

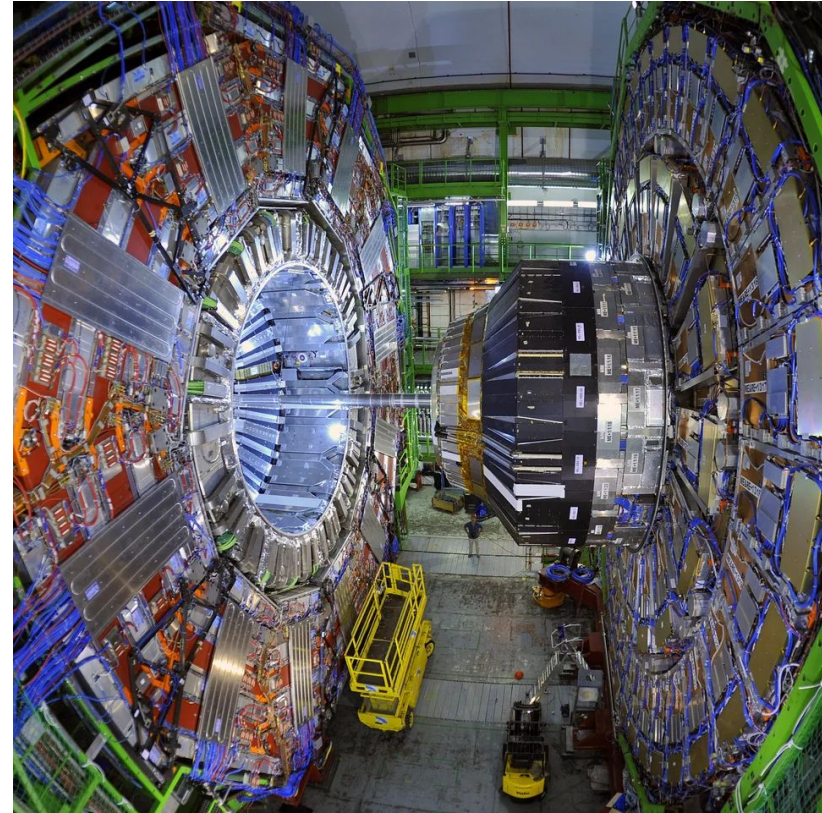
Any other higgses we should know about?

Marc Antoine Osherson



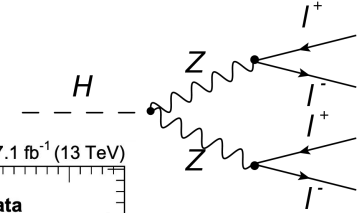
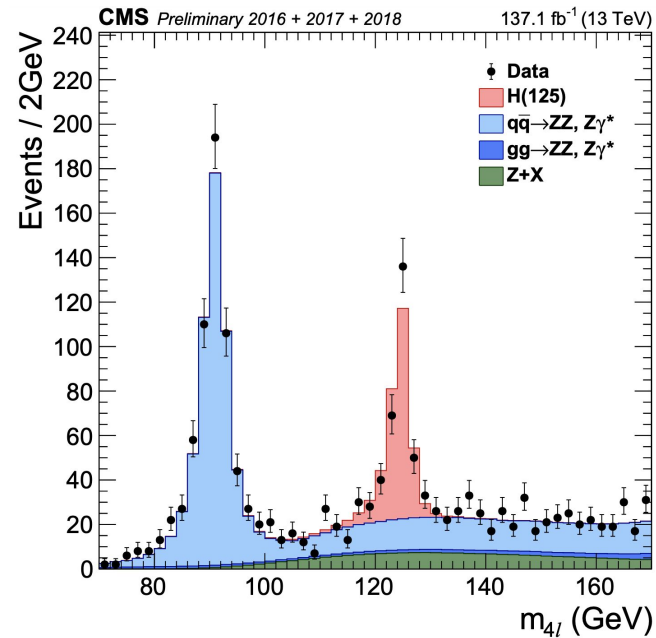
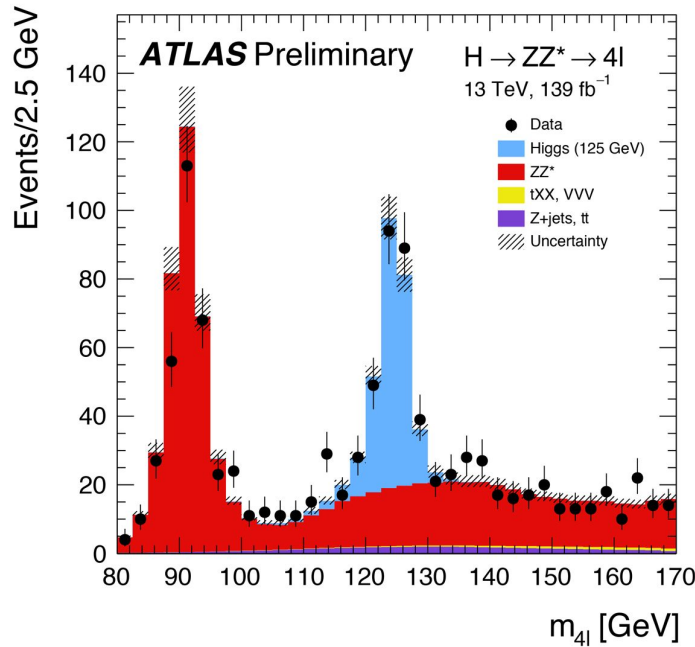


- Today I'll talk about:
 - Why an extended higgs sector
 - Experimental signature at the LHC:
 $X \rightarrow aa \rightarrow (bb)(bb)$
 - First results in this final state
 - The future of the LHC
 - CMS outer tracker upgrade
 - Results on proto-type modules
- This work is based on two public results about to be submitted by the CMS collaboration ([analysis to PLB](#), [detector work to JINST](#))



One Higgs Boson

- Coming up on the 10th anniversary of the discovery of “a particle consistent with the Higgs boson”!
- Significance well past 5σ !

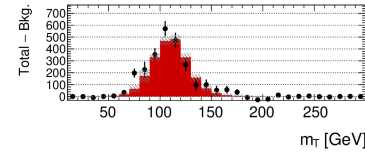
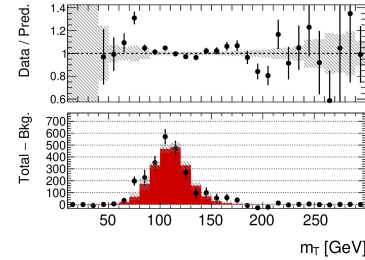
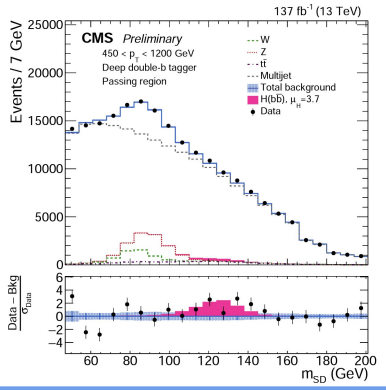
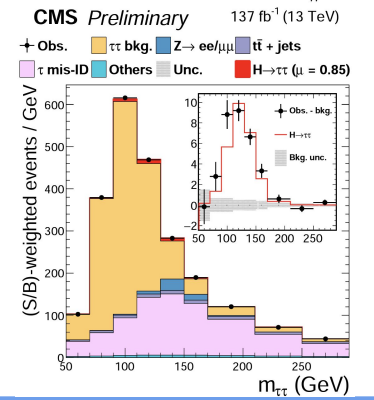
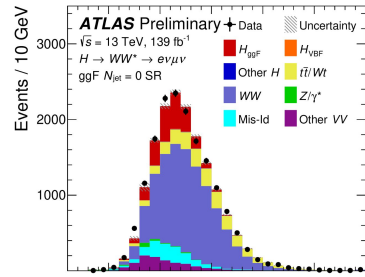
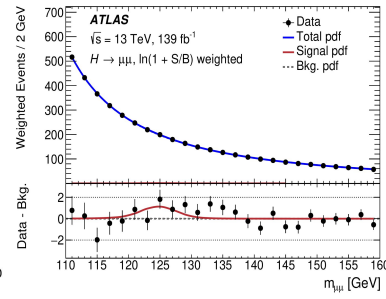
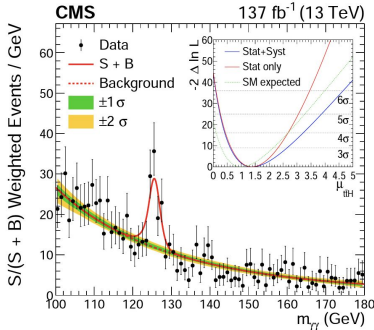




One Higgs Boson



- In the intervening years, successful measurements of more decay and production channels make it hard to doubt this is “the” Higgs boson:

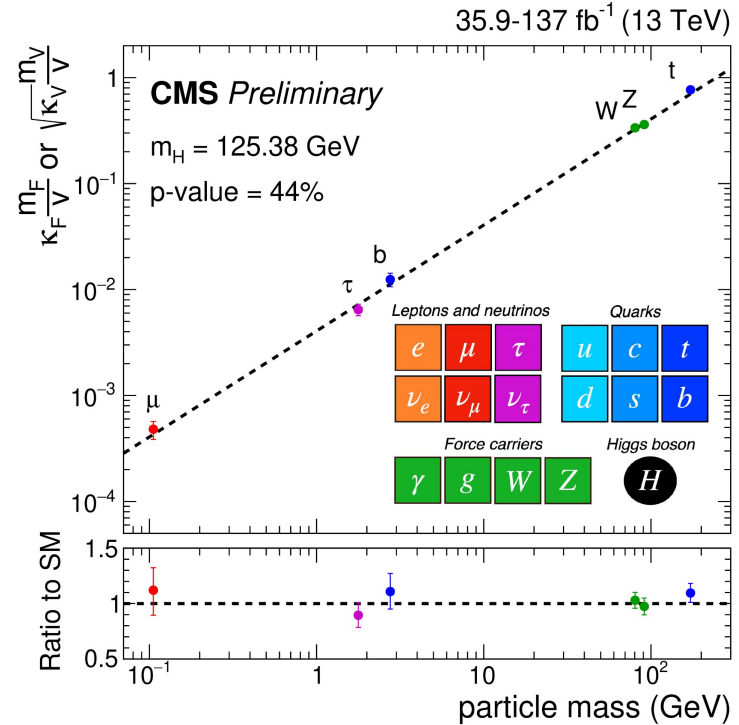
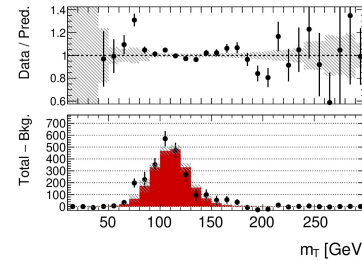
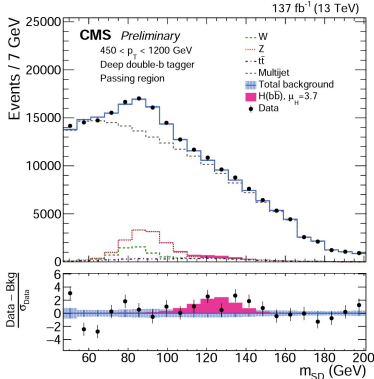
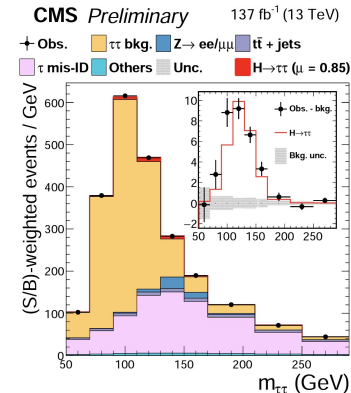
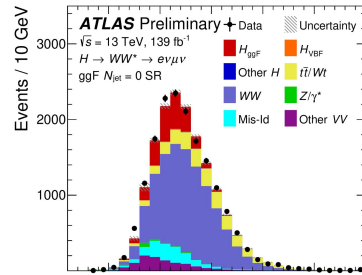
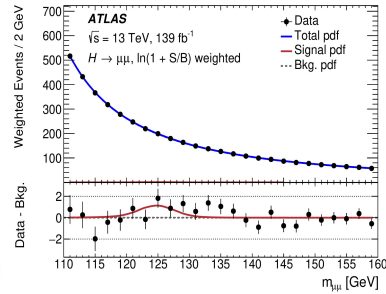
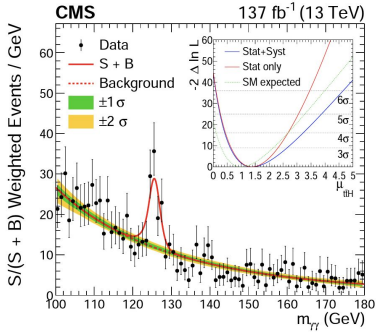




One Higgs Boson

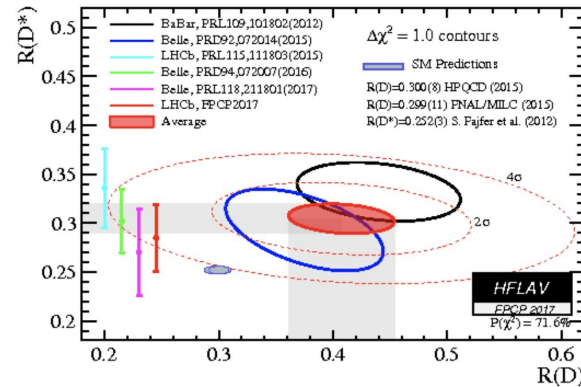
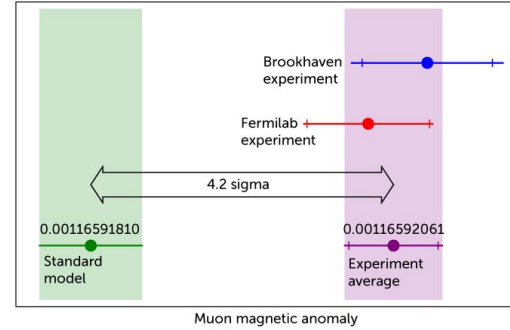
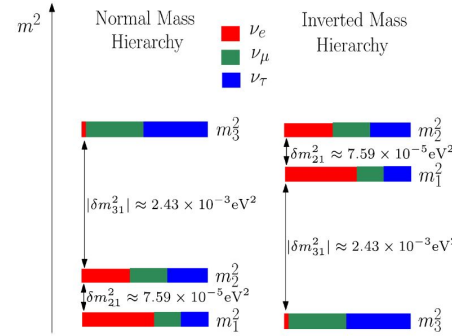


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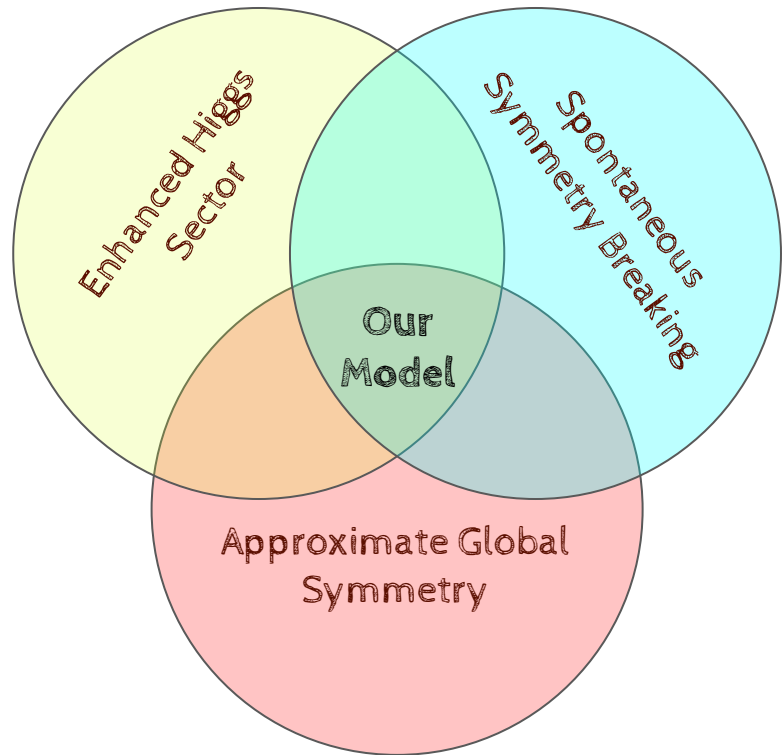
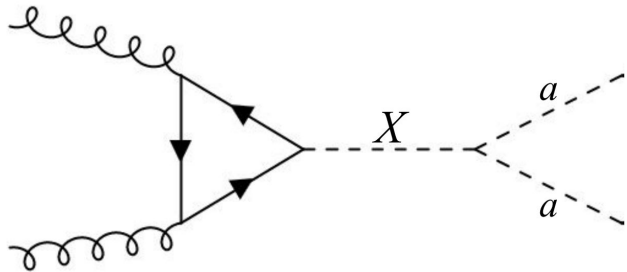


- Standard Model clearly not sufficient to fully describe our world.
- A non-inclusive list of concerns:
 - Dark matter
 - Neutrino mass
 - Matter-Antimatter asymmetry
 - Reactor antineutrino anomaly
 - μ magnetic moment anomaly
 - Flavor anomalies
 - Gravity

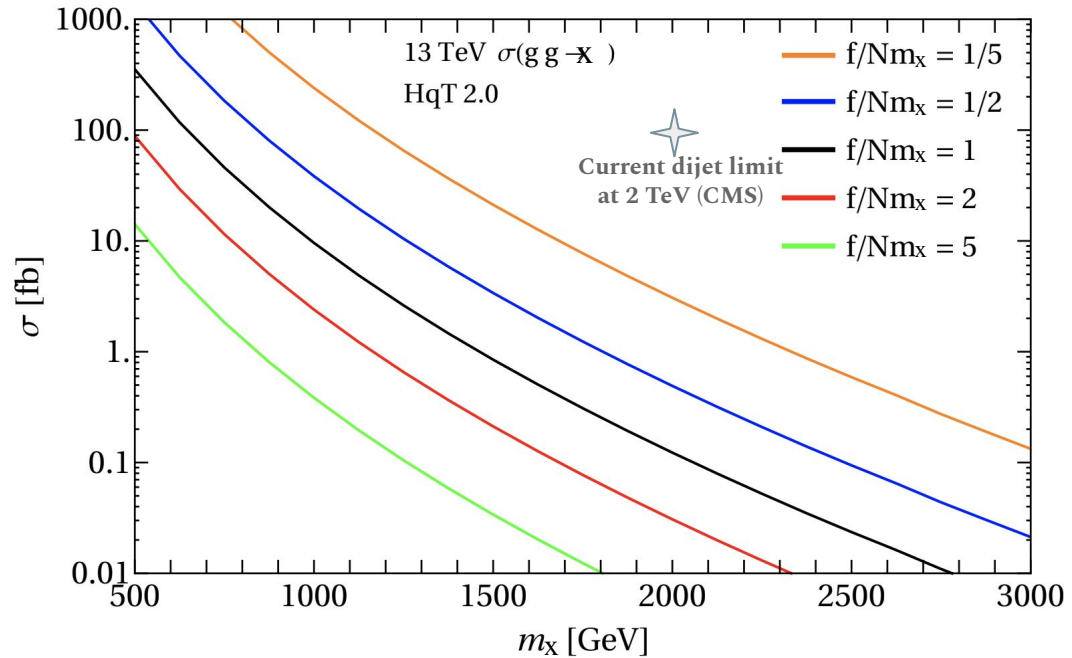
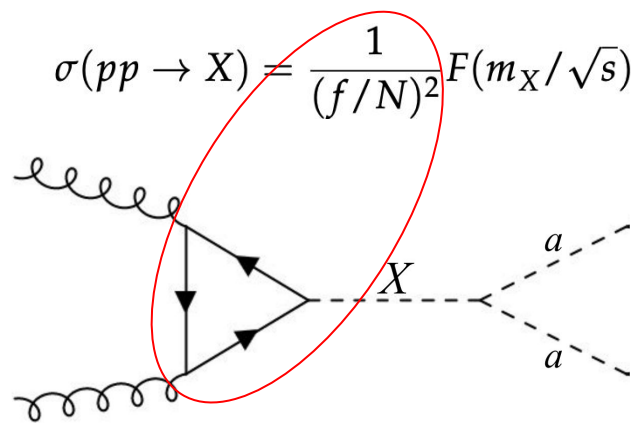
● Many proposed solutions to these questions posit an extended Higgs sector.



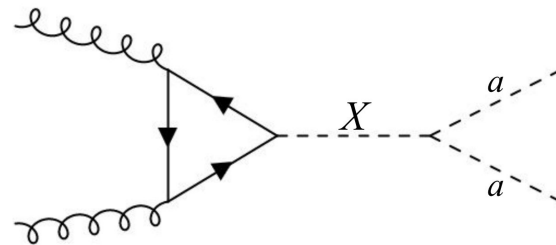
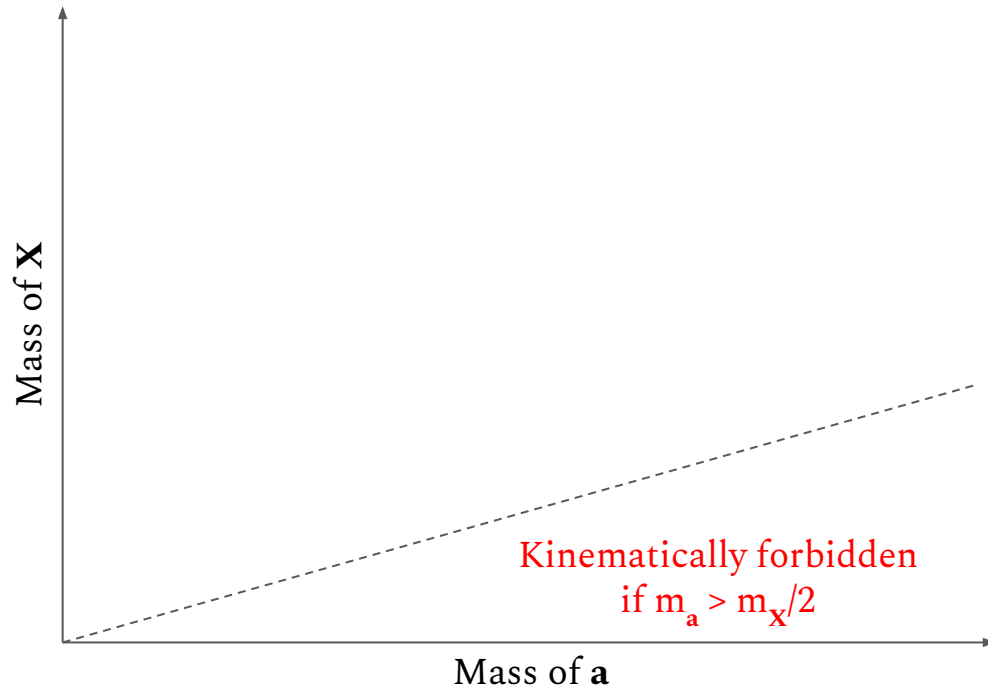
- Generally speaking, if:
 - There is an extended higgs sector
 - It has an approximate Global Symmetry
 - That symmetry is spontaneously broken
- We expect two new particles **X** and **a**:
 - **X** could be produced at hadronic colliders
 - Decay almost entirely to pairs of **a**
 - **a**s decay “like higgs” (i.e. coupling by mass):



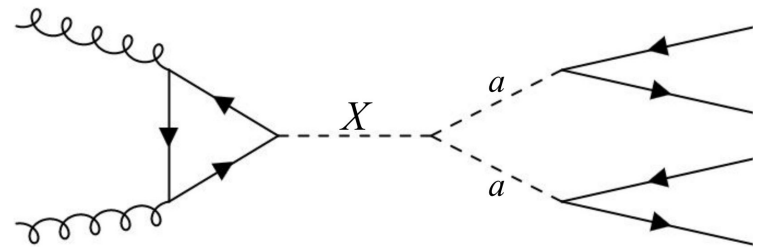
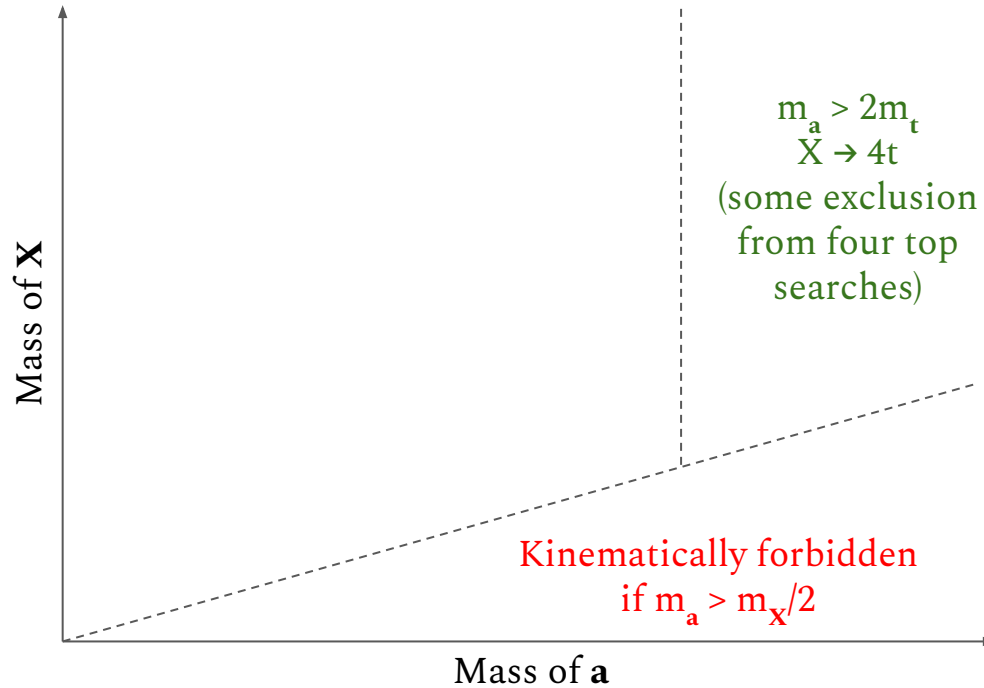
- Production depends only on mass of X and the ratio of the vacuum expectation value to the number of new (colored) fermions allowed in the loop:
 - Broad range of cross sections allowed, depending on model specifics



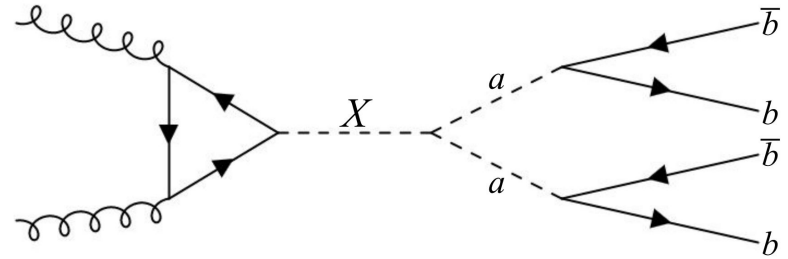
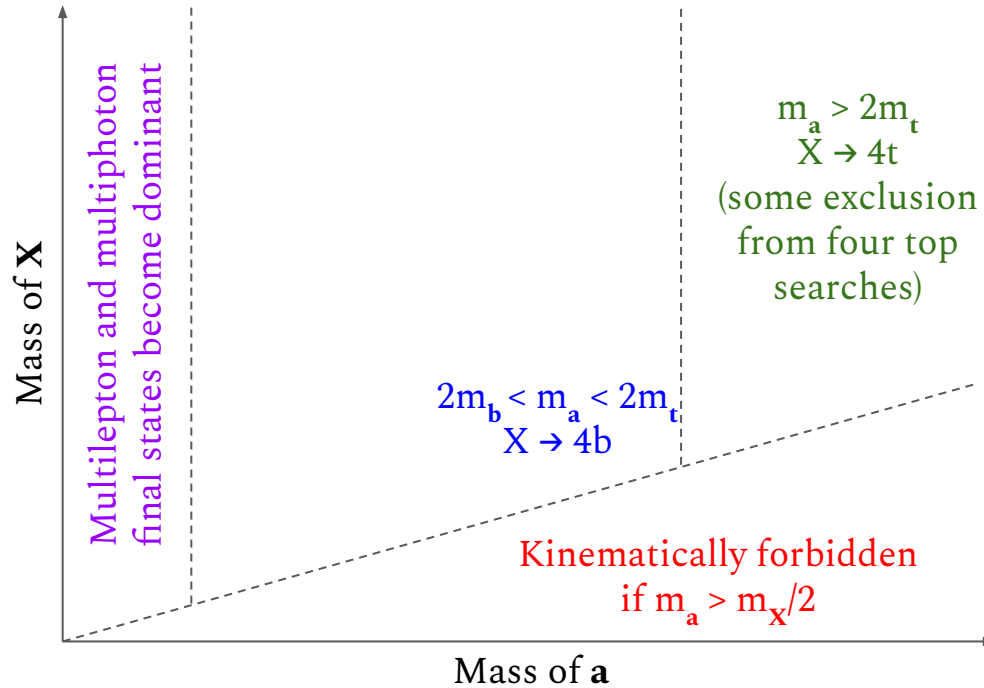
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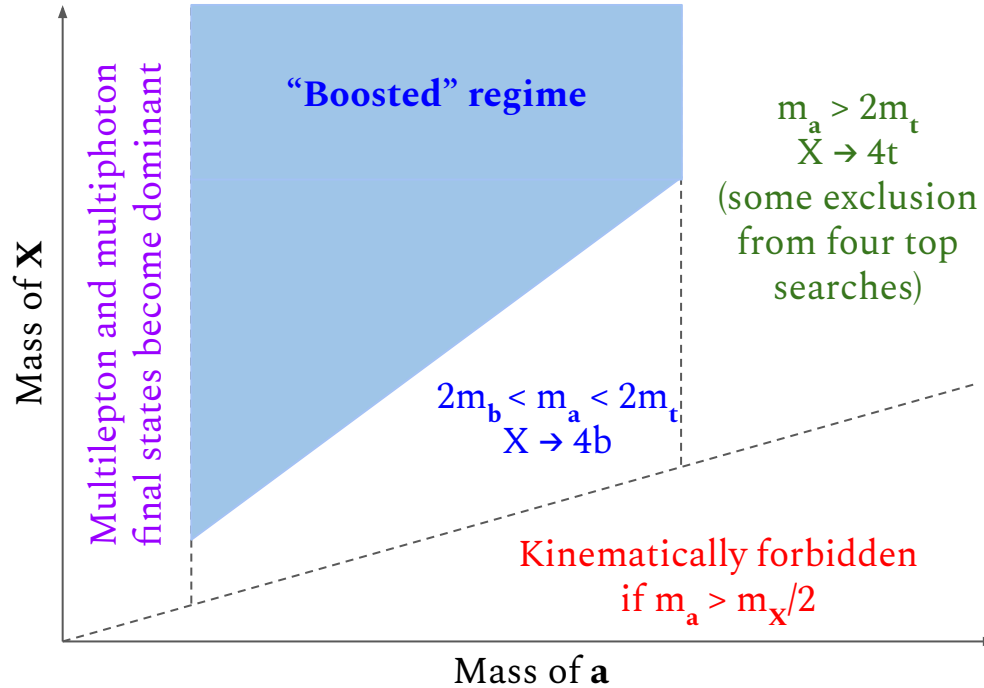


- Experimental signature depends on exact \mathbf{X} and \mathbf{a} masses
- My focus on “boosted” $\mathbf{a} \rightarrow b\bar{b}$ signature, when $m_{\mathbf{X}} \gg m_{\mathbf{a}}$

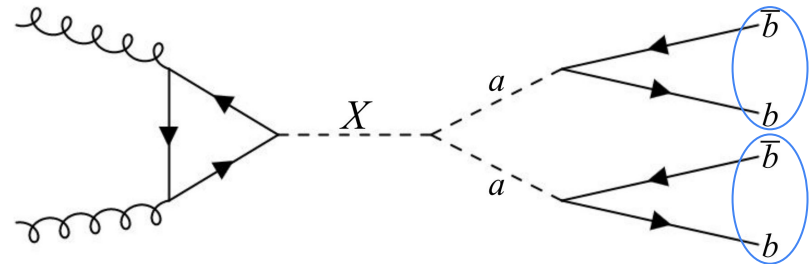


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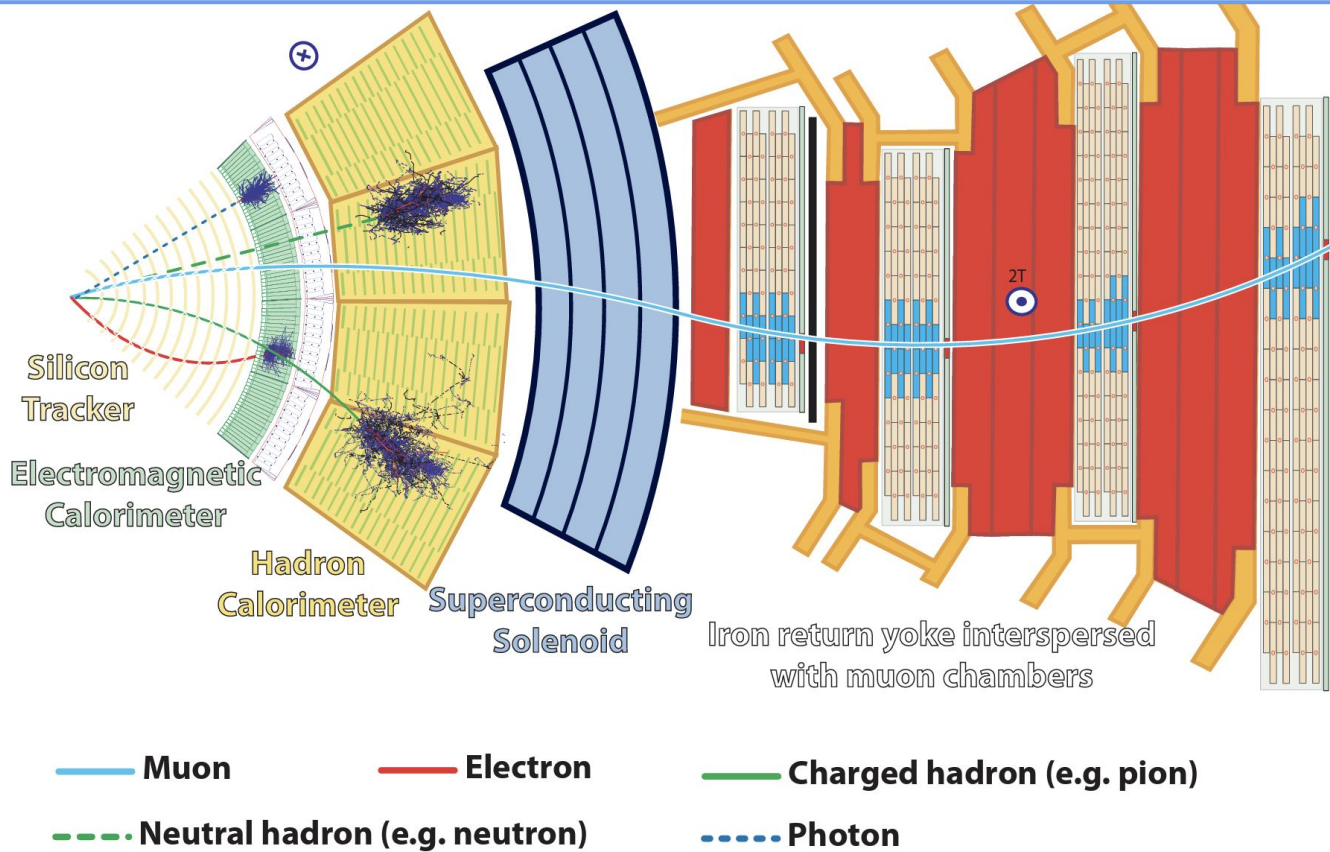
Search range:
 $1 \text{ TeV} < \mathbf{X} < 3 \text{ TeV}$
 $25 \text{ GeV} < \mathbf{a} < 100 \text{ GeV}$



Each \mathbf{a} will appear as one object in our detector: we won't reconstruct all four \mathbf{b} s

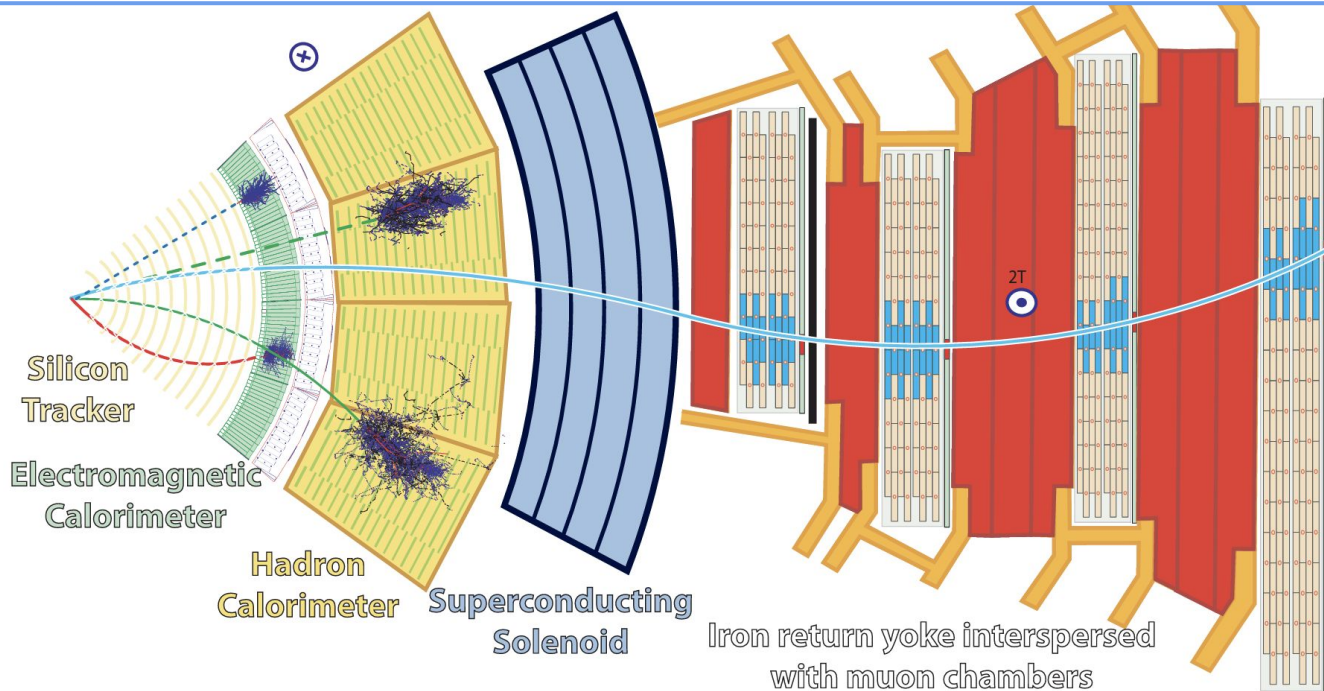


CMS and ATLAS have ample experience searching for similarly produced di-higgs signatures

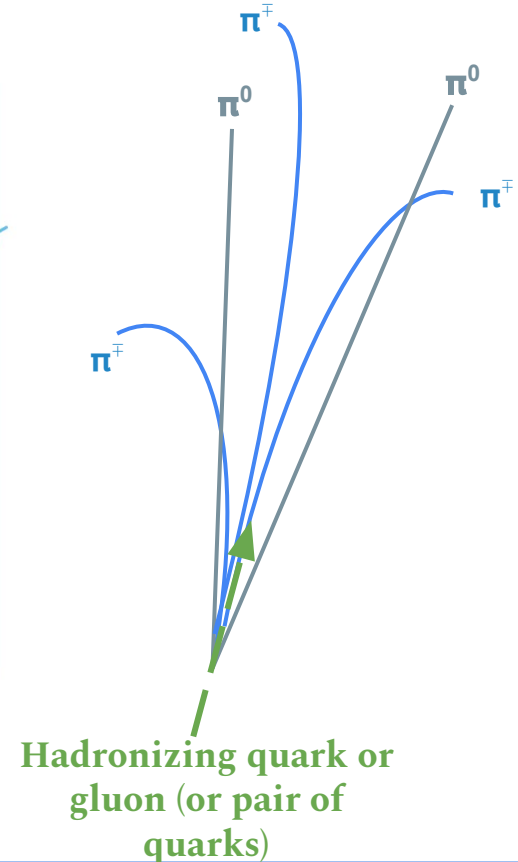


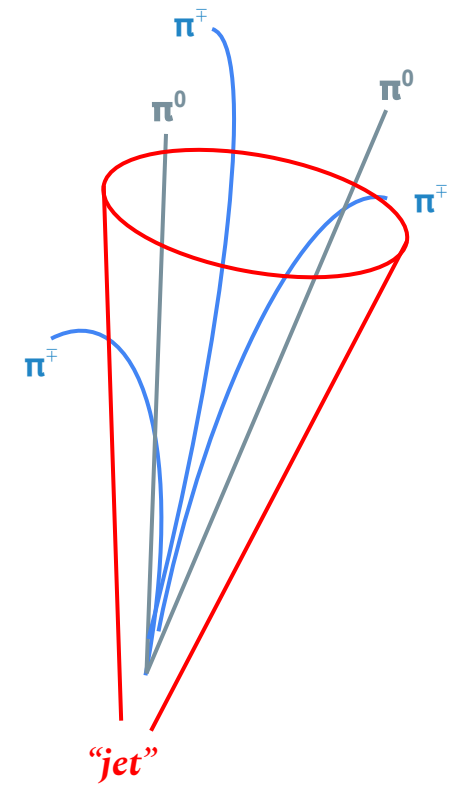
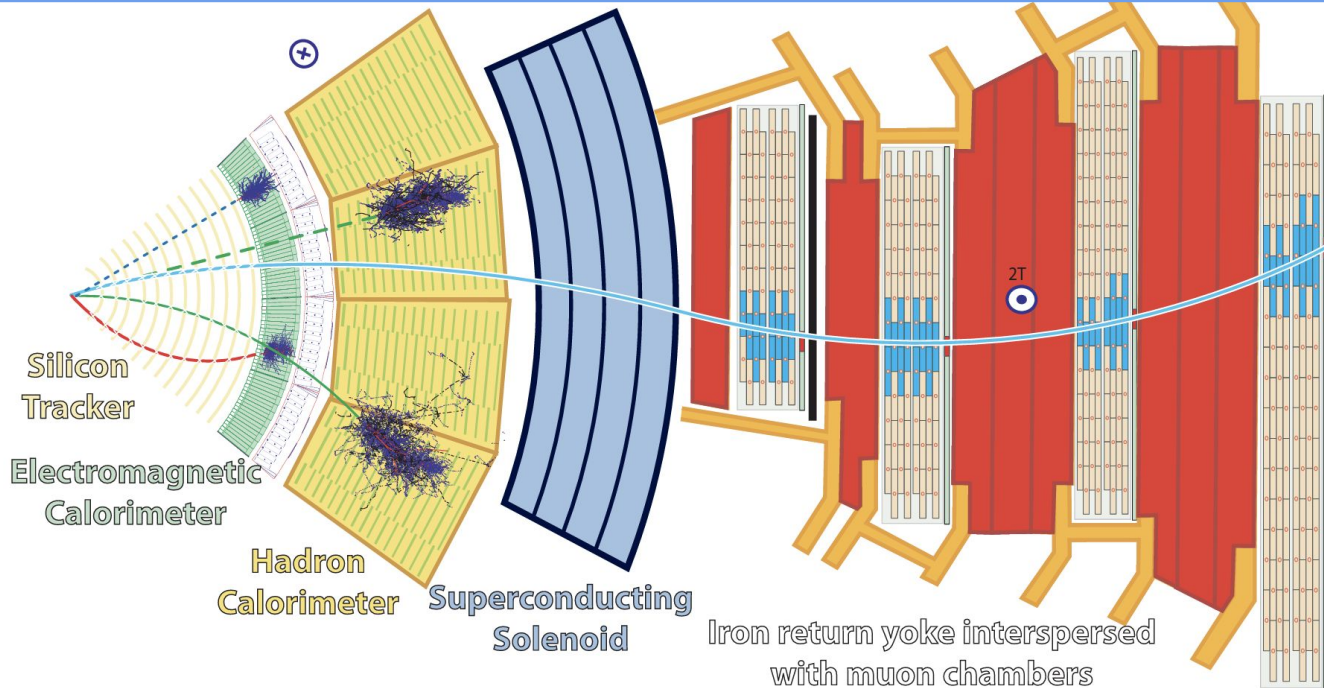


CMS Detector and Jets



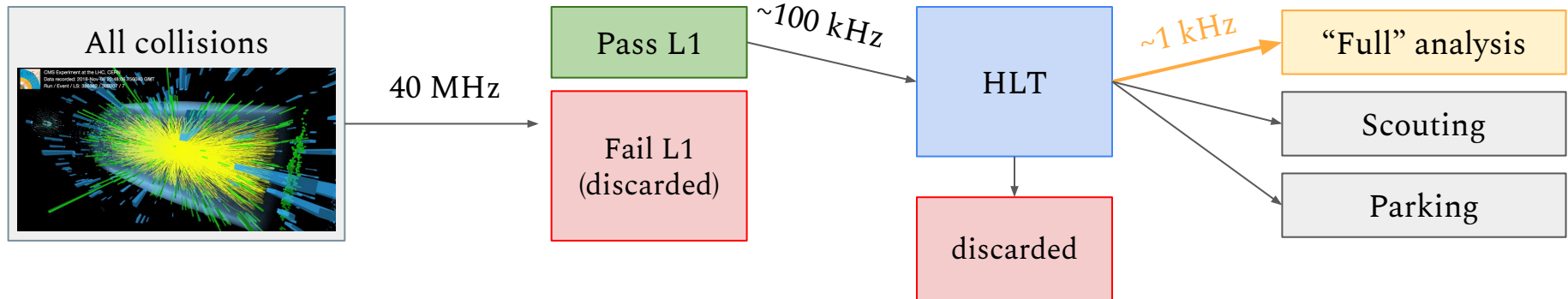
- Muon
- Electron
- Charged hadron (e.g. pion)
- - - Neutral hadron (e.g. neutron)
- - - Photon





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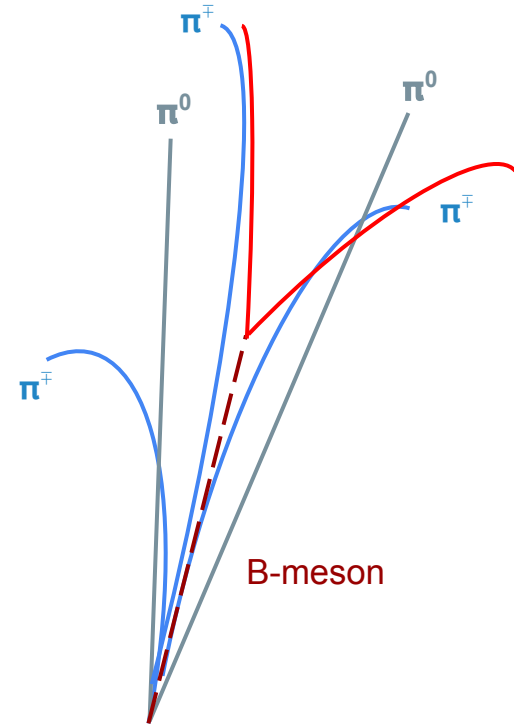
- LHC produces 40 million collisions per second
- CMS has the bandwidth to fully read out ~ 1 thousand per second
- Reduction implemented by two-tiered trigger system:
 - Level 1: using only calorimeter and muon detector information, flag events of interest
 - High-Level: fast reconstruction of entire events flagged by L1, written out based on pre-set criteria (colloquially: “triggers”)
- Our triggers keep events with **large jet transverse momentum** or **high total hadronic transverse momentum**



- b-quarks hadronize into B-mesons, with relatively long lifetime:

$$\begin{aligned} \text{Mass } m_{B^\pm} &= 5279.32 \pm 0.14 \text{ MeV} \quad (S = 1.1) \\ \text{Mean life } \tau_{B^\pm} &= (1.638 \pm 0.004) \times 10^{-12} \text{ s} \\ c\tau &= 491.1 \text{ } \mu\text{m} \end{aligned}$$

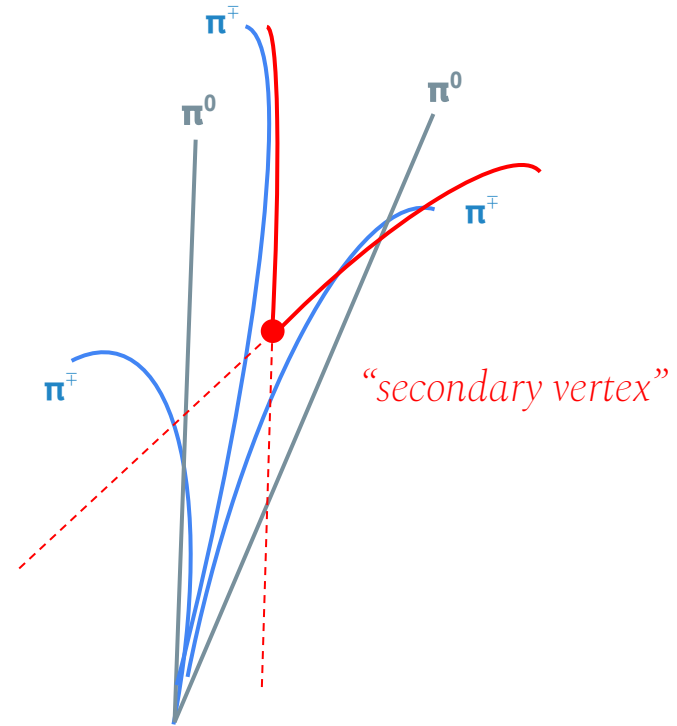
- Not stable enough to interact directly with the detector, but stable enough to travel some distance from the “*primary vertex*”: the point at which the b-quark itself was created.
- B-jet tagging algorithms combine secondary vertex information with particle multiplicities, momentum distributions and the presence of soft leptons to identify jets likely to have originated from a b-quark.



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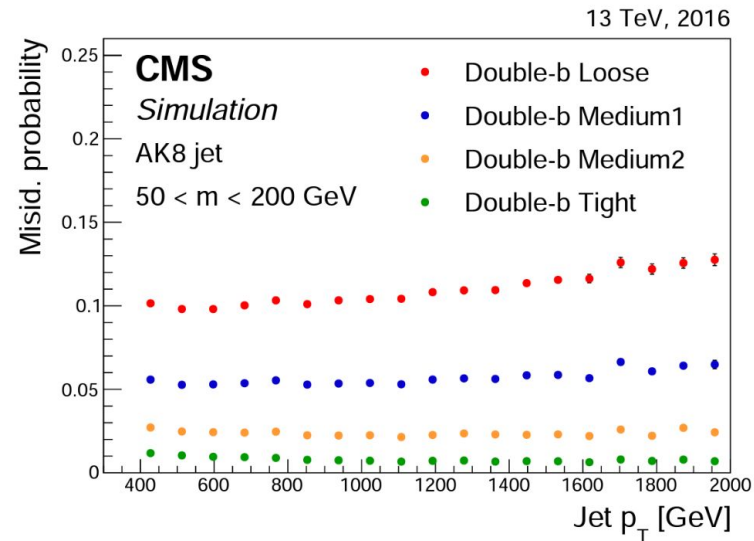
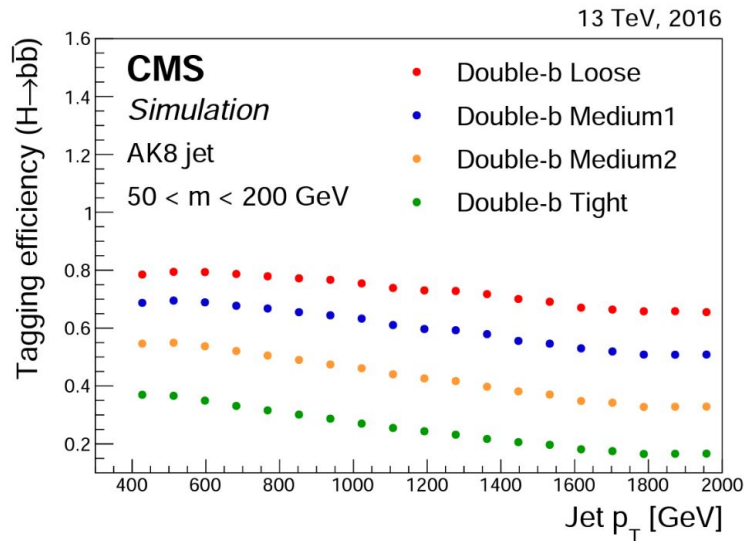
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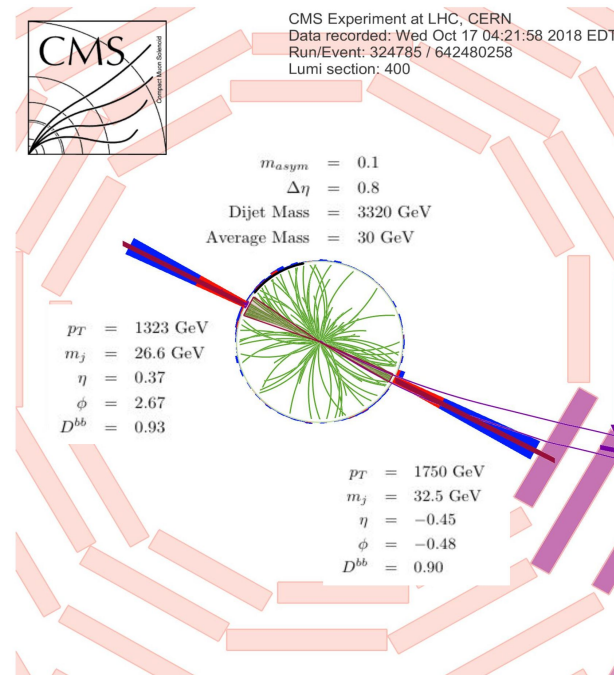
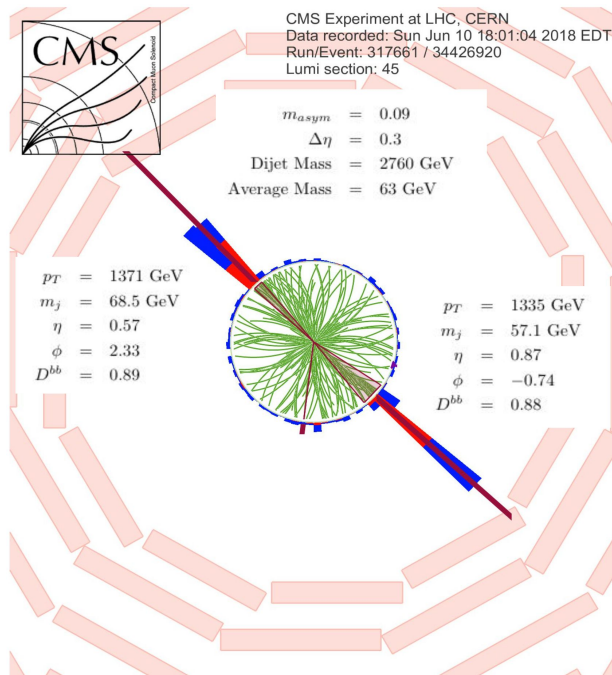




- Same concept can be used to tag jets originating from two b-quarks: look for two secondary vertices!
 - Many algorithms developed to do this. We use a relatively simple one: the “*double-b tagger*”.
 - More complicated methods, in particular using neural nets exist, but were not tuned to cover the full mass spectrum of **a** mass we are interested in.



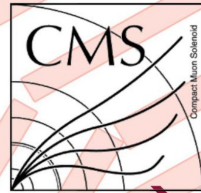
- Two candidate events to illustrate what our signal would look like:
 - Notice the large number of tracks not associated with significant calorimeter deposits



Two high p_T muons collinear with a jet: could have come from two b -quarks?

$X \rightarrow aa \rightarrow (bb)(bb)$

Basic requirements:
At least two jets,
High Jet p_T ,
High "Dijet Mass"



CMS Experiment at LHC, CERN
Data recorded: Sun Jun 10 18:01:04 2018 EDT
Run/Event: 317661 / 34426920
Lumi section: 45

$$m_{asym} = 0.09$$

$$\Delta\eta = 0.3$$

$$\text{Dijet Mass} = 2760 \text{ GeV}$$

$$\text{Average Mass} = 63 \text{ GeV}$$

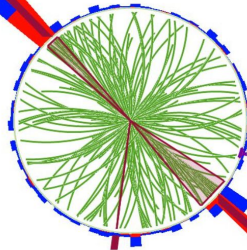
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$$m_j = 68.5 \text{ GeV}$$

$$\eta = 0.57$$

$$\phi = 2.33$$

$$D^{bb} = 0.89$$



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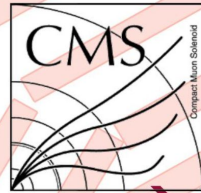
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Groomed Jet Mass (Soft Drop):
 We require two jets with similar
 mass:
 $(m_1 - m_2)/(m_1 + m_2) < 25\%$
 Define "average mass"



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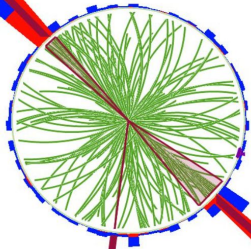
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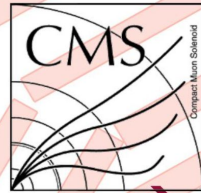
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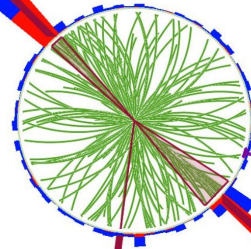
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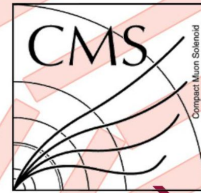
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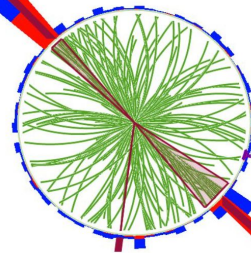
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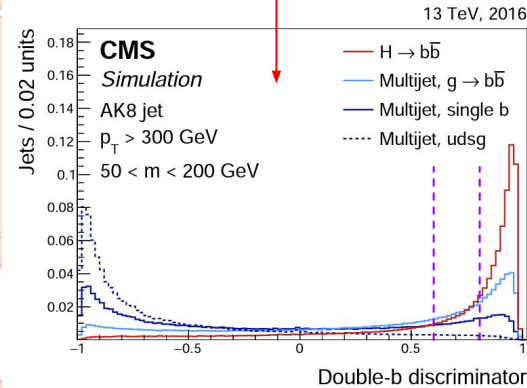
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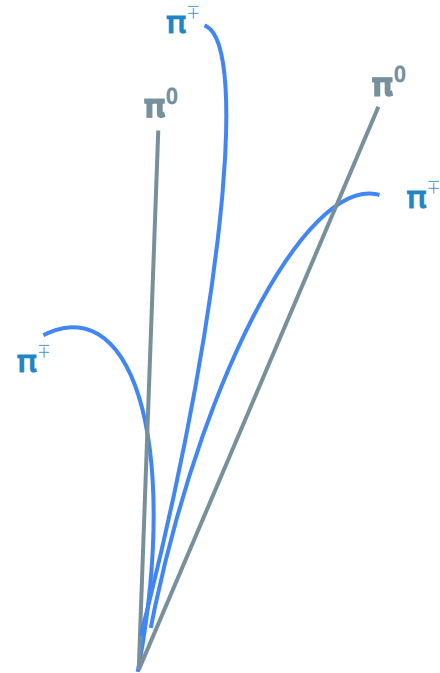


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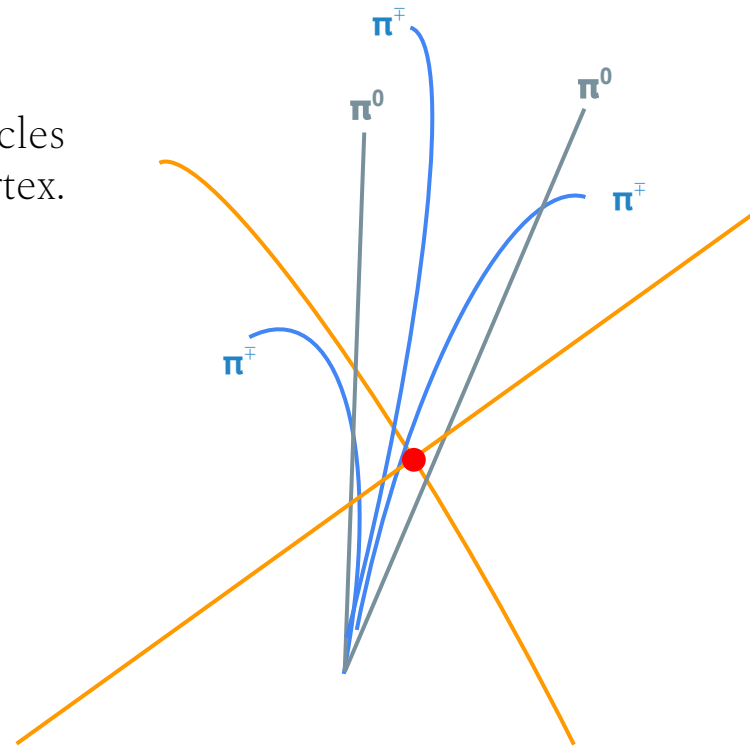
Both jets must score highly on the double-b tagger:
 (asymmetric requirement)
 Leading jet score > 0.8
 Subleading jet score > 0.6



- Three (non-negligible) source of background:
 - **pileup**: more than one proton-proton collision usually happens per bunch crossing. Stray particles can be clustered in a jet, faking a secondary vertex.

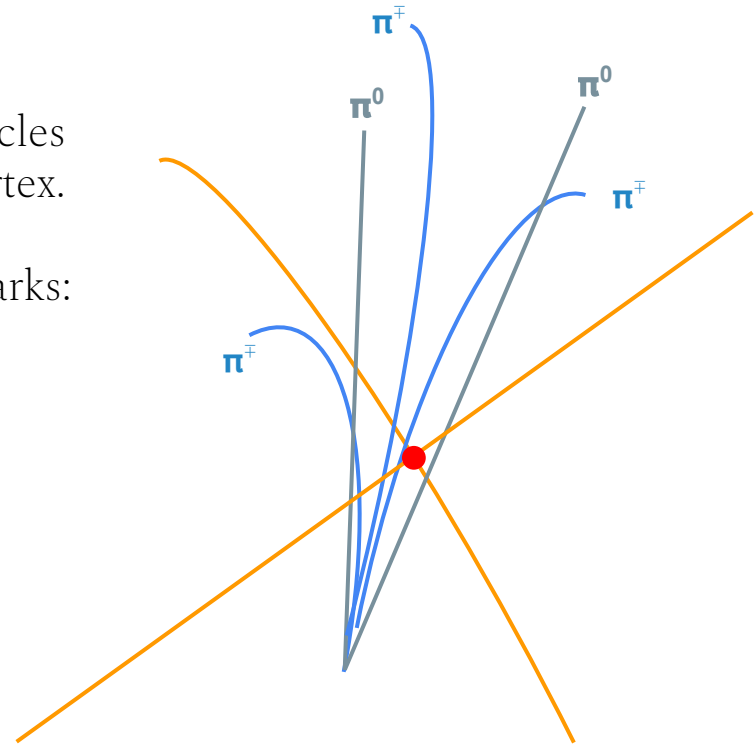
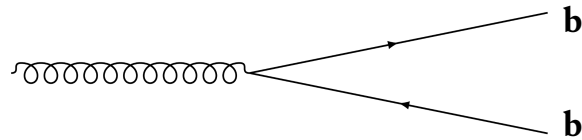


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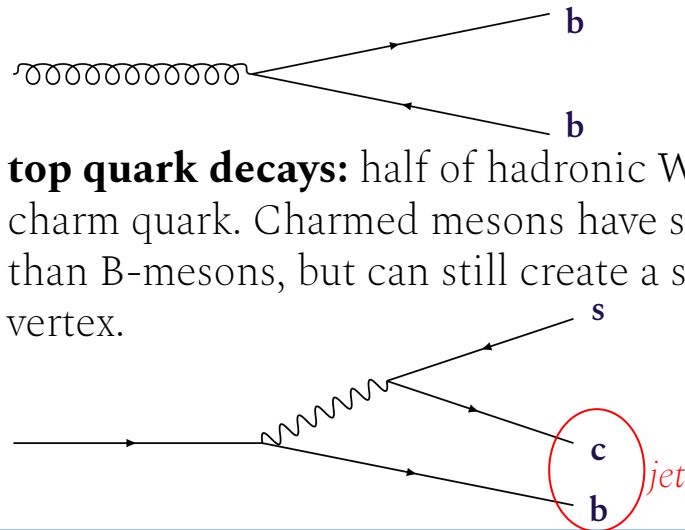
Tracks from other proton-proton collisions in the same bunch crossing

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 - **pileup**: more than one proton-proton collision usually happens per bunch crossing. Stray particles can be clustered in a jet, faking a secondary vertex.
 - **gluons decaying to pairs of b-quarks**: Truly irreducible background from real pairs of b-quarks:

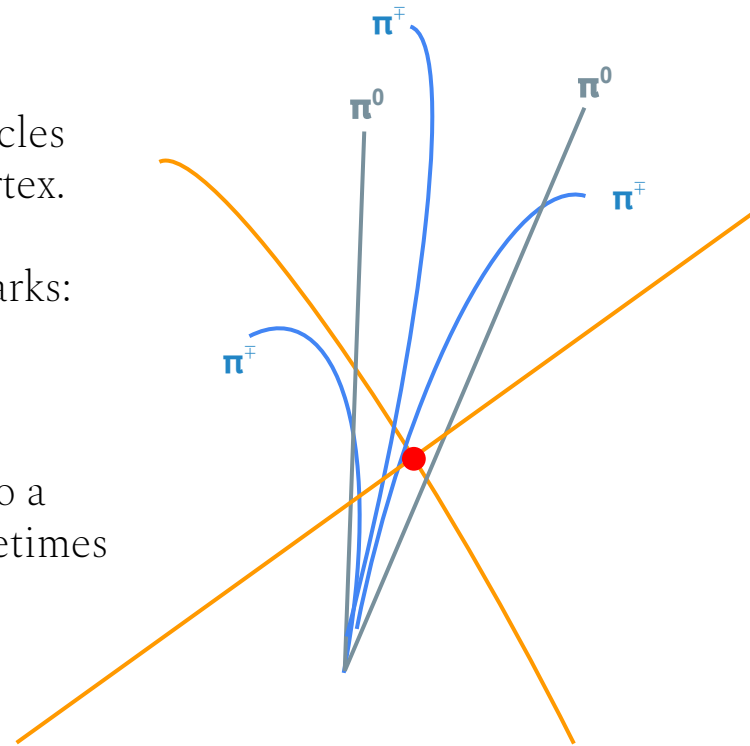


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- Three (non-negligible) source of background:
 - **pileup**: more than one proton-proton collision usually happens per bunch crossing. Stray particles can be clustered in a jet, faking a secondary vertex.
 - **gluons decaying to pairs of b-quarks**: Truly irreducible background from real pairs of b-quarks:

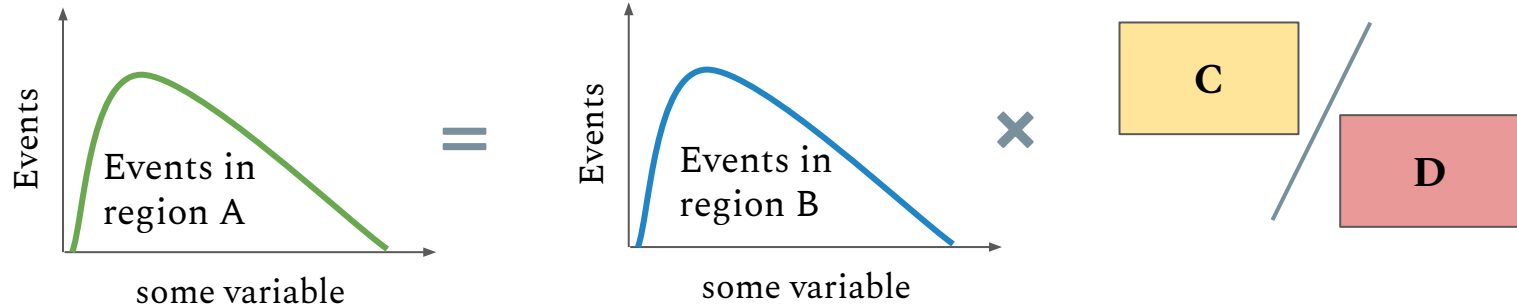
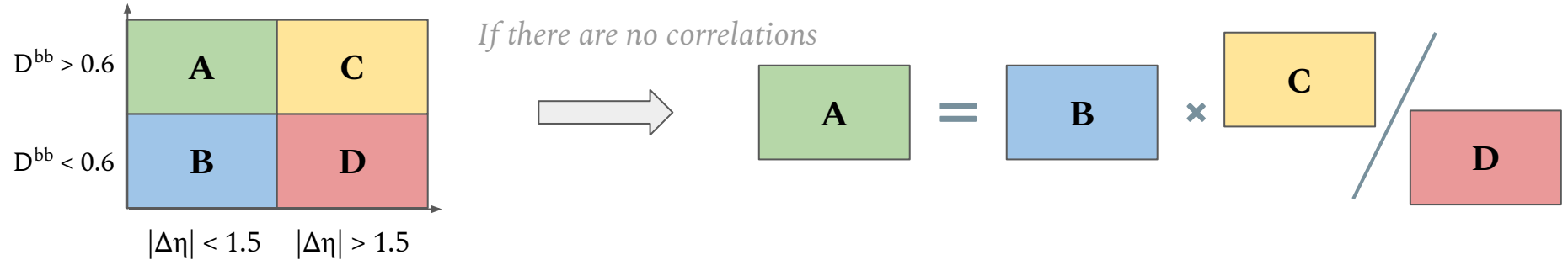


- **top quark decays**: half of hadronic Ws decay to a charm quark. Charmed mesons have shorter lifetimes than B-mesons, but can still create a secondary vertex.



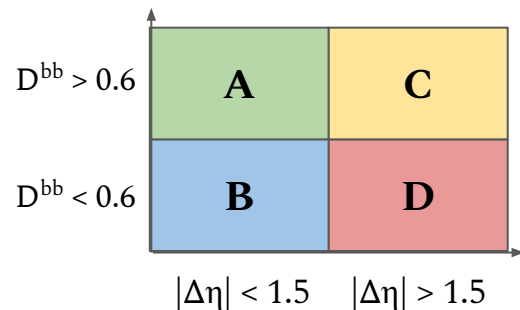
Tracks from other proton-proton collisions in the same bunch crossing

- Top quark pair background taken from simulation (with some corrections derived in data)
- Non-resonant backgrounds from “ABCD”-like method. **Ideally:**

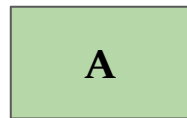
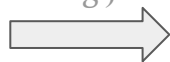




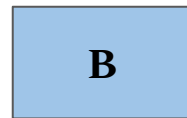
- Top quark pair background taken from simulation (with some corrections derived in data)
- Non-resonant backgrounds from “ABCD”-like method. **In practice:**



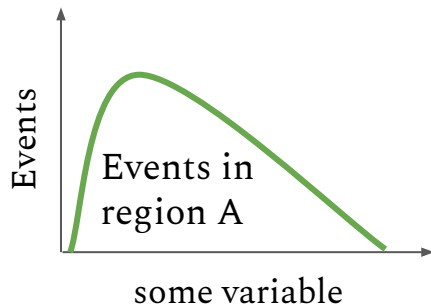
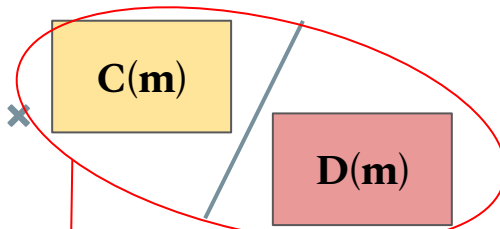
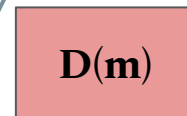
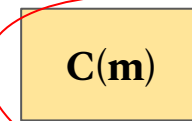
If there are additional correlations, for example on the subleading jet mass



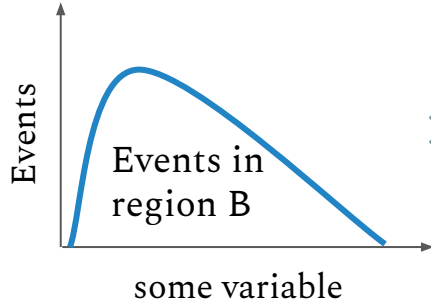
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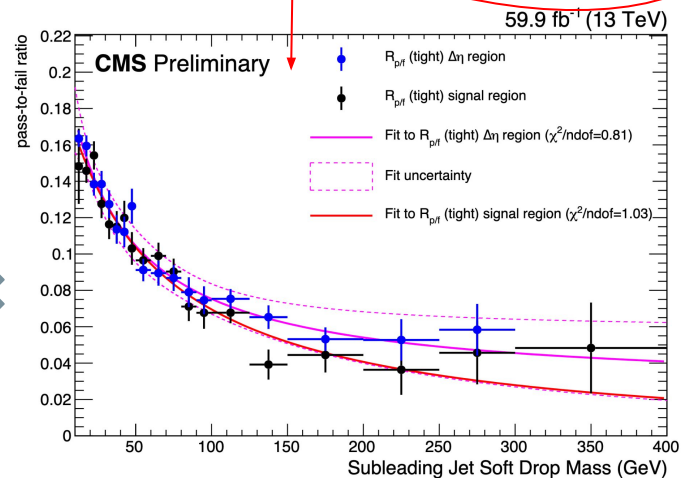
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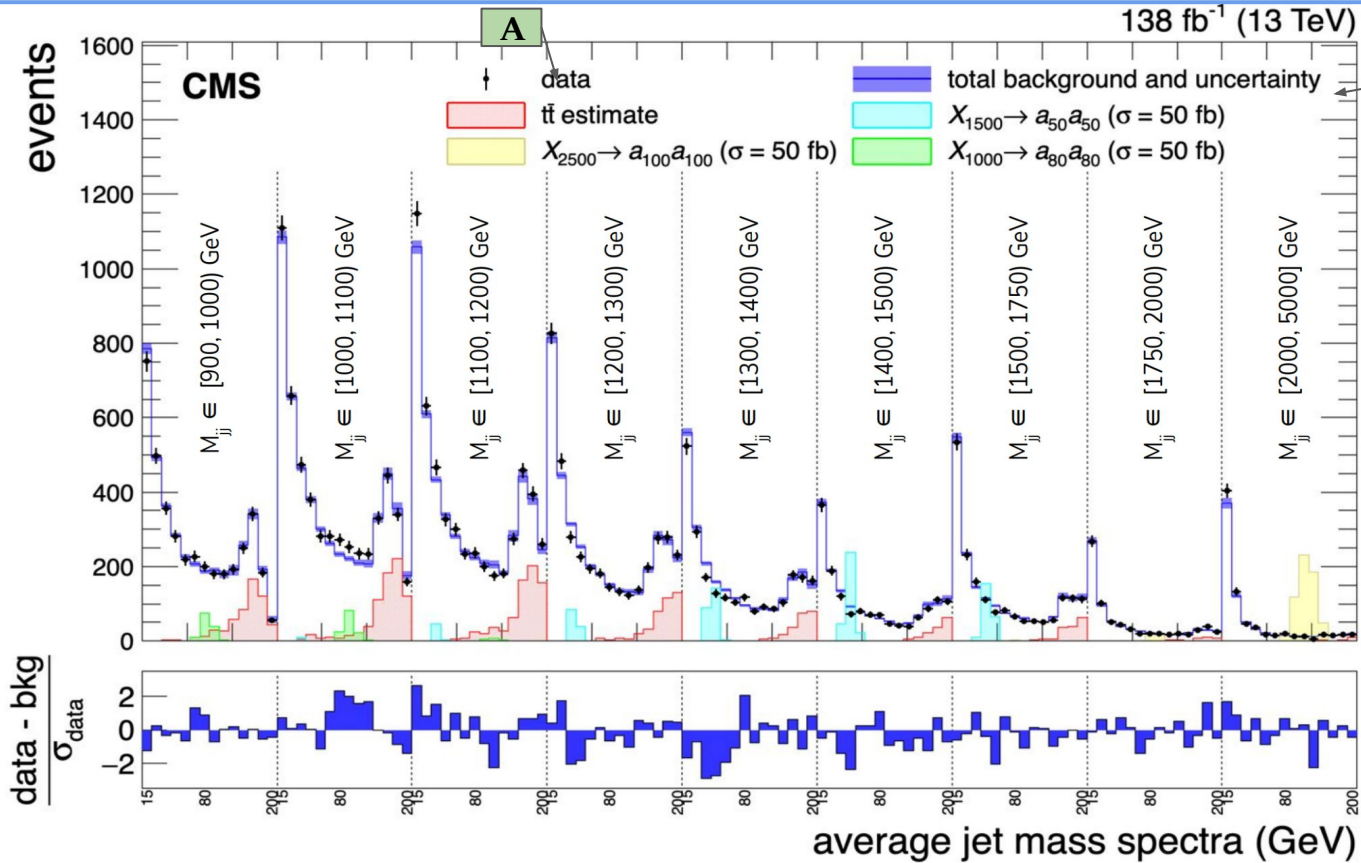


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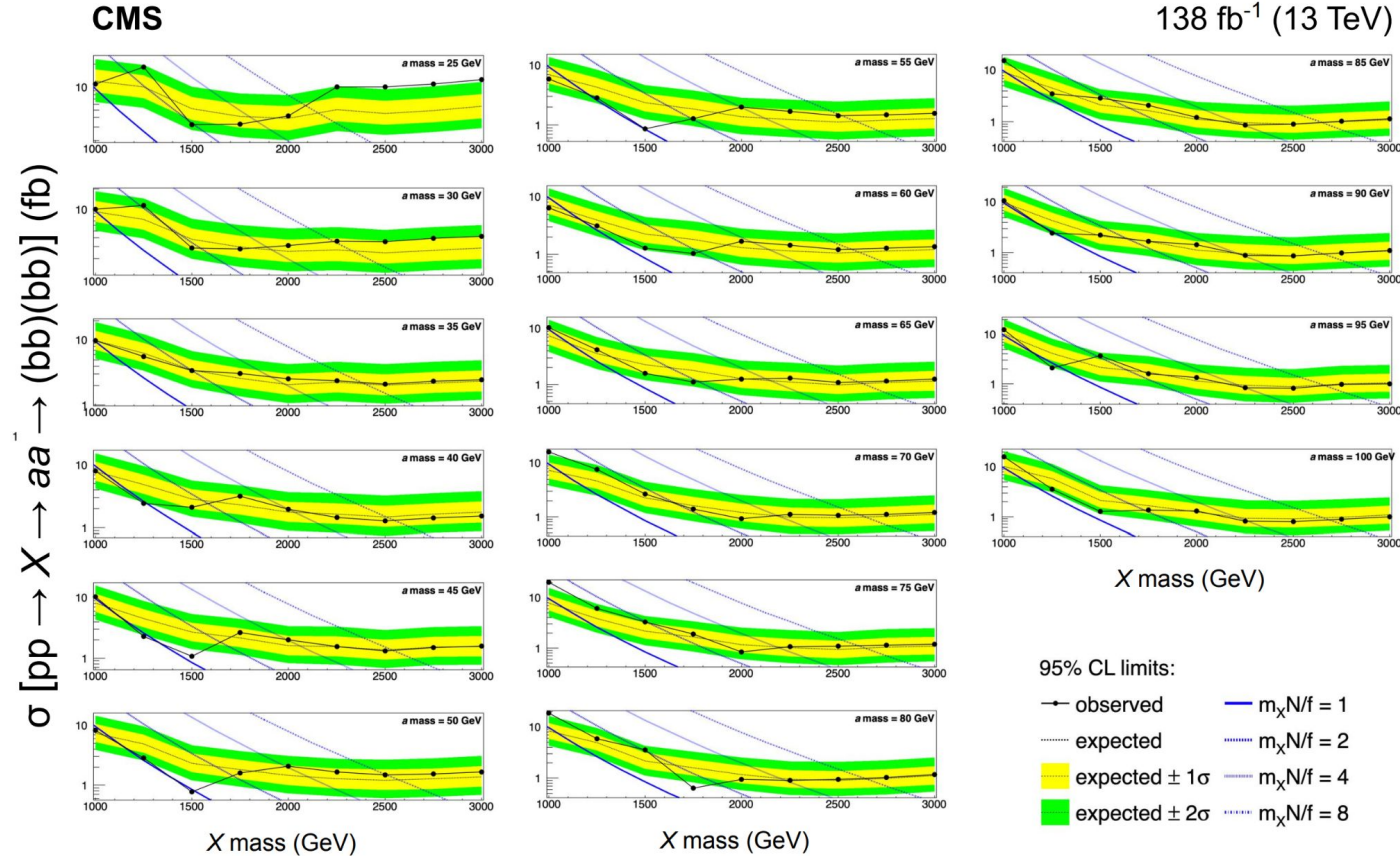


Exploiting Correlations



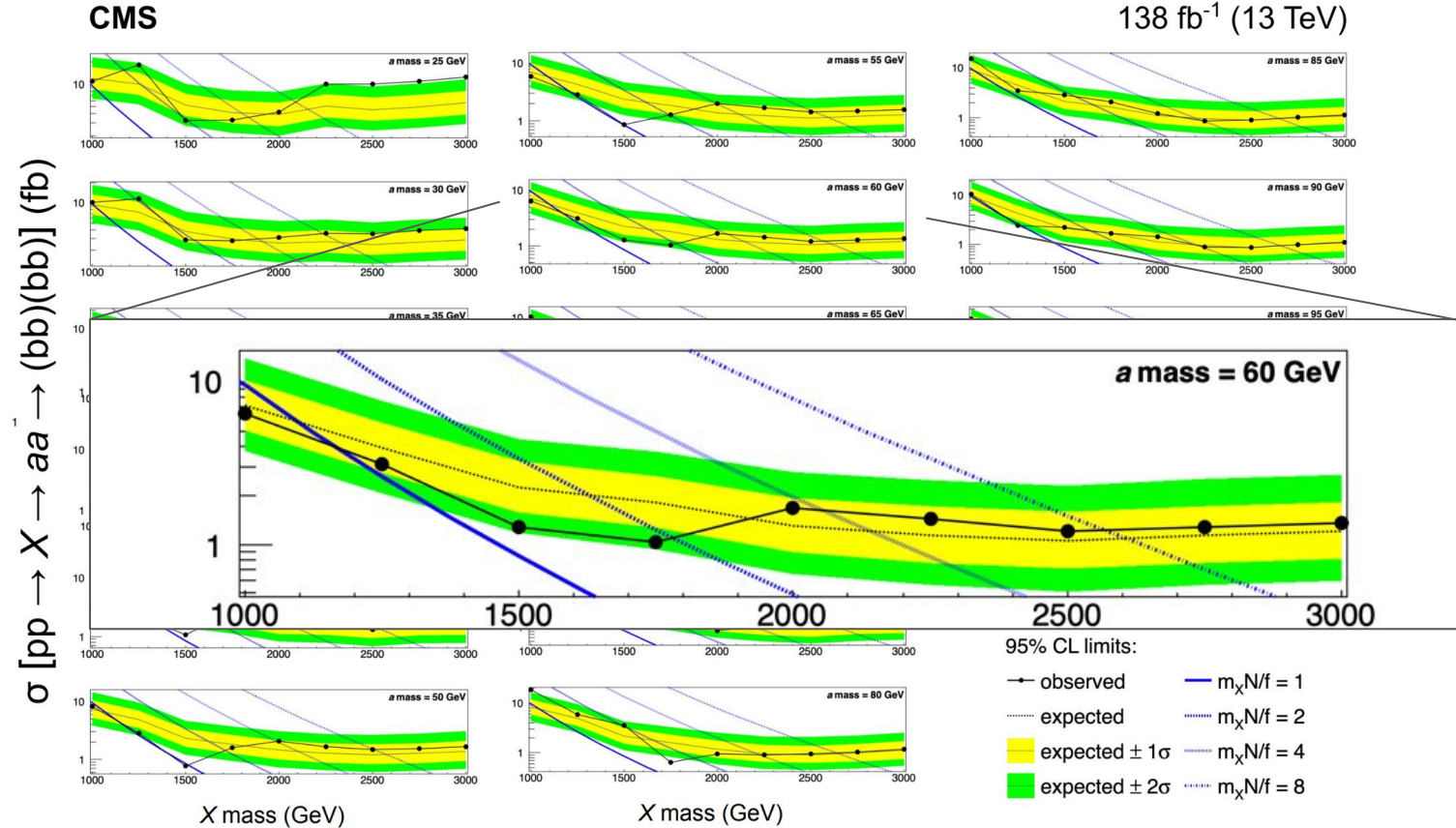


RUTGERS Limits on Extended Higgs Sectors



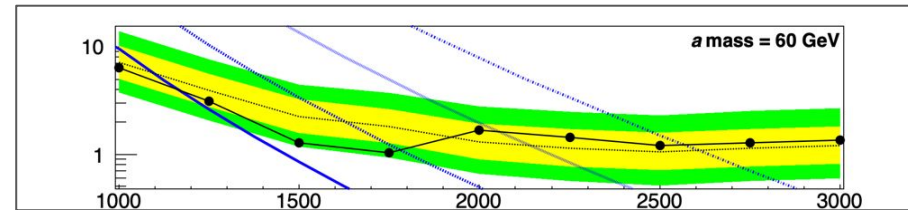
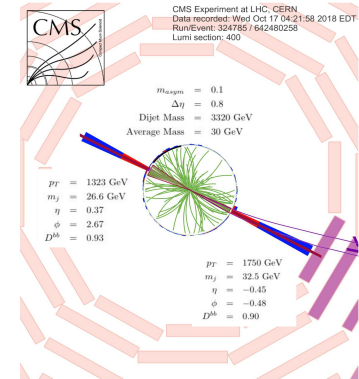
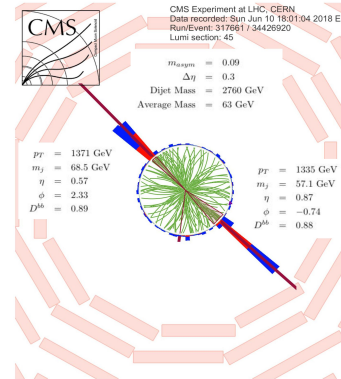
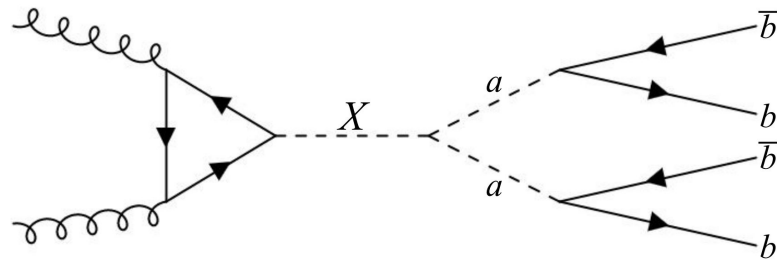


RUTGERS Limits on Extended Higgs Sectors

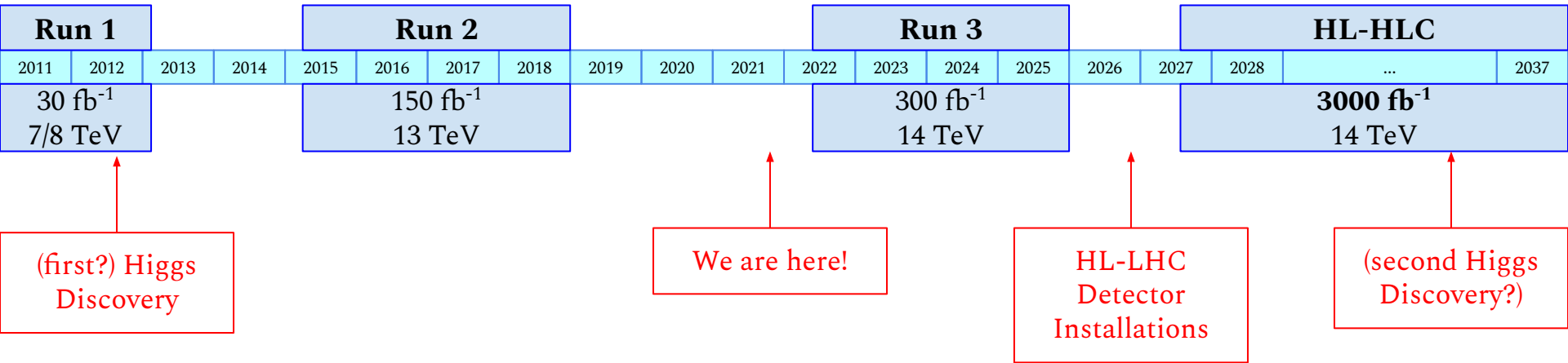


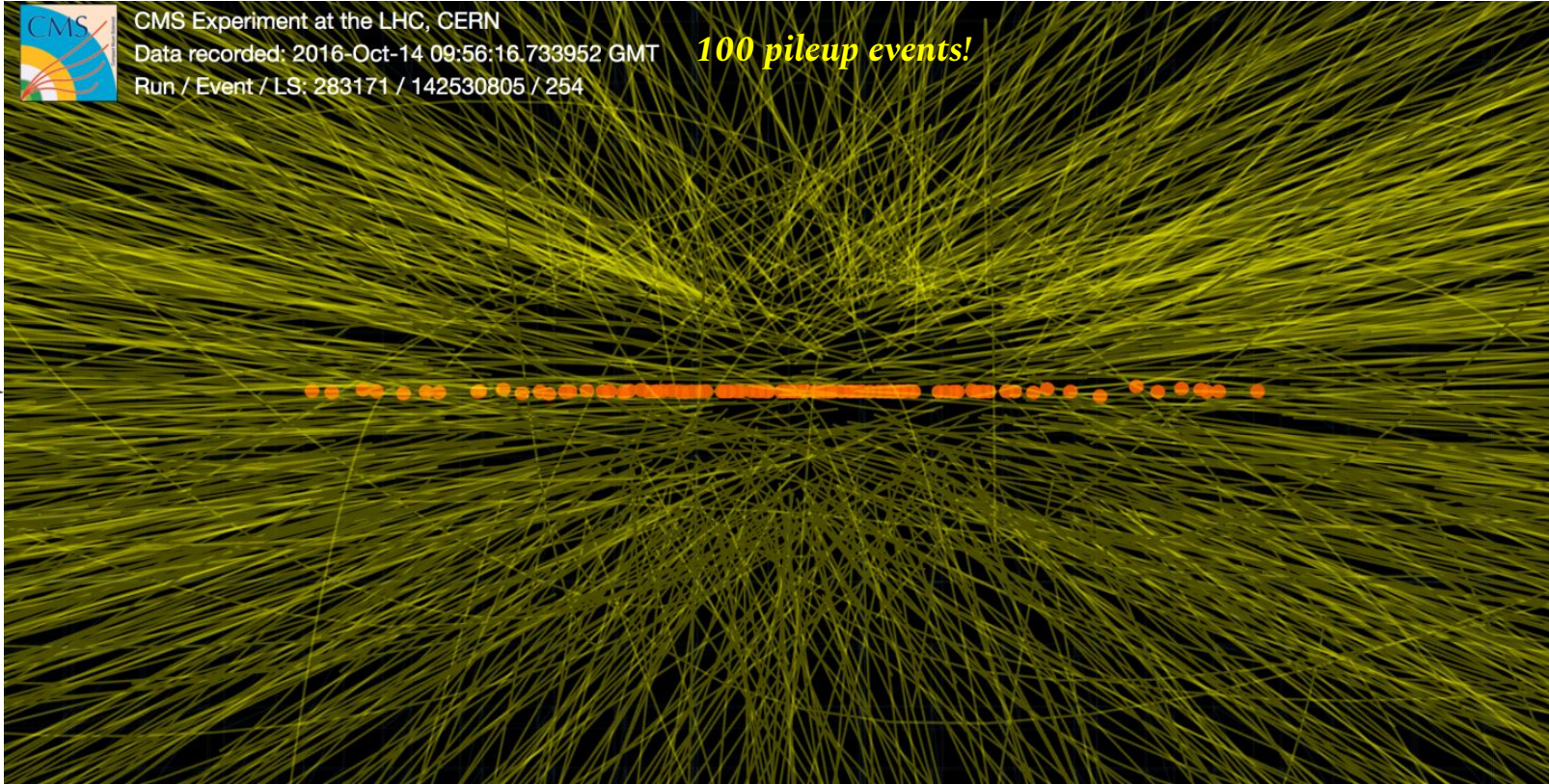
- First result for $X \rightarrow aa \rightarrow (bb)(bb)$ signature!
- Mass range probed: **a** from 25 to 100 GeV, **X** from 1 to 3 TeV
 - No new physics, but exclusion limits can be set on cross-sections $\sim 2\text{-}10\text{fb}$
 - More optimistic f/N scenarios largely excluded (at least up to ~ 2 TeV)
 - Full public result [here](#) (submitting to PLB).

- What's next?!



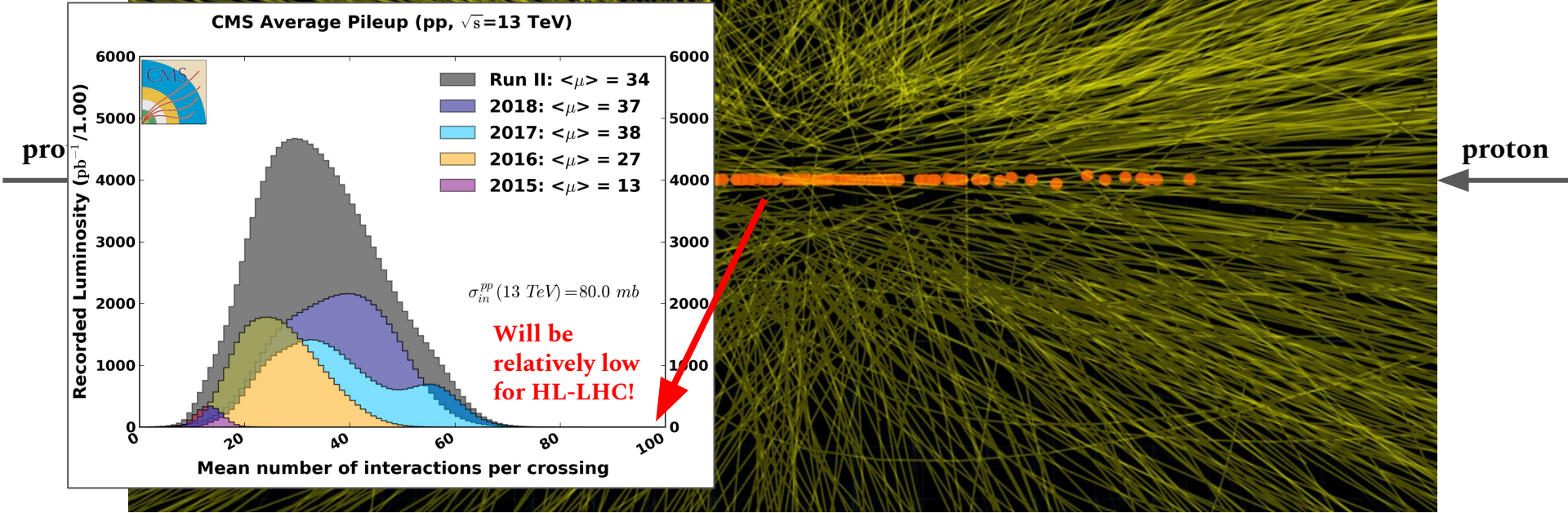
- Run III:
 - Double the integrated luminosity at slightly higher \sqrt{s}
 - No huge gain in sensitivity, but opportunity to implement new methods
- HL-LHC:
 - Factor of 10 increase in integrated luminosity: combined with improvement in techniques, could expose previously undetected signal ... at a cost.






 CMS Experiment at the LHC, CERN
 Data recorded: 2016-Oct-14 09:56:16.733952 GMT
 Run / Event / LS: 283171 / 142530805 / 254

100 pileup events!



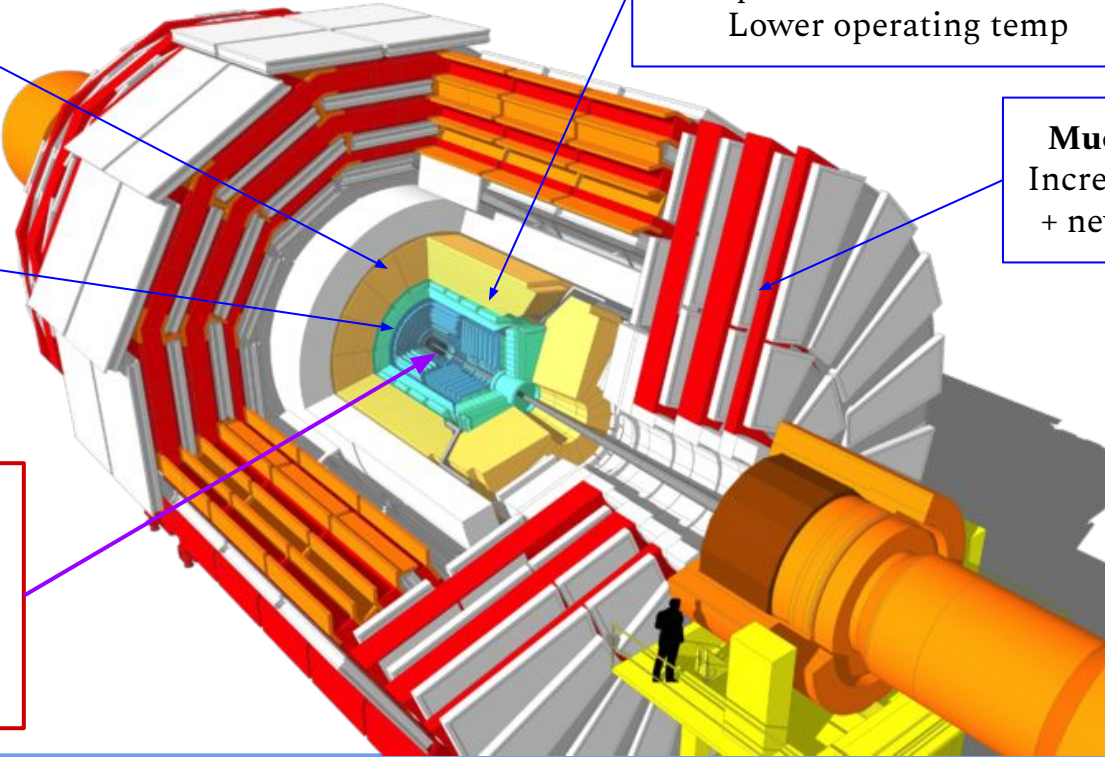


New Calorimeter Endcaps:
 Higher granularity
 Higher rad tolerance
 3D capable

New MIP timing detectors

Calorimeter Barrels:
 Replace FE/BE electronics
 Lower operating temp

Muon Detector:
 Increased coverage
 + new electronics

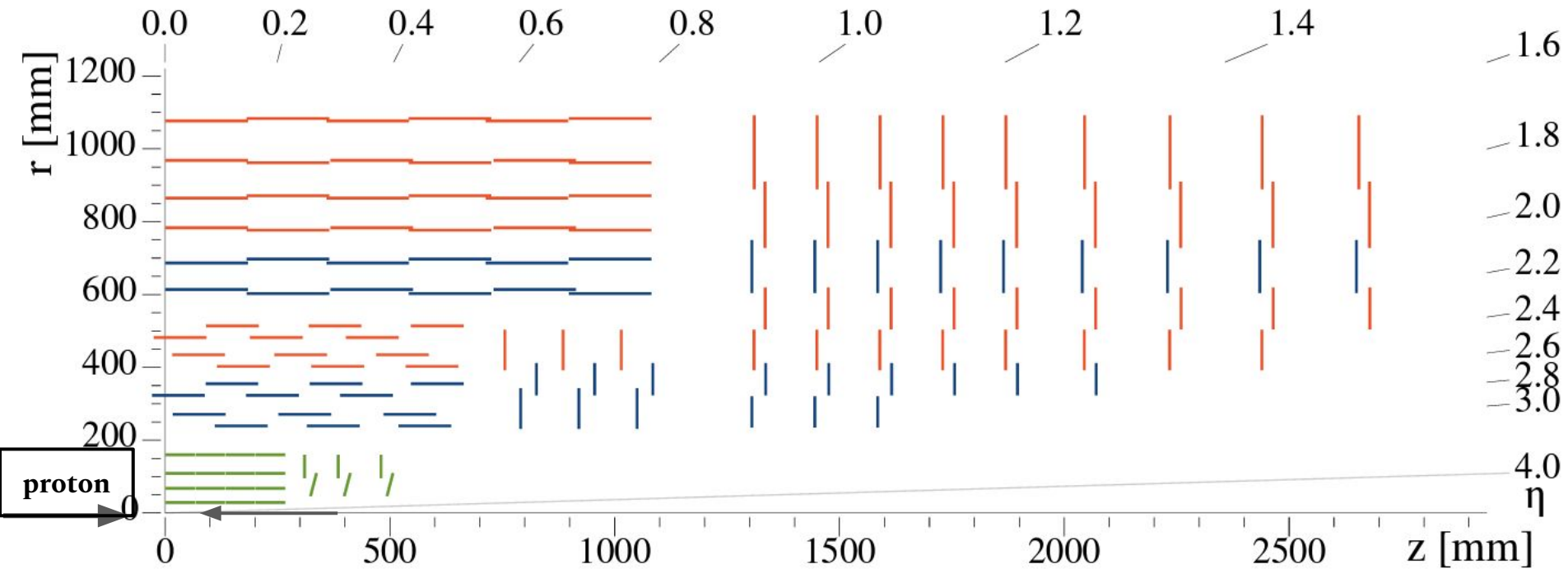


Rutgers involvement

Completely New Tracker!
 Increased coverage
 Higher granularity
 Higher rad tolerance
Track triggering!!

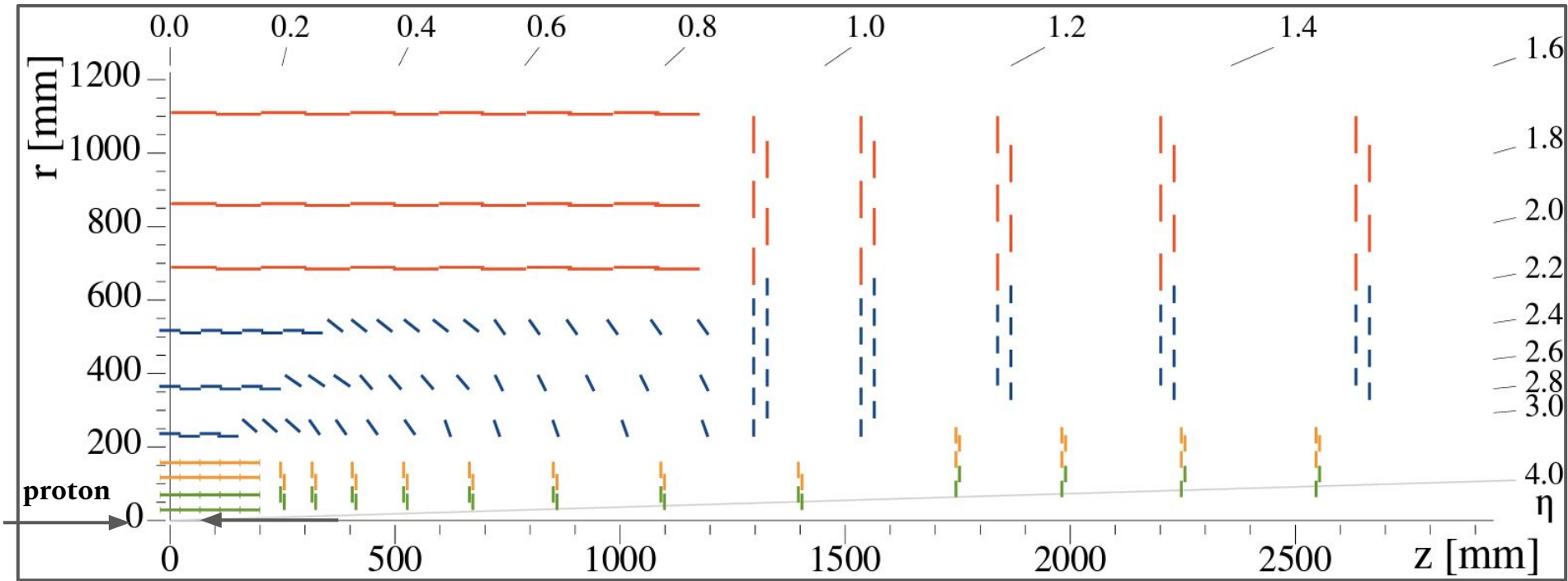


- CMS will completely replace the tracking system.

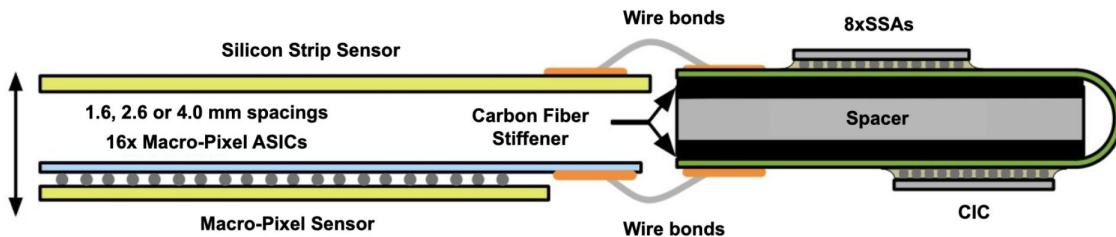
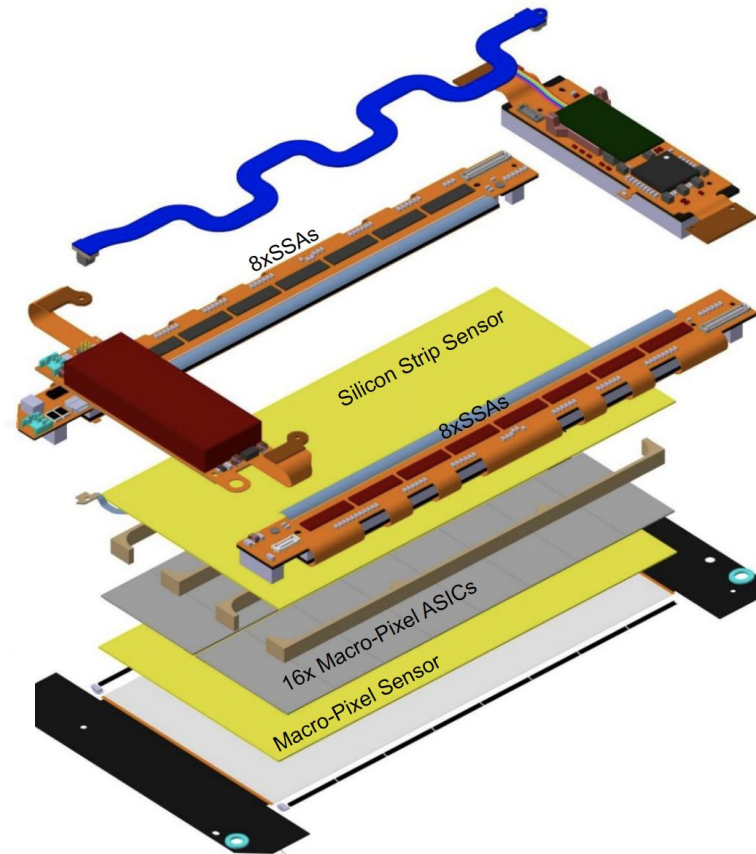




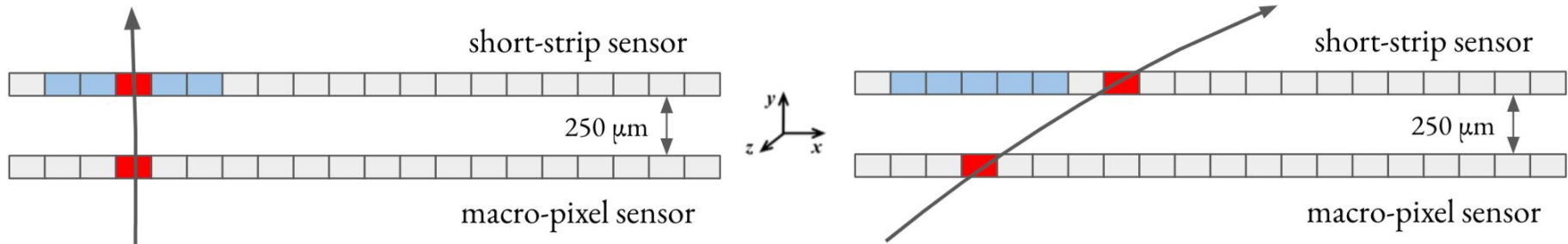
- CMS will completely replace the tracking system. The outer tracker will consist of two kinds of detectors: **Pixel-Strip Modules** and **2-Strip Modules**



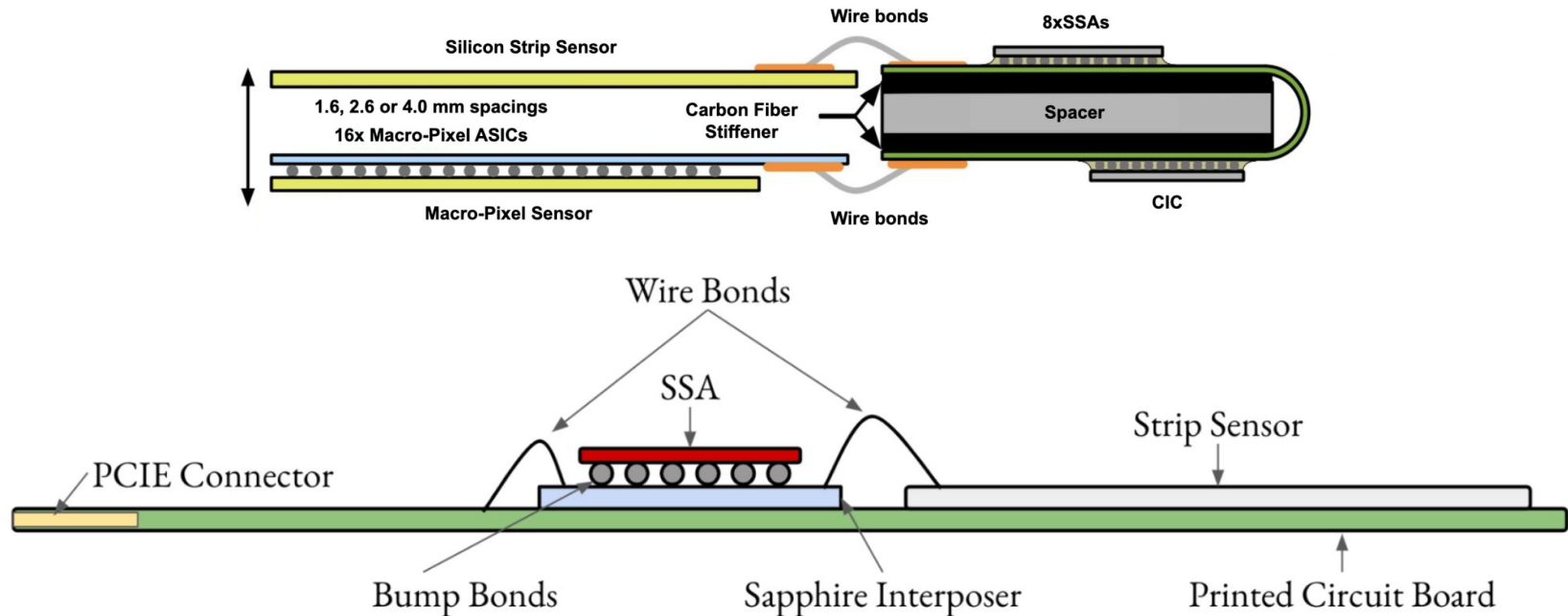
- The PS-module consists of two closely spaced silicon sensor planes: one with pixels and one with strips
- Each sensor instrumented by its own ASIC:
 - Short-Strip ASIC (SSA) reads out the strips and passes its output to the:
 - Macro-Pixel ASIC (MPA) reads out the pixels and collates information from the strip layer to make decisions for the L1 (see next slide)
 - 120 Strips per SSA, 1888 pixels per MPA



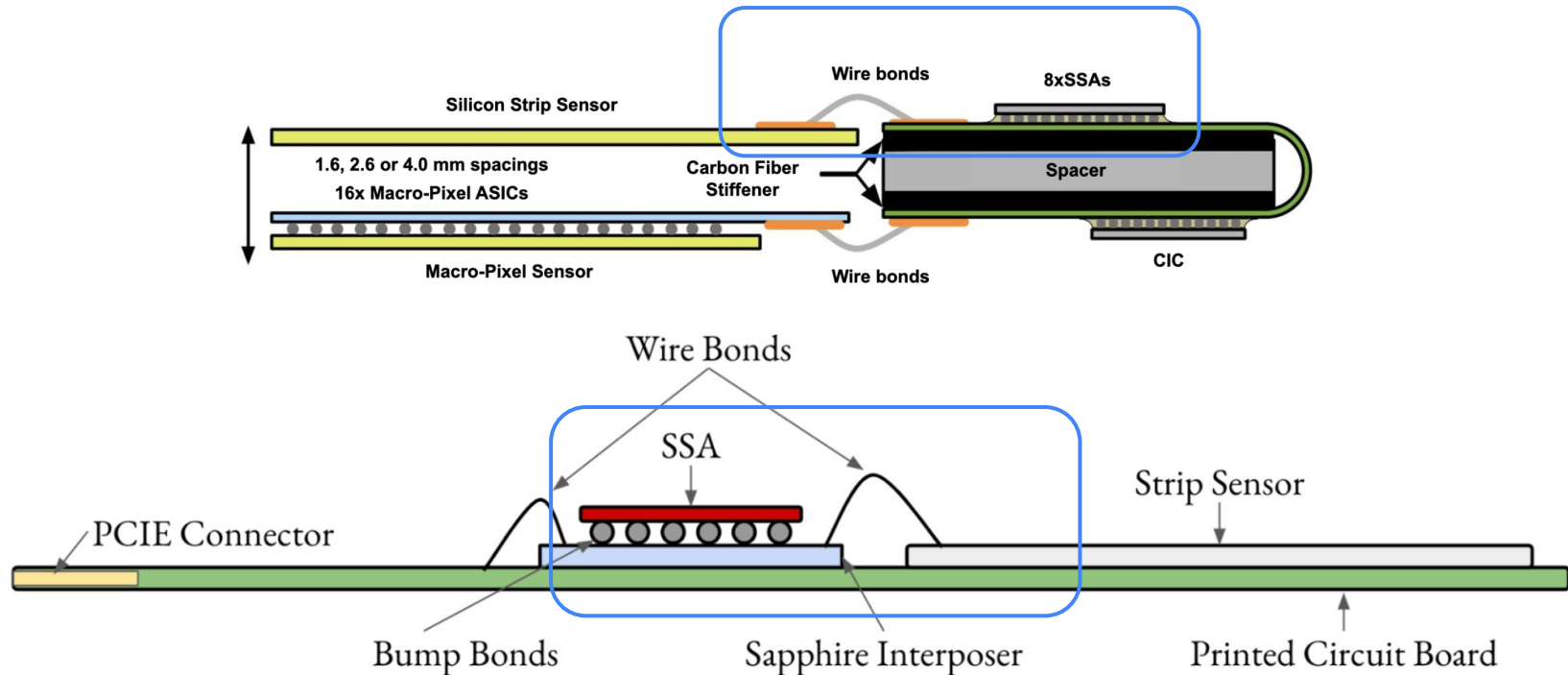
- In each beam crossing:
 - Each channel reports “hits” to the ASICs
 - ASICs cluster adjacent hits into “clusters”
- “Stubs” are formed from co-incident clusters in the strip and pixel layers
- Momentum discrimination built into the stub-formation logic!
 - Low momentum particle trajectories are bent by magnetic field!
- **Stub information passed to L1-trigger**



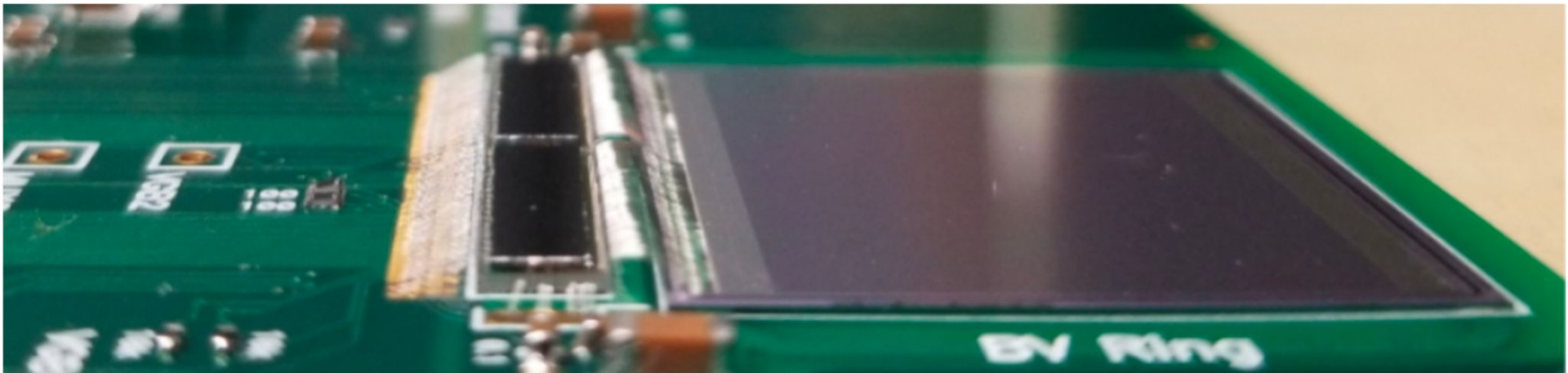
- The **2xSSA** module is designed to mimic the sensor-ASIC assembly.
 - Used to test ASIC performance in a “realistic” setting, including inter-chip communication



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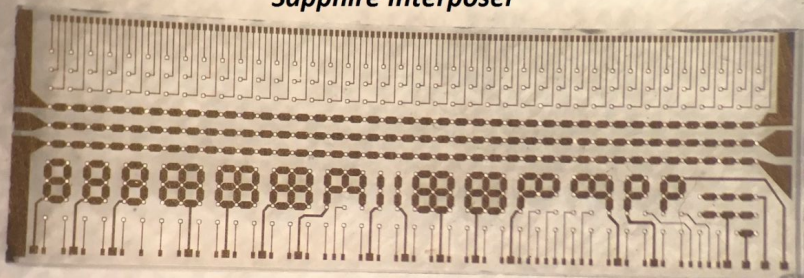


- The **2xSSA** module is designed to mimic the sensor-ASIC assembly.
 - Used to test ASIC performance in a “*realistic*” setting, including interchip communication
 - Module consists of a PCB with a 240 channel silicon strip sensor read out by two SSAs.
 - Strip pitch is 100 microns
 - DAQ was developed for SSAs using this setup
- Final product shown here, but many iterations before a successful A-to-Z assembly!

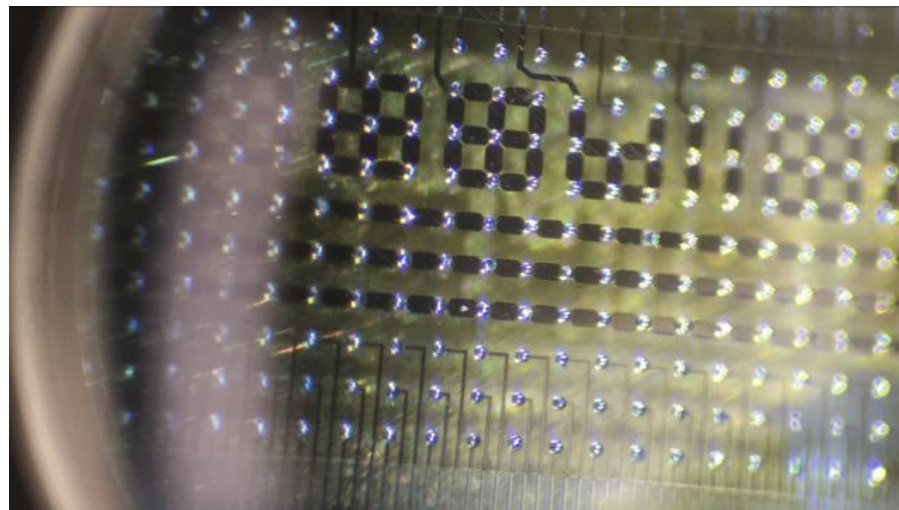


- Bump bonding the SSAs to the interposer proved quite complicated
- Initial plan was Indium bump bonds: **too much force on chip!**

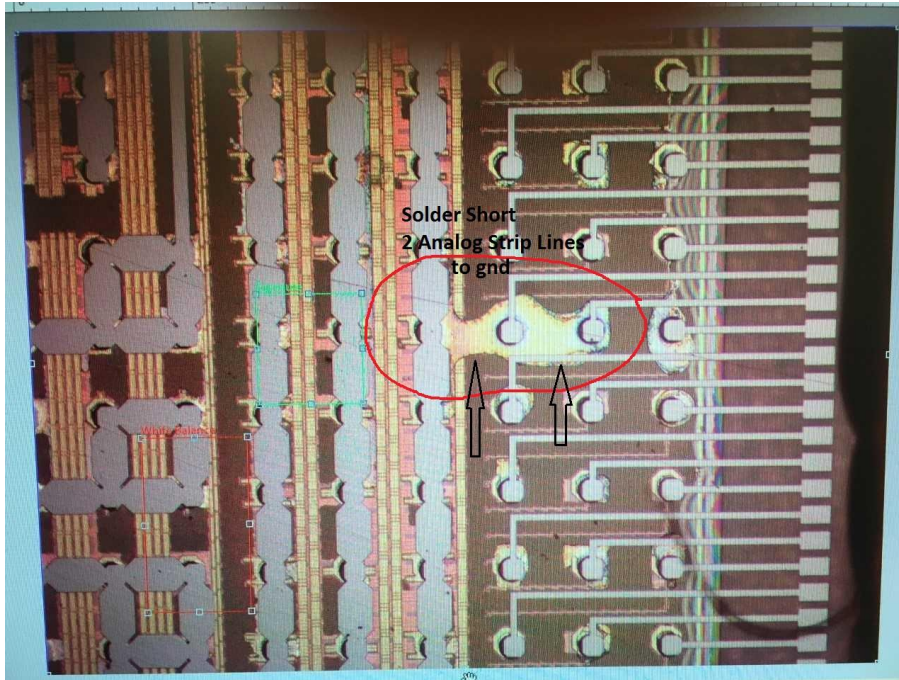
Sapphire Interposer



SSA Die Bumped with 7um Indium



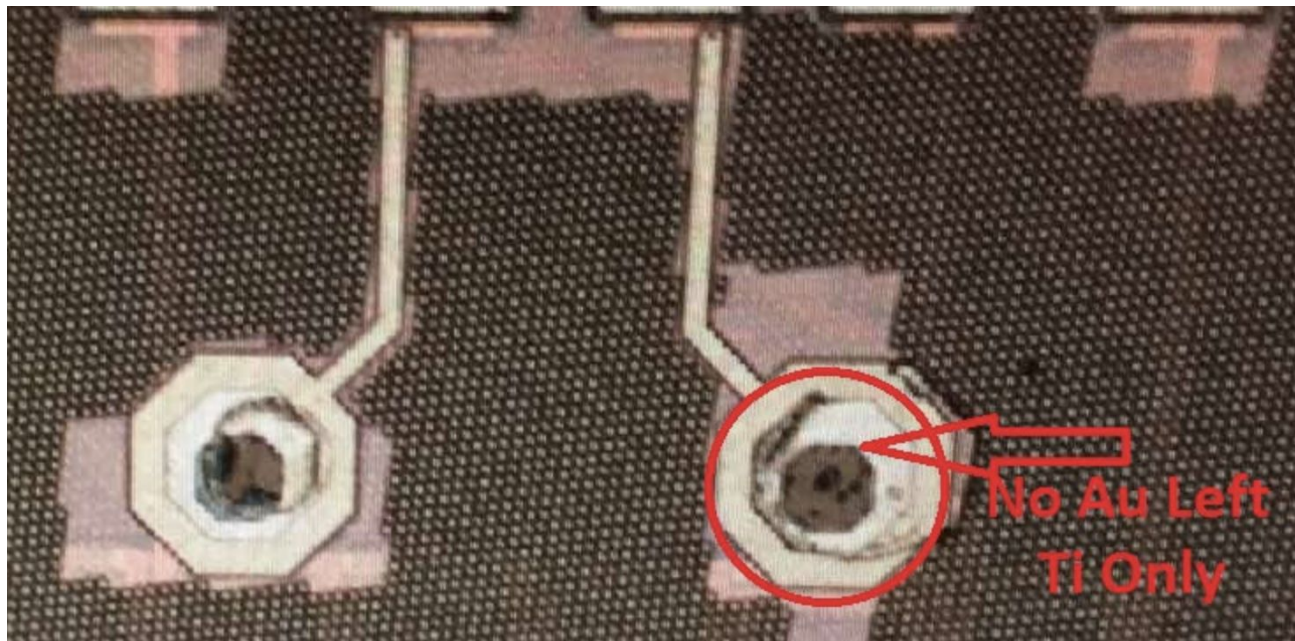
- Bump bonding the SSAs to the interposer proved quite complicated
- Next tried Lead-Tin alloy solder bumps: **No success ...**



Very small margin of error for bump placement.

Shorts can be catastrophic for the ASICs depending what is being accidentally connected

- Bump bonding the SSAs to the interposer proved quite complicated
- Next tried Lead-Tin alloy solder bumps: **No success ...**



Even when no mistakes are present, ASICs did not work correctly; sometimes didn't work at all!

Disassembling the device revealed a surprise: gold bump-bonding pads had vanished!

- Bump bonding the SSAs to the interposer proved quite complicated
- Next tried Lead-Tin alloy solder bumps: **No success ...**

Metallurgy!

Tin "scavenges" gold (literally pulls the gold atoms into the SnPb bump).

Without the gold, SnPb won't make a bond with Ti!

Solution: Add a layer of platinum to the bump-bonding pads before adding the solder.

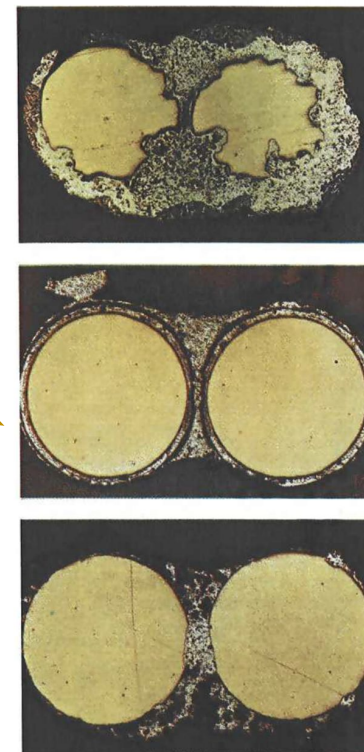
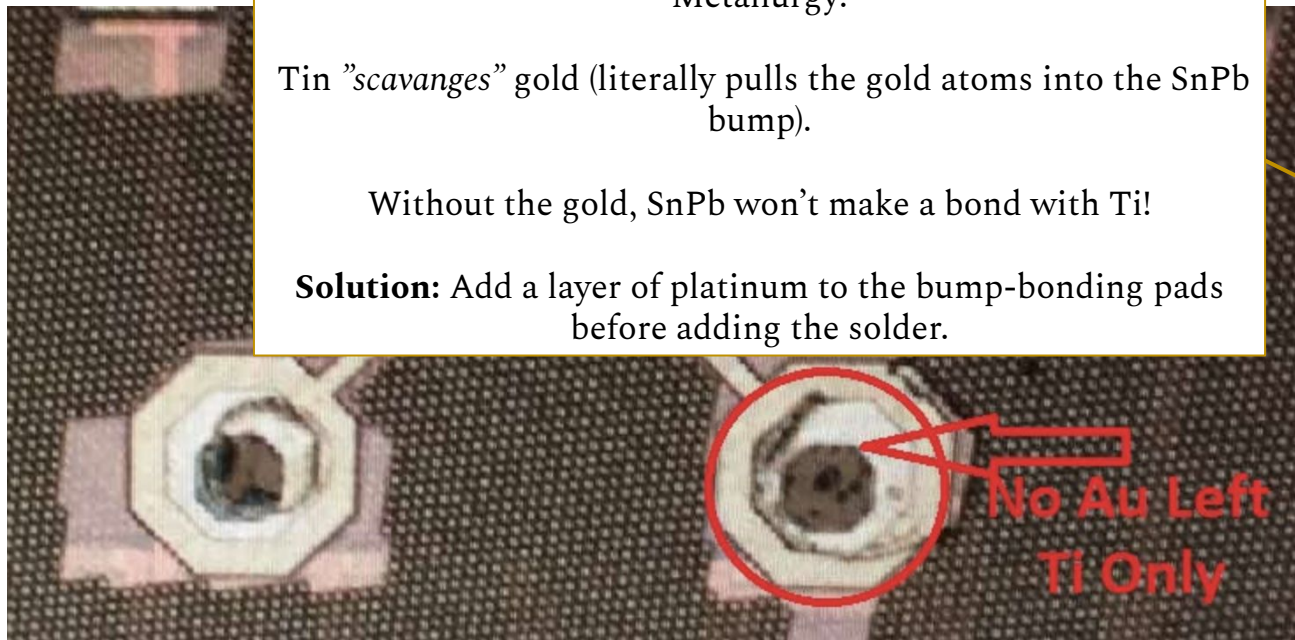
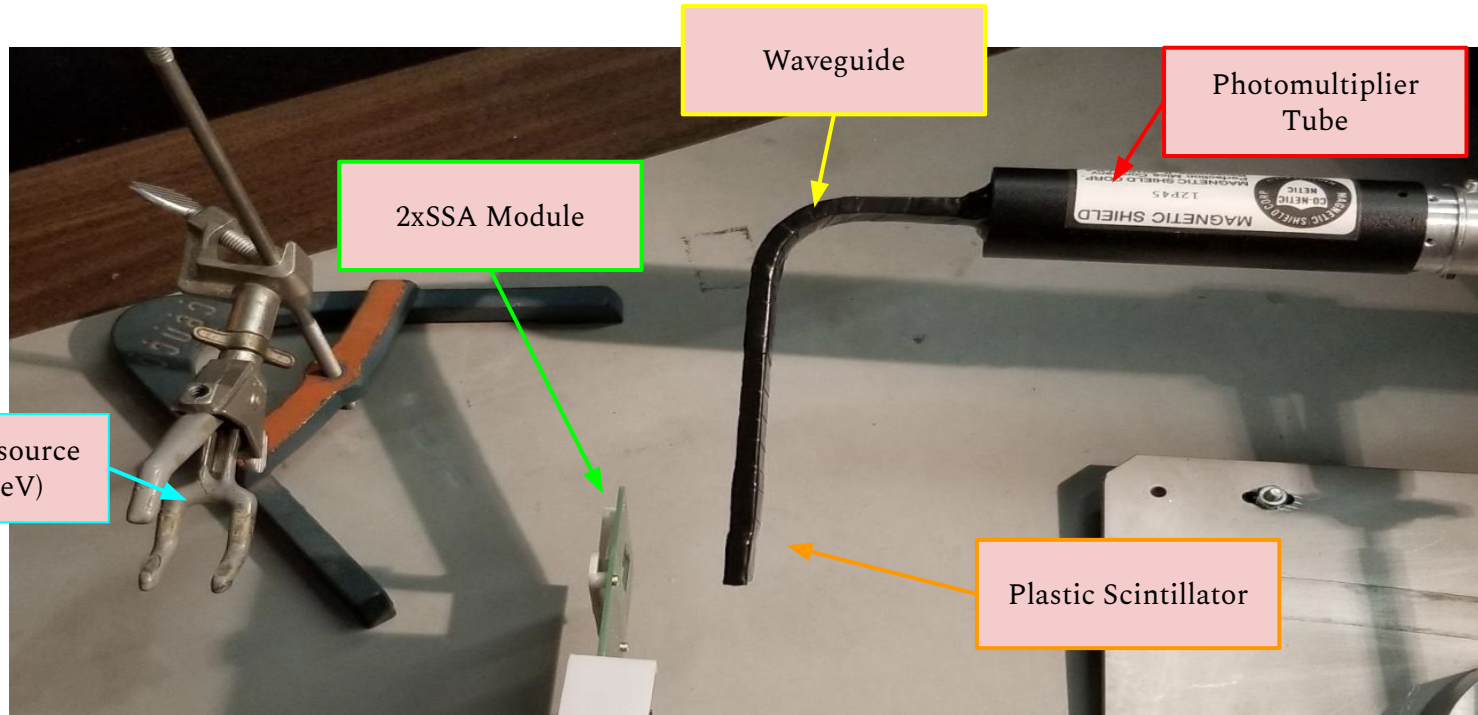


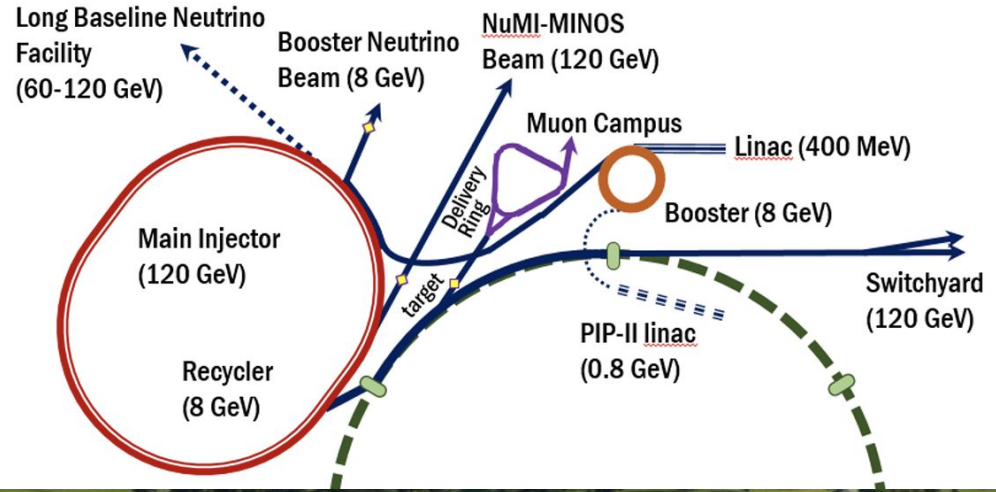
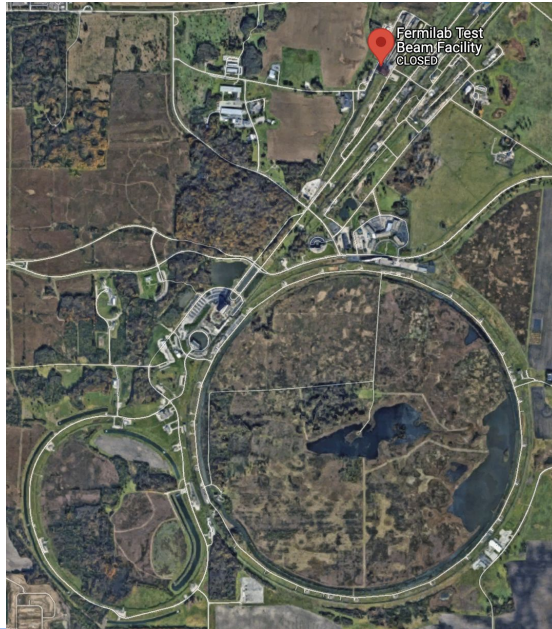
Fig. 2 Micrographs showing the differences in severity of attack on gold wires for different compositions of solder
(a) (top) Sn-40Pb, 240°C
(b) (middle) Sn-33Pb-18Cd, 260°C
(c) (bottom) Sn-29Pb-17.5In-0.5Zn, 245°C ×60

- Very simple but highly effective test setup at Rutgers: provided first “*triggered*” data ever taken with an SSA.

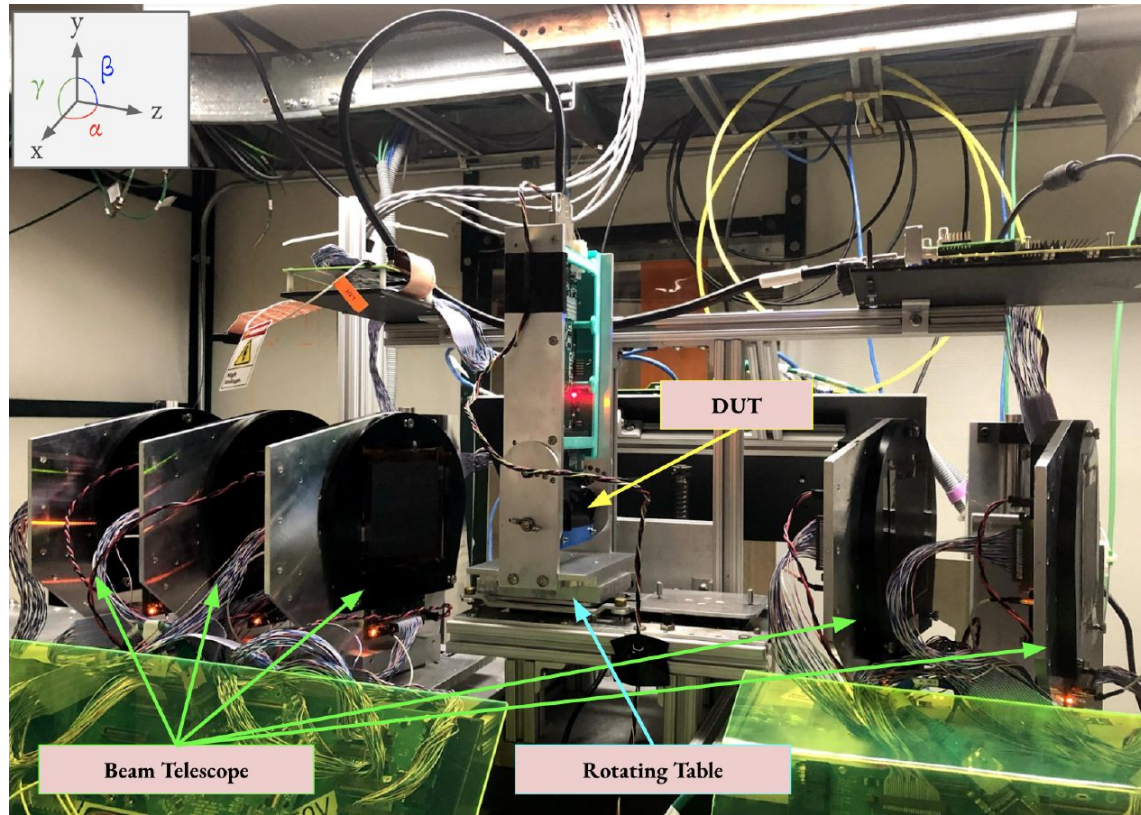


Beam Test!

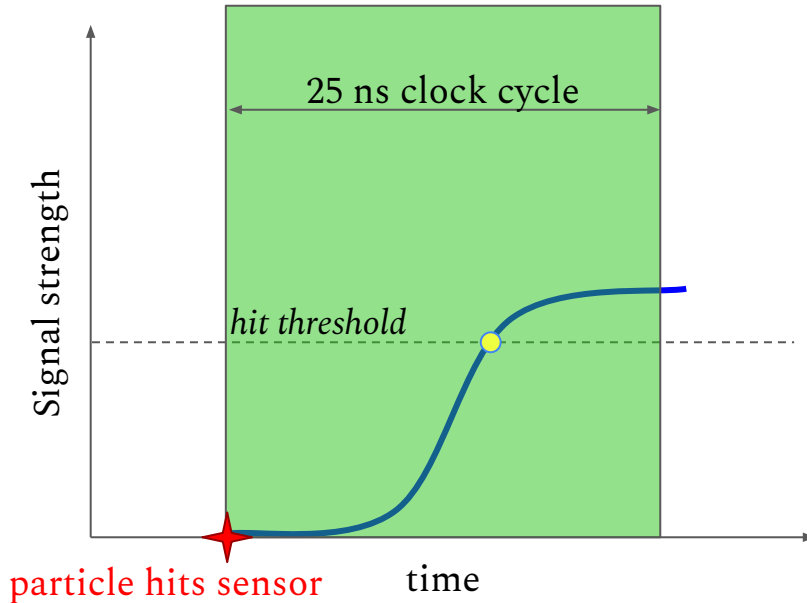
- Fermilab main injector beam (120 GeV protons) delivered to test beam facility
- Highly controlled environment!



- 2xSSA module taken to Fermilab to take beam from the main injector (considerable technological upgrade from our tabletop)
- Test beam facility equipped with a beam “telescope” consisting of pixel and strip planes (resolution of $\sim 15 \mu\text{m}$).
- Scintillator detector (not shown) simultaneously triggers module and telescope with a resolution of a few hundred picoseconds.
- Beam clock synced with telescope and module.

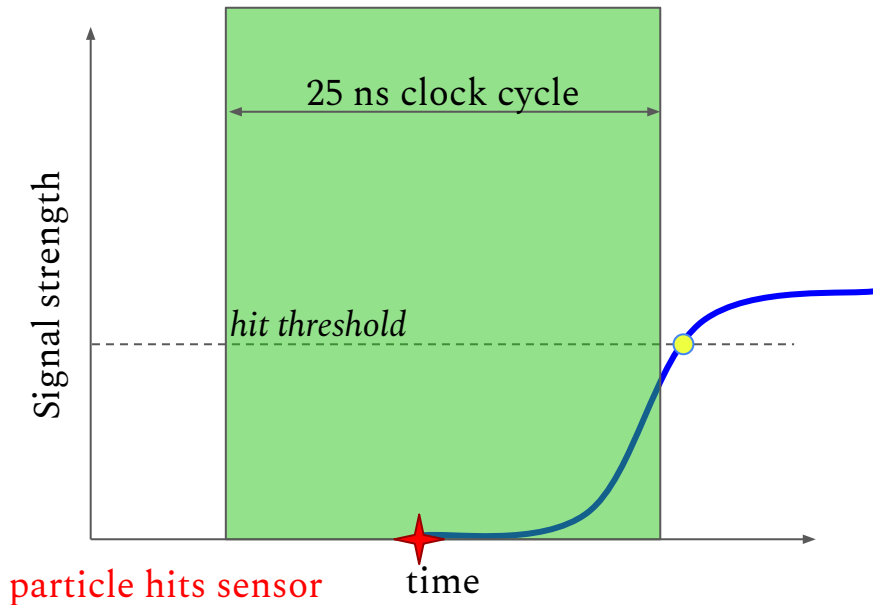


- Timing efficiency measured (sometimes called “*timewalk*”):
 - ASIC front-end takes non-negligible time to convert the electrons produced in silicon to a digitizable pulse:

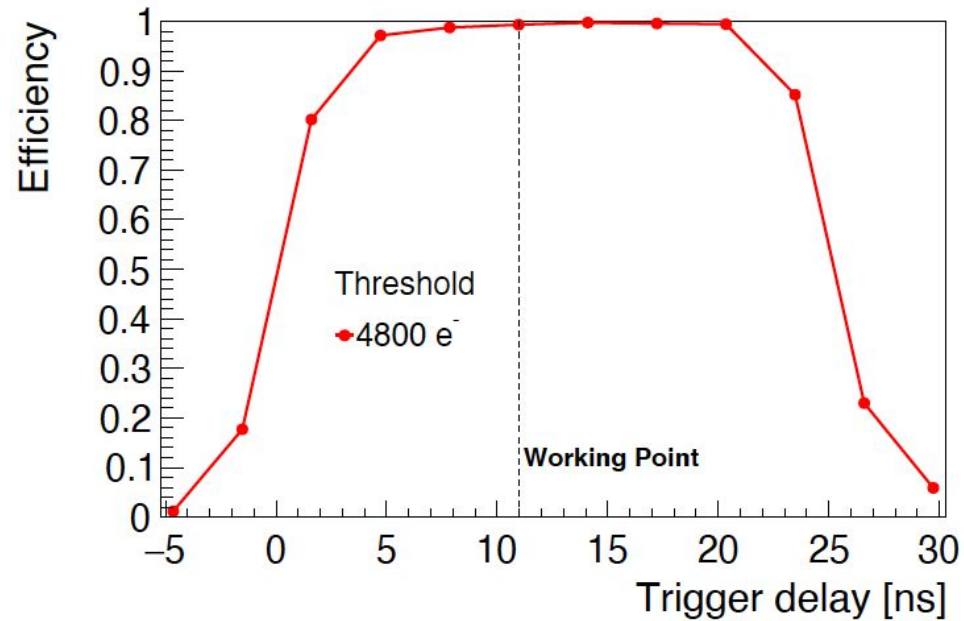
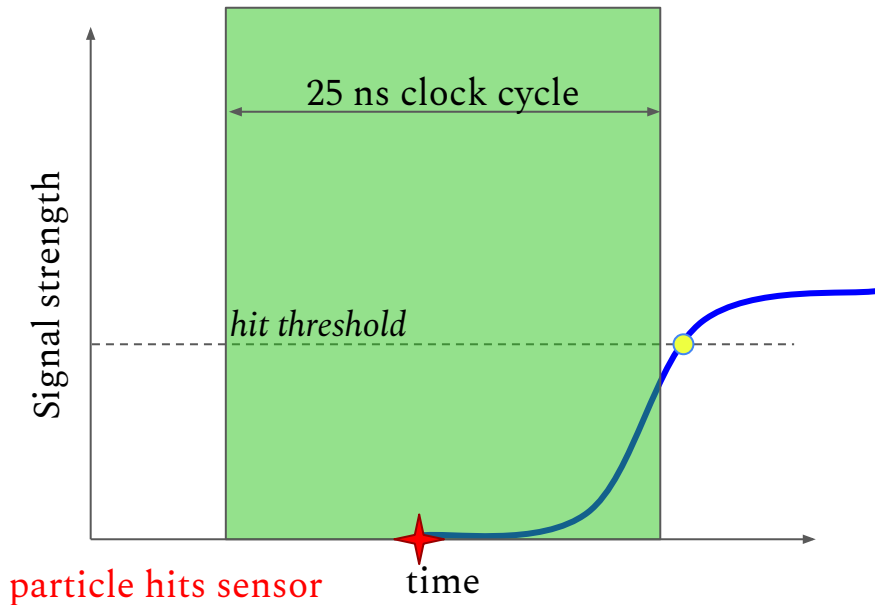




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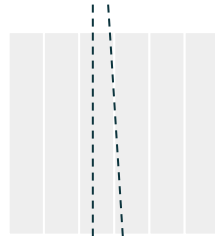


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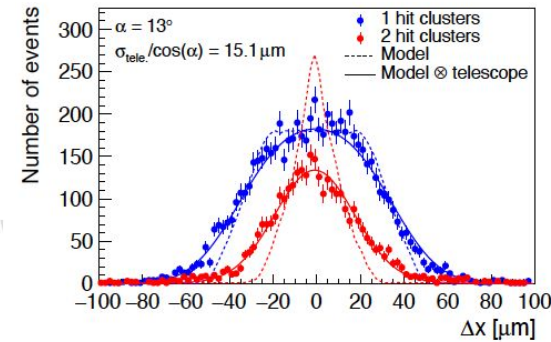
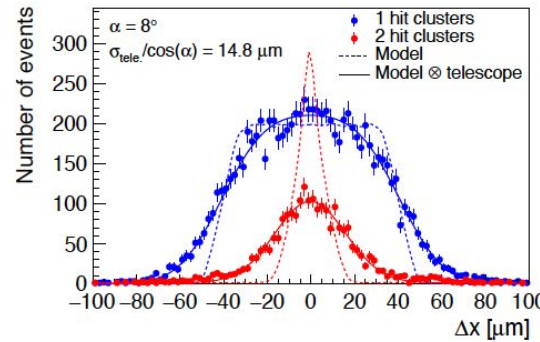
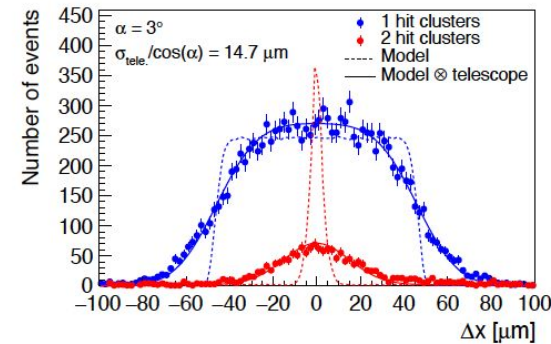
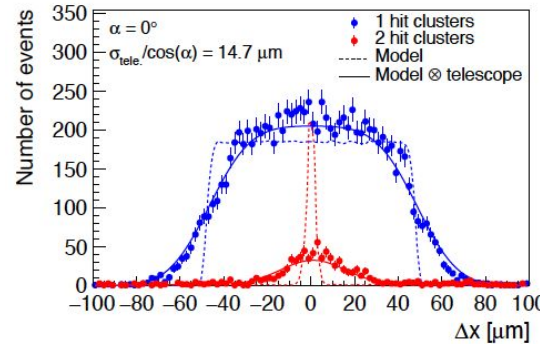
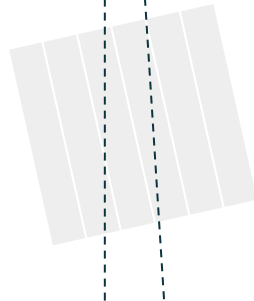


- Resolution measurement (only possible with telescope)
- Agrees with simple models of the system!

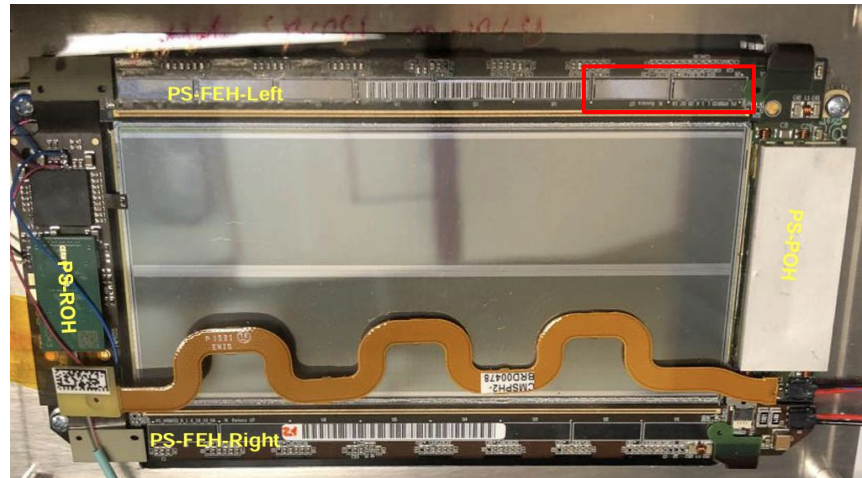
When strips are parallel to beam, a two-strip cluster indicates the particle crossed the strip boundary (very high resolution)



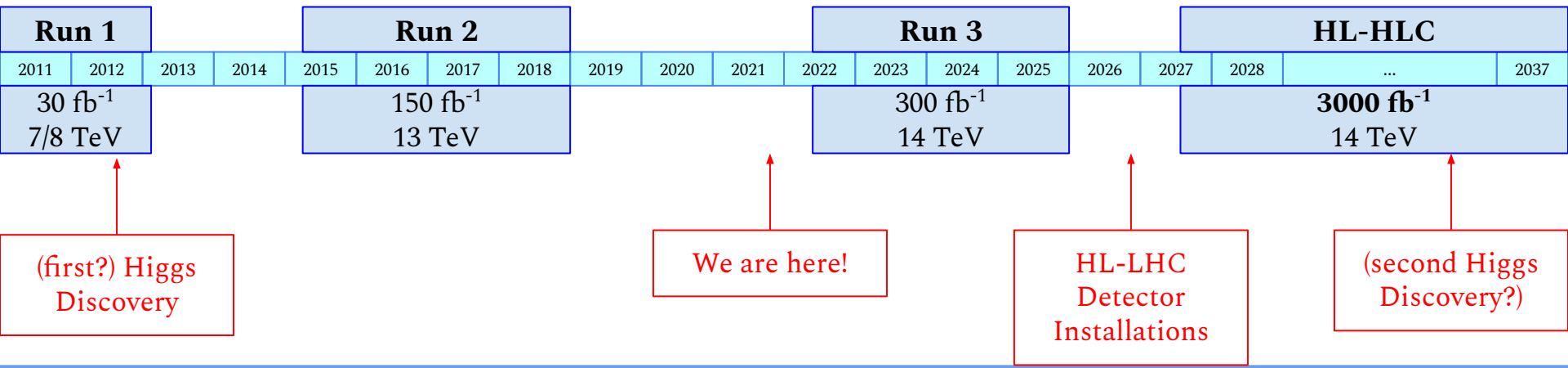
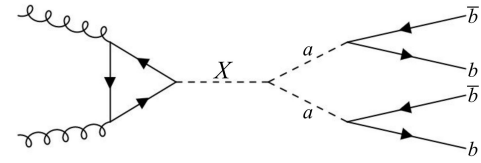
As the angle of the sensor w.r.t. the beam increases, the resolution for two hit clusters degrades (but improves for one hit clusters)



- 2xSSA module behaved exactly as indented (once correctly built)
- **Version 2** of the ASIC ordered confidently ordered from vendors as a result with no unexpected design changes
 - First full MPA+SSA hybrids being assembled now: incorporating **SSAv2**
 - DAQ fully implemented and tested through these beam tests
- Full beam test results submitted to JINST



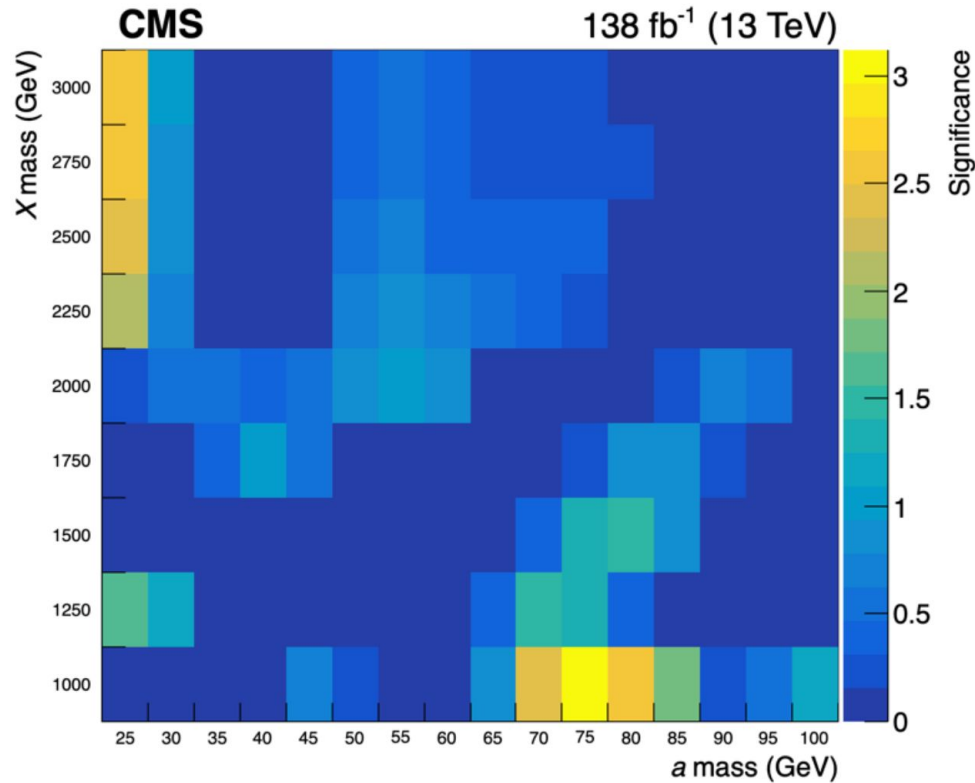
- First result for the $X \rightarrow aa \rightarrow 4b$ final state: no new physics
- By no means the final word!
 - **Analysis techniques and tools to be improved in Run 3**
 - **Next generation of detectors being prepared for HL-LHC**
 - Exciting times ahead!
- Many other decays worth thinking about: $tt+a$, $X \rightarrow ha$, $a \rightarrow \tau\tau$...



BACKUP (ANALYSIS)

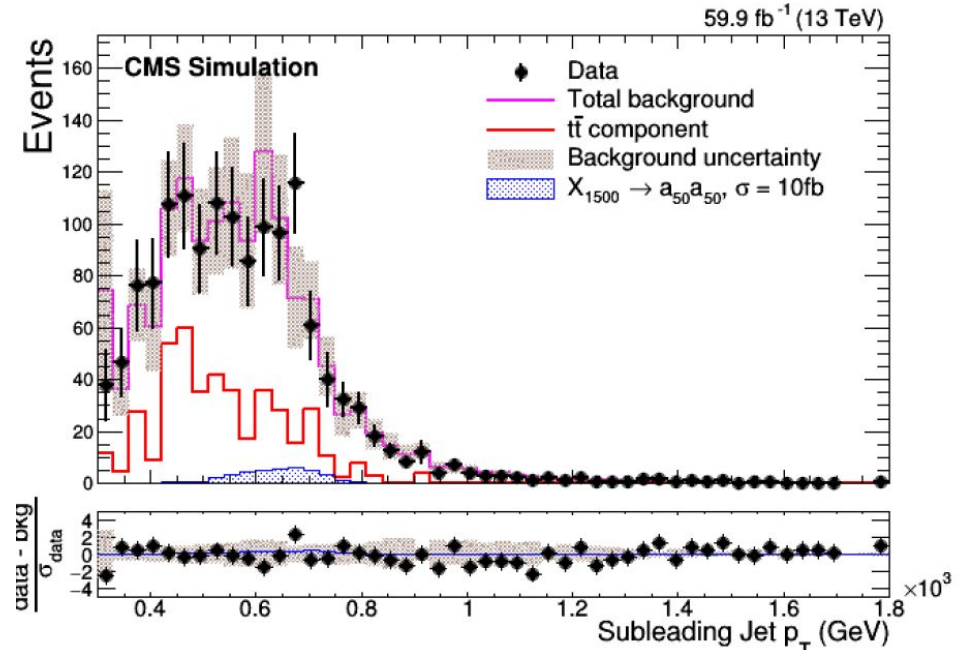
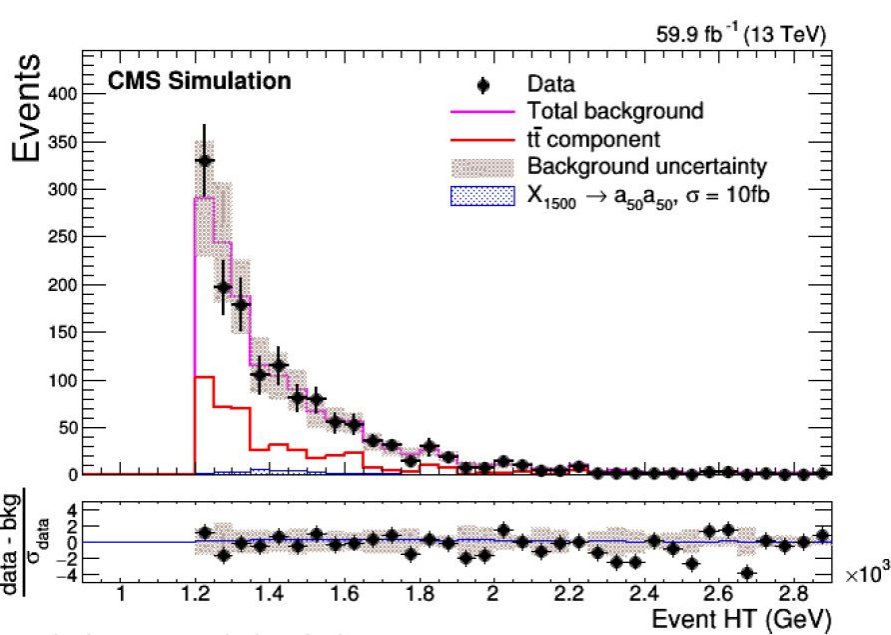
- All systematics considered in the analysis:

	signal	$t\bar{t}$	QCD background
luminosity \star^C	1.2–2.5%	1.2–2.5%	
double-b scale factor C	19–46%		
trigger efficiency C	1–5%	1–5%	
PDF C	4%	4%	
pileup C	1–10%	1–10%	
jet energy scale (correlated) C	2%	2%	
jet energy scale (uncorrelated) Y	2%	2%	
jet energy resolution C	10%	10%	
$t\bar{t}$ α C		100%	
$t\bar{t}$ normalization C		20%	
$R_{p/f}$ fit			5–30%
statistical uncertainty (failing region) \dagger			<1–100%



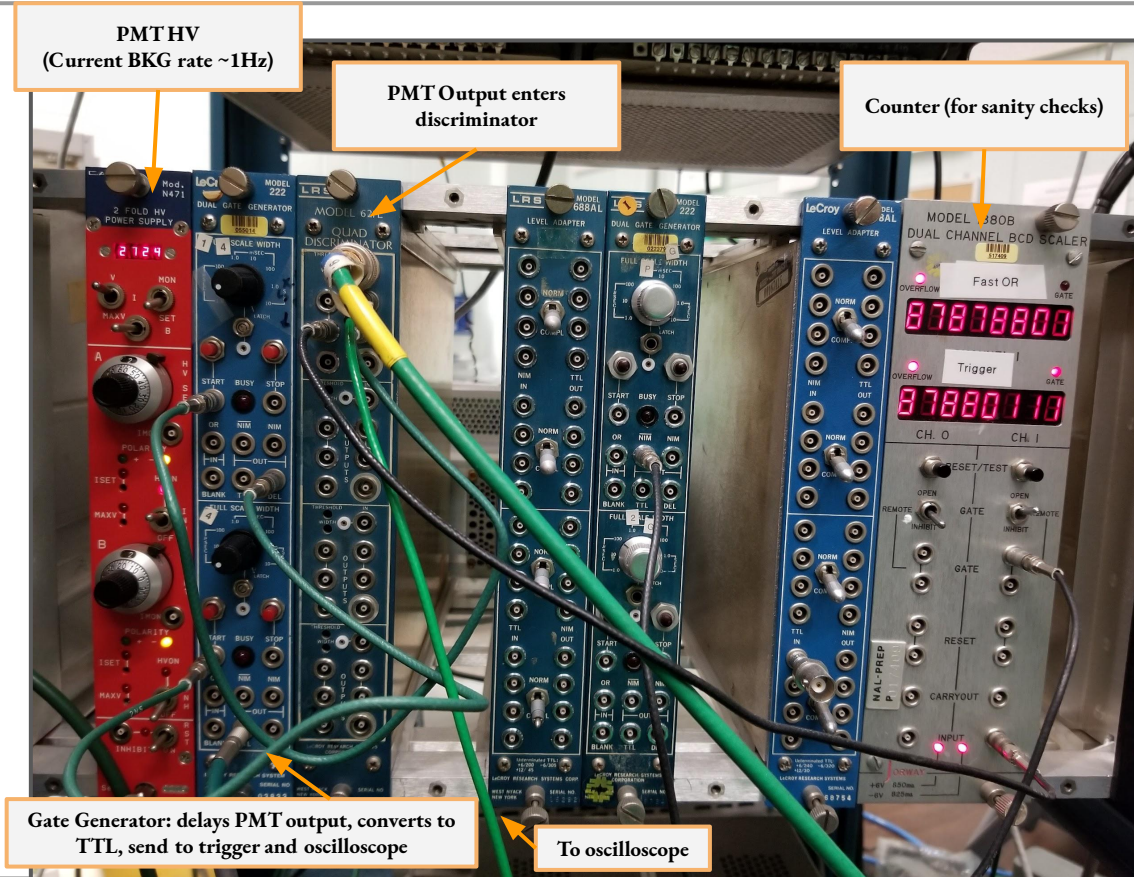


- ABCD method works well for a variety of kinematic variables

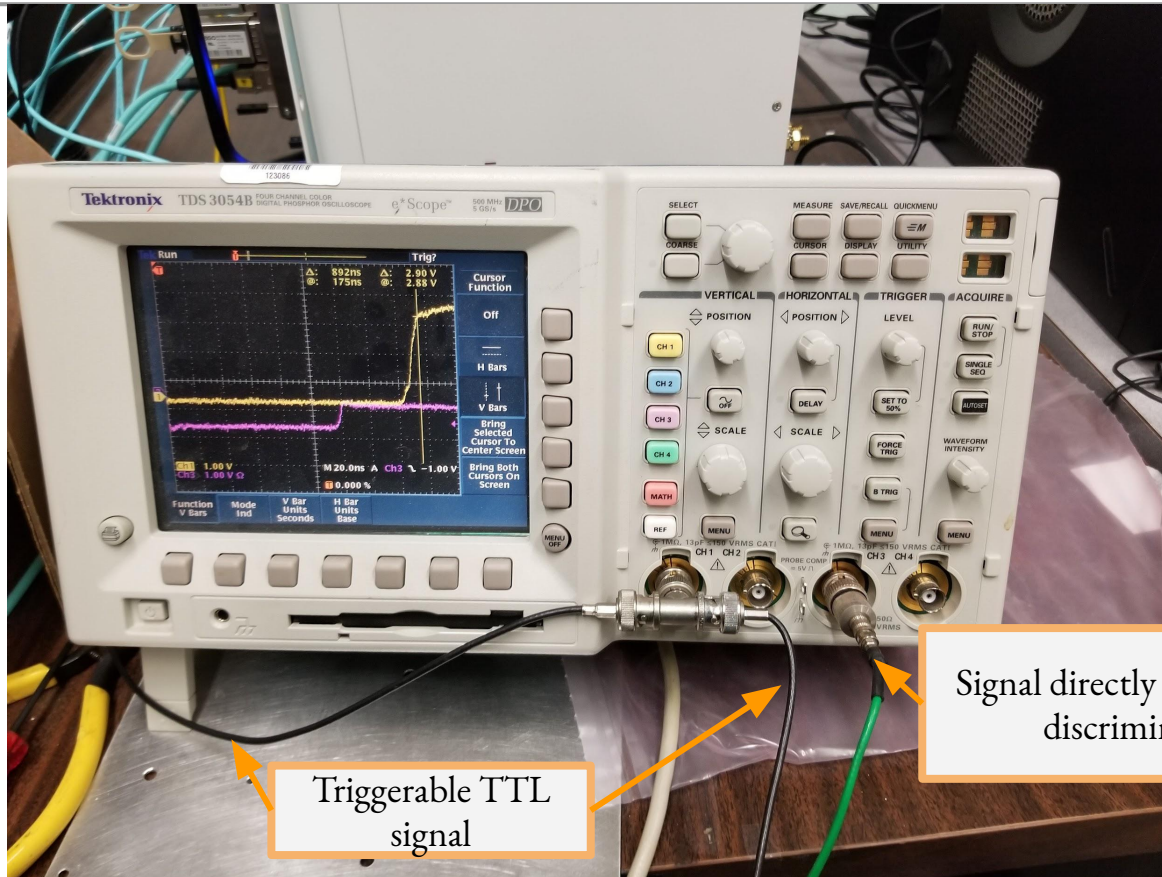


BACKUP (HARDWARE)

Tabletop “DAQ”



Tabletop “DAQ”



Triggerable TTL signal

Signal directly from PMT discriminator

- Efficiency and cluster size, comparing to a simple model

