LLP with Track Trigger
or
LHC Physics Under a New Lamppost

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Outline

- Physics:
  - Long-lived particles with ~cm lifetime decaying to jets
    - rare higgs decays
    - Dark Sector cascades
    - Low HT jetty final states

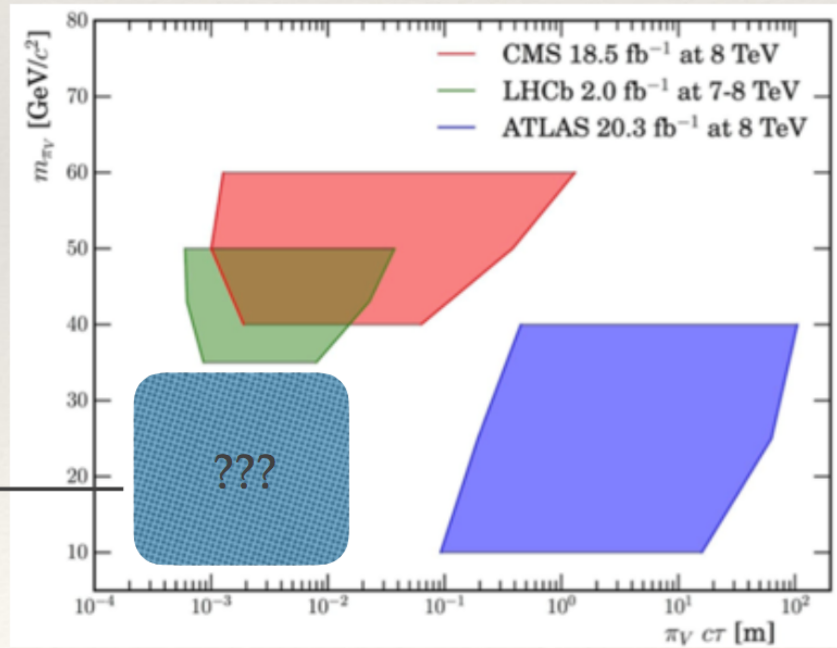
  } very hard to trigger
- CMS Track Finding @40 MHz
  - Prompt tracks
    - Yes, every track (p_T>2 GeV) in every LHC collision will be reconstructed with high efficiency
  - Displaced tracks and displaced jets
- Triggers based on (displaced) track jets
- Physics reach & discussion

arXiv:1705.04321v1 [hep-ph]

H(125) -> $\pi_V \pi_V$

BR(H -> $\pi_V \pi_V$) < 50%

Do we give-up on this region?



CMS-EXO-12-038
LHCB-PAPER-2016-065
CERN-PH-2015-065

Borrowed / stolen from M. Borsato

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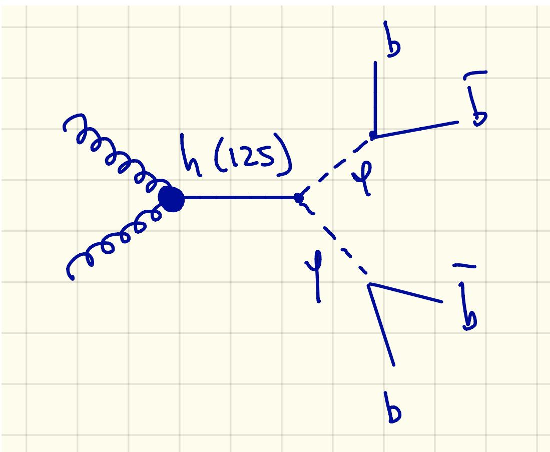
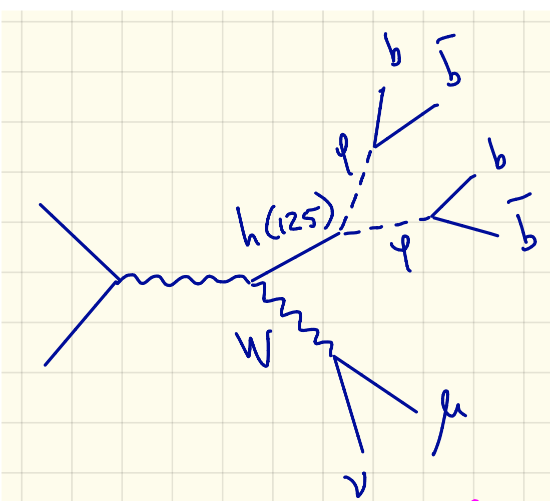
Stolen / borrowed from talk of Jose Francisco yesterday

Rare Higgs decays

- Since we share the vacuum with new physics (i.e. dark matter?), it's very unlikely to completely not couple to Higgs. It could show up as exotic Higgs decays
  - Branching fractions as small as 10^{-5-6}
- Very well theoretically motivated & studied (arXiv:1312.4992, Curtin, Strassler, et al)

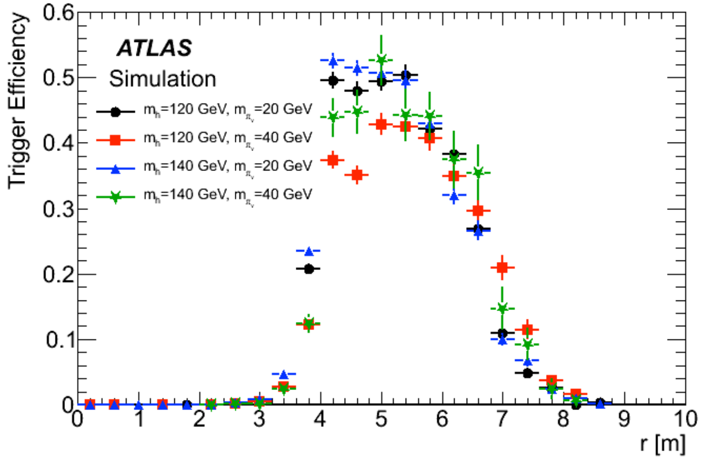


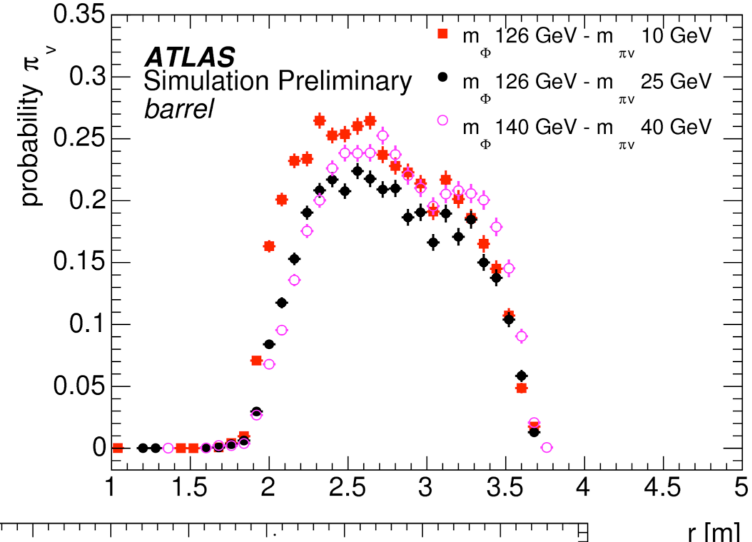


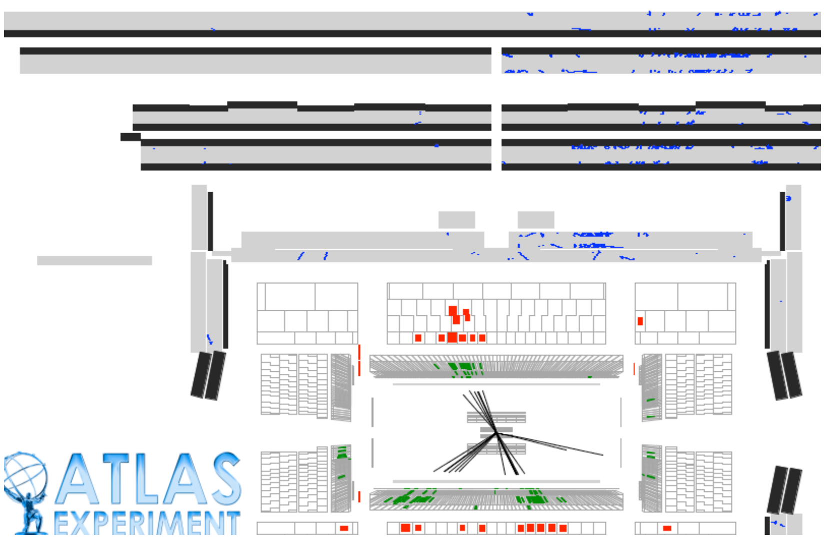
- Prompt decays of ϕ: hopeless, too little H_T in the event to pass first level of the trigger, and huge QCD bkg
- If ϕ is long-lived, then if we had events on tape, the background is almost zero
- The "plausible" way is to go to associated production with leptonically decaying W
  - Huge penalty (~200):
    - 1.4 pb / 44 pb
    - Br(μ/e) = 0.2, but single electron trigger will run at high threshold (35 GeV or more)

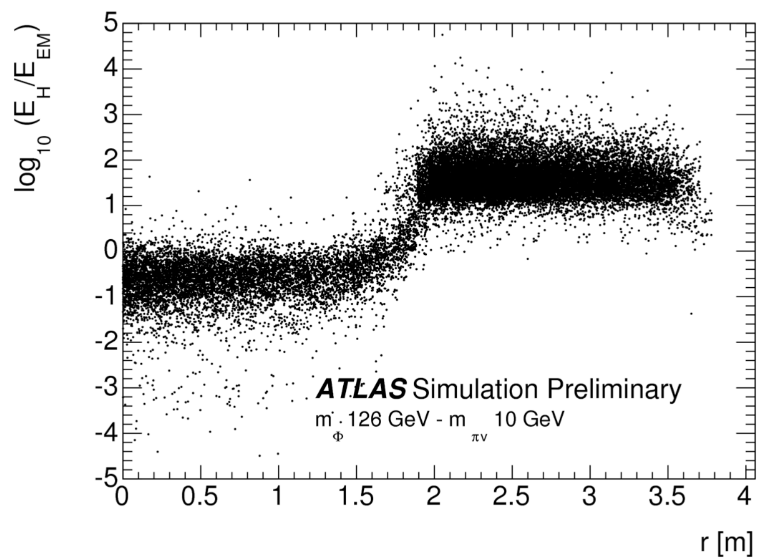
Passing Hardware Trigger: easier for large cτ

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





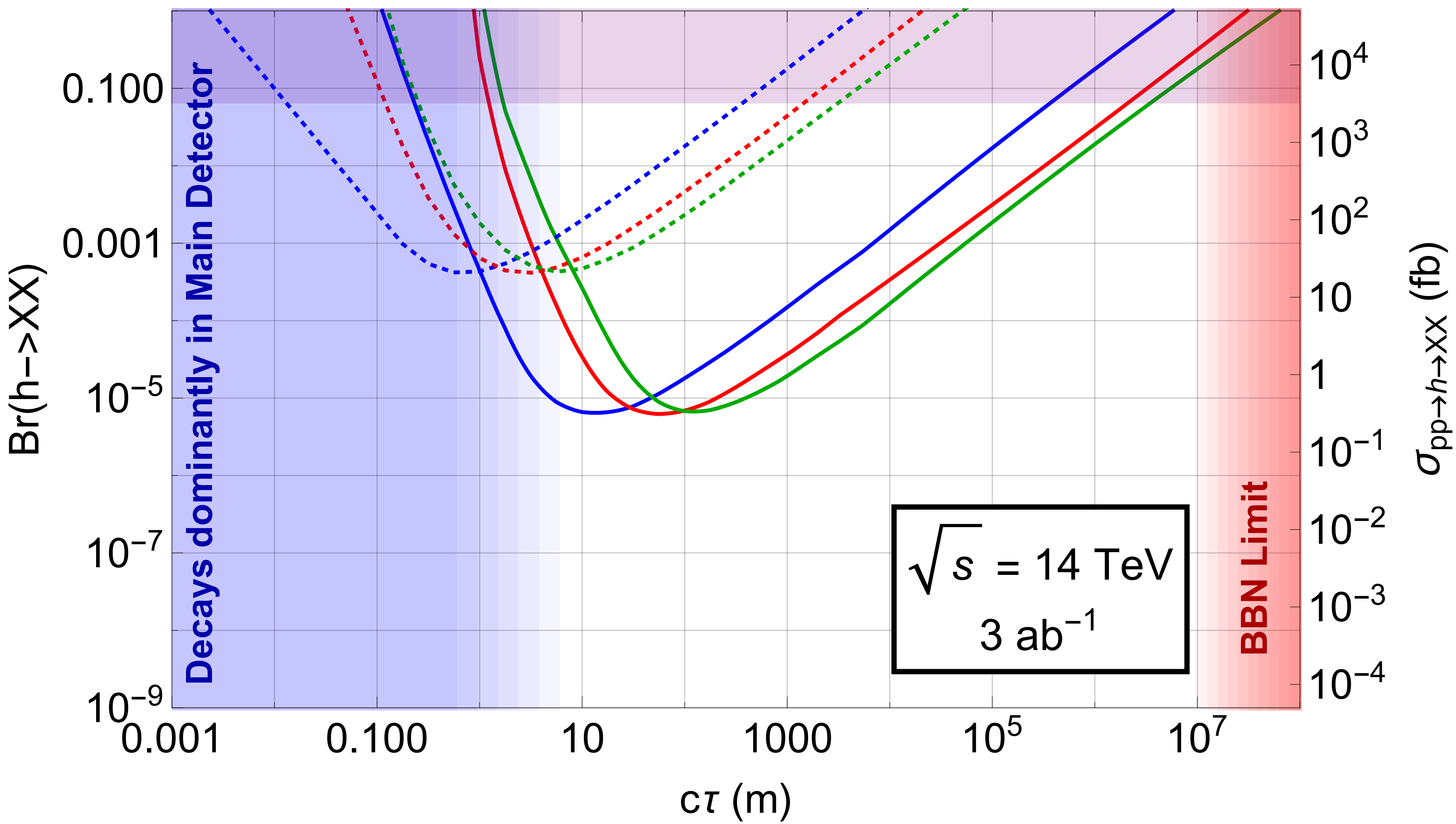




Even larger lifetimes: MATHUSLA

- Detector on the surface next to CMS or ATLAS
- Huge hit in acceptance, but can reach below 10^{-5}

arXiv:1606.06298 [hep-ph] and
Cristiano Alpigiani's talk this afternoon

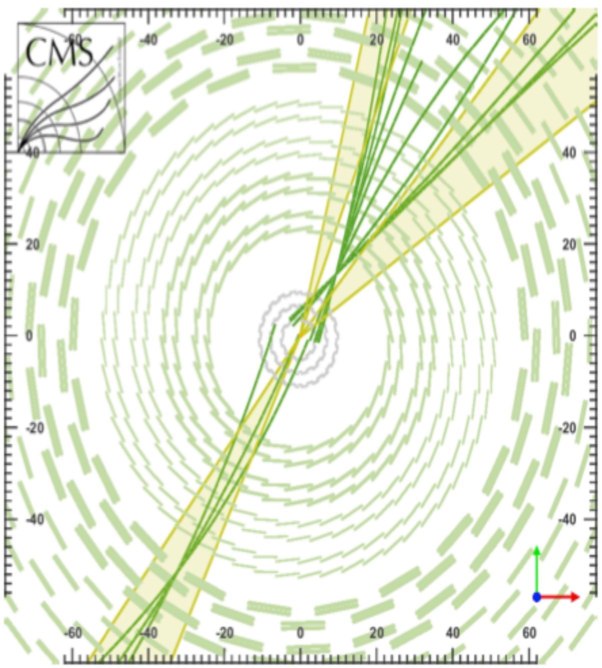


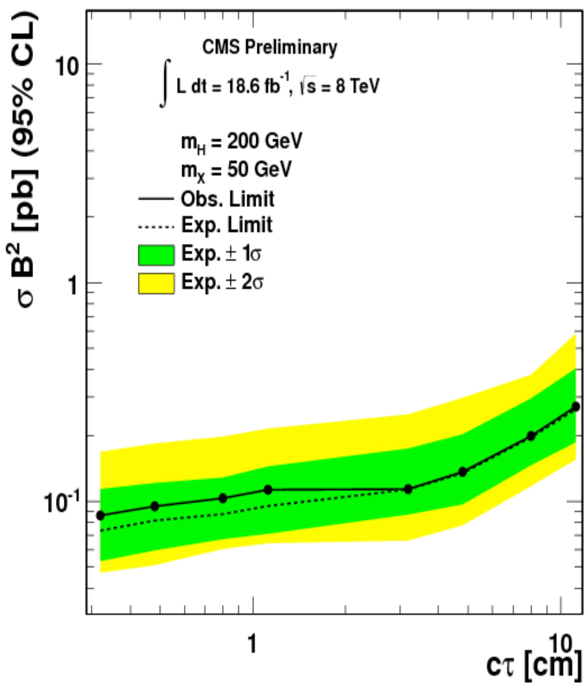
Small lifetimes

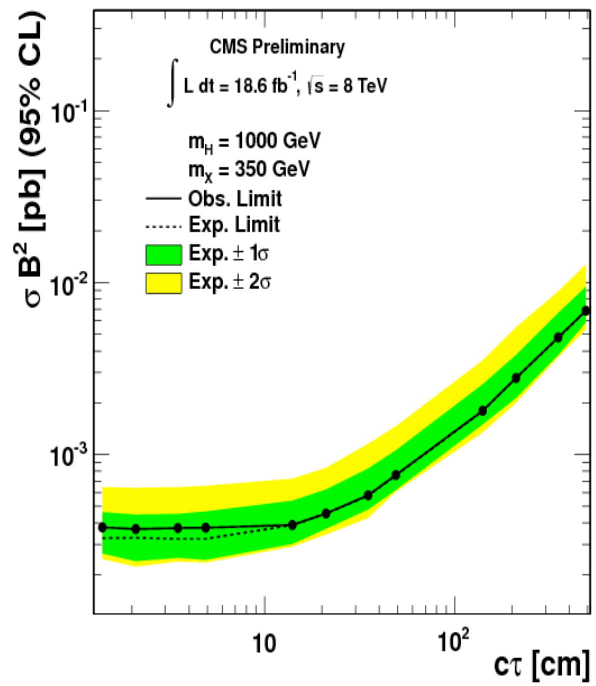
- The trick at CMS or ATLAS is to find a way to pass through hardware triggers – once full event information is available for the HLT, a displaced jet trigger is possible
  - Passing L1 for the h(125) was already a problem in Run 1

EXO-12-038

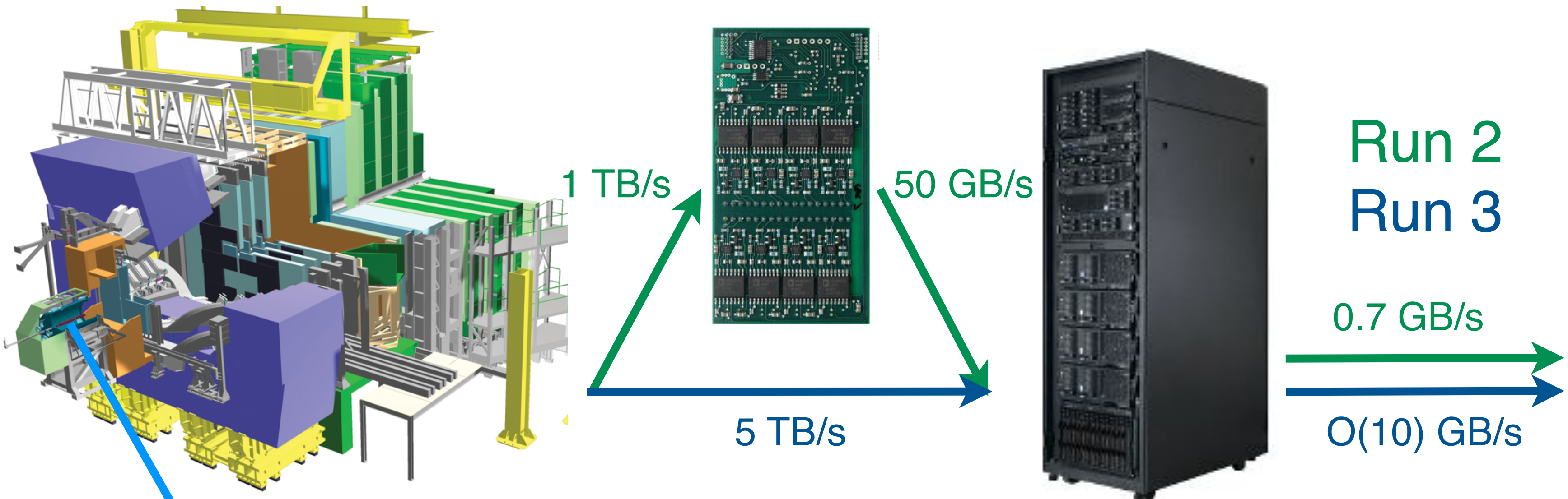
pp-> H -> XX ->jets

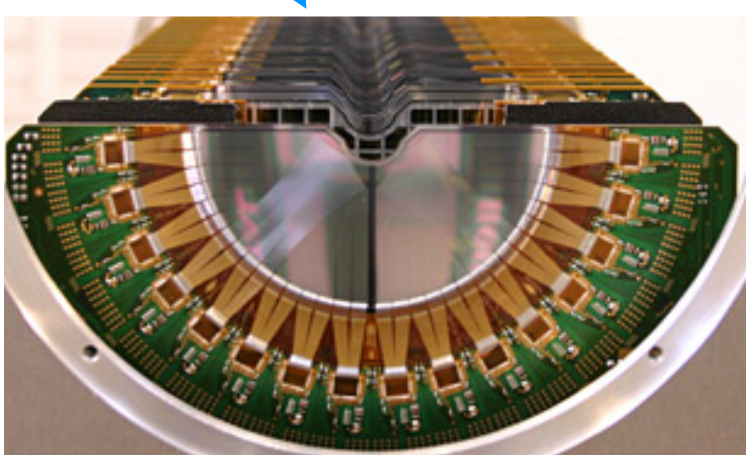






LHCb Trigger



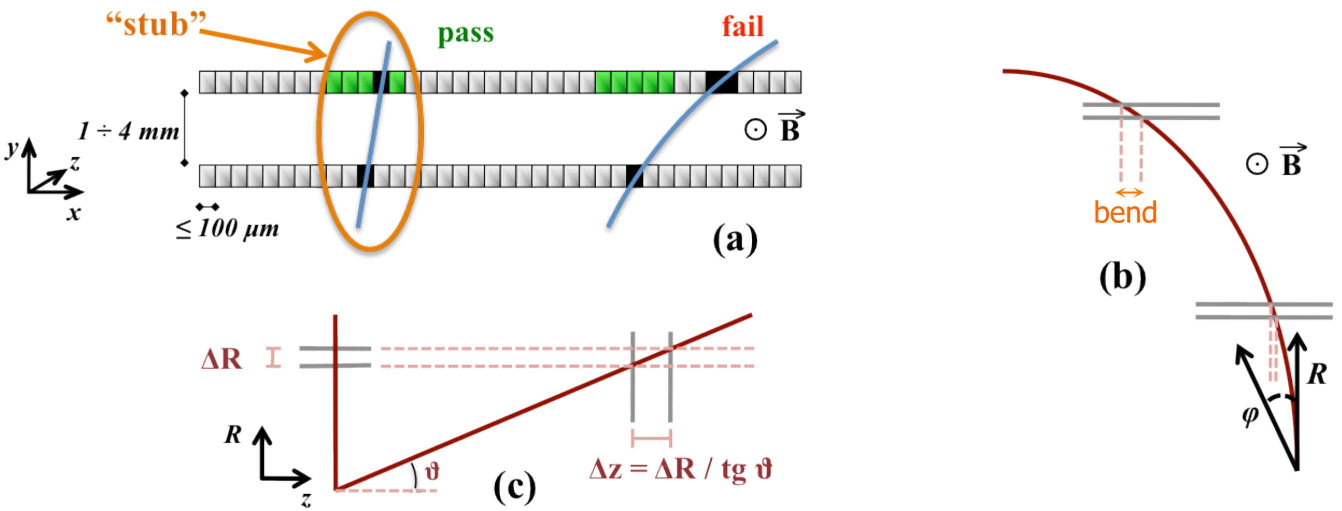


Leverage LHCb's τ resolution, a triggerless-readout system with real-time calibration in Run 3, and unique particle ID capabilities to

In HL-LHC stage, LHCb plans to take 100/fb
That's only factor of 30 penalty, as opposed to 200, and LHCb is better at finding displaced vertices than ATLAS and CMS

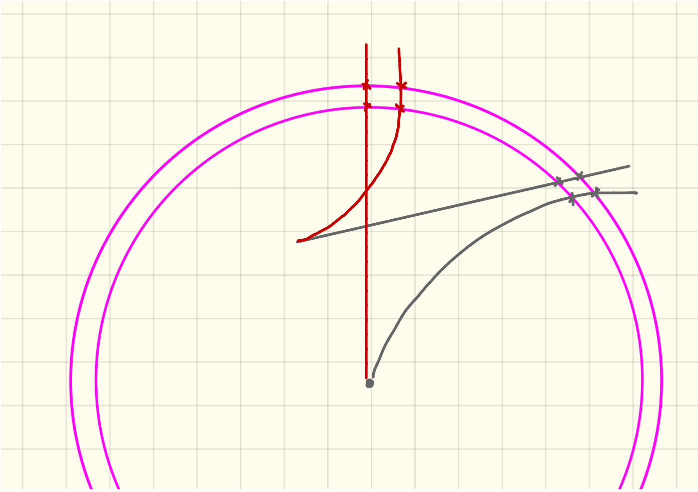
CMS: Track Trigger @40 MHz

- 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



What happens with off-pointing tracks?

- Toy MC!
- Perfectly cylindrical layers
  - Radii and stack separation as in real detector
- Shoot circular tracks and measure hit positions and bends in layers
  - "loose": track gives >=N stubs (max is 6)
  - "tight": fit the hits to a helix constrained to a beam spot, count hits within 300 um from the fitted position. Reasonable approximation of algorithm with pattern recognition tuned for prompt tracks

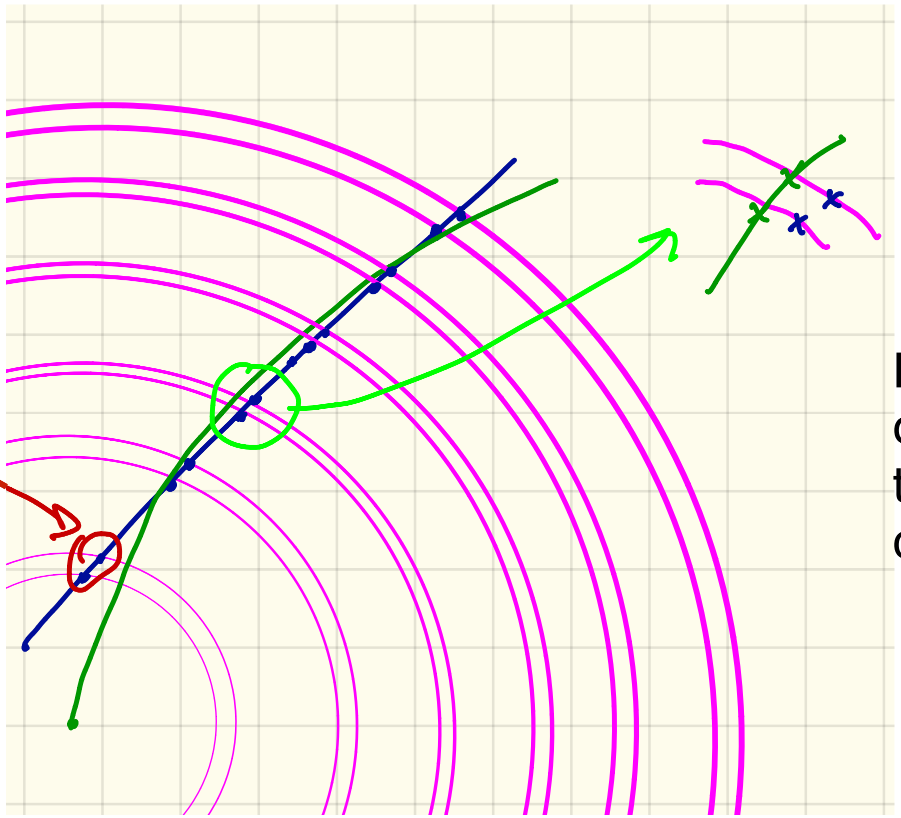


Off-pointing track bends are wrong

5 stubs "loose" track

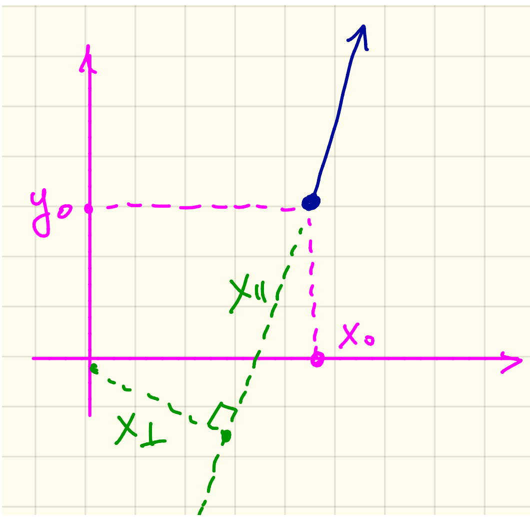
4 stub "tight" track

bend too large,
will not read out



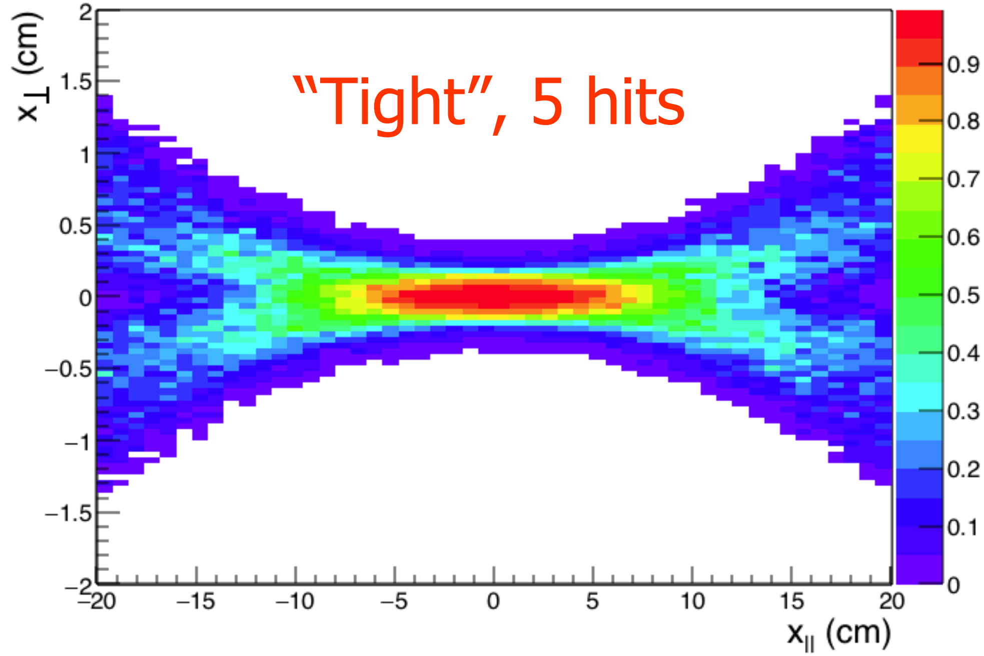
Residuals from circular fit are less then 300um for 4 of the stubs:

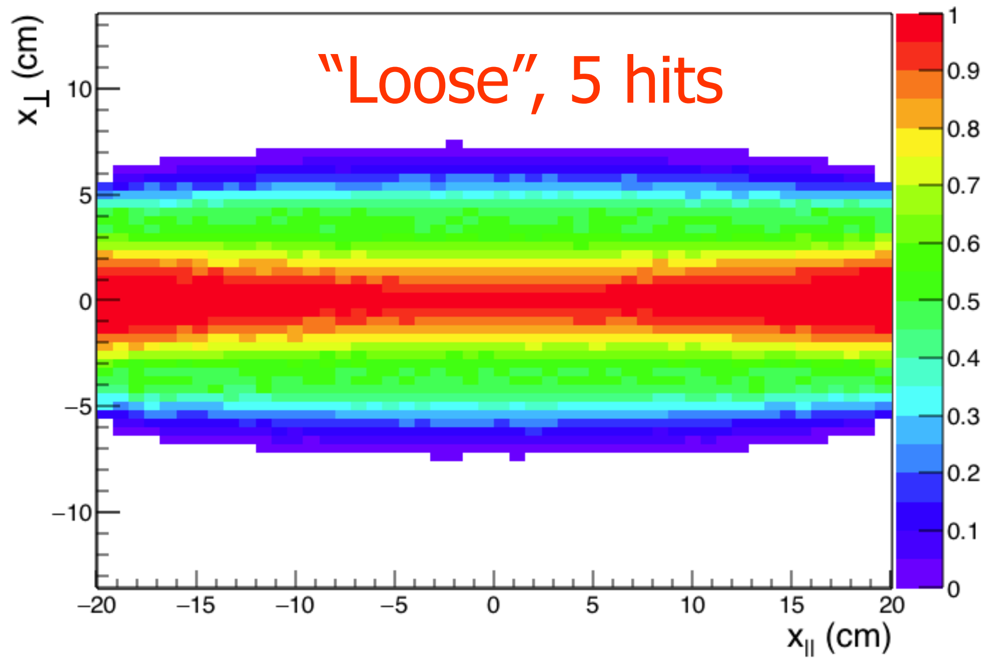
Track reconstruction parameterization



DCA resolution of a trigger track is about 100μm

Tracks of pT above 2 GeV, with pT spectrum form 40-80 GeV jets

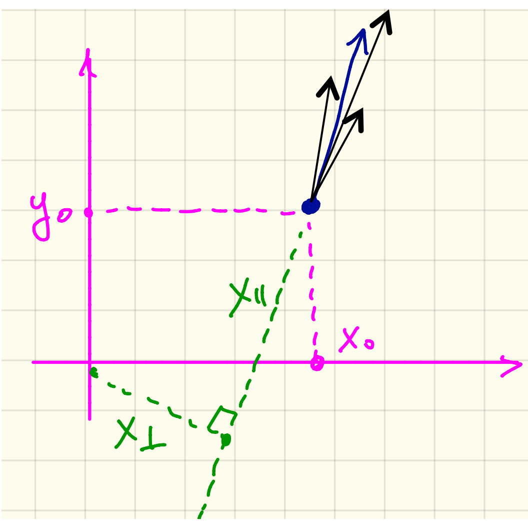




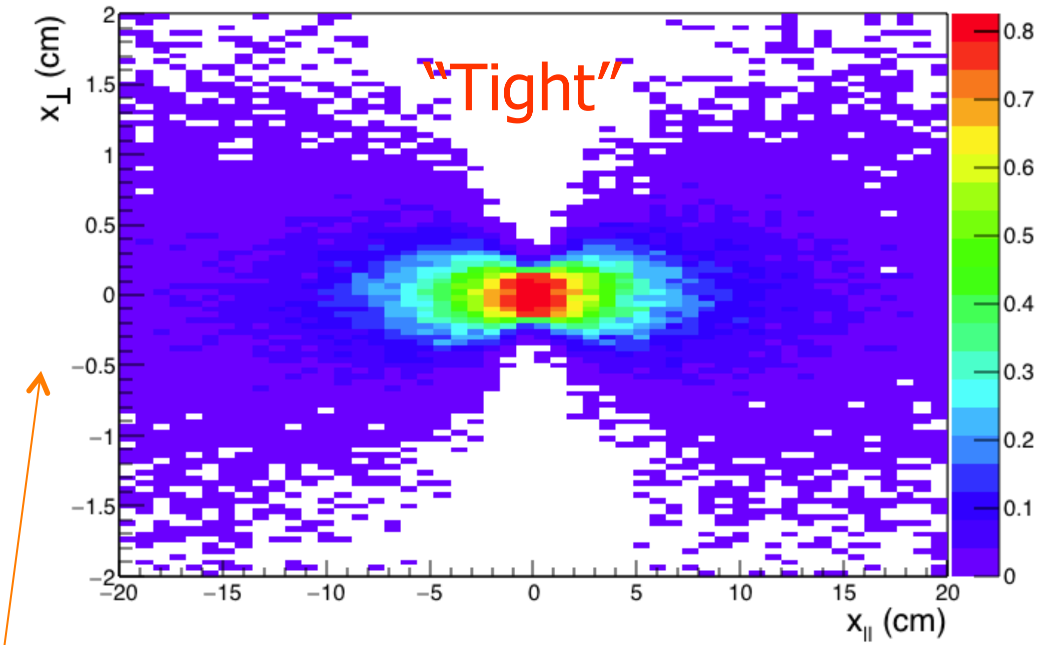
Jet reconstruction parameterization

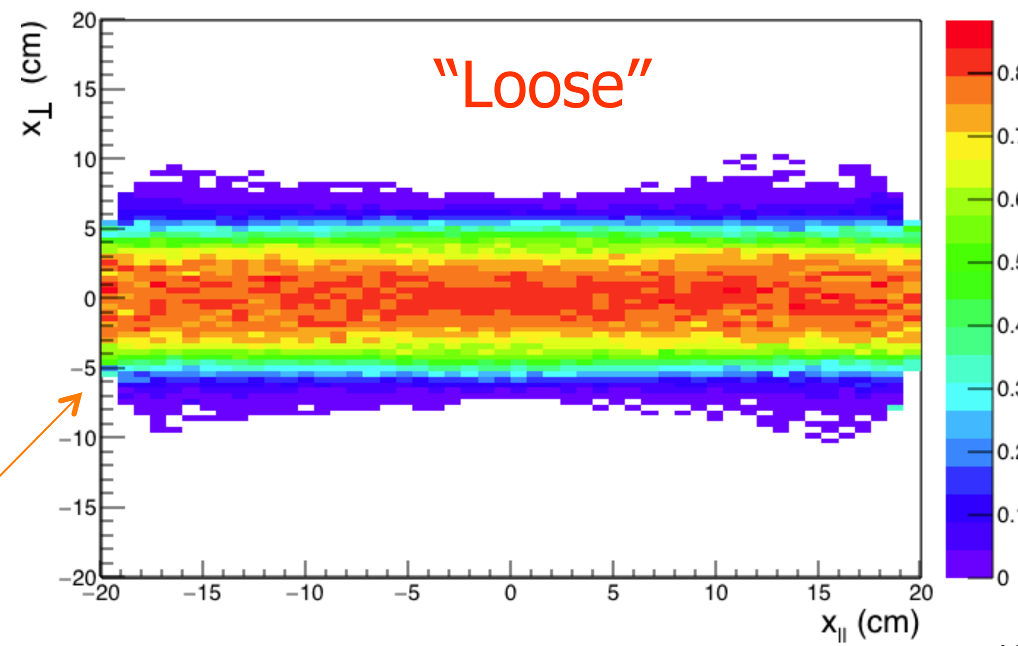
Efficiency = f(pT, $x_{||}$, $x_{\perp}$)

add flat 90% efficiency per track
>= 3 tracks with >=4 hits
>= 2 tracks with >=5 hits
Sum track pT > 10 GeV



Example plots for 40-80 GeV jets





Jet Triggers

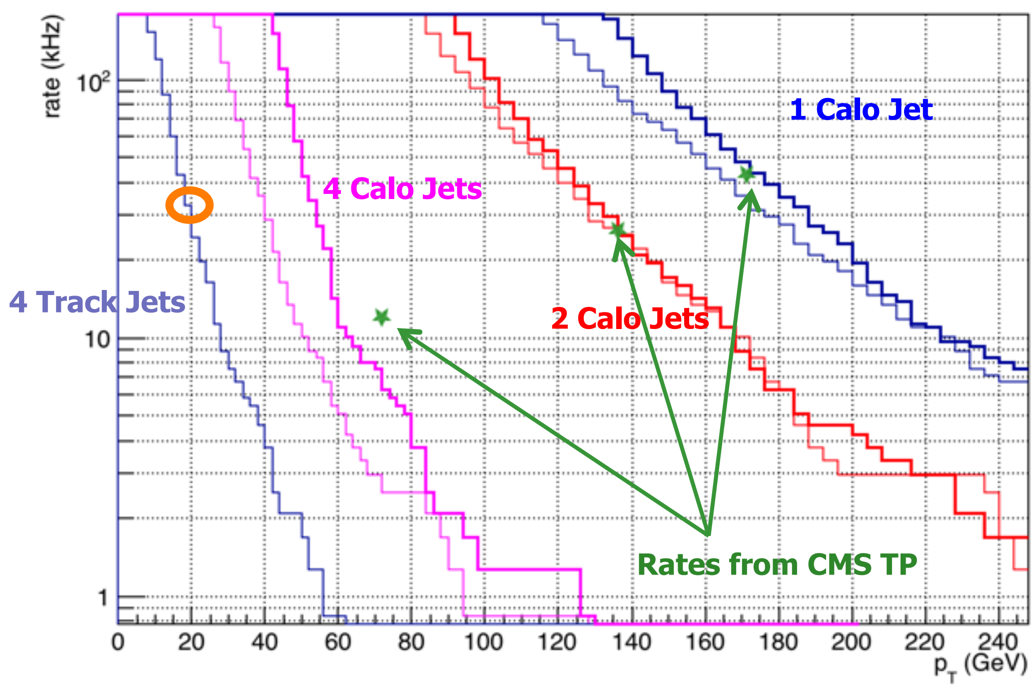
- CMS TP: Jets @L1 are started by calorimeter and then "confirmed" by the tracker
  - L1 calorimeter resolution + PU -> large uncertainty
  - If start with tracks, remove PU ~completely, end up with selection on the jet pT in charged tracks, have better acceptance to low pT jets, lower thresholds.
    - Lower sensitivity to fake tracks: only look at ones in jets
    - Also, get more useful for analysis jets – the ones that have a lot of tracks to do vertexing with.

Calo Jet pT smearing:

$$\sigma_{p_T} = \sqrt{N_{PU}^2 + S^2 \cdot p_T}$$

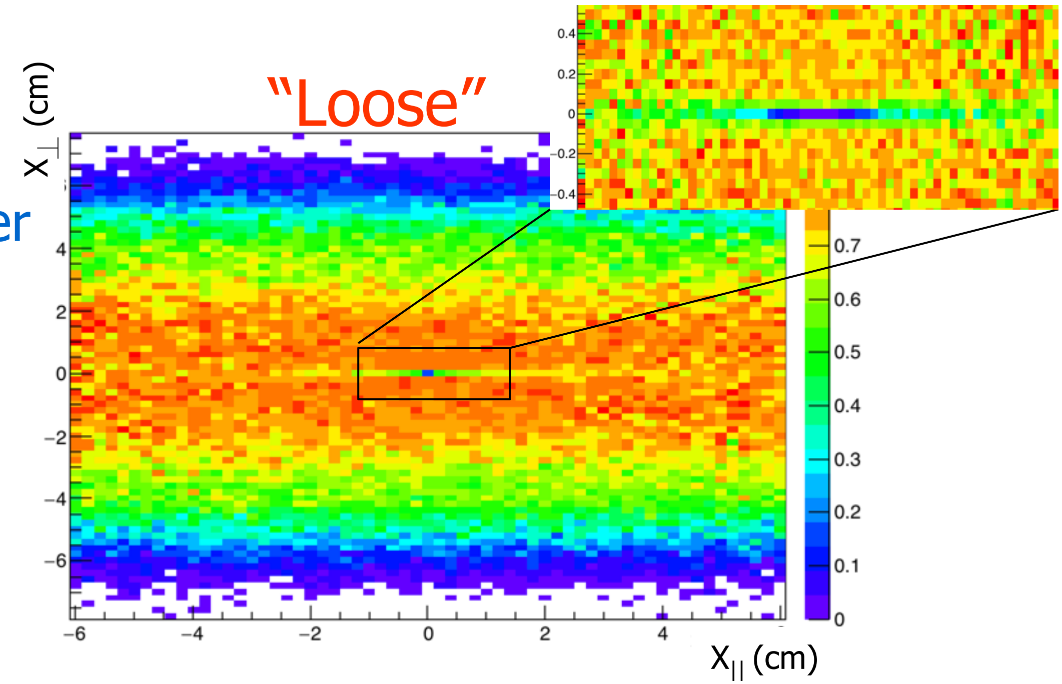
S = 0.9 $\mathrm{GeV}^{1/2}$, N_{PU}=25 GeV

Track Jet pT is sum pT of tracks above 2 GeV, assuming 90% eff

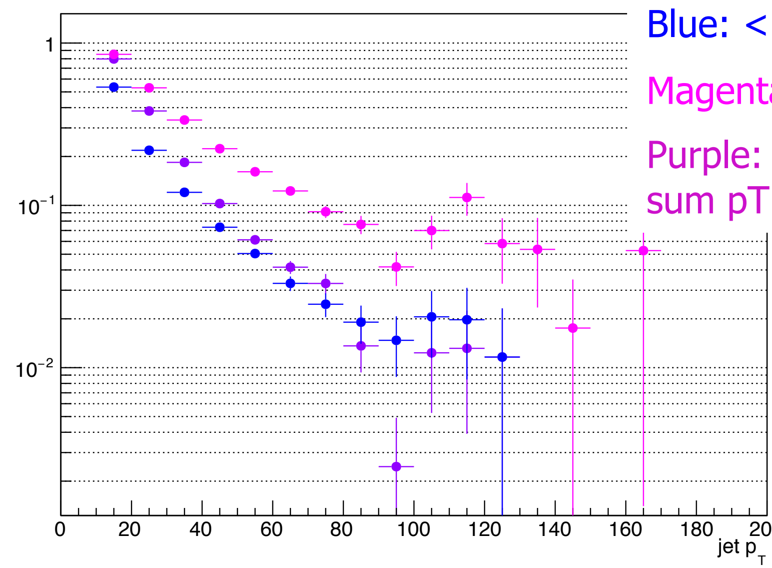


Jets with lifetime tag

- Track jets
  - require that >= 3 tracks in the jet have impact parameter greater then 300 μm
  - Prompt jets are reduced by factor >50



- Calo jets
  - (if only reconstructing prompt tracks)
  - Require no prompt tracks pointing to the jet
  - Huge background from PU jets
    - Need detailed PU simulation…



Blue: <= 1 track

Magenta: <= 2 tracks

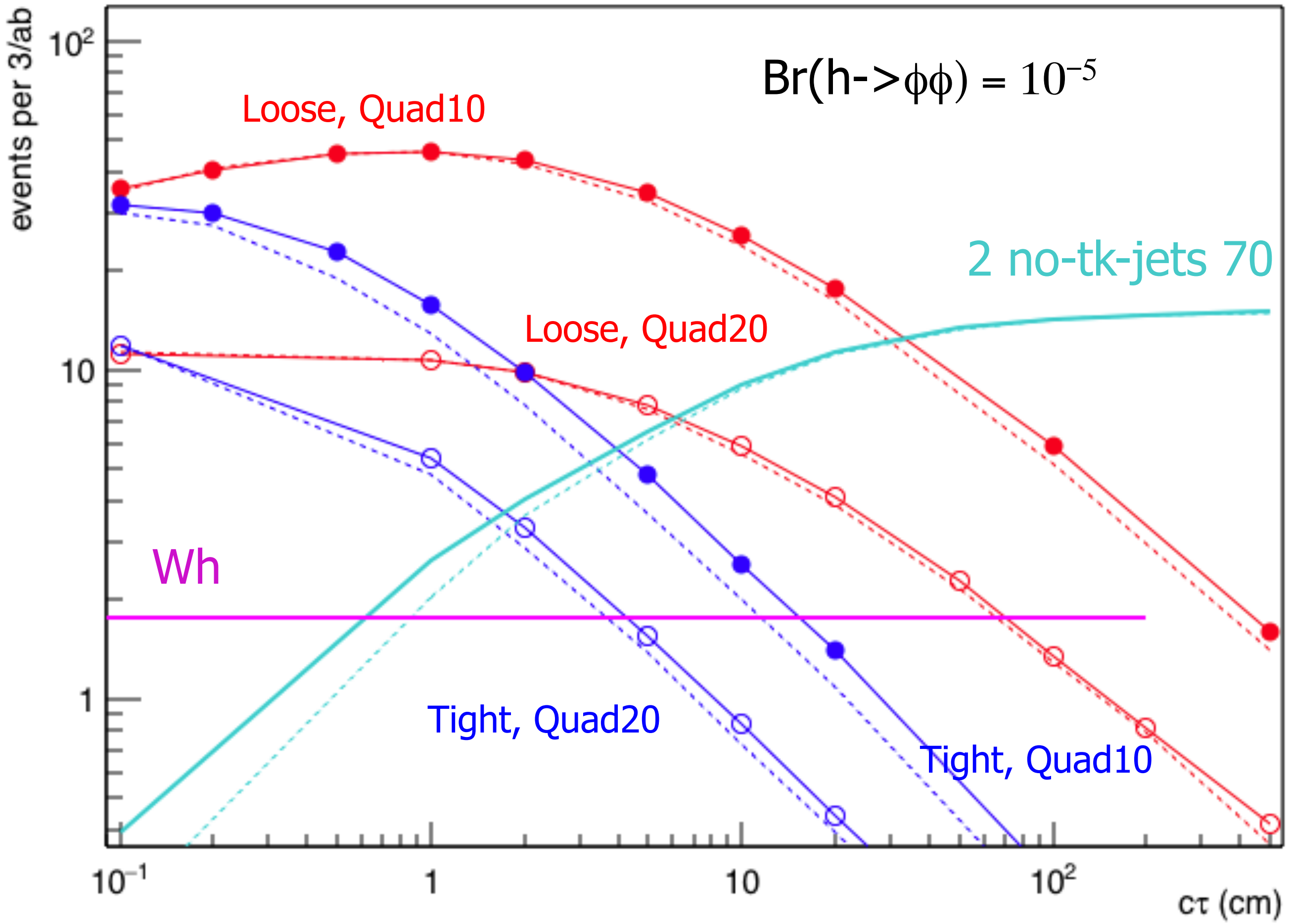
Purple: <= 2 tracks, sum pT < 10 GeV

Recap:

- Assume
  - "tight" tracks represents what the L1Tk can do ~easily
    - Prompt-like pattern recognition, 5-parameter fit
  - "loose" tracks is a realistic possibility
    - Both pattern recognition and fit allow for slightly non-prompt tracks
  - PU effects are small if starting with tracker for quad-jet trigger
  - PU effects are not overwhelming for calo jets above 70 GeV
- L1 Triggers
  - Quad jet (sum tracks per jet > 20 GeV)
  - Quad jet with a lifetime tag (sum tracks per jet > 10 GeV)
  - Two jets (> 70-100 GeV) without prompt tracks
- HLT
  - Can reconstruct secondary vertices

Offline

- For ggH assume that track jet reconstruction is easier offline, and we already required 4 displaced jets at L1
- For Wh require three track jets above 10 GeV
  - (requiring just two jet from the same ϕ changes efficiency by ~30%)



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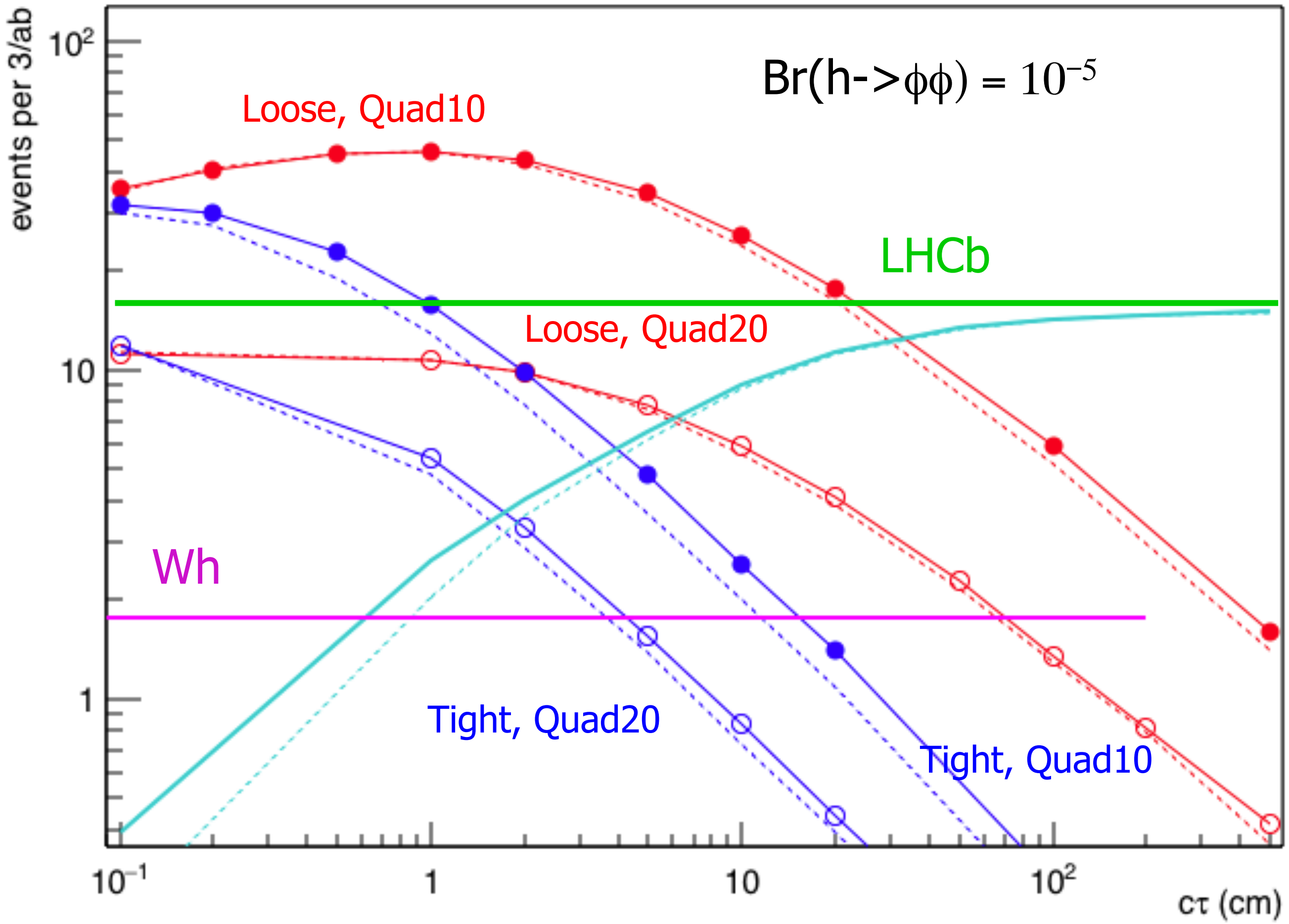
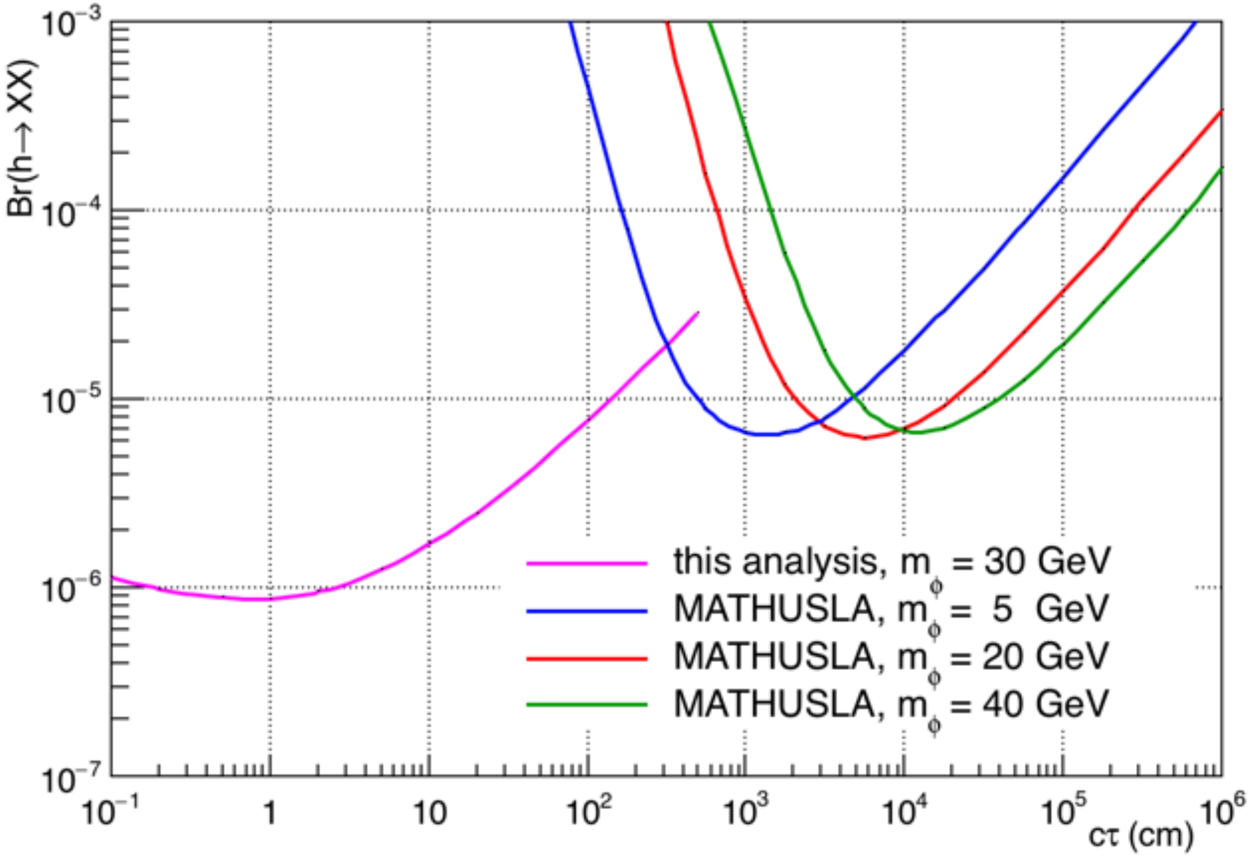


For LHCb, assume 100/fb total lumi, and require one f with daughters above 5 GeV in 2<|h|<5 range

Probably too optimistic?

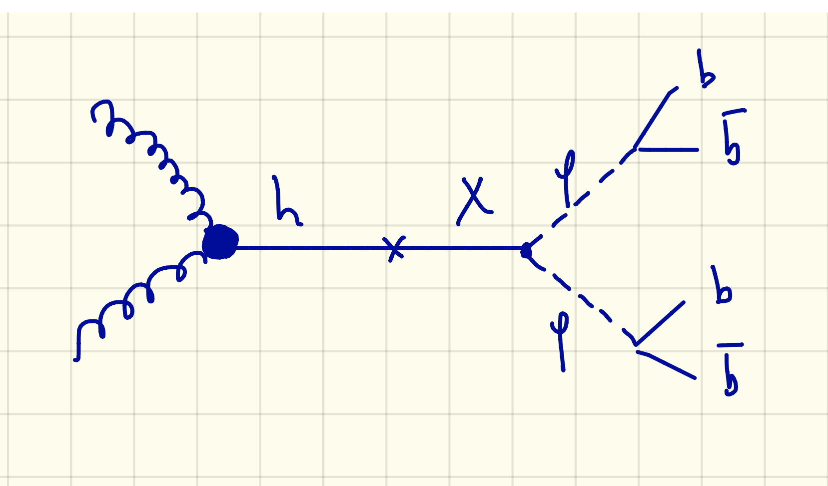
CMS + MATHUSLA

- Instead of N events for Br=10^{-5}, calculate Br that results in 4 events
- Very complementary coverage



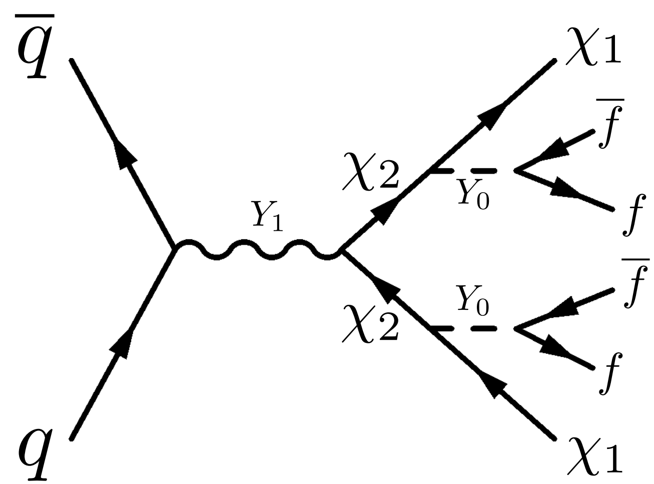
Beyond h(125)

- Recall some of the theoretical setups employed for X(750)
- If ϕ is a pseudo-Goldstone, there should be another massive scalar
  - h(125) decays to $\phi\phi$ through mixing with X, which is small
  - X decays to $\phi\phi$ with large branching, but production is small
    - Had to involve VLQ to explain large X(750) production, but it could be produced through the same mixing with h(125)



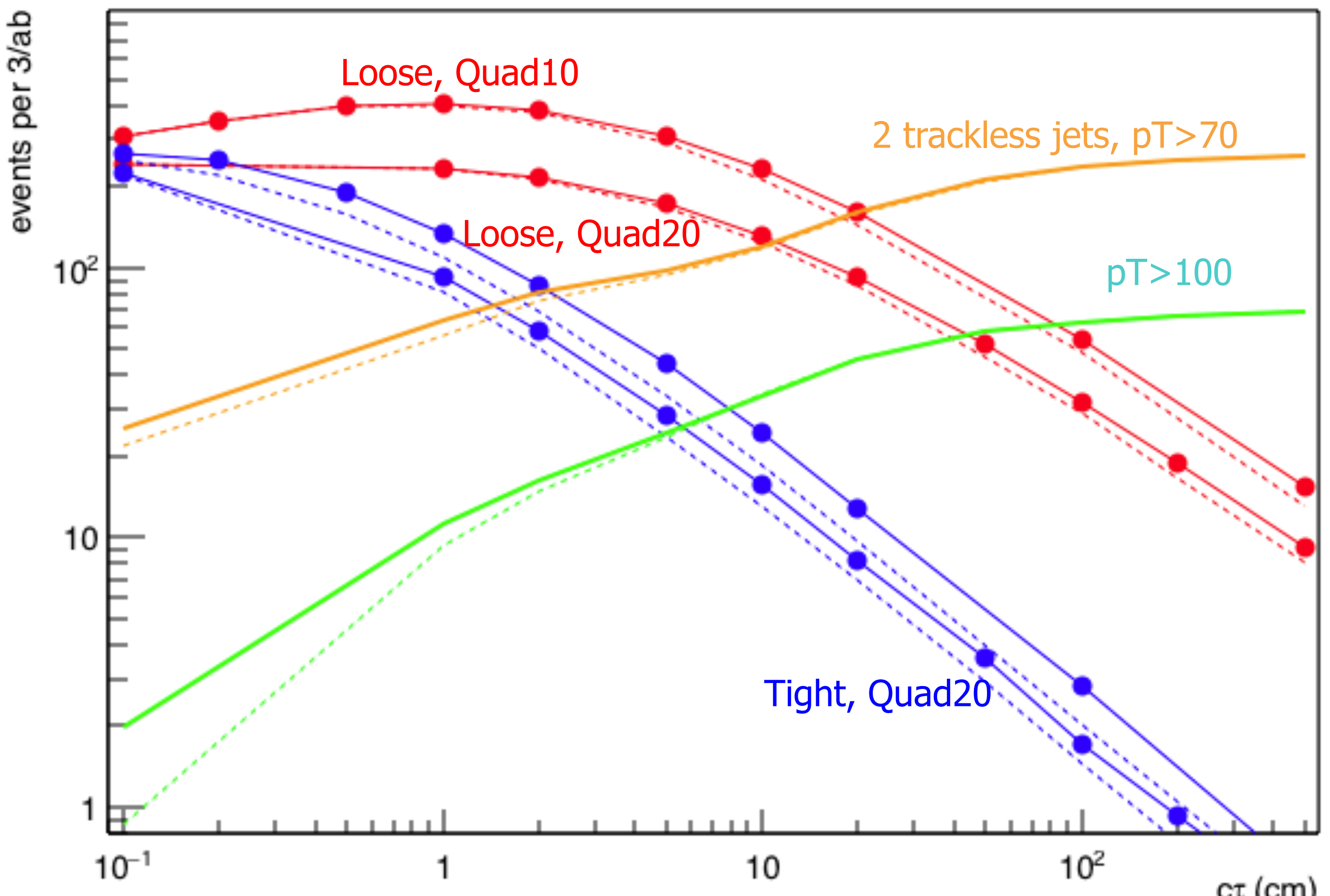
- Same final states occurs in simplified DM model
  - χ_2 and χ_1 are ~close in mass
  - χ_1 is invisible

arXiv:1704.06515



Much easier at higher mass

- M(X) = 250 GeV, M(ϕ) = 60 GeV
- Same σ x Br as for h(125) study above, 0.44 fb



Big potential gains from the “long-lived” track trigger

How realistic is this?

- Track fake rate is assumed to be small
  - only look in jets – fake tracks do not cluster
  - From CMS TP, quality cuts (for prompt tracks) reduce fake rate to below important
  - Not too bad an assumption
- Vertexing
  - Right now assume we can still vertex in events with slightly displaced jets – probably true, but breaks above some displacement
- Calorimeter jets
  - Really need PU simulation here. 70 GeV threshold for “small PU rate” is really just a barely educated guess. However, it is likely to be wildly optimistic (i.e. this trigger will be even less useful)

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No public plots so far that can be shown, but so far it appears that the displaced track reconstruction is uses only 50-70% more FPGA resources. Not a trivial sum of money, but peanuts compared to MATHUSLA / SHiP, etc.

Summary

- HL-LHC experiments are planning substantial improvements to detectors and trigger systems
  - Primary goals of the designs was to preserve detector performance at high PU
  - These detectors can do more!
- CMS has several demonstrated algorithms to do track finding @40 MHz
  - Some technology choices have already been made, but the parameters of the systems will not be fixed for a while longer
  - Now is the time to understand what kind of physics CAN be accessible with track trigger. This study shows that one can get jetty signals with pretty low HT to the HLT. The key is to have something in these events that makes offline analysis possible (lifetime tag, soft leptons, low mass resonances…) **There must be other applications – the community should make a physics case for them now while the design of the syste, is still somewhat in flux**
- Even in the era of trusting GEANT, back of the envelope and simple parameterized MC estimates can guide us to improve physics reach of the only future circular collider that we'll see before 2040-ies