Detector Optimisation for Future Colliders

Jenny List

KET Strategieworkshop
18./19. November 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

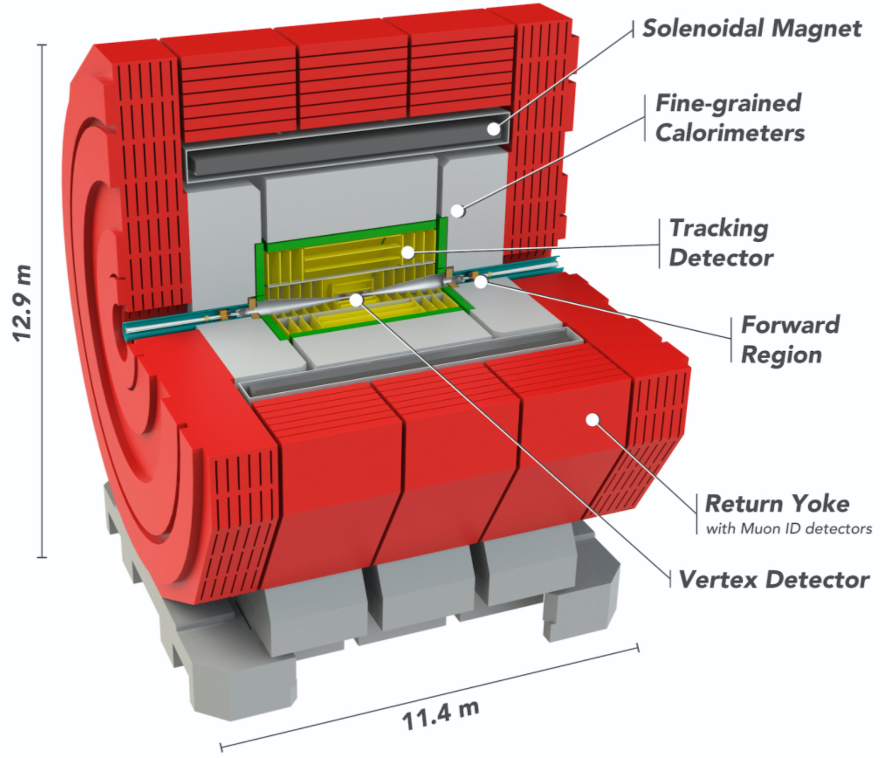
DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

What is Detector (Concept) Optimisation?

Linking Physics Goals and Technology R&D

Detector R&D
- basic technology R&D
- protoypes
- testbeam
- …



Physics goals
- Higgs
- Top
- Z,W
- …

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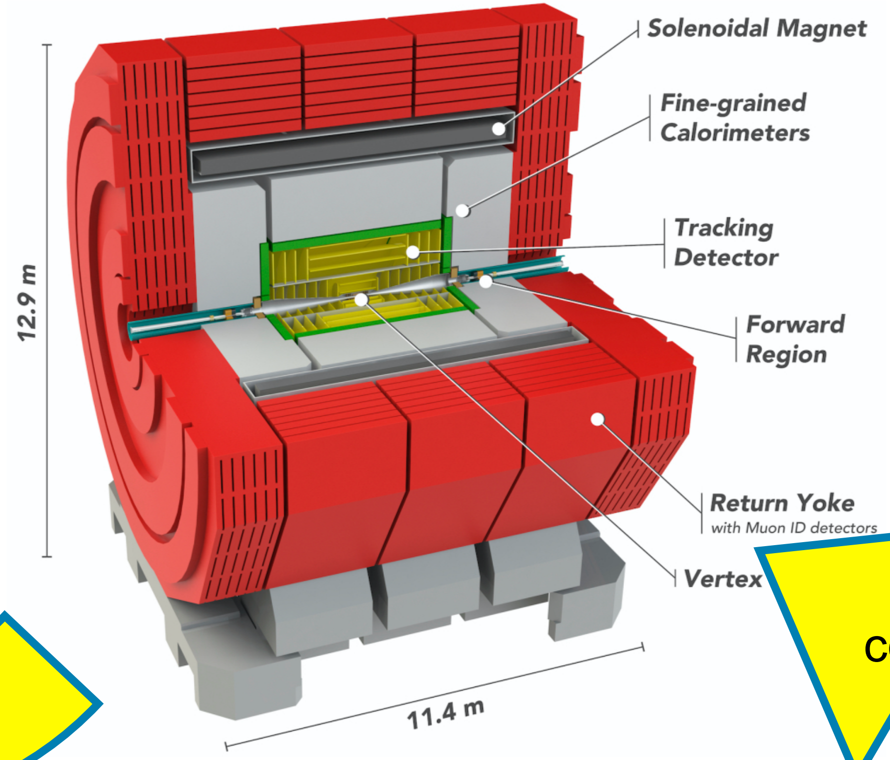

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technology requirements

concept performance requirements

What is Detector (Concept) Optimisation?

Linking Physics Goals and Technology R&D

informs
integration

performance
verification

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- basic technology R&D
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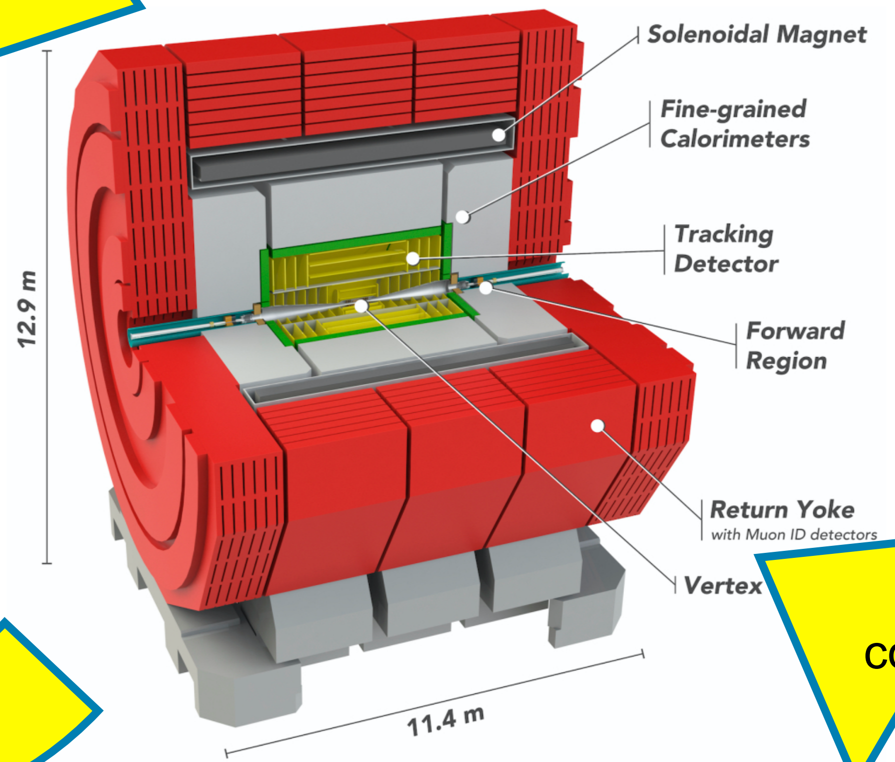

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technology
requirements

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Linking Physics Goals and Technology R&D

informs integration

performance verification

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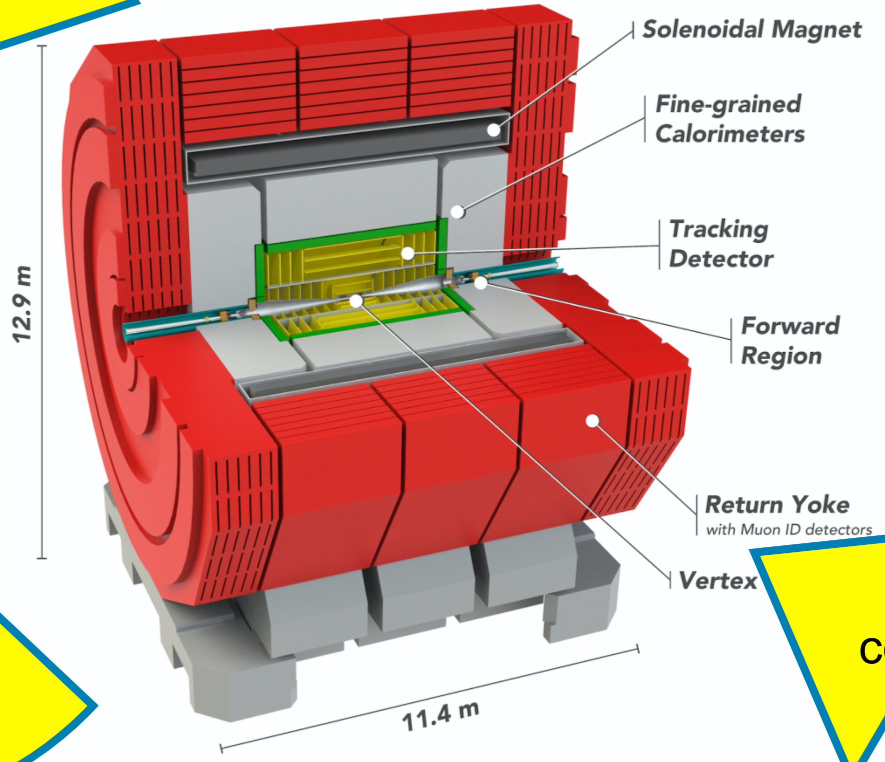

Accelerator Environment
- Time structure
- Back-grounds
- Radiation
- Space (L*)

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- …

technology requirements

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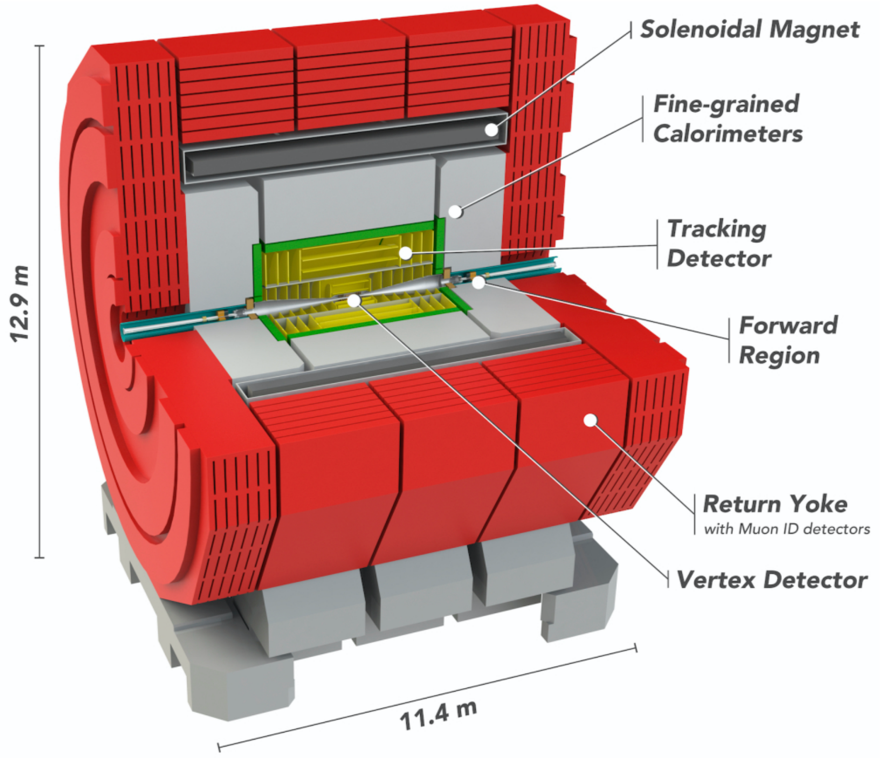
How do we do it?

"Digital twin" infrastructure links hardware & physics goals



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- **Realistic** mechanical, electrical and cooling **integration** of all subdetectors / components
- Translation to Geant4 at **adequate level of detail**
- Geant4 implementation and digitisation gauged against testbeam results from **real prototypes**
- Realistic **accelerator conditions**
- **Reconstruction algorithms at realistic level of sophistication making use of all detector features**

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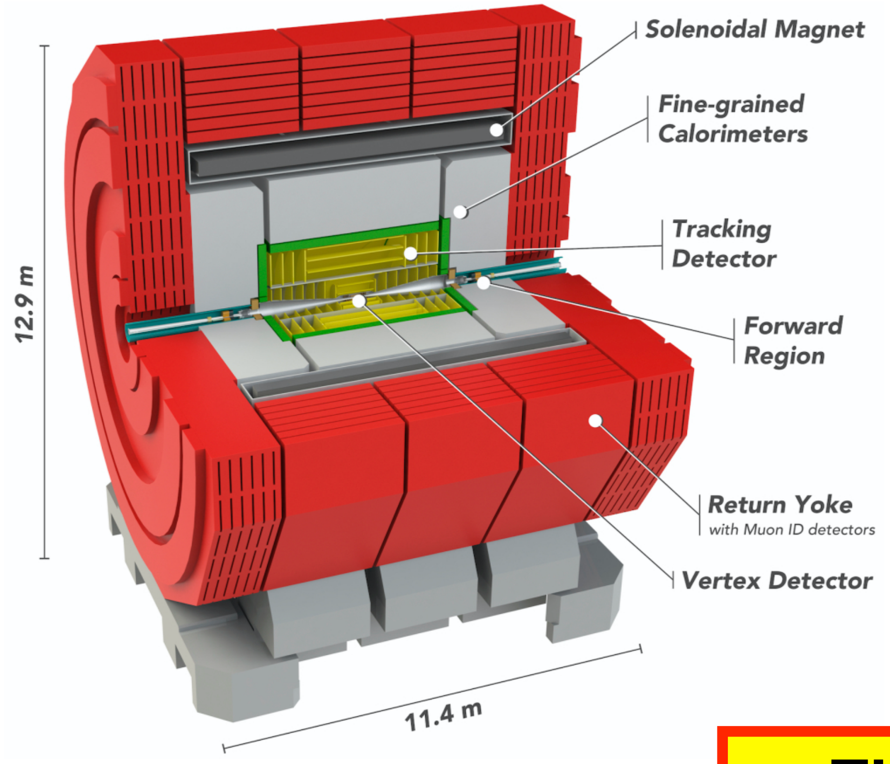

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=> THEN can start to vary properties of detector

(B-field, overall dimensions, calo cell sizes, postions of tracker layers, alternative technologies, ….)

What we achieved since a long time

Pioneered by ILD, SiD & CLICDET

From key requirements from physics:

- **p_t resolution** (total ZH x-section)

  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$

  ≈ CMS / 40

- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)

  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$

  ≈ CMS / 4

- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%

  ≈ ATLAS / 2

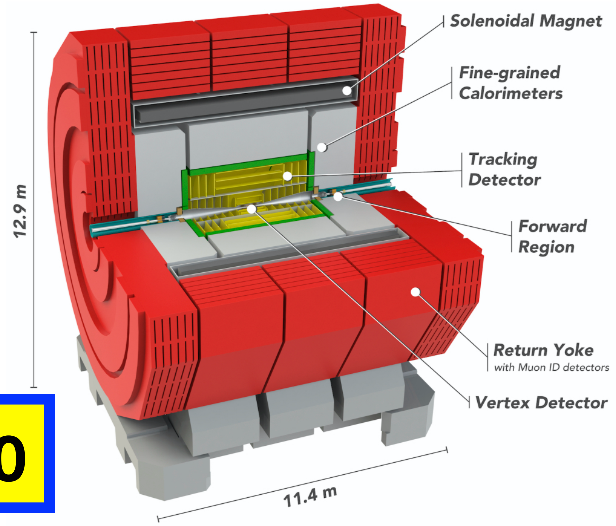
- **hermeticity** ($H \rightarrow$ invis, BSM) θ_{min} = 5 mrad

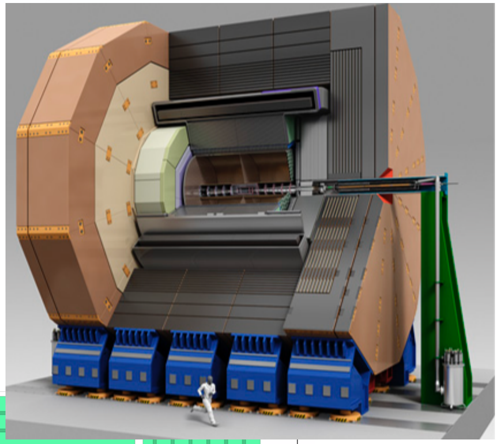
  ≈ ATLAS / 3

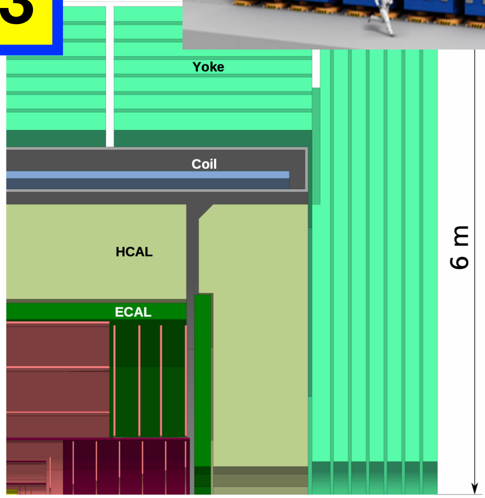
To key features of the detector:

- **low mass tracker**
  eg VTX: 0.15% rad. length / layer)

- **high granularity calorimeters**
  optimised for particle flow







Why do we keep doing this?

New questions & new ideas

- **Digital Twin infrastructure needs maintenance and modernisation**

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- **"Reconstruction algorithms at realistic level of sophistication making use of all detector features"**
  examples of rather recent additions / ongoing work
  - **From ParticleFlow to ErrorFlow:**
    evaluate jet-by-jet covariance matrix based on error propagation from individual PFOs
  - **Identification of charged hadrons and leptons in jets:**
    usage of PID in ParticleFlow, Vertexing, FlavourTagging - incl. strange-tagging & semi-leptonic B-decays
  - **Identification and constrained fitting of decays in detector volume, SM & BSM:**
    kinks, V0, prongs & Co => **long-lived exotic particles**

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- **The world is changing:**
  - **new** accelerator projects => new accelerator boundary conditions
    - eg LC bunch train structure => CC continuous collisions => up to which occupancies can eg a TPC be operated? At which price in field distortions? With which impact on momentum resolution?
  - **new** physics interests => new requirements
    - eg flavour physics: Kaon and proton ID at all momenta essential - are alternatives to TPC compatible with ParticleFlow? (Drift chamber, RICH => much more material in front of calorimeter…)
  - **new** technological possibilities => new opportunities
    - eg fast timing => **ToF PID**, ParticleFlow, background rejection, …

Time-of-Flight PID

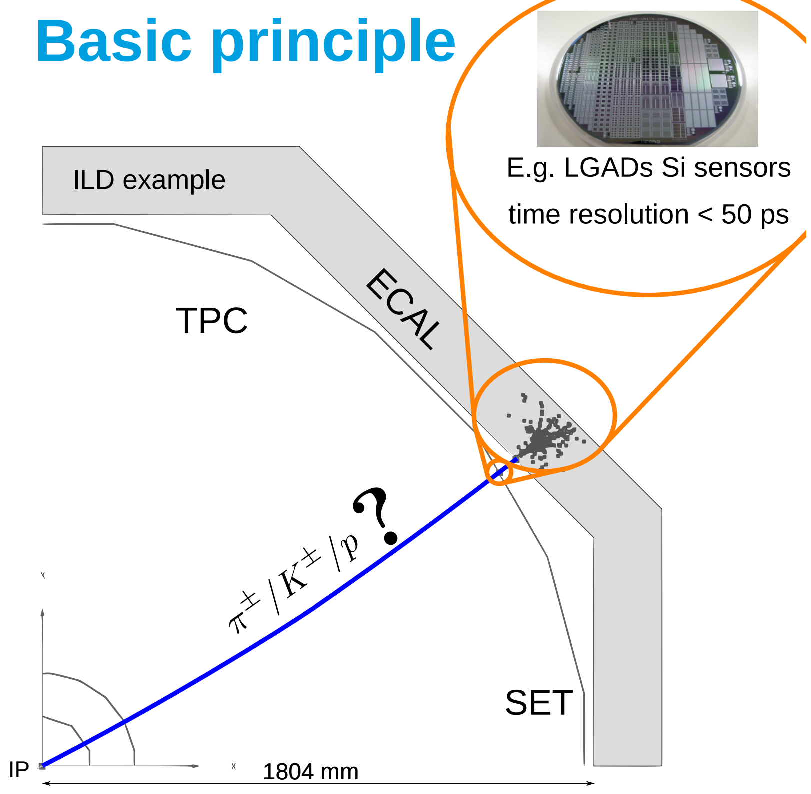
B.Dudar

What time resolutions do we need:

A. per particle ?

B. per hit ?

Basic principle



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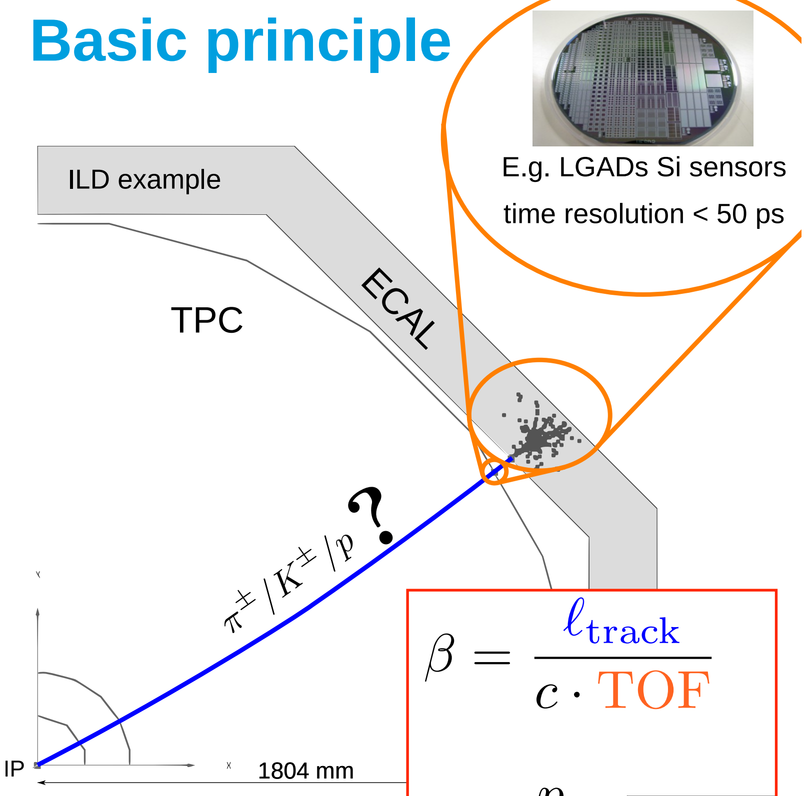

$$\beta = \frac{\ell_{\text{track}}}{c \cdot \text{TOF}}$$

$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

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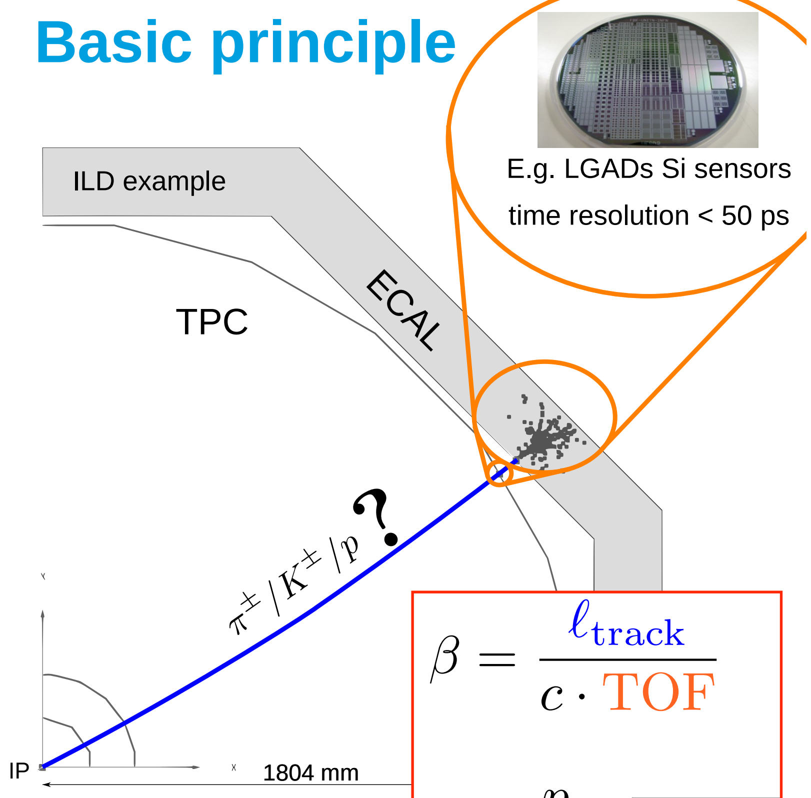

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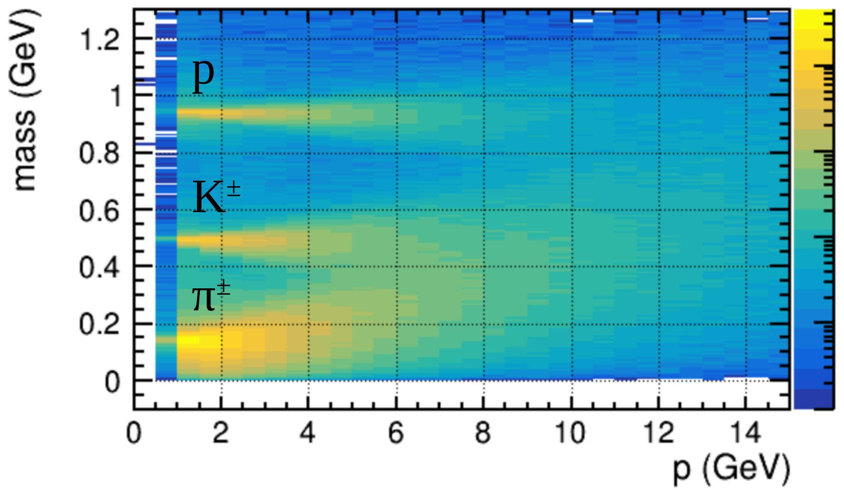

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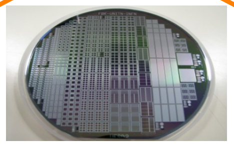
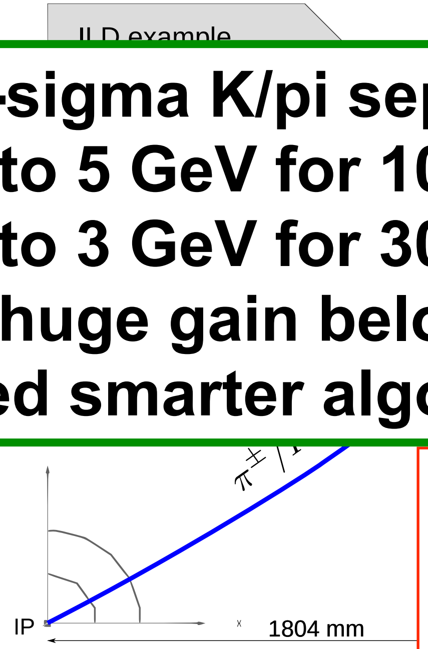


E.g. LGADs Si sensors



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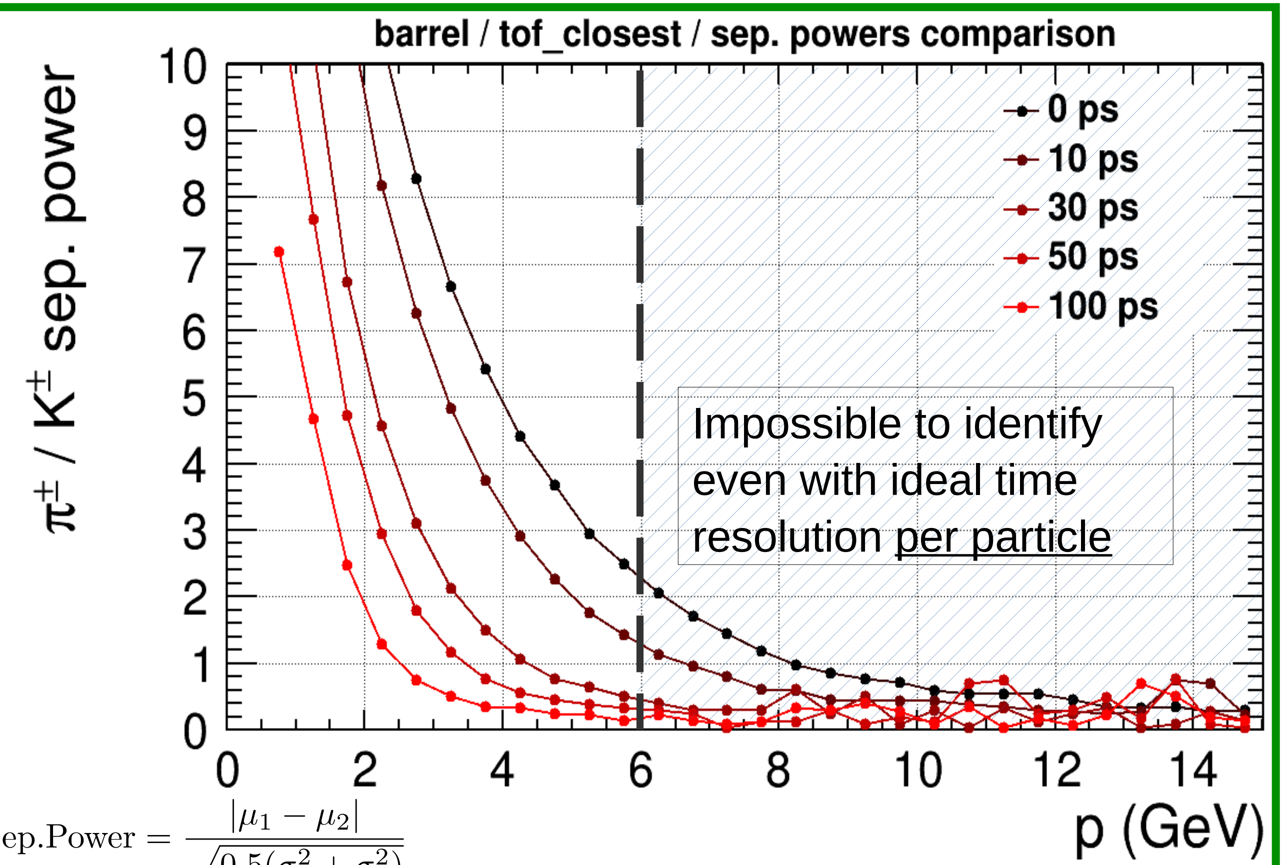
A: 2-sigma K/pi separation

- **up to 5 GeV for 10 ps**
- **up to 3 GeV for 30 ps**
- **no huge gain below 10 ps?**
- **need smarter algorithms?**



$$\text{Sep.Power} = \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}}$$

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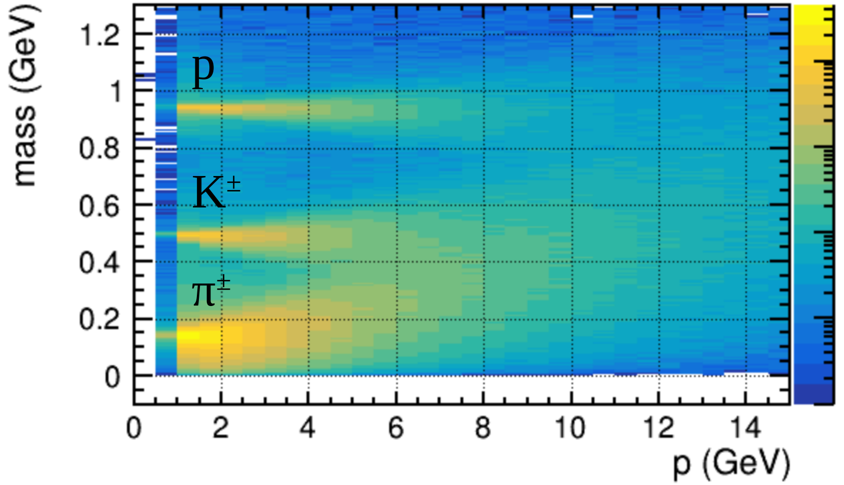

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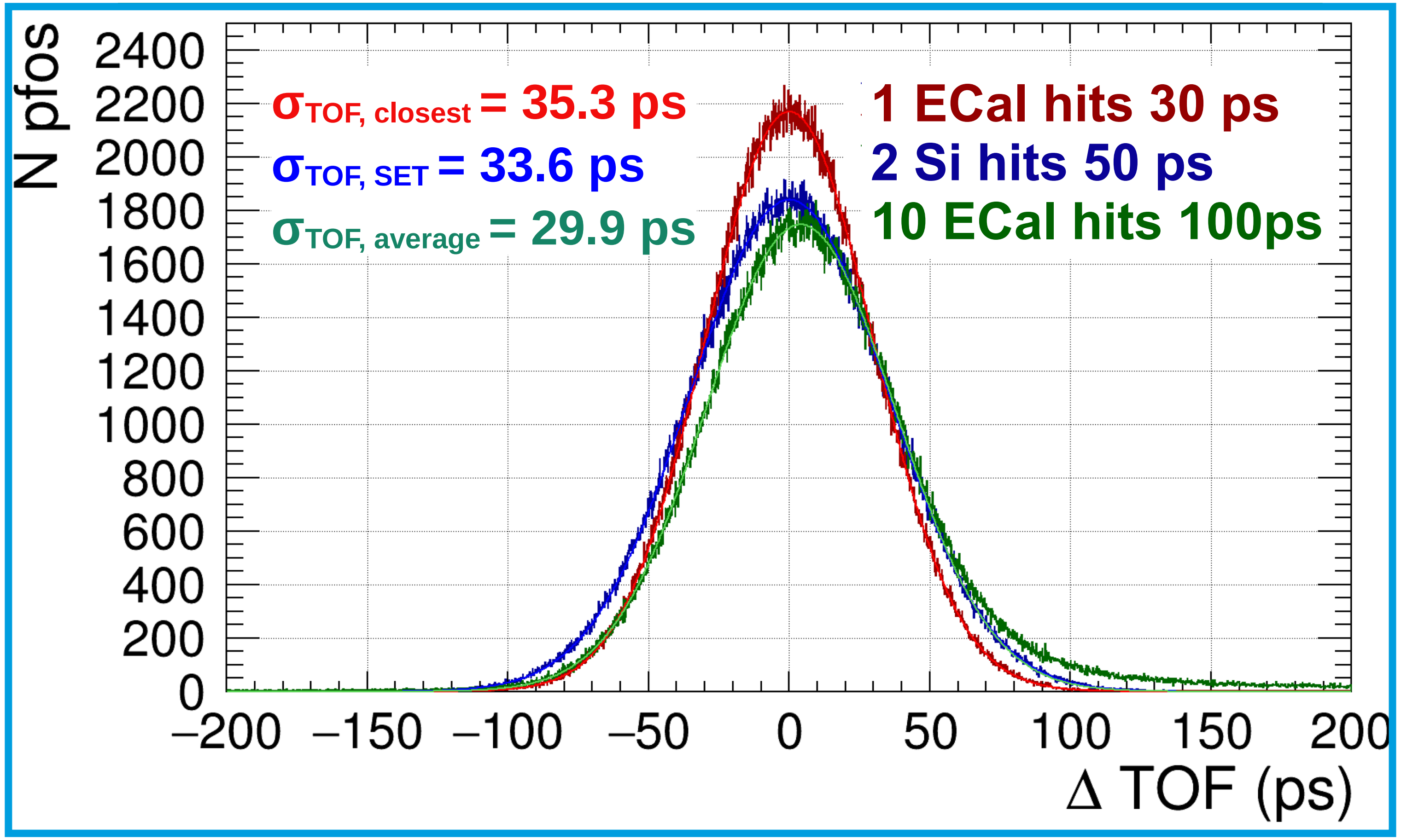

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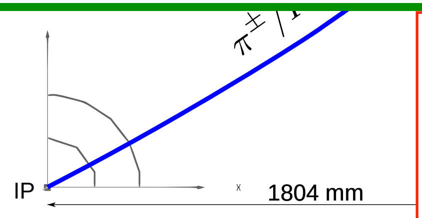

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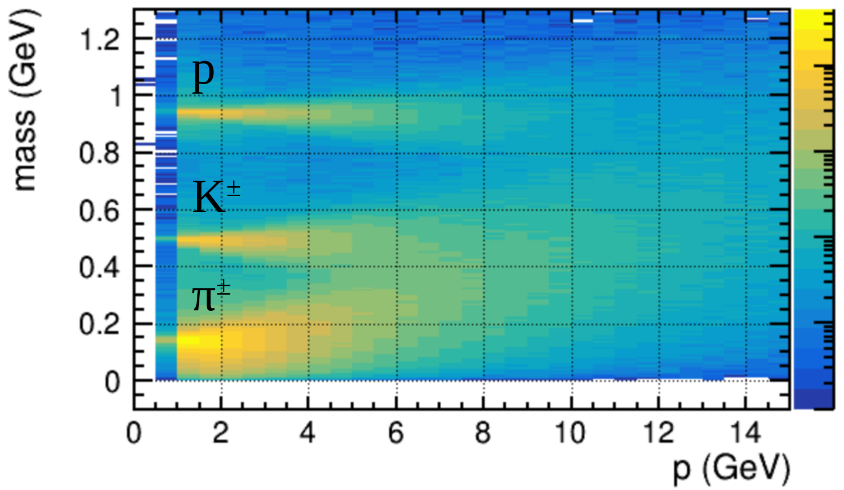

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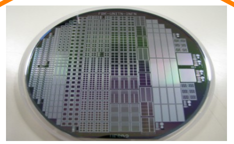
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ILD example

ps

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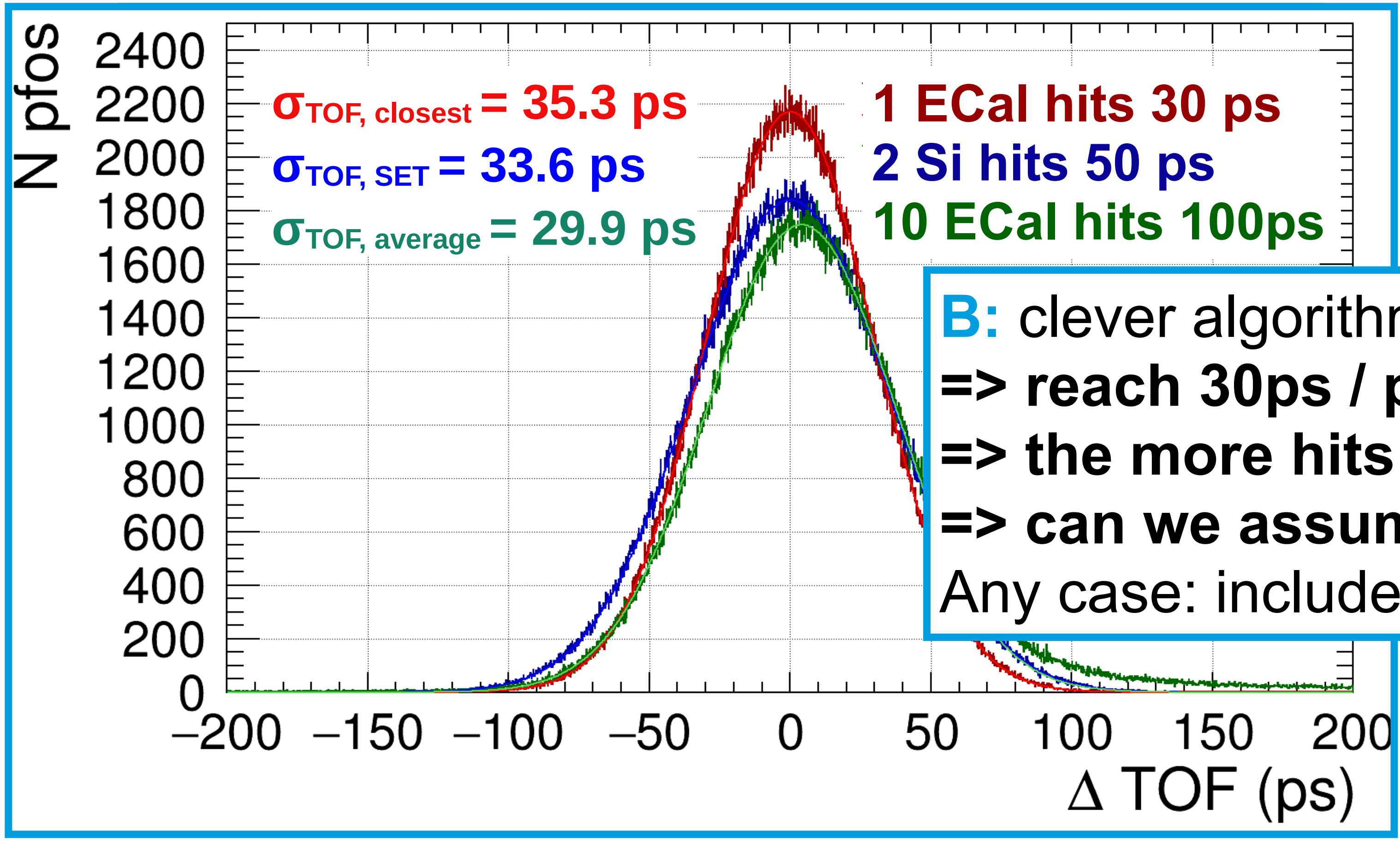
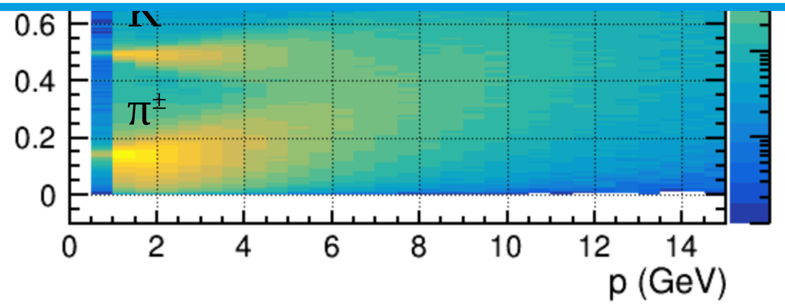


B: clever algorithms to combine hits
=> reach 30ps / particle by 30…100ps / hit
=> the more hits combined, the more bias / tails
=> can we assume better than 30ps per hit?
Any case: include more realistic digitisation etc



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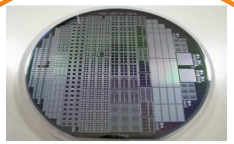

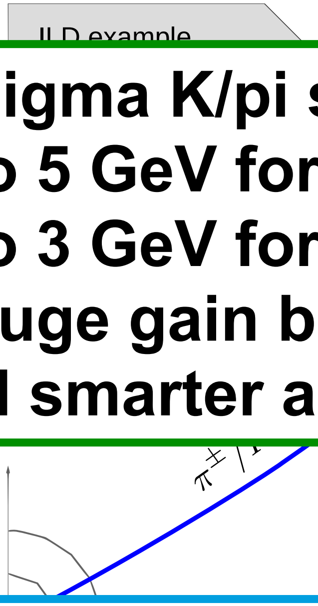

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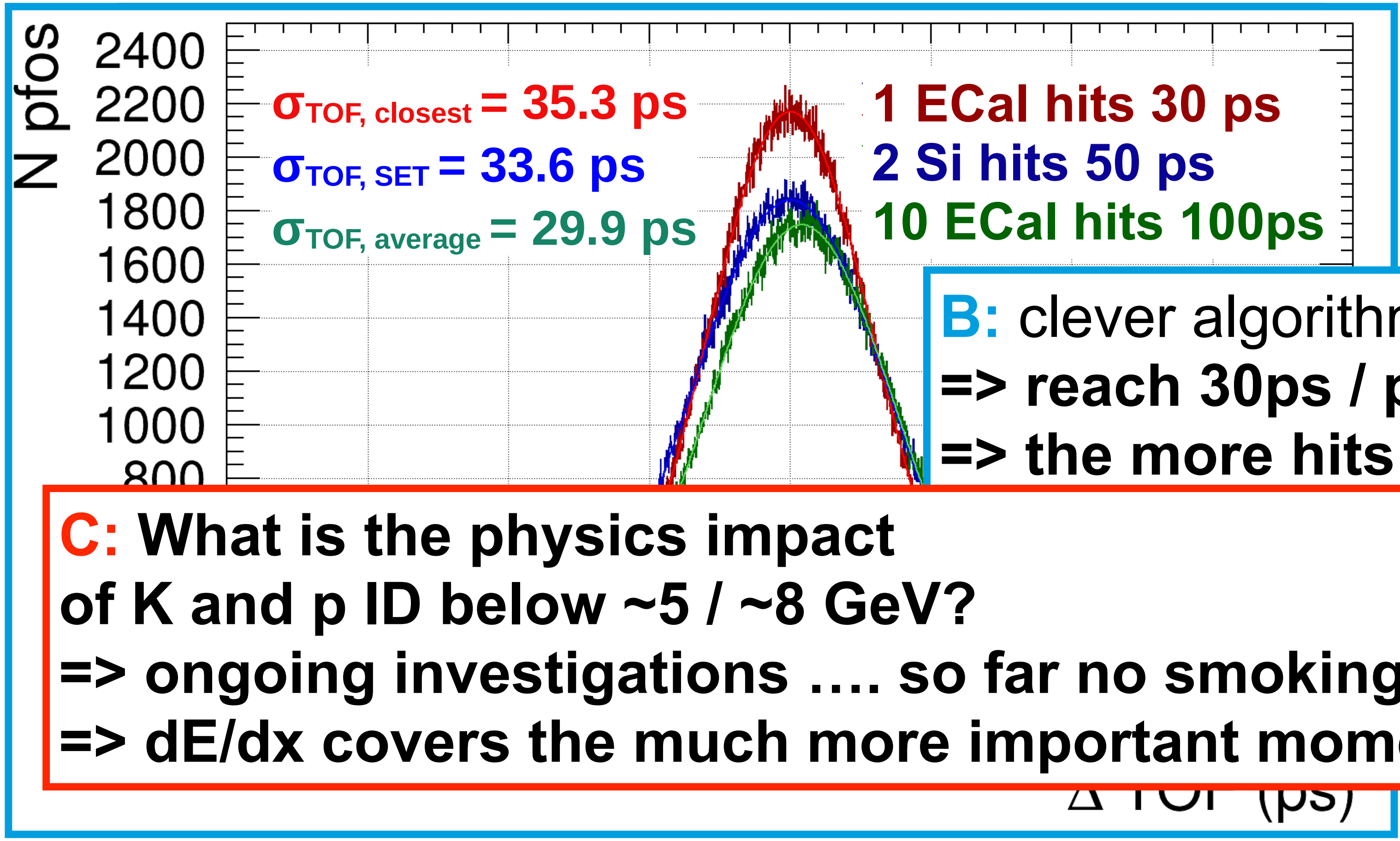

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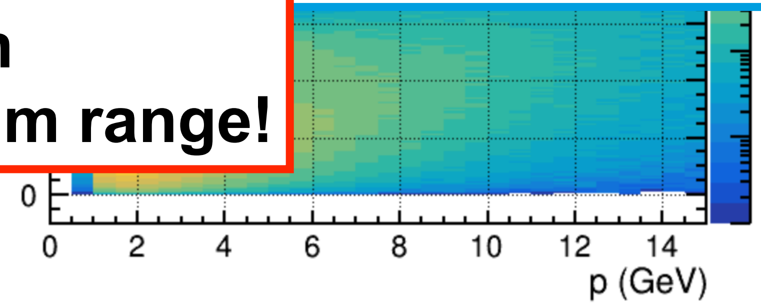
30ps per hit?

digitisation etc

C: What is the physics impact of K and p ID below ~5 / ~8 GeV?

=> ongoing investigations …. so far no smoking gun

=> dE/dx covers the much more important momentum range!



Strategic Impact of Detector Optimisation

… and why it is important now

- **we should get prepared for next collider:**
  - **European Strategy identified:** e+e- Higgs factory as the highest-priority next collider + acc & det R&D towards a ~100 TeV hadron collider
  - **Snowmass EF concludes:** “The most viable path forward for the energy frontier that has been identified during the Snowmass process is proceeding forward with the construction of a Higgs factory as soon as possible, to complement the experiments of the HL-LHC, enabling operation during or just after the operation of the HL-LHC.”
  - **still unclear wrt e+e-: Linear or circular? Where? - and: When?**

=> expect decisions by next European strategy ~2026/27
=> German community should prepare itself to have an impact — by scientific contributions (incl. detector science & data science!) important for all e+e- projects:

- **be well-prepared to take a leading role in whatever project emerges**
- **and drive eg decision about detector concepts and their technologies**
- **train students & postdocs in e+e- physics & experimental environment**
- **inform and motivate *strategic* detector R&D**

=> detector optimisation studies need to be part of a strategic preparation

Der Vorschlag für das BMBF-Strategiegespräch

Detektoroptimierung als Komponente der Verbünde für Strategische Detektorentwicklung

- **Wissenschaftliche Zielsetzung: Detektorentwicklung geleitet von wissenschaftlichen Zielen zukünftiger Experimente**
- **Stärke der (geplanten) Beteiligung in D:** ~ 20 FTE / 5MEUR aus der Verbundforschung + Matching + HGF (Einordnung unten), **davon kleiner Anteil für Detektoroptimierung, z.B. Bruchteil von FTE pro Uni.**
- Welche **besondere Expertise der beteiligten Institute** wird genutzt? Detektorentwicklung, deutsche Kernkompetenzen im Bereich Silizium, Kalorimetrie, Gasdetektoren; **dazu übergreifende Expertise in Elektronik, Software, Experiment-Konzepten und deren wissenschaftlichen Zielen**
- **Welchen Impact hat die deutsche Beteiligung? Mitgestaltung der europäischen und weltweiten R&D-Landschaft, Entwicklung zukünftiger Collider-Experimente**
- **Bezug zur Europäischen Strategie?** Implementierung der ECFA Detektor R&D Roadmap, **Integration in ECFA Higgs-Top-EWK Factory Studie**
- **Zeitskala: Aktuell bis zum Abschluss der nächsten European Strategy for Particle Physics: Die zwei nächsten FPs – 7/24 – 6/30**
- **Dringlichkeit in der Förderperiode 7/24-6/27:** Implementierung der ECFA Detektor Roadmap startet 2024; **fundierter deutscher Input zur nächsten europäischen Strategie und zur Entscheidung zu Zukunftsprojekten essentiell, Arbeit dazu muss in der nächsten FP erfolgen**

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Detektoroptimierung als Komponente der Verbünde für Strategische Detektorentwicklung

- **Wie wird das Vorhaben innerhalb der Community organisiert?** Drei Verbünde (Silizium, Kalorimeter, Gas) leisten die deutschen Beiträge zu den sich gerade formierenden DRD Collaborations entlang der Task-Force Struktur der ECFA Detector R&D Roadmap, **sowie zur ECFA Higgs-Top-EWK Factory Studie. Eine zentrale Unterstützung durch einen Hub am DESY (HGF) ermöglicht relativ kleinen Aktivitäten an den einzelnen Uni-Instituten erfolgreiche Beiträge mit hohem Impact auf europäischer (und weltweiter) Ebene.**
- **Welche großen nationalen bzw. internationalen Infrastrukturen werden genutzt? DESY, CERN Infrastruktur, insbesondere Testbeams.**
- **Worin liegt das Bundesinteresse? Strategische R&D zur Positionierung der deutschen Gruppen für zukünftige Projekte der Teilchenphysik, dadurch die Grundlage zur Nutzung zukünftiger Großgeräte**
- **Welche Technologieentwicklungen sind geplant? Besteht Möglichkeit/Interesse an Industrie-Transfer?** R&D Projekte: Technologieentwicklung in Sensoren, Elektronik, **Systemen, Software**. Industrietransfer in einigen Bereichen möglich. **Darüber hinaus Stärkung der Kontakte zwischen deutscher Industrie und CERN, Positionierung für industrielle Beiträge zum nächsten Großgerät**
- **Welche Nachhaltigkeits-Aspekte sind wichtig, wie werden sie adressiert? Optimierung von Detektortechnologien und Detektorkonzepten – auch hinsichtlich Energie- und Rohstoffbedarf.**

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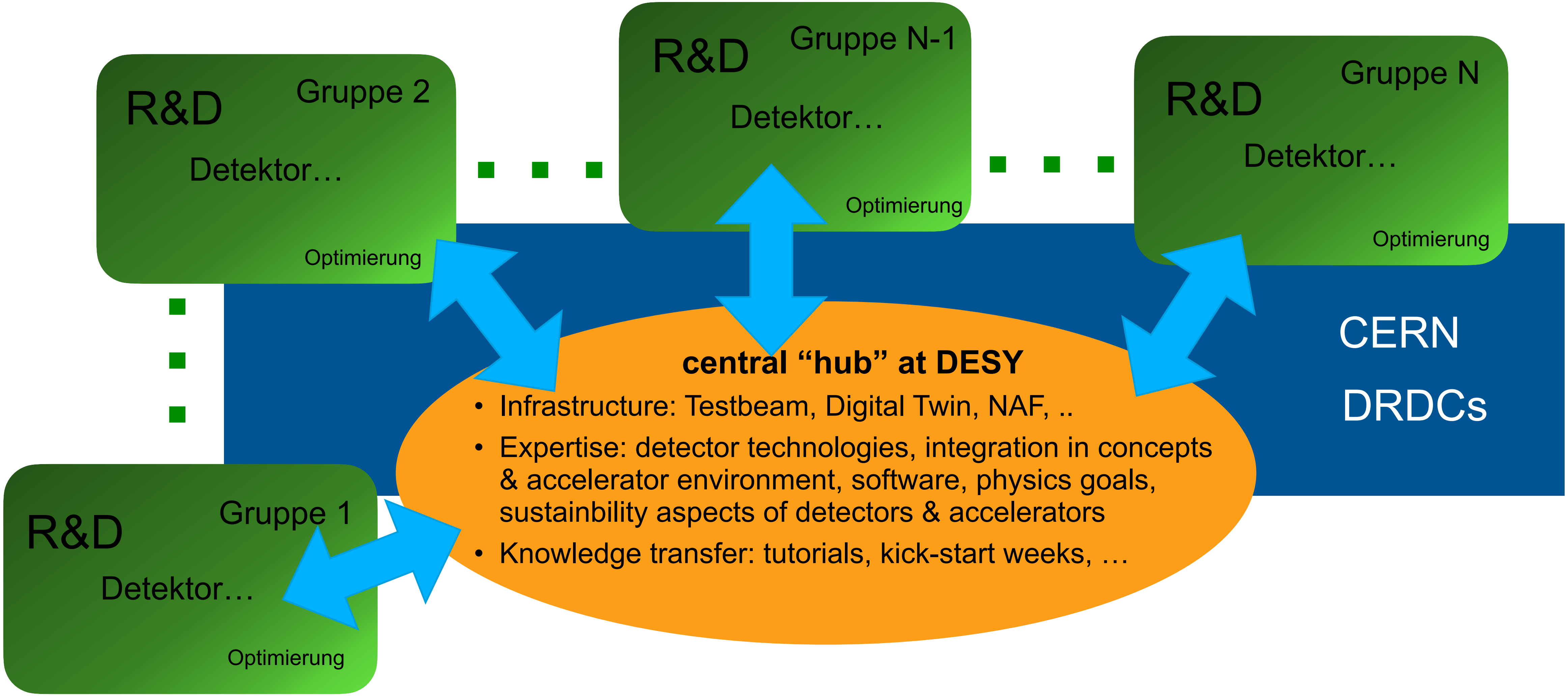
Allgemeiner: Wie können wir unsere physikalischen Ziele mit möglichst geringem Ressourceneinsatz erreichen?

A coherent program of HGF, MPG, Universities

… covering physics studies, development of software and analysis methods, and detector R&D



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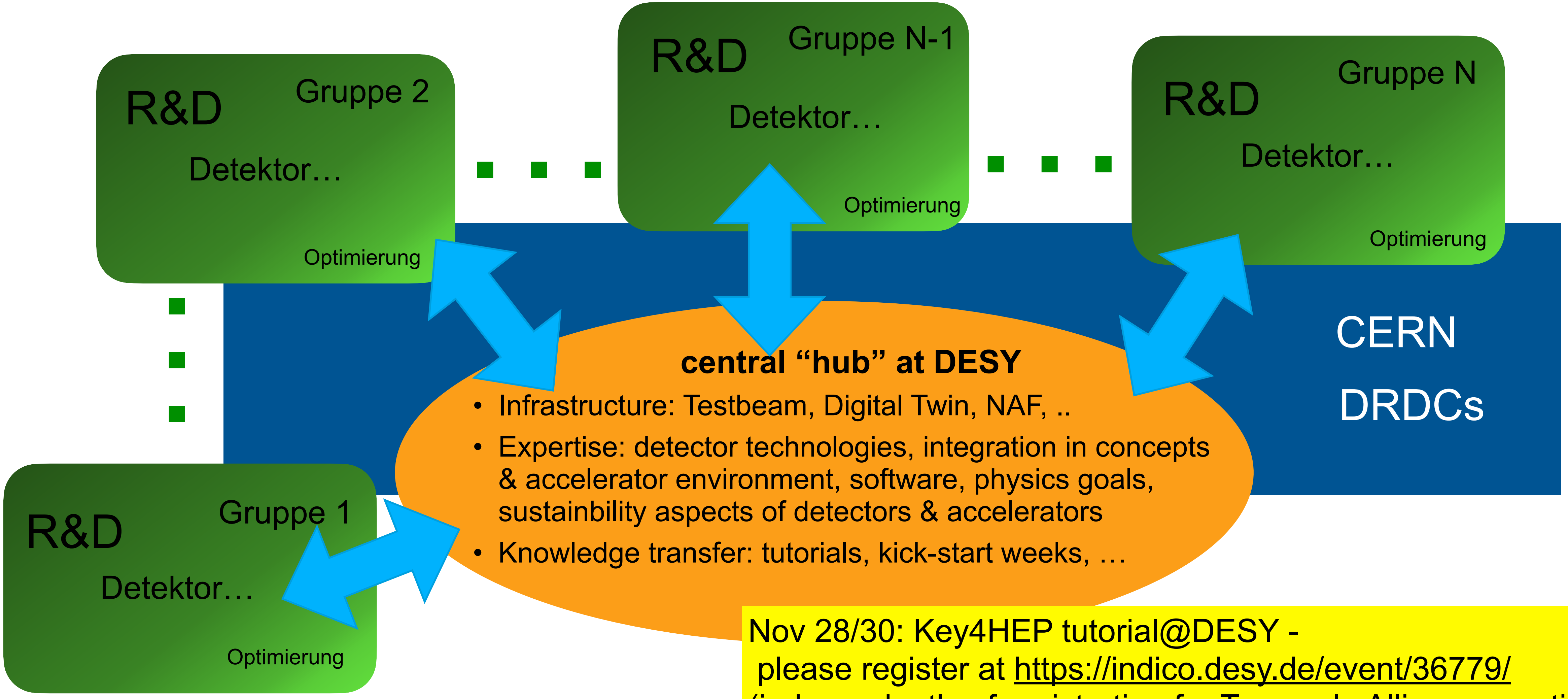


Nov 28/30: Key4HEP tutorial@DESY -
please register at https://indico.desy.de/event/36779/
(independently of registration for Terascale Alliance meeting!)

Backup

more examples

ErrorFlow

Y.Radkhorrami

- Covariance matrix for jet $C_{jet} = \Sigma C_{PFO} \oplus C_{confusion}$:
  - C_{PFO} from track fit for charged particles & V0s
  - C_{PFO} from cluster shape & intrinsic calo resolution for neutral PFOs
  - $C_{confusion}$ from parametrisations of confusion in PandoraPFA
- Advantage
  - jets with small hadronic energy fraction are better measured
  - can exploit this eg in kinematic fits

Application of kinematic fit to $e^+e^- \to ZH \to \mu\bar{\mu}bb$ events

Parameters of jets and leptons are variated within their uncertainties to satisfy 5 constraints:

Conservation of momentum (hard constraints):

- p_x: e^+e^- crossing angle: 14 mrad
  $\Sigma p_x = \sqrt{s} \times \sin 0.007 \approx 1.75$ GeV
- p_y: $\Sigma p_y = 0$
- p_z: $\Sigma p_z = 0$

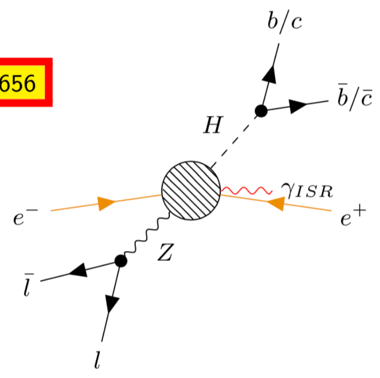
Conservation of total energy (hard constraint):

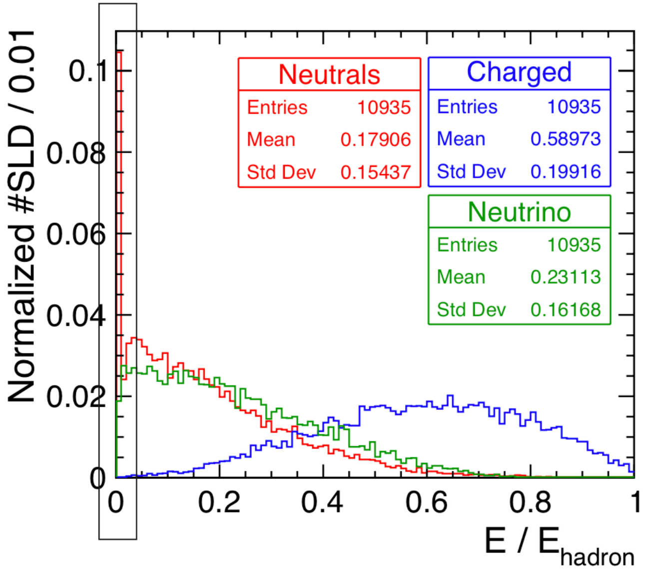
- $E_{lab} = 2\sqrt{(\frac{\sqrt{s}}{2})^2 + (\Sigma p_x)^2}$

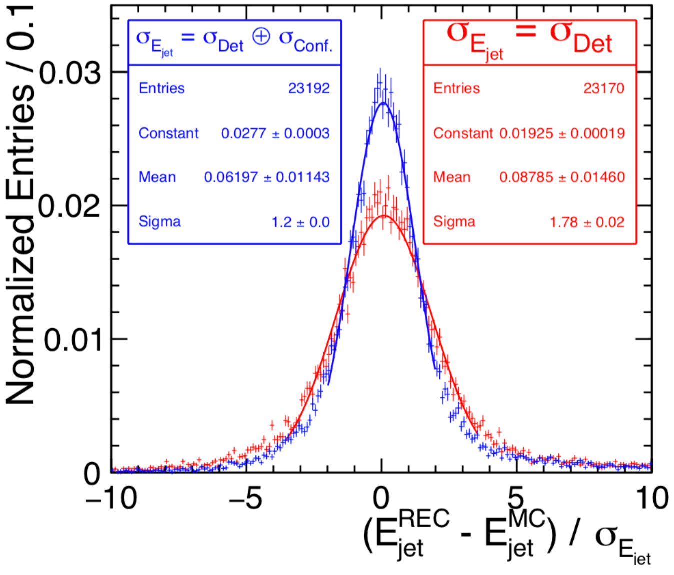
Constrain di-muon mass to agree with m_Z within its natural width (soft constraint):

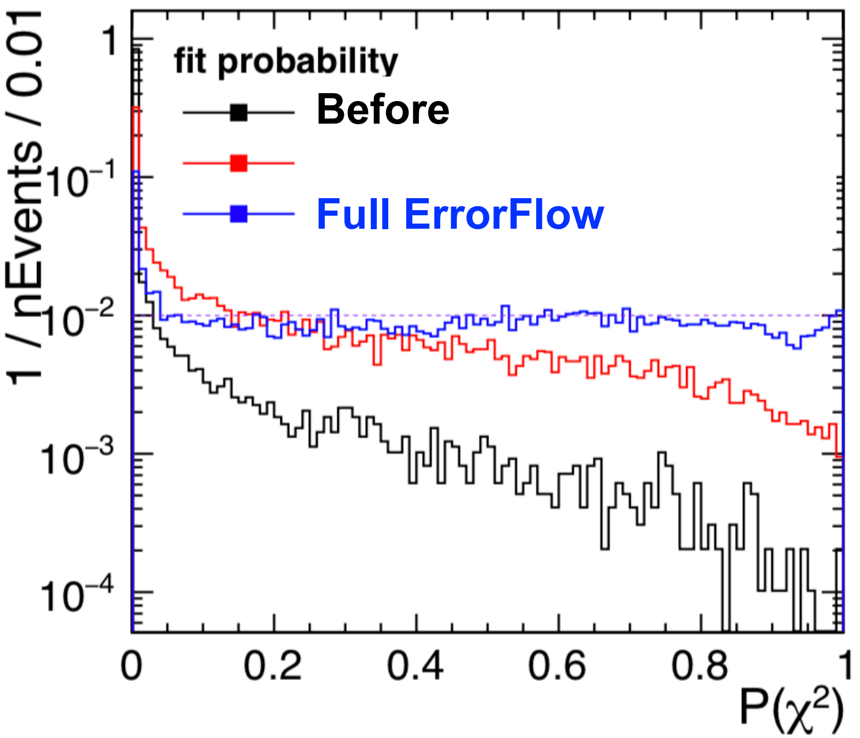
- $m_Z = 91.2$ GeV , $\sigma_{m_Z} = \frac{2.5}{2}$

arXiv:0901.4656









Semi-Leptonic B-decays

Y.Radkhorrami

- only ~30% of H->bb do **not** have a semi-leptonic B or D decay
  => significant impact on reconstructed di-jet mass
- **developed method to find E,p nu if**
  - identifie by presence of e or mu & 2nd vtx
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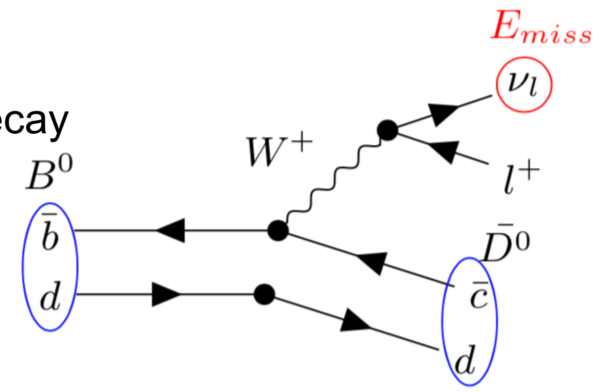

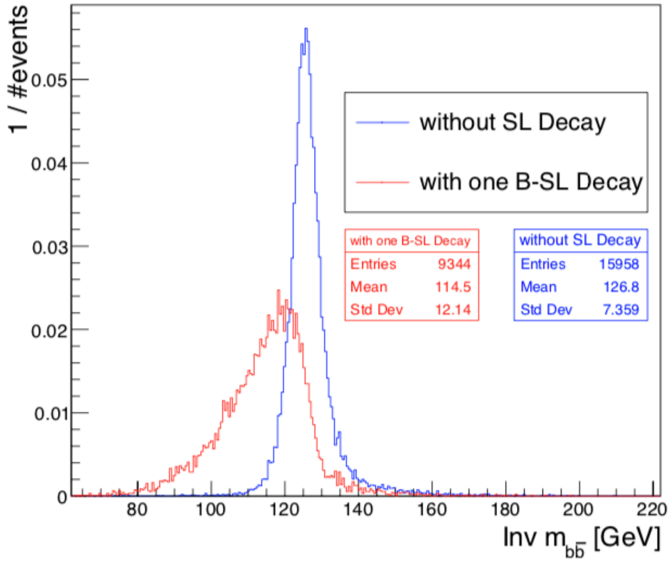

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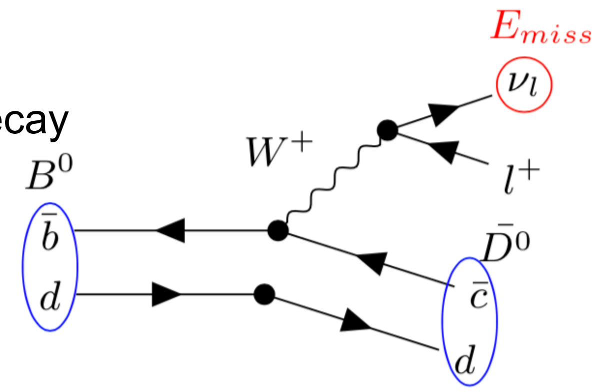

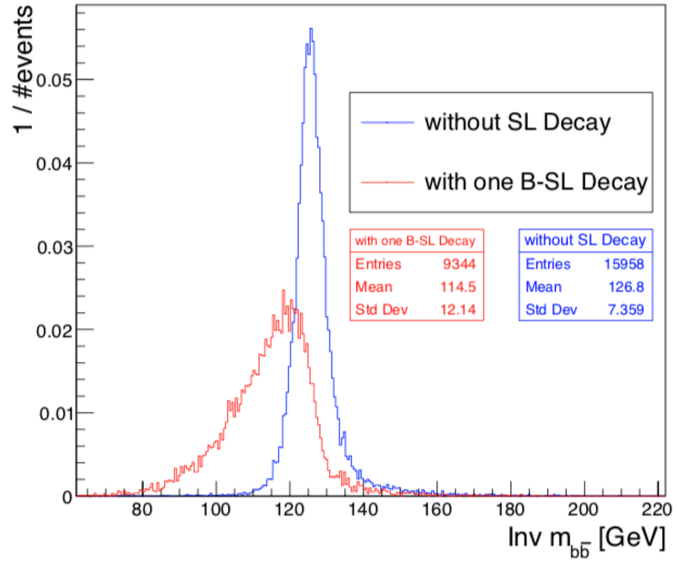

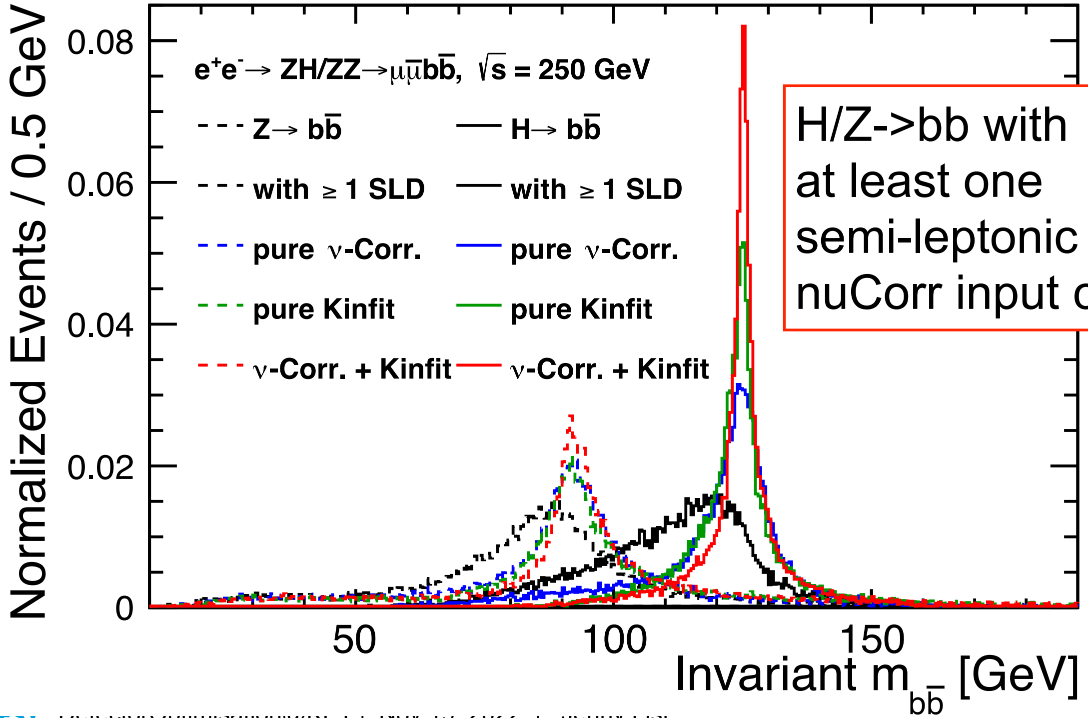

H/Z->bb with
at least one
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nuCorr input cheated

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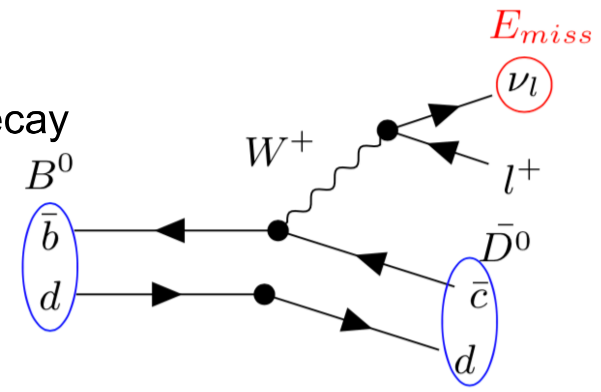

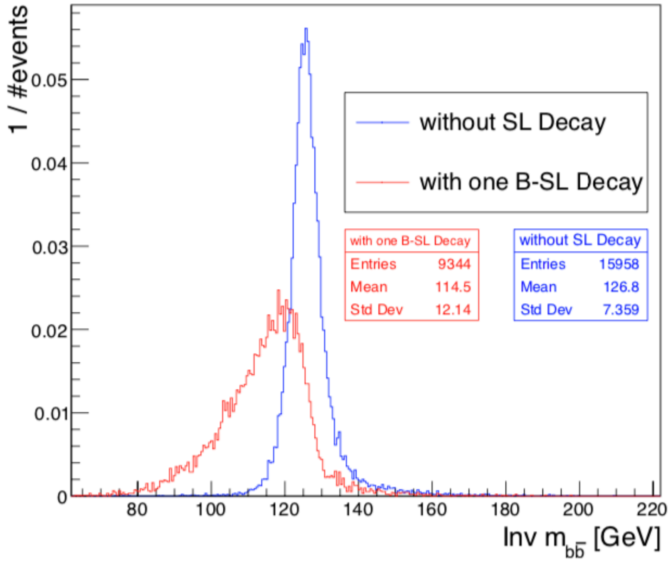

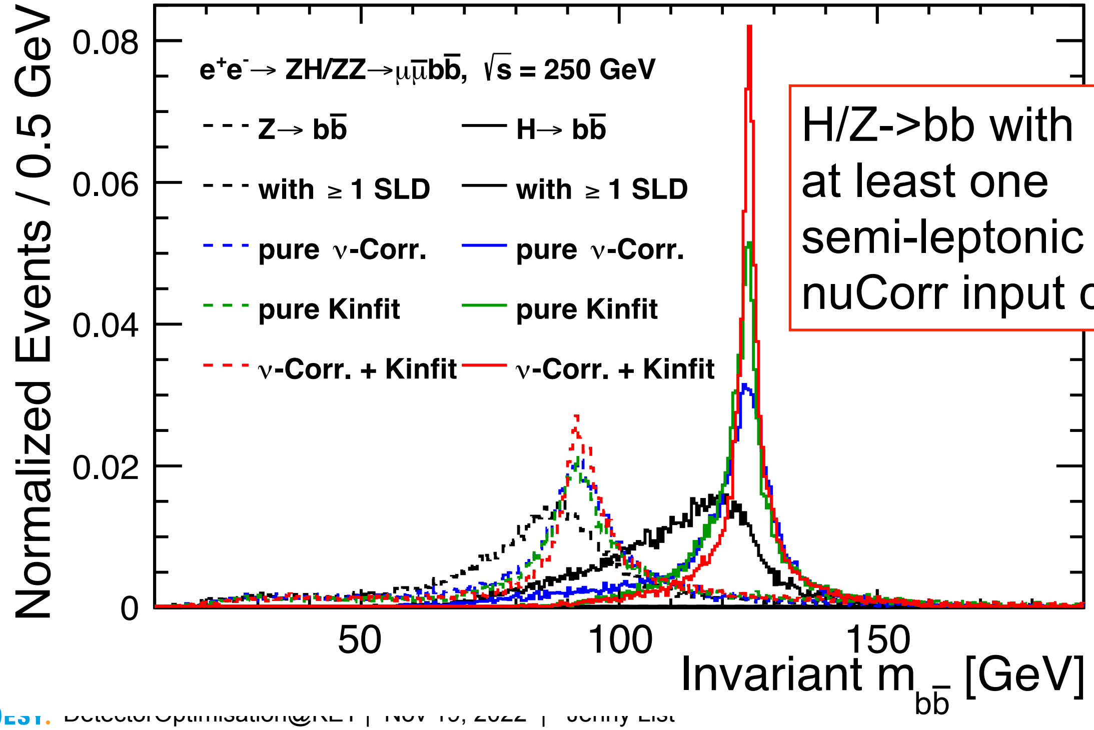

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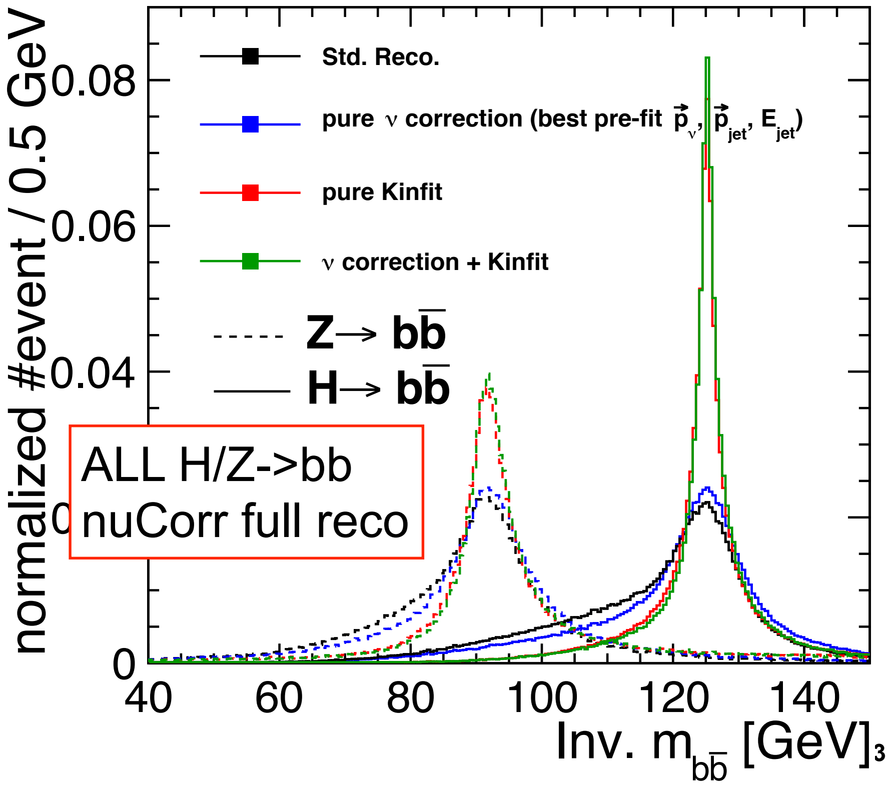

ALL H/Z->bb
nuCorr full reco

Semi-Leptonic B-decays

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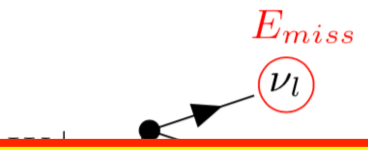
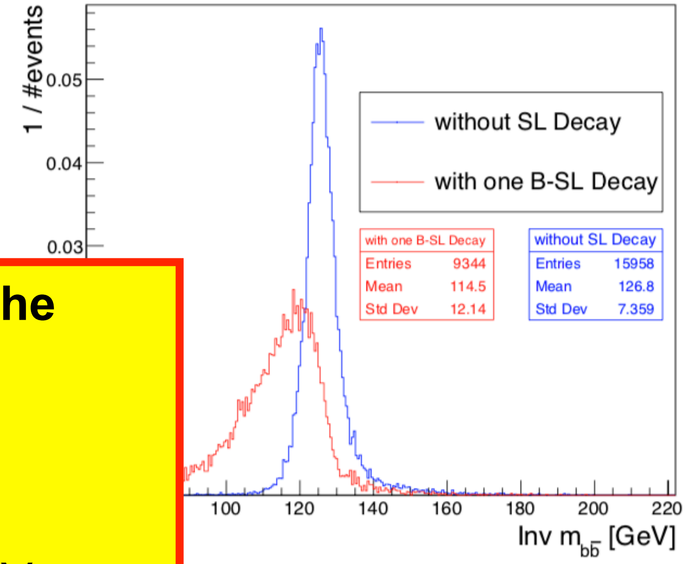


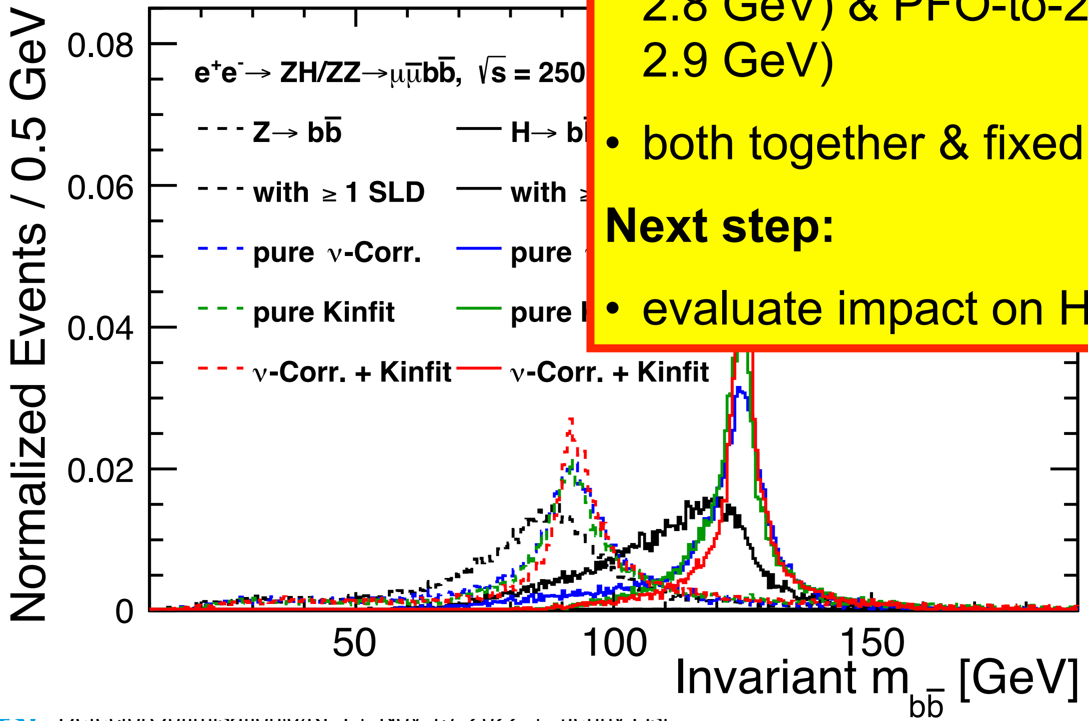


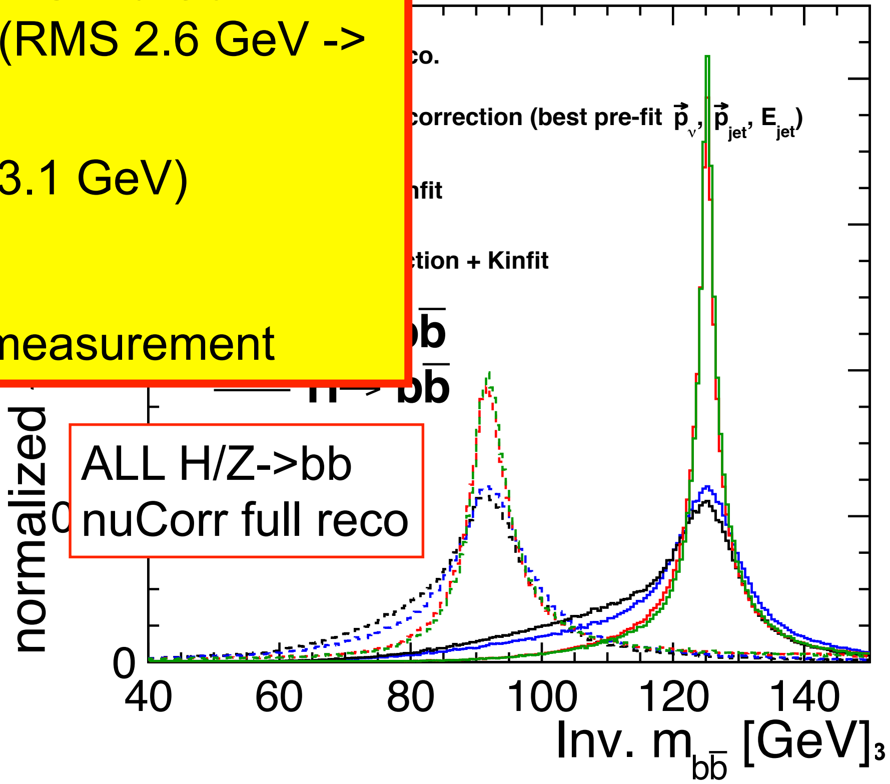
Detector optimisation question: What is limiting the performance?

- largest impact from precision of PFO momenta
  => RMS (Erec-Etrue) = 2.6 GeV
- some impact B hadron flight direction (RMS 2.6 GeV -> 2.8 GeV) & PFO-to-2nd-vtx assignment (RMS 2.6 GeV -> 2.9 GeV)
- both together & fixed B0 mass (RMS -> 3.1 GeV)

Next step:

- evaluate impact on Higgs self-coupling measurement

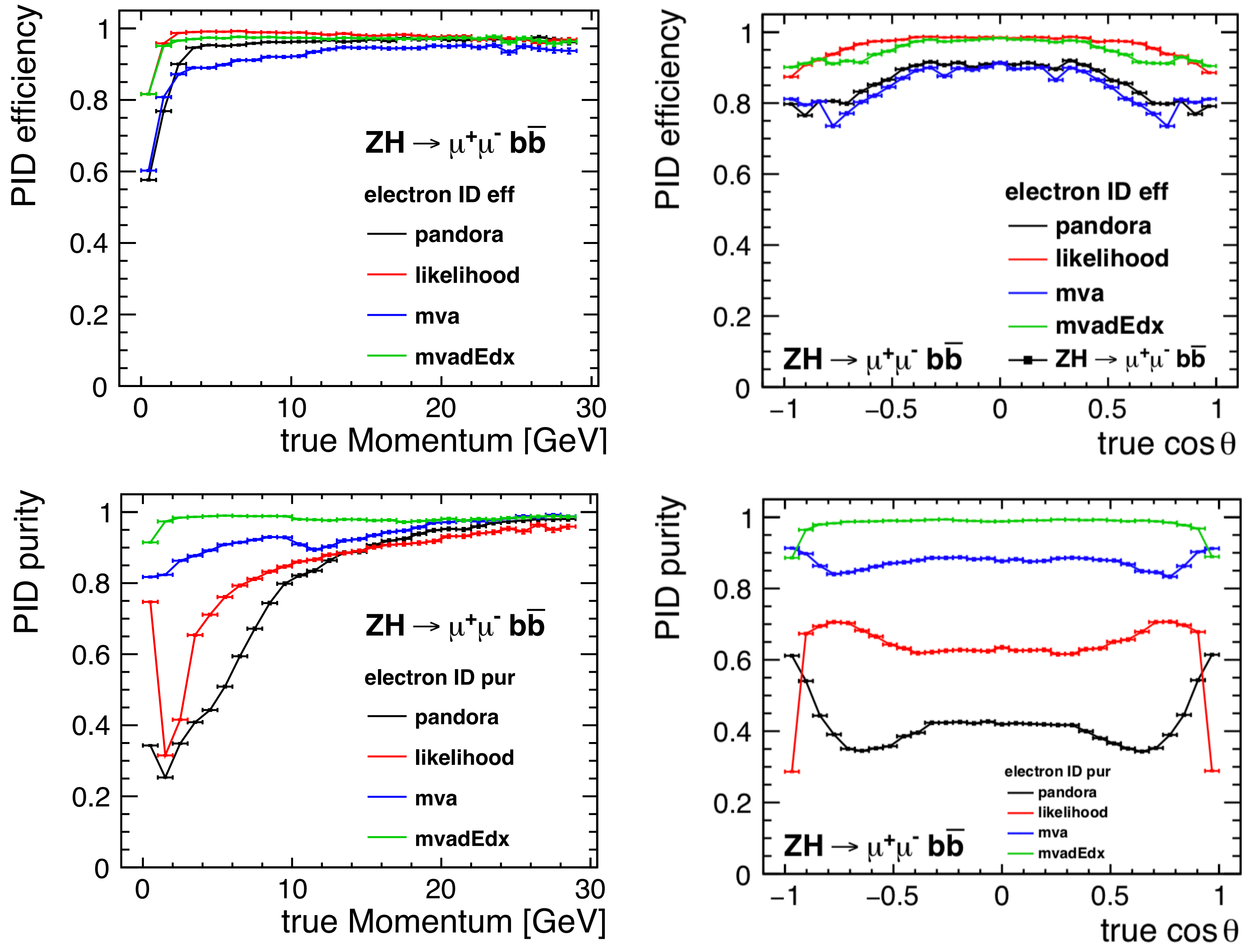




Identifying electrons (and muons) in b-jets

L.Reichenbach

- e and mu ID so far studied for isolated particles, eg Z->e+e-/ mu+mu-
- cell size in the calorimeter typically optimized wrt to jet energy resolution via particle flow
- first look into e/mu in H->bb:
  - black: raw particle flow
  - blue: incl. detailed cluster shape
  - green: blue + dE/dx



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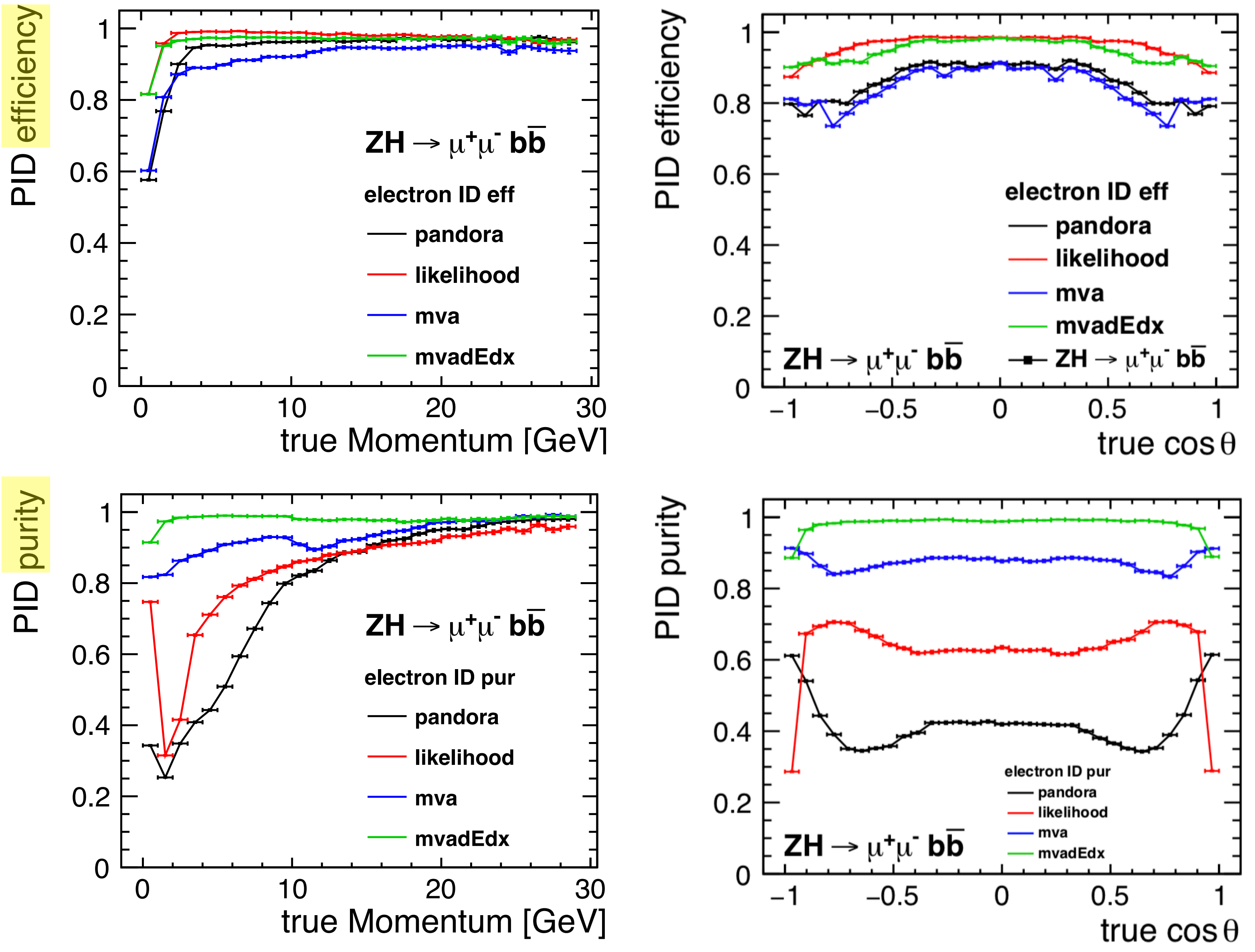

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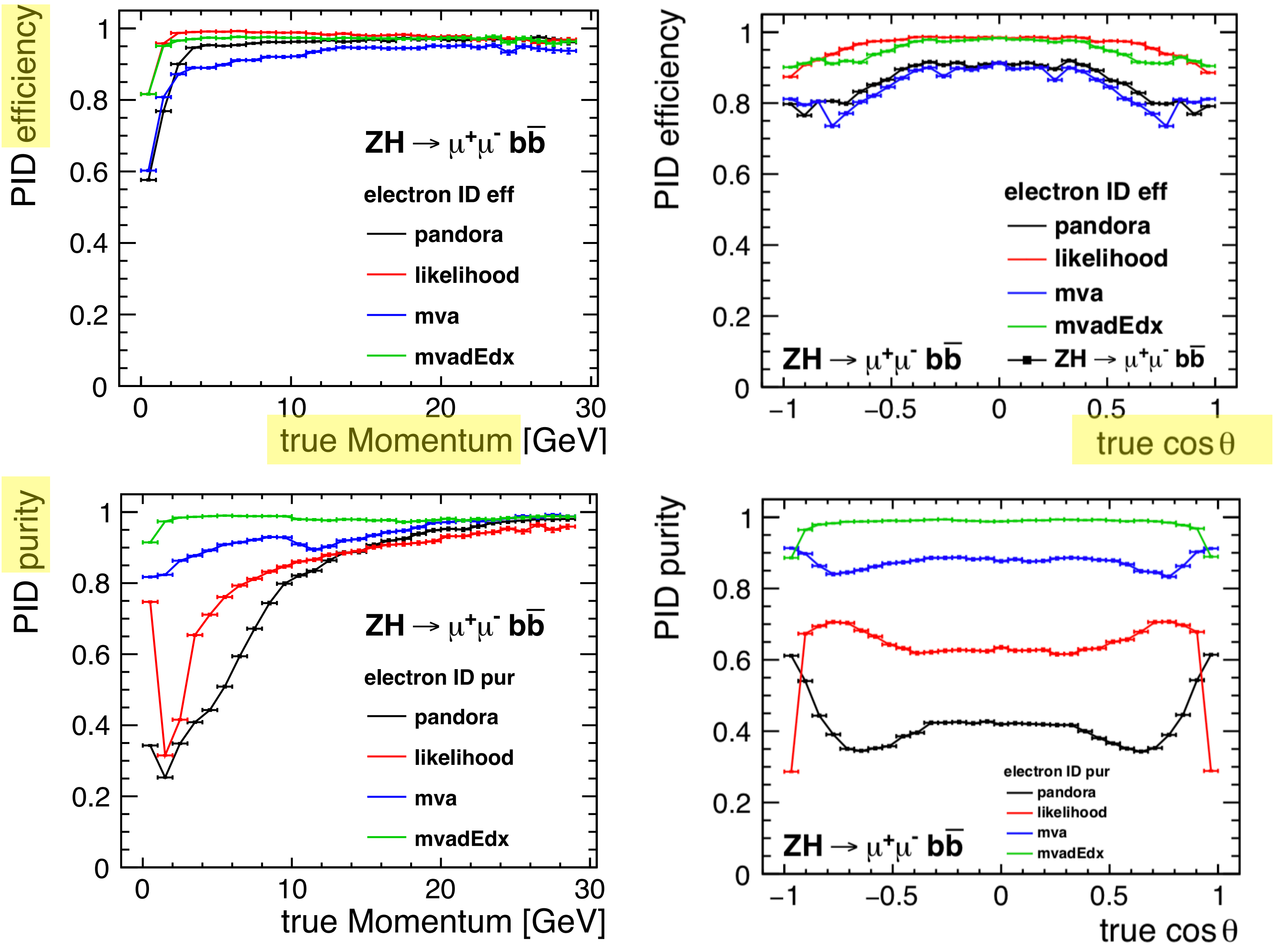

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dE/dx gives important contribution to e-ID up to 20 GeV