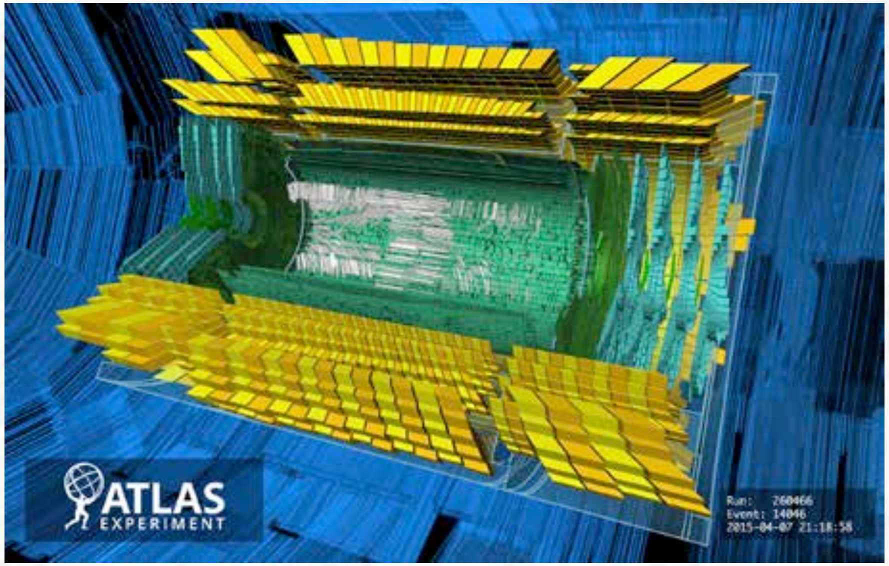
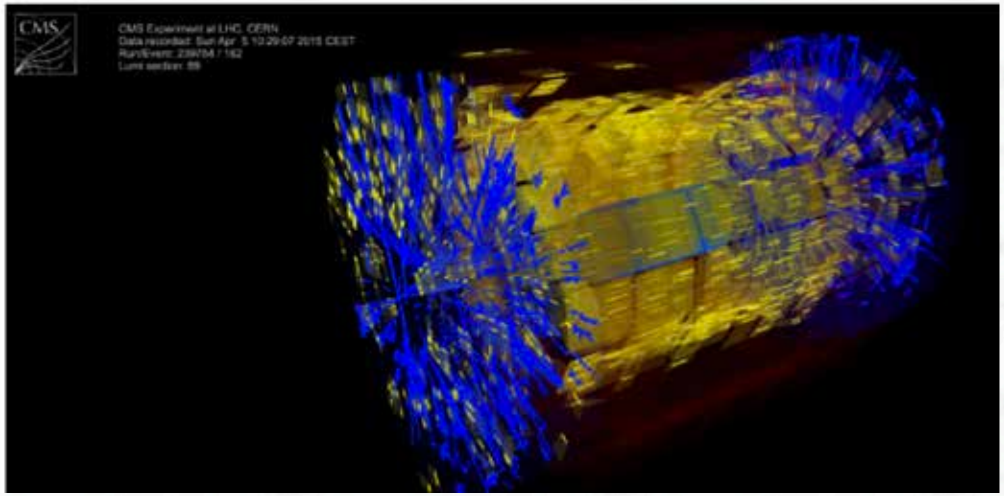
LHC Status and Plans for 2015 and Run 2



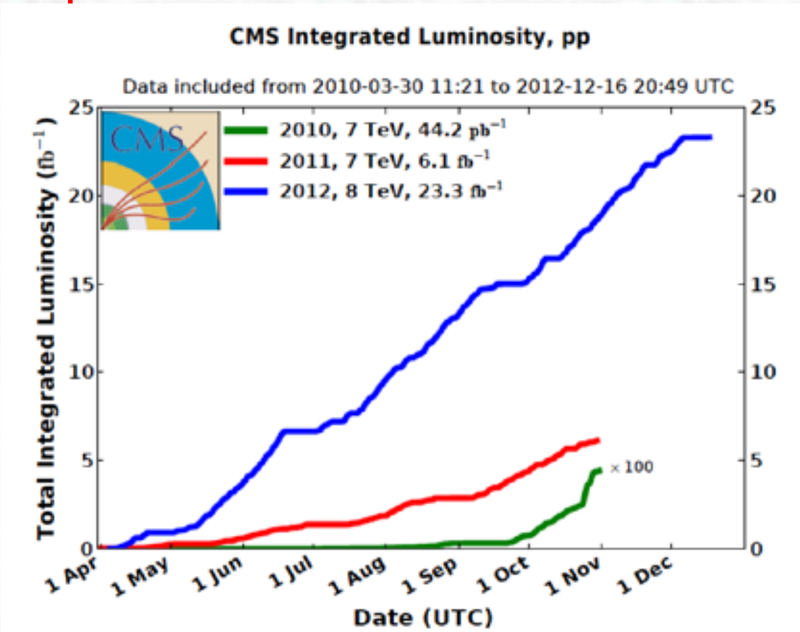
LHC Beam Splash events seen by the ATLAS and CMS detectors - 7 Apr 2015



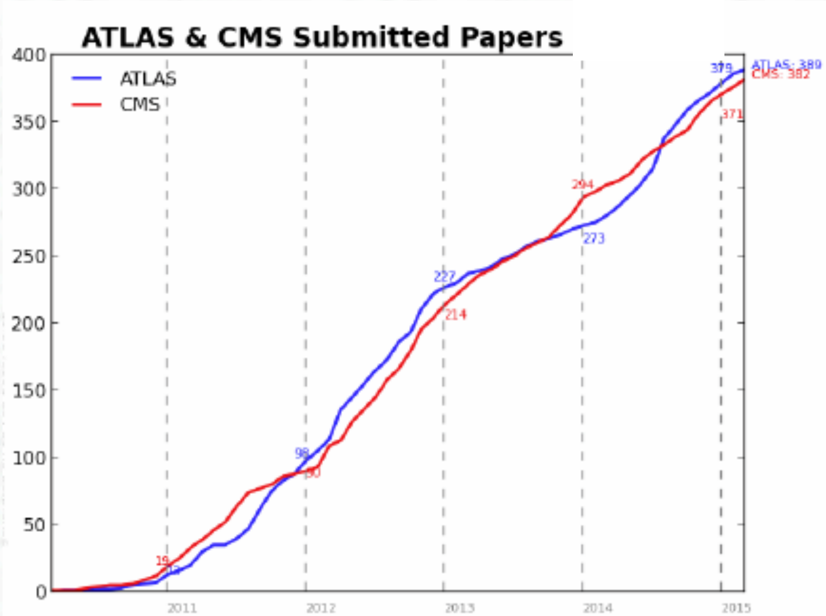
Karl Jakobs
Physikalisches Institut
Universität Freiburg

LHC Run 1 (2010-2012)

Input



Output



Steve Meyers at "Physics at LHC 2012":

"The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics."

LHC Run 1 (2010-2012)

About 6.000 ATLAS and CMS physicists operating the detectors, collecting and analysing the data

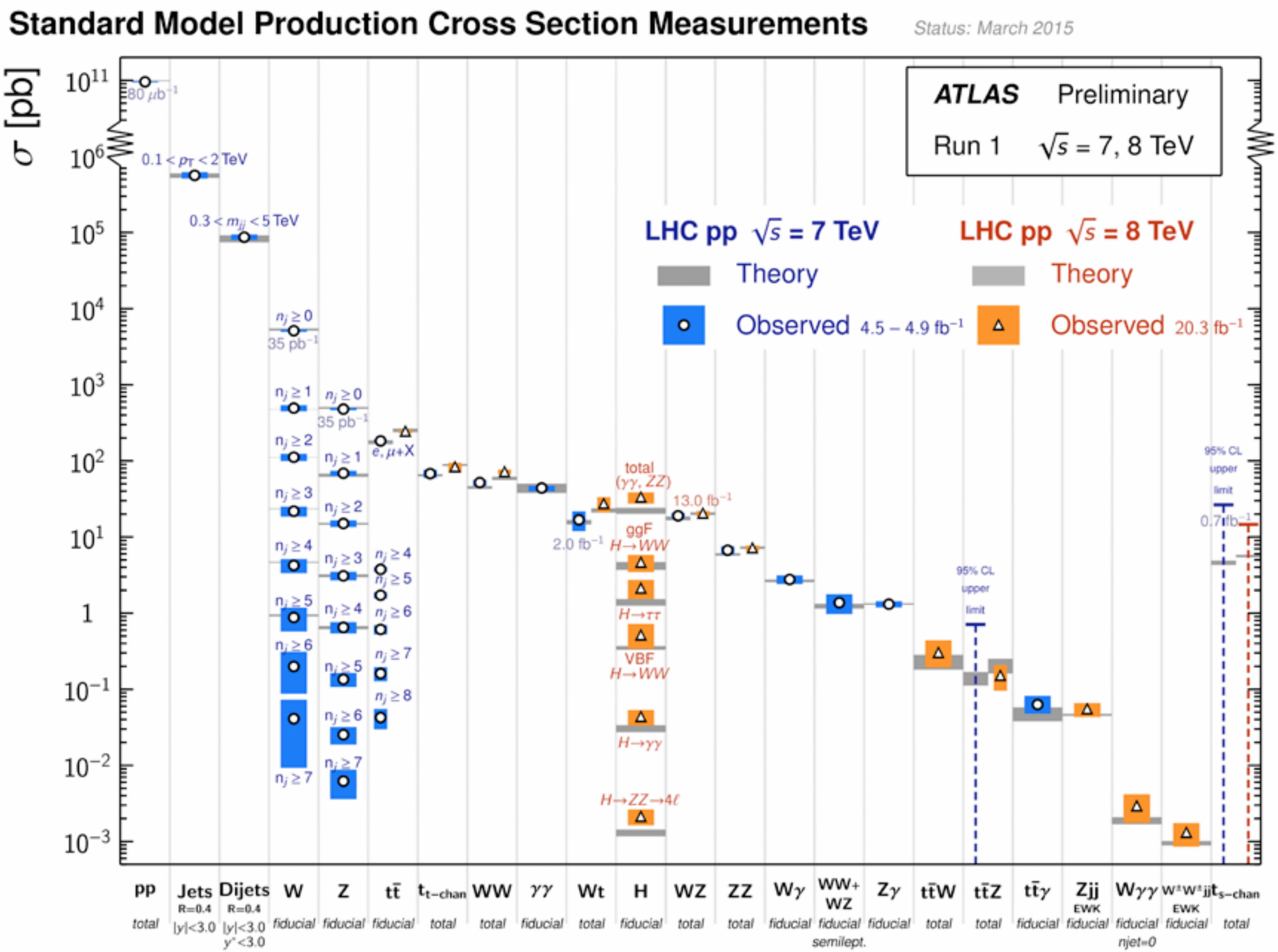
LHC Run 1 (2010-2012)

… + LHC machine

and theory

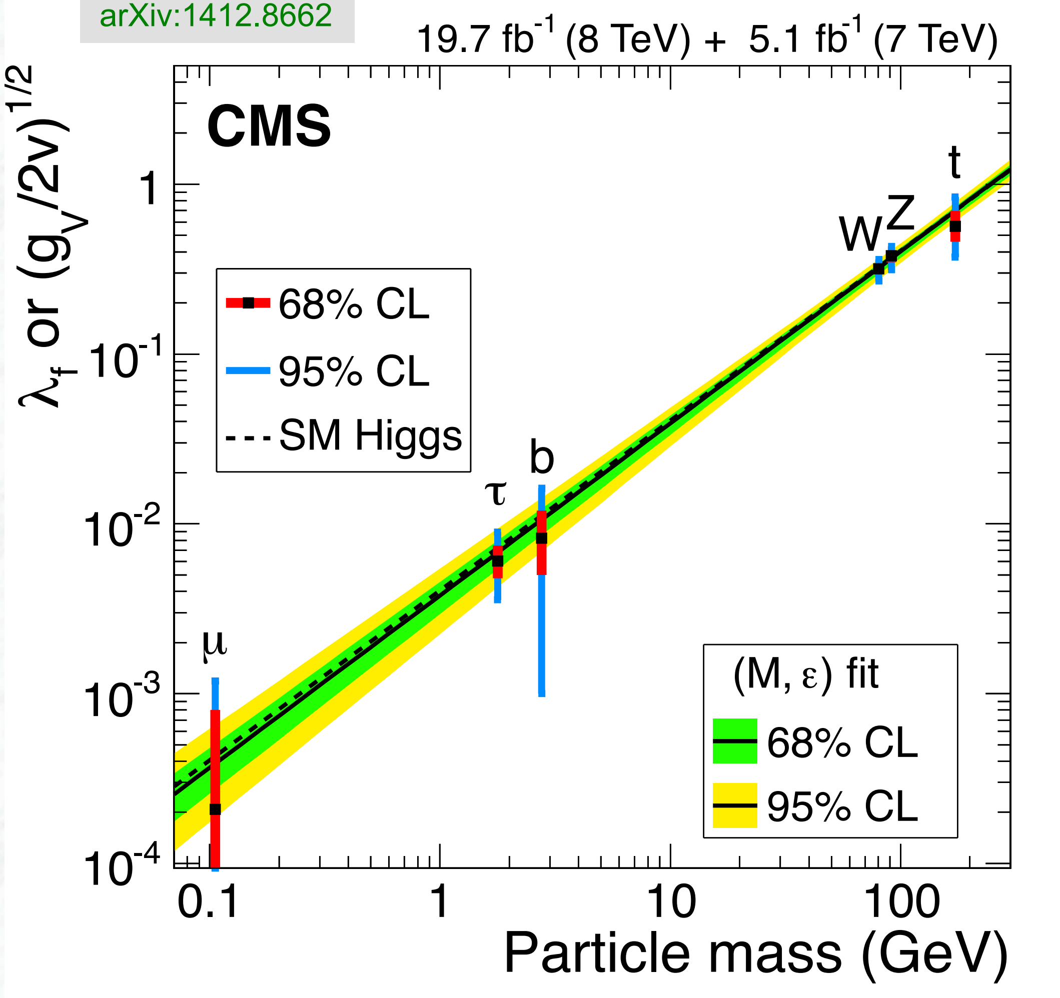
The Physics highlights

from Run 1


Standard Model Production Cross Section Measurements
Status: March 2015
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Observed 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Theory
Observed 20.3 fb⁻¹
σ [pb]
pp total
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ fiducial
t t-chan total
WW total
γγ fiducial
Wt total
H fiducial
WZ total
ZZ total
Wγ fiducial
WW+WZ fiducial semilept.
Zγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial
t s-chan total
95% CL upper limit

CMS results on Higgs boson couplings

arXiv:1412.8662



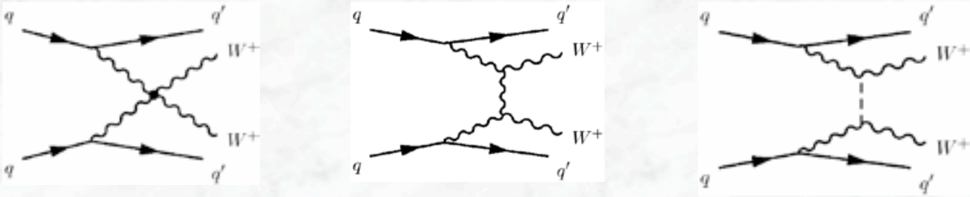
λ = Yukawa coupling for fermions

$\sqrt{g/2v}$ = couplings for W/Z bosons

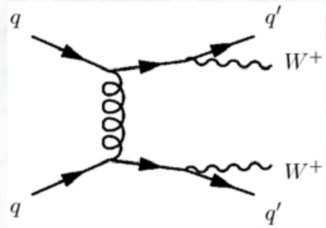
For the first time, non-universal, mass-dependent couplings observed

Evidence for El.weak $W^{\pm}W^{\pm}jj$ production

- Higgs boson needed in the SM to regularise VV scattering at high energies;
- Key experimental process: $W^{\pm}W^{\pm}$ scattering

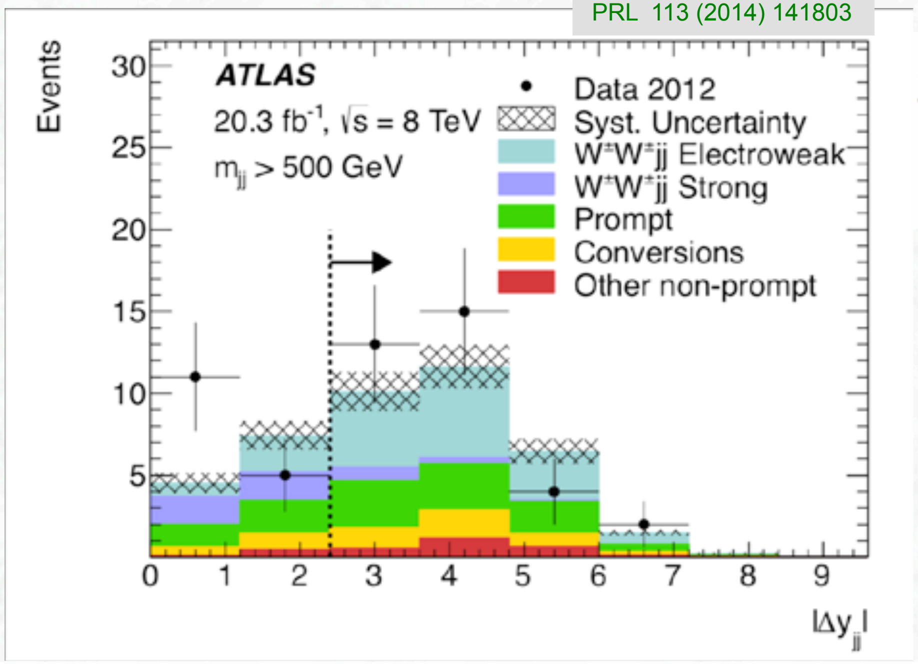


El. weak production



Strong production

PRL 113 (2014) 141803



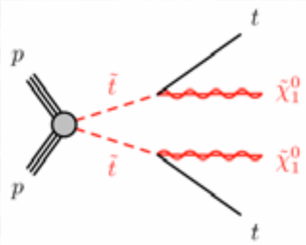
VBS enhancement by cutting on mass (m_{jj}) and rapidity separation Δy_{jj}

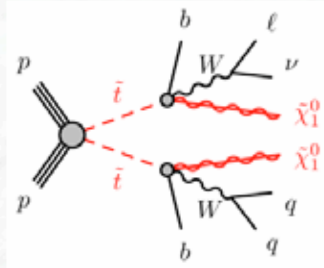
ATLAS: 3.6σ for el.weak production

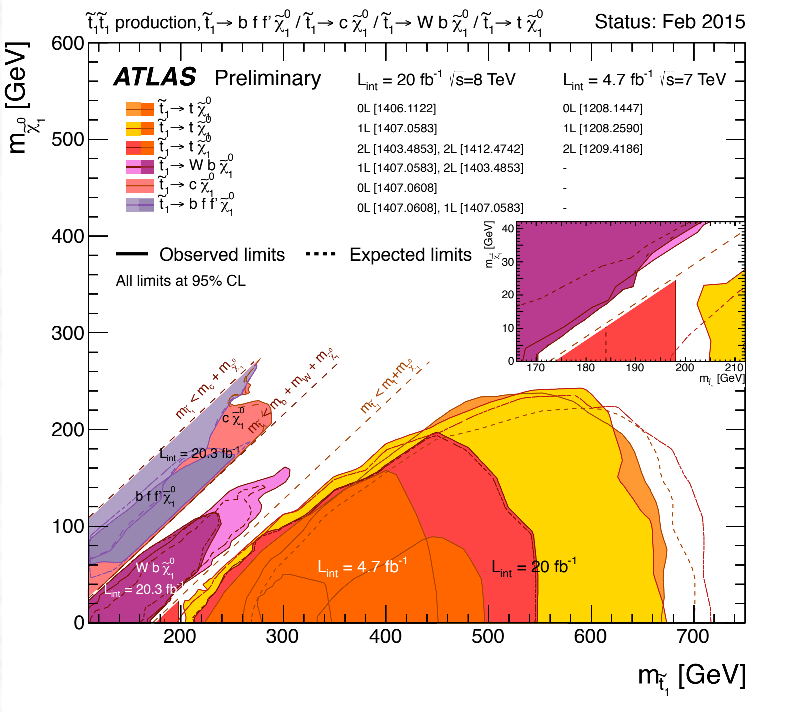
CMS: 2.0σ PRL 114 (2015) 051801

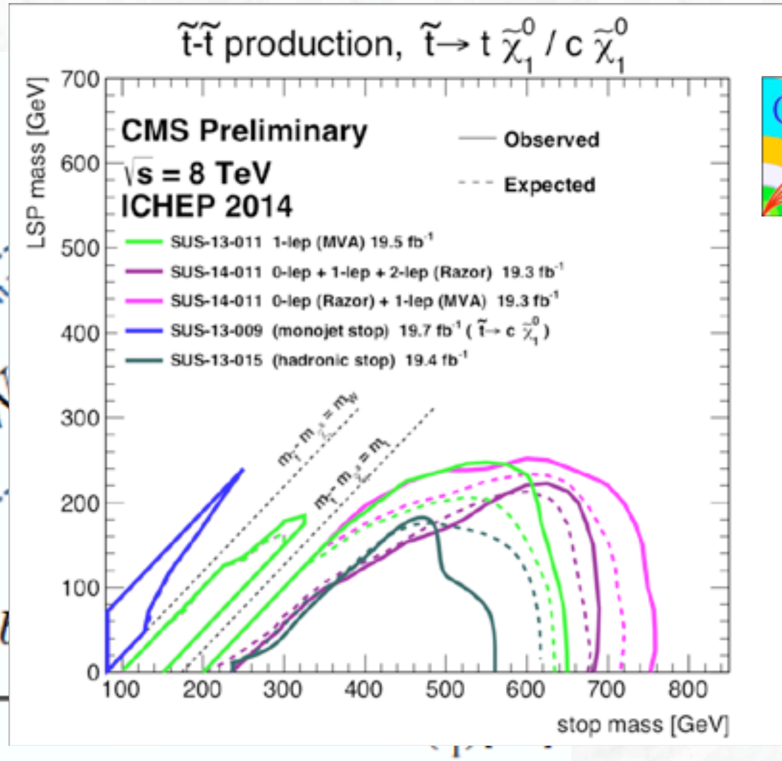
(expected: about 3.0σ)

Status of top squark searches

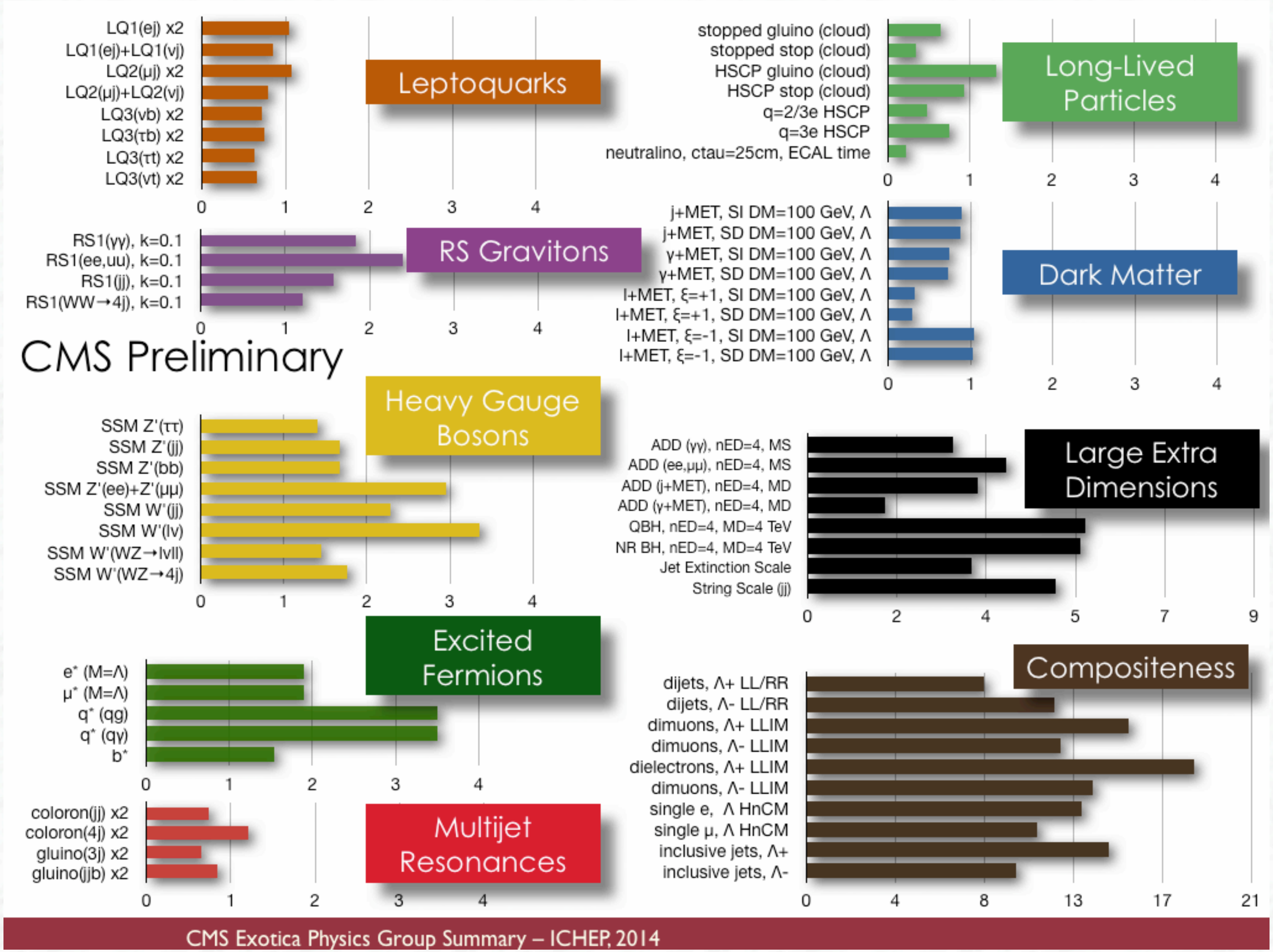








Results from other Searches for New Physics



Important physics questions for LHC Run 2

- The LHC has resumed operation and will soon deliver physics data at $\sqrt{s}$ = 13 – 14 TeV with higher luminosity

- A new energy range will be explored !!

Major physics topics:

(i) Extend the searches for New Physics

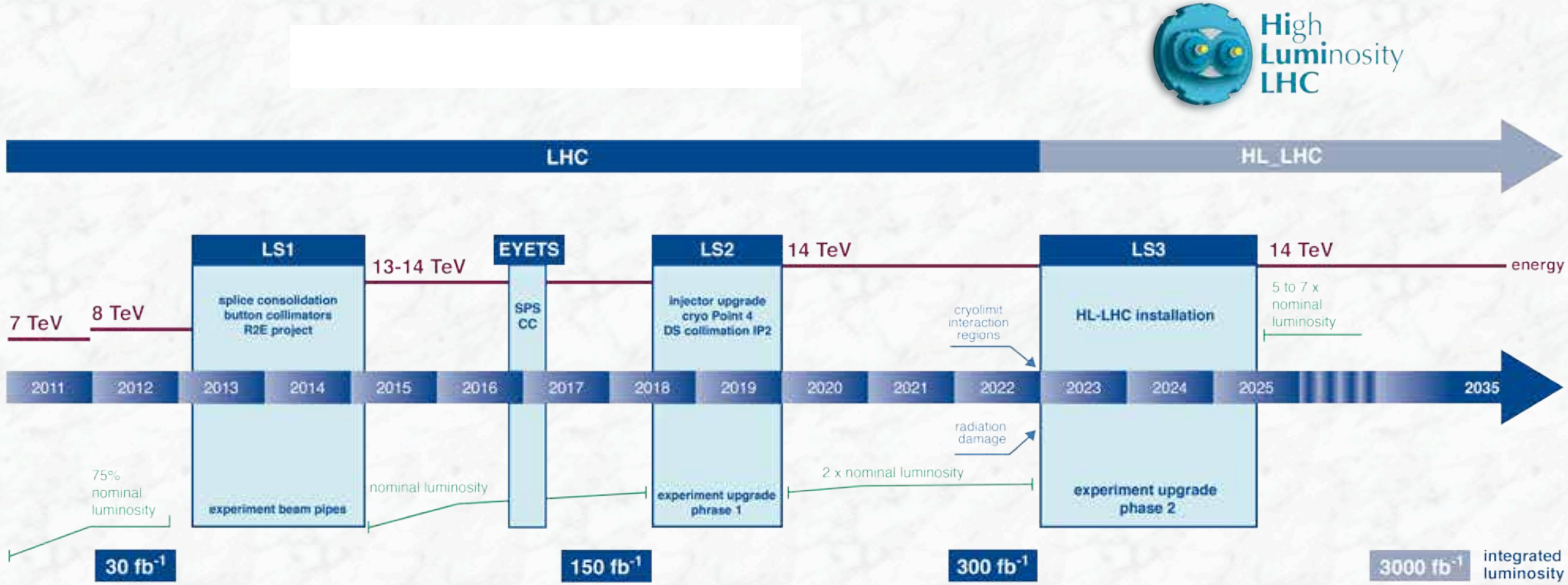
(ii) Precise measurements of the Higgs boson profile

(iii) Additional Higgs bosons?

(iv) Multi-bosons, Scattering of vector bosons

(v) Precision measurements
(m_W, m_{top}, Higgs couplings)

LHC / HL-LHC Plan



L= 0.75 $\cdot 10^{34}$ cm^{-2} s^{-1}

Δt_{bunch} = 50 ns

pile-up: μ ~ 40

L= 1.5 $\cdot 10^{34}$ cm^{-2} s^{-1}

Δt_{bunch} = 25 ns

pile-up: μ ~ 40

L= ~2 $\cdot 10^{34}$ cm^{-2} s^{-1}

Δt_{bunch} =25 ns

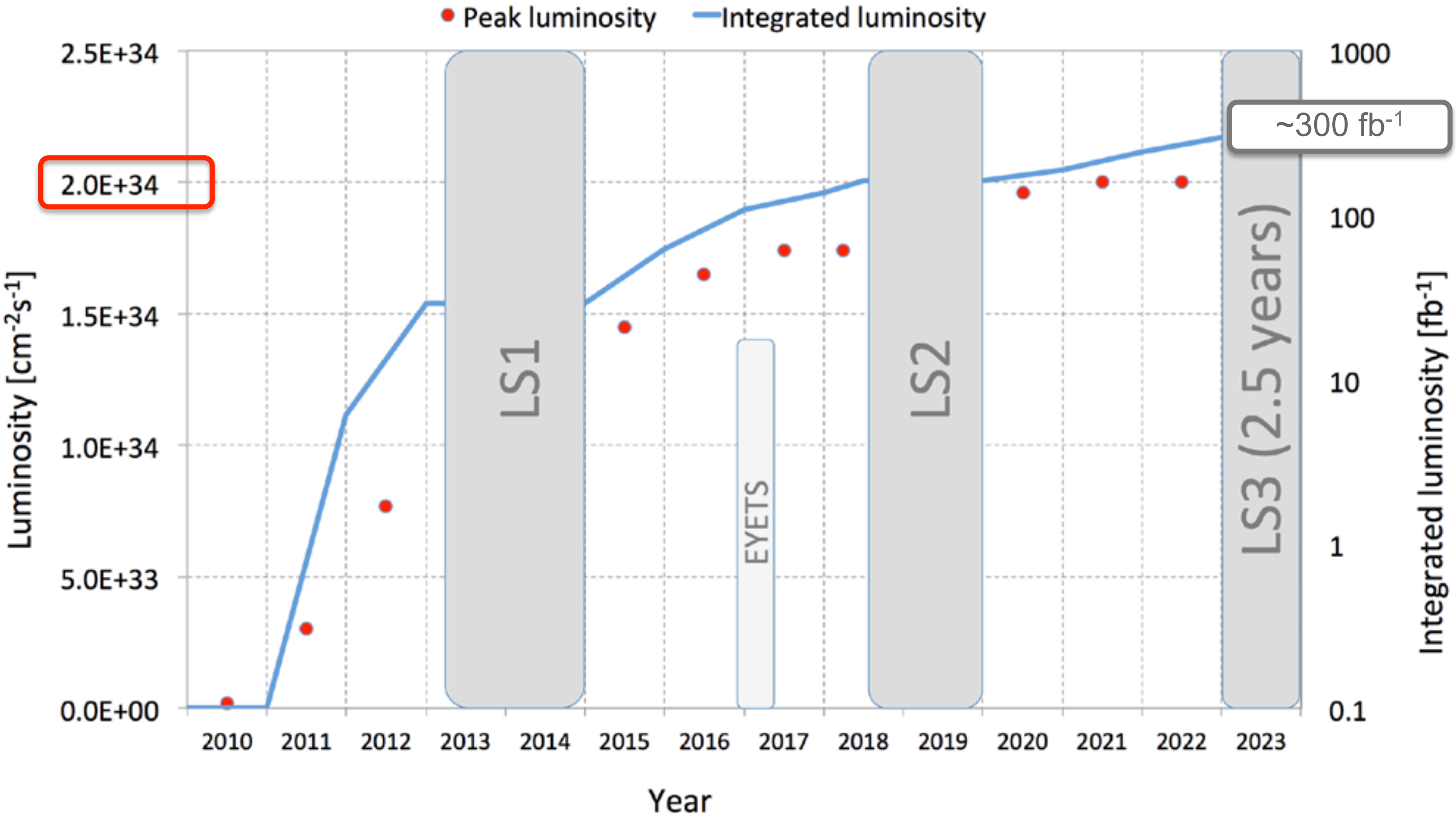
pile-up: μ ~ 60

L= 5 $\cdot 10^{34}$ cm^{-2} s^{-1}

Δt_{bunch} = 25 ns

pile-up: μ ~ 140

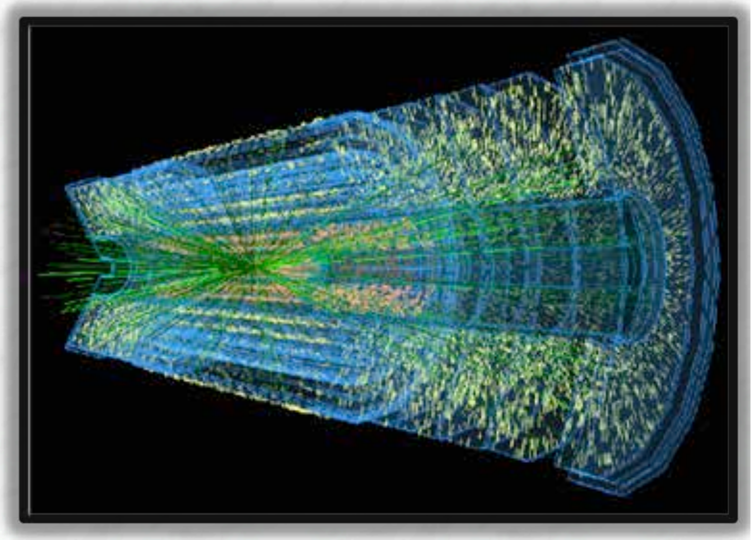
Luminosity evolution



Important components of the detector upgrades

To reach physics goals:

→ Replacement of the **Silicon Tracking Detectors** (ATLAS, CMS)
(Limited life time due to radiation damage,
and to maintain the performance,
e.g. b-tagging, at the higher luminosity
/ pile-up conditions)

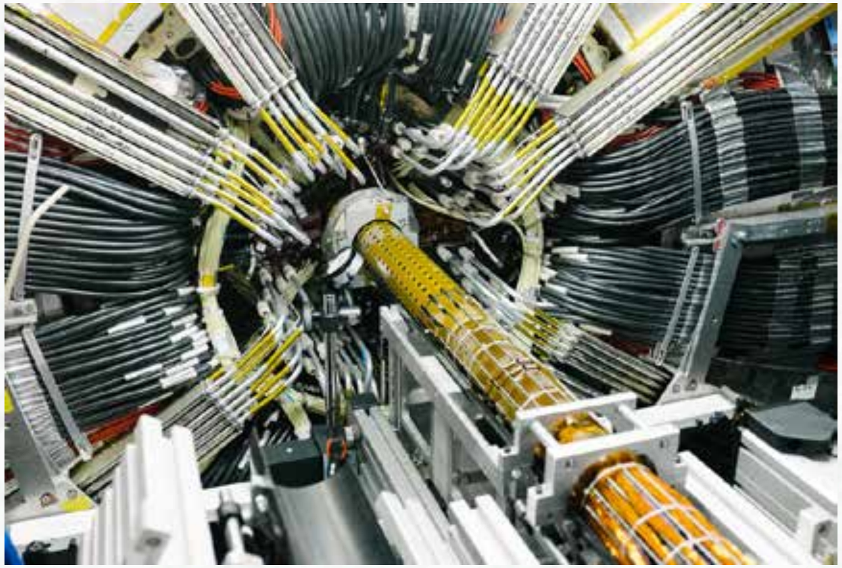


→ Optimisation / improvement of **Trigger Strategies** to keep thresholds at higher luminosities as low as possible

→ Adaptation / Improvement of the front-end **Electronics** of nearly all sub-detectors

ATLAS Upgrades

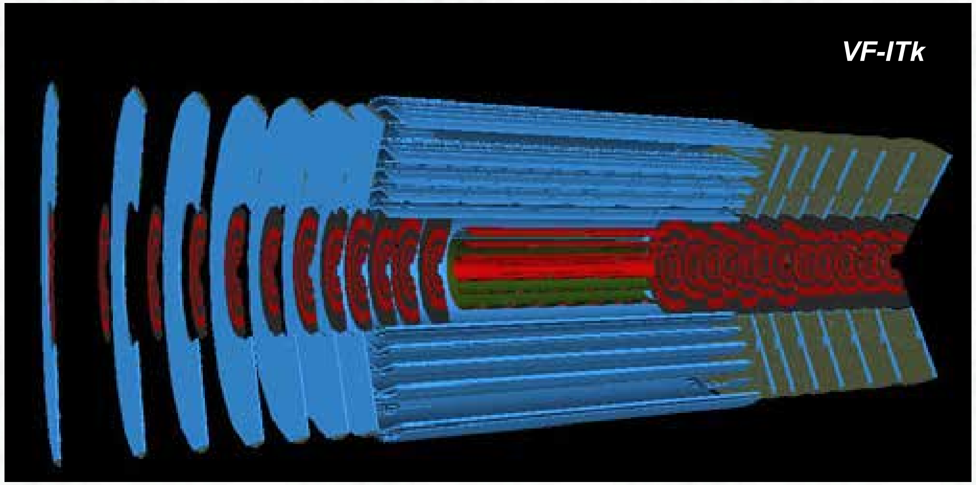
- Long Shutdown 1 (2013-2014):
  - New beampipe at r = 2.5 cm
  - New Insertable B-Layer (IBL), r = 3.5 cm
  - Pixel readout refurbished
  - More complete muon coverage
  - Fast Tracking for L2-trigger will come online during Run 2



IBL Installation, 7. May 2014

- Long Shutdown 2 (2018-2019):
  - New muon small wheel forward spectrometer
  - Topological L1-trigger processors

- Long Shutdown 3 (2023-2025):
  - Completely new tracking detectors (full silicon, $|\eta| < 4.0$ under discussion)
  - New trigger architecture (L0 / L1) input rate
  - Calorimeter electronics upgrade



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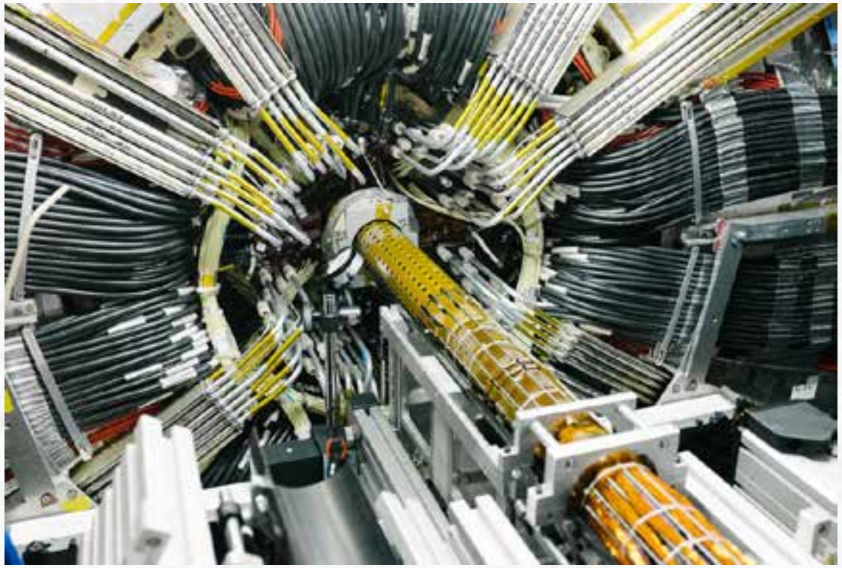

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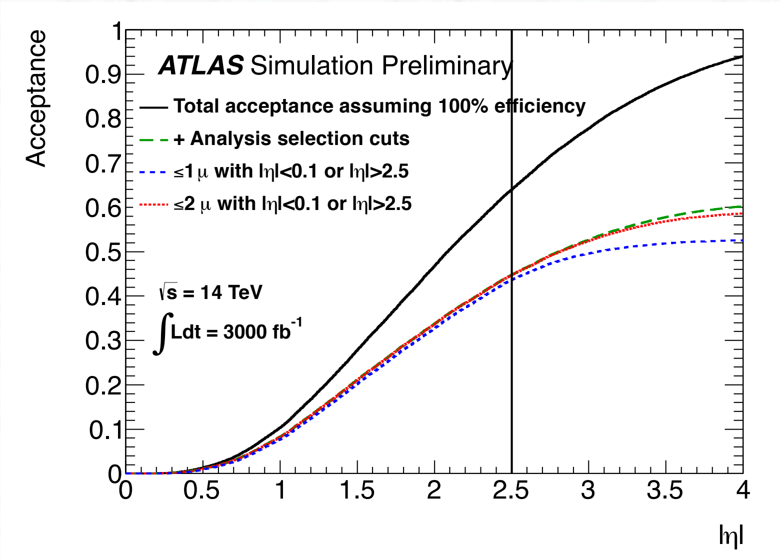


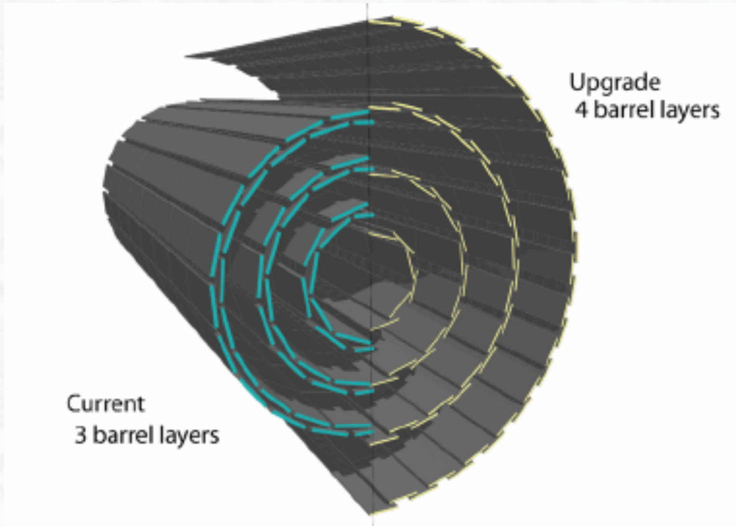
|η| dependence of H → ZZ* → 4l acceptance

CMS Upgrades

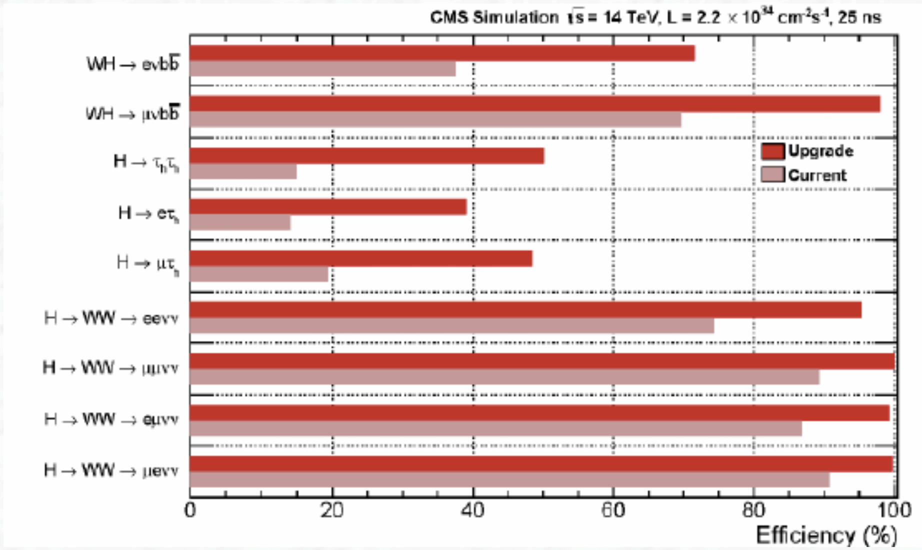
- Long Shutdown 1 (2013-2014):
  - Complete muon coverage
  - New HCAL photo-detectors

- Long Shutdown 2 (2018-2019):
  - New Pixel detector (2017)
  - New HCAL electronics
  - L1-trigger upgrade

- Long Shutdown 3 (2023-2025):
  - Completely new tracking detectors (full silicon, $|\eta| < 4.0$)
  - L1 track trigger
  - New forward calorimetry
  - …
  - High precision timing for pile-up mitigation



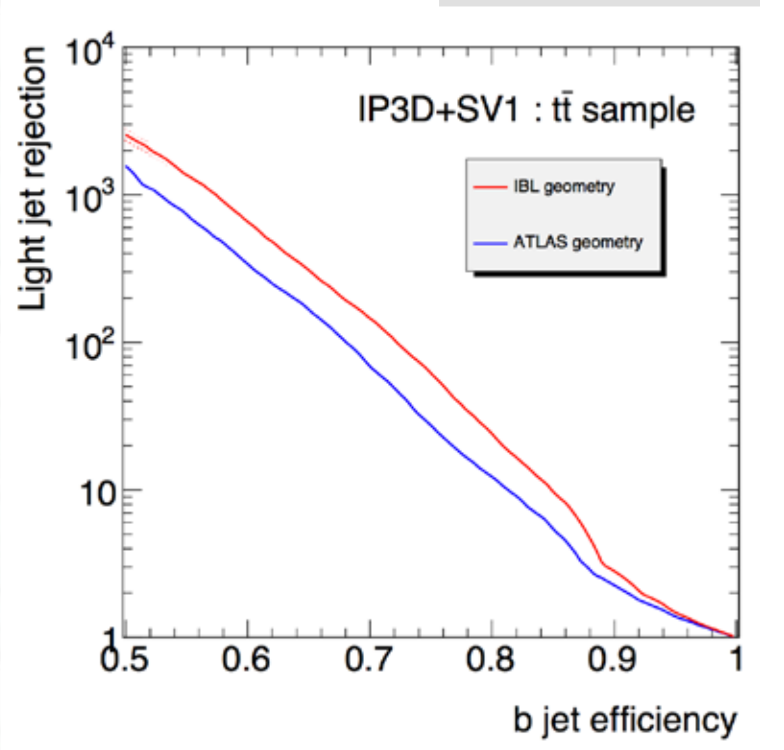
Pixel detector layouts (current vs. upgrade)



Improvements in trigger efficiency

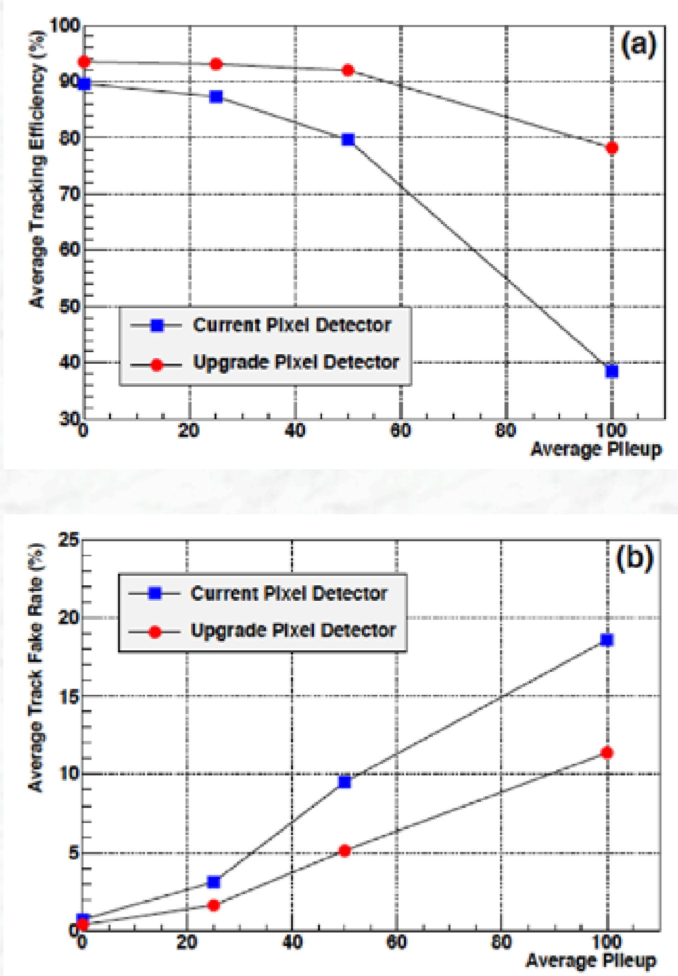
Performance improvements

CERN-LHCC-2010-013



ATLAS Improvement in b-tagging performance with the new IBL; ATLAS Technical Design Report

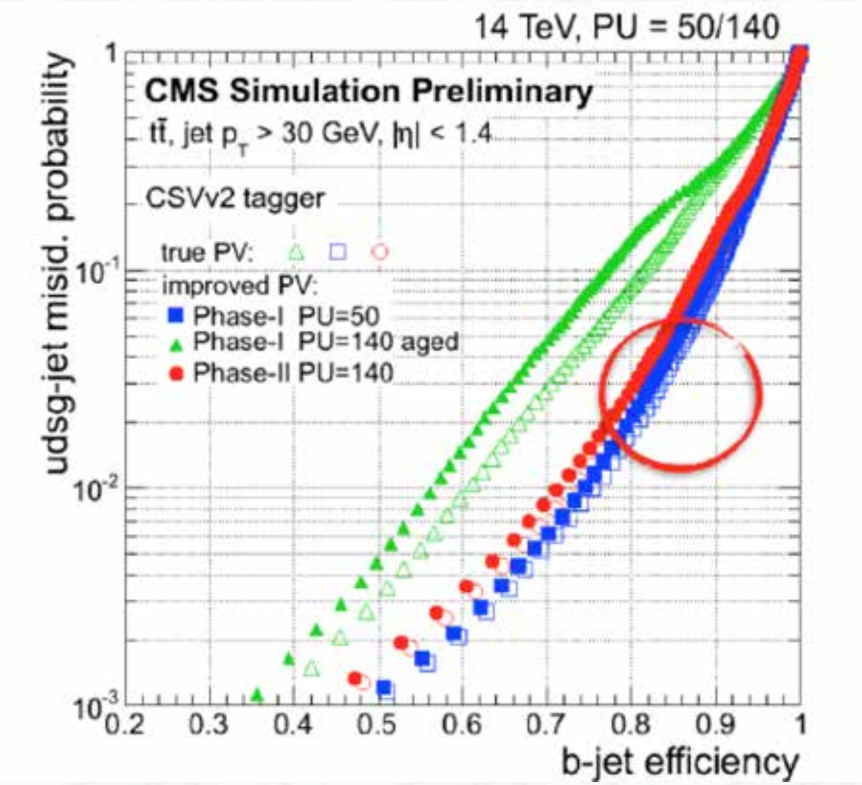
arXiv: 1307.7135



CMS improvement of (a) tracking efficiencies and (b) fake rates as a function of pile-up for tt events

b-tagging performance at HL-LHC

- The capability of tagging b-jets is critical for the success of the Higgs and BSM programs of the HL-LHC
- Improved tracking detector recover the required performance

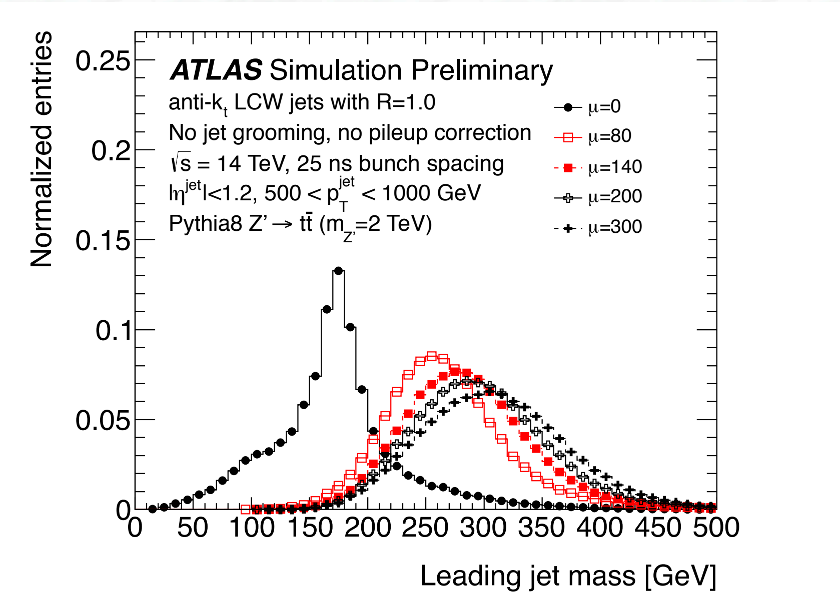


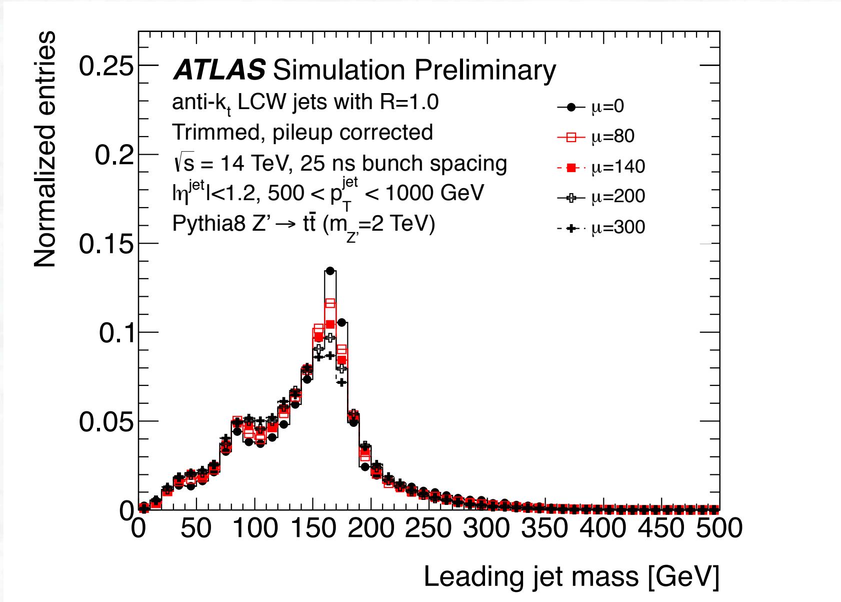
Jet performance at HL-LHC

Example: reconstruction of Z' → tt (hadronic decays)

High-p_T jets → jet substructure and pile-up mitigation plays a key role
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetSubstructureECFA2014

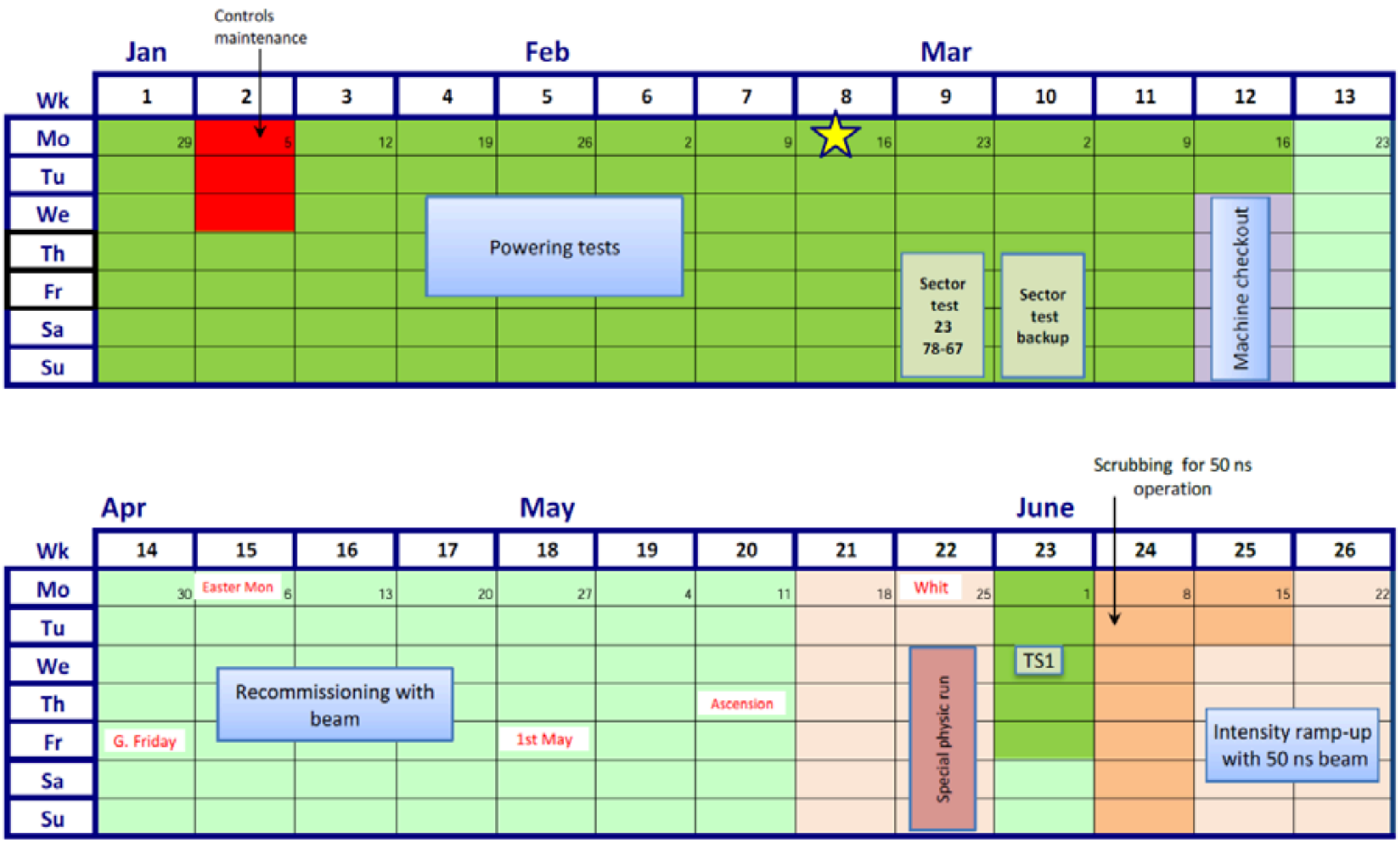
see also: arXiv:1306.4945 (Jet substructure techniques)

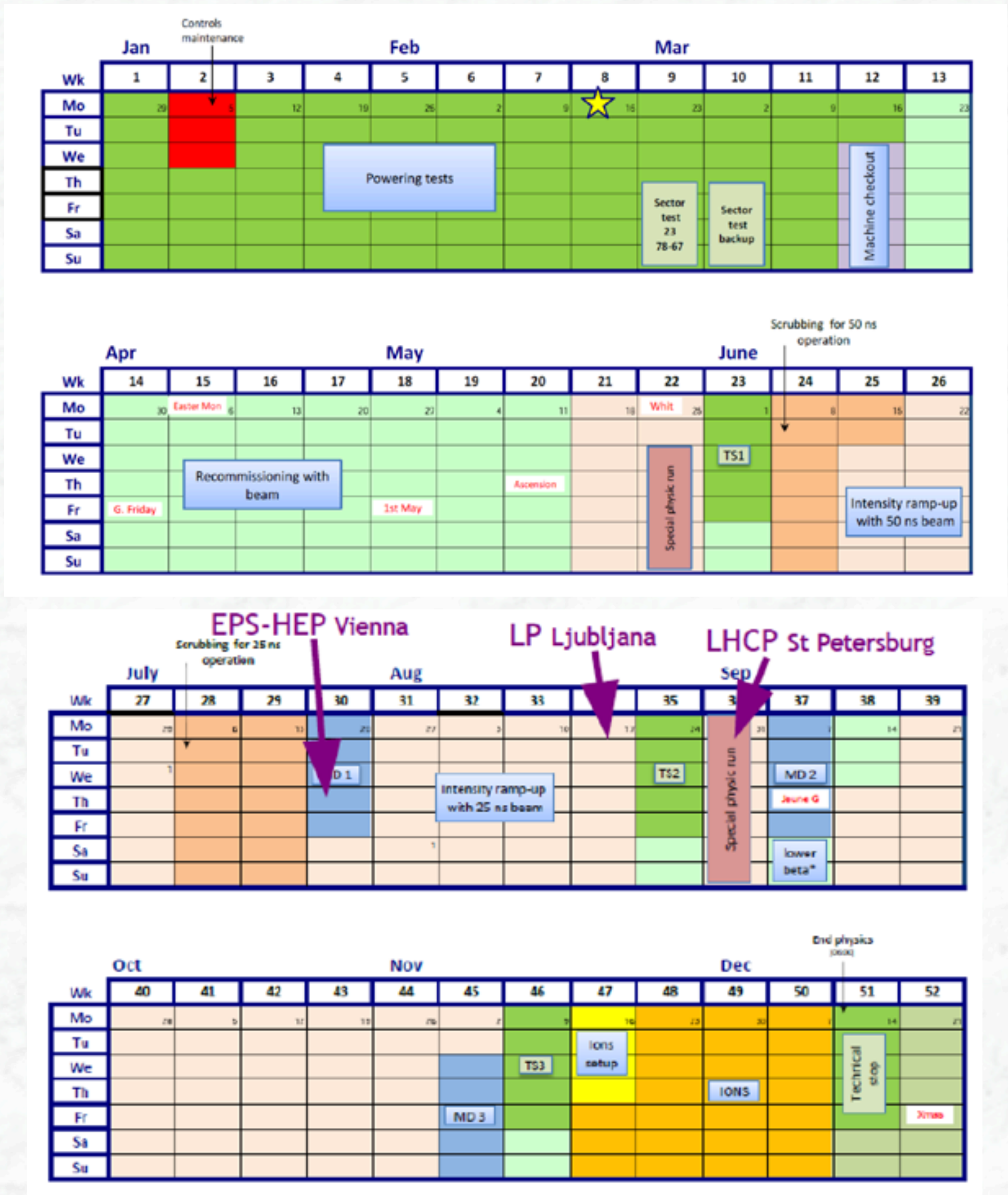




Schedule for restart

under revision




Controls maintenance
Jan
Feb
Mar
Wk
1 2 3 4 5 6 7 8 9 10 11 12 13
Mo
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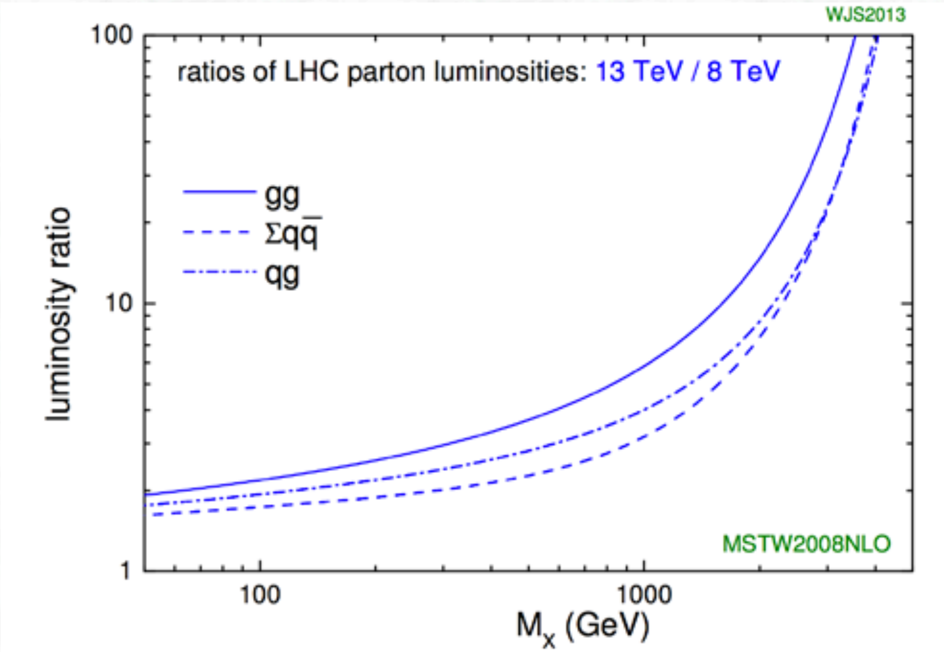
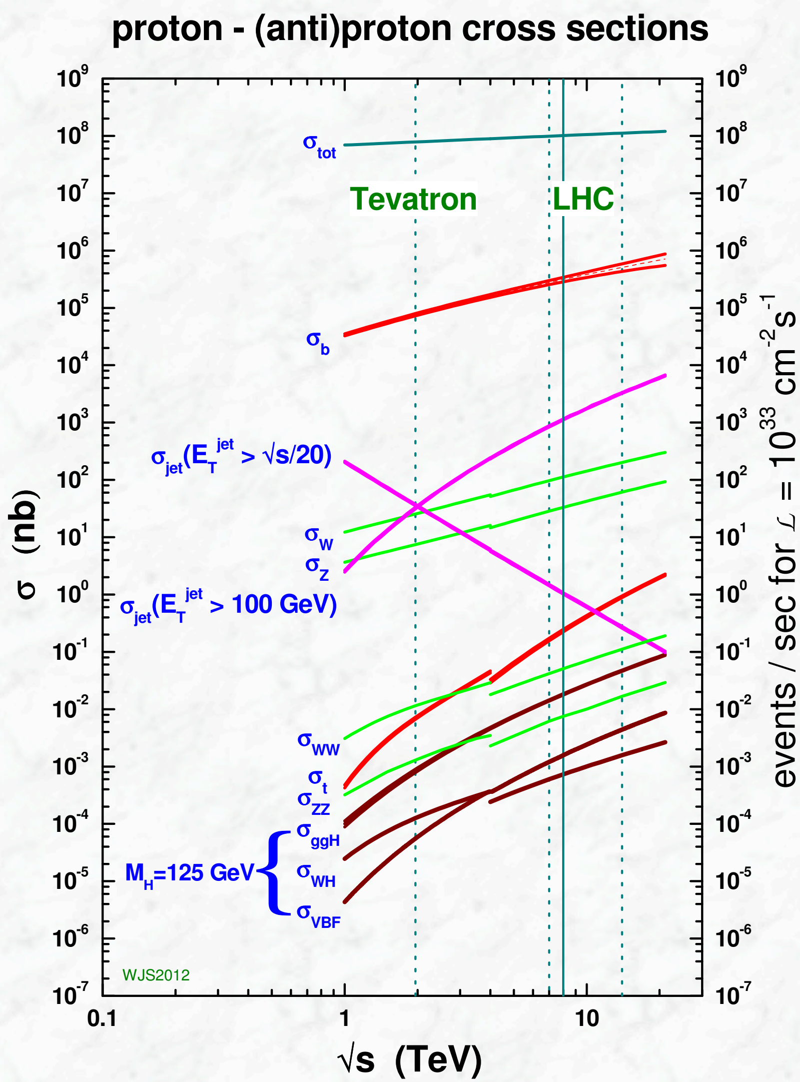
We
Th
Fr
Sa
Su
Powering tests
Sector test 23 78-67
Sector test backup
Machine checkout
Scrubbing for 50 ns operation
Apr
May
June
14 15 16 17 18 19 20 21 22 23 24 25 26
Easter Mon
Whit
TS1
Recommissioning with beam
Ascension
G. Friday
1st May
Special physic run
Intensity ramp-up with 50 ns beam
EPS-HEP Vienna
LP Ljubljana
LHCP St Petersburg
Scrubbing for 25 ns operation
July
Aug
Sep
27 28 29 30 31 32 33 35 37 38 39
MD 1
Intensity ramp-up with 25 ns beam
TS2
Special physic run
MD 2
Jeune G
lower beta*
End physics
Oct
Nov
Dec
40 41 42 43 44 45 46 47 48 49 50 51 52
Ions setup
TS3
IONS
MD 3
Technical stop
Xmas

Physics Prospects for Run 2 (and beyond)

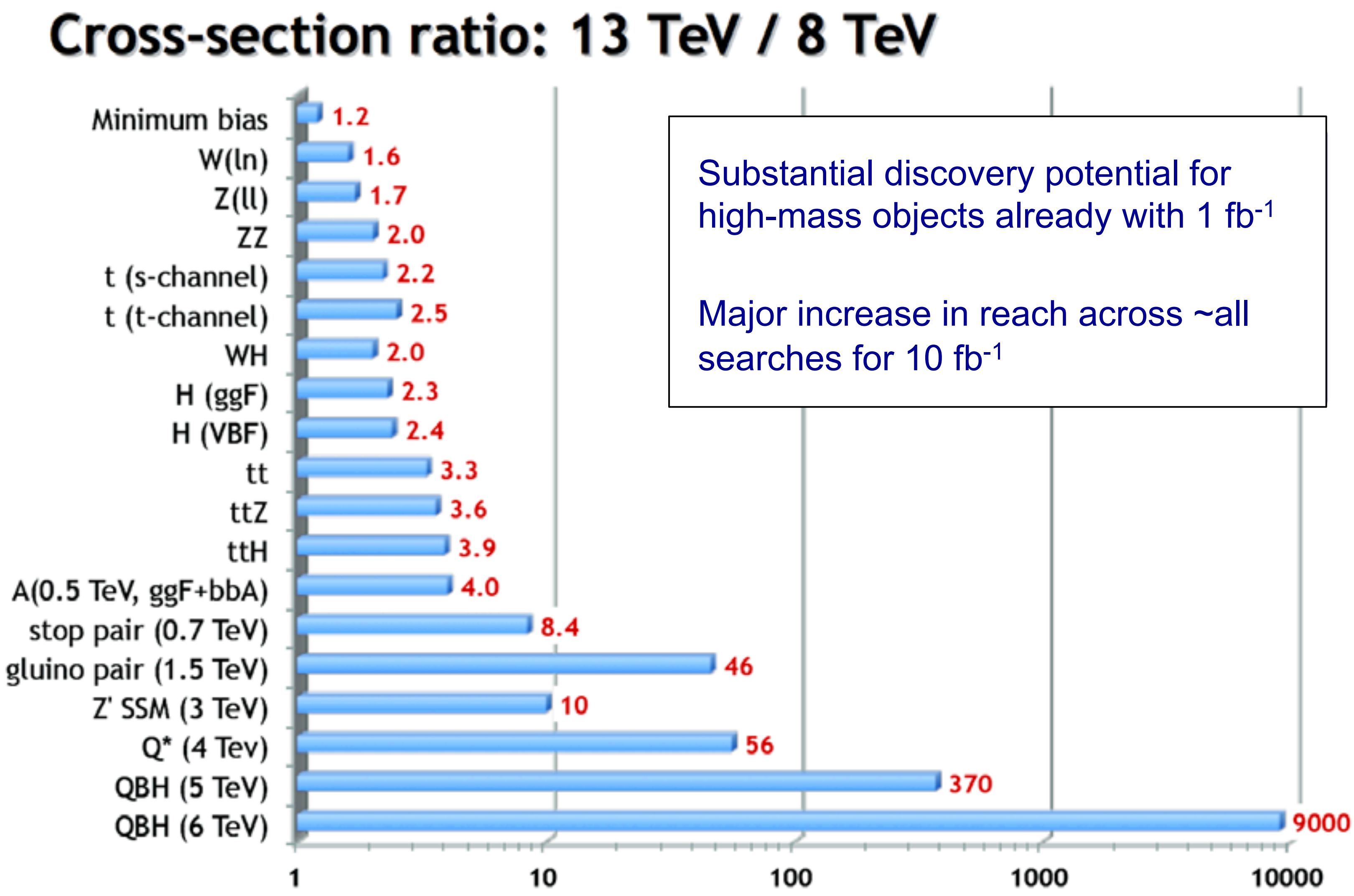
- Huge increase in cross section for many interesting physics processes

.. but also backgrounds increase, in particular tt, (difficult for low mass region)





Physics Prospects for Run 2 (and beyond)



Substantial discovery potential for high-mass objects already with 1 fb^{-1}

Major increase in reach across ~all searches for 10 fb^{-1}

"Early Physics" in 2015

- Inelastic pp collisions at $\sqrt{s}$ = 13 TeV

- Study of Minimum Bias events → tuning of Monte Carlo models

- Detector performance

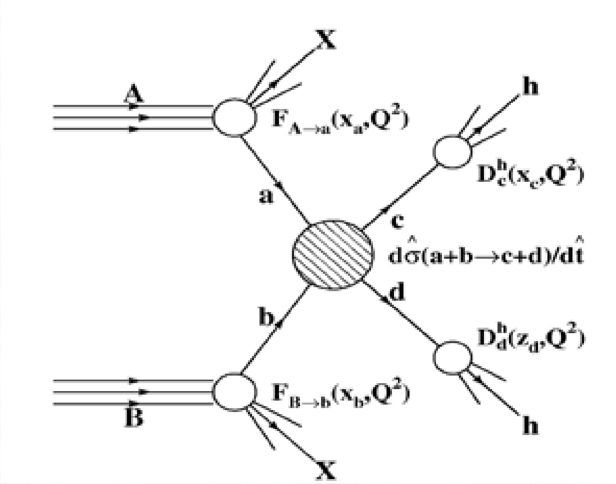
  use "standard candles": QCD jet production
  $Z \rightarrow \ell\ell$ ("tag-and-probe" for lepton performance)
  $Z \rightarrow \tau\tau$

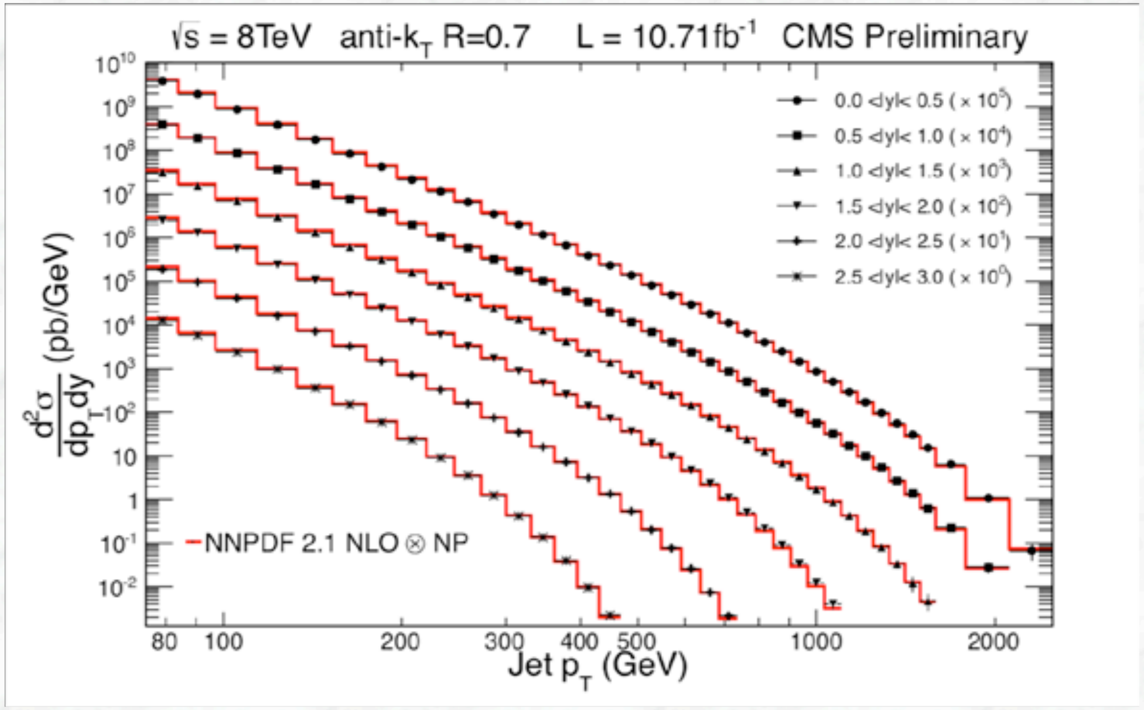
- Searches for New Physics (in a new energy regime)
  - Quark substructure, excited quarks, …
  - Heavy resonances decaying to di-leptons, tt, ..
  - Heavy / additional Higgs bosons

- Measurement of Standard Model processes (W, Z production, tt , direct photons,..)
  (as test of the Standard Model in a new energy domain,
  → valuable input to reduce theoretical uncertainties, e.g. PDFs)

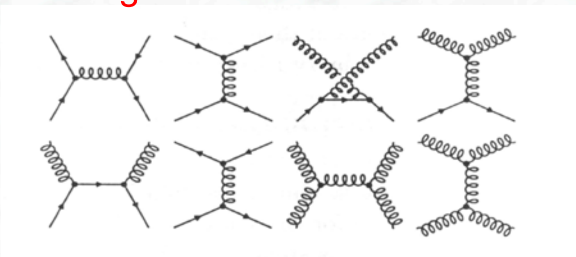
Double differential cross sections, as a function of p_T and rapidity y (full 2011 data set)

JHEP 1502 (2015) 153

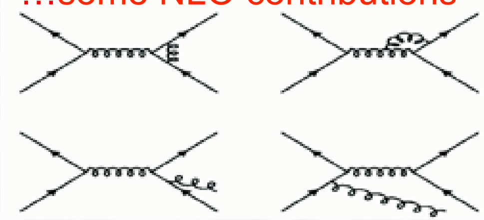




Leading order



…some NLO contributions



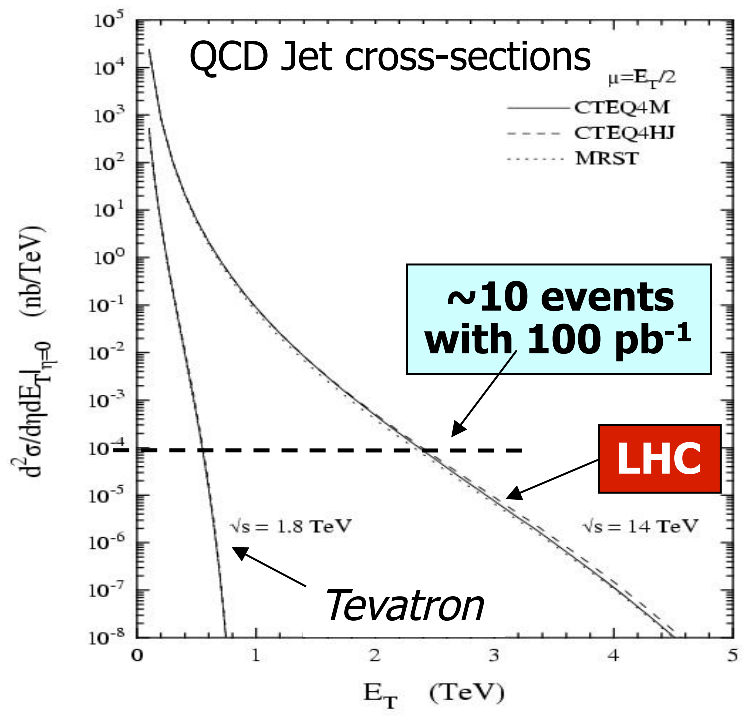
- Data are well described by NLO perturbative QCD calculations (NLOJet++), within the experimental and theoretical uncertainties

Jets from QCD production: LHC

- Rapidly probe perturbative QCD in a new energy regime

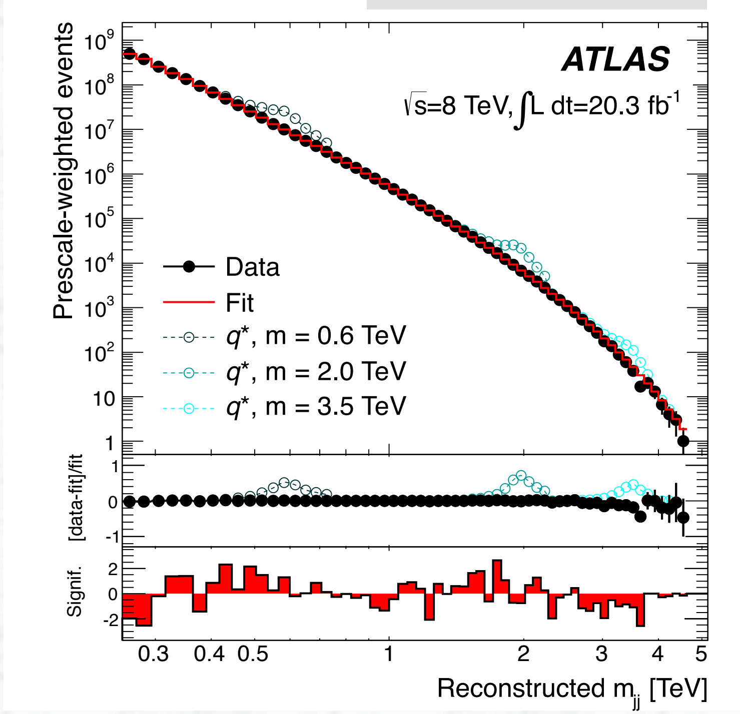
- Experimental challenge: understanding of the detector
  - main focus on jet energy scale
  - resolution

- Theory challenge:
  - improved calculations…
    (renormalization and factorization scale uncertainties)
  - pdf uncertainties



In addition: Sensitivity to New Physics

JHEP 1405 (2014) 059



- Di-jet mass spectrum provides large sensitivity to new physics

  e.g. resonances decaying into qq, excited quarks q*, ….

CDF (Tevatron), $L = 1.13\ fb^{-1}$: $\sqrt{s} = 1.96$ TeV — $0.26 < m_{q*} < 0.87$ TeV

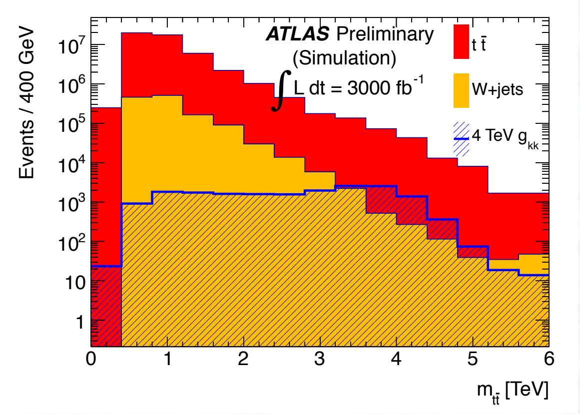
ATLAS (LHC), $L = 0.000315\ fb^{-1}$, $\sqrt{s} = 7$ TeV — exclude (95% C.L) q* mass interval $0.30 < m_{q*} < 1.26$ TeV

ATLAS (LHC), $L = 20.3\ fb^{-1}$, 8 TeV: exclude (95% C.L.) $m_{q*} < 4.09$ TeV

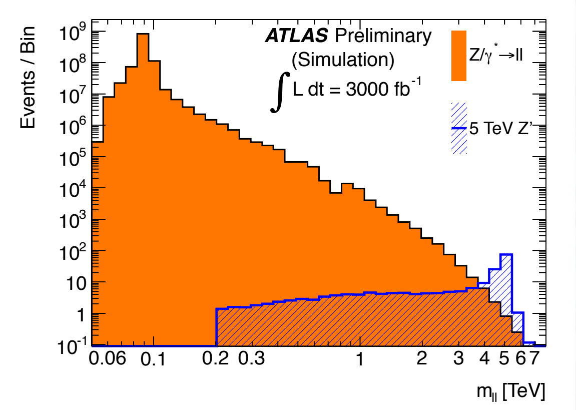
Resonance Searches

- Search for resonances in di-lepton, tt, di-boson (WW, WZ, ZZ) final states
- Huge sensitivity increase with higher energy (ultimate luminosity)

Kaluza-Klein gluon (4 TeV) $g_{KK} \rightarrow tt$



Z' (5 TeV), Z' → μμ



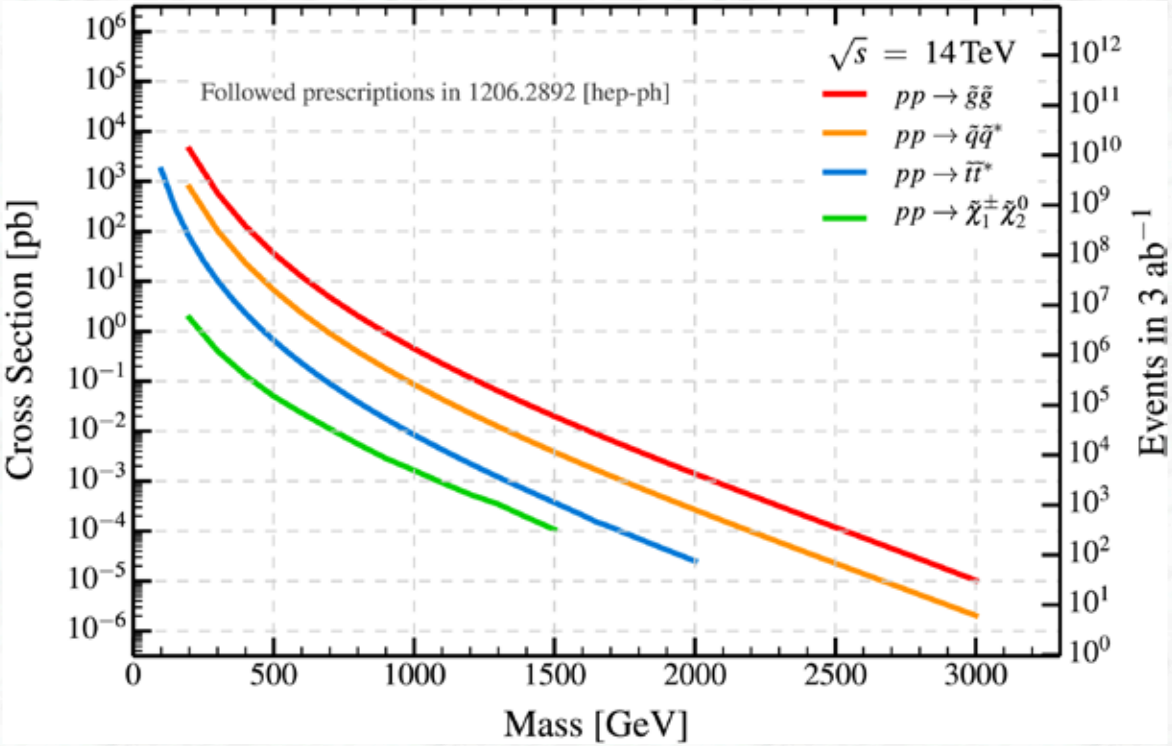
Exclusion limits on mass in TeV

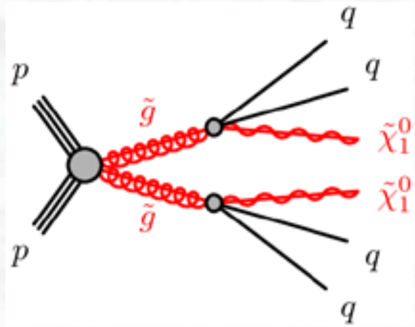
model	Now	300fb^{-1}	3000fb^{-1}
$Z'_{SSM} \rightarrow ee$	2.79	6.5	7.8
$Z'_{SSM} \rightarrow \mu\mu$	2.53	6.4	7.6
g_{KK}	2.0	4.3	6.7
$Z'_{topcolor}$	1.8	3.3	5.5

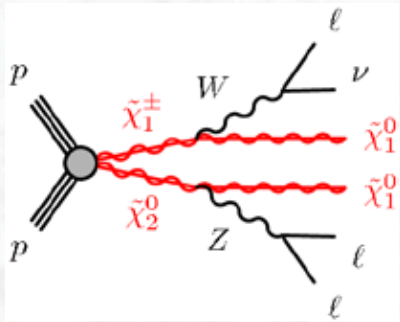
Very similar results by CMS (arXiv:1307.7135)

SUSY discovery / exclusion potential

NLO cross sections for the production of SUSY particles



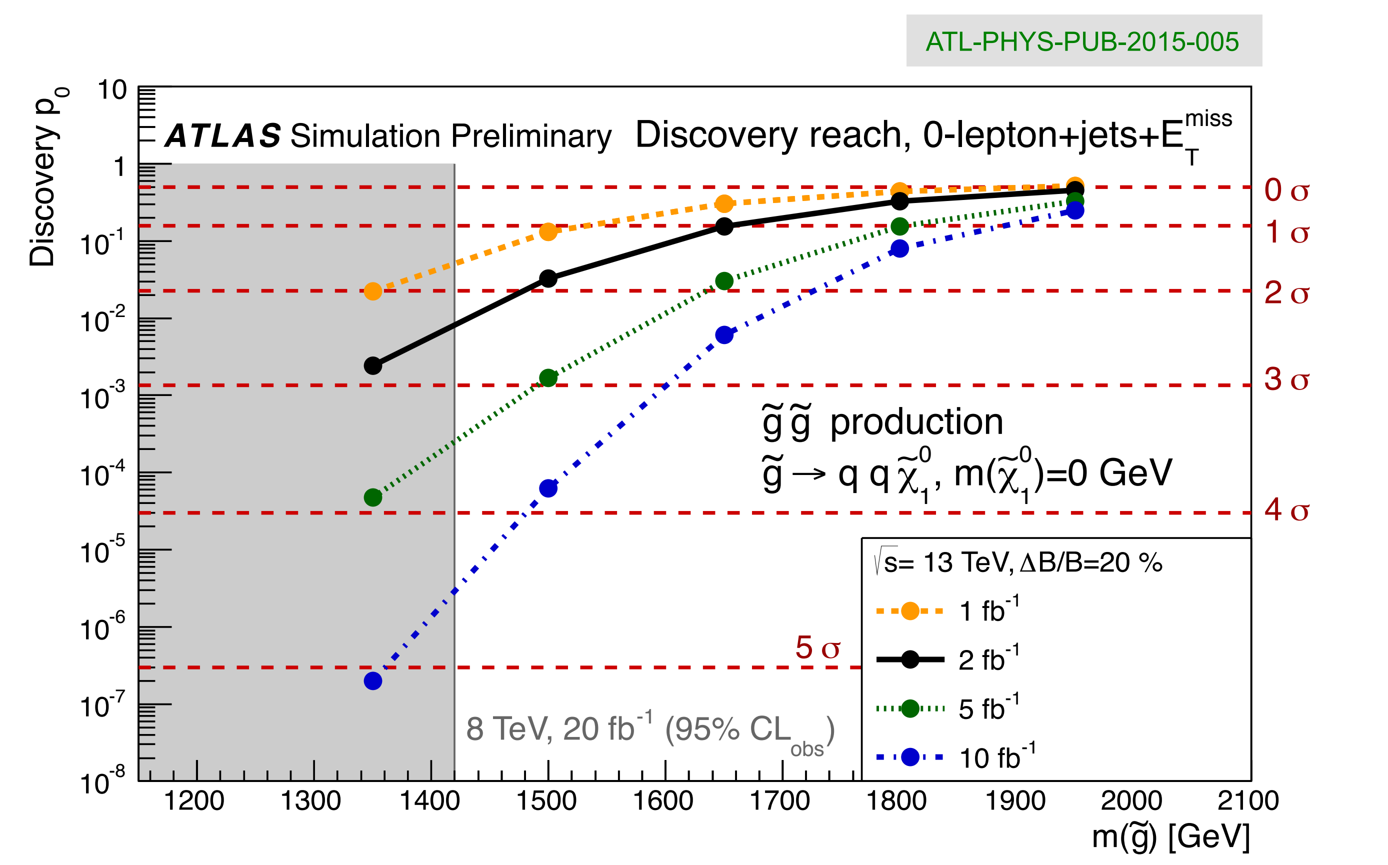




- Canonical searches assume R-parity conservation, lightest neutralino as LSP
  → E_T^{miss} signatures for strong production
  → Multi-lepton + E_T^{miss} signatures from el.weakino decays

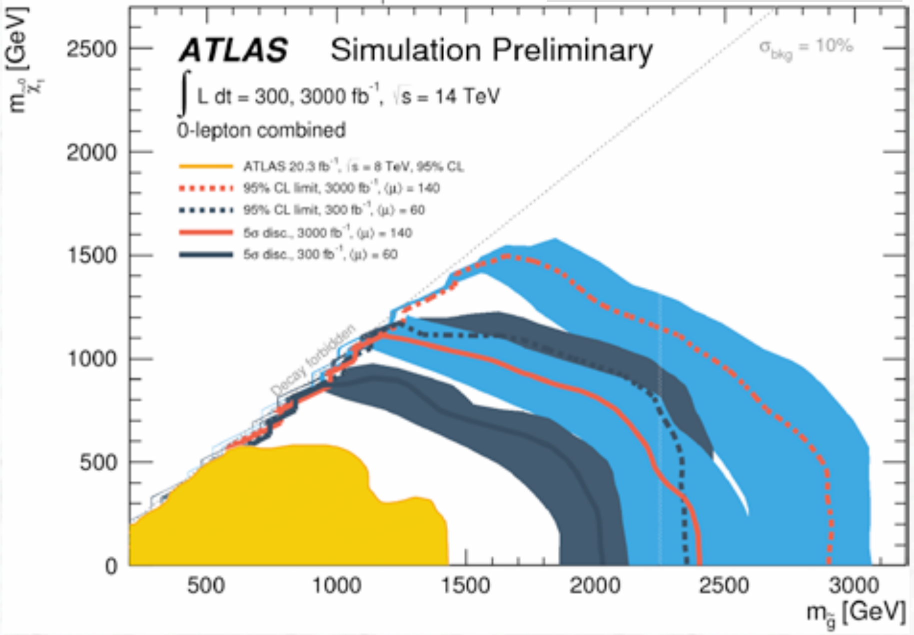
These searches will already be relevant in 2015

SUSY discovery reach in 2015

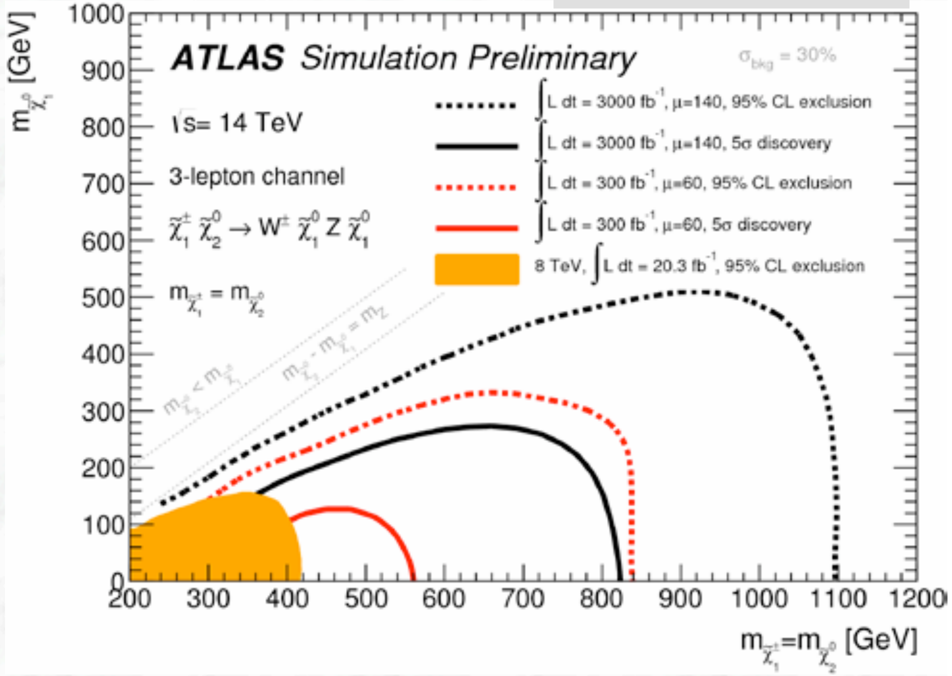


SUSY discovery / exclusion potential

ATL-PHYS-PUB-2014-010



ATL-PHYS-PUB-2014-010



Expected 95% CL exclusion and 5σ discovery contours

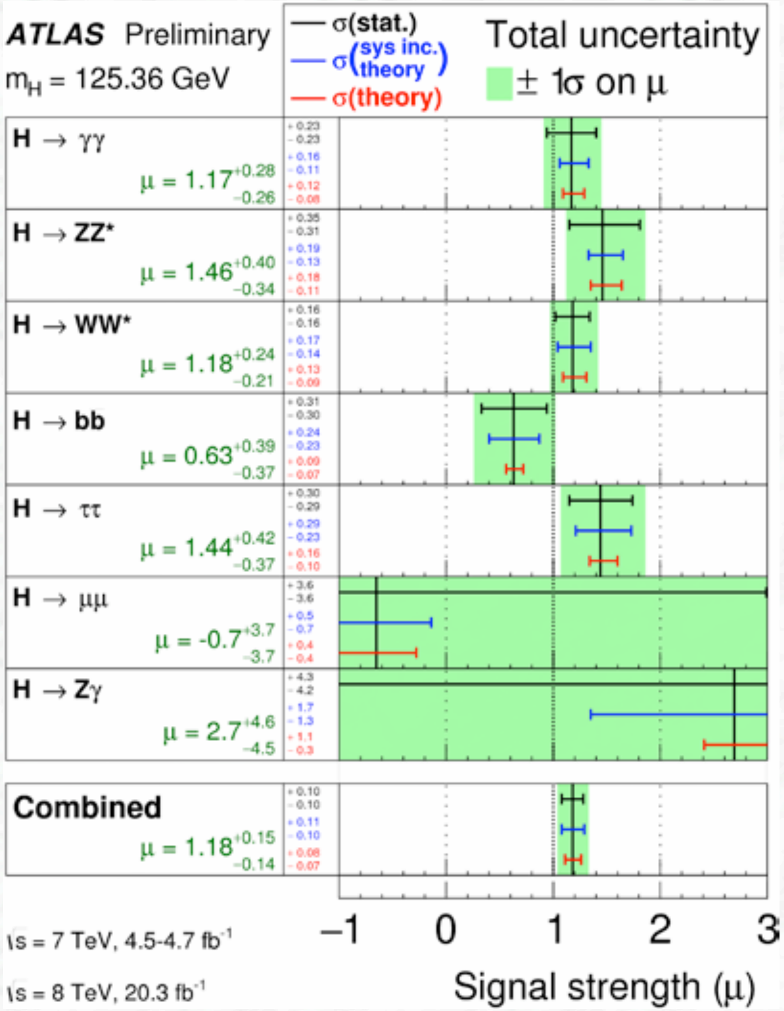
Large increase in mass range (current gluino mass limit: 1.3 TeV)		
Discovery range: up to	2.0 TeV	(300 fb^{-1})
	2.35 TeV	(3000 fb^{-1})
95% CL. exclusion:	2.35 TeV	(300 fb^{-1})
	2.95 TeV	(3000 fb^{-1})

Large increase in mass range (current chargino mass limit: 0.42 TeV)		
Discovery range: up to	0.56 TeV	(300 fb^{-1})
	0.82 TeV	(3000 fb^{-1})
95% CL. exclusion:	0.84 TeV	(300 fb^{-1})
	1.10 TeV	(3000 fb^{-1})

Higgs boson physics

Higgs boson parameters

ATLAS-CONF-2015-007



Current knowledge on signal strength and uncertainties

Comments:

- Statistical uncertainties still dominate (except H → WW*)
- Both experimental and theory uncertainties are sizeable
- At present: difficult to make reliable estimates on the experimental and theoretical systematic uncertainties for 300 fb^{-1} and in particular for 3000 fb^{-1}

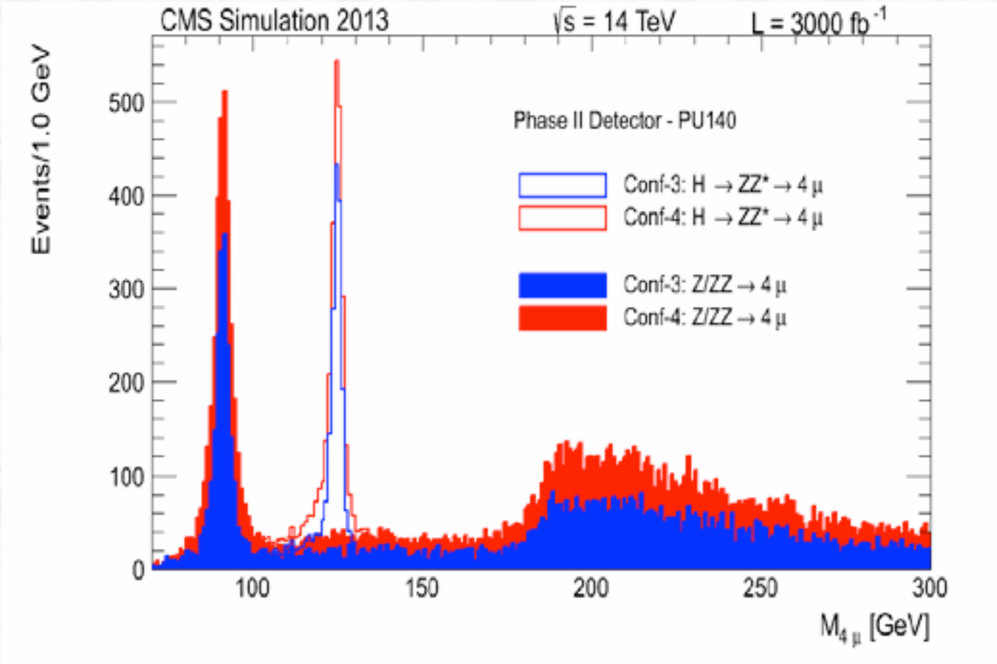
→ TAKE NUMBERS WITH CARE !

Remember that they have large uncertainties

Consolidation of Higgs boson signals

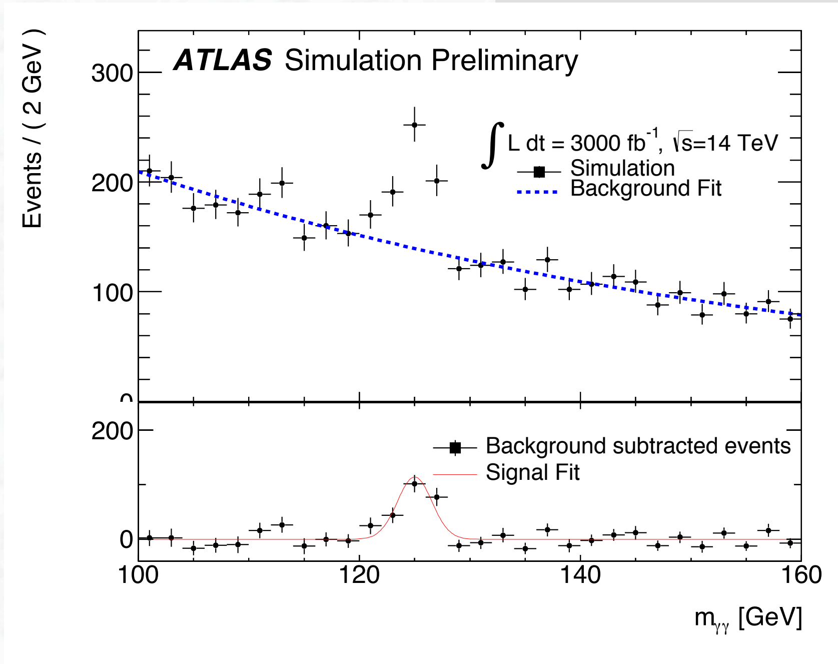
H → ZZ* → 4μ (inclusive)

CMS-PAS-FTR-13-003



ttH, H → γγ, + 1 Lepton

ATL-PHYS-PUB-2014-012

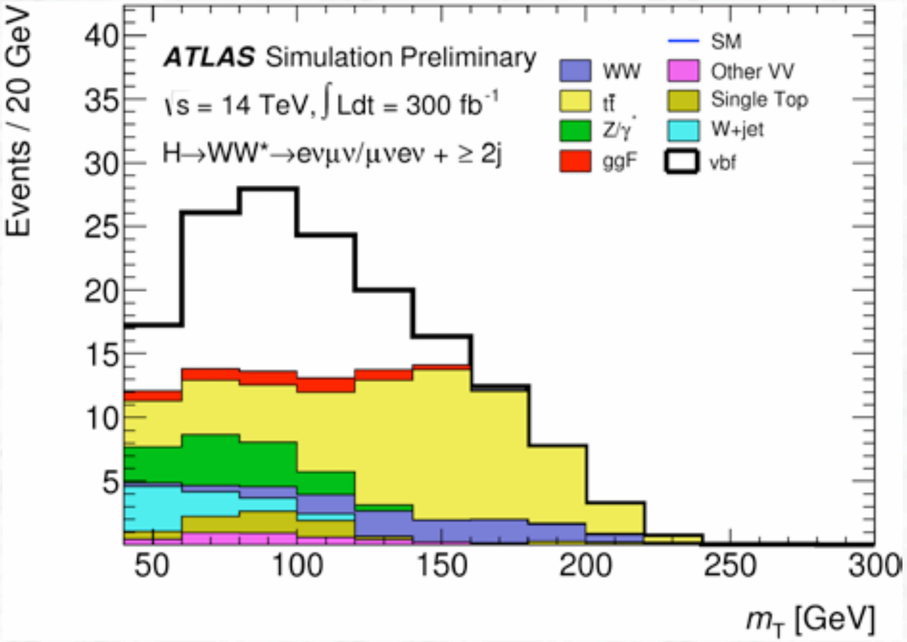


Conf-4 = conf-3 + η-coverage up to 4.0

- High statistics signals will become available during the next years (increased η – coverage of tracker will help)
- H → ZZ* and H → γγ remain "clean" channels
- Focus will be on differential measurements and classification, e.g. ttH production with H → 4ℓ , H → γγ

Consolidation of Higgs boson signals

$H \rightarrow WW^* \rightarrow \ell\nu\ \ell\nu$ (+2 jets) ATL-PHYS-PUB-2013-014



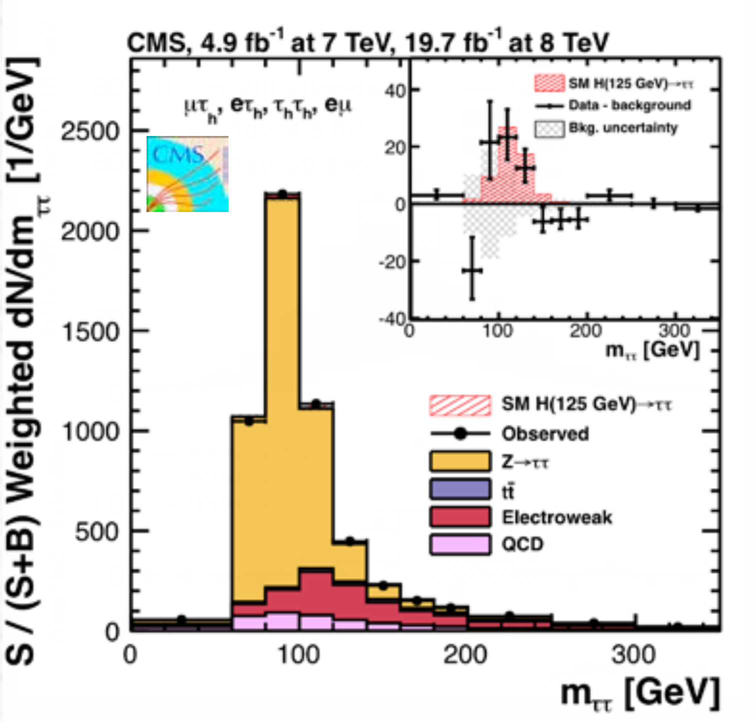
- A "more difficult" channel at high energy/luminosity
  - tt background increases faster than signal
  - Jet counting affected by pile-up
  - Analyses at high-luminosity require dedicated optimisations

- Expected uncertainty on μ-measurement:
  - Gluon fusion: for 300 [3000] fb^{-1}: ±(9 - 18)% [±(5 – 16)%]
  - VBF: ±(20 -21)% [±(9 – 15)%]

Range reflects impact of theory uncertainties: (no uncertainties – present uncertainties)

H → ττ decays

Present status: JHEP 1405 (2014) 104



Measured signal strengths in Run 1:

ATLAS: $\mu = 1.43\ ^{+0.43}_{-0.37}$ (4.5σ)
CMS: $\mu = 0.78 \pm 0.27$ (3.2σ)

Expected precision on μ:

300 fb^{-1}: ±(18–21%)
3000 fb^{-1}: ±(8–18%) (depending on pile-up rejection, no theory uncertainty)

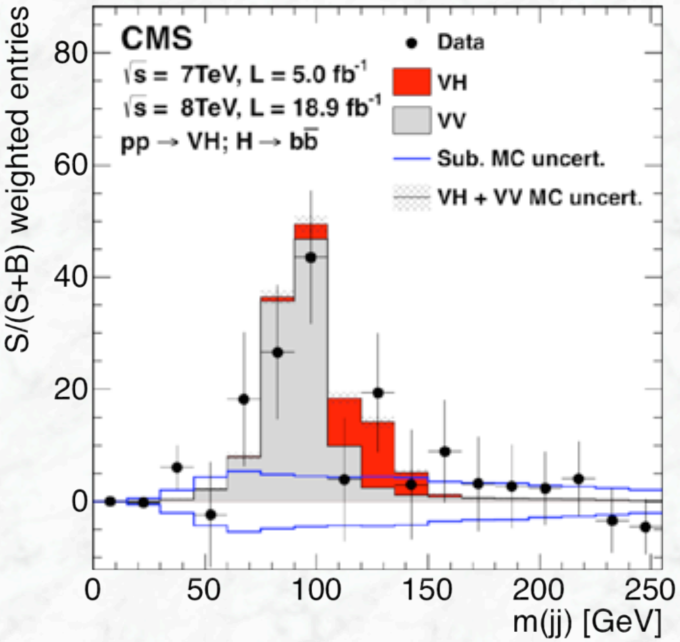
- 2015/16 data are important to consolidate the signal
- Basis analysis techniques (multivariate techniques, strong reliance on VBF-component) will be pursued
  Signal increases faster (factor 2.4) than major Z → ττ background (factor 1.7)

- However: high pile-up sensitivity, in particular in forward region
- ATLAS studies (ATL-PHYS-PUB-2014-018) strongly indicate that tracking up to η=4.0 has high potential to reject pile-up jets (tag-jets)

H → bb decays

Present status:

Phys. Rev. D89 (2014) 012003



Measured signal strengths in Run 1:

ATLAS: μ = 0.50 ± 0.36
CMS: μ = 1.0 ± 0.5

Expect 3.9σ (8.8σ) for 300 fb^{-1} (3000 fb^{-1})

Expected precision on μ:
300 fb^{-1}: ±26%
3000 fb^{-1}: ±(12–14%) (depending on theory uncertainty)

- 2015/16 data are important to establish a signal (most likely not > 5σ)
- Basis analysis techniques (multivariate techniques, focus on high-p_T region,
→ boosted jets, develop reconstruction techniques further)

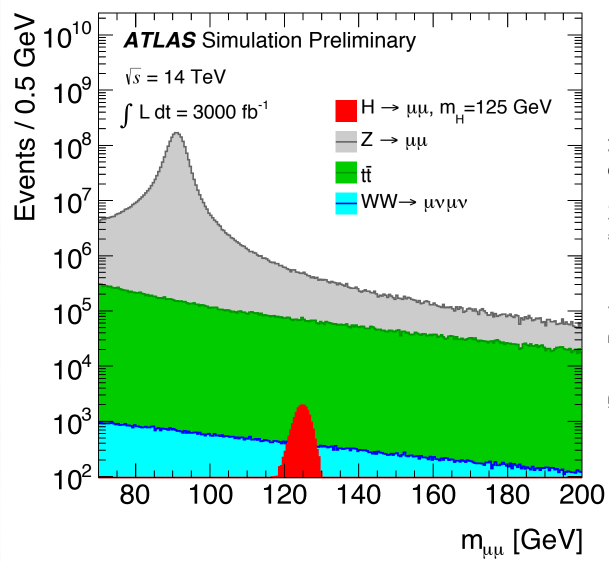
- Dominant backgrounds: Wbb, Zbb
How far can uncertainties be reduced?

Rare Higgs boson decays

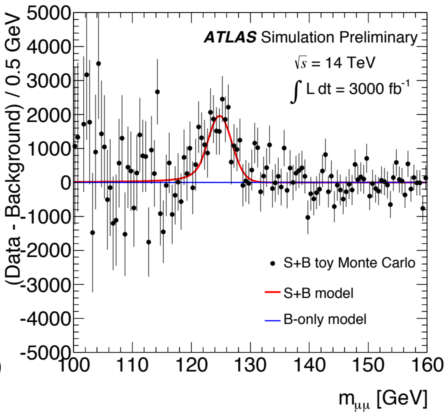
H → $\mu\mu$

- SM prediction: BR(H → $\mu\mu$) = $2.2 \cdot 10^{-4}$
- Run 1 limit: $\mu_{95} \sim 7$
- With 3000 fb^{-1}:

  - Observation at 7σ
  - Uncertainty of 20-25% on signal strength

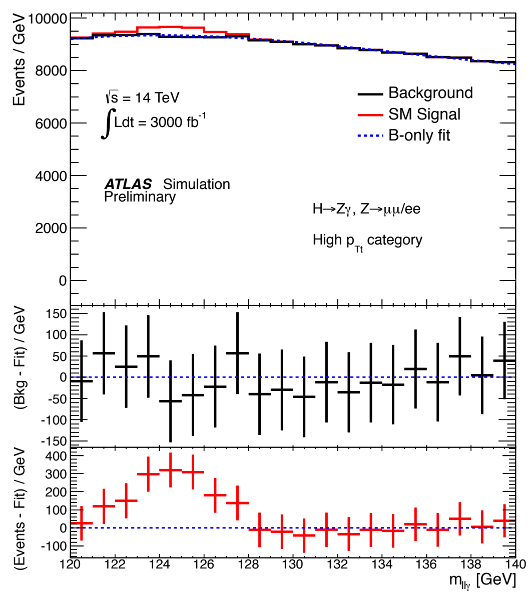


ATL-PHYS-PUB-2013-014



H → Zγ

- SM prediction:
  BR(H → $\mu\mu$) = $1.54 \cdot 10^{-3}$
- Run 1 limit: $\mu_{95} \sim 10$
- With 3000 fb^{-1}:
  Uncertainty of 20-30% on signal strength

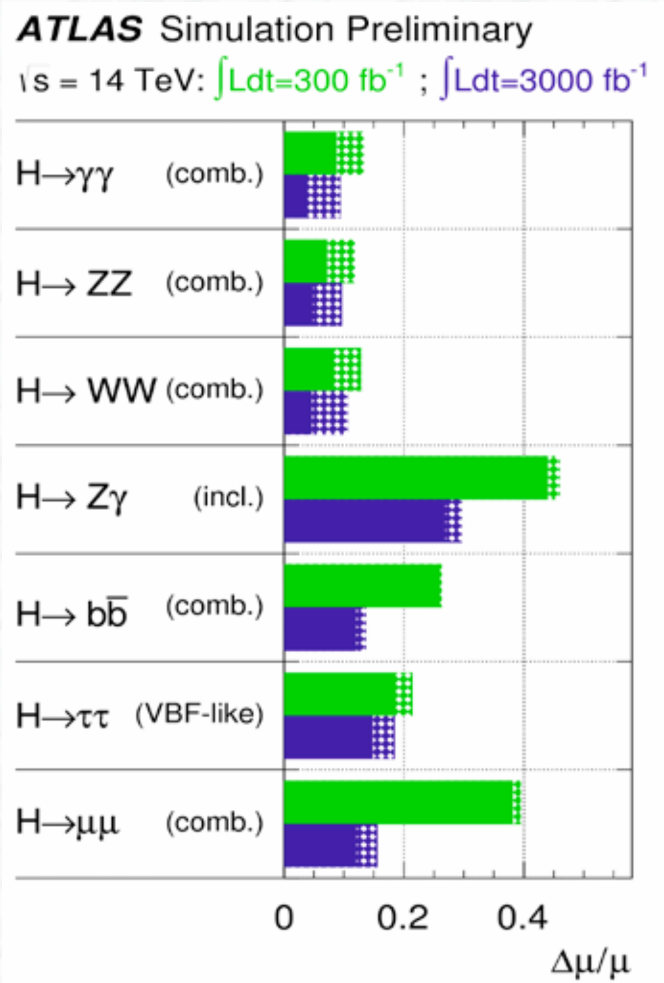


ATL-PHYS-PUB-2013-006

Estimated uncertainties on signal strengths in individual decay modes

ATL-PHYS-PUB-2013-016
CMS: arXiv:1307.7135

ATL-PHYS-PUB-2013-016



The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties

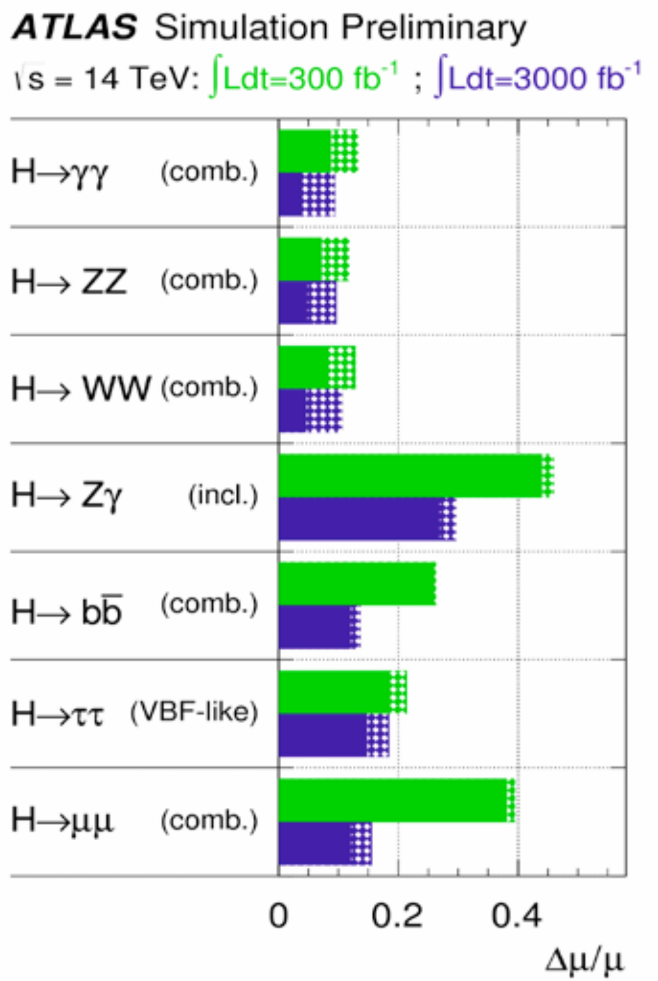
Process		Run 1 $\Delta\mu / \mu$	300 fb^{-1} $\Delta\mu / \mu$	3000 fb^{-1} $\Delta\mu / \mu$
H → γγ	ATLAS CMS	24% 23%	9 – 13% 6 – 12%	4 – 9% 4 – 8%
H → ZZ	ATLAS CMS	28% 31%	7 – 11% 7 – 11%	4 – 9% 4 – 7%
H → WW	ATLAS CMS	21% 28%	8 – 13% 6 – 11%	5 – 11% 4 – 7%
H → ττ	ATLAS CMS	30% 35%	18 – 21% 8 – 14%	15 – 19% 5 – 8%
H → bb	ATLAS CMS		26% 11 – 14%	12 – 14% 5 – 7%
H → μμ	ATLAS CMS		38 – 40% 40 – 42%	12 – 16% 20 – 24%
H → Zγ	ATLAS CMS		44 – 46% 62%	27 – 30% 20 – 24%

ATLAS range: (i) current theory uncertainties
(ii) no theory uncertainties

CMS range: (i) all syst. uncertainties left unchanged
(ii) 0.5*syst(theory), syst(exp) scaled by √L

Estimated uncertainties on signal strengths in individual decay modes

ATL-PHYS-PUB-2013-016



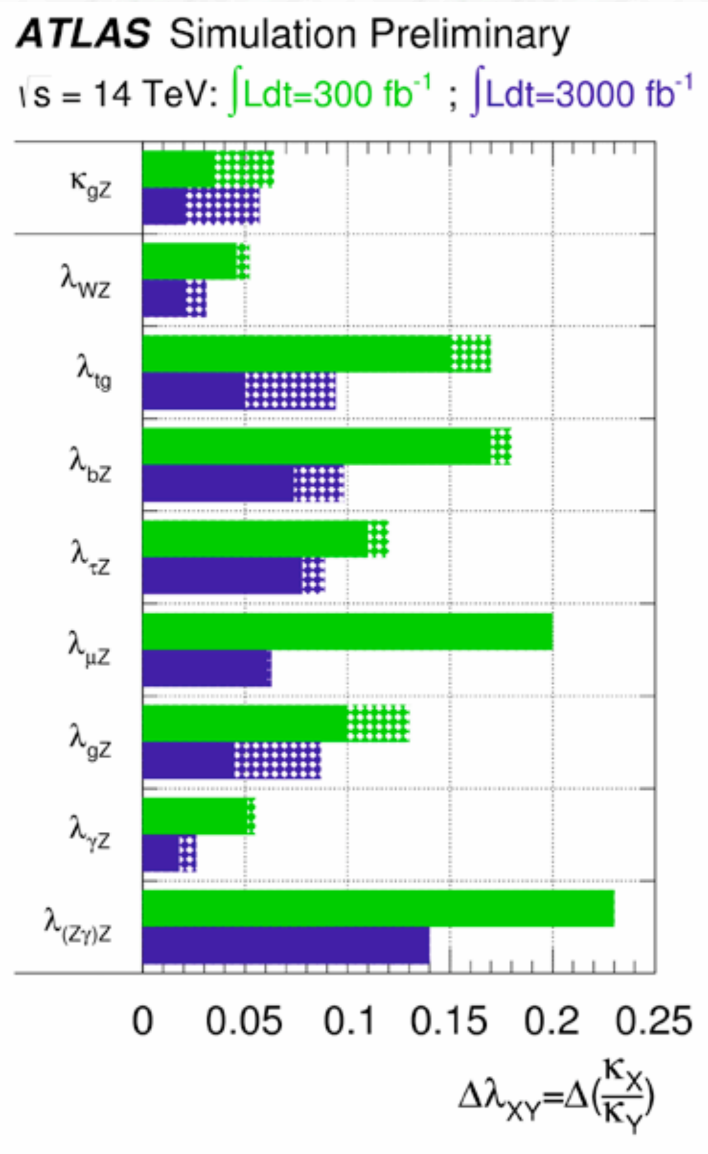
The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties

Estimated uncertainties on production modes:

$\Delta\mu/\mu$	$300\ fb^{-1}$		$3000\ fb^{-1}$	
	All unc.	No theory unc.	All unc.	No theory unc.
$gg \to H$	0.12	0.06	0.11	0.04
VBF	0.18	0.15	0.15	0.09
WH	0.41	0.41	0.18	0.18
$qqZH$	0.80	0.79	0.28	0.27
$ggZH$	3.71	3.62	1.47	1.38
ttH	0.32	0.30	0.16	0.10

Estimated uncertainties on coupling scale factor ratios

ATL-PHYS-PUB-2013-016



- Use fully generic benchmark model, no assumptions on new particles contributing through loops
- For the majority of coupling ratios the precision without theory uncertainties is significantly improved by more than a factor of two when going from 300 fb^{-1} to 3000 fb^{-1}

Estimated uncertainties on loop-induced Higgs boson couplings:

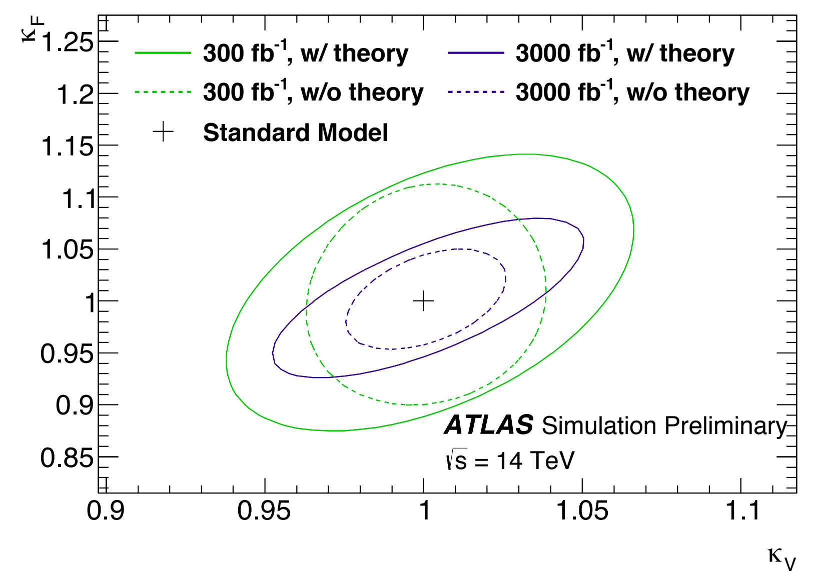
Nr.	Parameter	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
9	κ_g	8.9%	7.1%	6.3%	6.7%	4.1%	2.8%
	κ_γ	4.9%	4.8%	4.7%	2.1%	1.8%	1.7%
	$\kappa_{Z\gamma}$	23%	23%	23%	14%	14%	14%
	$BR_{i,u}$	<22%	<20%	<20%	<14%	<11%	<10%

Estimated results on coupling fits

Example: simple κ_F vs κ_V scenario

(one coupling scale factor for fermions and one for bosons)

ATL-PHYS-PUB-2013-016



Expected precision:

300 fb^{-1}:	κ_V:	±2.5% (no theory uncertainties)	±4.3% (current theory uncertainties)
	κ_F:	±7.1%	±8.8%
3000 fb^{-1}:	κ_V:	±1.7% (no theory uncertainties)	±3.3% (current theory uncertainties)
	κ_F:	±3.2%	±5.1%

More results on different benchmark scenarios in ATL-PHYS-PUB-2013-016

Conclusions

- Superb LHC Run 1 with a milestone discovery
- Huge progress in investigation of the Higgs boson profile in Run 1
- So far, no signals from New Physics;

- Run 2 about to start → We will enter a New Energy domain

  - Similar experimental conditions as in Run 1 (at the beginning, hopefully)
  - Refurbished experiments, highly motivated physicists and PhD students

→ High potential to explore new mass range
→ High potential for more precise measurement of the Higgs boson
HiggsTools can contribute significantly to that

- Exciting times ahead of us