Higgs Physics – Lecture 4

Higgs Physics at the LHC – suppressed and exotic channels, future directions

Ricardo Gonçalo – LIP

Course on Physics at the LHC – LIP, 11 May 2015

QUALIFICAR É CRESCER

QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL PORTUGAL 2007.2013

INVESTIGADOR FCT

UNIÃO EUROPEIA
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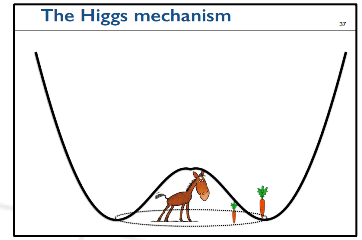
Outlook

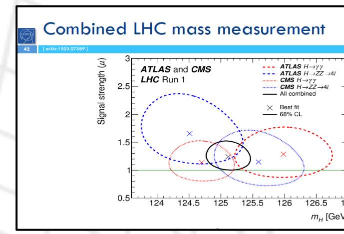
Program

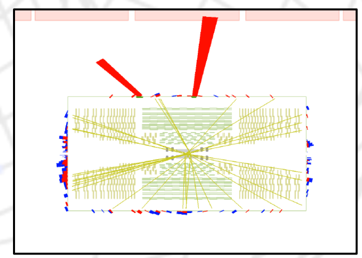
The standard model of particle physics	Prof. João Varela (LIP, IST)	23, 26 February
Statistical methods in data analysis	Dr. Pedrame Bargassa (LIP)	2 March
Detector physics and experimental methods	Dr. Michele Gallinaro (LIP), Dr. Pedro Silva (CERN)	9, 16 March
Top quark physics	Dr. Michele Gallinaro (LIP), Prof. António Onofre (LIP, UM))	23, 30 March, 13 April
Standard model Higgs and beyond	Dr. Pedro Silva (CERN), Dr. André David (CERN), Dr. Patricia Muino (LIP), Dr. Ricardo Gonçalo (LIP)	20, 27 April 4, 11 May
Supersymmetry	Dr. Pedrame Bargassa (LIP)	18, 25 May
B physics and rare decays	Dr. Nuno Leonardo (LIP)	1 June
Matter at high density and temperature	Prof. João Seixas (LIP, IST), Dr. Pietro Faccioli (LIP)	8, 15 June

Higgs lectures so far…

- Lecture 1
  - Higgs & EWSB introduction
- Lecture 2
  - Higgs boson properties
- Lecture 3
  - Detailed experimental searches
- This lecture
  - Missing channels and the future…



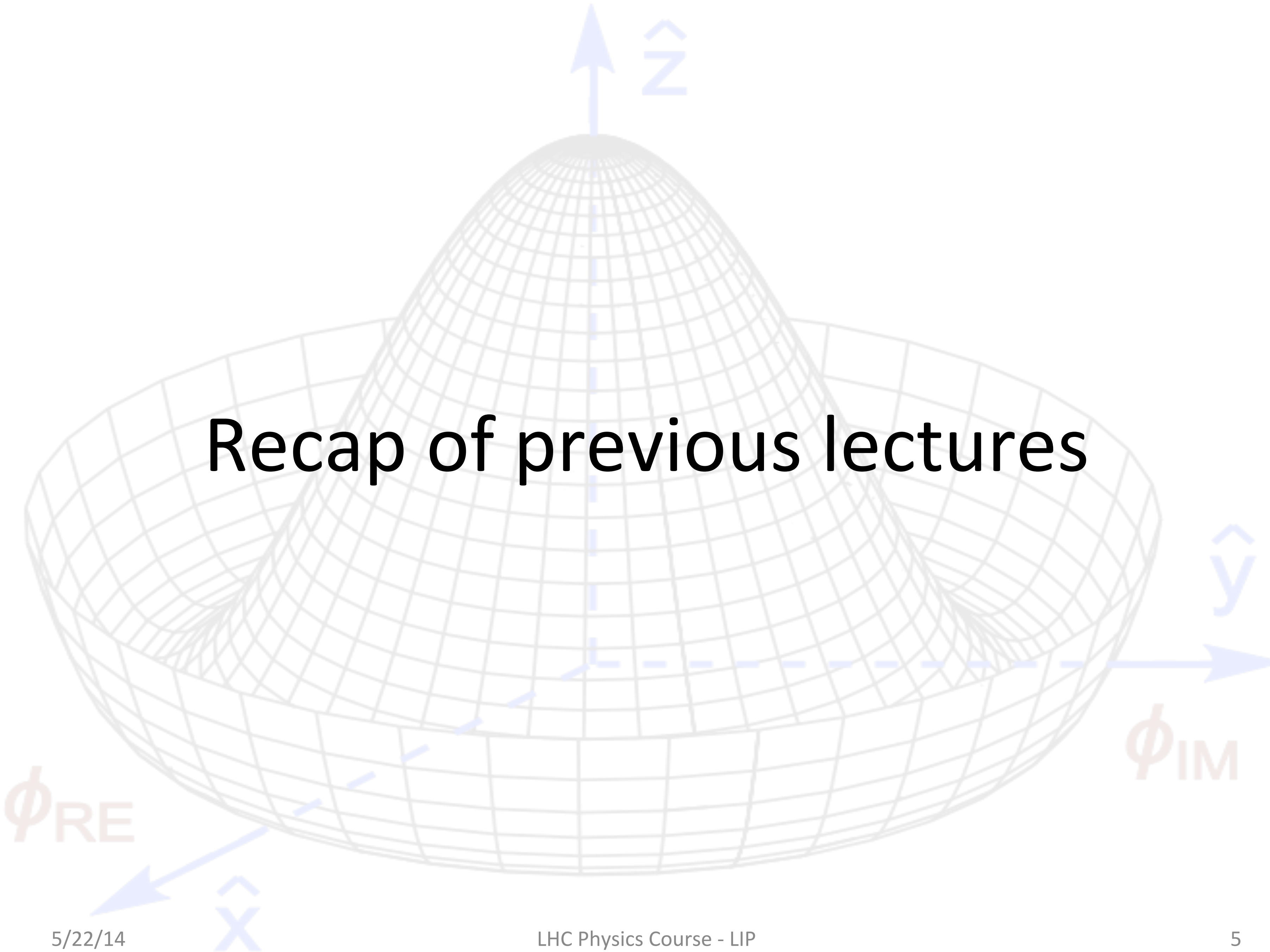


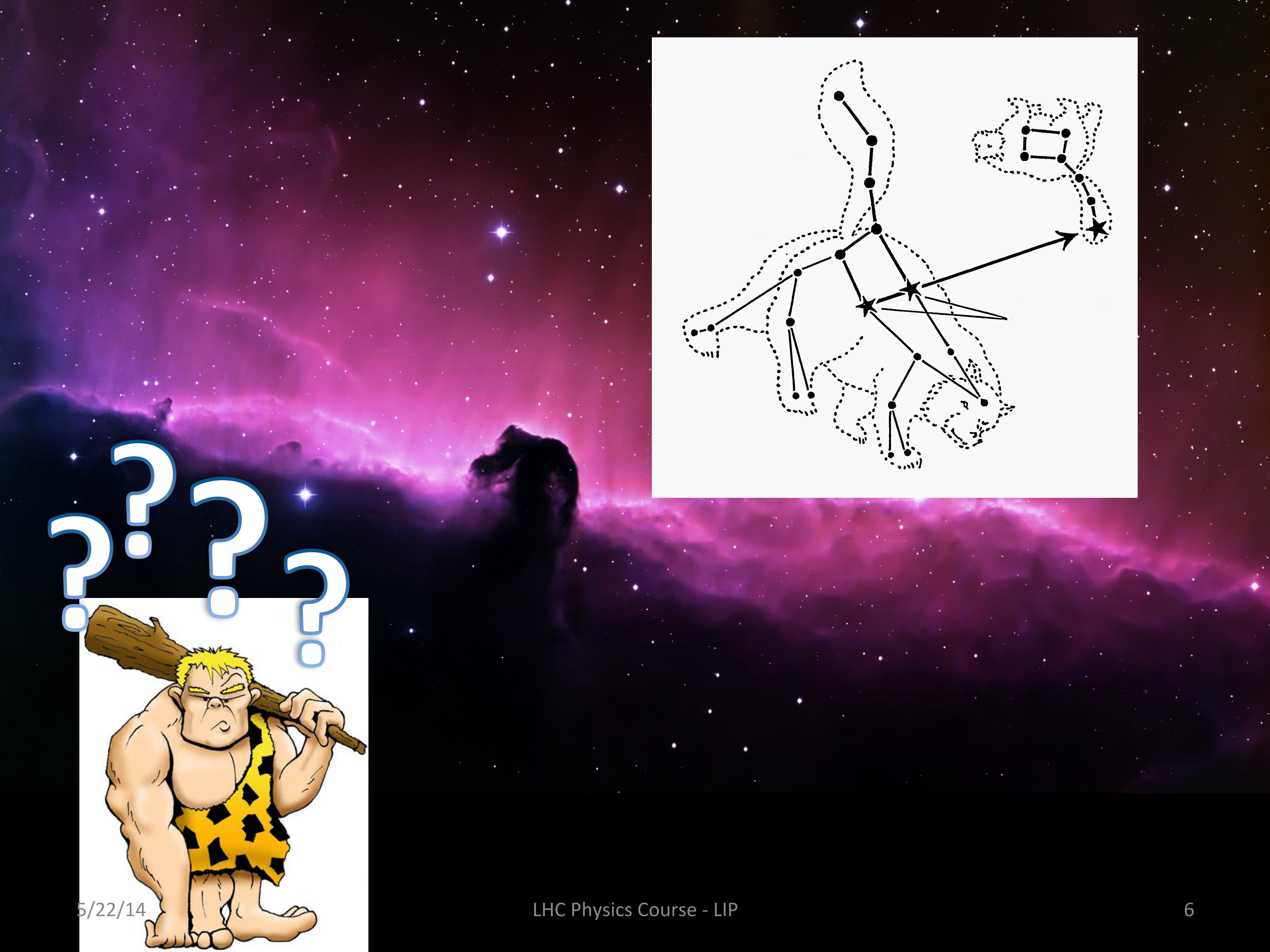


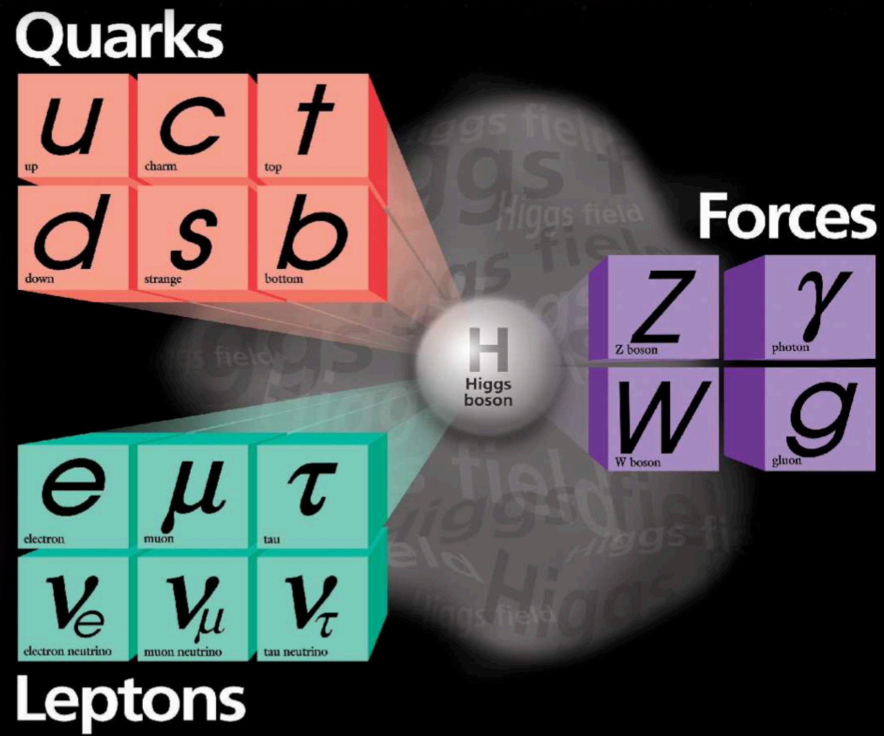
This lecture

- Recapitulation
  - What we know and what we don't
  - Higgs mechanism
  - Conclusions so far
- Beyond the Standard Model Higgs
  - 2HDM and Higgs CP
  - Constraints from Higgs couplings (see G.Hamity)
  - Charged Higgs (see A.Mehta)
  - A->Zh
  - Di-Higgs (hh->2b2gamma; hh->4b)
  - Future (see Rei's slides)

Recap of previous lectures






Quarks
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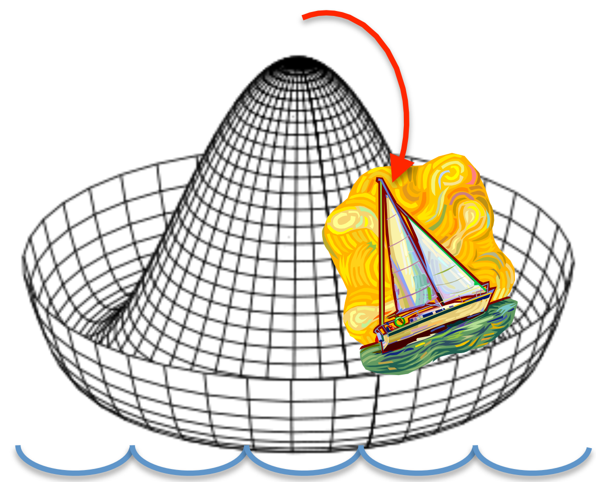
Leptons

The Standard Model Higgs Mechanism

- In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass



- The symmetry between the electromagnetic and the week interactions is broken:
  - Photon does not have mass
  - W, Z have a large mass

- Higgs mechanism:
  - mass of W and Z results from the Higgs mechanism

$$\phi = \begin{pmatrix} \frac{\phi_1 + i\phi_2}{\sqrt{2}} \\ \frac{\phi_3 + i\phi_4}{\sqrt{2}} \end{pmatrix}$$

see J.Varela's lecture

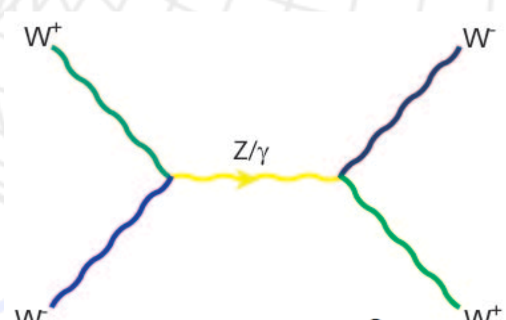
Added bonus

Non-zero average value of the Higgs field can also give masses to the quarks, electrons and muons – to all point-like particles.

Old theoretical problem affecting the quantum theory of the weak force :

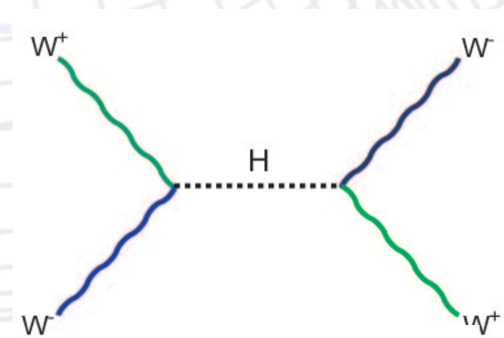
> the probability of two W's interacting becomes larger than 1 at high energies (> 1 TeV).

Solved by the Higgs field!



$$\lim_{E\to\infty} \mathcal{A} \propto E^2$$

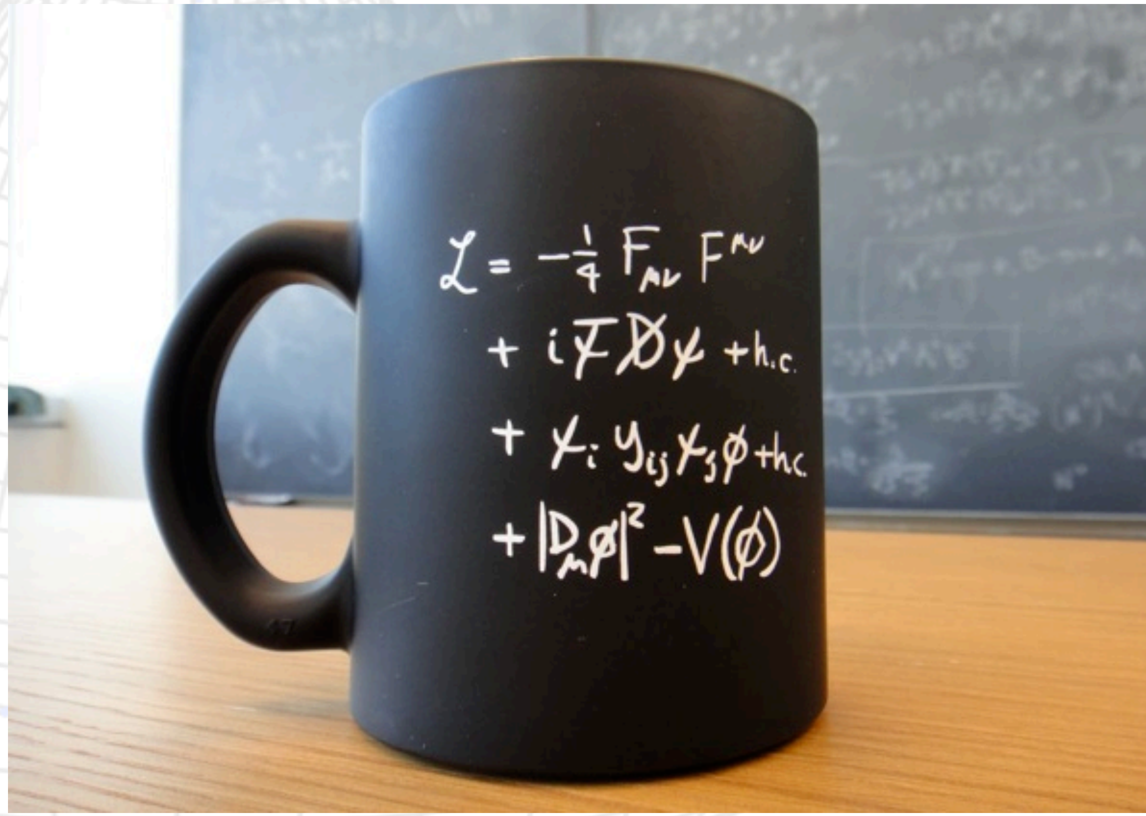
+



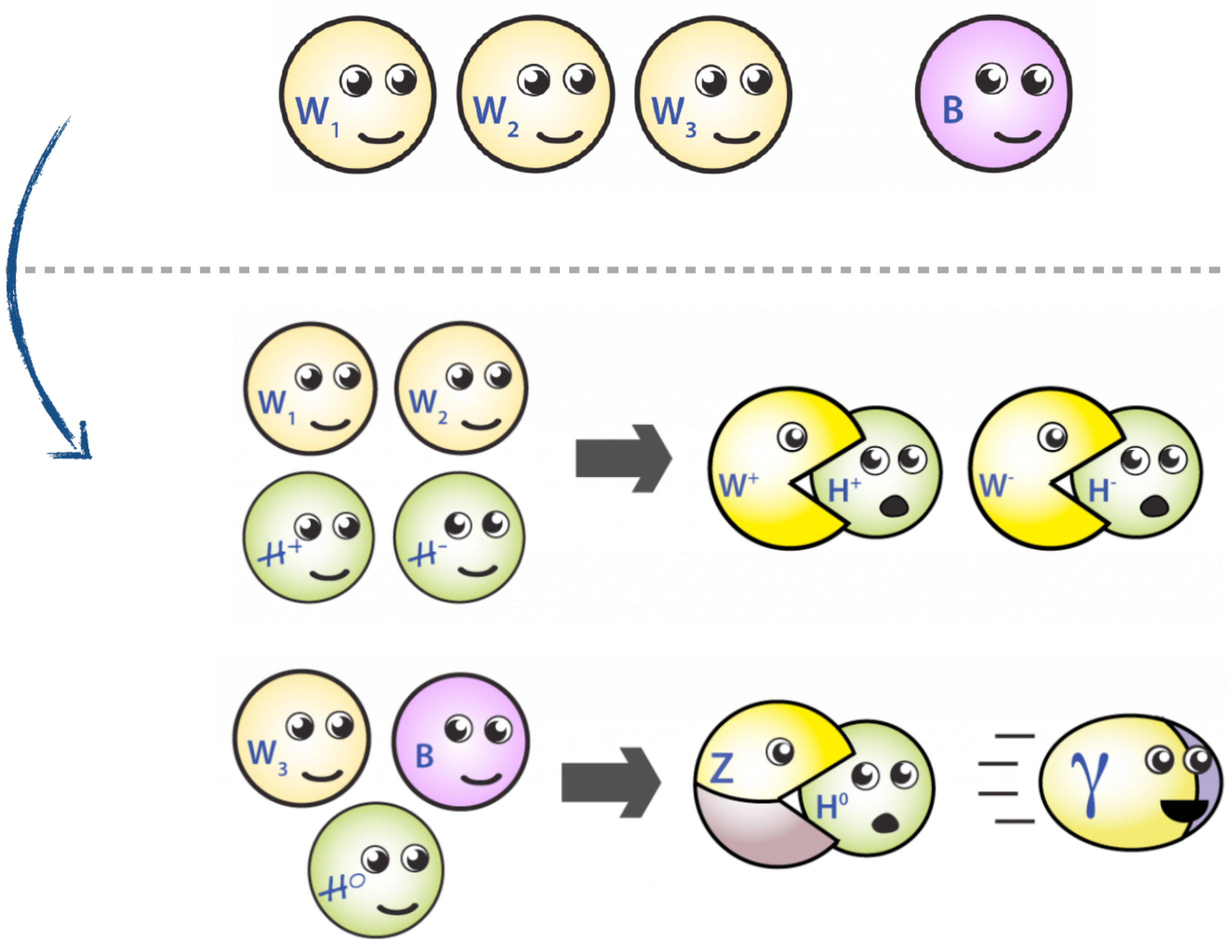
$$\lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

Lagrangians and coffee mugs

- Throughout history, we have been looking mostly at the second line
- Interactions between fermion matter particles transmitted by force carriers
- I.e. all of chemistry and most of physics
- Disclamer: gravity not on the mug



Electroweak symmetry breaking

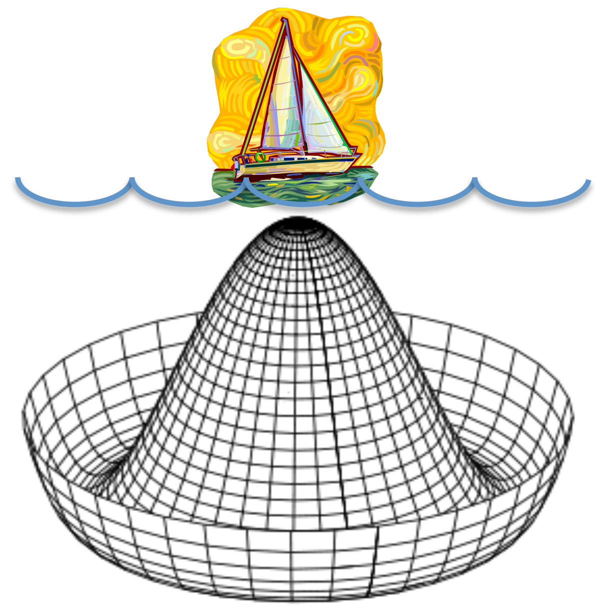


see P.Silva's lecture

Wikipedia wisdom

Electroweak Lagrangian before spontaneous symmetry breaking

$$\mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_h + \mathcal{L}_y.$$



Electroweak gauge bosons: B^0 W^0 $W^{\pm}$

$$\mathcal{L}_g = -\frac{1}{4} W^{a\mu\nu} W^a_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}$$

Fermion kinetic terms

$$\mathcal{L}_f = \overline{Q}_i i \not{D} Q_i + \overline{u}_i i \not{D} u_i + \overline{d}_i i \not{D} d_i + \overline{L}_i i \not{D} L_i + \overline{e}_i i \not{D} e_i$$

$$\mathcal{L}_h = |D_\mu h|^2 - \lambda \left(|h|^2 - \frac{v^2}{2} \right)^2$$

Higgs term (note: vacuum expectation value zero before symmetry breaking)

$$\mathcal{L}_y = -y_{u\,ij} \epsilon^{ab} \, h_b^\dagger \, \overline{Q}_{ia} u_j^c - y_{d\,ij} \, h \, \overline{Q}_i d_j^c - y_{e\,ij} \, h \, \overline{L}_i e_j^c + h.c.$$

Yukawa interaction term between Higgs field and fermions

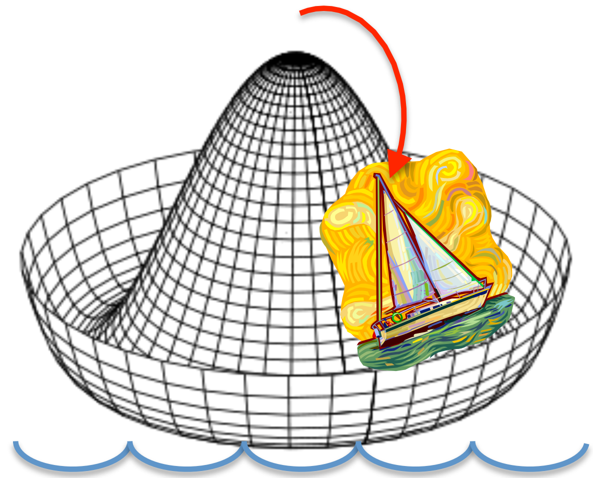
Wikipedia wisdom

After electroweak symmetry breaking

$$\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_H + \mathcal{L}_{HV} + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_Y$$

Spontaneous symmetry breaking:
New bosons γ and Z^0 from W^0 and B^0

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

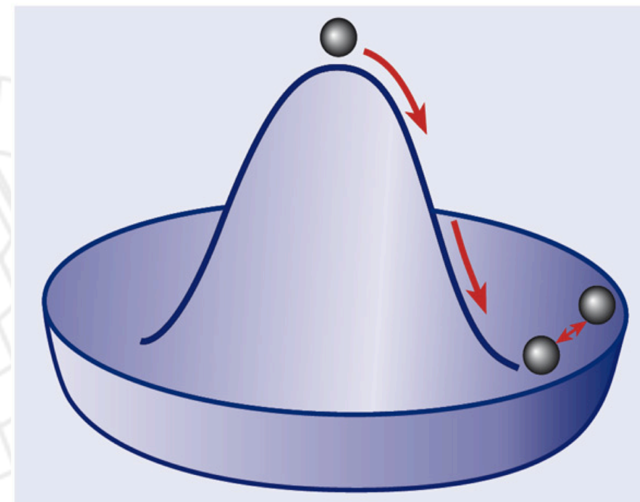


Kinetic terms: **notice boson masses** for Z^0, $W^\pm$, H

$$\mathcal{L}_K = \sum_f \overline{f}(i\partial\!\!\!/ - m_f)f - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} + m_W^2 W^+_\mu W^{-\mu}$$
$$-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \frac{1}{2}m_H^2 H^2$$

Wikipedia wisdom

Higgs boson mass: transverse oscillation modes



Higgs boson 3- and 4-point self-interaction

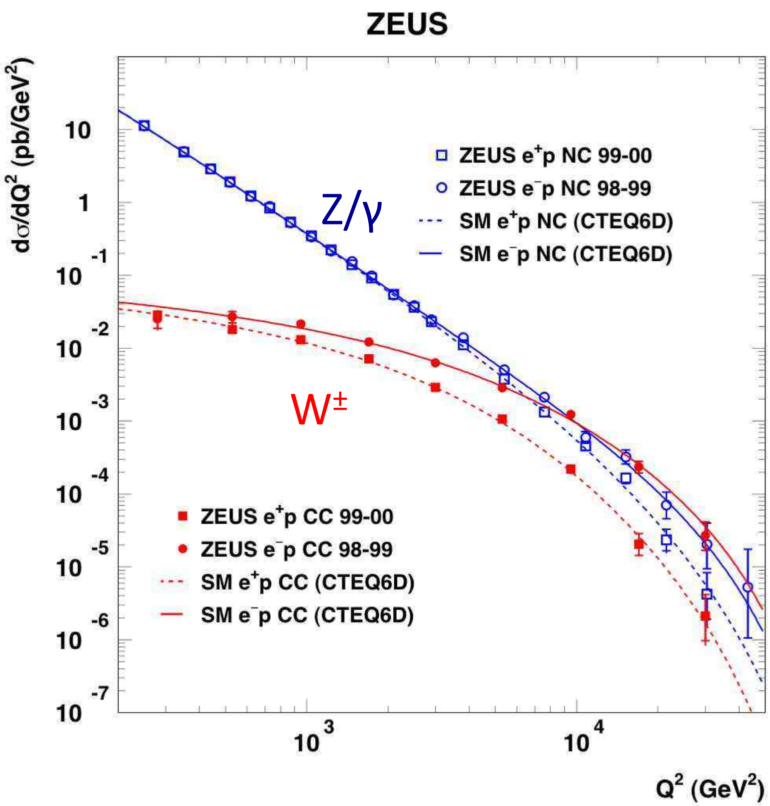
$$\mathcal{L}_H = -\frac{g m_H^2}{4 m_W} H^3 - \frac{g^2 m_H^2}{32 m_W^2} H^4$$

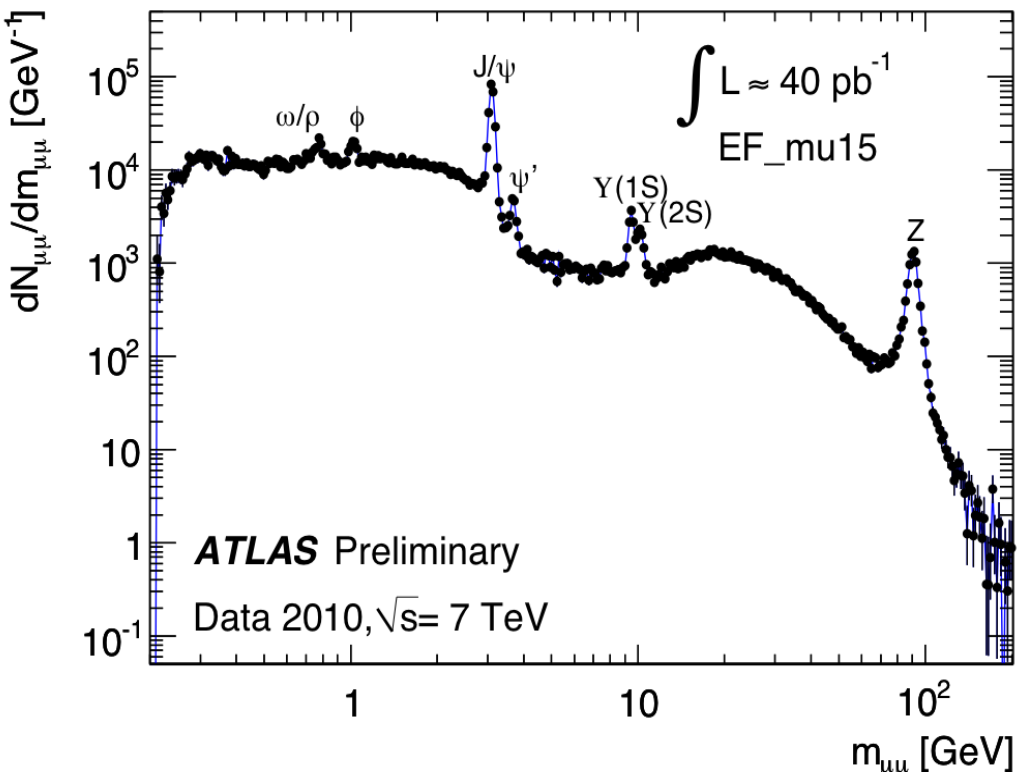
Yukawa interactions between Higgs and fermions:
note fermion masses!

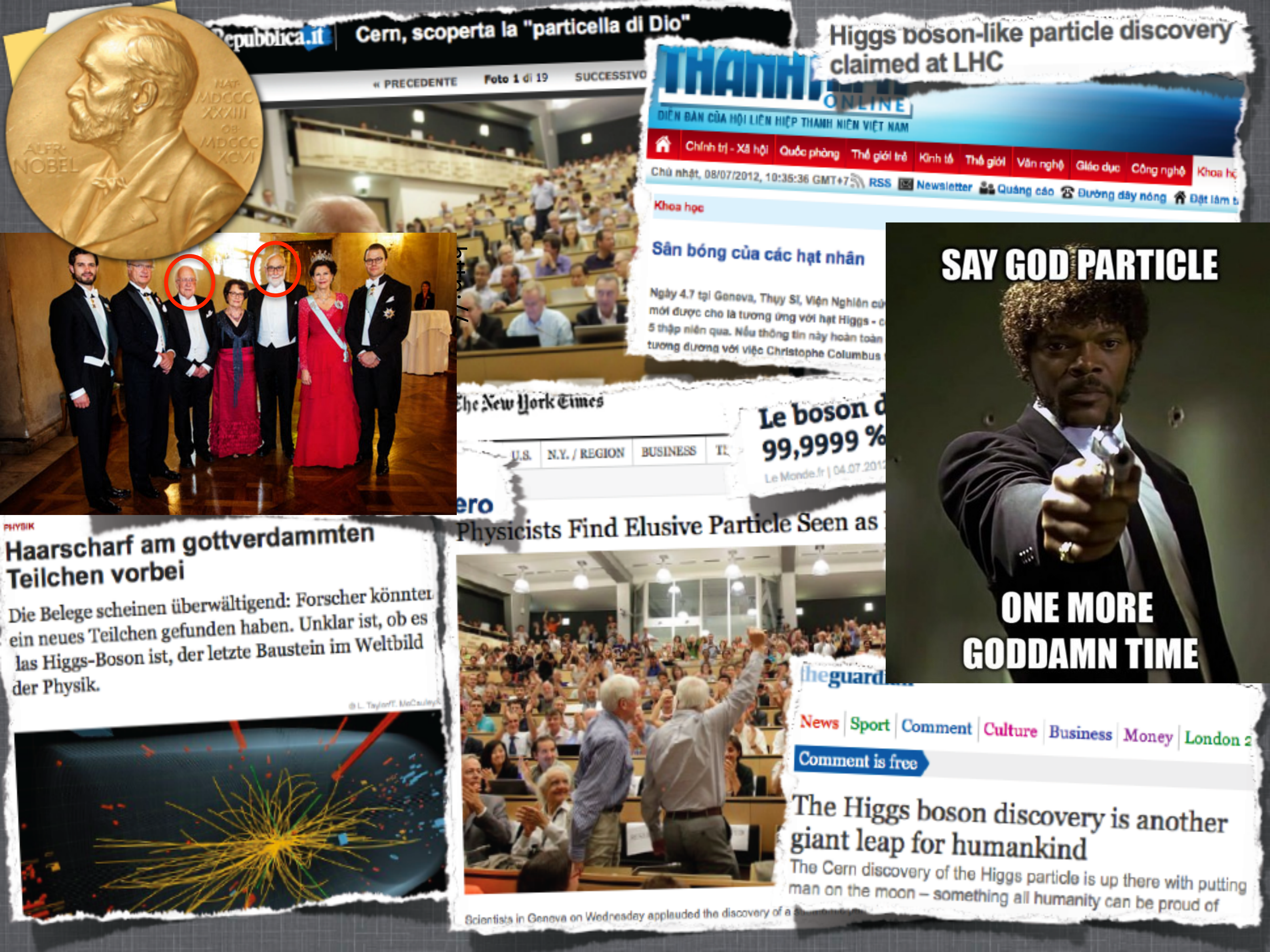
$$\mathcal{L}_Y = -\sum_f \frac{g m_f}{2 m_W} \bar{f} f H$$

Why does it matter?

- Because it's real!
  - Data shows Higgs mechanism (or something like it) needed in the theory
- Because it may lead us to new discoveries and a new understanding of Nature!
  - "There is nothing so practical as a good theory" (Kurt Lewin)







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Cern, scoperta la "particella di Dio"
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Higgs boson-like particle discovery claimed at LHC
SAY GOD PARTICLE
ONE MORE GODDAMN TIME
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Le boson
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Physicists Find Elusive Particle Seen as
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Haarscharf am gottverdammten Teilchen vorbei
Die Belege scheinen überwältigend: Forscher könnten ein neues Teilchen gefunden haben. Unklar ist, ob es das Higgs-Boson ist, der letzte Baustein im Weltbild der Physik.
theguardian
News
Sport
Comment
Culture
Business
Money
Comment is free
The Higgs boson discovery is another giant leap for humankind
The Cern discovery of the Higgs particle is up there with putting man on the moon – something all humanity can be proud of
Scientists in Geneva on Wednesday applauded the discovery of a

Going beyond the standard model

But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

Many possible theories

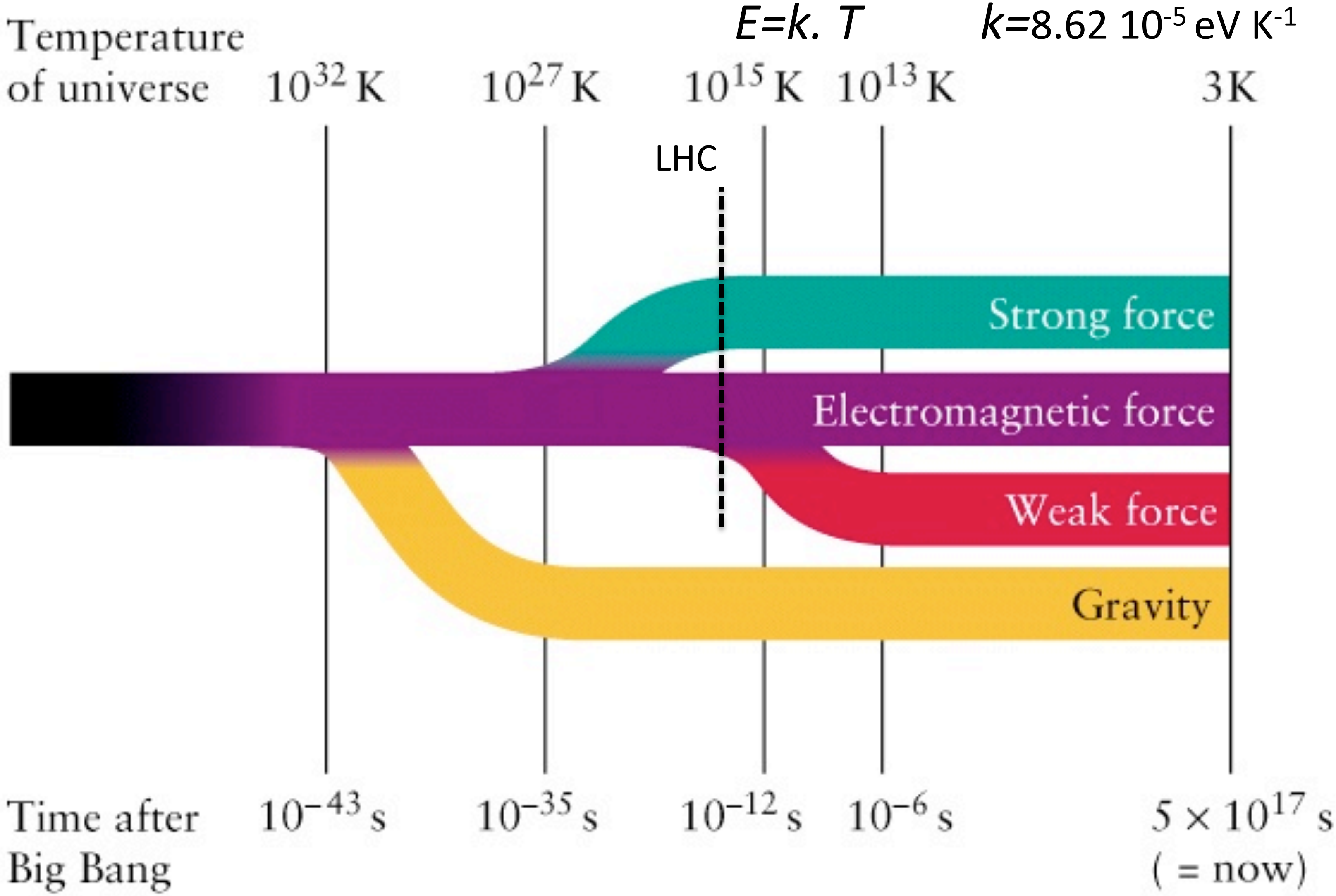
There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC

Forces and expansion of the Universe

E=k. T *k*=8.62 10^{-5} eV K^{-1}

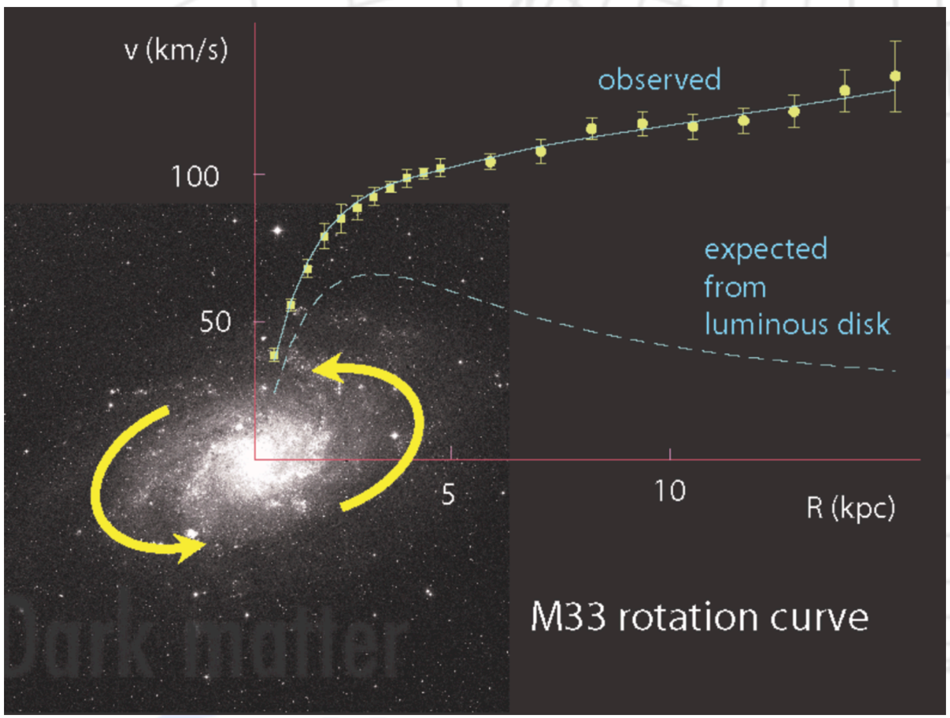


The dark side of the Universe

Long standing problem:

We know that ordinary matter is only ~4% of the matter-energy in the Universe.

What is the remaining 96%?



The LHC may help to solve this problem, discovering **dark matter**

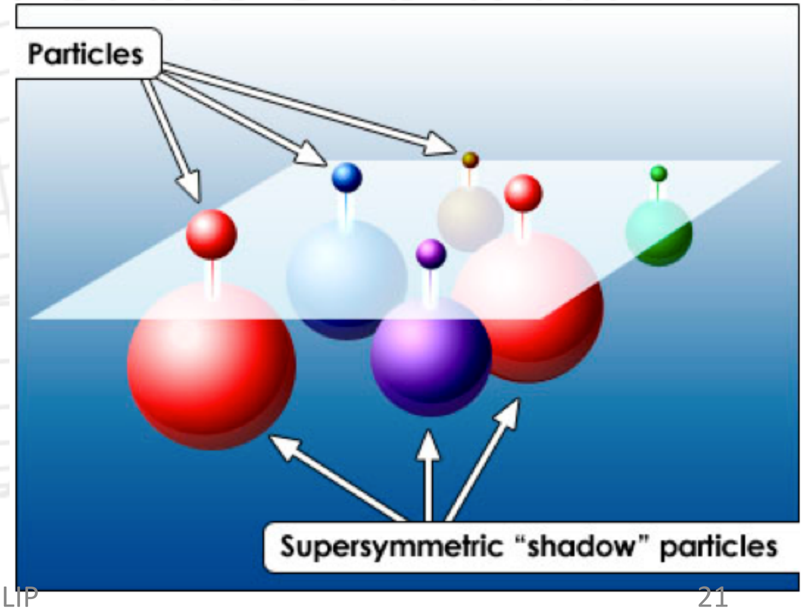
Supersymmetry

Some physicists attempting to unify gravity with the other fundamental forces have proposed a new fundamental symmetry:

- Every fermion should have a massive "shadow" boson
- and boson should have a massive "shadow" fermion.

This relationship between fermions and bosons is called supersymmetry (SUSY)

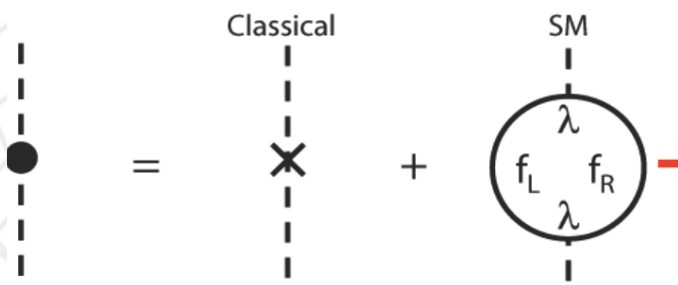
No supersymmetric particle has yet been found, but we will now explore a much bigger kinematic region … more news soon!



Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

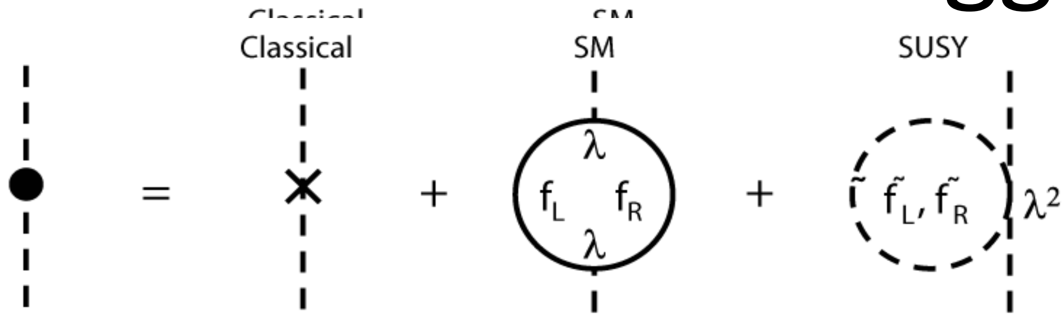
- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale of validity of the SM)
- Λ could be huge – e.g. the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

This is known as the hierarchy problem

SUSY and the Higgs mass



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

Higgs mass:

- correction has quadratic divergence!
  - Λ a cut-off scale – e.g. Planck scale

Cancellation

$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots$$

$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda / m_{\tilde{f}}) ,$$

Superpartners fix this:

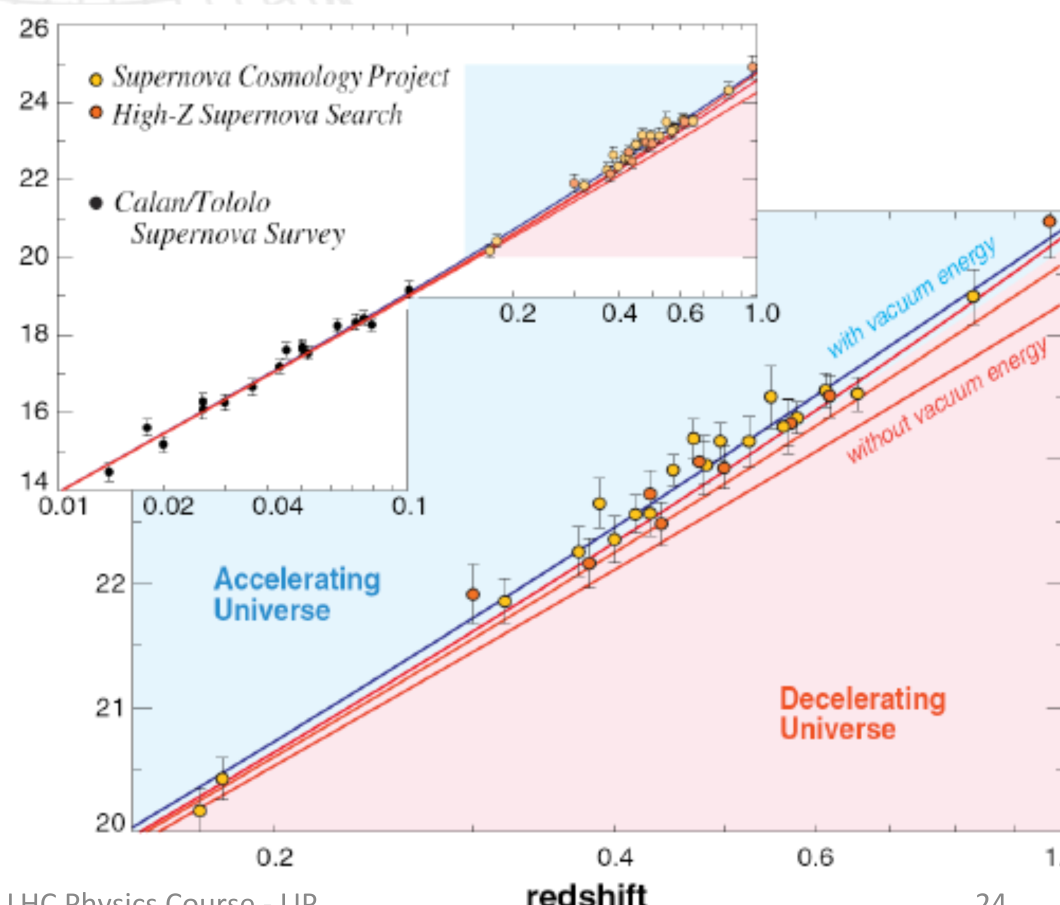
- Need superpartners at mass ~1-2 TeV
  - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.

The Universe expansion is accelerating

In 1998, two groups used distant Supernovae to measure the expansion rate of the universe: Perlmutter et al. (Supernova Cosmology Project), and Schmidt et al. (High-z Supernova Team)

They got the same result:
The Universe expansion is accelerating

Some form of energy (dark energy) fills space



Vacuum energy density

Dark energy responsible for acceleration of expansion is very small

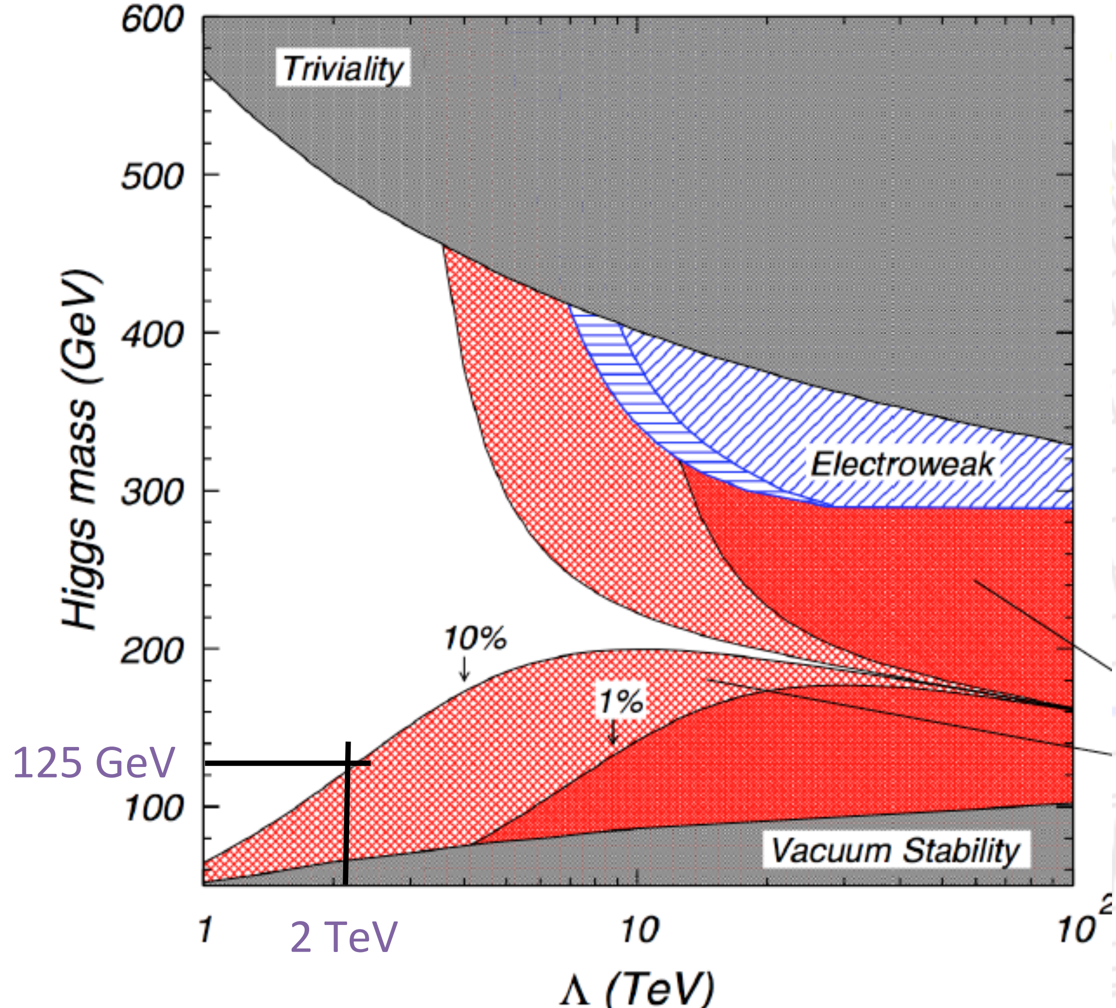
From particle physics we know that Vacuum has energy:

- potential energy of scalar fields
- energy of quantum fluctuations as predicted by quantum mechanics

This vacuum energy is 100 orders of magnitude larger than dark energy!

This huge discrepancy is known as the vacuum catastrophe.

New physics at a few TeV?

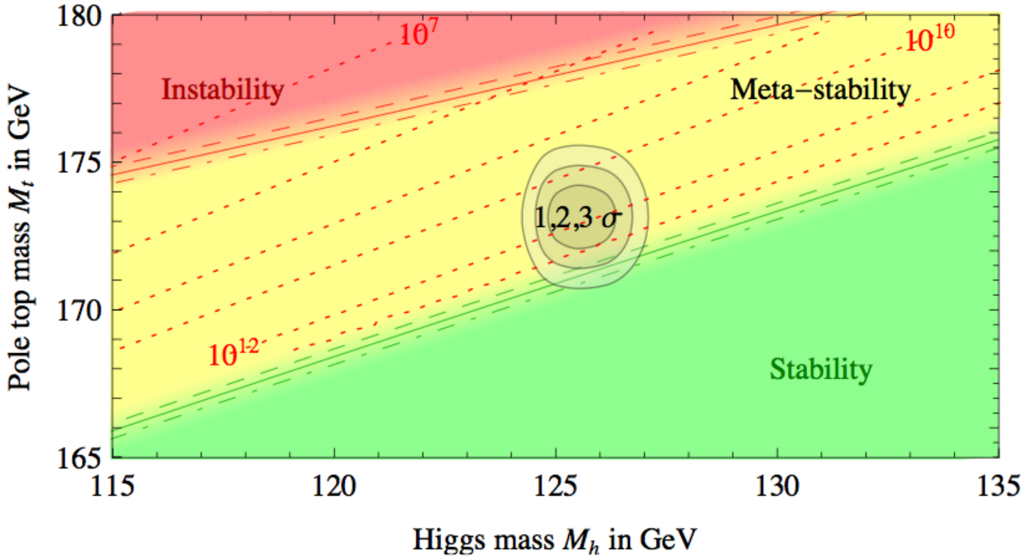


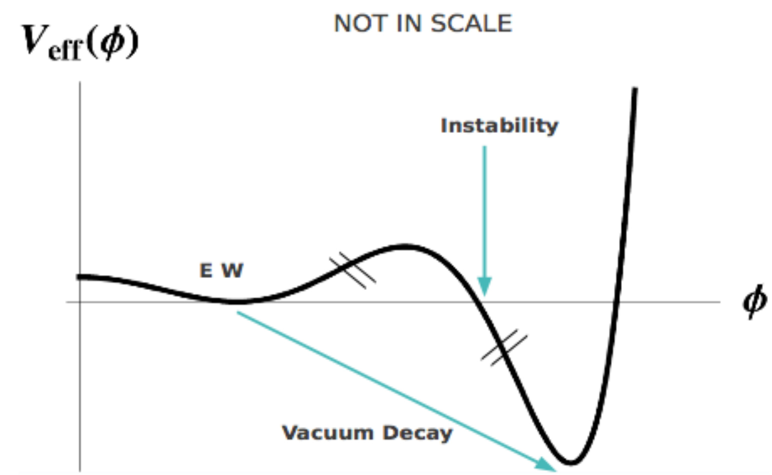
Naturalness implies Supersymmetry or another 'New Physics' below ~ 2 TeV

Excluded to avoid fine-tuning

Λ – Scale of New Physics

A bit of fun…





RG-improved potential

- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
  - See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

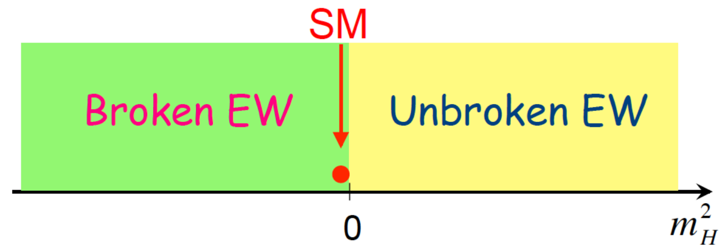
The universe seems to live near a critical condition

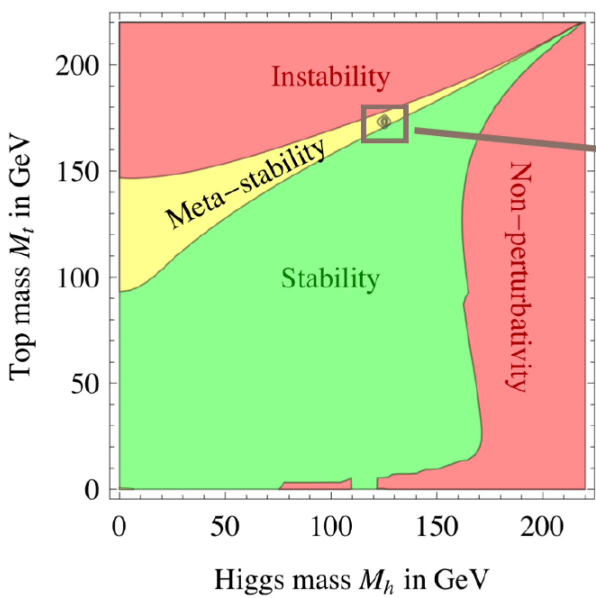
JHEP 1208 (2012) 098

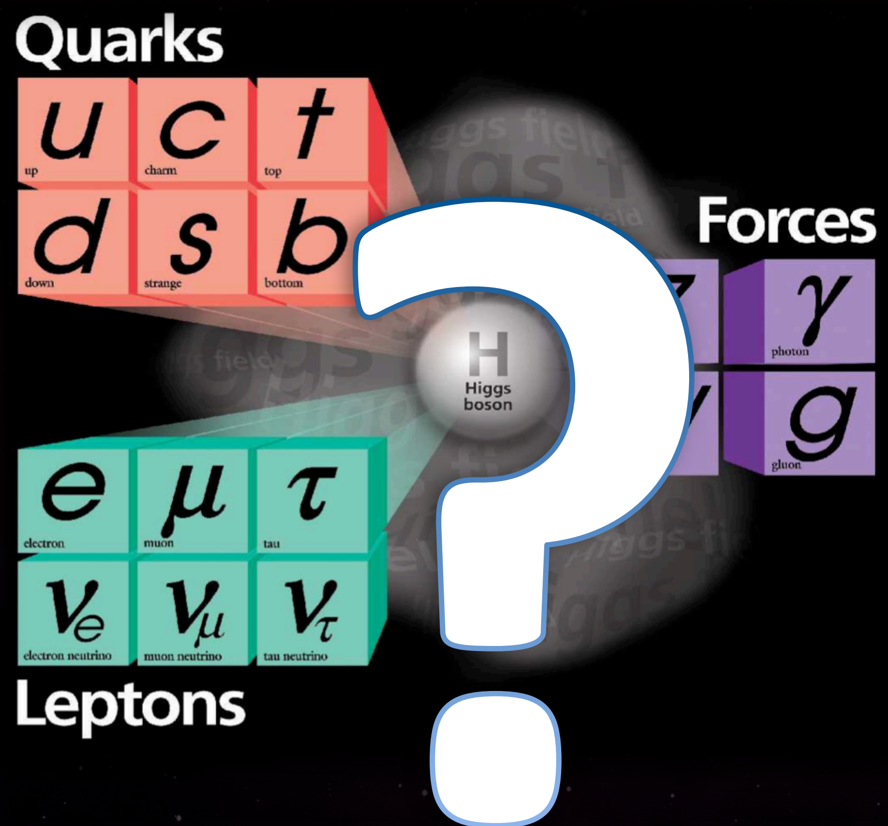
Why?!

Explained by underlying theory?

Anthropic principle?

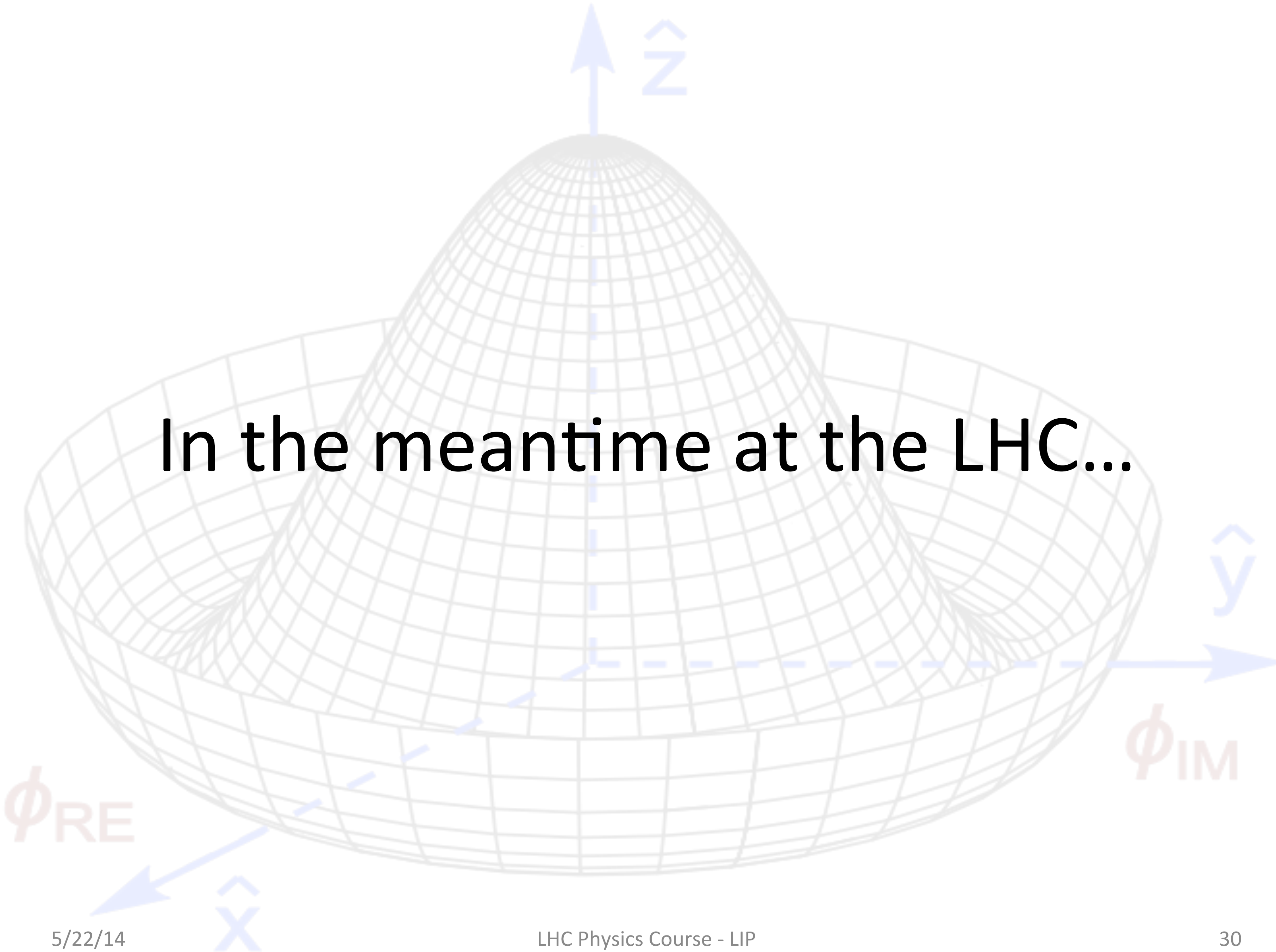




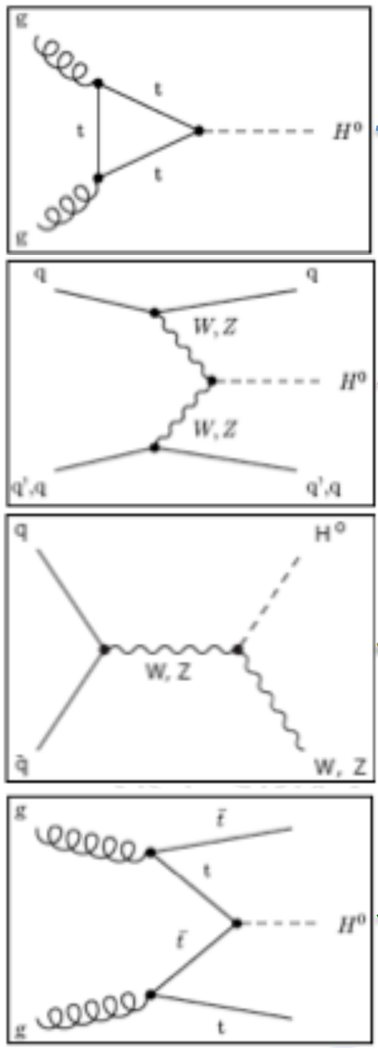


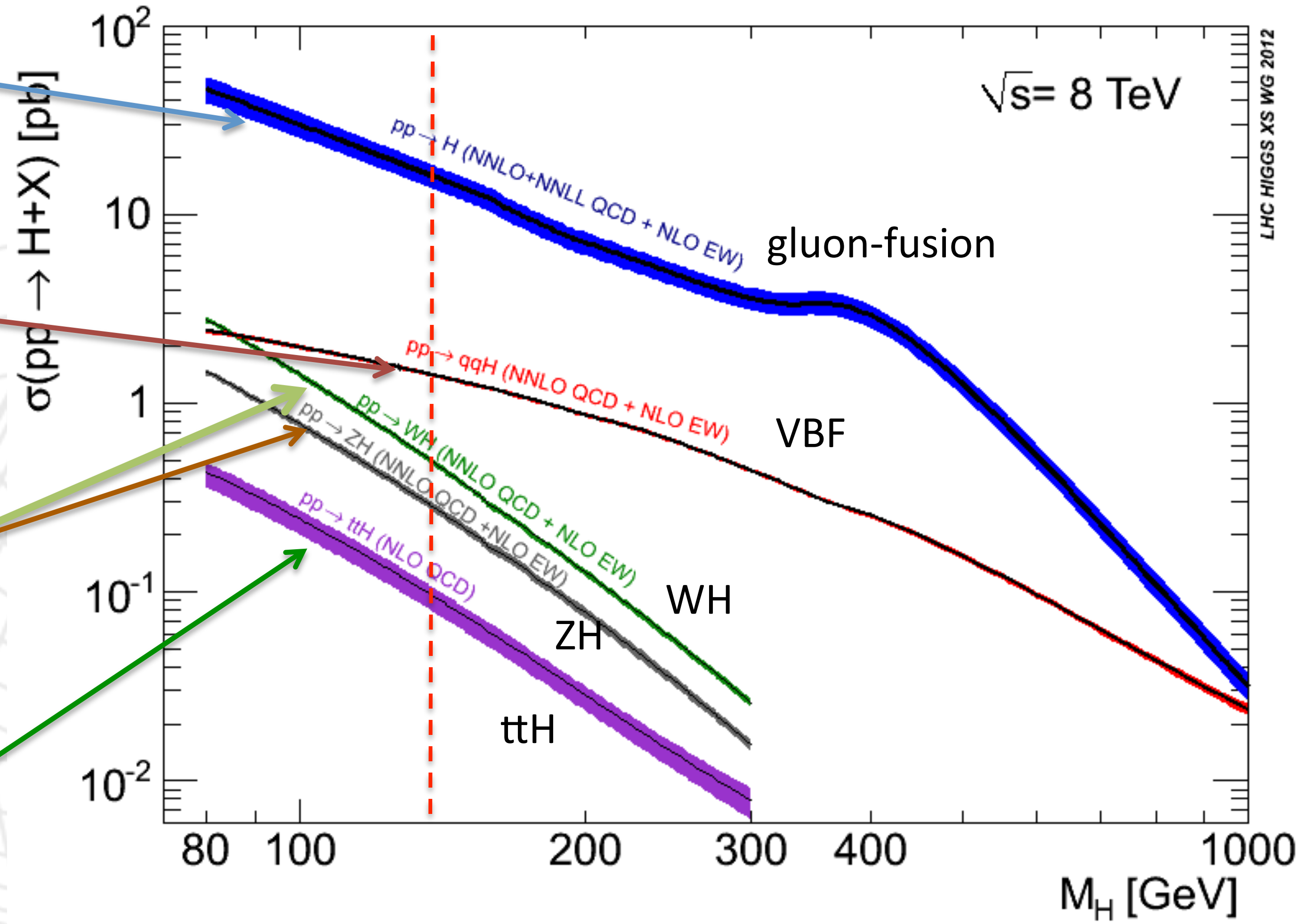
Back to the big questions!!

In the meantime at the LHC…

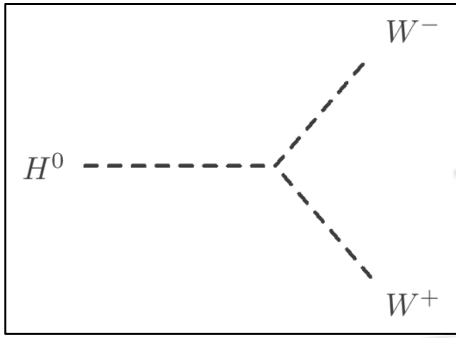


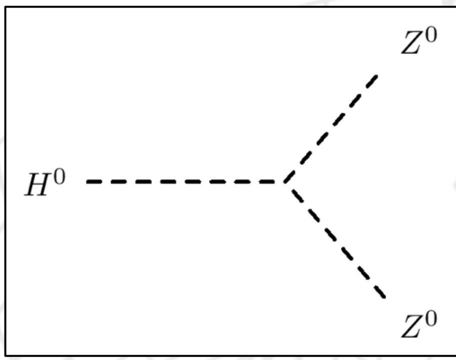
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

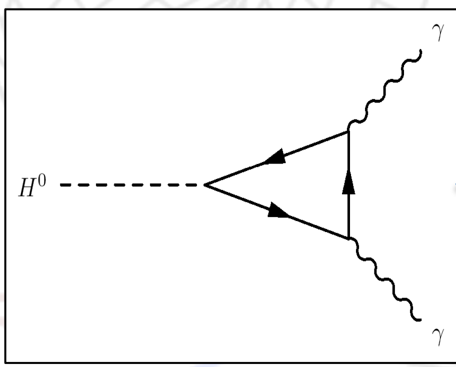


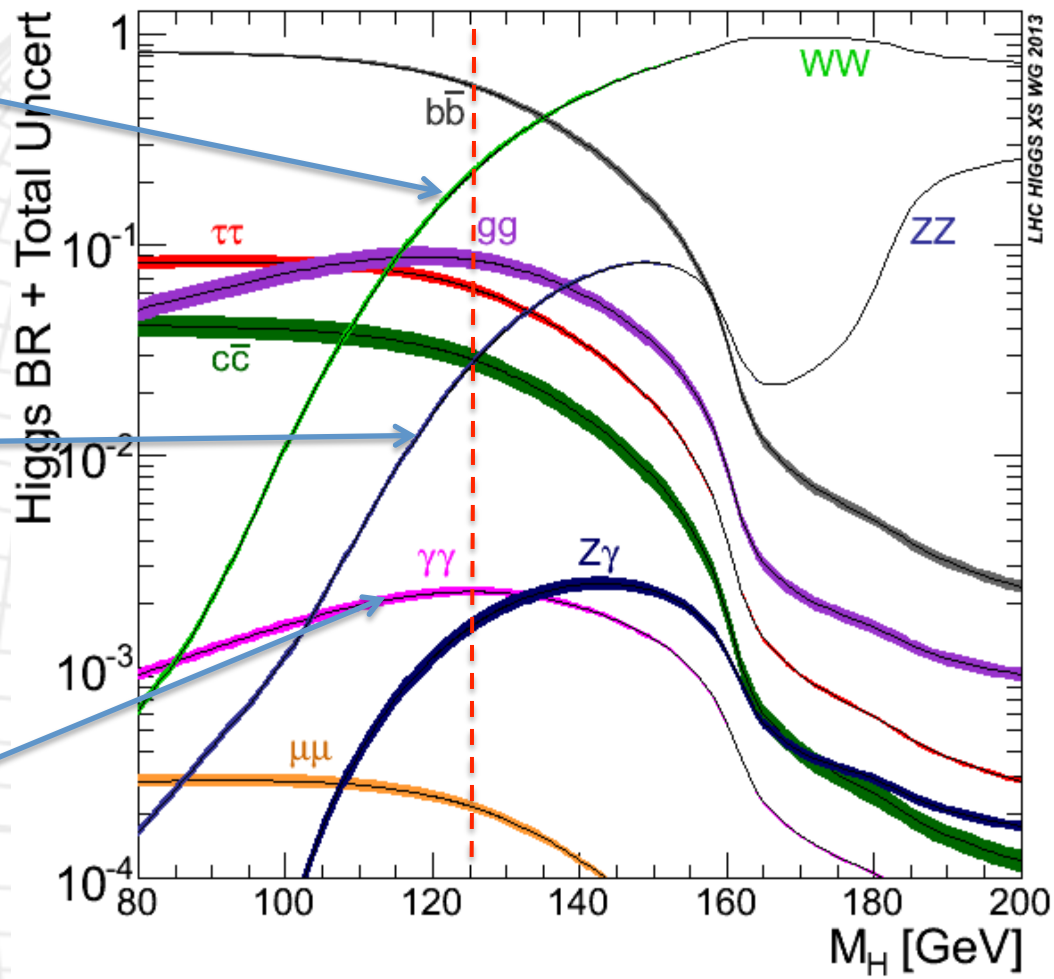


See previous lectures


W^-
H^0
W^+


Z^0
H^0
Z^0


γ
H^0
γ


Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
WW
$b\bar{b}$
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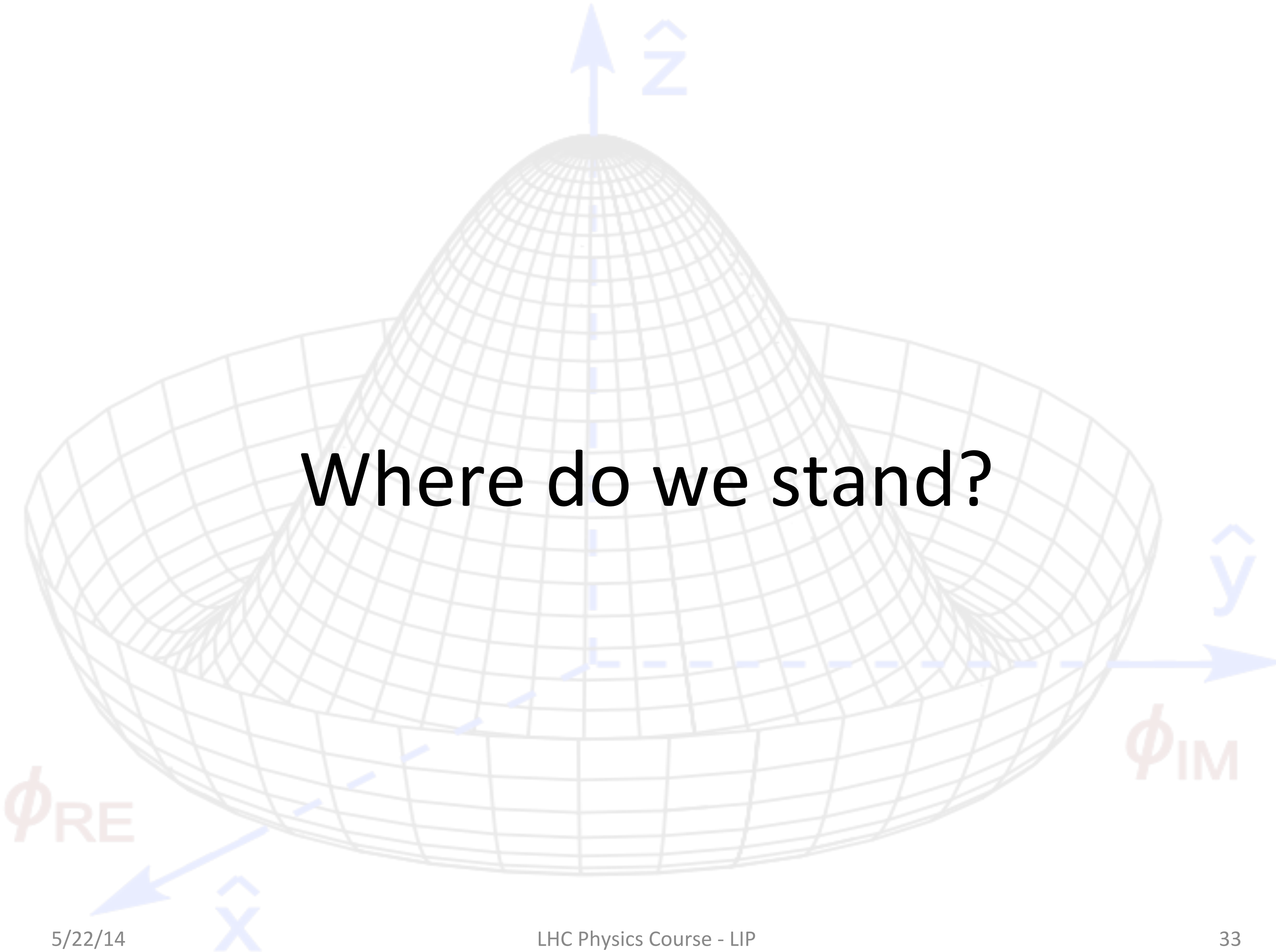
ZZ
$c\bar{c}$
γγ
Zγ
μμ

Where do we stand?



- Most modes available with current lumi explored
- Precision: obvious signal in bosonic decays
  - Mass around 125GeV
  - Signal strength consistent with SM – some questions
  - Main alternatives to $J^P = 0^+$ discarded – questions remain
- Fermion couplings seen in $H \rightarrow \tau\tau$ (4σ)
- Evidence for VBF production (3σ)
- Mainly indirect sensitivity to ttH coupling through loops
- Many direct searches for other Higgses turned out nothing (yet)

T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

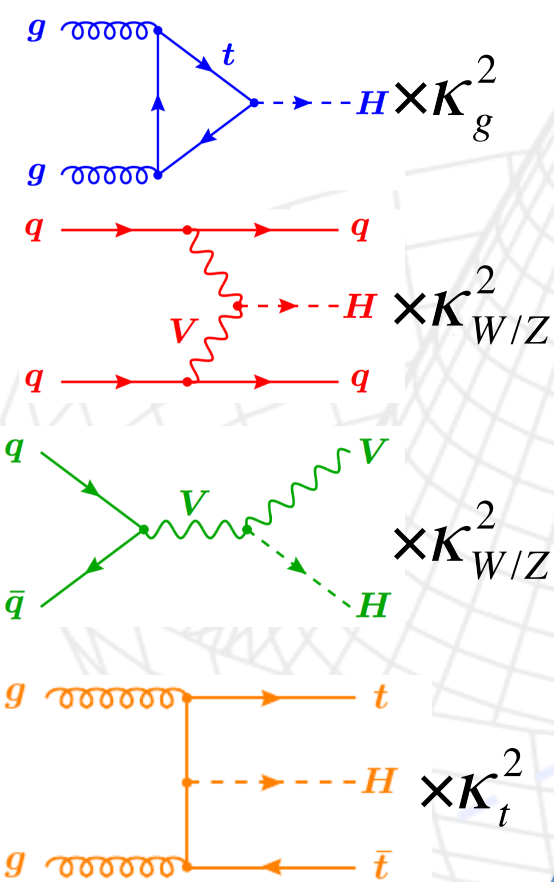
★ "seen" ☆ "tried" - "impossible"

	H→$b\bar{b}$			H→ττ			H→WW			H→ZZ			H→γγ			H→Zγ			H→inv.			H→μμ			H→$c\bar{c}$ H→HH		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	★	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	★	★		★	★		★	☆		★	☆	-		☆			☆	-		☆	-		
VH	★	☆	★	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆		☆	☆							☆	☆	-						-			-		

See A.David and P.Conde's lectures

Combining Higgs Channels

Production



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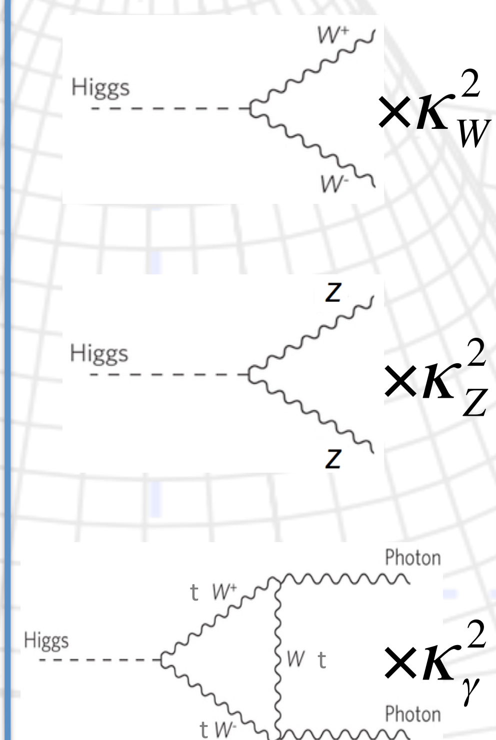
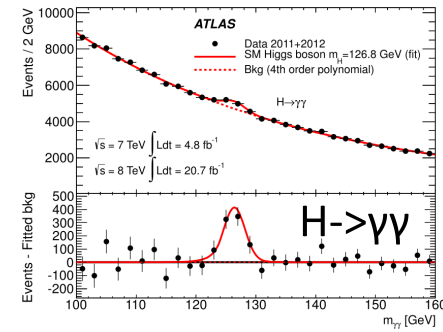
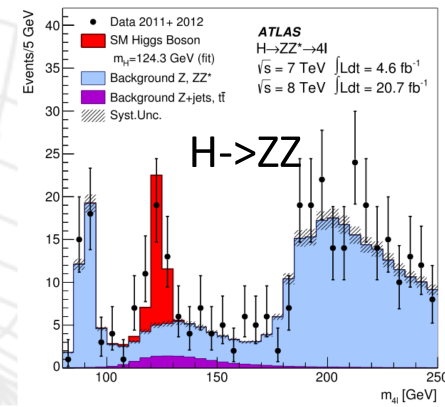
Decay

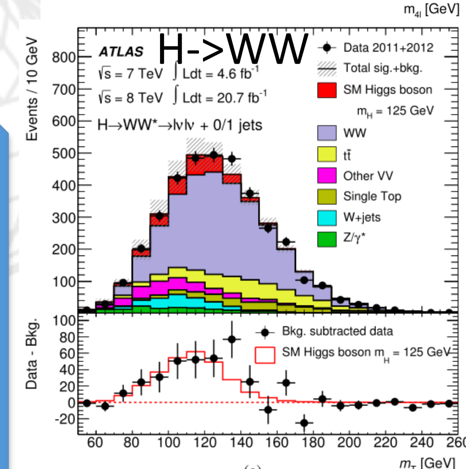


FIT

Backgrounds +







See A.David's lecture

A bit more technically

- **Assumptions:**
  - Single resonance (at $m_H = 125.5 GeV$)
  - No modification of tensor structure of SM Lagrangian:
    - i.e. H has $J^P = 0^+$
  - Narrow width approximation holds
    - i.e. rate for process i ➔ H ➔ f is: $$\sigma \times BR = \frac{\sigma_{i \to H} \times \Gamma_{H \to f}}{\Gamma_H}$$
- **Free parameters** in framework:
  - Coupling scale factors: κ_j^2
  - Total Higgs width: κ_H^2 $$\sigma_i = \kappa_i^2 \cdot \sigma_i^{SM}; \Gamma_f = \kappa_f^2 \cdot \Gamma_f^{SM}; \Gamma_H = \kappa_H^2 \cdot \Gamma_H^{SM}$$
  - Or ratios of coupling scale factors: $\lambda_{ij} = \kappa_i / \kappa_j$
- Tree-level motivated framework
  - Useful for **studying deviations** in data with respect to expectations
    - E.g. extract coupling scale factor to weak bosons κ_V by setting $\kappa_W = \kappa_Z = \kappa_V$
  - Not same thing as fitting a new model to the data

Higgs boson mass

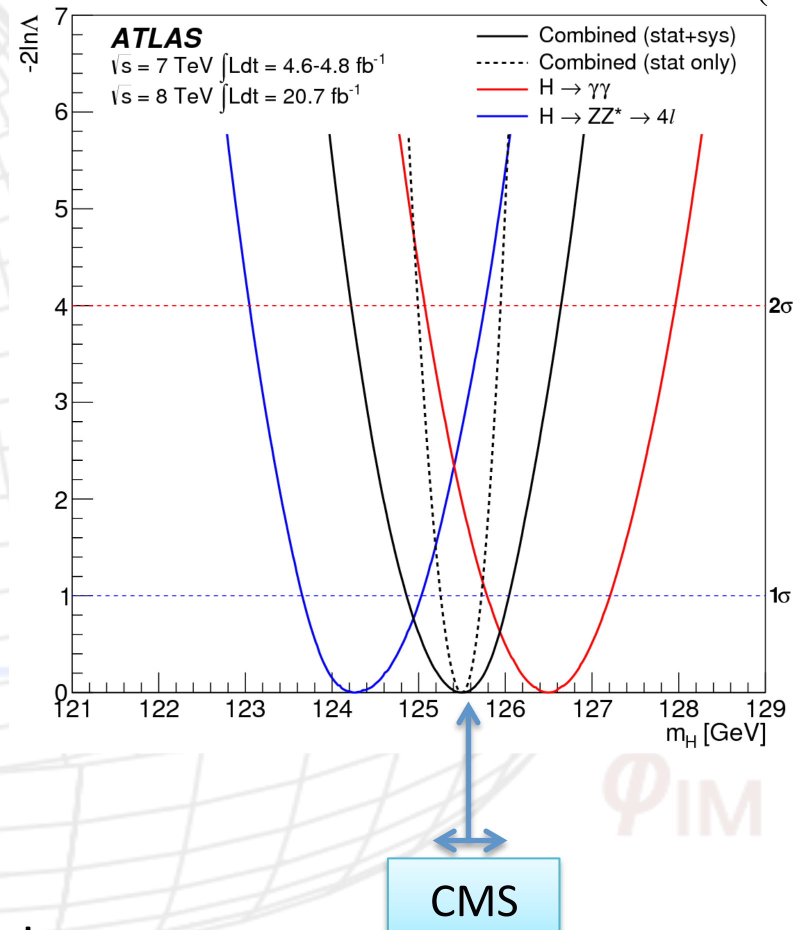
- **Mass:** around 125GeV
  - Used to be the only unknown SM-Higgs parameter, remember? ☺
- ATLAS: arXiv:1307.1427
  - $m_H^{H\to 4l} = 124.3 \pm 0.6(stat) \pm 0.5(sys)$
  - $m_H^{H\to\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(sys)$
  - Assuming single resonance: $m_H = 125.5 \pm 0.2(stat)\ ^{+0.5}_{-0.6}(sys)$
- Tension between channels!
  - Compatibility P=1.5% (2.4σ)
  - Rises to 8% with square syst.prior

BUT:

- CMS: arXiv:1312.5353
  - $m_H^{H\to 4l} = 125.6 \pm 0.4(stat) \pm 0.6(sys)$
- CMS: CMS-PAS-HIG-13-005
  - $m_H^{H\to\gamma\gamma} = 125.4 \pm 0.5(stat) \pm 0.6(sys)$
- Doesn't look like two different resonances!...

ATLAS: arXiv:1307.1427

$$\Lambda = \frac{L(m_H)}{L(\hat{m}_H)}$$

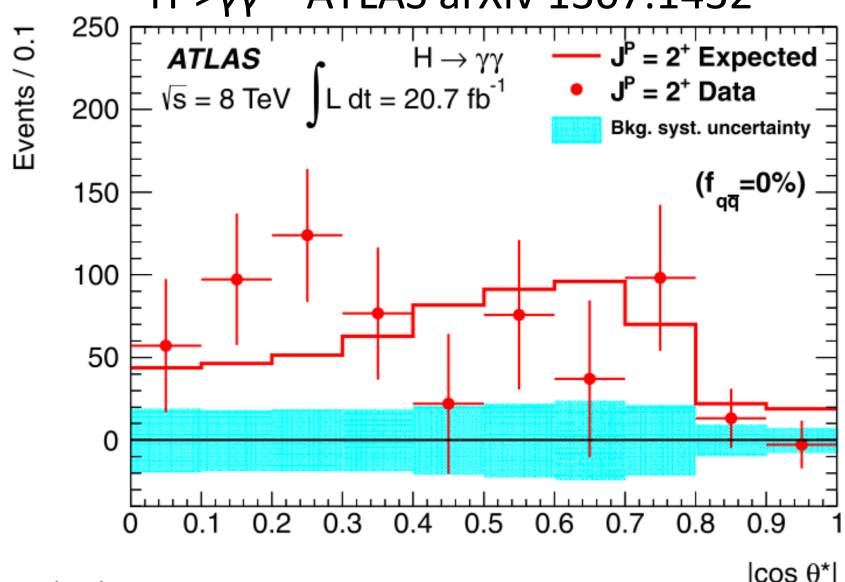


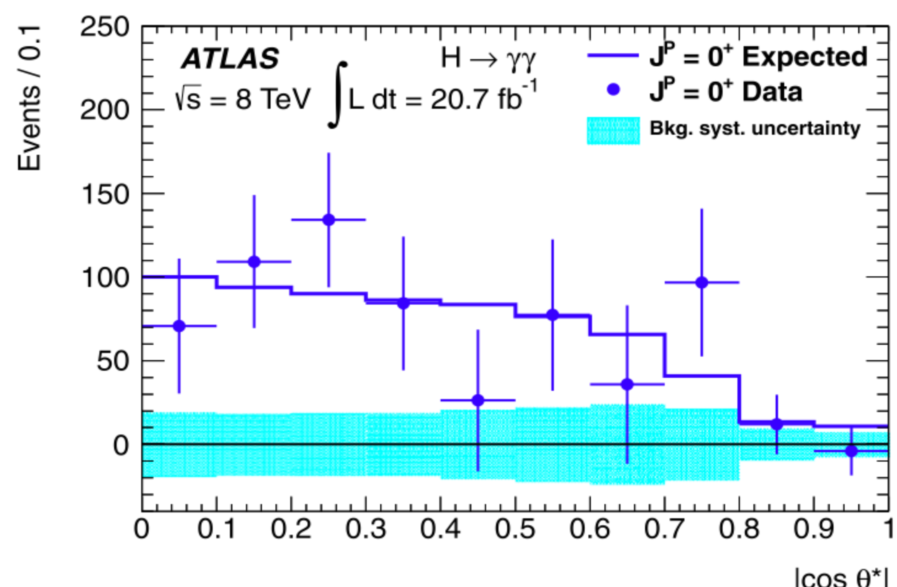
Spin and Parity

- Pure $J^P = 0^-, 1^+, 1^-$, and 2^+ excluded with 97.8, 99.97, 99.7, and 99.9% Confidence Level (ATLAS arXiv 1307.1432)
- But note: Higgs could have CP-violating component!

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

H->γγ – ATLAS arXiv 1307.1432





Direct Evidence of Fermion Couplings

- **Challenging** channels at the LHC!
  - Huge backgrounds (H->bb,H->ττ)
  - Or low rate: H->μμ

- ATLAS:

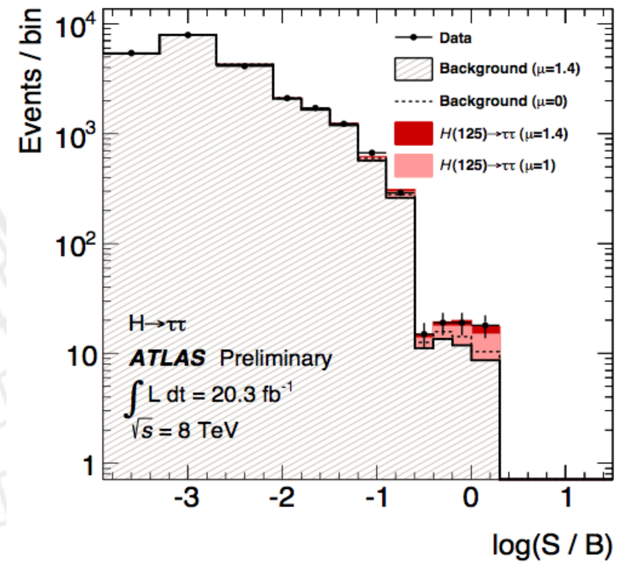
  4.1σ evidence of H->ττ decay 3.2σ exp.

  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}}$ = 1.4 ±0.3(stat) ±0.4(sys)

- CMS:
  - Combination of H->bb and H->ττ:

  3.8σ evidence (obs.) 4.4σ (expected)

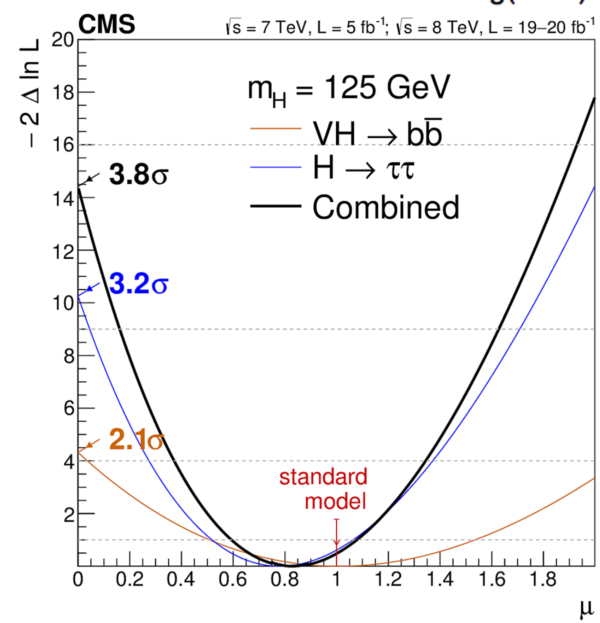
  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}}$ = 0.83 ±0.24



ATLAS-CONF-2013-108

CMS 1401.6527

Channel (m_H = 125 GeV)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
VH → $b\bar{b}$	2.3	2.1	1.0 ± 0.5
H → ττ	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24



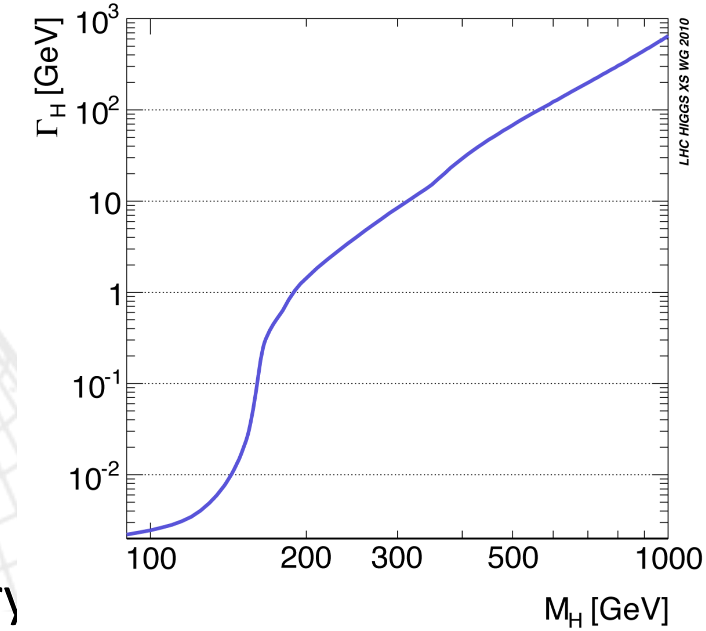
CMS 1401.6527

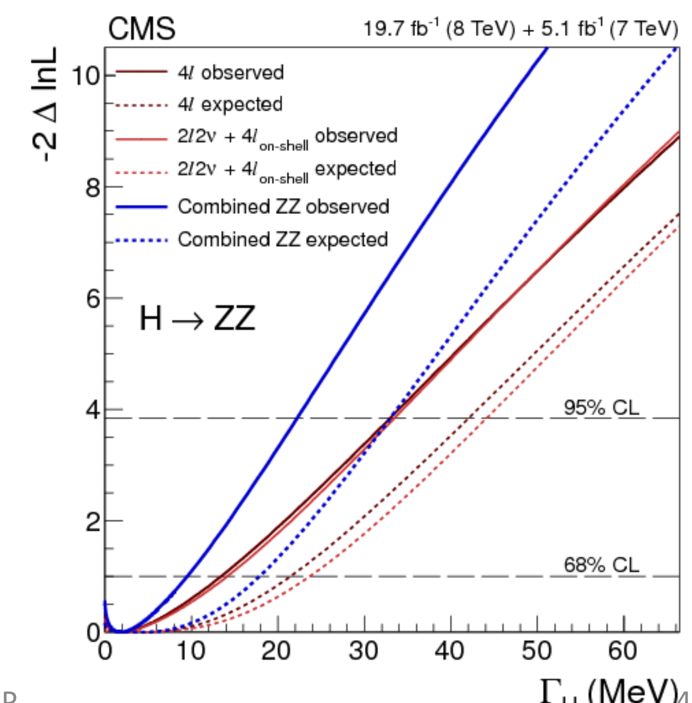
Higgs Width

- Total width not measurable at the LHC
  - Hadronic decays invisible in huge jet background
- Sensitivity can be achieved through "interferometric" measurement
  - **Use gg→H→ZZ with H on- or off-shell**
- Proof of principle done, although still very far from theoretically expected value (4MeV)
  - **Γ_H < 22 MeV at 95% CL**

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

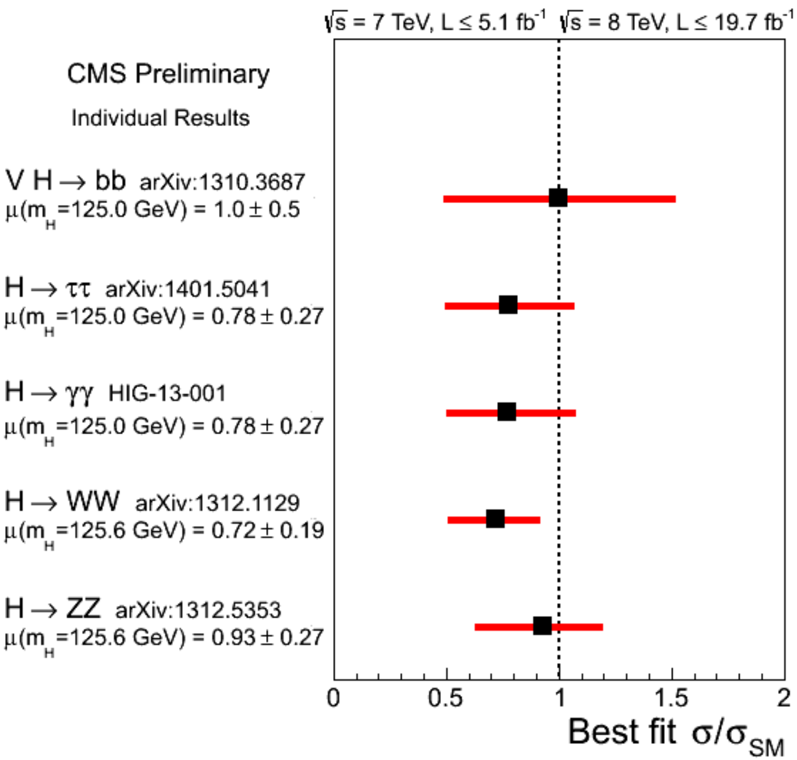
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$



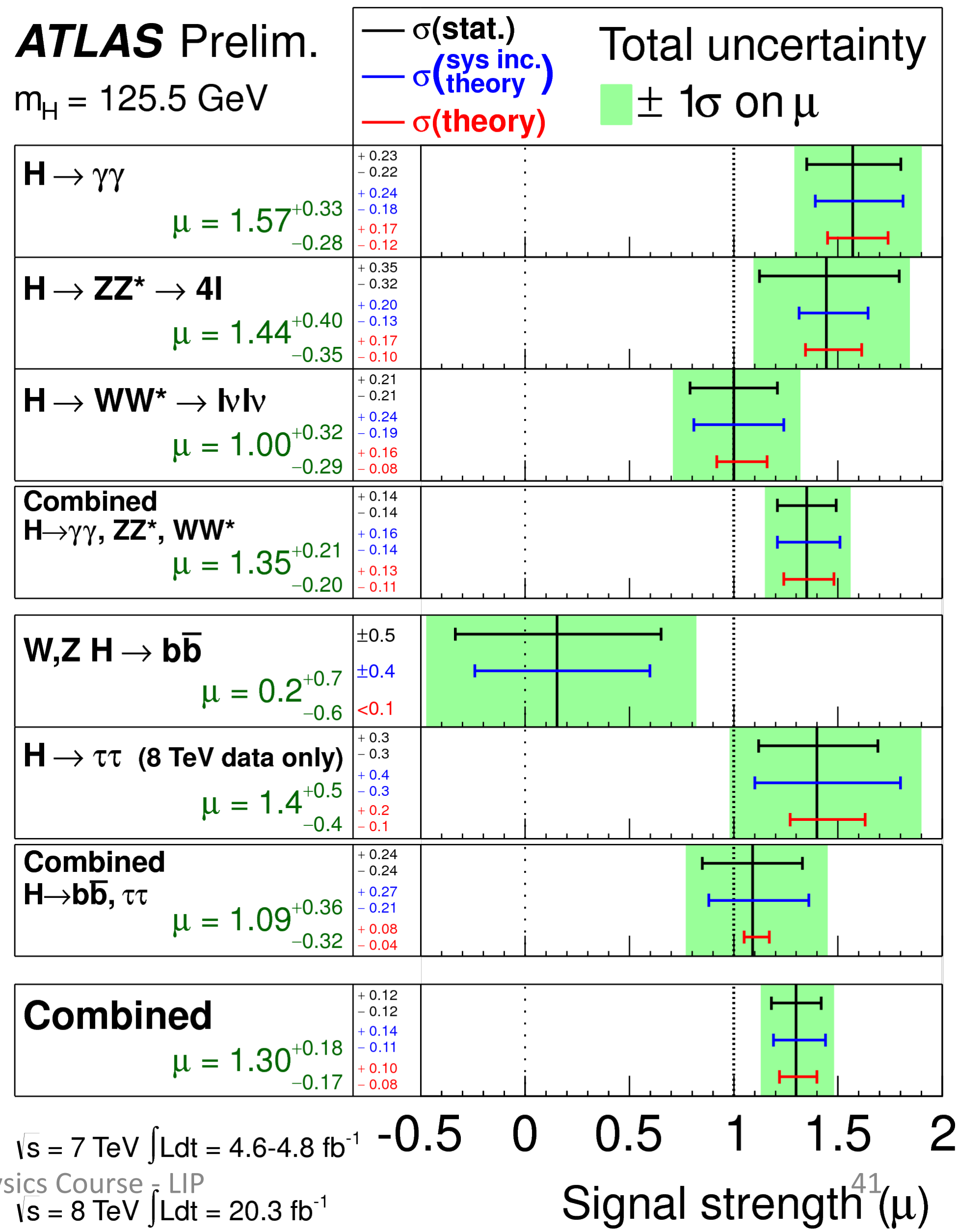


http://arxiv.org/pdf/1405.3455.pdf

Signal strength



$$\mu = \frac{\sigma_{meas}}{\sigma_{SM}}$$

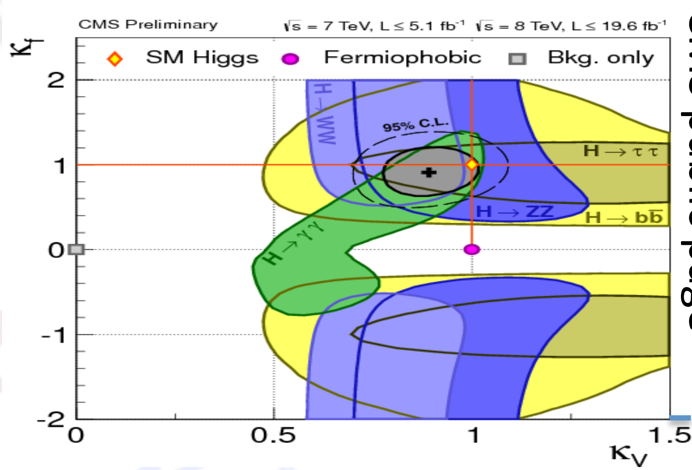


Take-home messages:

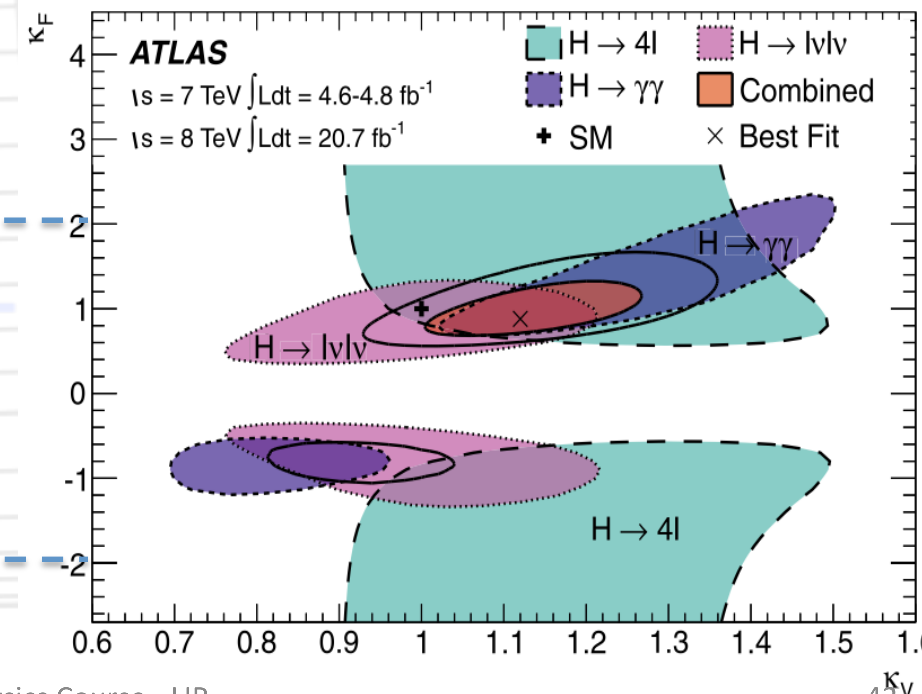
- Need more data!
- **Always run two experiments!**

Fermion and Boson couplings from fit

- Set one scale factor for all fermions ($\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \ldots$) and one for all vector bosons ($\kappa_V = \kappa_Z = \kappa_W$)
- Assume **no new physics**
- Strongest constraint to κ_F comes form gg->H loop
- ATLAS and CMS fits within 1-2σ of SM expectation (compatibility P=12%)
- Note ATLAS and CMS κ_V different – see signal strength below

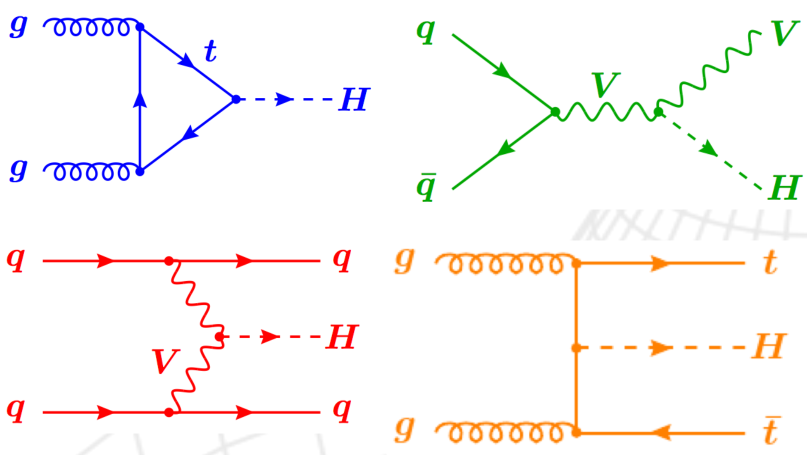


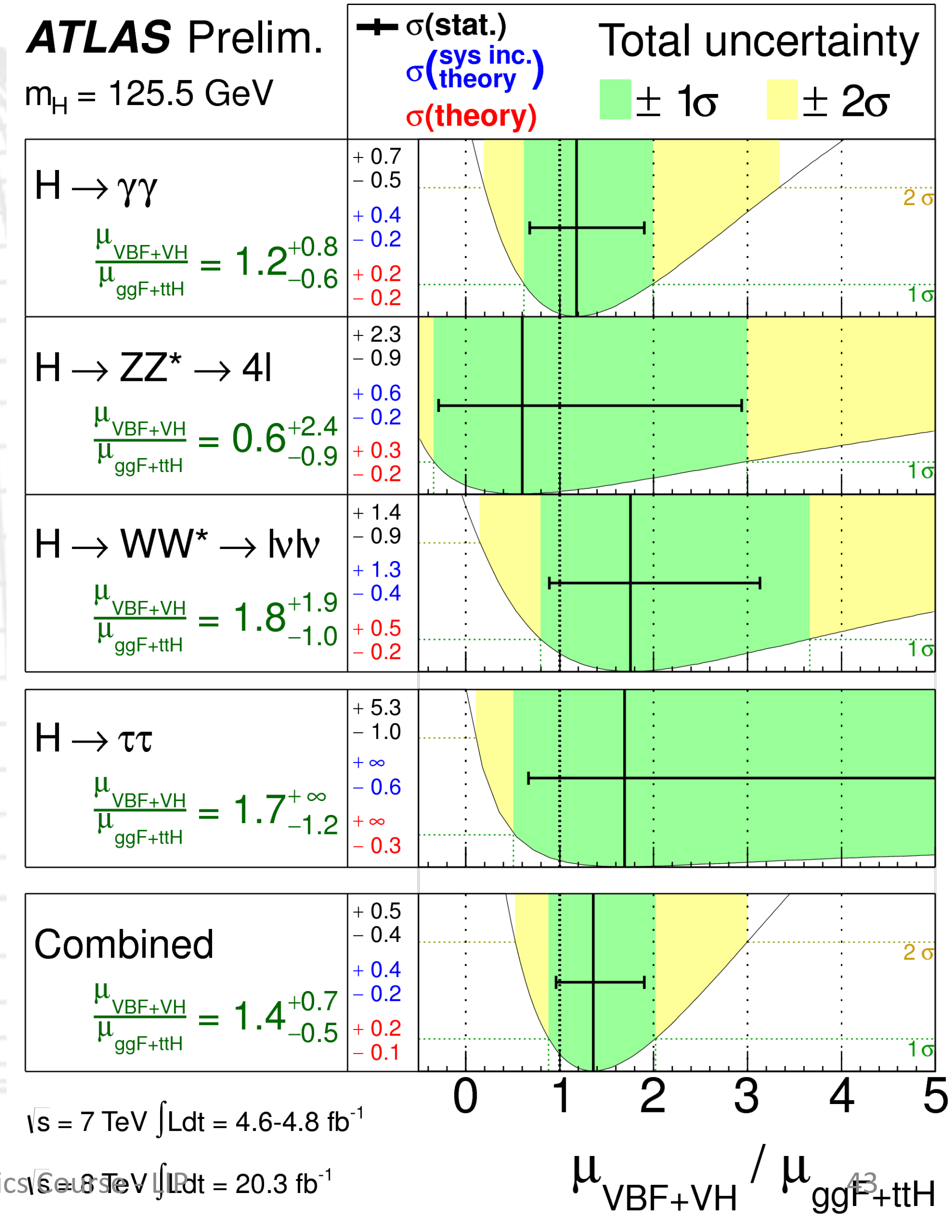
CMS public page



ATLAS 1307.1427

Production Modes

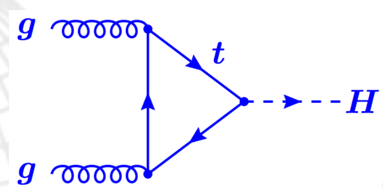


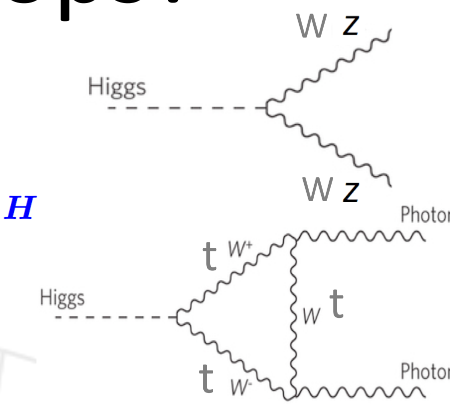


- Combination of channels allows consistency checks
- Evidence for VBF production (3σ)
- Sensitivity to top Yukawa coupling only through loops so far

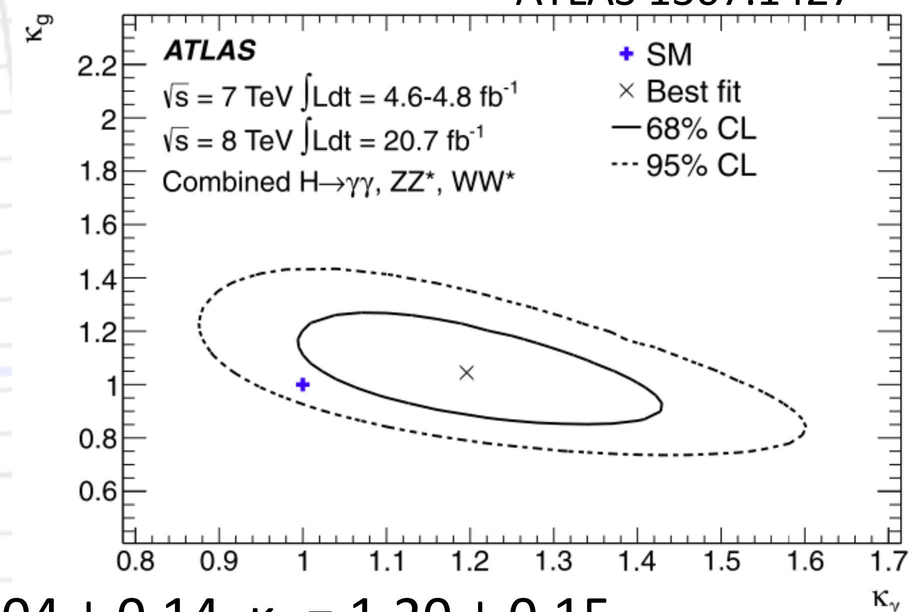
New Physics in the Loops?

- New heavy particles may show up in **loops**
  - Dominant **gluon-fusion** through a (mostly) top loop production for H->ZZ, H->WW and H->γγ
  - **H->γγ decay** through top and W loops (and interference)





ATLAS 1307.1427

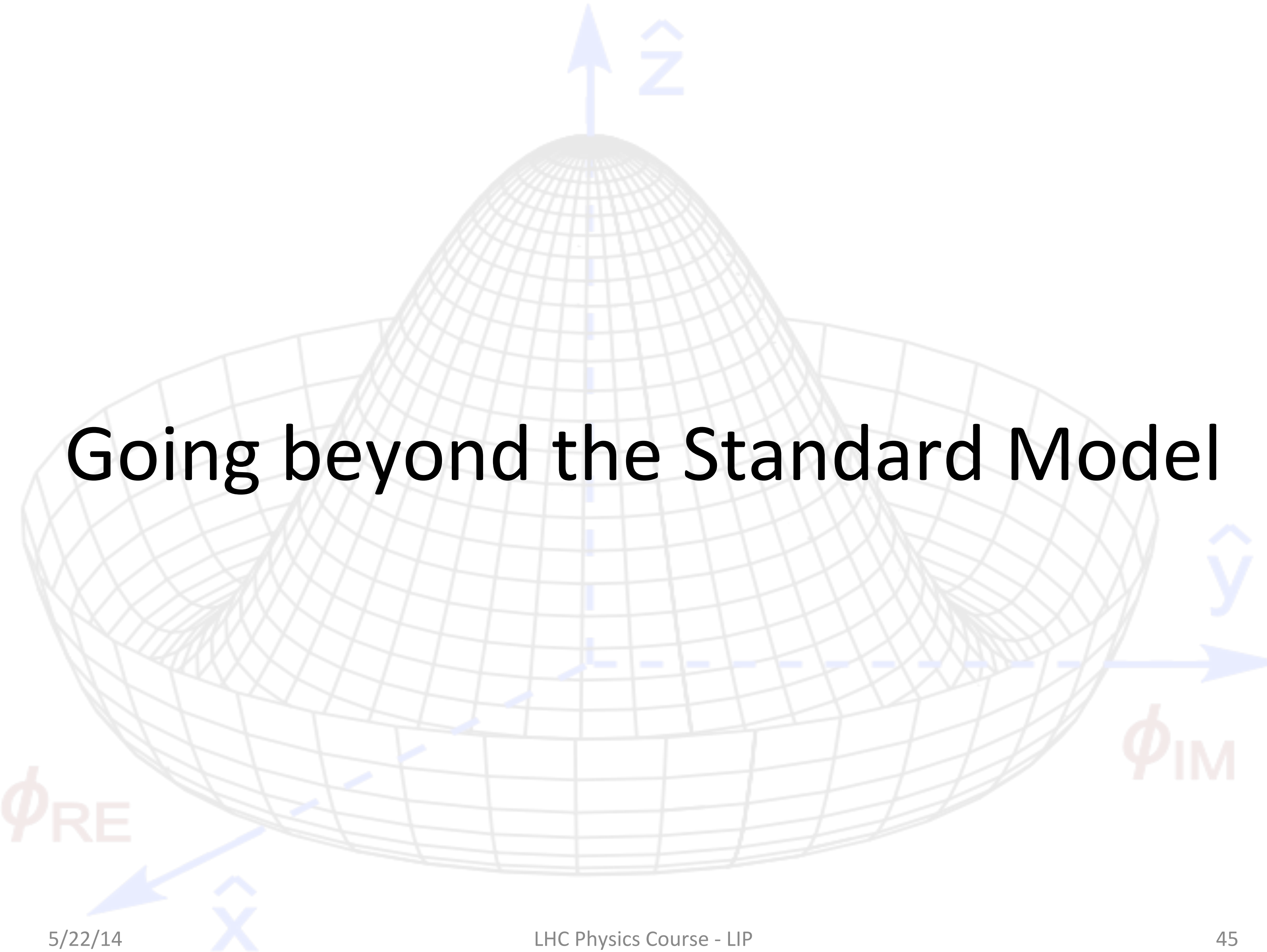


- Assume no change in Higgs width and SM couplings to known particles

- Introduce effective coupling scale factors:
  - κ_g and κ_γ for ggH and Hγγ loops

- Best fit values: $\kappa_g = 1.04 \pm 0.14$, $\kappa_\gamma = 1.20 \pm 0.15$
- Fit within 2σ of SM (compatibility P=14%)

Going beyond the Standard Model



Two Higgs Doublet Model (2HDM)

- No reason for simplest Higgs sector scenario to be true!
- One of the simplest alternatives: 2 Higgs doublets

$$\Phi_j = \begin{pmatrix} \phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix}$$

- Leads to 5 different Higgs bosons:
  - CP even (scalar): h, H
  - CP odd (pseudoscalar): A
  - charged: H^+, H^-
- Two doublets => two vacuum expectation values (mean field strength in the vacuum) – $\boldsymbol{v_1}$ **and** $\boldsymbol{v_2}$

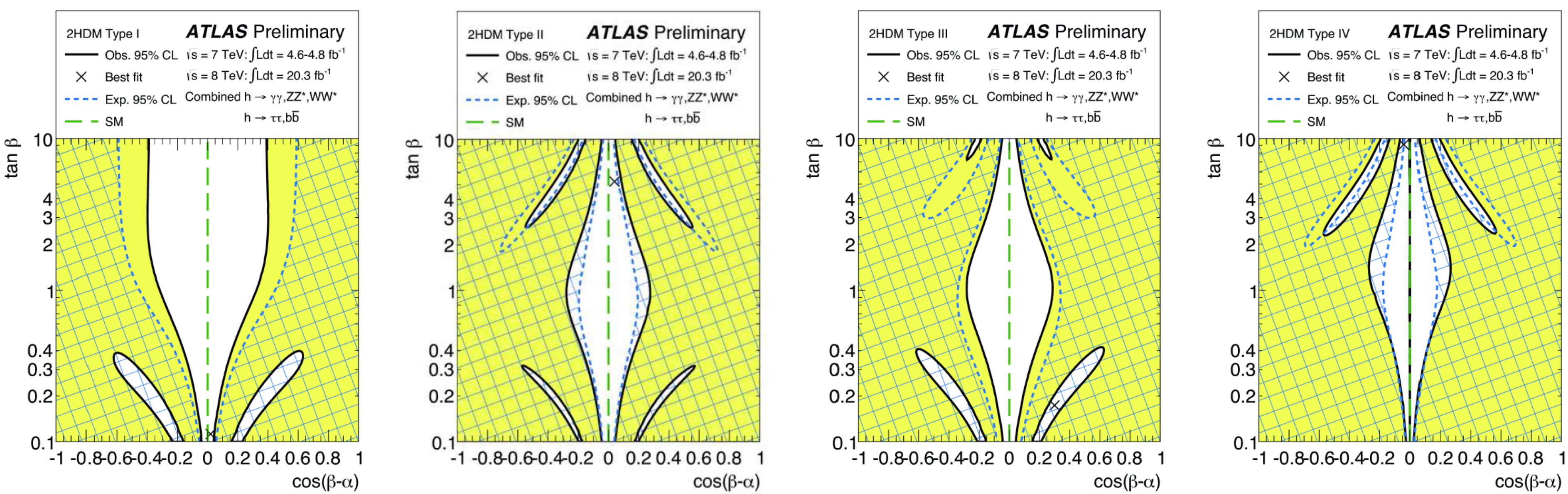
Two Higgs Doublet Model (2HDM)

- Free parameters:
  - 4 masses (Do we know one? Assume it's m_h)
  - $\tan\beta = v_1/v_2$ ratio of v.e.v.'s
  - Mixing angle of h and H: α
- 4 possible Yukawa coupling arrangements ("types")
- Most common SUSY benchmark (MSSM) is based on Type II
- If $\cos(\beta-\alpha) = 0$, h = Standard Model H^0

	Type I	Type II	Lepton Specific	Flipped
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Constraints from SM channels

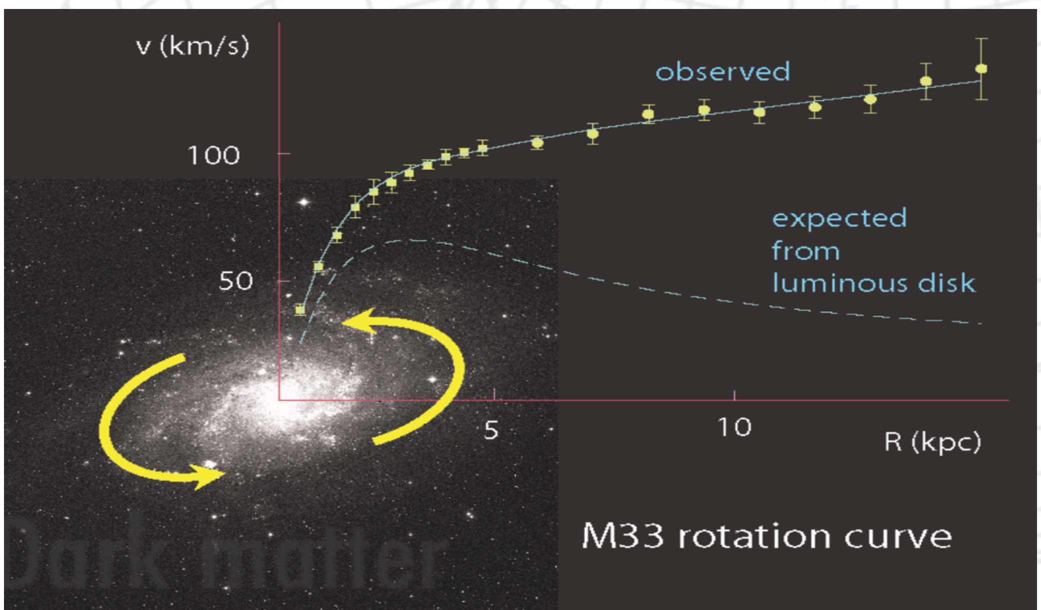
- What can our data already say about the 2HDM?
  - If it exists in Nature, then some of the measured rates (signal strength) are modified
  - Existing measurements can already rule out many possibilities
  - Used final states γγ, ZZ, WW, bb, ττ

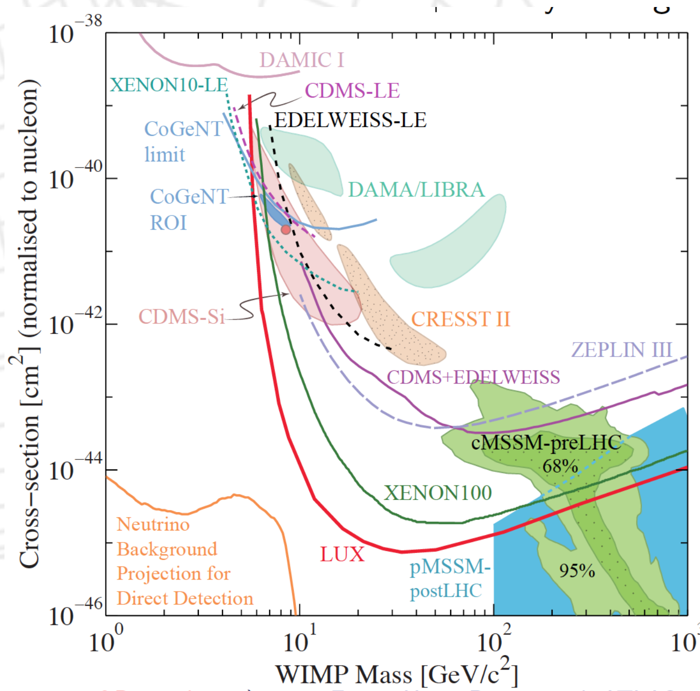


ATLAS-CONF-2014-010

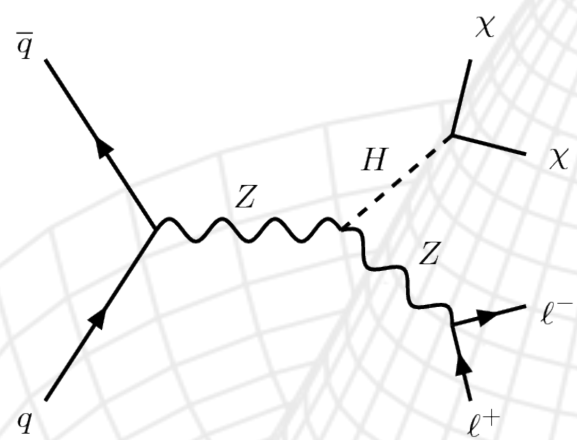
Invisible Higgs

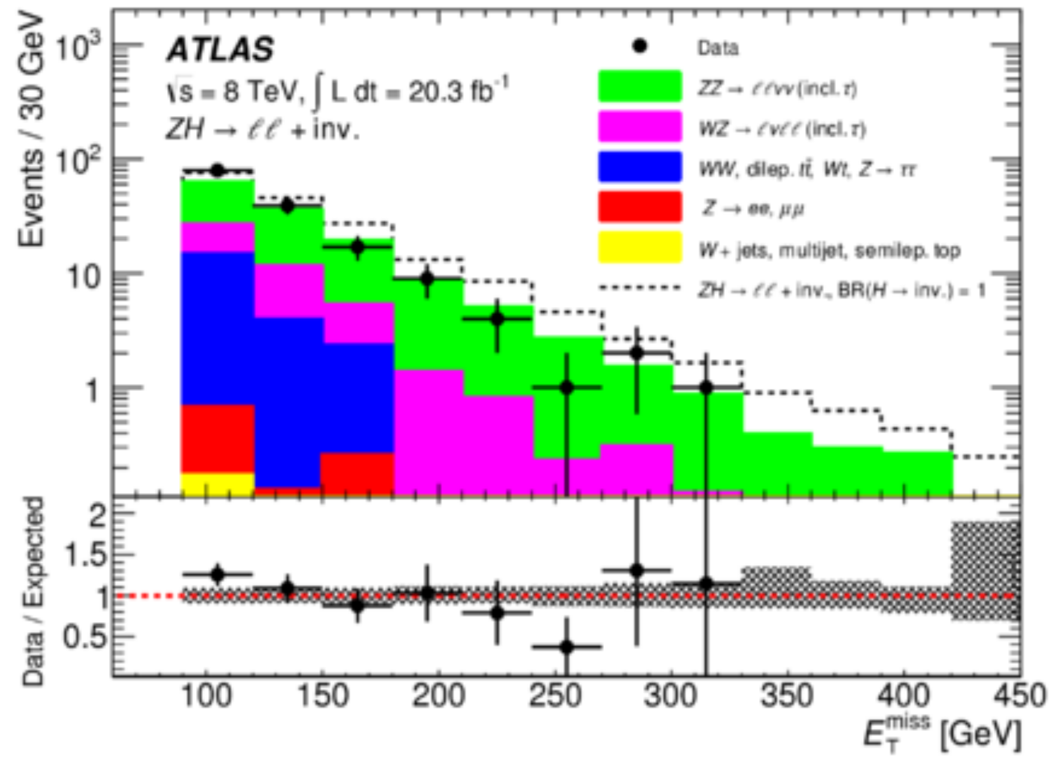
- Direct searches for Dark Matter usually hidden in deep caverns for low noise. But there is another way…
  - Dark matter has mass! Should couple to the Higgs. Do we see it?
  - Weakly interacting particles would leave no trace in detector – "Invisible" Higgs decays
  - Could be e.g. neutralinos in SUSY scenario
  - Would contribute to total Higgs width





Invisible Higgs





Require dileptons from Z

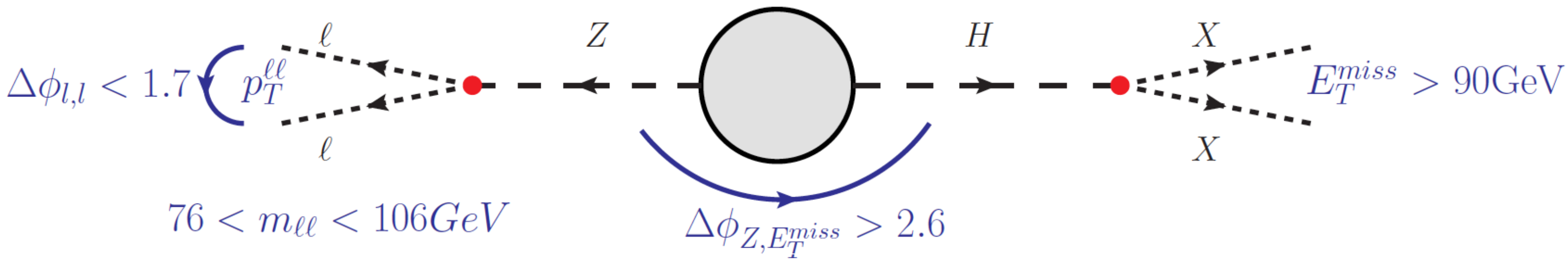
Back to back with Missing E_T and $p_T(\ell\ell)$

No jets

Main backgrounds ZZ, WZ

Claire Shepherd-Themistocleous - 26th Rencontres de Blois 2014

Z(H -> Invisible): Analysis Strategy

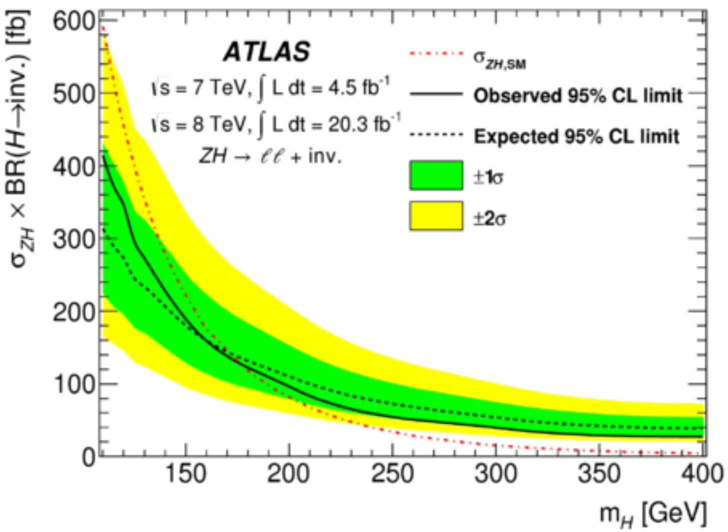


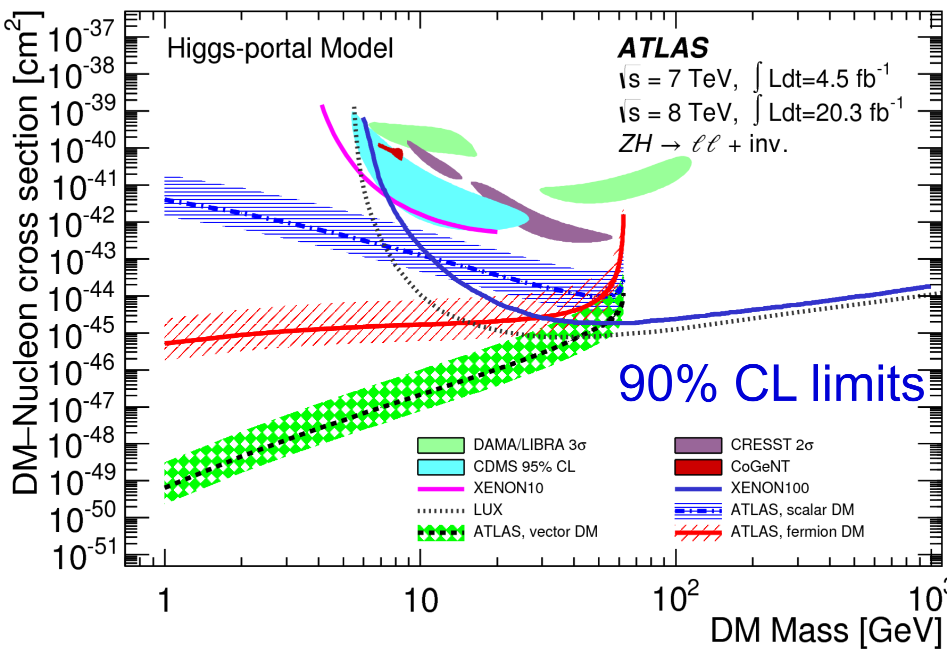
- Analysis cuts designed around the idea that the Z ($\ell\ell$ system) recoils off of the H (E_T^{miss}) for signal
- Most important background is Drell-Yan (Z) production with fake E_T^{miss} from mismeasured jets which is hard to estimate from MC
  - Estimated by 2 dimensional sideband fit of events failing one or both ❋

Requirement	Justification
$76 < m_{\ell\ell} < 106\text{GeV}$	Dilepton system consistent with $Z \rightarrow \ell\ell$
$E_T^{miss} > 90\text{GeV}$	Requiring the H to have p_T forces the Z to also have p_T
E_T^{miss} Cleaning Cuts	
$\Delta\phi_{\ell,\ell} < 1.7$	Boosted Z has leptons close together
$\Delta\phi_{Z,E_T^{miss}} > 2.6$	Z and H should be back-to-back
$\Delta\phi(E_T^{miss}, E_T^{miss,track}) < 0.2$	E_T^{miss} not correlated for background (E_T^{miss} from mismeasured jets) ❋
$\lvert E_T^{miss} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell} < 0.2$	Balance of Z and H momentum ❋
Central Jet Veto	Drell-Yan background tends to have one or more jets

R.Vanguri, Lake Louise Winter Institute 2015

Invisible Higgs





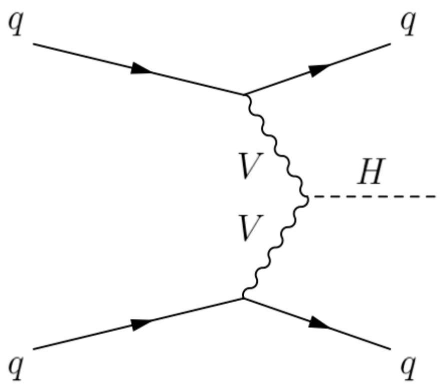
Upper limit Br to inv. 75%

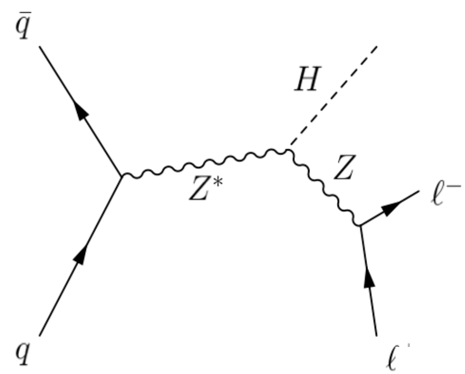
Upper limit interpreted as limit on DM-nucleon scattering cross section
Fox et al. Phys. Rev. D 85 050611

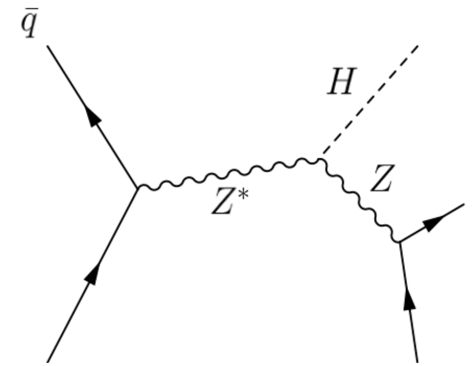
DM scenarios scalar, vector or Majorana fermion

Higgs-nucleon coupling 0.33 $^{+0.30}_{-0.07}$ Djouadi et al. Phys. Lett. B 709 65 (2012)

Invisible Higgs





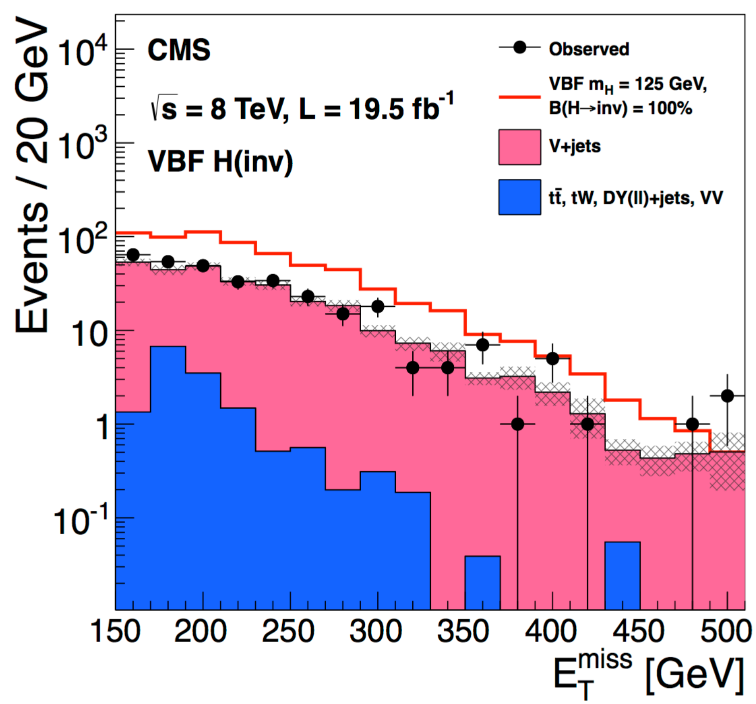


Other search channels:
Search in VBF and ZH , Z → ll and bb

VBF mode requires 2 jets in forward region
($\Delta\eta_{jj} > 4.2$) , E_t^{miss} > 130 GeV

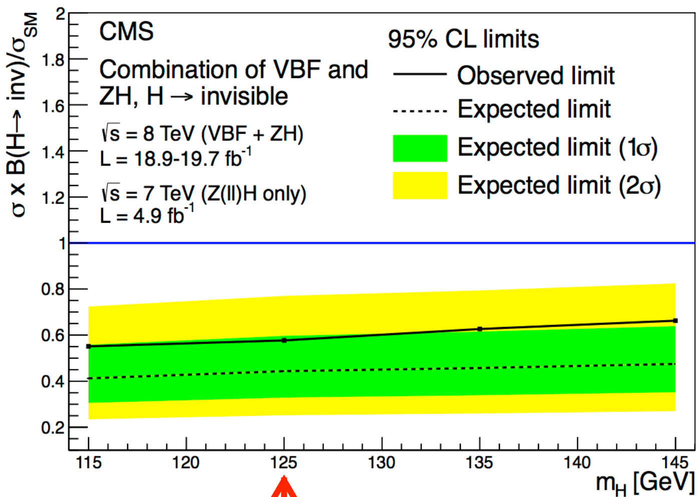
Central jet veto on any jet p_T > 30 GeV.

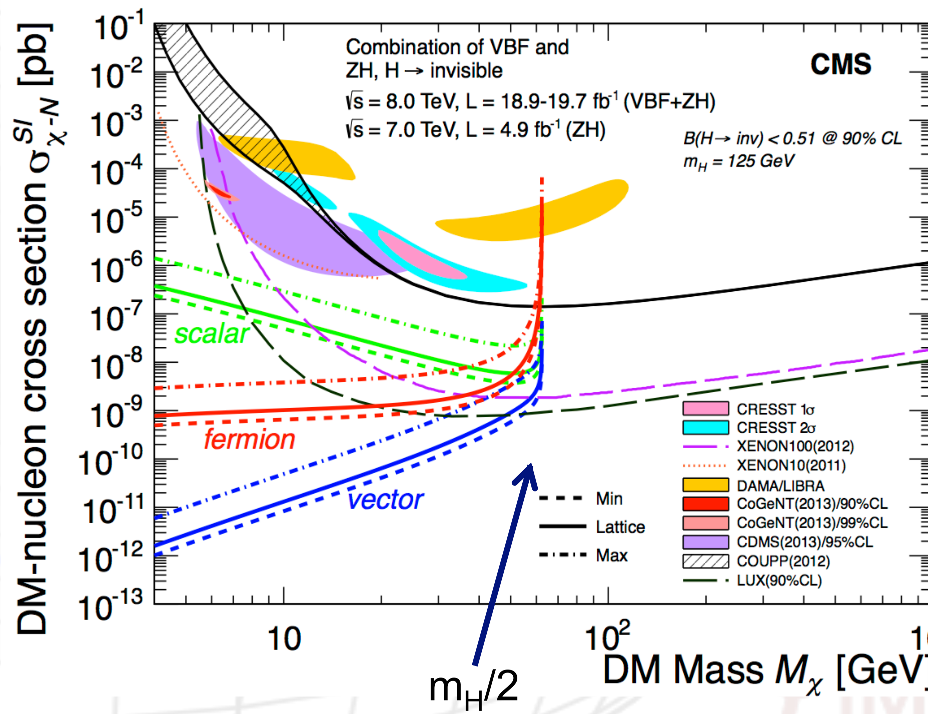
Dominant backgrounds
Z(νν) + jets, W(lν) + jets



Invisible Higgs

$7\ \text{TeV}\ 4.9\ fb^{-1}$ $8\ \text{TeV} \sim 19\ fb^{-1}$





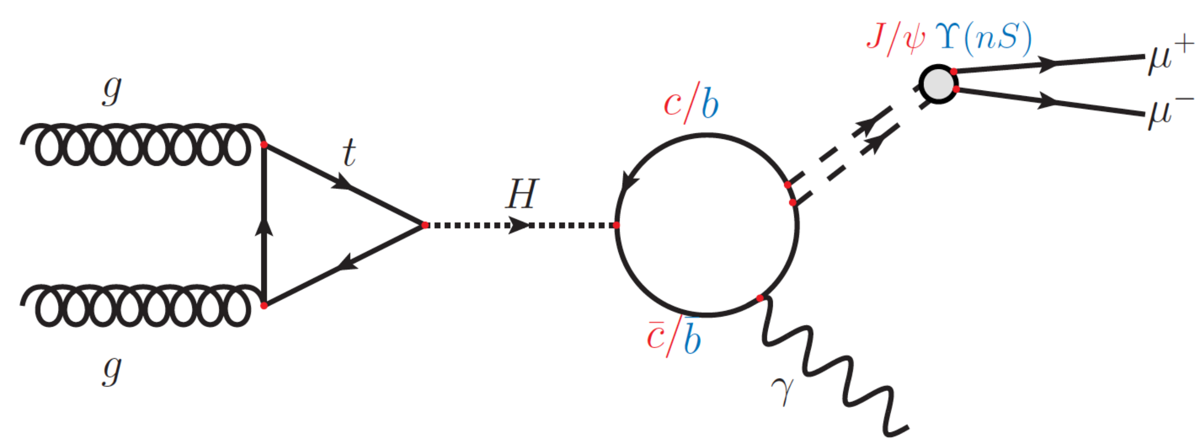
Upper limit on Br to invisible 0.58 for Higgs mass 125 GeV

Higgs nucleon coupling 0.33 (range 0.26 - 0.63)

DM scenarios scalar, vector or Majorana fermion

Rare decays

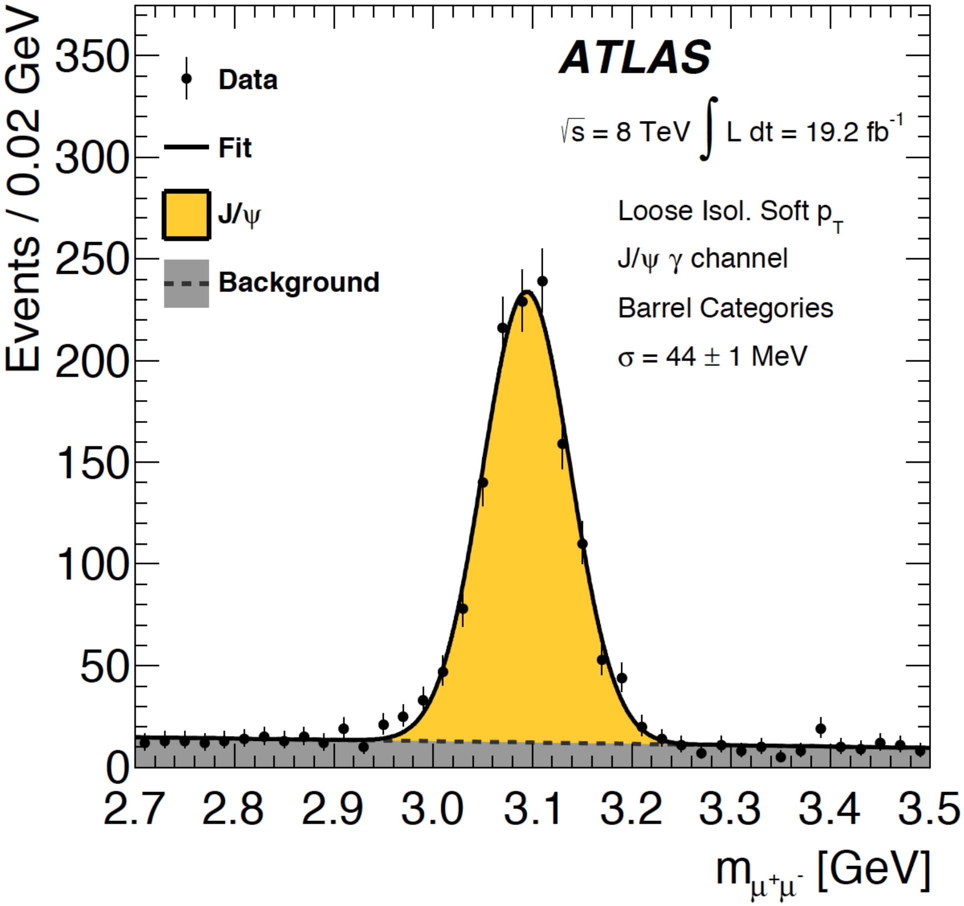
- Only way to probe Higgs decays to charm – charm Yukawa coupling – at LHC
- Deviations in coupling from SM value can lead to increase in branching fraction
- Analysis also probes Z decays to J/Ψ or ϒ(nS) plus γ – improved LEP limits by 2



Backgrounds

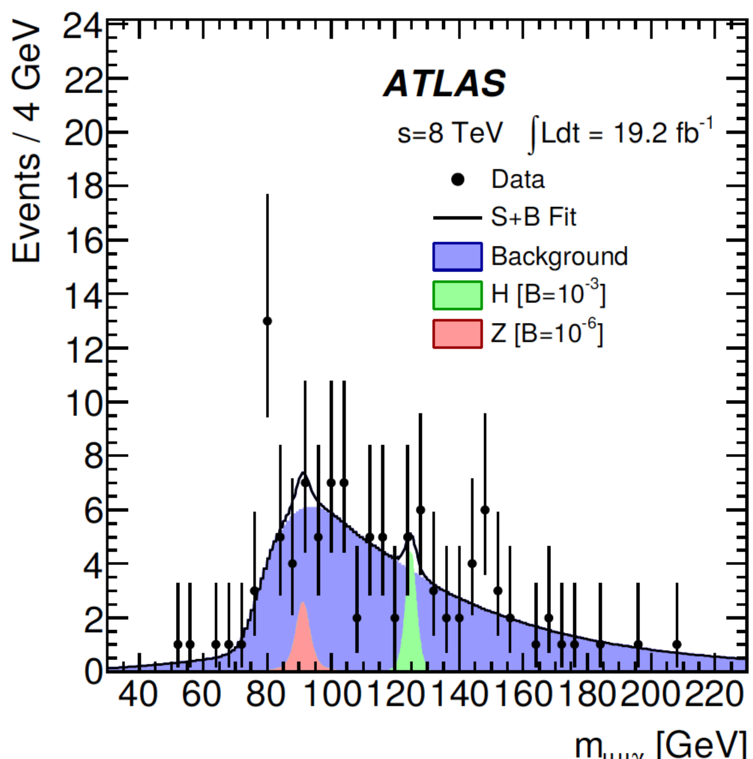
Dominant Backgrounds

- 56% Prompt J/ψ: Peaks in $m_{\mu\mu}$
  - $gg \rightarrow J/\psi g$ where g (jet) is misidentified as a γ
  - Suppressed by requiring γ be isolated since there is usually hadronic activity around a jet
- 41% Non-resonant: Smooth in $m_{\mu\mu}$
  - Production of a di-muon pair with invariant mass close to J/ψ



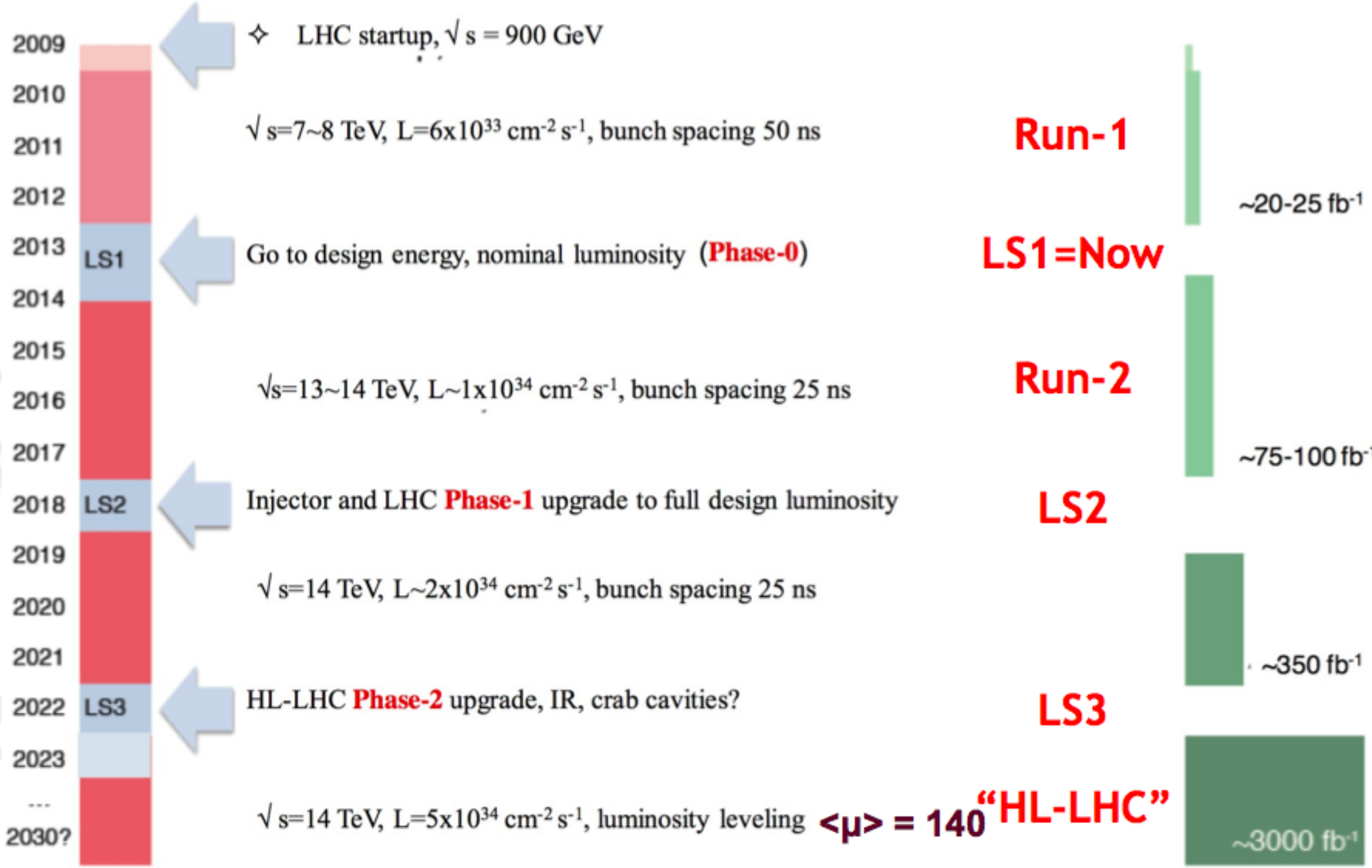
Results

- Upper limit set on branching fraction of H decay to J/Ψ plus γ at 95% confidence:
- Br (J/Ψ γ) < 1.5 x 10^{-3} (expected $1.2^{+0.6}_{-0.3}$ x 10^{-3})
- 540 ≈ SM Expectation



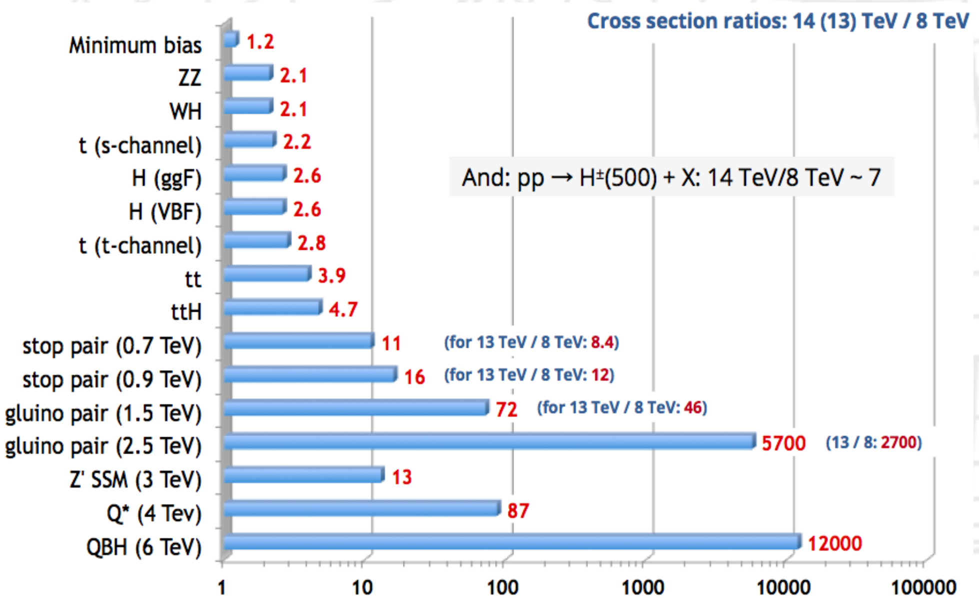
Looking into the future

Future LHC Running

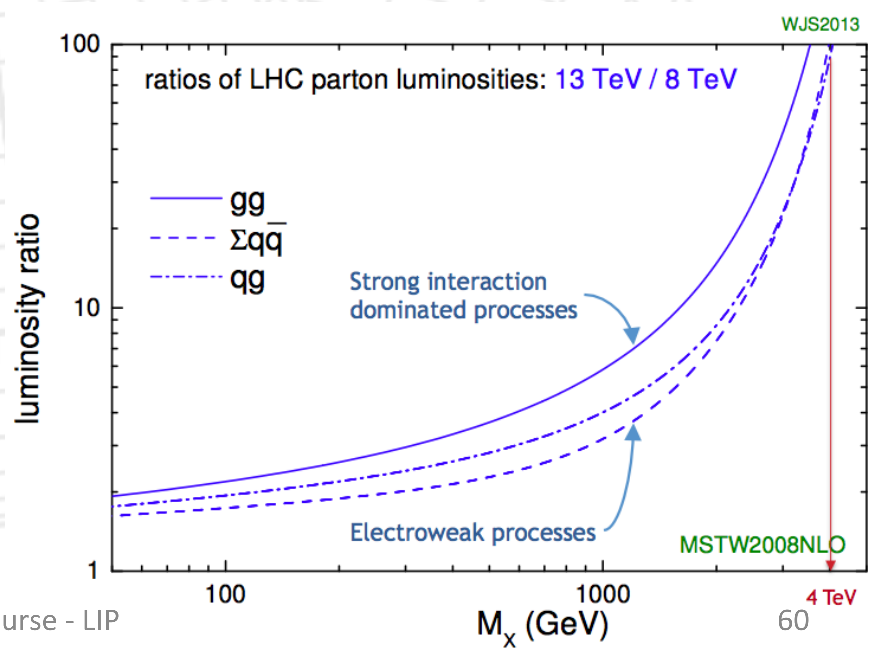


Not only more luminosity

- Higher centre of mass energy gives access to higher masses
- Hugely improves potential for discovery of heavy particles
- Increases cross sections limited by phase space
  - E.g. ttH increases faster than background (factor 4)
- But may make life harder for light states
  - E.g. only factor 2 increase for WH/ZH, H→bb and more pileup
  - Could be compensated by use of boosted jet techniques (jet substructure)



http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html



Run II/High-Lumi LHC Programme

Precision AND searches!

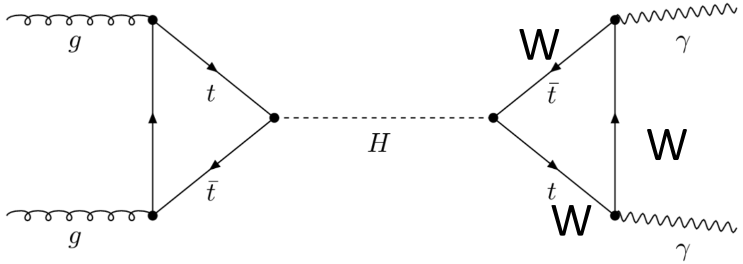
- Precision:
  - Continue to look for deviations wrt Standard Model
- Differential cross sections:
  - New physics in loops could modify event kinematics
- Complete measurement of properties:
  - E.g. CP quantum numbers:
  - Sensitivity in H→ZZ and VBF
  - Search for CP violation in Higgs sector
- Search for rare decay modes:
  - H→HH to access self coupling (long term!)
- Search for additional Higgs bosons:
  - E.g. 2-Higgs Doublet Model is a natural extension and predicted in SUSY

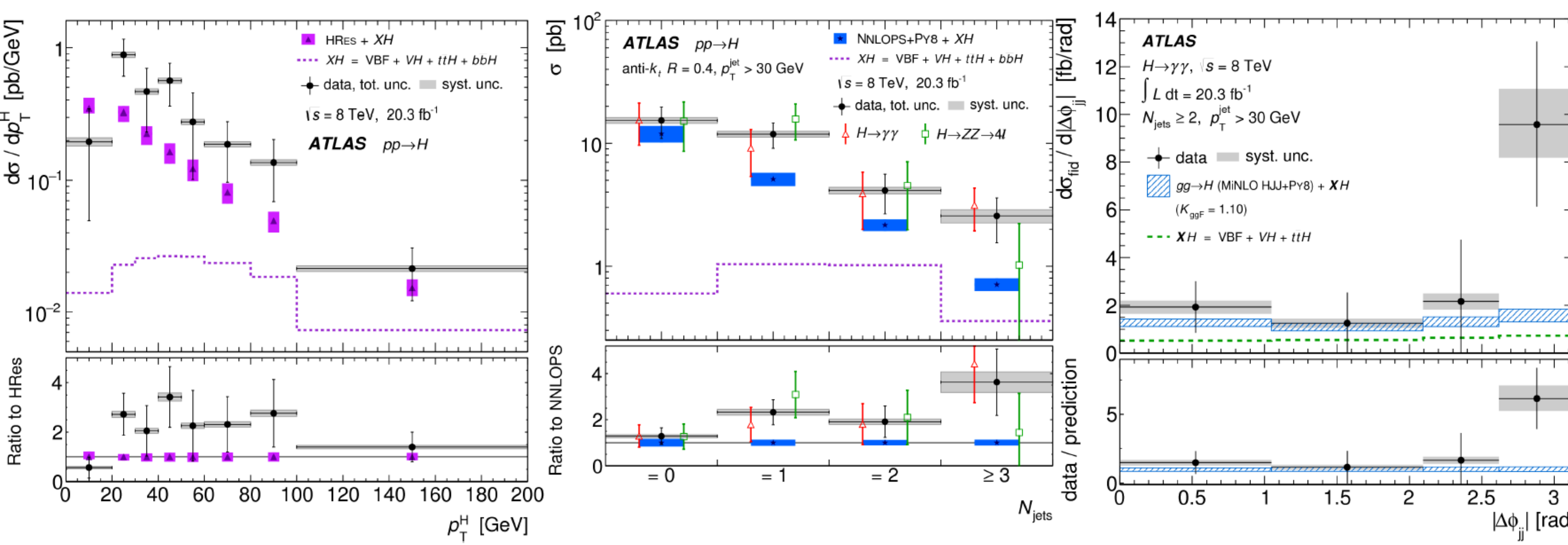
Luminosity	$H \to Z\gamma$	$H \to \mu\mu$	$H \to$ Invisible
300fb^{-1}	$2.3\ \sigma$	$2.3\ \sigma$	$Br < 23\%$
3000fb^{-1} HL-LHC	$3.9\ \sigma$	$7.0\ \sigma$	$Br < 8\%$

ATL-PHYS-PUB-2014-006 ATL-PHYS-PUB-2013-014 ATL-PHYS-PUB-2013-014

Higgs differential cross sections

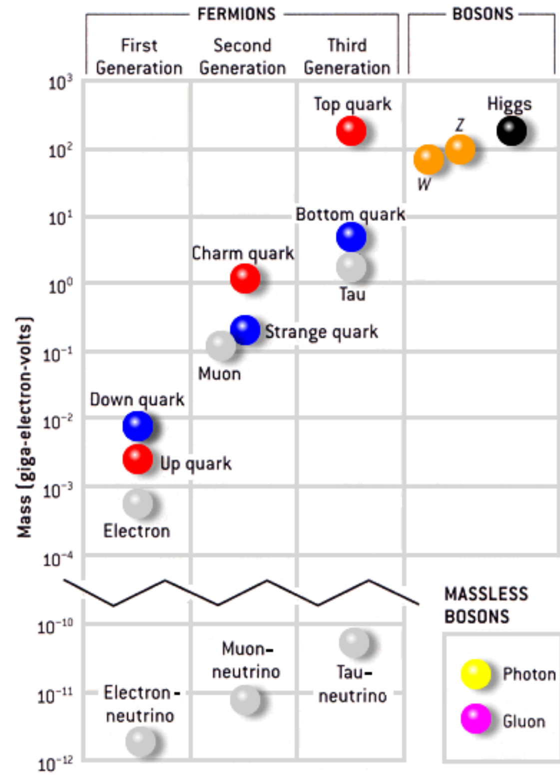
- Get access to the loop structure where there may be new physics
- ATLAS H→γγ and ZZ so far – more to come in run 2

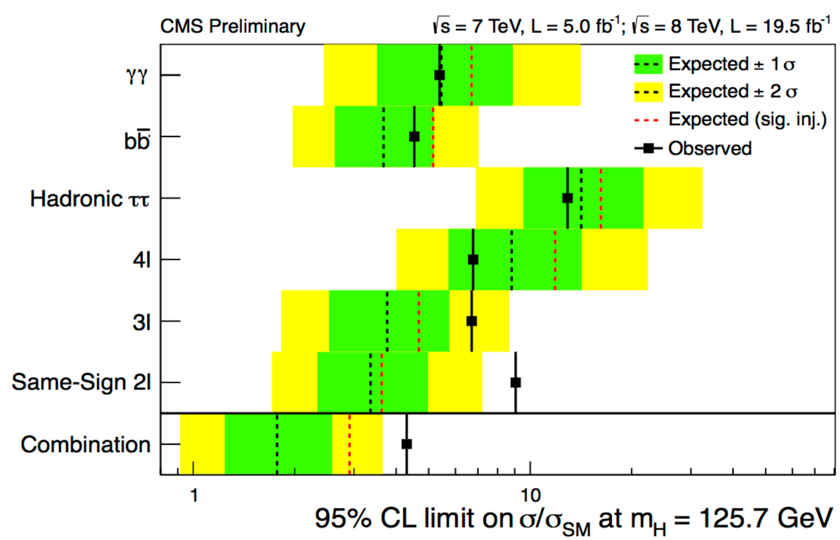


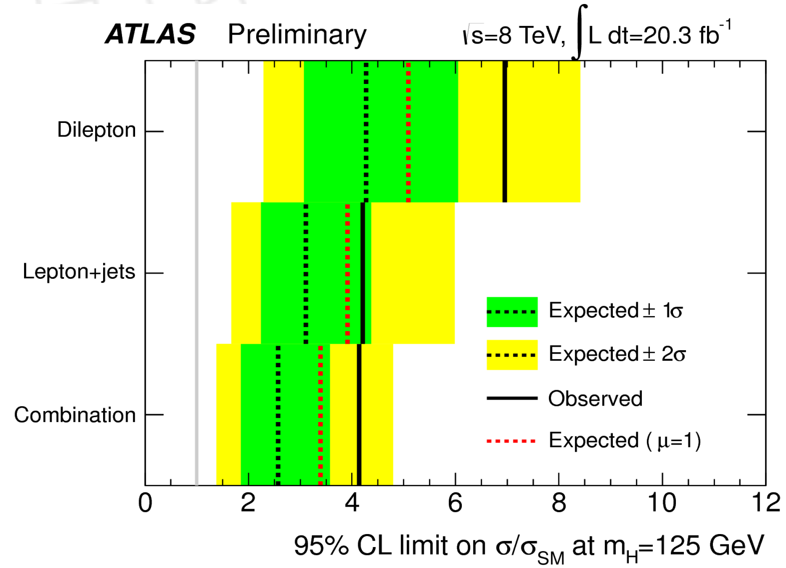


Another example: ttH

- Indirect constraints on top-Higgs Yukawa coupling from loops in ggH and ttH vertices
  - Assumes no new particles contribute to loops
- Top-Higgs Yukawa coupling can be measured directly
  - Allows probing for New Physics contributions in the ggH and γγH vertices
- Top Yukawa coupling $Y_t = \sqrt{2}M_t/vev = 0.996 \pm 0.005$
  - Does this mean top plays a special role in EWSB?

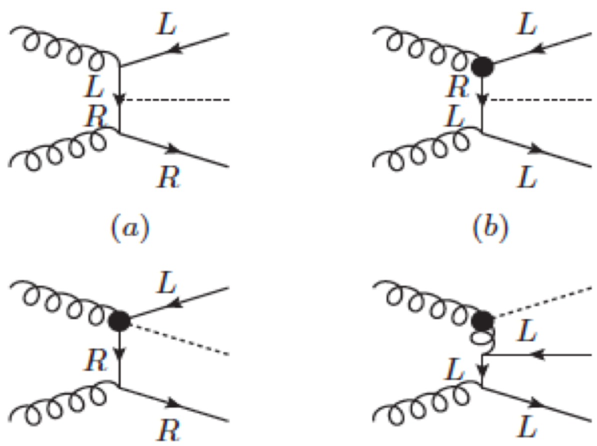




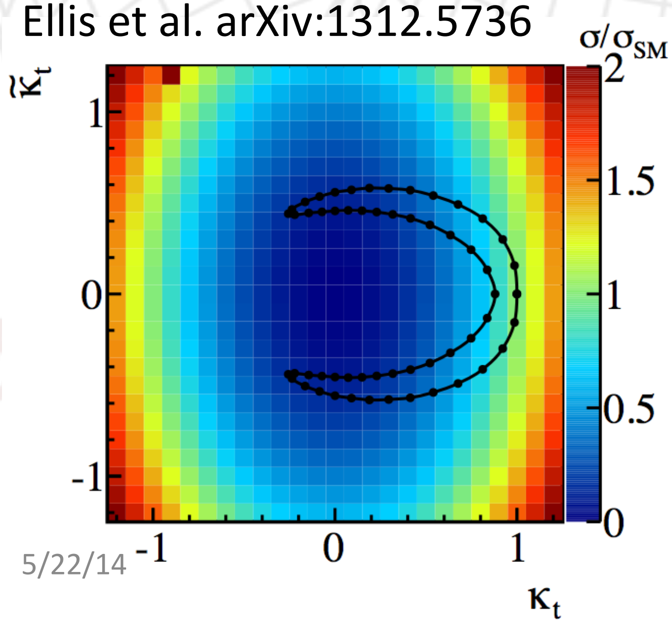


Sensitivity to New Physics

Degrande et al. arXiv:1205.1065



Ellis et al. arXiv:1312.5736

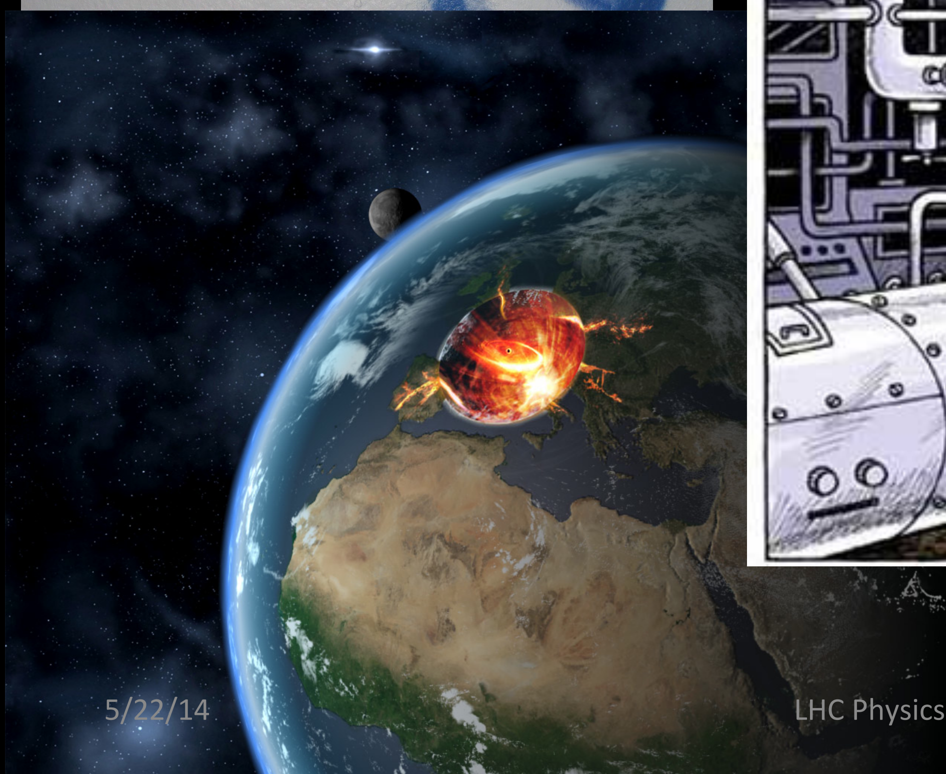


- Effective top-Higgs Yukawa coupling may deviate from SM due to new higher-dimension operators
  - Change **event kinematics –** go differential!
- ttH sensitive new physics: little Higgs, composite Higgs, Extra Dimensions,…
- In the presence of CP violation, Higgs-top coupling have scalar (κ_t)and pseudoscalar ($\tilde{\kappa}_t$)components
  - Strong dependence on ttH cross section
  - Note: Indirect constraints from electron electric dipole moment not taken into account (give $|\tilde{\kappa}_t| < 0.01$)

Summary

- Recapitulation:
  - Electroweak symmetry breaking
  - Higgs boson in Electroweak Lagrangian
  - Higgs boson production and decay at the LHC
  - The landscape at the end of LHC run I
- The Higgs sector beyond the Standard Model
  - Constraints from current data
  - Examples of rare and exotic channels
- Future Higgs measurements at LHC and beyond
  - Fundamental questions at the end of run I
  - Future LHC running – luminosity, energy, and physics reach
  - Higgs physics in future LHC analyses – Precision and Searches
  - An example: associated production with top-quark pair – SM and BSM

Backup Slides



Direct BSM Higgs Searches (ATLAS)

- FCNC in t→cH, H→γγ - upper limit on BR: Obs.(Exp.): 0.83%(0.53%) x SM for 125 GeV at 95% CL [ATLAS-CONF-2013-081]
- H→ZZ→llνν: Excl. 320 - 560 GeV [ATLAS-CONF-2012-016]
- H→ZZ→llqq: Excl. 300 - 310, 360 - 400 GeV. at 145 GeV 3.5 x SM [ATLAS-CONF-2012-017]
- H→WW→lνjj: at 400 GeV Obs.(Exp.) 2.3(1.6) x SM [ATLAS-CONF-2012-018]
- Higgs in SM with 4th fermion generation: model ruled out [ATLAS-CONF-2011-135]
- Fermiophobic H to diphoton Model ruled out [ATLAS-CONF-2012-013]
- MSSM neutral H [JHEP: JHEP02(2013)095]
- NMSSM a1 to μμ [ATLAS-CONF-2011-020]
- NMSSM H to a0a0 to 4γ [ATLAS-CONF-2012-079]
- H±→ cs [EPJC73 (2013) 2465]
- 2HDM WW(lνlν) [ATLAS-CONF-2013-027]

'It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth.'

Sherlock Holmes

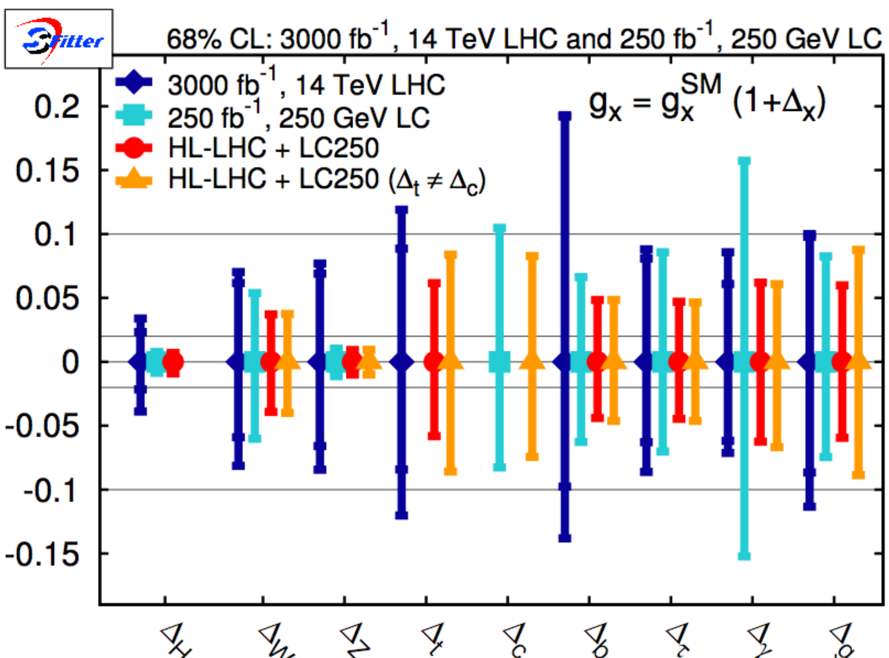
-The Beryl Coronet

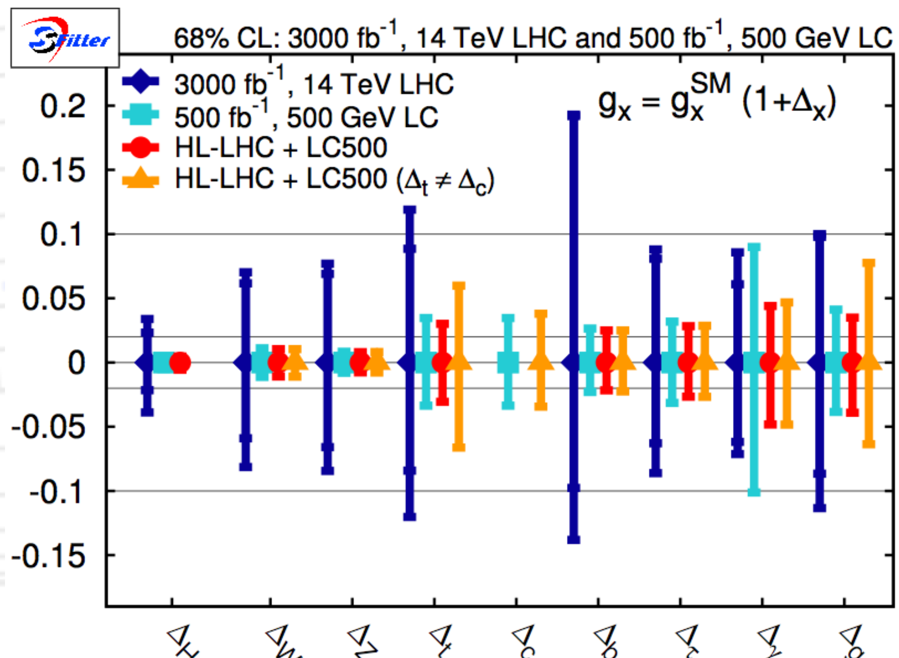
"THE PIPE WAS STILL BETWEEN HIS LIPS."

Future experimental programme

High-Luminosity LHC plus Linear Collider are "**dream team**" for Higgs properties!

- LHC ($\sqrt{s}$=14TeV and L=3000fb^{-1}) **systematics limited**
- Total width only at Linear Collider ($\sqrt{s}$=250GeV, L=250fb^{-1}: ≈10% accuracy)
- 2nd generation couplings (Δ_c, Δ_μ) challenging at LHC but possible at LC
- Δ_{top} opens up for LC500 ($\sqrt{s}$=500GeV, L=500fb^{-1}): ≈3-7% from HL-LHC + LC500
- Precision of **HL-LHC + LC** limited by LC statistical uncertainty, not systematics!
- **NOTE:** Not yet clear what machine will follow the LHC… but Higgs physics is a big part of it's physics motivation!

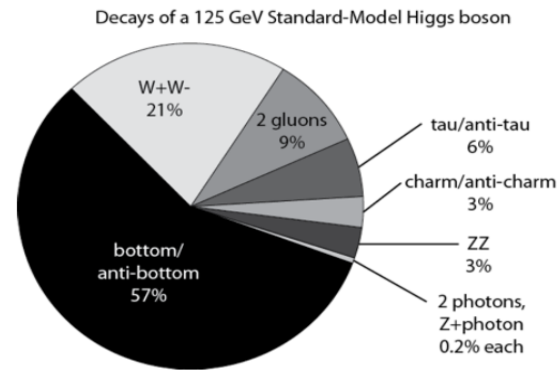




Klute et al, arXiv: 1301.1322

Event topology

For low M_H, H → bb is the dominant decay



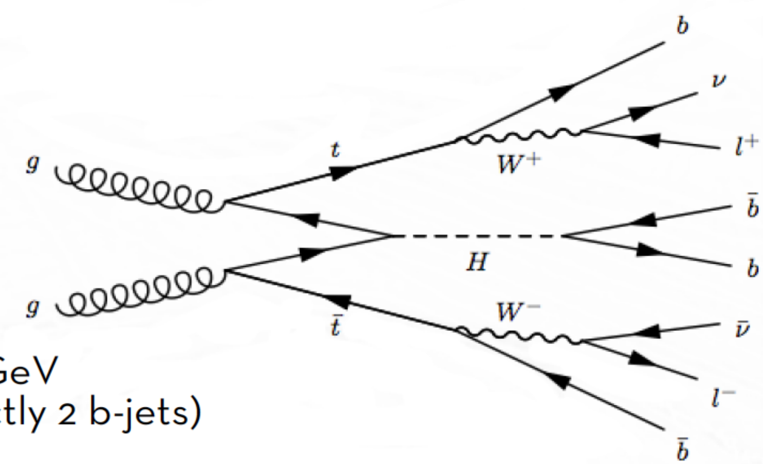
Consider Top and W decays:

l+jets

- Exactly 1 lepton with pT > 25 GeV & |η| < 2.5;
- At least 4 jets pT>25GeV & |η|<2.5, with at least 2 b-tagged ones;
- Veto of dilepton events;

Dilepton

- Exactly 2 leptons (e or μ) of opposite charge:
  leading l±: pT>25GeV & |η|<2.5
  subleading l±: pT>15GeV
- At least 2 jets, with at least 2 b-tagged ones;
- For eμ : H_T > 130 GeV
- For ee & μμ: M_{ll} > 15 GeV & |M_{ll} - 91 GeV|<= 8 GeV
  (M_{ll} > 60 GeV for events with exactly 2 b-jets)



B-tagged Jets with 70% efficiency 1% of light-jets mistag rate

Data at $\sqrt{s}$=8TeV recorded in 2012: $\mathcal{L}_{int}$ = 20.3 fb^{-1}

Higgs Property Measurements at LHC

- Higgs boson mass (M_H) & decay width (Γ_H)
  $\hookrightarrow$ M_H measured at 2-3 per mille precision. No sign of BSM in Γ_H, BR_{inv}.
- Higgs couplings to gauge bosons (g_V) and fermions (g_F)
  $\hookrightarrow$ Consistent with the SM prediction, $g_V \propto m_V^2$, $g_F \propto m_f$. Next, study in $d\sigma/dX$.
- Higgs boson quantum numbers J^{PC} and tensor structure
  $\hookrightarrow$ Evidence for scalar nature of 0^+. No evidence for CP-mixture.
- Higgs potential - Higgs self-coupling λ
  $\hookrightarrow$ Remains as an important territory to conquer in HL-LHC.
- Beyond the Standard Model Higgs (MSSM, 2HDM, etc.)
  $\hookrightarrow$ No evidence, but keep looking for BSM Higgs(es) and exotic Higgs decays.

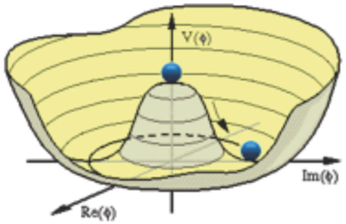
- We have observed the fist elementary particle of scalar - Higgs boson.
  - Brout-Englert-Higgs mechanism: what an incredible purely theoretical idea !!!
  - Experimentalists will make every endeavor for BSM physics discovery !!
- LHC - hadron collider now enters in precision measurement era !

The Terascale

Yukawa Couplings

Higgs Field

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}' + \mathcal{L}_{\rm Yuk} + \mathcal{L}_{\phi'}$$



$$\mathcal{L}_\phi = (\partial_\mu \phi^\dagger)(\partial^\mu \phi) - V(\phi)$$

Higgs Potential

$$\mathcal{L}_{\rm Yuk} = c_f(\bar{\psi}_L \psi_R \phi + \bar{\psi}_R \psi_L \phi)$$

Higgs Fermion Interaction

Gauge Boson masses: $i\partial_\mu \to i(\partial_\mu - ieA_\mu)$

Fermion masses: $c_f \bar{\psi}\psi\phi$

and $\phi' = \phi - \rho_0$

Vacuum expectation value

The SM Lagrangian

Free Fields

Interaction

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}'$$

Gauge Bosons

$$\mathcal{L}_0 = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^\mu\partial_\mu\psi$$

Fermions

$$\mathcal{L}' = e\bar{\psi}\gamma^\mu A_\mu\psi$$

Fermion-Boson Coupling

$$eA_\mu = \frac{g_s}{2}\lambda_\nu G^\nu_\mu + \frac{g}{2}\vec{\tau}\,\vec{W}_\mu + \frac{g'}{2}Y B_\mu$$

$$F_{\mu\nu}F^{\mu\nu} = G_{\mu\nu}G^{\mu\nu} + W_{\mu\nu}W^{\mu\nu} + B_{\mu\nu}B^{\mu\nu}$$

$$\boxed{\mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_h + \mathcal{L}_y.}$$

Electroweak Lagrangian before spontaneous symmetry breaking

$$\mathcal{L}_g = -\frac{1}{4}W^{a\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}$$

Electroweak gauge bosons: B^0 W^0 $W^\pm$

$$\mathcal{L}_f = \overline{Q}_i i \not{D} Q_i + \overline{u}_i i \not{D} u_i + \overline{d}_i i \not{D} d_i + \overline{L}_i i \not{D} L_i + \overline{e}_i i \not{D} e_i$$

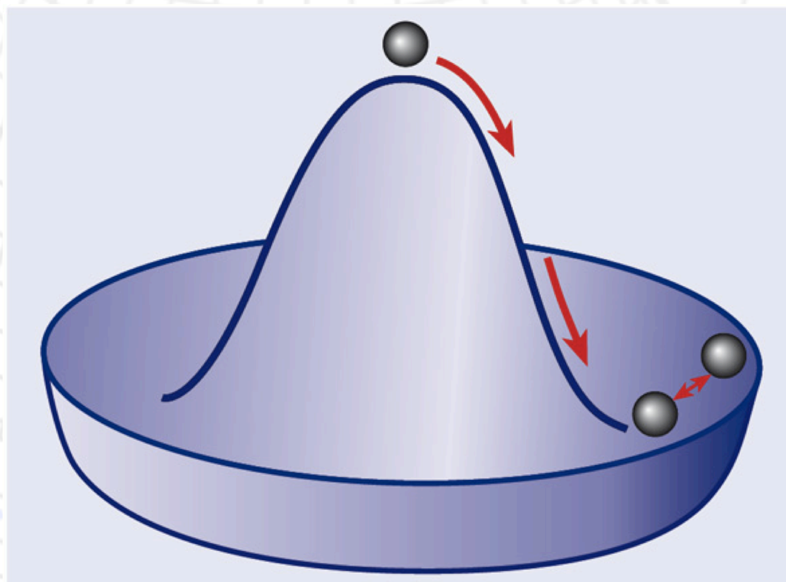
Fermion kinetic terms

$$\mathcal{L}_h = |D_\mu h|^2 - \lambda \left(|h|^2 - \frac{v^2}{2}\right)^2$$

Higgs term (note: vacuum expectation value zero before symmetry breaking)

$$\mathcal{L}_y = -y_{u\,ij}\epsilon^{ab} h_b^\dagger \overline{Q}_{ia} u_j^c - y_{d\,ij} h \overline{Q}_i d_j^c - y_{e\,ij} h \overline{L}_i e_j^c + h.c.$$

Yukawa interaction term between Higgs field and fermions



Massive Higgs boson: transverse oscillation mode

Spontaneous symmetry breaking:
New bosons γ and Z^0 from W^0 and B^0

$$\begin{pmatrix}\gamma \\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B^0 \\ W^0\end{pmatrix}$$

$$\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_H + \mathcal{L}_{HV} + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_Y$$

After sym. breaking

$$\mathcal{L}_K = \sum_f \overline{f}(i\partial\!\!\!/ - m_f)f - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} + m_W^2 W^+_\mu W^{-\mu}$$
$$-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \frac{1}{2}m_H^2 H^2$$

Kinetic terms: notice boson masses (Z,W,H)!

$$\mathcal{L}_N = eJ_\mu^{em}A^\mu + \frac{g}{\cos\theta_W}(J_\mu^3 - \sin^2\theta_W J_\mu^{em})Z^\mu$$

$$\mathcal{L}_C = -\frac{g}{\sqrt{2}}\left[\overline{u}_i\gamma^\mu\frac{1-\gamma^5}{2}M_{ij}^{CKM}d_j + \overline{\nu}_i\gamma^\mu\frac{1-\gamma^5}{2}e_i\right]W_\mu^+ + h.c.$$

Neutral and charged current terms: fermions and gauge boson interactions

$$\mathcal{L}_H = -\frac{gm_H^2}{4m_W}H^3 - \frac{g^2m_H^2}{32m_W^2}H^4$$

Higgs boson 3- and 4-point self-interaction

$$\mathcal{L}_{HV} = \left(gm_W H + \frac{g^2}{4}H^2\right)\left(W_\mu^+W^{-\mu} + \frac{1}{2\cos^2\theta_W}Z_\mu Z^\mu\right)$$

Higgs boson interaction with gauge bosons

Gauge boson self interaction:

$$\mathcal{L}_{WWV} = -ig[(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})(A^\nu\sin\theta_W - Z^\nu\cos\theta_W) + W^-_\nu W^+_\mu(A^{\mu\nu}\sin\theta_W - Z^{\mu\nu}\cos\theta_W)]$$

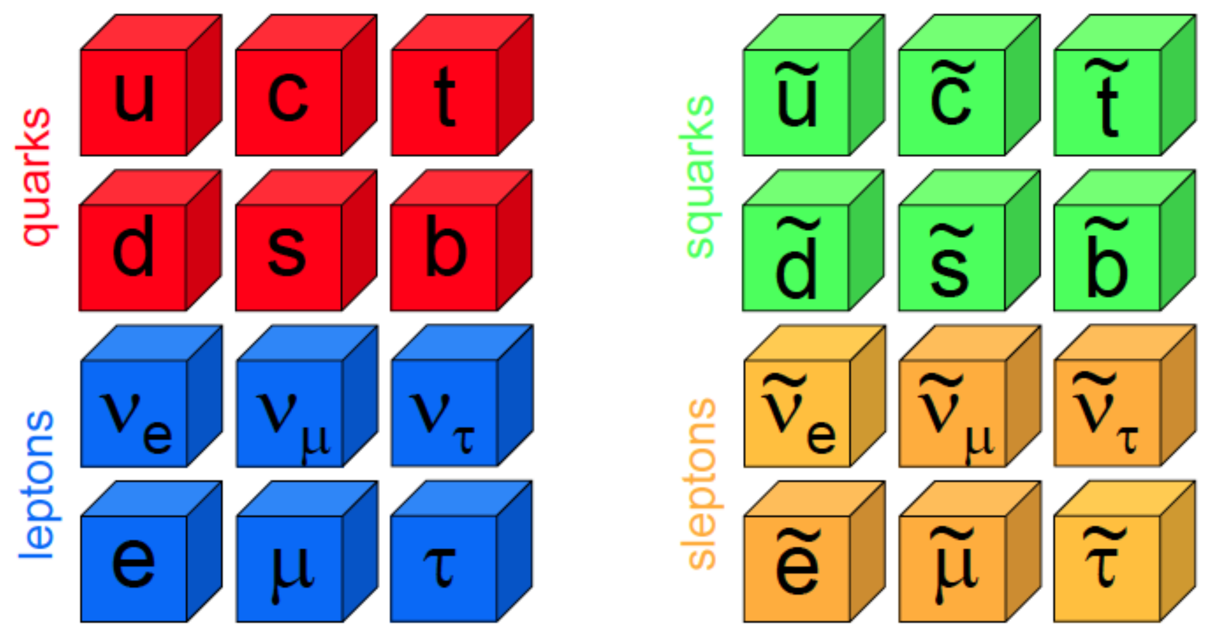
$$\mathcal{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W_\mu^+W^{-\mu} + (A_\mu\sin\theta_W - Z_\mu\cos\theta_W)^2]^2$$
$$- [W_\mu^+W_\nu^- + W_\nu^+W_\mu^- + (A_\mu\sin\theta_W - Z_\mu\cos\theta_W)(A_\nu\sin\theta_W - Z_\nu\cos\theta_W)]^2\Big\}$$

$$\mathcal{L}_Y = -\sum_f \frac{gm_f}{2m_W}\overline{f}fH$$

Yukawa interactions between Higgs and fermions: note fermion masses!

Supersymmetry

Double the whole table with a new type of matter?



Heavy versions of every quark and lepton

Supersymmetry is broken

Could DM be SUSY particles?

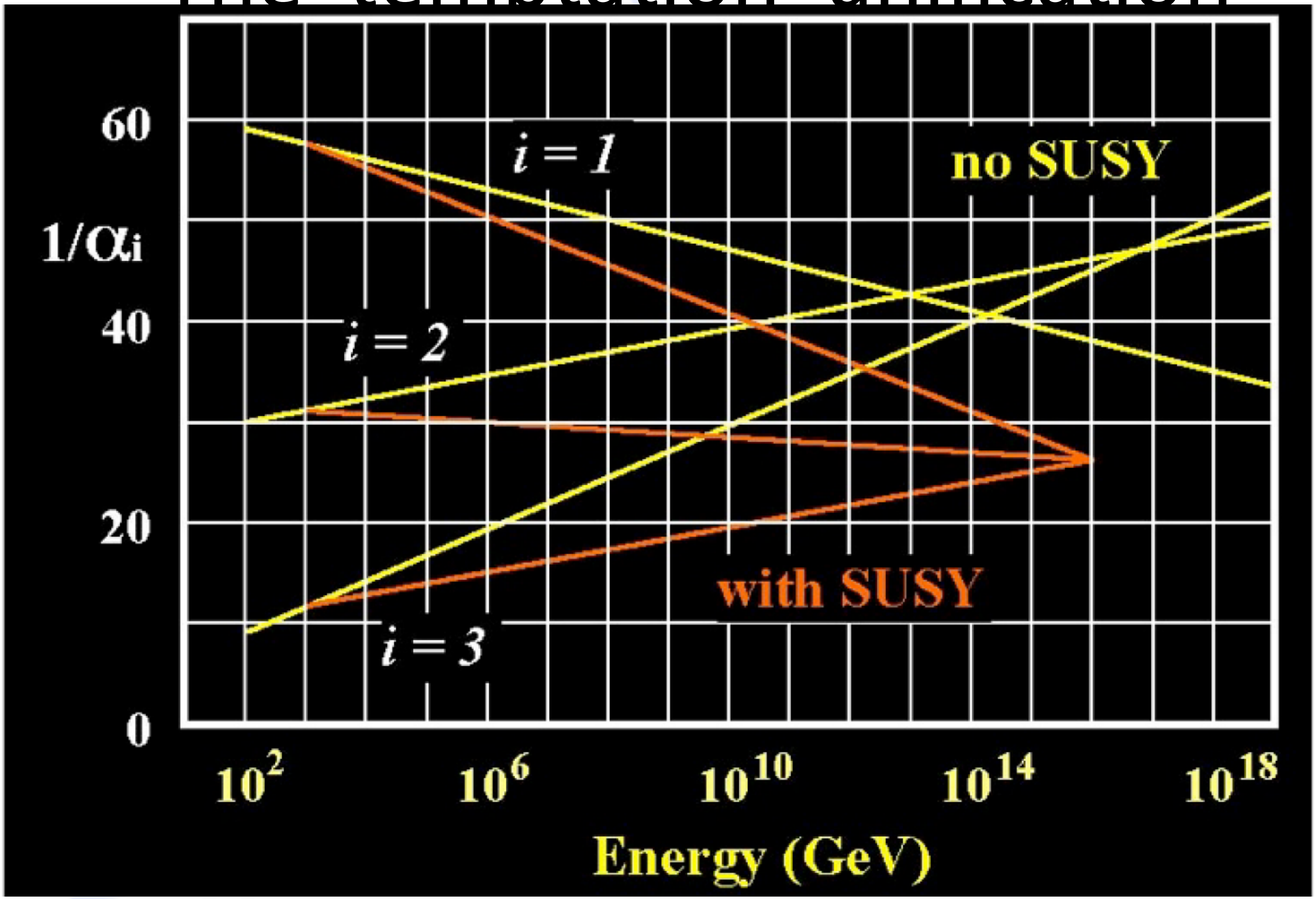
For every "normal" force quanta (boson), there are supersymmetric partners:

photon	photino
W, Z bosons	Wino, Zino
gluon	gluino
Higgs boson	higgsino

These "...inos" are prime suspects to be the galactic dark matter!

Relics from the Big Bang!

The temptation unification



Extra dimensions

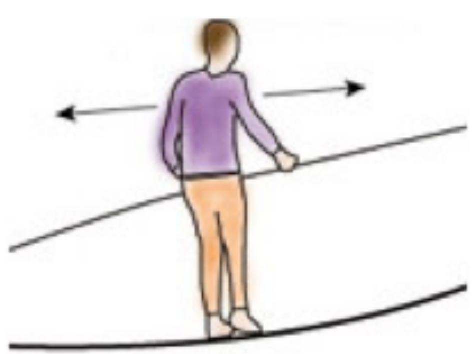
Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

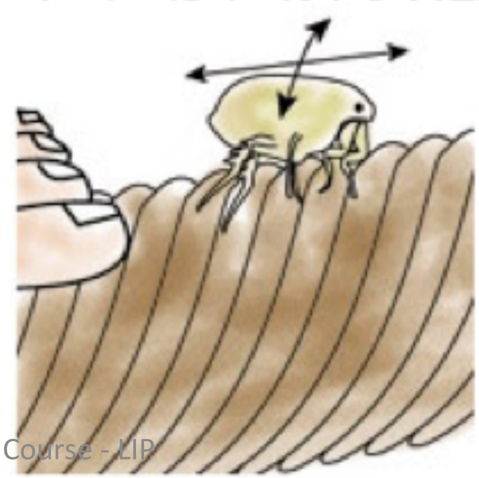
How can there be extra, smaller dimensions?

The acrobat can move forward and backward along the rope: **one dimension**

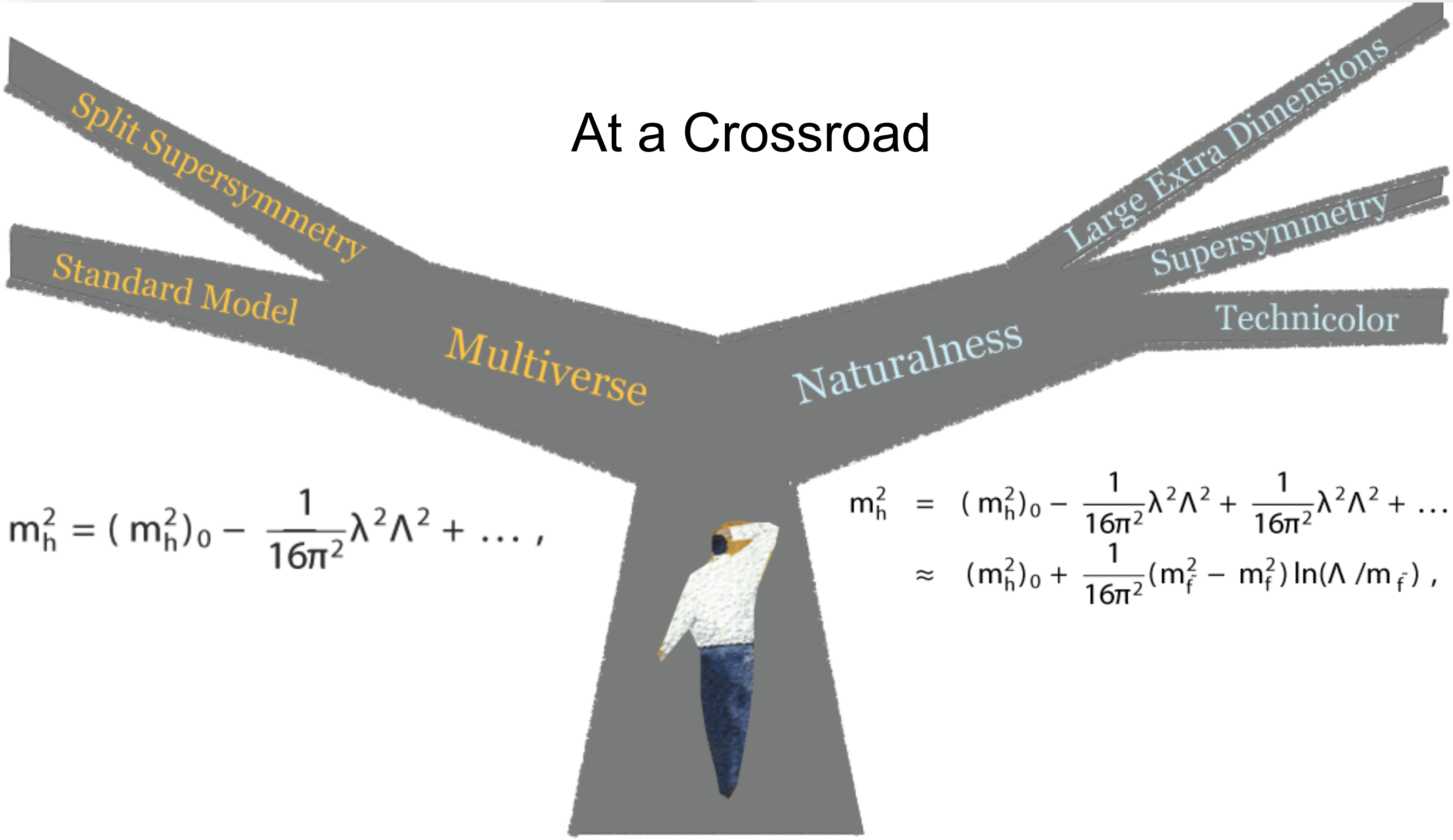
The flea can move forward and backward as well as side to side: **two dimensions**

But one of these dimensions is a small closed loop.





Naturalness

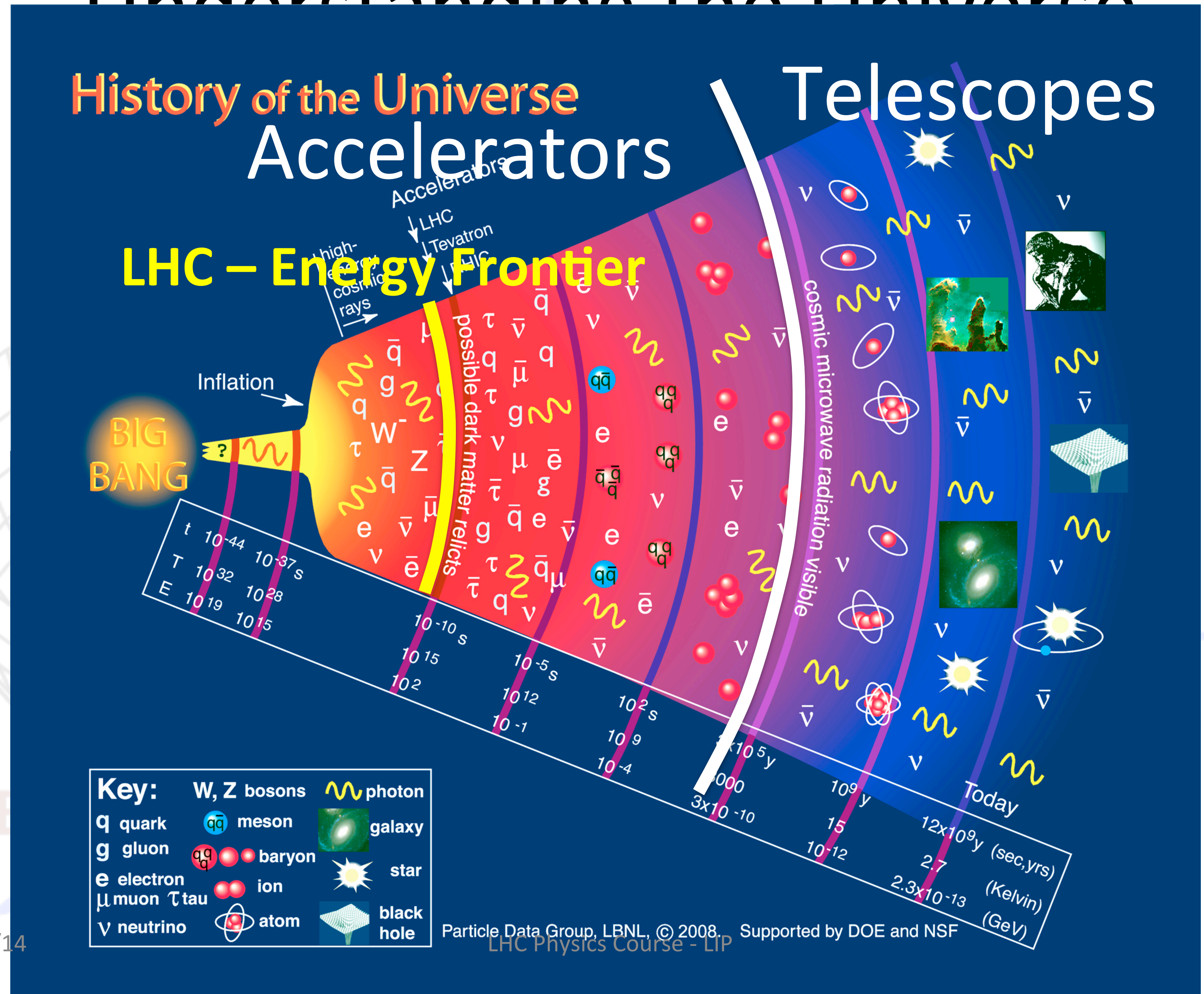


$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

$$\begin{aligned} m_h^2 &= (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots \\ &\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda / m_{\tilde{f}}) , \end{aligned}$$

Savas Dimopoulos, CERN Colloquium, Sep 20, 2012

Understanding the Universe

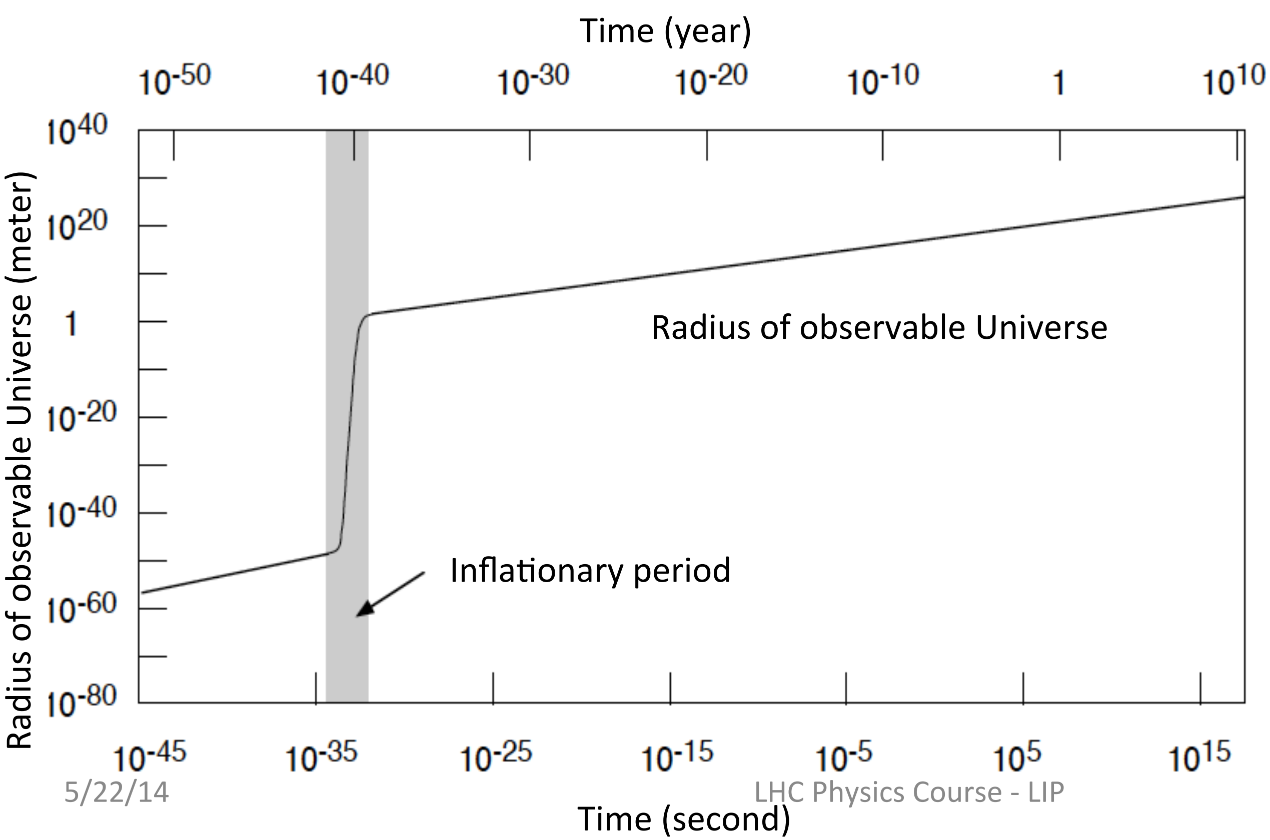


Cosmological inflation

In the very early universe, the physical vacuum undergoes a transition from a high energy state to a low energy state.

The resulting energy shift drives a dramatic exponential expansion.

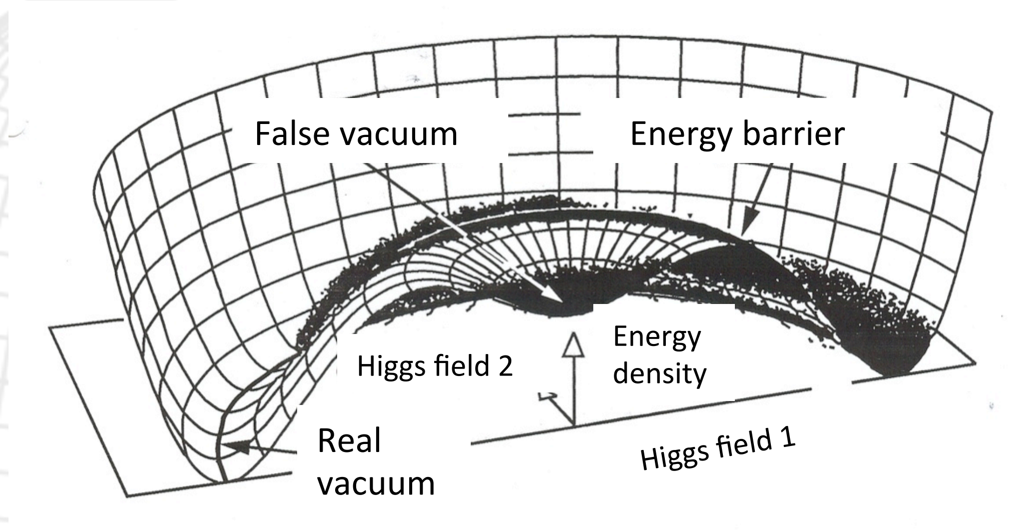
Explains why the Universe has a uniform Temperature (3 K)



The inflation theory was developed independently in the late 1970's by Alan Guth, Alexey Starobinsky, and others

Higgs like field and inflation

Before the inflation (10^{-34} s), the Higgs-like field is trapped is a state of false vacuum.



The Universe undergoes a super-cooling transition: the temperature decreases below the phase transition point but the Higgs field stays in the false vacuum state.

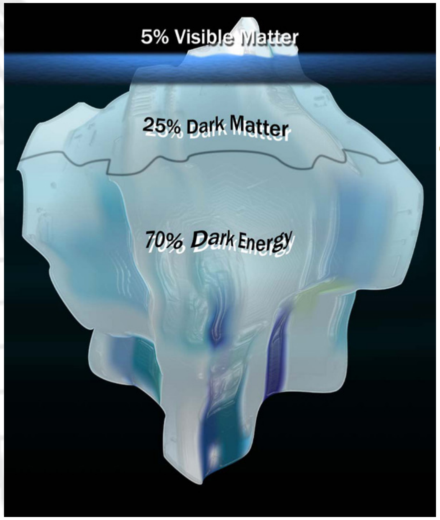
While the energy density of the Higgs field is positive, the Universe expands at accelerated rate (inflation) and the energy stored in the Higgs field increases.

Inflation stops when the Higgs field decays to the real vacuum.

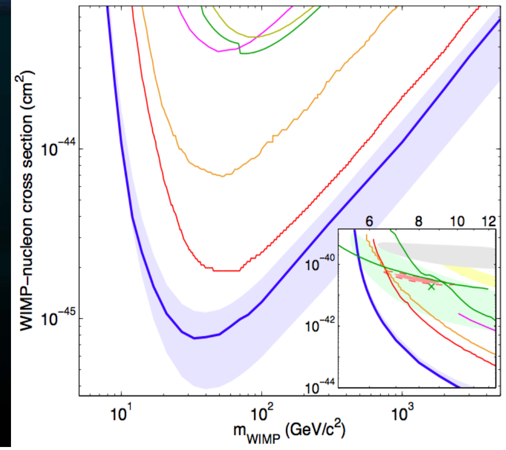
The energy released by the Higgs field is converted into matter particles.

So, where do we stand?

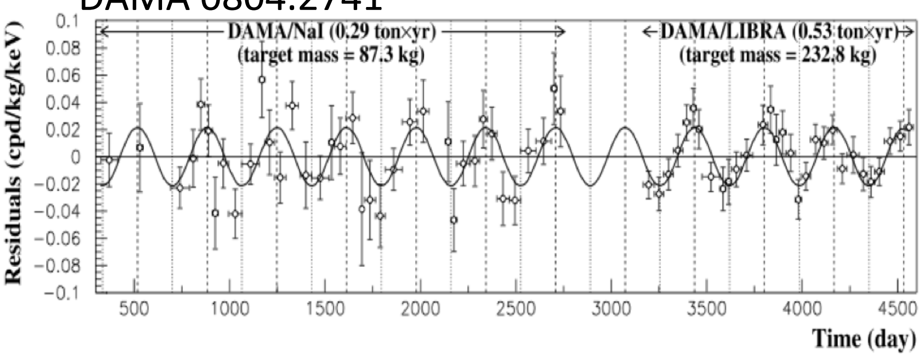
- We have found the **missing piece** of the Standard Model puzzle
- The current data show us a **SM-like** Higgs boson
  - Each channel not so well measured
  - But combination fits well with expectations
- **Is this the end of the story?**



LUX 1310.8214



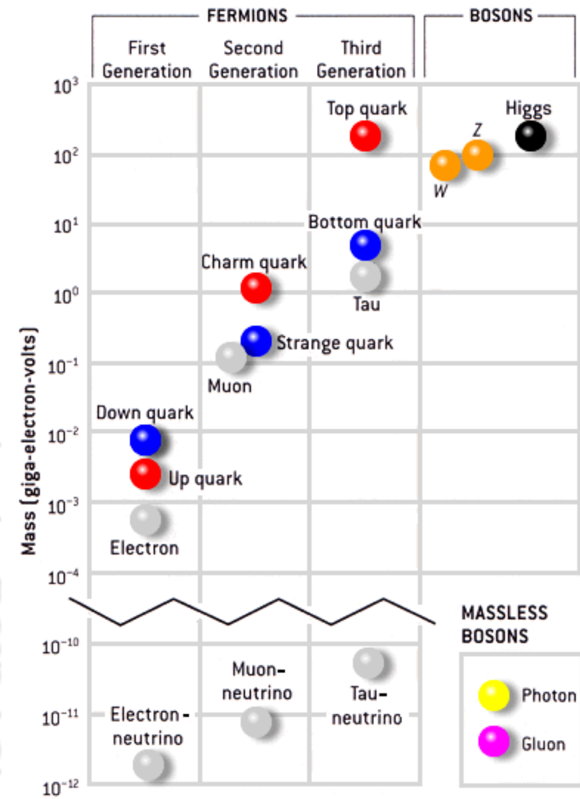
DAMA 0804.2741

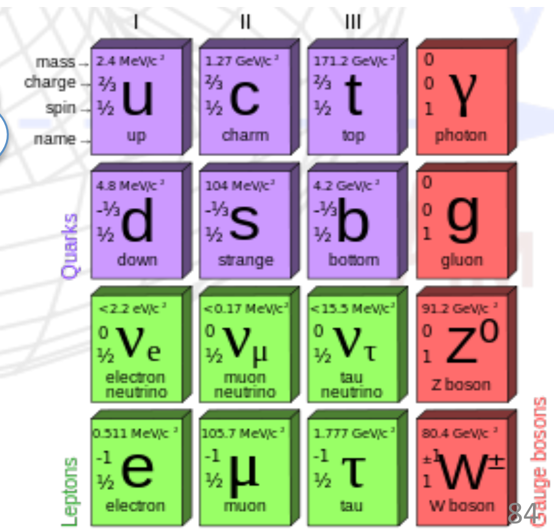


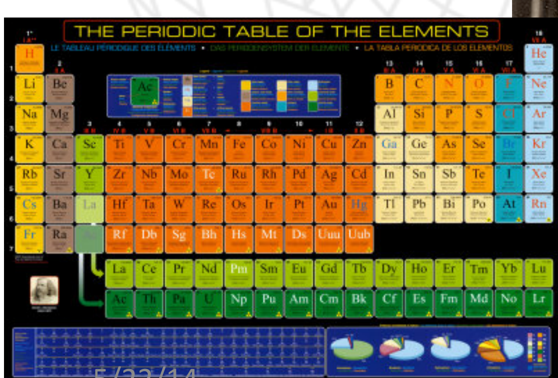
Discovery → Precision! (& a few more channels)

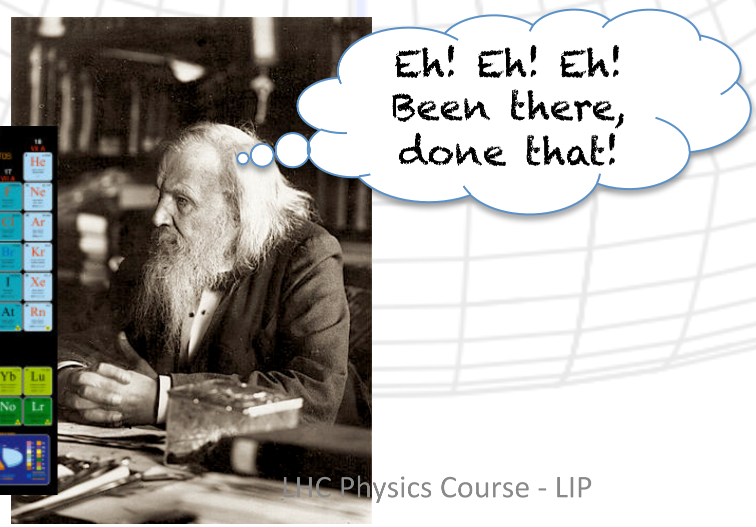
Many questions…

- Higgs mechanism says **how** to give mass to fundamental particles
- It doesn't say **why** fermion masses and Yukawa couplings are so different:
  - 10^{-10}GeV (ν) – 10^{2}GeV (t)
- Top mass at the EW scale. Does it play a special role in breaking it?
- (And by the way… why 3 families of leptons and quarks?)
- What is the underlying theory?

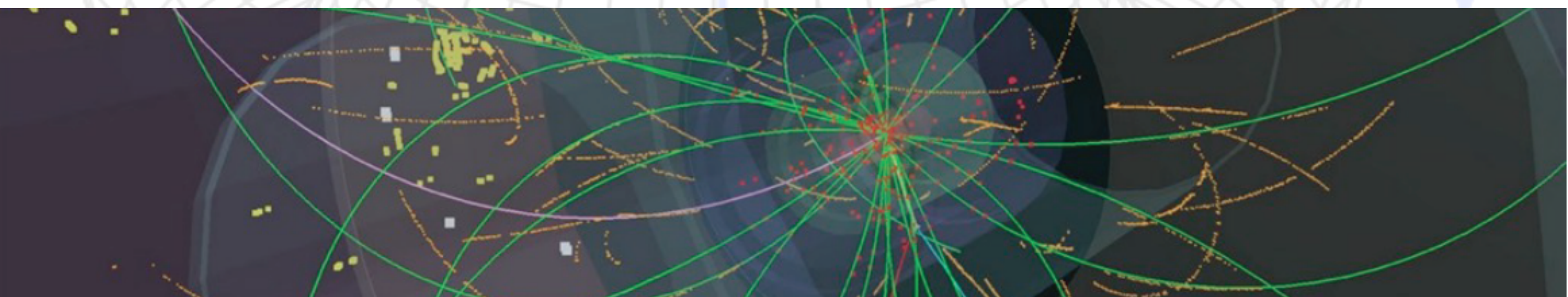








Luminosity and cross-section measurements



Cross section & Luminosity

Number of observed events

just count …

Background

measured from data or calculated from theory

$$\sigma = \frac{N^{obs} - N^{bkg}}{\int \mathcal{L}\,dt \cdot \varepsilon}$$

Luminosity

determined by accelerator, triggers, …

Efficiency

many factors, optimized by experimentalist

Cross section & Luminosity

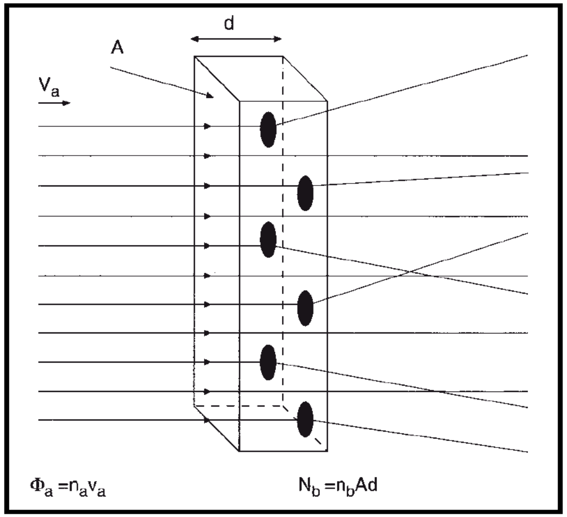
Luminosity
[Machine parameter]

$$\dot{N} = L \cdot \sigma$$

Event Rate
[Measured]

Cross Section

Cross section & Luminosity



$$\Phi_a = \frac{\dot{N}_a}{A} = n_a v_a$$

Φ_a : flux
n_a : density of particle beam
v_a : velocity of beam particles

$$\dot{N} = \Phi_a \cdot N_b \cdot \sigma_b$$

$\dot{N}$: reaction rate
N_b : target particles within beam area
σ_a : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

$$\dot{N} \equiv L \cdot \sigma$$

$$N = \sigma \cdot \underbrace{\int L\, dt}_{\text{integrated luminosity}} \qquad \sigma = N/L$$

Collider experiment:

$$\Phi_a = \frac{\dot{N}_a}{A} = \frac{N_a \cdot n \cdot v/U}{A} = \frac{N_a \cdot n \cdot f}{A}$$

$$L = f \frac{n N_a N_b}{A} = f \frac{n N_a N_b}{4\pi \sigma_x \sigma_y}$$

LHC:

N_x	~	10^{11}
A	~	.0005 mm^2
n	~	2800
f	~	11 kHz
L	~	10^{34} $cm^{-2}\ s^{-1}$

N_a : number of particles per bunch (beam A)
N_b : number of particles per bunch (beam B)
U : circumference of ring
n : number of bunches per beam
v : velocity of beam particles
f : revolution frequency
A : beam cross-section
σ_x : standard deviation of beam profile in x
σ_y : standard deviation of beam profile in y

Luminosity determination @ LHC

Absolute Methods:

Accuracy: 10%

Determination from LHC parameters; van-der-Meer separation scans ...
Rate measurement for standard candle processes ...

LHC Examples:

Rate of pp ➛ Z/W ➛ $\ell\ell/\ell\nu$ [needs: electroweak cross sections]

Accuracy: 5-10%
[PDF knowledge, ...]

Rate of pp ➛ γγ ➛ μμ, ee [needs: QED & photon flux]

Accuracy: 1% ?
[TDR; needs forw. tagging]

Optical theorem: σ_{tot} ~ Im f(0) [needs: forward elastic and total inel. x-sec]
Elastic scattering in Coulomb region ...

Accuracy: 5-10%
[needs σ_{tot}; needs forw. instrumentation]
TOTEM

Combination of the above ...

Accuracy: 2-3%

Relative Methods:

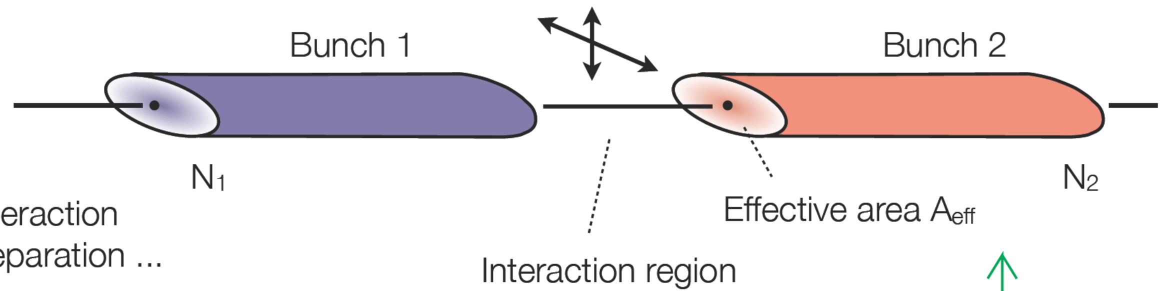
Particle counting; **LUCID @ ATLAS; HF, Pixels @ CMS**
[needs to be calibrated for absolute luminosity]

Aim: Luminosity accuracy of 2-3% ...

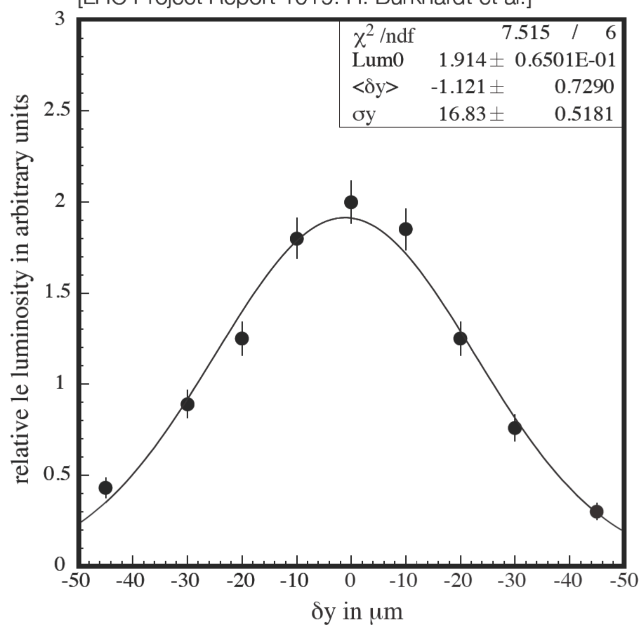
Van-der-Meer separation scan

Determine beam size ...

measuring size and shape of the interaction region by recording relative interaction rates as a function of transverse beam separation ...

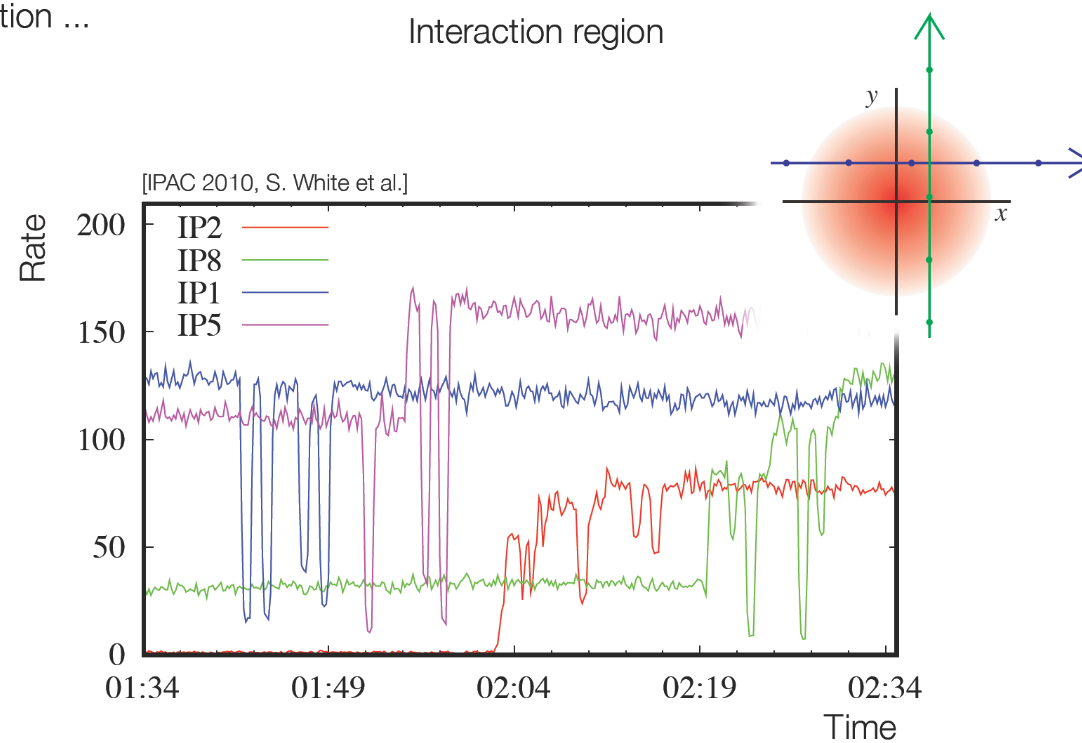


[LHC Project Report 1019: H. Burkhardt et al.]



$$\frac{L}{L_0} = \exp\left[-\left(\frac{\delta_x}{2\sigma_x}\right)^2 - \left(\frac{\delta_y}{2\sigma_y}\right)^2 \right]$$

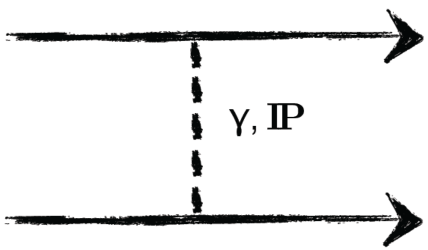
[IPAC 2010, S. White et al.]



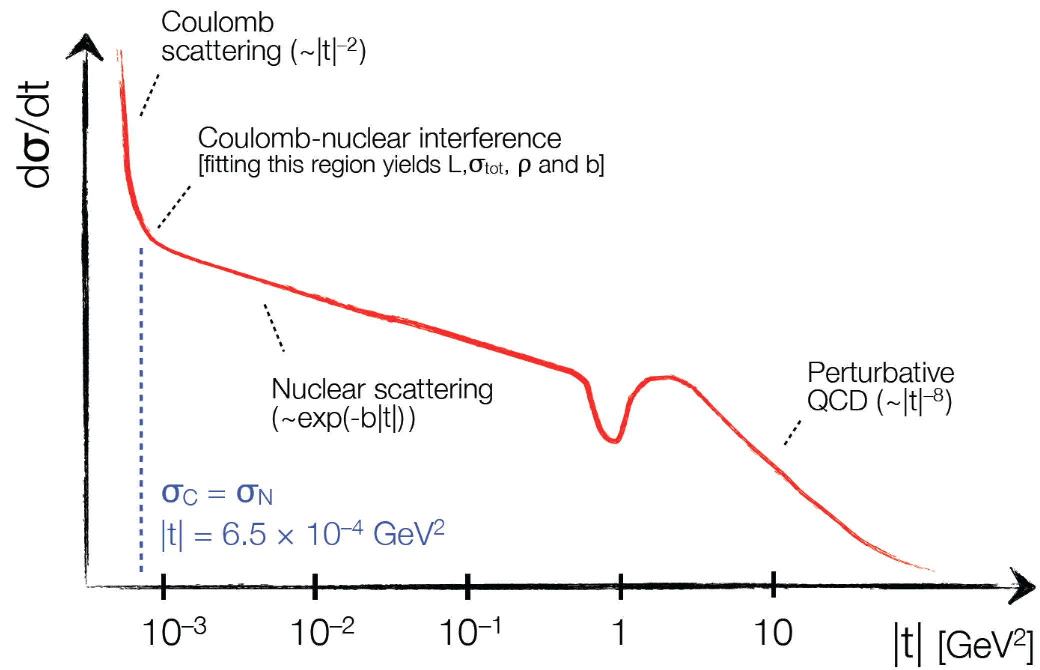
First optimization scans at LHC performed for squeezed optics in all IPs [November 2009].

Luminosity and elastic scattering

Elastic Scattering:



$$t = (p_i - p_i') \sim p^2\theta^2$$



Elastic Scattering at low t is sensitive to exactly known Coulomb amplitude ...

Shape of elastic scattering distribution can also be used to determine total cross section, σ_{tot}, and the parameters ρ and b ...

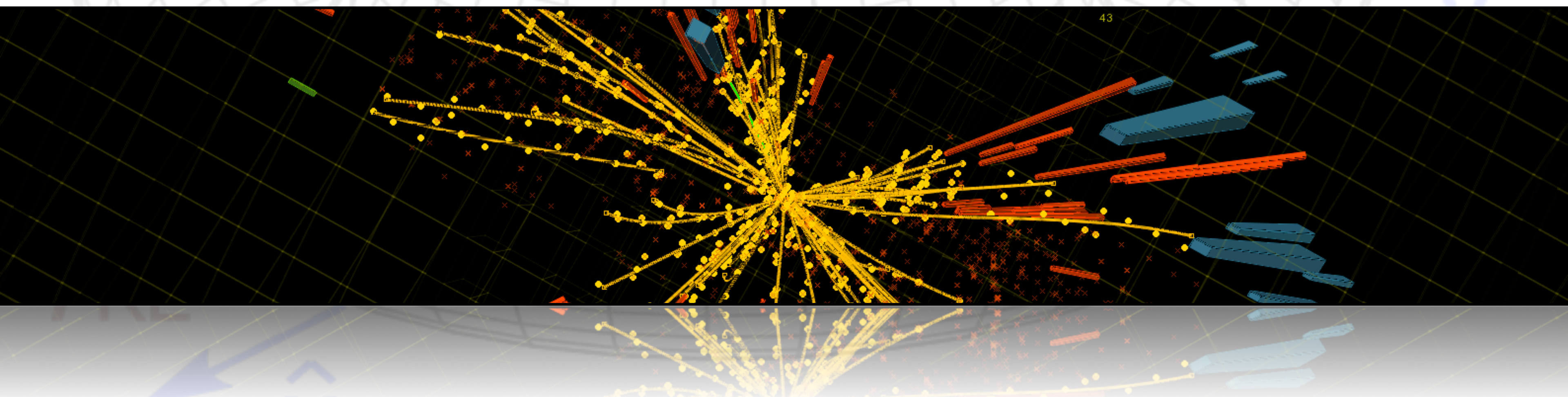
Perform fit to:

$$\frac{dN}{dt} = L\left(\underbrace{\frac{4\pi\alpha^2}{|t|^2}}_{\text{Coulomb Scattering}} - \underbrace{\frac{\alpha\rho\sigma_{tot}e^{\frac{-b|t|}{2}}}{|t|}}_{\text{Coulomb/nuclear Interference}} + \underbrace{\frac{\sigma_{tot}^2(1+\rho^2)e^{-b|t|}}{16\pi}}_{\text{Nuclear Scattering}}\right)$$

with:

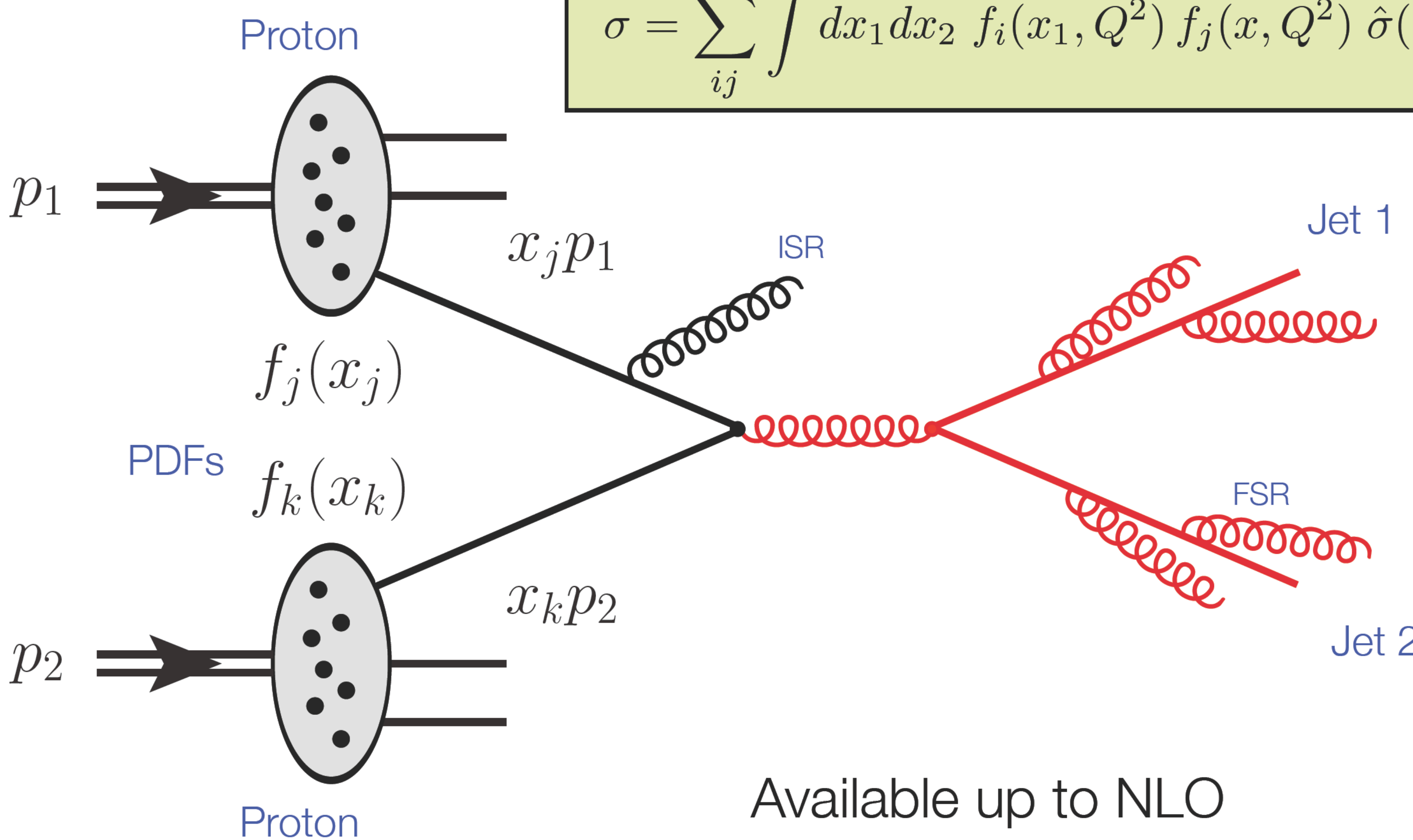
- ρ : ratio of the real to imaginary part of the elastic forward amplitude
- b : nuclear slope
- σ_{tot} : total pp ➛X cross section

Jet physics



Jet production @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \, f_j(x, Q^2) \; \hat{\sigma}(Q^2)$$



Available up to NLO

First NNLO calculations becoming available ...

Higher orders

At least next-to-leading order (NLO) required
to compare to precision measurements
[First NNLO calculations becoming available ...]

Various divergencies; artifacts of perturbation theory;
the full theory gives finite results ...
[But we don't know how to solve it]

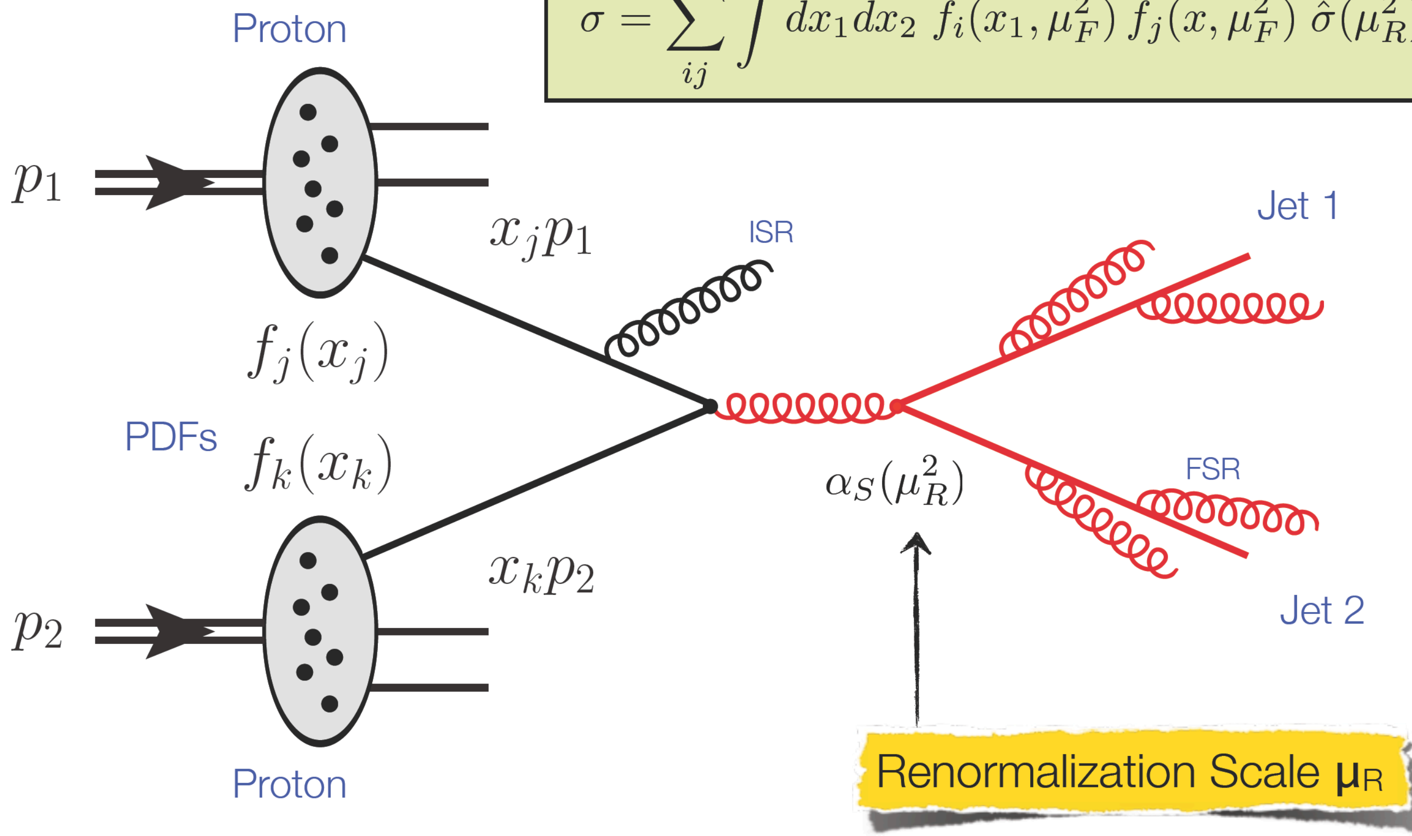
Ultraviolet (UV) divergences, i.e. at very large momenta
Solution: renormalization; choice of correct scale ...
["Status of peaceful coexistence with divergences", S.D. Drell]

Infrared (IR) divergences, i.e. at very small momenta
Solution: cancellations, factorization, IR-safe observables

Scale uncertainty

Factorization Scale μ_F

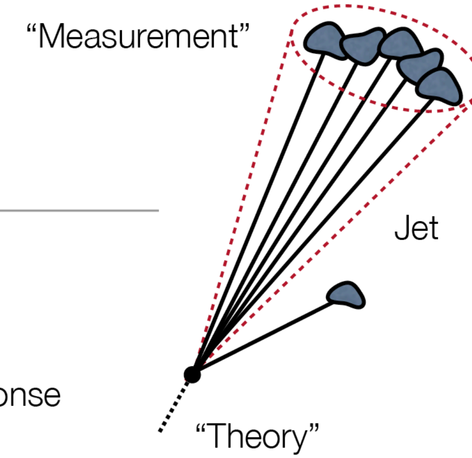
$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, \mu_F^2) \; f_j(x, \mu_F^2) \; \hat{\sigma}(\mu_R^2)$$

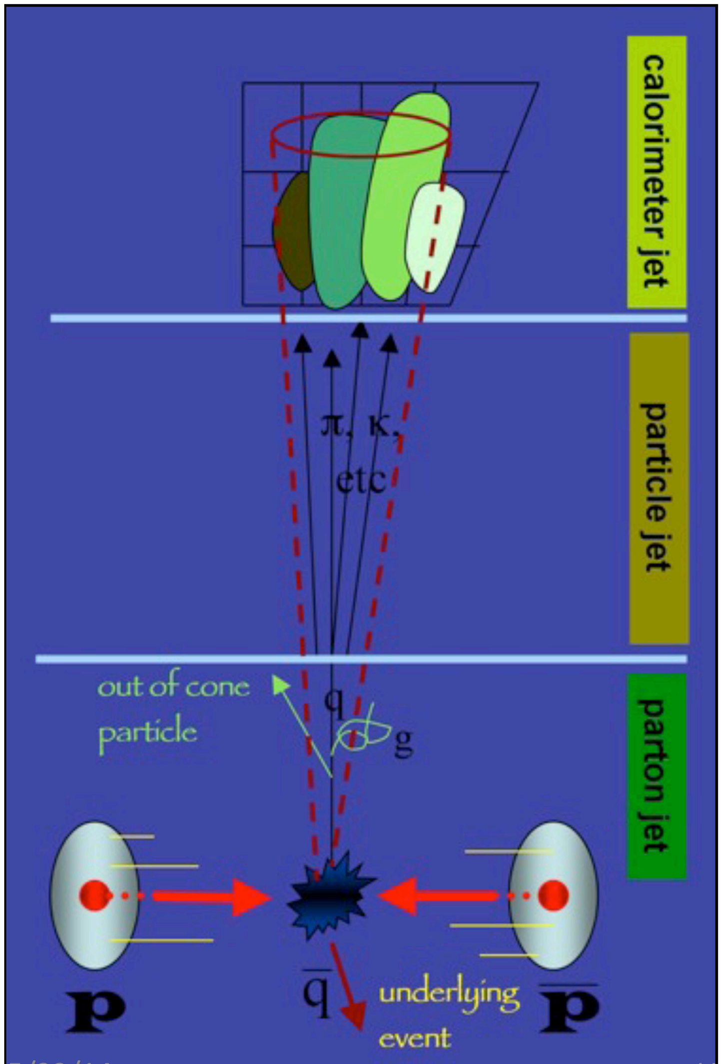


The default renormalization and factorization scales (μ_R and μ_F respectively) are defined to be equal to the p_T of the leading jet in the event

Scale uncertainty estimation: vary μ_R, μ_F within $[\mu_R/2, 2\mu_R]$ and $[\mu_F/2, 2\mu_F]$

Jet properties measurement





Calorimeter Jet
[extracted from calorimeter clusters]

Understanding of detector response
Knowledge about dead material
Correct signal calibration
Potentially include tracks

From measured energy to particle energy

Compensate energy loss due to neutrinos, nuclear excitation …

Hadron Jet
[might include electrons, muons …]

Hadronization
Fragmentation
Parton shower
Particle decays

From particle energy to original parton energy

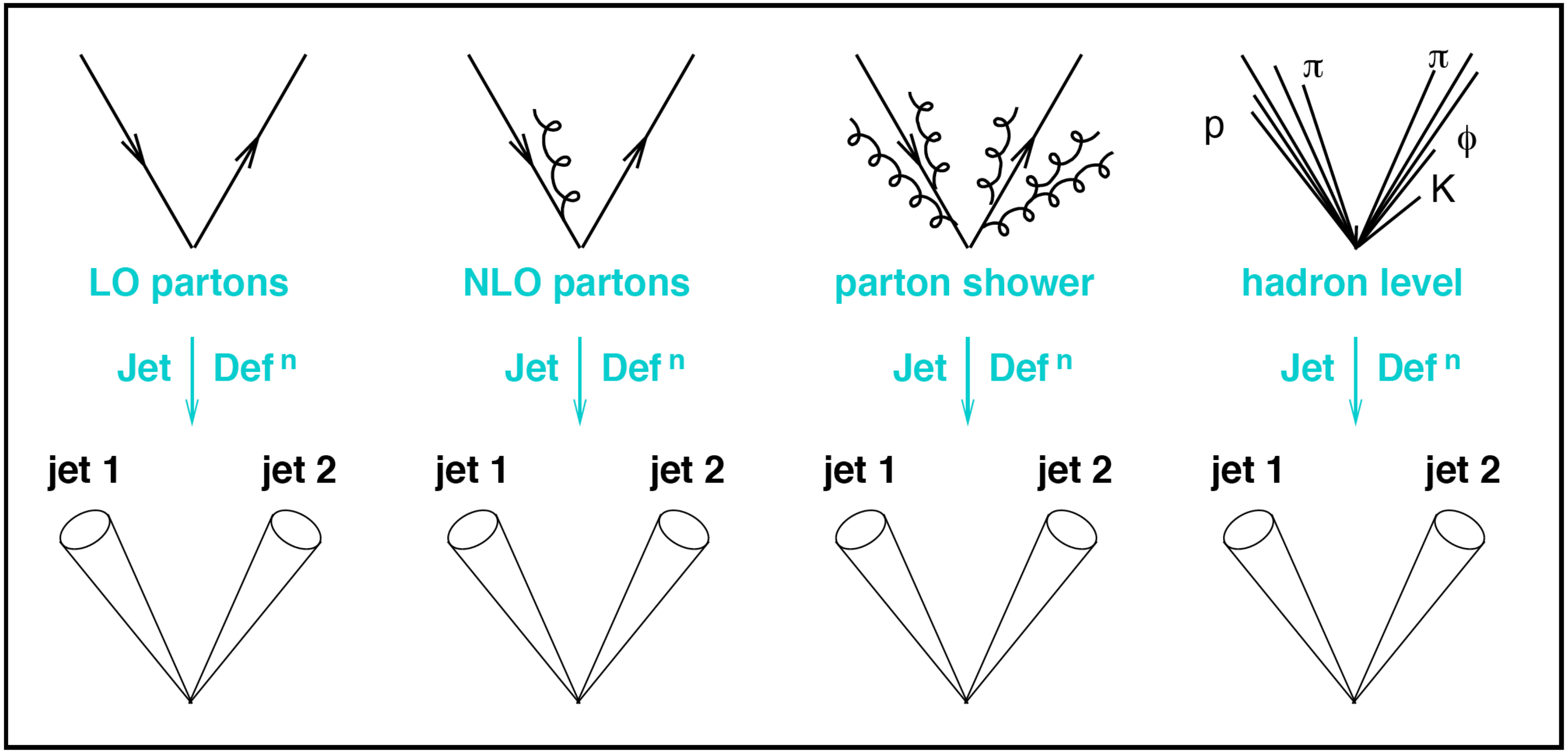
Compensate hadronization; energy in/outside jet cone
…

Parton Jet
[quarks and gluons]

Proton-proton interactions
Initial and final state radiation
Underlying event

Needs Calibration

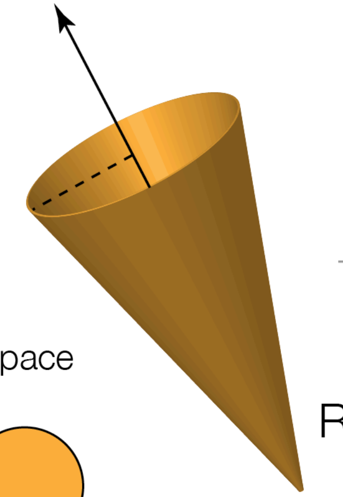
Jet properties measurement



Jets may look different at different levels

Robust jet definition ➛ stable on all jet levels

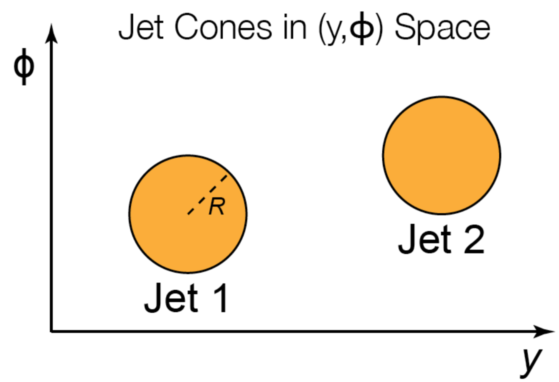
Jet reconstruction



Iterative cone algorithms:

Jet defined as energy flow within a cone of radius R in (y,ϕ) or (η,ϕ) space:

$$R = \sqrt{(y - y_0)^2 + (\phi - \phi_0)^2}$$



Sequential recombination algorithms:

Define distance measure d_{ij} ...

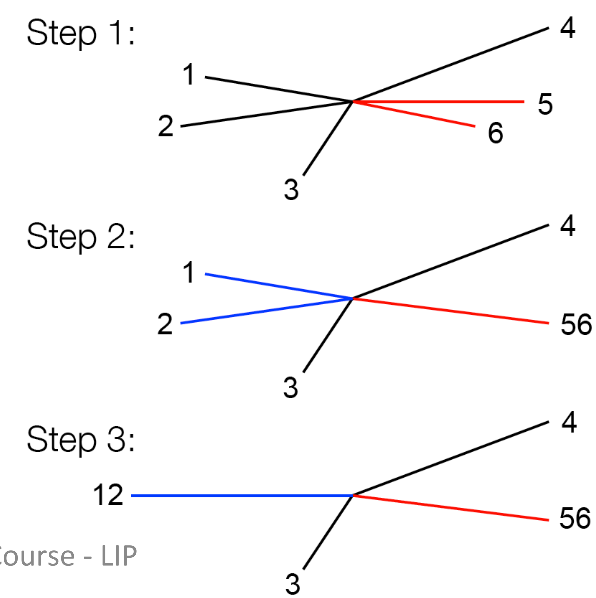
Calculate d_{ij} for all pairs of objects ...

Combine particles with minimum d_{ij} below cut ...

Stop if minimum d_{ij} above cut ...

e.g. k_T-algorithm:
[see later]

$$d_{ij} = \min\left(k_{T,i}^2, k_{T,j}^2\right) \frac{\Delta Rij}{R}$$



Sequential recombination

Jet algorithms performance

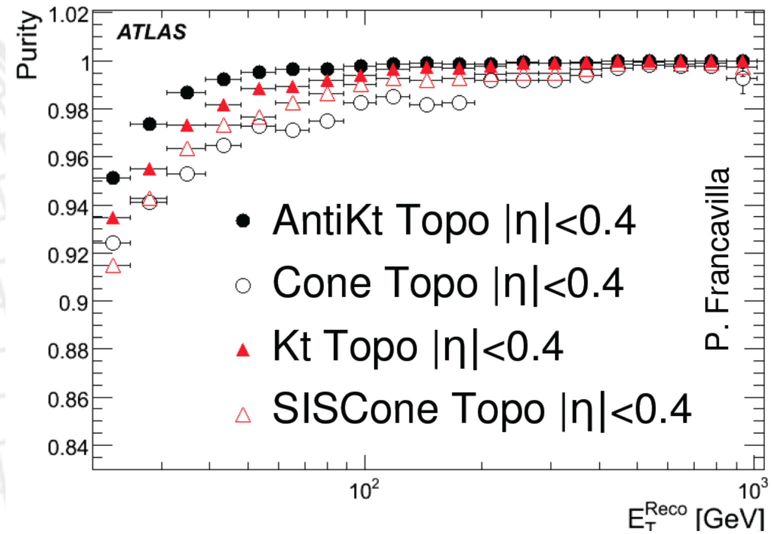
Anti-kt clustering algorithm:

in distance formula
replace P_T^2 by P_T^{2p}

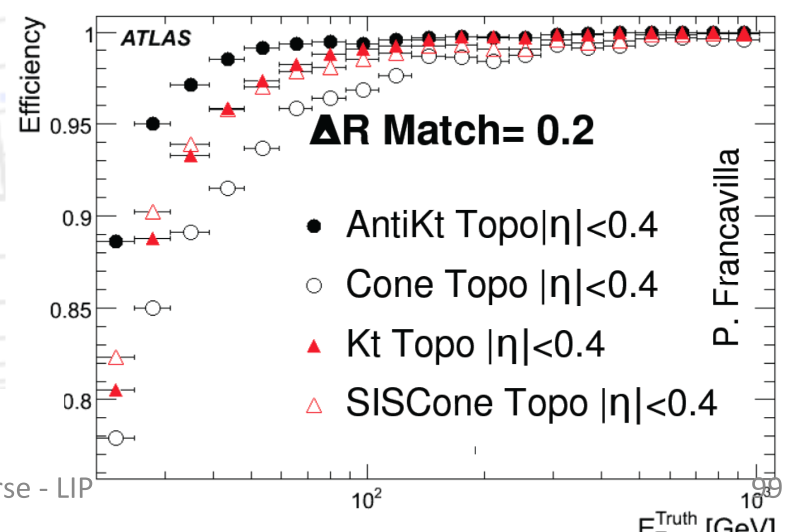
p=1 : standard Kt
p=-1 : anti-Kt

$$D_{ij} = \min(P_{Ti}^2, P_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2}$$

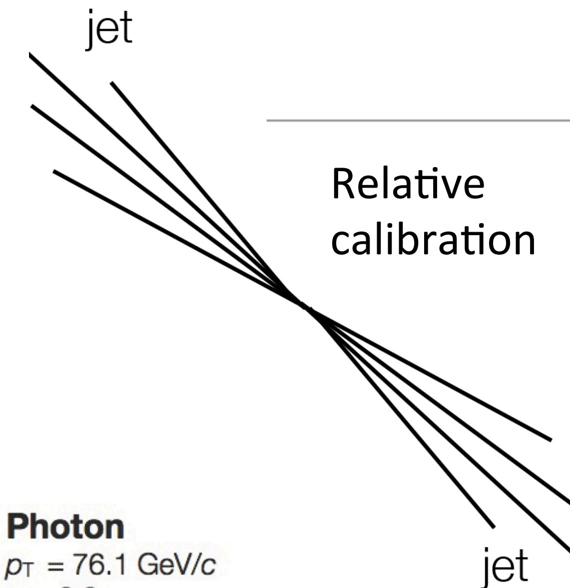
Purity = $N^{Reco}_{Matched}$ / N^{Reco}



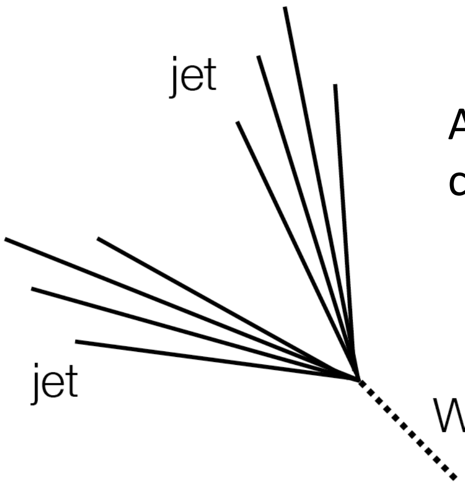
Efficiency = $N^{Truth}_{Matched}$ / N^{Truth}



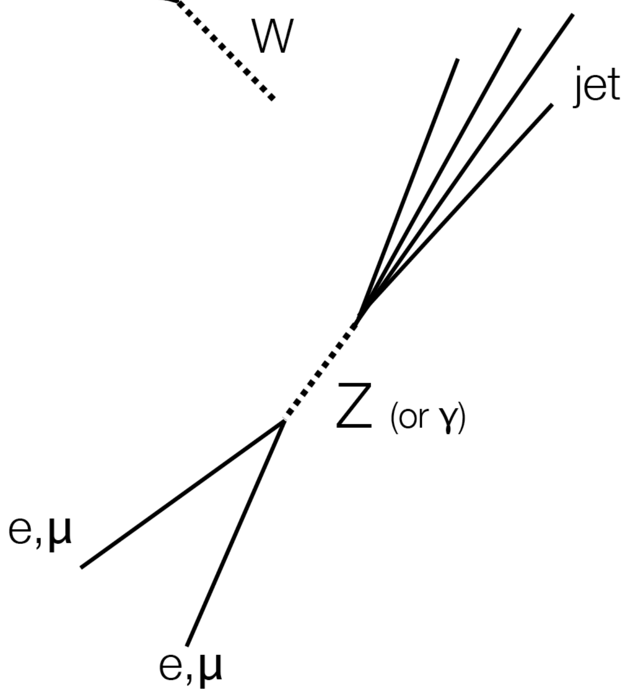
Jet energy calibration

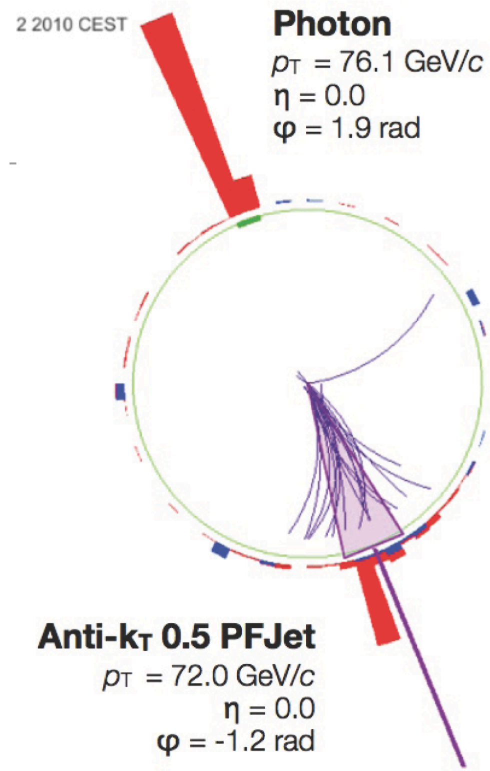


Relative calibration



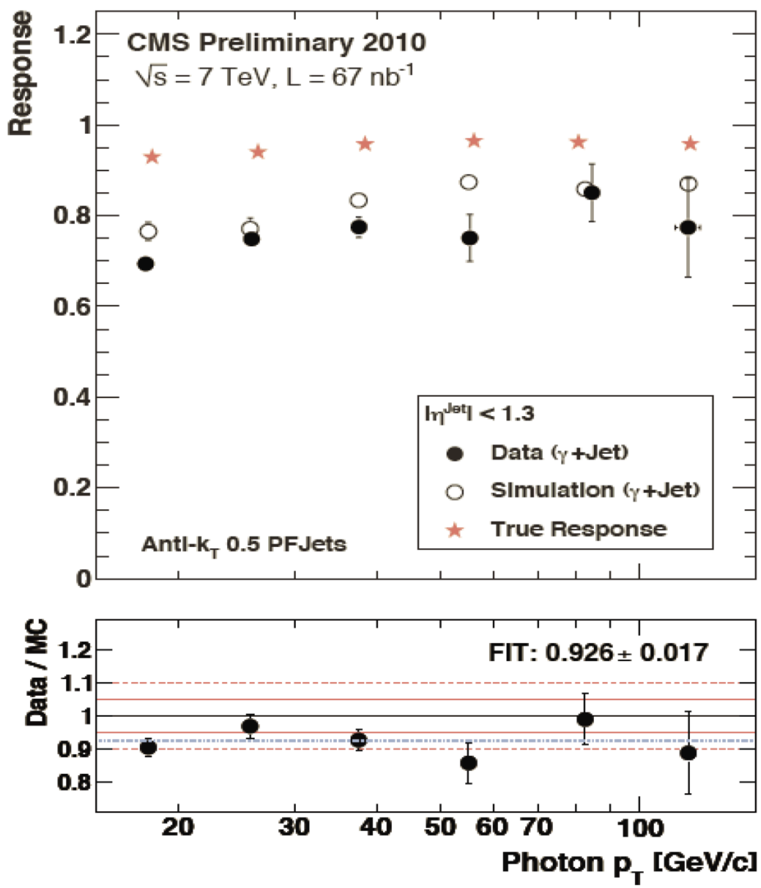
Absolute calibration



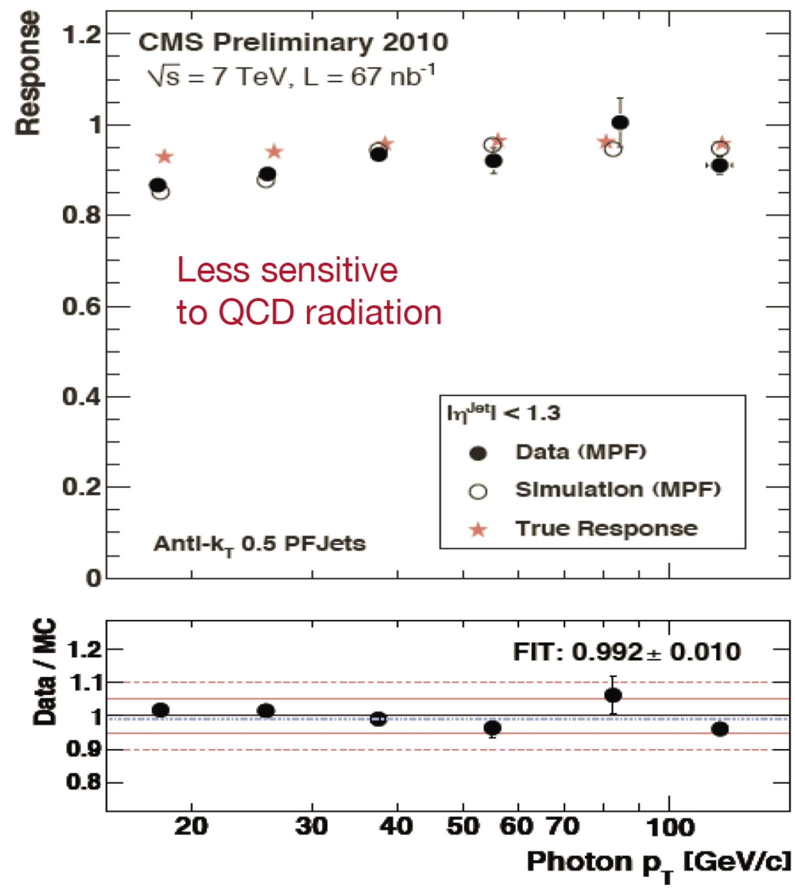


Jet energy calibration

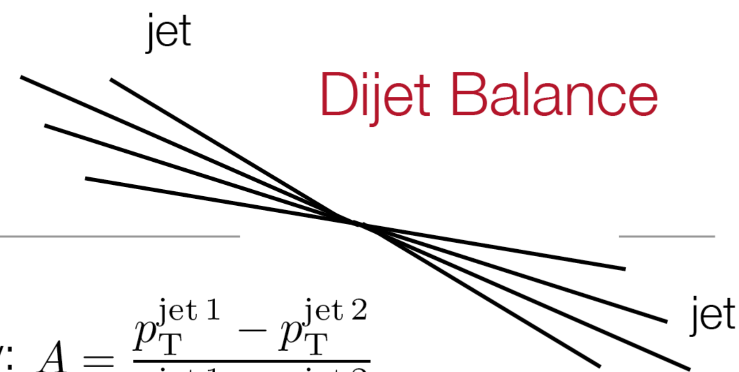
Simple Photon+jet balance
Bias due to soft veto on second jet



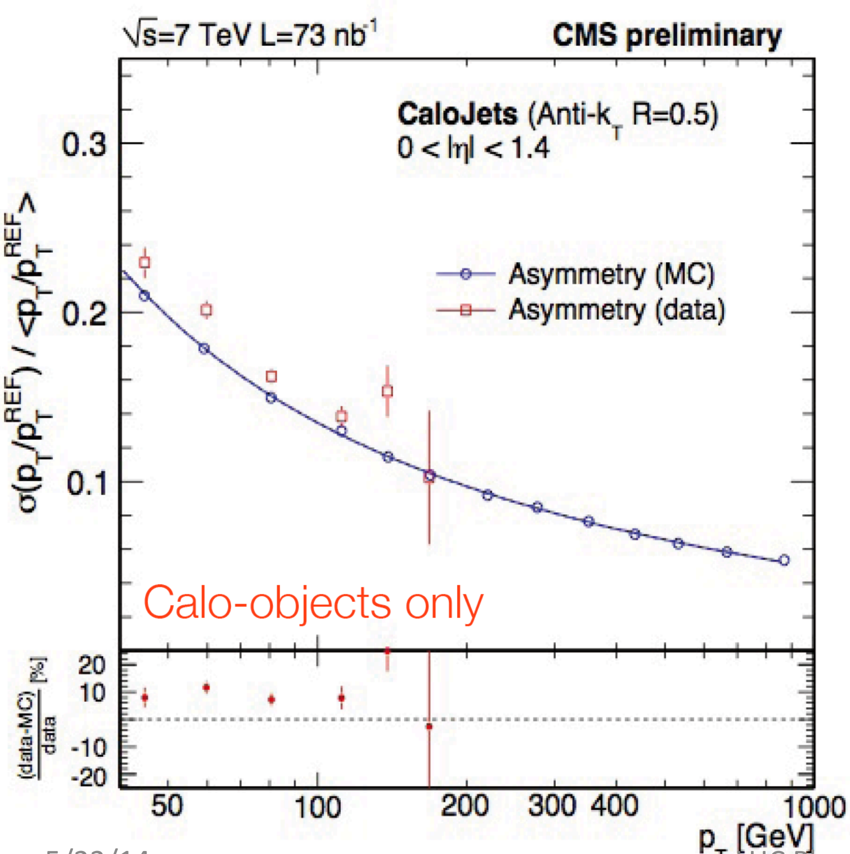
MET projection fraction method
Sums over non-photon E_T for balance

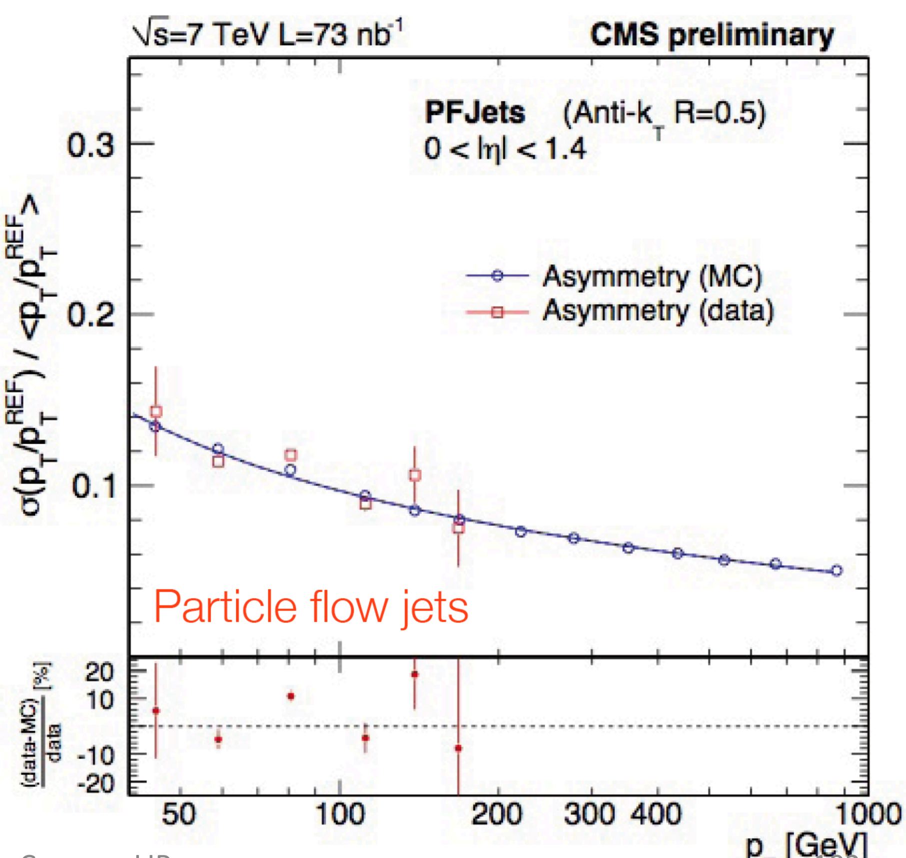


Jet energy resolution



Resolution: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$ using p_T asymmetry: $A = \frac{p_T^{\text{jet 1}} - p_T^{\text{jet 2}}}{p_T^{\text{jet 1}} + p_T^{\text{jet 2}}}$



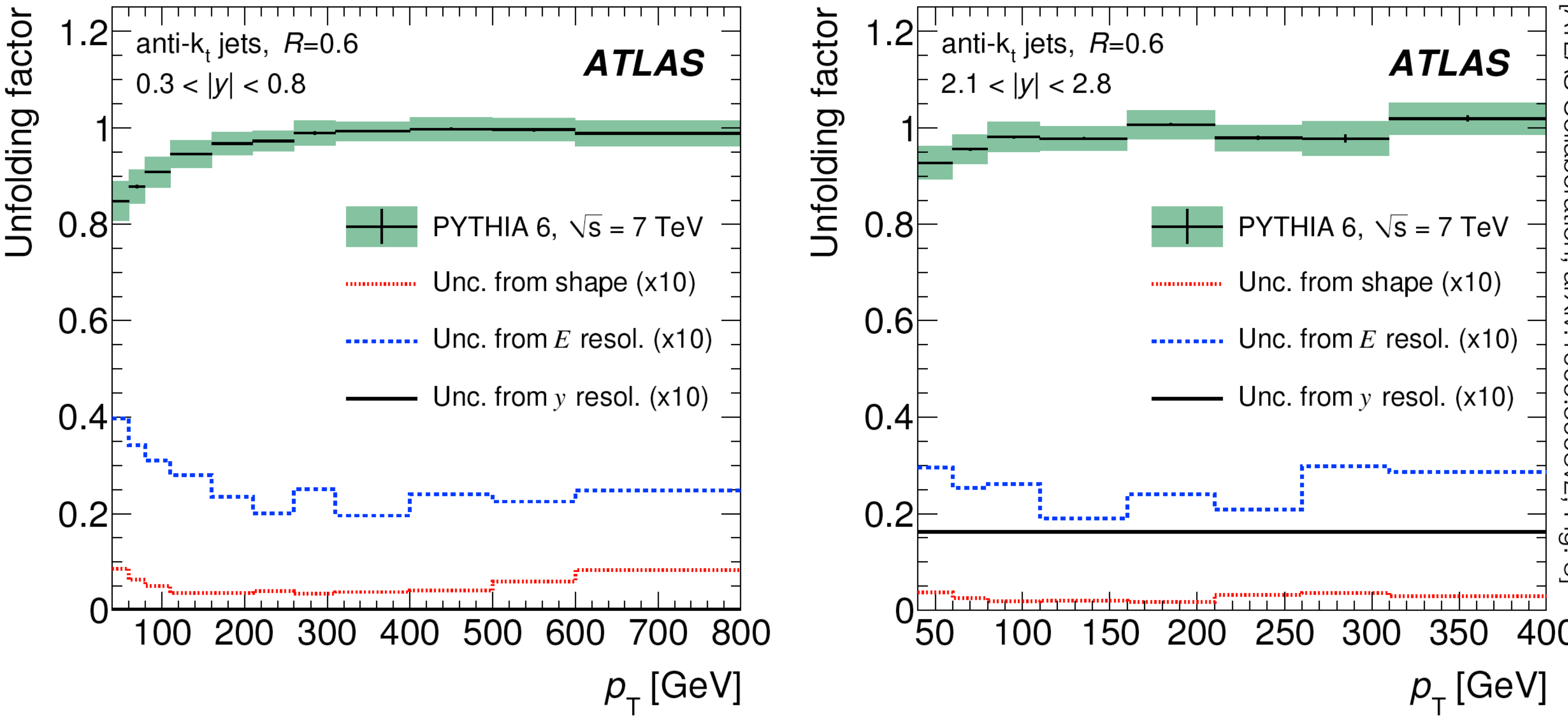


Resolution unfolding

['bin-by-bin' unfolding]

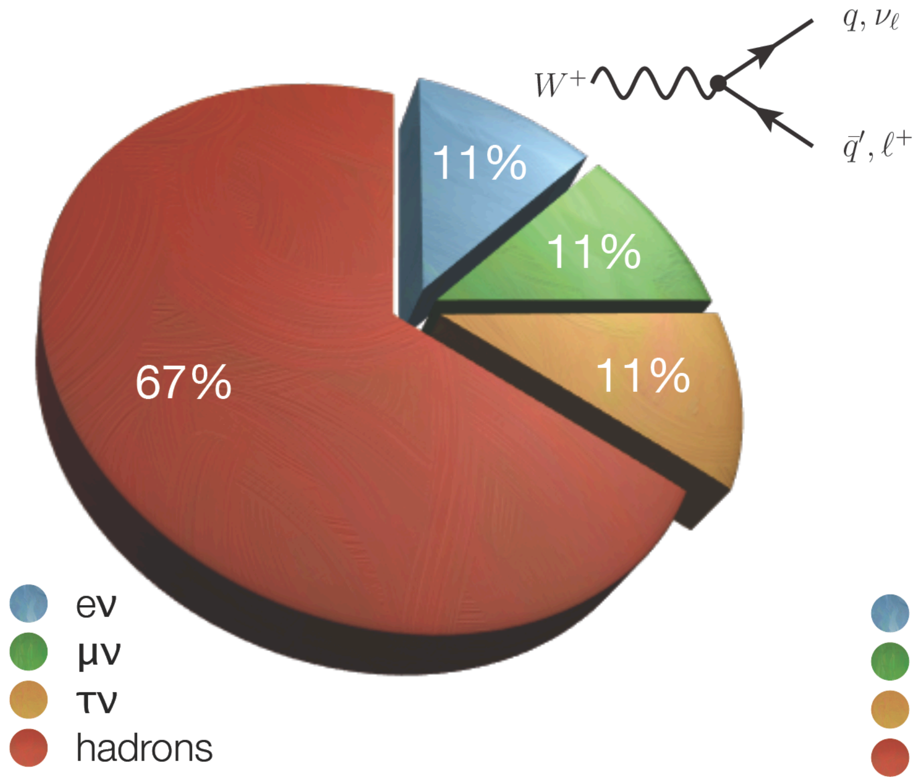
$$N_{\text{part}} = N_{\text{meas}} \cdot \frac{N^{\text{MC}}_{\text{part}}}{N^{\text{MC}}_{\text{meas}}}$$

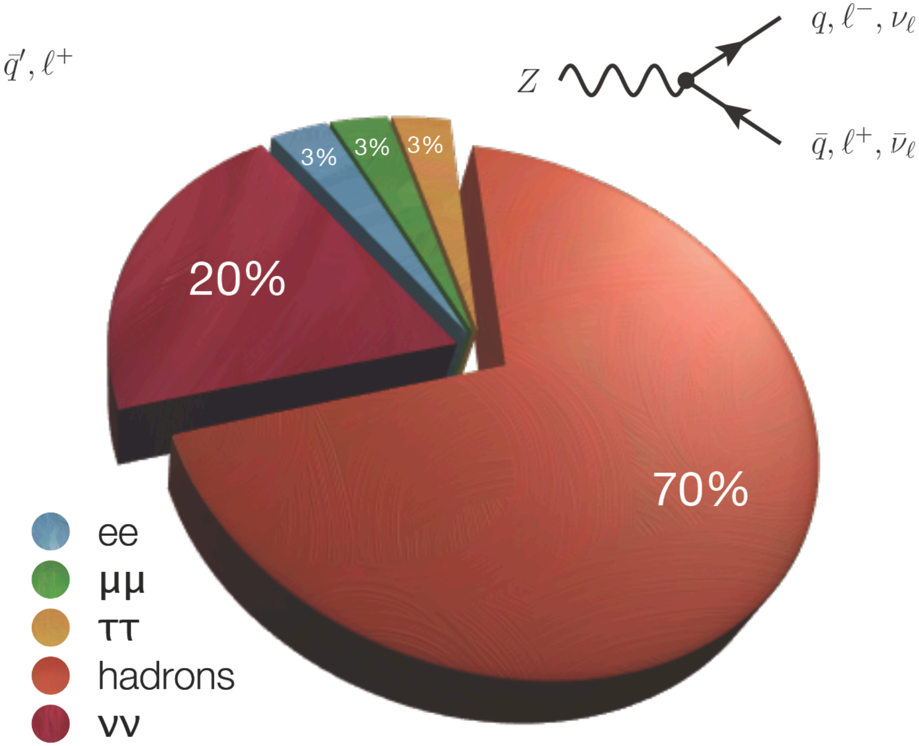
Measured spectrum =
Real spectrum ⊗ Experim. resolution



[ATLAS Collaboration; arXiv:1009.5908v2; Fig. 8]

W and Z boson decays



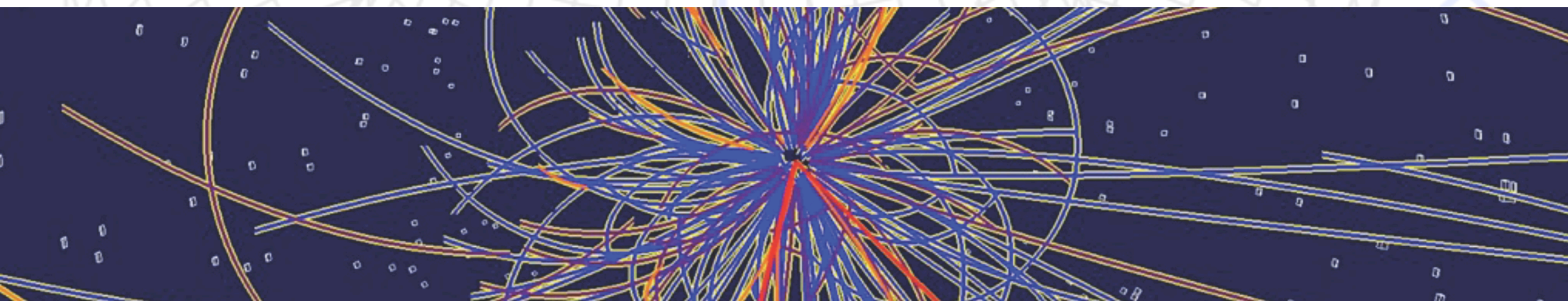


Leptonic decays (e/μ): very clean, but small(ish) branching fractions

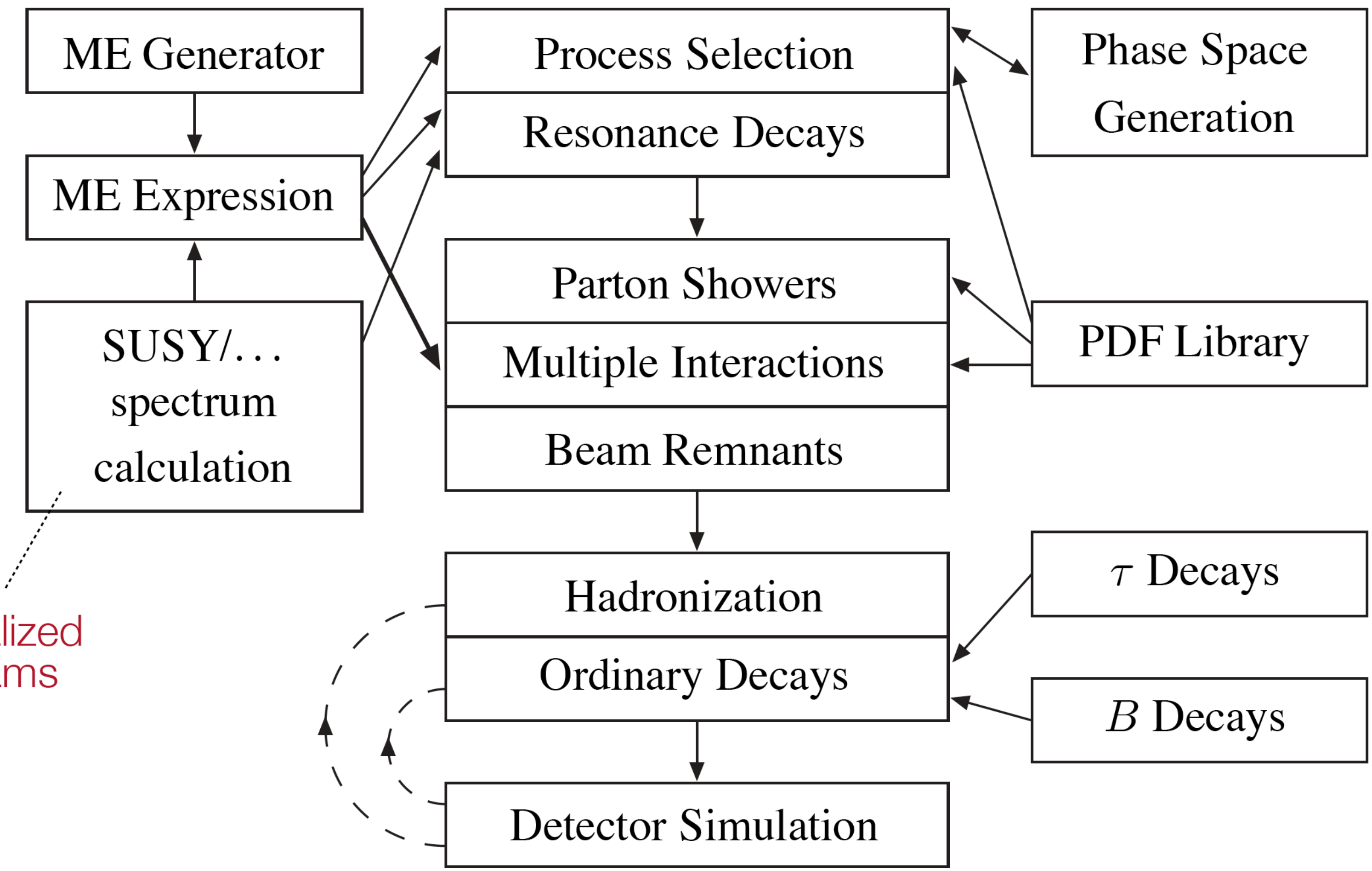
Hadronic decays: two-jet final states; large QCD dijet background

Tau decays: somewhere in between…

Monte Carlo Generators



Monte Carlo overview



Use
specialized
programs

Monte Carlo interfacing

Many specialized processes already available in Pythia ...

but, processes usually only implemented in lowest non-trivial order ...

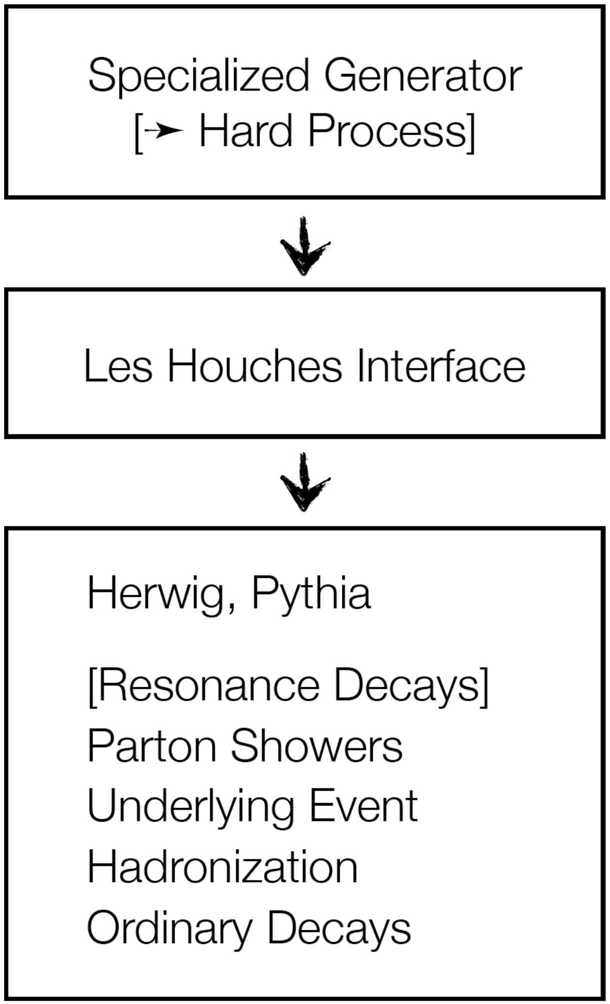
Need external programs that ...

- include higher order loop corrections or, alternatively, do kinematic dependent rescaling
- allow matching of higher order ME generators
  [otherwise need to trust parton shower description ...]
- provide correct spin correlations often absent in Pythia ...
  [e.g. top produced unpolarized, while $t \rightarrow bW \rightarrow bl\nu$ decay correct]
- simulate newly available physics scenarios ...
  [appear at rapid pace; need for many specialized generators]

Les Houches Accord ...

Specifies how parton-level information about the hard process and sequential decays can be encoded and passed on to a general-purpose generator.

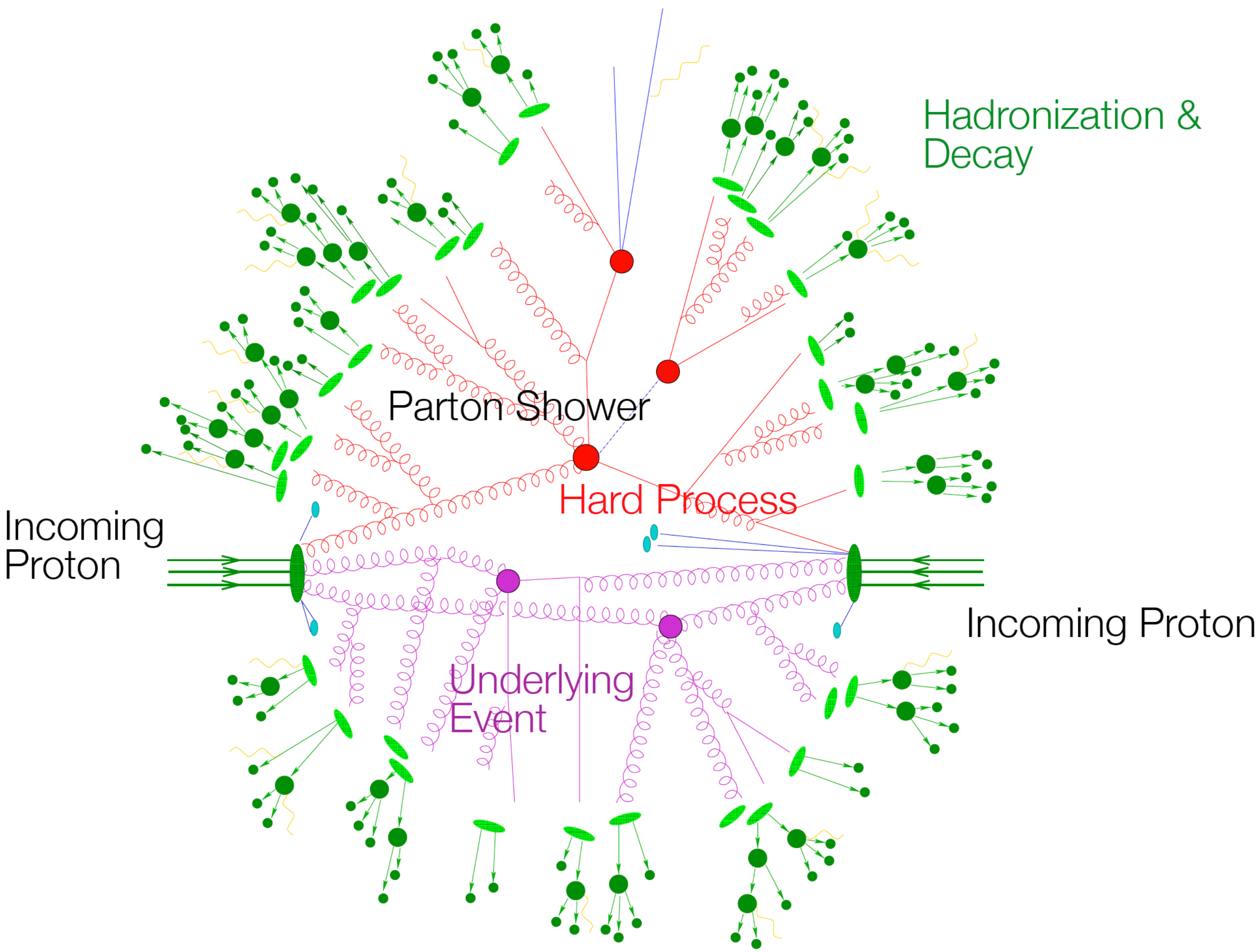
Les Houches generator files



Specialized Generators:
[some examples]

AcerMC	:	ttbb, ...
ALPGEN	:	W/Z + ≤ 6j, nW + mZ + kH + ≤ 3j, ...
AMEGIC++	:	generic LO
CompHEP	:	generic LO
GRACE [+Bases/Spring]	:	generic LO [+ some NLO loops]
GR@PPA	:	bbbb
MadCUP	:	W/Z+ ≤ 3j, ttbb
HELAS & MadGraph	:	generic LO
MCFM	:	NLO W/Z+ ≤ 2j, WZ, WH, H+ ≤ 1j
O'Mega & WHIZARD	:	generic LO
VECBOS	:	W/Z+ ≤ 4j

From Partons to Jets



[T. Gleisberg et al., JHEP02 (2004) 056]

Parton splitting

$$d\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}P_{a\to bc}(z)dz$$

Splitting probability
determined by splitting functions $P_{q\to qg}$

$$P_{\mathrm{q}\to\mathrm{qg}} = \frac{4}{3}\frac{1+z^2}{1-z}$$

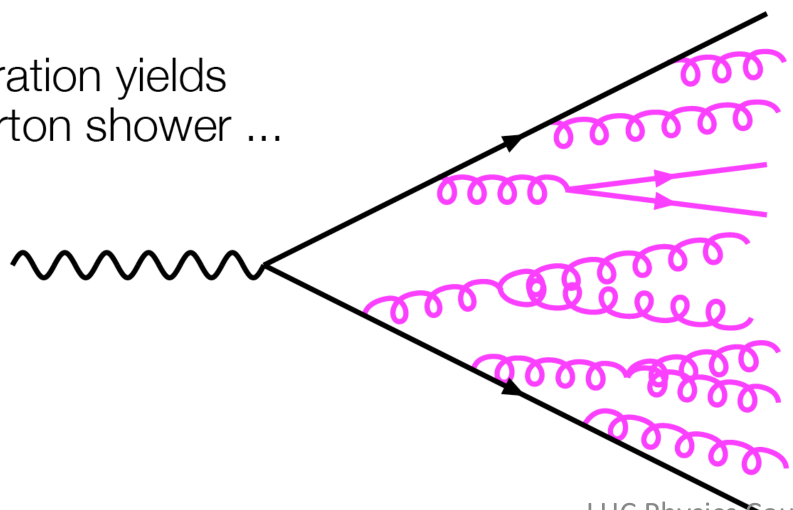
$$P_{\mathrm{g}\to\mathrm{gg}} = 3\frac{(1-z(1-z))^2}{z(1-z)}$$

$$P_{\mathrm{g}\to\mathrm{q\bar{q}}} = \frac{n_f}{2}(z^2+(1-z)^2)$$

Same splitting functions
as used for PDF evolution

z : fractional momentum of radiated parton
n_f : number of quark flavours

Iteration yields
parton shower ...



Need soft/collinear cut-offs to
avoid non-perturbative regions ...
[divergencies!]

Details model-dependent

e.g. $Q > m_0 = \min(m_{ij}) \approx 1$ GeV,
$z_{min}(E,Q) < z < z_{max}(E,Q)$ or
$p_\perp > p_{\perp min} \approx 0.5$ GeV

Hadronization models

Non-perturbative transition from partons to hadrons ...
[Modeling relies on phenomenological models available]

Models based on MC simulations
very successful:

Generation of complete final states ...
[Needed by experimentalists in detector simulation]

Caveat: tunable ad-hoc parameters

Most popular MC models:

Pythia	:	Lund string model
Herwig	:	Cluster model

Lund String Model

Lund String Model

[Andersson et al., Phys. Rep. 97 (1983) 31]

QCD potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(1/r^2)}{r} + kr$$

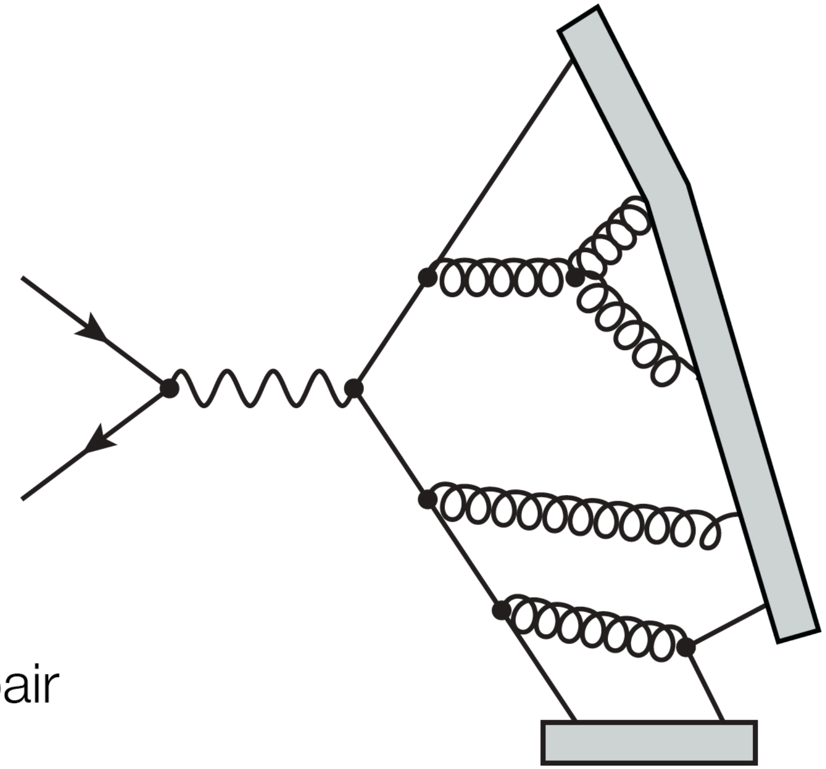
String formation between initial quark-antiquark pair

String breaks up if potential energy large enough new quark-antiquark pair

Gluons = 'kinks' in string

At low energy: hadron formation

Very widely used ...
[default in Pythia]



After: Ellis et al.,
QCD and Collider Physics

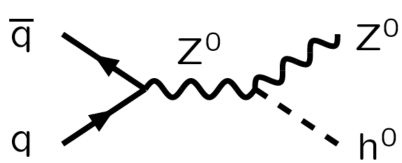
Overview of MC generators

Structure of basic generator process [by order of consideration]

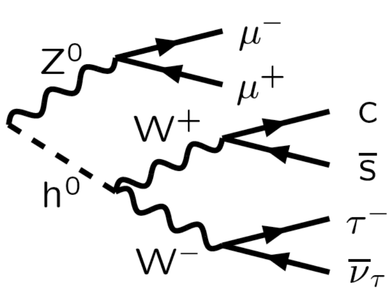
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modeled; at small

Matrix elements (ME)

1. Hard subprocess:
   $|M|^2$, Breit Wigners, PDFs

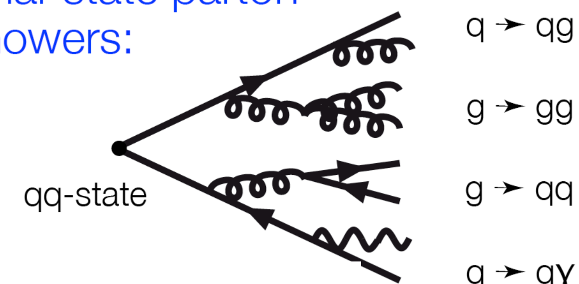


2. Resonance decays:
   Includes particle correlations

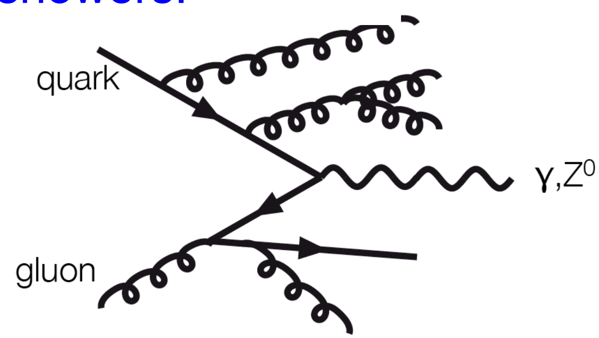


Parton Shower (PS)

3. Final-state parton showers:



4. **Initial-state parton showers:**



[from G.Herten]