MINISTÈRE
DE L'ENSEIGNEMENT SUPÉRIEUR,
DE LA RECHERCHE
ET DE L'INNOVATION

Search for additional neutral Higgs bosons decaying to τ leptons pairs in the CMS experiment at LHC

Journées de Rencontres Jeunes Chercheurs 2019 – Logonna-Daoulas

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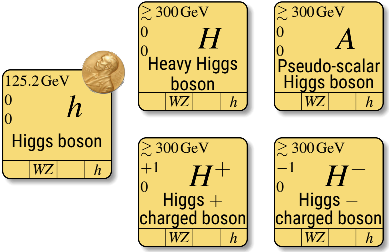
Institut de Physique des deux Infinis – Lyon

November 29, 2019

Higgs bosons in the MSSM

Minimal Supersymmetric extension of Standard Model



▷ The CMS Collaboration. “Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV”. *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

1. Phenomenology
   - Neutral Higgs bosons decays
   - $H \to \tau\tau$ final states
   - $H \to \tau\tau$ backgrounds
2. $H \to \tau\tau$ analysis
   - Background estimation: the embedding technique
   - Background estimation: the fake factor method
   - Results (2017 CMS data, $\mu\tau_{\mathrm{h}}$ channel)
3. Smart parallelisation

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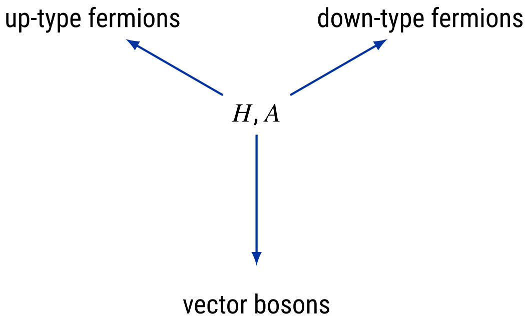
3. Smart parallelisation

$H \to \tau\tau$?



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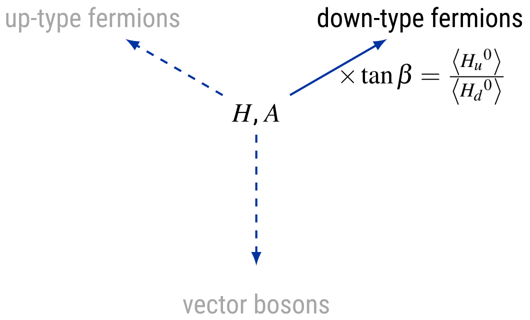
$H \to \tau\tau$? – enhanced and suppressed couplings



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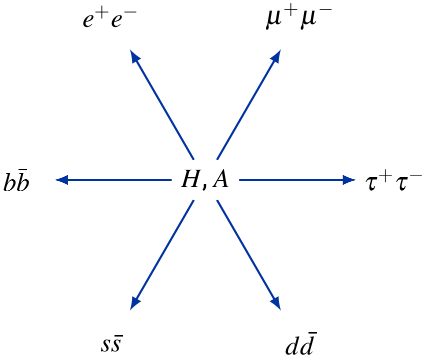
$H \to \tau\tau$?



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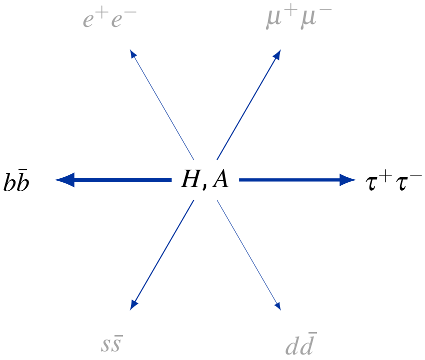
$H \to \tau\tau$? – Higgs couplings and particules masses



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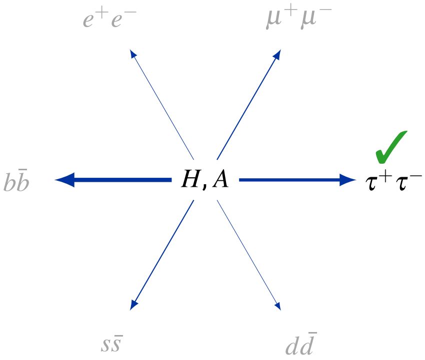
$H \to \tau\tau$? – avoid hadronic background



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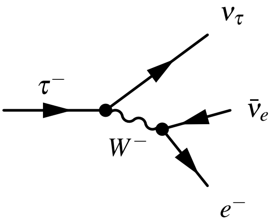
τ decay modes



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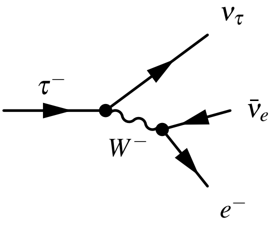
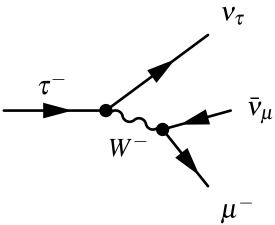
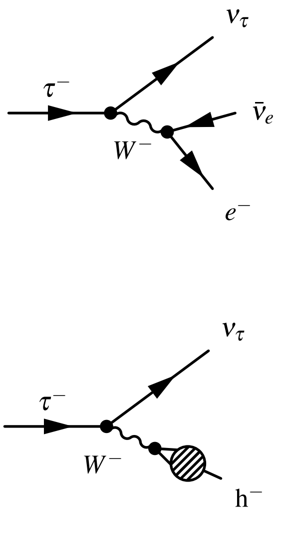




τ decay modes



$H \to \tau\tau \to L_1 L_2$

$\tau \to e + \nu_e \Rightarrow e$	$\tau \to \mu + \nu_\mu \Rightarrow \mu$	$\tau \to \text{hadrons} + \nu_\tau \Rightarrow \tau_\mathrm{h}$
17.8 %	17.4 %	64.8 %

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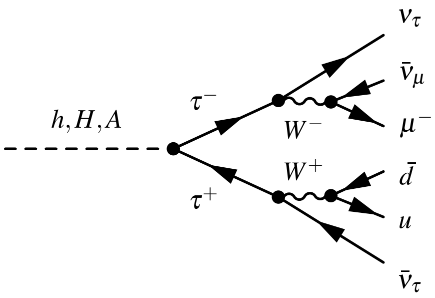

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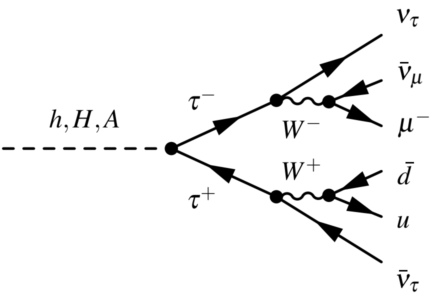
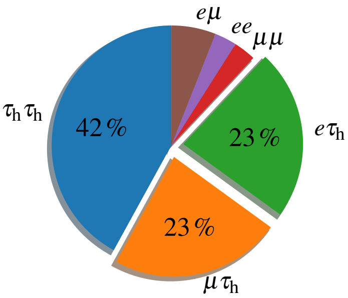
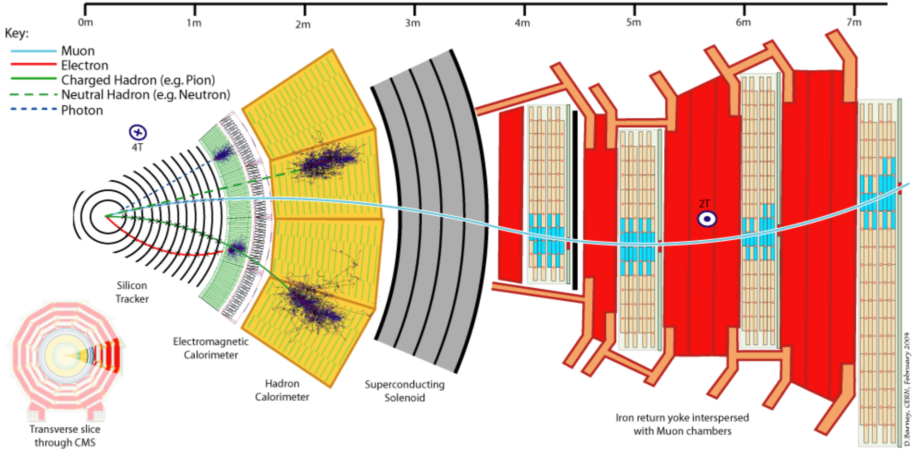




The CMS detector



Neutrinos and missing transverse energy (MET)

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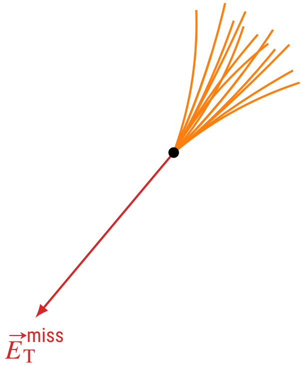
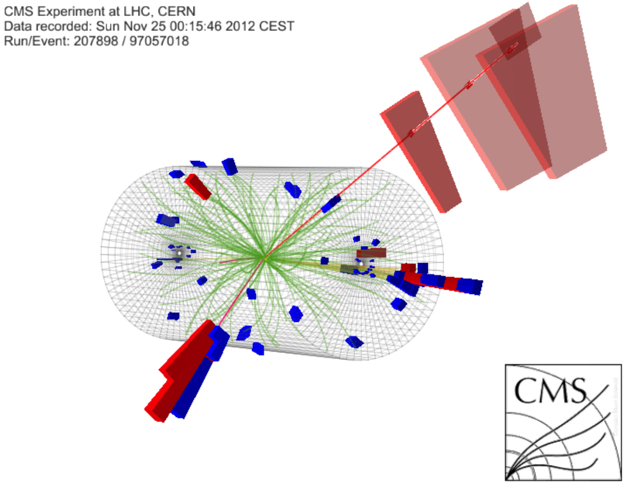
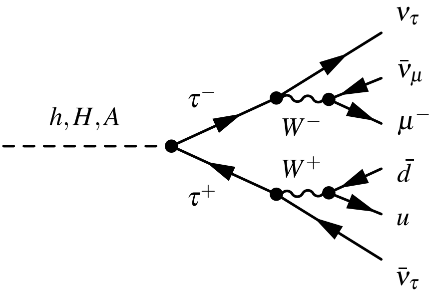


Event display: $h \to \tau\tau \to \mu\tau_{\rm h}$ candidate



Discriminant variable?

- E_T^{miss} due to neutrinos.
- No invariant mass!



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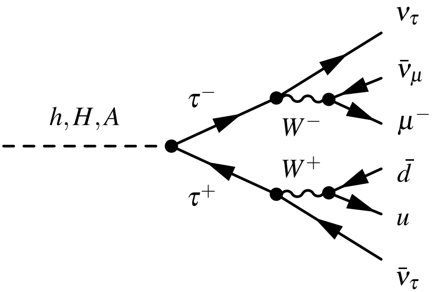
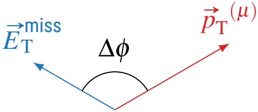
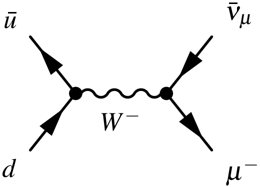


- ▶ ${E_\mathrm{T}}^{\text{miss}}$ due to neutrinos.
- ▶ No invariant mass!
- ▶ For muon and ${E_\mathrm{T}}^{\text{miss}}$,

$$m_\mathrm{T}(\mu, {E_\mathrm{T}}^{\text{miss}}) = \sqrt{2 p_T^{(\mu)} {E_\mathrm{T}}^{\text{miss}} (1 - \cos\Delta\phi)}$$



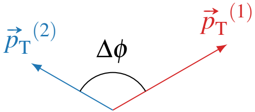


Discriminant variable: m_T^{tot}

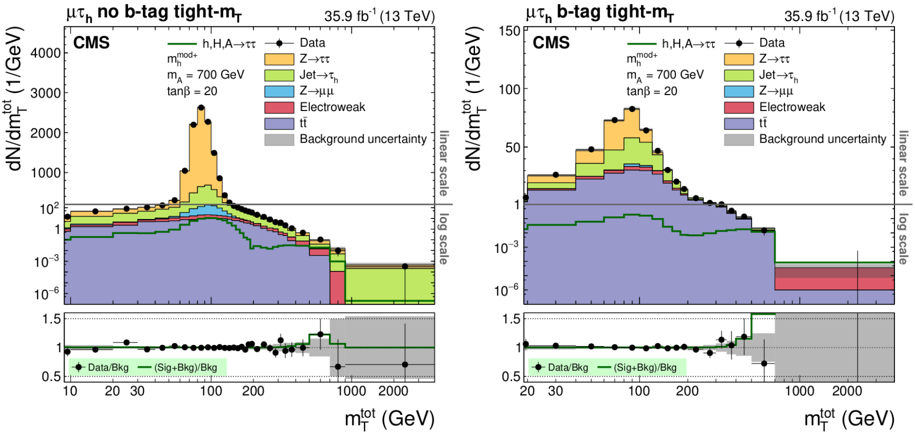
- For L_1, L_2 and $E_T{}^{miss}$ system,

$$m_T^{tot} = \sqrt{m_T^2(L_1, E_T{}^{miss}) + m_T^2(L_2, E_T{}^{miss}) + m_T^2(L_1, L_2)}$$

$$m_T(1,2) = \sqrt{2 p_T^{(1)} p_T^{(2)} (1 - \cos\Delta\phi)}$$



Results for 2016 $\mu\tau_h$ channel



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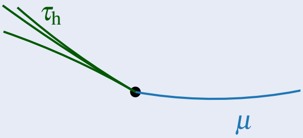
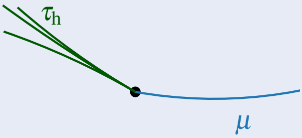
Backgrounds: Drell-Yan

Drell-Yan (especially $Z \to \tau\tau$)

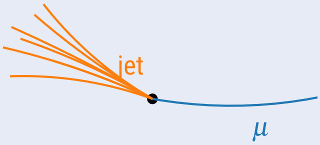


$H \to \tau\tau \to \mu\tau_h$

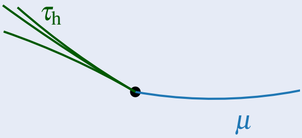


Backgrounds: $W+$jets

$W+$jets

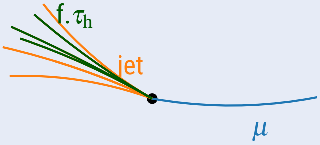


$H \to \tau\tau \to \mu\,\tau_h$

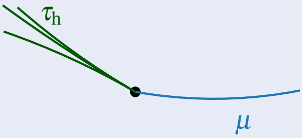


Backgrounds: $W+$jets

$W+$jets, jet $\to$ fake τ_h

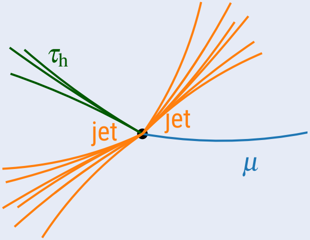


$H \to \tau\tau \to \mu\tau_h$

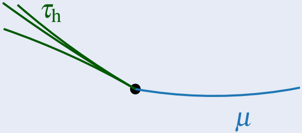


Backgrounds: $t\bar{t}$

$t\bar{t}$

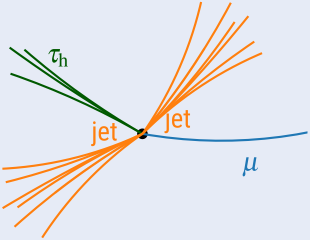


$H \to \tau\tau \to \mu\tau_h$

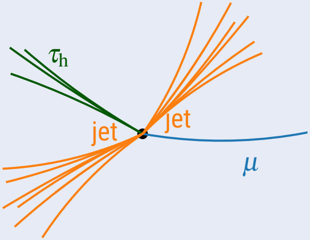


Backgrounds: $t\bar{t}$

$t\bar{t}$

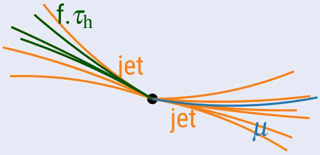


H production with b-jets

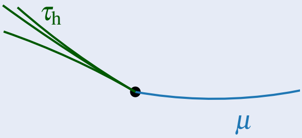


Backgrounds: QCD

QCD

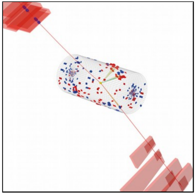


$H \to \tau\tau \to \mu\tau_h$



Embedded events

$Z \to \mu\mu$ data



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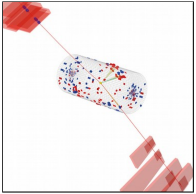
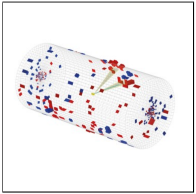


Remove $\mu\mu$ system



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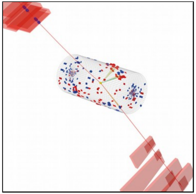

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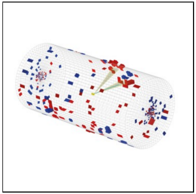
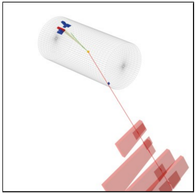


Simulate $Z \to \tau\tau$
(τ with same kinematics as μ)



Embedded events

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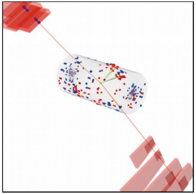

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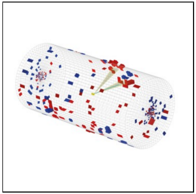
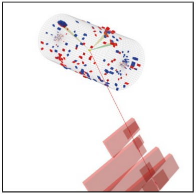


$Z \to \tau\tau$ embedded event



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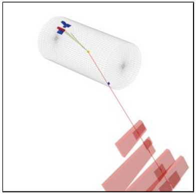

The Fake Factor method

- How many events contain misidentified τ_h? (fake taus)

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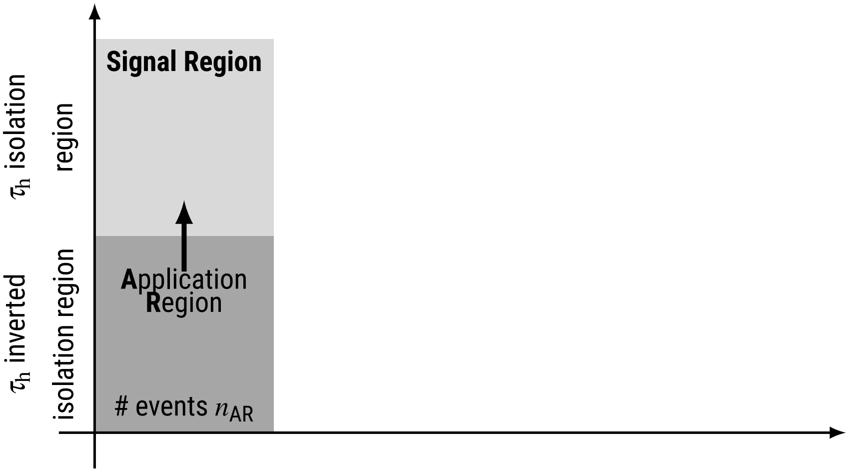
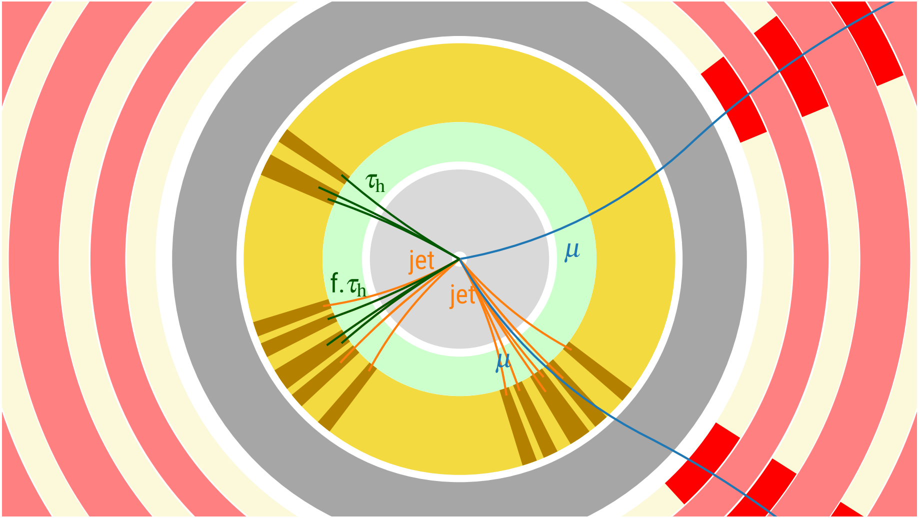


Particles isolation – qualitatively



The FF method: determination regions definitions

$t\bar{t} + $jets

Estimation from simulated samples, same selection as in SR.

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Same as SR, except:

- transverse mass $m_T^{(\ell)} > 70\,\mathrm{GeV}$ ($m_T^{(\ell)} < 50\,\mathrm{GeV}$ in the SR);
- no b-jet (allowed in the SR).

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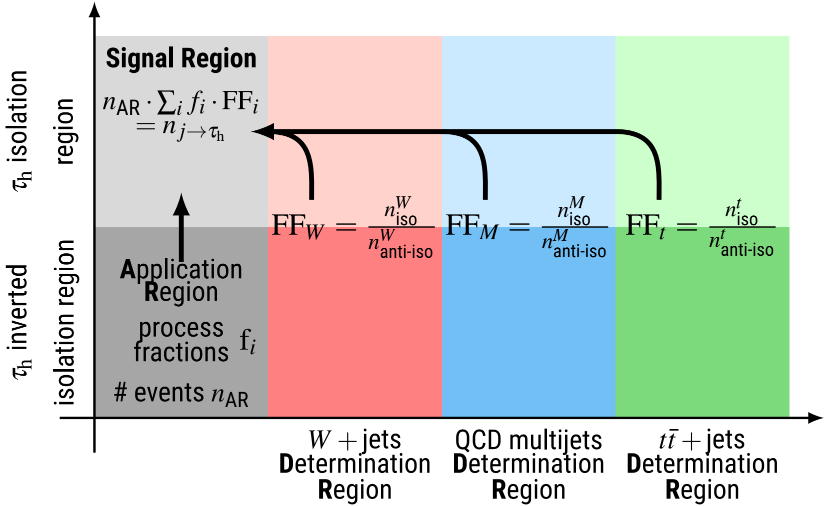
QCD multijets

Same as SR, except:

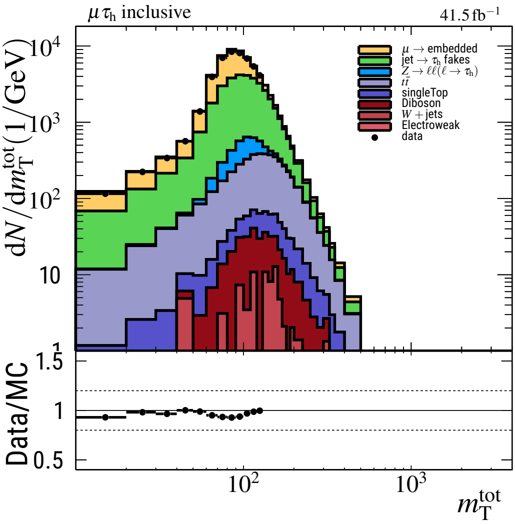
- same signs for L_1 and L_2 electric charges (opposite signs in the SR).

The FF method



Results!

Preliminary results for 2017 $\mu\tau_h$ channel



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3. **Smart parallelisation**

Starting point

- Post-processing (plotting, *datacards*):
  - 120 datasets, up to 17 systematics[1], up and down;
  - $\sim$ 3500 files per channel.
- Script running in few minutes **without systematics**.
- Expected time **over 30 minutes** with systematics.

[1] Parameters to modify.

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- Script running in few minutes **without systematics**.
- Expected time **over 30 minutes** with systematics.
- On a computer with lots of CPUs, would it be possible to **get faster**?

[1] Parameters to modify.

"Dask provides advanced parallelism for analytics, enabling performance at scale for the tools you love"

▷ *Dask: Scalable analytics in Python*. URL: https://dask.org/.

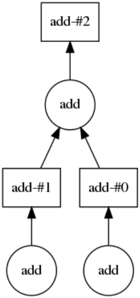
Basic example: without dask

```python
#!/usr/bin/python3

import time

def add(a,b):
    time.sleep(1)
    return a+b

starting_time = time.time()

x = add(1,2)
y = add(3,4)
z = add(x,y)

ending_time = time.time()

print("It took {} ms.".format(int((ending_time-starting_time)*1000)))
print("Result is {}.".format(z))
```

```
computer:~/directory$ ./this_script.py
It took 3003 ms.
Result is 10.
```

Basic example: with dask – introducing *delayed objects*

```python
#!/usr/bin/python3

import time

def add(a,b):
    time.sleep(1)
    return a+b

import dask
add = dask.delayed(add)

x = add(1,2)
y = add(3,4)
z = add(x,y)

z.visualize('add_in_parallel')

starting_time = time.time()
result = z.compute()
ending_time = time.time()

print("It took {} ms.".format(int((
    ending_time-starting_time)*1000))
    )
print("Result is {}.".format(result))
```

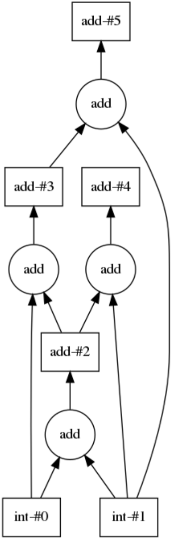


add_in_parallel.png

```
It took 2006 ms.
Result is 10.
```

Adding more steps

```python
#!/usr/bin/python3

import time

import dask

def add(a,b):
    time.sleep(1)
    return dask.delayed(a+b)

x = add(1,2)
y = add(3,4)
z = add(x,y)

a = add(x,z)
b = add(y,z)
c = add(a,y)

to_compute = [a, b, c]

dask.visualize(
    *to_compute,
    filename='multiple_output')

dask.compute(*to_compute)
```



multiple_output.png

Using Dask in $H \to \tau\tau$ analysis

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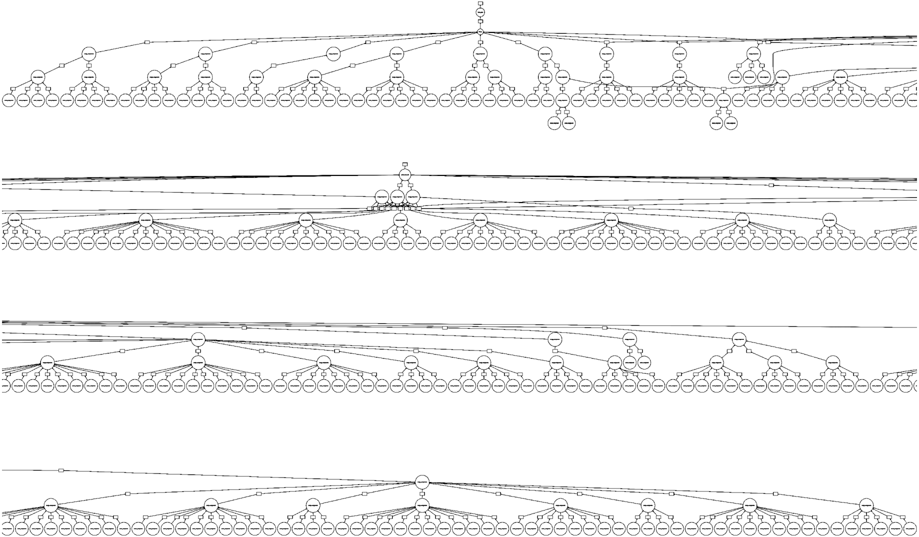
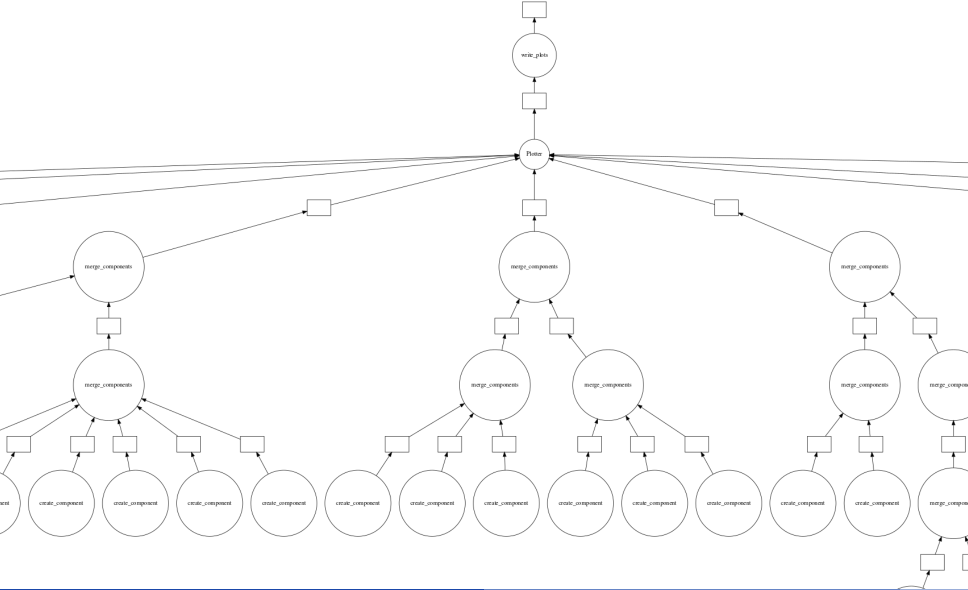
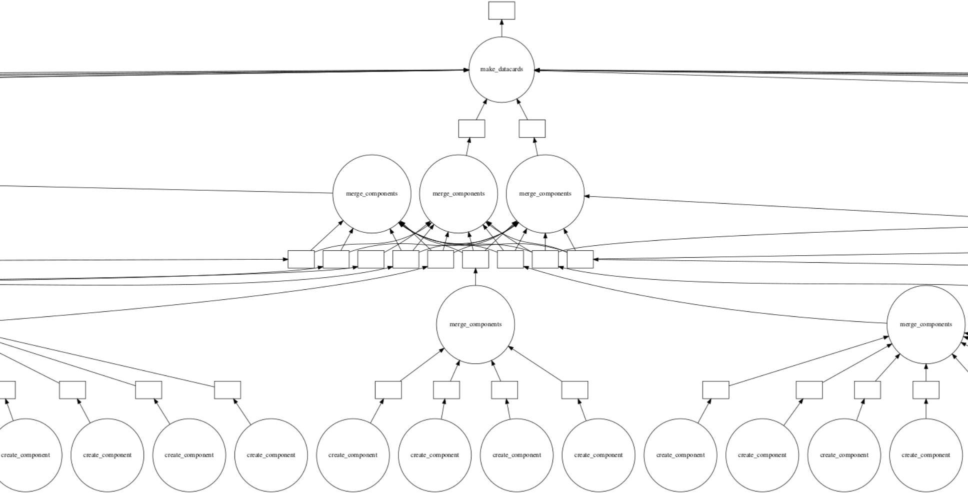


Using Dask in $H \to \tau\tau$ analysis



Using Dask in $H \to \tau\tau$ analysis



Conclusion

$H \to \tau\tau$ analysis

- $H \to \tau\tau$ provides best chances to observe new Higgs bosons.
- Good agreement with CMS 2017 data in the $\mu\tau_\mathrm{h}$ channel.

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  - full RunII combination,
  - use 3 channels: $\tau_\mathrm{h}\tau_\mathrm{h}$, $\mu\tau_\mathrm{h}$, $e\tau_\mathrm{h}$.

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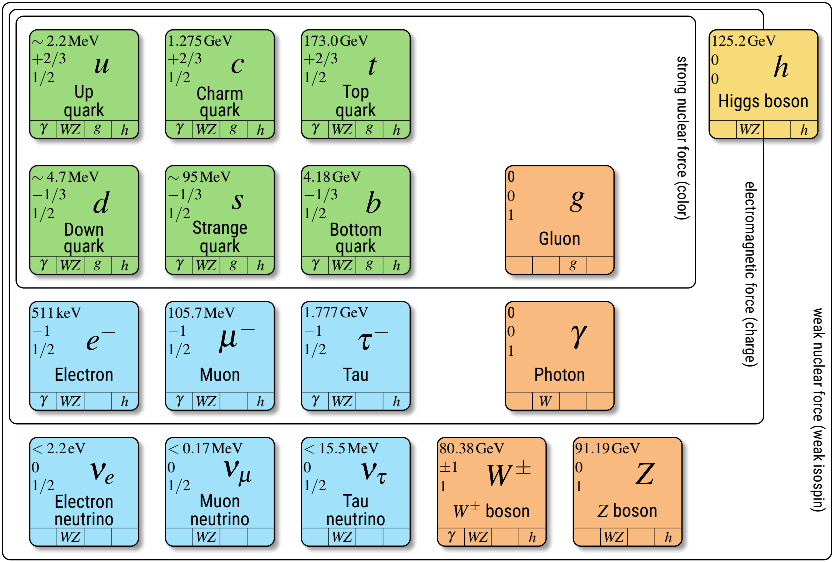
DASK

- Optimize CPU usage.
- Script $\sim$ 10 times faster!

Thank you for your attention!

lucas.torterotot@ipnl.in2p3.fr

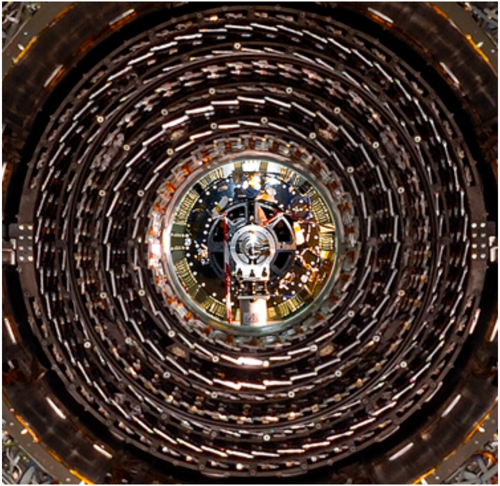
The Standard Model



The CMS detector

The CMS detector – Silicon tracker (pixels)

detects charged particles going through



⟵ 1 m ⟶

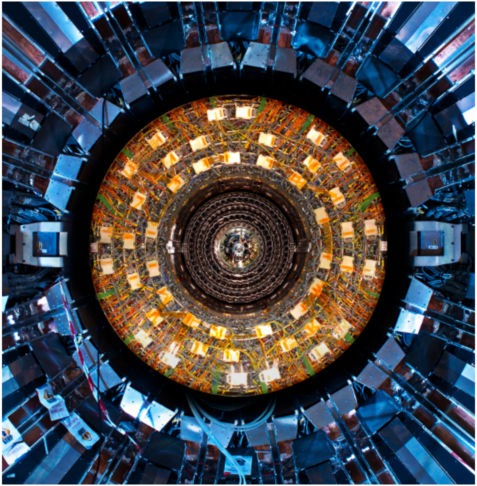
The CMS detector – Silicon tracker (strips)

detects charged particles going through

$\longleftarrow 2\,\mathrm{m} \longrightarrow$

The CMS detector – Electromagnetic calorimeter (ECAL)

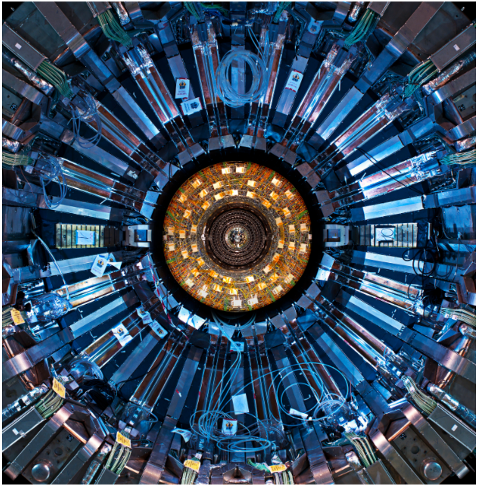
stops photons and electrons, measure their energies



⟵ 3 m ⟶

The CMS detector – Hadron calorimeter (HCAL)

stops hadrons (protons, neutrons, ...), measure their energies



$\longleftarrow 5\,\mathrm{m} \longrightarrow$

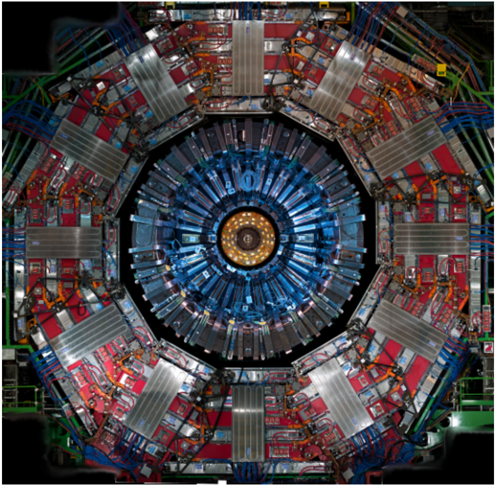
The CMS detector – Superconducting solenoid

creates a $4\,\mathrm{T}$ magnetic field which bends charged particles trajectories

$\longleftarrow 7\,\mathrm{m} \longrightarrow$

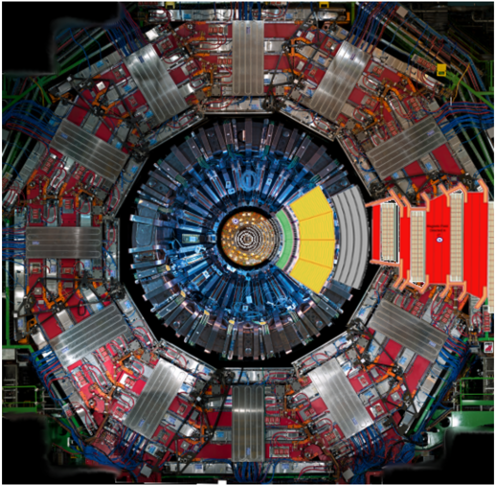
The CMS detector – Muon system

detects muons going through



⟵ 15 m ⟶

The CMS detector



⟵ 15 m ⟶

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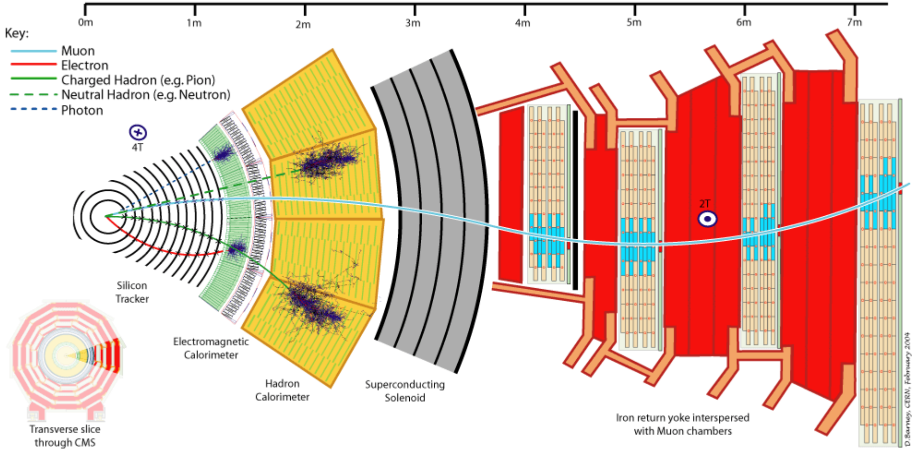
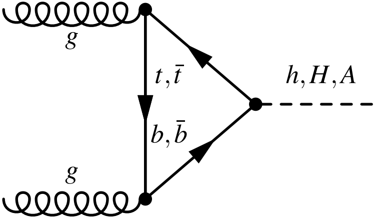
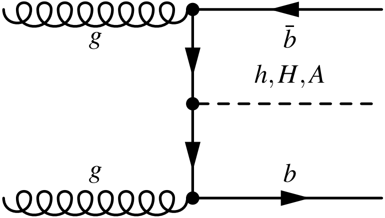
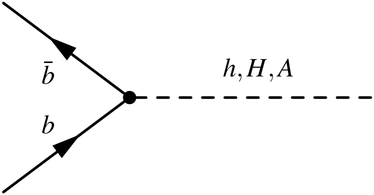



g
t, t̄
b, b̄
h, H, A
g


g
b̄
h, H, A
g
b

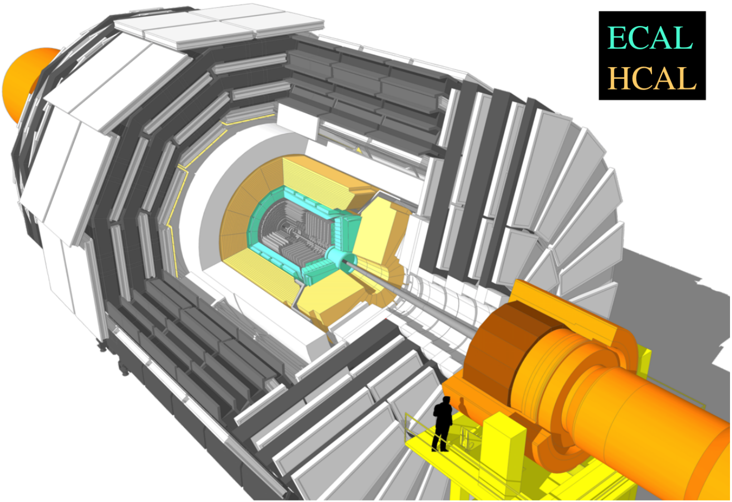

b̄
h, H, A
b

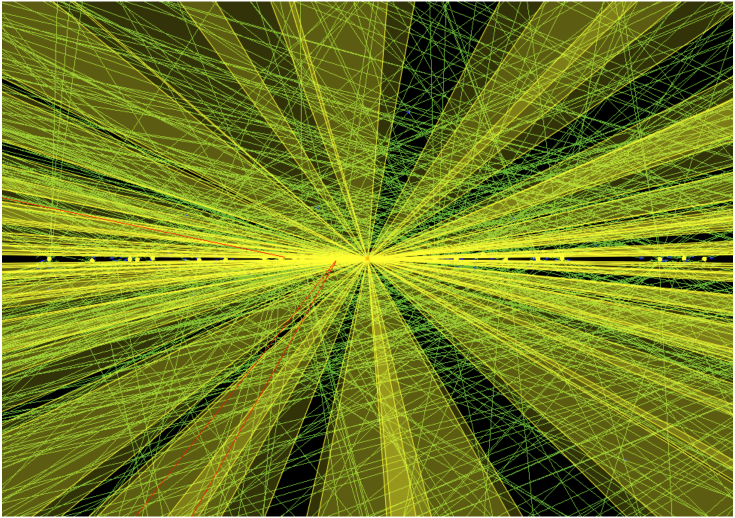
The FF method

- Maybe the DR are not $100\,\%$ pure in terms of process-of-interest.
- To ensure purity, slighlty change FF_i definition

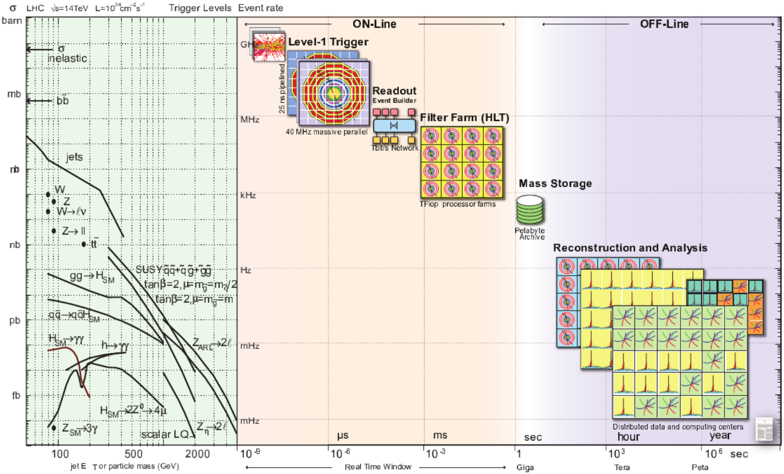
$$\mathrm{FF}_i = \frac{n_{\text{iso}}}{n_{\text{anti-iso}}} \rightsquigarrow \mathrm{FF}_i = \frac{n_{\text{iso}} - n_{\text{iso}}^{\text{rest}}}{n_{\text{anti-iso}} - n_{\text{anti-iso}}^{\text{rest}}}$$

n_x^{rest} = impurity of backgrounds other than from the process-of-interest in the DR, MC-driven.

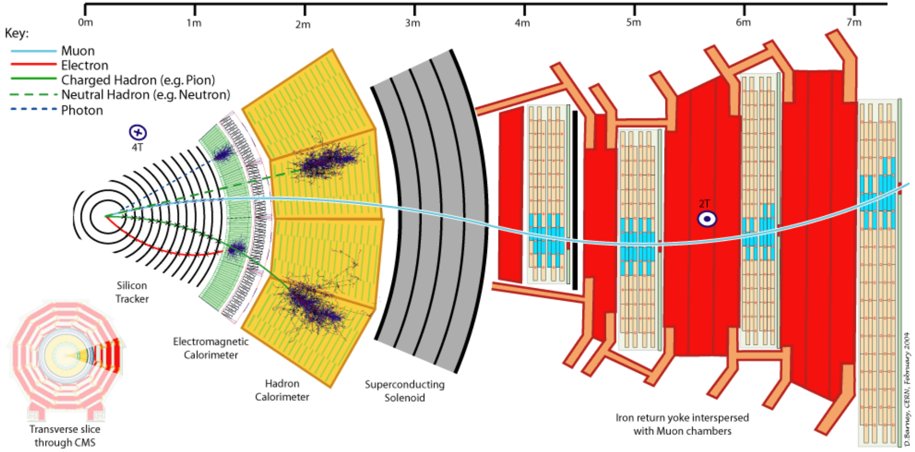

ECAL
HCAL



Triggers


σ LHC √s=14TeV L=10^34 cm^-2 s^-1
Trigger Levels Event rate
barn
mb
nb
pb
fb
σ inelastic
bb̄
jets
W
Z
W→ℓν
Z→ll
tt̄
gg→H_SM
qq̄→qq̄H_SM
H_SM→γγ
h→γγ
H_SM→2Z^0→4ℓ
Z_SM→3γ
scalar LQ
SUSY q̃q̃+q̃g̃+g̃g̃
tanβ=2,μ=m_g̃=m_q̃/2
tanβ=2,μ=m_g̃=m_q̃
Z_ARL→2ℓ
Z_η→2ℓ
100
500
2000
jet E_T or particle mass (GeV)
ON-Line
OFF-Line
GHz
MHz
kHz
Hz
mHz
Level-1 Trigger
25 ns pipelined
40 MHz massive parallel
Readout
Event Builder
Tbit/s Network
Filter Farm (HLT)
TFlop processor farms
Mass Storage
Petabyte Archive
Reconstruction and Analysis
Distributed data and computing centers
μs
ms
sec
hour
year
10^-9
10^-6
10^-3
1
10^3
10^6
sec
Real Time Window
Giga
Tera
Peta

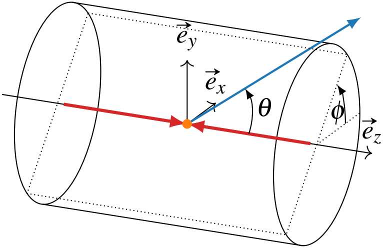
Event reconstruction



Event reconstruction: jets

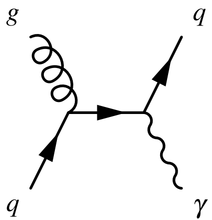
"anti-k_T" algorithm: $d_{ij} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right)\frac{\Delta R_{ij}^2}{R^2} < 0.4$

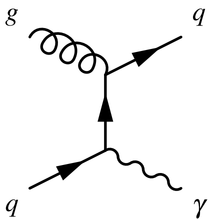
$$\Delta R_{ij}^2 = \Delta\phi^2 + \Delta\eta^2, \quad \eta = -\ln\tan\frac{\theta}{2}$$

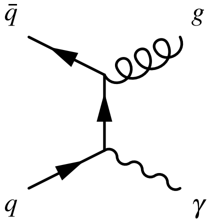


▷ M. Cacciari, G. P. Salam & G. Soyez. "The Anti-k_T jet clustering algorithm". *Journal of High Energy Physics* **04** (2008), p. 063. DOI: 10.1088/1126-6708/2008/04/063. arXiv: 0802.1189 [hep-ph].

$\gamma+$jet events: Feynman graphs examples







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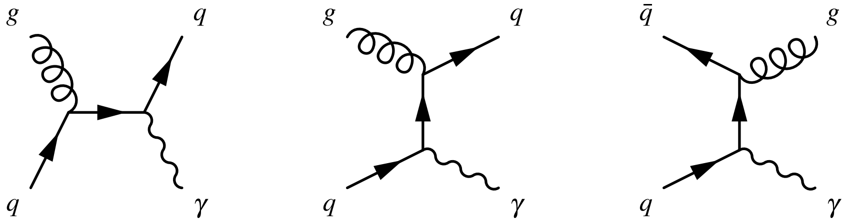
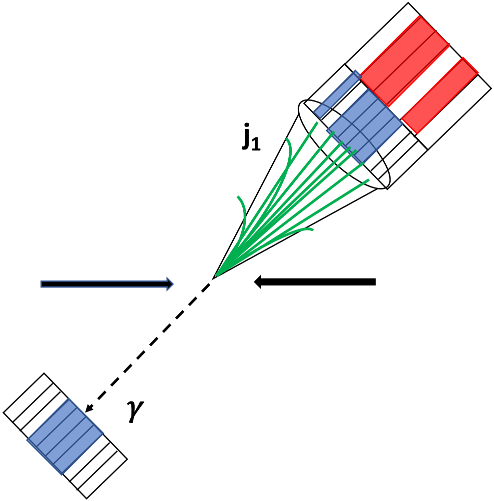


- Only 2 "particles" (physics objects) in final state:
  - photon (well known);
  - jet (to calibrate).
- No neutrino $\Rightarrow$ no real $E_{\mathrm{T}}^{\text{miss}}$.

$\gamma+$jet events: what it looks like IRL



$\gamma+$jet events: jet calibration, balancing method

- The physics of the events gives

$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}} = \vec{0} \Rightarrow \boxed{p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} = p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}}}$$

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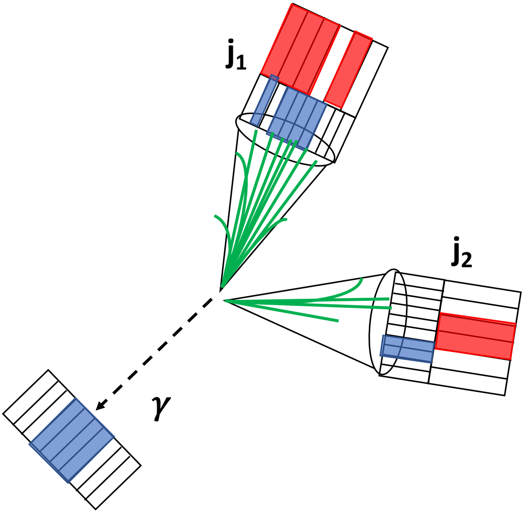
- For the reconstructed objects, the balancing response is then defined as

$$\vec{p}_{\mathrm{T}\,\mathrm{reco}}^{\,\gamma} + \underbrace{R_{bal}\vec{p}_{\mathrm{T}\,\mathrm{reco}}^{\,\mathrm{jet}}}_{\vec{p}_{\mathrm{T}\,\mathrm{ptcl}}^{\,\mathrm{jet}}} = \vec{0} \Rightarrow \boxed{R_{bal} = \frac{p_{\mathrm{T}\,\mathrm{reco}}^{\,\mathrm{jet}}}{p_{\mathrm{T}}^{\,\gamma}}}$$

$\gamma+$jet events: world is not perfect



$\gamma +$ jet events: world is not perfect

- Imbalance due to the presence of additionnal jets.

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- Use the jet with higher p_{T}: $\boxed{R_{bal} = \frac{{p_{\mathrm{T}}}_{\text{reco}}^{1^{\text{st}}\text{jet}}}{{p_{\mathrm{T}}}^{\gamma}}}$.

$\gamma+$jet events: world is not perfect

- Imbalance due to the presence of additionnal jets.
- Use the jet with higher p_{T}: $\boxed{R_{bal} = \frac{p_{\mathrm{T}\,\text{reco}}^{1^{\text{st}}\text{jet}}}{p_{\mathrm{T}}{}^{\gamma}}}$.
- To avoid correction on additonnal jets: define $\boxed{\alpha = \frac{p_{\mathrm{T}\,\text{reco}}^{2^{\text{nd}}\text{jet}}}{p_{\mathrm{T}}{}^{\gamma}}}$ and extrapolate to $\alpha = 0$.

$\gamma +$ jet events: jet calibration, MPF method

- Considering balance between photon and *all other particles*,

$$\vec{p}_{\mathrm{T}\,\mathrm{ptcl}}^{\,\gamma} + \vec{p}_{\mathrm{T}\,\mathrm{ptcl}}^{\,\mathrm{recoil}} = \vec{0}$$

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Run 2018 ABCD responses, $\alpha = 0.15$, $\eta \in [0, 1.3]$

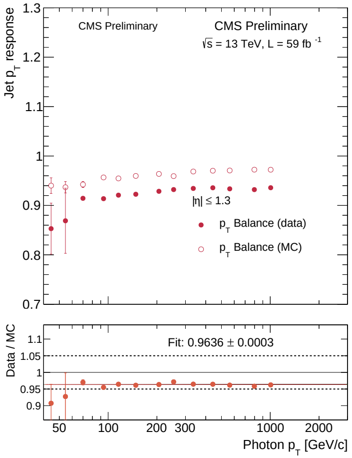


Figure: *Balancing*

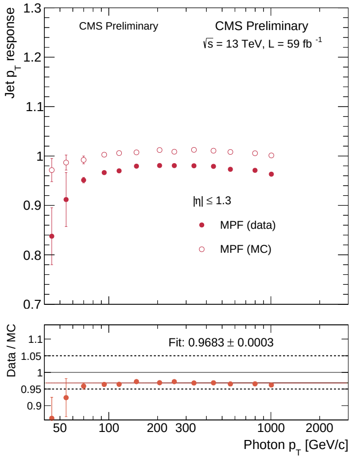
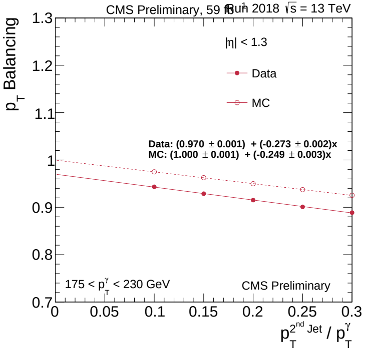


Figure: *MPF*

Run 2018 ABCD responses, extrapolation, $p_T \in [175, 230]\mathrm{GeV}, \eta \in [0, 1.3]$



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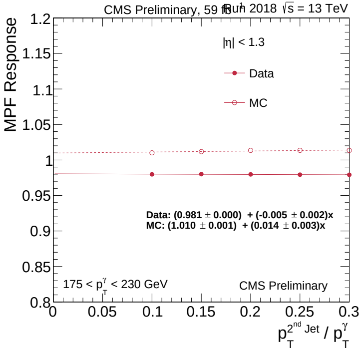

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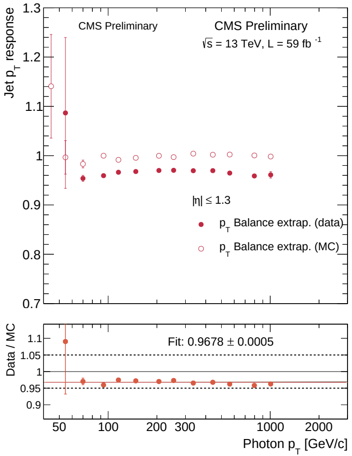

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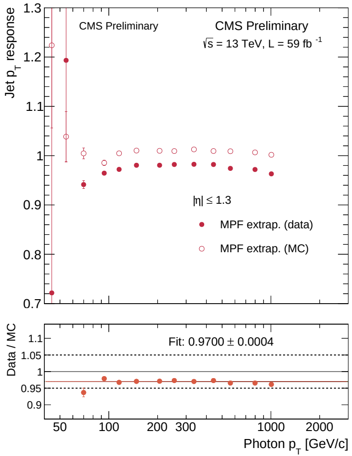

Figure: *MPF*

Jet Energy Resolution

- Remember R_{bal} definition,

$$R_{bal} = \frac{p_{\mathrm{T}\,\text{reco}}^{1^{\text{st}}\text{jet}}}{p_{\mathrm{T}\,\text{reco}}^{\gamma}}$$

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Then

$$R_{bal} = \underbrace{\frac{p_{\mathrm{T}}{}^{1^{\mathrm{st}}\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{1^{\mathrm{st}}\mathrm{jet}}_{\mathrm{ptcl}}}}_{\sigma_{\mathrm{jet}}=\mathrm{JER}} \times \underbrace{\frac{p_{\mathrm{T}}{}^{1^{\mathrm{st}}\mathrm{jet}}_{\mathrm{ptcl}}}{p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}}}}_{\mathrm{PLI}} \times \underbrace{\frac{p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}}}{p_{\mathrm{T}}{}^{\gamma}_{\mathrm{reco}}}}_{\sigma_{\gamma}\equiv 1}$$

- PLI: Particle Level Imbalance (pile-up, radiations, neutrinos...), $\to 0$ when $\alpha \to 0$.

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$$R_{bal} = \underbrace{\frac{p_{\mathrm{T}}{}^{1^{st}\text{jet}}_{\text{reco}}}{p_{\mathrm{T}}{}^{1^{st}\text{jet}}_{\text{ptcl}}}}_{\sigma_{\text{jet}}=\text{JER}} \times \underbrace{\frac{p_{\mathrm{T}}{}^{1^{st}\text{jet}}_{\text{ptcl}}}{p_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}}}}_{\text{PLI}} \times \underbrace{\frac{p_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}}}{p_{\mathrm{T}}{}^{\gamma}_{\text{reco}}}}_{\sigma_{\gamma}\equiv 1}$$

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$$\boxed{\text{JER} = \sigma_{\text{jet}} = \sqrt{\sigma^2_{R_{bal}} - \sigma^2_{\text{PLI}}}}$$

Run 2018 ABCD jet resolution

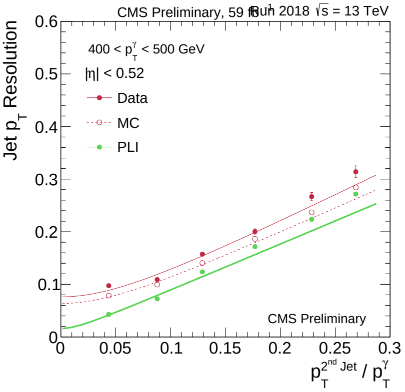

Figure: *Extrapolation*

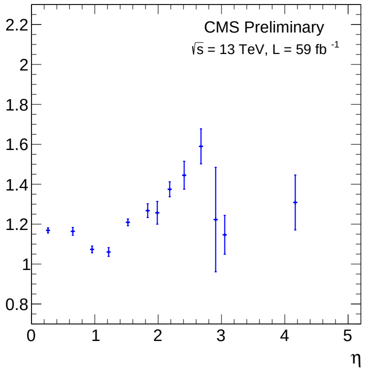

Figure: *Scale factor*

Run 2018 ABCD jet resolution

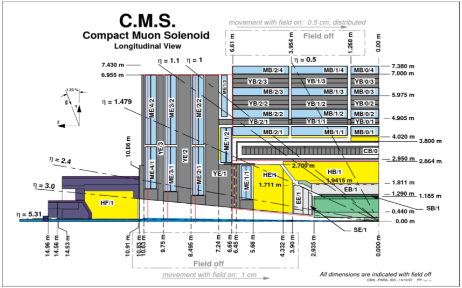

Figure: *CMS and η values*

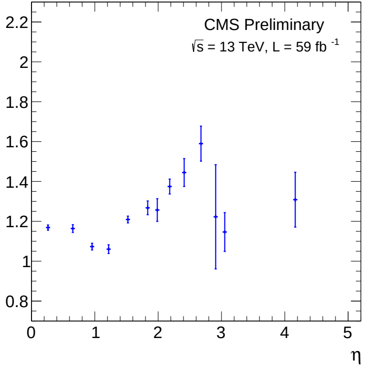

Figure: *Scale factor*