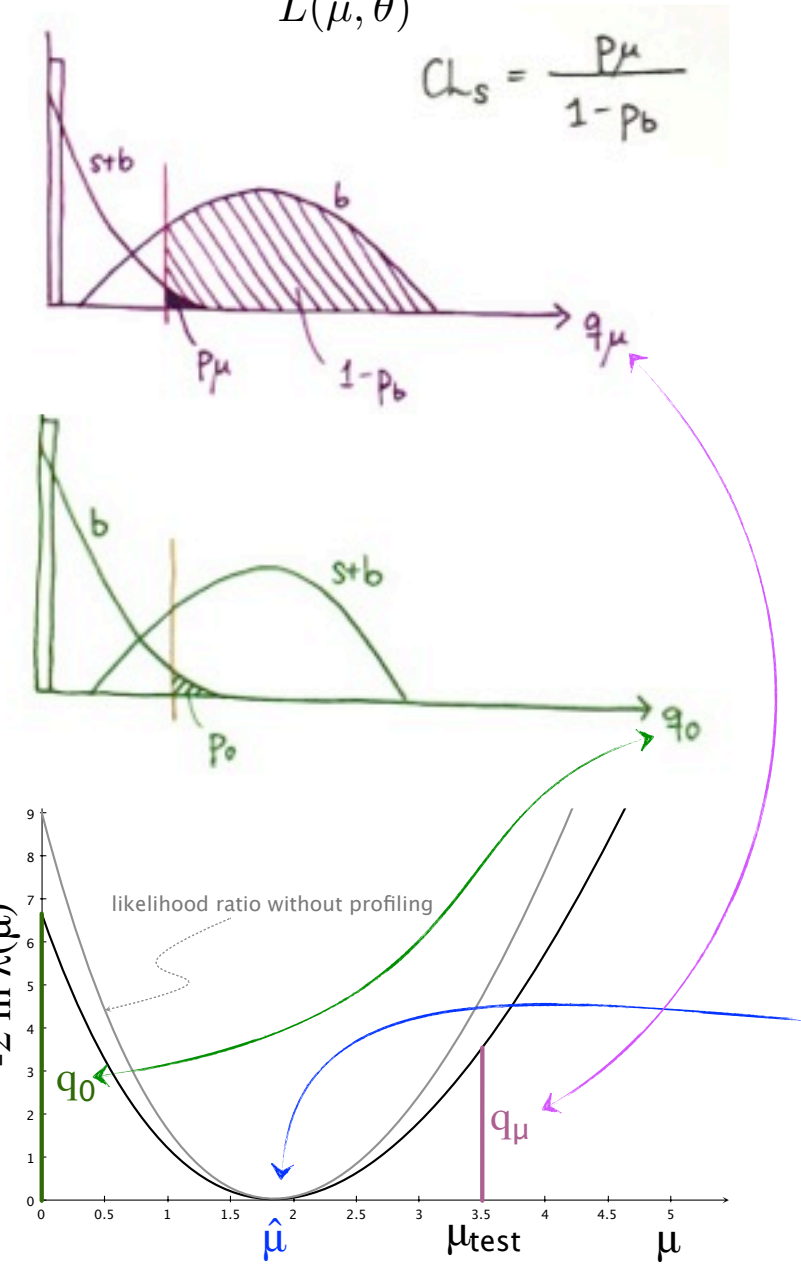
Evolution of Model Complexity





Thumbnail of the statistical procedure

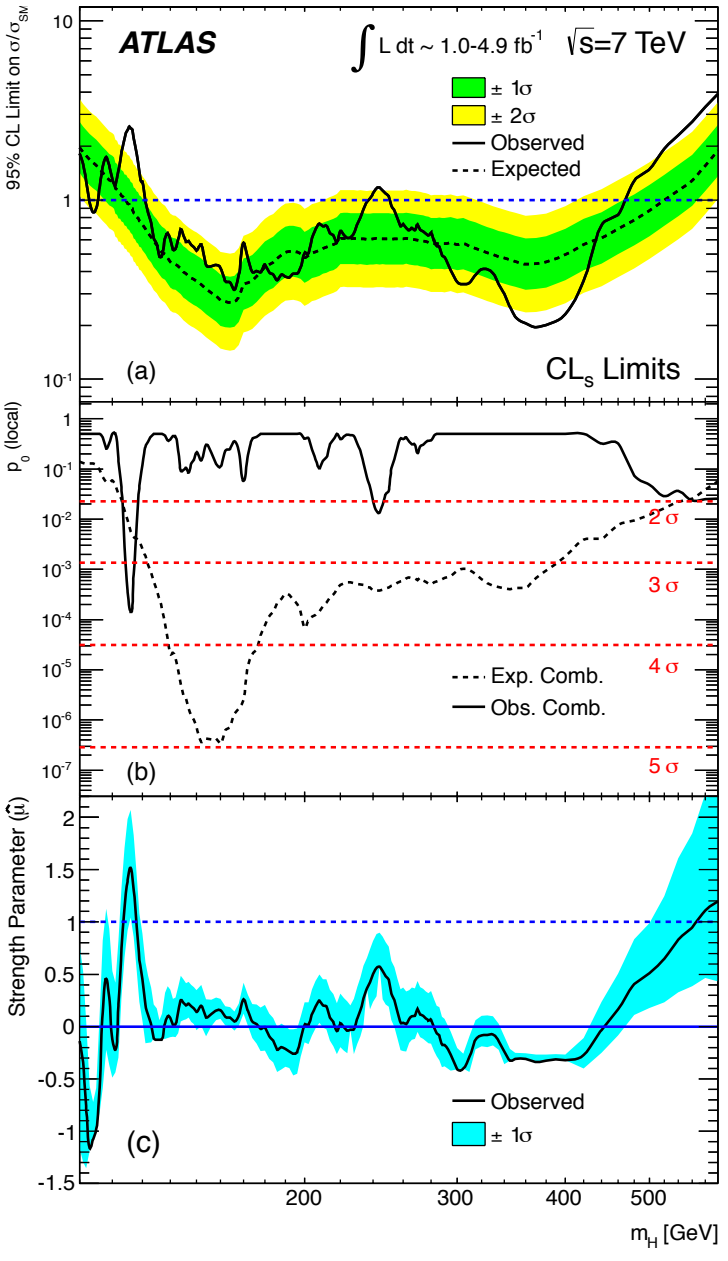
$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$



CL_s to test signal hypothesis

p_0 to test background hypothesis

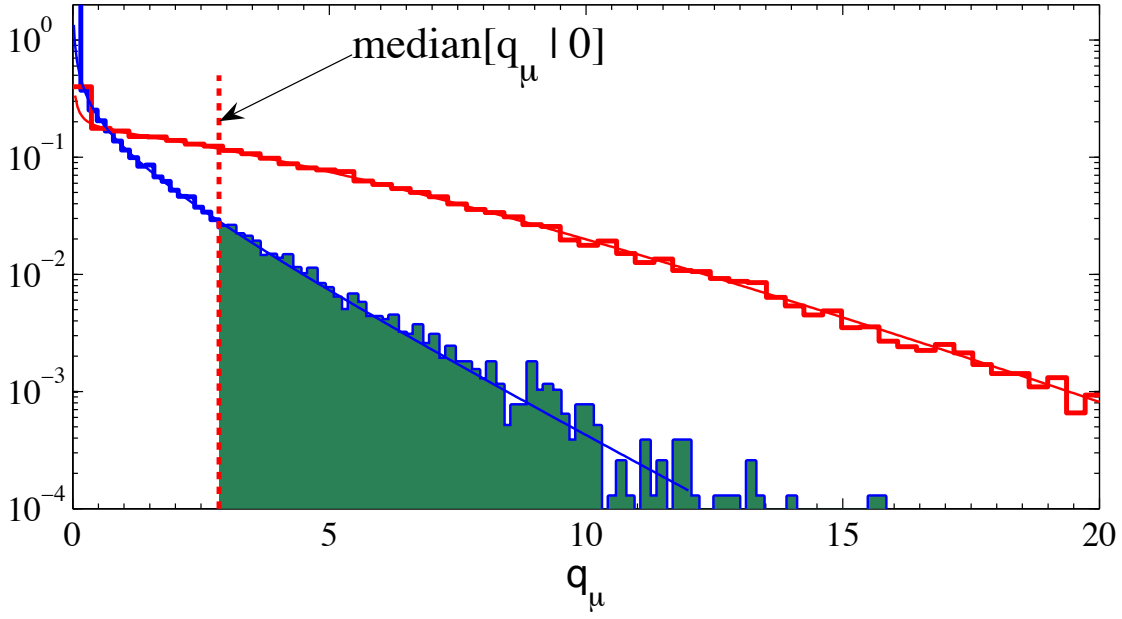
$\hat{\mu}$ to estimate signal strength

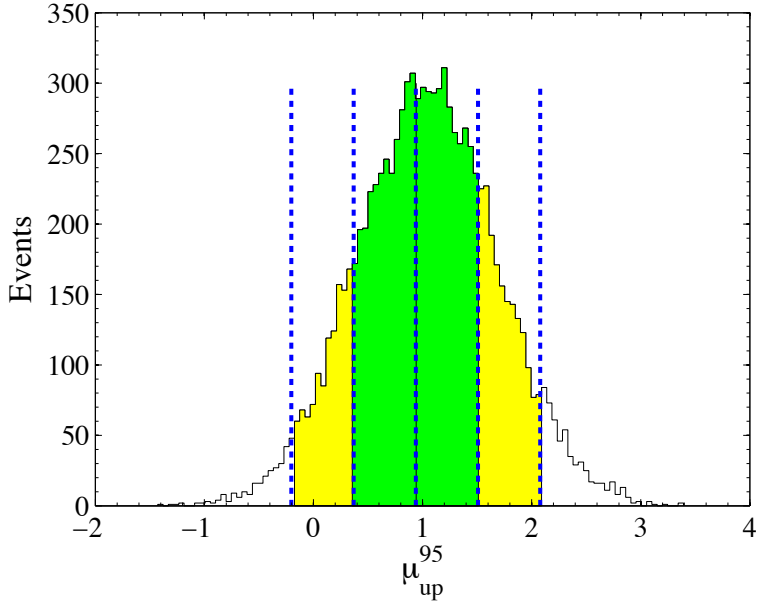


Comparison of asymptotic and ensembles

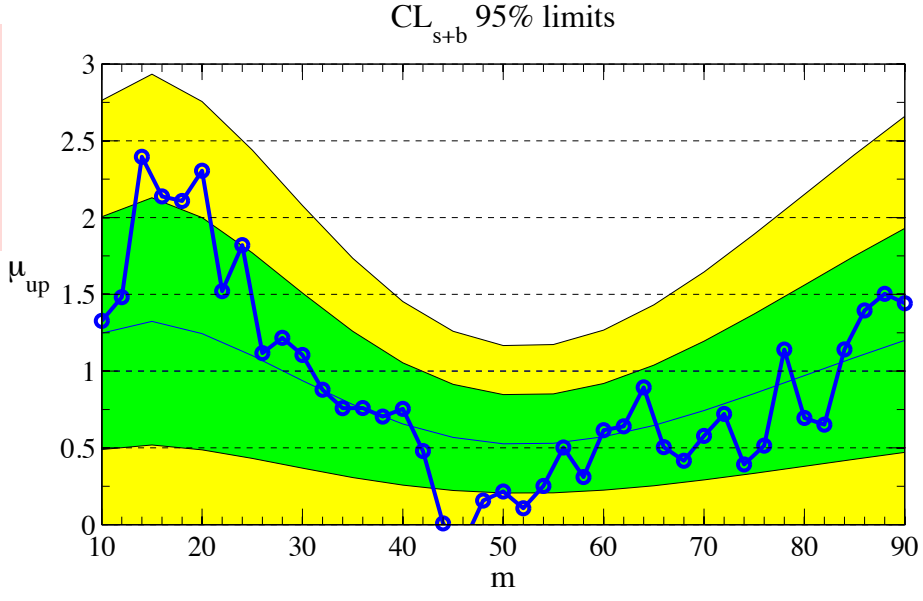
The standard discovery threshold of 5σ corresponds to a probability of $3 \cdot 10^{-7}$

This would require ~10 million CPU hours with our present model complexity



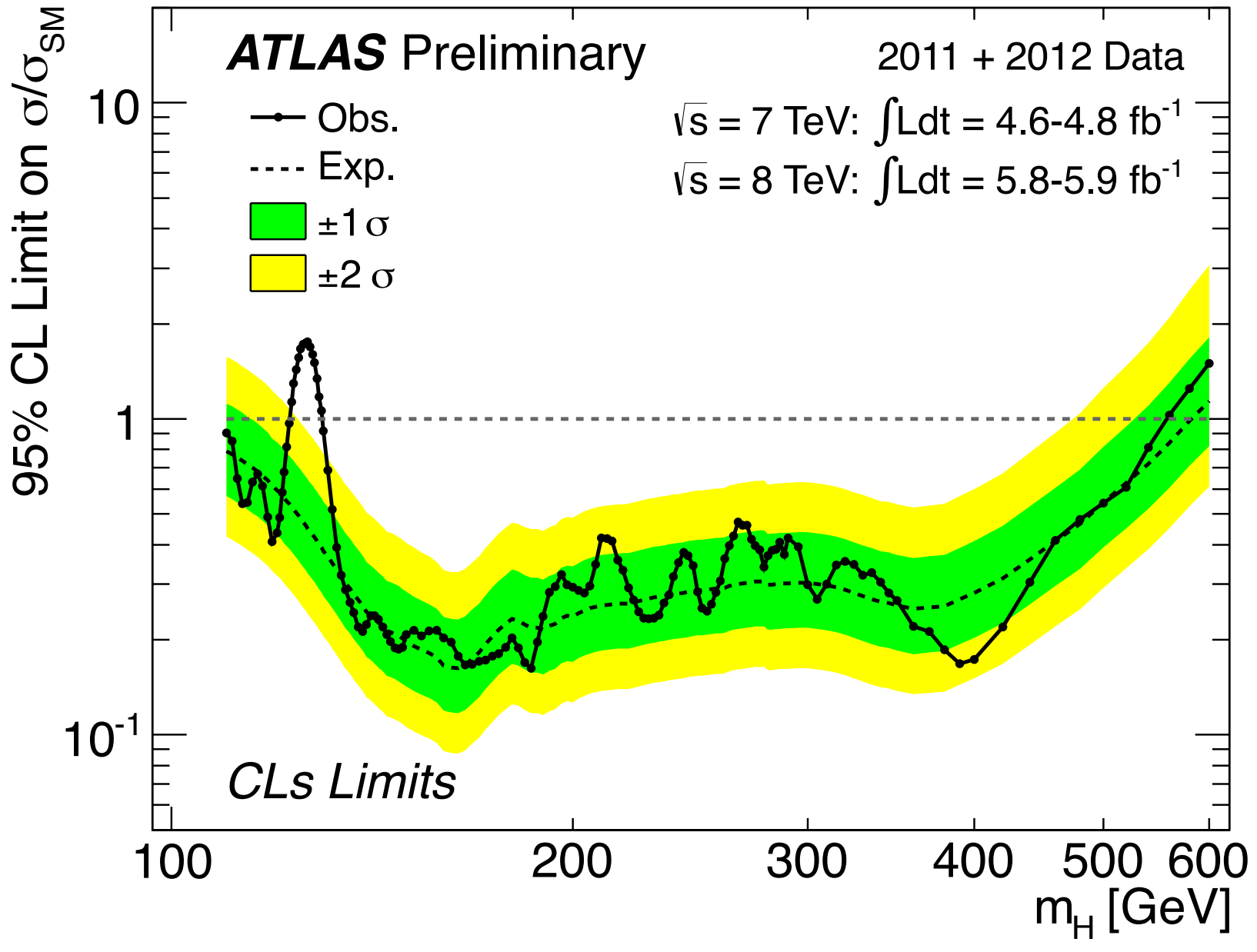


Recent formal developments allow us to predict these distributions analytically. Now a critical aspect of the Higgs search!

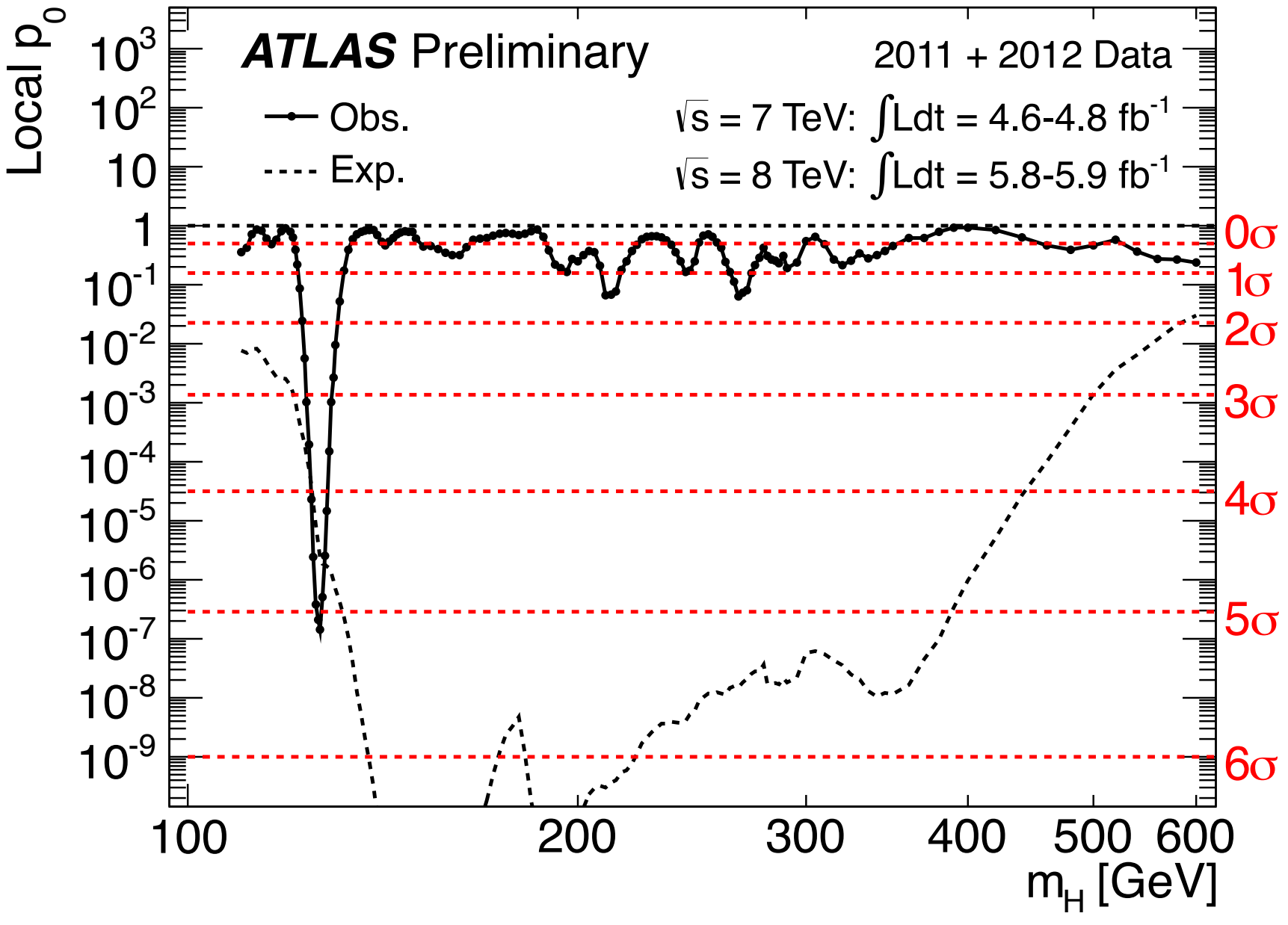


G. Cowan, KC, E. Gross, O. Vitells
Eur.Phys.J. C71 (2011) 1554
[arXiv:1007.1727]

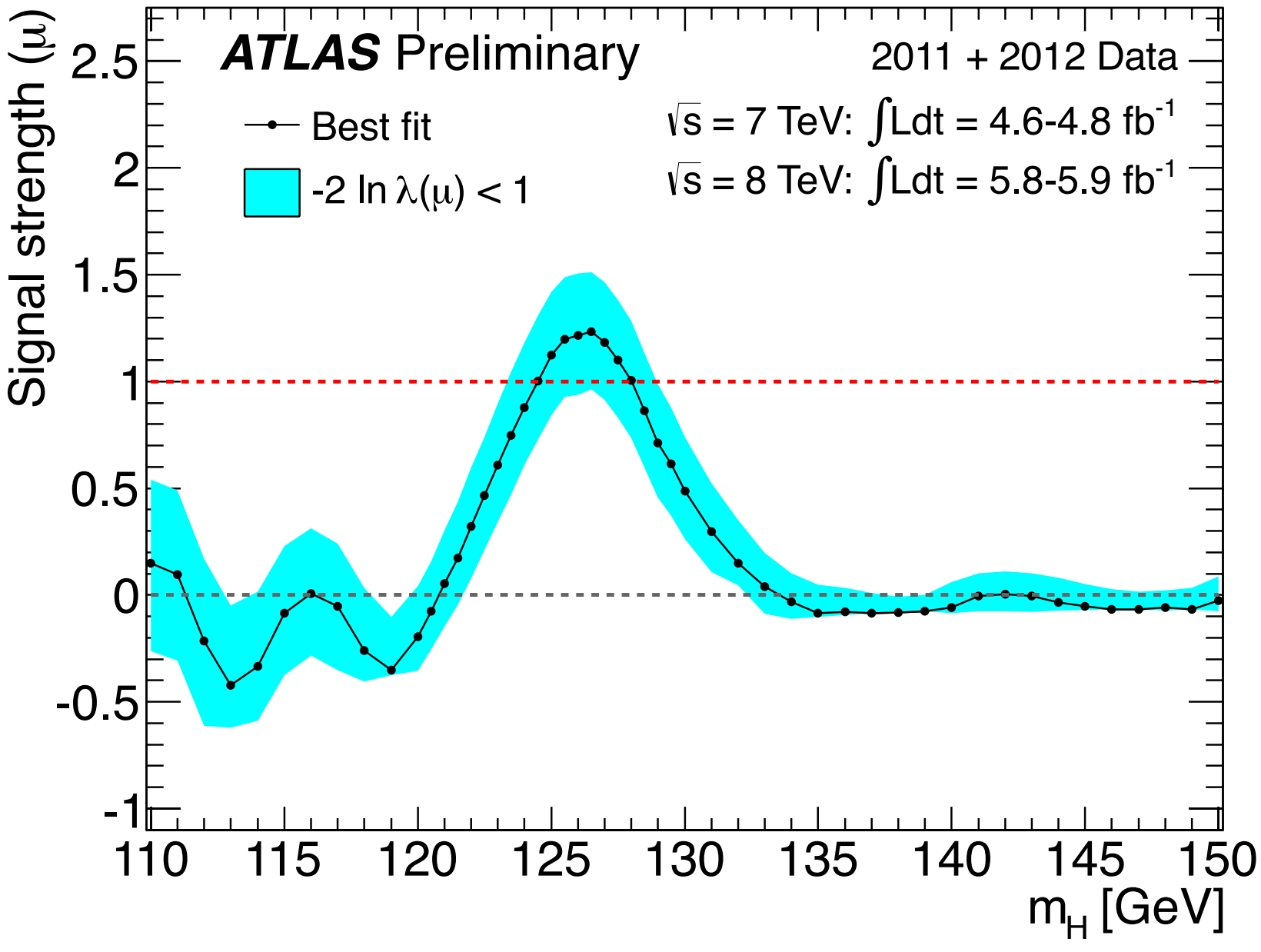
Where the Higgs is not



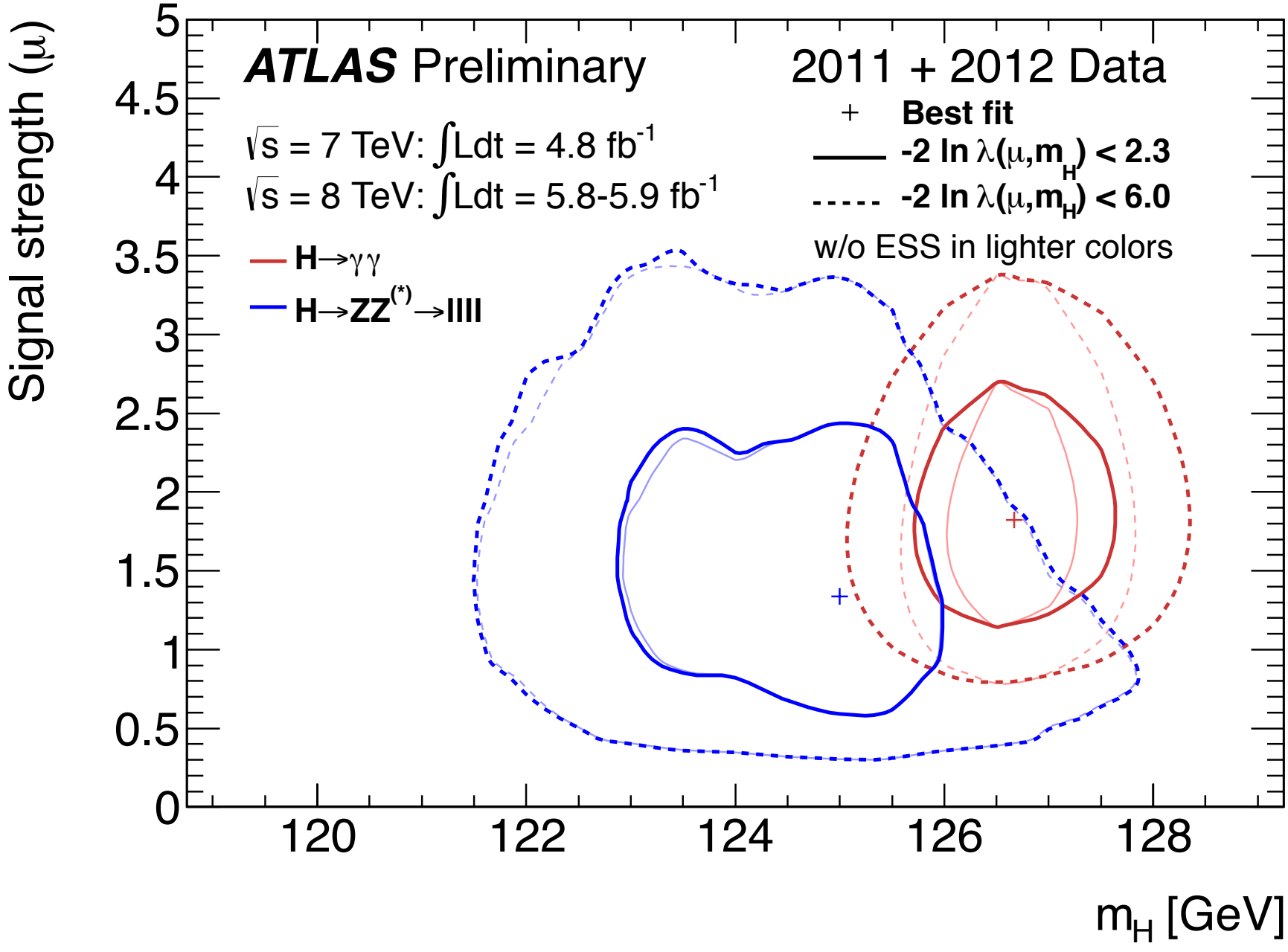
Consistency with the background



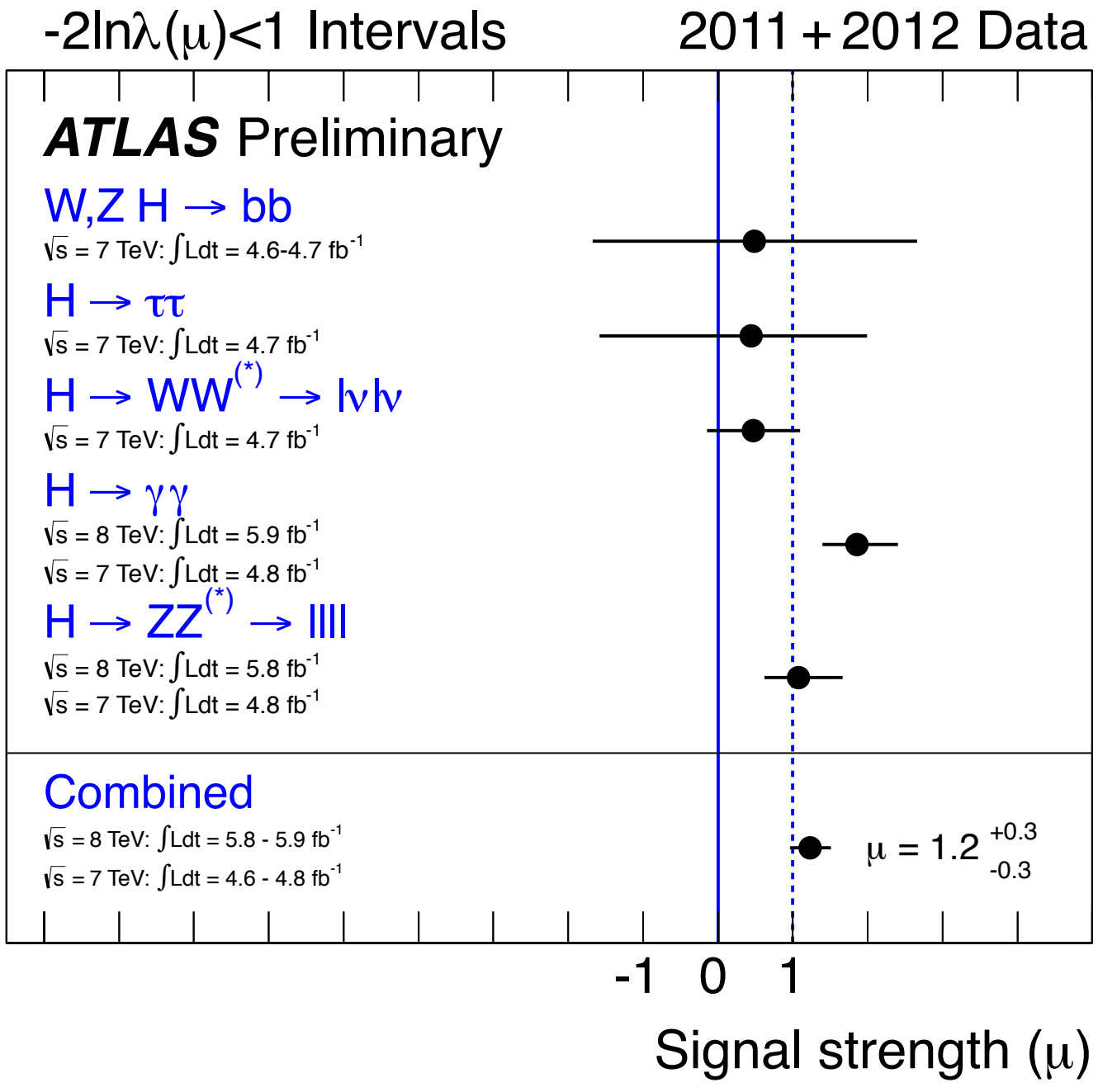
Consistency with the predicted rate



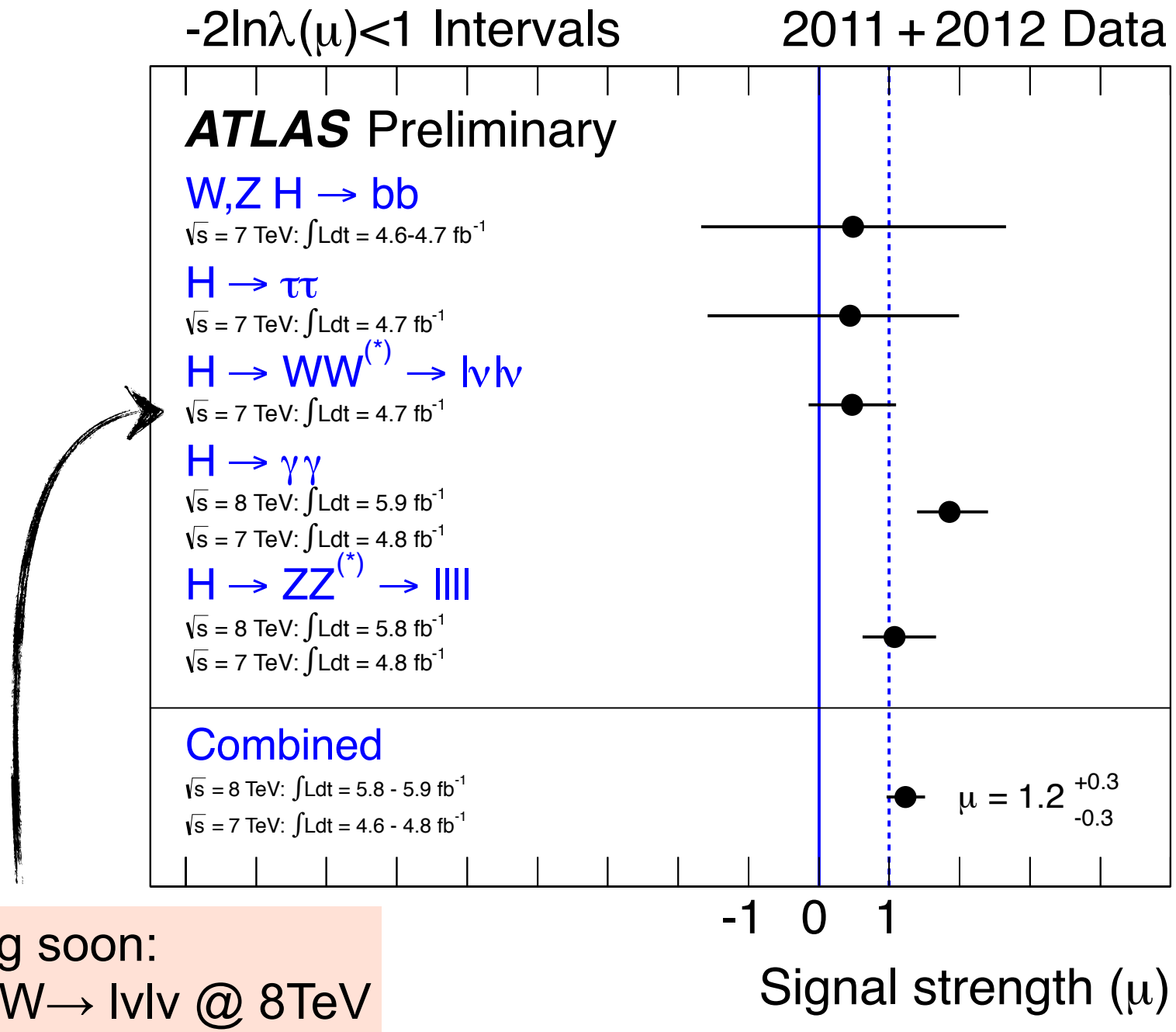
Consistency in mass



Consistency among channels

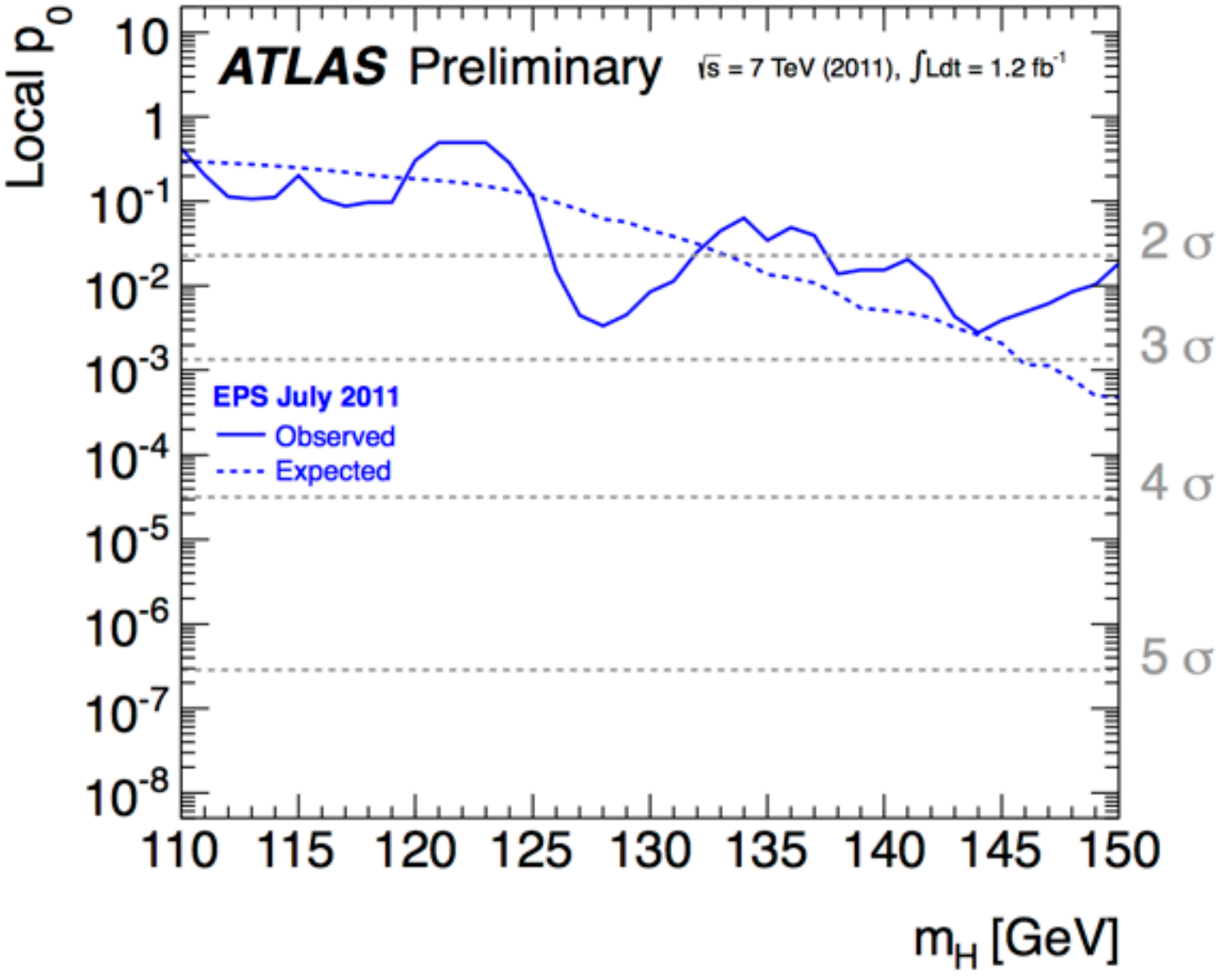


Consistency among channels

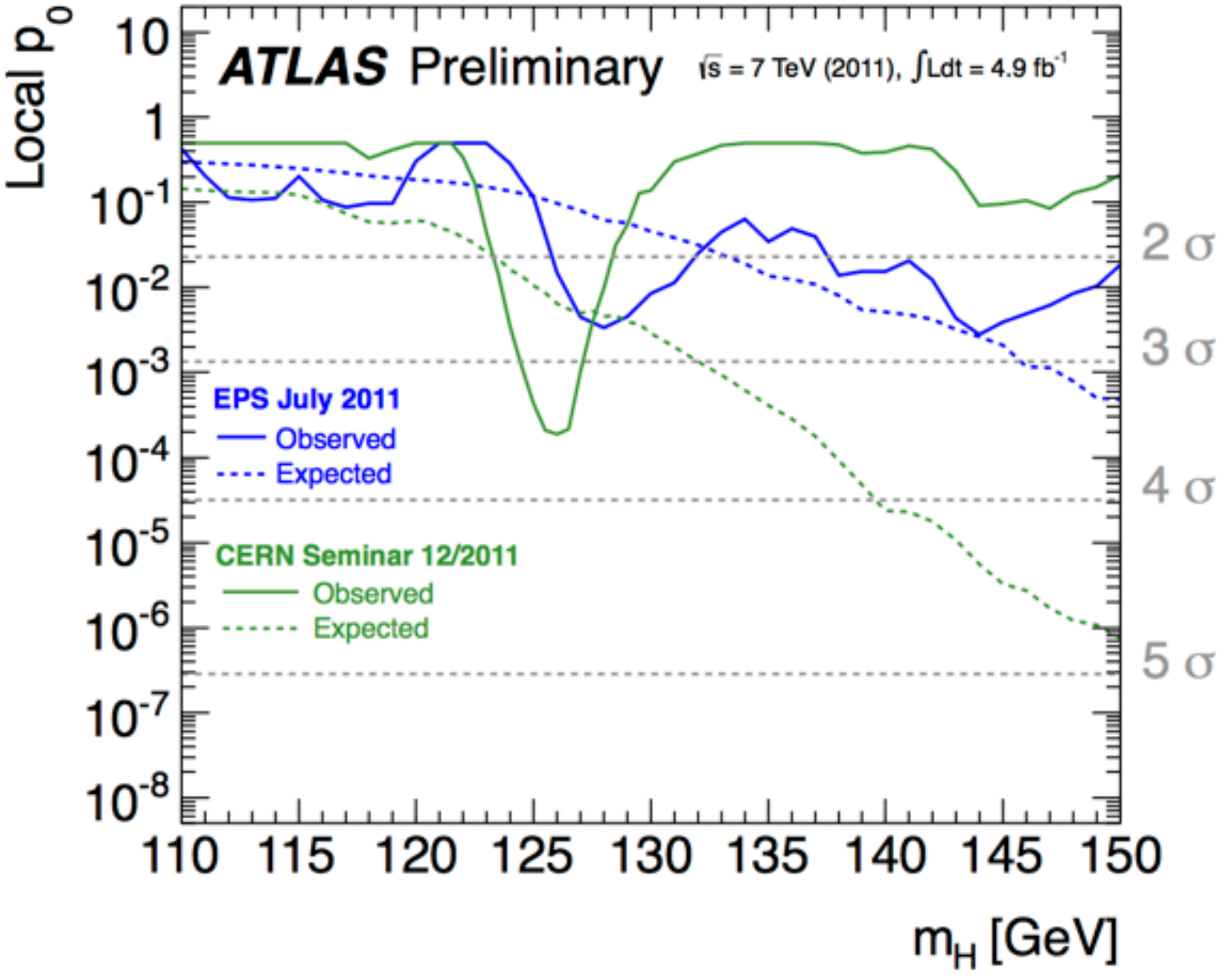


Coming soon:
H→ WW→ lνlν @ 8TeV

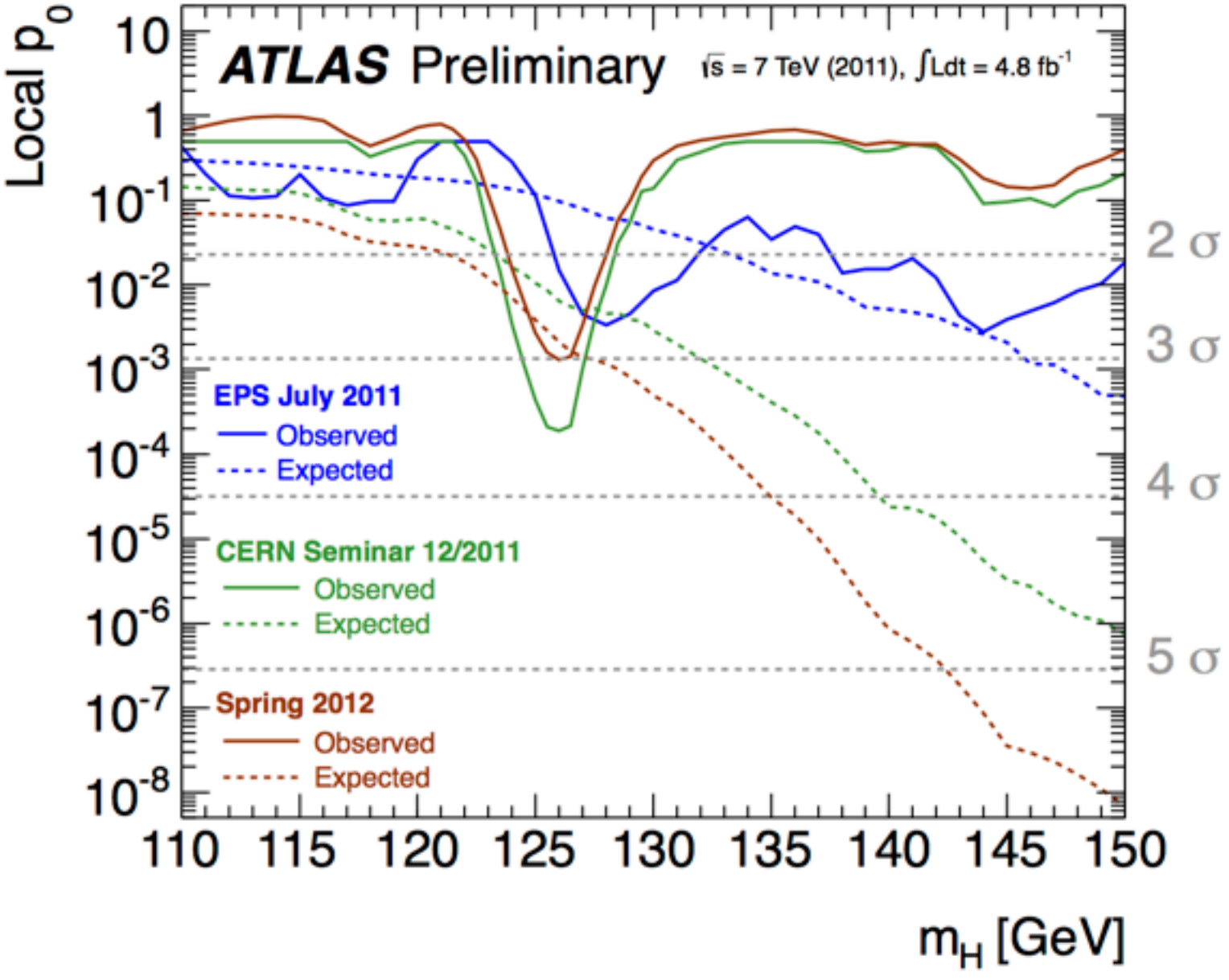
Evolution of the excess



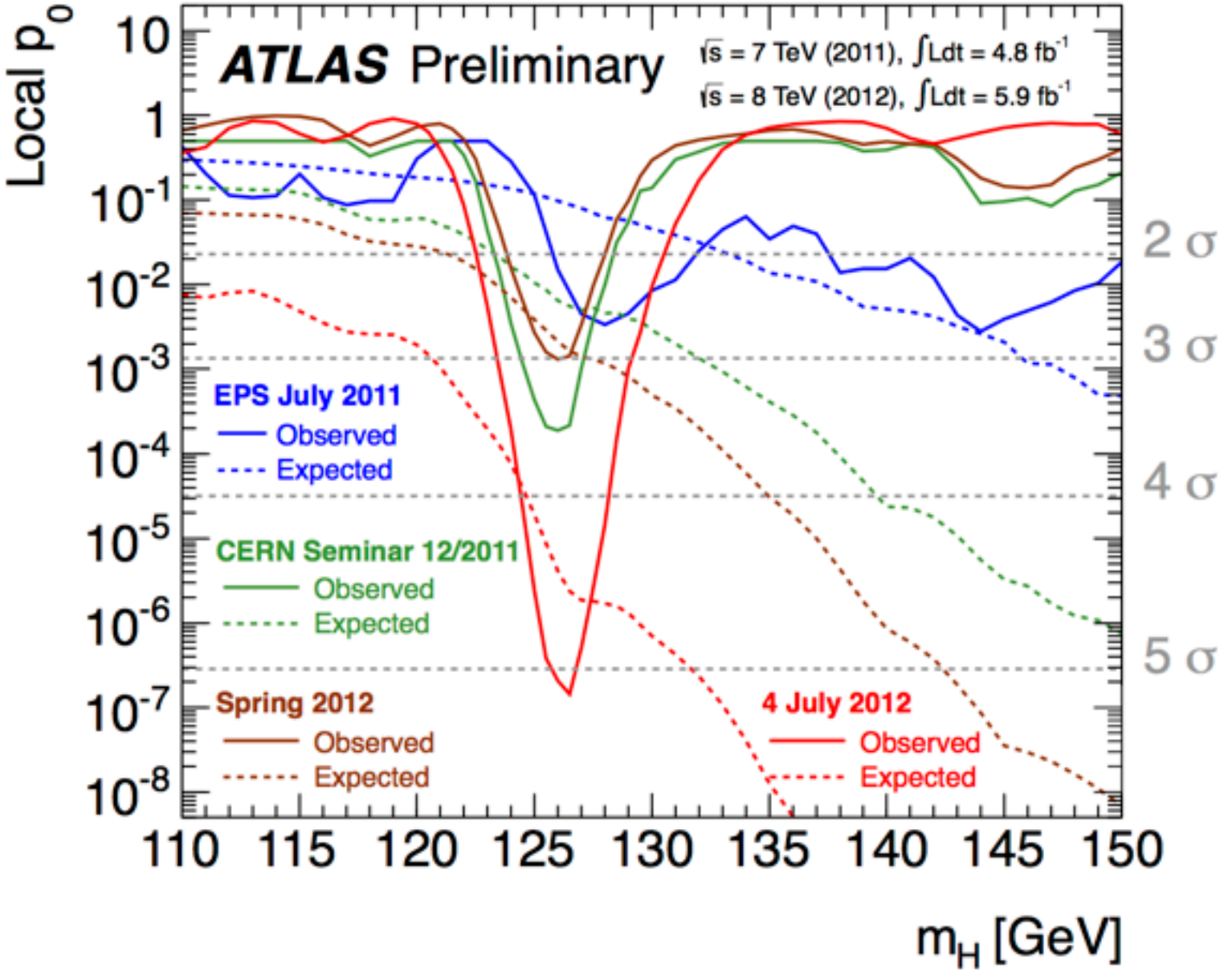
Evolution of the excess



Evolution of the excess

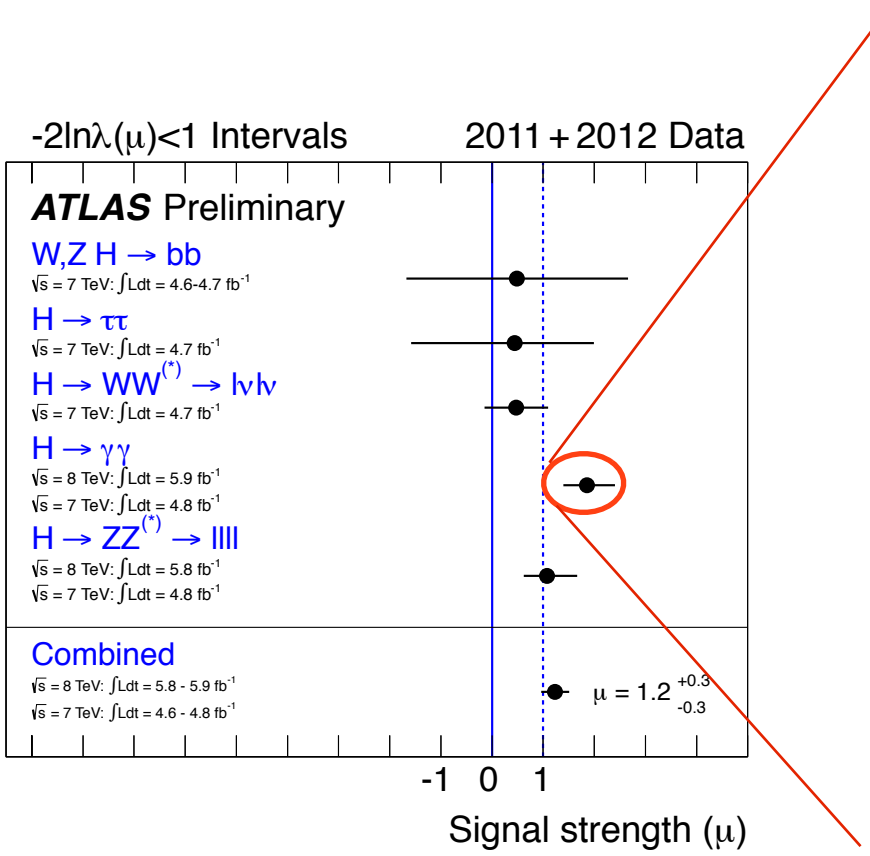


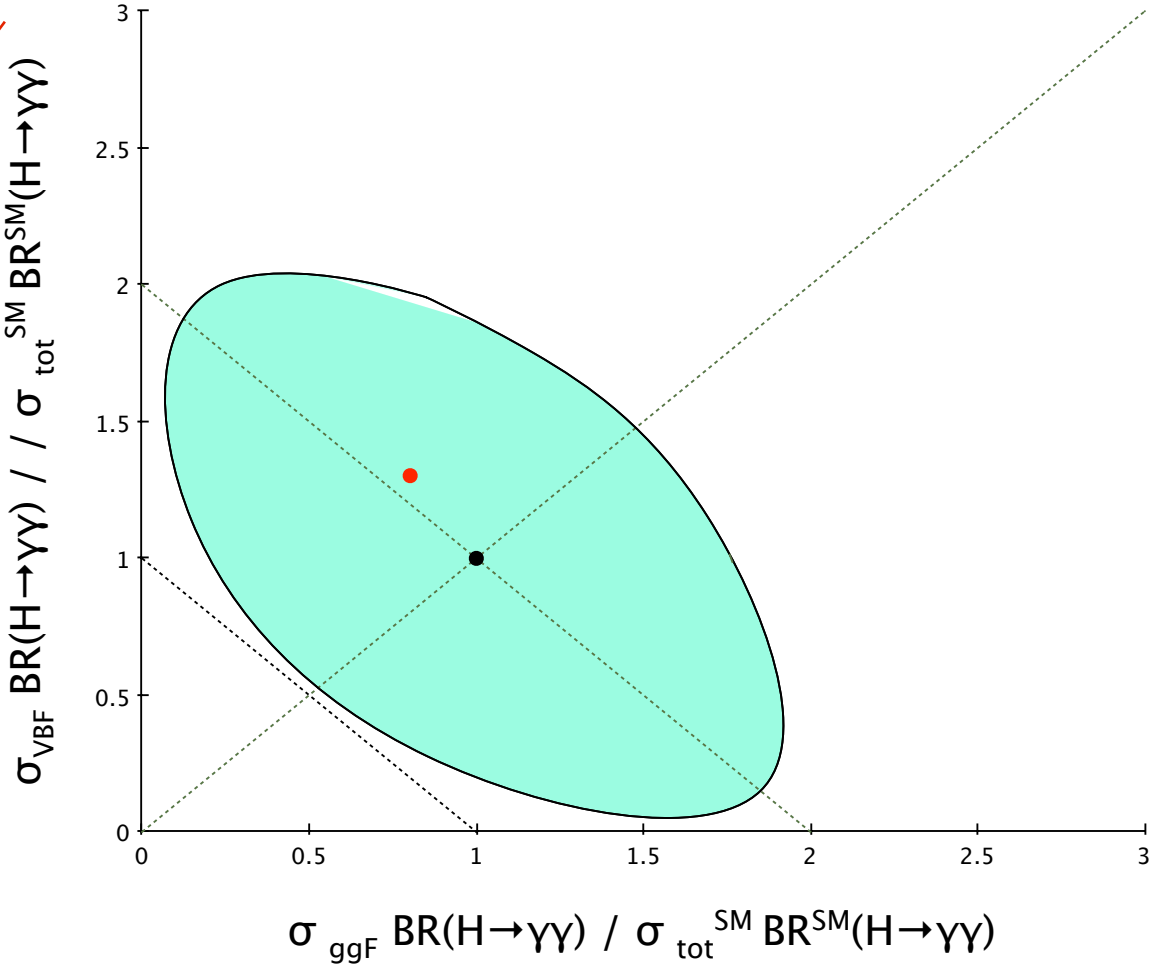
Evolution of the excess



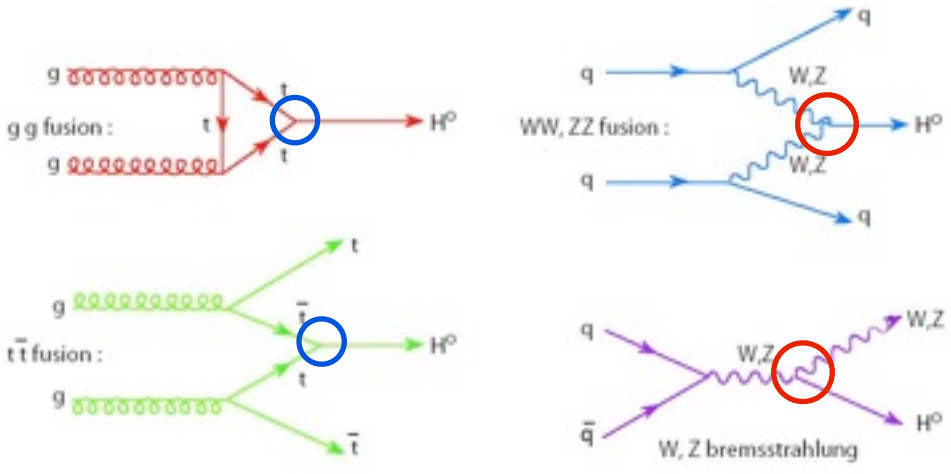
What's next for this "Higgs-like" particle

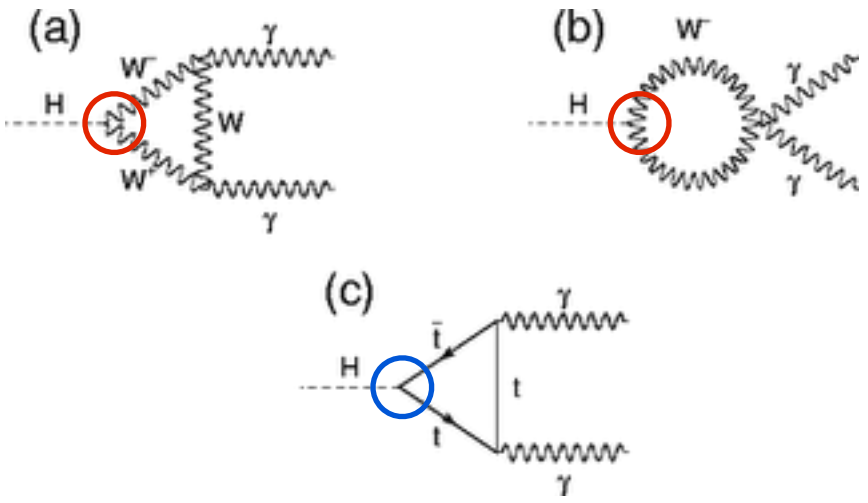
We need to study the different production modes



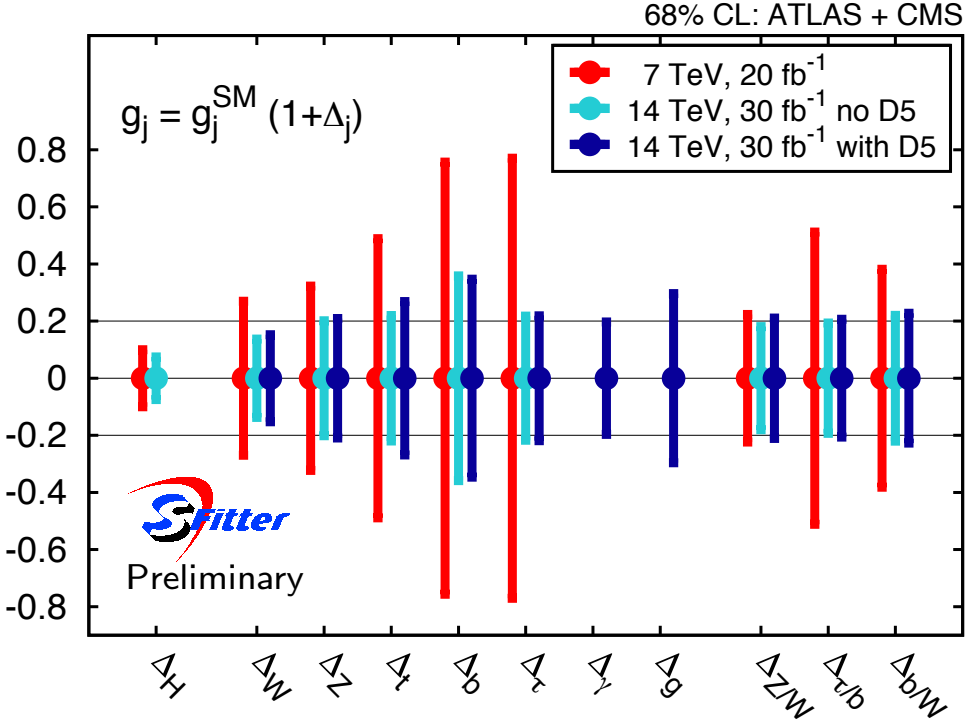


What's next for this "Higgs-like" particle

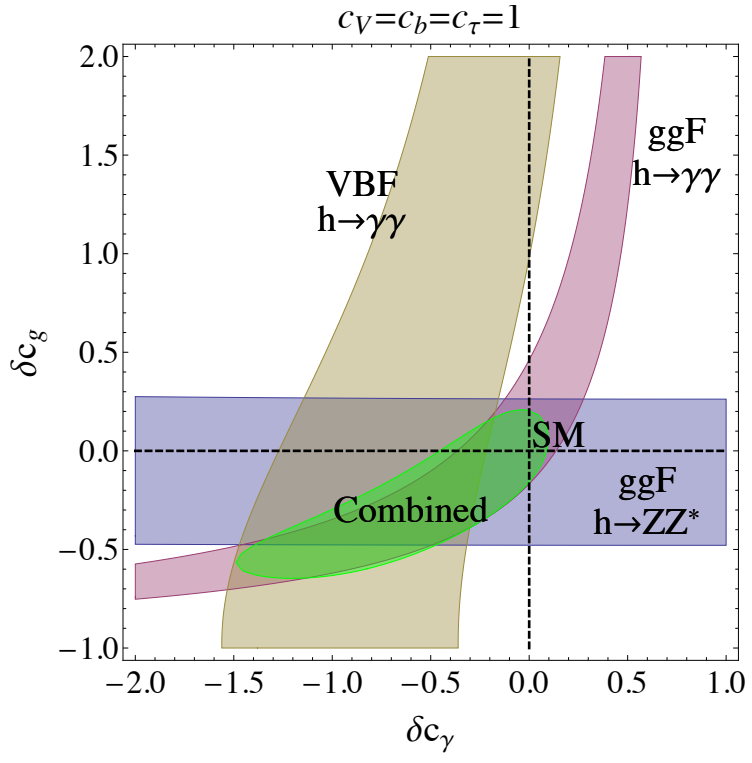




[Dührssen, Klute, Lafaye, Plehn, Rauch, Zerwas]



Carmi, et al. [arXiv:1202.3144

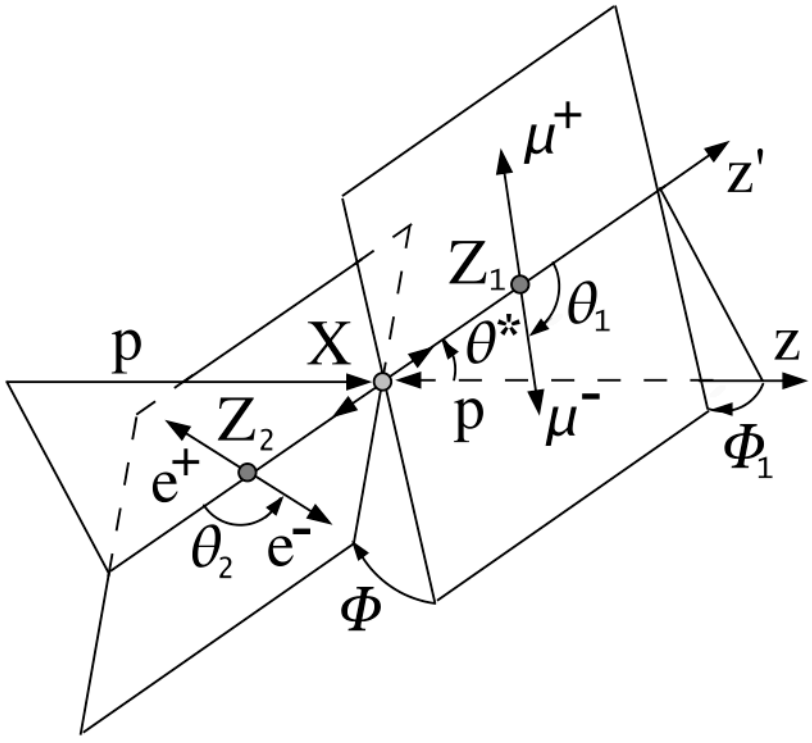


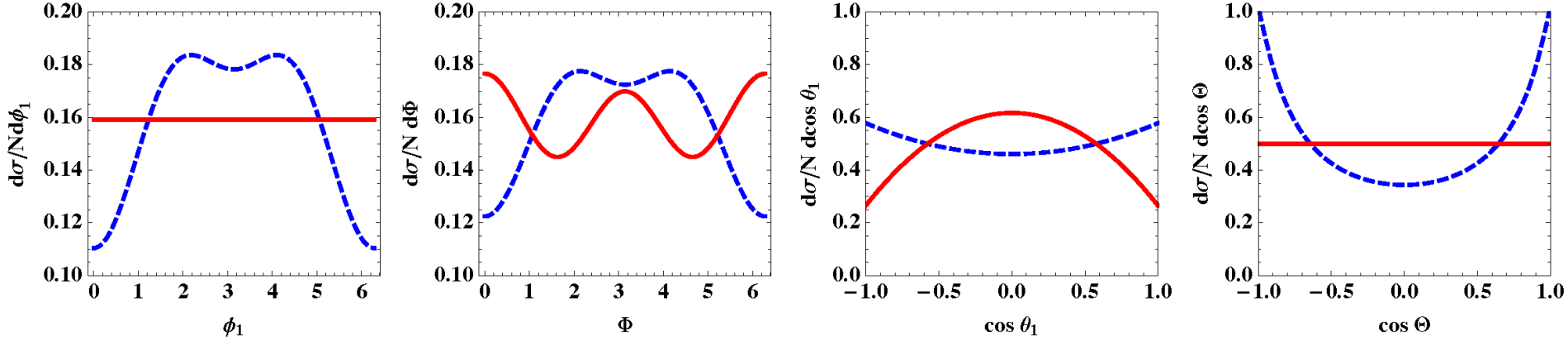
What's next for this "Higgs-like" particle

We need to measure discrete quantum numbers

The observation of H→γγ excludes the possibility that the particle is Spin-1 via the Landau-Yang theorem

Spin and CP properties to be measured in various channels





Gainer, et al. [arXiv:1108.2274]

Conclusions



We have observed a new particle with a mass near 126 GeV at the 5σ level!

...and this is just the beginning.



