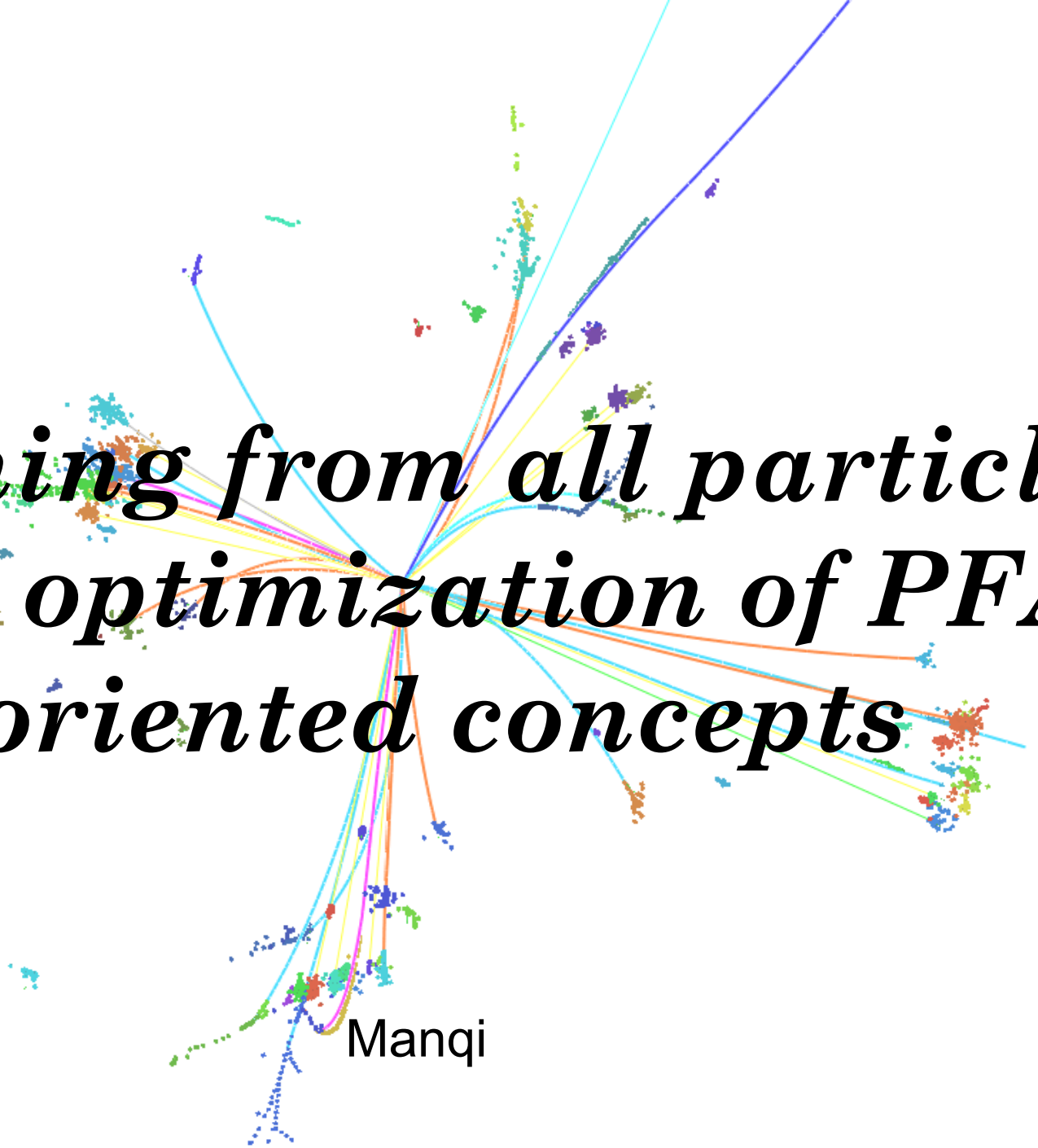
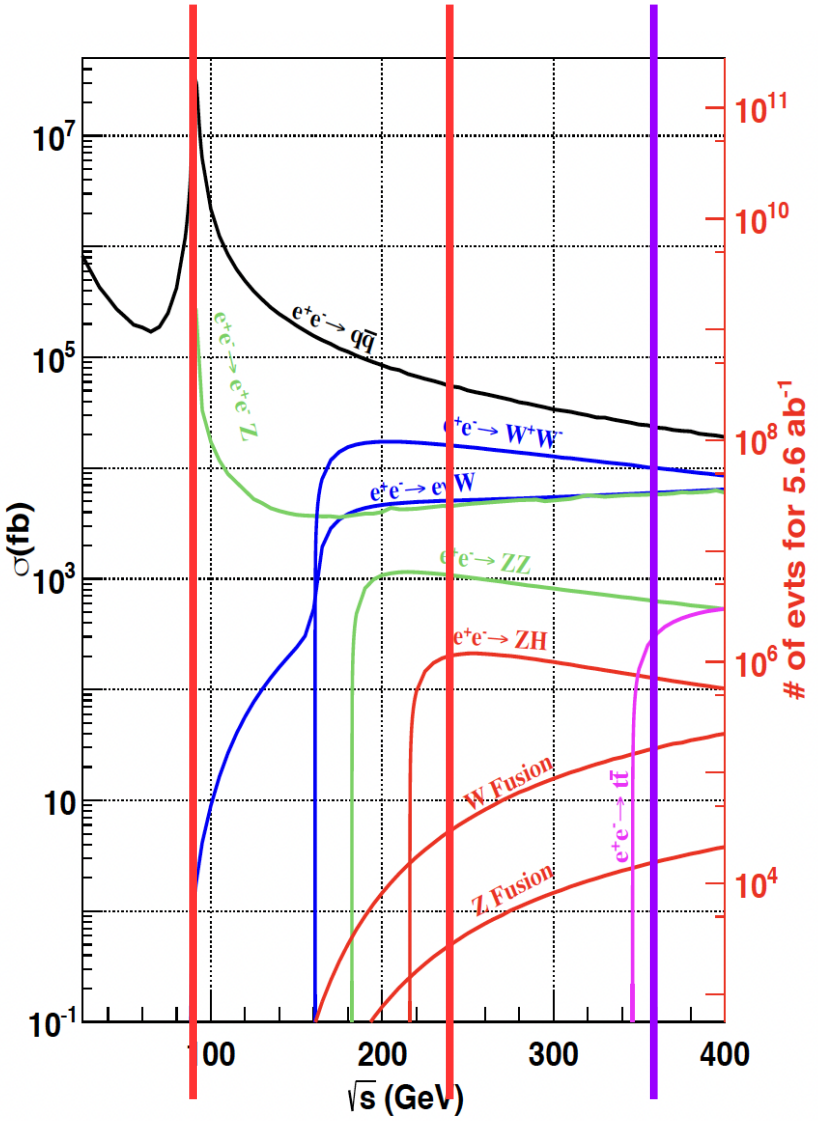
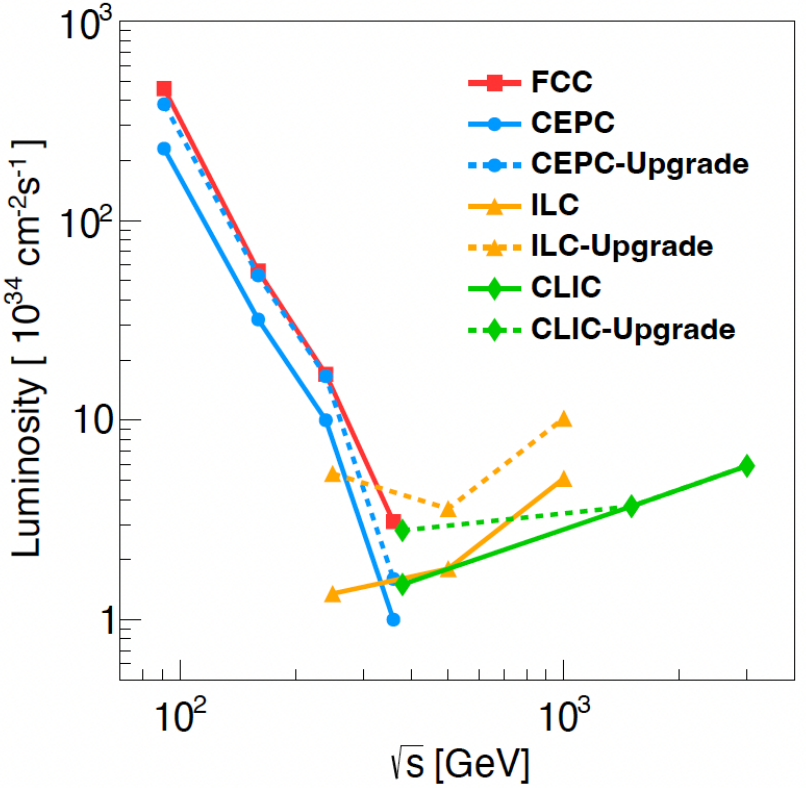


Learning from all particles, and optimization of PFA oriented concepts

Manqi

Yields ~ Xsec * Lumi * Time





- CEPC: 100 km main ring circumference
- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

Physics metrics

- ~ 500 Citables (inspire)
- Higgs: 2019, CPC
- ESPPU input: 2019 ArXiv
- Snowmass input: 2022 ArXiv
- **Flavor physics: 2025, CPC**
- **New physics: 2025 CPC**
- **Current focus**
  - **EW White paper**
  - **QCD studies**
  - Reco & Det. Optimization
  - **…**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Precision Higgs physics at the CEPC*

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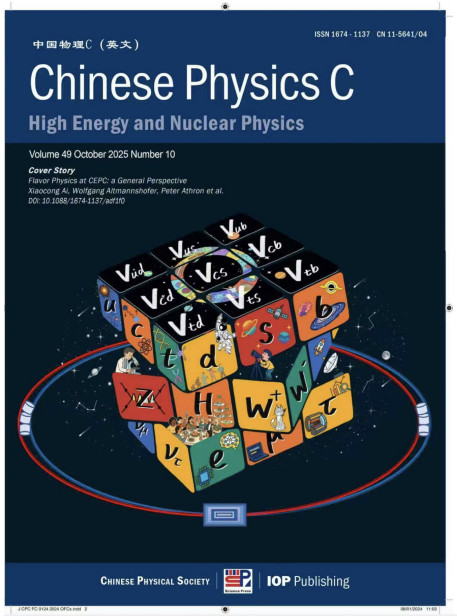
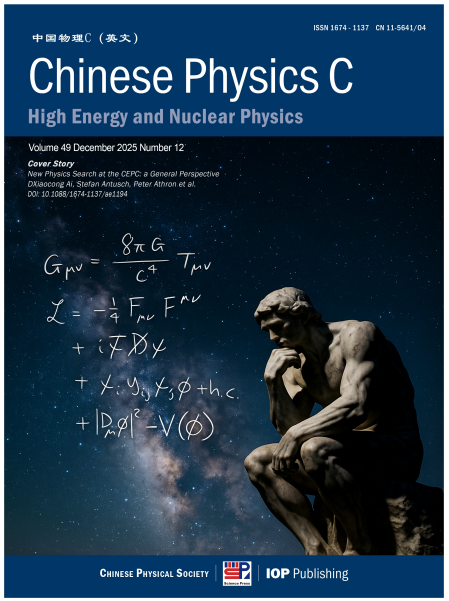
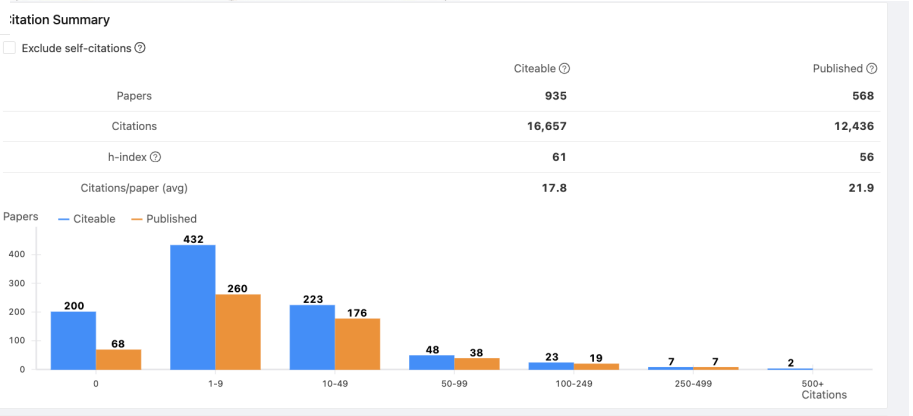
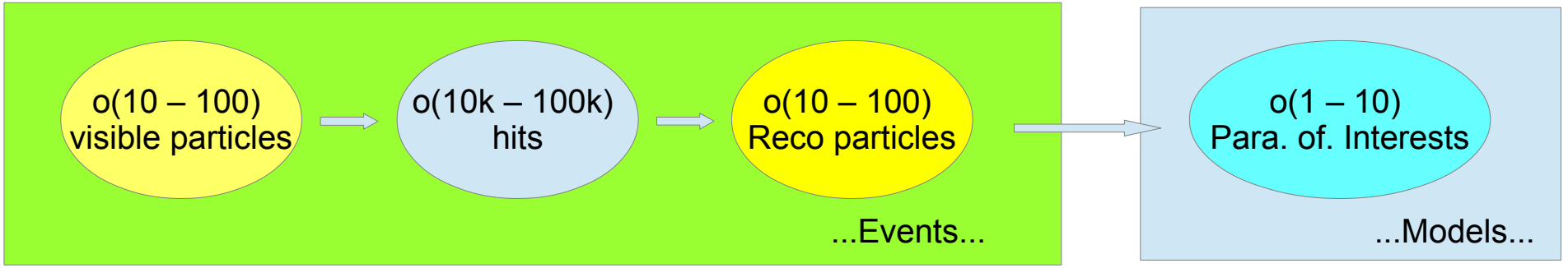


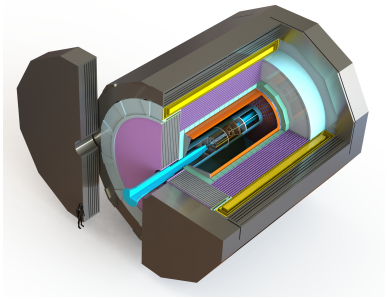


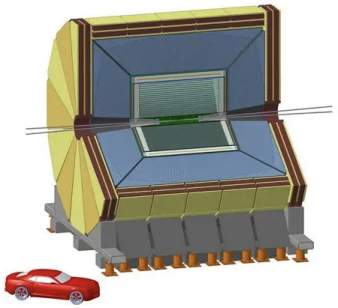


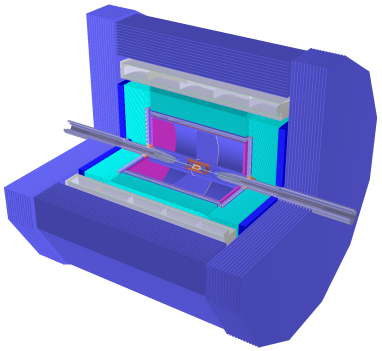
- *Boost horizon by orders of magnitudes*
  Address/answers profound mysteries: mass/matter origin, nature of Dark Matter, Phase Transitions, evolution and fate of the Universe...

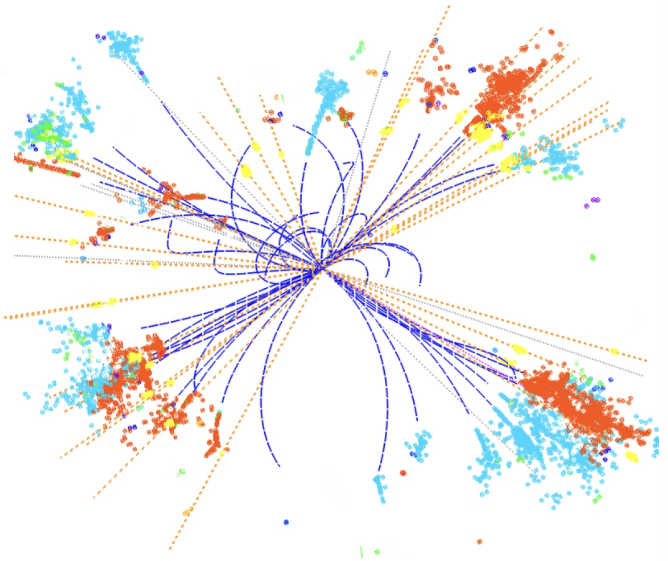
Information flow

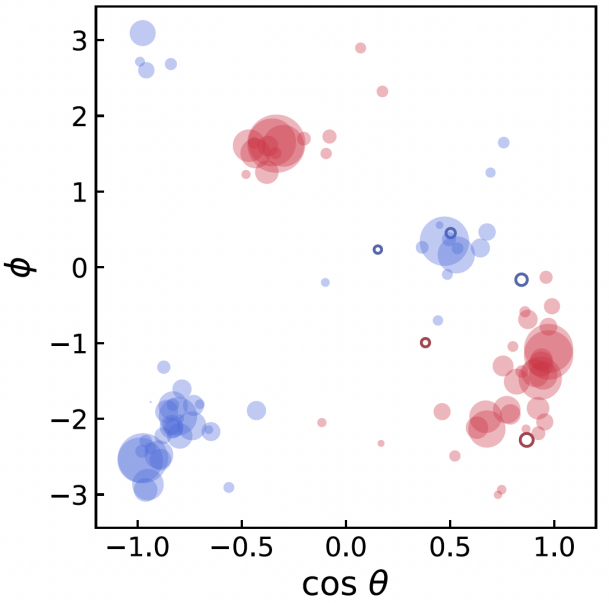




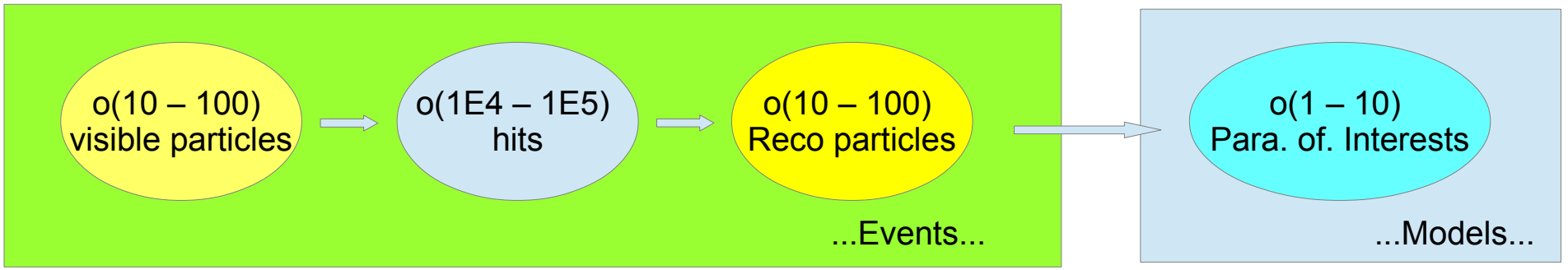








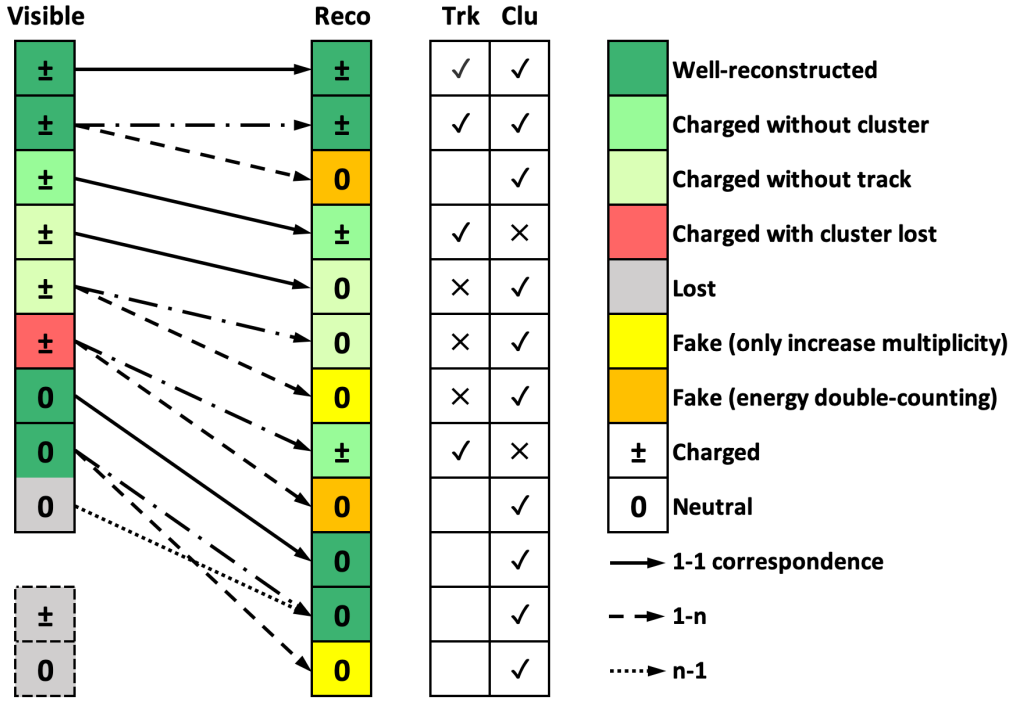
Learning from all particles

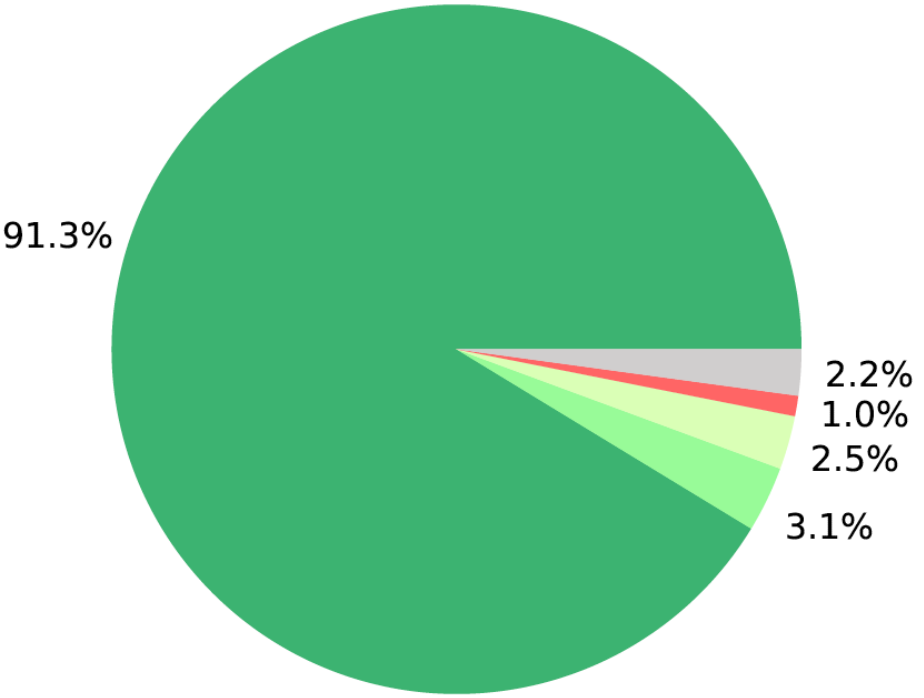


- Reconstructed particles quality...: **1-1 correspondence reco + detector design**

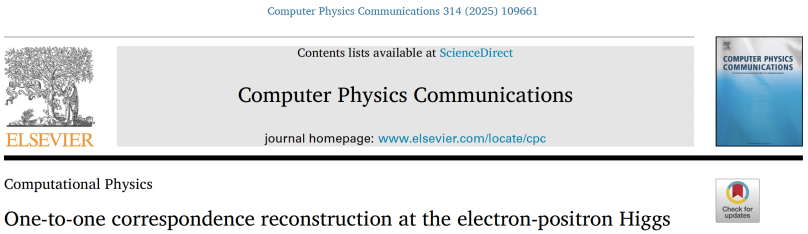
- **Holistic approach** using all reco particles
  - Physics object reconstruction: Jet origin id
  - Identifying the nature of physics events: Signal & Backgrounds
  - Advanced color singlet identification
  - ...

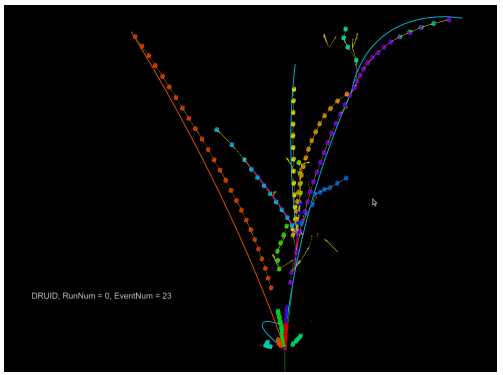
1-1 correspondence reconstruction

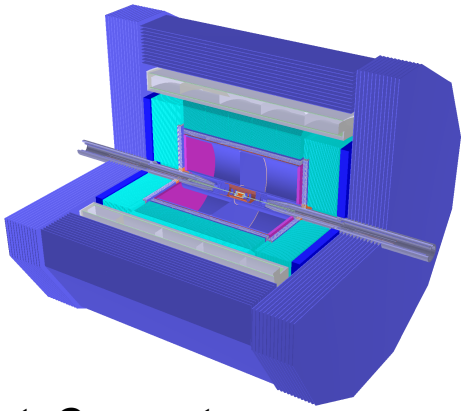




https://arxiv.org/abs/2411.06939

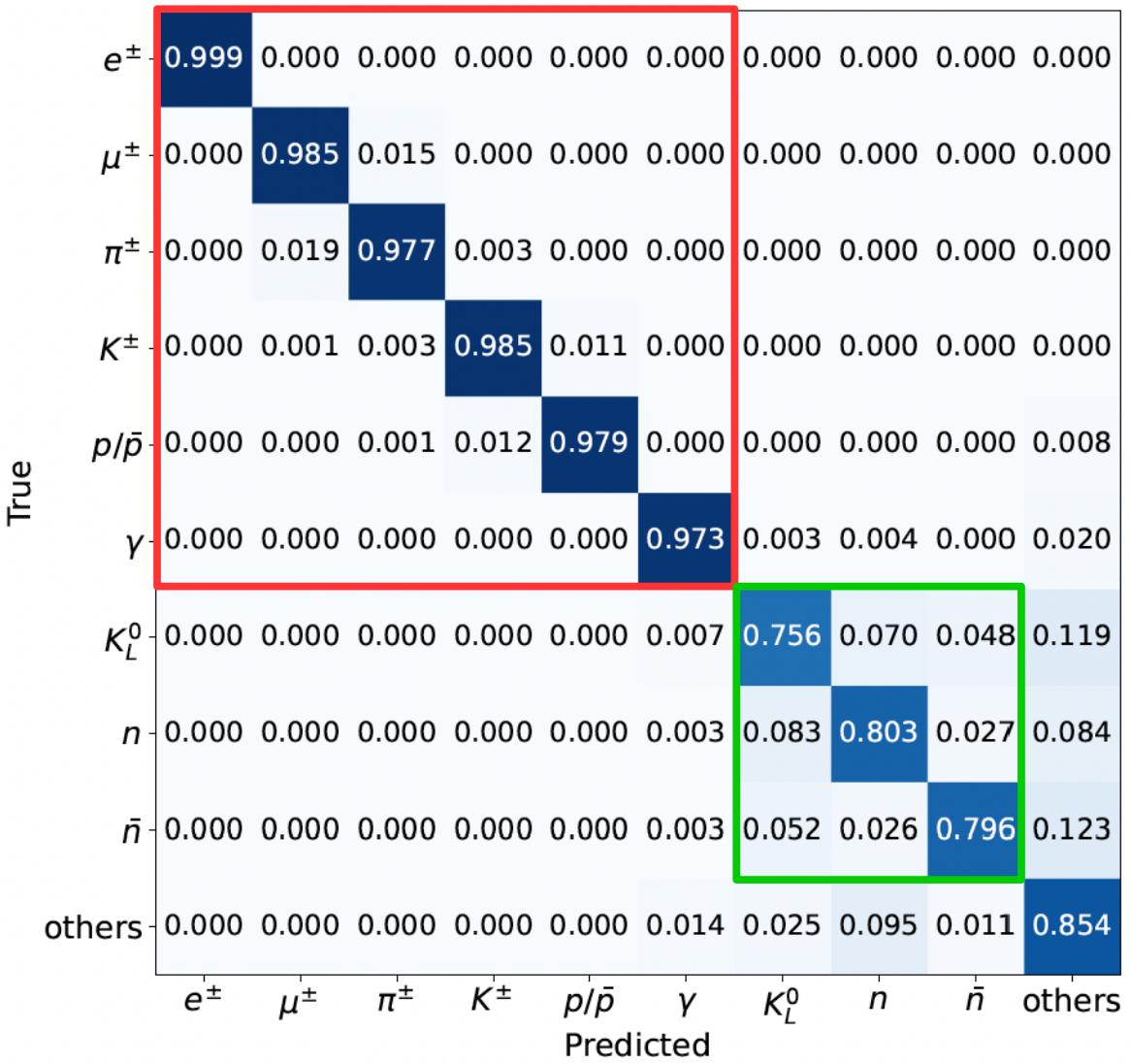


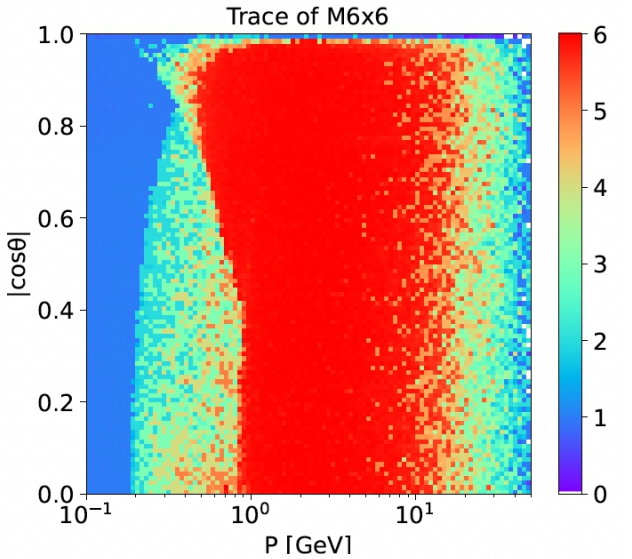


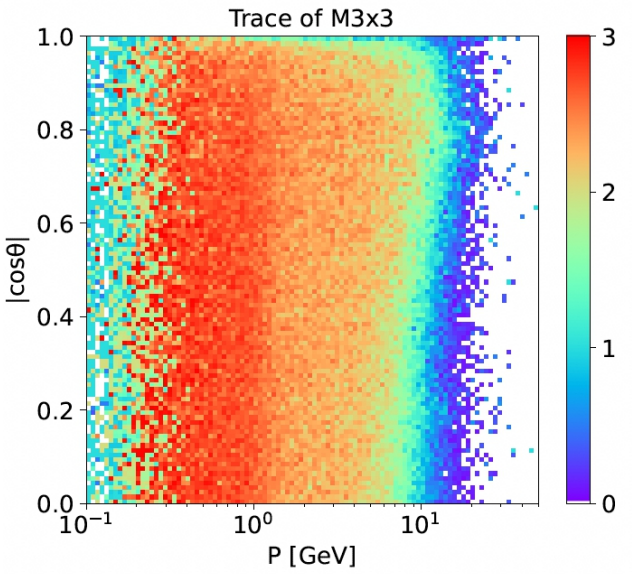


AURORA det. Concept with 5d calo.

Pid: differential performance

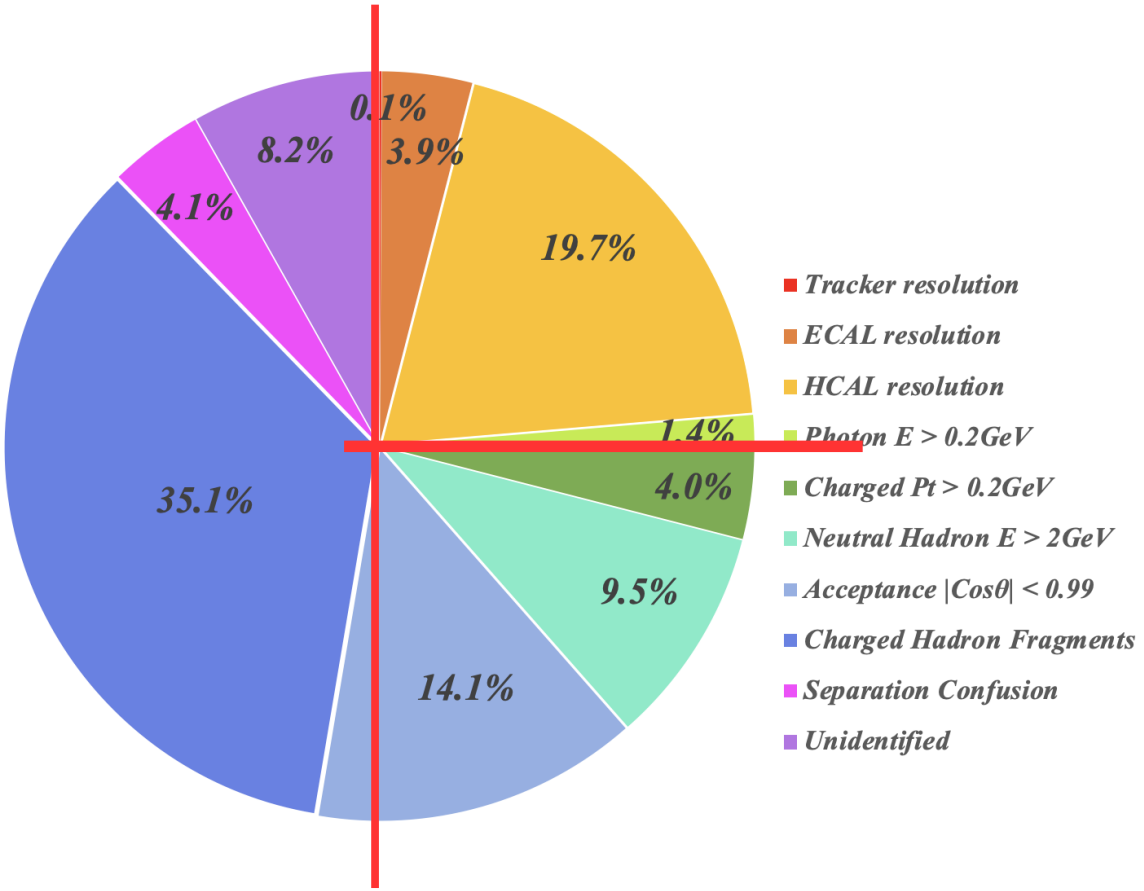


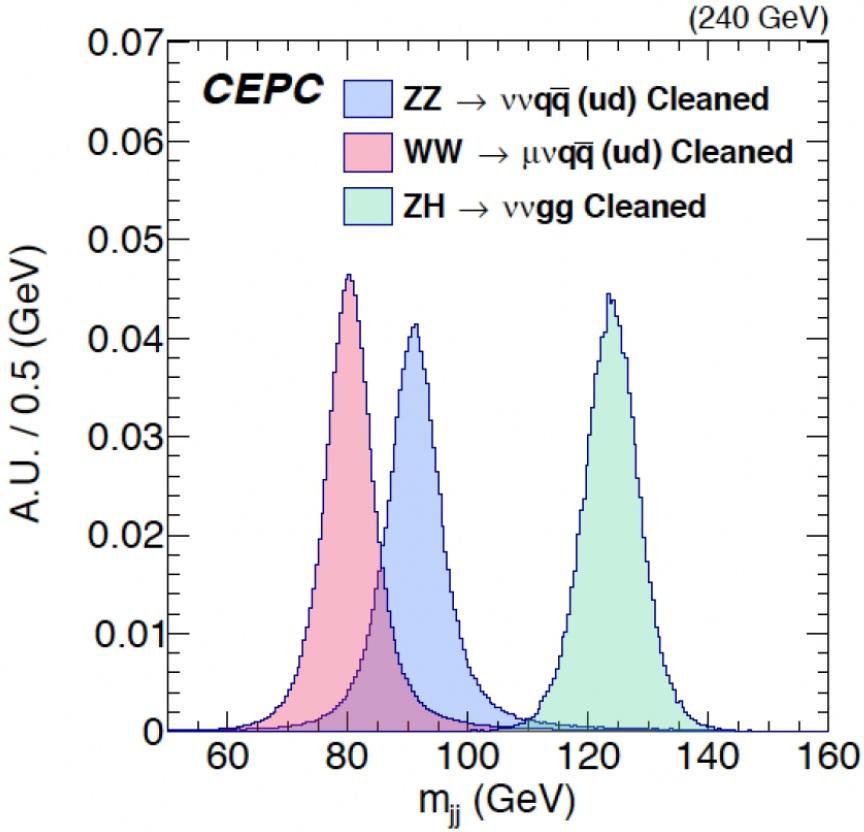




Neutral Hadron ID: 5d Calorimetry with ToF capability (δt~100 ps/hit)

BMR & Decomposition



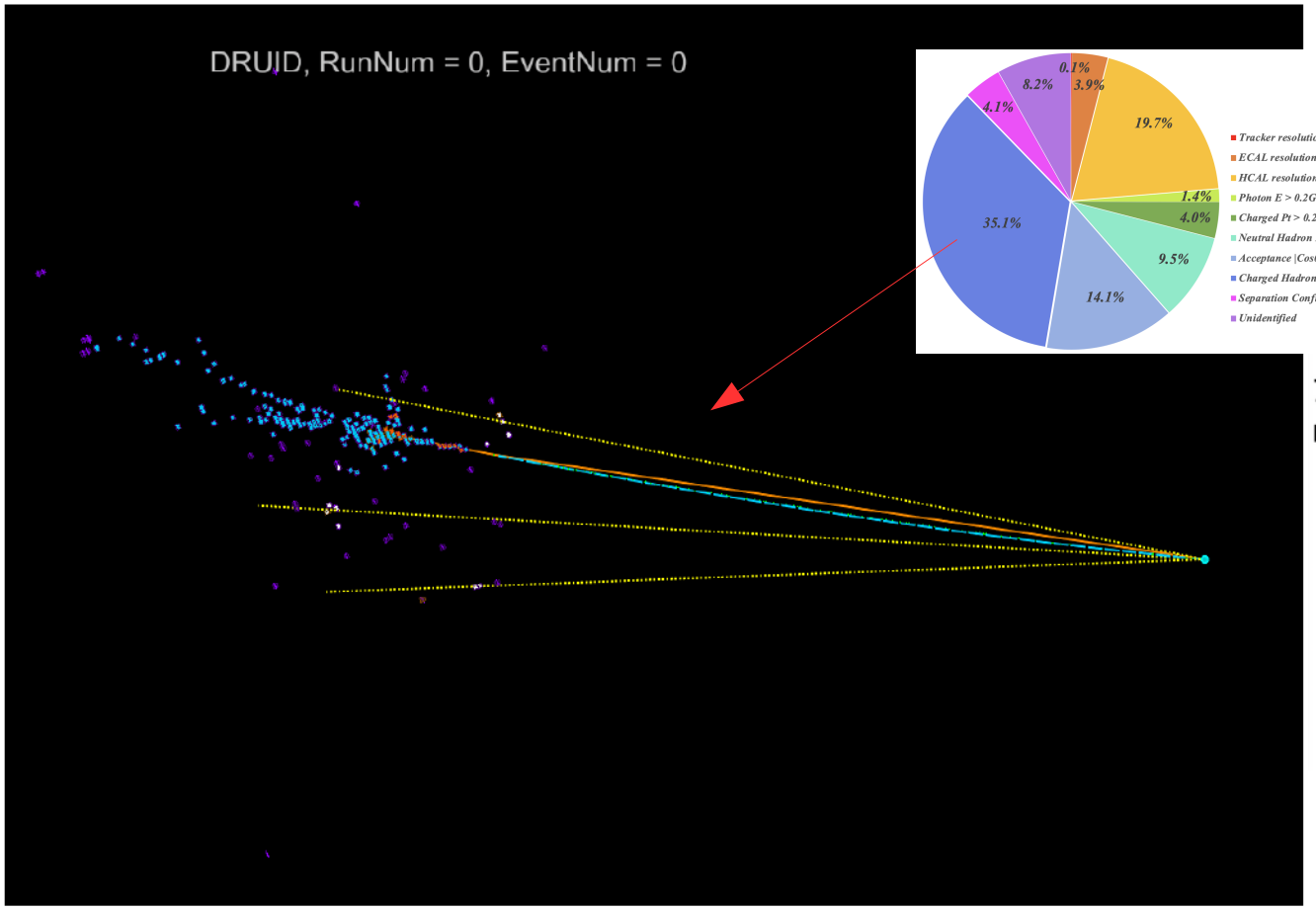


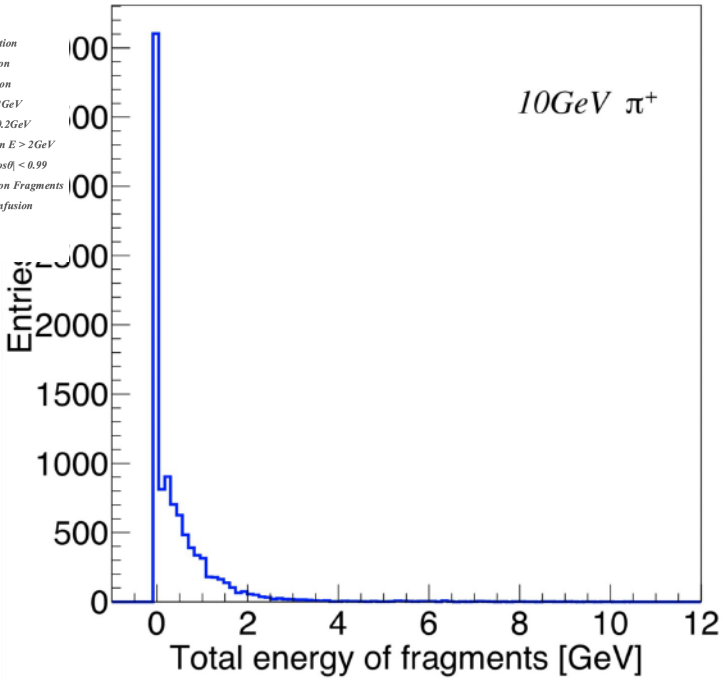
CEPC CDR baseline: TPC + SiW ECAL + RPC HCAL, BMR of 3.8%

Confusion & Acceptance & Intrinsic Resolution: 50%, 25%, 25%

Key contributions: Fragments (leading confusion) & Intrinsic HCAL resolution

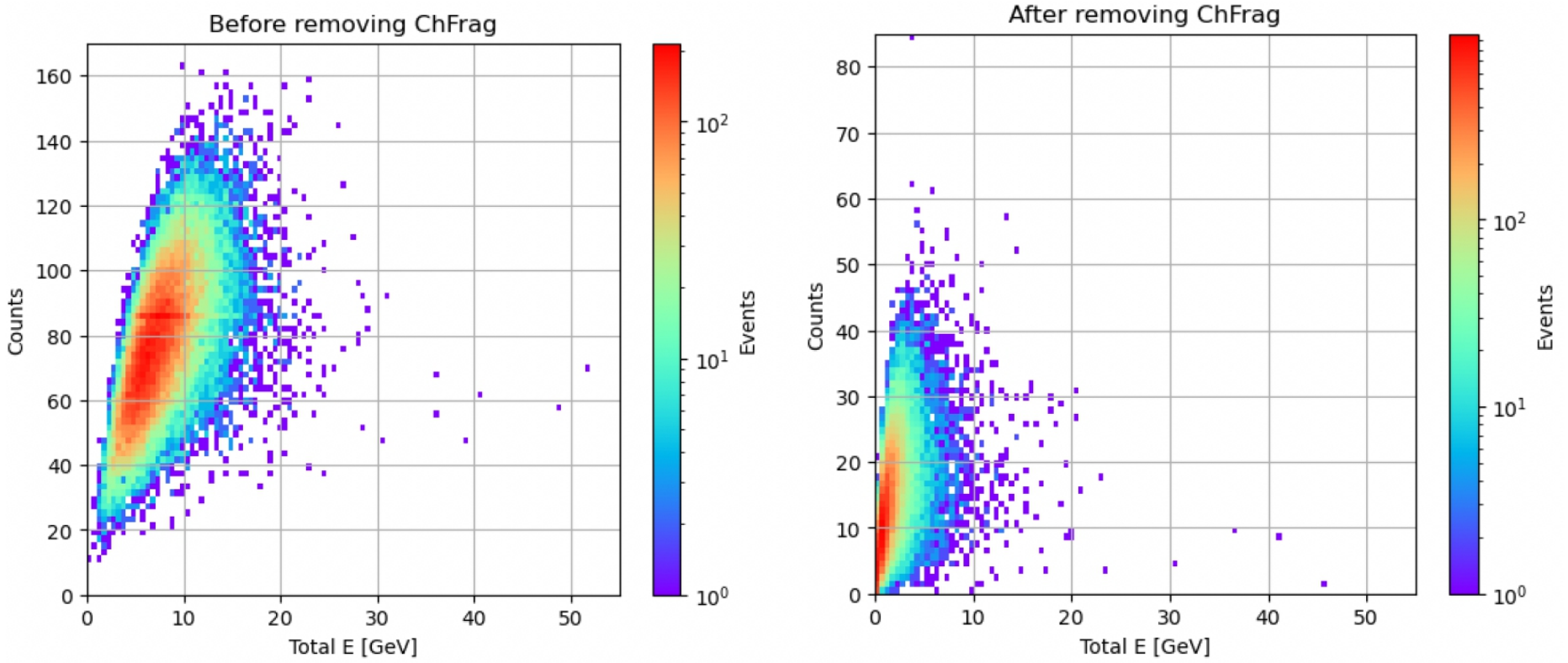
Cluster splitting: the most severe confusions





Time/pattern recognition may help a lot, in identify the charged cluster fragmentations without arise the threshold for the neutral hadron significantly...

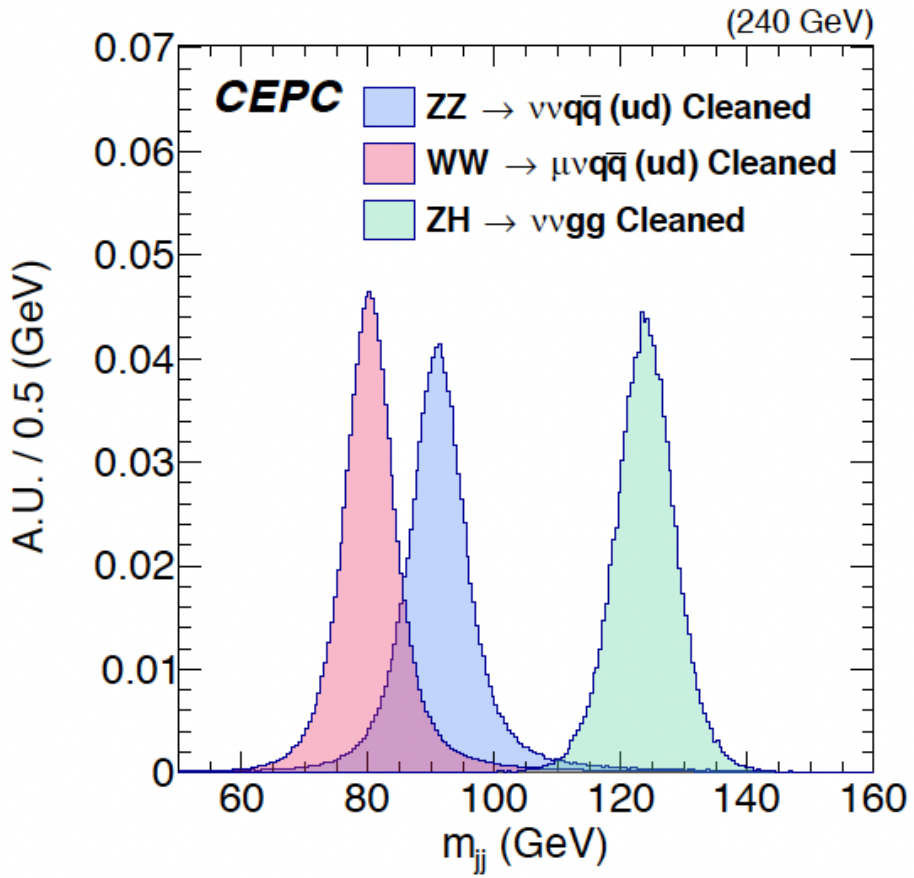
Confusion: frag. Identification & veto

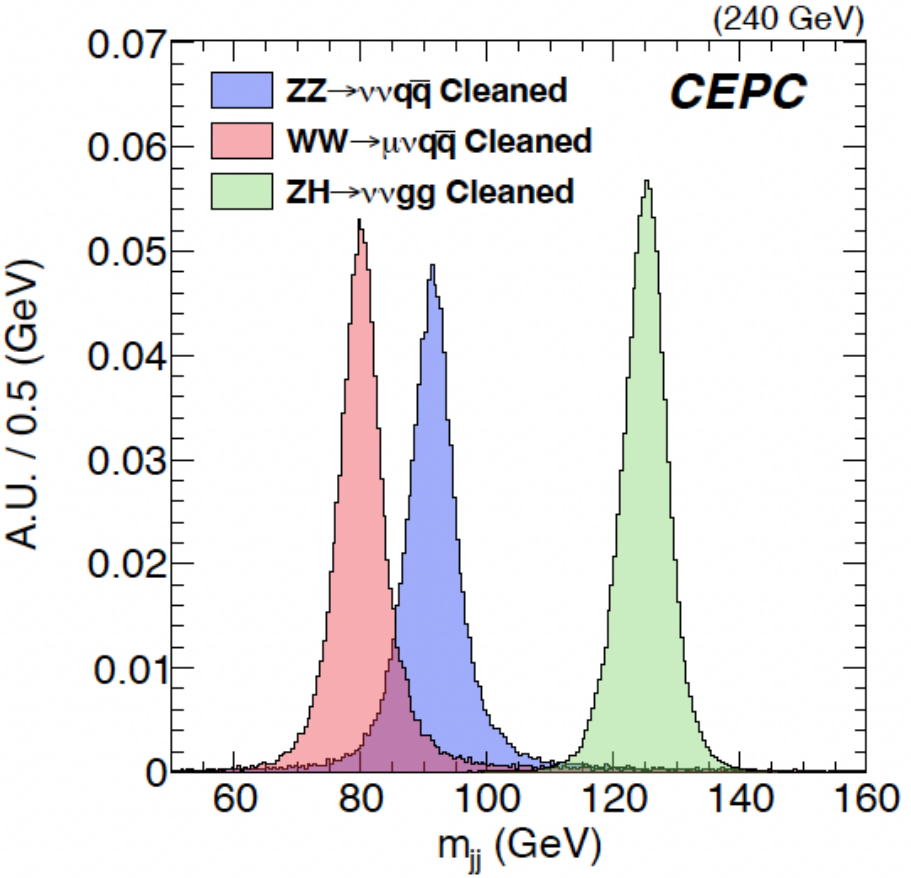


Fake particle originated Confusion reduced by 1 order of magnitude, at nominal vvH, H→gg event, at the cost of create mis-vetoed energy of < 1 GeV.

Frag Total Energy (MPV/Mean): 6.3/7.6 GeV → 0.7/1.4 GeV

BMR of 2.7% reached



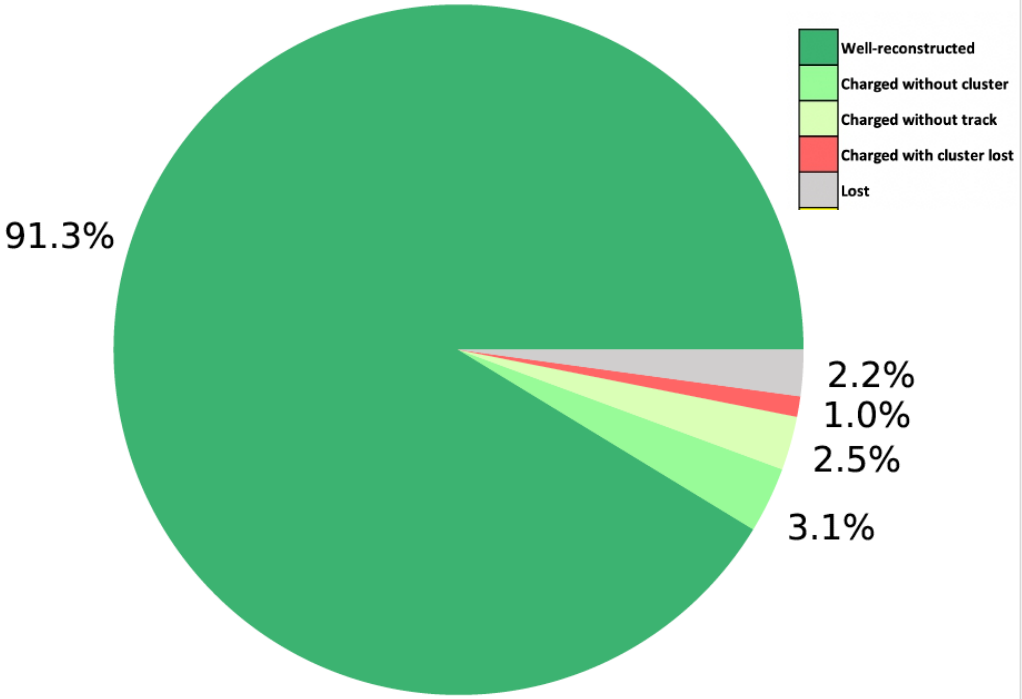


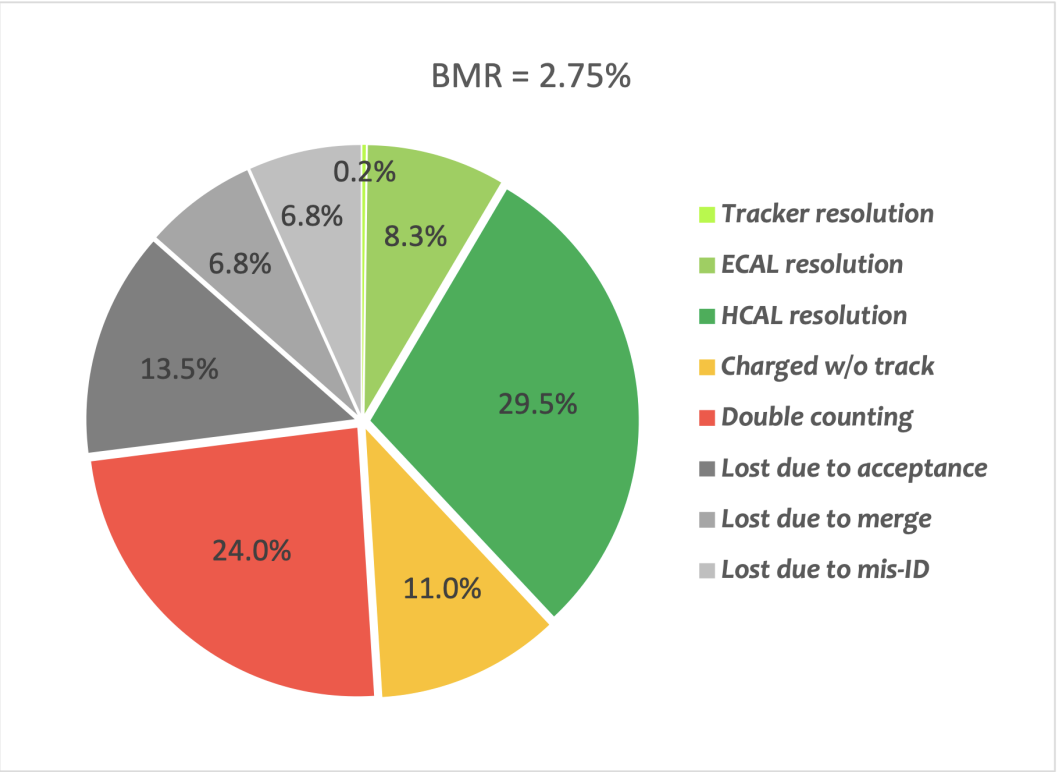
Detector change (usage of high density scintillating glass HCAL): BMR 3.7% → 3.4%;

AI enhanced reconstruction: 3.4% → 2.8%.

Recent update: further optimization + Pid, etc, current value ~2.6%

BMR decomposition @ AURORA



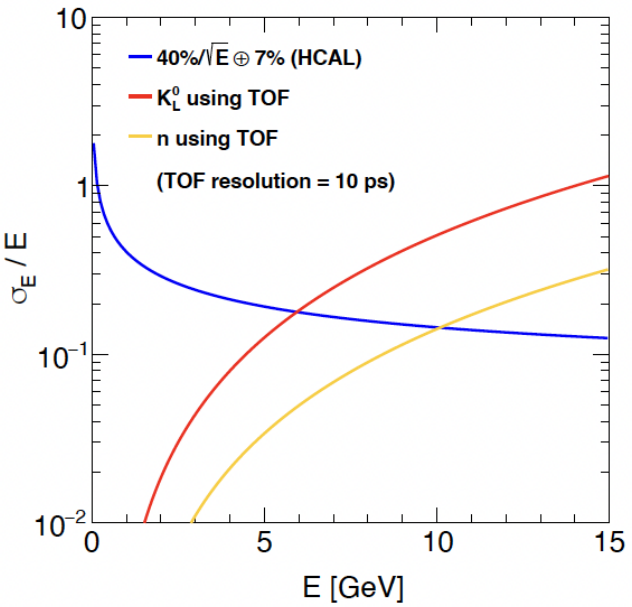


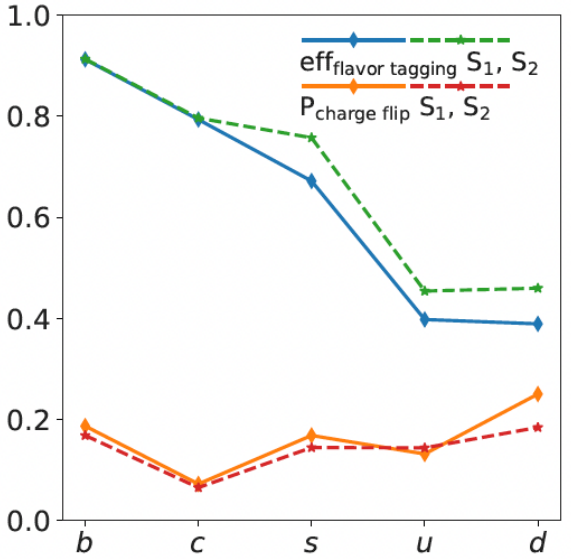
1-1 corresponding type: contributing to the BMR via resolution: ~o(0.1 – 0.001) of its mean value

Double Counting & Lost type: contributing to the BMR ~o(1) to its mean value

Perspectives with 1-1 correspondence

Jet (hadronic events) with Calo	Jet with PFA Charged in Tracker Neutral in Calo	Jet with 1-1 Charged in Tracker + **ToF** Neutral in Calo + **ToF**

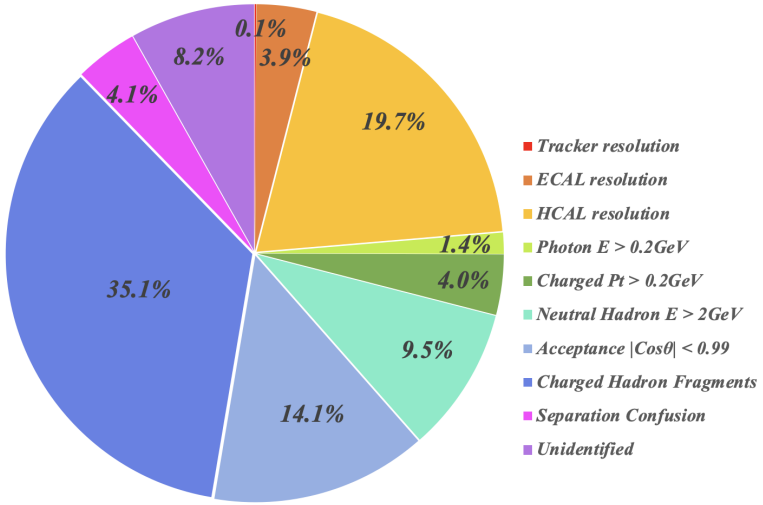




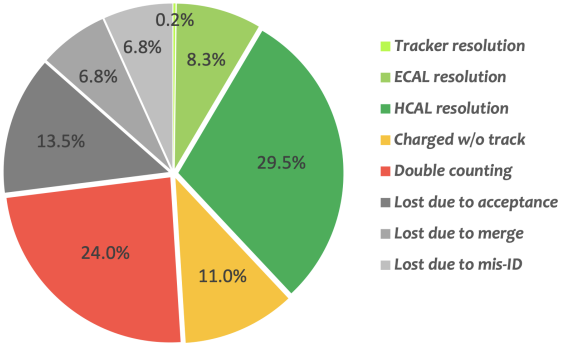
- 5d calo is critical: ToF for all visible particle, thus Pid...
  - Assume Low energy neutrons & secondary particles can be tamed... still challenge...

BMR decomposition & evolution...

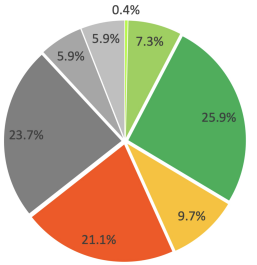
2016 - CDR: BMR ~ 4%

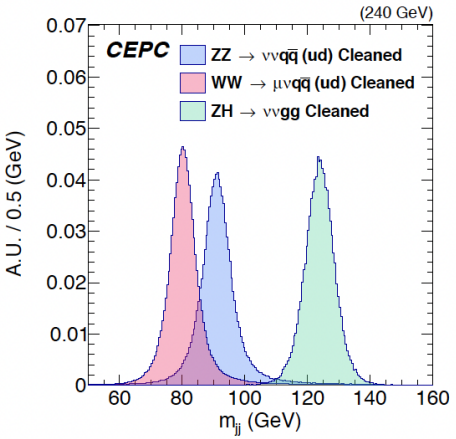


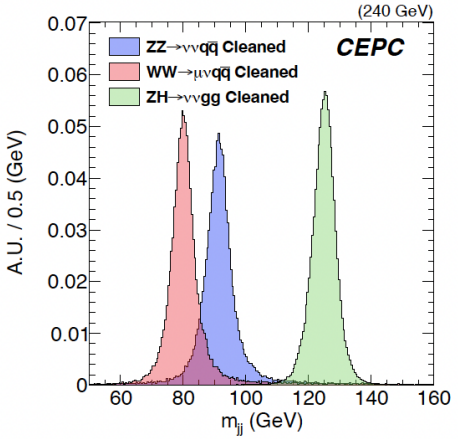
2024 - AURORA: BMR ~ 2.7%

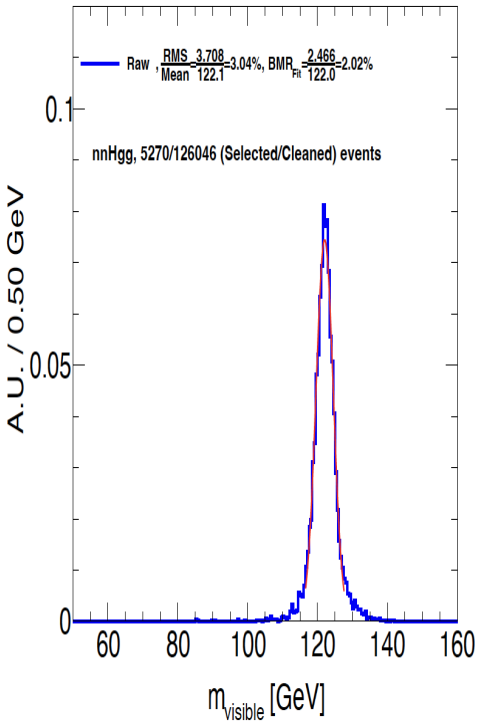


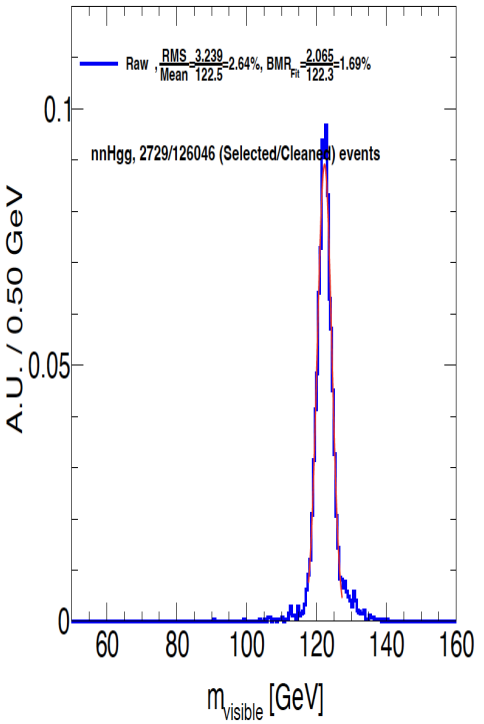
Future: BMR ~ 2.0%



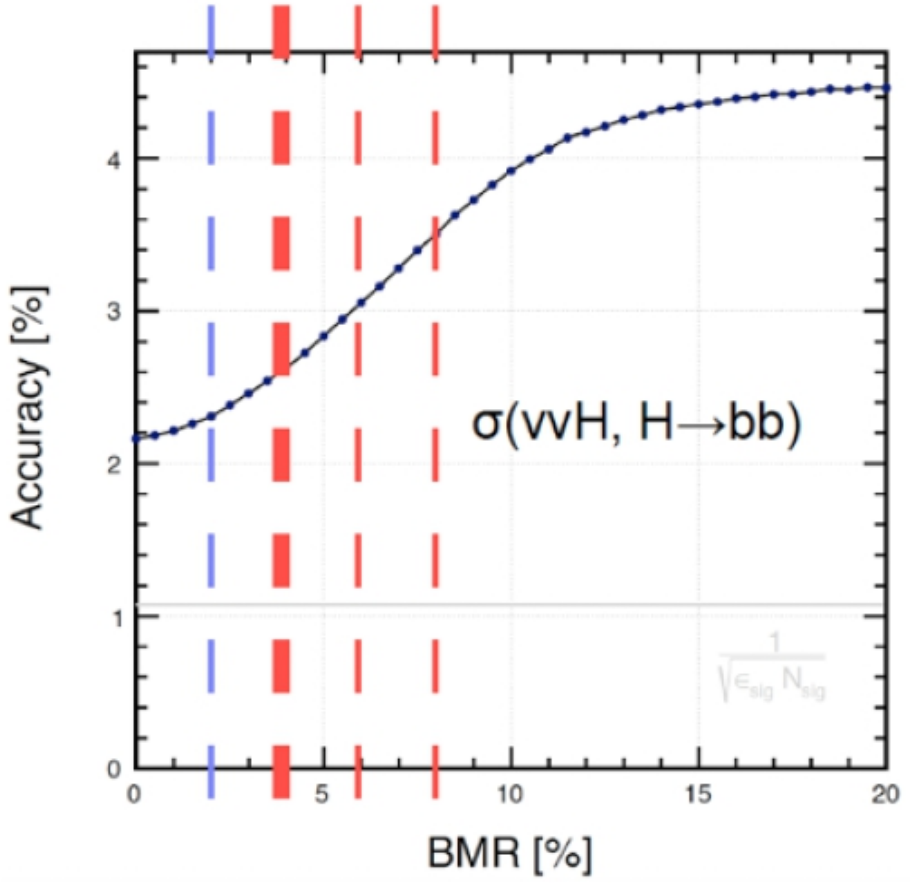


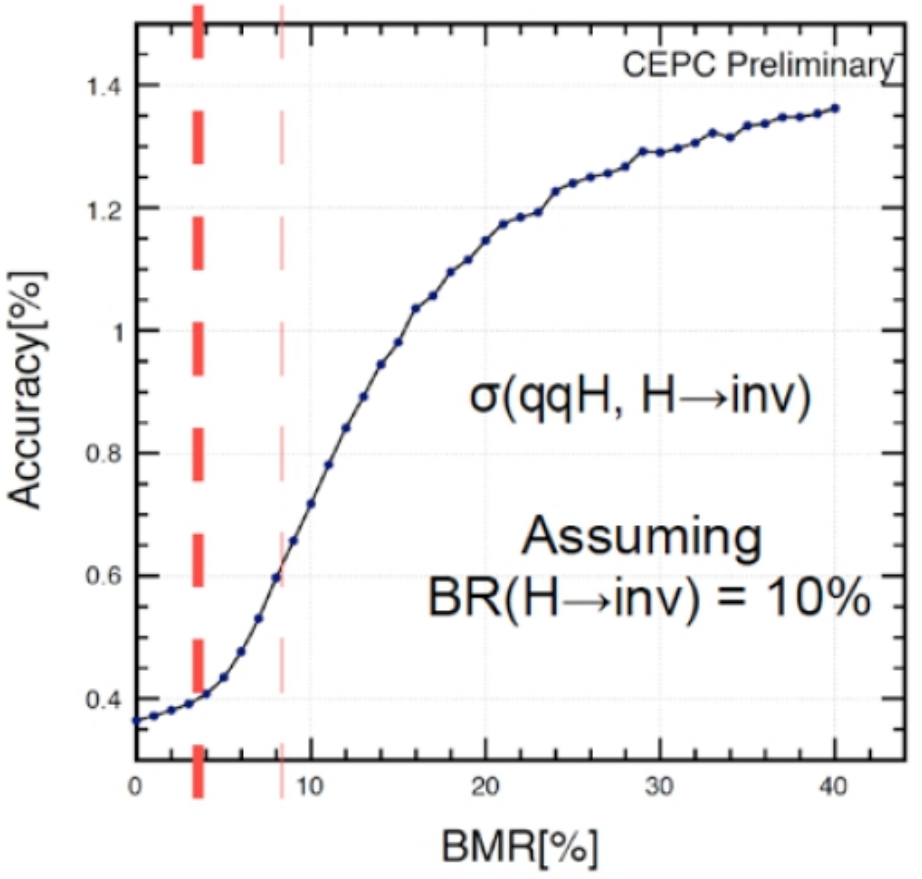






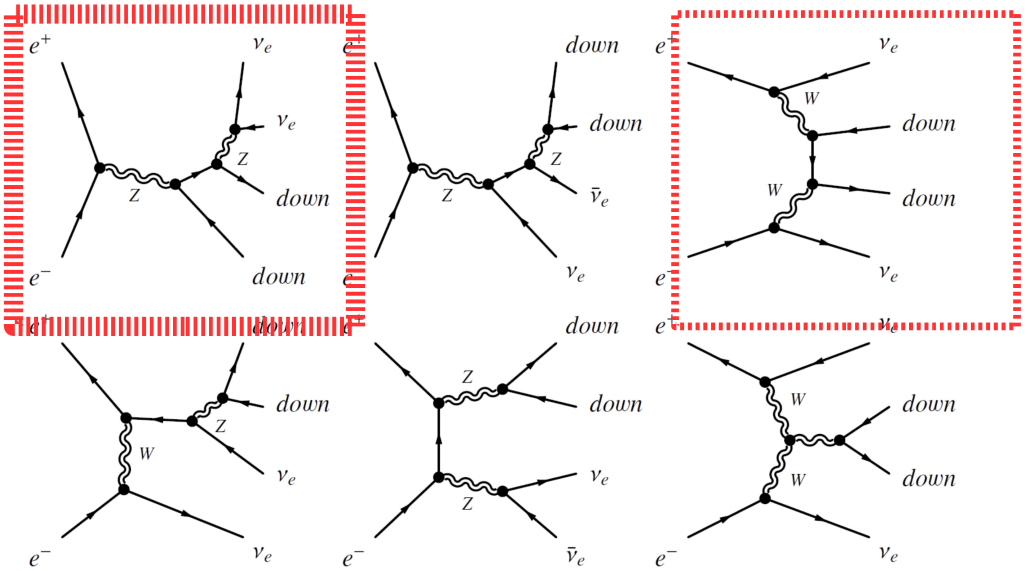
Impact on physics benchmarks...

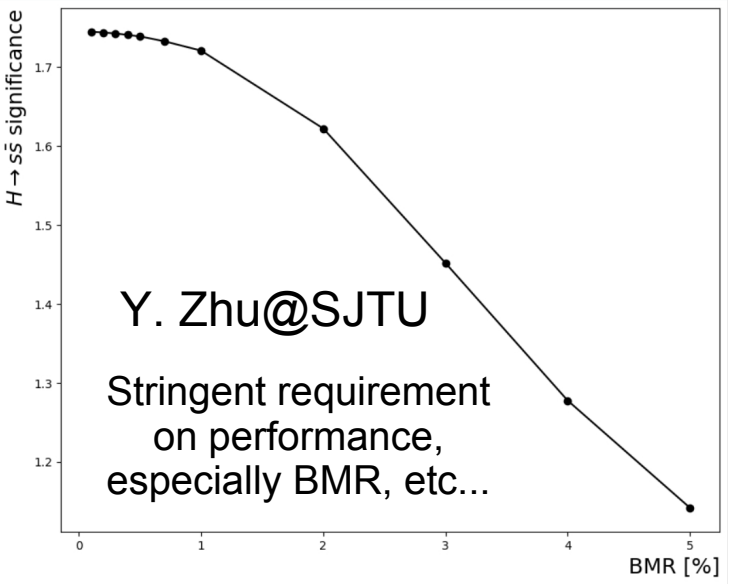


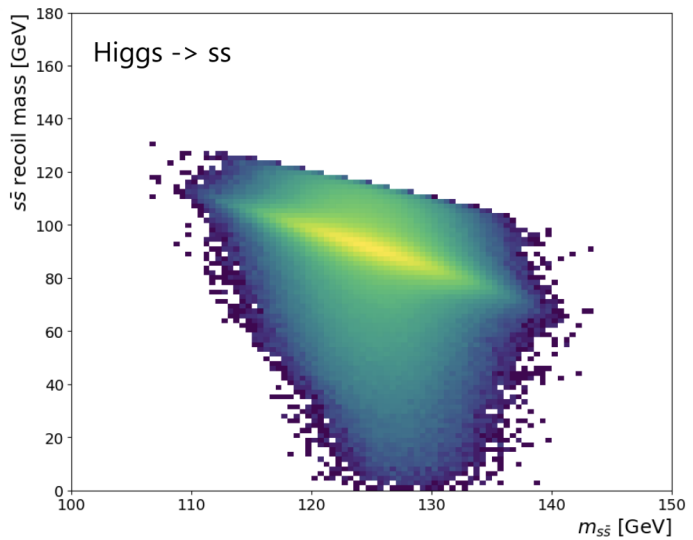


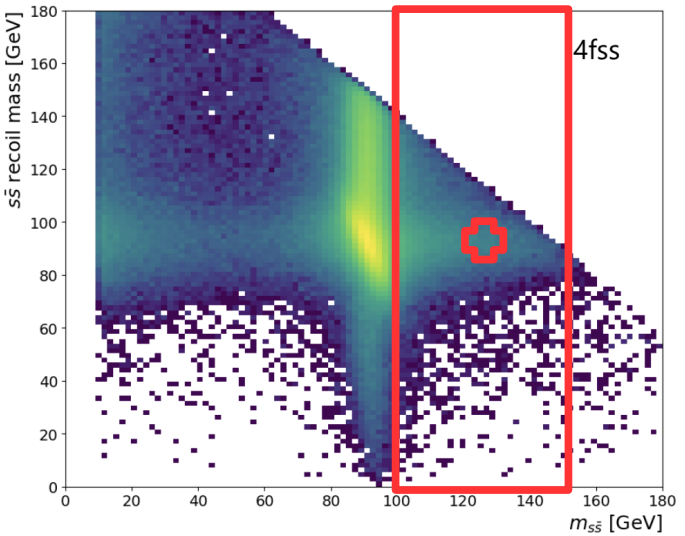
Accuracies of Higgs measurements improved by ~ o(10%) with conventional analysis...
Critical for g(HZZ) & new physics detection...
Personal Anticipation: larger impact with sophisticated Analysis, i.e., holistic analysis.

H→ss : anticipated 3-8 sigmas

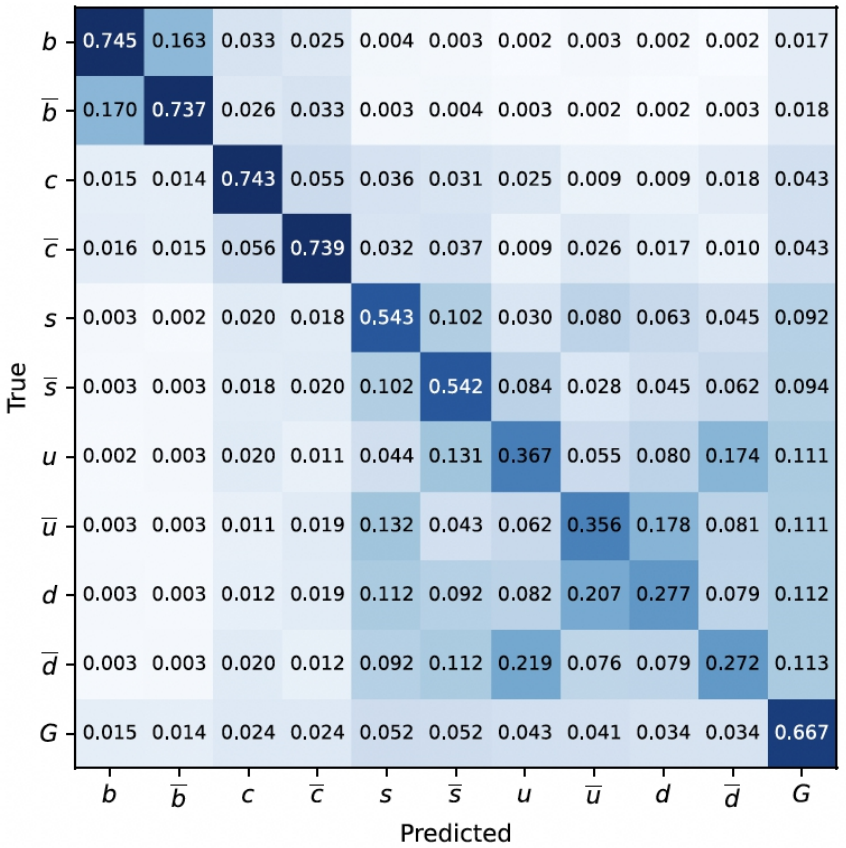


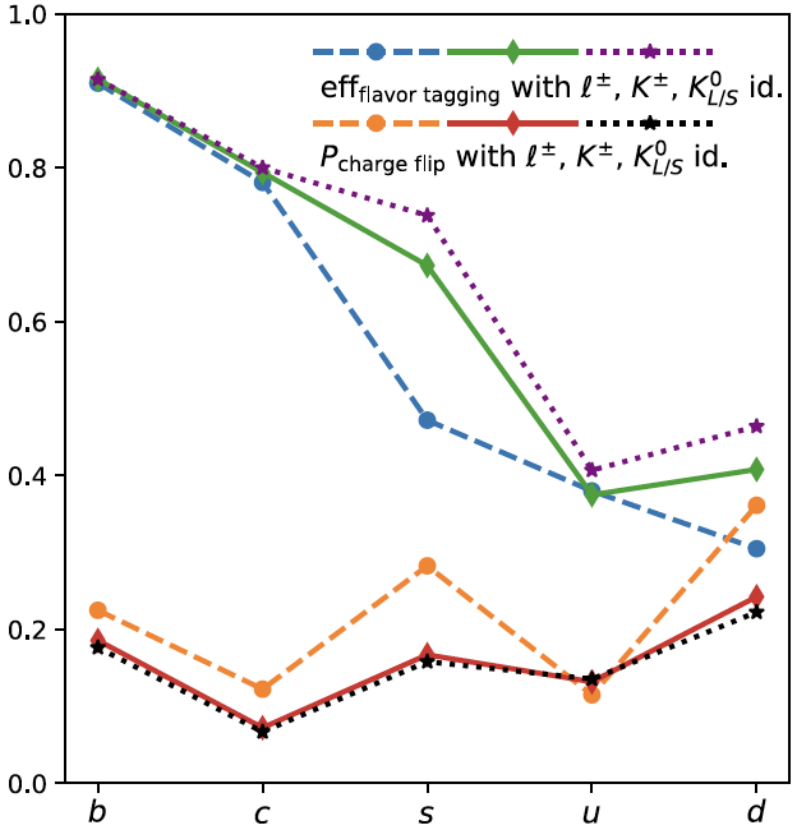






Holistic Reco: Jet origin id





- 11 categories (5 quarks + 5 anti quarks + gluon) identification, realized at Full Simulated di-jet events at CEPC CDR baseline with Arbor + ParticleNet
- Published in PRL *132, 221802 (2024)*. Comment from the referee: *"demonstrate the world-leading performance of tagger", "a "game changer" and opens new horizons for precision flavor studies at all future experiments."*

https://arxiv.org/abs/2310.03440
https://arxiv.org/abs/2309.13231

A old diagnosis of TRD performance

- In the standard of 1-1 correspondence
  - Visible energy decomposition
  - BMR decomposition
  - Pid

https://indico.ihep.ac.cn/event/25992/

- *This diagnosis needs dedicated MCTruth info, Many Thanks to Fangyi for preparing the sample & update the software*

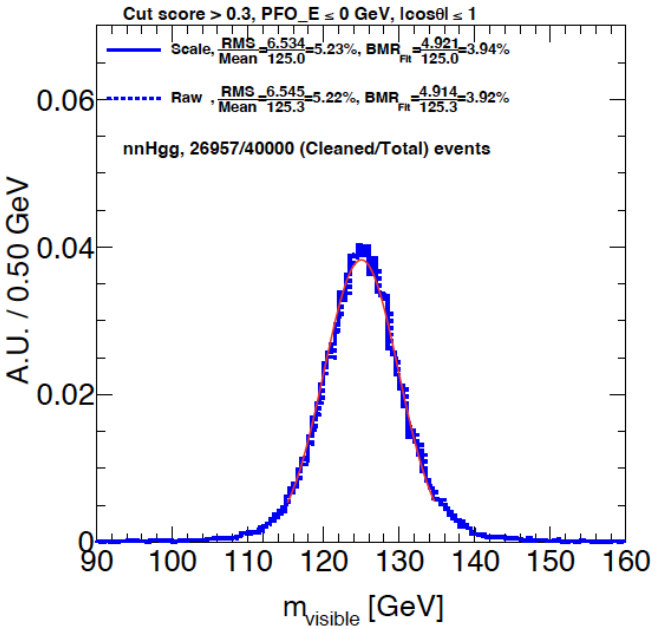
- *The simulation still has subtitles... especially in the characterize the 2ndary generated in simulation → to be updated.*

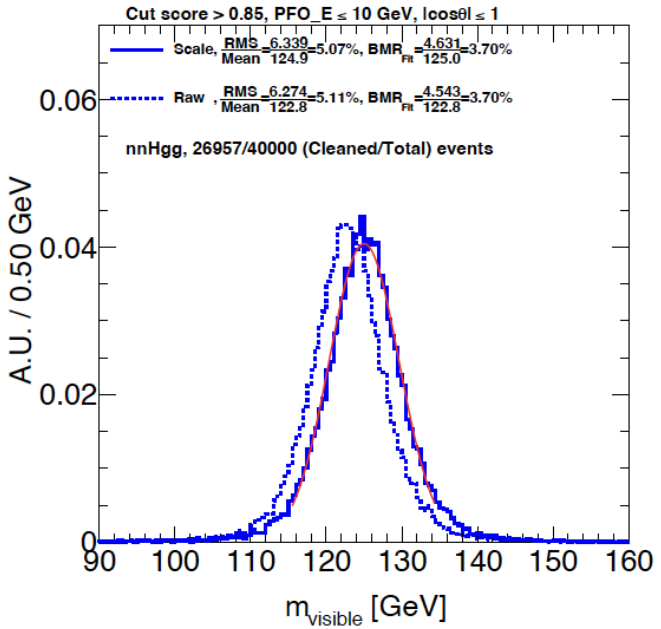
- Based on Ref-TDR setup at Spring, 2025, 2 times more Xstal bars compared to final version

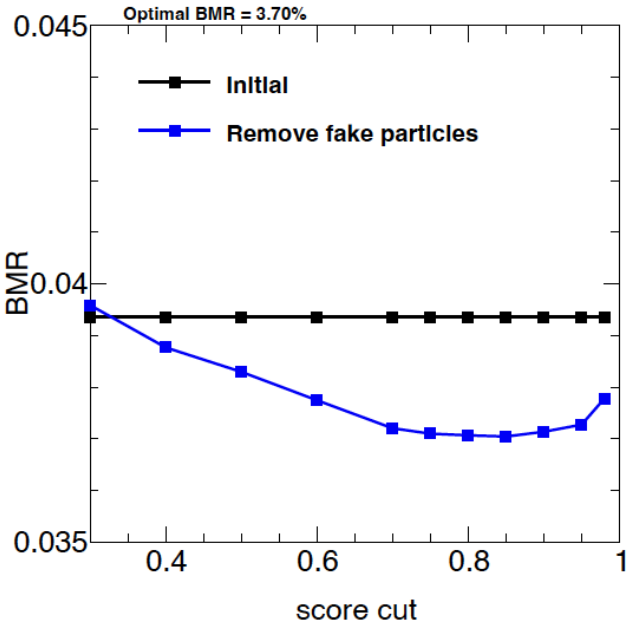
Ref-TDR ChFrag veto

BMR 3.94% -> 3.7% (rel. 6%)

Fangyi's version:
https://code.ihep.ac.cn/guofangyi/cepcsw-release/-/tree/CyberPFA-6.0.8-dev?ref_type=heads
branch CyberPFA-6.0.8-dev

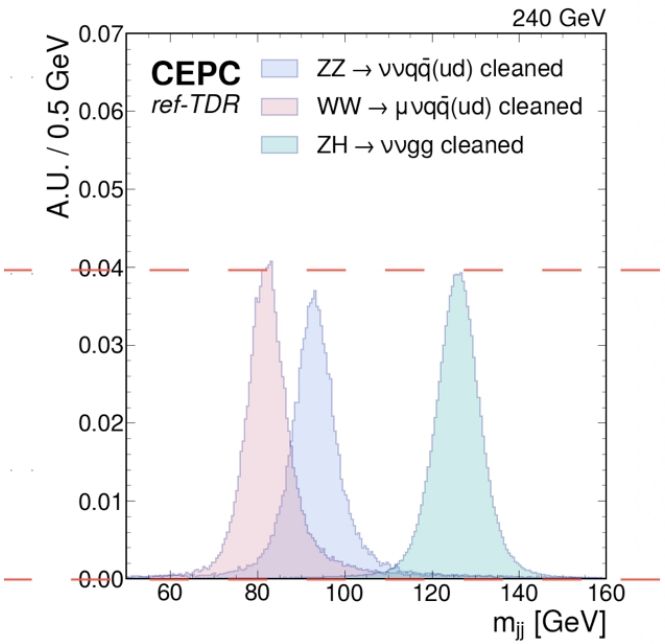


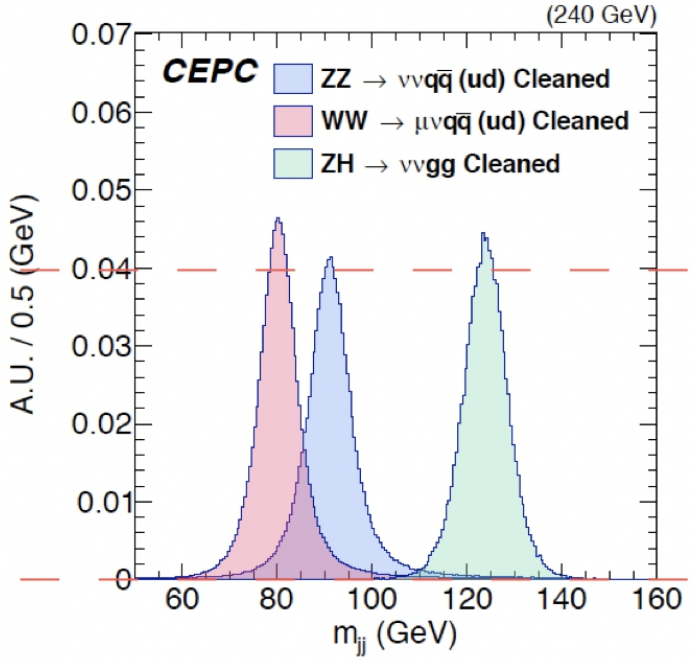


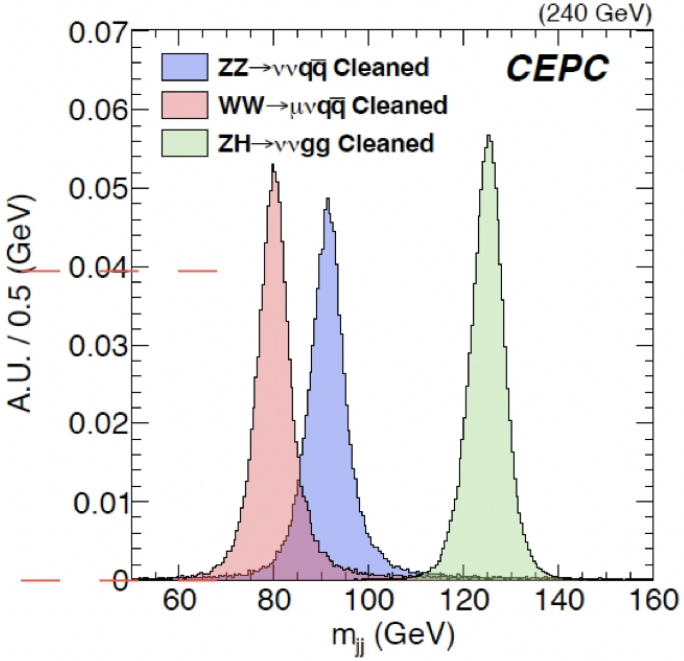


ChFrag Veto: compared to AURORA (3.7/3.4→2.7), much less efficient in TRD as the leading bottleneck is not the fragments

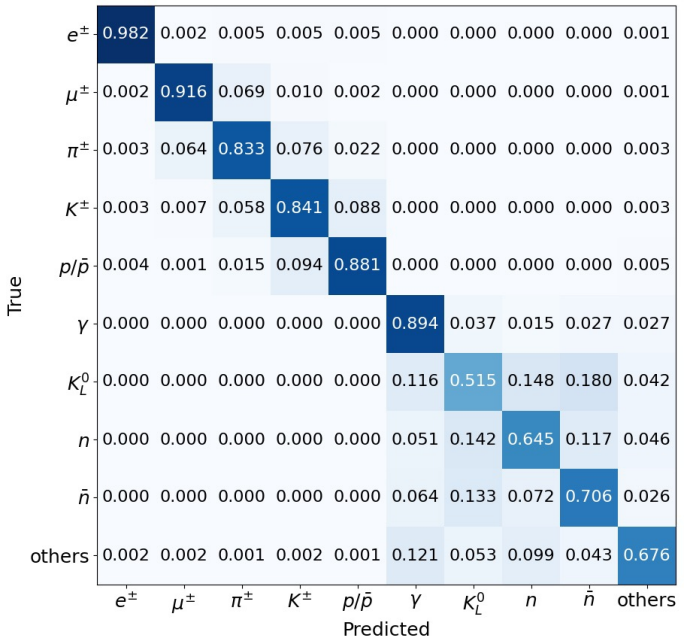
BMR comparison

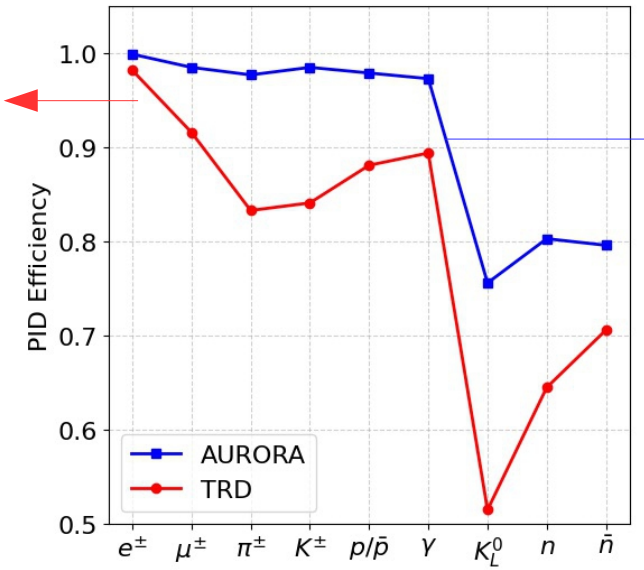


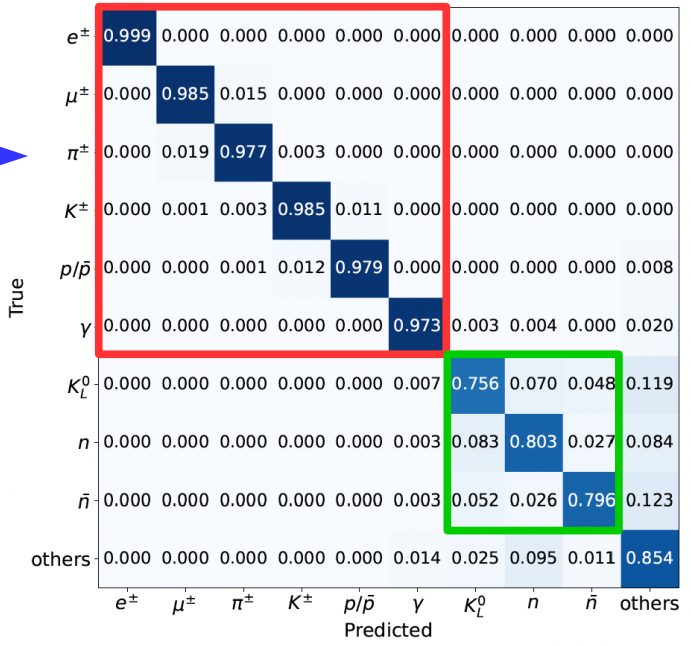


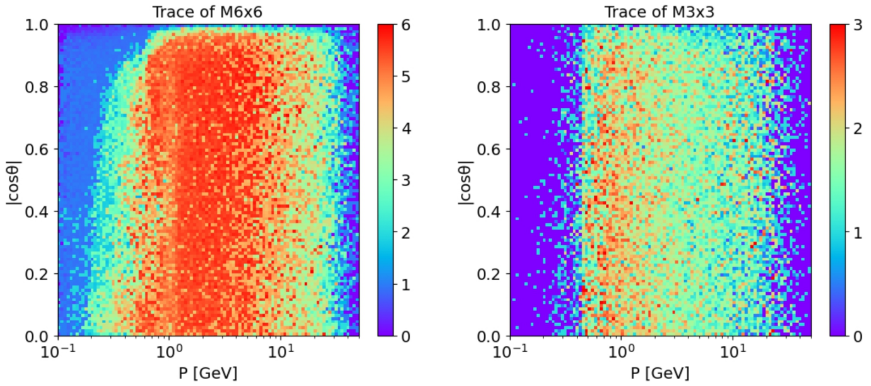


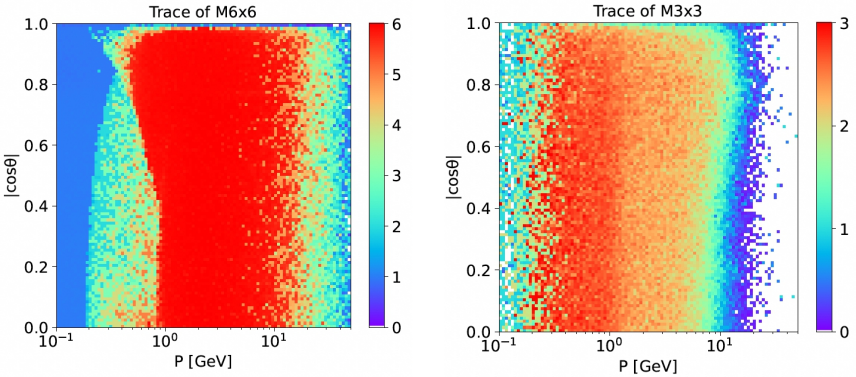
Pid









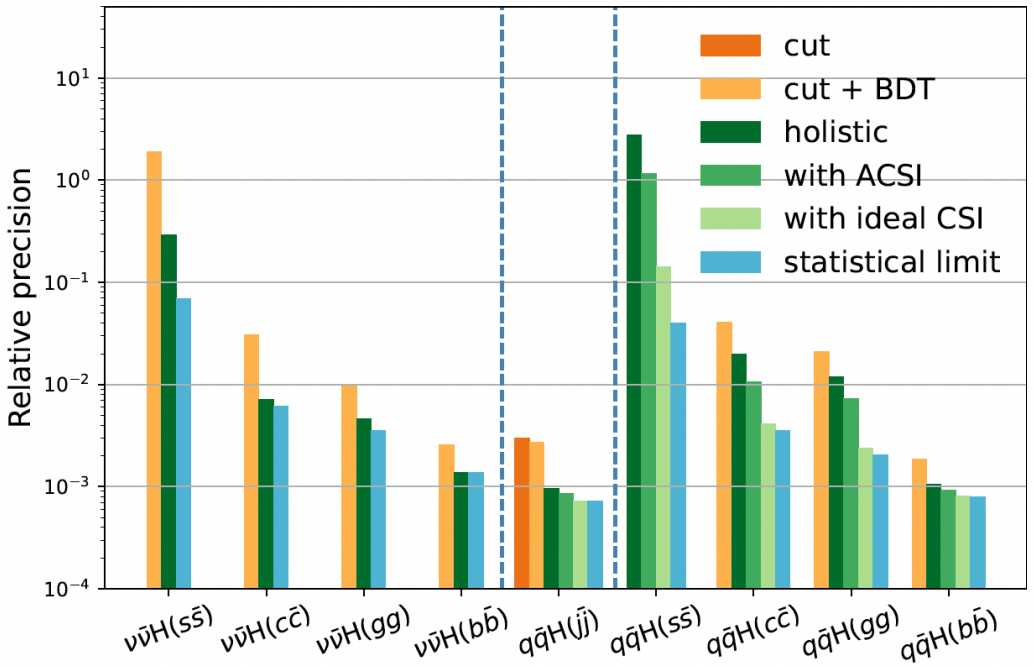


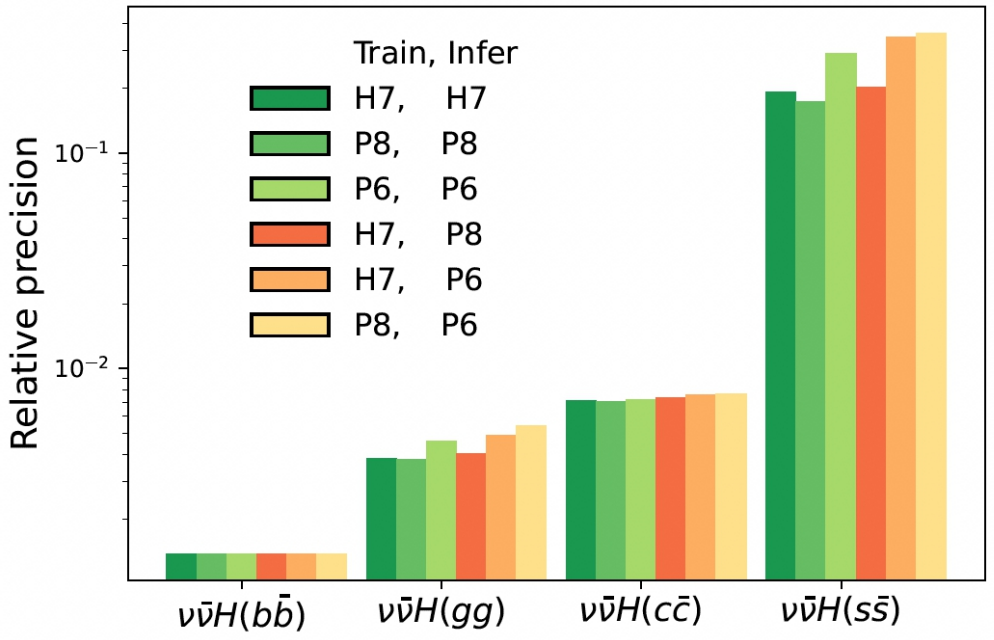
Kaon id: TDR has larger inner TPC radius. To be verified & confirmed quantitatively.

Lepton & neutral Kaon id: relatively limited info. From ECAL in TRD.

Muon det. Info not available in current PFA (both Cyber & Arbor), to be improved.

Holistic approach + ACSI



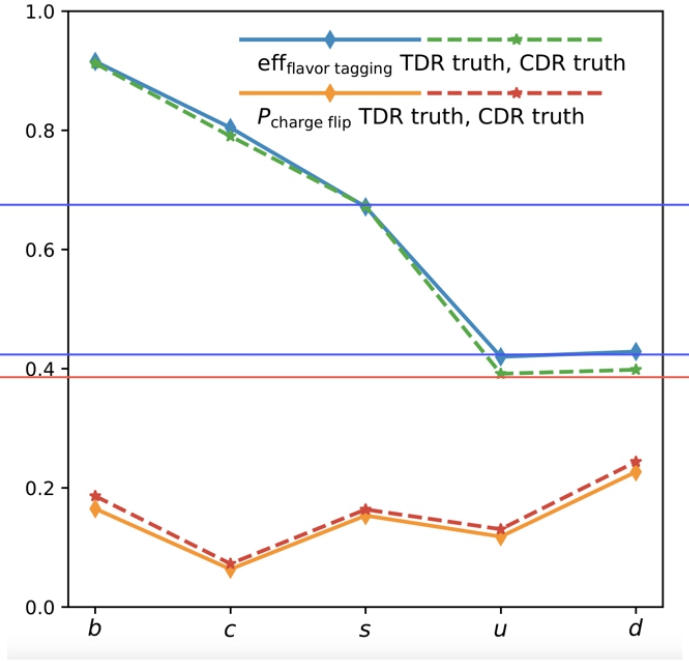


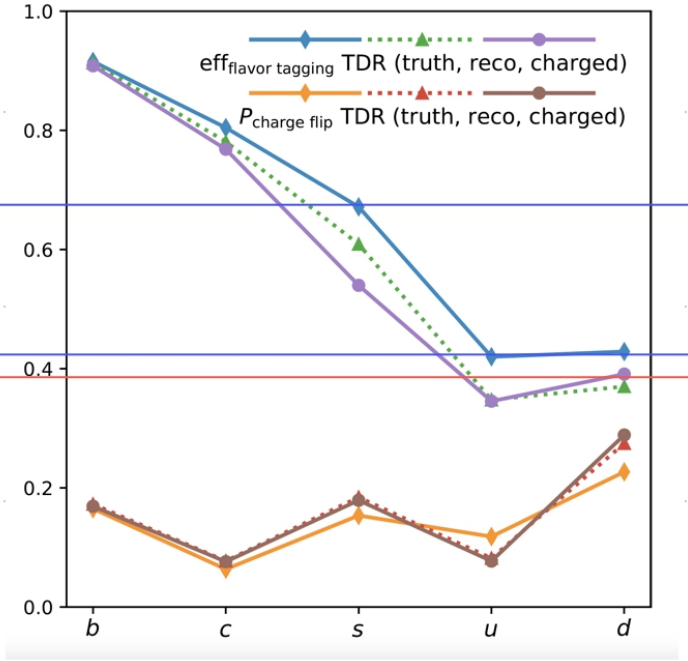
Holistic + ACSI: improves the accuracy by 2 – 6 times,
in principle free from human intervene (if the simulation is good enough...)
Strongly depends on Hadronization modes...

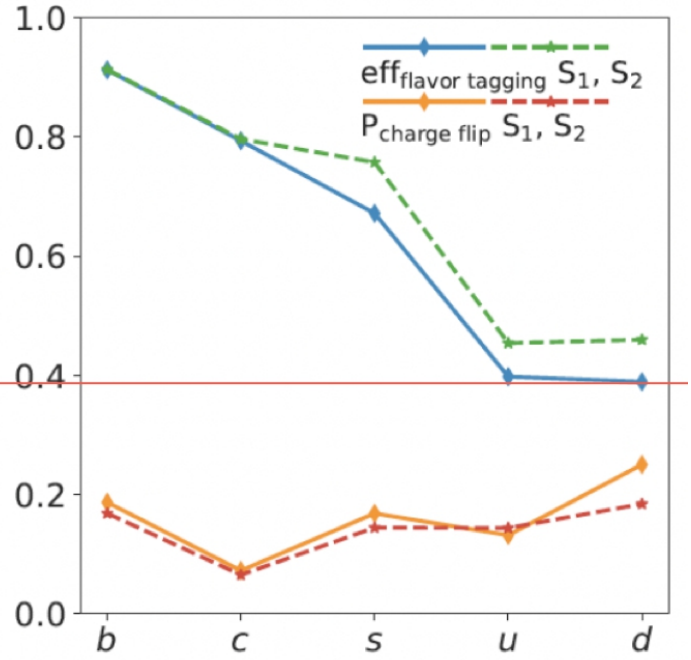
ACSI makes a leap even from Holistic, but still has significant room to improve.

H→ss within the reach at toy analysis: clarify the conditions to confirm this decay mode.

JoI at TRD, CDR & AURORA (ideal)





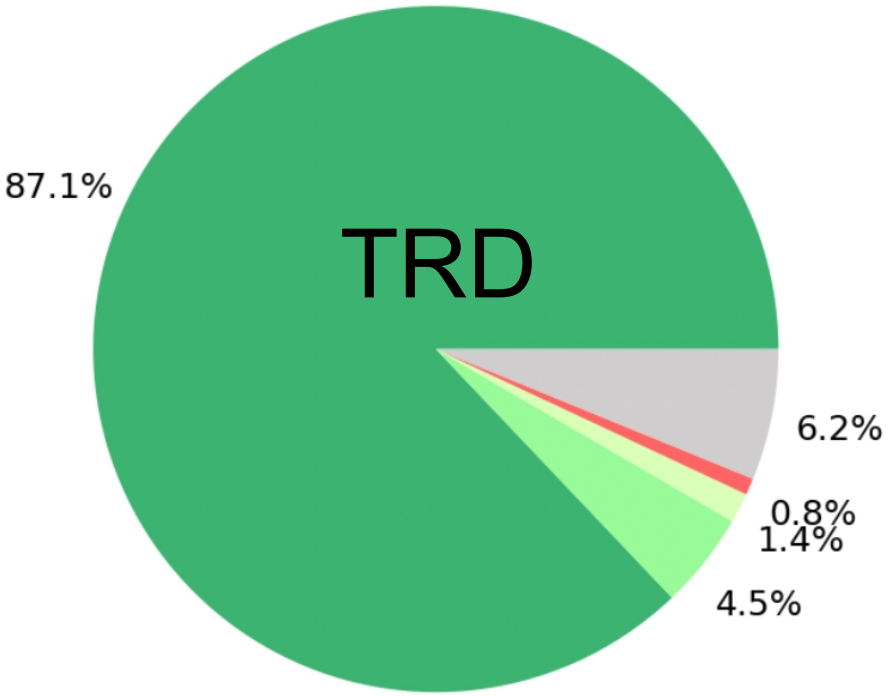


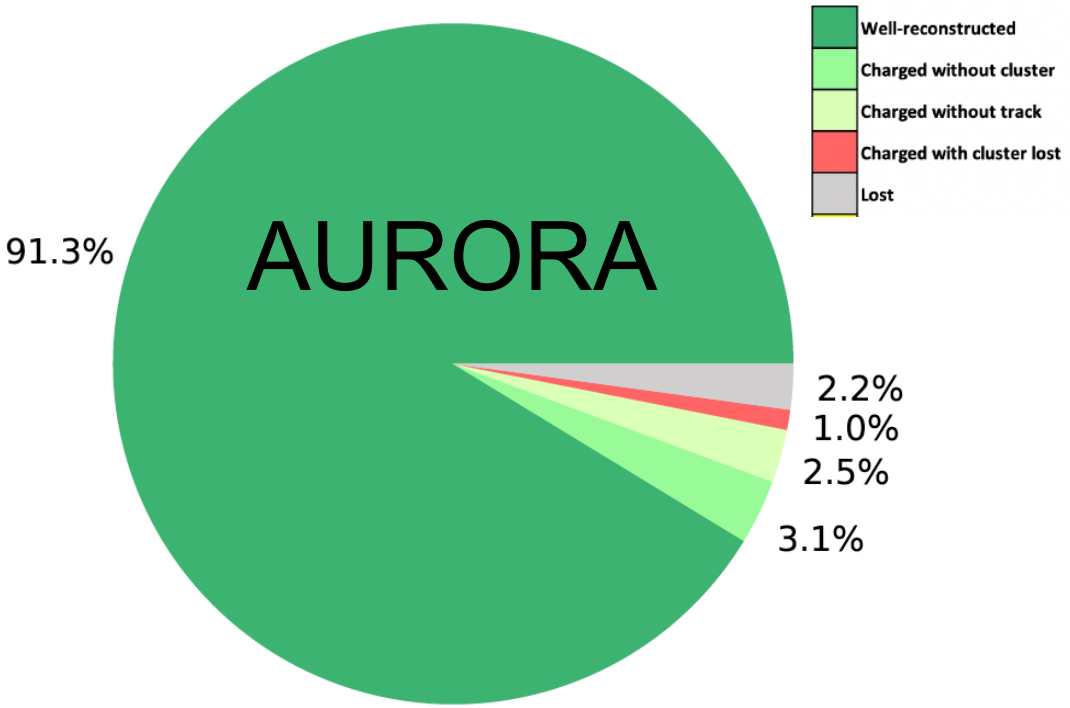
Using truth Pid, TRD has better JoI than CDR detector, as it uses longer Barrel + stitching VTX

Pid at TRD is limited, will degrade the H→ss measurement... (software version 0401, not 1-1)

Neutral Hadron ID has strong impact on Light Quark ID: highly appreciated in H→ss

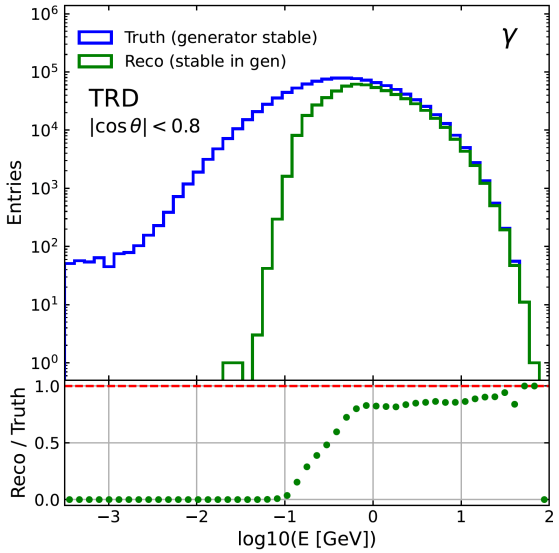
Visible Energy

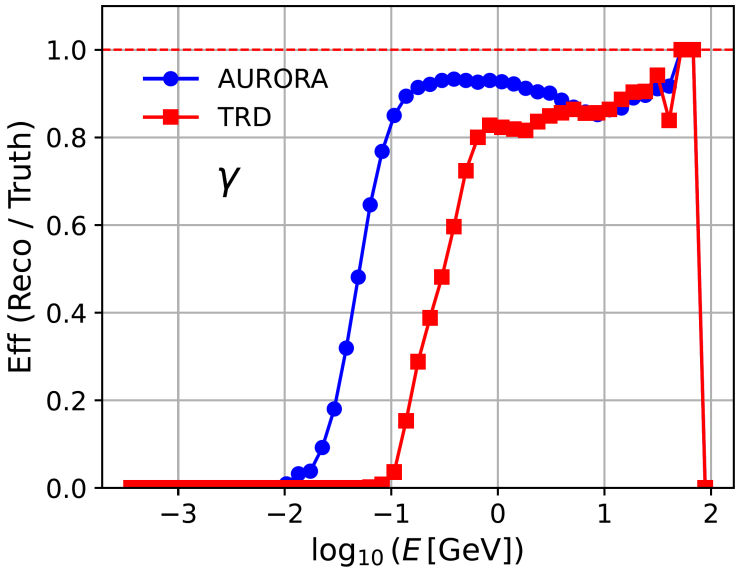


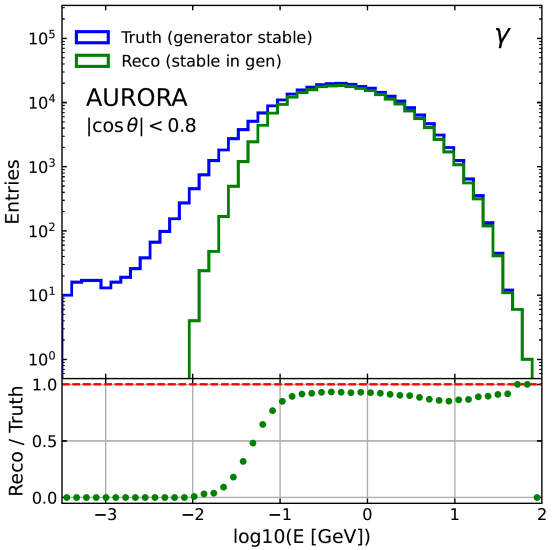


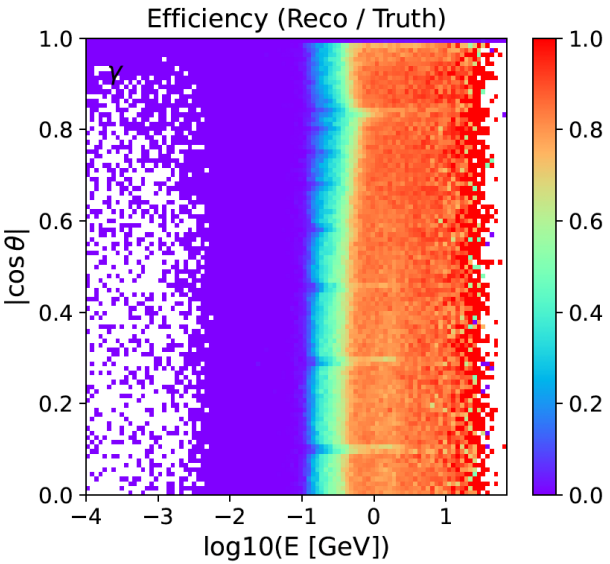
- TDR Ref-det:
  - Ch. wo. Cluster: increased by 50%
  - Ch. wo. Track: reduced to half (Tracking in TRD is actually better)
  - Ch. wi. Cluster Lost: (Double counting) reduced by 20%
  - Lost contribution increased 3 times (5 time if subtract 1% of irreducible Lost due to Acceptance)

Photon reco. efficiency

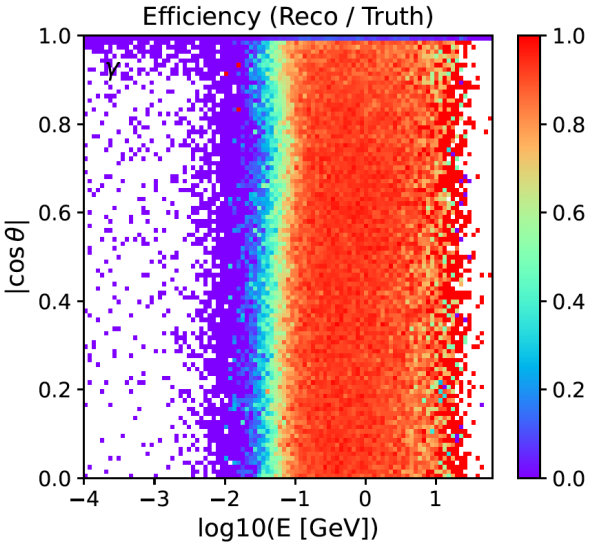








- Converted photon included,
- 10 GeV valley caused mainly by photon merging in pi-0

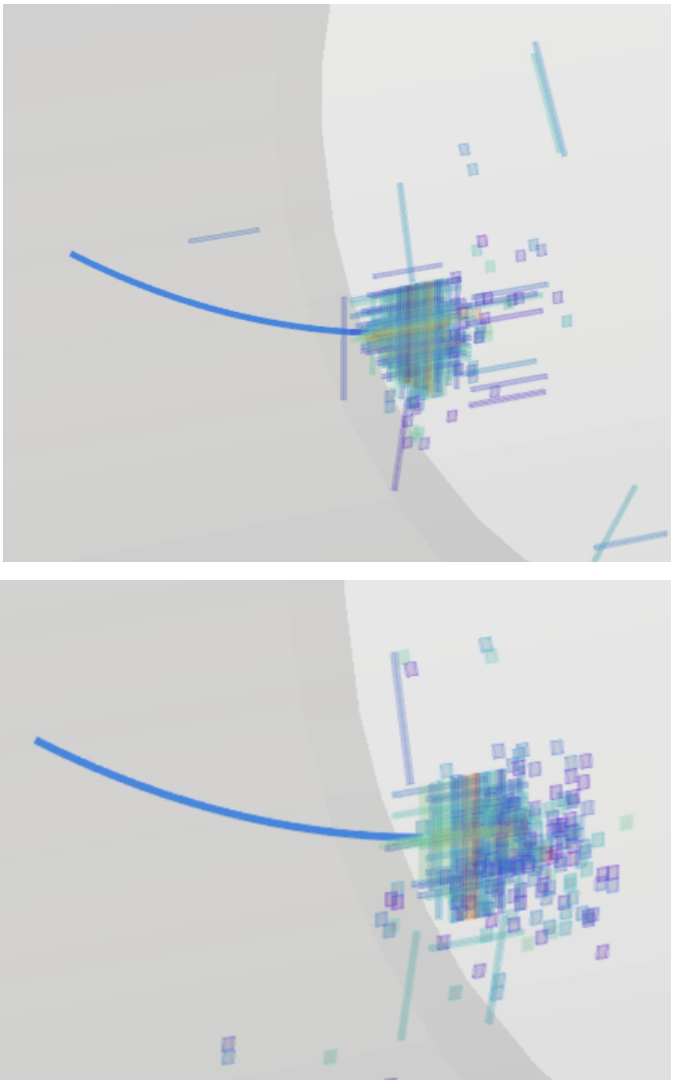


Thoughts on the Det. optimization

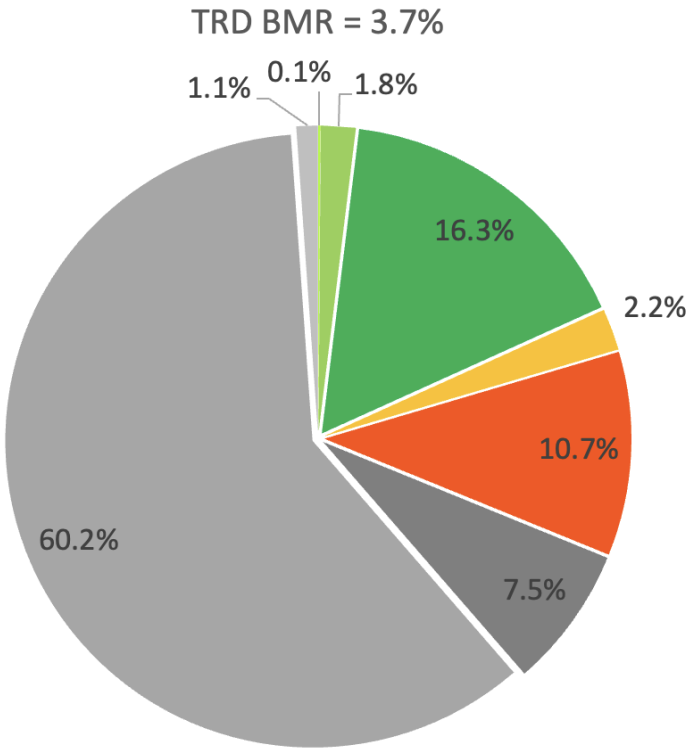
- Si-W ECAL: better BMR & Pid
- Xstal ECAL: excellent EM resolution
- 5-d calorimeter is appreciated

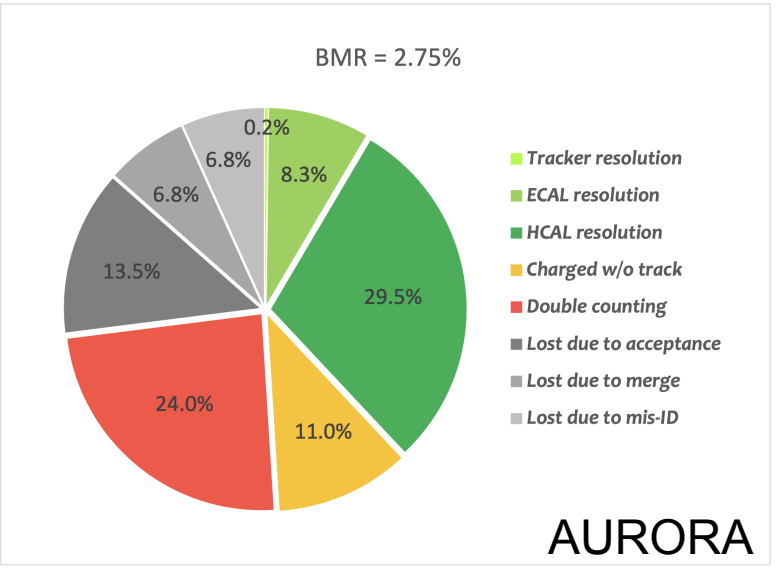
- In TRD, the bottleneck is the inefficiency of cluster reconstruction, esp. neutral particles in the jets. Primarily due to the fact that Xbar configuration has large shower volume, causing severer shower overlap – merging

- The current reco need to strength its ability neutral particle reco. While scaling behavior V.S. the bar length & B-Field could be a good starting point.



BMR decomposition



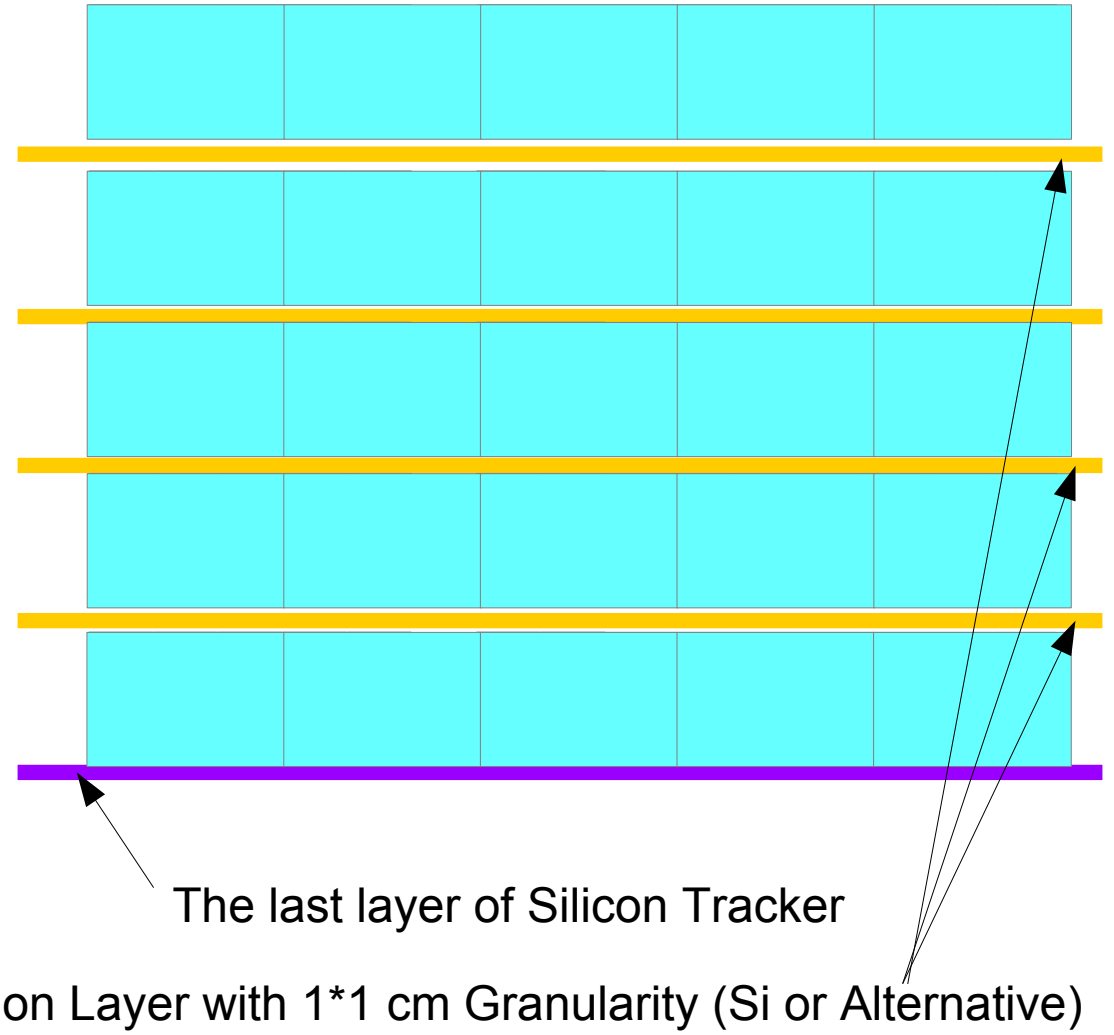


- TRD decomposition: Scaled from AURORA model
- Leading item: Lost due to merge & inefficiency - estimated from two independent methods.
  - Lost Truth Level Particle
  - Lost Total Energy (in taking into account the Double Counted ones).

Design-3: Crystal Tile + Mesh

- Geometry
  - Single Crystal Tile Dimension:

    6cm *6cm *6 cm = 216 cc
  - Number of Tiles ~ 110 k
  - Inner Area: 80 m^2
  - Total Readout Channel:
    - 110k*(1, 2, 4)? (Crystal)
    - 800000*4 = 3.2 M (Si)
- Comments
  - Should quantify the inhomogeneity response with SiPM couple to larger volume Tile

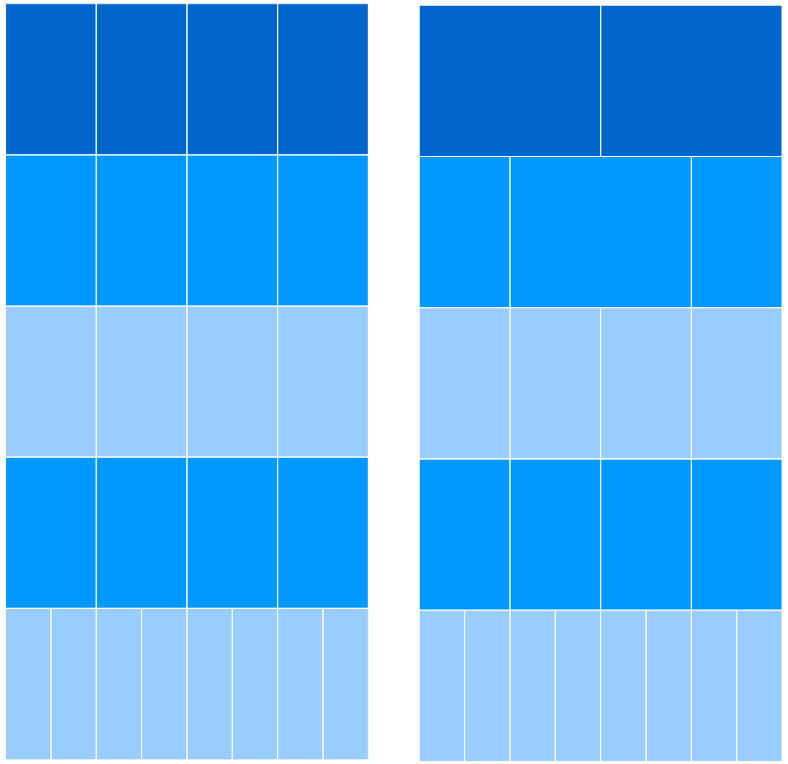


Summary

- We propose and realize the concept of 1-1 correspondence reconstruction
  - Within the reach of current technology & strongly boost the discovery power
  - A novel standard to quantify the global detector performance
- BMR achieved 2.7% at AURORA (CDR detector + GSHCAL), with a future perspective of 2%
  - Roadmap established & Needs lots of developments
- Diagnosis with 1-1, TDR Ref Det
  - Improves its BMR to 3.7% (relative. 6%)
  - The bottle neck is “LOST particle”: inefficiency to reconstruct neutral particles
  - Has limited Pid performance, but better tracking (esp. Low momentum ones). Comparing AURORA with TRD provides quite some insights & possible synergies.
  - The granularity & configuration of calo, especially ECAL, should be re-optimized, iterated with Reco. Tool development
- Possible scenarios: share the Positioning + timing, and the energy measurements task between Si/Xstal: worth quantitative study

Back up

Design-1: Crystal/Glass pillars



TDR Total Xstal Volume ~ 24 m^3.

Conceptual para: 5 layers:

First Layer: 1*1*6 cm^3

Last 4 layers: 2*2*6 cm^3

Total readout channels 1.6 Million
Compared to ~ 570 k SiPM readout in Xstal Bar: 7% increase of the ECAL cost.

Needed study: EM resolution evolution with increasing of longitudinal seg (gap, mech, cooling...)

Similar structure could be also used in HCAL, significantly reducing the channel num.

Full absorption HCAL could tolerant much larger cell size, at the cost of glass & total volume increase ~ 10% of the cost.

IP

Full Glass ECAL should also be explored, with much more readout channels.

Warning: No free lunch!

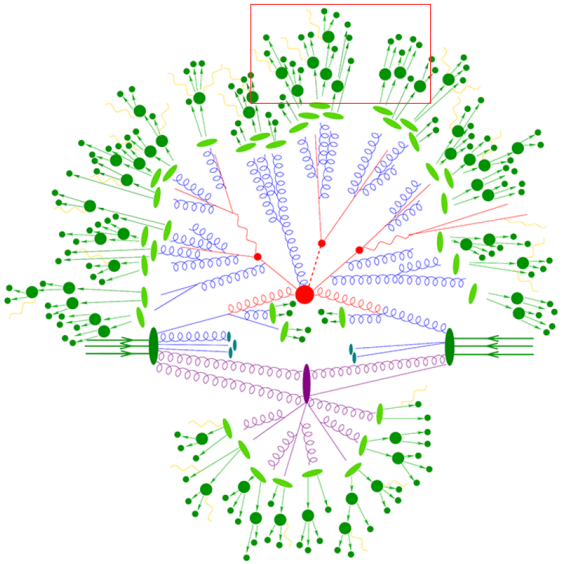
- **Key Problem: Data – MC Discrepancy,** especially for supervised learning
- Solution
  - Better Simulation (inject more attention & information!)
  - Robust AI tools less dependent on Simulation: From supervised learning, to non/weakly-supervised, enhanced, LLM...

- **Hadronization & impacts...**
- **Beam induced backgrounds & machine protection**
- Event building with realistic detector time response, including electronic pulse shape & time sequence...
- TPC & Tracker:
  - Dependence of dE/dx or dN/dx performance on the shifting distance & readout threshold/Noise
  - **Ion distortion & possible correction**
  - B-Field mapping
  - Mechanic stability
  - Low Pt track reconstruction
- Calorimeter
  - SiPM: response uniformity & Dynamic range, especially towards large Tile/Bar configuration in ECAL
  - Requirement on the Attenuation length for scintillating materials...
  - Homogenates in space & stability in time
  - Development of Energy & Time Estimator...
- Dead zone/dead channel tolerance
- Performance degrading with Noise: rates, intrinsic, and radiation relevant ones
- Calibration Procedure & Monitoring methodologies...
- ...

Targeted studies

- **Usage of Timing**, especially at 5d calorimetry
  - **Clustering with time**
  - **PFA of the Space Time**... to reconstruct all final state particles in the data stream continuum, and correctly associate them with different VTX & sources, including Beam Induced Background

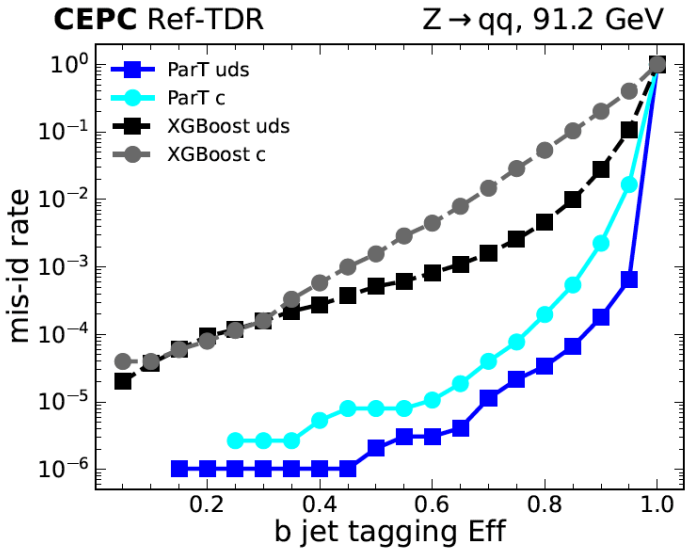
- ***Holistic approach with sufficient categories (Multi-class identification)***
  - ~o(100) categories is sufficient... to identify almost all physics events at a Higgs factory
  - ~o(10) is probably sufficient for Z factory
  - Free of human intervene – in principle
  - In progress & to understood the scaling/optimization
- ***Color singlet identification & iteration with QCD studies***
- ***From leaves to the Tree:***
  - Id the parenting info of final state particles; i.e., *B→D→K→pi0→γ...*
- ***Longer term: Learning from all particle → hits***
- ...

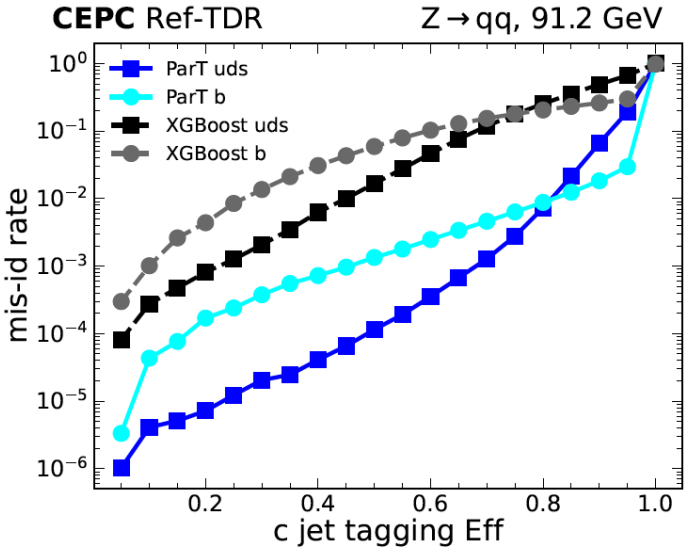


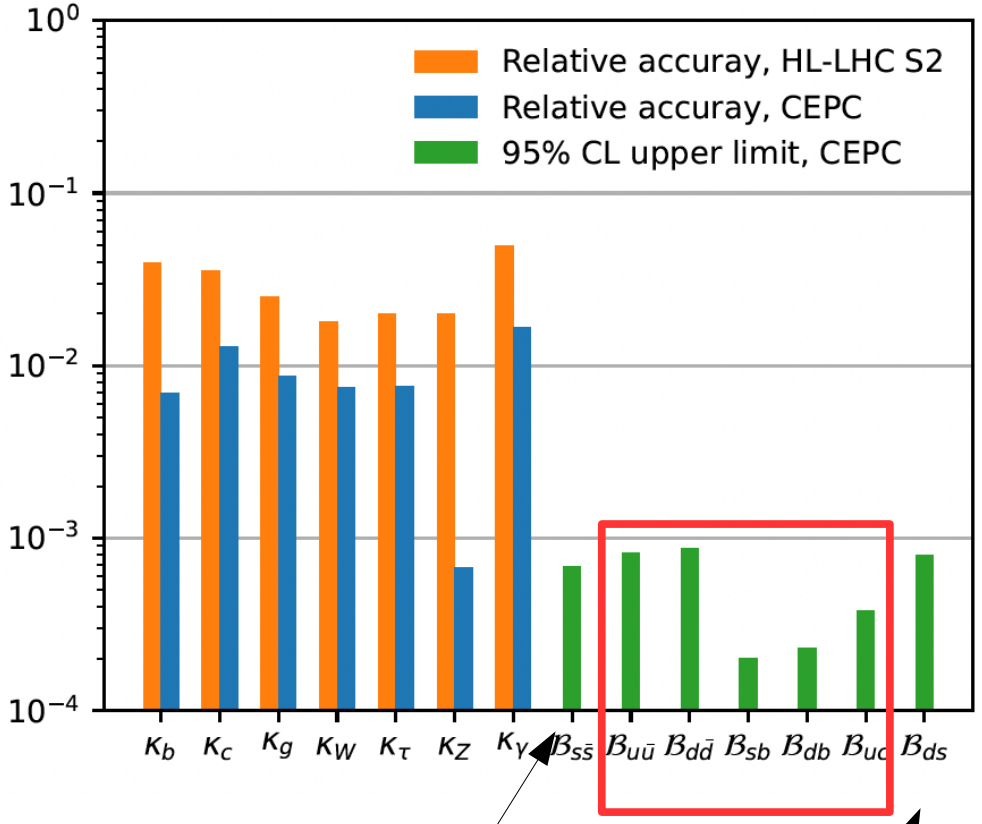
Summary

- ***... Higgs factory should and could have excellent detector & reconstruction...***
- ***AI enables us to learning from all the particles: enhance the discovery power ~ 3 times...***
  - *Holistic approach*
    - *Reco: Jet origin id, 'see' the quark & gluons...*
    - *Analysis: Processing in principle free from Human intervene.*
      - *+ ACSI for full hadronic events*
  - *1-1 correspondence reconstruction: excellent PID + BMR of 2.7%*
    - *5-d calo is the key*
    - *Long term: learning from all hits*
- ***Multiple challenges, intriguing prospects, and significant synergies.***
  - *Precise Simulation is critical, need profound understanding & development*
  - *To explore other methodologies: non/weakly-supervised, enhanced, LLM...*
  - *Lots more to explore, with unsupervised, LLM, ... rich interplay & synergies.*
  - ***...***

Impact on Physics





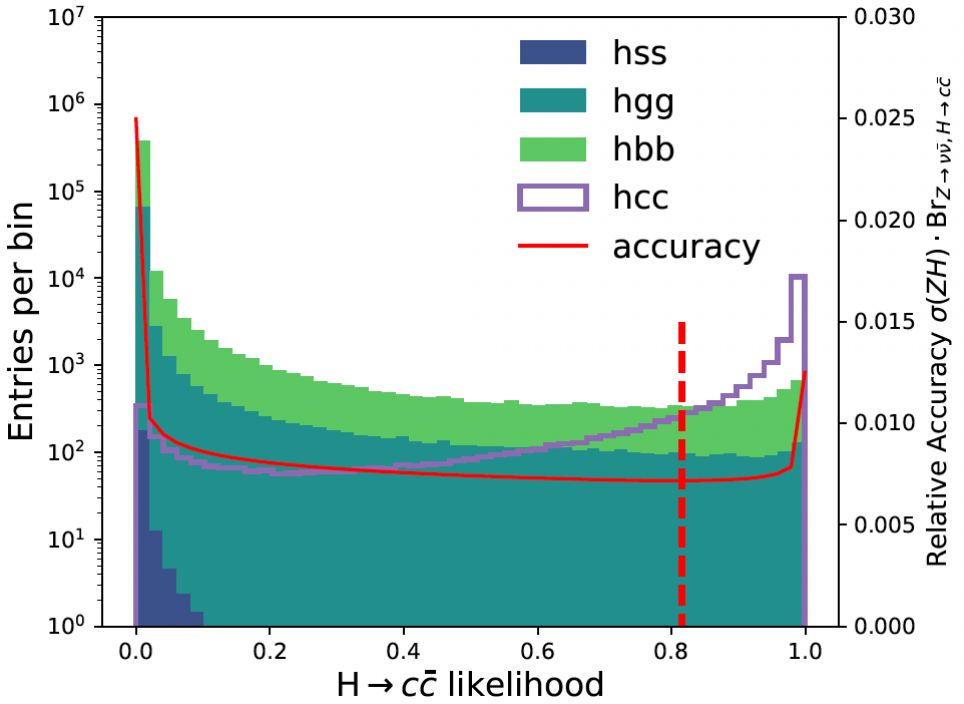


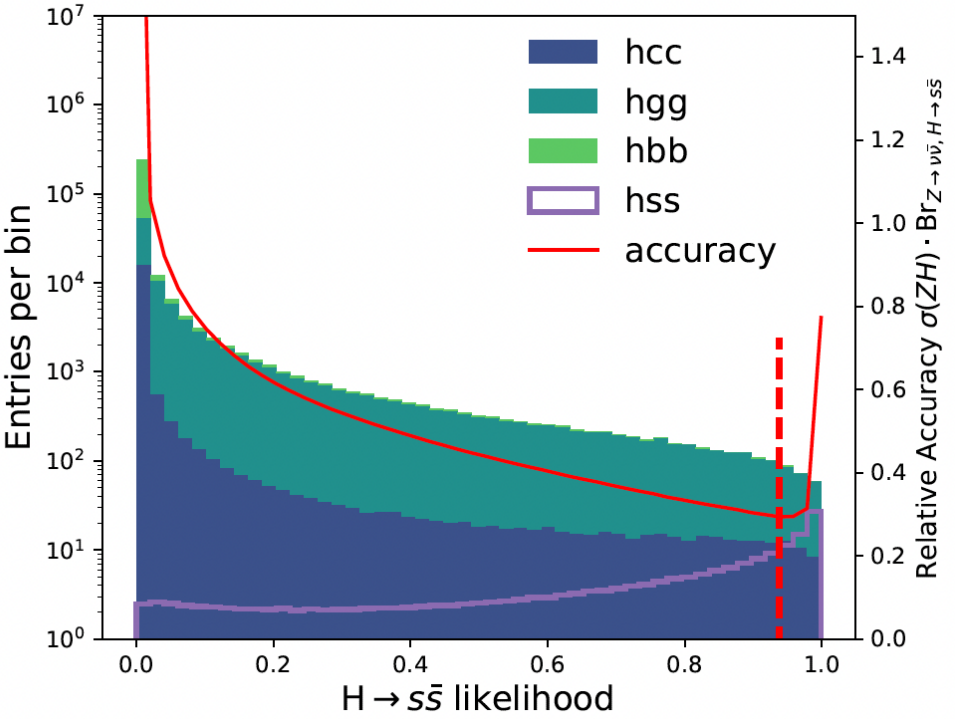
Improved by ~3 times

Improved by 1-2 orders of magnitudes
~ 2 folds improvement at H->cc & Vcb

Presumably... firstly quantified

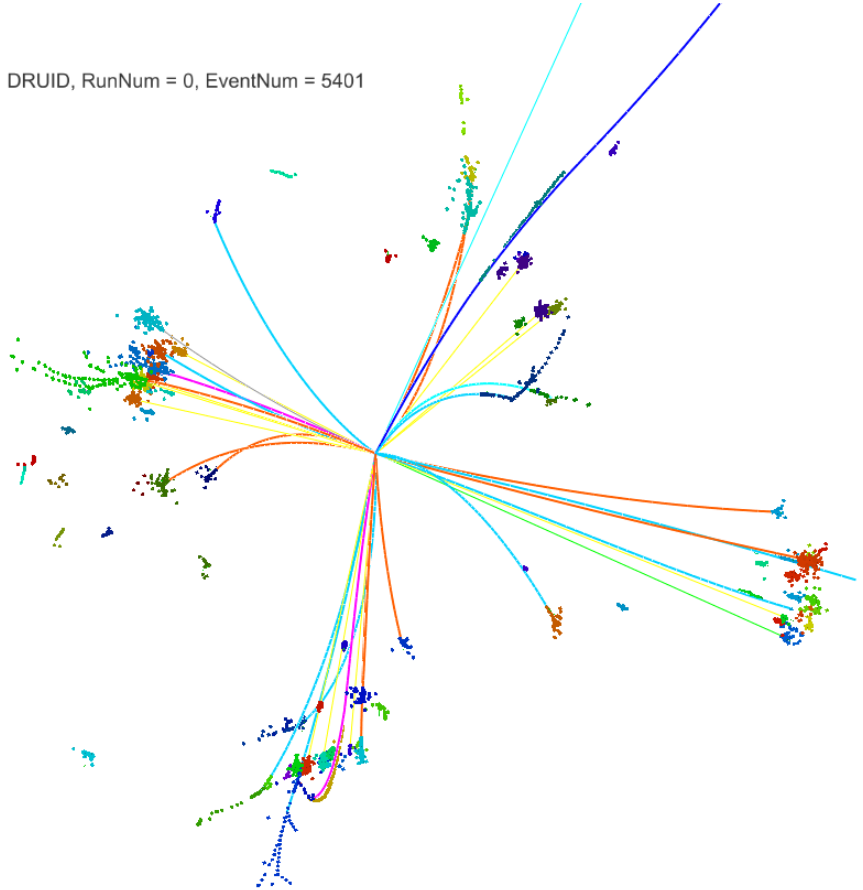
Holistic Analysis: vvH, H→2 jet

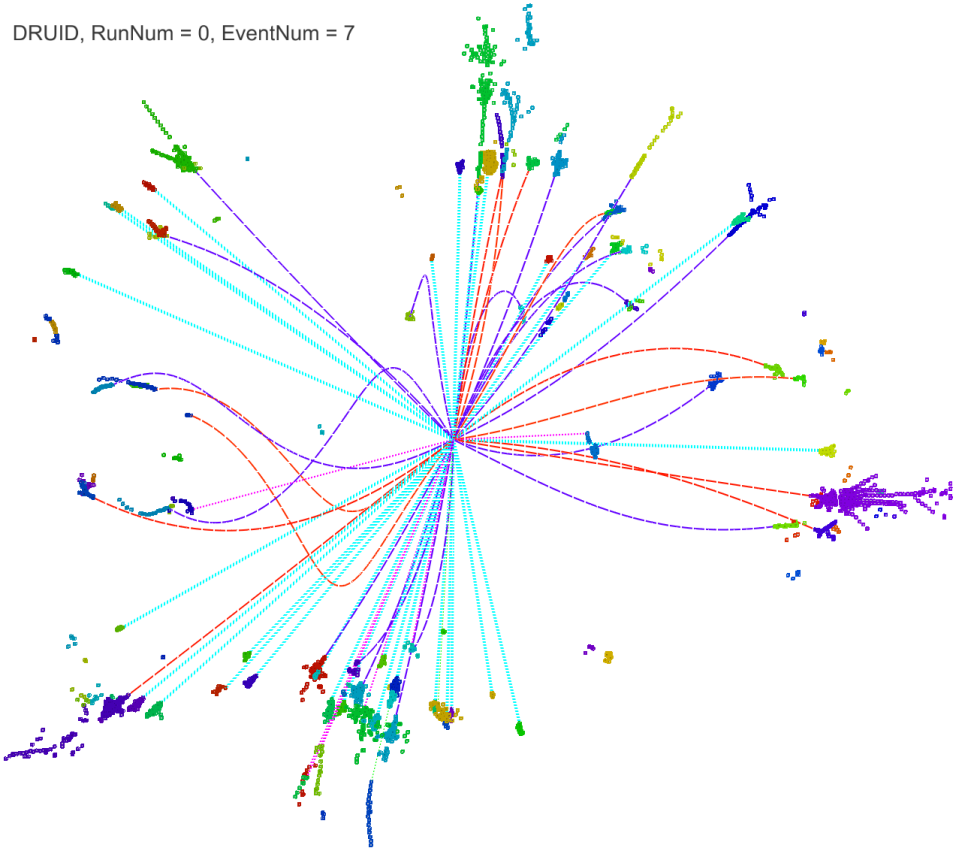




- vvH, H→bb/cc/gg/ss measurements: 4 kinds classification
- Simplified analysis with irreducible background...
- H→bb/cc/gg: close to the statistic limits - 2-6 times better than previous studies (include other bkgrd, BDT based, etc)
- H→ss: close to confirmation!

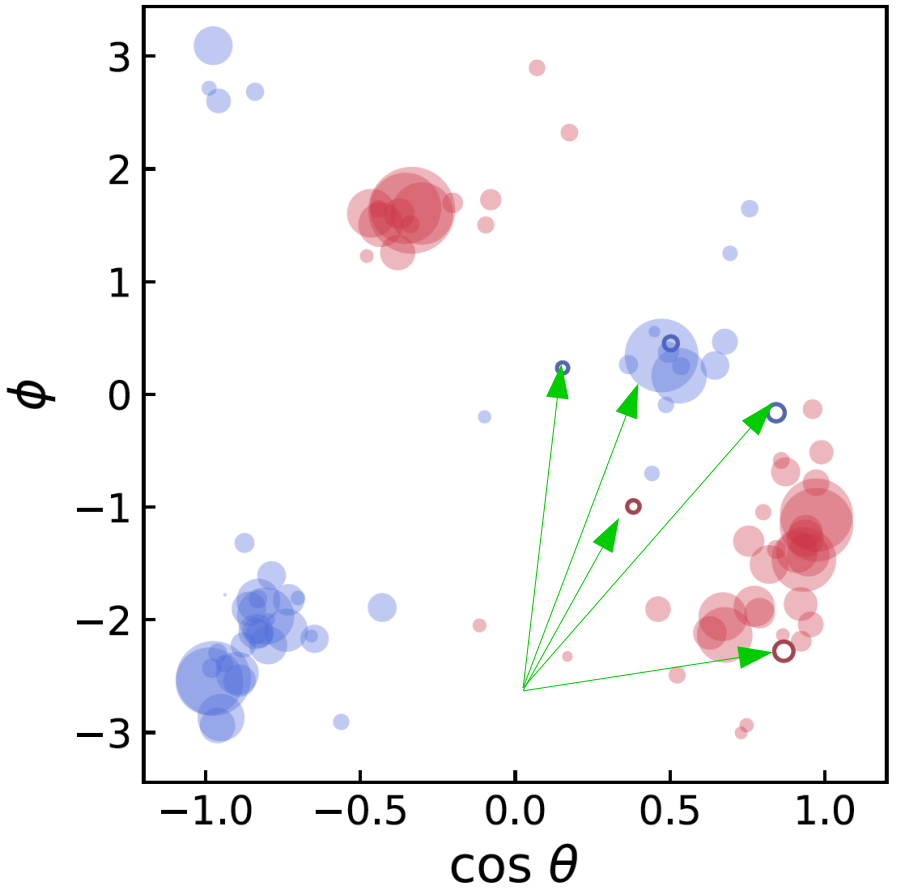
Color Singlet Identification

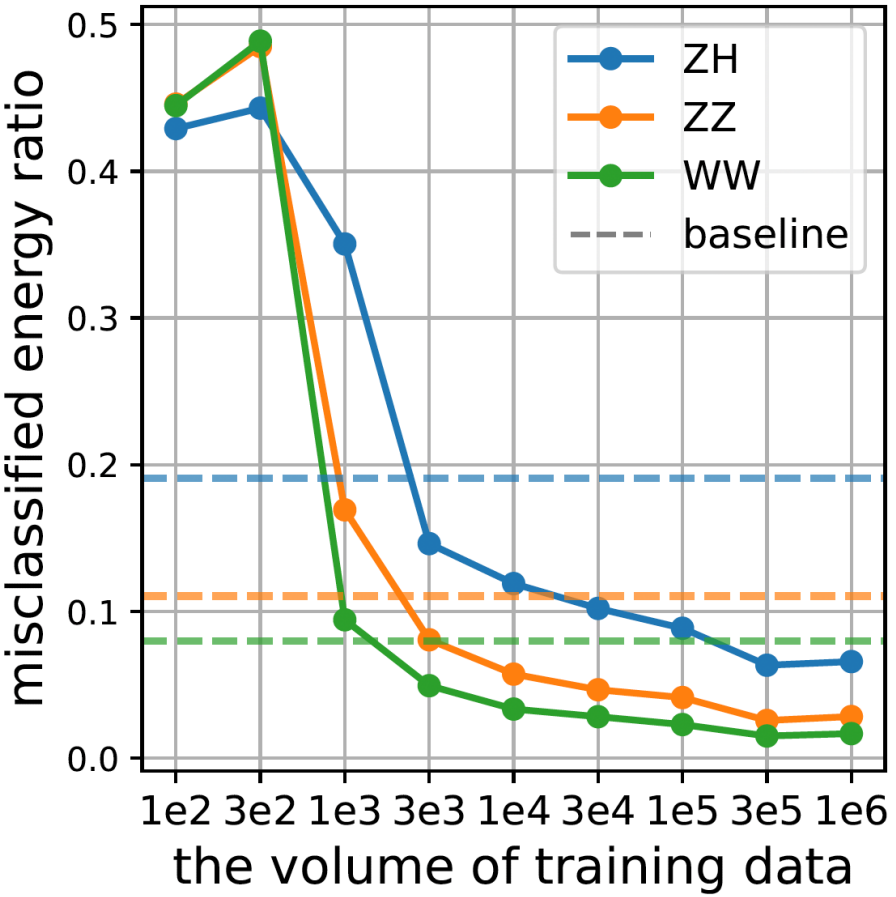




at full hadronic ZH event

Advanced CSI: A coloring game



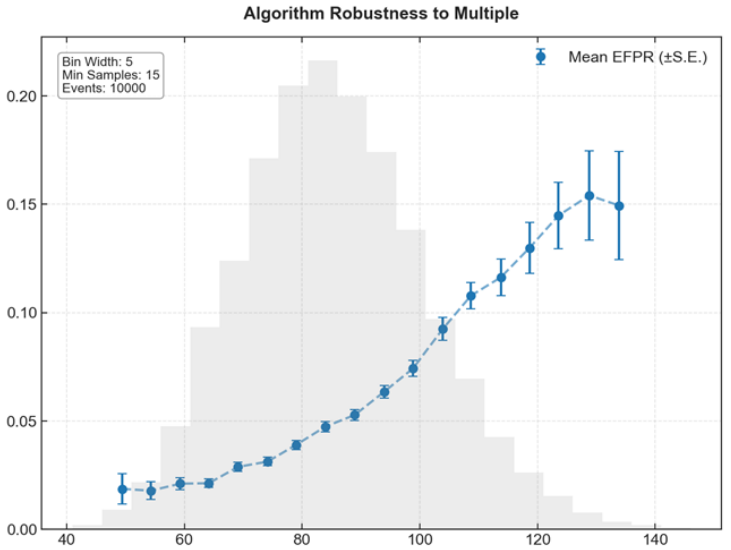


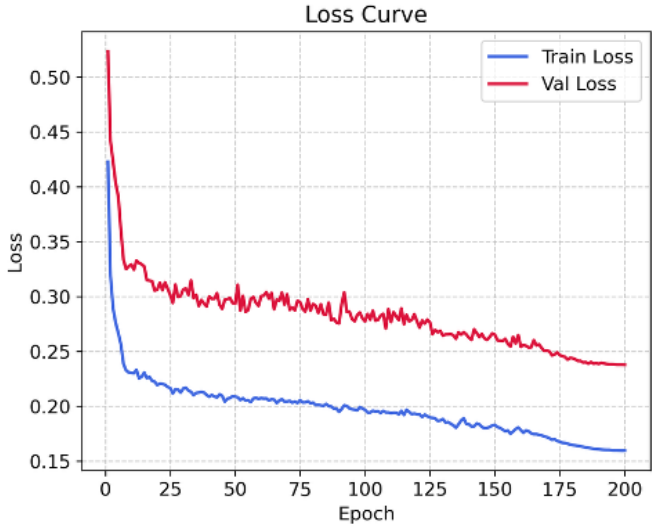
Mid classified energy ratio: reduced by 3-5 folds compared to conventional (jet clustering + matching)

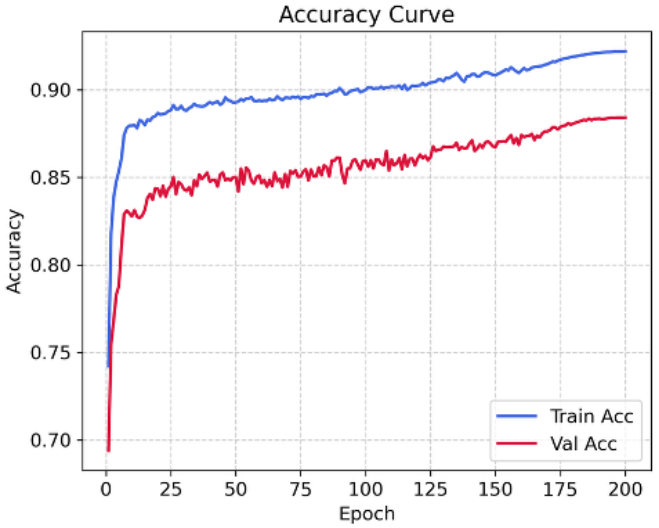
Grouping: Applicable to Higgs self coupling, ... Pile up veto, and hit clustering, etc.

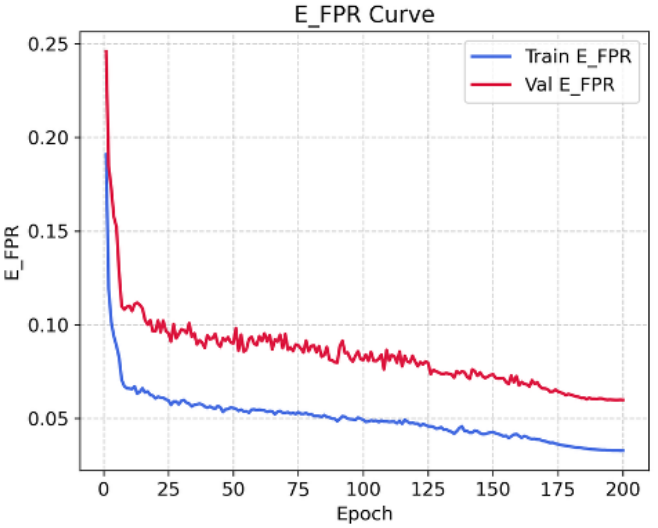
ACSI: exploration & optimization

Mis-classifed energy ratio	Classical	Original Version	Mamba
WW	7.9%	1.7%	**1.36%**
ZZ	11%	2.8%	**2.35%**
ZH	19%	6.6%	**5.97%**





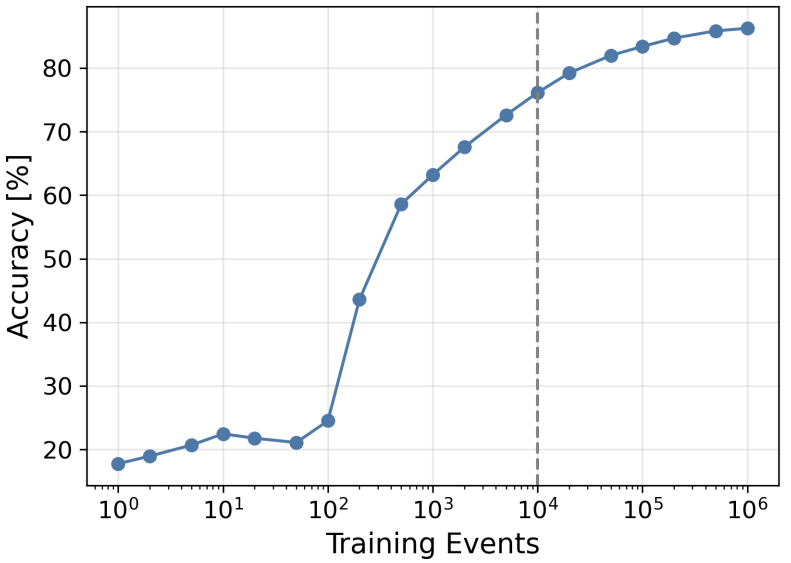


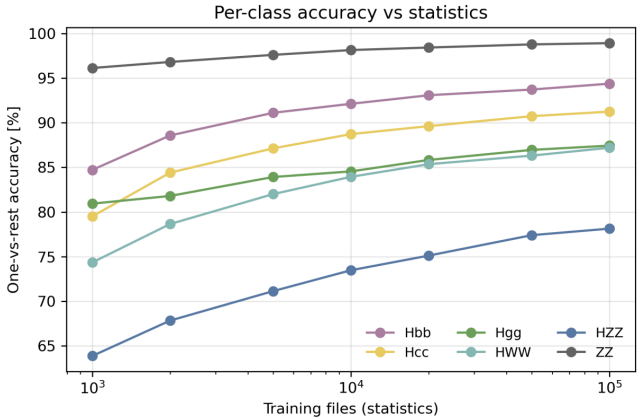


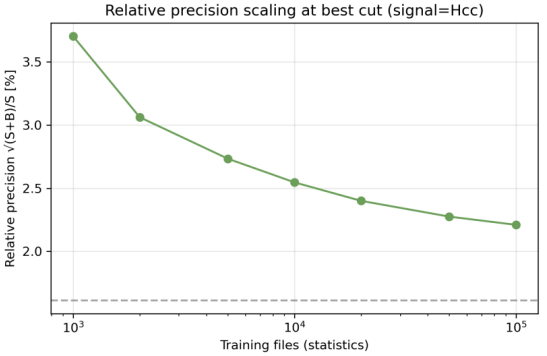
Trained on WW+ZZ+ZH & tested on ZH event

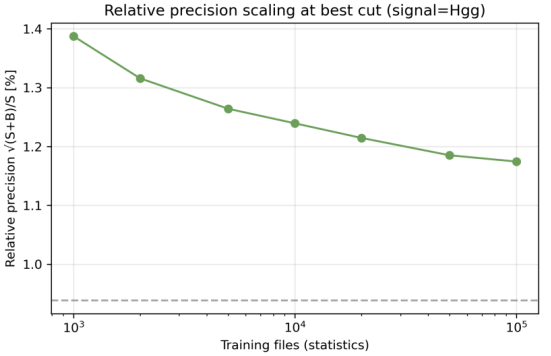
Multi-heads: Training in progress...

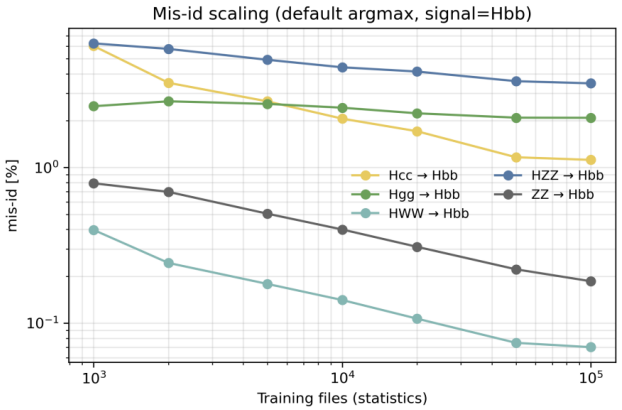
- bb, cc, gg, WW/ZZ → 4q
- H→ss
- H→uu, dd, FCNCs

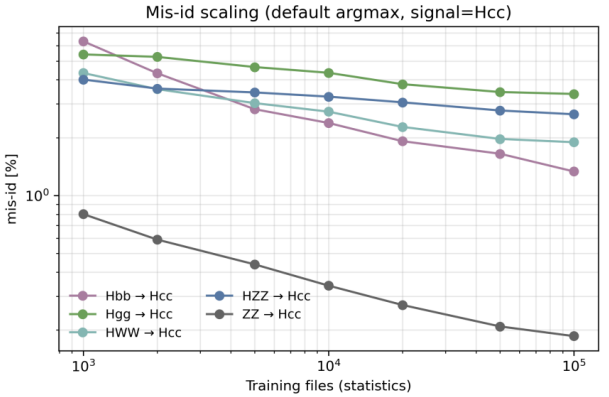


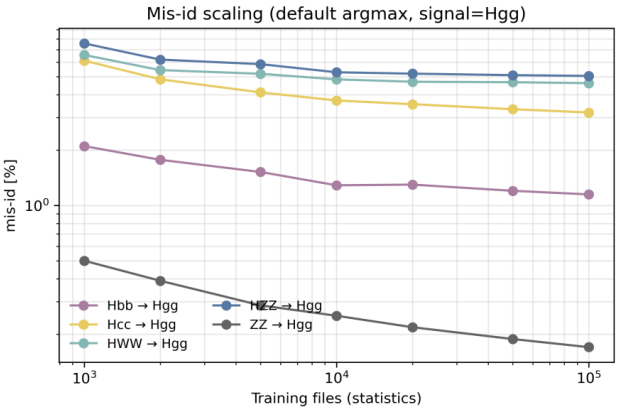

Per-class accuracy vs statistics
One-vs-rest accuracy [%]
Training files (statistics)
Hbb
Hcc
Hgg
HWW
HZZ
ZZ

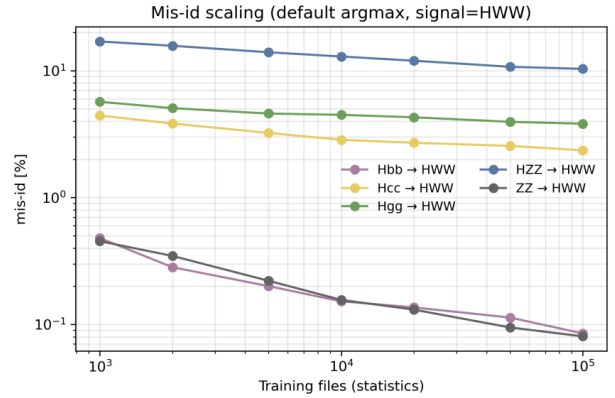

Relative precision scaling at best cut (signal=Hcc)
Relative precision √(S+B)/S [%]
Training files (statistics)

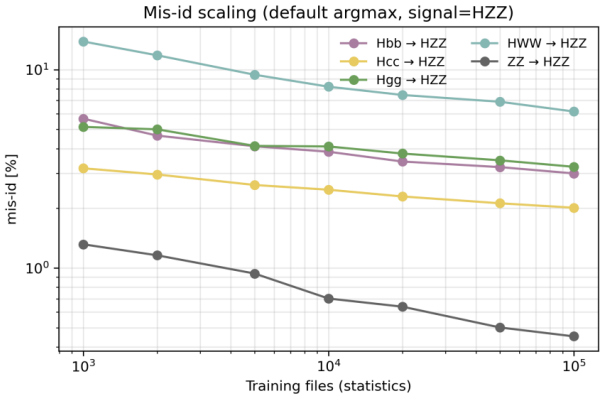

Relative precision scaling at best cut (signal=Hgg)
Relative precision √(S+B)/S [%]
Training files (statistics)

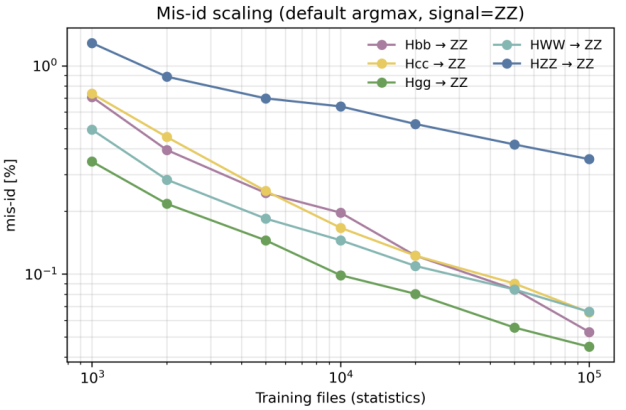

Mis-id scaling (default argmax, signal=Hbb)
mis-id [%]
Training files (statistics)
Hcc → Hbb
Hgg → Hbb
HWW → Hbb
HZZ → Hbb
ZZ → Hbb


Mis-id scaling (default argmax, signal=Hcc)
mis-id [%]
Training files (statistics)
Hbb → Hcc
Hgg → Hcc
HWW → Hcc
HZZ → Hcc
ZZ → Hcc

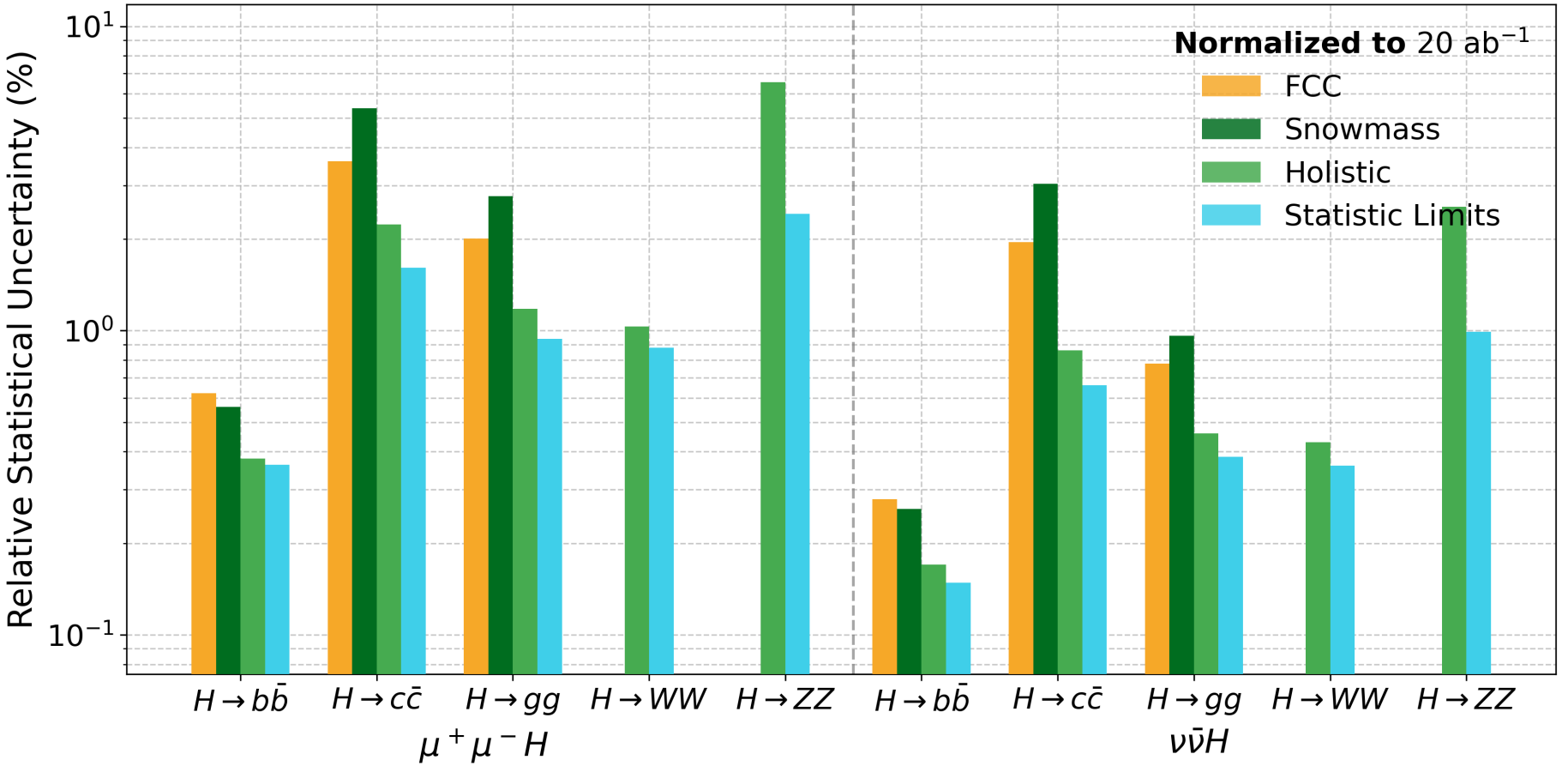

Mis-id scaling (default argmax, signal=Hgg)
mis-id [%]
Training files (statistics)
Hbb → Hgg
Hcc → Hgg
HWW → Hgg
HZZ → Hgg
ZZ → Hgg


Mis-id scaling (default argmax, signal=HWW)
mis-id [%]
Training files (statistics)
Hbb → HWW
Hcc → HWW
Hgg → HWW
HZZ → HWW
ZZ → HWW


Mis-id scaling (default argmax, signal=HZZ)
mis-id [%]
Training files (statistics)
Hbb → HZZ
Hcc → HZZ
Hgg → HZZ
HWW → HZZ
ZZ → HZZ

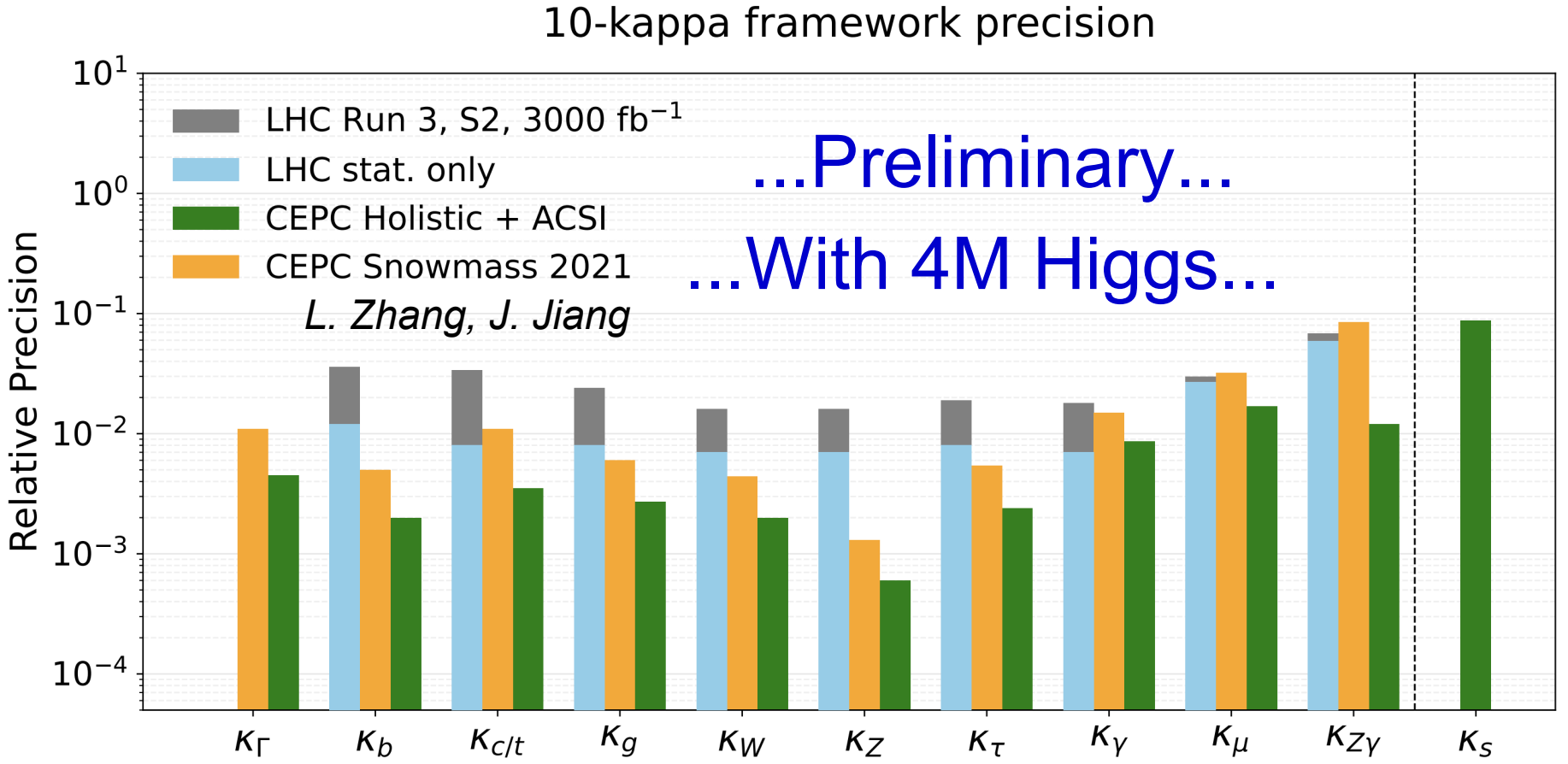

Mis-id scaling (default argmax, signal=ZZ)
mis-id [%]
Training files (statistics)
Hbb → ZZ
Hcc → ZZ
Hgg → ZZ
HWW → ZZ
HZZ → ZZ

Holistic @ llH + vvH



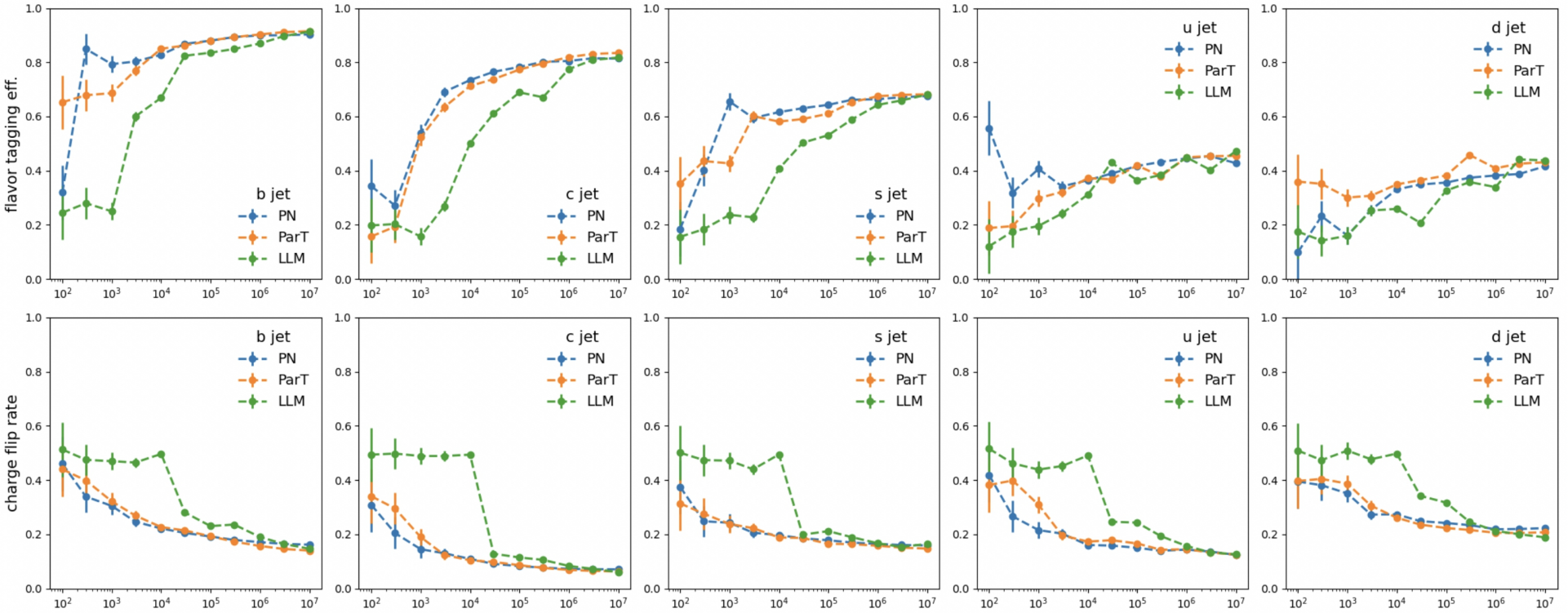
- Snowmass → holistic : improvement of 2-4 folds

Comparison with HL-LHC



- LHC mainly dominated by theoretical/systematic...
- CEPC Holistic/ACSI approach the statistic limit – more luminosity is appreciated
- CEPC numbers not include theoretical uncertainties...
- CEPC numbers are based on fast simulation: modeling an 1-1 correspondence Detector.

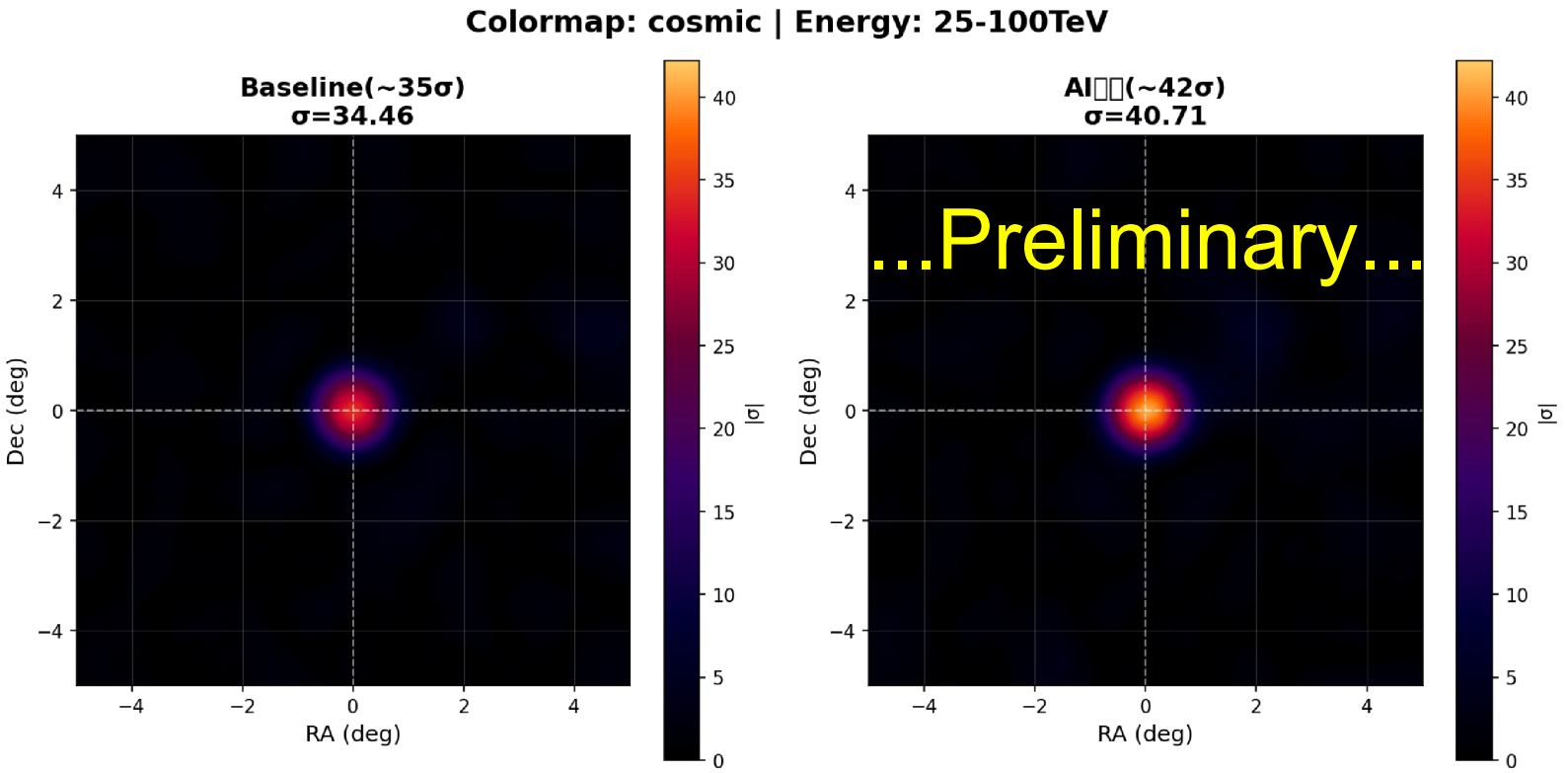
From specialized Models to LLM



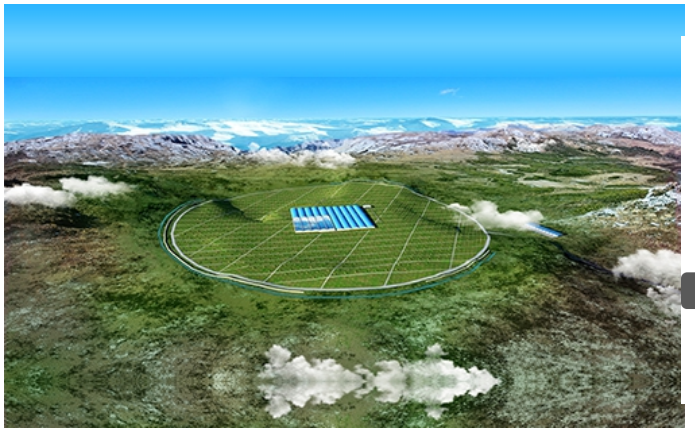
- Comparable result with different scaling behavior
- Para. Numbers: PN 360k, ParT 2.4M, BINBBT(Large Language Base Model) 150 M
- More details at: *https://arxiv.org/pdf/2412.00129*

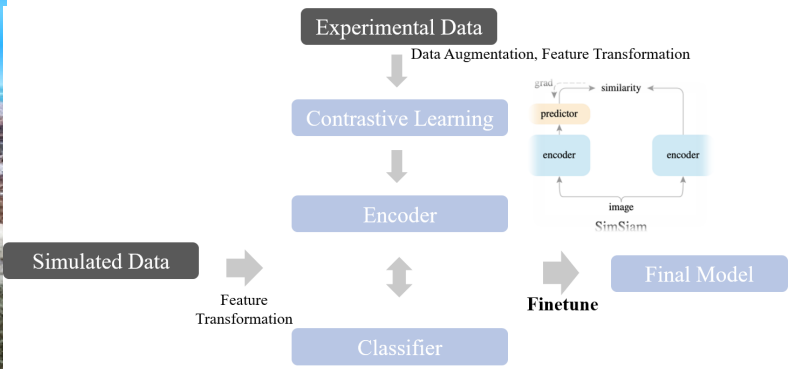
超对称
Super Symmetry Technologies

LHASSO: Learning from all hits

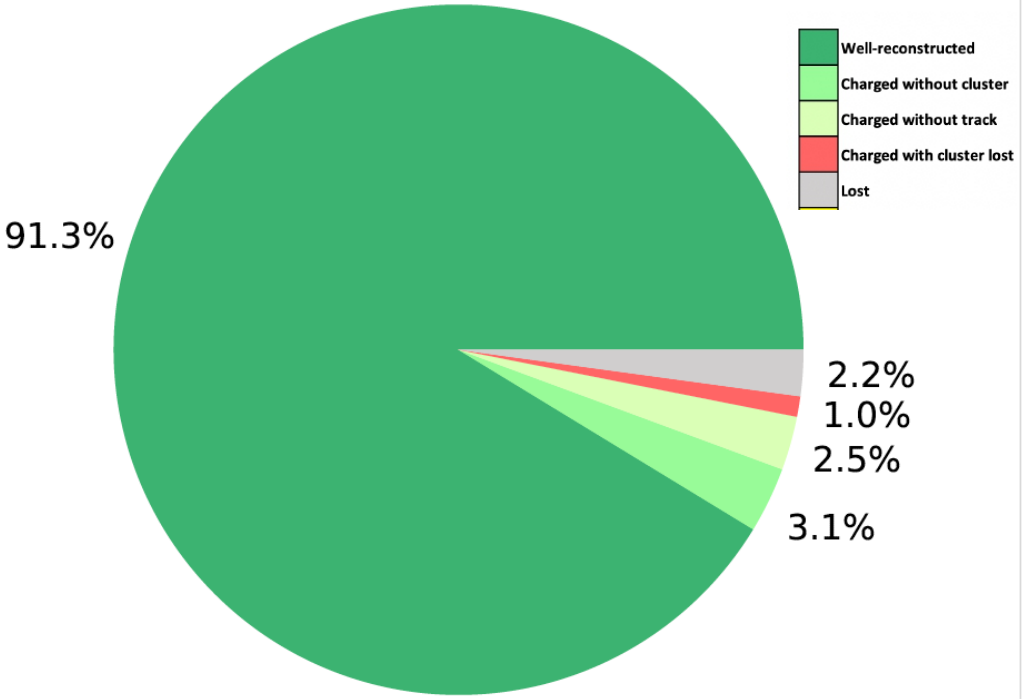


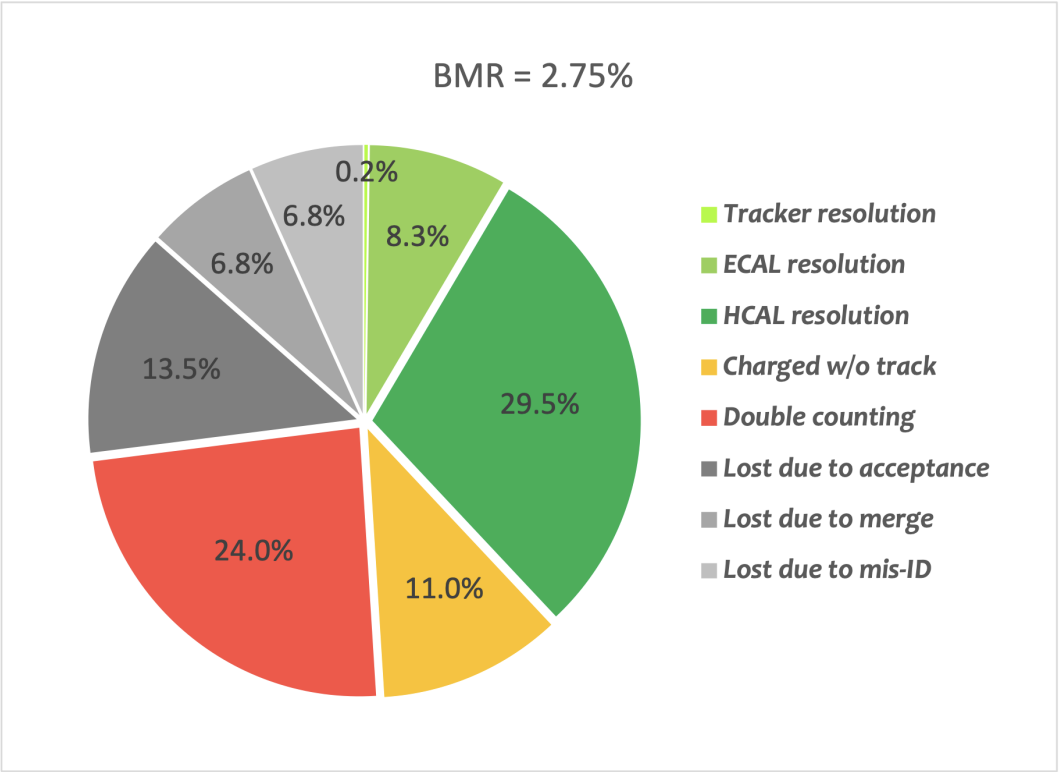
1 month of data





BMR decomposition @ AURORA

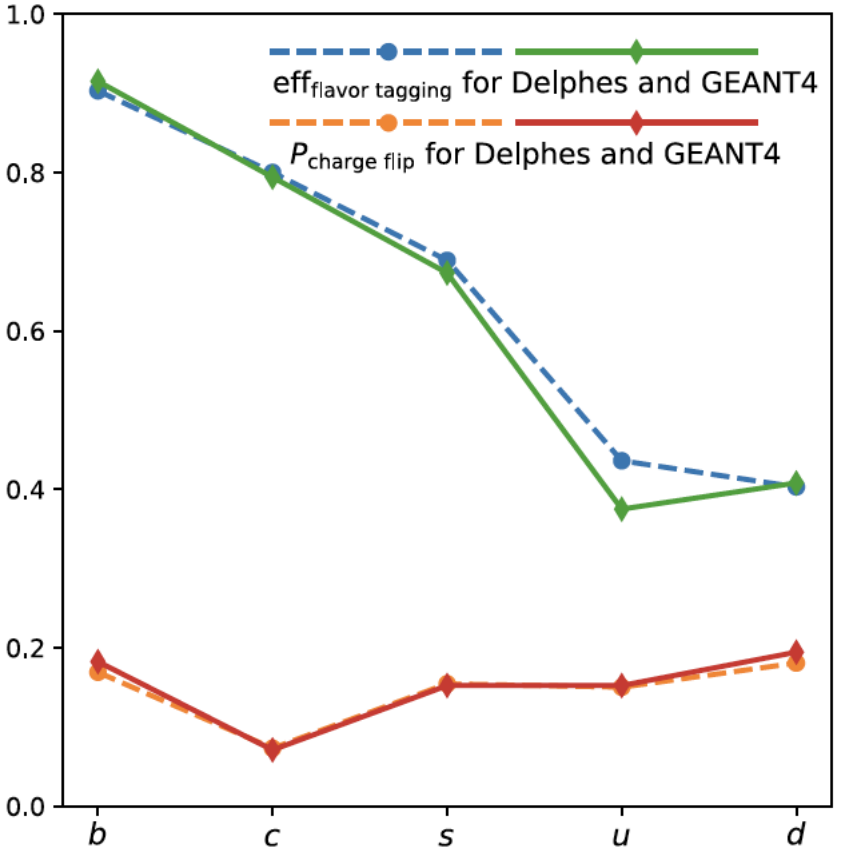


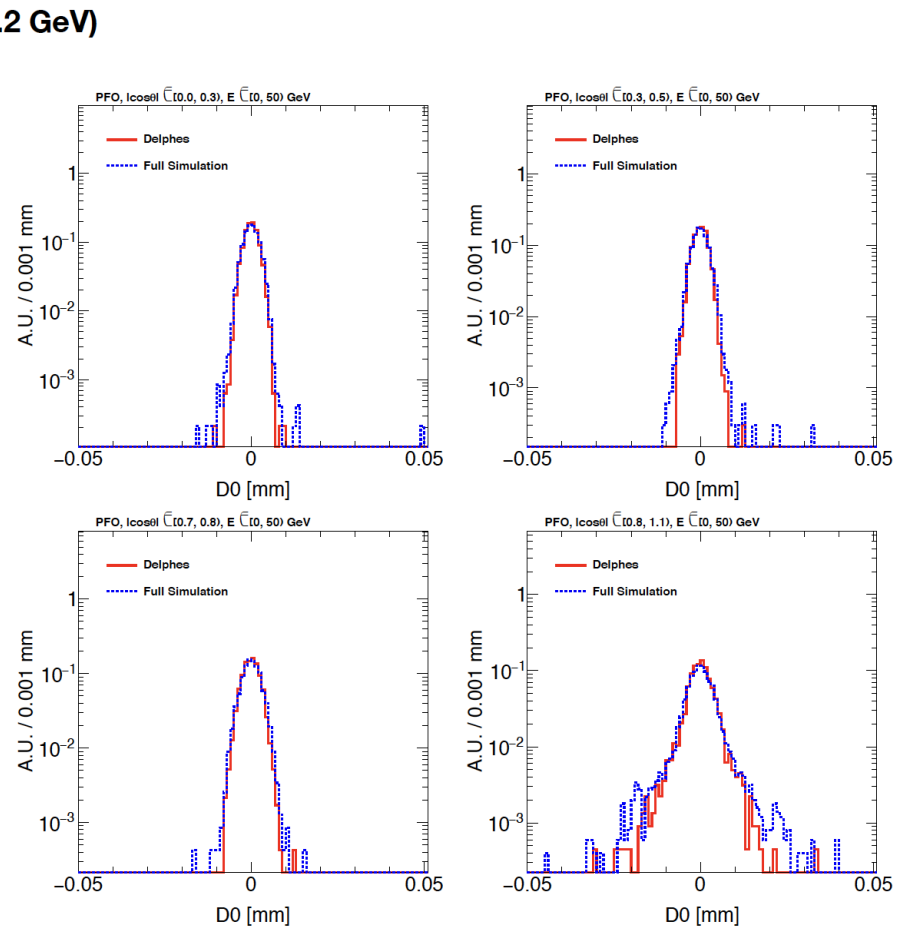


1-1 corresponding type: contributing to the BMR via resolution: ~o(0.1 – 0.001) of its mean value

Double Counting & Lost type: contributing to the BMR ~o(1) to its mean value

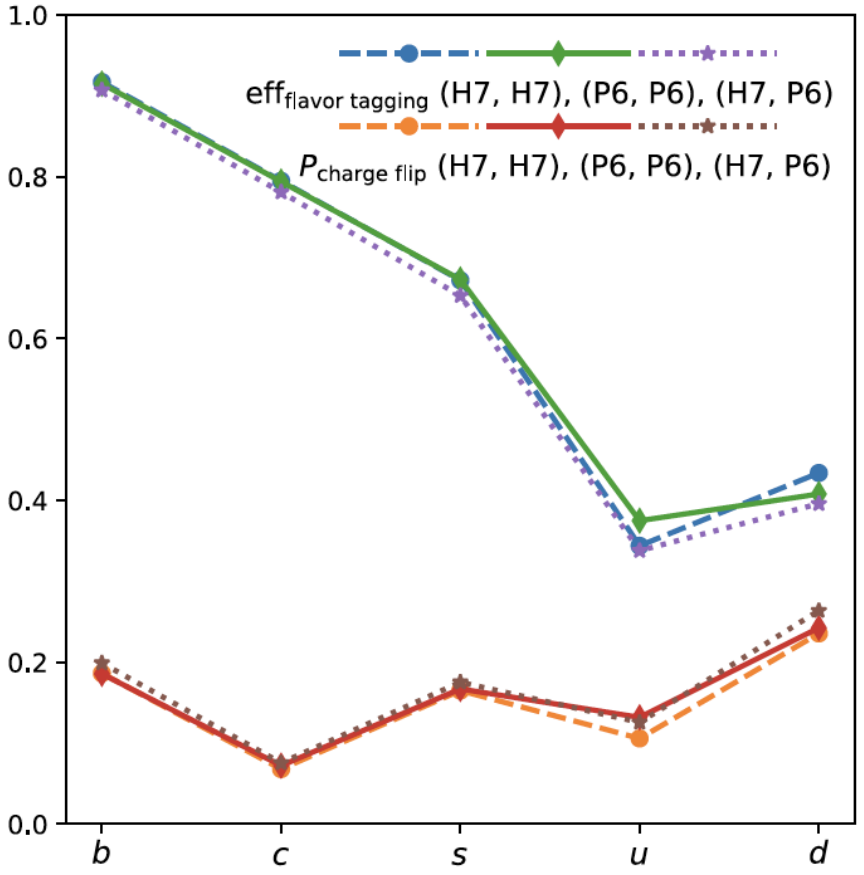
Fast/Full Simulation

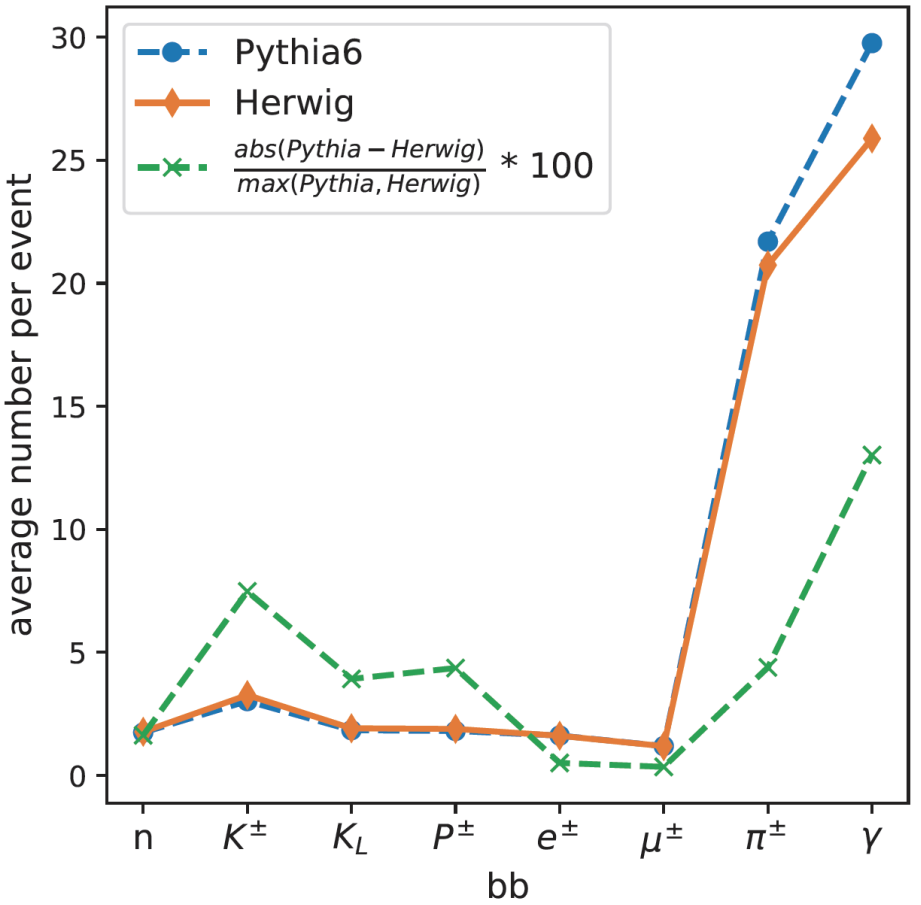




- Delphes ~ Perfect PFA (1 – 1 correspondence..)

V.S. Hadronization models





- Much severer descriptions.. in exclusive measurements (i.e., specific hadron generation, decay, etc)

GSHCAL: simulation

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Full Length Article

GSHCAL at future e^+e^- Higgs factories

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ARTICLE INFO

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CEPC
HCAL
Glass scintillator

ABSTRACT

The excellent jet energy resolution is crucial for the precise measurement of the Higgs properties at future e^+e^- Higgs factories, such as the Circular Electron Positron Collider (CEPC). For this purpose, a novel design of the particle flow oriented hadronic calorimeter based on glass scintillators (GSHCAL) is proposed. Compared with the designs based on gas or plastic scintillators, the GSHCAL can achieve a higher sampling fraction and more compact structure in a cost-effective way, benefiting from the high density and low cost of glass scintillators. In order to explore the physics potential of the GSHCAL, its intrinsic energy resolution and the contribution to the measurement of the hadronic system was investigated by Monte Carlo simulations. Preliminary results show that the stochastic term of hadronic energy resolution can reach around 24% and the Boson Mass Resolution (BMR) can reach around 3.38% when the GSHCAL is applied. Besides, the key technical R&D of high-performance glass scintillator tiles is also introduced.

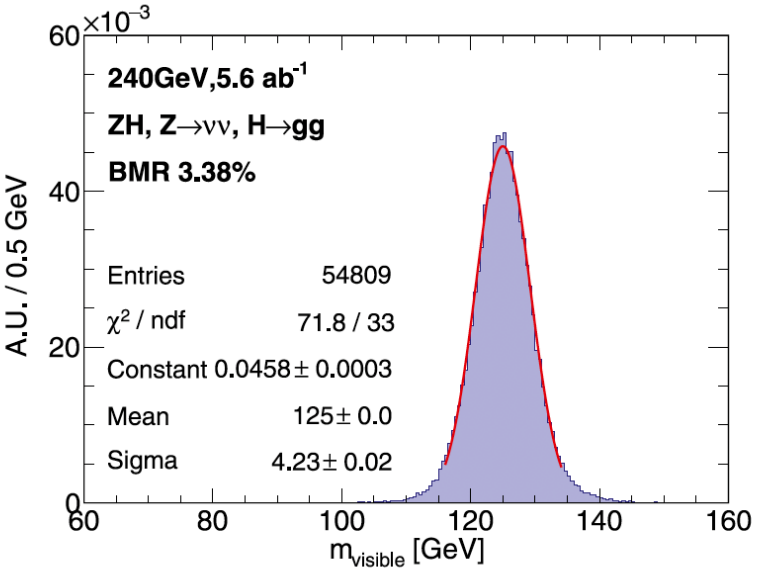
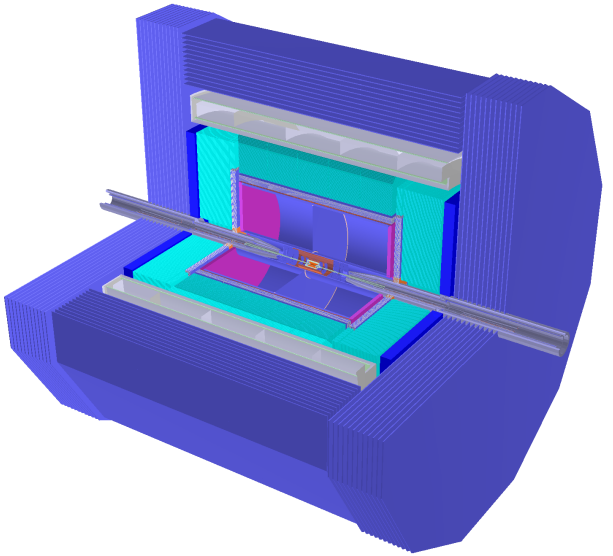


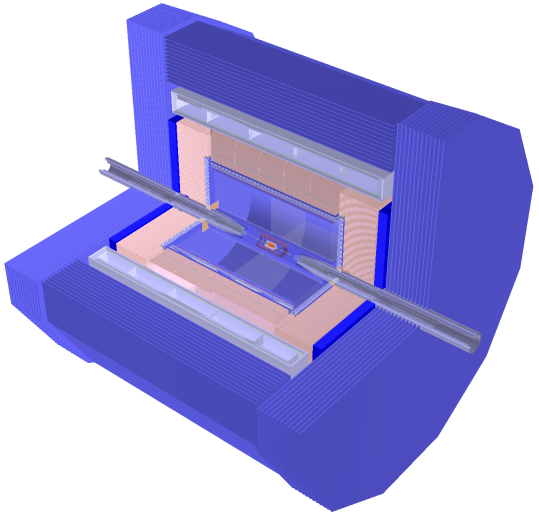
Fig. 5. Distribution of the reconstructed total visible invariant mass for $\nu\bar{\nu}H \to \nu\bar{\nu}gg$ channel. The distribution is fitted with a Gaussian function extented to ±2 standard deviations.

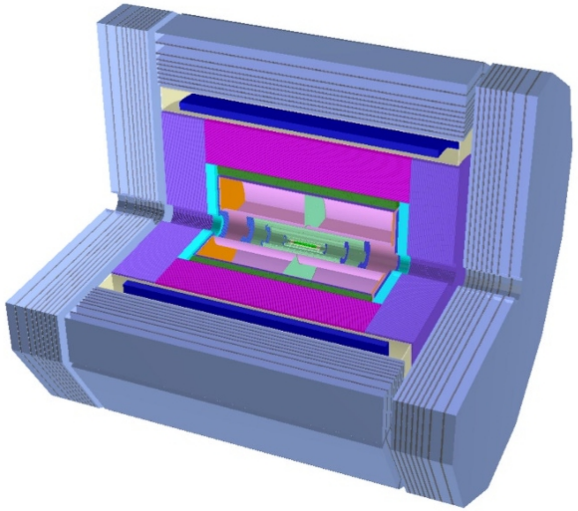
Table A.1
AURORA detector geometry parameters.

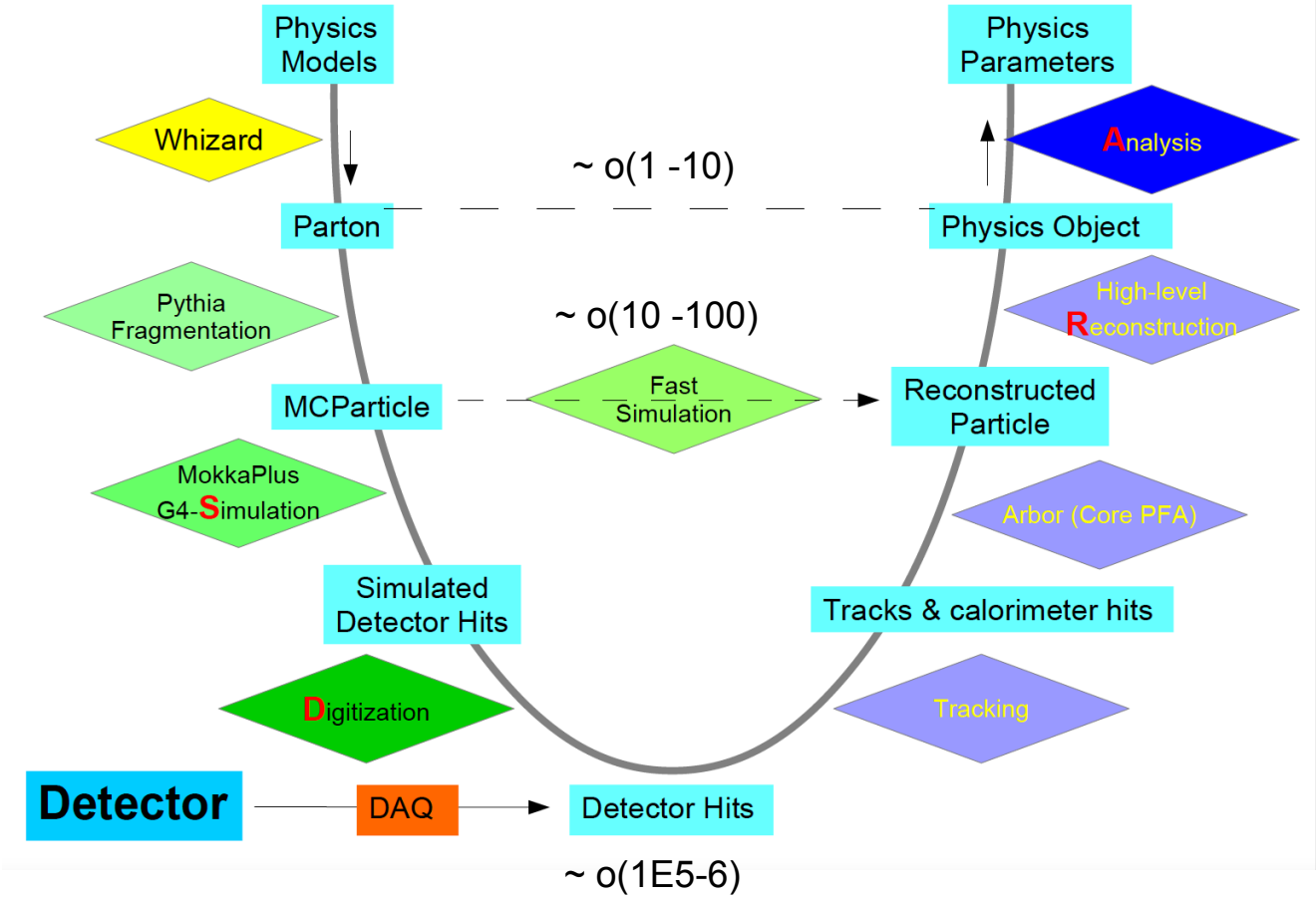
Sub-detector	Thickness (mm)	Inner radius (mm)	Outer radius (mm)	Length (mm)	Volume (m^3)	Transverse cell size	#Layers	#Channels
Vertex	-	-	16–60 155	125–250 736	-	$25 \times 25\ \mu m^2$	6	5.3×10^8
Si-strip Tracker	-	-	300 1810	1288 4600	-	$20\ \mu m \times 2$ cm	3	3.0×10^7
TPC	-	300	1800	4700	47	$1 \times 6\ mm^2$	220	2.9×10^6
ECAL	173	1845	2018	5250	15	$1 \times 1\ cm^2$	30	2.5×10^7
HCAL	1145	2072	3250	7590	180	$2 \times 2\ cm^2$	48	1.8×10^7
Solenoid	700	3275	3975	7750	120	-	-	-
Yoke	1200	4000	5200	10500	470	-	-	-



CEPC Detector & Reconstruction







PFA oriented Approach: **Arbor, etc**