SUSY and Naturalness in Run 2 and beyond

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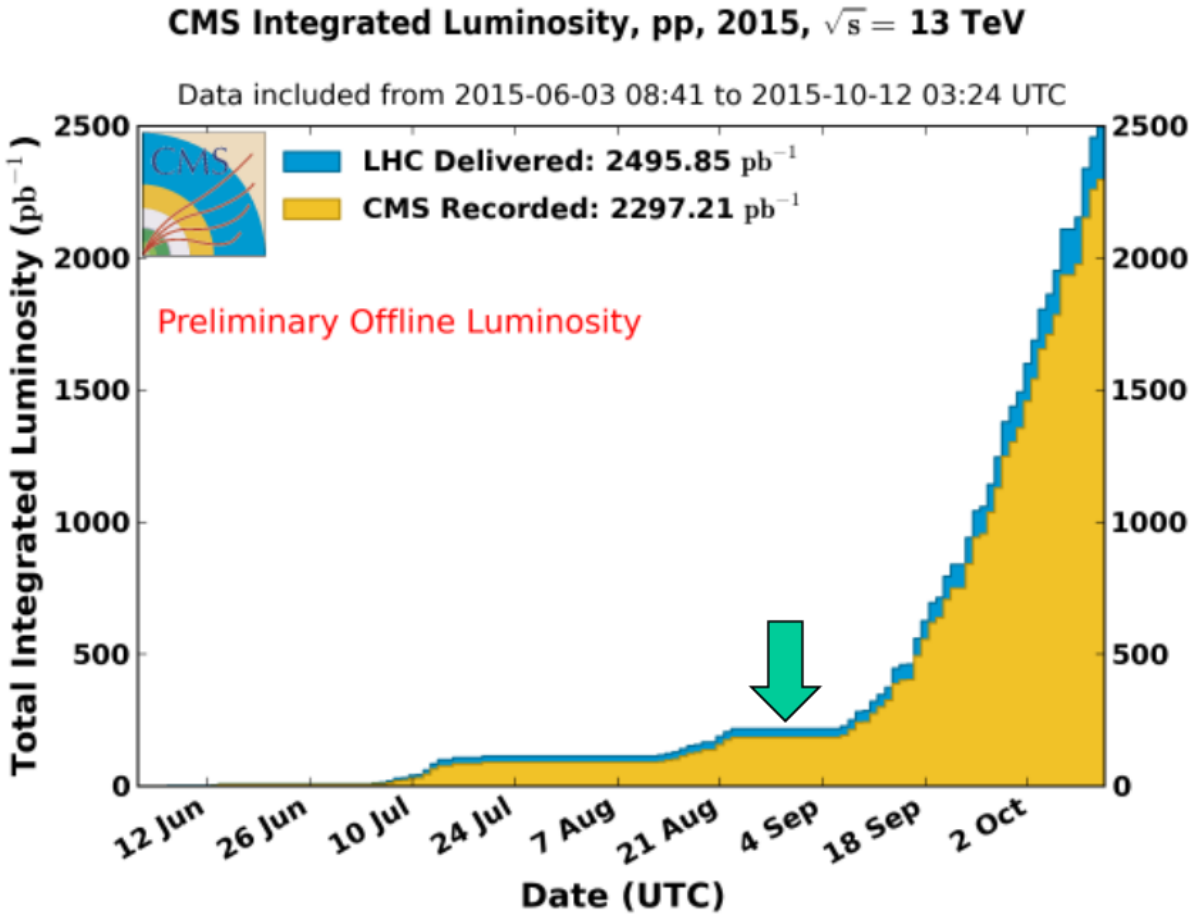
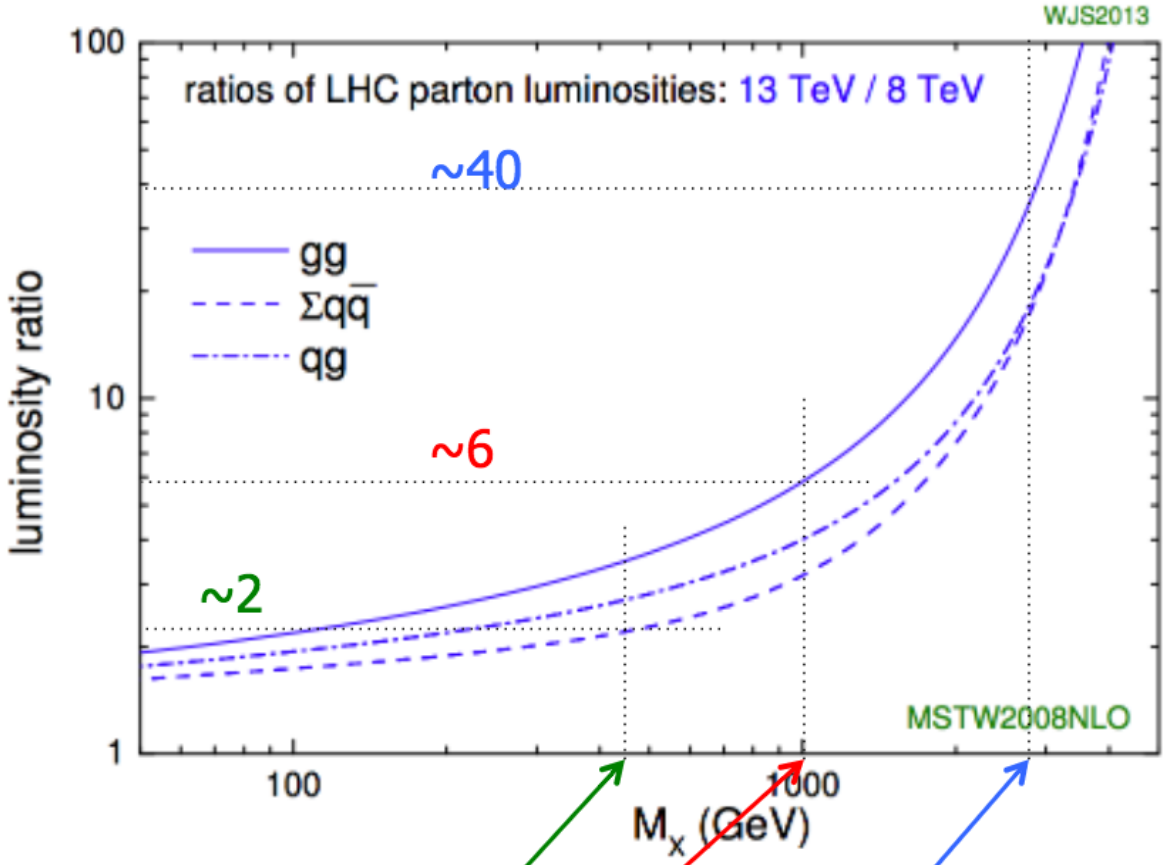
Outline

- Continuation of the Run 1 program
- New features
  - substructure tools, event shapes, …
- Gaps
- After Run 2
  - new experimental possibilities?

Run 2 so far

- Public results with <100/pb
  - mostly detector re-commissioning
- Will likely have 3+ /fb by the end of the year



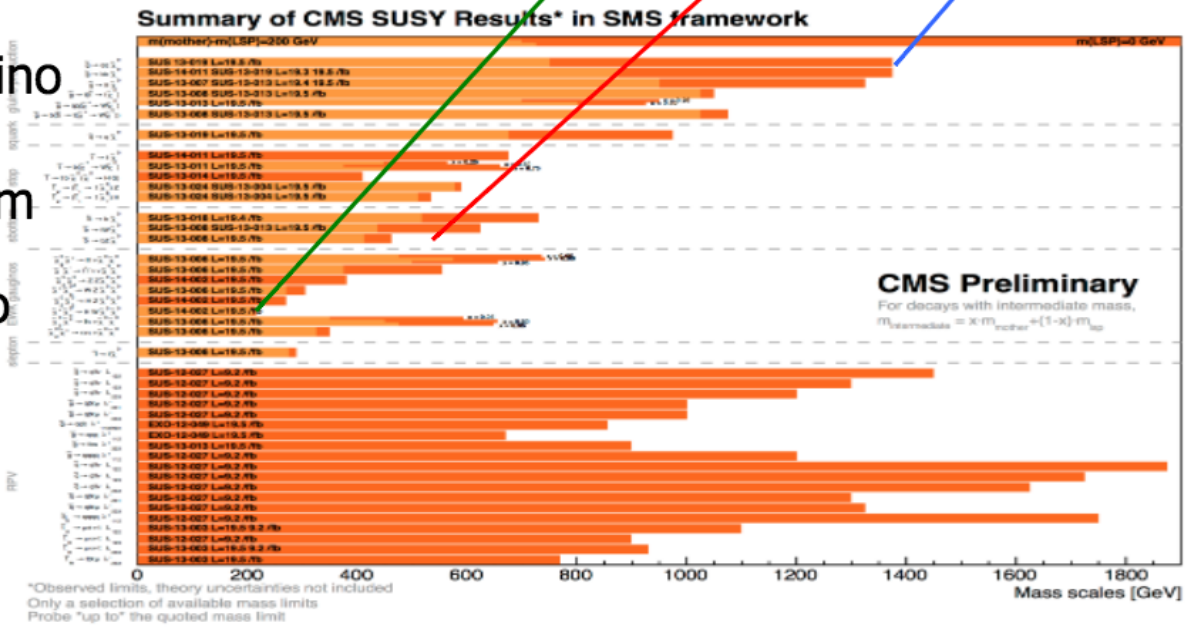


SM top:
815/247 ~ 3.3

gluino

Stop/sbottom

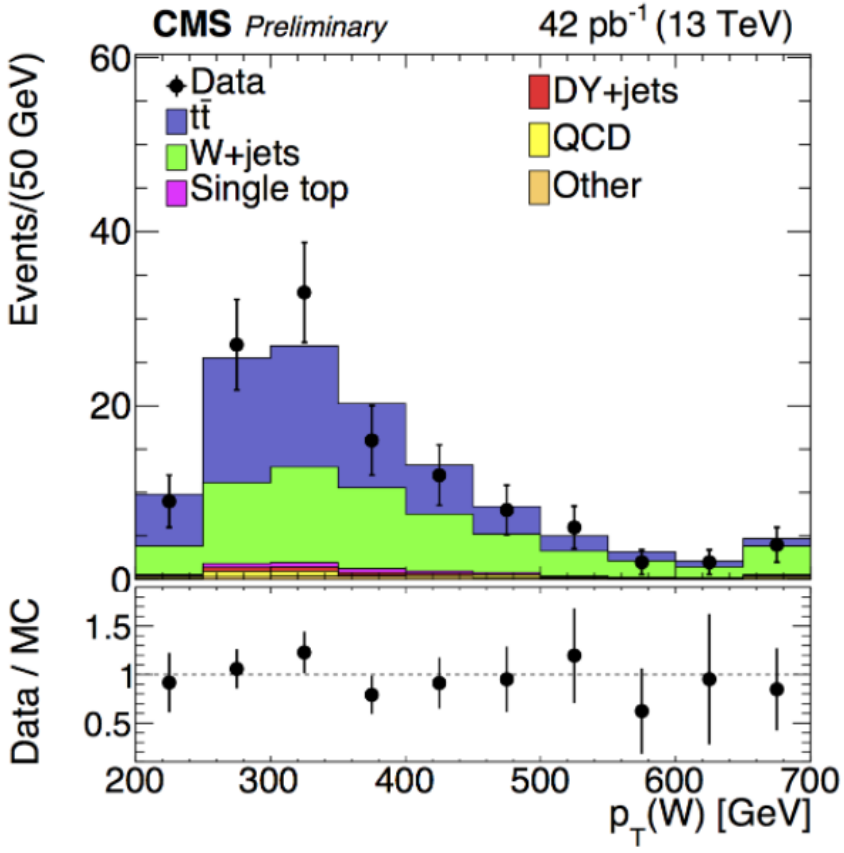
higgsino

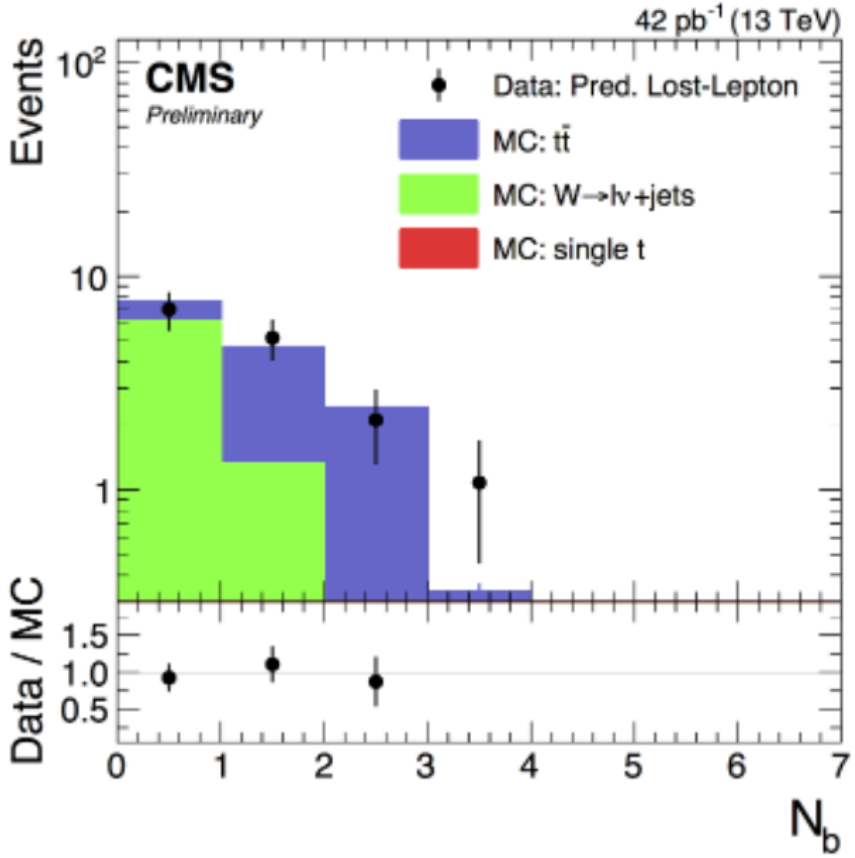


Excluded cross sections range from ~10 fb (high mass gap, low bg) to ~ 1pb (low mass gap)

Heavy gluinos/squarks

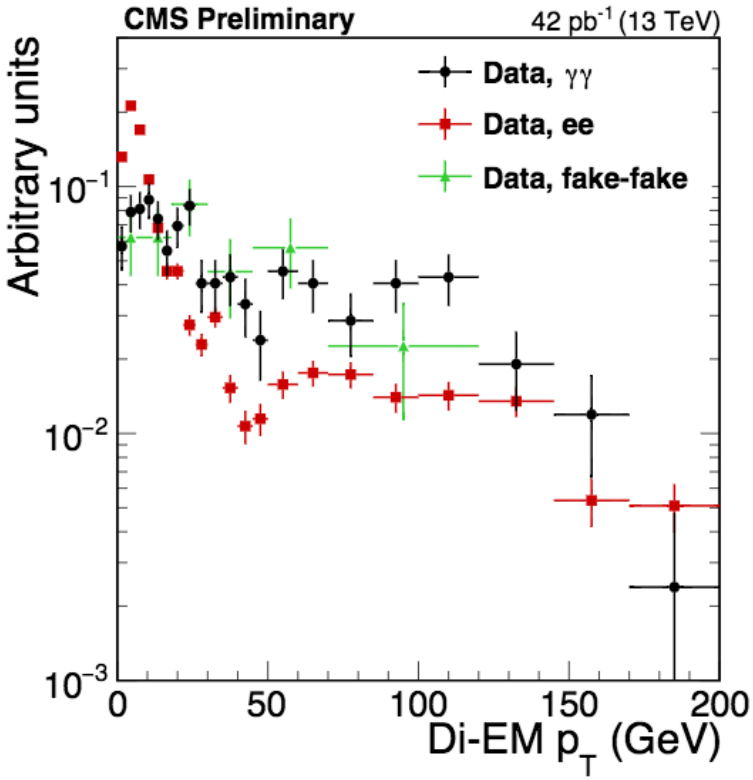
- Classic jets+MET
  - boxes in HT, MET, #jets and #b's
- Analysis re-established, all control regions look good

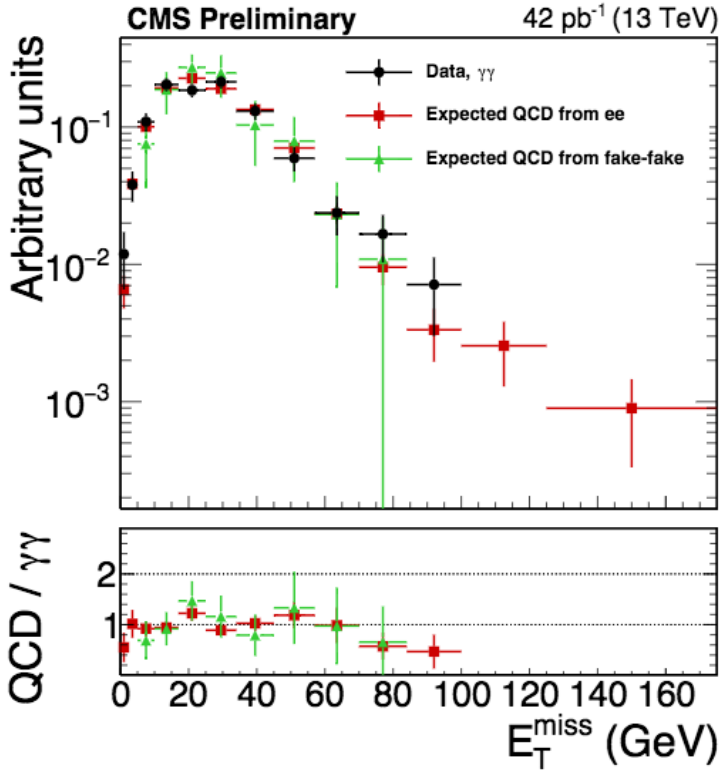




Heavy gluinos/squarks

- Classic gauge-mediation is photons+jets+MET
- Easier then all-hadronic: can "calibrate" MET using non-isolated photons or DY
- Analysis re-established:

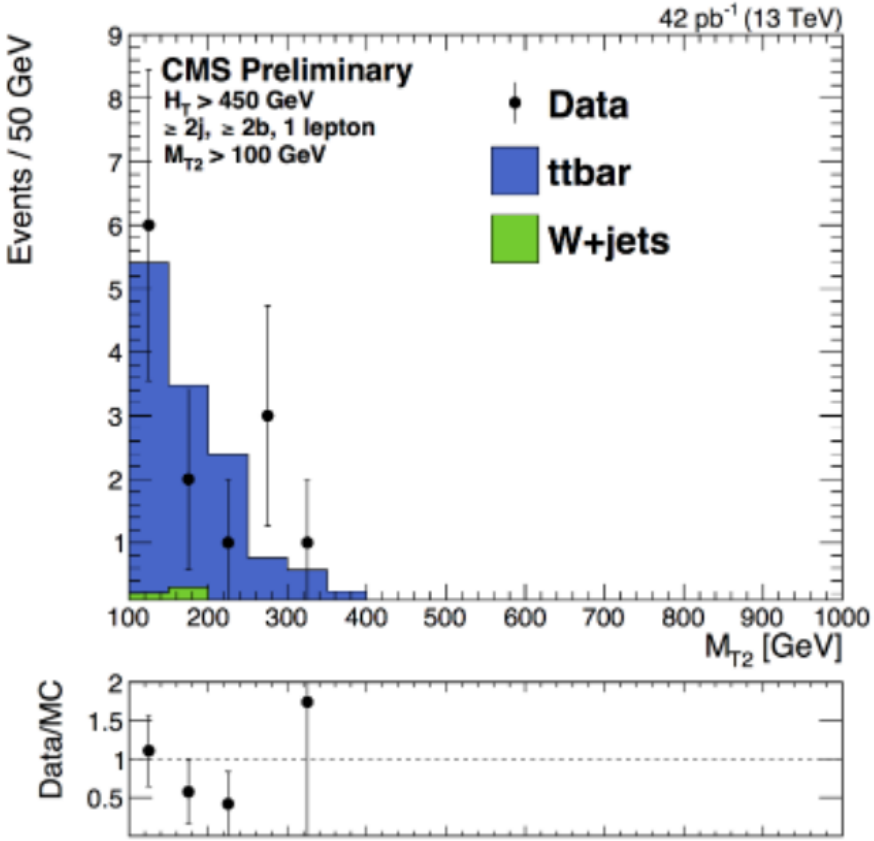




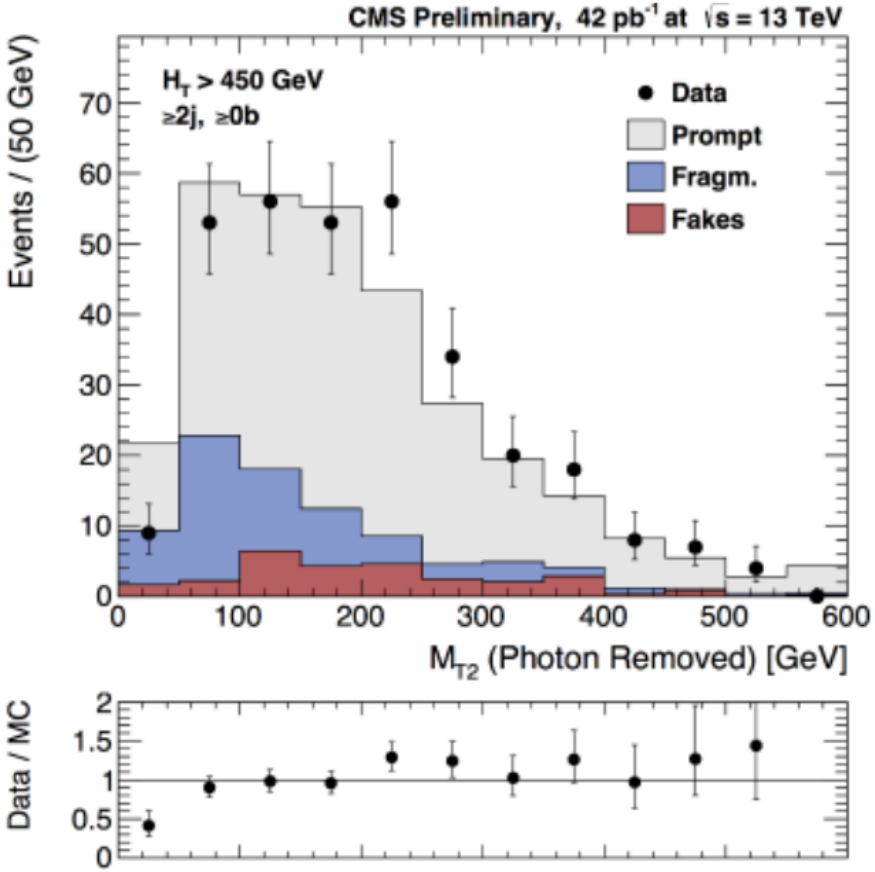
Heavy gluinos/squarks

- Host of "smart" variables
  - alphaT, razor, MT2

1-lepton control region, 2b

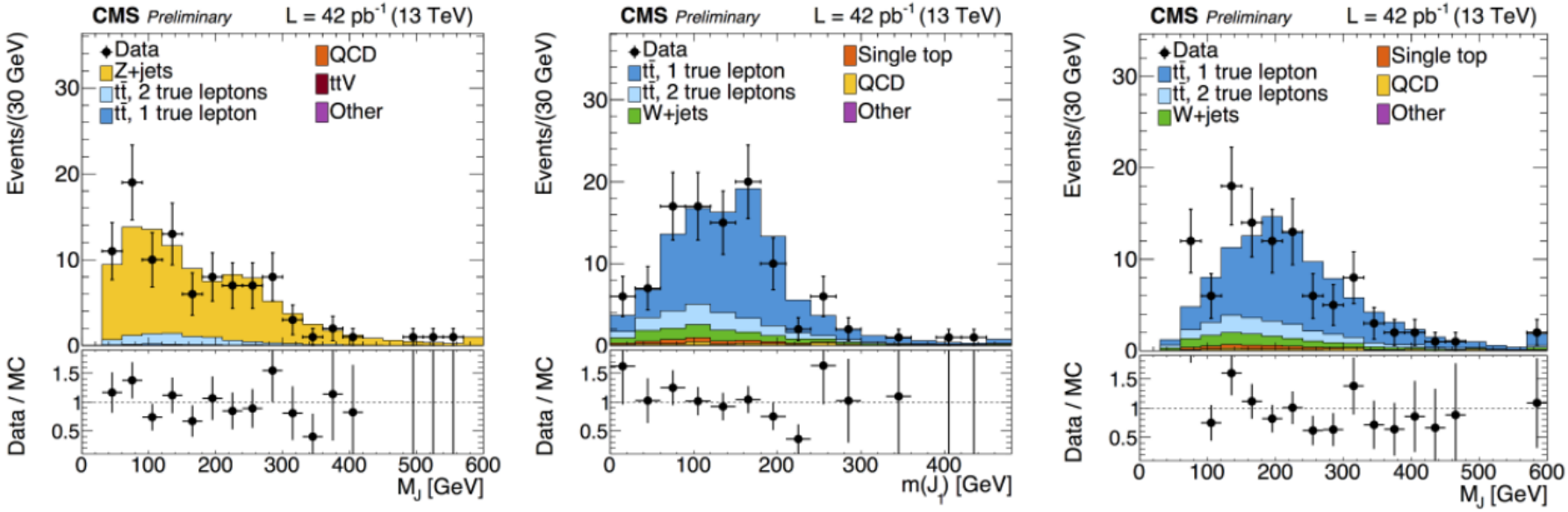


Photon control region, 0b



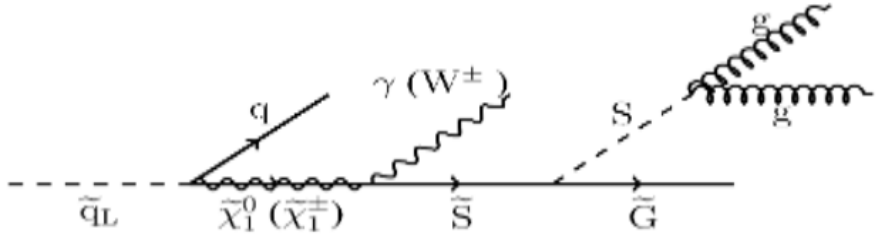
Many-jetted SUSY

- Long cascades reduce MET signature
- Background for huge numbers of jets is hard to control -> forward to substructure tools! (or, back to event shapes!)
  - 1-lepton + jets. MT to reduce semileptonic top
  - Start from AK4 jets and cluster them into R=1.2 jets. MJ = sum of fat jet masses (cf. accidental substructure, Lisanti, Wacker, & friends)
  - Signal at high MJ, most of the top is below $2m_t$
  - Main subtlety is to describe ISR

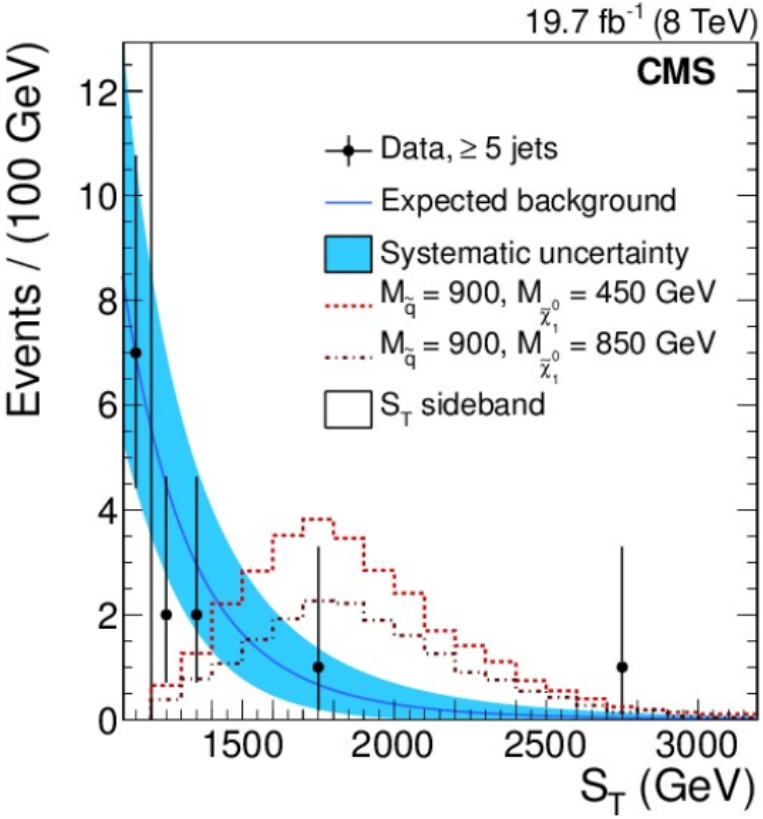


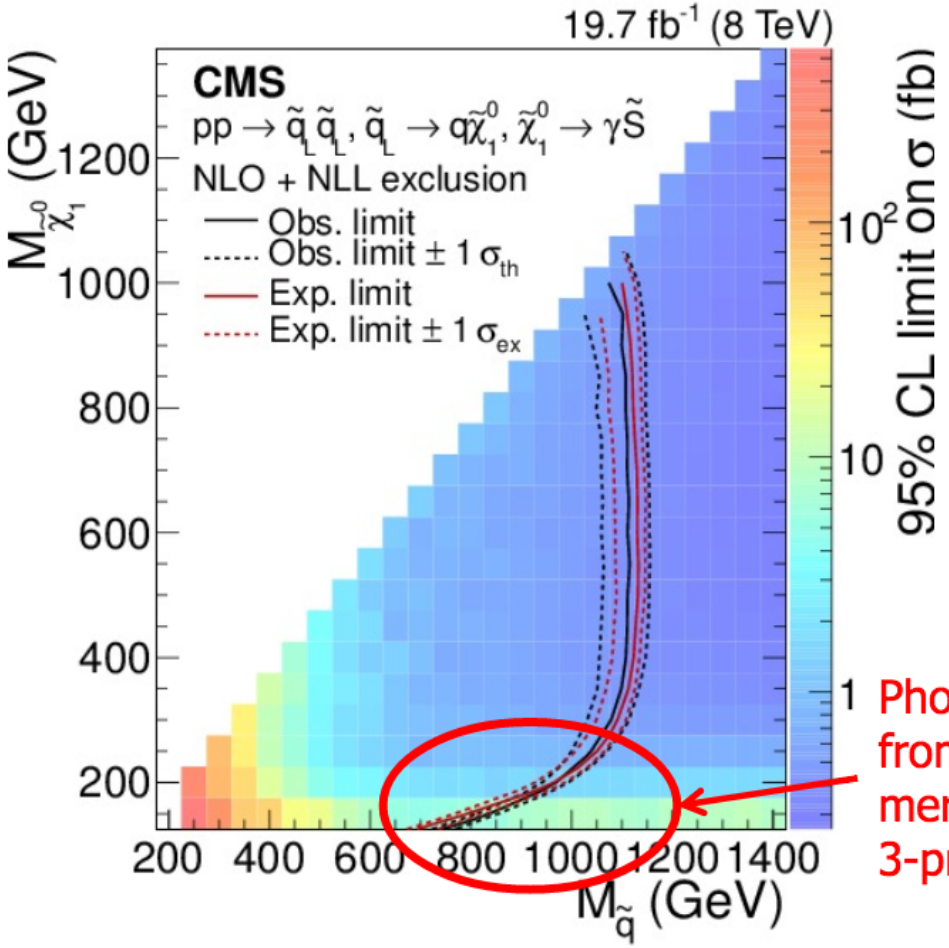
SUSY with jet substructure

- Need for substructure analyses in SUSY: Stealth SUSY



Two photons + >=5 jets
ST distribution invariant of Nj

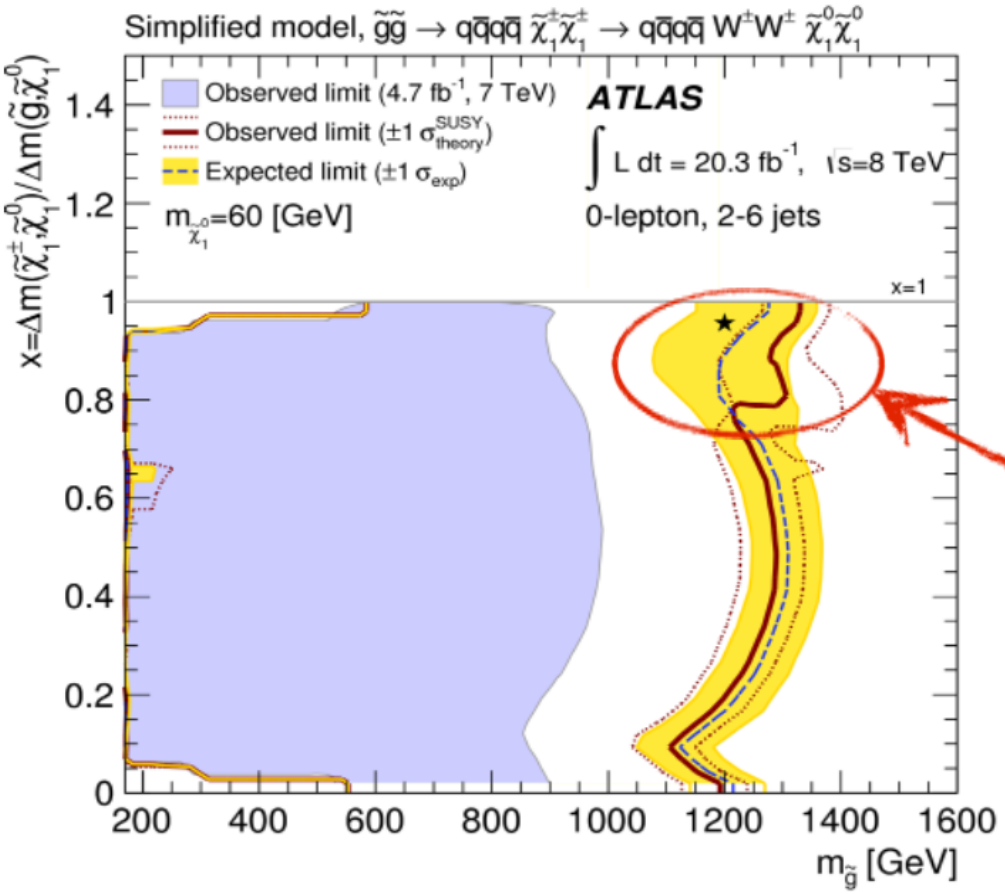


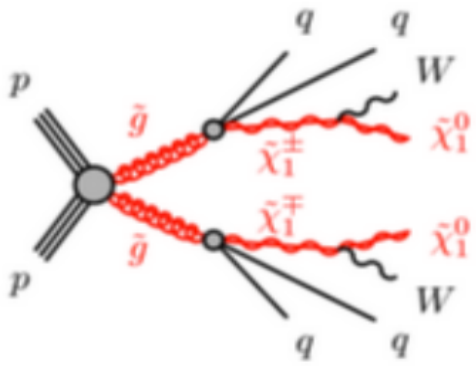


Photons and jets from singlet merge into a 3-pronged object

SUSY with jet substructure

- Run 1 pushed allowed region for colored particles into high masses, but barely nudged electroweak ones -> mass hierarchy -> boosted decay products

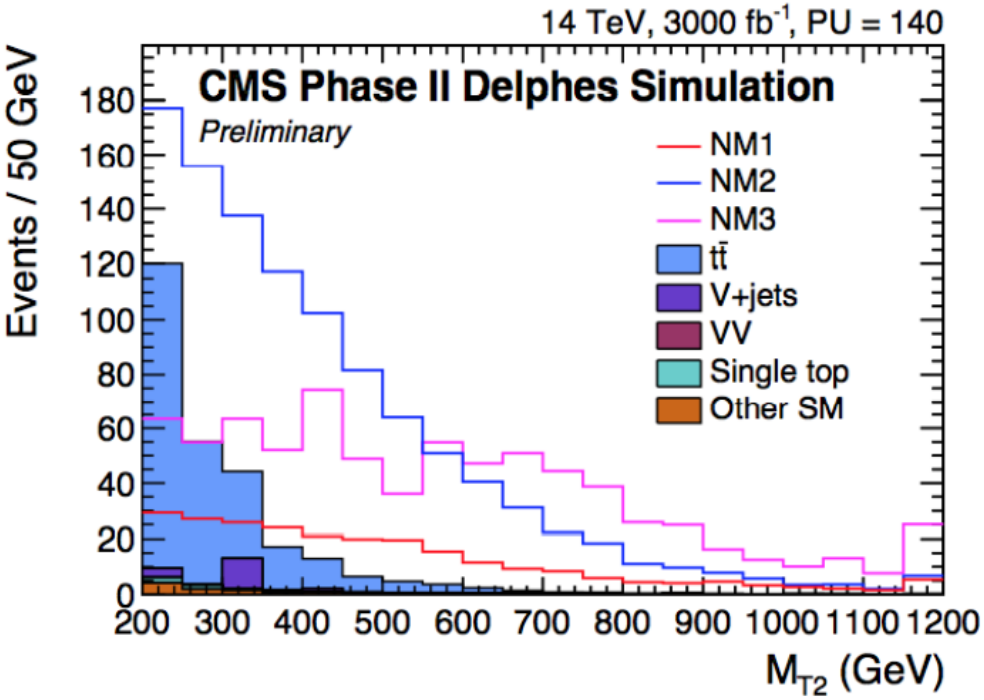


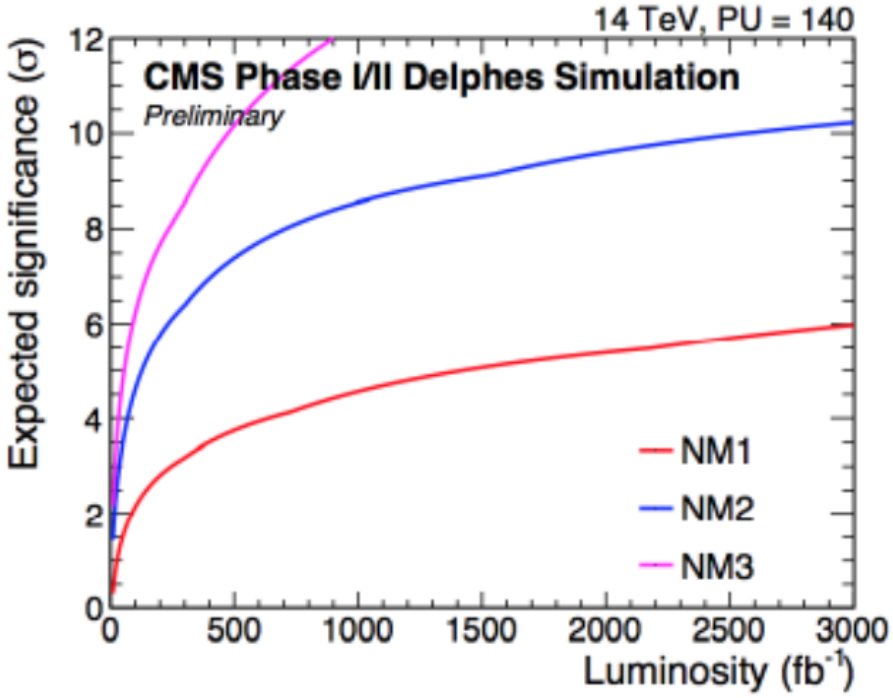


Boosted W→ jj region

Natural SUSY – still wide open

- Three example models for HL-LHC
  - Gluino at ~1.7 TeV, stops and sbottoms at 1.1 TeV
  - different gaugino sectors
- M_{T2} search for Natural SUSY
  - Lepton veto
  - N_j>=8, H_T>2TeV, N_b>3





We've had 30 years to grow comfortable with conventional theories, but naturalness need not adhere to convention.

To truly test naturalness, we should consider the most radical theories that still play by the same rules (calculable Higgs mass controlled by symmetries).

Electroweakinos

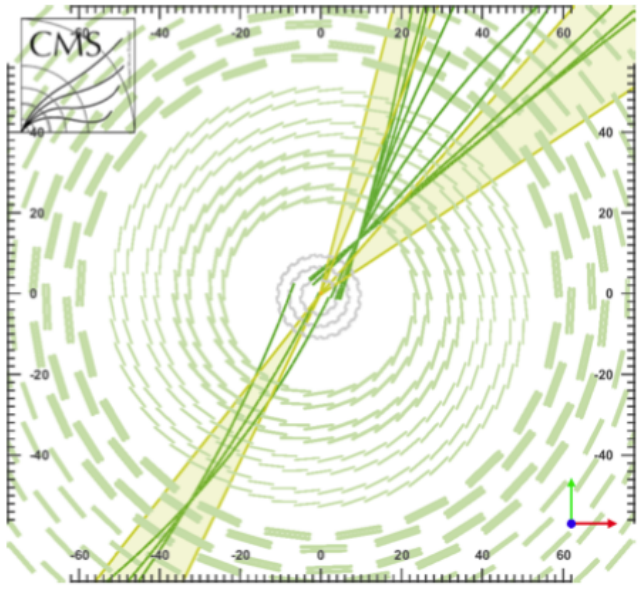
- If only electroweakinos are accessible, the events are quiet and the reach is low
  - Triggering is very hard for compressed spectrum, have to rely on ISR -> results in much reduced efficiency
- Of course LSP can be a LOSP and a portal to the hidden sector
  - In which case some of the LOSP energy may come back to our sector
  - Longish lifetimes are generically possible
- Similar final states for rare higgs decays, i.e. h->XX -> bbbb, bb$\tau\tau$, with displaced X decays. Here have to rely on VBF/VH

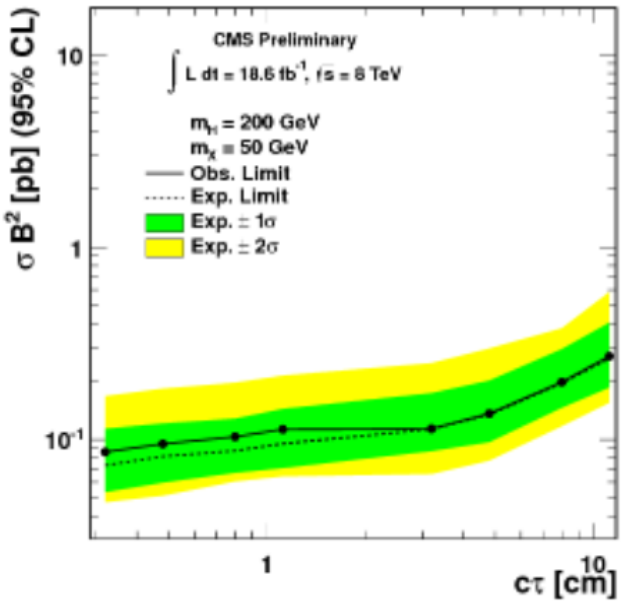
Sensitivity to low mass states decaying into displaced jets is arguably the largest gap in the LHC program

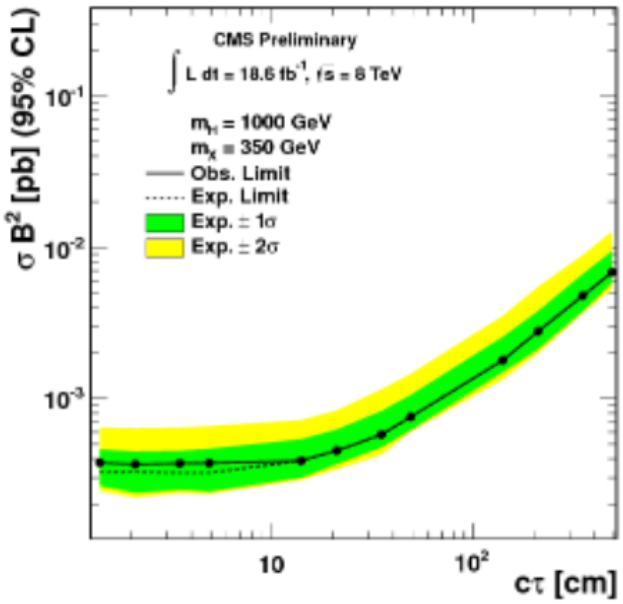
Long-Lived Particles decaying into jets

- decays into jets is tricky - at least for decay products of the H(125)
  - triggering is the main challenge
  - both CMS and ATLAS have dedicated triggers based on specific range on decay lengths
- CMS: HLT trigger on jets with no prompt tracks
  - offline: vertex made out of the two displaced jets, no sensitivity for H(125), not much sensitivity at 200 GeV
  - New for Run 2: high IP tracking at HLT, allows for explicit requirement of displaced tracks, i.e. in VBF-tagged events.

EXO-12-038

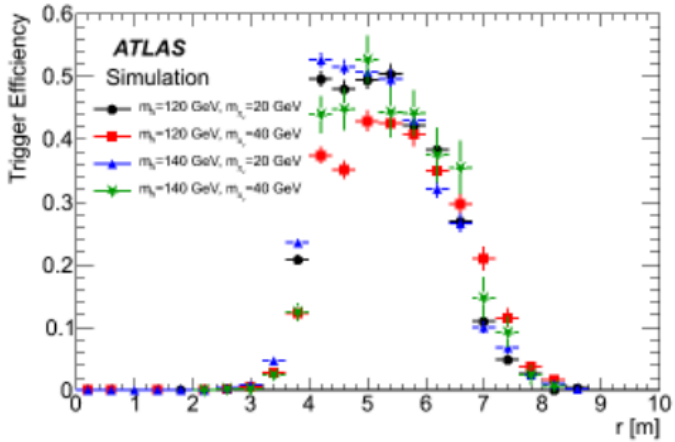


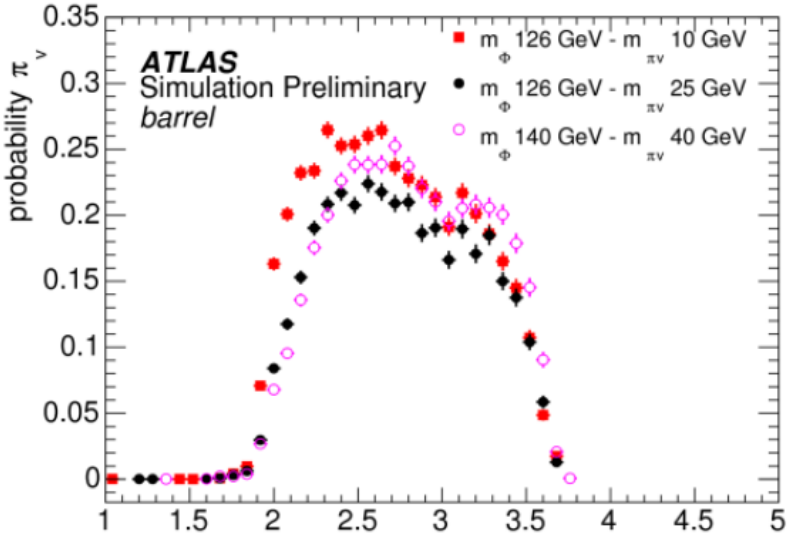


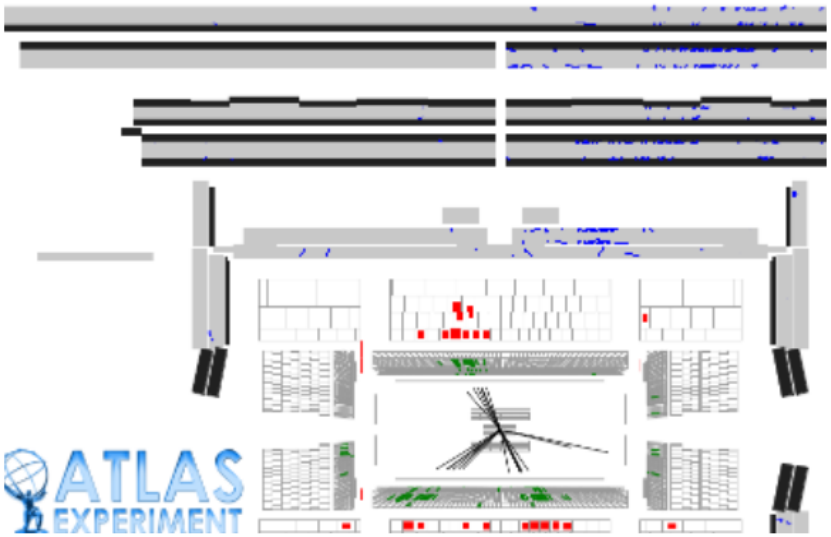


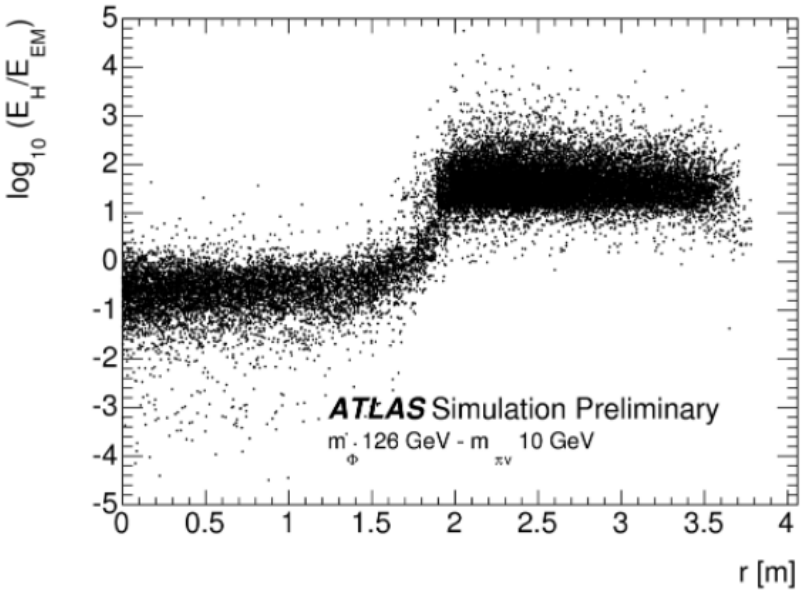
Long-Lived Particles decaying into jets

- ATLAS has focused on utilization of more unusual objects
  - decays in HCAL (no signals in ECAL)
  - decays outside HCAL (vertex in a muon system)
  - extra muon in the event

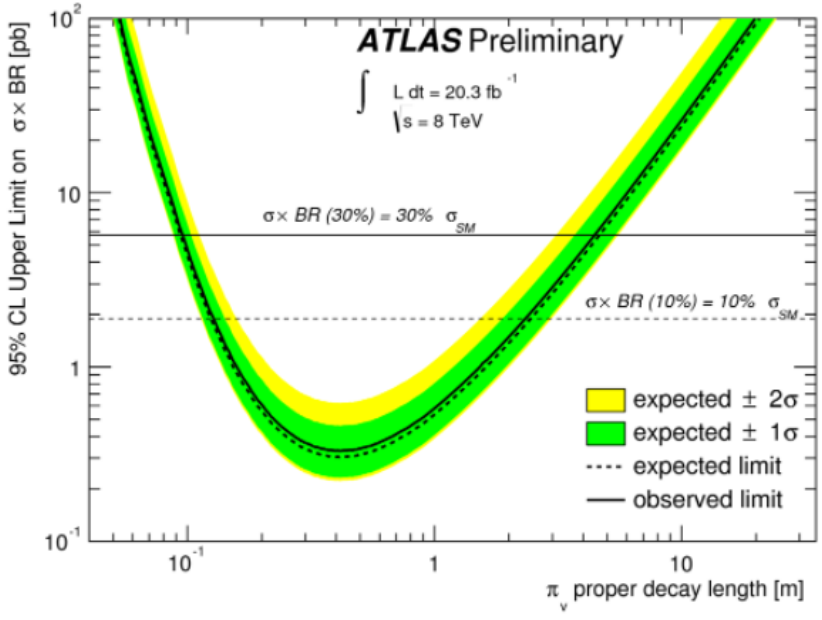


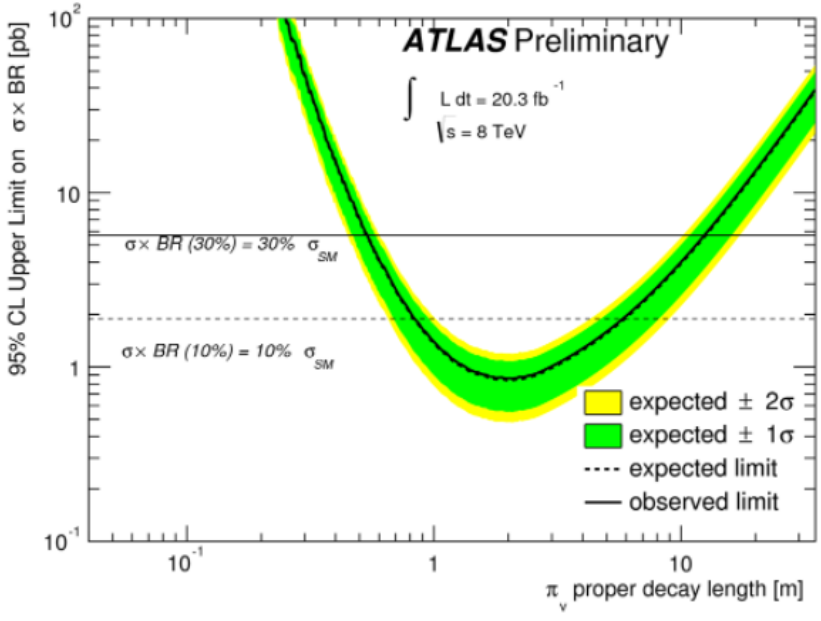


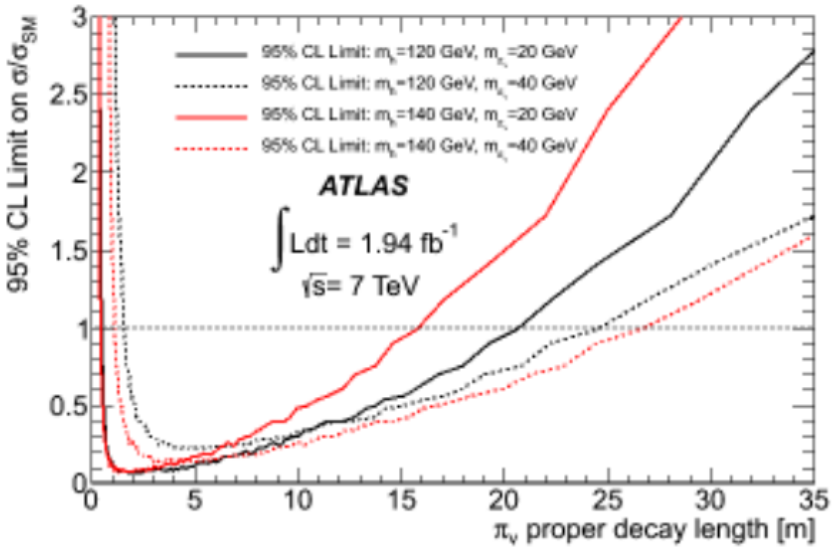




Long-Lived Particles decaying into jets



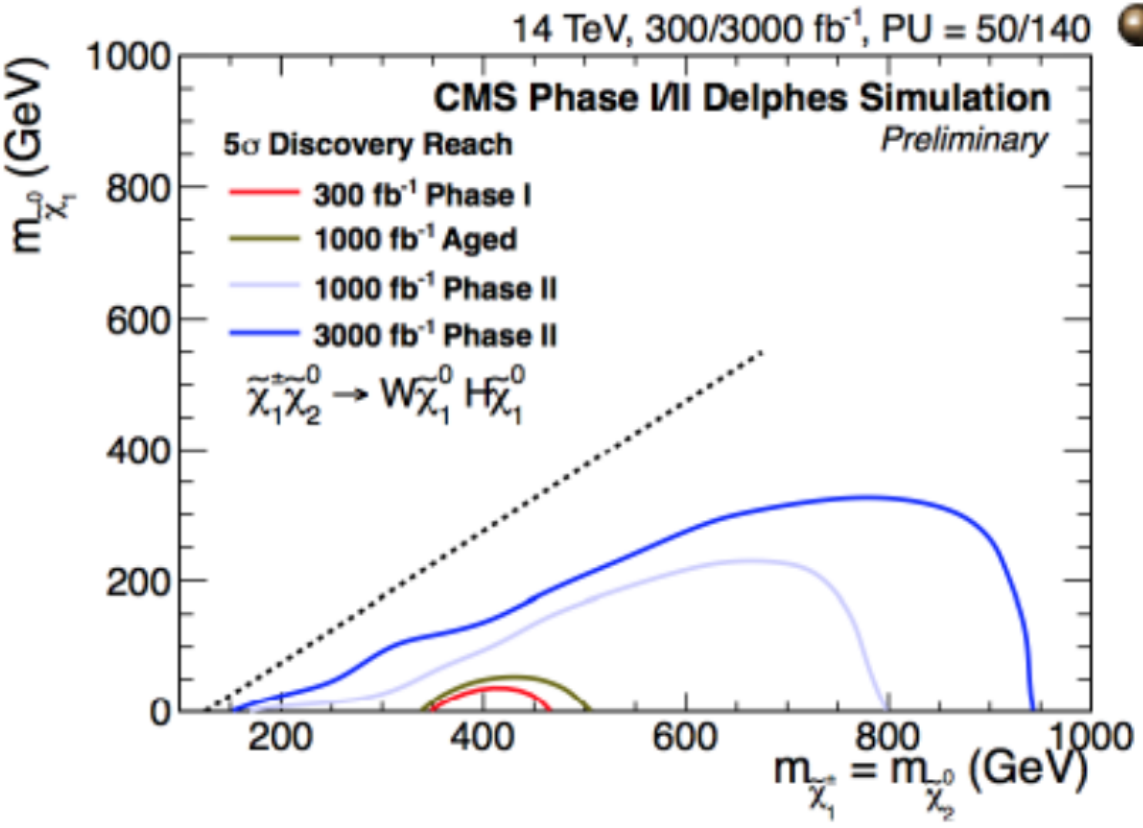




- Require two long-lived particles per event
- Most sensitivity at cτ around 100 cm and Br ~ few %
- extending sensitivity to low lifetimes is paramount

Detectors need to be upgraded

lepton + bb + MET



- Degradation from
  - b-tagging x 0.67
  - trigger:
    - e: pT> 40 GeV -> 50 GeV
    - μ: |η|<2.4 -> 1.1
  - Lepton identification x 0.84
  - some degradation from reduced MET resolution due to calorimeter radiation damage

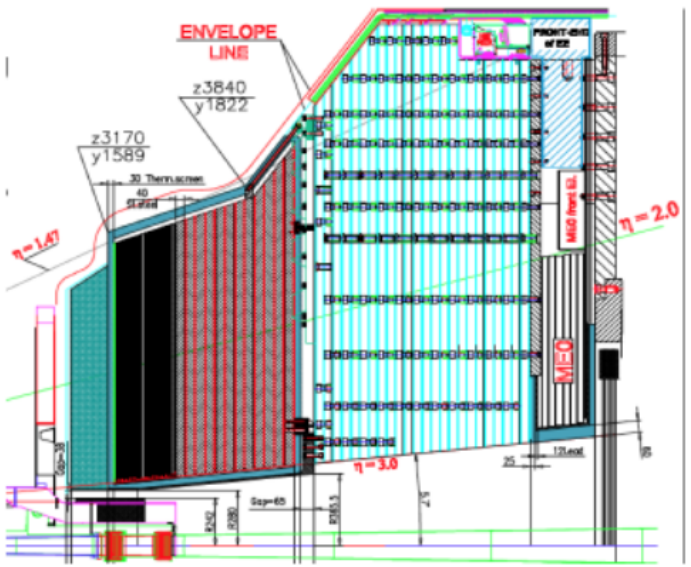
Phase 2 upgrades

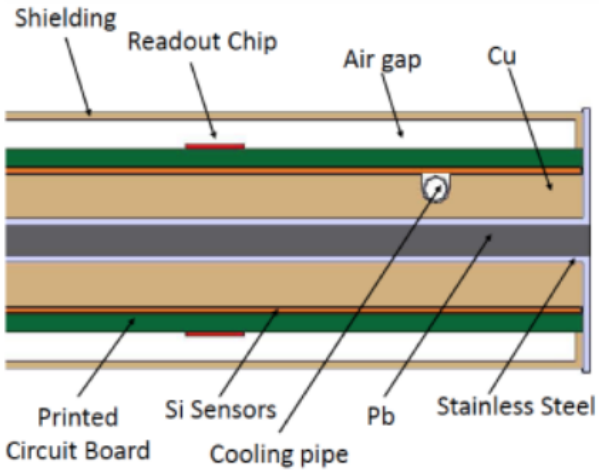
- Upgraded CMS will have
  - New tracker
  - New forward ($1.5<\eta<3.0$) calorimeter
  - Faster DAQ
  - (+ extra muon stations, calo electronics)
- All these upgrades are aimed at preserving performance at high PU – but it's an opportunity to do much more – ie. new lampposts to look under
- Other possibility: fast timing
  - forward calorimeter clusters
  - tracks
- Although major features / costs are about to be frozen, still a lot of wiggle room for new ideas/optimization

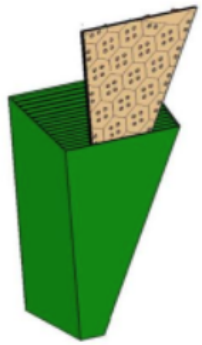
High Granularity Calorimeter

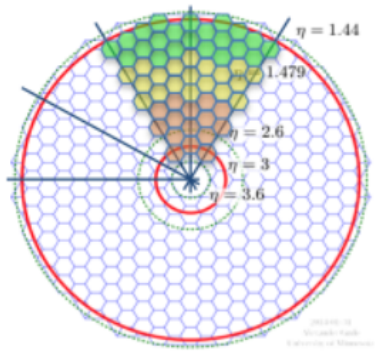
J. Mans

- Silicon-lead/copper EM (25 X_0, 1λ)and silicon/brass front hadron (3.5 λ) calorimeter
  - 8.7 M channels, pad sizes 0.9 cm^2 or 0.45 cm^2 depending on η
- Scintillator-brass backing calorimeter (5.5 λ, low radiation zone)









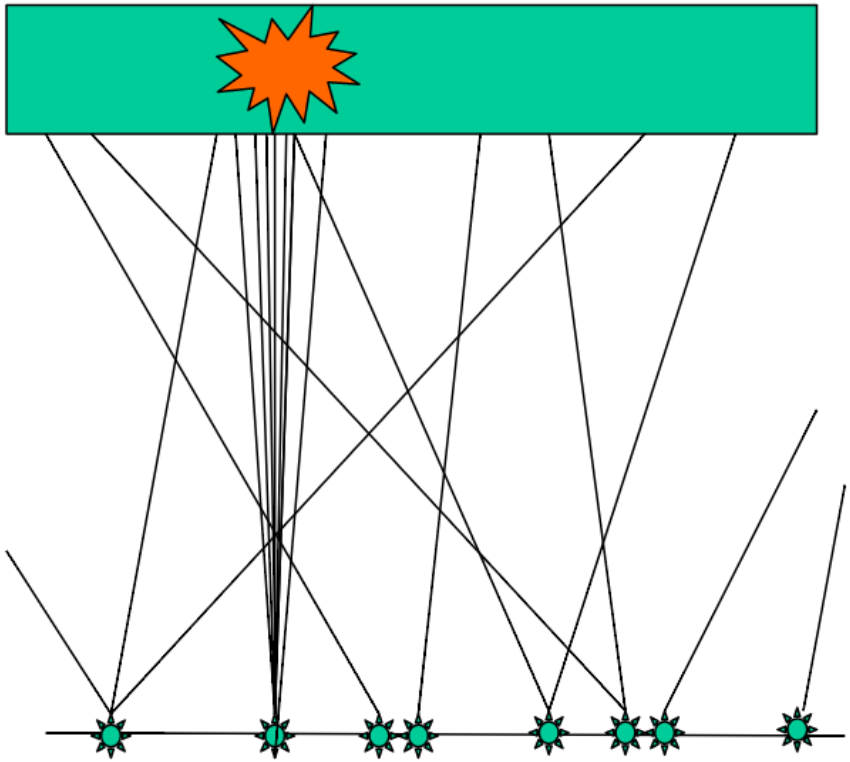
- Although only in the forward region (1.5-3), a lot of Higgs / any O(100 GeV) particle decay products falls there. May have good timing resolution, excellent pointing, etc…

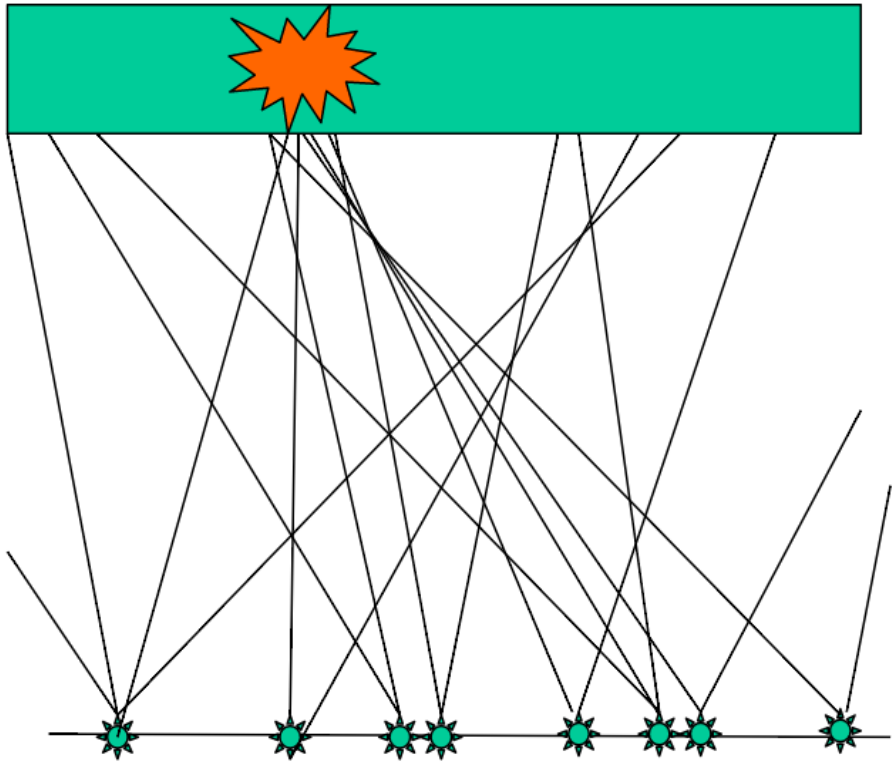
Tracking

- Both ATLAS and CMS need new trackers (old ones start failing shortly after several hundred fb^{-1})
- An opportunity to make better ones:
  - lower mass
  - better resolution
  - better pattern recognition
  - a trigger-friendly device
  - better coverage (up to $\eta \sim 4$), so that the tracker span is larger then the VBF rapidity gap

Surviving 140 events pileup

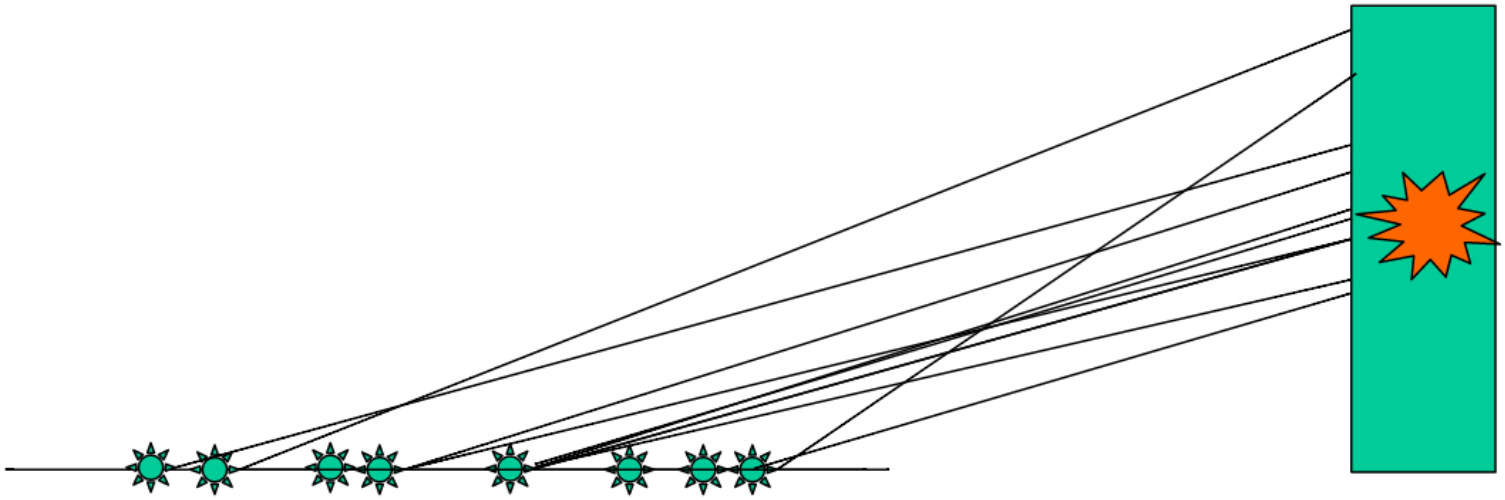
- Tracker is essential for jet identification





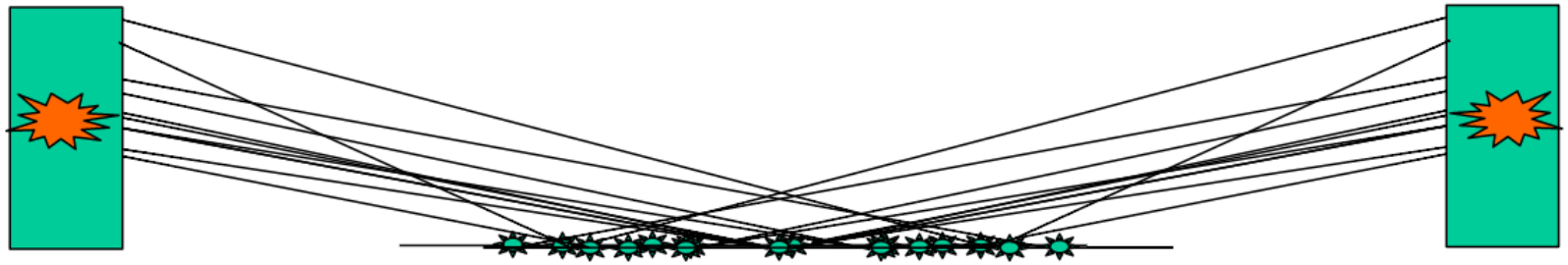
Jet ID at $\eta \sim 4$

- $\eta=4$ is $\theta=0.037$
- typical separation between PU vertices at that angle is $\sim 40\mu$
- removal of fake jets is still a challenge



Picosecond Timing

- Complementary to tracking – works best at small angles



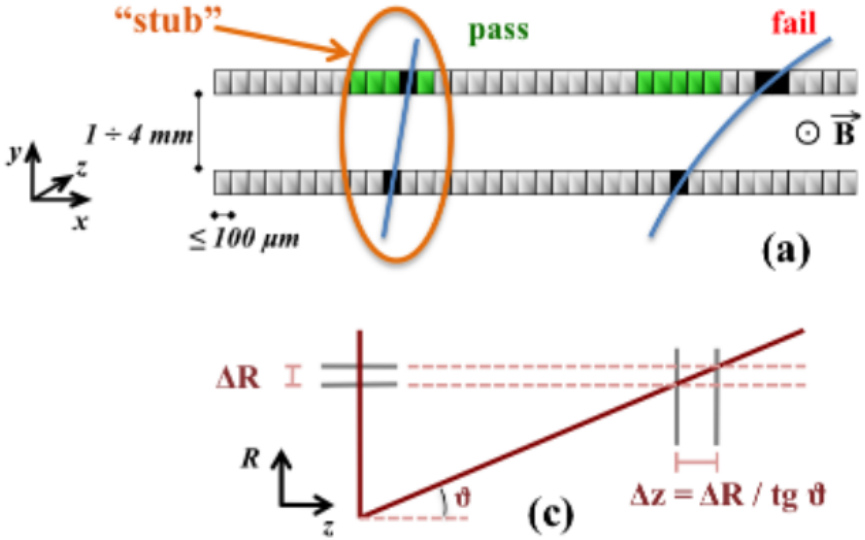
$$t_F = t_{vtx} + (Z_{HF} - Z_{vtx})/c$$
$$t_B = t_{vtx} + (Z_{HF} + Z_{vtx})/c$$

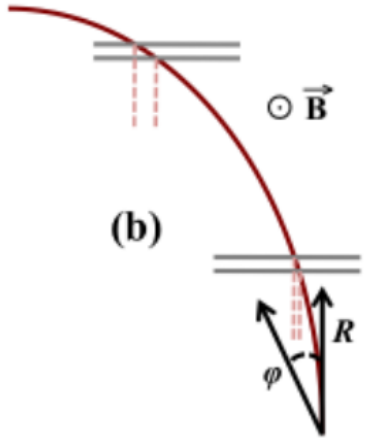
$$t_{vtx} = \frac{1}{2}(t_F + t_B) - Z_{HF}/c$$
$$Z_{vtx} = \frac{1}{2}c(t_B - t_F)$$

- $\sigma(t_{vtx}) \sim \sigma(Z_{vtx}/c) \sim 300$ ps
- Need resolution of 10 ps or better
- Has to be a separate large area device
  - Probably expensive and technically challenging

Track Trigger

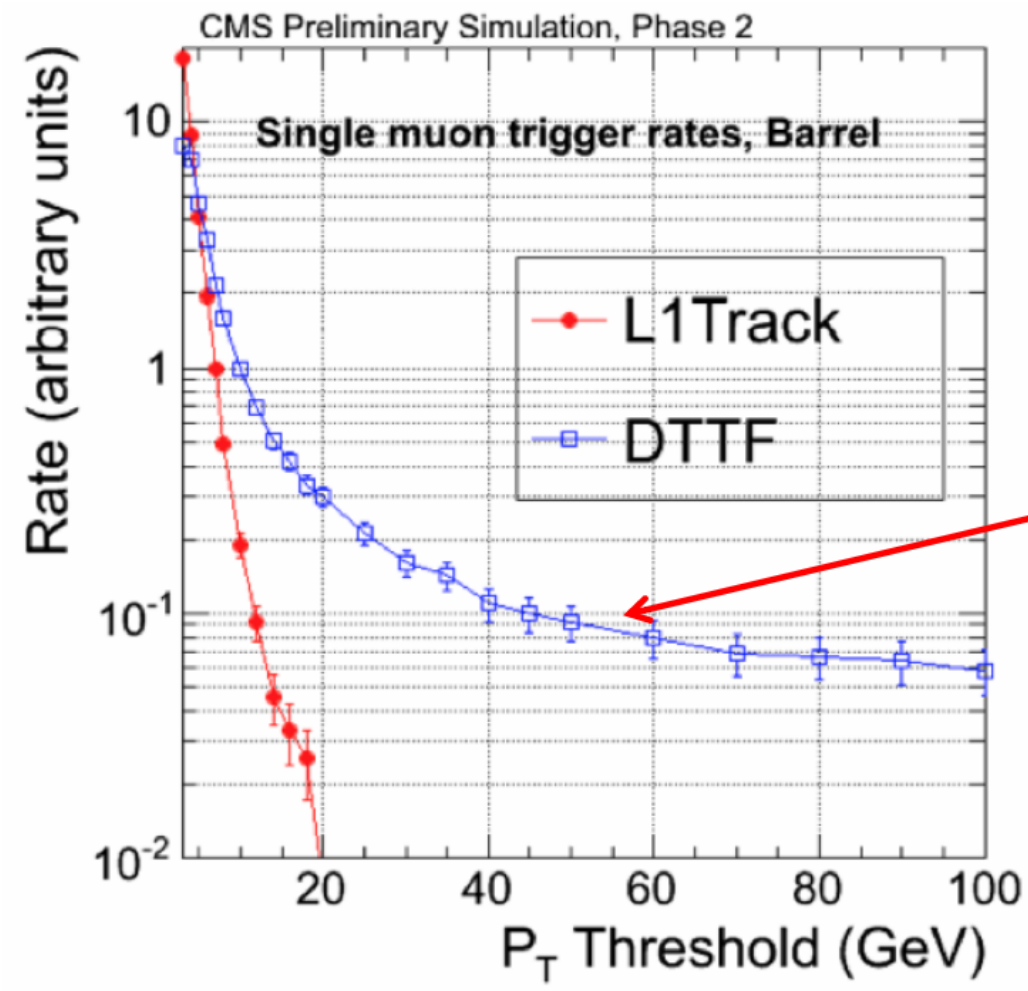
- Challenge is to read out all the hits – enormous amount of information, can not be done at required latencies
- Solution: have the two sensor both run strips along the beam
  - Make strips shorter (as short as a couple of mm -> macro pixels) to deal with occupancy and provide a Z measurement
  - The pair of hits measures pT of the track that left them
  - The electronics that measures that pT can live on the module – a factor of order 100 in the occupancy, sufficient to make readout of the high pT hits possible





Need for L1 Track Trigger

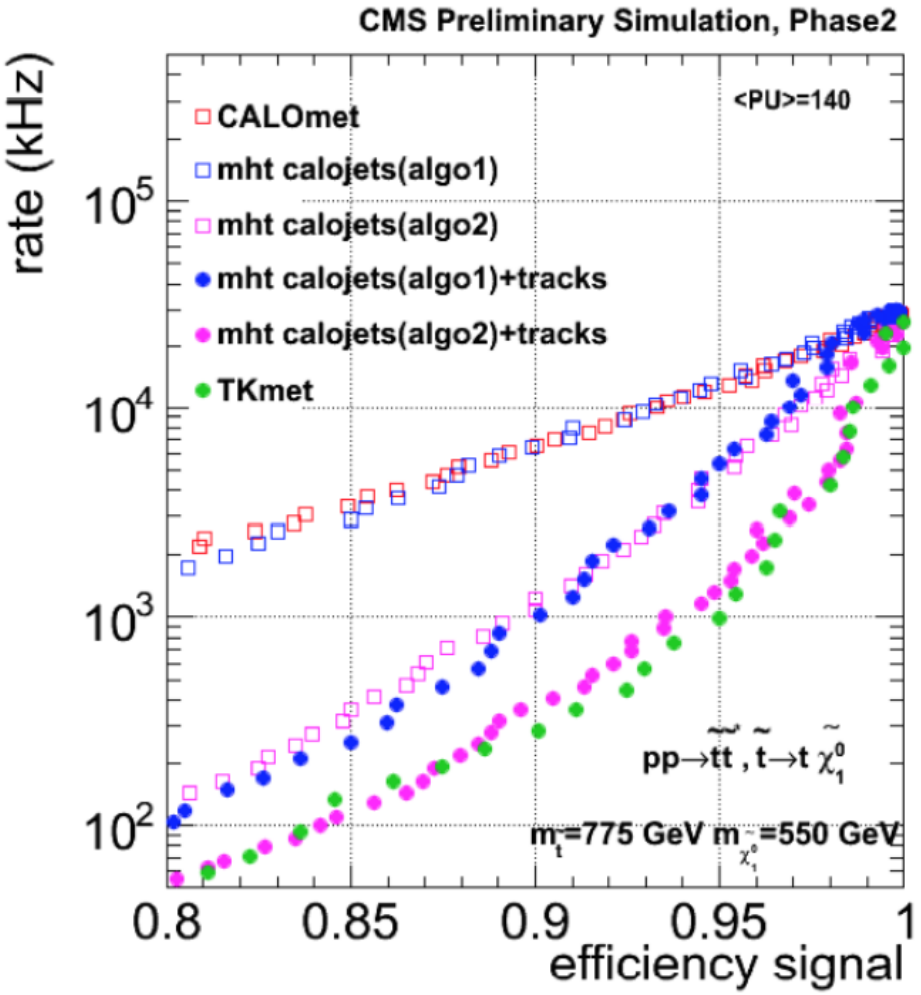
- have to have it for muons



Flattening of the rate due to poor momentum resolution

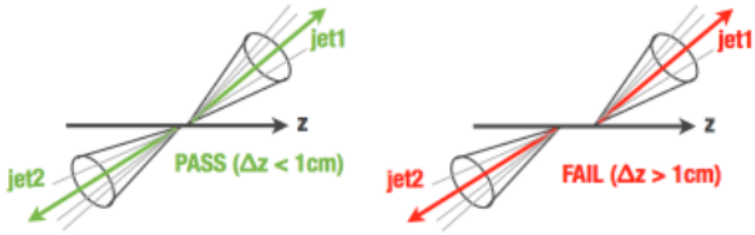
L1 Track Trigger can do more

- Construct TkMET – missing ET using just L1 tracks
  - **works better then L1 Calo MET!**



Compare:

- Calorimeter only
- Calorimeter with PV confirmation using L1Tracks



- TkMET

L1Tracks: new lamp post?

- track jets! Almost unaffected by PU
  - very low HT multi-jet trigger @L1?
- calo jets without L1 tracks
  - shorter lifetime analog of "no-EM" jets
- secondary vertices at L1
  - could probably be done if FPGA performance improves as it did
- other ideas?

Summary

- Run 2 is on the way!
  - ~3-4/fb results for winter / Moriond
  - several anomalies to follow up on, plus new opportunities at twice the energy: hopefully a lot of exciting discoveries soon!
- Contingency planning
  - HL-LHC program has been centered around "long hard slog" measurements and searches
  - The opportunities are much brighter and diverse then that – but the community needs to come up with a broad program that can be argued for.