LLR Ecole Polytechnique
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Calorimeter for Future Higgs Factory

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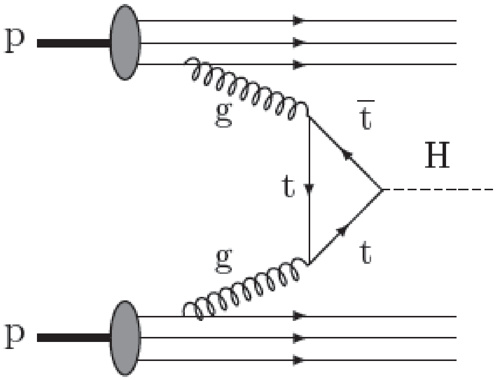
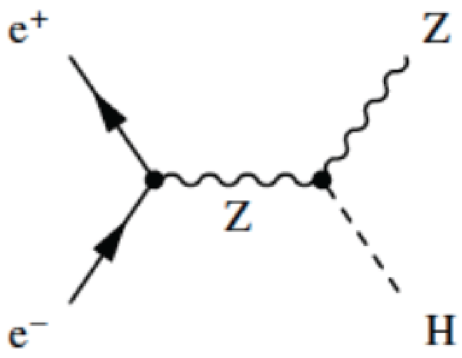
Why e+e- machine

pp collisions / e+e- collisions



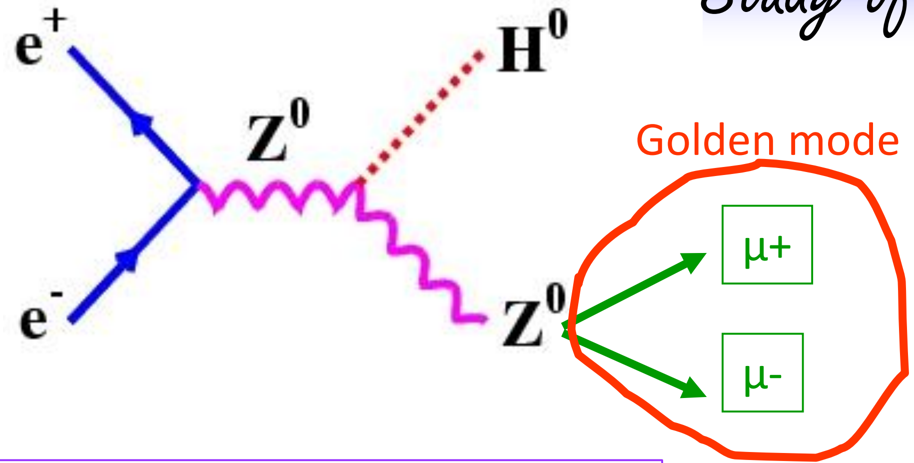


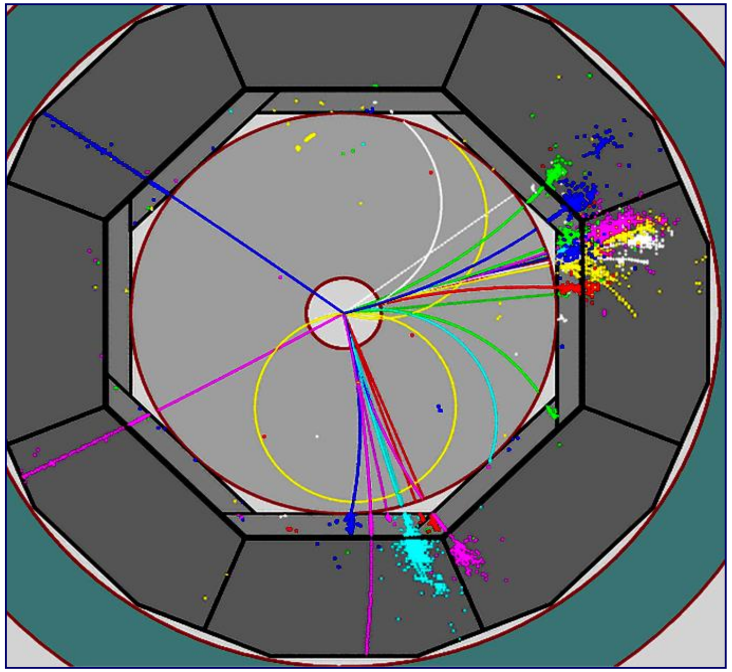
From L.Linssen (CERN)

p-p collisions	e^+e^- collisions
Proton is compound object → Initial state unknown → Limits achievable precision **(i.e. PDF)**	**e^+/e^- are point-like** → Initial state well defined (√s / opt: polarisation) → High-precision measurements ⇐
High rates of QCD backgrounds → Complex triggering schemes ⇐ → High levels of radiation ⇐	**Cleaner experimental environment** → Less / no need for triggers → Lower radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
Very high-energy **circular** pp colliders feasible	High energies (>≈350 GeV) require **linear** collider

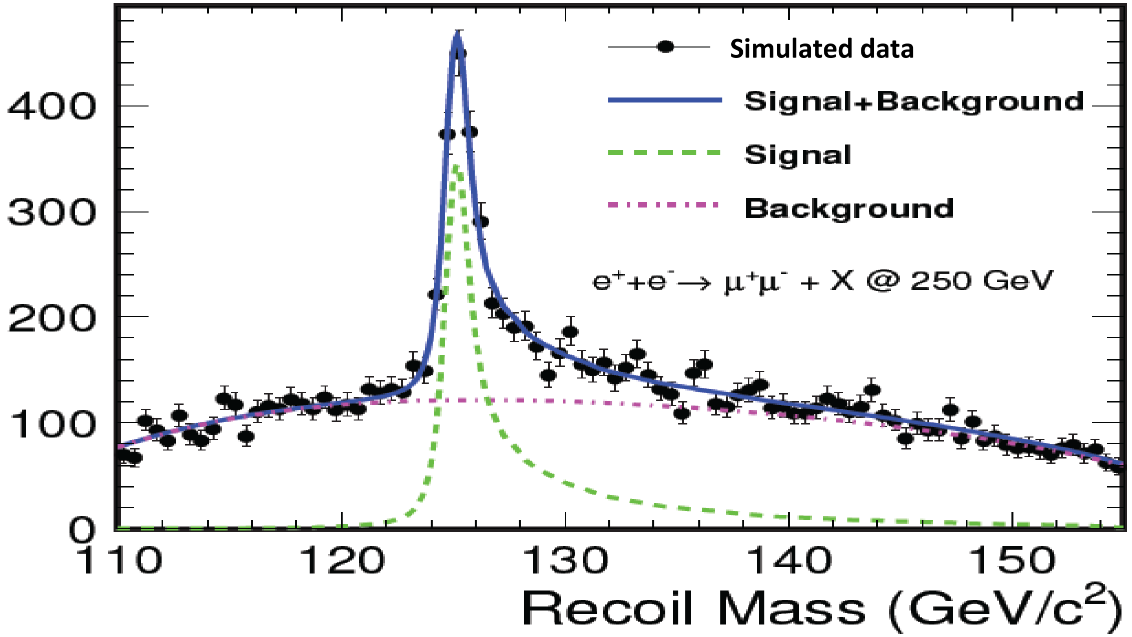
Why lepton colliders are so powerfull ?

Study of Higgs





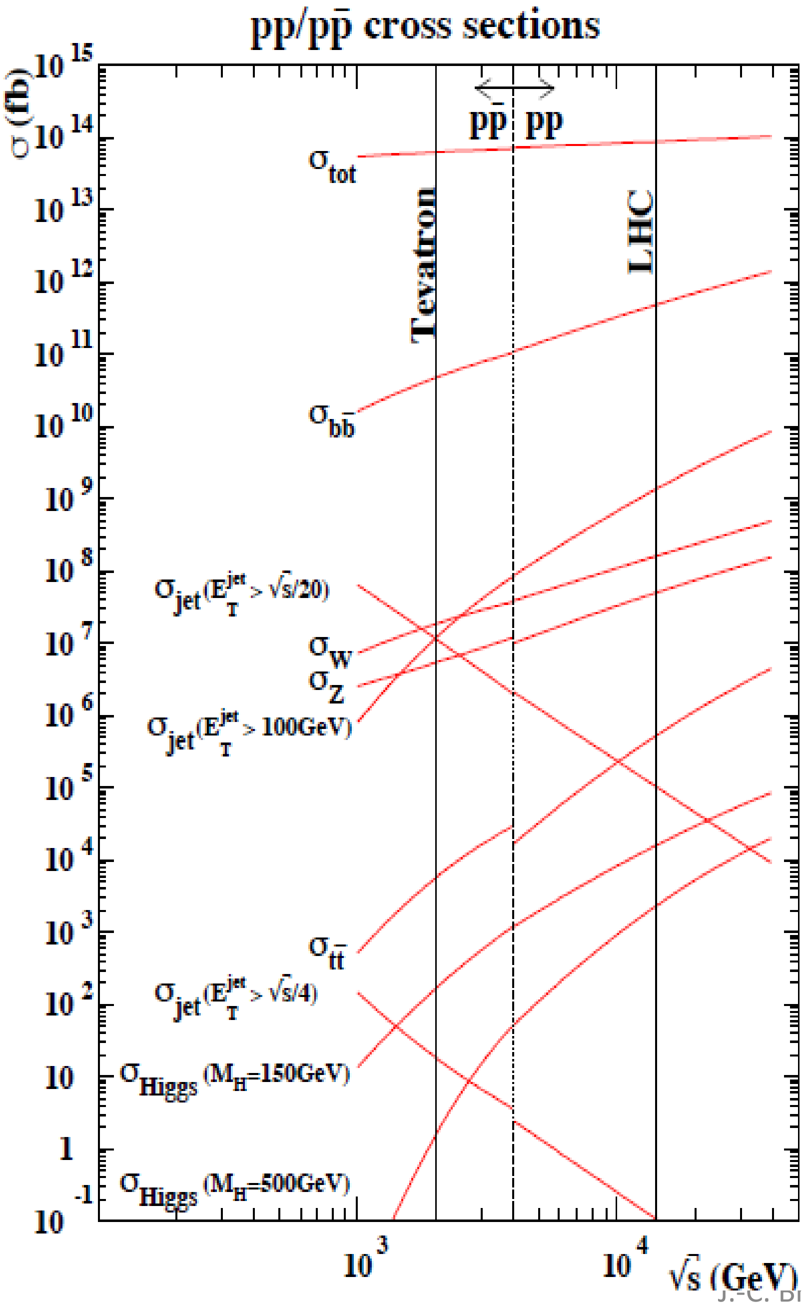
Select 2 muons with mass in the Z mass region
Signal is in the recoil mass to this 2 muons

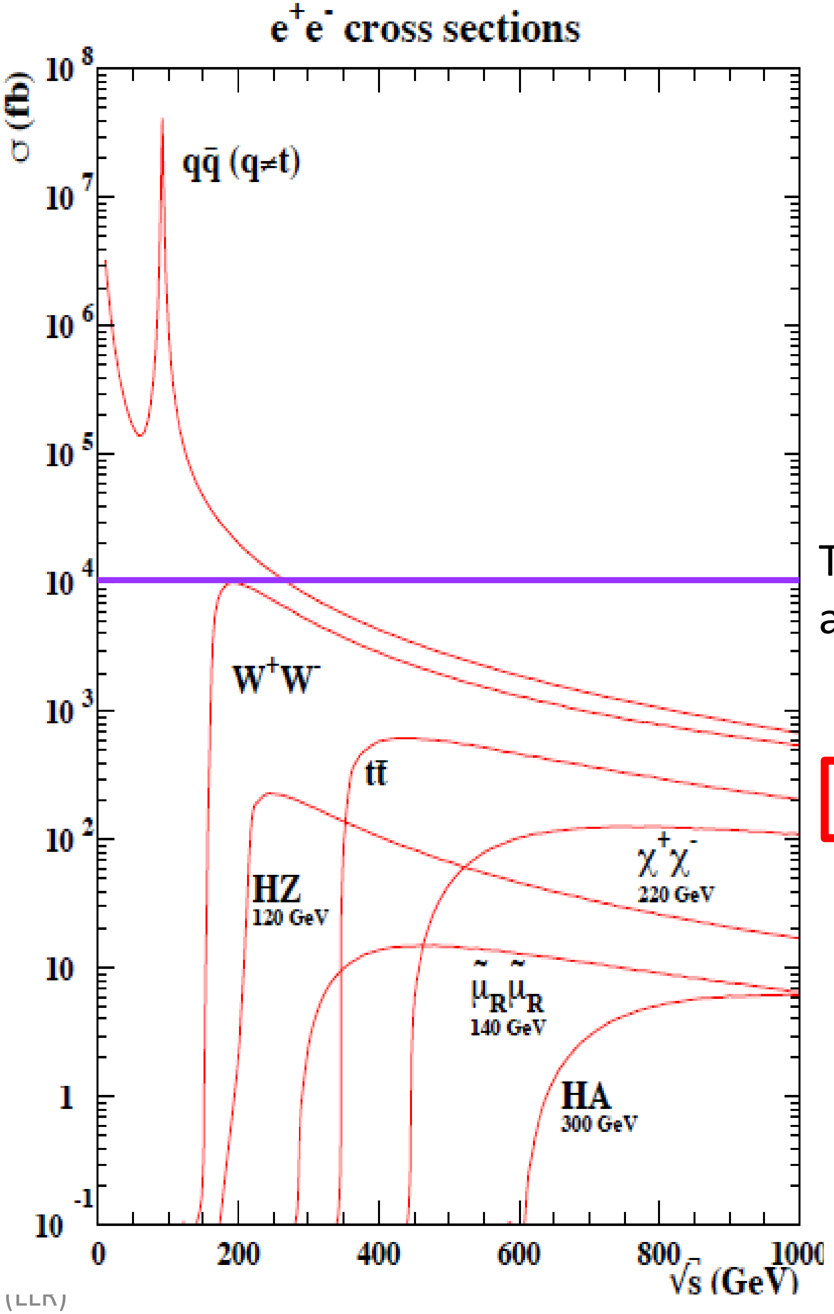


Example of application:
Search for invisible Higgs decays

TRIGGER

Higgs/Total ≈ 10^{-10}

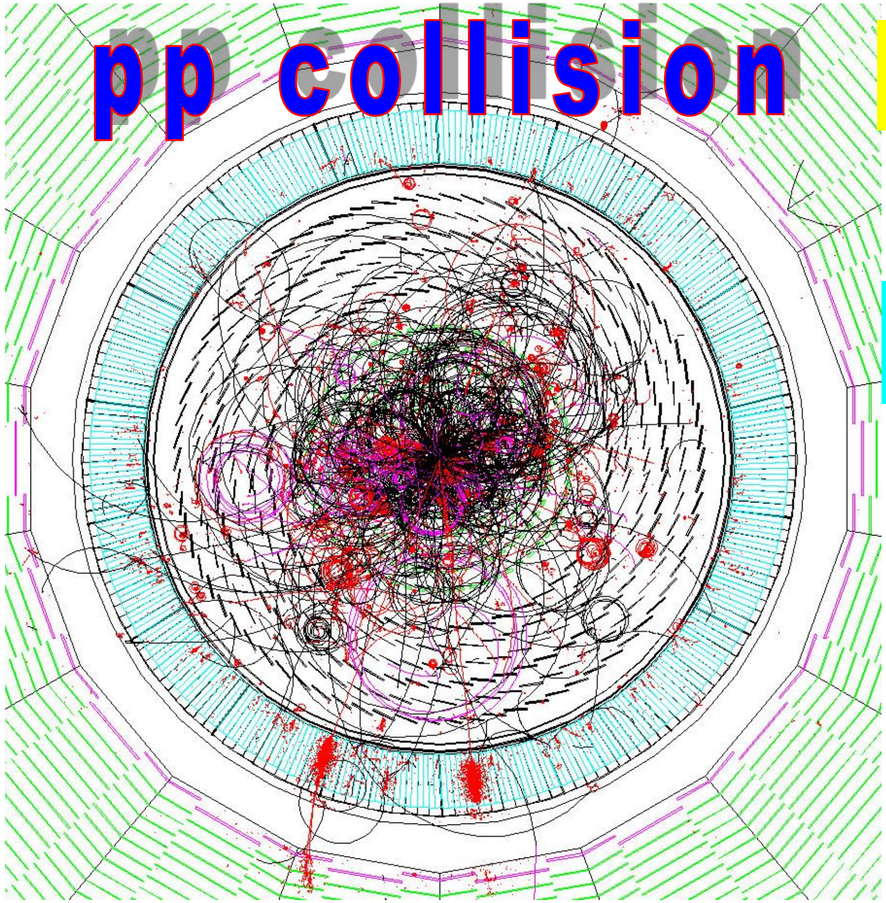




Total cross section already around 10^4

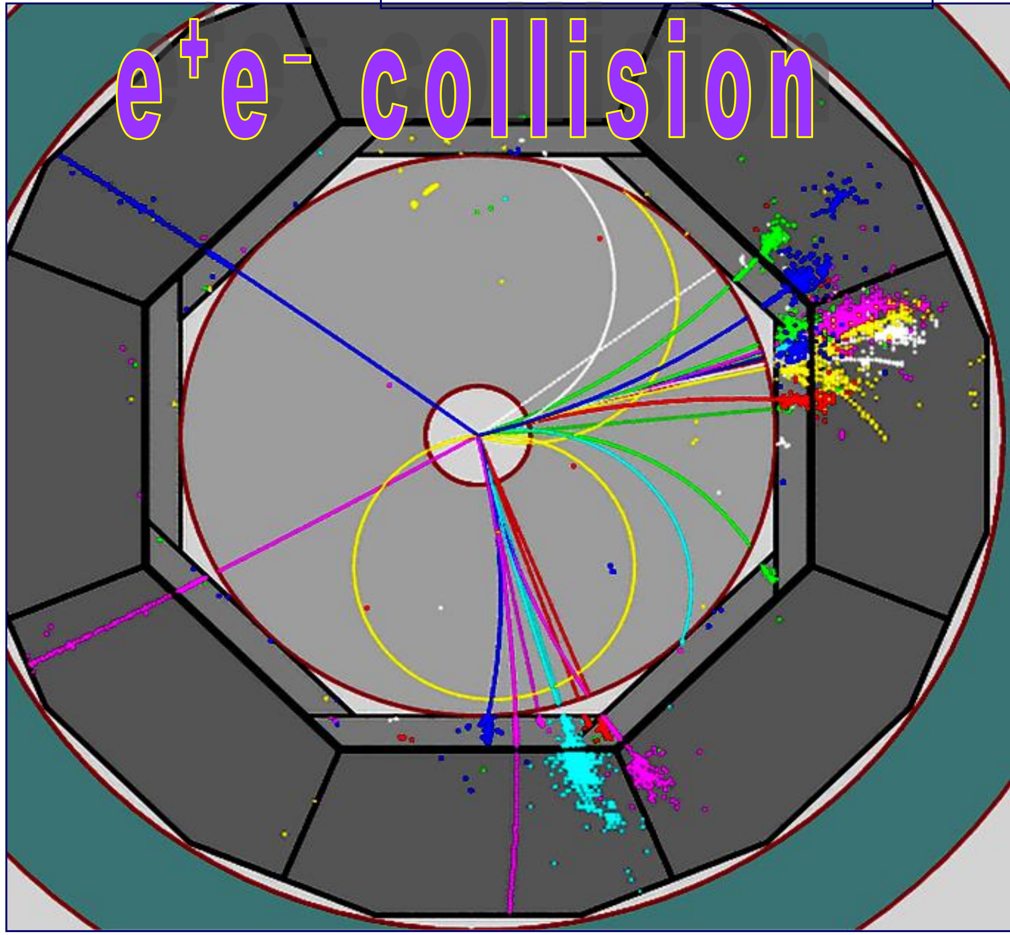
Higgs/Total ≈ 10^{-2}

Why such a machine , in addition to HL-LHC



One “Higgs event”

After removing the 2 muons,
All the rest of the event is
Coming from the Higgs decay

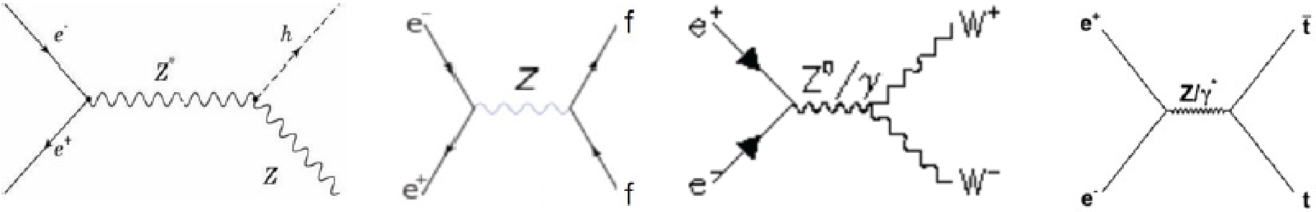


Analysis at LHC was a fantastic success !!

LHC has discovered (open the door) and will reach a precision at O(5-10%)

FHF will probe the underlying theory with a precision better than 1%

CEPC physics program (from M.Ruan 2023)



Operation mode			ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]			240	91	160	360
Run time [years]			7	2	1	-
CDR (30 MW)		L / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	**3**	**32**	**10**	-
		$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
		Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	-
Run Time [years]			10	2	1	5
TDR (Latest)	**30 MW**	L / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	**5.0**	**115**	**16**	0.5
		$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
		Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
	50 MW	L / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	**8.3**	**192**	**26.7**	**0.8**
		$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1.0
		Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

- **The centerpiece: precise measurement of the Higgs boson properties (width, couplings, mass …)**
- **huge measurement potential for precision tests of SM: electroweak physics, flavor physics, QCD**
- **Searching for exotic or rare decays of H, Z, B and τ, and new physics**
- **Top quark physics**

An extremely versatile machine with a broad spectrum of physics opportunities → Far beyond a Higgs factory

FCC-ee Physics landscape

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
“boosted” B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau\nu$
$B_s \to D_s K/\pi$
$B_s \to K^*\tau\tau$
$B \to K^*\nu\nu$
$B_s \to \varphi\nu\nu$ ...

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ , R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

FCC-ee Detector requirements

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution
(stochastic and noise)

Flavor
“boosted” B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 µm

luminosity

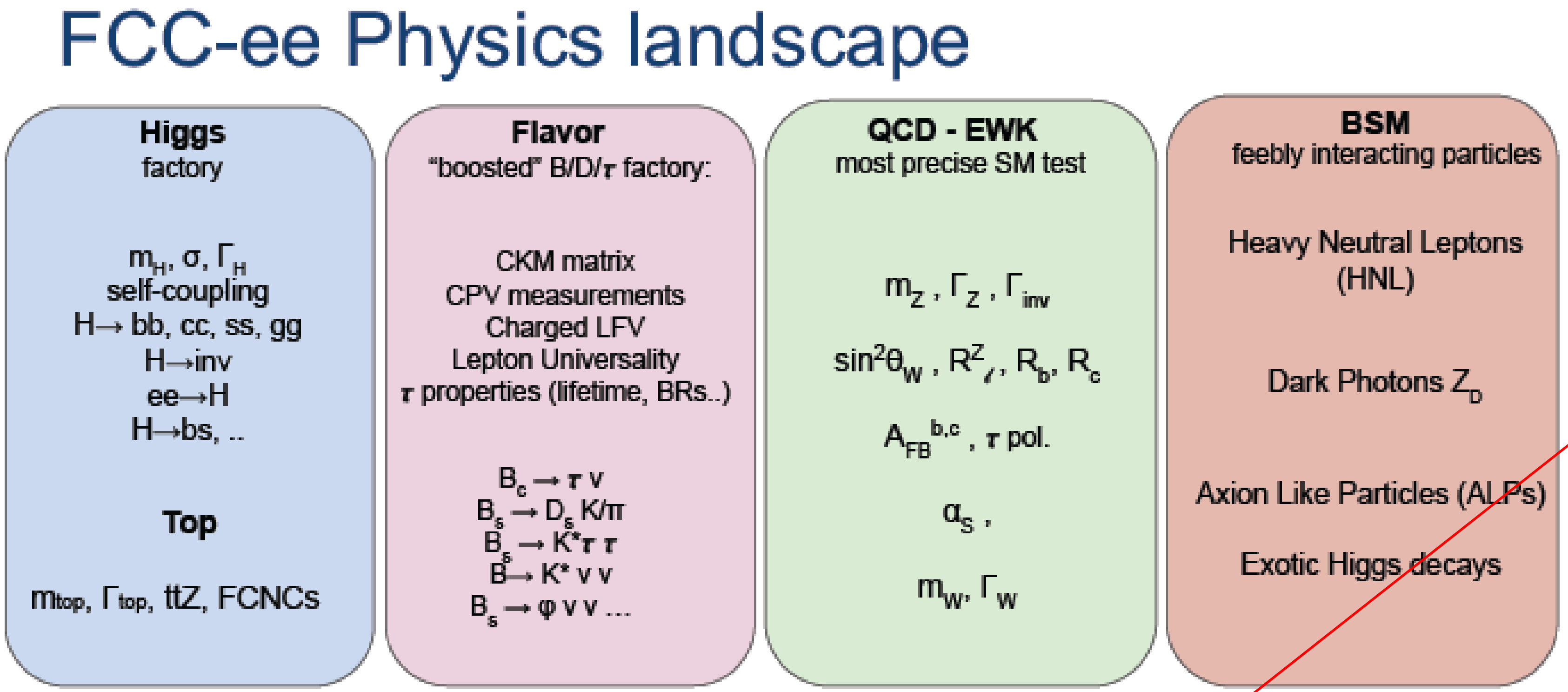
BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

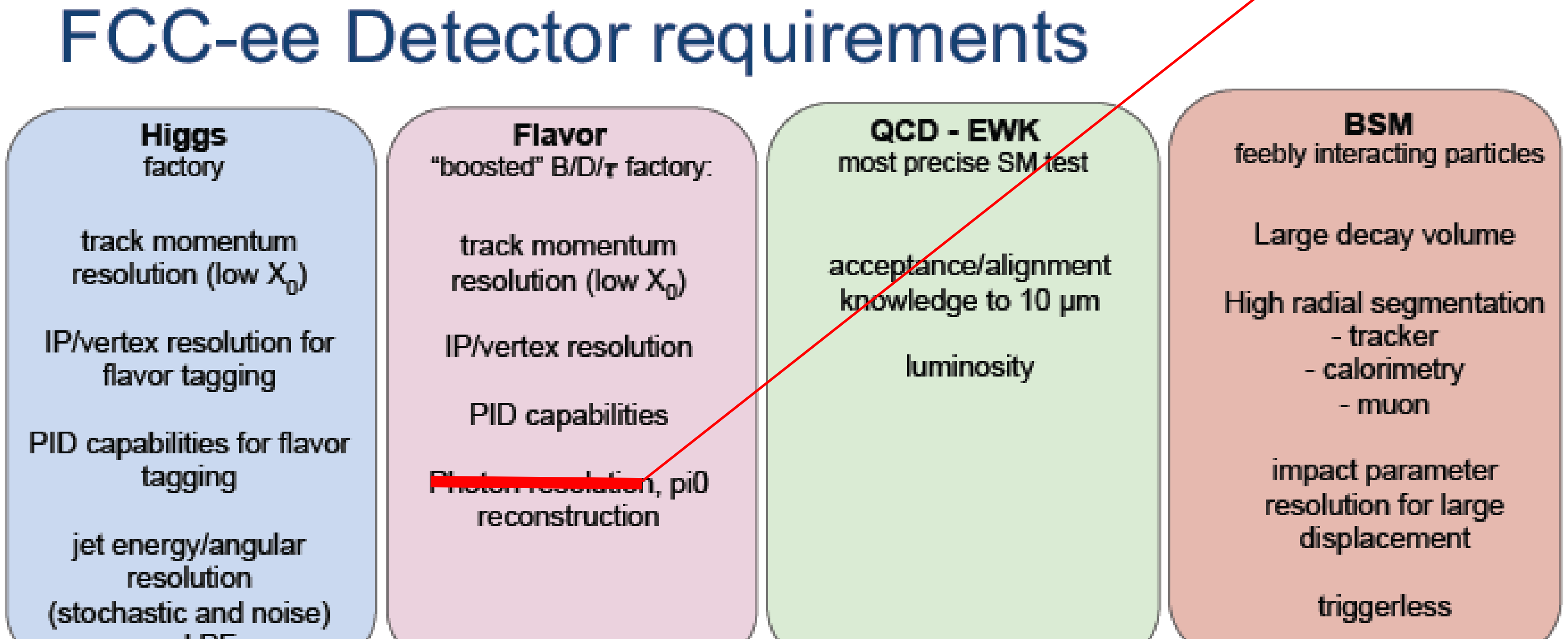
impact parameter resolution for large displacement

triggerless



FCC-ee Physics landscape

Higgs factory	**Flavor** "boosted" B/D/τ factory:	**QCD - EWK** most precise SM test	**BSM** feebly interacting particles
m_H, σ, Γ_H self-coupling H→ bb, cc, ss, gg H→inv ee→H H→bs, .. **Top** m_{top}, Γ_{top}, ttZ, FCNCs	CKM matrix CPV measurements Charged LFV Lepton Universality τ properties (lifetime, BRs..) $B_c \to \tau\nu$ $B_s \to D_s K/\pi$ $B_s \to K^*\tau\tau$ $B \to K^* \nu\nu$ $B_s \to \varphi\nu\nu$ ...	m_Z, Γ_Z, Γ_{inv} $\sin^2\theta_W$, R^Z_ℓ, R_b, R_c $A_{FB}^{b,c}$, τ pol. α_S, m_W, Γ_W	Heavy Neutral Leptons (HNL) Dark Photons Z_D Axion Like Particles (ALPs) Exotic Higgs decays



FCC-ee Detector requirements

Higgs factory	**Flavor** "boosted" B/D/τ factory:	**QCD - EWK** most precise SM test	**BSM** feebly interacting particles
track momentum resolution (low X_0) IP/vertex resolution for flavor tagging PID capabilities for flavor tagging jet energy/angular resolution (stochastic and noise)	track momentum resolution (low X_0) IP/vertex resolution PID capabilities ~~Photon resolution~~, pi0 reconstruction	acceptance/alignment knowledge to 10 μm luminosity	Large decay volume High radial segmentation - tracker - calorimetry - muon impact parameter resolution for large displacement triggerless

$$B \to \pi^\circ \pi^\circ$$

is comparable to

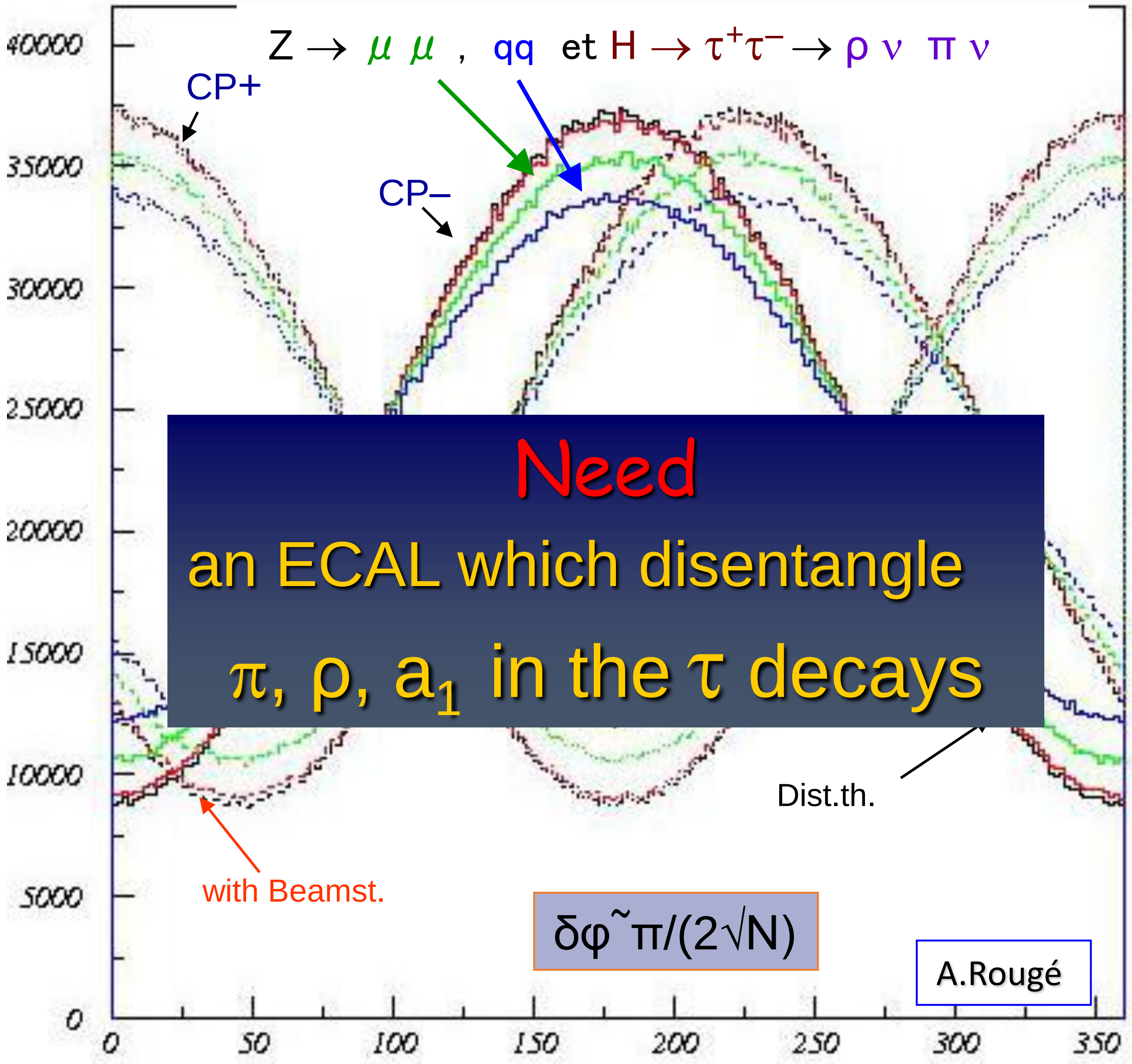
$$\tau \to h + n(\pi^\circ)\,\nu$$

In addition to 1C-fit of pi0 mass (and B)
The most important is to know

The number of photon(s)
i.e.
Energy threshold and S/N at low energy

CP violation, Higgs sector

$e^+ e^- \to ZH$



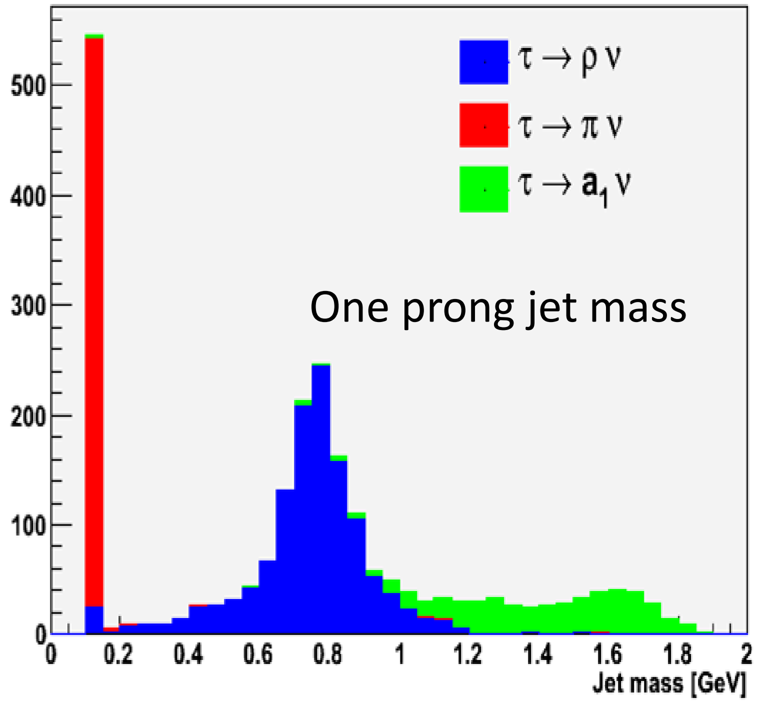
Need

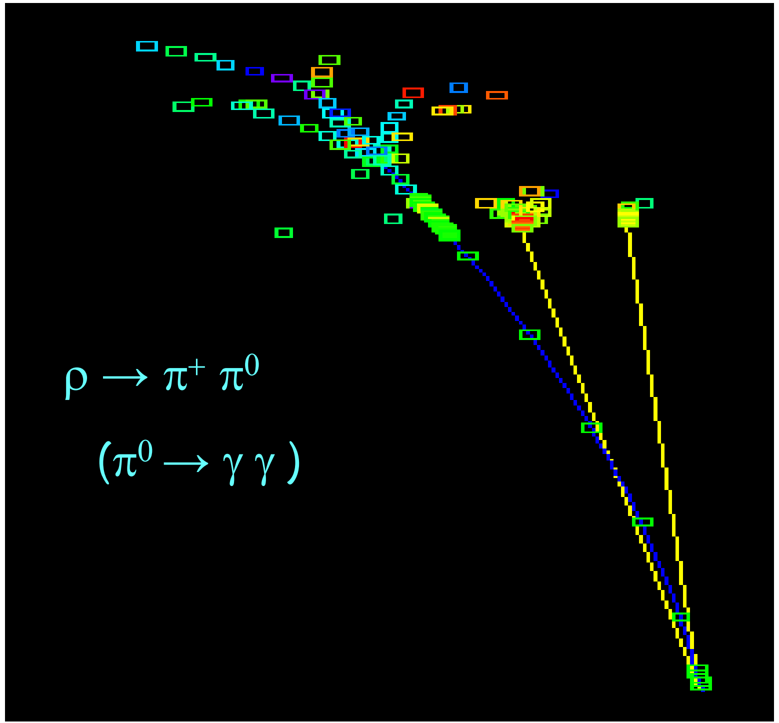
an ECAL which disentangle

π, ρ, a_1 in the τ decays

$\delta\varphi \sim \pi/(2\sqrt{N})$

A.Rougé

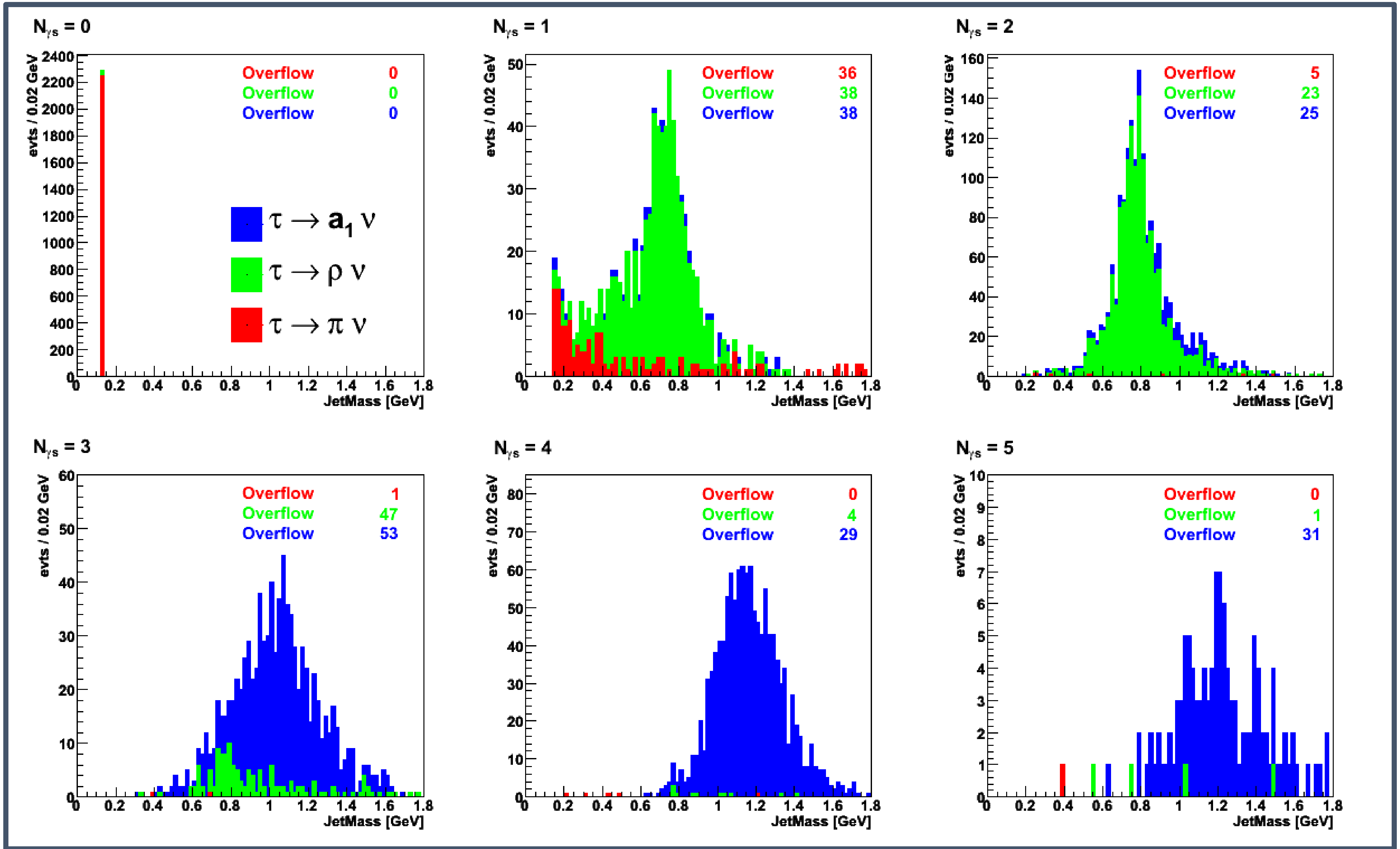


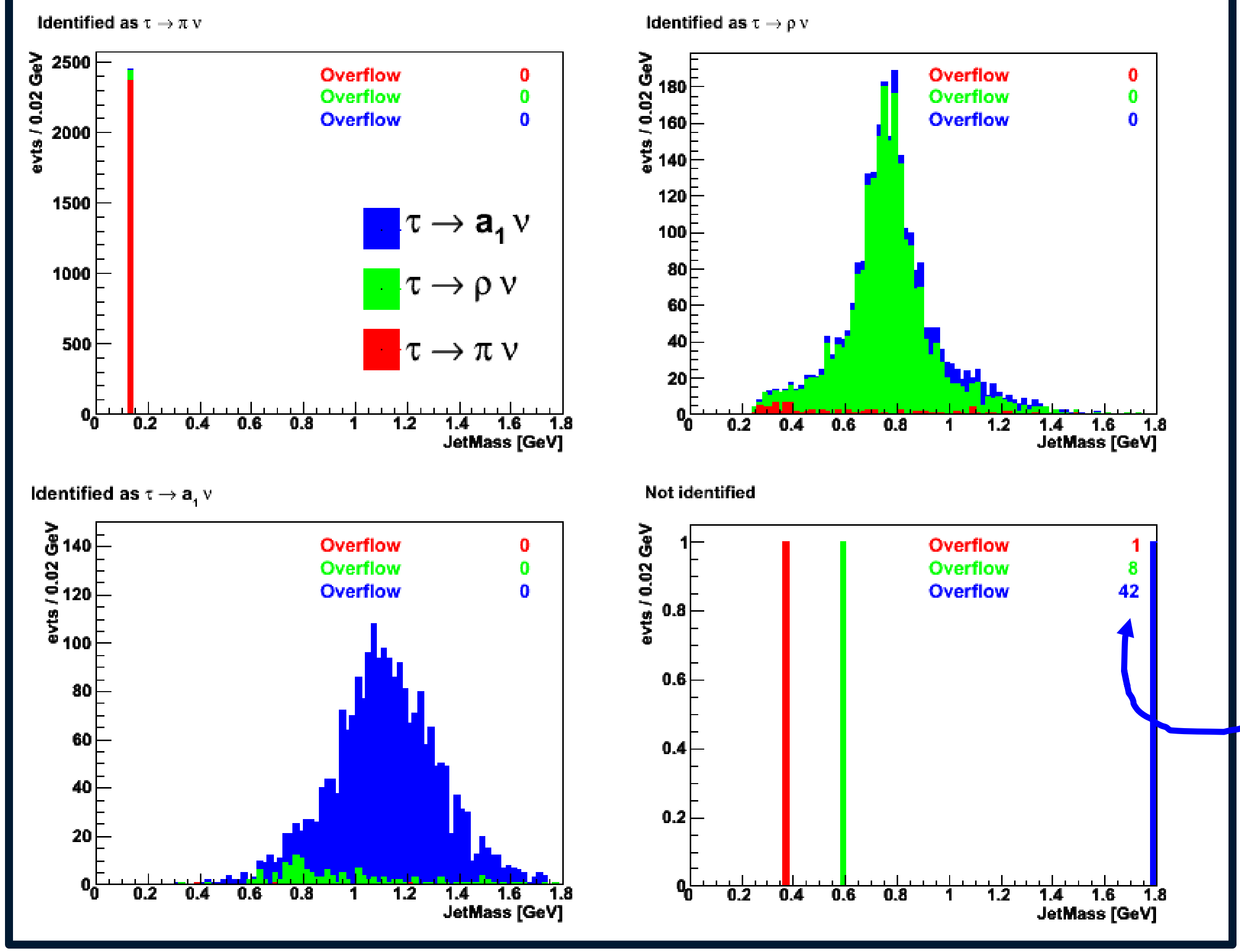


$\rho \to \pi^+\,\pi^0$

$(\pi^0 \to \gamma\,\gamma)$

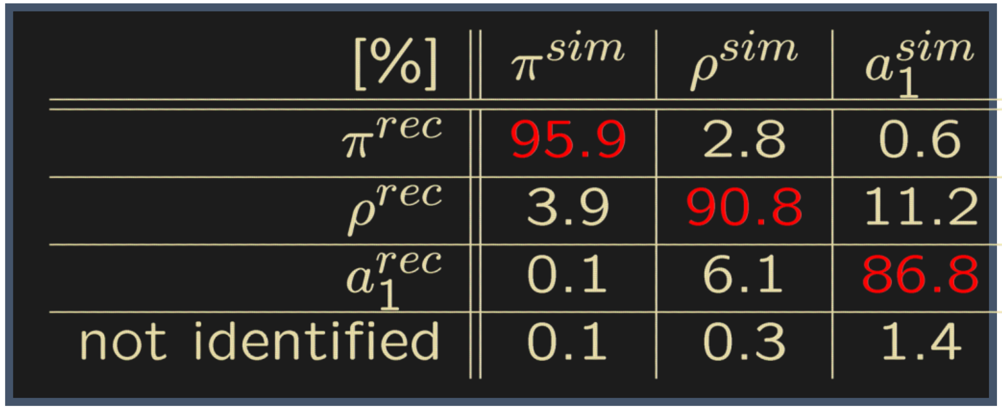
Jets with one prong and … N photons (thanks to high granularity ECAL)





Excellent separation and mass peaks!

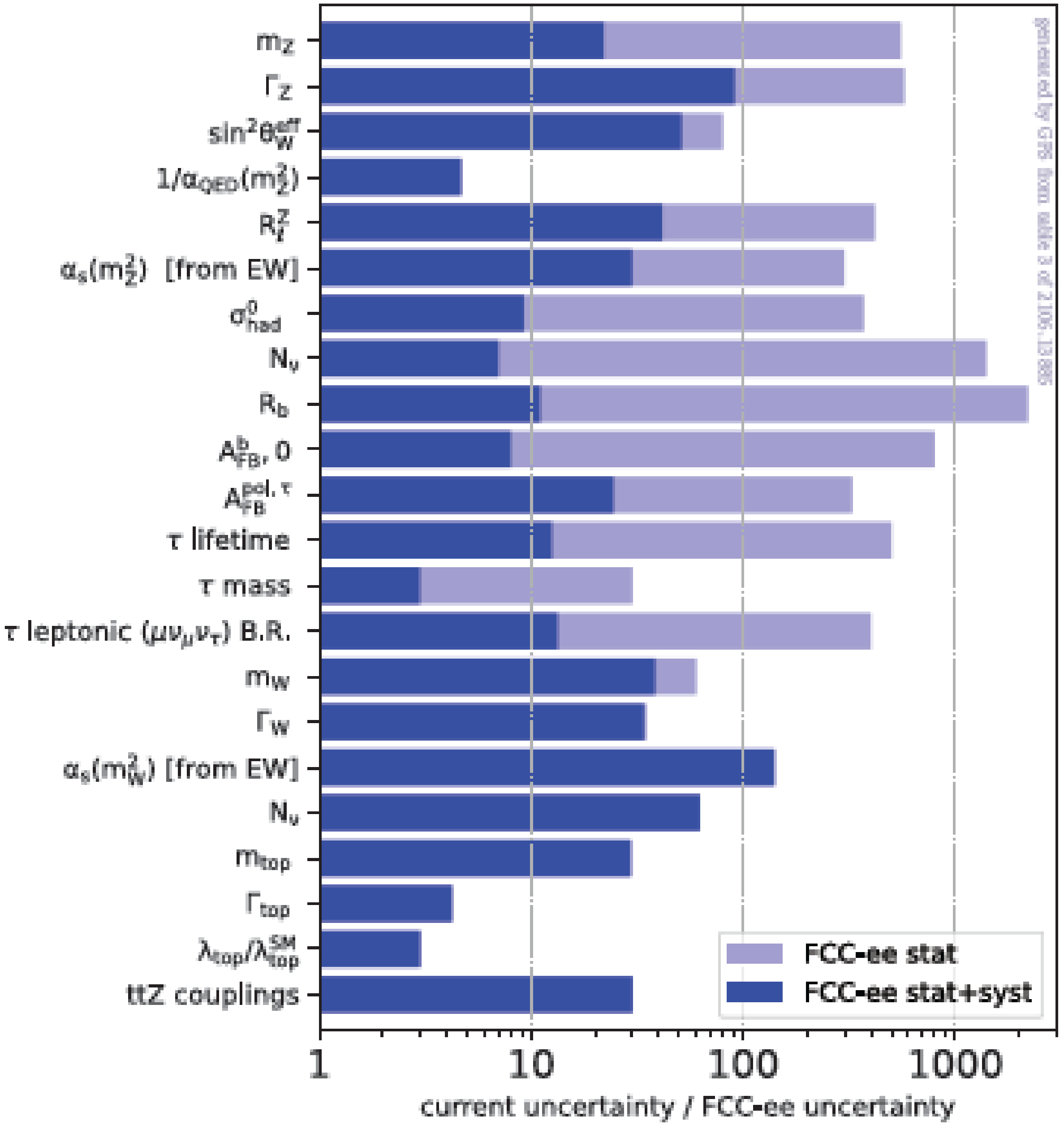
Radiative correction
(H→ττγ and one jet is in fact τγ)



[%]	π^{sim}	ρ^{sim}	a_1^{sim}
π^{rec}	95.9	2.8	0.6
ρ^{rec}	3.9	90.8	11.2
a_1^{rec}	0.1	6.1	86.8
not identified	0.1	0.3	1.4

It was about
70 – 75 % in ALEPH

FCC precision gain



Where PFA is essential

SYSTEMATICS

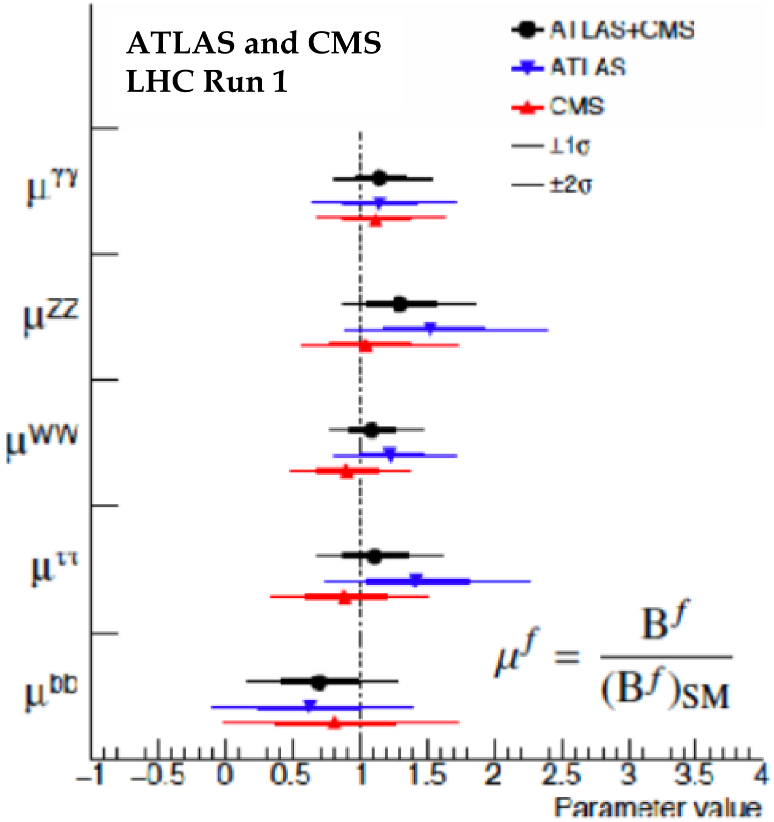
What about the Higgs physics ,

the most important and best argument to non scientist for this FHF

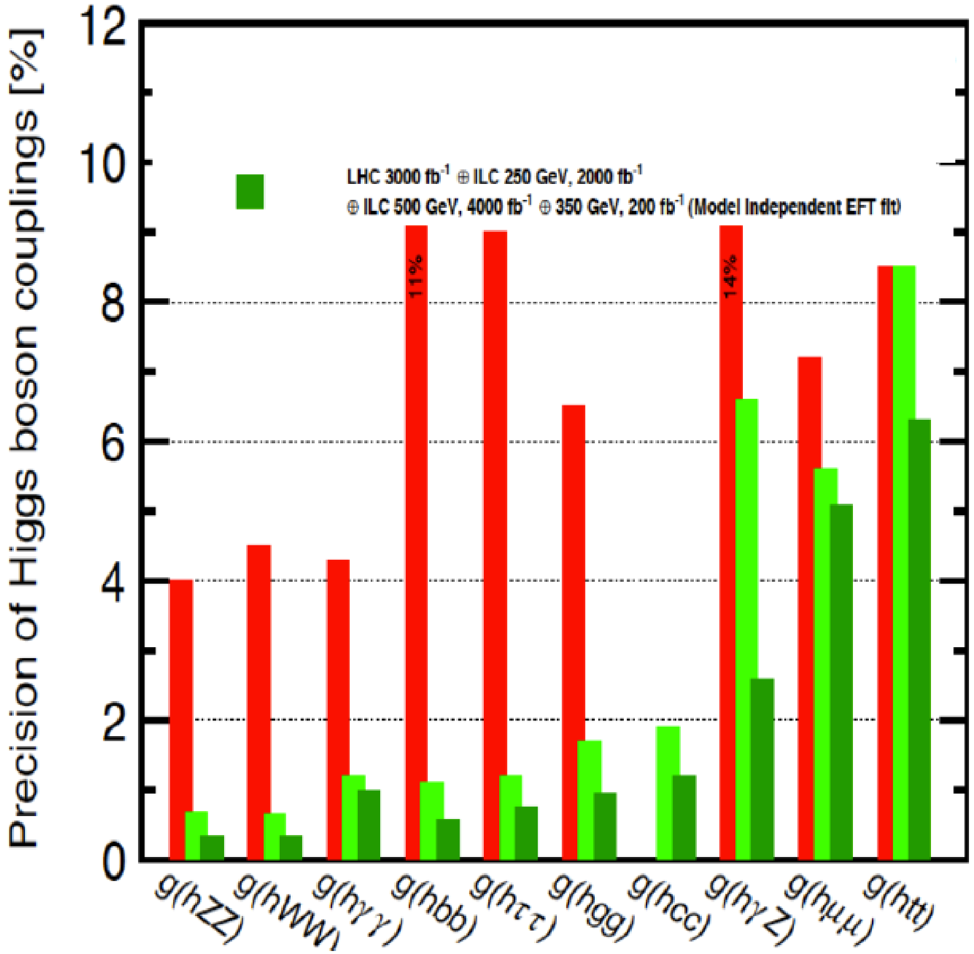
Example on the expected precision on Higgs couplings (ILC here)

Run 1

ATLAS+CMS [1606.02266]



[K. Fujii, et al., arXiv:1710.07621]



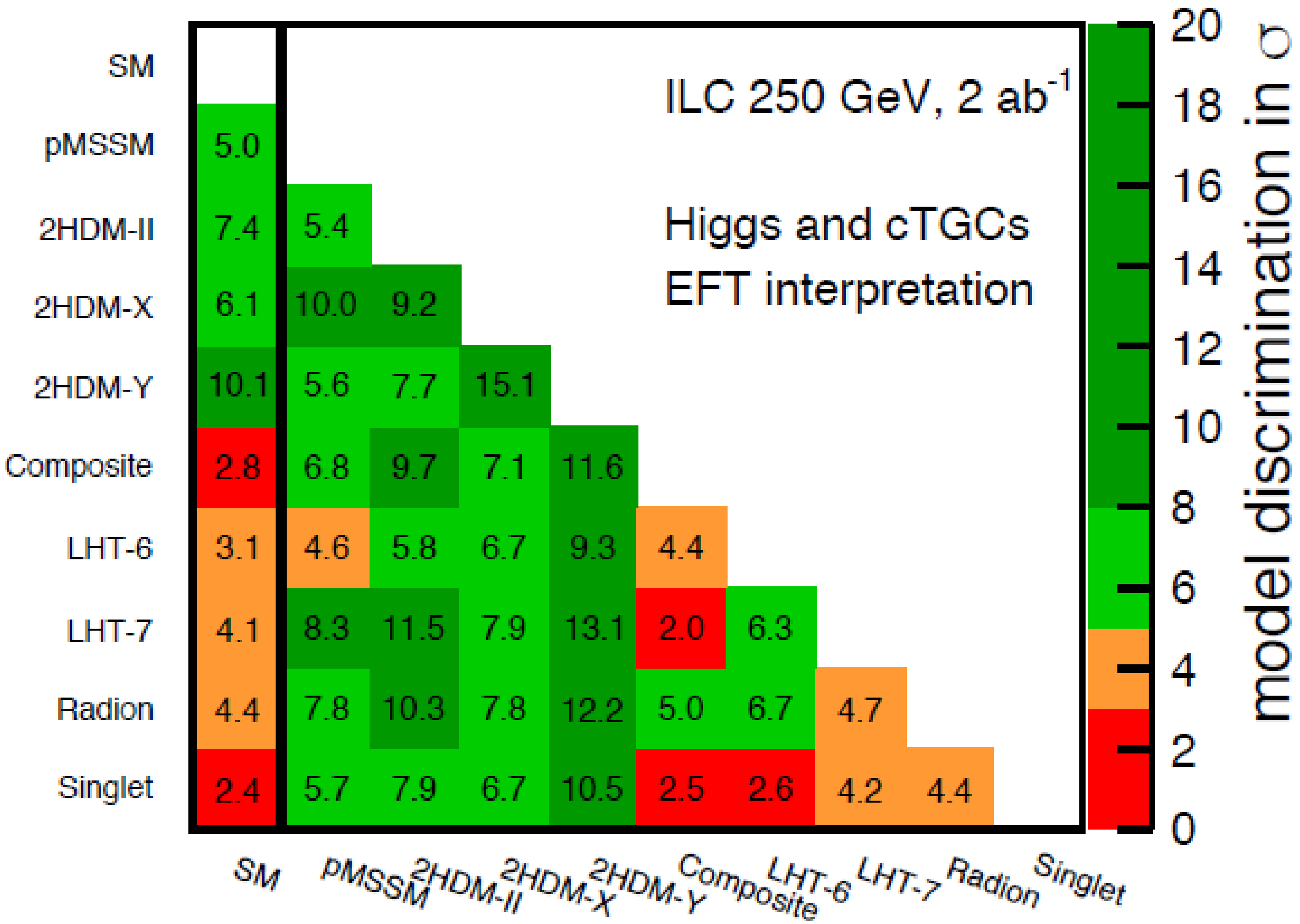
🟥 **HL-LHC** 3000 fb-1 ATLAS
Model dependent

🟩 **HL-LHC** 3000 fb-1 ATLAS
and ILC 250 GeV 2000 fb-1
(model independent)

Identifying the new physics

Which center of mass energy ?

ILC250



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

250 GeV and good luminosity is already sufficient

Even if running at 500 GeV would be also very interesting (or at least above the top threshold or better above the ttH threshold)

Why are the jets so important at FHF ?

Multi bosons	Multifermions + Boson(s)
ZH	e^+e^- H , e+e− Z
WW	νν H , νν Z
ZZ	ttH
ZHH	e ν W
ZZZ	νν WW, νν ZZ
ZWW	ttbar

Etc … but also the taus decays reconstruction for SUSY, CP… etc

typical processes at FHF 250

Multi bosons	Multifermions + Boson(s)
ZH	e^+e^- H , e+e− Z
WW	$\nu\nu$ H , $\nu\nu$ Z
ZZ	ttH
ZHH	e ν W
ZZZ	$\nu\nu$ WW, $\nu\nu$ ZZ
ZWW	ttbar

Etc … but also the taus decays reconstruction for SUSY, CP… etc

Bosons Tagging

Z to	BR
$\ell^+ \ell^-$	10%
qq (jets)	70%

W to	BR
$\ell^\pm \nu$	32%
qq' (jets)	68%

H(125,SM) to	BR
$\ell^+ \ell^-$	<15%
qq(jets) ,WW*,ZZ*	>85%

In order to **use** all the produced events (the luminosity of the machine)

It is needed to tag the bosons **W,Z,H in their decays to jets (using the 2 jets mass)**

How to reach such precisions

The golden mode is very interesting , in particular because
It is independent from the Higgs decays,
When searching for invisible modes (SUSY LSP or other WIMP)

But statistically, there are more interests in …

The jets

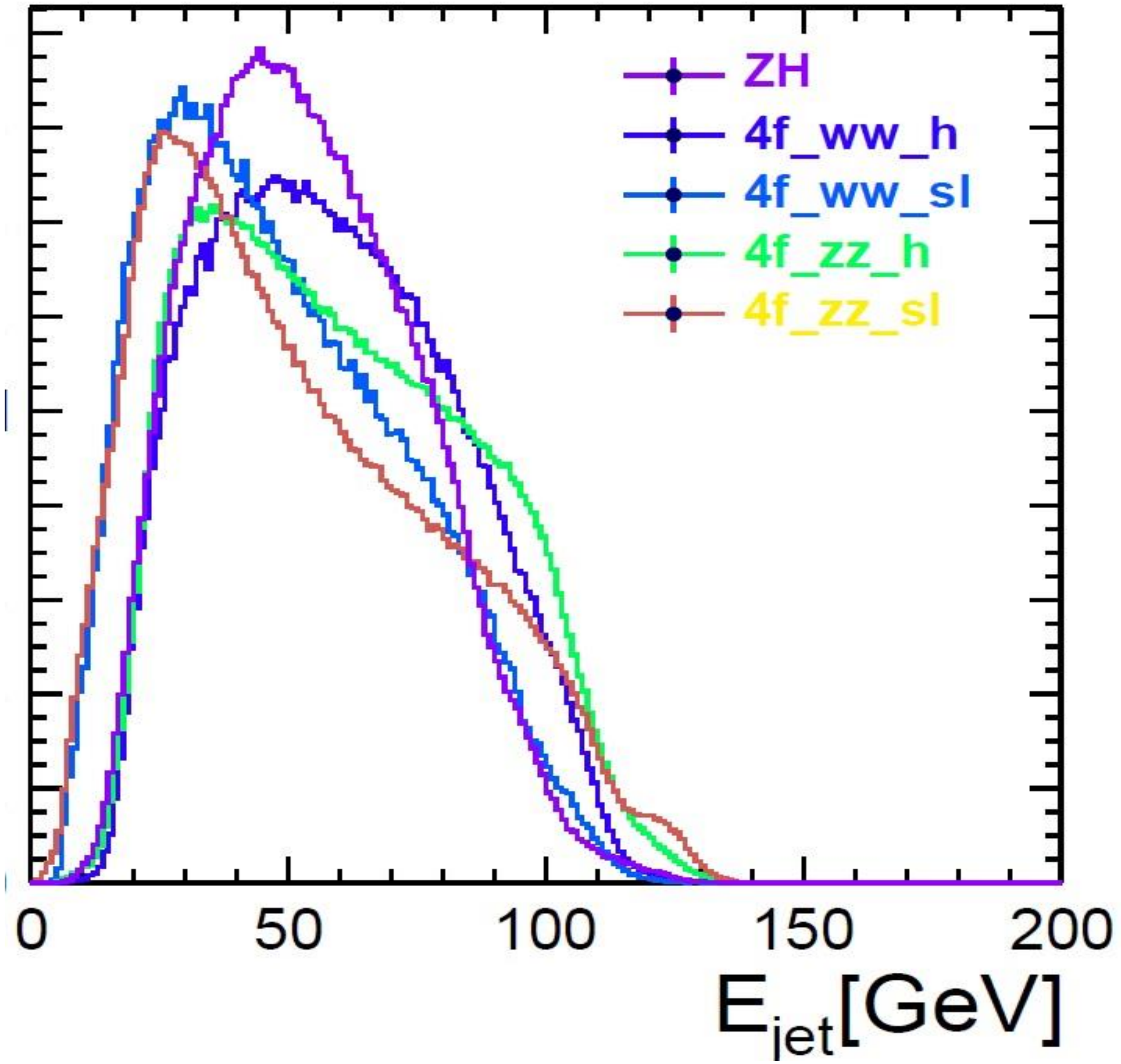
Which jet energies are we talking about ?

The Jacobian peak is
at 50 GeV or lower

But need to measure jets up to
the maximum energy

and to think about running
ILC at 500 GeV
(we don't want to change the detector
to run at 500 GeV)

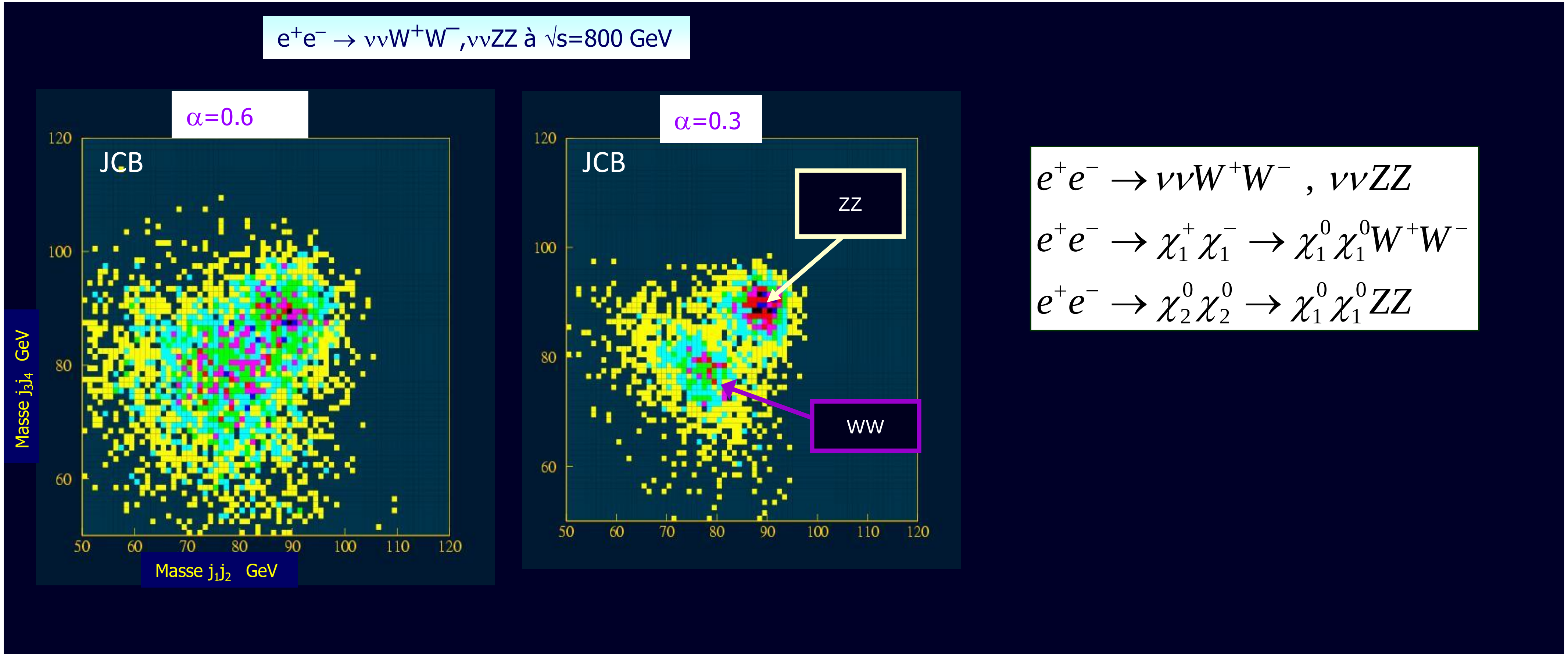
$\sqrt{s}$ = 250 GeV



Example of W,Z separation versus jet energy precision

Physics versus performance on the jets

Example 3 Longitudinal W_L coupling, Coupling in SuSy, etc…
(e+e- →ννWW, ννZZ , *séparation WW/ZZ*)
Going from a=0.3 to a=0.6 is equivalent to a loss of 45% of the luminosity (running time)



$e^+e^- \rightarrow \nu\nu W^+W^-$,ννZZ à √s=800 GeV

$$e^+e^- \rightarrow \nu\nu W^+W^- \;,\; \nu\nu ZZ$$
$$e^+e^- \rightarrow \chi_1^+\chi_1^- \rightarrow \chi_1^0\chi_1^0 W^+W^-$$
$$e^+e^- \rightarrow \chi_2^0\chi_2^0 \rightarrow \chi_1^0\chi_1^0 ZZ$$

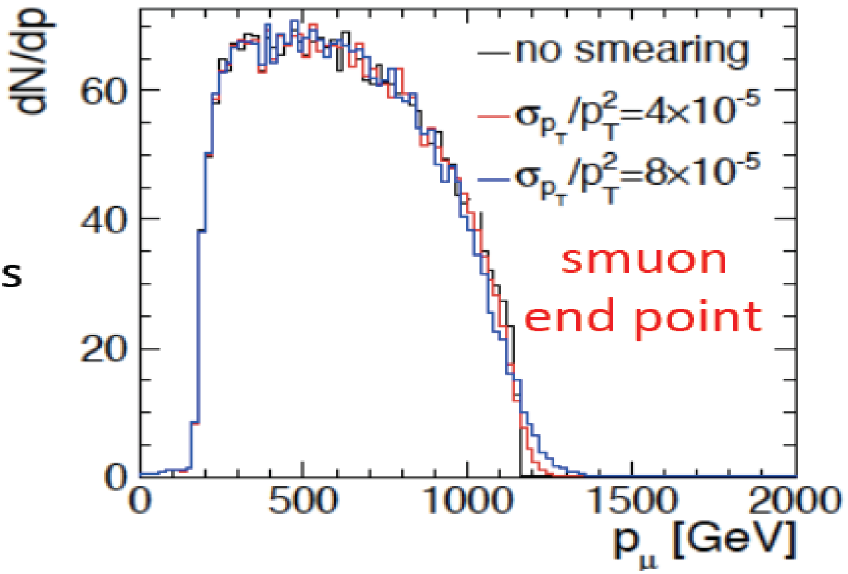
Which detector to have good performances for the ILC physics program

momentum resolution:

e.g, ZH with Z➔μμ, Smuon endpoint

$$\boxed{\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\ \mathrm{GeV}^{-1}}$$

for high p_T tracks

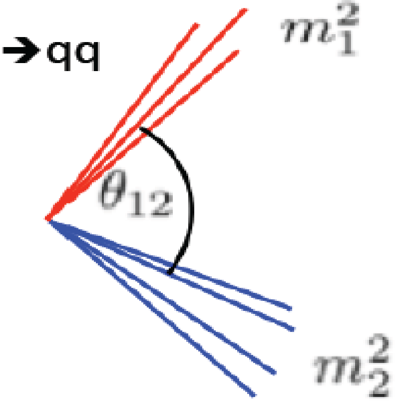


jet energy resolution:

e.g. W/Z/H di-jet mass separation, ZH with Z➔qq

$$\boxed{\frac{\sigma_E}{E} \sim 3.5-5\,\%}$$

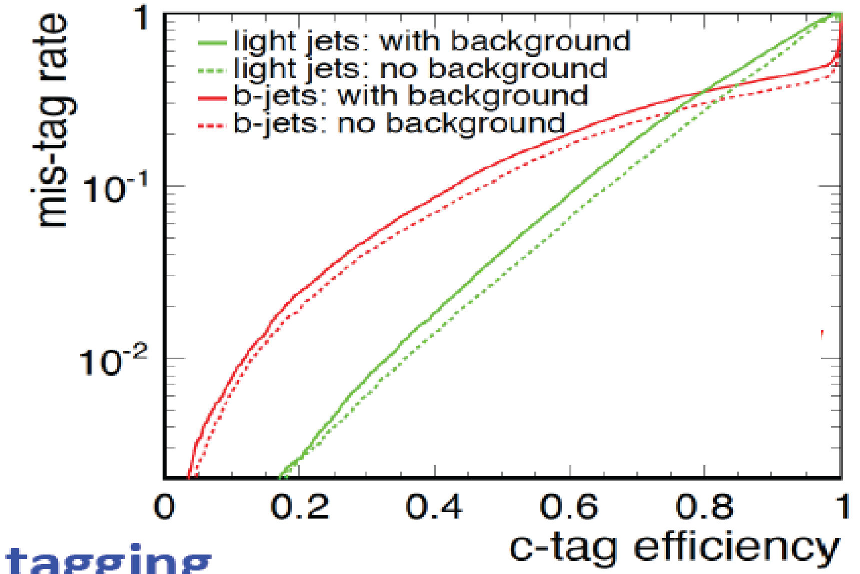
(for high-E jets, light quarks)



impact parameter resolution:

e.g. c/b-tagging, Higgs BR

$$\boxed{\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$



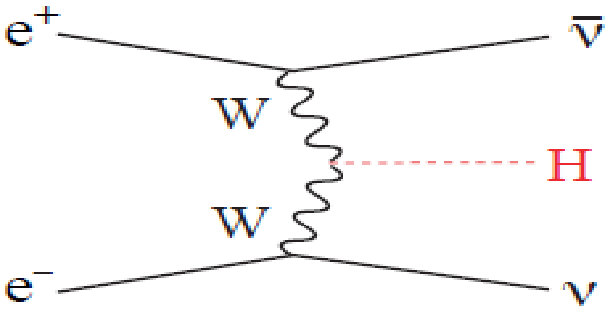
angular coverage, very forward electron/photon tagging

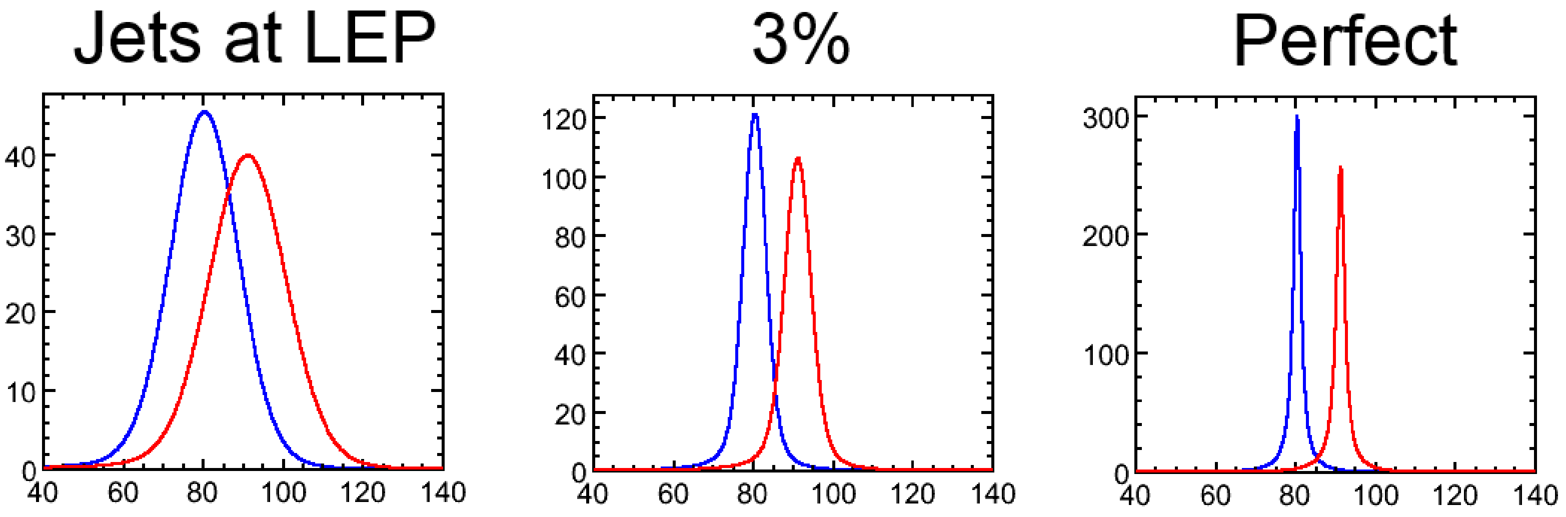
Why 3%

Examples:

- W Fusion with final state neutrinos requires reconstruction of H decays into jets

- Jet energy resolution of ~3% for a clean W/Z separation

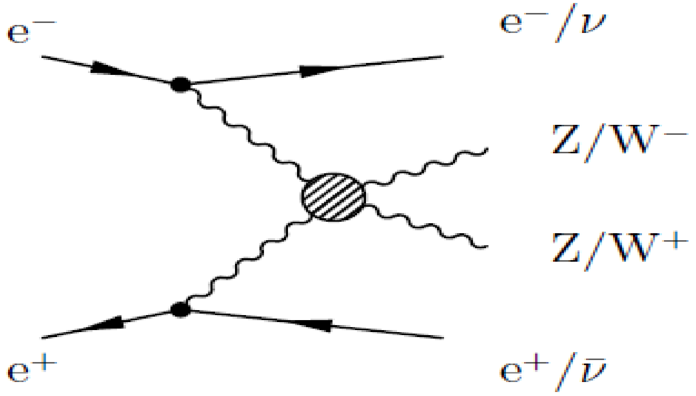



Jets at LEP

3%

Perfect

M. Thomson



How to reach this precision ?

Particle Flow Algorithm (PFA)

I propose this method in 1995 to help a student (F.Braems) searching for long lived particles at LEP 1, decaying into 2 jets. The standard resolution as given by Energy Flow with ALEPH detector was not sufficient.

I propose therefore to forget the neutral hadron(s) in jets and used only charged tracks and photons, which give a much better resolution. BUT it was based on fast simulation and of course people at that time did not believe it is possible reconstructing individuals photons in jets !! I therefore modified and adapt an old algorithm (A.Rougé fro WA4) to be used in τ decays and jets framework. ALEPH photons reconstruction !!!

How to go further for next collider ?

Integrate the reconstruction of neutral hadron(s)

First we (Henri Videau and myself) give the name of the method , made the first tests and try to see how it can work. PFA calorimeter would do the best job for that

How to reach this precision ?

PFA : « Particle Flow » Algorithm

With HEP detectors, the charged tracks are better measured than photon(s)
which are themselves better measured than neutral hadron(s)

Resolution on the charged track(s)	$\Delta p/p$	~ few 10^{-5}
Resolution on the photon(s)	$\Delta E/E$	~ 12%
Resolution on the h°	$\Delta E/E$	~ 45%

$$E_{\text{jet fraction}} = \underset{65\%}{E_{\text{charged tracks}}} + \underset{26\%}{E_{\gamma}} + \underset{9\%}{E_{h^0}}$$

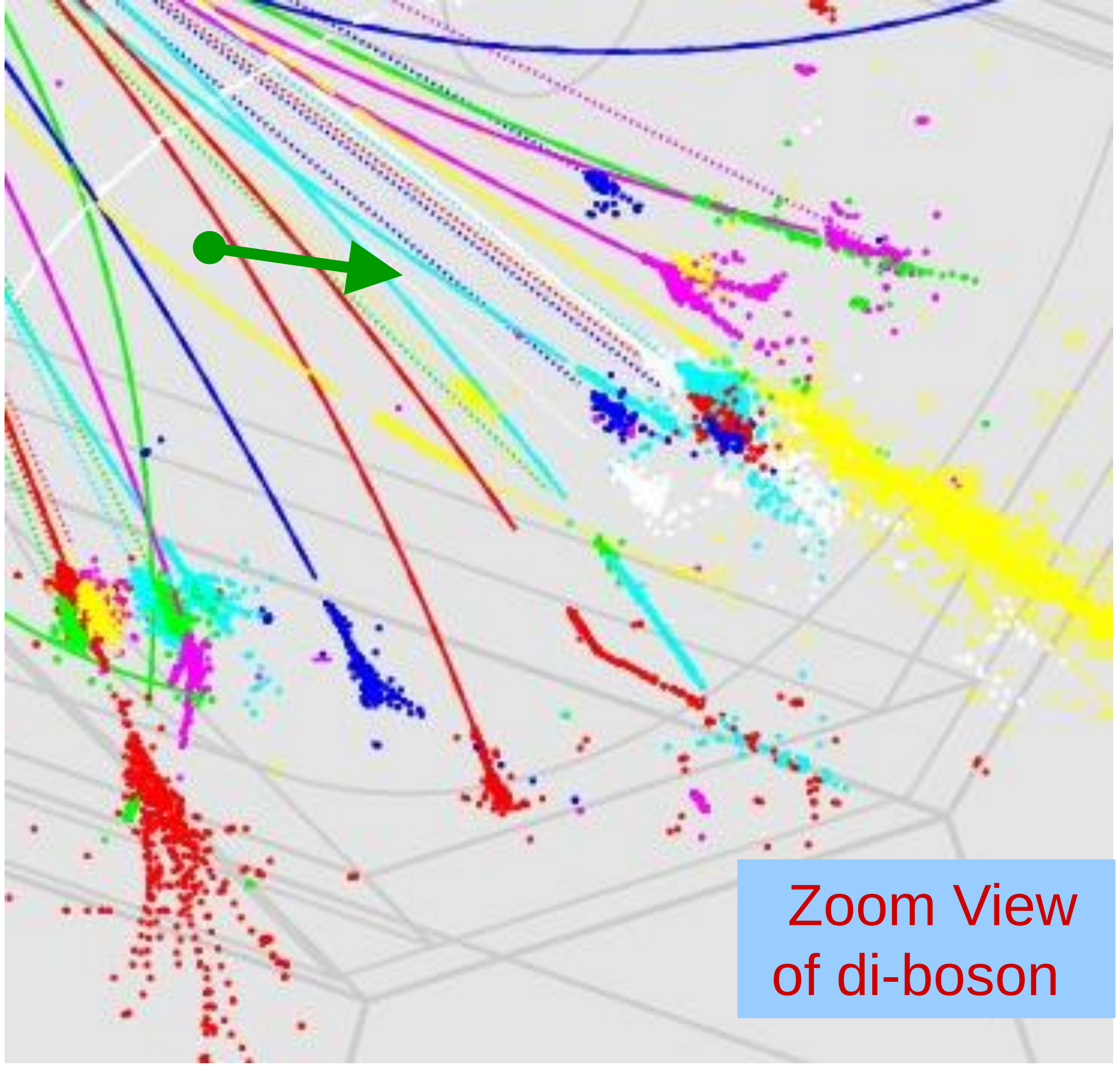
With a perfect detector, no confusion between species and individual reconstruction

$$\sigma^2\,\text{jet} = \sigma^2\text{ch.} + \sigma^2\,\gamma + \sigma^2\,h^0 \quad \text{gives about } \sigma^2\,\text{jet} = (0.14)^2\,E_{\text{jet}}$$

Real life and real detector →

- σ^2threshold → Energy threshold to be rec. (depends on species)
- σ^2efficiency → loss of particles (not reconstructed)
- σ^2confusion → Mixing between particles in the calorimeter

HOW


Zoom View of di-boson

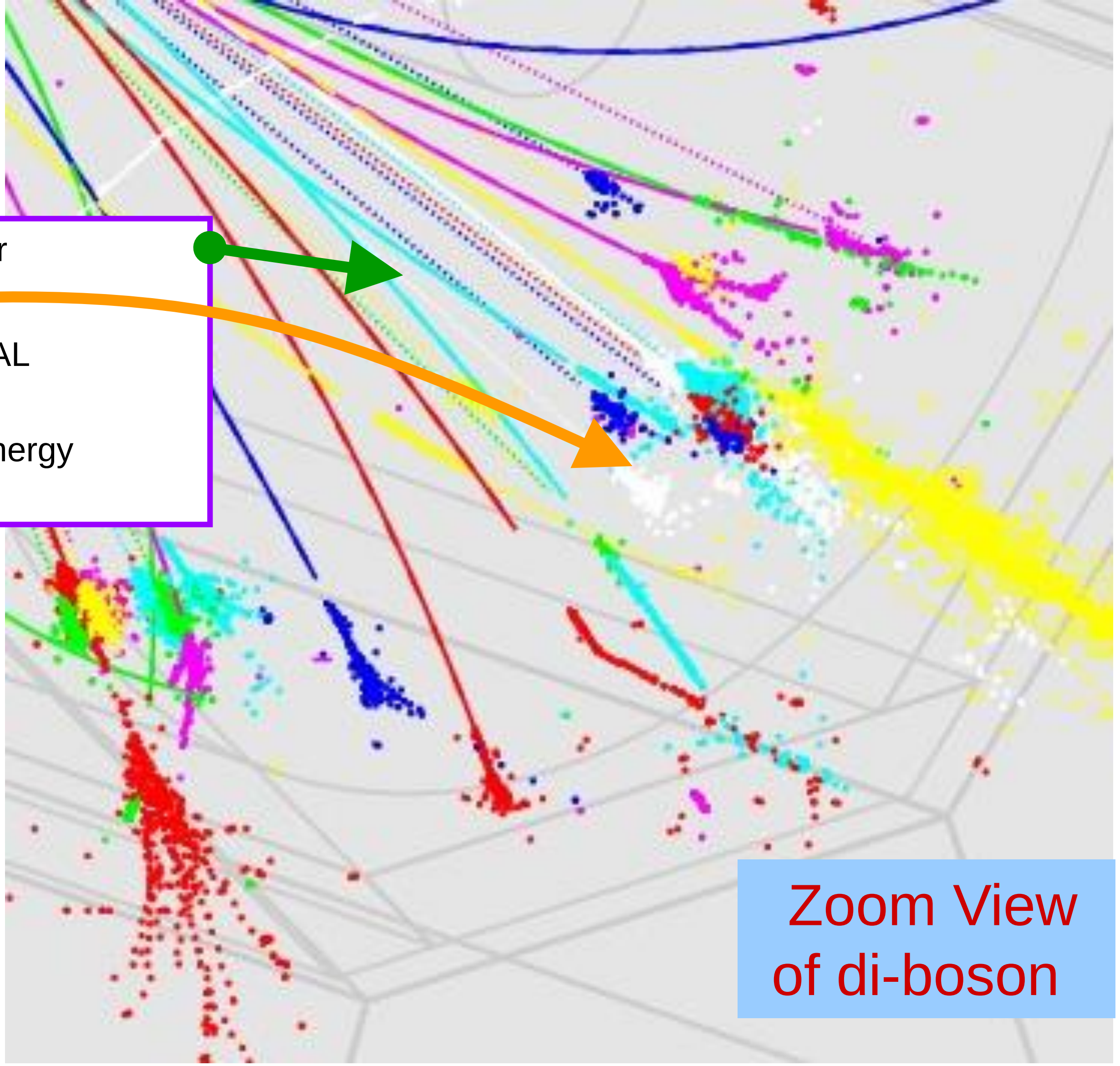
HOW

❶ find the charged particles in the tracker

❷ the photon(s) in the ECAL

❸ the neutral hadron(s) in the ECAL, HCAL

Process ❷ and ❸ are possible only if there is no mixing between deposited energy from different particles



Zoom View of di-boson

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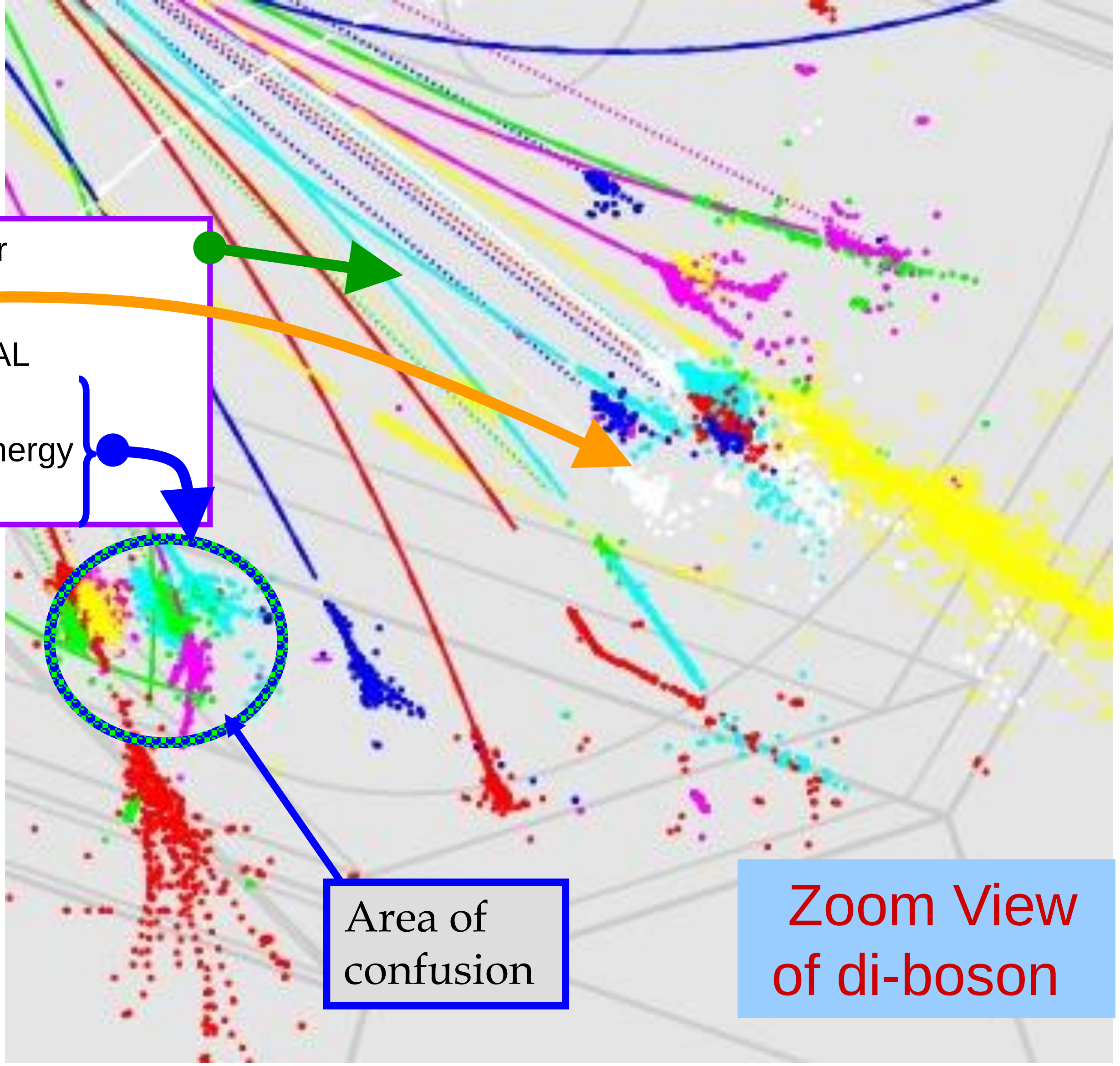

Area of confusion

Zoom View of di-boson

HOW

❶ find the charged particles in the tracker

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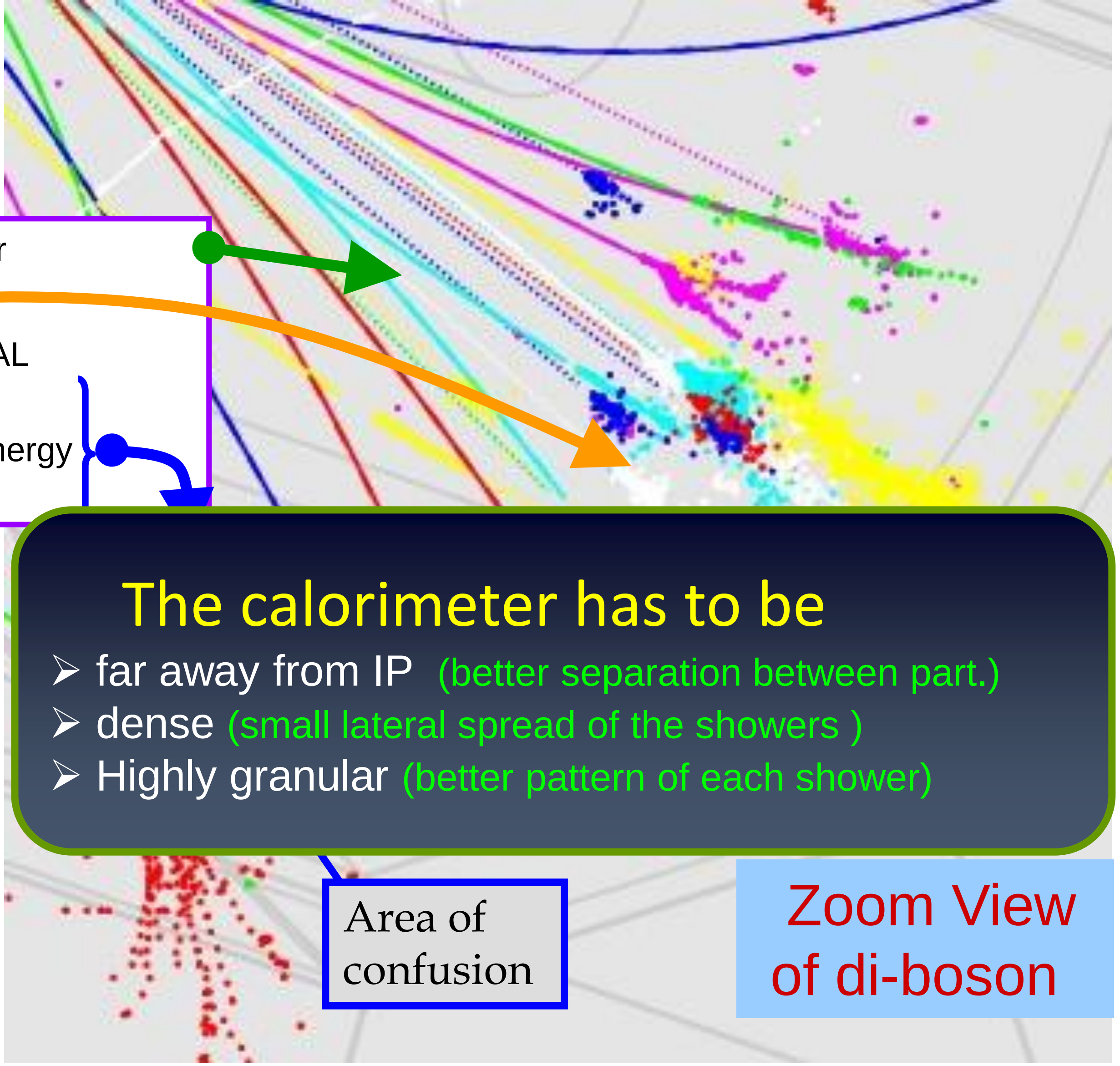


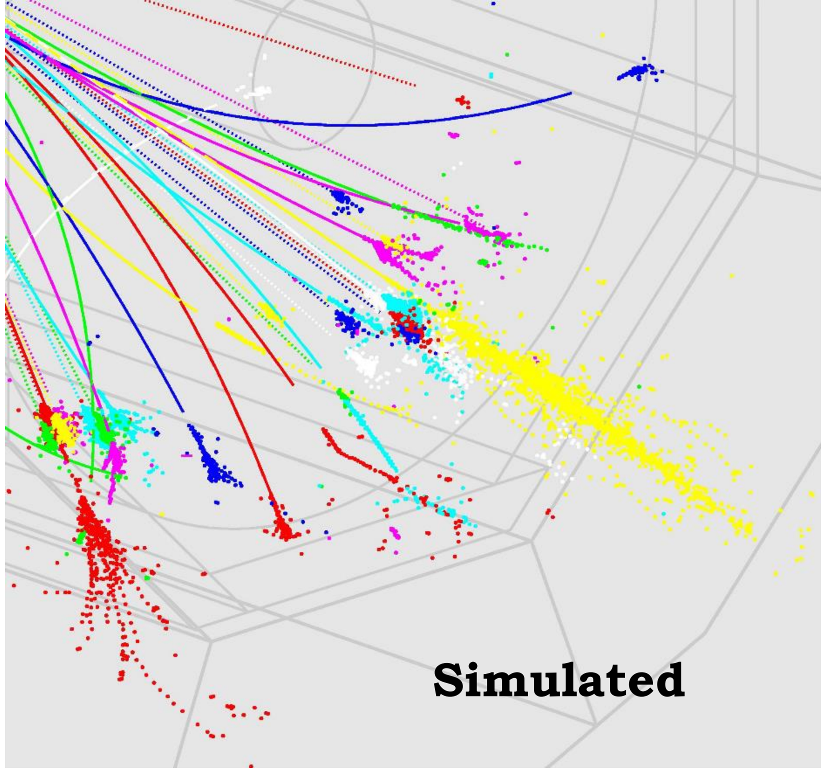
Area of confusion

Zoom View of di-boson

The calorimeter has to be

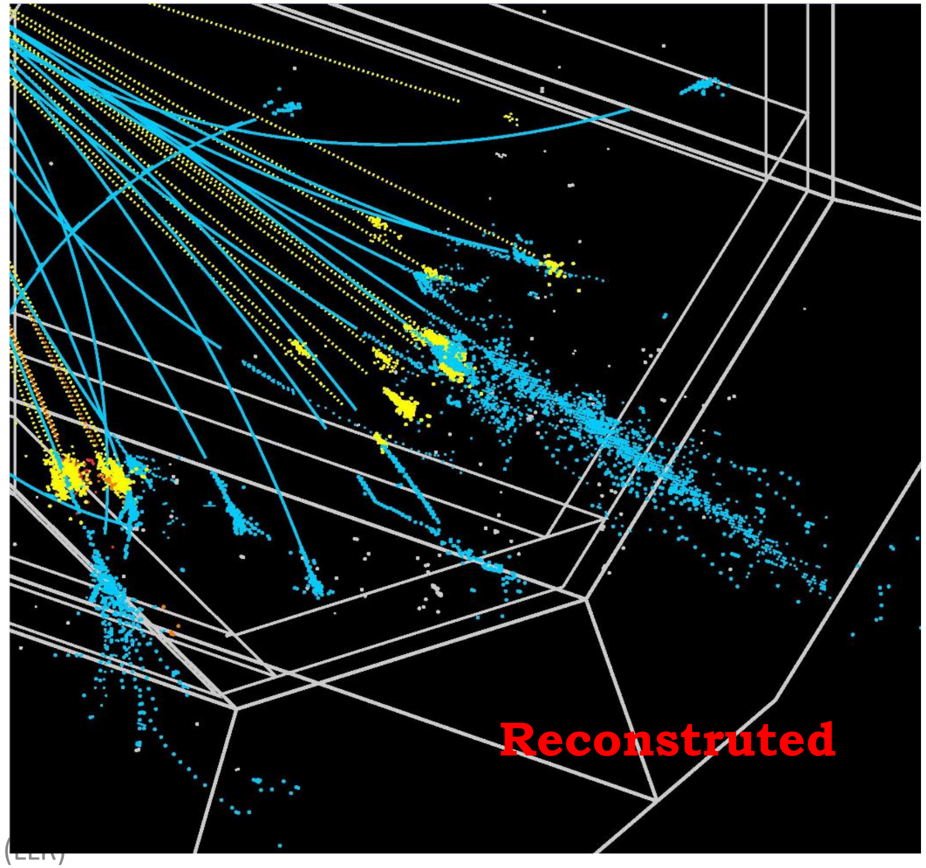
- far away from IP (better separation between part.)
- dense (small lateral spread of the showers)
- Highly granular (better pattern of each shower)

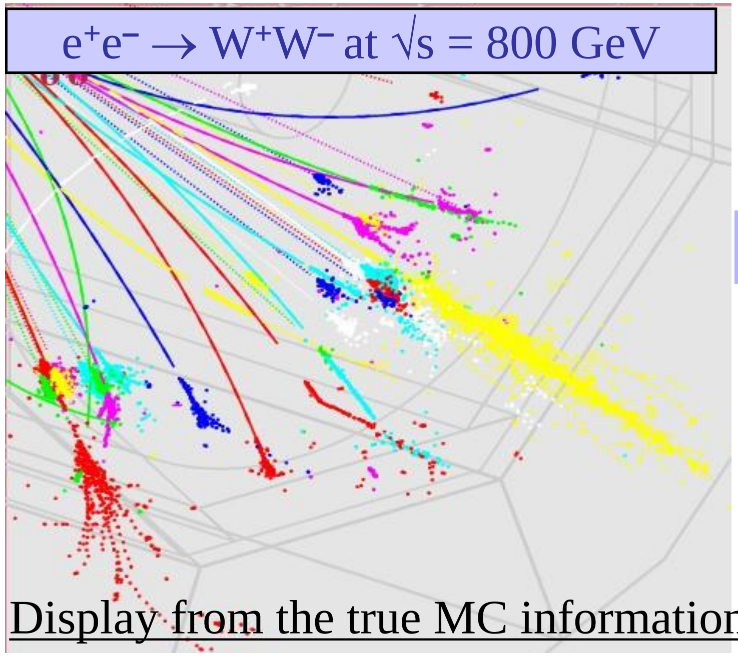
Associate
the deposited energy
With the depositing particle



Blue : charged tracks associated

Yellow : reconstructed photons

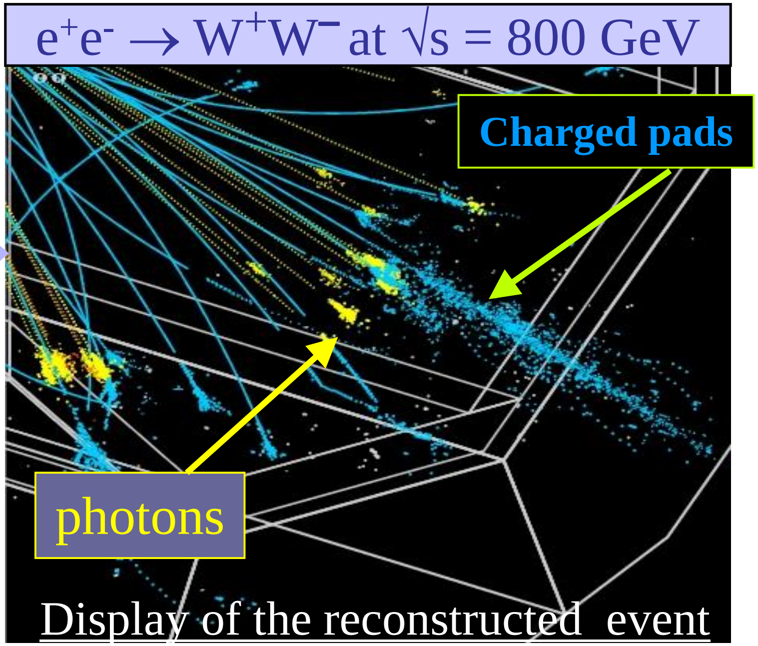




$e^+e^- \rightarrow W^+W^-$ at $\sqrt{s} = 800$ GeV

Display from the true MC informations

Reconstruction

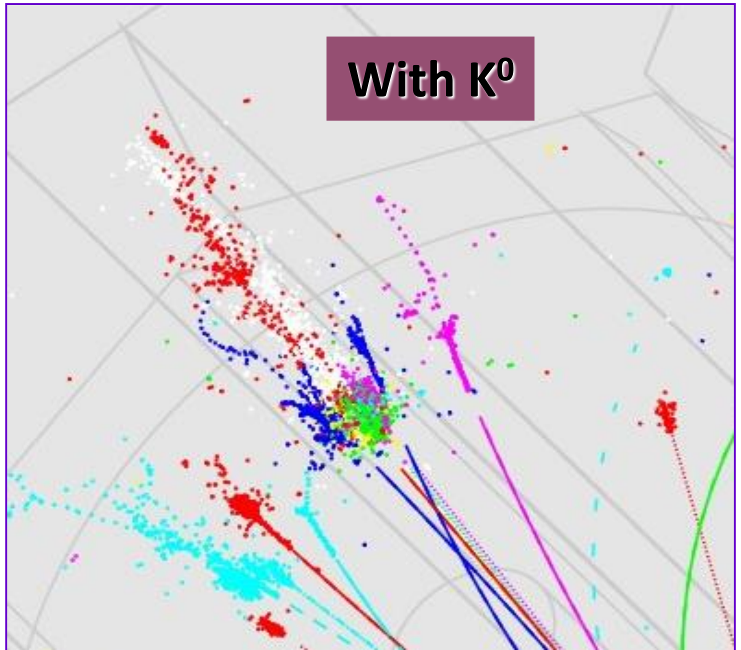


$e^+e^- \rightarrow W^+W^-$ at $\sqrt{s} = 800$ GeV

Charged pads

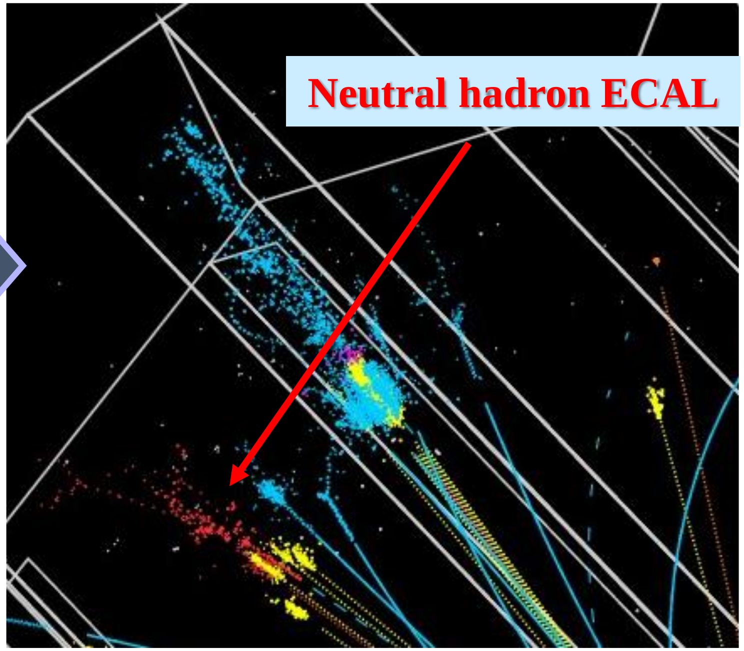
photons

Display of the reconstructed event



With K^0

Reconstruction



Neutral hadron ECAL

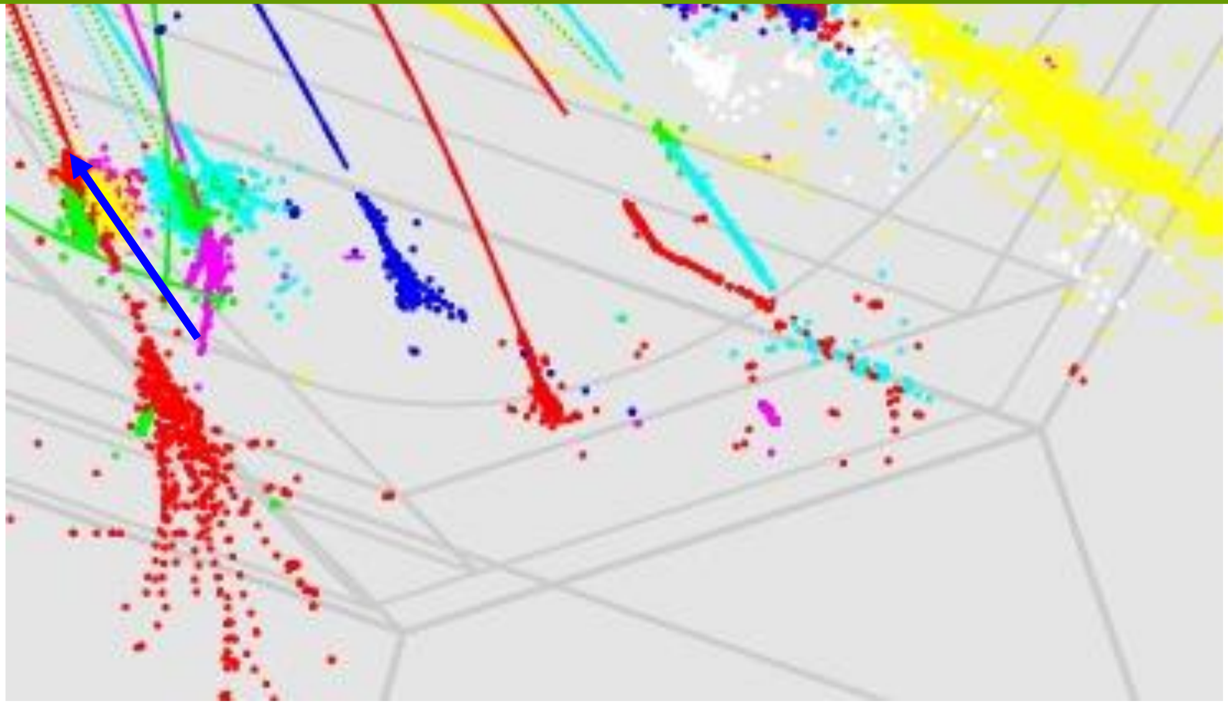
Associate
the deposited energy
With the depositing particle

Quality of the «photo»

- Détector readout in 3D
- Small pixel size
- ECAL AND HCAL inside the coil

The calorimeter has to be

- far away from IP (better separation between part.)
- dense (small lateral spread of the showers)
- Highly granular (better pattern of each shower)



J.-C. Brient (LLR)

What PFA is & What it is not

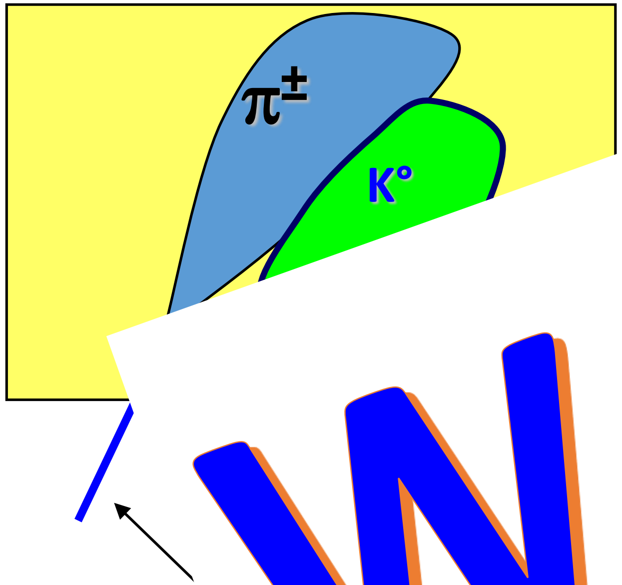
CMS is doing that

…

It is NOT PFA !!

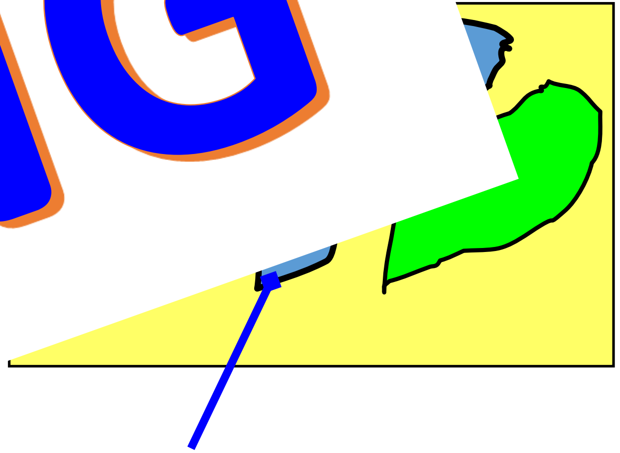
EFLOW

Partially applied
in ALEPH (no neutral hadrons)



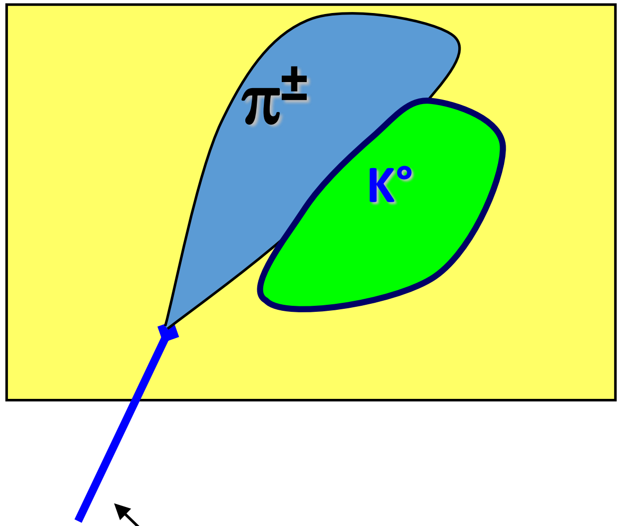
WARNING

at is the one
est energy resolution
single charged hadron



BEST calo for that is a camera with large pixels number

What PFA is & What it is not



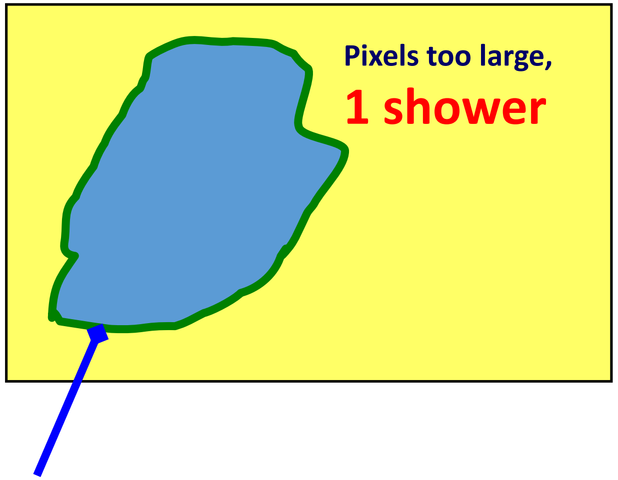
Tracker info.

CMS is doing that

…

It is NOT PFA !!

EFLOW

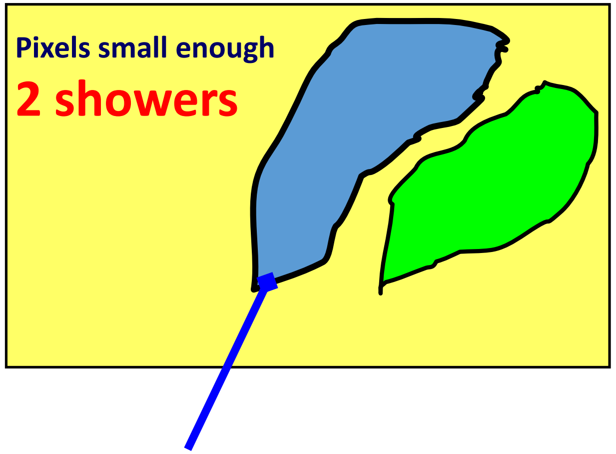


BEST calo for that is the one with the best energy resolution for single charged hadron

Good method for crystal calo or Compensated calo like IDEA

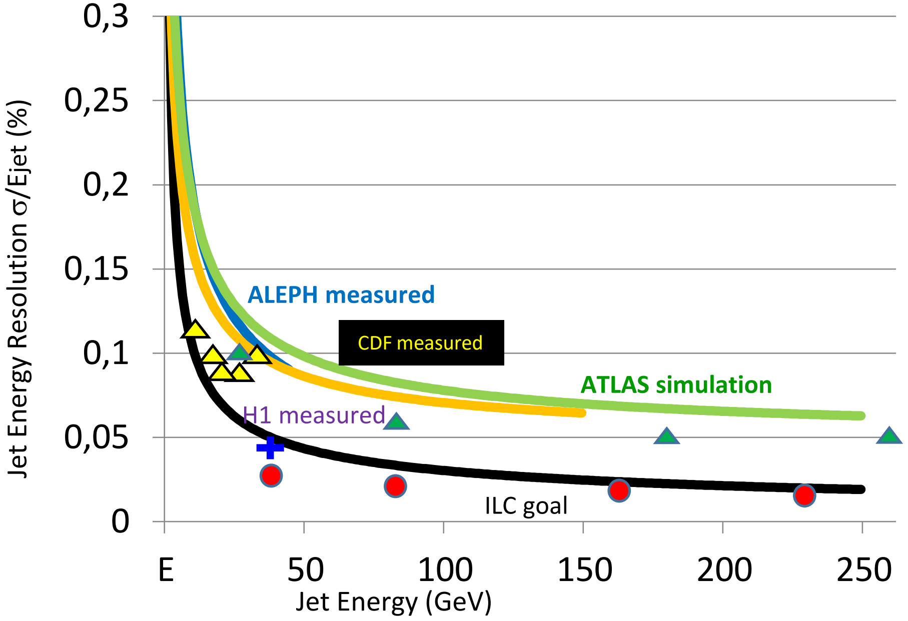
Partially applied
in ALEPH (no neutral hadrons)

PFA



BEST calo for that is a camera with large pixels number

Jet energy resolution



✚ TESLA TDR 2000 – **PFA _LLR**
JETS with G4 sim. & rec

● PANDORA 2014 - **PFA**
JETS with full G4 sim. & rec

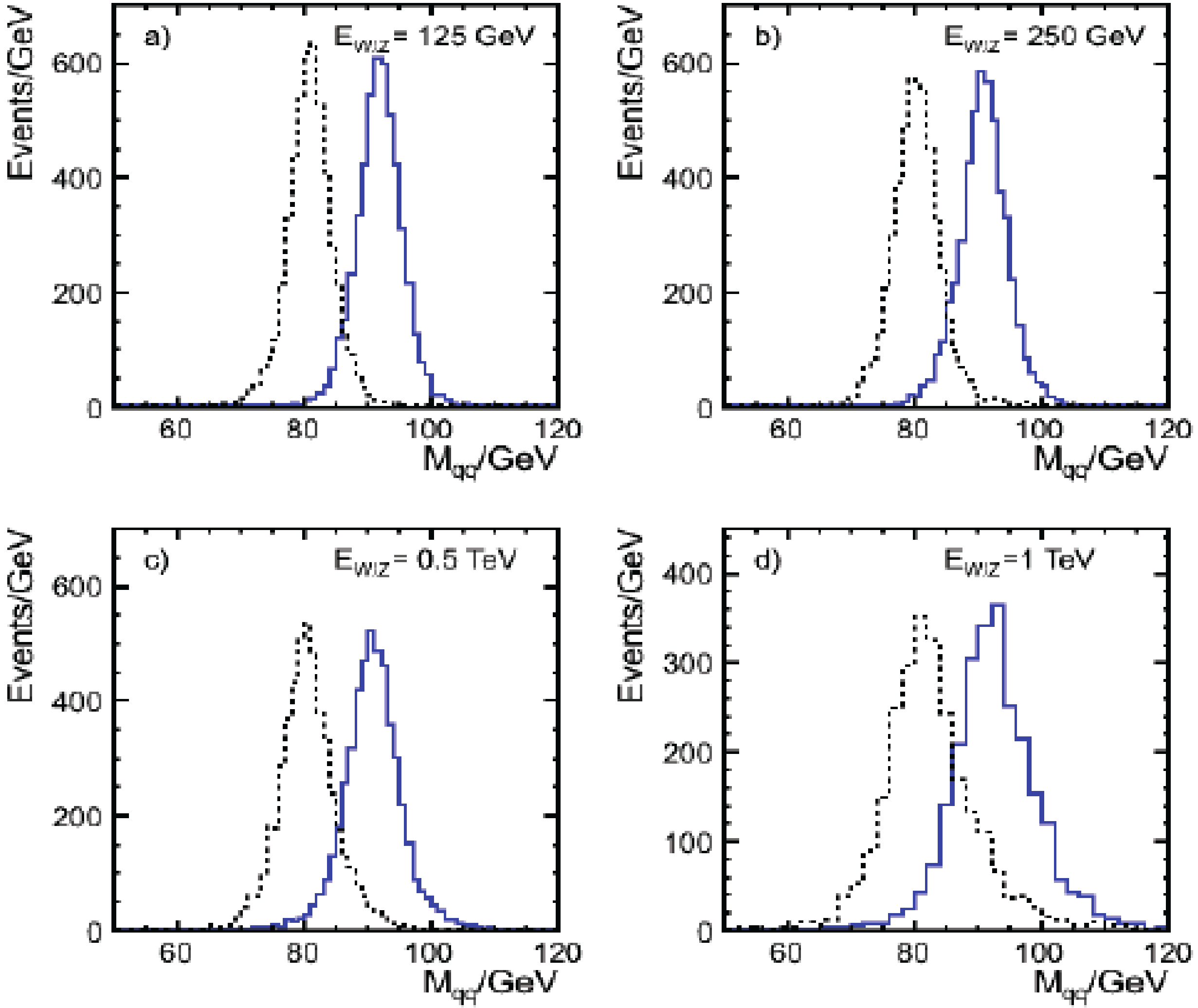
▲ DREAM/IDEA : Measured TB 2012
on single pion (Wigmans dream)

rms$_{90}$

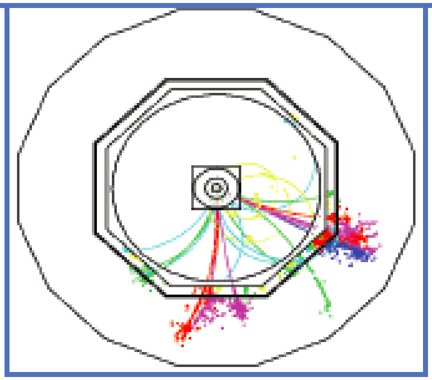
E_{JET}	σ_E/E_j
45 GeV	3.7 %
100 GeV	2.8 %
250 GeV	2.9 %
500 GeV	3.0 %
1 TeV	3.2 %

$$e^+e^- \rightarrow WW \rightarrow u\bar{d}\nu\mu$$
$$e^+e^- \rightarrow ZZ \rightarrow d\bar{d}\nu\bar{\nu}$$

We can also think about H → ZH → Z WW* versus ZZZ*

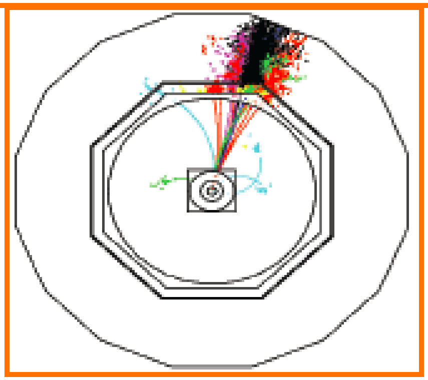


ILC-like energies



Clear separation of W/Z di-jet mass peaks

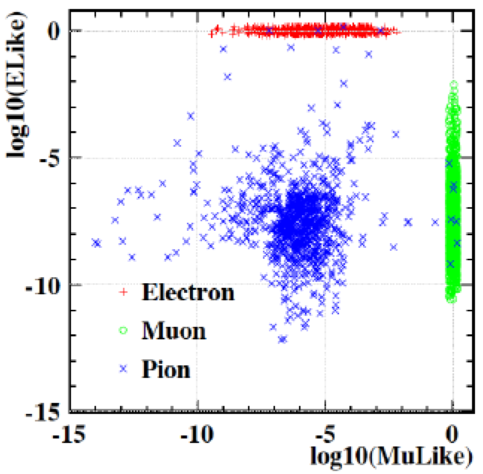
CLIC-like energies

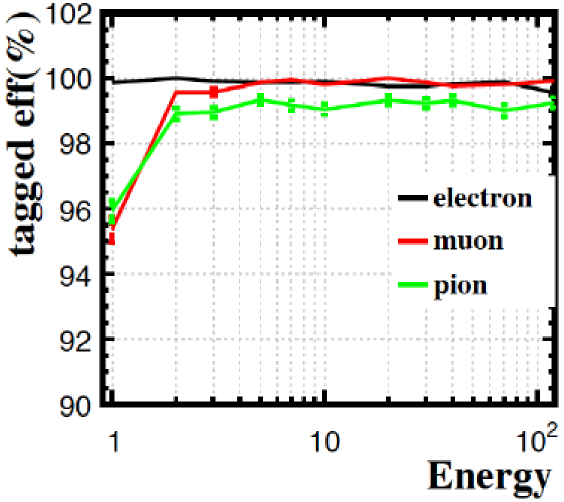


W and Z still resolved from monojet invariant mass

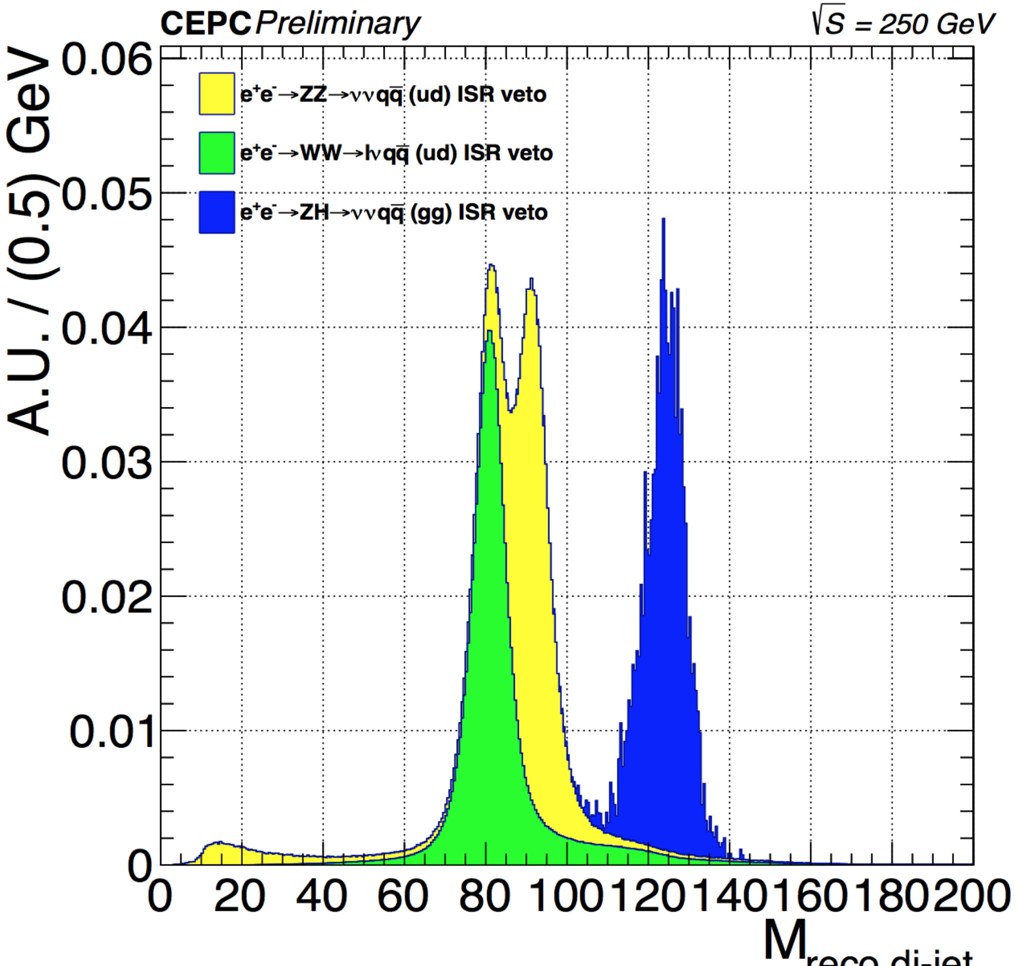
Granularity at the level of 1x1 cm or better and > 25 layers (ECAL & HCAL)

"Lepton identification at particle flow oriented detector for the future e^+e^- Higgs factories,"
Eur. Phys. J. C77 no. 9, (2017) 591, arXiv:1701.07542

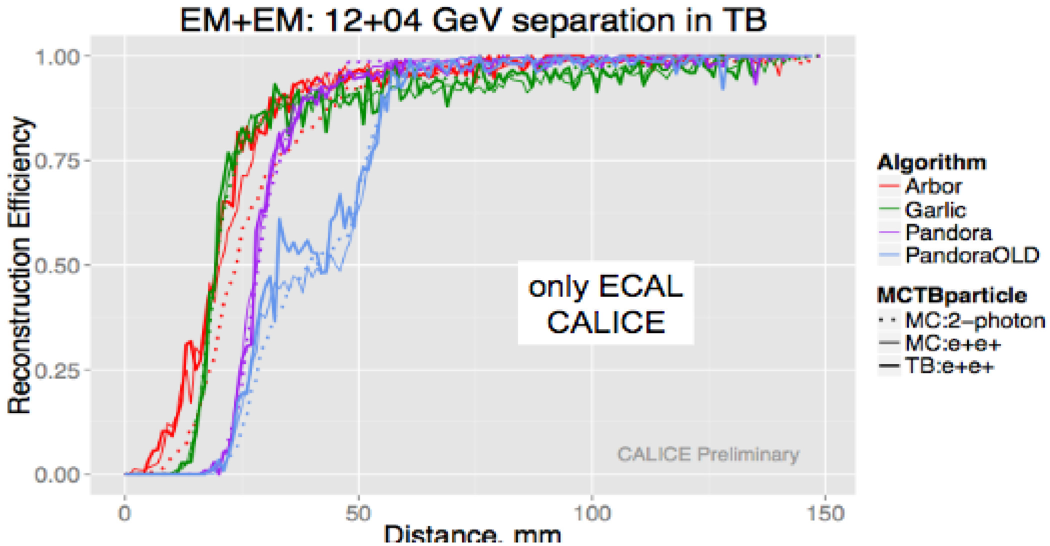




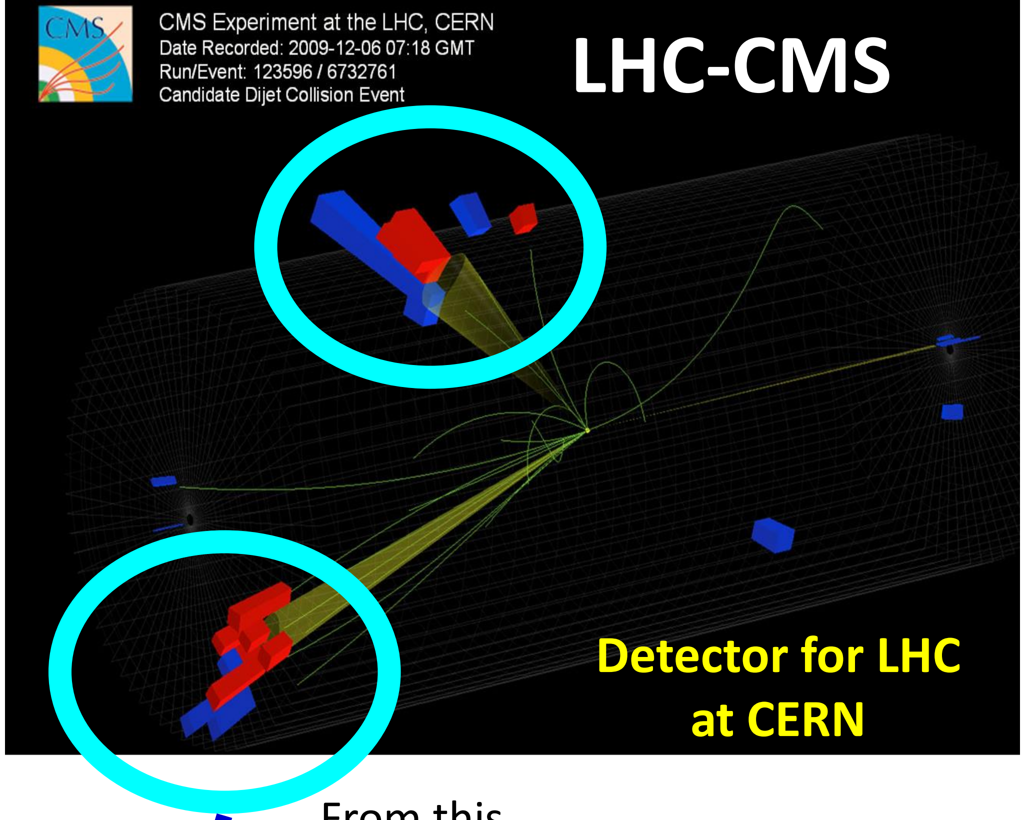
Recent progress with ARBOR PFA software (I2PI-Lyon, IHEP-Beijing)



It is not only in Geant4



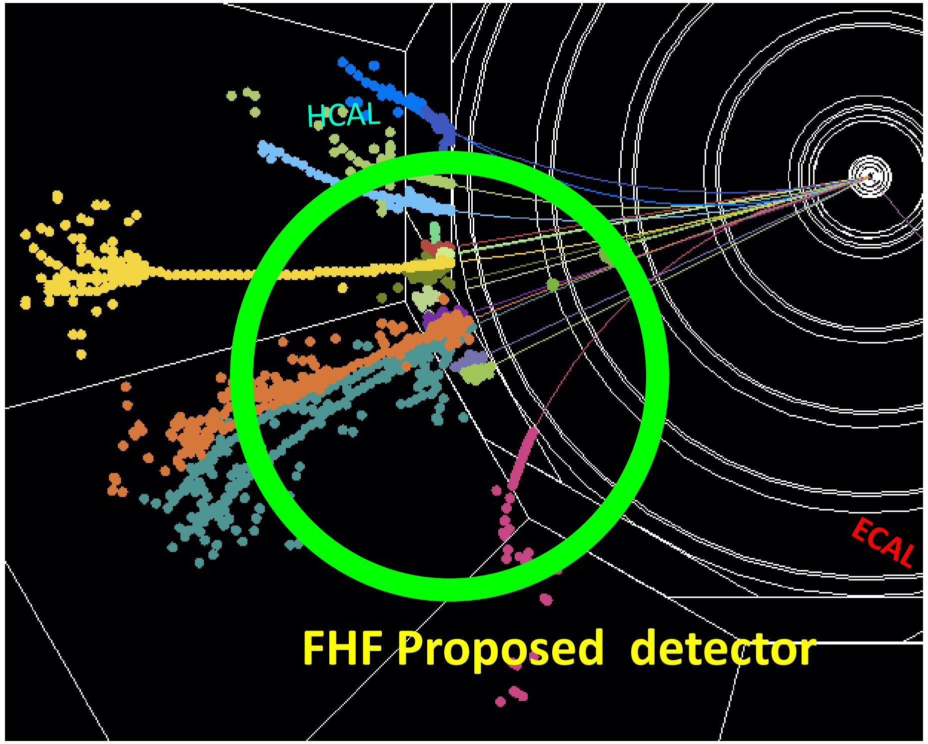
WANT an
IMAGING DEVICE
at the level of Calorimeter



LHC-CMS

Detector for LHC at CERN

From this



FHF Proposed detector

to that

PHOTO with

100M pixels every 500 ns

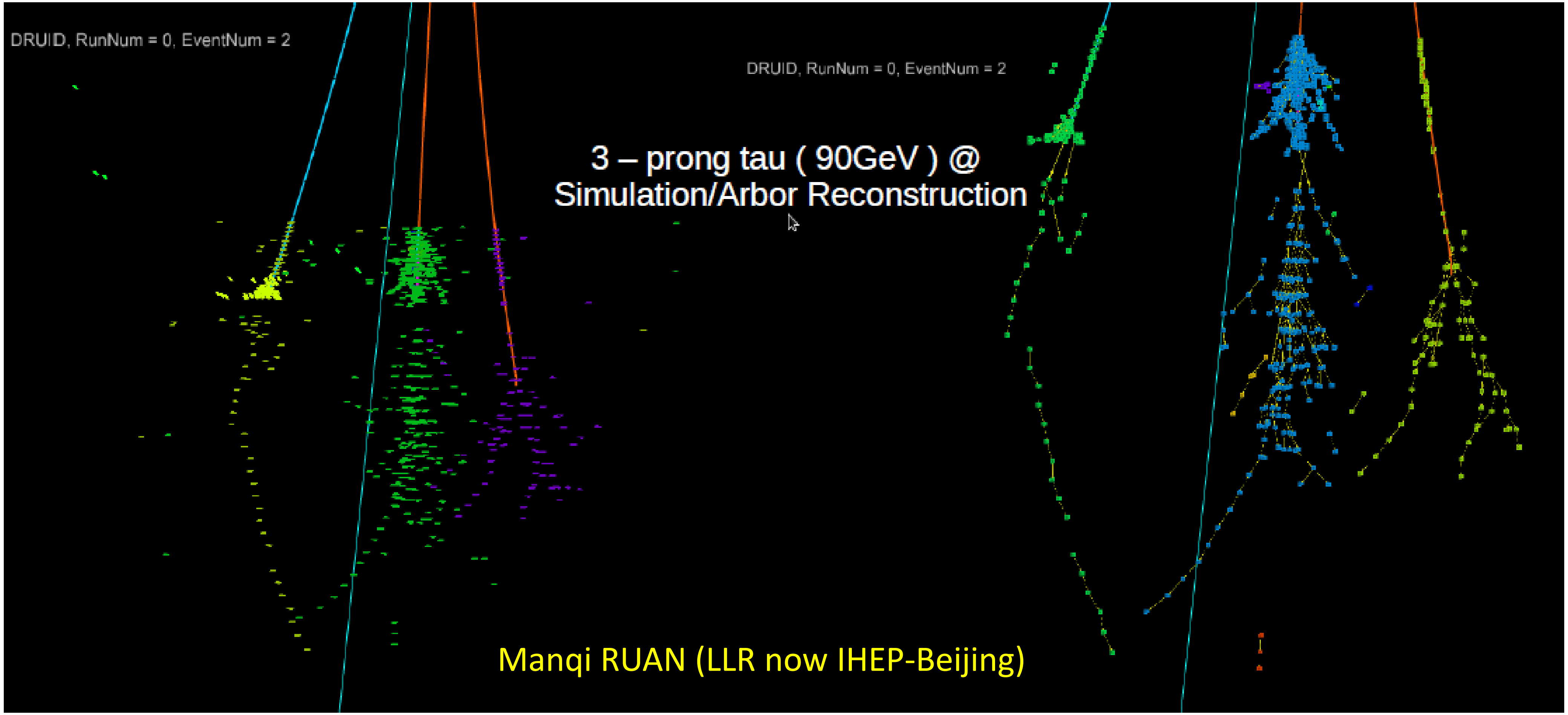
The best combination for PFA (my understanding)

HGCAL for the ECAL (silicon-tungsten), but for low radiation experimental condition …

SDHCAL for HCAL

save cost, solve muon PID !!! , better stability than (any device with SiPM…),
smaller pixel size allows better pattern and tracking in HCAL,

What you can do with Silicon-Tungsten ECAL and SHCAL



WARNING

At FCCee/CEPC , it is expected that the systematics errors dominate Tau polarization here

Table : Results for $\mathcal{A}_e$ *and* $\mathcal{A}_\tau$ in the analysis. The first error is statistical, the second systematic

ALEPH

Tau decays channels	$\mathcal{A}_\tau$ %	$\mathcal{A}_e$ %
$h^\pm\ \nu$	$15.21 \pm 0.98 \pm 0.49$	$15.28 \pm 1.30 \pm 0.12$
$\rho^\pm\ \nu$	$13.79 \pm 0.84 \pm 0.38$	$14.66 \pm 1.12 \pm 0.09$
a1 ($3h^\pm$)	$14.77 \pm 1.60 \pm 1.00$	$13.58 \pm 2.11 \pm 0.40$
a1 ($h^\pm\ 2\pi°$)	$16.34 \pm 2.06 \pm 1.52$	$15.62 \pm 2.72 \pm 0.47$
electron	$13.64 \pm 2.33 \pm 0.96$	$14.09 \pm 3.17 \pm 0.91$
muon	$13.64 \pm 2.09 \pm 0.93$	$11.77 \pm 2.77 \pm 0.25$
$h^\pm$ inclusive	$14.93 \pm 0.83 \pm 0.87$	$14.91 \pm 1.11 \pm 0.17$
Combined	$14.44 \pm 0.55 \pm 0.27$	$14.58 \pm 0.73 \pm 0.10$

Tau polarization here

Table : Summary of the systematics uncertainties (%) $\mathcal{A}_\tau$ in the analysis

ALEPH

sources	**h**	**ρ**	**3h**	**h 2π°**	**e**	**μ**	**Incl. h**
selection		0.01			0.14	0.02	0.08
tracking	0.06		0.22			0.10	
ECAL En. Scale	0.15	0.11	0.21	1.10	0.47		
PID	0.15	0.06	0.04	0.01	0.07	0.07	0.18
misid	0.05				0.08	0.03	0.05
photon	**0.22**	**0.24**	**0.37**	**0.22**			
Non-τ Bkg	**0.19**	0.08	0.05	**0.18**	0.54	0.67	0.15
τ BR	0.09	0.04	0.10	0.26	0.03	0.03	0.78
modeling			0.70	0.70			0.09
MC stat	**0.30**	**0.26**	**0.49**	**0.63**	**0.61**	**0.63**	**0.26**
Total	**0.49**	**0.38**	**1.00**	**1.52**	**0.96**	**0.93**	**0.87**

In red, errors which do not scale with luminosity

What to do

- Ultra granular calorimeter for PFA , extract the best from ultra granular !!
- Made a preliminary choose of the technology

HGCAL will be a fantastic test for these ideas (even if …)

New ideas !!

- Use the timing for PID, for PFA, for Compensation etc…
- Find the good way to have more for less money
- think about new idea like fractal dimension (see M.Ruan with PID)

Circular collider with high luminosity !!

… SYSTEMATICS uncertainties versus the detector

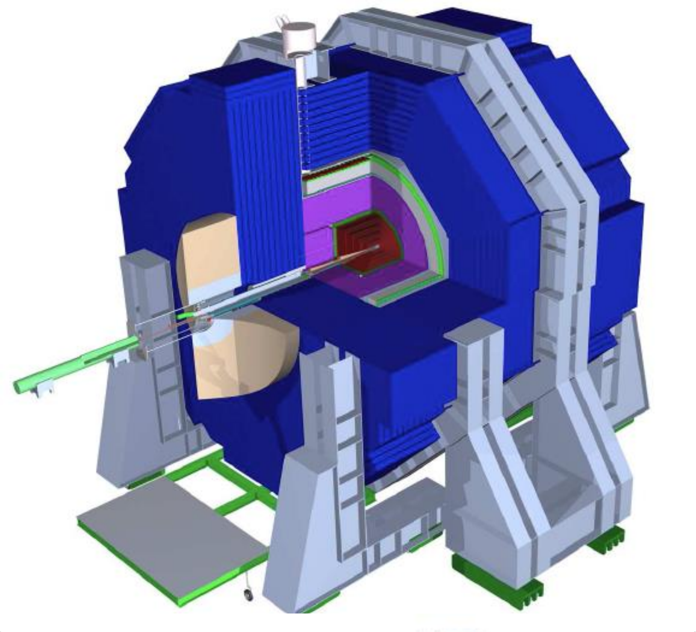
Thanks you

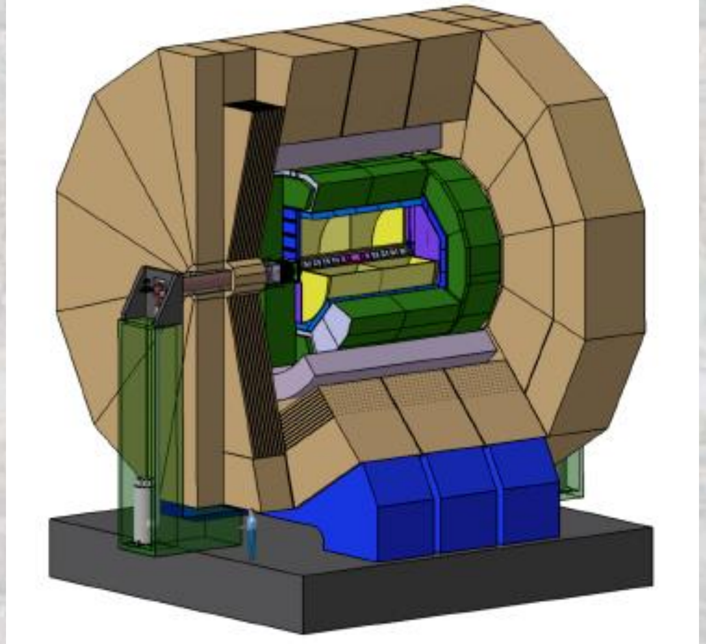
BACK UP

Two Detectors

- SiD
  - High B field (5 Tesla)
  - Small ECAL ID
  - Small calorimeter volume
    - Finer ECAL granularity
  - Silicon main tracker
- ILD
  - Medium B field (3.5 Tesla)
  - Large ECAL ID
    - Particle separation for PFA
  - TPC for main tracker

Based on PFA idea



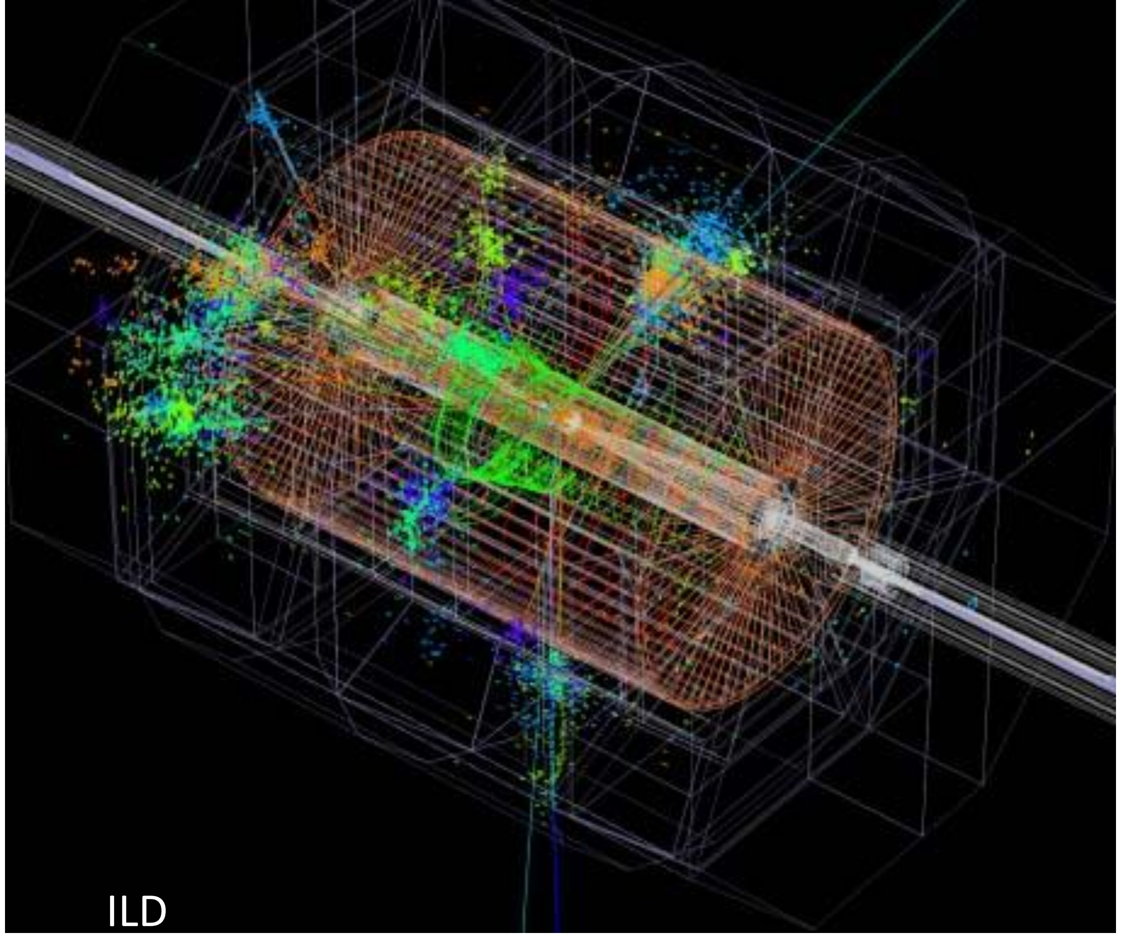


ILC Detectors

PFA
(particle flow algorithm)

Jet Energy Measurement:

- Charged particles
  - Use trackers
- Neutral particles
  - Use calorimeters
- Remove double-counting of charged showers
  - Requires high granularity

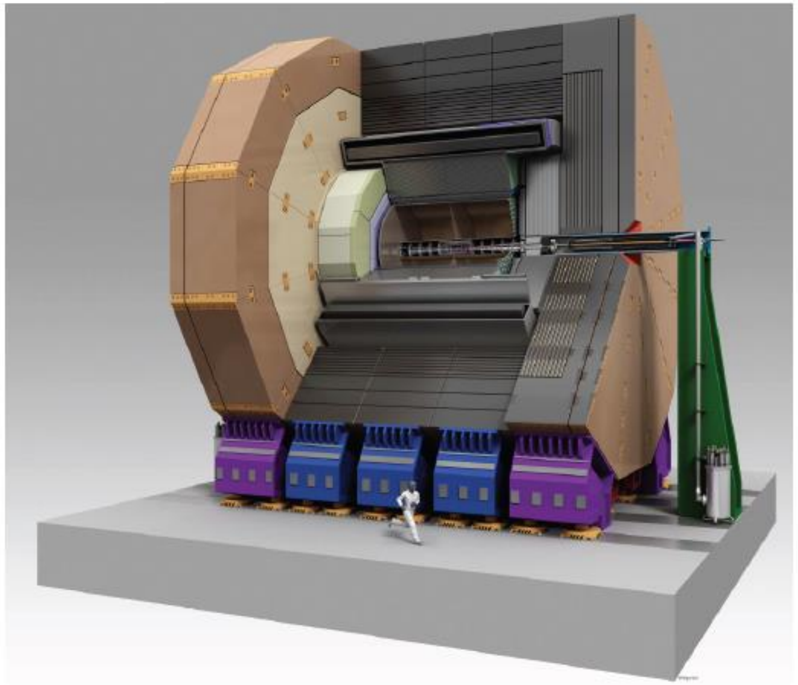


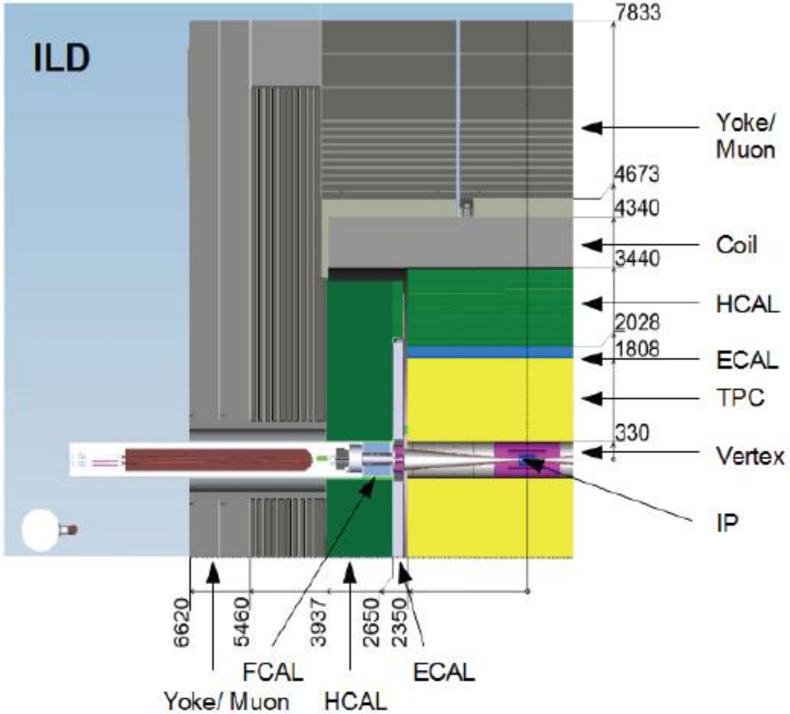
#ch	ECAL	HCAL
ILC (ILD)	100M	10M
LHC	76K(CMS)	10K(ATLAS)

X10^3 for ILC
Need new technologies !
(Si pads, GEM, RPC, etc.)

Jet energy resolution ~ ½ of LHC

ILD detector at ILC





ILD: "International Large Detector"

- Silicon vertex detector
- Time Projection Chamber as tracker
- ... surrounded by Silicon envelope
- Fine-grained calorimetry (PFA)
- Large (L) and small (S) options under study
- Final focus quadrupoles inside the detector

	ILD-L (DBD)	ILD-S
B-field	3.5 T	4 T
TPC outer radius	180 cm	146 cm
Coil inner radius	344 cm	310 cm

The pending questions

a) Calibration of 100 millions channels and signal stability (we want same response for same collision)

b) Capability to make zero suppress “on site” (we don’t want to read empty pixel)

c) Keep S/N ≥ 10 at MIP level and coherent noise under control (noise , radio/TV , telephone call)

d) Multiplexing for the quantity of signal line out (we don’t want to have 100M cables)

e) Power management due to large number of channels (we don’t want to burn our electronics readout)

f) KEEP the COST UNDER CONTROL (we want an affordable cost)

A possible set of answers

a) Choose stable device (silicon) or control & monitor the signal stability (Scint. or Micromegas)

b) ADC& digital memory in readout chip, close to active layer. Read memories at each end of bunch train

c) i.e. Silicon PIN diodes …. AC/DC coupling , ground loop , etc… a lot of R&D (EMC study)

d) Large number of Channels/VFE ASIC… (KPIX, SKIROC), but only few readout line

e) Power pulsing (thanks to machine structure) → reduced the power to dissipate… no cooling inside

f) CMS HGCAL

Granularity , compactness, homogeneity

\---

large number of pixel layers, small pixel size, compactness

with

External constraints from

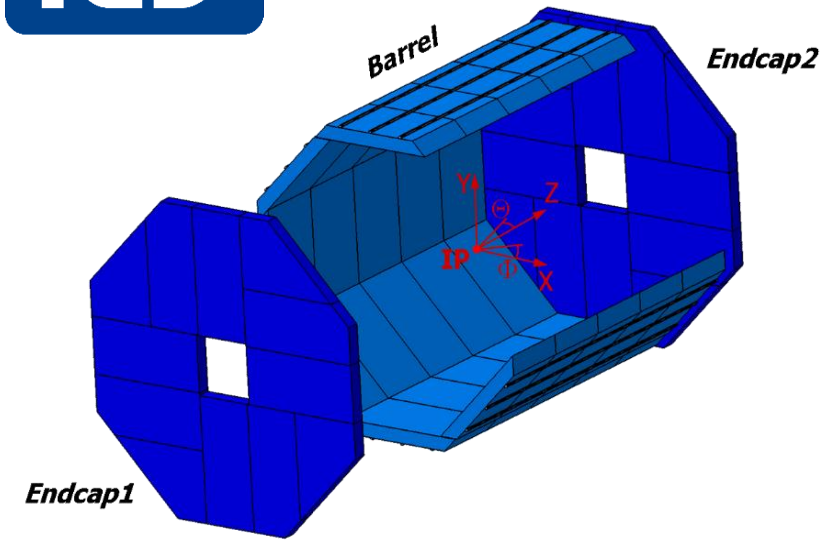
- The large B-Field (protection against machine background),
- The accelerator time structure,
- and of course the **COST**

leads to

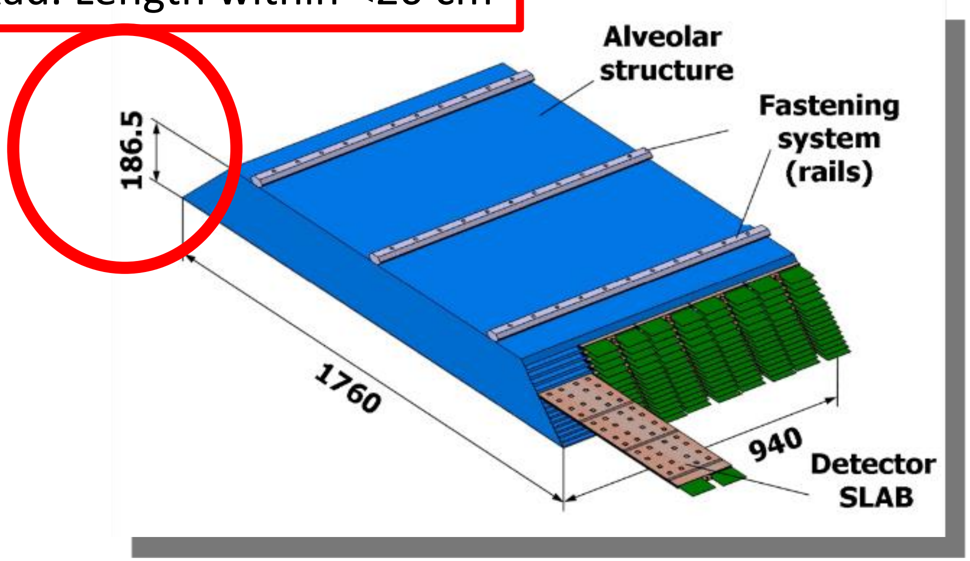
The camera ….. (we call that sampling calorimeter)
Radiator in Tungsten for compactness, small width pixels for em showers

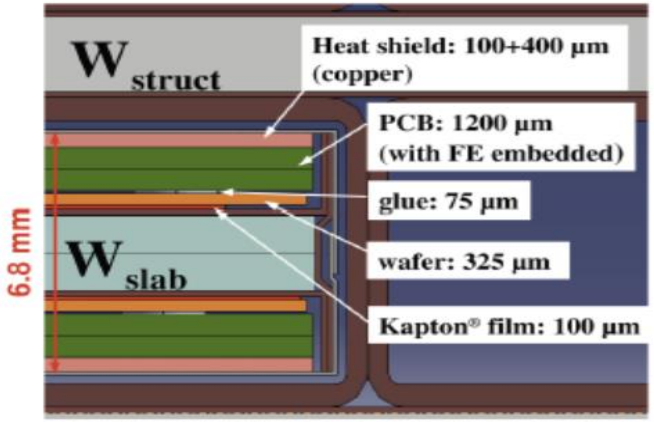
and for the active layers

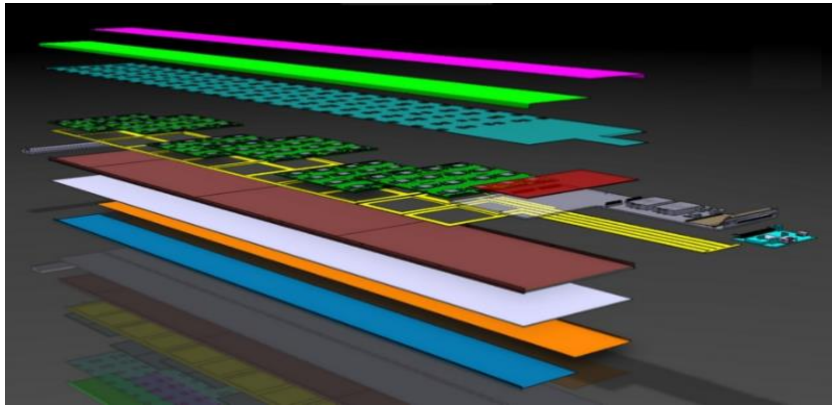
- Pixels in silicon PIN diode (R&D on MAPS with digital readout)
- Possible small size scintillator strips , read by SiPM (HGCAL)

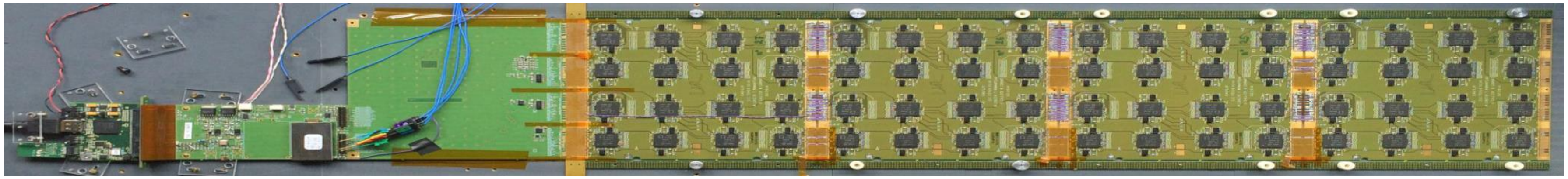


20 to 30 readout layers
and 24 Rad. Length within <20 cm







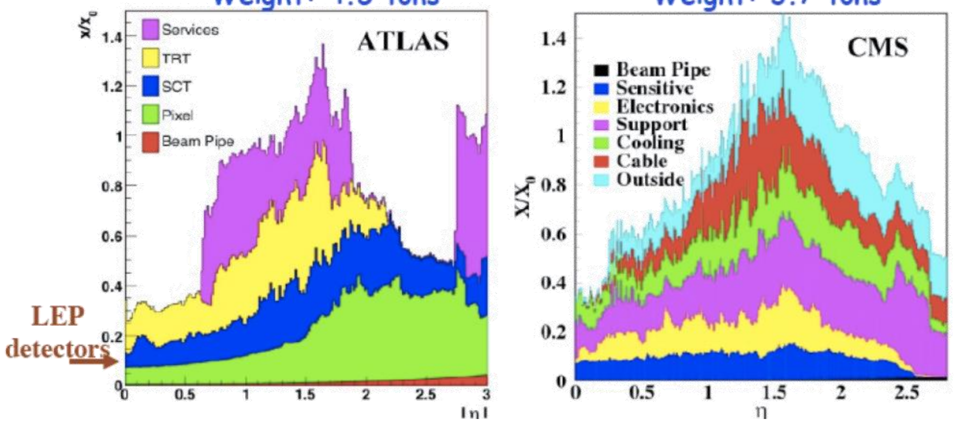


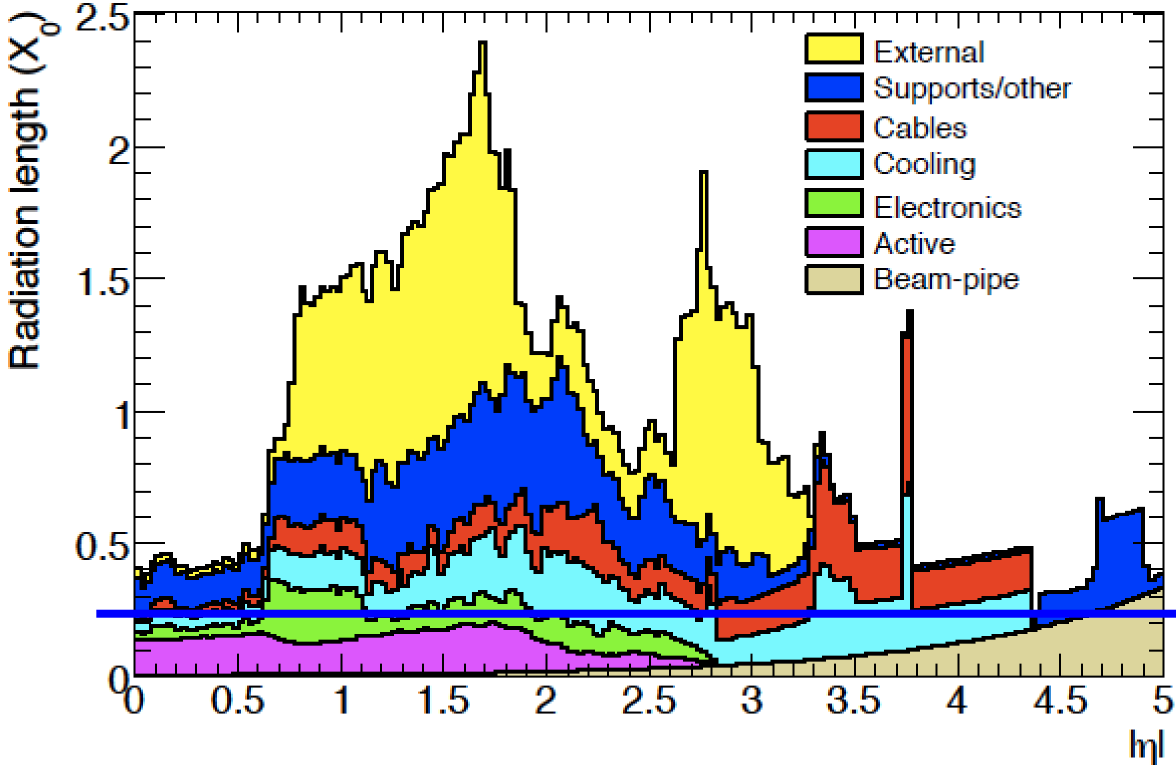
Material budget is VERY IMPORTANT

Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons

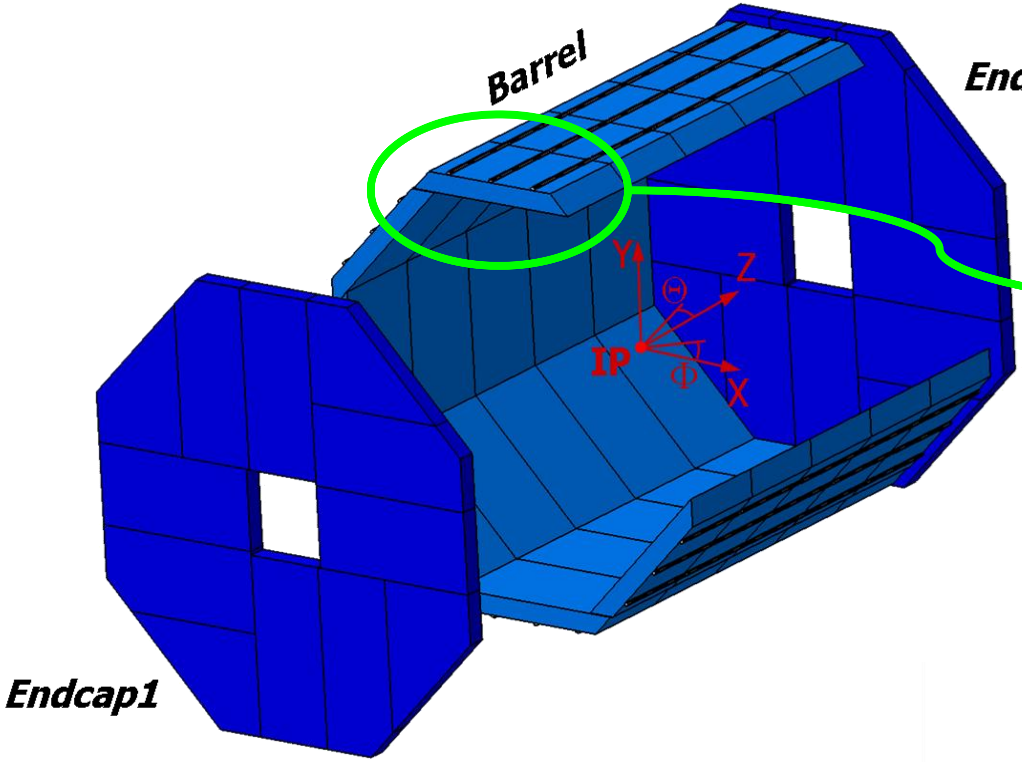
Weight: 3.7 tons



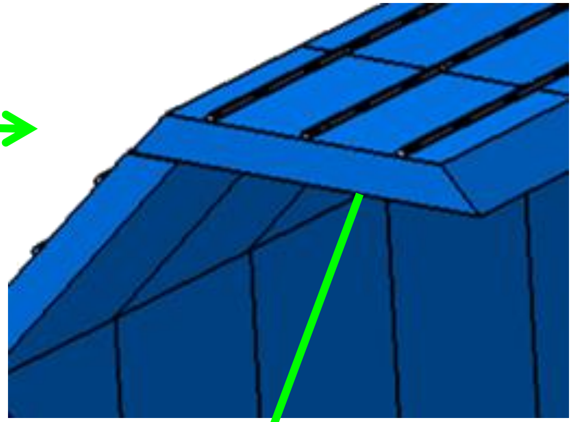


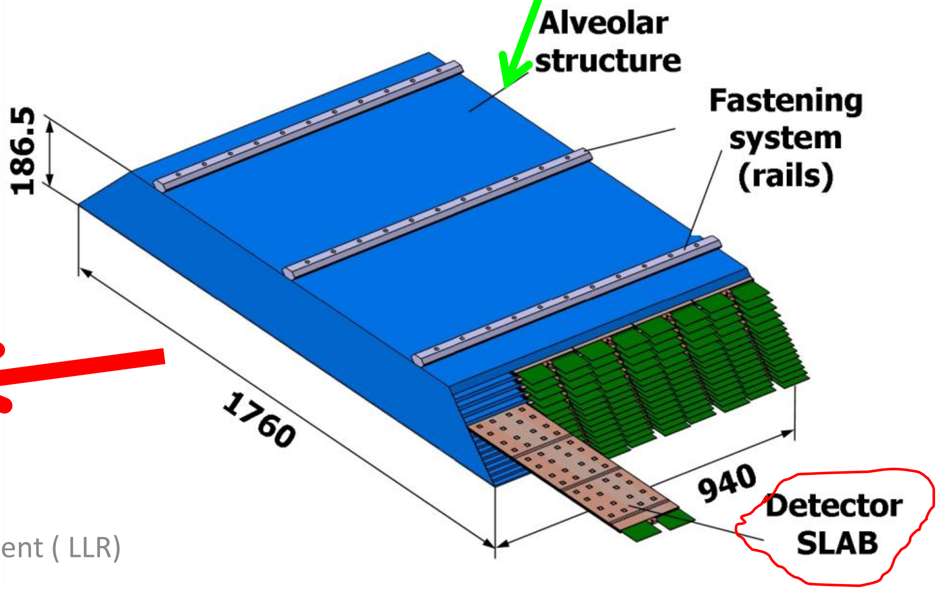
ALEPH measured

ECAL GEOMETRY



No DEAD ZONE !!!



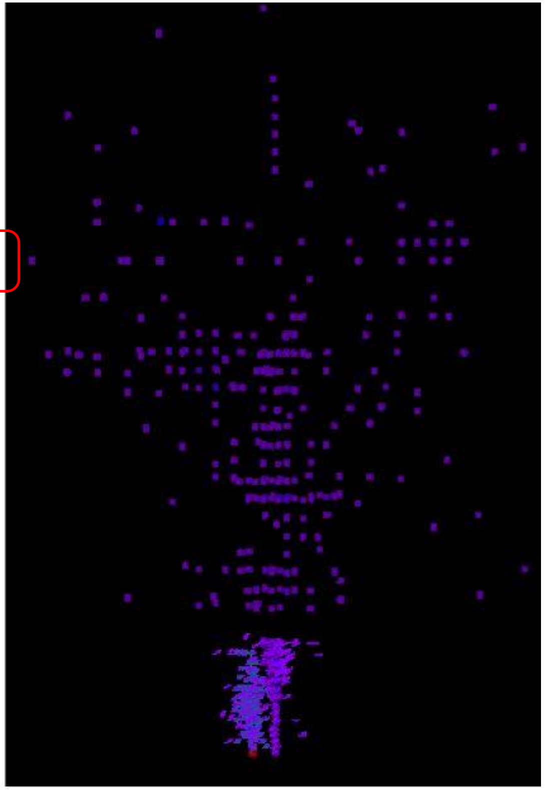


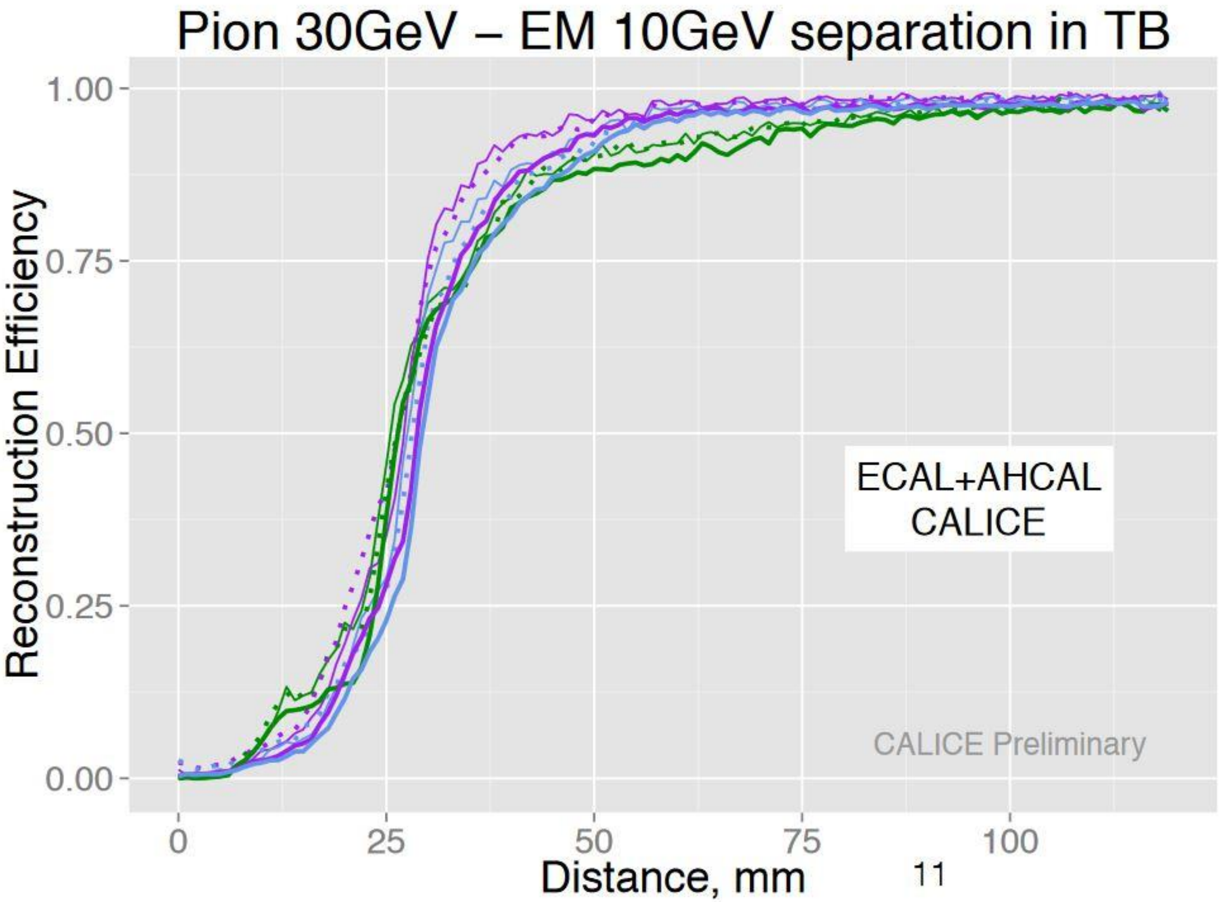
Carbon fiber –Tungsten structure with Alveola to slide in the active layers.

Hadron-EM separation: 30+10 GeV
π^+–e^+ (TB+MC), π^+–γ (MC)

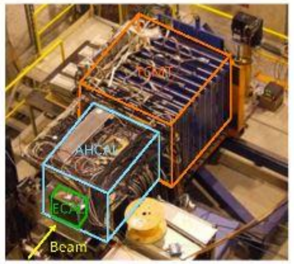
Probability to reconstruct exactly one γ & one π^+ for Pandora or one γ for Garlic (which does not reconstruct hadrons), Arbor not used for AHCAL.

Good agreement between TB and MC.





11



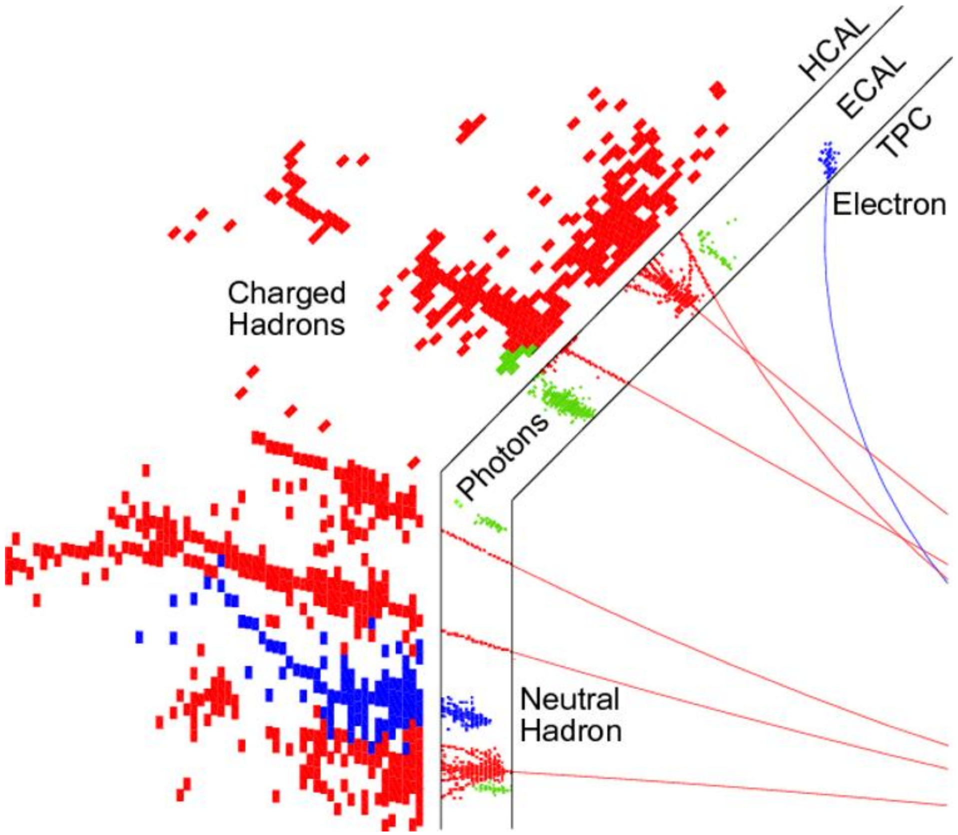
Data: π^+, e^+ CERN'07, ECAL+AHCAL
MC: π^+, e^+, γ TBCERN0807_p0709

PFA: Pandora (v00-14 & v02-04)
Garlic (v2.11), only ECAL

K.Shpak- 2017

Confusion term

- Base measurement as much as possible on measurement of charged particles in tracking devices
- Separate of signals by charged and neutral particles in calorimeter

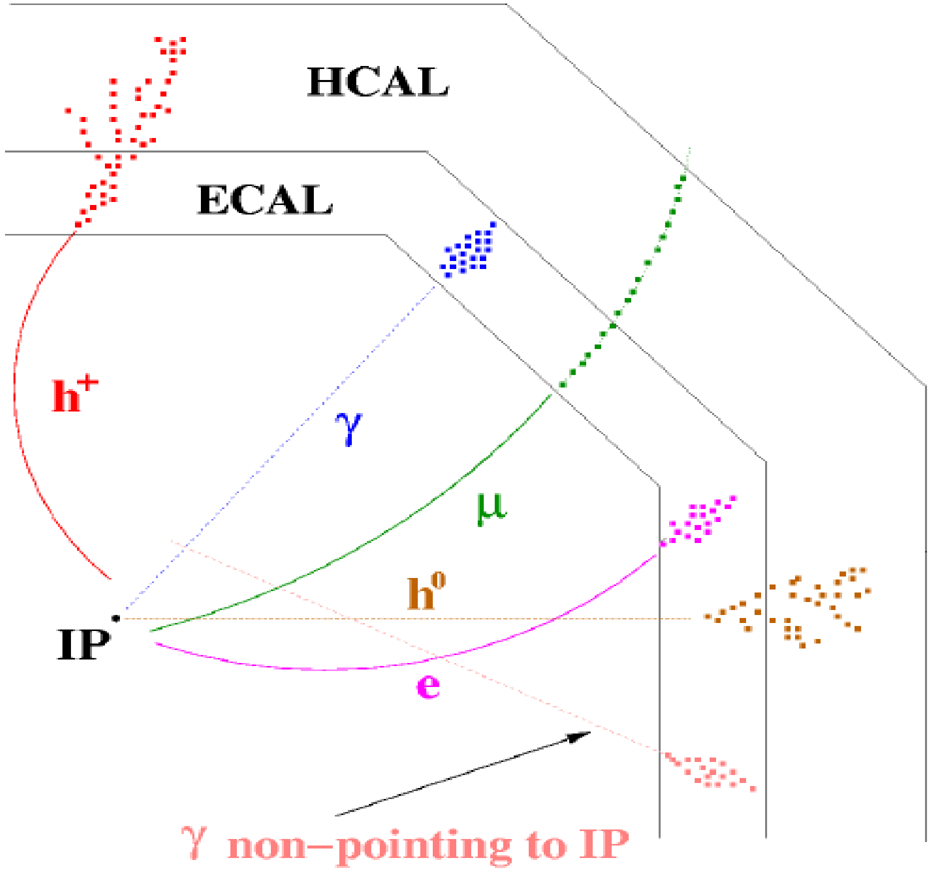


- Complicated topology by (hadronic) showers
- Overlap between showers compromises correct assignment of calo hits

⇒ Confusion Term

Need to minimize the confusion term as much as possible !!!

- large radius and length
  - →to separate the particles
- large magnetic field
  - →to sweep out charged tracks
- “no” material in front of calorimeters
  - →stay inside coil
- small Molière radius of calorimeters
  - →to minimize shower overlap
- **high granularity of calorimeters**
  - →to separate overlapping showers



Particle flow as privileged solution for experimental Challenges => Highly granular calorimeters!!!

Emphasis on tracking capabilities of calorimeters

Higgs CP – admixture in h ττ

Eibun Senaha *et al*,
Phys. Lett. B 762, 315 (2016)
modified parameters

CP violation other than quarks
Explaining the cosmological observation (matter-antimatter)

○ SUSY: Type3 - 2HDM
(fermion couples to both Higgs doublets
with Higgs-mediated FC processes at tree level)

several values on EDM
Current value $|d_e| < 8.7 \times 10^{-29}$ **e cm**

○ Higgs CP admixture

$$\Delta\mathcal{L}_{h\tau\tau} = -\frac{\kappa_\tau y_\tau}{\sqrt{2}} h\tau^+(\cos\phi + i\sin\phi\gamma_5)\tau^-$$

ATLAS : **κτ ~ 10% , CMS: κτ ~ 4%**

hττ CP-pahse φ with 3000 fb^{-1}
√S = 13 TeV: **120 mrad** arXiv:1708.02882
√S = 14 TeV: **90 mrad** arXiv:1408.0798

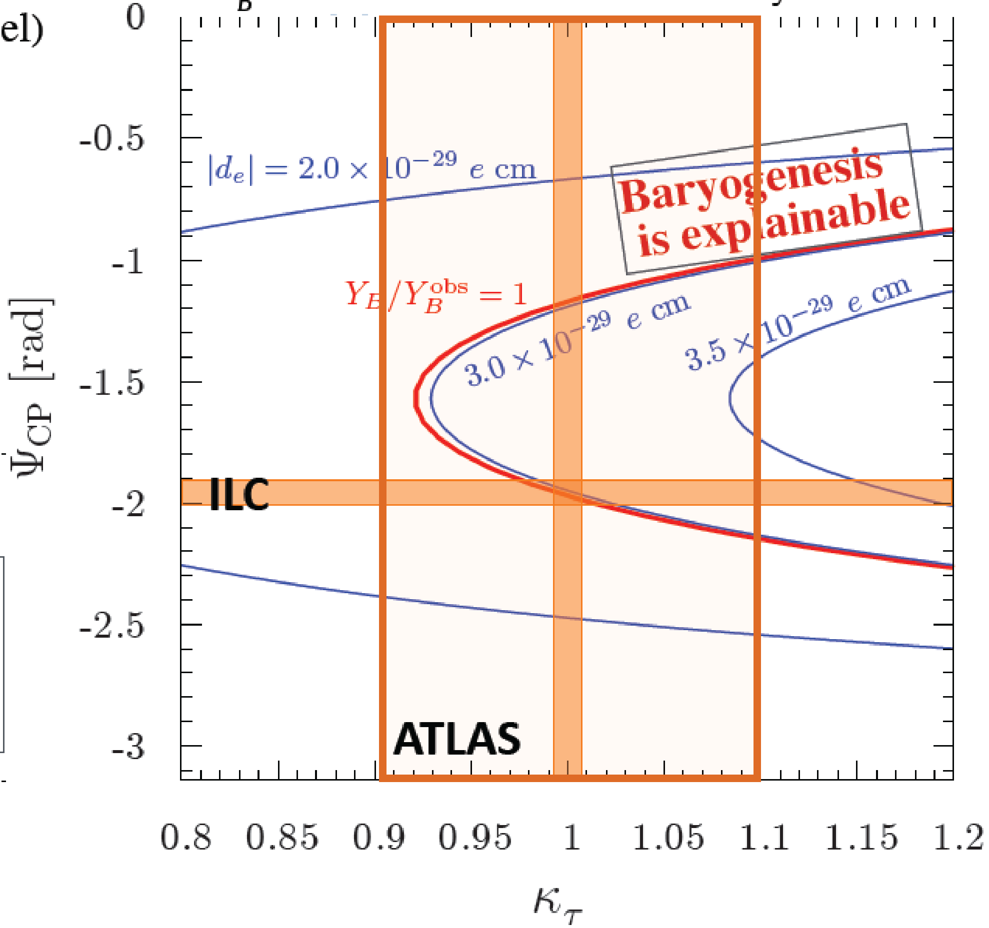
ILC 250 (2 ab^{-1})

CP-pahse φ: 75mrad
precision on κ_τ ~1.9%

How to do that ?

***D. Jeans et al*,**
Phys. Rev. D 13 June (2018)

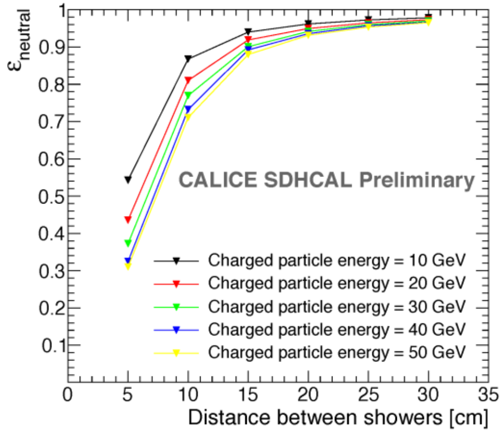
$Y_B \equiv n_B/s$: s is a 2HDM parameter
$Y_B^{\rm obs} = 8.59 \times 10^{-11}$:observation by Plank

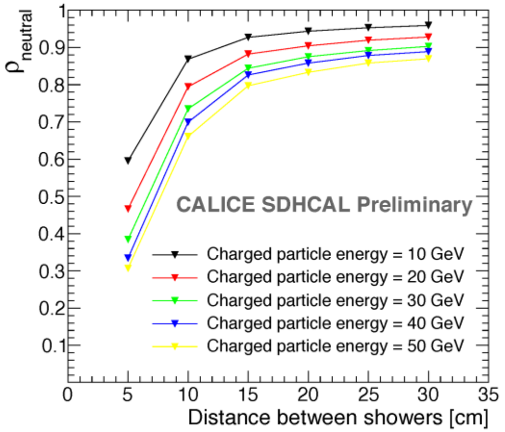


Precise verification on Baryongenesis models by **measuring κτ and CP-pahse mixture,** and also **future EDM measurement**

Particle separation and particle ID

SDHCAL: Separation of 10 GeV neutral hadron from charged hadron [CALICE-CAN-2015-001]

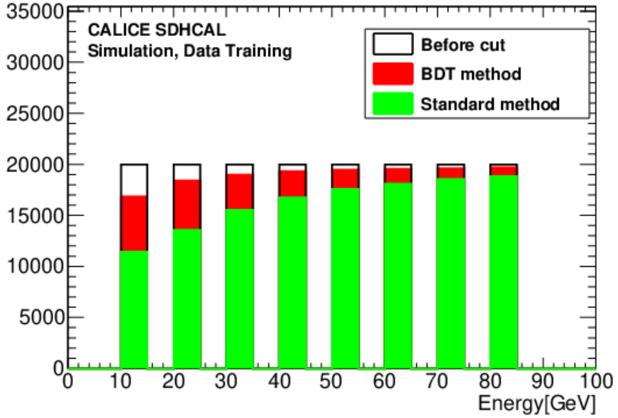


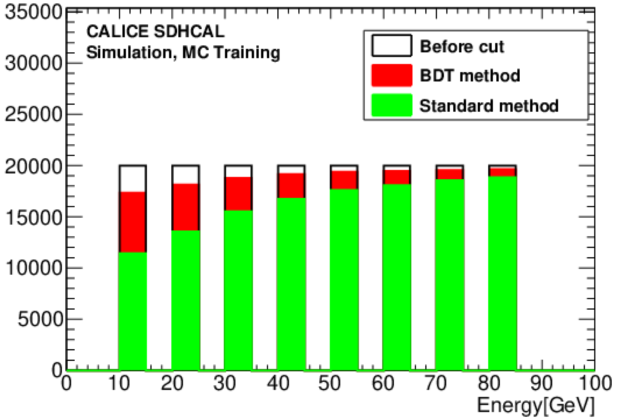


More than 90% efficiency and purity for distances ≥ 15 cm

SDHCAL: Multi-variate analysis for Particle ID

[arxiv:2004.02972, accepted by JINST]

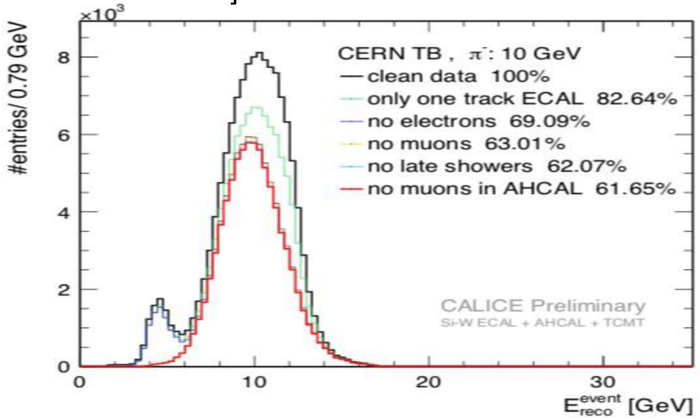




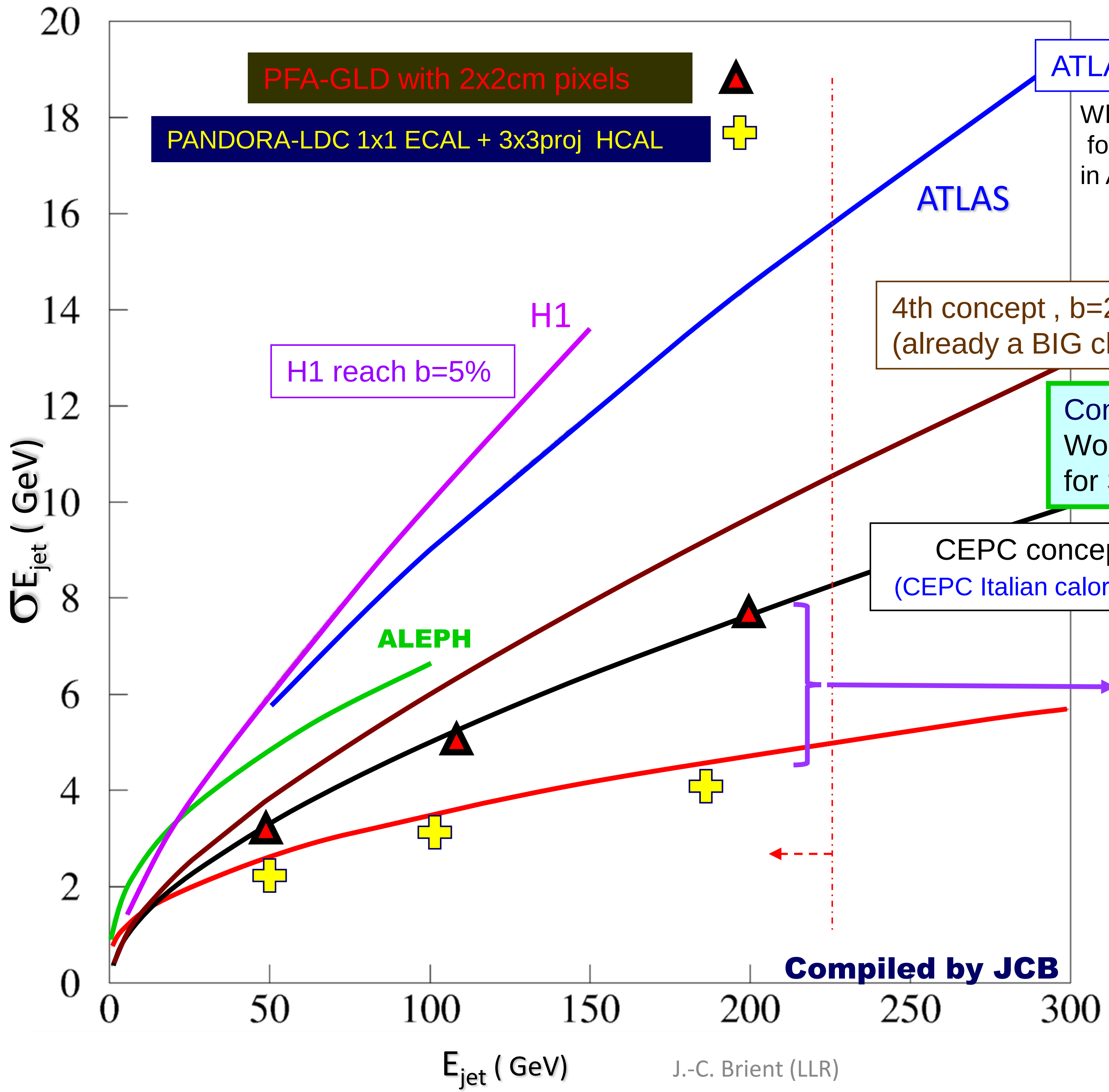
BDT enhance pion selection efficiency at small energies

SiW ECAL: Tracking capabilities to select single π-events

[CALICE-CAN-2017-002]



Successful data cleaning thanks to high granularity



ATLAS hope for b=3%

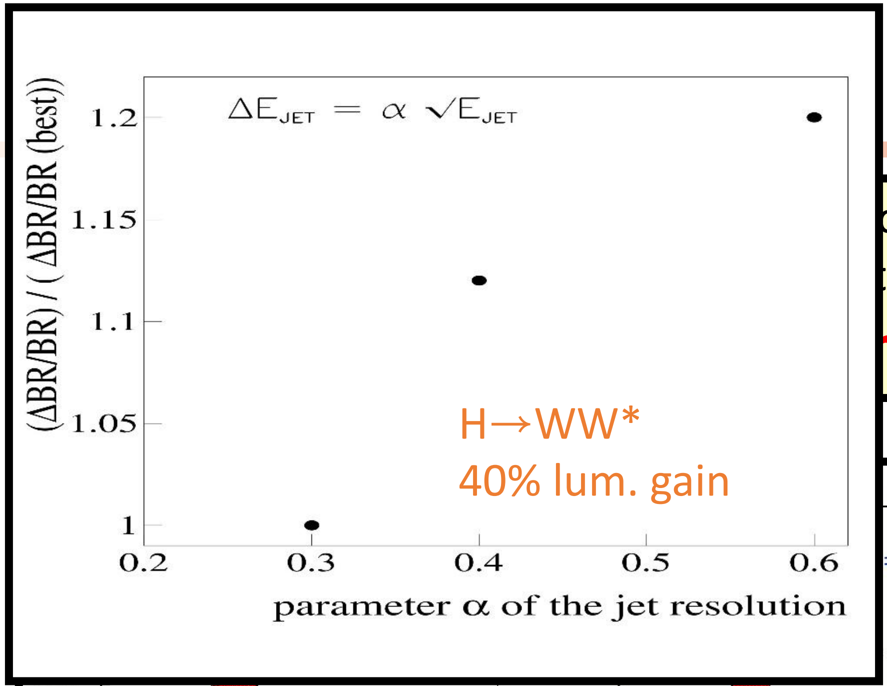
While the stochastic term is smaller
for H1, the resolution is better
in ATLAS because b is smaller

4th concept , b=2%
(already a BIG challenge)

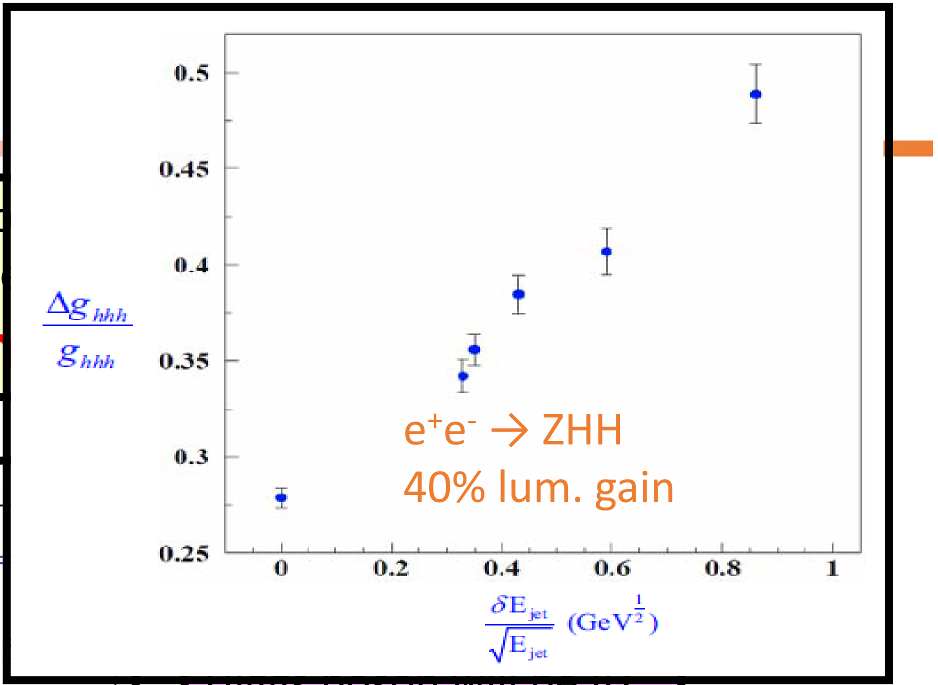
Constant term of CMS, ATLAS
Would be about 0.5 to 0.7 %
for SINGLE em particle

CEPC concept , b=1%
(CEPC Italian calorimeter)

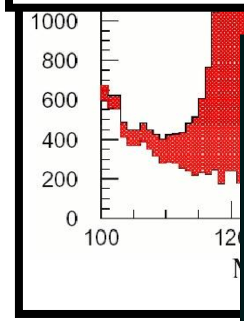
Going from CEPC calorimeter (Italian) to ILD calorimeter is equivalent to loose 30% of the luminosity…in the precision on the Higgs coupling



H→WW*
40% lum. gain

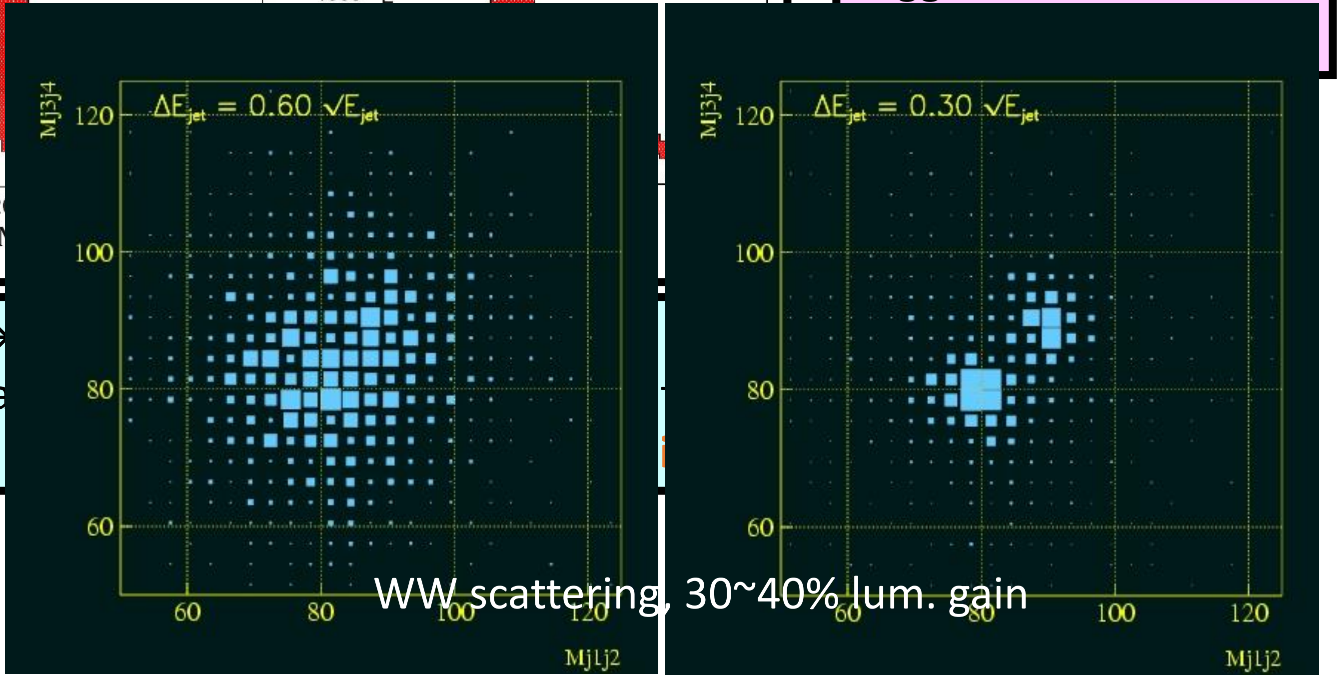


e^+e^- → ZHH
40% lum. gain

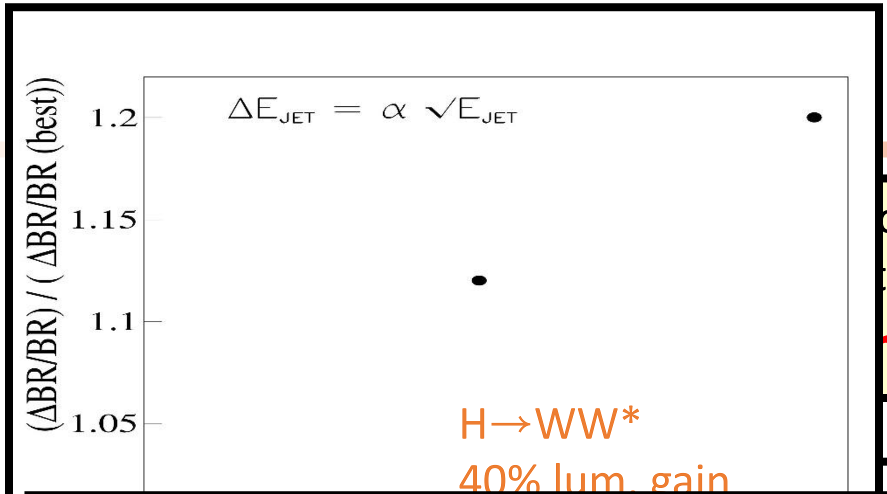


Higgs boson will be ILC

e^+e^- → ZH →
Invariant ma



WW scattering, 30~40% lum. gain



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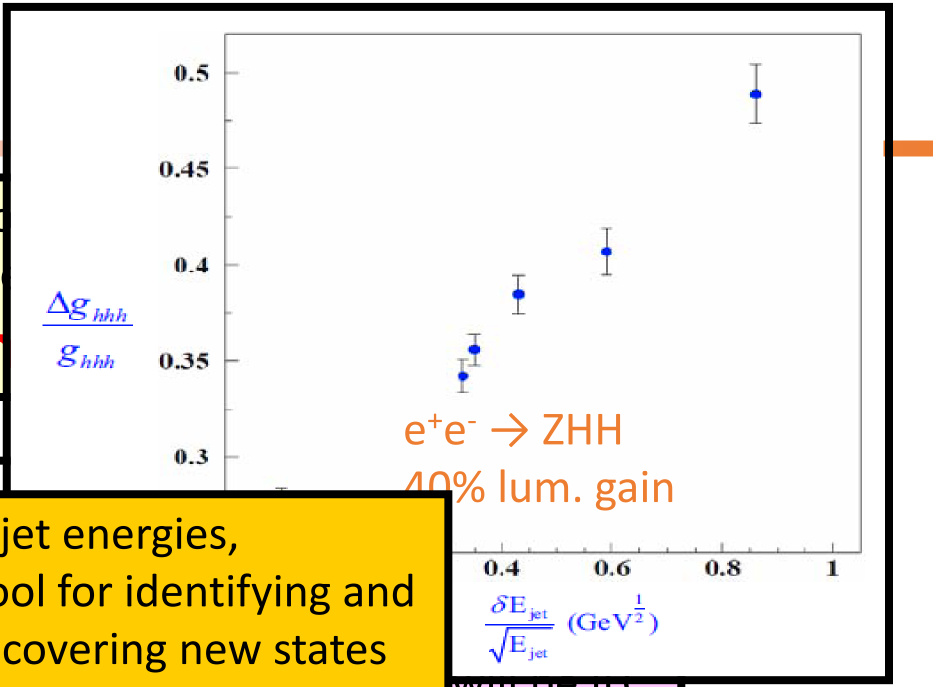
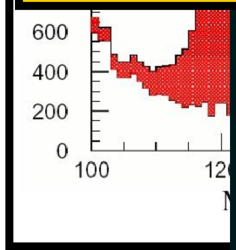


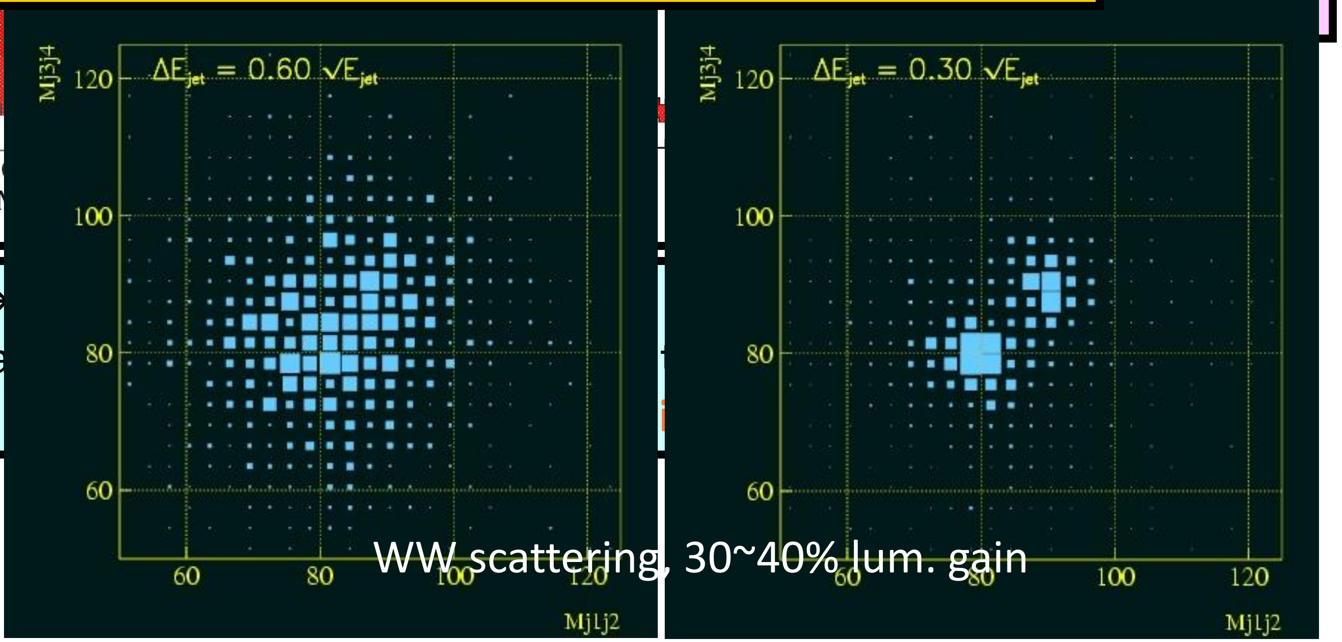
$e^+e^- \rightarrow$ ZHH
40% lum. gain

Precise jet energy resolution for typical ILC jet energies, say σ_E/E ~ 30%/√E, would be an essential tool for identifying and distinguishing W's, Z's, H's, and top, and discovering new states or decay modes.

will be ILC



$e^+e^- \rightarrow$ ZH →
Invariant ma

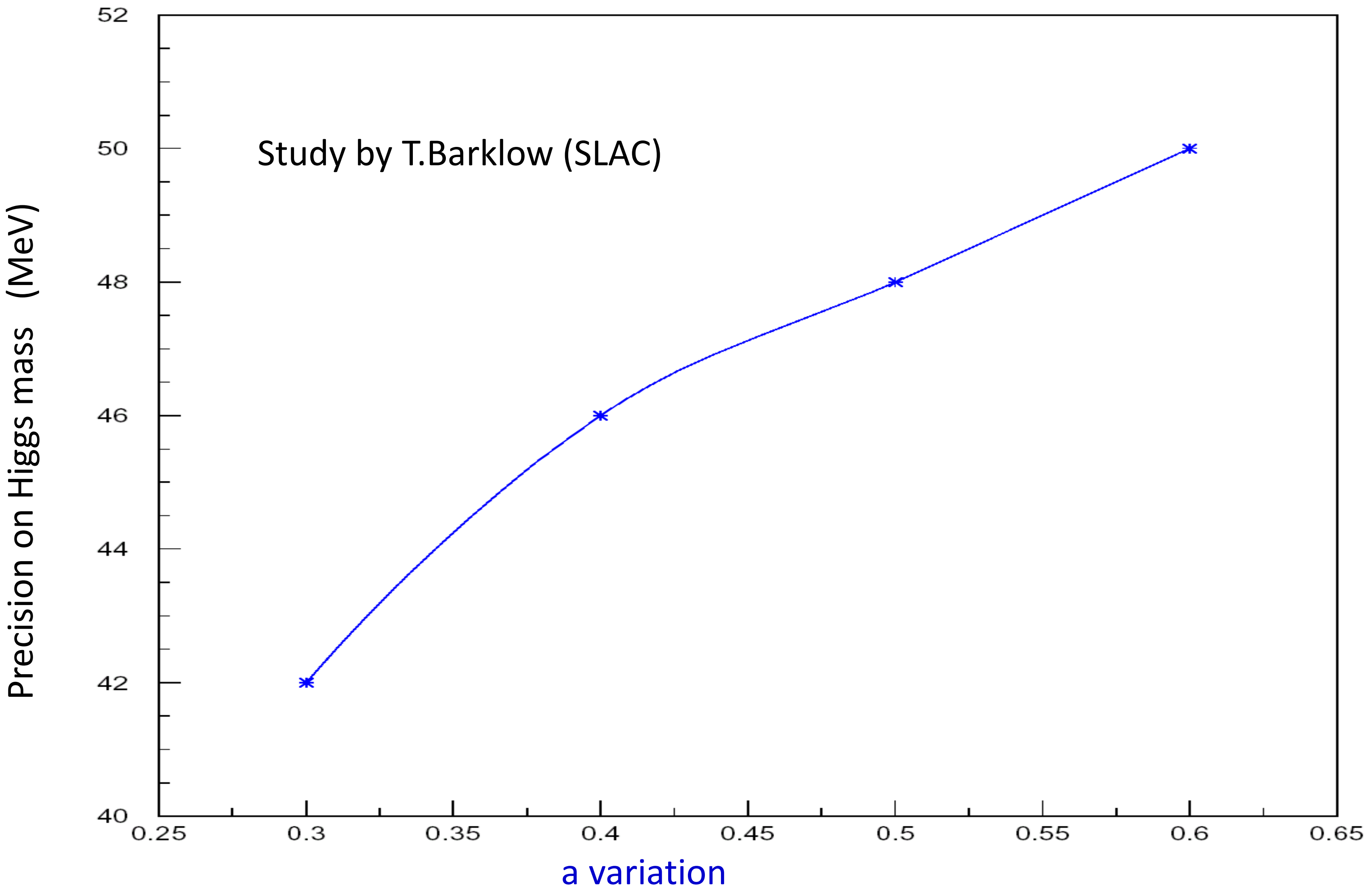


WW scattering, 30~40% lum. gain

Exemple

Mass measurement of the Higgs in ZH to 4 jets

Going from a=0.3 to a=0.6 is equivalent to a loss of 45% of the luminosity (running time)

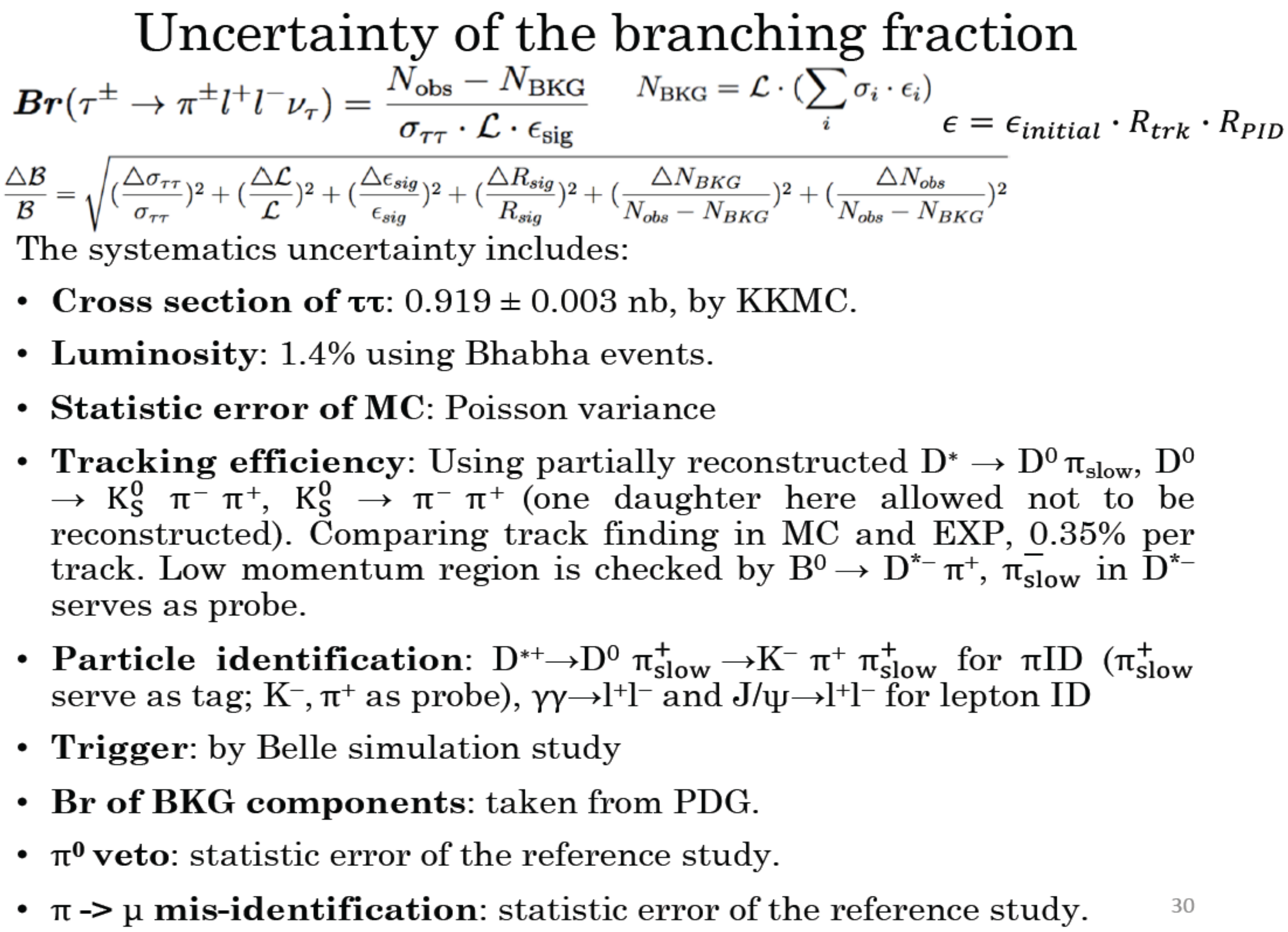


$\tau^\pm \to \pi^\pm \nu_\tau \mu^+ \mu^-$

From BELLE-II

Systematics for BELLE-II measurement

Syst. of N_{BKG}		
MC size	1.7%	x
Luminosity	1.4%	
ee → ττ	0.3%	
Tracking	1.4%	x
Trigger	0.3%	
PID	3.7%	x
Br's of BKG	1.0%	
π-μ mis-id	1.5%	x
Total	4.9%	



Uncertainty of the branching fraction

$$\boldsymbol{Br}(\tau^\pm \to \pi^\pm l^+ l^- \nu_\tau) = \frac{N_{\text{obs}} - N_{\text{BKG}}}{\sigma_{\tau\tau}\cdot\mathcal{L}\cdot\epsilon_{\text{sig}}} \qquad N_{\text{BKG}} = \mathcal{L}\cdot\left(\sum_i \sigma_i\cdot\epsilon_i\right) \qquad \epsilon = \epsilon_{initial}\cdot R_{trk}\cdot R_{PID}$$

$$\frac{\Delta\mathcal{B}}{\mathcal{B}} = \sqrt{\left(\frac{\Delta\sigma_{\tau\tau}}{\sigma_{\tau\tau}}\right)^2 + \left(\frac{\Delta\mathcal{L}}{\mathcal{L}}\right)^2 + \left(\frac{\Delta\epsilon_{sig}}{\epsilon_{sig}}\right)^2 + \left(\frac{\Delta R_{sig}}{R_{sig}}\right)^2 + \left(\frac{\Delta N_{BKG}}{N_{obs} - N_{BKG}}\right)^2 + \left(\frac{\Delta N_{obs}}{N_{obs} - N_{BKG}}\right)^2}$$

The systematics uncertainty includes:

- **Cross section of ττ**: 0.919 ± 0.003 nb, by KKMC.
- **Luminosity**: 1.4% using Bhabha events.
- **Statistic error of MC**: Poisson variance
- **Tracking efficiency**: Using partially reconstructed $D^* \to D^0 \pi_{slow}$, $D^0 \to K_S^0 \pi^- \pi^+$, $K_S^0 \to \pi^- \pi^+$ (one daughter here allowed not to be reconstructed). Comparing track finding in MC and EXP, 0.35% per track. Low momentum region is checked by $B^0 \to D^{*-}\pi^+$, π_{slow} in D^{*-} serves as probe.
- **Particle identification**: $D^{*+} \to D^0 \pi^+_{slow} \to K^- \pi^+ \pi^+_{slow}$ for πID (π^+_{slow} serve as tag; K^-, π^+ as probe), $\gamma\gamma \to l^+l^-$ and $J/\psi \to l^+l^-$ for lepton ID
- **Trigger**: by Belle simulation study
- **Br of BKG components**: taken from PDG.
- **π^0 veto**: statistic error of the reference study.
- **π -> μ mis-identification**: statistic error of the reference study.

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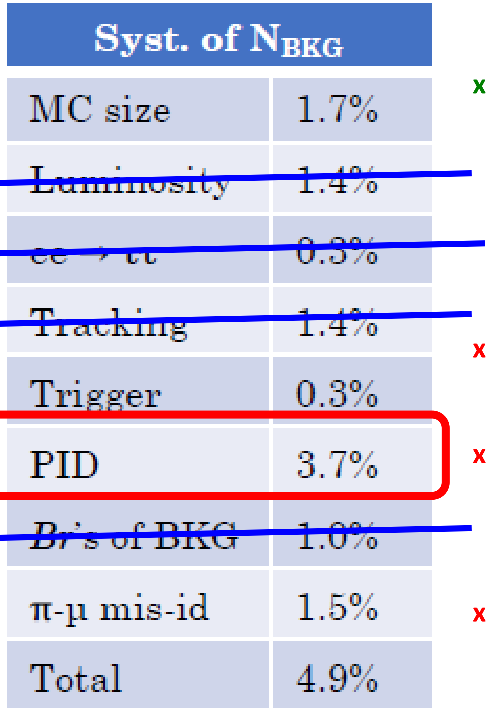
$\tau^{\pm} \rightarrow \pi^{\pm} \nu_{\tau}\, \mu^{+}\mu^{-}$

For FCCee



Syst. of N_{BKG}		
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~~Luminosity~~	~~1.4%~~	
~~$ee \rightarrow \tau\tau$~~	~~0.3%~~	
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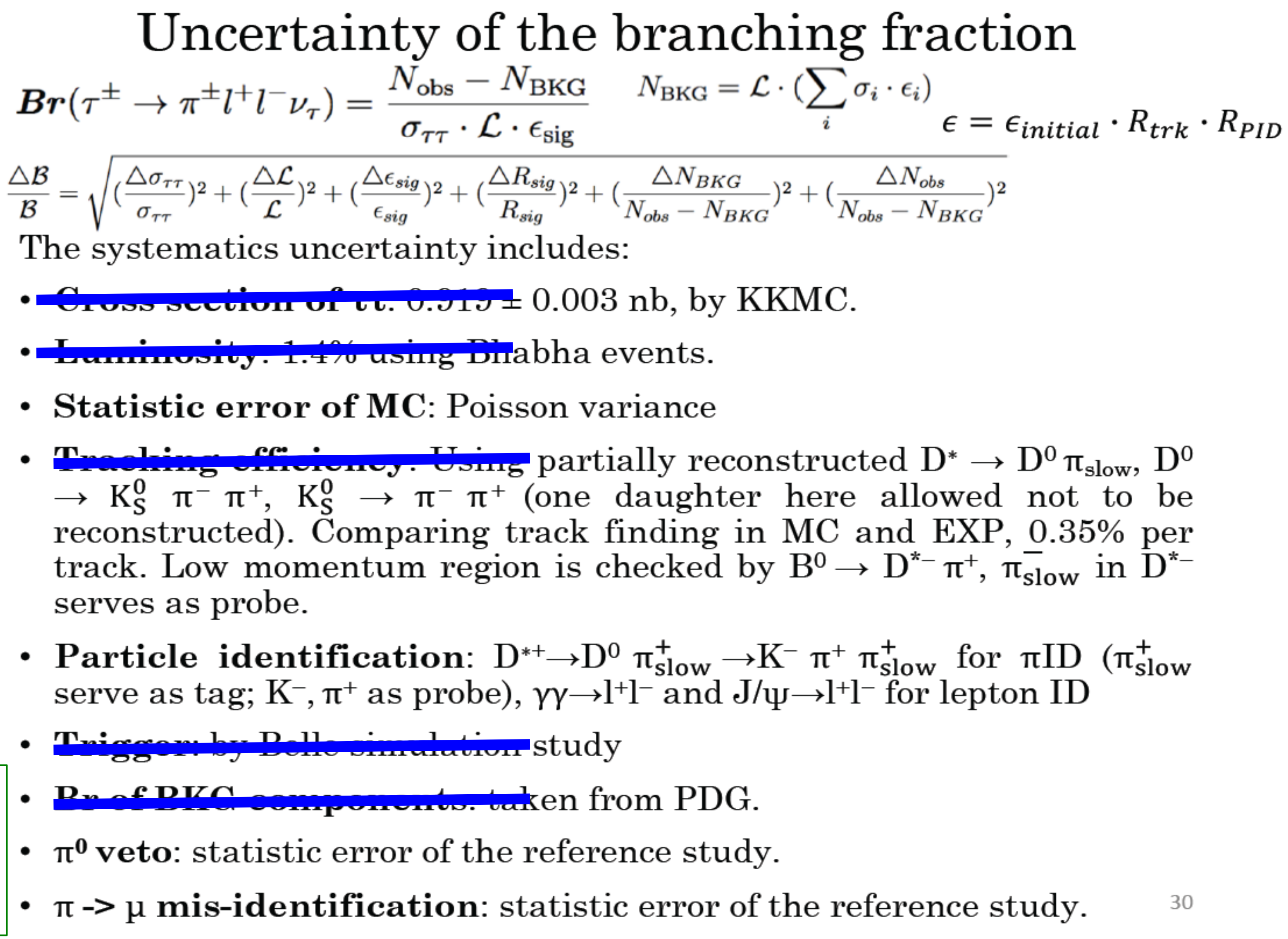
Trigger	0.3%	
PID	3.7%	x
~~Br's of BKG~~	~~1.0%~~	
π-μ mis-id	1.5%	x
Total	4.9%	

But for FCCee , it is not obvious,
PID for 3 close tracks !!
(due to boost of the 3 prongs in tau decays @Z peak)



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POSSIBLE solution : TRACKING in CALO

→ SDHCAL (1x1cm² and not 4x4 like AHCAL or HGCAL)

(Verified in ALEPH real data)

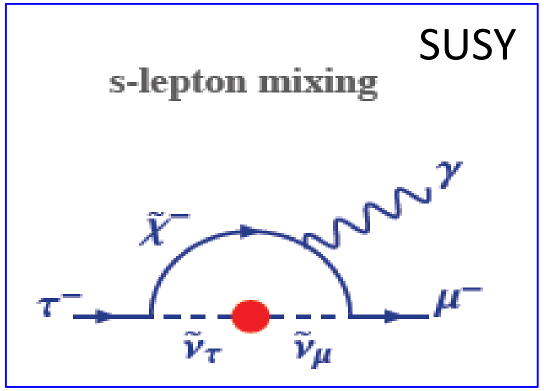
Do we need a good ECAL energy resolution for a good resolution in the mass ($\mu^{\pm}\gamma$) ?

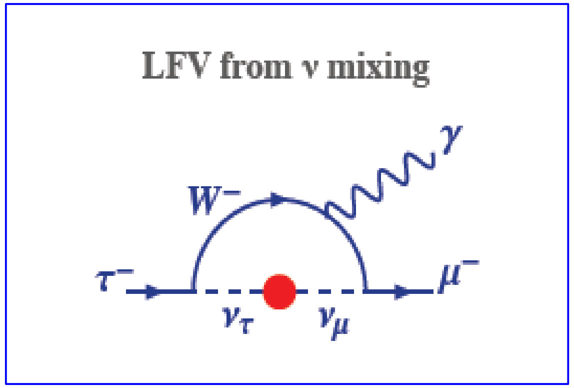
Another rare decays

$$\tau^{\pm}\longrightarrow\mu^{\pm}\gamma$$

BSM

SM





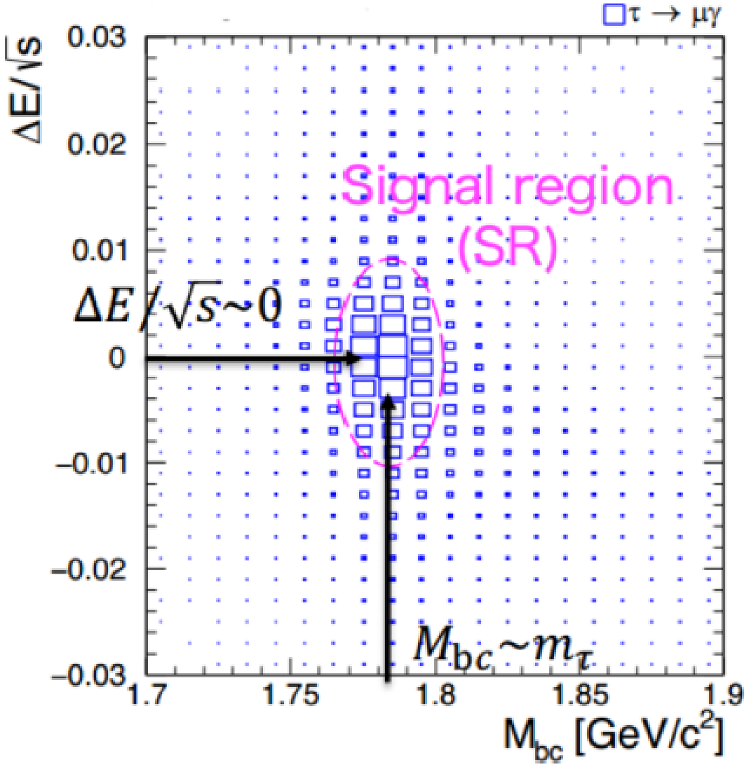
Any signal means NP

$$\mathcal{B}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\ell_1 i}U_{\ell_2 i}\frac{\Delta m^2_{i1}}{M^2_W}\right|^2$$

Unmeasurable small rates (10^{-54}-10^{-49})

Do we need a good ECAL energy resolution for a good resolution in the mass ($\mu^{\pm}\gamma$) ?

NO



signal region

- $M_{bc} = \sqrt{(E_{\text{beam}}^{\text{CM}})^2 - \left(p_{\ell\gamma}^{\text{CM}}\right)^2} \sim M_\tau$
- $\Delta E = \left(E_{\ell\gamma}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}\right) \sim 0\ \text{GeV}$
- for background M_{bc} distribution will vary smoothly without peaking