Long Term Prospects for the LHC at High Luminosity

How will the LHC look at 45 years old?

J. Nash

What will be the legacy of the LHC?

- The machine which discovered the SM Higgs Boson?
- The machine which found the cracks in the SM?
- The machine which finally found SUSY?
- The machine which finally ruled out SUSY?
- The machine which found the new and unexpected and led to a different view of the universe?

Big questions for the future of the LHC

- Should we keep running the LHC?
  - What other options do we have?
  - Have we had our return on investment?
- If "yes" how much integrated luminosity do we need?
  - Doesn't make sense to run forever
- How high can we push the instantaneous luminosity
  - Determines how long we need to run to meet our goal
  - Has a big impact on the accelerator and the detectors

Should we keep running the LHC?

Yes!

Why we should keep running the LHC

- This machine is our Energy Frontier machine
  - Now, and until we can agree what new pathway to follow to extend the energy frontier
    - Options are being thought about
      - TLEP
      - Muon collider
      - HE LHC
- This machine is our Higgs Factory for at least the next decade
- It is also the tool we will have to explore any new discoveries we uncover when we raise the energy of the machine in 2015

The European Strategy for Particle Physics

- Full exploitation of the LHC is the number one priority for the European particle physics community.
  - *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.*

Motivations for the upgrade

- The LHC has just had its first run near design luminosity and has already delivered a major discovery.
  - The new Boson which has been discovered demands extensive studies to establish its properties
    - Is this the SM Higgs Boson?
    - Does it behave as expected?
  - The LHC is the only machine we will have to study this Boson for at least the next decade
    - The community has made a huge investment in the LHC, and the incremental cost of getting maximum scientific output from the machine has to be exploited
- What we haven't discovered yet
  - The energy is about to increase to 13 (14) TeV

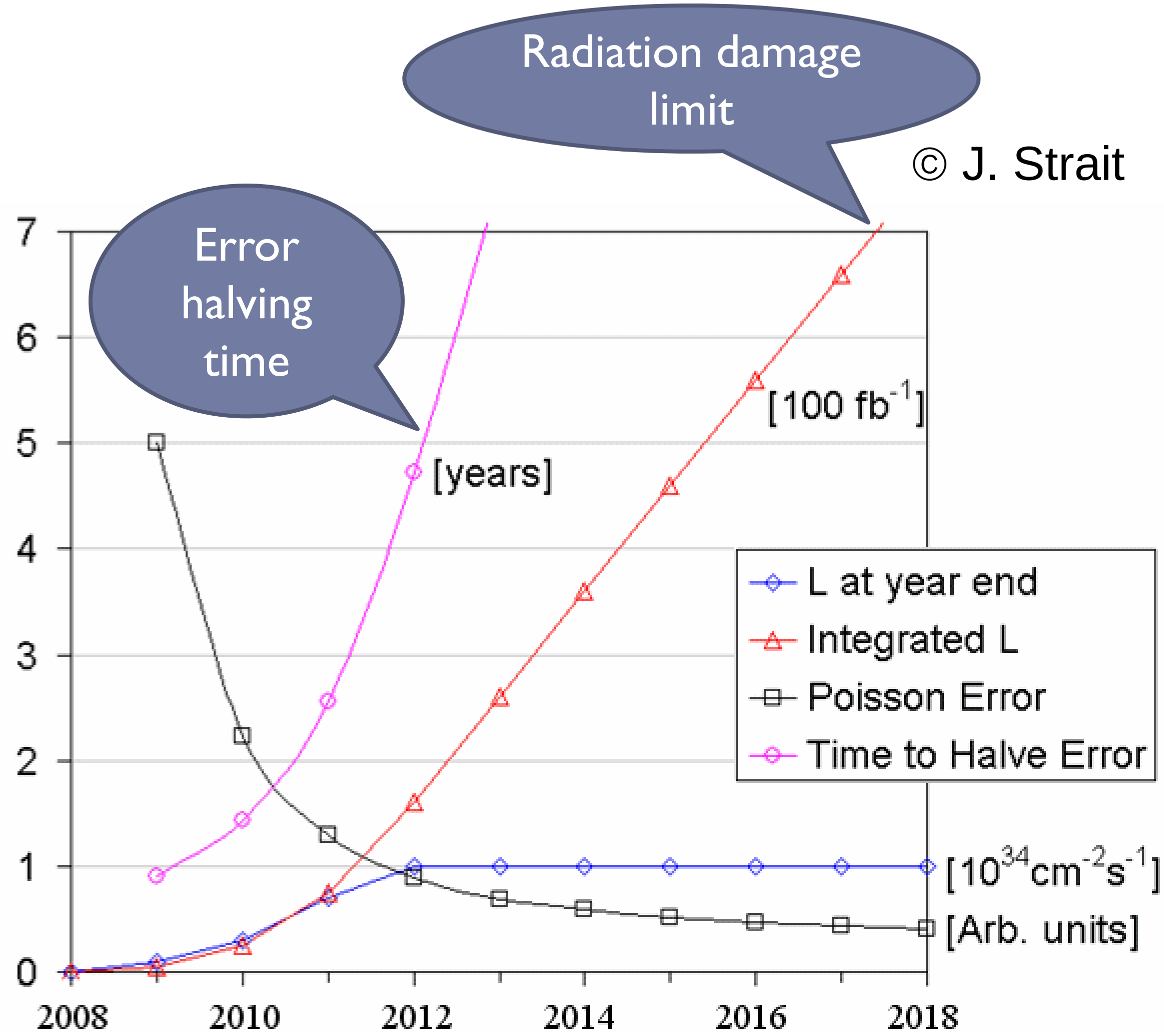
Simple minded motivation for when to make luminosity upgrades

- If the integrated luminosity/year remains fixed
  - The time it takes to reduce the statistical error on measurements where we are statistically limited grows rapidly
    - We know that there will be measurements which will still be statistically limited
  - How do we motivate ourselves to wait a decade to collect enough data for the next significant "update" of results
- Much better investment of effort/machine time to try and increase the luminosity collected/year
  - Have to be careful that by doing so we don't decrease the effectiveness of the data collected
  - Discoveries come early – precision tends to take time

Practical reasons to upgrade the LHC

- Hardware ageing
  - Machine elements
  - Detector elements
- Foreseeable luminosity evolution

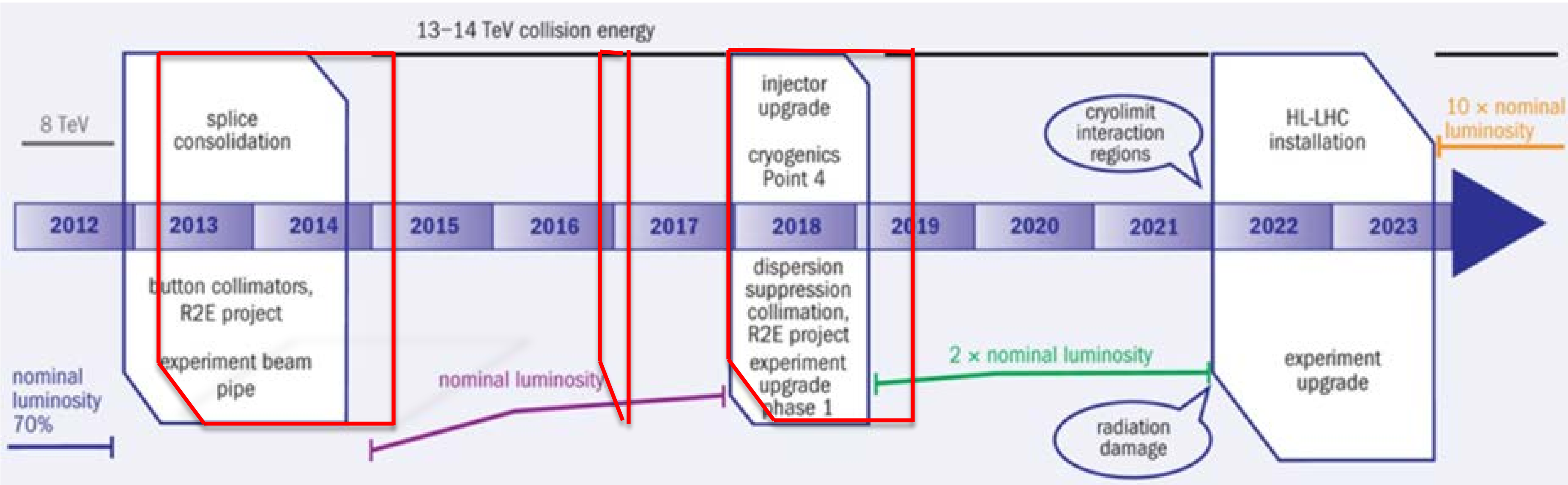
⇒ a major luminosity upgrade



Outline

- A quick overview of the current roadmap
- What physics can we do?
- What are the challenges for the machine?
- What are the challenges for the detectors?

Luminosity upgrades of the LHC



L. Rossi

Reaching for design energy and luminosity

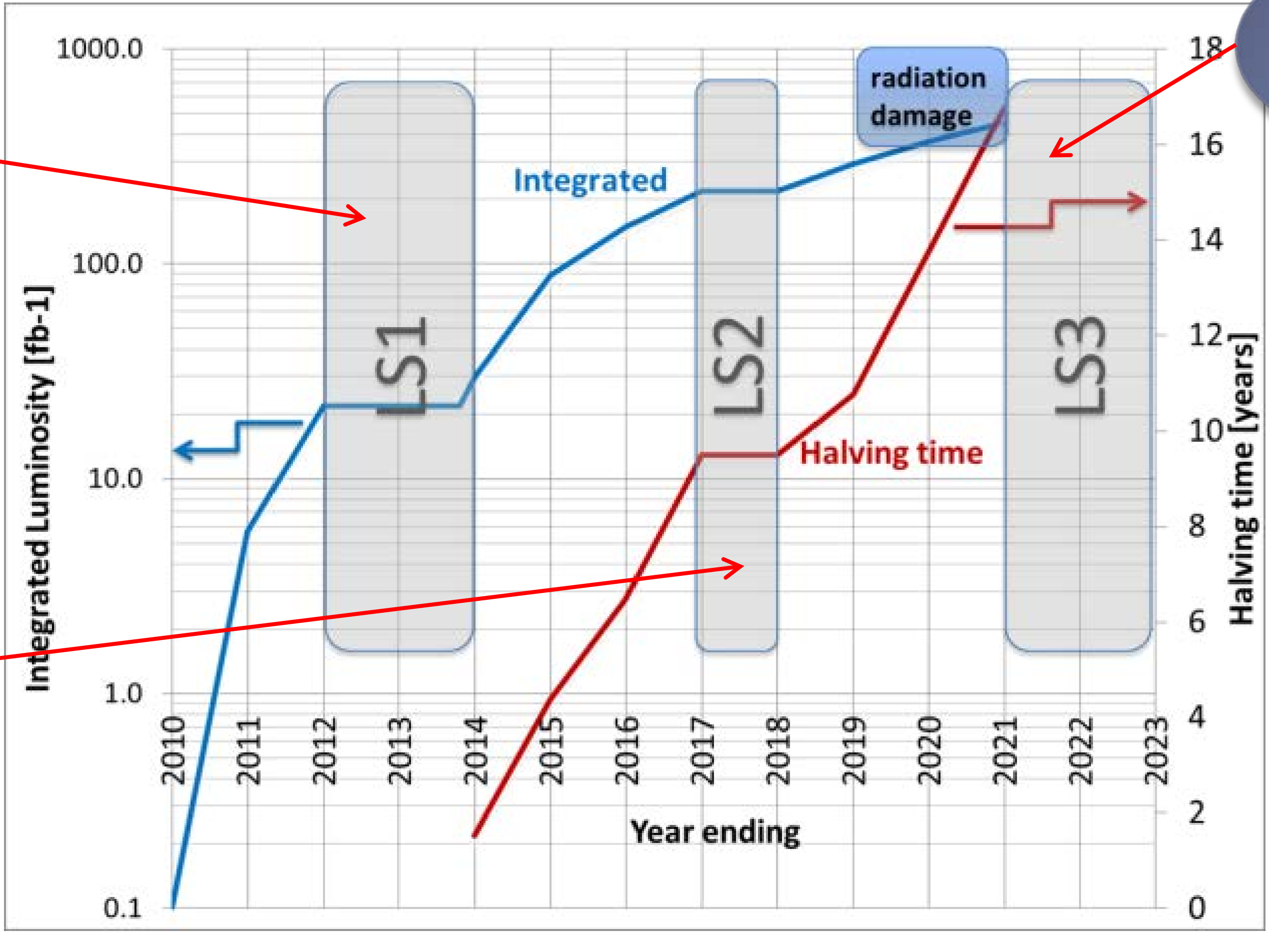
The ultimate luminosity of the LHC (about a factor of two in peak lumi)

High Luminosity Running of the LHC. Substantial changes to machine and experiments

The Shutdowns -

LS1: Shut down to fix interconnects and overcome energy limitation (LHC incident of Sept 2008)

LS2: Shut down to overcome beam intensity limitation



Full upgrade

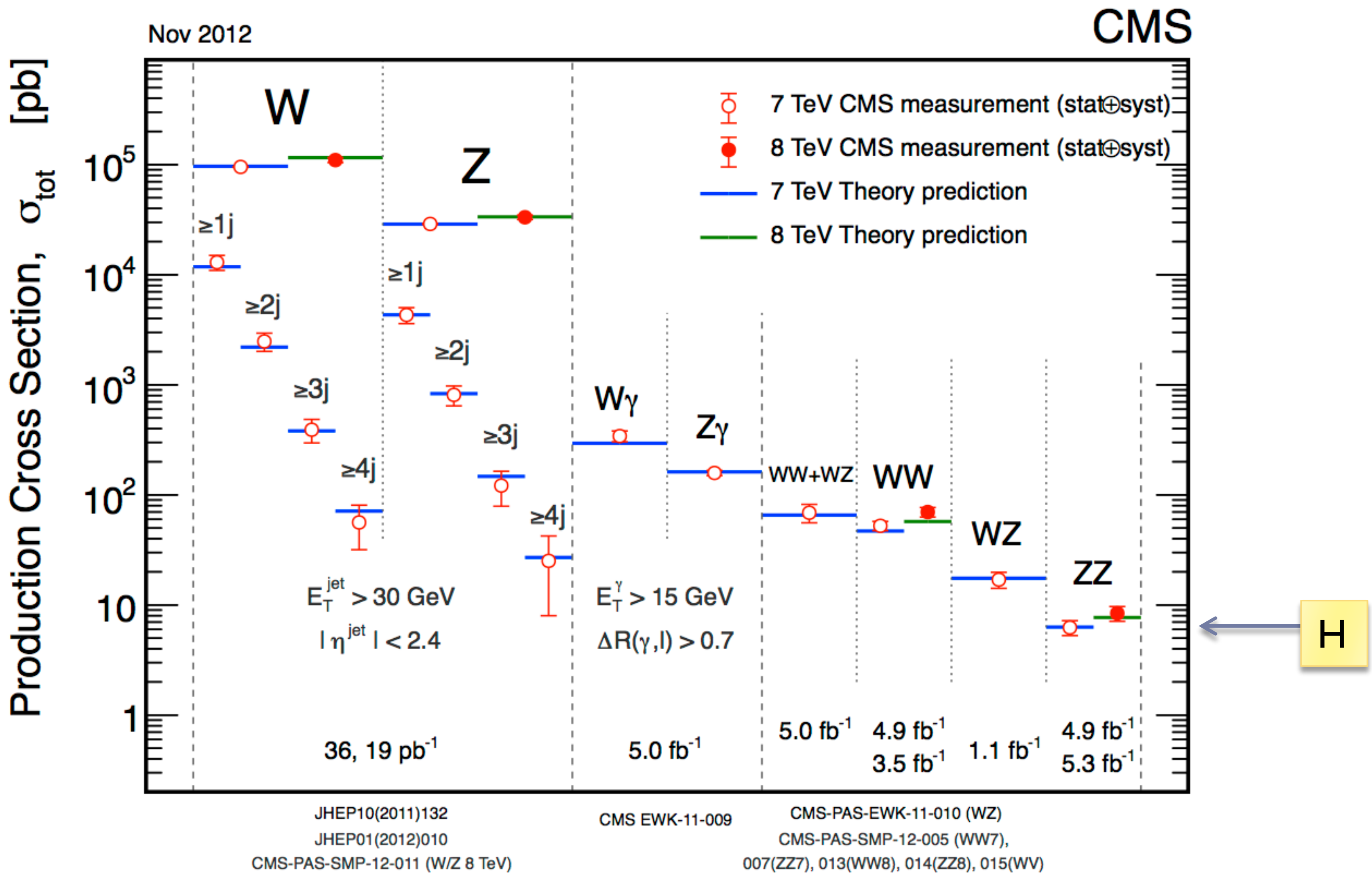
Look carefully at the time it takes to reduce statistical errors by a factor of 2 (halving time)

Physics Programme at the HL-LHC

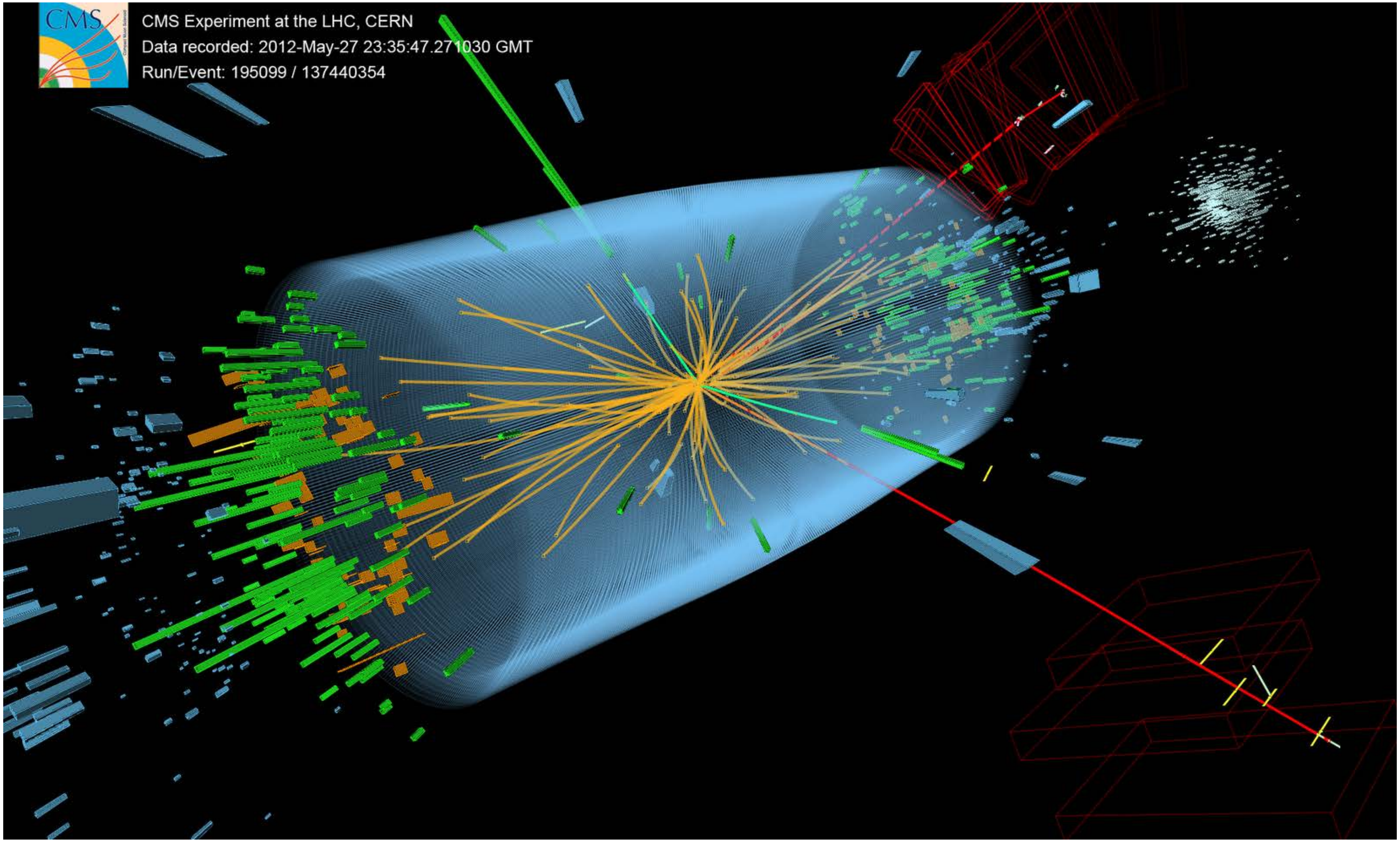
- Higgs Boson Physics
  - *Parameter* studies
  - Rare decay modes
- Extending the range of searches for new physics
  - SUSY
  - Z',W',…
- Exploring the spectroscopy of any new discoveries
  - This could potentially be one of the most exciting pieces of work for this upgrade

Standard Model Measurements

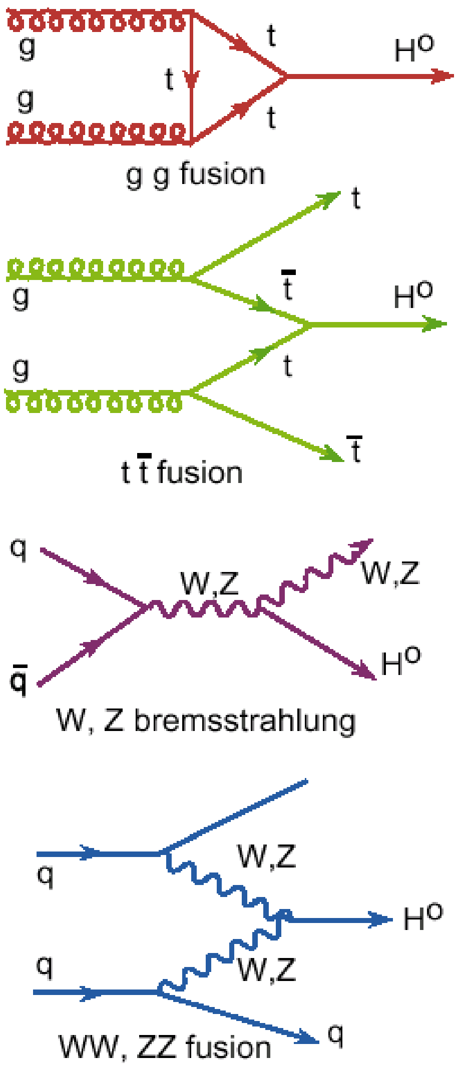
SM processes need to be understood extremely well to extract signals from the LHC

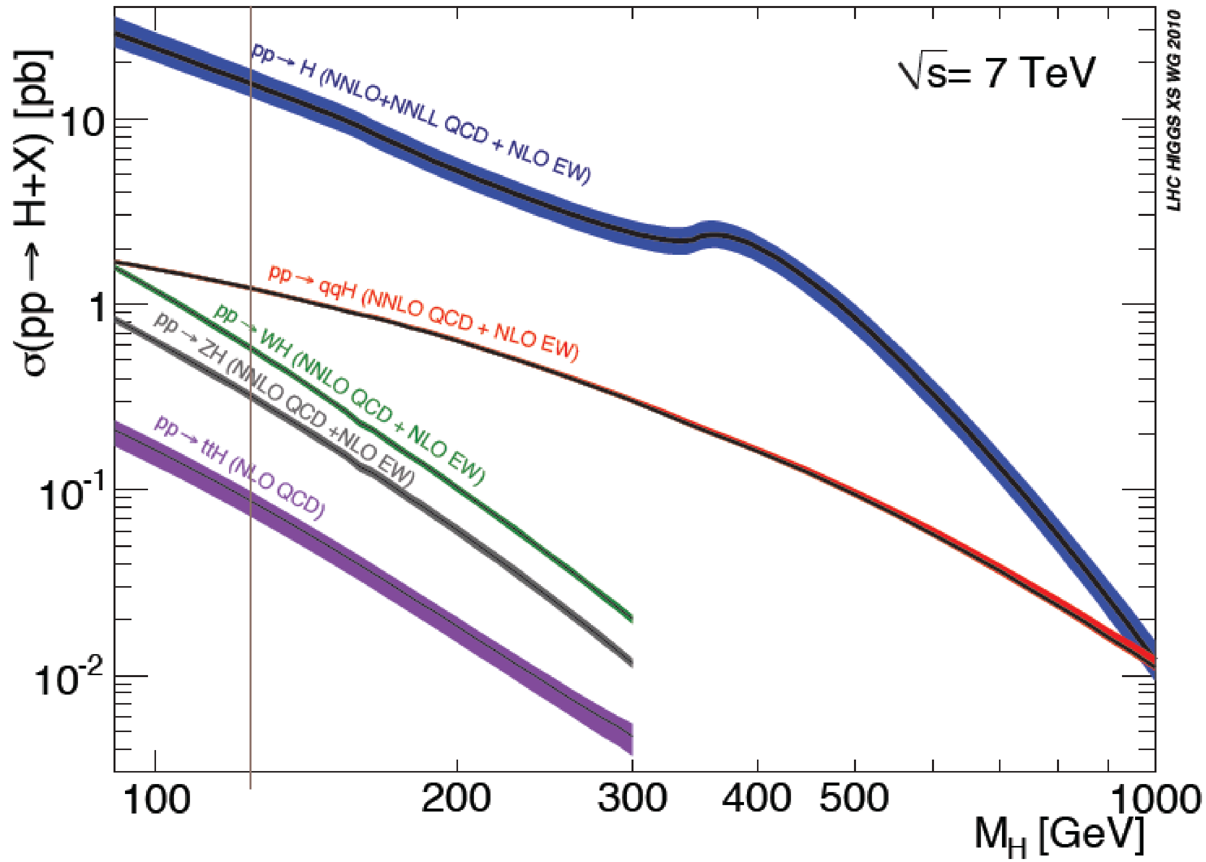


Search for the SM Higgs Boson



SM Higgs Boson: Production Cross-section





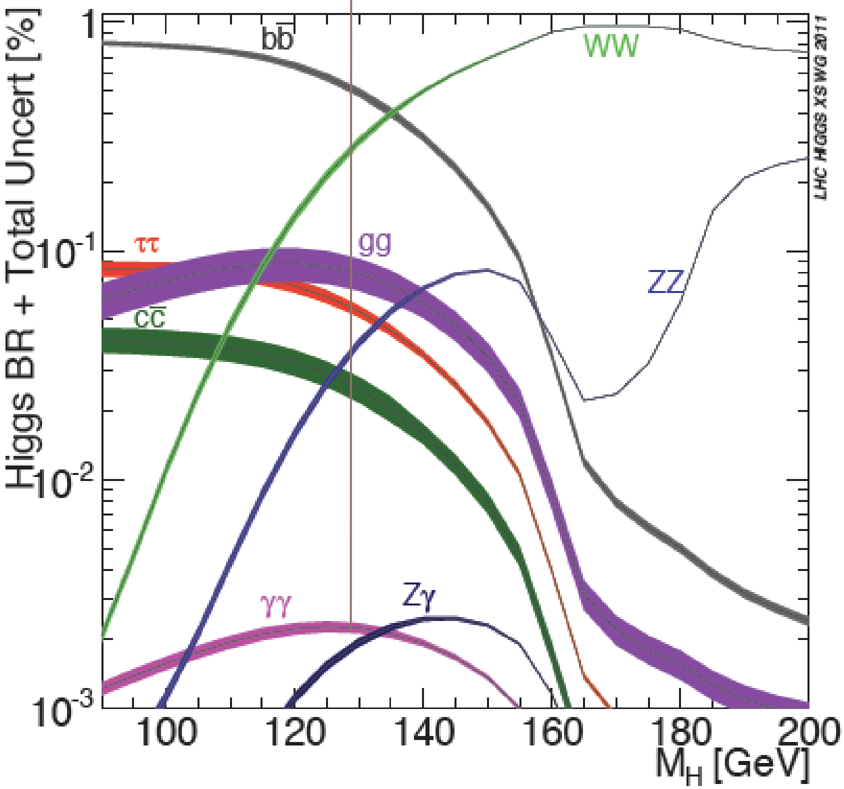
Integrated Luminosity
~5 fb^{-1} at $\sqrt{s}$=7TeV and ~ 21 fb^{-1} at $\sqrt{s}$=8TeV
potentially produced
~500k SM Higgs bosons (m_H=125 GeV)

SM Higgs Boson: Decay Modes

- Natural Width: Γ_H ~ few MeV
- The best instrumental mass resolution achievable is ~1GeV
- High Resolution Channels

$$H \rightarrow ZZ \rightarrow 4l,\ H \rightarrow \gamma\gamma$$

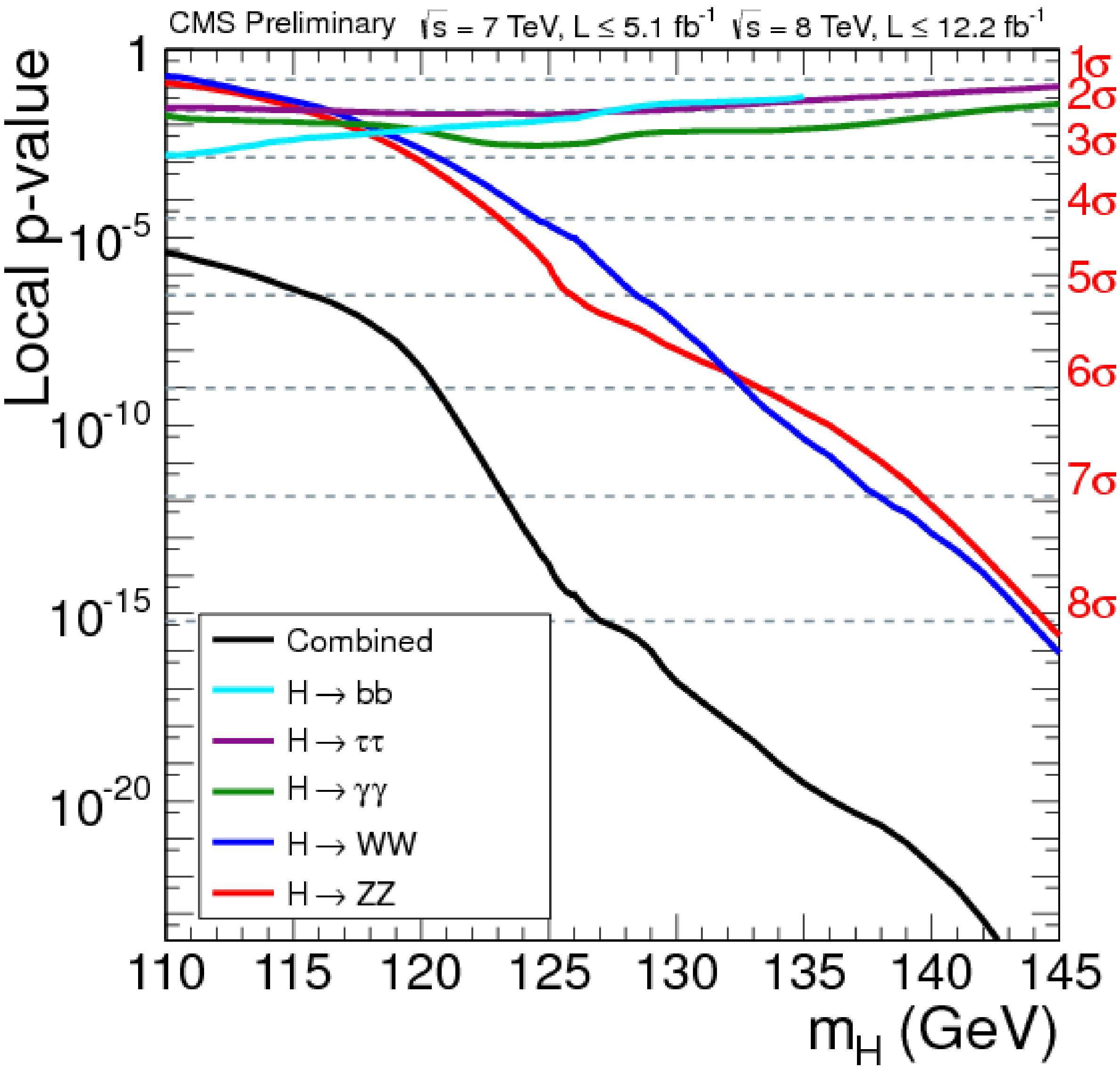
decay branching fraction



At m_H ~125 GeV many decay modes are detectable
Makes it easier to establish whether it is a SM Higgs boson or not

Higgs Search – The main channels

Channel	m_H range [GeV/c^2]	data set [fb^{-1}]	Data used CMS [fb^{-1}]	m_H resolution
1) $H \rightarrow \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \rightarrow$ tau tau	110-145	5+12/fb	2011+12	15%
3) $H \rightarrow bb$	110-135	5+12/fb	2011+12	10%
4) $H \rightarrow WW \rightarrow l\nu l\nu$	110-600	5+12/fb	2011+12	20%
5) $H \rightarrow ZZ \rightarrow 4l$	110-1000	5+12/fb	2011+12	1-2%



Expected Sensitivity

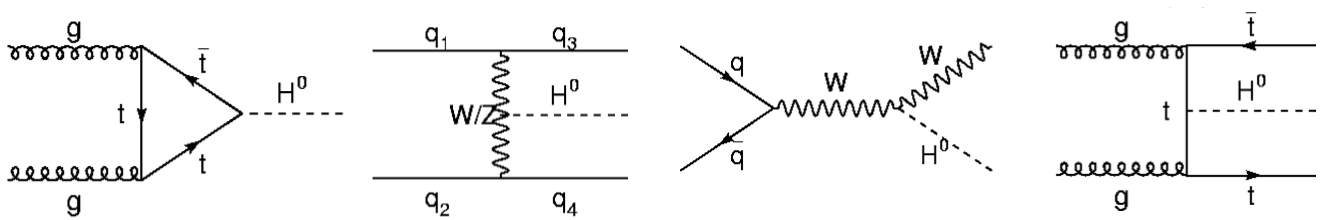
ZZ is the most sensitive channel (with excellent mass resolution)

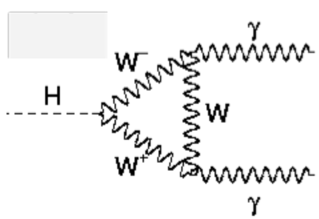
WW also has high sensitivity (although poor mass resolution)

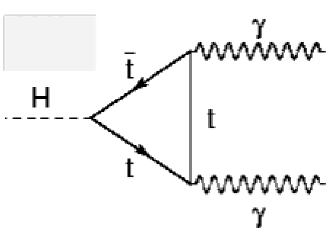
Gamma gamma should have reasonable sensitivity (with excellent mass resolution)

Measuring the Boson's properties at high Luminosity

- Properties of the signal inferred from the combination of the information provided by the Boson decay analyses
- Current CMS Input



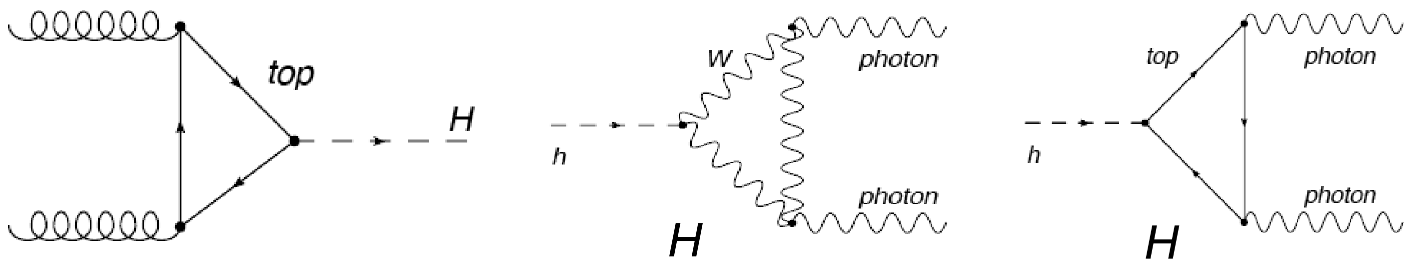




	Untagged	VBF-tag	VH-tag	ttH-tag
H→γγ	✔	✔		
H→bb			✔	✔
H→ττ	✔	✔	✔	
H→WW	✔	✔	✔	
H→ZZ	✔			

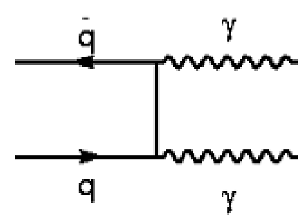
Search for the SM Higgs in the $\gamma\gamma$ channel

Signal:

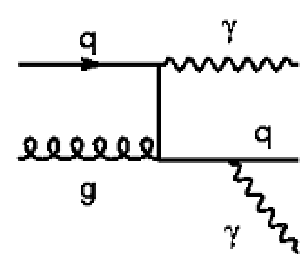


Background: essentially from QCD processes

Irreducible: QCD processes

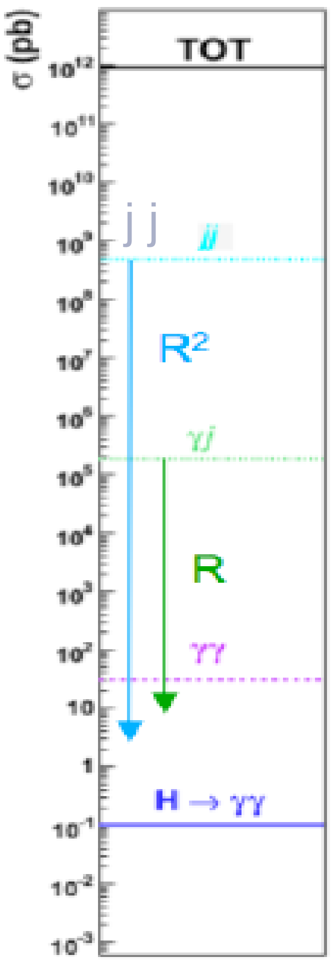


Reducible: Compton (gq→γq, q(jet)→γ)

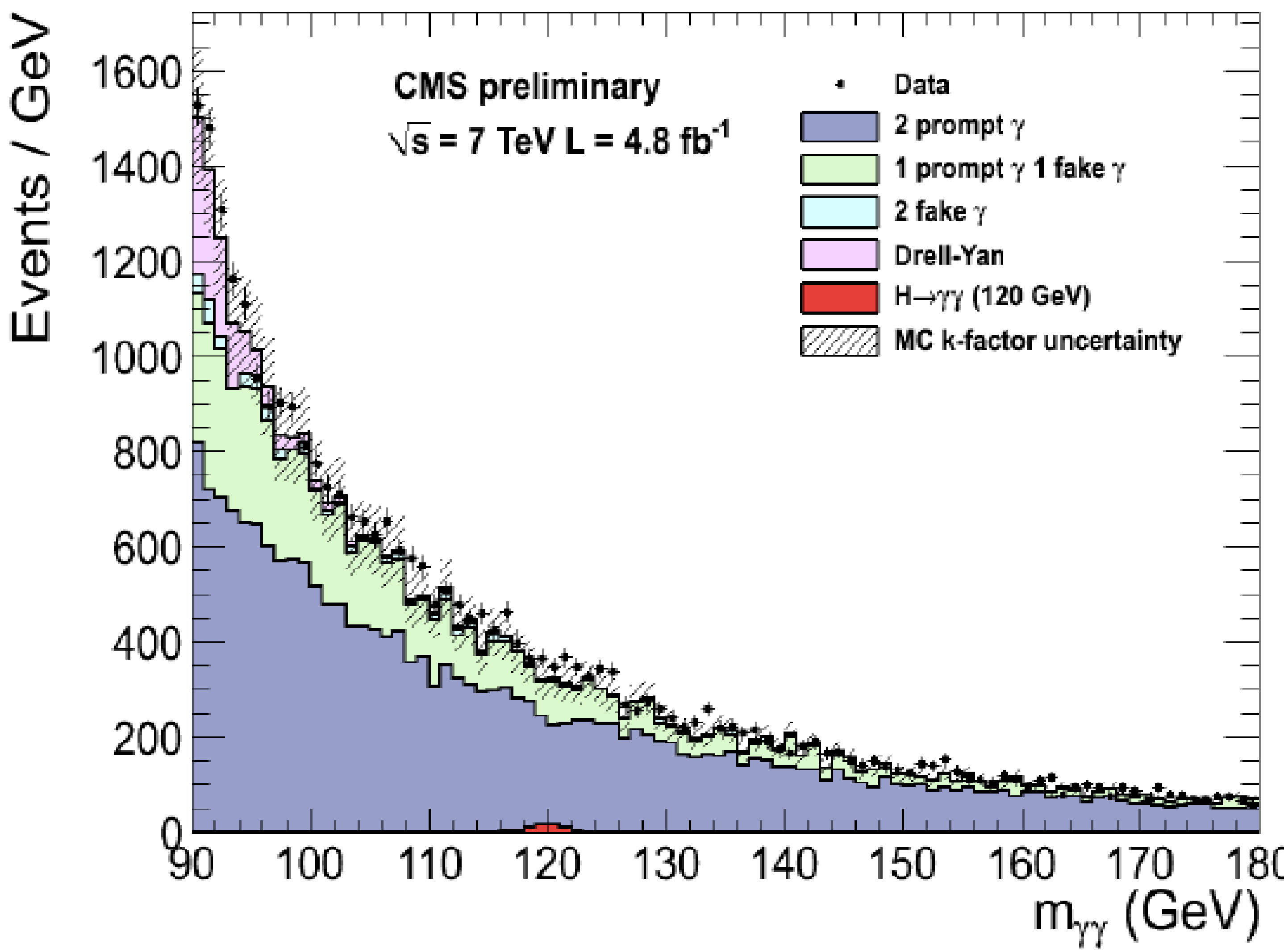


CMS PAS HIG-12-015

Search in γγ channel: Reducing Background



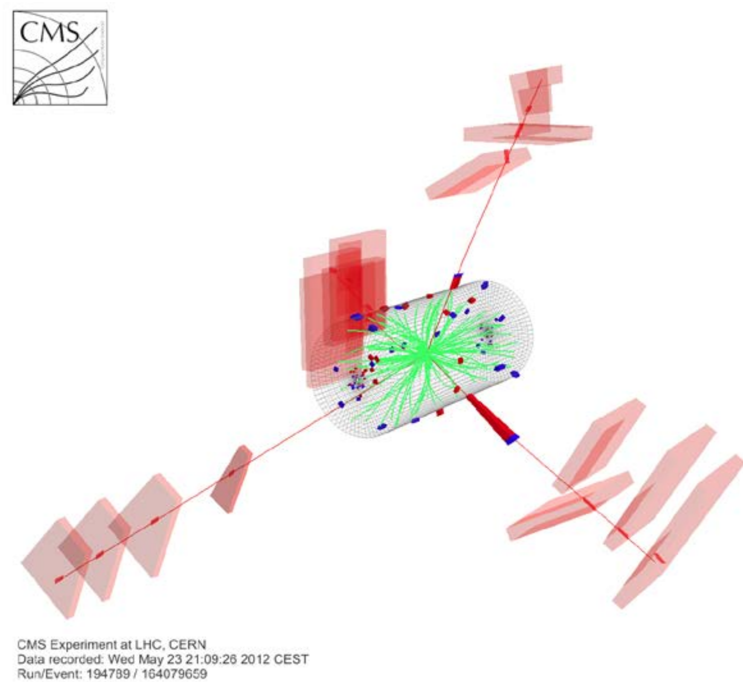
R ~ O(8000)



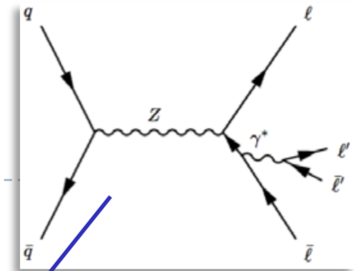
Higgs to ZZ search

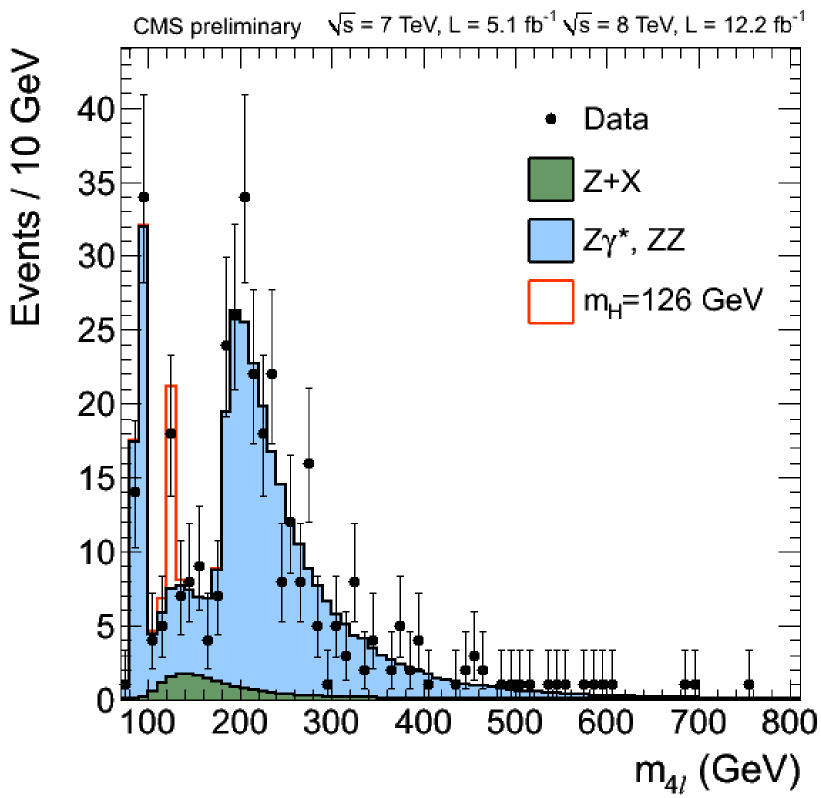
- Look for 4 leptons
  - Relatively high P_T.
    - P_T μ >5 GeV
    - P_T e > 7 GeV
  - From the same vertex
  - Isolated
  - Opposite sign pairs consistent with Z
- Excellent Mass resolution
- Low Backgrounds
  - Flat in interesting range
  - Irreducible ZZ modeled with theory
  - Reducible Z+X, Zbb, top from data

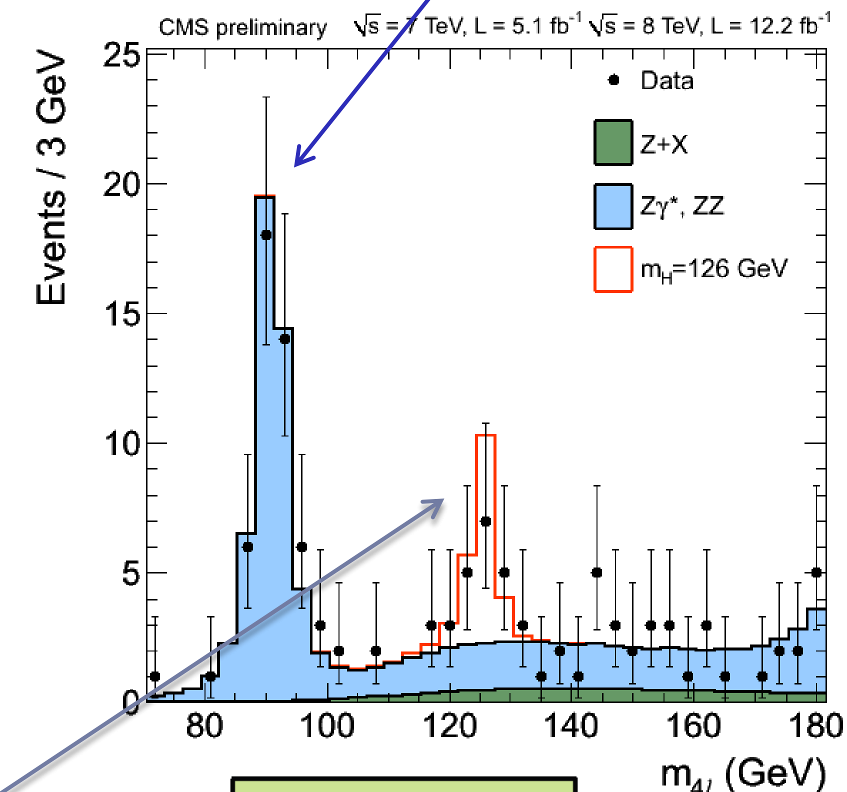
CMS PAS HIG-12-041



Signal in the 4 lepton mass







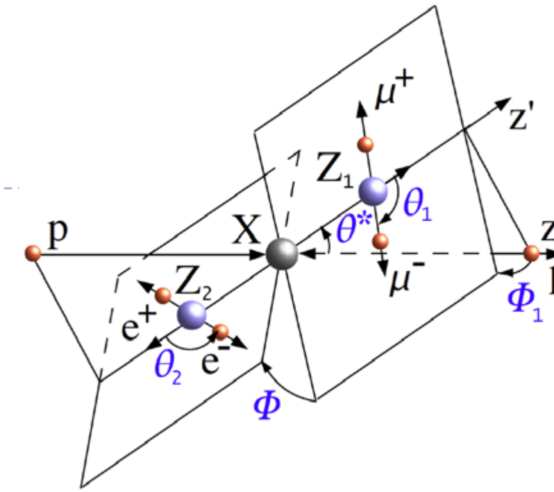
The signal is still there !
But still only a handful of events

$121.5 < m_{4l} < 130.5$ GeV

	Exp. Bkg.	$m_H = 126$	Data
4e	1.25	2.20	3
4μ	2.09	4.26	6
2e2μ	3.14	5.97	8
Total	6.48	12.43	17

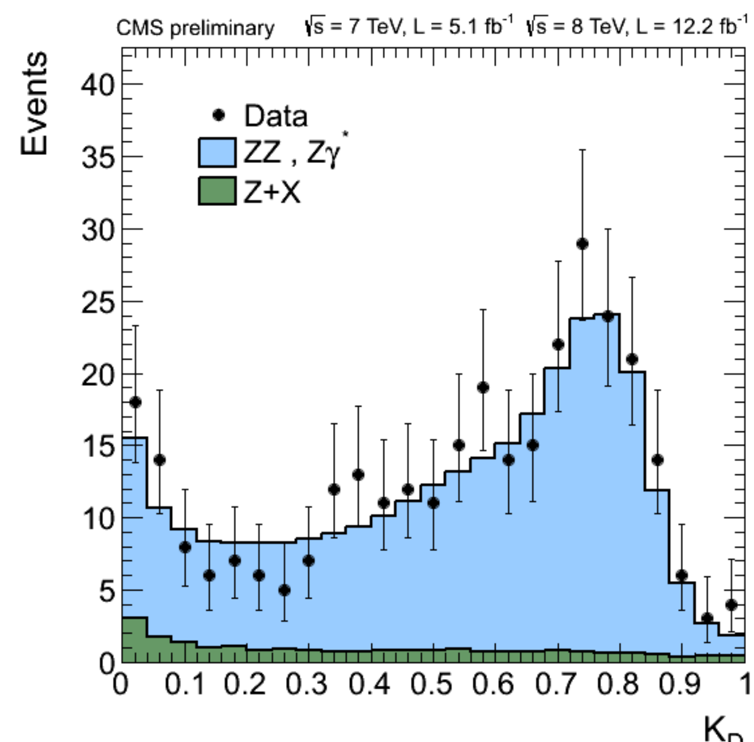
Kinematic Discriminants

- Build a kinematic discriminant from the decay angles of the leptons
- Validated with independent implementations of the kinematic discriminants either using directly the matrix element or using the Boosted Decision Trees (BDT) multivariate classification technique trained with the MC samples, and similar performance was observed.



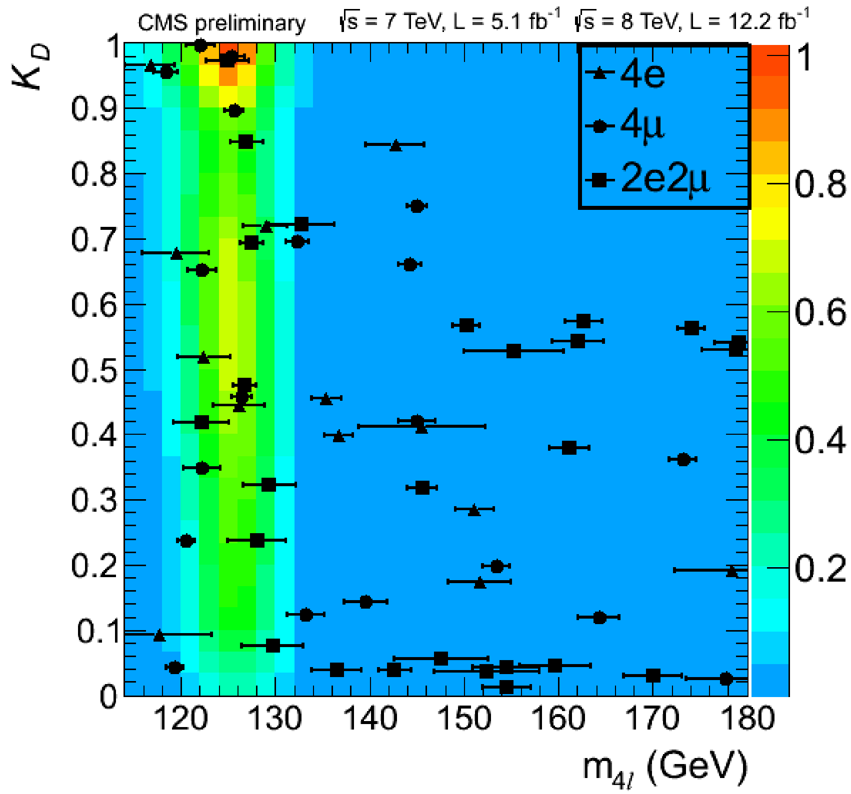
$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

$$\vec{\Omega} = \{\theta^*, \Phi_1, \theta_1, \theta_2, \Phi\}$$

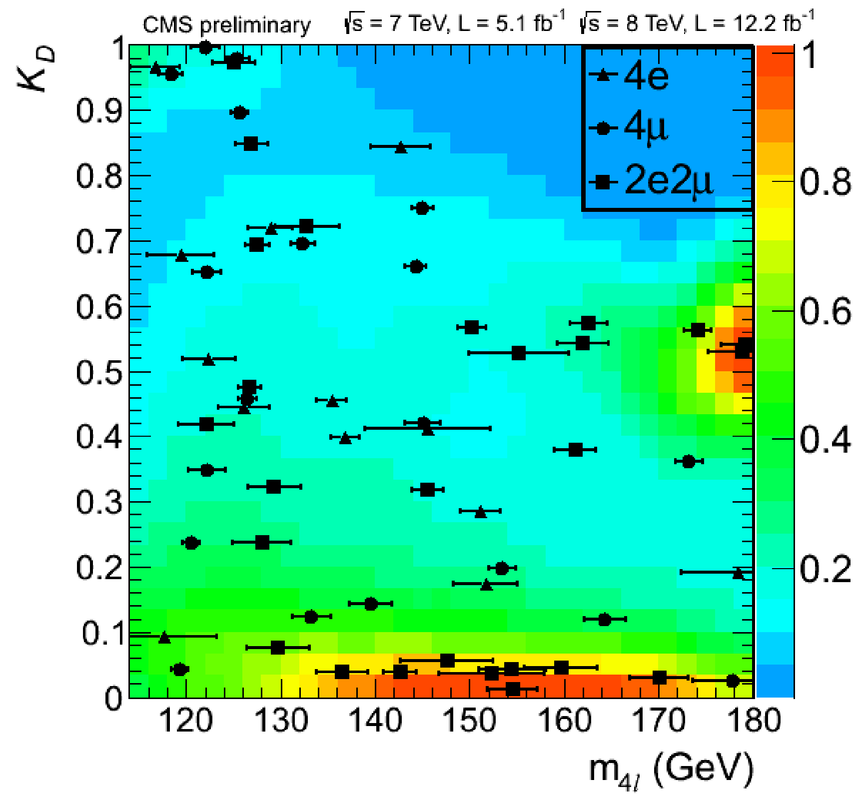


Signal and Background compared to the kinematic discriminant

Higgs Signal



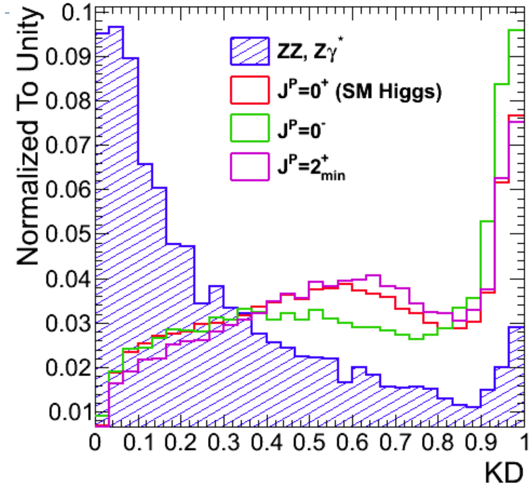
Background

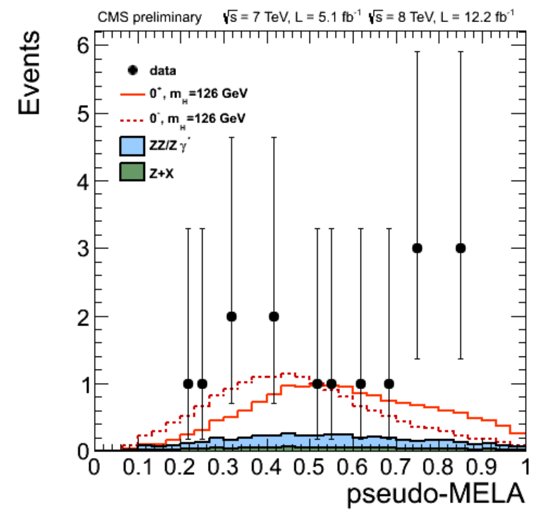


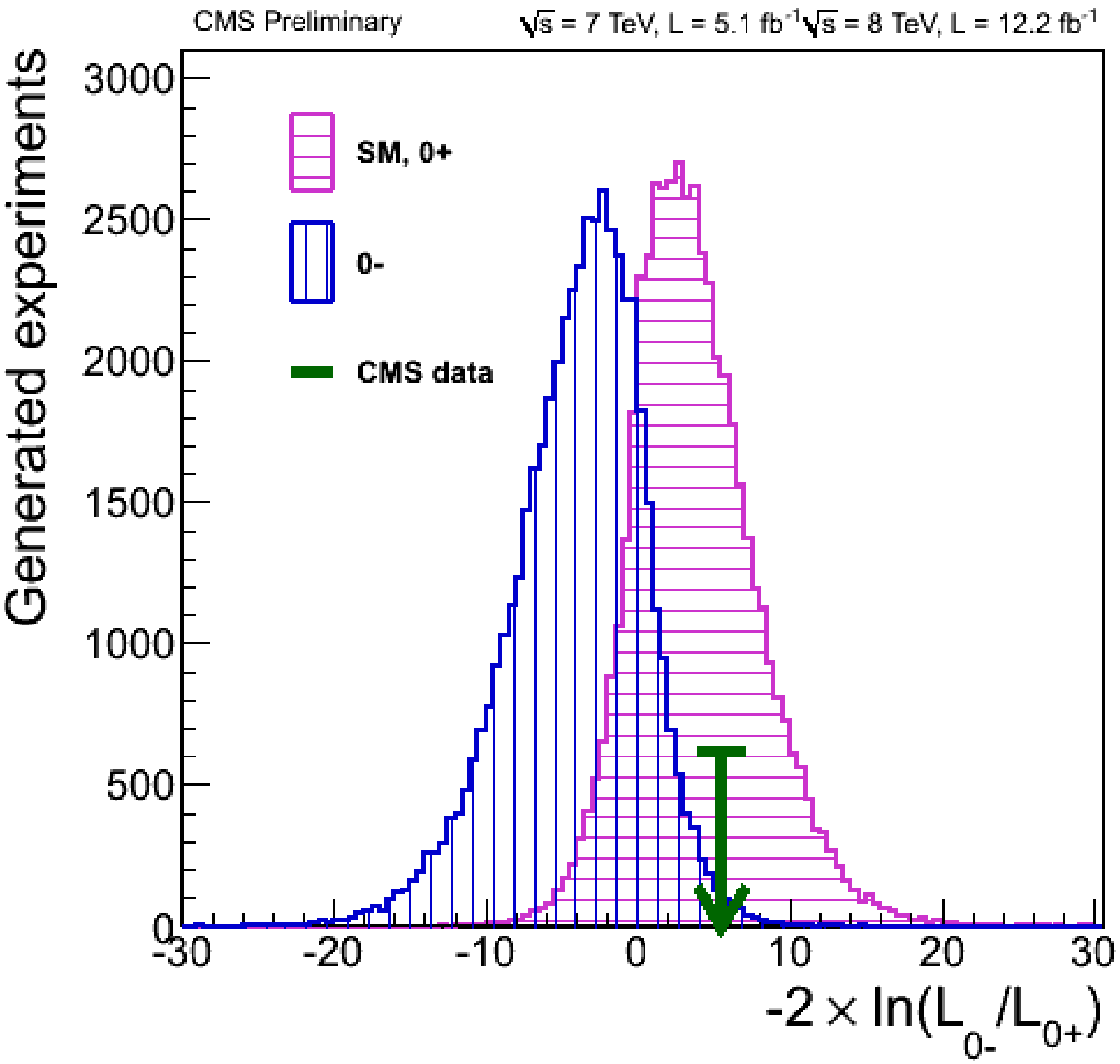
Extracting properties -

- Build a discriminator to compare the 0^+ and 0^- hypothesis
- Calculate the likelihood that the data is compatible with each hypothesis
- Use toy monte-carlo to see how consistent a given likelihood ratio is for each hypothesis

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$







0+ vs. 0-

Expected separation: 1.93 σ

Observed:

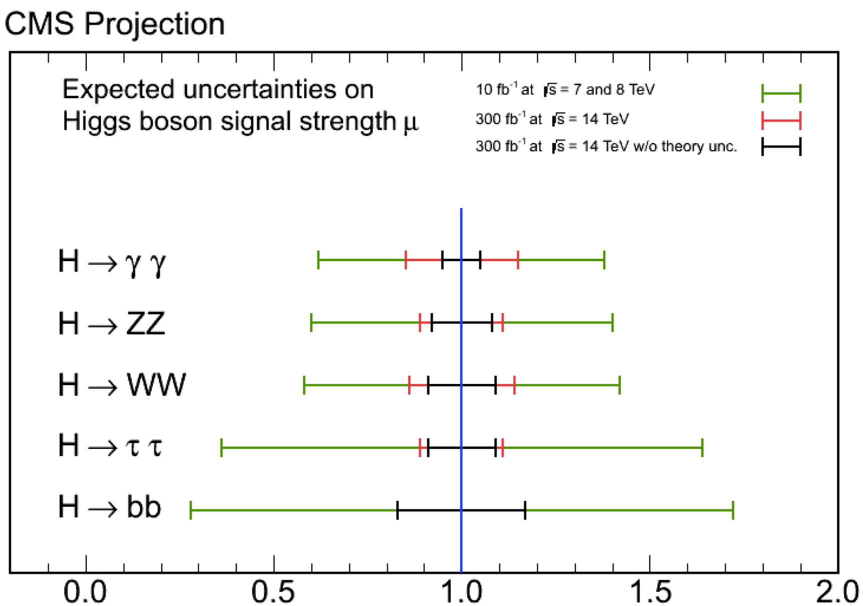
0-. - - is consistent with observation within 2.45 σ

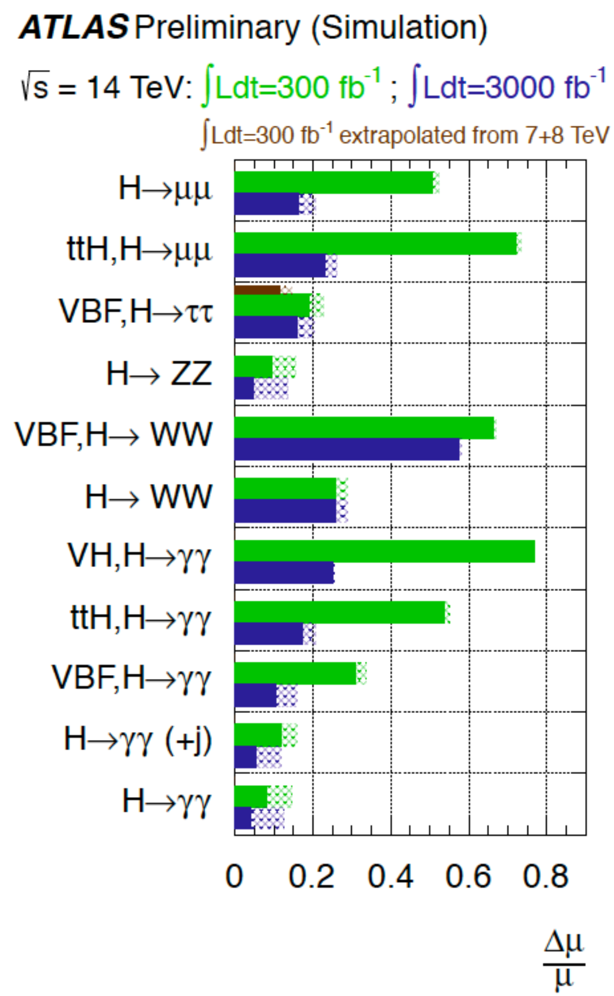
0+ -. - - is within 0.53 σ

Benchmarks: How well can we measure the properties of this Boson?

- Some General assumptions in these estimates
  - The systematic errors will scale with (Luminosity)^(-1/2)
    - A challenge to the experimentalists
    - Many of the systematic uncertainties are "data driven" and should improve with more data collected
  - The theoretical errors will reduce by a factor of 2
    - A challenge to the theorists
  - The statistical errors on the measurements will decrease
    - A challenge to the machine
    - A challenge to the experimentalists (high pile up)

First guesses at how well properties can be measured with high luminosity

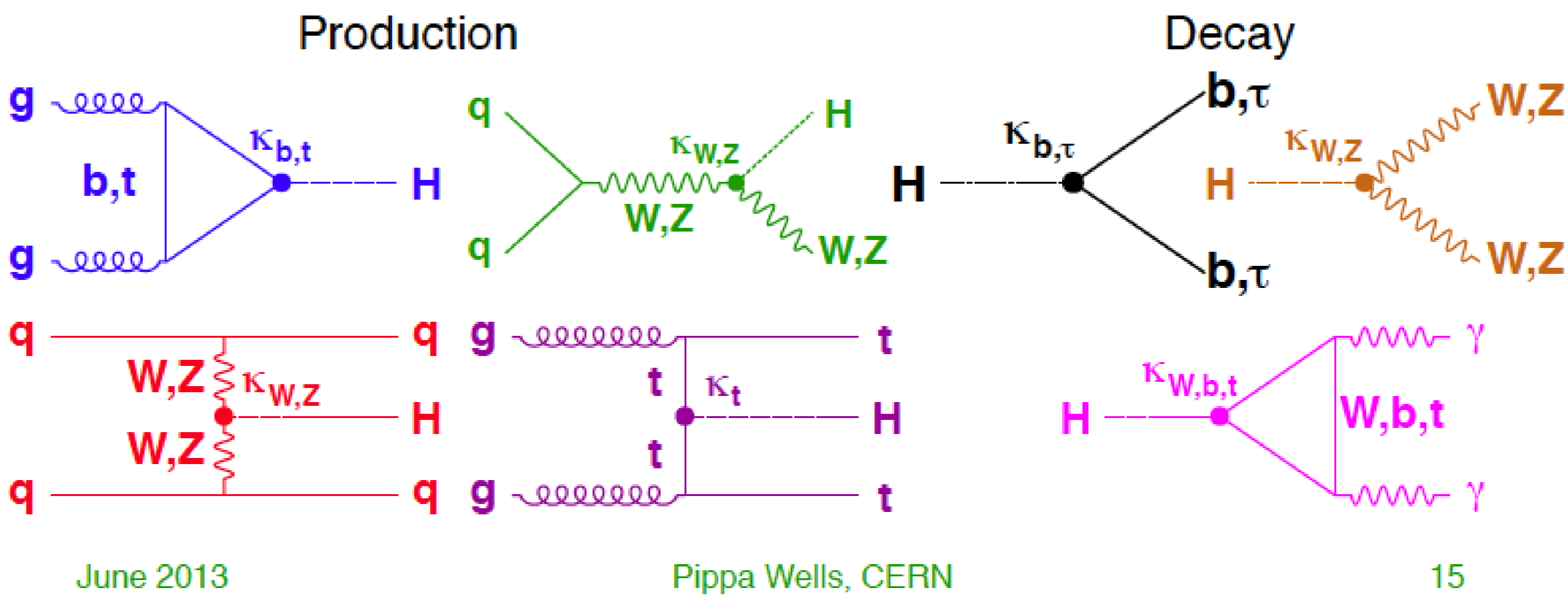




Some Caveats:

- These are preliminary studies
- Assumptions about scaling …

If we assume the SM, how well can we constrain it?



A general set of Coupling scale factors

http://arxiv.org/abs/1209.0040v1

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} \quad : \quad \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

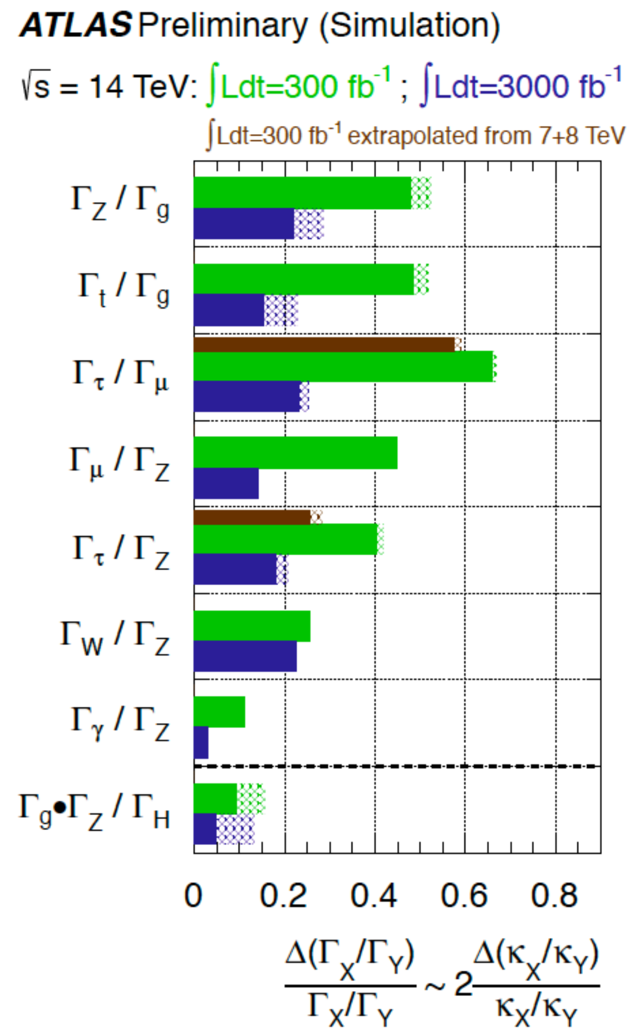
$$(\sigma \bullet BR)(X \to H \to ff) = \frac{\sigma_X \bullet \Gamma_{ff}}{\Gamma_{tot}}$$

$$\Gamma_{Total} = \sum \Gamma_{SM} + \Gamma_{BSM}$$

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

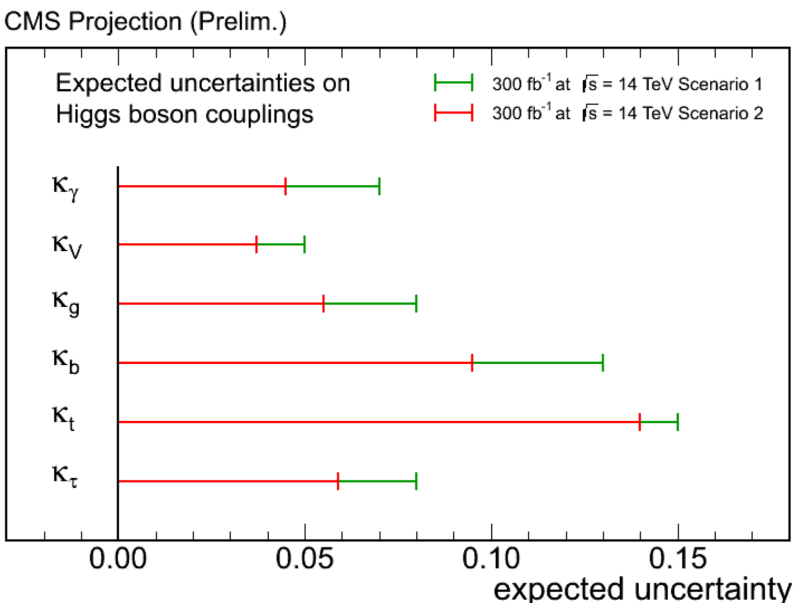
Measuring the couplings

- There will be a lot of Higgs Boson events to study at the HL-LHC
- Not trivial to extrapolate the experimental performance
  - History has shown the experimentalists manage to reduce systematic errors with increasing luminosity
  - Many of the systematic errors are determined by using data distributions.



CMS projections for Higgs property measurements

300/fb



Scenario 1:

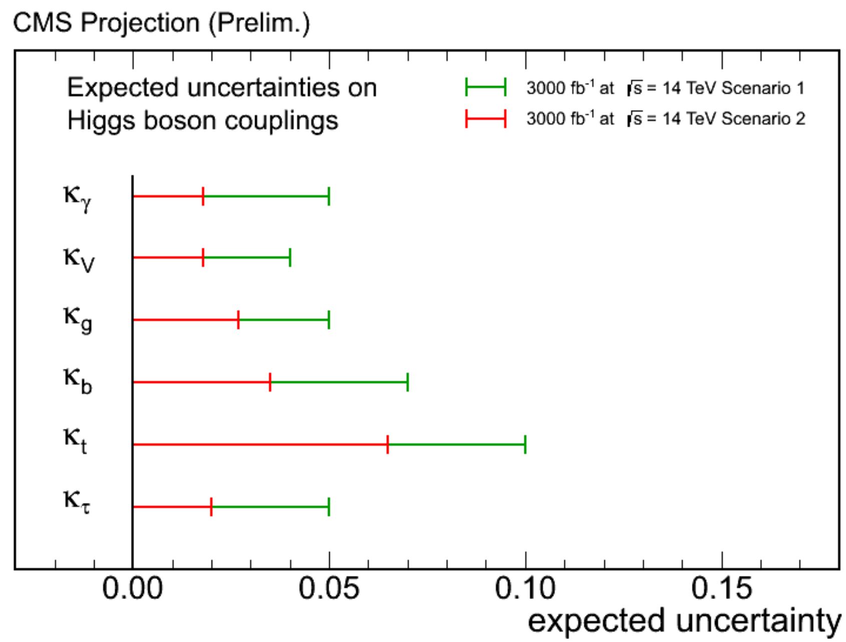
- 2012 systematics

Scenario 2:

- theory syst: scaled by a factor ½
- other systematics scaled by 1/√L

3000/fb

Theoretical errors very important!



Estimate how well the couplings can be measured with 3000/fb

CMS

Numbers in brackets are % uncertainties on coupling deviations for [scenario 2, scenario 1]

L (fb^{-1})	κ_γ	κ_V	κ_g	κ_b	κ_t	κ_τ
300	[5, 7]	[4, 5]	[6, 8]	[10, 13]	[14, 15]	[6, 8]
3000	[2, 5]	[2, 3]	[3, 5]	[4, 7]	[7, 10]	[2, 5]

Goal: ultimate precision of ~5% or better

Scenario 1:
- 2012 systematics

Scenario 2:
- theory syst: scaled by a factor ½
- other systematics scaled by 1/√L

ATLAS

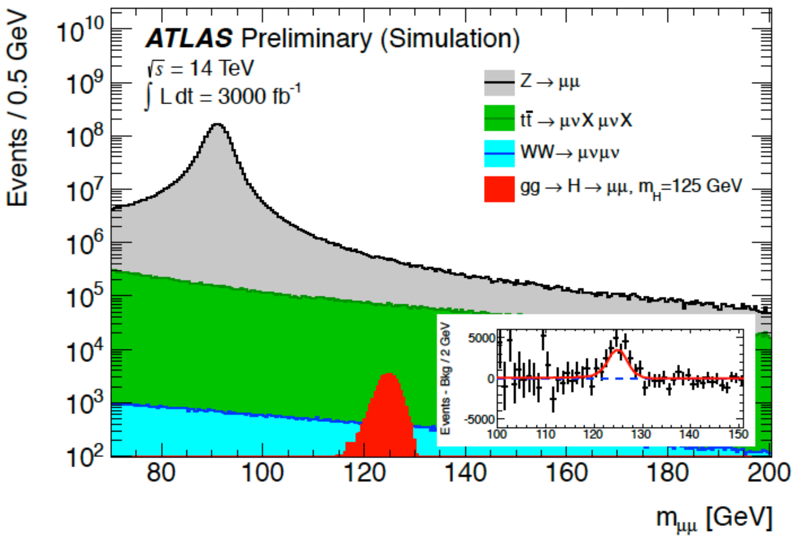
	$300\,fb^{-1}$	$3000\,fb^{-1}$
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

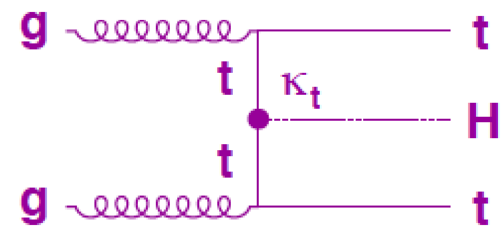
Alternatively assume universal Vector/Fermion couplings

Theoretical uncertainties

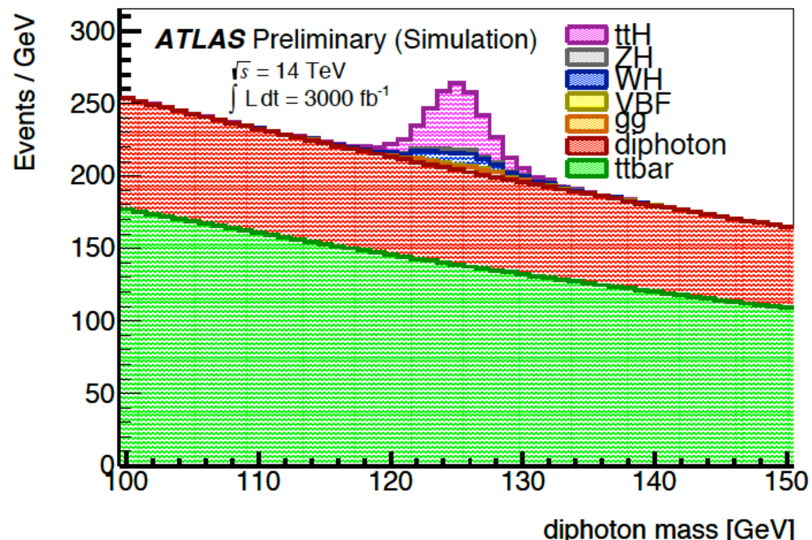
- Theoretical predictions for known and new processes are critical
  - Missing higher order (QCD) radiative corrections are estimated by varying factorisation and renormalisation scales (0.5 ~ 2.0)
  - Electroweak corrections
  - Treatment of heavy quarks
  - PDF uncertainties (which also depend on the order of calculation available)
  - m_H=125 GeV @ 14 TeV: $\sigma(pp(gg) \rightarrow H+X)$ scale $^{+9}_{-12}$%, PDF ±8.5%
- PDF uncertainties can be reduced by future precise experimental measurements at LHC, including
  - W, Z σ and differential distributions for lower x quarks
  - High mass Drell-Yan measurements for higher x quarks
  - Inclusive jets, dijets for high x quarks and gluons
  - Top pair differential distributions for medium/large x gluons
  - Single top for gluon and b-quark
  - Direct photons for small/medium x gluons

Rare Higgs decays with High Luminosity

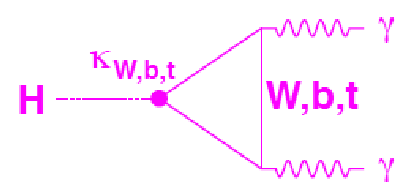




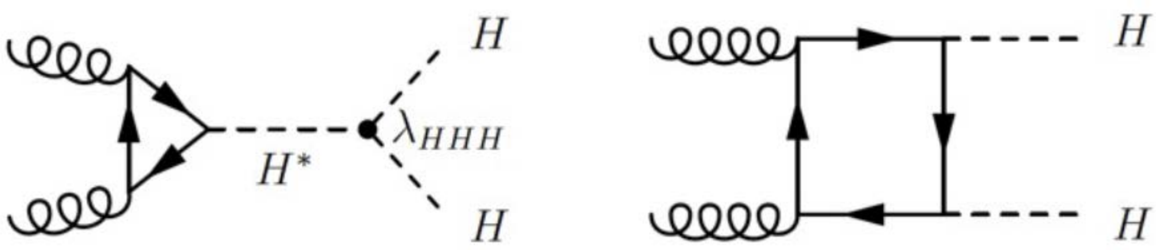
With 3000/fb ATLAS expects
H-> μμ – 6σ signal



With 3000/fb ATLAS expects
ttH:
H->μμ 30 Events
H->γγ 100 events

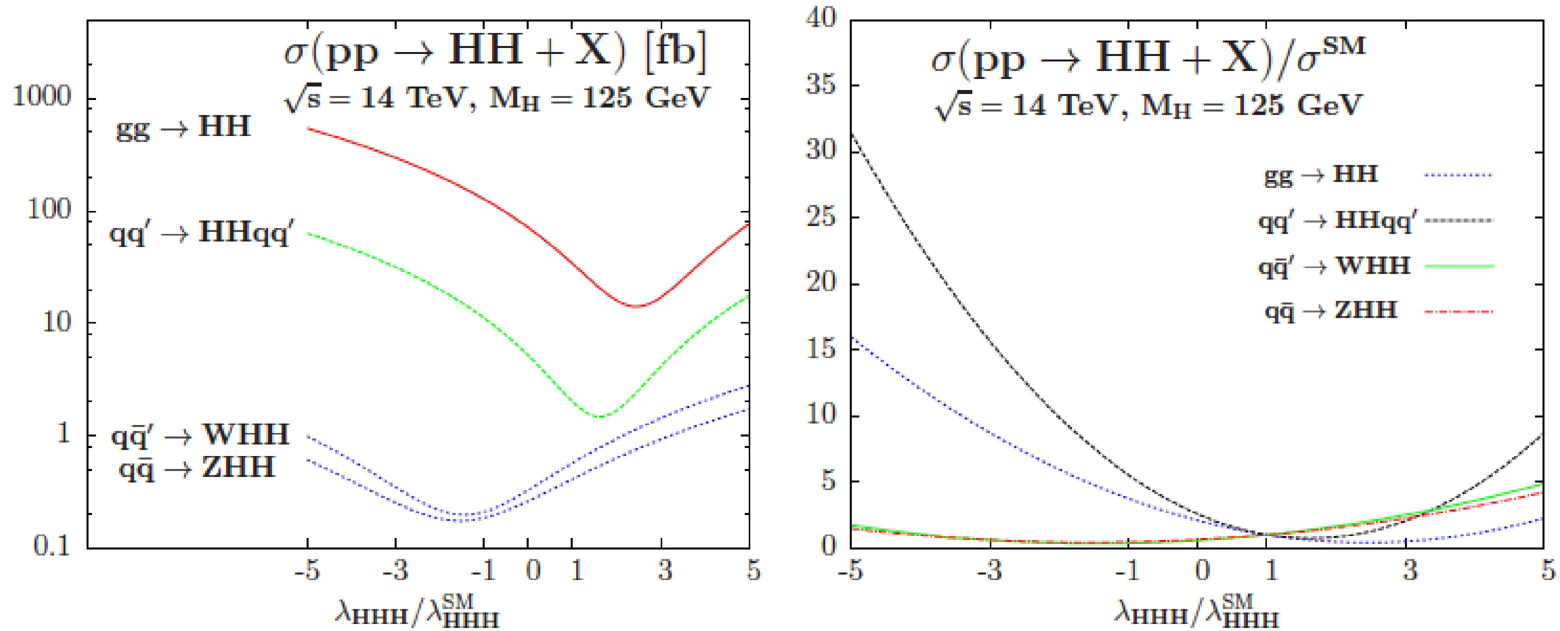


Higgs Self couplings



We hope to have access to measuring the Higgs Self coupling with 3000/fb

Cross sections are small



Higgs Self Coupling – experimental pieces

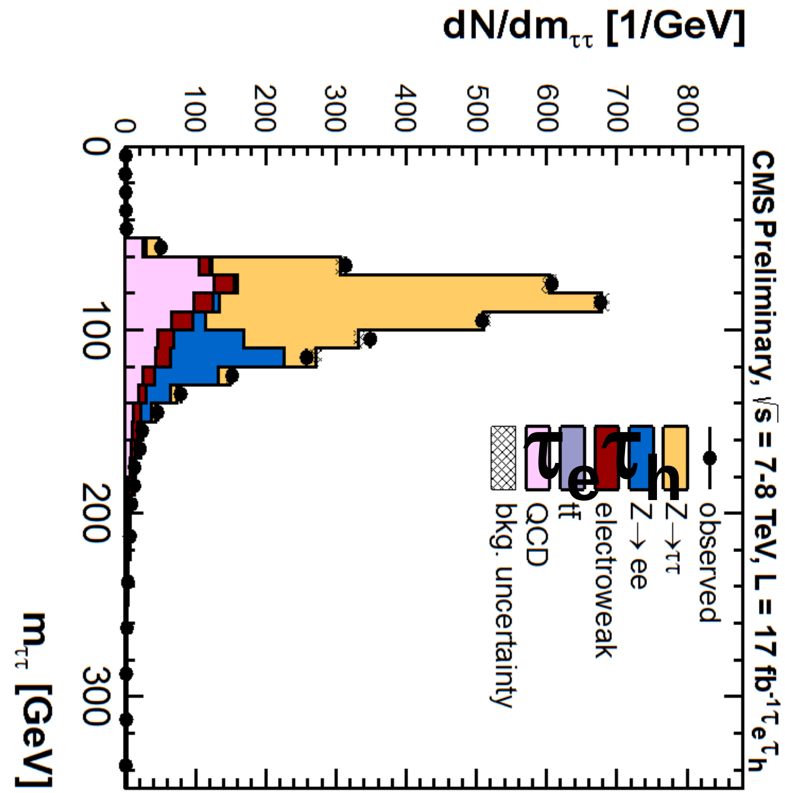
- The number of events is small
- The channels are challenging
  - HH->$bb\gamma\gamma$
  - HH->$bb\tau\tau$
- How do we do this experimentally in the challenging hadron environment?

Looking for rare signals in big background – experimental techniques

- The needle in a haystack problem tends to be solved in one of two ways these days
- “old school”
  - Think about the difference between background and data
  - Develop “cuts” which separate the two
- “New age”
  - Think about which observables are sensitive to the difference between background and data
  - Throw everything into a “Neural net” or “BDT” or “multivariate analysis” and let machine learning choose an optimal *weighting* for each event
  - This method can in principle give better sensitivity but shouldn’t be used blindly

H→ττ – background modeling

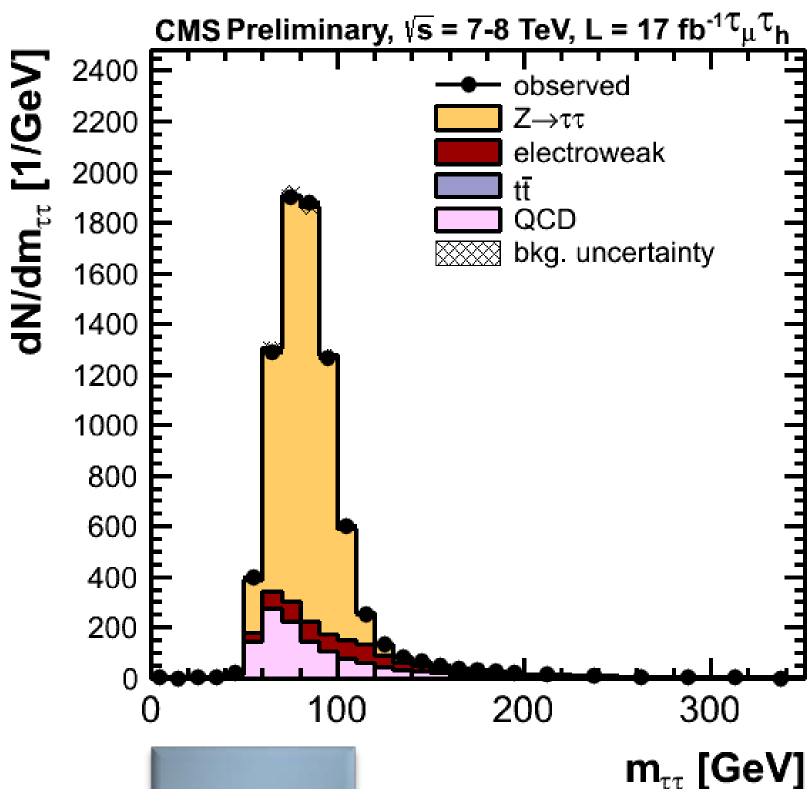
- **Z→ττ**
  - Estimated from Z→μμ with muon replaced by simulated tau decay – normalization from Z→μμ
- **QCD**
  - Shape and normalization from LS/OS or fakerate
- **Z→ee(/μμ)**
  - From simulation: POWHEG, corrected for measured rates for jets and e/(μ) to fake a τ
- **Diboson/W+jets**
  - From simulation: MADGRAPH, normalization from sideband
- **ttbar**
  - From simulation:MADGRAPH, normalization from sideband

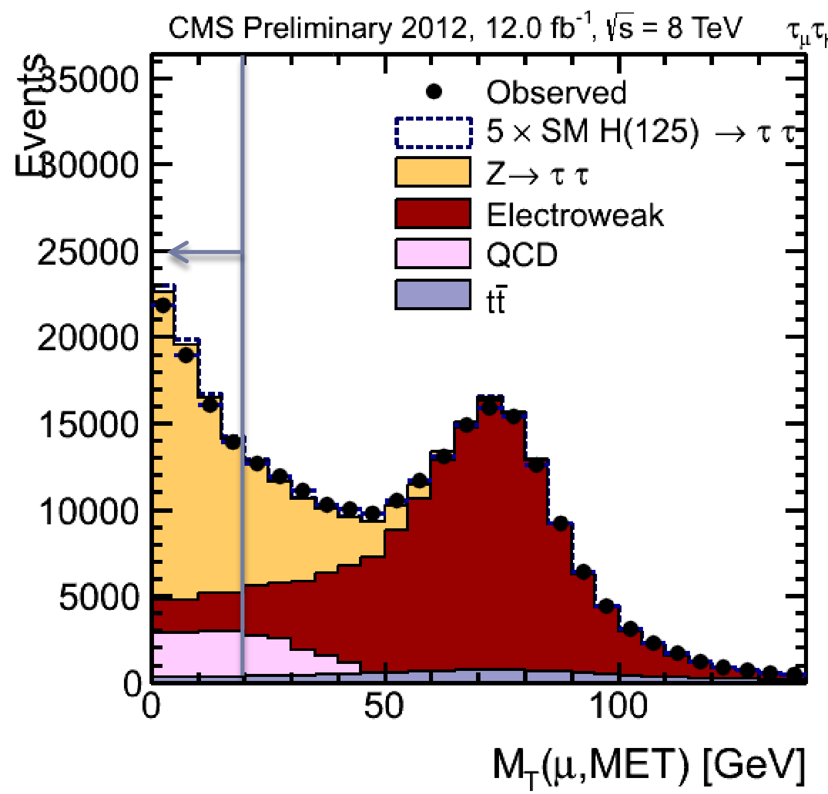


Background e.g. 0-jet category, $\tau_e\tau_h$ final state

Use M_T to reduce EW background

$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos\Delta\phi_{\ell,\nu})}$$

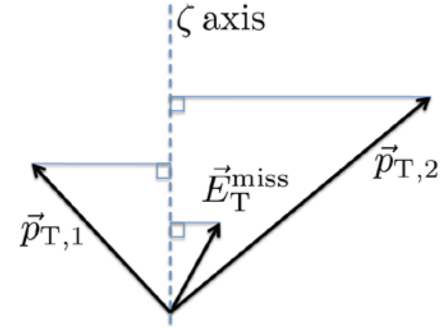


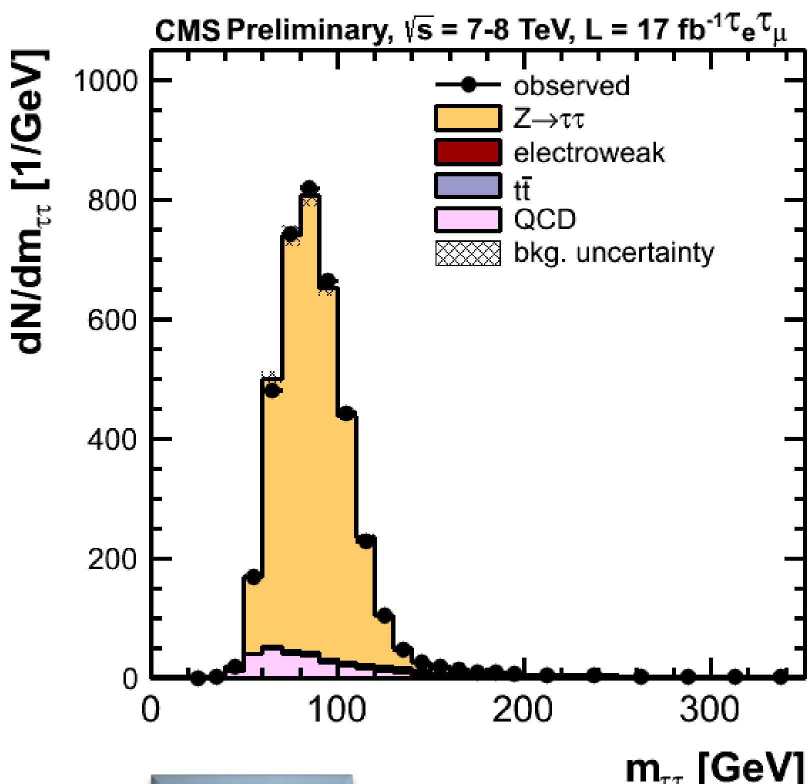


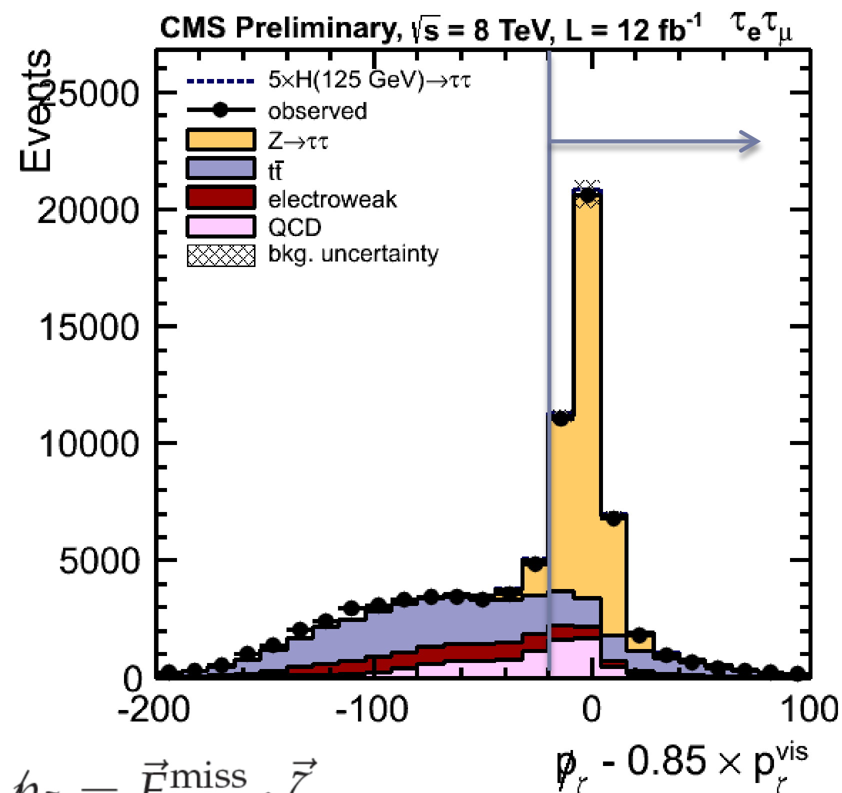
$\tau_\mu \tau_h$

Neutrinos from tau decays very different than those from W decays (collinear with leptons for Tau decays)

Suppress top and EW backgrounds







$\tau_e\tau_\mu$

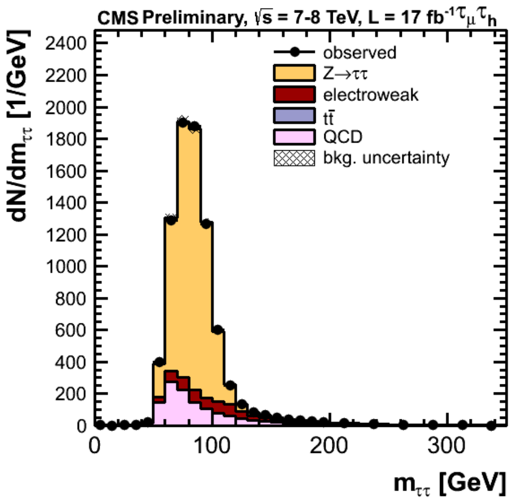
$$\not{p}_\zeta = \vec{E}_T^{miss} \cdot \vec{\zeta},$$

$$p_\zeta^{vis} = \vec{p}_{T,1} \cdot \vec{\zeta} + \vec{p}_{T,2} \cdot \vec{\zeta},$$

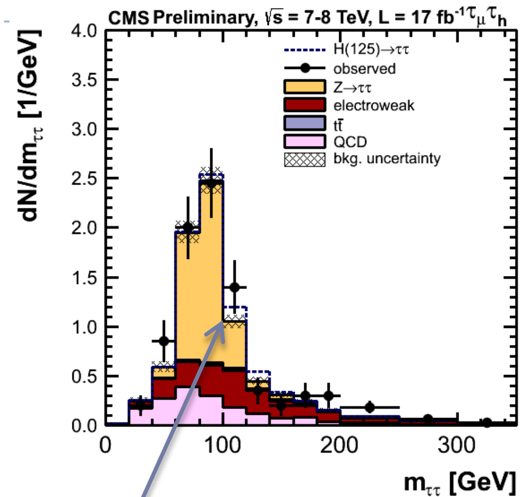
μ-h

$\tau_\mu \tau_h$

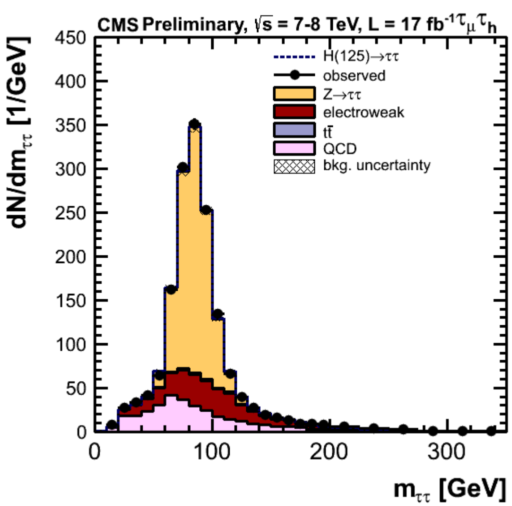
0-jet



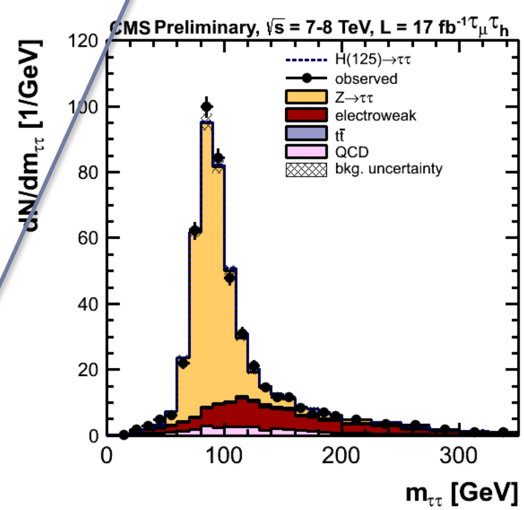
VBF



1-jet Low Pt



1-jet High Pt

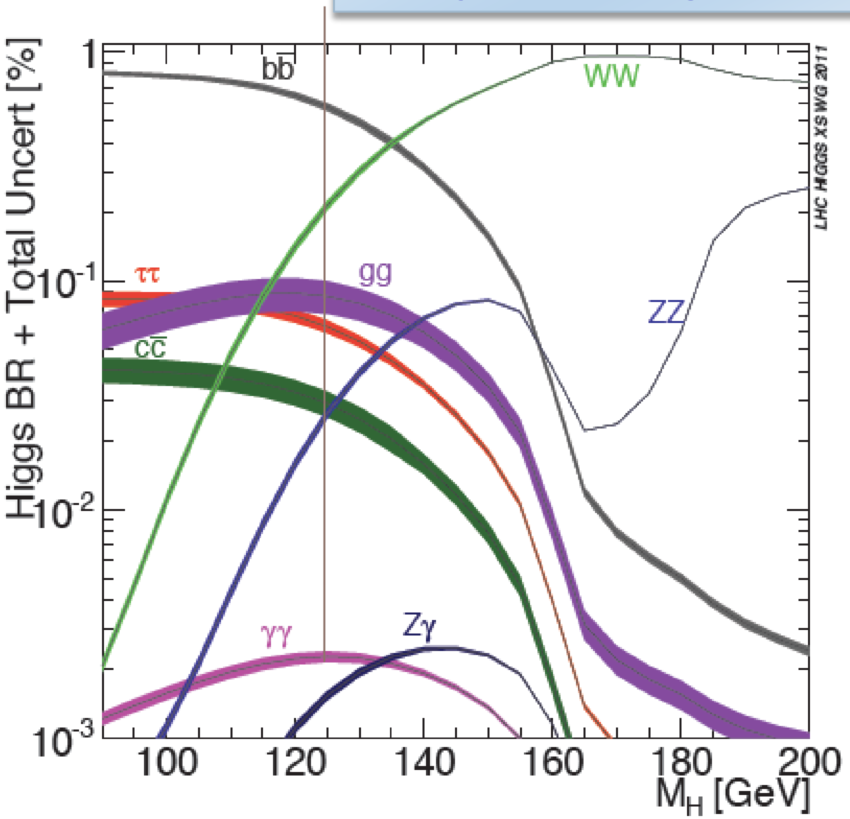


The signals are very small

H-bb

- Most of our produced Higgs particles are decaying in this mode
- Unfortunately for experimentalists, they are really quite difficult to separate from the background
- Exploit production methods with cleaner signatures to help
  - But much lower cross sections for VH
- Throw the kitchen sink method at selecting events

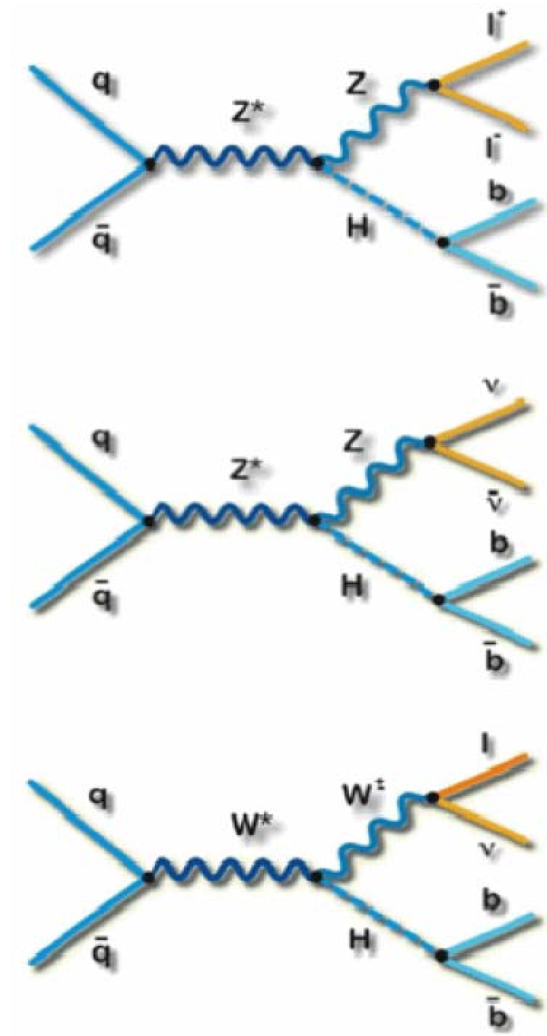
decay branching fraction



Z->bb

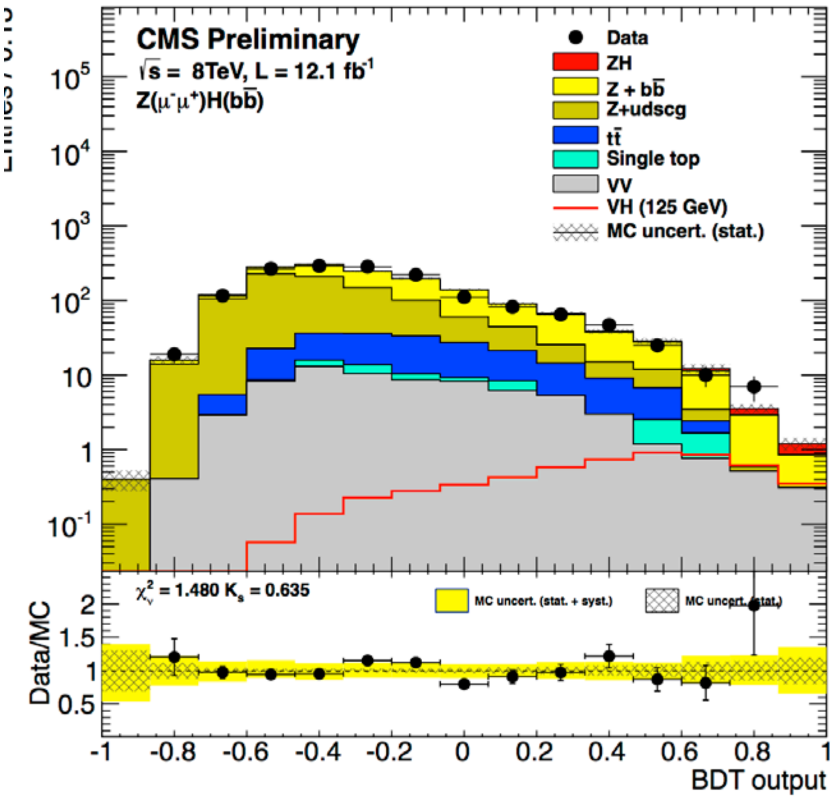
- By far, largest BR for m_H<130 GeV (~60%)
- Key piece of the observation puzzle
- Tests specific production & decay couplings
- But σ_{bb}(QCD) ~ 10^7 σxBR(H-> bb)!

CMS PAS HIG-12-044

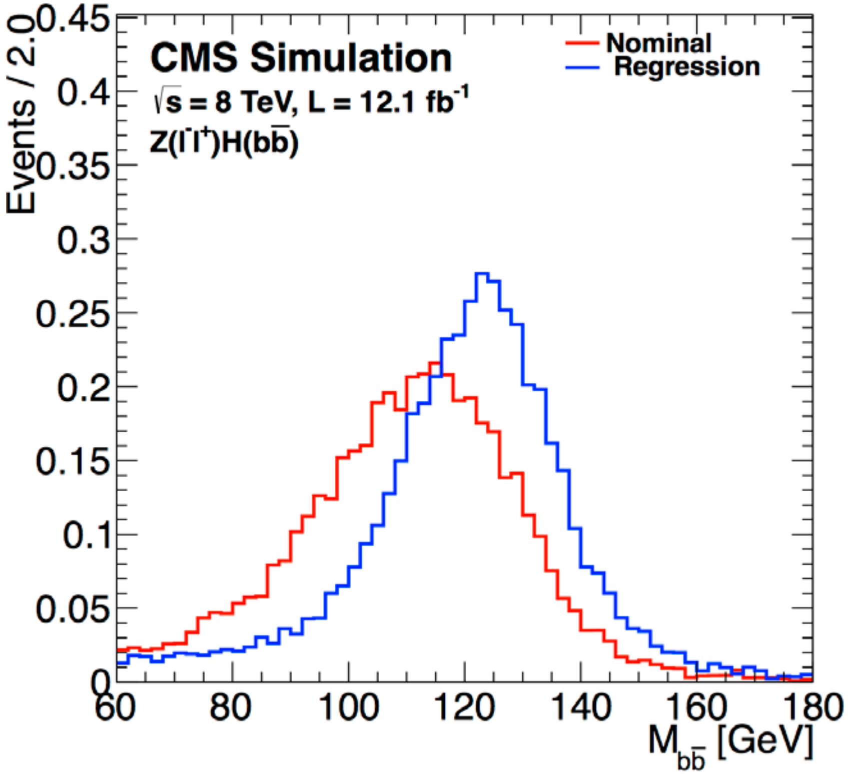


Use many BDTs to look at different signals in different P_T regions

Example of BDT output

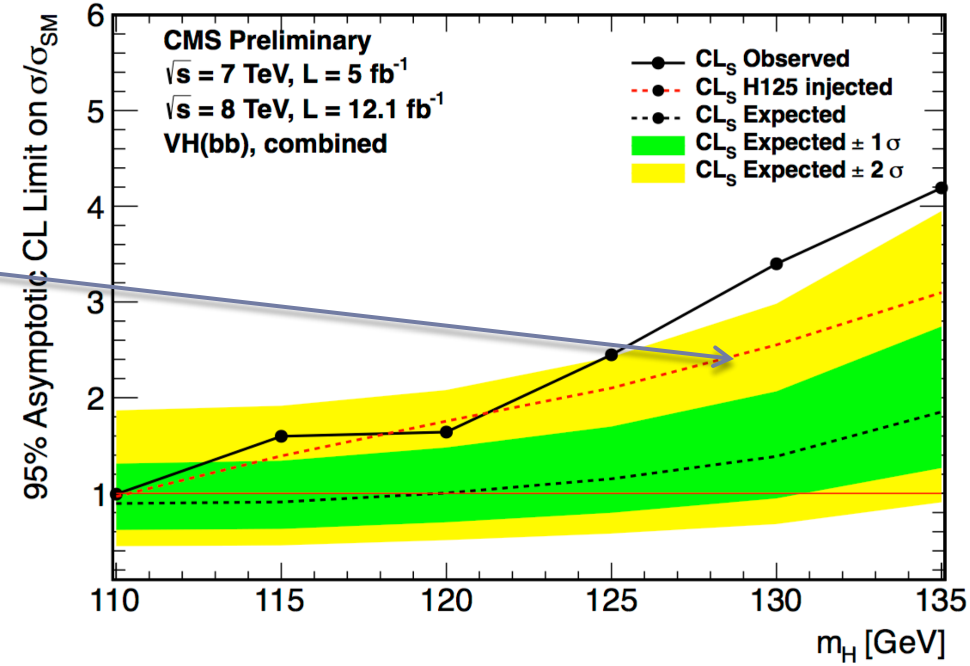


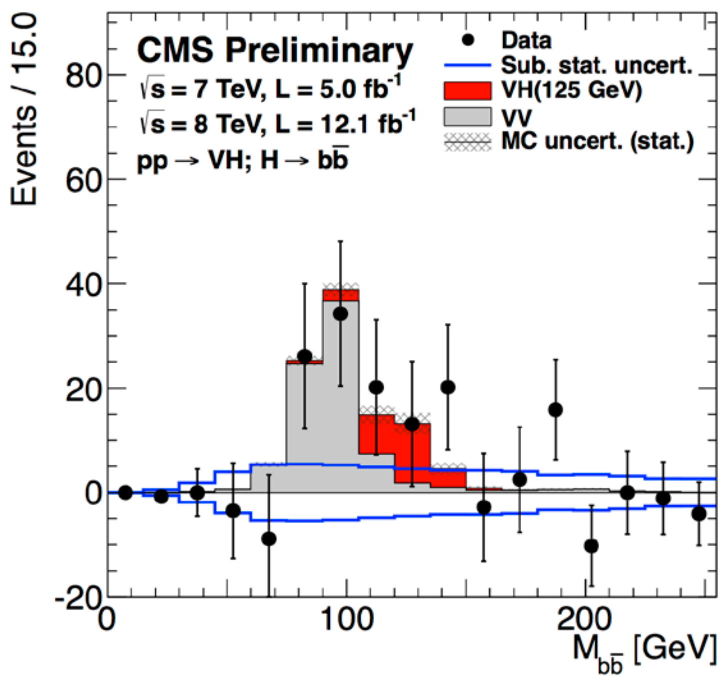
Use regression on b jets to improve resolution

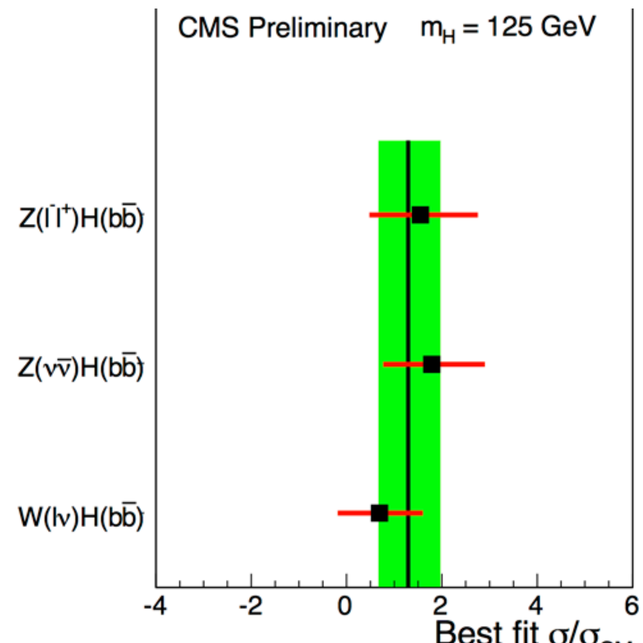


Z->bb results

Injected Higgs signal not so different than the observed

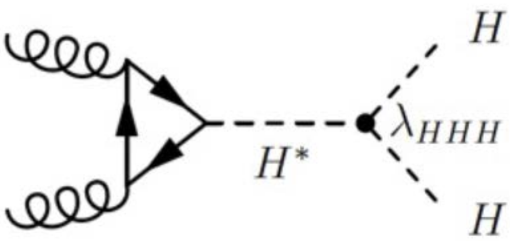




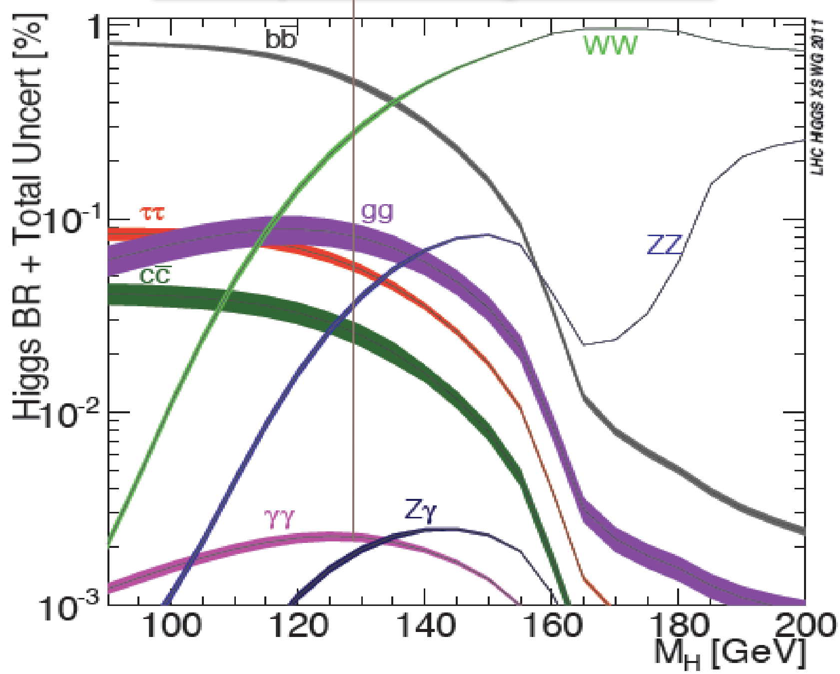


Significance of excess at $m_H \approx 125$ GeV
Observe 2.2σ (expected is 2.1σ)

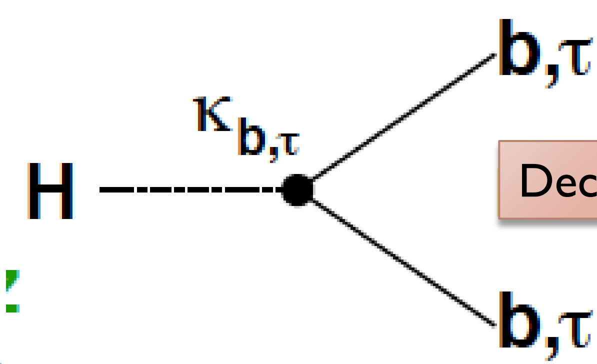
Higgs self coupling potential channels



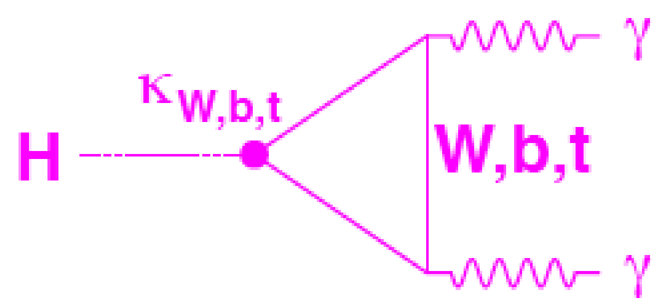
decay branching fraction



Can't use bbWW decay (this is like tt)



Decay Modes



Prospects for measuring self coupling – theory colleagues have been looking!

	HH	$b\bar{b}\gamma\gamma$	$t\bar{t}\gamma\gamma$	ZH	S/B	$S/\sqrt{B}$
Cross-section NLO [fb]	8.92×10^{-2}	5.05×10^{3}	1.39	3.33×10^{-1}	1.77×10^{-5}	6.87×10^{-2}
Reconstructed Higgs from bs	4.37×10^{-2}	4.01×10^{2}	8.70×10^{-2}	1.24×10^{-3}	1.09×10^{-4}	1.20×10^{-1}
Reconstructed Higgs from γs	3.05×10^{-2}	1.78	2.48×10^{-2}	3.73×10^{-4}	1.69×10^{-2}	1.24
Cut on M_{HH}	2.73×10^{-2}	3.74×10^{-2}	7.45×10^{-3}	1.28×10^{-4}	6.07×10^{-1}	7.05
Cut on $P_{T,H}$	2.33×10^{-2}	3.74×10^{-2}	5.33×10^{-3}	1.18×10^{-4}	5.44×10^{-1}	6.17
Cut on η_H	2.04×10^{-2}	1.87×10^{-2}	3.72×10^{-3}	9.02×10^{-5}	9.06×10^{-1}	7.45
Cut on $\Delta R(b,b)$	1.71×10^{-2}	0.00	3.21×10^{-3}	7.44×10^{-5}	5.21	16.34
"Detector level"	1.56×10^{-2}	0.00	8.75×10^{-3}	8.74×10^{-3}	8.92×10^{-1}	6.46

Table 7: Cross-section values of the HH signal and the various backgrounds expected at the LHC at $\sqrt{s} = 14$ TeV, the signal to background ratio S/B and the significance $S/\sqrt{B}$ for $\int \mathcal{L} = 3000$ fb^{-1} in the $b\bar{b}\gamma\gamma$ channel after applying the cuts discussed in the text.

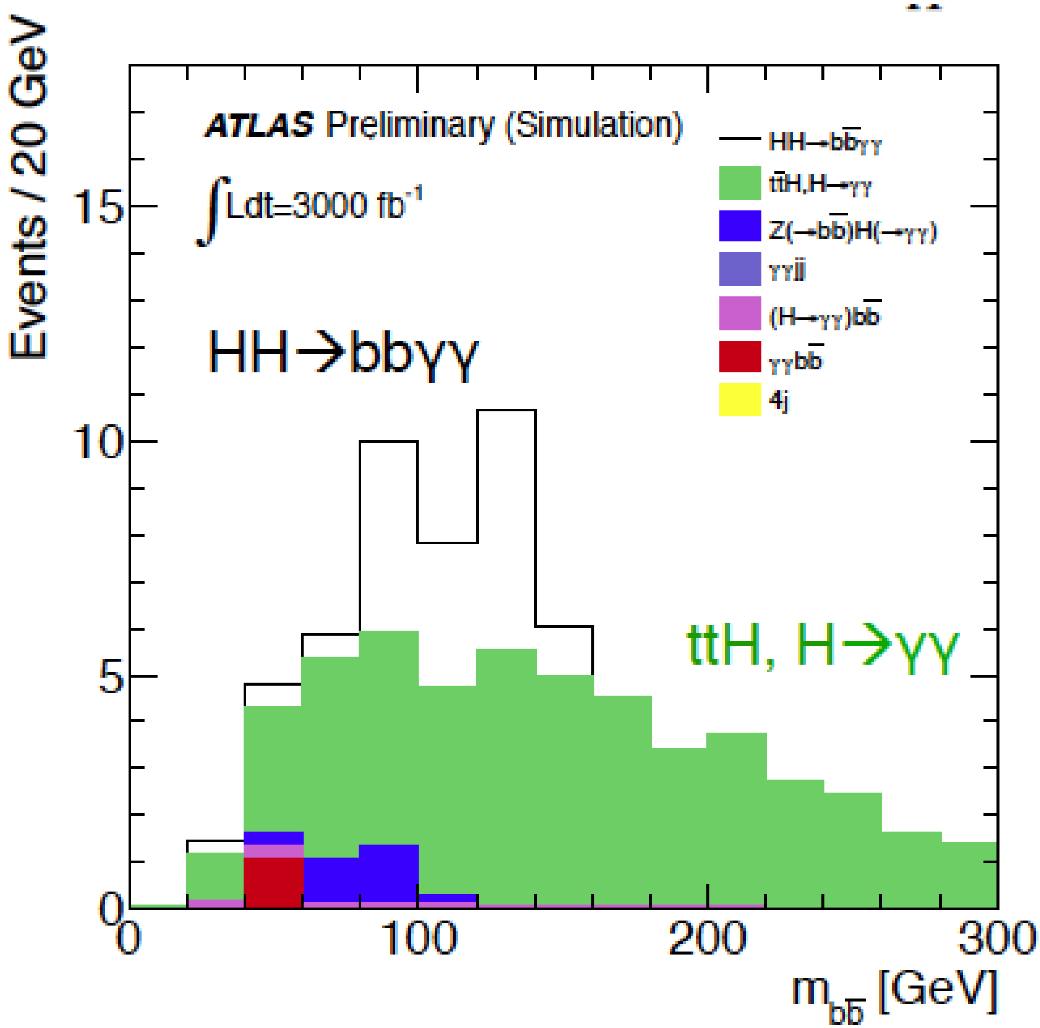
Expect about 50 events with 3000/fb

The measurement of the Higgs self-coupling at the LHC: theoretical status

J. Baglio, A. Djouadi, R. Grober, M. M. Muhlleitner, J. Quevillon, M. Spira

- E.W.N. Glover, J.J. van der Bij, Physics Letters **B219** (1989) 488–492.
- S. Dawson, S. Dittmaier and M. Spira, Phys. Rev. **D58** (1998) 115012.
- A. Djouadi, W. Kilian, M. Mühlleitner and P.M. Zerwas, Eur. Phys. J. **C10** (1999) 45–49 .
- U. Baur, T. Plehn, and D. Rainwater, Phys. Rev. Lett. **89** (2002) 151801, Phys. Rev. **D67** (2003) 033003, Phys. Rev. **D68** 033001, Phys. Rev. **D69** (2004) 053004 .
- T. Binoth, S. Karg, N. Kauer, and R. Rückl, Phys. Rev. **D74** (2006) 113008.
- M.J. Dolan, C. Englert, and M. Spannowsky, arXiv:1206.5001.
- J. Baglio, A. Djouadi, R. Grober, M. M. Muhlleitner, J. Quevillon, M. Spira, http://arxiv.org/abs/1212.5581
- Florian Goertz, Andreas Papaefstathiou, Li Lin Yang, José Zurita http://arxiv.org/abs/1301.3492

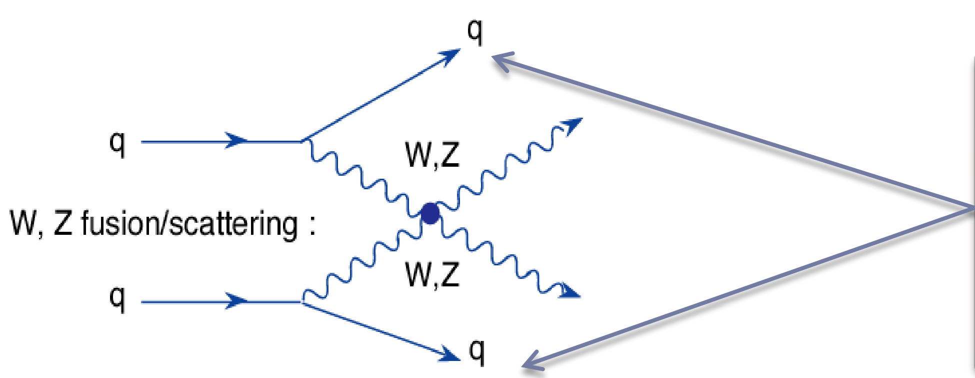
Projection for Higgs Self coupling



This channel for ATLAS alone would give about a 3σ signal.

DiBoson scattering

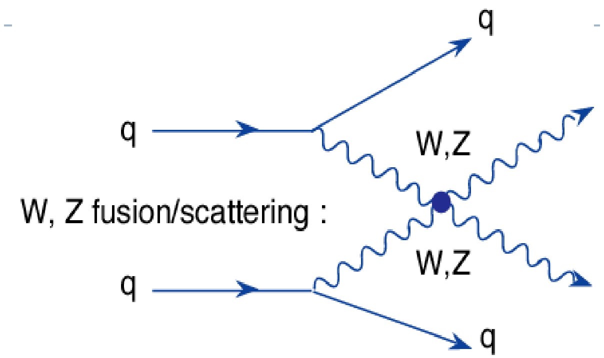
- The Higgs mechanism gets rid of the problem of unitarity violation at the TeV scale
- We should check the behaviour of Di-Boson scattering at the TeV scale to make sure nothing else is going on!
- For these events, we need to “tag” the forward jets from the quarks



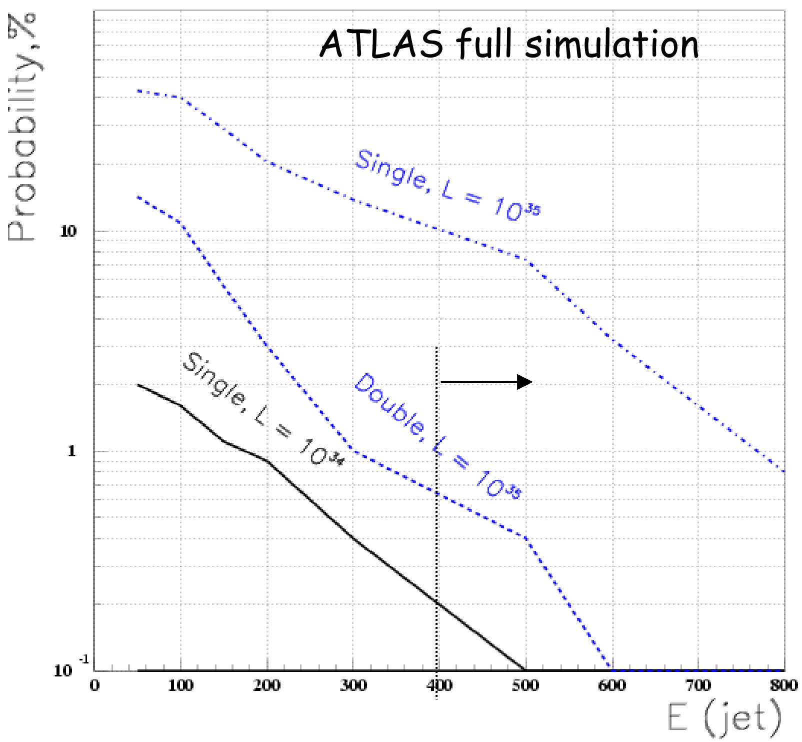
Jets from these quarks are widely separated in rapidity.
Tend to be in the very forward detectors

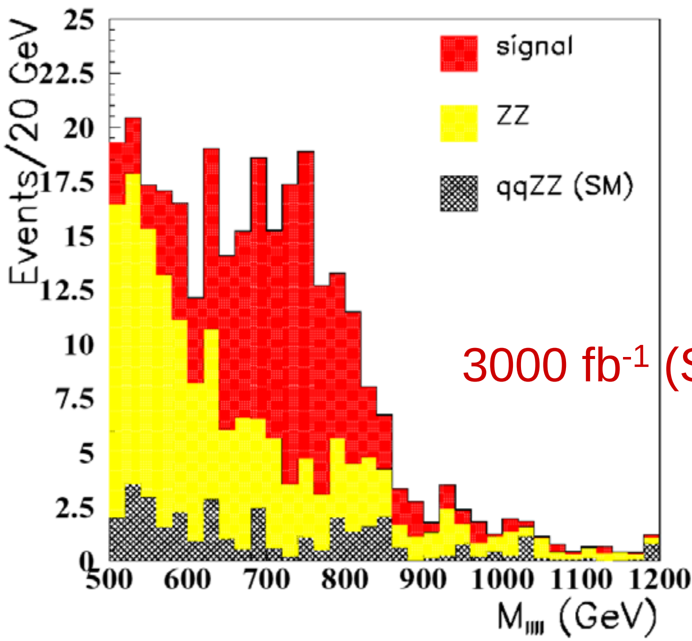
WW scattering

Forward tagging is essential
Potential signals are small



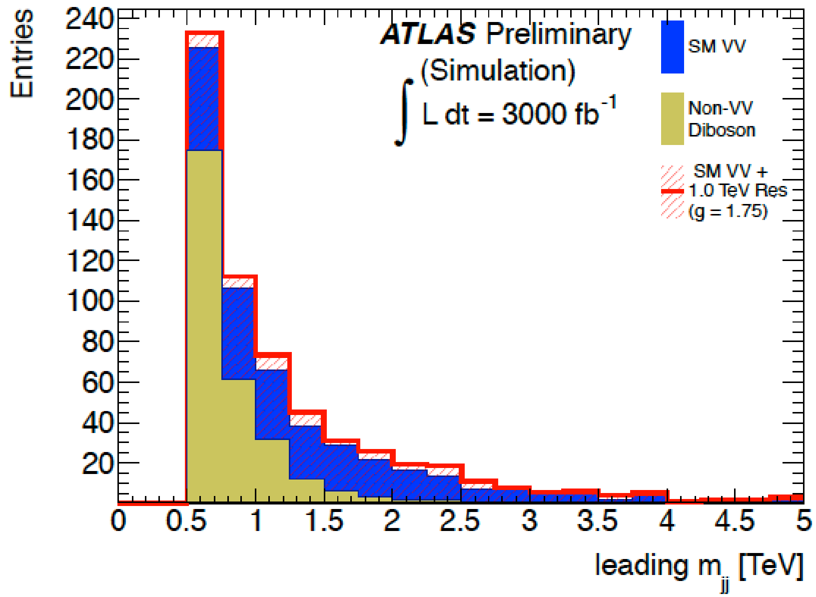
Fake fwd jet tag (|η| > 2) probability from pile-up (preliminary ...)

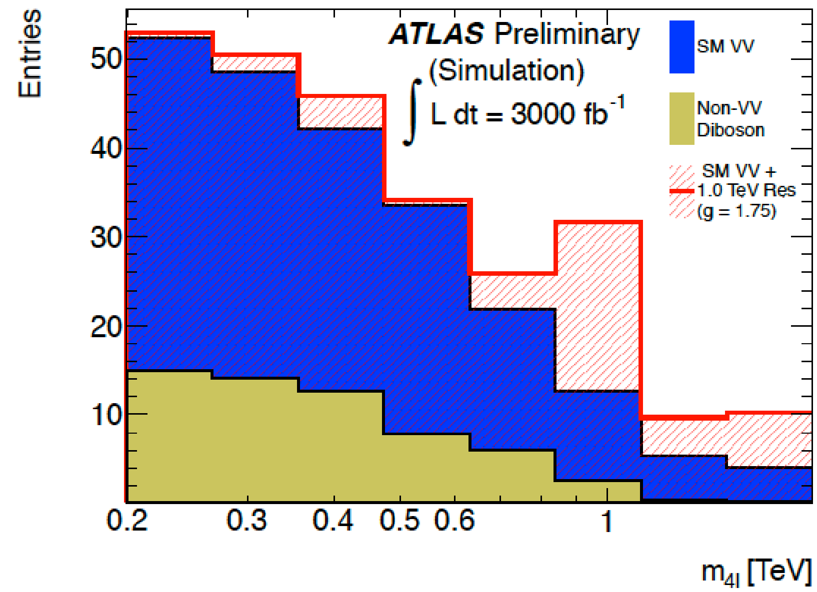




3000 fb^{-1} (SLHC)

Looking for non-VV Diboson at HL-LHC





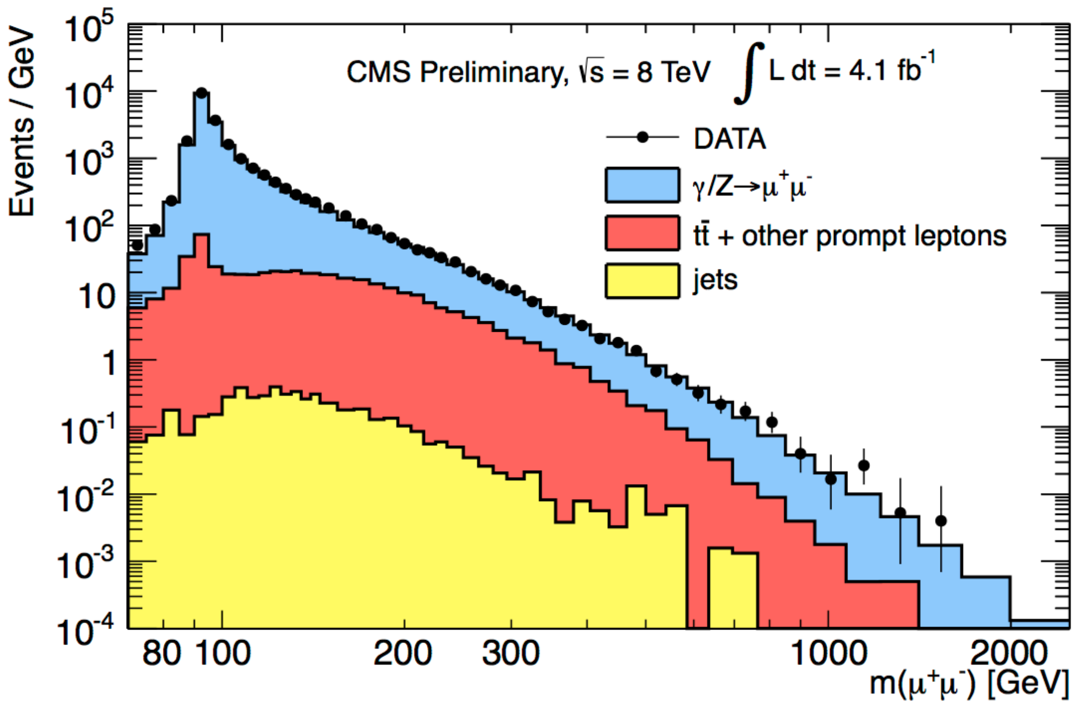
ATLAS Anomalous WBS model	Sensitivity $300\ \text{fb}^{-1}$	Sensitivity $3000\ \text{fb}^{-1}$
$m_{\text{resonance}} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{\text{resonance}} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{\text{resonance}} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ

HL-LHC luminosity essential for these measurements

Looking for other new physics- Z' resonances

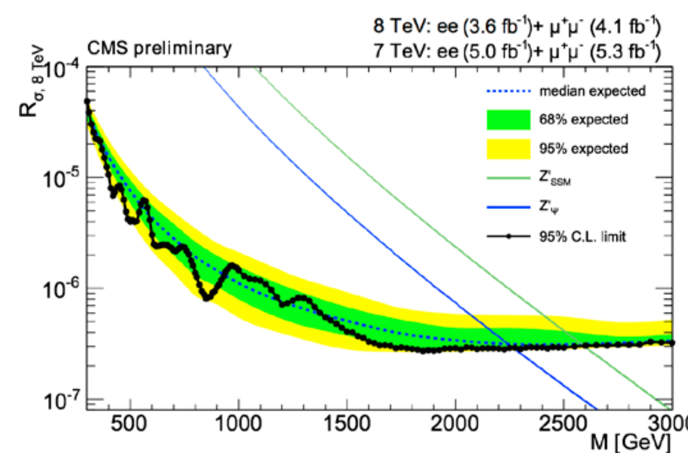
- Higher luminosity (and energy) extends the reach of a proton machine in looking for resonances.
- This is a very simple analysis, just make a plot of the invariant mass of pairs of leptons.
- Have to be careful about the performance of the detectors at very high energies
  - For example the calorimeters which give precision measurements of the momentum at TeV scales can have channels in saturation
  - Need to correct for this effect by looking at the shower of energies in the calorimeters.

Search for Z'->dilepton what we see now



A *straightforward* search.
Isolated Leptons with reasonably high P_T (e 35 GeV, μ 45 GeV)
$M(Z'_{SSM}) > 2590$ GeV (95%CL)
$M(Z'_{\psi}) > 2260$ GeV (95%CL)

CMS PAS EXO-12-015

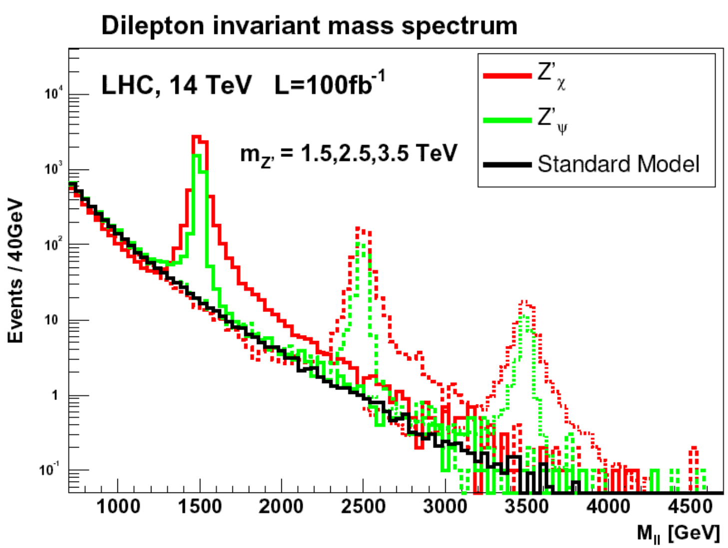


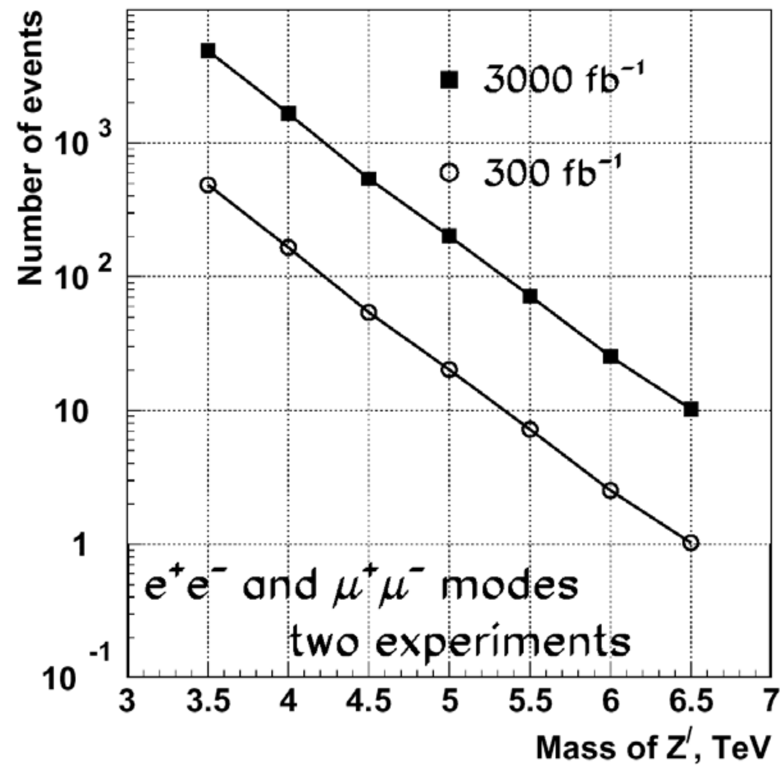
More data continues to extend the mass limits.
Higher energy will move this much more quickly after the coming shutdown

HL-LHC Physics: Adding reach with more luminosity

- HL-LHC extends reach for Z'
  - Cross sections fall with E
  - More luminosity gives access to higher E

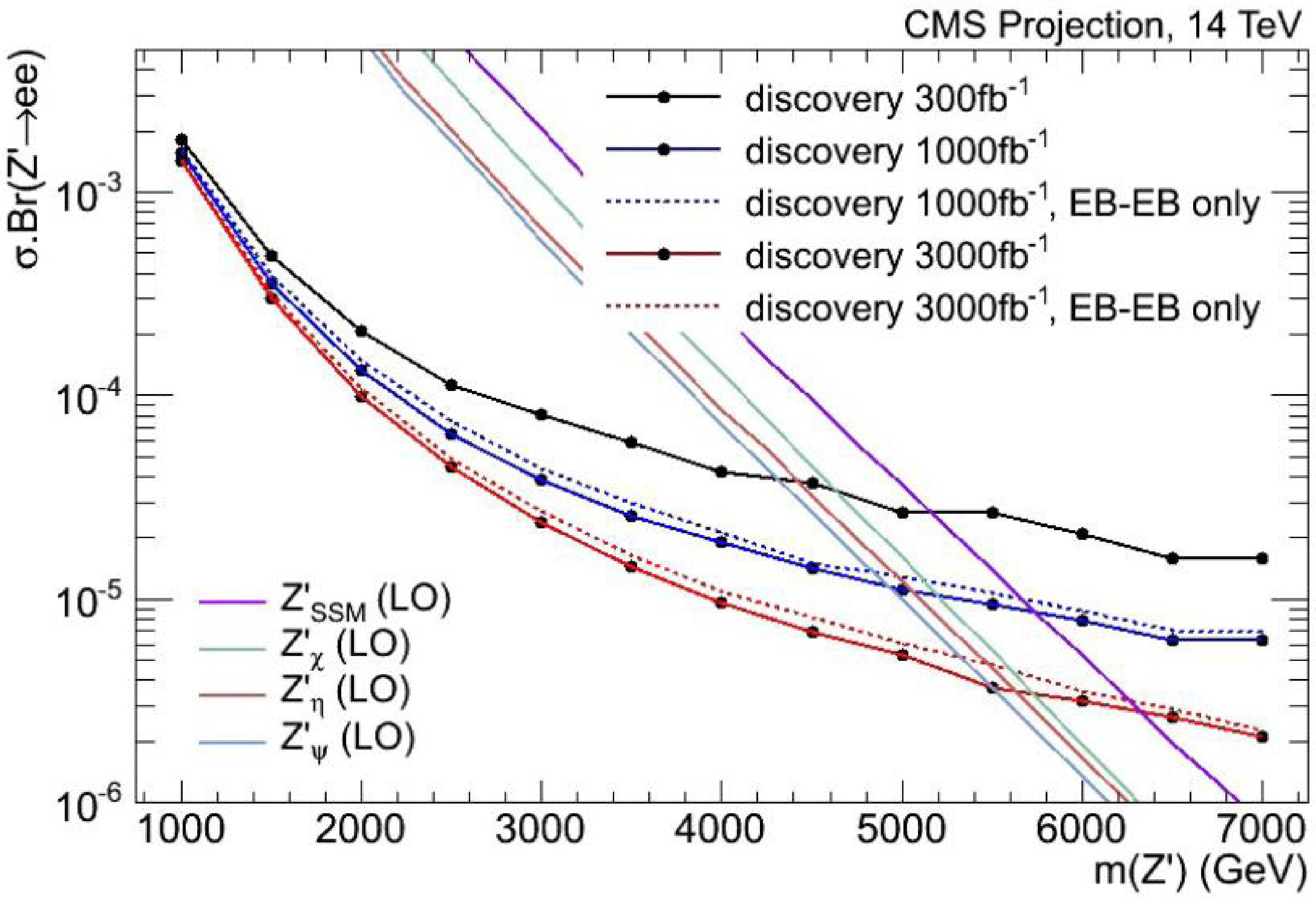
Just needs the Integrated Luminosity!



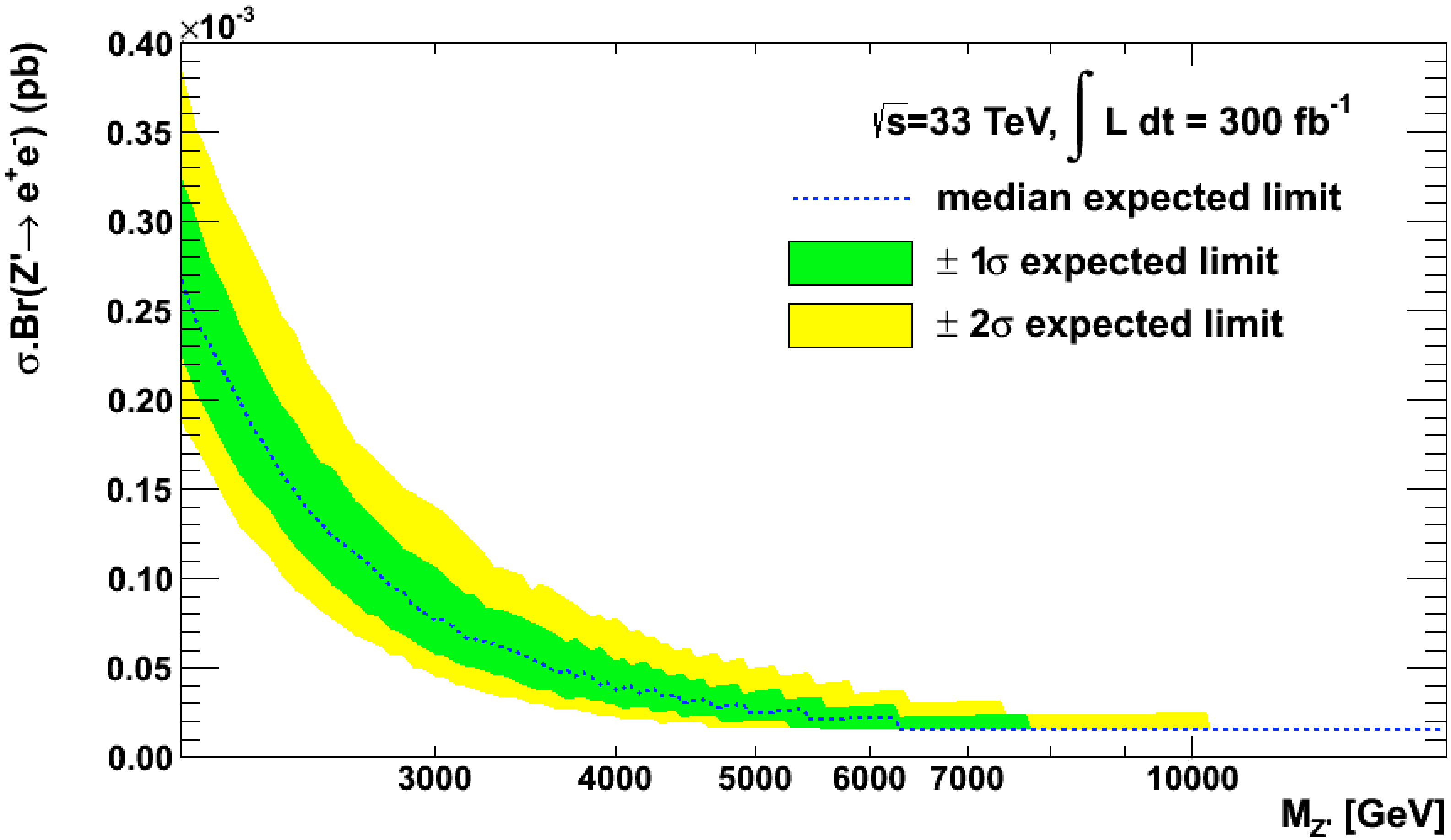


Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

Projected reaches in Z' searches

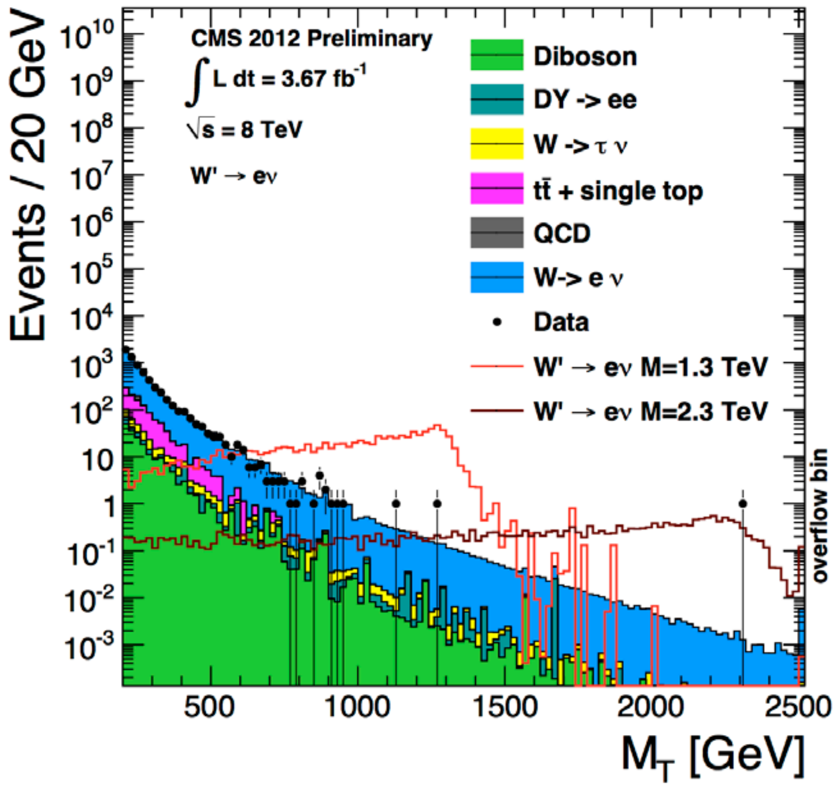


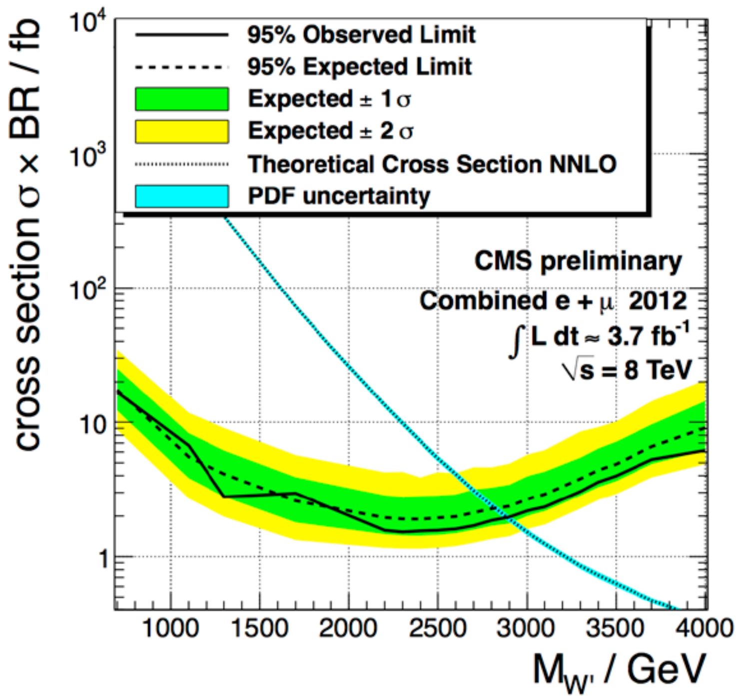
Resonances - Higher energy would clearly help extending the LHC reach



Search for W'

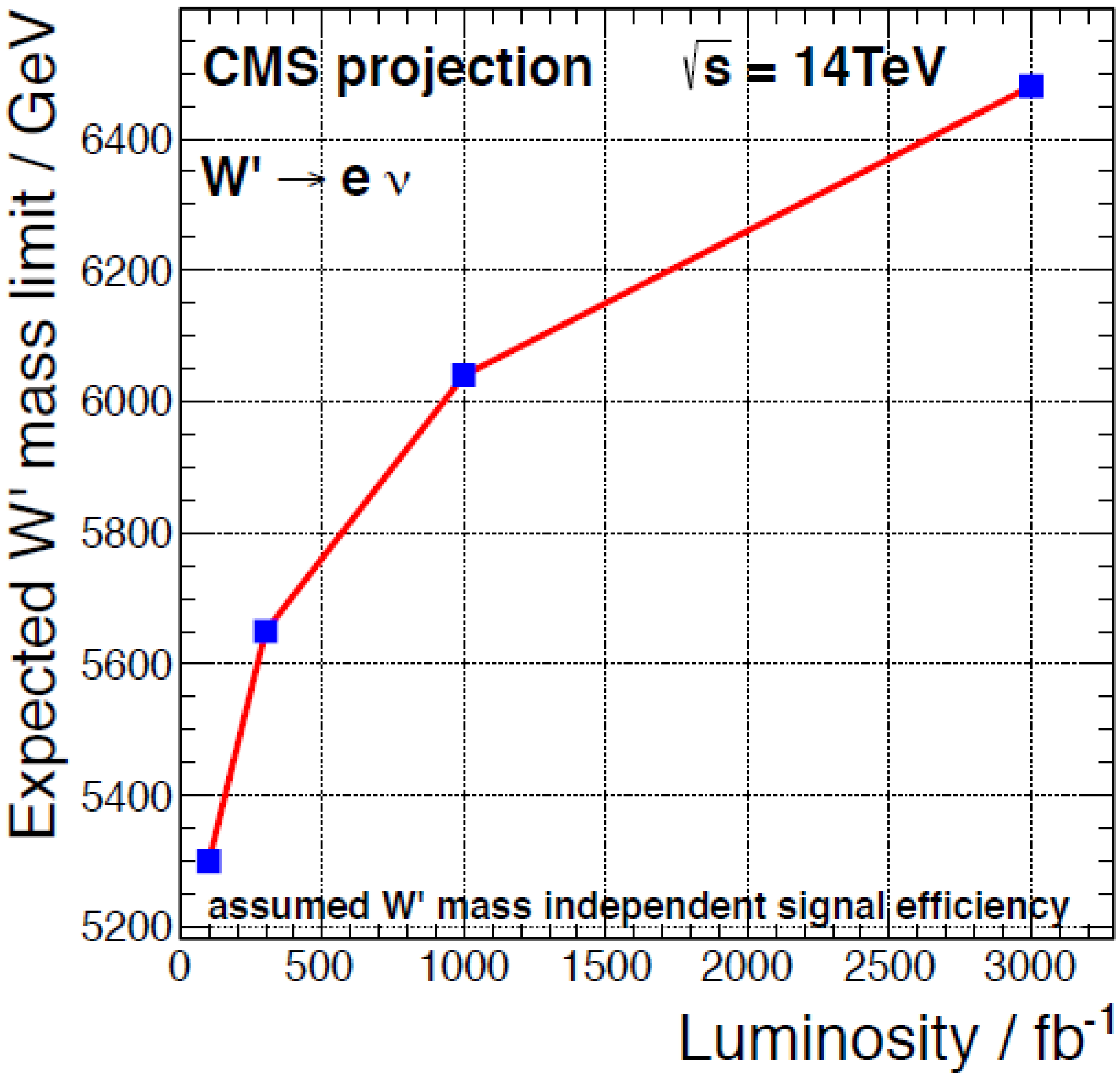
$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$





CMS PAS EXO-12-010

Isolated Leptons with Missing ET
Look at MT
$M(W'_{SSM}) > 2.85$ TeV (95%CL)

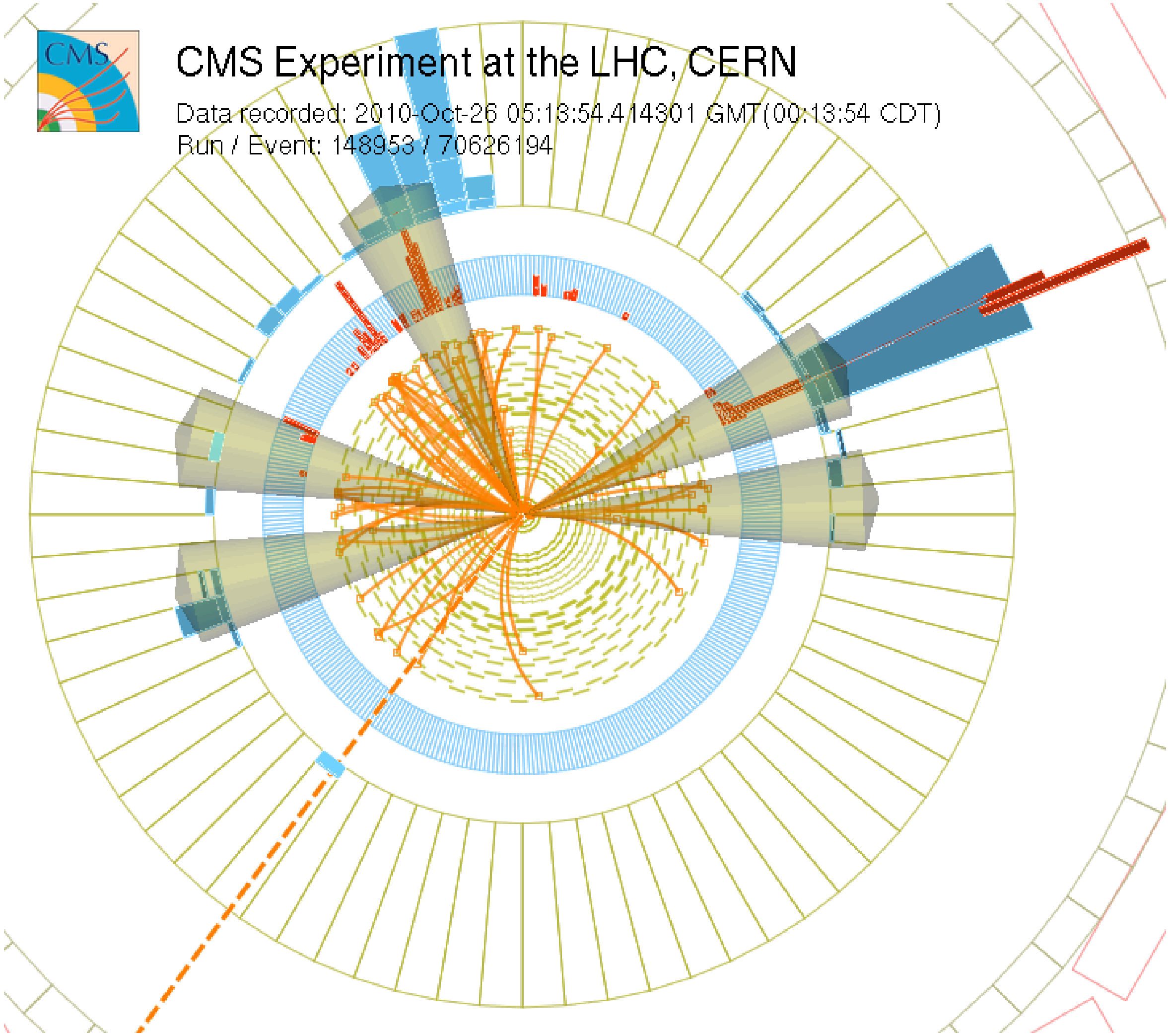


W' limits

The gain on the limits we can set on these sorts of decays are slow with increasing luminosity.

Would hope to see some hints when we go to 13 TeV if there is something new.

Search for SUSY particles



Beyond SM – SUSY searches

SUSY $h \to b\bar{b}$ event in CMS detector

$pp \to \tilde{u}_L + \tilde{g}$

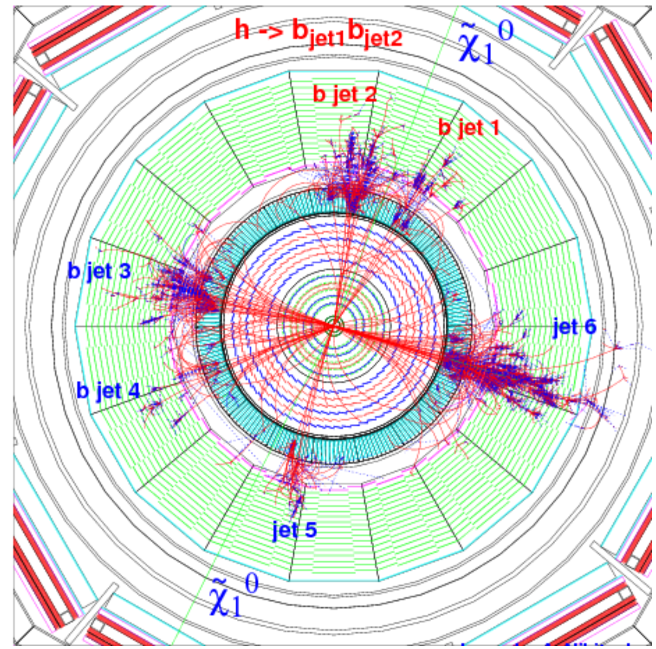
$\tilde{g} \to \tilde{t}_1 + \bar{t}$

- $\to W^- + \bar{b}$ (jet$_4$, E_t = 113 GeV)
  - $\to s$(jet$_5$, E_t = 79 GeV) + $\bar{c}$
- $\to \tilde{\chi}_2^+ + b$ (jet$_3$, E_t = 536 GeV)
  - $\to \tilde{\chi}_1^+ + Z \to \nu\bar{\nu}$
    - $\to \tilde{\chi}_1^0 + W^+ \to \nu\tau \to e\nu\nu$

$\tilde{u}_L \to \tilde{\chi}_2^0 + u$ (jet$_6$, E_t=1200 GeV)

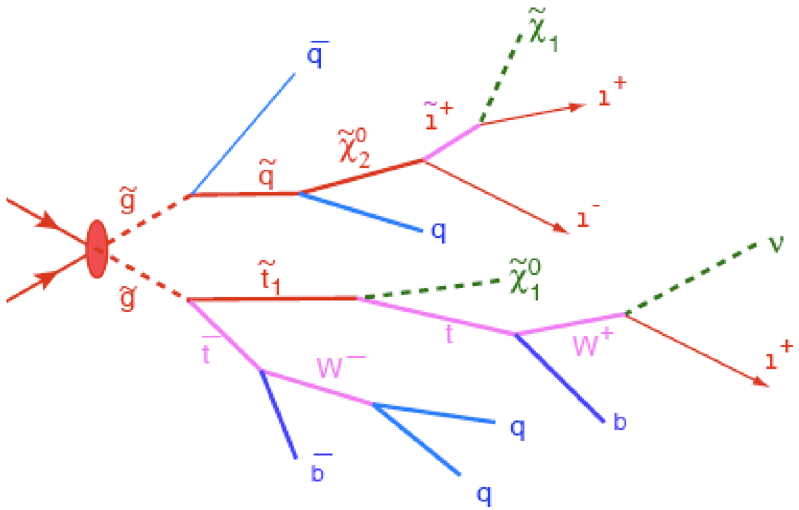
- $\to \tilde{\chi}_1^0 + h \to b\bar{b}$ (jet$_1$, E_t=206, GeV; jet$_2$, E_t=320 GeV)

mSUGRA
m_0=1000 GeV, $m_{1/2}$=500 GeV
A_0=0, $\tan\beta$ =35, μ>0
$m(\tilde{g})$ =1266 GeV
$m(\tilde{u}_L)$ = 1450 GeV
$m(\tilde{t}_1)$ = 1026 GeV
$m(\tilde{\chi}_2^0)$ = 410 GeV
$m(\tilde{\chi}_1^0)$ = 214 GeV
$m(h)$ = 119 GeV



HL-LHC detectors must be able to cope with complicated topologies
This machine will be our only tool for understanding what is the spectrum of any newly discovered physics for some time

SUSY search strategies



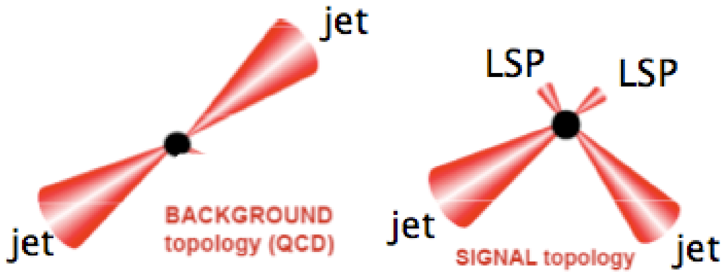
- Missing E_T.
- b-quark jets
- Leptons
- Lots of potential QCD background to fight

- CMS strategy:a programme of searches based on missing E_T and event topologies (MET+jets+N_{lep}/Nγ)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	(Di-)photon + jet + MET	Photon + lepton + MET

An Example of Search for Supersymmetry

PRL101:221803 (2008) & CMS-PAS-SUS-09-001



$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

- **No direct dependence on calorimetric MET**
- **Originally proposed for di-jets but now generalized for Njets**
- **Perfectly balanced events (QCD) have α_T = 0.5 (cut at α_T >0.5)**
- **Due to built-in correlation α_T is very robust against jet mis-measurements**

α_T for 2 jets: $\alpha_T = \frac{E_{T2}}{M_T} \leq 0.5$

Expectation for QCD: α_T = 0.5
Jet mismeasurements: α_T<0.5

α_T for n jets: $\alpha_T = \frac{1}{2}\frac{H_T - \Delta H_T}{M_T}$

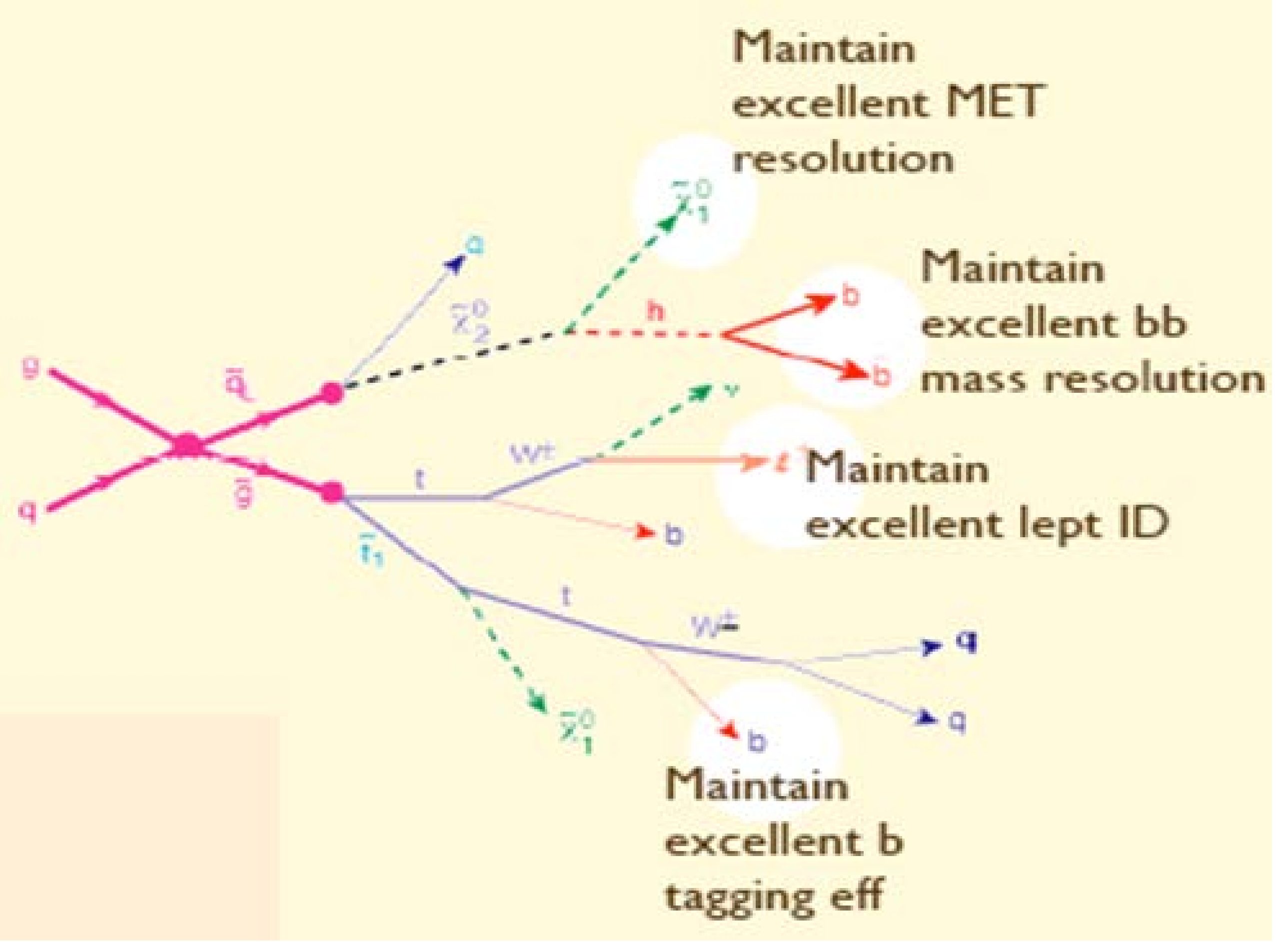
(form two pseudo-jets – defined by balance in "pseudo-jet" $H_T = \Sigma E_T$)

Spill-over in a_T>0.5 from:
(a)Processes with genuine MET (EWK, TOP, and SUSY ☺)
(b)Some remnant QCD

SUSY what if we find it- how well will we explore the spectrum?

- HL-LHC statistics would be vital in reaching understanding of complicated SUSY channels
- Performance of the detector here is vital
  - B-tagging
  - Lepton id

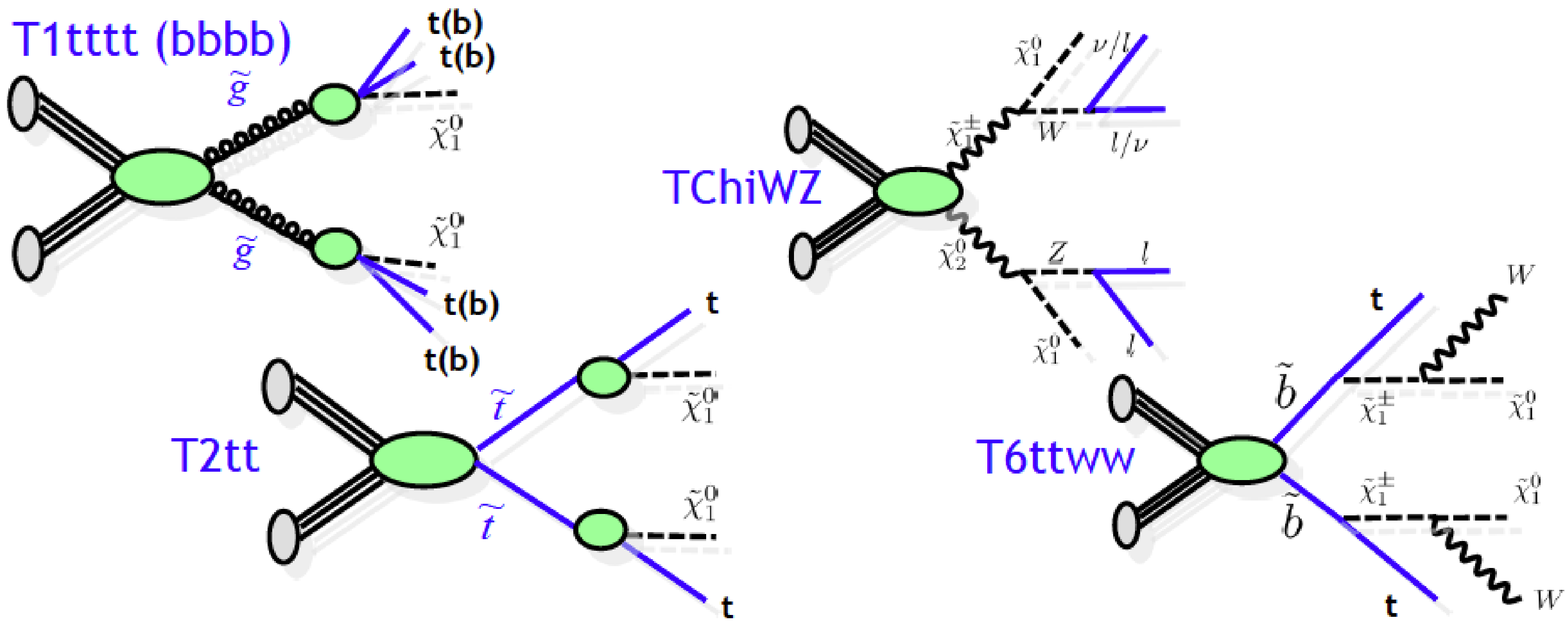
Here we need a lot of Integrated Luminosity, but it needs to be high quality. Lower pile-up is important.



Some sample SUSY Topologies

Gluon pair production

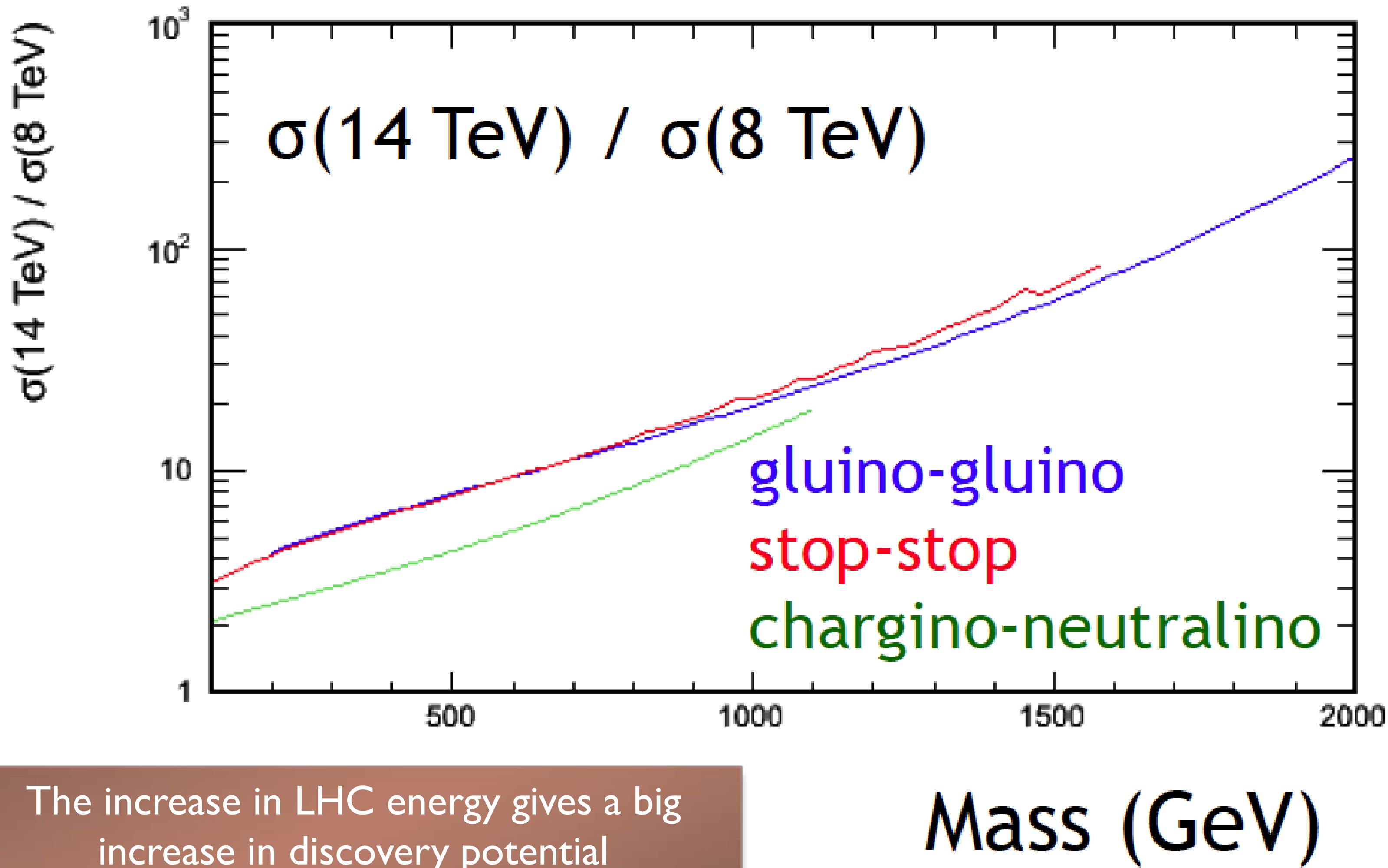
EWKino production



Direct stop production

Direct sbottom production

SUSY cross sections 14 TeV vs 8 TeV



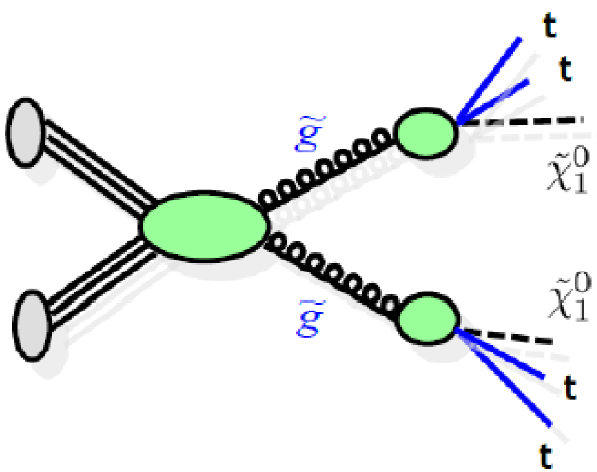
The increase in LHC energy gives a big increase in discovery potential

SUSY searches – gains from increasing luminosity

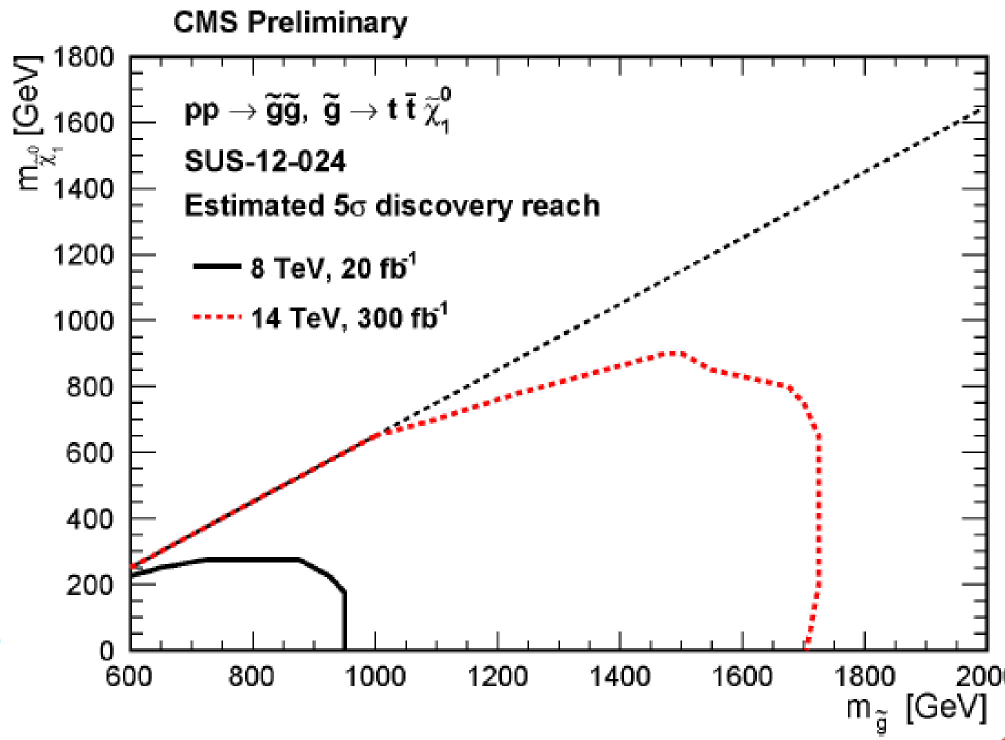
- The big increase in discovery potential comes from the increasing of the machine energy which will take place in 2015.
- Increasing luminosity pushes the discovery limits, but the return is slower than an increase in energy.
- Should we find something new in 2015, the increased luminosity will be essential in order to look at the spectroscopy of anything we discover.

SUSY searches – gluinos

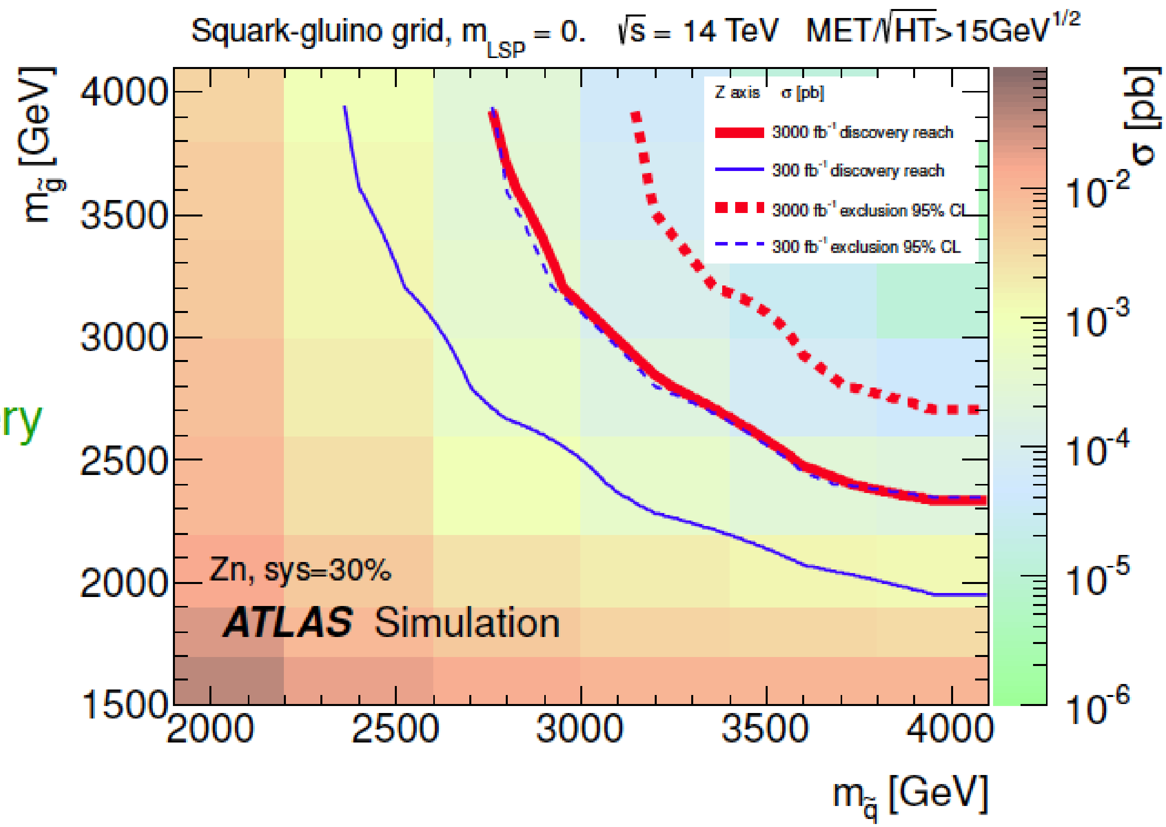
- Can discover (5σ) gluinos up to **1.7 TeV with 300 fb^{-1} @ 14 TeV**



Search in the final state with:
0-lepton + jets + MET + btags



J. Olsen – Snowmass pre-meeting



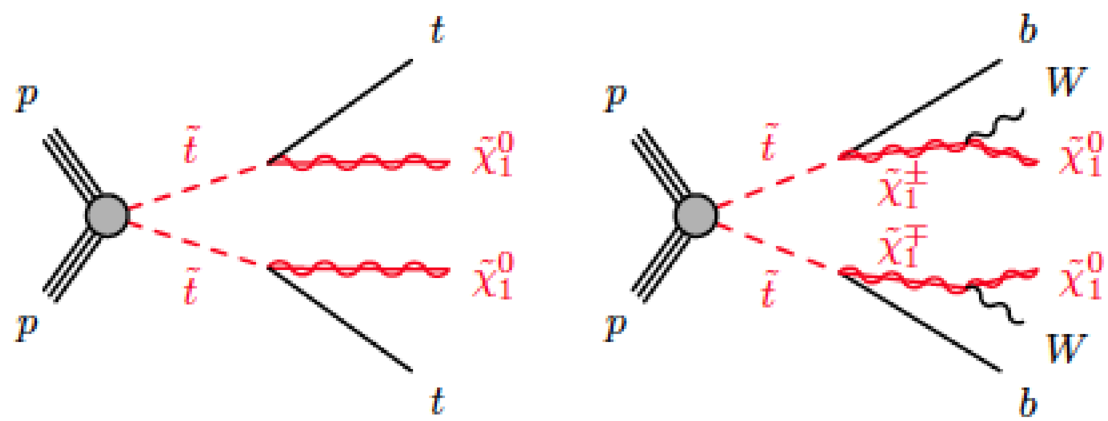
SUSY at HL-LHC

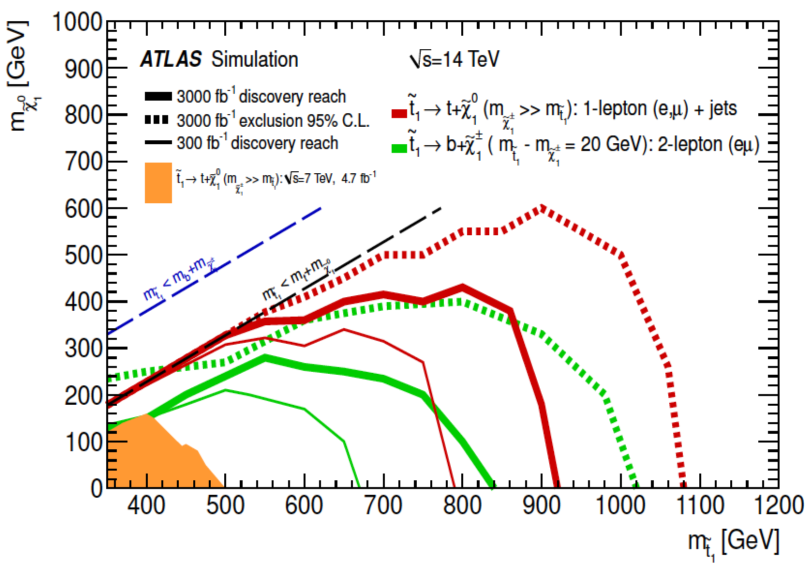
The increased luminosity pushes out the limits which will be accessible with the LHC

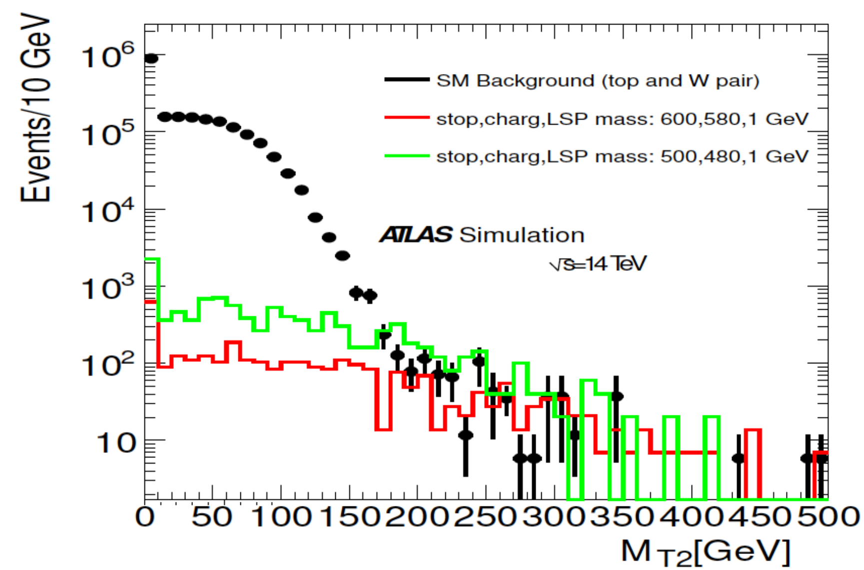
Typically around 400-500 GeV

ATLAS – third generation SUSY

Gain in reach of around 100 GeV at HL-LHC

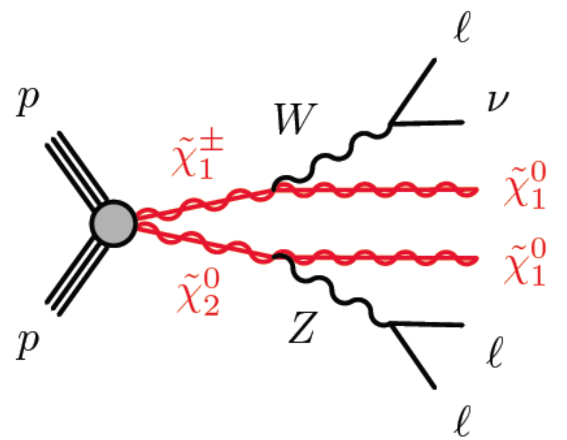


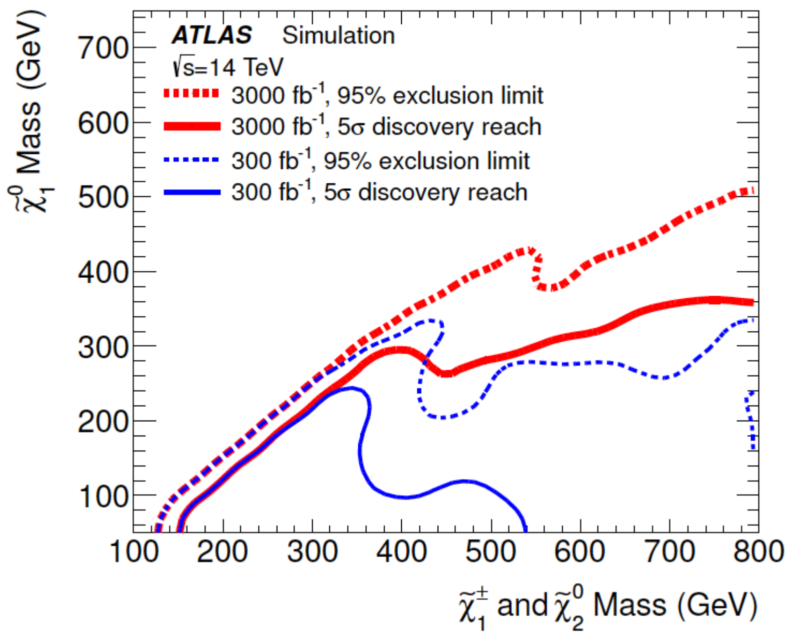


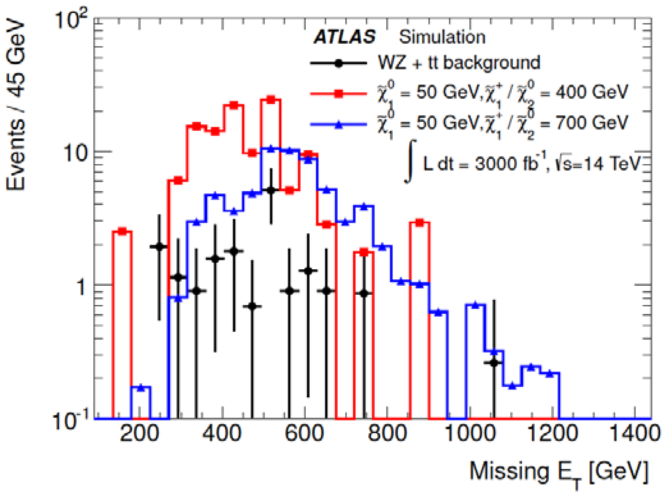


SUSY electroweak production

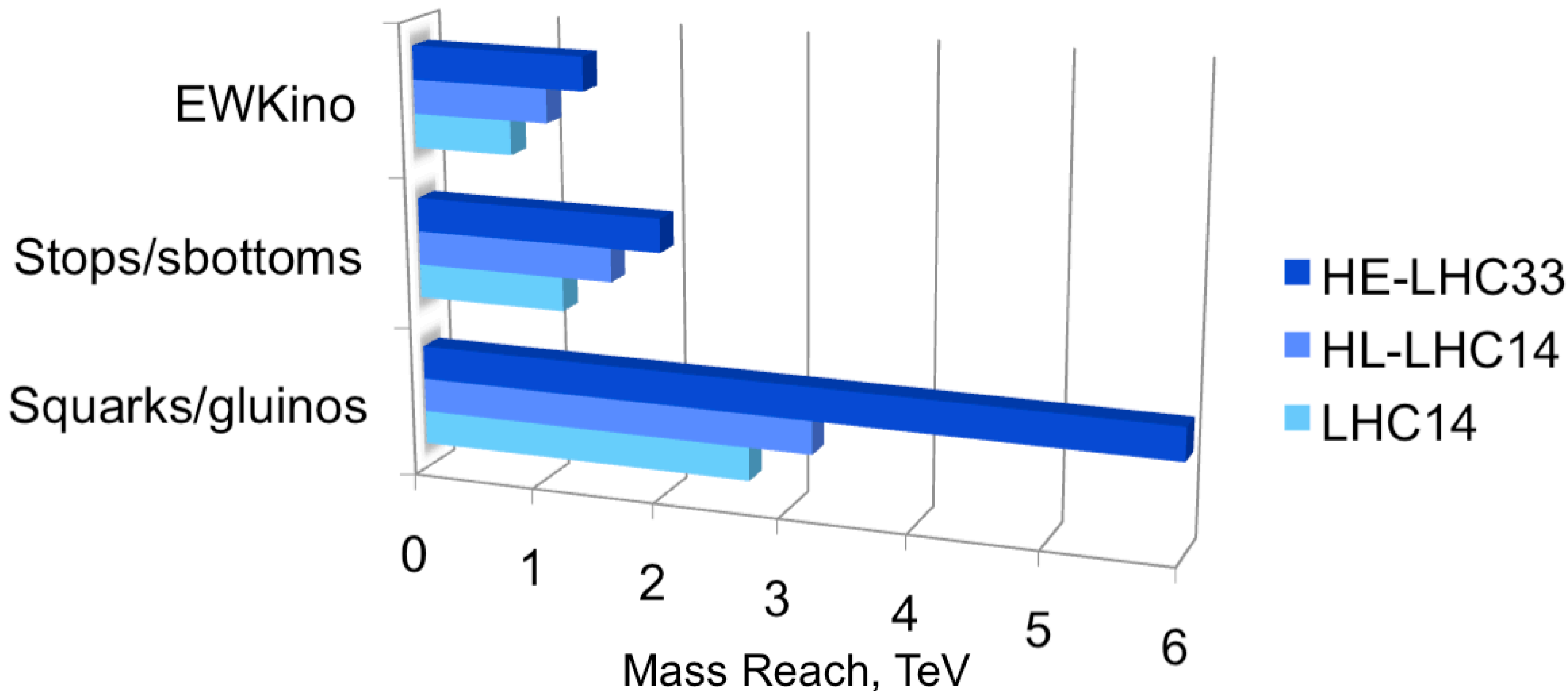
- **Multi-lepton final states**
- **gains with high luminosity in these channels**





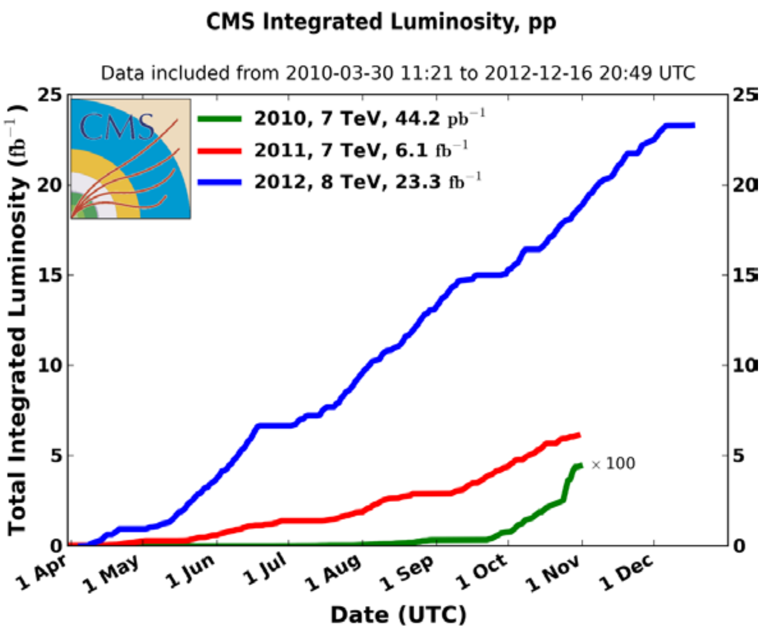


Examples – expected reach for LHC upgrades



The HL-LHC Machine – A brief look at the accelerator

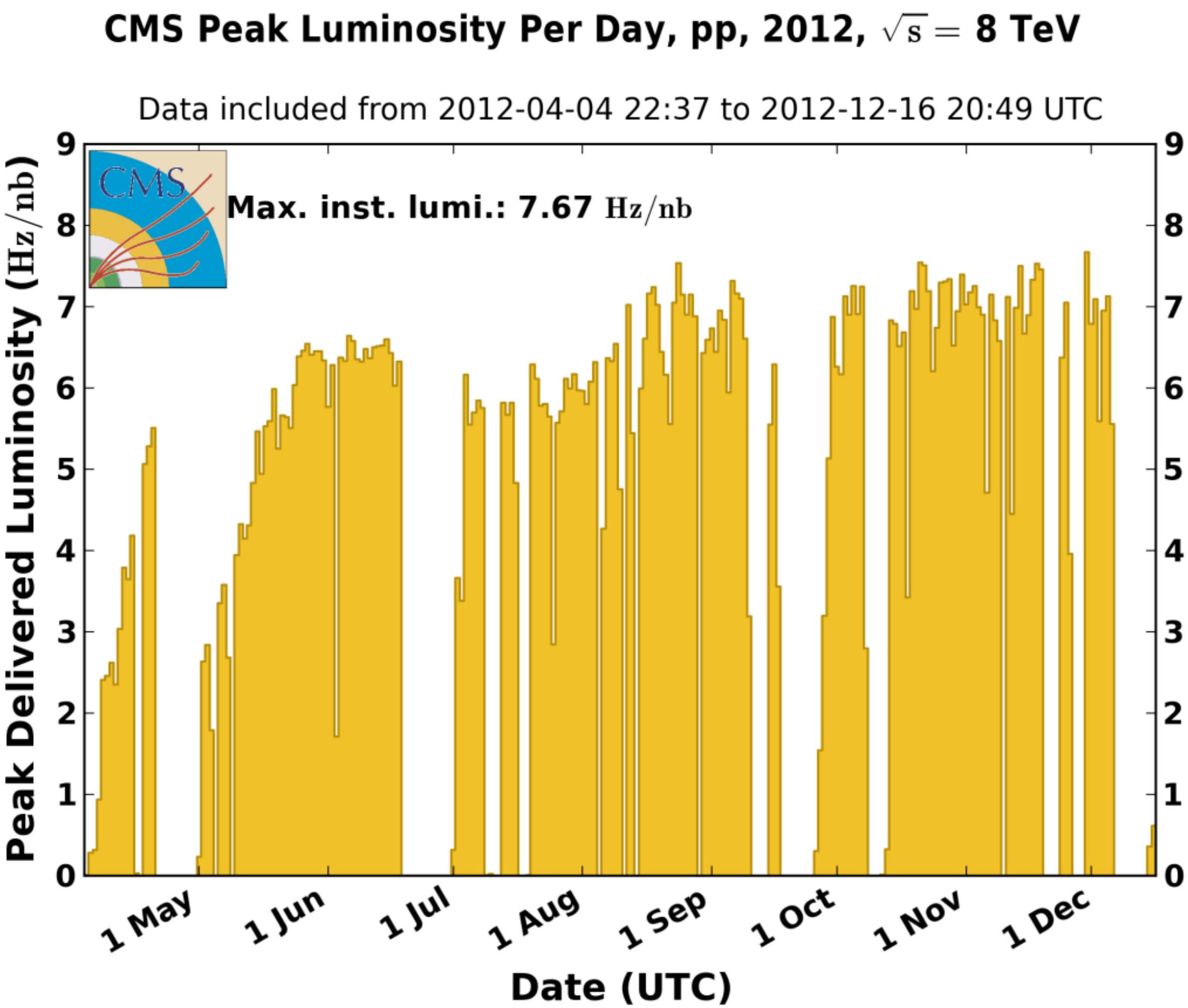
Challenges for the LHC machine



- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Machine commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - … Production & exploration
- 2012: **23 fb^{-1}**
  - Higher energy, 8 TeV
  - Smaller β^*
  - Increased bunch current

- How to keep this trend
  - It has looked easy so far!
- The machine is however rapidly approaching its limits

Sergio Bertolucci



Peak LHC Luminosity

Approaching the design peak luminosity

This produce about 750 Higgs Bosons per hour!

75% of Design Luminosity @ Half design Energy and Half the number of bunches!!

Peak Luminosity

$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi\varepsilon_n \beta^*} F$$

- N_b number of particles per bunch
- n_b number of bunches
- f_r revolution frequency
- ε_n normalised emittance
- β^* beta value at Ip
- F reduction factor due to crossing angle

- N_b, ε_n → injector chain
- β^* → LHC insertion
- F → beam separation schemes
- n_b → electron cloud effect

L. Evans – EDMS Document 974861

Peak Performance: Luminosity

Beam current

Geometrical Luminosity factor

$$L = \gamma \frac{f_{rev}\, n_b\, {N_b}^2}{4\pi \varepsilon_n \beta^*} R$$

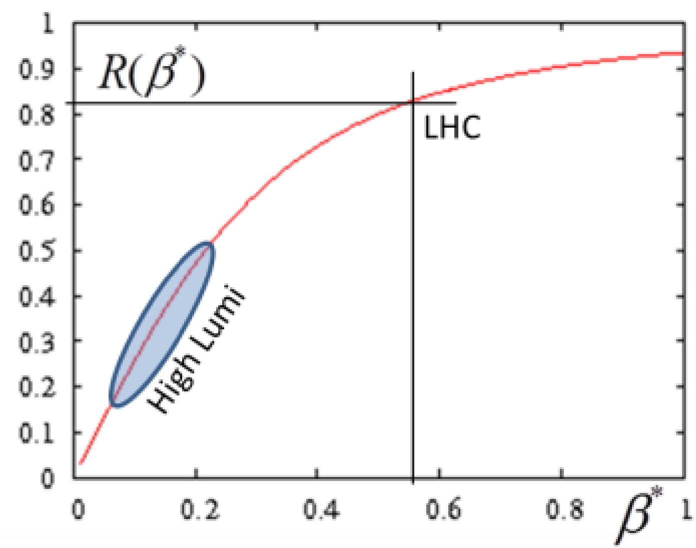
energy

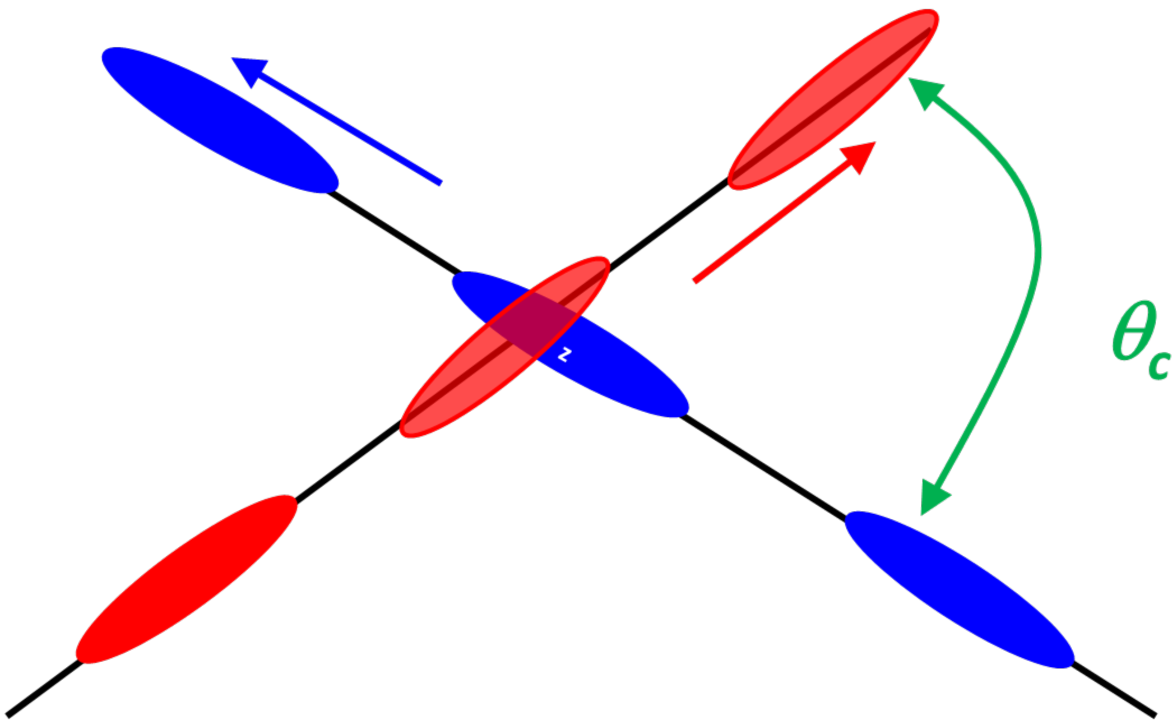
Beam size

$$R = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma\right)^2}}$$

The beam current and emittance limitations: involve the Injector chain and the whole ring
Changing β* involves «only» 2 Interaction Regions – new final focus systems will be required

With a stronger focusing for higher luminosity, some luminosity is lost because of the geometrical factor





Crossing Angle

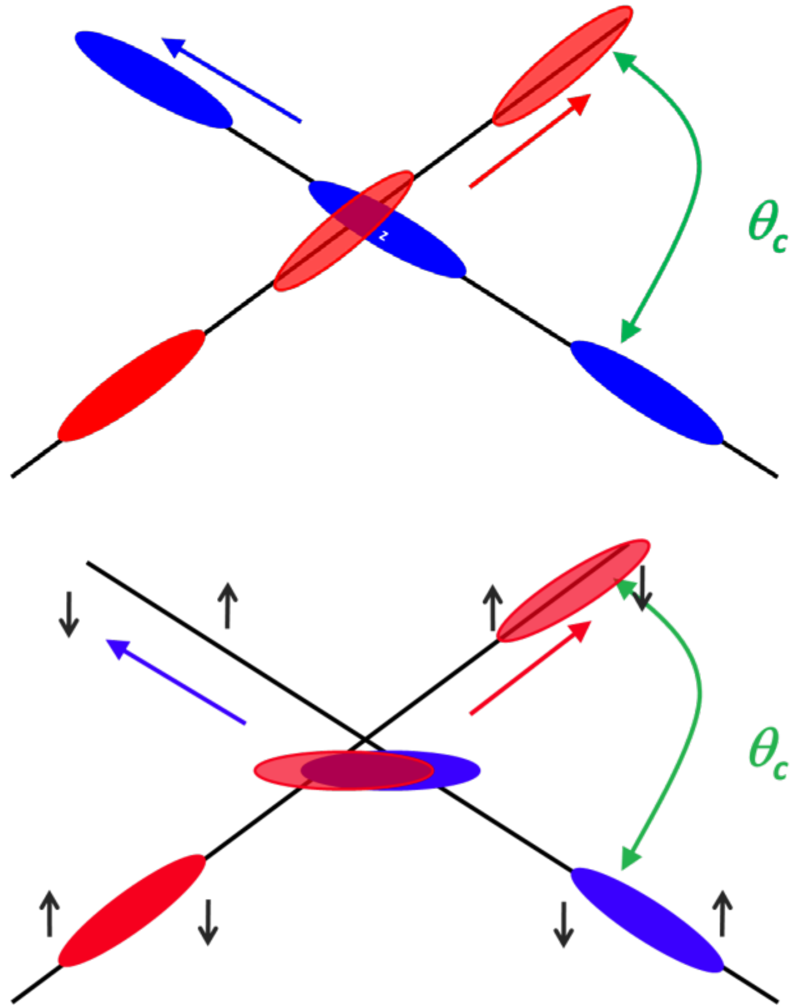
The bunches in the LHC are separated by 25 ns

They need a finite crossing angle so that luminosity is not lost by interactions taking place away from the interaction point (parasitic interactions)

The crossing angle however reduces the luminosity

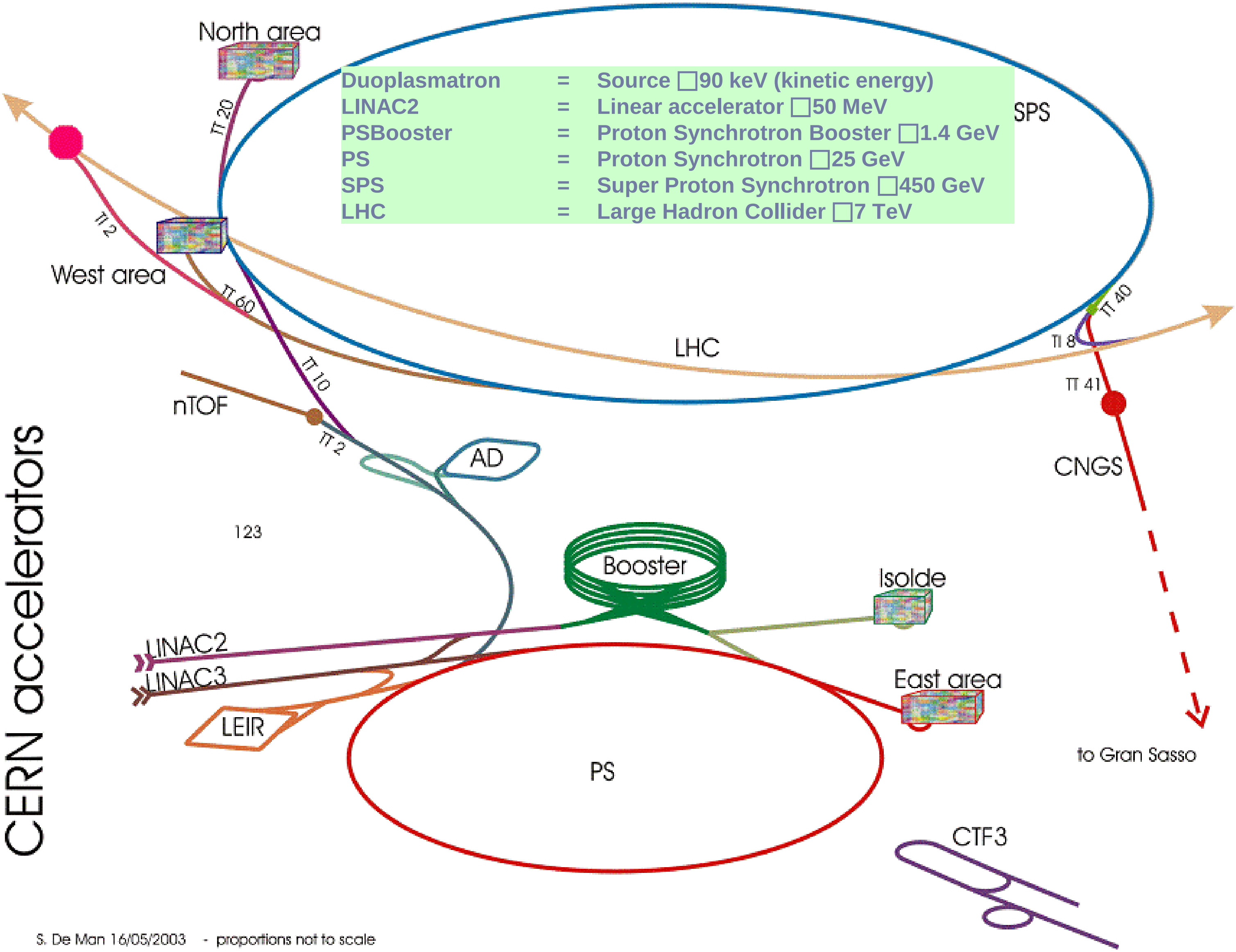
Crab Cavities

- Rotation of the beams allows a recovery of some of the lost geometrical factor due to the crossing angle.
- This is a new technology at proton machines and will require significant R&D to be successful.

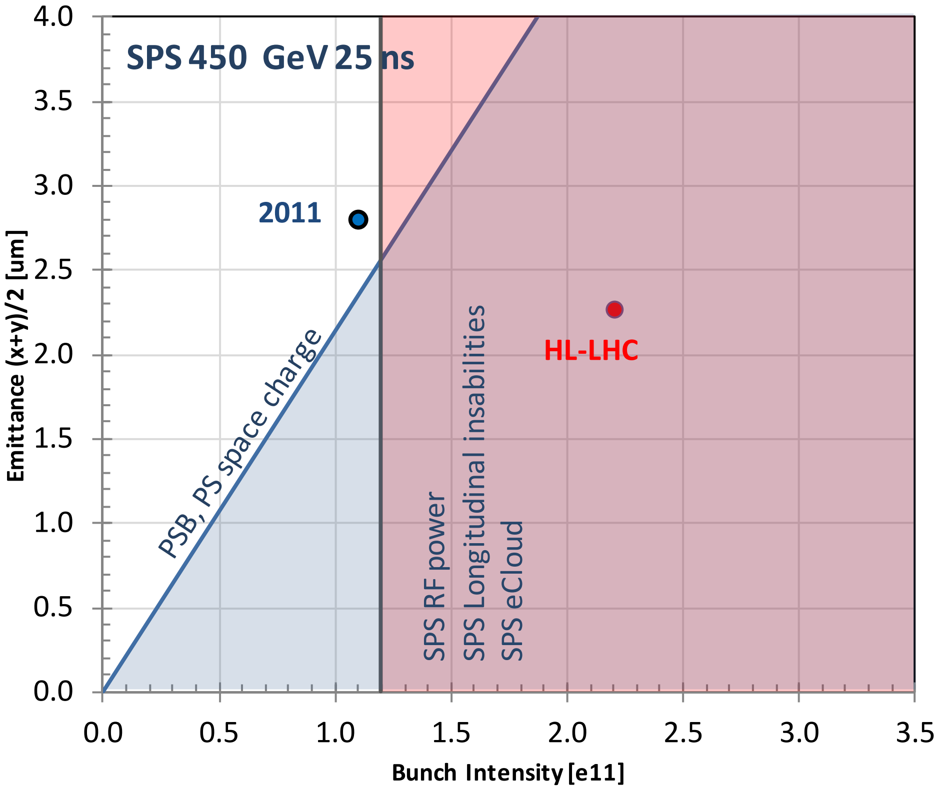


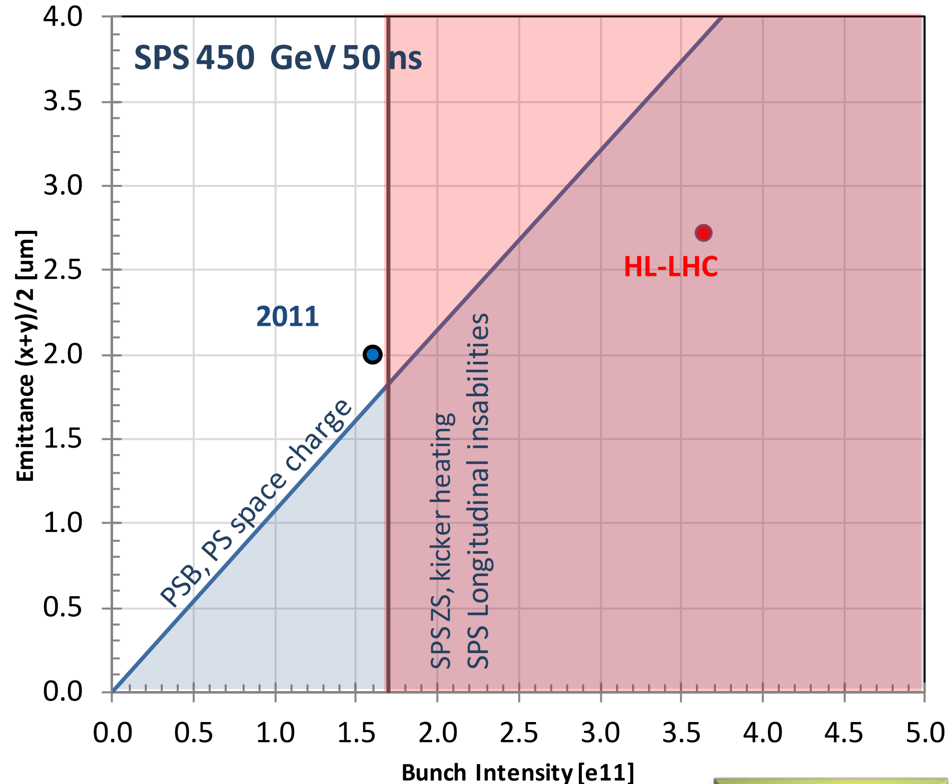
LHC injector complex

Duoplasmatron	=	Source □90 keV (kinetic energy)
LINAC2	=	Linear accelerator □50 MeV
PSBooster	=	Proton Synchrotron Booster □1.4 GeV
PS	=	Proton Synchrotron □25 GeV
SPS	=	Super Proton Synchrotron □450 GeV
LHC	=	Large Hadron Collider □7 TeV



Injectors: 2011 to post-LS2



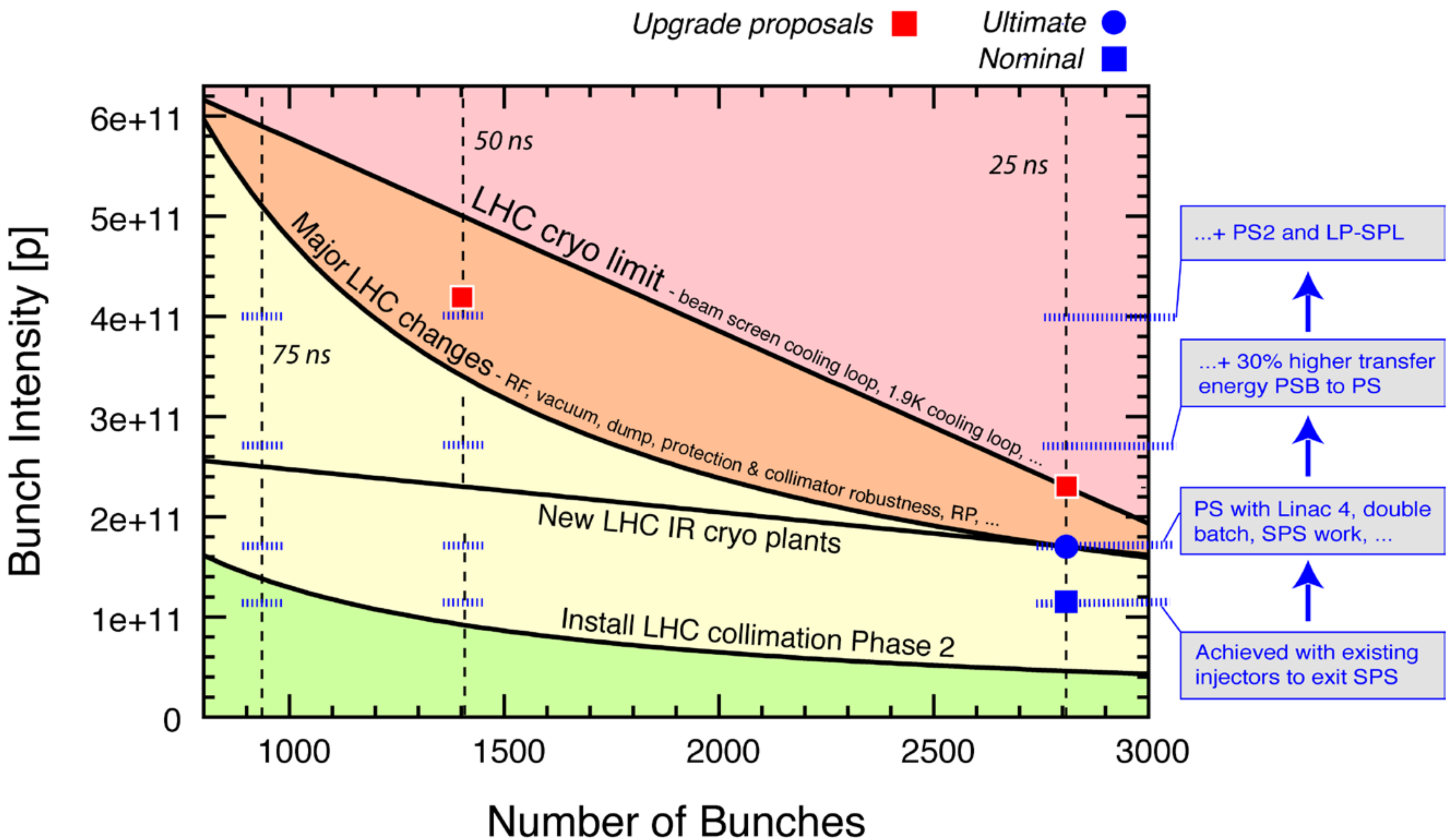


Brennan Goddard

- 2011/12 was excellent:
  - 1.6e11 with 2.5 um for 50 ns (at LHC flat-top)
  - Around 1.1 e11 with 2.8 um for 25 ns, extracted from SPS
- Large improvement is required for either 25 or 50 ns beam!

Summary of LHC Intensity Limits (7 TeV)

R. Assman @ Chamonix 2010



Increasing Luminosity - some issues

Accelerator Physicist

- The easiest way to achieve high luminosity at the LHC is to put lots of current in a smaller number of bunches
  - This has a nasty side effect of many more interactions per crossing (up to 500 pp events per crossing!)

Experimentalist

- Integrated Luminosity is the vital statistic
- Lots of luminosity is not so useful if it results in a lot of interactions in each crossing
- The more stable the conditions the better

HL-LHC Parameters

Parameters agreed on at the 2nd HL-LHC Coordination Group

-maximum of 140 events per crossing

➔ $L = 5\ 10^{34}\ cm^{-2}\ sec^{-1}$ for 25ns

➔ $L = 2.5\ 10^{34}\ cm^{-2}\ sec^{-1}$ for 50ns

Pile-up density leveling

➔ Leveling options?

-goal for integrated annual luminosity:

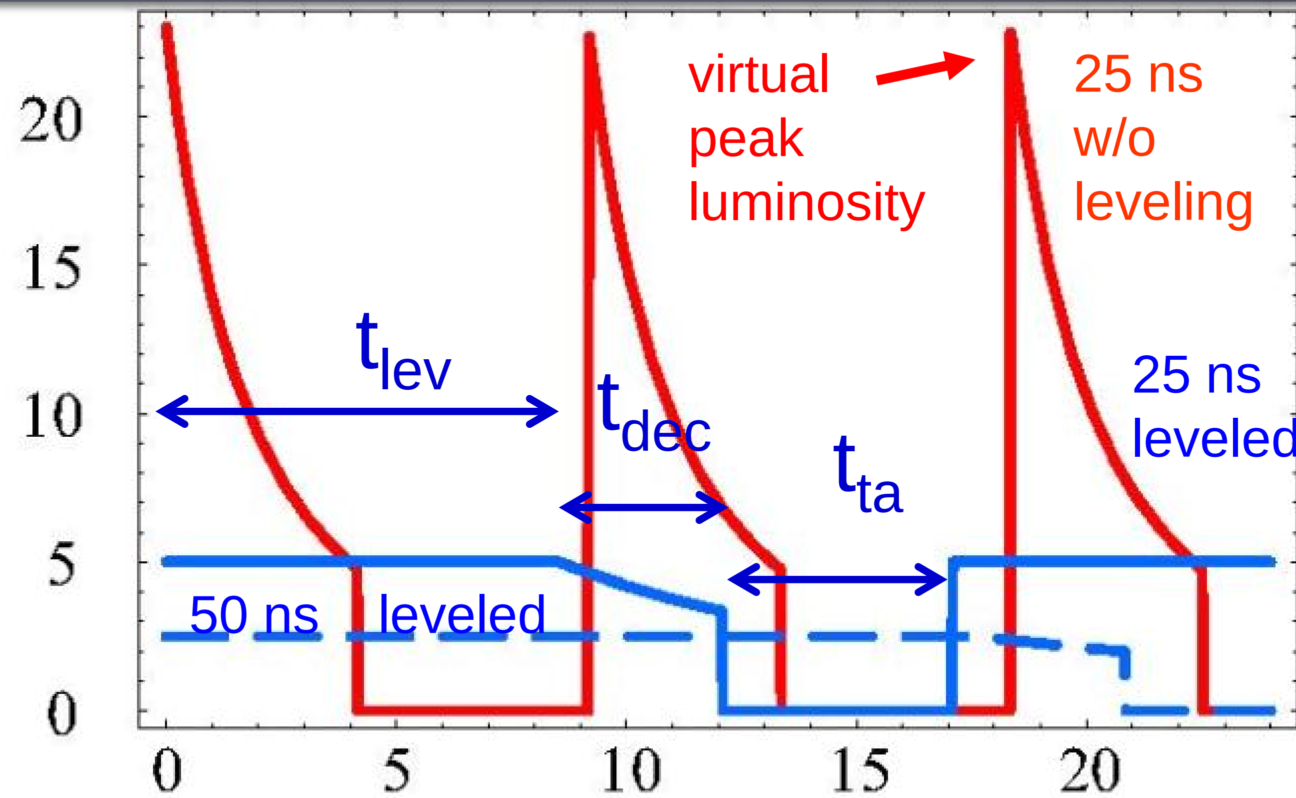
➔ $250\ fb^{-1}$ per year

-Total luminosity for HL-LHC project

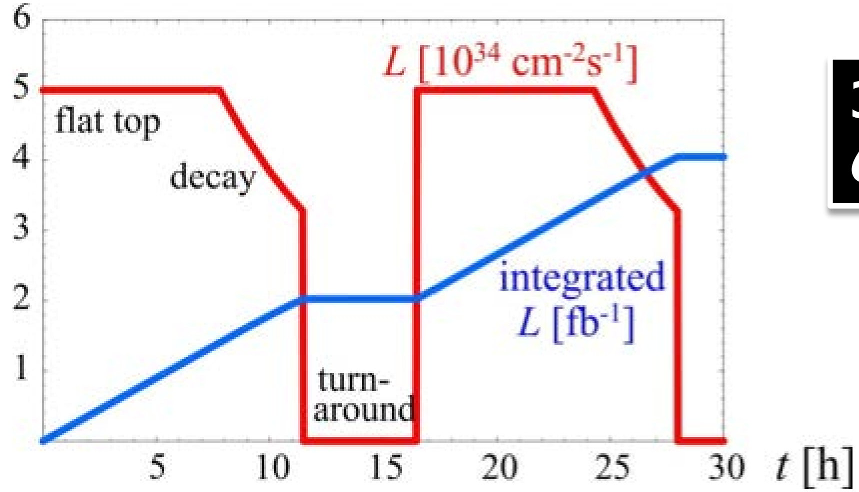
➔ $3000\ fb^{-1}$ total

Luminosity Leveling

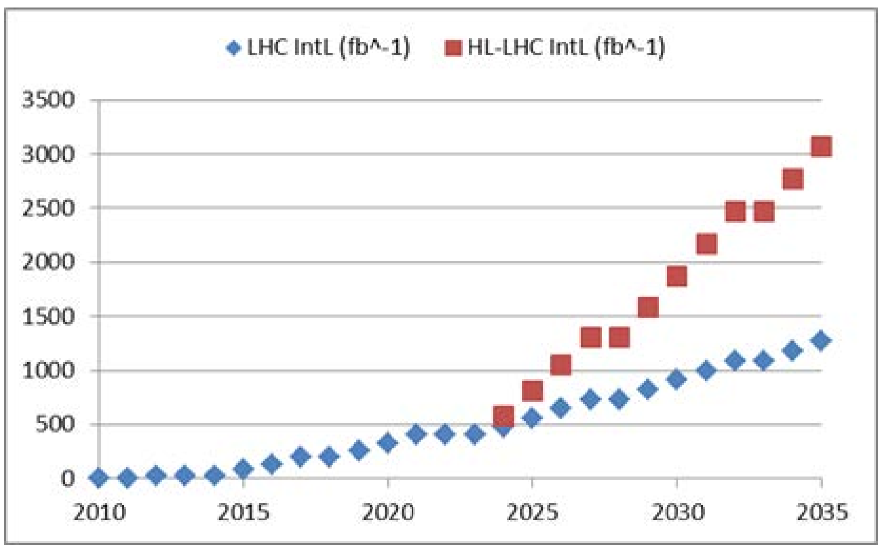
Leveling reduces the pile-up seen in the detectors.
Protons are "stored" in the beam
Integrated luminosity the key -Reduce the number of fills, turnaround time …



Final goal : 3000 fb^{-1} by 2030's…



3/fb per day
60% of efficiency



HL-LHC

Consolidation only

HL-LHC Performance Estimates

'Stretched' Baseline Parameters following 2nd HL-LHC-LIU:

Parameter	nominal	25ns	50ns
N	1.15E+11	**2.2E+11**	**3.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.12**	**0.89**
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**18.5**	**17.2**
IBS longitudinal [h]	61 -> 60	**20.4**	**16.1**
Piwinski parameter	0.68	**3.12**	**2.85**
geom. reduction	0.83	**0.305**	**0.331**
beam-beam / IP	3.10E-03	**3.3E-03**	**4.7E-03**
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**
Virtual Luminosity	$1.2\ 10^{34}$	**$24\ 10^{34}$**	**$26\ 10^{34}$**
Events / crossing (peak & leveled L)	19 -> 28	**476** / **140**	**207** / **140**

6.2 10^{14} and 4.9 10^{14} p/beam

→ sufficient room for leveling (with Crab Cavities)

Virtual luminosity (25ns) of $L = 7.4 / 0.305\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 24\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 5)

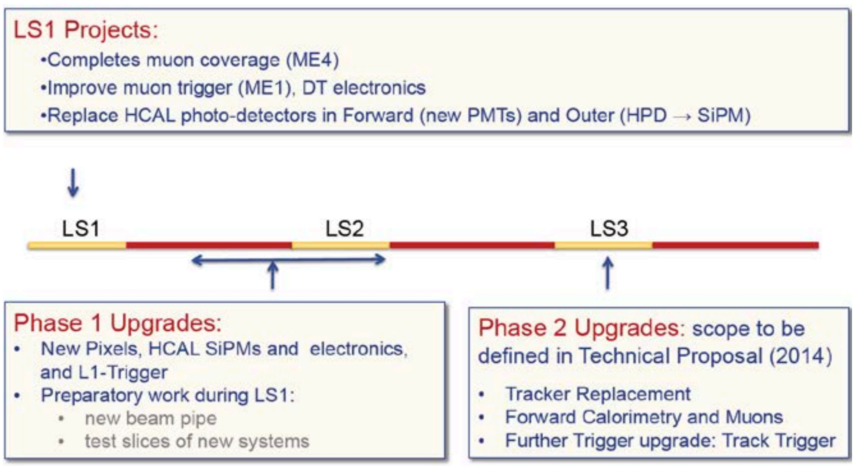
Virtual luminosity (50ns) of $L = 8.5 / 0.331\ 10^{34}\ cm^{-2}\ s^{-1}$

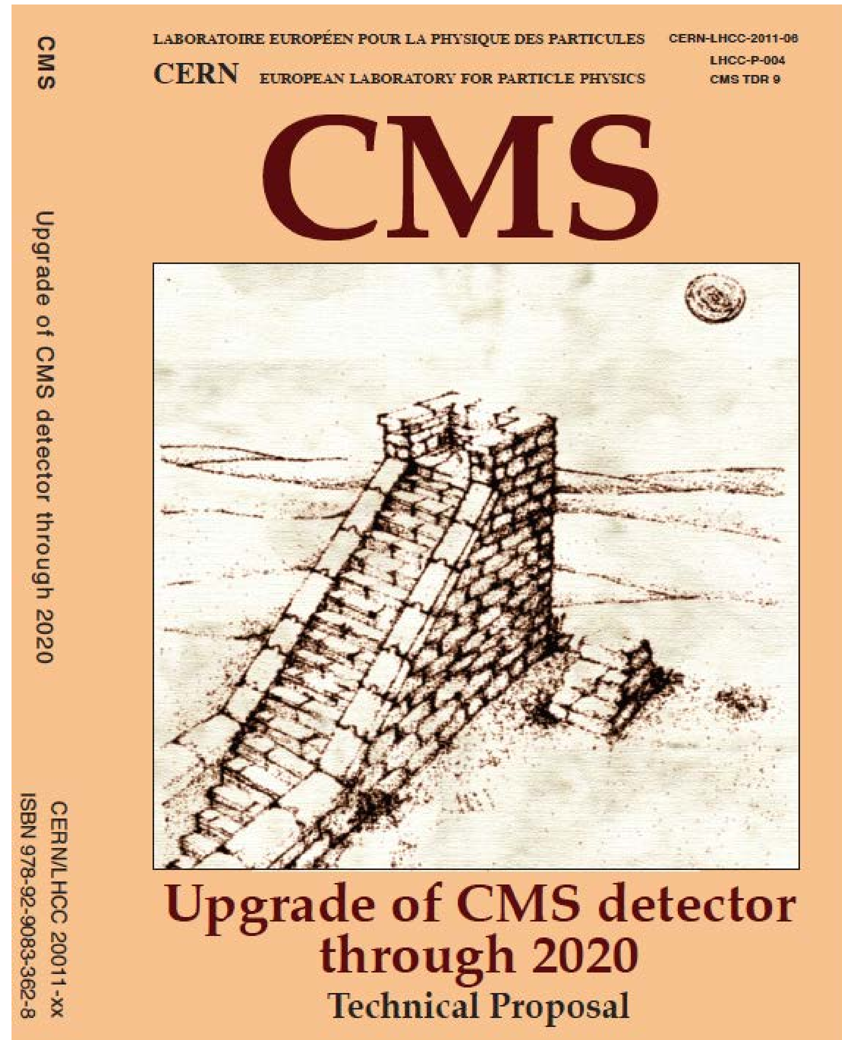
$= 26\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 10)

(Leveled to 5 $10^{34}\ cm^{-2}\ s^{-1}$ and 2.5 $10^{34}\ cm^{-2}\ s^{-1}$)

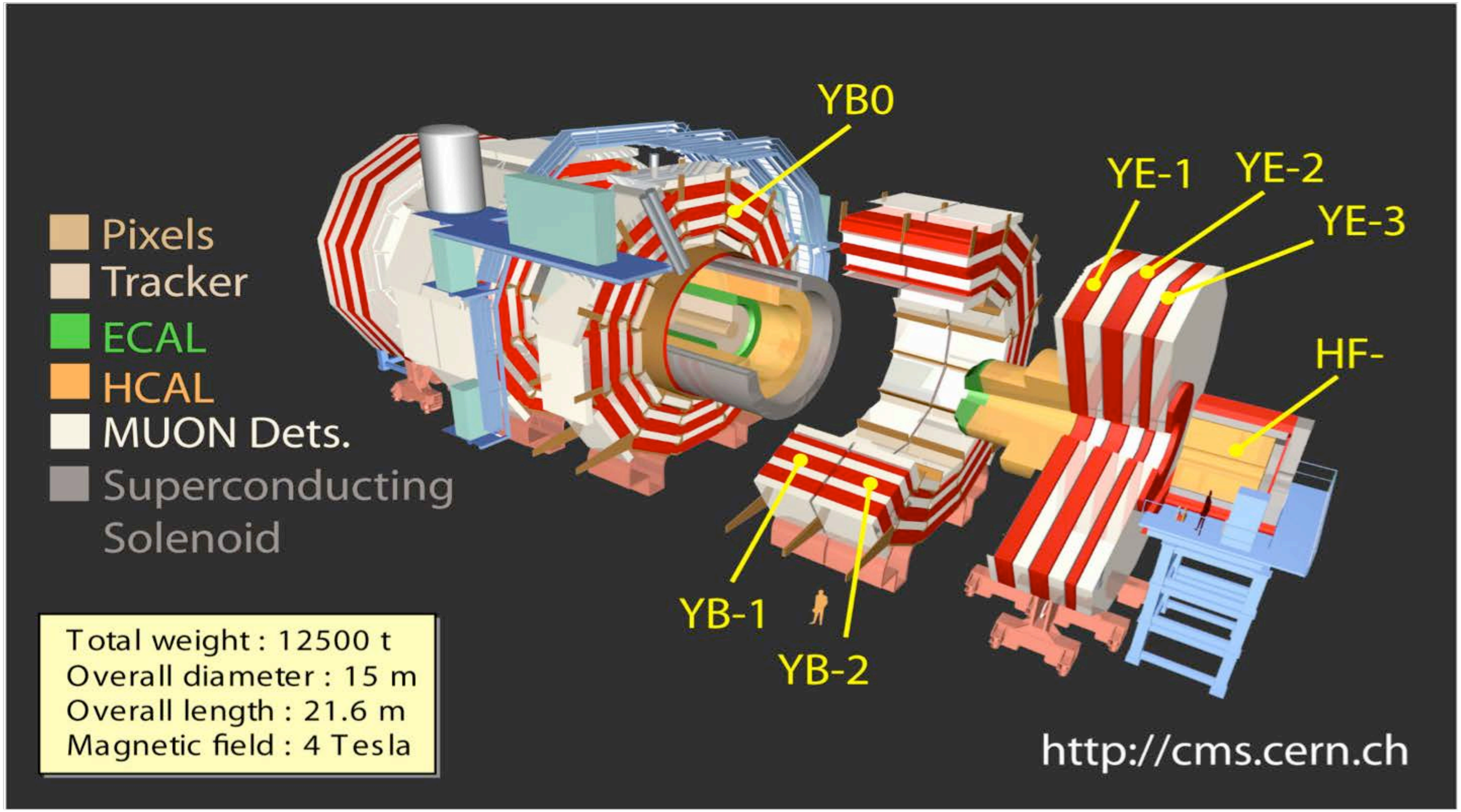
Challenges for the detectors

The detectors have been preparing programmes to deal with the increasing luminosity of the LHC in the coming decades



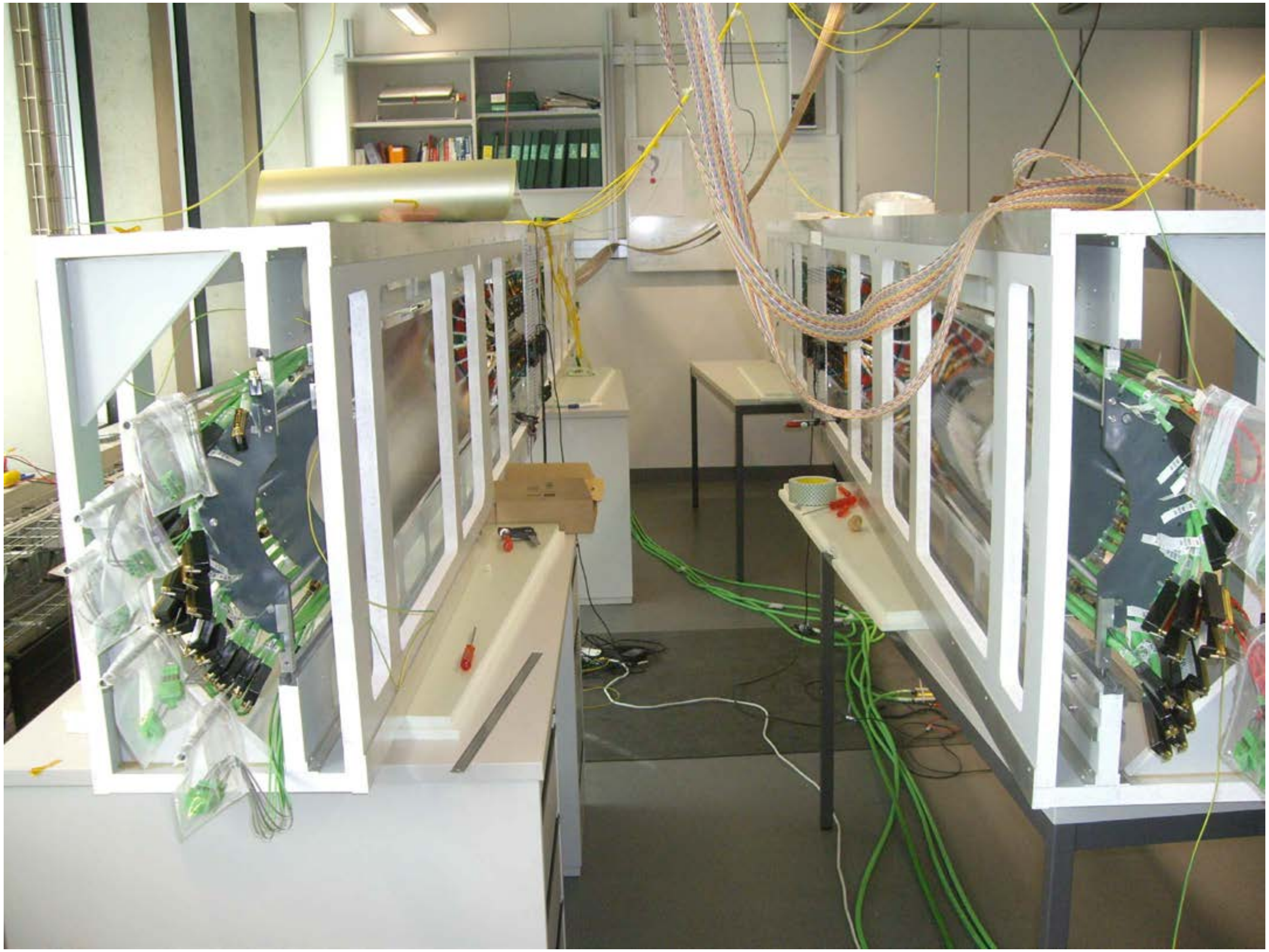


The CMS Detector

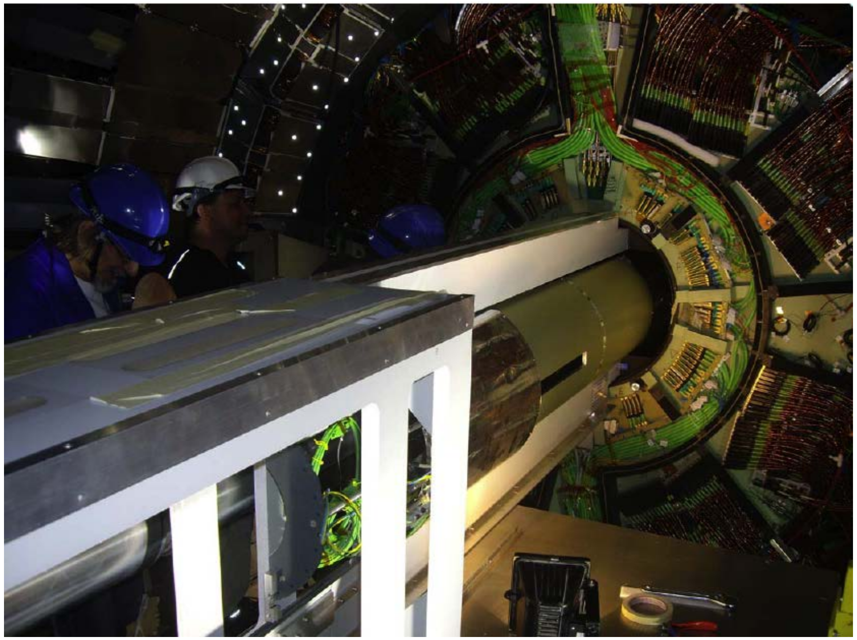


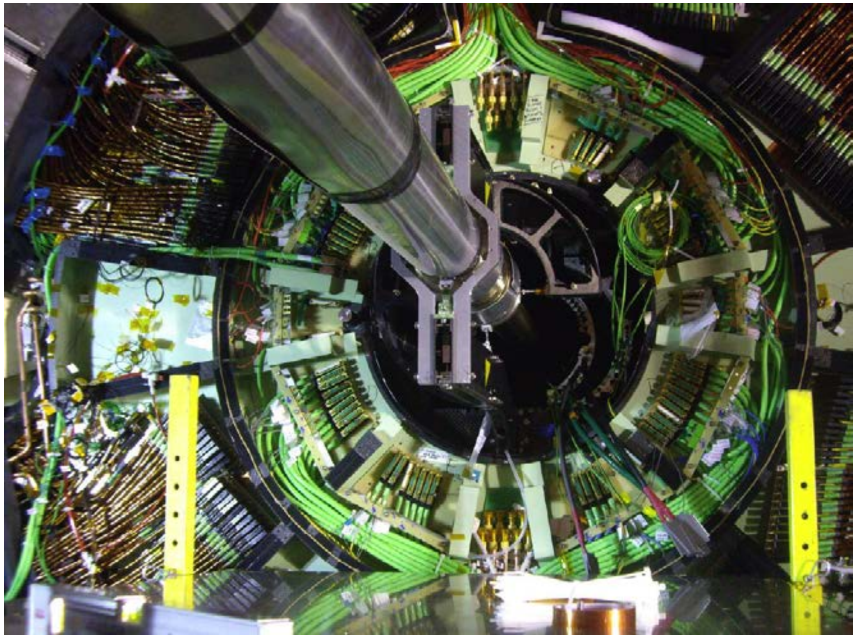
Minus end just before closure

CMS Pixel system can be removed in a very short time period



Trial insertion of Pixel system



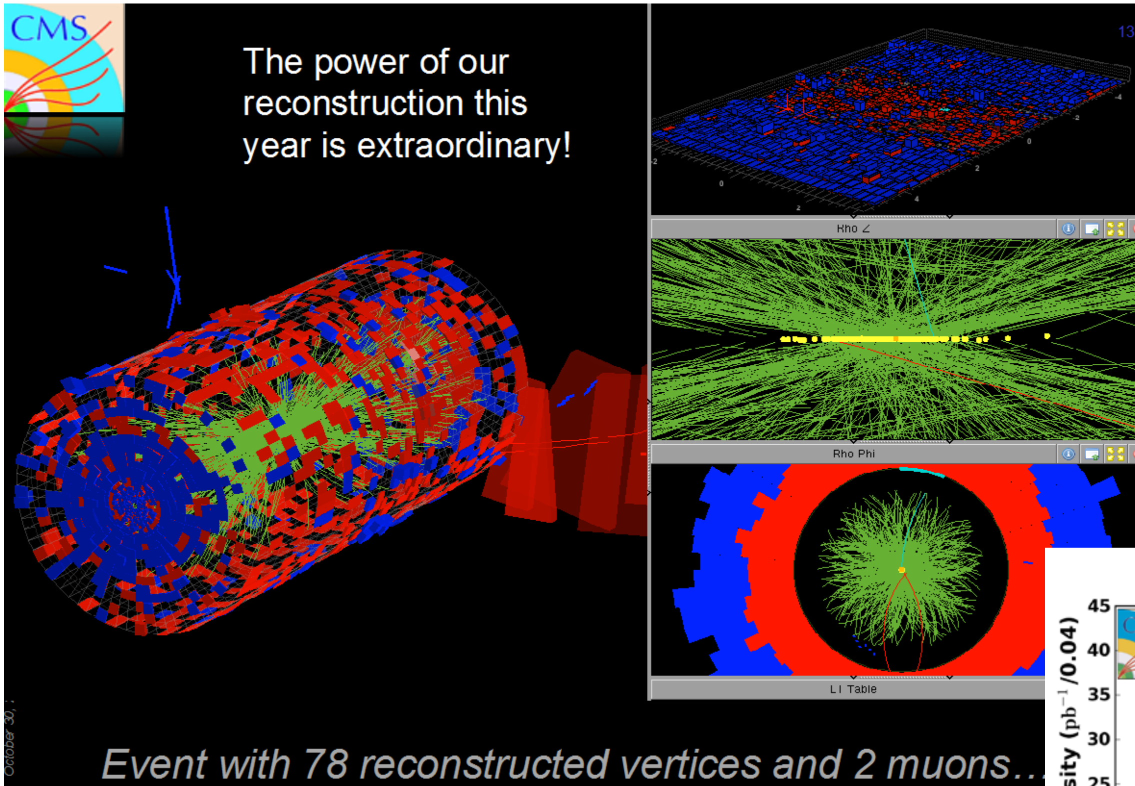


Insertion of the Pixel was done in a few hours

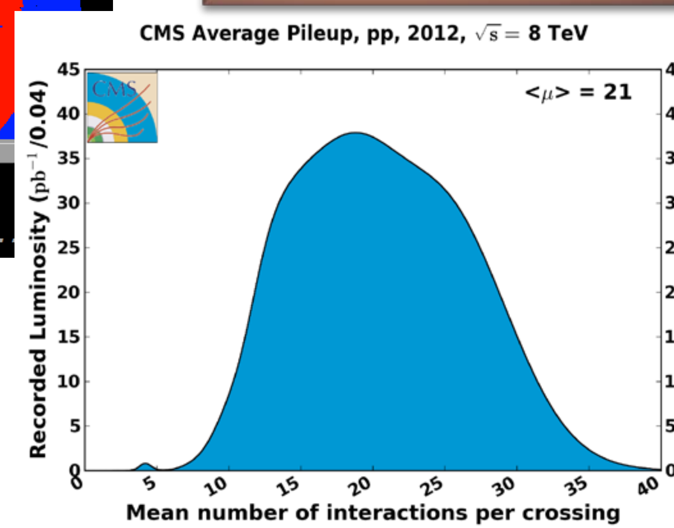
Reminder: CMS Upgrade Scope

System	LS1/LS2	LS3
Pixel	New Pixel Detector	
Tracker		New Tracking System (incl Pixel)
HCAL	Back End Electronics + PD replacement	HF/HE?
ECAL	Trigger Primitive Transmission	EE?
Muons	ME4/2, ME1/1 ,RPC endcap, Minicrate spares, some CSC Electronics	Electronics replacement
Trigger	HCAL/RCT/GCT to µTCA	Complete replacement

More luminosity means more pileup



Because the LHC is running with 50ns bunch spacing, pile-up is already at design levels.

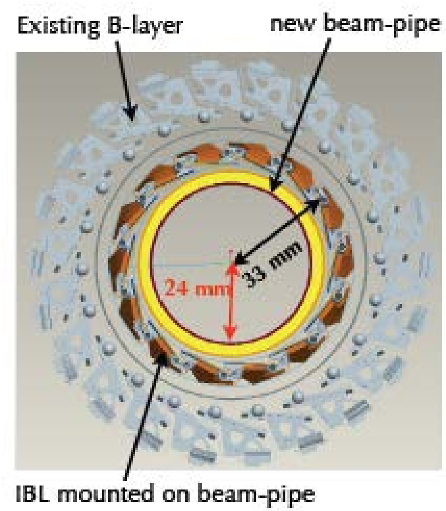


First stage of upgrades must cope with about a factor of two above the design luminosity of the LHC.

The inner tracking layers are crucial

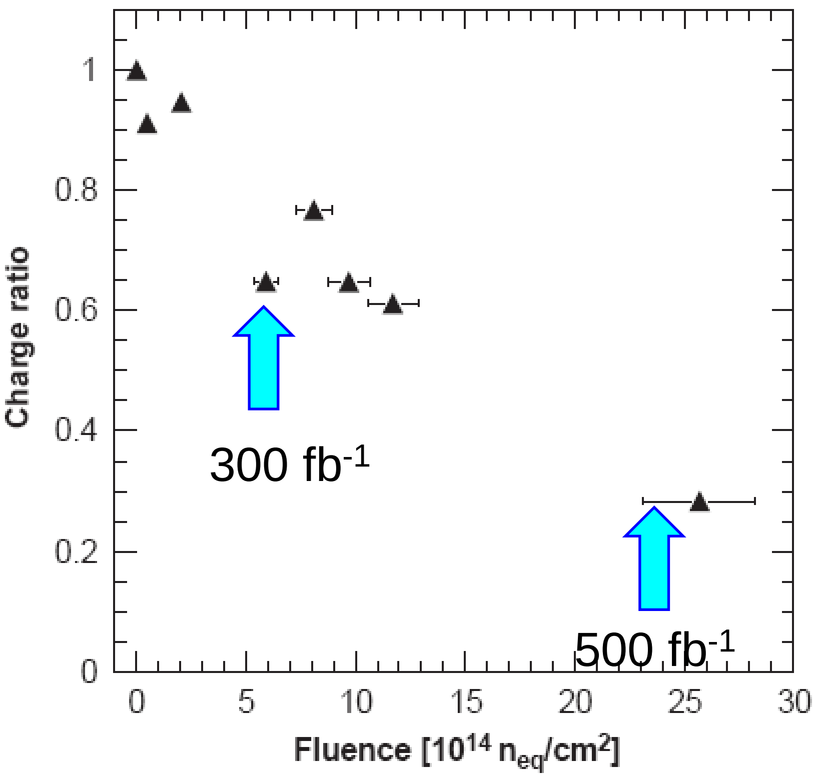
Atlas Inner B Layer (IBL) upgrade

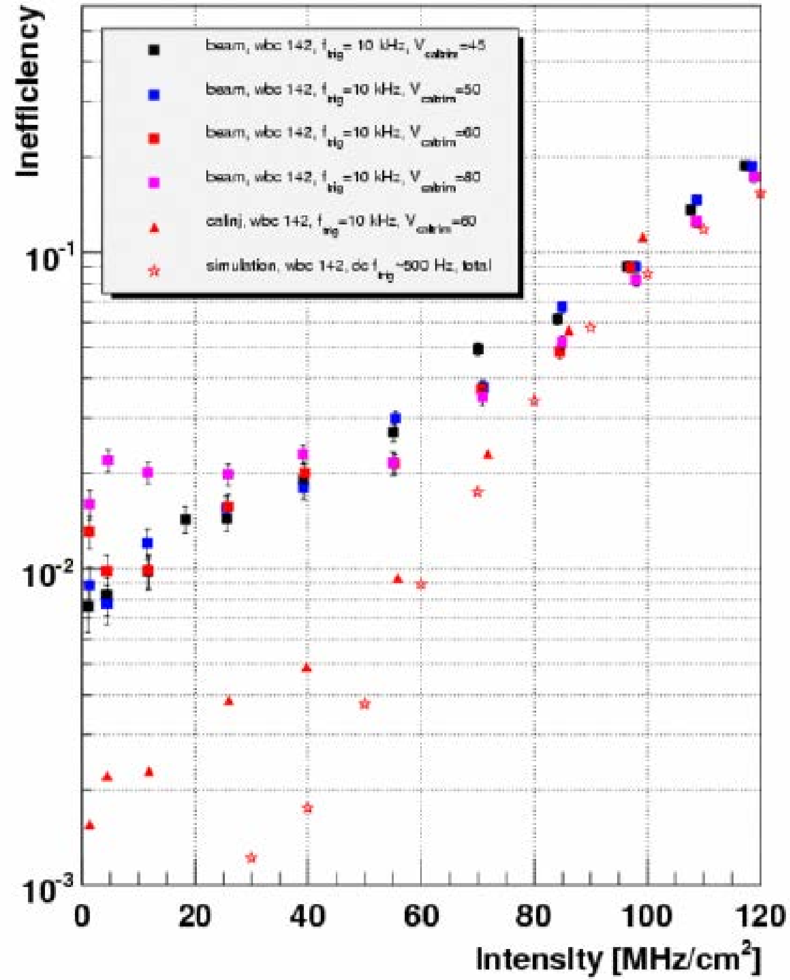
- A new tracking layer installed inside the existing Pixel detector
- Installed around a new beam-pipe with a smaller inner radius
- IBL Modules and staves - Status
  - Sensors & Chips done, Bump-bonding: processing of sensor and electronic wafers
    completed - first batch of bare modules received, under assembly and qualification
  - First IBL stave assembled and systematically tested
- Installed this shutdown



Limitations in Phase 1

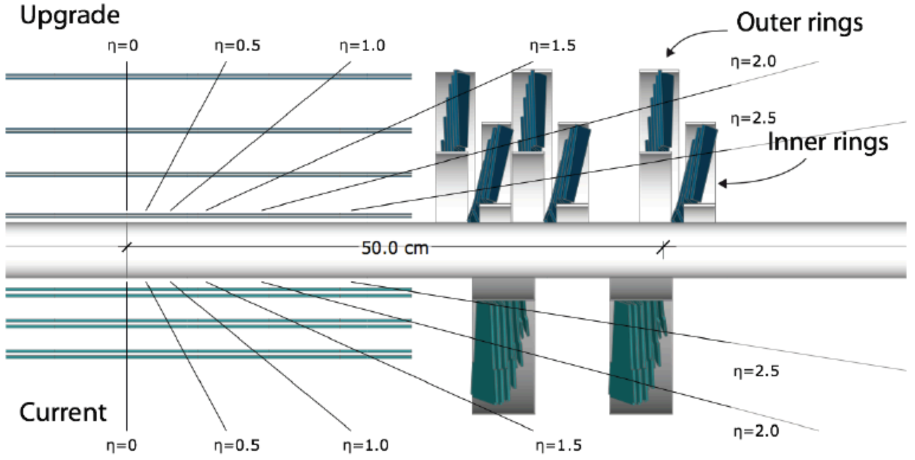
- Radiation damage due to integrated luminosity.
  - Sensors designed to survive $6\times10^{14} n_{eq}/cm^2$ (~ 300 fb^{-1}).
  - n-on-n sensors degrade gradually at large fluences

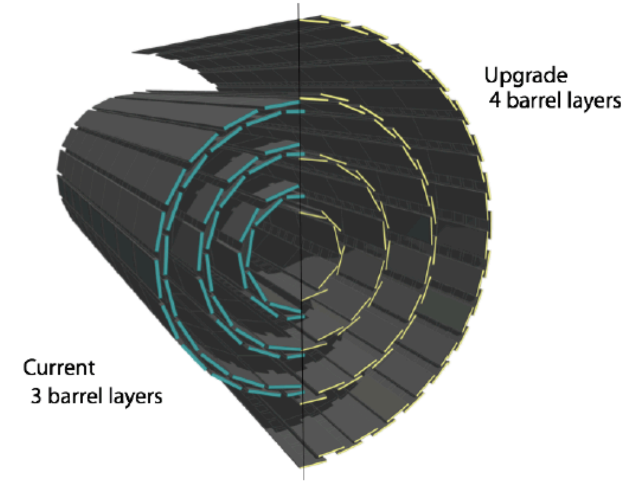




Dead time will rise to ~12% due to increase in peak luminosity

CMS Phase I Tracking upgrade





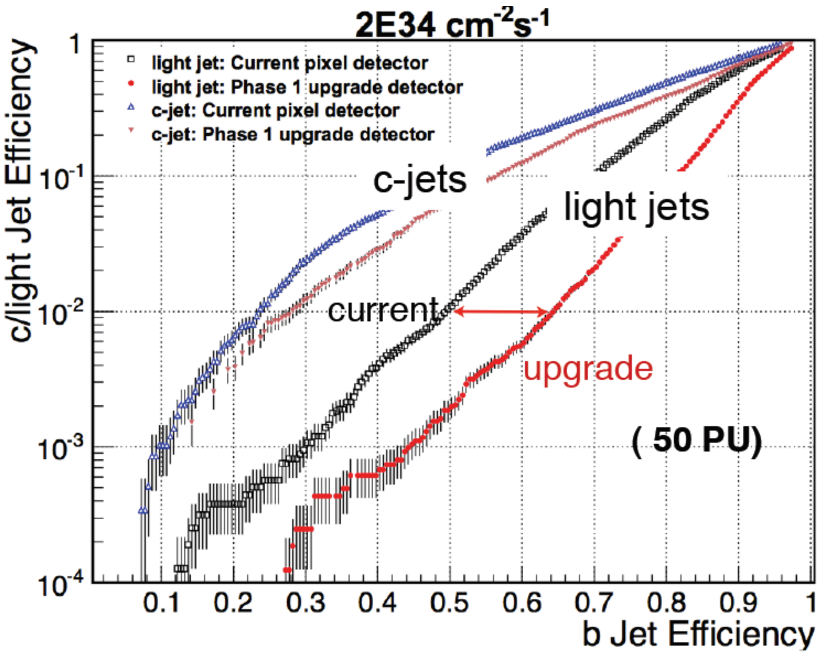
Upgraded Pixel Detector

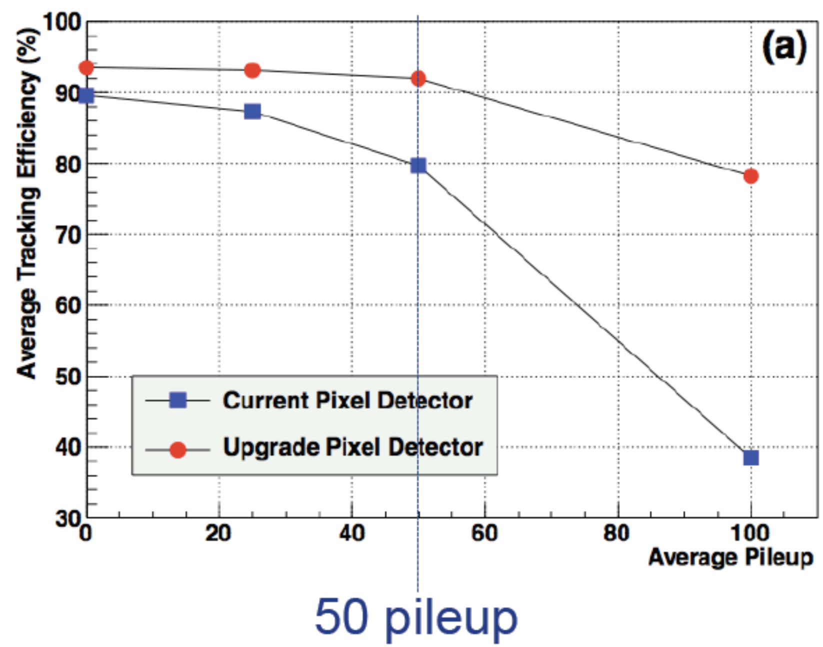
- **4 layers**: improved tracking efficiency (and lowers fake rate)
- **Less material**, better radial distribution
- **New readout chip** recovers inefficiency at high pileup

- Baseline L = $2x10^{34}$ $cm^{-2}sec^{-1}$ & 25ns → 50 pileup
- Tolerate L = $2x10^{34}$ $cm^{-2}sec^{-1}$ & 50ns → 100 pileup
- Survive Integrated Luminosity of $500fb^{-1}$ (Layer 1 2x $250fb^{-1}$)

- To be installed in Year End Technical Stop 2016-17

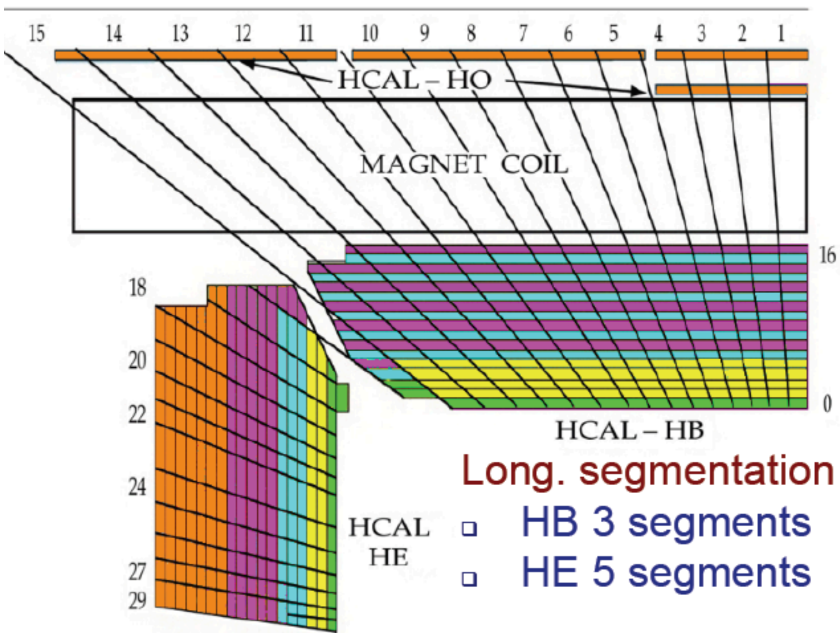
Improvements with new inner trackers





Substantial improvements in b-tagging and tracking efficiency in the higher pileup environment expected later in the decade

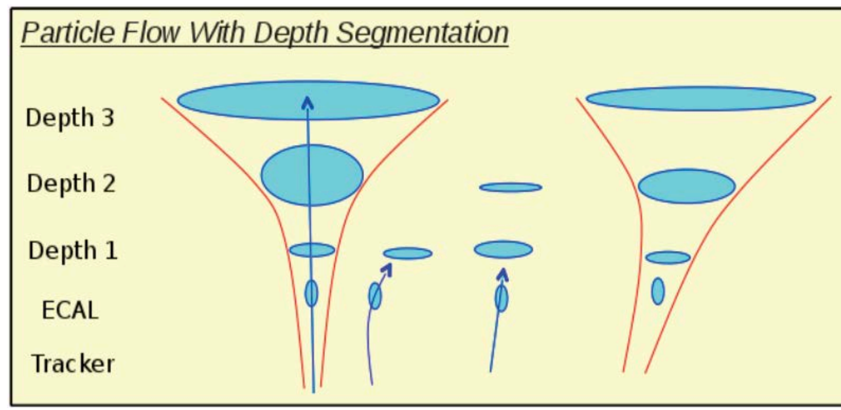
CMS – Hadronic Calorimeter Upgrade



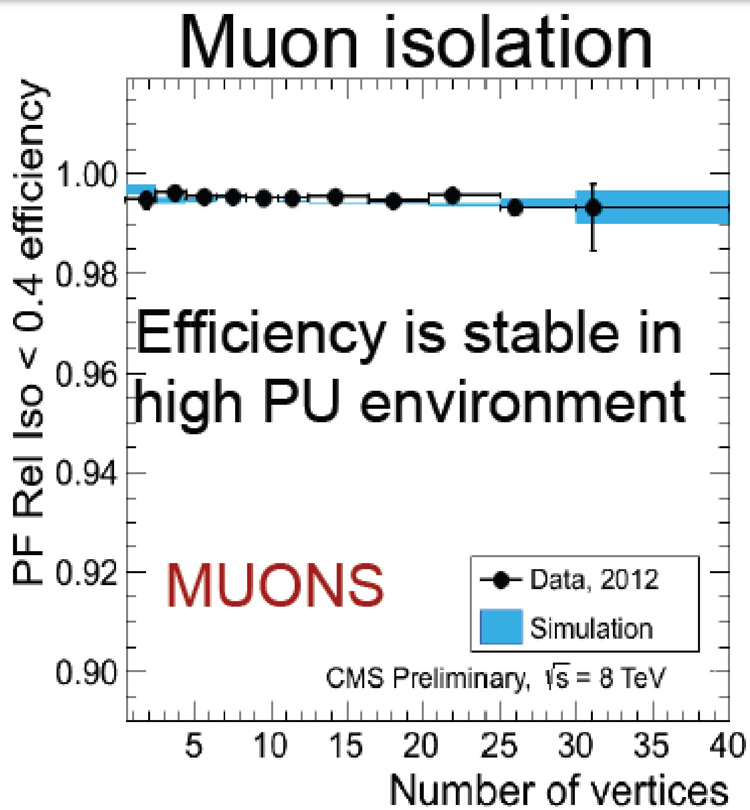
Long. segmentation

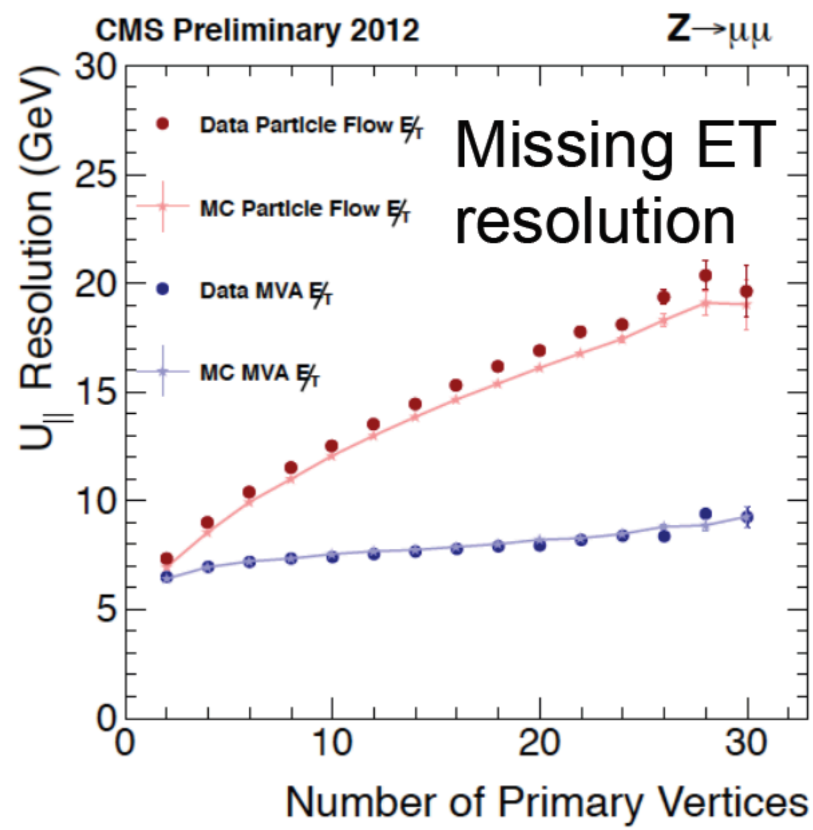
- HB 3 segments
- HE 5 segments

CMS will upgrade its Hadron Calorimeter with new photo-detectors allowing depth segmentation

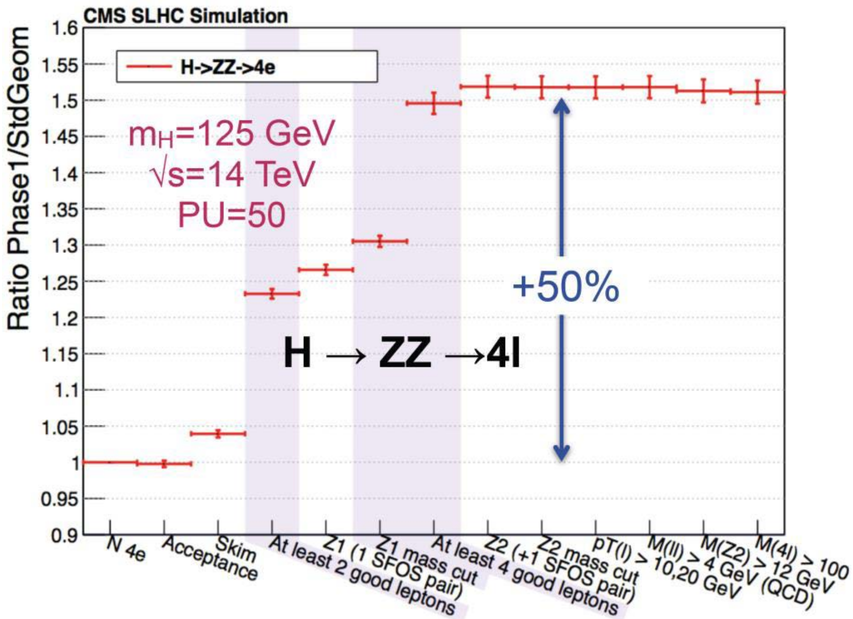


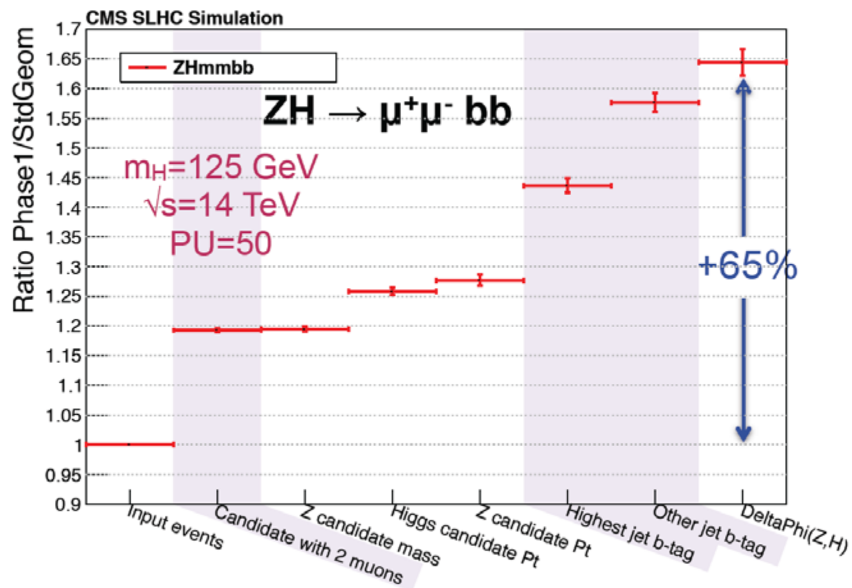
Using particle flow to mitigate pileup





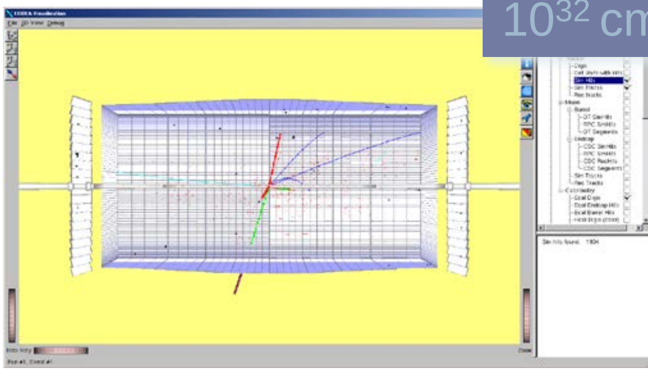
Improvements in Higgs measurements from Phase 1 detectors.



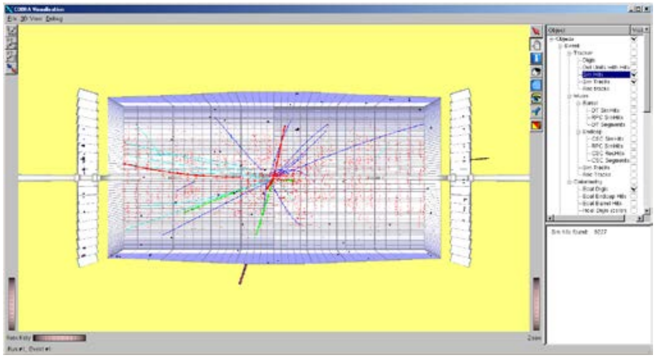


Detector Challenges from LHC to HL-LHC

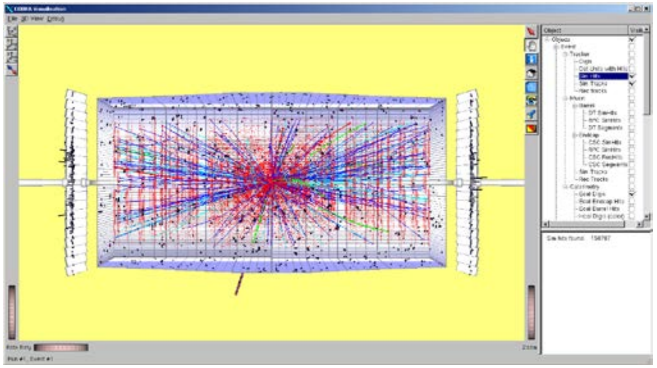
10^{32} cm^{-2} s^{-1}



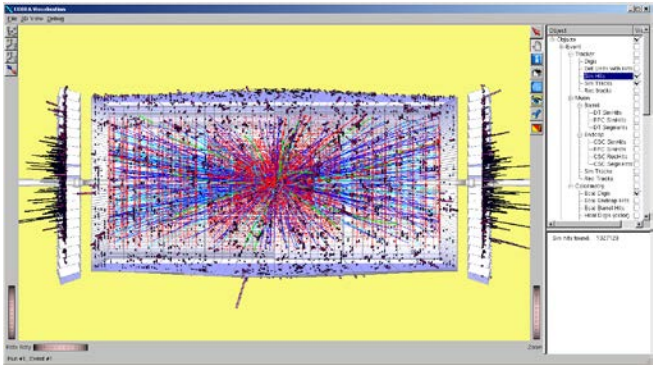
10^{33}



10^{34}

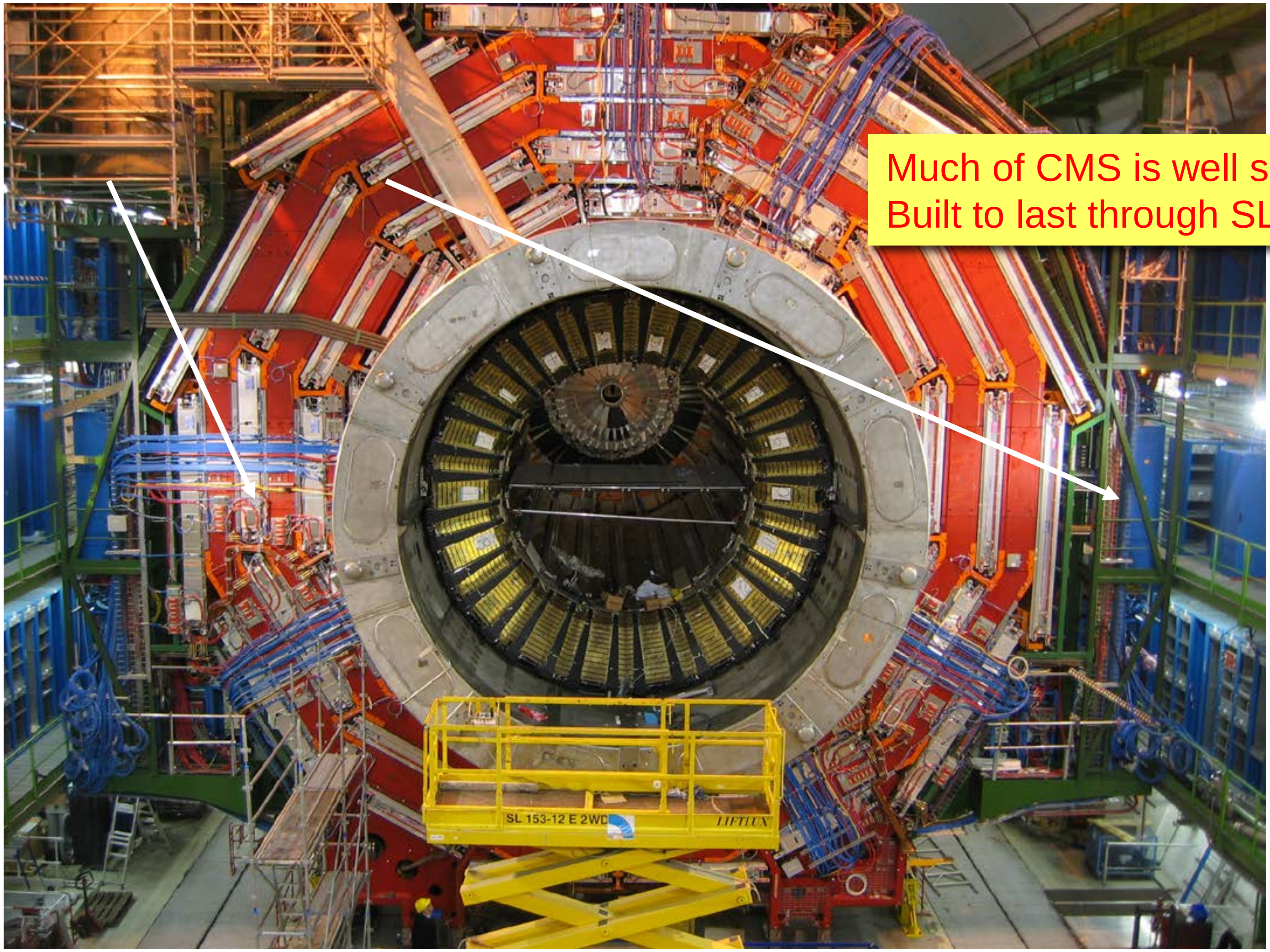


10^{35}



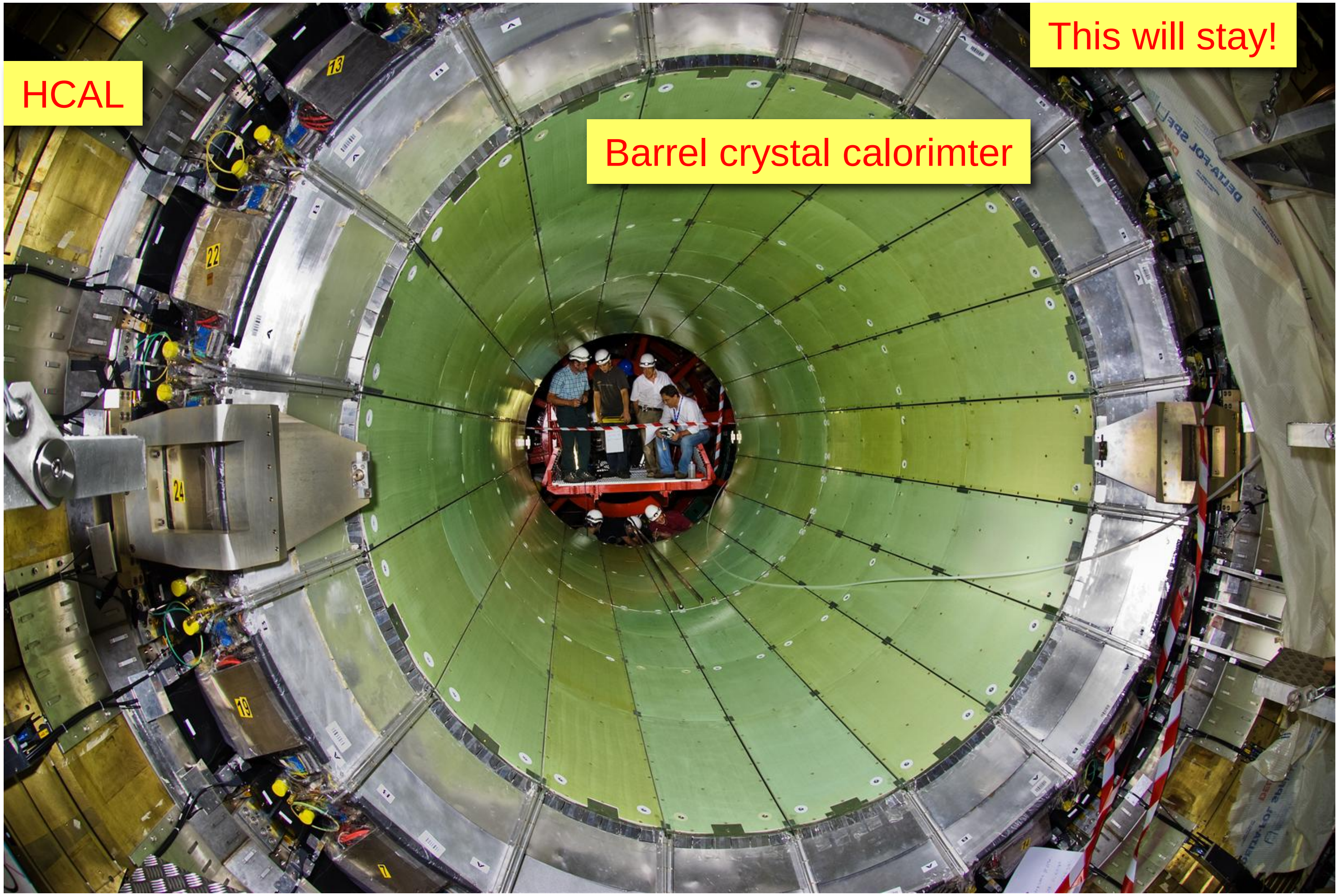
The trackers are the key detectors which will require upgrading for HL-LHC Phase 2 – Pile up will reach above 140 events/crossing

CMS - What stays, what goes phase 2



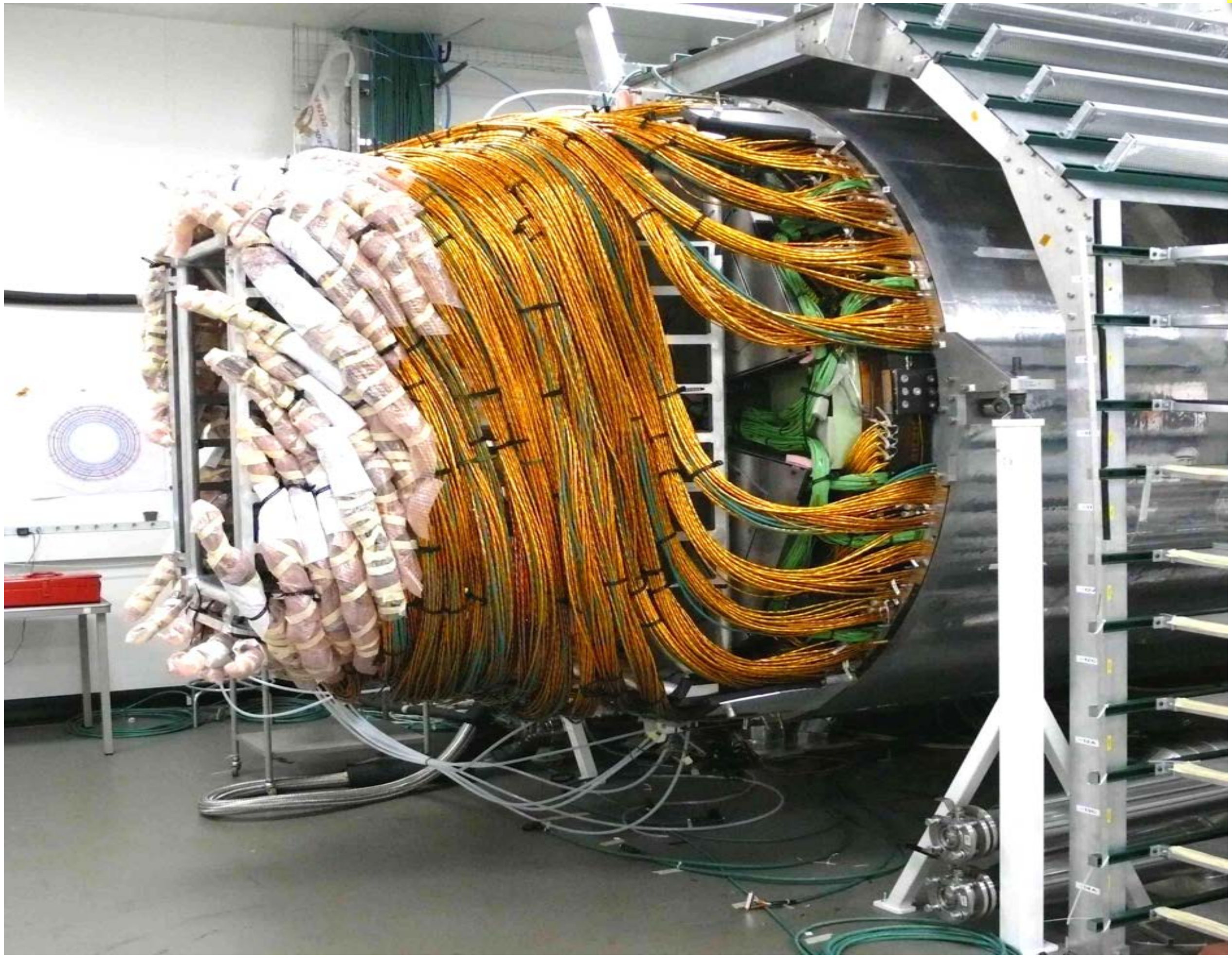
Much of CMS is well shielded and
Built to last through SLHC

Reminder what CMS will need to upgrade

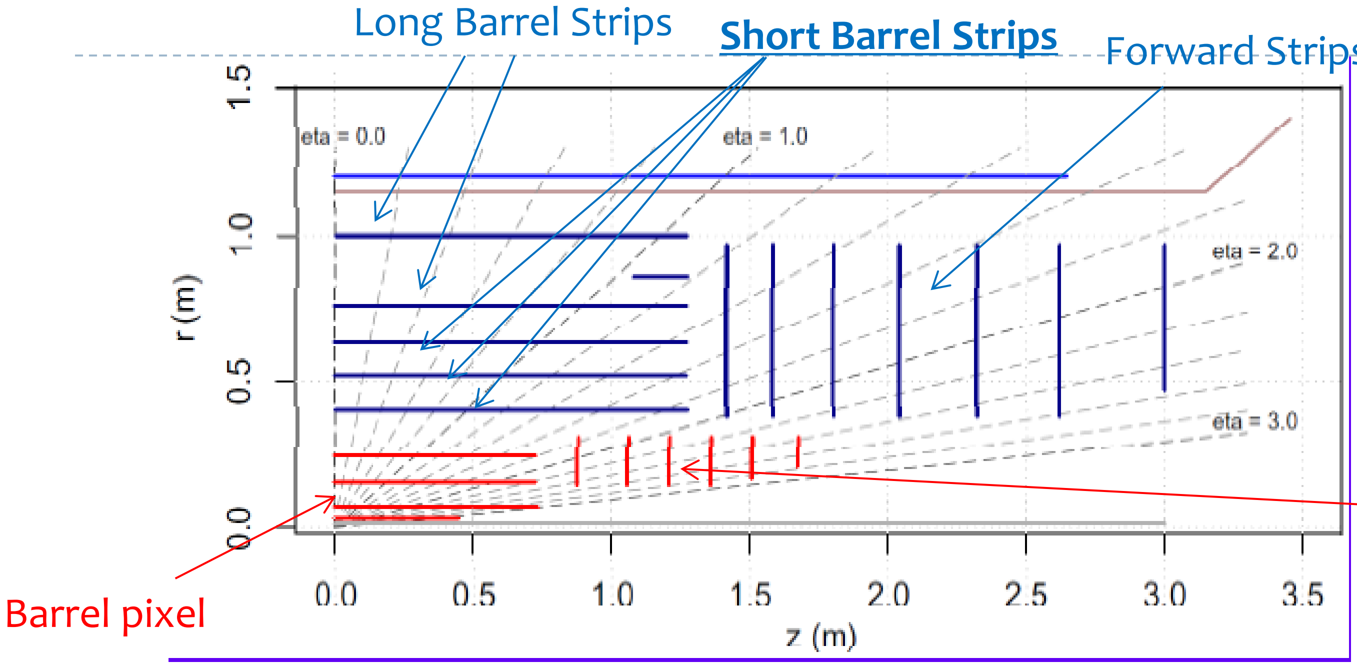


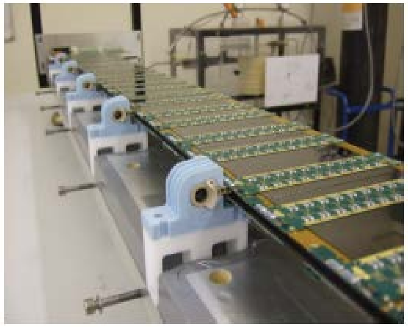
Tracker Readied for Transport to Pt5

This will be replaced



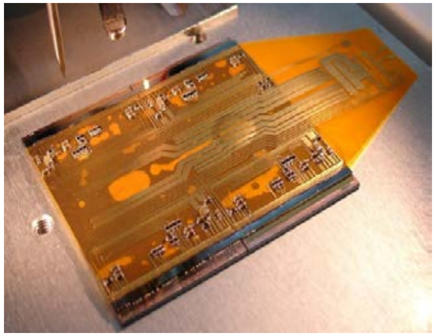
Phase 2 – ATLAS New All-silicon Inner Tracker



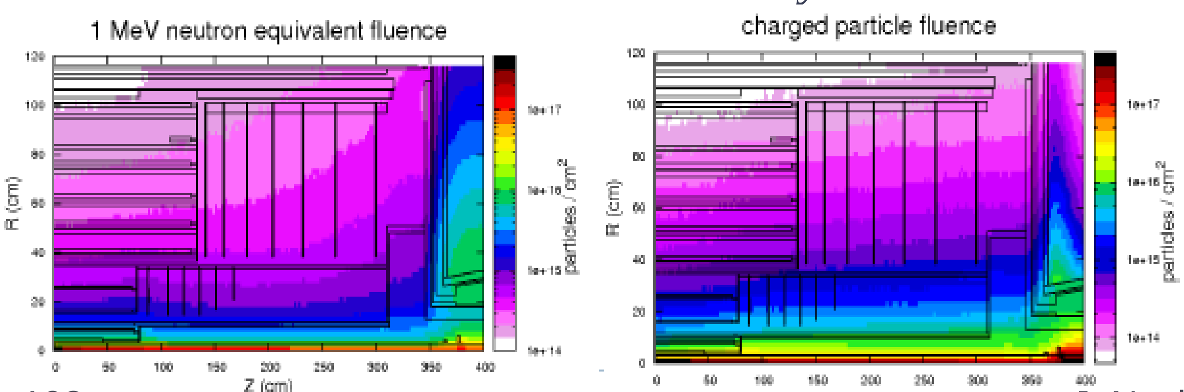


Microstrip Module Prototypes

Baseline layout of the new ATLAS inner tracker
Aim to have at least 14 silicon hits everywhere



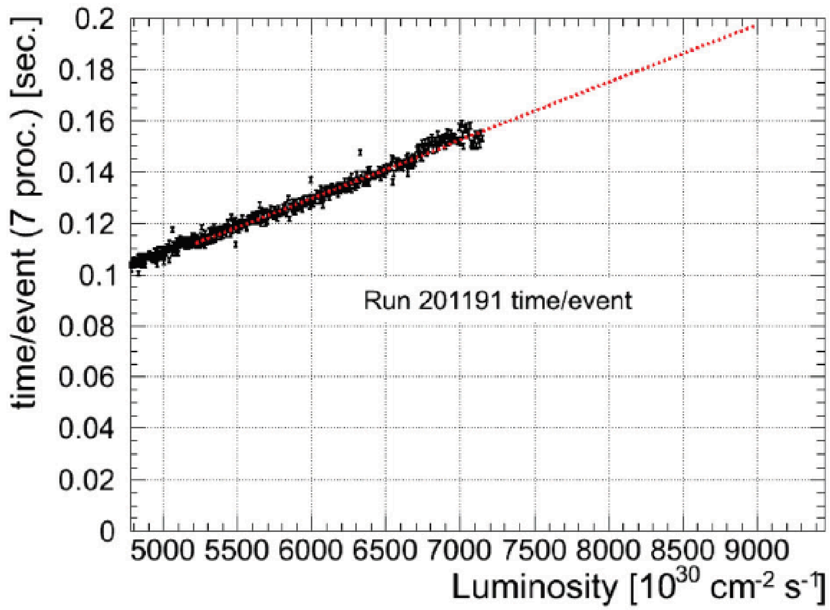
Pixel Quad Module Prototype

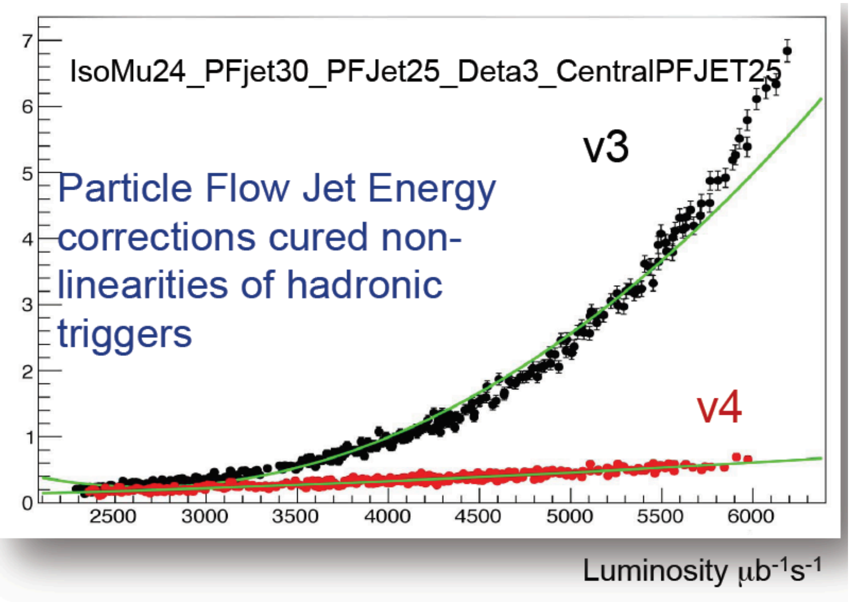


14 TeV collisions; integrated luminosity = 3000fb⁻¹

Trigger performance as luminosity increases will be vital

Both experiments will have major upgrades to their triggers to allow more information and processing



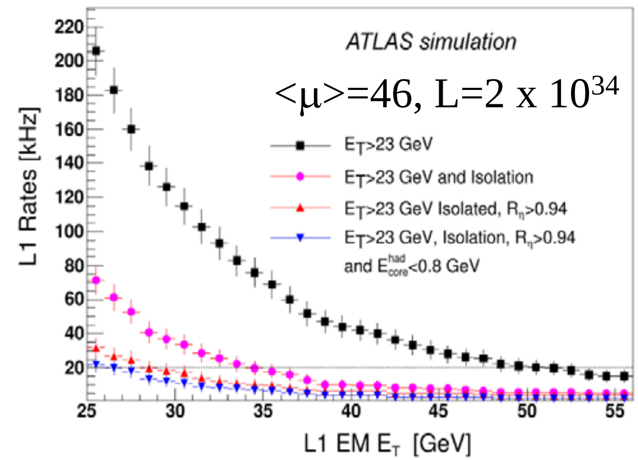


HLT Trigger processing time versus luminosity

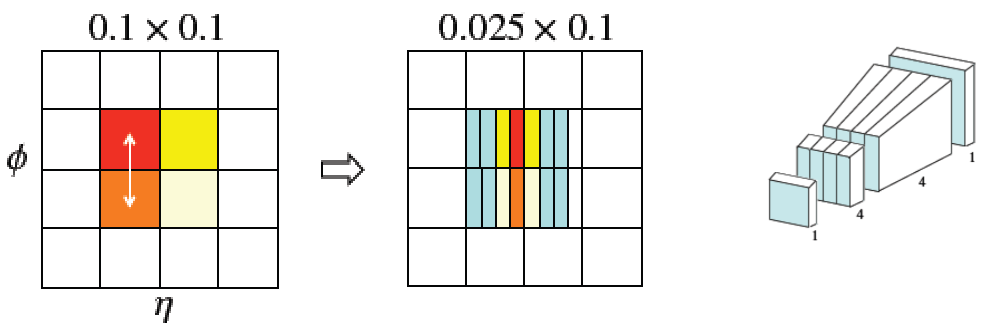
Hadronic trigger versus luminosity – vital to find/fix non-linearities in the system

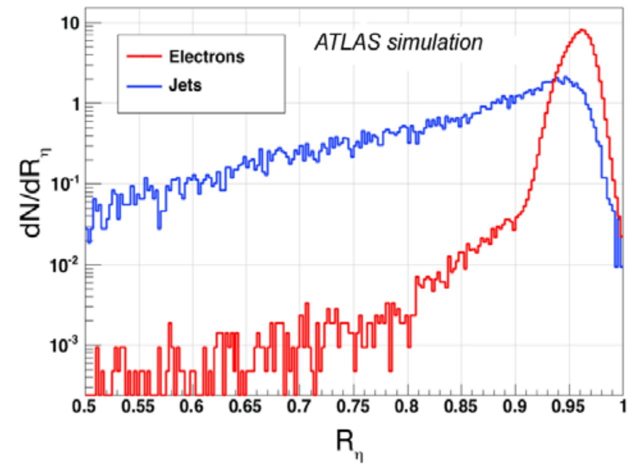
ATLAS LVL1 Calorimeter and Trigger

- Key target is to maintain high efficiency for Level-1 triggering on low PT leptons and photons
- In the calorimeter this implies changes to the front-end electronics to allow greater granularity to be exploited at Level-1.
- Trigger upgrades include topological trigger, cluster and jet energy processor, feature extractors, muon sector logic and CTP



electron rate vs threshold





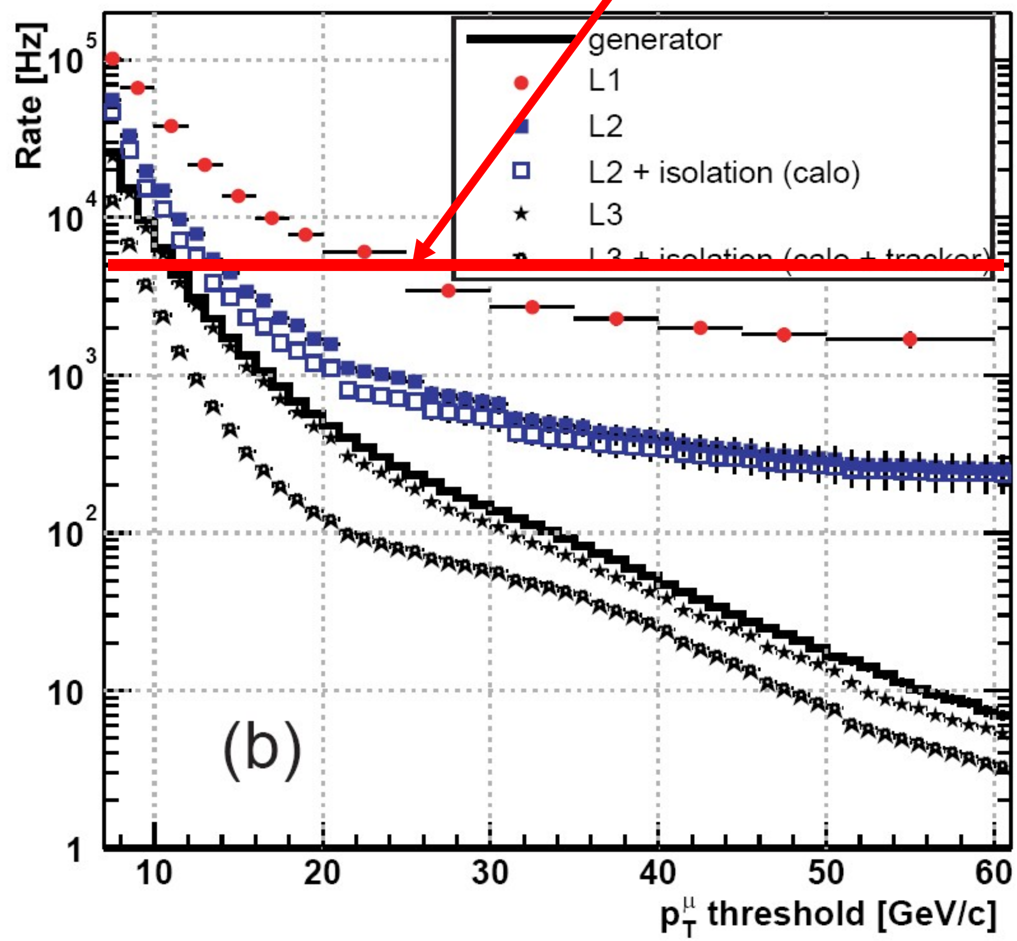
Distribution of the R_η parameter for electrons and jets, defined as the ratio of the energy in the 3x2 over the energy in the 7x2 clusters of the 2nd layer of the EM calorimeter.

P.Allport

CMS Level 1 Trigger

The Level 1 muon Trigger has no discrimination for P_T > ~ 20 GeV/c

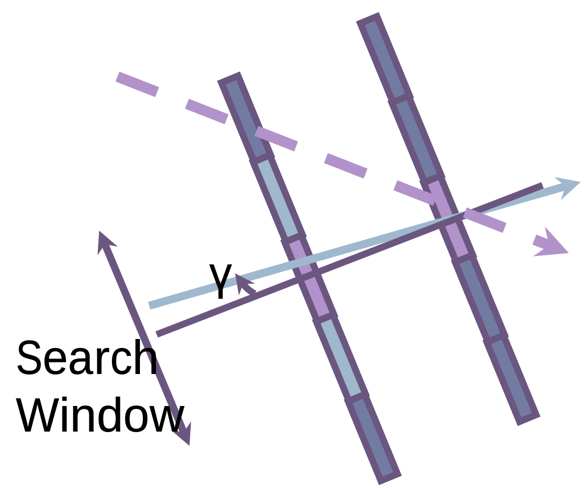
- The trigger/daq system of CMS will require an upgrade to cope with the higher occupancies and data rates at HL-LHC
- One of the key issues for CMS is the requirement to include some element of tracking in the Level 1 Trigger
  - One example: There may not be enough rejection power using the muon and calorimeter triggers to handle the higher luminosity conditions at HL-LHC
- Adding tracking information at Level 1 gives the ability to adjust P_T thresholds
- Single electron trigger rate also suffers
  - *Isolation criteria are insufficient to reduce rate at* $\mathcal{L} = 10^{35}\ cm^{-2}.s^{-1}$



Phase II – CMS Track Trigger

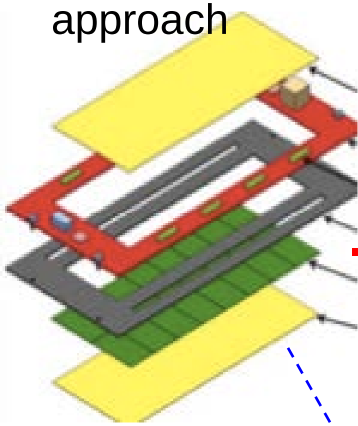
- A completely new tracking system
  - Able to handle the very extreme environment
    - High pileup implies high occupancy and in some areas high radiation exposure
  - Able to participate in the Level I Trigger Decision

- Take advantage of large magnetic field of CMS
- Correlate hits in two close silicon detector layers
  - Higher Pt objects will be correlated between layers
- Form Pt Stubs

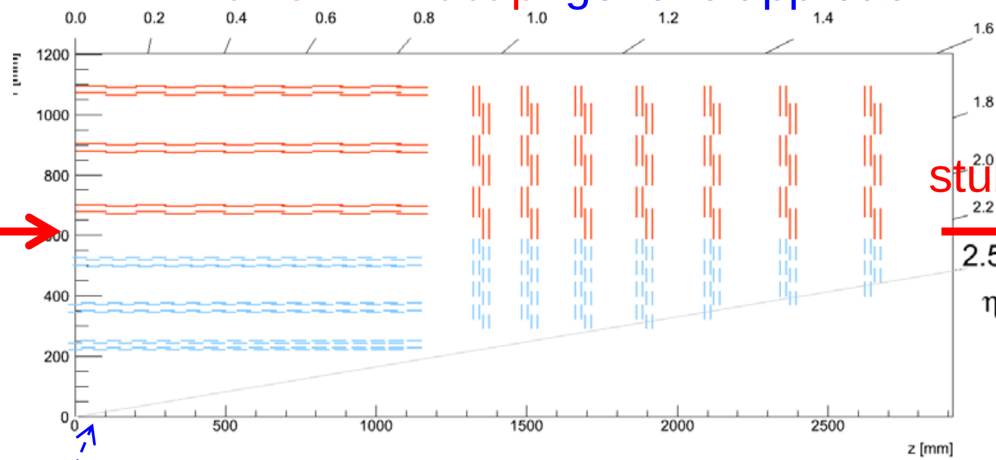


CMS Tracker with L1 trigger – concepts being explored

Conventional approach



Barrel + Endcap: generic approach

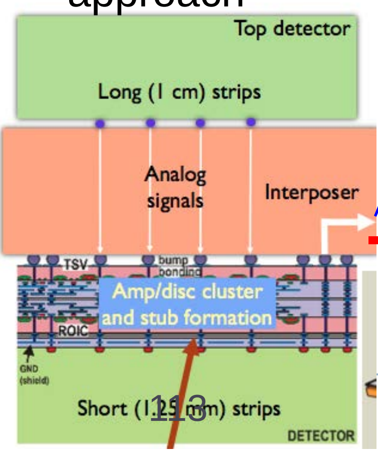


stubs

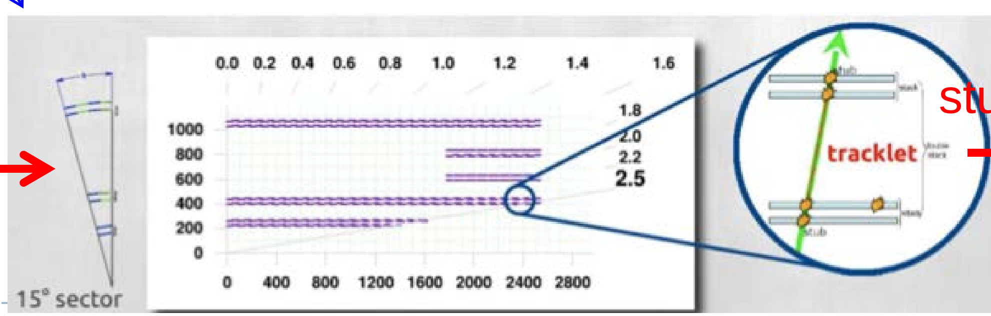
Generic Back-end processing

D. Abbaneo

Aggressive approach



Long Barrel approach

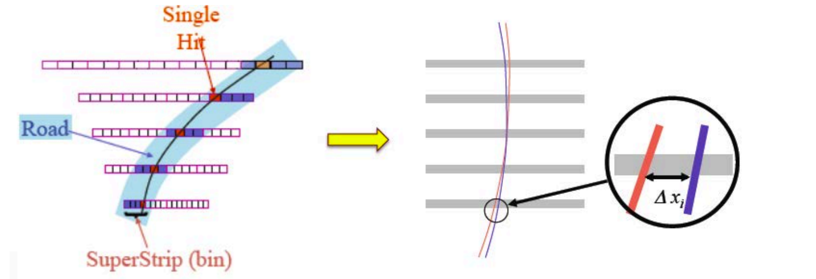


stubs

Special Back-end processing

ATLAS Fast Track Project

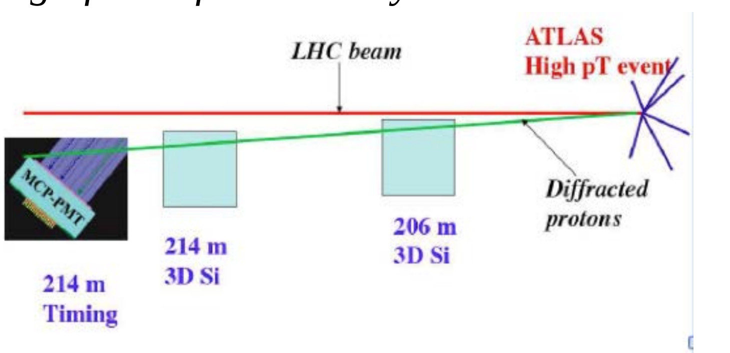
- Fast TracK (FTK): Global hardware based tracking by start of L2
  - Descendent of the CDF Silicon Trigger (SVT)
  - Inputs from Pixel and SCT.
  - Data in parallel to normal read-out.
  - Provides inputs to L2 in ~ 25 μs with track parameters at ~offline precision
    for b tagging, tau ID and lepton isolation
  - Two phases:
    - Pattern recognition (10^9)
    - Track fitting



Pattern recognition in coarse resolution (superstrip→road)

Track fit in full resolution (hits in a road)
$F(x_1, x_2, x_3, \ldots) \sim a_0 + a_1\Delta x_1 + a_2\Delta x_2 + a_3\Delta x_3 + \ldots = 0$

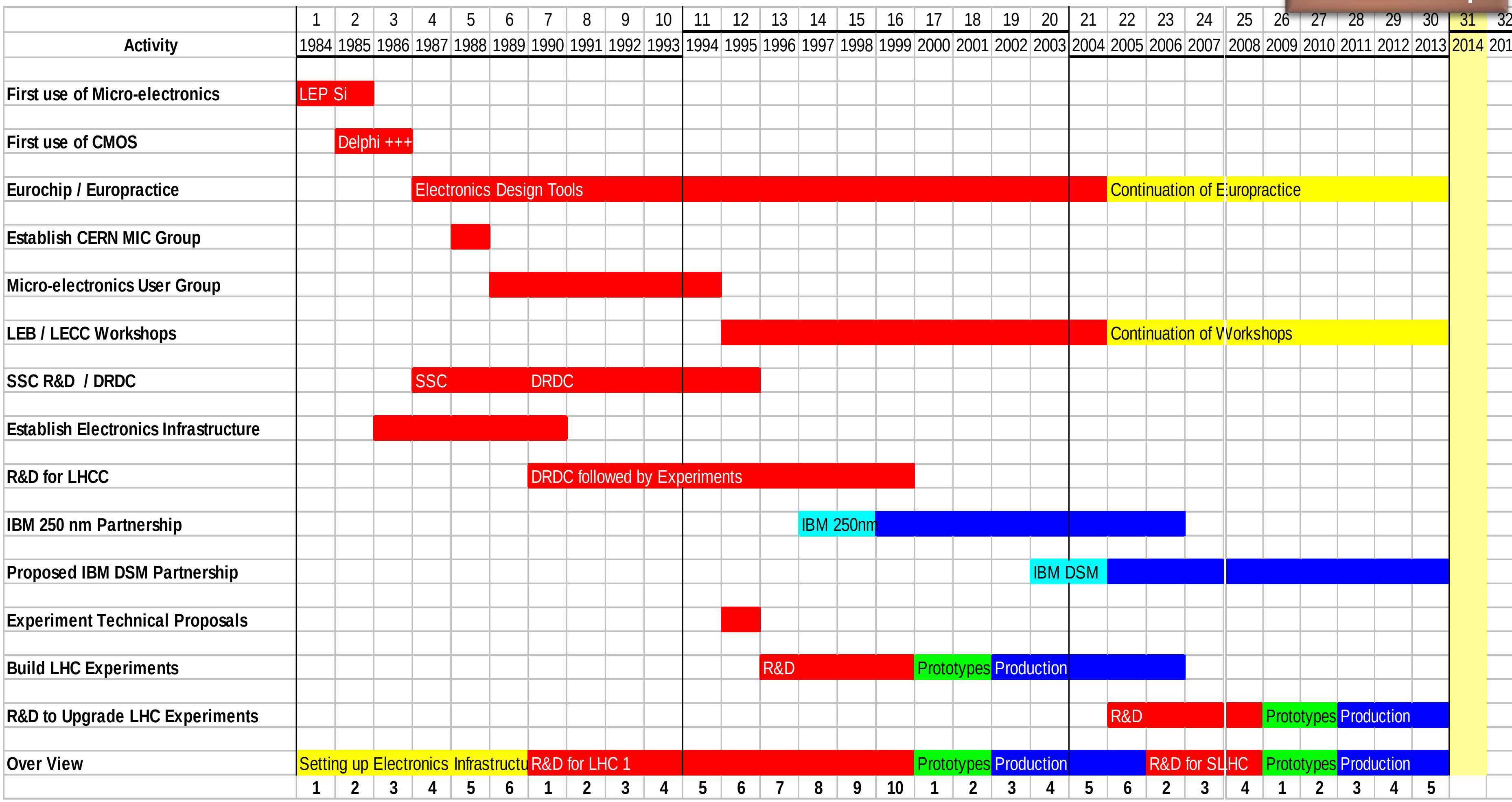
→ *New High Speed Optical link (HOLA) cards installed with dual outputs to allow testing of FTK functionality with real data*



P.Allport

LHCC Meeting March 2004

Peter Sharp



Time needed for Phase II R&D

- There were about 10 years of R&D for the initial build of The LHC detectors
- Followed by
  - 2 years proto-typing
  - 5 years production-install-commission
- To get a new big detector ready by 2022 the timescale of 2014 for a Technical Proposal (first design) just fits.
  - The detectors for phase II are the same scale as major sub-detectors were for the LHC, and technically more complex
- We will need to ensure we are doing enough focused R&D to be ready to make designs and decisions.

Big Questions

- Can the theoretical errors which will limit the extraction of the Higgs coupling constants from the LHC data be reduced?
- Is there anything we should be looking for at the LHC which we are missing?
- Will the experimental data lead the theorists or will the theorists lead the direction of the experimental searches in the next phase of LHC operation?
- If we find something new (example SUSY), are there new tools/observables we can use to deduce the spectroscopy of new states?

Conclusions

- The physics programme for the LHC machine will be rich for the coming decades
- Maximizing the physics this machine can deliver will require efforts to keep increasing the luminosity
- Increased luminosity will require changes in the detectors to keep delivering improving results
- The roadmap of changes for this decade is well described
- There are substantial challenges for the machine and the detectors in delivering and using the luminosity in the next decade
  - There is much work to do now – a perfect opportunity for the next generation to design and build its LHC detectors