Perspectives in LHC physics

Where are we and where are we going?

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UC-Davis California USA

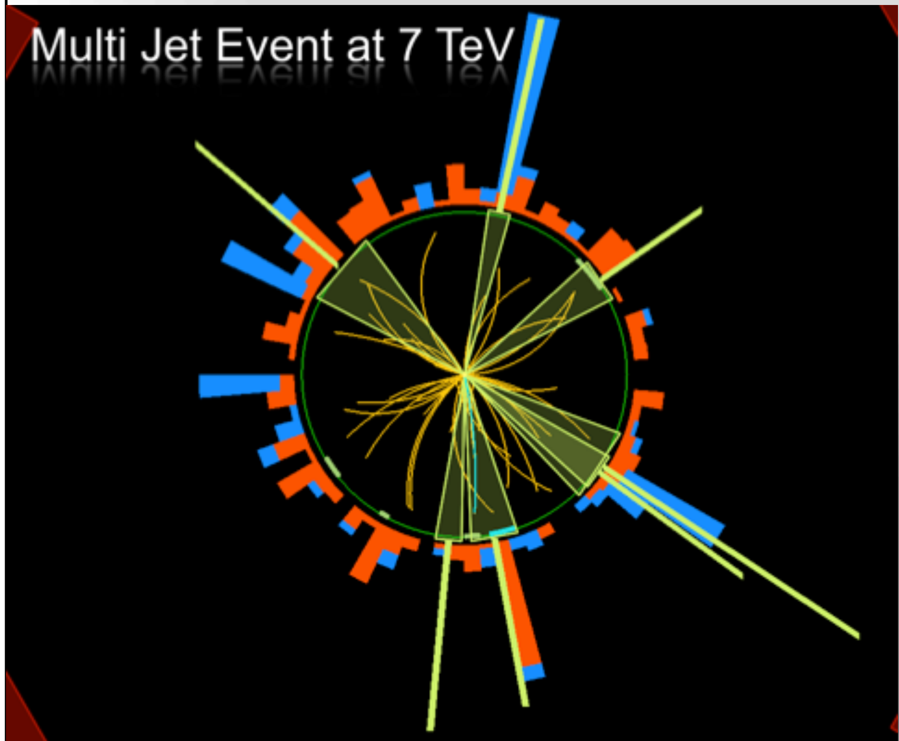
BUE, Cairo, Egypt

IPPP, Durham, UK

8 August 2013

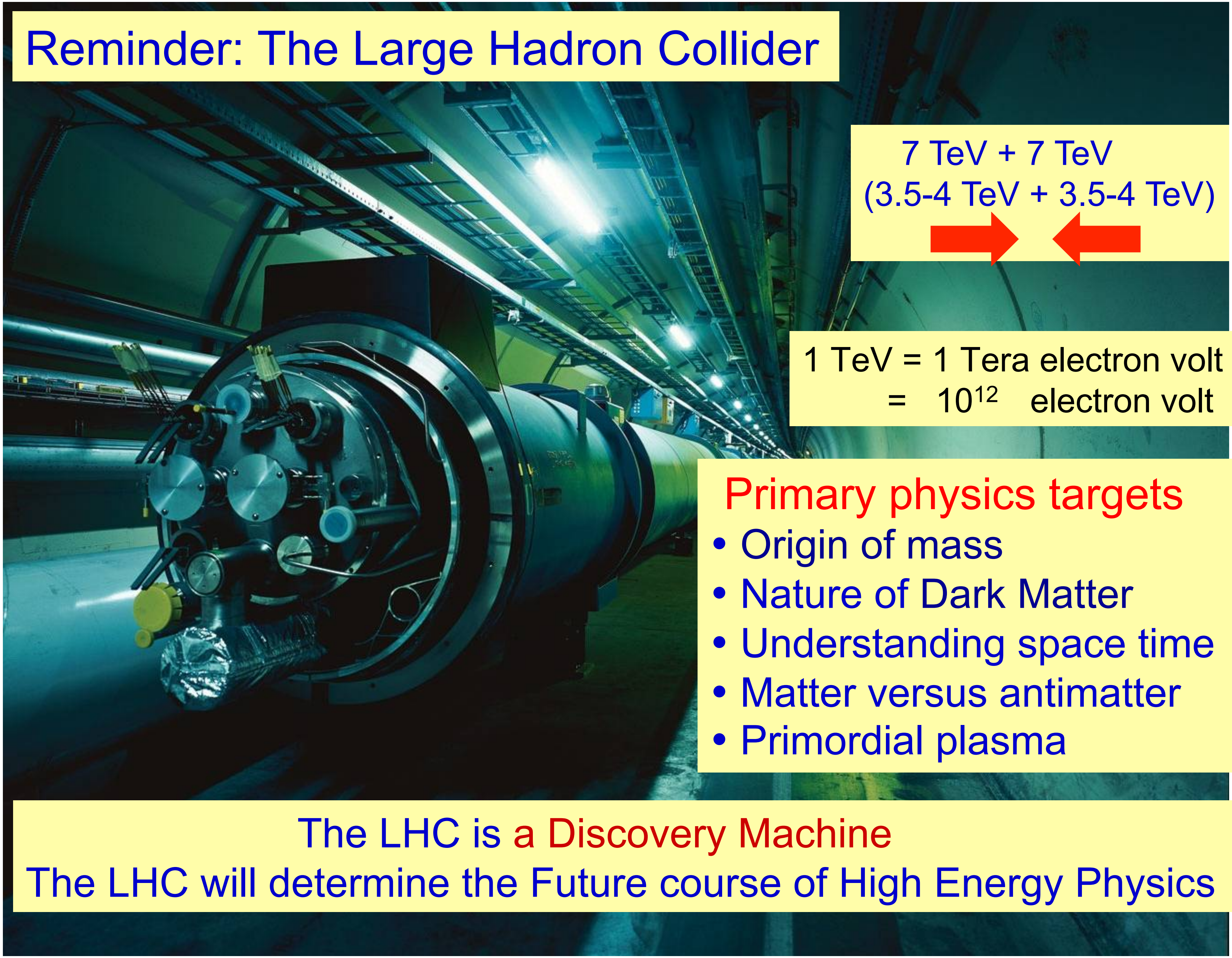
2013 MCnet Summer School

on Monte Carlo Event Generators for the Large Hadron Collider



Outline

- Introduction
- SM Physics results and questions from Run I
- The Higgs at last!
- Where is the new physics?
- Upgrade plans and physics opportunities at the LHC for the next 20 years
- Summary



Reminder: The Large Hadron Collider

7 TeV + 7 TeV
(3.5-4 TeV + 3.5-4 TeV)

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

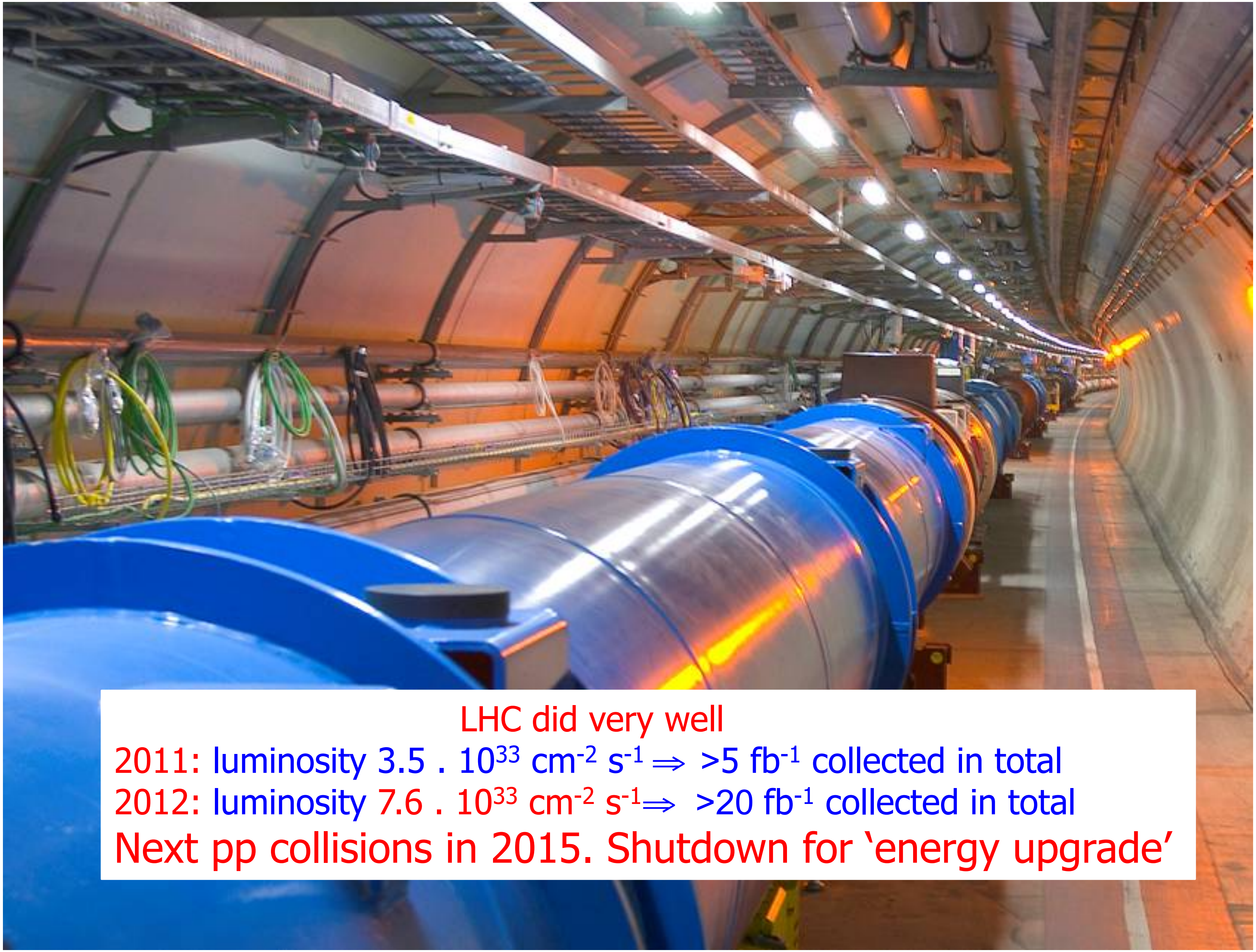
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

The LHC is a Discovery Machine
The LHC will determine the Future course of High Energy Physics

4th of July…

But the LHC is MUCH more…

- Top quark studies
- Electro-weak precision physics
- Perturbative QCD studies
- B-physics (eg. B_s to μμ)
- Heavy Ions (PbPb, pPb…)
- Soft physics, total cross sections
- Connections to cosmic rays
- ….



LHC did very well

2011: luminosity 3.5 . 10^{33} cm^{-2} s^{-1} $\Rightarrow$ >5 fb^{-1} collected in total

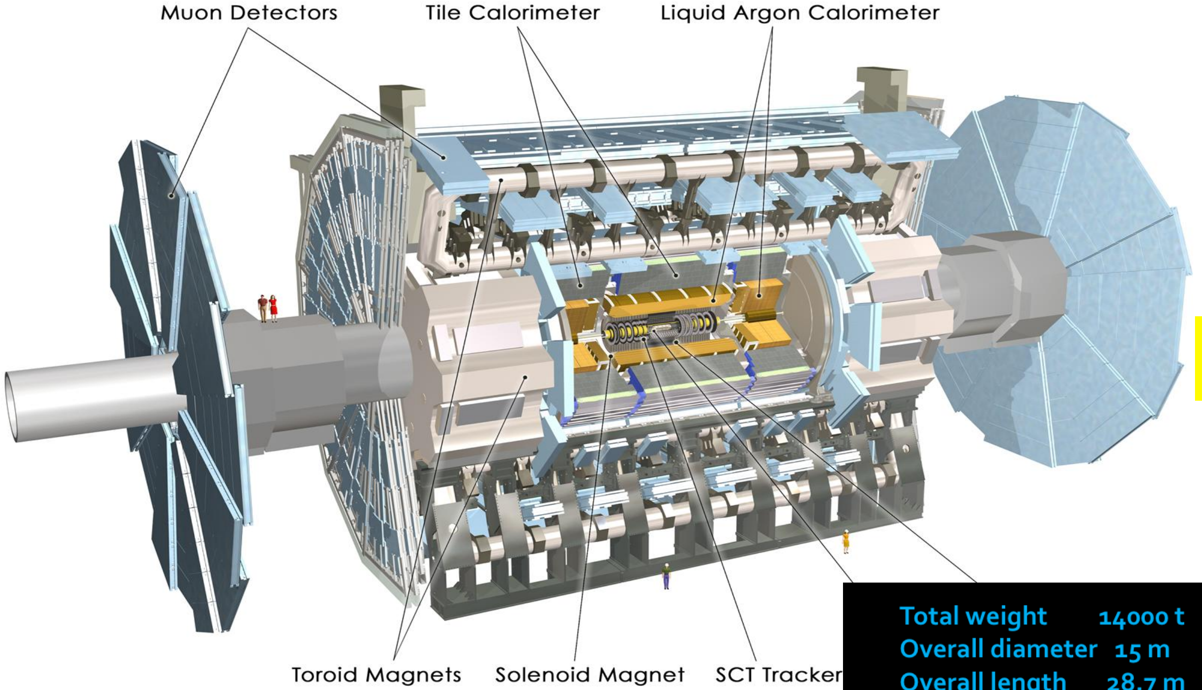
2012: luminosity 7.6 . 10^{33} cm^{-2} s^{-1} $\Rightarrow$ >20 fb^{-1} collected in total

Next pp collisions in 2015. Shutdown for ‘energy upgrade’

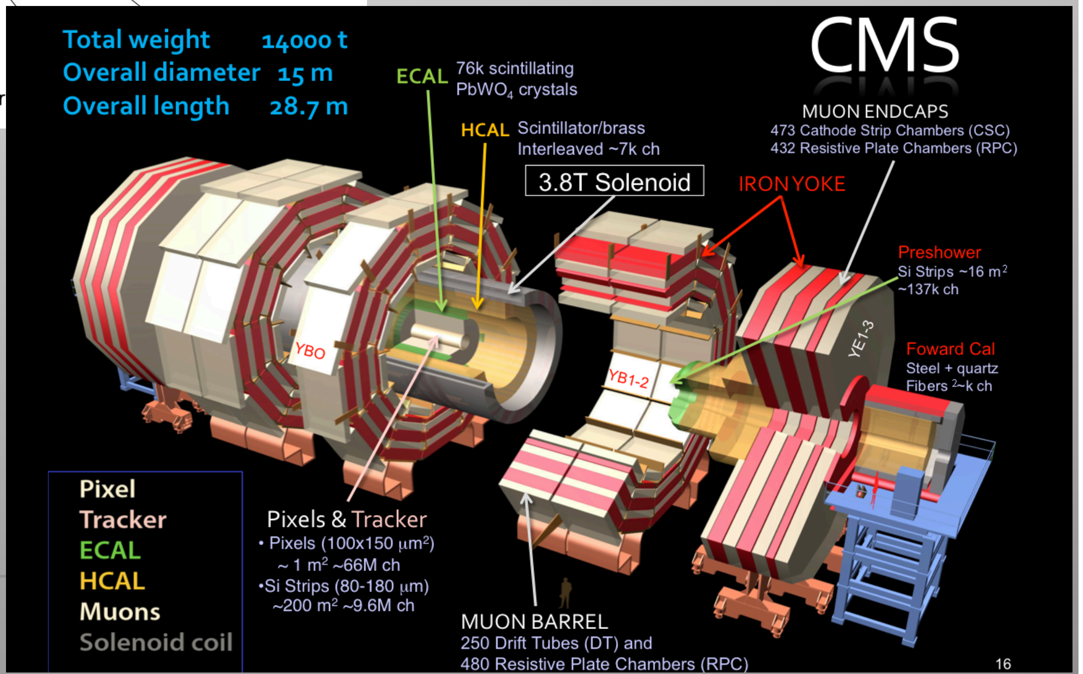
Experiments at the LHC

The Higgs Hunters @ the LHC

LHC: pp collisions at 7/8 TeV



The ATLAS experiment



The CMS experiment

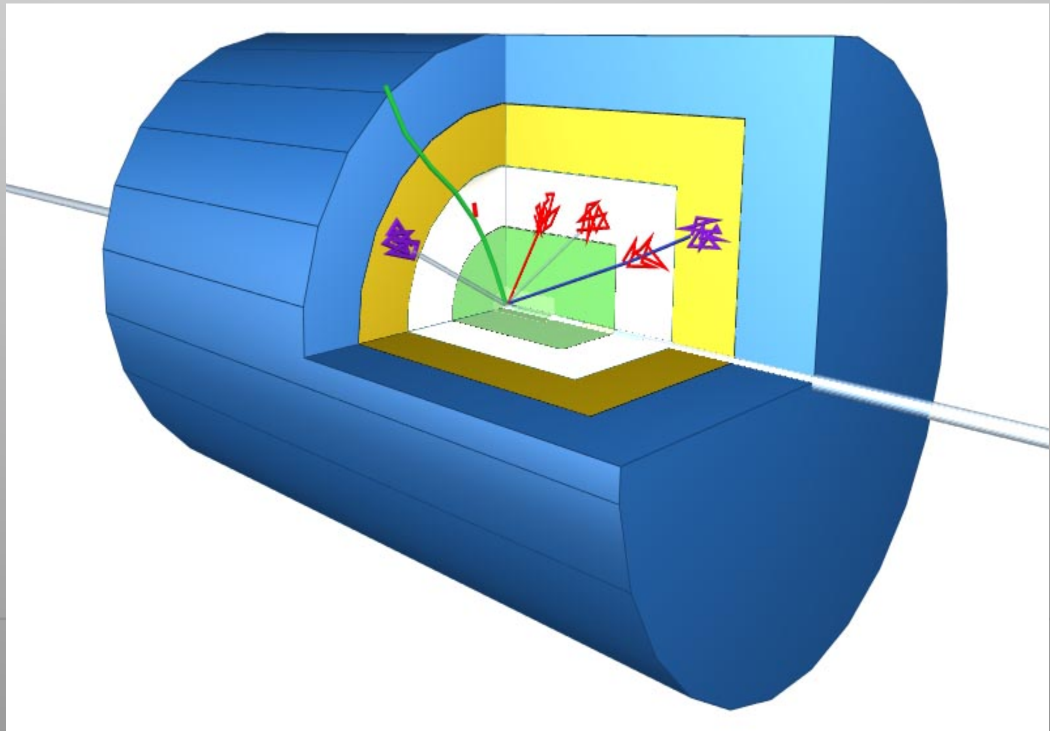
These experiments use different technologies for their detector components

Schematic of a LHC Detector

Physics requirements drive the design!

Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.



Such an experiment has ~ 100 Million read-out channels!!

The experiments are in good shape!

ATLAS

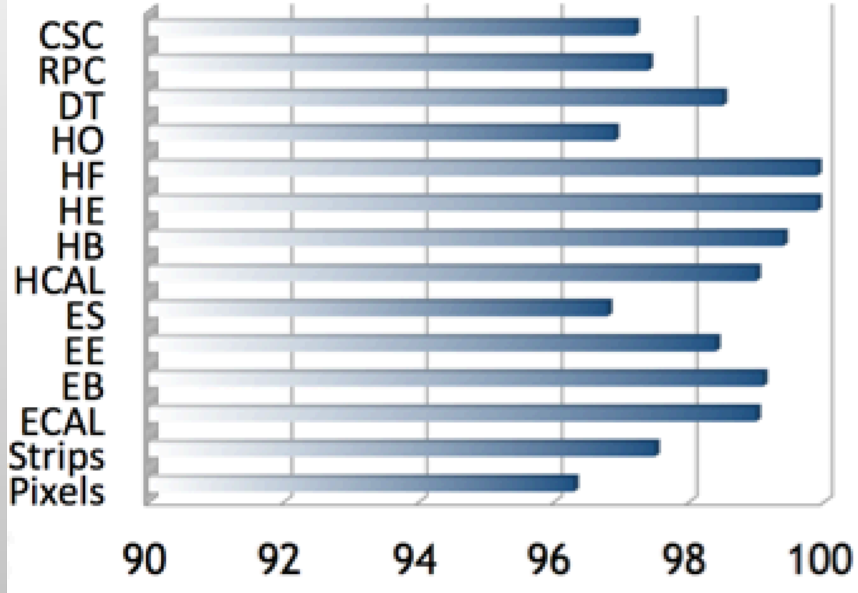
Fraction of non-operational detector channels: (depends on the sub-detector)

Few permil (most cases) to 4%

Data-taking efficiency = (recorded lumi)/(delivered lumi):~ 94.6%

Good-quality data fraction, used for analysis : ~ 93.6%
(will increase further with data reprocessing)

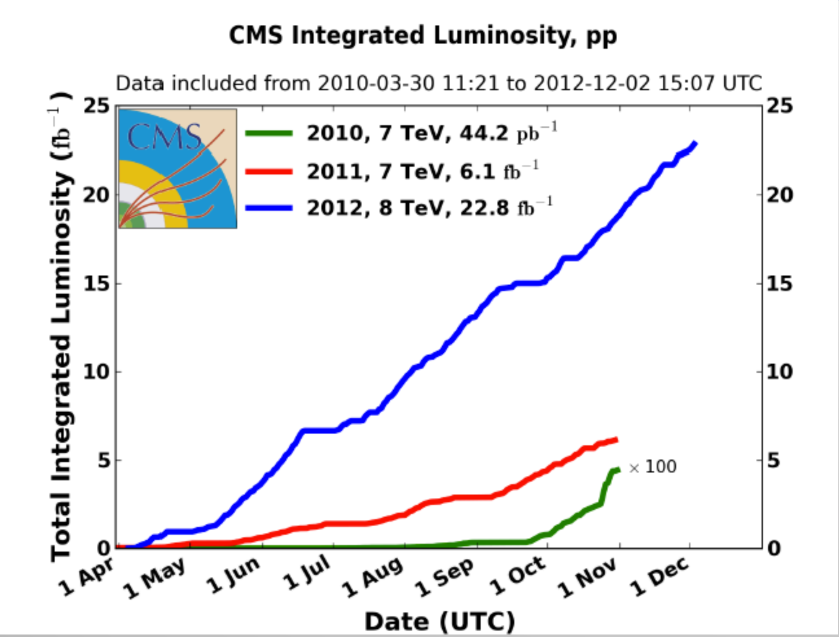
CMS



Pile-Up 2012!!

An issue for jet measurements

We had 3 Fantastic years!



Some of the key moments the last years

Data Taking Challenges

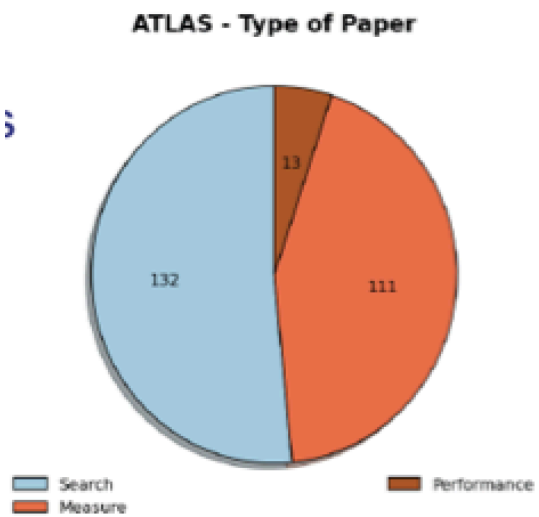
- Collider: 20M bunch crossings per second
- ~ 30 events per bunch crossing: pile-up
- Trigger on 400 events/sec (+ another 400-600 Hz of parked data in CMS): keep the interesting (incl. unknown) physics
- Total data volume in eg ATLAS: 5 billion detector events, 120 PB of data (simulation and data). Several billion Monte Carlo events (produce ~ 10^9 events/2 months)
- ATLAS+CMS > 500 papers so far

  > ~600 papers for all experiments

No attempt to cover everything ☺ but

examples to illustrate the LHC

Most examples from CMS/ATLAS



Monte Carlos are very important

For our daily work…

- Guidance on the background to the signal (direct or training)
- Signal acceptance
- Systematic error evaluation
- Comparison with theory

- Parton shower mechanisms
  - Pythia6, Pythia8, Herwig6, Herwig++
  - Sherpa with its own shower and multi-leg matching.
  - ThePEG (Herwig++, Ariadne), Phantom, Hydjet, Pyquen, Cosmic generators, ExHuME, Pomwig, BcGenerator, HARDCOL, PHOJET, Regge-Gribov generators, CASCADE, etc.
- Matrix element generators
  - LO: Madgraph, Alpgen, Sherpa
  - NLO: aMC@NLO, SherpaNLO, Powheg, MiNLO + Powheg, etc.
- Decay Tools
  - Tauola, Tauola++, EvtGen, Photos, Madspin (to be integrated) etc.

Examples from CMS embedded in the exp. software

+ specific NP signal MCs (via LHE files), cross section calculators MCFM, FEWZ, …etc…

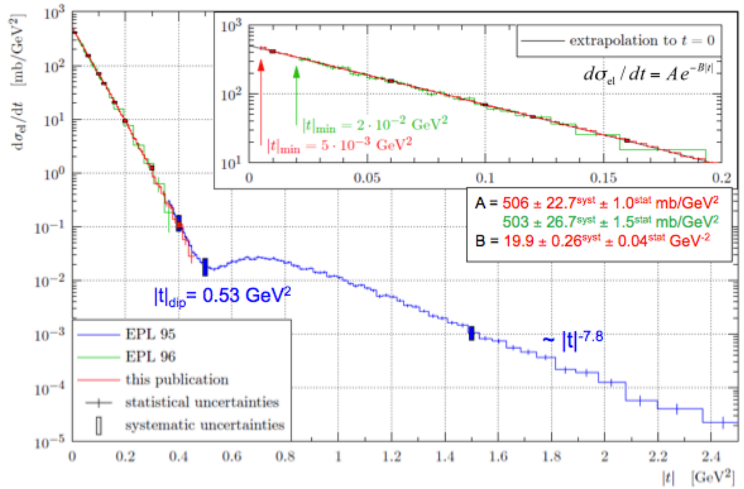
Experimentalists always want more, better (HO), faster, well tuned MC…

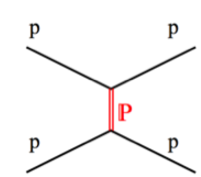
Elastic/Total pp Cross Section

TOTEM = Roman Pots + Forward Detectors
TOTEM uses the same IP as CMS (IP5)

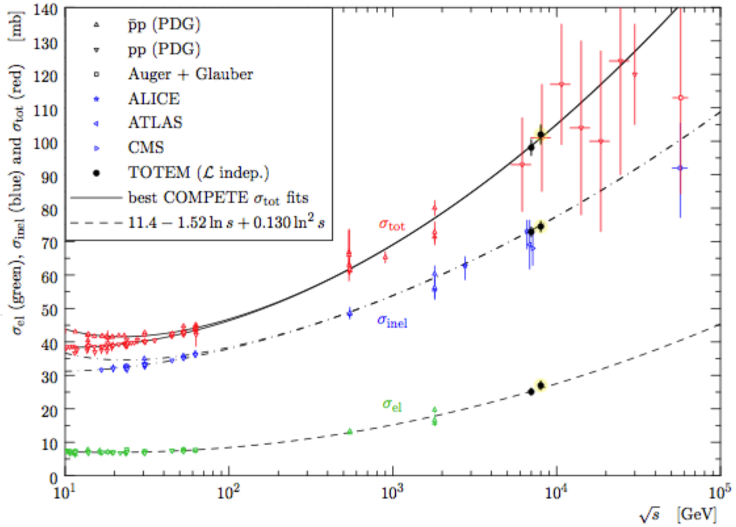
EPL 101 21004 (2003)

7 TeV elastic differential cross section





8TeV cross sections



$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{dN_{el}/dt|_0}{N_{el}+N_{inel}}$$

$$\boxed{\sigma_{tot} = (101.7 \pm 2.9) mb}$$

$$\sigma_{inel} = (74.7 \pm 1.7) mb$$

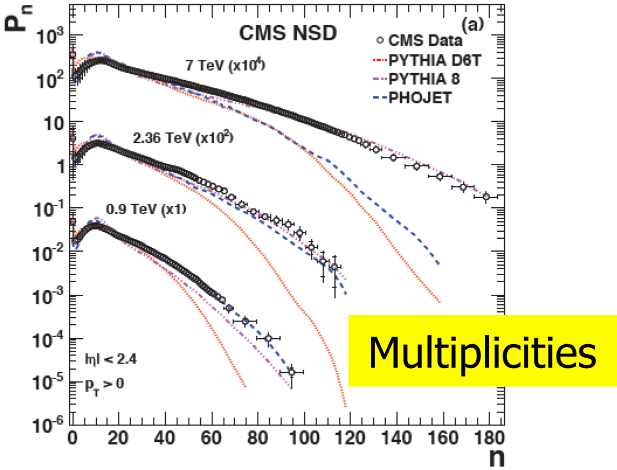
$$\sigma_{el} = (27.1 \pm 1.4) mb$$

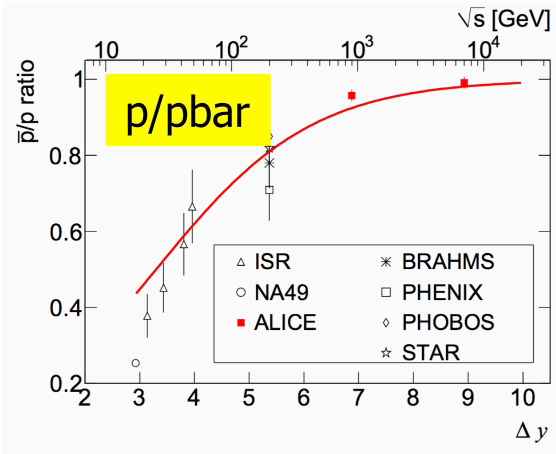
Future: •High beta measurements for Coulomb-Nuclear interference, ALFA

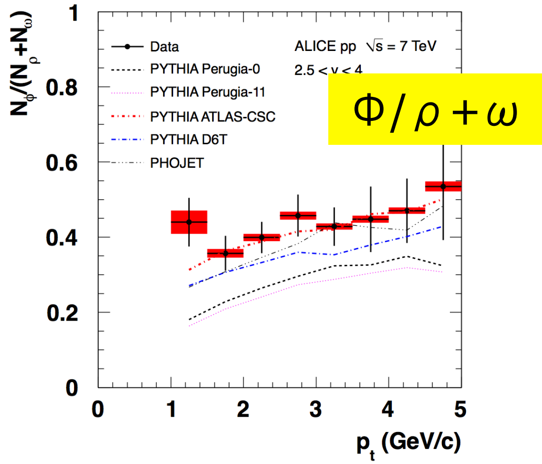
Will be measured again at 13-14 TeV in 2015.
Are the MCs updated?

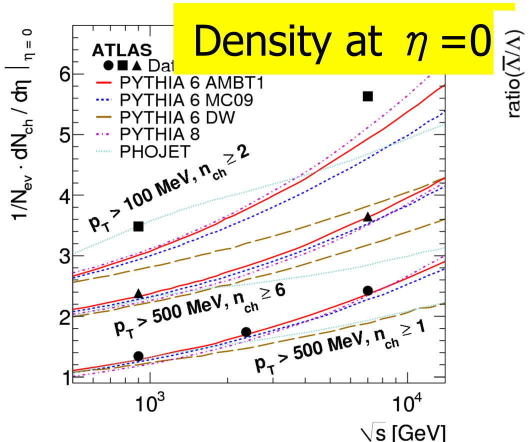
Understanding Particle Production

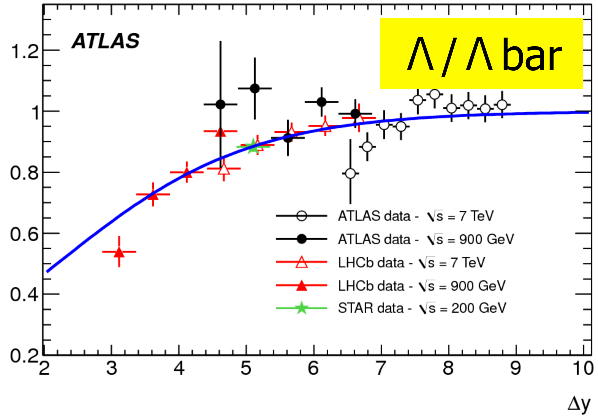
- Single particles, multiplicities etc. vs phenomenological models…
- LHC detectors are excellent and complementary for such studies

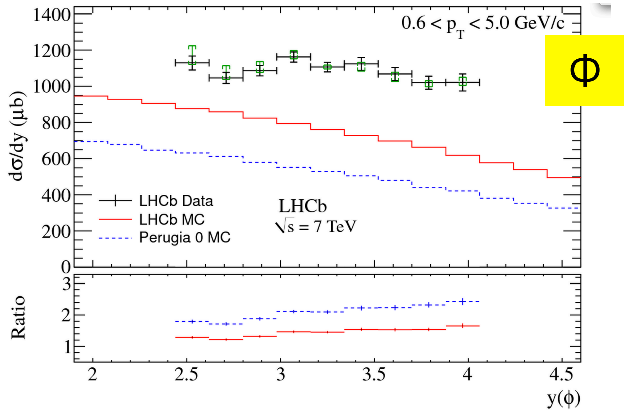










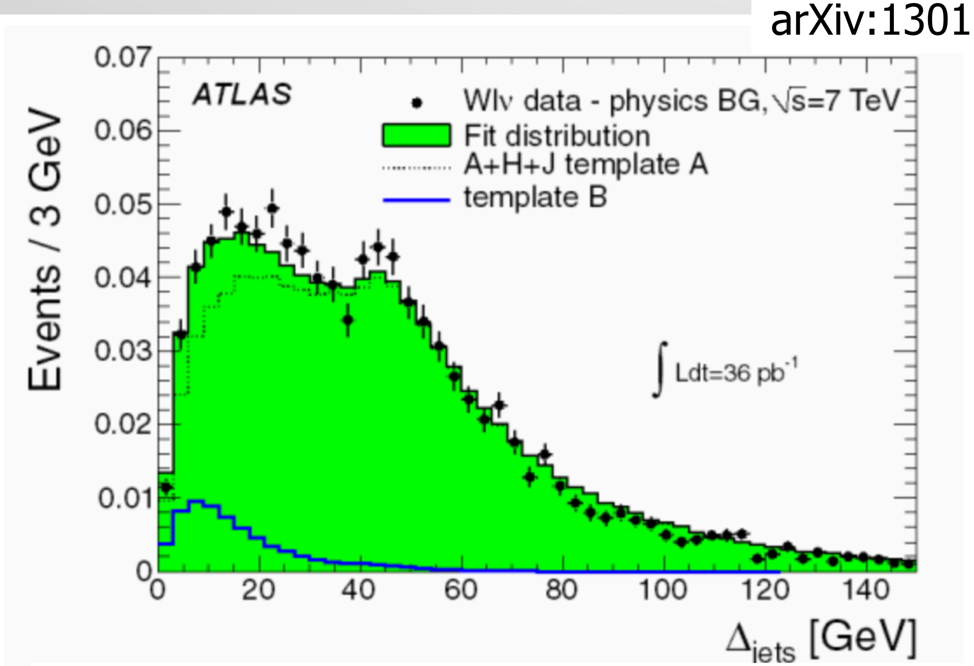


Should we organize a (or a few) more Universal Tunes of the MCs?
Strangeness suppression typically not well reproduced in present tunes

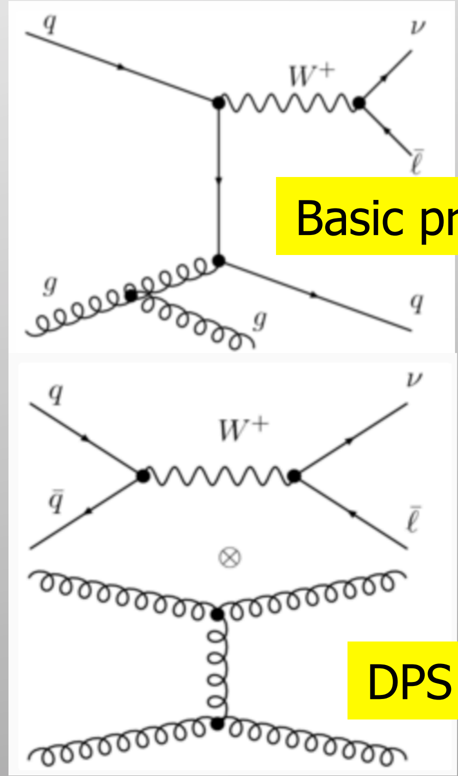
Double Parton Scattering

Example: angular correlations study of W+ 2jet events: The fraction of the cross section attributed to DPS= 0.08 ± 0.01 (stat.) ± 0.02 (sys.)

arXiv:1301.6872



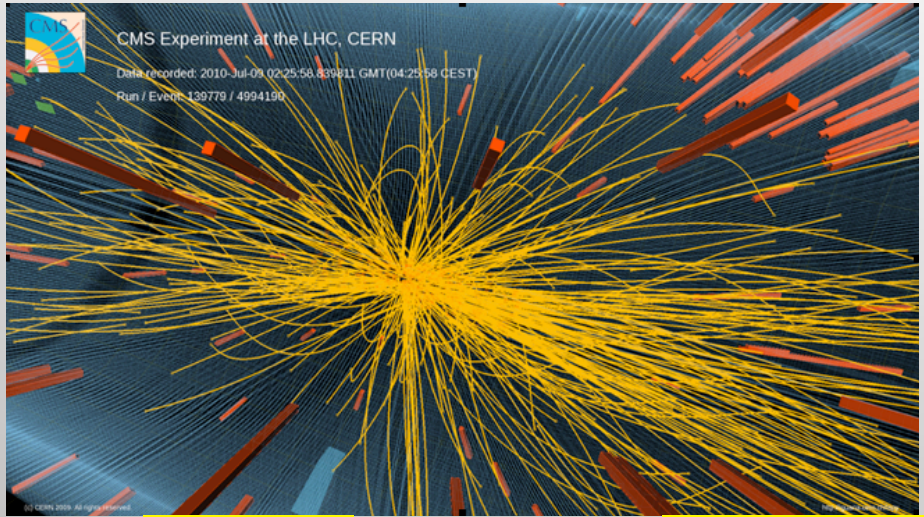
Difference between the transverse momenta of the two jets (p_T > 20 GeV)



DPS can be important for searches where after cuts only a few events remain…

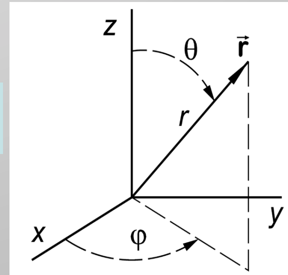
How well do we control DPS at the LHC energies in MCs?
A worry for 14 TeV?

Correlations Between Produced Particles



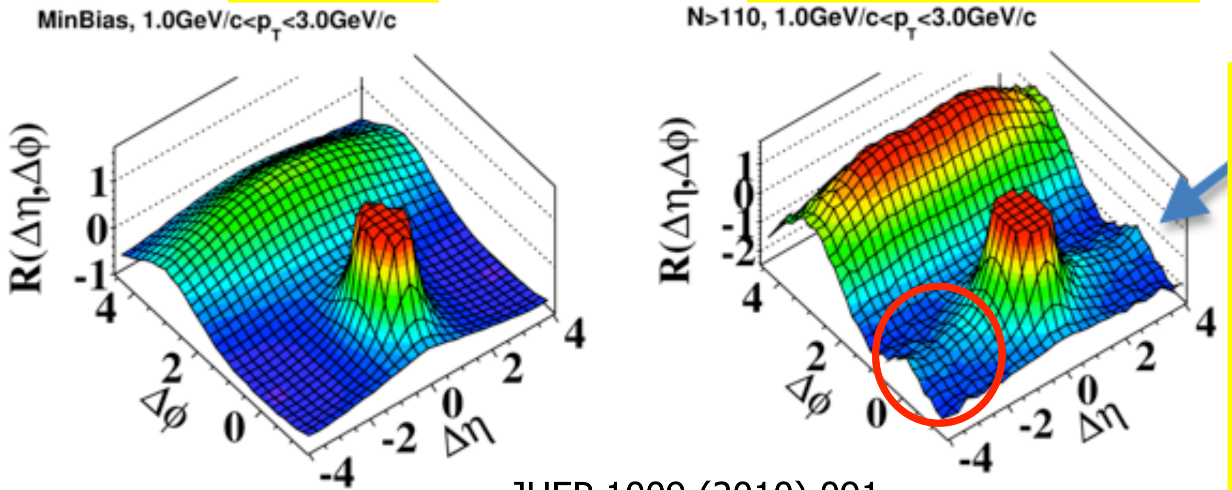
- Select high multiplicity events
- Study the correlation between two charged particles in the angles φ (transverse): Δφ and θ (longitudinal): Δθ

η= -ln tanθ/2



All events

High multiplicity events



JHEP 1009 (2010) 091

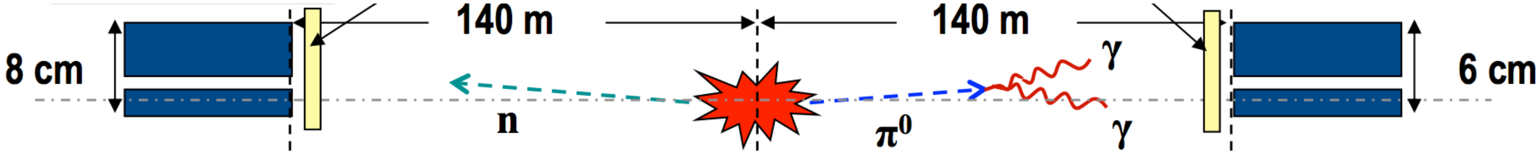
A new phenomenon in the 'stronge force'?
- Multiple interactions?
- C-glass condensates?
- Hydrodynamic models?

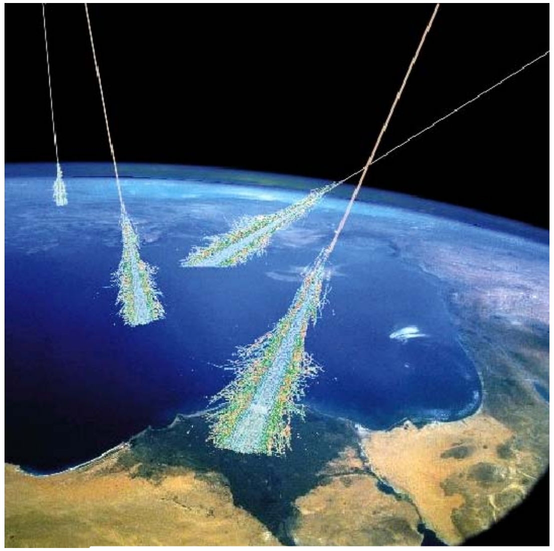
…

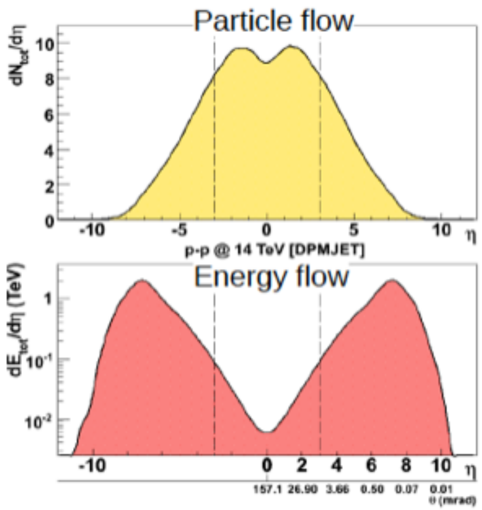
Understanding the "Ridge" in pp collisions in MC? Need for new measurements?

Forward Particles Measurements

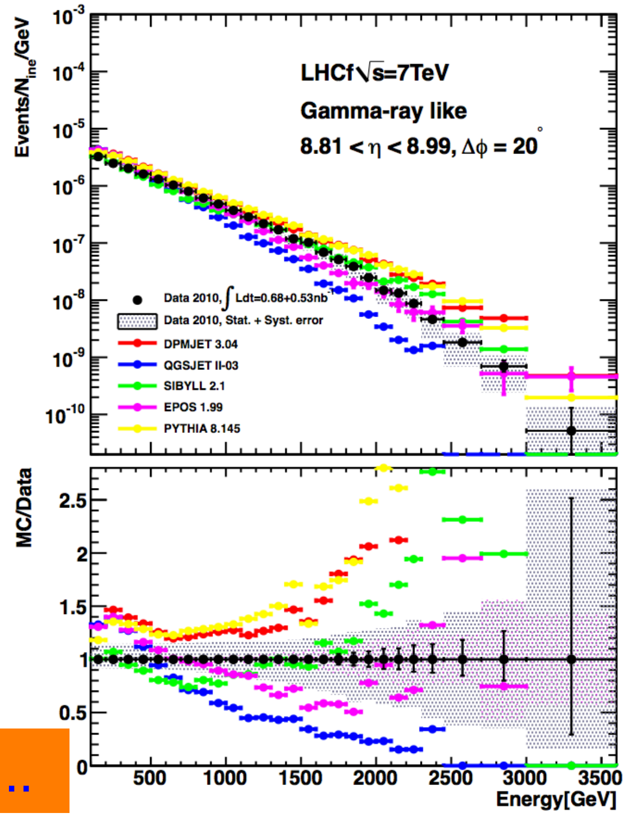
- LHCf uses the same Interaction Point as ATLAS (IP1)
- LHCf has forward detectors at zero degrees seen from the IP (140 away from the IP): Measure the forward photons/pions for cosmic ray studies







DESY-PROC-2012-03



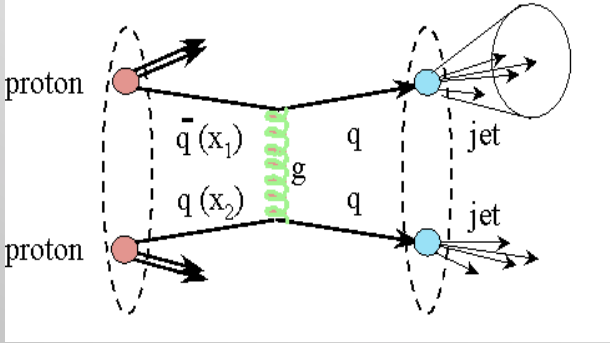
Forward gamma measurement compared to Monte Carlos for Cosmic Ray studies

No model reproduces the data well !!

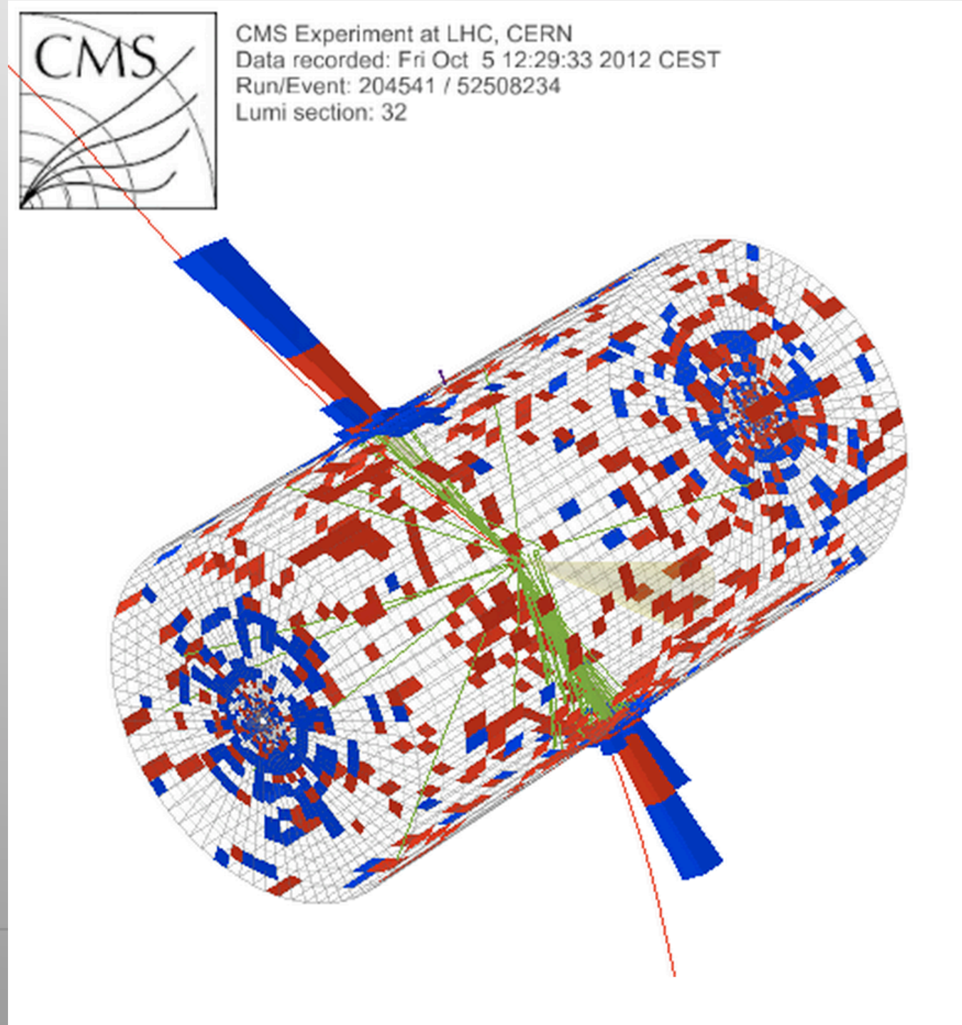
LHC data connection with cosmic rays? Workshop…

Strong Interaction: Jets Production!

Study the strong force using jet production



Di-jet invariant mass = 5.15 TeV (R=1.1 jets)

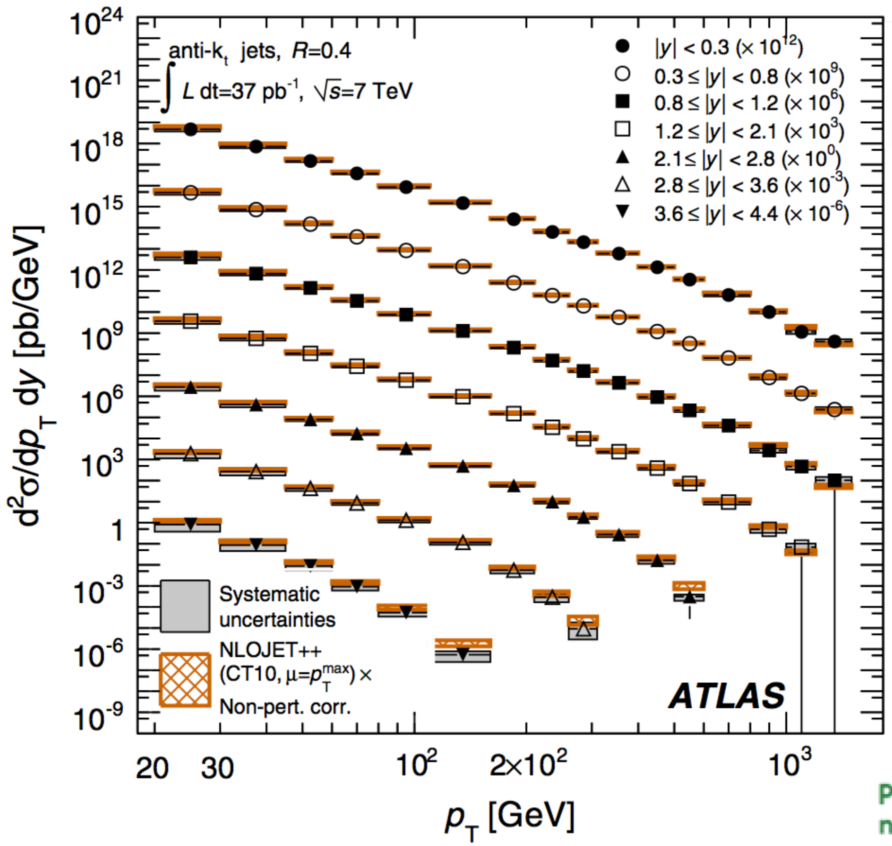


Jets of particles emerge after a high energy parton-parton scattering

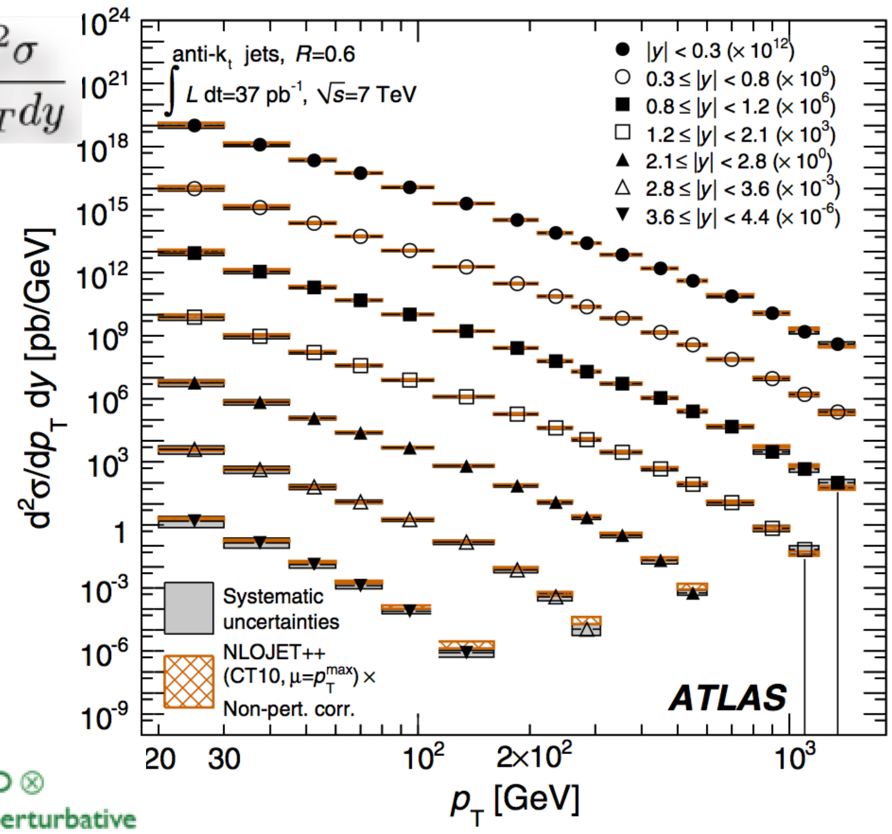
In this event more than 60% of the full proton-proton energy ends up in jets

Inclusive Jet Production (7 TeV)

Phys.Rev. D86 (2012) 014022



$$\frac{d^2\sigma}{dp_T dy}$$

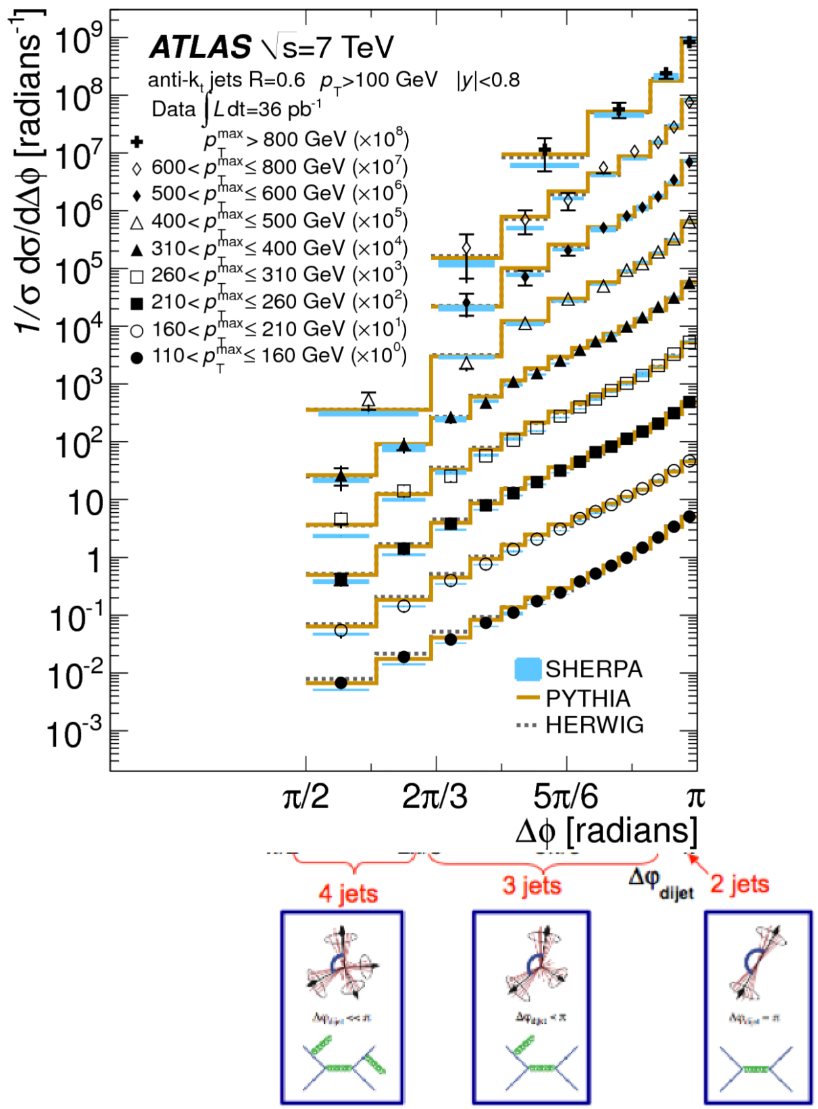


pQCD ⊗ non-perturbative corrections

Agreement with NLO calculations over the full range, up to 2 TeV jets
The anti-kT jet algorithm is used in most studies. The ‘cone’ chosen for this algorithm is different for ATLAS and CMS -> no direct comparison possible
ATLAS uses R=0.4 and R=0.6

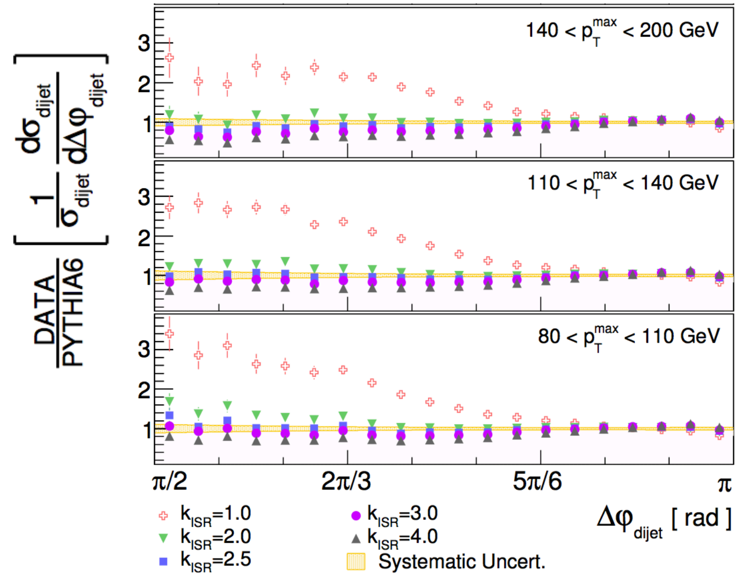
Azimuthal Correlations Between Jets

PRL 106 (2011) 172002



Azimuthal correlations between the two most leading jets are sensitive to the QCD radiation in the event, both initial and final rad.

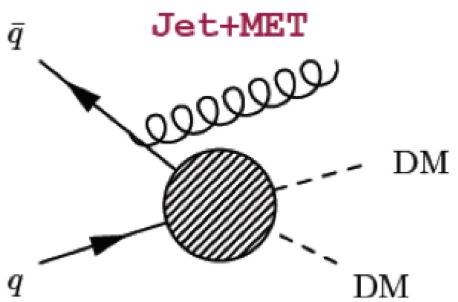
PRL 106 (2011) 172002



Initial state radiation (ISR) became very important for certain searches at the LHC!!

The Dark Matter Connection

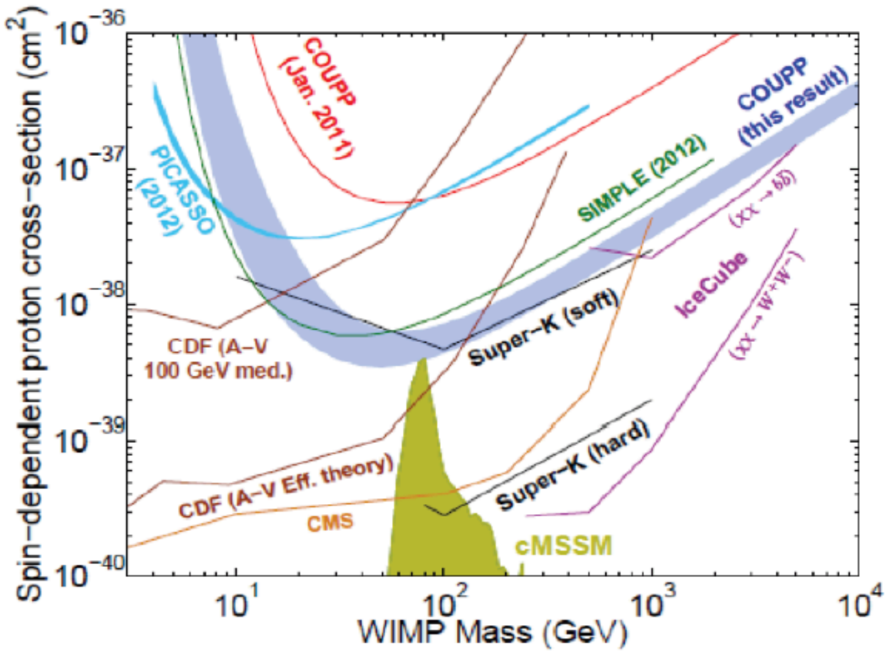
Searches for mono-jets (mono-photons) can be used for
Direct searches for Dark Matter (DM)
-> Spin dependent and spin independent cross sections of DM with matter



Effective contact
interaction approach

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$



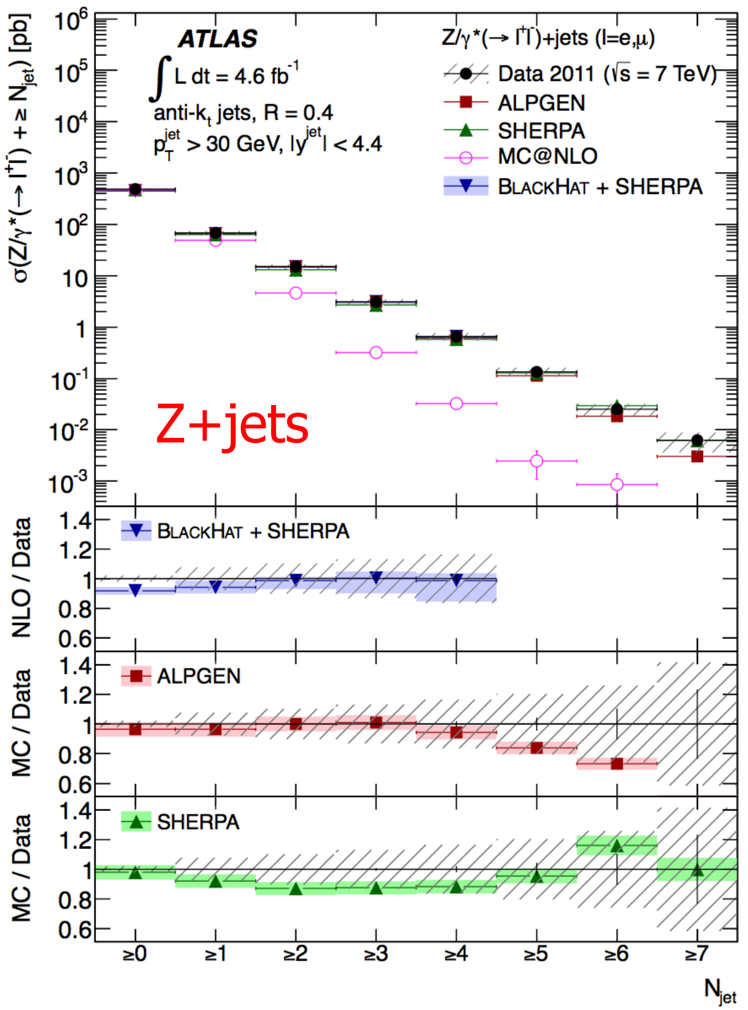
Collider searches are very competitive!!

Similarly some SUSY searches with compressed spectra rely on ISR, for the for trigger: AMSB with semi-stable gauginos arxiv:1202.4847 (ATLAS)

Do we control ISR well enough so that we can rely on it for searches?

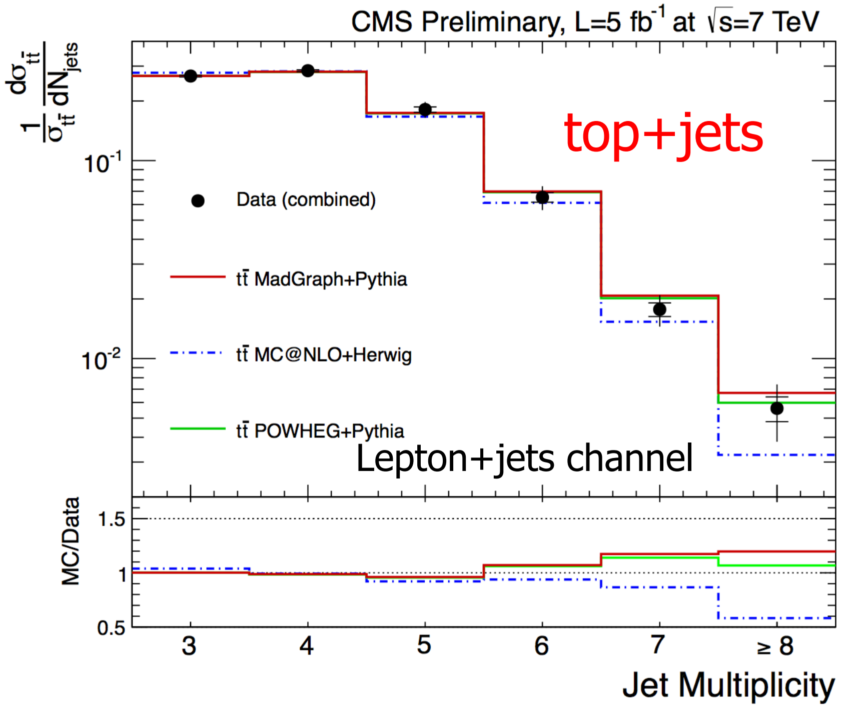
Vector Boson+Jets and Top+Jets

arXiv:1304.7098



High statistics and precision at the LHC allows for W/Z+jets and top+jets studies

CMS-PAS-12-018



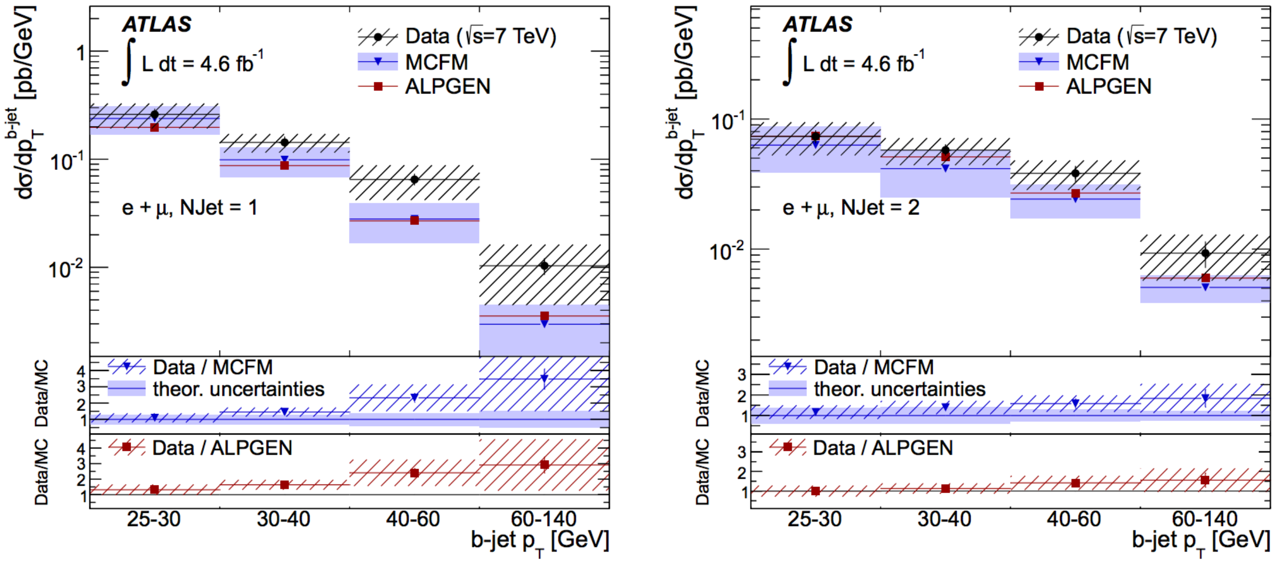
Good description by theory for both processes

Important backgrounds for searches, eg for SUSY searches

Z,W + b-jet Production

W+b jets

arXiv:1302.2929



Excellent b-tagging in the experiments allows for further more sophisticated measurements such as associated b-jet production

Also Z+b results

W+1 b-jet cross section on the high side
W+2 b-jets cross section agrees with prediction

Gluon splitting issues?

Z+b jets

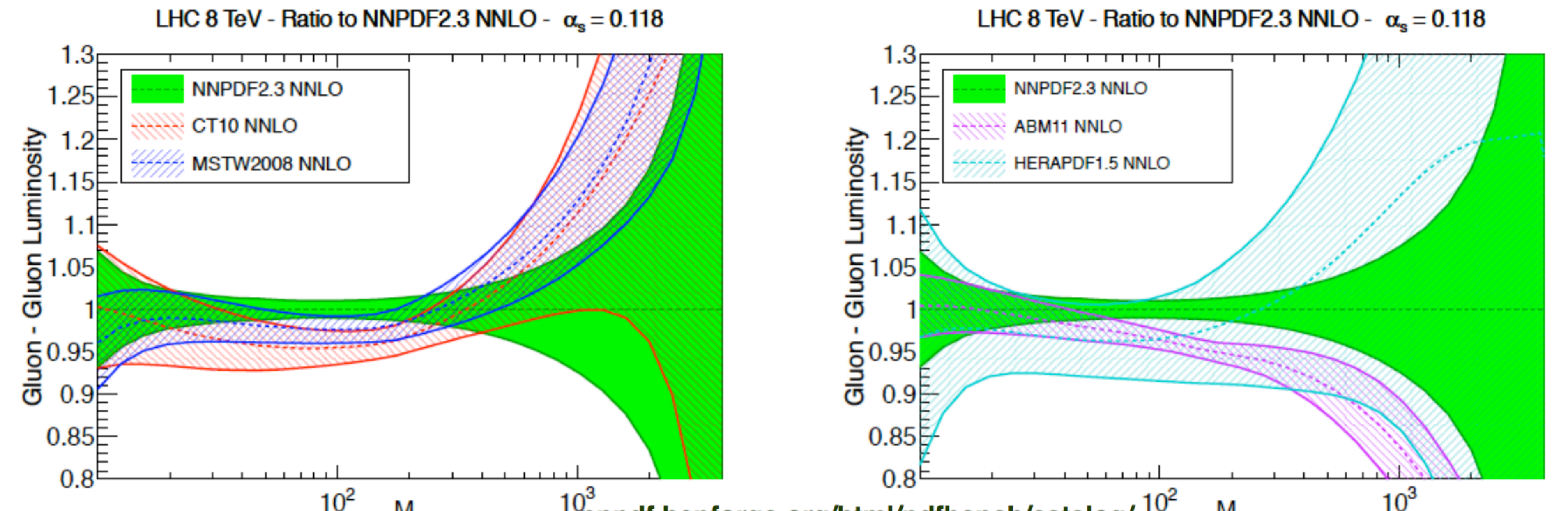
CMS-PAS-SMP-13-004

Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)+1b)$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)+2b)$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01

CMS preliminary

Parton Distributions

- Parton distributions (PDFs) are an essential ingredient of the LHC program
- Several PDFs available at NNLO: ABM, MSTW, CT, NNPDF, HERAPDF,…
- Studied within the experiments in PDF groups, and across experiments with the fitters in PDF4LHC

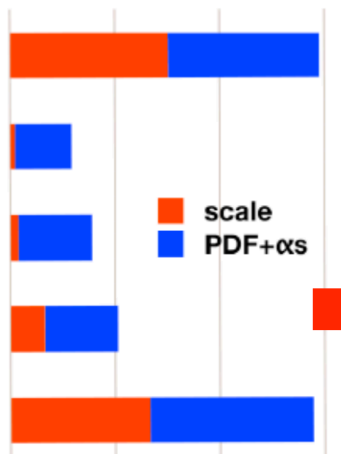


nnpdf.hepforge.org/html/pdfbench/catalog/

PDFs groups provide central values and error envelopes that differ
-> different choice of data used as input, different TH treatment especially for heavy flavors,…

PDF Precision

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



1) PDFs fundamental limit for Higgs boson characterization in terms of couplings

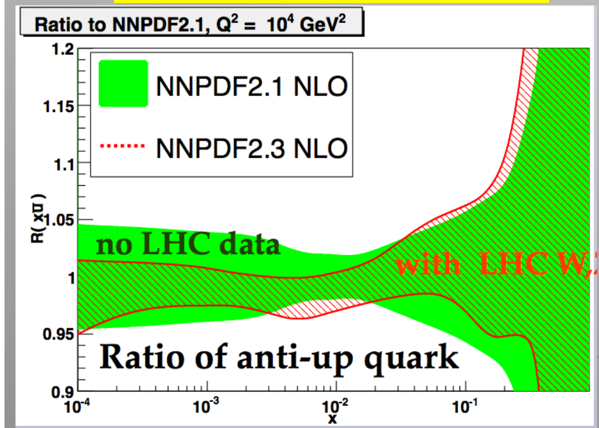
J. Campbell, ICHEP12

Precision on Higgs cross section from PDFs (and α_s)

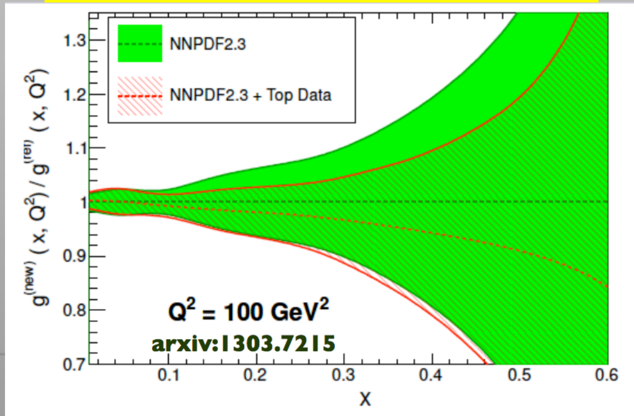
What is the ultimate precision on PDFs? Now and in future?

Include LHC data!

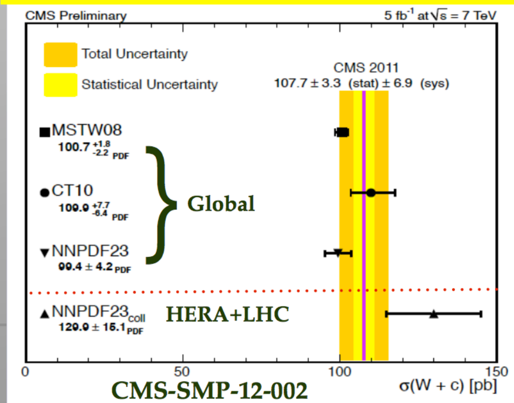
W, Z data included



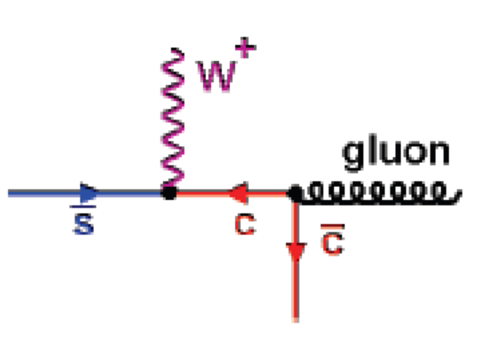
Top quark data included



W+c data to tag s-quark
->strangeness supp. ~0.5

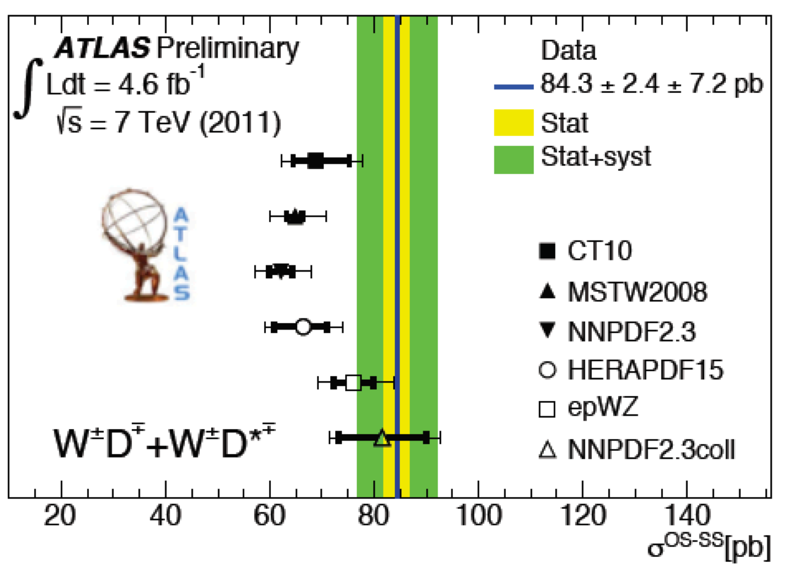


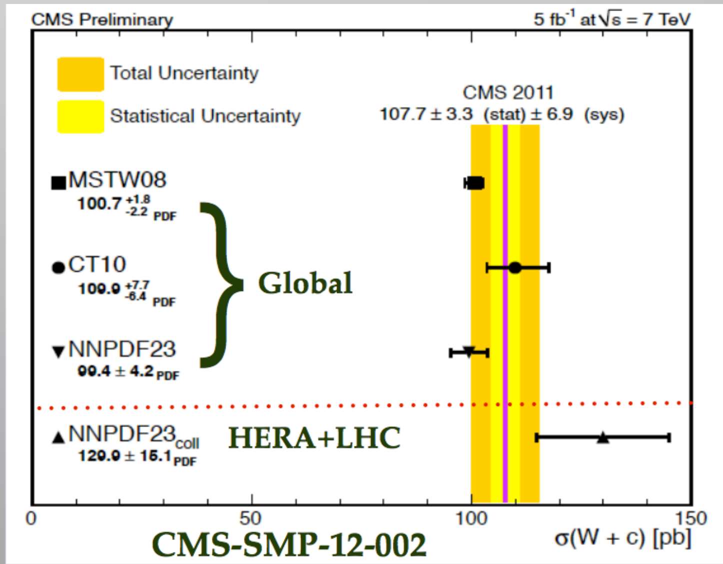
Strange Sea



- experimental techniques for c identification
  - ATLAS: D reconstruction from tracks combination
  - CMS: jets with c content using secondary vertices
- theory predictions
  - ATLAS: aMC@NLO
  - CMS: MCFM

CMS and ATLAS do not quite agree on the sea strangeness suppression…

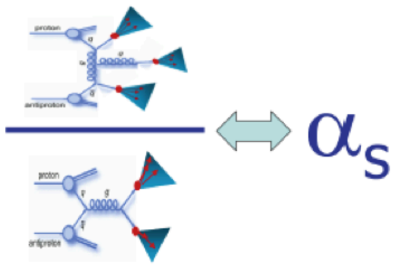




MSTW, NNPDF2.3: strange sea most suppressed; CT10: less suppressed; epWZ: unsuppressed; NNPDF2.3collider: anti-s>anti-d

3-jet to 2-jet Cross Section Ratios

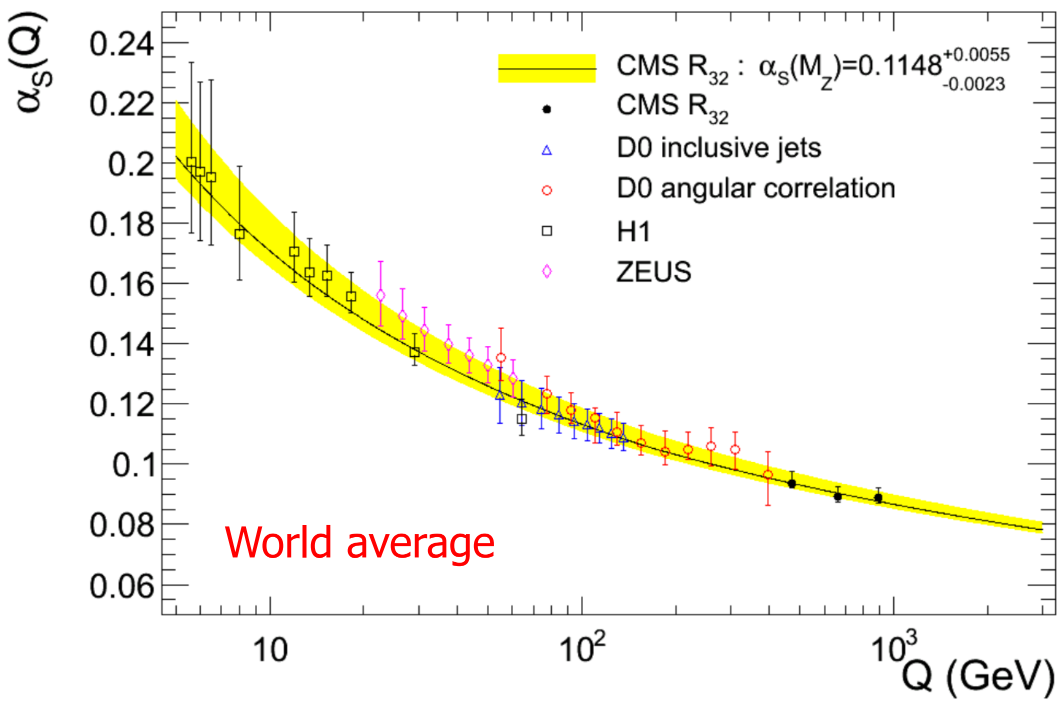
This measurement is sensitive to the fundamental QCD parameter α_s
Di-jets within the range of 420 - 1390 GeV, p_T of all jets larger than 150 GeV



$$R_{32} = \frac{d\sigma_{3+}/dp_{\mathrm{T}}}{d\sigma_{2+}/dp_{\mathrm{T}}} \propto \alpha_s(Q)$$

$$Q = \langle p_{\mathrm{T}1,2} \rangle = \frac{p_{\mathrm{T}1} + p_{\mathrm{T}2}}{2}$$

$\langle p_{\mathrm{T}1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$
420–600	474	$0.1147\,^{+0.0061}_{-0.0021}$	$0.0936\,^{+0.0040}_{-0.0014}$
600–800	664	$0.1132\,^{+0.0050}_{-0.0031}$	$0.0894\,^{+0.0031}_{-0.0019}$
800–1390	896	$0.1170\,^{+0.0058}_{-0.0032}$	$0.0889\,^{+0.0033}_{-0.0018}$



$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp.}) \pm 0.0018\,(\mathrm{PDF})^{+0.0050}_{-0.0000}\,(\mathrm{scale}) = 0.1148\,^{+0.0055}_{-0.0023}$$ arXiv:1304.7498

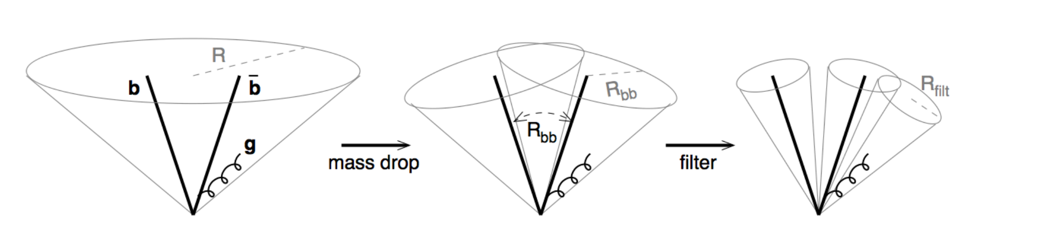
ATLAS prelim: $\alpha_s(M_Z) = 0.111 \pm 0.006(\mathrm{exp.})\,^{+0.016}_{-0.003}(\mathrm{theory})$. ATLAS-CONF-2013-041

How precise can we extract α_s at the LHC or elsewhere?

New Directions: Boosted Jets & Substructure

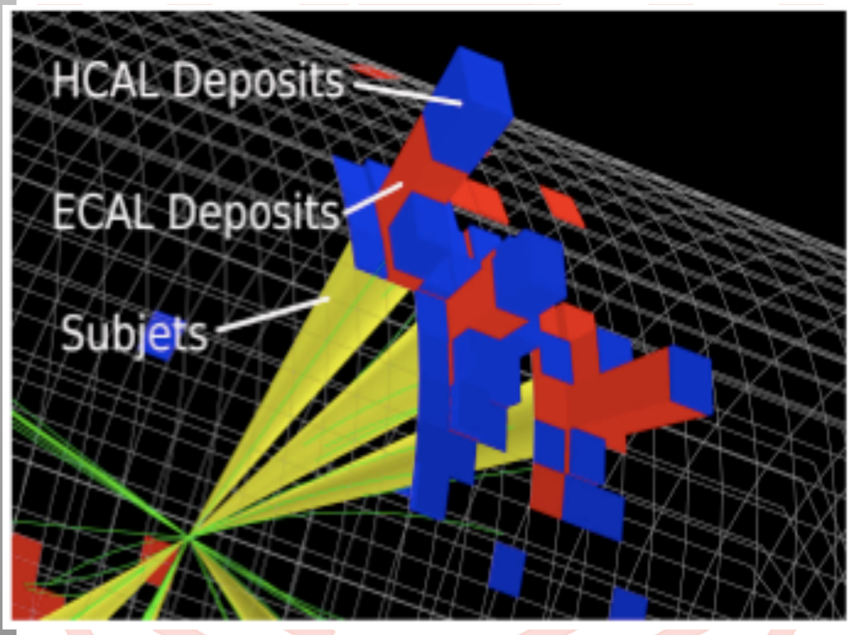
Analyse boosted/merged jets

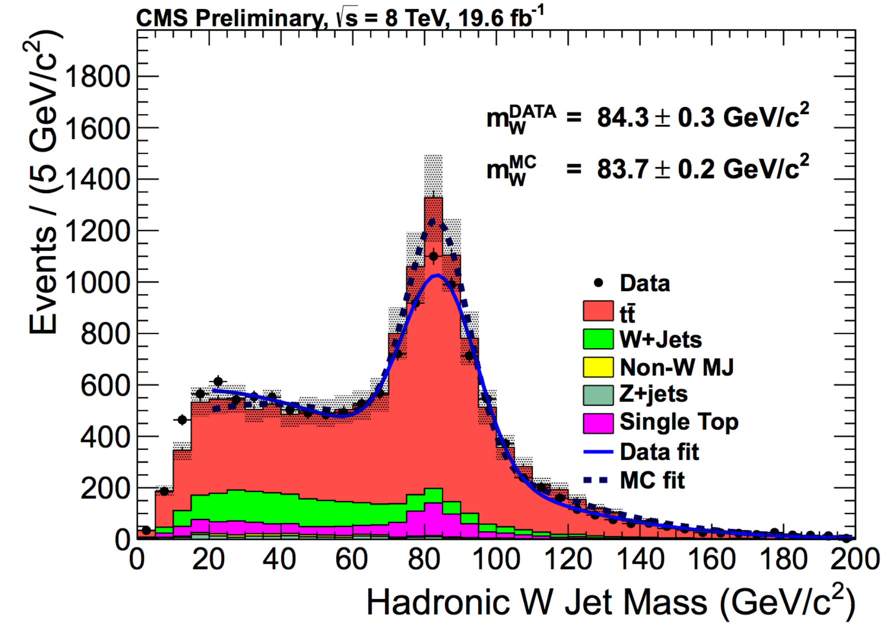
arXiv:0802.2470



- Start from Cambridge-Aachen FAT jets and apply jet "pruning" to find sub-jets
- Many methods being developed to analyse the jet substructure: grooming-> mass drop filtering, trimming, pruning…

Example: Boosted top events with b-jet and two merged jets from the W





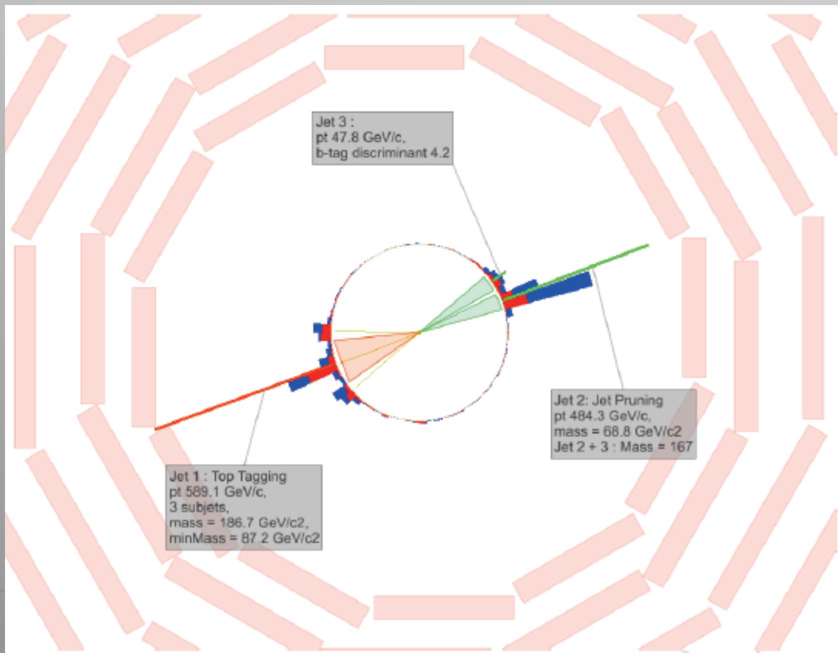
Eg used in tt Resonance Searches

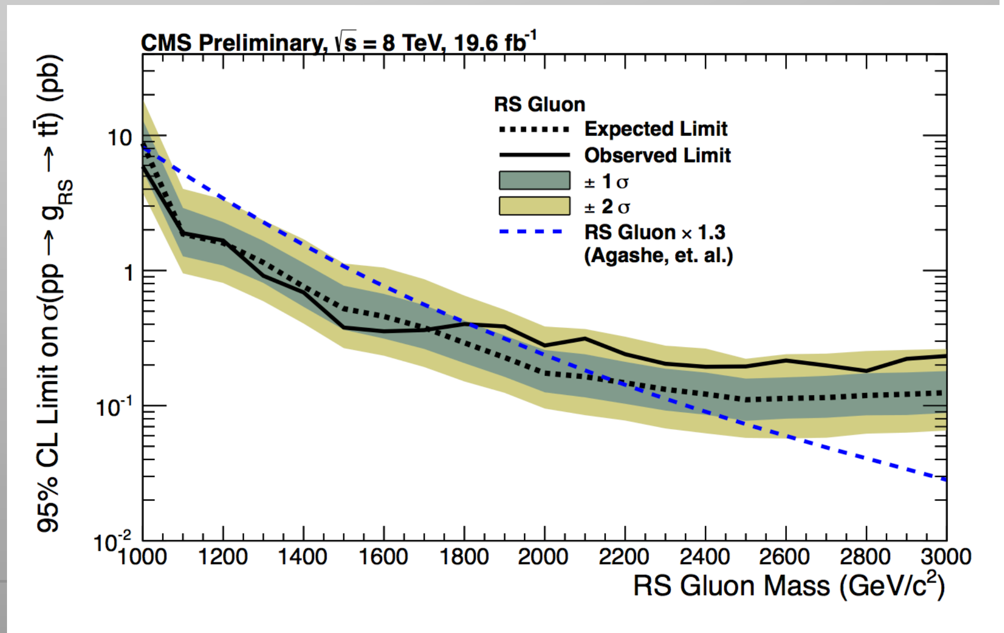
- Search in the all hadronic decay channel for the tops
- Tops are boosted for high mass Z'-like objects, jets merge
- Start from Cambridge-Aachen FAT jets and apply jet pruning to find sub-jets
- QCD background estimate from data (miss-tag method)

CMS-EXO-11-006

Particle flow an asset for this study!

Exclude KK-Gluons 1<M<1.8 TeV

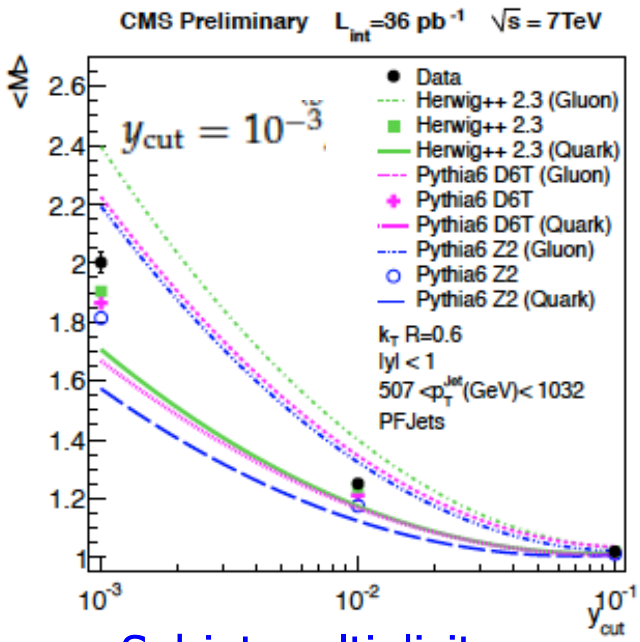




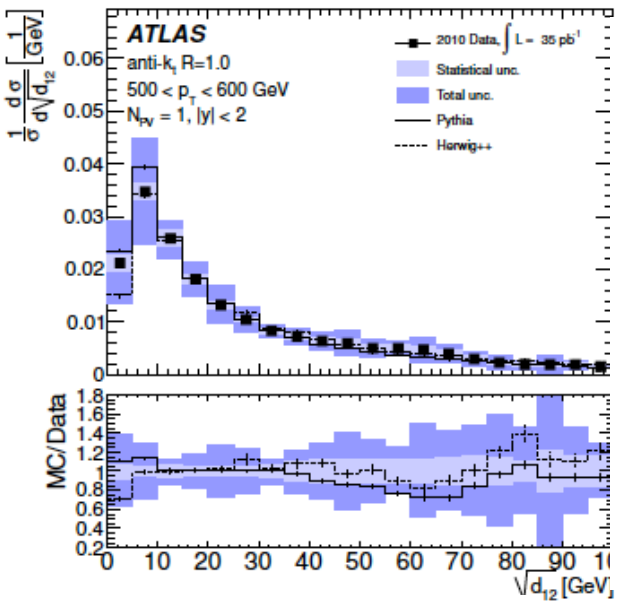
Detailed QCD Jet-structure Studies

- Detailed QCD jet studies such as substructure grooming are important to get:
  - Deeper insight into pQCD evolution in jets
  - To perform searches for New Physics in a new way
  - New Tests for MC programs!!

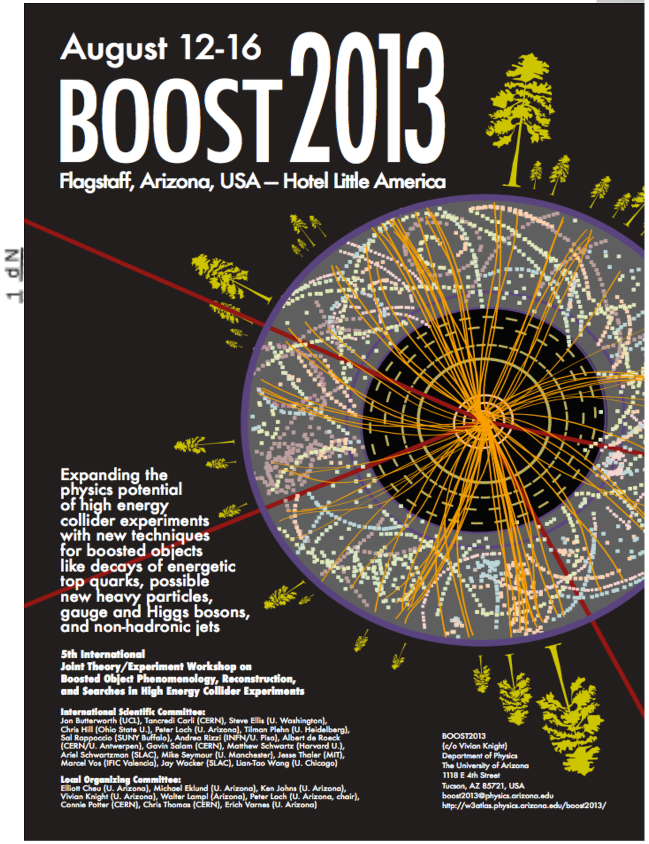
CMS-QCD-10-41



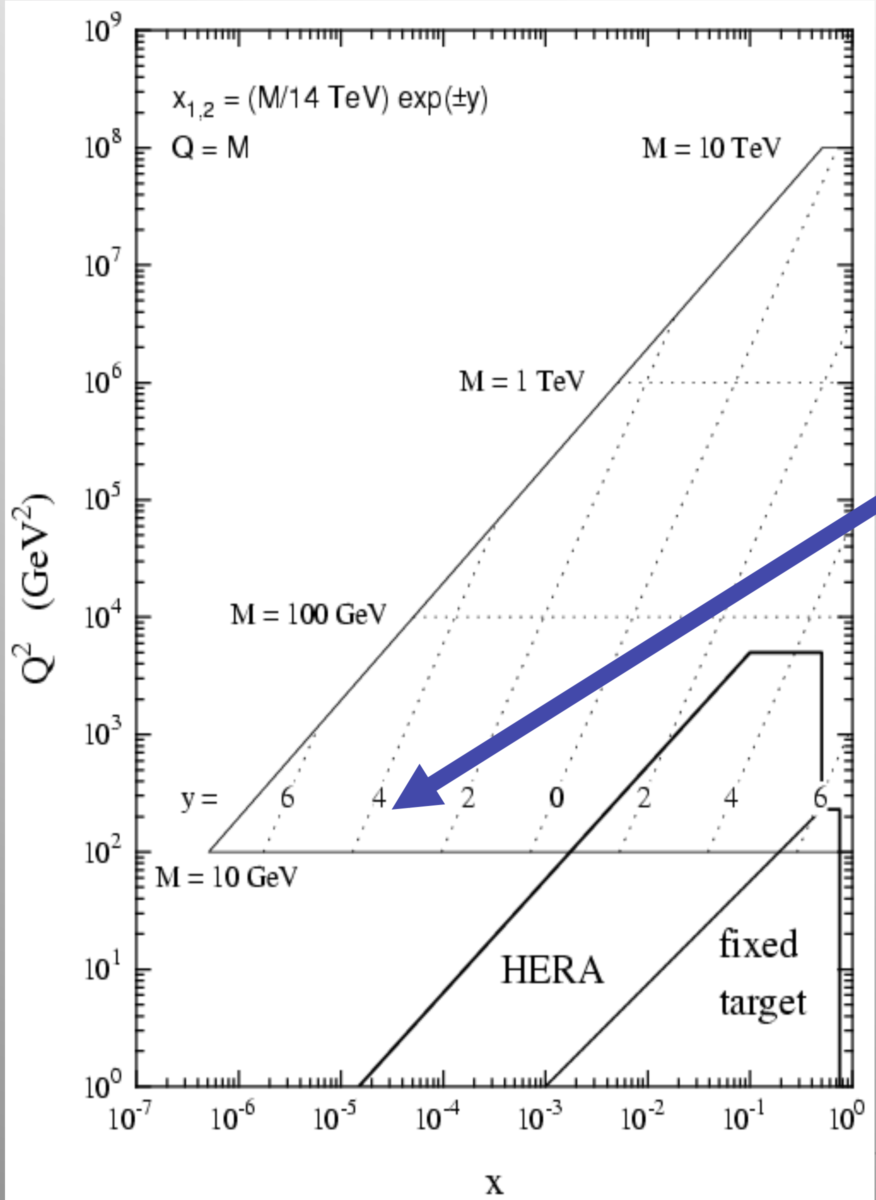
Subjet multiplicity



k_T splitting scale



Low-x Studies at the LHC



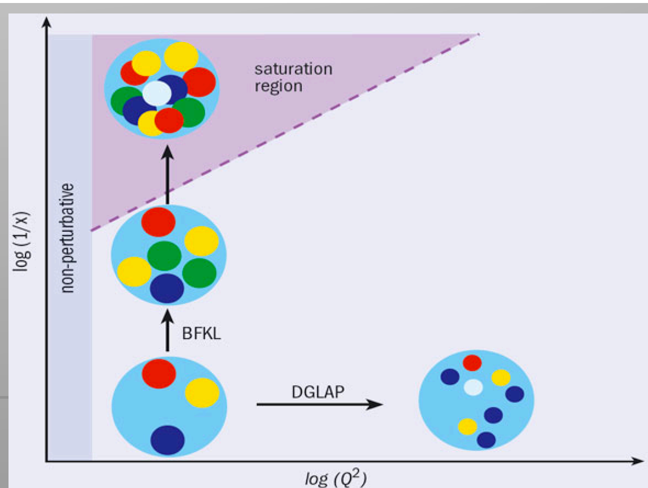
High energy of the LHC allows to access regions of low Bjorken-x Detector coverage to large | η | is important! Typical measurements:

- Low mass Drell-Yan, Jpsi…
- Prompt photon production
- Jet production with large rapidity

QCD Dynamics studies:

DGLAP: Dokshitzer, Gribov, Lipatov, Altarelli Parisi

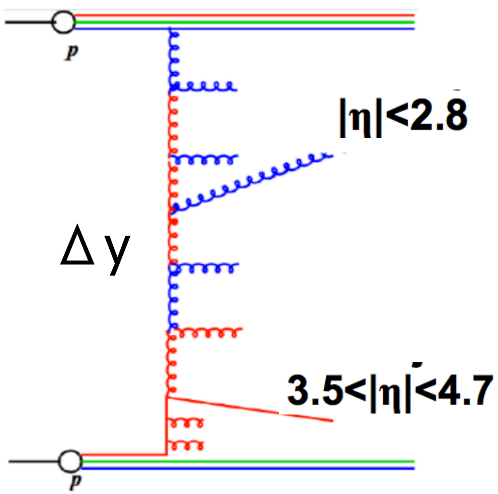
BFKL: Balitskii, Fadin, Kuraev, Lipatov



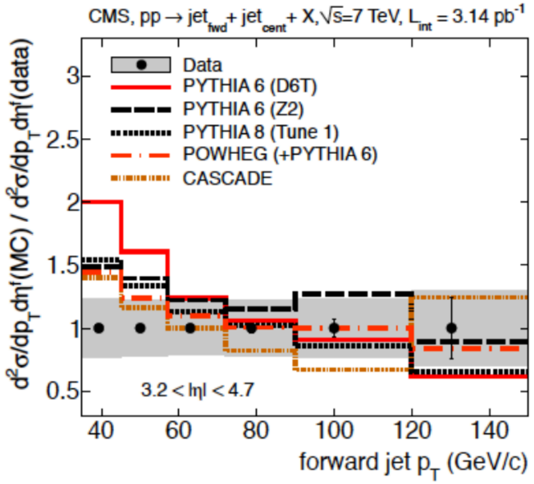
Low-x: Mueller-Navelet Jet Studies

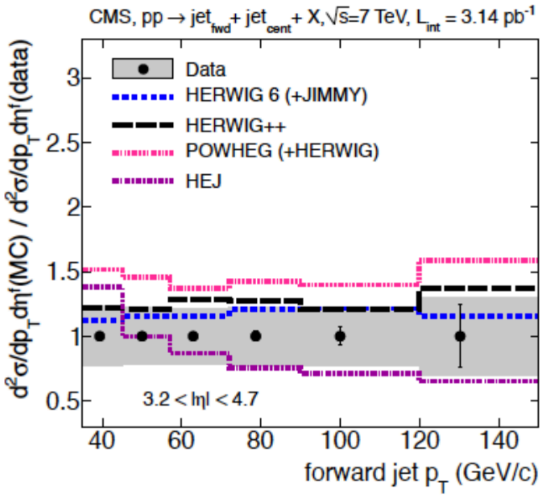
- Look at correlations between jets -with p_T> 35 GeV- at large rapidity distance
- Proposed in the early '90's to as sensitivity test to BFKL and DGLAP evolution

CMS-PAS-FSQ-12-002

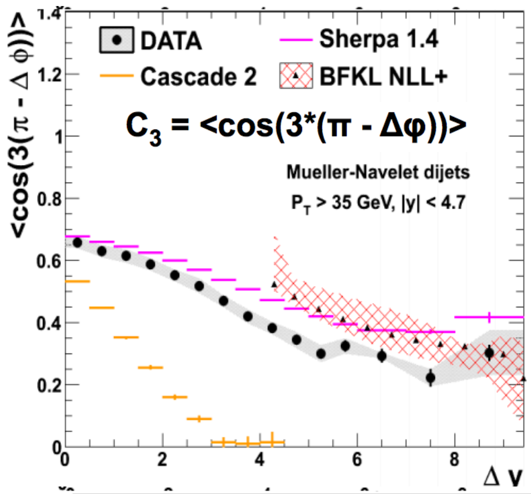


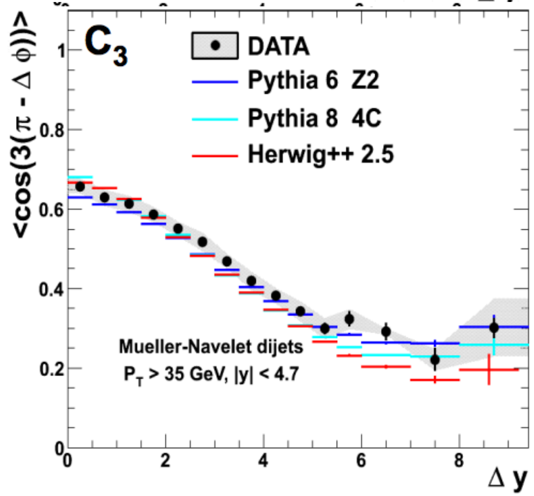
central + forward jet





azimuthal correlation vs Δ y

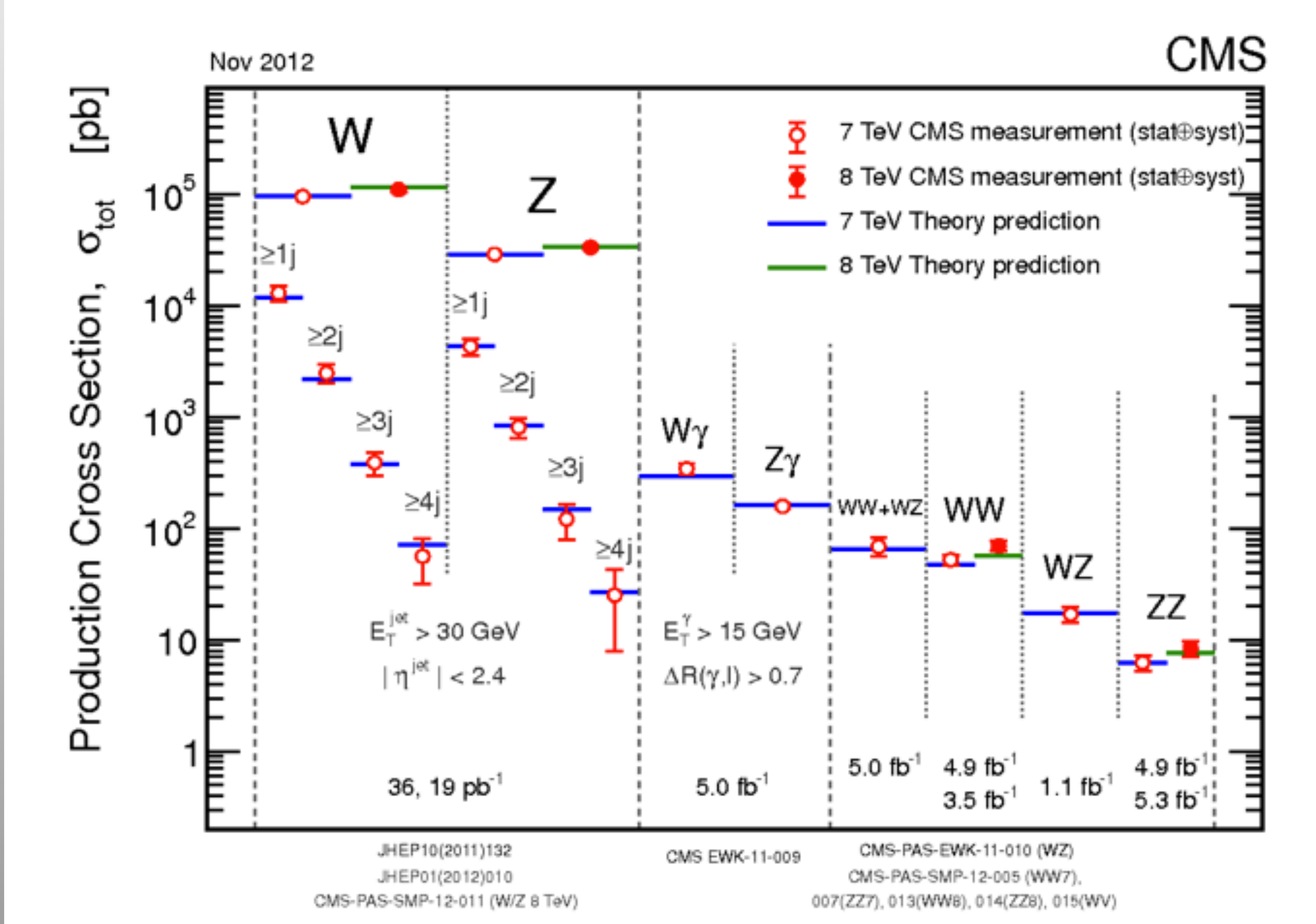




No model describes all these measurements very well

Do we need more dedicated measurements on low-x QCD effects?

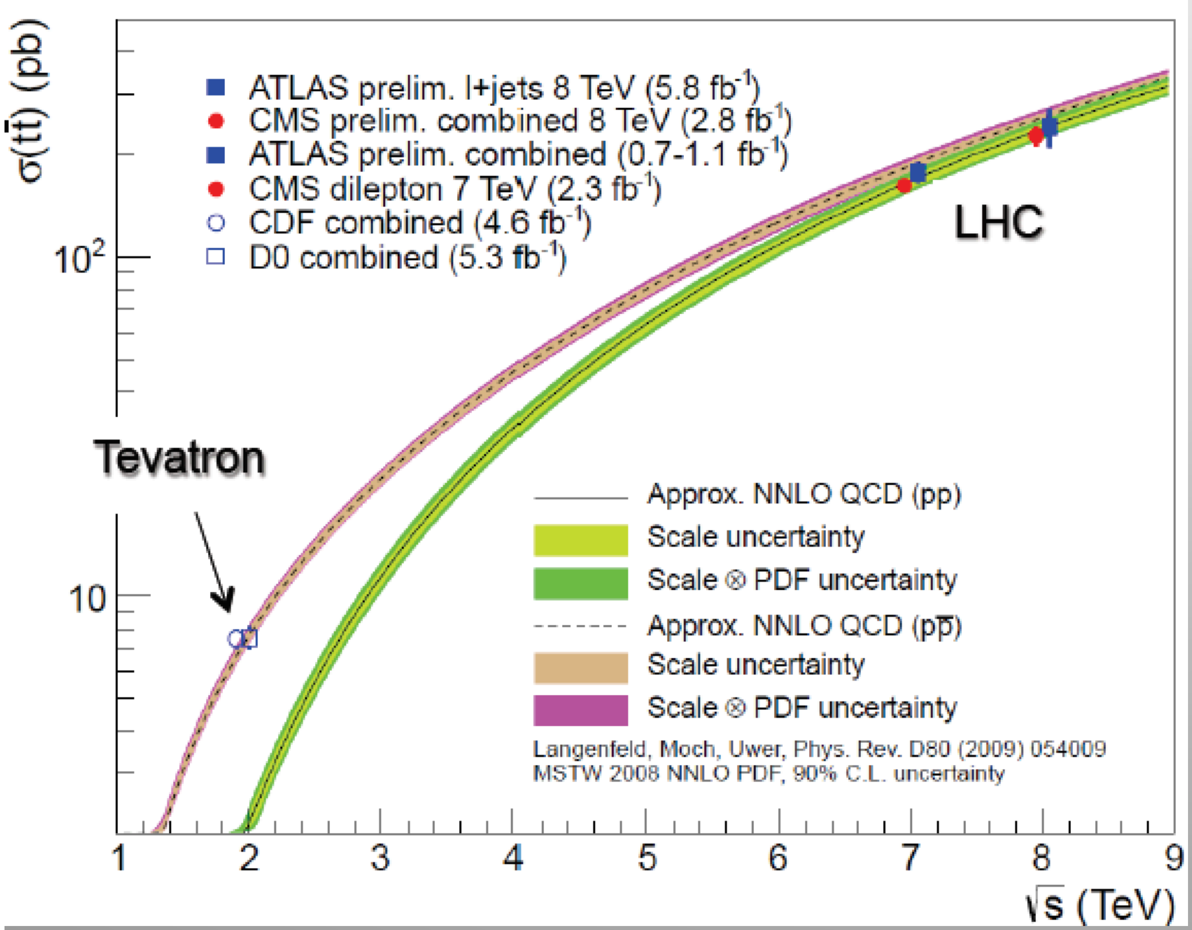
Vector Boson Production Overview

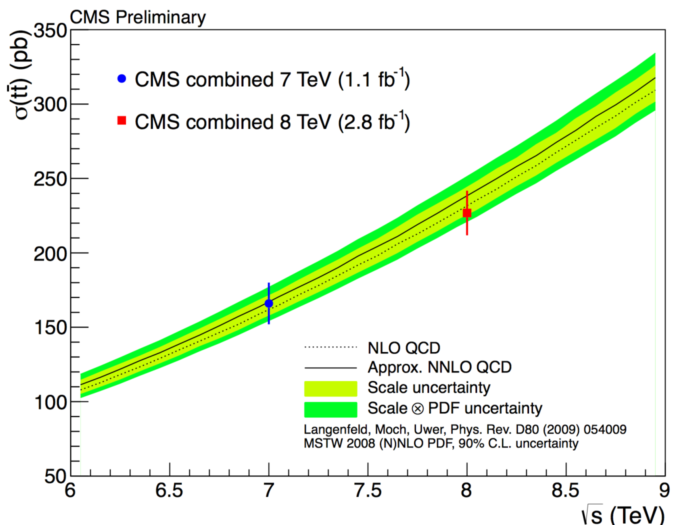


Heavy boson and di-boson measurements in good agreement with EWK calc.

Top Cross Sections

Excellent agreement with theory (approx. NNLO)



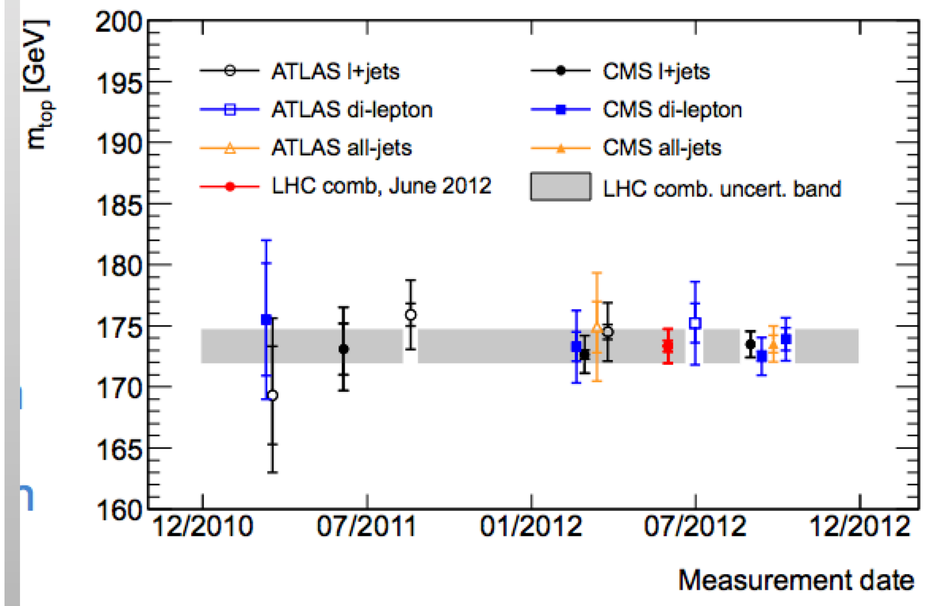


Now precision/agreement within ~5% of NNLO

Precision Measurements: top Mass

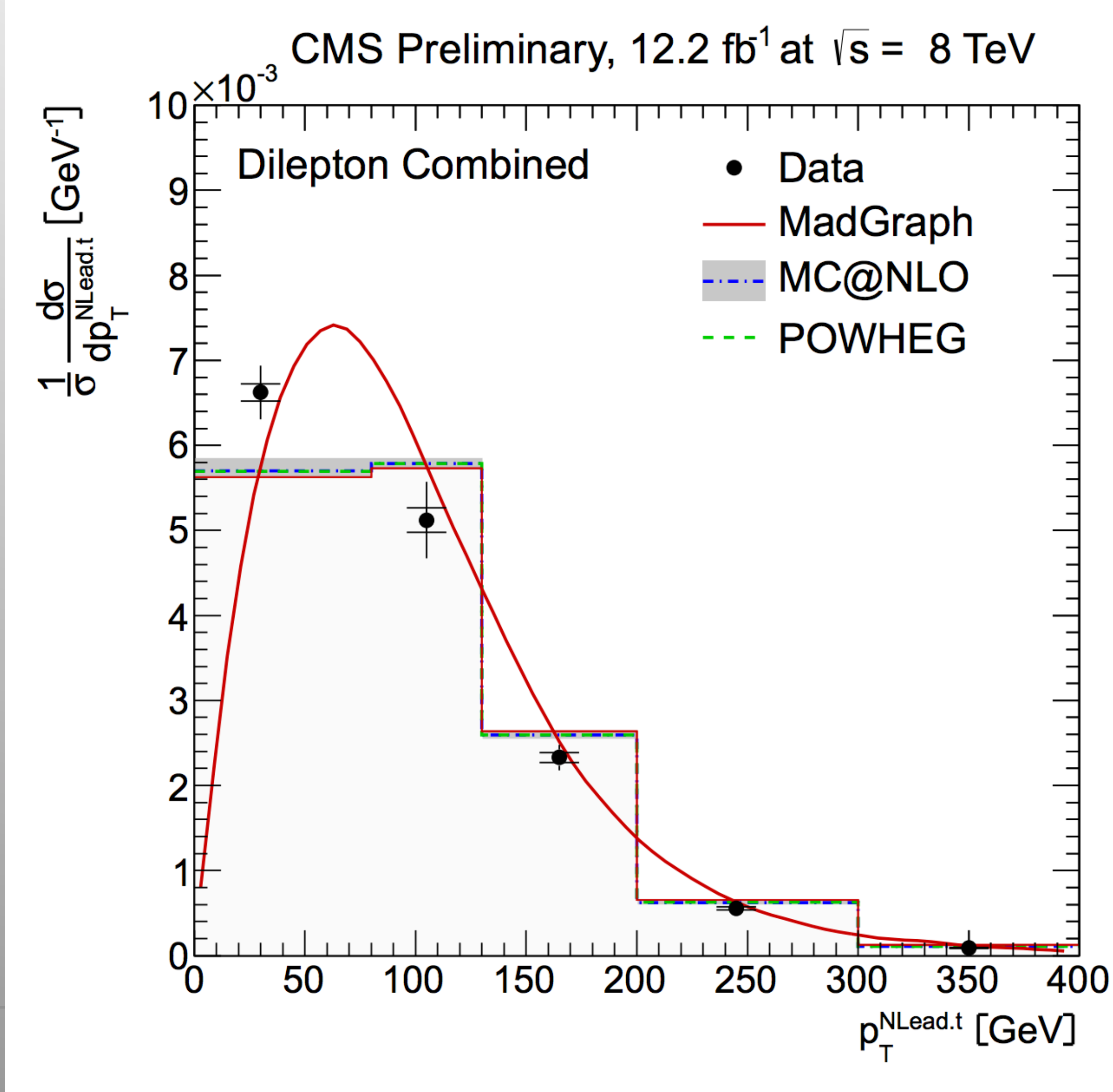
Very significant progress over the last 12 months
LHC Experiments now as precise as those of the Tevatron (16 year effort)

- QCD is responsible for most of the uncertainty: non-perturbative QCD effects including hadronisation, colour (re-)connection and UE tunes
- Tune/constrain these models with more precision using dedicated studies of ttbar events by eg looking at the bias in reconstructed top mass as a function of kinematic event variables
- Aside: the mass definition is a topic of discussion: how to connect the MC mass in our LO or NLO MC matrix elements to a properly defined top quark mass scheme

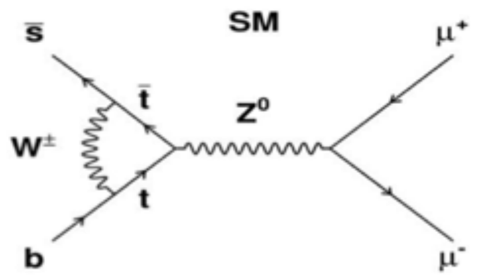


Precision on the mass now better than 1%
Important for EWK studies, Higgs, see later…

Issues: P_T distribution of the top quark



Rare Decays: B_s and B_d to μμ



Mode	SM prediction
$B_s \to \mu^+\mu^-$	$(3.54 \pm 0.30) \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$(0.11 \pm 0.01) \times 10^{-9}$

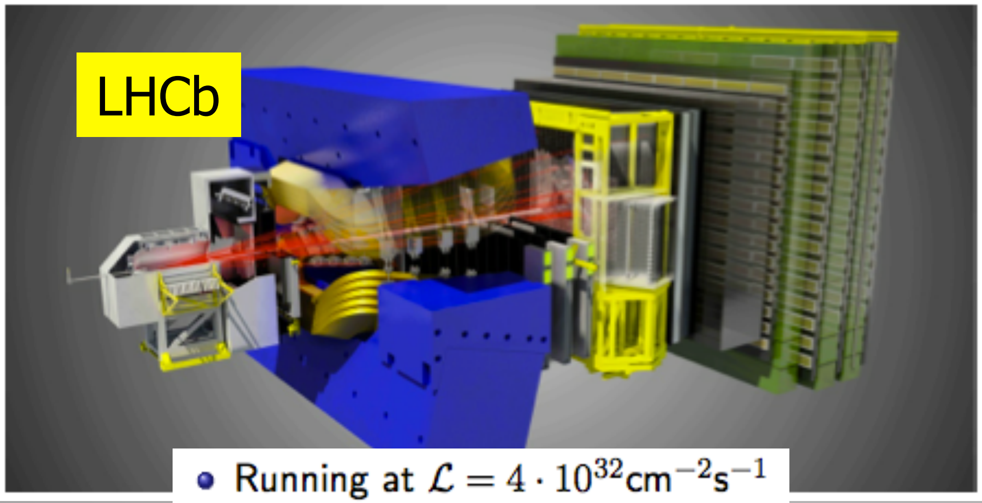
A. Buras et al., arXiv:1208.0934

DeBruyn et al., arXiv:1204.1737

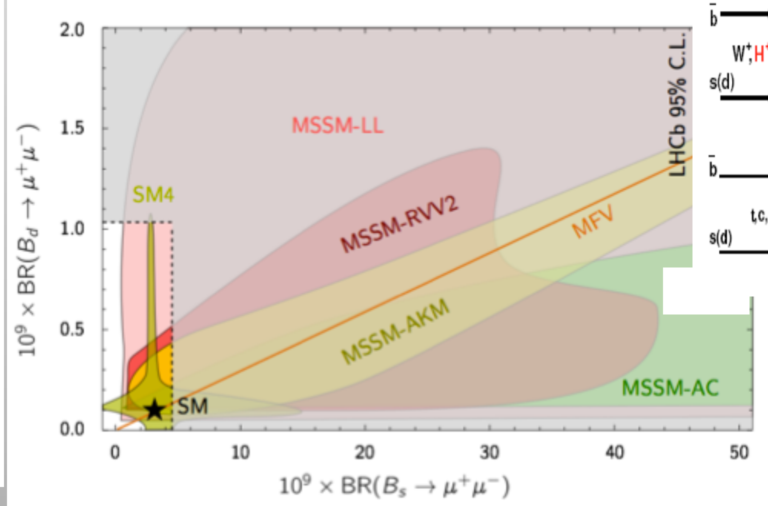
C. Davies, arXiv:1203.3862 (and ref. therein)

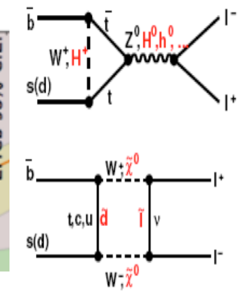
Since many years this decay has been chased CDF, D0, CMS, ATLAS and LHCb

New (pseudo) scalars can modify the SM predictions



- Running at $\mathcal{L} = 4 \cdot 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$





LHCb: Plethora of flavor measurements: D0 oscillations, observation of new B meson decays, CP asymmetry studies, CKM angle measurements,..

Rare Decays: B_s and B_d to μμ

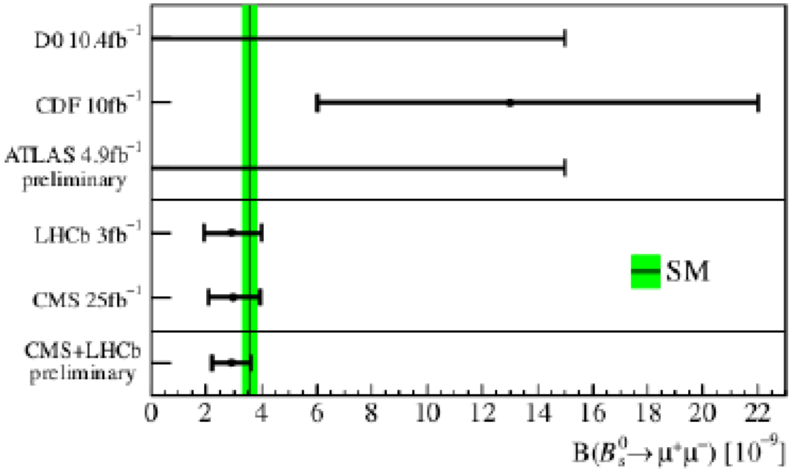
Combining LHCb and CMS (both with a significance of ~ 4σ)

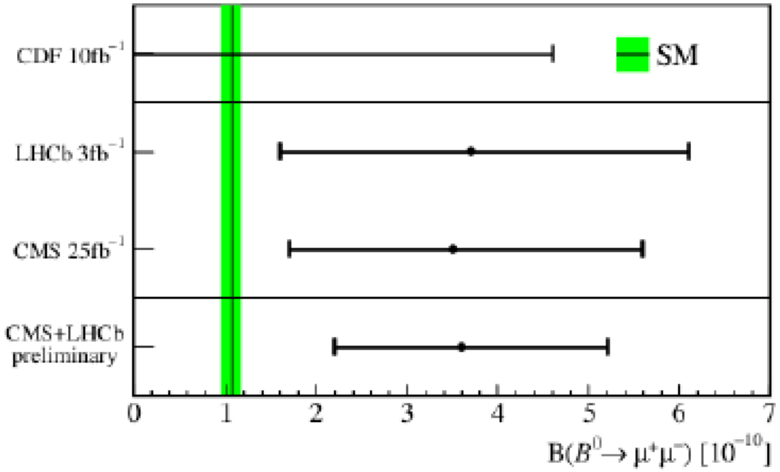
new @ EPS2013

Observation:

$$\text{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\text{BR}(B^0 \to \mu^+\mu^-) = 3.6^{+1.6}_{-1.4} \times 10^{-10}$$





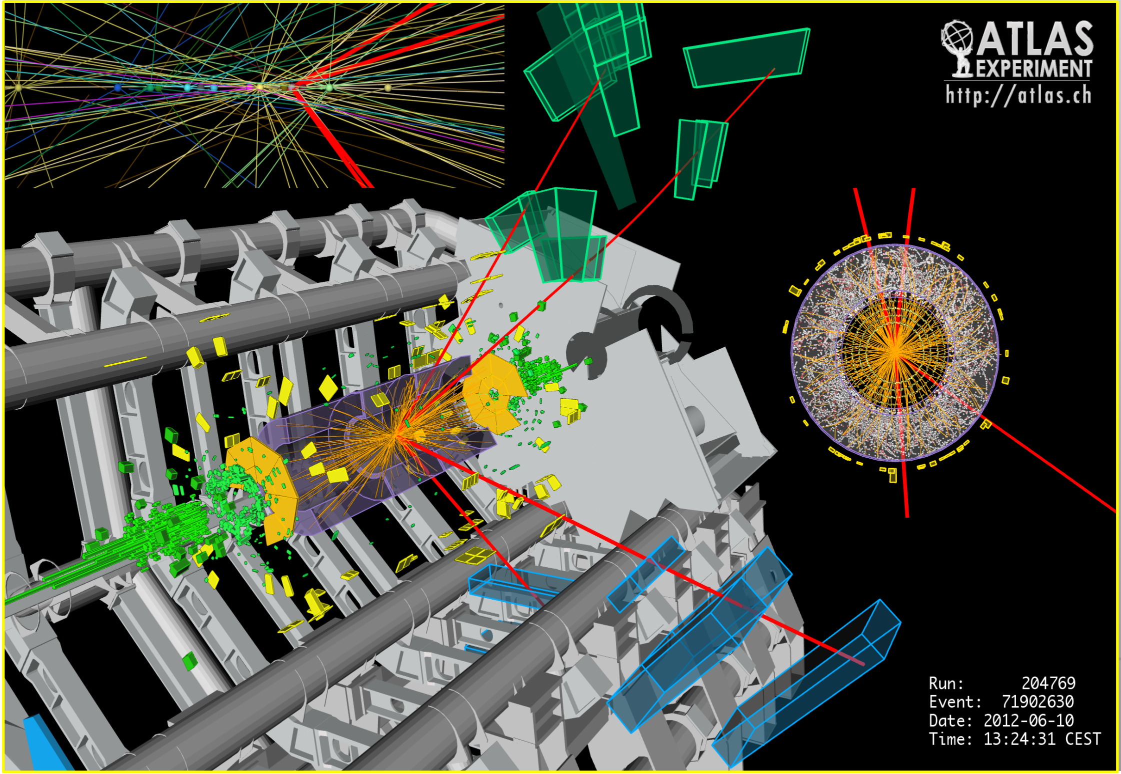
Searches for the Higgs Particle

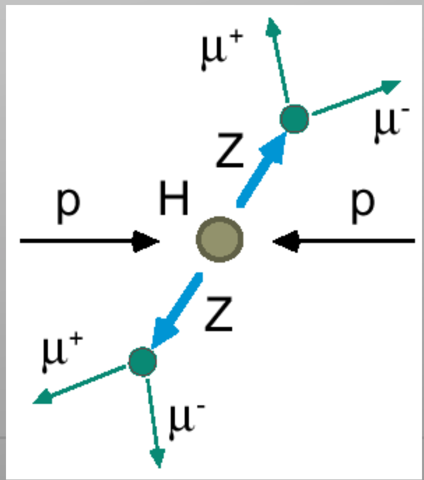
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

Example: Higgs(?) decays into ZZ and each Z boson decays into μμ

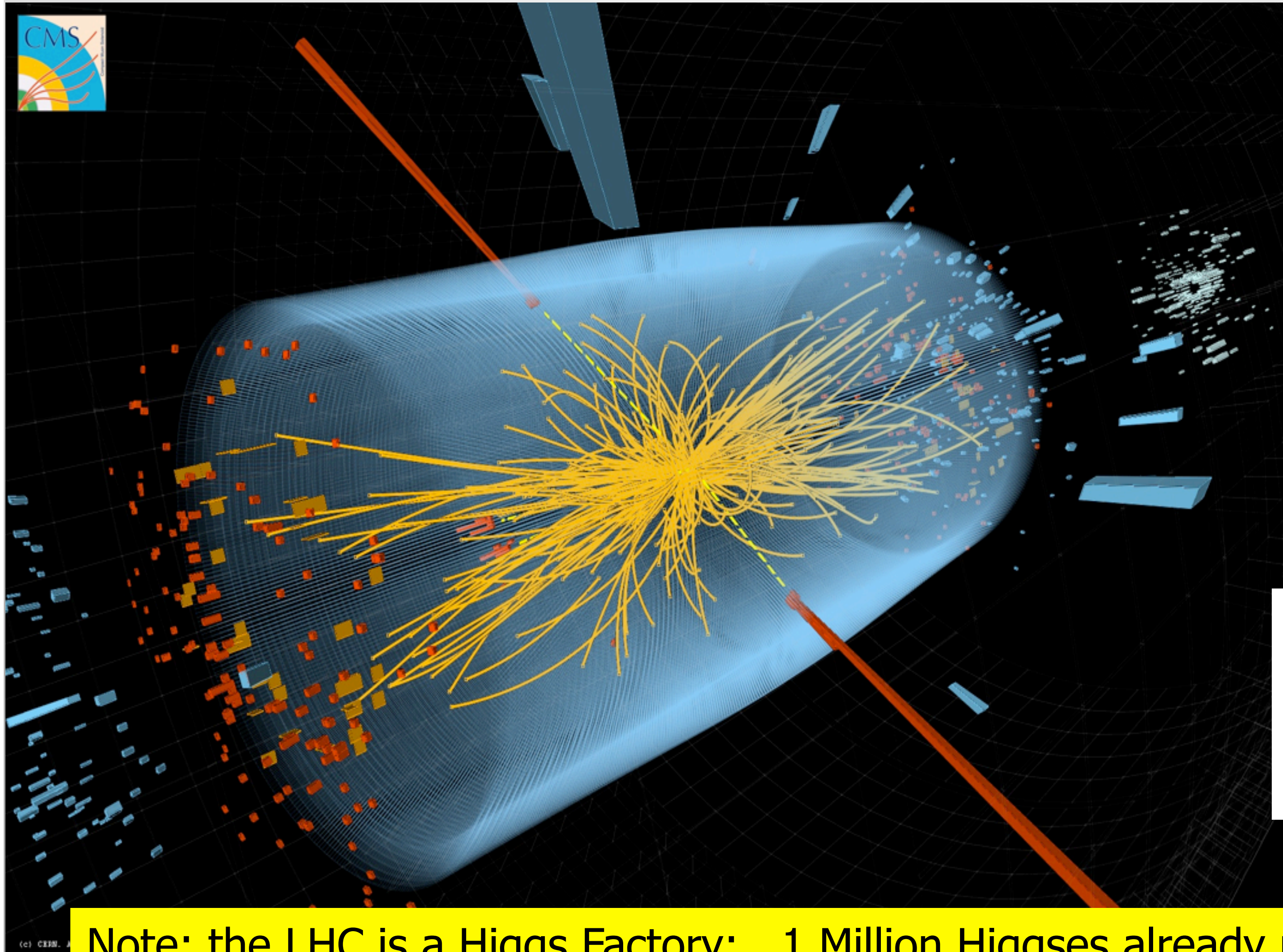
So we look for eg 4 muons in the detector

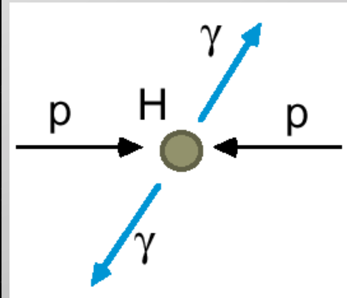
But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for on event by event (we can reconstruct the total mass with the 4 muons)





A Collision with two Photons





A Higgs or
a ‘background’
process without
a Higgs?

Note: the LHC is a Higgs Factory: 1 Million Higgses already produced
15 Higgses/minute with present lumi.

July 4th 2012

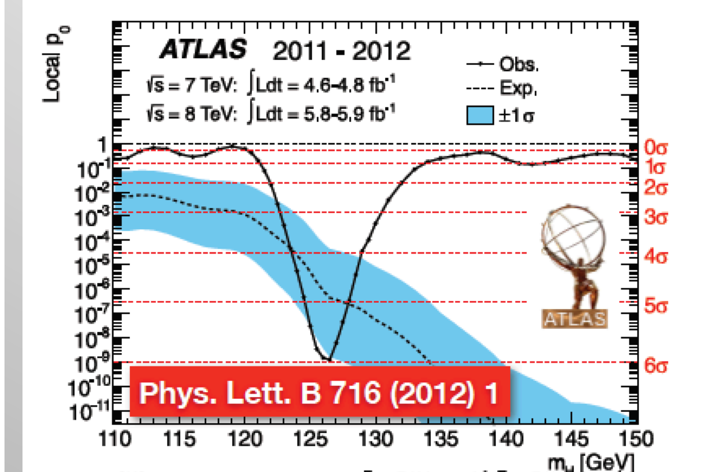
- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

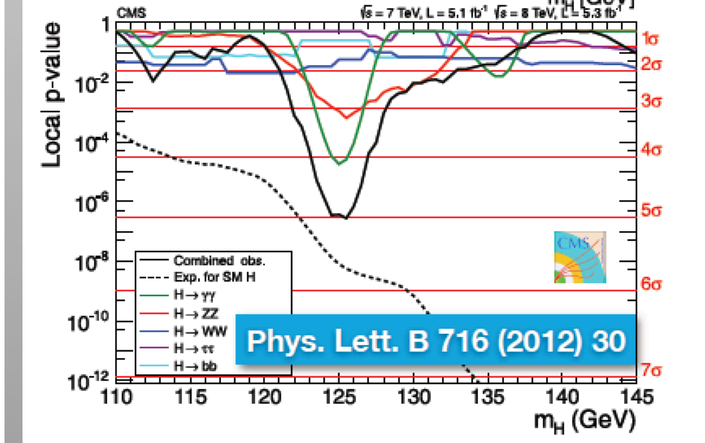
CERN

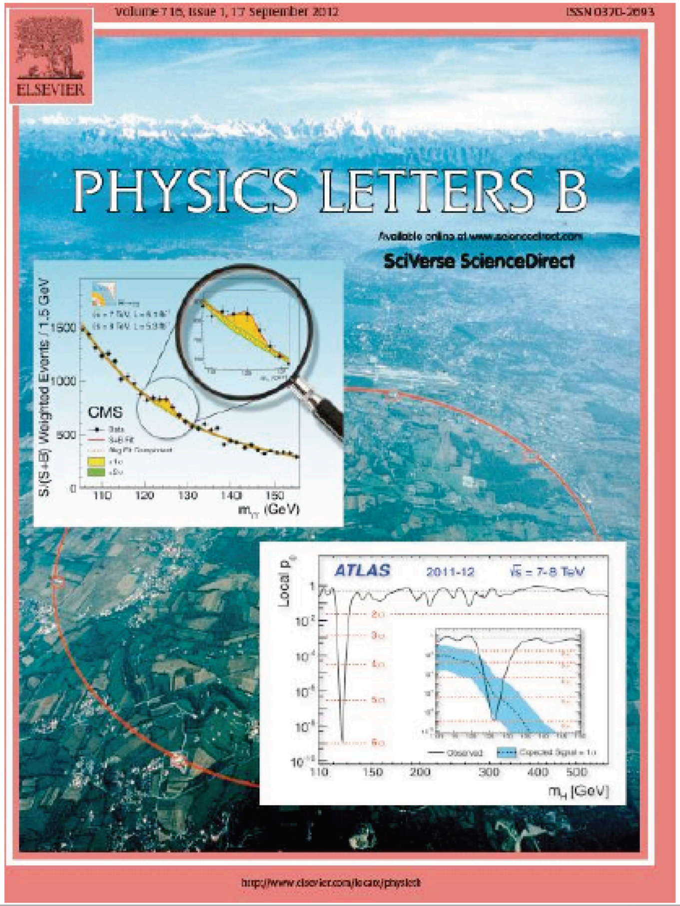
Melbourne

Followed live around the world…

Higgs Discovery July 2012

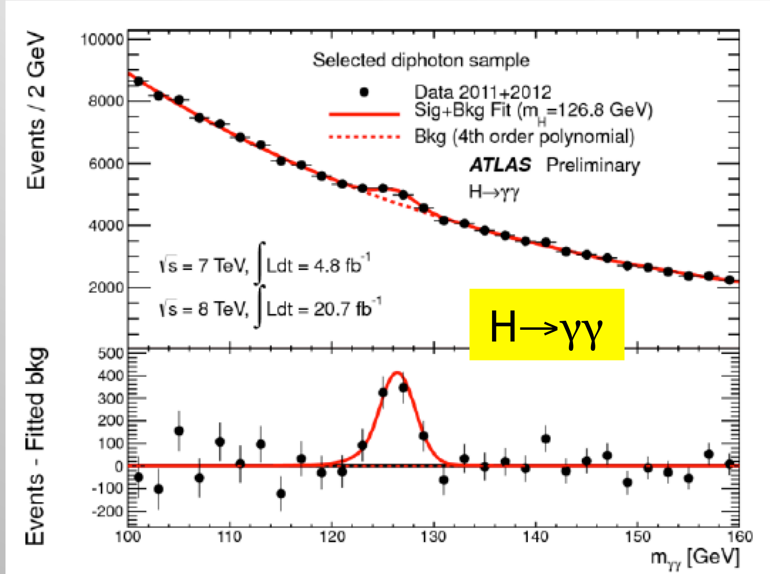


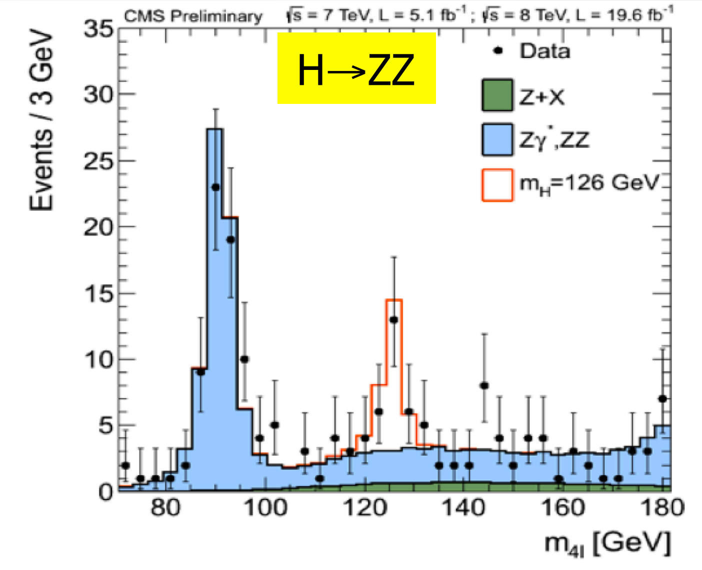


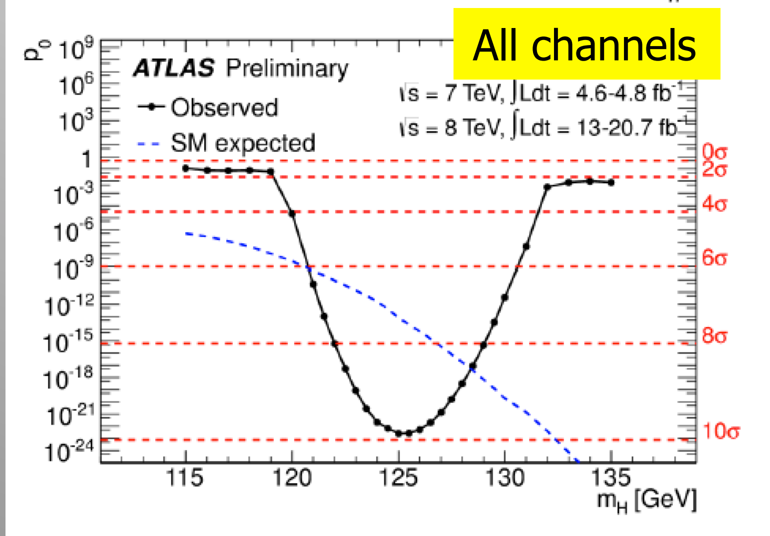


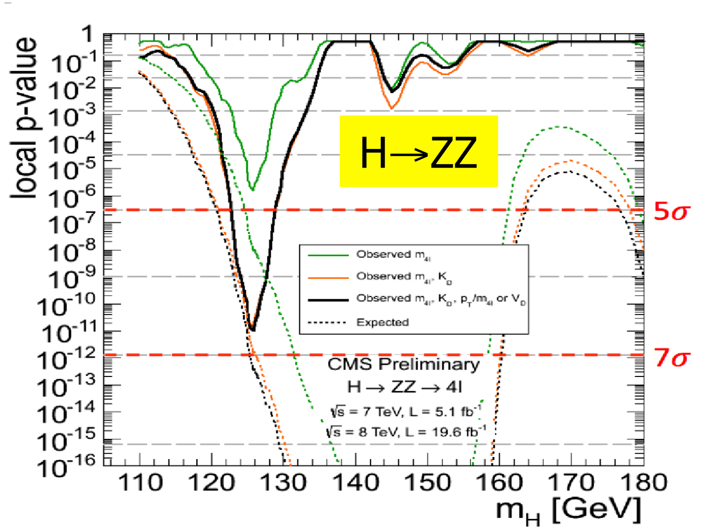
Both articles have now been cited >1400 times (approx constant 100/month)

Update with the Full 2012 Data Sample









Increased data sample with a factor of ~3

The particle is clearly still with us, now with a significance of >10σ !!

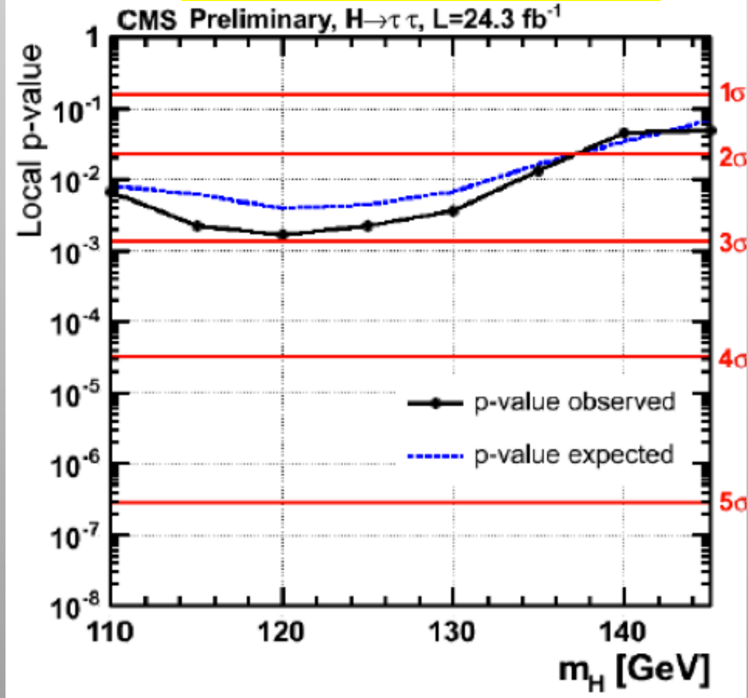
We have entered the phase of measuring properties of the new particle

Does this Particle Decay into Fermions?

- The BEH Mechanism was proposed in 1964 to give mass to the W and Z boson
- Does it also give mass to the fermions? Does the particle couple to fermions?

⇒ Direct test: check for the decays H→ tau tau and H → b quark pairs

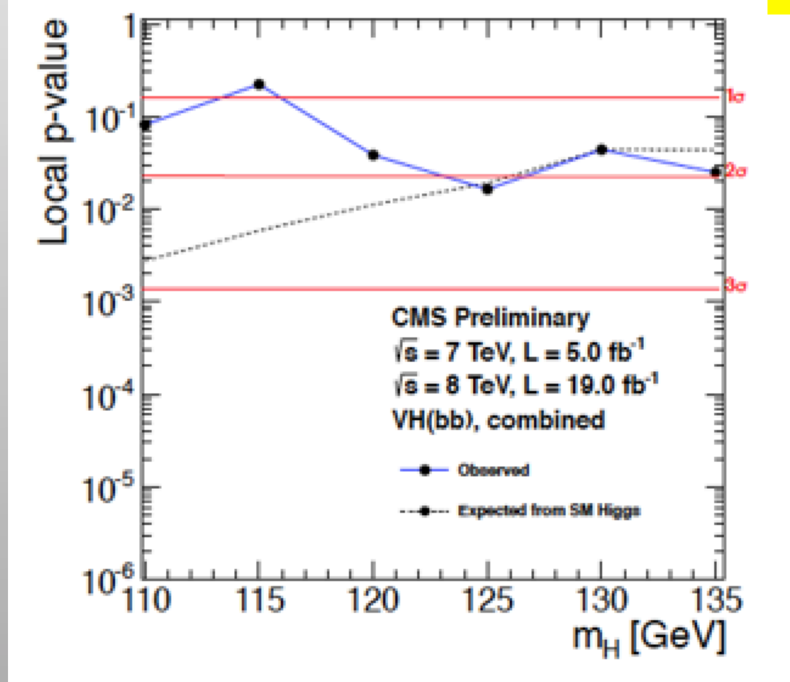
Higgs →ττ leptons



Significance 2.85σ at 125 GeV

Higgs → b-quark pairs

CMS



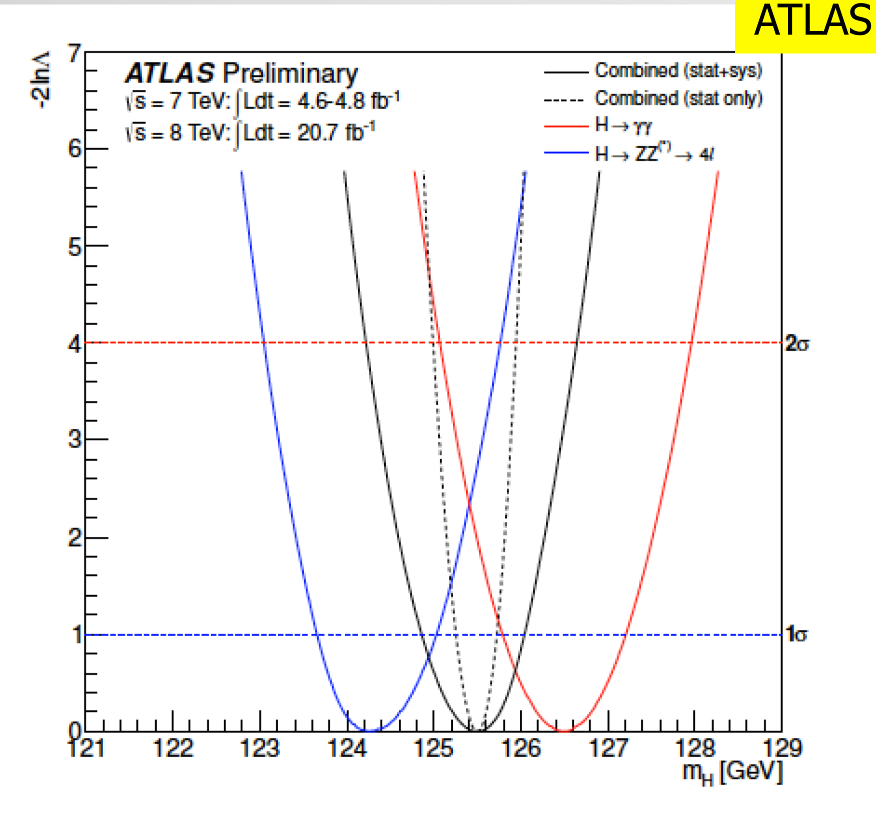
Significance 2.1σ at 125 GeV

A mild excess is building up also for these channels ~ 3.4σ

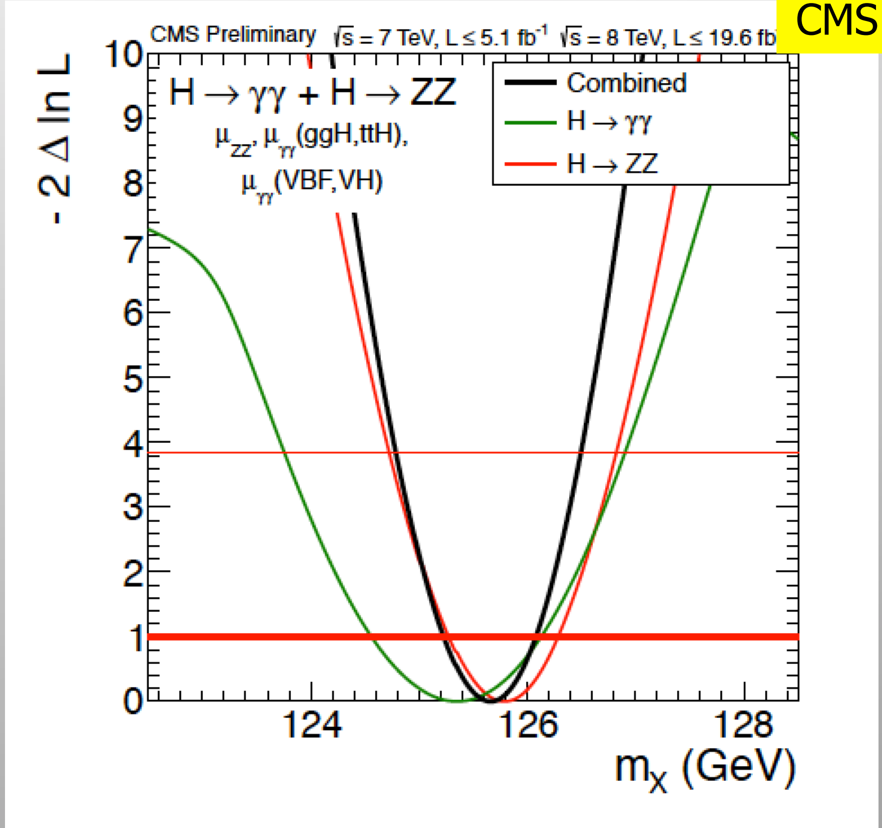
The Mass of the Particle

Determine the mass from ZZ and 2-photon channels which show a peak!

ATLAS



CMS



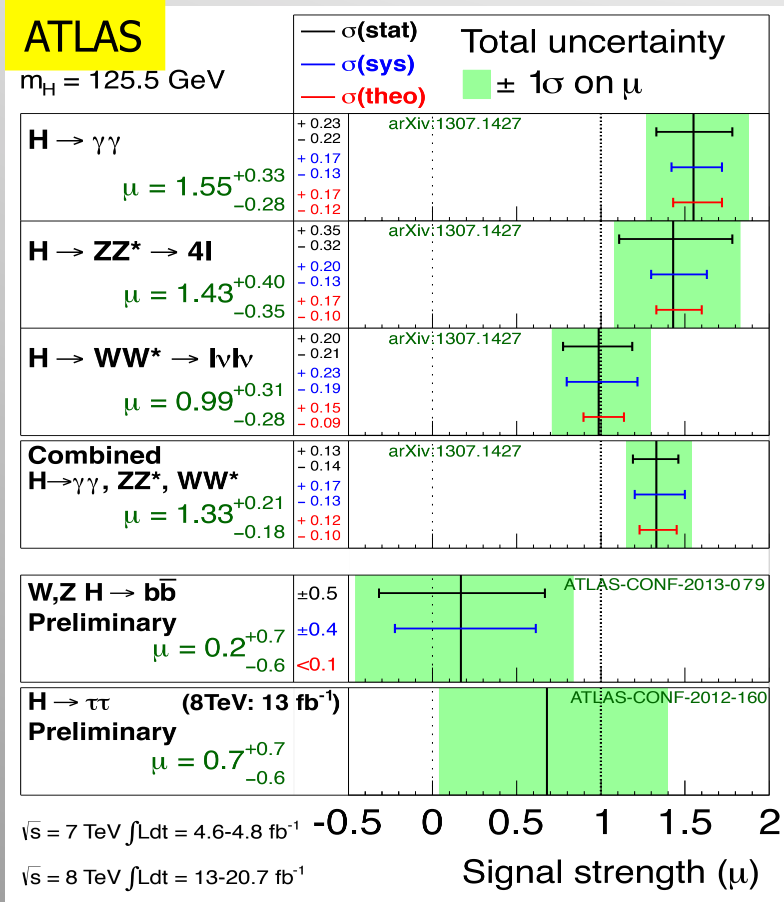
$\hat{m}_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)\ \mathrm{GeV}$

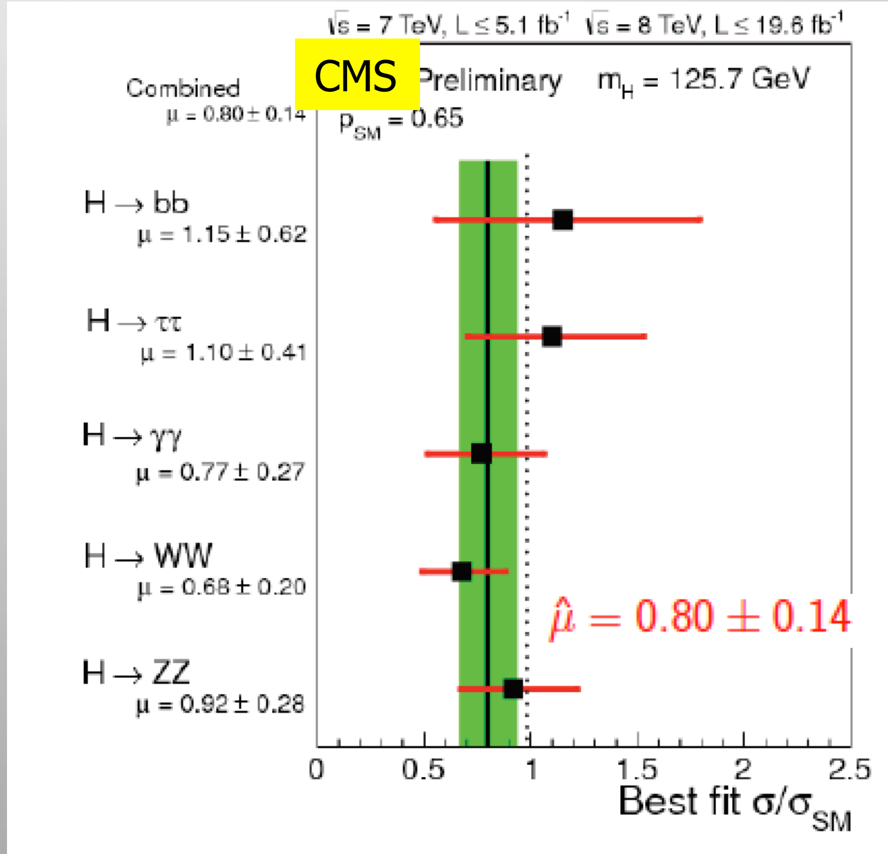
$\hat{m}_H = 125.7 \pm 0.3(stat) \pm 0.3(syst)\ \mathrm{GeV}$

ATLAS and CMS observe the same particle!! ☺

Signal Strength

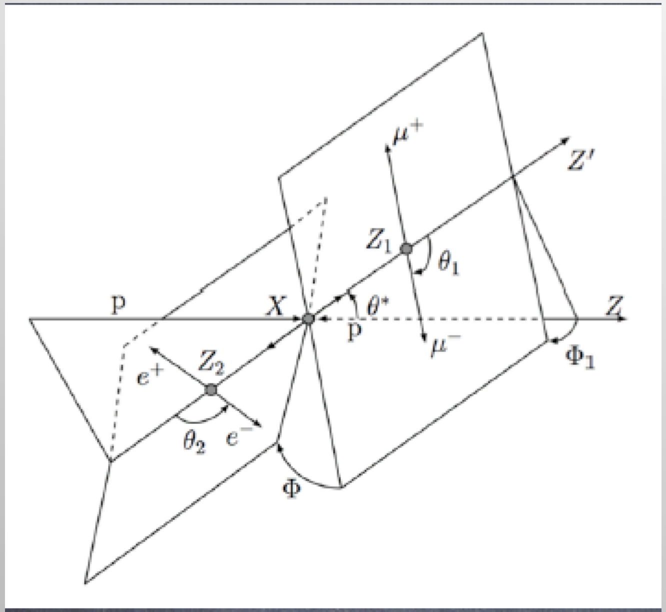
- Signal strength μ is the observed over Standard Model expected cross section
- For μ=1 the production rate is compatible with Standard Model expectation





ATLAS a bit above and CMS a bit below μ=1…

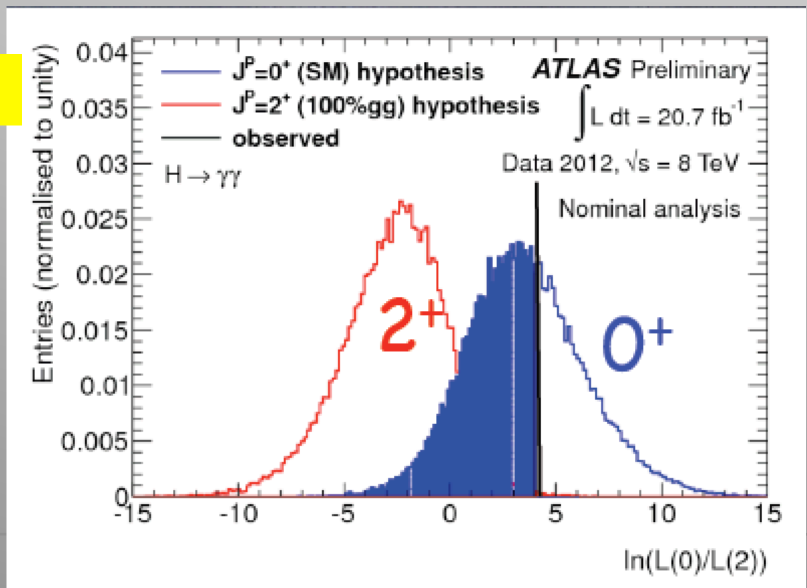
The Spin of the New Particle



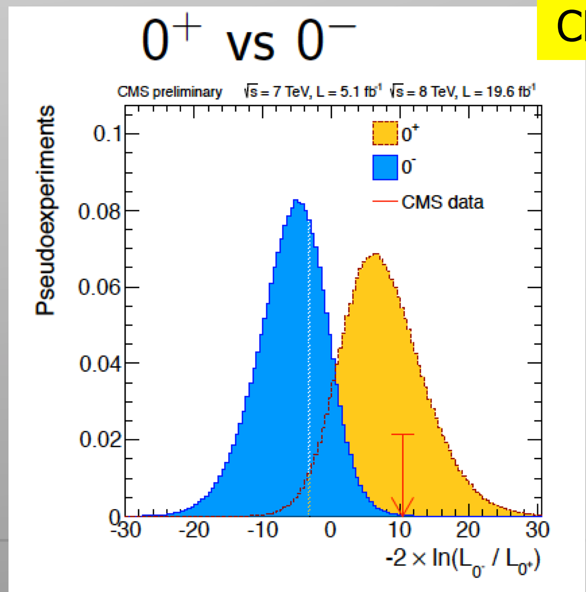
- Study angular correlations in the decays of the particle; build likelihoods and test spin- and parity hypotheses
- Use the ZZ, 2-photon and WW final states

=> Particle consistent with a 0^+ state!!

ATLAS

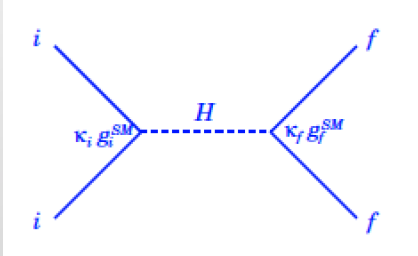


CMS

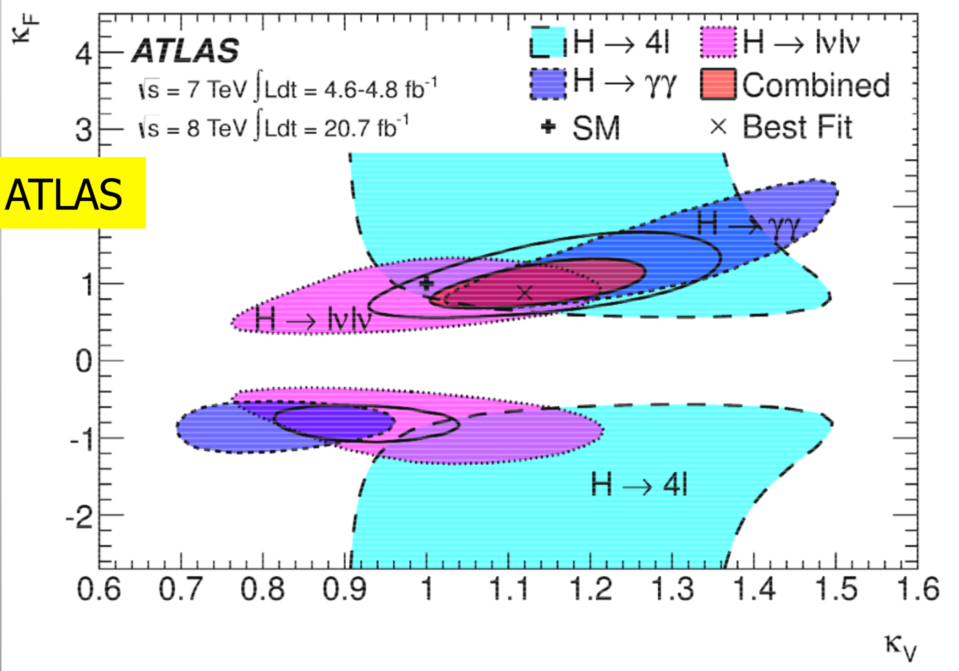


Couplings to the New Particle

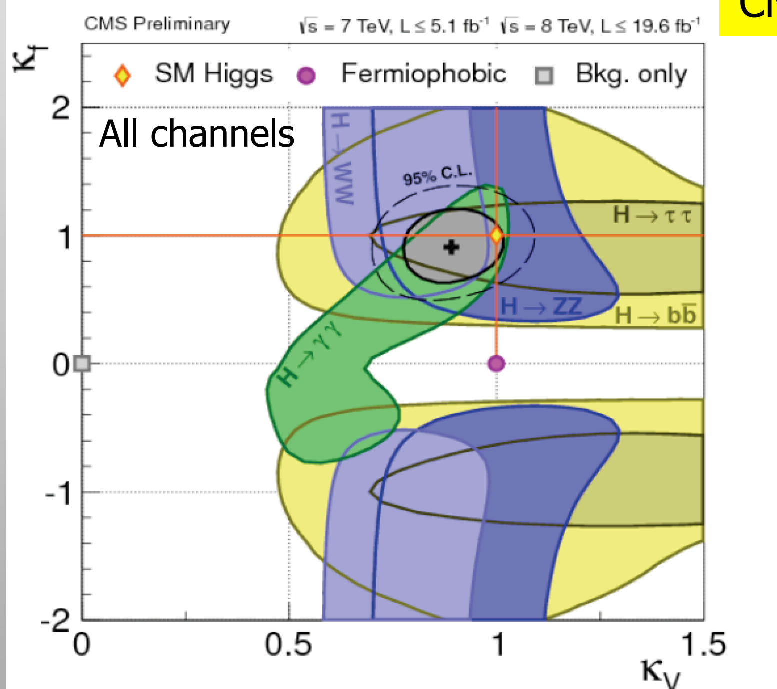
- Use information of all production and decay channels
- κ_f and κ_V are scale factors w.r.t. the Standard Model values for fermions and vector bosons



ATLAS

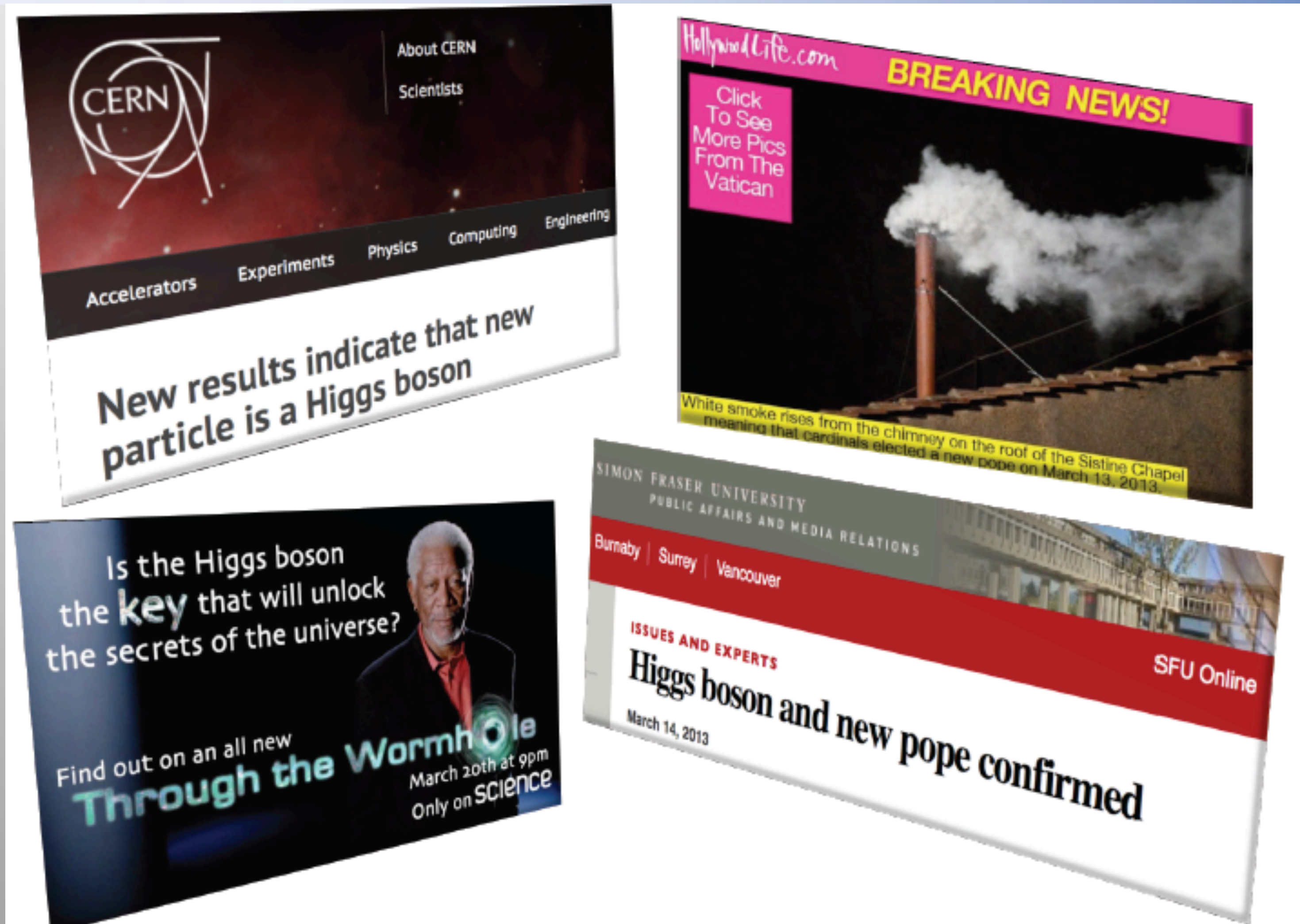


CMS



⇒ Couplings compatible Standard Model values, but large uncertainties …Future data will decide…

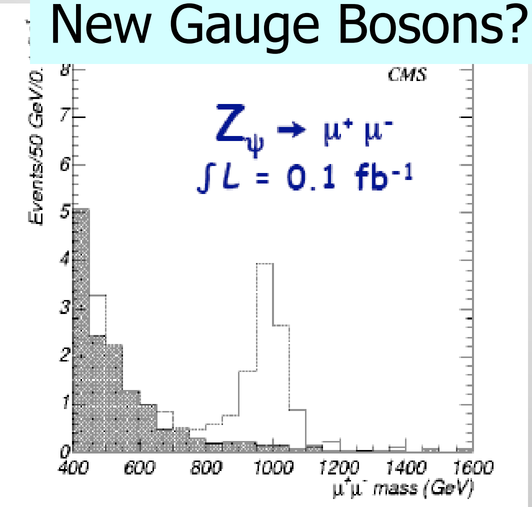
March 2013 News



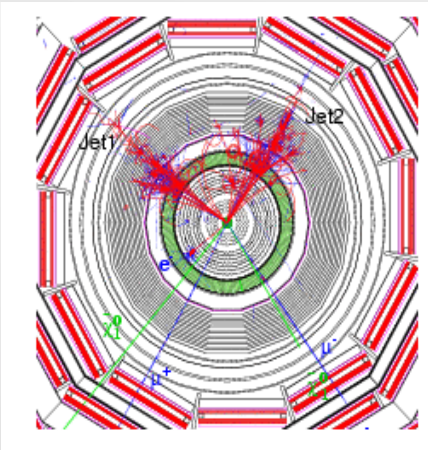
Following the data released by ATLAS and by CMS last March, we now call it a Higgs boson (instead of a Higgs-like boson)

New Physics at High Energies?

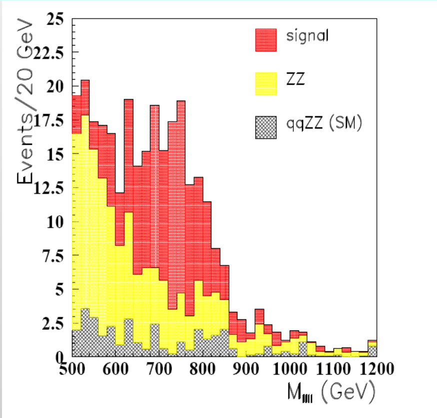
New Gauge Bosons?



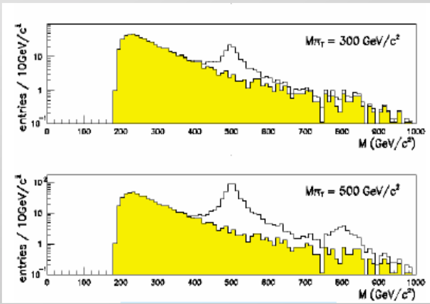
Supersymmetry



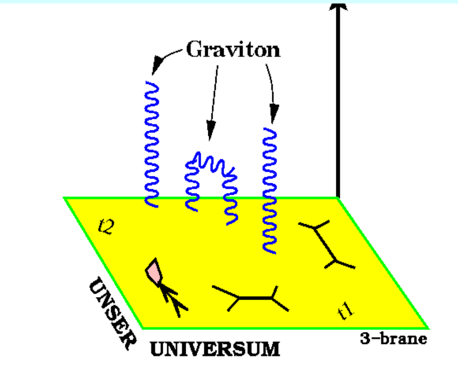
ZZ/WW resonances?



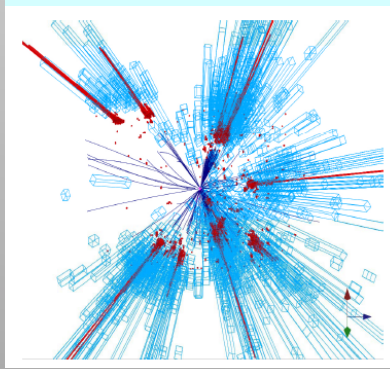
Technicolor?



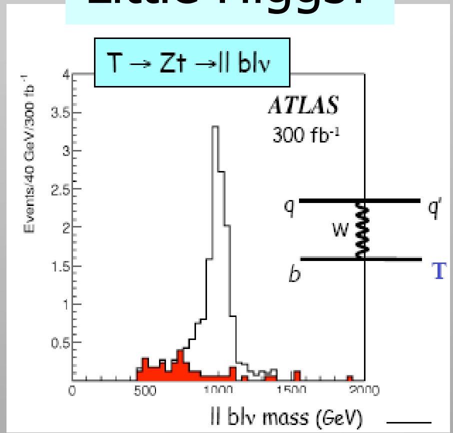
Extra Dimensions?



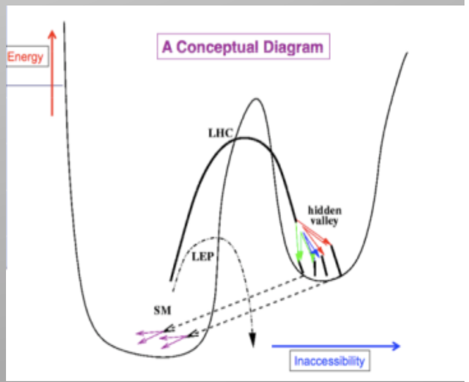
Black Holes???



Little Higgs?



Hidden Valleys?

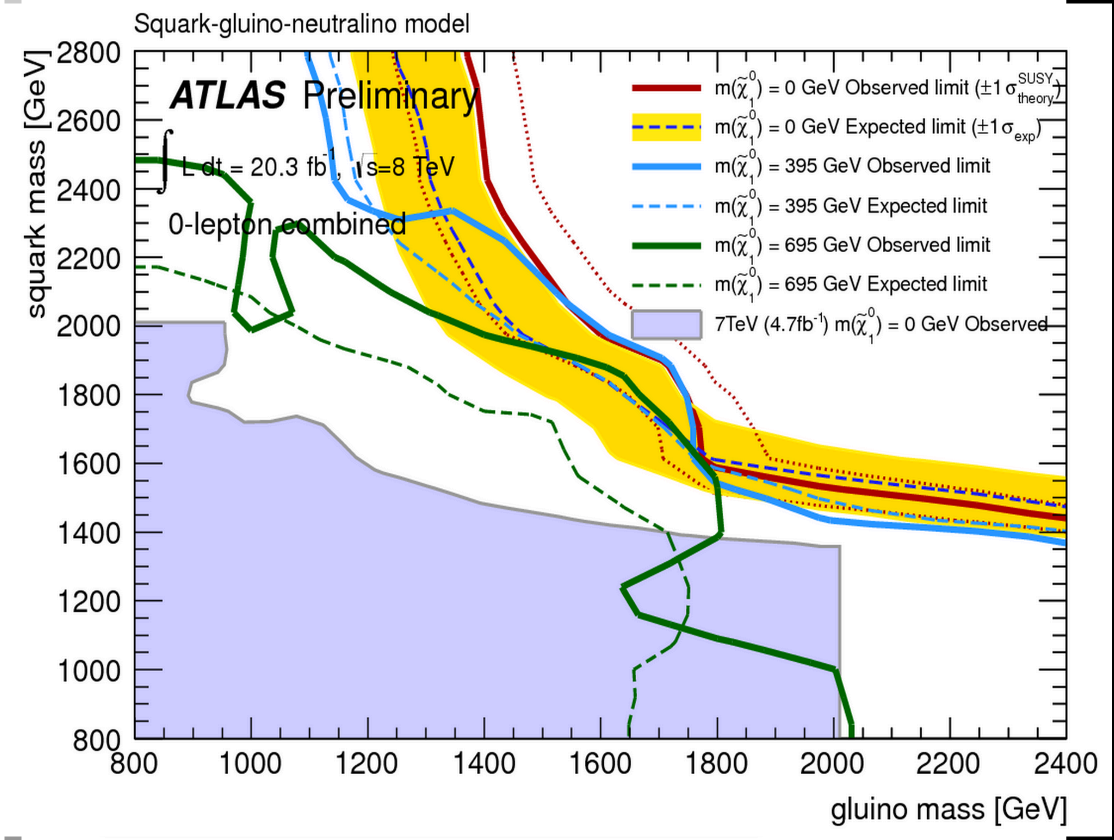


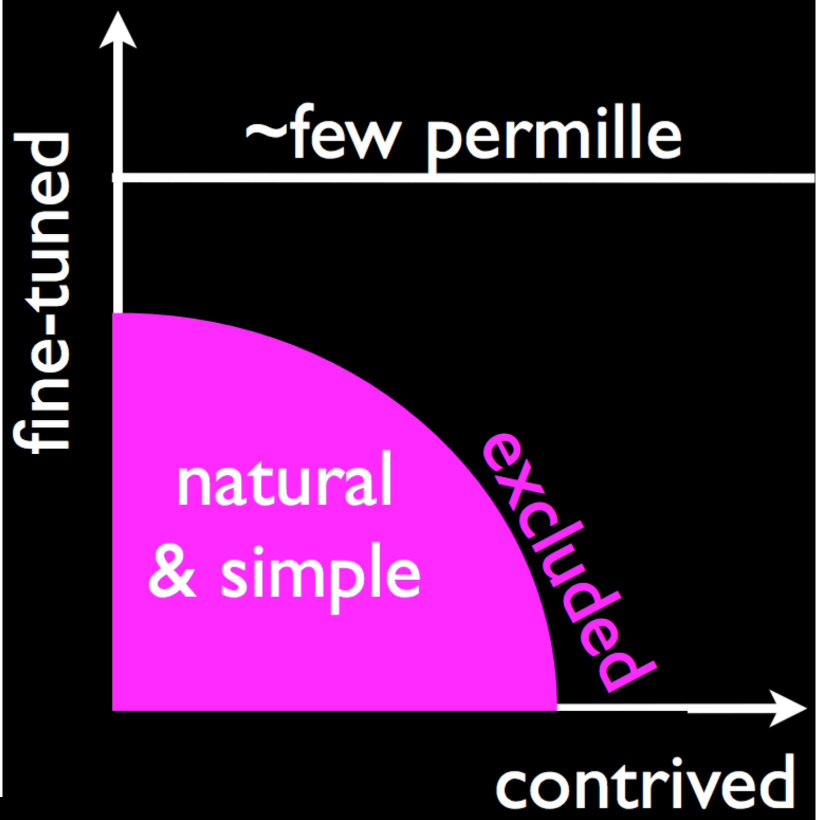
We do not know what is out there for us…
A large variety of possible signals. We have to be ready for that

Supersymmetry? New Physics?

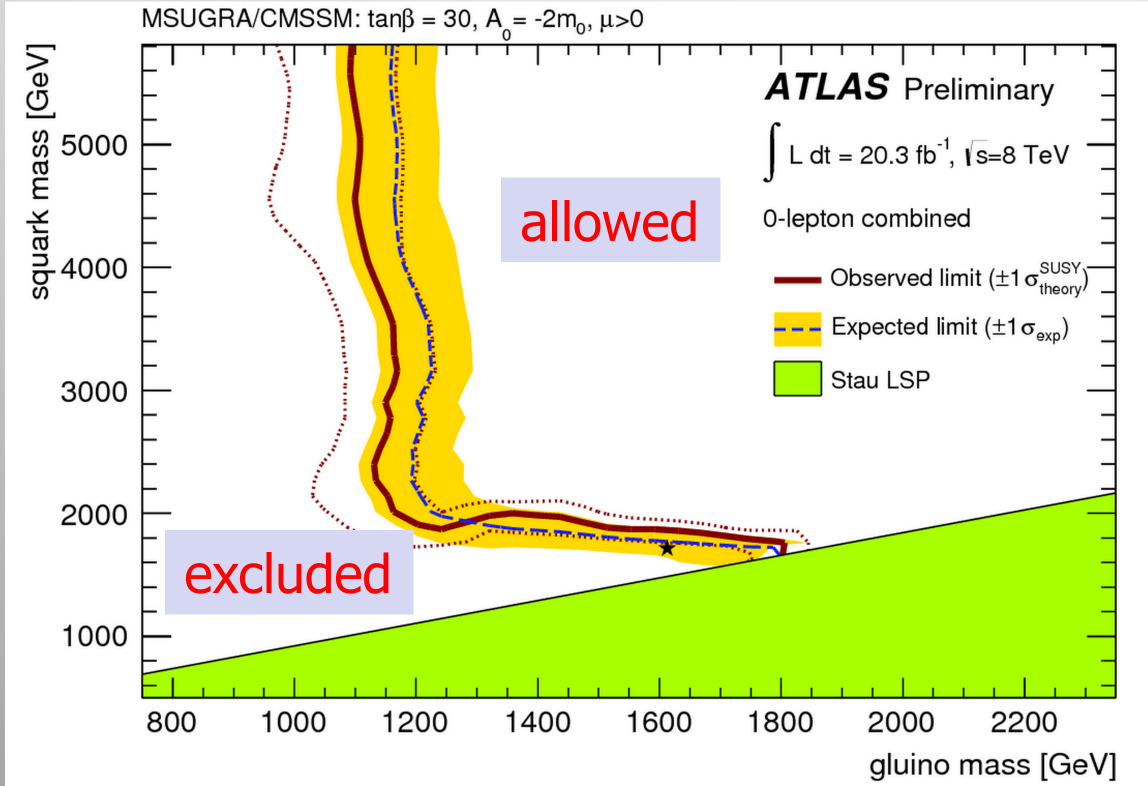
H. Murayama

no sign of new physics





SUSY Searches: No signal yet to date…



- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the next years

m_0 and $m_{1/2}$ are SUSY parameters at the GUT scale

Masses of SUSY particles are larger than 1000 GeV!!!

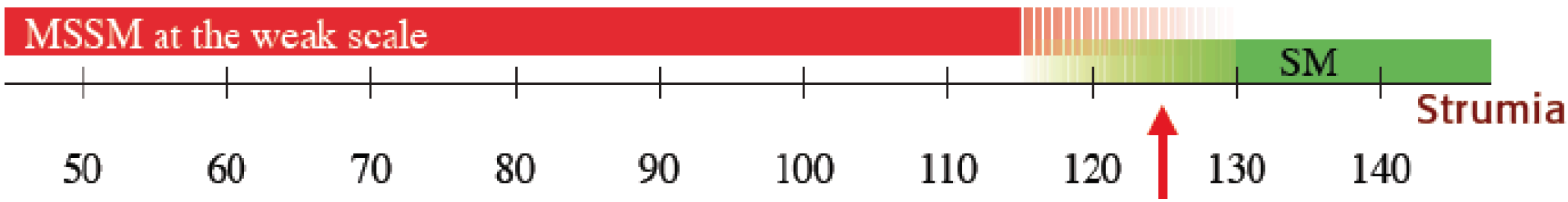
So these particles are heavier than 1000 times the proton

Explore other than the simplest/constrained SUSY models

A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



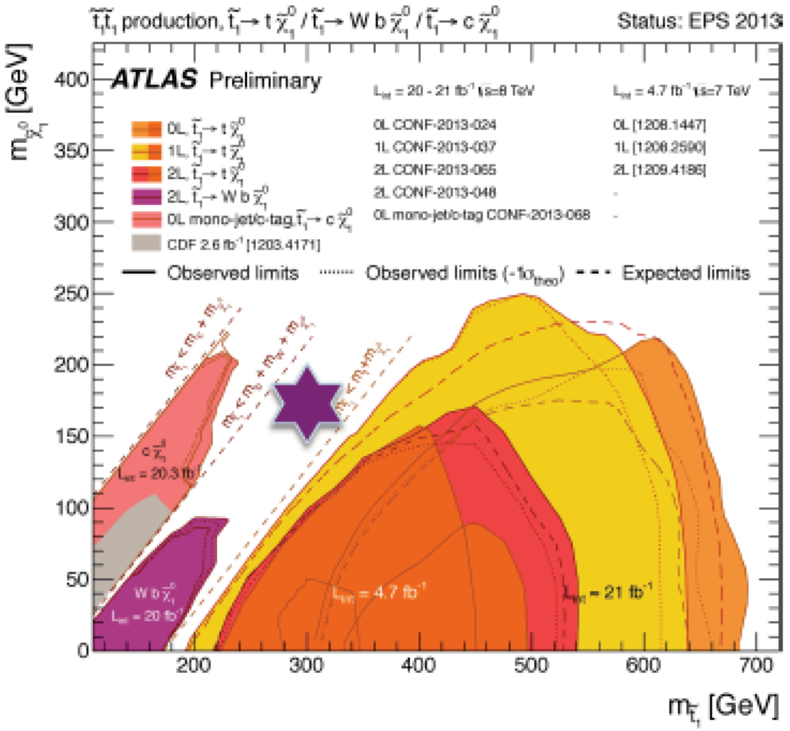
The Higgs:
so simple yet so unnatural

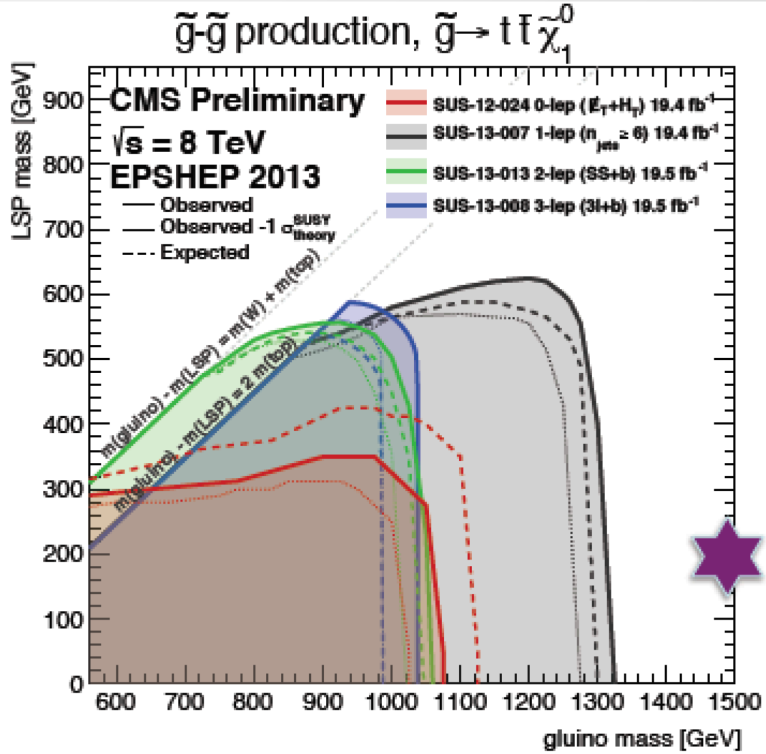
Guido Altarelli

Stockholm Nobel Symposium
May 2013

Naturalness: Requires Top squarks < ~1 TeV, gluino < ~1.5 TeV…
So far no evidence found…

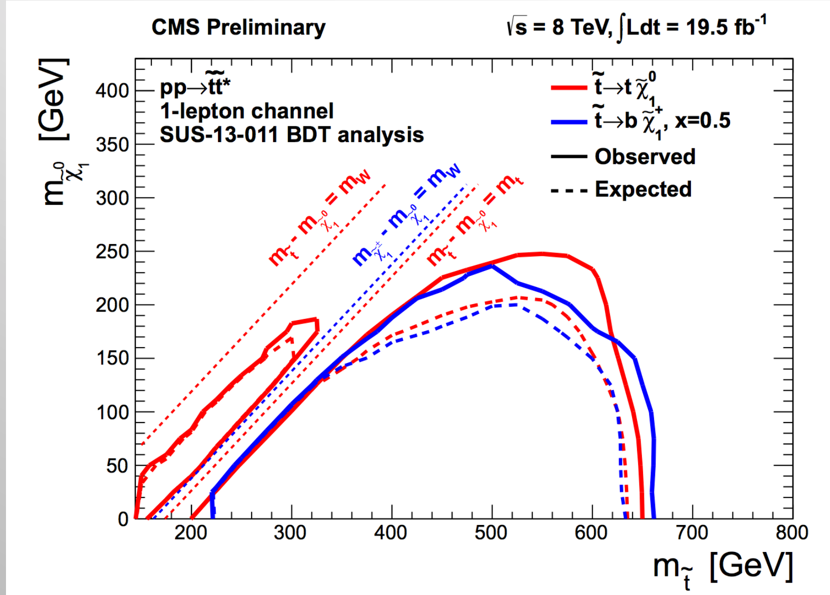
Constraints on Top Squarks



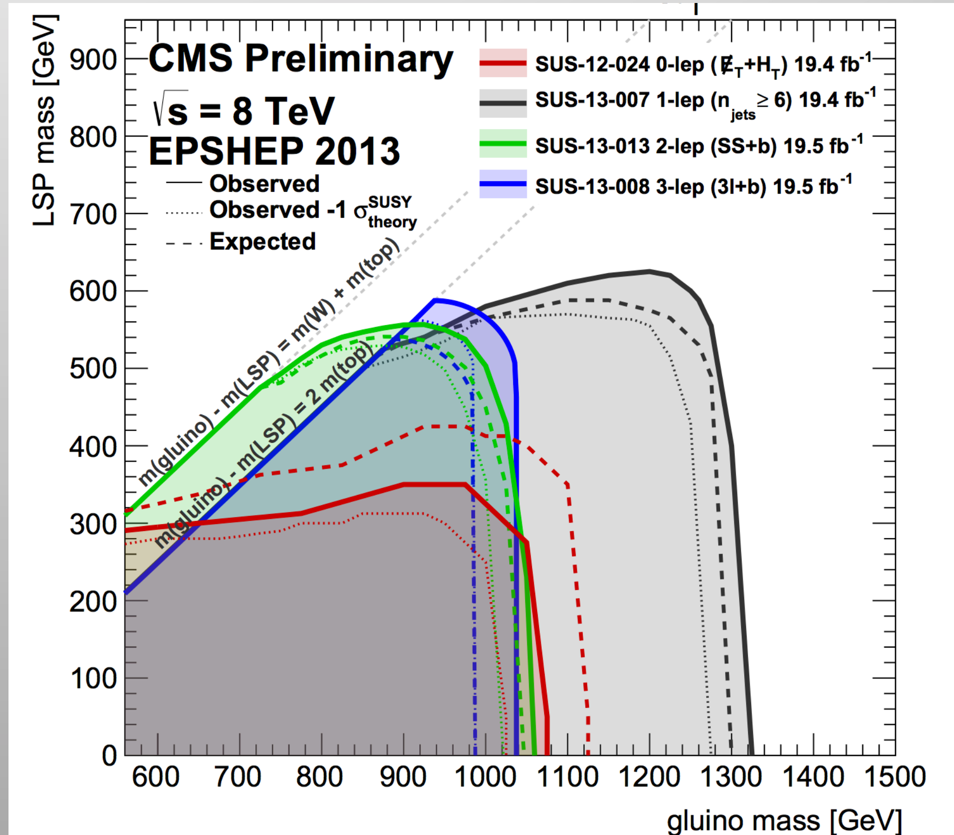


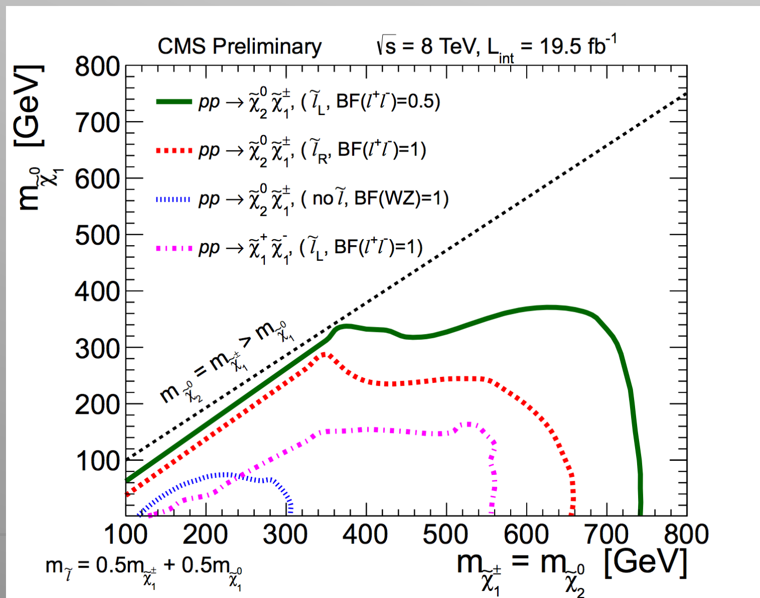
- Vigorously probed using many different analyses
- However, **pretty natural** scenarios still allowed, e.g
  - **M(g)=1.5 TeV, m(t)=300 GeV, m(LSP)=150 GeV**
- LHC (and HL-LHC) will be able to discover such scenarios

SUSY Searches: LSP limits…



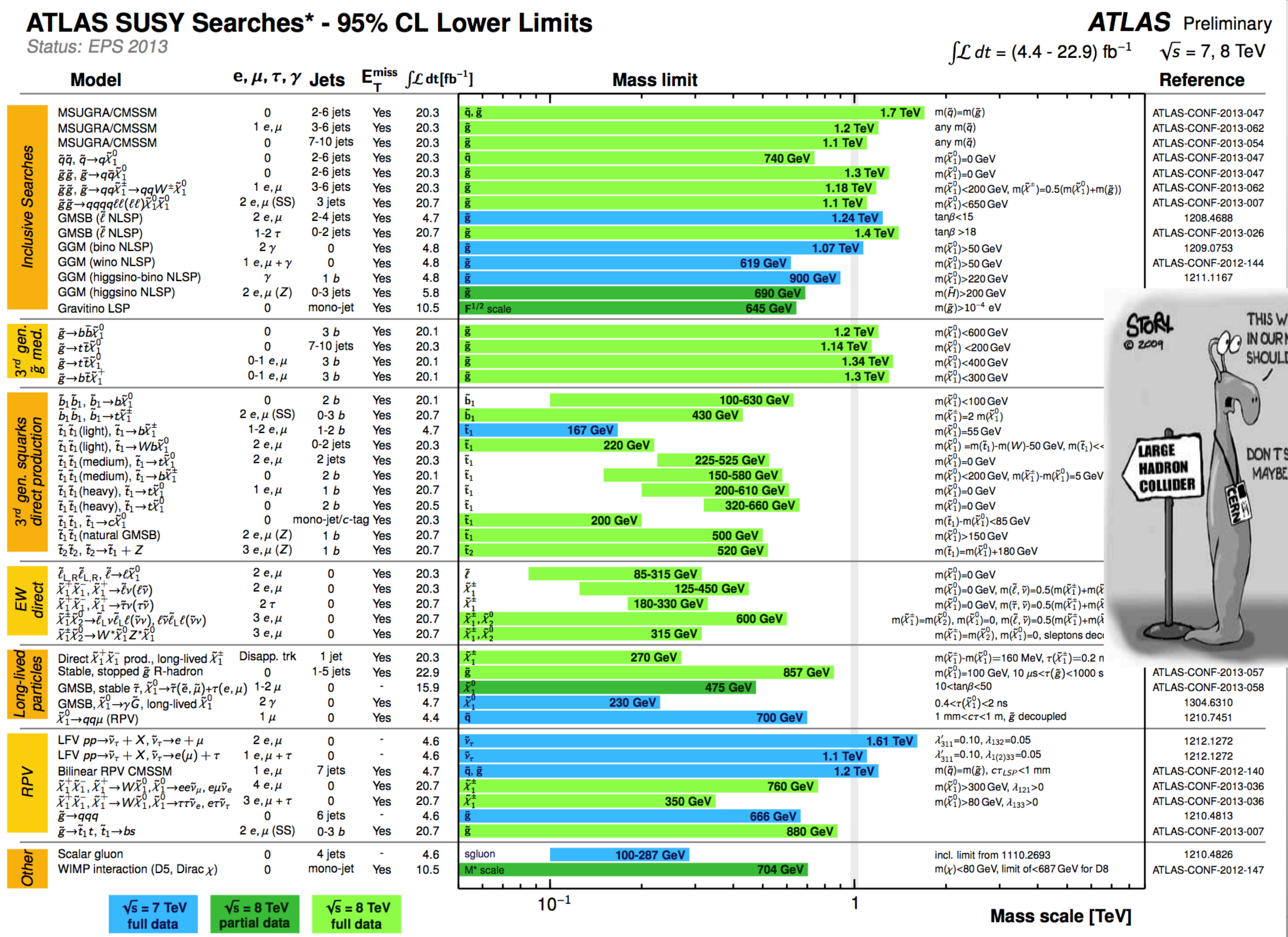
Various limits on sparticles





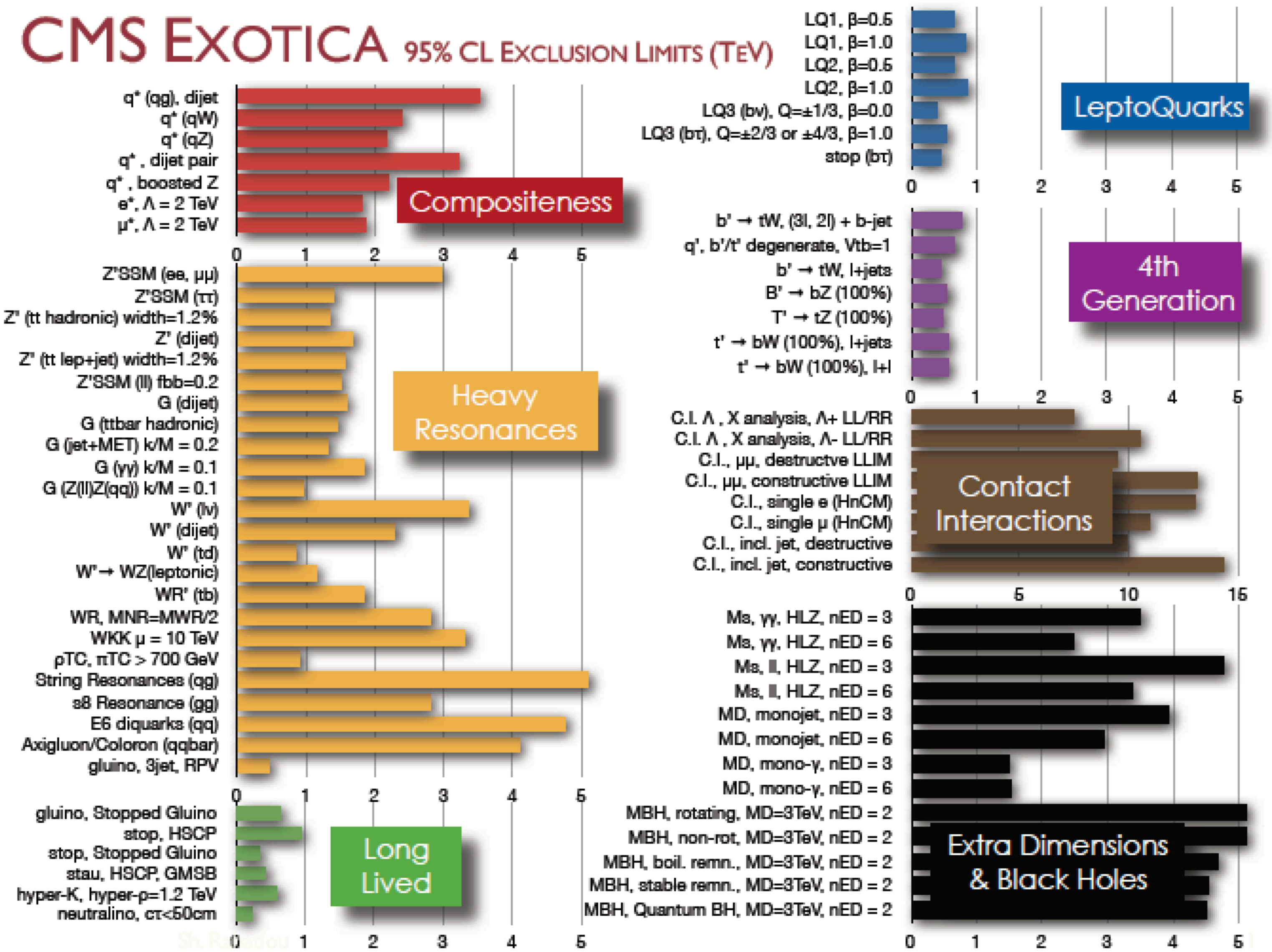
But could hide in contrived scenarios

Searches for SUSY



*similar results obtained by CMS

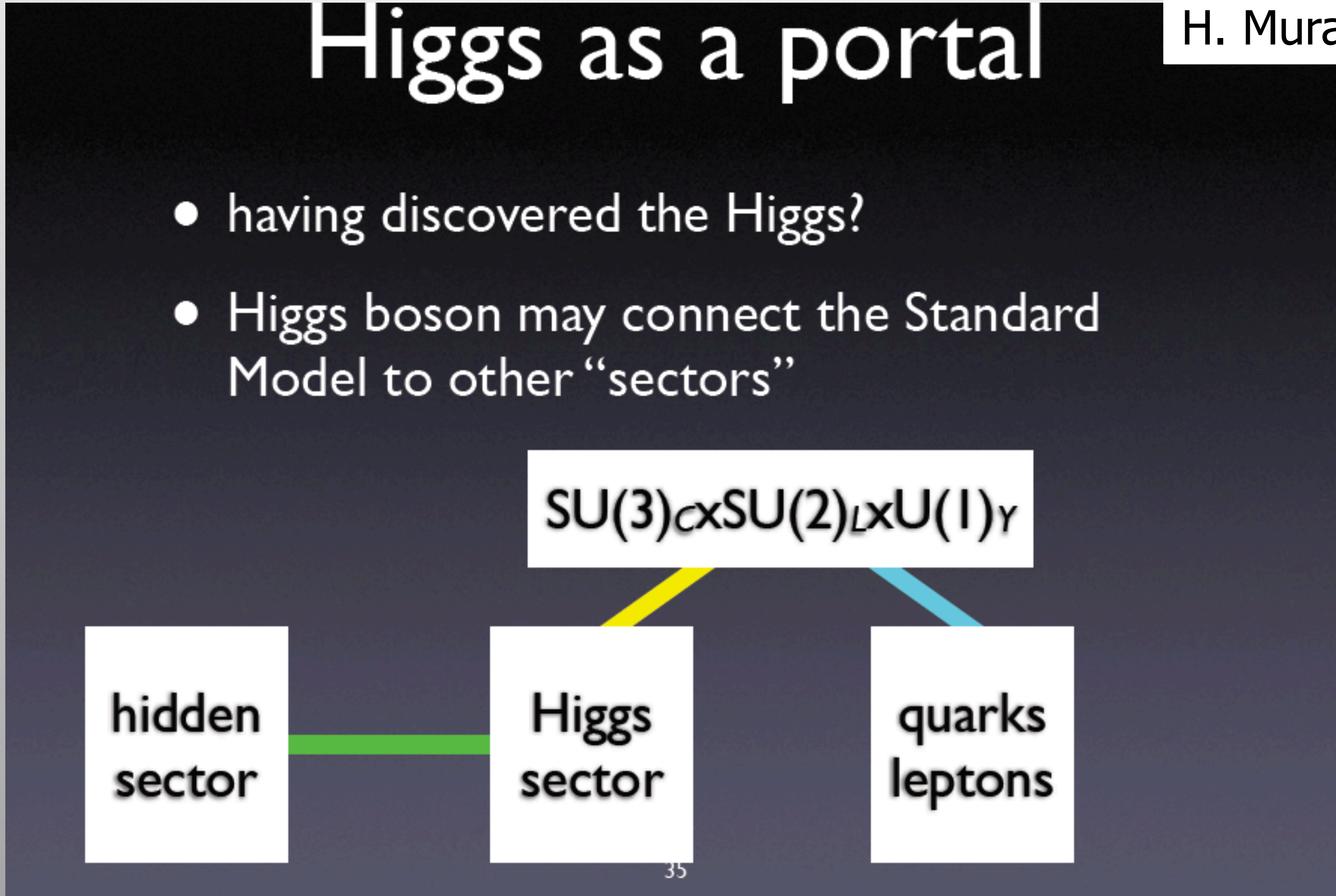
Searches for Exotica



*similar results obtained by ATLAS

What is Next?

H. Murayama



Need for precision measurements with ~100x the present statistics

LHC upgrade ! Experiment upgrades!! (Other machines?)

The Future…

The Future of the LHC

LHC luminosity forecast

~30/fb at 3.5 & 4 TeV **2012 DONE**

~400/fb at 6.5-7 TeV **2021 goal (?)**

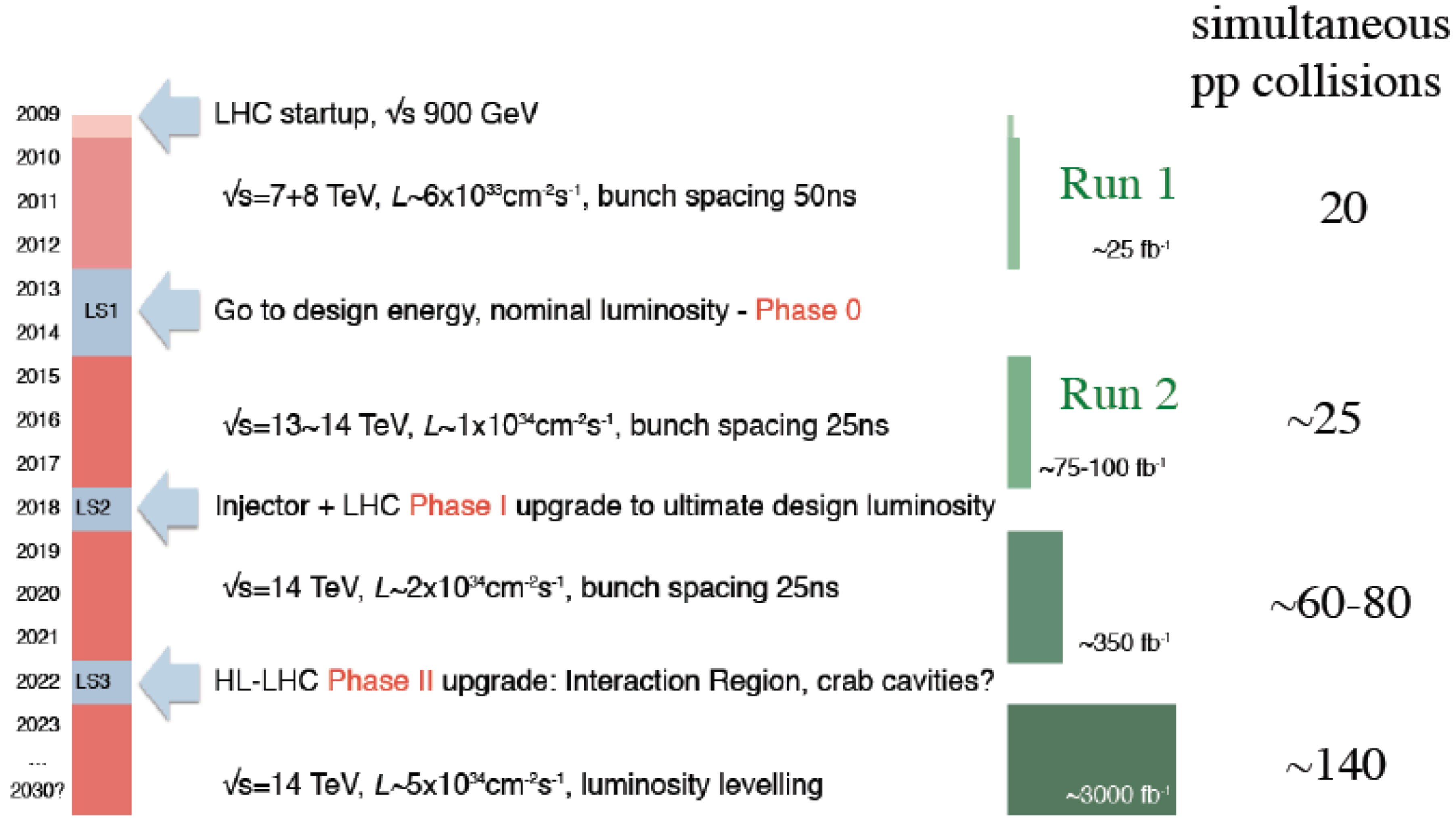
~3000/fb at 7 TeV **2035 goal (??)**

question: how do we get 3000/fb by 2035?

*answer: with **HL-LHC***

Discussion on the Machine in the backup

LHC schedule

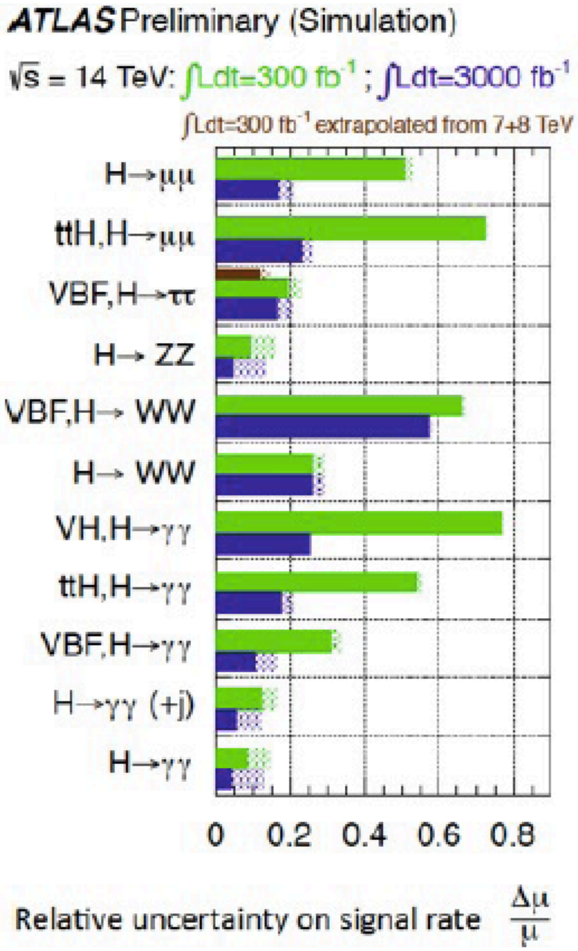


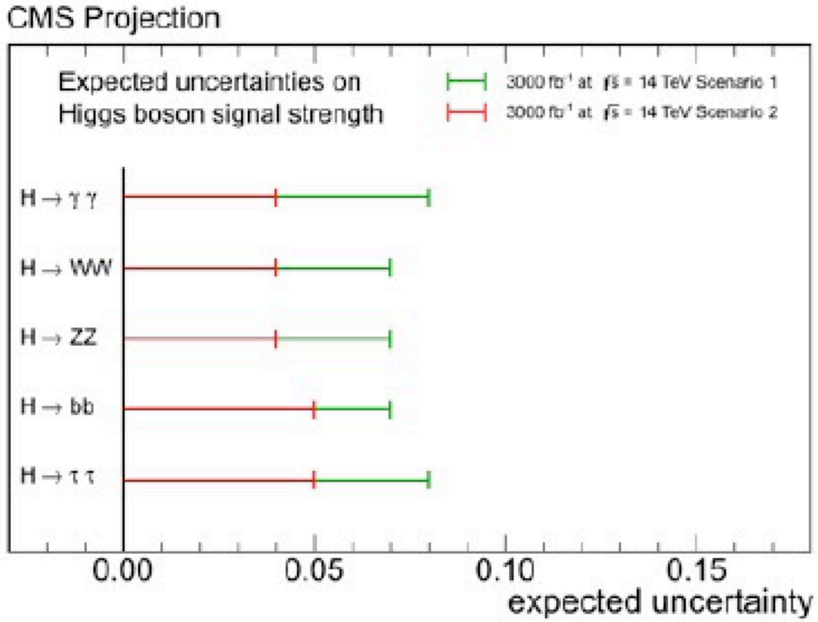
Key Questions for the Future

- **Is it *the* Higgs boson?**
  - Does it couple to matter exactly as predicted?
  - Does it couple to gauge bosons exactly as predicted?
  - Are there more Higgs bosons?
- **Does the Higgs boson decay to non-SM particles?**
  - E.g. to Dark Matter?
- **How do bosons interact**
  - Does Higgs boson cor
  - Are there new gauge g
- **What protects the Higgs**
  - Is Nature Supersymme
    - Is Dark Matter a SUSY particle?
  - Are there new generations of fermions?
  - Is there some other new dramatic physics coming in at the TeV scale
    - Are there extra dimensions of space?
    - Is there a new strong interaction?

Higgs mass precisions ~ 100-200 MeV enough?
Estimate that we can reach 50-100 MeV (HL-LHC)
Higgs self coupling precision > 20% needed?
Higgs Couplings? Few %? Better?
(J. Wells et al., arXiv:1305.6397)

Higgs Physics: coupling strength





L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$	$H \to \tau\tau$	$H \to Z\gamma$	$H \to inv.$
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ 1/√L

Based on parametric simulation

Extrapolated from 2011/12 results

Higgs coupling strength modifiers

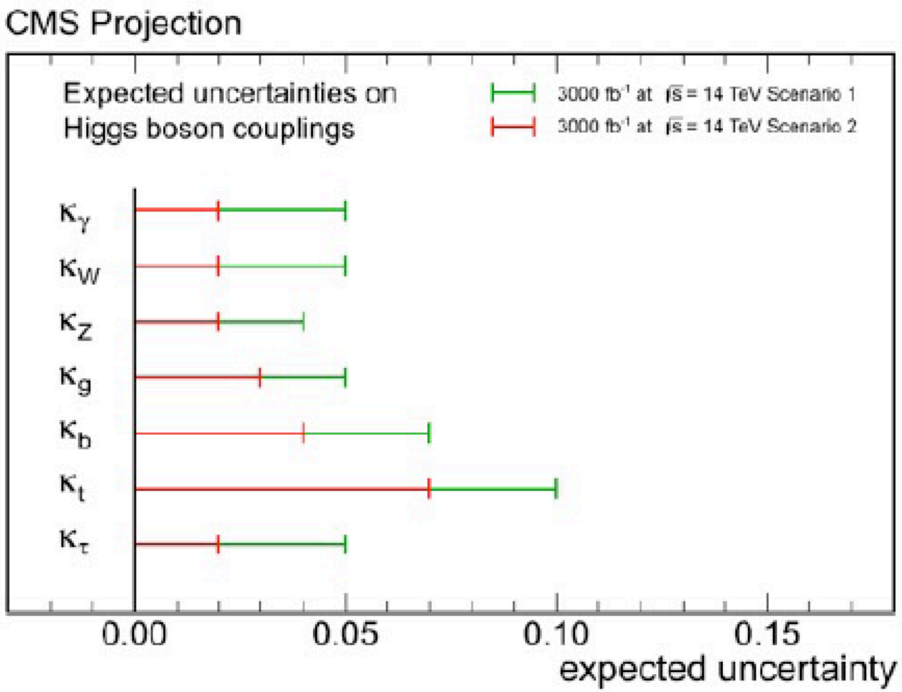
κ_g, κ_γ, $\kappa_{Z\gamma}$: loop diagrams ➜ allow potential new physics
κ_W, κ_Z: vector bosons
κ_t, κ_b: up- and down-type quarks
κ_τ, κ_μ: charged leptons
total width from sum of partial widths

alternatively:

$$\Gamma_{\text{tot}} = \sum \Gamma_{ii} + \Gamma_{\text{BSM}}$$

$$\text{BR}_{\text{BSM}} = \Gamma_{\text{BSM}} / \Gamma_{\text{tot}}$$

assumption here κ_W, $\kappa_Z < 1$



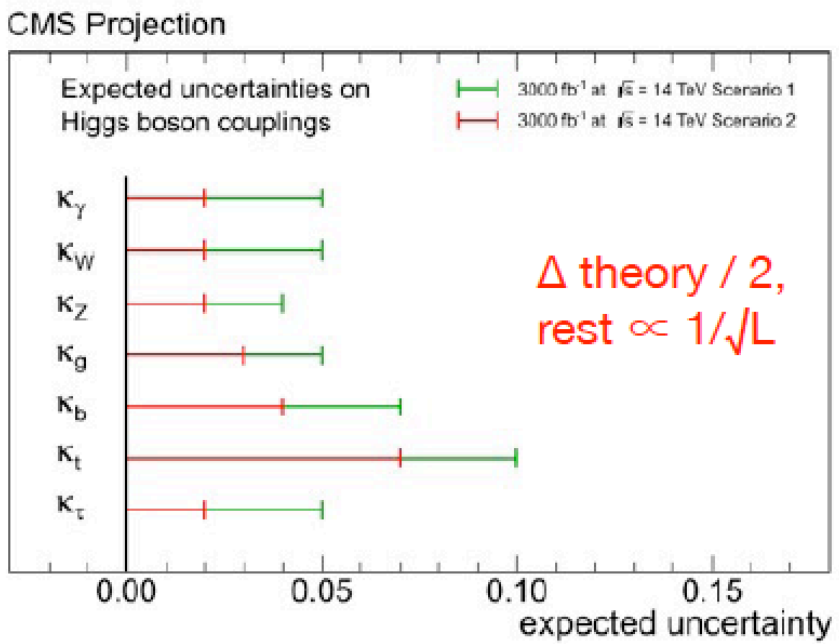
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	BR_{inv}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[7, 11]

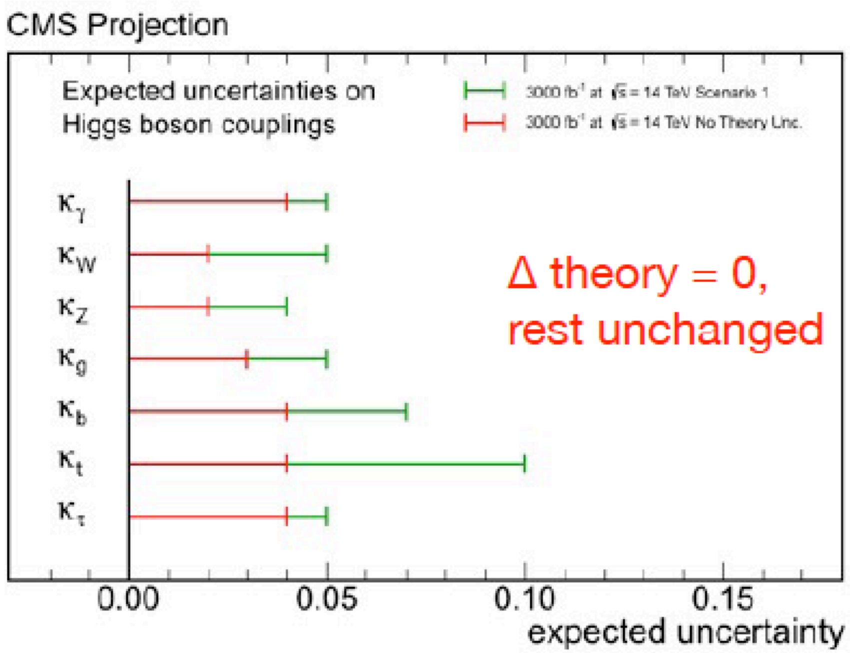
coupling precision 2-10 %

Higgs Physics: Theoretical Uncertanties

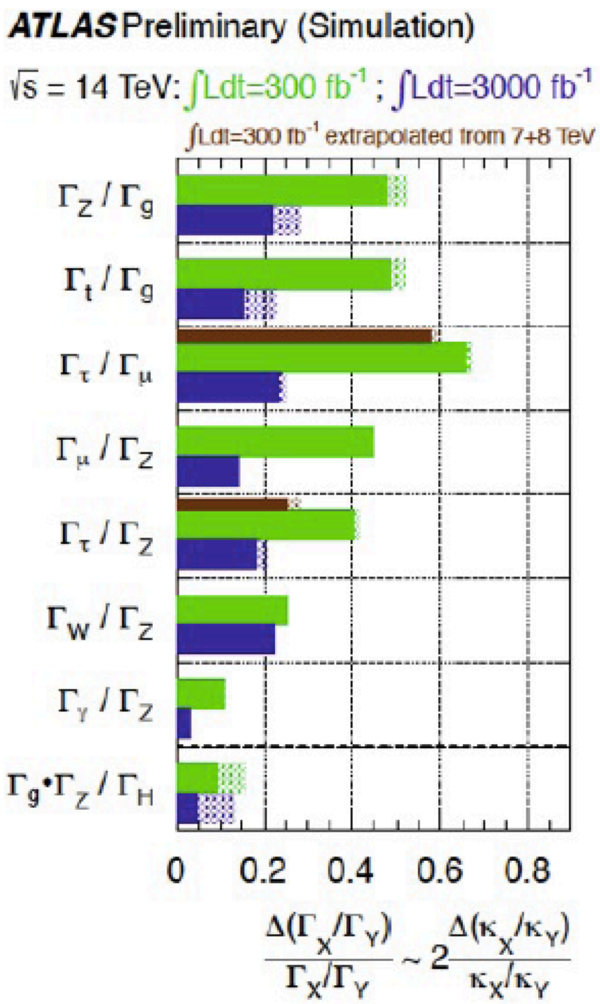
To test the importance of theoretical uncertainties we show the effect of removing them.

Theoretical uncertainties dominated by QCD scale and PDF uncertainties.
Uncertainty on BR become relevant at few % precision.





Higgs Physics: Ratio Measurements



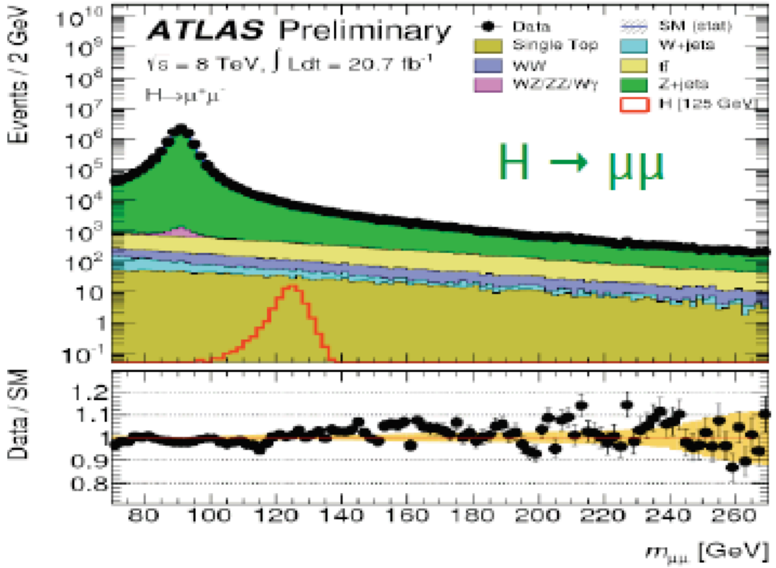
No assumption on total width required for ratios of coupling parameters.

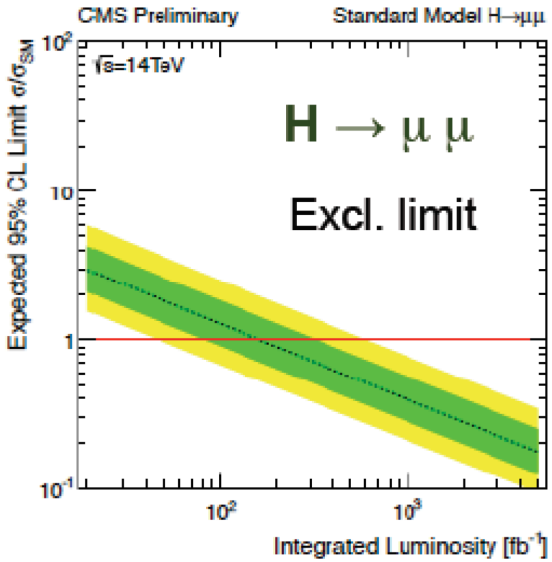
Ratios of partial widths are related to couplings via $\Gamma_X/\Gamma_Y = \kappa_X/\kappa_Y$.

Theoretical uncertainty important also for ratio measurements

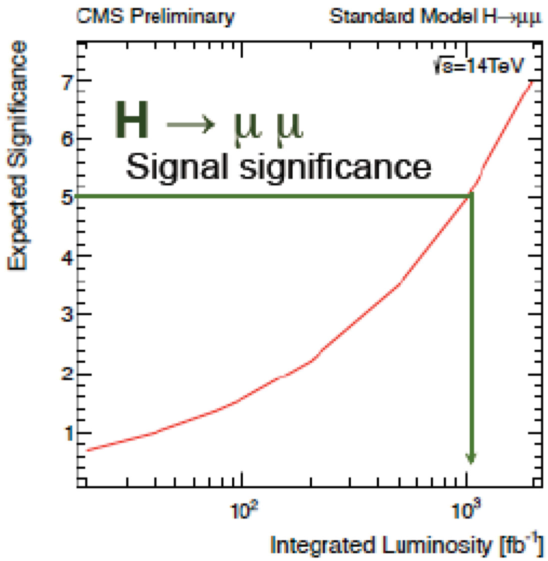
	3000 fb^{-1}	
	w/theory uncert.	wo/theory uncert.
Γ_Z/Γ_g	0.28	0.22
Γ_t/Γ_g	0.23	0.15
Γ_τ/Γ_μ	0.25	0.23
Γ_τ/Γ_μ (extrap)		
Γ_μ/Γ_Z	0.14	0.14
Γ_τ/Γ_Z	0.21	0.18
Γ_τ/Γ_Z (extrap)		
Γ_W/Γ_Z	0.23	0.23
Γ_γ/Γ_Z	0.029	0.029
$\Gamma_g \bullet \Gamma_Z/\Gamma_H$	0.13	0.047

Rare Higgs Decays





- The decay H→μμ can be observed with a significance of 5 sigma
- measurement of the Hμμ coupling with a precision of ~10%

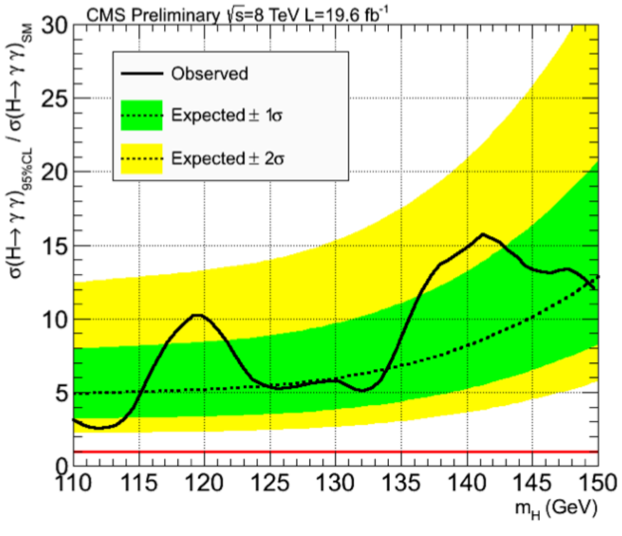


Rare Higgs Decays

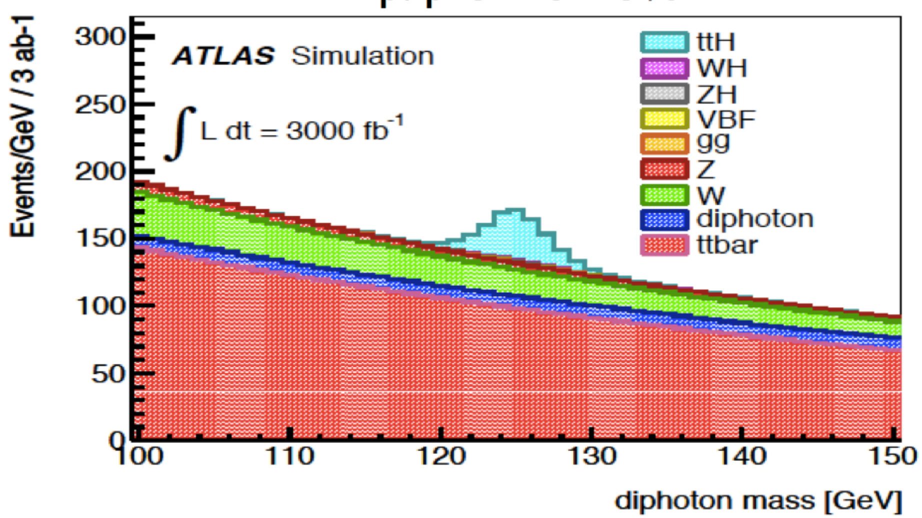
Rare decays: ttH, H→γγ

CMS-HIG-13-015 (20/fb @ 8 TeV)

	Observed	Expected	Expected (No Syst.)
Hadronic Channel	6.8	9.2	8.8
Leptonic Channel	10.7	8.0	7.7
Combined	5.4	5.3	5.1

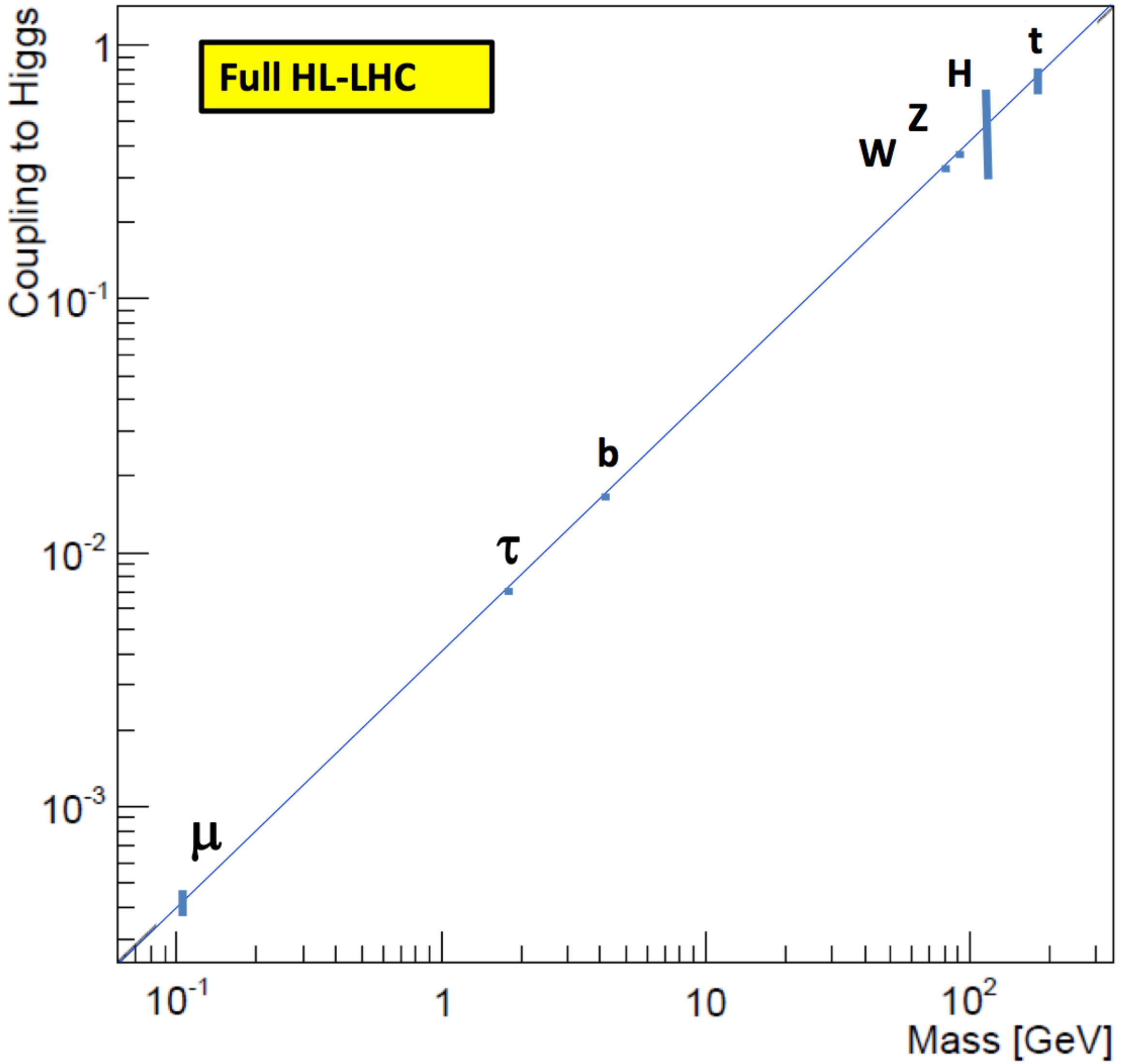


ATLAS projection, 3000 /fb @ 14 TeV
Δμ/μ of 15-20%



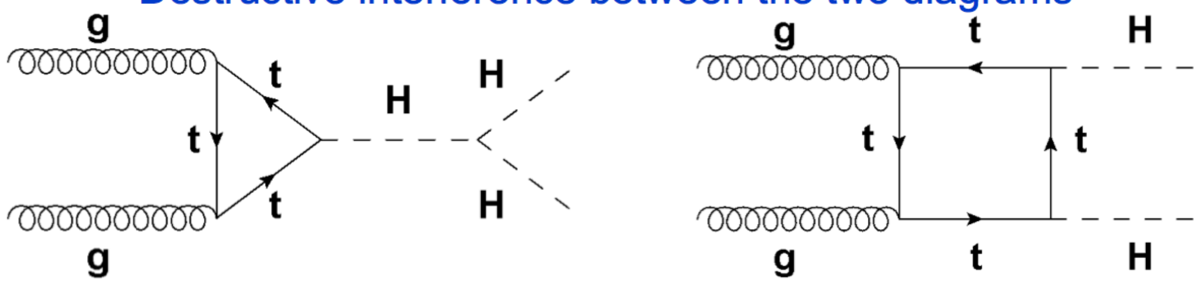
Expected with High Luminosity LHC

A Blondel
Sendai June '13



Higgs Self Coupling

Destructive interference between the two diagrams



Many channels to investigate. Most promising ones:

$b\bar{b}W^+W^-$ (large BR but large bkg.)

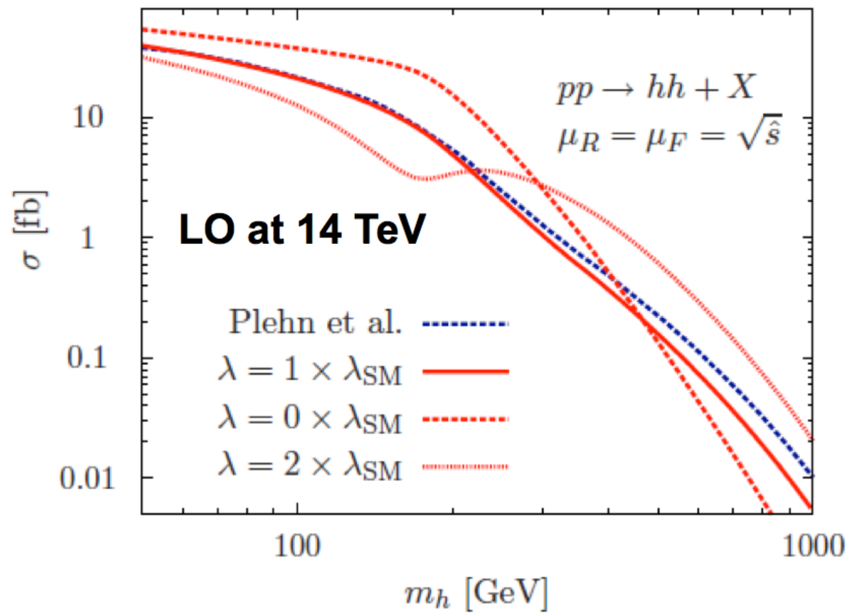
$b\bar{b}\gamma\gamma$ (clean but small BR)

$b\bar{b}\tau^+\tau^-$

$b\bar{b}\mu^+\mu^-$ will do

$b\bar{b}b\bar{b}$

Taken from "Higgs self-coupling measurements at the LHC" by M. J. Dolan, C. Englert and M. Spannowsky, JHEP 10 (2012 112.

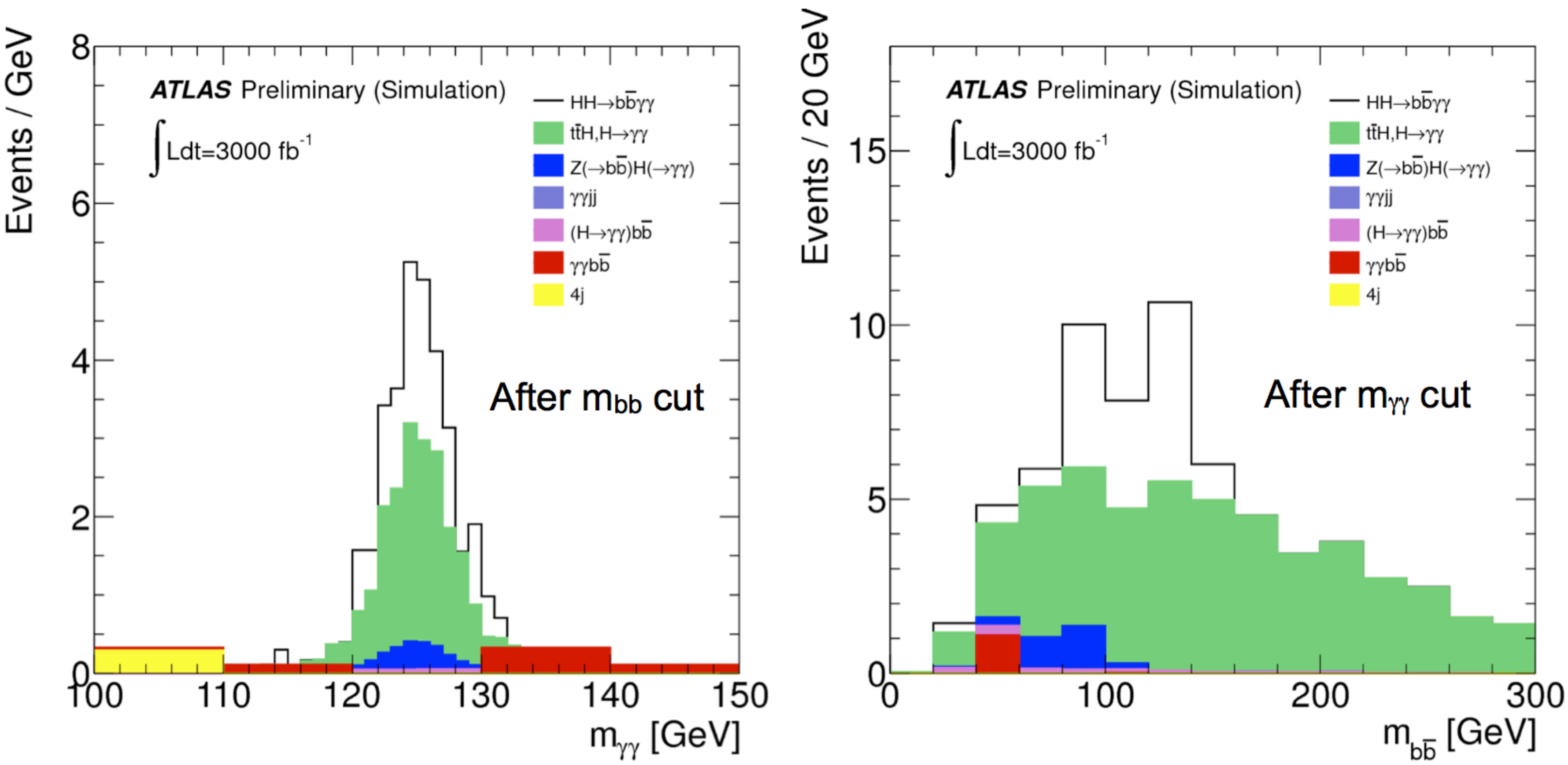


NLO cross-section at m_H=125 GeV:

σ = 34 fb$^{+18\%}_{-15\%}$ (QCD scale) ± 7% (PDF+α_s) ± 10% (EFT)

Higgs Self Coupling

HH→bb̄γγ



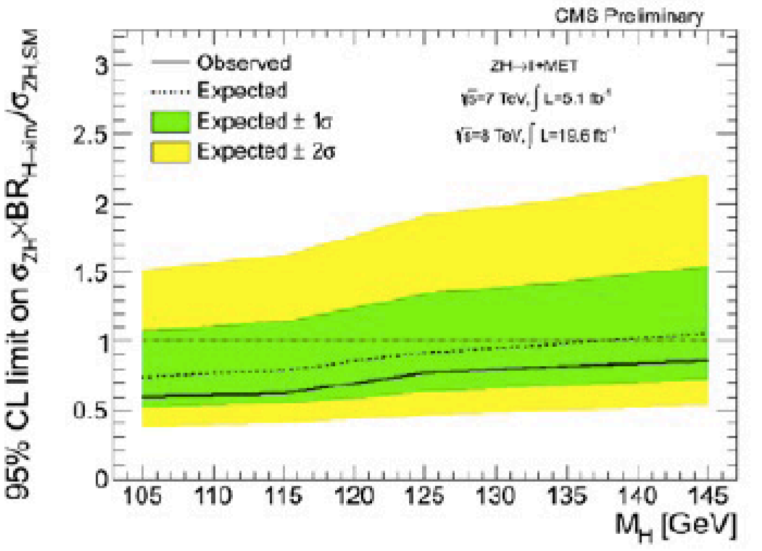
A sensitivity of 3σ per experiment is within reach with L=3000 fb^{-1}

Higgs Physics: Invisible Decays

Accessible via VBF and ZH production.

Results available from ATLAS and CMS using ZH production. Assuming SM production cross section, observed (expected) 95% CL limits are

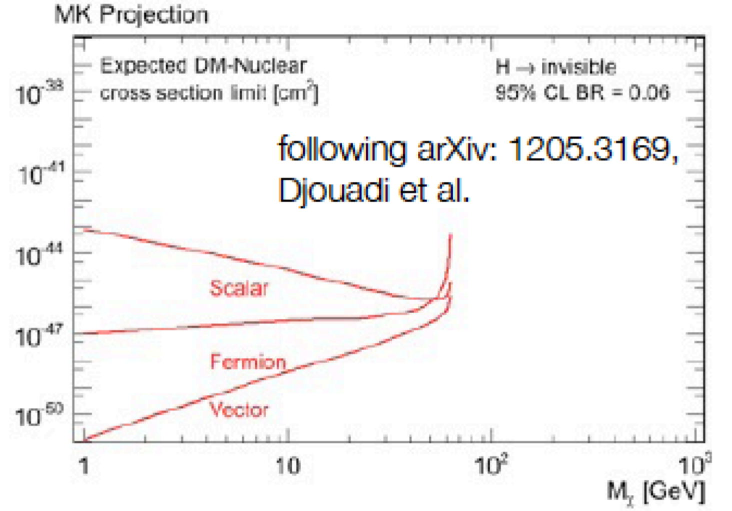
ATLAS: BR_{inv} < 65% (81%)
CMS: BR_{inv} < 75% (95%)



Estimate from CMS for future performance based in ZH analysis

L (fb^{-1})	$H \to$ inv.
300	[17, 28]
3000	[6, 17]

Connection to Dark Matter searches



Extended Higgs coupling fit has sensitivity to BR_{BSM}

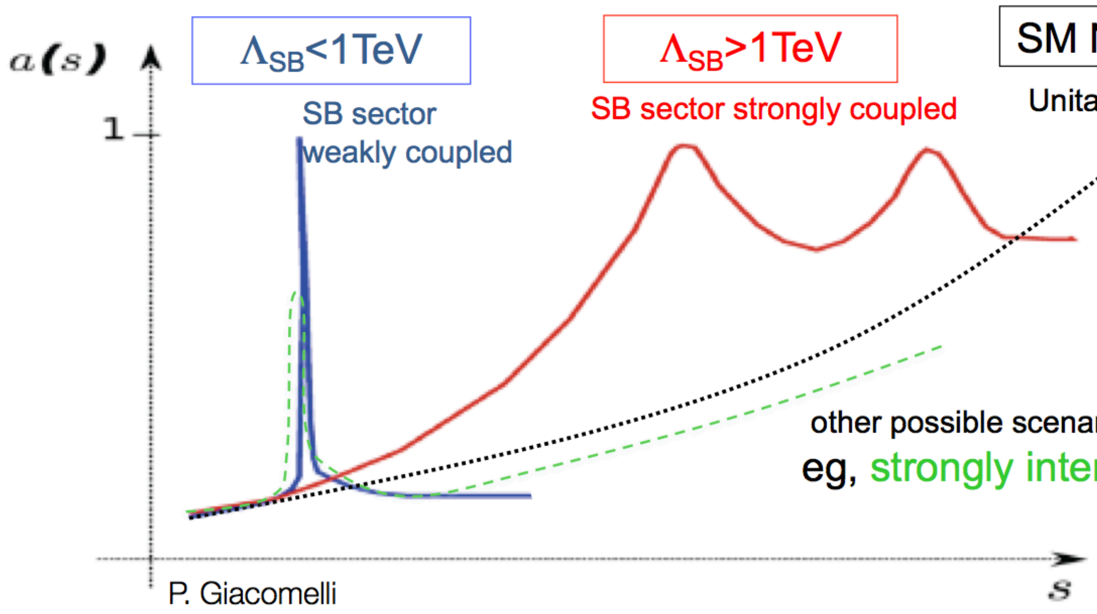
L (fb^{-1})	BR_{inv}
300	[14, 18]
3000	[7, 11]

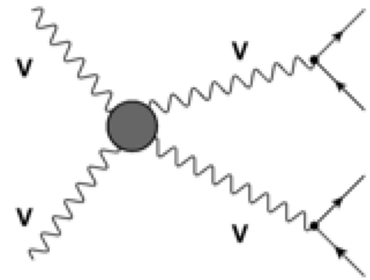
$$\Gamma_{tot} = \sum \Gamma_{ii} + \Gamma_{BSM}$$

$$BR_{BSM} = \Gamma_{BSM} / \Gamma_{tot}$$

VV Scattering

VV Scattering spectrum, σ(VV→VV) vs M(VV)
is the fundamental probe to test the nature of the BEH boson or to find an alternative EWSB mechanism





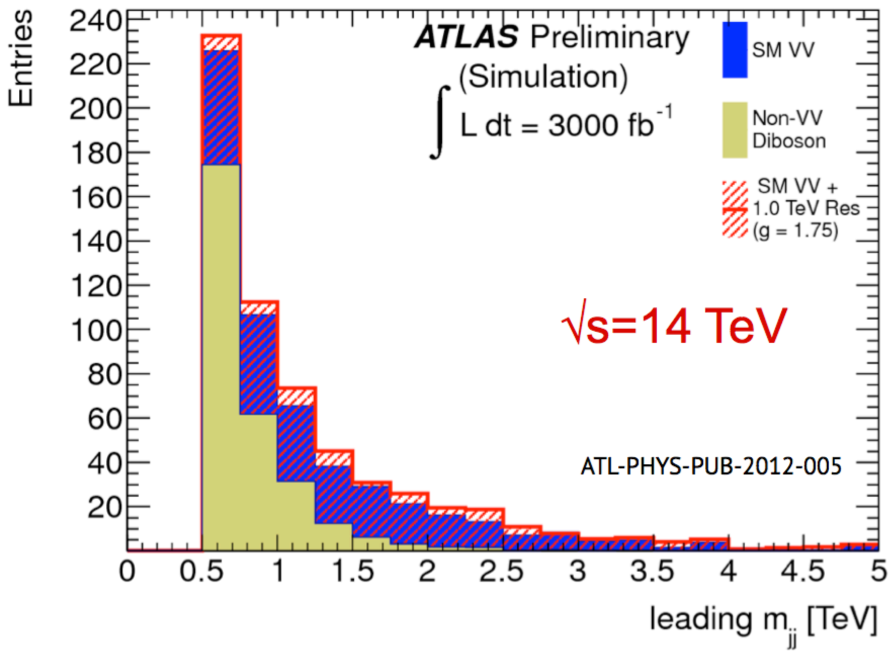
BSM models predict TeV-scale resonances "paired" with a light scalar particle

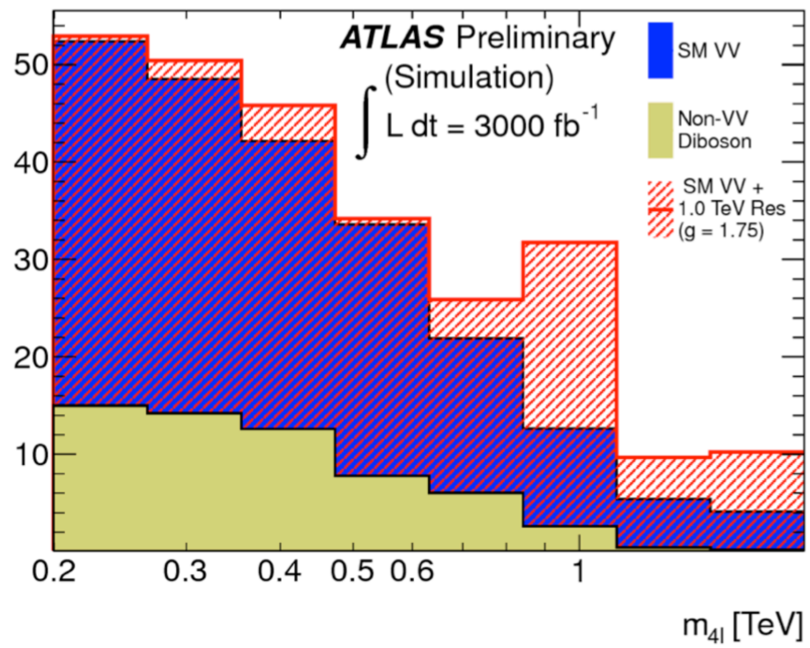
Search for possible resonances in VBF spectrum

Verifying the details of this process is essential to confirm whether this Higgs Boson is a fundamental particle

VV Scattering

pp→ZZ+2j→4ℓ+2j channel



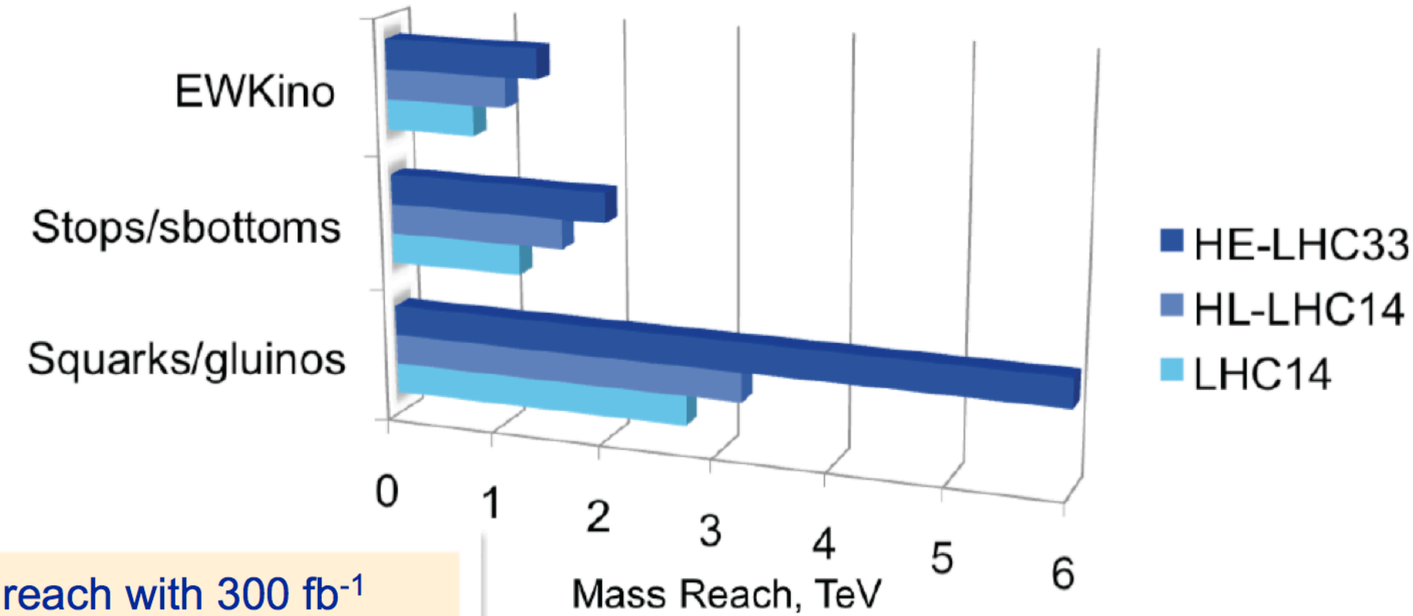


model	300 fb^{-1}	3000 fb^{-1}
$m_{\text{resonance}}$ = 500 GeV, $g = 1.0$	2.4σ	7.5σ
$m_{\text{resonance}}$ = 1 TeV, $g = 1.75$	1.7σ	5.5σ
$m_{\text{resonance}}$ = 1 TeV, $g = 2.5$	3.0σ	9.4σ

Sensitivity to anomalous ZZ resonances in Vector boson scattering

Searches for New Particles

- LHC at 14 TeV expands the reach for SUSY particles to much higher masses. (HE-LHC at 33 TeV does it even more)
- As expected, the gain with HL-LHC is more modest (~25%) in this case.

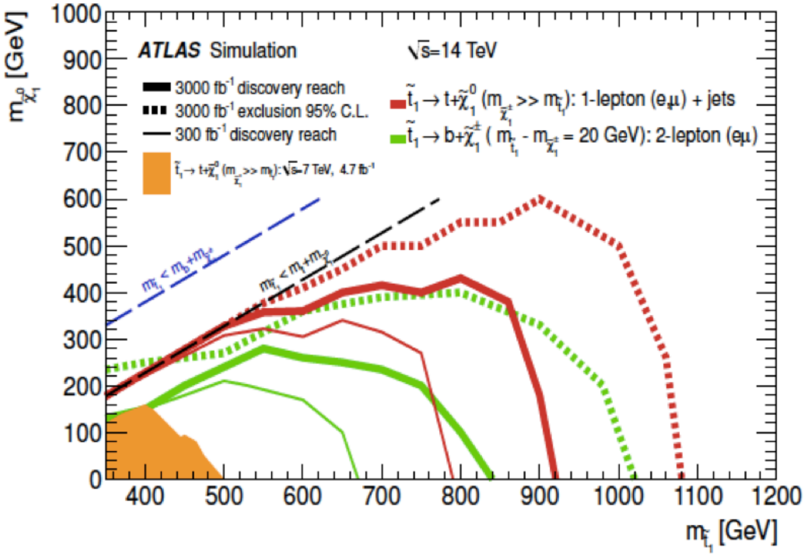


SUSY reach with 300 fb^{-1}
EWKinos up to ~ 800 GeV
Stops,sbottoms up to ~ 1TeV
squarks,gluinos up to ~2.5 TeV

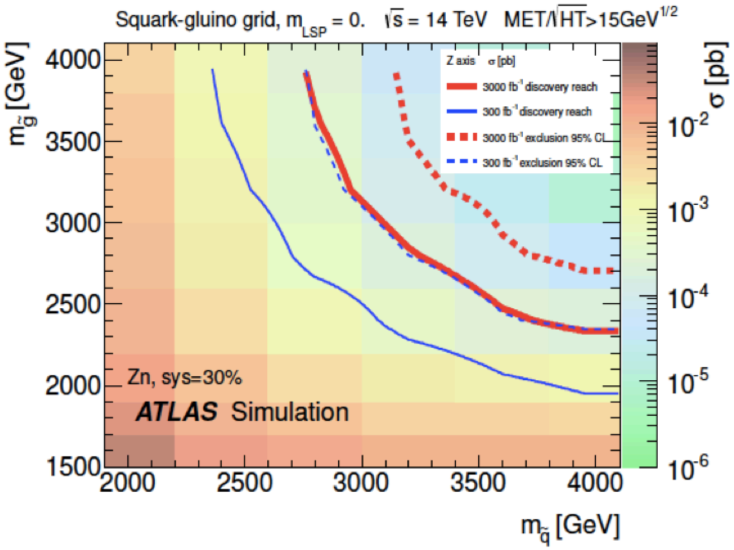
Examples of SUSY Searches

5σ discovery reach (solid lines) and 95% CL exclusion limits (dashed lines)
With $300 fb^{-1}$ (thin lines) and $3000 fb^{-1}$ (thick lines)

Stop-neutralino



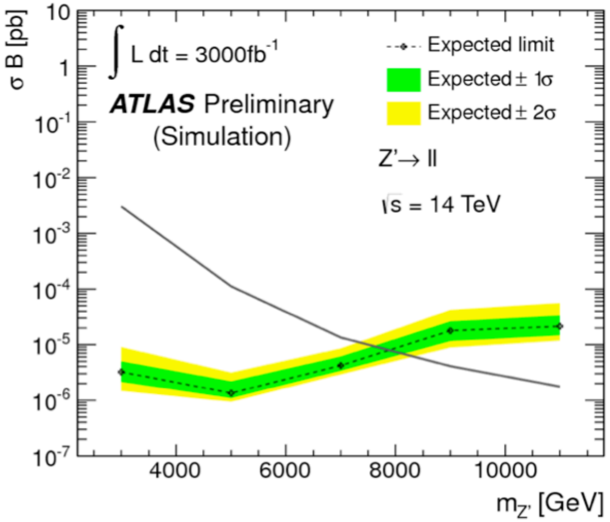
Squark-gluino



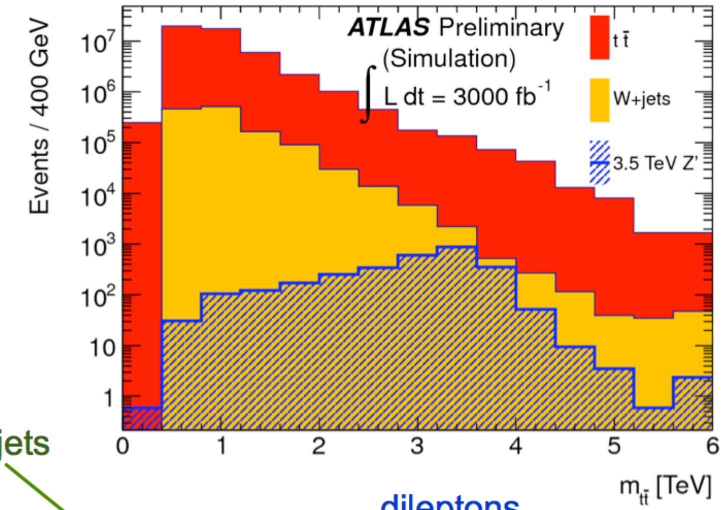
Going from $L=300\ fb^{-1}$ to $L=3000\ fb^{-1}$ the sensitivity to 1st and 2nd gen squarks and gluinos improves by ~400-500 GeV, while to stops by about 200 GeV

HL-LHC gluino:
Exclusion 2.7 TeV
Discovery 2.3 TeV

High Mass Resonance Searches

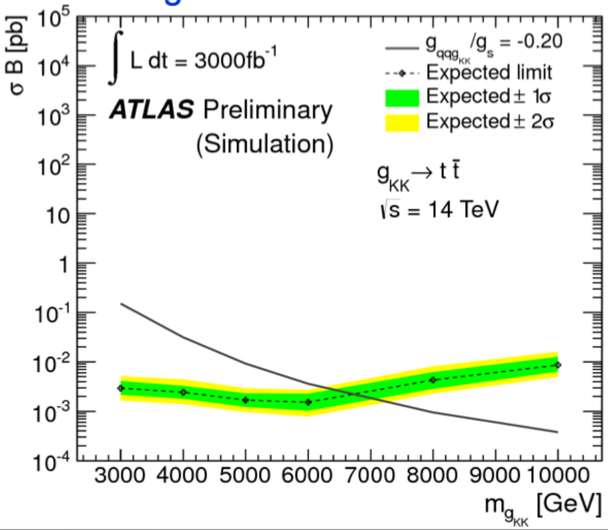


Z' Topcolour



lepton+jets

Kaluza-Klein gluons in extra-dimensional models



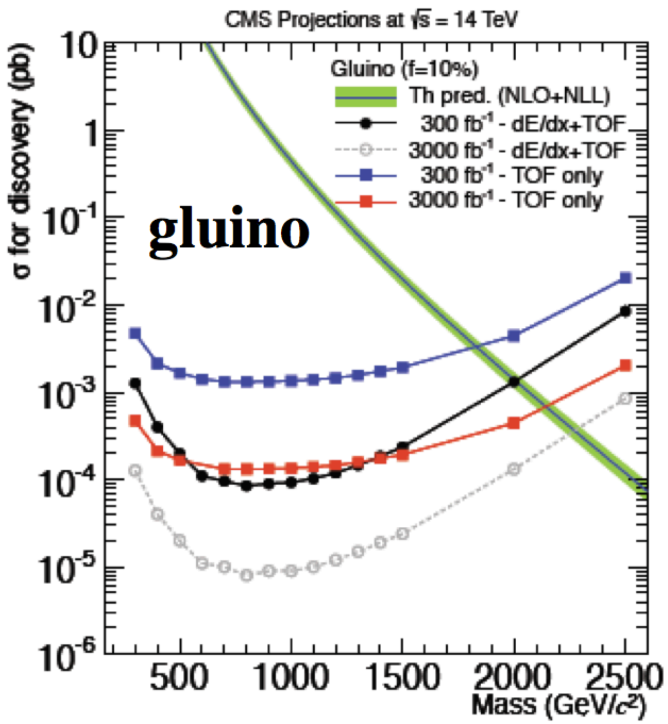
dileptons

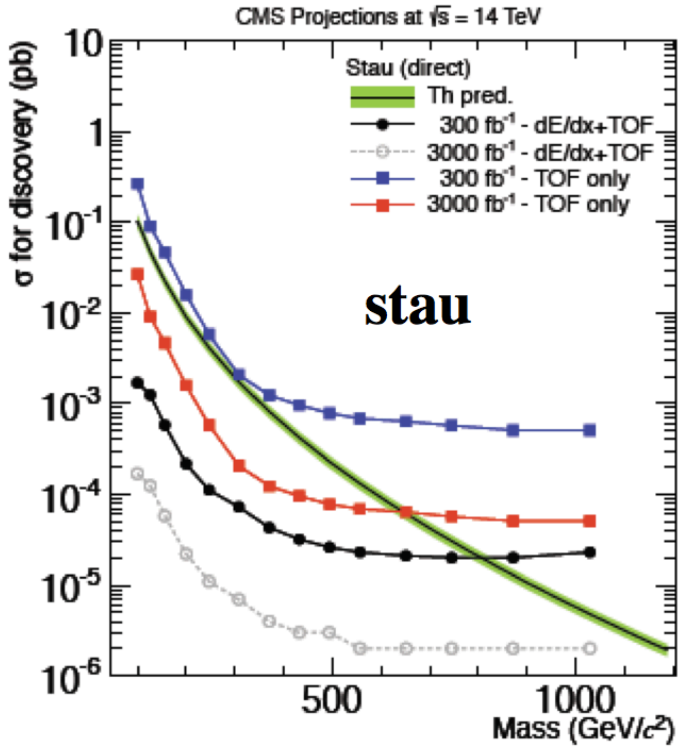
model	$300\ \mathrm{fb}^{-1}$	$1000\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\mathrm{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

Summary of expected limits for various signatures in the Sequential Standard Model. All mass limits are in TeV.

Meta-stable gluinos and staus

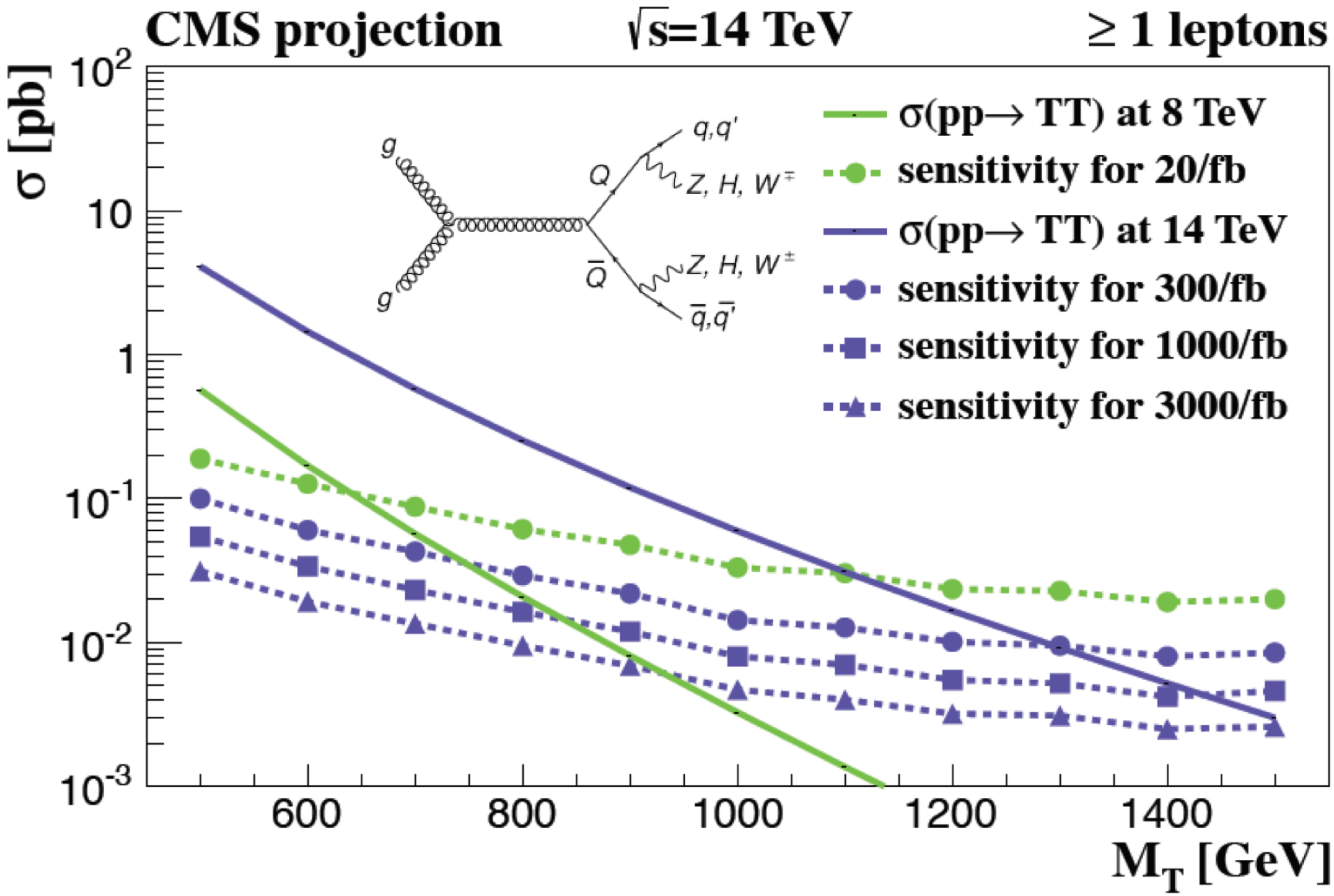
- Metastable sparticles occur in many scenarios of new physics
  - E.g. Split-SUSY $\tilde{g}$, GMSB stau, ….





	$M(\tilde{g})$ [TeV]	$M(\tilde{\tau})$ [TeV]
Run-1 data 95% CL limit	>1.0	0.27
300 fb^{-1} 5σ discovery	1.8-2.0	~0.8
3000 fb^{-1} 5σ discovery	2.1-2.3	~1.2

Vector-like Top Quarks

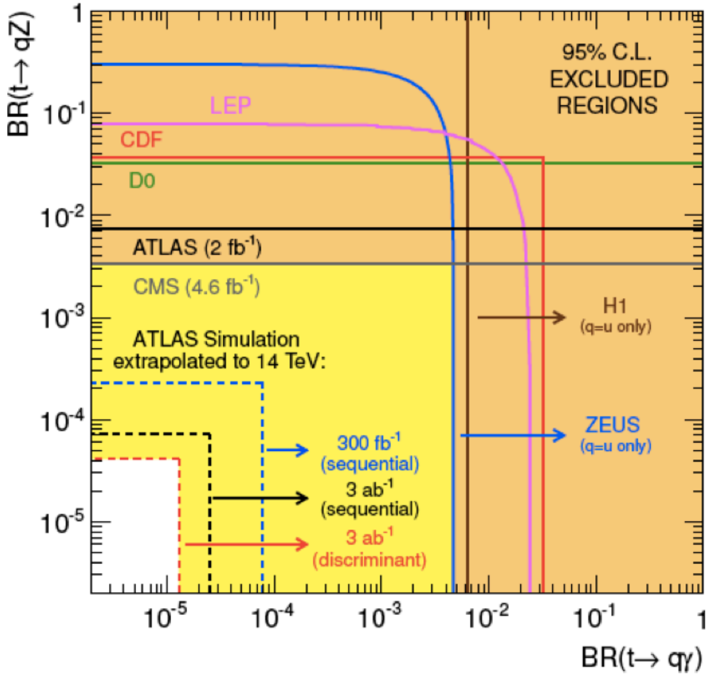


- Probe >1.5 TeV with 3000 fb^{-1}

Rare Decays of Top Quarks

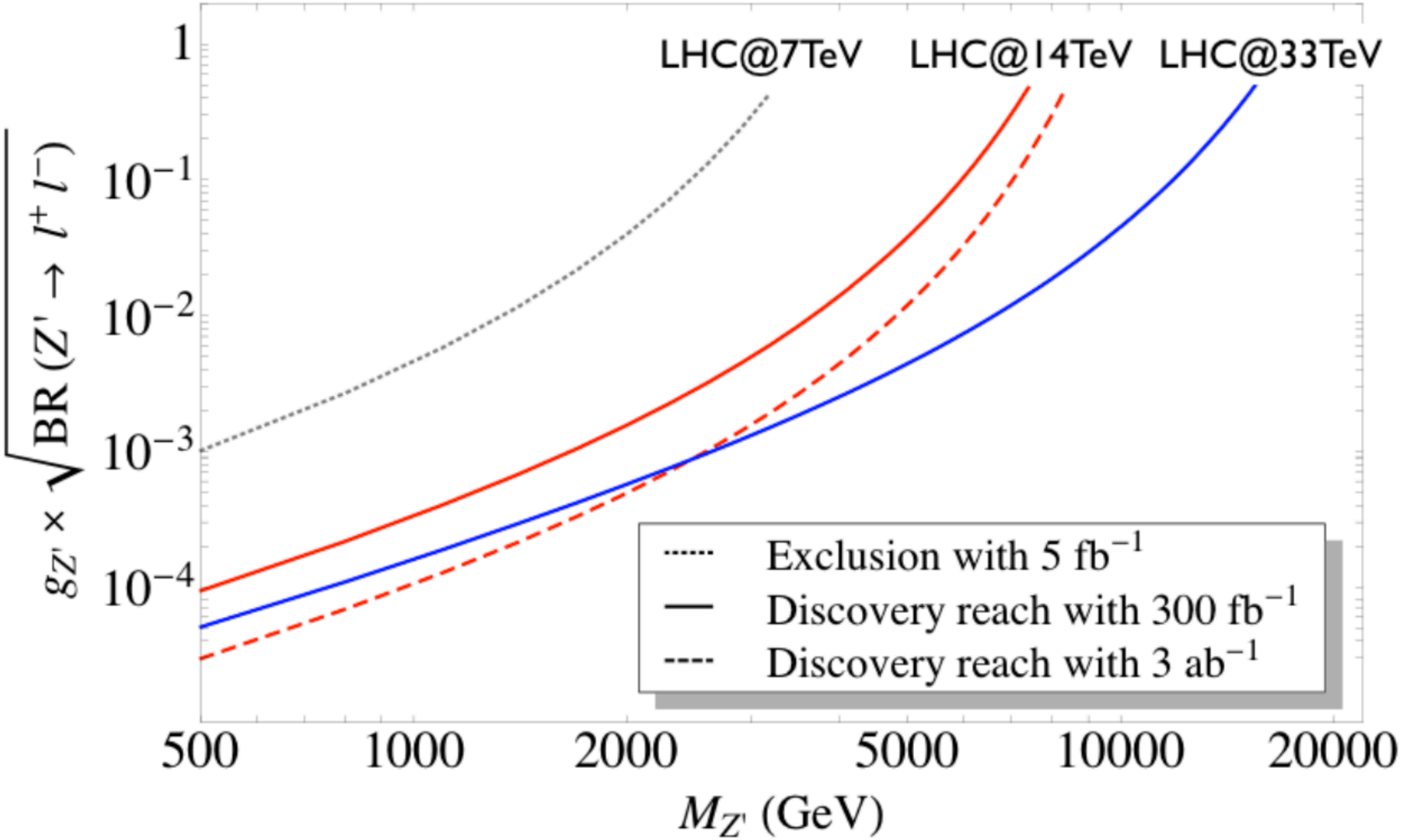
Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$	TC2	RS
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—	$\sim 10^{-11}$
$t \to uZ$	8.0×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—	$\sim 10^{-9}$
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—	$\sim 10^{-11}$
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\sim 10^{-6}$	$\sim 10^{-9}$
$t \to cZ$	1.0×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\sim 10^{-4}$	$\sim 10^{-5}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8.5×10^{-5}	2×10^{-4}	$\sim 10^{-4}$	$\sim 10^{-9}$

- LHC is a top factory
  - In 3000 fb^{-1} 0.5 billion observed ttbar events per experiment
- In SM top quark decays to Wb nearly 100%
  - Observing decays to other modes clear sign of new physics
  - Interesting region starts at $\sim 10^{-4}$
- HL-LHC will probe $\sim 3 \times 10^{-5}$ at least



HE-LHC: Zprime Production

HE-LHC: a high energy LHC of 28-33 TeV?



Discovery reach becomes more interesting with 33 TeV for M> 2.5 TeV

Upcoming Workshop

A study for the luminosity upgrade of the LHC

The high energy upgrade will need a dedicated study in due time as well…

Wait for some results of the 14 TeV, >100 fb^{-1} run…

Conclusion

- The LHC has produced a wealth of data at the highest energies in the laboratory. Lots to be tested/compared with Monte Carlo predictions.
- The most spectacular result is the discovery of a 126 GeV boson, within present precision, consistent with a SM Higgs. Deviations are still possible. No sign of New Physics yet
- The new 126 GeV Higgs boson and the increased reach at high mass and precision sets the scene for the LHC program/upgrade & future facilities.
- The nominal energy LHC (13-14 TeV) will start in 2015. 300 fb^{-1} of data (10x today) guaranteed. HL-LHC should give 3000 fb^{-1} by ~2030-2035, after a machine and detector upgrade. Full study ongoing. A High Energy pp collider next? ILC?...
- Monte Carlo programs will continue to play a prominent role for getting results in experimental high energy physics. We need to make sure that there is a continuing effort in these program

Backup

Experiment Upgrades: ATLAS

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	...	2030
Prepare for:			Phase 0,I	LS1				Phase I,II	LS2			Phase II	LS3			

"Phase-0" upgrade: consolidation
$\sqrt{s}$ = 13~14 TeV, 25ns bunch spacing
$L_{inst} \simeq 1 \times 10^{34}$ $cm^{-2}s^{-1}$ ($\mu \simeq 27.5$)
$\int L_{inst} \simeq 50$ fb^{-1}

"Phase-I" upgrades:
ultimate luminosity
$L_{inst} \simeq 2\text{-}3 \times 10^{34}$ $cm^{-2}s^{-1}$ ($\mu \simeq 55\text{-}81$)
$\int L_{inst} \gtrsim 350$ fb^{-1}

"Phase-II" upgrades:
$L_{inst} \simeq 5 \times 10^{34}$ $cm^{-2}s^{-1}$ ($\mu \simeq 140$) w. leveling
$\simeq 6\text{-}7 \times 10^{34}$ $cm^{-2}s^{-1}$ ($\mu \simeq 192$) no level.
$\int L_{inst} \simeq 3000$ fb^{-1}

ATLAS has devised a 3 stage upgrade program

- New insertable pixel b-layer (IBL)
- New Al beam pipe
- New pixel services
- Complete installation of EE muon chambers
- New evaporative cooling plant
- Consolidation of detector services
- Specific neutron shielding
- Upgrade magnet cryogenics

- New Small Wheel (nSW) for the forward muon Spectrometer
- High Precision Calorimeter L1-Trigger
- Fast TracKing (FTK) for L2-trigger
- Topological L1-trigger processors
- New forward diffractive physics detectors (AFP)

- Completely new tracking detector
- Calorimeter electronics upgrades
- Upgrade part of the muon system
- Possible L1-trigger track trigger
- Possible changes to the forward calorimeters

From M. Diemoz

Experiment Upgrades: CMS

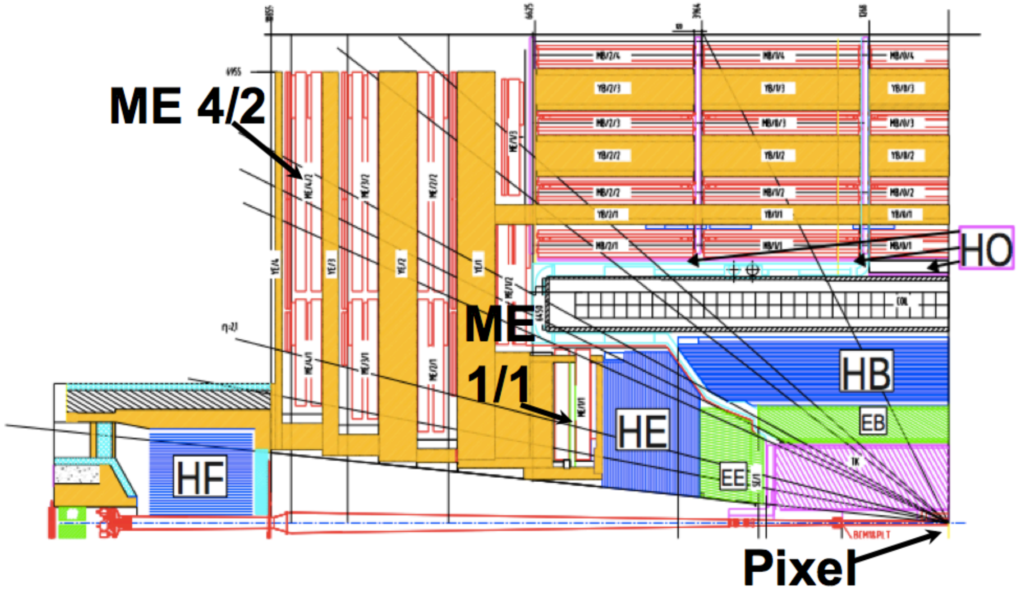
•LS1 Projects

•Complete Muon coverage (ME4)

•Improve muon operation, DT electronics

•Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPMs)

•DAQ1→DAQ2



LS1 LS2 LS3

Phase 1 Upgrades

•New Pixel detector, HCAL electronics and L1-Trigger upgrade

•GEMs for forward muon det. under review

•Preparatory work during LS1

-New beam pipe for pixel upgrade

-Install test slices of pixel, HCAL, L1-trigger

-Install ECAL optical splitters for L1-trigger

Phase 2: being defined now

•Tracker replacement, L1 Track-Trigger

•Forward: calorimetry, muons and tracking

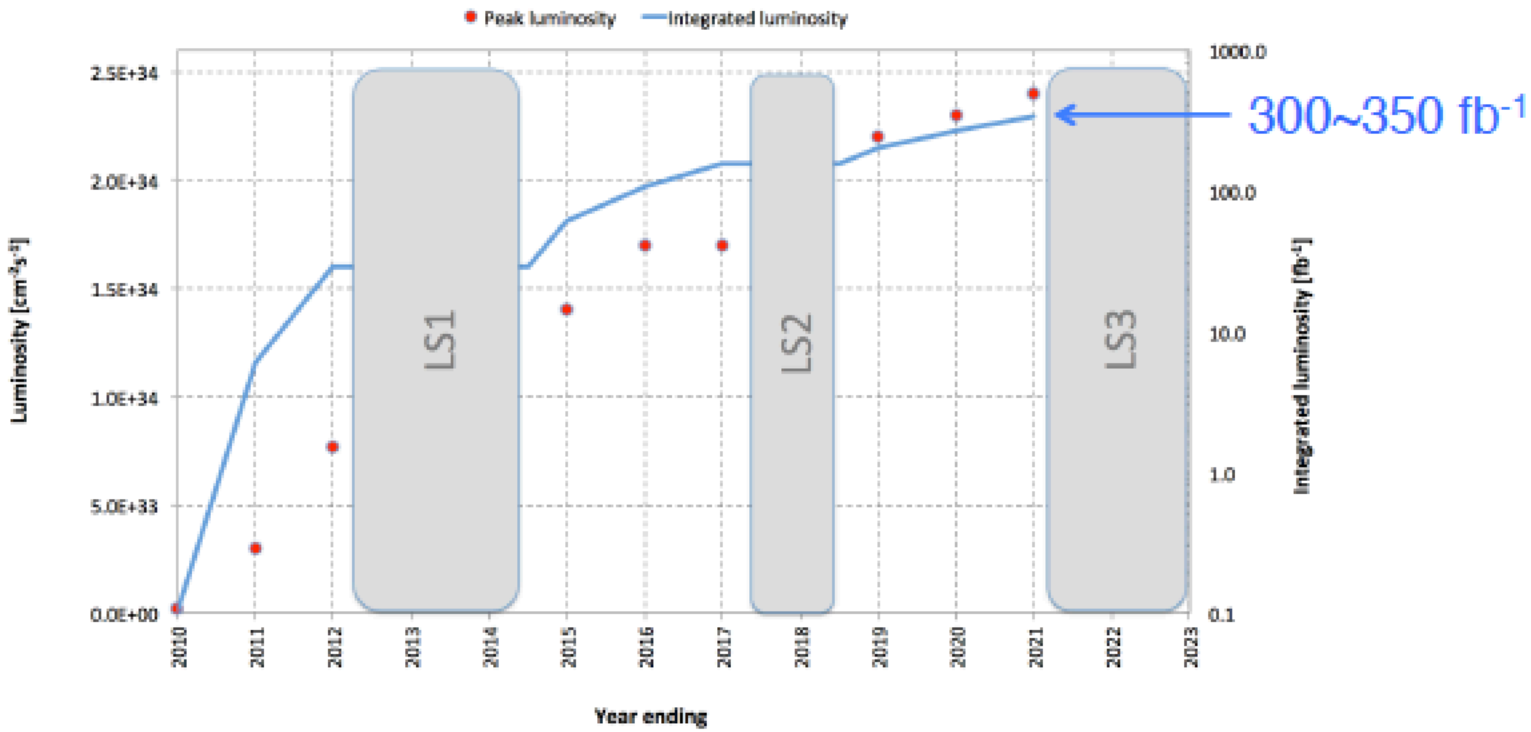
•High precision timing for PU mitigation

•Further Trigger upgrade

•Further DAQ upgrade

LHC schedule till ~2022

Approved LHC programme



- LS1: fix interconnects and overcome energy limitation
- LS2: overcome beam intensity limitation (collimation, cryogenics, injector upgrade for high intensity, low emittance bunches)
- By 2022, luminosity is saturated, and final focus Inner Triplet magnets in interaction regions reach the end of their useful life due to radiation damage → Upgrade: High Luminosity LHC.

LHC 'Near' Future

European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

European Strategy
Update

The High Luminosity Upgrade

High-Luminosity LHC (HL-LHC)

luminosity goals:

leveled peak luminosity: $L = 5\text{x}10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$
(upgraded detector pile up limit ~140)

"virtual peak luminosity": $L \geq 20\text{x}10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$

integrated luminosity: 200 - 300 fb^{-1} / yr

total integrated luminosity: ca. 3000 fb^{-1} by ~2035

HL-LHC – LHC modifications

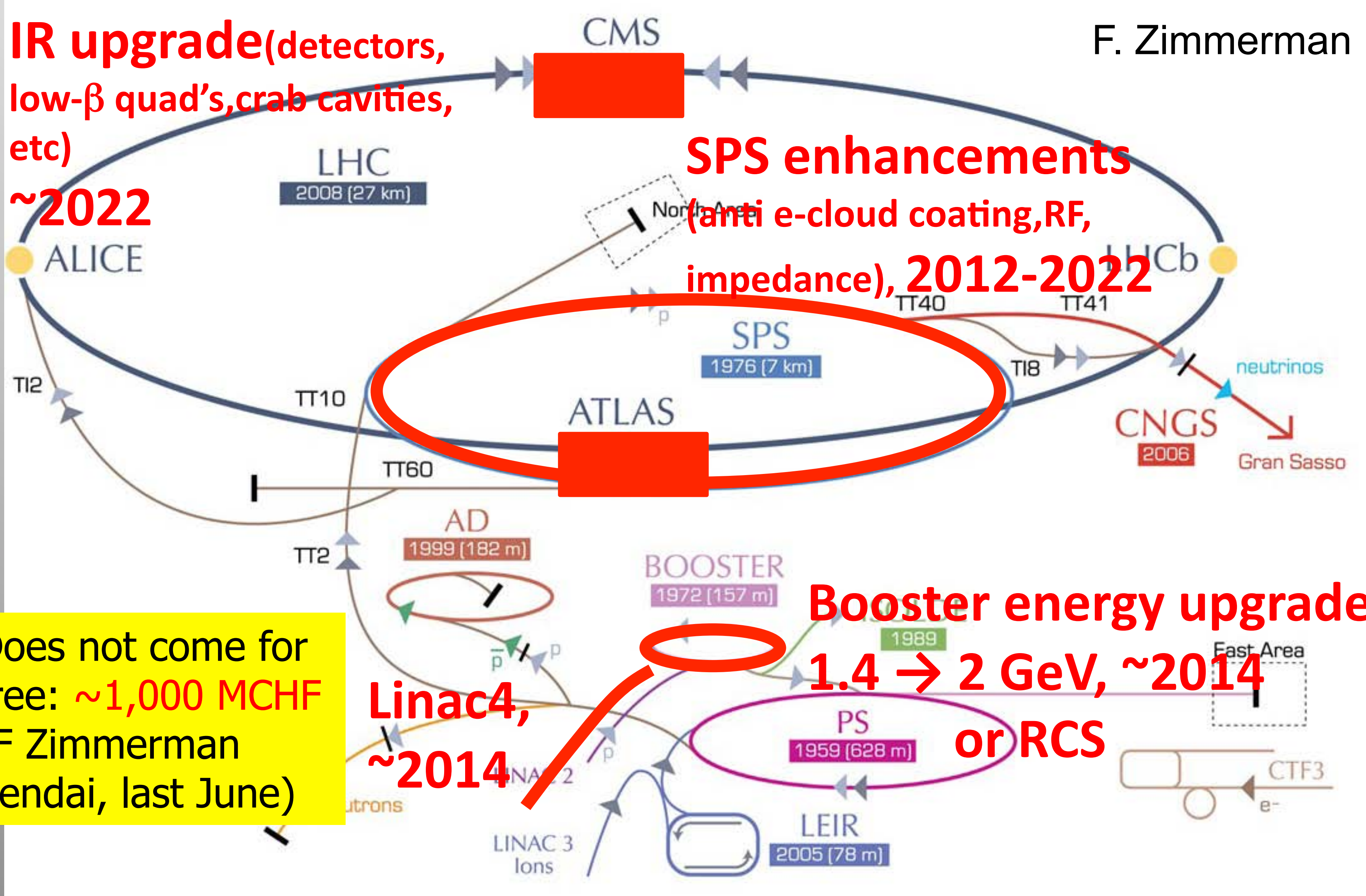
F. Zimmerman

IR upgrade(detectors, low-β quad's,crab cavities, etc)
~2022

SPS enhancements
(anti e-cloud coating,RF, impedance), 2012-2022

Booster energy upgrade
1.4 → 2 GeV, ~2014
or RCS

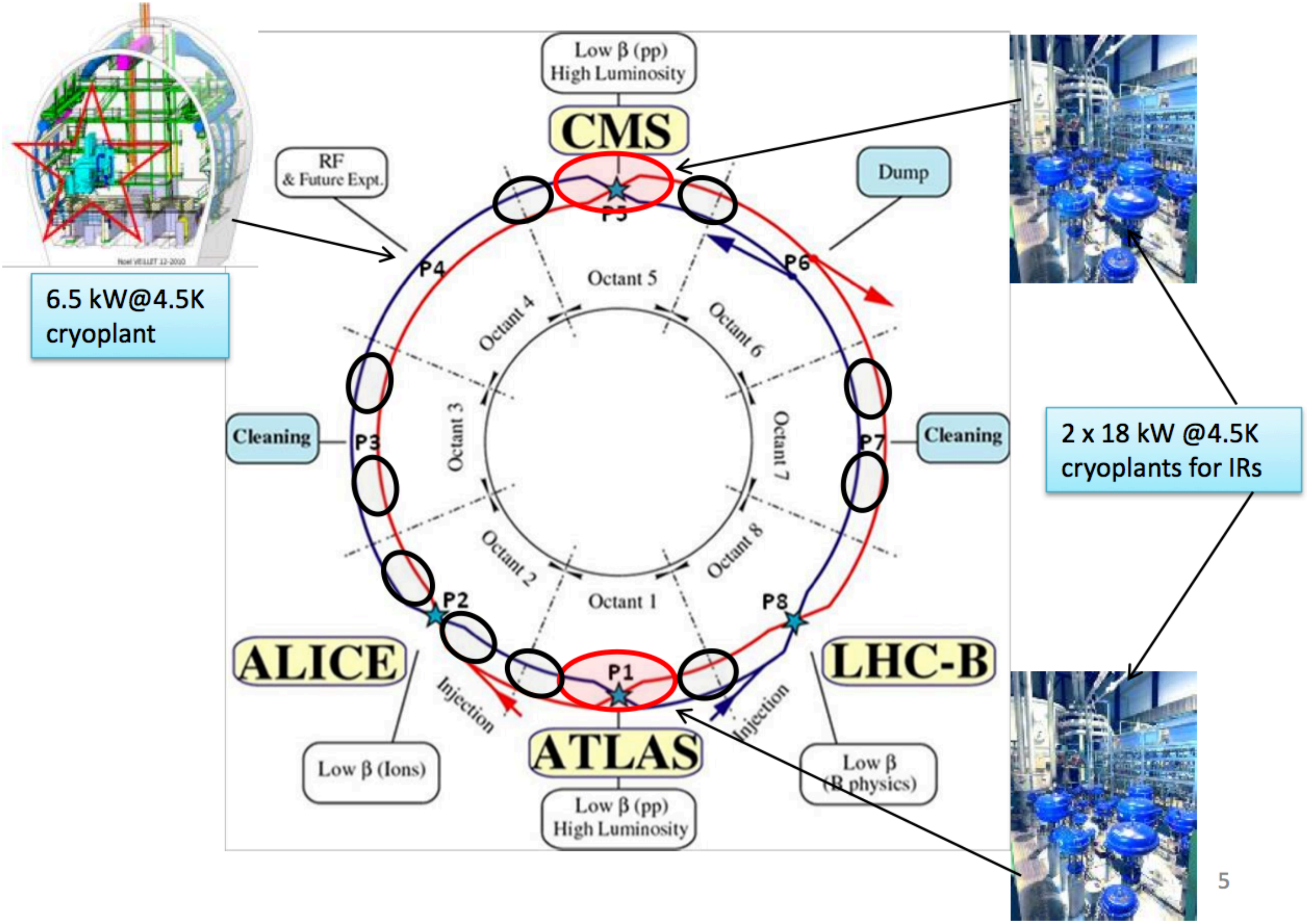
Linac4,
~2014



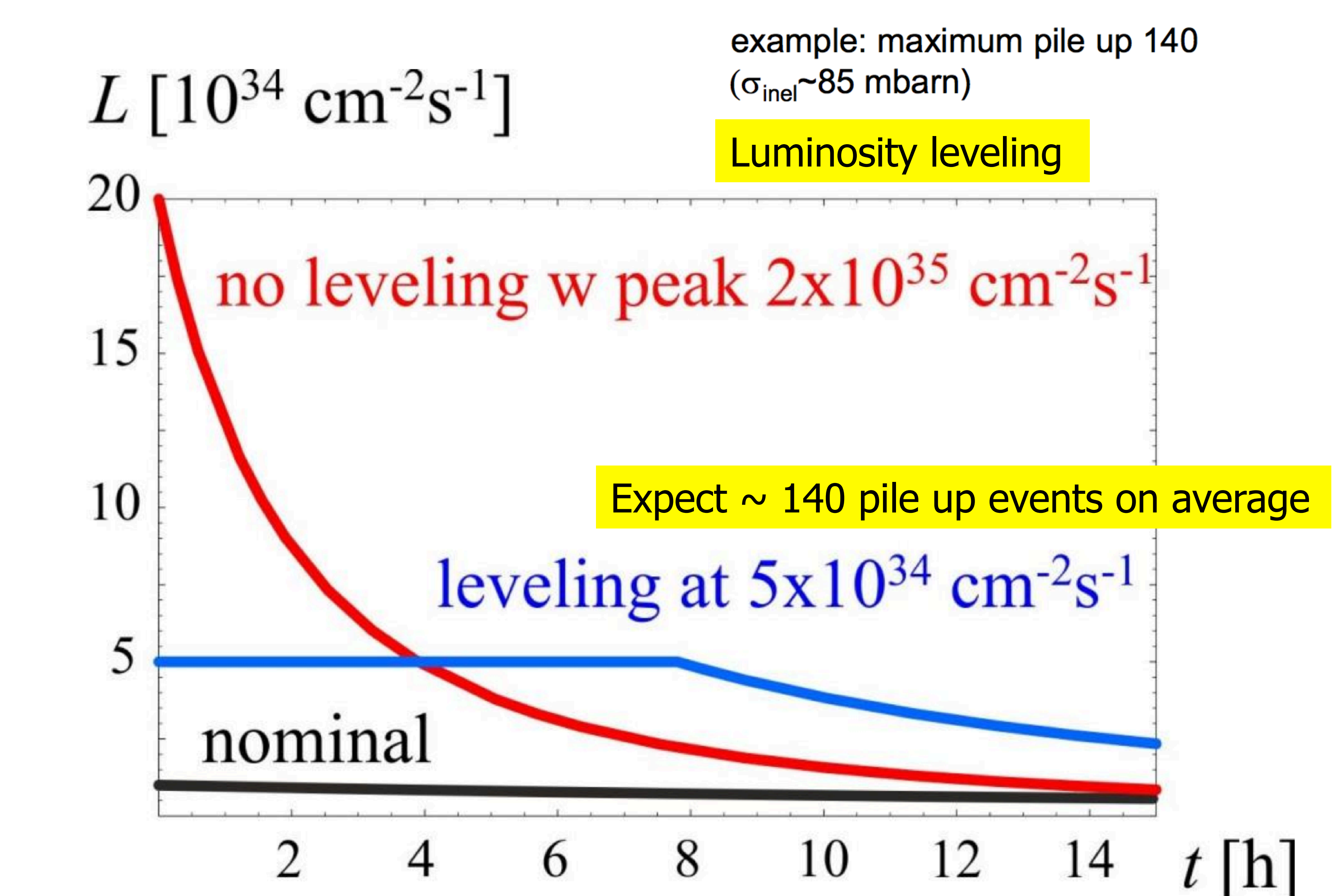
Does not come for free: ~1,000 MCHF (F Zimmerman Sendai, last June)

The High Luminosity Upgrade

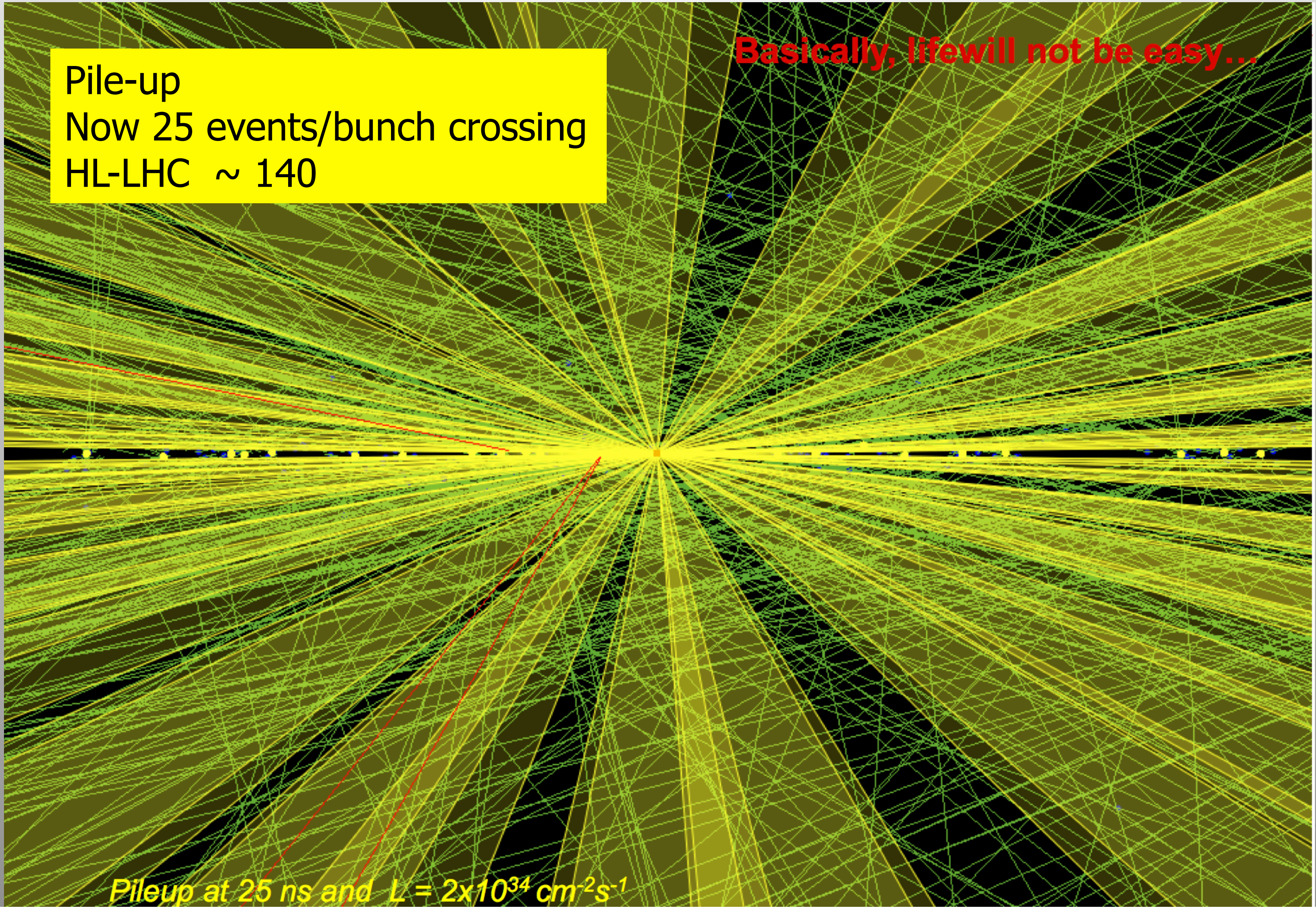
in LHC: 1.2 km of new equipment …



The High Luminosity Upgrade

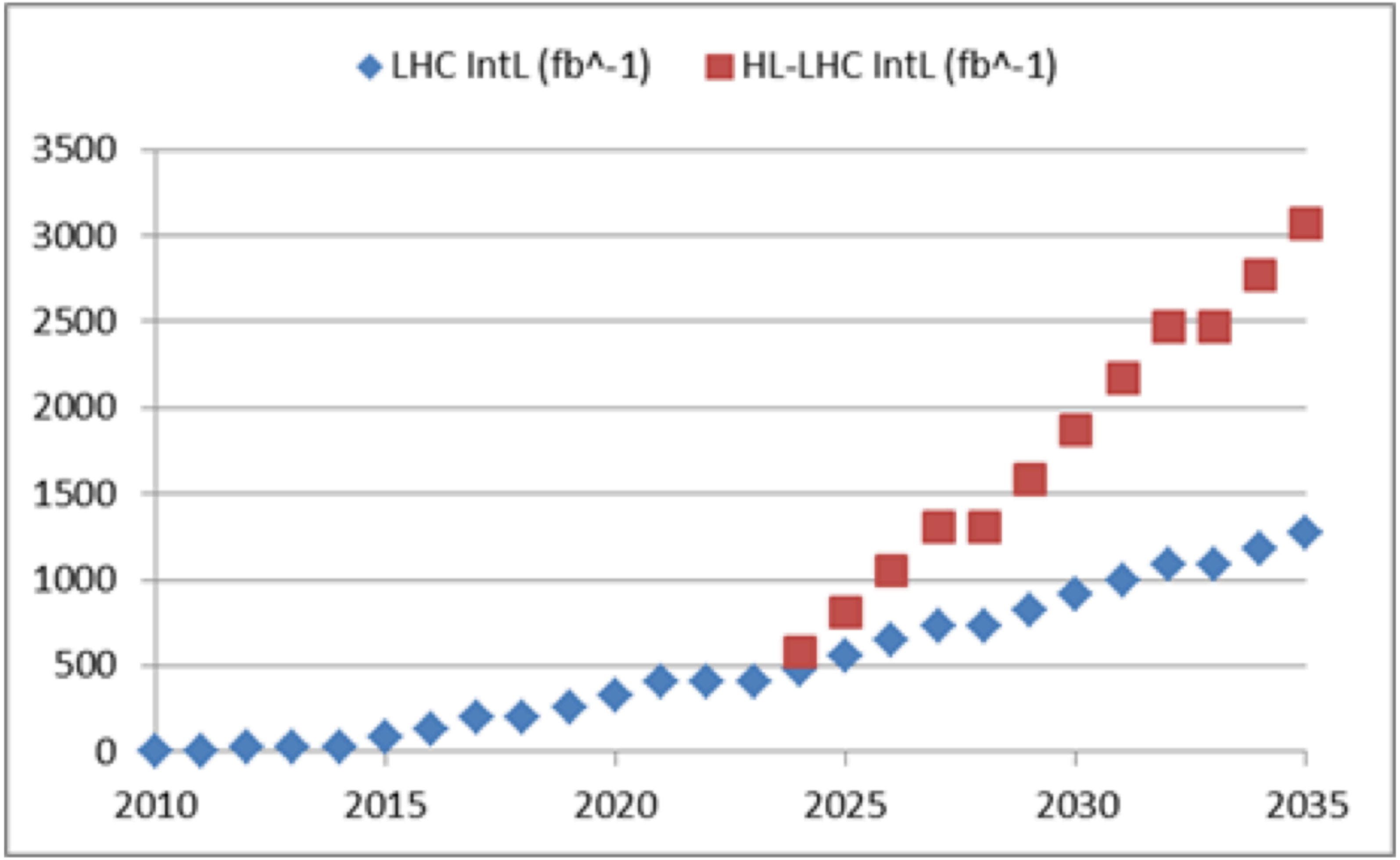


The Challenge for the Experiments



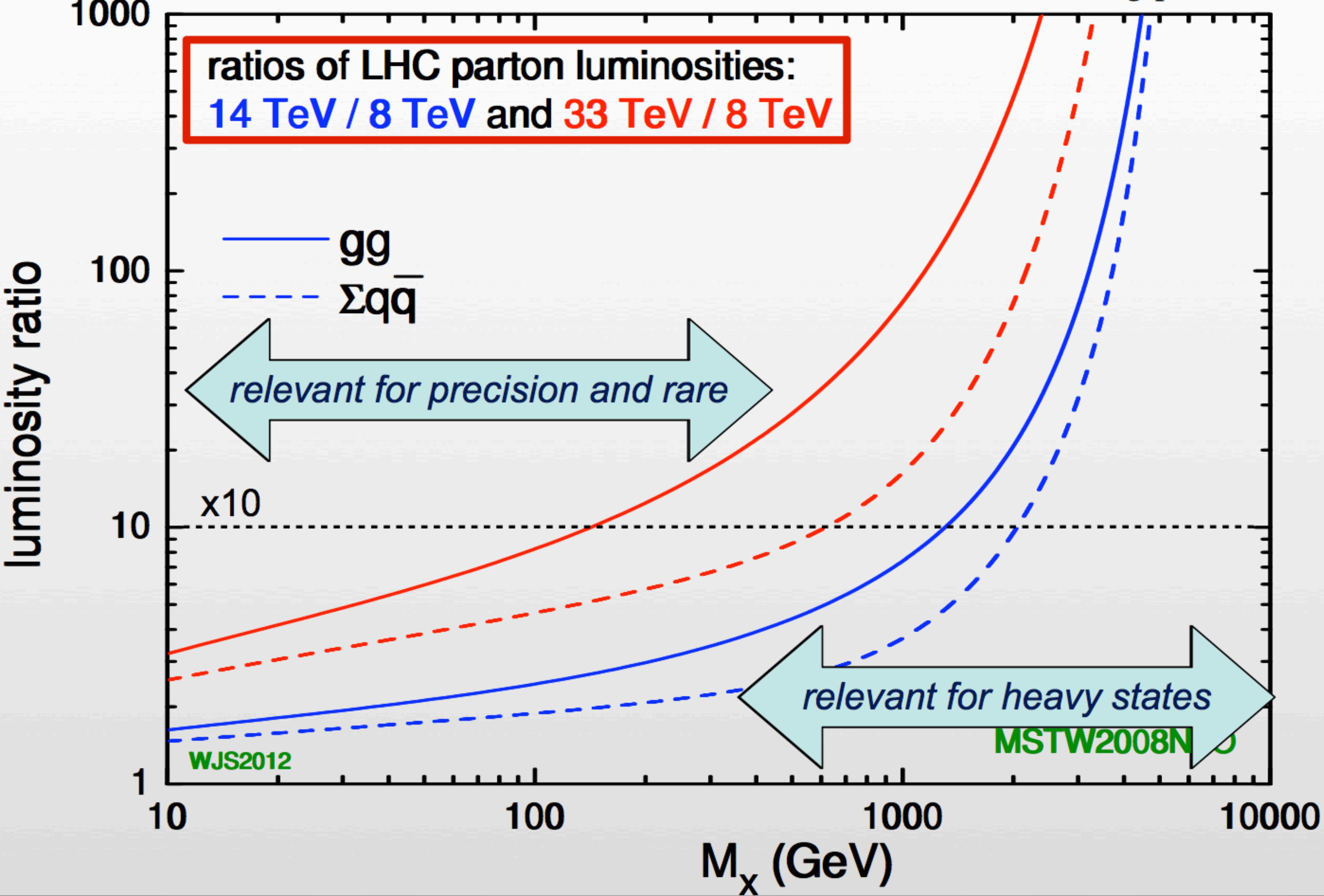
The High Luminosity Upgrade

The expected integrated luminosity profile

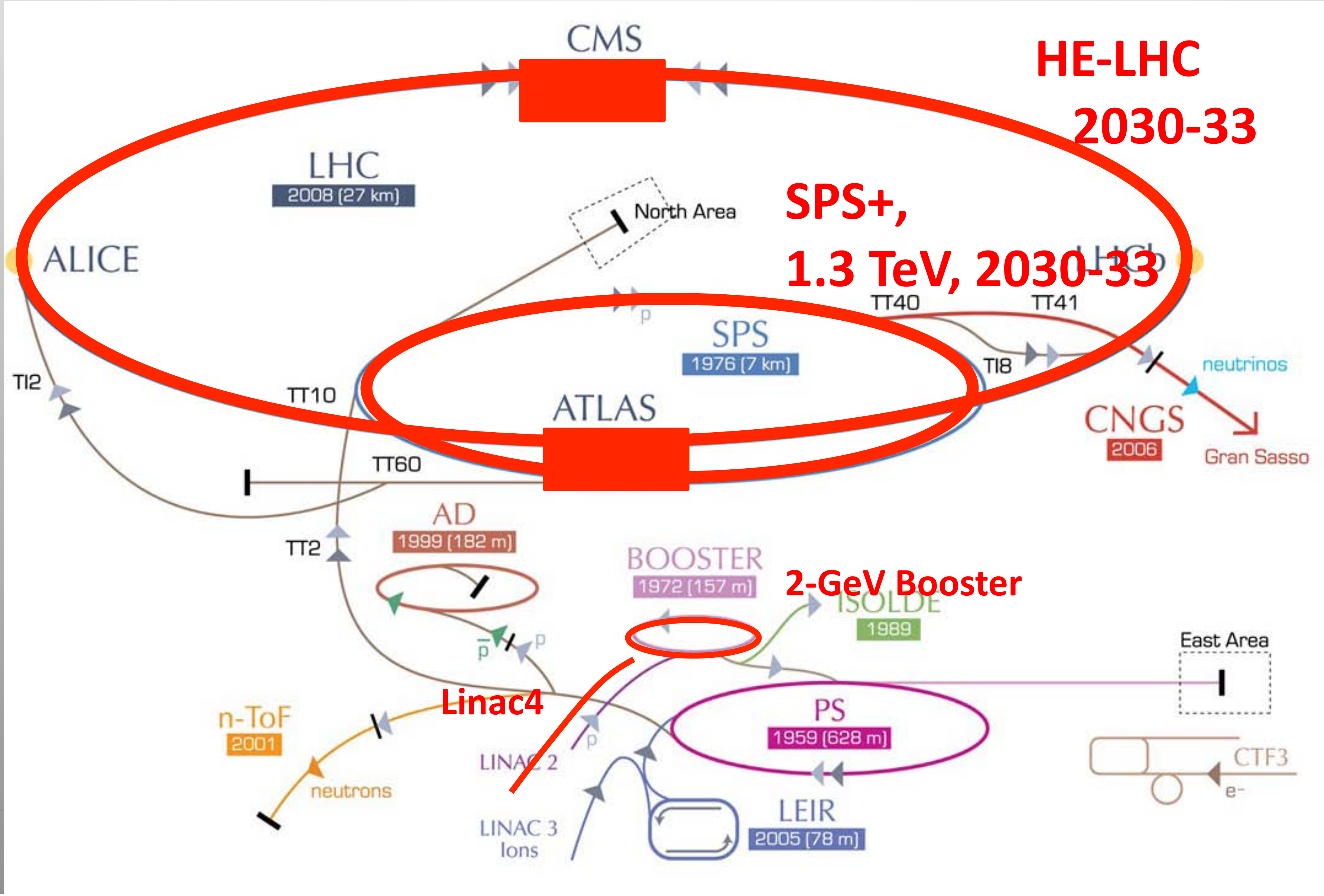


Higher Energies

W.J. Stirling, private communication



High Energy LHC



High Energy-LHC

High Energy-LHC (HE-LHC)

CERN working group since April 2010

EuCARD AccNet workshop HE-LHC'10, 14-16 October 2010

key topics

beam energy 16.5 TeV; 20-T magnets

cryogenics: **synchrotron-radiation heat**

radiation damping & emittance control

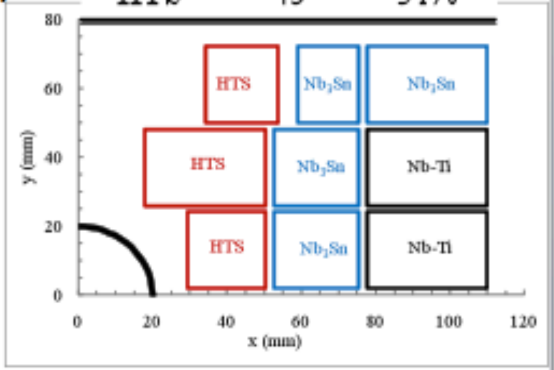
vacuum system: synchrotron radiation

new injector: energy > 1 TeV

parameters

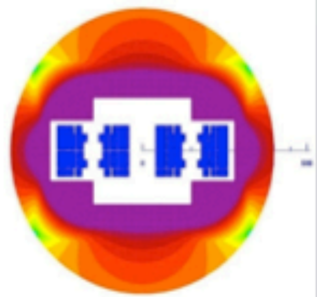
	LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches	2808	1404
IP beta function [m]	0.55	1 (x), 0.43 (y)
number of IPs	3	2
beam current [A]	0.584	0.328
SR power per ring [kW]	3.6	65.7
arc SR heat load dW/ds [W/m/ap]	0.21	2.8
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0

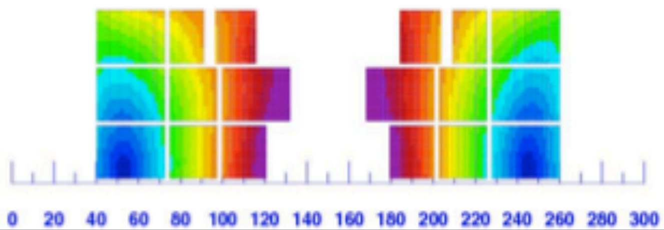
	Turns	%
Nb-Ti	40	28%
Nb_3Sn	58	41%
HTS	45	31%



E. Todesco

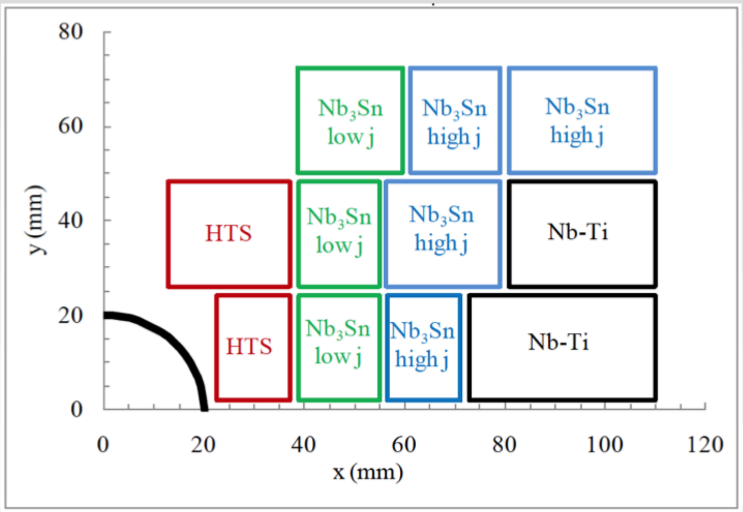
hybrid magnet





High Energy-LHC

Re-equip existing LHC tunnel with high field magnets



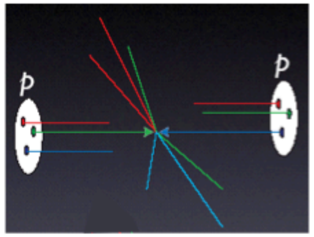
Conceptual layout of 20 T dipole magnet (Nb_3Sn and HTS)

Intense R&D required

L. Rossi and E. Todesco

Circumference	26.7 km
Maximum dipole field	20 T
Injection energy from SC-SPS	1.3 TeV
Maximum c.o.m. energy	33 TeV
Peak luminosity	5×10^{34} cm^{-2}s^{-1}

Very High Energy LHC ?



- VHE-LHC
  - 80 km (100 km) electron ring could set the stage for a future very high energy hadron collider (Ecm = 100 TeV)
    - as LEP preceded the LHC
  - Proposed lepton collider ring (TLEP) in part motivated by this long term possibility
  - VHE-LHC needs physics justification