The Physics Program of the High Luminosity LHC

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Outline

- Brief LHC introduction
- The High Luminosity LHC upgrade
- The physics case for High Luminosity LHC
  - Understanding Electro-weak Symmetry Breaking
  - Search for Beyond the Standard Model physics
- Summary and Outlook

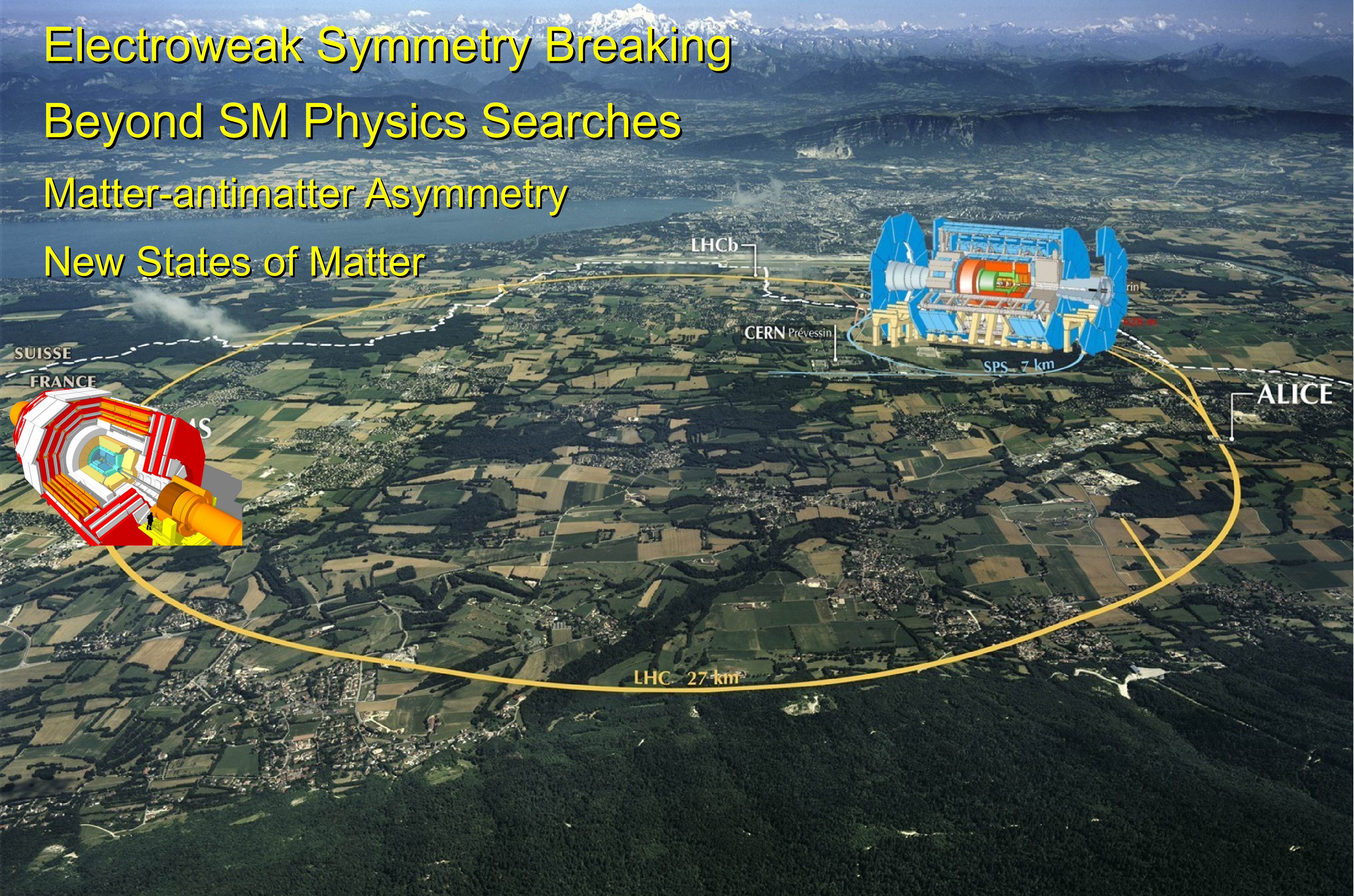
The Large Hadron Collider

Large Hadron Collider

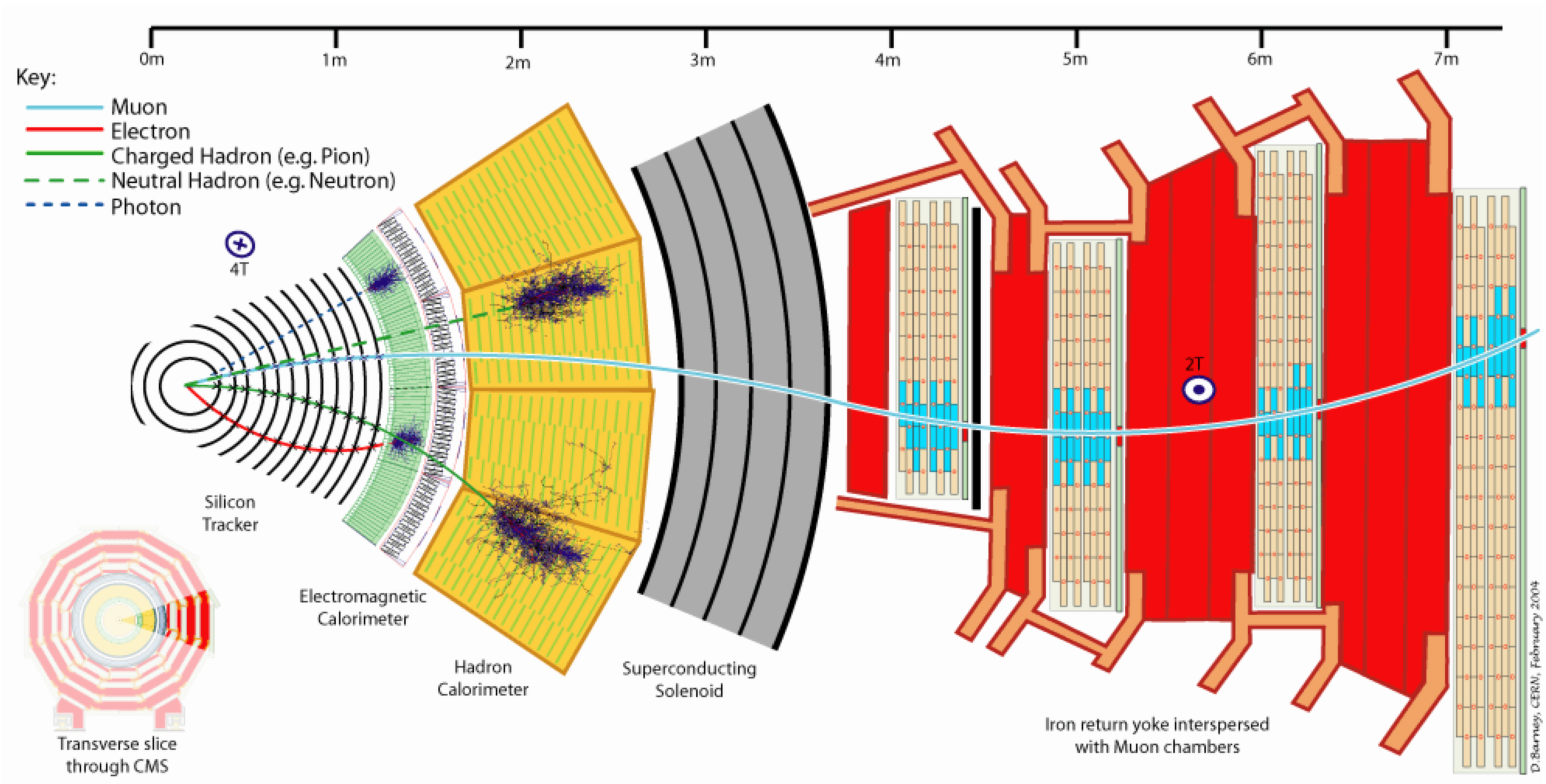
27 km proton-proton collider at CERN

Large Hadron Collider Goals

- Electroweak Symmetry Breaking
- Beyond SM Physics Searches
- Matter-antimatter Asymmetry
- New States of Matter



The CMS Experiment

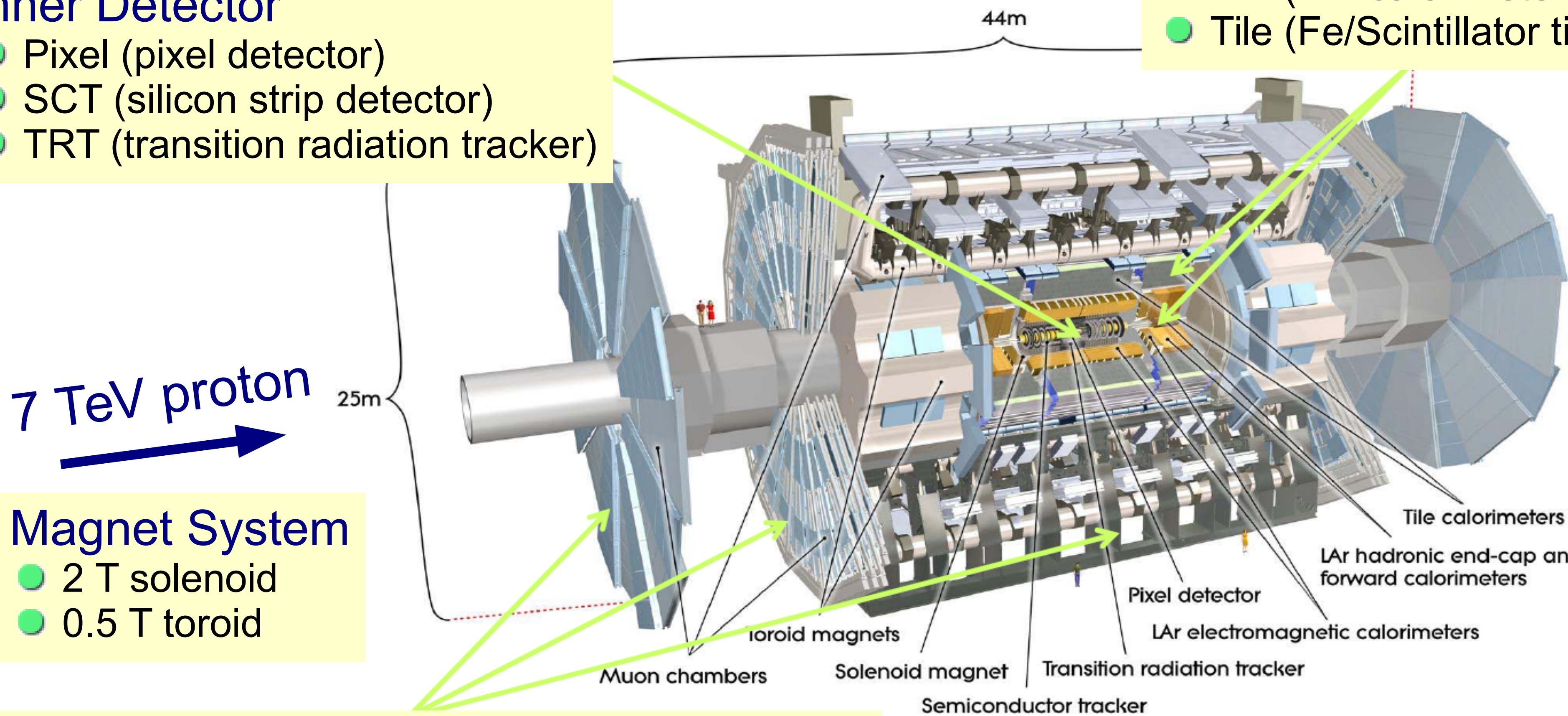


Not shown:
Trigger system for selecting
the 0.0025% most interesting collisions

The ATLAS Experiment

Inner Detector
- Pixel (pixel detector)
- SCT (silicon strip detector)
- TRT (transition radiation tracker)

Calorimeter
- LAr (EM calorimeter)
- Tile (Fe/Scintillator tile)



Magnet System
- 2 T solenoid
- 0.5 T toroid

Muon Spectrometer
- MDT,CSC (precise momentum measurement)
- RPC,TGC (trigger chambers)

Trigger/DAQ System
- 100 kHz L1 rate (HW trigger)
- ~1 kHz to tape

Collision Energy and Luminosity

- Particle production in LHC driven by two parameters
  - Center-of-mass energy ($\sqrt{s}$)
    – sets the cross-section (σ)
    (probability of interaction)
  - Luminosity (L)
    – measure of collision rate

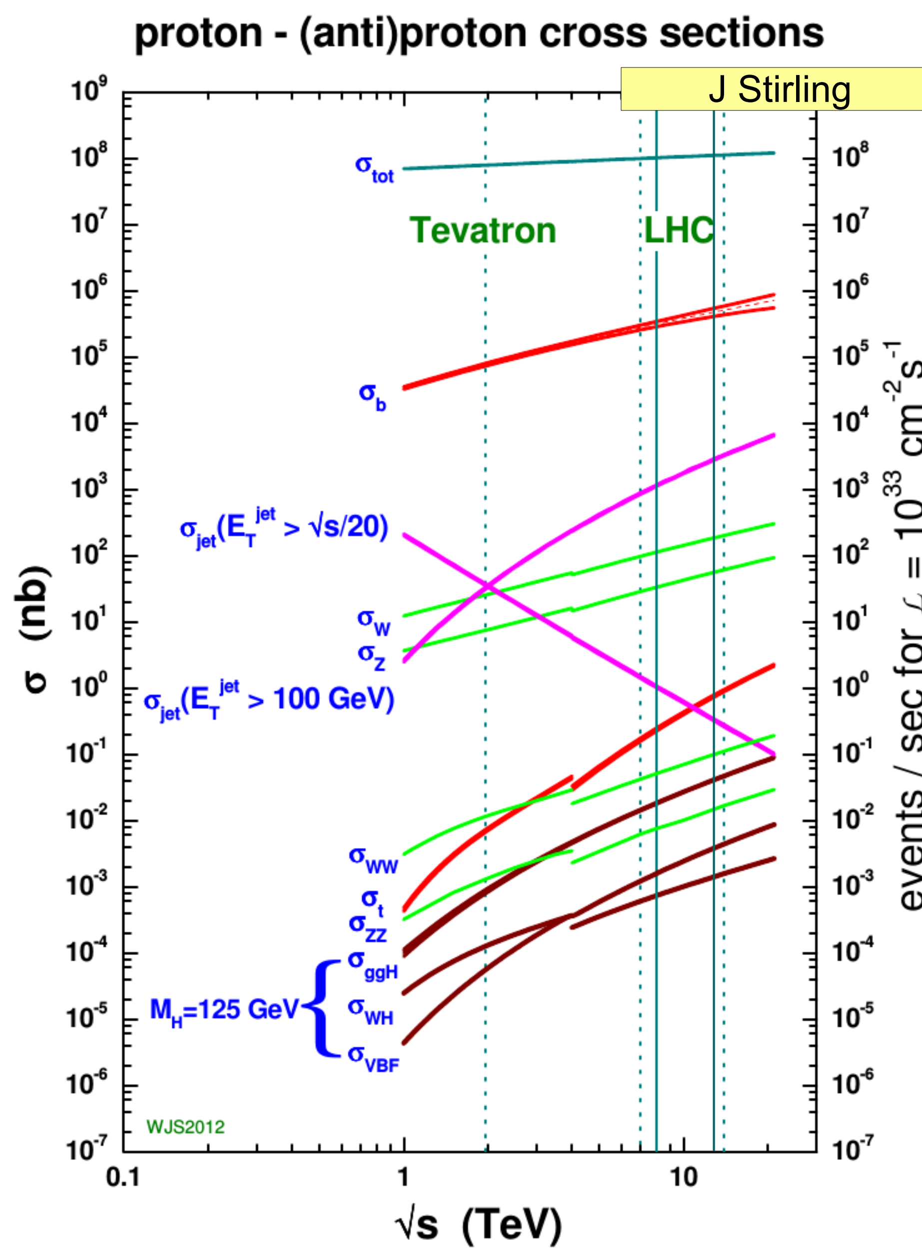
- Instantaneous production rate:

  Rate = $\sigma(\sqrt{s})$ x L → [10^{34} cm^{-2}s^{-1}]

  [barn=100fm^2=10^{-24} cm^2]
  [femtobarn=10^{-39} cm^2]

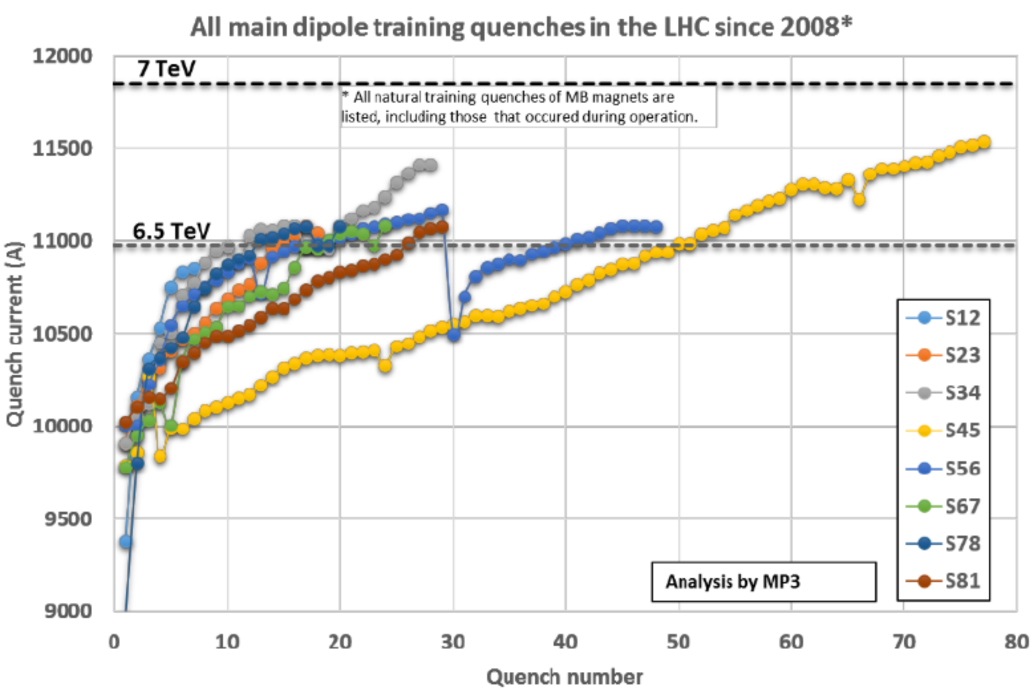
- Integrated rate most important:

  Events = $\sigma(\sqrt{s})$ x $\int L\, dt$ → [fb^{-1}]



Collision Energy

- Center-of-mass energy is limited by bending power in main dipole magnets
  - Superconducting magnets
  - Need to be "trained" by having controlled quenches as current is ramped up
  - Limited by time and safety



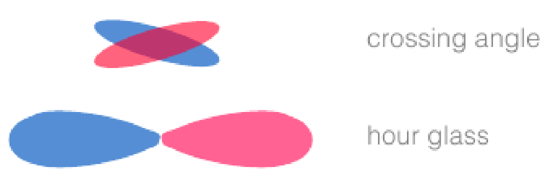
- Started at $\sqrt{s}$=7 TeV
- Now at $\sqrt{s}$=13 TeV after safety upgrade in 2013/14
- Design is $\sqrt{s}$=14 TeV, while ultimate could be $\sqrt{s}$=15.4 TeV

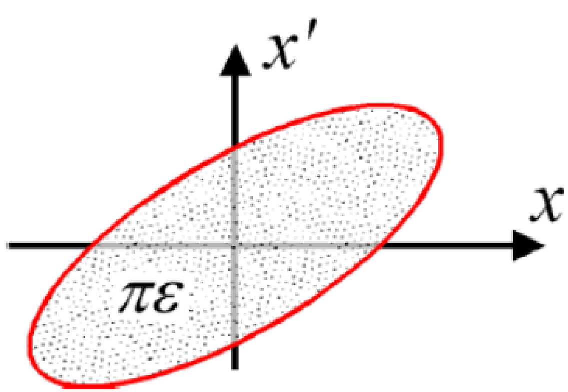
Luminosity

- Luminosity is a function of the LHC beam parameters

$$L = \frac{N^2 n_b f}{4\pi\sigma^*_x\sigma^*_y}F = \frac{N^2 n_b f\gamma}{4\pi\varepsilon_n\beta^*}F$$

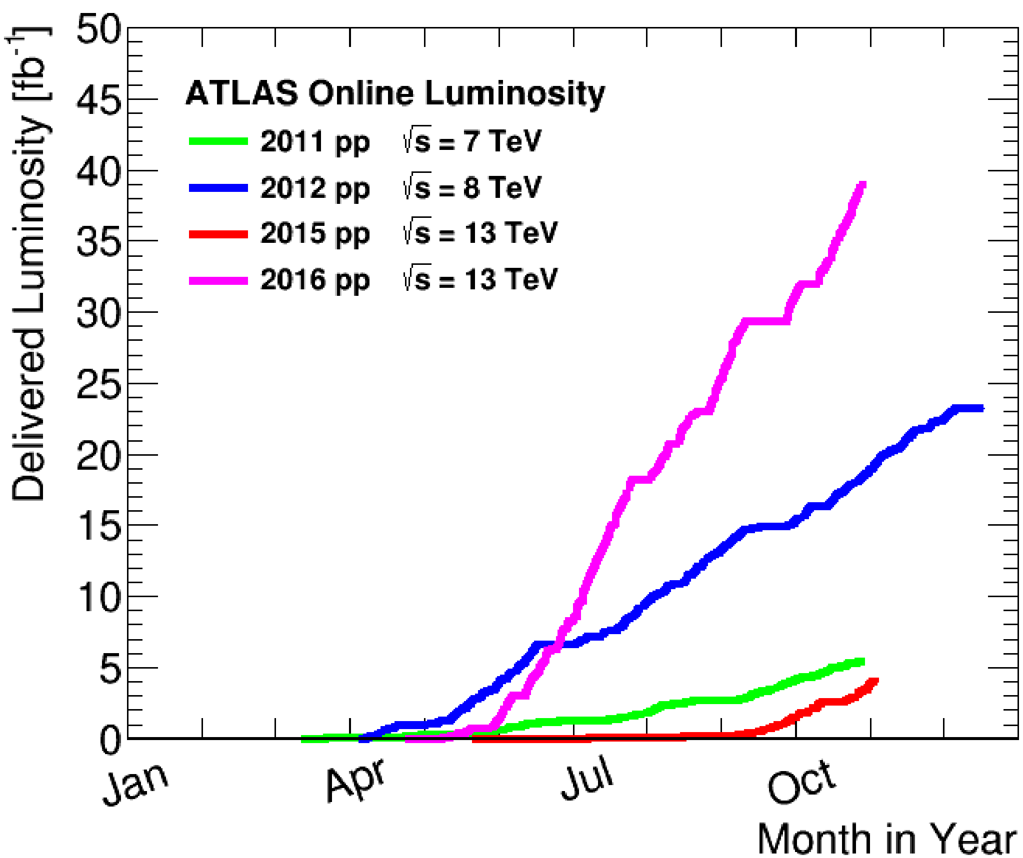
N	**number of particles per bunch**
n_b	**number of bunches / beam**
f	revolution frequency
σ*	**beam size at interaction point**
F	reduction factor due to crossing angle
ε	emittance
ε_n	**normalized emittance = εγβ**
β*	**beta function at IP**

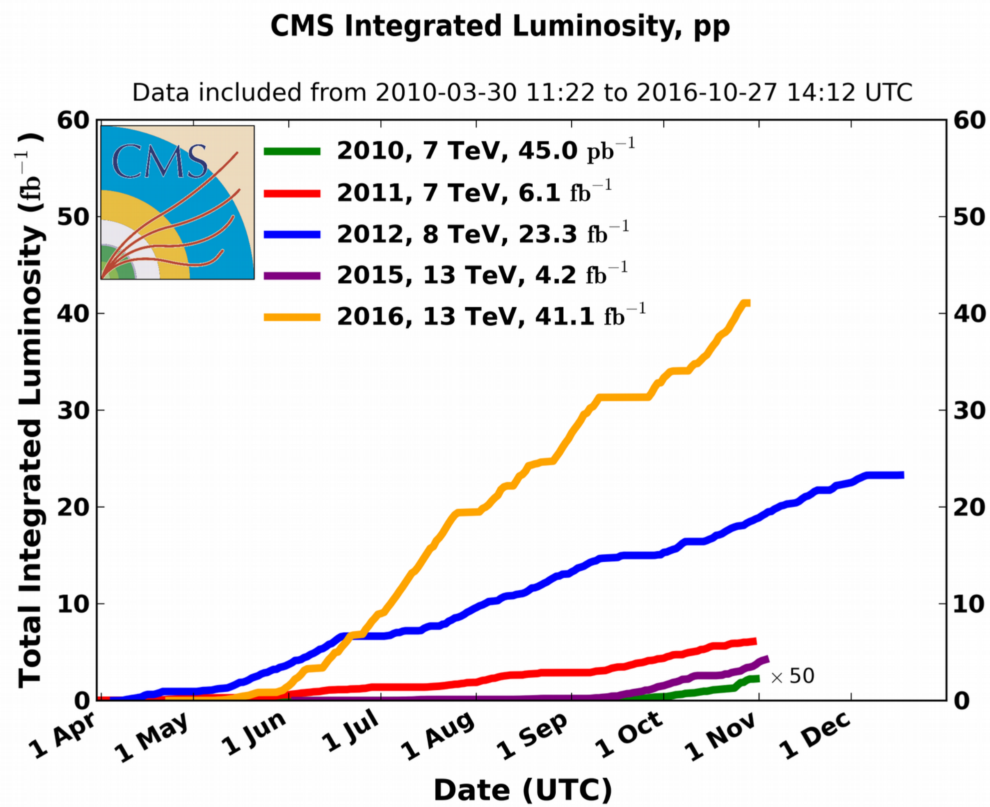




LHC Performance so far

- 2016 was a record breaking year for LHC p-p collisions
  - Peak luminosity: ~1.5x10^{34} cm^{-2}s^{-1} (design: 10^{34} cm^{-2}s^{-1})
  - ~40 fb^{-1} delivered to ATLAS and CMS each





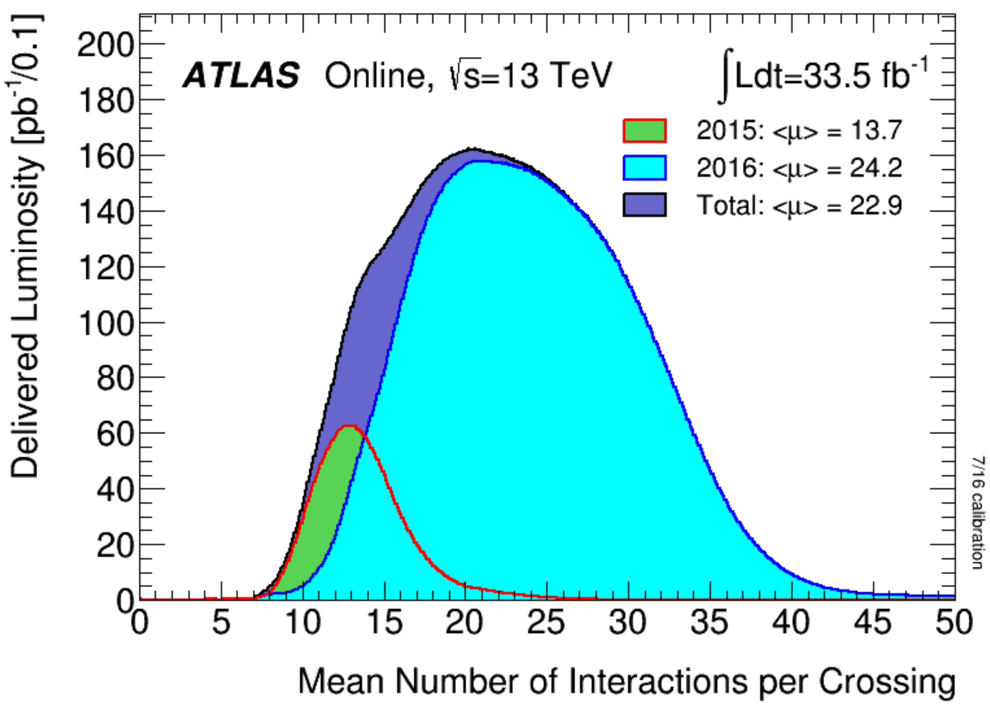
- About 90% of delivered luminosity was recorded and is good for physics analysis
  - Only ~13 fb^{-1} used in public results so far

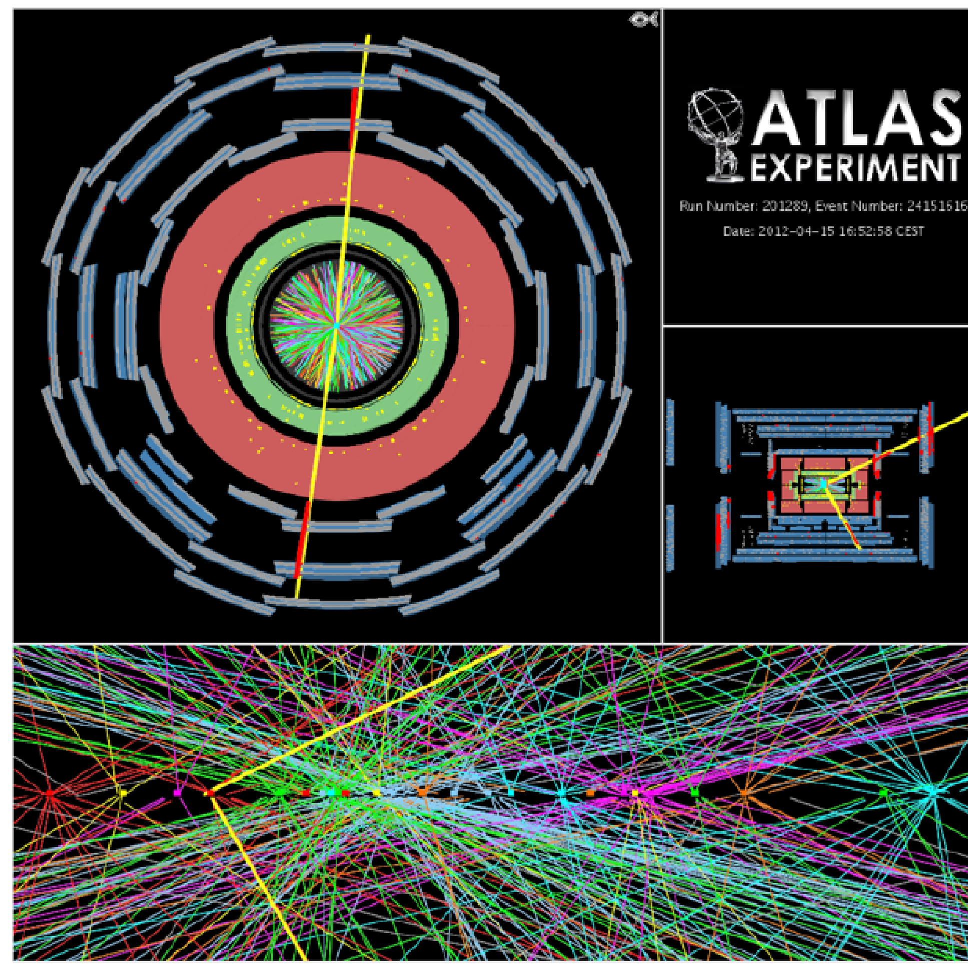
Pile-up Interactions

Down-side to high luminosity:

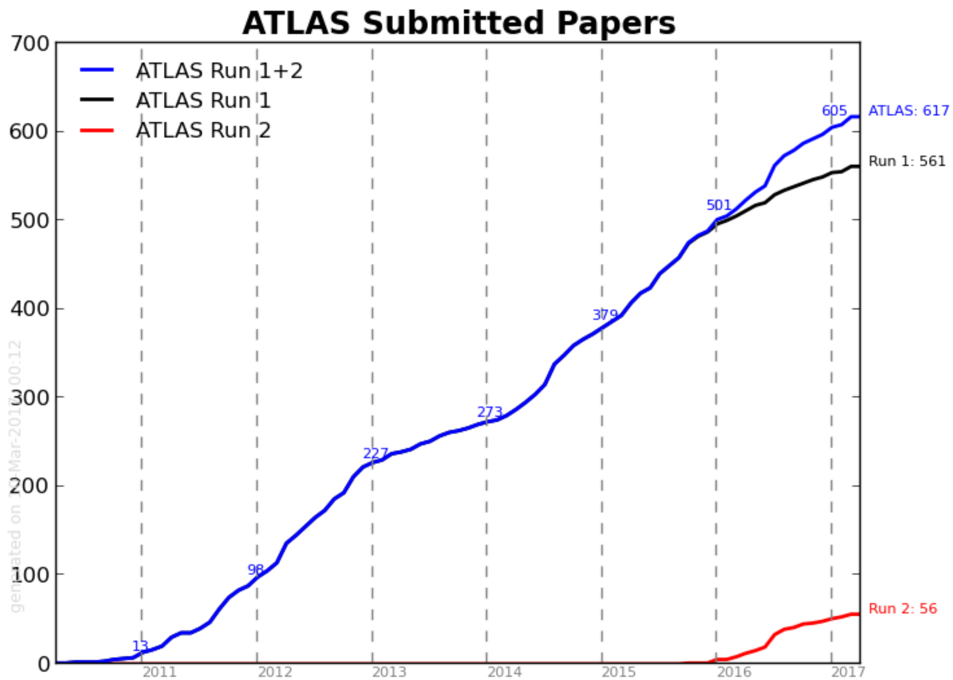
multiple simultaneous interactions per crossing (pile-up) as crossing rate is limited to ~31.5 MHz

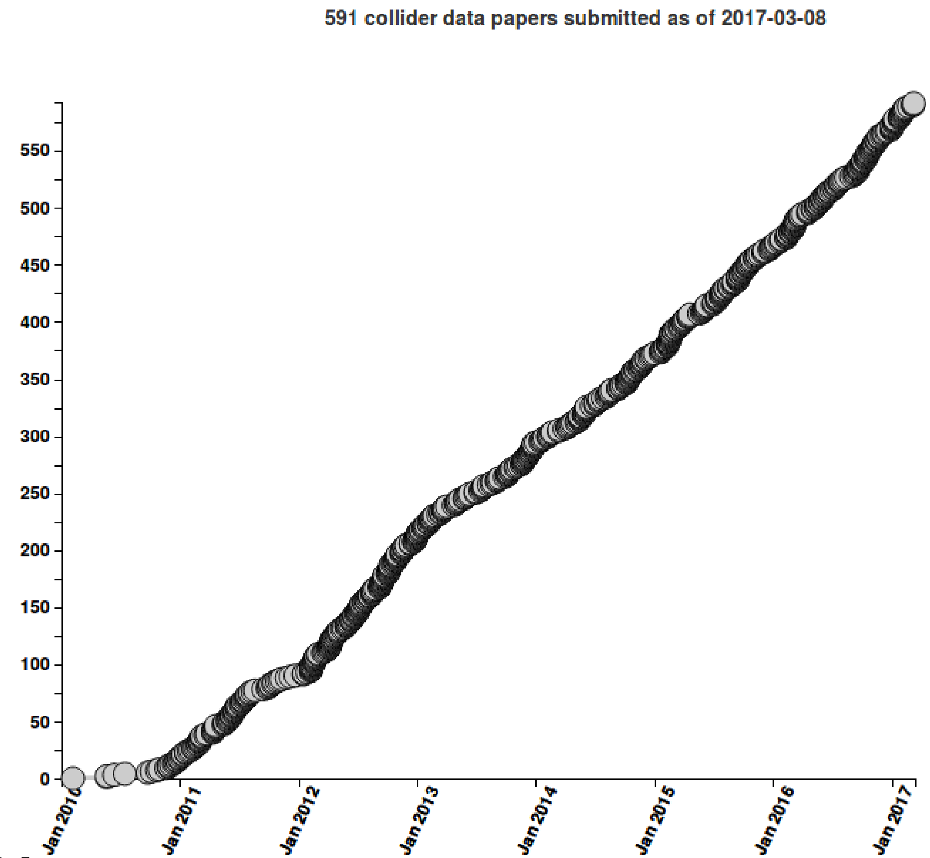
Introduces potential confusion and performance degradation as not all particles are coming from collision of interest





LHC Physics Output



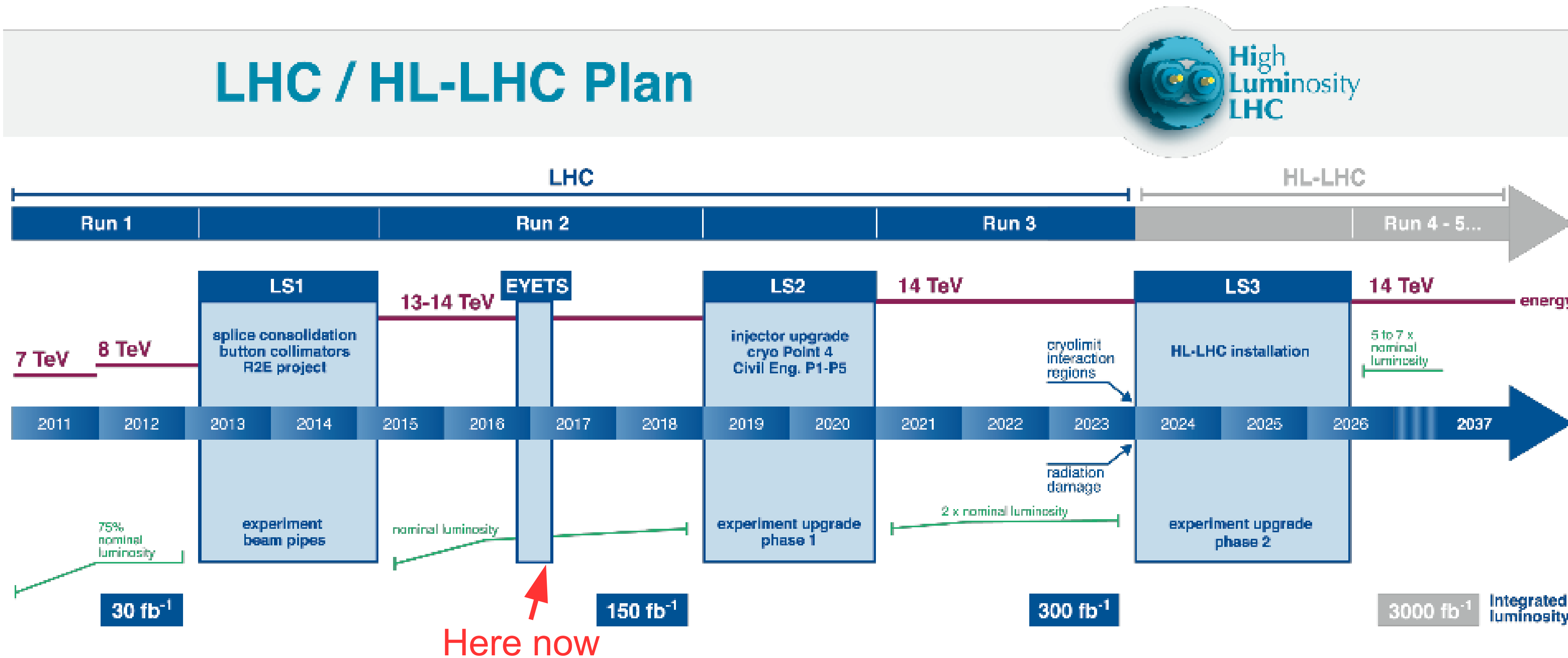


- Full set of physics results here:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/
- Will later show a small selection of current Run-1/2 results
  - Primarily to highlight where higher luminosity is needed
- Many more results from 2016 data to come in next months

The High Luminosity LHC Upgrade

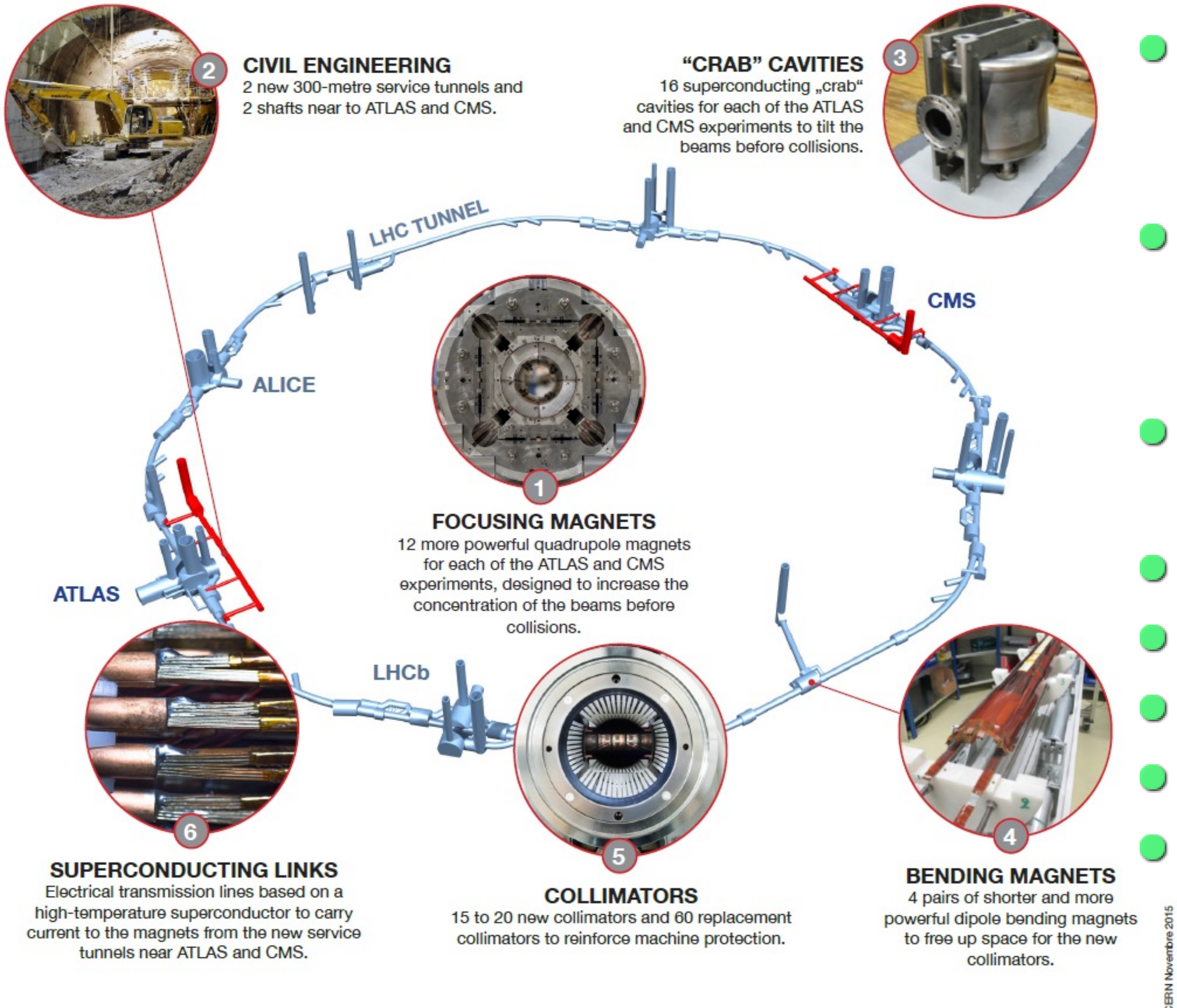
HL-LHC Upgrade Plans

- LHC to deliver 300 fb^{-1} by 2023 (end of Run-3)
- HL-LHC goal is deliver 3000 fb^{-1} in 10 years
  - Implies integrated luminosity of 250-300 fb^{-1} per year
  - Requires peak luminosities of 5-7x10^{34} $cm^{-2}s^{-1}$ while using luminosity leveling (3-5 hours at peak luminosity)
- Design for "ultimate" performance 7.5x10^{34} $cm^{-2}s^{-1}$ and 4000 fb^{-1}



HL-LHC Upgrade Project

Major intervention on more than 1.2 km of the LHC



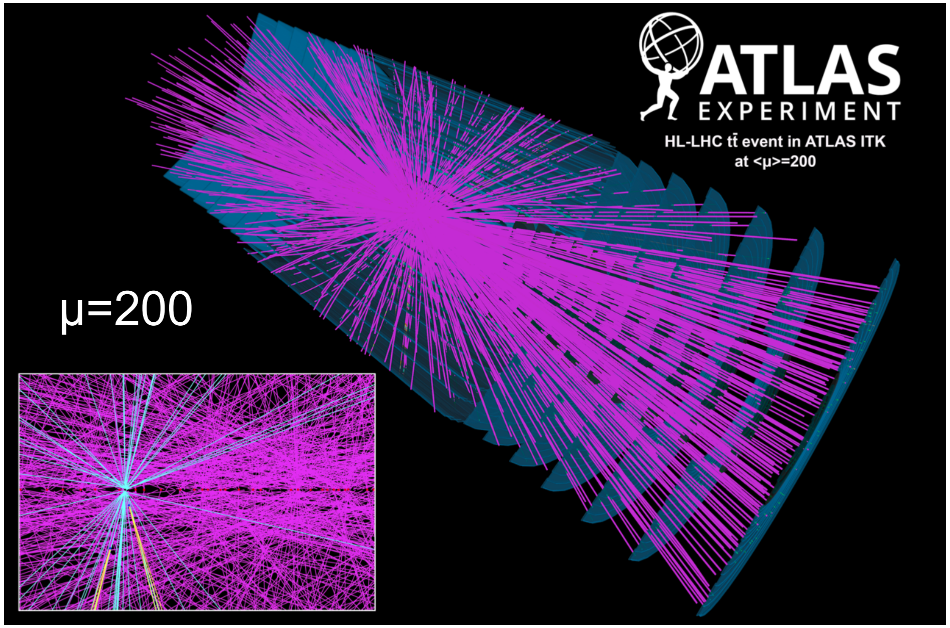
- New IR-quads Nb_3Sn
  (more focusing in
  inner triplet magnets)
- Crab Cavities
  (compensate crossing
  angle by tilting beams)
- New 11 T Nb_3Sn
  (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Cold powering
- Machine protection
- …

Machine upgrade approved by CERN council in June 2016

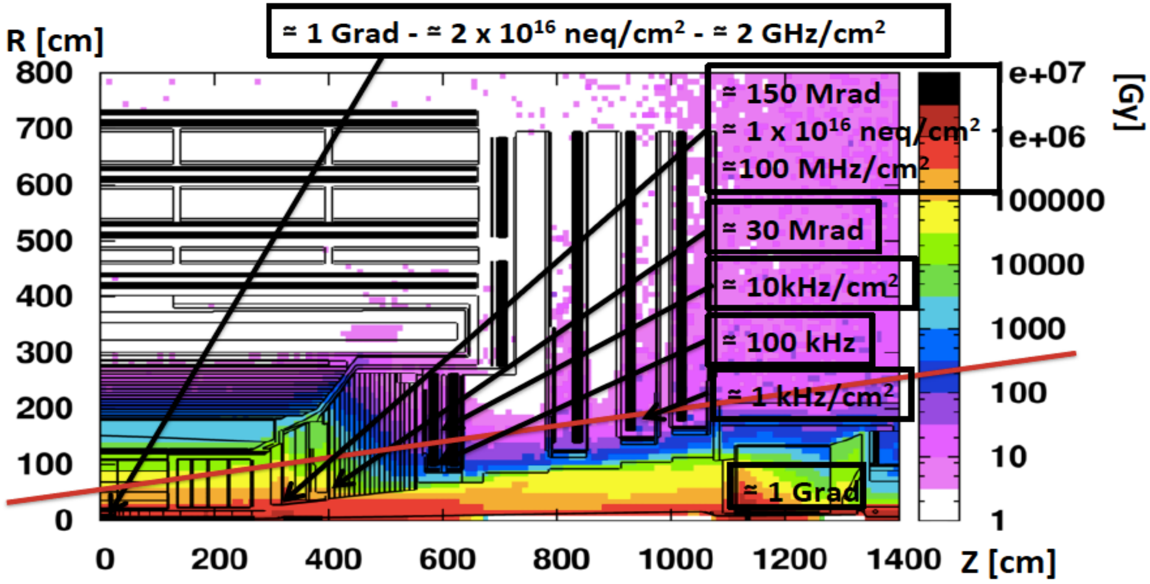
The High-Luminosity Challenge

HL-LHC provides an extreme challenge to the experiments

Very high pile-up

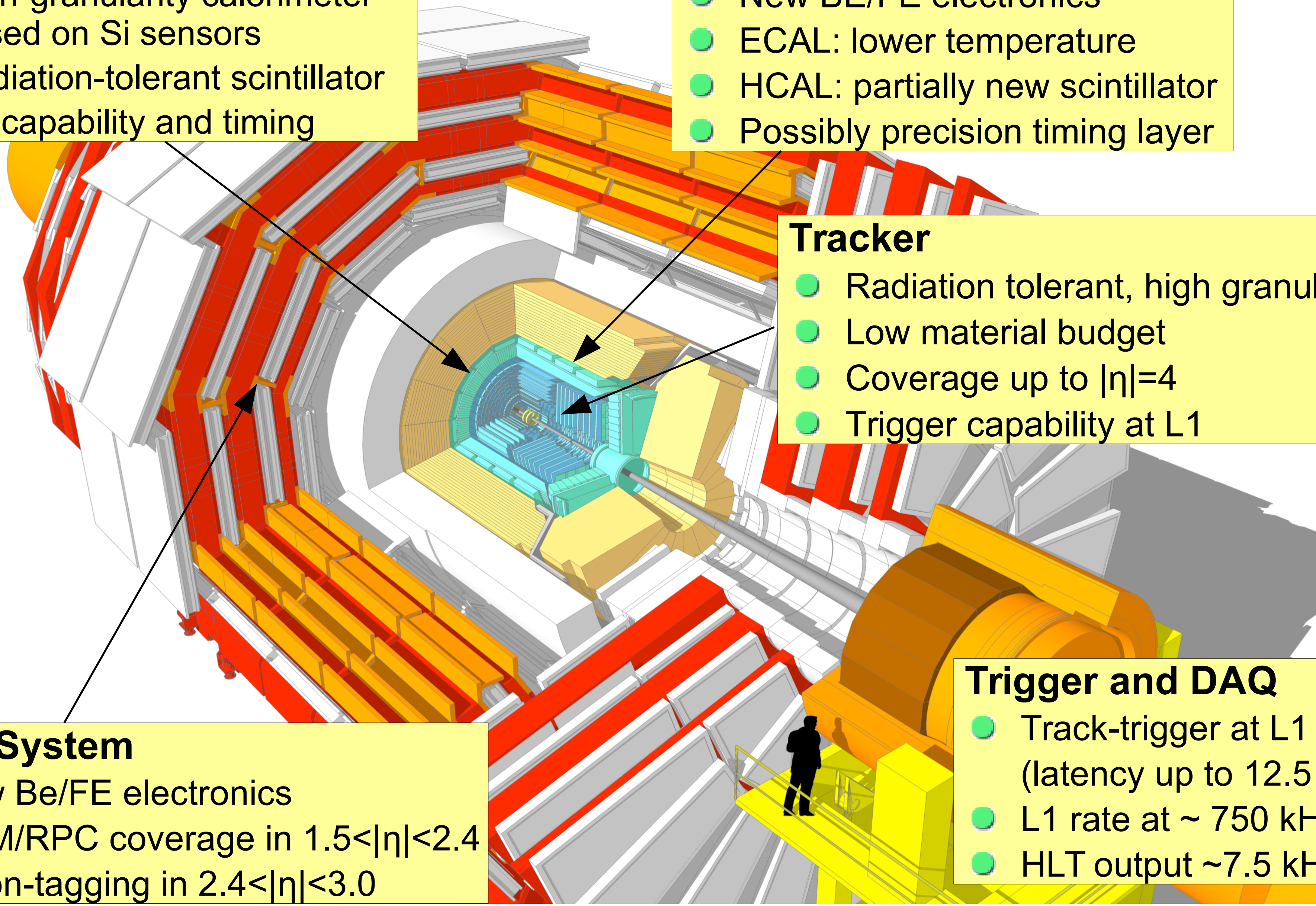


Intense radiation levels



- Major experimental upgrades needed to:
  - Improve radiation hardness and replace detectors at end-of-life
  - Provide handles for mitigating pile-up (high granularity, fast timing)
  - Allow higher event rates to maintain/improve trigger acceptance
- Goal is to maintain or improve over current performance

Detector Upgrades – CMS



Endcap Calorimeter
- High-granularity calorimeter based on Si sensors
- Radiation-tolerant scintillator
- 3D capability and timing

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator
- Possibly precision timing layer

Tracker
- Radiation tolerant, high granularity
- Low material budget
- Coverage up to $|\eta|=4$
- Trigger capability at L1

Muon System
- New Be/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon-tagging in $2.4<|\eta|<3.0$

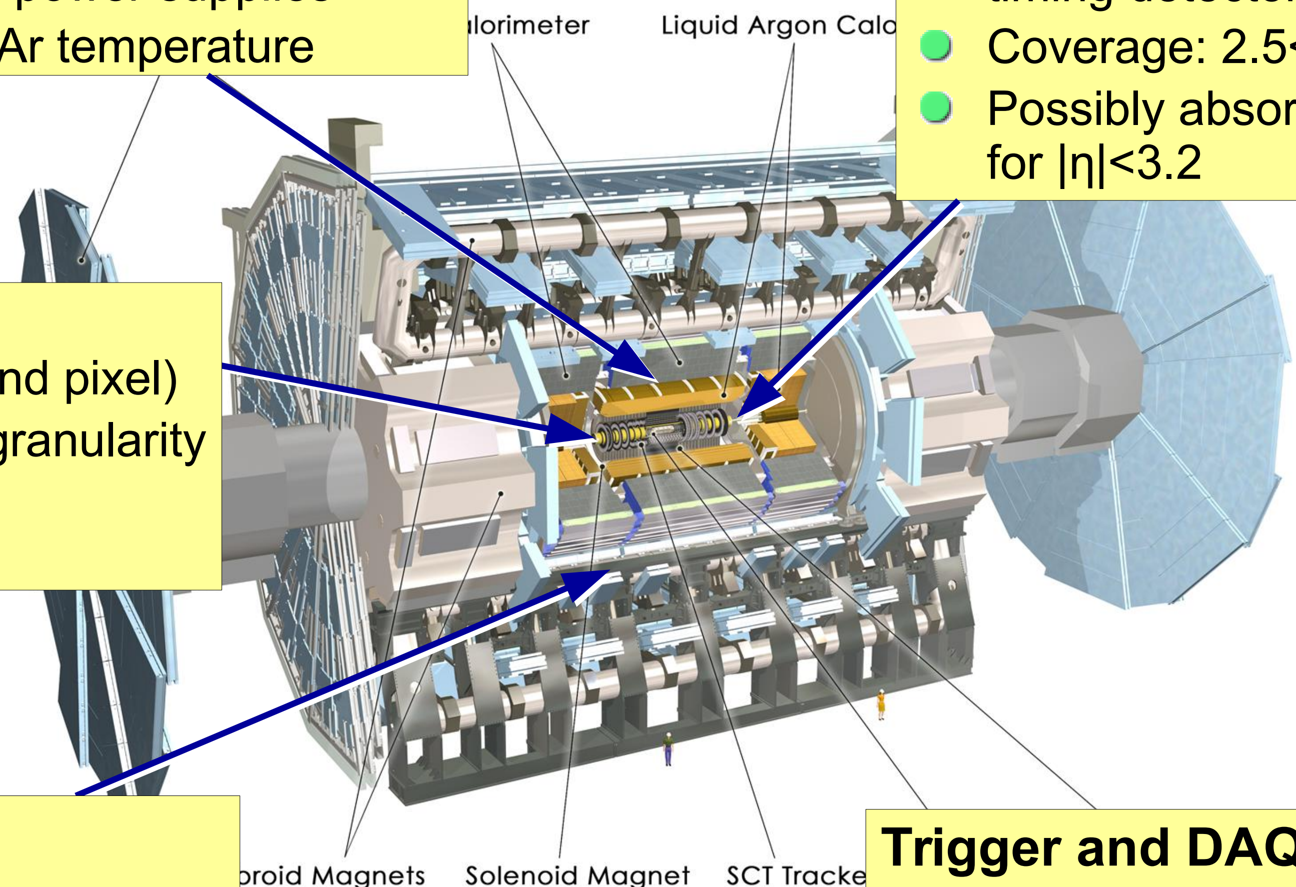
Trigger and DAQ
- Track-trigger at L1 (latency up to 12.5 μs)
- L1 rate at ~ 750 kHz
- HLT output ~7.5 kHz

Detector Upgrade – ATLAS

Calorimeters
- New BE/FE electronics
- New HV power supplies
- Lower LAr temperature

(Timing detector)
- High granularity timing detector
- Coverage: 2.5<|η|<4.2
- Possibly absorber for |η|<3.2

Tracker
- All silicon tracker (strip and pixel)
- Radiation tolerant, high granularity
- Low material budget
- Coverage up to |η|=4

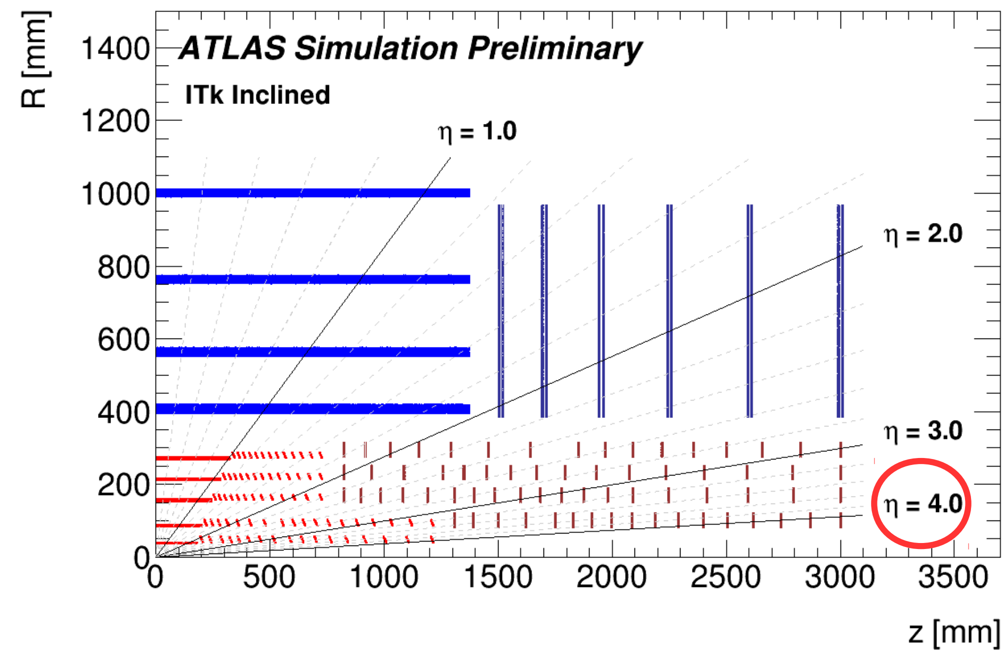


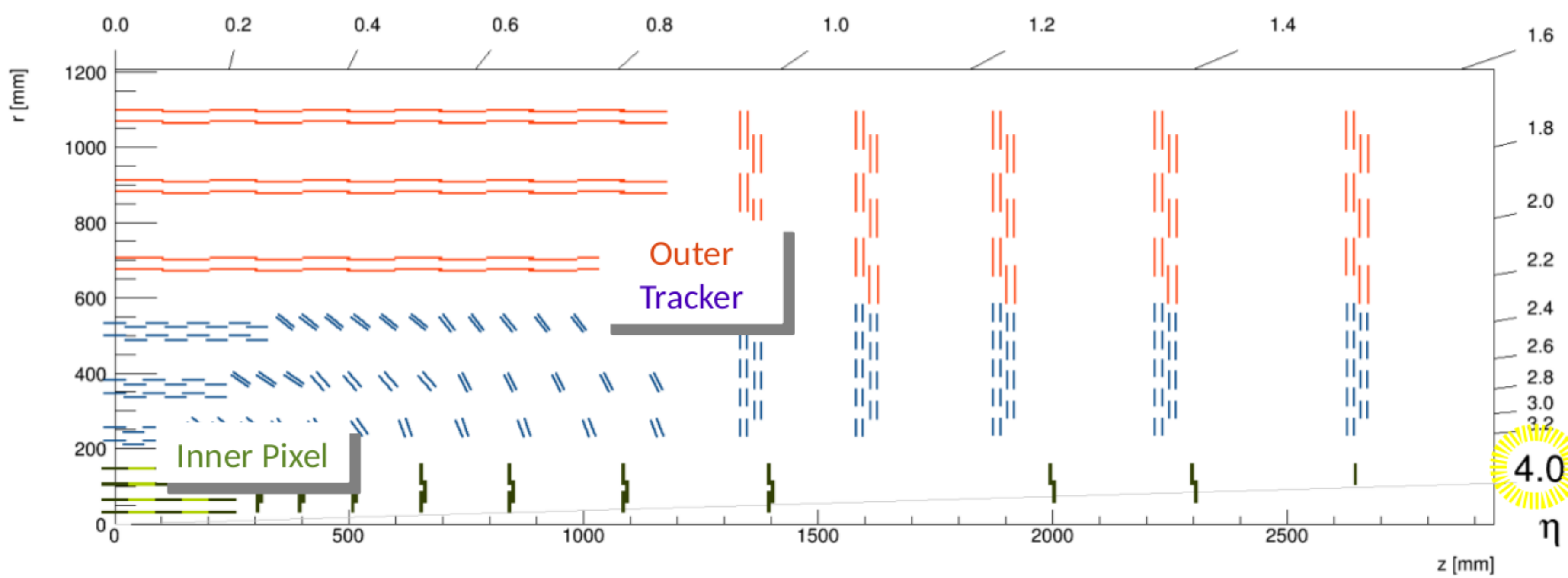
Muon System
- New BE/FE electronics
- New RPC layer in inner barrel
- Muon-tagging in 2.7<|η|<4.0 (under study)

Trigger and DAQ
- L0 rate at ~ 1 MHz (latency up to 10 μs)
- Possible hardware L1 track trigger
- HLT output ~10 kHz

Extended Silicon-based Tracker

- Higher granularity trackers
  - Pixel size: 50x50 or 25x100 μm²
- Both ATLAS and CMS plan to extend tracker coverage from η~2.7 to η~4 with pixel extension
  Provides multiple benefits
  - Extended lepton coverage (with forward muon tagger)
  - Forward b-tagging
  - Improved vertexing
  - Pileup suppression

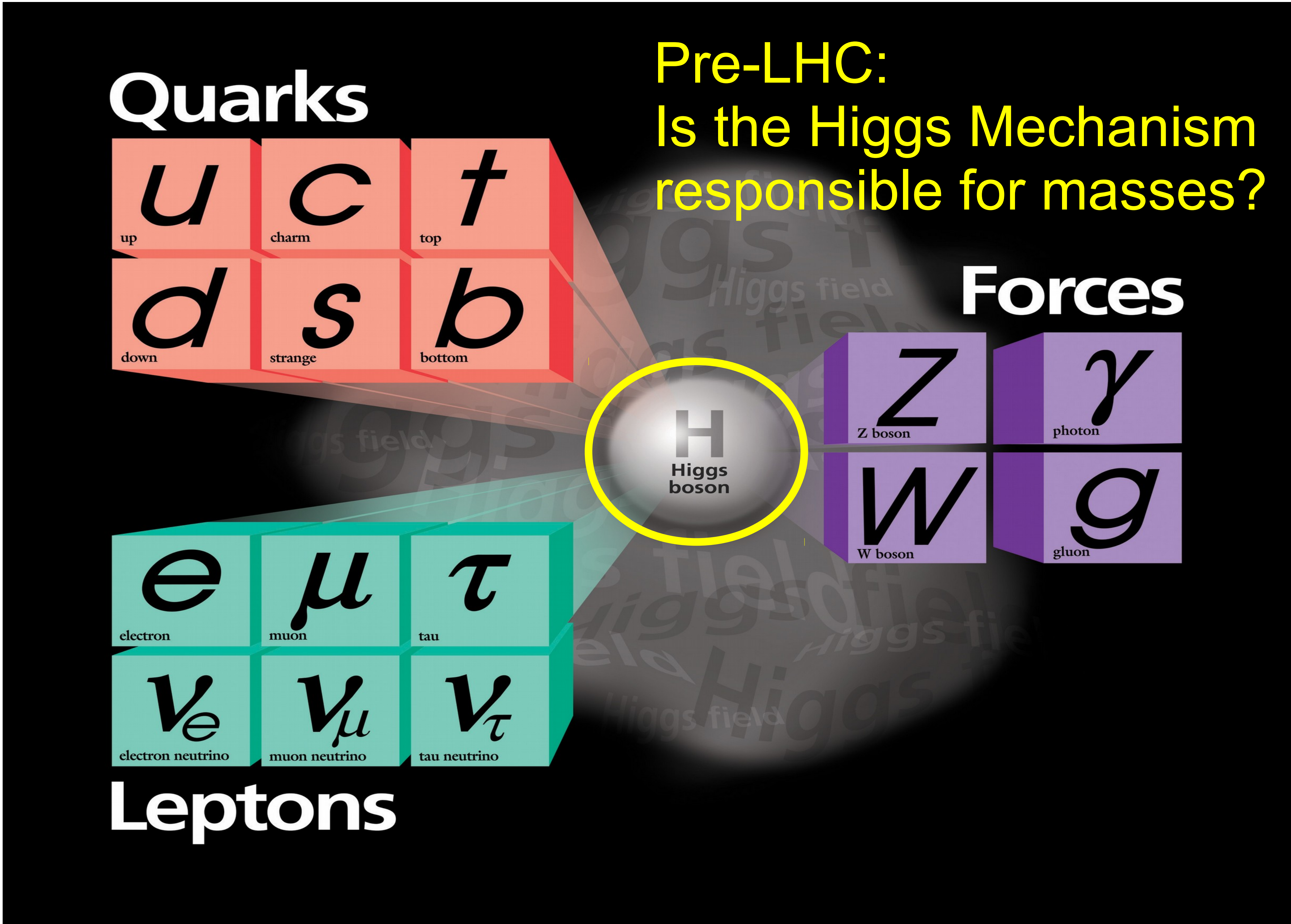




The HL-LHC Physics case

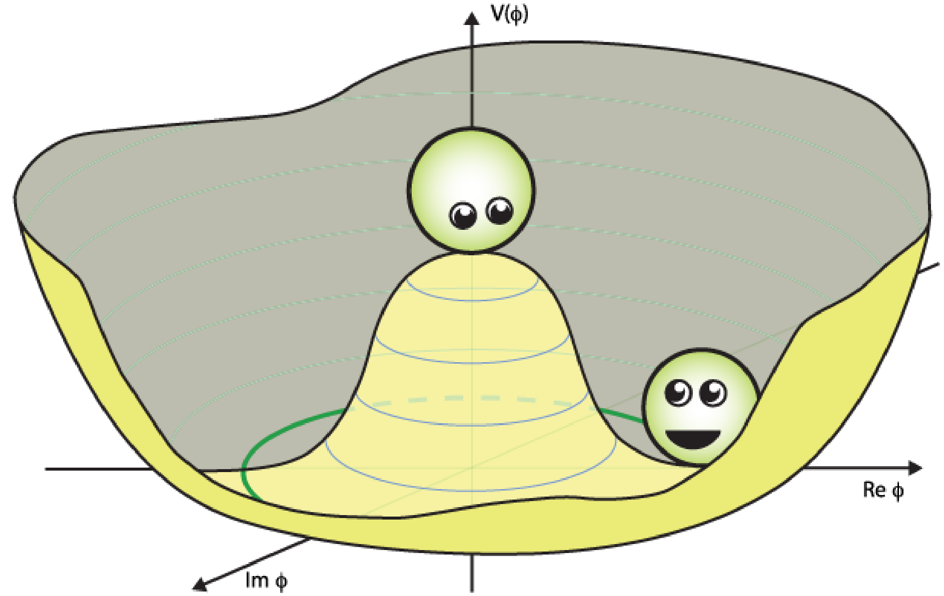
Understanding EW Symmetry Breaking

Standard Model



The Brout-Englert-Higgs Mechanism

- In electro-weak gauge theory, gauge symmetry implies all bosons are massless
  - But W and Z bosons massive
- Brout-Englert-Higgs mechanism introduces mass by spontaneous symmetry breaking of Higgs field

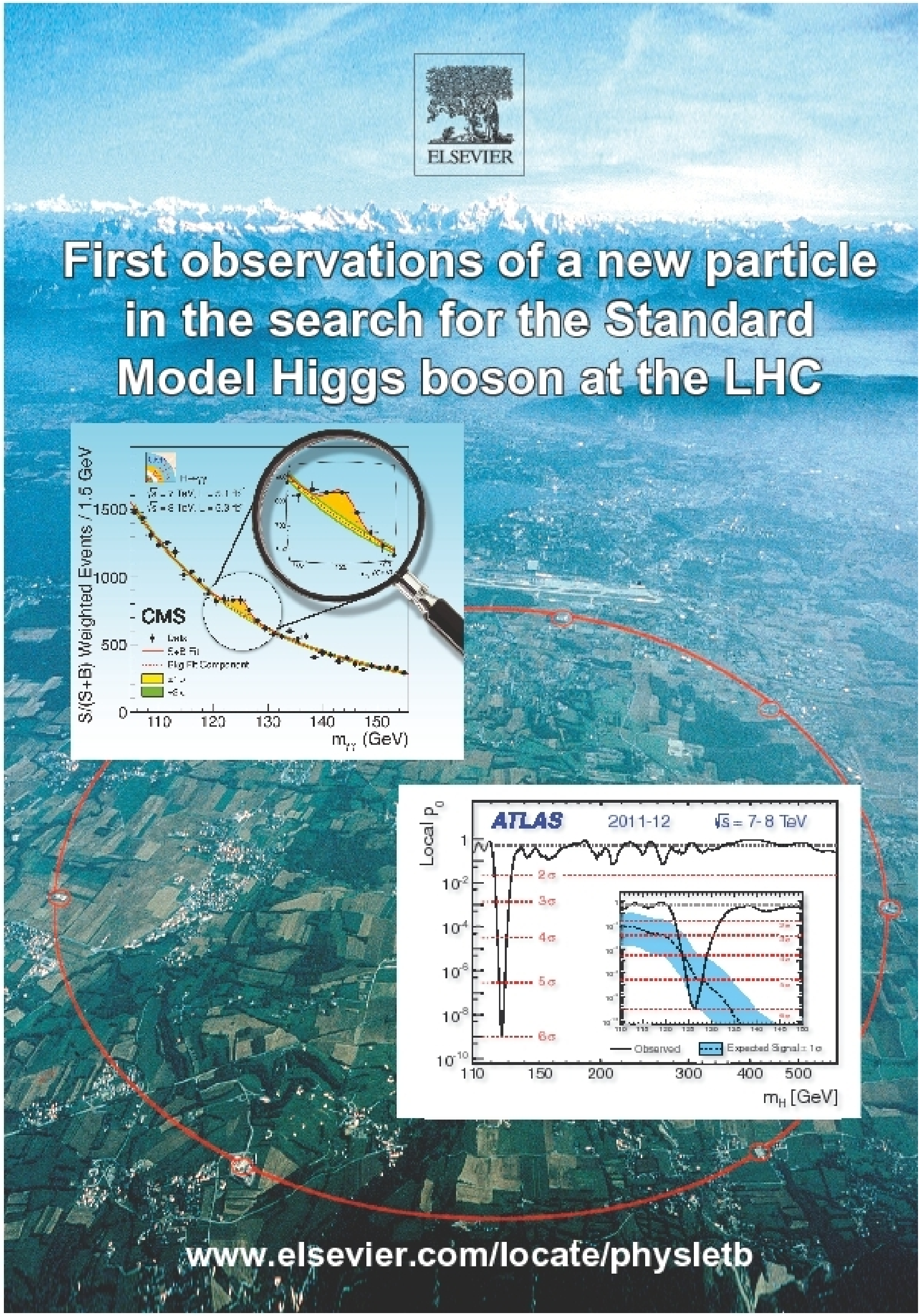


$$V(\phi) = \mu^2_{<0} |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi^i_L \psi^j_R \phi$$

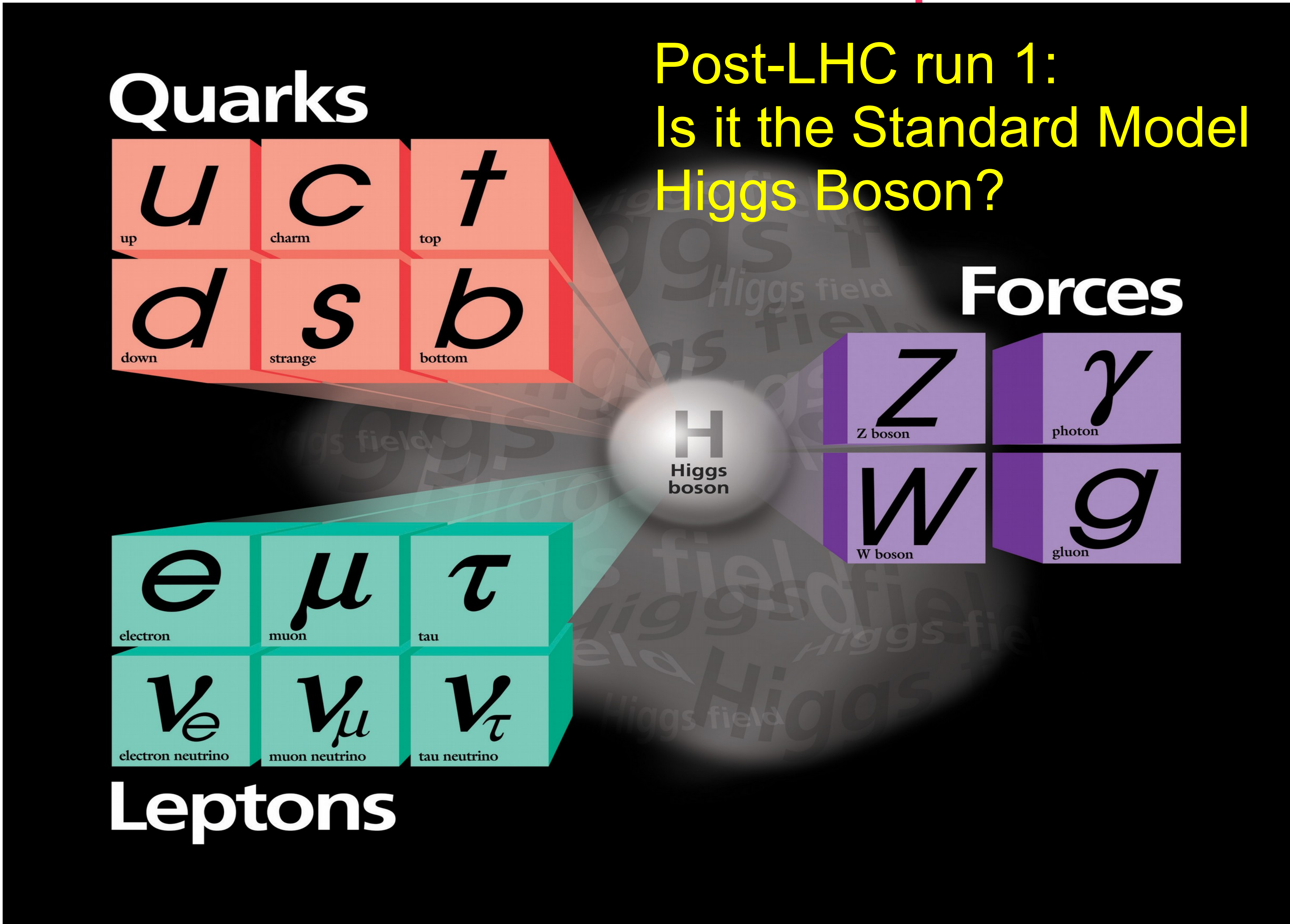
- Results in one new scalar boson (Higgs boson)
  - Only fundamental scalar particle in SM
  - Couples to other particles in proportion to their mass
  - Mass of boson itself not predicted

Higgs Boson Discovery

- In 2012 (Run-1) ATLAS and CMS both saw new 125 GeV particle at >5σ significance
- Consistent with Higgs Boson
- Nobel Prize to
  - François Englert
  - Peter Higgs

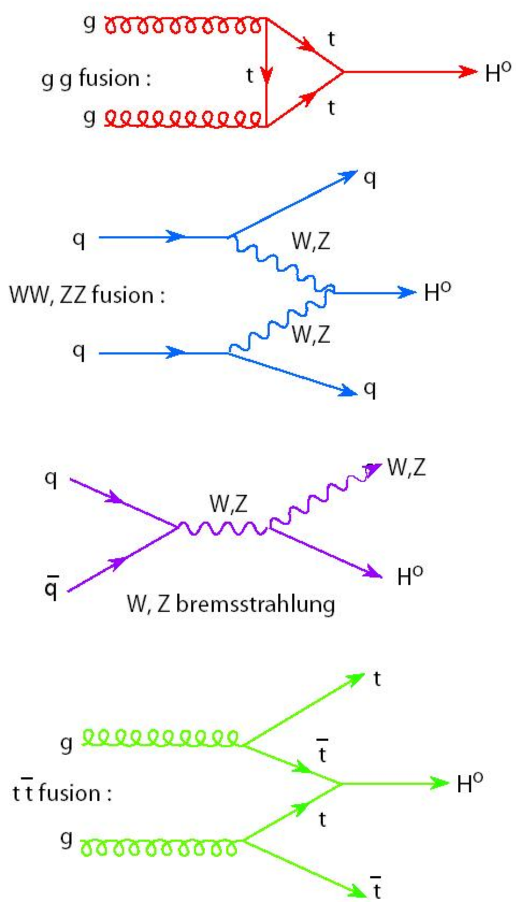


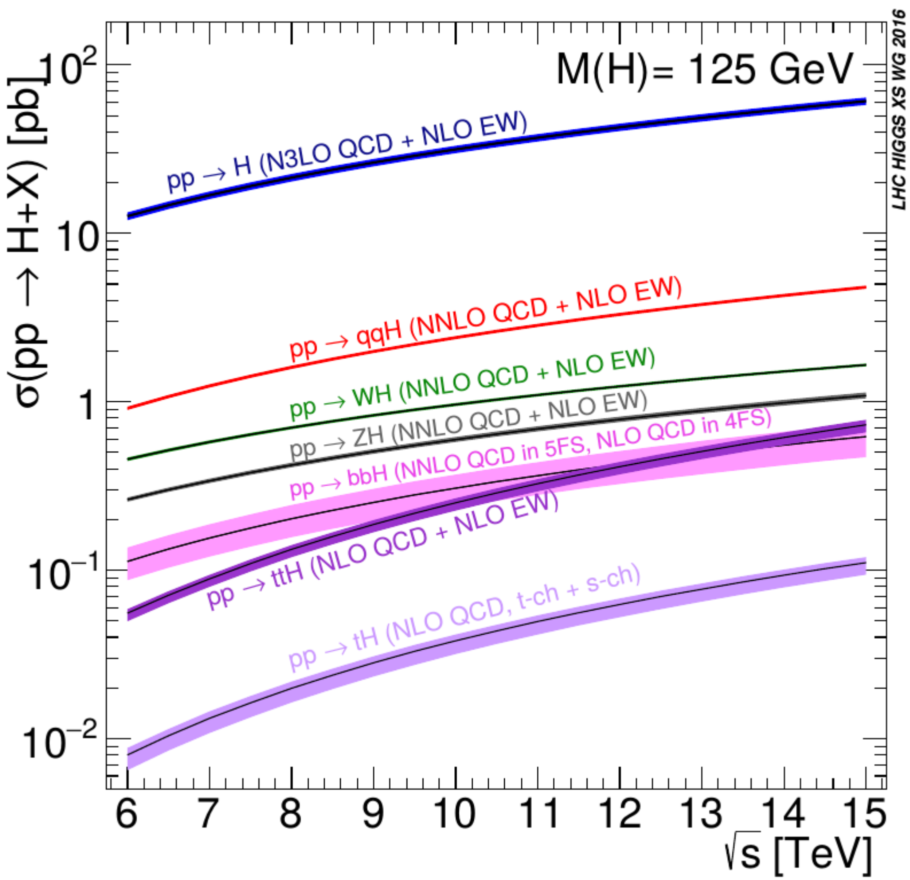
Standard Model Complete?



Higgs Boson Production at the LHC

- At LHC, Higgs dominantly produced in gluon fusion
- Other production channels important too
  - Helps identify Higgs production
  - More precise predictions

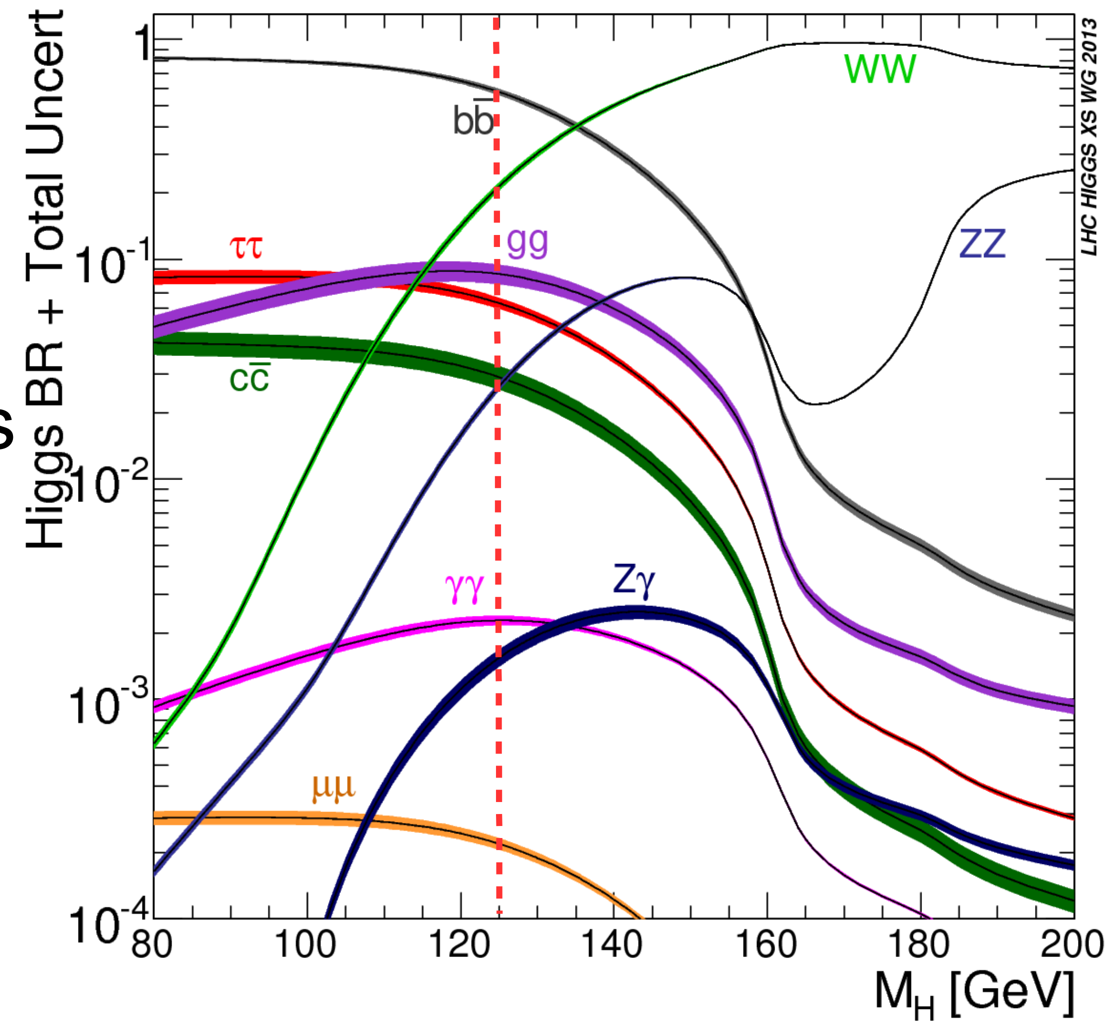




Total cross section at $\sqrt{s}$=14 TeV: 57 pb → ~0.5 Hz of Higgs at L=10^{34}cm^{-2}s^{-1}

The Higgs Boson Properties

- Higgs boson couples to mass of decays particles
  - Will decay mostly to heaviest particles allowed
- The Higgs does not couple directly to photons and gluons
  - Decays to these through loops with heavy particles (top quarks, W bosons)

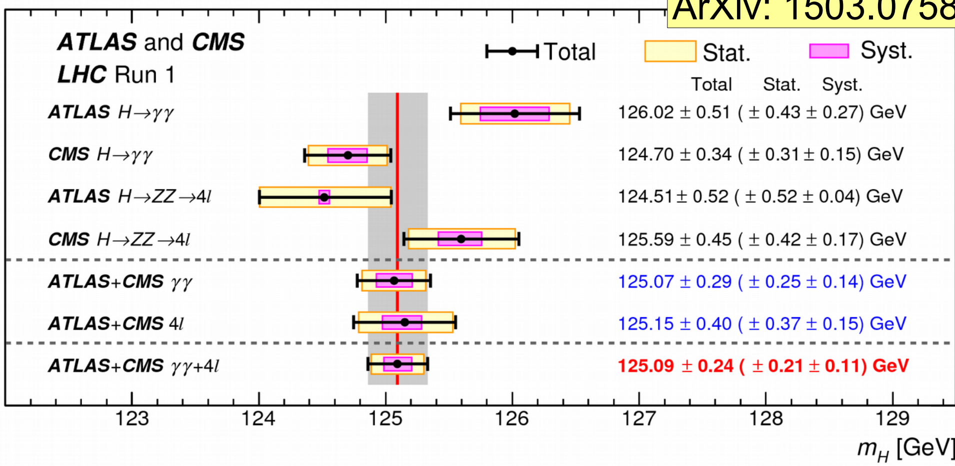


Higgs Boson Properties from Run-1

Mass measured to 0.2% precision

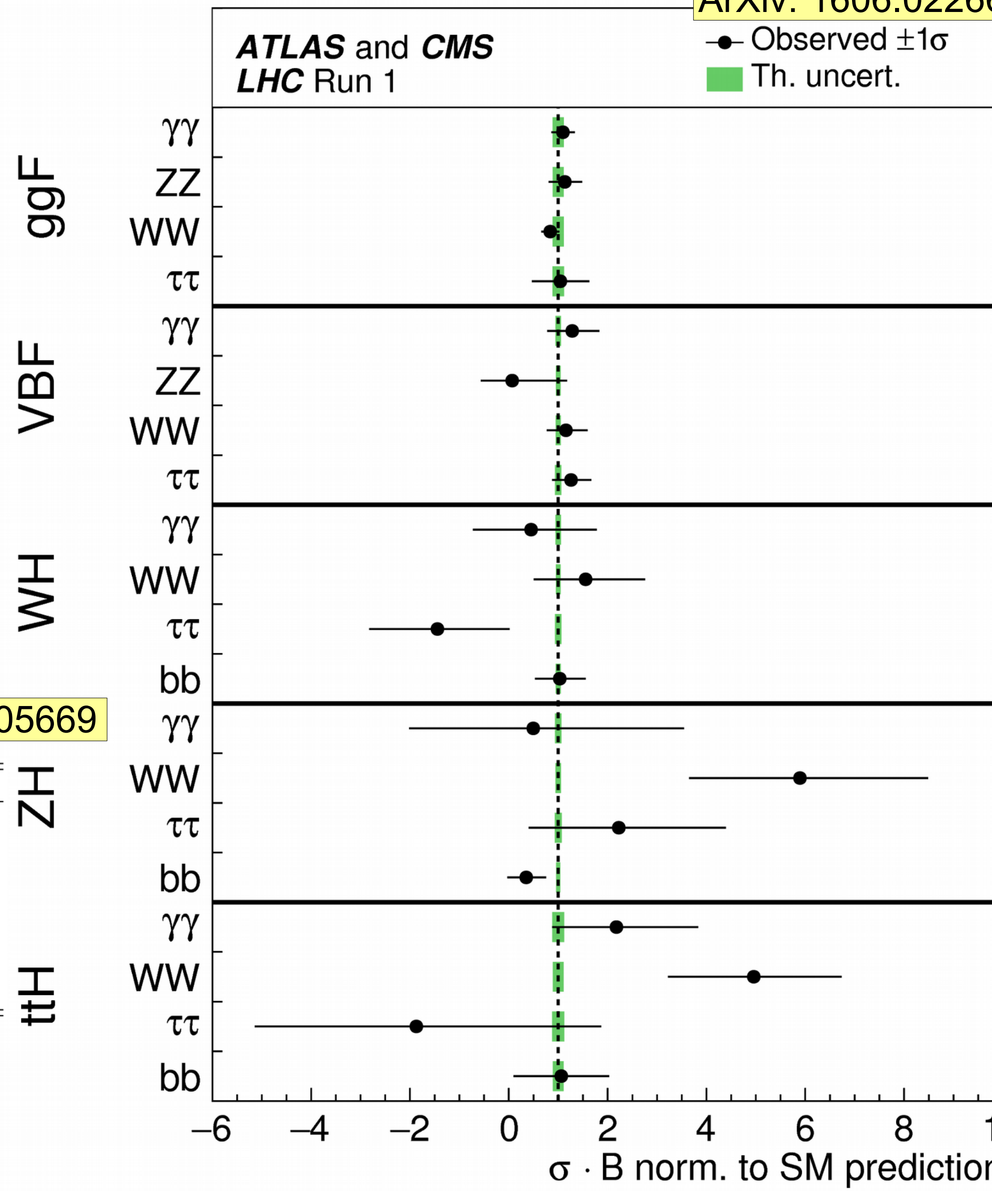
M_H=125.09±0.24 GeV

ArXiv: 1503.07589



Couplings consistent with SM at 2.5σ

ArXiv: 1606.02266



Angular distributions consistent with spin-0 and even parity

ArXiv: 1506.05669

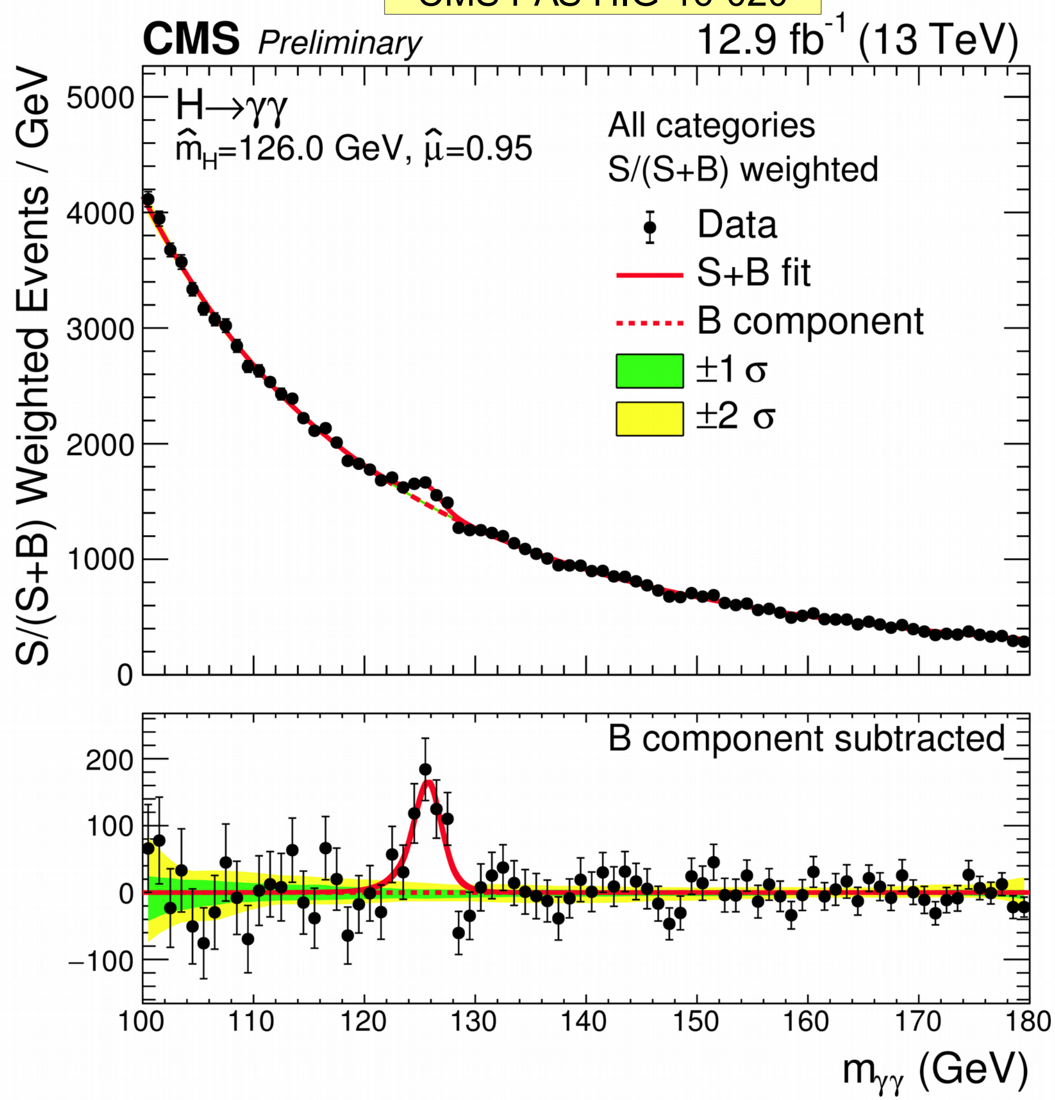
Tested Hypothesis	$p^{\rm alt}_{{\rm exp},\mu=1}$	$p^{\rm alt}_{{\rm exp},\mu=\hat\mu}$	$p^{\rm SM}_{\rm obs}$	$p^{\rm alt}_{\rm obs}$	Obs. CL$_s$ (%)
0^+_h	$2.5\cdot10^{-2}$	$4.7\cdot10^{-3}$	0.85	$7.1\cdot10^{-5}$	$4.7\cdot10^{-2}$
0^-	$1.8\cdot10^{-3}$	$1.3\cdot10^{-4}$	0.88	$<3.1\cdot10^{-5}$	$<2.6\cdot10^{-2}$
$2^+(\kappa_q=\kappa_g)$	$4.3\cdot10^{-3}$	$2.9\cdot10^{-4}$	0.61	$4.3\cdot10^{-5}$	$1.1\cdot10^{-2}$
$2^+(\kappa_q=0;\ p_{\rm T}<300GeV)$	$<3.1\cdot10^{-5}$	$<3.1\cdot10^{-5}$	0.52	$<3.1\cdot10^{-5}$	$<6.5\cdot10^{-3}$
$2^+(\kappa_q=0;\ p_{\rm T}<125GeV)$	$3.4\cdot10^{-3}$	$3.9\cdot10^{-4}$	0.71	$4.3\cdot10^{-5}$	$1.5\cdot10^{-2}$
$2^+(\kappa_q=2\kappa_g;\ p_{\rm T}<300GeV)$	$<3.1\cdot10^{-5}$	$<3.1\cdot10^{-5}$	0.28	$<3.1\cdot10^{-5}$	$<4.3\cdot10^{-3}$
$2^+(\kappa_q=2\kappa_g;\ p_{\rm T}<125GeV)$	$7.8\cdot10^{-3}$	$1.2\cdot10^{-3}$	0.80	$7.3\cdot10^{-5}$	$3.7\cdot10^{-2}$

Still room for much more detailed studies with more luminosity

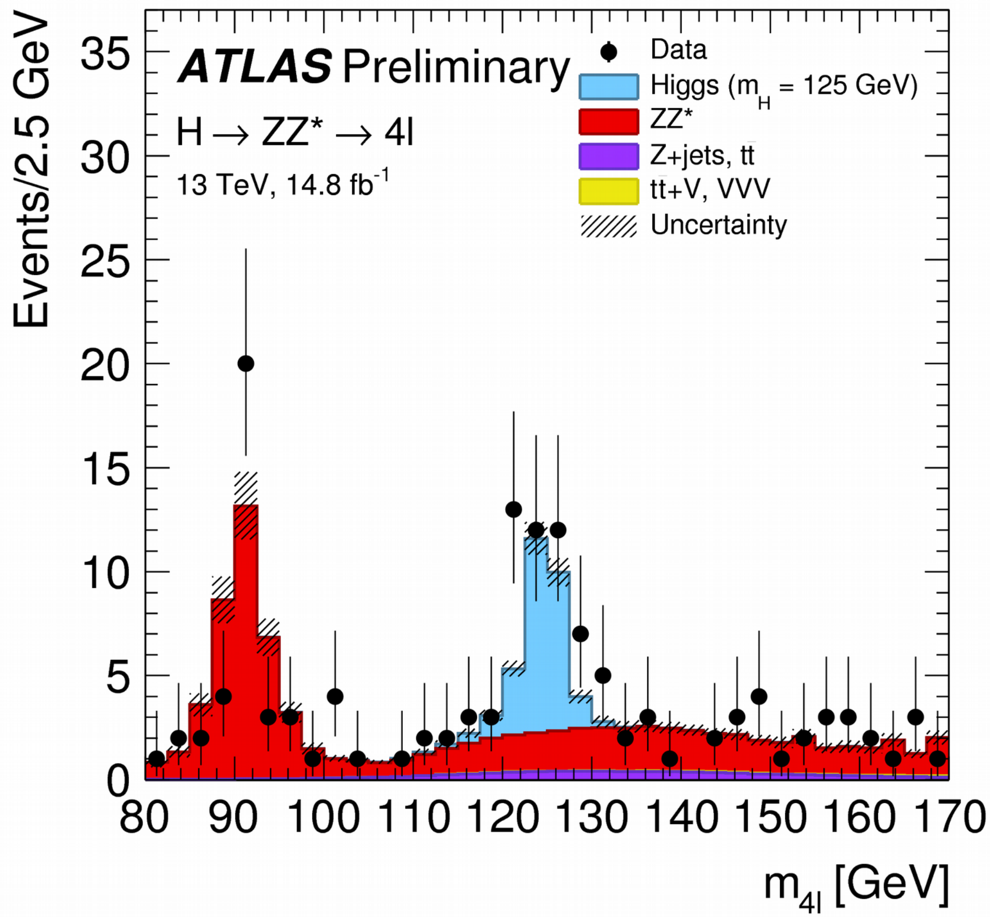
Higgs Boson Production at 13 TeV

Clear observation of Higgs Boson at 13 TeV in bosonic decay modes

CMS PAS HIG-16-020



ATLAS-CONF-2016-079

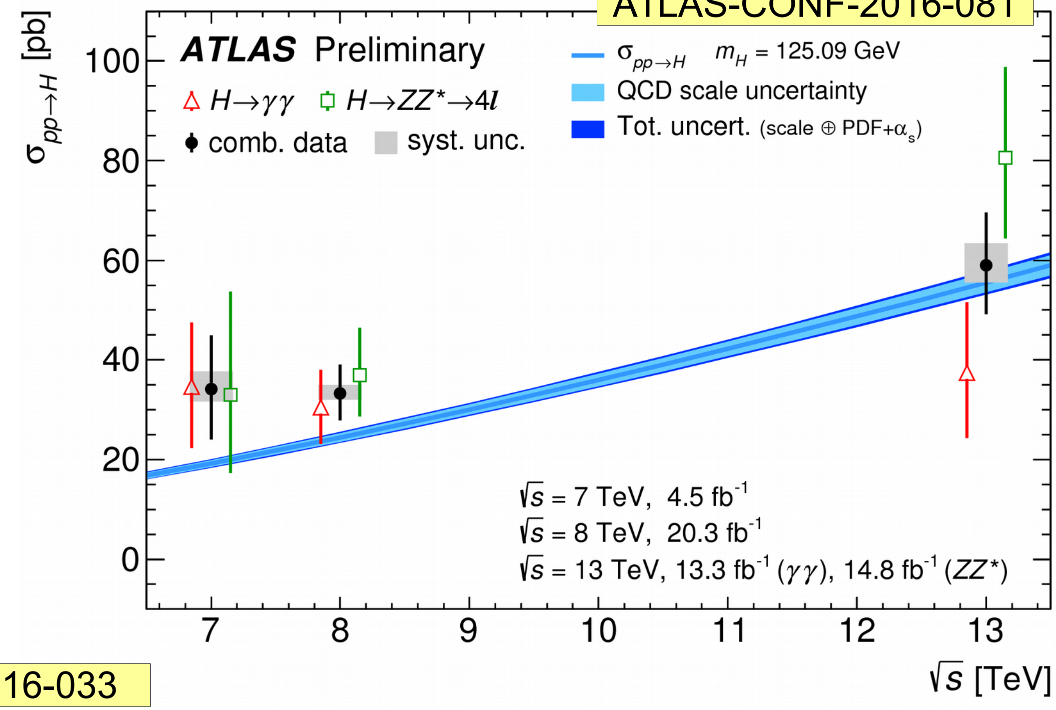


Overall significance of Higgs Boson signal: ~10σ

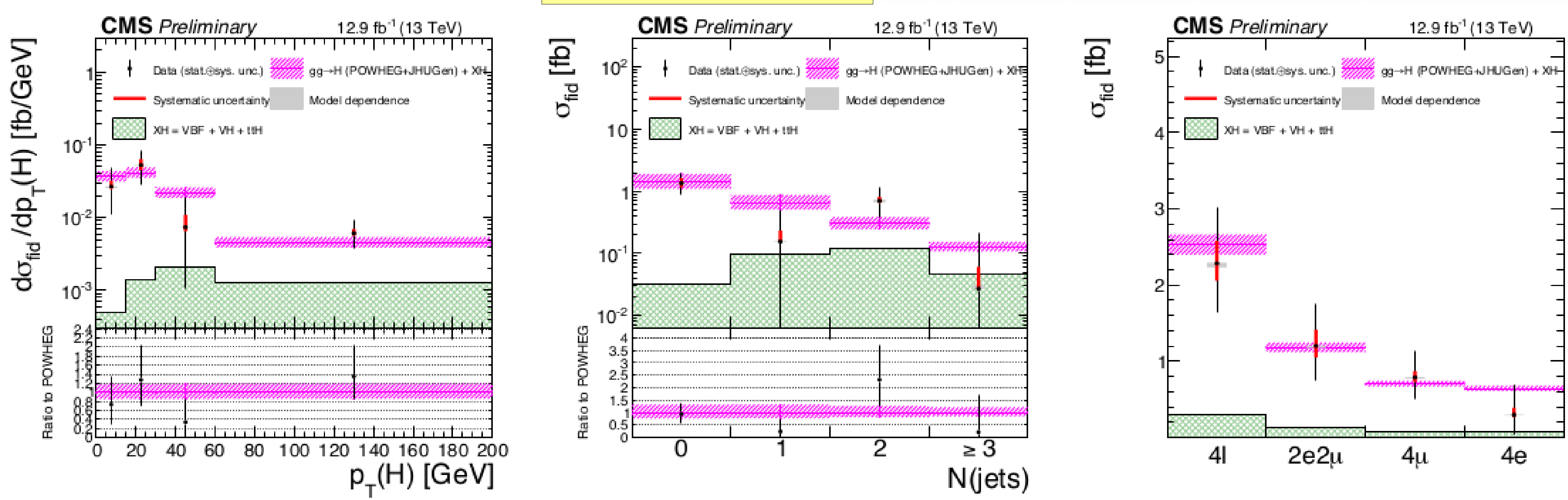
Higgs Boson Cross Sections

- With the new data have started detailed studies of Higgs Boson production
  - Dependence on center-of-mass energy
  - Differential cross sections
  - Productions channels

ATLAS-CONF-2016-081

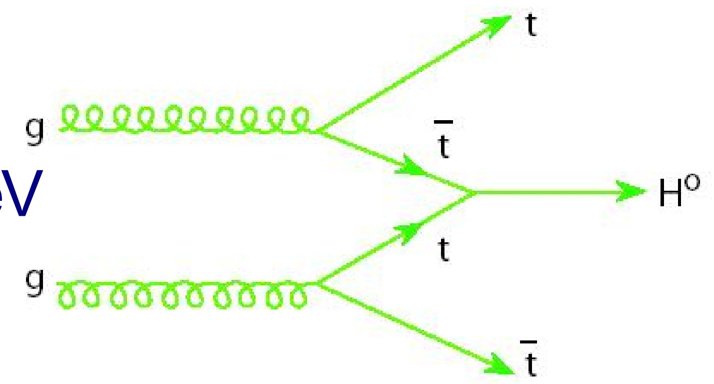


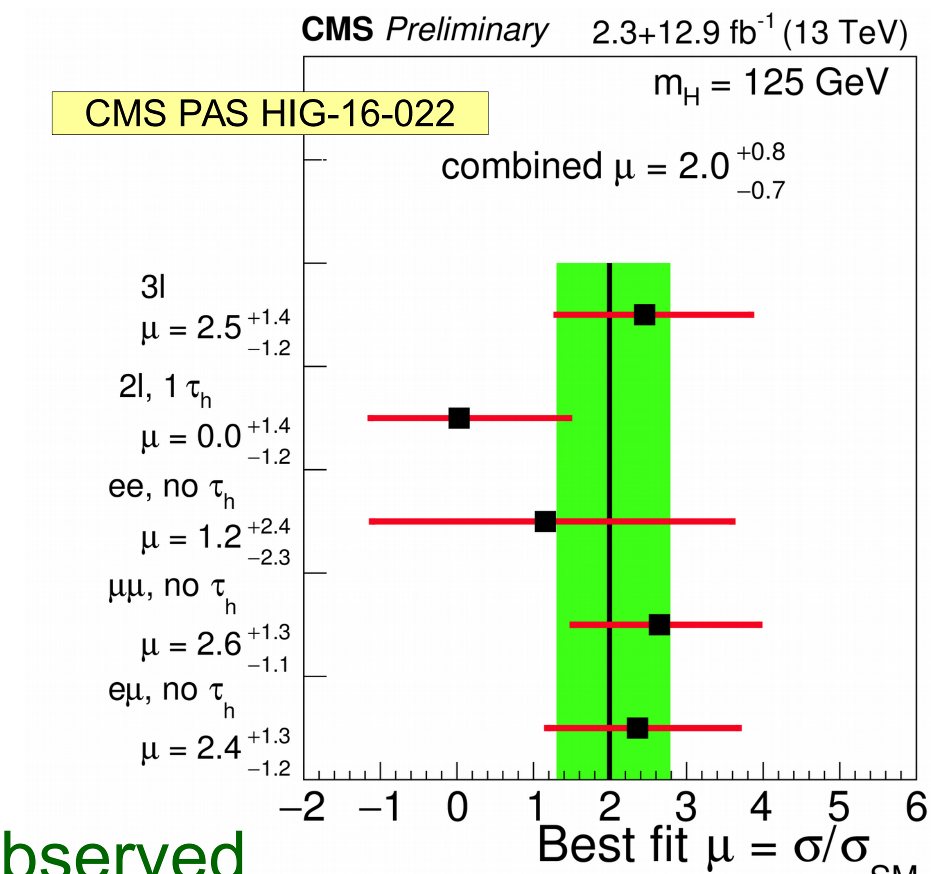
CMS PAS HIG-16-033

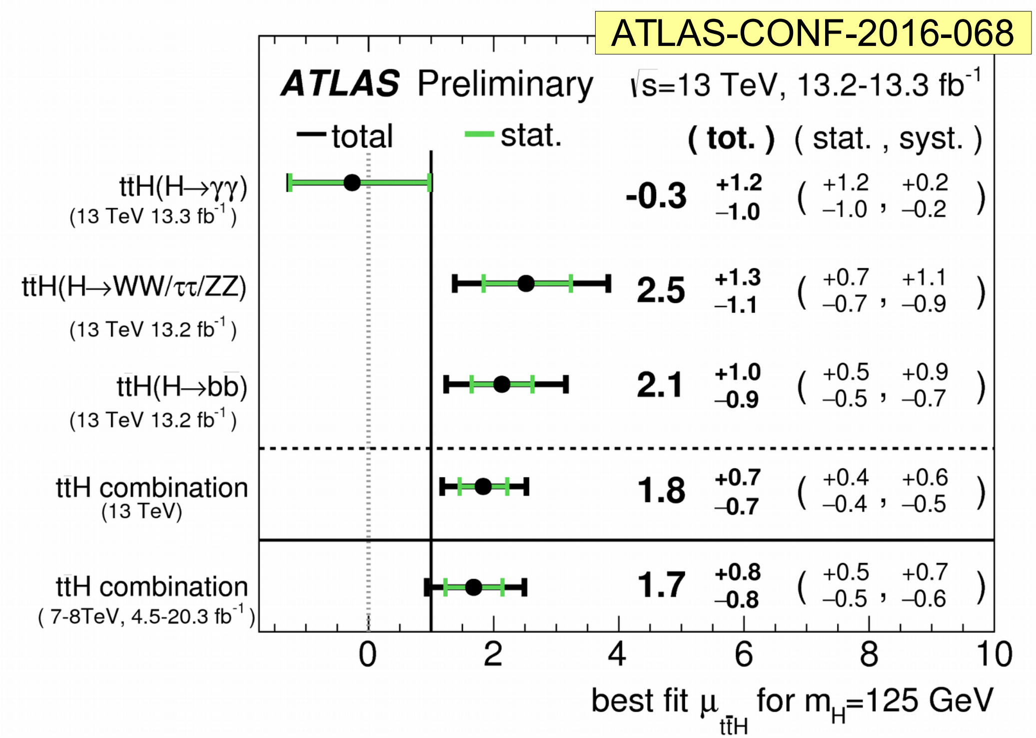


Search for ttH Production at 13 TeV

- ttH directly probes the top-Higgs Yukawa coupling instead of loop in ggH
  - Benefits from higher x-section at 13 TeV
- See slight excess in many channels
  - Also seen in some Run-1 results





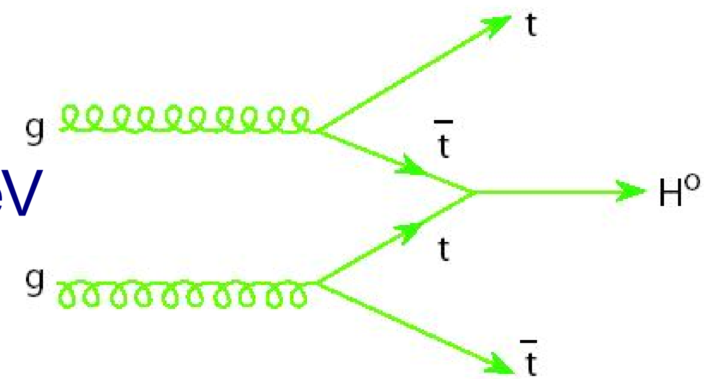


Observed significance: 3.2σ (Expected: 1.7σ)

Observed significance: 2.8σ
Expected: 1.8σ

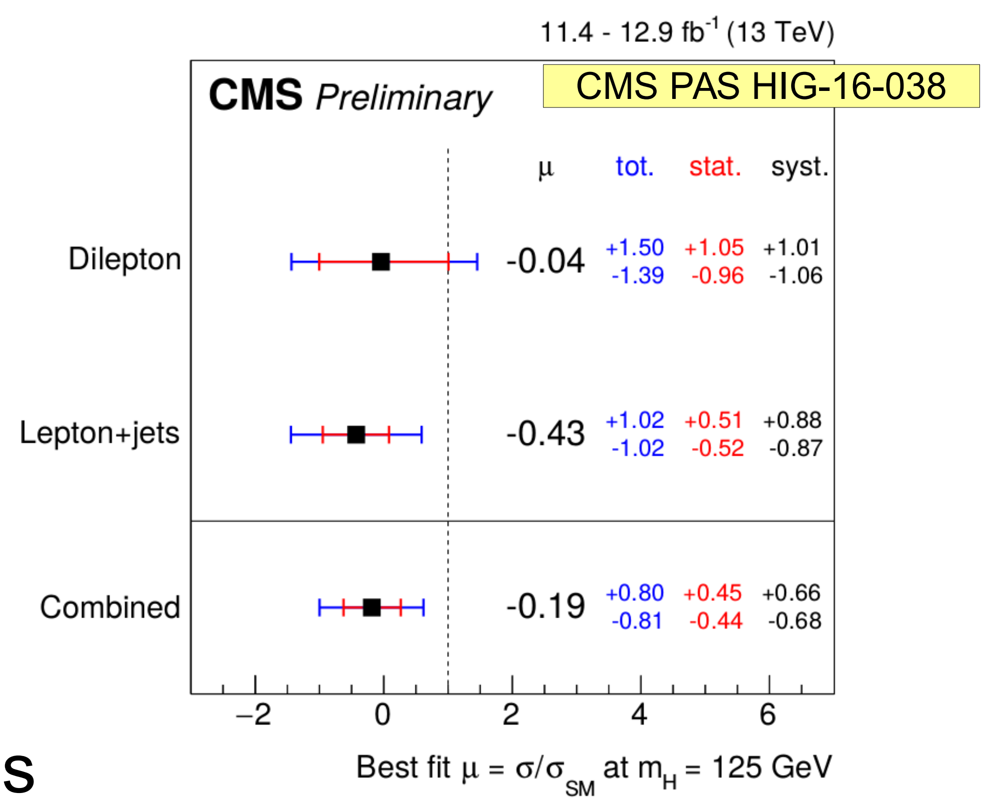
Search for ttH Production at 13 TeV

- ttH directly probes the top-Higgs Yukawa coupling instead of loop in ggH
  - Benefits from higher x-section at 13 TeV
- See slight excess in many channels
  - Also seen in some Run-1 results



Latest CMS result for ttH, $H \to b\bar{b}$ has a slight deficit wrt SM

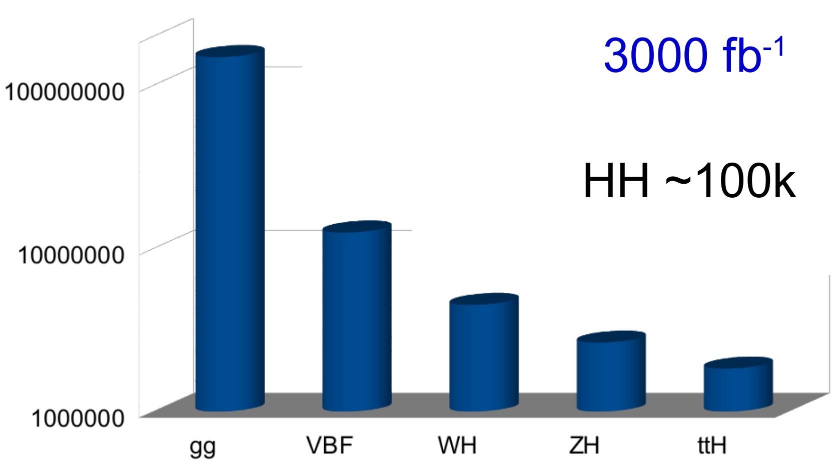
All are still consistent with SM due to the large uncertainties



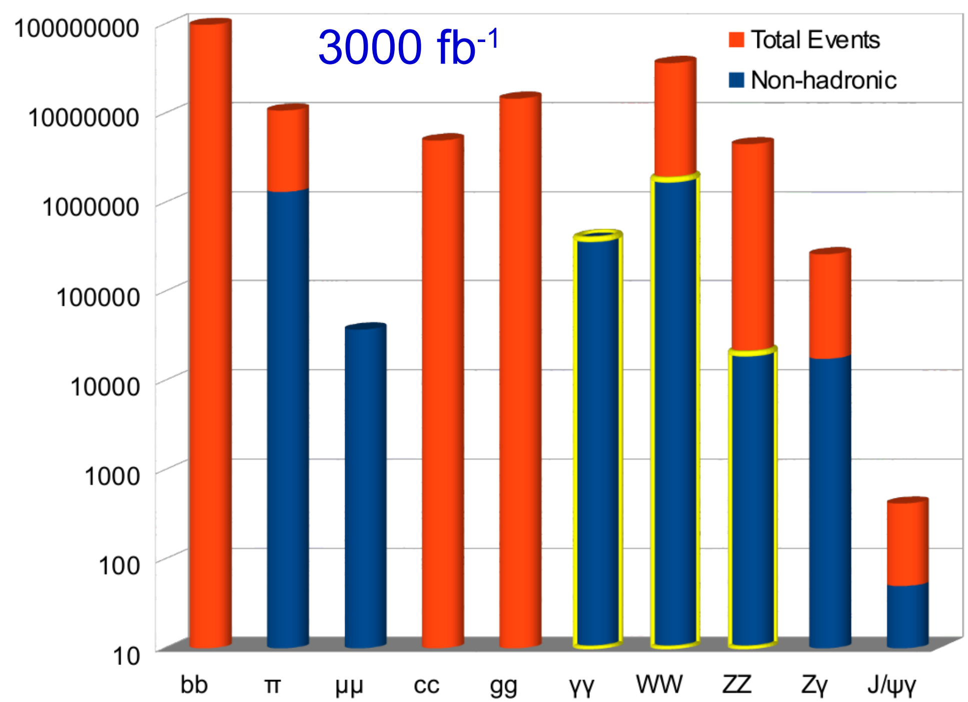
Higgs program at HL-LHC

- Higgs boson studies are a major component of HL-LHC physics program
- Main Higgs measurements at HL-LHC:
  - Higgs couplings
  - Rare Higgs decays
  - Higgs differential distributions
  - Higgs self-coupling
  - Heavy Higgs searches

Higgs Production Channels



Higgs Decay Channels



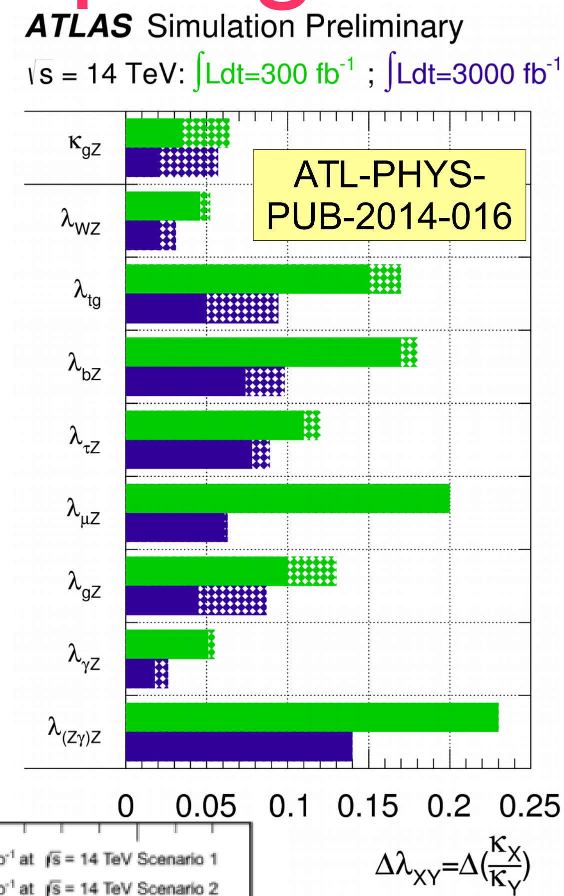
Physics Projections

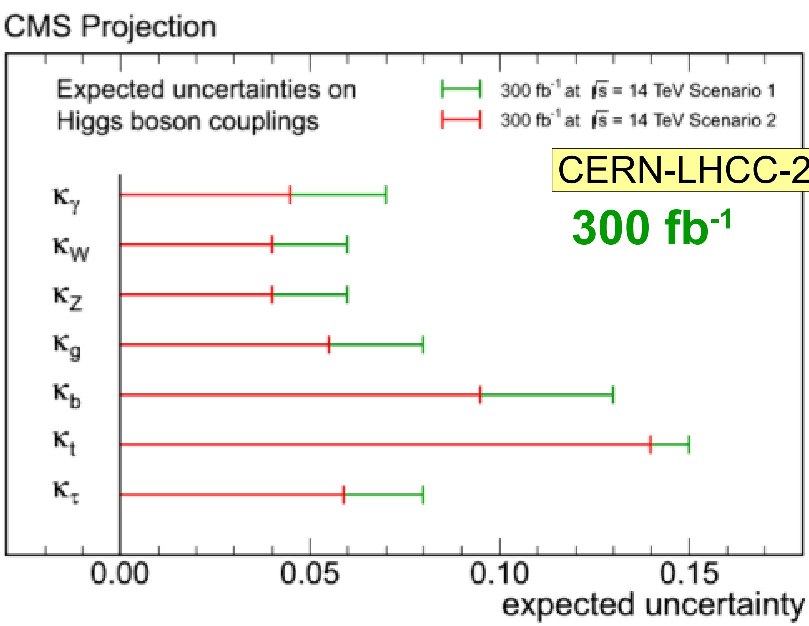
HL-LHC Physics prospects done in two ways:

- Parameterized detector performance
  - Event-generator level particles smeared with detector performance parameterized from full simulation and reconstruction of upgraded HL-LHC detectors
  - Effects of pile-up included for either $5x10^{34}$ $cm^{-2}s^{-1}$ (140 pile-up events) or $7x10^{34}$ $cm^{-2}s^{-1}$ (200 pile-up events)
  - Analysis mostly based on existing 8 TeV analyses with simple re-optimization for higher luminosity
- Extrapolation of Run-1 or Run-2 results
  - Scale signal and background to higher luminosities
  - Correct for different center-of-mass energy
  - Assume unchanged analysis (not re-optimized for higher luminosity)
  - Assume same detector performance as in Run-1/2 (some use corrections based on studies in first approach)

Projections for Higgs Couplings

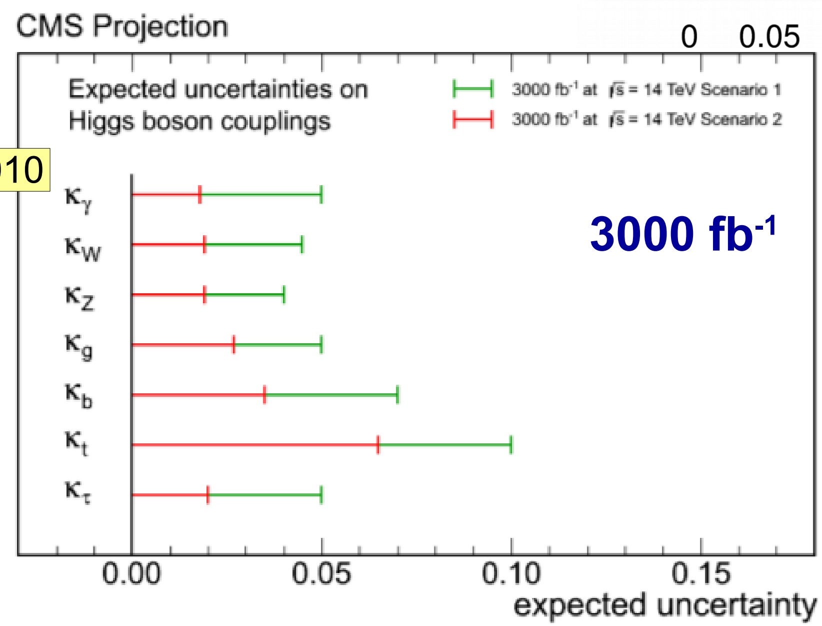
- Full set of HL-LHC coupling projections are based on Run-1 analyses
  - Assumes μ=140 in case of ATLAS
  - Same as Run-1 performance for CMS
- Higgs coupling precision (per experiment):
  - 3-5% for W, Z and γ
  - 5-10% for t, b and τ
  - ~7% for μ
- Do not include improved detector designs or improvements in analysis techniques





CERN-LHCC-2015-010

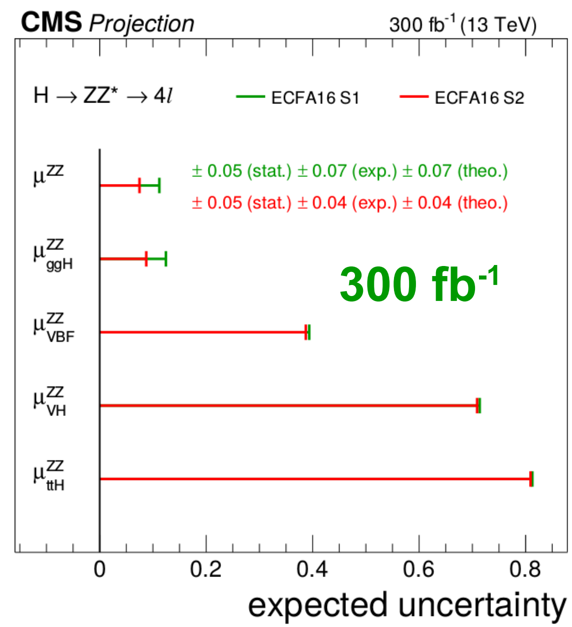
300 fb⁻¹

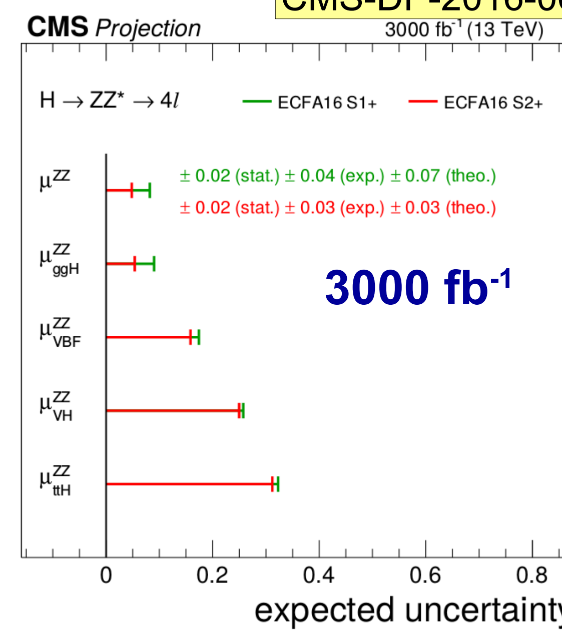


Projections based on Run-2 Analysis

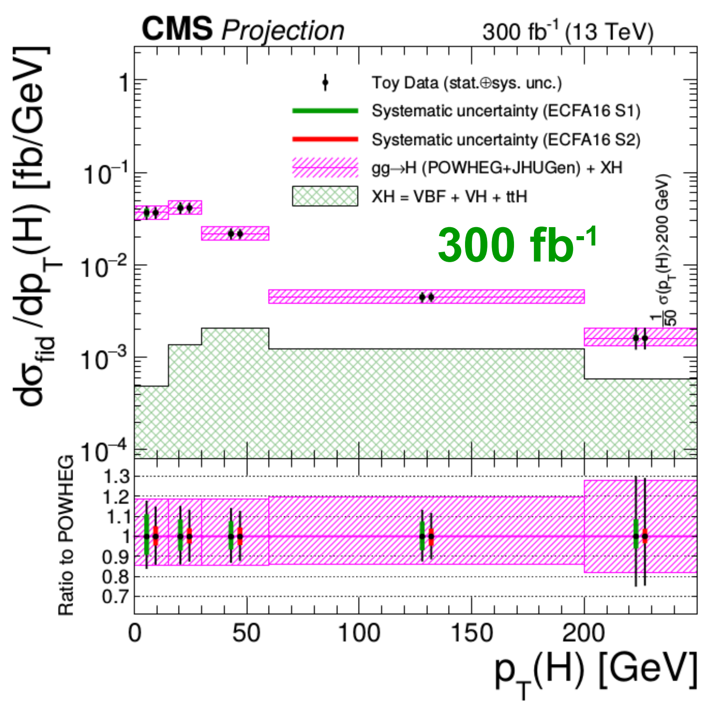
- H→γγ and H→ZZ projections updated to 13 TeV (12.9 fb^{-1}) based Run-2 analyses
- H→ZZ added expected degradation at μ=200
  - Reduced lepton efficiency
  - Increased misidentification
- Can make precise differential $p_T(H)$ cross section measurements

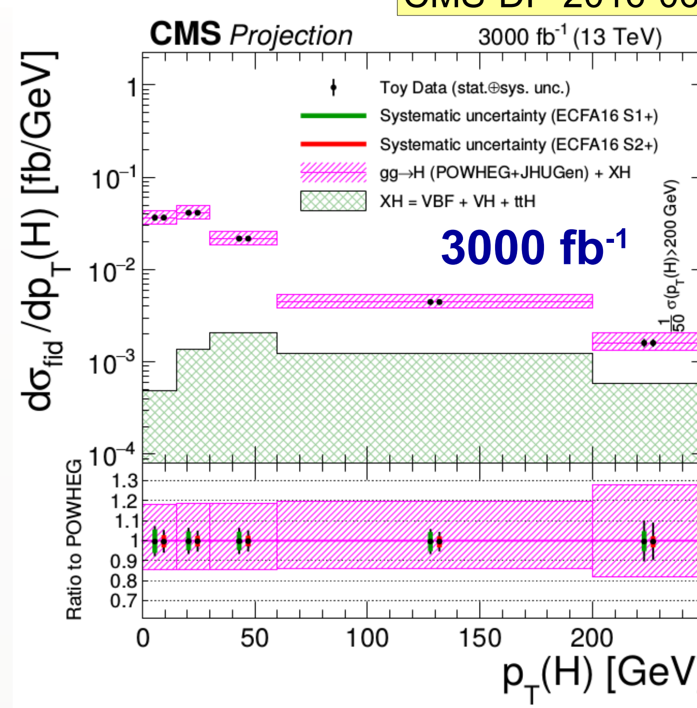
CMS-DP-2016-064





CMS-DP-2016-064

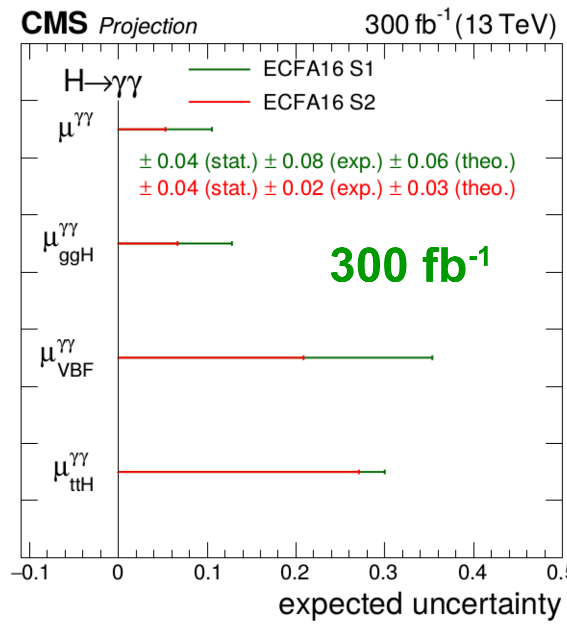


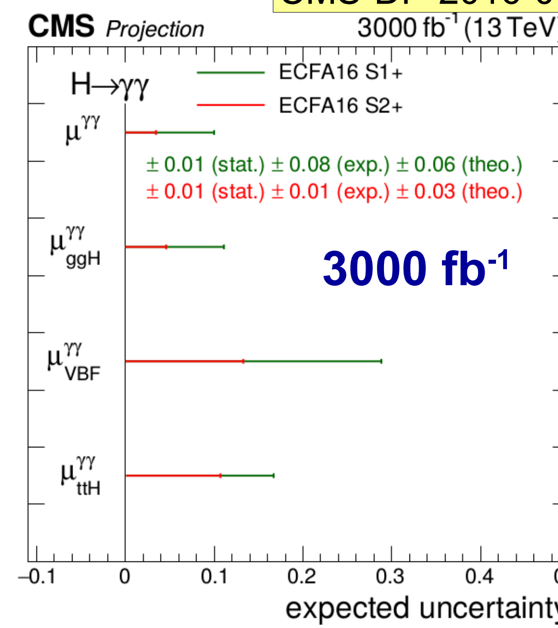


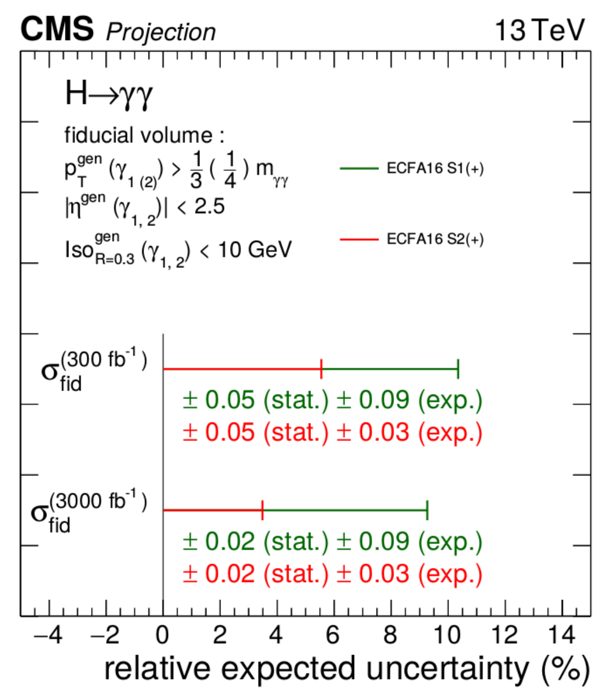
Projections based on Run-2 Analysis

CMS-DP-2016-064

- H→γγ and H→ZZ projections updated to 13 TeV (12.9 fb^{-1}) based Run-2 analyses
- H→γγ added expected degradation at μ=200
  - Beamspot ~5cm
  - Vertex identification reduced from 80% to 40%
  - Photon ID efficiency decreased by 2.3% (10%) in EB (EE)
- Theory uncertainties can become dominant at HL-LHC
- Decouple by measuring fiducial cross section
  - Can achieve ~4% precision

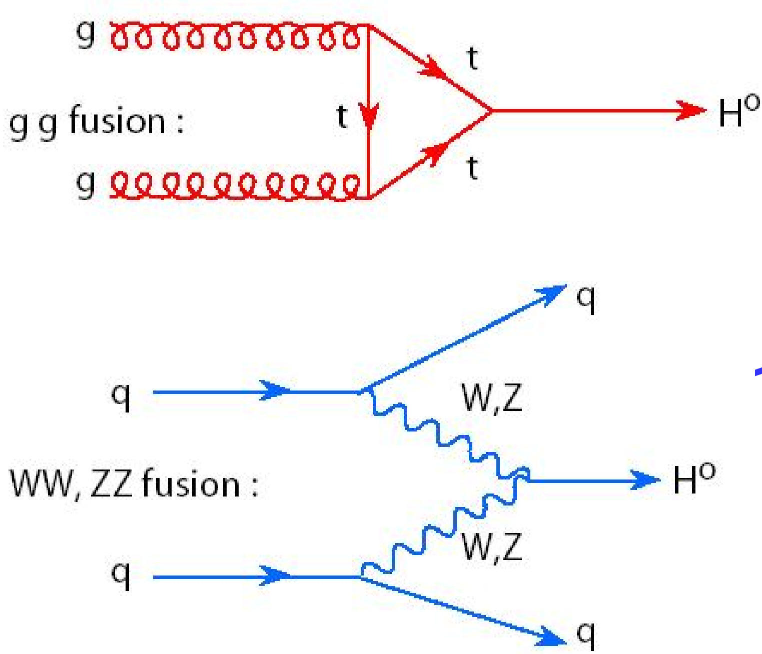


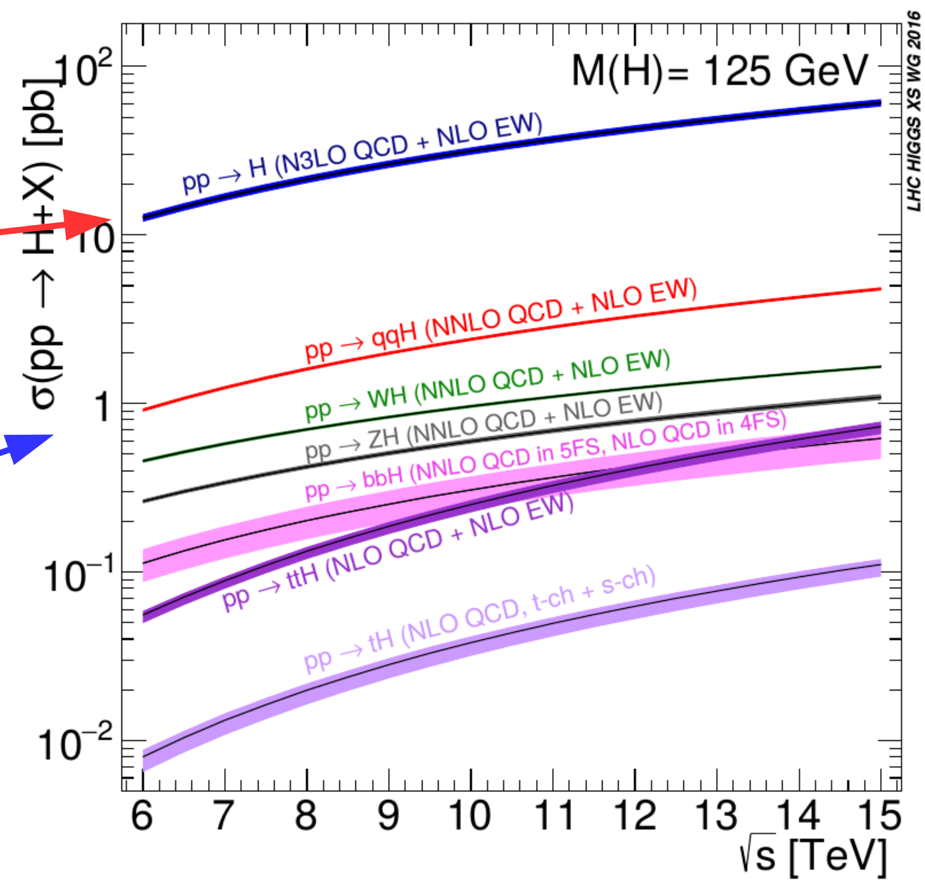




Advantage of Vector-Boson-Fusion

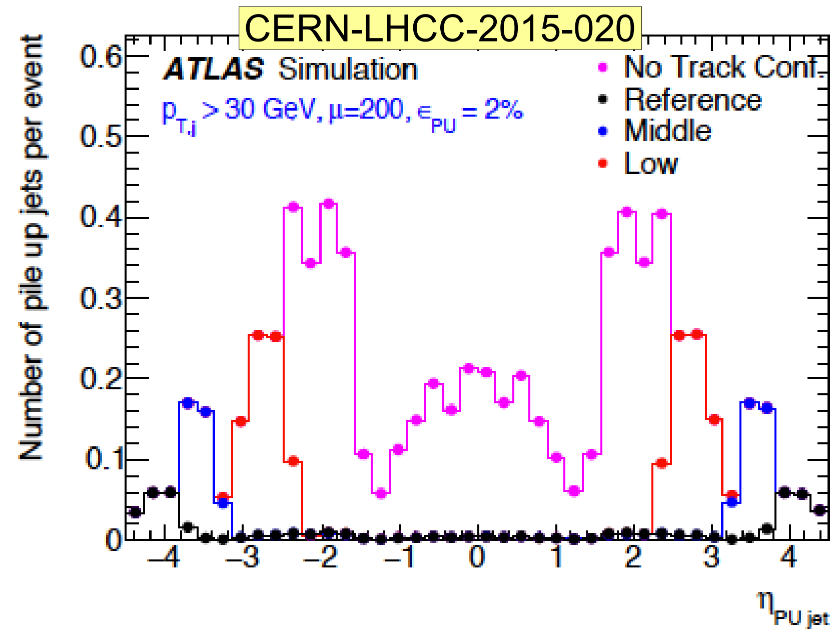
- Can reduce theoretical uncertainties by measuring Higgs decays in Vector-Boson-Fusion production
  - Cross section uncertainty reduced by factor ~4
  - Factor 10 less statistics
  - Better signal/background from requiring two forward jets from VBF scattering

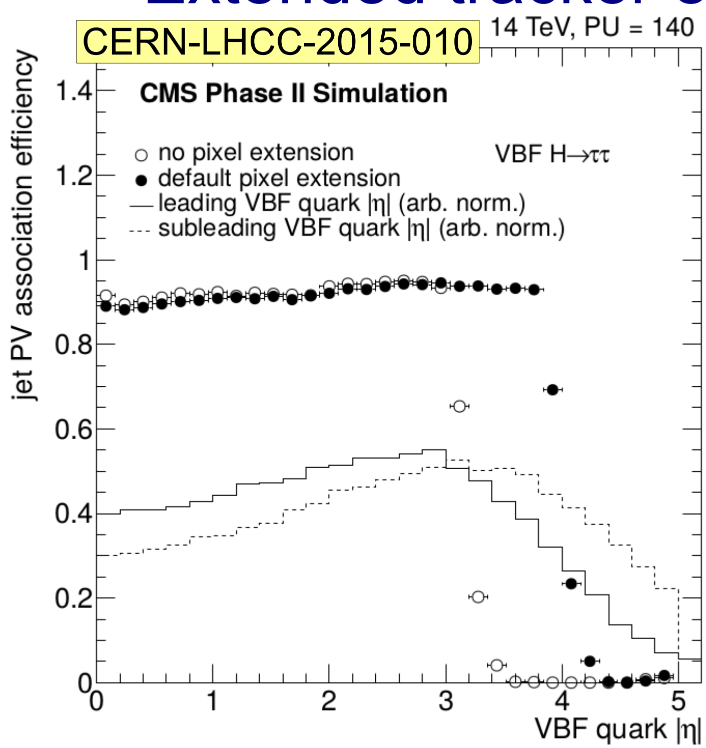


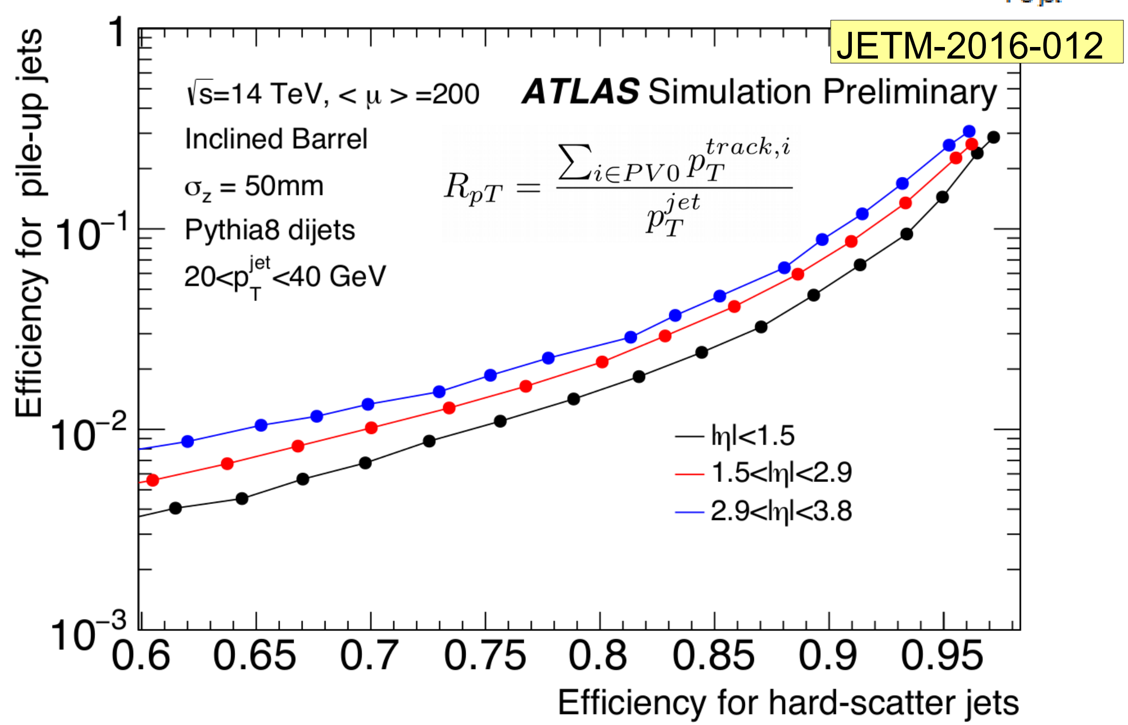


Pile-up Jet Suppression

- At 200 pile-up, every events has ~5 pile-up jets (p_T>30 GeV)
- Can suppress these by using tracking to associate them to either pile-up or hard-scatter vtx
- For VBF Higgs production need to use jets out to η~4
  - Extended tracker enables this

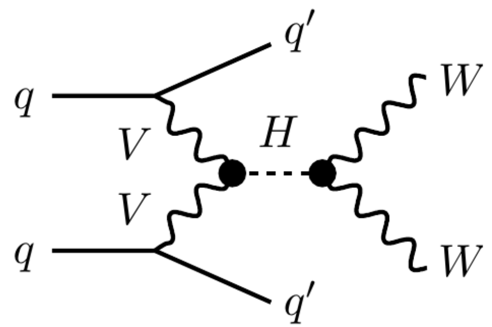


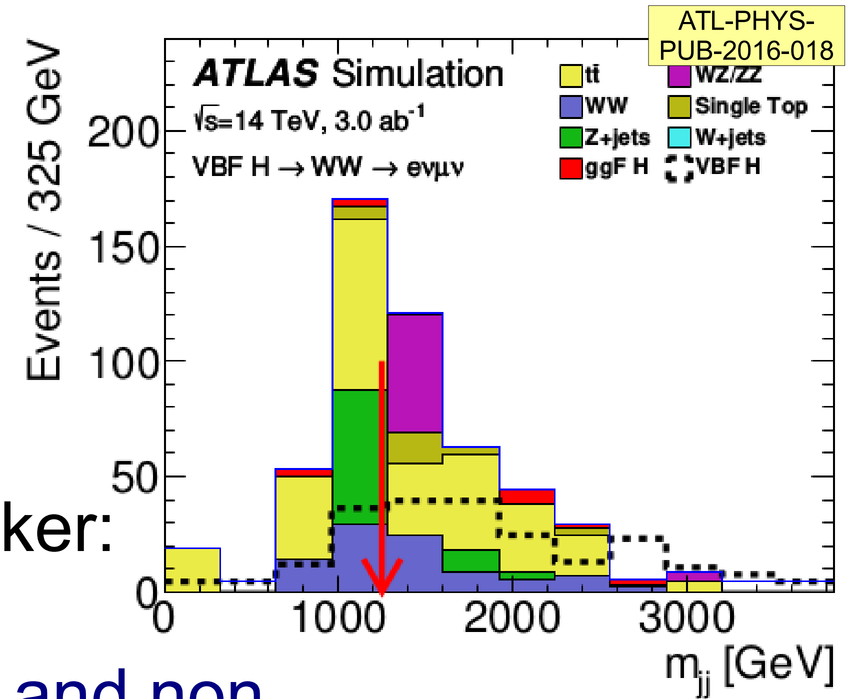




VBF H→WW→eνμν Analysis

- Physics gain of forward tracker studied in VBF H→WW analysis





- After BF selection with forward tracker:
  - ~200 signal events
  - ~400 background events from $t\bar{t}$ and non Higgs WW

Signal precision and significance

Tracker coverage	Δ_μ Full	Δ_μ 1/2	Δ_μ None	Significance (σ) Full	Significance (σ) 1/2	Significance (σ) None
$\|\eta\|<4.0$	0.20	0.16	0.14	5.7	7.1	8.0
$\|\eta\|<3.2$	0.25	0.21	0.20	4.4	5.2	5.4
$\|\eta\|<2.7$	0.39	0.32	0.30	2.7	3.3	3.5

← Different levels of background uncertainties with respect to Run-1 H→WW analysis

Factor two gain in precision from extended tracker coverage

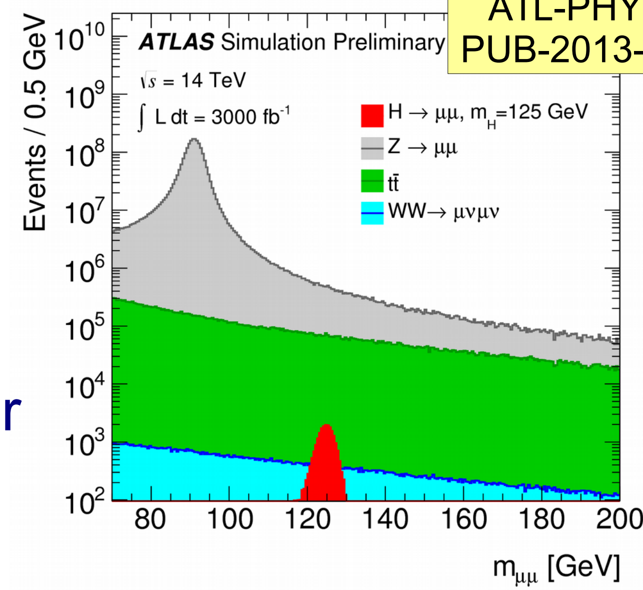
Rare decays: $H\to\mu^+\mu^-$ and $H\to J/\psi\gamma$

Probes Higgs coupling to 2nd generation quarks/leptons

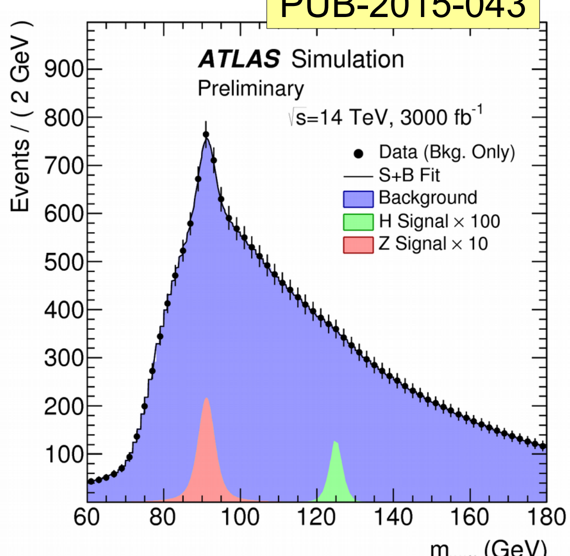
$H\to\mu^+\mu^-$

- $BR(H\to\mu^+\mu^-)=2.2\times10^{-4}$ in SM
  - Combined Run-1 and Run-2 limit is 3.5xSM
- Expect significance of ~2σ with 300 fb^{-1} and ~7σ with 3000 fb^{-1} in inclusive channel
  - Improved tracker resolution not accounted for (~30% improvement on mass resolution)
  - Also specific channels like ttH, $H\to\mu^+\mu^-$

ATL-PHYS-PUB-2013-014



ATL-PHYS-PUB-2015-043



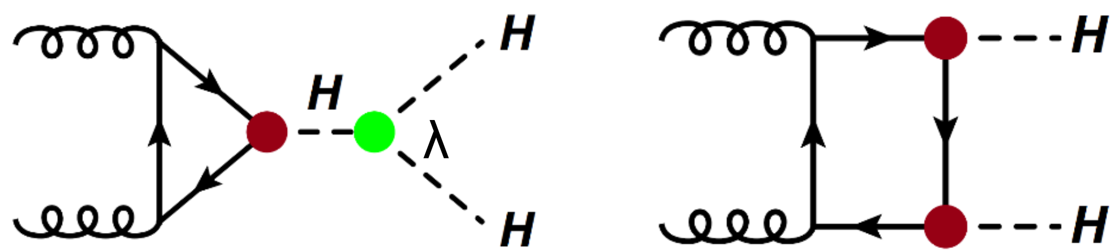
$H\to J/\psi\gamma$ (coupling to charm quark)

- $BR(H\to J/\psi\gamma)=2.9\times10^{-6}$ in SM
  - ATLAS Run-1 limit at 95% CL: $BR(H\to J/\psi\gamma)<1.5\times10^{-3}$
- Multivariate analysis for HL-LHC projection
  - With 3000 fb^{-1} will have just 3 signal events and 1700 background events
  - Expected limit at 95% CL: $BR(H\to J/\psi\gamma)<(44^{+19}_{-12})\times10^{-6}$

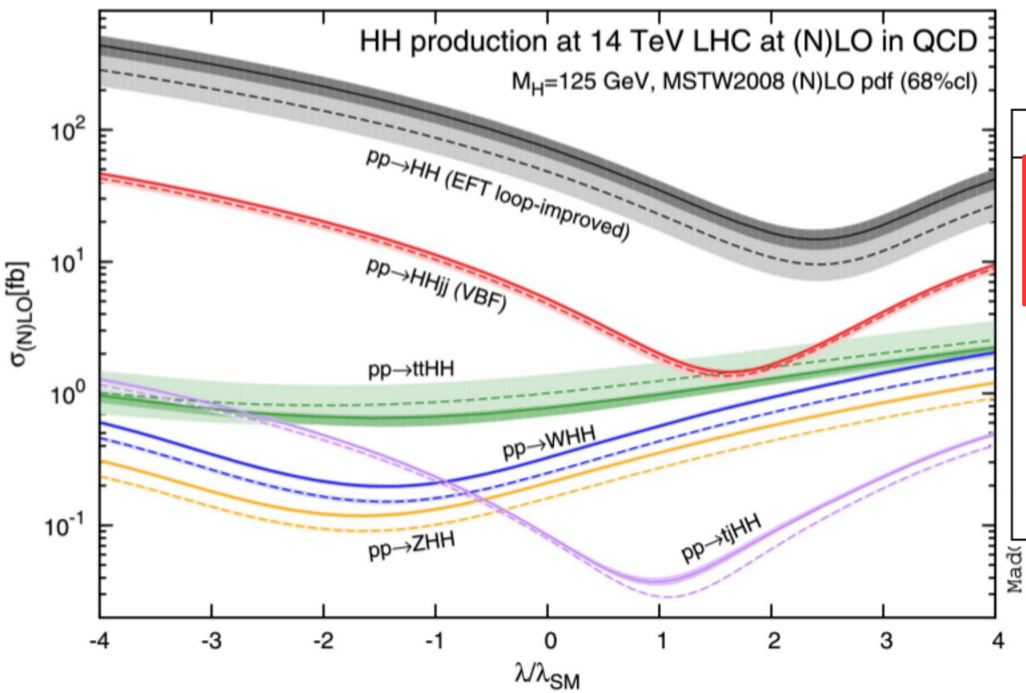
Higgs Self Coupling

- Measurement of Higgs pair production major goal of HL-LHC program
  - Requires full HL-LHC luminosity to reach SM sensitivity
- Allows for a measurement of self coupling λ

$$V(\phi) = \mu^2_{<0}\left|\phi\right|^2 + \lambda\left|\phi\right|^4 + Y^{ij}\psi^i_L\psi^j_R\phi$$



- Extremely challenging due to low cross section (SM: 40 fb)

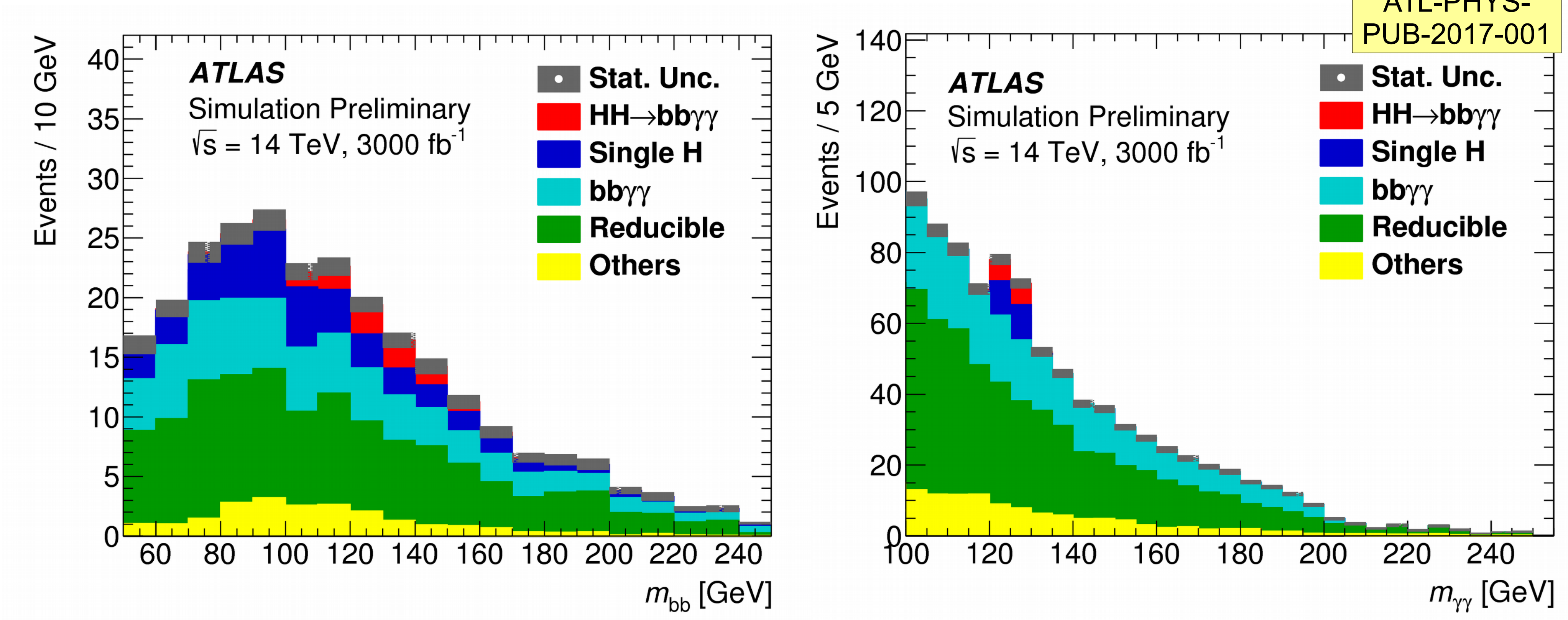


Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	4.1×10^4
$b\bar{b} + W^+W^-$	25%	3.1×10^4
$b\bar{b} + \tau^+\tau^-$	7.4%	9.0×10^3
$W^+W^- + \tau^+\tau^-$	5.4%	6.6×10^3
$ZZ + b\bar{b}$	3.1%	3.8×10^3
$ZZ + W^+W^-$	1.2%	1.4×10^3
$\gamma\gamma + b\bar{b}$	0.3%	3.3×10^2
$\gamma\gamma + \gamma\gamma$	0.0010%	1

HH→b$\bar{b}$γγ Analysis

- Low statistics, but high purity channel
- After selections expect 9.5 signal events and 91 background events
- Corresponds to signal significance of 1.05σ

ATL-PHYS-PUB-2017-001



95% CL limits on self-coupling (ignoring systematics): $-0.8<\lambda/\lambda_{SM}<7.7$

Higgs Self Coupling Projections

CMS extrapolations from Run-2 analyses:

Channel (CMS-DP-2016-064)	Median expected limits in μ_r ECFA16 S1	Median expected limits in μ_r ECFA16 S2	Median expected limits in μ_r Stat. Only	Z-value ECFA16 S1	Z-value ECFA16 S2	Z-value Stat. Only	Uncertainty as fraction of $\mu_r = 1$ ECFA16 S1	Uncertainty as fraction of $\mu_r = 1$ ECFA16 S2	Uncertainty as fraction of $\mu_r = 1$ Stat. Only
$gg \to HH \to \gamma\gamma bb$ (S1+/S2+)	1.3	1.3	1.3	1.6	1.6	1.6	0.64	0.64	0.64
$gg \to HH \to \tau\tau bb$	7.4	5.2	3.9	0.28	0.39	0.53	3.7	2.6	1.9
$gg \to HH \to VVbb$		4.8	4.6		0.45	0.47		2.4	2.3
$gg \to HH \to bbbb$		7.0	2.9		0.39	0.67		2.5	1.5

ATLAS simulations (HH→bbbb is Run-2 extrapolations):

Channel	Expected limit in μ: Full Syst.	Expected limit in μ: Stat. only	Significance: Full Syst.	Significance: Stat. only	Limits on λ/λ_{SM} at 95% CL: Full Syst.	Limits on λ/λ_{SM} at 95% CL: Stat. only
gg→HH→γγbb (ATL-PHYS-PUB-2017-001)			1.05σ			$-0.8<\lambda/\lambda_{SM}<7.7$
gg→HH→ττbb (ATL-PHYS-PUB-2015-046)	4.3		0.6σ		$-4<\lambda/\lambda_{SM}<12$	
gg→HH→bbbb (ATL-PHYS-PUB-2016-024)	5.2	1.5			$-3.5<\lambda/\lambda_{SM}<11$	$0.2<\lambda/\lambda_{SM}<7$
ttHH→$t_{had}t_{lep}$bbbb (ATL-PHYS-PUB-2016-023)				0.35σ		

Higgs Self Coupling Projections

CMS extrapolations from Run-2 analyses:

Channel CMS-DP-2016-064	Median expected limits in μ_r			Z-value			Uncertainty as fraction of $\mu_r = 1$		
	ECFA16		Stat.	ECFA16		Stat.	ECFA16		Stat.
	S1	S2	Only	S1	S2	Only	S1	S2	Only
$gg \to HH \to \gamma\gamma bb$ (S1+/S2+)	1.3	1.3	1.3	1.6	1.6	1.6	0.64	0.64	0.64
$gg \to HH \to \tau\tau bb$	7.4	5.2	3.9	0.28	0.[illegible]9	[illegible]53	3.7	2.6	1.9
$gg \to HH \to VVbb$		4.8	4.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.3
$gg \to HH \to bbbb$		7.0	2.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].5

ATLAS simulations (HH→bbbb is R[illegible]

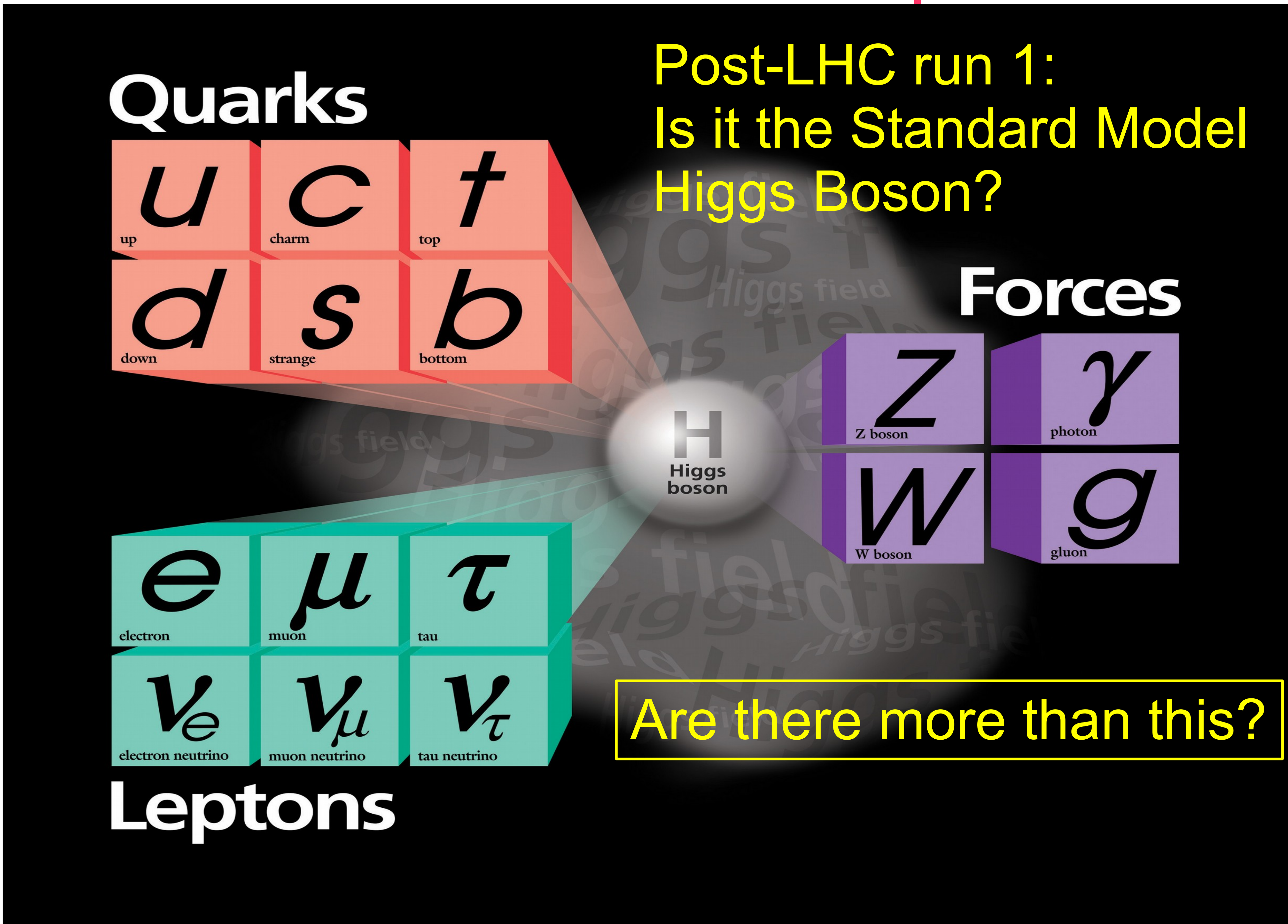
Channel	Expected limit in μ		Significance		[illegible]	
	Full Syst.	Stat. only	Full Syst.	Stat. only	Full Syst.	Stat. only
gg→HH→γγbb (ATL-PHYS-PUB-2017-001)			1.05σ			$-0.8<\lambda/\lambda_{SM}<7.7$
gg→HH→ττbb (ATL-PHYS-PUB-2015-046)	4.3		0.6σ		$-4<\lambda/\lambda_{SM}<12$	
gg→HH→bbbb (ATL-PHYS-PUB-2016-024)	5.2	1.5			$-3.5<\lambda/\lambda_{SM}<11$	$0.2<\lambda/\lambda_{SM}<7$
ttHH→$t_{had}t_{lep}$bbbb (ATL-PHYS-PUB-2016-023)				0.35σ		

Even with HL-LHC will need to combine multiple channels and exp to be sensitive to SM λ

The HL-LHC Physics case

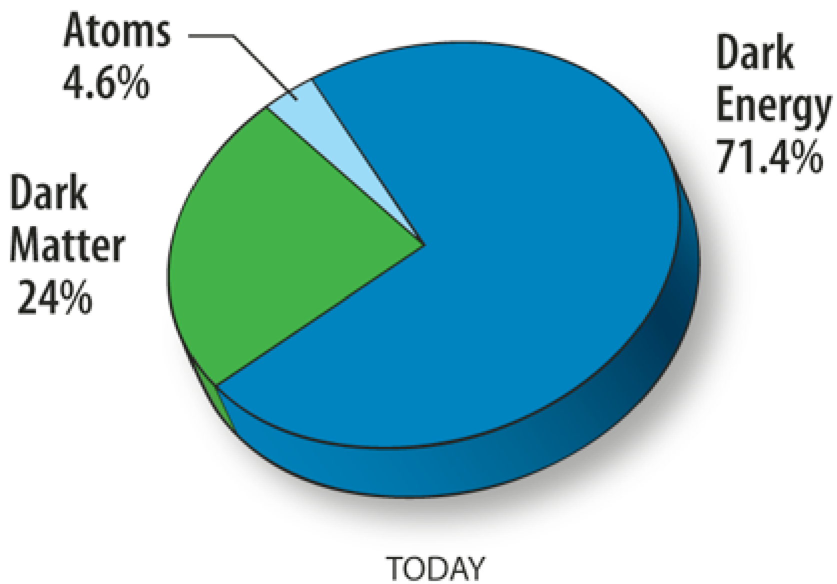
Beyond the Standard Model

Standard Model Complete?

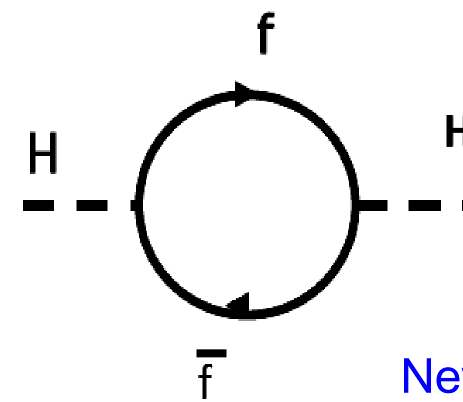


Motivation for Beyond SM Physics

Nature of Dark Matter?



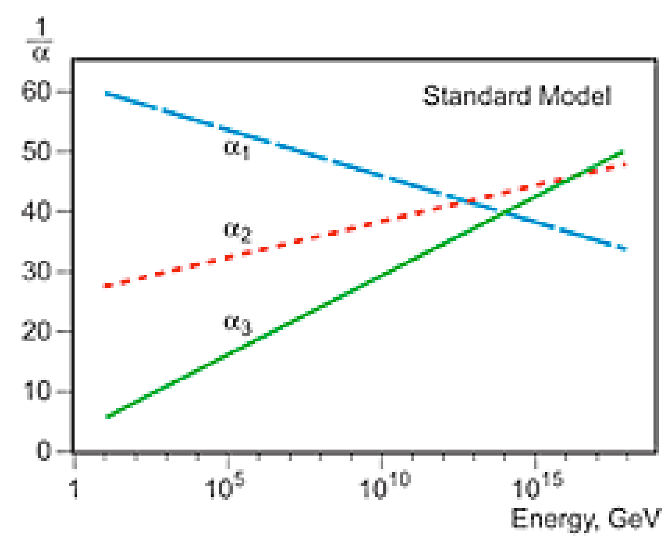
Finetuning?



New physics cut-off

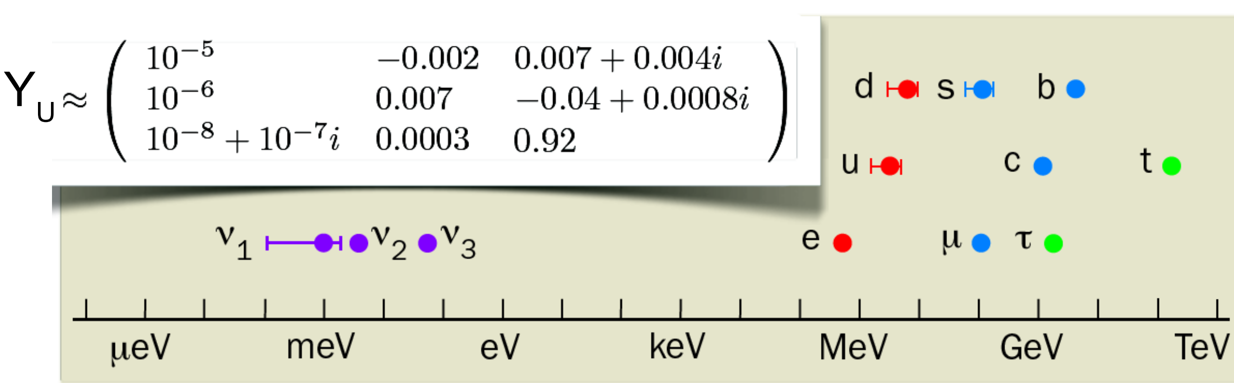
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots .$$

Unification of forces?



Origin of mass hierarchy and flavor?

$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007+0.004i \\ 10^{-6} & 0.007 & -0.04+0.0008i \\ 10^{-8}+10^{-7}i & 0.0003 & 0.92 \end{pmatrix}$$



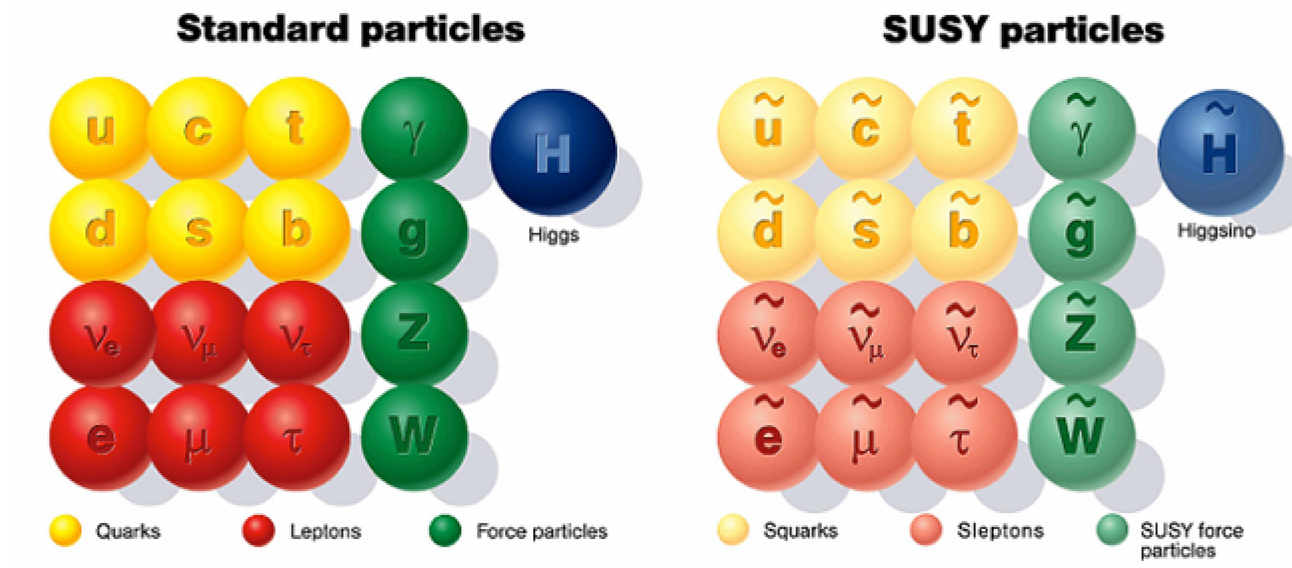
New Physics Models?

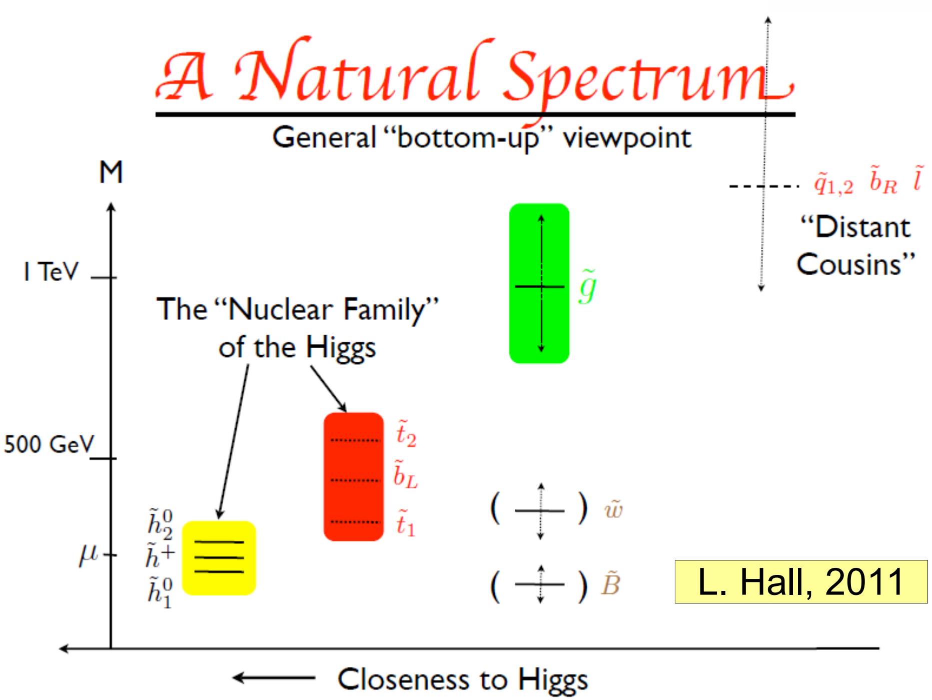
H. Murayama

- Very wide range of BSM models to address open questions
  - Some already (partly) excluded by LHC results
  - Some need HL-LHC data or cannot be excluded

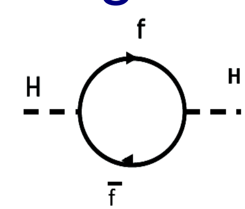
Supersymmetry

- Well-motivated SM extension
  - Solution to hierarchy problem
  - Provides DM candidate
  - Unifies gauge-couplings





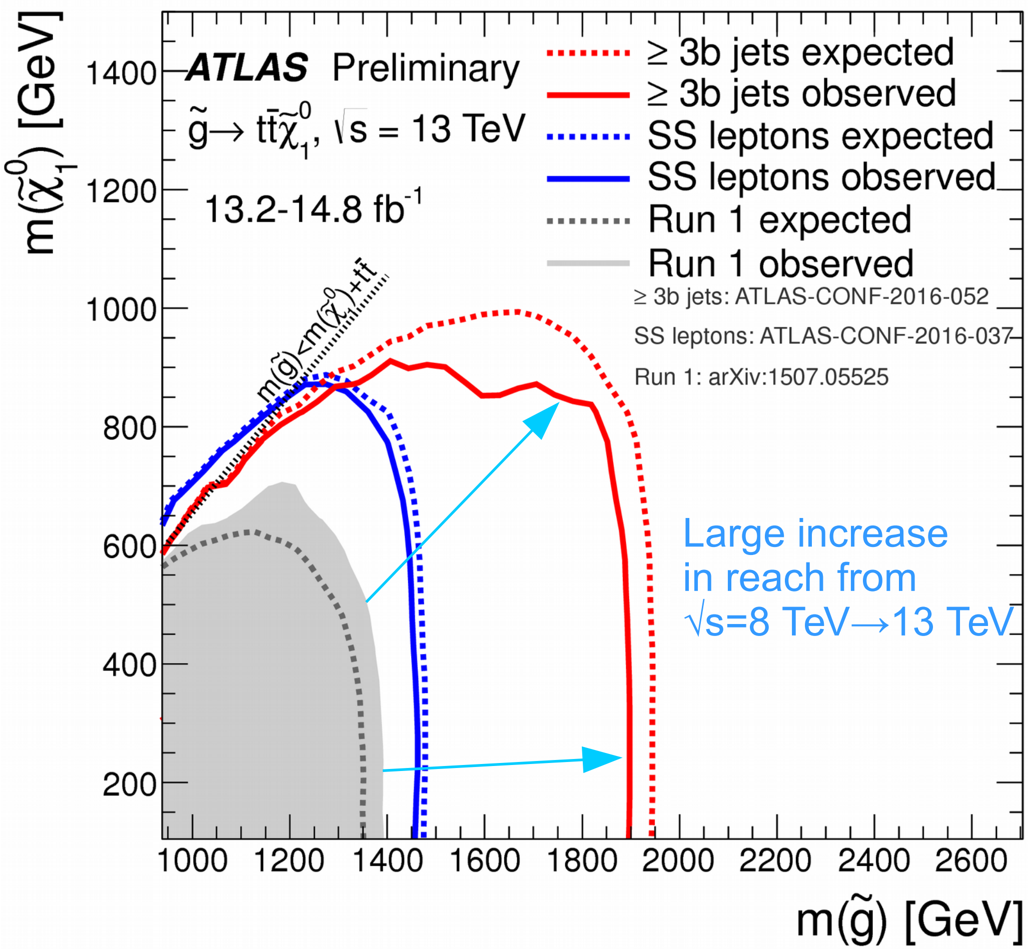
- To be "Natural" SUSY has to have some new particles at TeV-scale
  - Light stop and gluino to regularize light Higgs boson

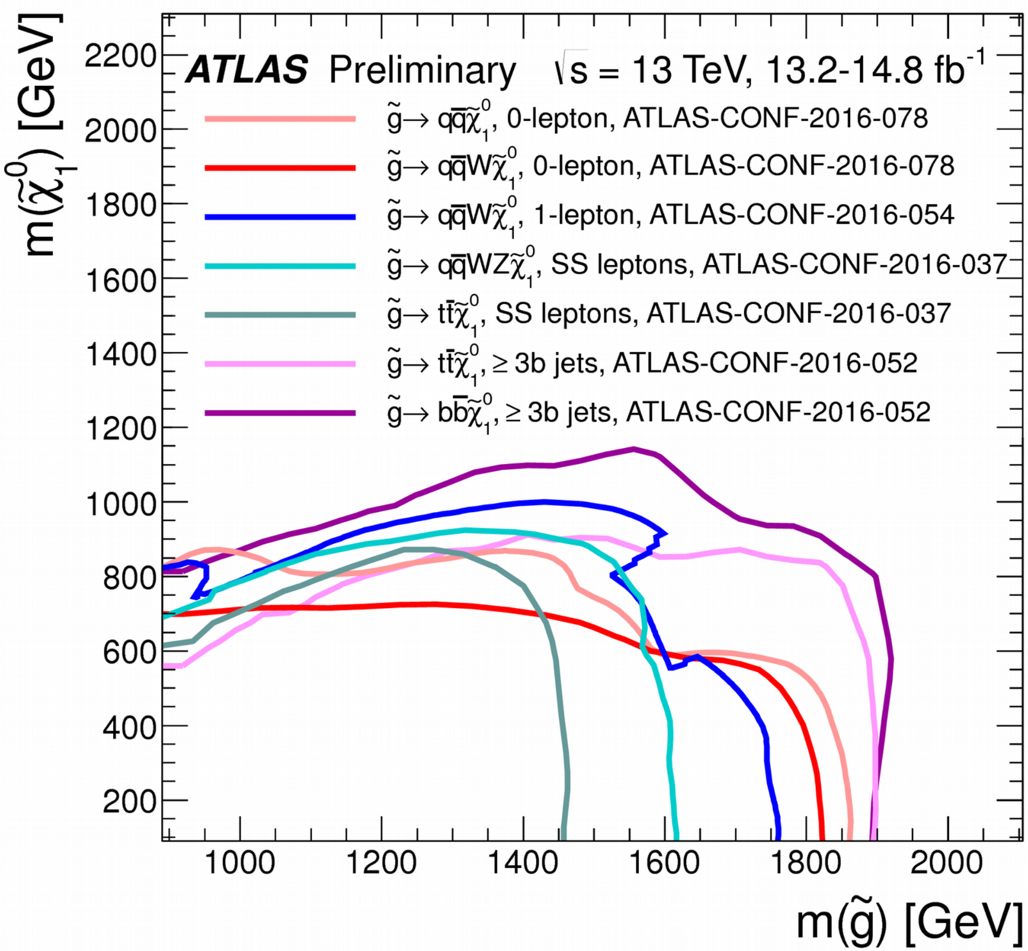


  - Light higgsinos

Status of Gluino Searches

- LHC highly sensitive to TeV-scale colored sparticles
  - Wide set of searches for gluinos in different decay modes

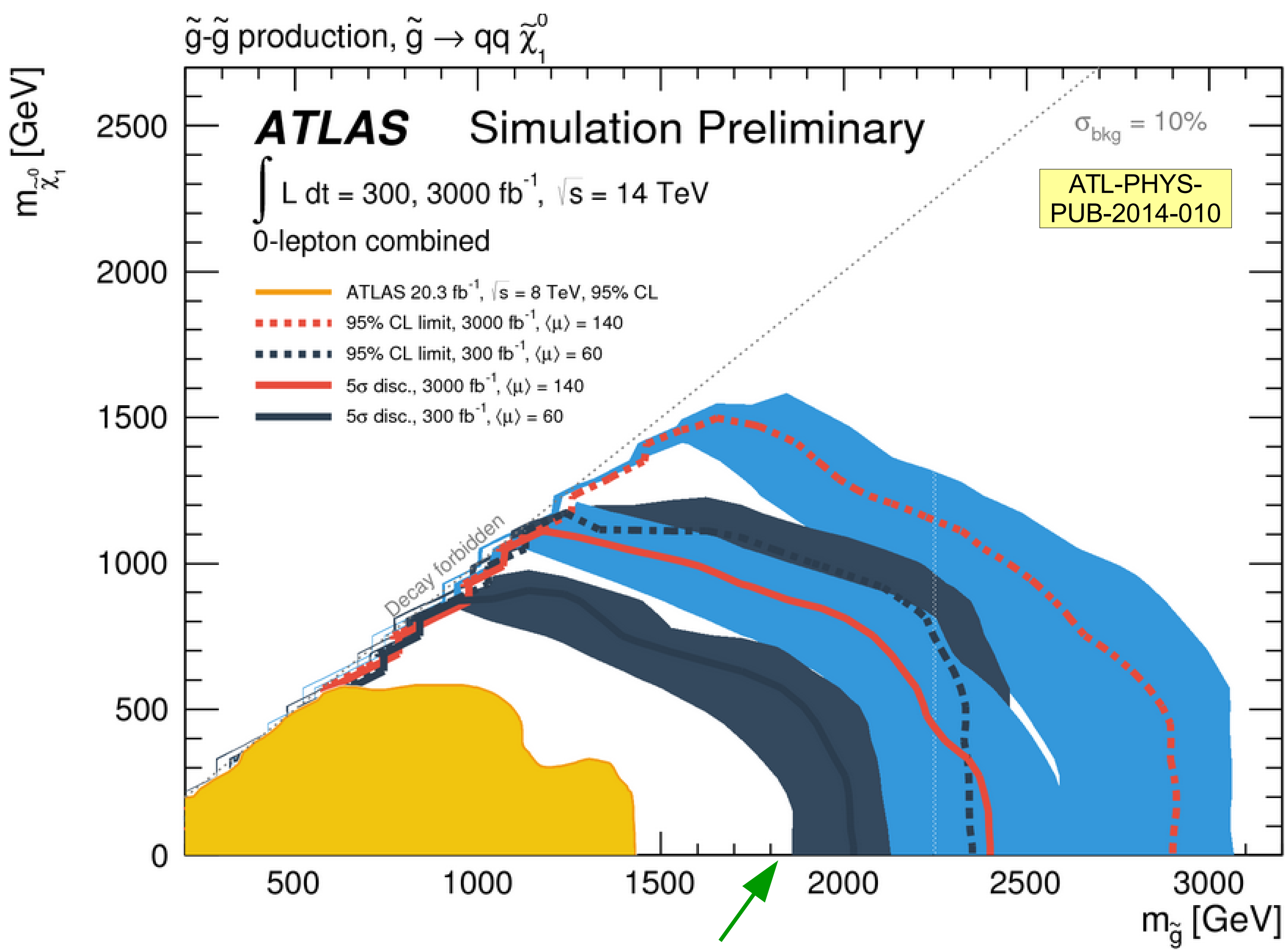




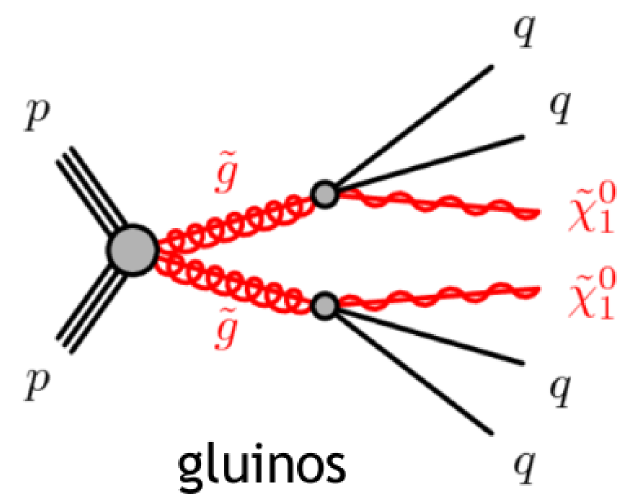
Gluino limits for light neutralino at 1.6-1.9 TeV
At the high end of “Natural SUSY” expectation

Search for Gluino Pairs at HL-LHC

HL-LHC would significantly extend sensitivity to higher mass gluinos



Current limit

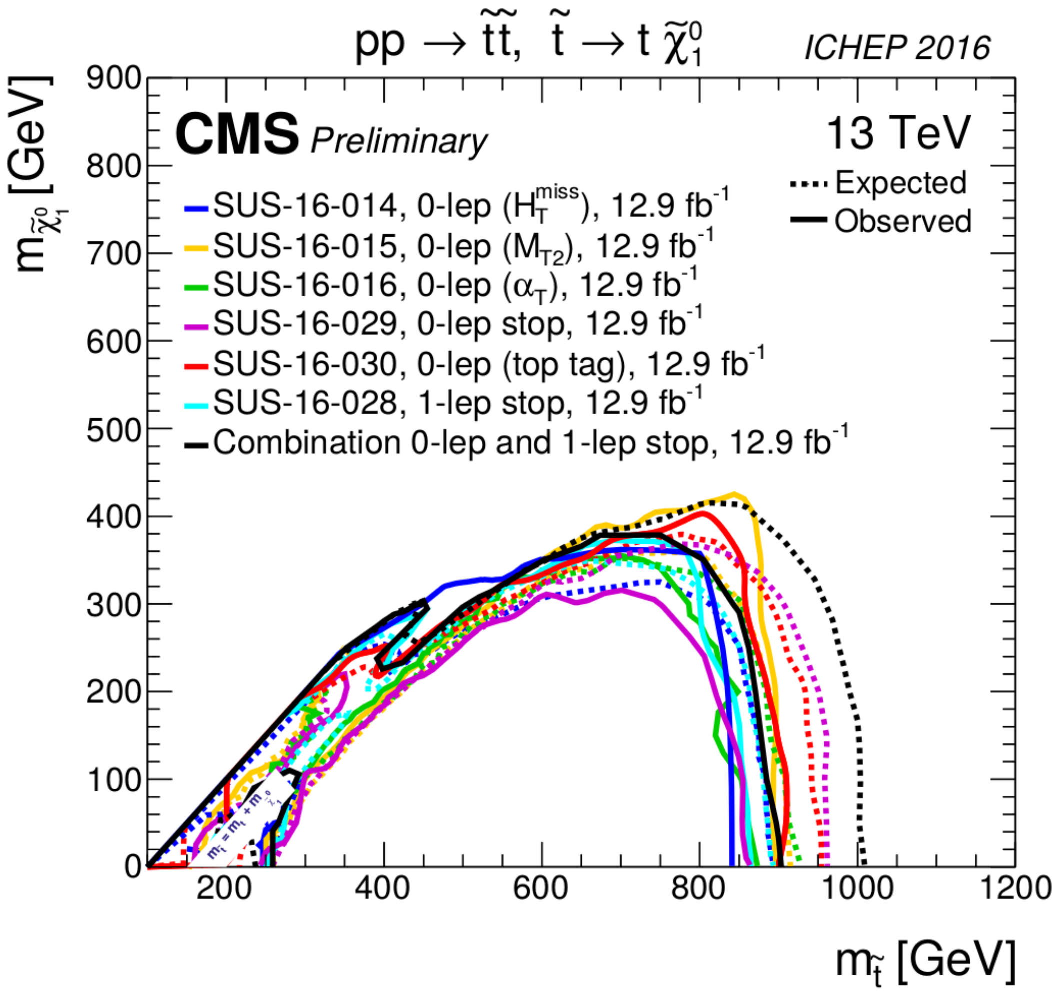


Expect to discover gluinos up to ~2 TeV for neutralinos up to 1 TeV

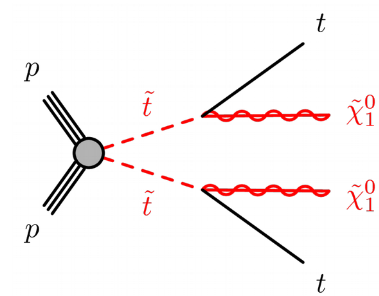
Exclude gluinos up to ~3 TeV

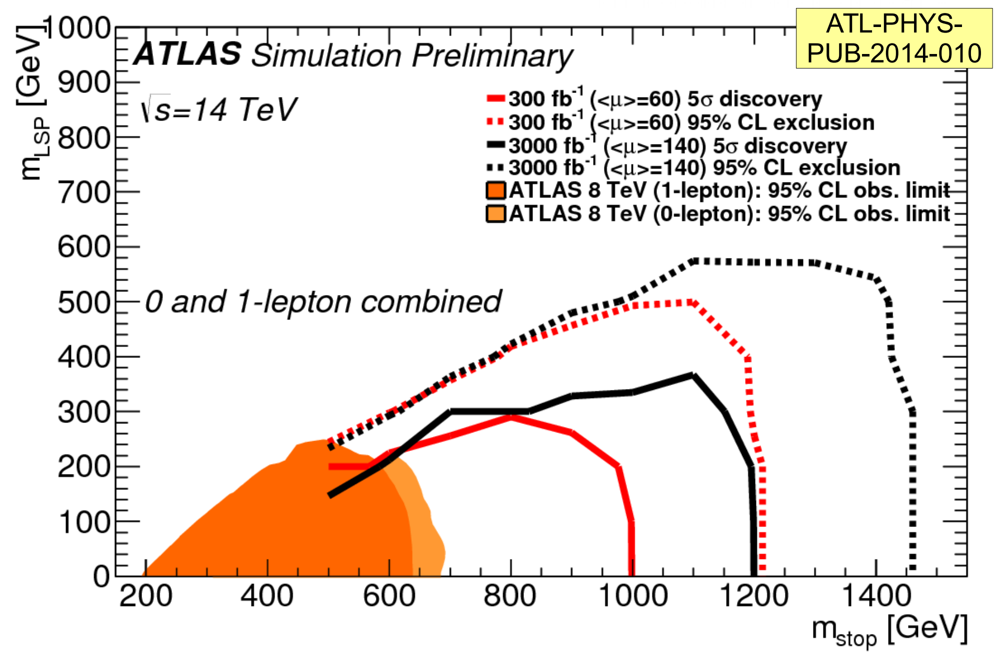
Stop Quark Searches

- Multiple Run-1 and Run-2 searches dedicated to stop searches
  - Specialized search regions to fill in low-mass stop "holes"



Basic projections done for HL-LHC



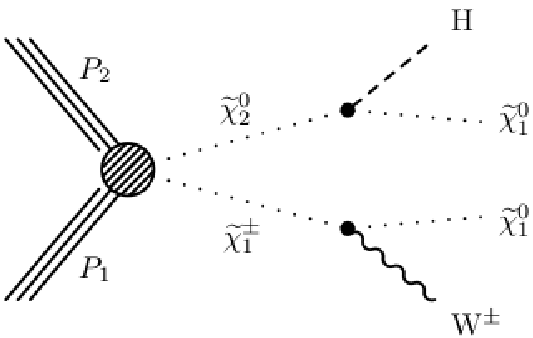


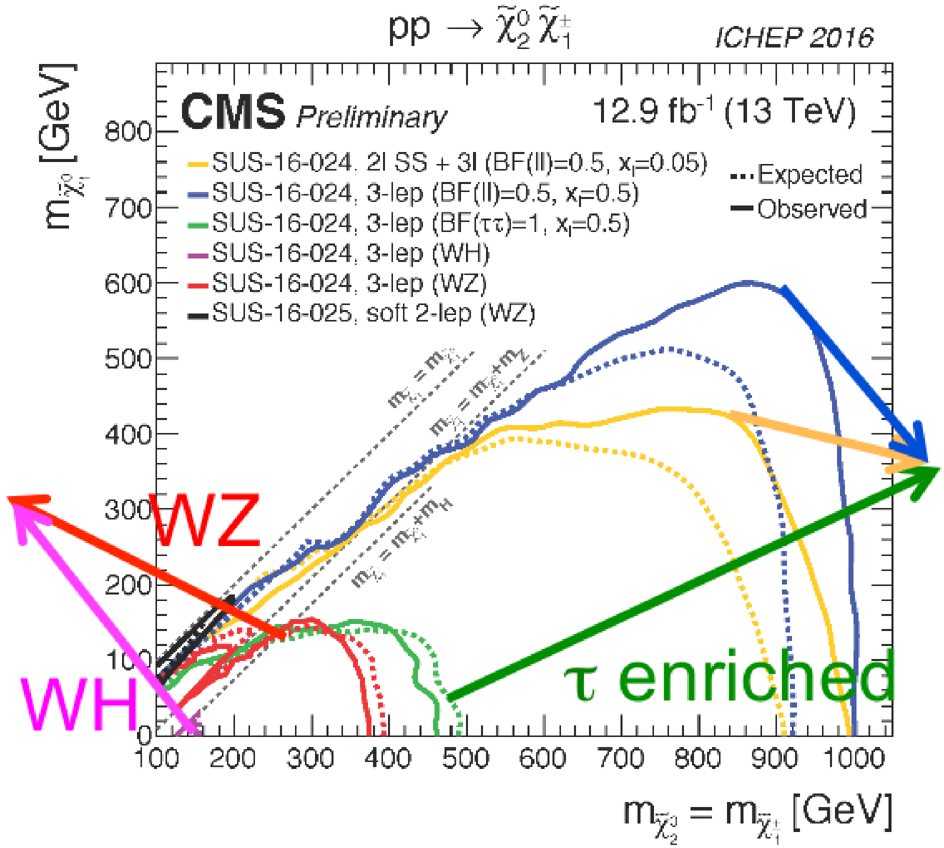
Stop mass mostly constrained to be above ~900 GeV
HL-LHC will push this toward 1.5 TeV

Chargino/Neutralino Searches

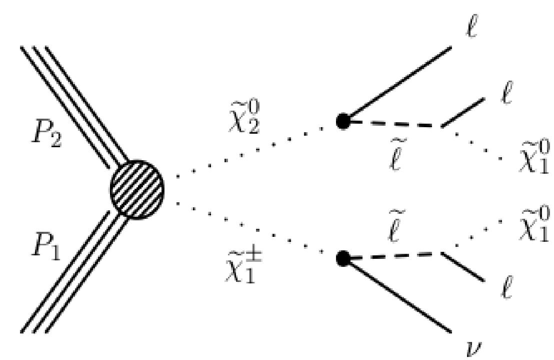
EWKinos primarily searched for in leptonic channels

Lower BR to l: decay via bosons, e.g.





High BR to l: decay via $\tilde{l}$, e.g.



Exclusion reach strongly dependent on decay modes

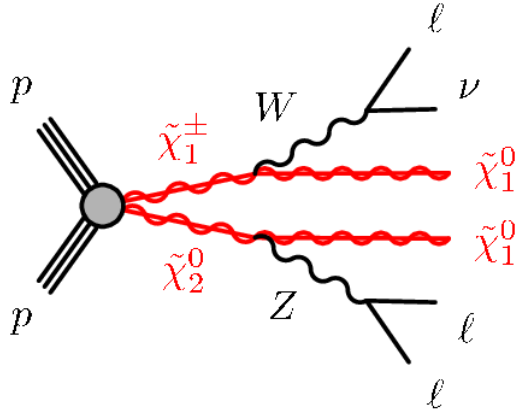
Note: above limits assume pure wino-nature for $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+$

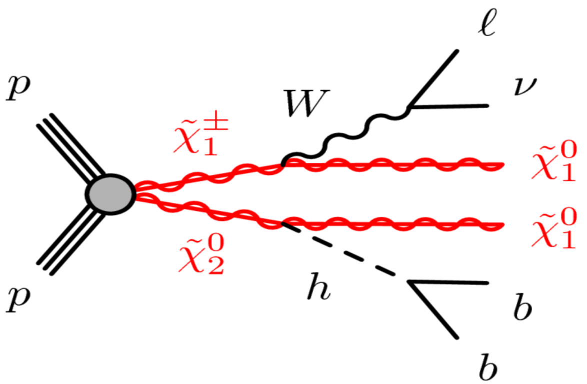
Higgsino production cross section is lower

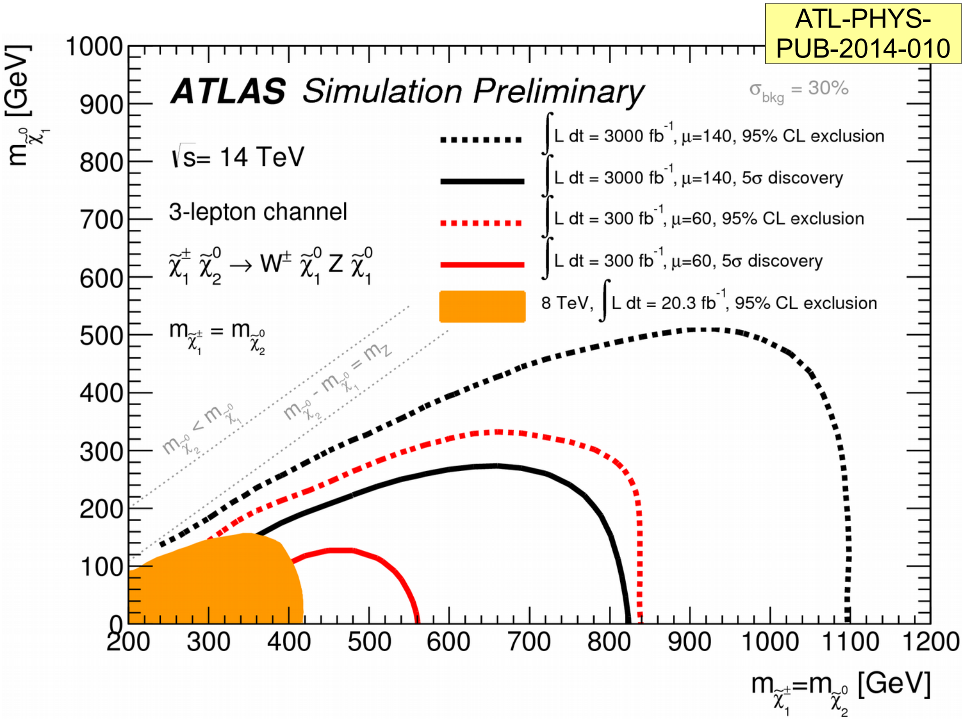
Mass degenerate states require specialized searches

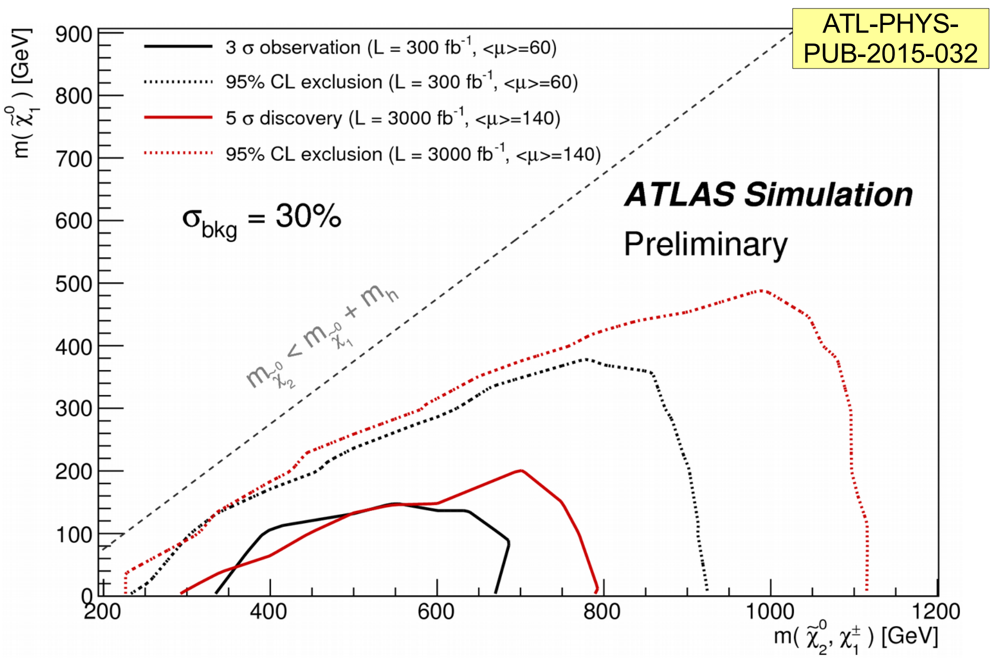
Chargino/Neutralino HL-LHC Searches

Projection for chargino-neutralino production in two channels:





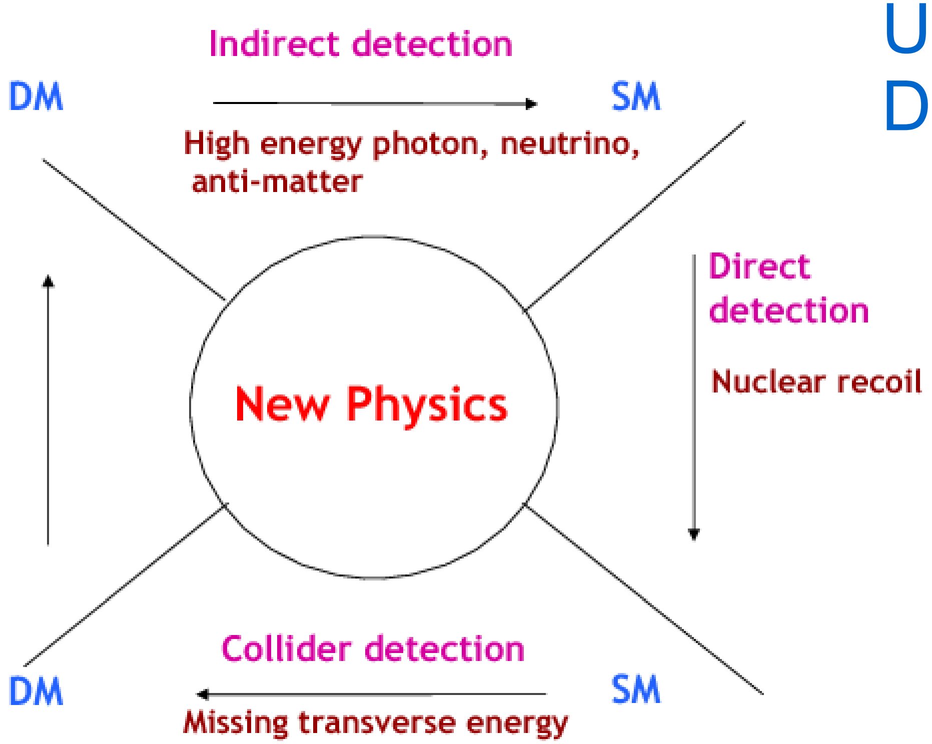




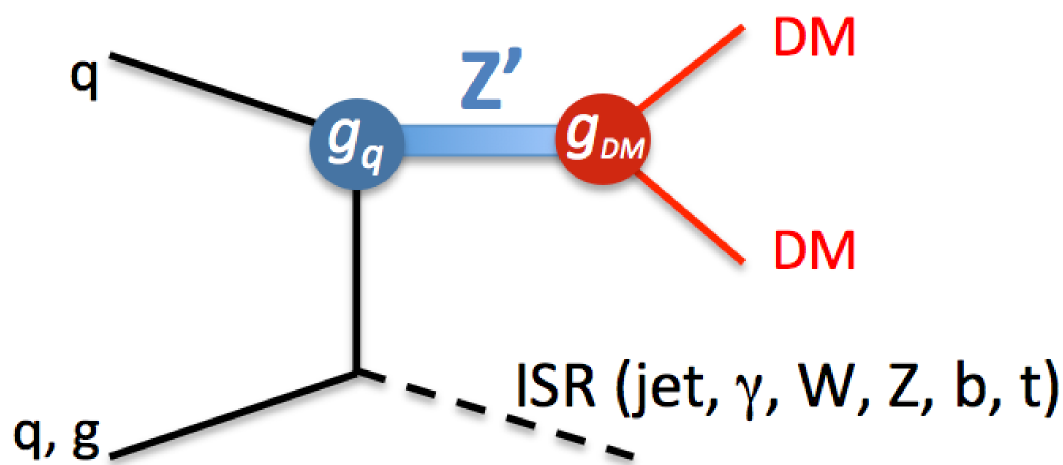
Discovery reach up to ~800 GeV
Very limited reach without HL-LHC

Search for Dark Matter at the LHC

- LHC can complement direct and indirect searches for dark matter by directly produce dark matter

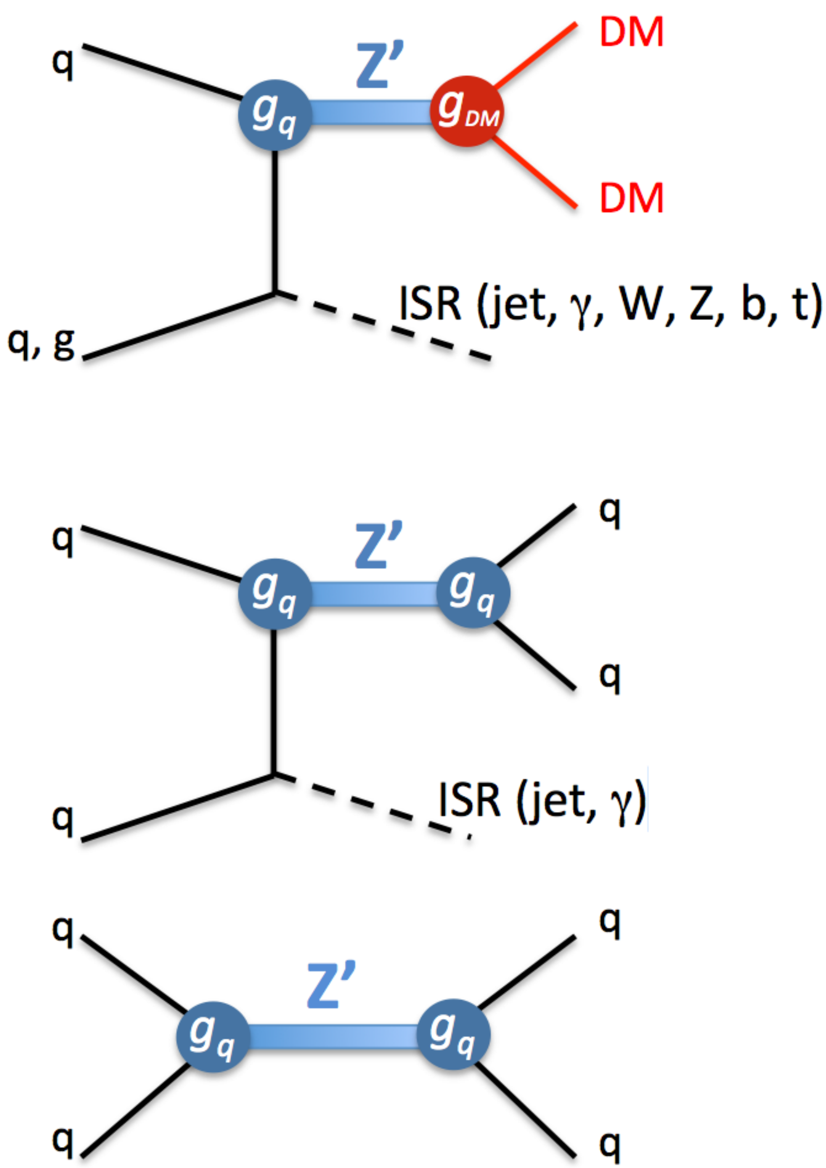


Use “mono-X” topology to boost DM particles and make them visible

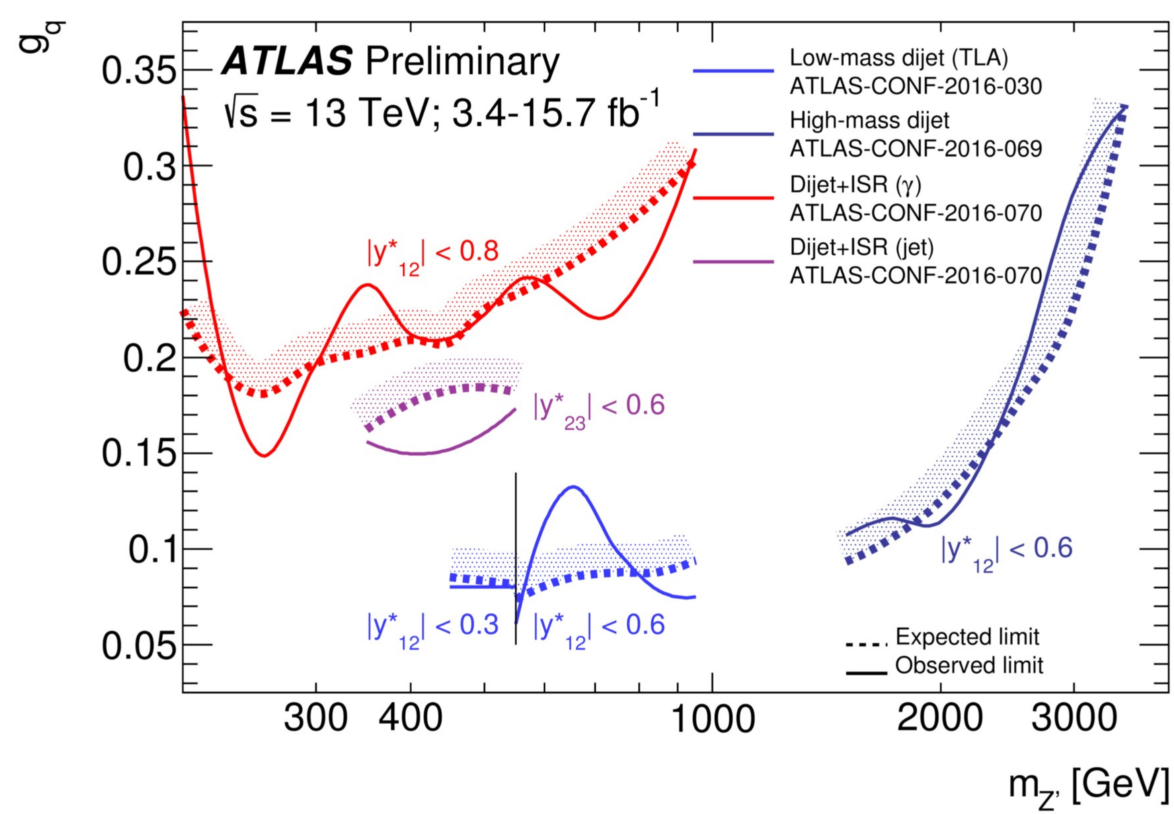


DM through Di-jet Searches

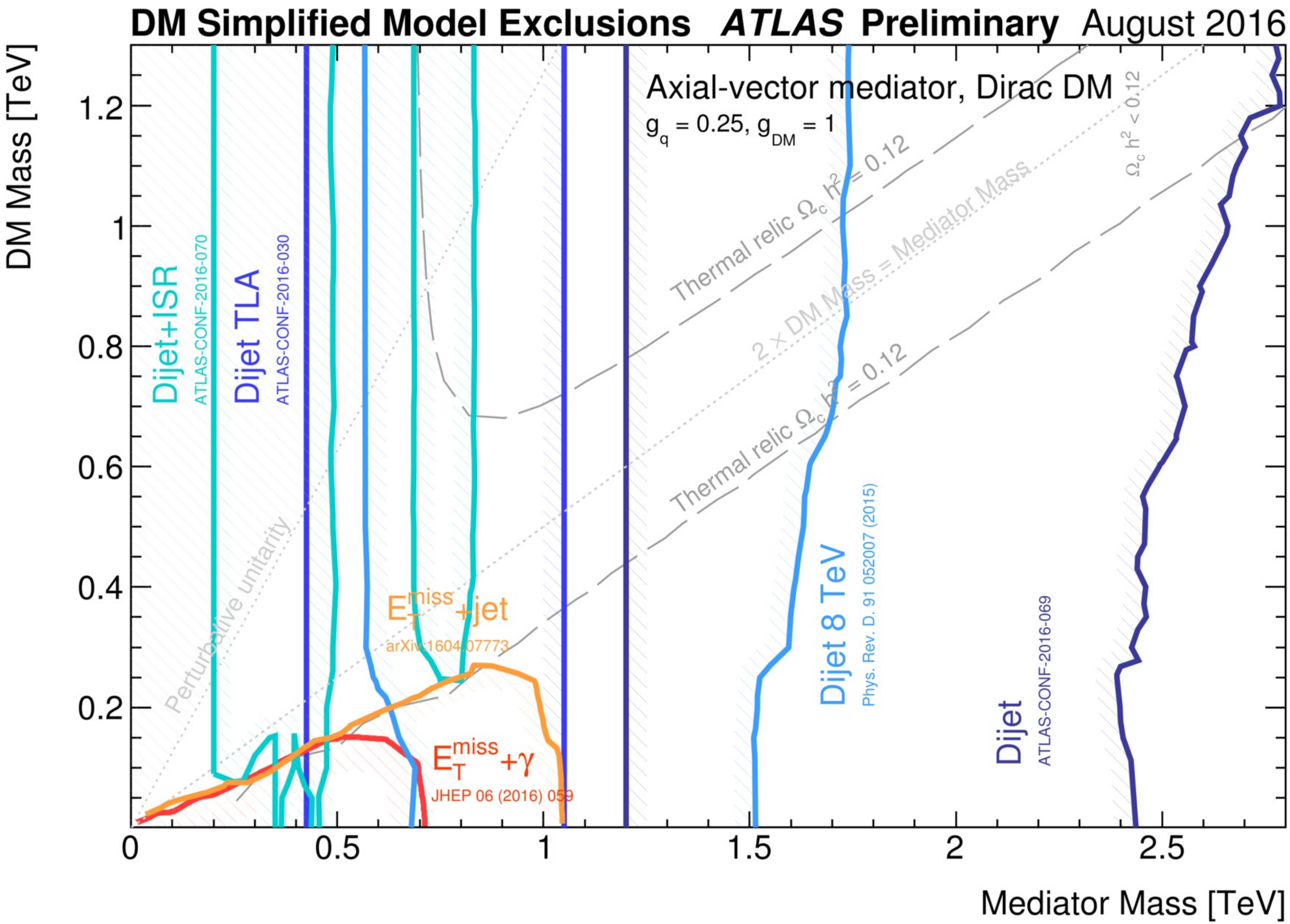
- LHC can detect mediator between DM and SM if it is light enough
  - Complements mono-X searches



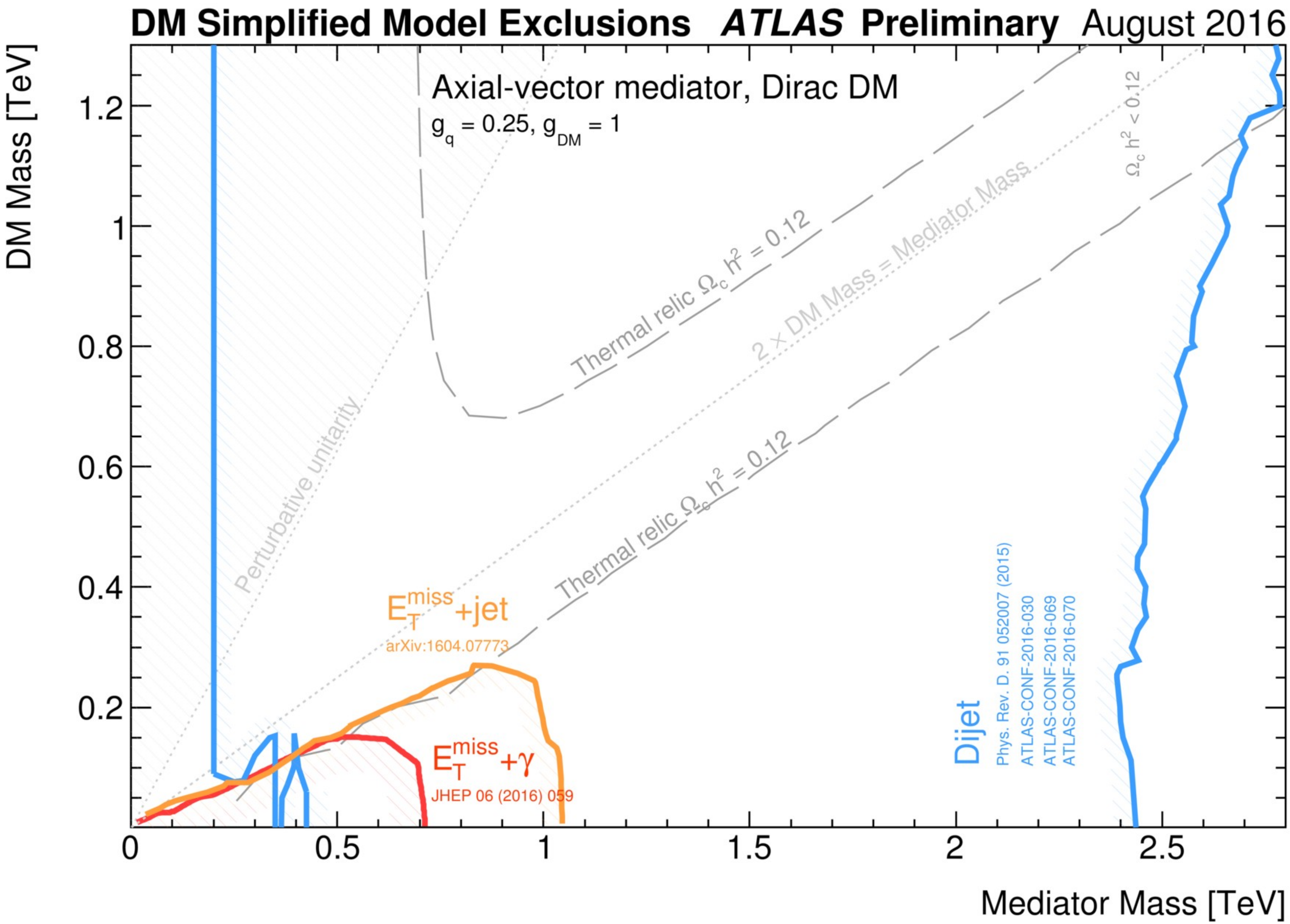
Search for bump in di-jet mass spectrum – dedicated techniques at low mass



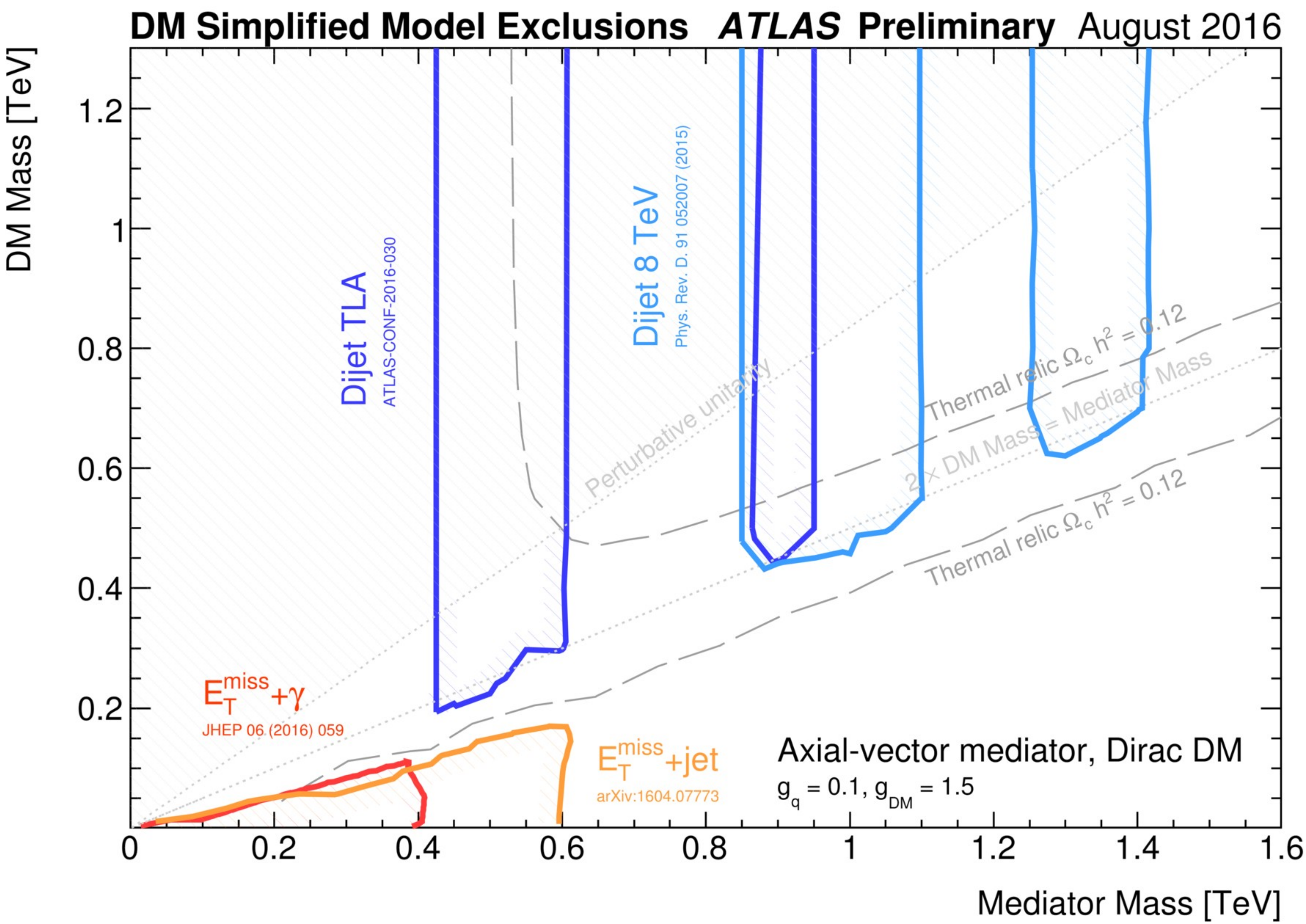
Dark Matter Interpretations



Dark Matter Interpretations - Combined

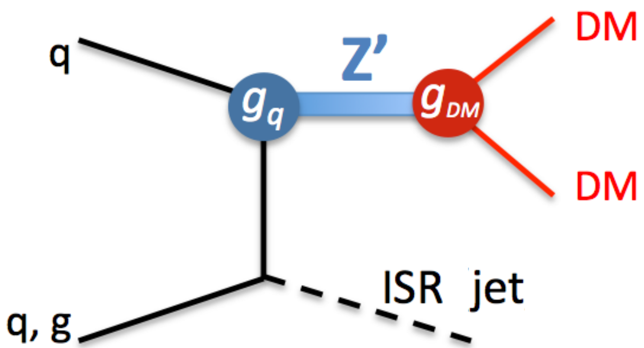


Exclusion for Different Model Point

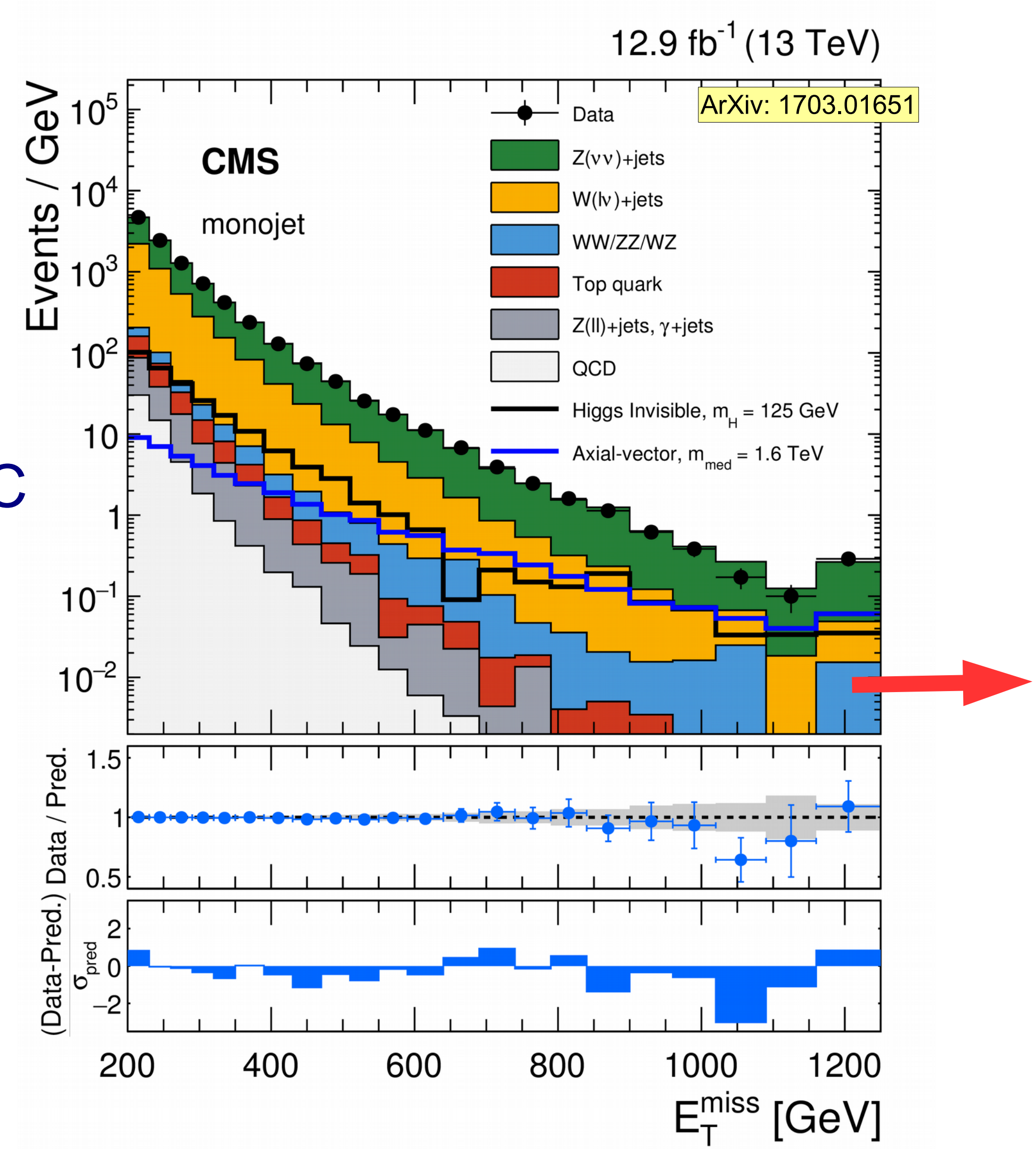


Mono-Jet Search at HL-LHC

- Mono-jet search mostly most sensitive to DM production
- Has been projected to full HL-LHC based on Run-2 analysis



- Fit for excess in E_T^{miss} bins
  - Extend to 2.4 TeV for HL-LHC
- Main backgrounds assumed to be real E_T^{miss} from
  - Z(→νν)+jet(s)
  - W(→νℓ)+jet(s)
- Backgrounds will be estimated using data-driven techniques
  - Projection depends strongly on how well systematics can be controlled



Mono-Jet Search at HL-LHC

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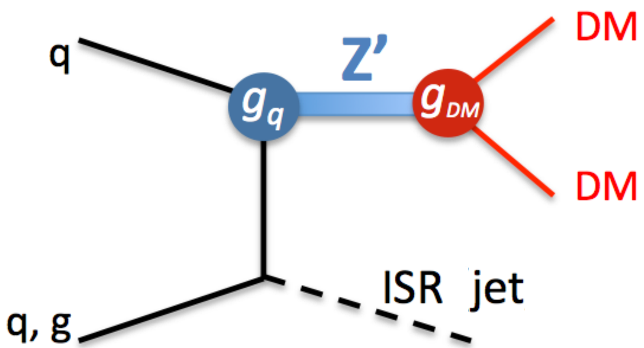
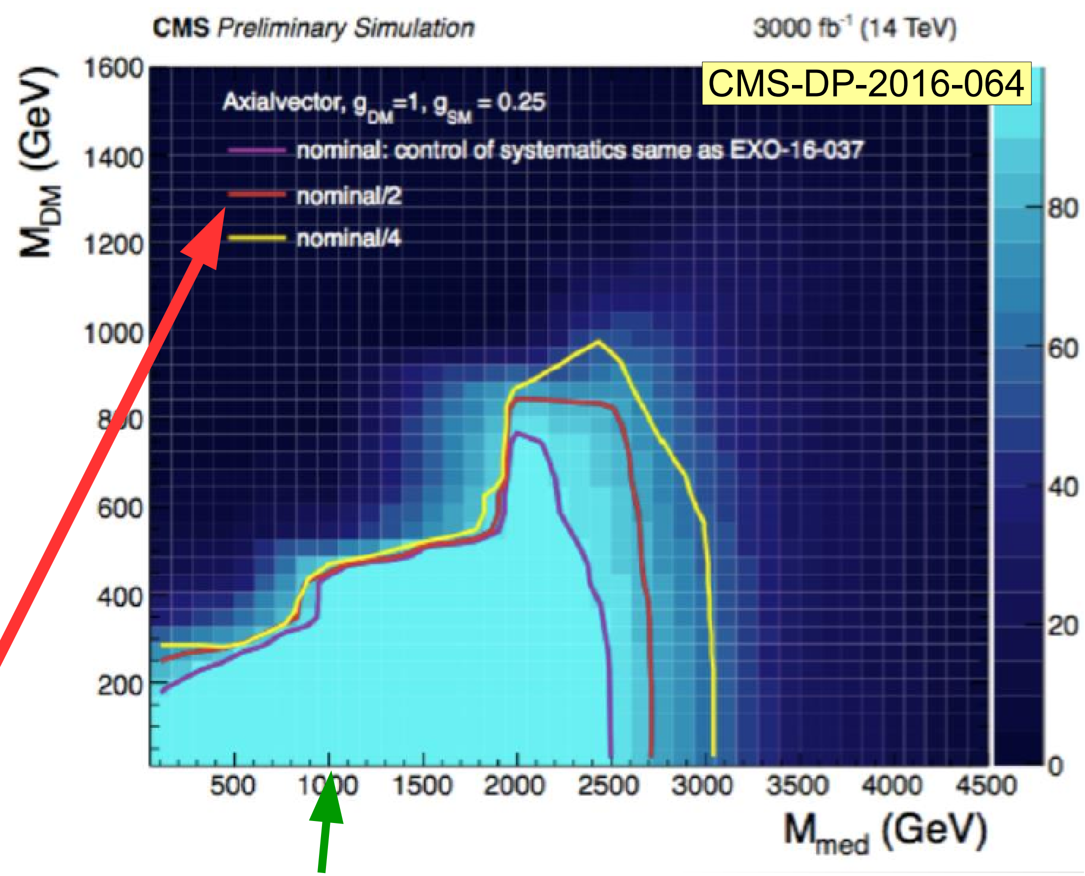


- Fit for excess in E_T^{miss} bins
  - Extend to 2.4 TeV for HL-LHC
- Main backgrounds assumed to be real E_T^{miss} from
  - Z(→νν)+jet(s)
  - W(→νℓ)+jet(s)
- Backgrounds will be estimated using data-driven techniques
  - Projection depends strongly on how well systematics can be controlled

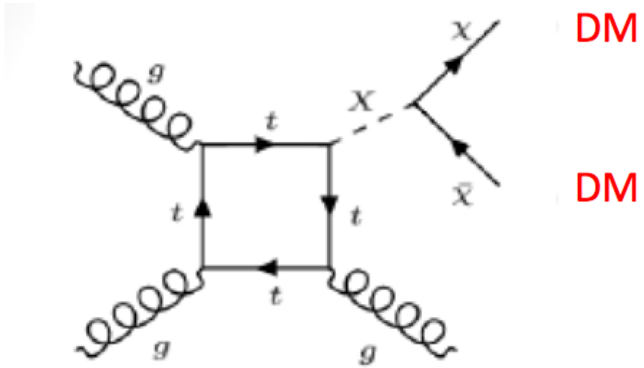
Sensitivity to axial-vector mediator driven by high E_T^{miss} bins



Current limit

Mono-Jet Search at HL-LHC

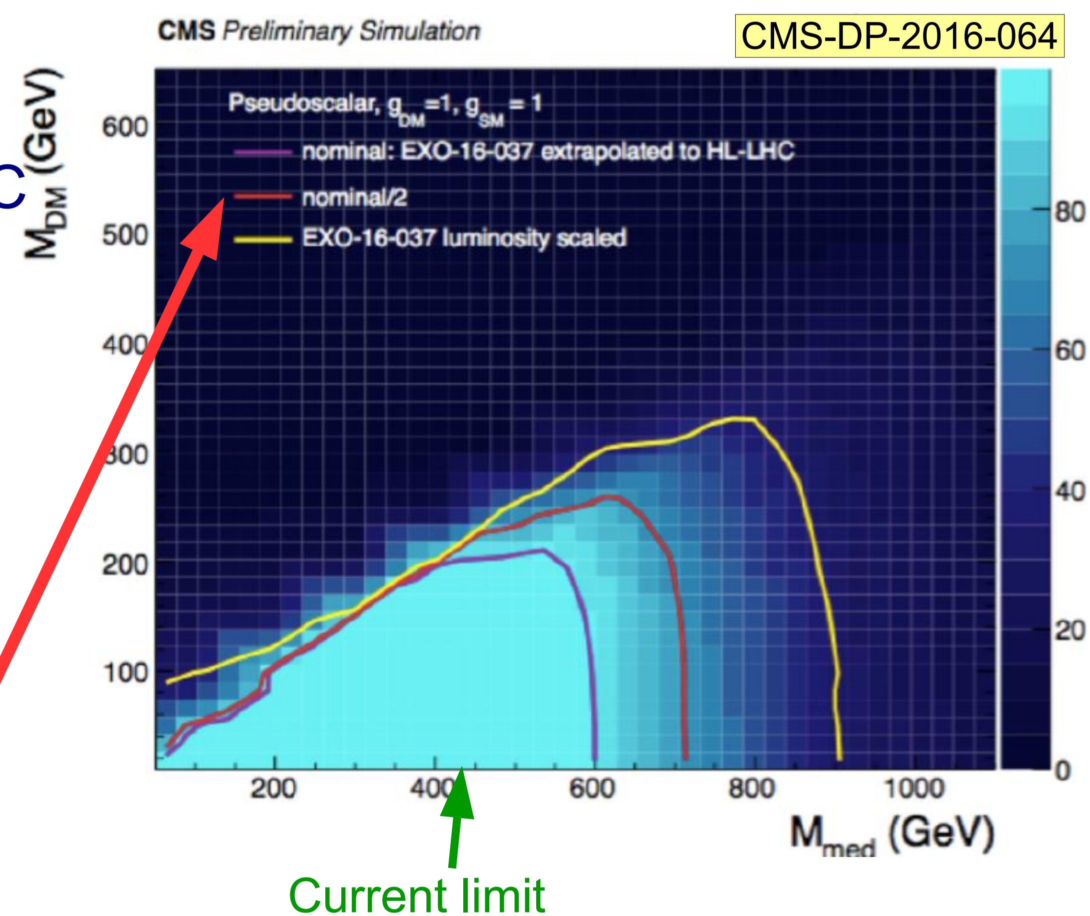
- Mono-jet search mostly most sensitive to DM production
- Has been projected to full HL-LHC based on Run-2 analysis



LHC has unique sensitivity to pseudo-scalar mediator

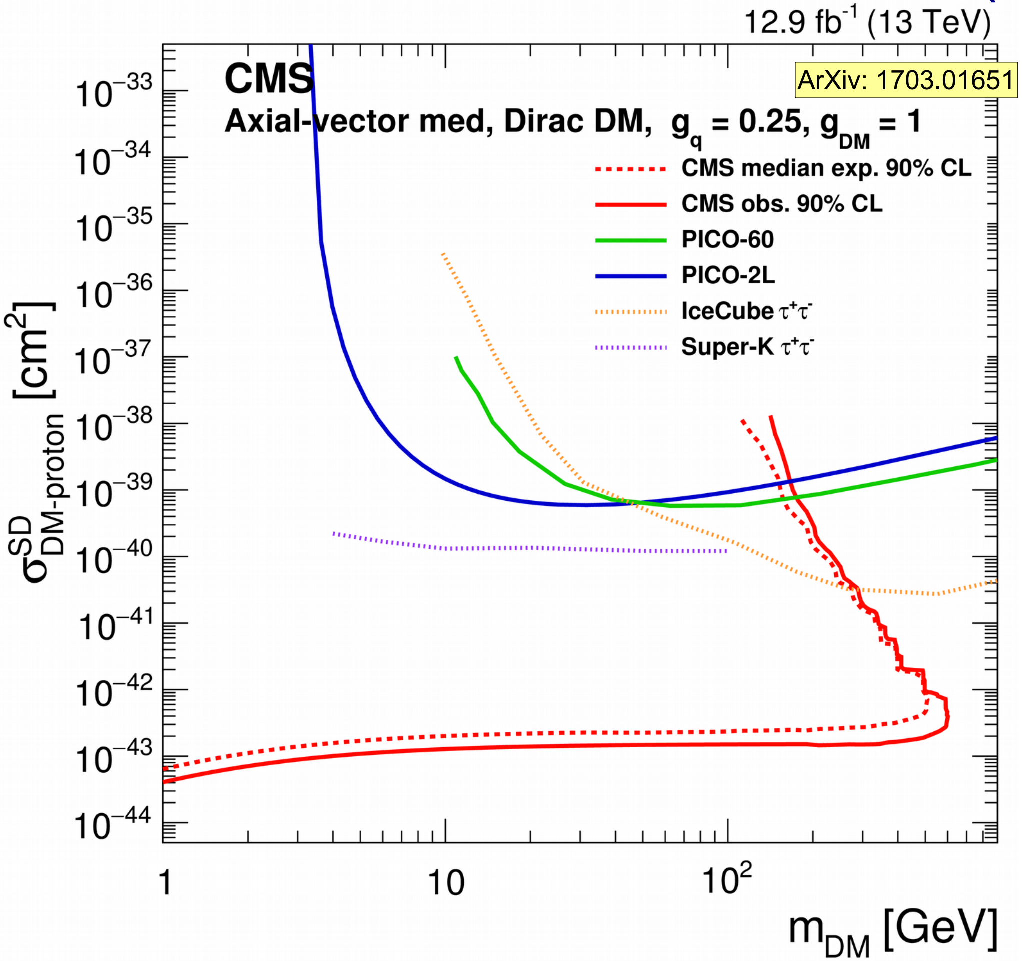
Driven by lower E_T^{miss} bins

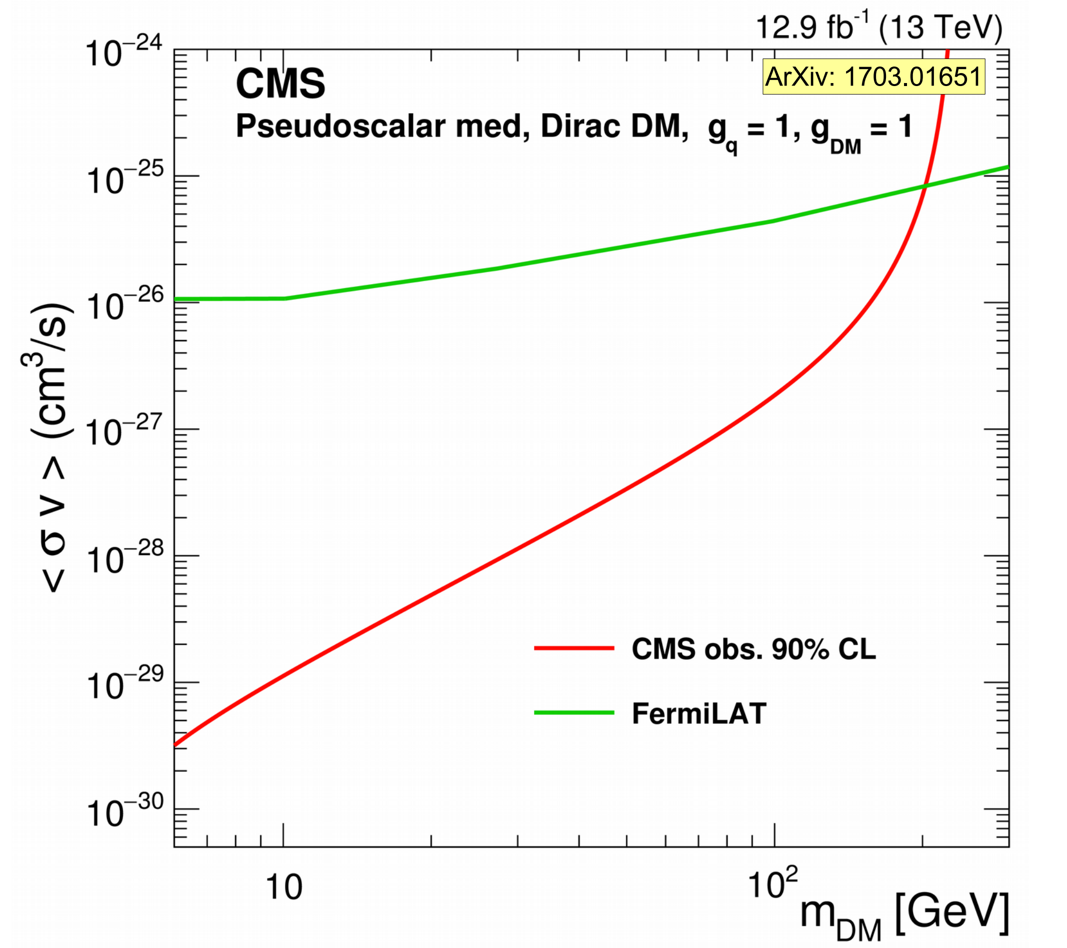
- Fit for excess in E_T^{miss} bins
  - Extend to 2.4 TeV for HL-LHC
- Main backgrounds assumed to be real E_T^{miss} from
  - Z(→νν)+jet(s)
  - W(→νℓ)+jet(s)
- Backgrounds will be estimated using data-driven techniques
  - Projection depends strongly on how well systematics can be controlled



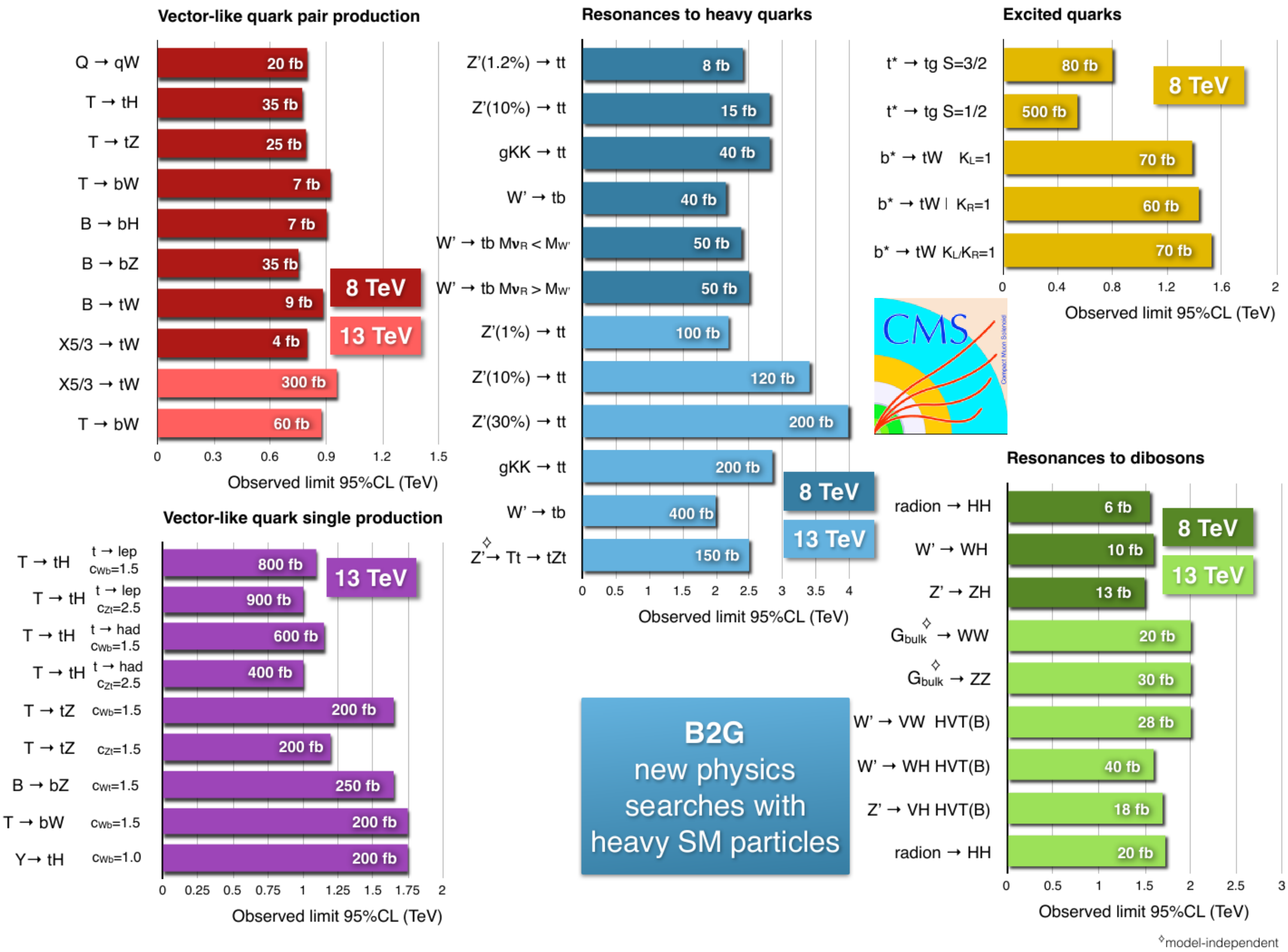
Comparison to non-LHC Searches

- For vector and scalar mediators, only competitive with direct detection searches for very light DM
- For axial-vector and pseudoscalar mediators competitive
  - No combined projections of mono-jet+di-jets available yet
  - Cross section scales as $(m_{med})^{-4}$

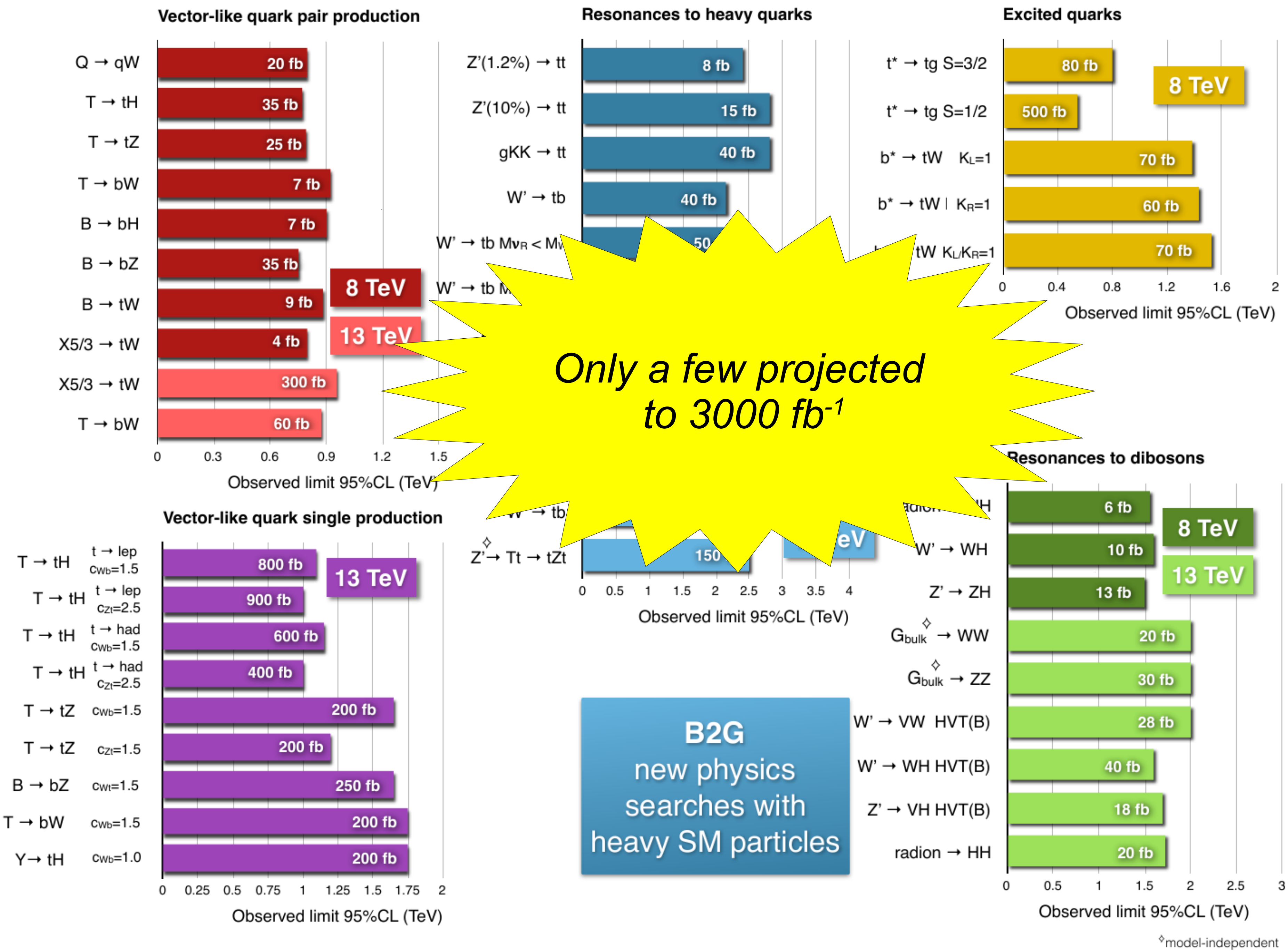




Vast set of other BSM Searches

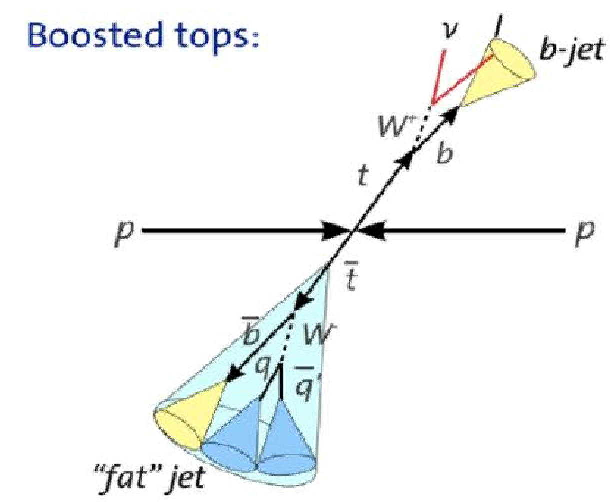


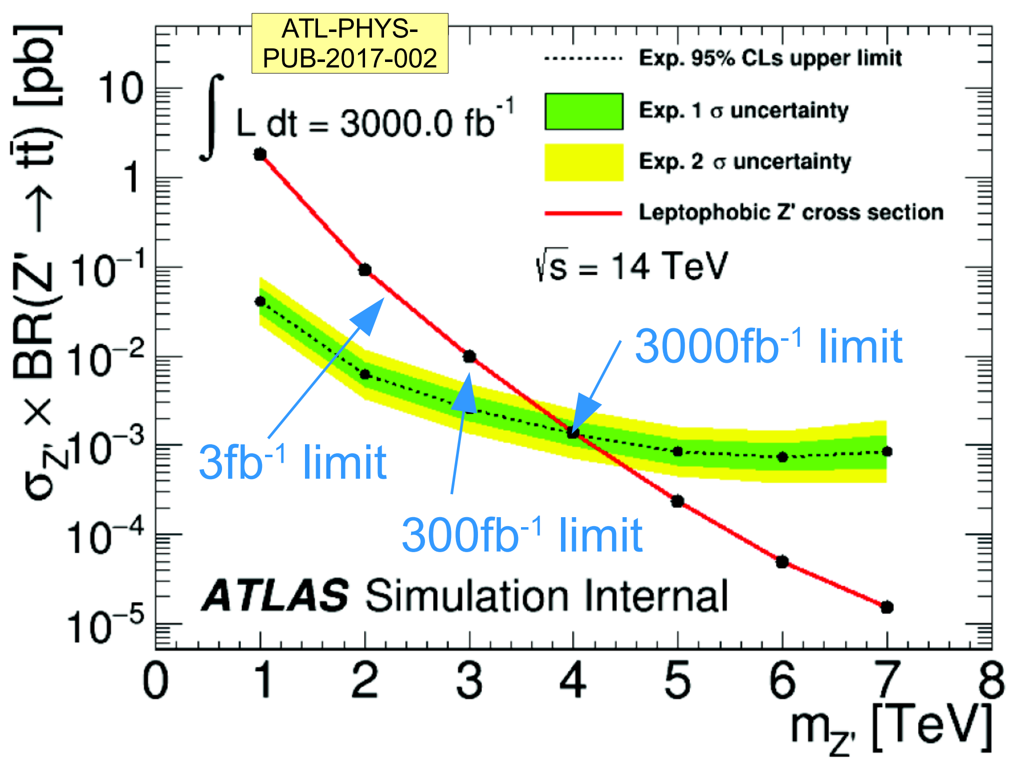
Vast set of other BSM Searches

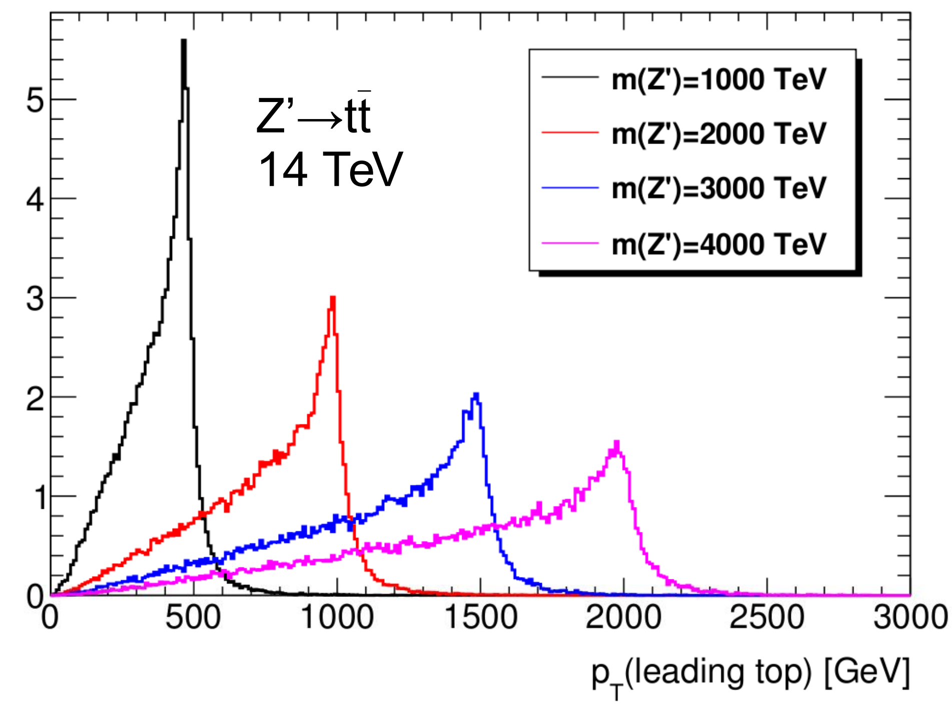


Heavy Z'→$t\bar{t}$ Search

- At HL-LHC search mass reach in multi-TeV range for BSM particles
- Decay products can be very boosted
  - Requires ability to separate closely produced particles such a boosted top
  - High-granularity trackers, such as 5-layer pixel detectors help improve performance over current detector



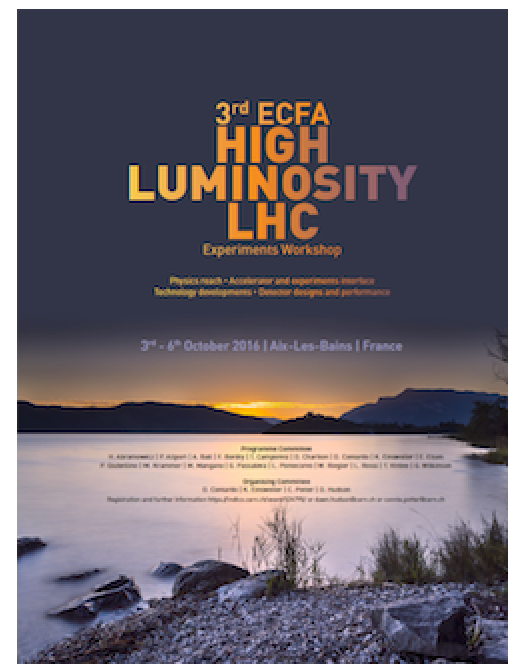




Summary and Outlook

Summary and Outlook

- High-Luminosity LHC is a very challenging environment, but maximizes the physics output of the LHC project
- Major detector upgrades planned for optimal performance
  - Should be as good or better than now in most areas
- Precision Higgs measurements are the main physics driver for HL-LHC and detector upgrades
  - Will study the Higgs Boson in great detail
- HL-LHC also extends sensitivity to Beyond SM Physics
  - New TeV-scale physics could be discovered or be very strongly disfavored after HL-LHC
- Technical Design Reports are now in preparation and will come over the next year



Please stay tuned

Much more information in presentations at HL-LHC Experiments workshop
https://indico.cern.ch/event/524795/timetable/

Backup

Systematics Treatment

- With large statistics at HL-LHC, systematics can be dominating in measurement precision
  - Hard to predict how these will evolve with luminosity/time
- Both experiments start from current systematics with a slightly different approach
- ATLAS approach:
  - Experimental systematics scaled to best guess for HL-LHC
  - Results provided with current theory systematics and without theory systematics
- CMS approach:
  - Provide results in two scenarios:
    - Scenario 1: Current experimental and theory systematics
    - Scenario 2: Experimental scaled with luminosity ($1/\sqrt{L}$) until a certain best achievable uncertainty level
      The current theory systematics is halved
- Both approach aim to bracket the achievable precision

Wanted Reduction in Theory Uncertainties

ATL-PHYS-PUB-2014-016

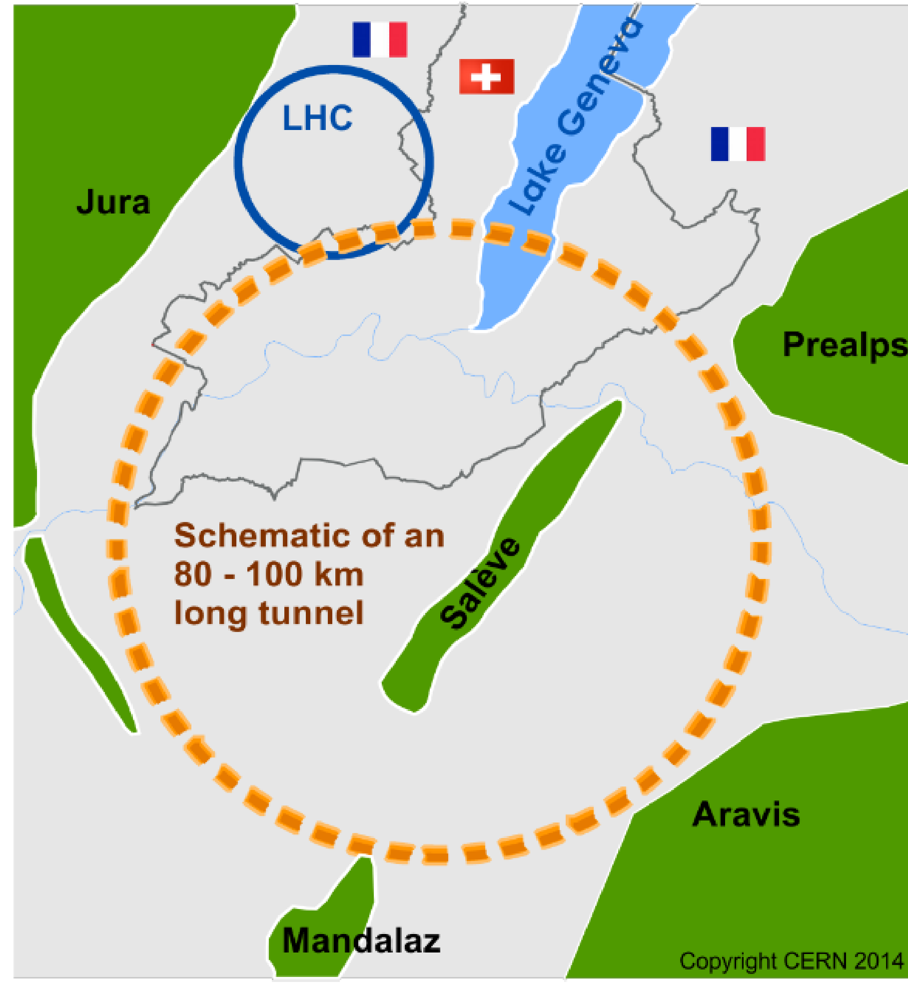
Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j $\to$ 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j $\to$ 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j $\to$ VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j $\to$ VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

Table 6: Estimation of the deduced size of theory uncertainties, in percent (%), for different Higgs coupling measurements in the generic Model 15 from Table 5, requiring that each source of theory systematic uncertainty affects the measurement by less than 30% of the total experimental uncertainty and hence increase the total uncertainty by less than 10%. A dash "-" indicates that the theory uncertainty from existing calculations [10–12] is already sufficiently small to fulfill the condition above for some measurements. The same applies to theory uncertainties not mentioned in the table for any measurement. The impact of the jet-bin and p_T related uncertainties in $gg \to H$ depends on analysis selections and hence no single number can be quoted. Therefore the range of uncertainty values used in the different analysis is shown.

CERN is Studying Next Collider

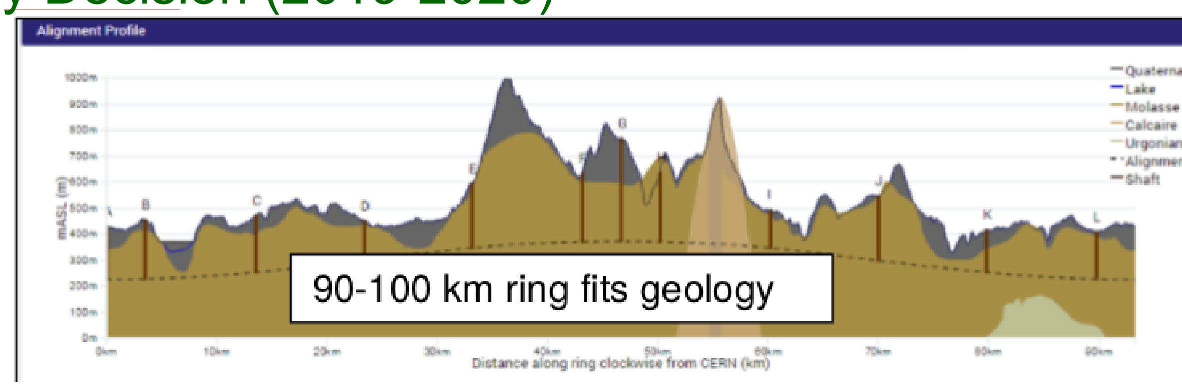
Conceptual design studies of colliders in ~100 km ring

- pp collider (FCC-hh)
  - Primary motivation for FCC studies
  - $\sqrt{s}$~100 TeV, L~2x10^{35} cm^{-2}s^{-1}
    4 IPs and 20 ab^{-1}/expt
  - Also studying FCC-hh dipoles (16T) in LHC tunnel (HE-LHC with $\sqrt{s}$~30 TeV)
- e$^+$e$^-$ collider (FCC-ee)
  - $\sqrt{s}$~90-350 GeV, L~200-2x10^{34}cm^{-2}s^{-1}
    2 IPs and 20 ab^{-1}/expt
- pe collider (FCC-he):
  - $\sqrt{s}$~3.5 TeV, L~10^{34} cm^{-2}s^{-1}



Goal: CDR for next European Strategy Decision (2019-2020)

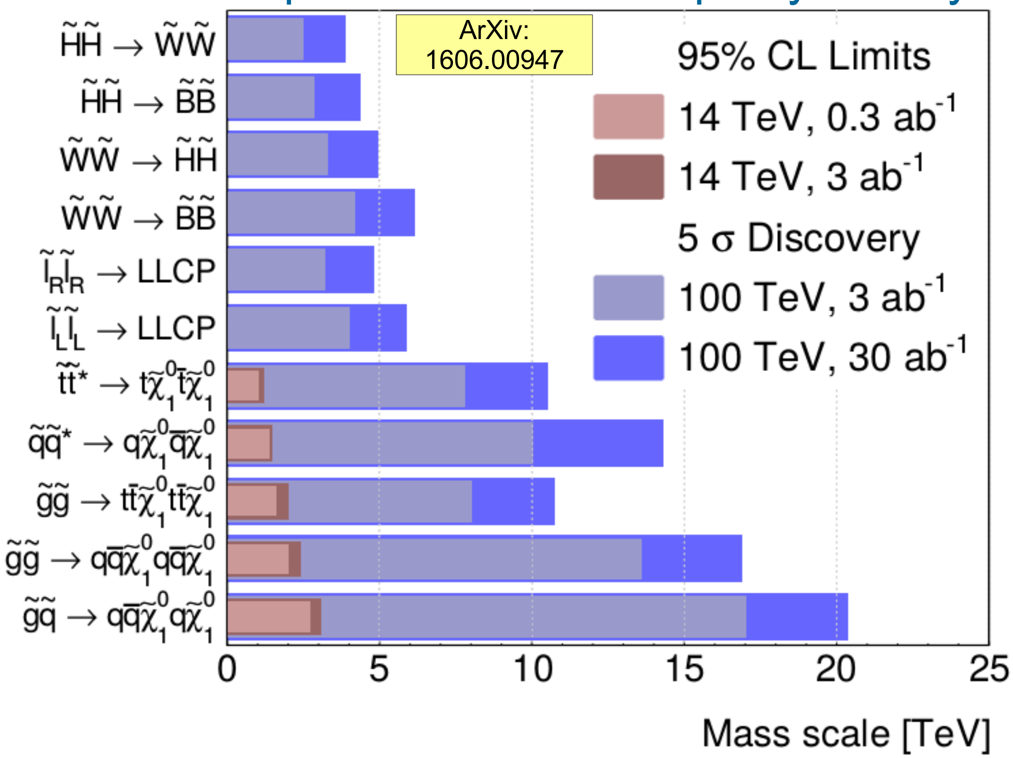
Machine studies are site-neutral, but FCC at CERN would greatly benefit from existing laboratory infrastructure and accelerators



Physics Program for FCC-hh

- Main physics goals of FCC-hh
  - Directly explore energy range up to 50 TeV for New Physics
  - Conclusive exploration of EWSB dynamics
  - Give final verdict on heavy WIMP dark matter

Expected reach for supersymmetry



Expected precision for di- and tri-Higgs production and Higgs self-couplings:

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

Physics Program for FCC-ee

- High-precision Higgs couplings
- Indirect sensitivity to energy-scale of O(100 TeV) through precision EW parameter measurements

Possible Higgs coupling precision

	ILC	FCC-ee	CEPC	CLIC
σ(ZH)	0.7%	0.4%	0.51%	1.65%
g_{bb}	0.7%	0.42%	0.57%	0.9%
g_{cc}	1.2%	0.71%	2.3%	1.9%
g_{gg}	1.0%	0.80%	1.7%	1.4%
g_{WW}	0.42%	0.19%	1.6%	0.9%
$g_{\tau\tau}$	0.9%	0.54%	1.3%	1.4%
$g_{\mu\mu}$	9.2%	6.2%	17%	7.8%
g_{inv}	<0.29%	<0.45%	<0.28%	<0.97%

Current EW precision

Quantity	Theory error	Exp. error
M_W [MeV]	4	15
$\sin^2\theta^{\ell}_{\rm eff}$ [10^{-5}]	4.5	16
Γ_Z [MeV]	0.5	2.3
R_b [10^{-5}]	15	66

Future EW precision?

Quantity	ILC	FCC-ee	CEPC	Projected theory
M_W [MeV]	3–4	1	3	1
$\sin^2\theta^{\ell}_{\rm eff}$ [10^{-5}]	1	0.6	2.3	1.5
Γ_Z [MeV]	0.8	0.1	0.5	0.2
R_b [10^{-5}]	14	6	17	5–10

Also m_{top} measured to ~10 MeV precision from threshold scan

Anomalous HZZ Coupling

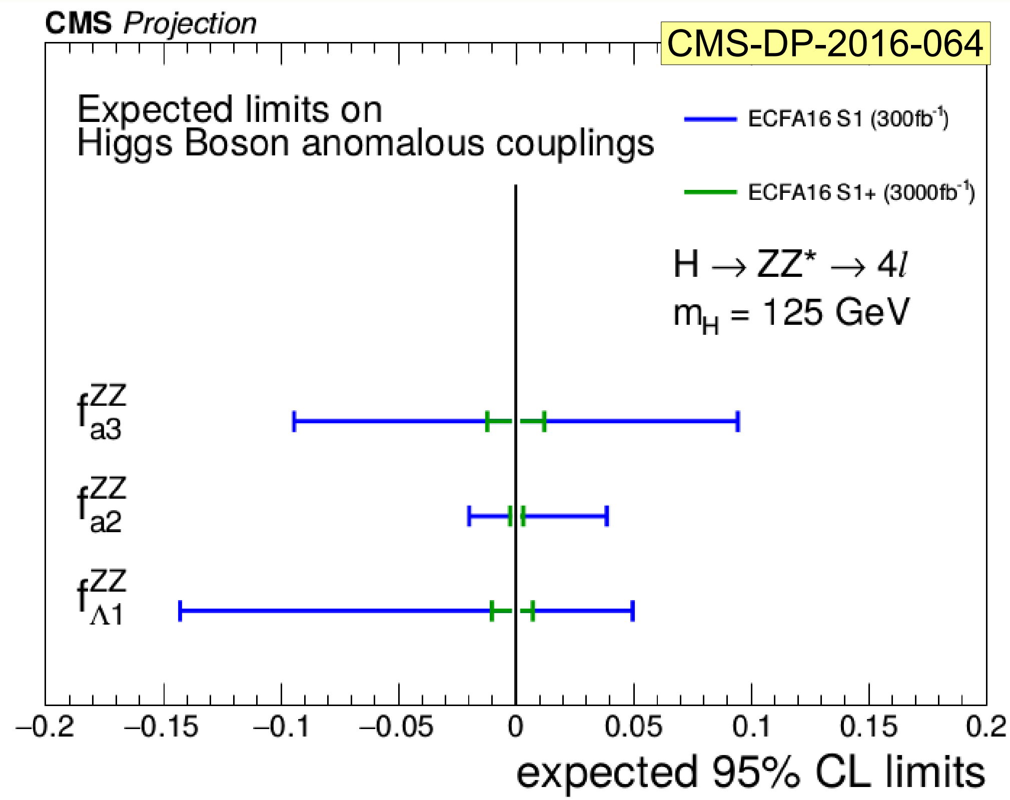
Generic decay amplitude of $H \to ZZ$ for spin-0 particle:

$$A(H \to VV) \sim \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{\Lambda_1^2}\right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- Test for anomalous HZZ couplings a_i:

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}, \ \phi_{ai} = \tan^{-1}(a_i/a_1)$$

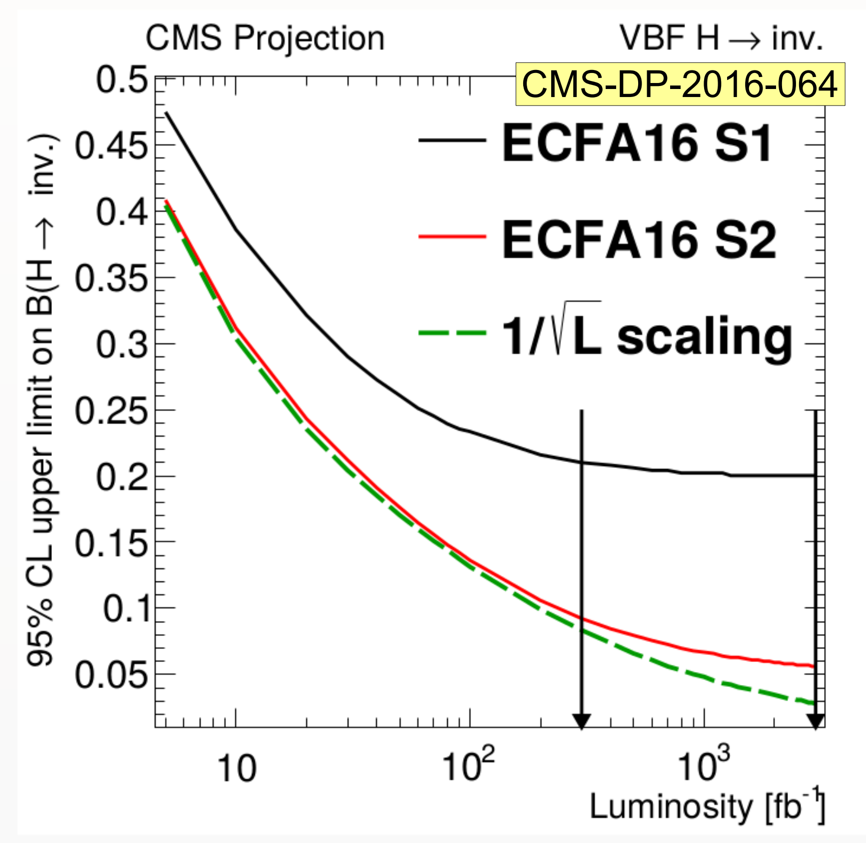
- Interference contribution becomes more dominant at smaller values of f_{ai} x $\cos(\varphi_{ai})$



Higgs to Invisible

- Main backgrounds:
  - Z(ℓℓ)+jets
  - W(ℓv)+jets
  - QCD multijet
- Current BR(H→inv) limit (expected):
  - BR<0.30 @ 95% CL (CMS)
  - BR<0.31 @ 95% CL (ATLAS)
- Projected upper limit (CMS) as as function of luminosity:

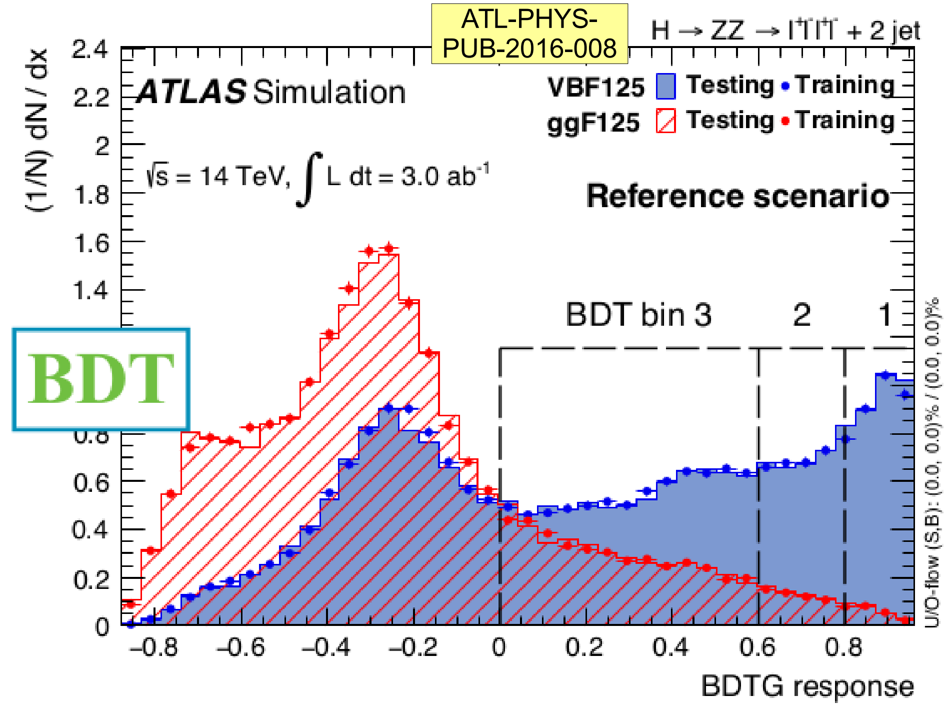
	ECFA16 S1	ECFA16 S2	$1/\sqrt{L}$ scaling
300 fb^{-1}	0.210	0.092	0.084
3000 fb^{-1}	0.200	0.056	0.028



Summary of Recent ATLAS Higgs Results

Channel	Result	*HH* Channel	Result
VBF $H\to W^+W^-$	$\Delta\mu/\mu \simeq$ 14 to 20%	$HH\to bb\tau\tau$ (FULL uncertainties)	0.6 σ $-4 < \lambda_{HHH} / \lambda_{SM} < 12$
VBF $H\to ZZ\to 4\ell$	$\Delta\mu/\mu \simeq$ 15 to 18%		
ttH, $H\to\gamma\gamma$	$\Delta\mu/\mu \simeq$ 17 to 20%	$HH\to bbbb$ (p_T(jet)> 75 GeV, FULL uncertainties)	$-3.4 < \lambda_{HHH} / \lambda_{SM} < 12$
VH, $H\to\gamma\gamma$	$\Delta\mu/\mu \simeq$ 25 to 35%		
off-shell $H\to ZZ\to 4\ell$	$\Delta\mu/\mu \simeq$ 50% $\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV	$HH\to bb\gamma\gamma$ (stat. uncertainties only)	1.3 σ $-1.3 < \lambda_{HHH} / \lambda_{SM} < 8.7$
$H\to Z\gamma$	$\Delta\mu/\mu \simeq$ 30% 3.9 σ	$ttHH$, $HH\to bbbb$ (stat. uncertainties only)	0.35 σ
$H\to J/\psi\ \gamma$	BR $< 44\times10^{-6}$ @95% CL		
$t\to Hq$	BR $\lesssim 10^{-4}$ @95% CL		

VBF H→ZZ*→ℓℓℓℓ

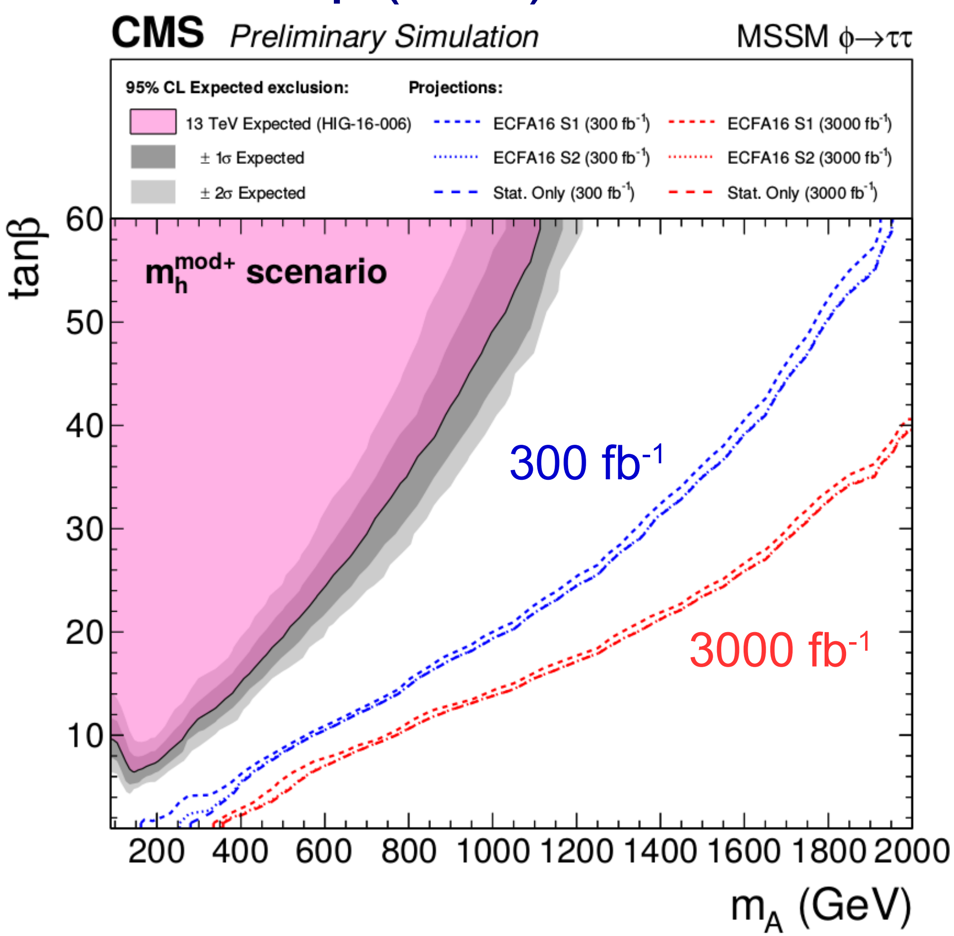


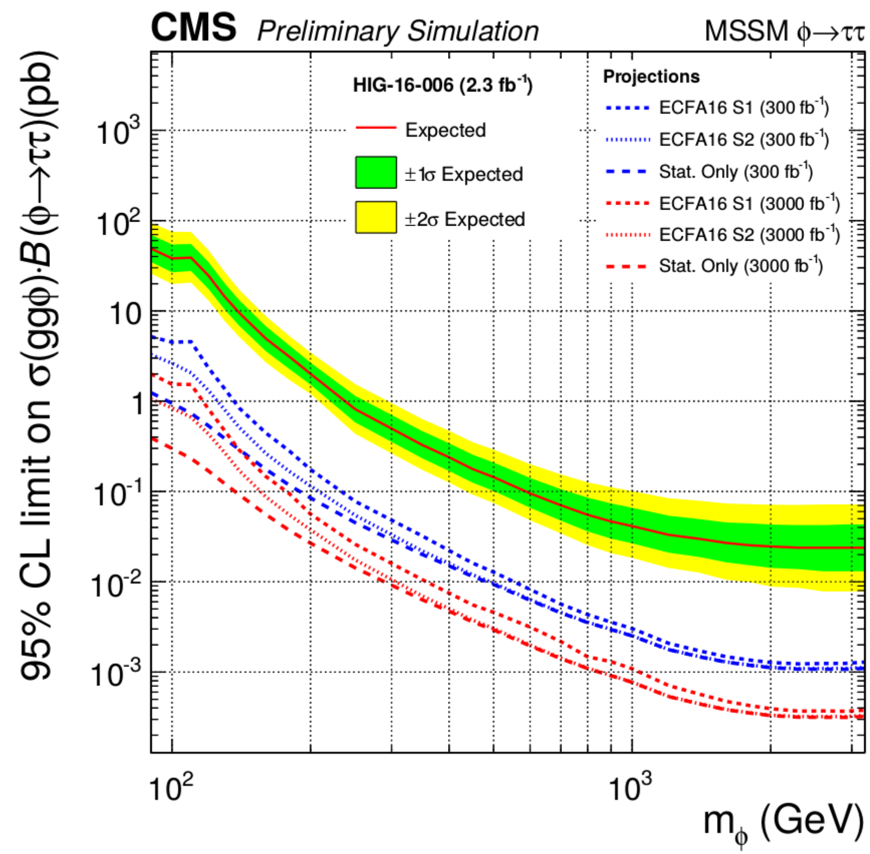
- Initial selection:
  - 2 jets with m(jj)>130 GeV
  - 4 leptons consistent with H→ZZ*→ℓℓℓℓ
- Use BDR to separate ggF and VBF
  - Large pile-up contribution in ggF
- 190 signal events and 330 background events
- Results with full systematics (signal QCD scale) and statistics only:

	$\langle\mu_{PU}\rangle = 200$ FULL	$\langle\mu_{PU}\rangle = 200$ NONE	$\langle\mu_{PU}\rangle = 140$ FULL	$\langle\mu_{PU}\rangle = 140$ NONE
$\Delta\mu$	0.18	0.15	0.17	0.13
Significance	7.2 σ	10.2 σ	7.7 σ	11.1 σ

Search for Heavy Higgs→ττ

- One of the most sensitive channels for constraining extended Higgs
- Cross section limits:
  - ggφ (→ττ)
  - bbφ (→ττ)



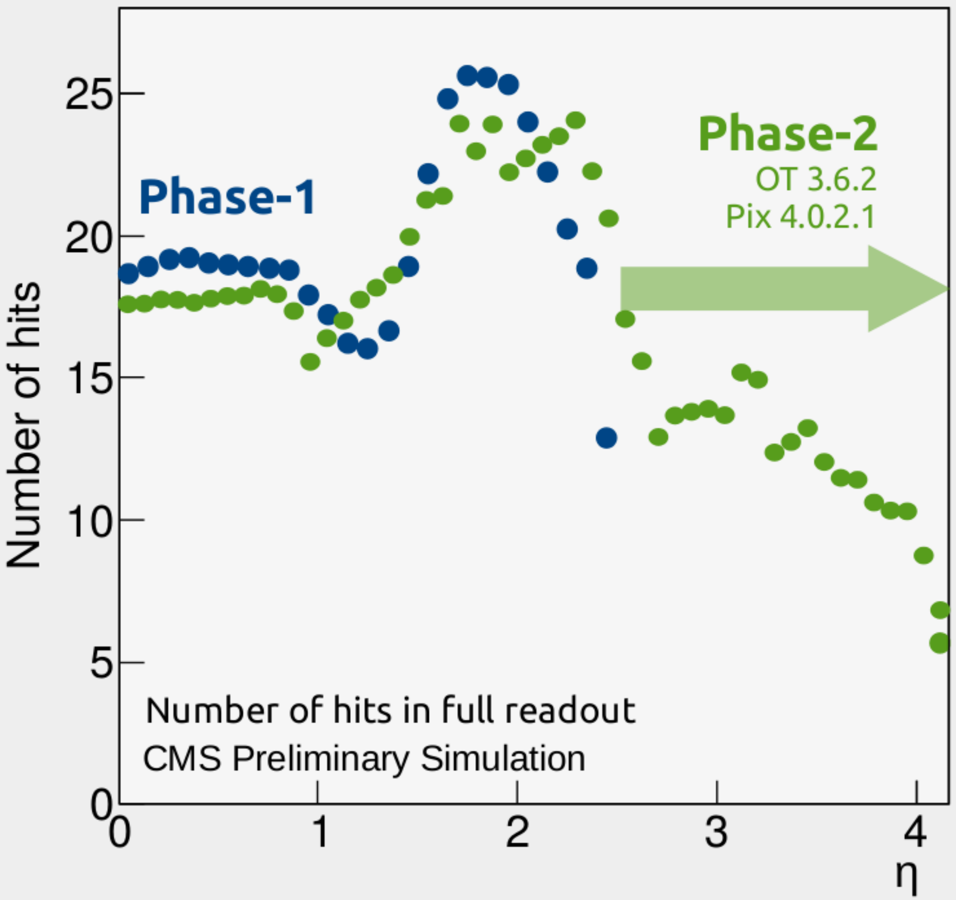


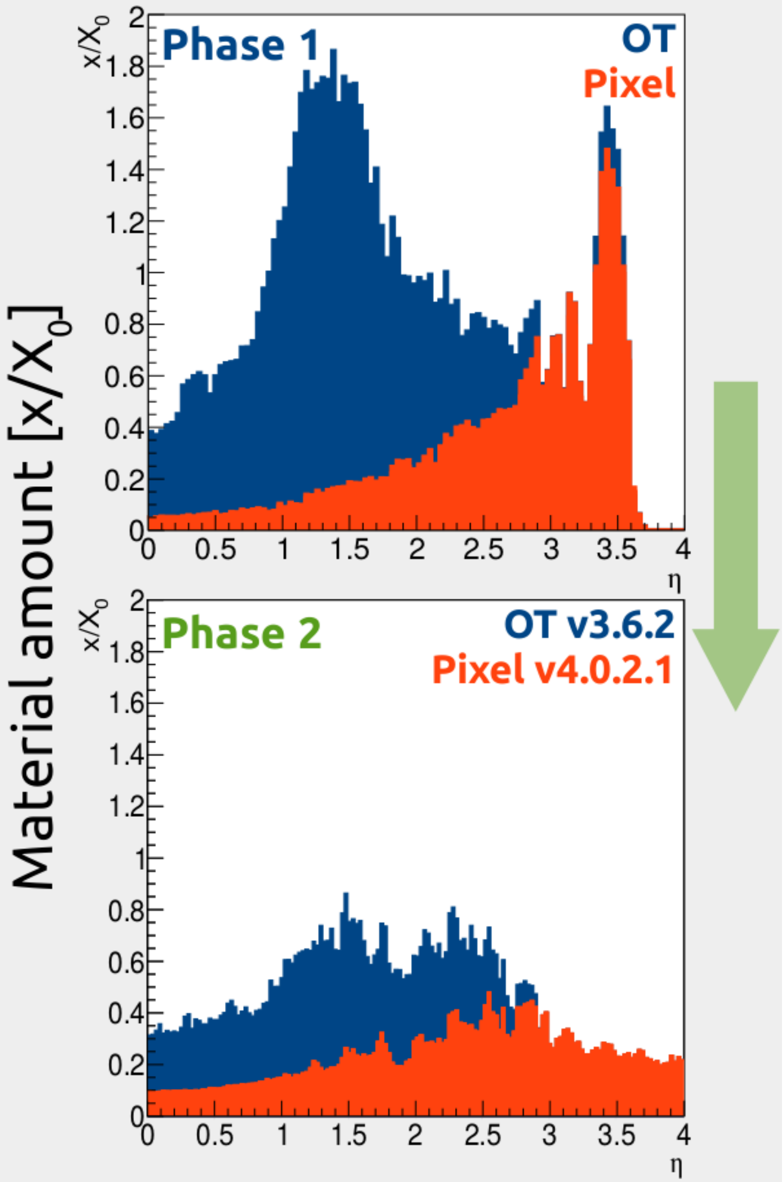
- Model dependent limits:
  - m^{mod+} benchmark
- Sensitivity at high m_A is still dominated by statistics

CMS Tracker Changes

	Phase-1	→	Phase-2
Outer Tracker	~200 m²	Silicon surface	~200 m²
	9.3 M	Strips	43.7 M
	–	MacroPixels	164 M
	15 148	Modules	13 556
	100 kHz	readout rate	750 kHz /40 MHz
Pixel Bar + Fw + Ext	~1 m^2	Silicon surface	4.7 m^2
	66 M	Pixels	1870 M
	1440	Modules	4136
	100 kHz	readout rate	750 kHz

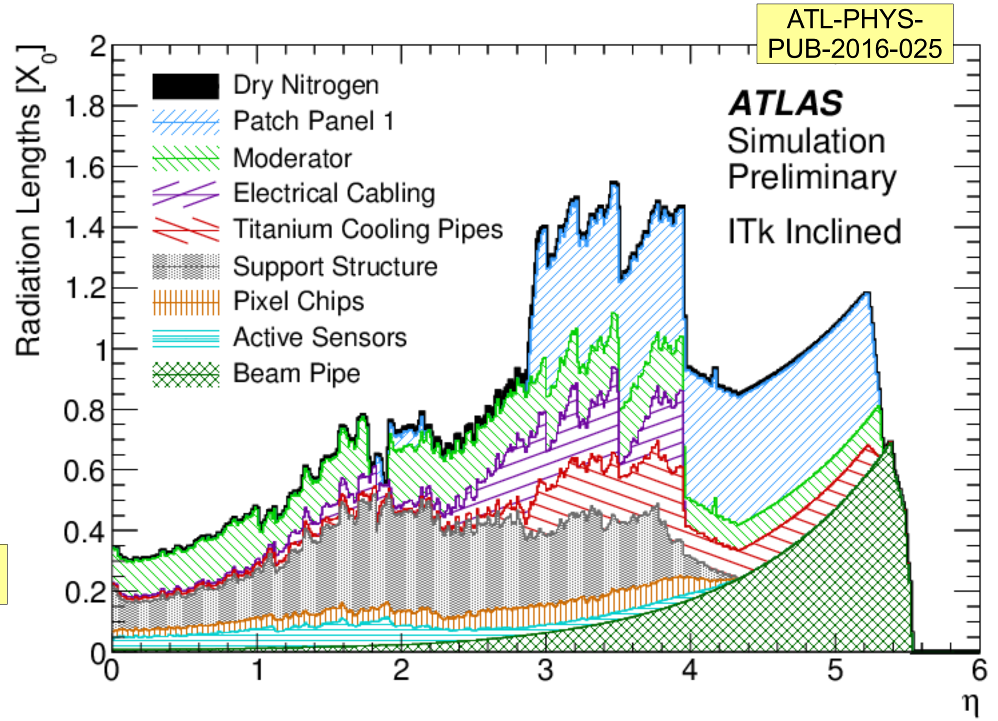
CMS Tracker Comparison

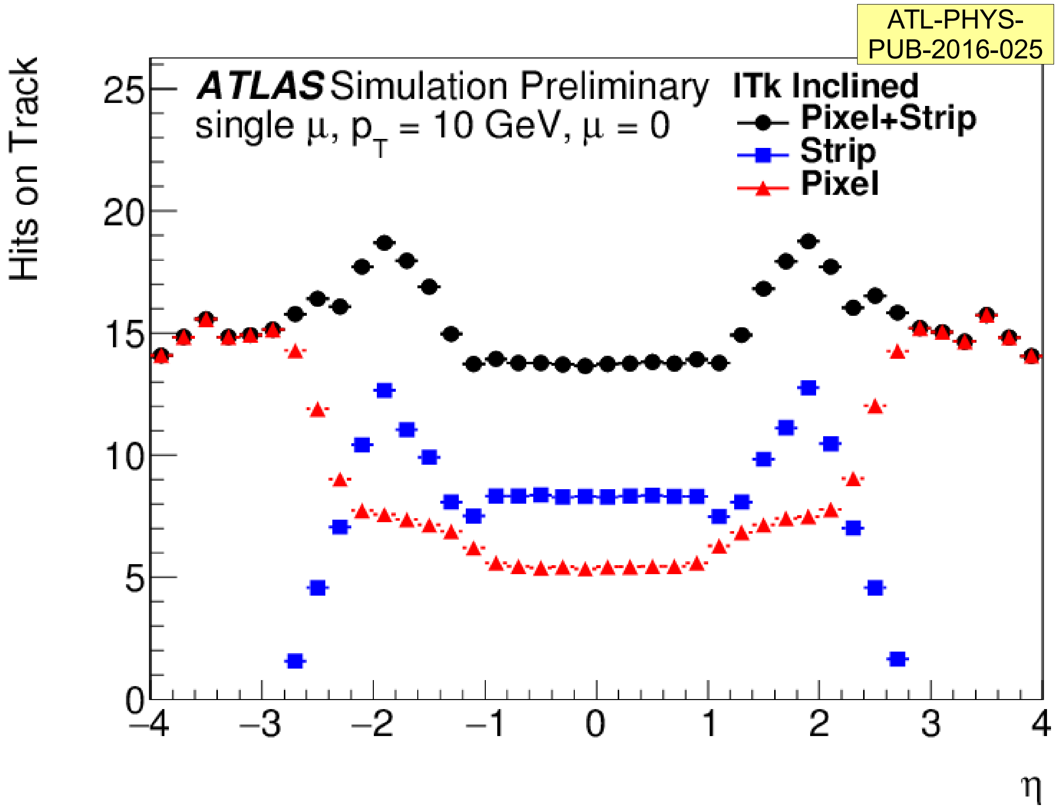




ATLAS Tracker Hits and Material

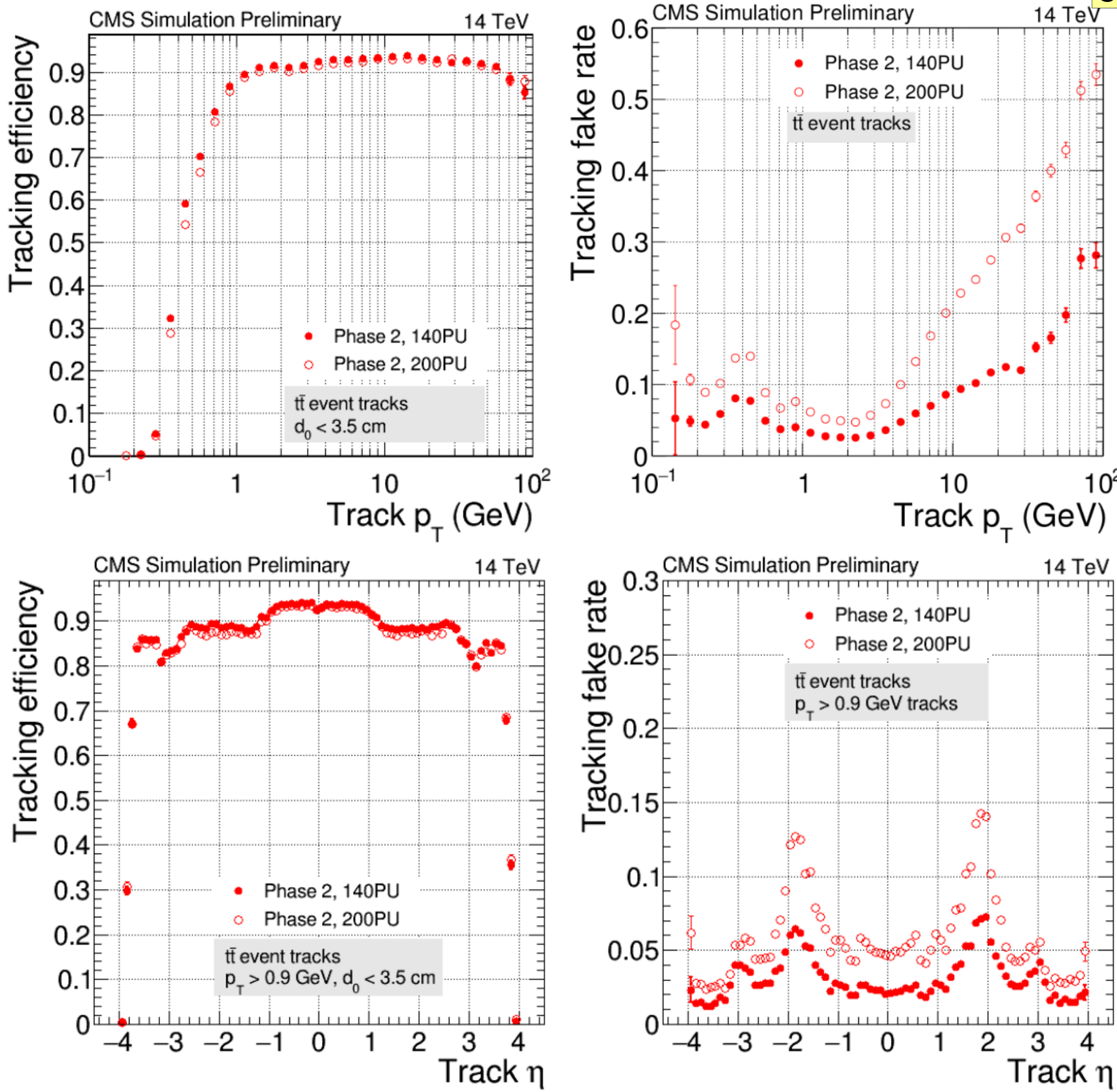
Optimized for at least 13 hits, minimum material and coverage up to η=4



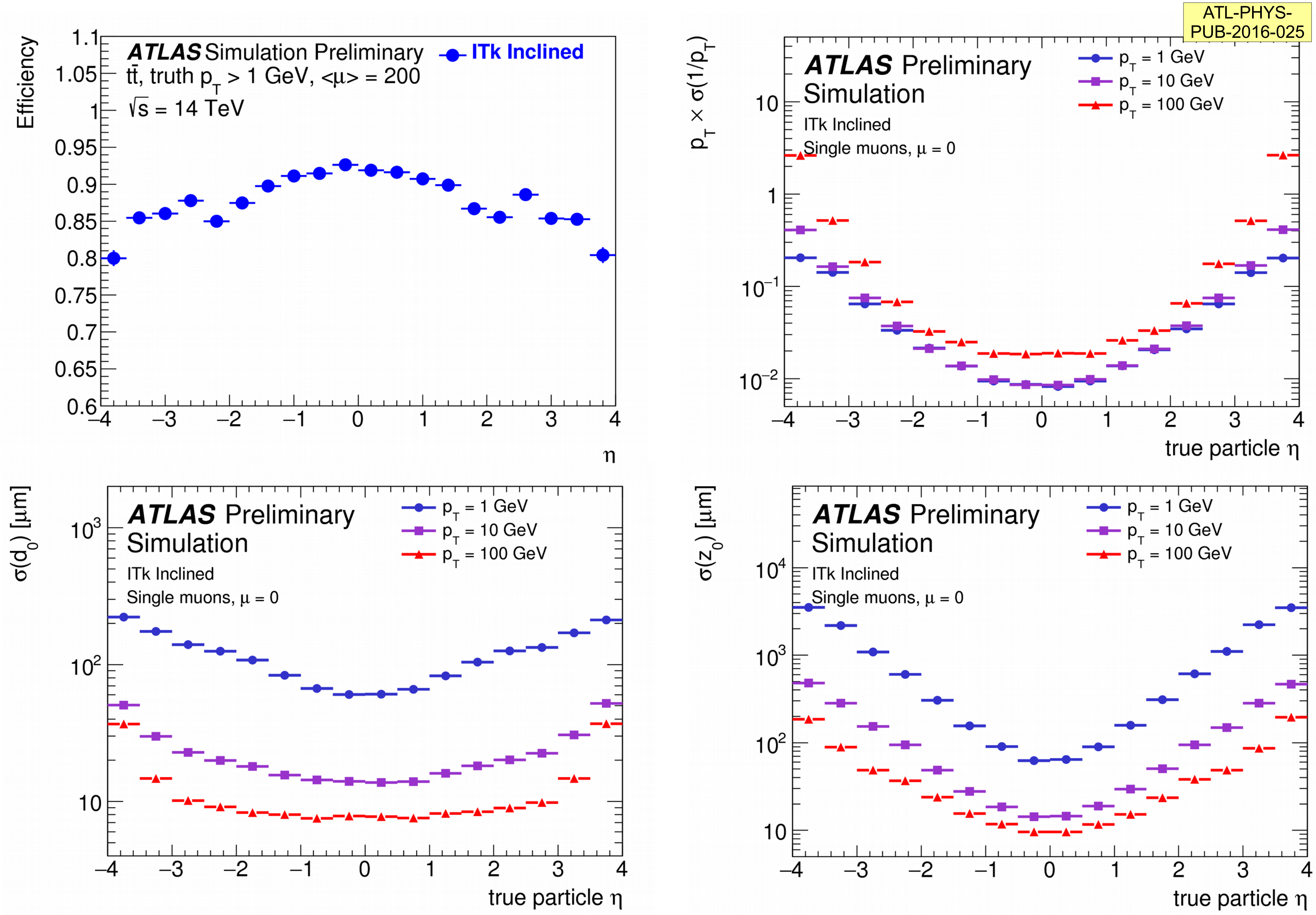


CMS Tracker Performance

CMS-DP-2016-065

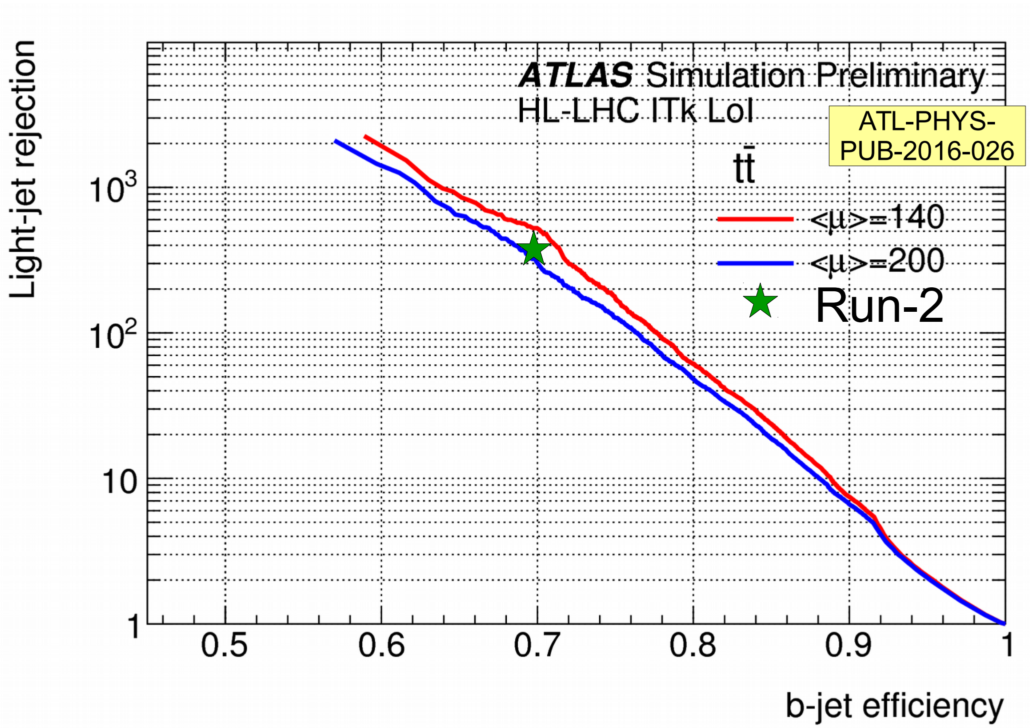


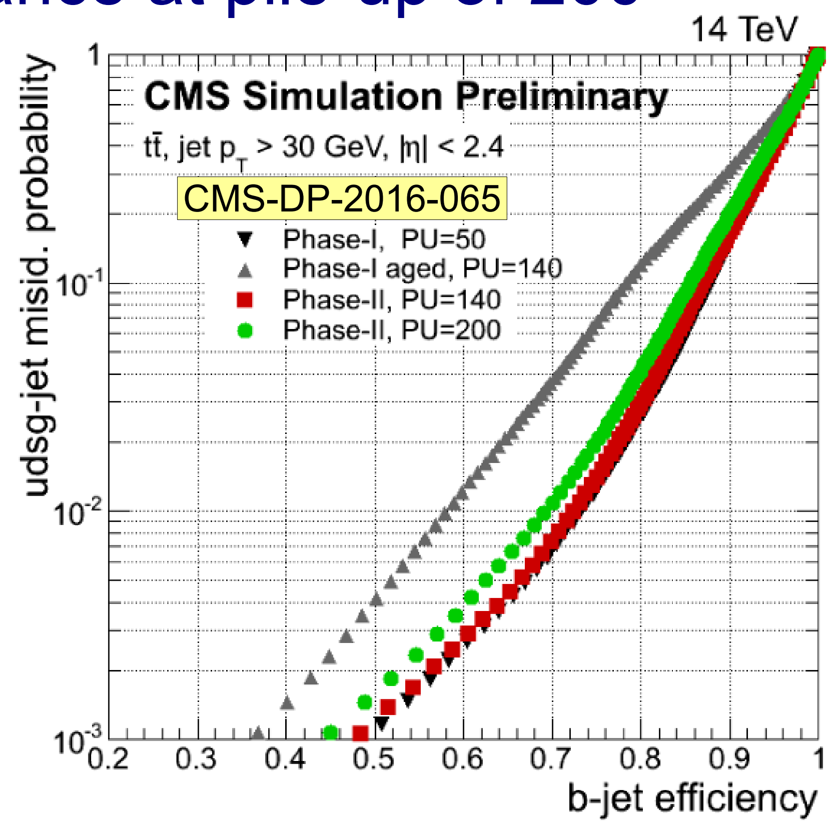
ATLAS Tracker Performance



B-tagging for HH→b$\bar{b}$b$\bar{b}$

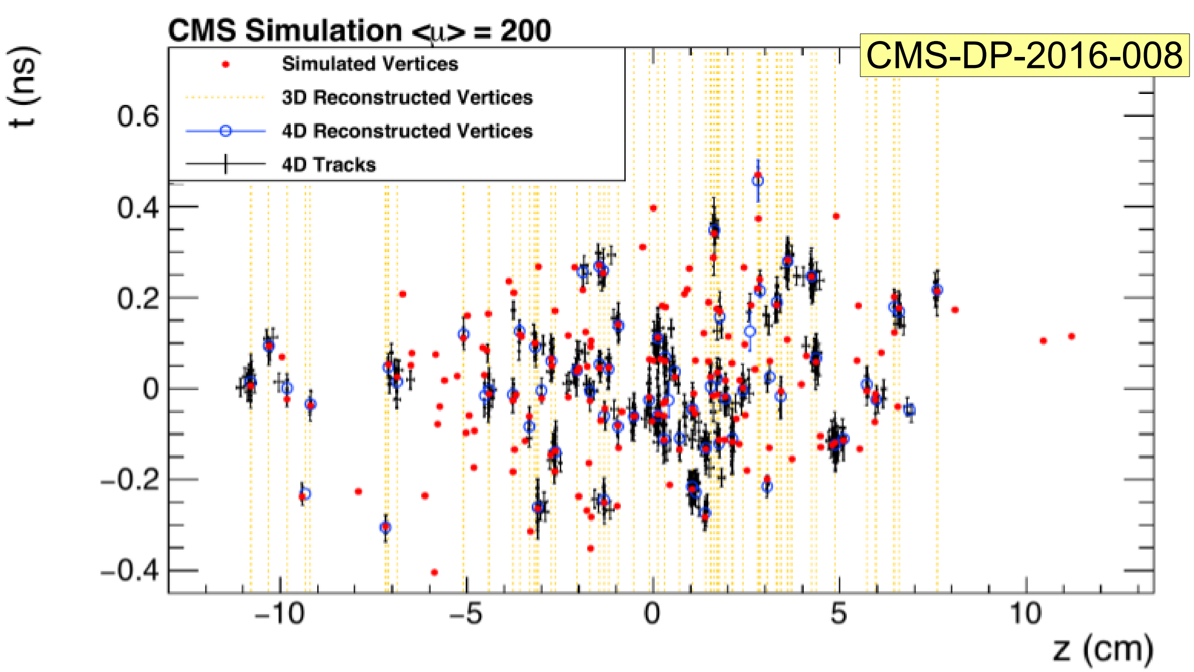
- Efficient and highly rejecting b-tagging also critical for HH→b$\bar{b}$b$\bar{b}$ measurement
  - Current projections assume performance as in Run-2
- Both experiments have demonstrated ability to match current performance at pile-up of 140 events
- Both pixel detectors still being optimized
  - Aim to achieve Run-2 performance at pile-up of 200





CMS Precision Timing for Charged Particles

- Assume sufficient timing performance for charged hadrons, e.g. from dedicated LYSO+SiPM layer in the central region, and from HGCAL or dedicated layer in the forward region
- Traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit, with vertices reconstructed both in position along the beamline and in time within the bunch crossing
- Provides further suppression of charged particles from pile-up for jets, missing energy, lepton isolation etc

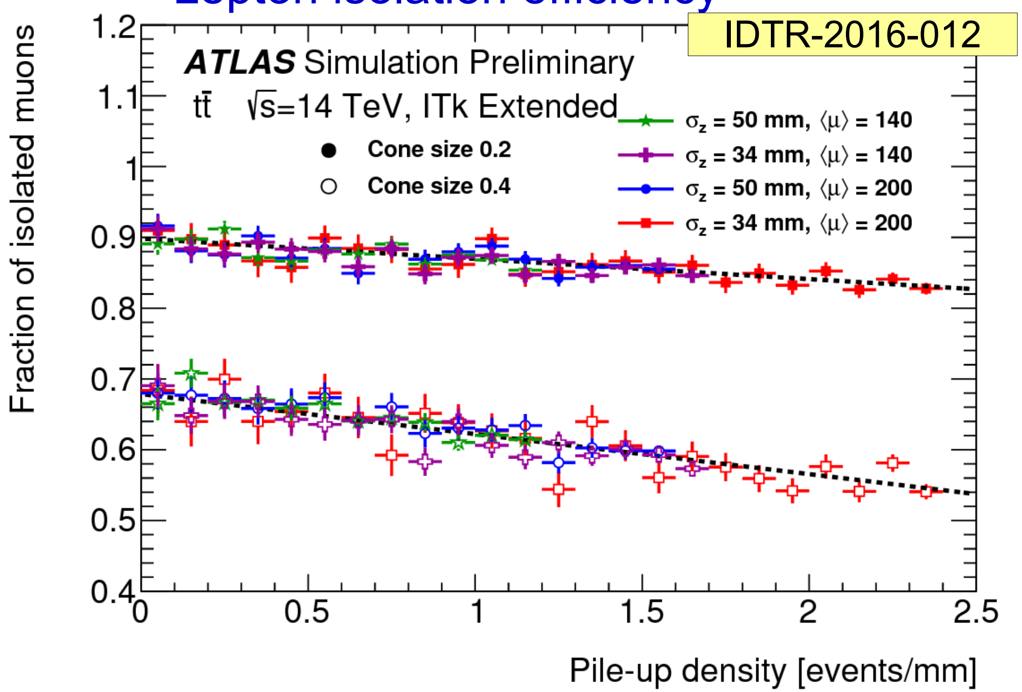


20 ps resolution assumed for charged particles with p_T>1 GeV

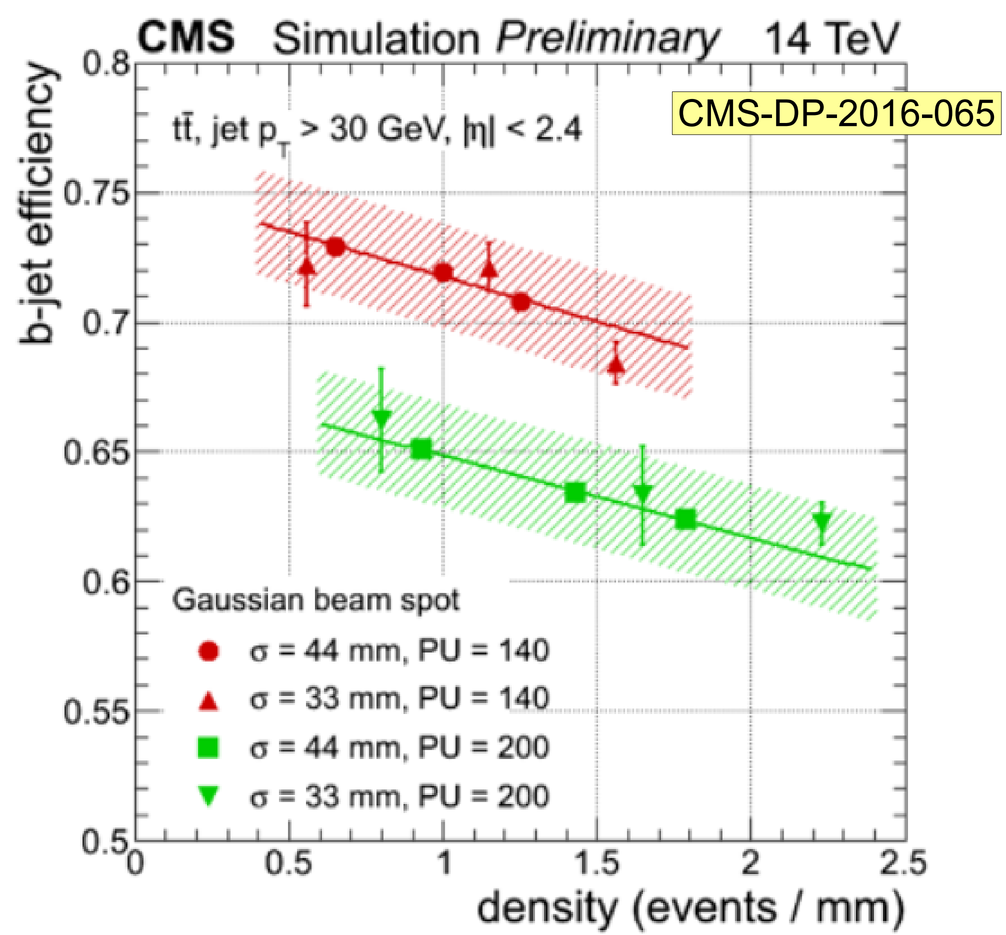
Pile-up vs Pile-up Density

- So far mostly considered effects due to overall pile-up
- Find that many quantities depend more on pile-up density – how many in pile-up collisions per mm in z
- This can be mitigated by changing beam-profile
  - I.e. spreading vertices out better in z

Lepton isolation efficiency



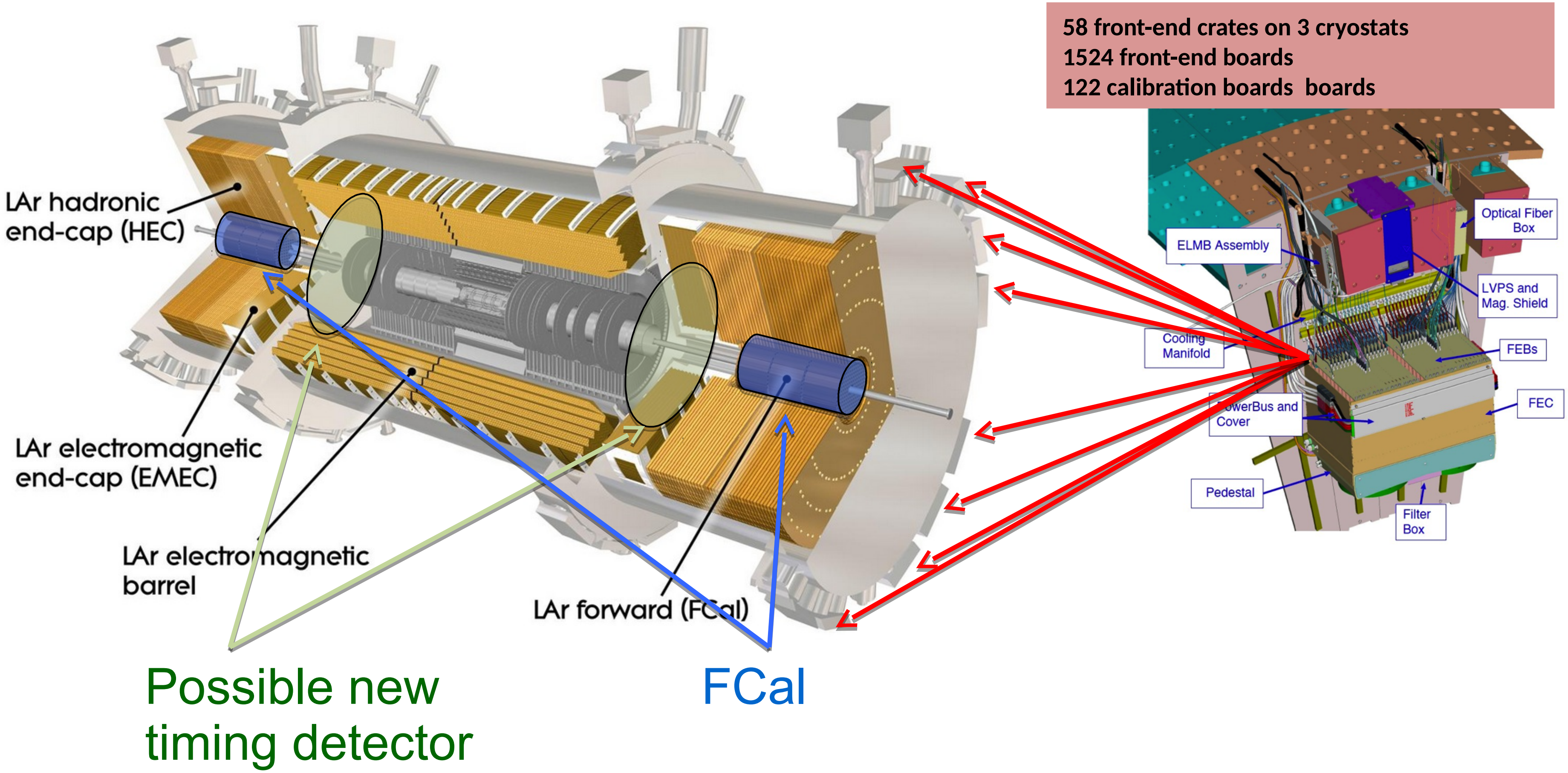
B-tagging efficiency



LAr Calorimeter Upgrades

- Upgrade of all readout electronics
  - To remove trigger constraints and improved radiation hardness
- Possibly add new high-granularity precision timing detector in front of endcap calorimeters
  - Primarily to reduce effect of pile-up on jets
- Replacement of FCal evaluated, but found risky and unnecessary

58 front-end crates on 3 cryostats
1524 front-end boards
122 calibration boards boards

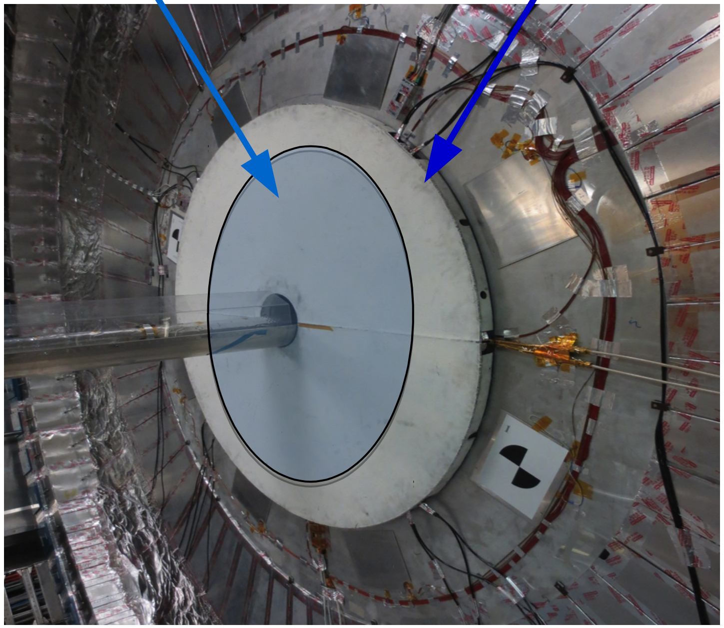


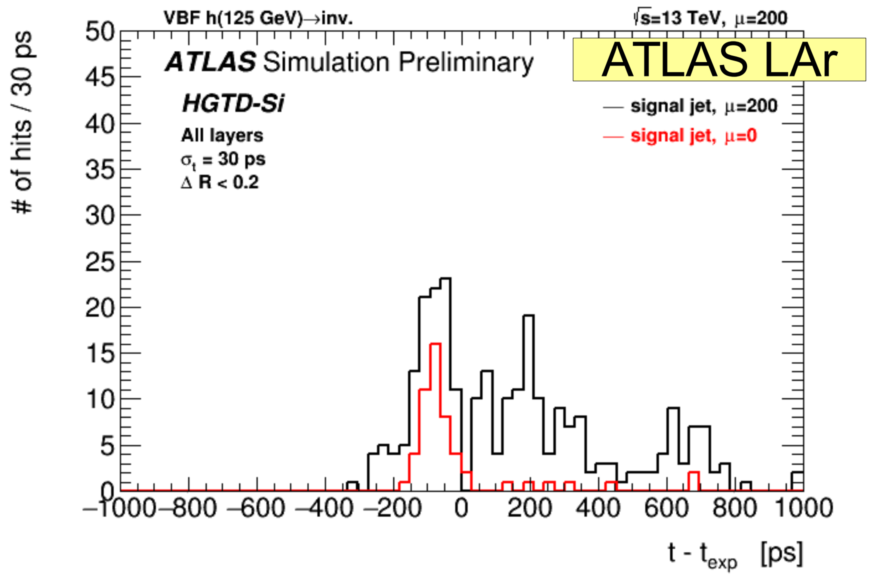
High Granularity Timing Detector

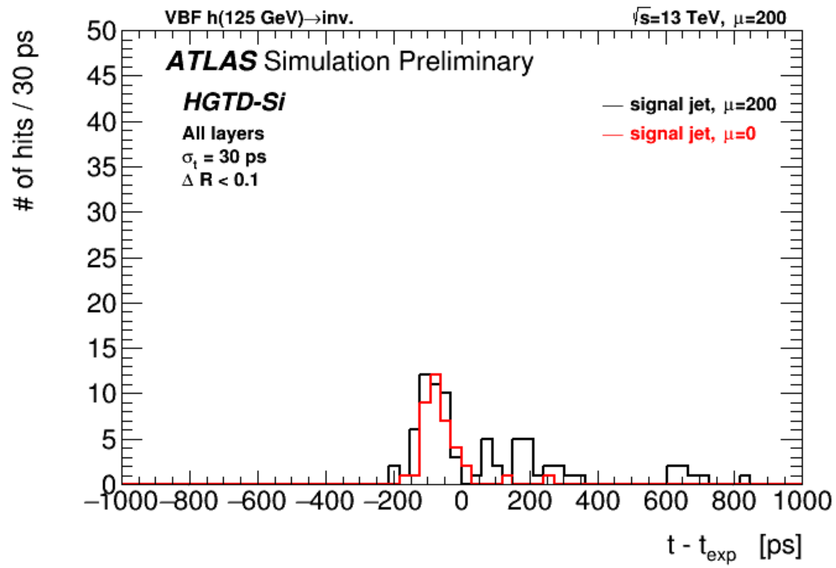
- Additional pile-up rejection can be achieved using precise timing
  - Different time of flight and different collisions times in event
- ATLAS considering thin timing device
  - Four layers silicon sensors
  - Coverage for 2.4<|η|<4.2
  - Possible Tungsten absorber for |η|<3.2
  - Timing target: 30-50 ps per MIP
- Provide additional sensitivity to VBF
  - Possibly also enhance the jet trigger

High-granularity timing detector

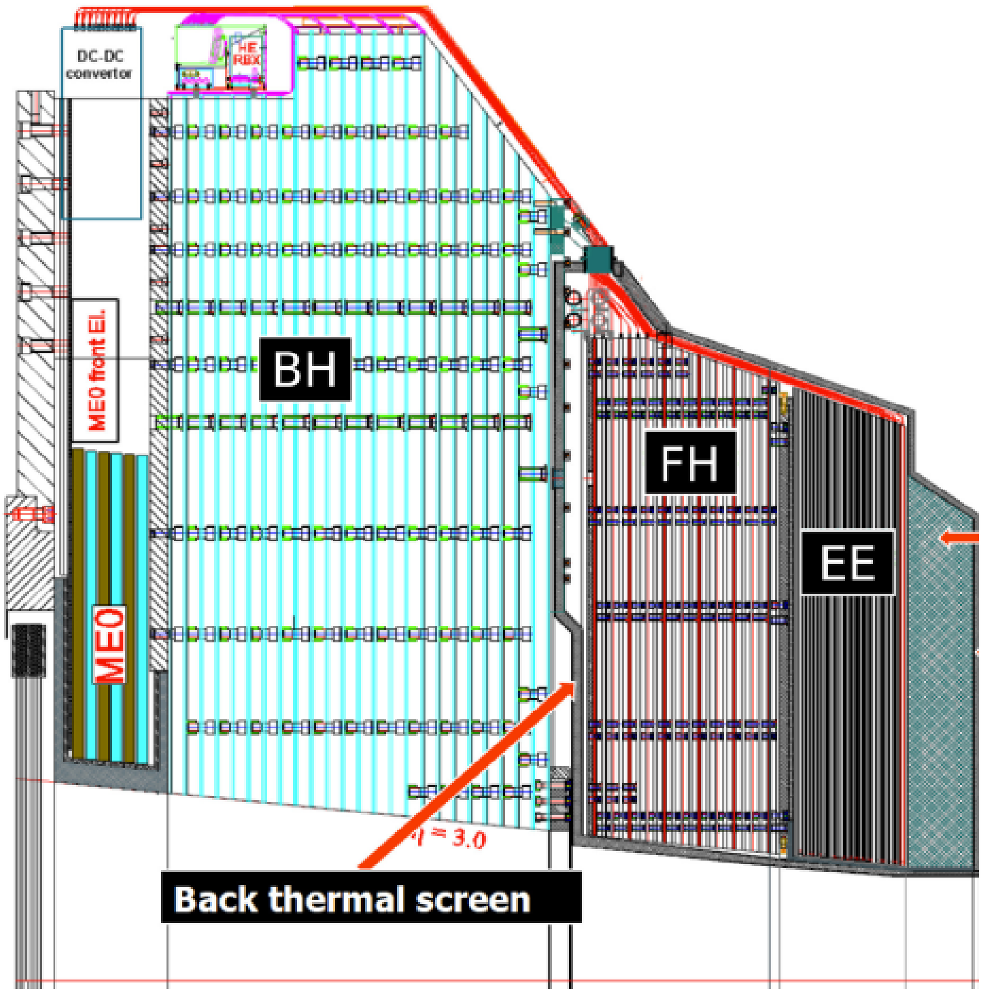
Minimum bias scintillators







New CMS Endcap Calorimeter



Construction:
- *Hexagonal Si-sensors built into modules.*
- *Modules with a W/Cu backing plate and PCB readout board.*
- *Modules mounted on copper cooling plates to make wedge-shaped cassettes.*
- *Cassettes inserted into absorber structures at integration site (CERN)*

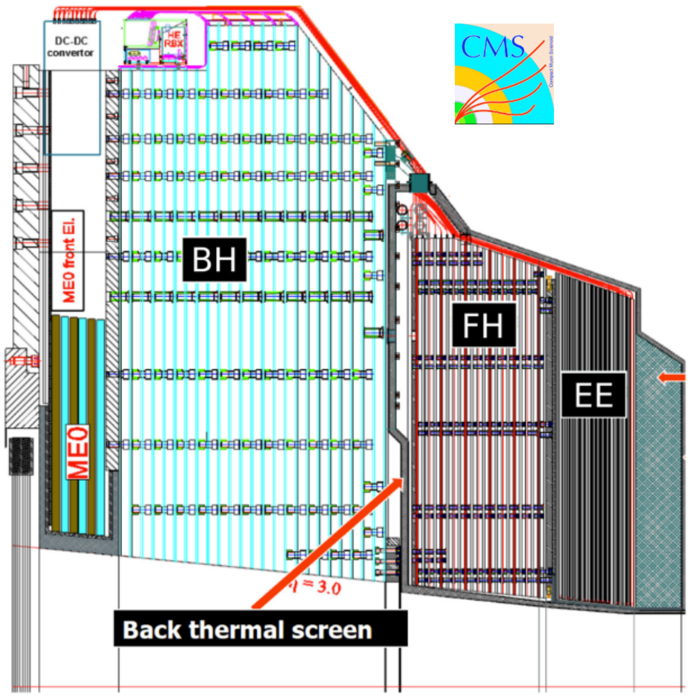
Key parameters:
- *593 m^2 of silicon*
- *6M ch, 0.5 or 1 cm^2 cell-size*
- *21,660 modules (8" or 2x6" sensors)*
- *92,000 front-end ASICS.*
- *Power at end of life 115 kW.*

System Divided into three separate parts:

EE – Silicon with tungsten absorber – 28 sampling layers – 25 X_o (~1.3 λ)
FH – Silicon with brass (now stainless steel) absorber – 12 sampling layers – 3.5 λ
BH – Scintillator with brass absorber – 11 layers – 5.5 λ

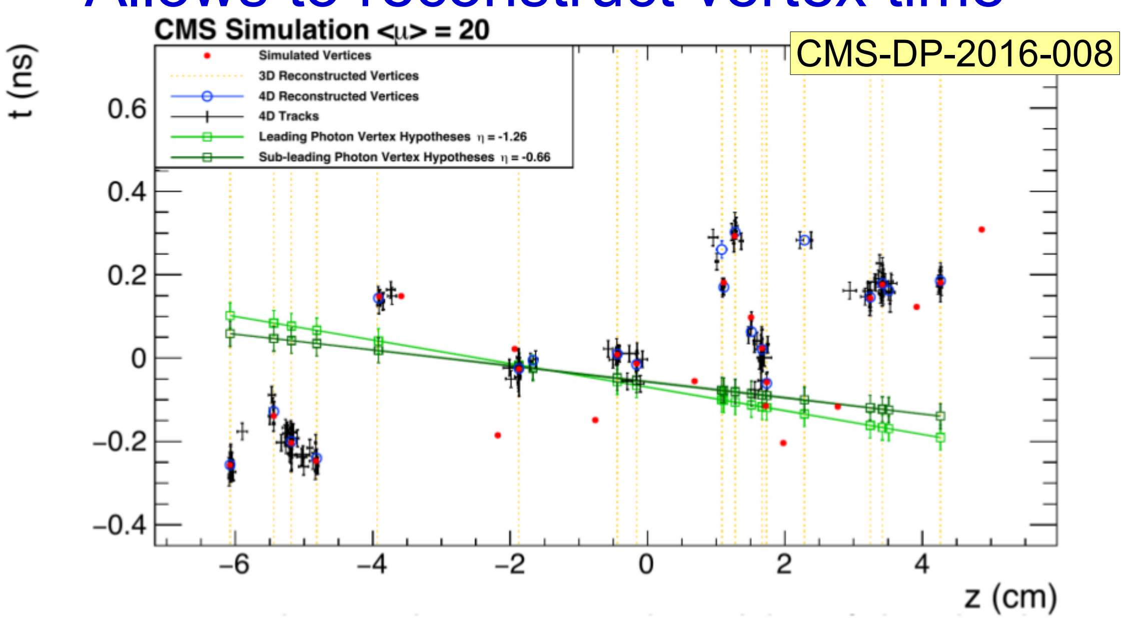
EE and FH are maintained at – 30°C. BH is at room temperature.

Timing Detectors in CMS

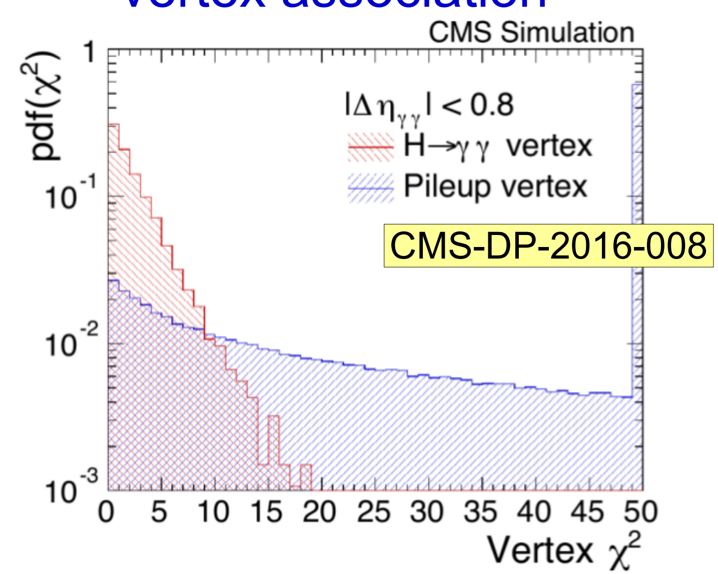


- Endcap calorimeter (1.5<|η|<3) replaced by multi-layer silicon-based calorimeter
  - Current calorimeter not rad-hard enough
- Use of silicon allows intrinsic time resolution down to 50 ps for large signal
- Barrel calorimeter electronics upgraded to also provide precision timing (30 ps)
- Additional timing layer for charged particles in front of calorimeter under consideration

Allows to reconstruct vertex time

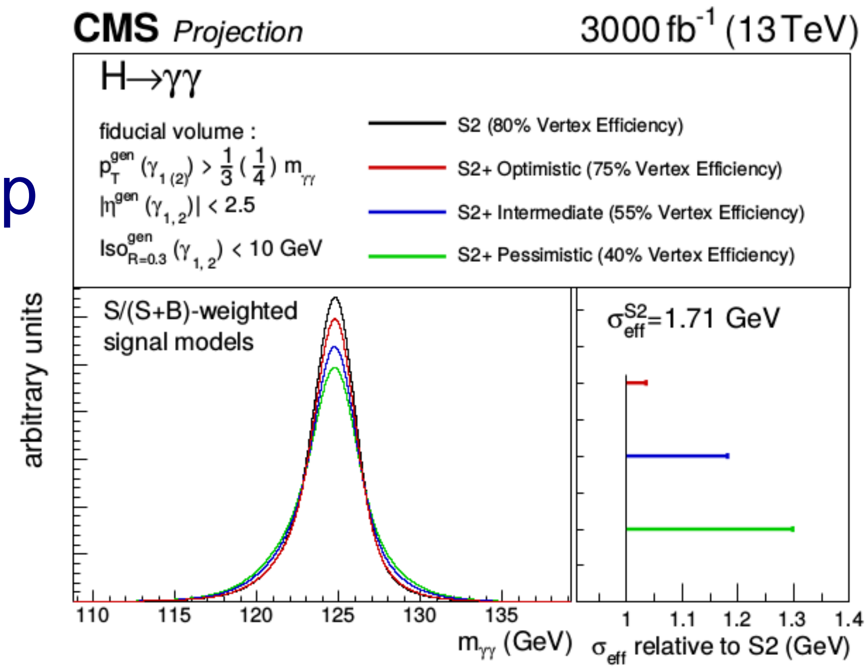


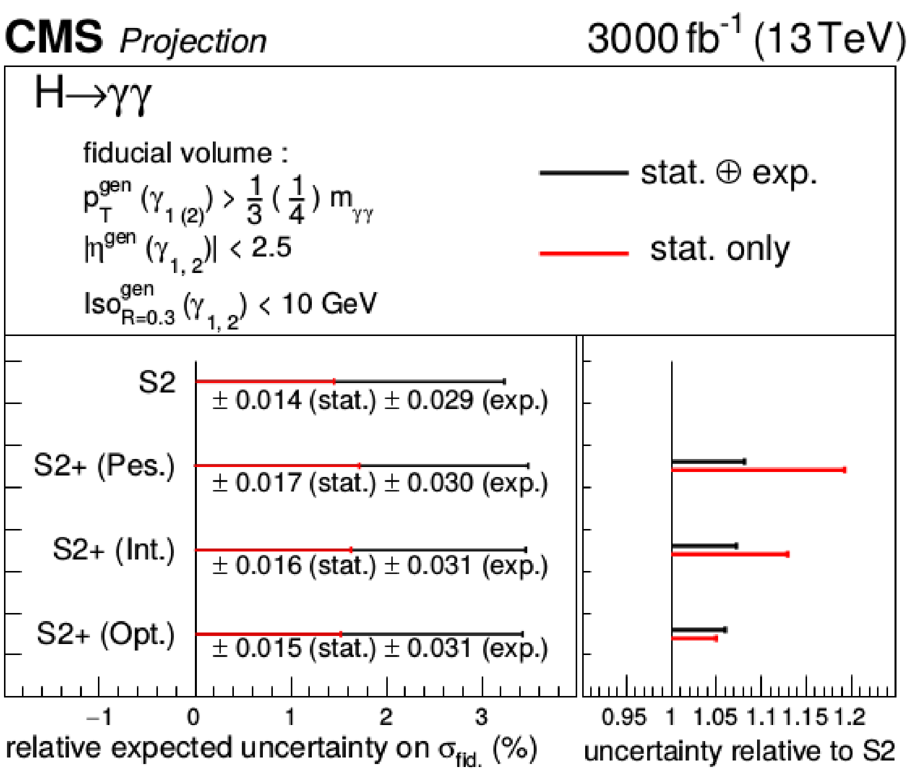
Example: Improved H→γγ vertex association



H→γγ with Timing Detector

- Vertex selection efficiency drops with increase in pileup
  - ~80% now → ~40% at 200 pileup
- Results in large degradation of mass resolution
- Impact on fiducial cross section measurement investigated





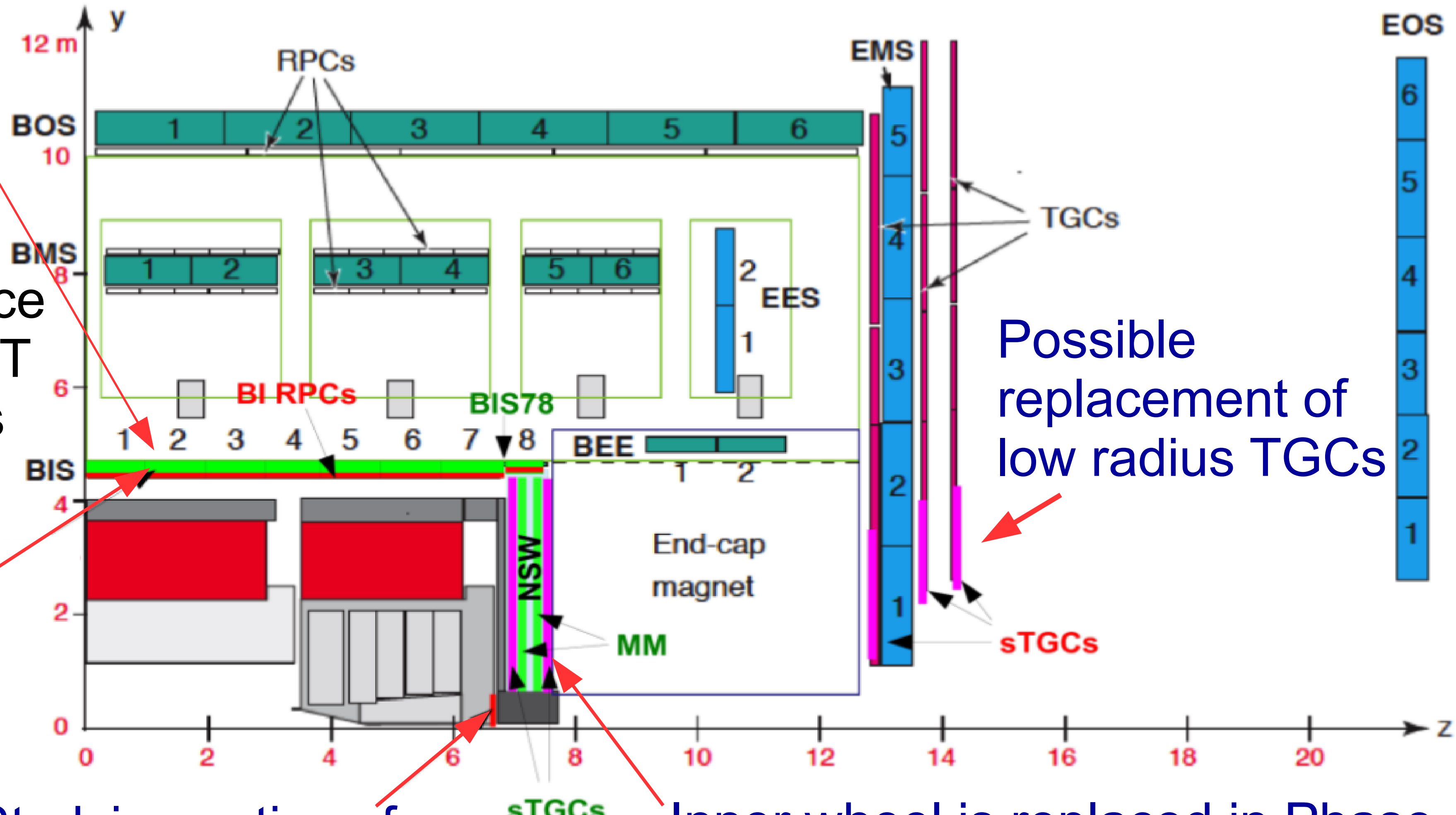
With full use of calorimeter and charged particle timing information vertexing efficiency can be almost full recovered

Corresponds to effectively 30% more luminosity

Muon System Upgrades

Readout electronics to be replaced everywhere to support higher trigger rate and MDT hardware trigger
Power system to be replaced (maintenance and radiation issues)
RPCs added to inner station to increase acceptance/robustness

Will replace some MDT chambers to make space for RPCs



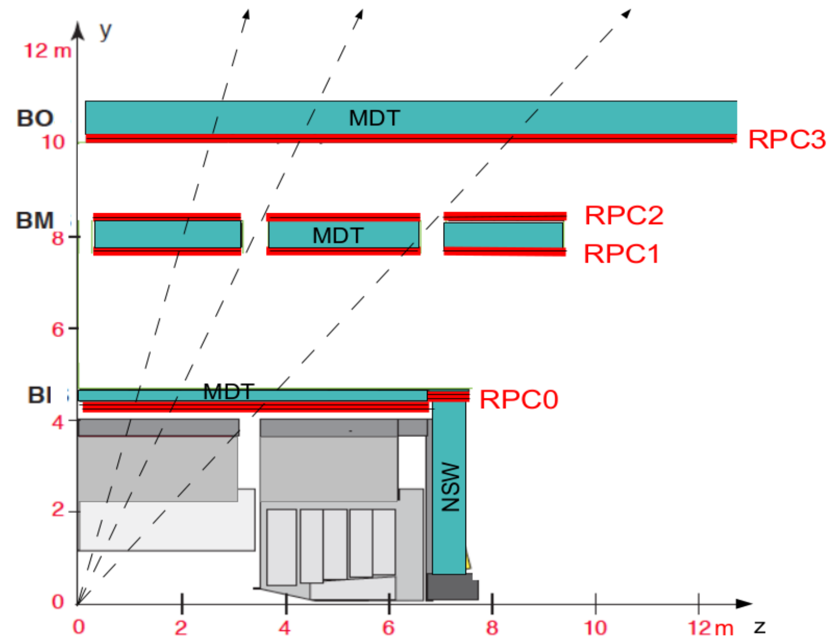
Possible replacement of low radius TGCs

Studying options for large η muon tagger

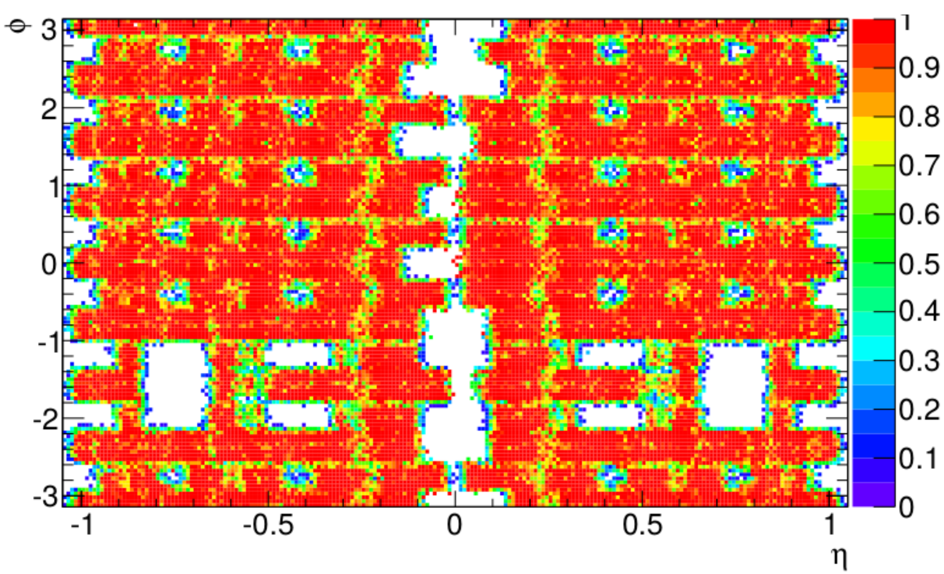
Inner wheel is replaced in Phase-I

Muon Barrel Upgrade

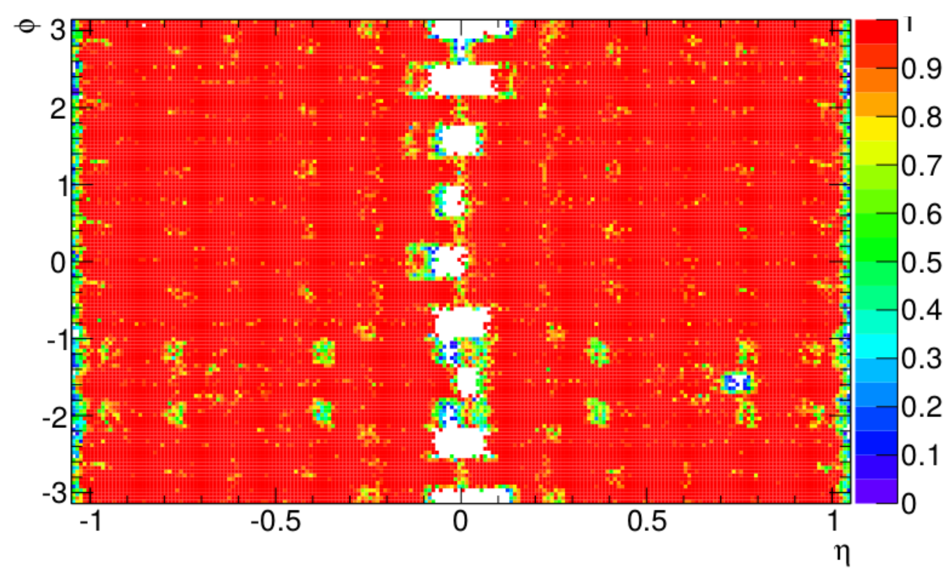
- To survive HL-LHC, gains on existing RPCs will need to be lowered
  - Reduces muon trigger efficiency
  - Also existing acceptance only 78%
- Will add new inner RPC station
  - Allows for 3 out of 4 layer coincidence or even inner and outer RPC only
  - Increases efficiency to 92-96%
- RPC chosen over MicroMegas
  - Also add RPCs at $1<|\eta|<1.3$ in Phase-I



Acceptance without BI upgrade

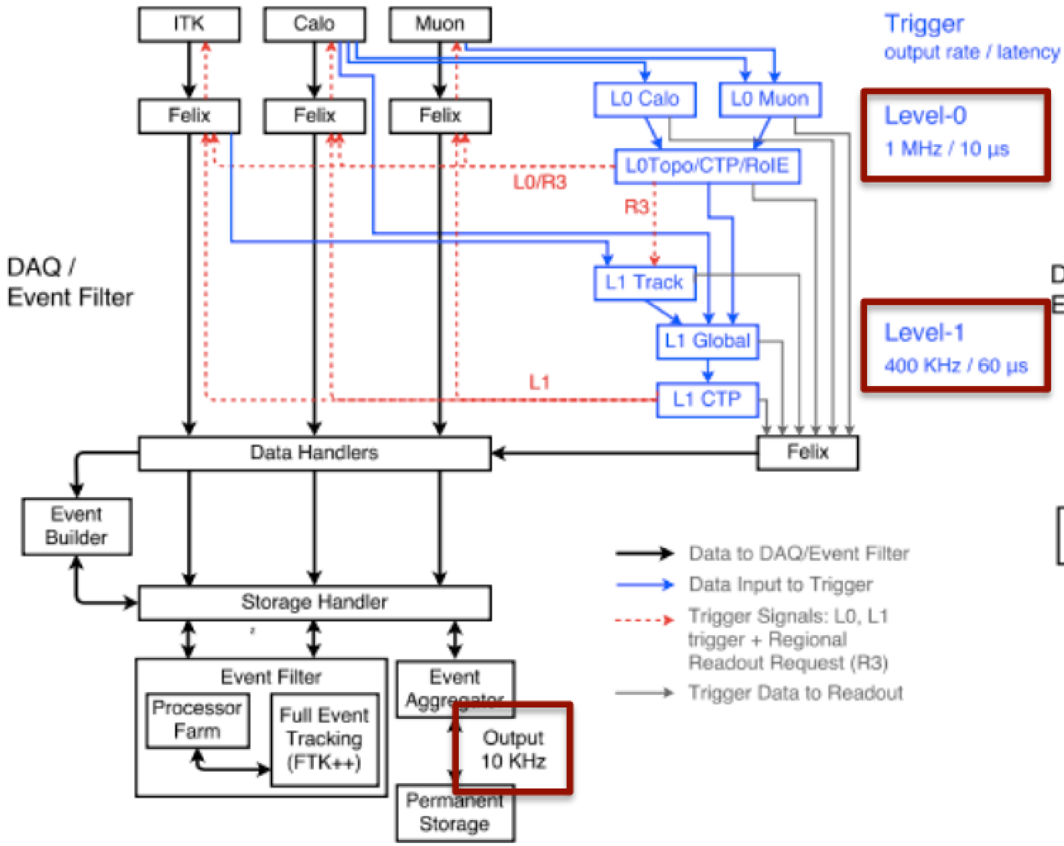


Acceptance with BI upgrade

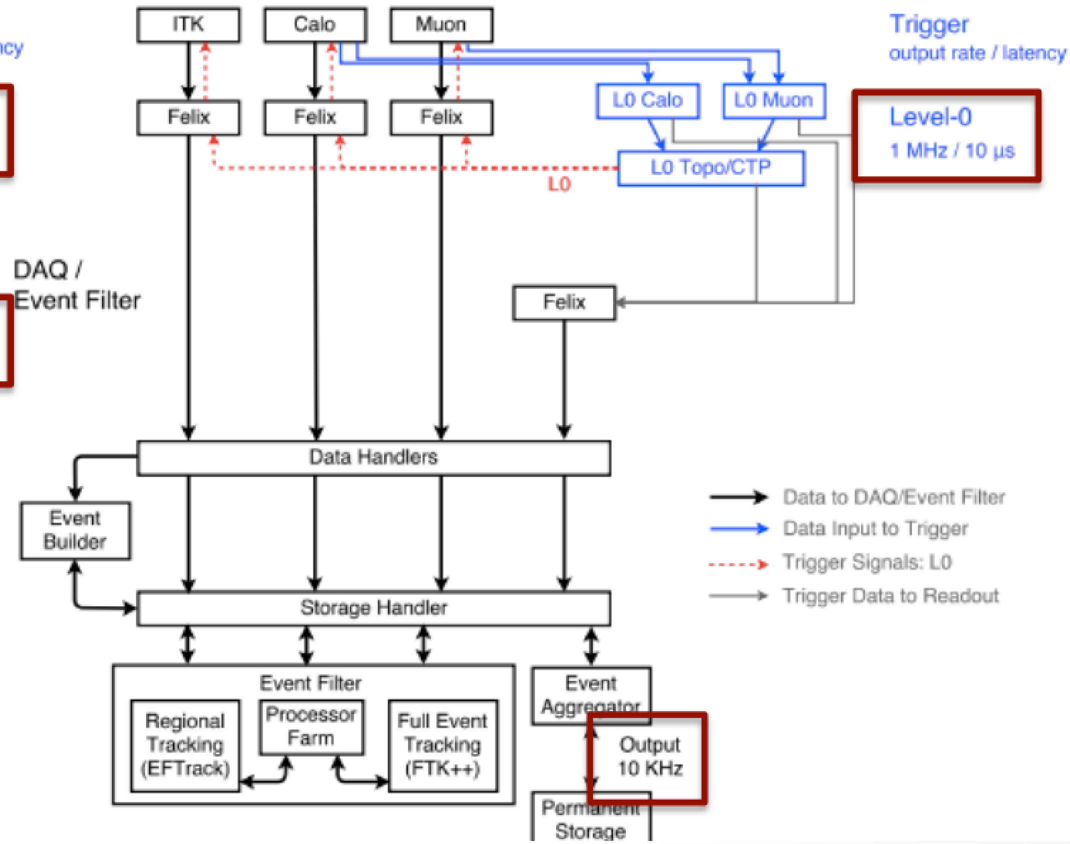


ATLAS Trigger Schemes

Level-0 + Level-1 hardware trigger



Level-0 only hardware trigger

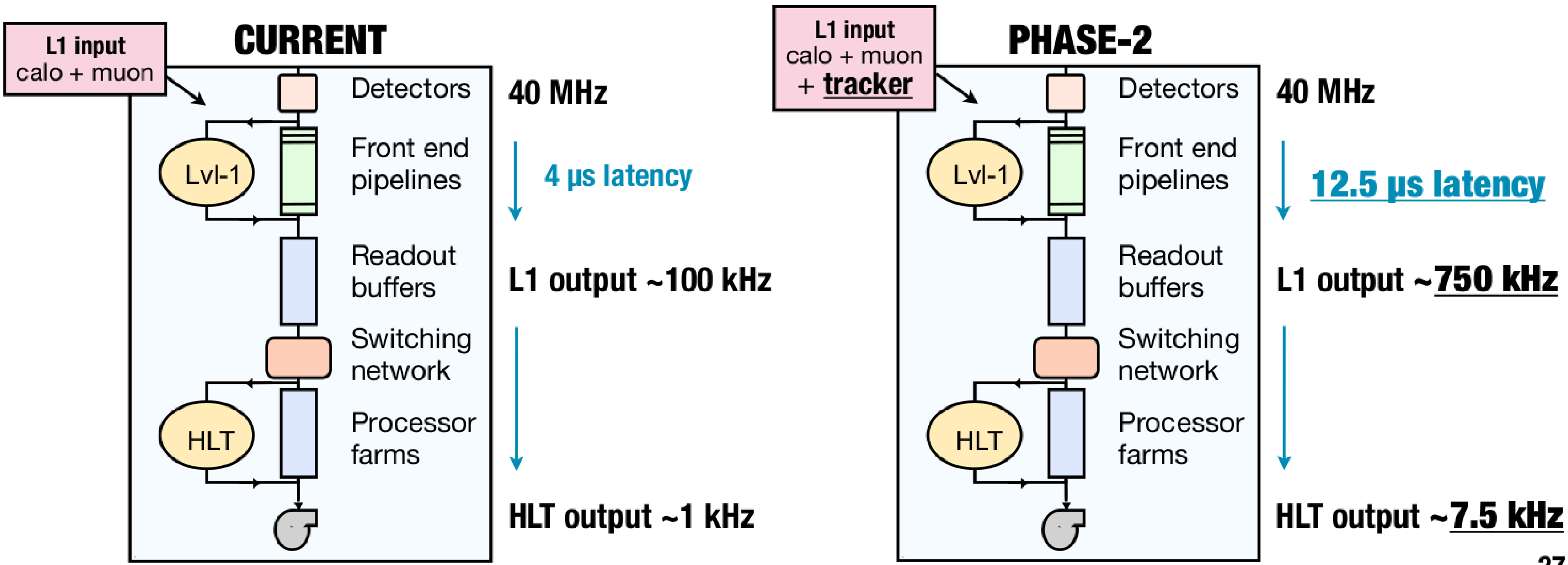


Rates and Latencies

Level 0:	1 MHz, 10 µs	Level 0:	1 MHz, 10 µs
Level 1:	400 kHz, 60 µs		
EF output:	10 kHz	EF output:	10 kHz

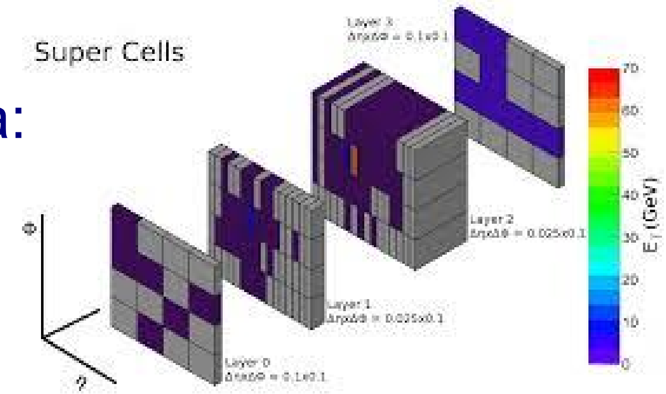
CMS Trigger System

- Current Level-1 trigger uses only calorimeter and muon information
- Phase-II upgrades
  - Replace calorimeter electronics
  - Increase latency and Level-1 accept rate
  - Use tracking at Level-1 based on doublet seeds
  - Global track-trigger correlator

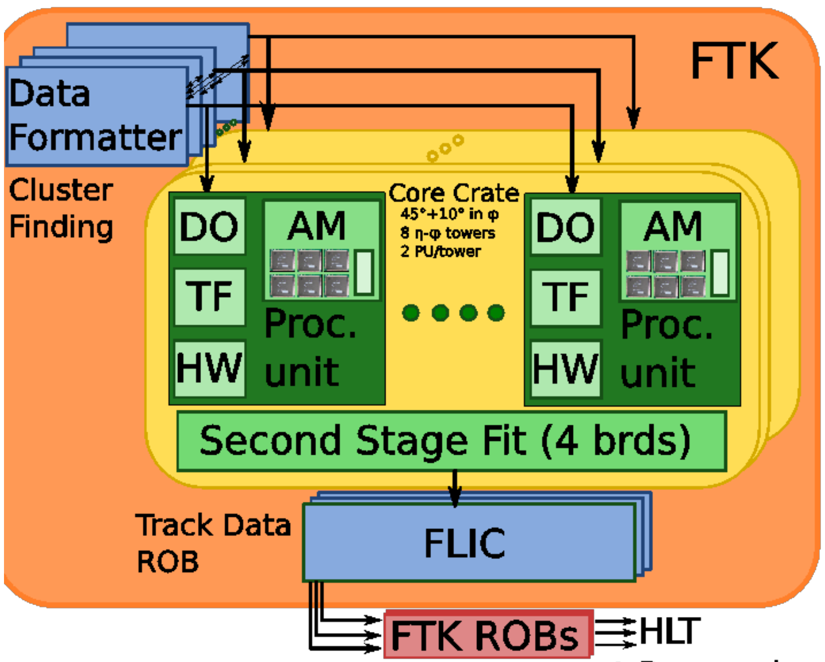


TDAQ Upgrades

- Level-0 trigger use Phase-I upgrades
  - Advanced algos with finer-granularity calo data:
    Incl. longitudinal segmentation for e/γ/τ
    0.1x0.1 towers for jets/$E_{T,miss}$
  - Use NSW hits to confirm endcap muons



- MDT information added to muon trigger
  - Sharpens turn-on curve and thus rejection power
  - Also allows looser RPC trigger selection, increasing acceptance
  - Multiple options for MDT track finding under consideration



- Level-1 mainly adds tracking
  - Also plan to have full granularity calorimeter data available
- Track-trigger builds on FTK design
  - Pattern recognition with custom-made Associate-Memory chips
  - Track fitting in FPGAs
- FTK currently under installation
  - Expected to be commissioned in 2017

ATLAS Example Trigger Menu

- For most trigger channels, expect to maintain same or even lower trigger threshold as in Run-1
  - Hadronic triggers challenging due to pile-up

Description	Run 1 Threshold	HL-LHC Threshold	L0 Rate	EF Rate
isolated e	20-25	22	200	2.20
di-electron	17, 17	15, 15	90	0.08
forward e	–	35	40	0.23
single γ	40–60	120	66	0.27
di-photon	25, 25	25, 25	8	0.18
single μ	25	20	40	2.20
di-muon	12, 12	11, 11	20	0.25
e-μ	17, 6	15, 15	65	0.08
τ	100	150	20	0.13
di-tau	40,30	40, 30	200	0.08

Total non-hadronic L0 rate: ~750 kHz, EF rate: 5.7 kHz

Description	Run 1 Threshold	HL-LHC Threshold	L0 Rate	EF Rate*
single jet	200	180	60	0.6
large-R jet	–	375	35	0.35
four jet	55	4 x 75	50	0.50
forward jets	–	180	30	0.30
HT	–	500	60	0.60
MET	120	200	50	0.50
JET + MET	150, 120	140, 125	60	0.30

Total hadronic L0 Rate: ~250 kHz, EF Rate: 3.15 kHz

750 kHz (leptonic) + 250 kHz (hadronic) = 1000 kHz

CMS Example Trigger Menu

- Menu without track-trigger has 1.5 MHz rate μ=140
  - Track-trigger gives factor 5.5 reduction: 260 kHz
  - Use 1.5 safety factor: 390 kHz
- Menu with track-trigger has 500 kHz rate μ=200
  - With 1.5 safety factor: 750 kHz
  - Without track-trigger: ~4 MHz

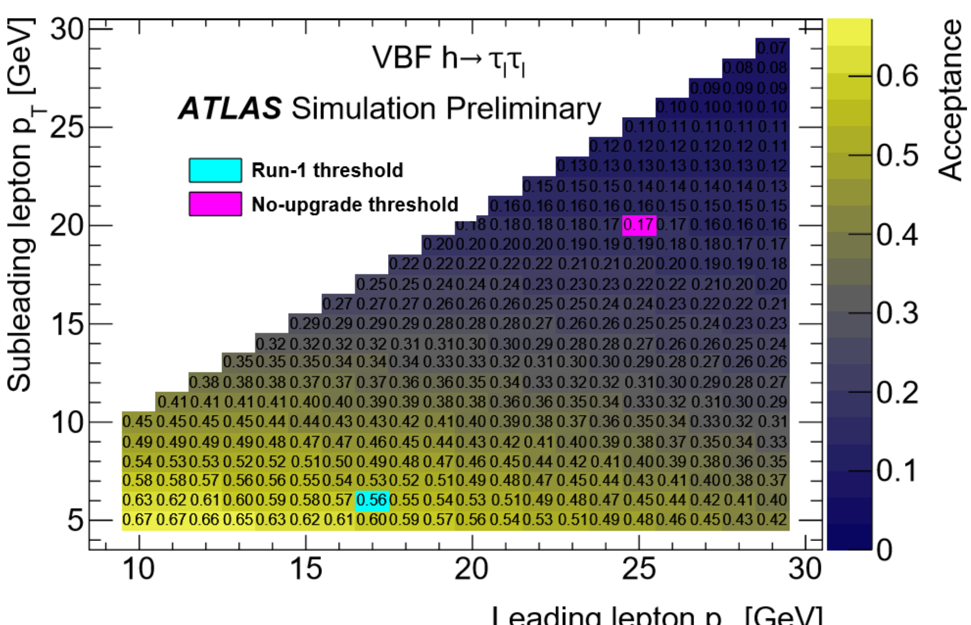
L1 Menu with L1 Track Trigger: PU140

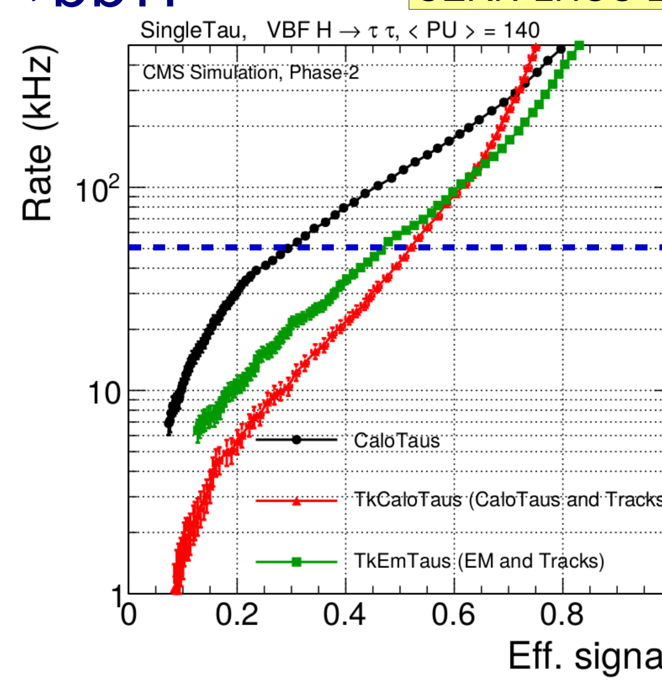
$L = 5.6 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ $\langle PU \rangle = 140$	Level-1 Trigger with L1 Tracks		Rates w/o L1 Track Trigger
Trigger Algorithm	Rate [kHz]	Offline Threshold(s) [GeV]	Rate [kHz]
Single Mu (tk)	14	18	139
Double Mu (tk)	1.1	14 10	177
ele (iso tk) + Mu (tk)	0.7	19 10.5	160
Single Ele (tk)	16	31	78
Single iso Ele (tk)	13	27	89
Single γ (tk isol)	31	31	70
ele (iso tk) + e/γ	11	22 16	88
Double γ (tk isol)	17	22 16	53
Single Tau (tk)	13	88	34
Tau (tk) + Tau	32	56 56	55
ele (iso tk) + Tau	7.4	19 50	42
Tau (tk) + Mu (tk)	5.4	45 14	52
Single Jet	42	173	185
Double Jet (tk)	26	2@136	144
Quad Jet (tk)	12	4@72	175
Single ele (tk) + Jet (tk)	15	23 66	60
Single Mu (tk) + Jet (tk)	8.8	16 66	64
Single ele (tk) + H_T^{miss} (tk)	10	23 95	73
Single Mu (tk) + H_T^{miss} (tk)	2.7	16 95	
H_T (tk)	13	350	
Rate for above Triggers	180		1000
Est. Total Level-1 Menu Rate	**260**		**1500**

Triggering on H→ττ

- H→ττ channel critical for understanding fermionic coupling and measuring Higgs CP properties
- Difficult to trigger on efficiently
  - Two narrow, fairly soft jets with 1-3 charged tracks
- Existing calorimeter-only L1 triggers not sufficient
  - Acceptance drops quickly as thresholds are raised
- Adding fast track trigger can give large rate reduction
- CMS estimate: 50 kHz L1 rate for 45% eff. for VBF H→ττ
  - Same triggers also useful for HH→bbττ

CERN-LHCC-2015-010





$HH \to b\bar{b}\tau^+\tau^-$ Analysis

- Consider all combinations of leptonic/hadronic ττ final states:

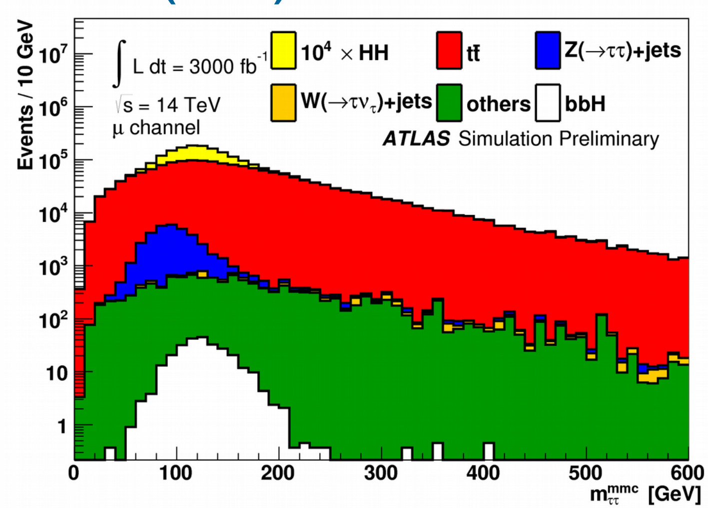
Event yields for 3000 fb-1 using a cut-based analysis strategy:

	Signal events:	Background events:
τLEP τLEP	9	6,200
τLEP τHAD	20	880
τHAD τHAD	19	830

Signal significance for SM coupling:

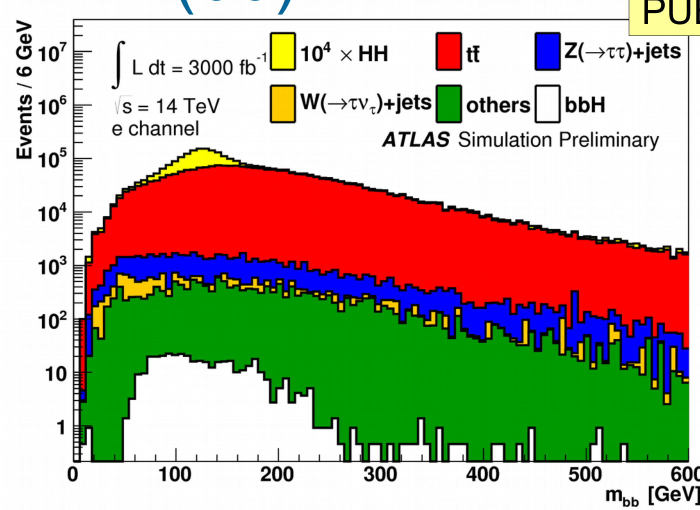
Channel	Significance	Combined in channel	Total combined
e + jets	0.31	0.43	0.60
μ+jets	0.30		
$\tau_{had}\tau_{had}$	0.41	0.41	

$m(\tau^+\tau^-)$



$m(b\bar{b})$

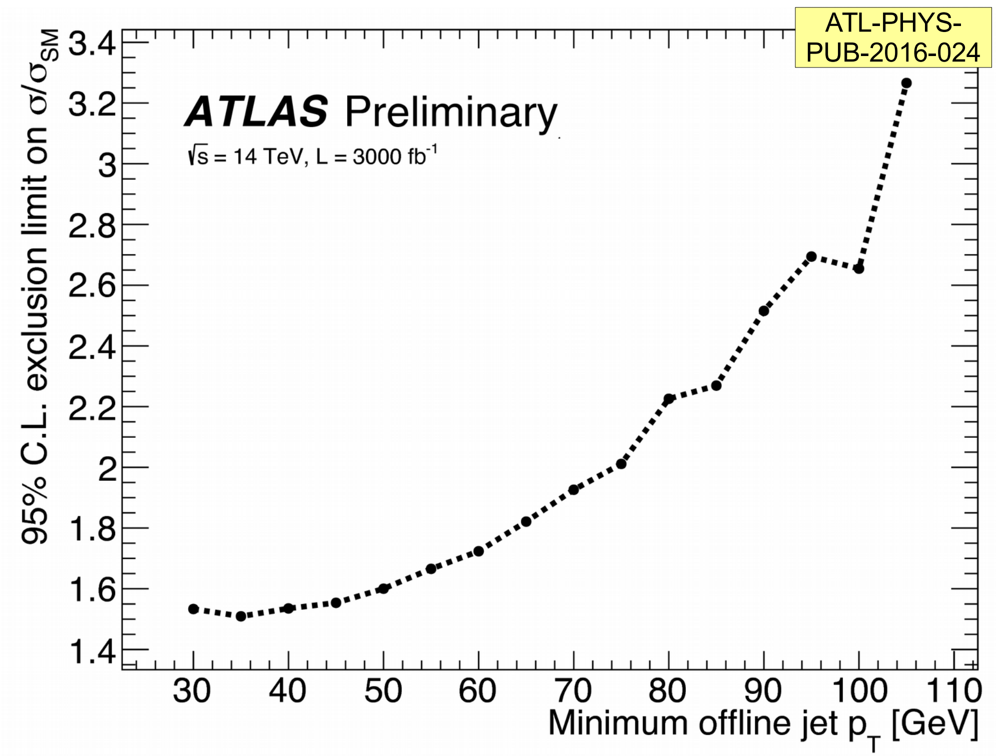
ATL-PHYS-PUB-2015-046



95% CL limits on self-coupling: $-4<\lambda/\lambda_{SM}<12$

Triggering on HH→b$\bar{b}$b$\bar{b}$

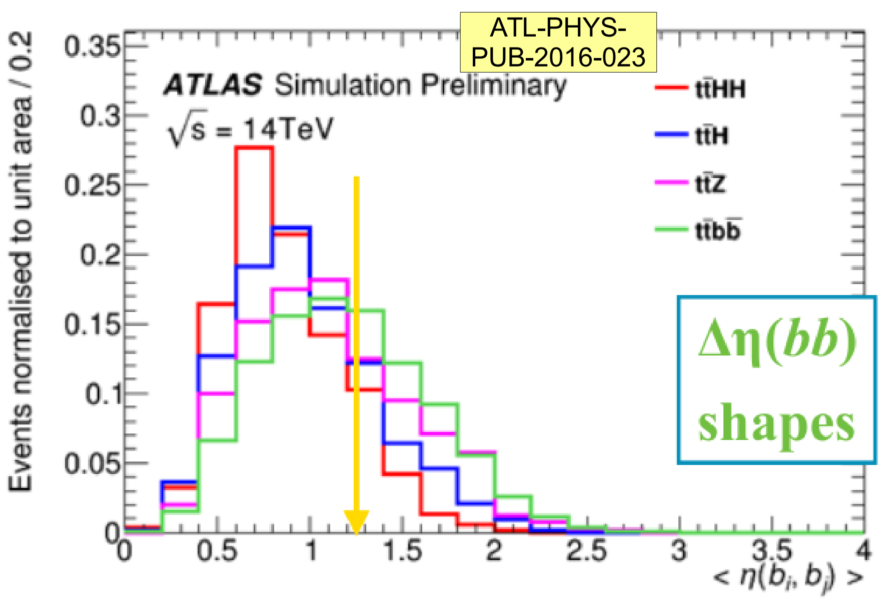
- HH→b$\bar{b}$b$\bar{b}$ channel also difficult to trigger on at L1
  - Very large rate of multi-jets and pile-up jets
- Plan to also use track trigger to suppress pile-up jets in 4-jet trigger
- Still likely to only be efficient at 70-75 GeV
- ATLAS estimate this will reduce sensitivity by ~30% compared to current 30 GeV
  - Better trigger strategy is under investigation

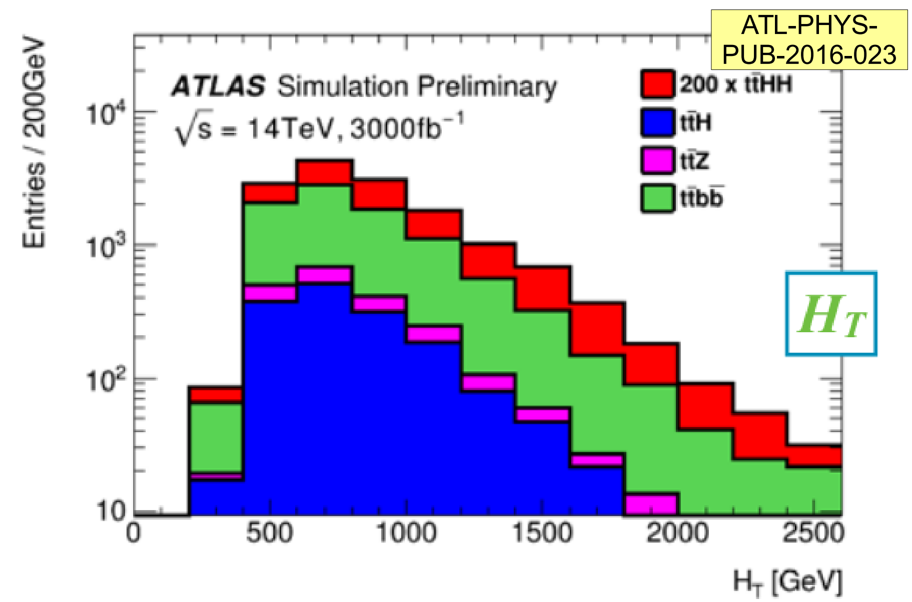


Jet Threshold [GeV]	Background Systematics	σ/σ_{SM} 95% Exclusion	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Lower Limit	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Upper Limit
30 GeV	Negligible	1.5	0.2	7
30 GeV	Current	5.2	-3.5	11
75 GeV	Negligible	2.0	-3.4	12
75 GeV	Current	11.5	-7.4	14

Search for $t\bar{t}HH$ Production

- $\sigma(t\bar{t}HH)$ only ~1fb, but more handles to suppress backgrounds
  - Use $HH \rightarrow b\bar{b}b\bar{b}$ final state and semi-leptonic $t\bar{t}$ decay
  - Signature: 6 b-jets, 2 light jets, lepton and missing energy
- Simple cut-based analysis
  - No cuts on Higgs candidate mass due to combinatorics



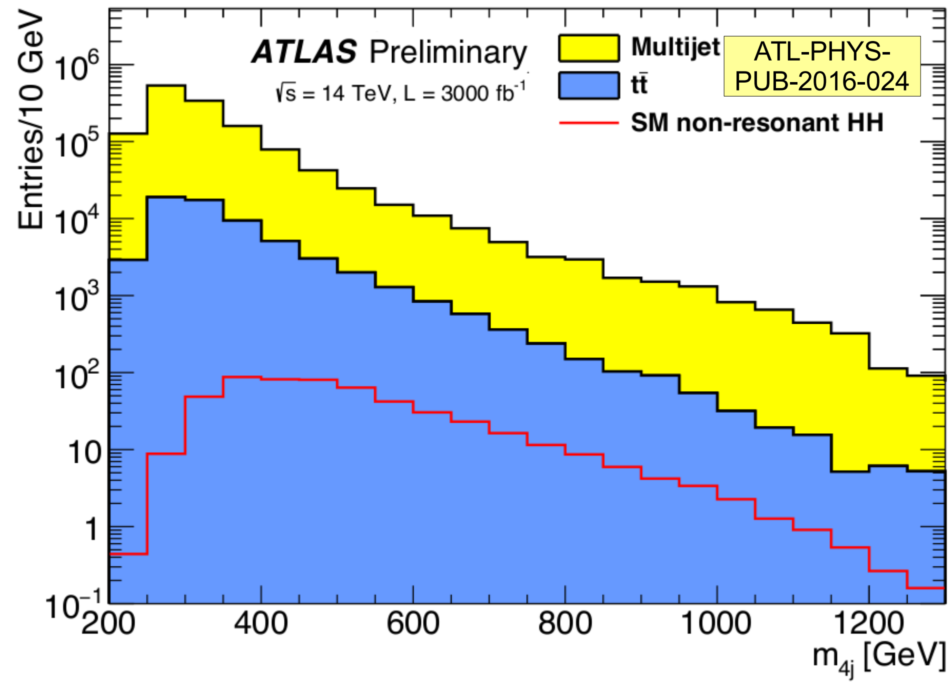


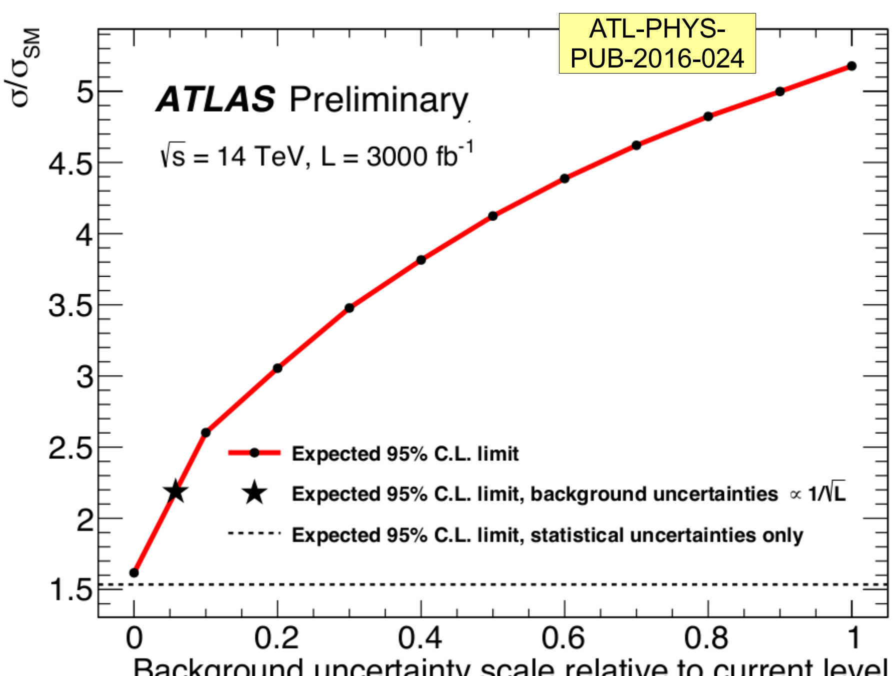
- Selection with ≥5 b-tags:
  - 25 signal events, 7100 background events
  - Background dominated by c-jets from W mis-tagged as b
- Significance for $t\bar{t}HH$ production without systematics: 0.35σ

HH→$b\bar{b}b\bar{b}$ Analysis

- HH→bbbb analysis dominated by large multi-jet background
  - Very difficult to simulate
  - Instead extrapolate from Run-2 assuming unchanged performance
- Multijet background is estimated from control regions (CRs)
  - Systematics uncertainty assigned from CR differences
  - These will decrease with luminosity

Run-2 m_{4j} extrapolated to 3000 fb^{-1}, 14 TeV

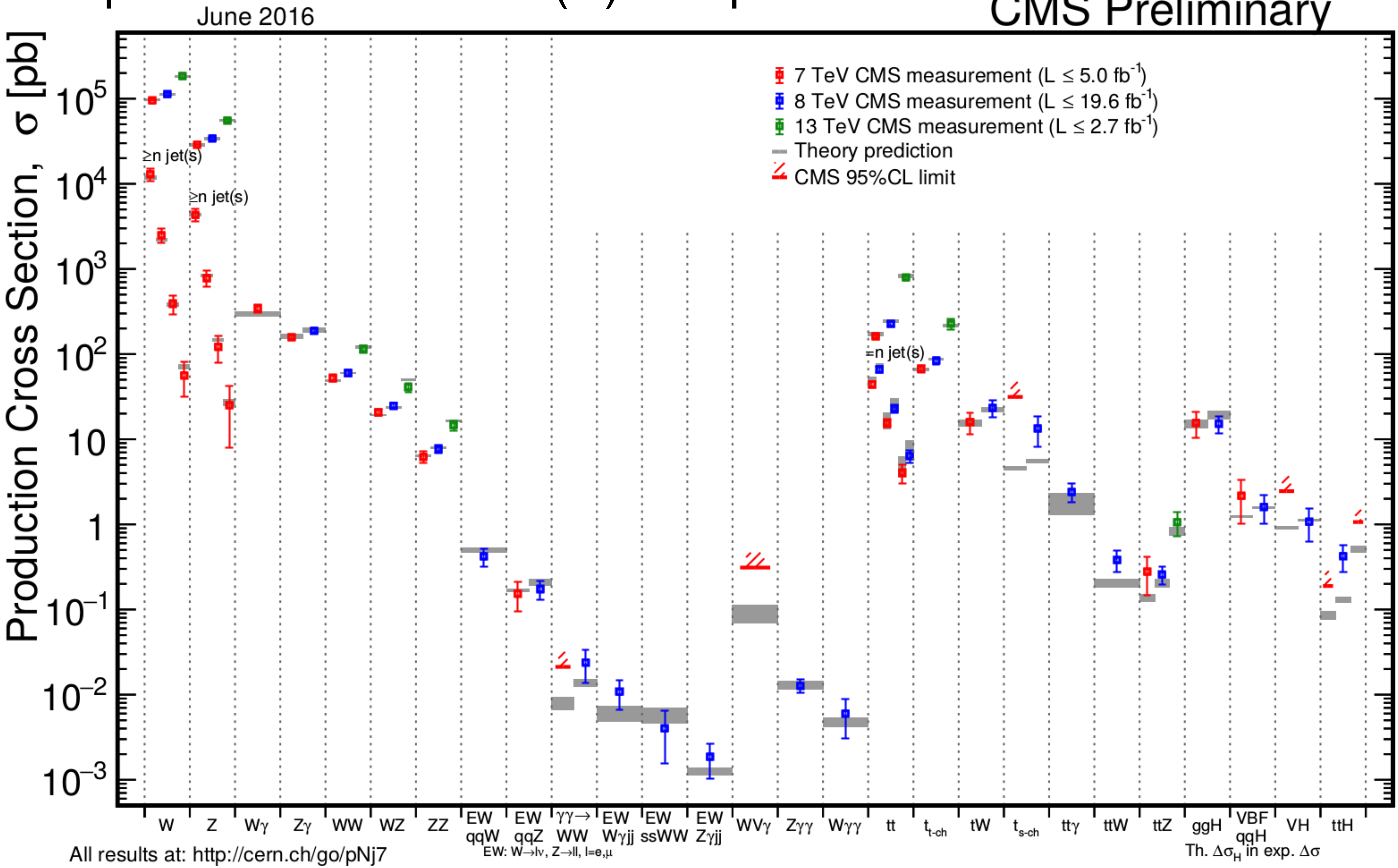




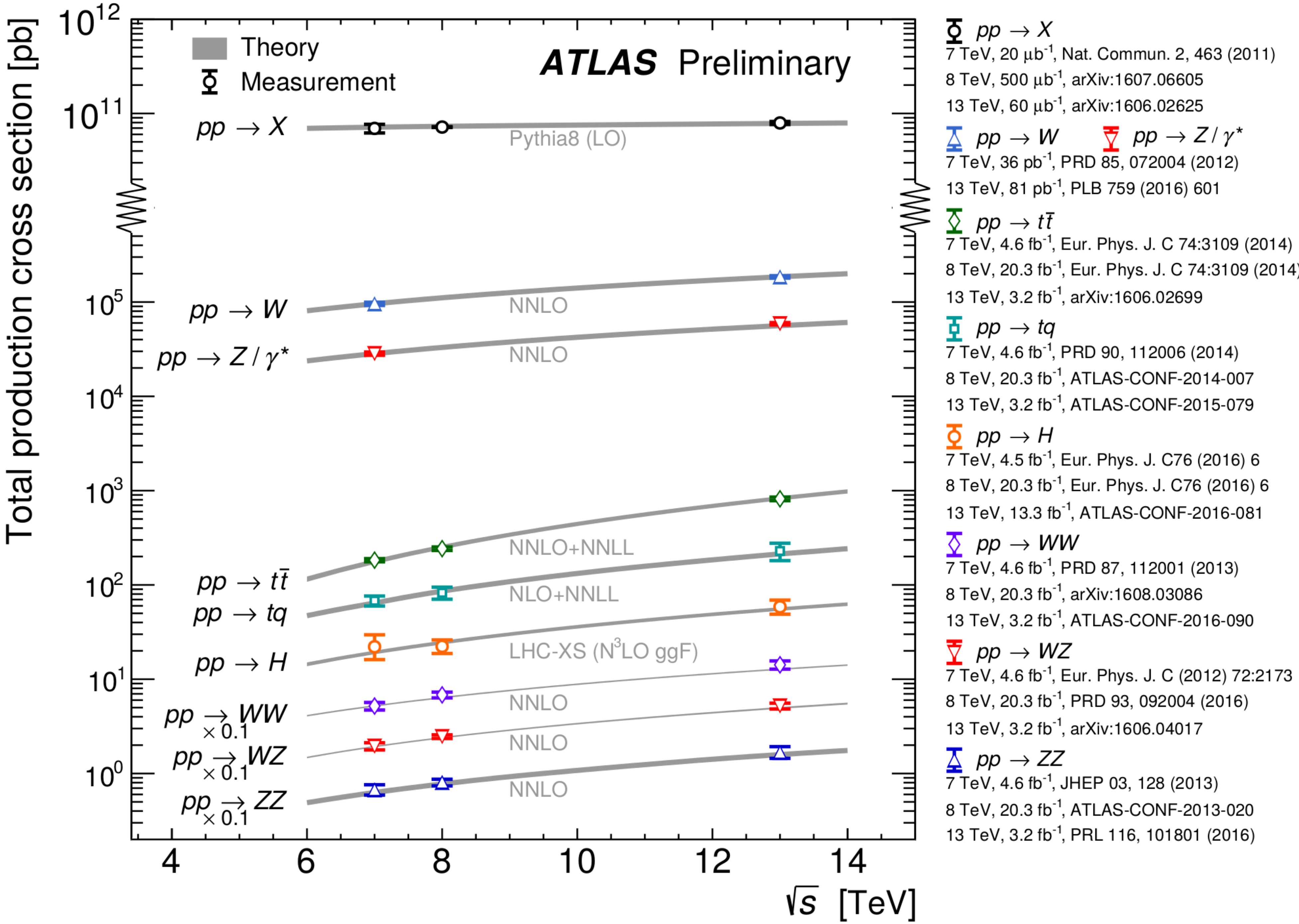
- Neglecting systematics expect
  $0.2<\lambda/\lambda_{SM}<7$ at 95% CL
  - Best of the measurements
- If assuming todays systematics:
  $-3.5<\lambda/\lambda_{SM}<11$ at 95% CL
  - Similar to HH→$b\bar{b}\tau^+\tau^-$

SM Measurements

Vast effort on precision SM measurements with comparisons to the latest (N)NLO predictions



SM Measurements



EW Vector-Boson-Scattering

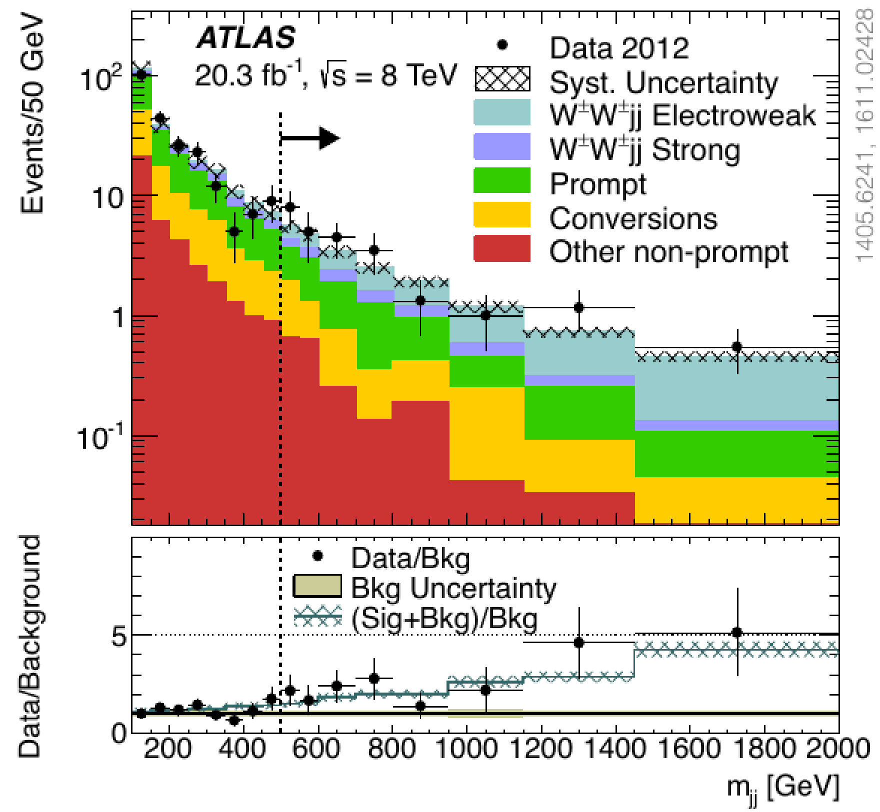
Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

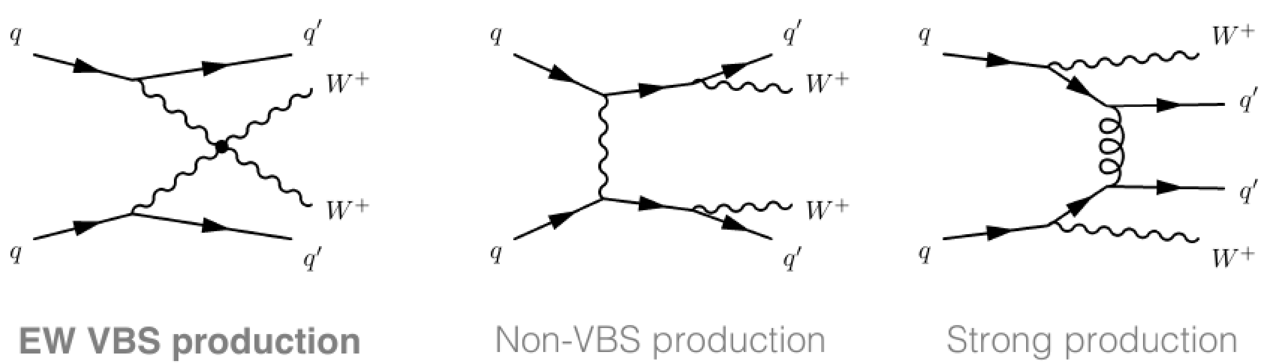
$$A_{Z,\gamma}\left(W^+W^- \to W^+W^-\right) \propto \frac{1}{\upsilon^2}(s+t)$$

Higgs boson restores unitarity of total amplitude:

$$A_H\left(W^+W^- \to W^+W^-\right) \propto -\frac{m_H^2}{\upsilon^2}\left(\frac{s}{s-m_H^2}+\frac{t}{t-m_H^2}\right)$$

Same-sign WW selection greatly reduces strong production.
Removes s-channel Higgs process:



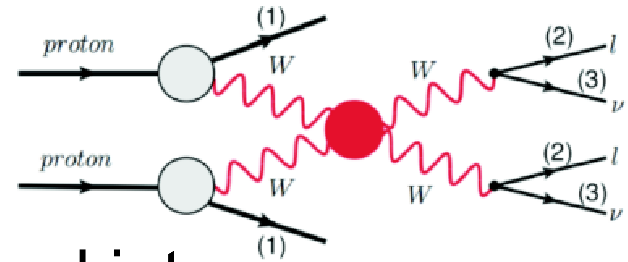


Look for VBS scattering in high dijet invariant mass distributions

ATLAS finds 3.6σ evidence for EW production (2.3σ expected)

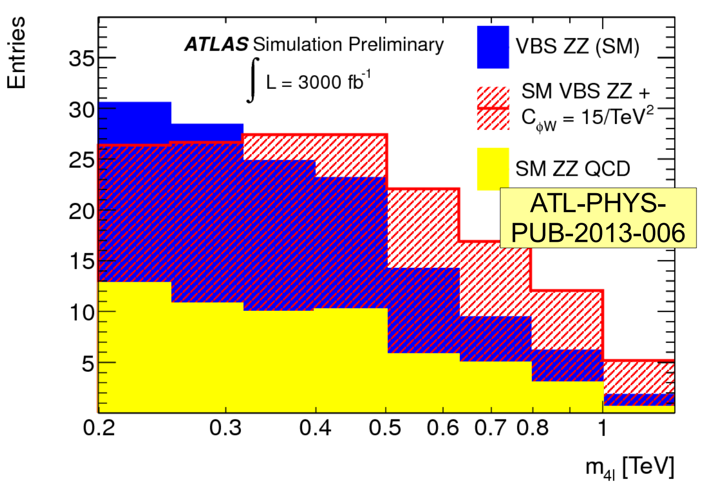
Vector Boson Scattering

- Vector Boson Scattering probes the quartic gauge boson couplings and EW symmetry breaking

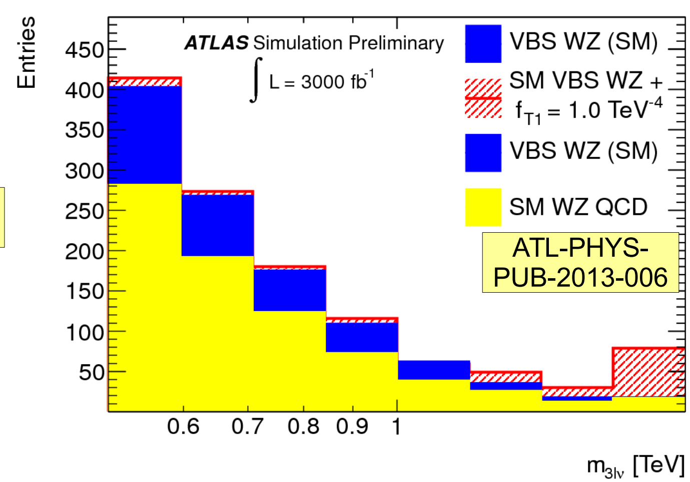


- Striking experimental signature of two forward jets
  - Provides additional motivation for forward tracker extension
- Using leptonic decays clean observations on ZZ, WZ and $W^{\pm}W^{\pm}$ boson scattering
  - Sensitive to dimension-6/8 operators at TeV scale
  - Precision on SM $W^{\pm}W^{\pm}$ boson scattering ~6% with 3000 fb^{-1}

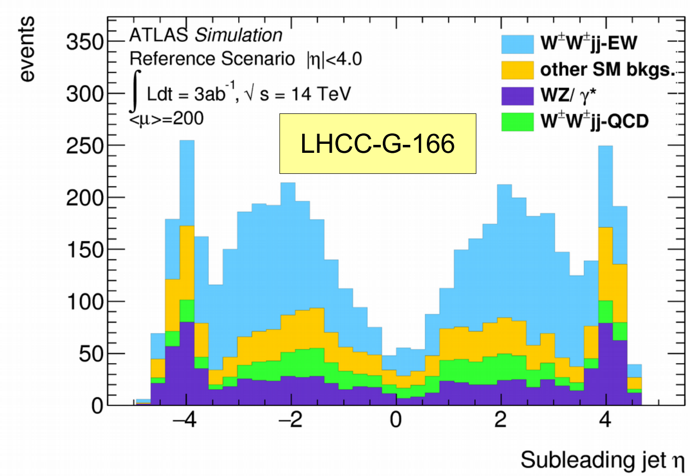
$ZZ \to \ell\ell\ell\ell$



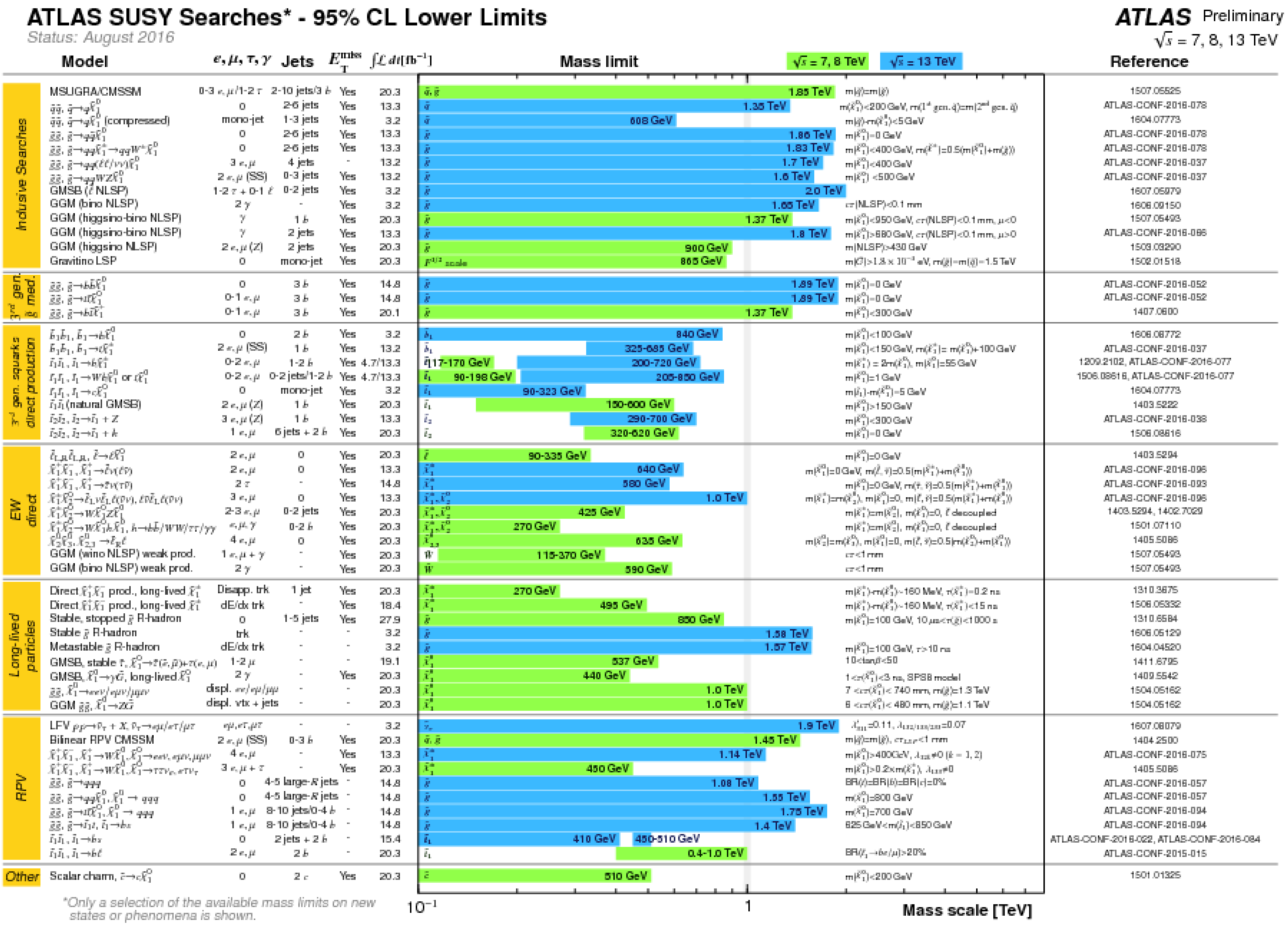
$WZ \to \ell\nu\ell\ell$



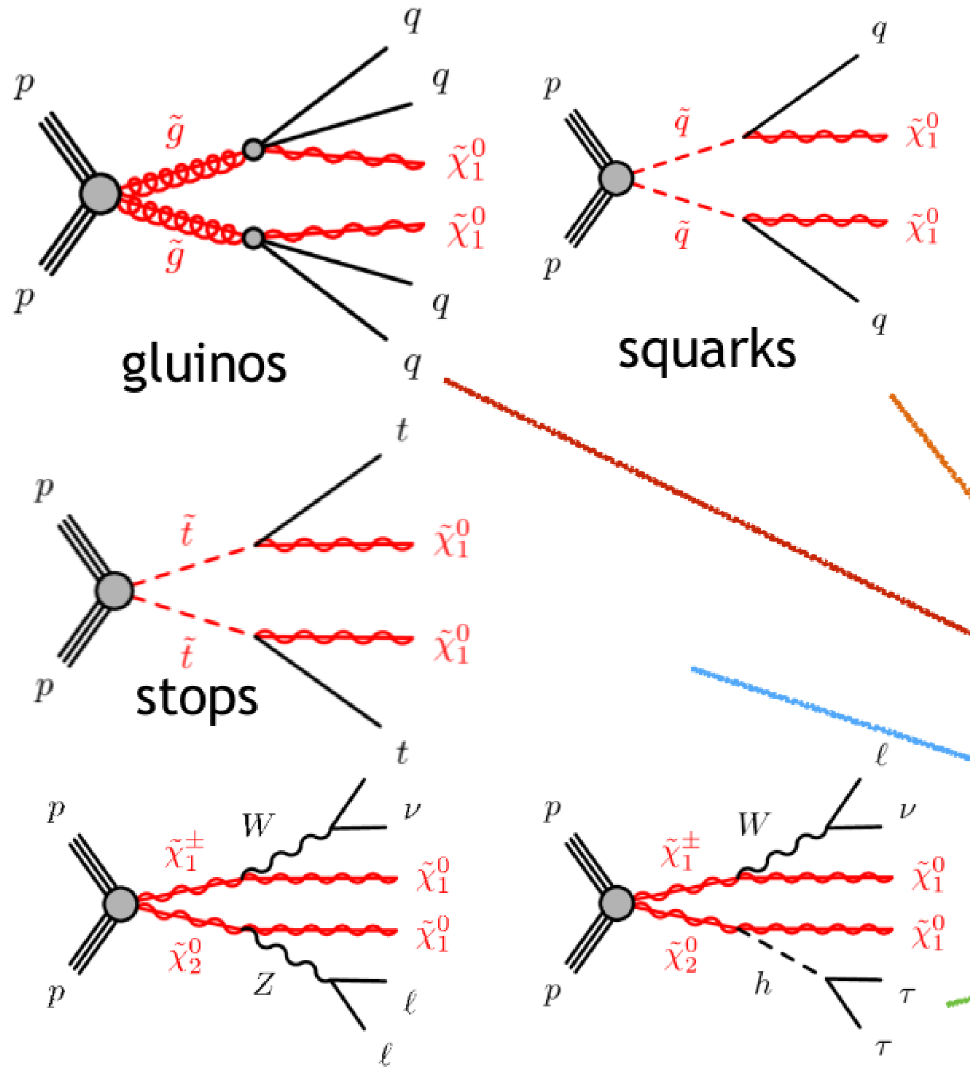
$W^{\pm}W^{\pm} \to \ell\nu\ell\nu$

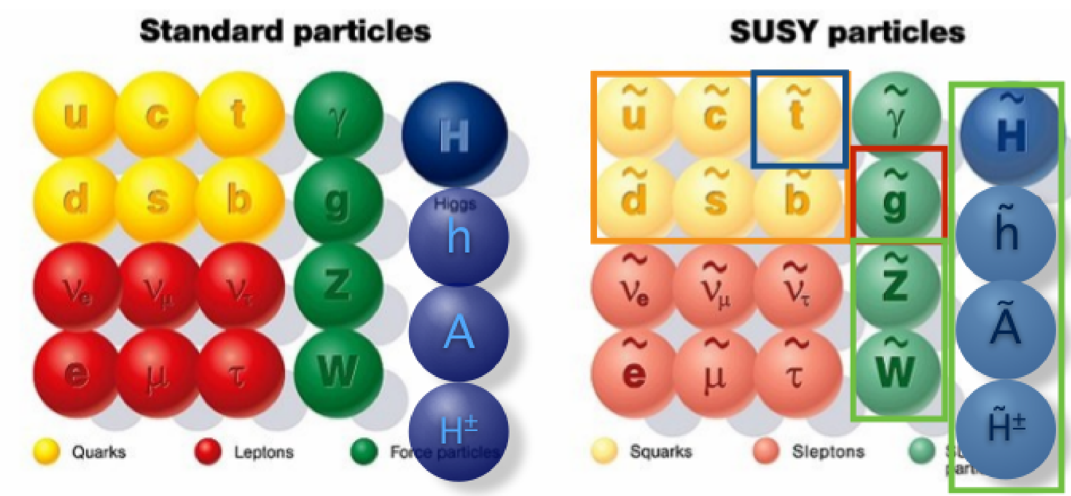


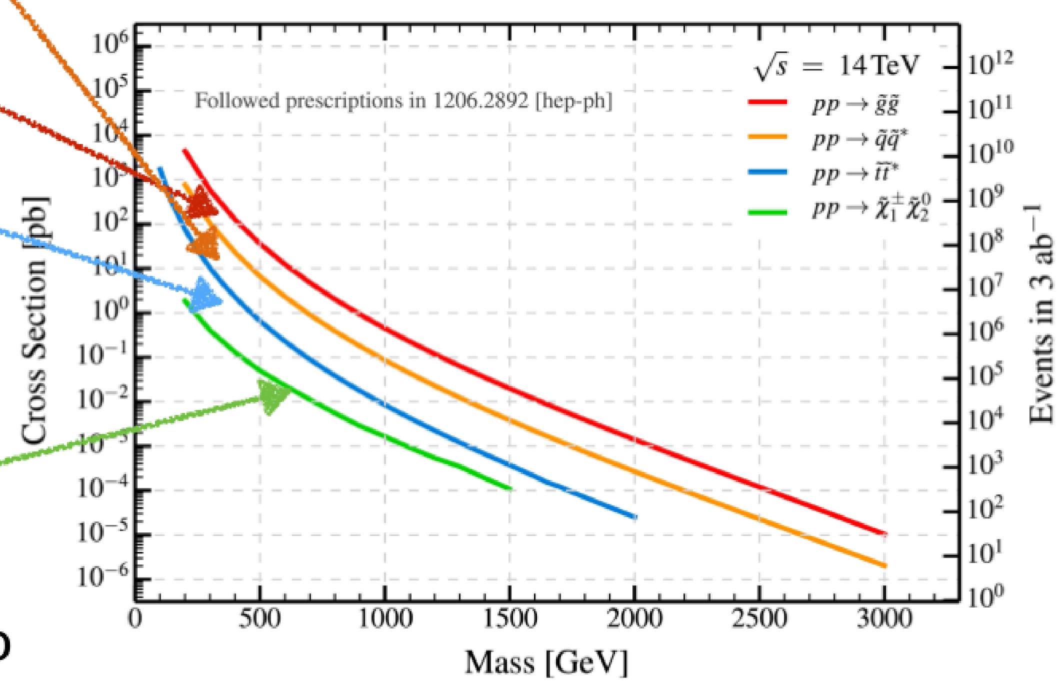
SUSY Status


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: August 2016
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
∫L dt[fb⁻¹]
Mass limit
√s = 7, 8 TeV
√s = 13 TeV
Reference
Inclusive Searches
3rd gen. g̃ med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
*Only a selection of the available mass limits on new states or phenomena is shown.
10⁻¹
1
Mass scale [TeV]

Supersymmetry Production at LHC







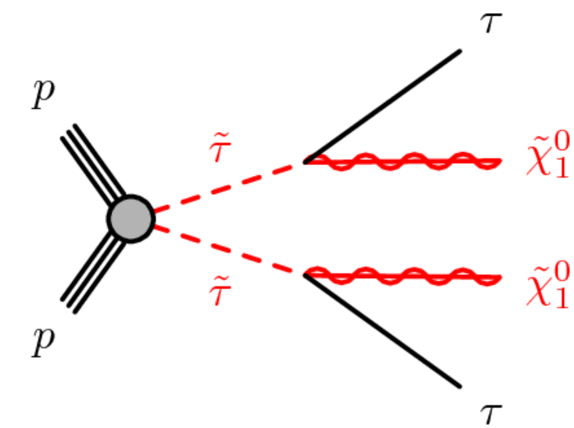
neutralinos ($\tilde{\chi}^0$) & charginos ($\tilde{\chi}^\pm$):
superpositions of Higgsinos, Wino, Bino

Lightest neutralino normally assumed to stable (Dark Matter candidate)

Search for Stau Pair Production

Finally HL-LHC will have sensitivity to direct slepton production

- Studied search for stau pairs
  - Require two hadronic tau decays and large E_{Tmiss}
  - Final discriminant: $m_T(\tau_1,E_{Tmiss})+ m_T(\tau_2,E_{Tmiss})$



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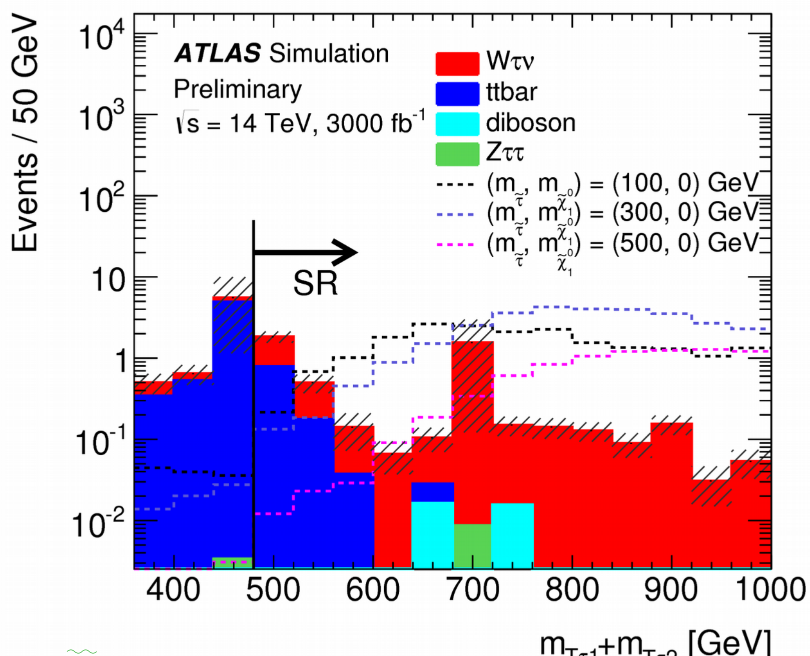
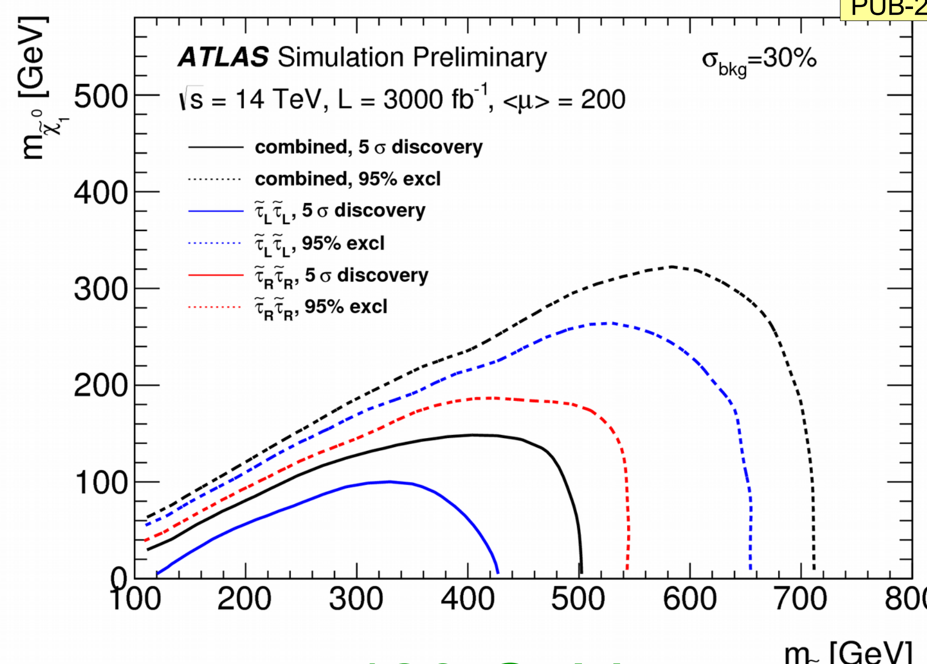


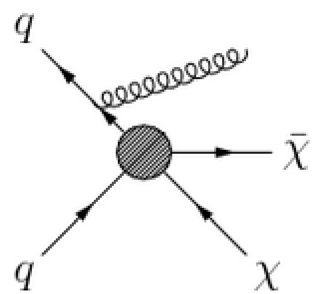


For $\tilde{\tau}_L$, expect to have 5σ discovery up to ~420 GeV, while even with 3000 fb^{-1}, do not achieve 5σ sensitivity for $\tilde{\tau}_R$

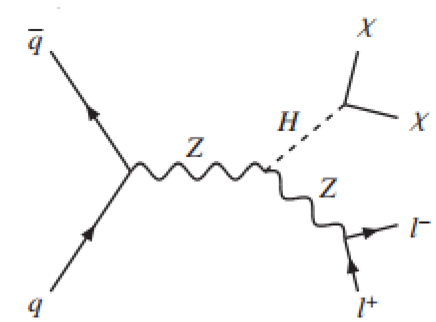
Search for WIMP Candidates

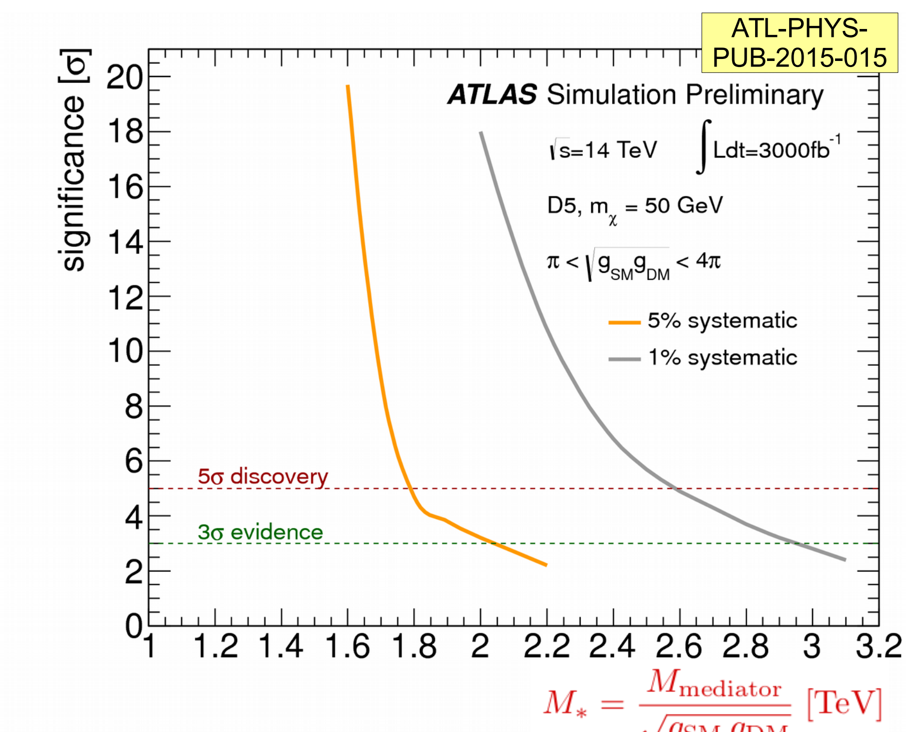
- ATLAS also has sensitivity to non-SUSY WIMP models

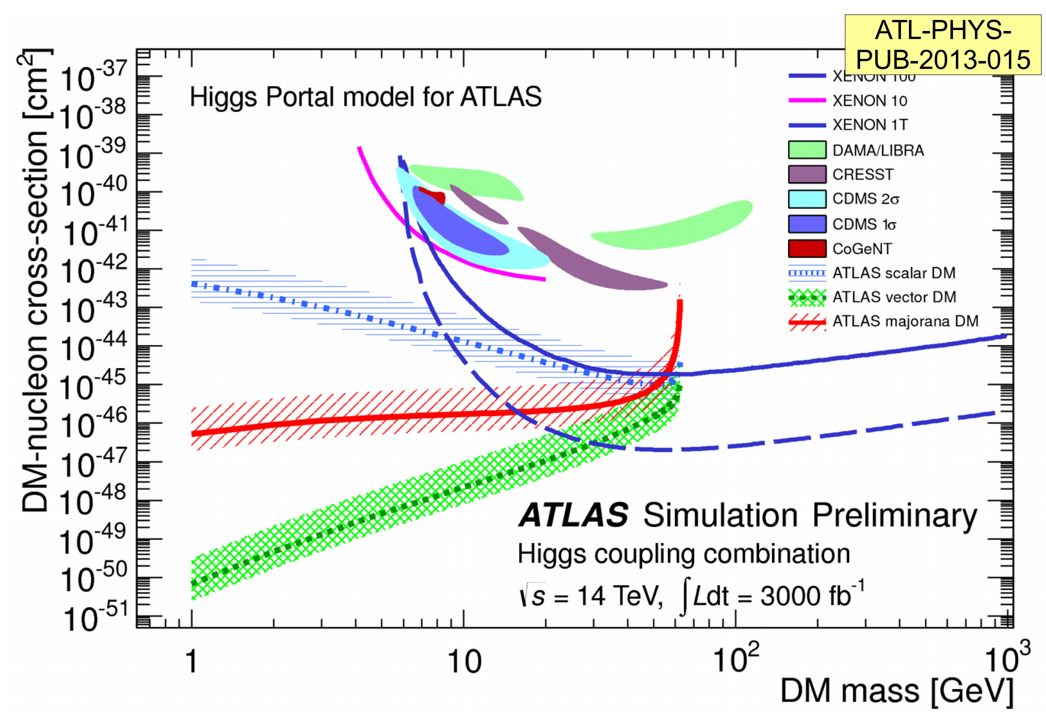
For example with canonical mono-jet signature:



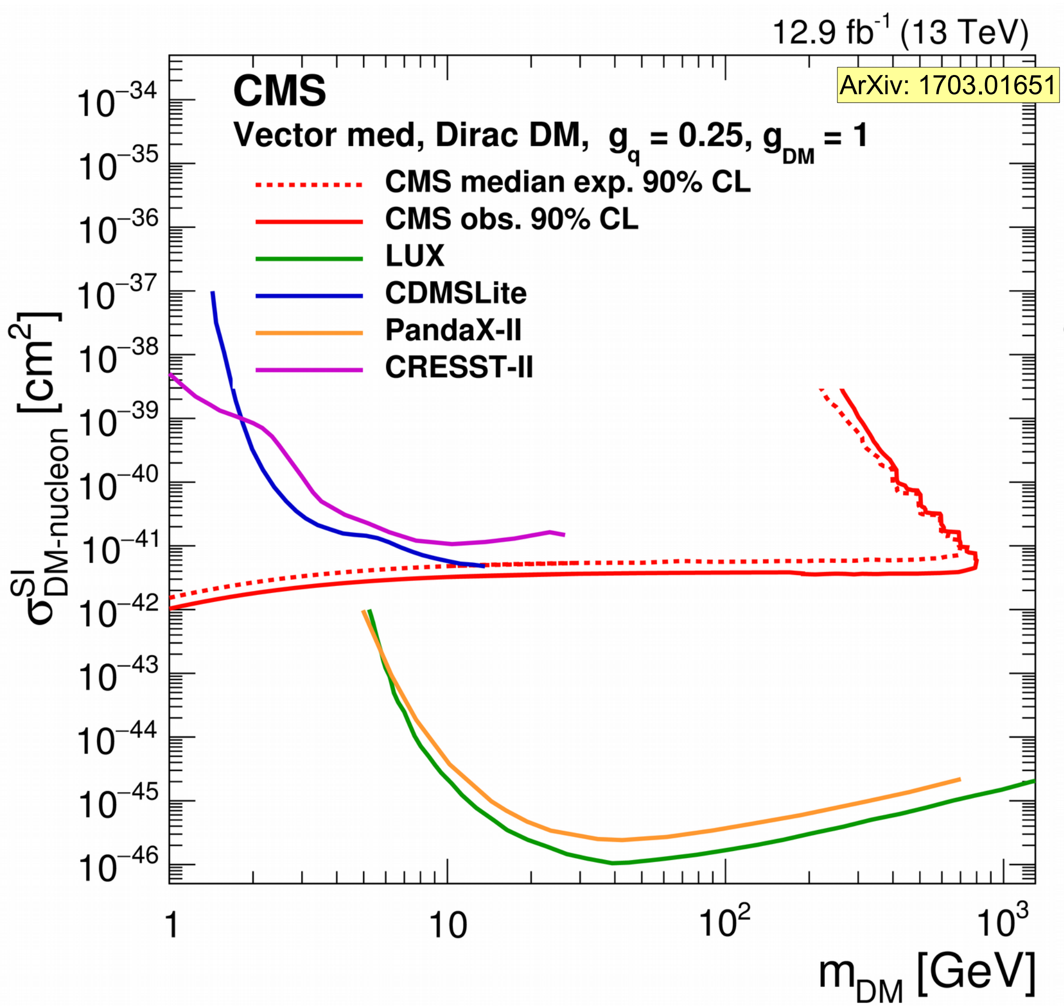
Or invisible Higgs Boson decays:

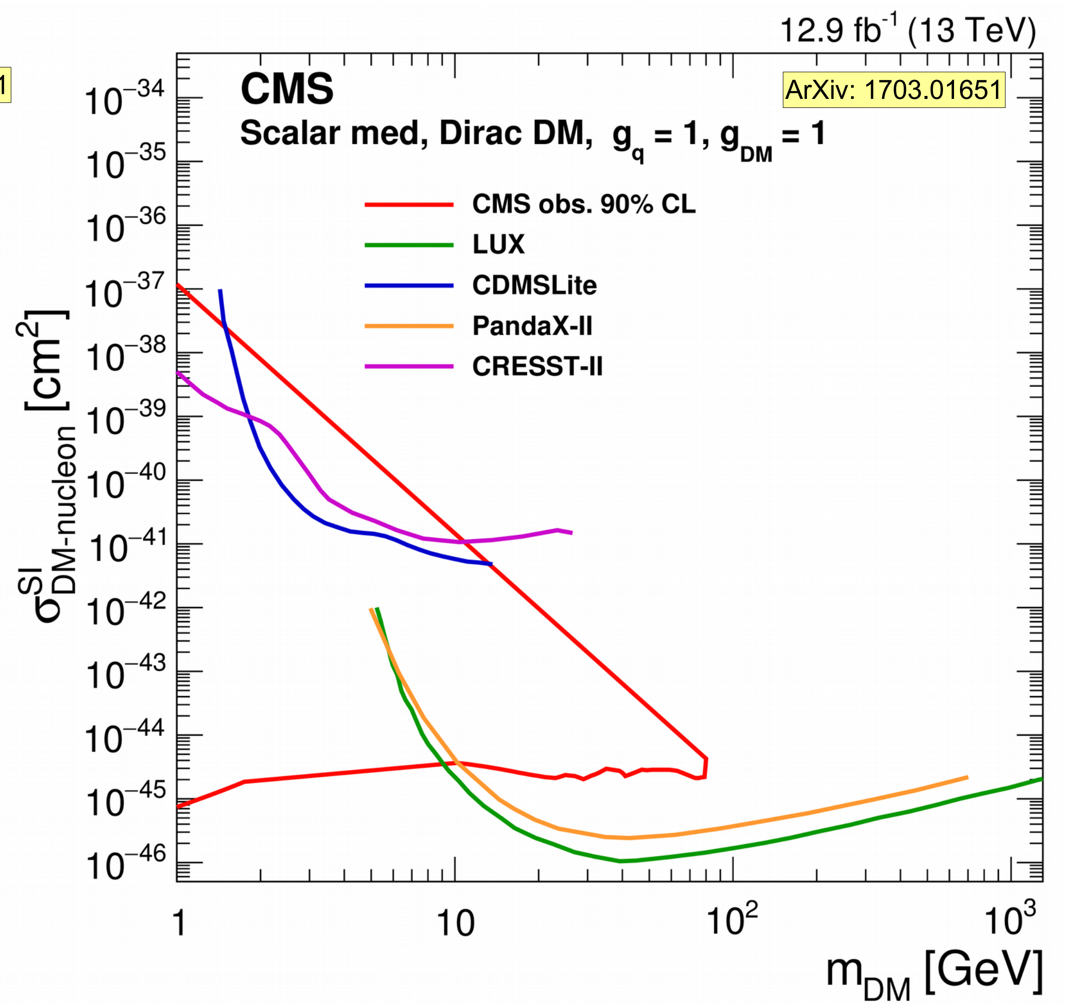




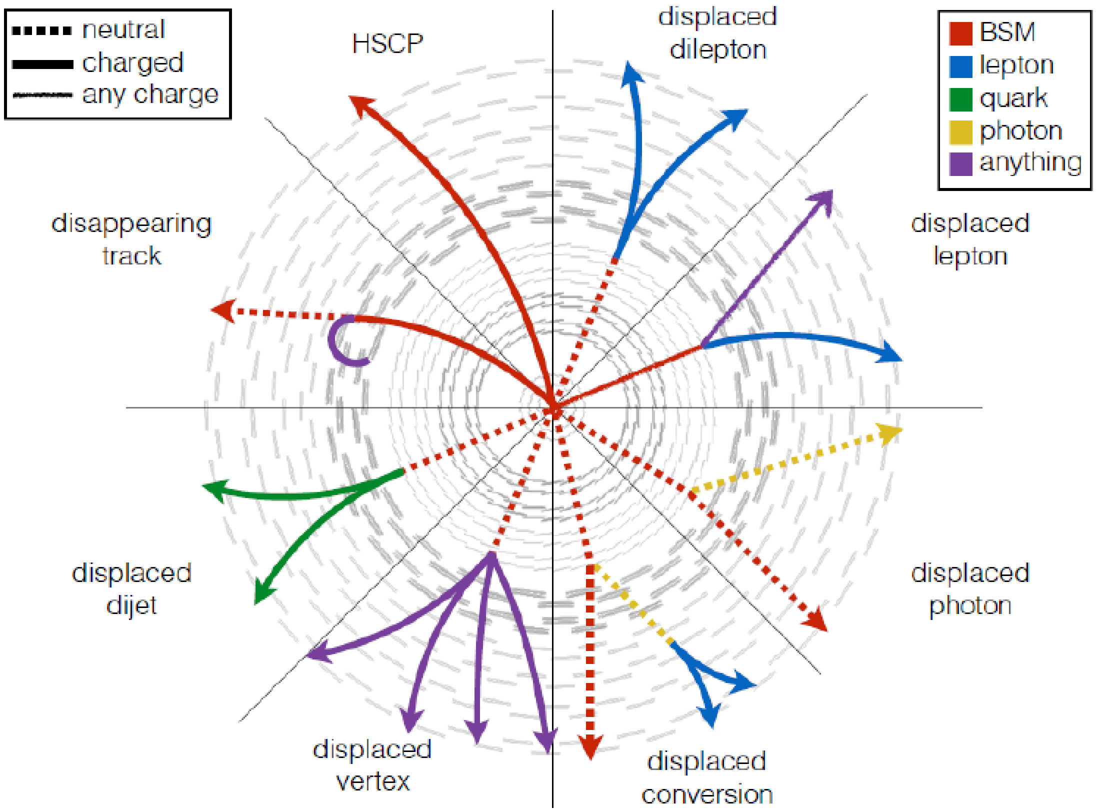


Comparison to non LHC Searches

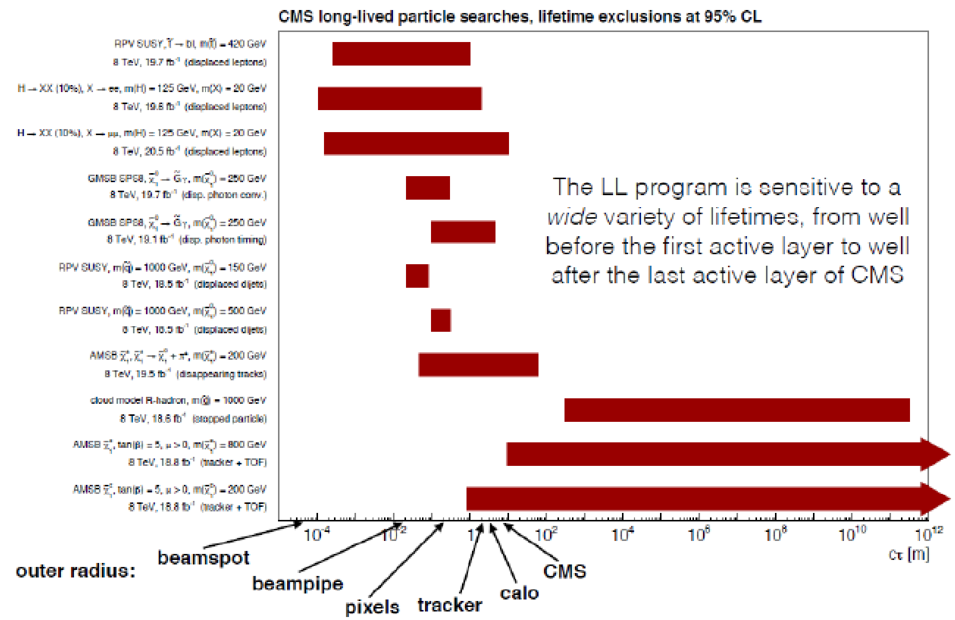




Special Signatures from LLP



Variety of dedicated techniques to cover whole range of lifetimes ($c\tau$)



Issues and opportunities with LLP signatures:

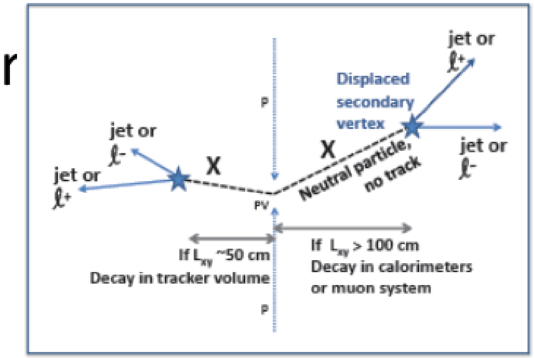
- **Non-standard** objects, **custom** trigger/reconstruction/simulation
- Need to maintain **dedicated** detector capabilities

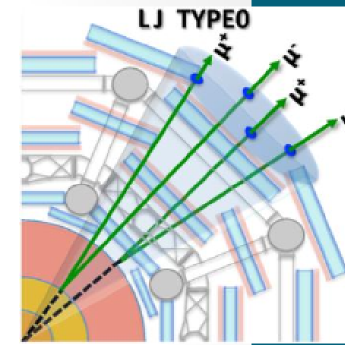
Potential gains from HL-LHC from high luminosity, track-trigger, fast timing, better directionality.

Displaced Muons from LLP

Long-lived neutral particle (X) decays after some cτ to displaced leptons or jets.

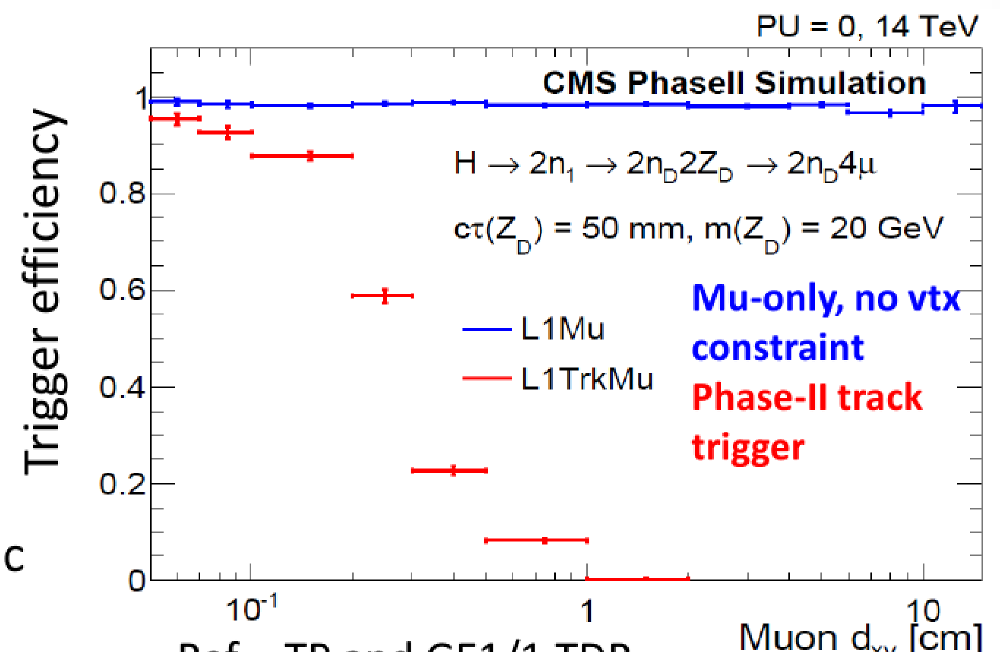
Example signature: **displaced muons** (possibly collimated)





ATLAS EXOT

Experimental challenge: trigger such displaced signatures (note: phase-II track triggers with vertex constraint).



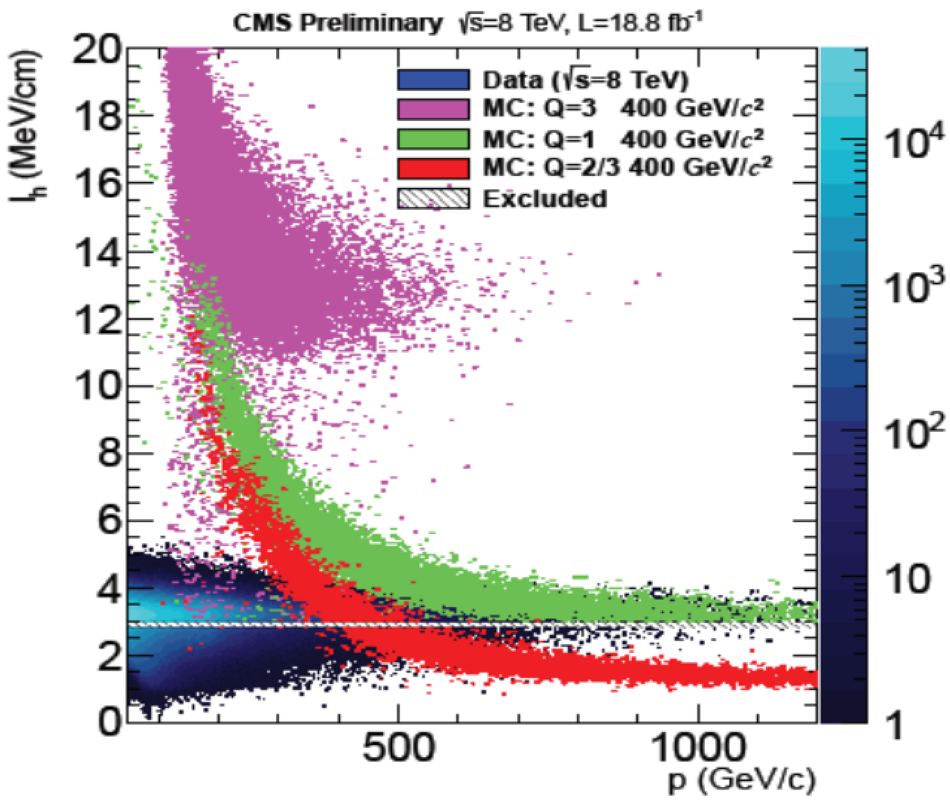
Ref = TP and GE1/1 TDR

Possible models: dark photons, inelastic thermal-relic DM, etc.

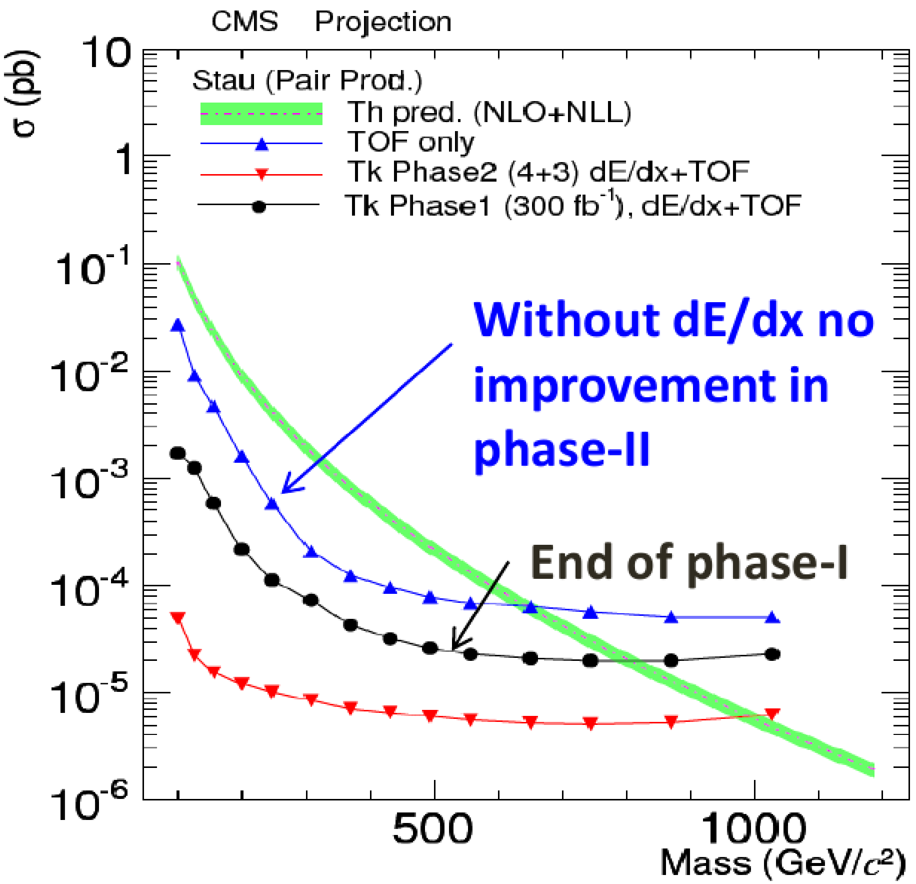
See also talk by Alexei Safonov on CMS muon performance & trigger

Impact of Detector Capabilities

Impact of dE/dx readout in CMS tracker



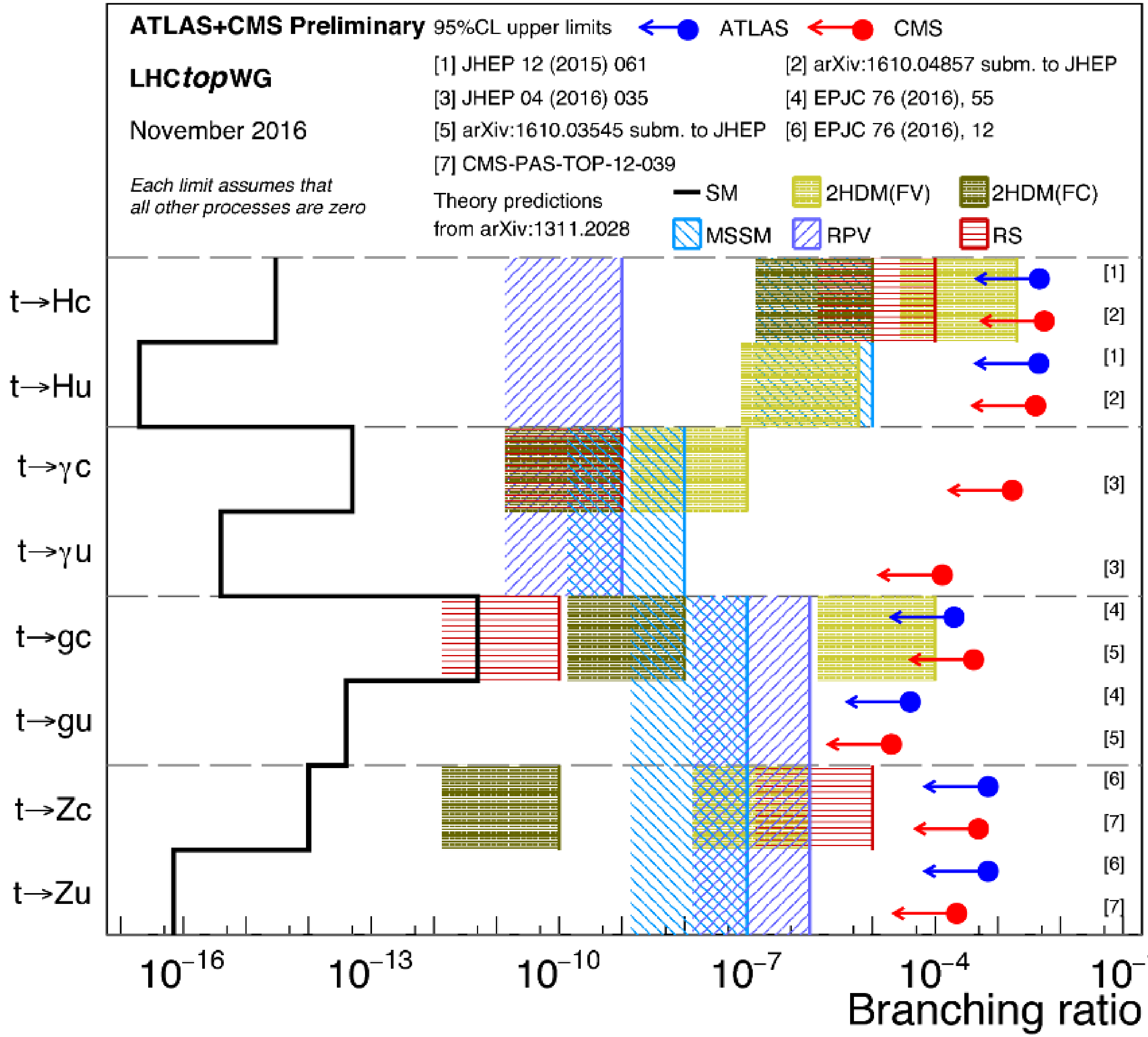
dE/dx information used in searches for heavy stable charged particles (HSCP), fractionally/multiple charged particles. But also to identify noise and background in „standard analyses“.



Physics studied demonstrated the need to keep dE/dx capability.

CMS TP and CMS-PAS-EXO-14-007

Flavor-Changing Neutral Currents in top



Search for t→Zq and t→Hq Decays

- Search for $t\bar{t}$ with one t→Wb decay and one FCNC t decay
  - Reconstruct as much as possible of top decays to obtain maximal discrimination

For t→Zq use kinematic χ^2 fit using leptonic Z decays:

$$\chi^2 = \frac{\left(m_Z - m^{\mathrm{reco}}_{\ell_1\ell_2}\right)^2}{\sigma_Z^2} + \frac{\left(m_W - m^{\mathrm{reco}}_{\ell_3\nu}\right)^2}{\sigma_W^2} + \frac{\left(m_t - m^{\mathrm{reco}}_{\ell_3\nu j_b}\right)^2}{\sigma_{t\to Wb}^2} + \frac{\left(m_t - m^{\mathrm{reco}}_{\ell_1\ell_2 j_u}\right)^2}{\sigma_{t\to Zq}^2}$$

Expected 95% CL limit assuming equal t→Zu and t→Zc: ~2.5x10^{-5}

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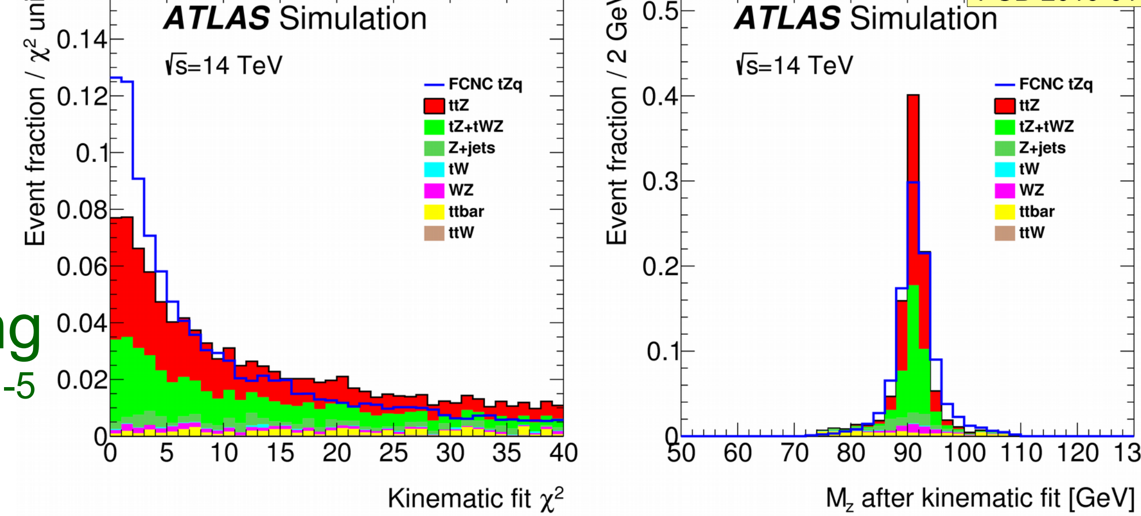

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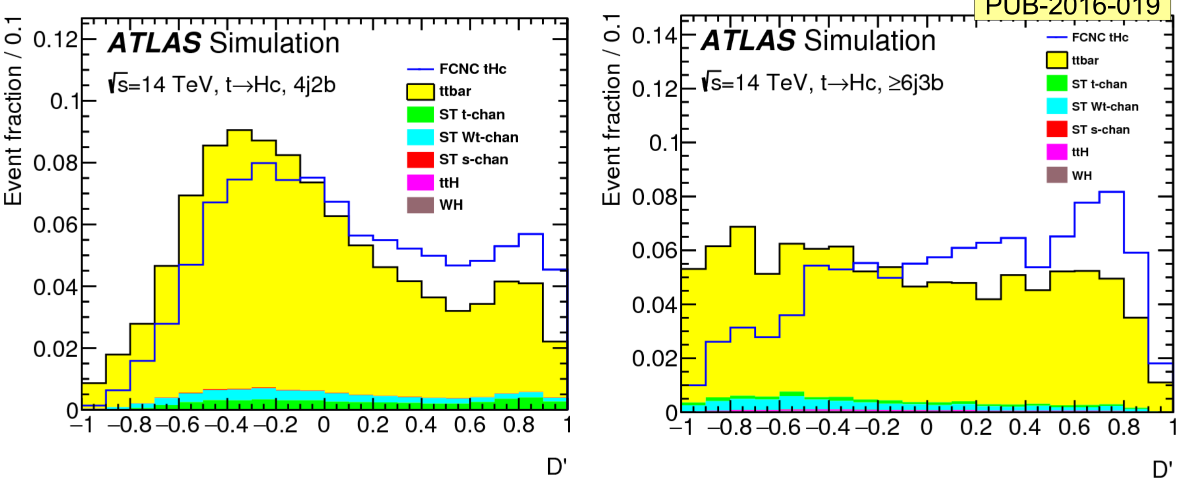

For t→Hq use H→$b\bar{b}$ and kinematic discriminant

Furthermore split in categories based on reconstructed topology (#jets, #b-jets, ...)

Expected 95% CL limit assuming equal t→Hu and t→Hc: ~1.1x10^{-4}