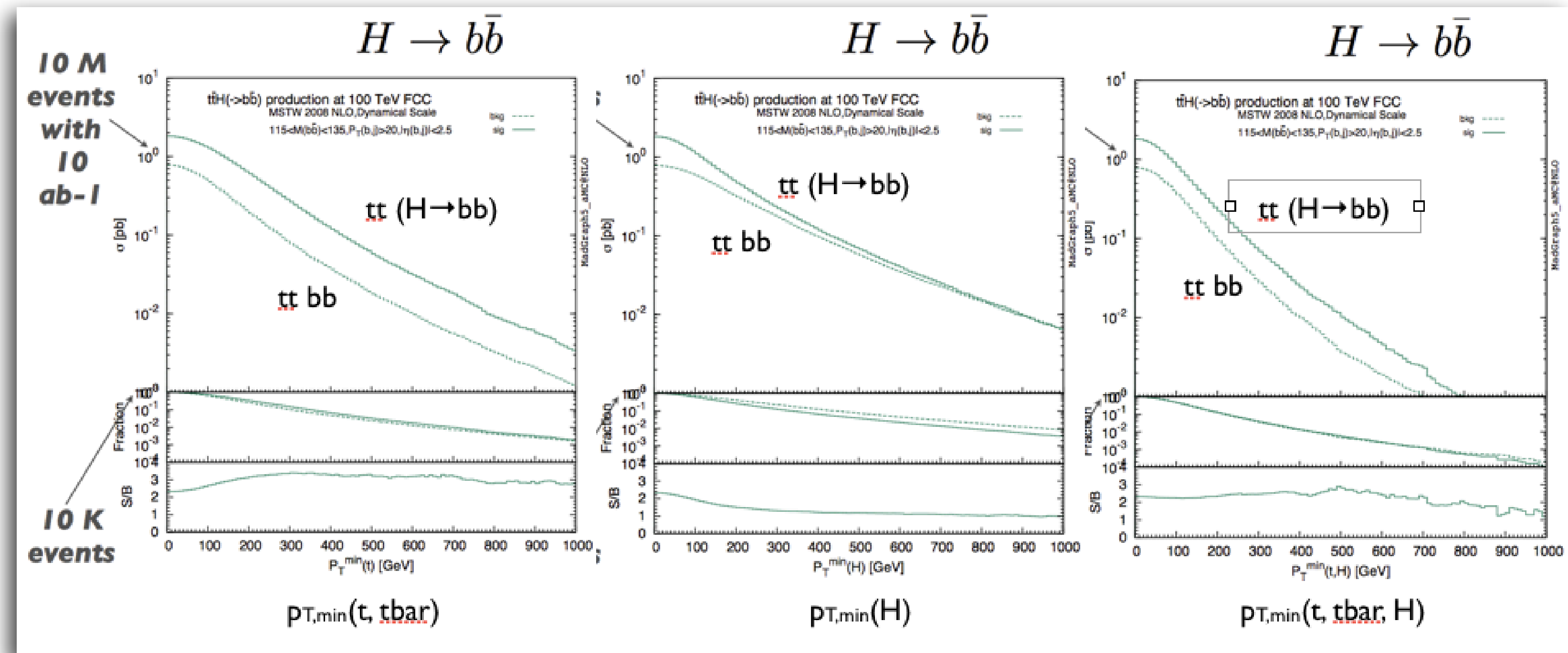

SKIP

Physics with boosted objects at 100 TeV

- Extended applications and new measurement opportunities -- including precision physics -- with “standard” (i.e. O(≲ TeV)) boosted objects. Example: ttH

$115<M(b\bar{b})<135, P_T(b,j)>20, |\eta(b,j)|<2.5$

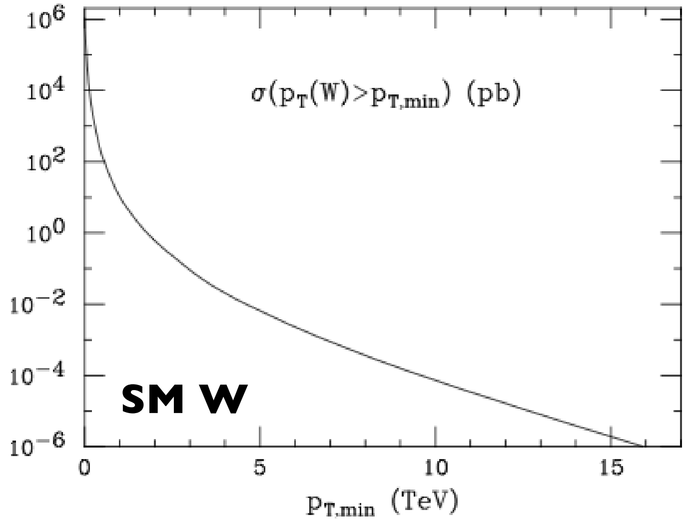


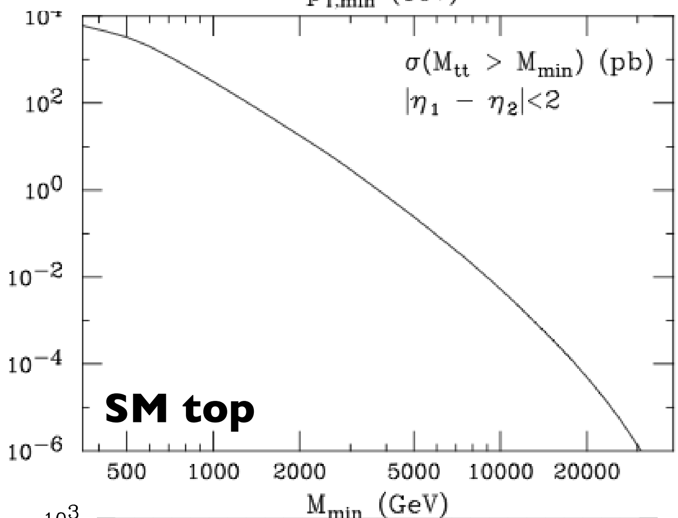
H-S Shao and MLM, preliminary, H&BSM@100 TeV wshop
Plehn, Reimitz, Schnell, : arXiv:1507.08169

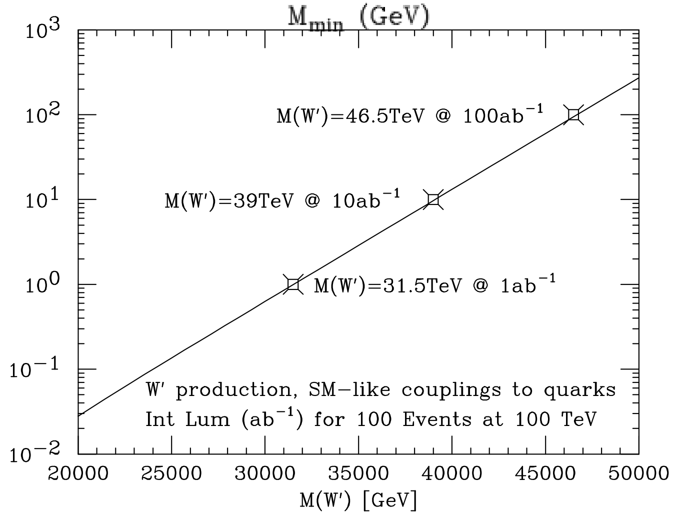
- Opportunities and challenges of hyper-boosted -- O(> 5-10 TeV) -- objects (examples: next page)

➡ crucial ingredient in the definition of benchmarks for detector design

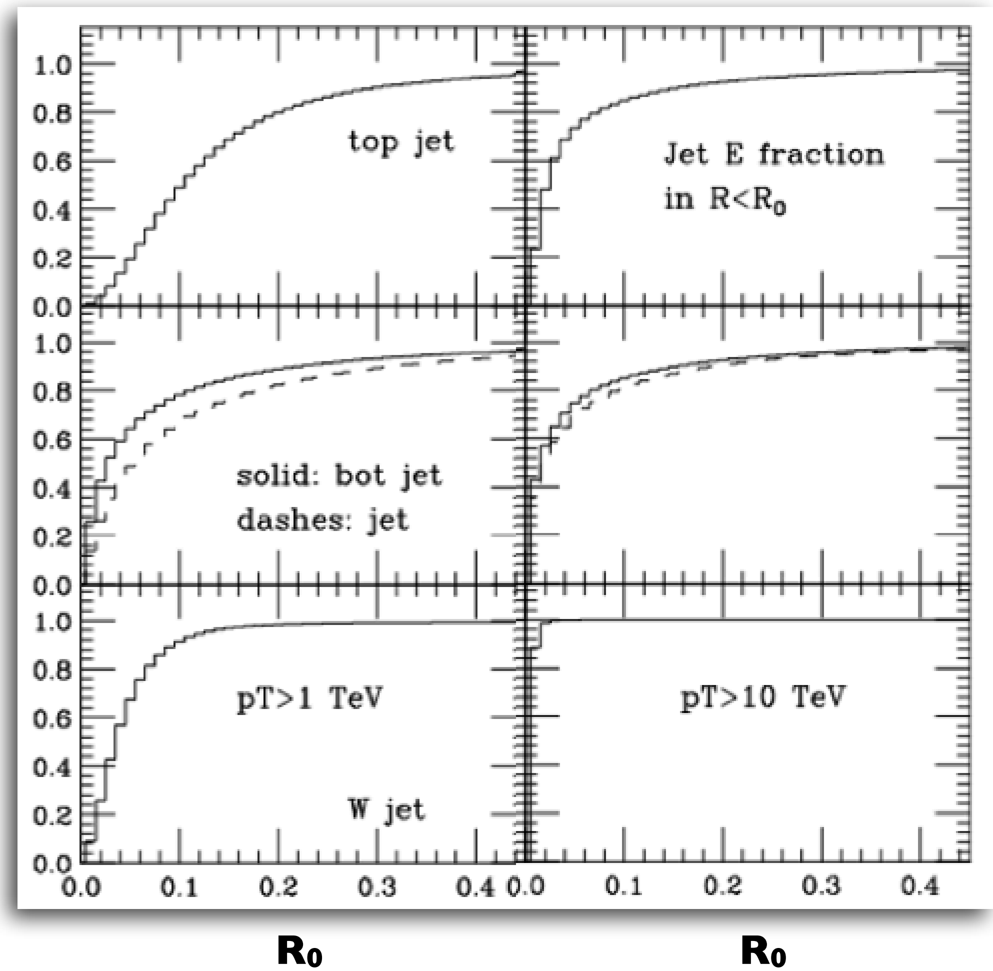
high-p_T rates and jet structure: examples







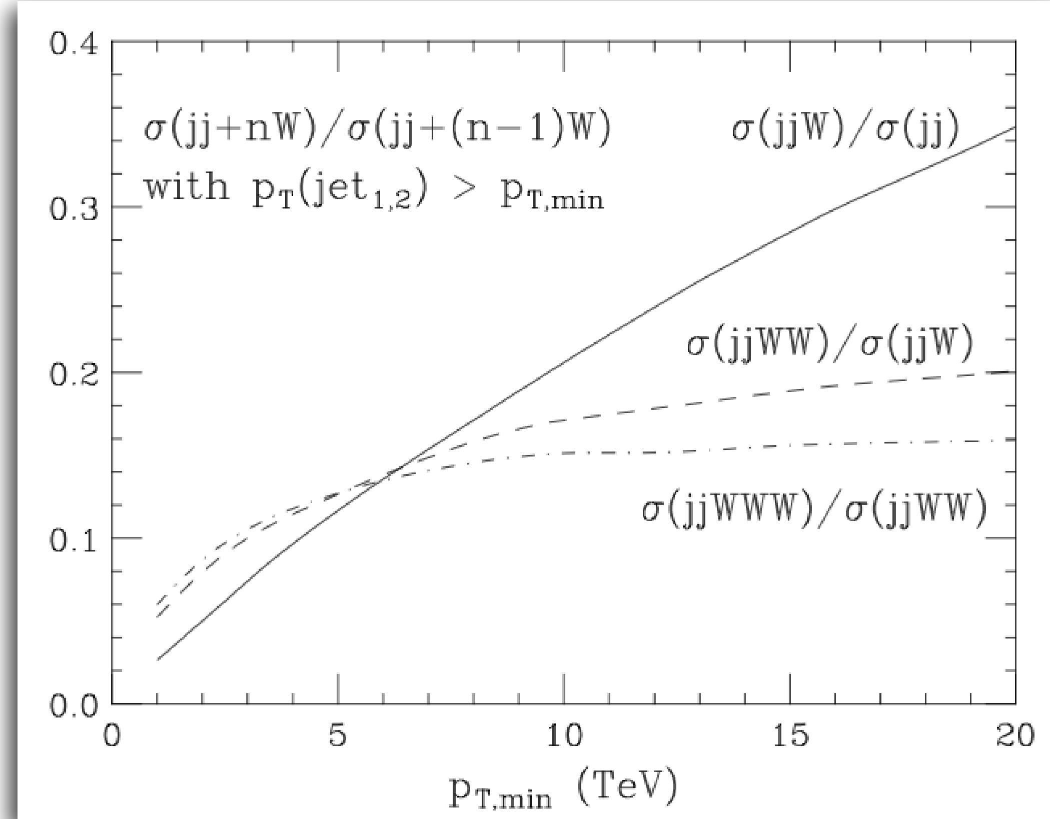
Jet E fraction in $R<R_0$

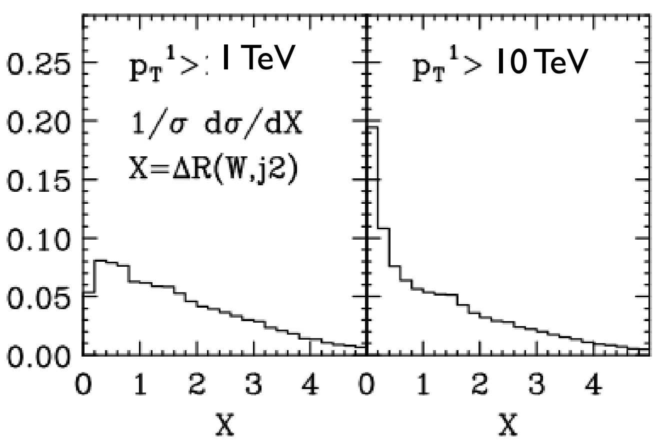


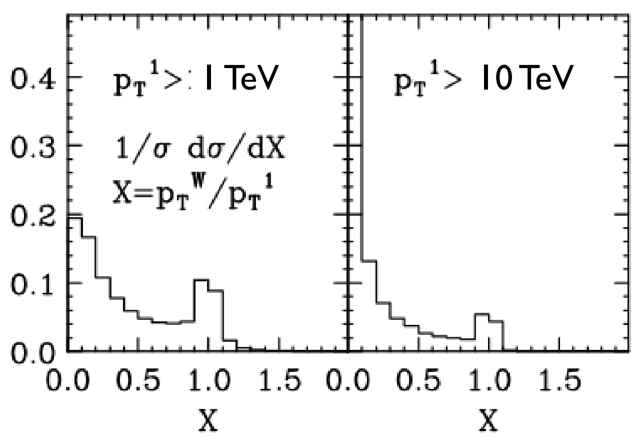
⇒ **needs tagging capability up to p_T ~10-15 TeV**

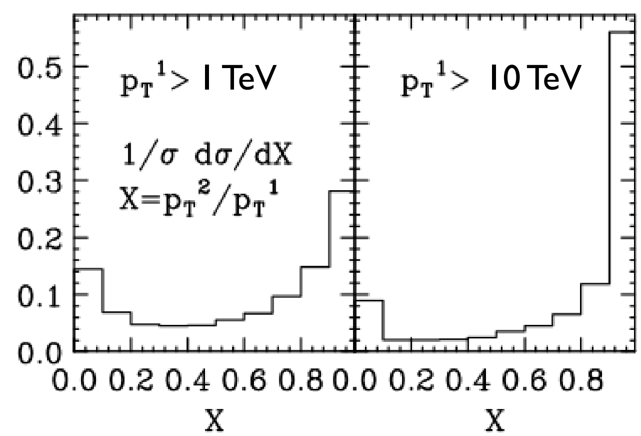
M.L. Mangano BOOST2015 panel discussion

EW structure of high-pt jets









M.L. Mangano BOOST2015 panel discussion

Slide #2: flavor a task for (future) colliders

$$q\bar{q} \to V_L V_L \qquad \sqrt{s} \lesssim \frac{8\pi v^2}{\sqrt{6} m_{b,c,s,d,u}}$$

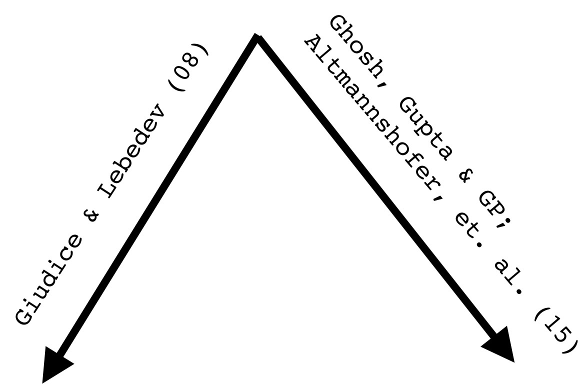
(where V_L is the longitudinal boson)

$$\approx 200,\ 1\times10^3,\ 1\times10^4,\ 2\times10^5,\ 5\times10^5\ \text{TeV}\,.$$

Appelquist & Chanowitz (87).

$$q\bar{q} \to nV_L \qquad \sqrt{s} \lesssim 23,\ 31,\ 52,\ 77,\ 84\ \text{TeV}\,.$$

Maltoni, Niczyporuk & Willenbrock (01); Dicus and H.-J. He (05).



Fire-works in Higgs phys.: $m_{\text{light}} \propto \left(\frac{h}{\Lambda}\right)^n$

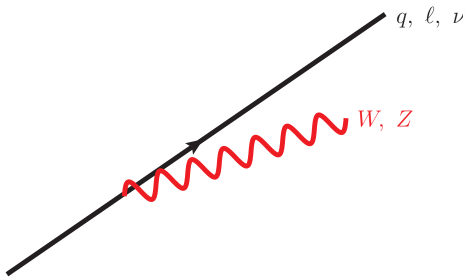
New EW sector: $m_{\text{light}} \propto \langle \bar{f}_{\text{TC}} f_{\text{TC}} \rangle, \not{h}$

Do you care?

(i) in both cases TeV scale emerge => boosted h+light/c-jet;

(ii) possible direct test in $h \to$ light; exclusively approachable but \w large BGs => new venue for new type of jet substructure.

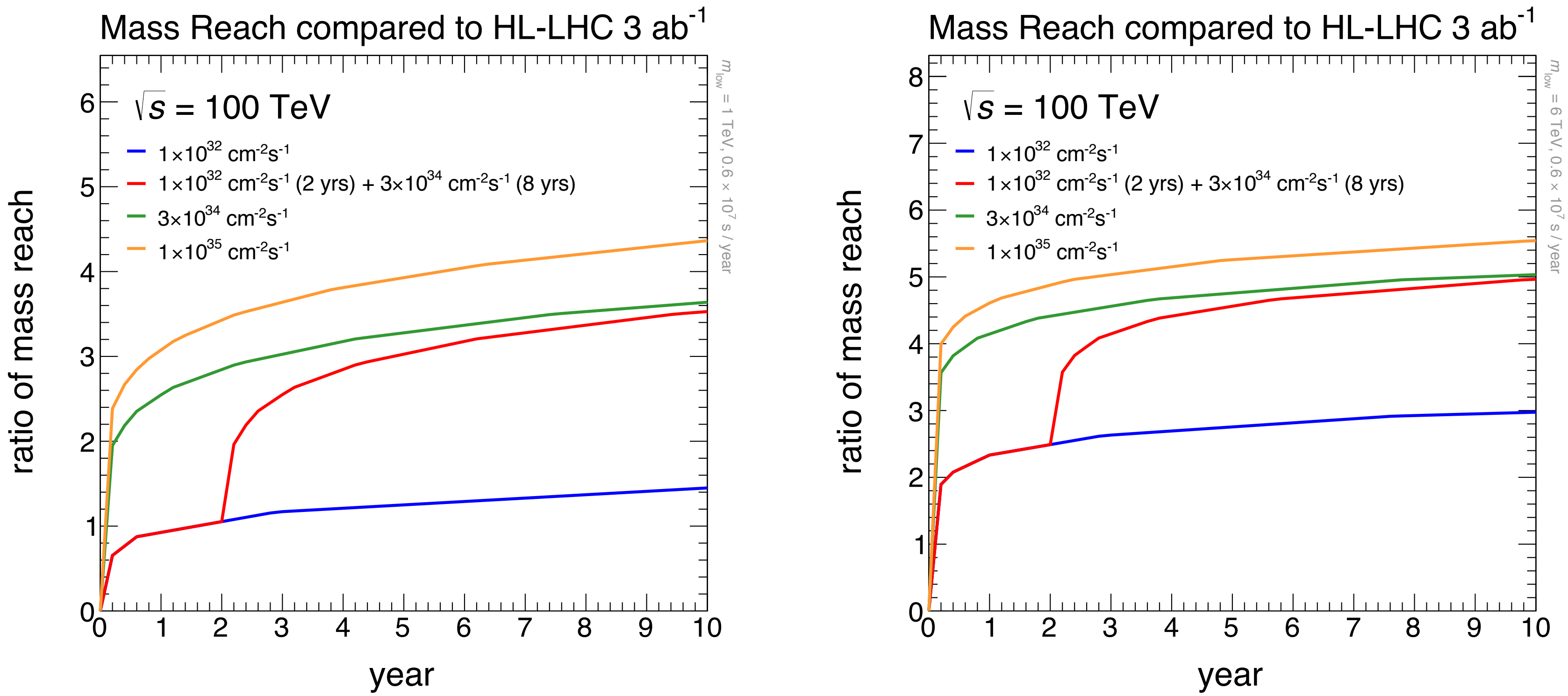
- Primary goal: testing physics responsible for the weak scale.
  - New physics couples strongly to W/Z/h/t.
  - Probing NP into 10s TeV, highly boosted...
- All weak scale particles become light.



Offers important handles to NP.
EW symmetry "restoration", id. quark, neutrino…

- Top quark becomes light too.
  - Top at 100 TeV ≈ bottom at Tevatron.

Environment at 100 TeV



reach of qqbar resonance for
different luminosity scenarios

- Pileup perhaps similar to (or too much above) that the HL-LHC.


SKIP

Future machines: e^+e^- colliders

- **Our next collider could be an e^+e^- project**
  - Large rings (100 km), high luminosity at 250-350 GeV
  - Linear machines, 250-350-500 and beyond 1 (ILC) - 3 TeV (CLIC)
- **Boosted objects at high energy e^+e^- :**

  focus on W-Z-H-t discrimination (as opposed to fighting QCD)

  → jet substructure resolution will be excellent

  → every Higgs/top is sacred: high efficiency mandatory

  → must control systematics to per mil level
- **Jet reconstruction more demanding than at LEP/SLC:**
  - presence of $\gamma\gamma \rightarrow$ hadrons "pile-up"
  - abundant multi-jet final states

ILC: "shovel-ready"
TDR 2013
Cavities deployed in industry

CLIC: "proof of principle"
CDR 2012
CLIC test facility

CEPC: "moving fast"
preCDR 2015

FCC-ee: "concept stage"
CDR 2018-19?

experiment with new algorithms → long inv k_t, VLC, Georgi's global jets, Xcone?
adapt grooming algorithms & taggers to e^+e^- environment/requirements

Full simulation of most relevant benchmark processes are available
Some interest + manpower, special session during LCWS

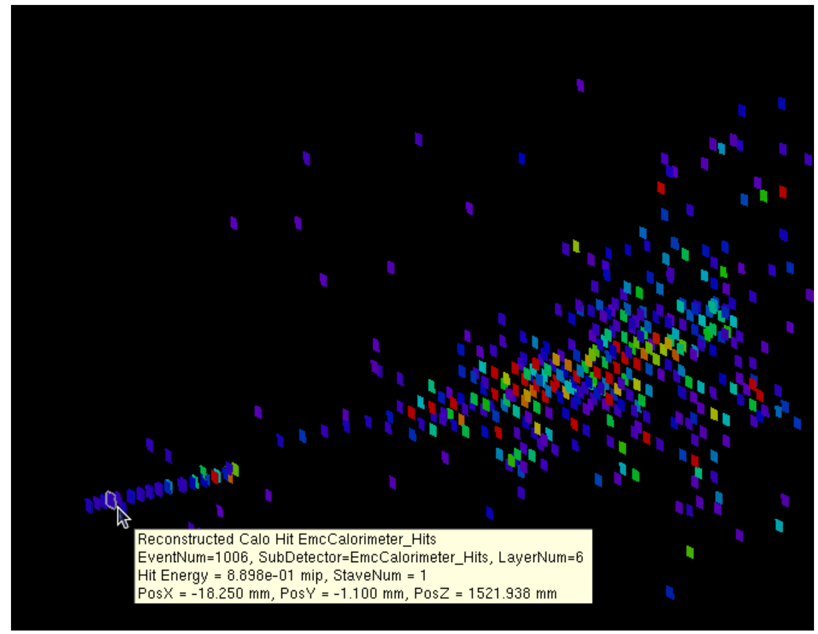
Ultra-granular detectors

- **highly granular calorimeters (CALICE)**
  - Lateral segmentation, well below shower size
    << Moliere radius (~50 um-1 cm)

    ½ the interaction length (~5-10 cm)
  - Longitudinal segmentation:

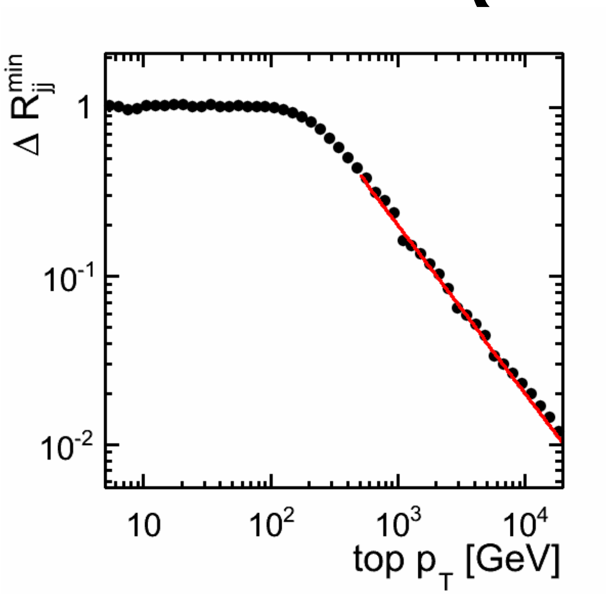
    30 EM + 30 Hadronic
- **Particle Flow Jet Energy resolution**
  - Theoretical limit: $\delta E/E \sim 21\%/\sqrt{E}$.
  - In practice: $\delta E/E \sim 3\%$

    (confusion, even at few 100 GeV)
  - Is the real gain in jet substructure?



Detailed MC + data for two-track separation, potential and limitations of PF
e^+e^- experiments → CMS forward calorimeter → FCC-hh?

Questions for FCC-hh



Substructure analyses may drive detector granularity / size

Insist on resolving sub-jets in at least some detectors?

For top: separation between partons in t → Wb → bqq system

To distinguish W, Z, H (QCD rejection not unlike τ-tagging)

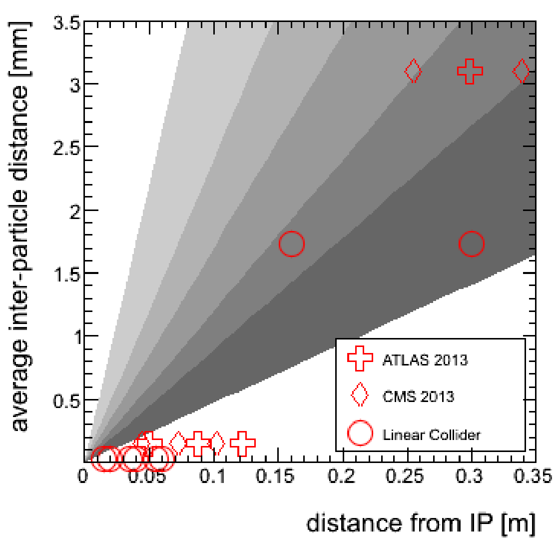
Granularity << 0.01 at 10 TeV (increase R, B → solenoid cost μ stored energy)

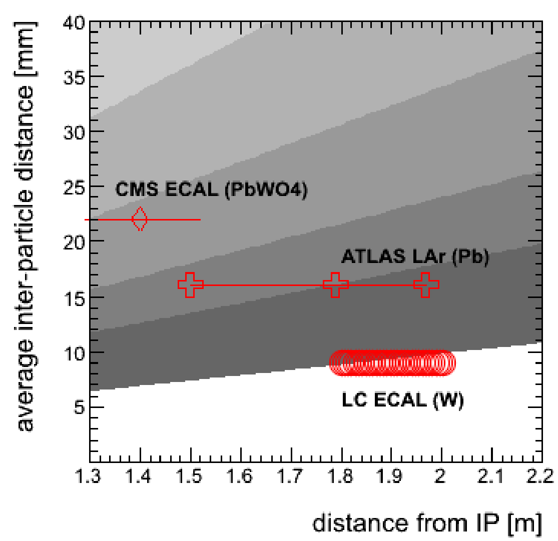
Insist on connecting tracks to clusters for particle flow?

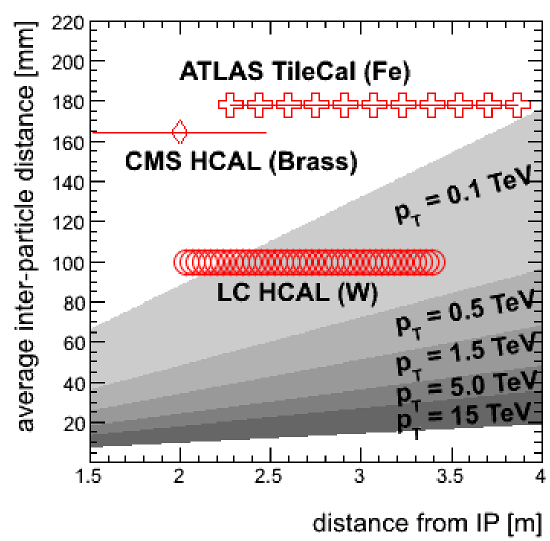
Tracker segmentation, Moliere radius OK

Hadronic system seems daunting even with Tungsten (λ=10 cm)

Ultra-segmented many-layer calorimeter (cost >> tracker cost)



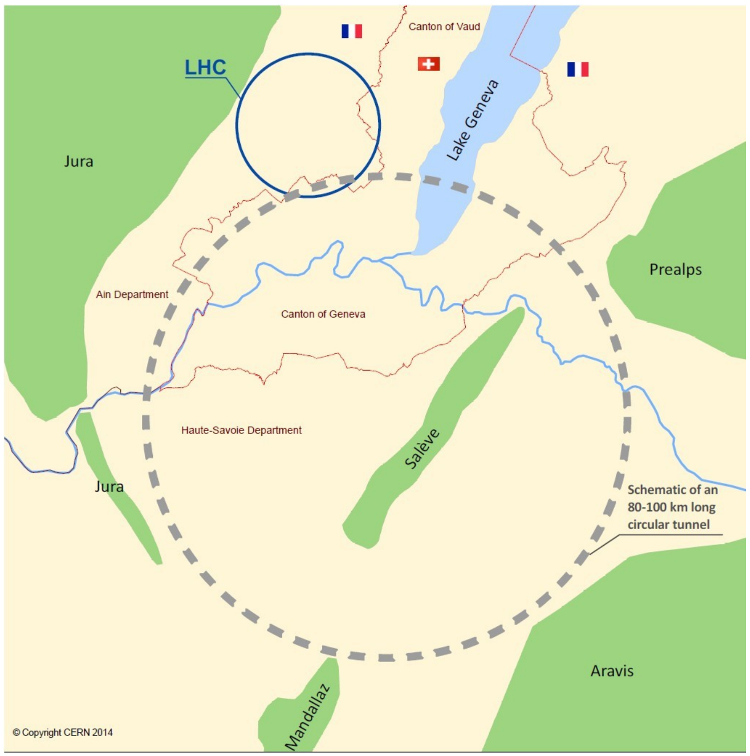


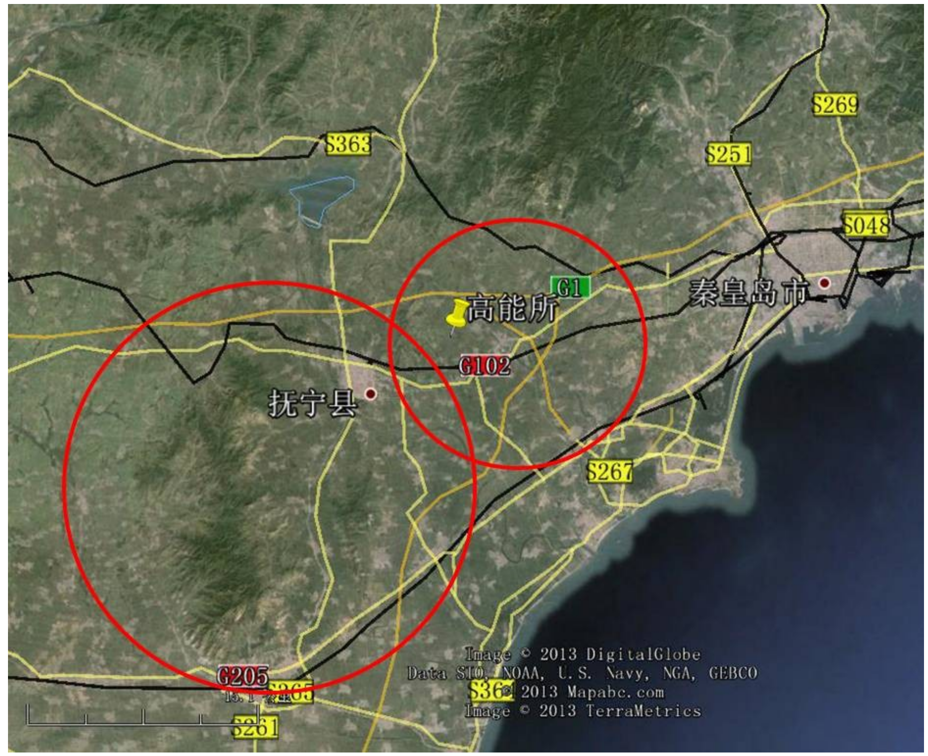


Detailed MC + data for two-track separation, potential and limitations of PF

Future machines: hadron colliders

- 50-80-100 km ring full of 16 T magnets
- pp collisions up to 100 TeV





If you like boosted objects, you are going to love this machine
Can detectors, jet reconstruction and substructure analysis simply be scaled up?

Questions the LHC can answer

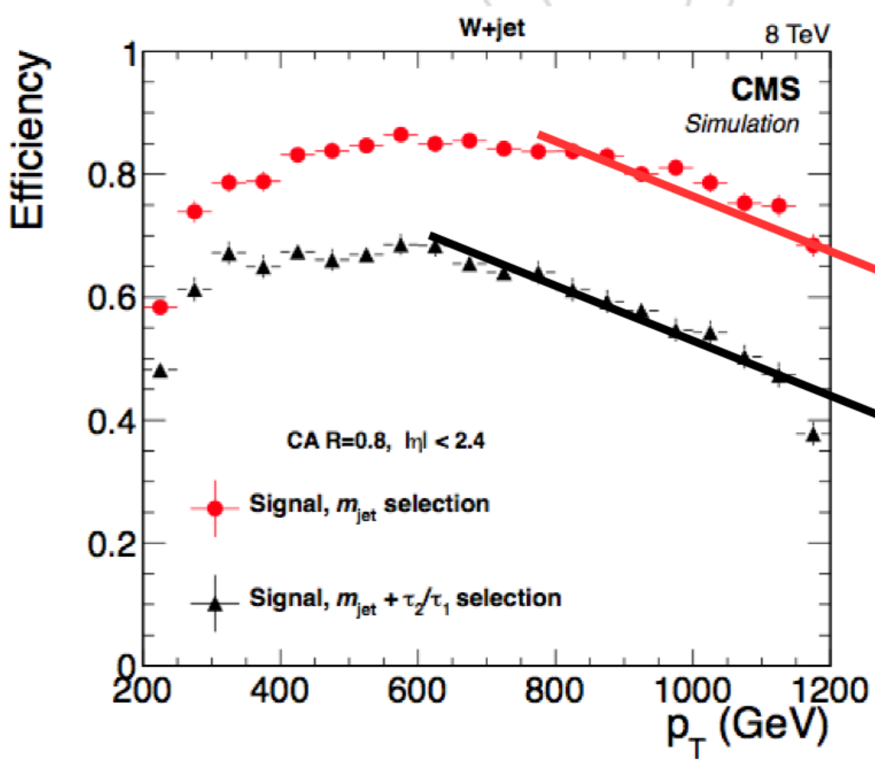
- Understand cores of highest p_T jets:
  - Fine-grained jet shapes? Multiplicities?
- Do boosted objects behave as expected?
- Test tracker-based (or EM-based) substructure in realistic environment

Questions the BOOST report could answer

- Does Delphes' model predict jet substructure performance?
- MC studies to derive granularity/size requirement for FCC-hh
- Which techniques can deal with hyper-boost best?
- (Comparison of jet algorithms for e^+e^- machines)

More boost

- Lets recount a story from last year

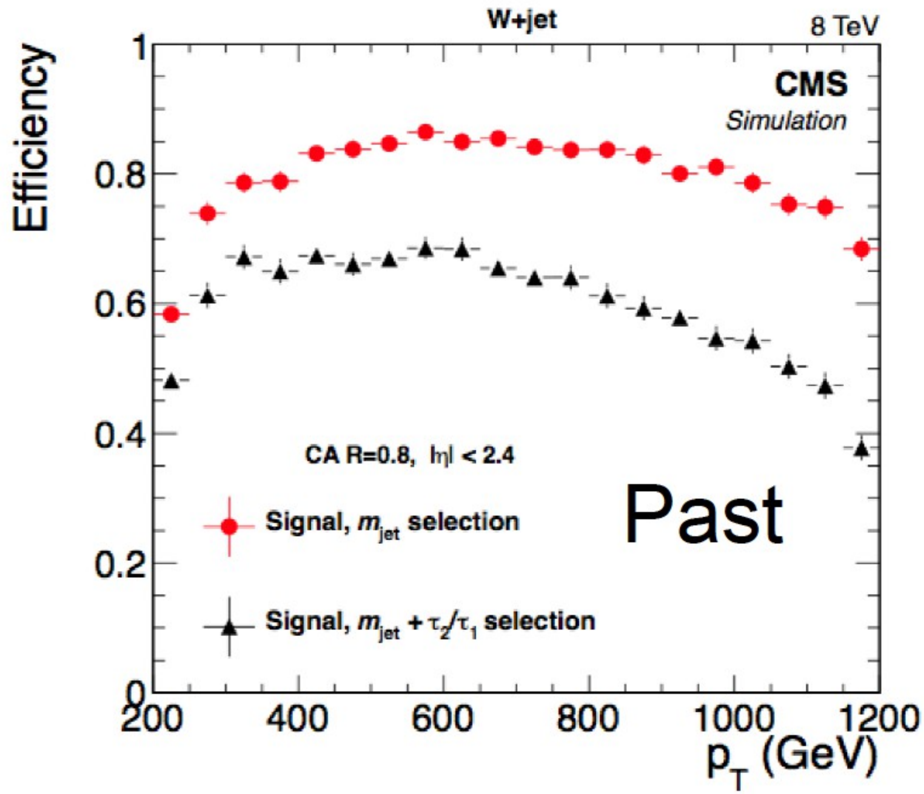


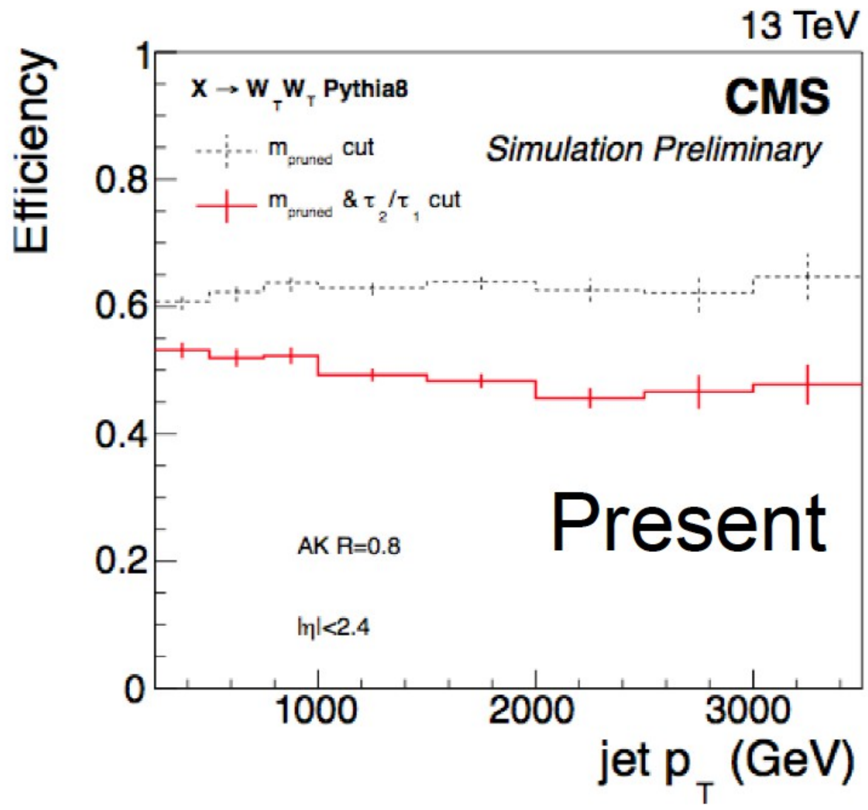
In CMS at 8 TeV
Boosted V Tagging Efficiency
starts to drop down

Effect is substantial at high p_T

Was a major concern from Run II jet reconstruction

After fix





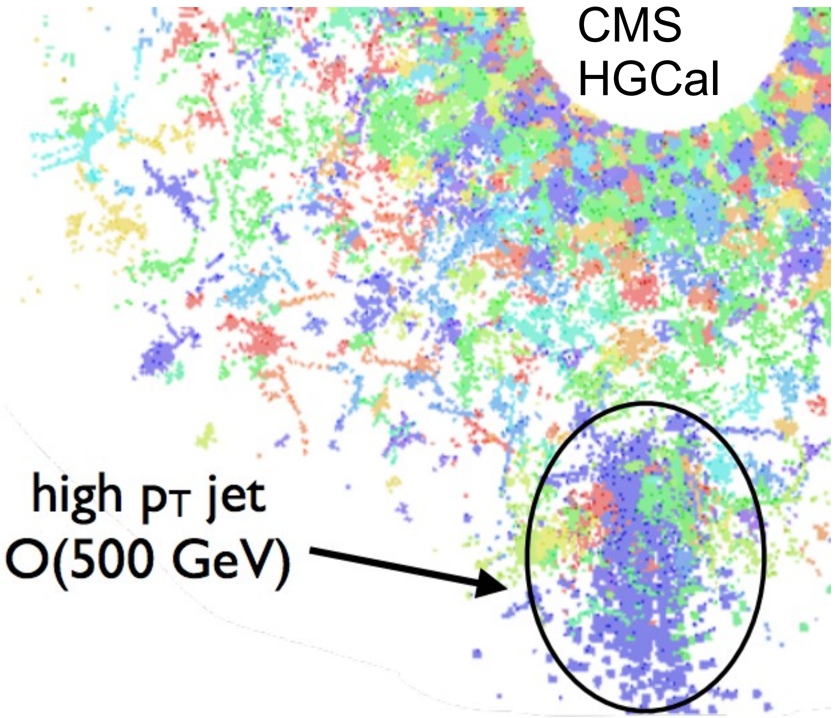
Reconstruction robust up to 4 TeV

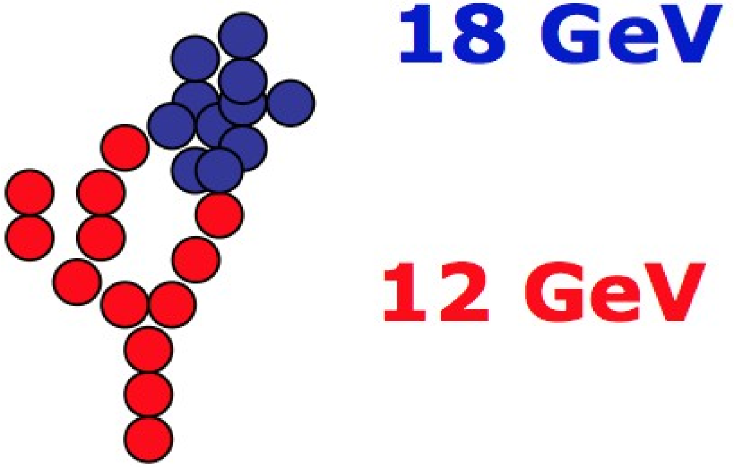
Going beyond will be a challenge

Main fix came from maximizing the granularity

Questions

- Is there a benchmark we can study? (τ)
- What needs to be proved for high granularity calo?
- Are their other ways to tag the high pT?
- What are the right fake rates?/efficiencies?
  - If QCD is lower we can go loose





Slide #3: phenomenological issues

♦ Aspects of “superboosted" jets -

Given a detector, minimal angular scale: $\theta_{\rm had} \approx \frac{d_{\rm had}}{r_{\rm HCAL}} \approx 0.1 \times \frac{\lambda_{\rm HCAL}}{20\,{\rm cm}} \times \frac{2\,{\rm m}}{r_{\rm HCAL}}$

Superboosted jets: substructure cannot be probed within the HCAL:

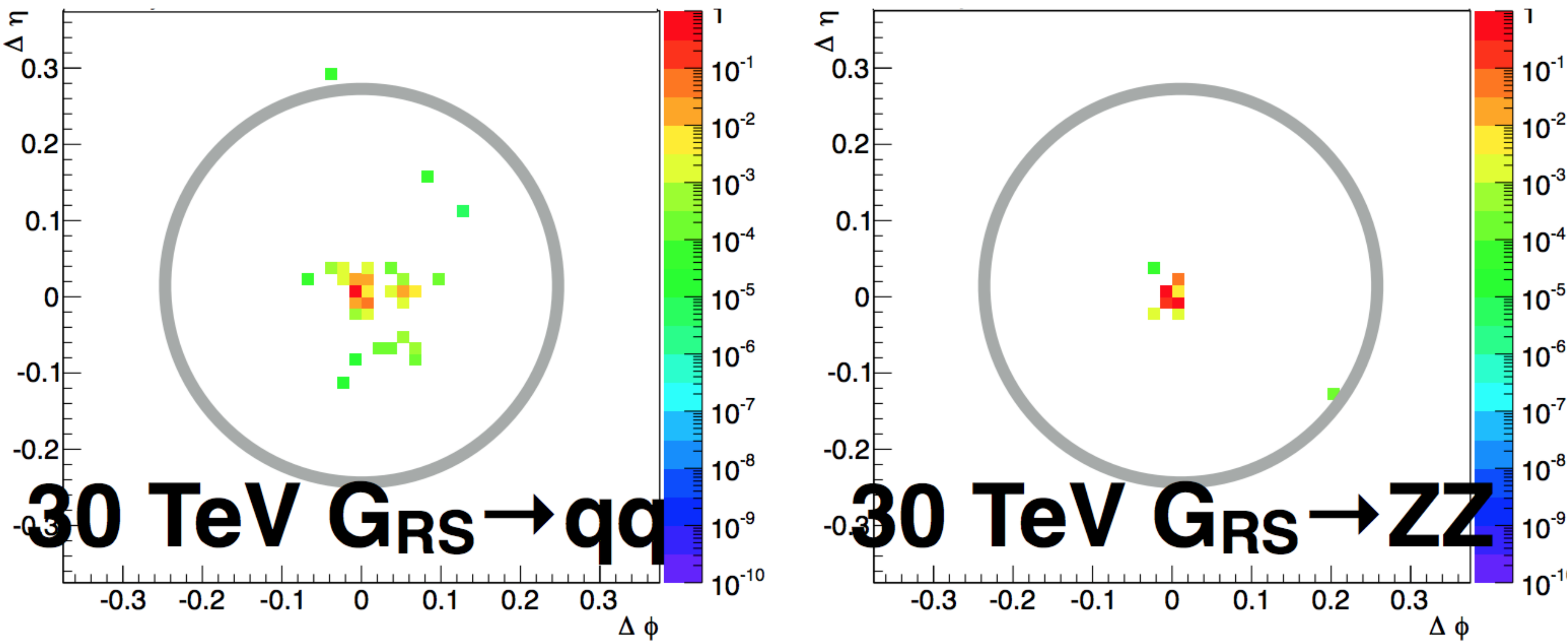
$$\delta R_{\rm superboost} \sim \frac{2m_{W,Z,H,t}}{p_T} \lesssim \theta_{\rm had} \sim 0.1 \qquad {p_T}^{W,Z,H,t}_{\rm superboosted} \gtrsim 1.6, 1.8, 2.5, 3.4\,{\rm TeV}$$

(i) is there a way out?
(ii) how bad is this ? [loosing O(20%) of the jet substructure]
(iii) is this true for coloured states? (like top)
(iv) are “EW/h-sub-Sudakov” the next tau’s? (can we, ignore EW corrections)
(v) is E mismatch a useful handle?

What is the physics motivation?

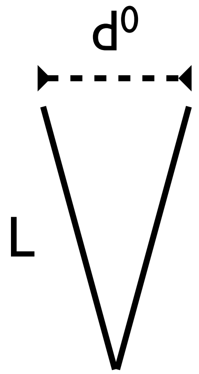
Boosted objects become points at very high boost

High boost means a very small size

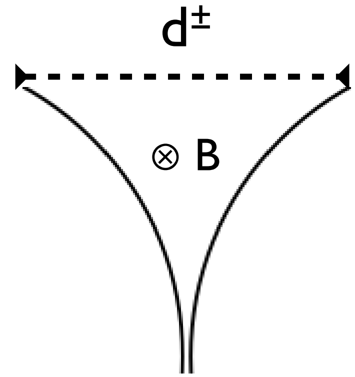


http://indico.cern.ch/event/340703/session/97/contribution/121

Scaling laws



$$d^0 \sim L \cdot k_\perp/p_T$$
$$\sim L \cdot 2m/E_T$$



$$d^\pm \sim L \cdot 0.3\, BL / p_T$$
$$\sim 0.3\, N_{part}\, (BL^2) / E_T$$

$k_\perp$: transverse p w.r.t. jet axis
p_T : particle pT (GeV)
E_T : jet pT
L: calorimeter inner radius (m)
B: magn field (Tesla)
N_{part} : # of particles in the jet

$\langle z \rangle = \langle p_T \rangle / E_T \sim 1/N_{part}$

For 14 TeV $\xrightarrow{\times 7}$ 100 TeV:

$m \to m$, $E_T \to 7\text{x}\, E_T$

$BL^2 \to \sim 7\text{x}\, BL^2 \Rightarrow B \to \sim 1.5\text{x}\, B$, $L \to \sim 2\text{x}\, L$

$d^\pm \to d^\pm$ $\quad d^0 / d^\pm \to 1/3 \times d^0 / d^\pm$

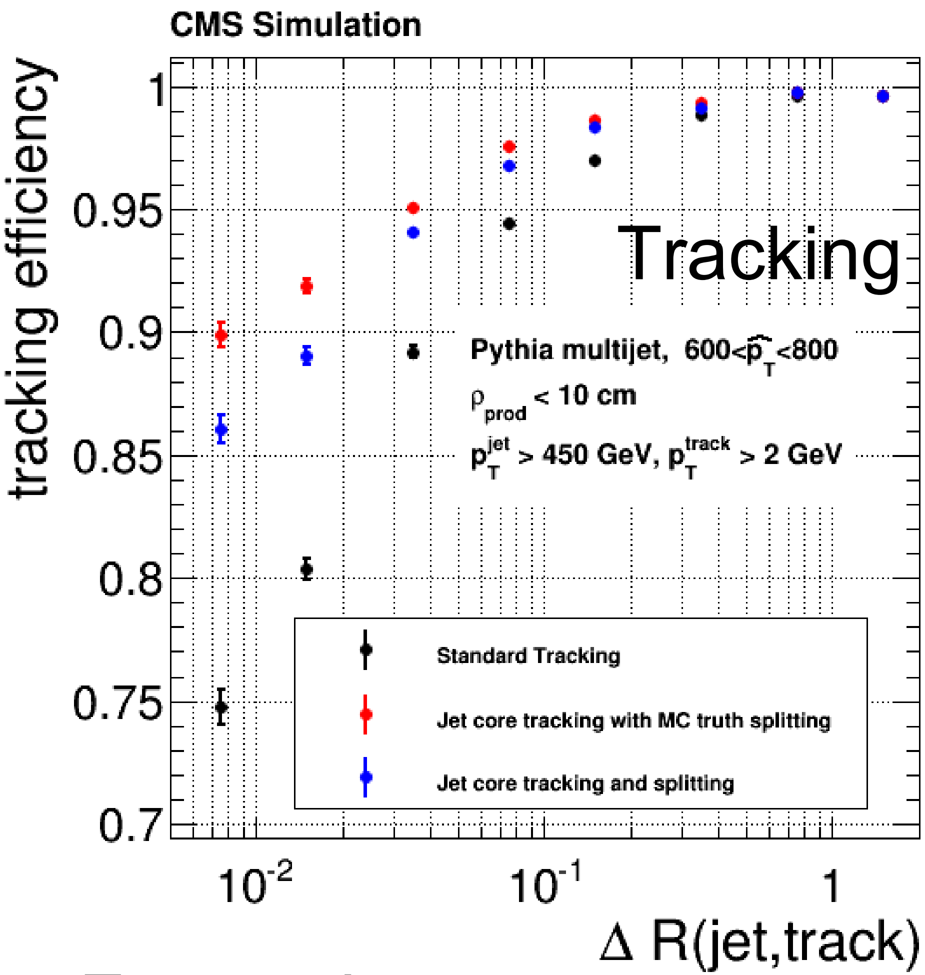
$\Rightarrow$ neutral core density grows much more than charged core's density

NB: $N_{channels} \sim (L/d)^2 \Rightarrow$

$N^\pm_{channels} \to \sim 4\text{x}\, N^\pm_{channels}$
$N^0_{channels} \to \sim 10\text{x}\, N^0_{channels}$

Tracking : 60%
Ecal : 30%
Hcal : 10%

Size Metrics



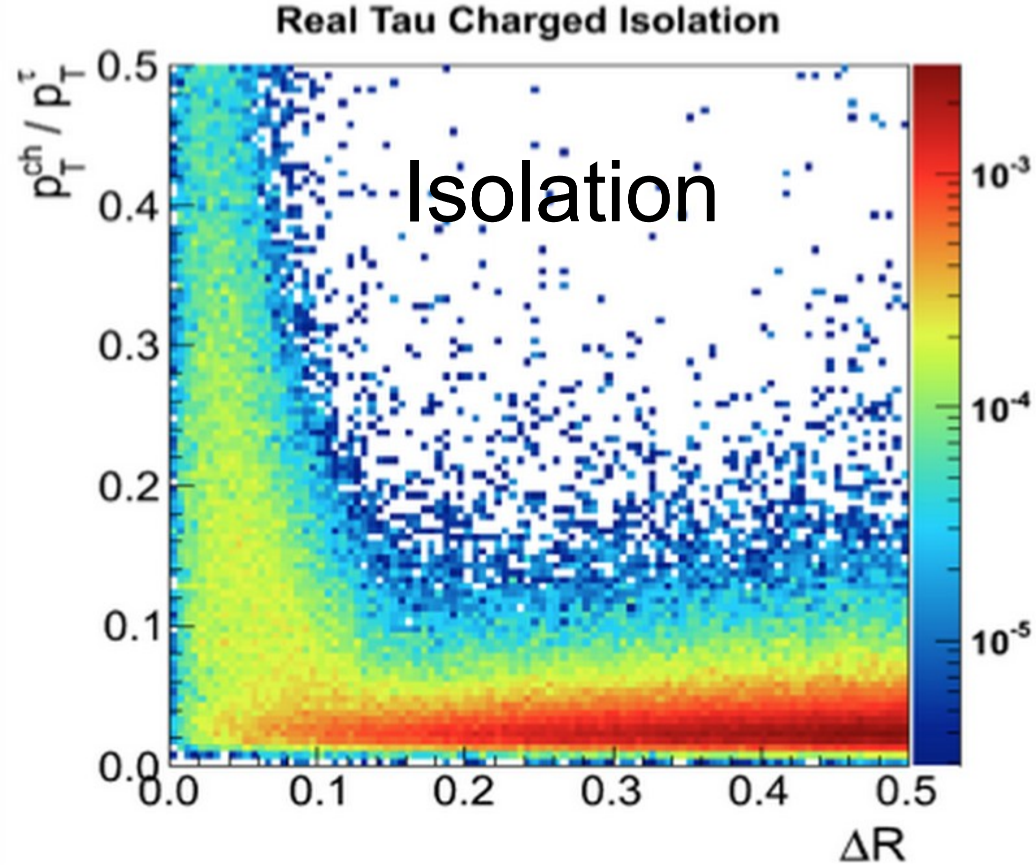
Current LHC :
Ecal 0.02x0.02 in η φ 2x2cm(Moliere)
Hcal 0.08x0.08 in η φ 10x10cm(λ_I)

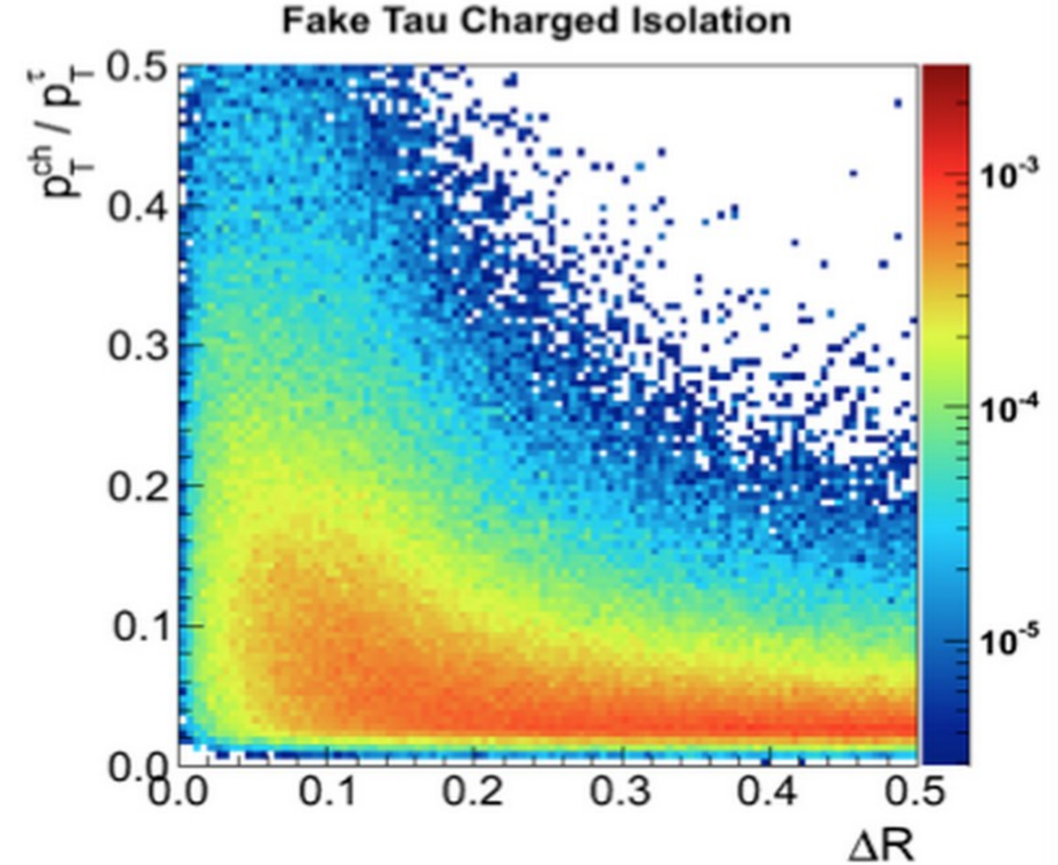
Future LHC :
Ecal 0.01x0.01 in η φ 1x1cm
Hcal 0.01x0.01 in η φ 1x1cm

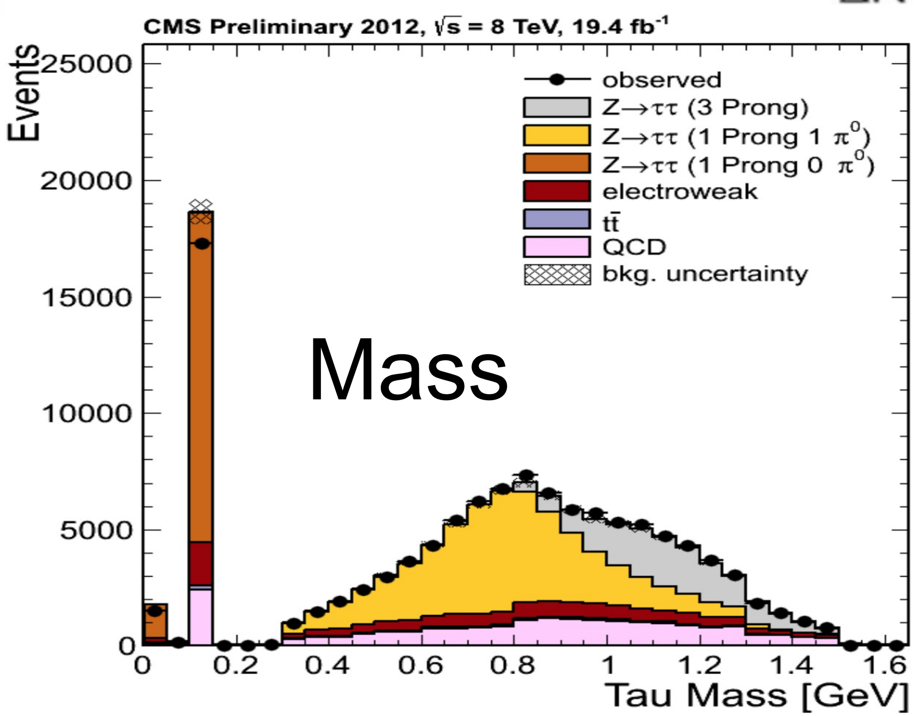
Sub Moliere/Nuclear interaction
Resolved by resolving the shower

fundamental limit in LHC is 0.01

Future detector :
Tracking => scales < 1/R (depends on rate of hit sharing)
Ecal/Hcal => scales with 1/R







Boost of tau @ 8 TeV is similar
As the boost of a W at 100 TeV

Tau id poses an alternative approach


SKIP

Slide #1: (additional) theoretical inputs

♦ Layman comment: theorists involvement => matching onto advance MC tools - cross communication with NLO/NNLO ?

Talks by: Larkoski; Moult; Thaler …

(apologies to people involved in other work)

Instructive discussion with Marat on prospects for automation.

partial list of recent works: -

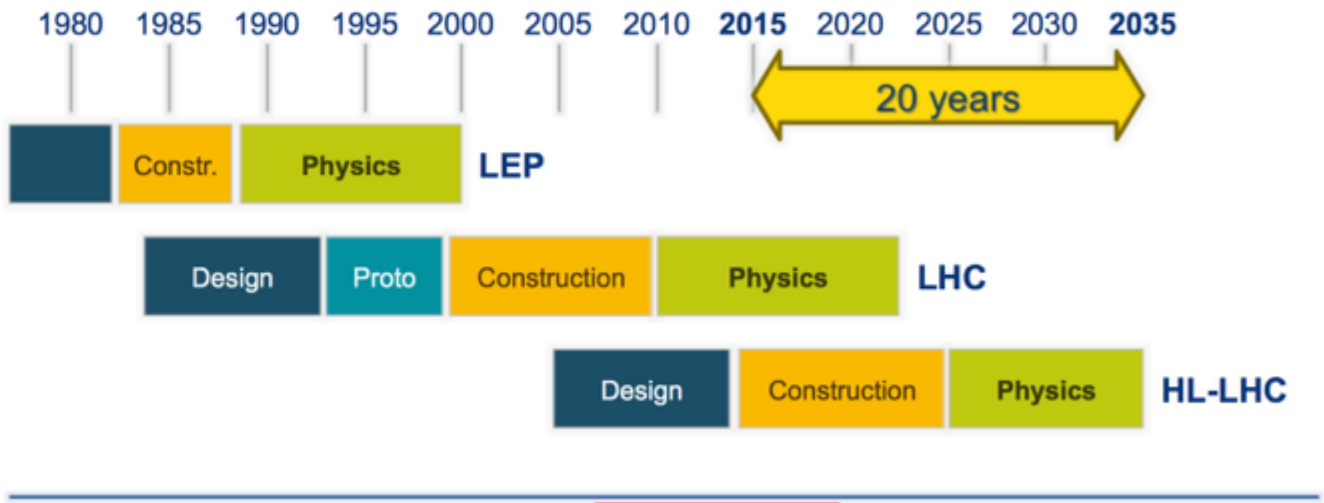
Farhi, Feige, Freytsis & Schwartz; Becher, Frederix, Neubert & Rothen; Larkoski, Moult & Neill (15);
Gerwick, Hoeche, Marzani & Schumann (14);
GENEVA: Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh & Zuberi (12,15) and more …

♦ Energy/precision frontier why? => understanding flavor.

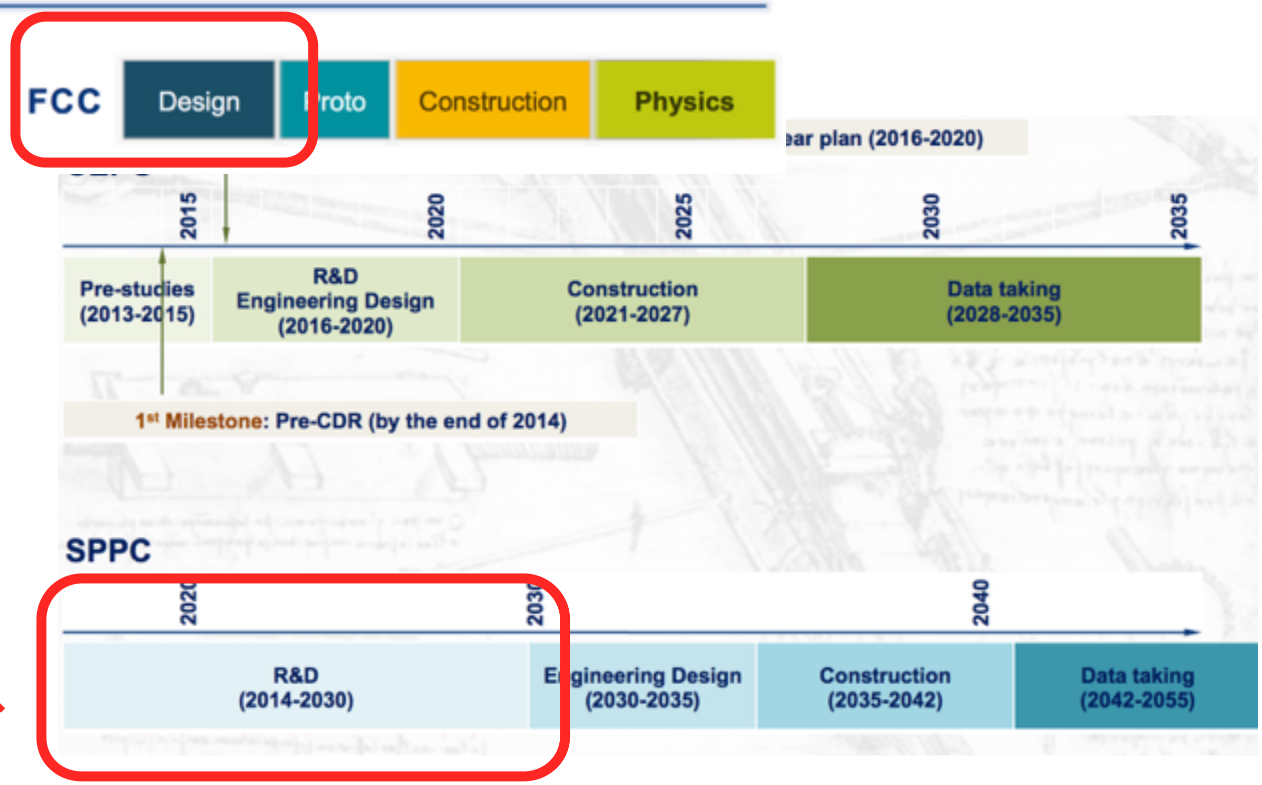
Higgs in minimal standard model, 2 roles:

(i) induce electroweak gauge boson masses & unitarization (high-E consistency);

(ii) induce fermion masses & unitarization (high-E consistency) <=> not tested directly!



Time to start thinking about it seriously is now.



Opportunities of building radically new detectors, doing completely different analysis.
cf. LHC vs SppS…