High Luminosity LHC Physics and the CMS Detector Upgrade

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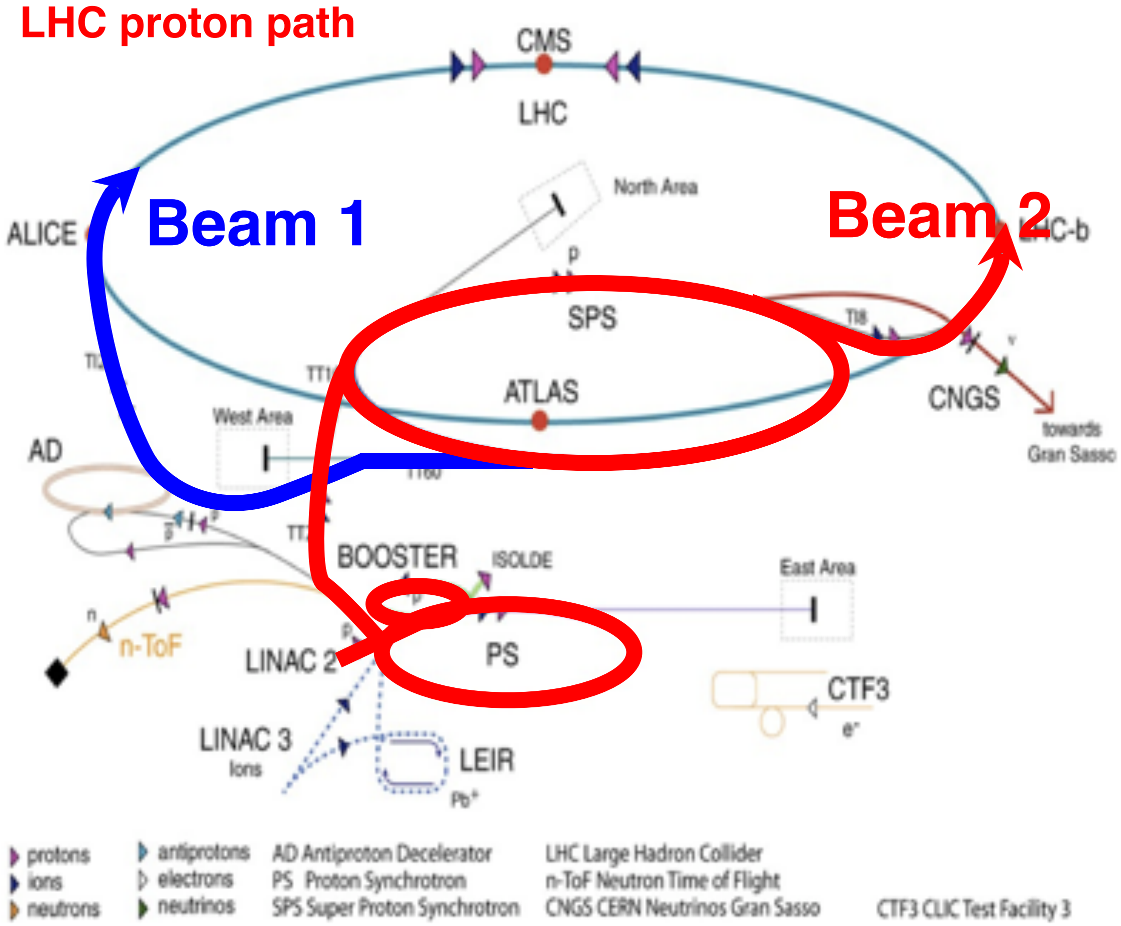
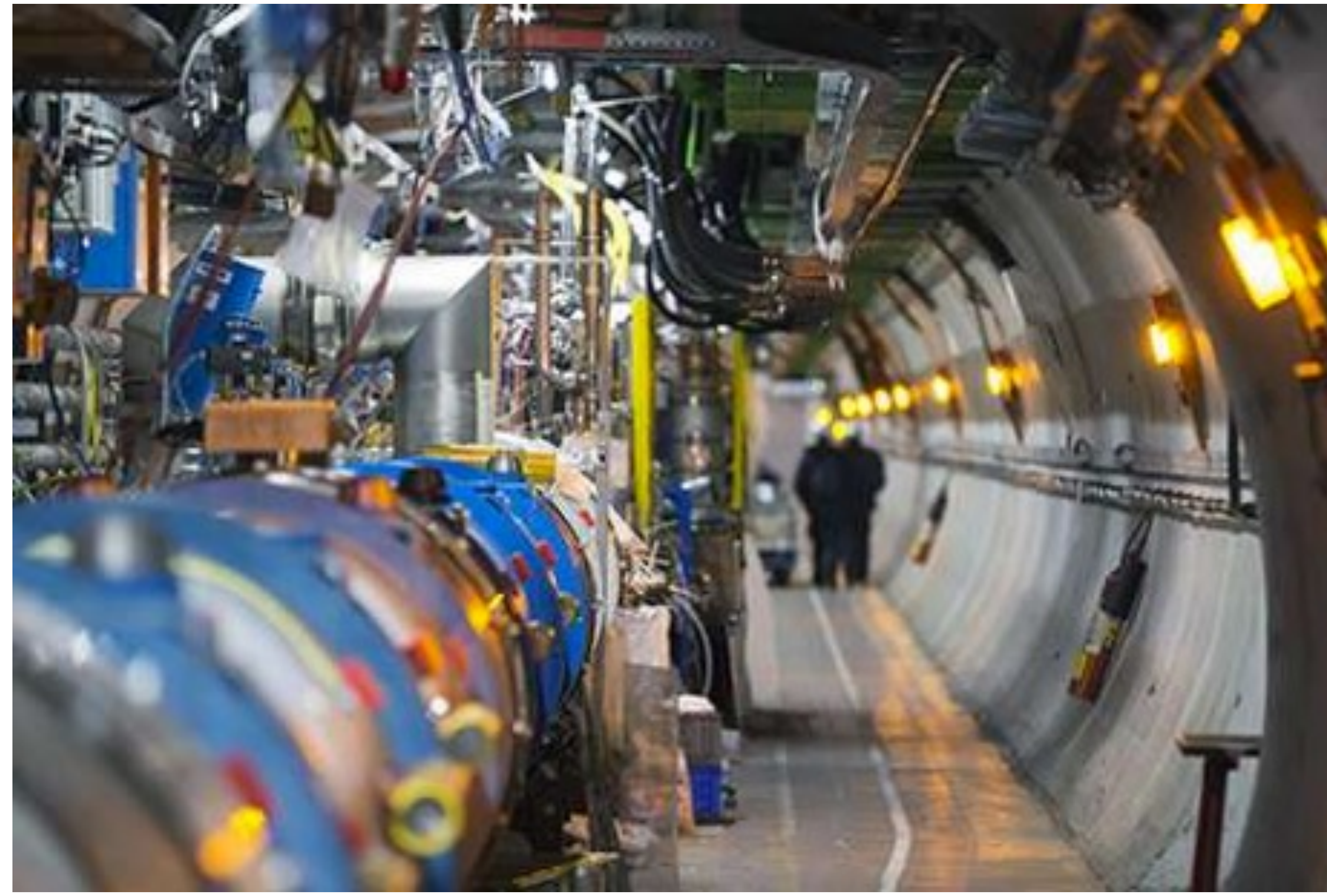
Outline

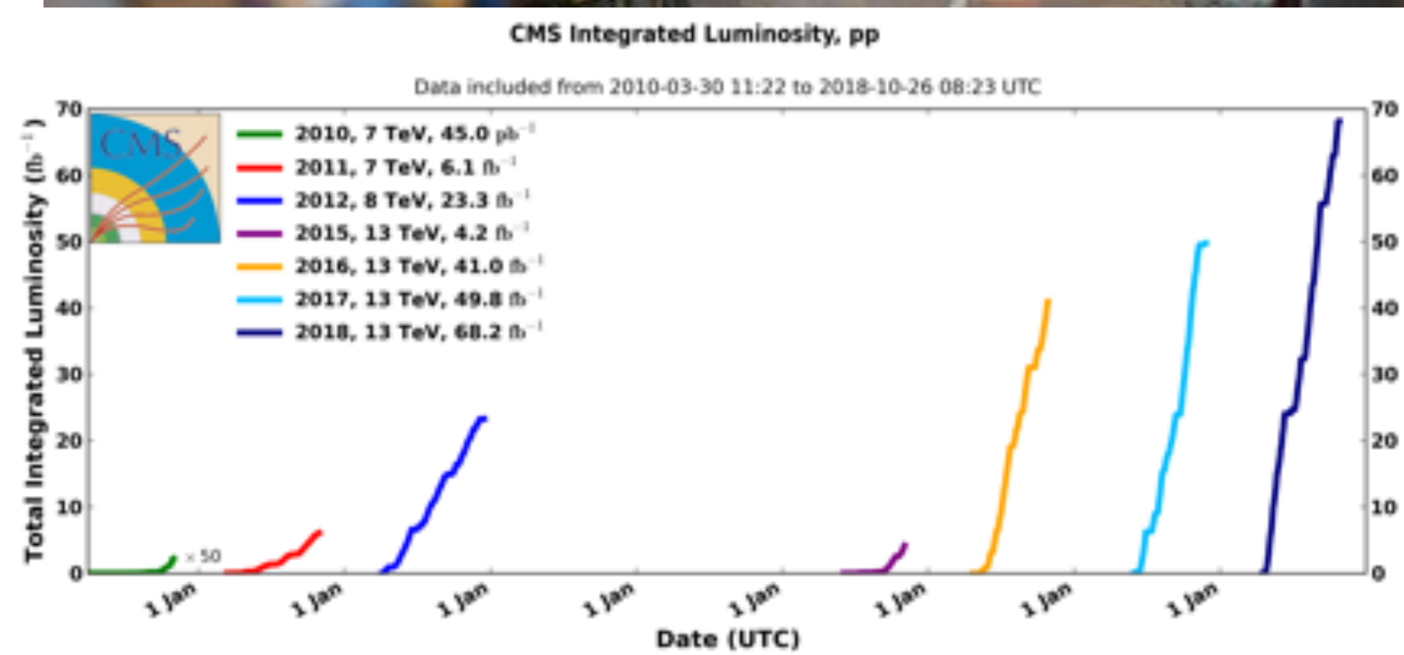
- **LHC: Past, Present, and Near Future**
- **High Luminosity LHC Overview**
  - **Collider**
  - **Physics Goals and Projections**
  - **Detector Requirements**
- **CMS Upgrade overview**
- **CMS Outer Tracker needs/design**
  - **Thermal & Tensile testing**
- **Conclusions**

LHC So Far: Runs 1 and 2

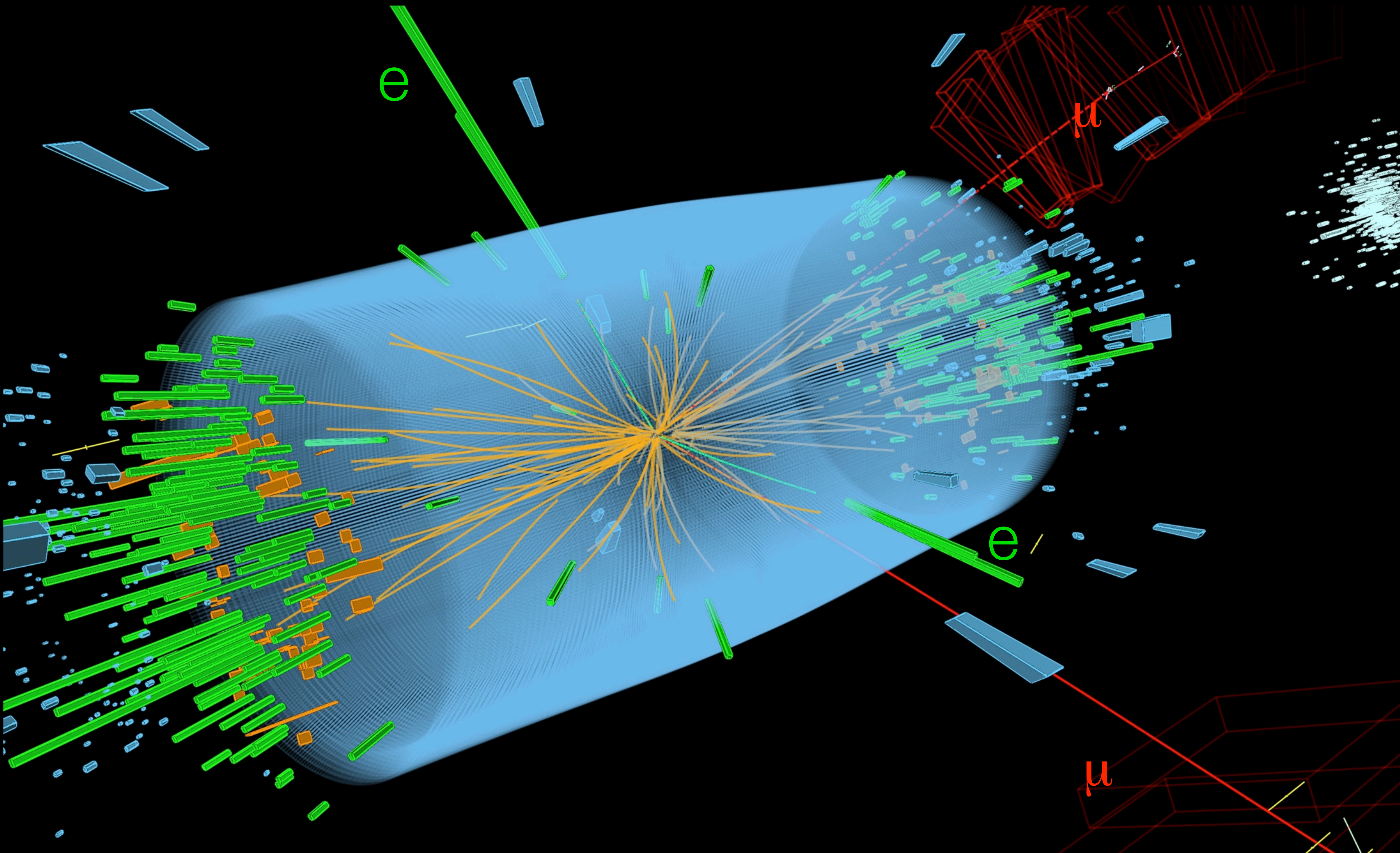
- 7 years of exemplary running after initial issue
- pp collisions at CoM energies of 7, 8, and 13 TeV
- ~150 fb^{-1} at 13 TeV



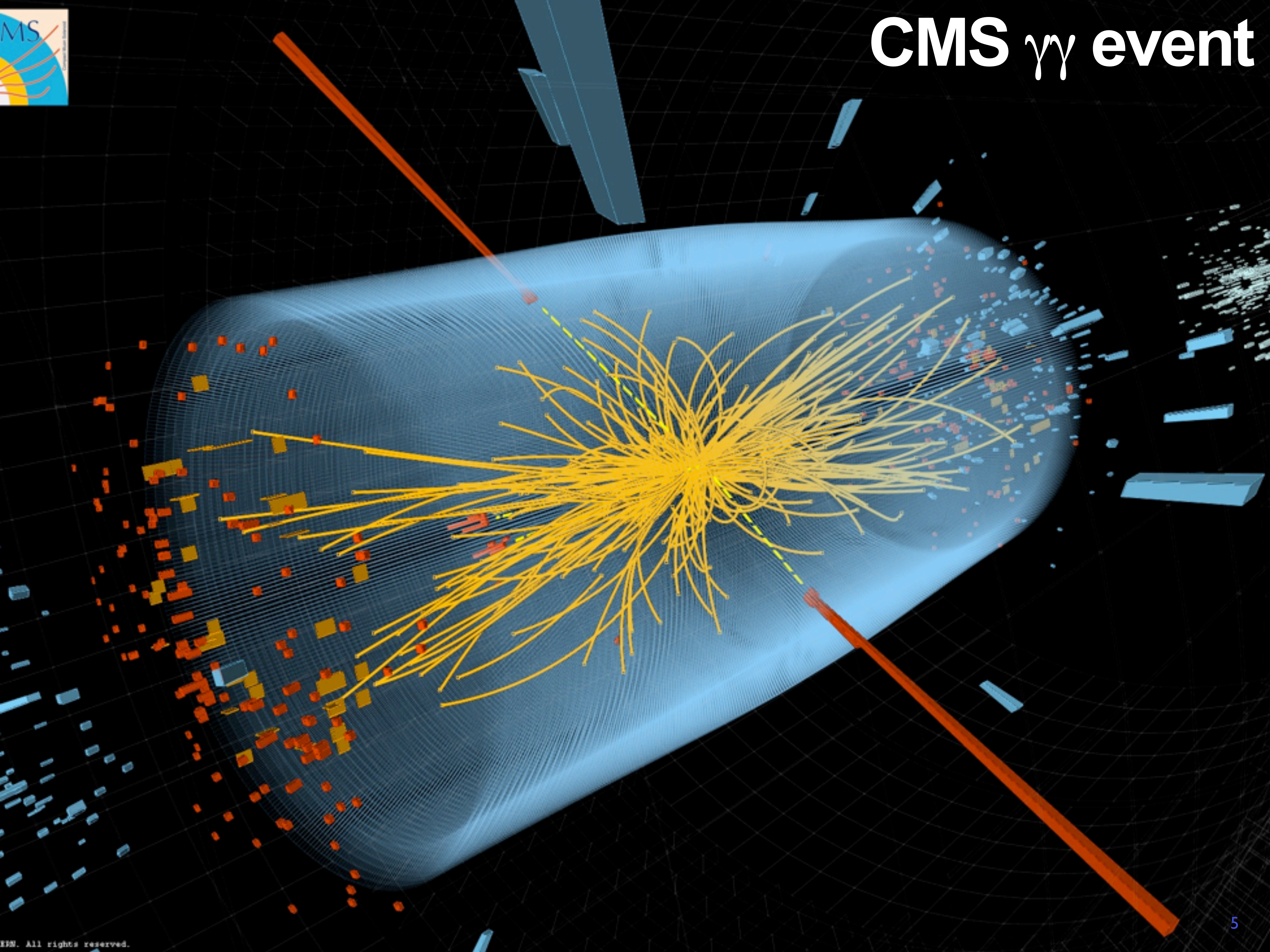




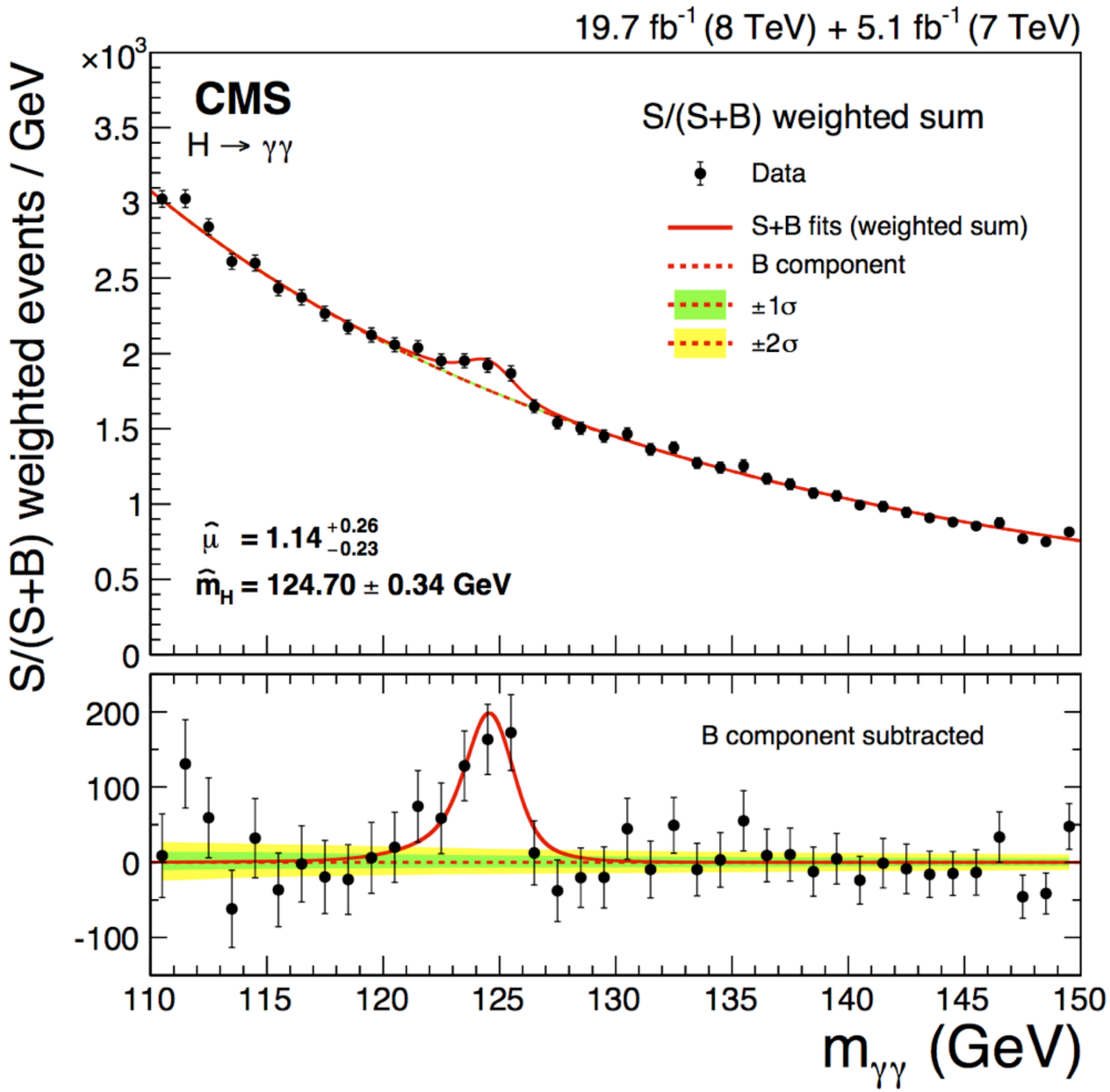
CMS ZZ$\rightarrow$eeμμ event



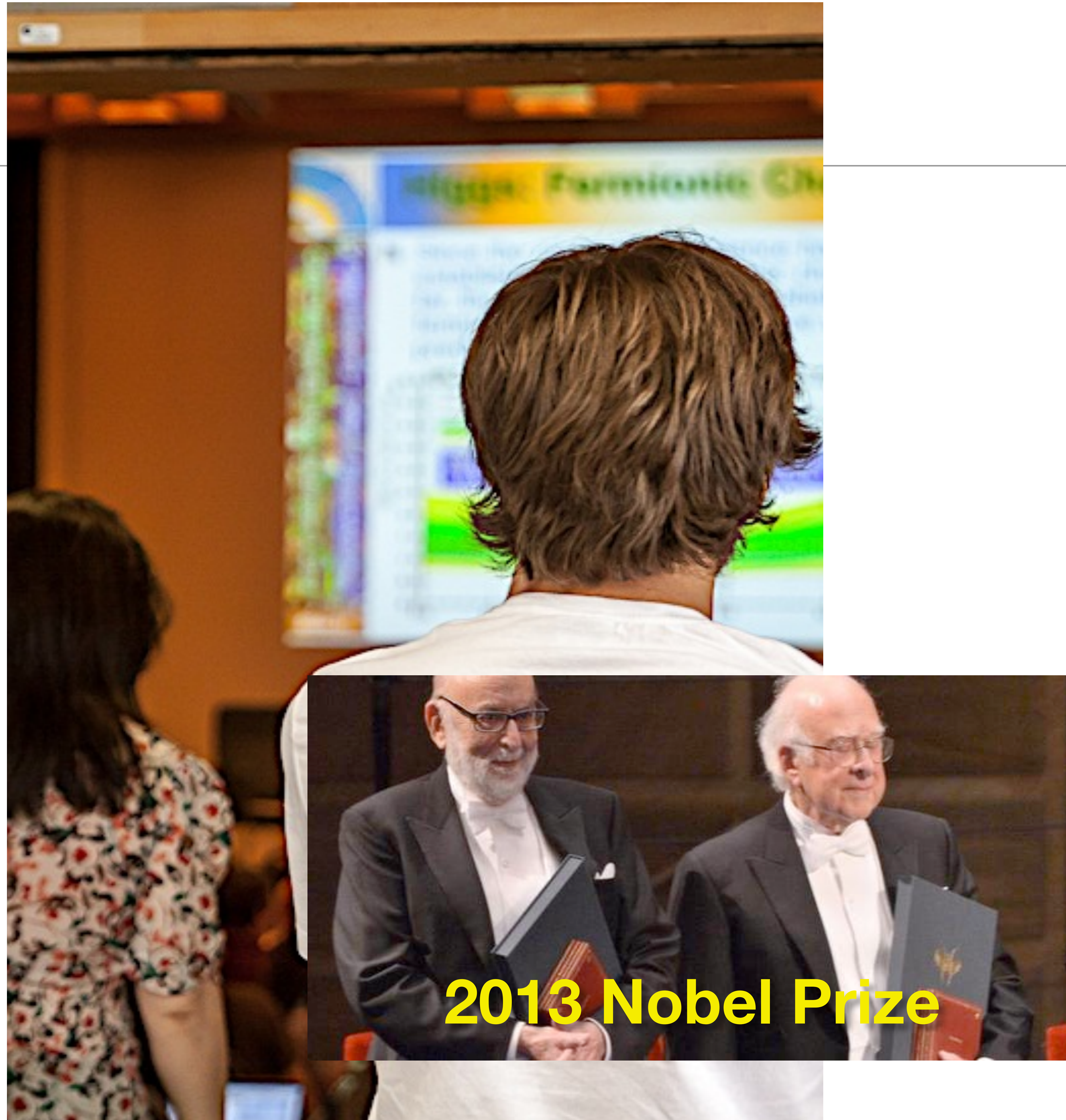
CMS γγ event



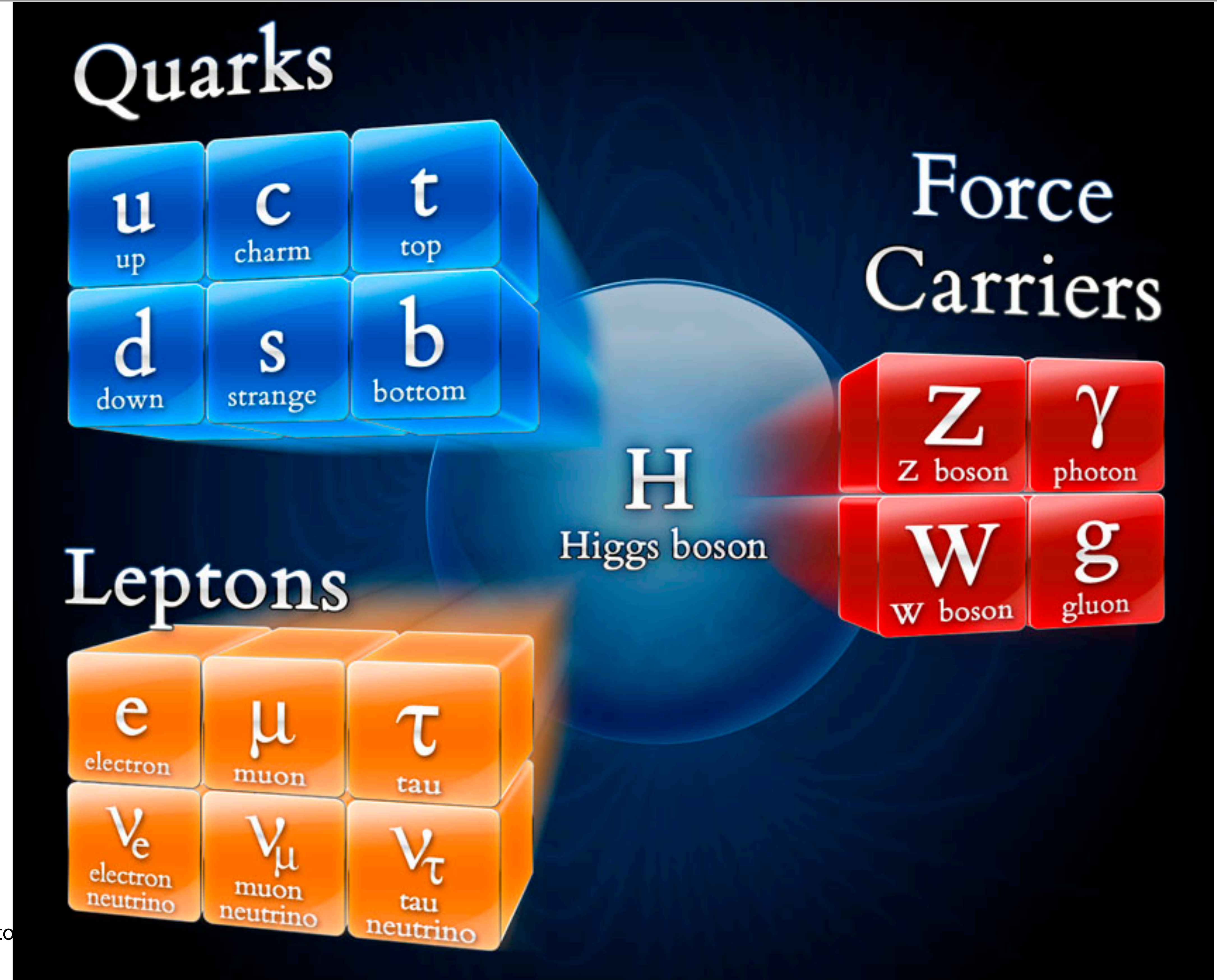
J. Gunion's channel: H → gamma gamma




I FOUND A NEW PARTICLE


2013 Nobel Prize

The Standard Model as of July 4, 2012



What is left to learn?

Why do these particles have the masses that they do?

Is the Higgs particle actually THE Higgs?

Are there other Higgs bosons?

Why are there three families?

How do neutrinos get their mass?

Do the 4 forces all unify at some scale?

Is gravity special?

Why is there CP violation?

Where is the universe's antimatter?

Dark matter in the universe?

Dark energy in the universe?

CMS analysis of Higgs Decay Measurements

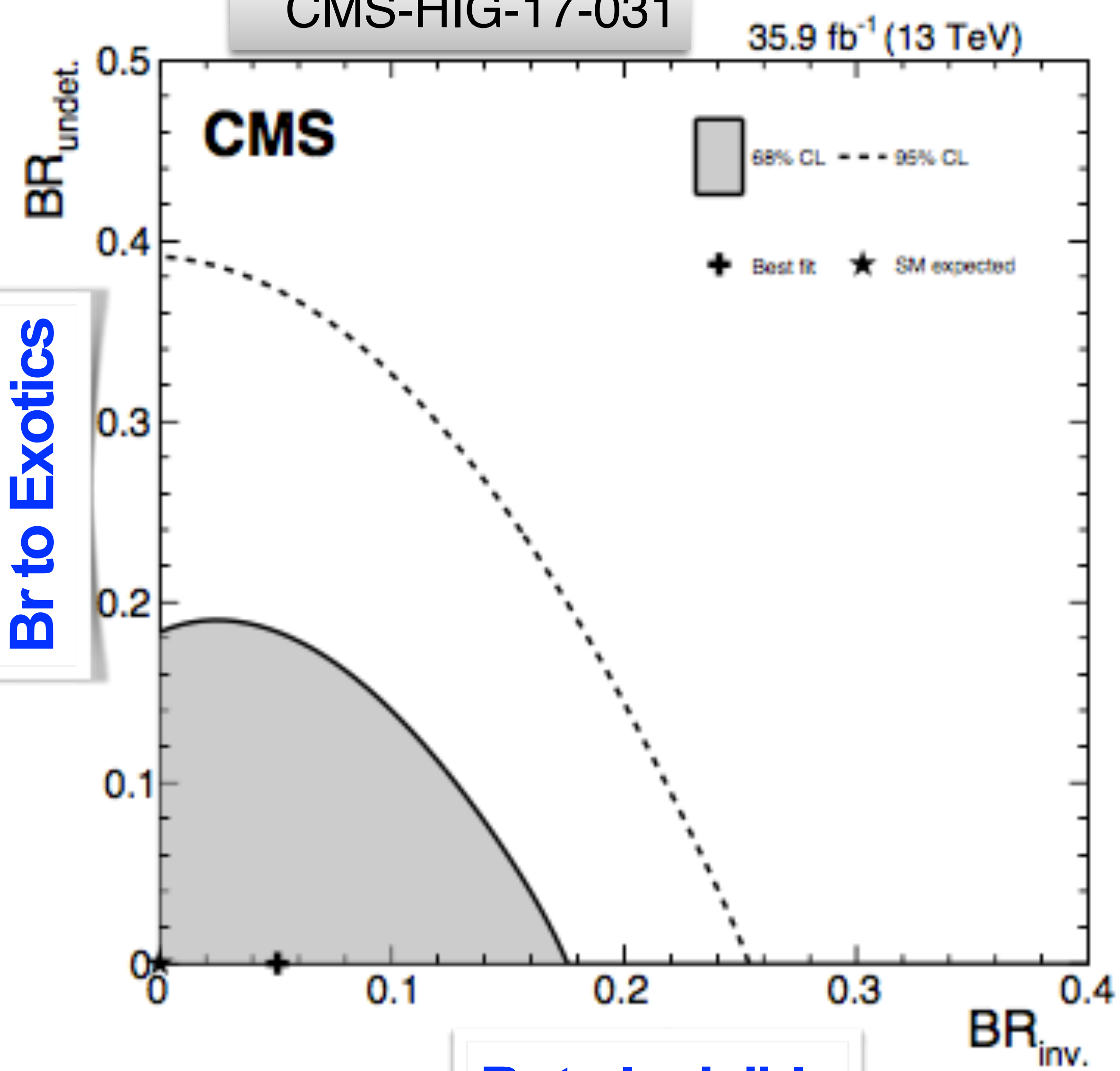
All channel measurements of Higgs boson's production and decay at $\sqrt{s}$ = 13 TeV

Allowed branching ratio to as-yet-unseen decays

< 20% (@ 68% CL)

< 40% (@ 95% CL)

CMS-HIG-17-031



Br to Exotics

Br to Invisible

- **Direct searches and Higgs decays to exotics still well motivated!**

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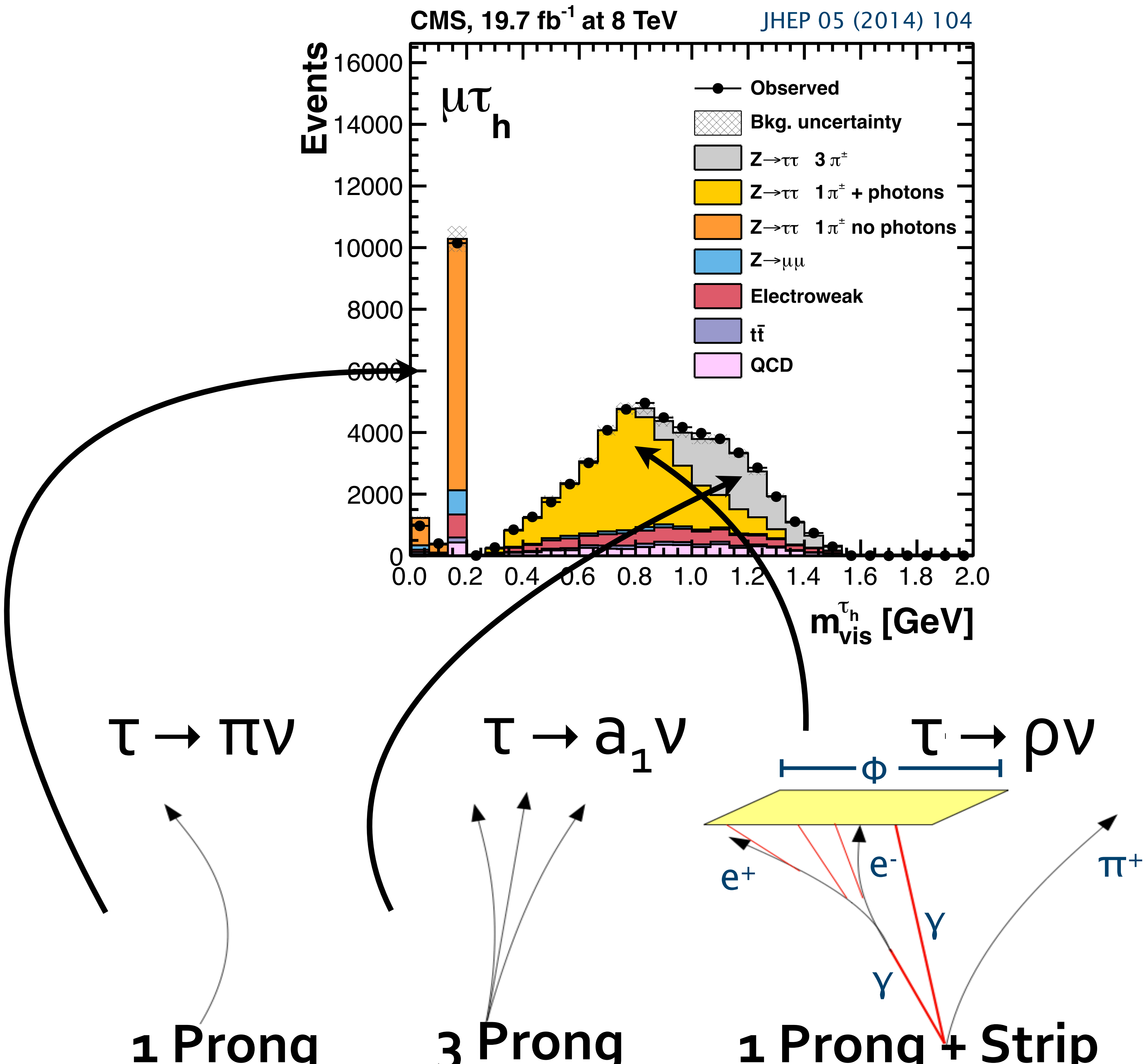
CMS Isolated hadronic tau decay identification

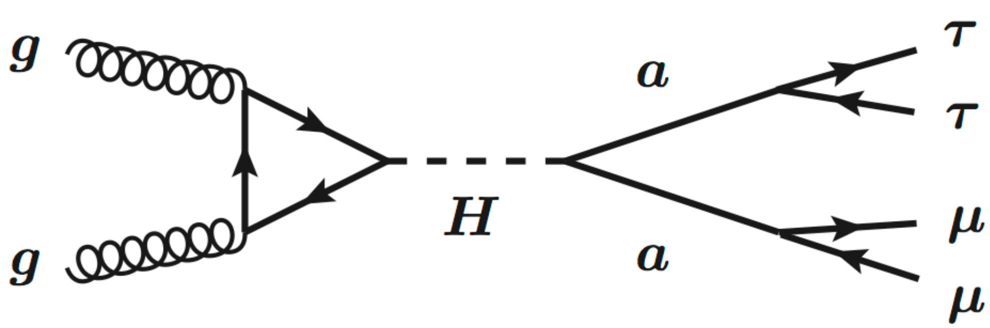


Hadron Plus Strips: Sophisticated and highly performant technique.

However, reconstruction fails for non-isolated (e.g., overlapping) taus

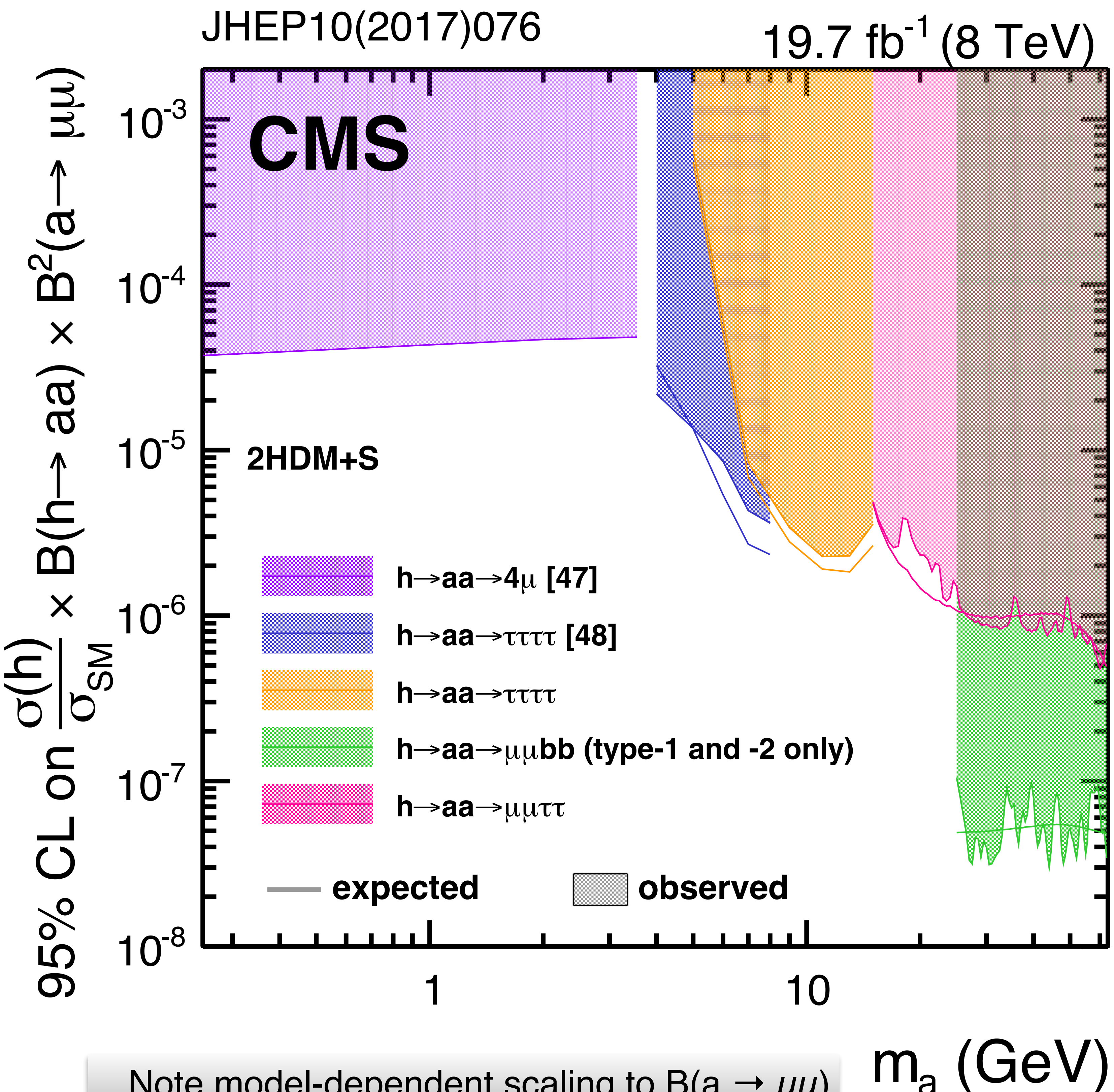
https://indico.cern.ch/event/197461/contribution/0/attachments/290954/406673/CMS_4July2012_Final.pdf

Searches for light pseudoscalars @ Run 1



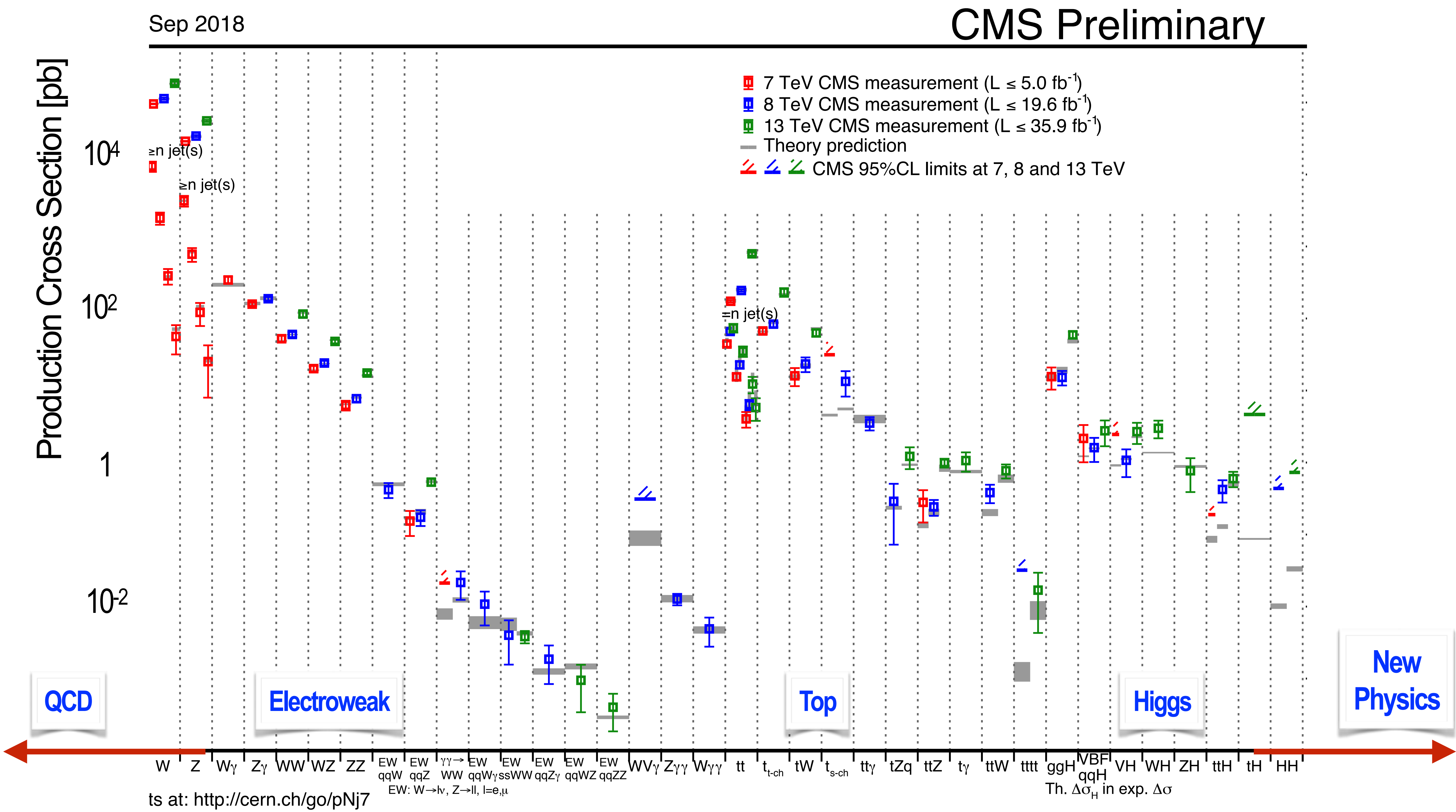
2HDM+Singlet, e.g., NMSSM, yield expanded H sector

- Neutral scalars:
  - h_1, h_2, h_3
- Neutral pseudoscalars:
  - a_1, a_2
- Charged scalar:
  - $H^{\pm}$



Note model-dependent scaling to B(a → $\mu\mu$)

LHC Run-2



Studying cross sections from ~ mb to ~ fb

BSM Search Status √s=13 TeV, 2016 data

Heavy gauge bosons

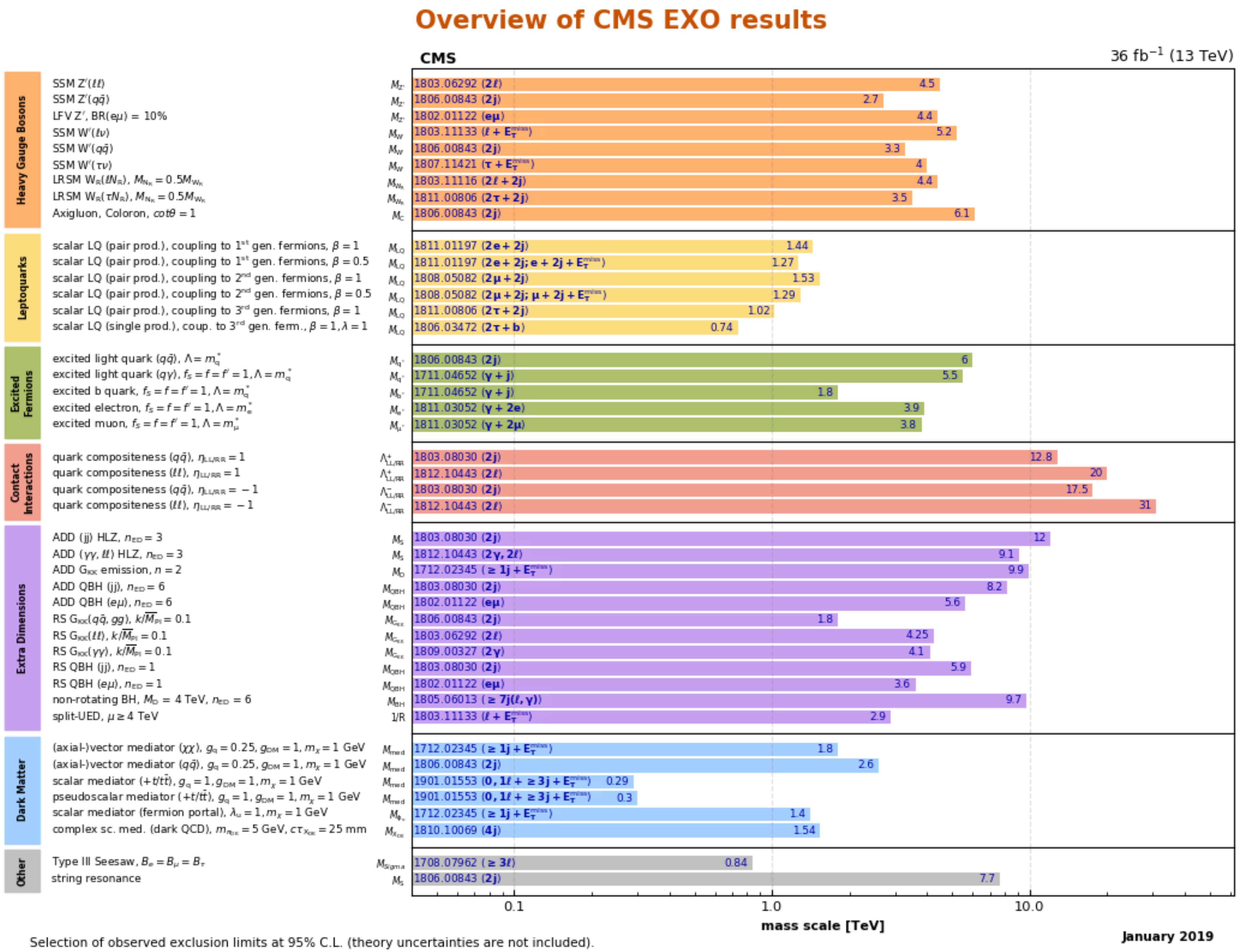
Leptoquarks

Excited fermions

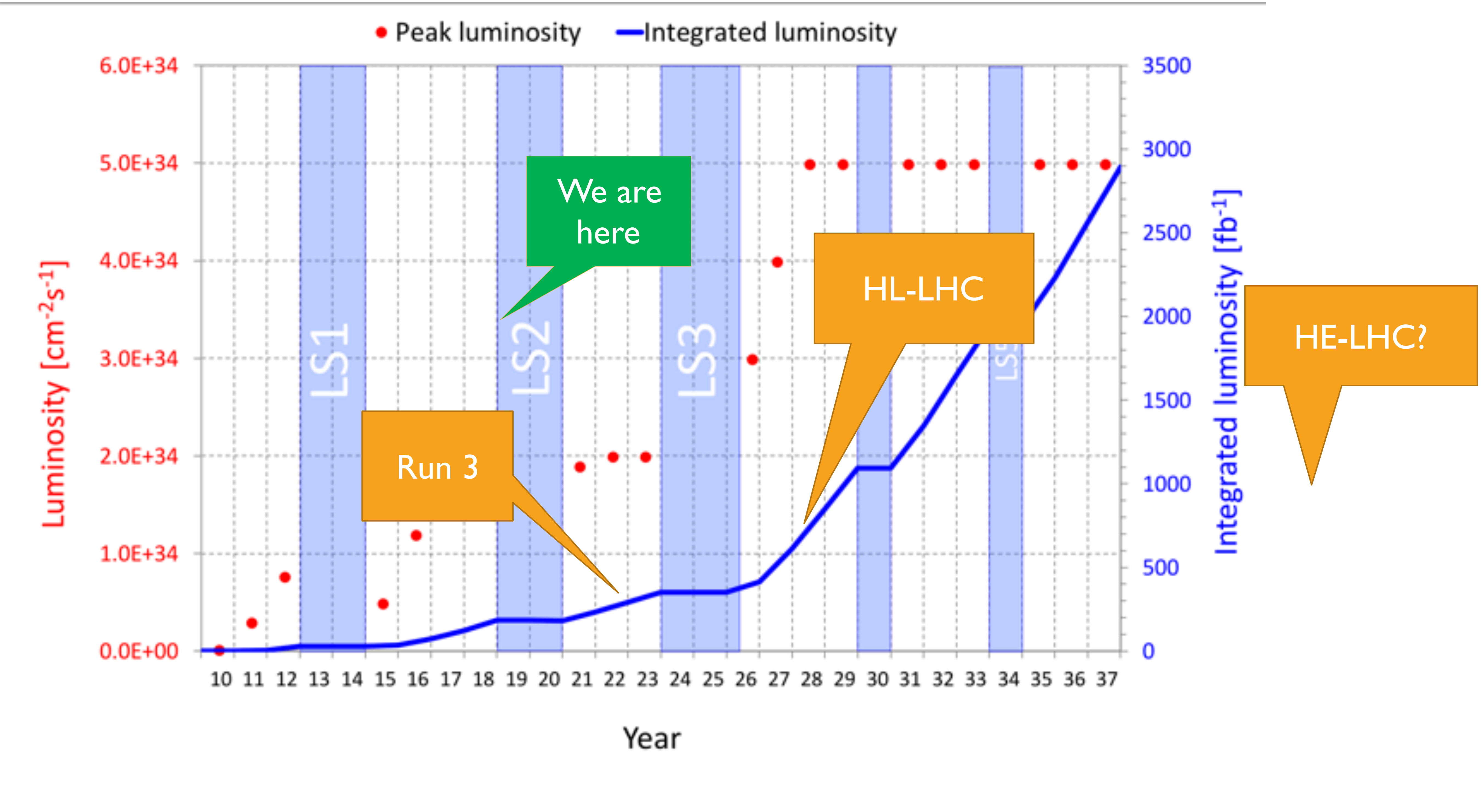
Contact interactions

Extra dimensions

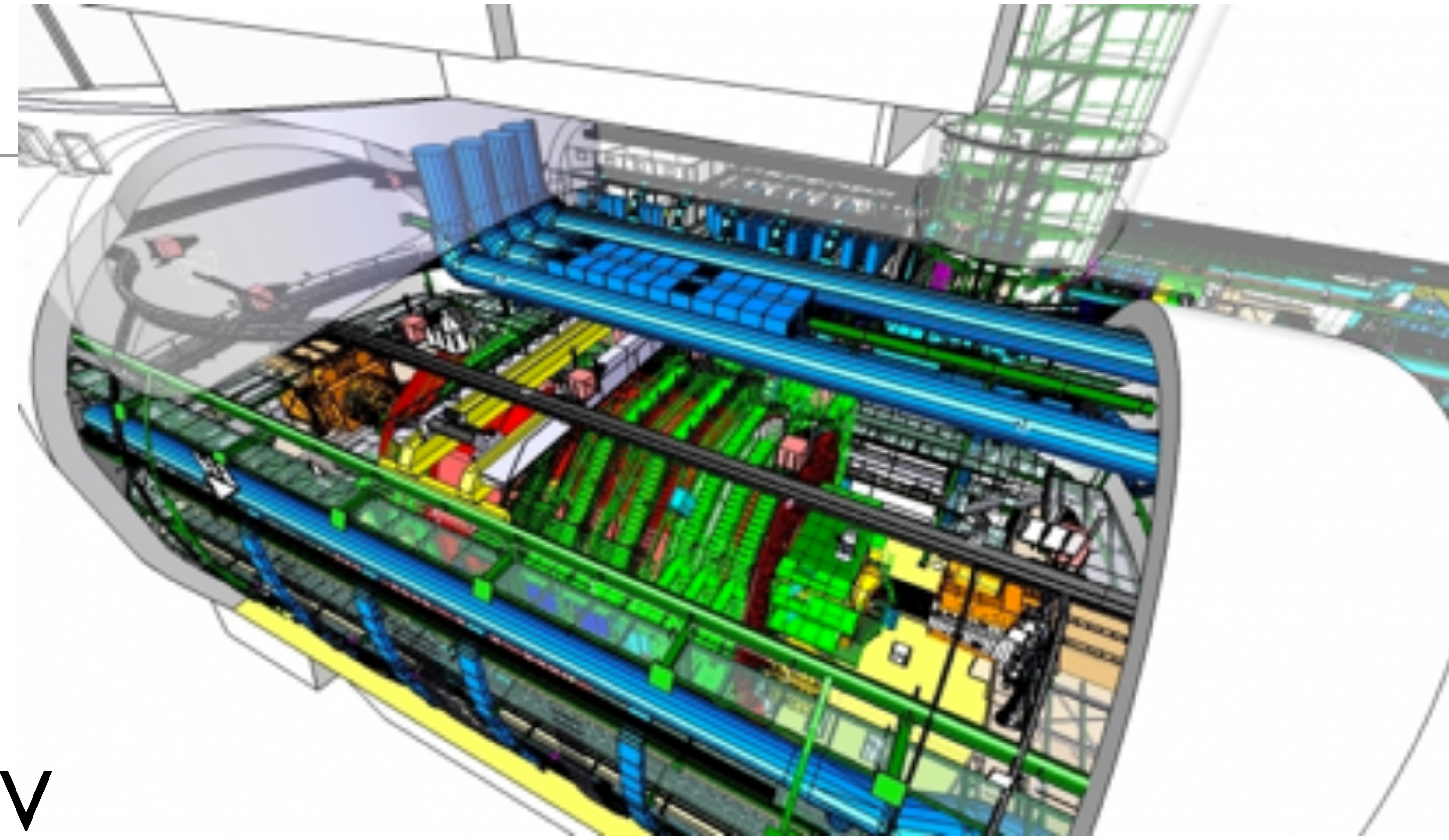
Dark Matter



LHC Upgrade Plans



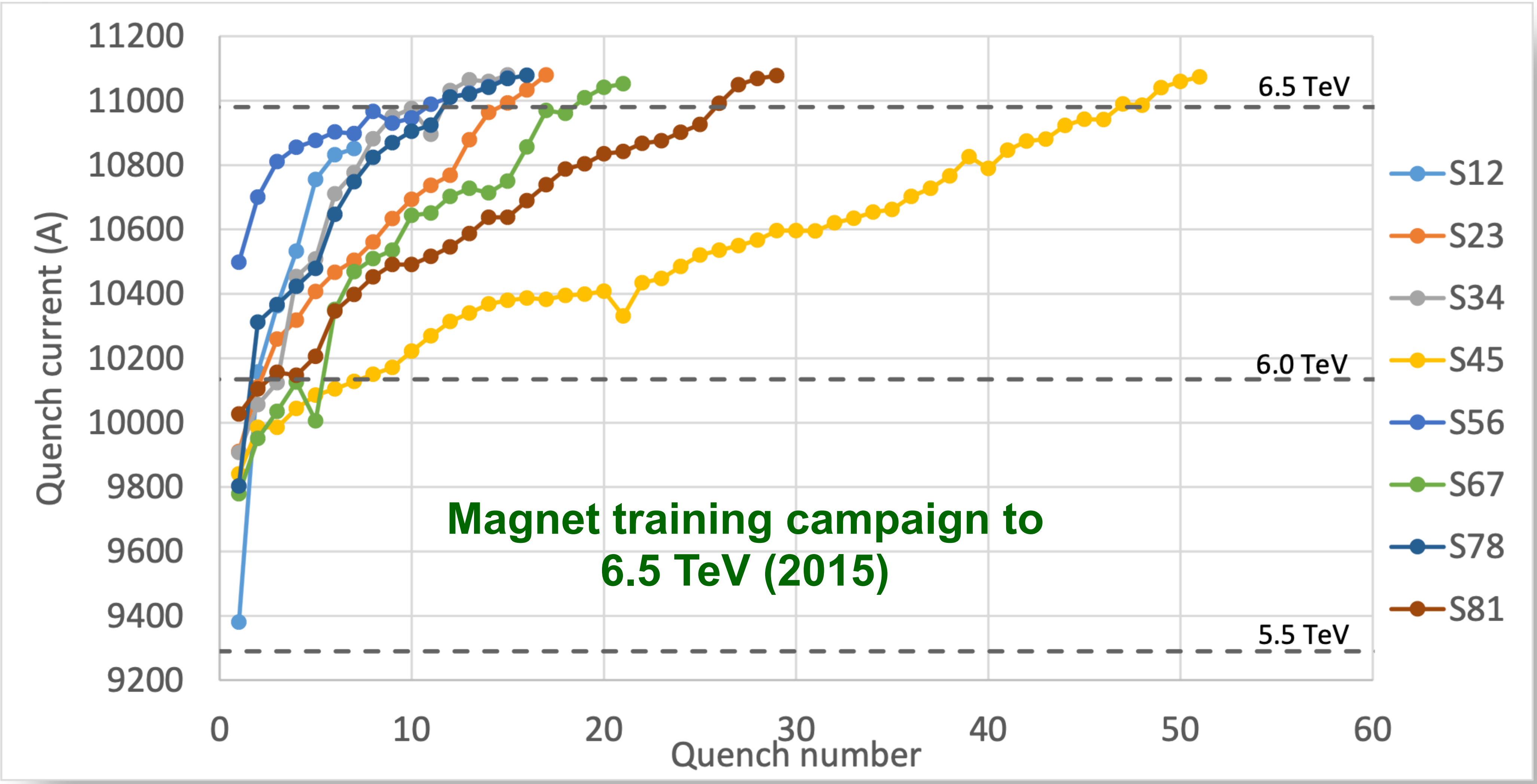
Long Shutdown 2



- 2019-2020
- Increase center of mass energy from 13 to 14 TeV
- 50% higher instantaneous luminosity
- Double size of sample in shorter time (30→150 fb^{-1}/ year)
- Upgrade selected detectors

Magnets

- All dipole magnets were trained for 6.5 TeV operation in 2015.
- Will be trained for 7 TeV during the shutdown



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High Luminosity LHC

High-Luminosity LHC

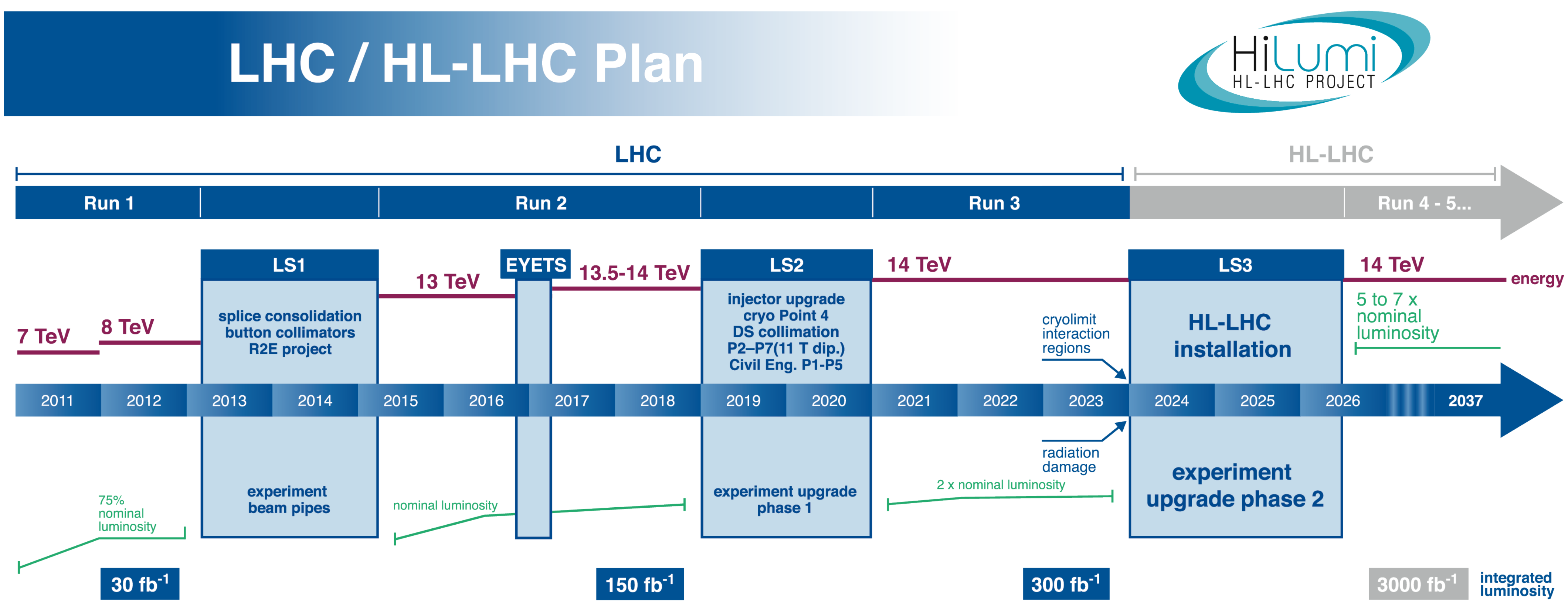
- Decade-long run @ 14 TeV. 3000/fb/experiment

- **Study Higgs with maximum available precision**
- **Continue hunt for new particles with x10 $\int L dt$**

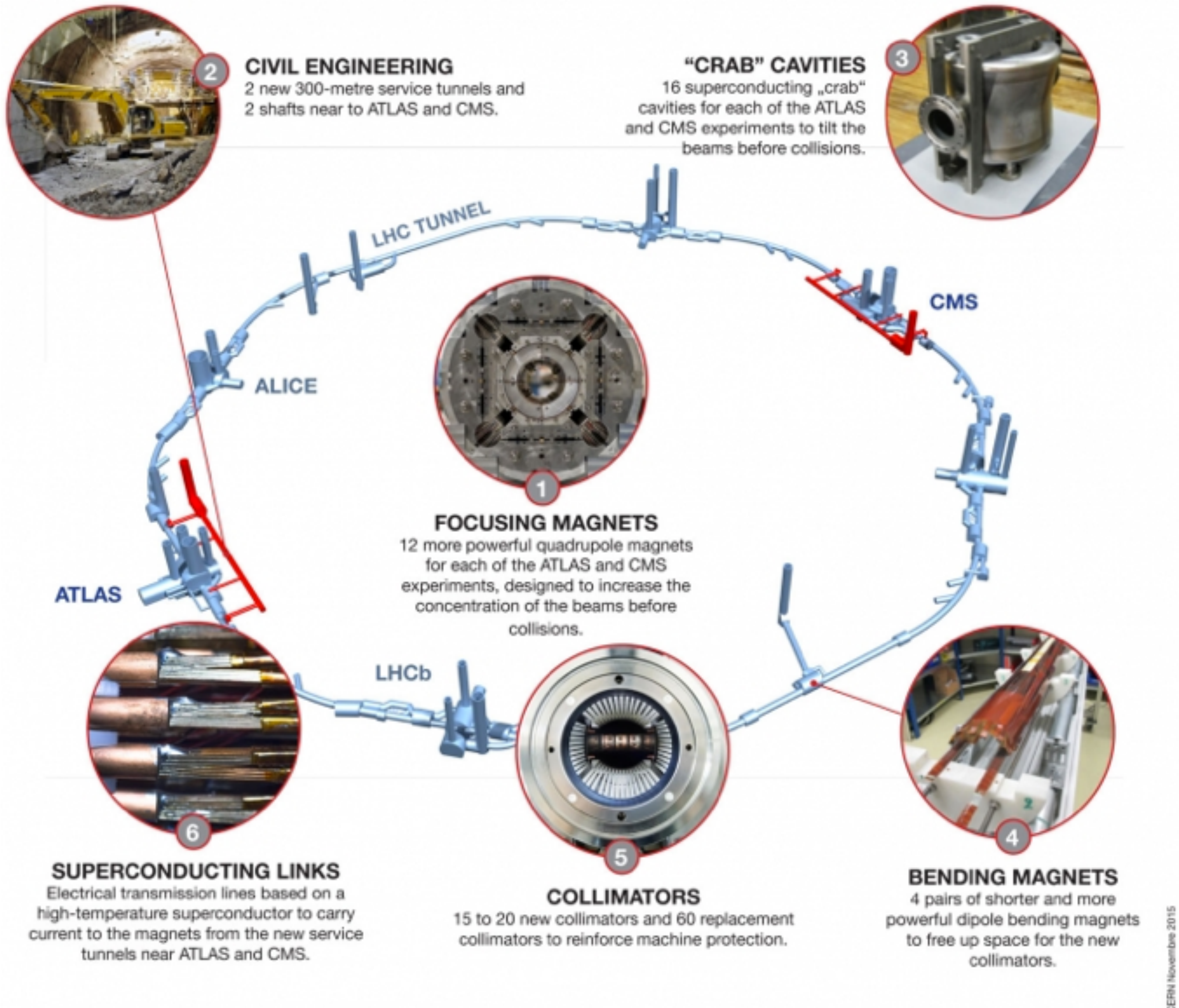
  Access higher masses, rare processes, weakly-produced states

  Targeted searches: test new models

- **Major challenges: radiation damage and pileup**

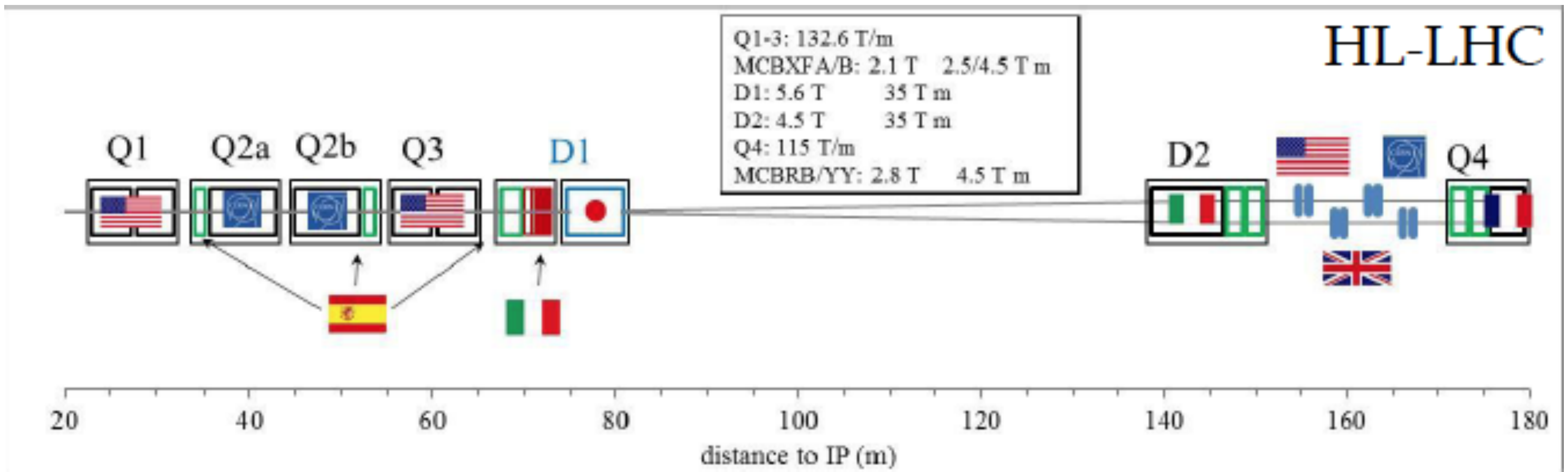


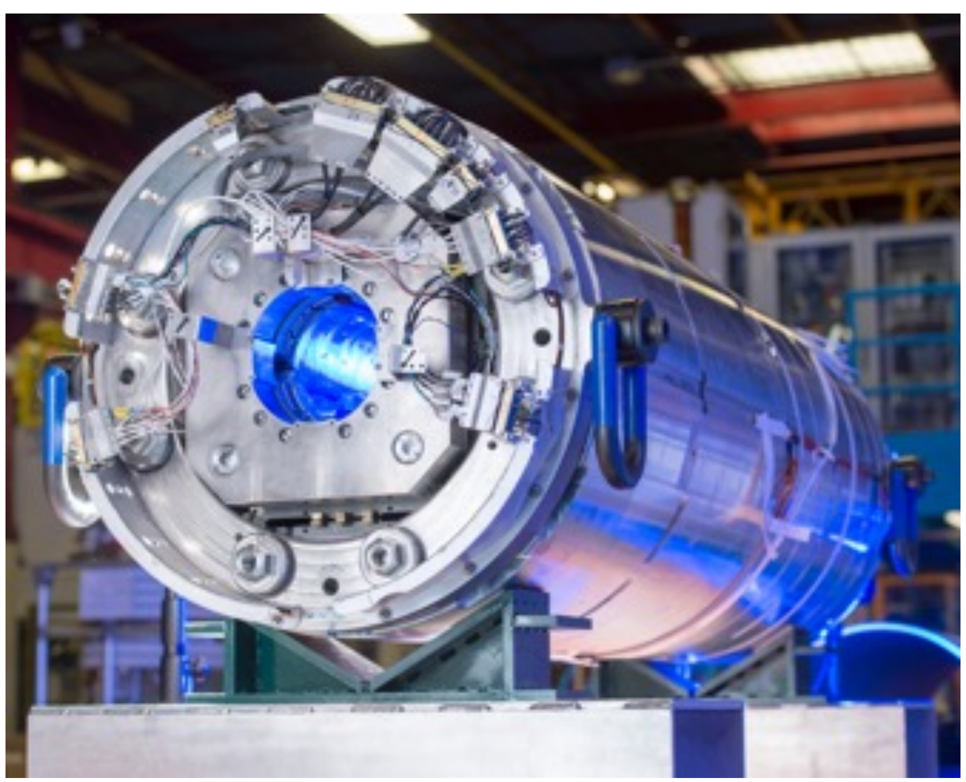
HL-LHC Accelerator Upgrades



Quadrupoles

stronger focusing magnets for higher instantaneous luminosities





The new main quadrupole magnets, for the insertion regions of ATLAS and CMS, exploit a key innovative technology providing fields beyond 10 Tesla. They are built from **niobium-tin (Nb_3Sn), using a unique design that allows the peak magnetic field strength to be increased by around 50% compared with the current LHC dipoles, bringing it from about 8 to about 12 T.**

Physics Analysis @ HL-LHC

HL-LHC Physics Slate

- **Standard Model**
  - Ultimate precision measurements and constraints

3 billion top / exp.

- **Higgs**
  - Precise determination of H(125) properties
  - Search for new phenomena in the Higgs sector

Higgs factory:
150 million H and 120 k HH

- **Direct Searches**
  - Supersymmetry
  - Long-lived particles
  - Dark Matter
  - Heavy Resonances

Novel approaches, better detectors: stringent tests of BSM scenarios

- **Flavor**
  - CKM metrology and QCD spectroscopy
  - Rare decays → flavor anomalies ?

Low-P_T/high-P_T complementarity

- **Heavy Ions**
  - Precision study of material properties of QCD media
  - Study HI-like behavior in small systems (pp and pA)

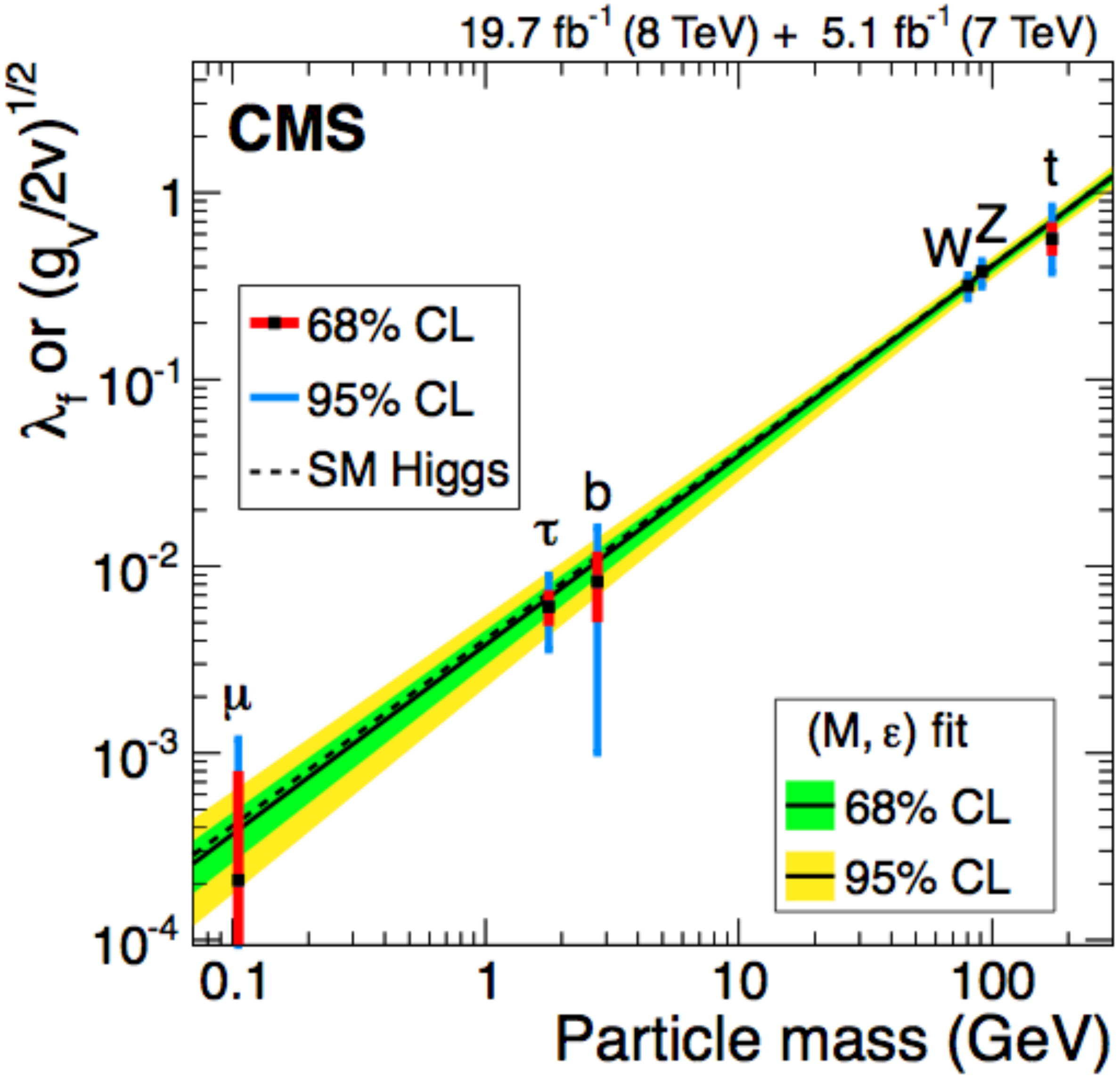
Precise differential measurements

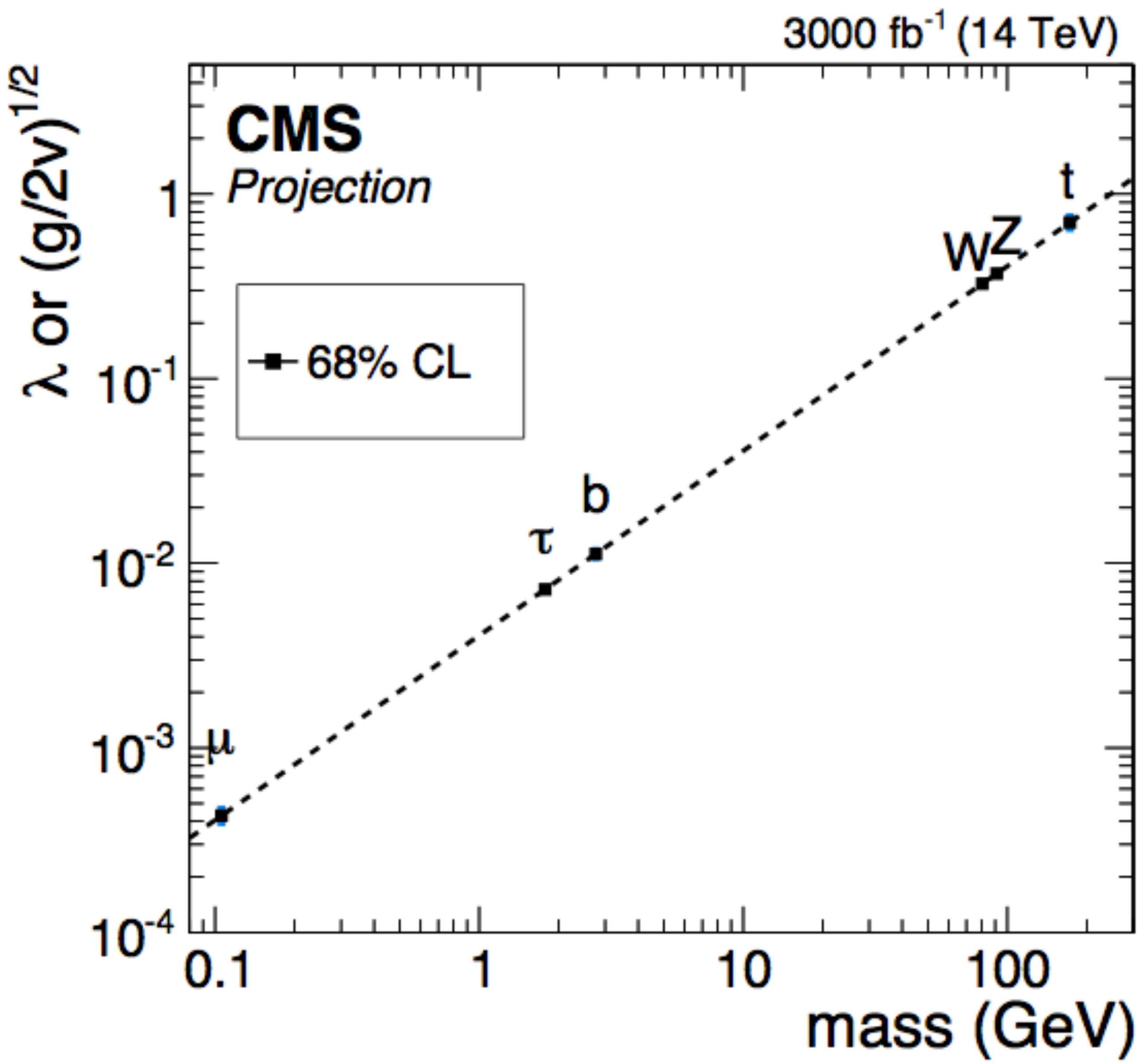
Higgs

6.5 Year Anniversary of Higgs Announcement! Now Entering Era of Precision Higgs Physics

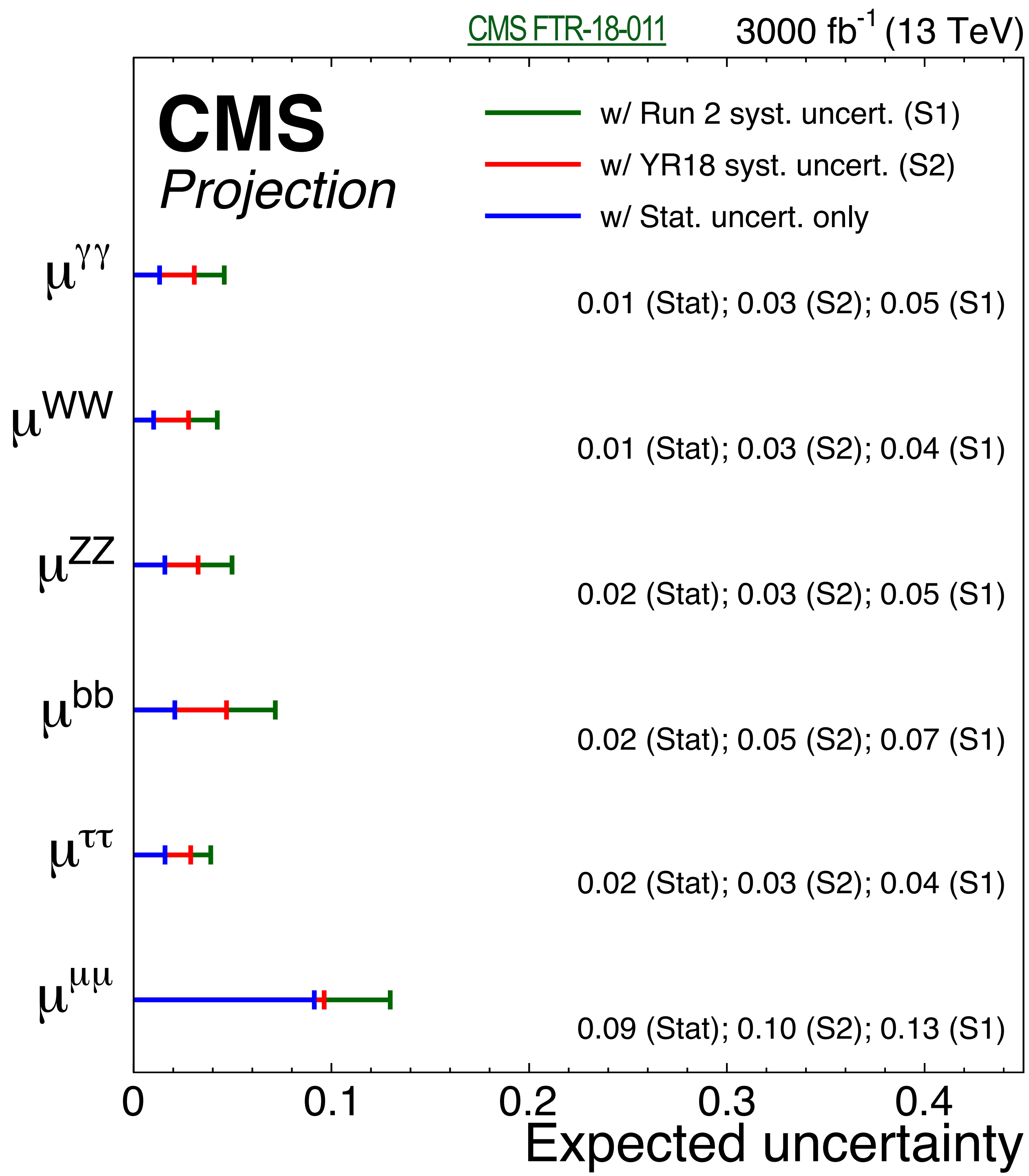
- Higgs couplings, past and future.

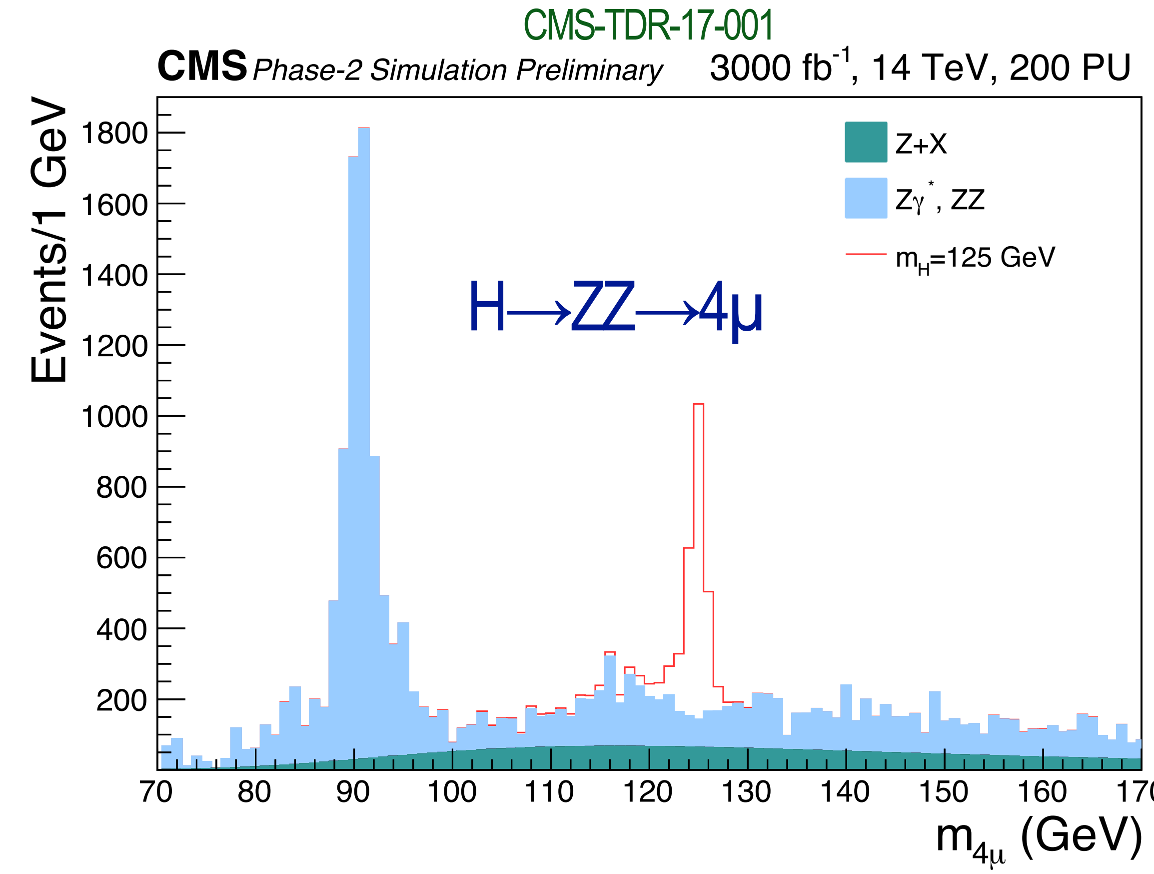
- **US Study (Snowmass): HL-LHC competitive with ILC**

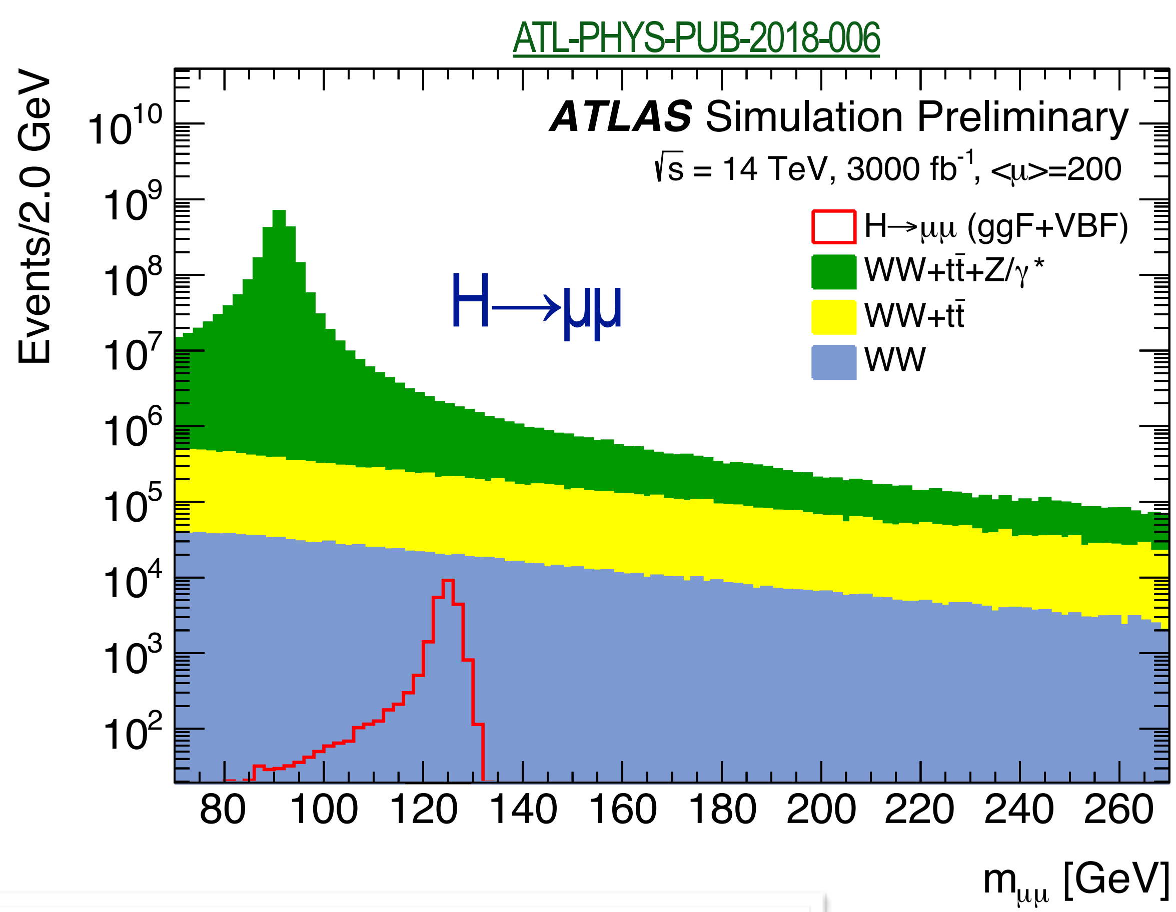




Higgs Measurements

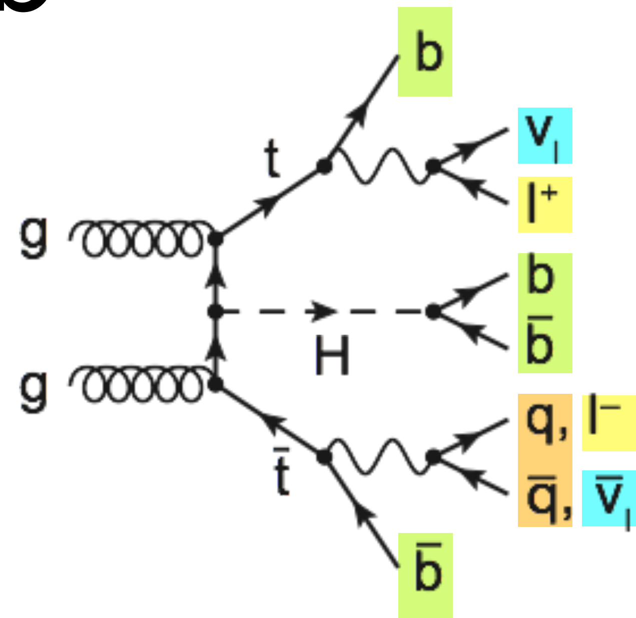




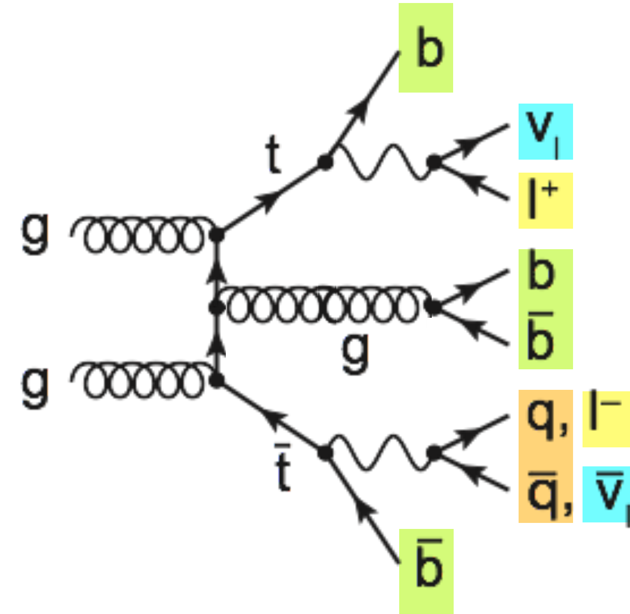


Signal strength uncertainties: most channels ~3%, bb ~5%, μμ ~10%

ttH, H → bb

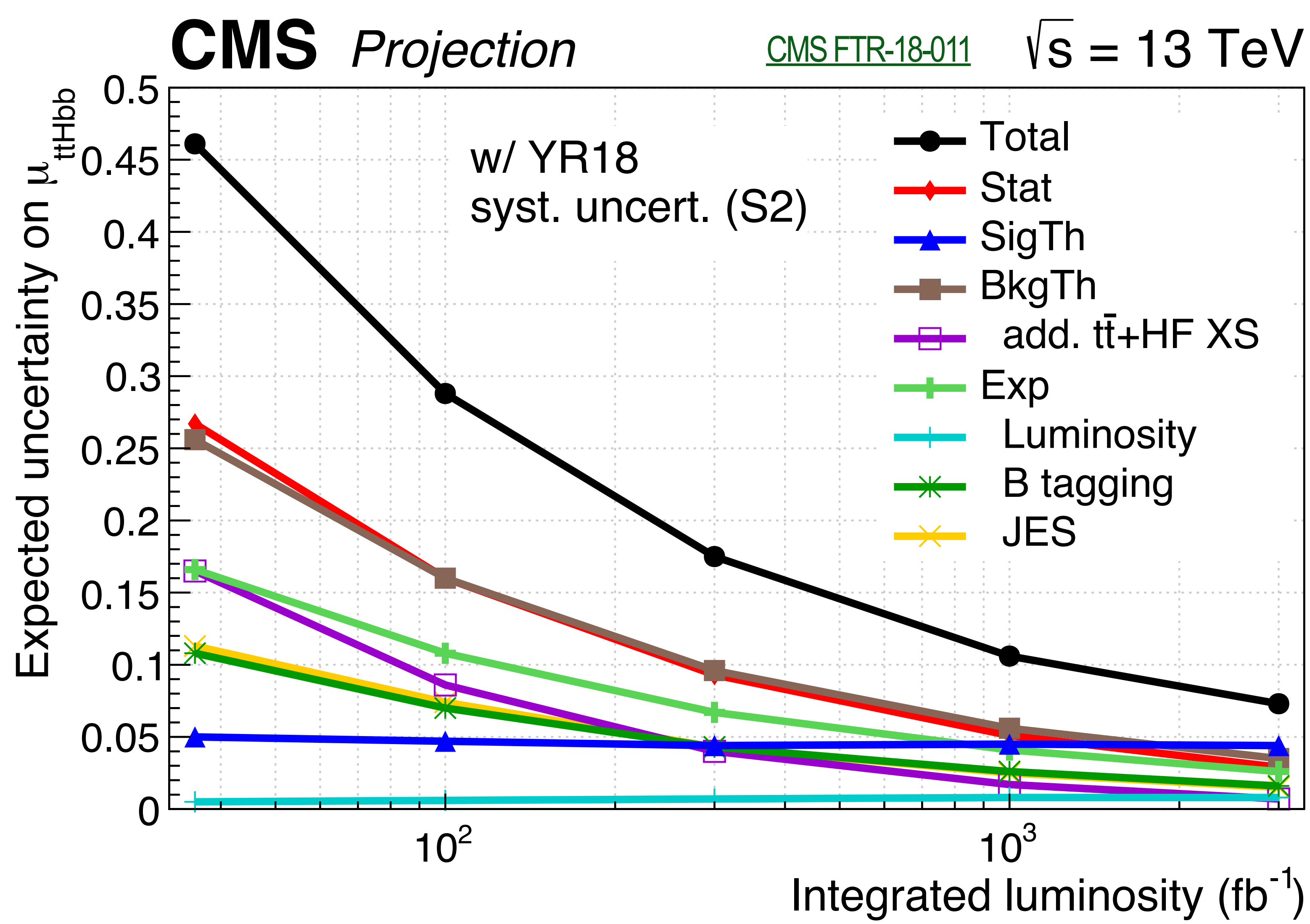


ttH signal

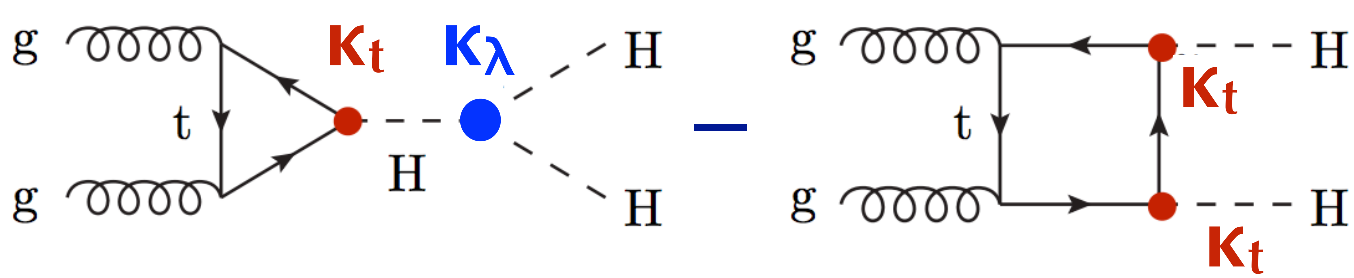


tt+HF background

- For 3ab^{-1} CMS expects $\delta\mu \sim 7\%$
  - tt+HF background constrained by data
  - dominant uncertainty: signal theory

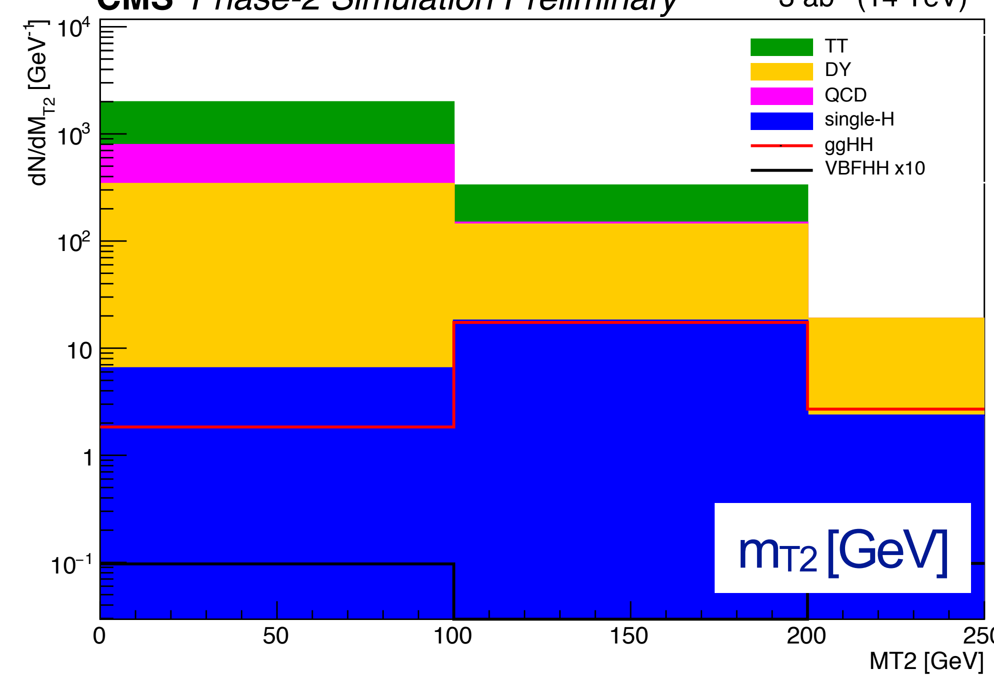


HH

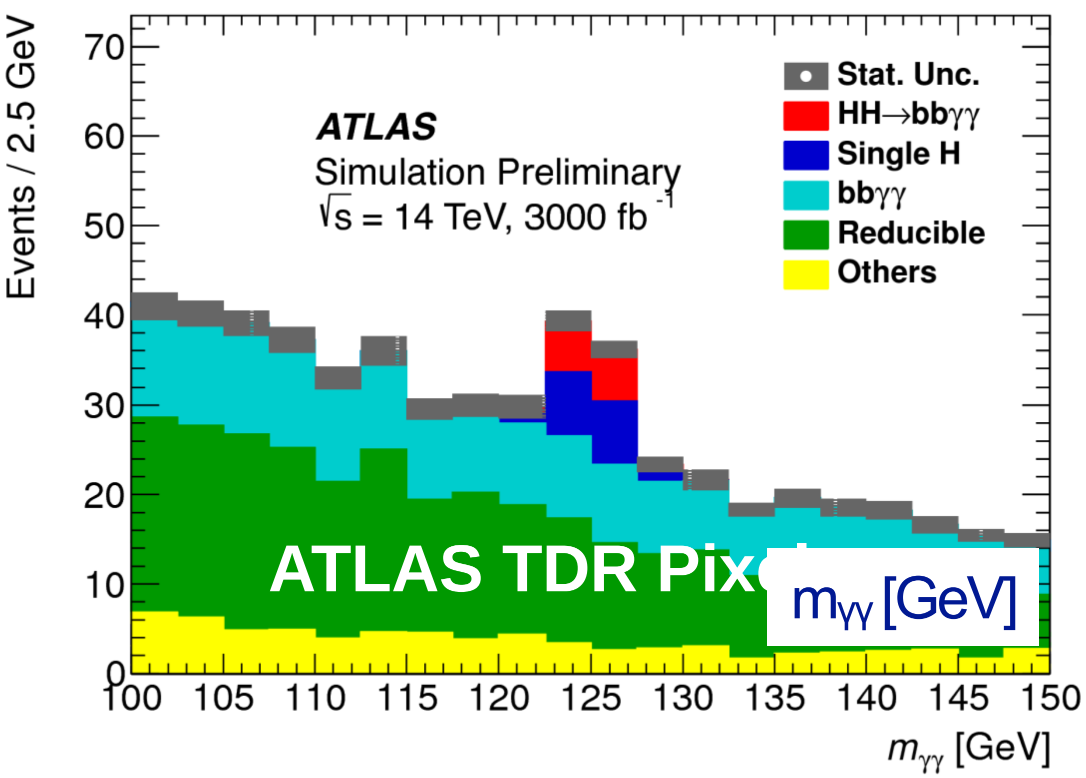


- HL-LHC ultimate goal: observation of trilinear coupling
- 120k HH events expected
- High backgrounds (bbbb, bbττ) or small BR (bbγγ)
- Additional constraints on κ_λ, e.g. from differential measurements of single Higgs

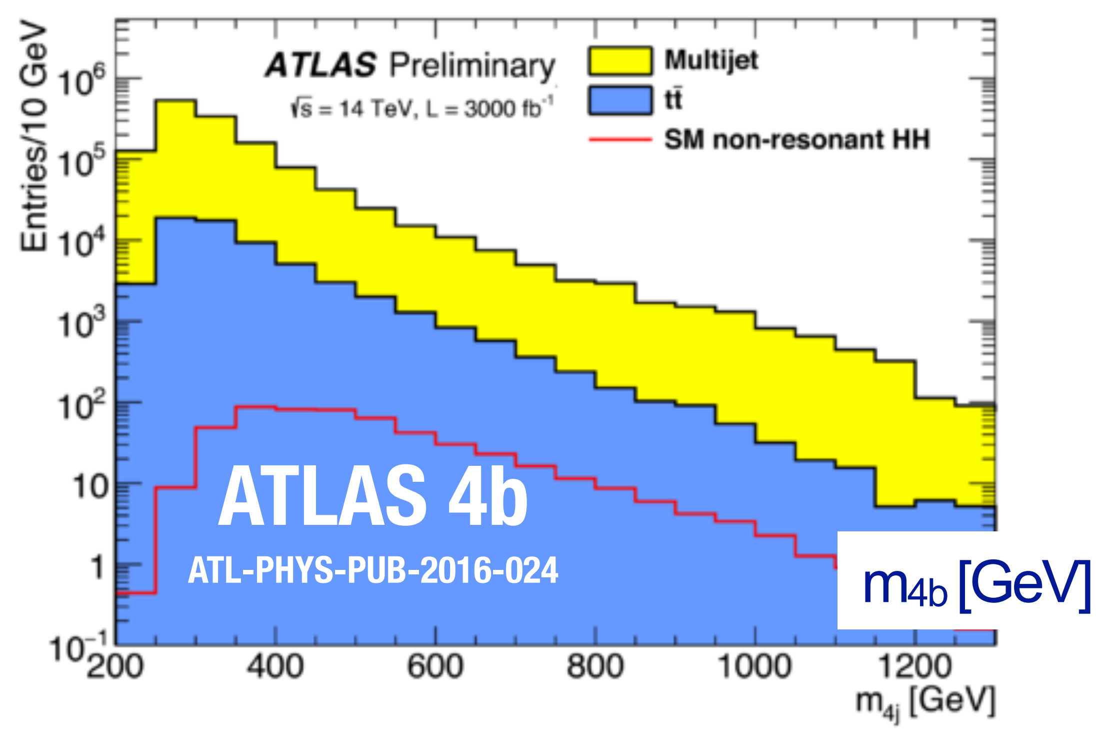
HH→bbττ CMS-TDR-17-007



HH→bbγγ ATL-PHYS-PUB-2017-001



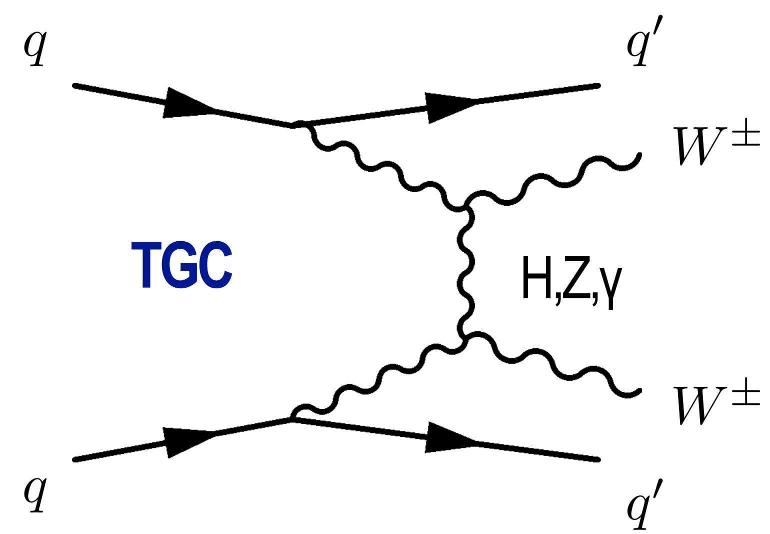
HH→bbbb



Being updated for YR2018: expect 2-3σ significance per experiment

Longitudinal Vector Boson Scattering

- Unitarity of $V_L V_L \rightarrow V_L V_L$ cross section at TeV scale: Scalar Higgs and/or new physics to cancel divergence
- Direct test of EW-symmetry breaking mechanism
- HL-LHC improved forward detectors and acceptance



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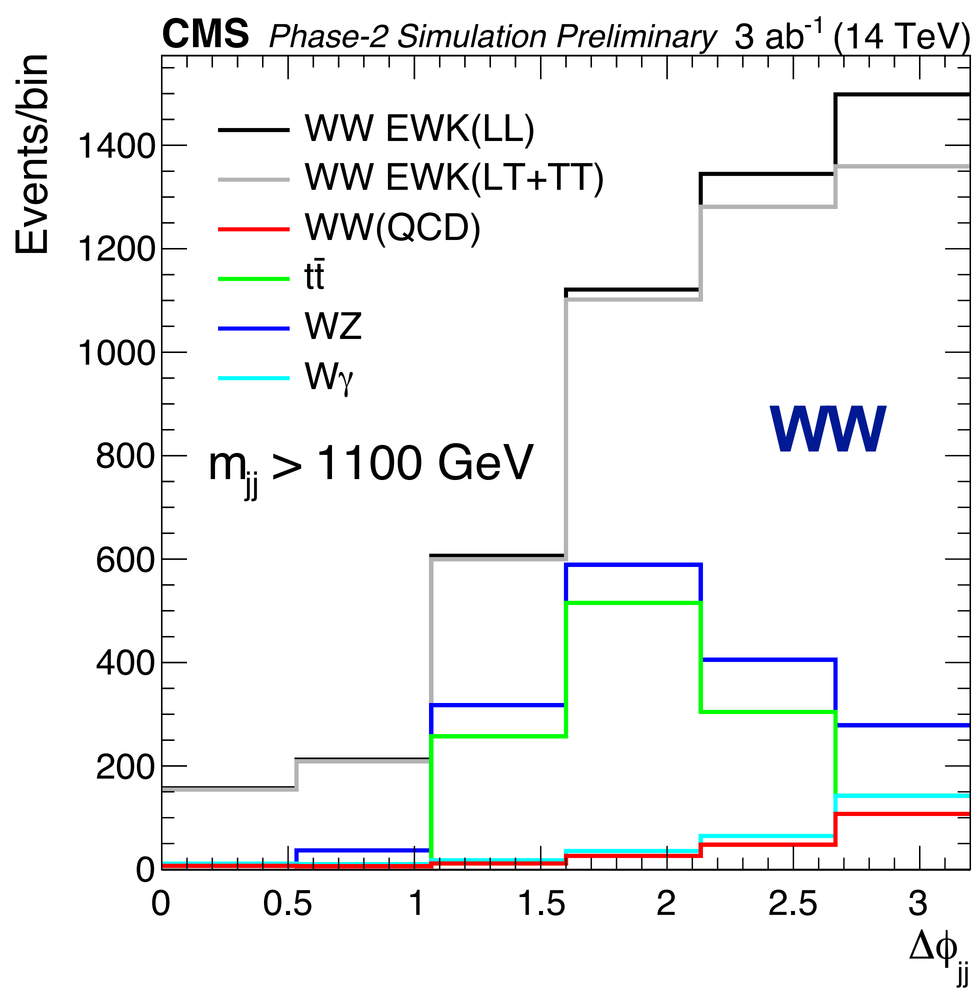

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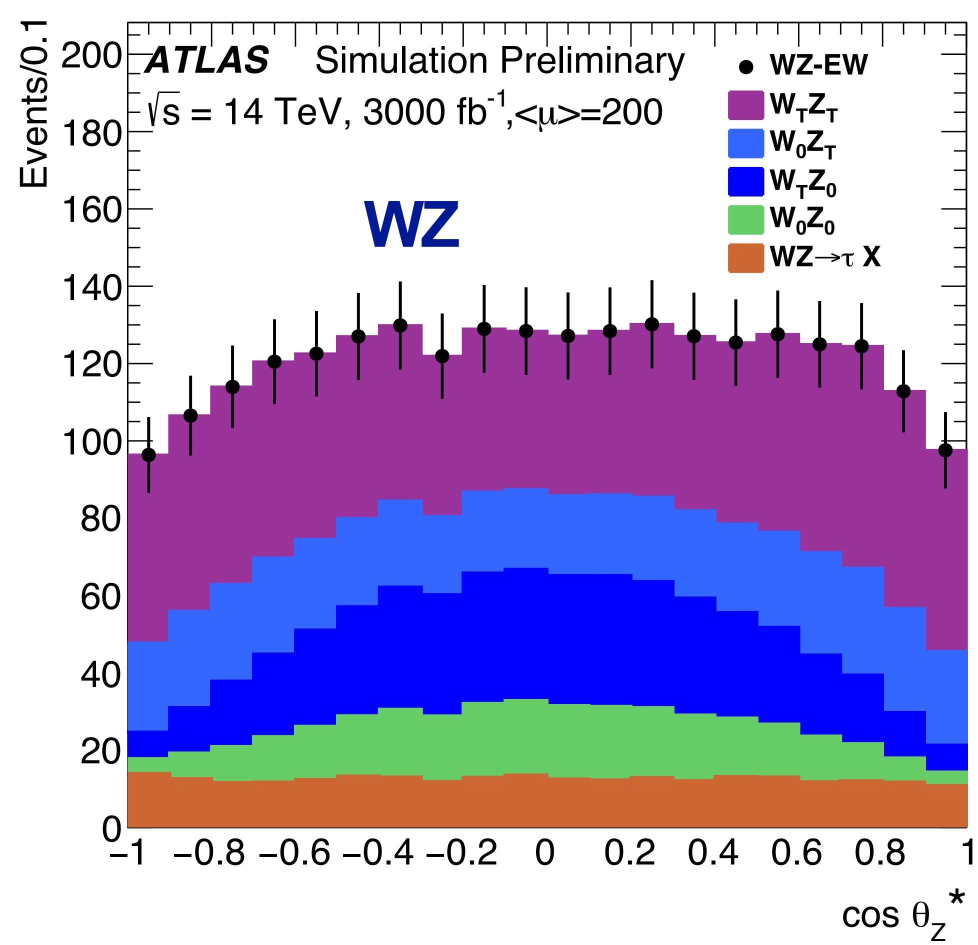
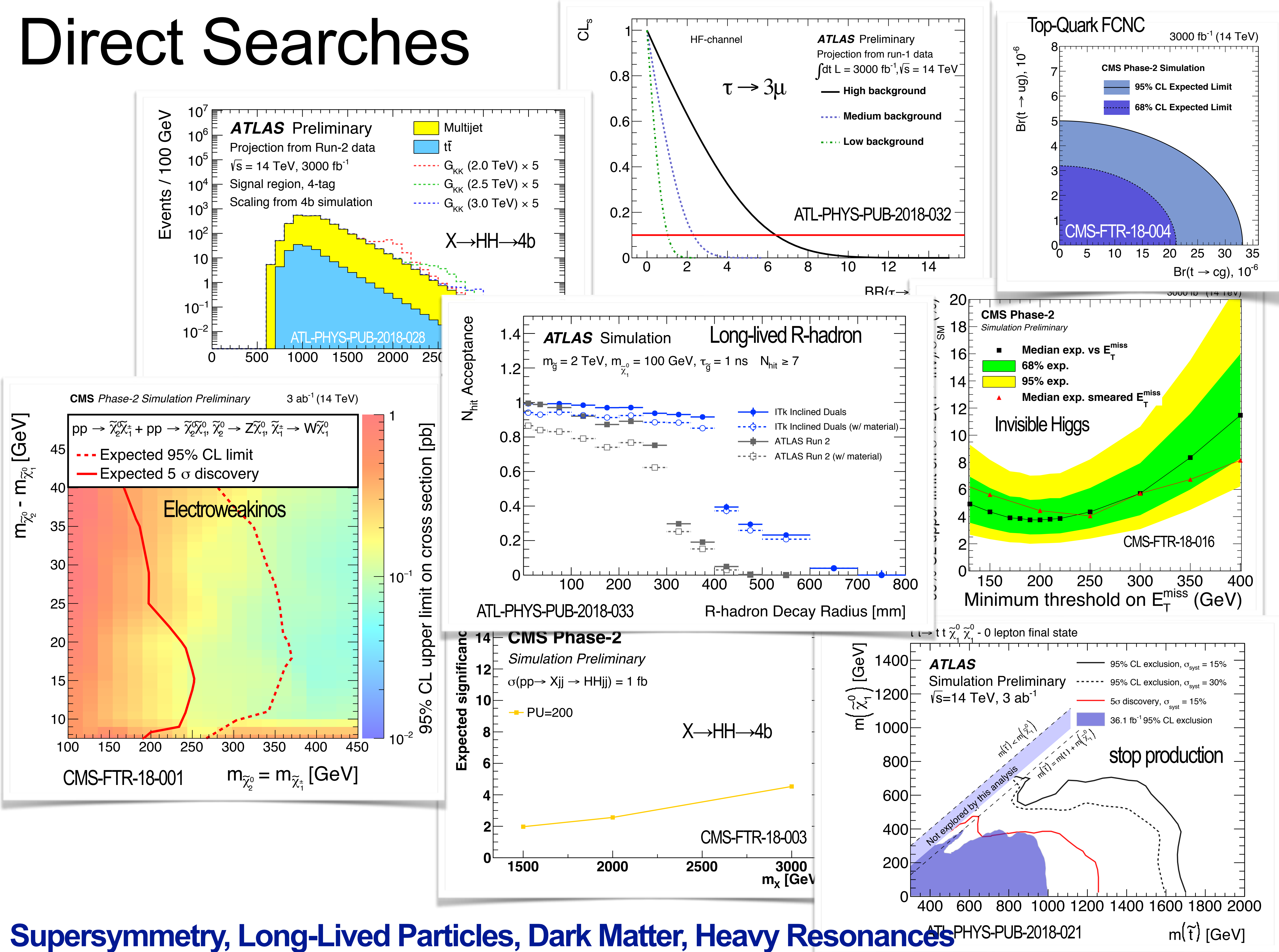


Expect $V_L V_L$ - scattering discovery significance: ~ 3σ per experiment

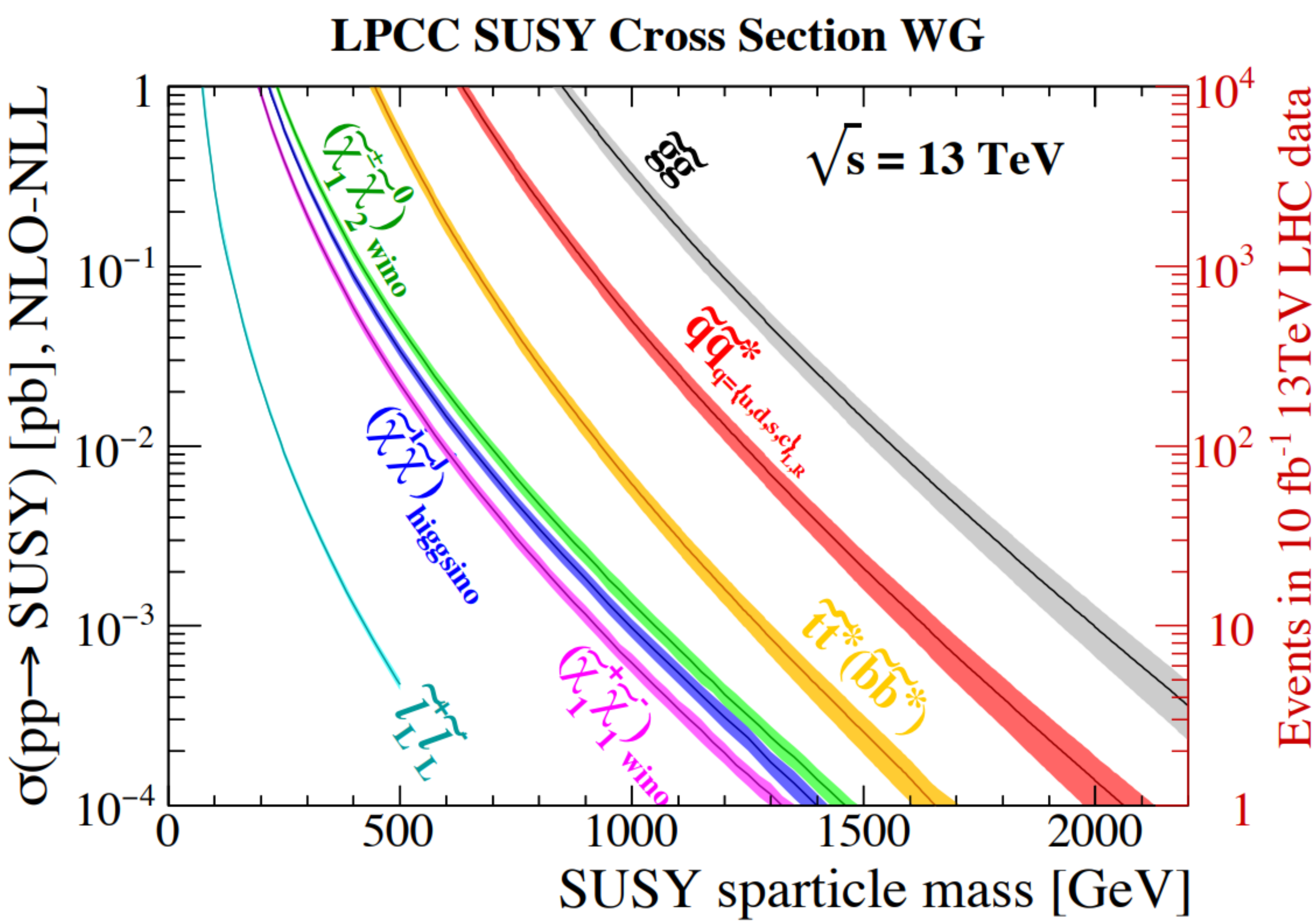
Direct Searches

Direct Searches

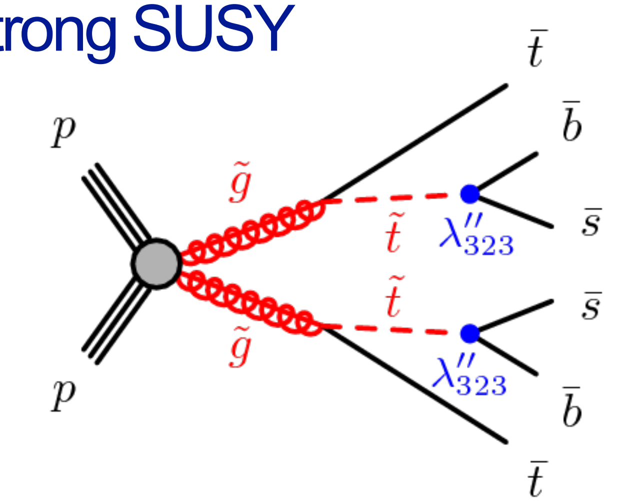


Supersymmetry, Long-Lived Particles, Dark Matter, Heavy Resonances

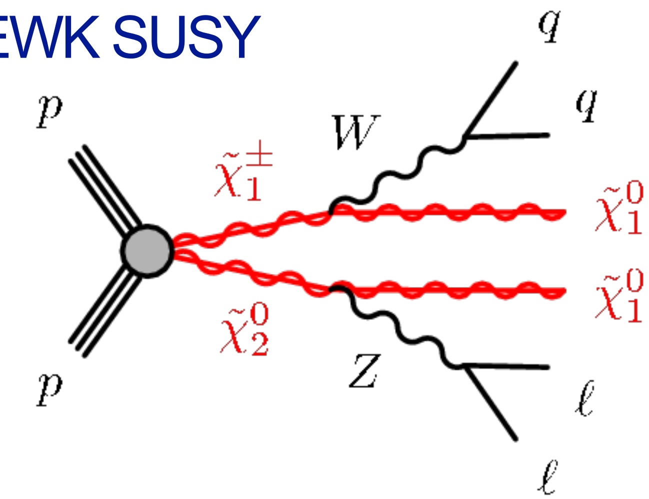
Supersymmetry

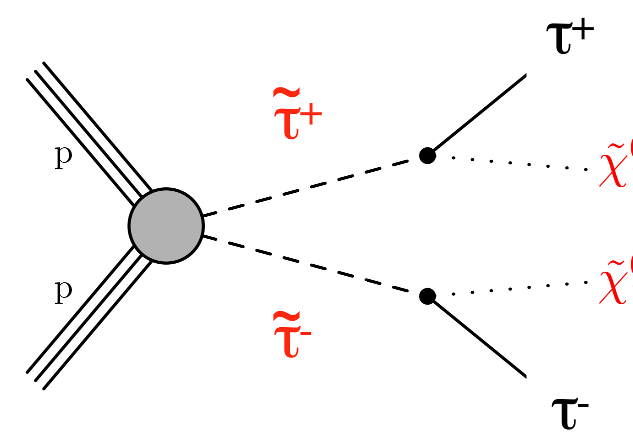


Strong SUSY



EWK SUSY

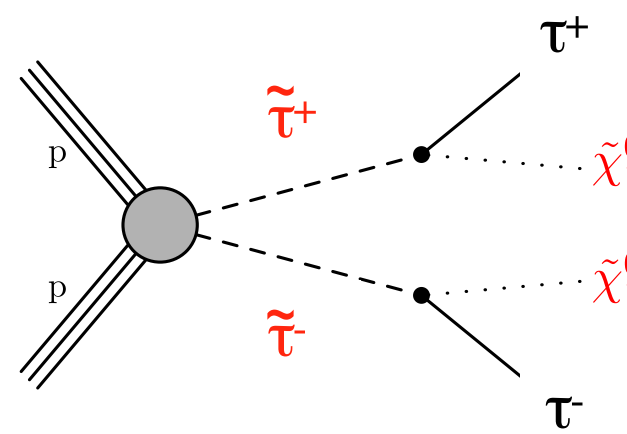


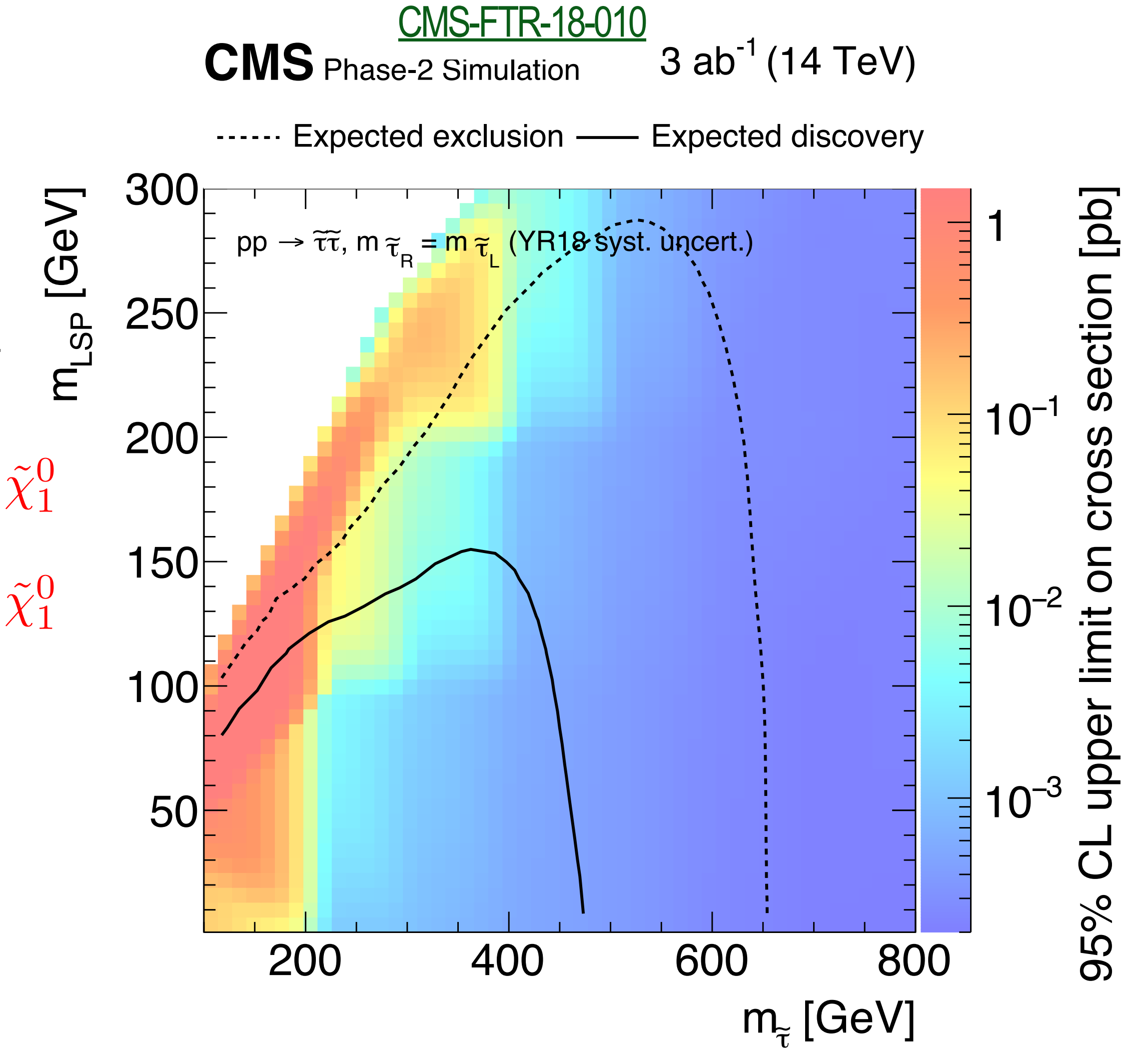


- Strong SUSY (σ≳1 pb at m = 500 GeV): many scenarios up to 1 TeV already excluded
- Electroweak SUSY (σ < 0.1 pb at m = 500 GeV): could still be light

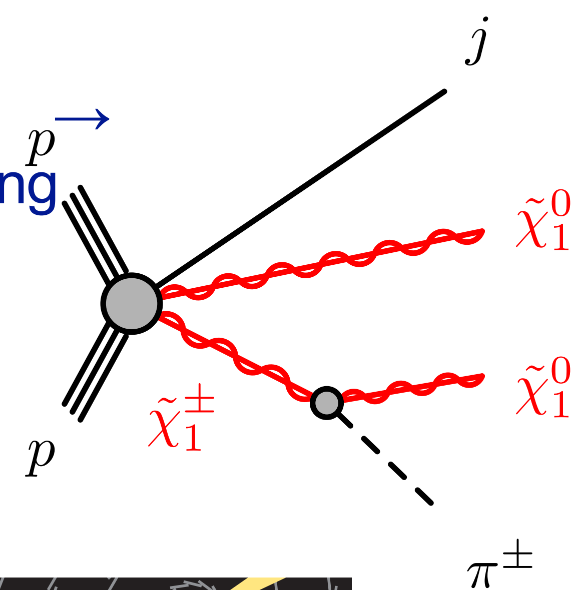
Electroweak SUSY

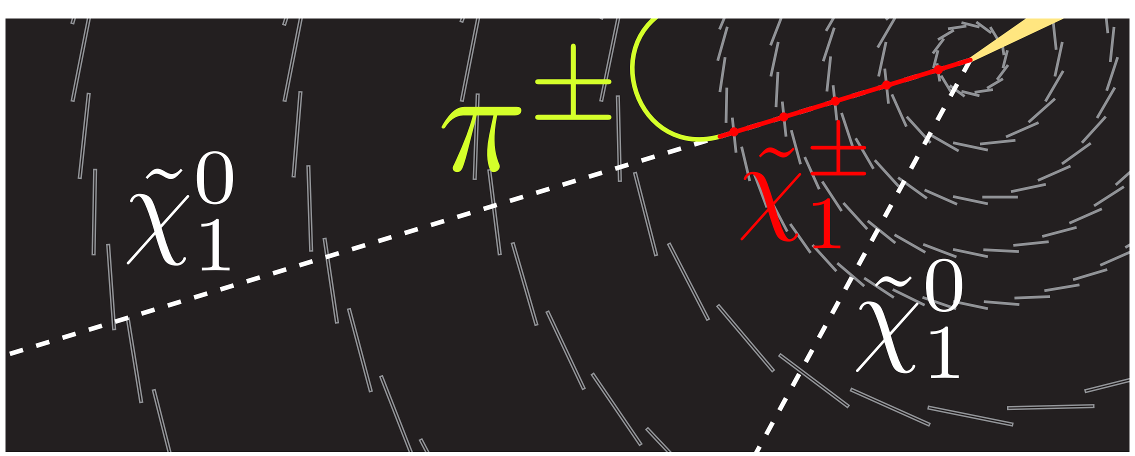
- Stau pairs:
  - Final state: $\tau_h\tau_h$ or $\ell\tau_h$ + MET
  - 2016 data: no sensitivity
  - HL-LHC excl. limit: 650 GeV

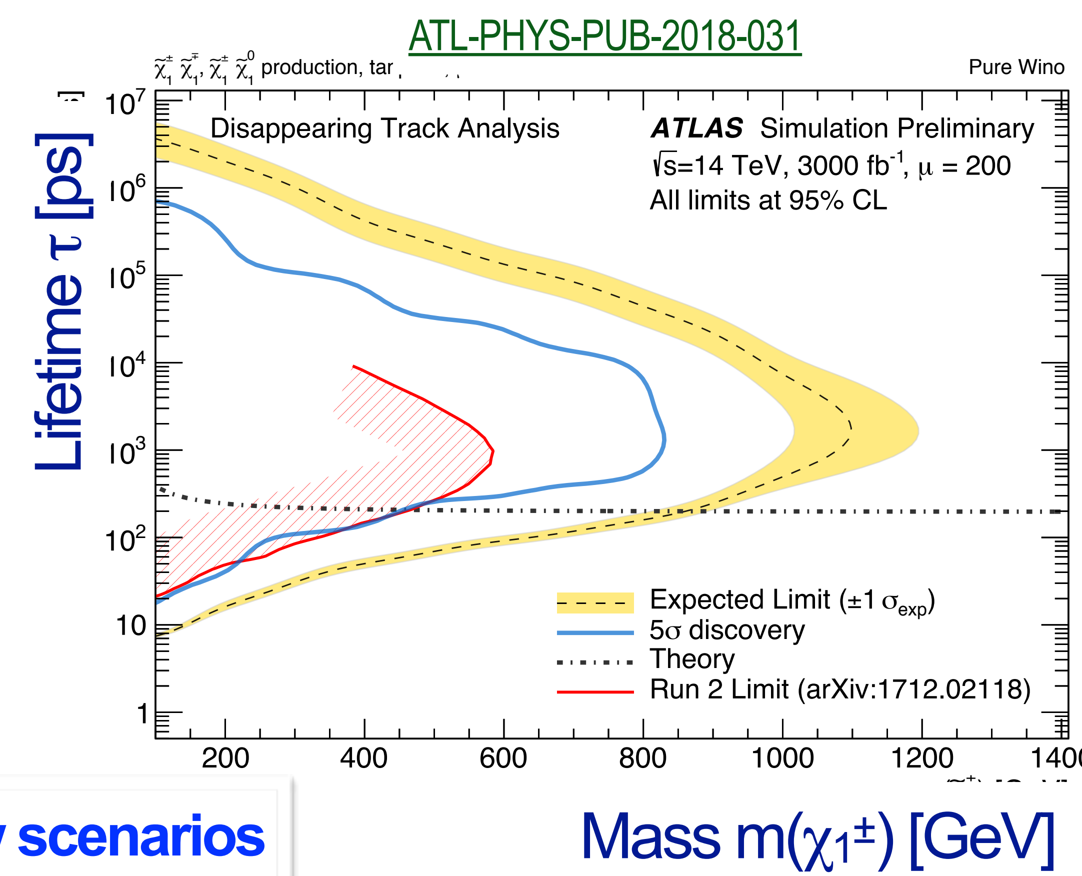




- Electroweakinos:
  - degenerate mass scenarios compressed spectra and/or long lifetimes
  - Use ISR jet for triggering
  - Disappearing tracks



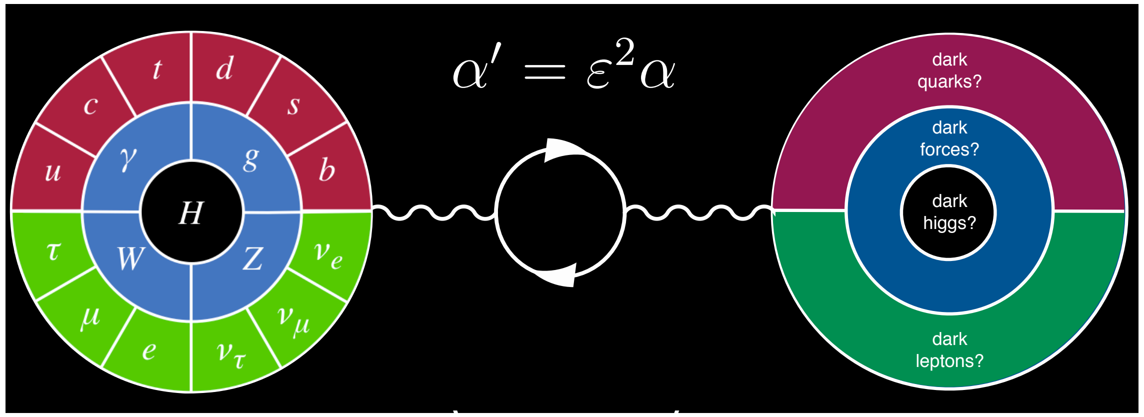




Sensitivity to new scenarios

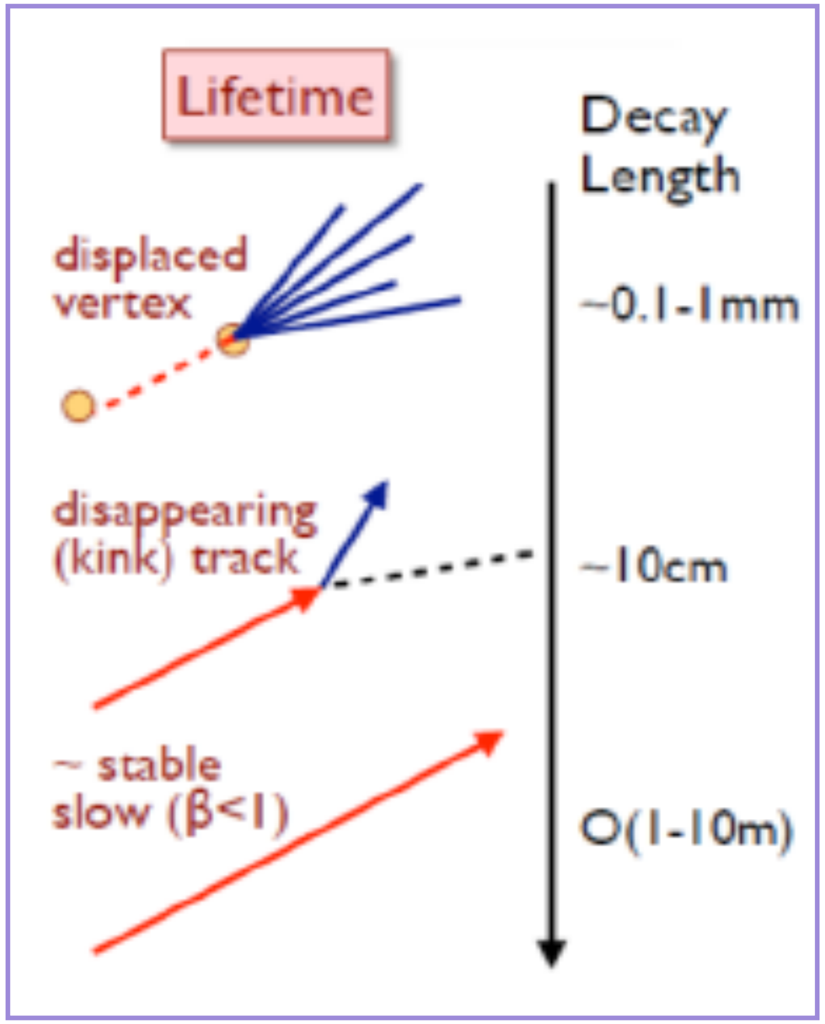
Long-Lived Particles

- Various scenarios: mass degeneracy, small couplings, heavy mediators,
- Direct detection or collateral event features → creative use of experiments
- Significant benefits from improved detectors

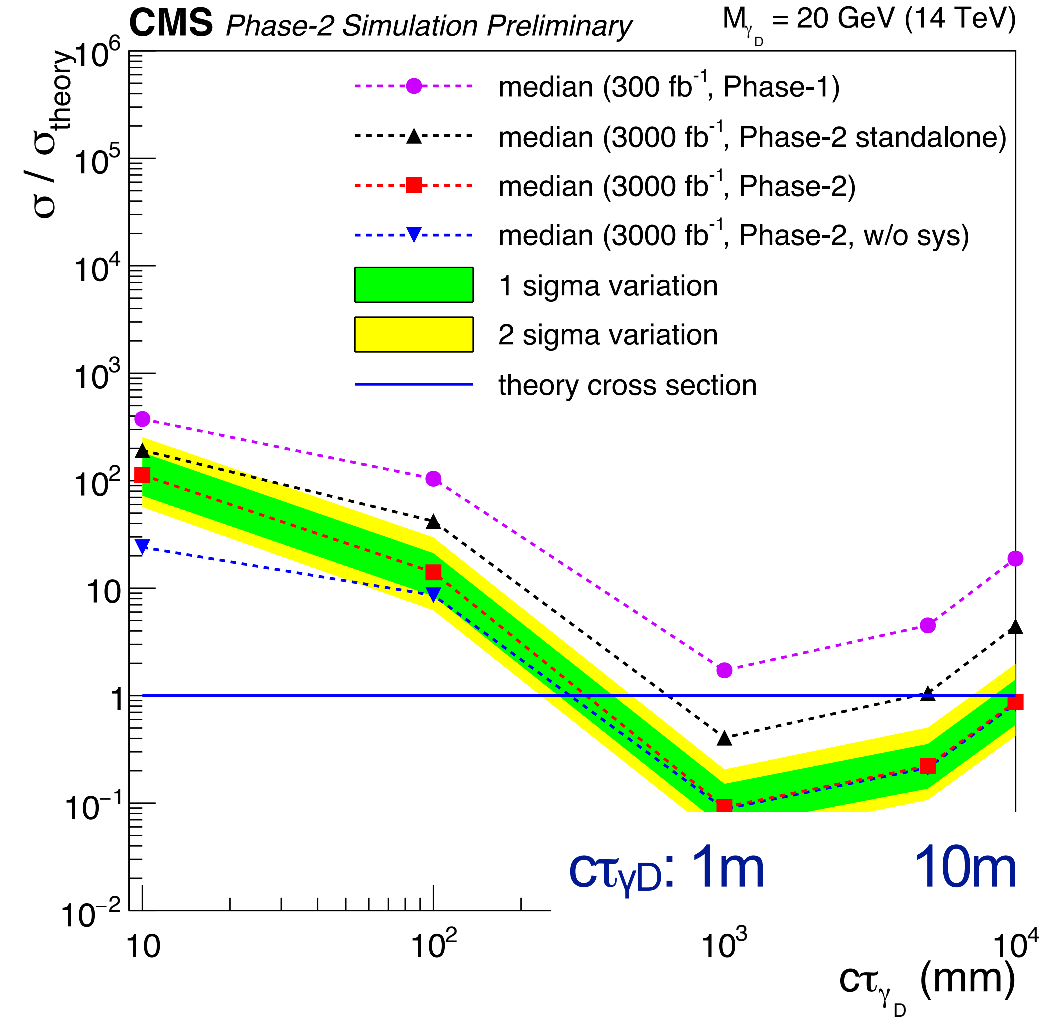


Dark photons: $\gamma_D \rightarrow \mu\mu$

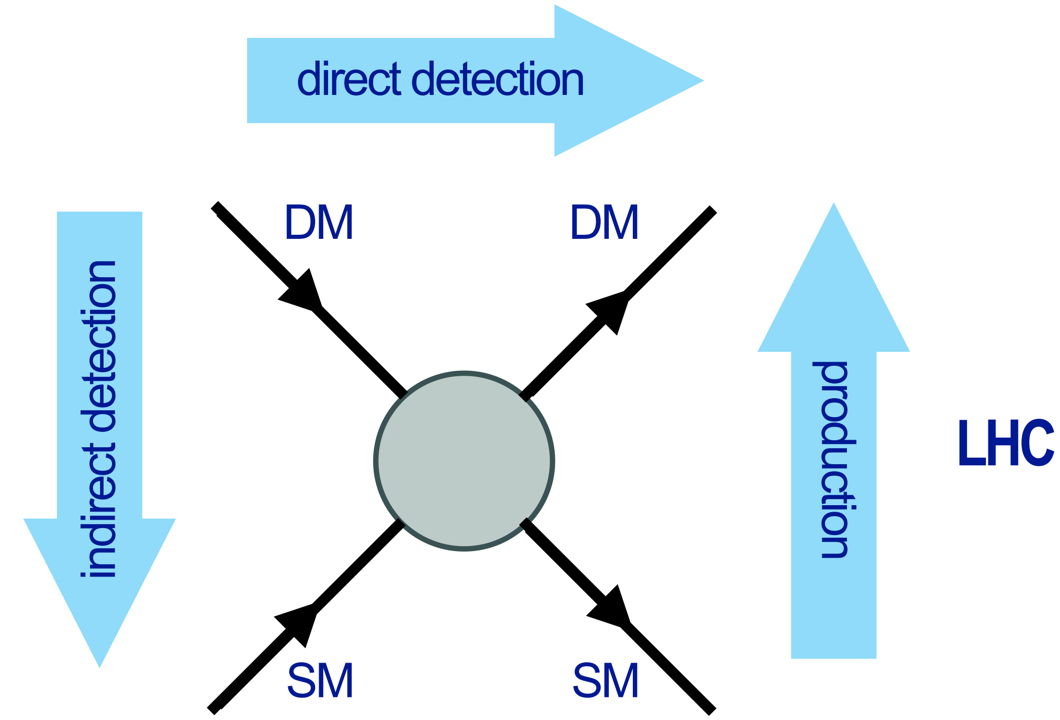
$\tau \sim 1/\varepsilon^2$



CMS-FTR-18-002

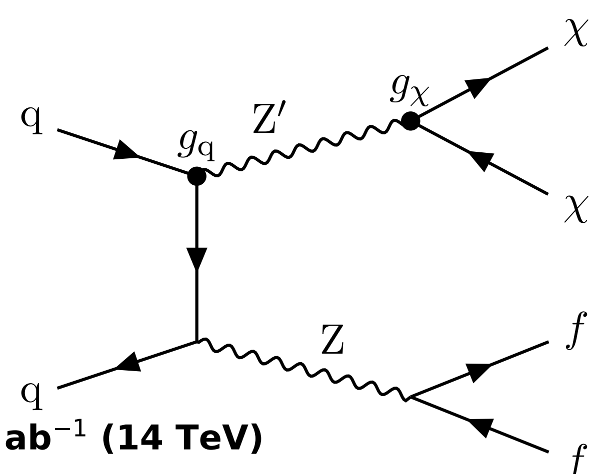


Dark Matter Searches

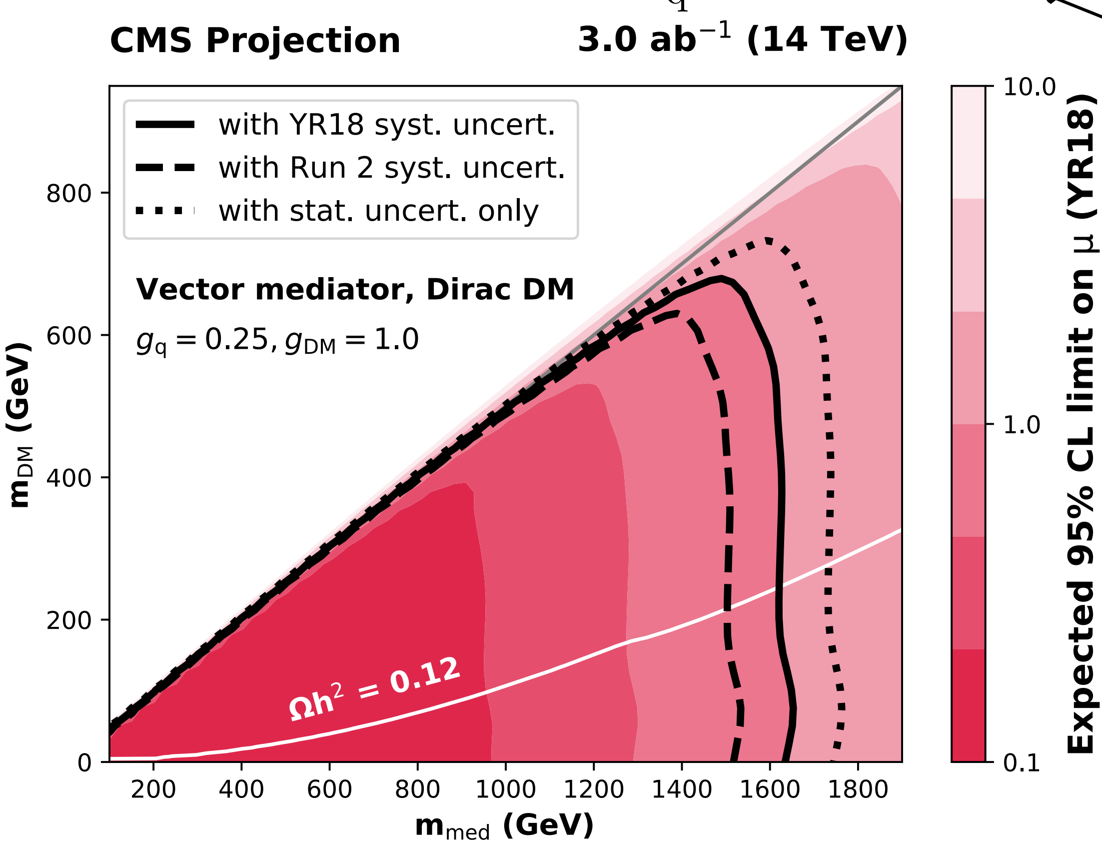


- DM known to exist in universe
  - will its elementary nature be revealed at LHC ?
- Use simplified models for comparison with direct detection experiments

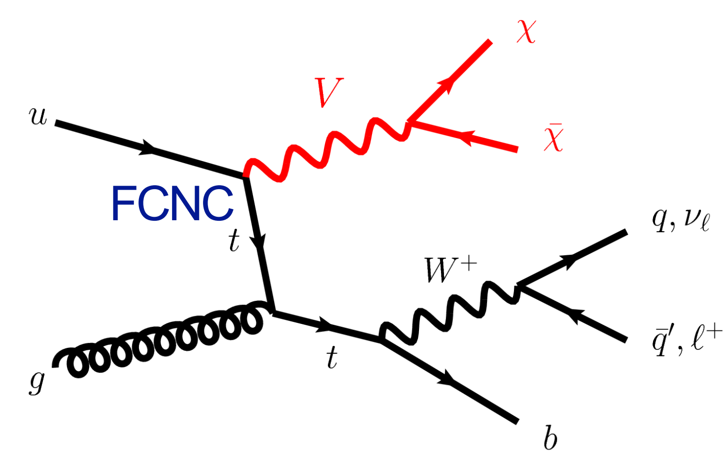
mono-Z



CMS-FTR-18-007



mono-top:



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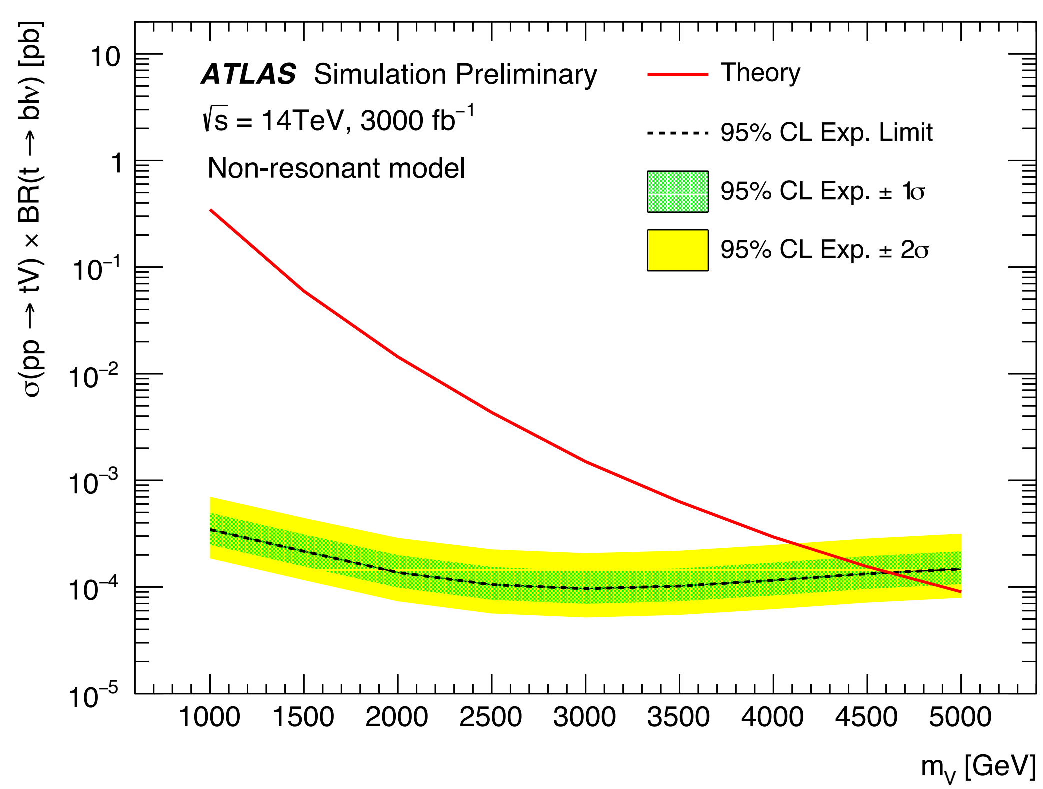
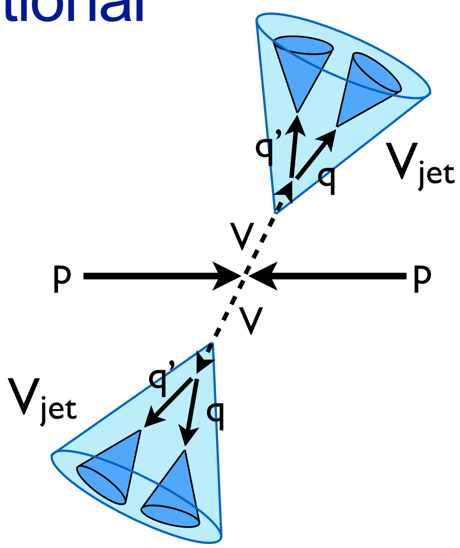


Heavy Resonances

- Heavy Vector Triplet (HVT) model: composite Higgs and three additional vector bosons Z' and W'$^{\pm}$
  Z' and W'$^{\pm}$ $\rightarrow$ WW, WZ or ZZ
- Randall-Sundrum Gluon:
  G $\rightarrow$ tt



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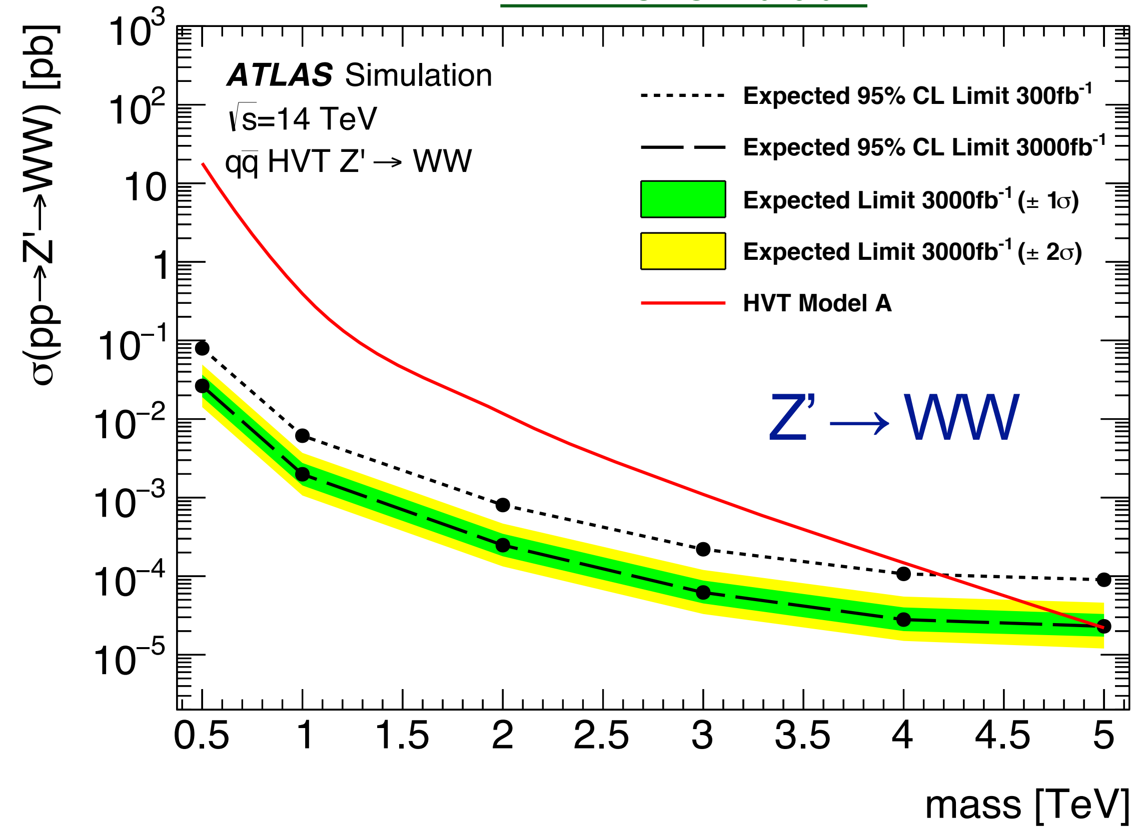

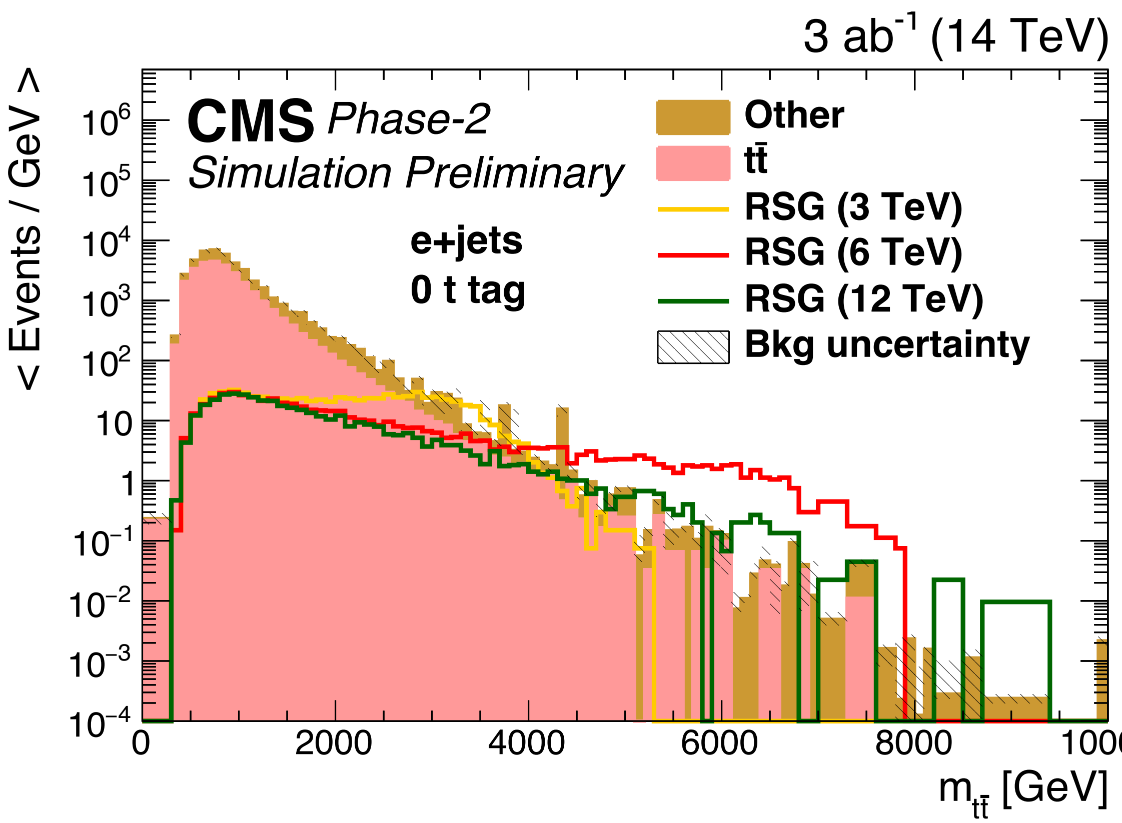

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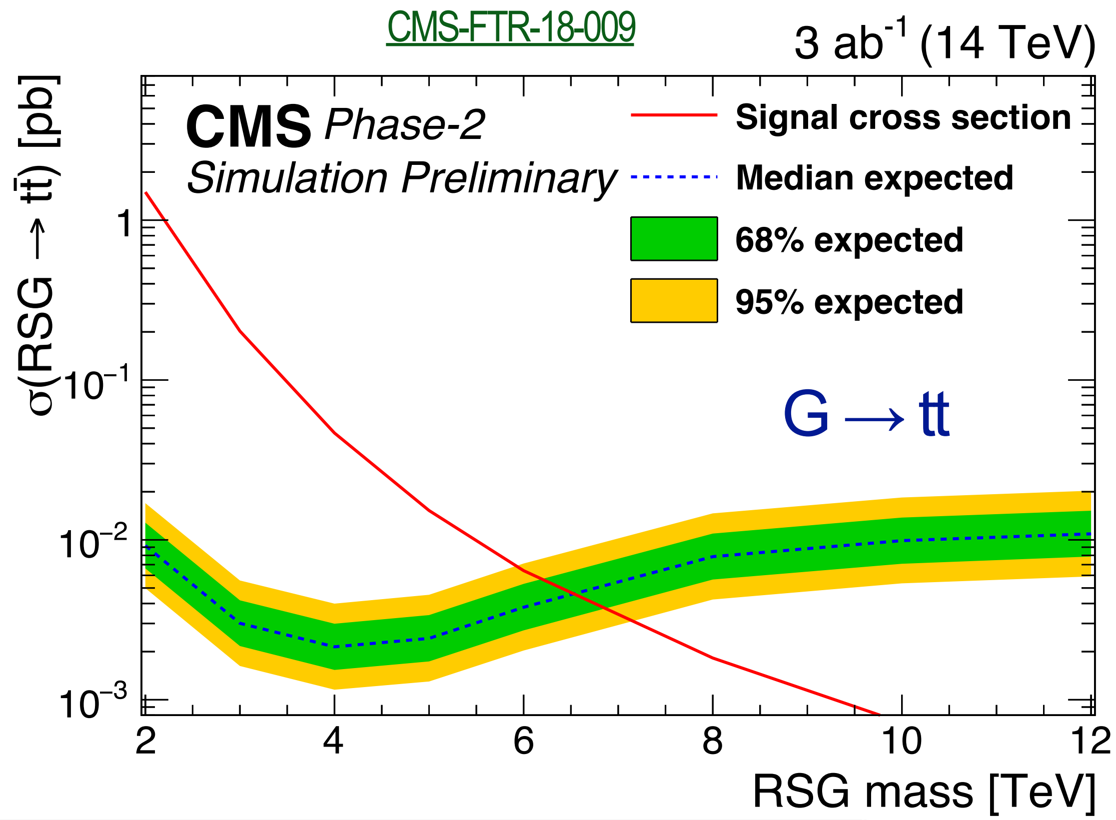
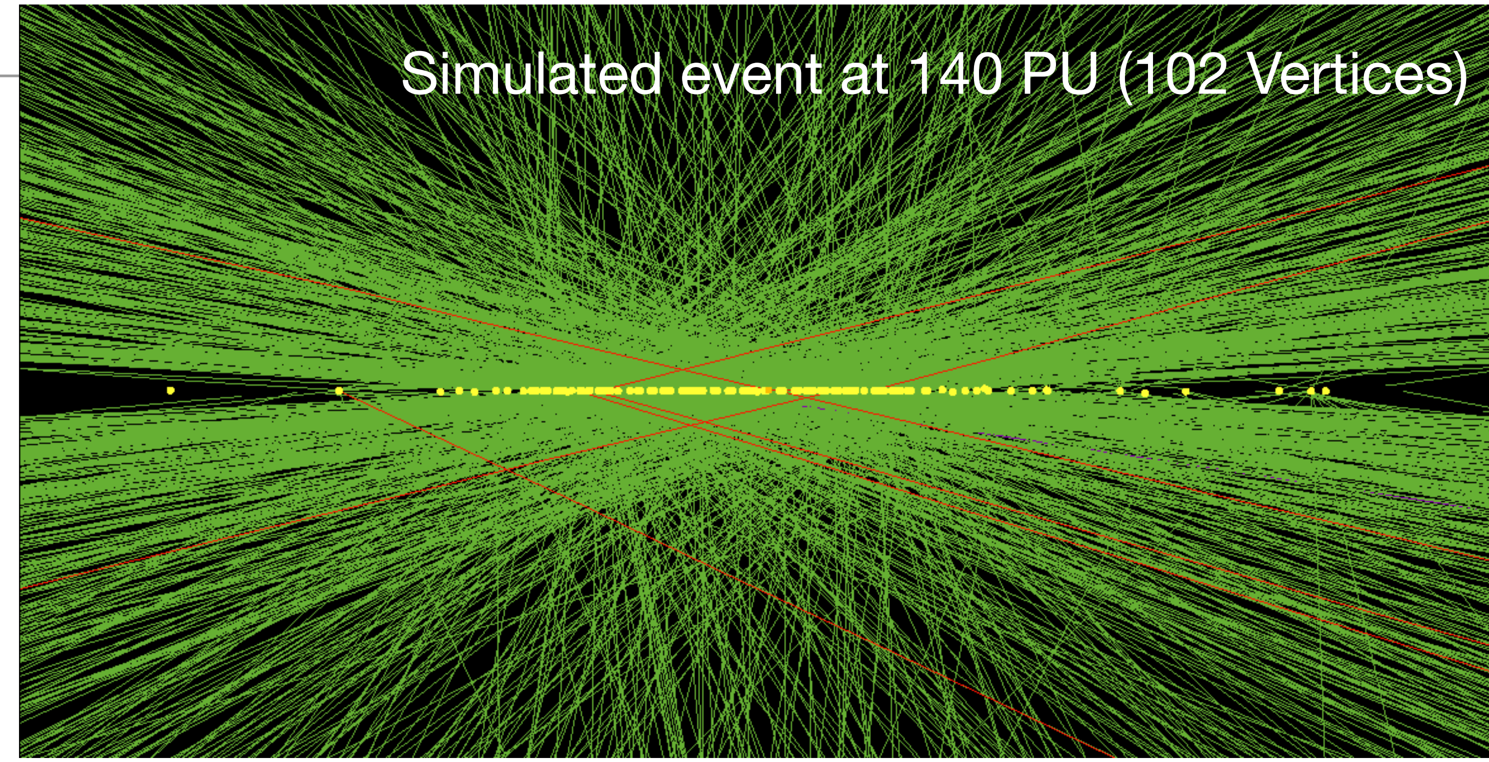


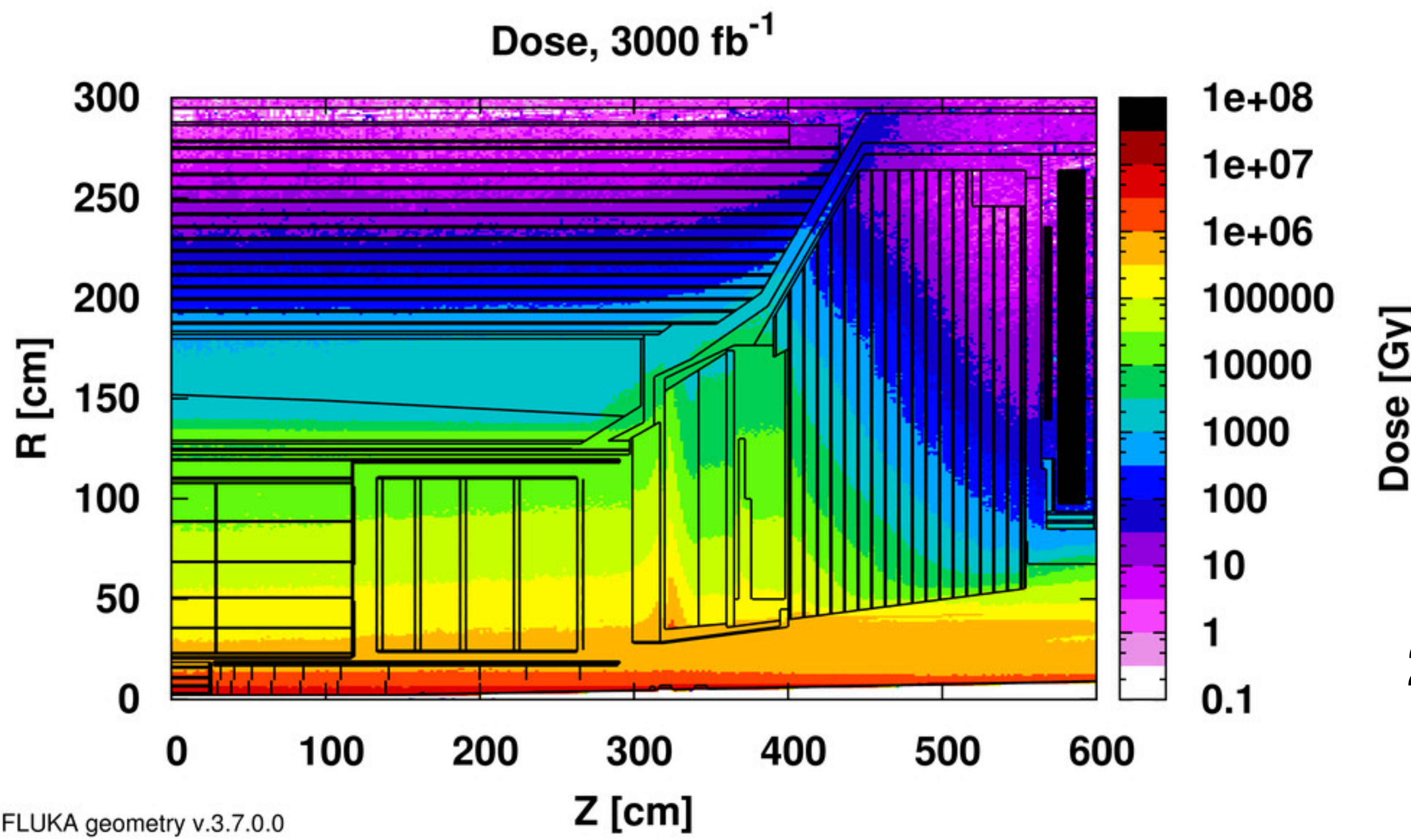
Mass reach: exclusion up to 5-6 TeV at HL-LHC (~10-11 TeV for HE-LHC)

Detectors to Enable HL-LHC Physics Program

HL-LHC: The Crucible



Pile-up (#overlapping hard scatters per bunch crossing) up to 200



Radiation levels up to $2 \times 10^{16}\ n_{eq}\ /cm^2$

CMS Phase-2 upgrade scope (TDR, interim TDR and TP references)

L1-Trigger/HLT/DAQ

https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters

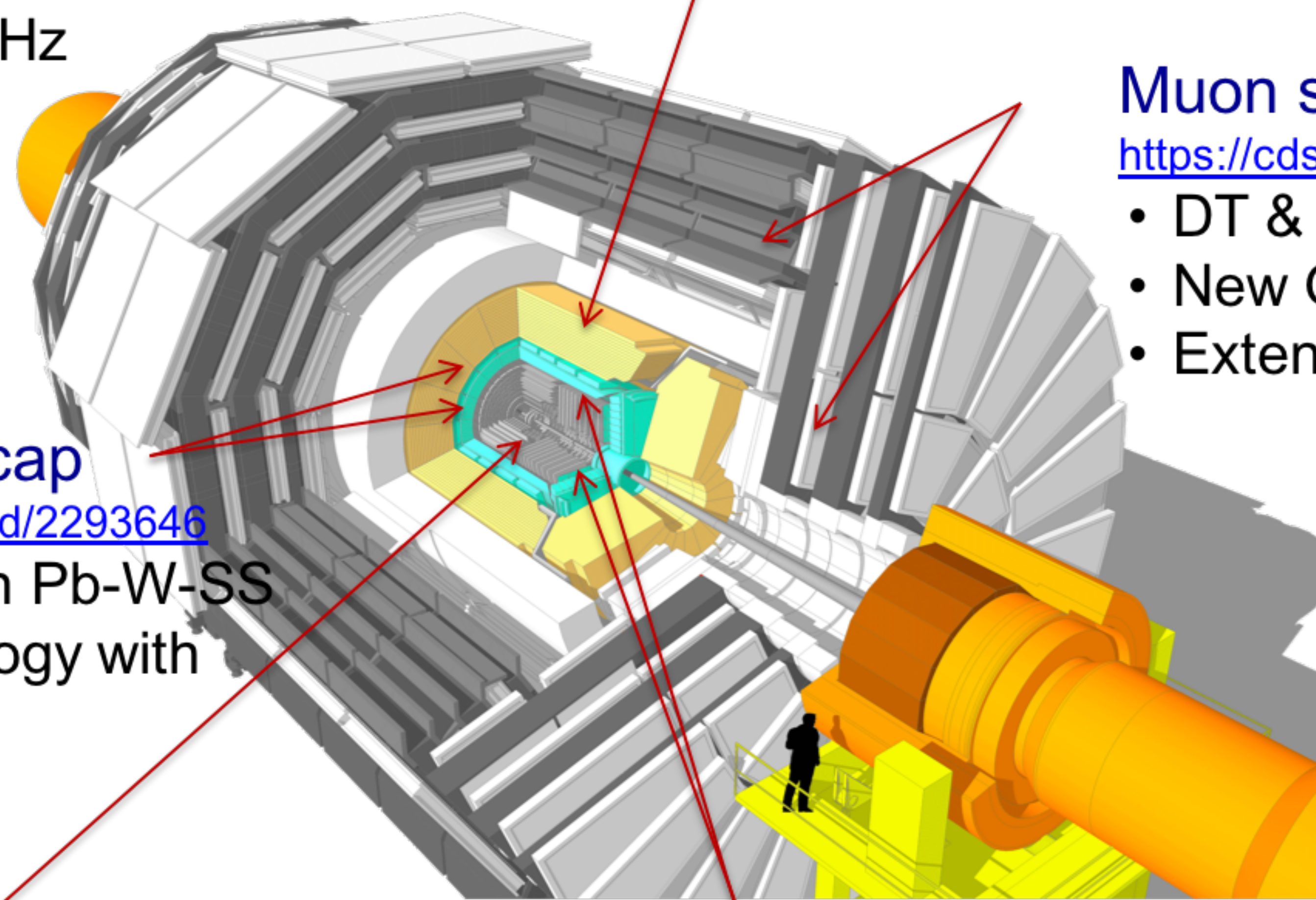
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap

https://cds.cern.ch/record/2293646

- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264

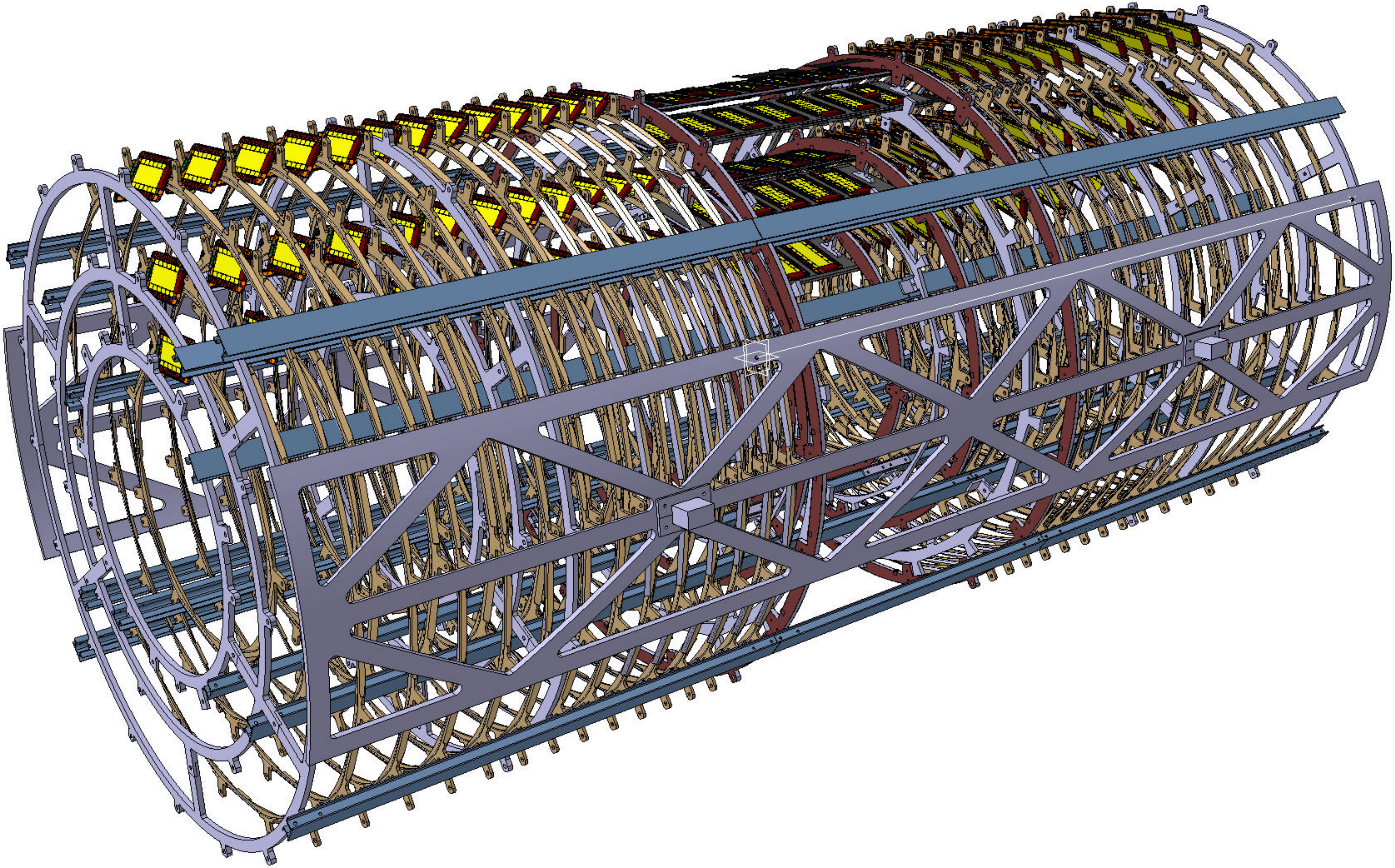
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector

https://cds.cern.ch/record/2296612

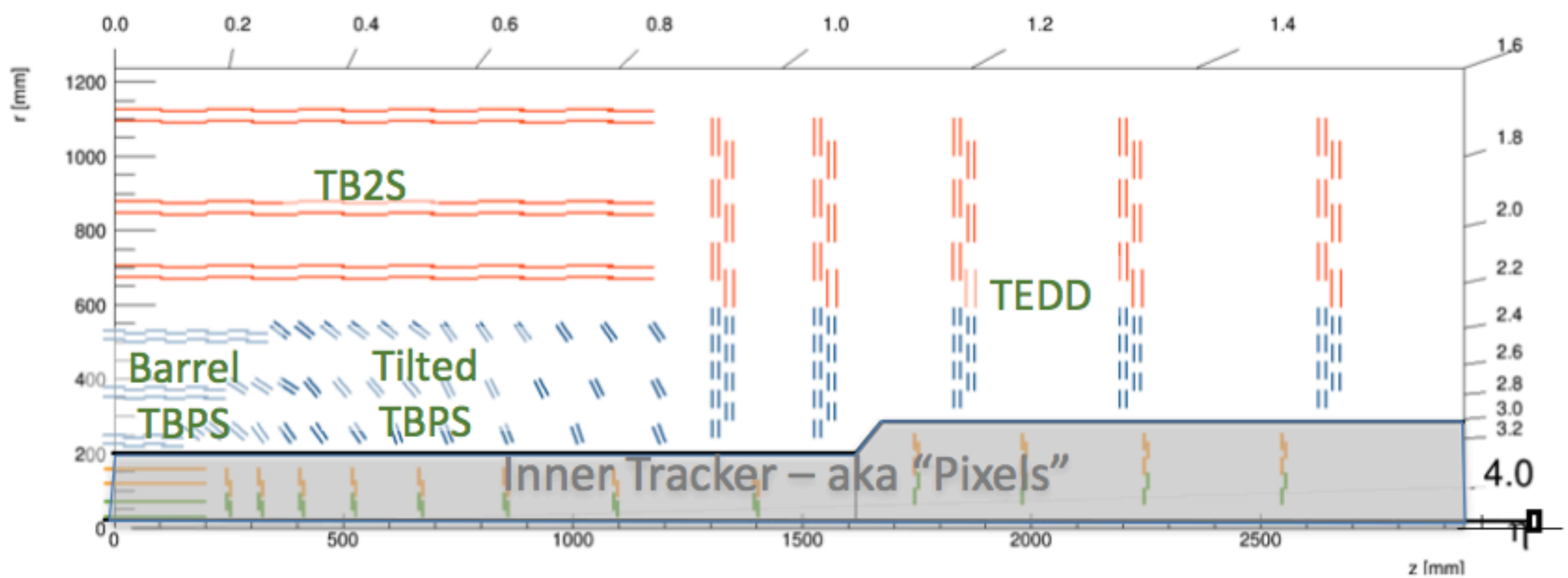
- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

CMS High Luminosity LHC Tracker Detector



HL-LHC CMS Outer Tracker

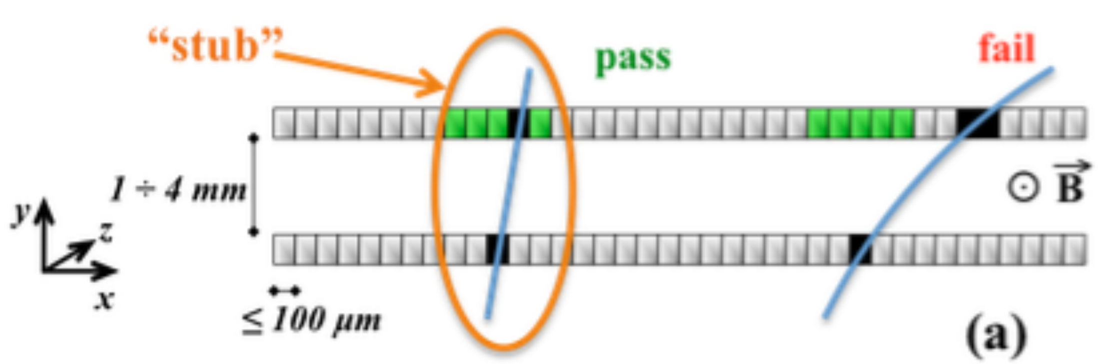
- **Goal: similar tracking and vertexing performance in extreme environment (with better coverage and less material)**



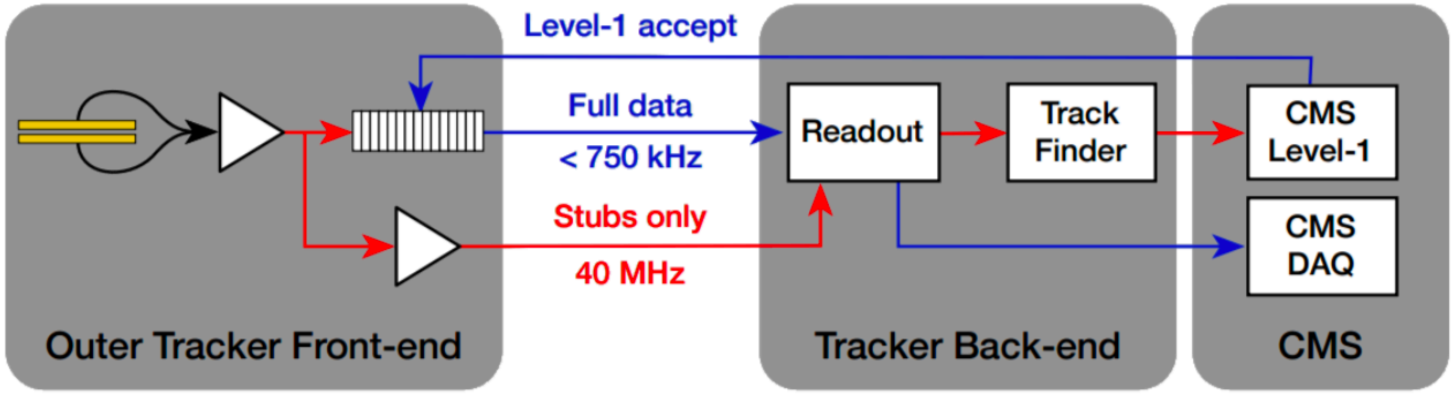
- **New requirement: triggering @ L1**

p_T modules:

p_T > 2 GeV → x10-100 reduction

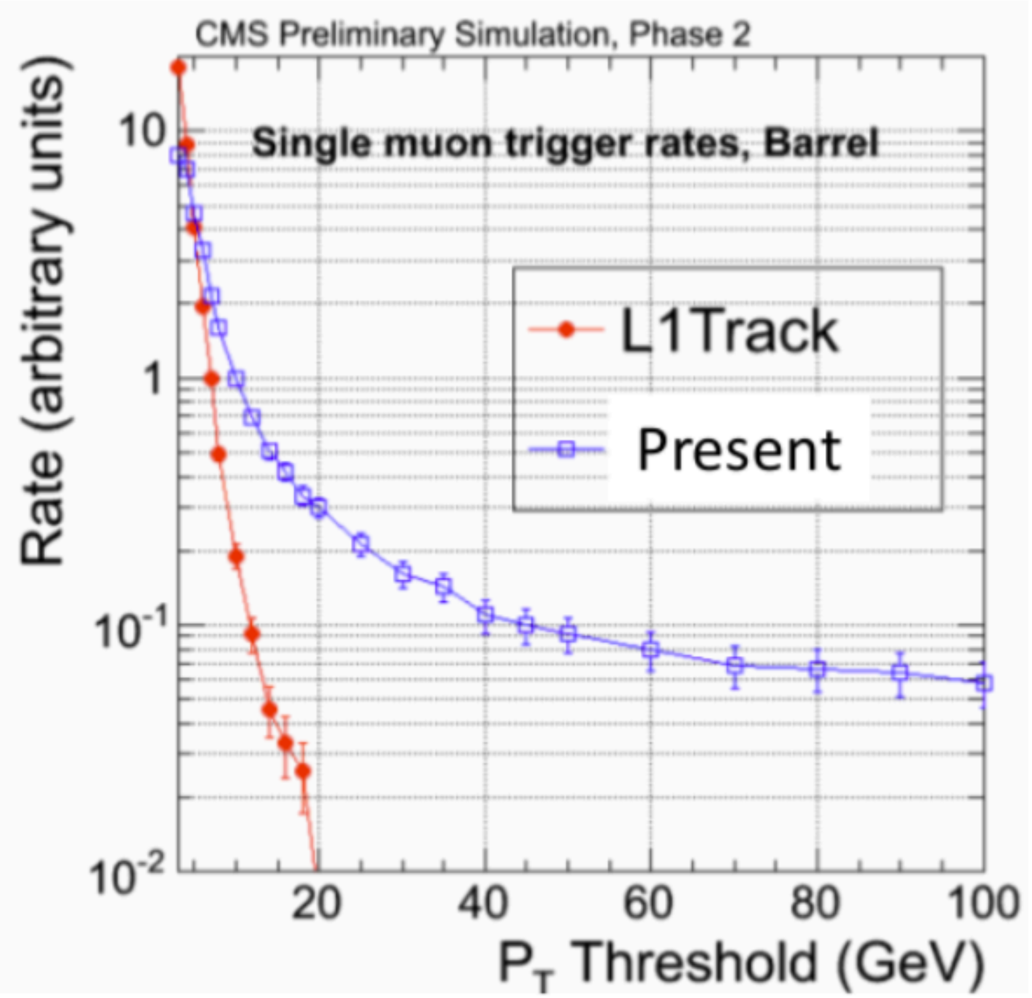


Transverse Momentum Modules



- Local rejection of low-pT tracks

- Exploit bending of charged particle tracks in CMS' 4T B-field
- Correlate hits from 2 closely spaced sensors to form stubs
- Tuneable offset and window for homogeneous pT threshold throughout the Outer Tracker

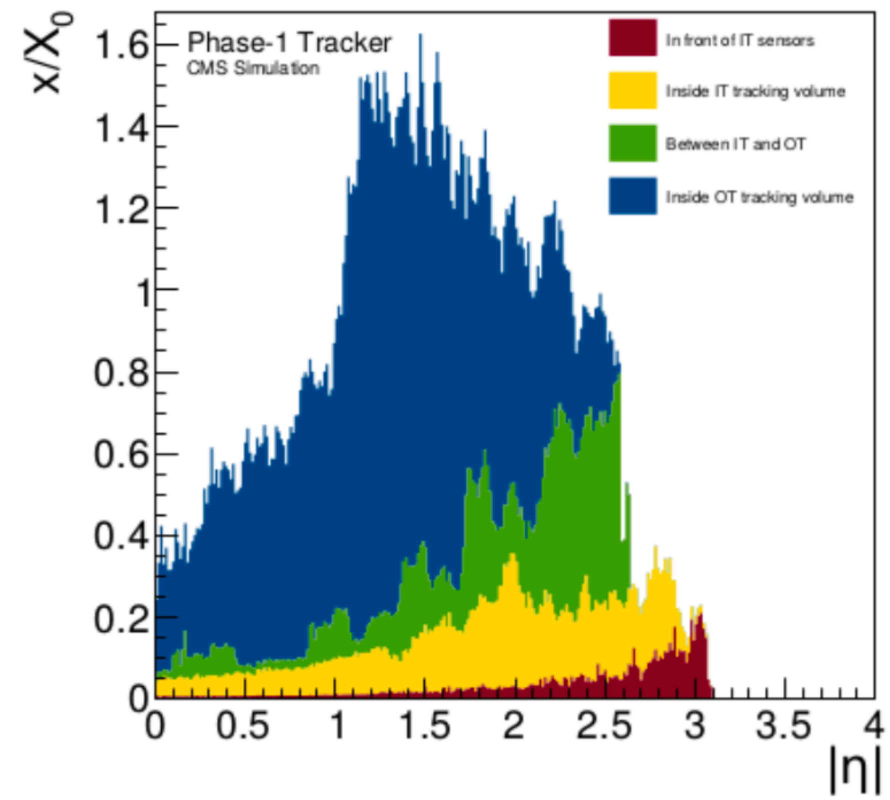


- Tracker input to the L1 trigger

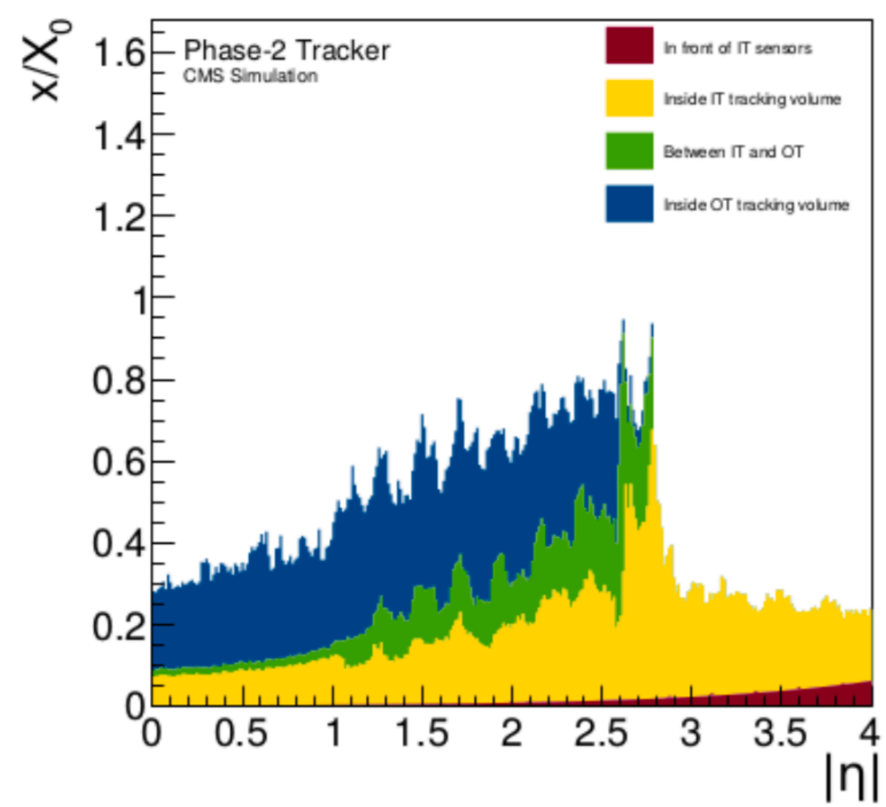
- Stub information sent out at 40 MHz
- Two data streams: trigger information and hit data
- Full data read-out at ~750 kHz

Outer Tracker Layout

- **Classic barrel + end cap design**
  - **6 barrel layers**
  - **5 discs per end cap**
- **From 9.5 million channels to…**
  - **200 m² of active silicon sensors**
  - **44 million strips**
  - **174 million macro pixels (r < 60 cm)**
- **while vastly reducing material**
  - **Light-weight mechanics and modules**
  - **Improved routing of services**
  - **Tilted barrel section**

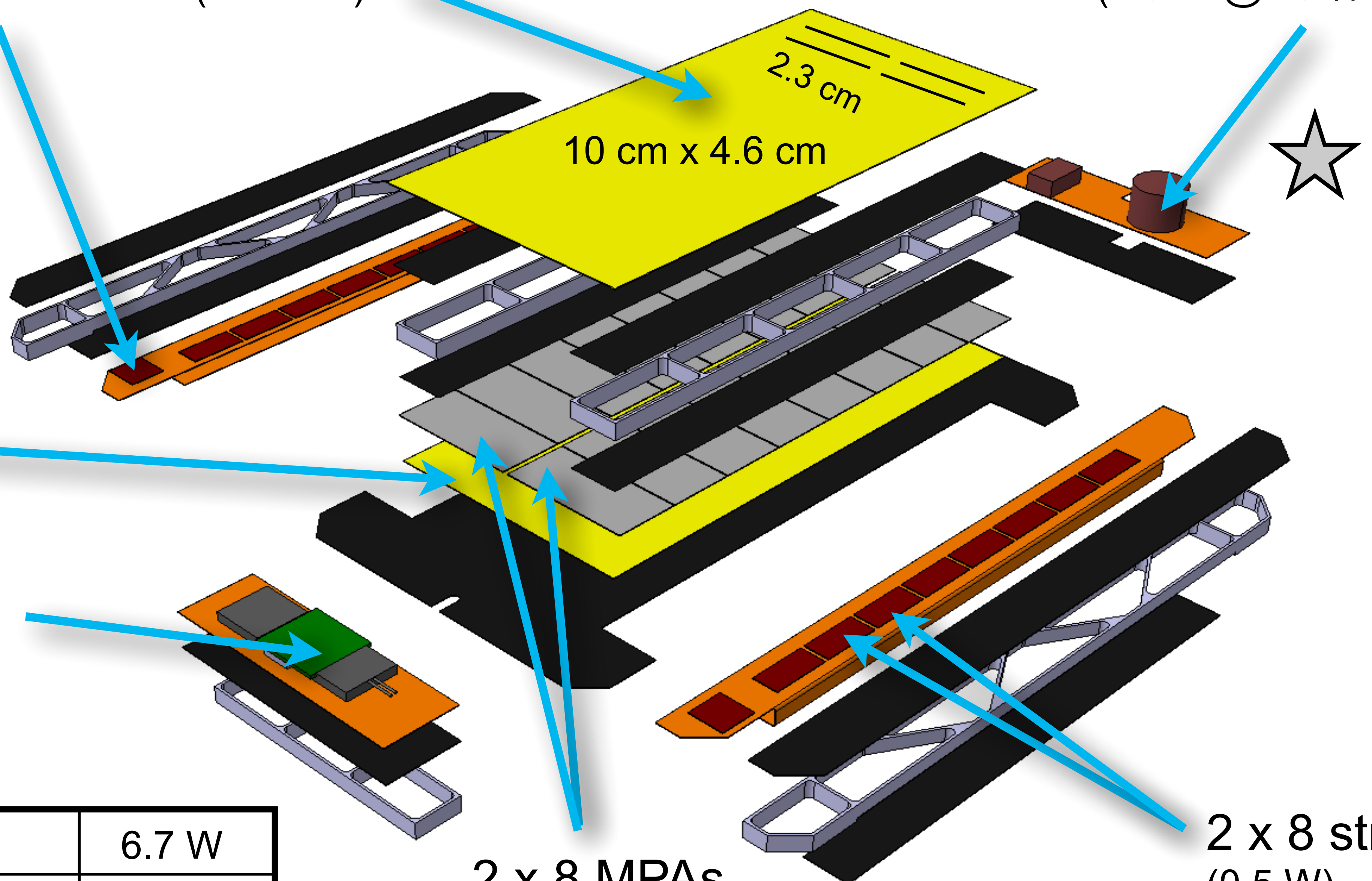


Now



HL-LHC

PS Module



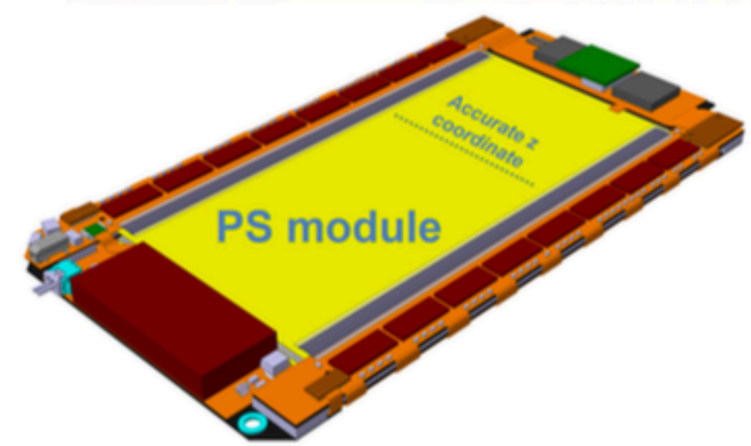
- **M**acro **P**ixel **A**sic
- performs correlation and produces stubs
- 3.0 W

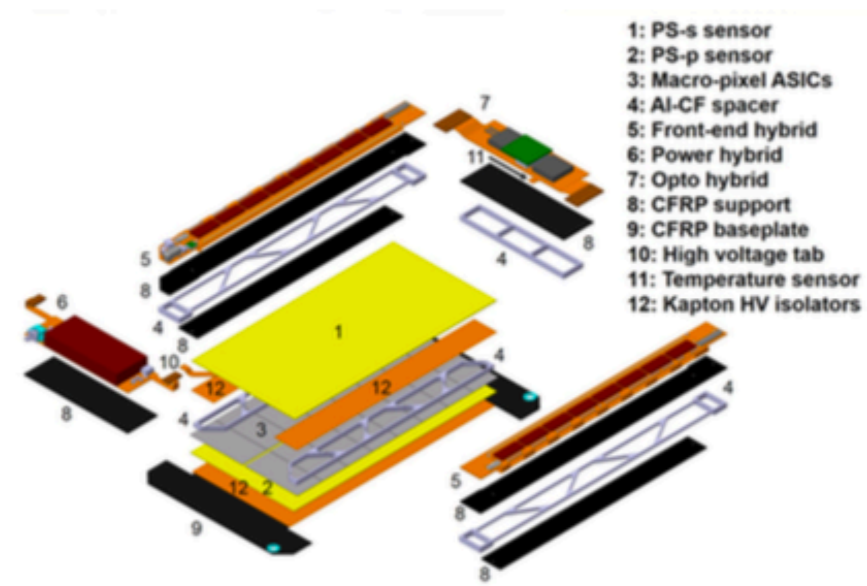
total FE power	6.7 W
1.6 mm module	7.4 W
2.6 mm module	8.1 W
4.0 mm module	7.7 W

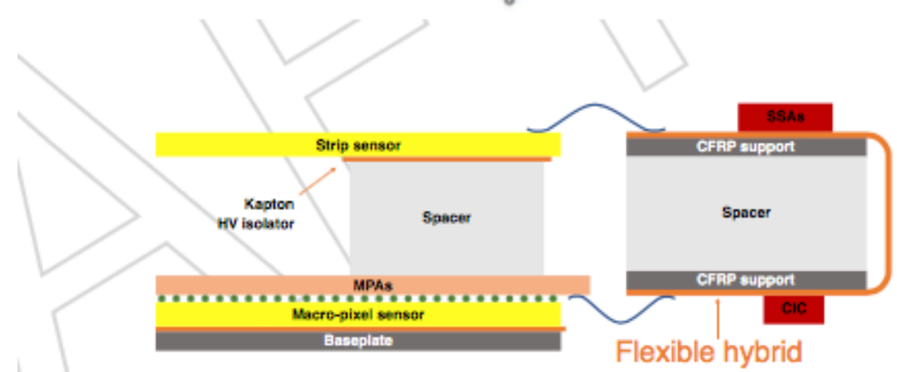
Outer Tracker key parameters CMS-TDR-17-001

- Module mechanics

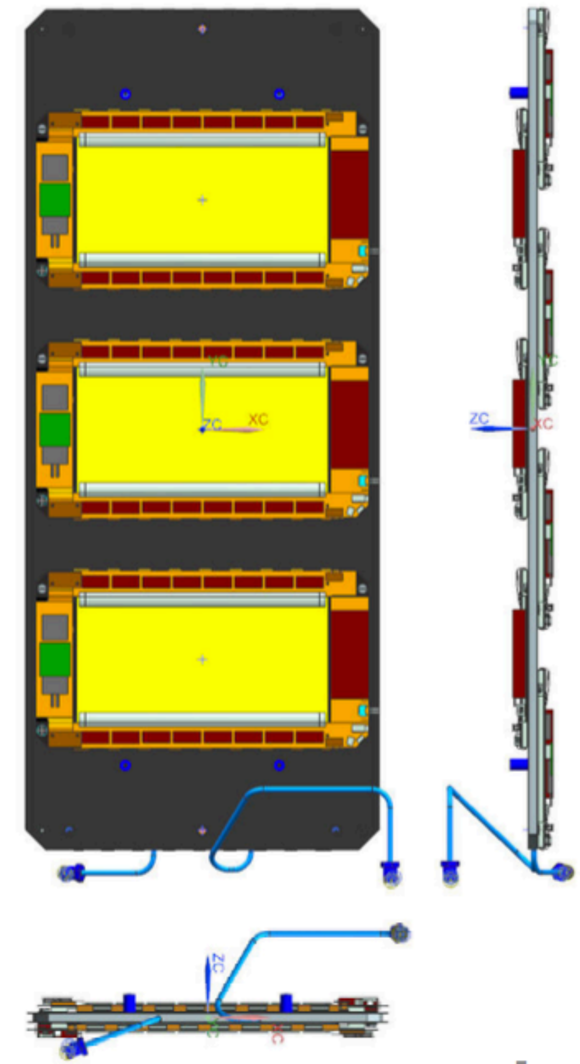
- Use Al-CF spacers. High k and low CTE. (Alternatives under study: AlN? Foam/kapton?)
- Use of CFRP plates
- Minimal glue layers to permit good heat conduction while providing necessary structural strength
- 1000V isolation between conductive surfaces at HV and those at ground. Safety margin of 400V. Use kapton tape-wrapped Al-CF.







OT Detector Mechanics

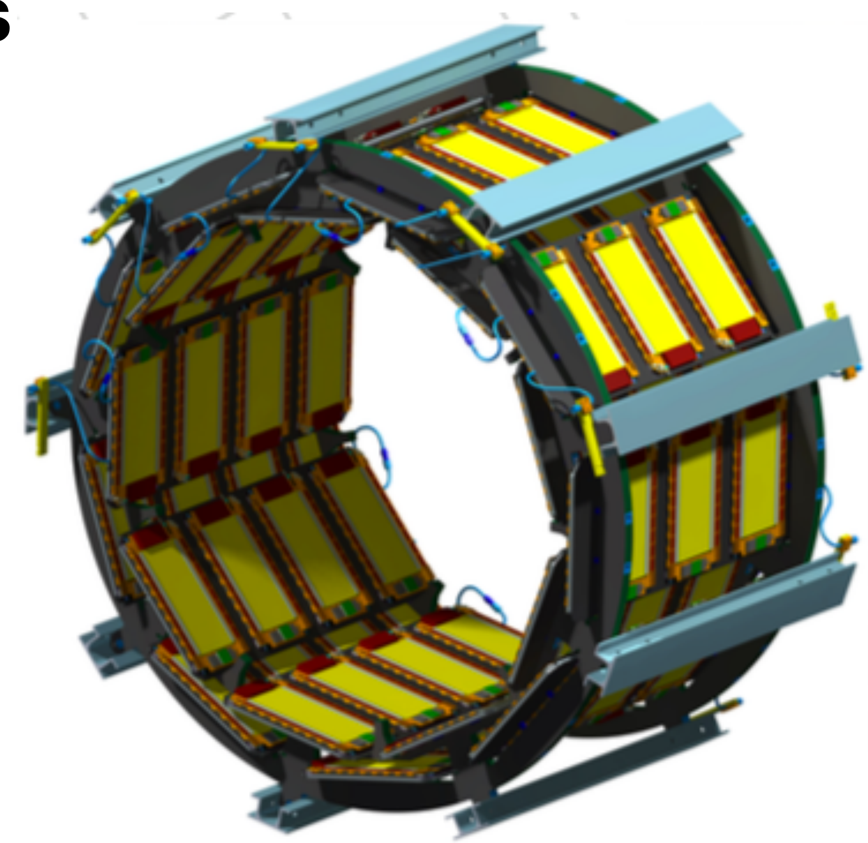


- Mechanical structures

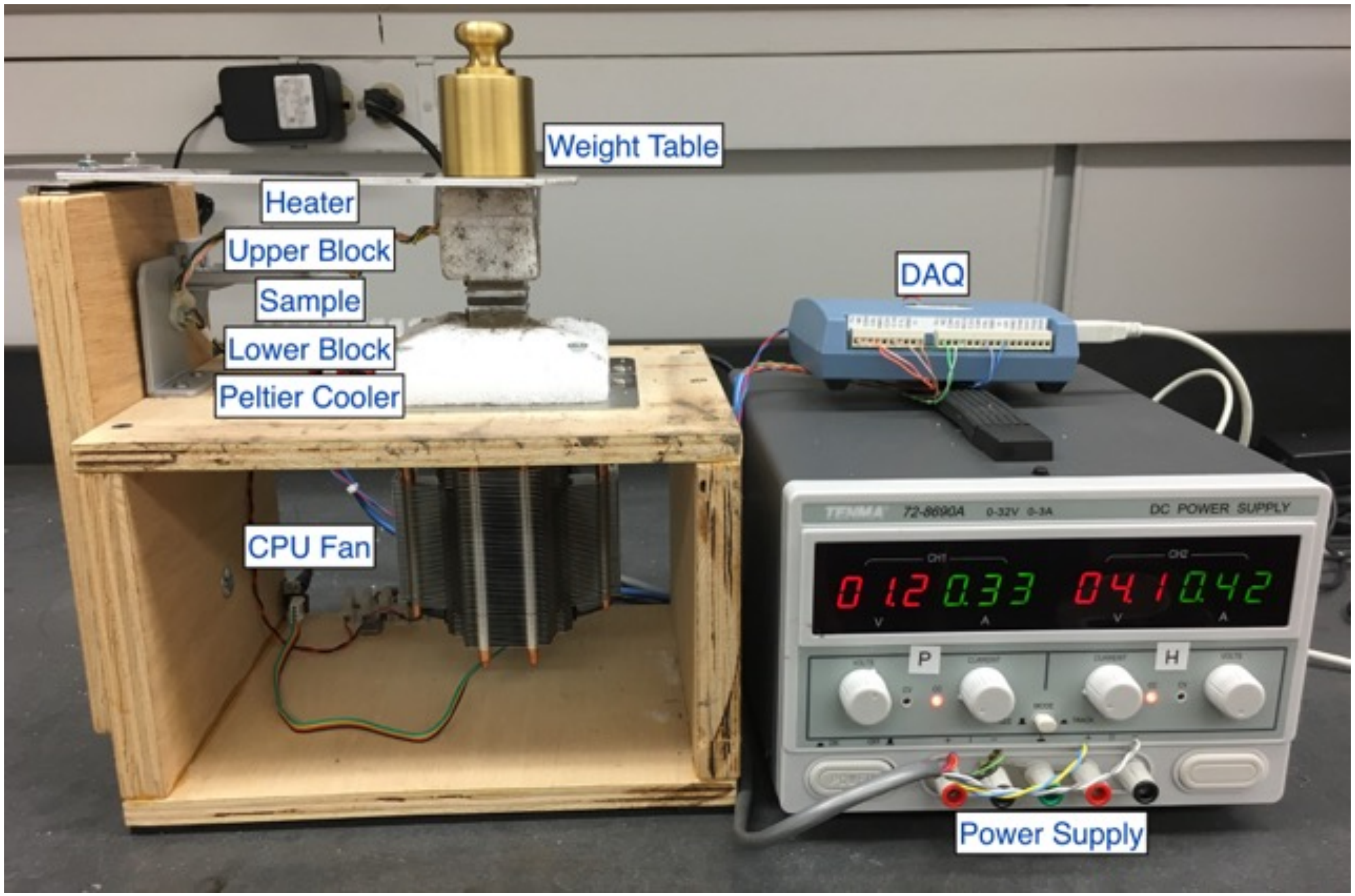
- **952 Central PS modules mounted on planks: C-foam core with C-fiber skins, embedded dual-phase CO_2 cooling loop**

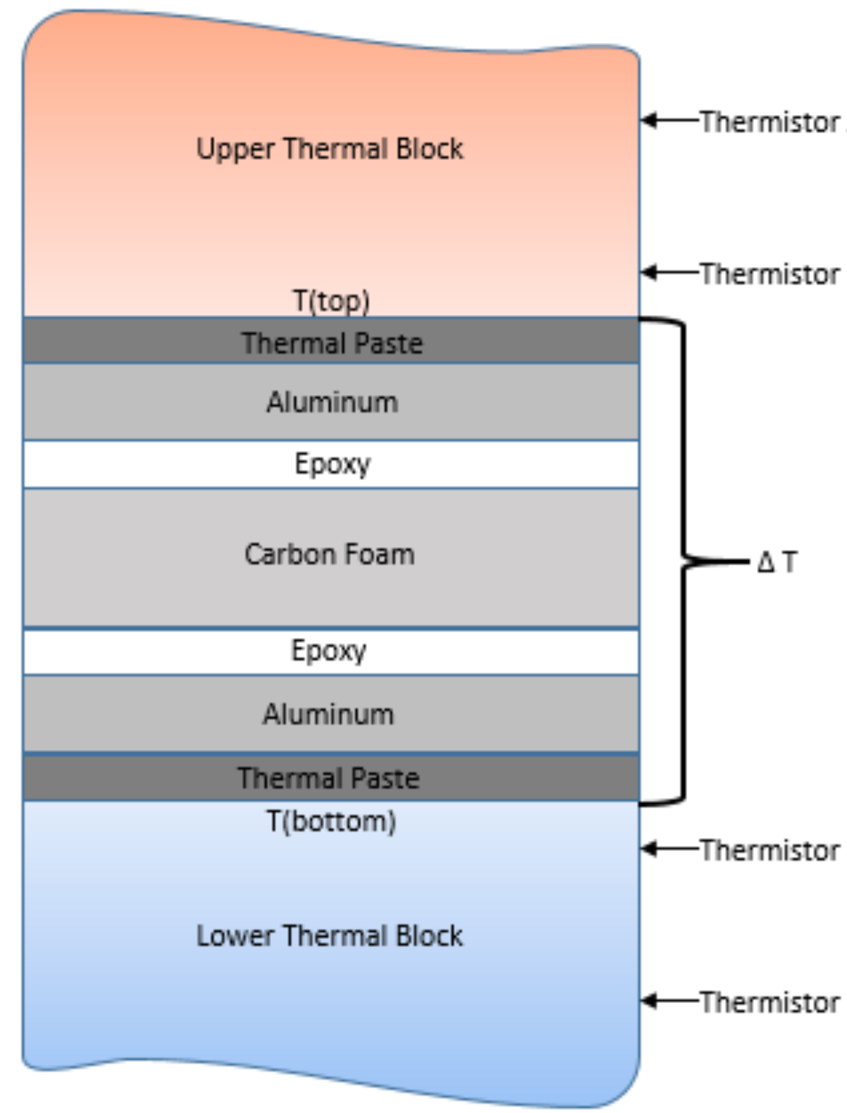
  layer 1: 328mm → layer 3: 695mm

- **Planks attached to end support rings to create barrel flat sections**
- **Phase change adhesive used to make thermal connection to modules**
- **Plank dimensions: trade-off between stiffness, material budget, heat flow**



Thermal Conductivity Testing @ UC Davis

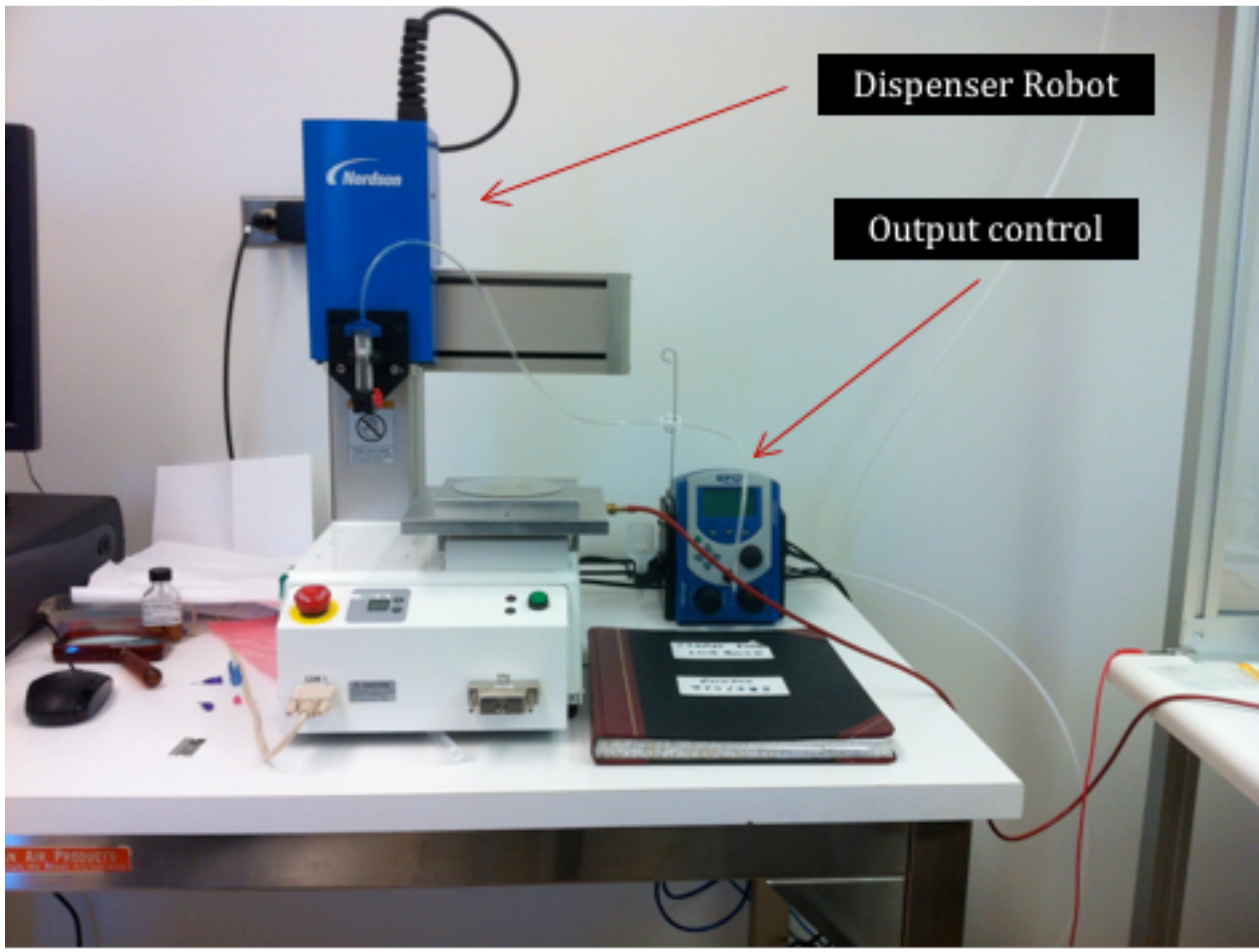


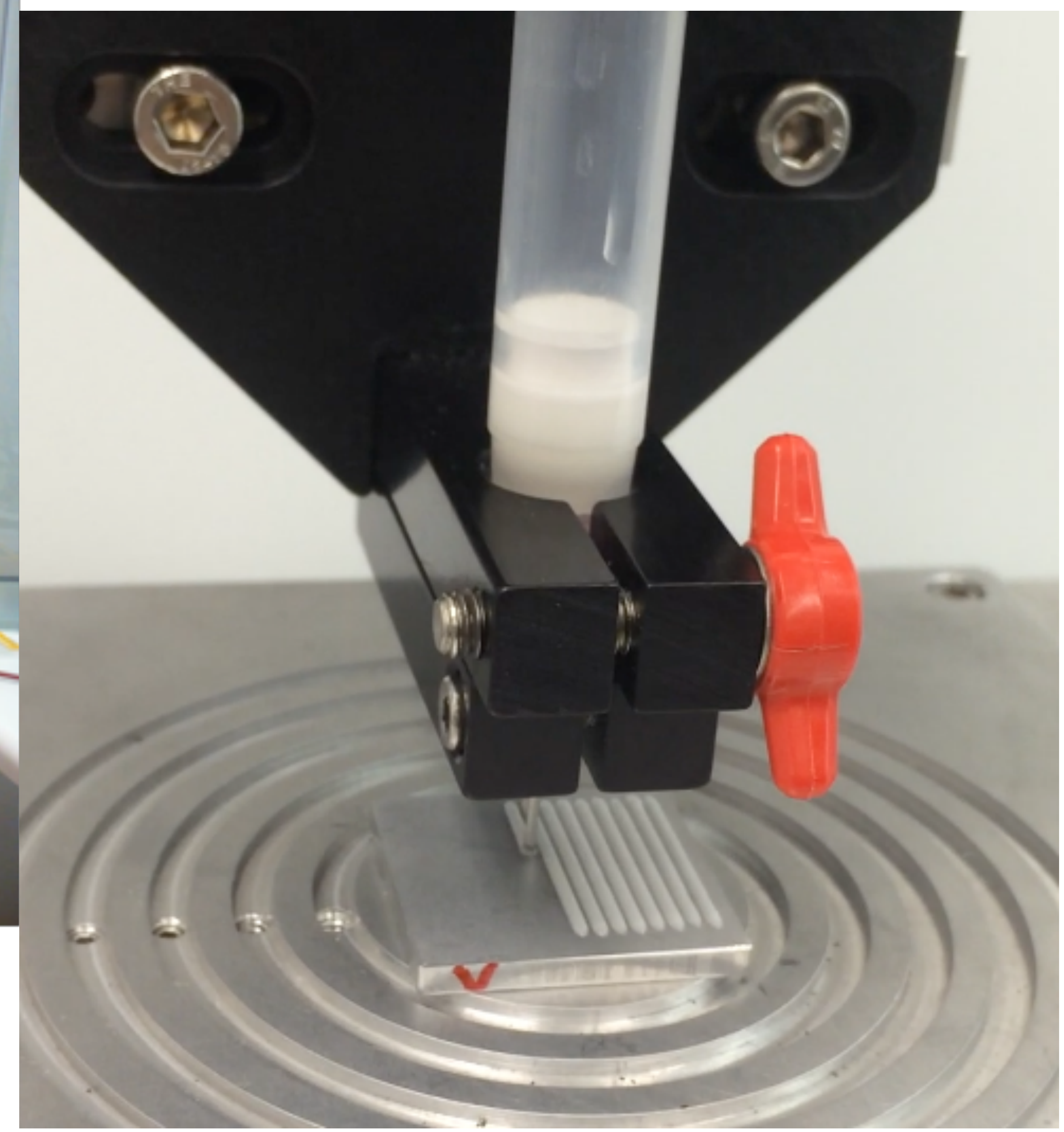


- **Heat introduced at the top of stack and removed from the bottom**
- **Measure thermal resistance of a sample by calculating the temperature drop across the interface**

Robotic dispenser:

- **EFD Nordson automated epoxy dispenser**
- **Use to build sample stacks for thermal testing**

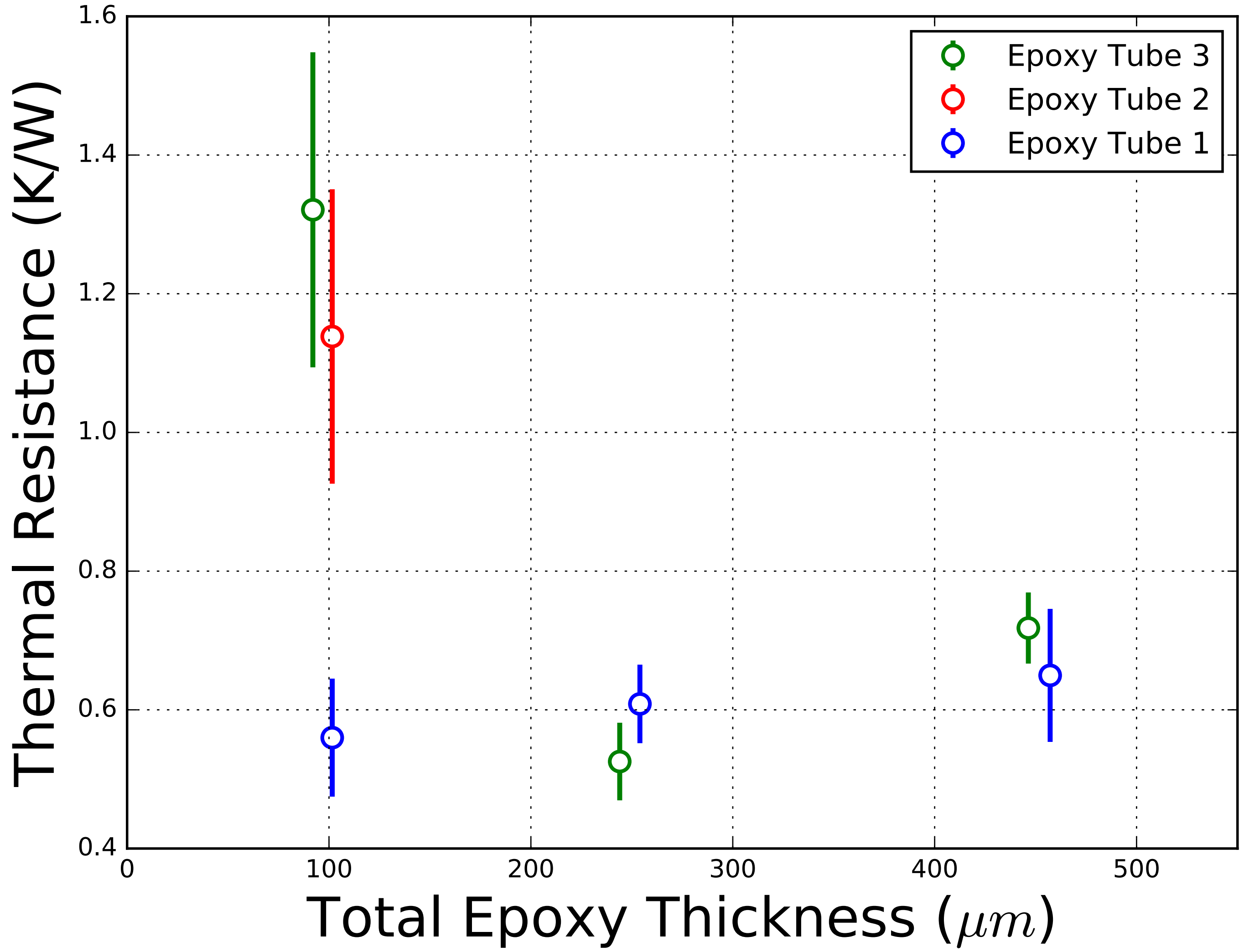


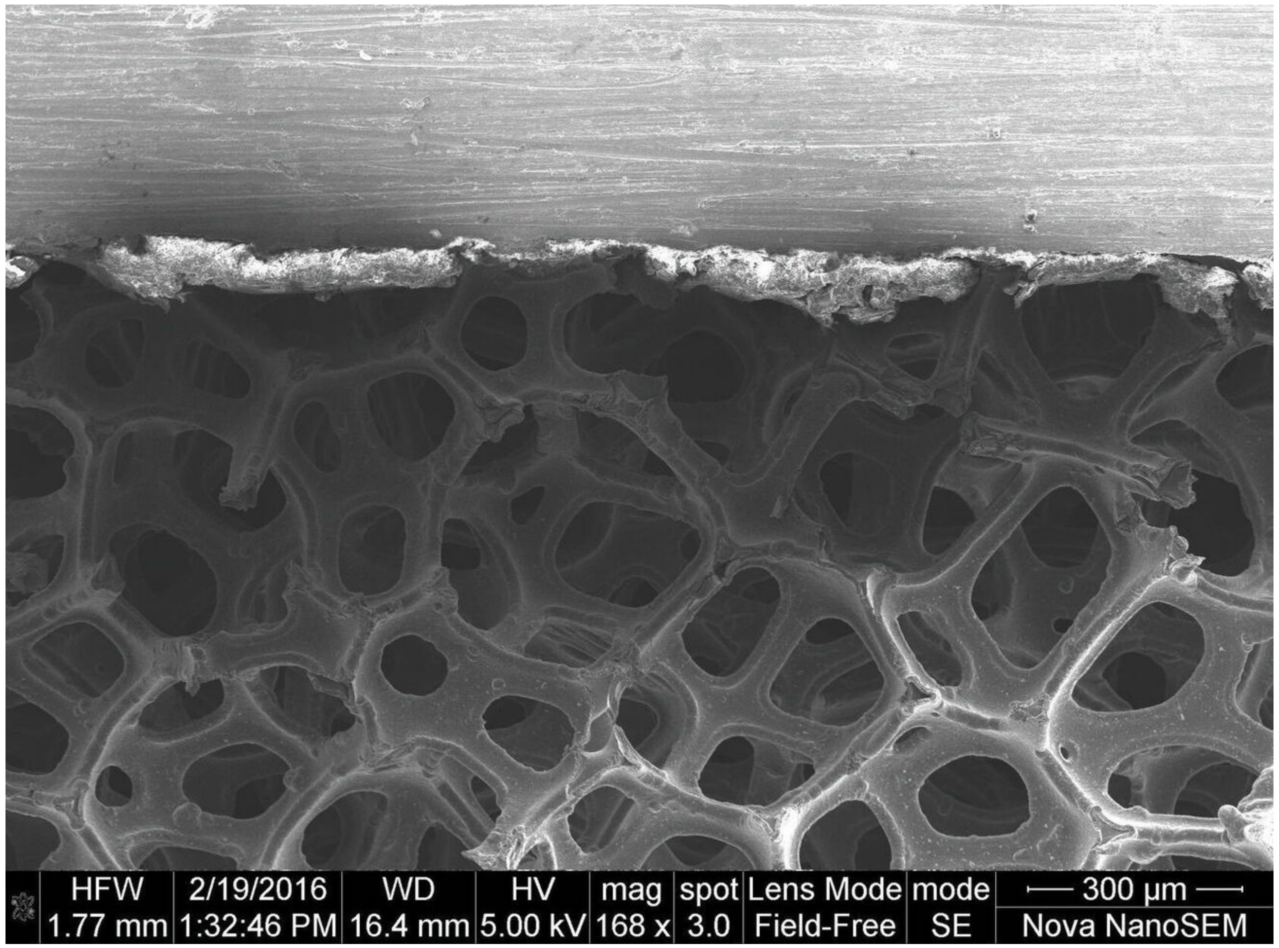


Results

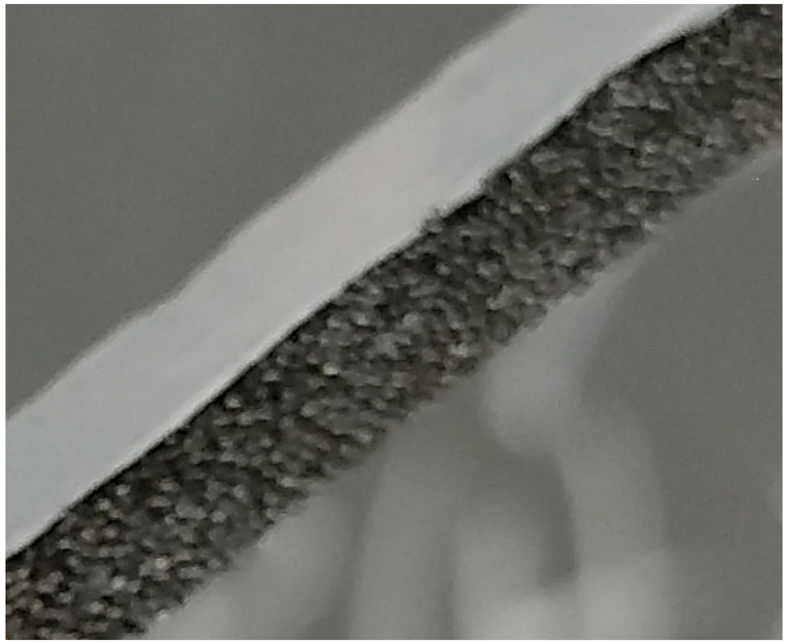
- **"Thermal and Tensile Strength Testing of Thermally-Conductive Adhesives and Carbon Foam"**

JINST 12 P01010 (2017)

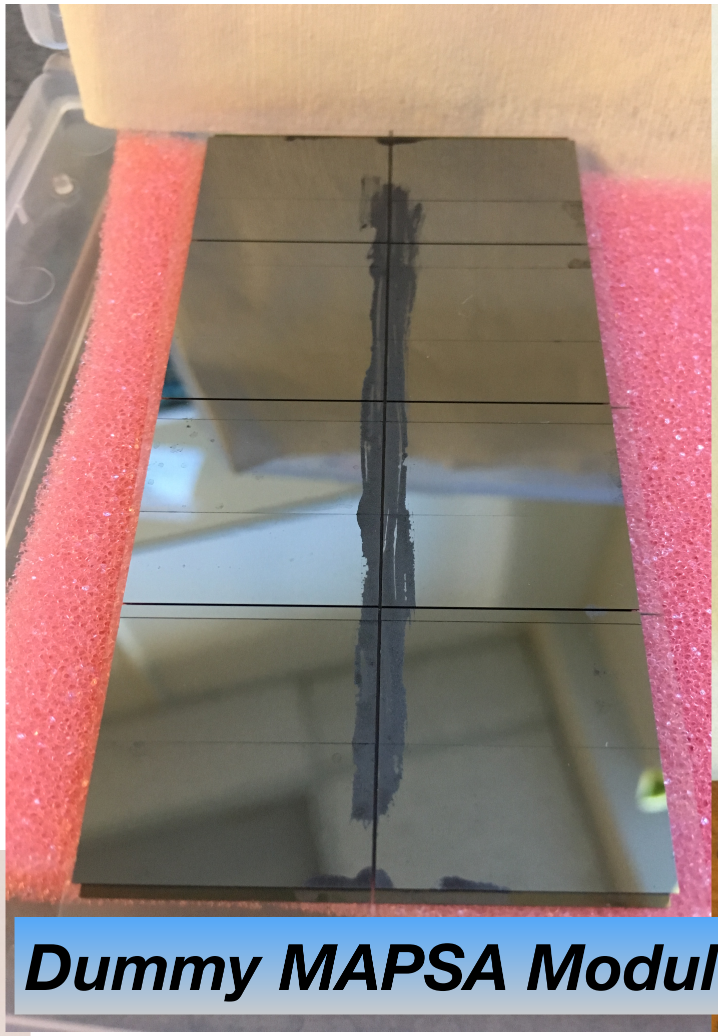




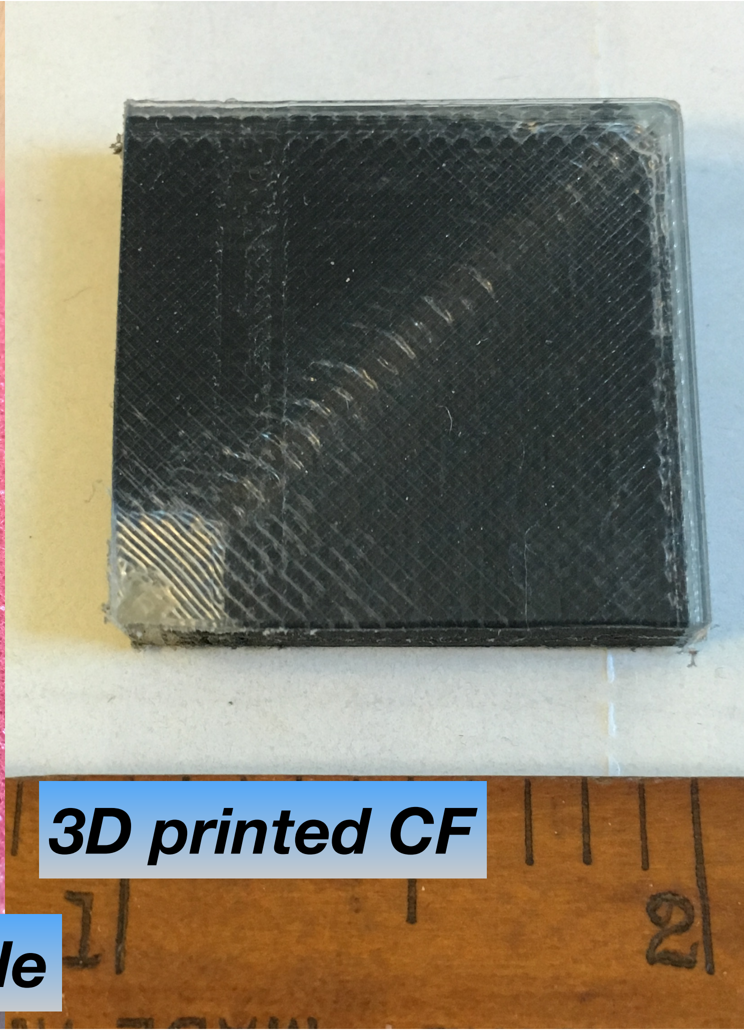
Variety of samples under study



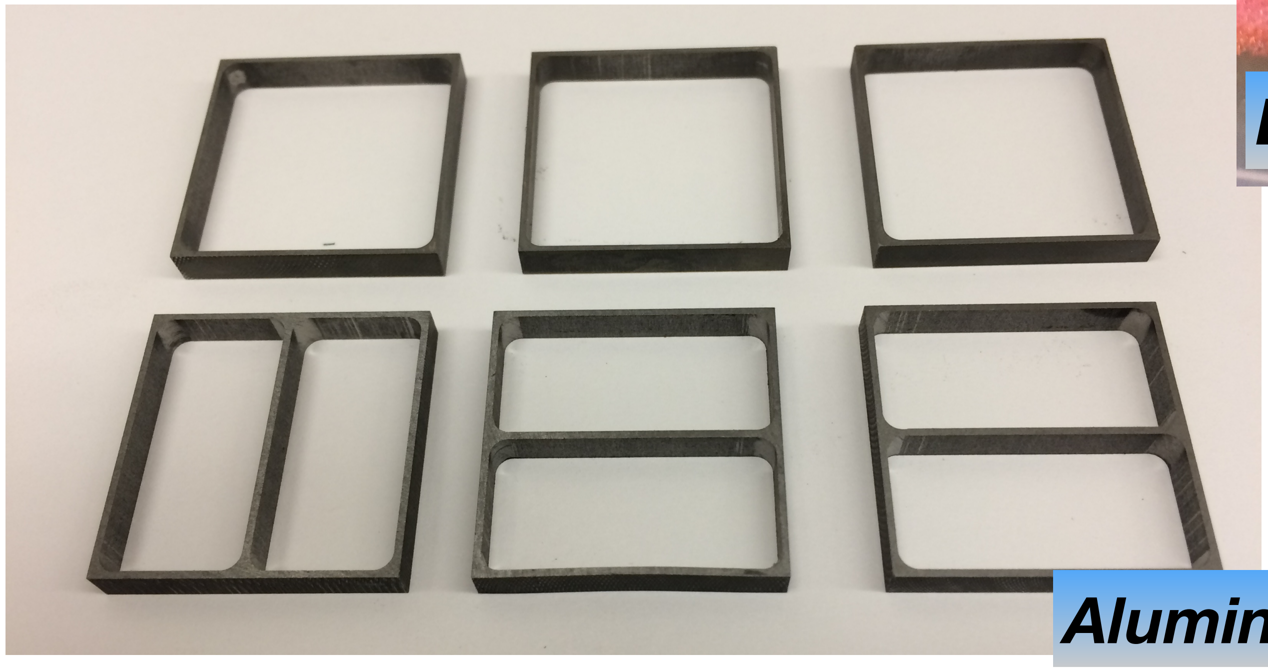
PS Module spacer alternatives



Dummy MAPSA Module



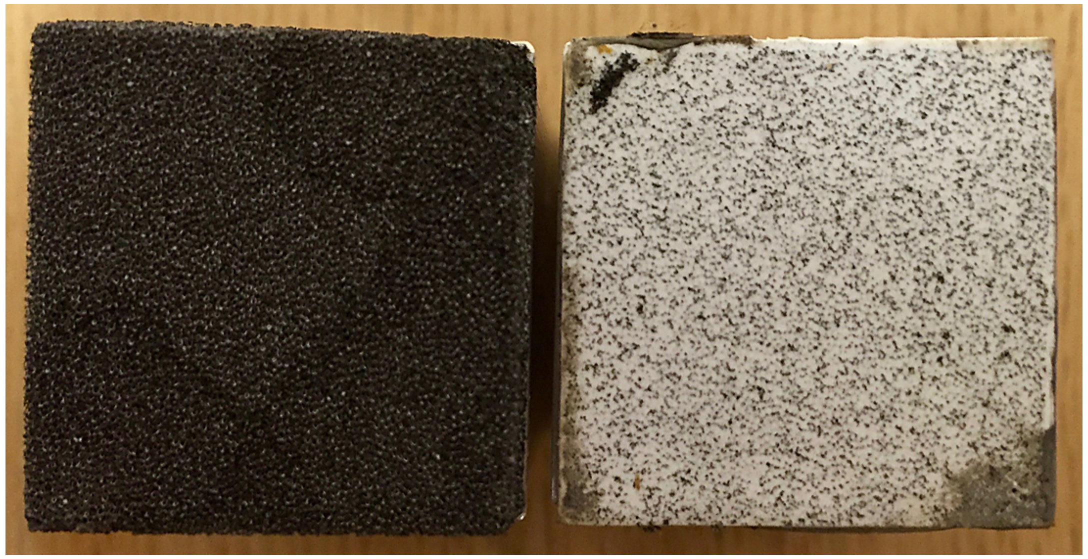
3D printed CF



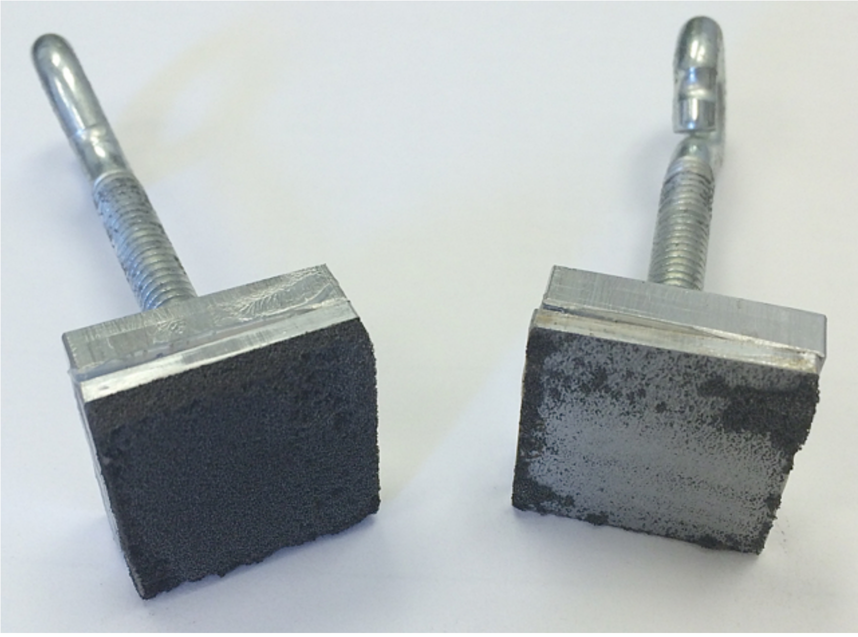
Aluminized Carbon Fiber

Tensile Strength Testing

- Goals: compare epoxy alternatives, validate use of thermal tape instead of BN epoxy
- Test tensile strength after p, n irradiation
- Test RBF bonding



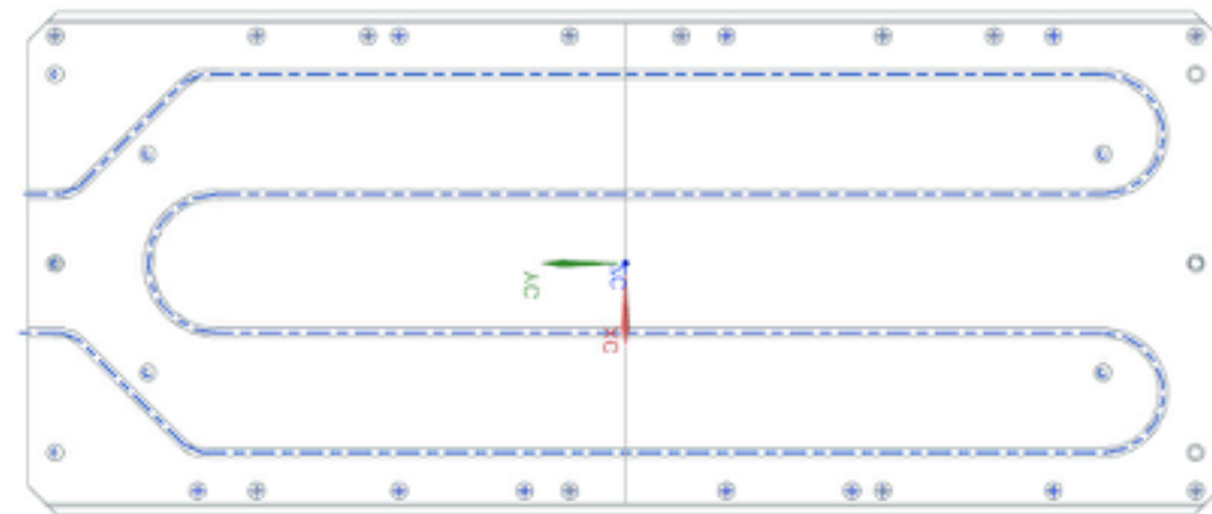
Tape failure mode

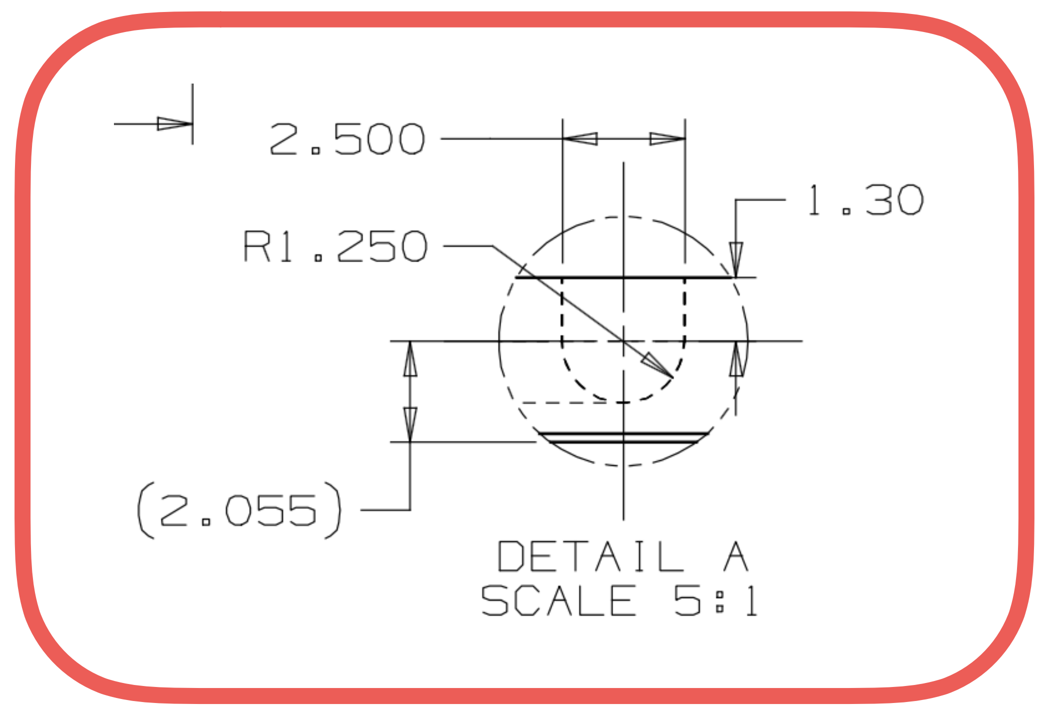


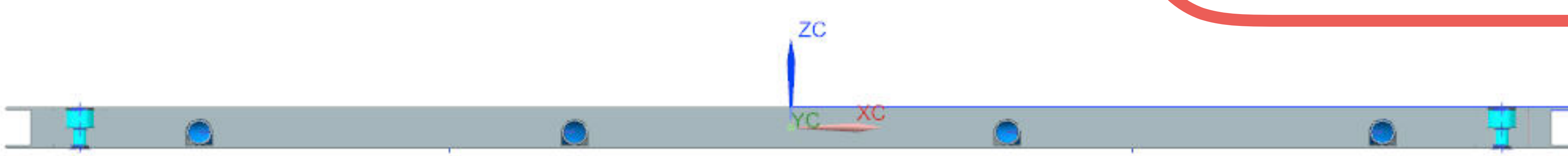
Epoxy: mixed mode of brittle tensile failure in carbon foam and delamination

Plank thermal testing

- **Build scaled down plank section with C-foam/C-fiber and cooling pipe to study heat transfer through channel**
  - **Measure versus: epoxy type, amount, application method, channel cross section**
  - **Measure heat flow with IR camera and RTDs**
  - **Compare with FEA, other measurements**



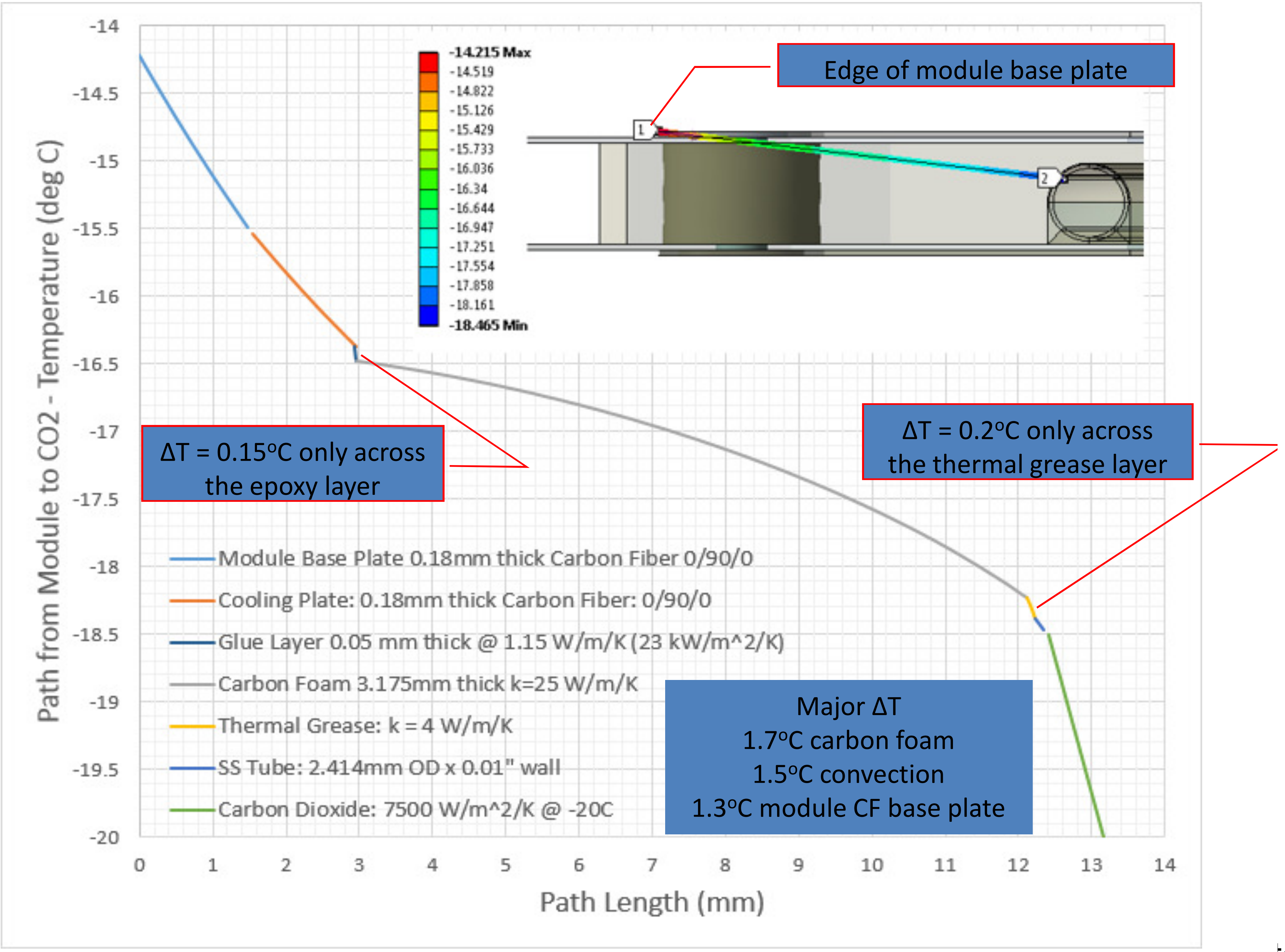




Fermilab Plank FEA

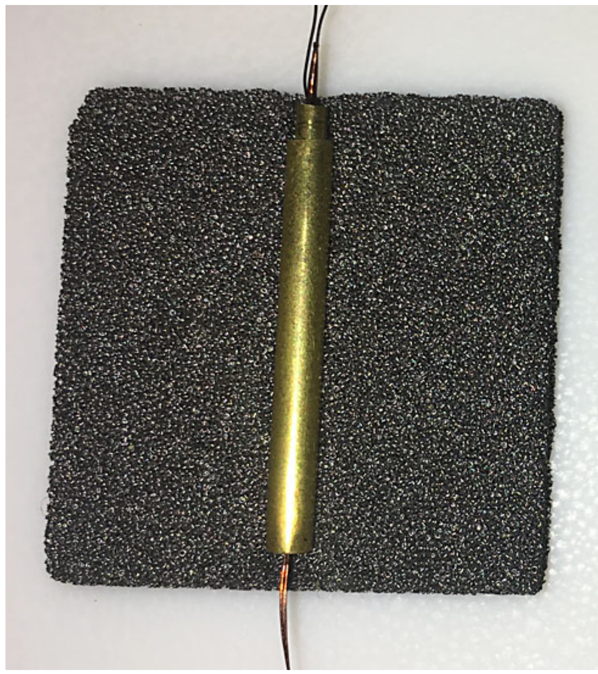
Temperature along path from Module end to Tubing

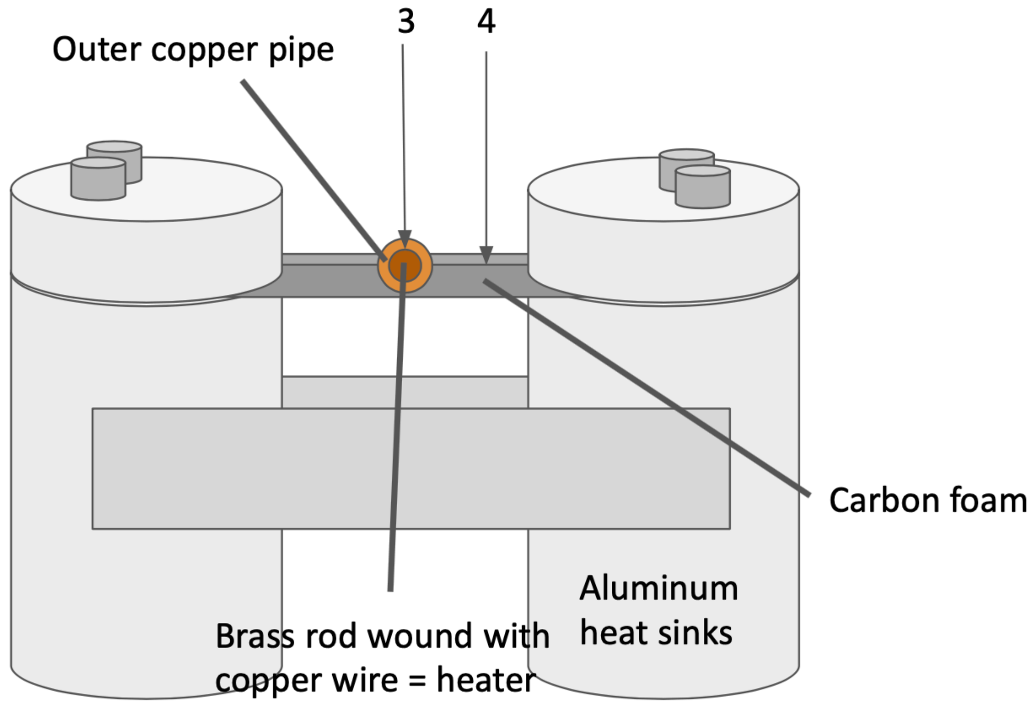
- 4-Pass Tubing optimized, CF 0/90/0 Layup, 1/8" (3.18mm) thick Carbon Foam

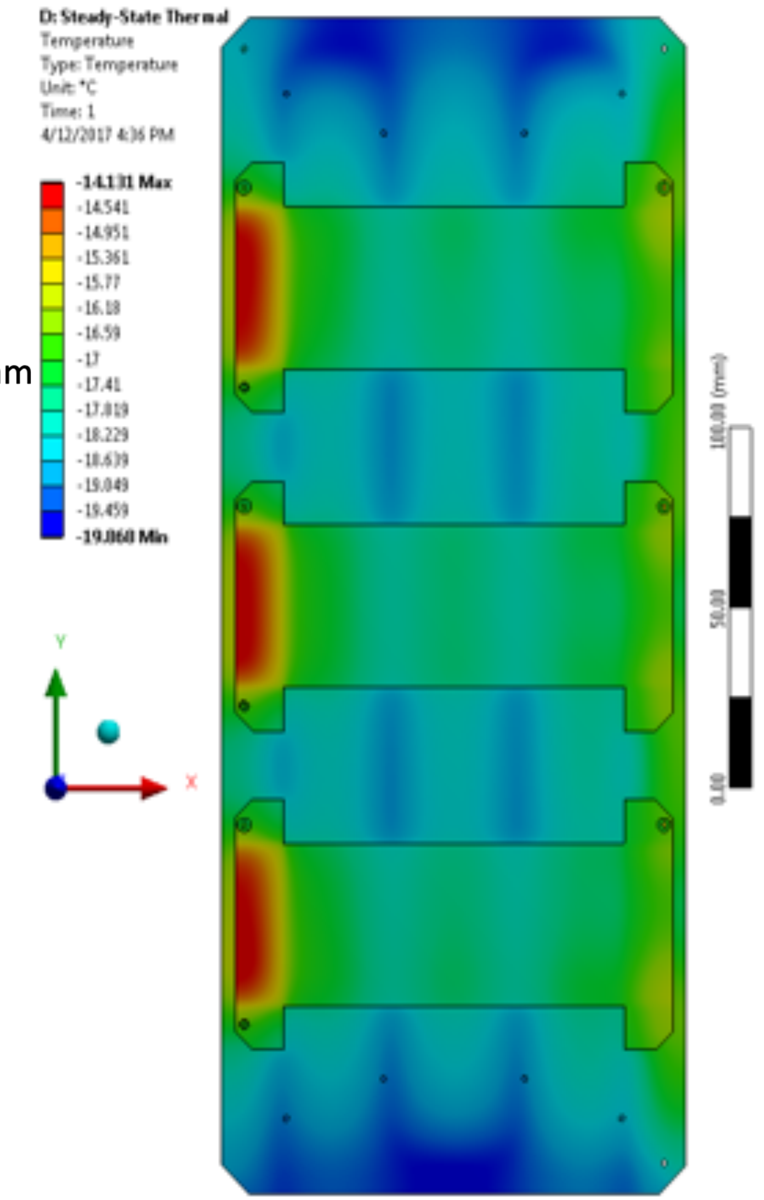


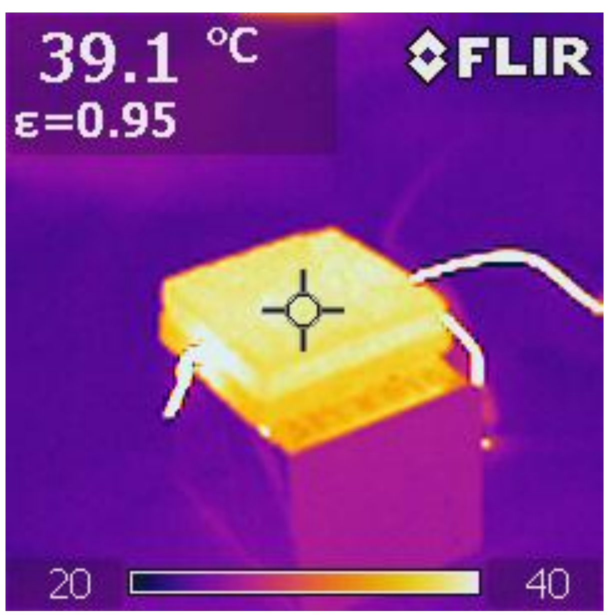
Fermilab plank cooling FEA versus mockups

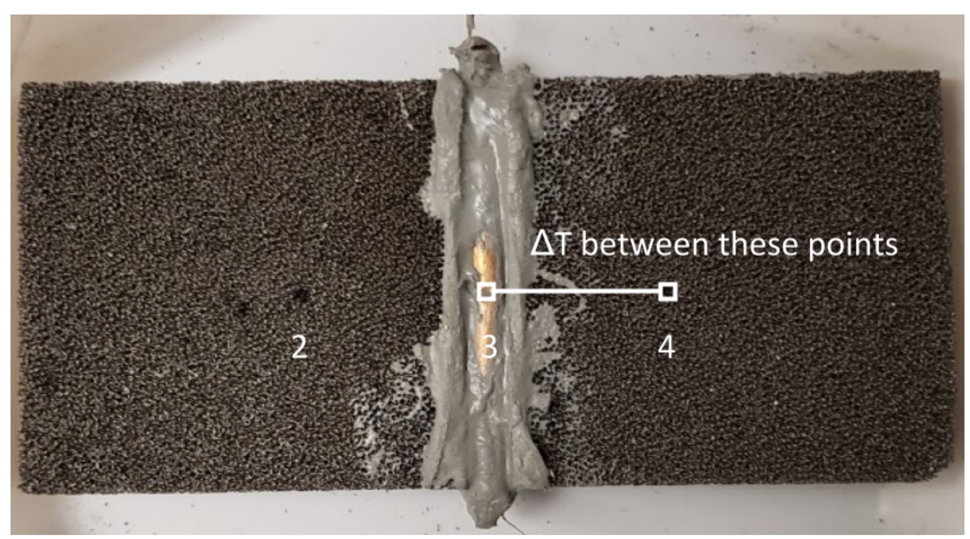
- Heat flow symmetric so study with heater pipe











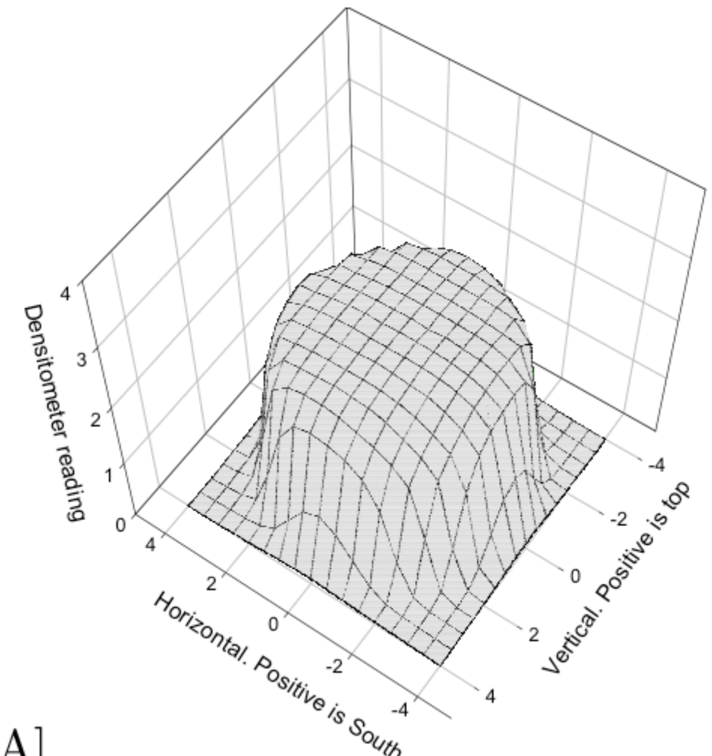
Radiation Damage Testing

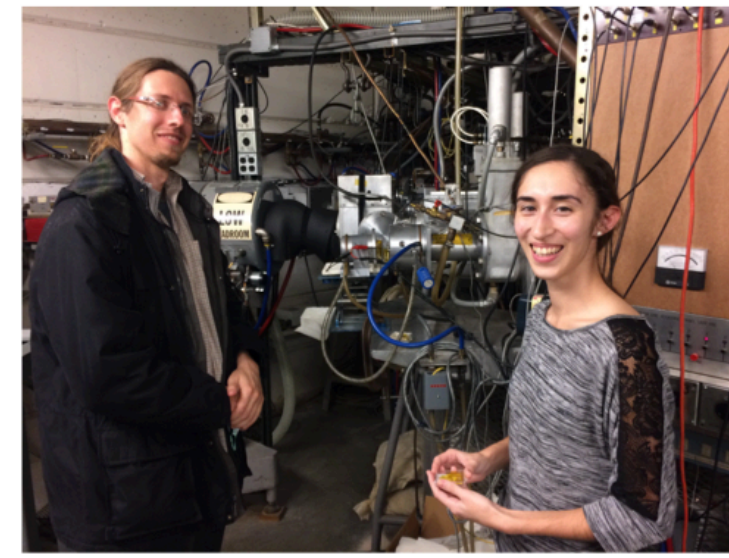
- **Thermal and mechanical tensile testing of epoxy-foam structures before and after neutron radiation**
  - **k: virtually no change (<~ 1%) after 10^{14} n/cm^2 fluence**
  - **Tensile strength after irradiation:**

    sample with 125um epoxy - failed at 600N.

    sample with 200um epoxy - mount to machine failed
- **Further radiation testing is needed to fully validate designs**
  - **neutrons to 10^{15}/cm^2**
  - **protons under study @ UC Davis Crocker Cyclotron**

UC Davis Radiation Facilities: Crocker Cyclotron





Particle	Energy [MeV]	Intensity [μA]
proton	1.25 – 68	15
deuteron	15 – 40	10
alpha	5 – 80	20
helium	6 – 130	1

- Flat profile over 5 cm diameter
- Max Flux ~ 3 x 10^{11} p/cm^2/s

- Very useful for Total Ionization Damage studies.
- Can deliver 100 MRad in < 30 mins

Thermalized neutron beam under development.

Useful for in-situ neutron-induced effects in electronics or sensors

Conclusions

- Along with Higgs discovery and measurements, myriad results and searches from first ~decade of LHC. A rousing success!
- At present, sitting on 150/fb of 13 TeV data to analyze
- HL-LHC is the future, with bold physics program requiring even bolder accelerator and detector advances

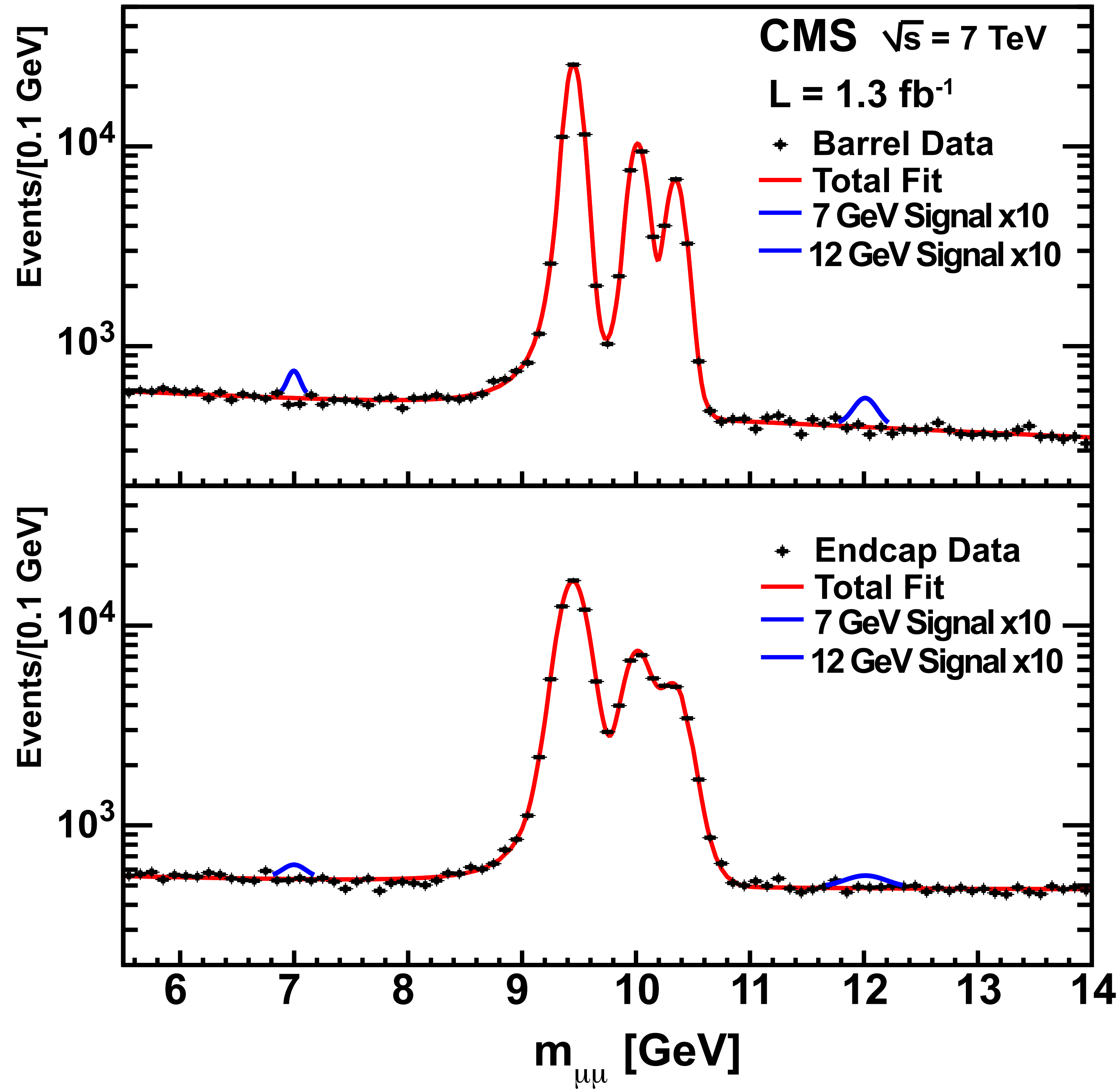
(Some of) team at UC Davis

Backup

Search for light pseudoscalars at 7 TeV

Direct production

- $a \rightarrow \mu\mu$
- Large cross sections and large backgrounds
- Bump hunt in m(μμ) around Upsilon peaks
- Challenge: efficient dimuon triggering and reconstruction at low mass

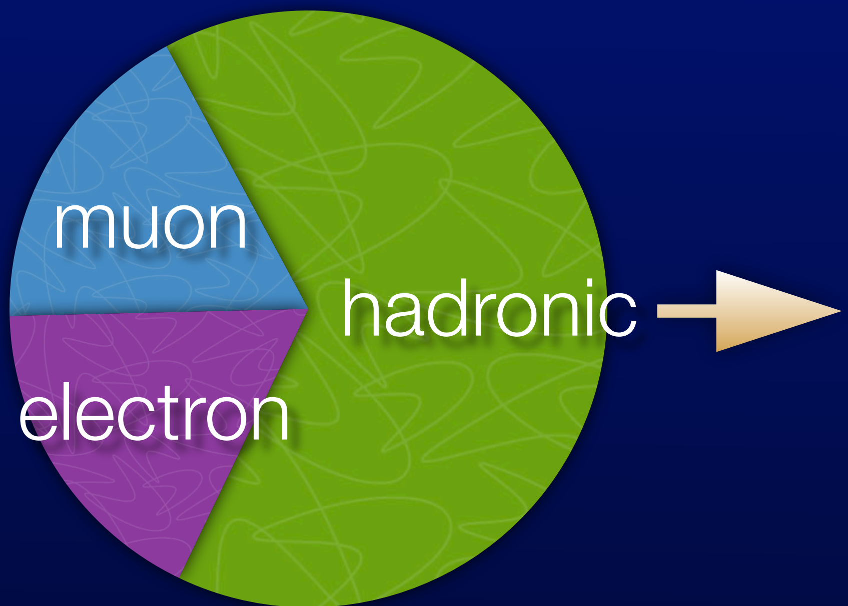


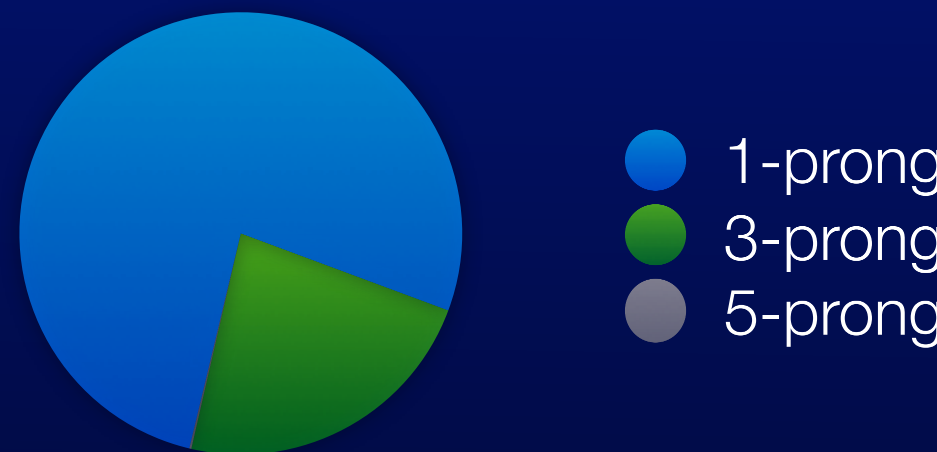
▹ PRL 109, 121801 (2012)

Tau Lepton Decays

$\tau_\tau = 290.6$ fs

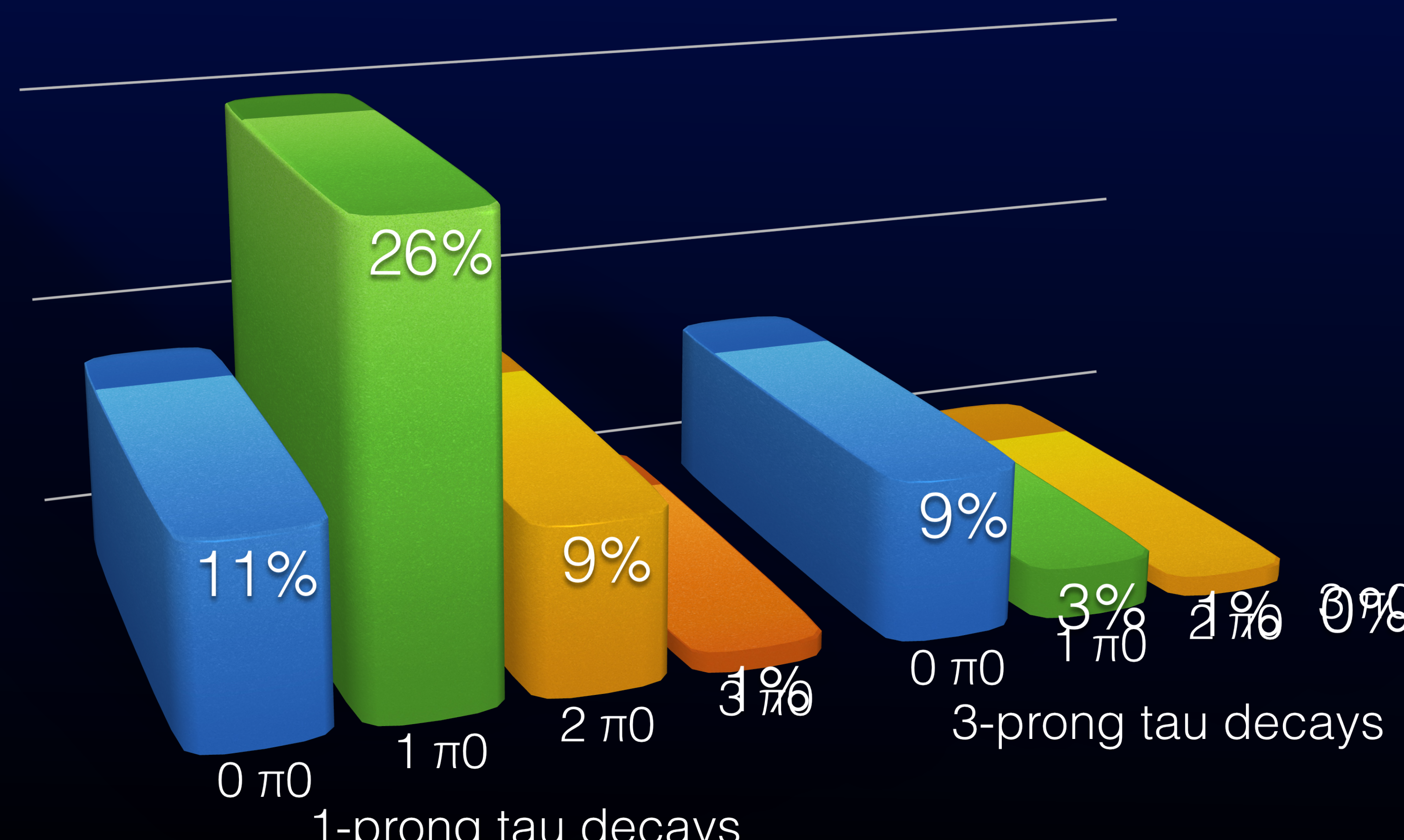
$c\tau_\tau = 87.11$ μm



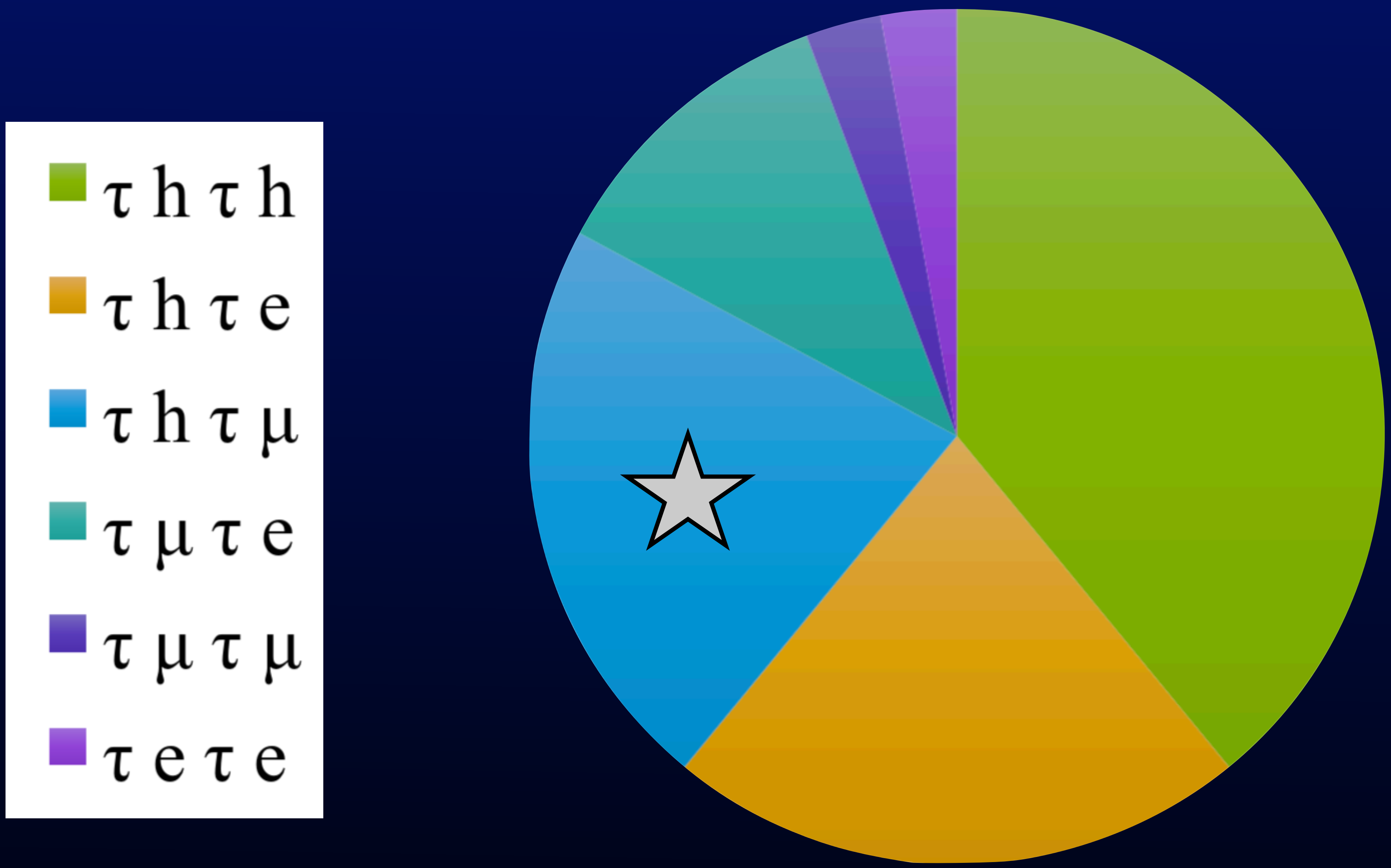


Hadronic

neutral pions:



DiTau Decay Rates



mode	%
$\tau_h\tau_h$	44
$\tau_h\tau_l$	44
$\tau_l\tau_l$	12

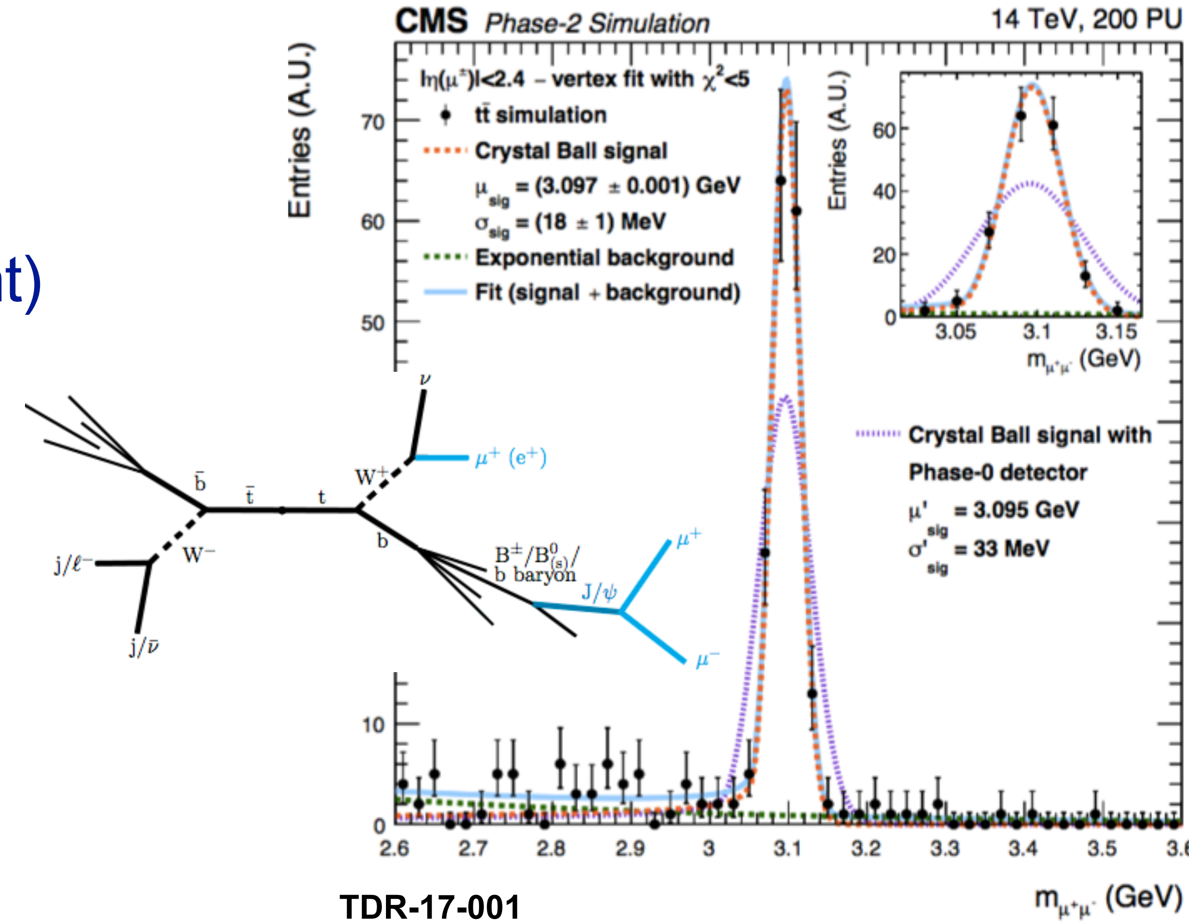
trade-off: BF ↔ efficiency

★ *focus so far*

Ultimate Precision Top Mass

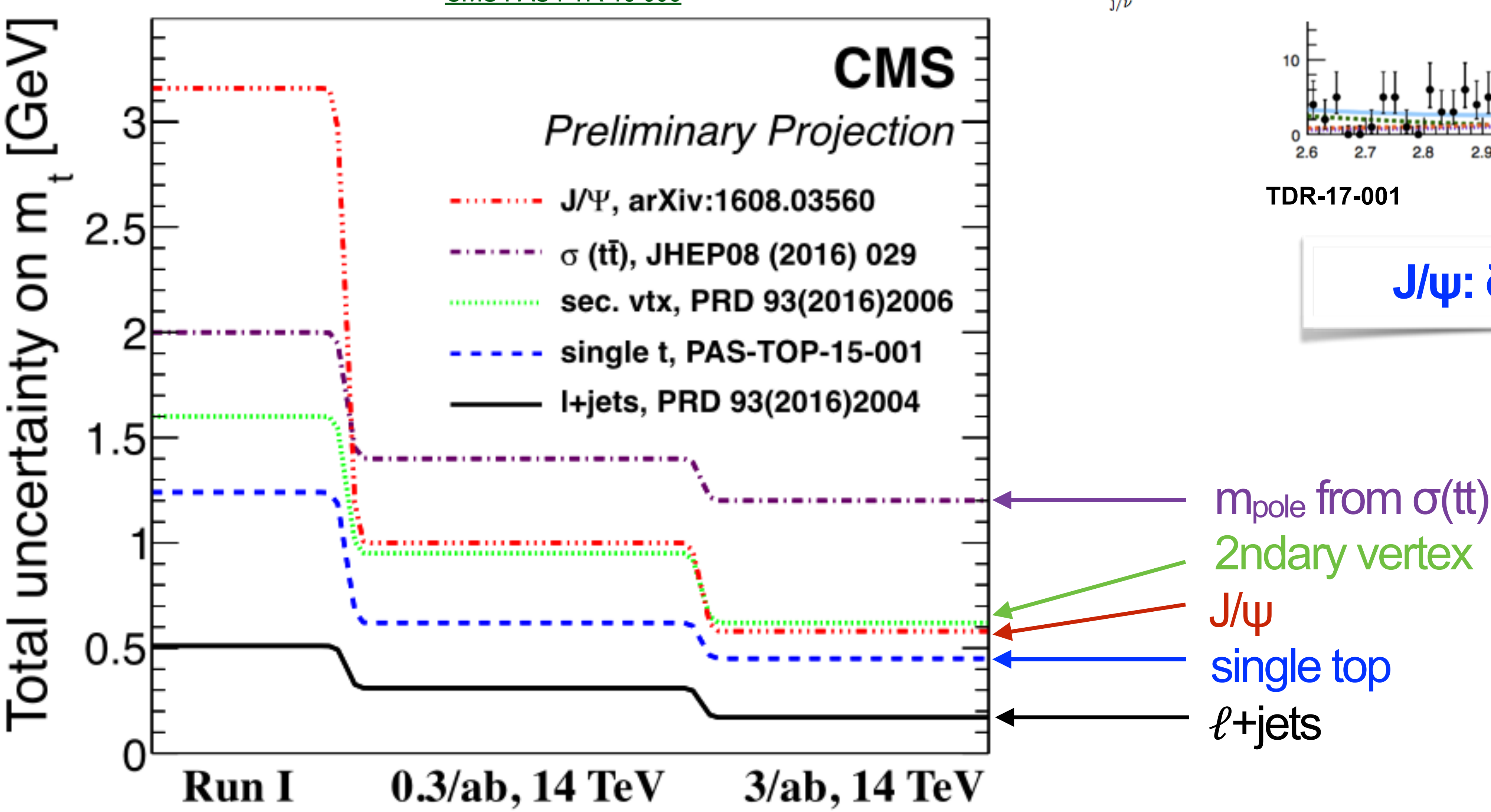
- More statistics → samples and calibration
- Better systematics (both theory and experiment)
- Combination of different methods arXiv:1807.06617

$t \to bW \to J/\psi\, X \ell\nu$



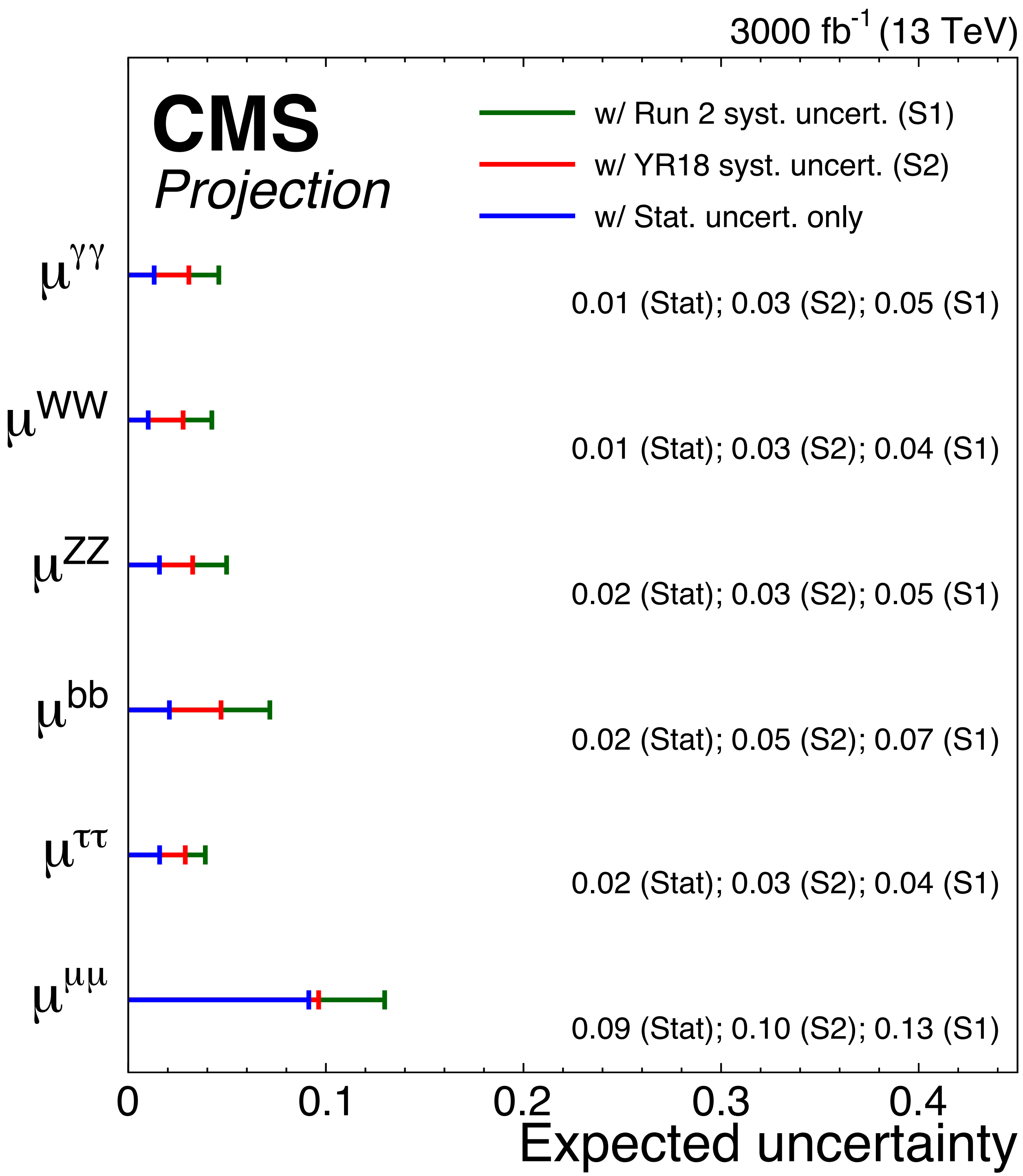
J/ψ: $\delta m_{top} \sim 0.5$ GeV

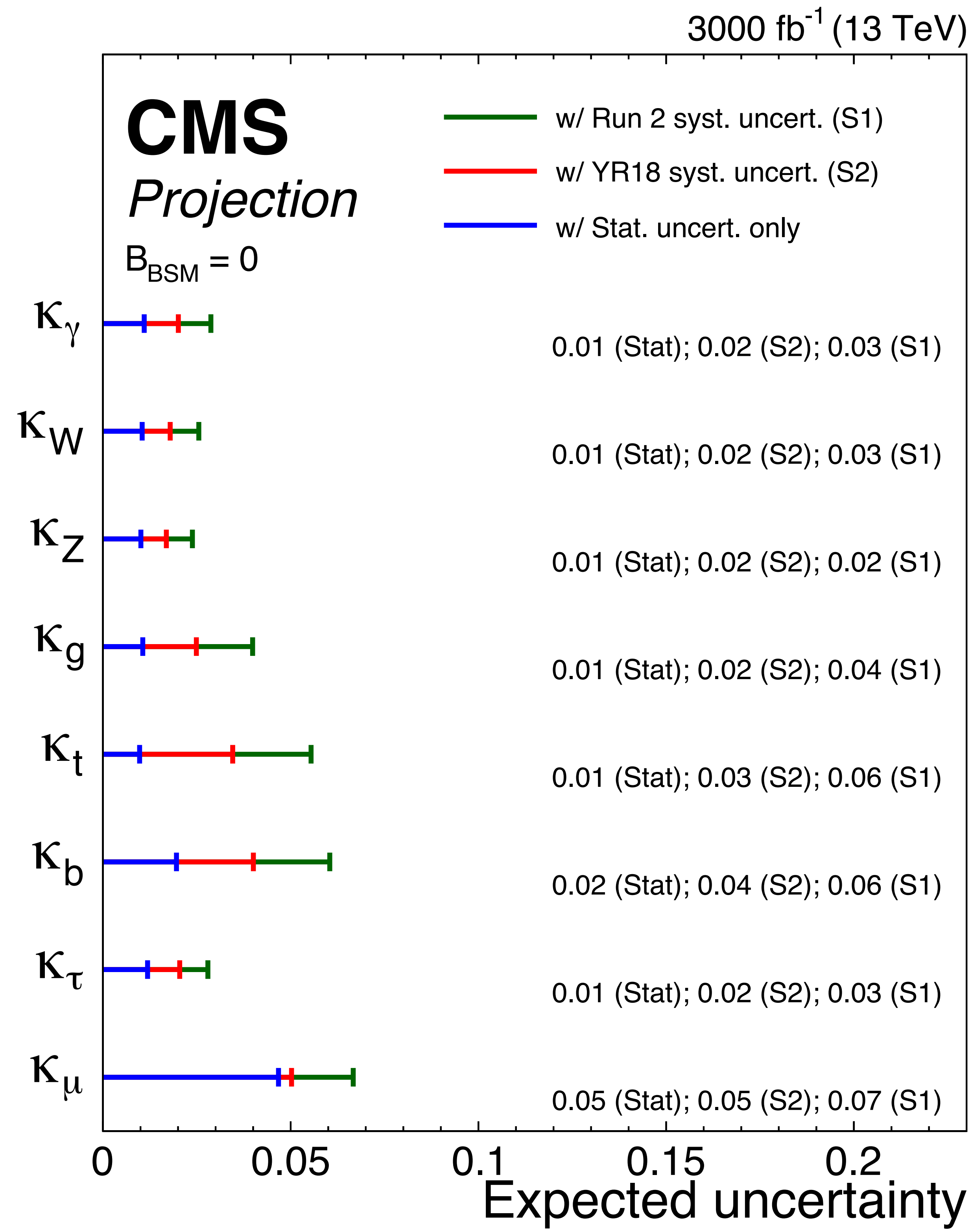
CMS-PAS-FTR-16-006



Higgs Couplings

CMS FTR-18-011





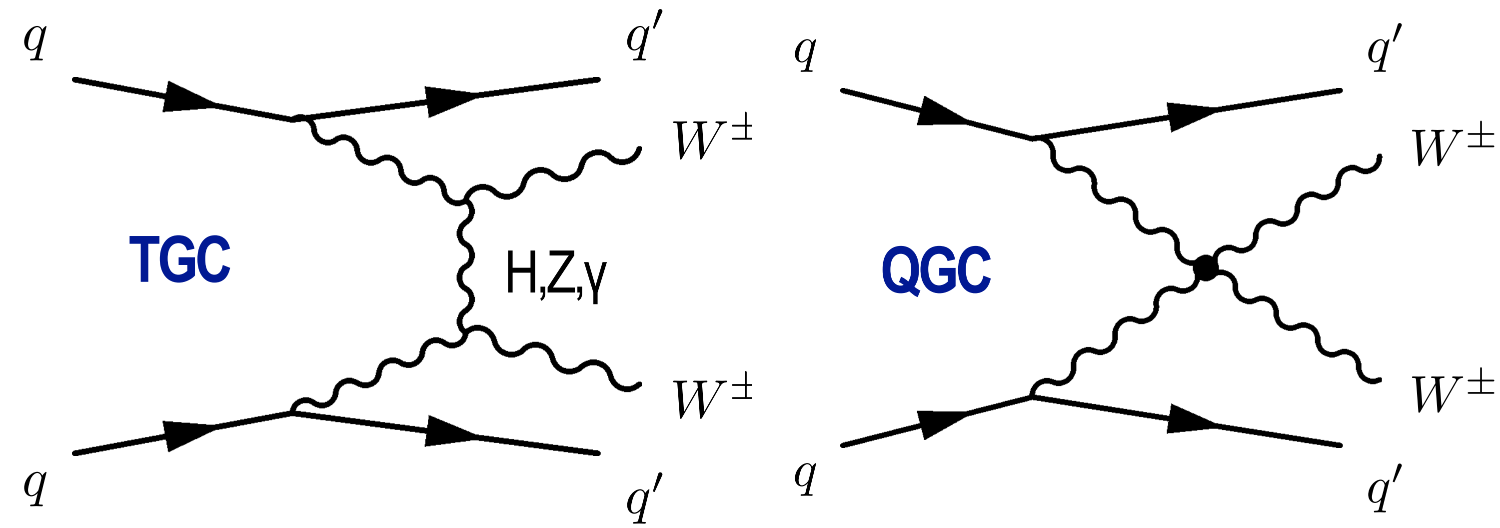
Combination of ATLAS and CMS underway

κ: 2-4%, κ_μ ~5%

Vector Boson Scattering

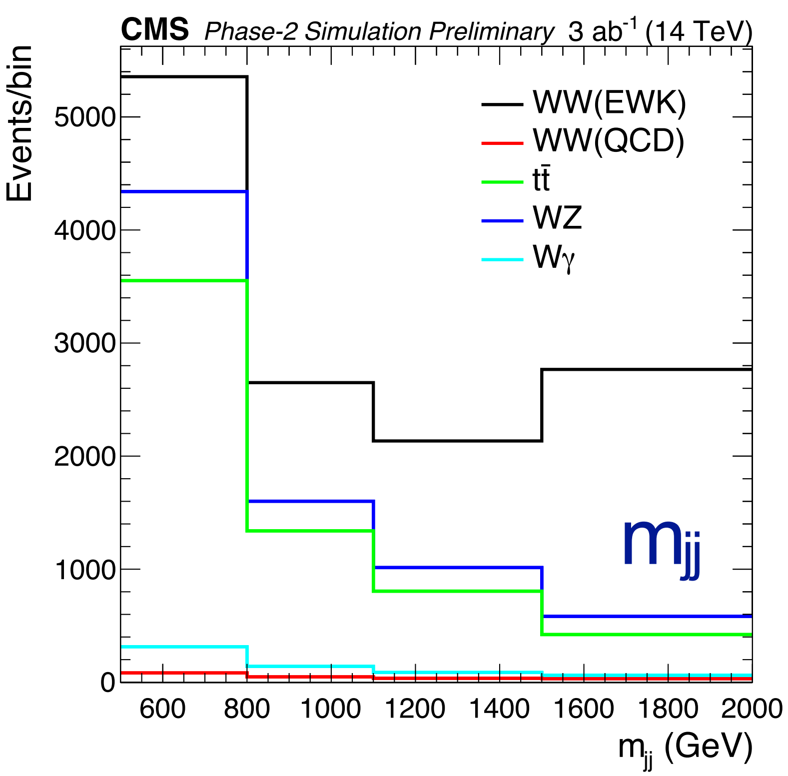
- Triple and quartic gauge couplings
- Electroweak WW and WZ scattering observed in Run-2

ATLAS-CONF-2018-033 arXiv:1709.05822



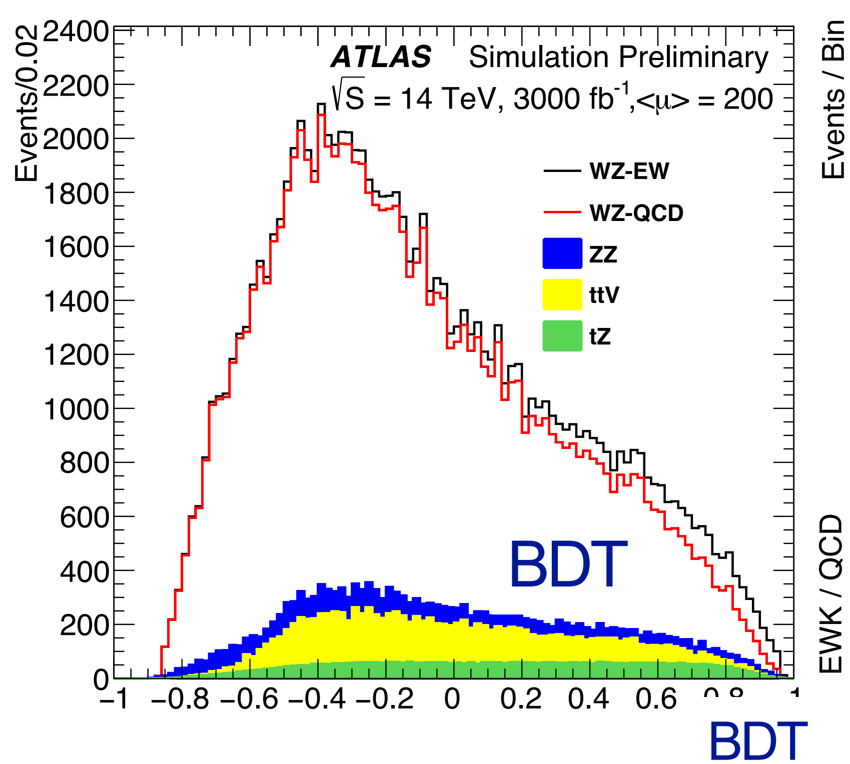
- WW, WZ, ZZ studied for YR2018

WW CMS-FTR-18-005



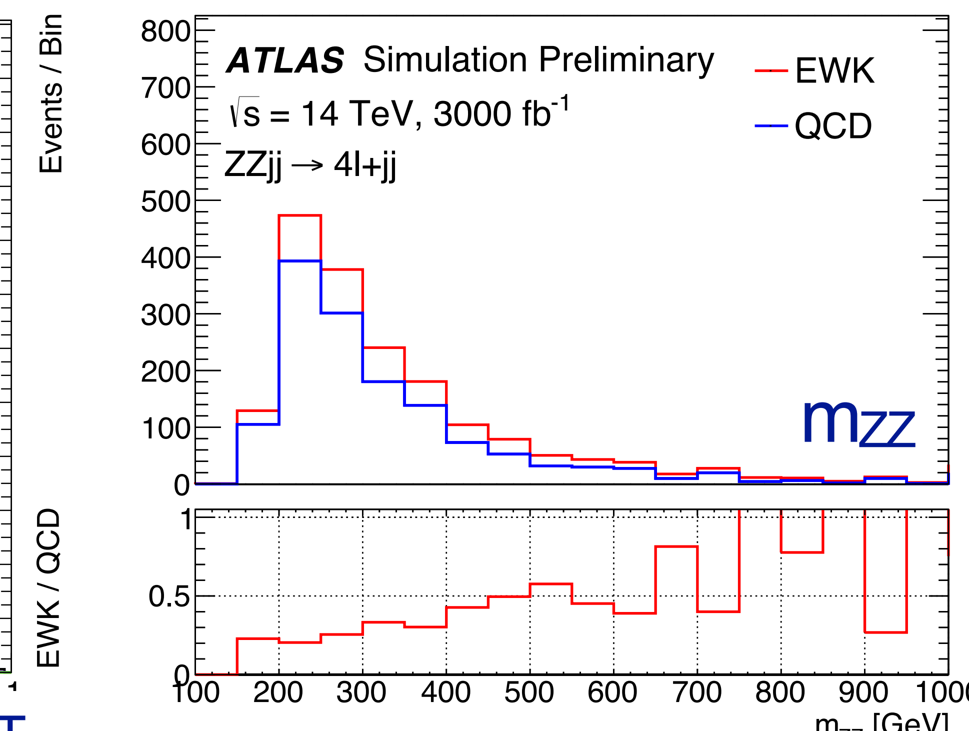
δσ ~ 3% and < 10% in Run 3

WZ ATL-PHYS-PUB-2018-023



δσ 5 - 10%

ZZ ATL-PHYS-PUB-2018-029

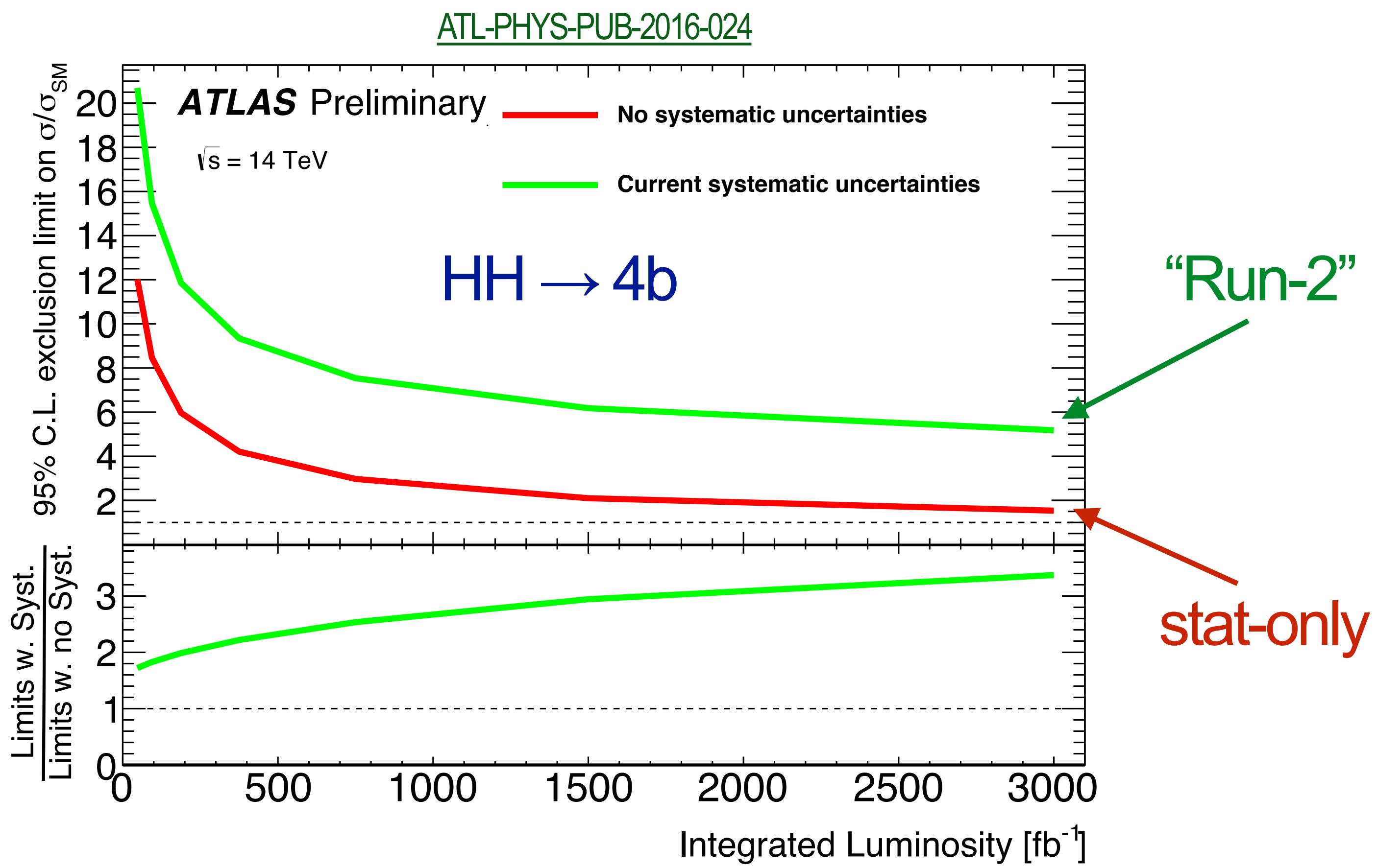


δσ ~10%

HL-LHC Projected Uncertainties

- Effort to make realistic projections,
  → assumptions affect conclusions

- Systematic uncertainties
  will be limiting factor
  for more and more measurements



- ATLAS and CMS common approach
  - Statistical uncertainties scale as 1/√L
  - Theory: assume reduction by factor 2
  - Experimental systematics scale as 1/√L → until "floor"

  - "Floor" values for all physics objects estimated and agreed
  - Keeping "Run-2" and "stat-only" for comparison

Expect to exceed expectations

BSM Searches in the Higgs Sector

- CP even established, but CP odd admixt not excluded
  - HVV in production and decay

CP odd

$$A(\mathrm{HVV}) \sim \left[\boxed{a_1^{\mathrm{VV}}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_1+q_2)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

SM

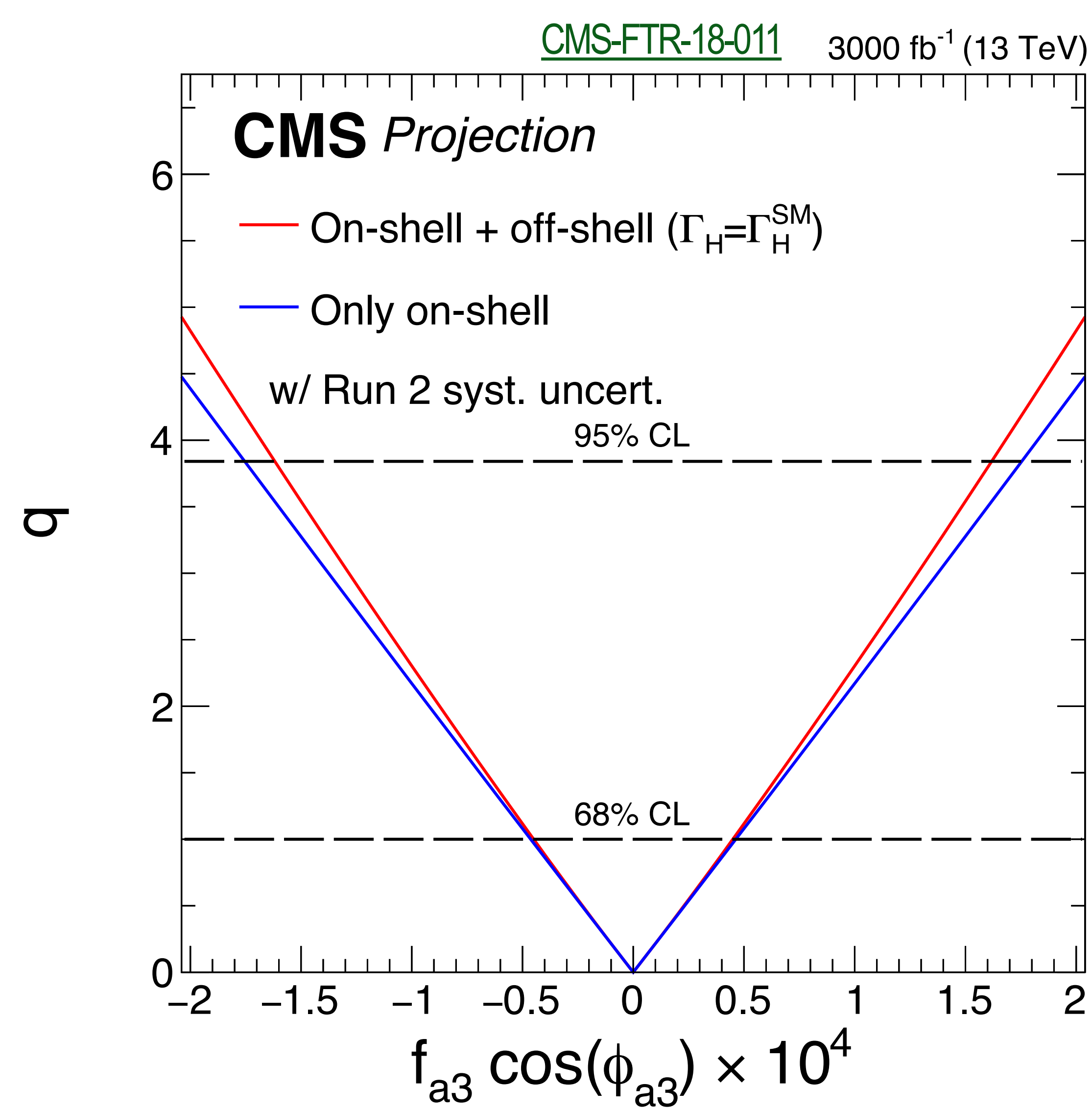
$$f_{ai} = |a_i|^2 \sigma_i \Big/ \sum |a_j|^2 \sigma_j \qquad \phi_{ai} = \arg\left(a_i / a_1\right)$$

  - Hff in decay:
    - require fermion with observable polarisation: $H \to \tau\tau$
    - No projections available yet

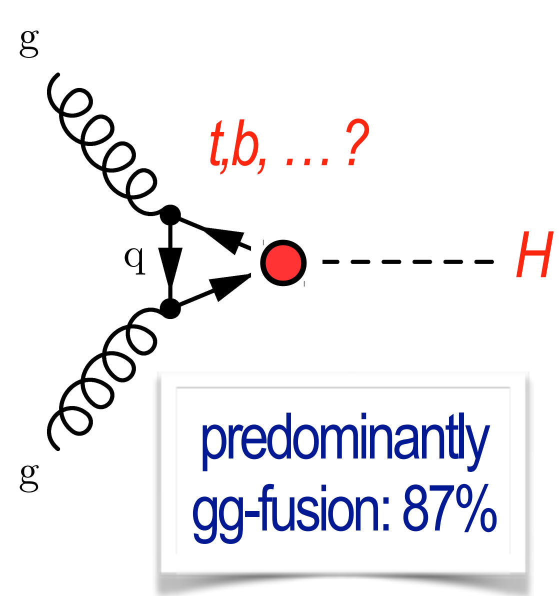
- Invisible Higgs decays: CMS-FTR-18-016
  unseen SM (e.g. neutrino) or BSM (e.g. DM)
  B_{inv} < 4% (20%) HL-LHC (Run2) @95 CL

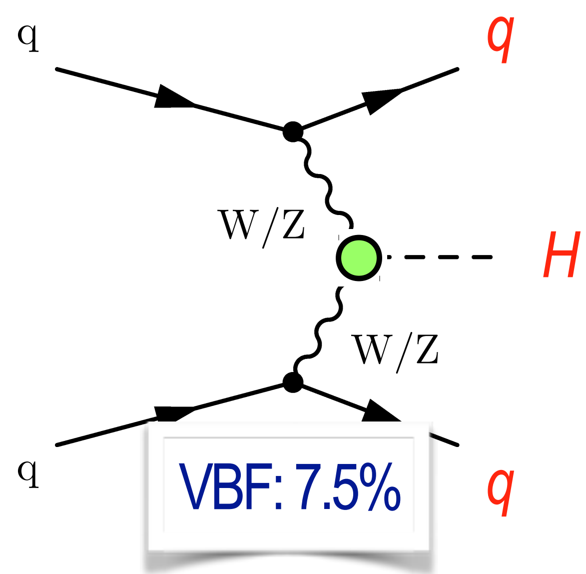
- Exotic decays: CMS-FTR-18-011
  H→BSM or forbidden SM decays (for $\kappa_V \leq 1$)
  B_{BSM} < 6% (34%) HL-LHC (Run2) @95 CL

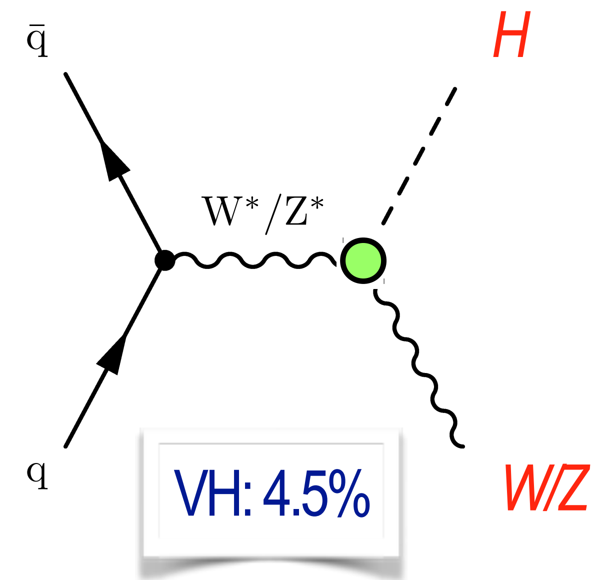
- Rare SM decays: e.g. H→J/psi γ ATL-PHYS-PUB-2015-043
  B(H→J/\psiγ) < 44 x 10^{-6} @ 95 CL (20 x SM)

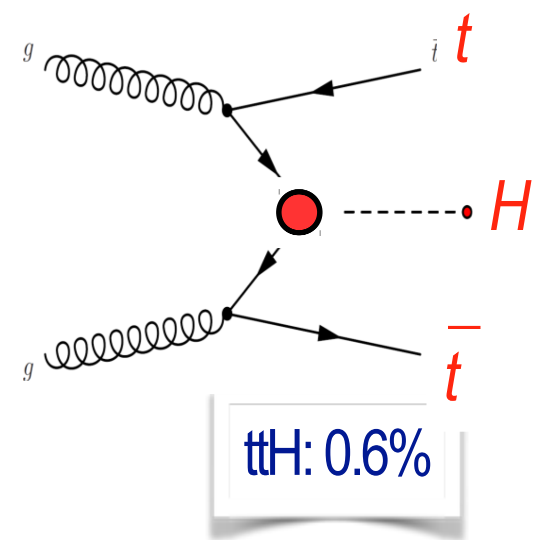


Higgs Production and Decay



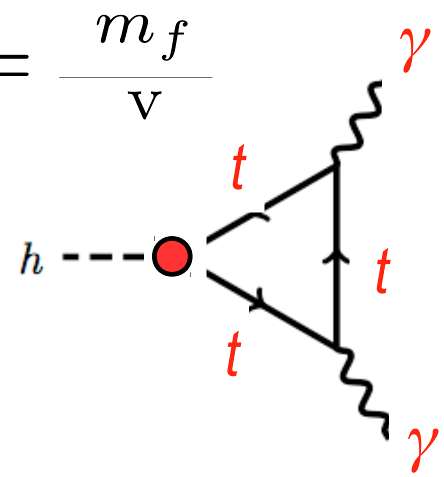


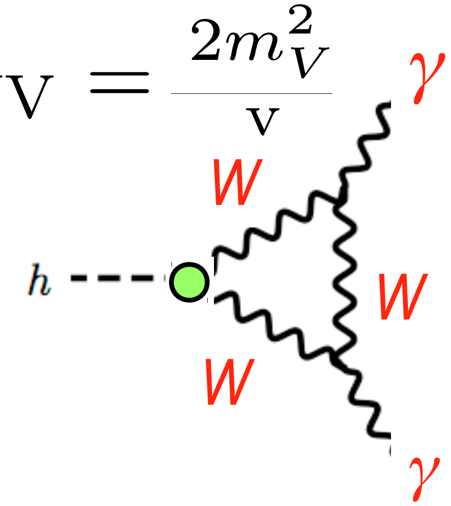




- "κ-model": Fit of scale-factors κ to the data assuming SM processes

$$\kappa_{\mathrm{Hff}} = \frac{m_f}{\mathrm{v}} \qquad \kappa_{\mathrm{HVV}} = \frac{2m_V^2}{\mathrm{v}}$$



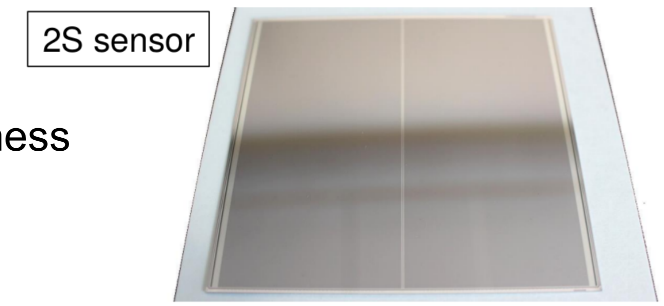


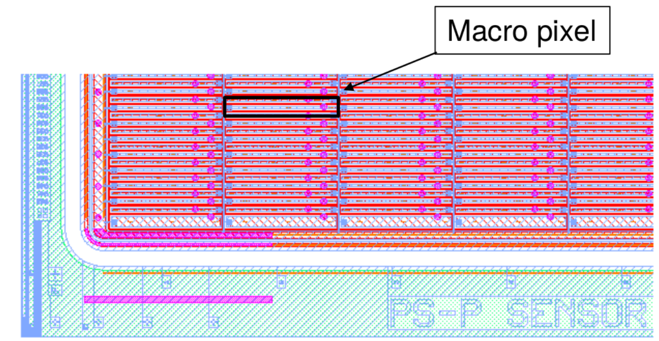
Silicon Sensors for the Outer Tracker

Surviving in > 10^{15} n_{eq} cm^{-2}

Sensor baseline design

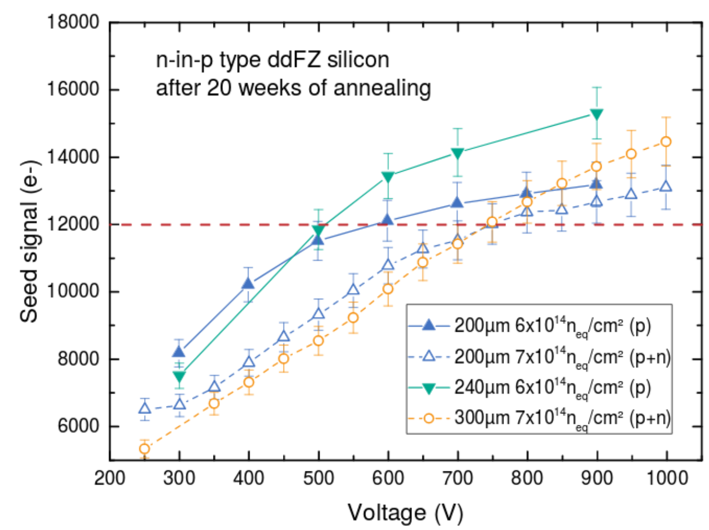
- n-in-p planar sensors, with 200 – 240µm active thickness
- HV stable up to 800V
- 3 sensor variants (15 in the current tracker!):
  - 2S: 10 x 10 cm^2, 2032 strips, AC read-out by **CBC** → σ ~ 1000 e^-
  - PS-s: 5 x 10 cm^2, 1920 strips, AC read-out by **SSA** → σ ~ 700 e^-
  - PS-p: 5 x 10 cm^2, 30208 macro pixels, DC read-out by **MPA** → σ ~ 175 e^-

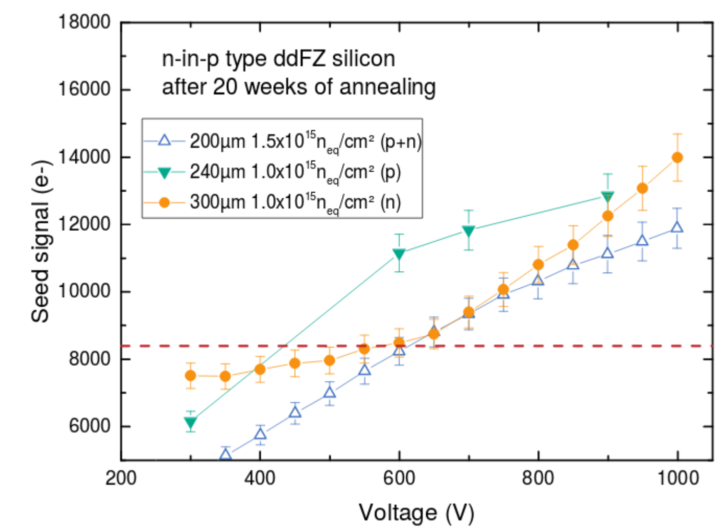




Sensor performance studies

- Leakage currents
- Charge collection efficiencies





→ Final decision on material and isolation technique forthcoming!

FZ or ddFZ

p-stop or p-spray

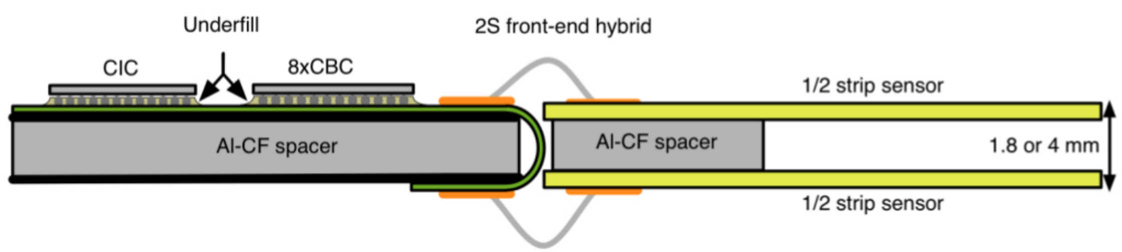
OT Electronics

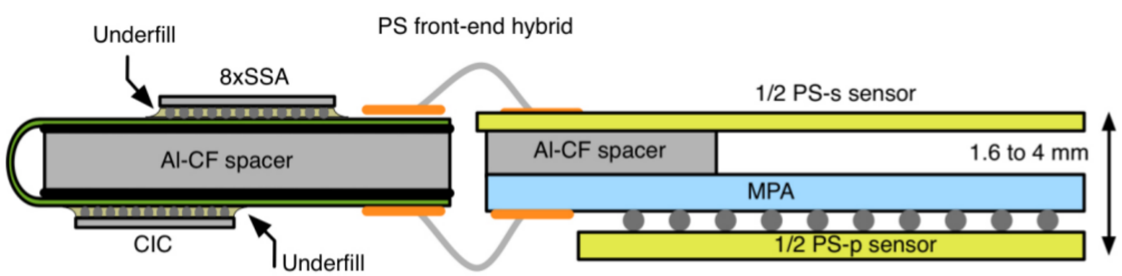
Aggregating and transferring signals

Read-out ASICs

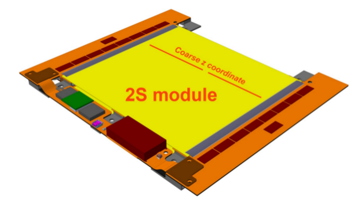
- 2S module: **CBC,** PS module: **SSA** and **MPA**

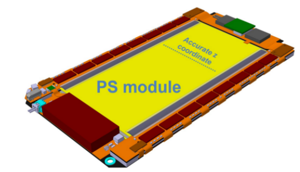
Connection to both sensors via flex hybrid





→ **Ongoing R&D: chip prototyping, firmware development**





2S Module Front-End

16x CMS Binary Chip (**CBC**)
Read-out of both strip sensors
Stub data creation
Inter-chip communication

PS Module Front-End

16x Short Strip ASIC (**SSA**)
Strip read-out
1x Macro Pixel ASIC (**MPA**)
Pixel R/O, stub logic

L1 and channel data

HV, I2C, clock

2x Common Concentrator IC

Buffers, aggregates, and sparsifies each chip's data

HV, I2C, clock

Data

Service Hybrid

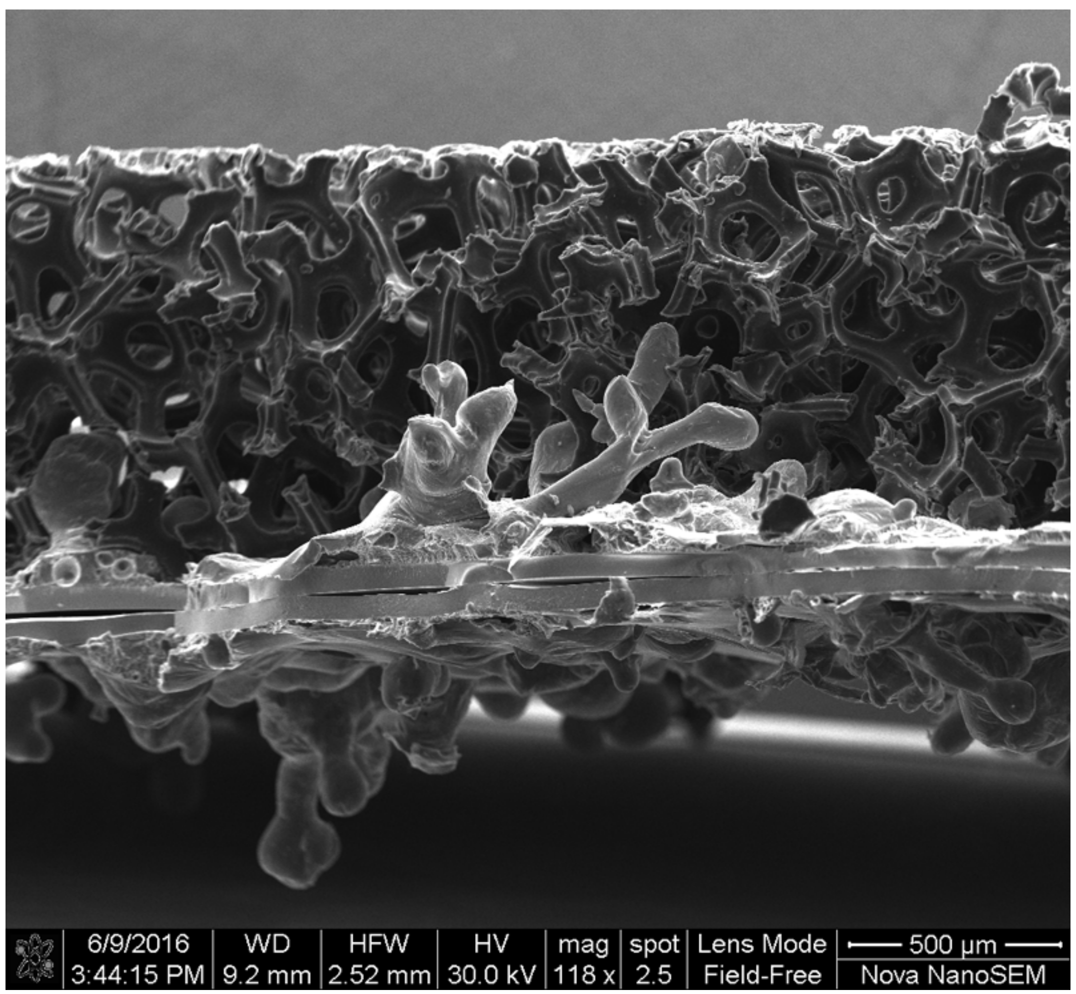
DC-DC converter
HV connectors
LpGBT distributes clock & trigger, I^2C master
Optical output by **VTRx+**

to BE

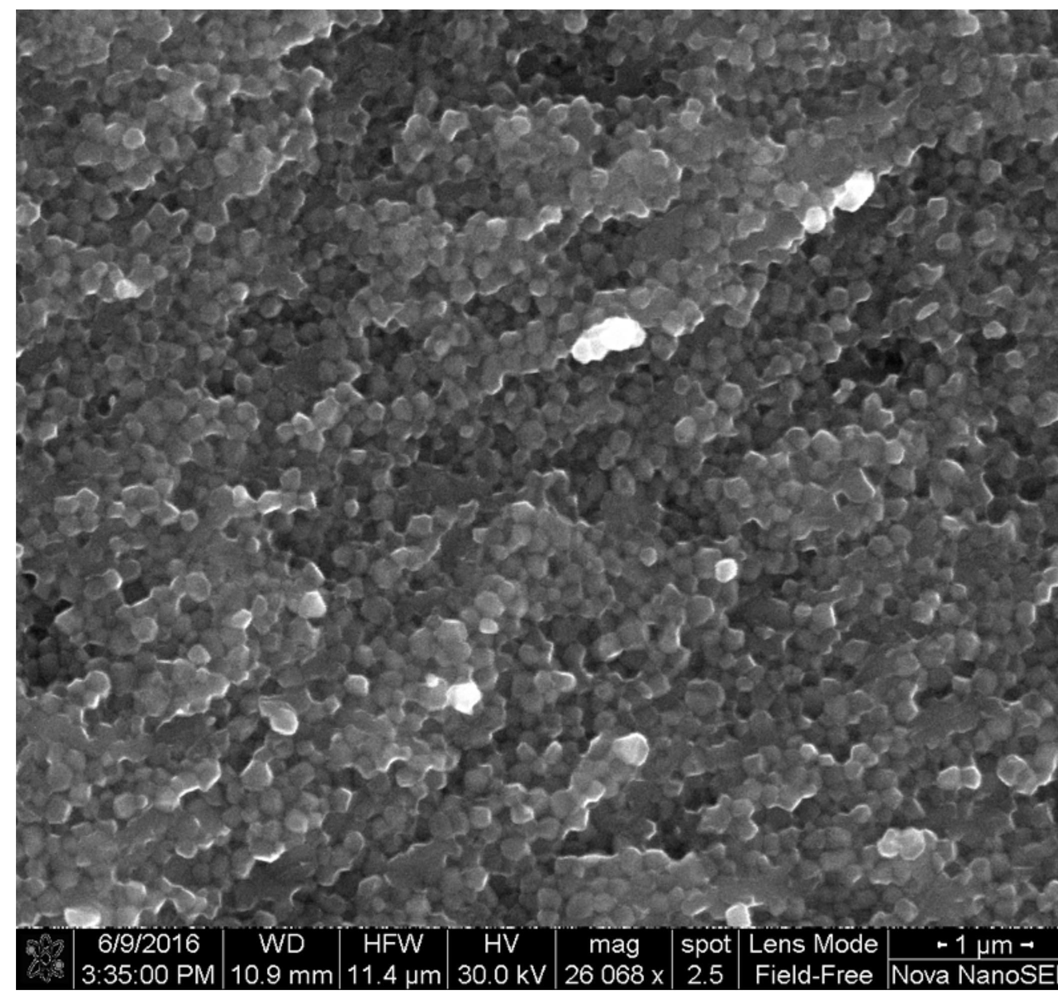
RBF

- **"Reactive Bonding Film for Bonding Carbon Foam Through Metal Extrusion"**

  JINST 12 T03005 (2017), http://arxiv.org/abs/1606.07677, [physics.ins-det], 2016.

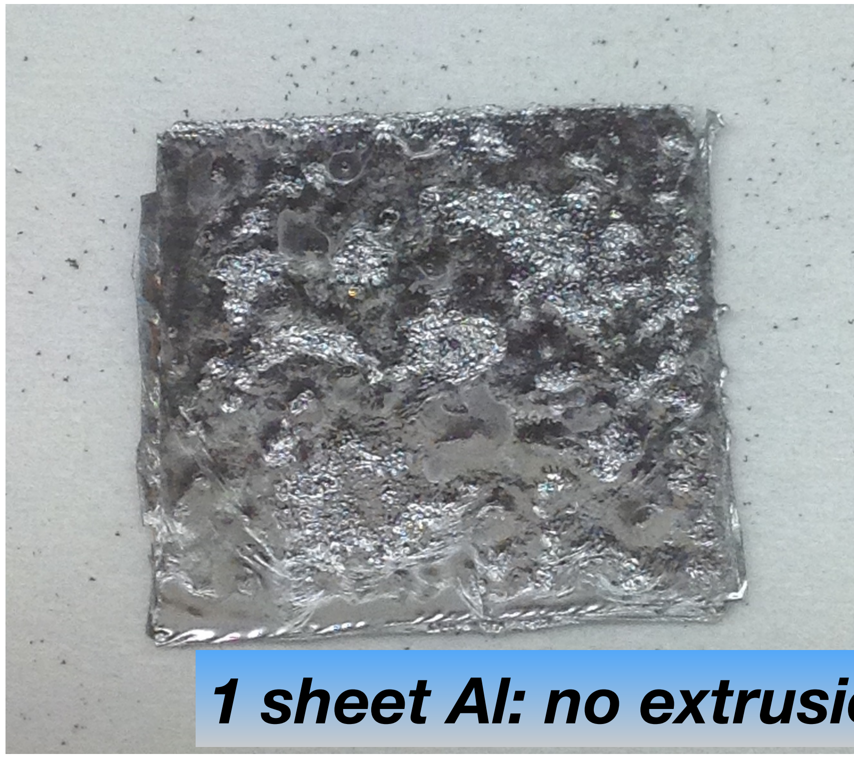


Lock-and-key structures from successful bonding

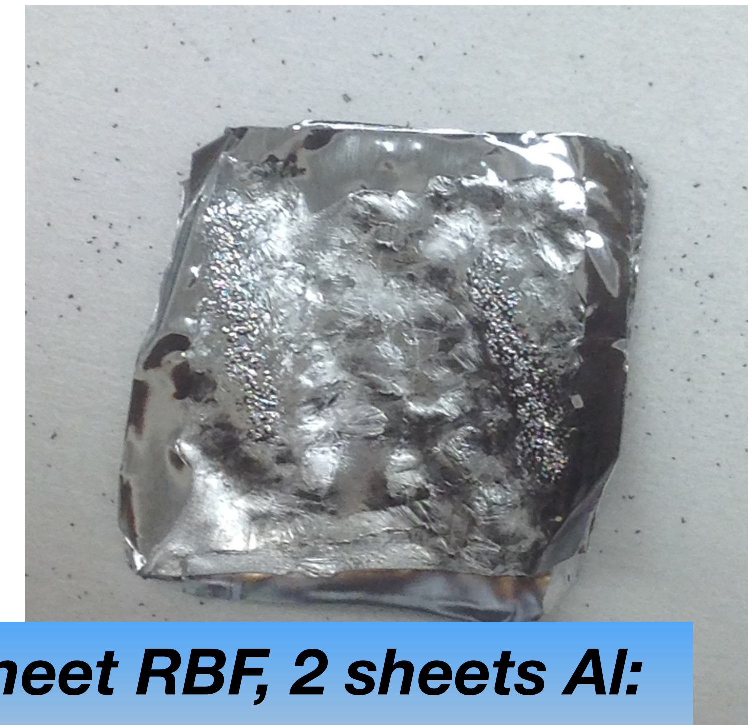


Nickel-Aluminide Fused ceramic

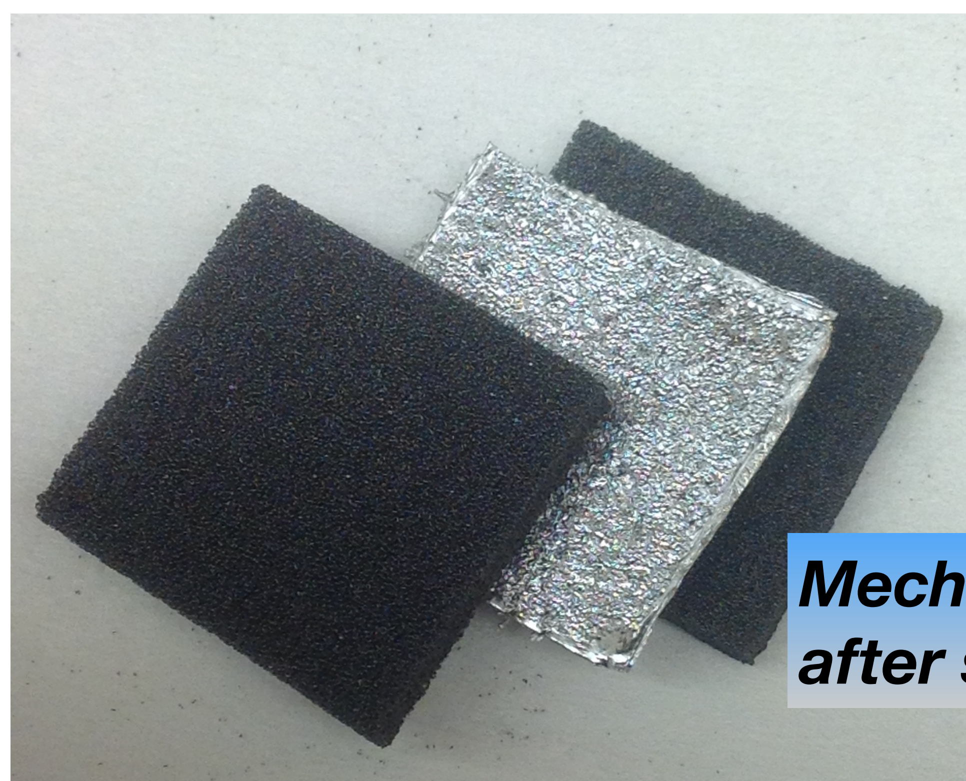
RBF Results



1 sheet Al: no extrusions

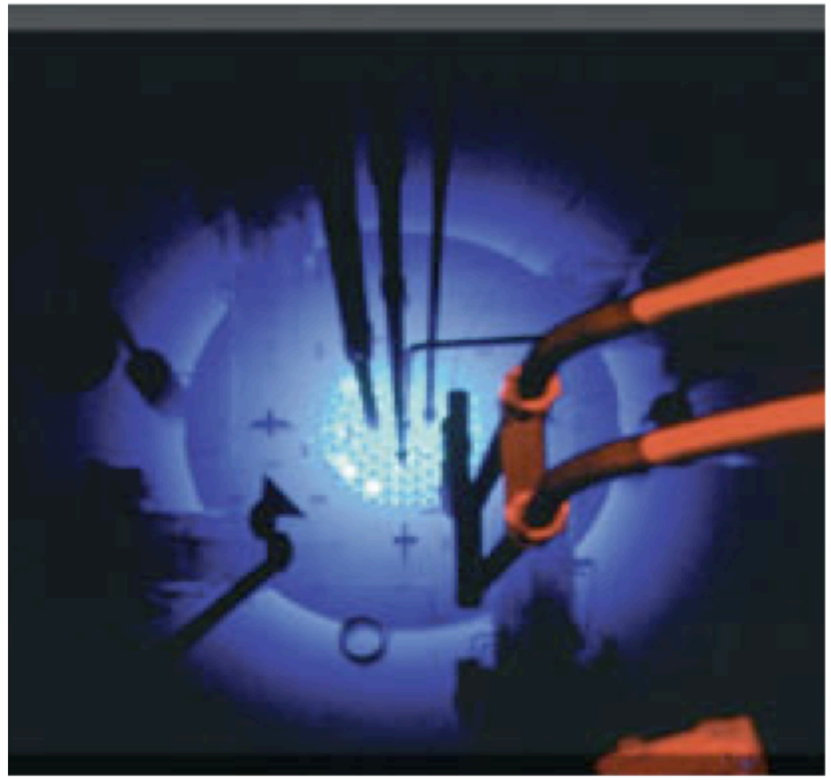


1 sheet RBF, 2 sheets Al: incomplete melting



Mechanically-separated sample after successful bonding

UC Davis Radiation Facilities: McClellan Reactor



TRIGA Mark II Reactor:
2 MW max, 1.5 MW typ, ~1000 MW per 20 ms pulsed

Reactor managed by UC Davis. Easy access for experimenters

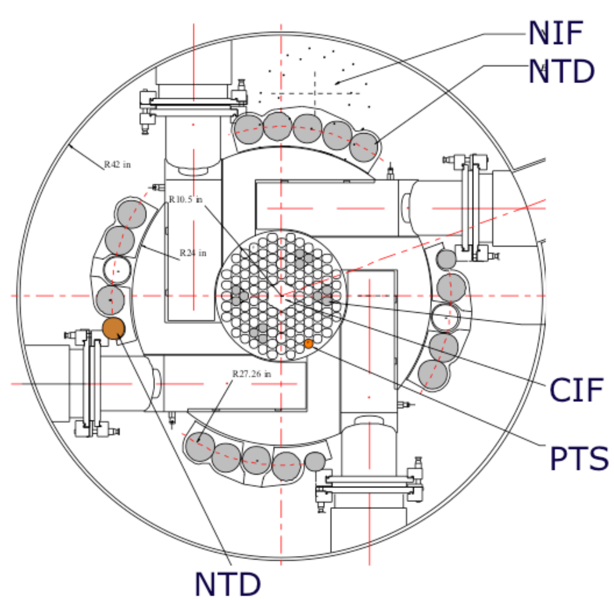
Various exposure locations

Heavy Water shield possible for thermalization

UCDAVIS

MNRC McCLELLAN NUCLEAR RESEARCH CENTER

Irradiation Facilities



	Φ_{th} (n/cm²s)	Φ_{fast} (n/cm²s)
CIF	1.0×10^{13}	5.2×10^{12}
PTS	5.2×10^{12}	5.2×10^{12}
NTD	3.1×10^{11}	1.2×10^{10}
NIF	1.5×10^{8}	1.5×10^{10}

CMS Detector

Not that big...