The Physics Program of the High Luminosity LHC and Beyond

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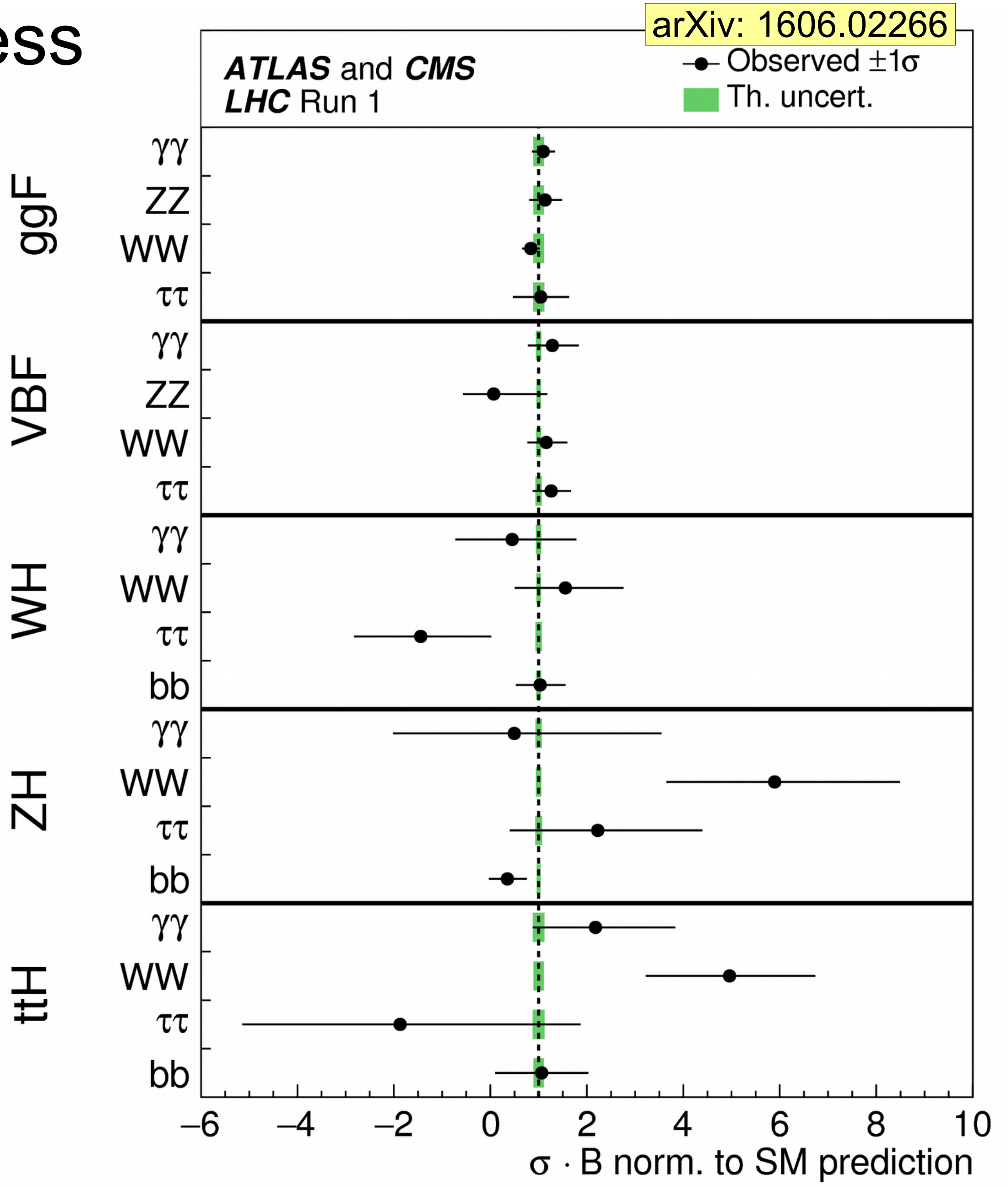
The 3rd KMI International Symposium

Introduction

- Higgs discovery huge success for the LHC program
- Detailed measurements of its properties in progress
  - So far appears consistent with SM predictions
- Searches for BSM signals so far negative and are quite constraining
- However, to achieve ultimate possible precision much more luminosity needed in many cases

Strong motivation for High-Luminosity LHC

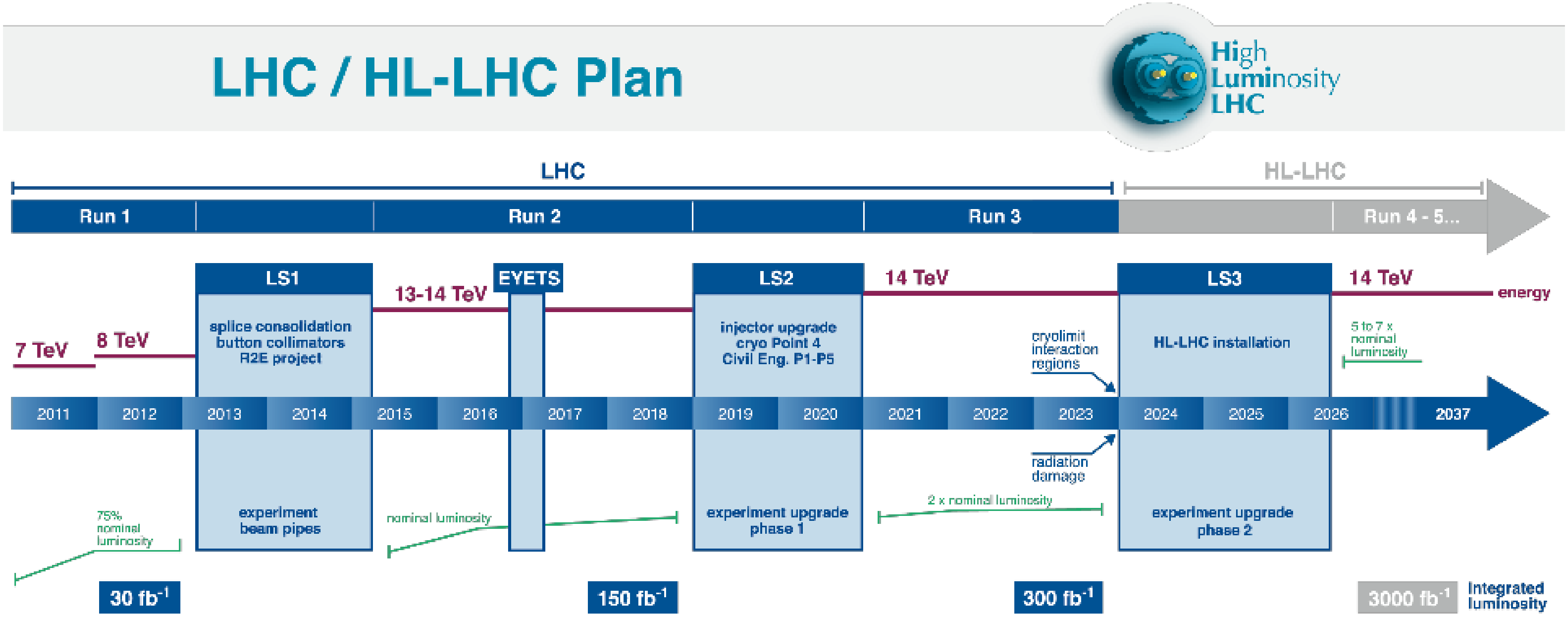


arXiv: 1606.02266

HL-LHC Upgrade

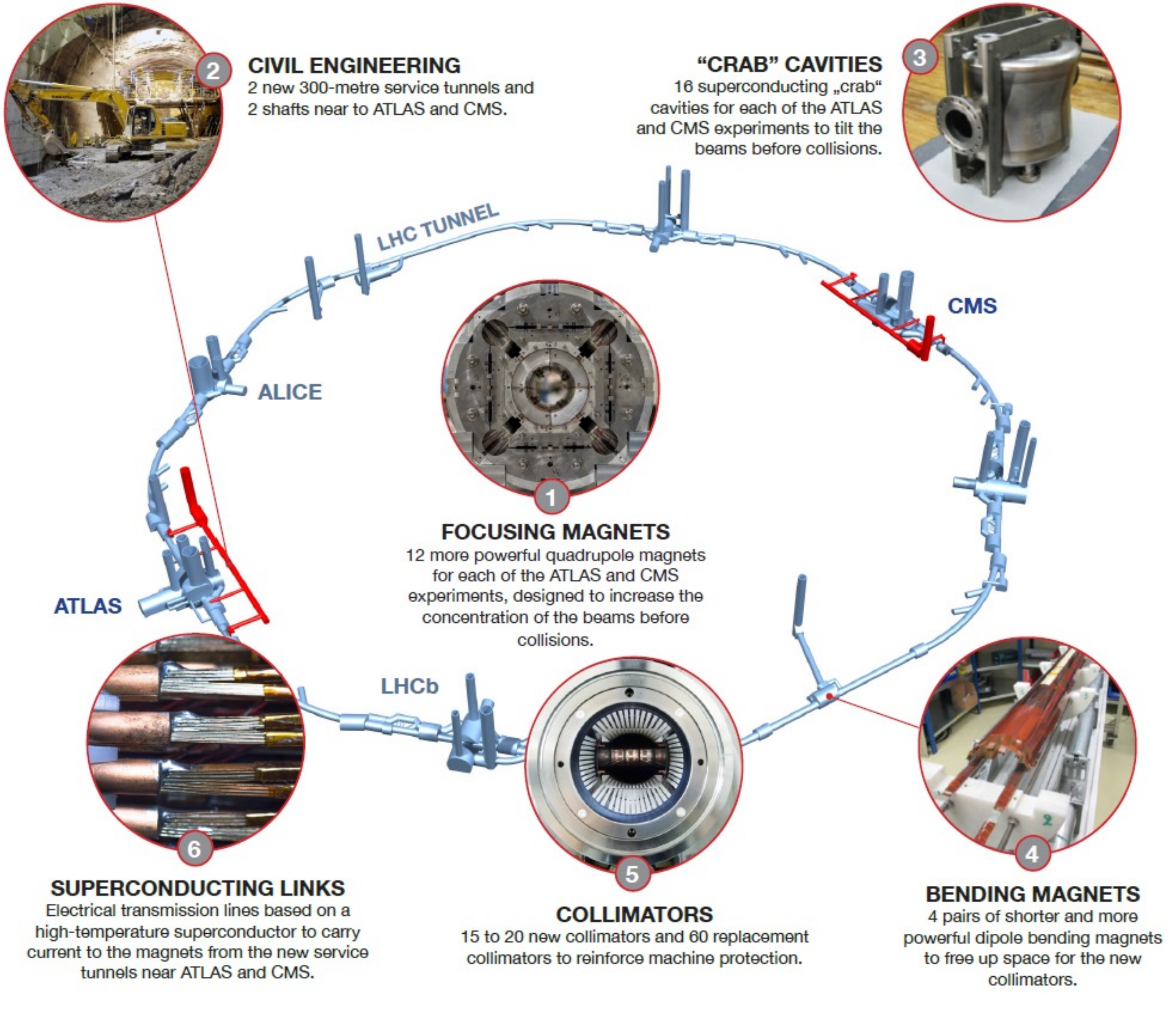
HL-LHC Planning

- 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 $5\text{-}7 \times 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ while using luminosity leveling (3-5 hours at peak luminosity)
- Design for "ultimate" performance 7.5×10^{34} $\text{cm}^{-2}\text{s}^{-1}$ and 4000 fb^{-1}



HL-LHC Project

Major intervention on more than 1.2 km of the LHC



CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

“CRAB” CAVITIES
16 superconducting „crab“ cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

CERN Novembre 2015

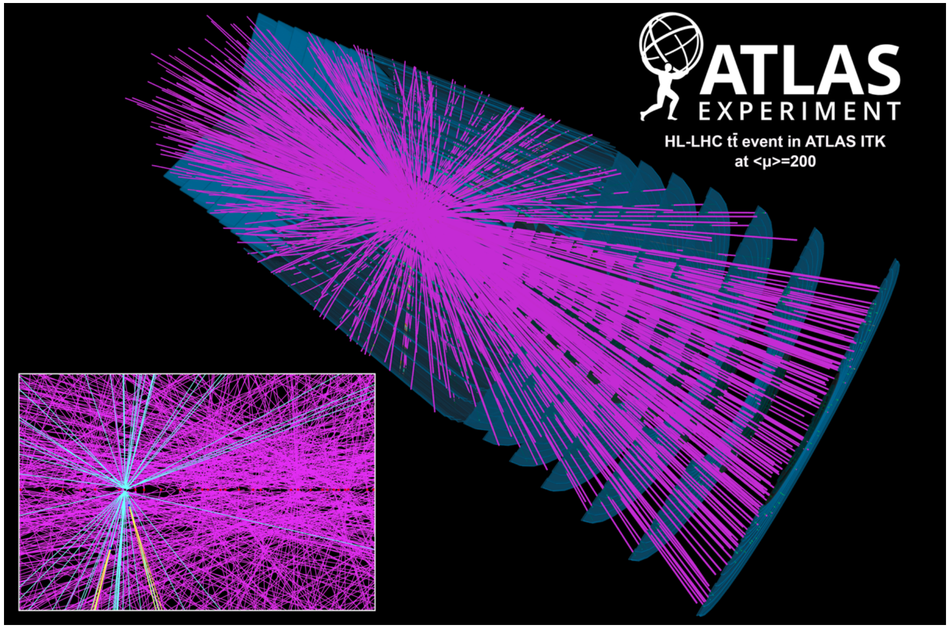
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

Machine upgrade approved by CERN council in June 2016

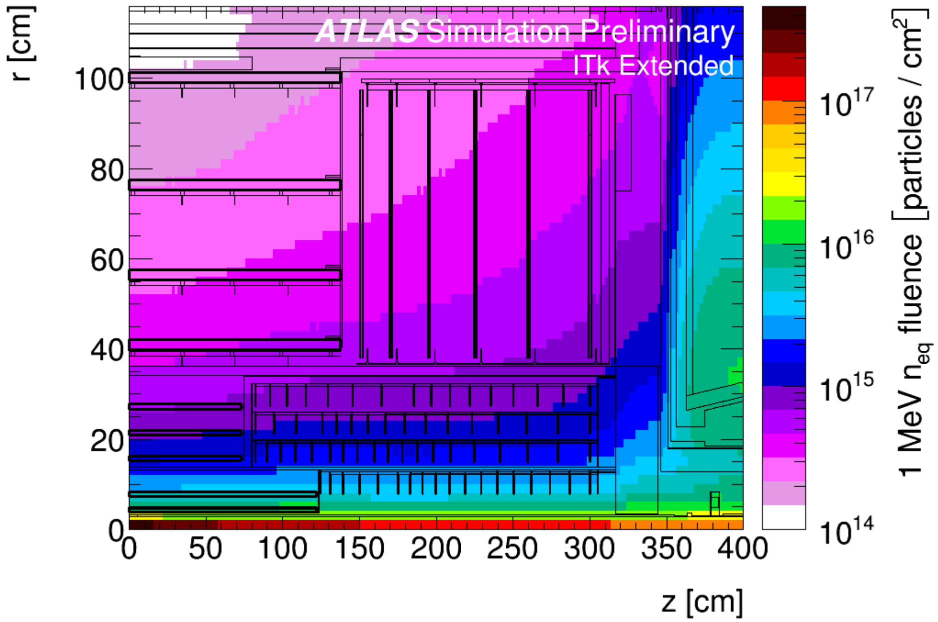
The High-Luminosity Challenge

HL-LHC provides an extreme challenge to the experiments

Very high pile-up

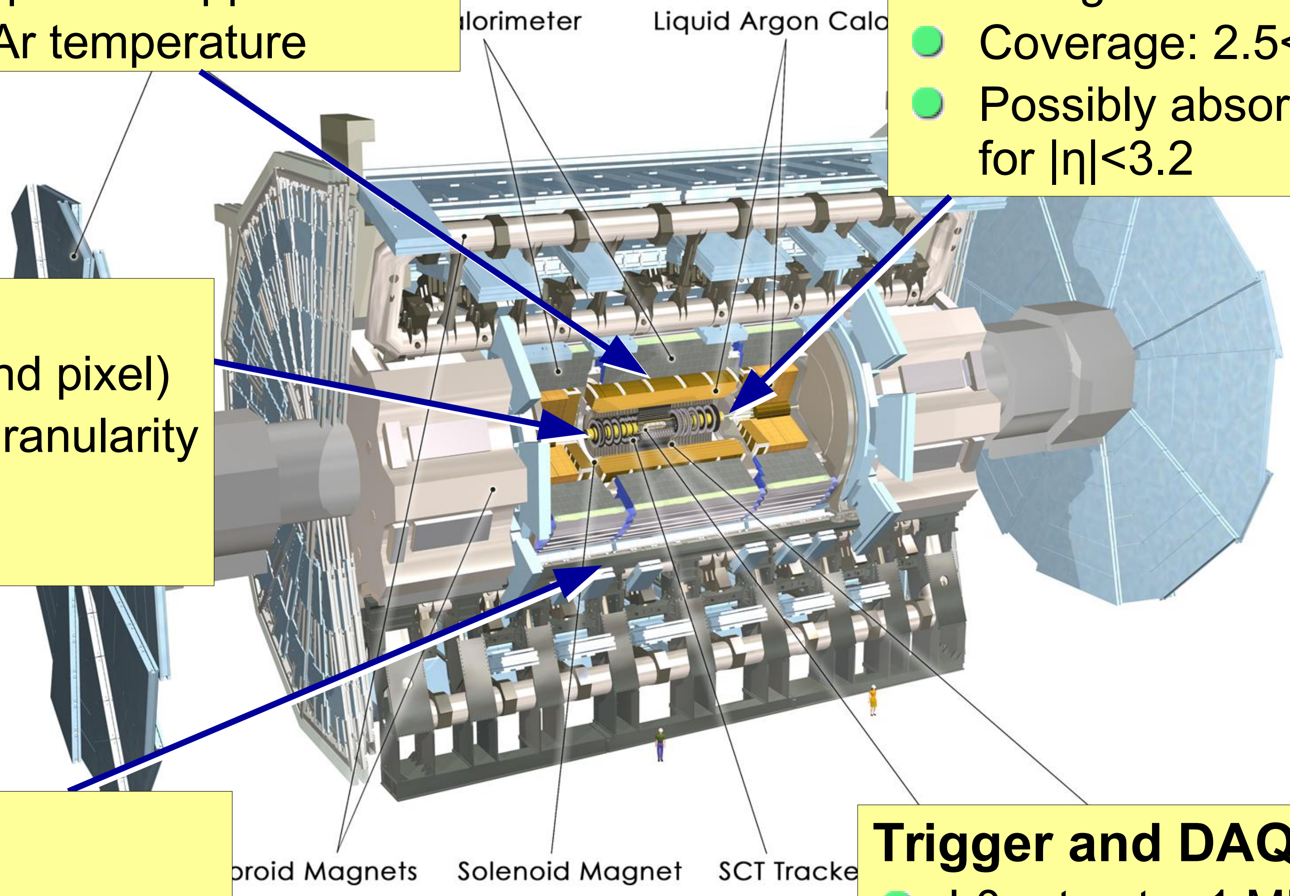


Intense radiation levels



- Major experiment 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 Upgrade – ATLAS



Calorimeters

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

(Timing detector)

- High granularity timing detector
- Coverage: $2.5<|\eta|<4.2$
- Possibly absorber for $|\eta|<3.2$

Tracker

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

Muon System

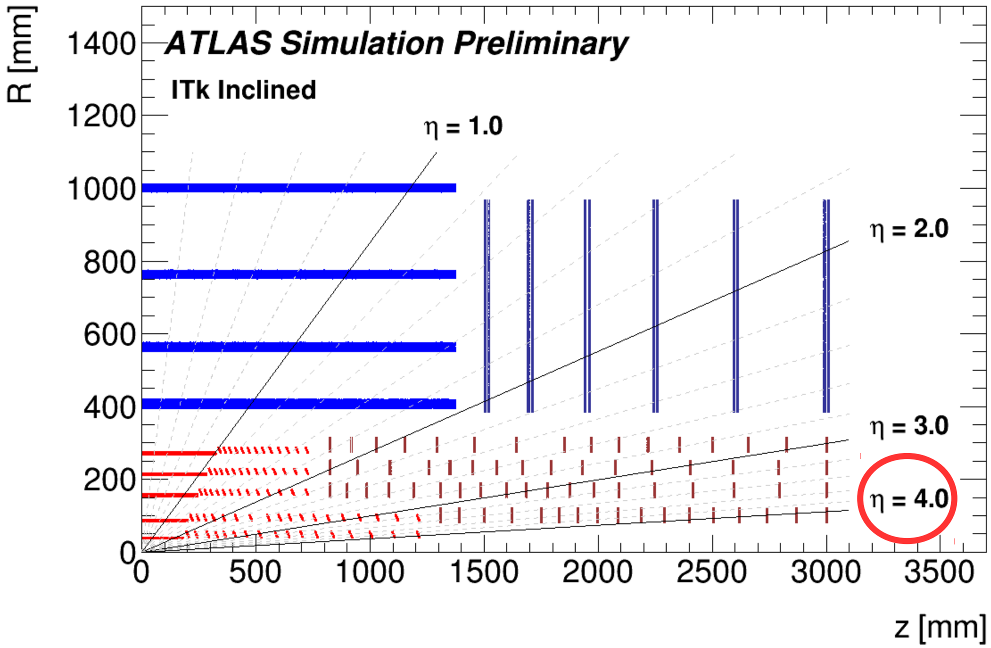
- New BE/FE electronics
- New RPC layer in inner barrel
- Muon-tagging in $2.7<|\eta|<4.0$ (under study)

Trigger and DAQ

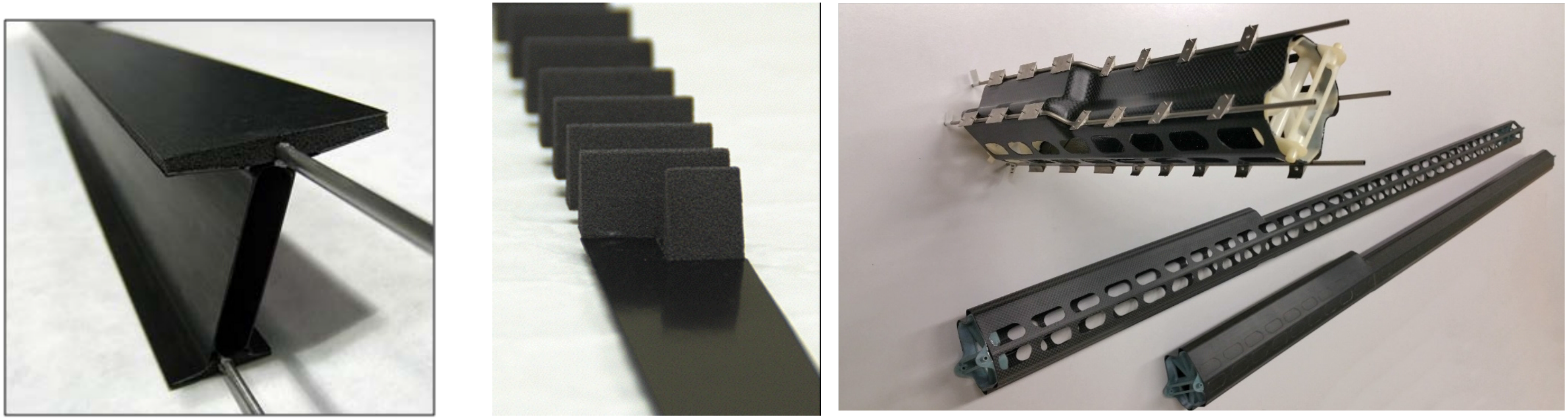
- L0 rate at ~ 1 MHz (latency up to 10 μs)
- Possible hardware L1 track trigger
- HLT output ~10 kHz

Extended Silicon-based Tracker

- ATLAS (and CMS) plan to extend tracker coverage to η~4 with pixel extension
- Provides multiple benefits
  - Extended lepton coverage (with forward muon tagger)
  - Forward b-tagging
  - Improved vertexing
- Primary benefit is pile-up suppression



Possible support structures for large η pixel detector

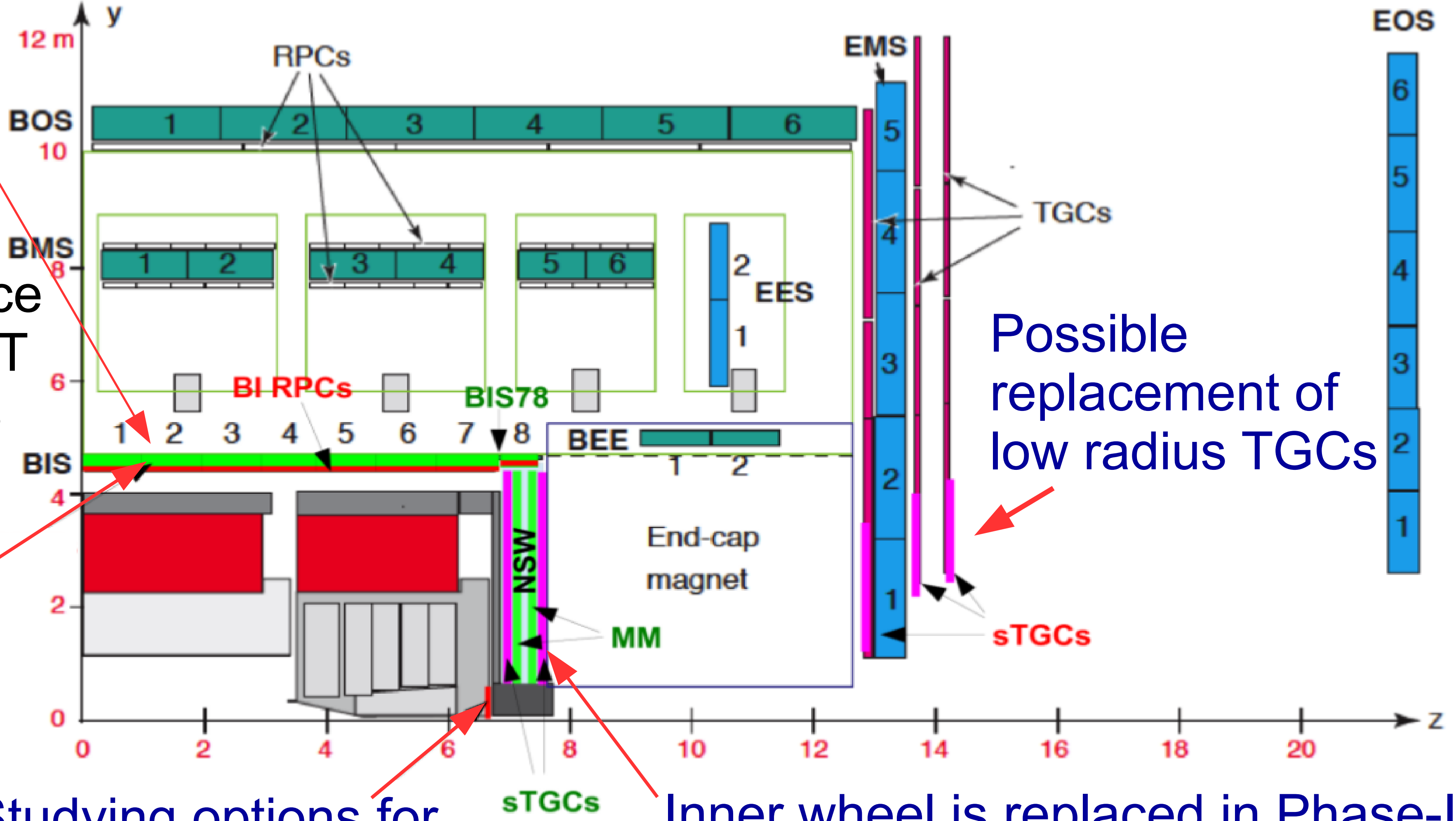


Muon System Upgrades

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

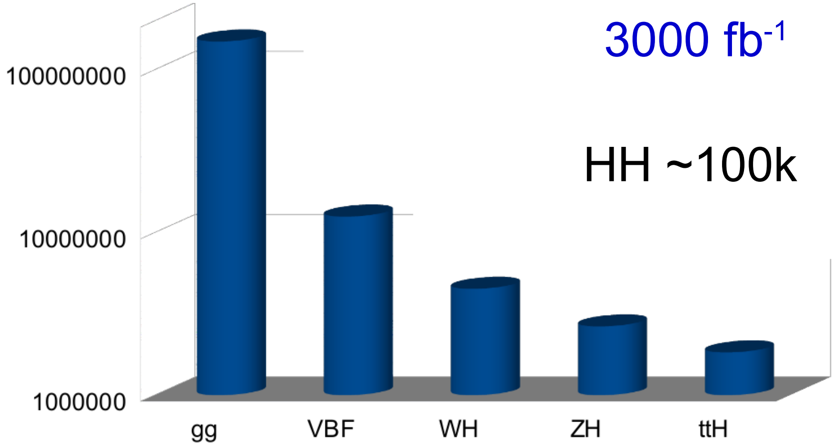
Inner wheel is replaced in Phase-I

Higgs Physics at HL-LHC

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

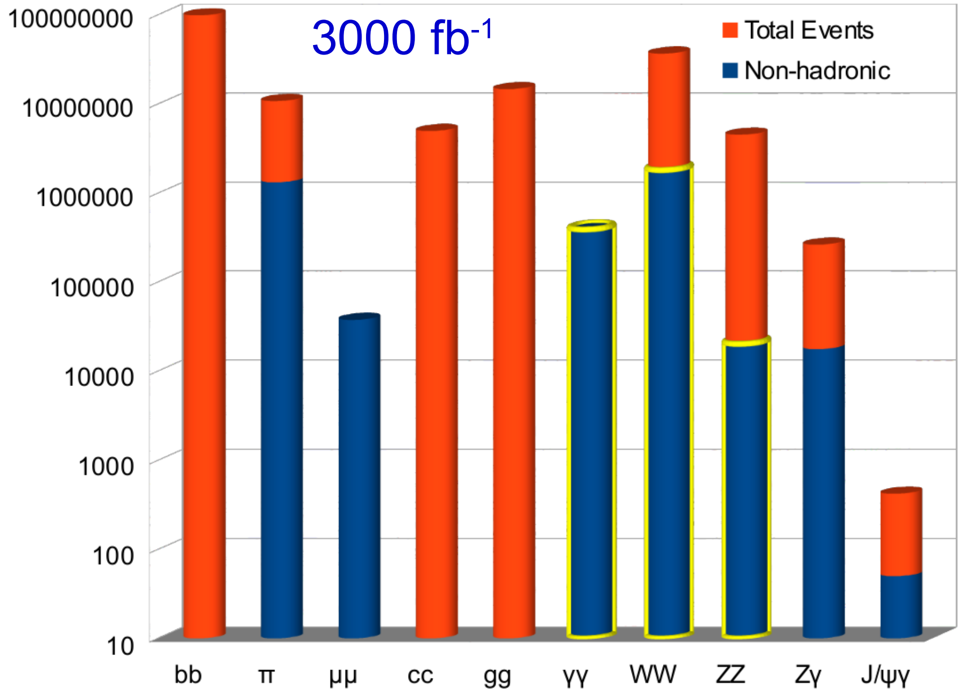
Higgs Production Channels



3000 fb^{-1}

HH ~100k

Higgs Decay Channels



3000 fb^{-1}

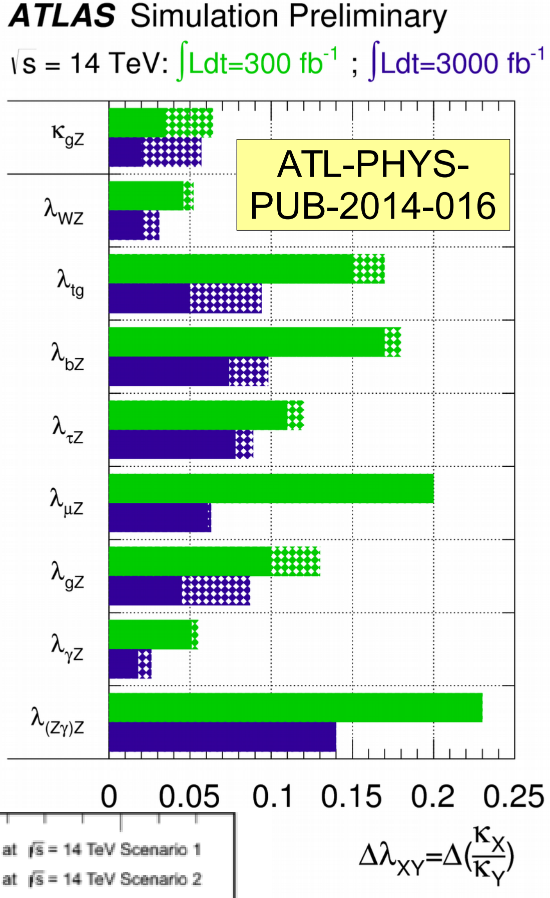
Physics Projections

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
  - For 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
  - ~7% for μ
  - 5-10% for t, b and τ
- Do not include improved detector designs or improvements in analysis techniques



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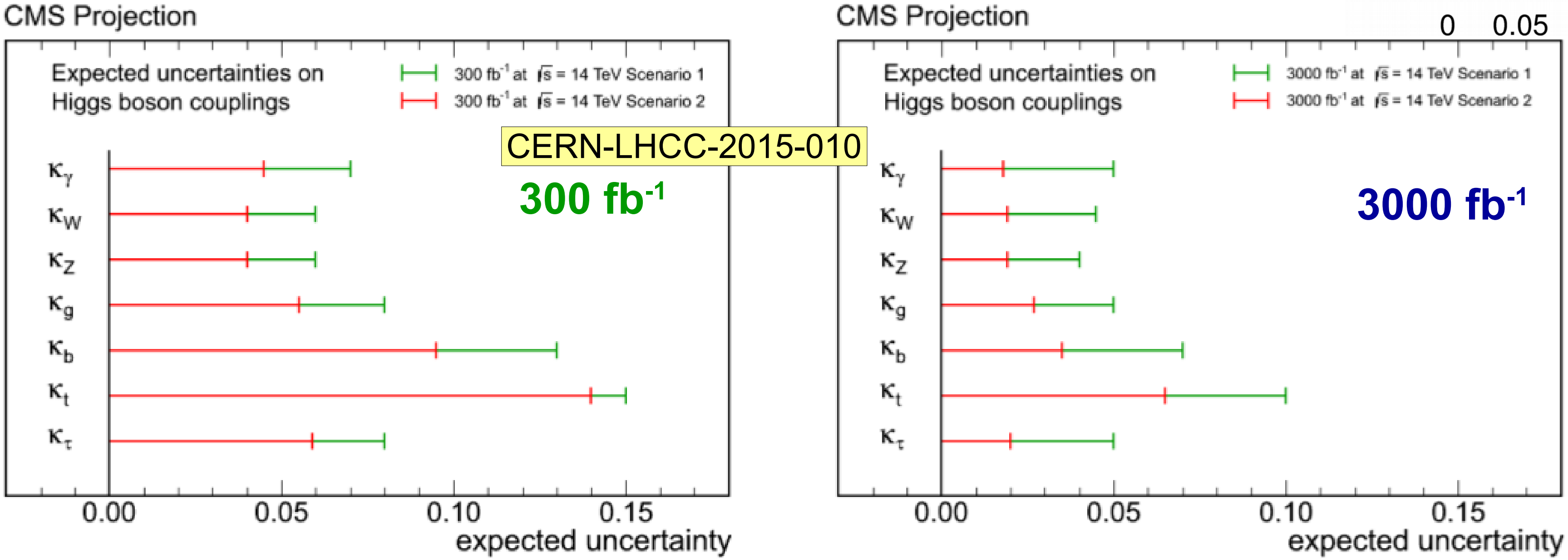


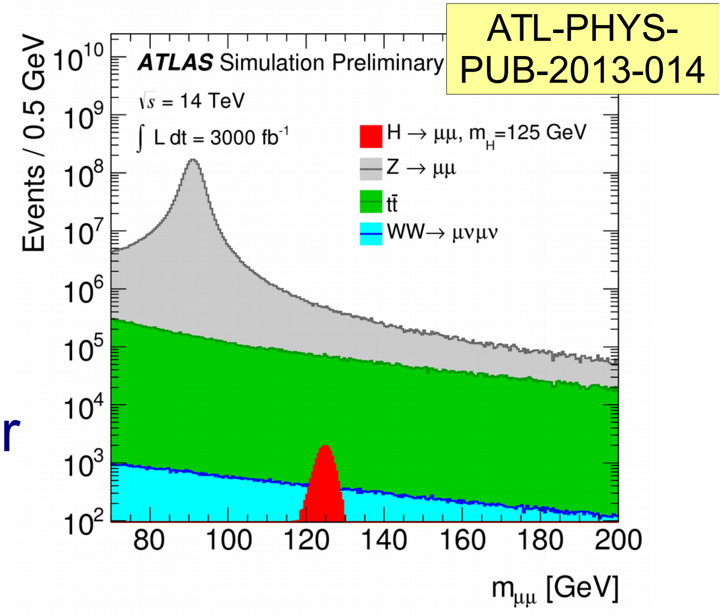
CERN-LHCC-2015-010

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

Probes Higgs coupling to 2nd generation quarks/leptons

$H \rightarrow \mu^+\mu^-$

- BR($H \rightarrow \mu^+\mu^-$)=2.2×10^{-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, $H \rightarrow \mu^+\mu^-$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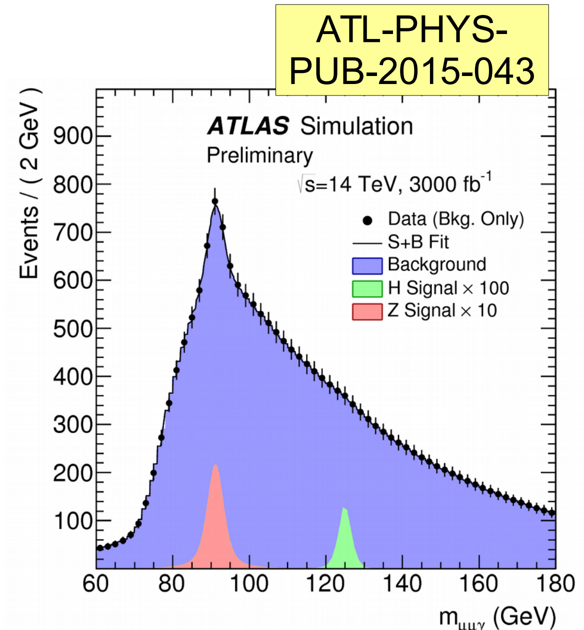
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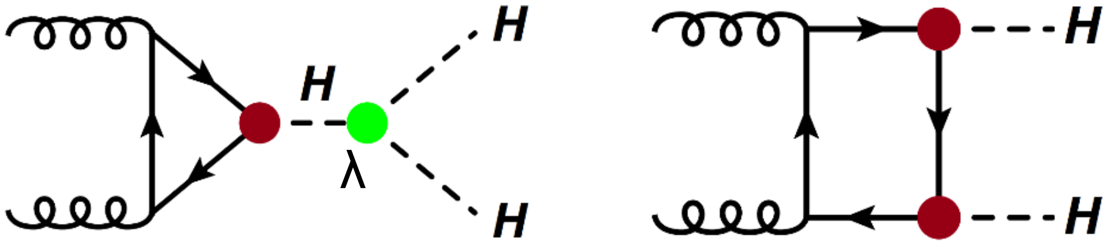
$H \rightarrow J/\psi\gamma$

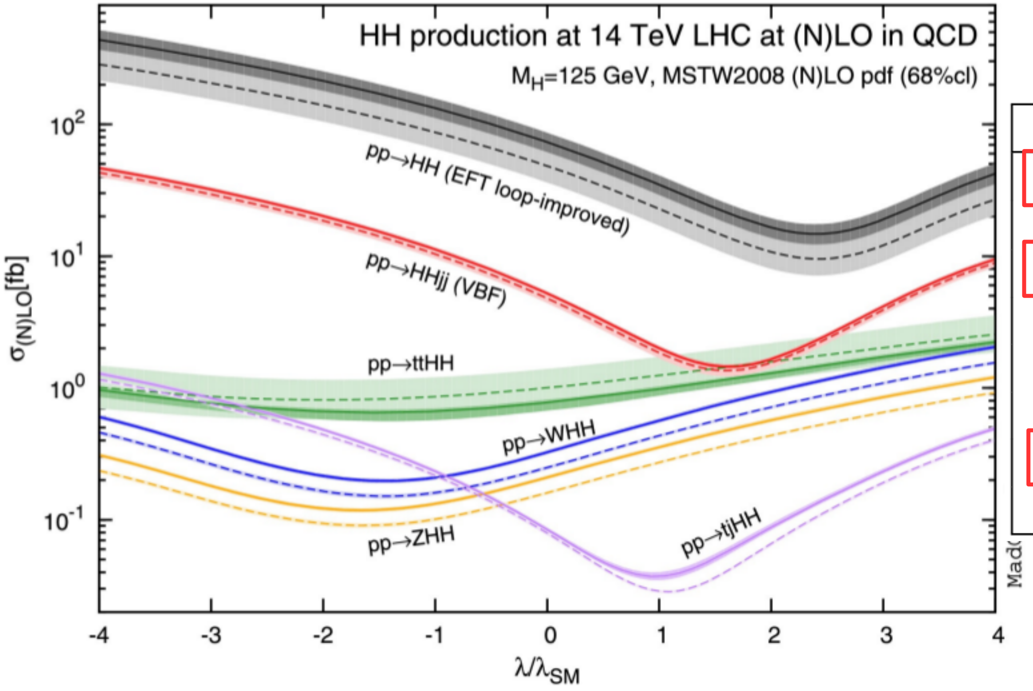
- BR($H \rightarrow J/\psi\gamma$)=$2.9 \times 10^{-6}$ in SM
  - ATLAS Run-1 limit at 95% CL: BR($H \rightarrow J/\psi\gamma$)<$1.5 \times 10^{-3}$
- Multivariate analysis for HL-LHC projection
  - With 3000 fb^{-1} will have just 3 signal events and 1700 background events
  - Expected limit at 95% CL: BR($H \rightarrow J/\psi\gamma$)<$(44^{+19}_{-12}) \times 10^{-6}$

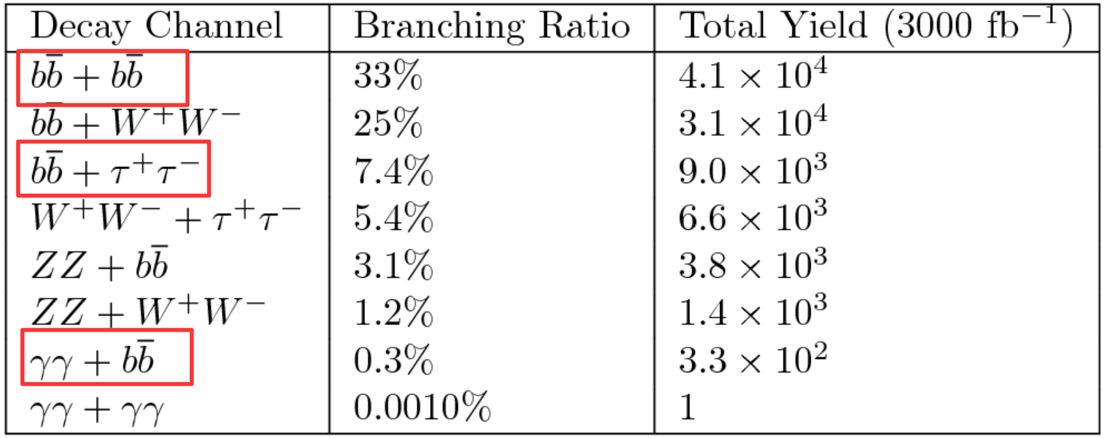
Higgs Self Coupling

- 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



- 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→$b\bar{b}\gamma\gamma$ Analysis

- Low statistics, but high purity channel
- After selections expect 8.4 signal events and 47 background events
- Corresponds to signal significance of 1.3σ

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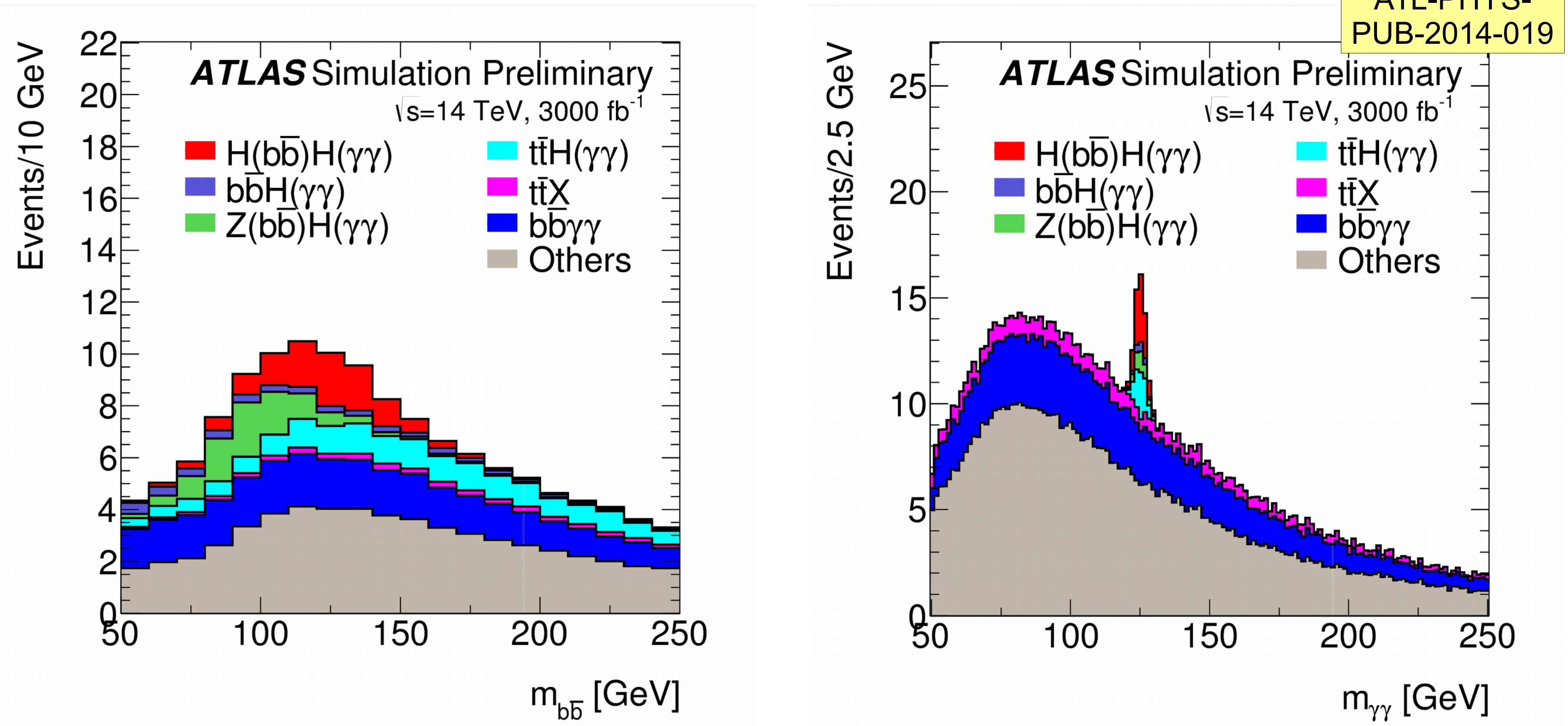


95% CL limits on self-coupling (ignoring systematics): $-1.3<\lambda/\lambda_{SM}<8.7$

HH→$b\bar{b}\tau^+\tau^-$ Analysis

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

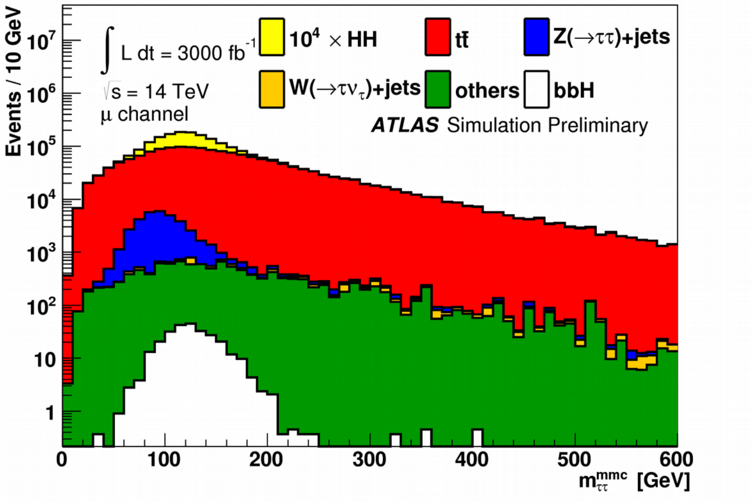
Event yields for 3000 fb-1 using a cut-based analysis strategy:

	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		
$\tau_{\text{had}}\tau_{\text{had}}$	0.41	0.41	

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



m($b\bar{b}$)

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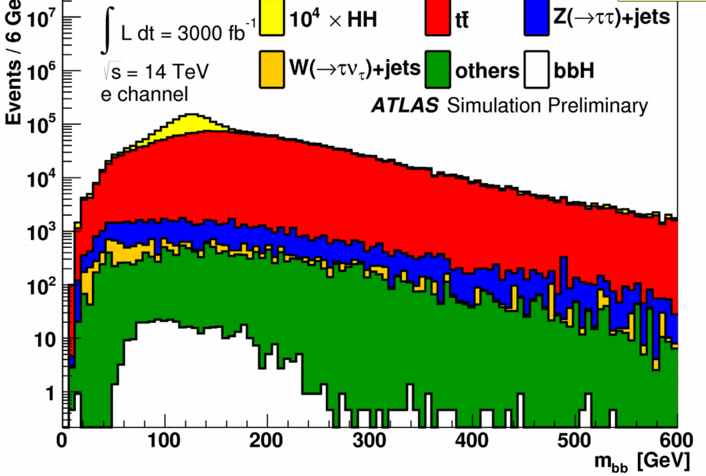
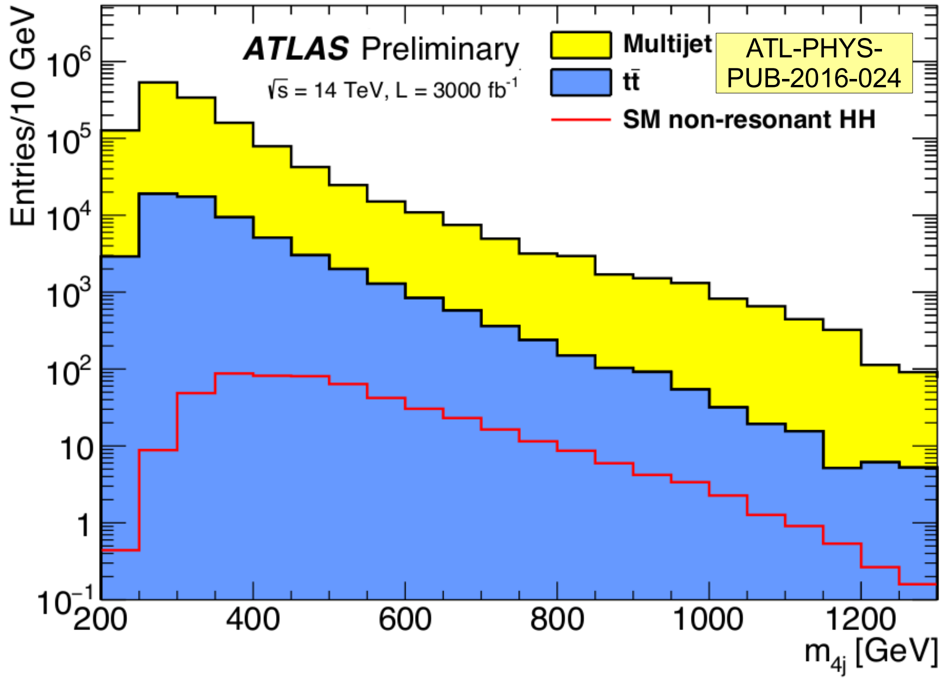


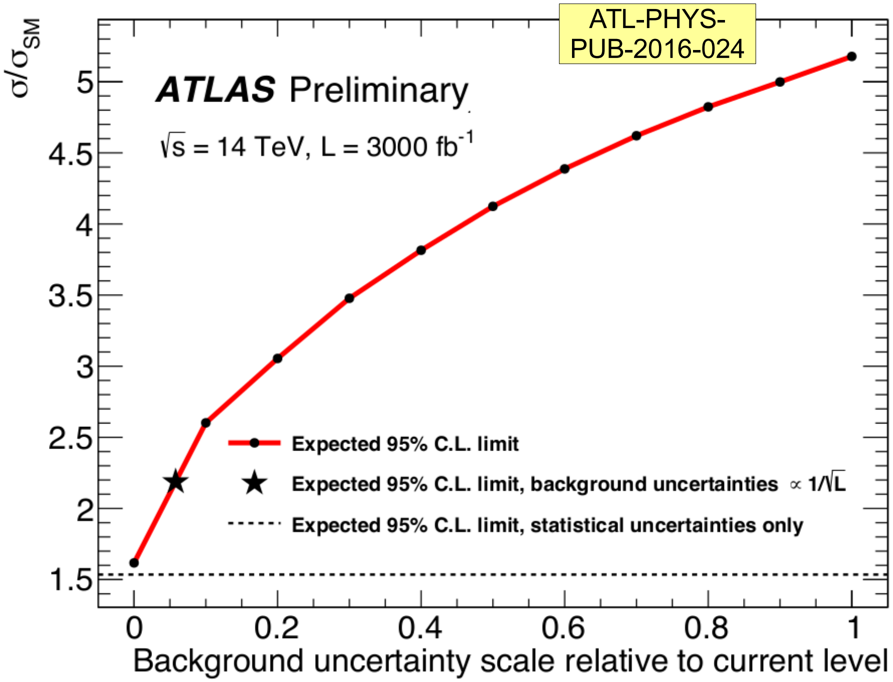
95% CL limits on self-coupling: $-4<\lambda/\lambda_{SM}<12$

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





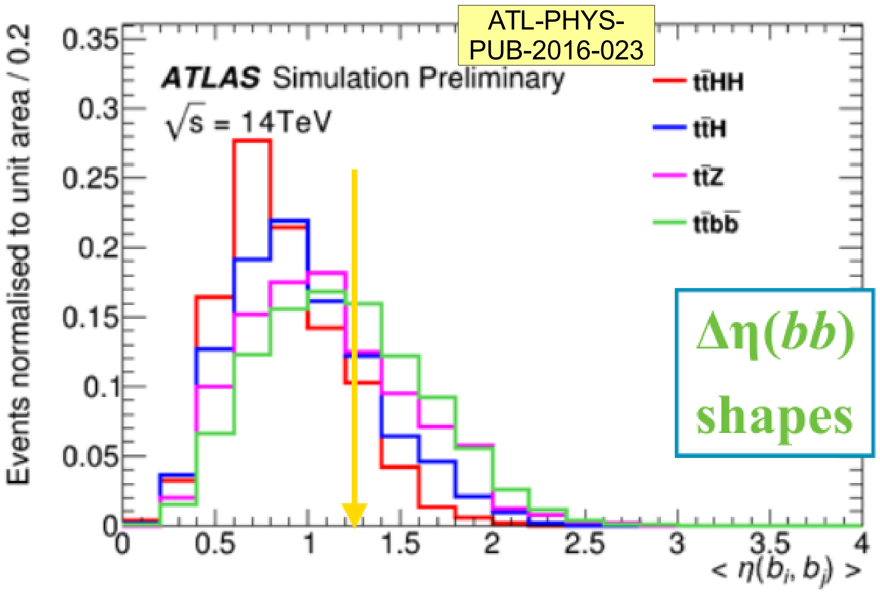
- Neglecting systematics expect

  $0.2<\lambda/\lambda_{SM}<7$ at 95% CL
    - Best of the measurements
- If assuming todays systematics:

  $-3.5<\lambda/\lambda_{SM}<11$ at 95% CL
    - Similar to HH→$b\bar{b}\tau^{+}\tau^{-}$

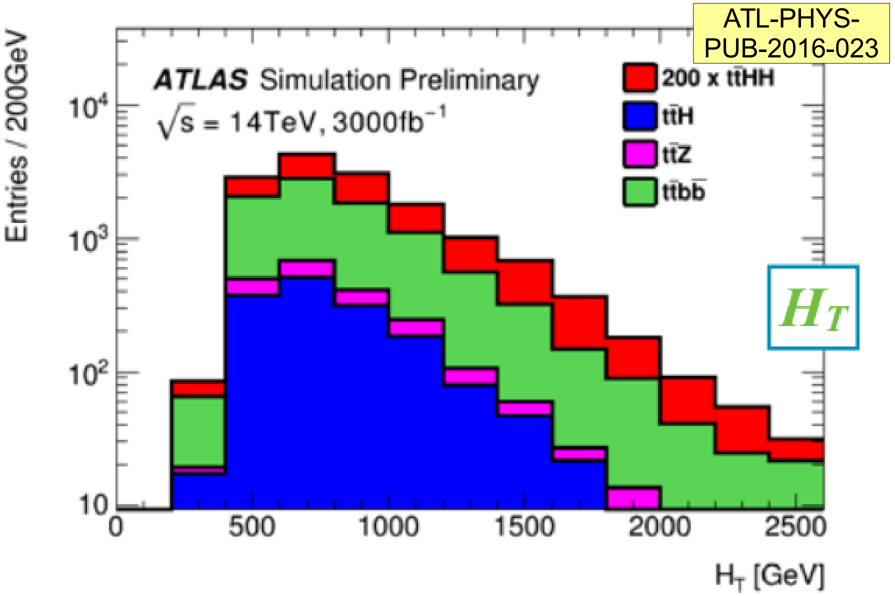
Search for $t\bar{t}HH$ Production

- $\sigma(t\bar{t}HH)$ only ~1fb, but more handles to suppress backgrounds
  - Use $HH\rightarrow b\bar{b}b\bar{b}$ final state and semi-leptonic tt 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



ATL-PHYS-PUB-2016-023

Δη(*bb*) shapes



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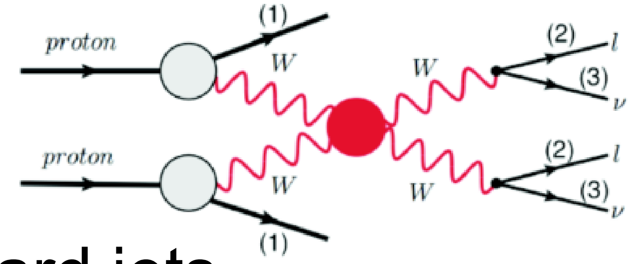
H_T

- 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

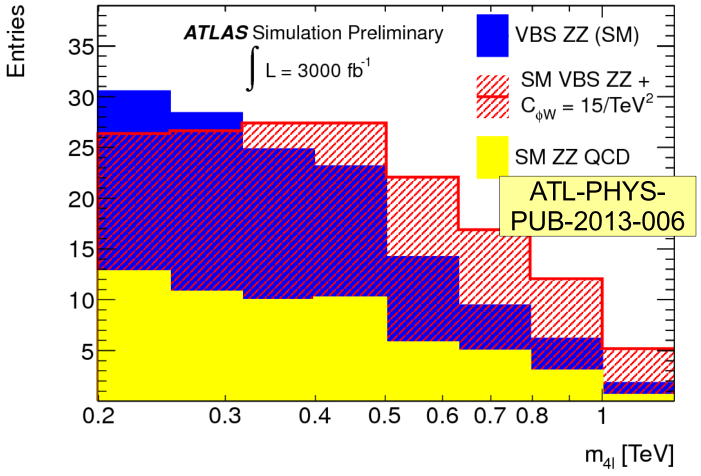
Precision Measurements

Vector Boson Scattering

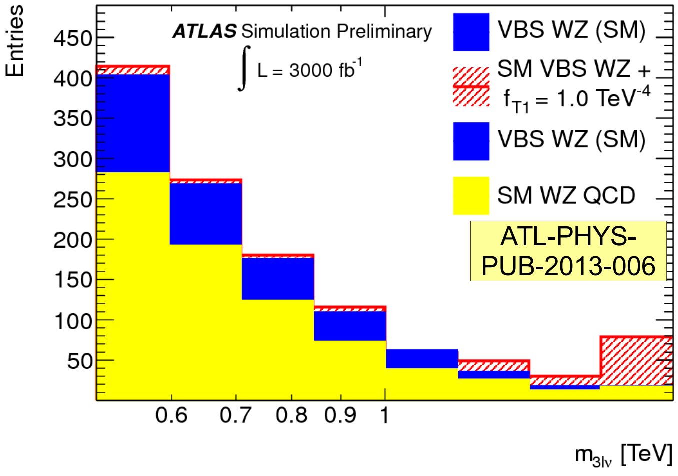


- Vector Boson Scattering probes the quartic gauge boson couplings and EW symmetry breaking
- Striking experimental signature of two forward jets
  - Provides additional motivation for forward tracker extension
- Using leptonic decays clean observations on ZZ, WZ and $W^{\pm}W^{\pm}$ boson scattering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

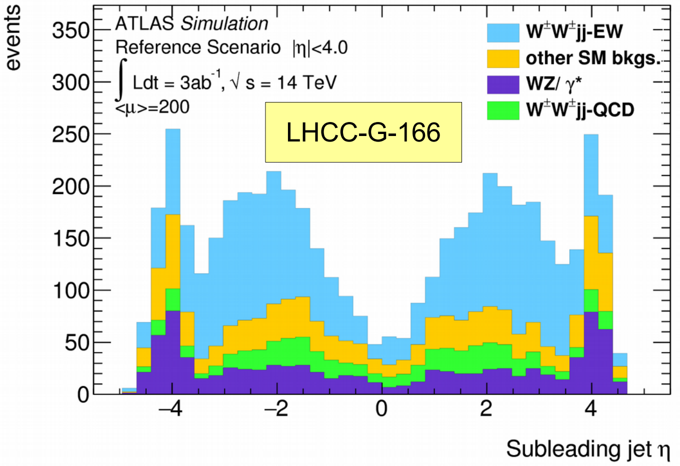
$ZZ\to\ell\ell\ell\ell$



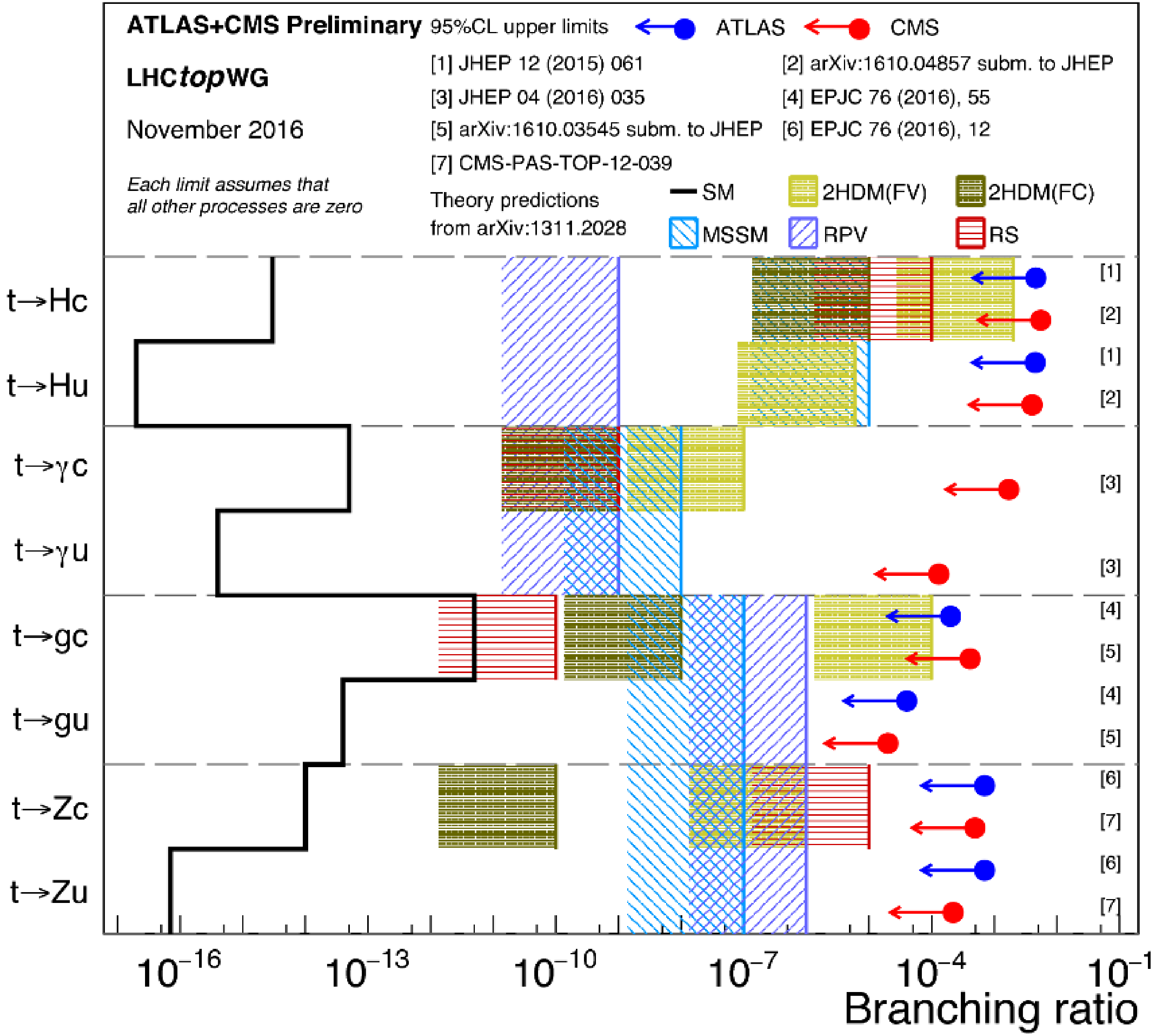
$WZ\to\ell\nu\ell\ell$



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



Flavor-Changing Neutral Currents in top



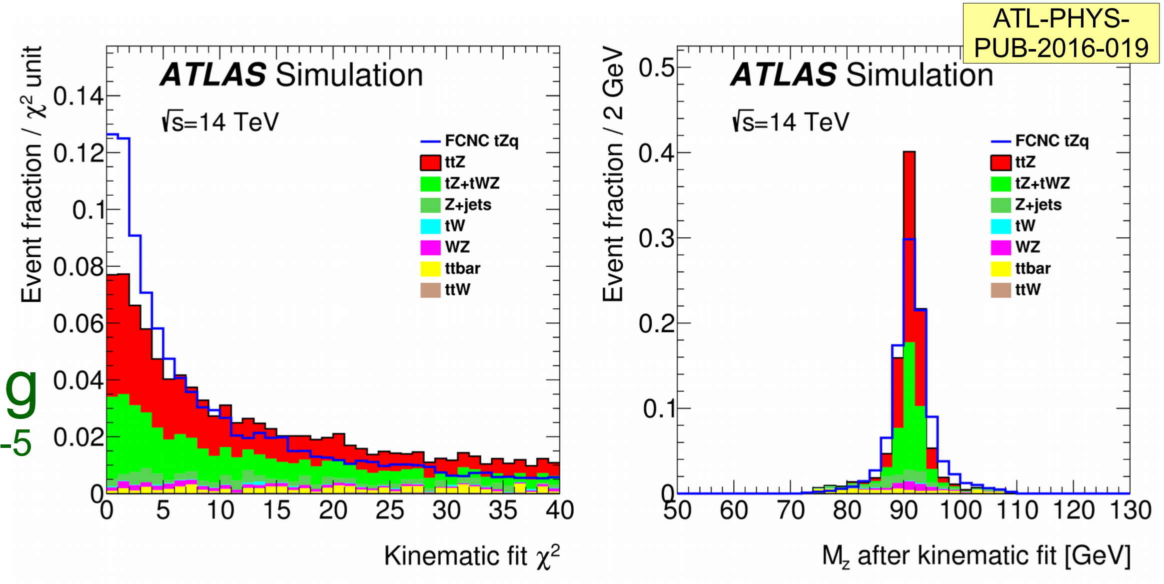
Search for t→Zq and t→Hq Decays

- 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:

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

Expected 95% CL limit assuming equal t→Zu and t→Zc: ~$2.5\text{x}10^{-5}$



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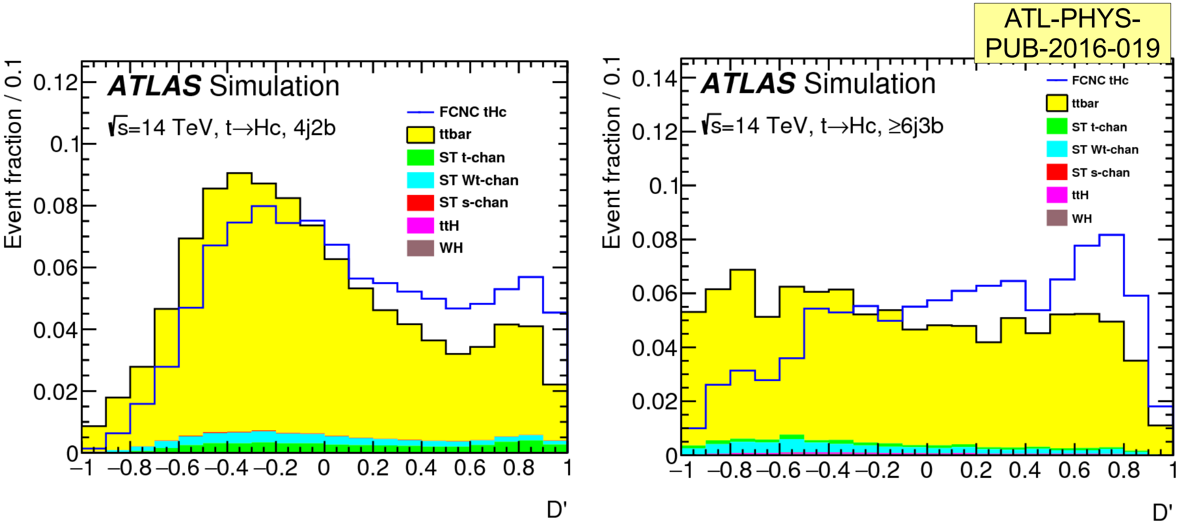

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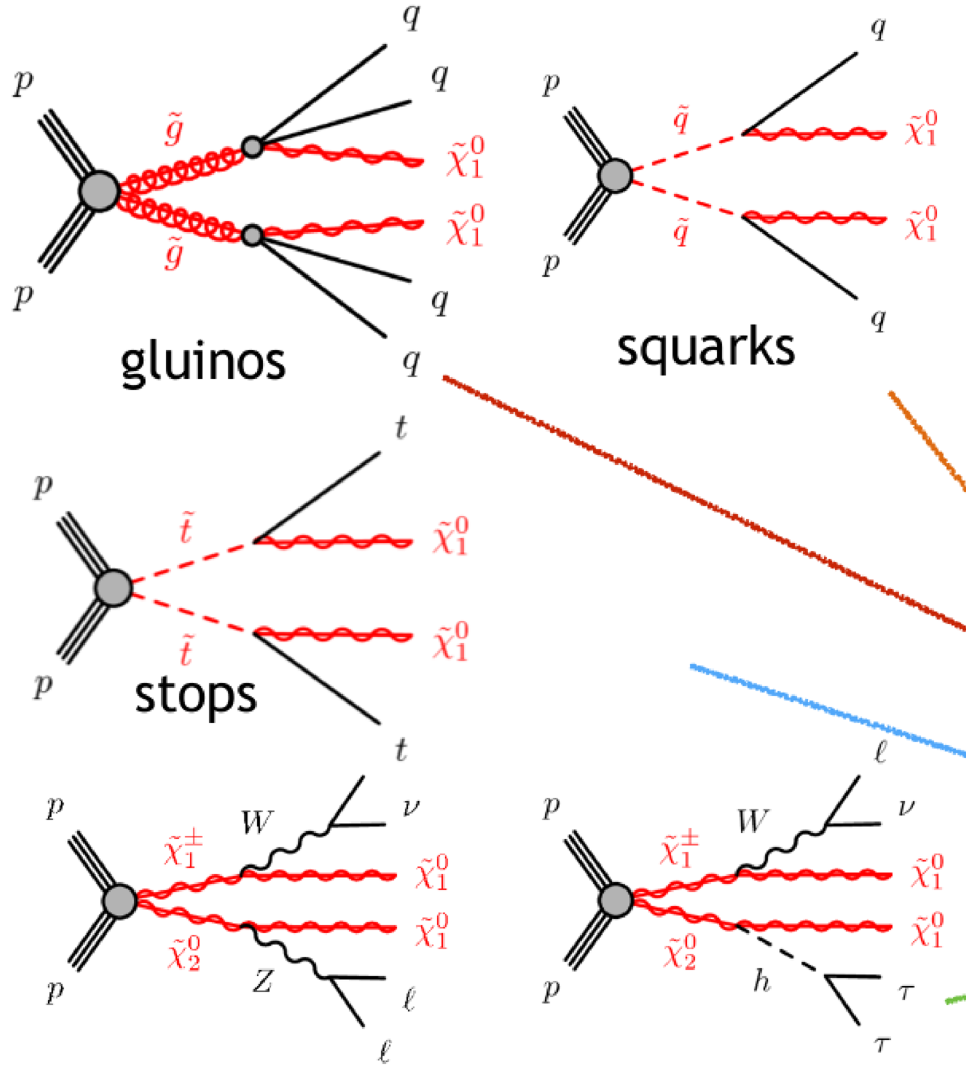
For t→Hq use H→$b\bar{b}$ and kinematic discriminant

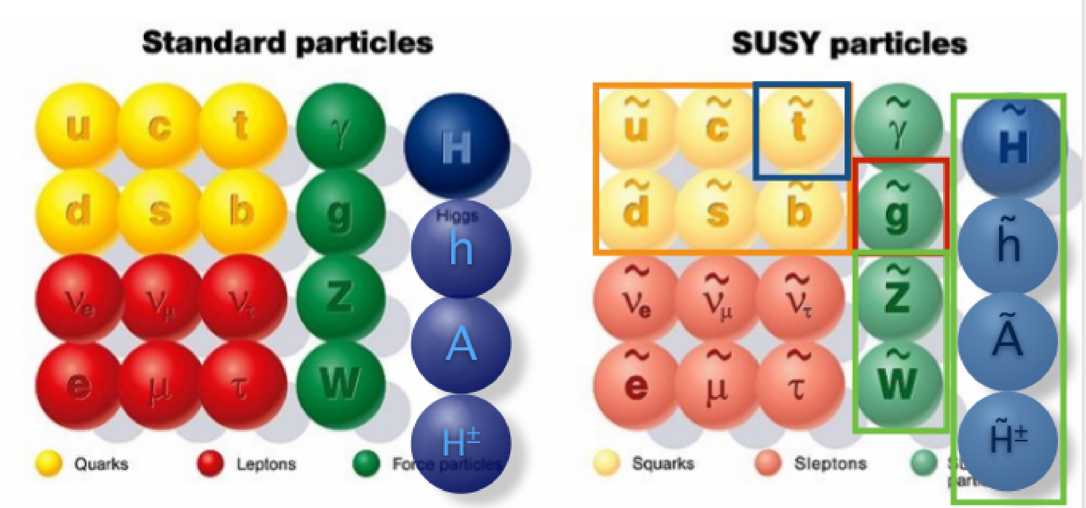
Furthermore split in categories based on reconstructed topology (#jets, #b-jets, …)

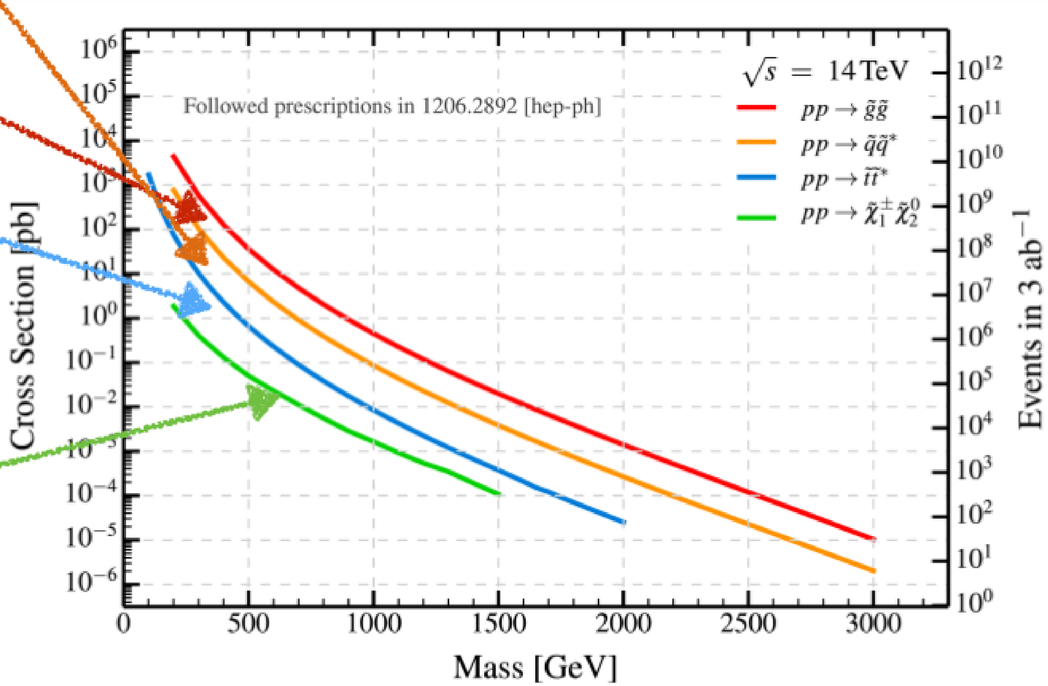
Expected 95% CL limit assuming equal t→Hu and t→Hc: ~$1.1\text{x}10^{-4}$

Beyond the Standard Model

Supersymmetry Production at LHC





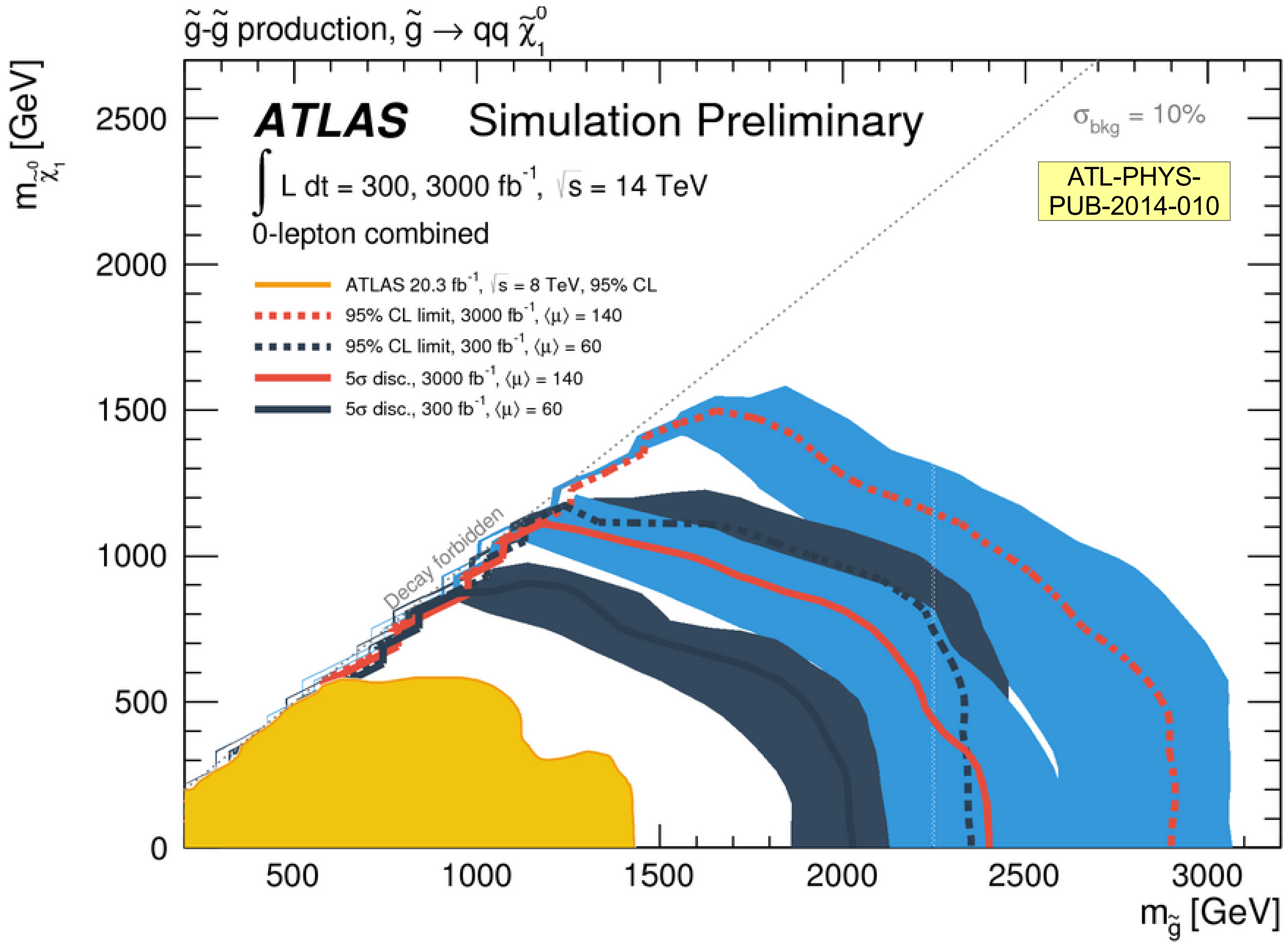


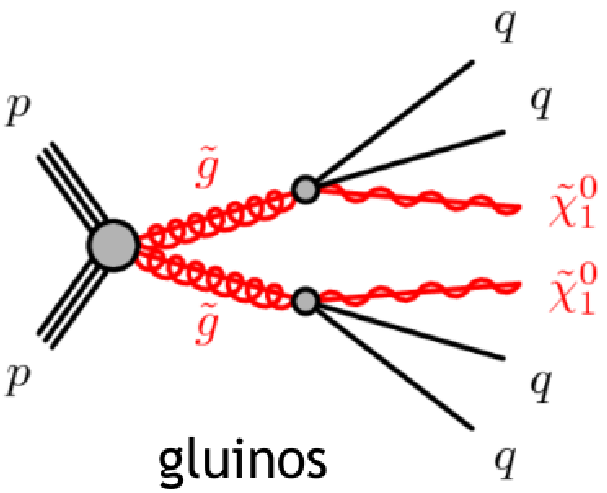
neutralinos ($\tilde{\chi}^0$) & charginos ($\tilde{\chi}^\pm$):
superpositions of Higgsinos, Wino, Bino

Lightest neutralino normally assumed to stable (Dark Matter candidate)

Search for Gluino Pair Production

In “natural SUSY” expect relatively light gluinos (~few TeV)
For example search in four jets+$E_{T,miss}$ channel for $\tilde{g}\rightarrow qq\tilde{\chi}$





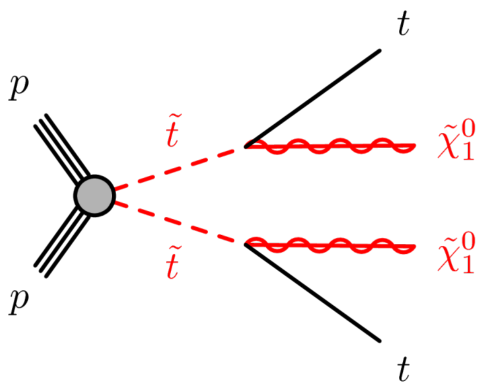
Expect to discover gluinos up to ~2 TeV for neutralinos up to 1 TeV

Exclude gluinos up to ~3 TeV

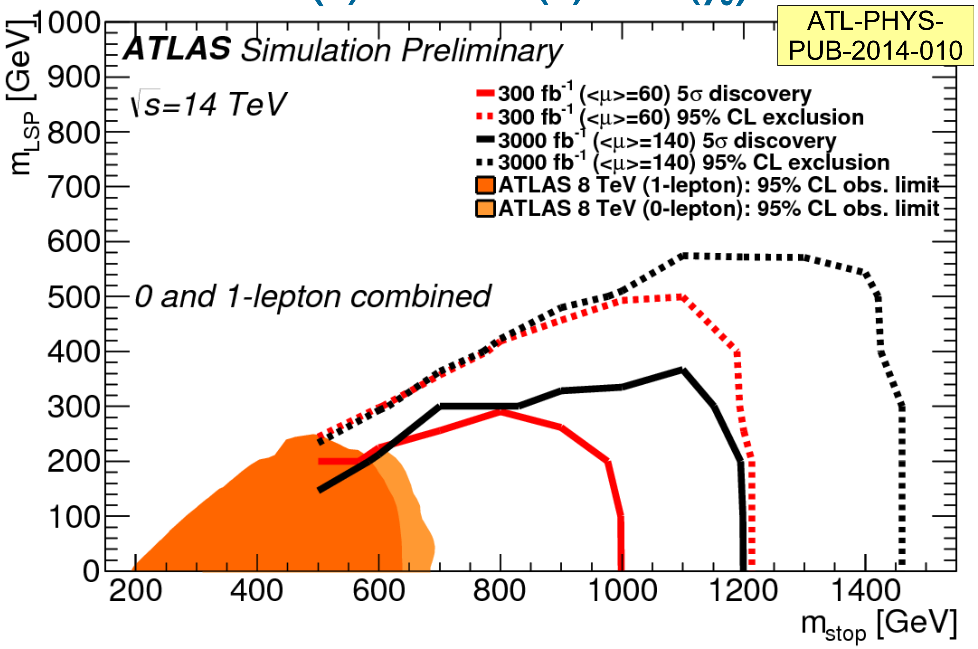
Search for Stop Pair Production

In “natural SUSY” also expect light stops (<~1 TeV)

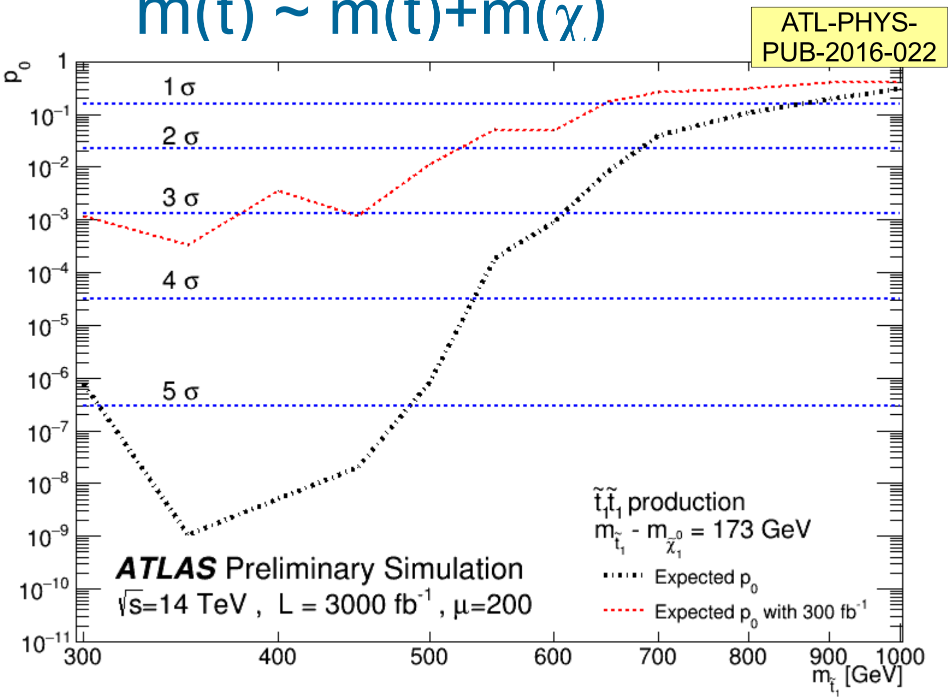
- Search for $\tilde{t}\to t\tilde{\chi}$ in two scenarios:
  - $m(\tilde{t}) >> m(t)+m(\tilde{\chi})$ using both 0 and 1 leptonic top decay
  - $m(\tilde{t}) \sim m(t)+m(\tilde{\chi})$ (compressed) using 2 leptonic top decays



$m(\tilde{t}) >> m(t)+m(\tilde{\chi})$



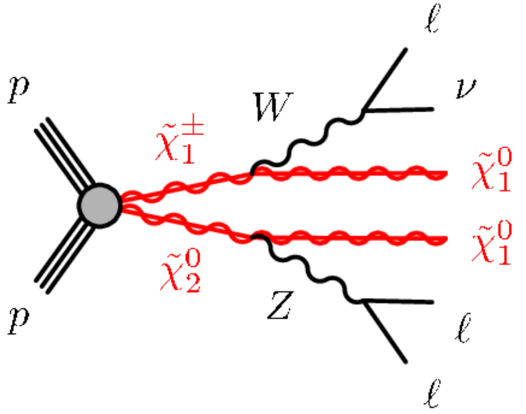
$m(\tilde{t}) \sim m(t)+m(\tilde{\chi})$

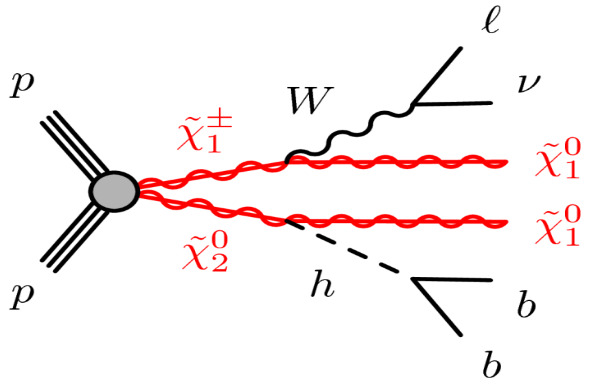


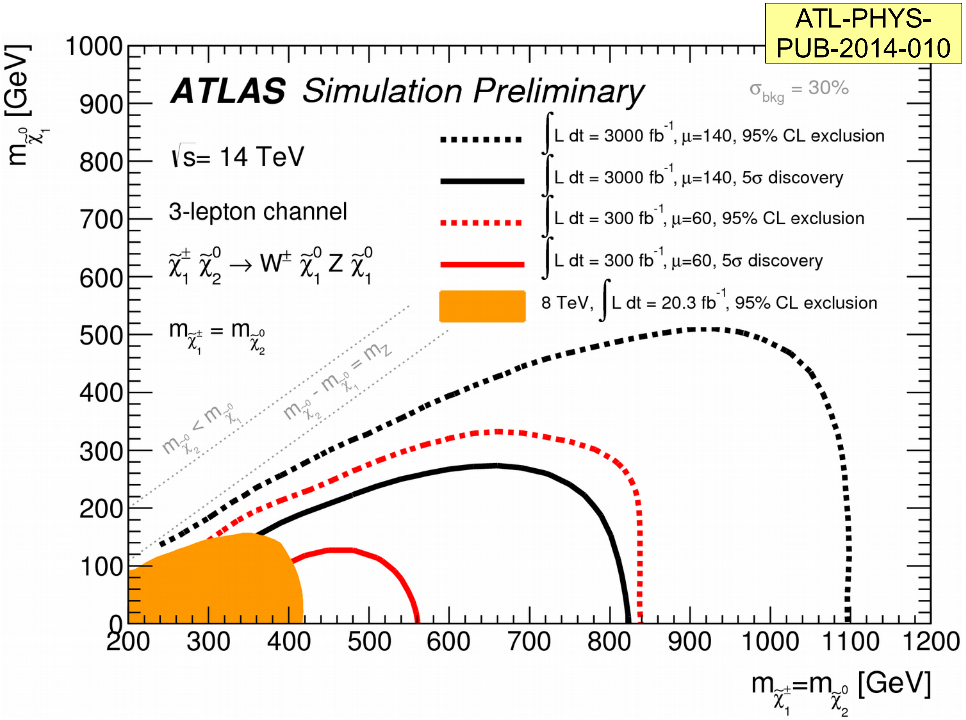
For uncompressed stop, can discover up to 1.2 TeV
For compressed stop, only 0.5 TeV

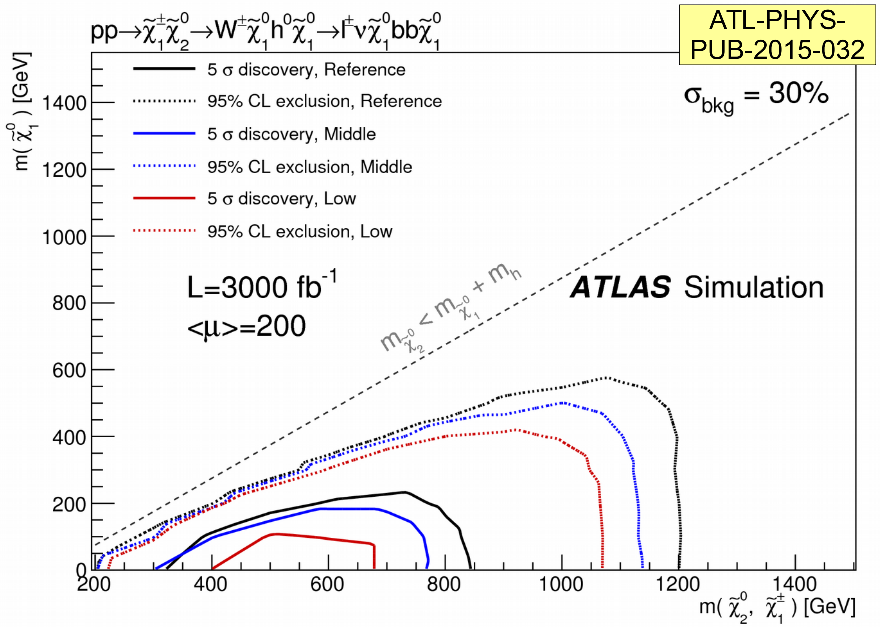
Search for Chargino-Neutralino Production

Projection for chargino-neutralino production in 2 channels:





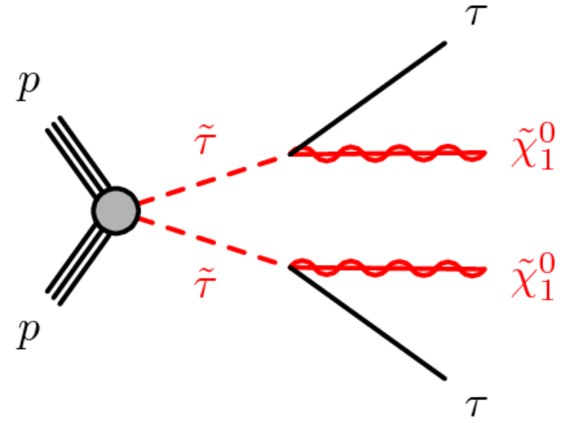

ATL-PHYS-PUB-2014-010


ATL-PHYS-PUB-2015-032

Discovery reach up to ~850 GeV

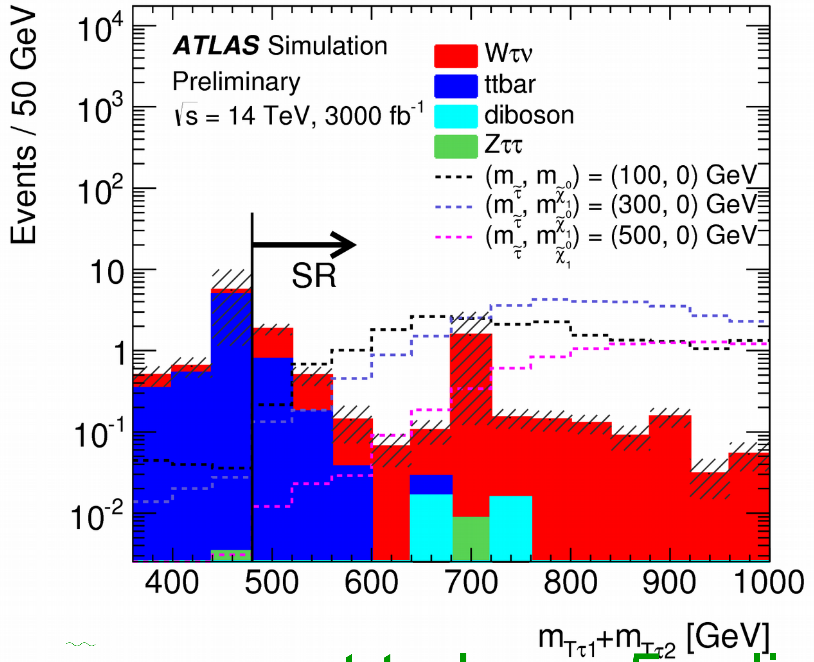
Search for Stau Pair Production

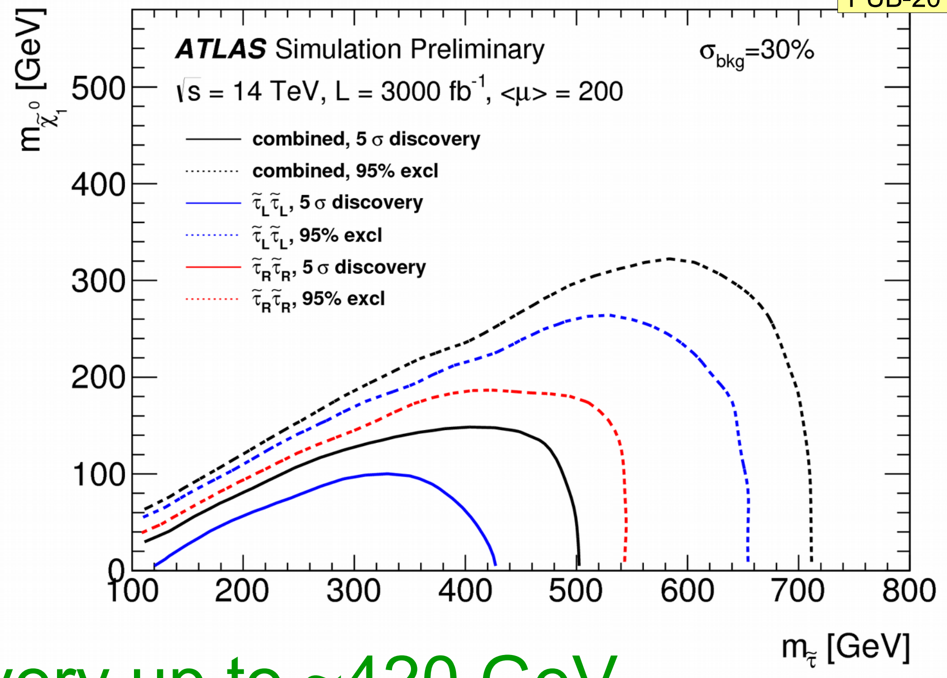
Finally HL-LHC will have sensitivity to direct slepton production



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

ATL-PHYS-PUB-2016-021



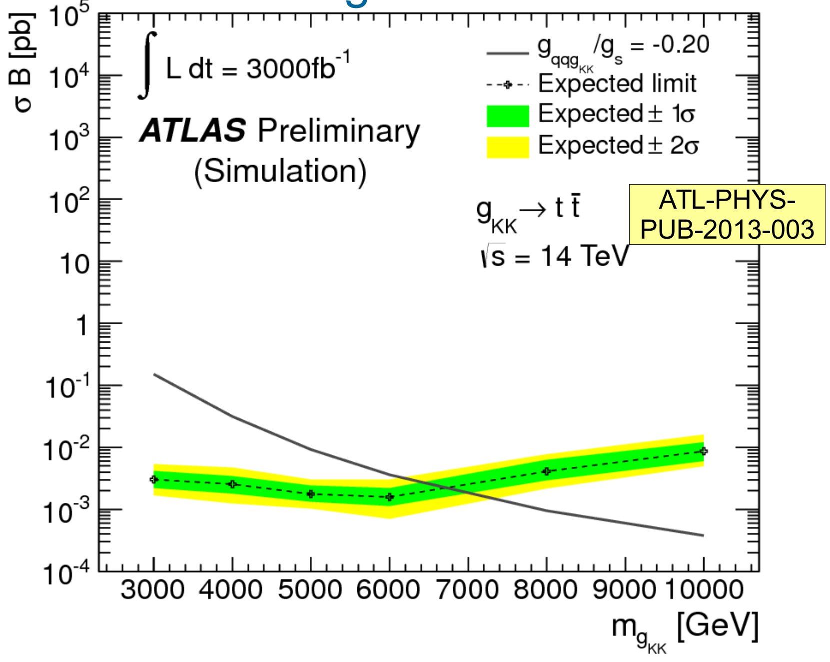


For $\tilde{\tau}_L$, expect to have 5σ discovery up to ~420 GeV, while even with 3000 fb^{-1}, do not achieve 5σ sensitivity for $\tilde{\tau}_R$

Search for Heavy Resonances

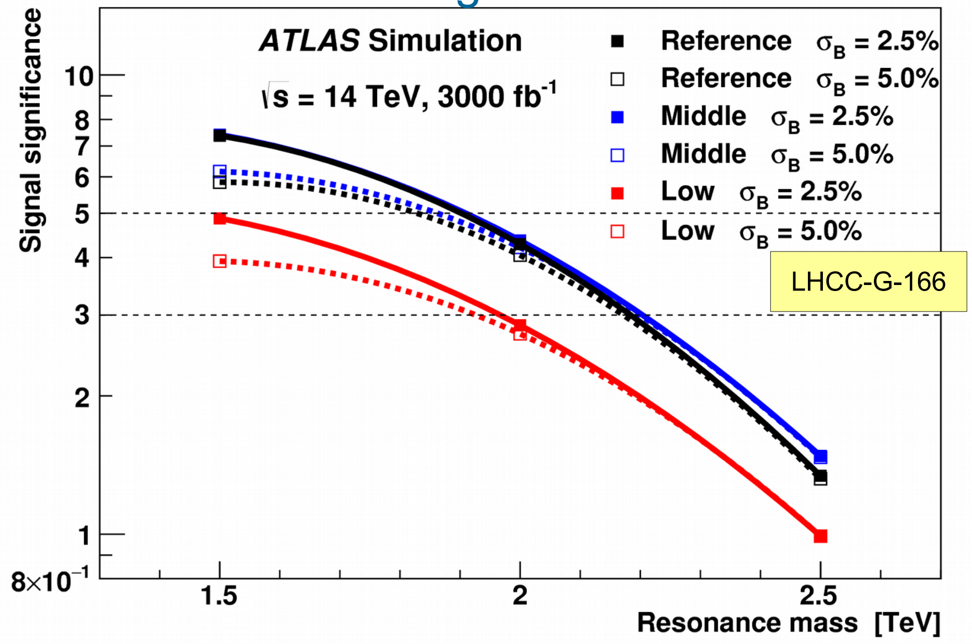
- New physics could be anywhere
  - Search for resonances in all final states di-leptons, di-jets, di-top, di-bosons (γγ, WW, WZ, ZZ, hh)…
- Only a few of these projected up to 3000 fb^{-1} so far
  - Many channels do not gain that much by more luminosity as they are close to kinematic end-point
  - More luminosity most interesting if something seen before

Kaluza-Klein gluon excitation→$t\bar{t}$



ATL-PHYS-PUB-2013-003

Kaluza-Klein graviton excitation→$t\bar{t}$

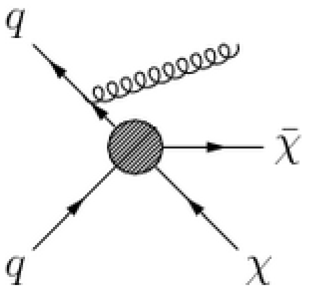


LHCC-G-166

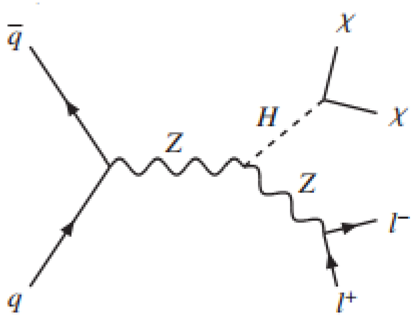
Search for WIMP Candidates

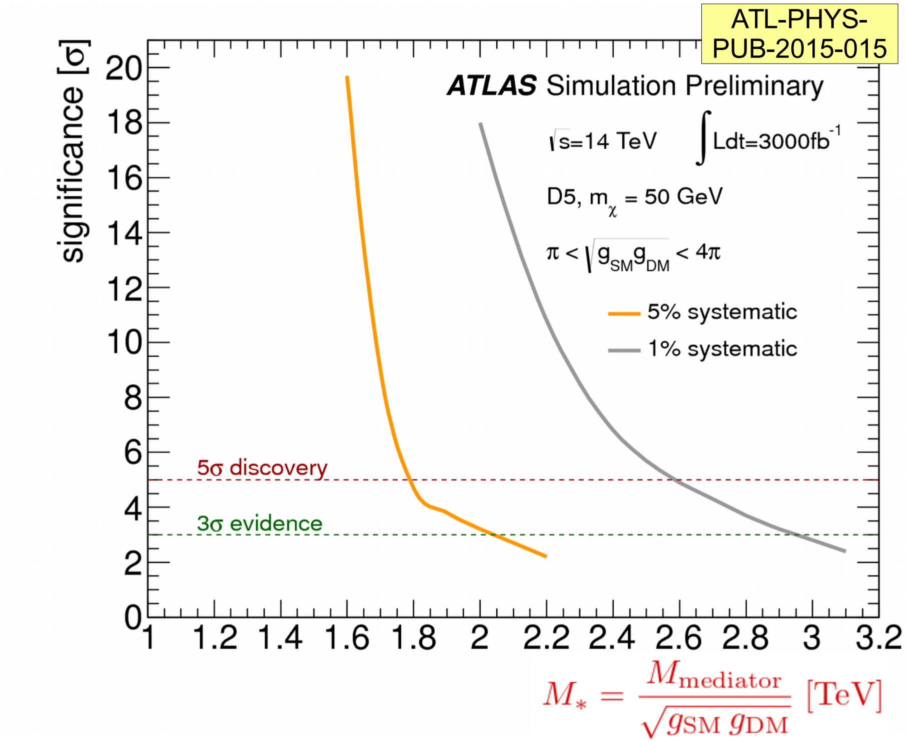
- ATLAS also has sensitivity to non-SUSY WIMP models

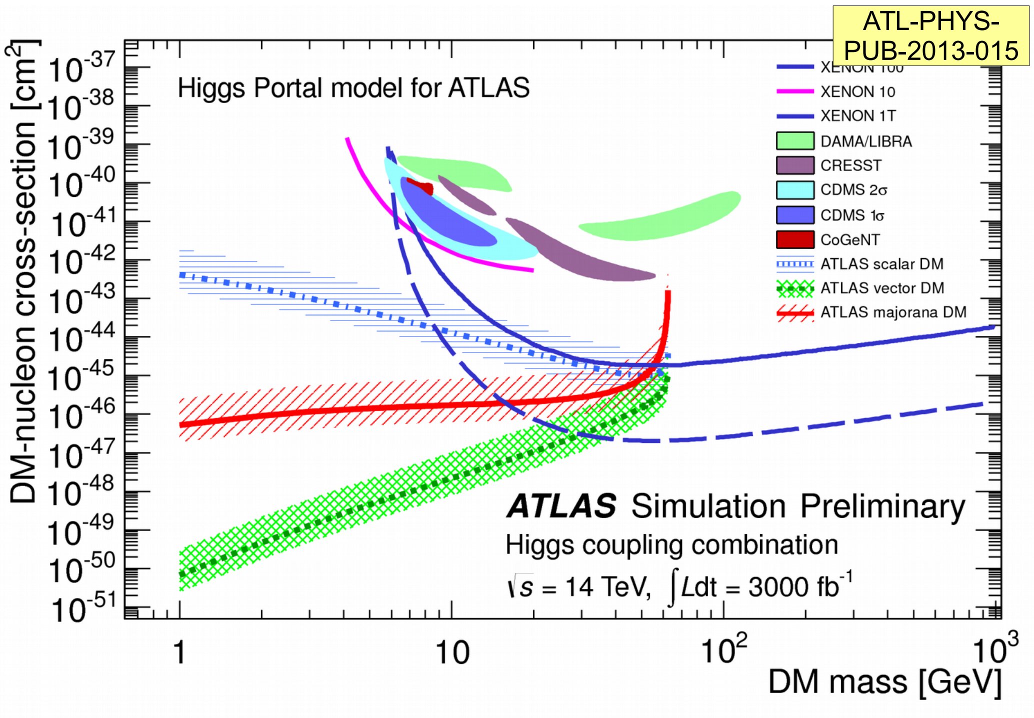
For example with canonical mono-jet signature:



Or invisible Higgs Boson decays:





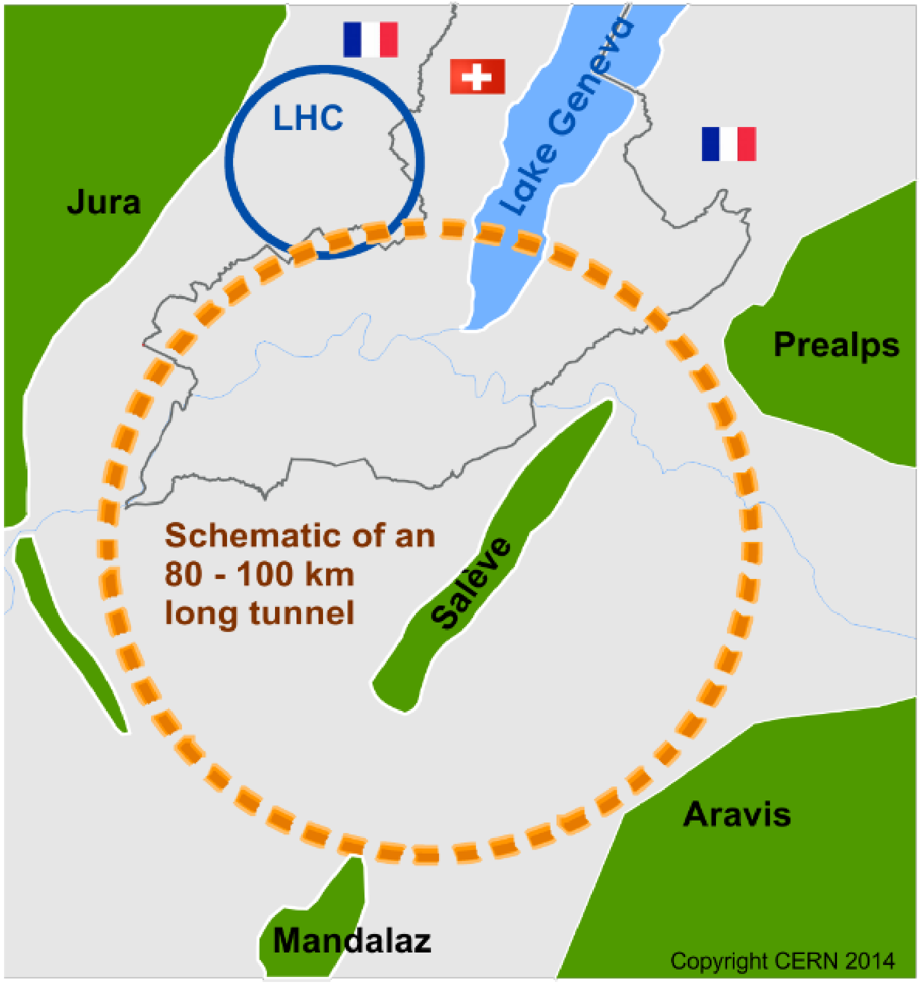


Future Circular Colliders

CERN is Studying Next Collider

Conceptual design studies of colliders in ~100 km ring

- pp collider (FCC-hh)
  - Primary motivation for FCC studies
  - √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 √s~30 TeV)
- e$^+$e$^-$ collider (FCC-ee)
  - √s~90-350 GeV, L~200-2x10^{34}cm^{-2}s^{-1}
2 IPs and 20 ab^{-1}/expt
- pe collider (FCC-he):
  - √s~3.5 TeV, L~10^{34} cm^{-2}s^{-1}

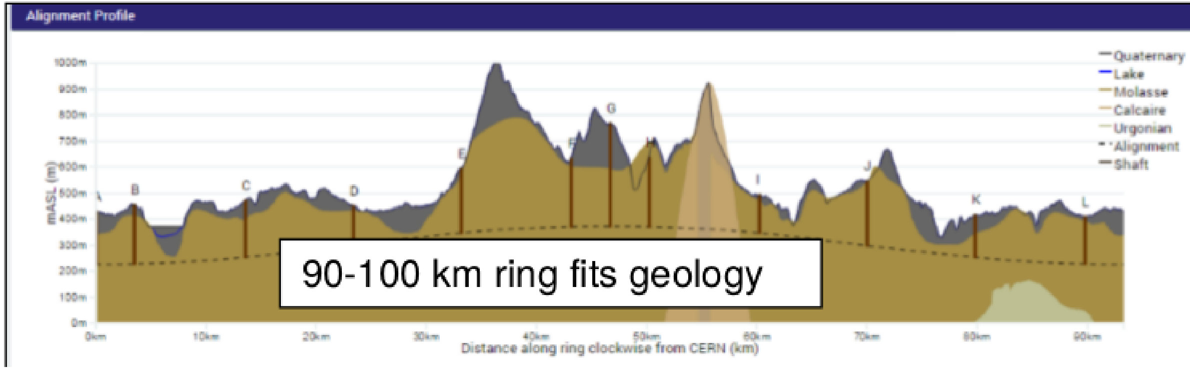


Schematic of an 80 - 100 km long tunnel

Copyright CERN 2014

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

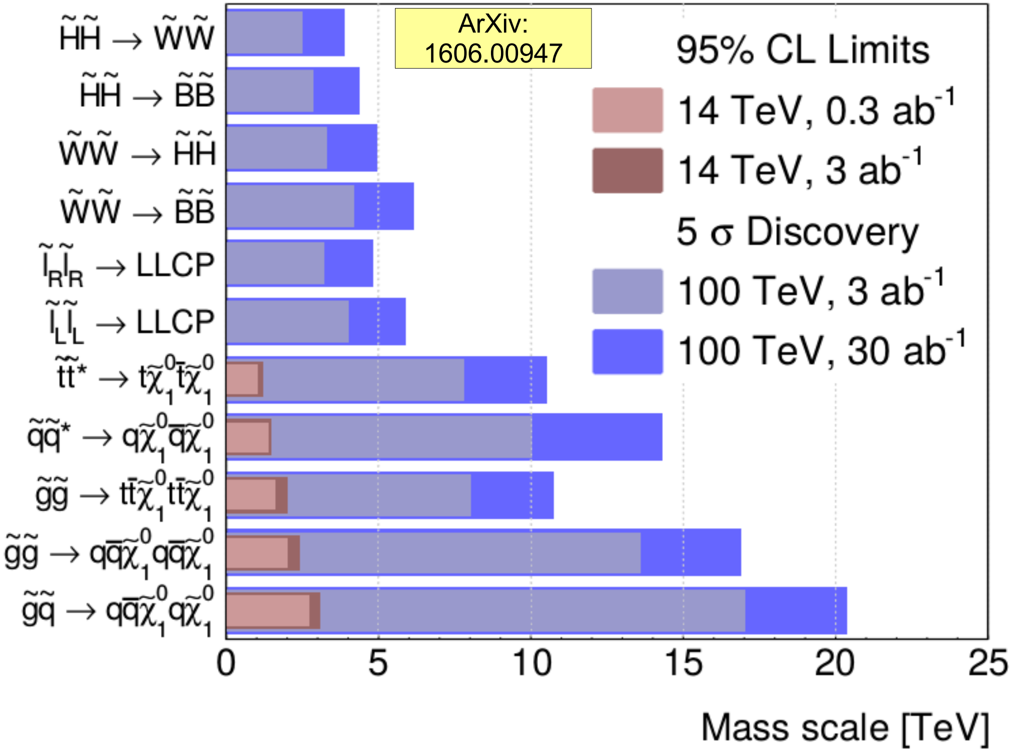


90-100 km ring fits geology

Physics Program for FCC-hh

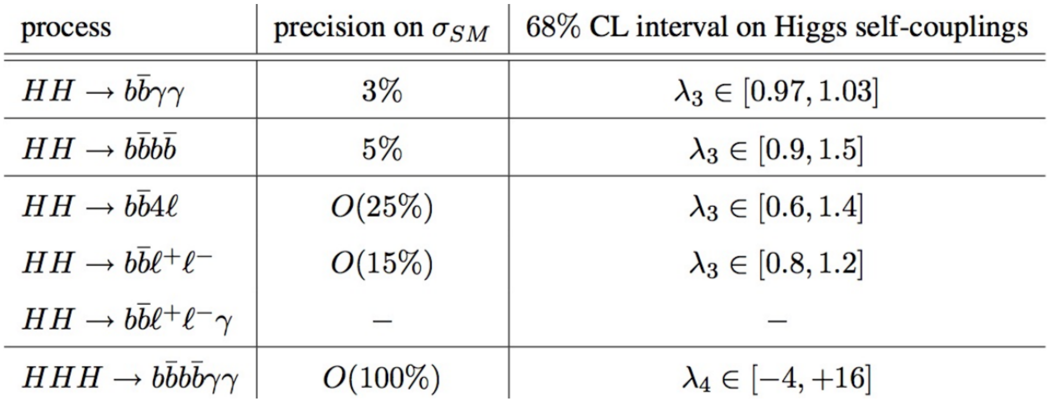
- Main physics goals of FCC-hh
  - Directly explore energy range up to 50 TeV for New Physics
  - Conclusive exploration of EWSB dynamics
  - Give final verdict on heavy WIMP dark matter

Expected reach for supersymmetry



ArXiv: 1606.00947

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
$\sin^2\theta^\ell_{\mathrm{eff}}$ $[10^{-5}]$	4.5	16
Γ_Z [MeV]	0.5	2.3
R_b $[10^{-5}]$	15	66

Future EW precision?

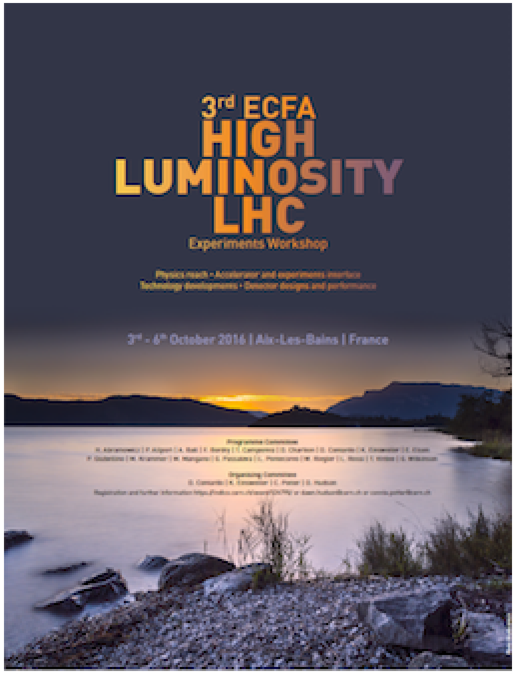
Quantity	ILC	FCC-ee	CEPC	Projected theory
M_W [MeV]	3–4	1	3	1
$\sin^2\theta^\ell_{\mathrm{eff}}$ $[10^{-5}]$	1	0.6	2.3	1.5
Γ_Z [MeV]	0.8	0.1	0.5	0.2
R_b $[10^{-5}]$	14	6	17	5–10

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

Summary

Summary

- High-Luminosity LHC 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, but wide range of measurements and Beyond Standard Models searches are possible
- Technical Design Reports in preparation and will come over the next ~1 year
- Next generation colliders for the ultimate studies of Higgs and multi-TeV New Physics are under study at CERN
  - Conceptual Design Reports in ~2 years

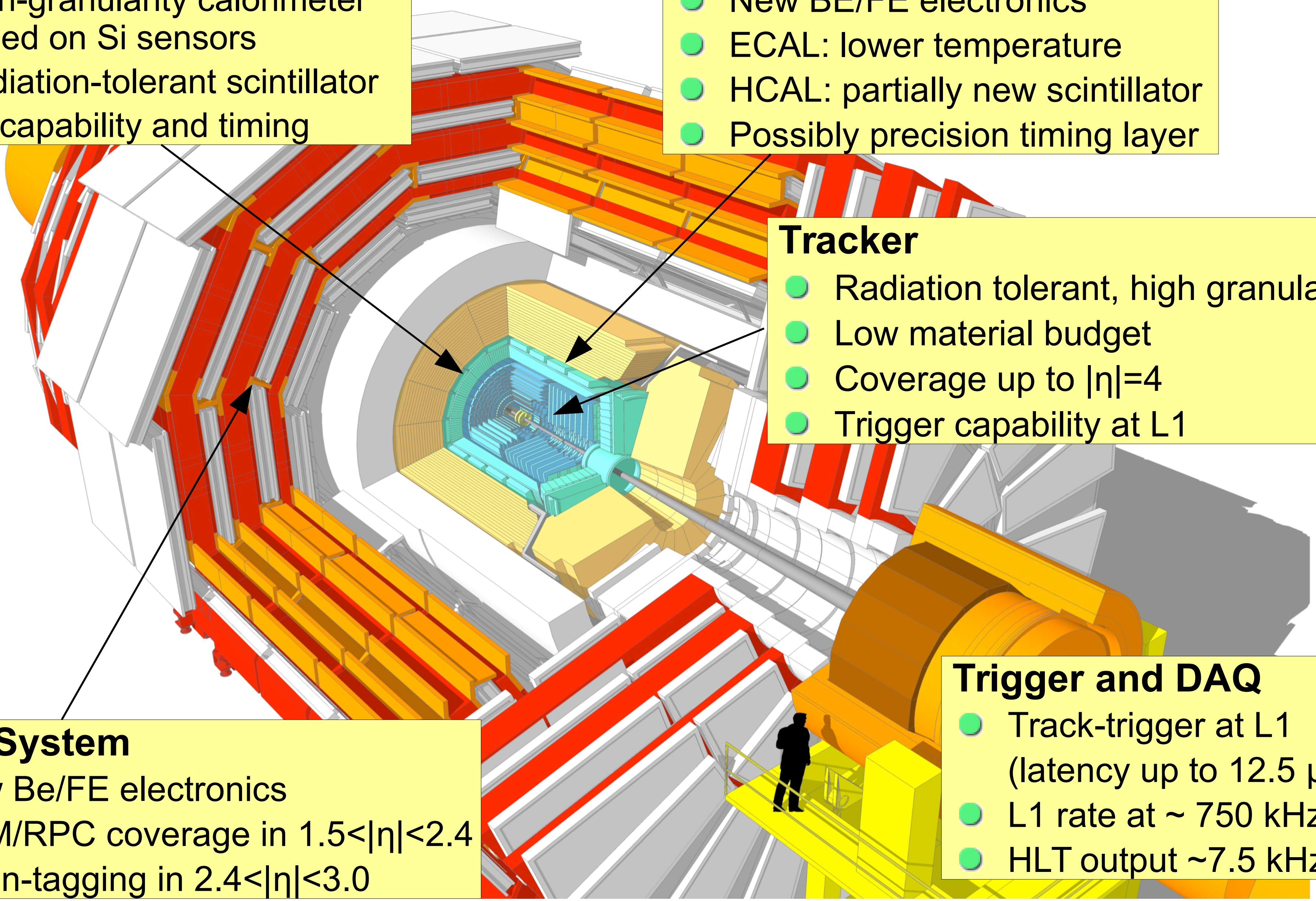


Please stay tuned

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

Backup

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 |η|=4
- Trigger capability at L1

Muon System

- New Be/FE electronics
- GEM/RPC coverage in 1.5<|η|<2.4
- Muon-tagging in 2.4<|η|<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

Anomalous HZZ Coupling

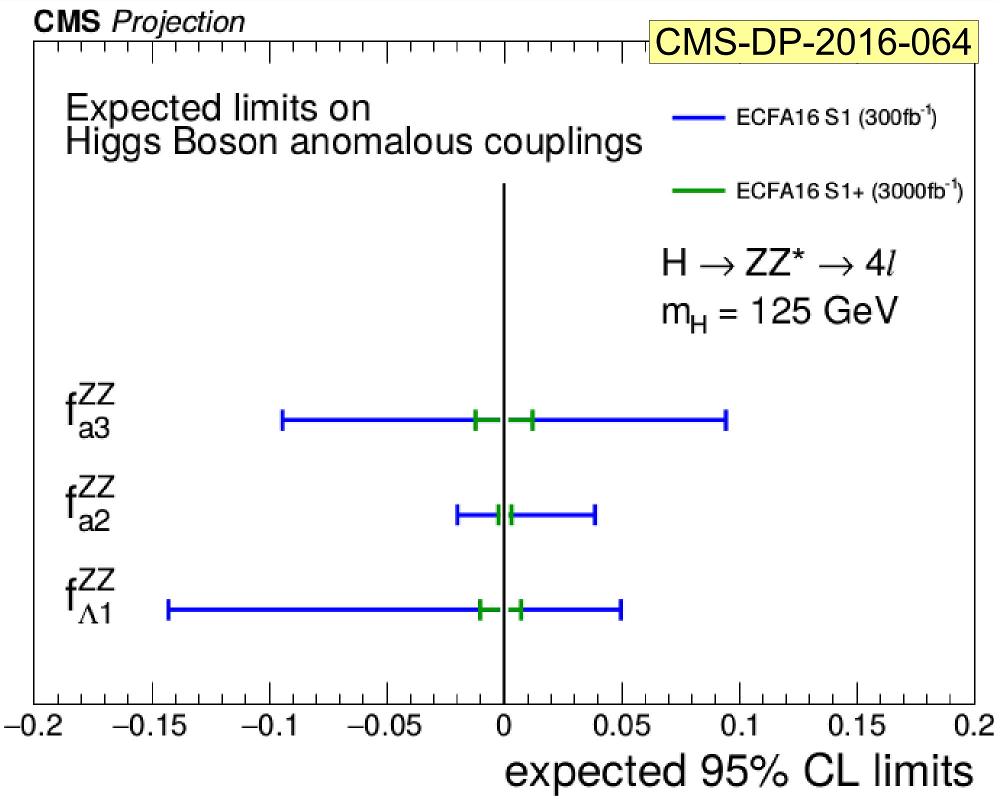
Generic decay amplitude of $H \to ZZ$ for spin-0 particle:

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

- Test for anomalous HZZ couplings a_i:

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

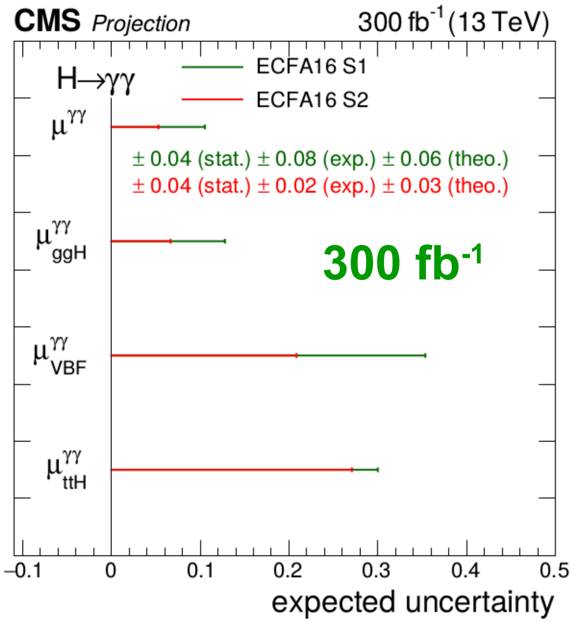
- Interference contribution becomes more dominant at smaller values of f_{ai} x $\cos(\varphi_{ai})$

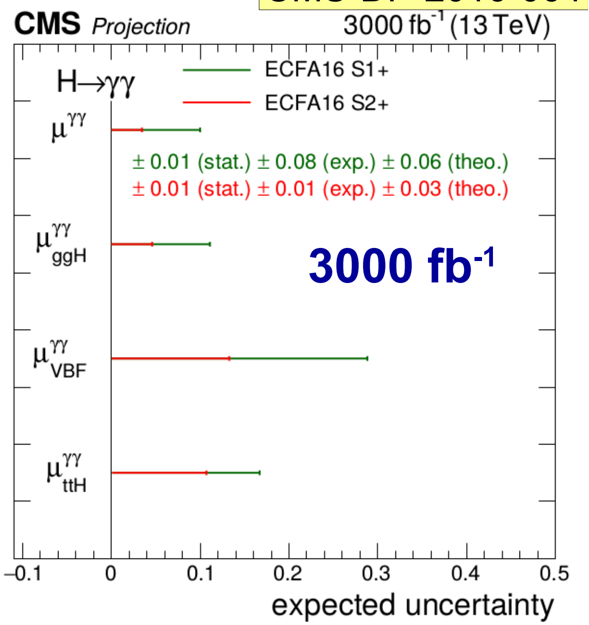


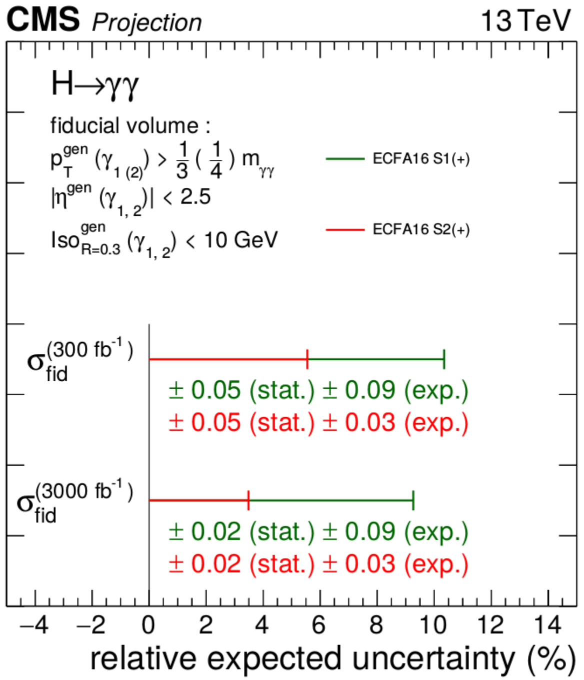
Projections based on Run-2 Analysis

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 become dominate at HL-LHC
- Decouple by measuring fiducial cross section
    - Can achieve ~4% precision



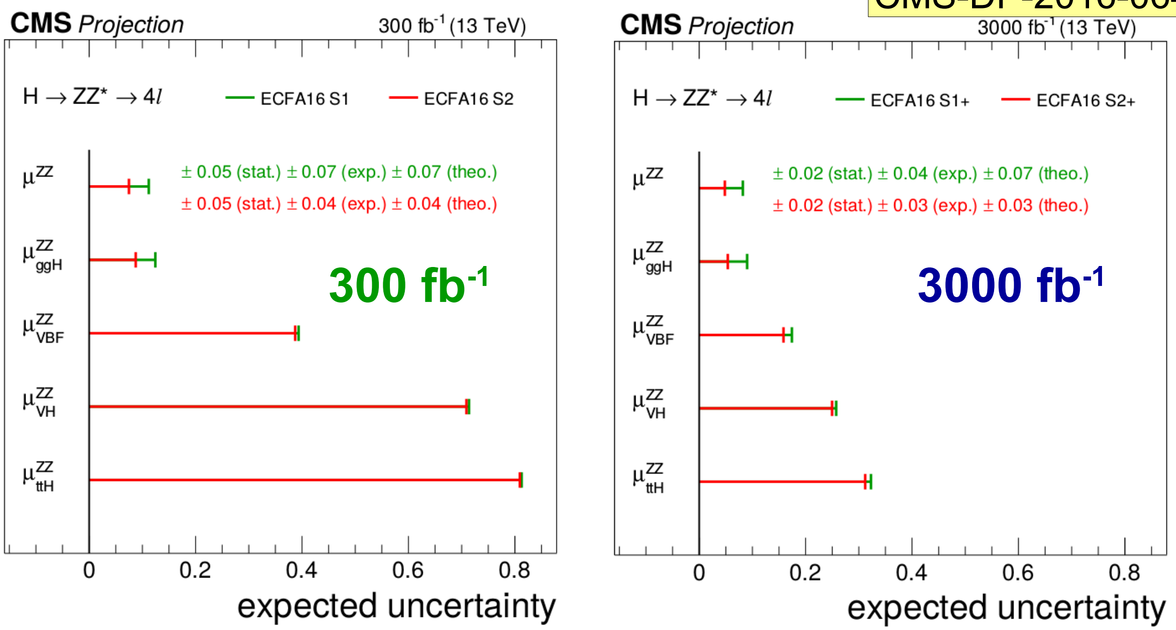




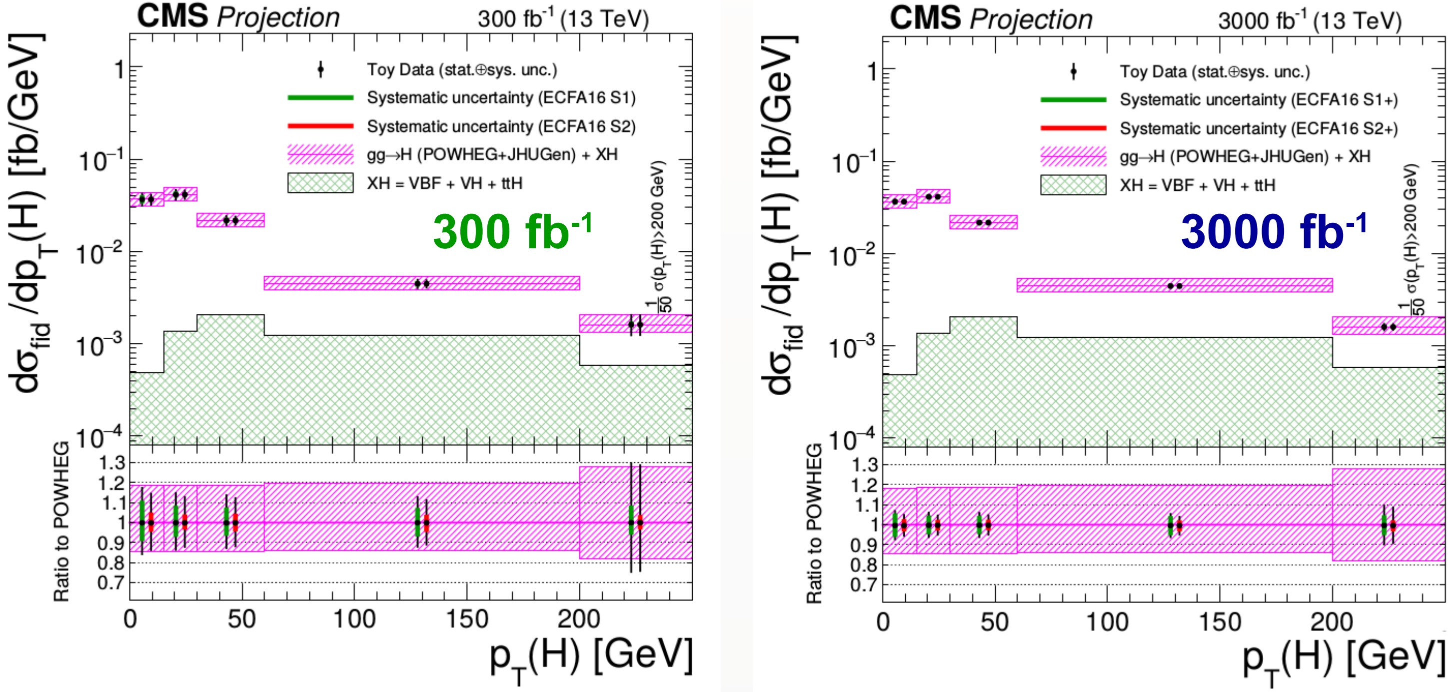
Projections based on Run-2 Analysis

- 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

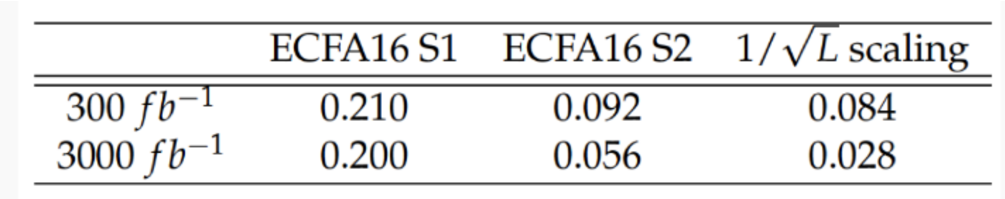


CMS-DP-2016-064

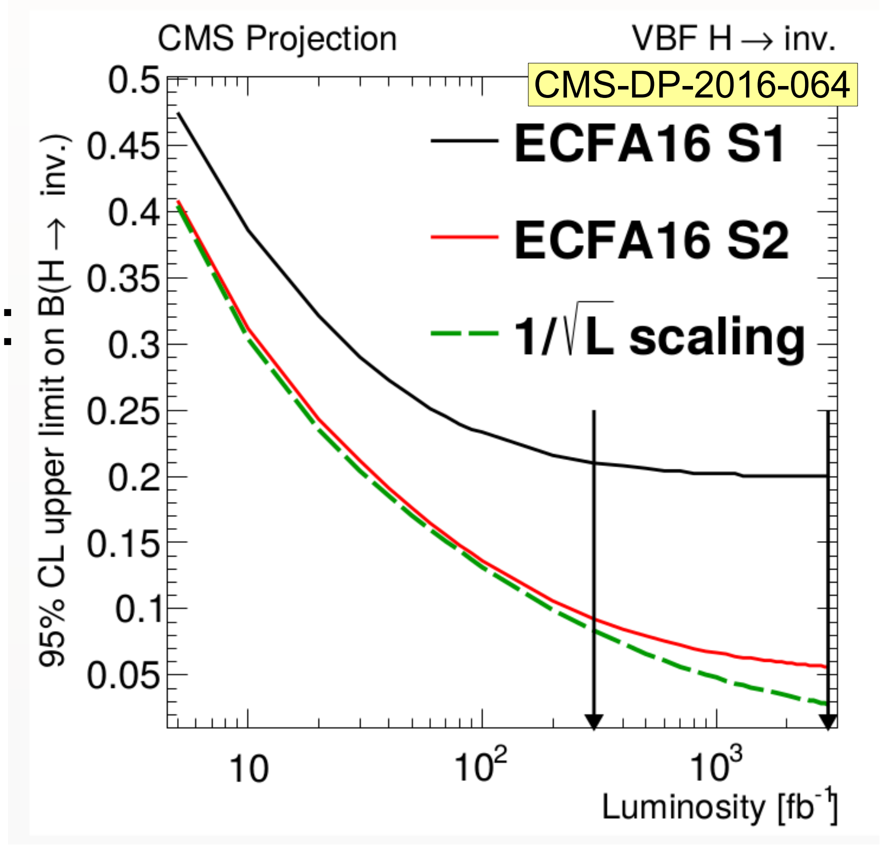


Higgs to Invisible

- 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

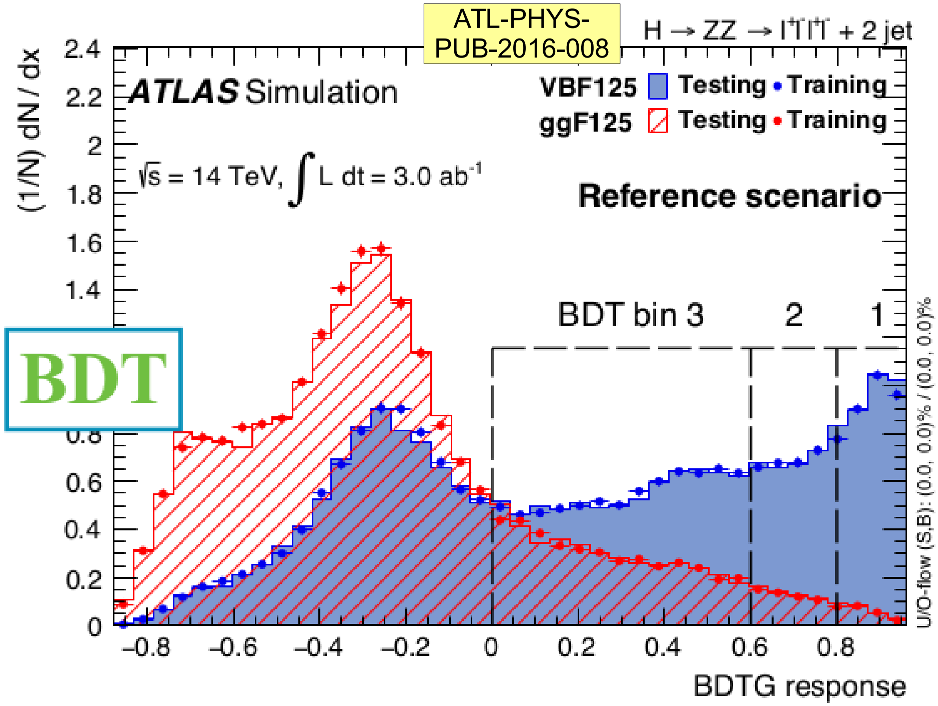


Summary of Recent ATLAS Higgs Results

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 $< 44 \times 10^{-6}$** @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:



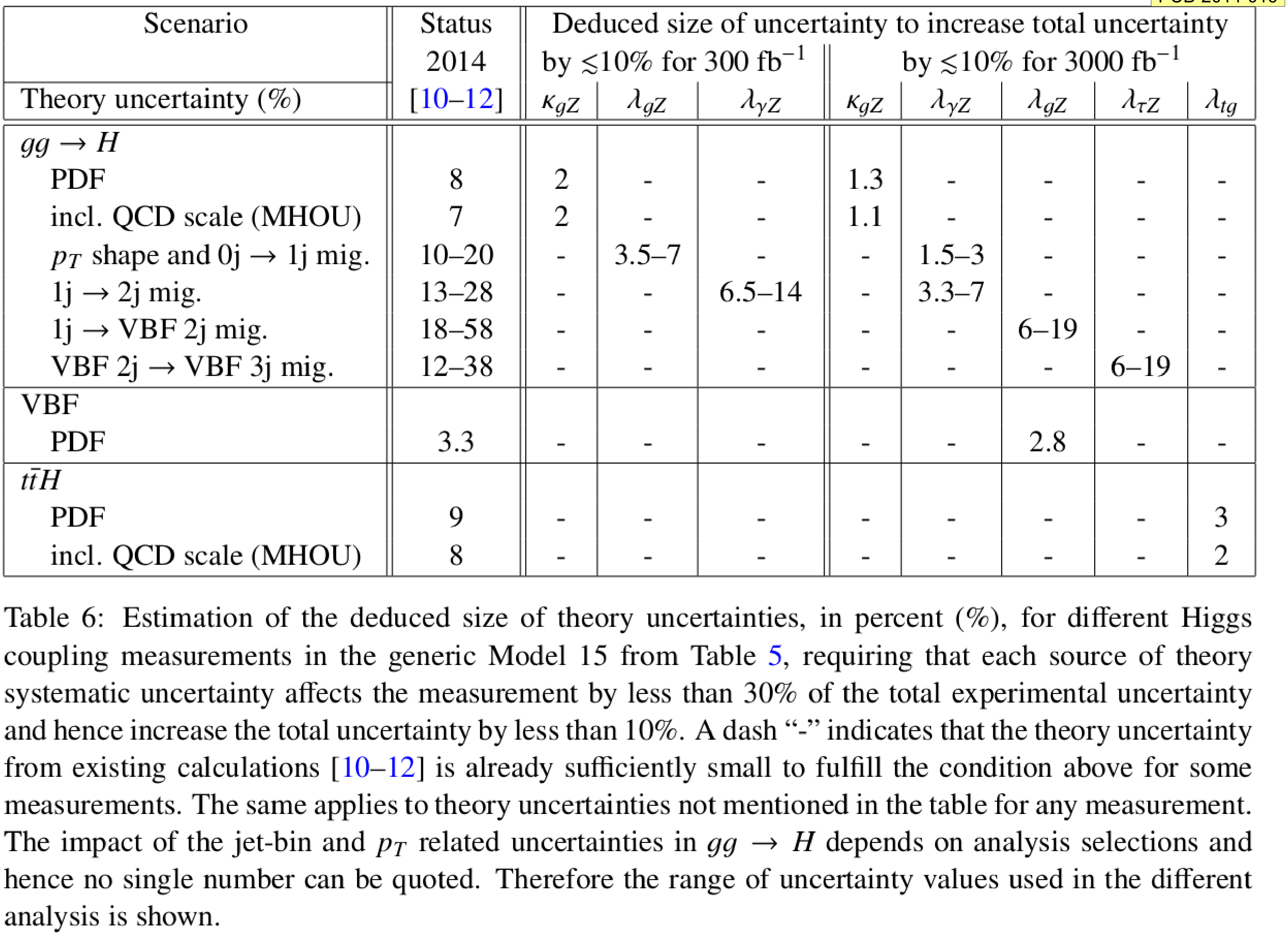
	$\langle\mu_{PU}\rangle = 200$ FULL	$\langle\mu_{PU}\rangle = 200$ NONE	$\langle\mu_{PU}\rangle = 140$ FULL	$\langle\mu_{PU}\rangle = 140$ NONE
Δμ	0.18	0.15	0.17	0.13
Significance	7.2 σ	10.2 σ	7.7 σ	11.1 σ

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	Deduced size of uncertainty to increase total uncertainty							
	2014	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 → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → 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

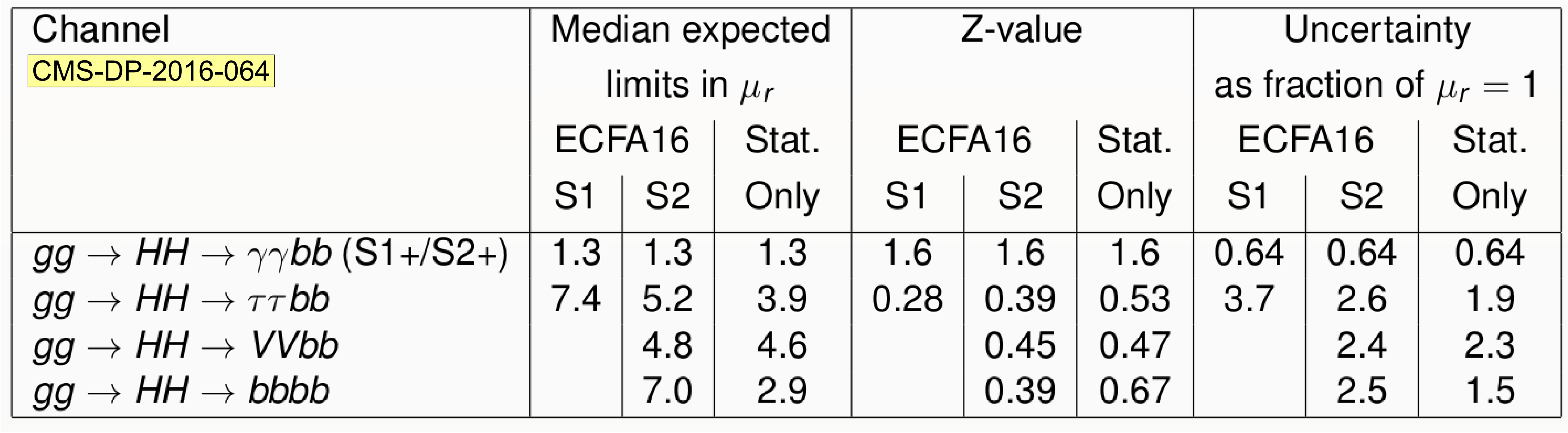
Table 6: Estimation of the deduced size of theory uncertainties, in percent (%), for different Higgs coupling measurements in the generic Model 15 from Table 5, requiring that each source of theory systematic uncertainty affects the measurement by less than 30% of the total experimental uncertainty and 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.

Higgs Self Coupling Projections

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

Channel	Expected limit in μ		Significance		Limits on λ/λ_{SM} at 95% CL	
	Full Syst.	Stat. only	Full Syst.	Stat. only	Full Syst.	Stat. only
gg→HH→γγbb ATL-PHYS-PUB-2014-019			1.3σ		$-1.3<\lambda/\lambda_{SM}<8.7$	
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		

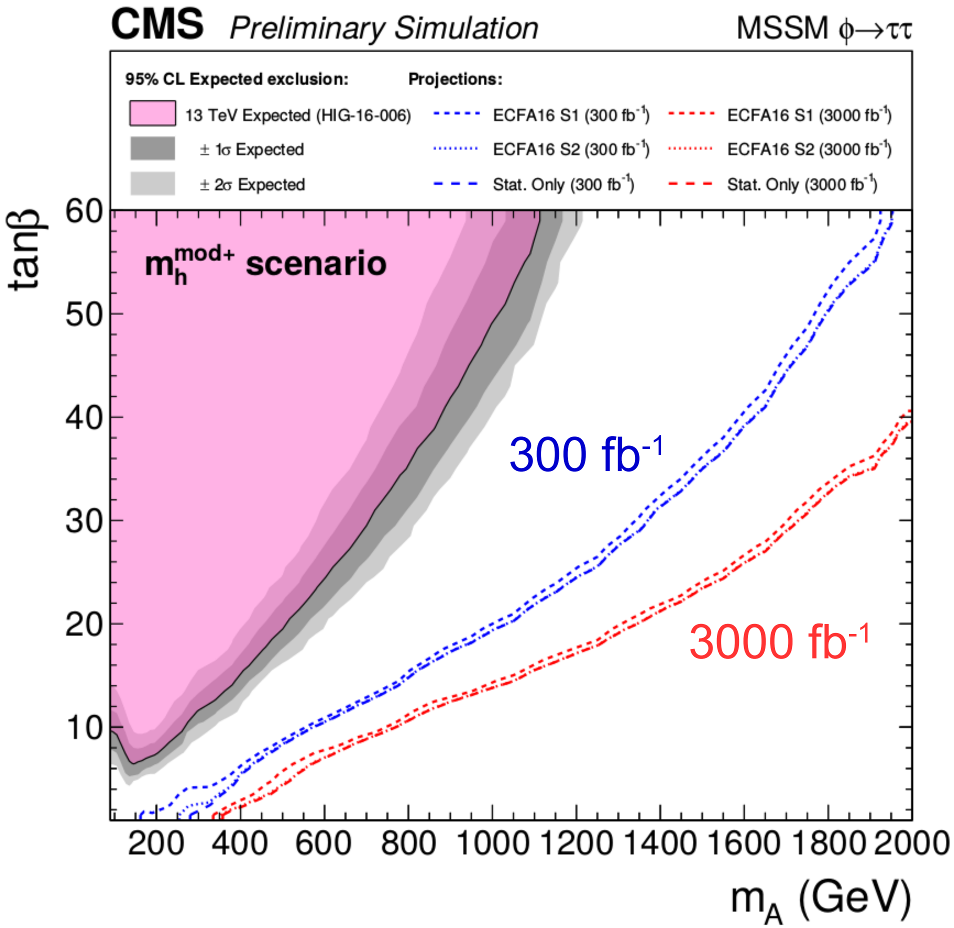
CMS extrapolations from Run-2 analyses:

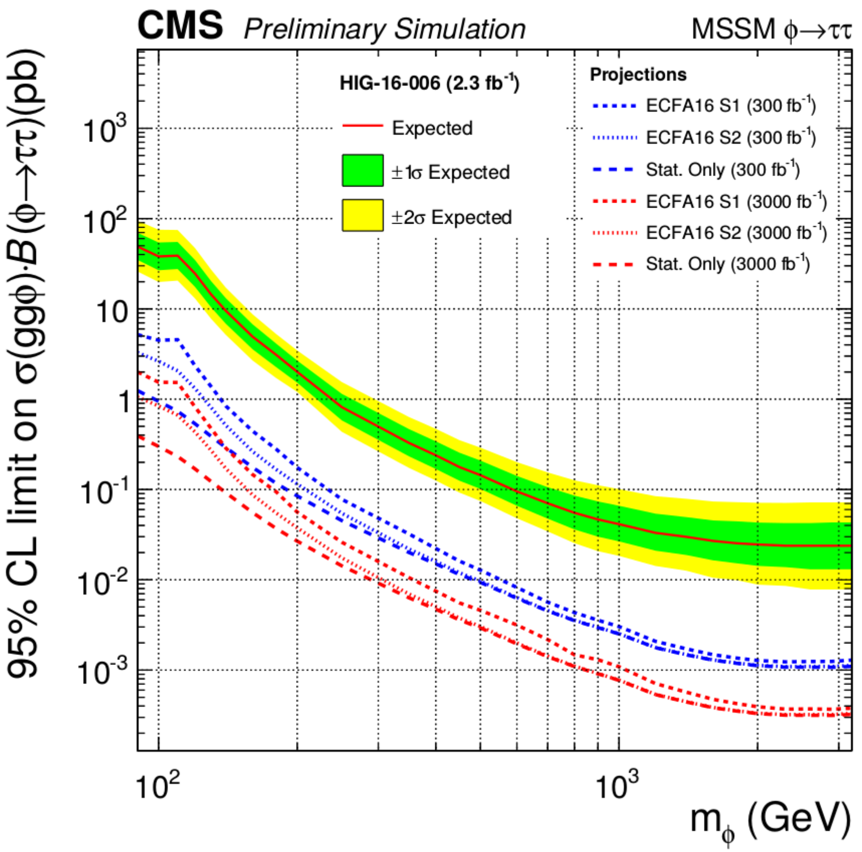


Channel CMS-DP-2016-064	Median expected limits in μ_r			Z-value			Uncertainty as fraction of $\mu_r = 1$		
	ECFA16		Stat.	ECFA16		Stat.	ECFA16		Stat.
	S1	S2	Only	S1	S2	Only	S1	S2	Only
$gg \to HH \to \gamma\gamma bb$ (S1+/S2+)	1.3	1.3	1.3	1.6	1.6	1.6	0.64	0.64	0.64
$gg \to HH \to \tau\tau bb$	7.4	5.2	3.9	0.28	0.39	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

Search for Heavy Higgs→ττ

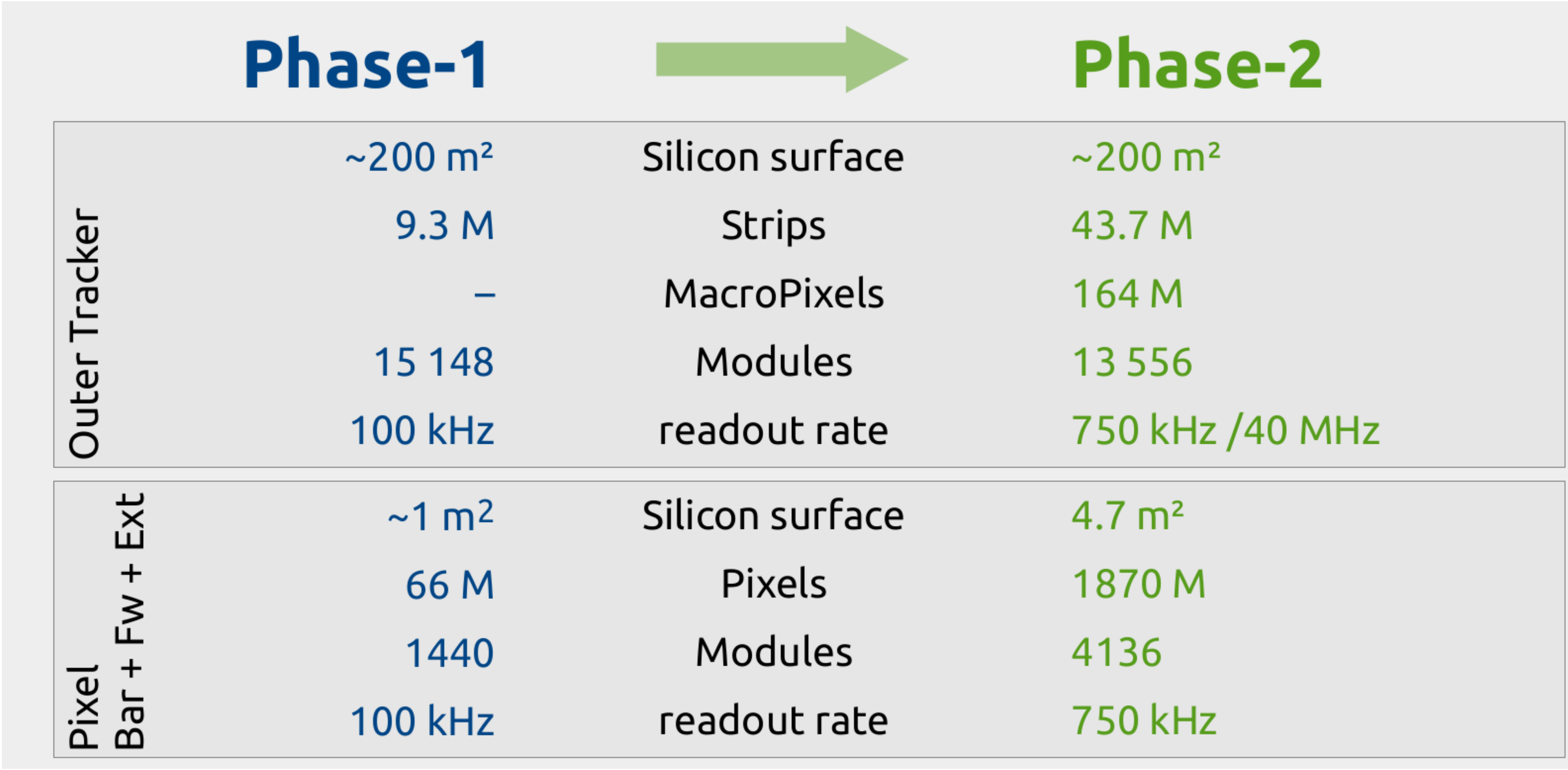
- One of the most sensitive channels for constraining extended Higgs
- Cross section limits:
  - ggφ (→ττ)
  - bbφ (→ττ)





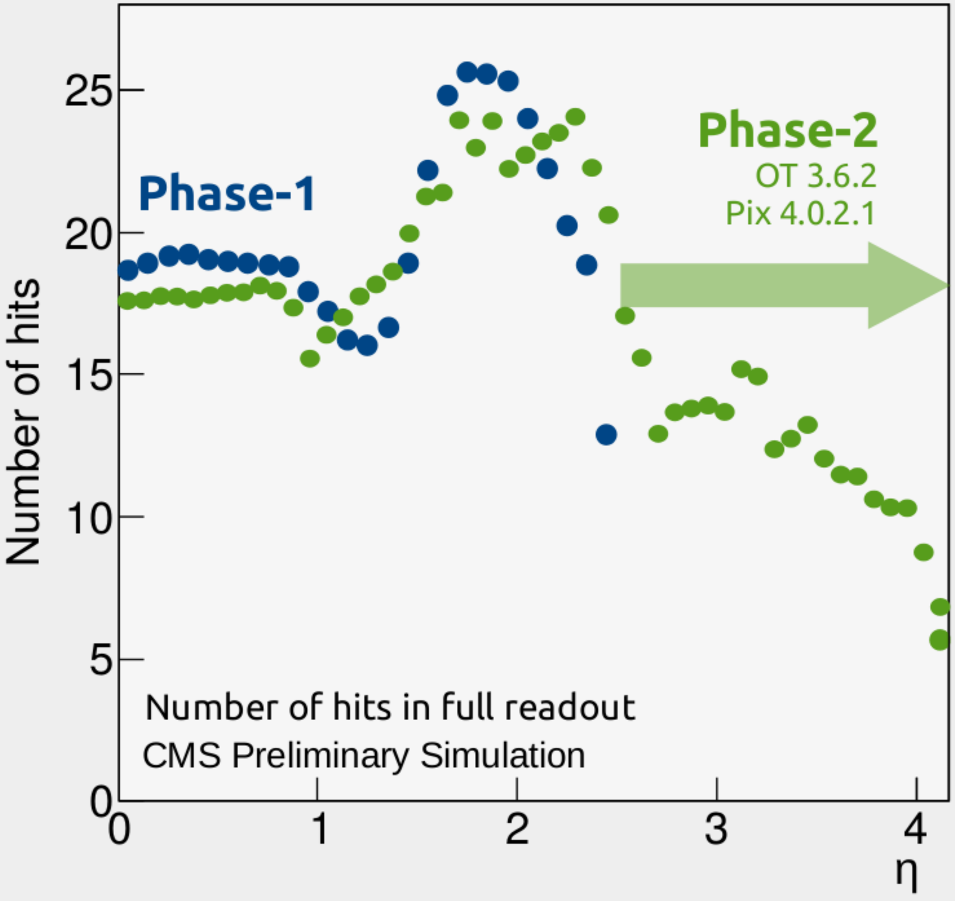
- Model dependent limits:
  - m^{mod+} benchmark
- Sensitivity at high m_A is still dominated by statistics

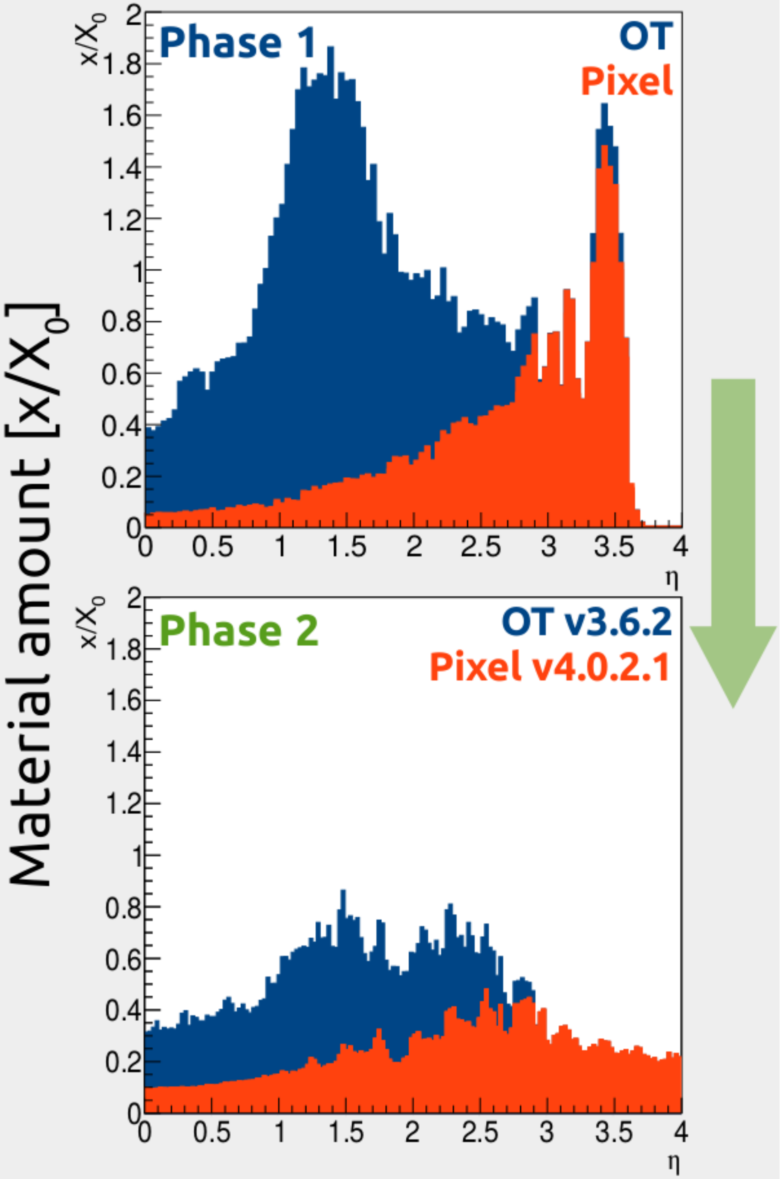
CMS Tracker Changes



	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 m2	Silicon surface	4.7 m²
	66 M	Pixels	1870 M
	1440	Modules	4136
	100 kHz	readout rate	750 kHz

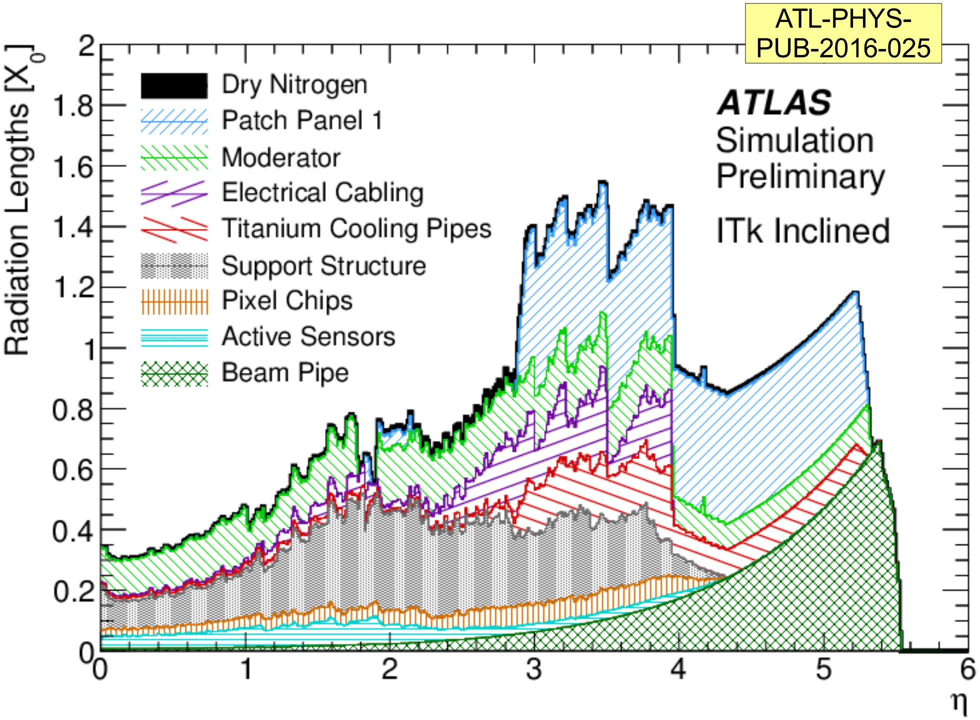
CMS Tracker Comparison

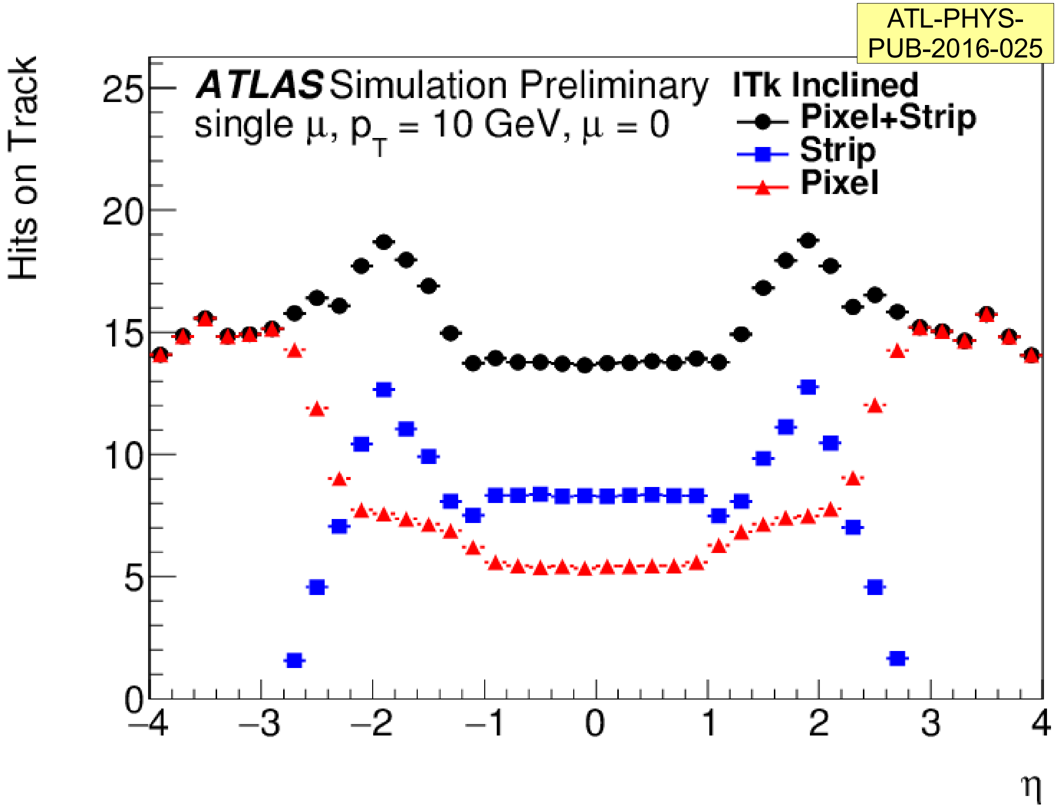




ATLAS Tracker Hits and Material

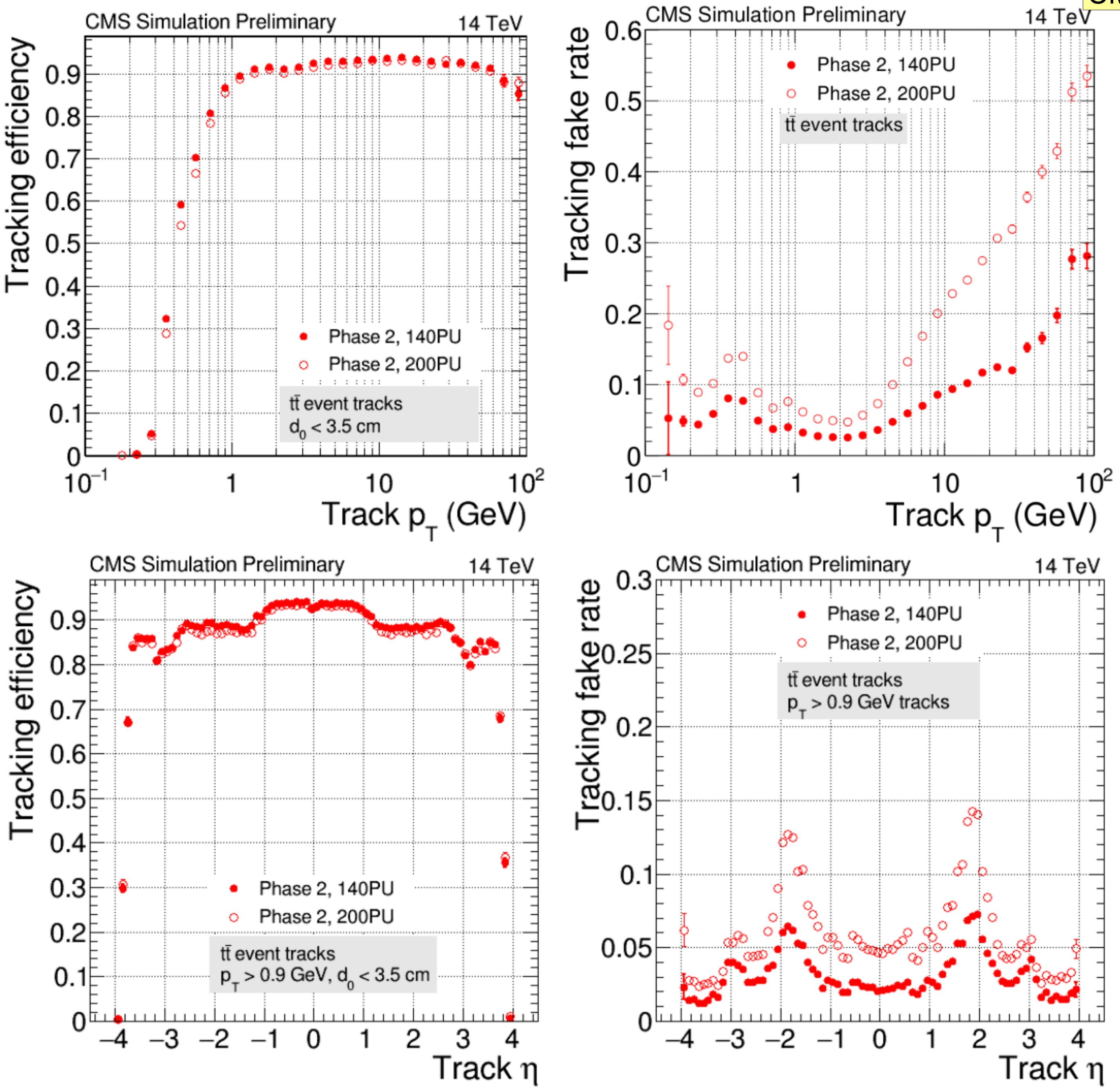
Optimized for at least 13 hits, minimum material and coverage up to η=4





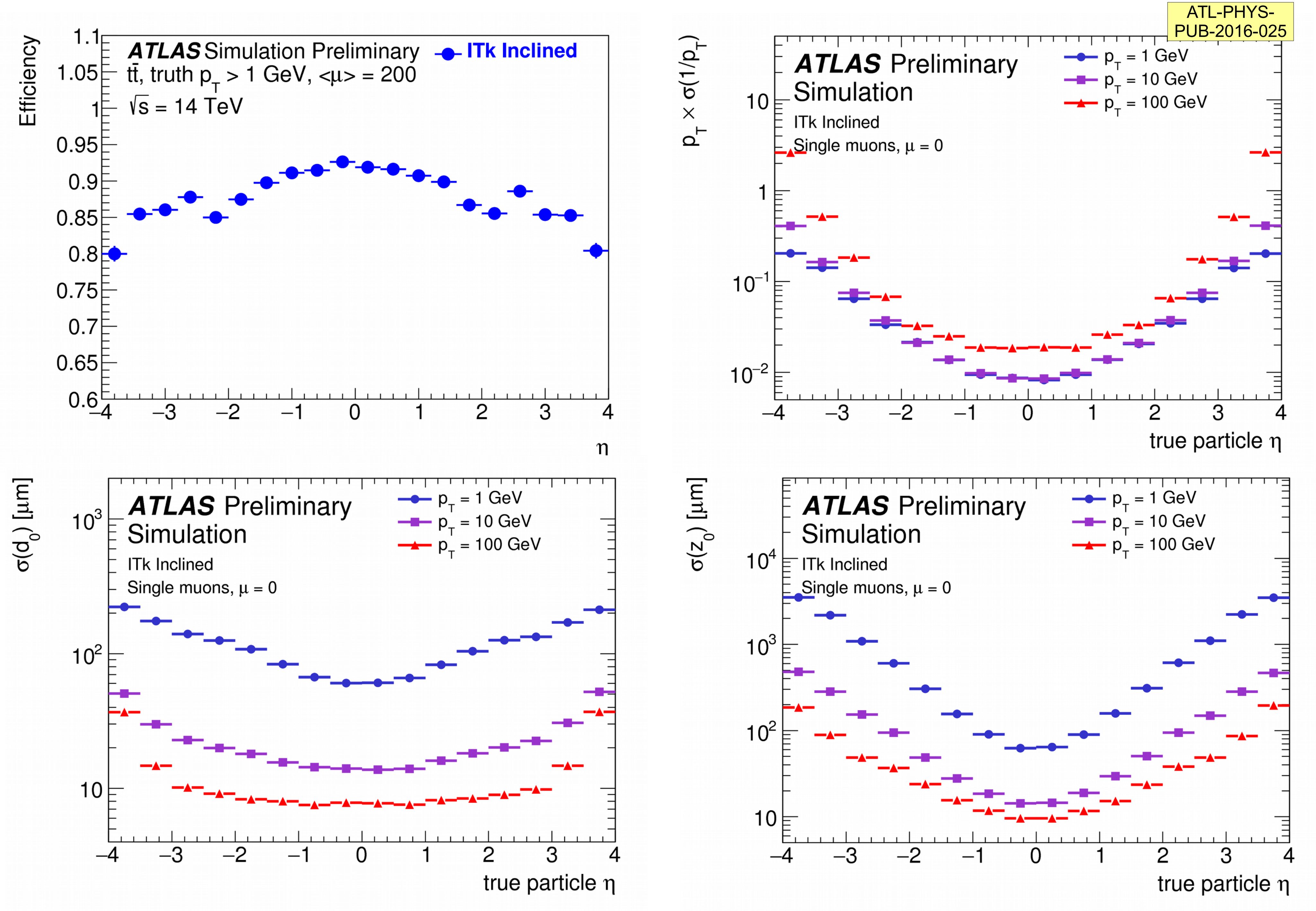
CMS Tracker Performance

CMS-DP-2016-065



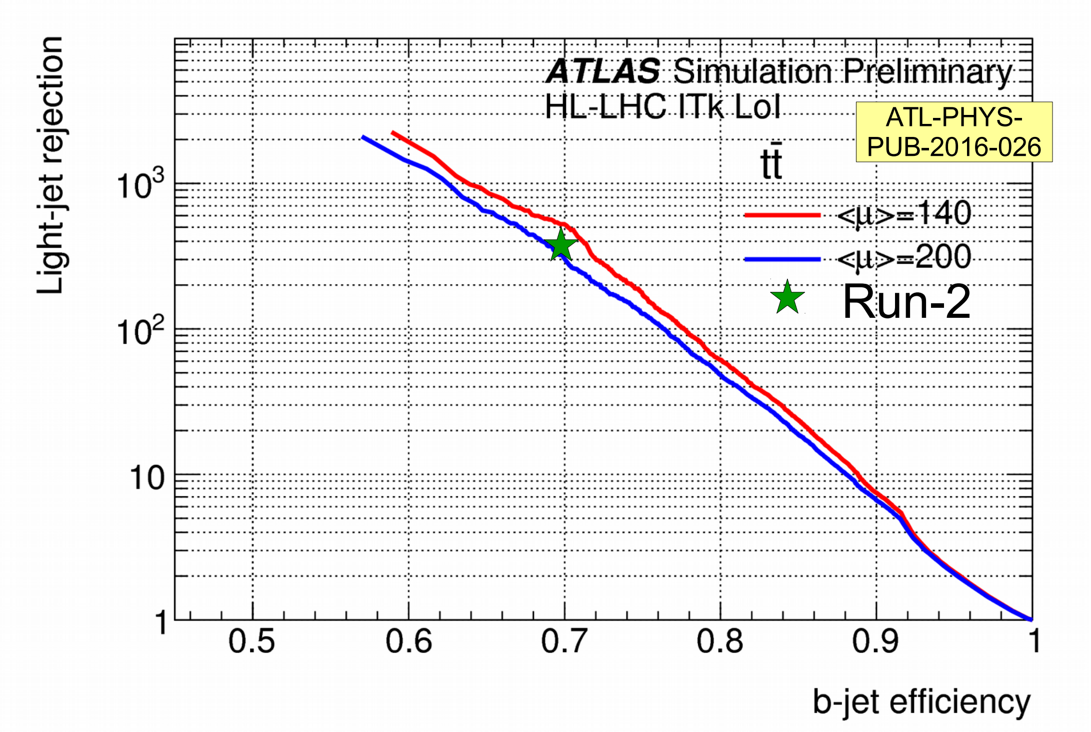
ATLAS Tracker Performance

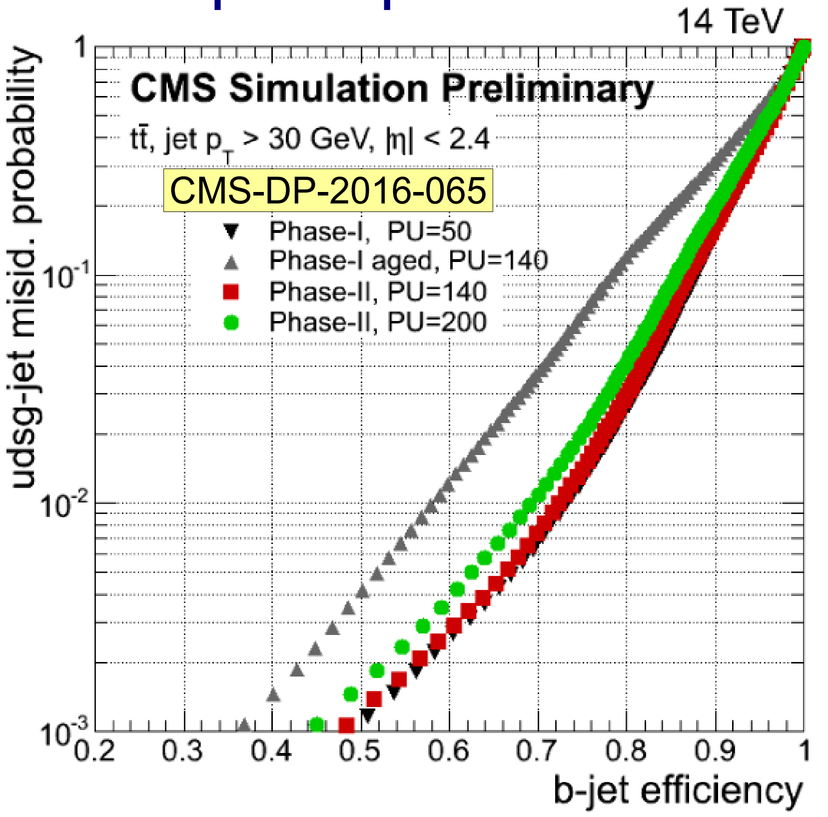
ATL-PHYS-PUB-2016-025



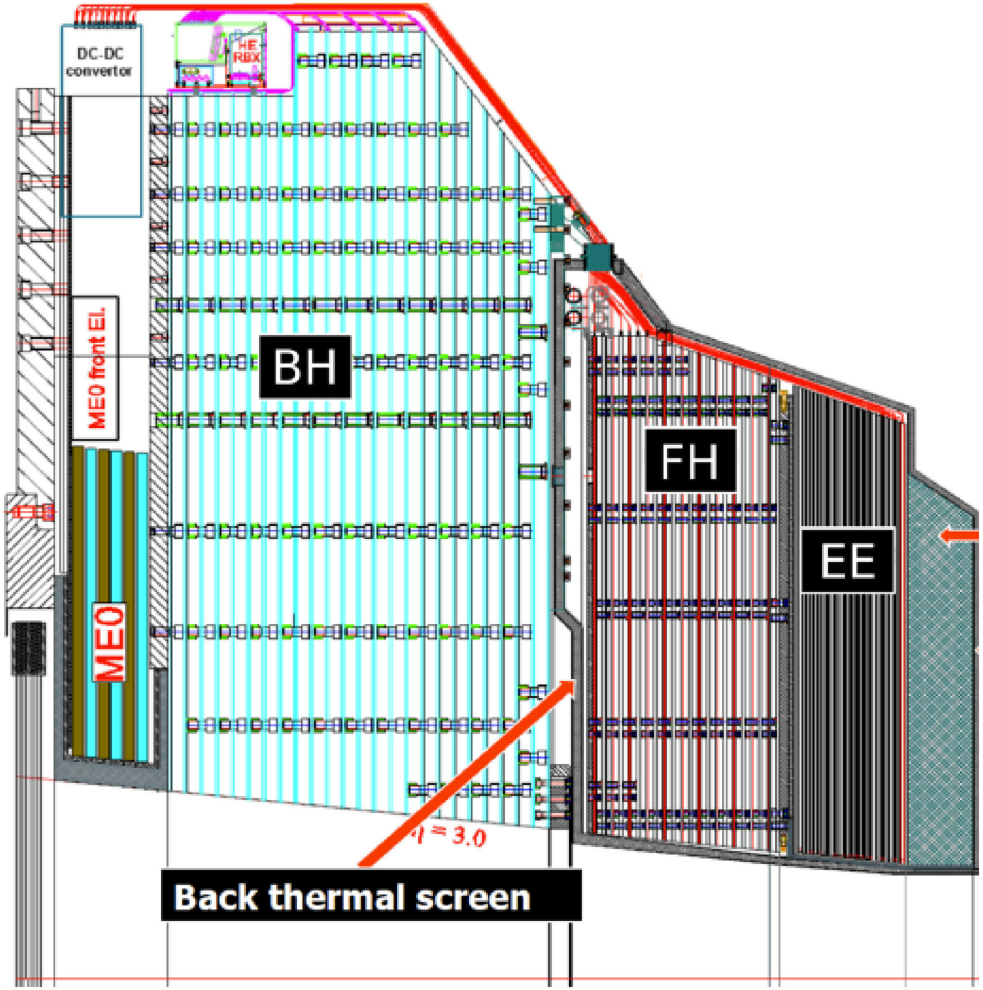
B-tagging for $HH\to b\bar{b}b\bar{b}$

- Efficient and highly rejecting b-tagging also critical for $HH\to b\bar{b}b\bar{b}$ 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





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.*

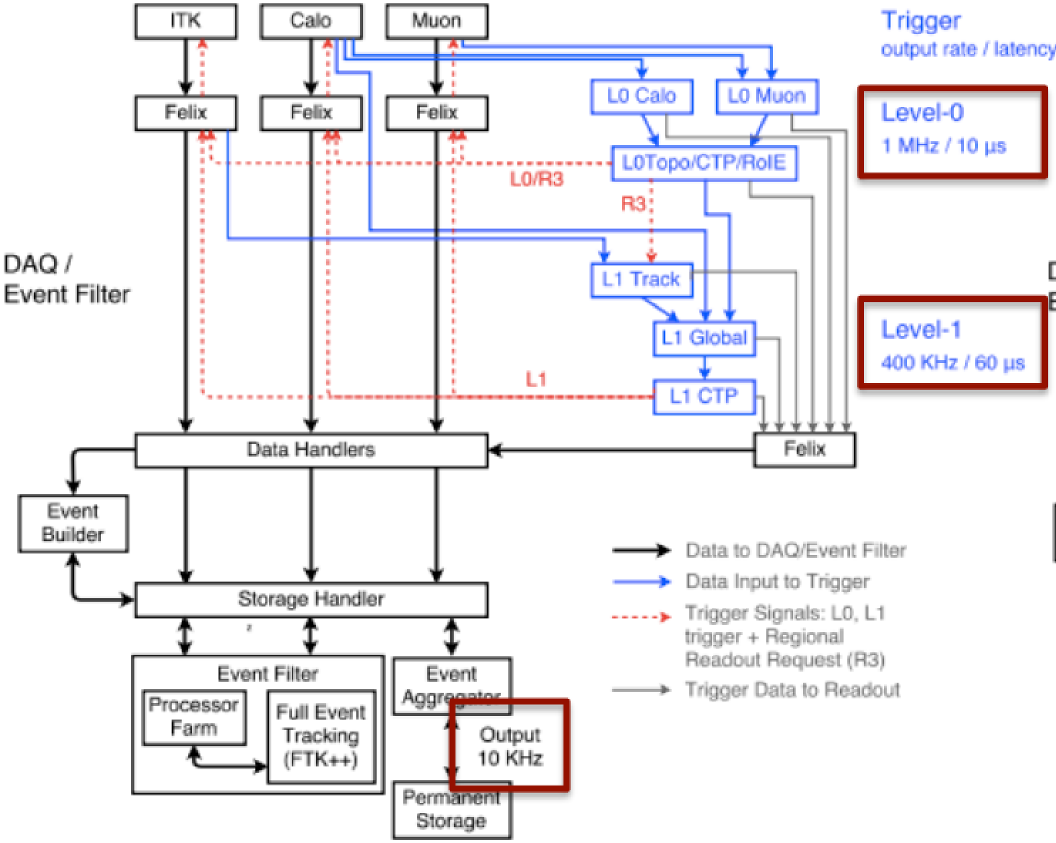
System Divided into three separate parts:

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

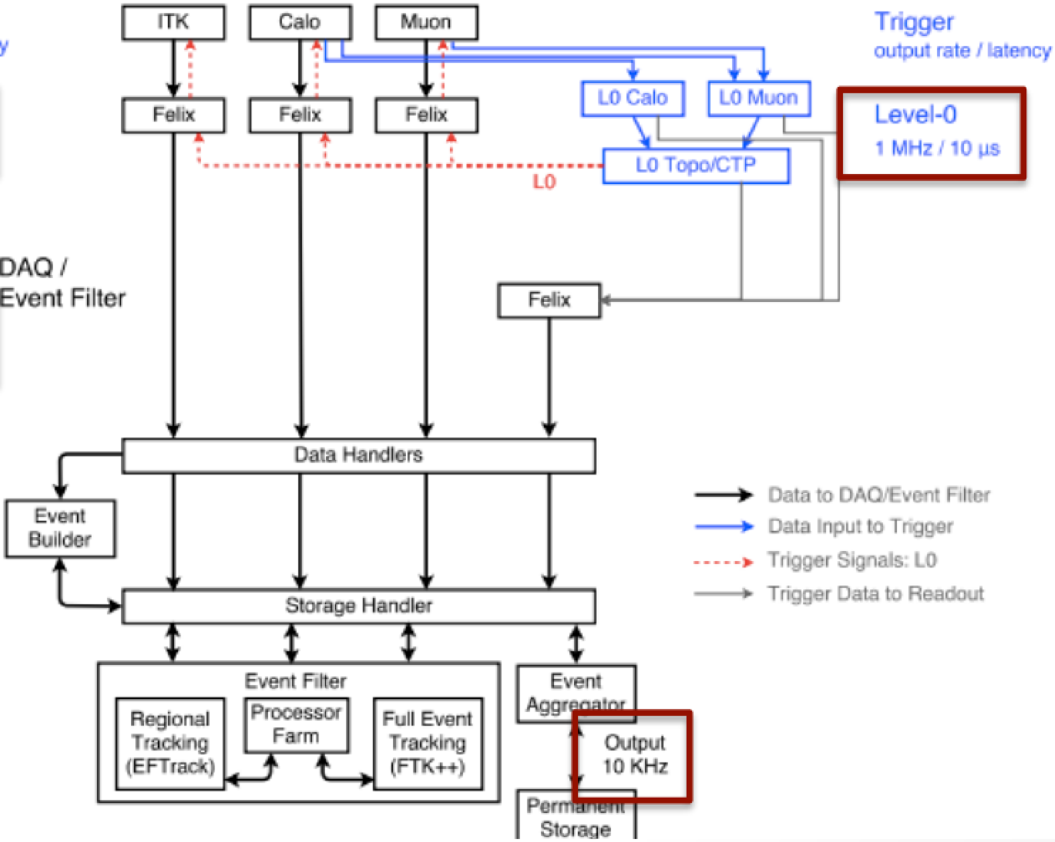
EE and FH are maintained at – 30°C. BH is at room temperature.

ATLAS Trigger Schemes

Level-0 + Level-1 hardware trigger



Level-0 only hardware trigger



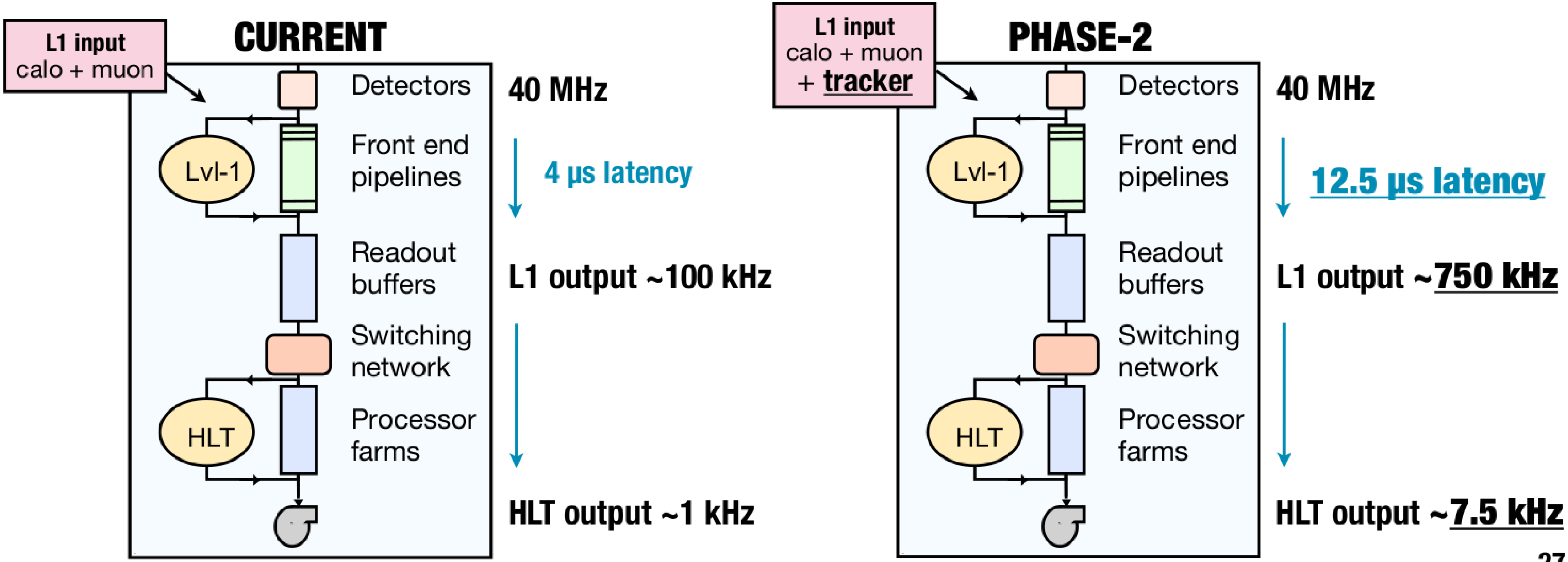
Rates and Latencies

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

Level 0: 1 MHz, 10 μs
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



L1 input
calo + muon

CURRENT

Detectors
Front end pipelines
Readout buffers
Switching network
Processor farms

Lvl-1
HLT

40 MHz
4 μs latency
L1 output ~100 kHz
HLT output ~1 kHz

L1 input
calo + muon
+ **tracker**

PHASE-2

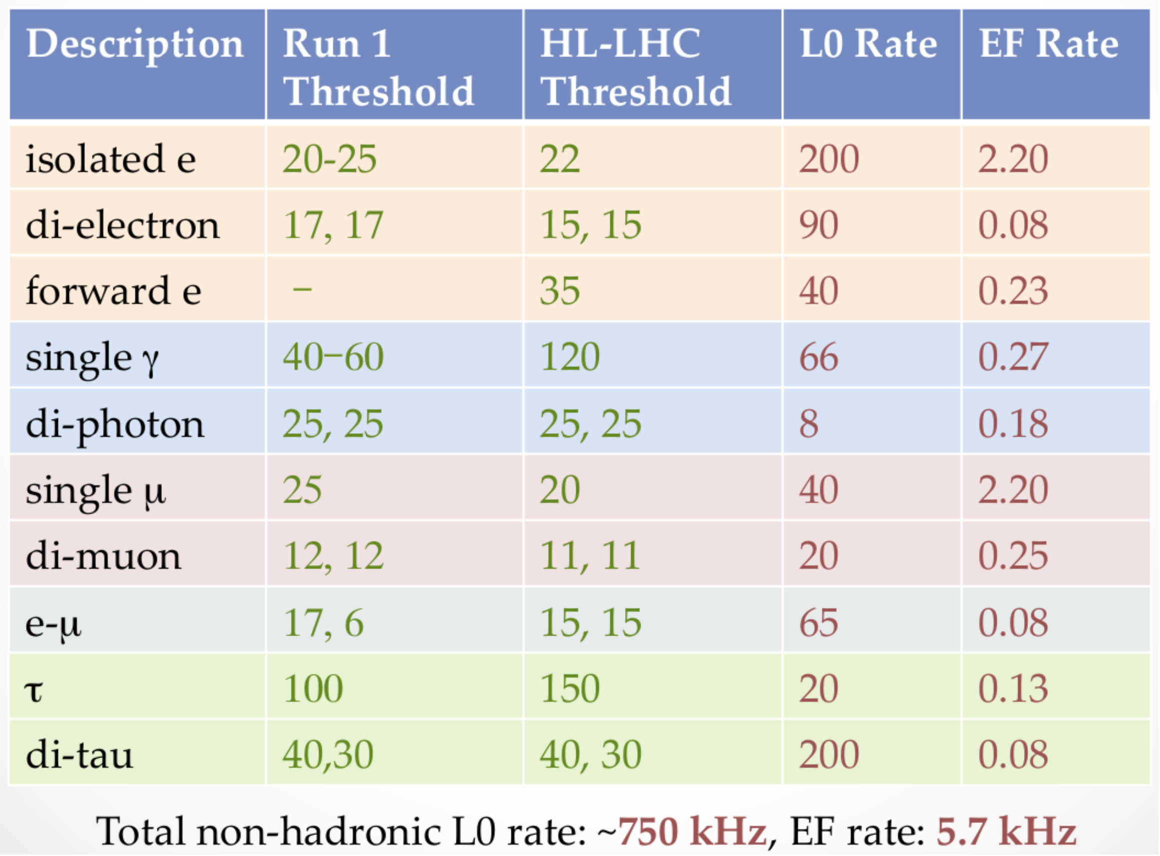
Detectors
Front end pipelines
Readout buffers
Switching network
Processor farms

Lvl-1
HLT

40 MHz
12.5 μs latency
L1 output ~750 kHz
HLT output ~7.5 kHz

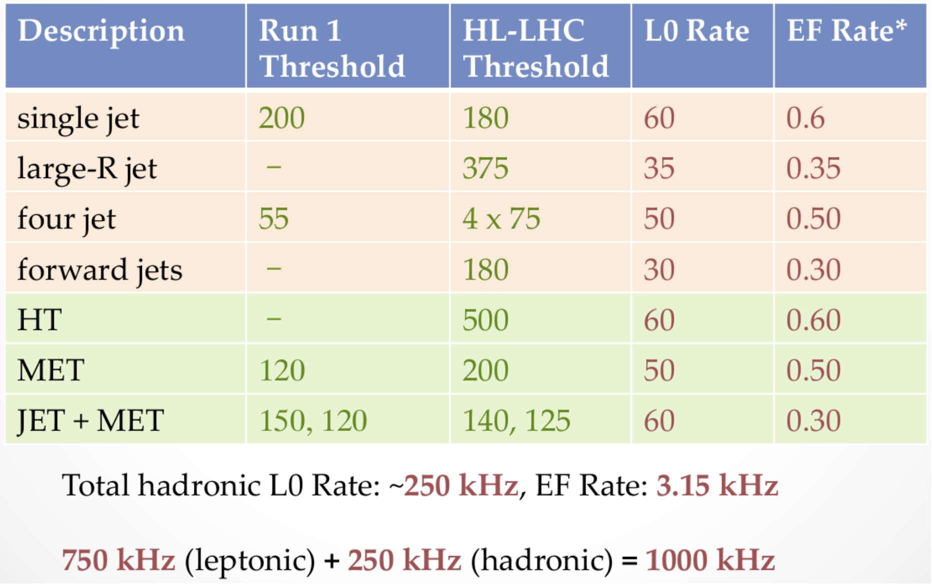
ATLAS Example Trigger Menu

- 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



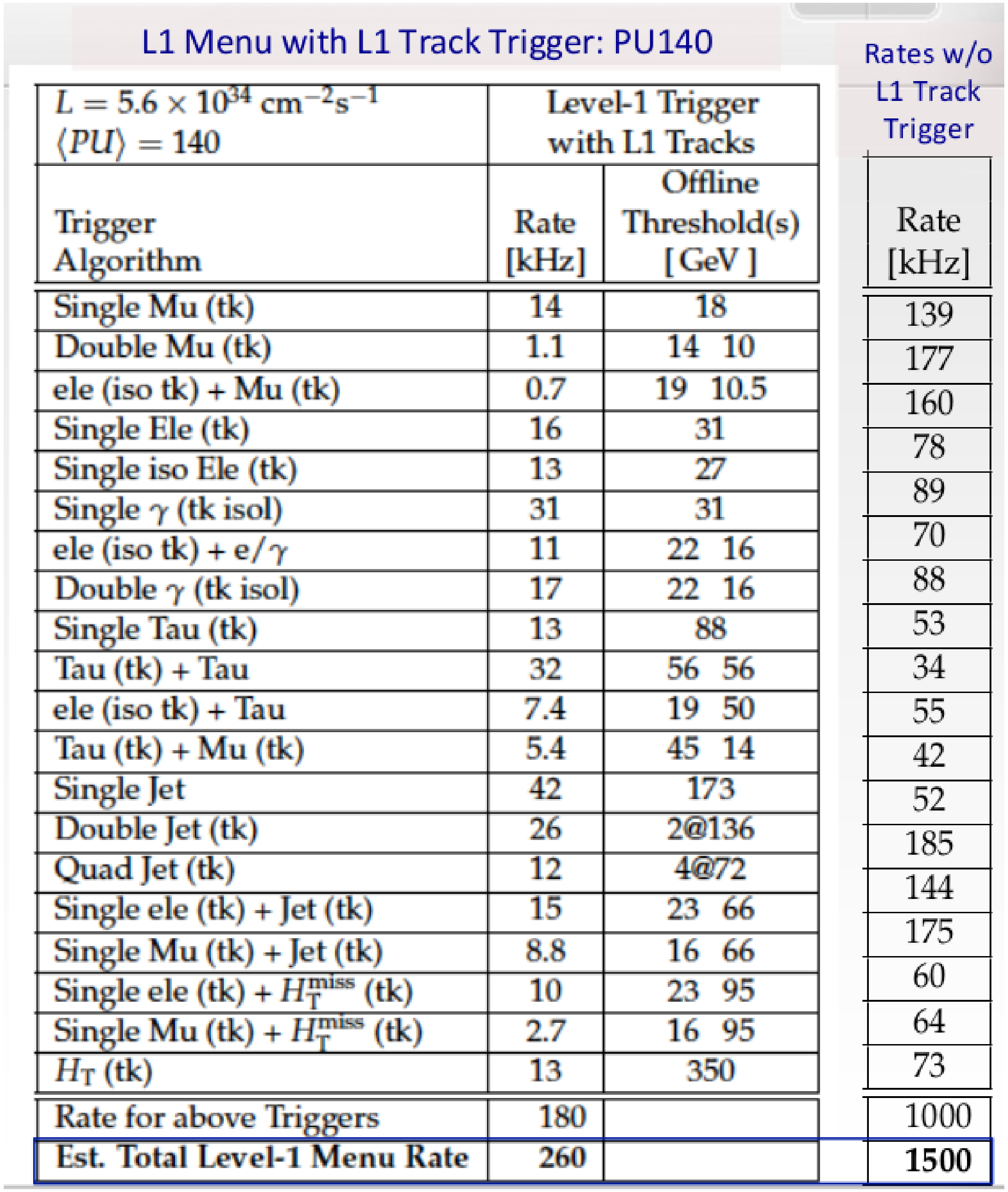
Description	Run 1 Threshold	HL-LHC Threshold	L0 Rate	EF Rate*
single jet	200	180	60	0.6
large-R jet	–	375	35	0.35
four jet	55	4 x 75	50	0.50
forward jets	–	180	30	0.30
HT	–	500	60	0.60
MET	120	200	50	0.50
JET + MET	150, 120	140, 125	60	0.30

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



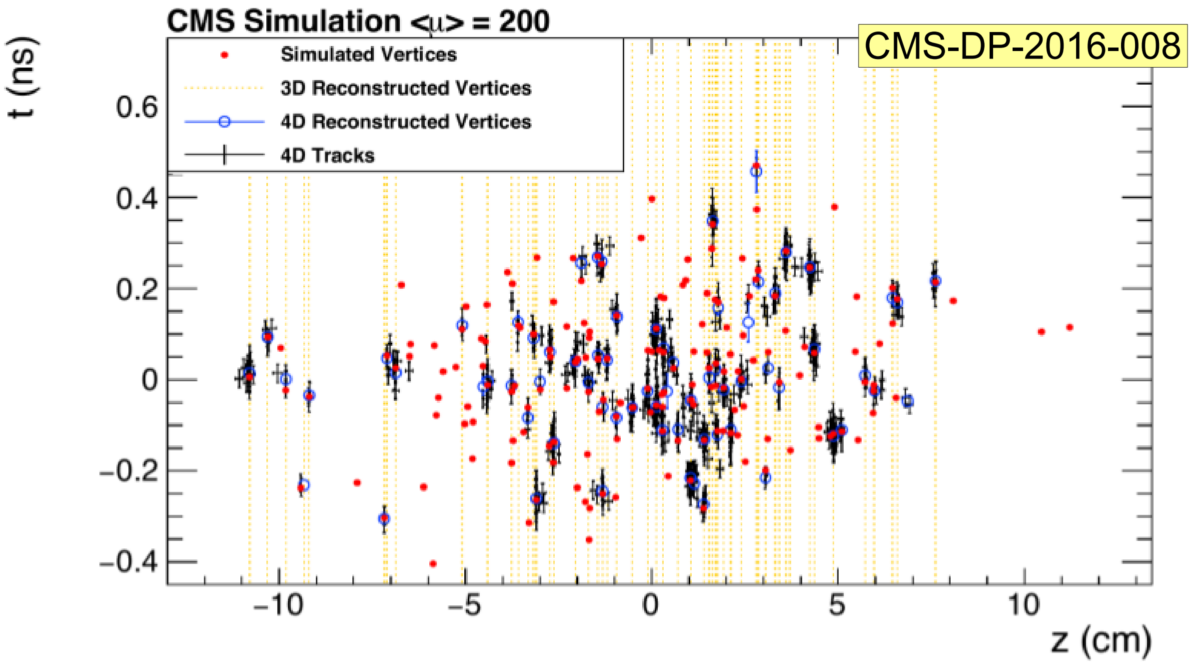
L1 Menu with L1 Track Trigger: PU140

Rates w/o L1 Track Trigger

$L = 5.6 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\langle PU \rangle = 140$	Level-1 Trigger with L1 Tracks		
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**

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



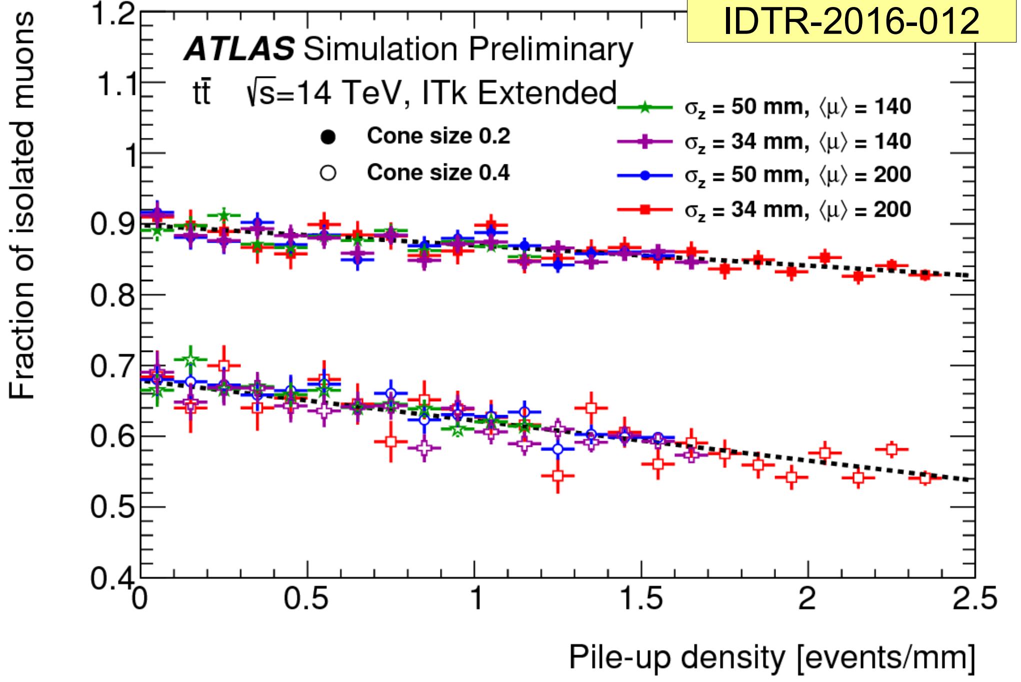
20 ps resolution assumed for charged particles with p_T>1 GeV

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

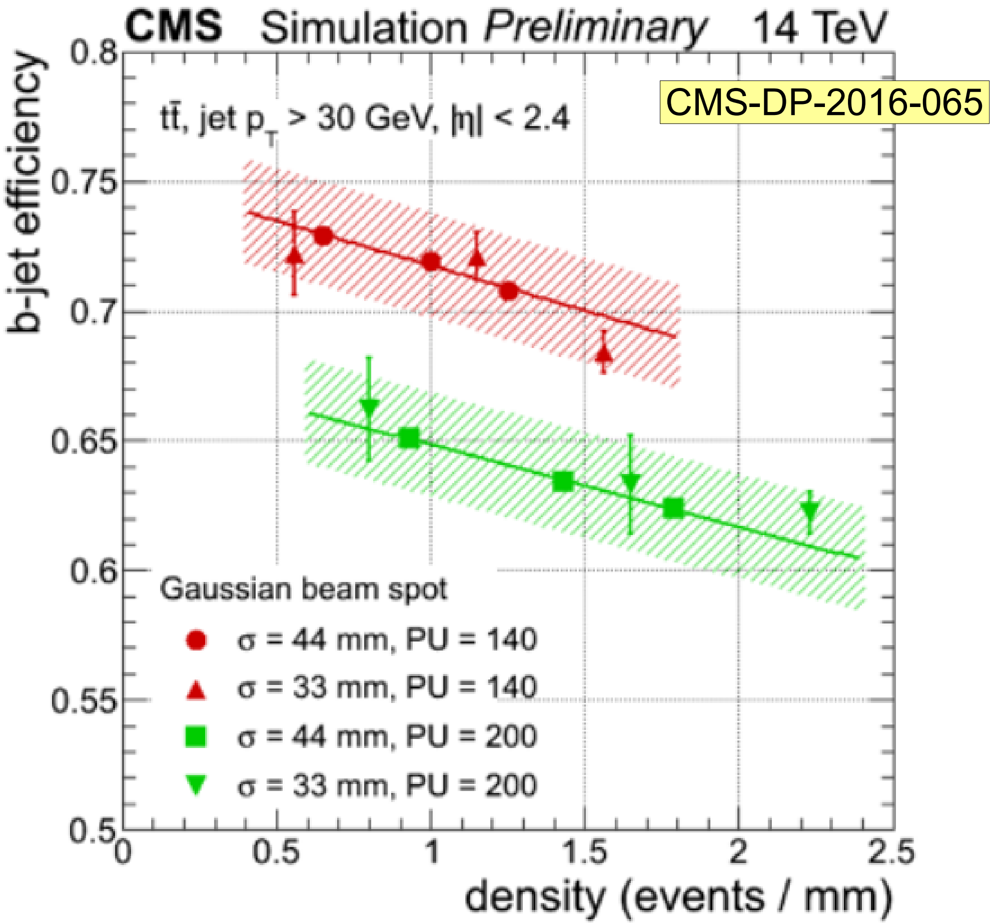
Lepton isolation efficiency

IDTR-2016-012



B-tagging efficiency

CMS-DP-2016-065



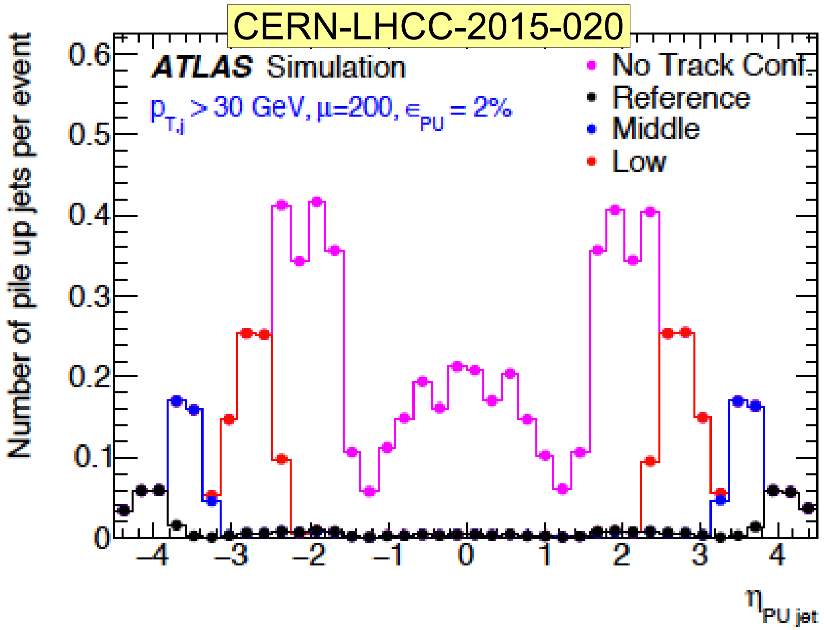
Higgs Impact on Upgrade Design

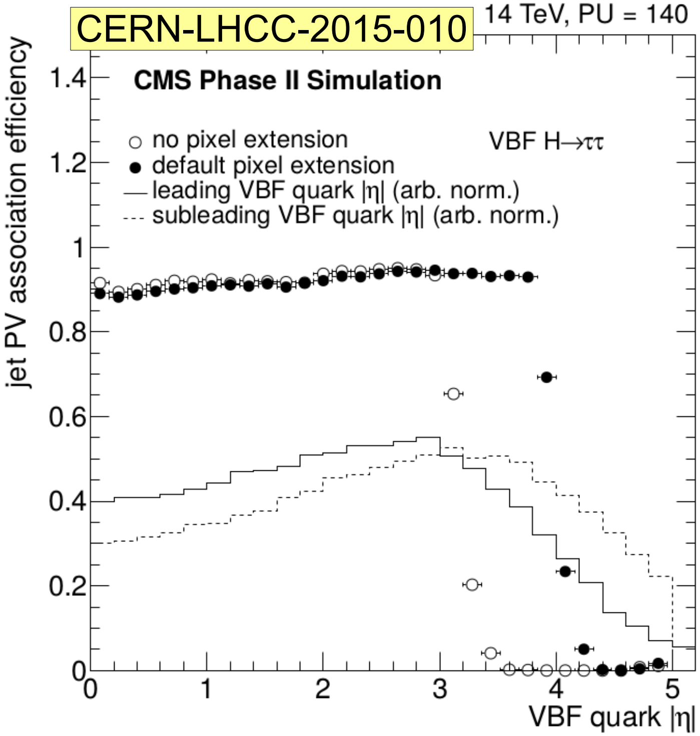
- The design of the upgraded HL-LHC detectors is complex process
    - Want ultimate performance, but limited by what can reasonably be upgraded during long shutdown and by cost
- Higgs measurements are corner stone of the HL-LHC physics program and they provide prime motivation for many upgrades beyond current detector capabilities

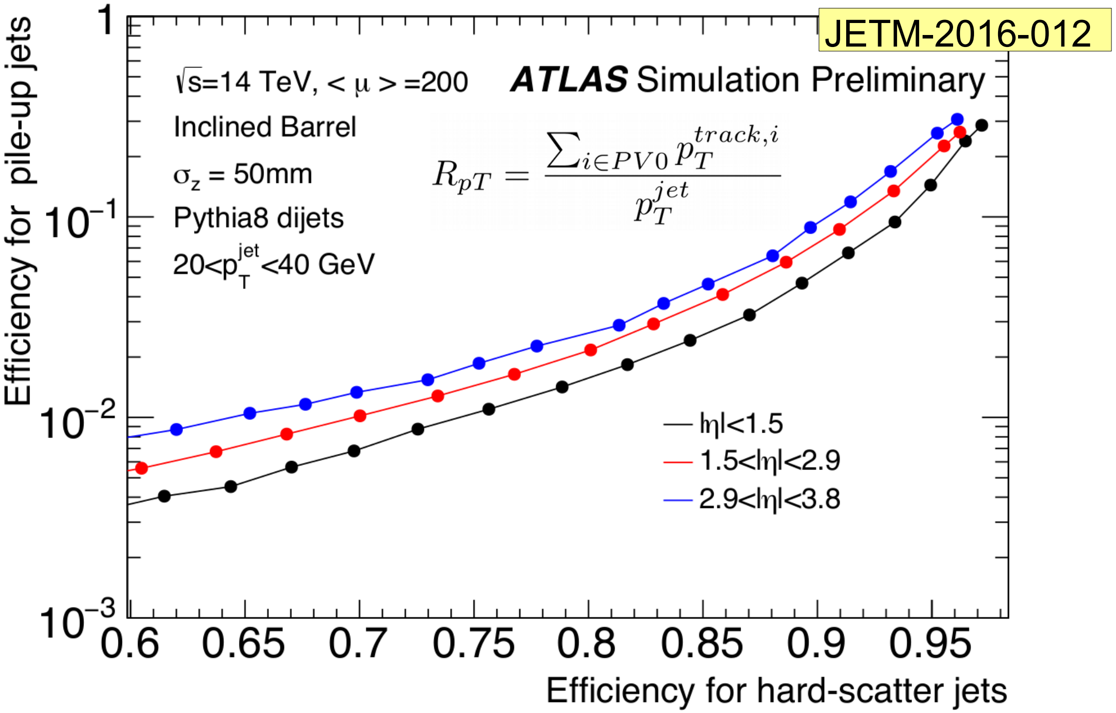
- Will highlight four different cases:
    - Pile-up jet suppression in VBF Higgs production
    - $H\to\gamma\gamma$ reconstruction with precision timing detector
    - $H\to\tau\tau$ triggering
    - $HH\to b\bar{b}b\bar{b}$ triggering and reconstruction

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

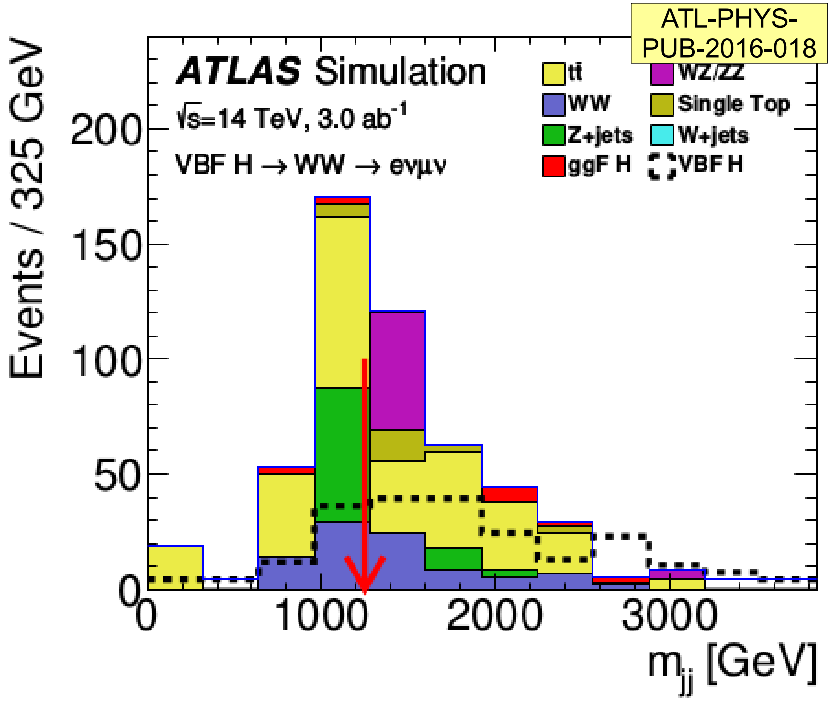

CERN-LHCC-2015-020


CERN-LHCC-2015-010


JETM-2016-012

VBF H→WW→eνμν Analysis

- Physics gain of forward tracker studied in H→WW analysis
- Simple cut based analysis:
  - 2 forward jets (|η|>2) in opposite hemispheres
  - No jet above 30 GeV in between jets
  - e/μ in between forward jets
  - Missing E_T>20 GeV
- After selection:
  - ~200 signal events
  - ~400 background events from $t\bar{t}$ and non Higgs WW



ATL-PHYS-PUB-2016-018

Signal precision and significance

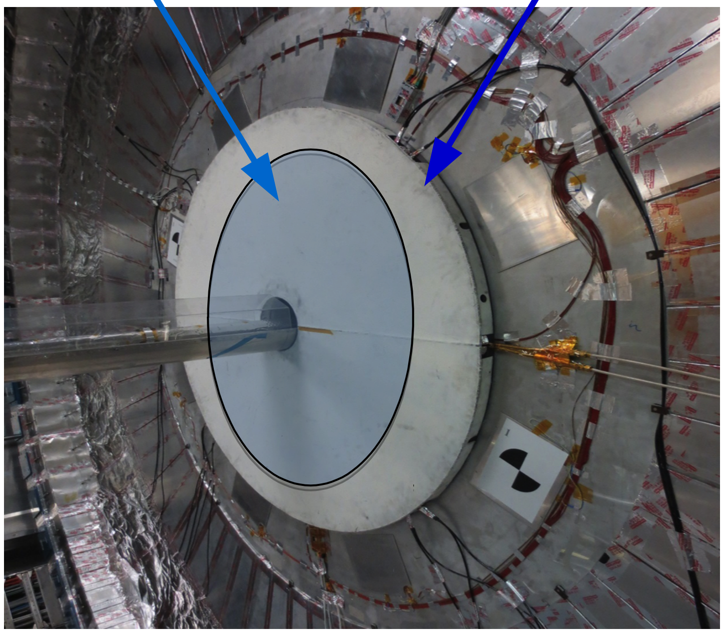
Tracker coverage	Δ_μ			Significance (σ)		
	Full	1/2	None	Full	1/2	None
|η|<4.0	0.20	0.16	0.14	5.7	7.1	8.0
|η|<3.2	0.25	0.21	0.20	4.4	5.2	5.4
|η|<2.7	0.39	0.32	0.30	2.7	3.3	3.5

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

Factor two gain in precision from extended tracker coverage

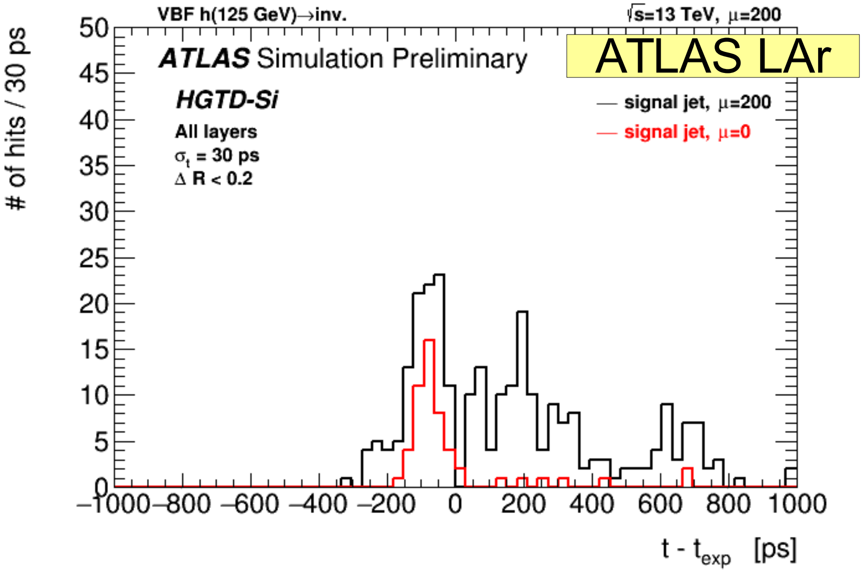
High Granularity Timing Detector

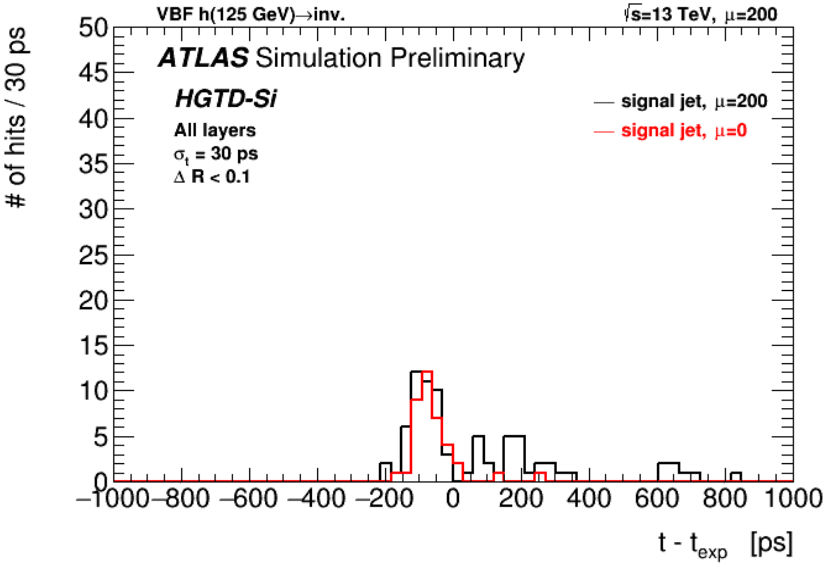
- Additional pile-up rejection can be achieved using precise timing
  - Different time of flight and different collisions times in event
- ATLAS considering thin timing device
  - Four layers silicon sensors
  - Coverage for 2.4<|η|<4.2
  - Possible Tungsten absorber for |η|<3.2
  - Timing target: 30-50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



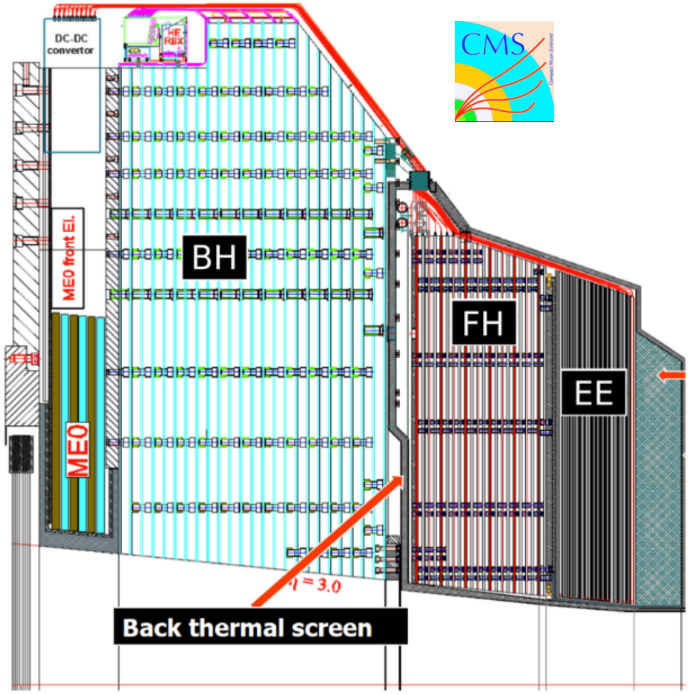
High-granularity timing detector

Minimum bias scintillators



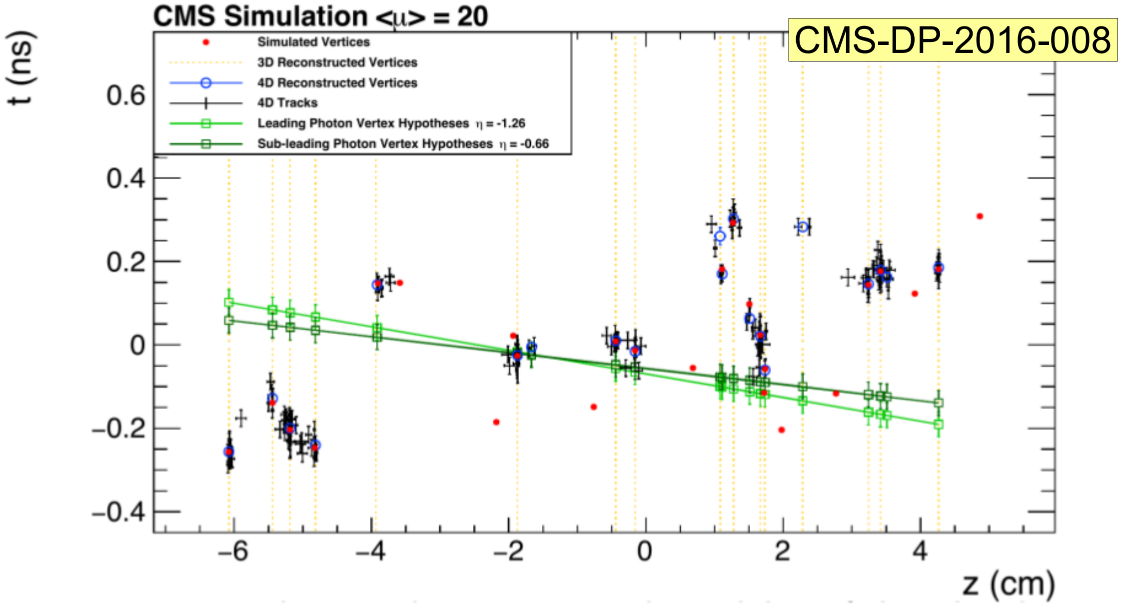


Timing Detectors in CMS



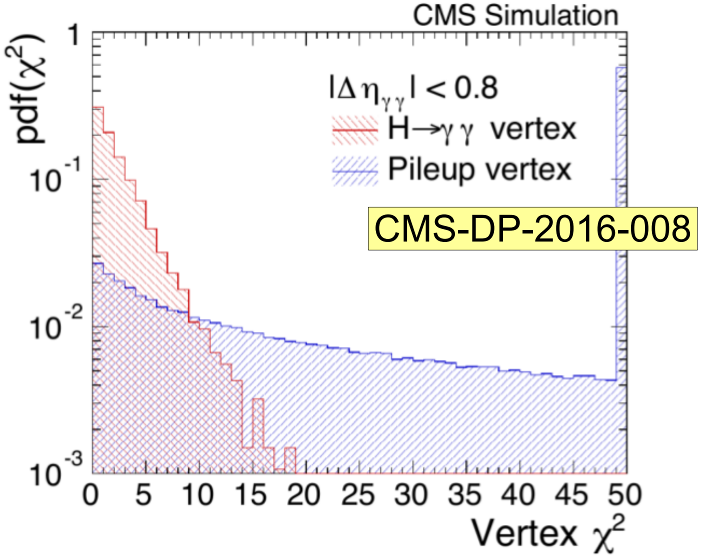
- Endcap calorimeter (1.5<|η|<3) replaced by multi-layer silicon-based calorimeter
  - Current calorimeter not rad-hard enough
- Use of silicon allows intrinsic time resolution down to 50 ps for large signal
- Barrel calorimeter electronics upgraded to also provide precision timing (30 ps)
- Additional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

Allows to reconstruct vertex time



CMS-DP-2016-008

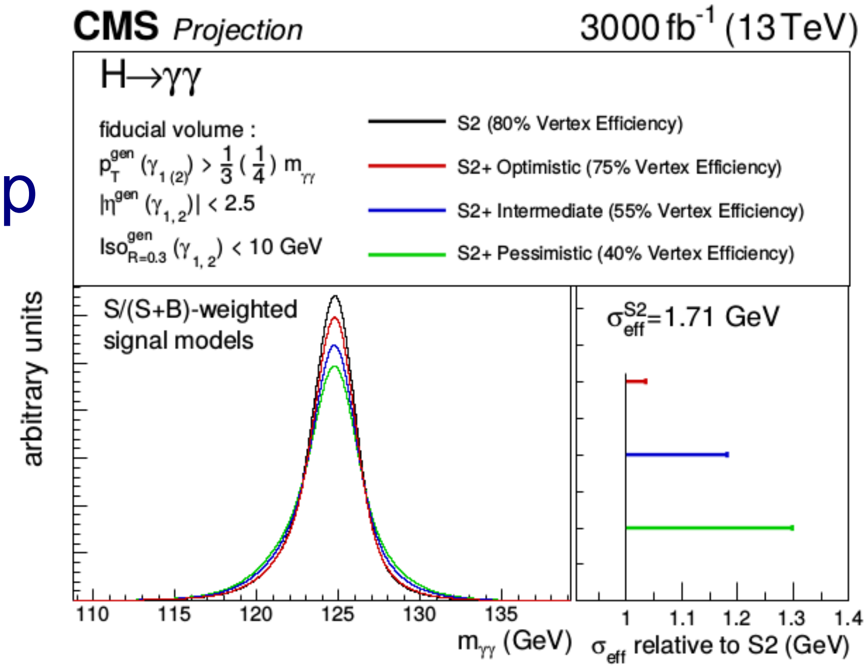
Example: Improved H→γγ vertex association

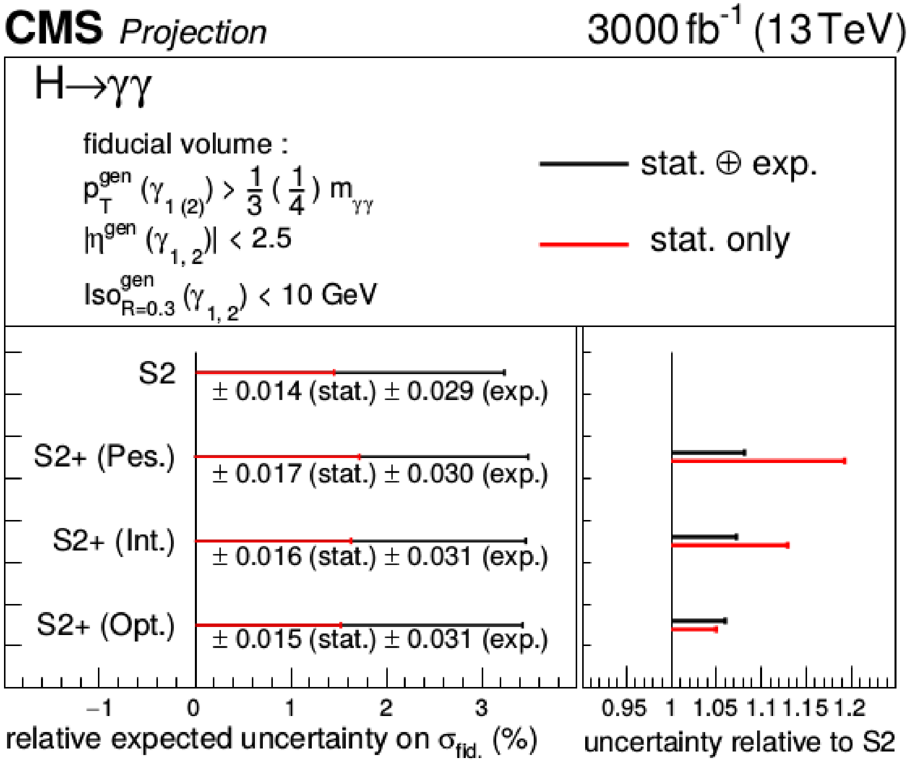


CMS-DP-2016-008

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





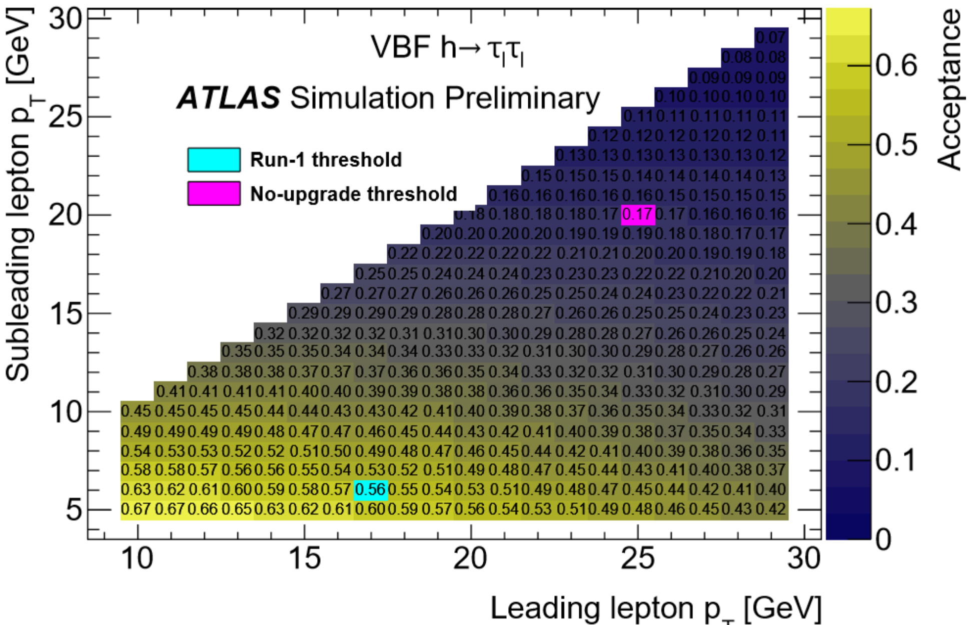
With full use of calorimeter and charged particle timing information vertexing efficiency can be almost full recovered

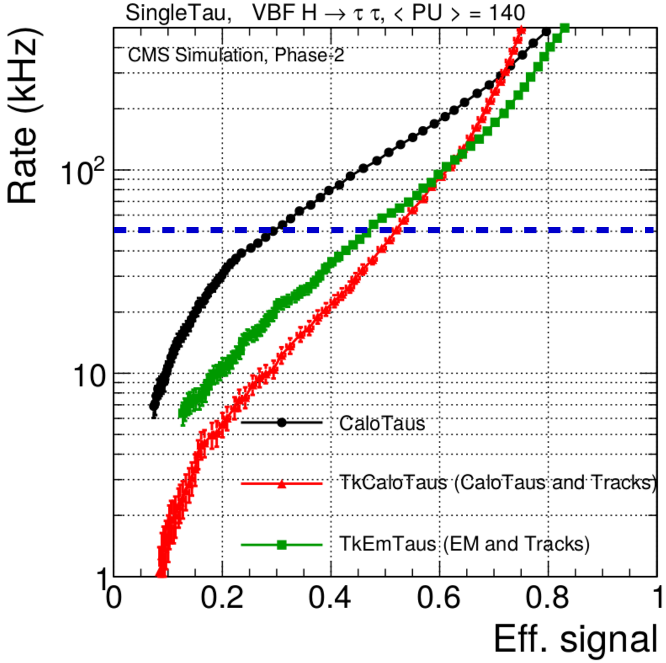
Corresponds to effectively 30% more luminosity

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

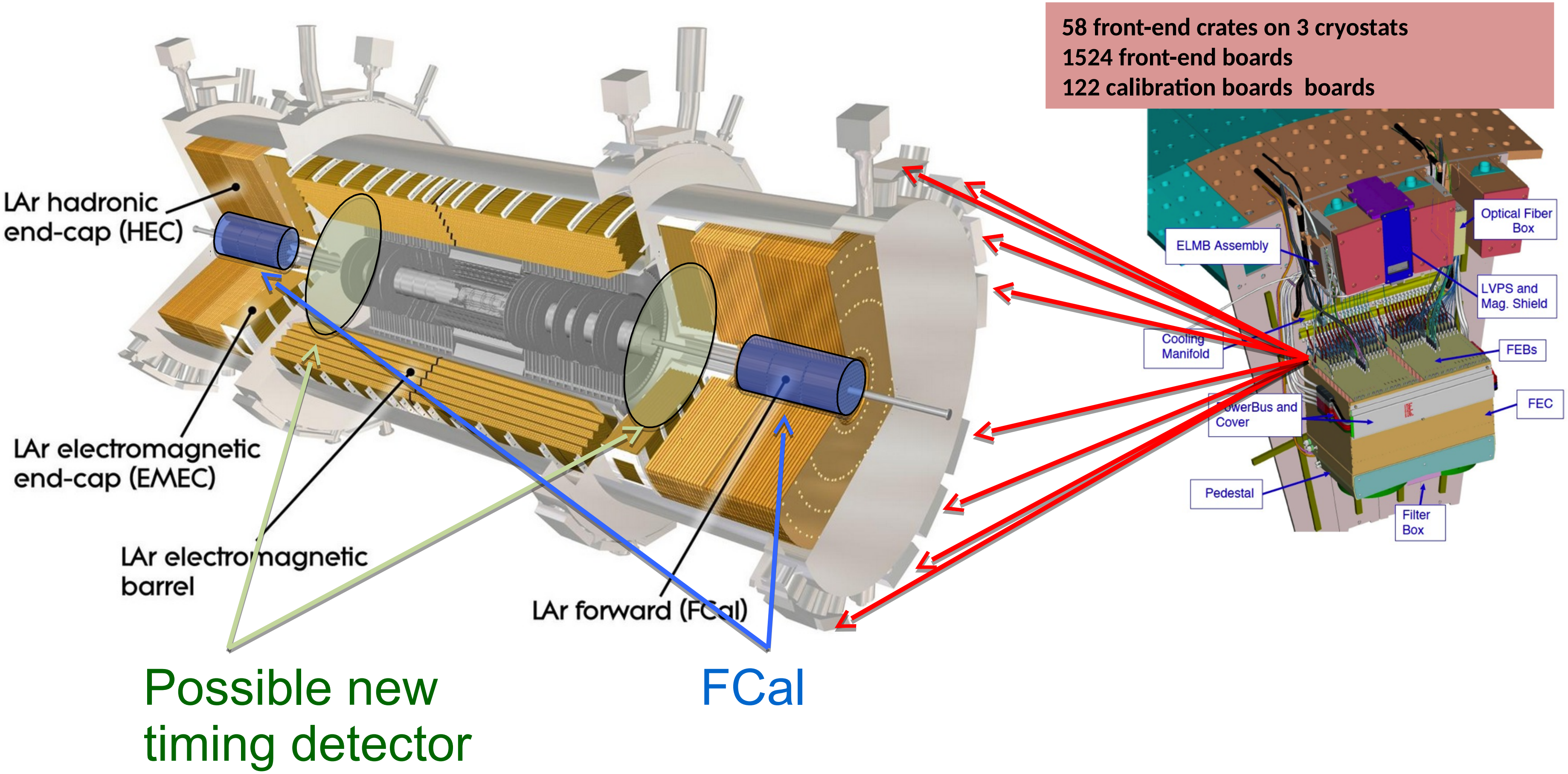
CERN-LHCC-2015-010





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



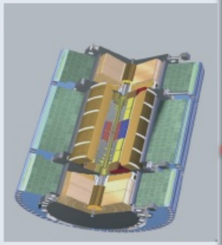
58 front-end crates on 3 cryostats
1524 front-end boards
122 calibration boards boards

LAr Electronics Upgrade

- In Phase-I upgrade Level-1 trigger output path
  - Factor 10 increase in granularity – reused in Phase-II
- Phase-II upgrade of readout electronics
  - Digital readout to back-end at 40 MHz
  - Alleviates current latency and trigger rate constraints
  - In addition original electronics only designed for 1000fb^{-1}

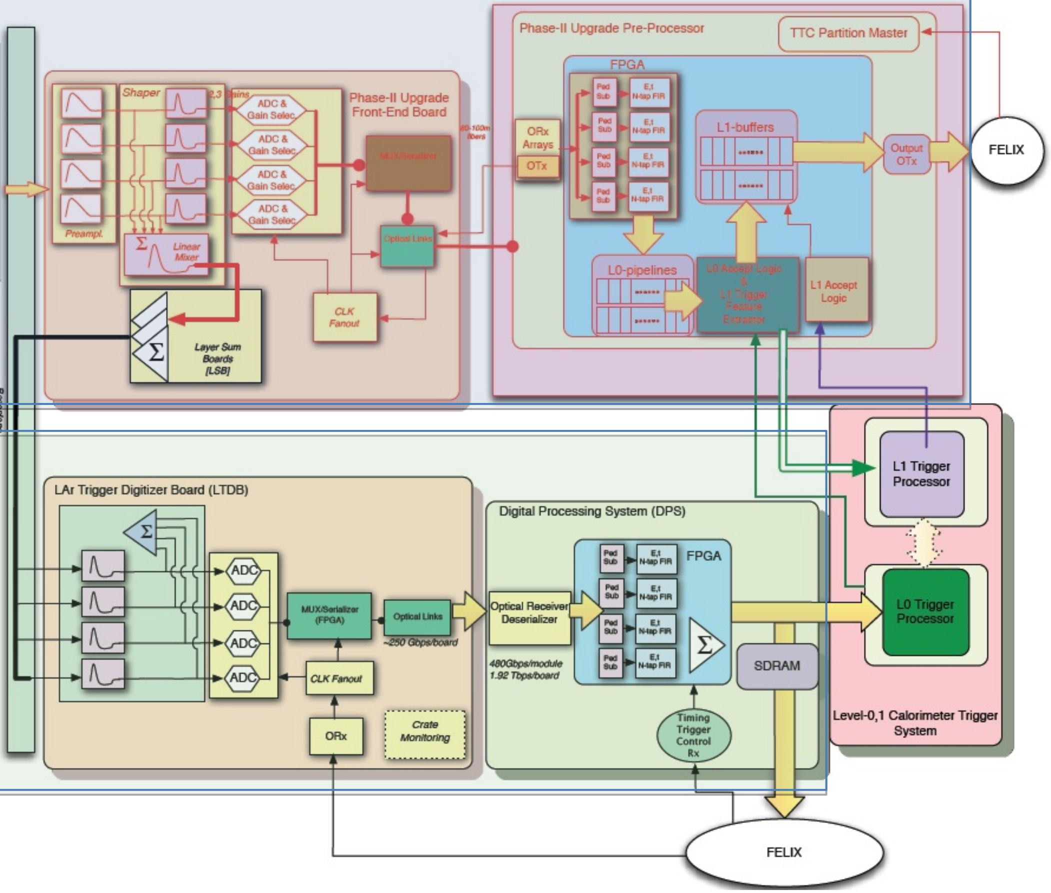
LAr Phase II Electronics Upgrade:

- Re-use Phase I Trigger Upgrade
- New FE Boards (FEB2)
- High Bandwidth Optical Links
- BE: LAr Pre-PRocessor Boards (LPPR)



LAr Phase I Upgrade:

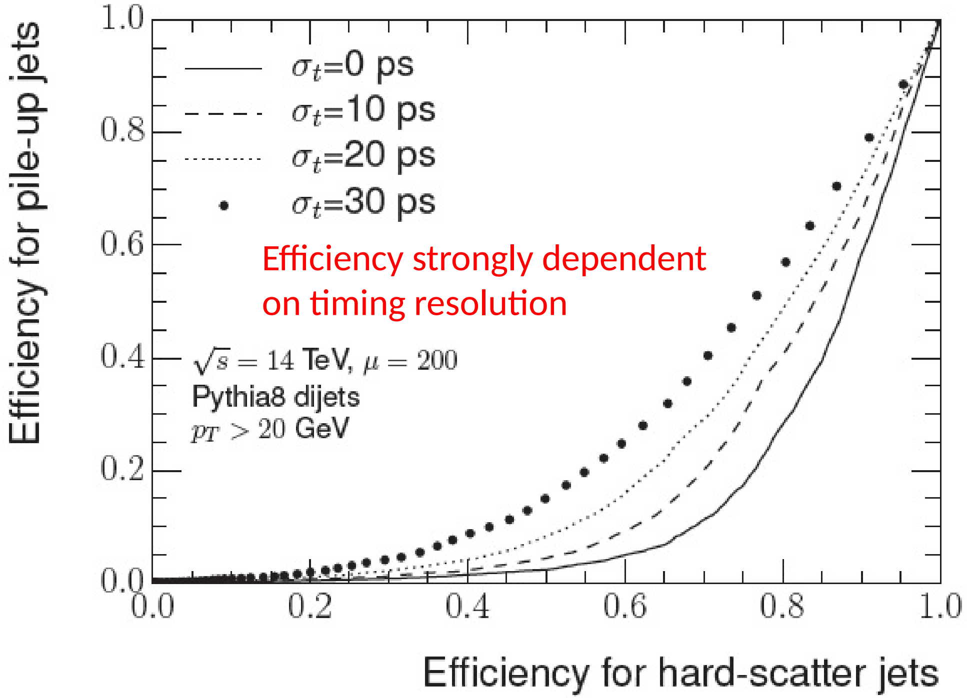
- New Layer Summing Boards
- New Baseplanes
- FE: Trigger Digitizer Board (LTDB)
- BE: Digital Processing System (LDPB)



High-Granularity Timing Detector

- Evaluating option of adding thin, high-granularity timing detector in front of end-cap calorimeter (2.5<|η|<4.2)
  - Multiple layers of silicon and optional tungsten absorber
  - Pad size: 1x1mm^2 – 3x3 mm^2
  - Timing precision: 30-50 ps
- Precise timing use to reject pile-up jets
  - Possibility for use in trigger also being studied

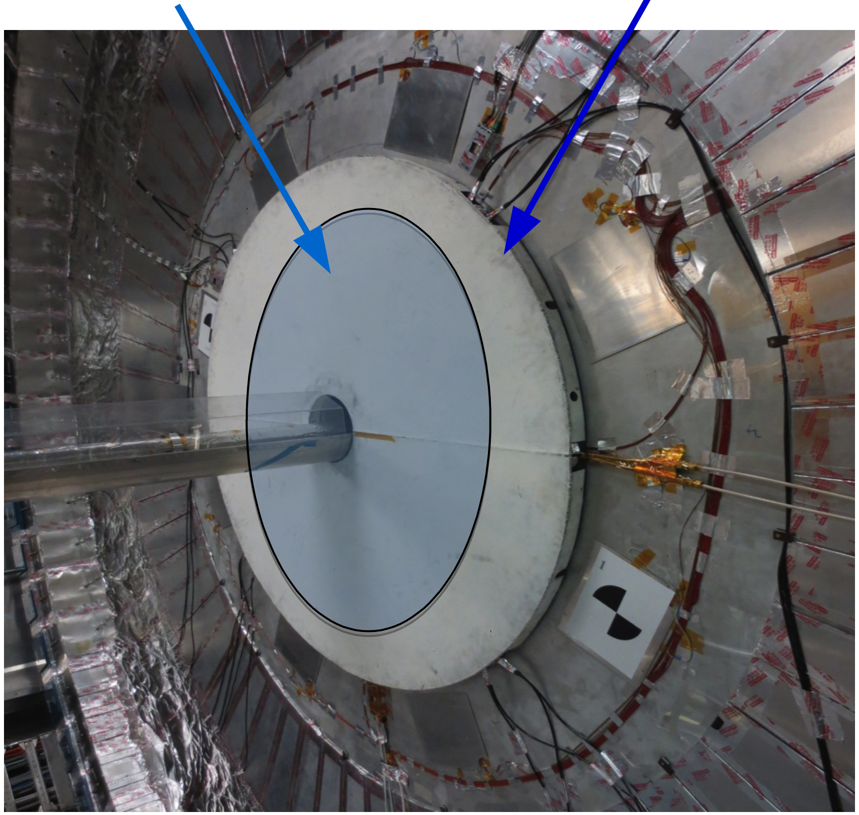
Pile-up jet rejection power:



Efficiency strongly dependent on timing resolution

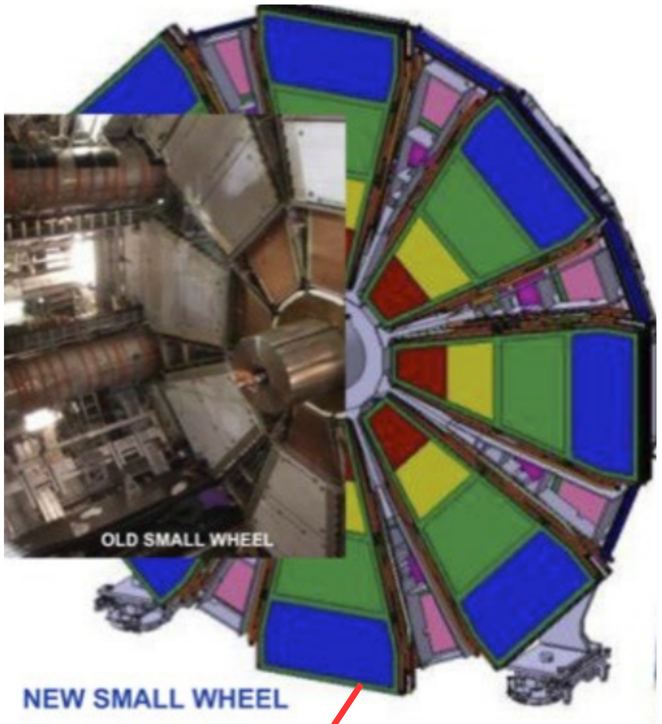
High-granularity timing detector

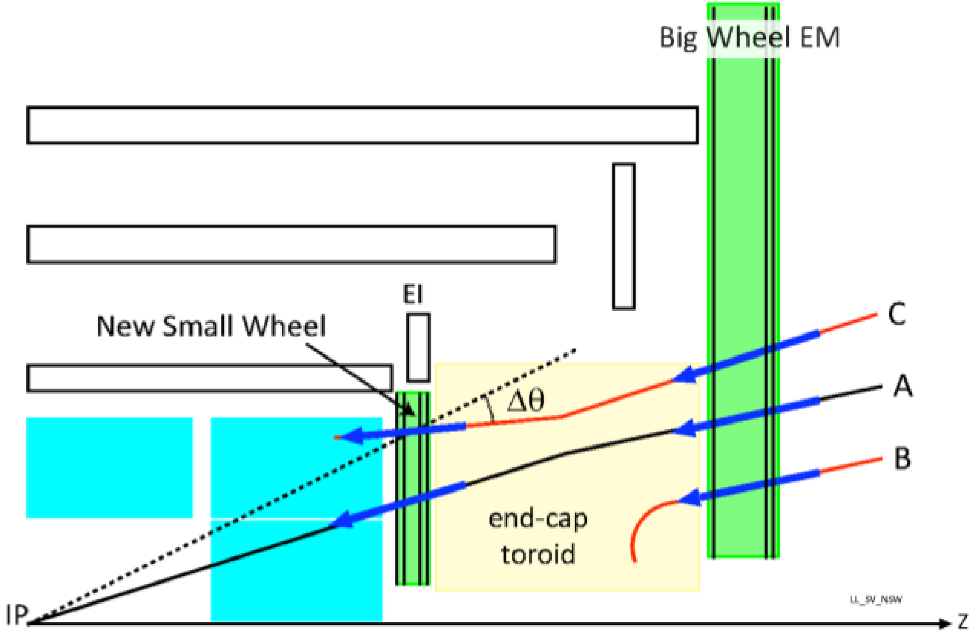
Minimum bias scintillators

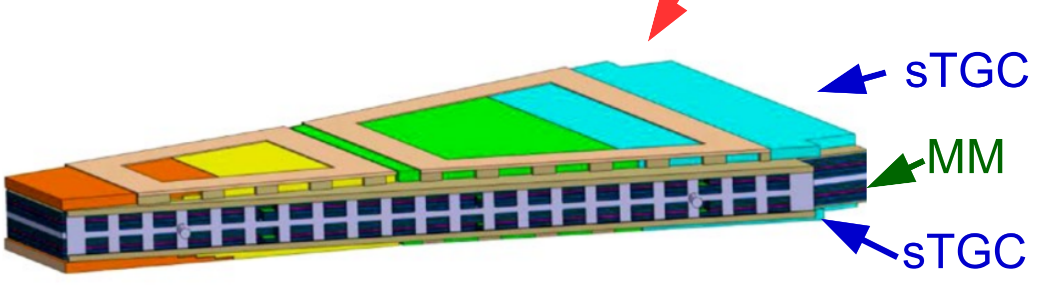


New Small Wheel

- Will replace inner wheel of muon end-cap in Phase-I
  - Increased hit rate capability
  - Rejection of fake L1 muon triggers
- MicroMegas – precision tracker
  - Spatial resolution <100μm
  - Good track separation
- Small strip TGC – trigger detector
  - Bunch ID with good timing resolution
  - Track vector with <1mrad resolution



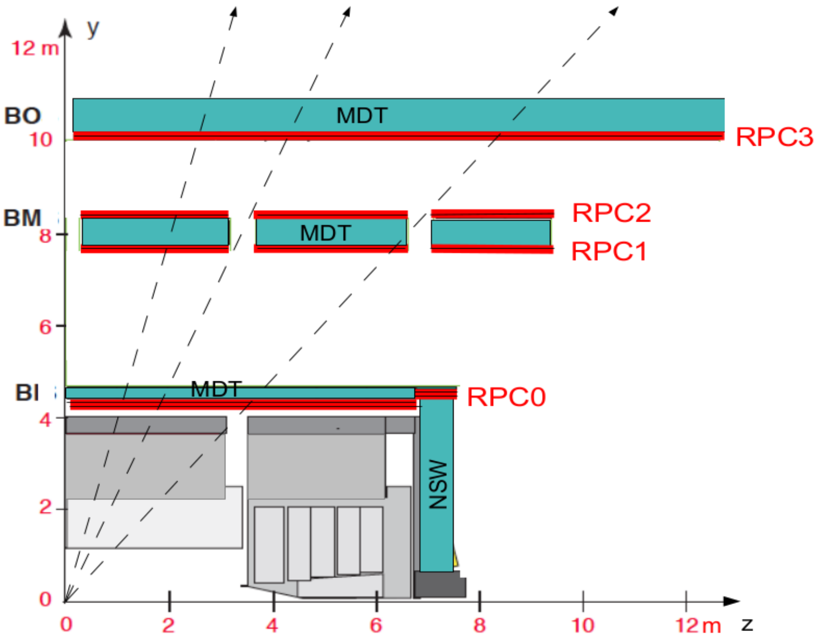




Chamber production expected to start very soon

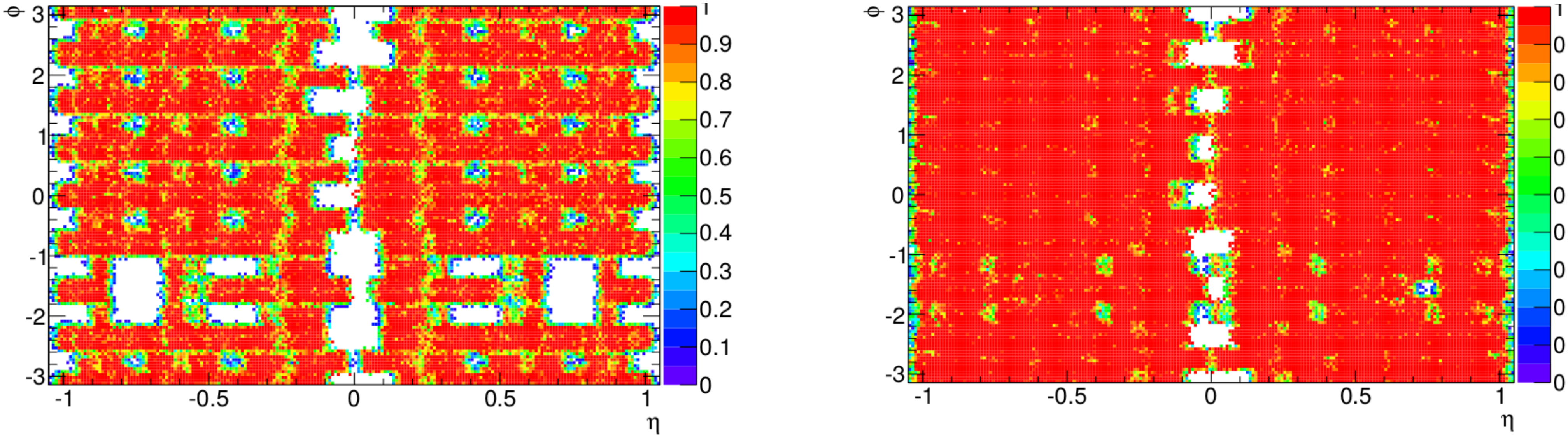
Muon Barrel Upgrade

- 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



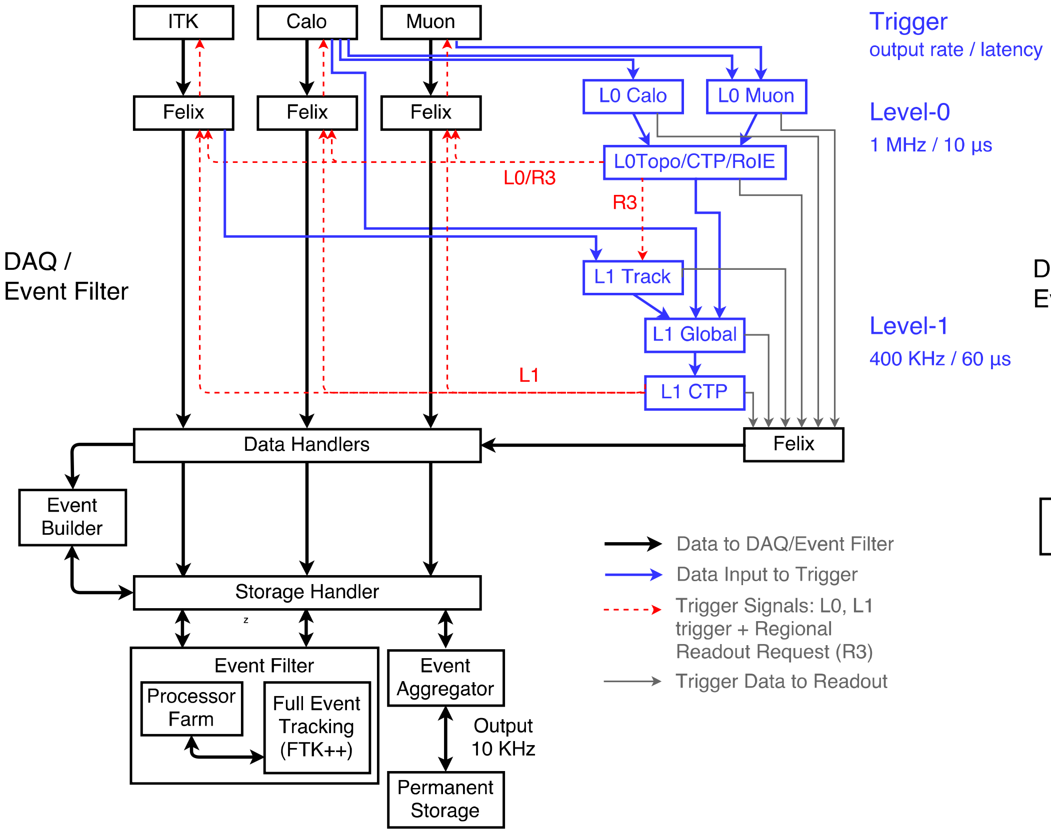
Acceptance without BI upgrade

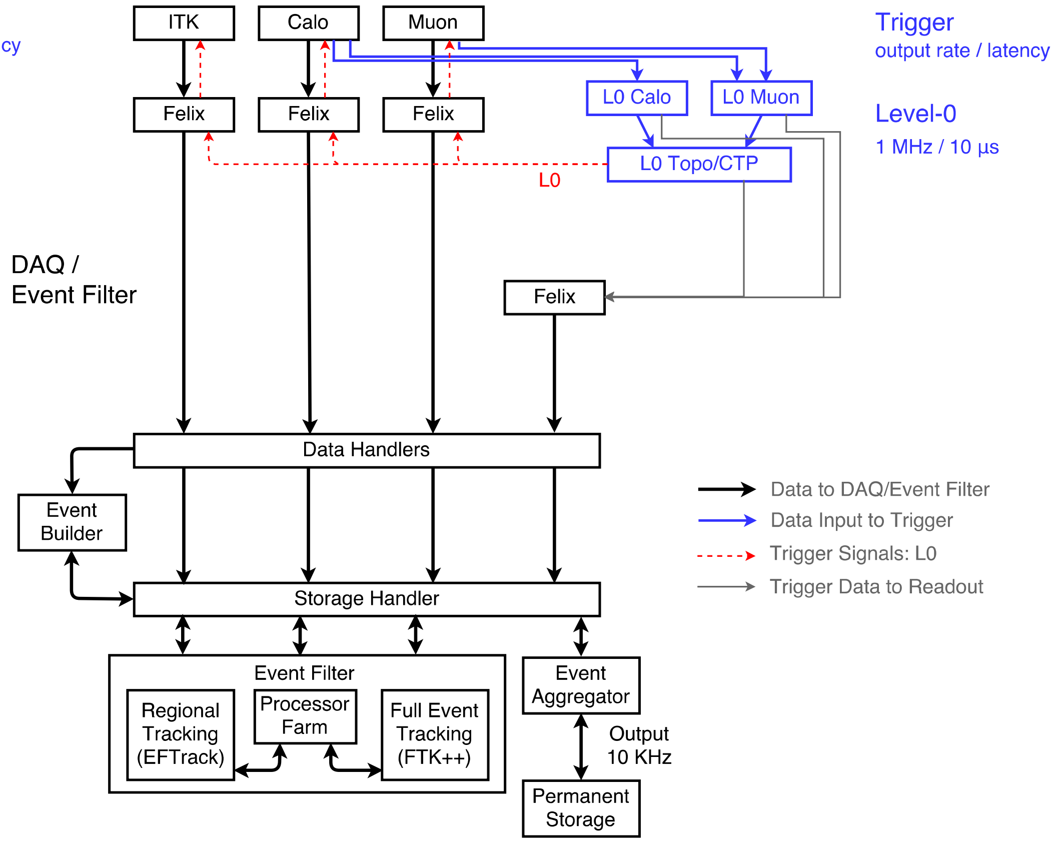
Acceptance with BI upgrade



Upgrade of TDAQ Architecture

Deciding between two-level hardware trigger with hardware tracking at Level-1 and a high bandwidth single-level trigger

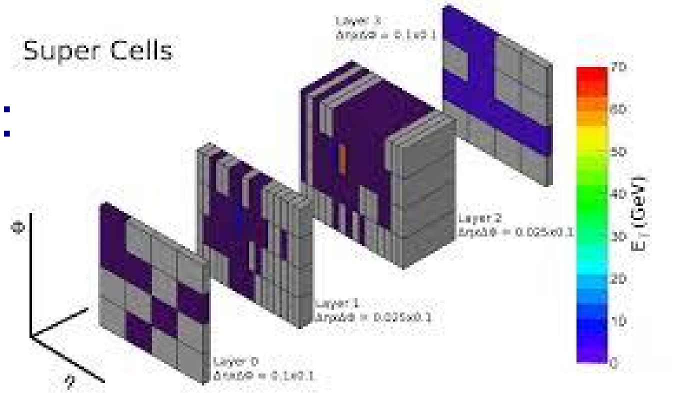


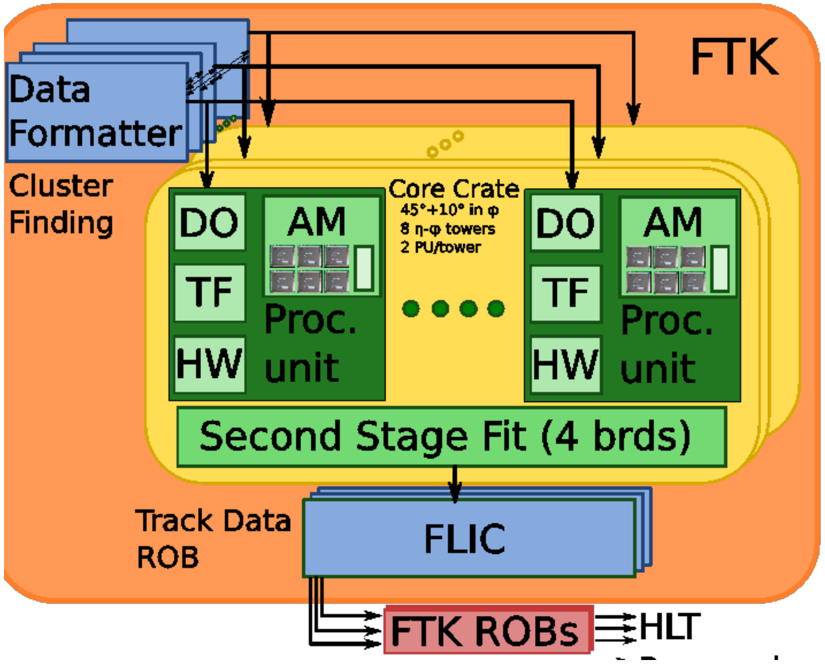


Low latency (25 µs) two-level system also under consideration
Trades latency for higher trigger rate and thus increased trigger acceptance in certain channels – max rate TBD

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

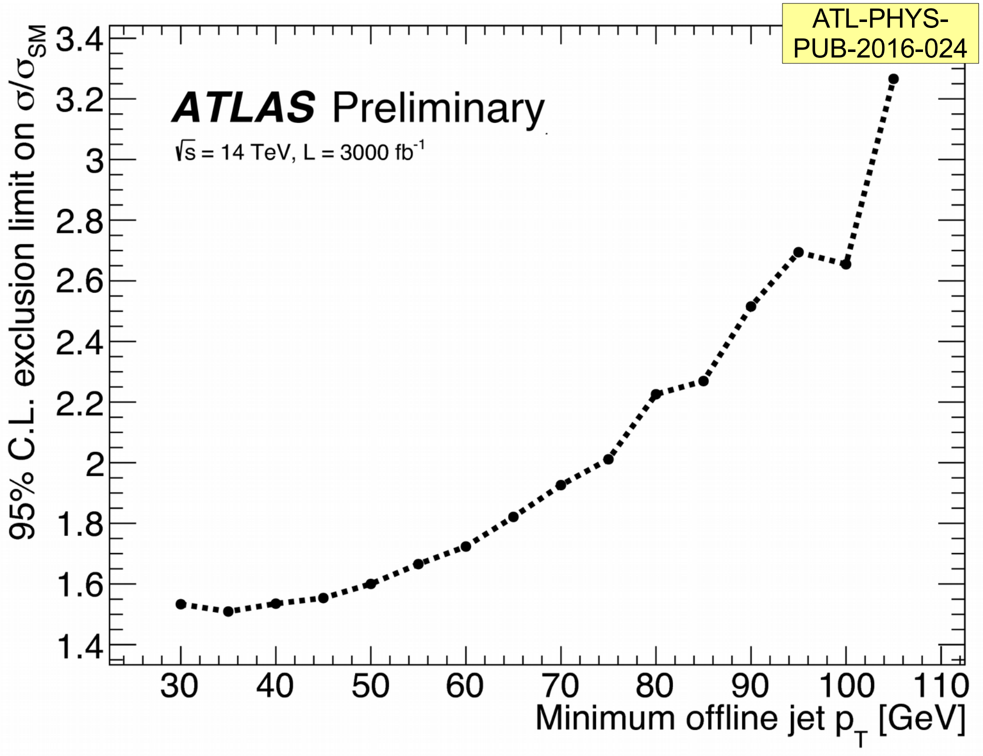




- Level-1 mainly adds tracking
  - Also plan to have full granularity calorimeter data available
- Track-trigger builds on FTK design
  - Pattern recognition with custom-made Associate-Memory chips
  - Track fitting in FPGAs
- FTK currently under installation
  - Expected to be commissioned in 2017

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



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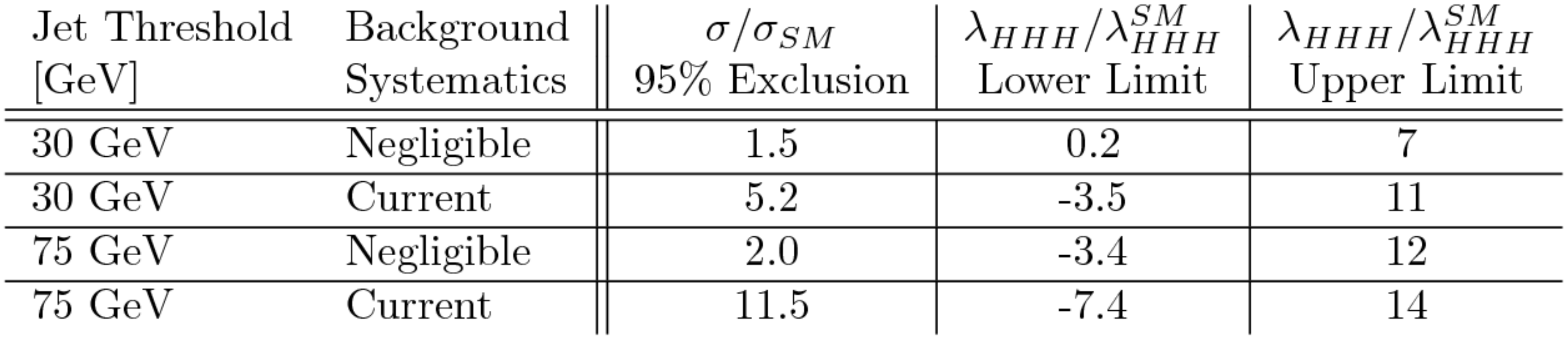

Jet Threshold [GeV]	Background Systematics	σ/σ_{SM} 95% Exclusion	$\lambda_{HHH}/\lambda^{SM}_{HHH}$ Lower Limit	$\lambda_{HHH}/\lambda^{SM}_{HHH}$ Upper Limit
30 GeV	Negligible	1.5	0.2	7
30 GeV	Current	5.2	-3.5	11
75 GeV	Negligible	2.0	-3.4	12
75 GeV	Current	11.5	-7.4	14