Options for CMS upgrade / 2

Workshop on detectors for High Energy Physics and applications

Milano, January 13th, 2015

- *A. Benaglia*, M. Lucchini

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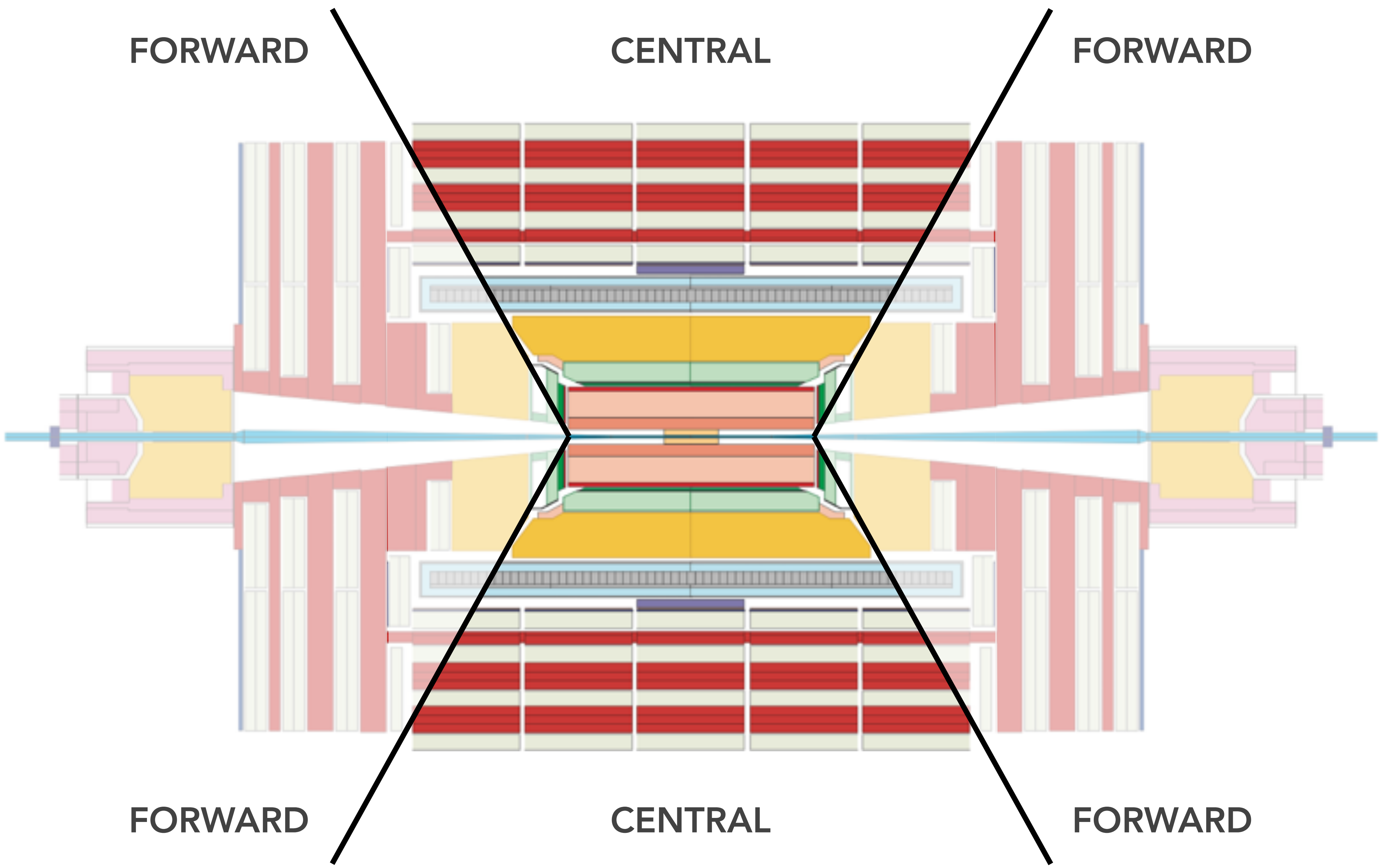
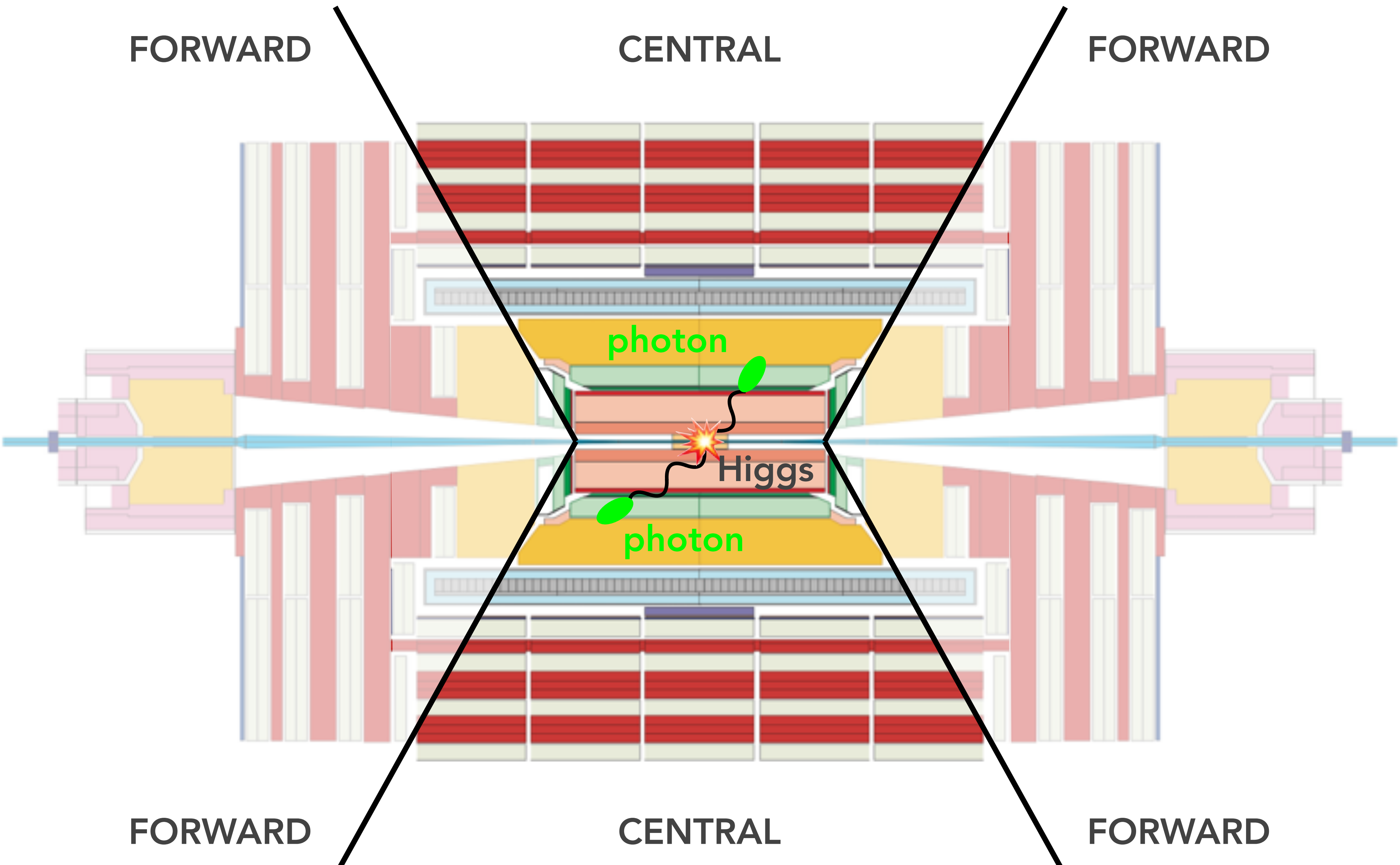
Why we need good detectors in the forward regions



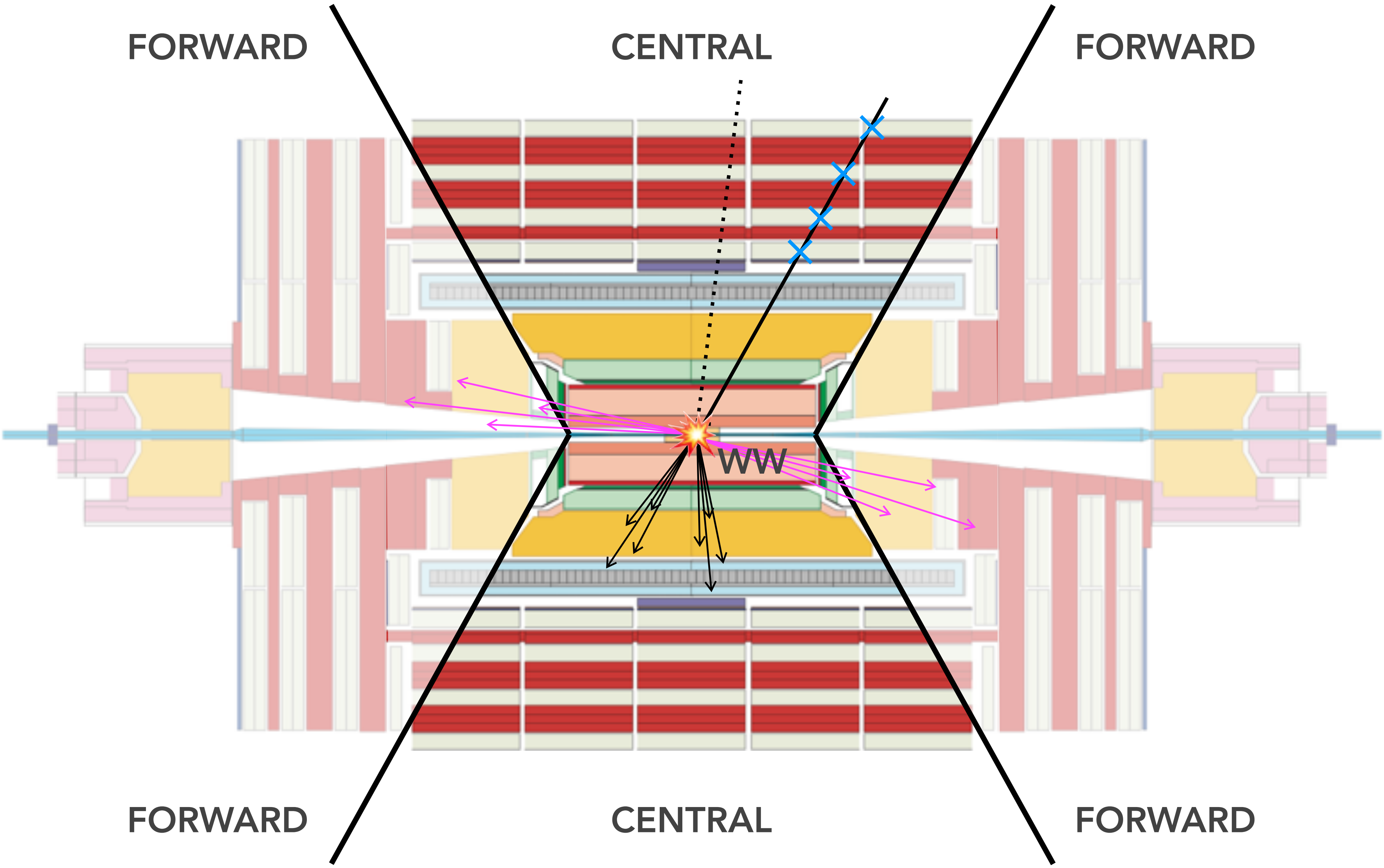
Why we need good detectors in the forward regions

- Many interesting events (e.g. **H → γγ decays**) occur in the central part of the detector



Why we need good detectors in the forward regions

- … but we have at least one important case where we need to well reconstruct particles (jets) in the forward region: **vector boson scattering**



Vector boson scattering: the process

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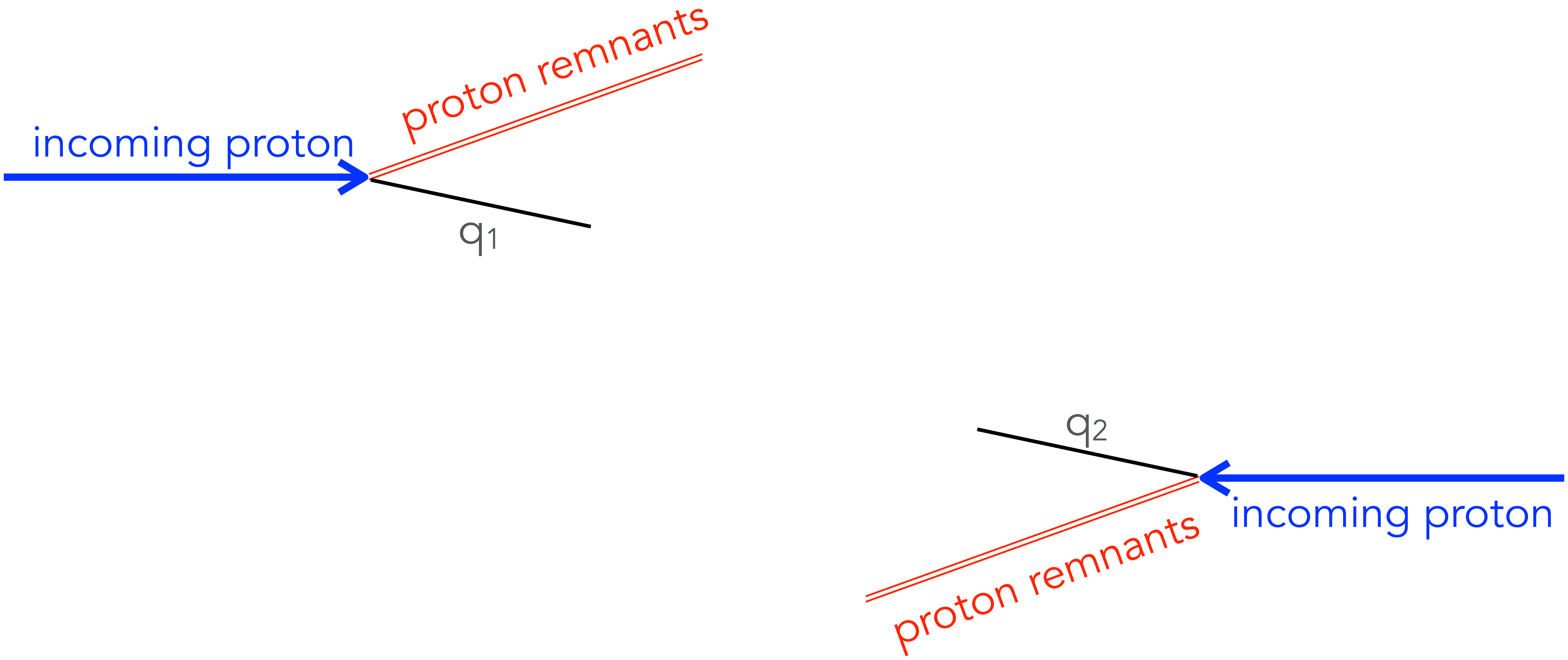

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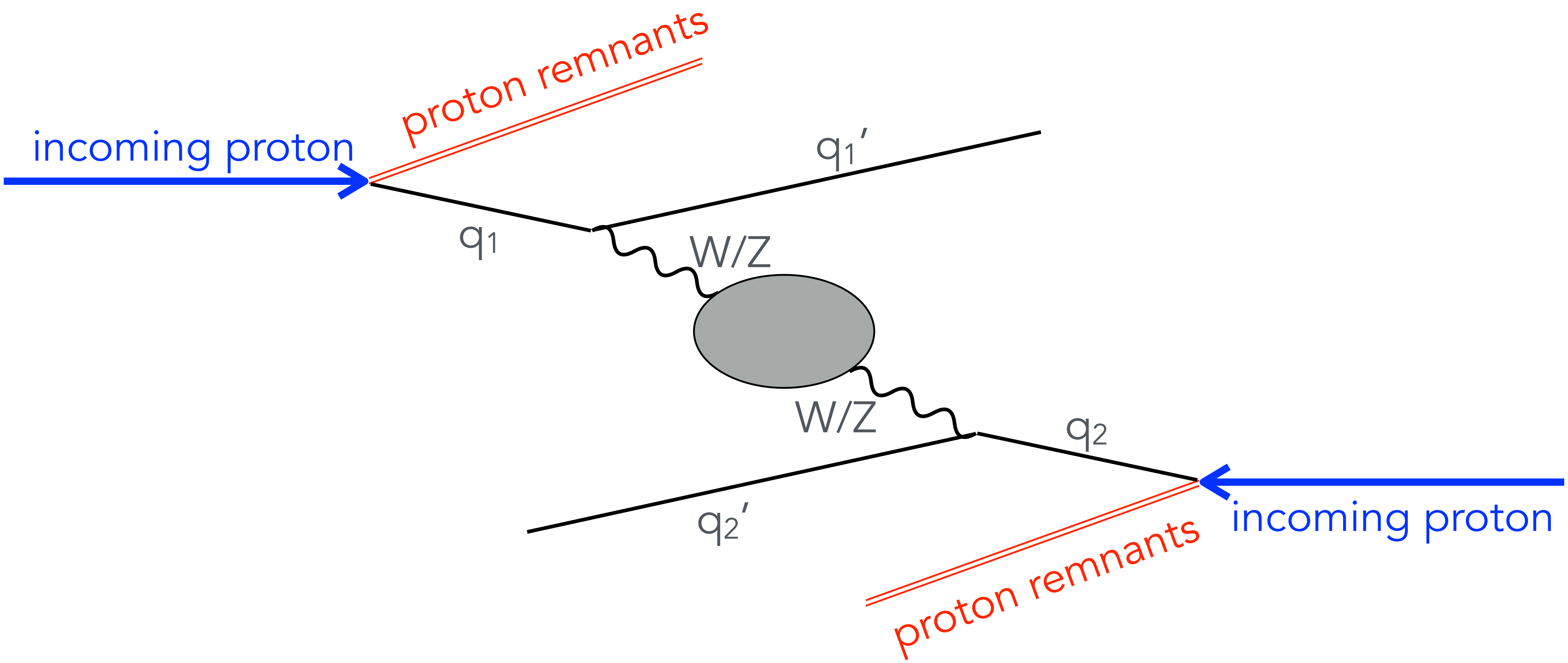

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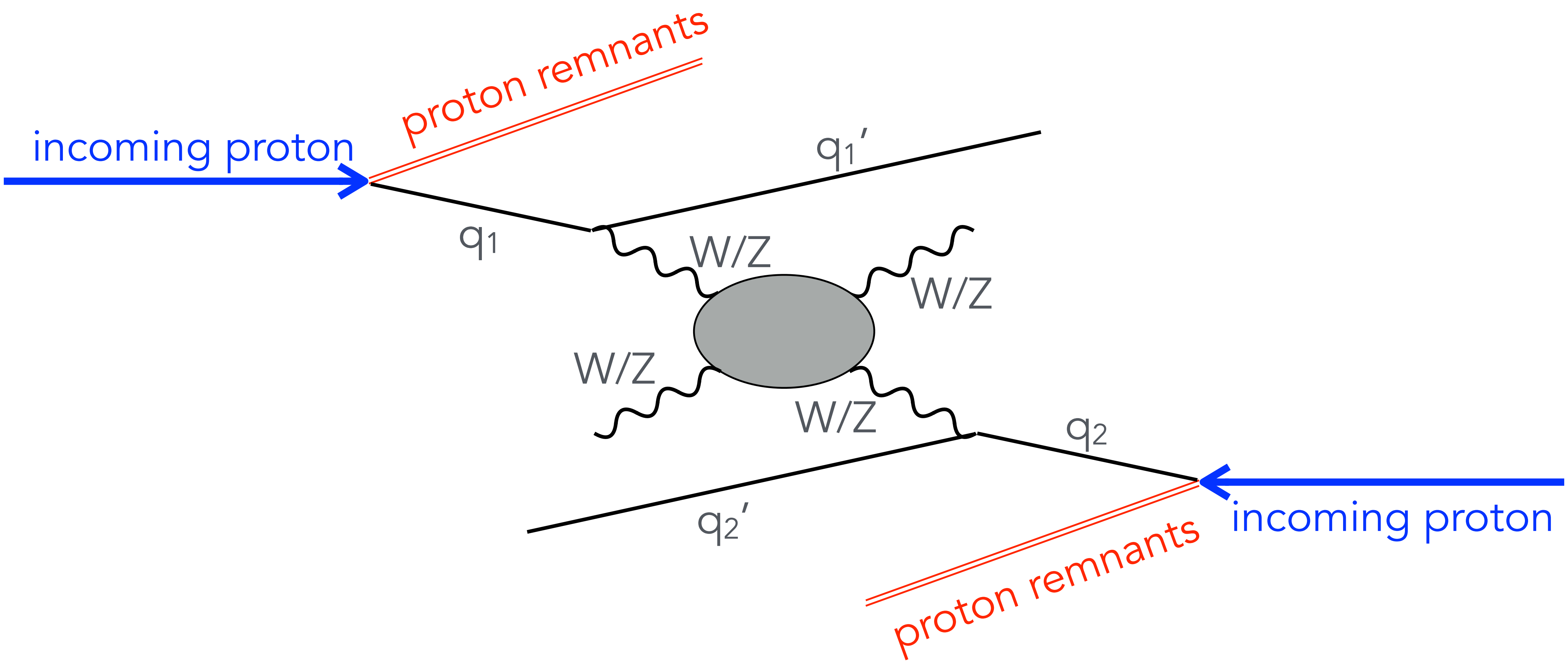

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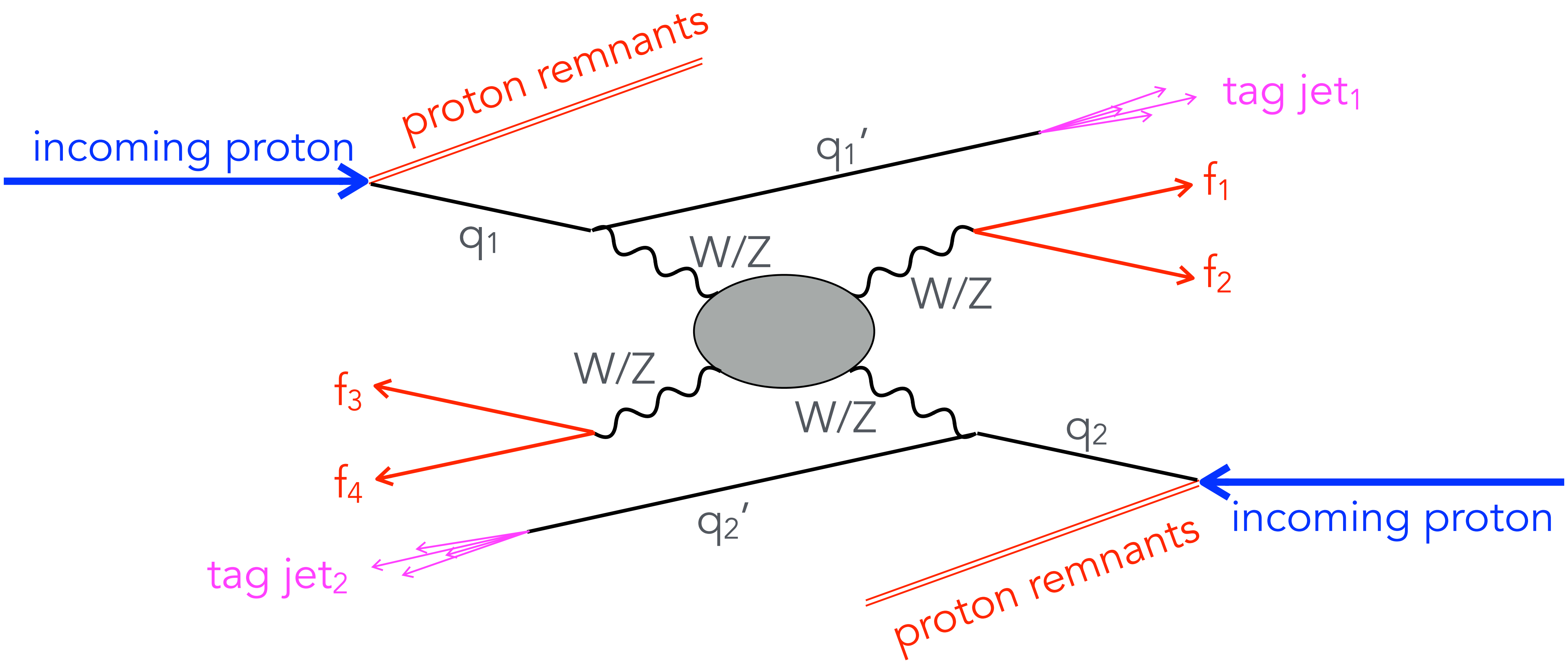

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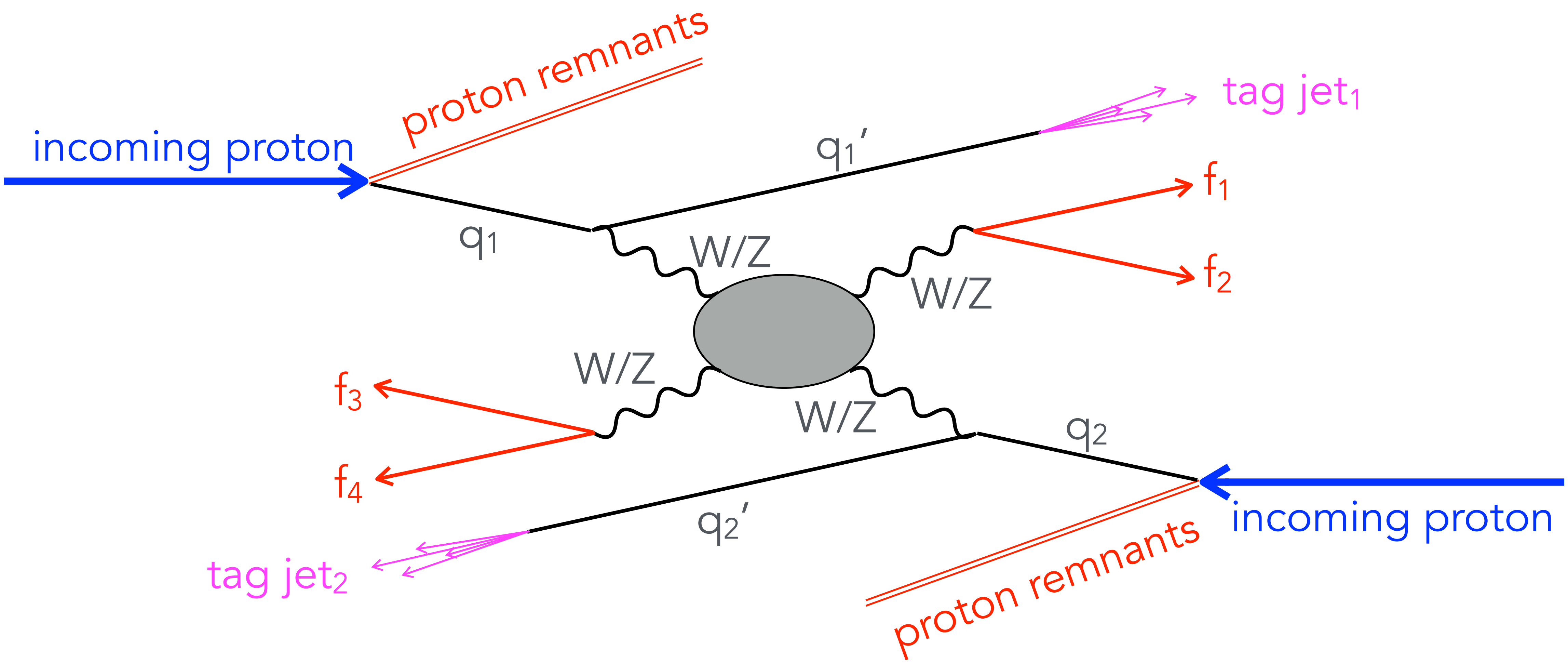
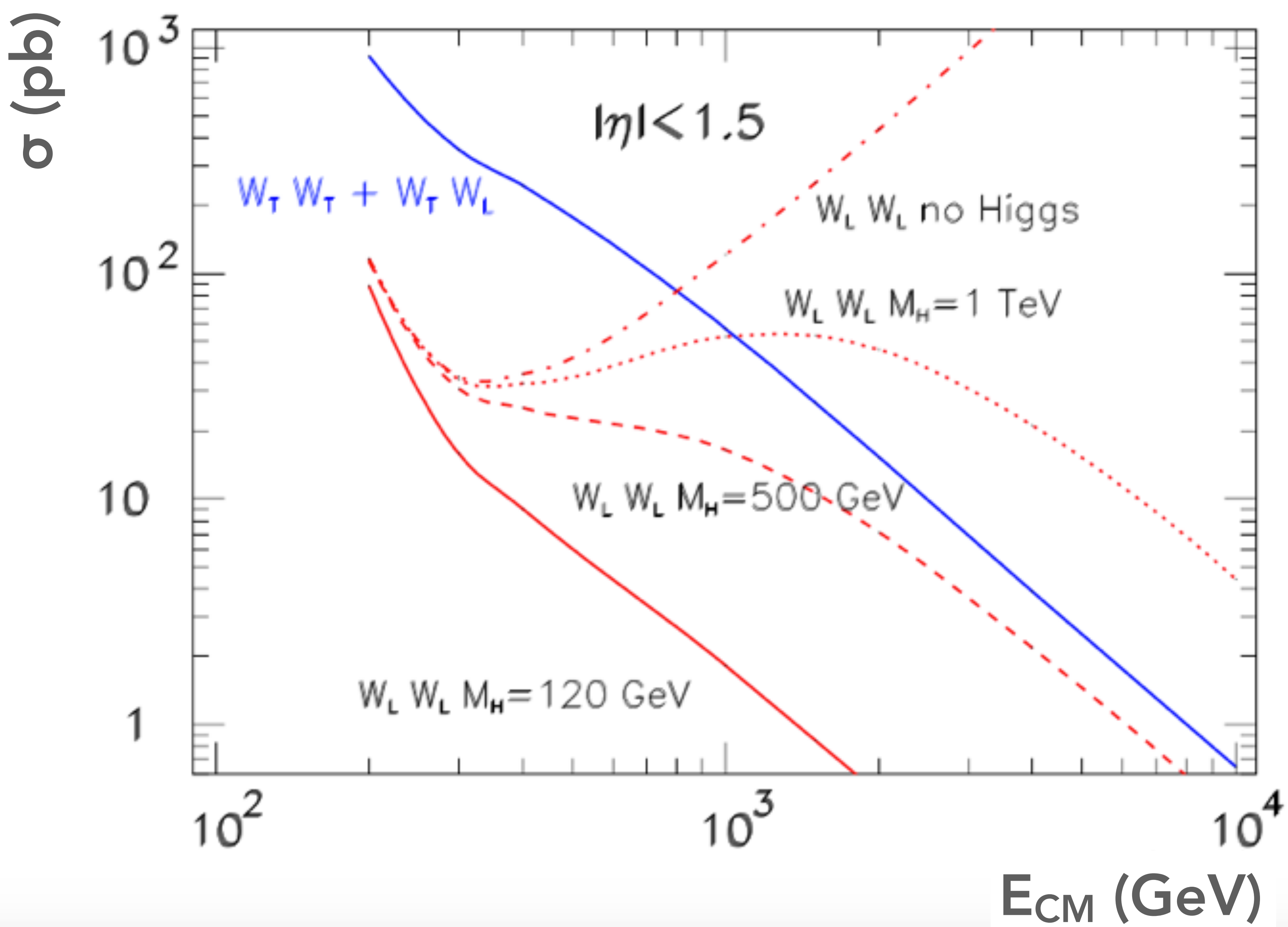


- two **fermion pairs** in the central part of the detector
  - eν+μν, eν+qq, μν, qq+qq
- two **high energy 'tagging' jets** in the forward and backward region

Vector boson scattering: the importance

- **WW scattering** is the **smoking gun** for the **EWSB mechanism**!

$W^+W^+ \rightarrow W^+W^+$



- without the Higgs, $W^+_L W^-_L \rightarrow W^+_L W^-_L$ **diverges**
- a Higgs-like particle **regularizes** the cross-section
- the shape of the cross-section is sensitive to the **characteristics of the Higgs boson**

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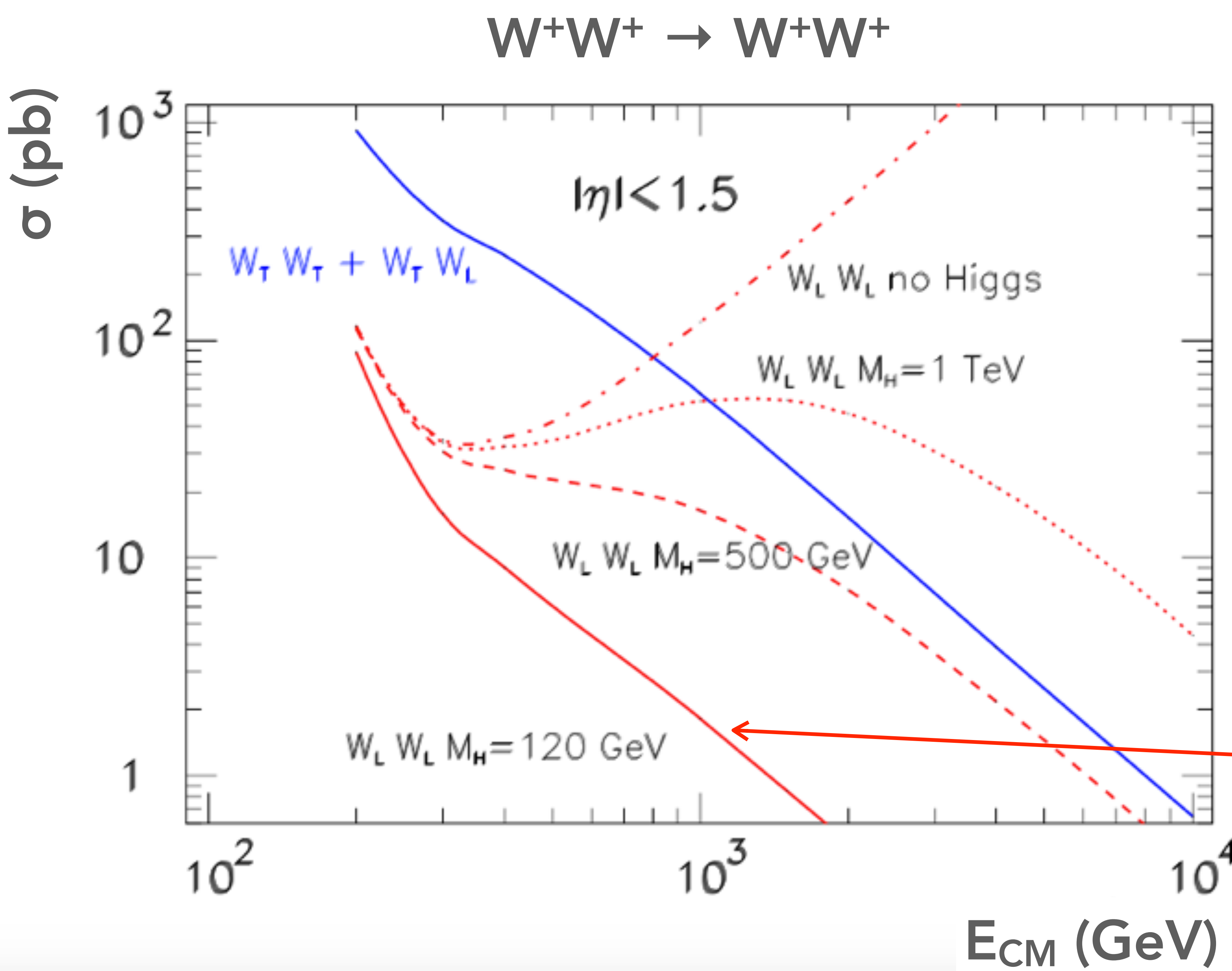

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is it the same Higgs we discovered in 2012?

Vector boson scattering: the importance

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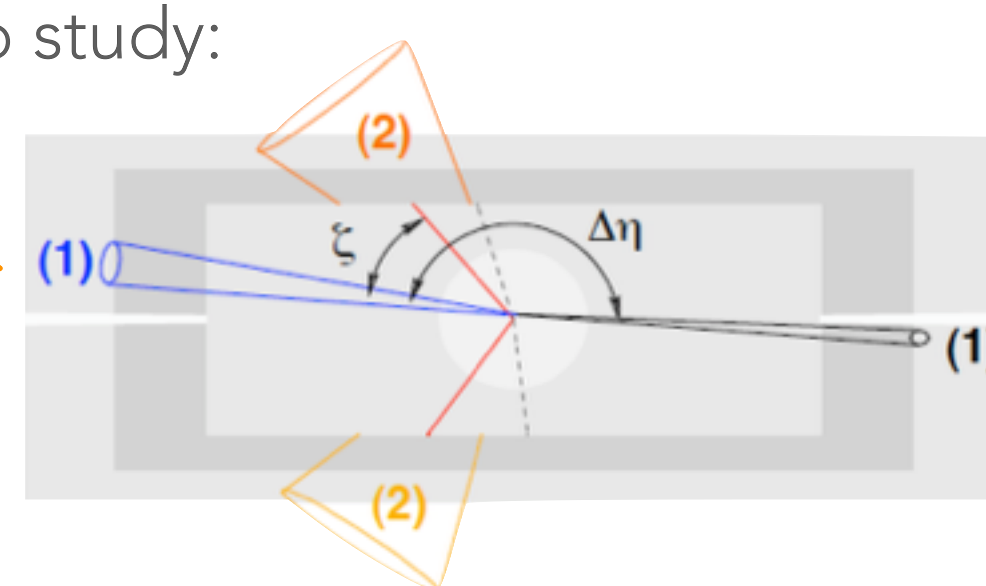
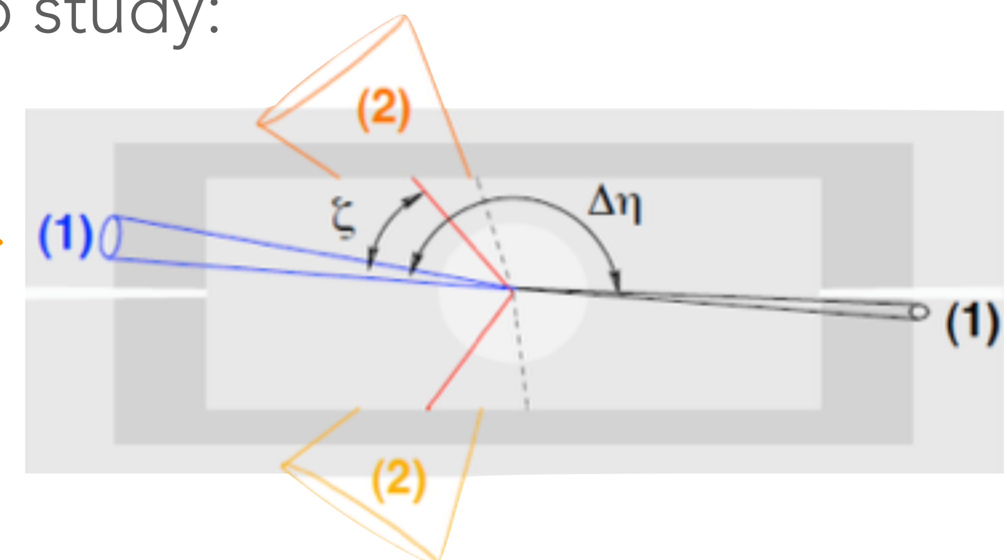
  - need the help of **two high-energy forward jets** to **tag** the event (1)

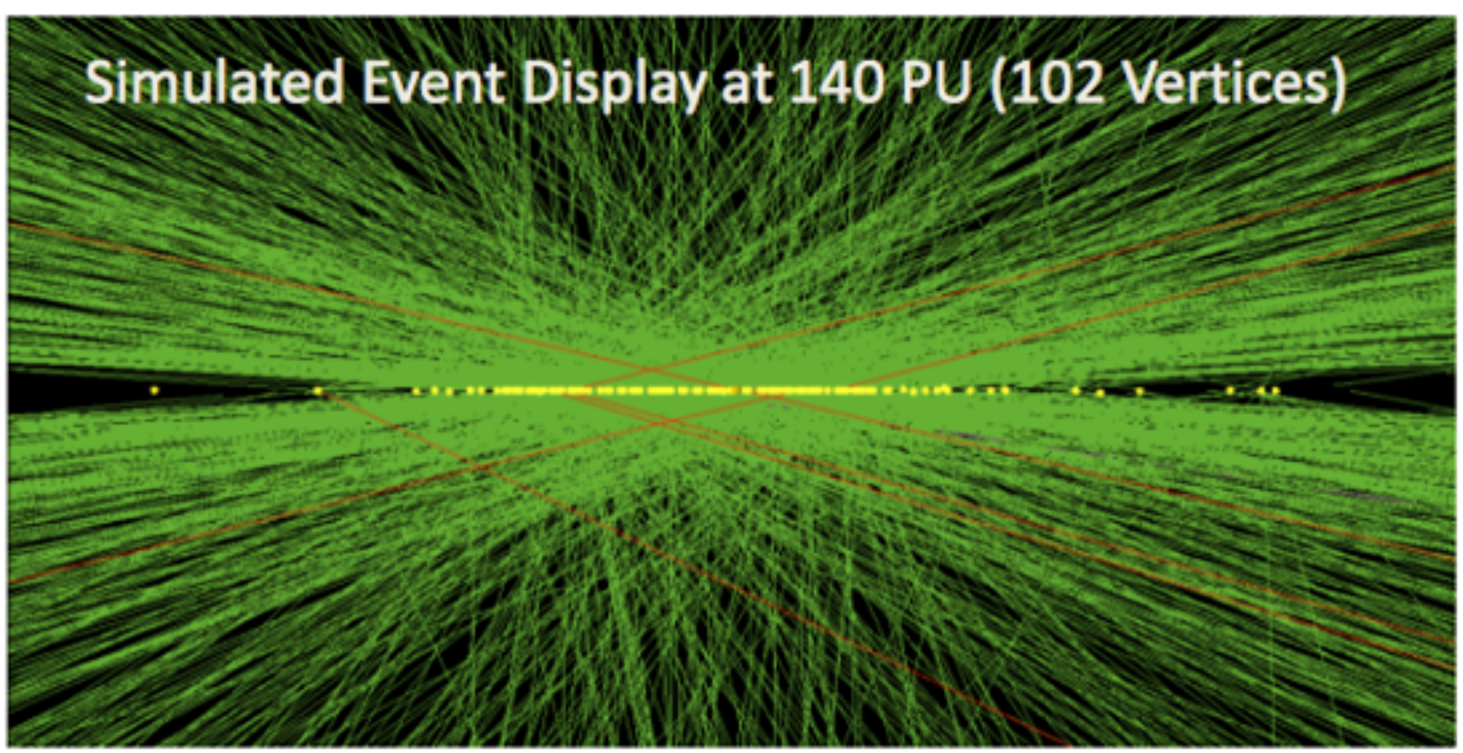


Vector boson scattering: the importance

- **WW scattering** is the **smoking gun** for the **EWSB mechanism**!

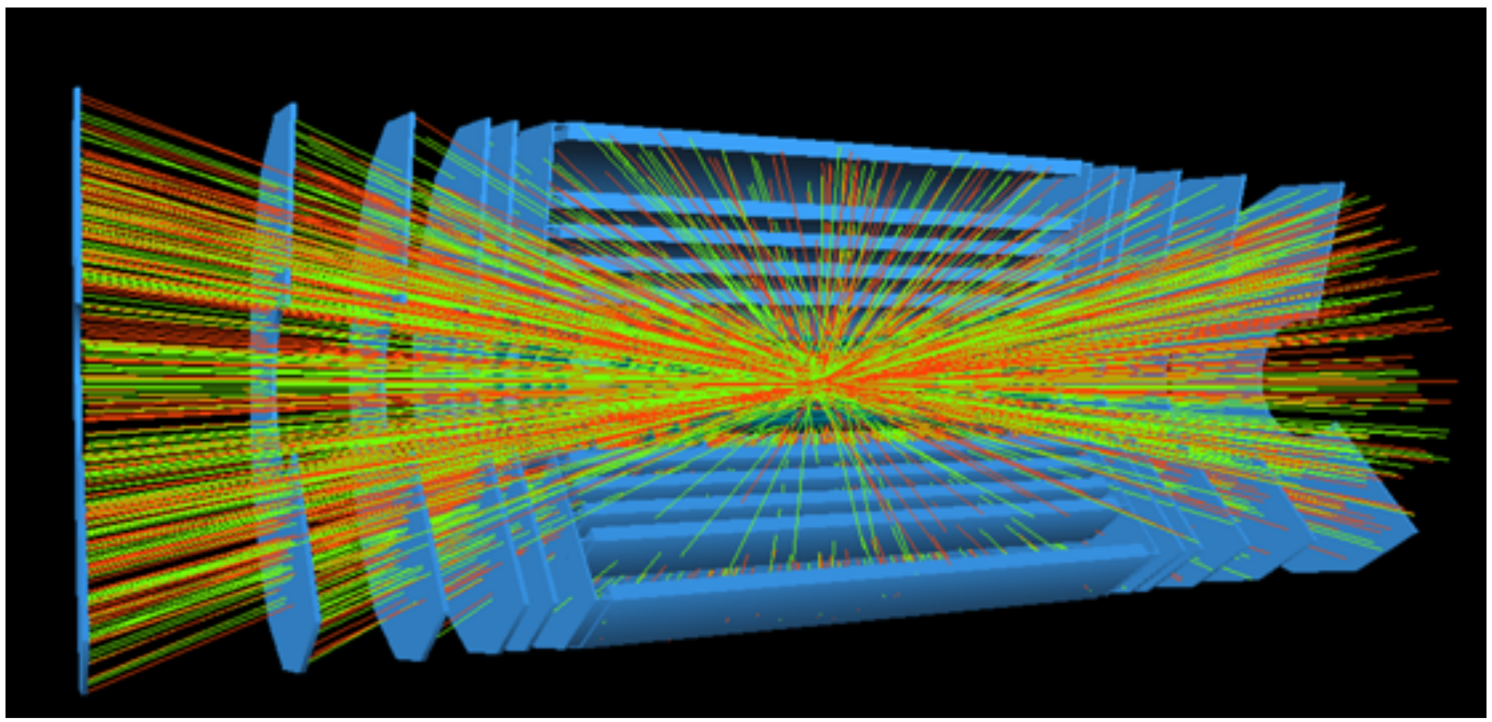
- **But:** it is a very **difficult and rare process** to study:
  - need the help of **two high-energy forward jets** to **tag** the event (1)
  - need the full 3000 fb^{-1} from HL-LHC



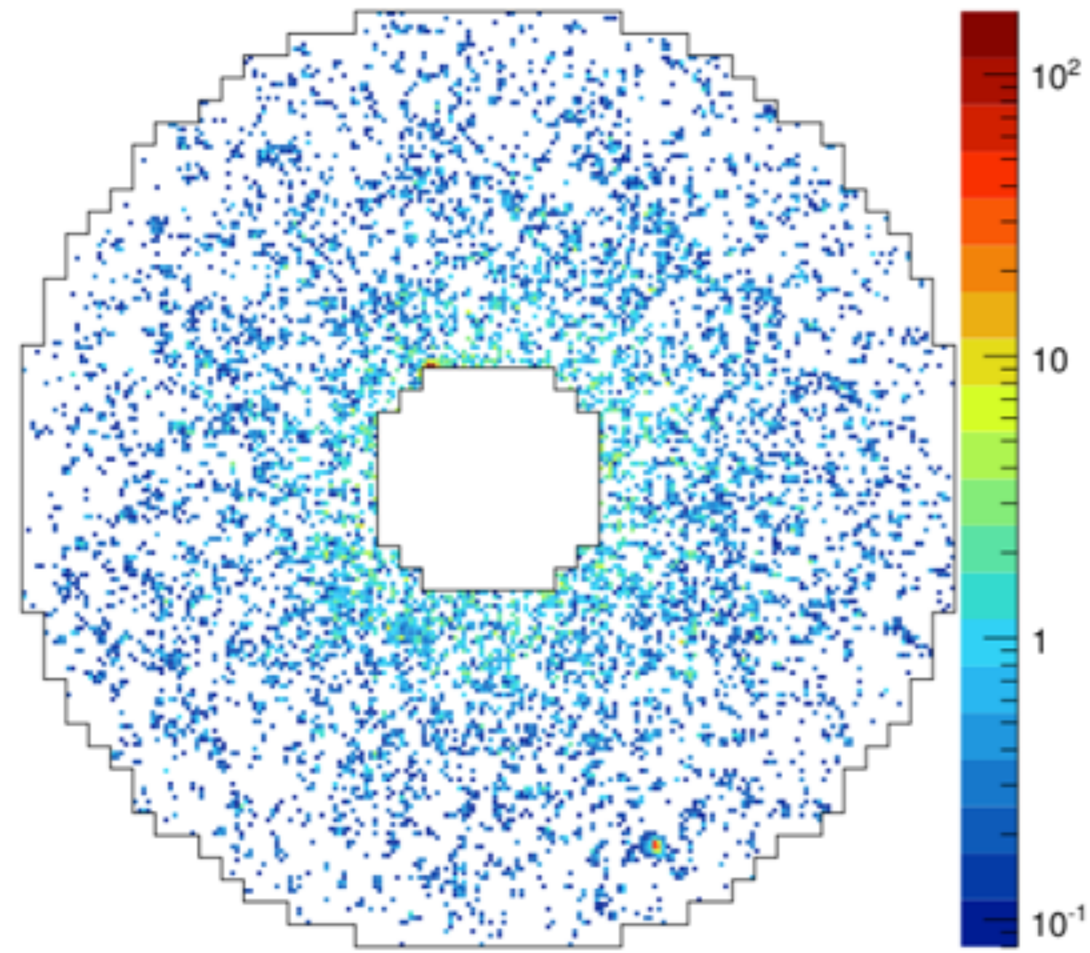


price to pay for luminosity:
a lot of pileup!

Pile up affects mostly the forward region



event display of a 140 PU
event in ATLAS

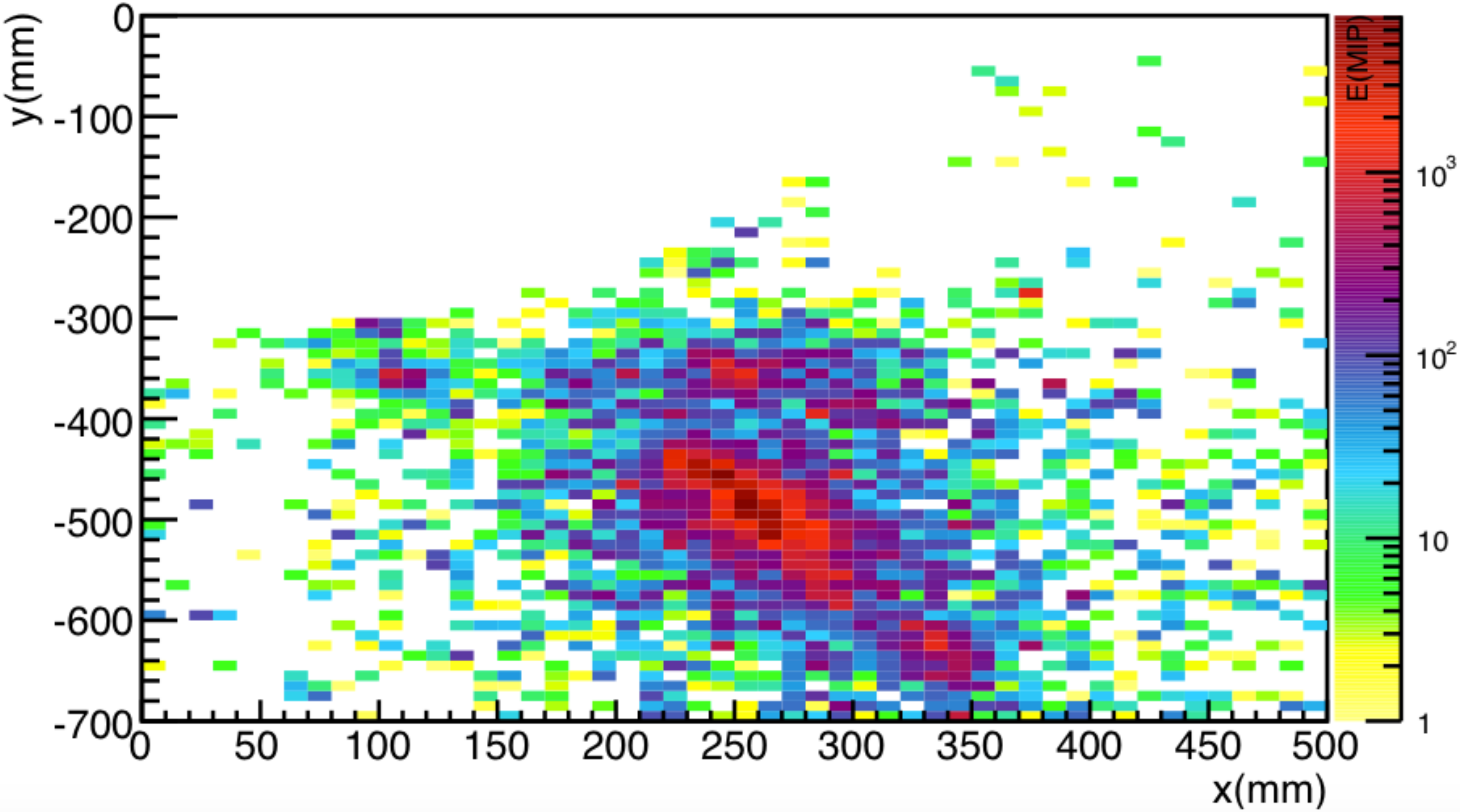


energy distribution in one CMS
ECAL endcap @ PU = 140

Pile up affects mostly the forward region

high-energy jet in the forward region

PU = 0



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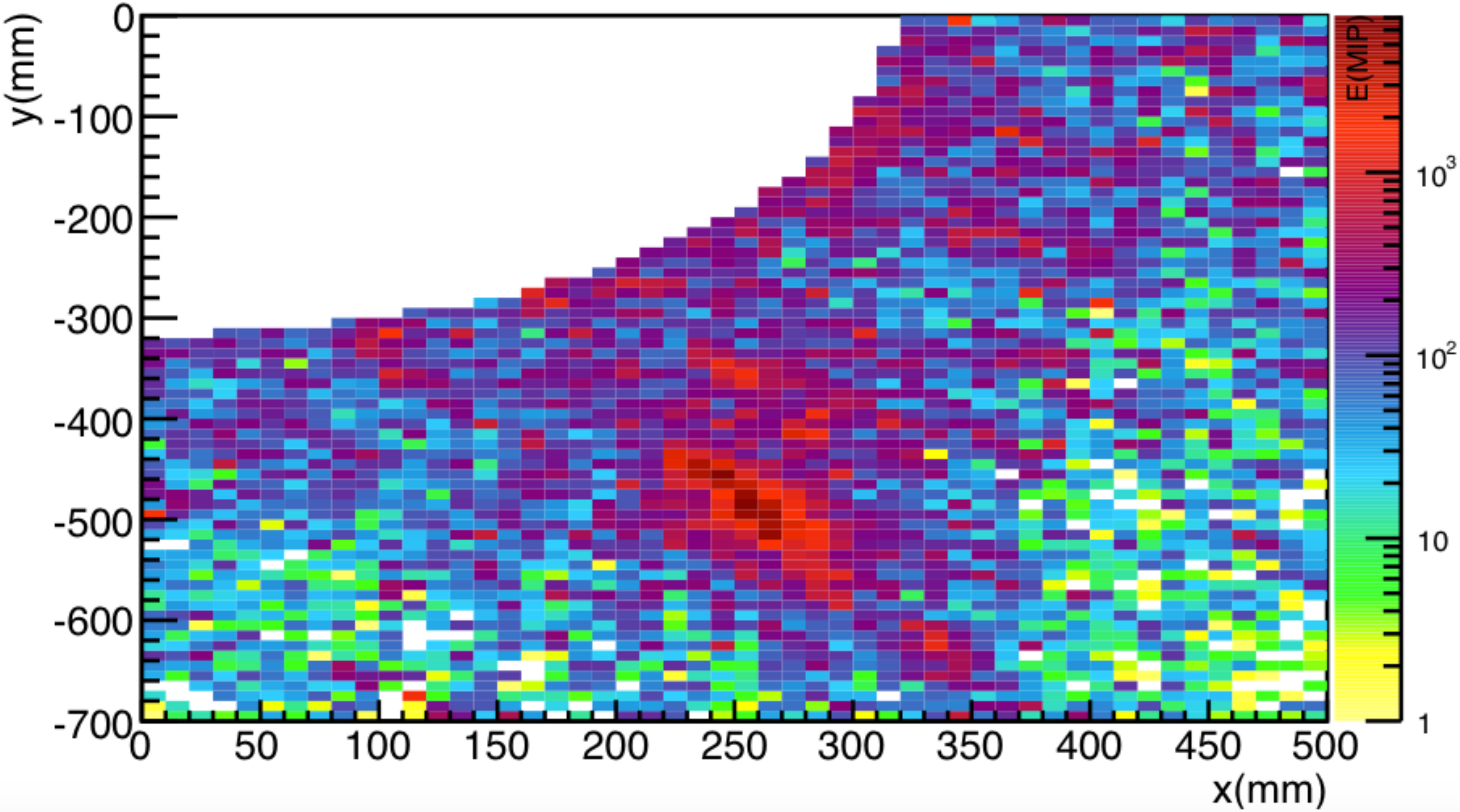
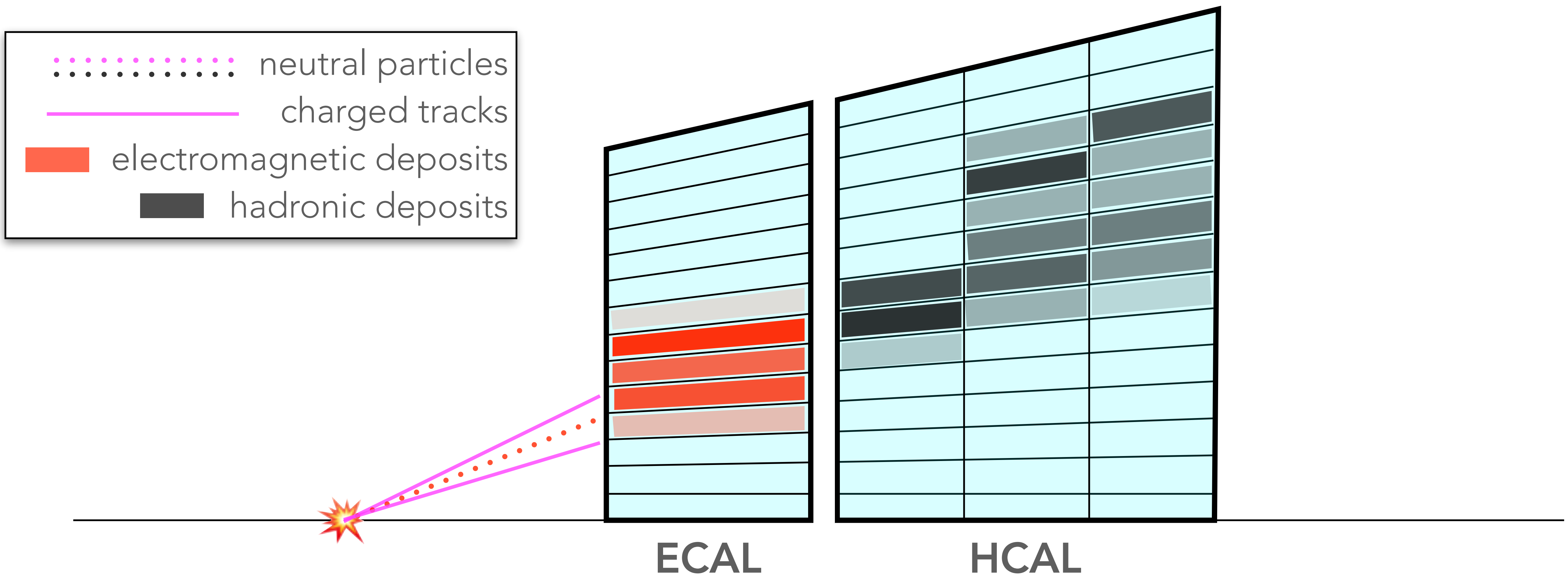


Reconstructing jets
the standard approach



- similar to the Shashlik + HE rebuild case

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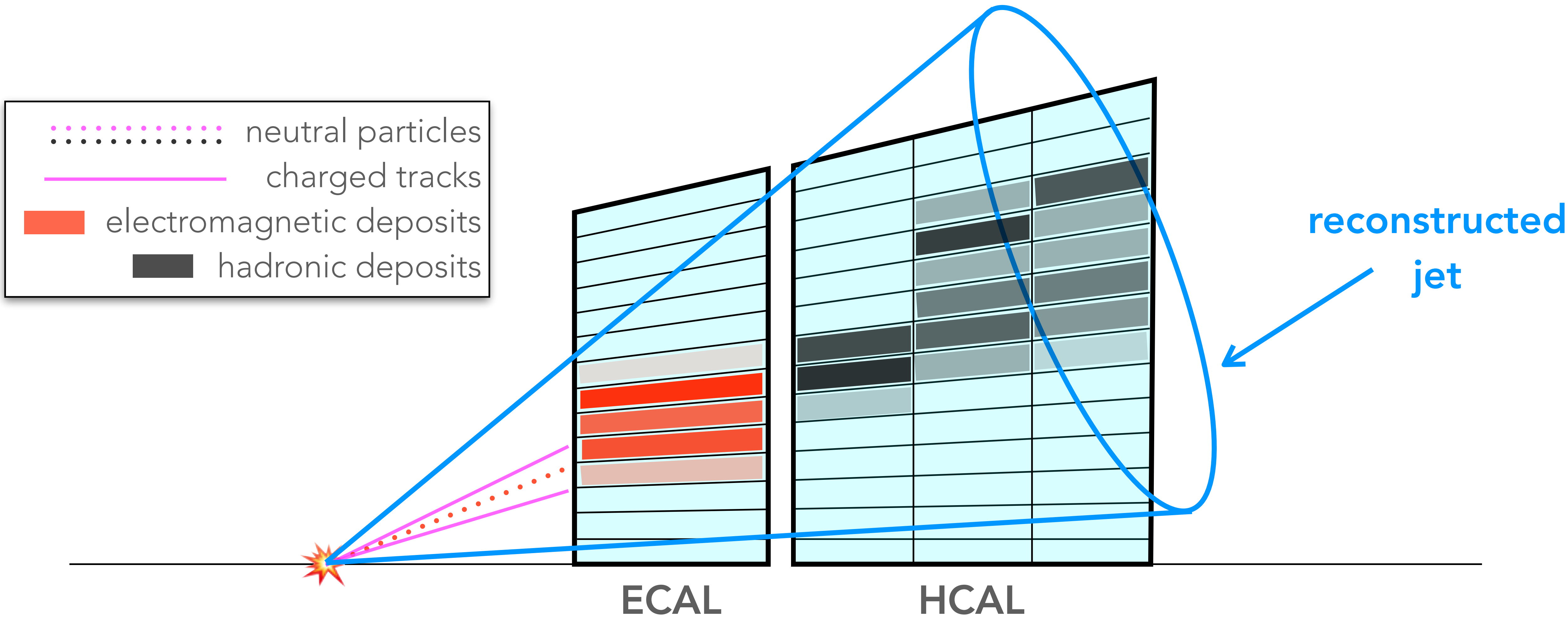

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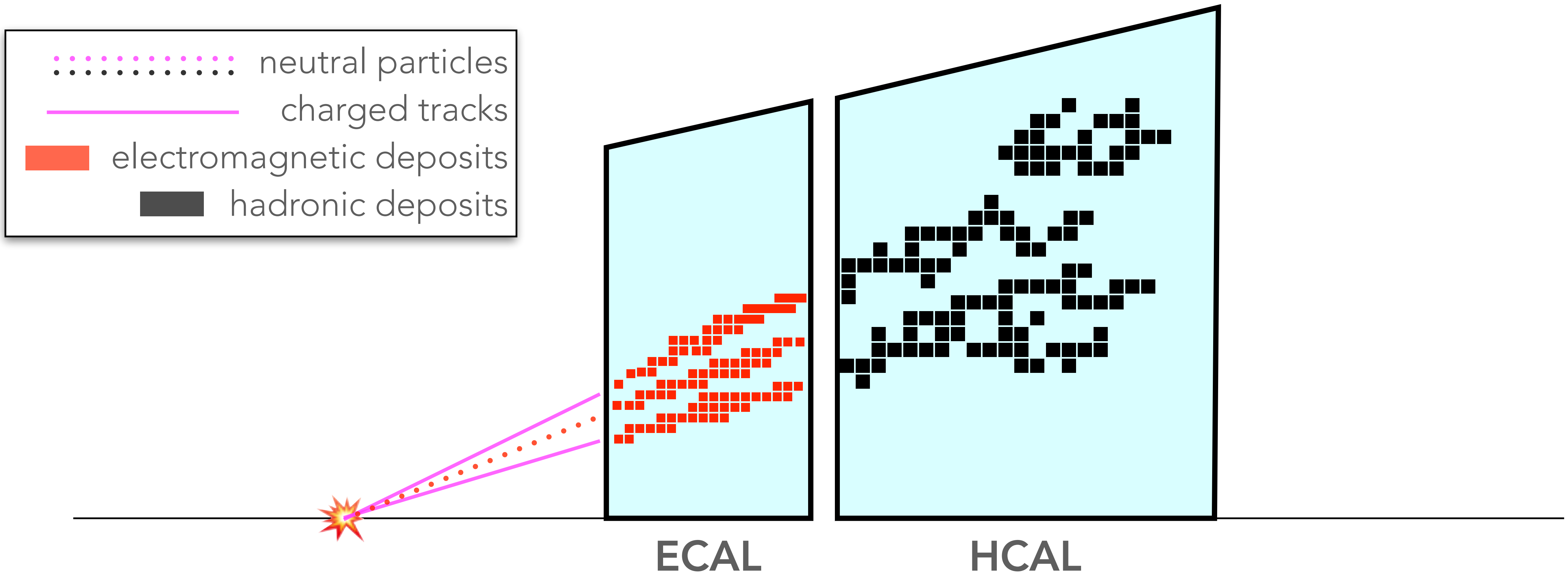
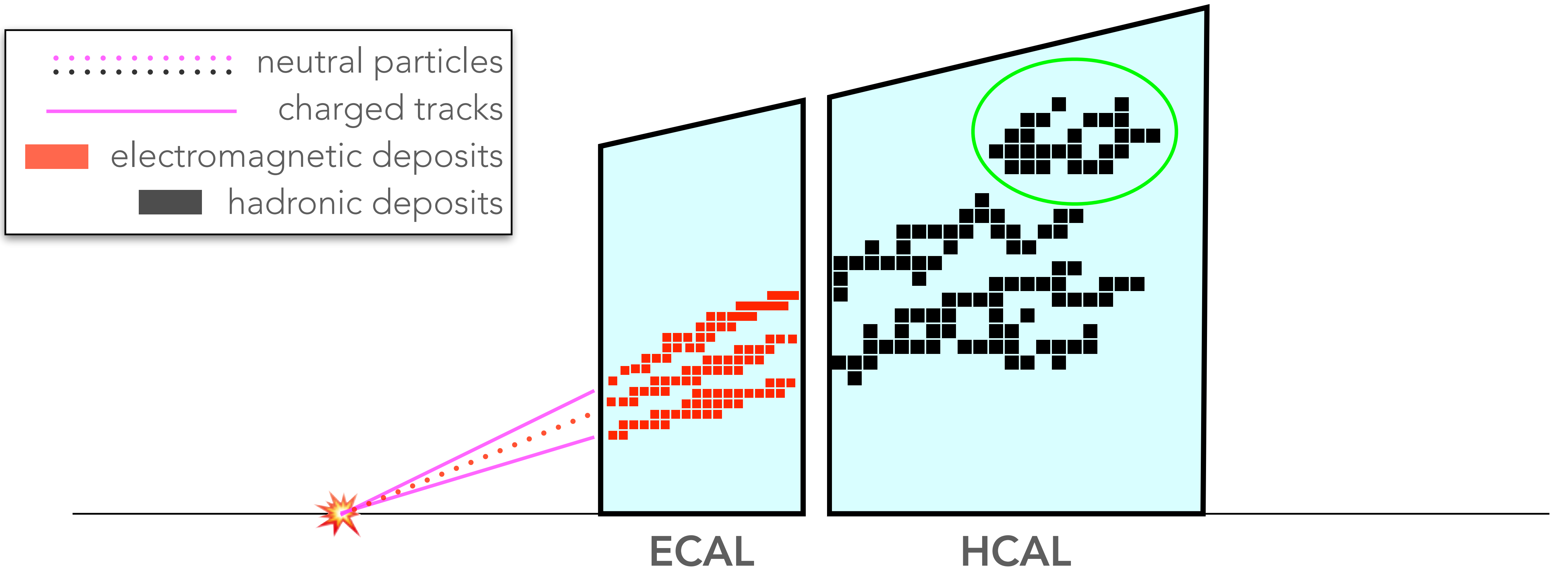
Reconstructing jets
the high granularity approach



- now imagine that the calorimeters have **enough granularity** to **'see'** the **shower development**:

Reconstructing jets

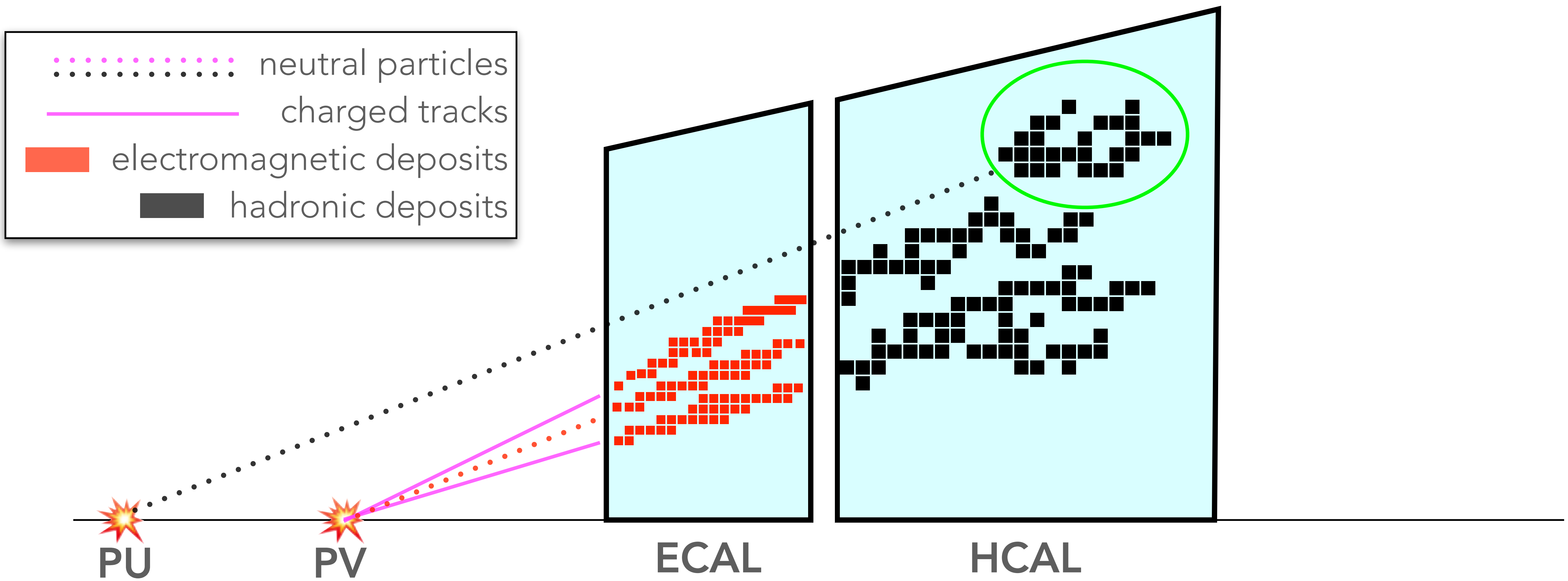
the high granularity approach



- for example, a **neutron cluster** can be identified (isolated from the rest of the shower, no tracks associated)

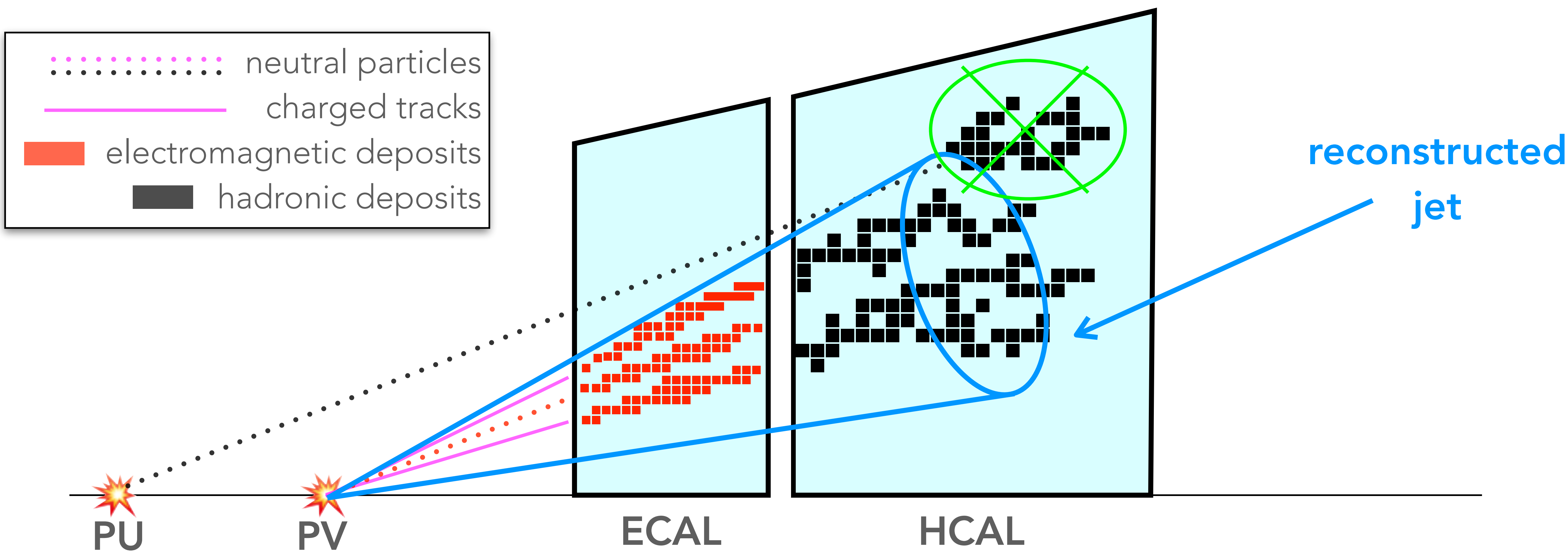
Reconstructing jets

the high granularity approach



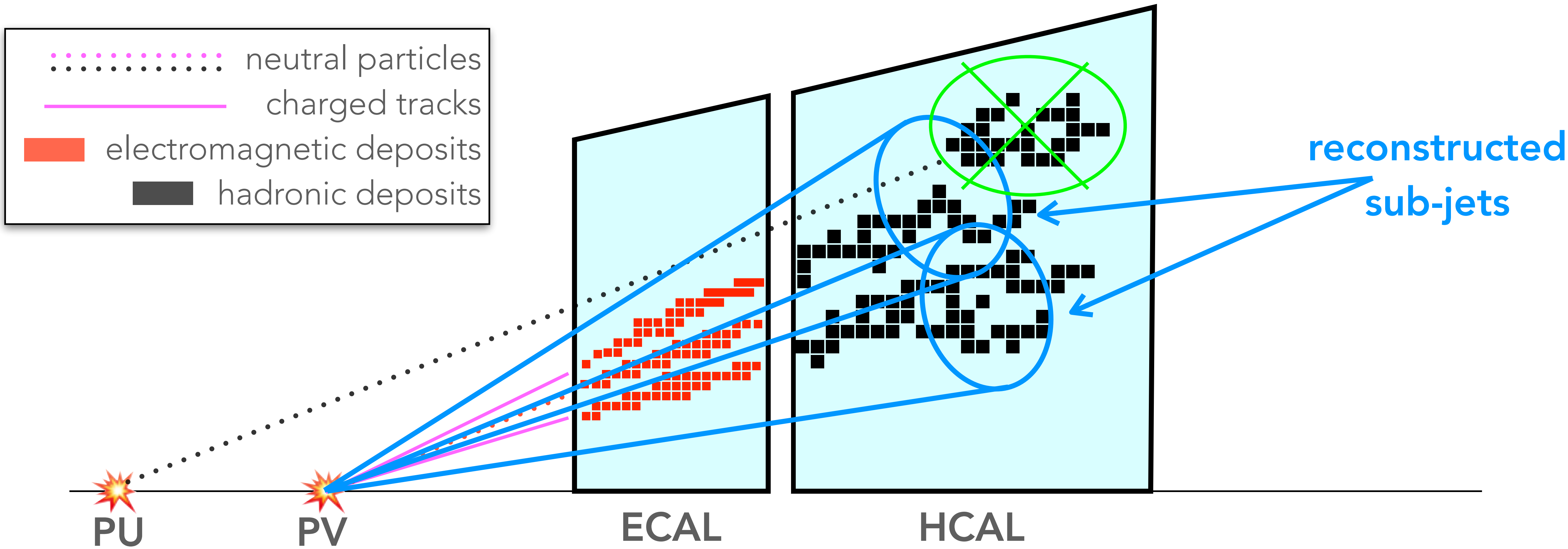
- thanks to longitudinal segmentation, the **cluster axis** can be computed, and **traced back** to the proton-proton axis
- if the cluster vertex is incompatible with the primary vertex (PV), this is likely to be coming from a PU vertex

Reconstructing jets
the high granularity approach



- the jet can then be reconstructed without the spurious pile up contribution ⇒ **granularity for vertexing** and **pile up rejection**
- these will be **key features** for a lot of Physics searches at the HL-LHC: vector boson scattering, VBF $H \rightarrow \tau\tau$, VBF $H \rightarrow$ invisible, dark matter, …

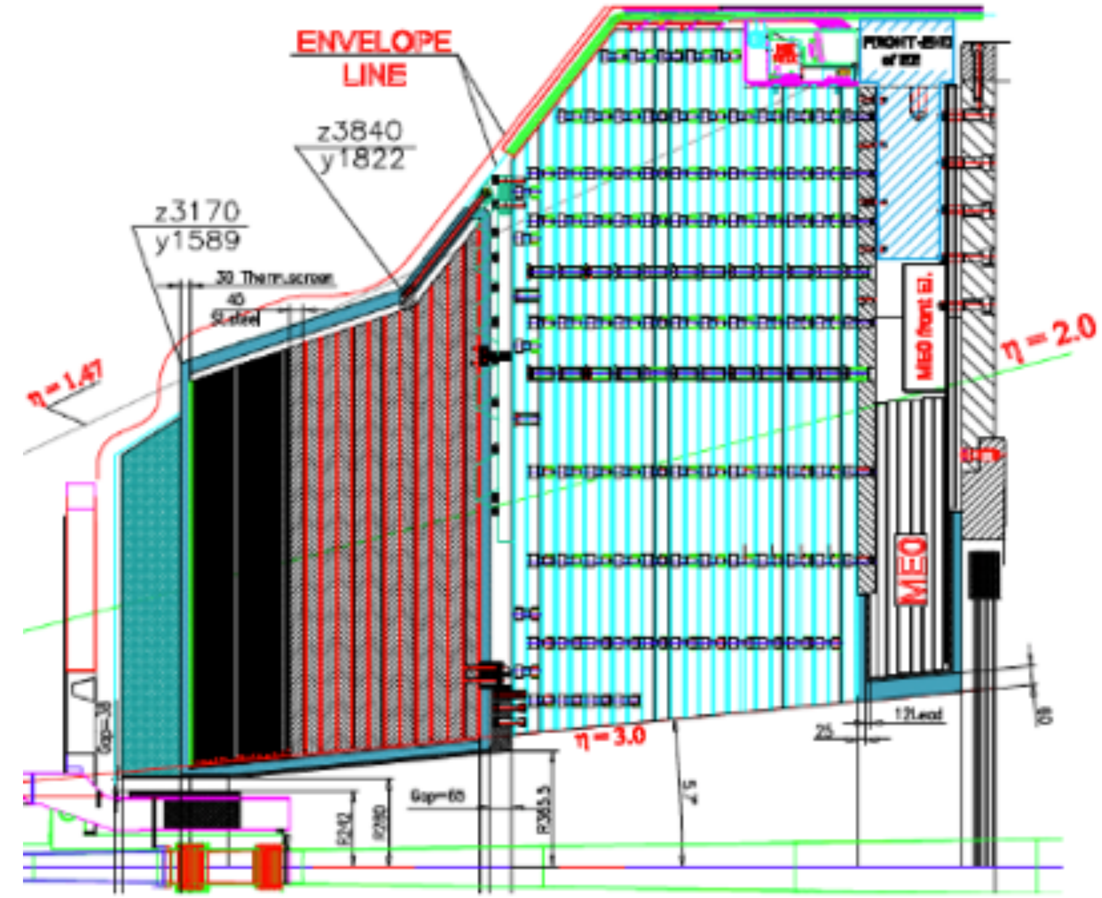
Reconstructing jets
the high granularity approach

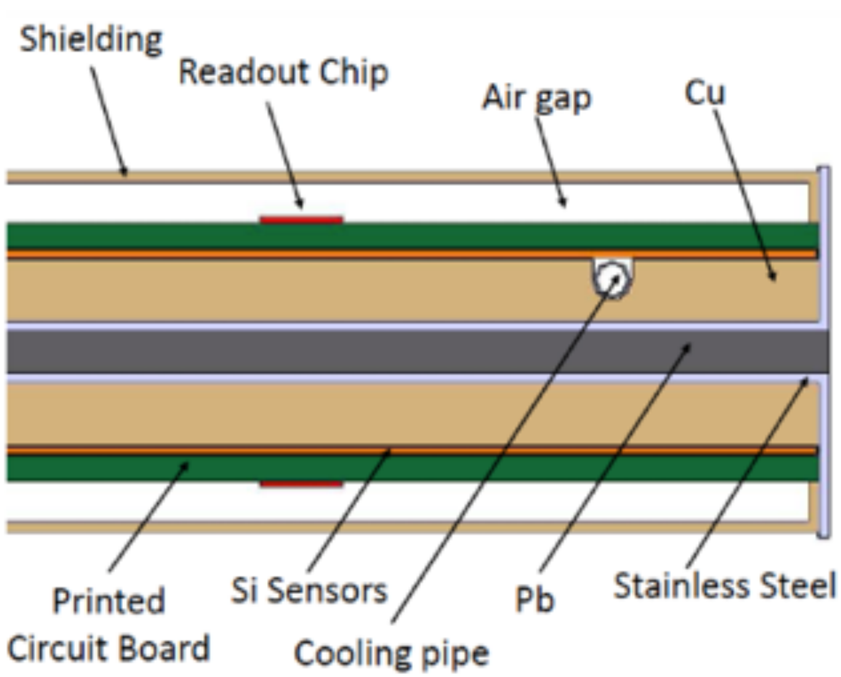


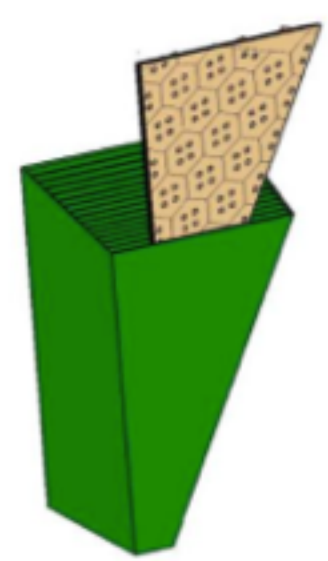
- the internal shape of the jet can be further studied and internal sub-components identified ⇒ **granularity for jet tomography**
- these will be **key features** for a lot of Physics cases at the HL-LHC: gluon/quark jet separation, boosted W bosons, soft PU removal, …

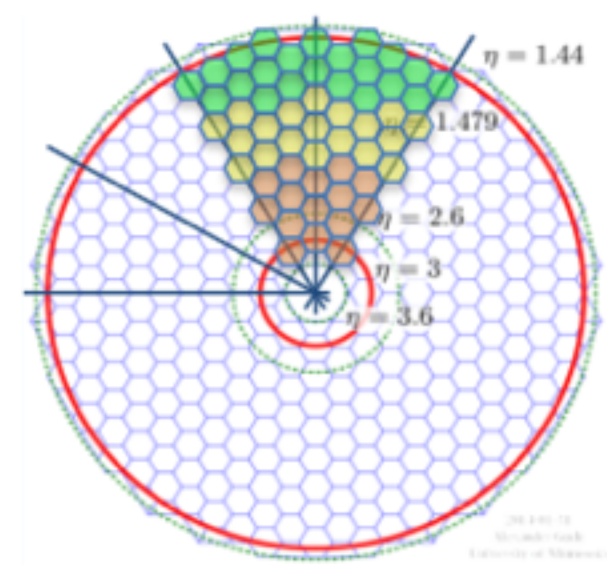
Upgrade concept 2: All-Silicon calorimeter + scint. backing calorimeter

- **Silicon/lead-copper-tungsten** e.m. (25 X_0, 1 λ) and **silicon/brass** front hadron (3.5 λ) calorimeter
  - 6.8 M channels, pad sizes 1.05 cm^2 or 0.53 cm^2 depending on η
- **Scintillator-brass** backing calorimeter (5.5 λ, low radiation zone)







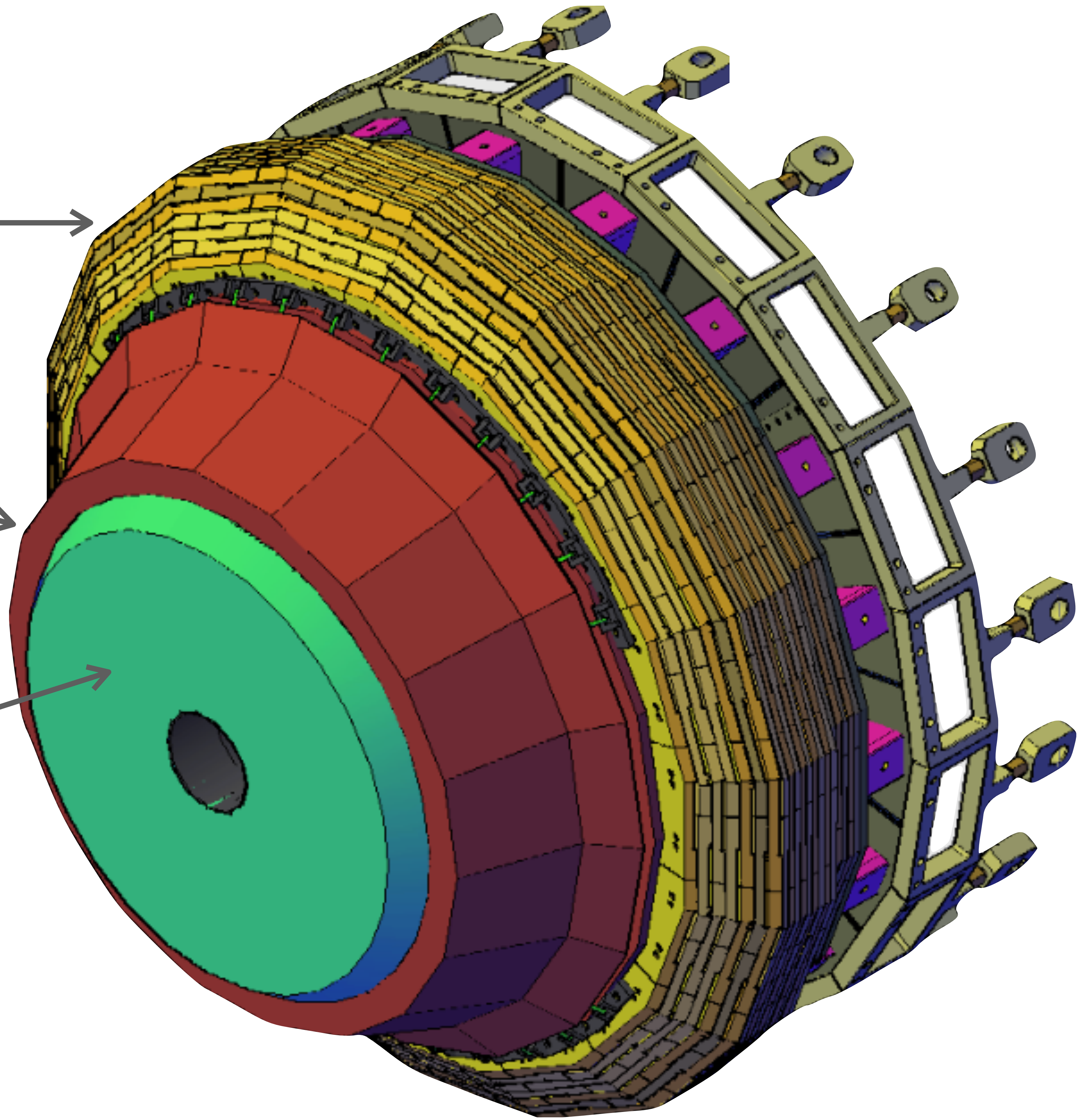


Mechanical structure

backing
hadronic
calorimeter

high
granularity
calorimeter
(HGC)

front
shielding



Mechanical structure

wedges
to be glued
together to form a
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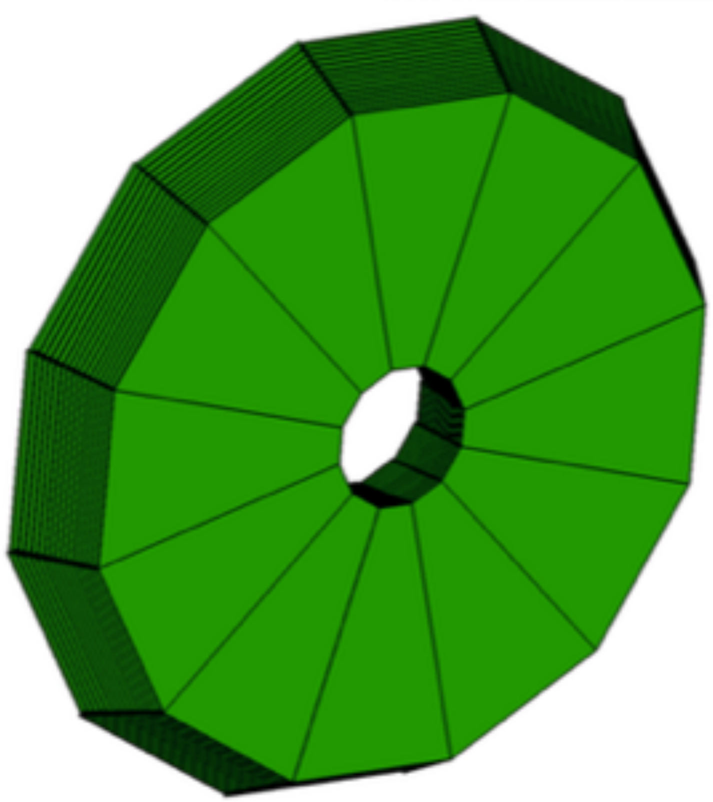
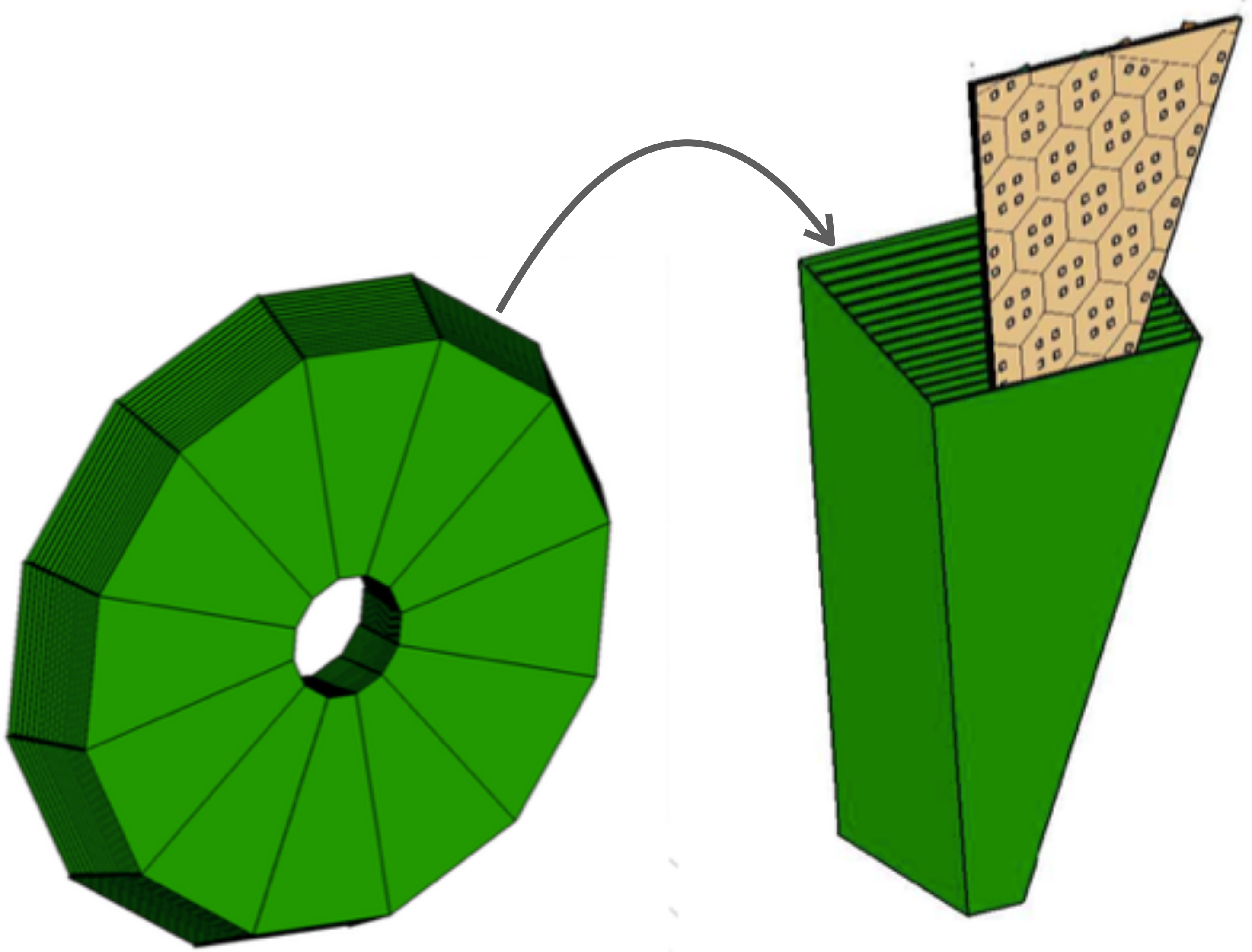
structure



Mechanical structure

wedges to be glued together to form a **monolithic structure**

Wedge: carbon fibre structure with embedded W plates (3° tilt). Cassettes slid into slots



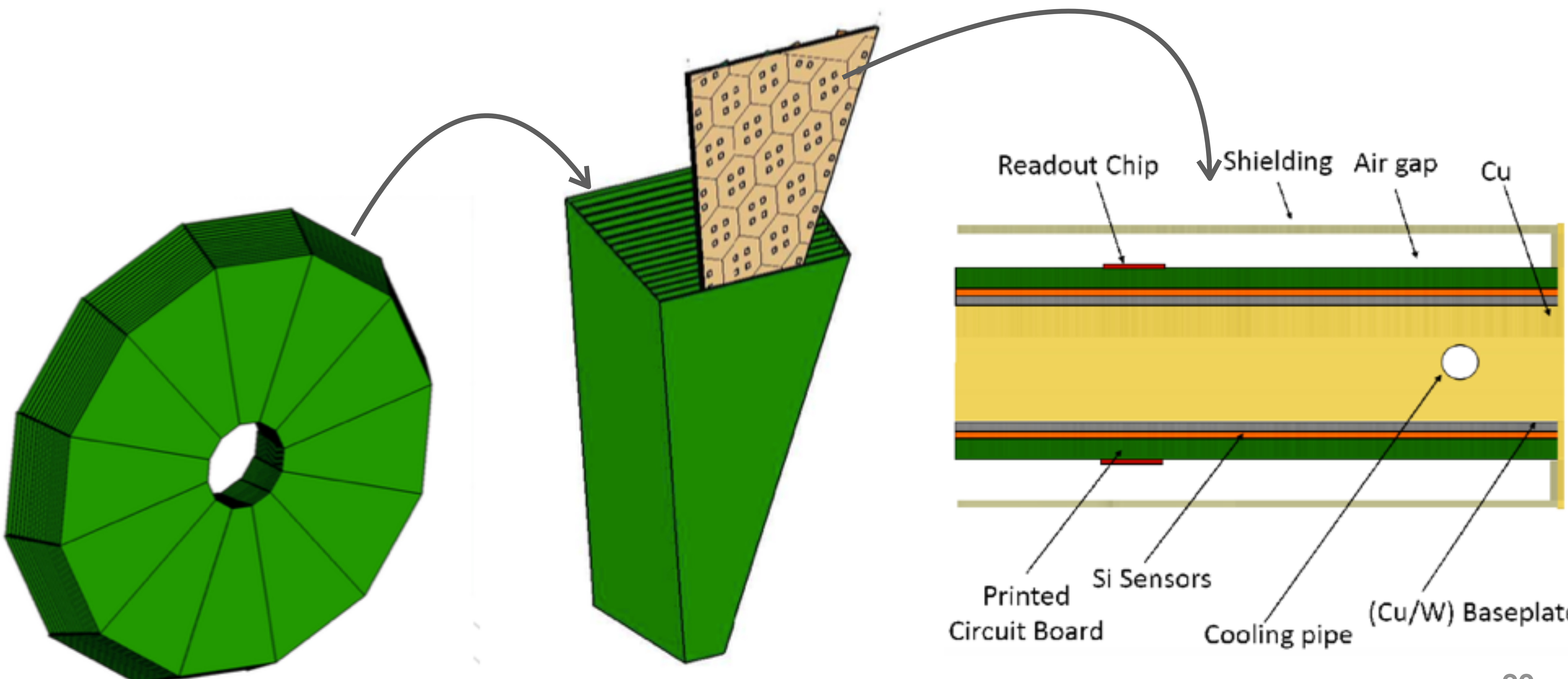
Mechanical structure

wedges to be glued together to form a **monolithic structure**

Wedge: carbon fibre structure with embedded W plates (3° tilt). Cassettes slid into slots

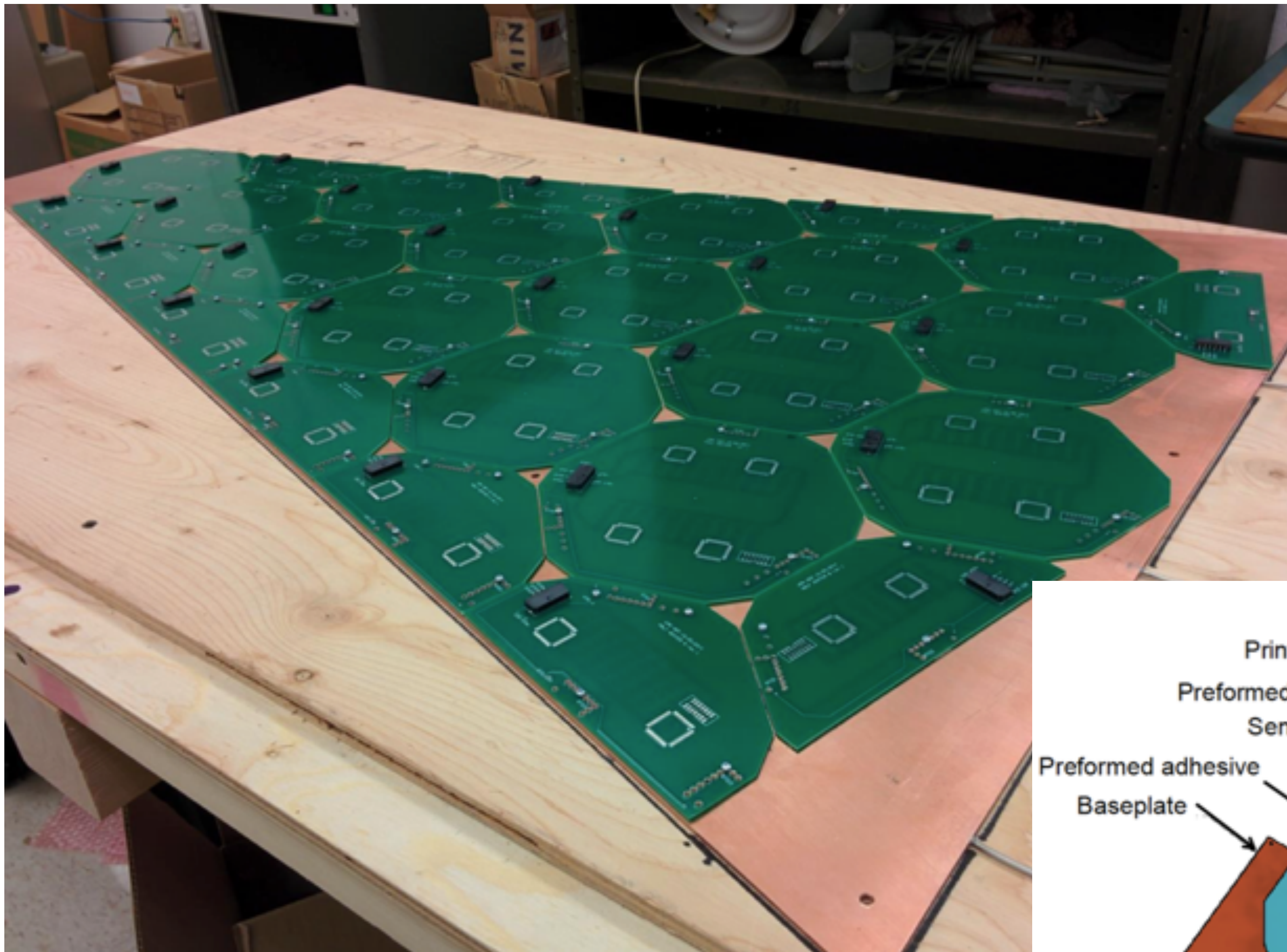
Section of a **cassette**:

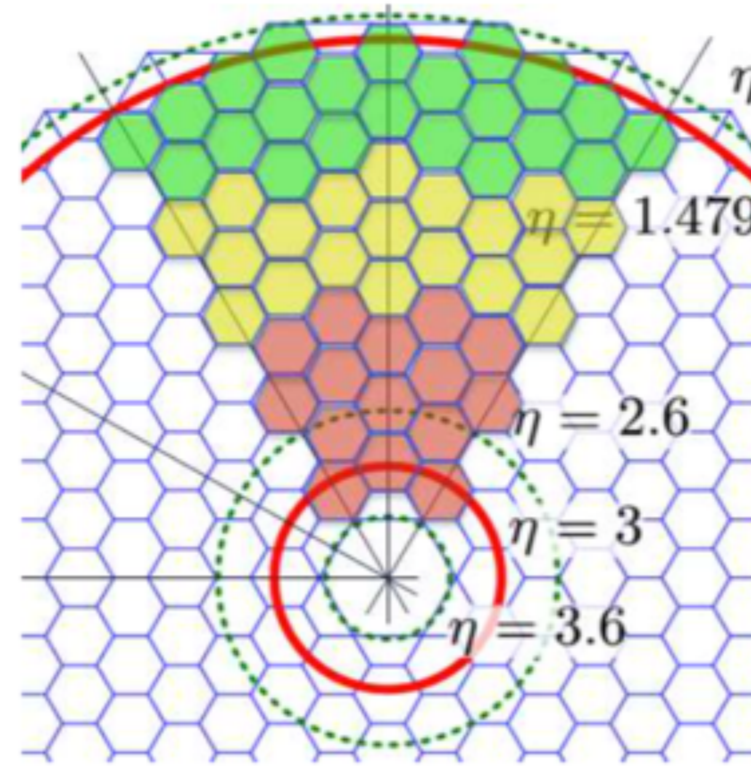
- 6mm Cu plate+pipes in the middle for cooling
- Cu/W baseplate for modules in HGC-ECAL

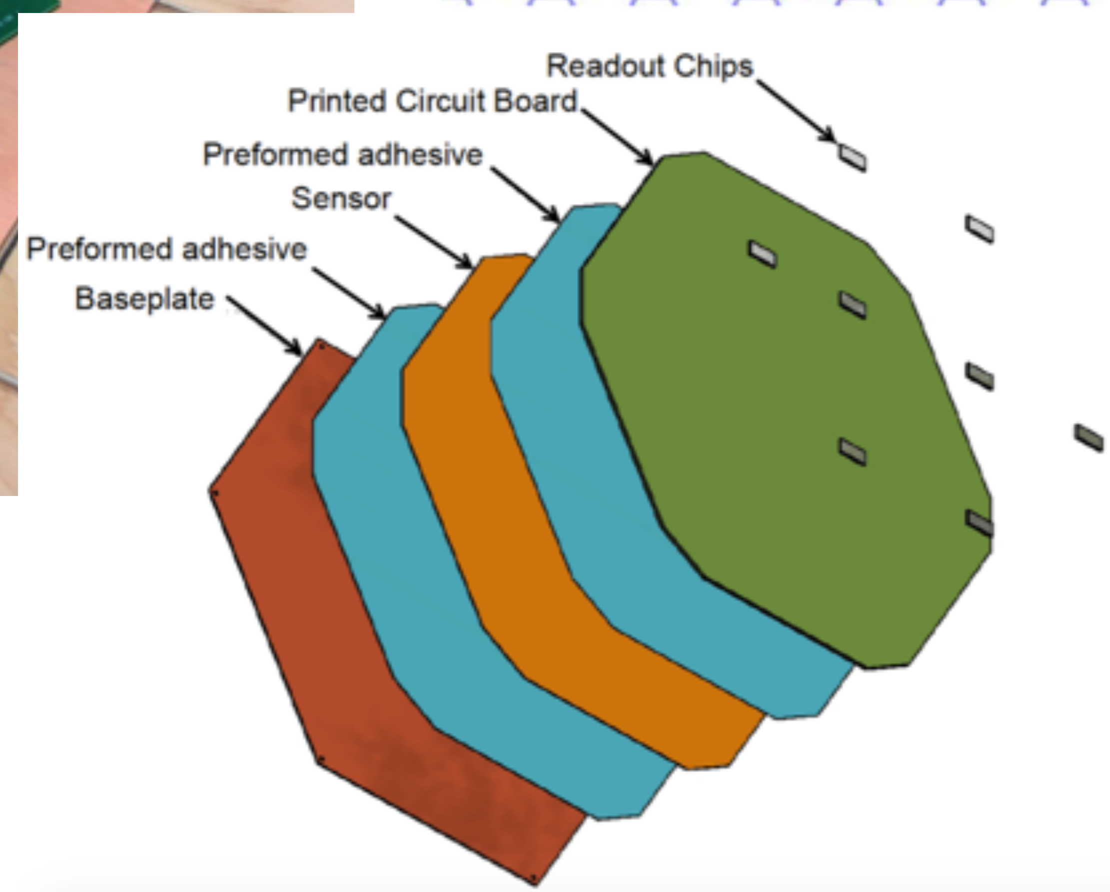


Modules mechanics

300 μm / 256 ch
200 μm / 256 ch
100 μm / 512 ch



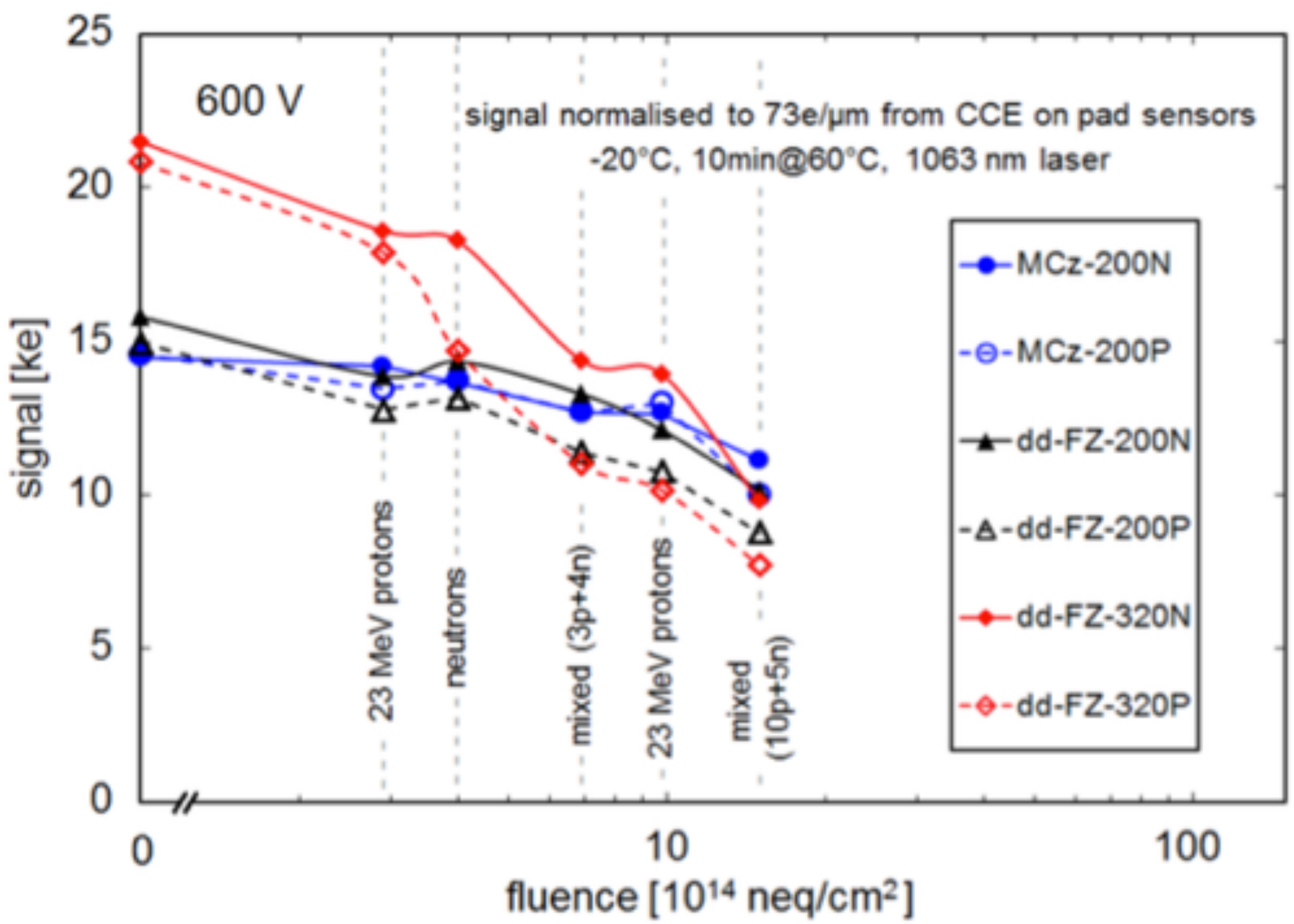


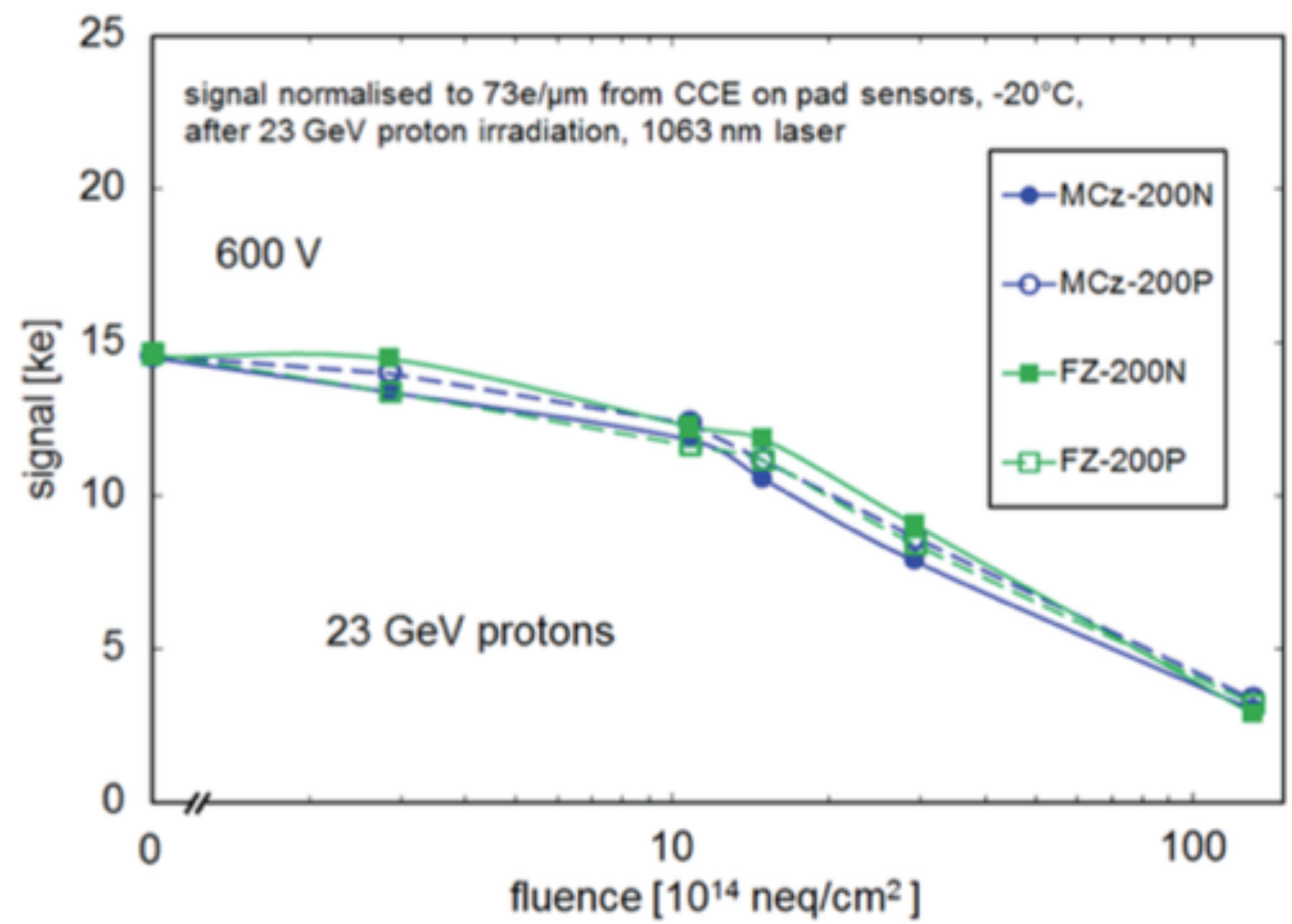


	E-HG	H-HG	Total
Area of silicon (m^2)	395	209	604
Channels	4.80M	1.96M	6.76M
Detector modules	14.5k	7.6k	22.1k
Weight (one endcap) (tonnes)	18	81	99
Number of Si planes	29	12	41

Challenges: radiation hardness

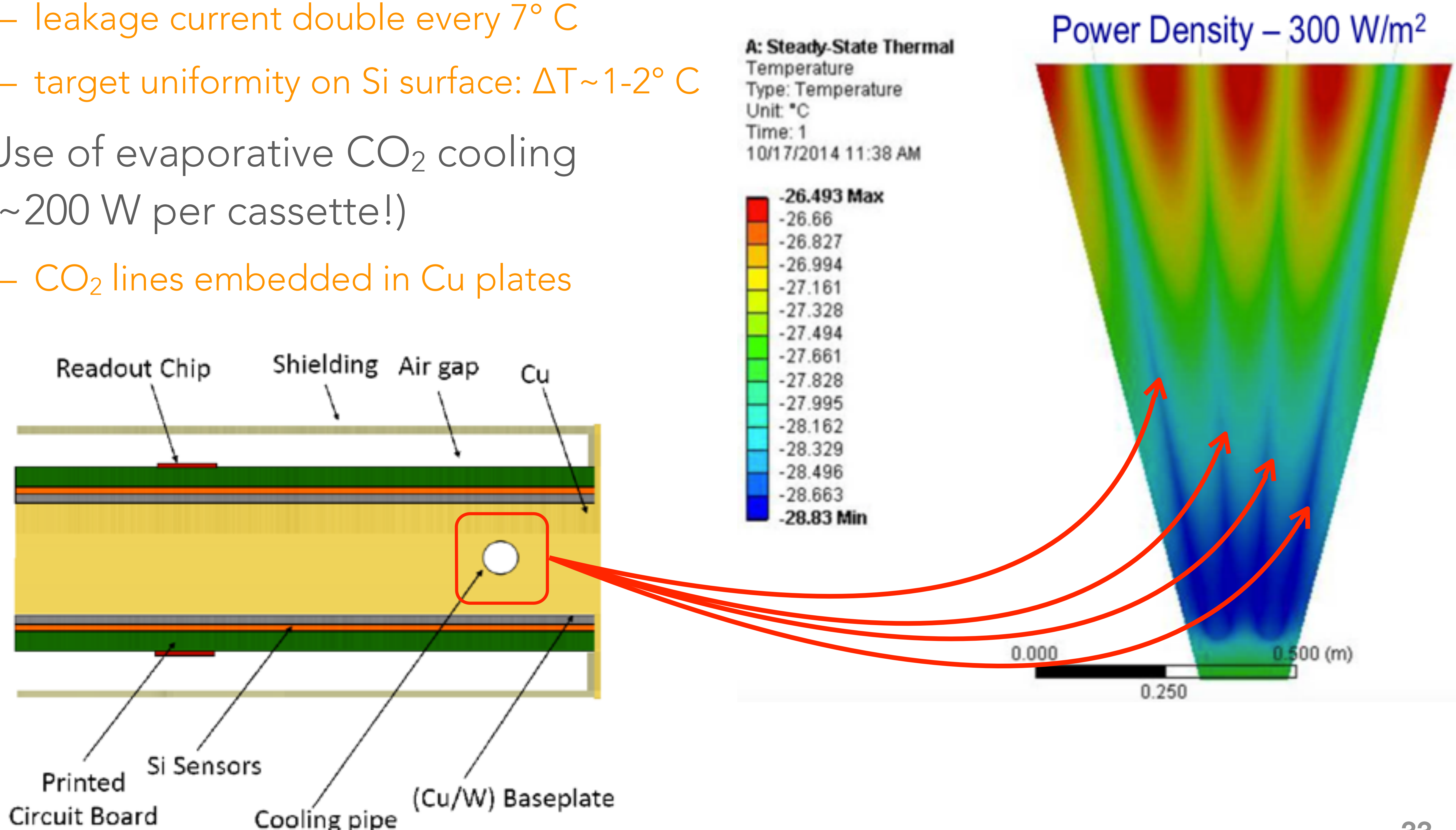
- @ HL-LHC, the silicon sensors of the HGC will be exposed to hadron fluences ranging from **~2·10^{14}** up to **~10^{16} 1 MeV neutron equivalent / cm^{2}**
- similar to the fluences expected in the CMS Phase II Tracker
  - shared R&D
  - but: neutron dominated (instead of charged hadrons)





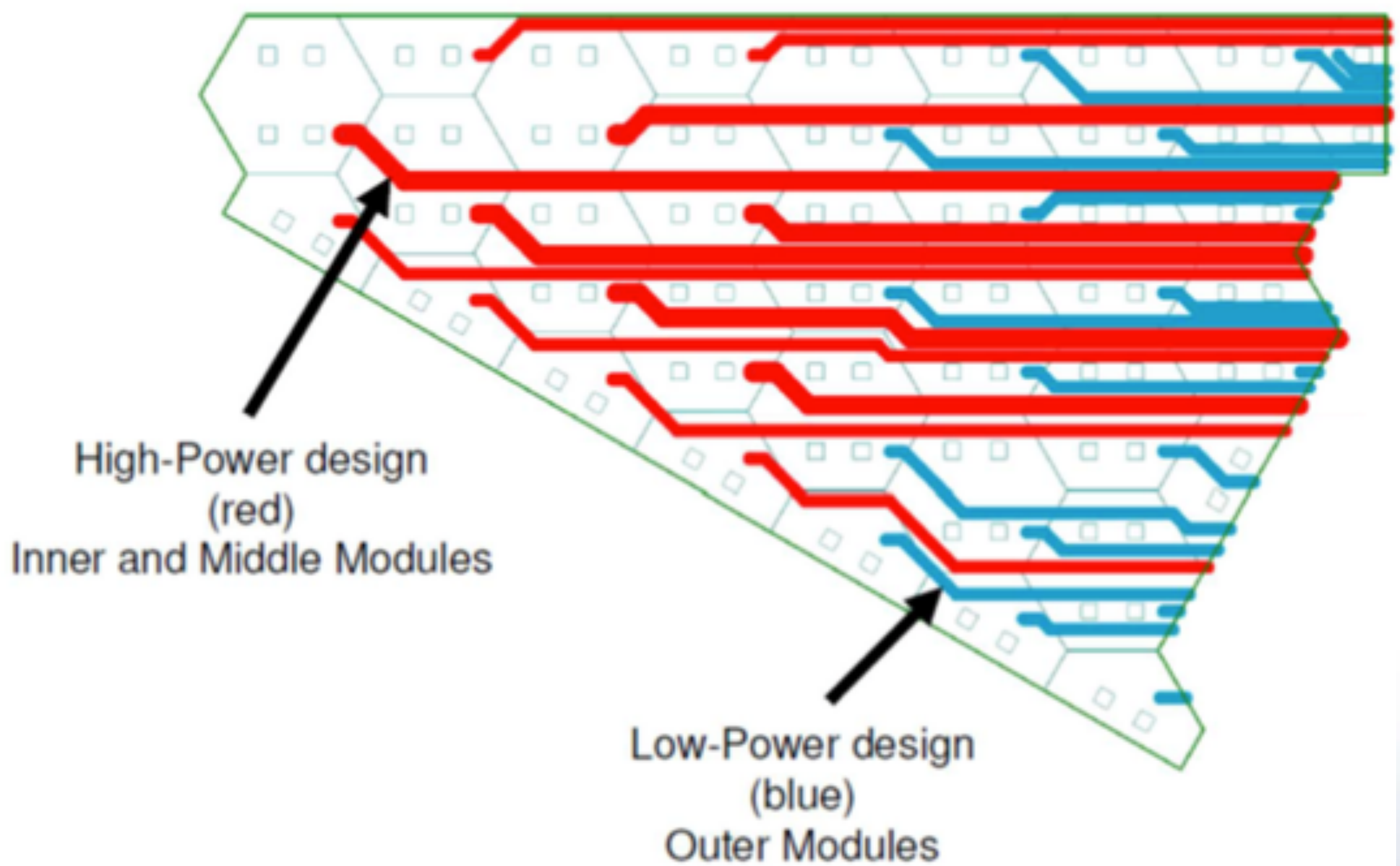
Challenges: cooling

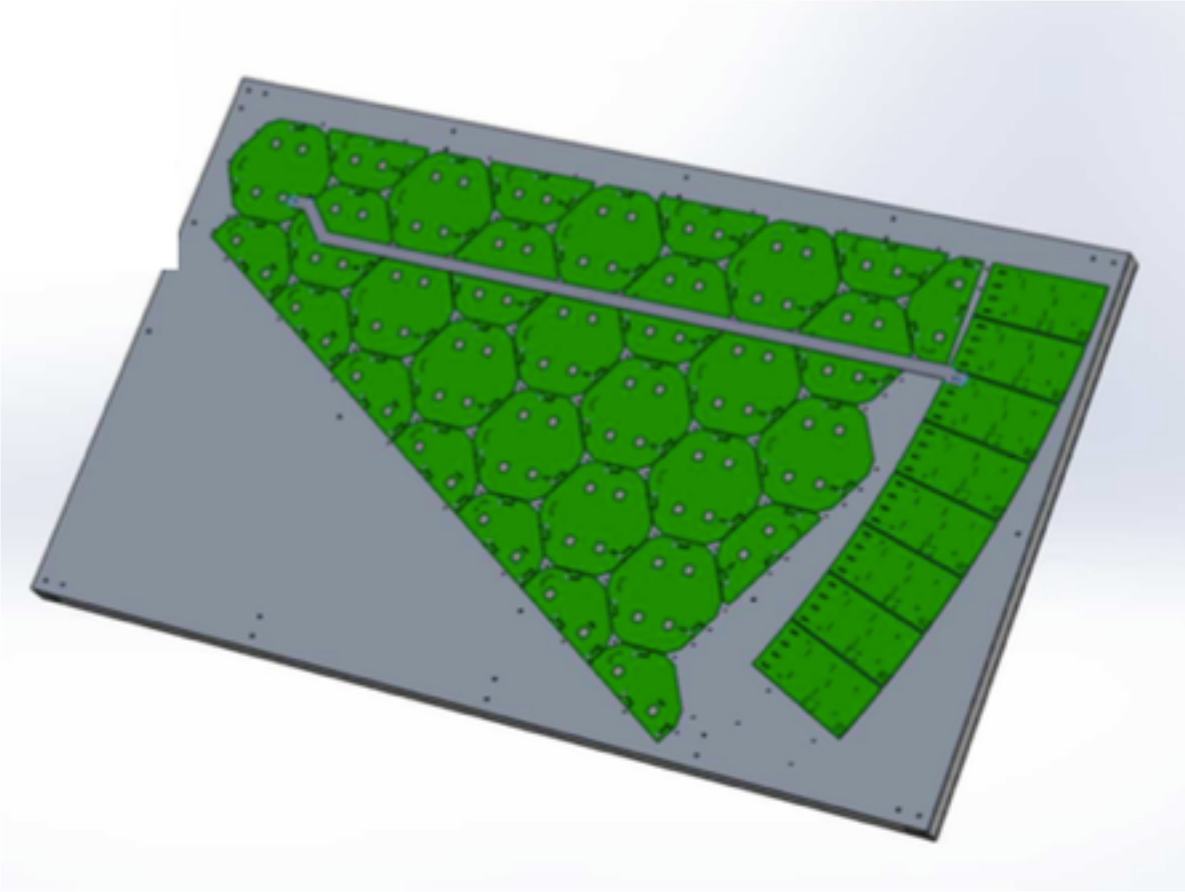
- **Operation at -30° C** to mitigate silicon radiation damage
  - leakage current double every 7° C
  - target uniformity on Si surface: ΔT~1-2° C
- Use of evaporative CO_2 cooling (~200 W per cassette!)
  - CO_2 lines embedded in Cu plates



Challenges: data links and services

- Distribute data signal and power using narrow (0.5 mm thick) PCBs



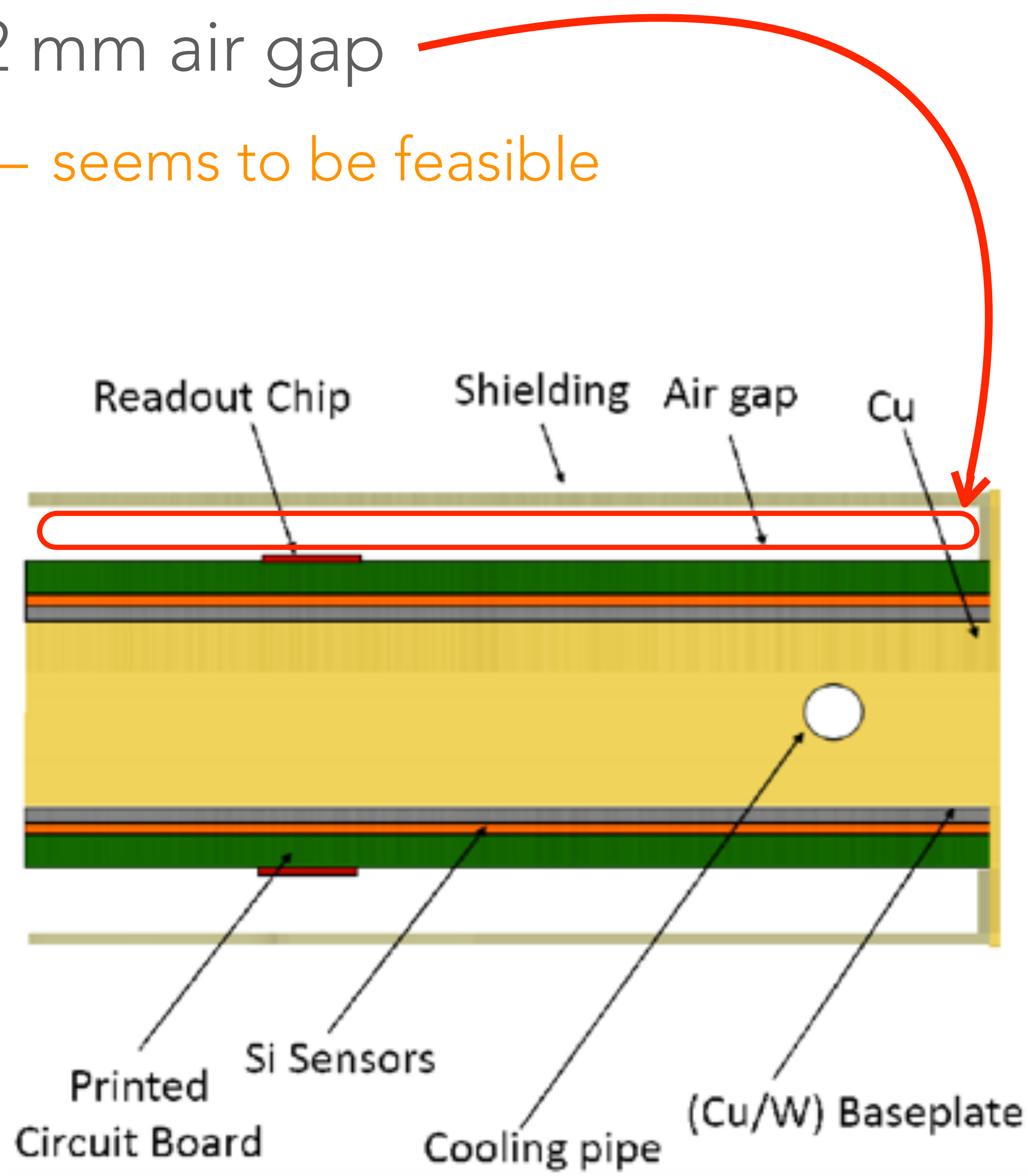


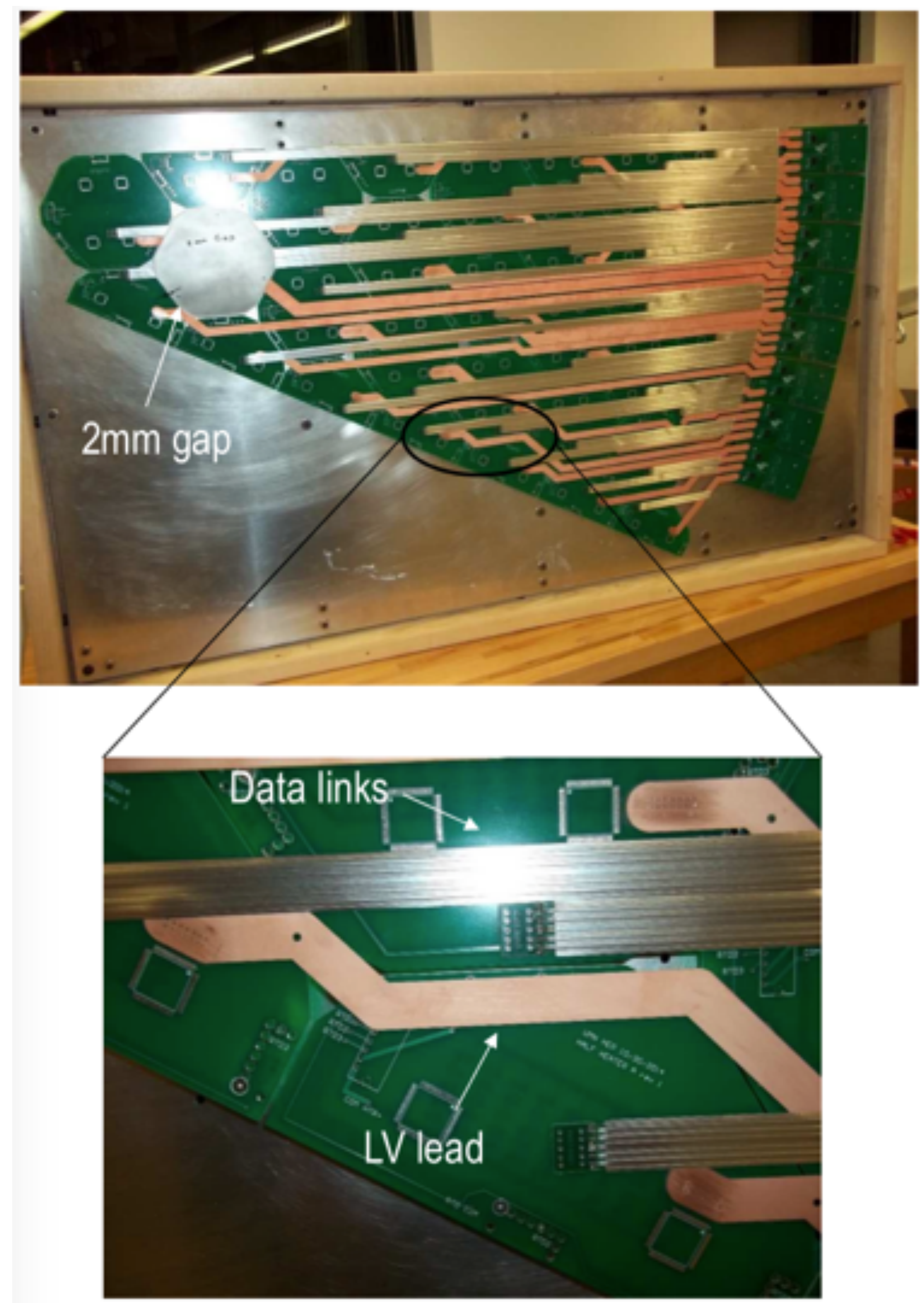
- heavy copper for power distribution
- twinax cables for data links

Challenges: data links and services

- Distribute data signal and power using narrow (0.5 mm thick) PCBs

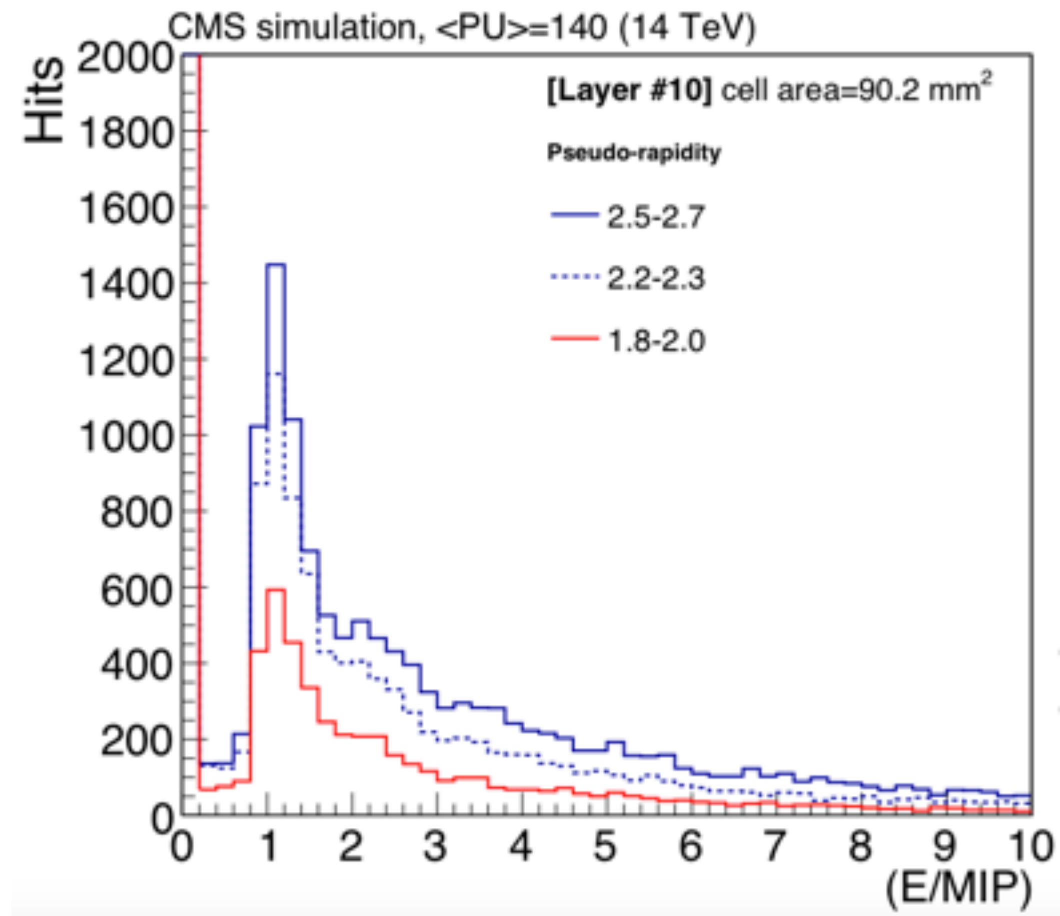
- Everything has to fit within the allowed 2 mm air gap
  - seems to be feasible



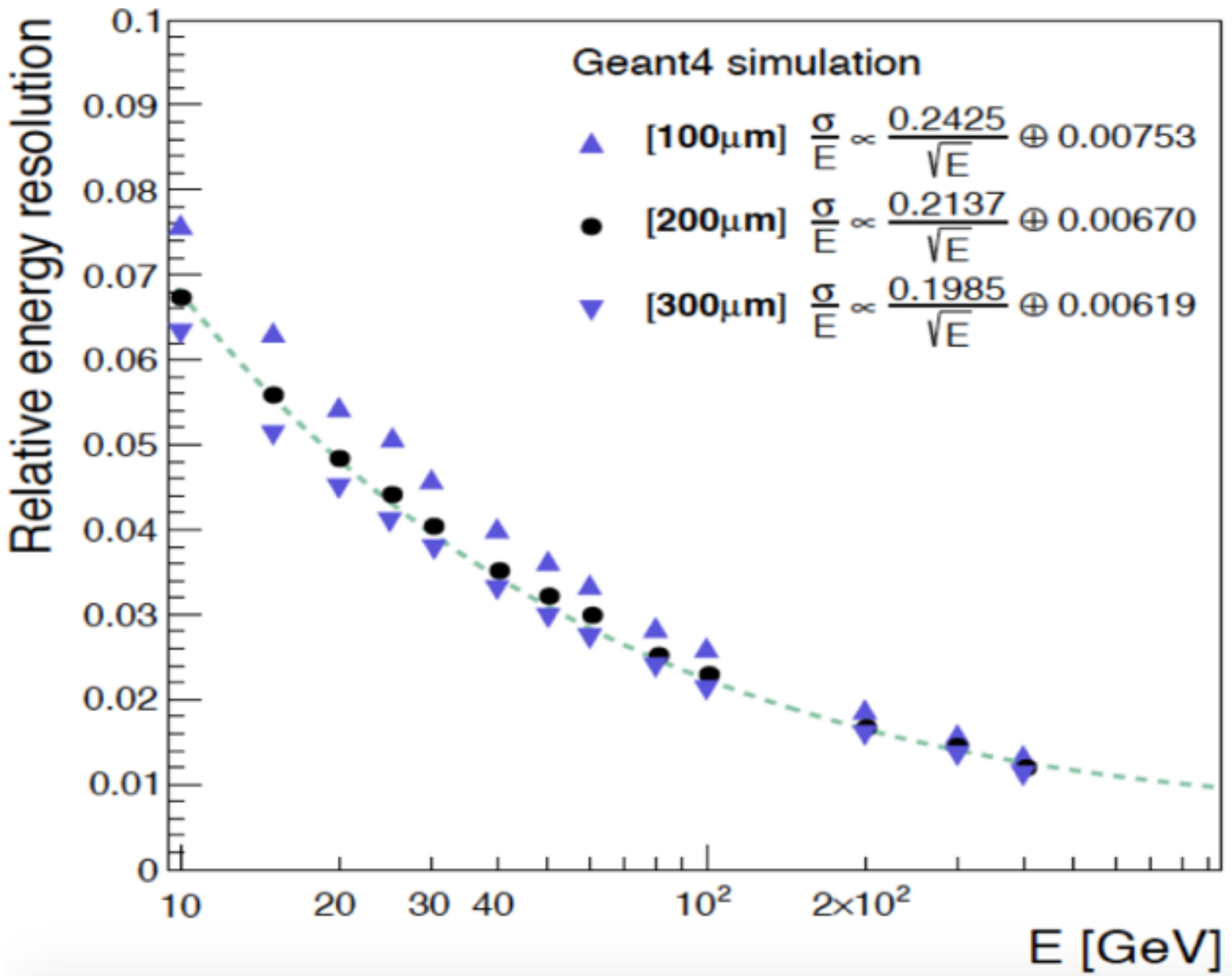


Challenges: calibration

- Goal: **HGC** is targeting a **constant term smaller than 1%**
  - In order to keep the contribution to the constant term below 0.5%, the **inter-calibration error** has to be kept **below 5%**
  - there are 8.7 M channels!
- Electronics inter-calibration at 1 % level by charge pulse injection
- Sensors inter-calibration from MIP signal
  - instrument each wafer with a special low-noise cell to have 1 MIP sensitivity
  - sensors uniformity within a wafer?



Expected performance (e.m. part)

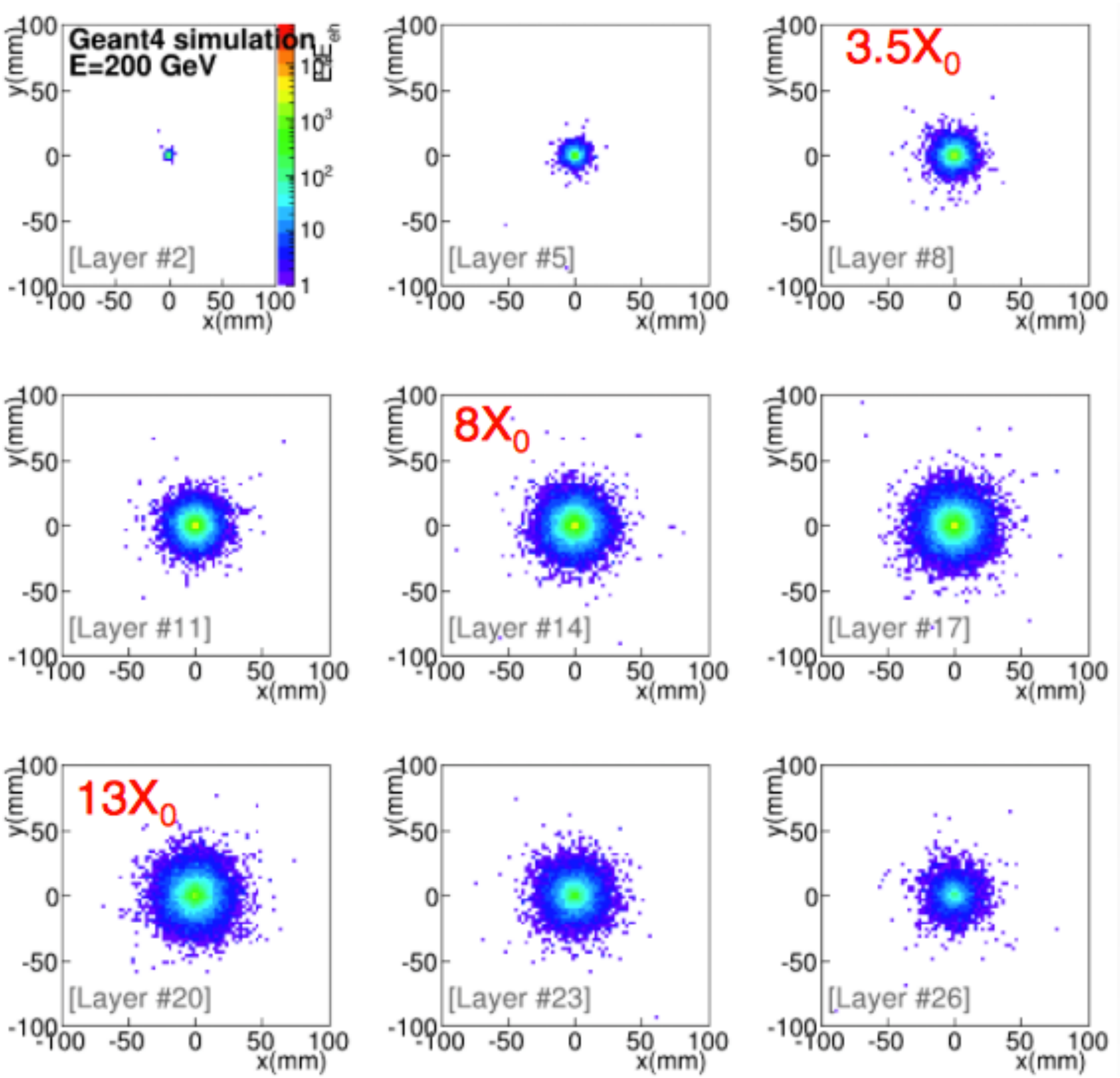


cfr. present ECAL:

$\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$

Expected performance (e.m. part)

- Improvements expected from longitudinal segmentation:



can 'see' the shower development in the different layers

Physics at e^+e^- colliders

- **e^+e^-** colliders provide a **clean** environment for **precision physics**

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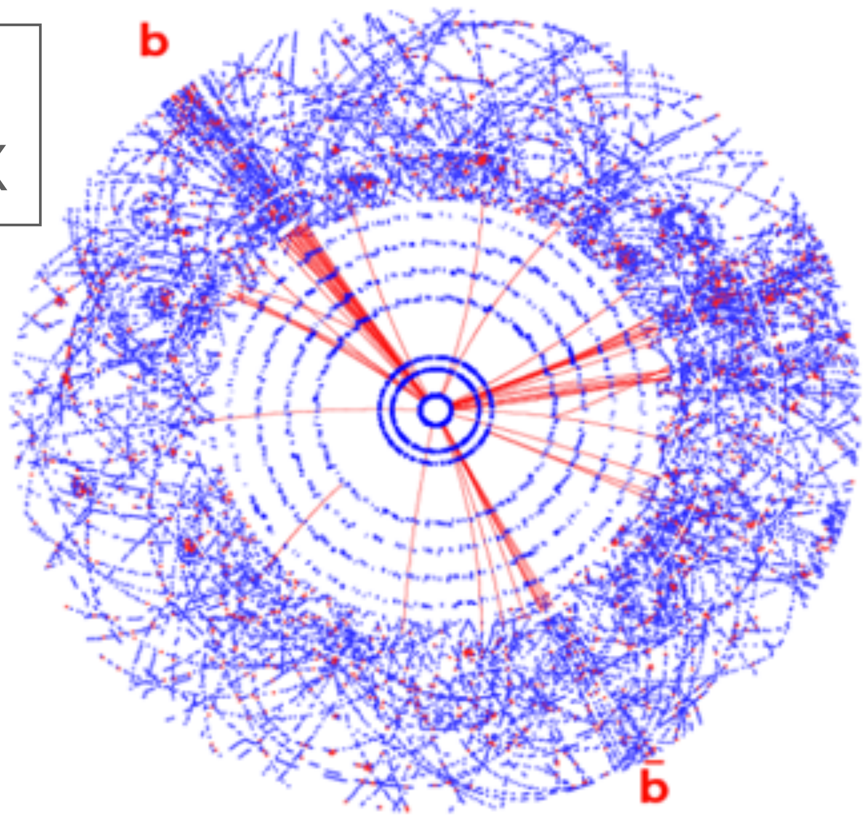
LHC
$pp \rightarrow H+X$



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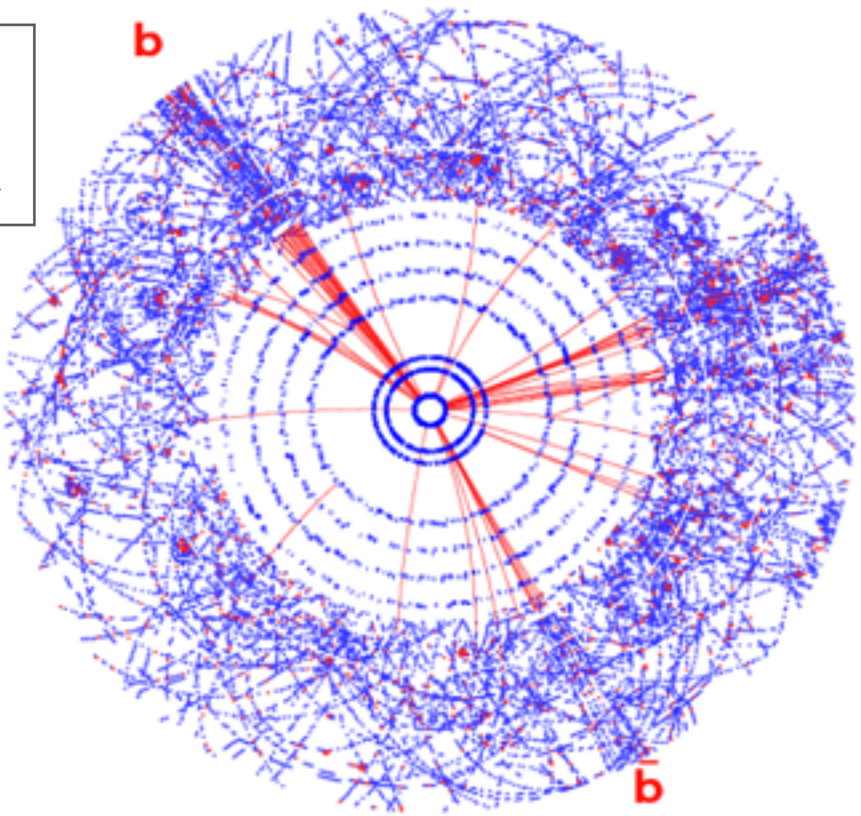

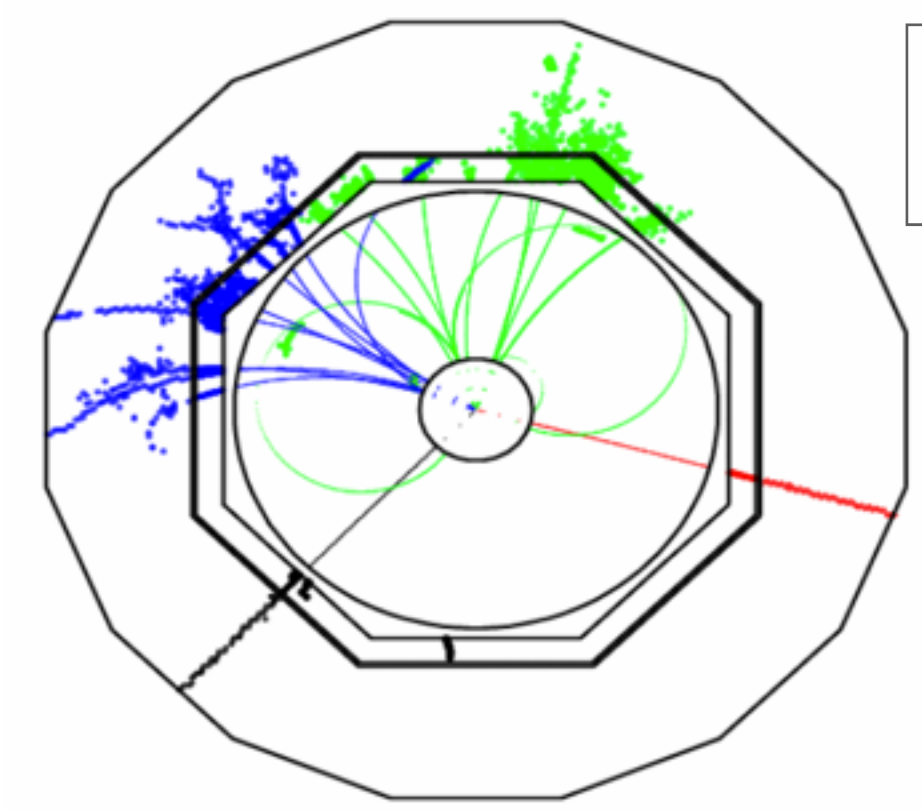

ILC
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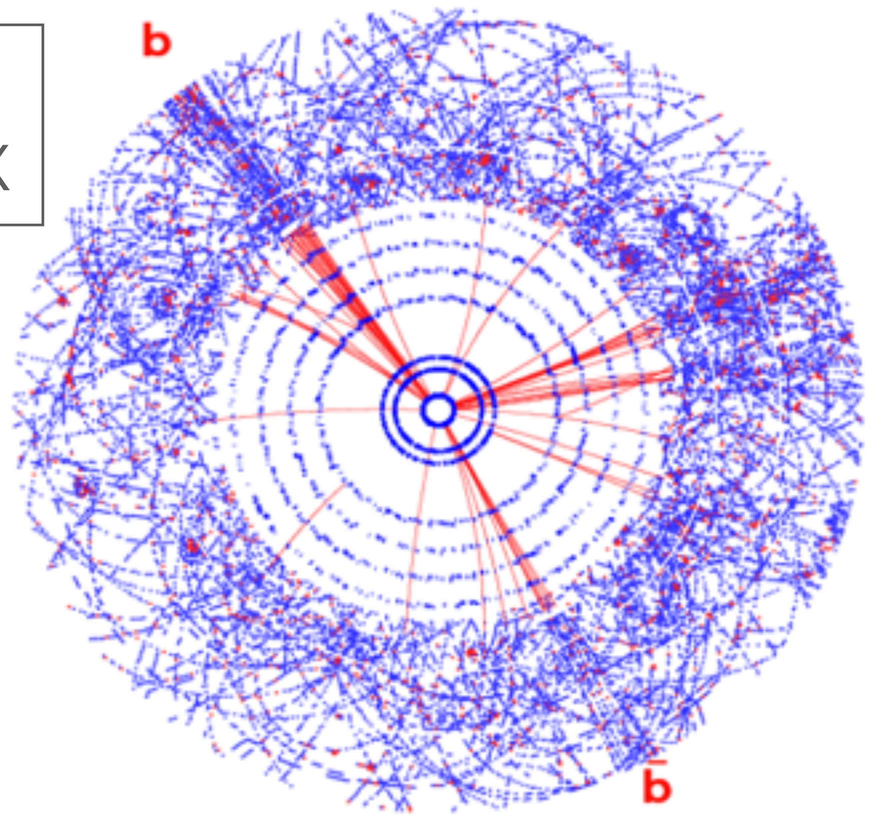
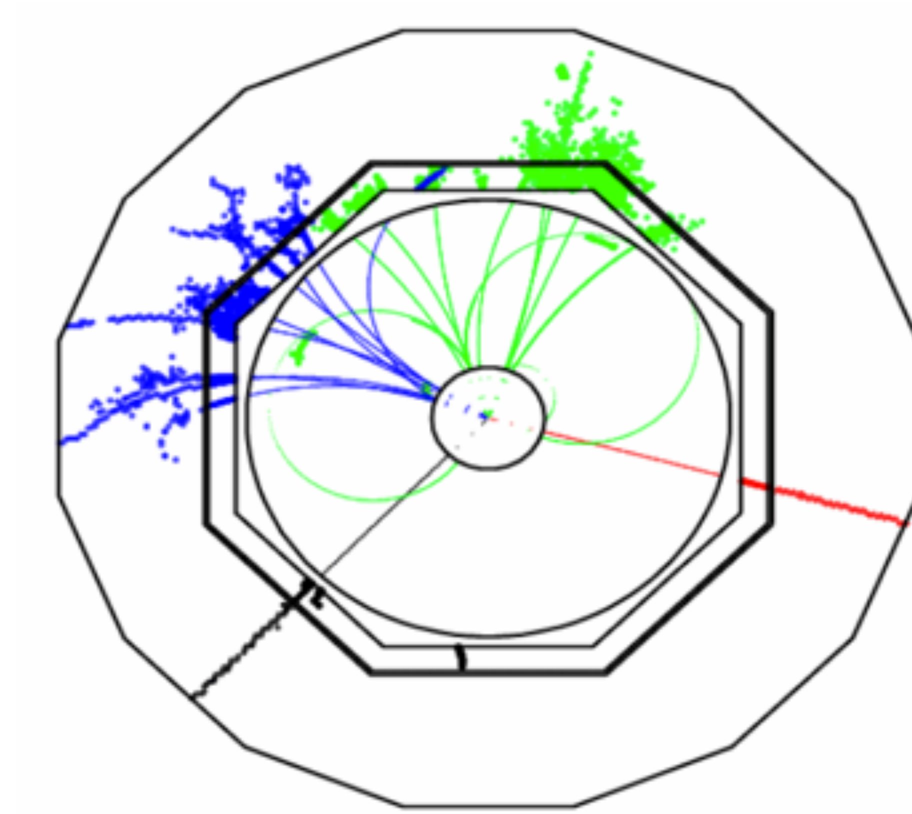


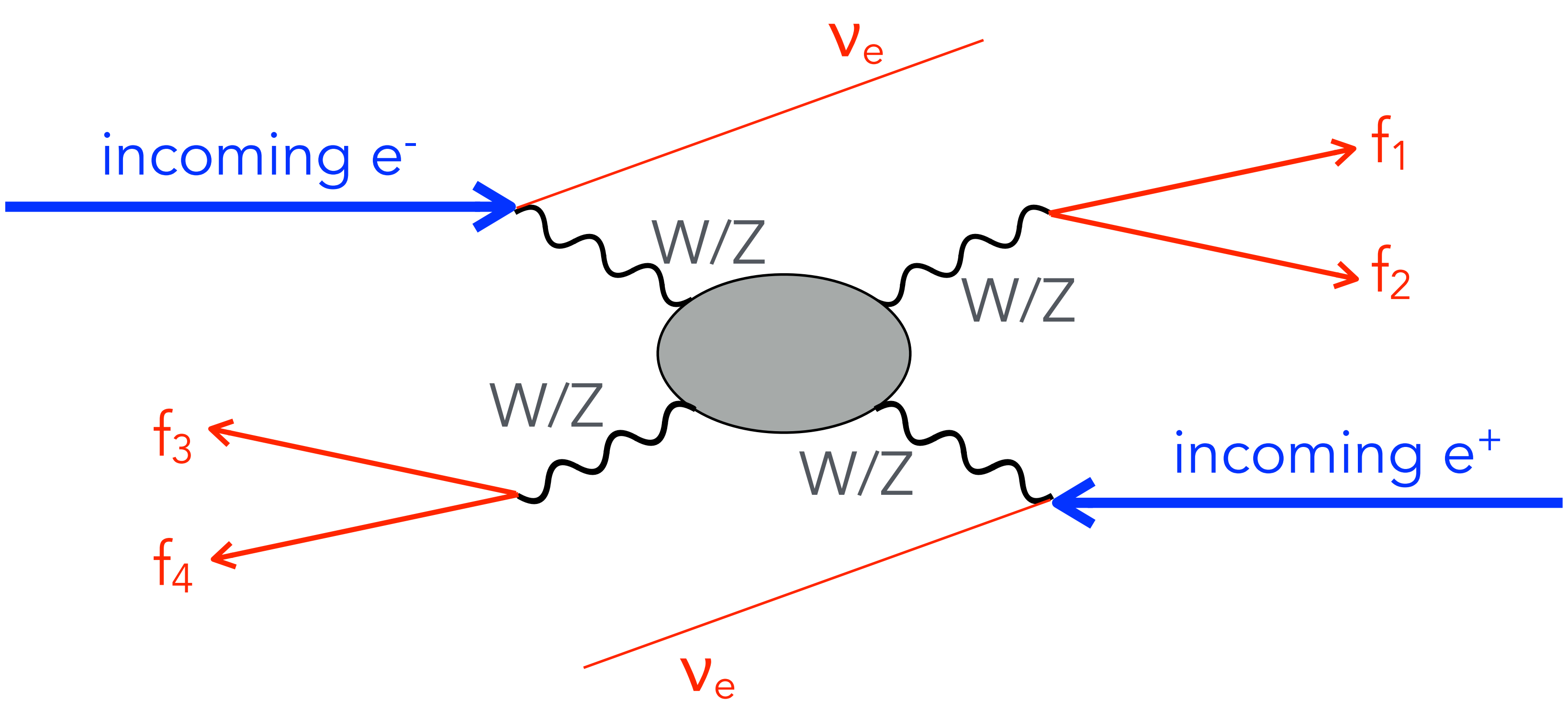


ILC
$ee \rightarrow HZ$

- Precision studies/measurements:
  - Higgs sector, SUSY particle spectrum, SM particles (e.g. W, top) and much more
  - High-multiplicity final states ubiquitous, **often 6/8 jets**

Physics at e^+e^- colliders

- Any future collider experiment geared towards precise measurements requires **very good jet energy resolution** to maximize physics reach.
- Oft-quoted example: **vector boson scattering**



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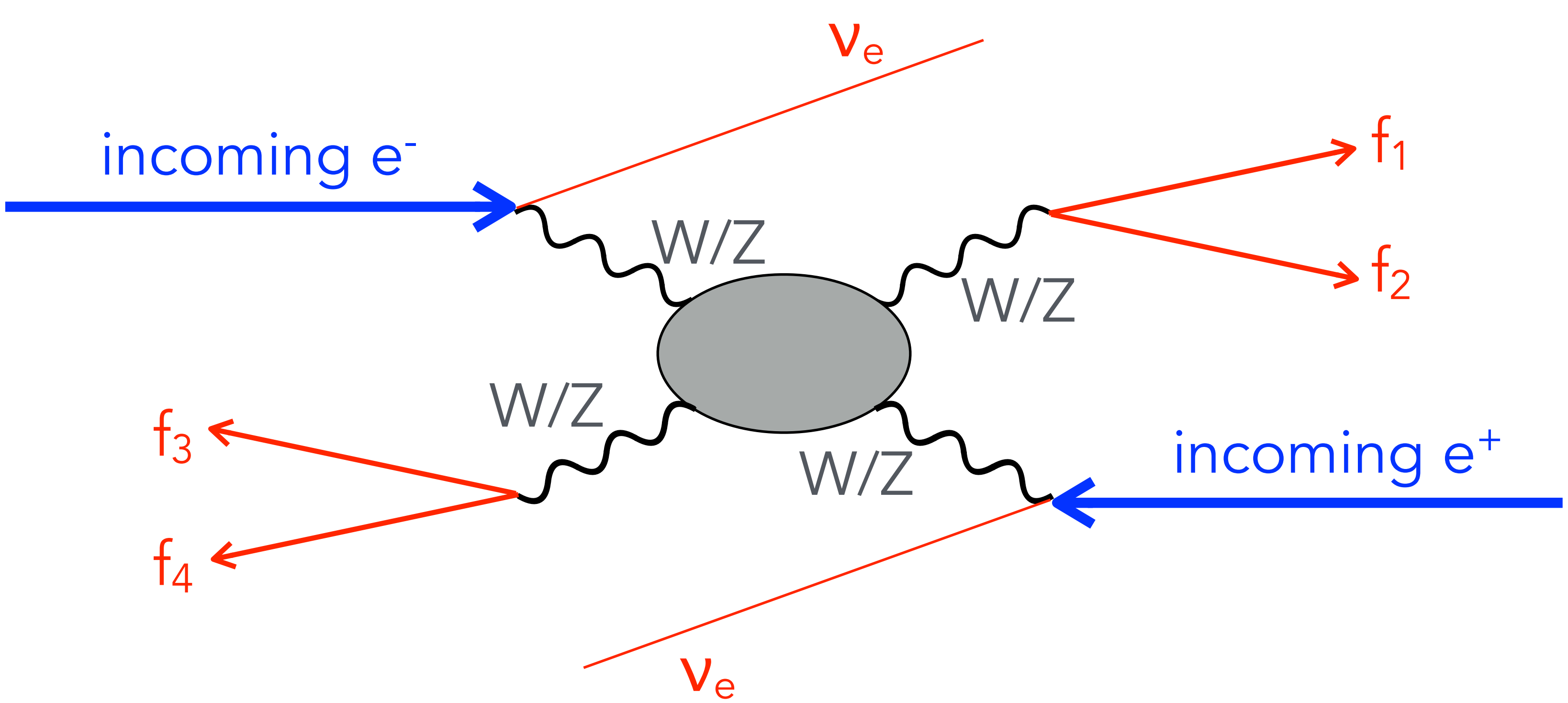

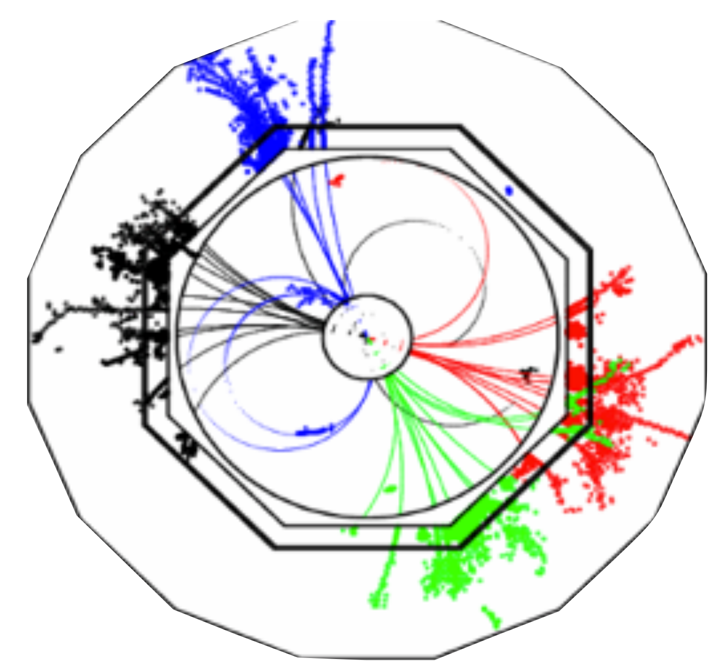

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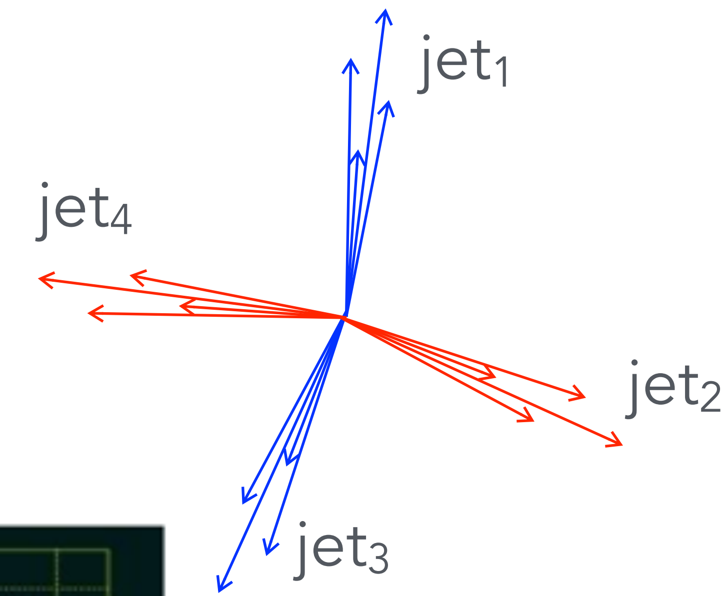
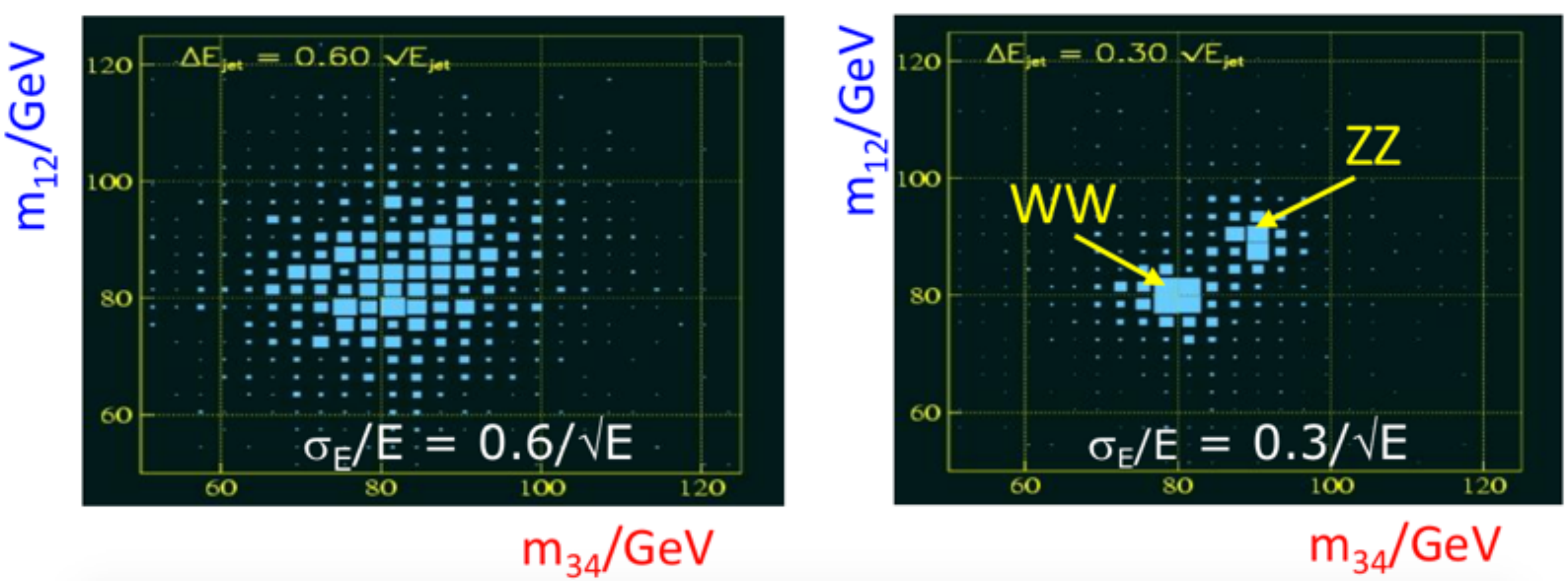
- Any future collider experiment geared towards precise measurements requires **very good jet energy resolution** to maximize physics reach.
- Oft-quoted example: **vector boson scattering**

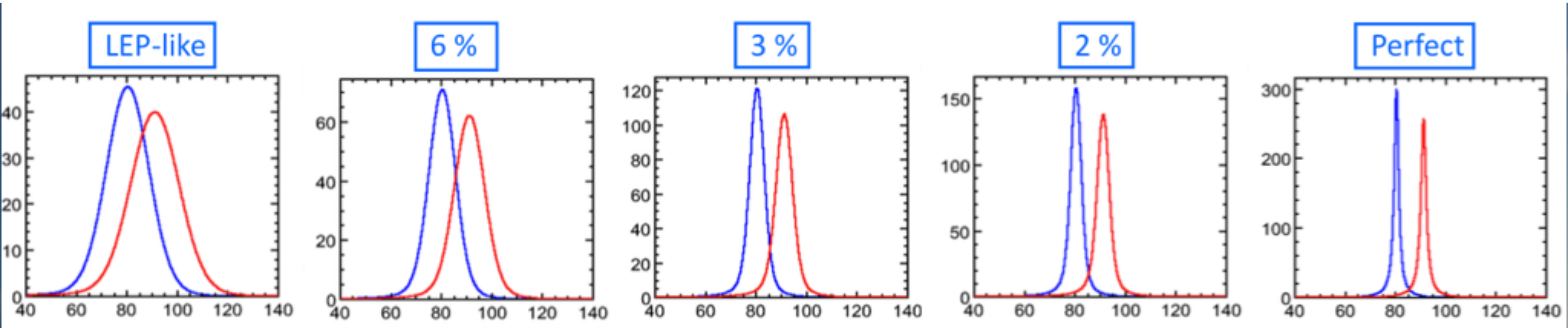


reconstruction of two di-jet masses discriminates between WW and ZZ final states



LC jet energy resolution requirements

- Gauge boson width sets 'natural' goal for jet energy resolution:

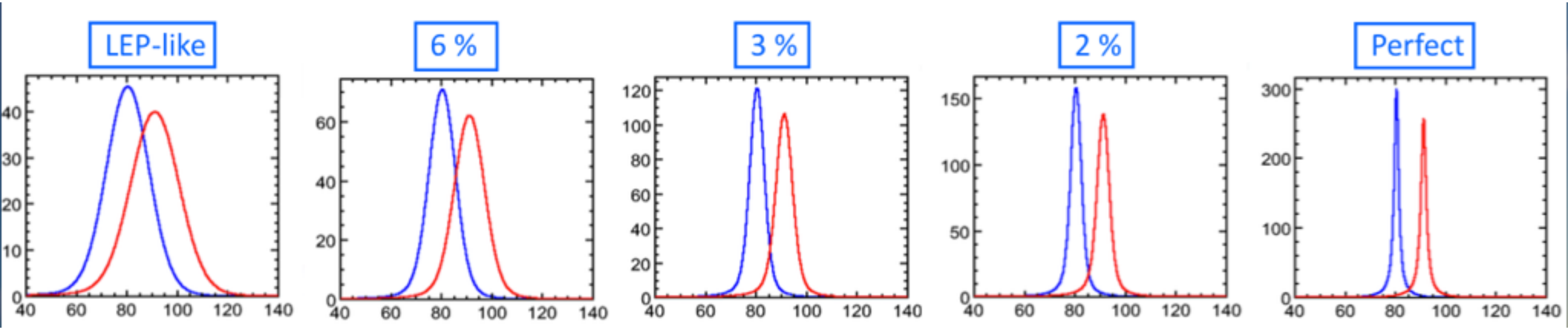


Jet E res.	W/Z sep
Perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

- 3-4% jet energy resolution gives decent 2.6-2.3 σ W/Z separation
- Sets a reasonable choice for LC jet energy goal
  - For W/Z separation, not much further gain, limited by natural widths

LC jet energy resolution requirements

- Gauge boson width sets 'natural' goal for jet energy resolution:

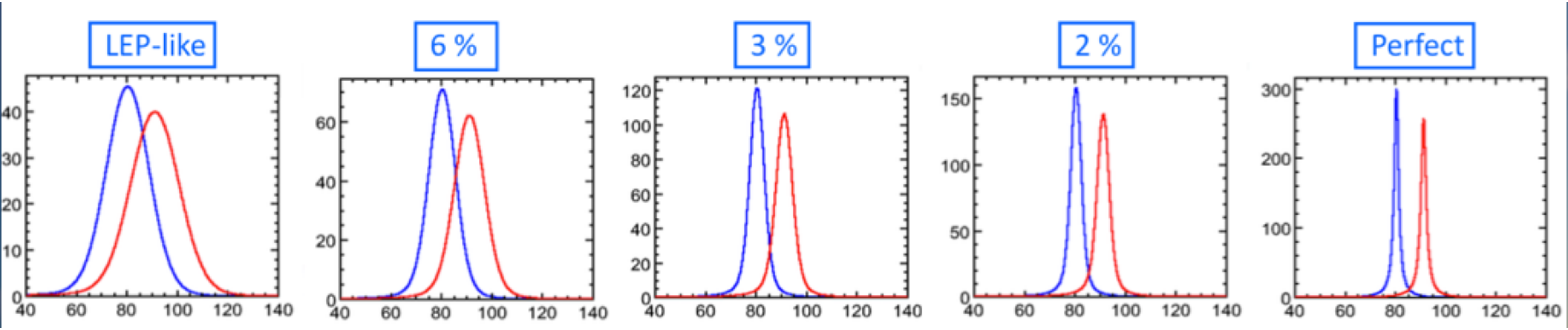


Jet E res.	W/Z sep
Perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

Goal: ~3.5% jet energy resolution for 100-500 GeV jets

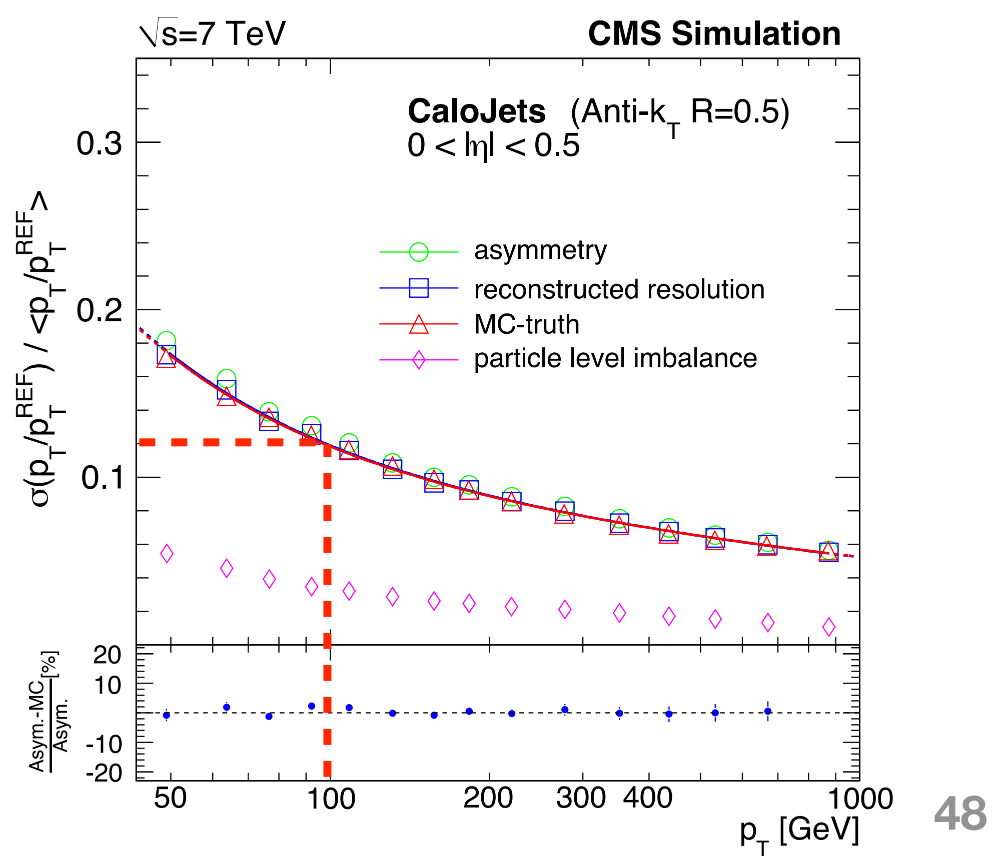
LC jet energy resolution requirements

- Gauge boson width sets 'natural' goal for jet energy resolution:



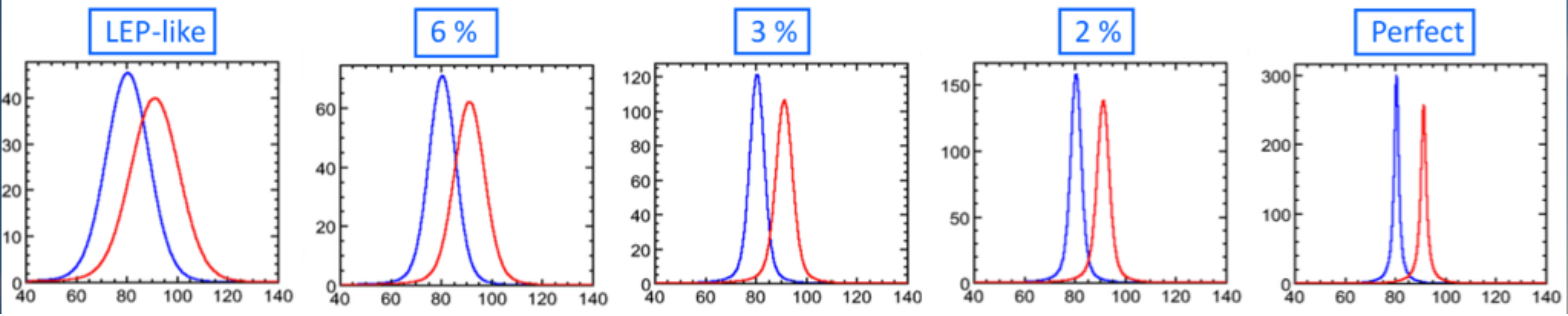
Jet E res.	W/Z sep
Perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

cfr. with CMS:



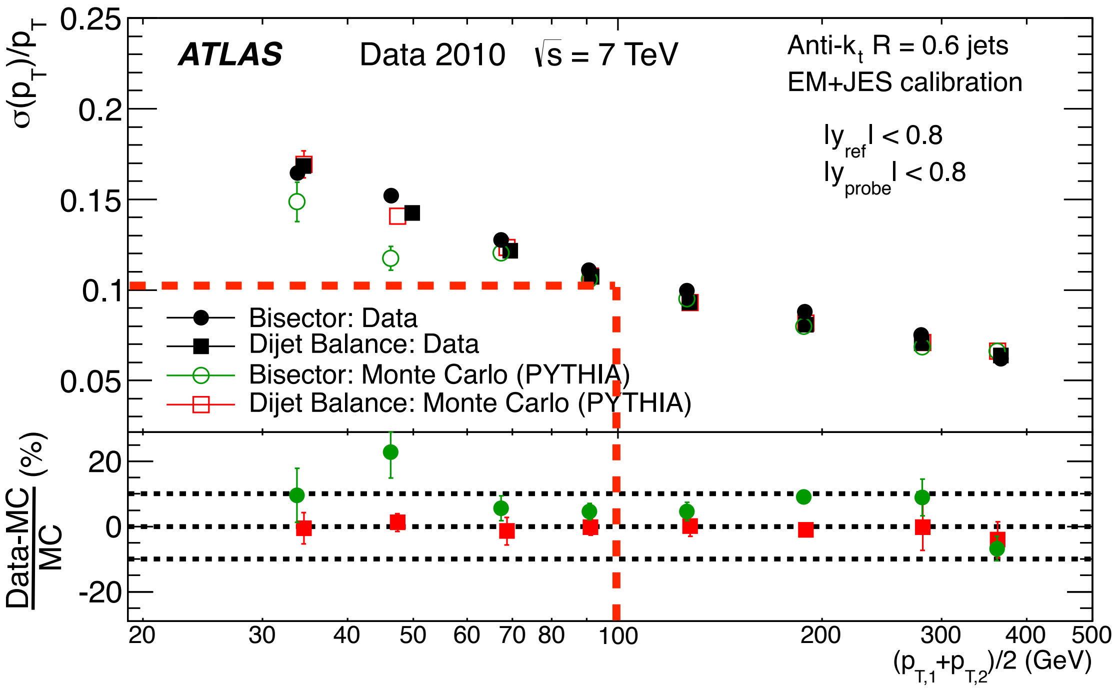
LC jet energy resolution requirements

- Gauge boson width sets ‘natural’ goal for jet energy resolution:



Jet E res.	W/Z sep
Perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

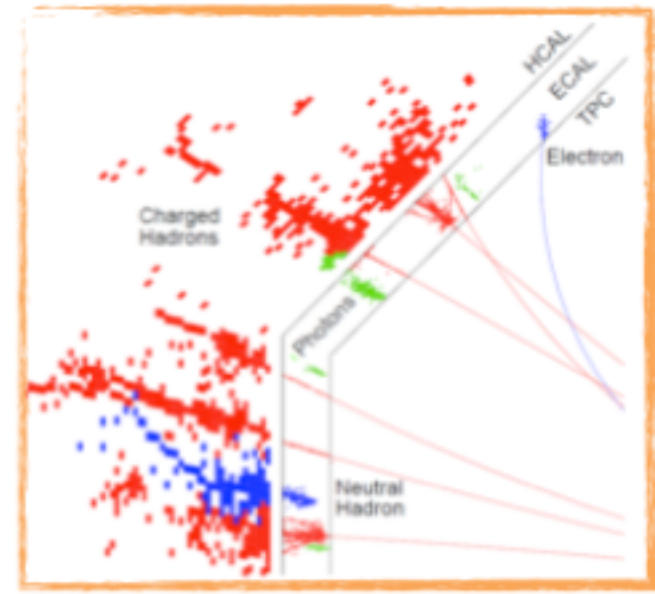
cfr. with ATLAS:



Particle flow calorimetry

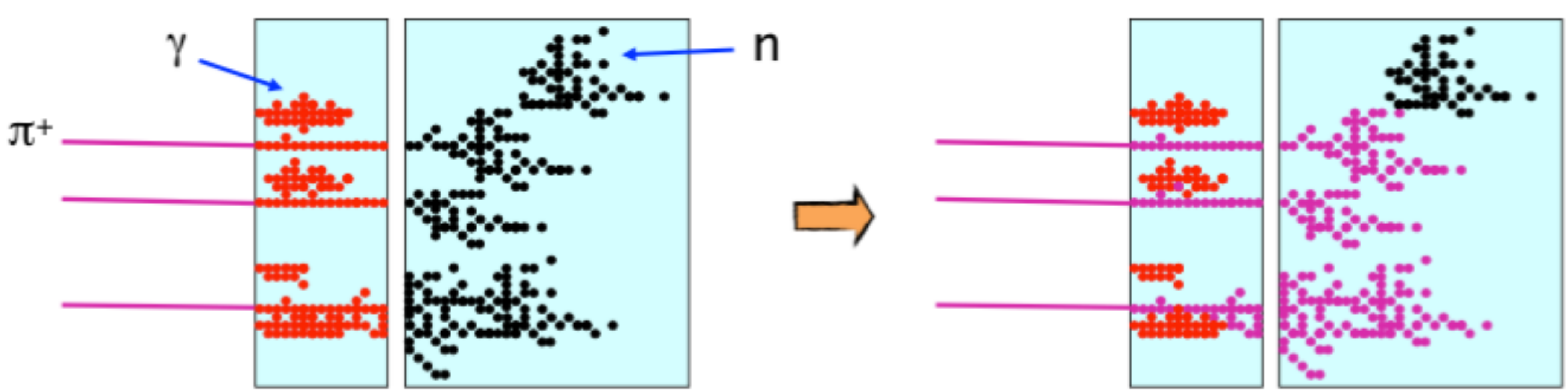
In a typical jet:

- 60 % of jet energy in charged hadrons
- 30 % in photons (mainly from $\pi^0 \to \gamma\gamma$))
- 10 % in neutral hadrons (mainly n and K_L)



Traditional calorimetric approach:

- Measure all components of jet energy in ECAL/HCAL
- Approximately 70% of energy measured in HCAL: $\sigma_E/E \approx 60\% / \sqrt{E(\mathrm{GeV})}$



$E_{JET} = E_{ECAL} + E_{HCAL}$ $\Rightarrow$ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

Fine granularity Particle Flow Calorimetry: reconstruct individual particles.

- Charged particle momentum measured in tracker (essentially perfectly)
- Photon energies measured in ECAL: $\sigma_E/E < 20\% / \sqrt{E(\mathrm{GeV})}$
- Only neutral hadron energies (10% of jet energy) measured in HCAL: much improved resolution.

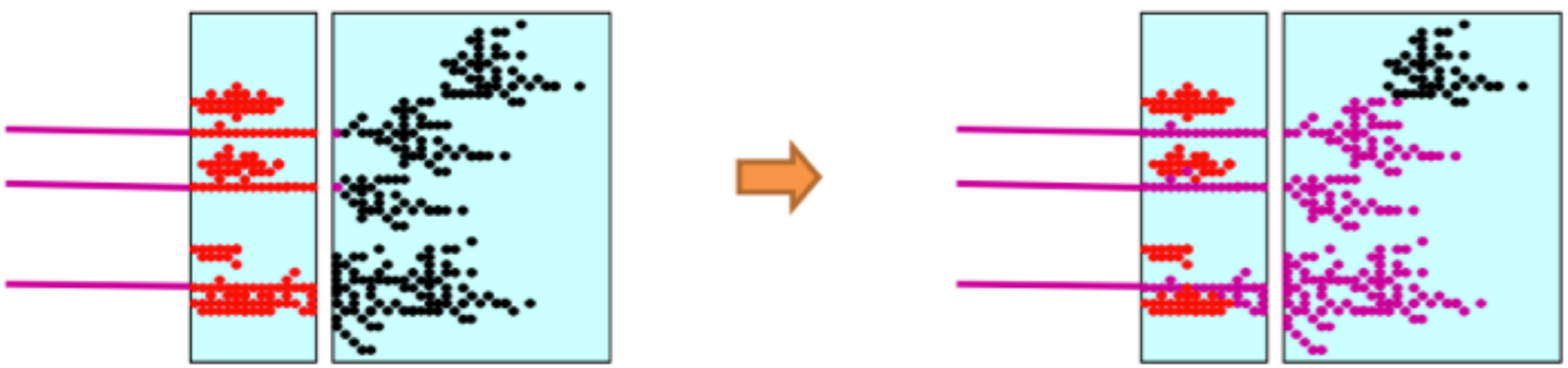
Particle flow calorimetry

Hardware: need to be able to resolve energy deposits from different particles

- Requires highly granular detectors (as studied by CALICE)

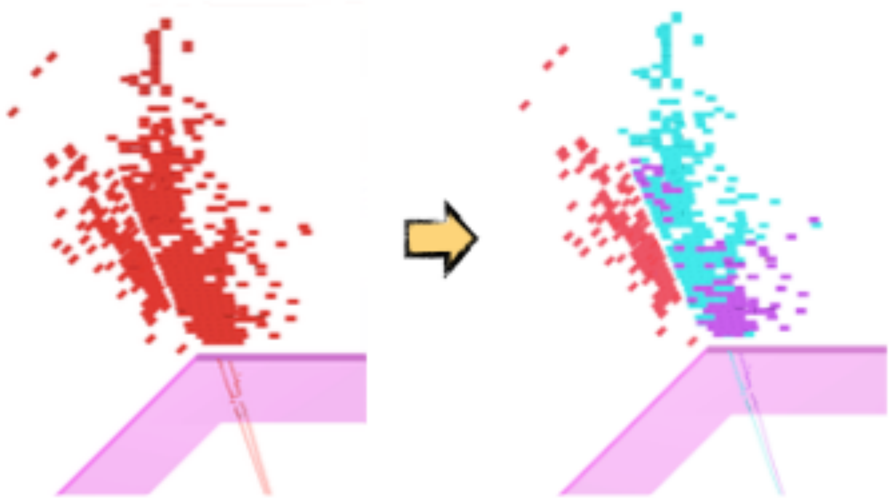
Software: need to be able to identify energy deposits from each individual particle

- Requires sophisticated reconstruction software

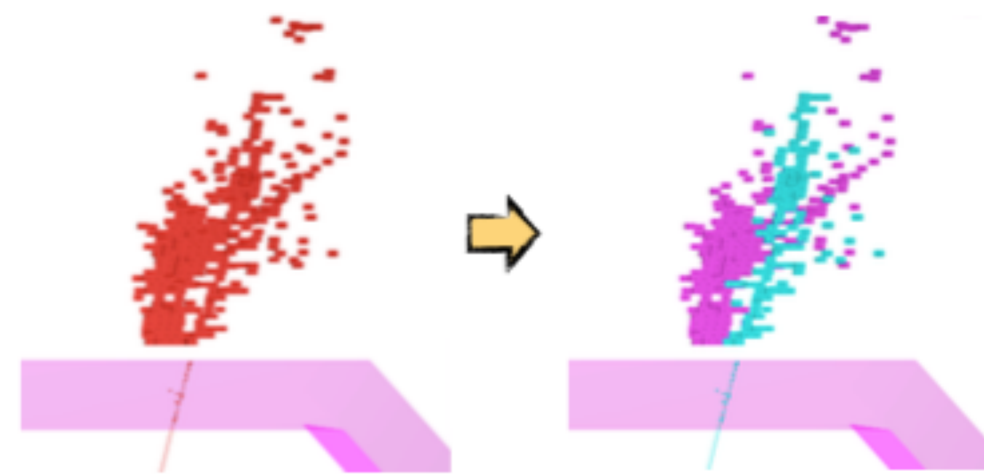


Particle Flow Calorimetry = HARDWARE + SOFTWARE

Particle flow calorimetry

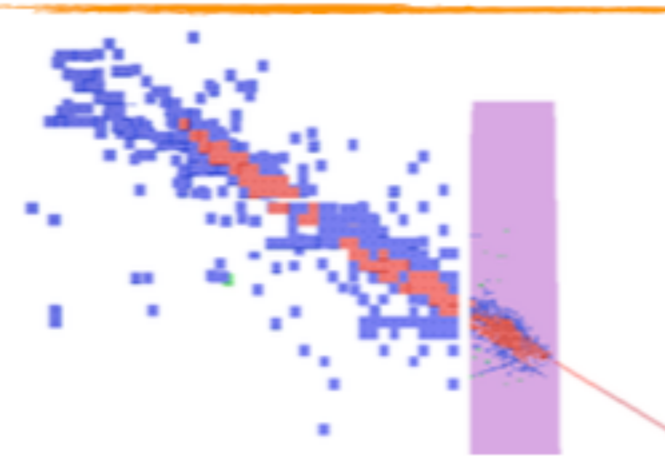


1. Multiple tracks associated to single cluster – split cluster.



2. Cluster energy much greater than track momentum – split cluster.

3. Track momentum much greater than cluster energy – bring in nearby clusters and reconfigure.



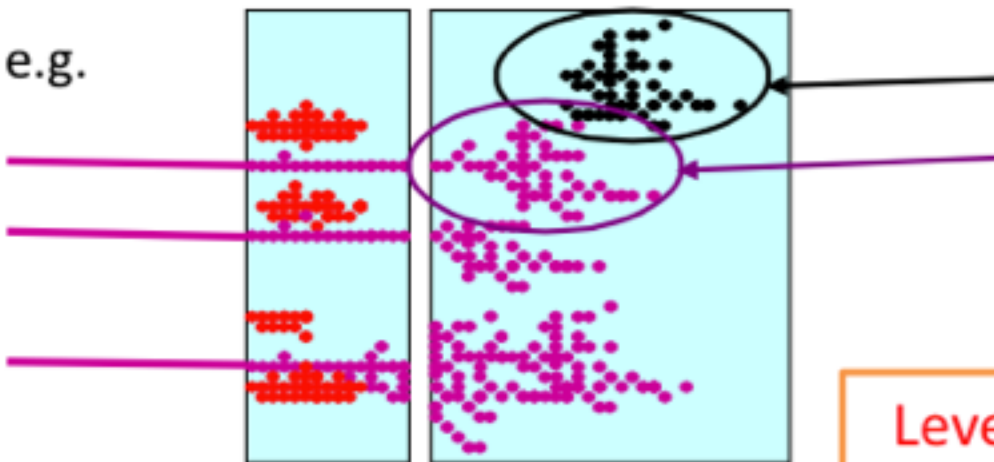
4. If, and only if, no E/p match emerges, can force track-cluster consistency ⇒ energy flow.

Particle flow calorimetry

The challenge for particle flow algorithms:

- Avoid double counting of energy from same particle
- Separate energy deposits from different particles

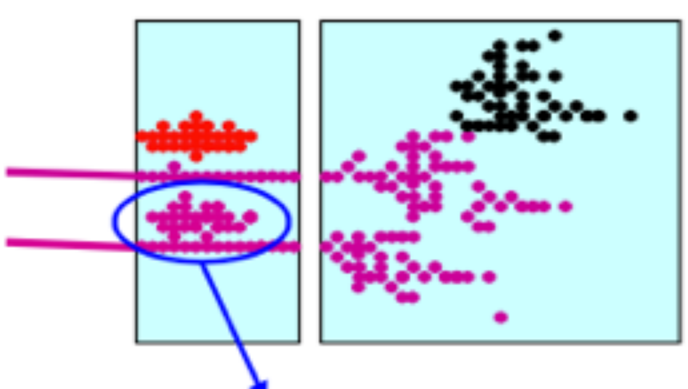
e.g.



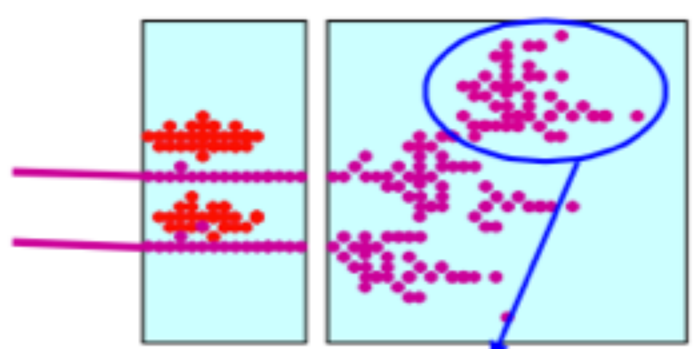
If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution, not intrinsic calorimetric performance

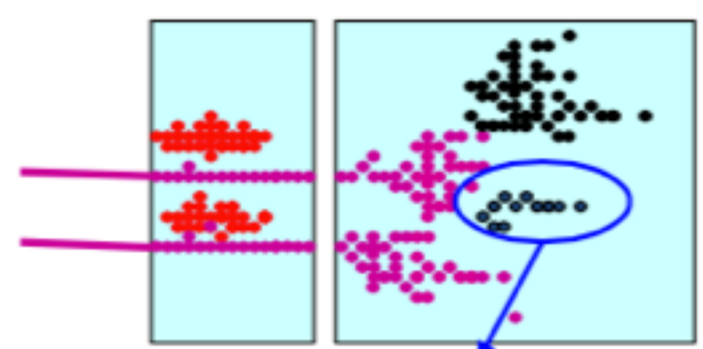
Three types of confusion:



Failure to resolve photons



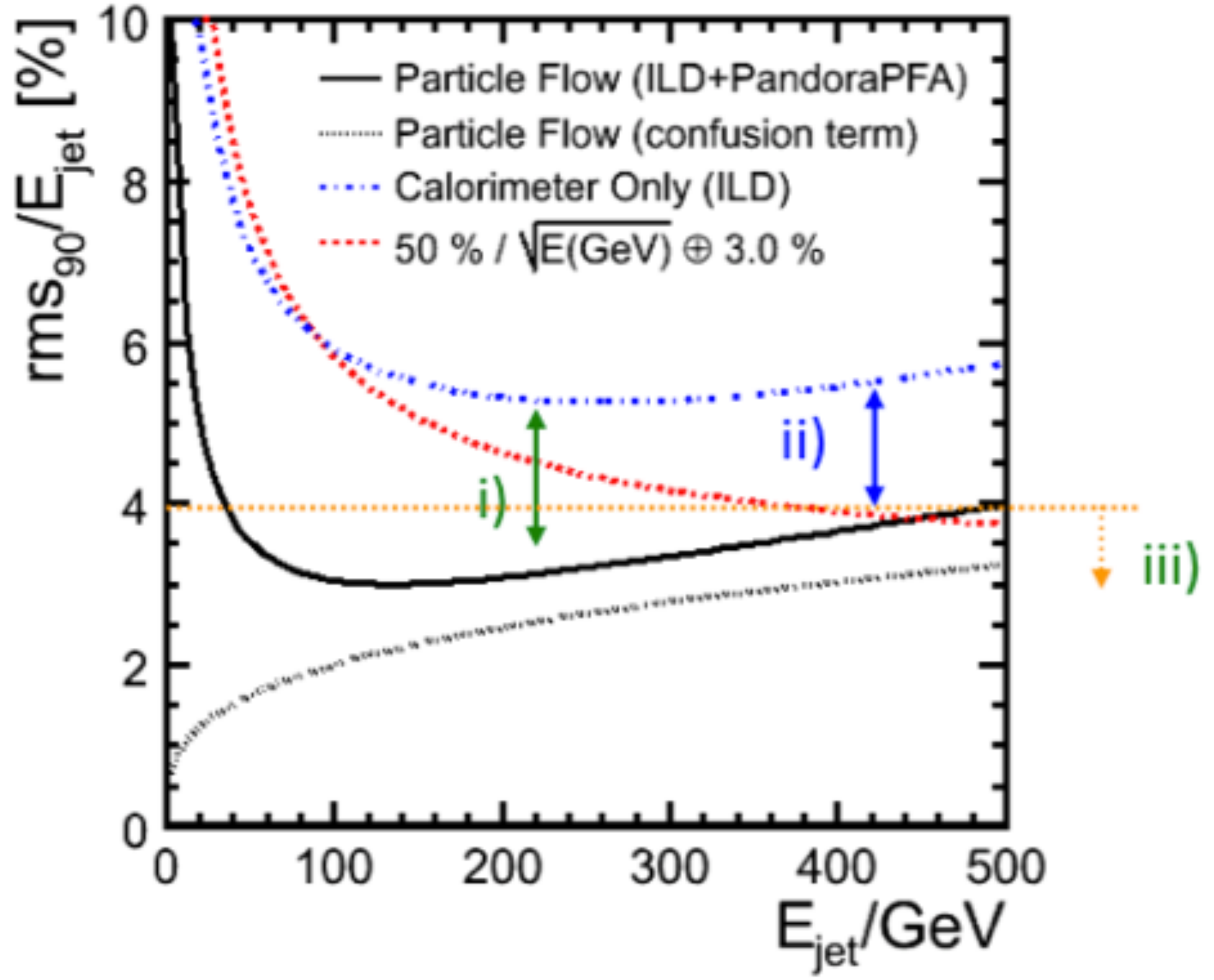
Failure to resolve neutral hadrons



Reconstruct fragments as separate neutral hadrons

Particle flow calorimetry

- ILD/SiD intended for PFA, but also good conventional calorimeters:
  - ECAL ~15%/√E
  - HCAL ~55%/√E



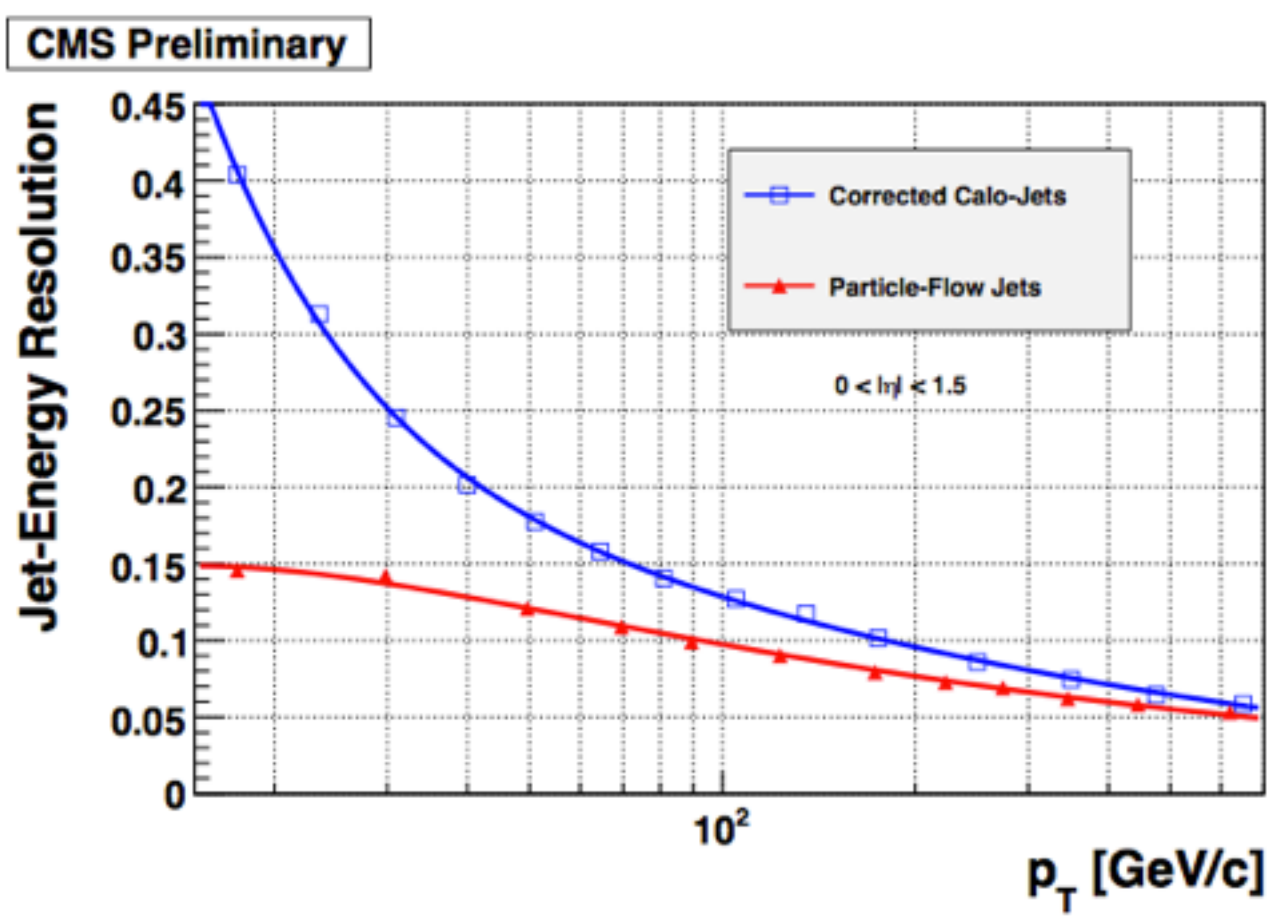
i) PandoraPFA: always wins over purely calorimetric approach

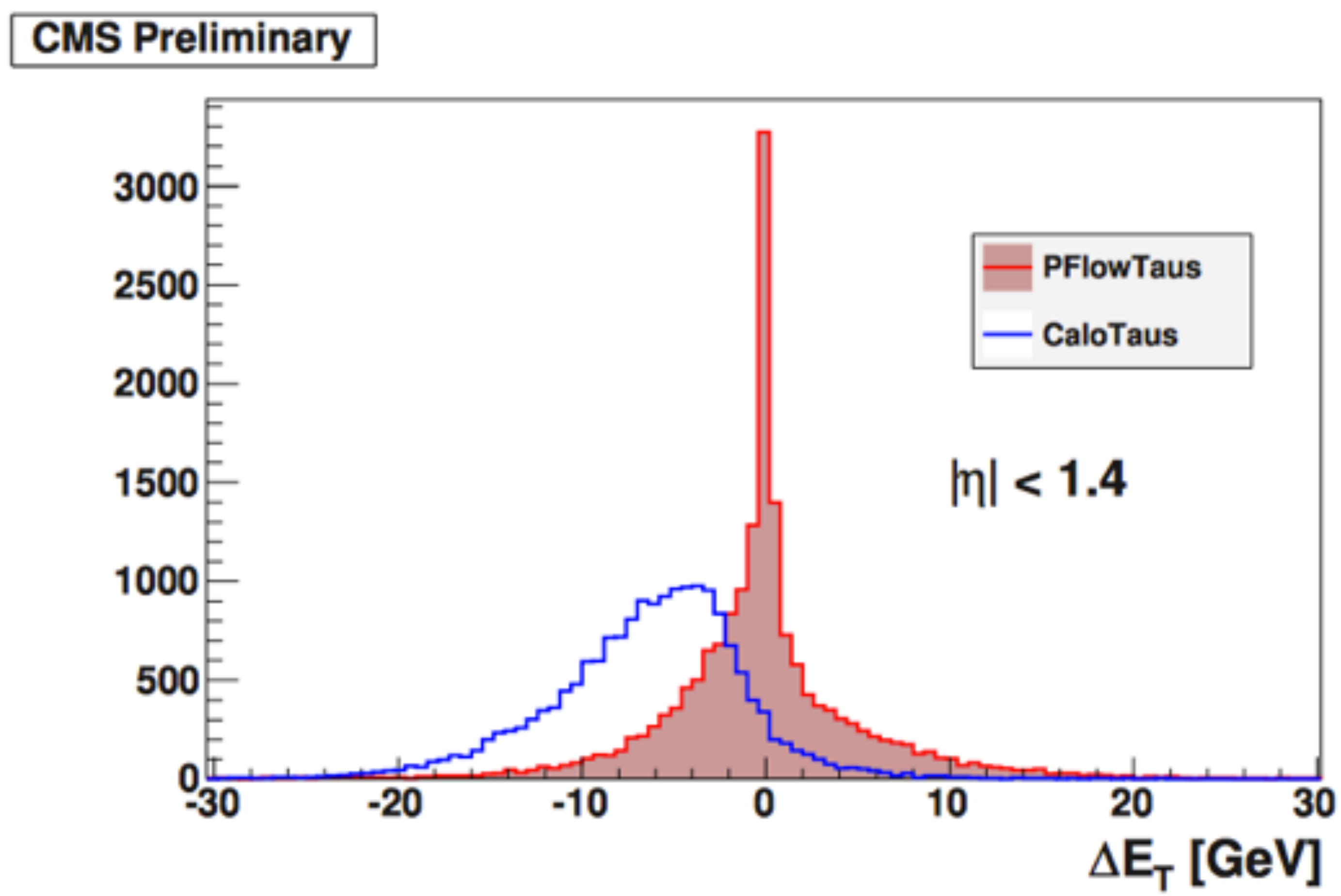
ii) PandoraPFA: effect of leakage clear at high energies

iii) PandoraPFA/ILD: Resolution better than 4 % for E_{JET} < 500 GeV

Particle flow calorimetry

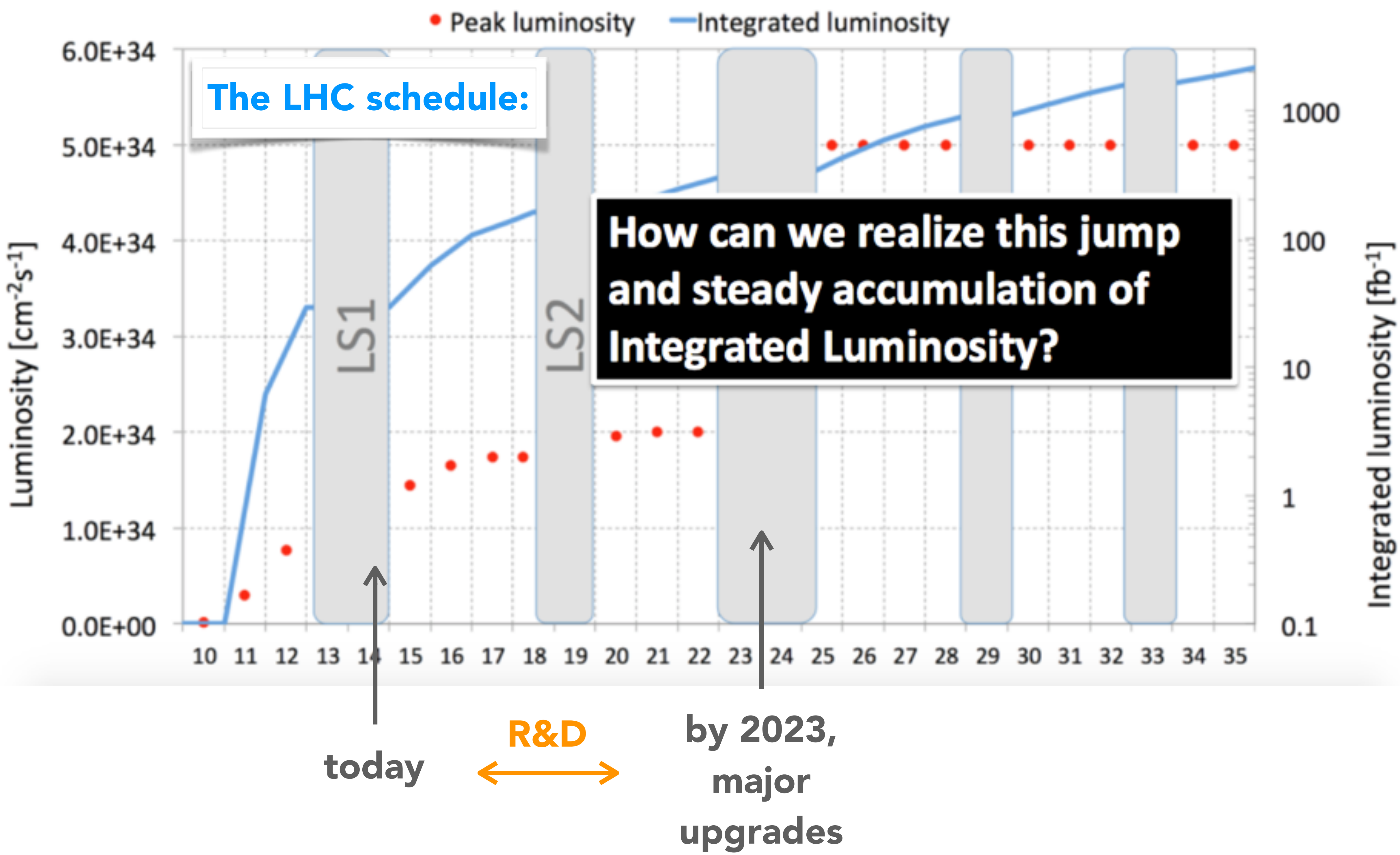
- Particle flow in action: the CMS example



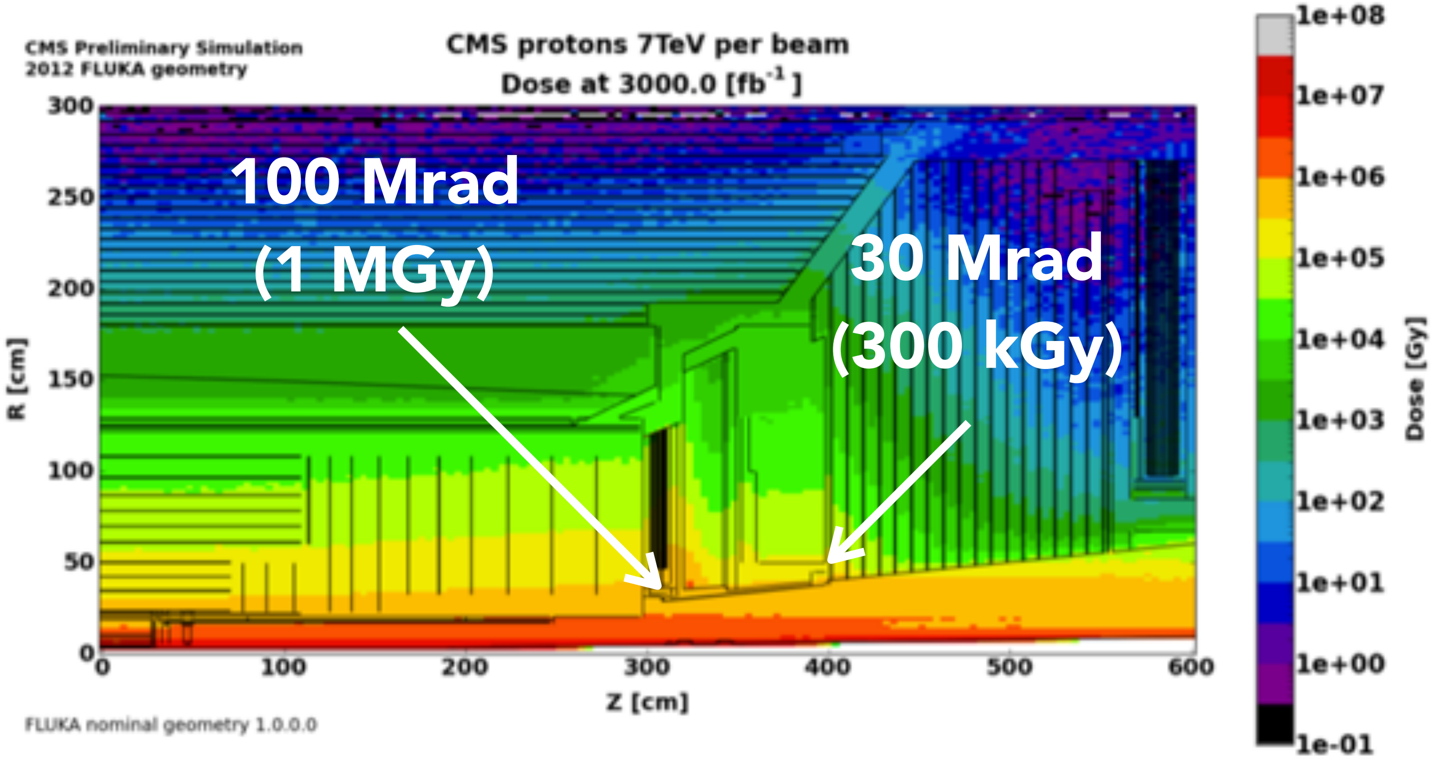


Bonus material

CMS needs a large R&D effort to survive to 2036…



… because of two major challenges:

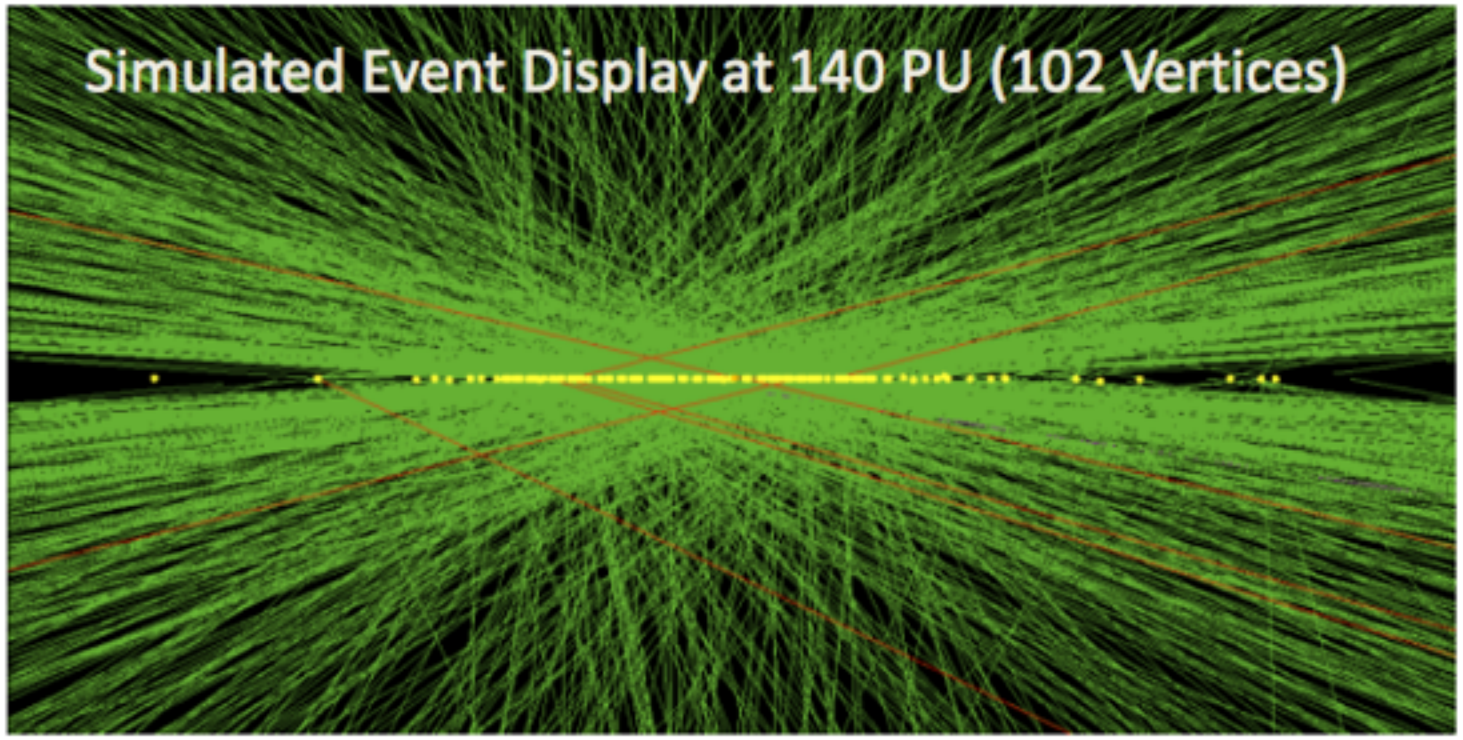


radiation levels in the detector

- predicted neutron fluence of about 10^{16} n/cm^2 in forward regions
- ionizing dose up to 150 Mrad in CMS electromagnetic calorimeter (η~3)

pile up

- 140 average simultaneous interactions
- many events with up to 180 interactions per bunch crossing



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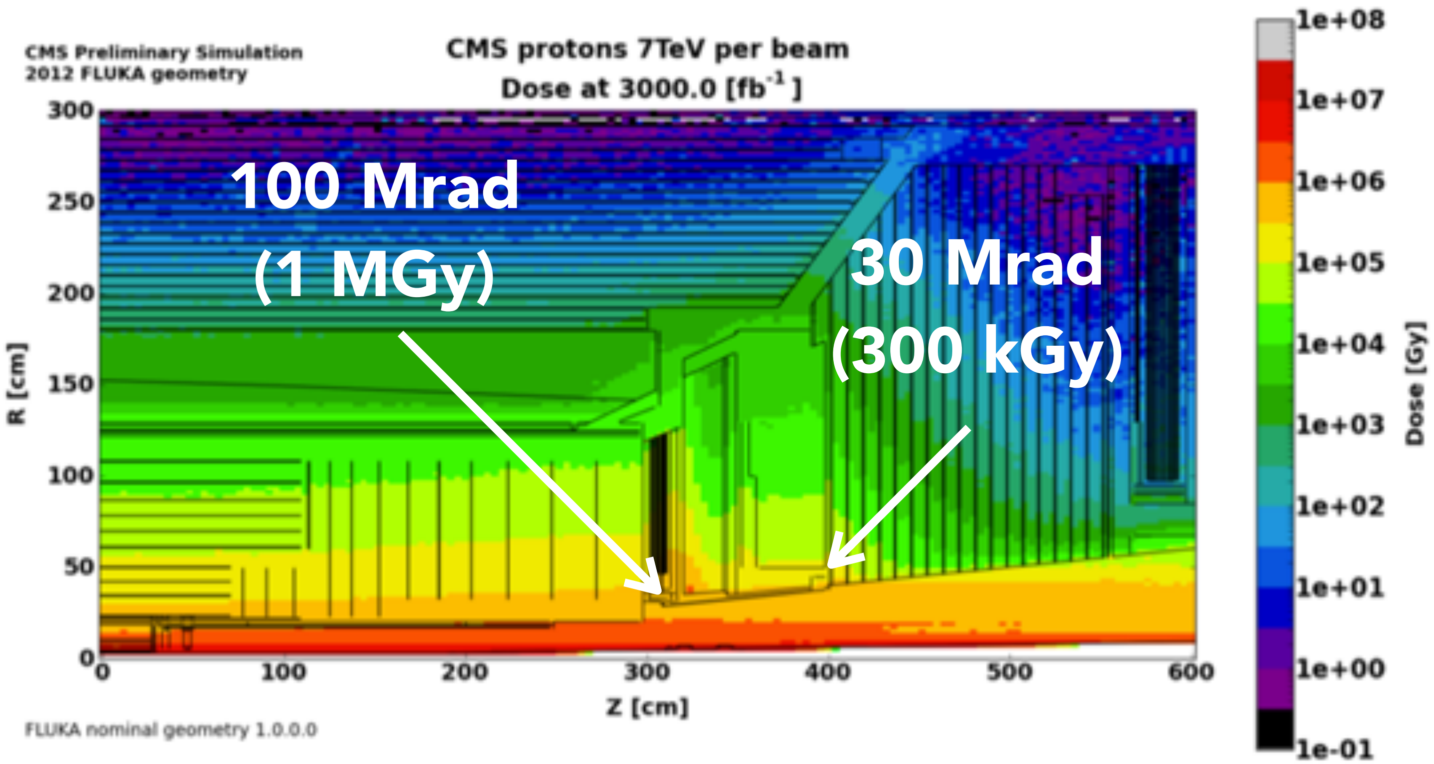


radiation levels in the detector

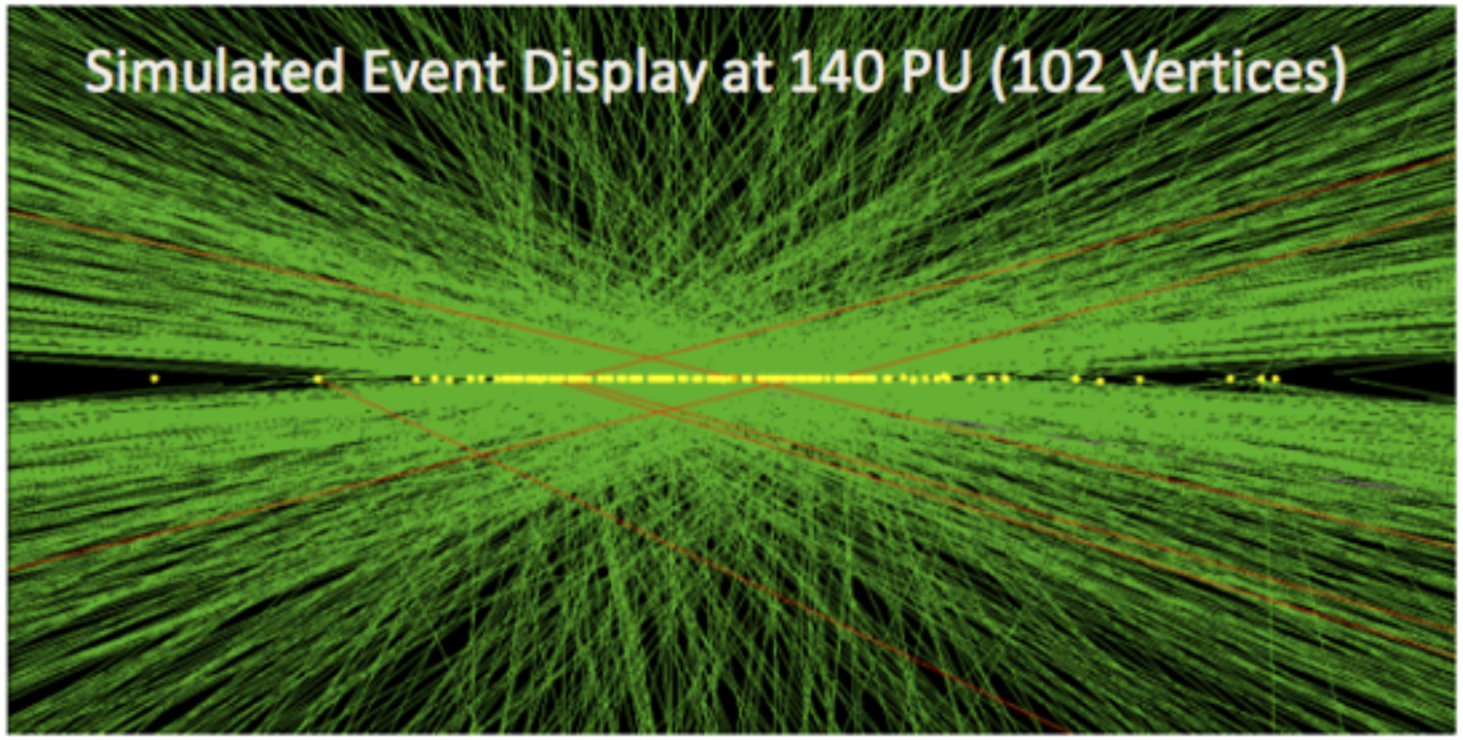
- predicted neutron fluence of about 10^{16} n/cm^2 in forward regions
- ionizing dose up to 150 Mrad in CMS electromagnetic calorimeter (η~3)

need rad-tolerant materials

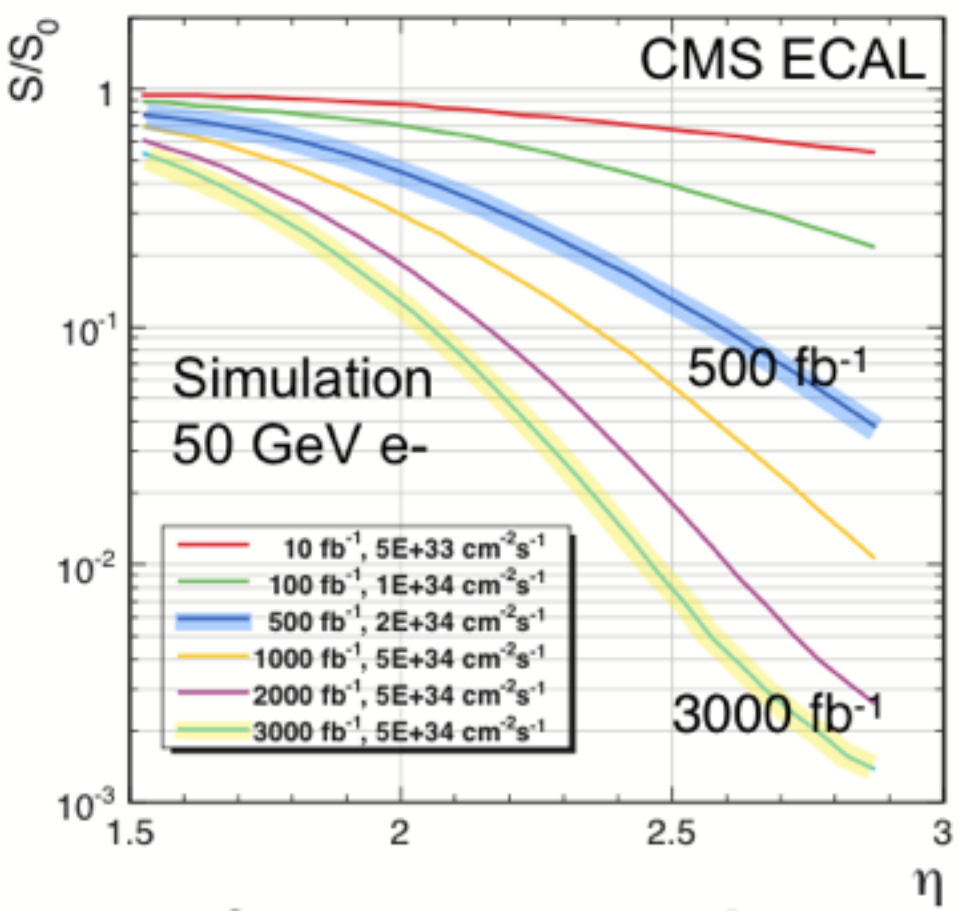
pile up

- 140 average simultaneous interactions
- many events with up to 180 interactions per bunch crossing

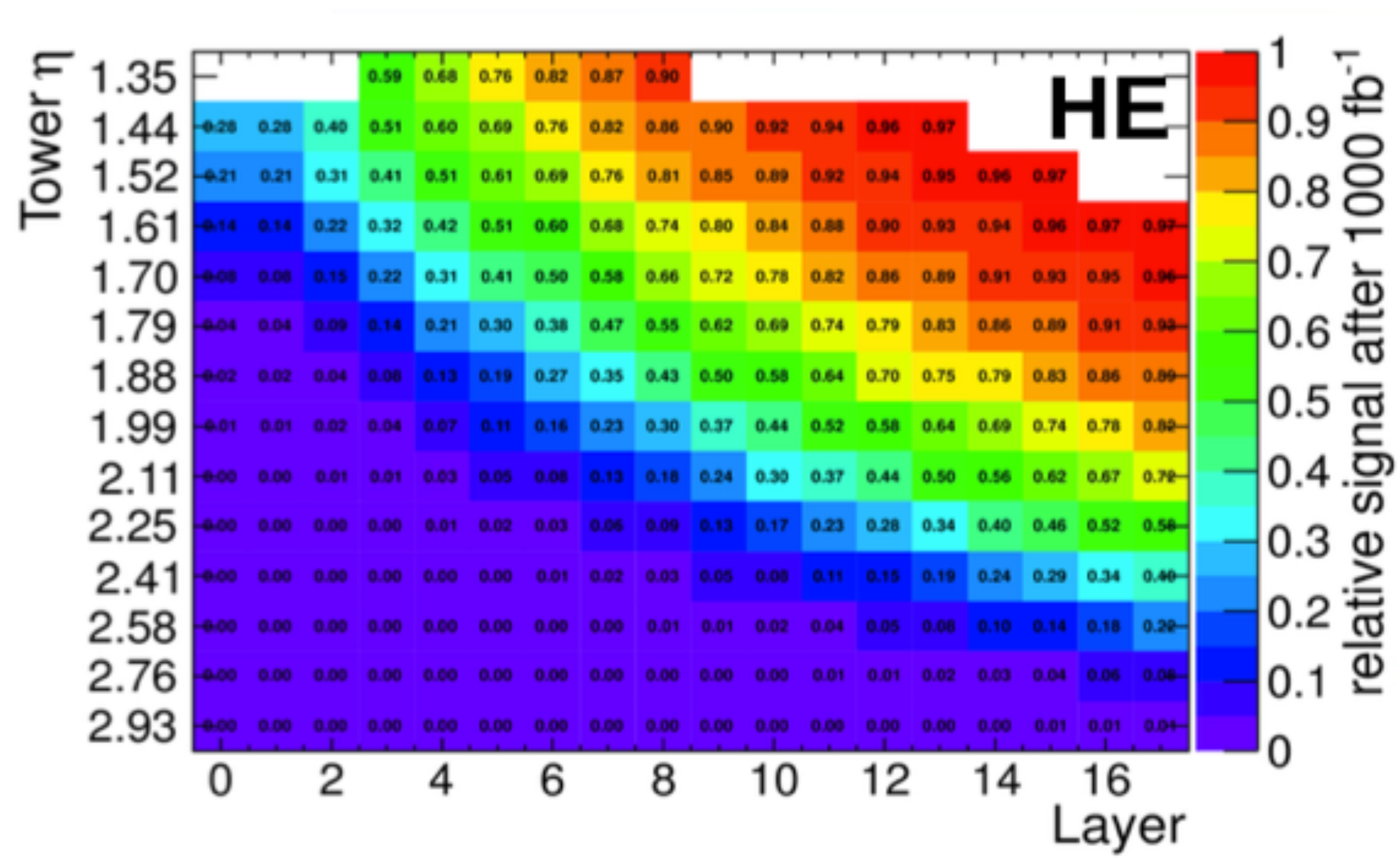
need fast-response detectors



ECAL and HCAL endcaps will need to be replaced during LS3



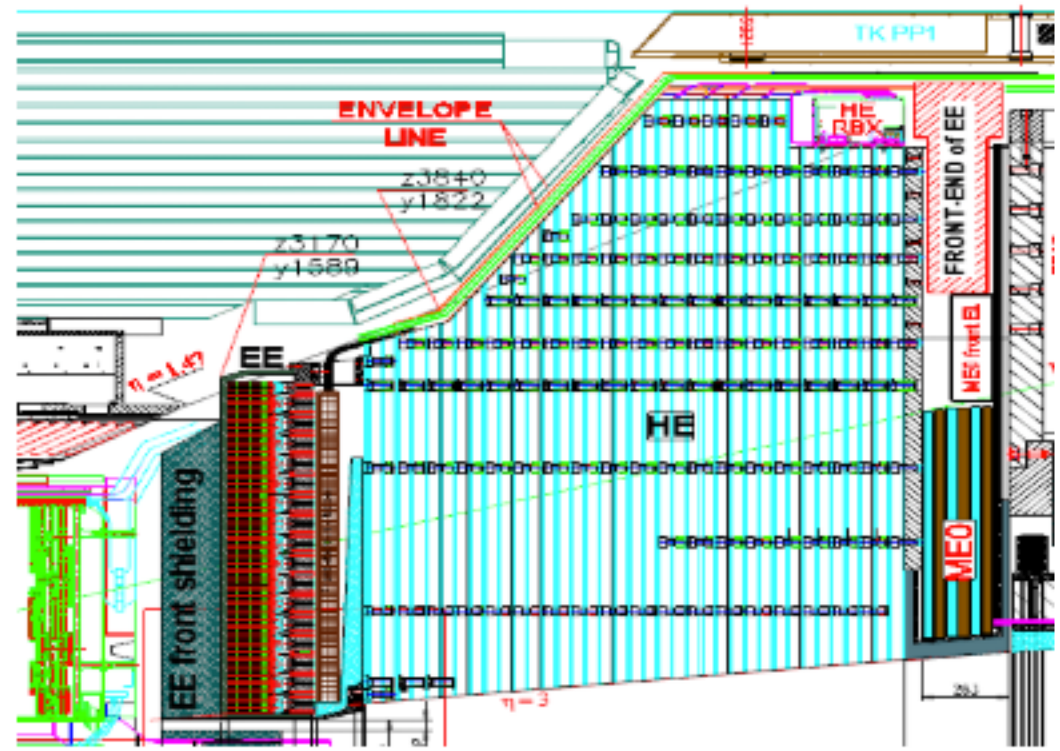
predicted ECAL endcap signal response versus integrated luminosity and η

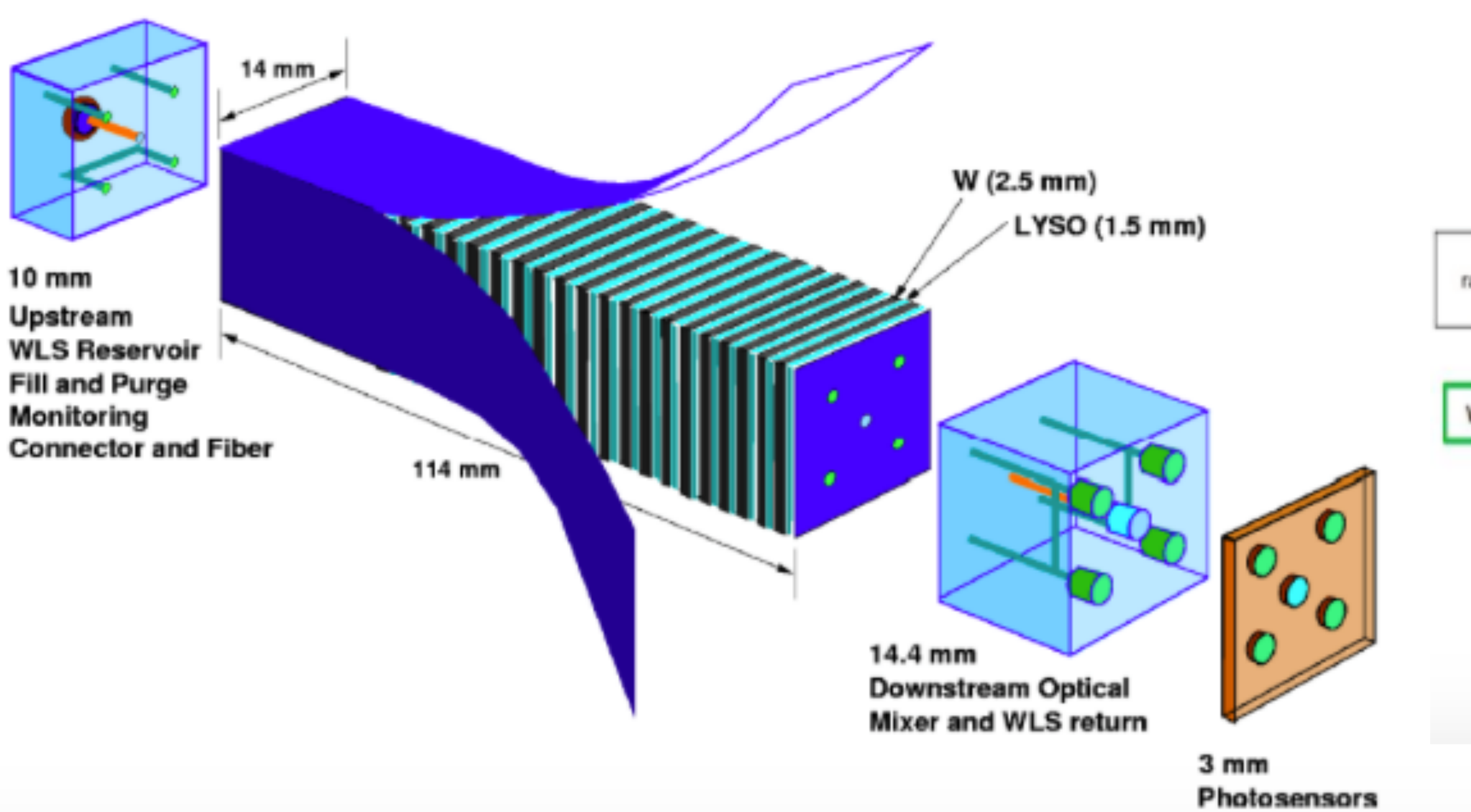


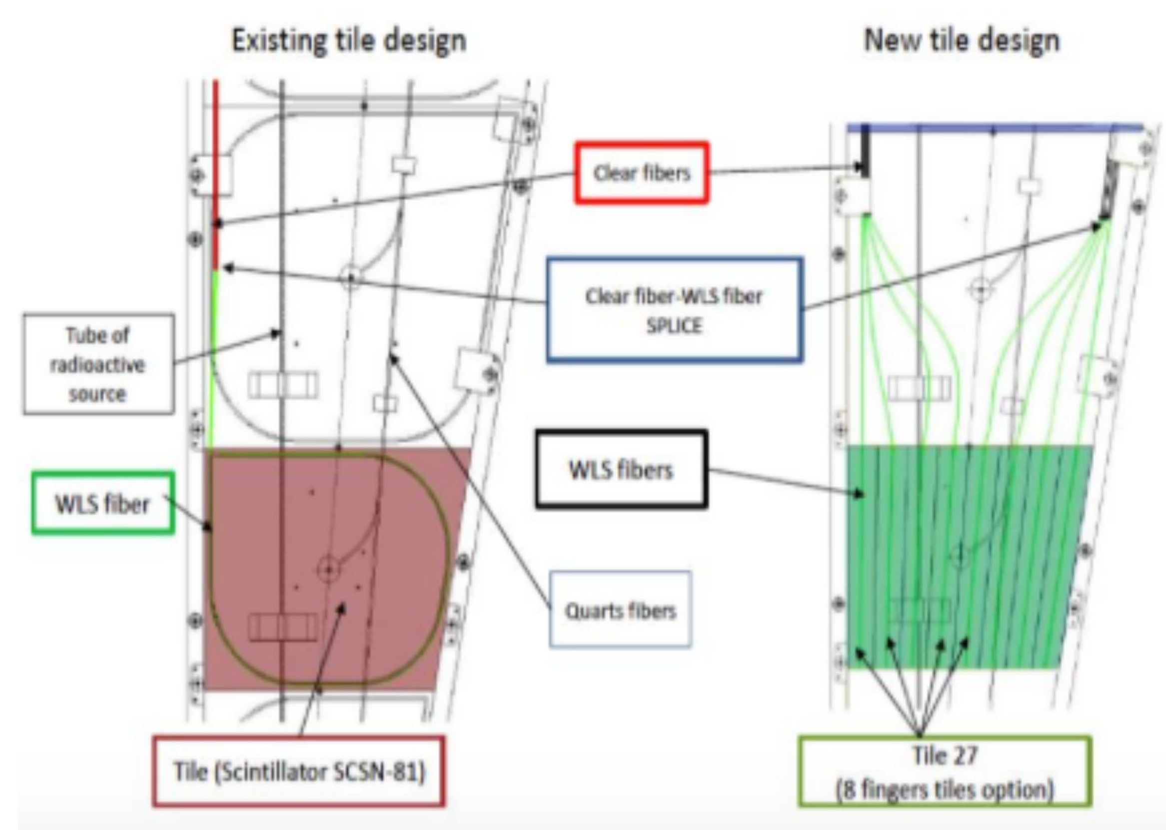
predicted HCAL endcap signal response after 1000 fb^{-1} versus active layer and η

Upgrade concept 1: LYSO e.m. Shashlik + HCAL rebuild

- **Electromagnetic** calorimeter
  - Compact Pb/LYSO Shashlik using WLS based on quartz capillaries and readout using GaInP SiPMs
- **Hadron** calorimeter:
  - Scintillator-based hadron calorimeter with 30% of volume replaced by "finger tiles" and 10% by a solution with higher radiation tolerance

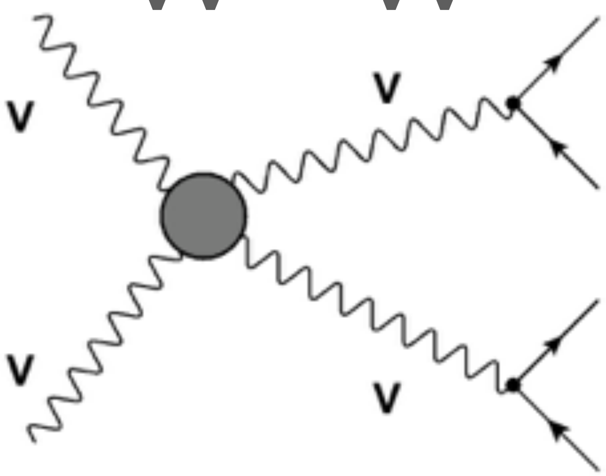


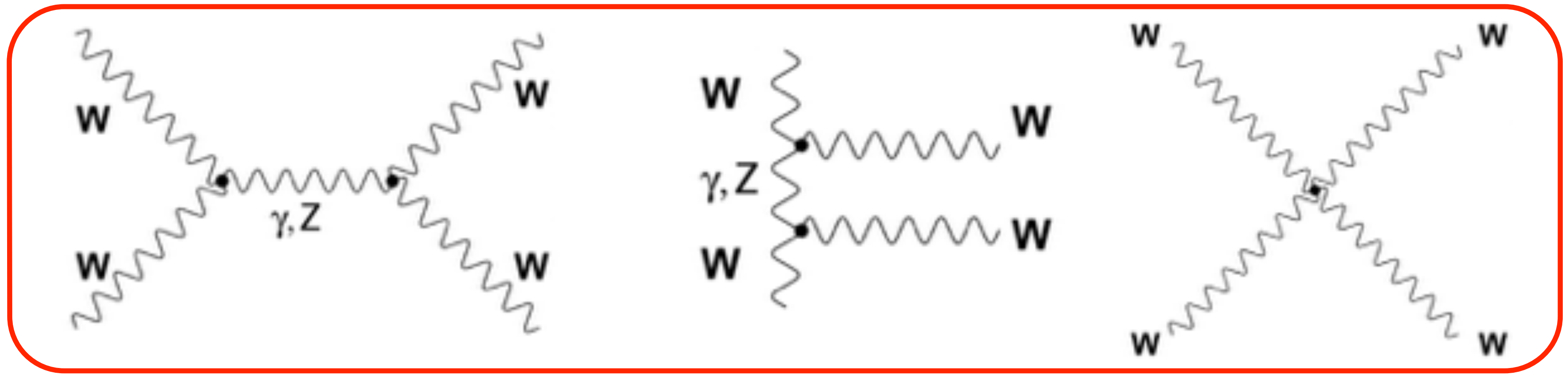




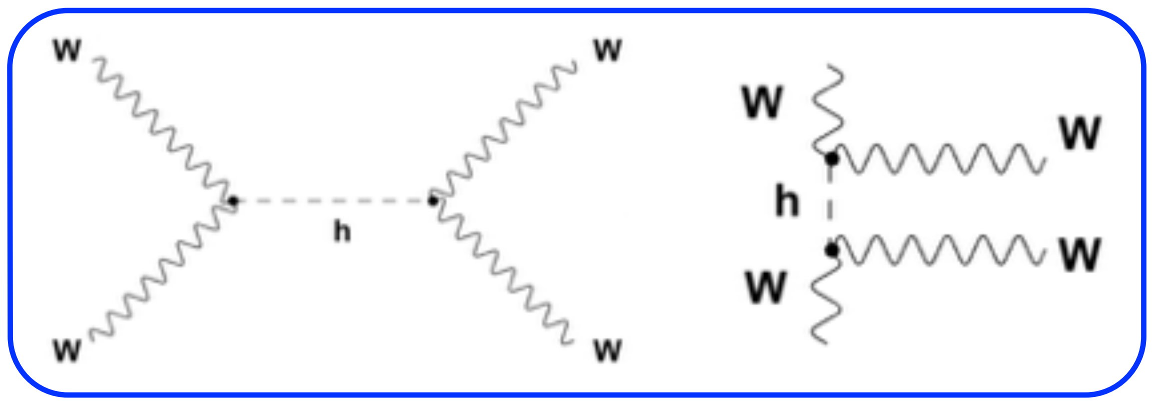
Vector boson scattering: the maths

VV → VV



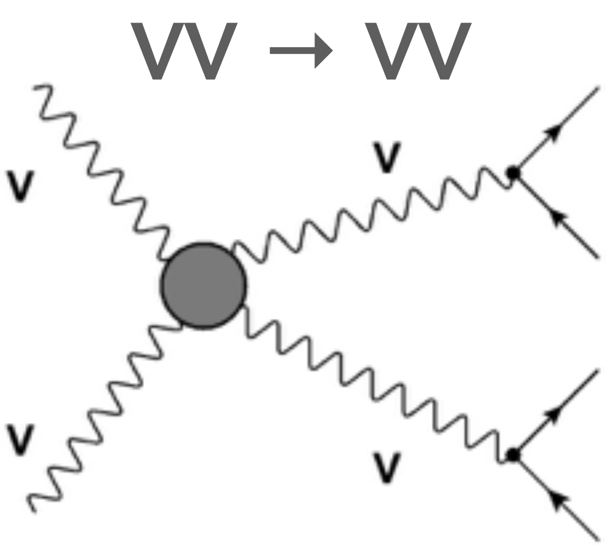


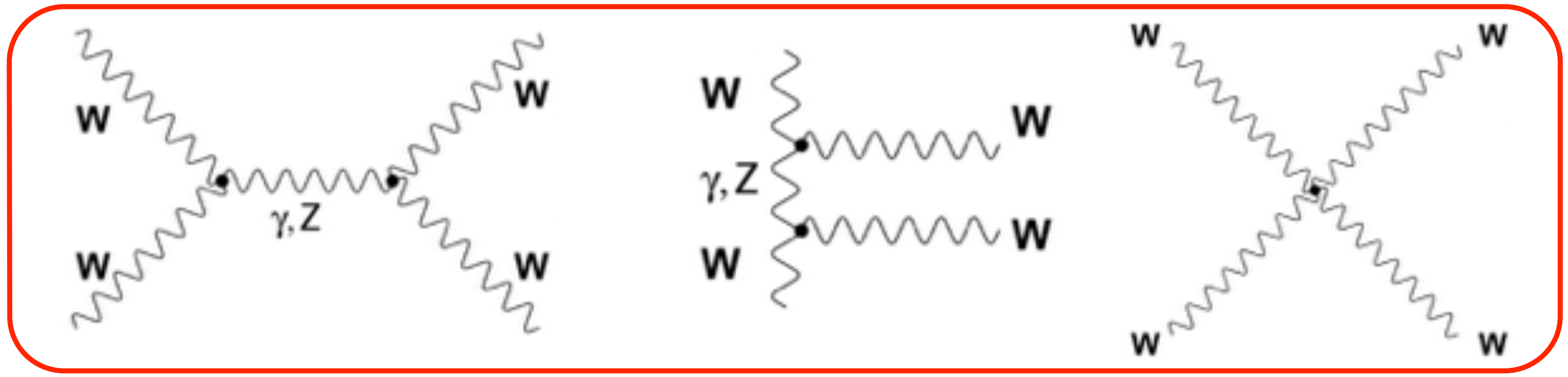
s-channel *t*-channel QGC



only if a Higgs-like particle exists

Vector boson scattering: the maths





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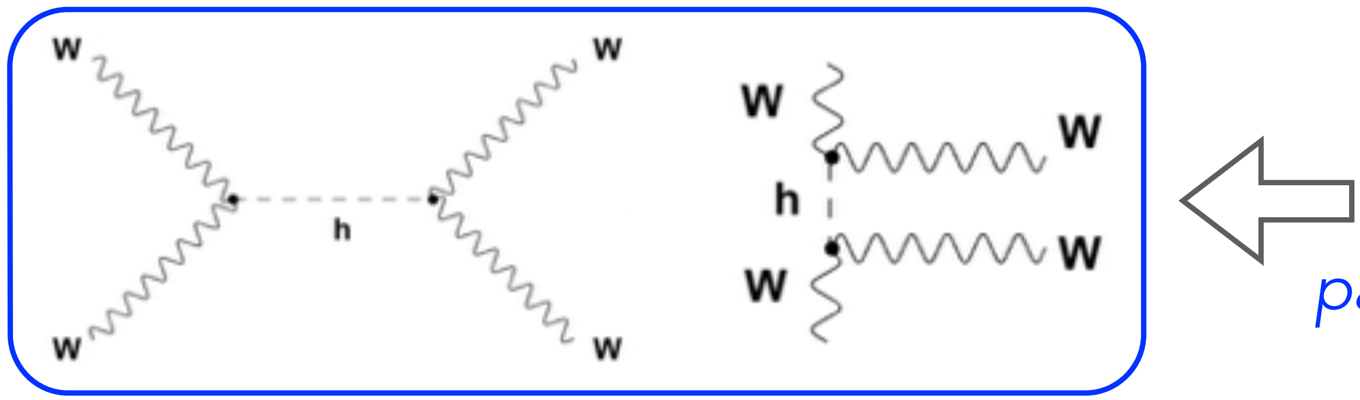

only if a Higgs-like particle exists

Theorists can compute the cross-section (i.e. the probability) of this process:

$$\sigma(W_L^+ W_L^- \to W_L^+ W_L^-) \sim \left(s + t - \left[\frac{s^2}{s - m_H^2} - \frac{t^2}{t - m_H^2} \right] \right)$$

magic trick of the Higgs particle

without the Higgs, $W^+_L W^-_L \to W^+_L W^-_L$ violates unitarity (prob. > 1) at $\sqrt{s} \simeq$ 1.2 TeV