Bonn-Cologne Graduate School
of Physics and Astronomy

# Tau lepton reconstruction with energy flow and the search for $R$-parity violating supersymmetry at the ATLAS experiment

Sebastian Fleischmann

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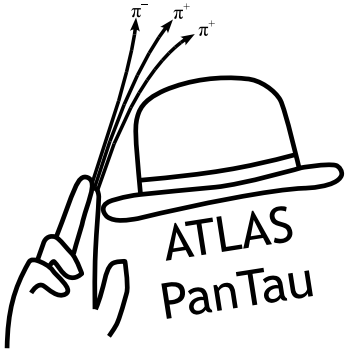
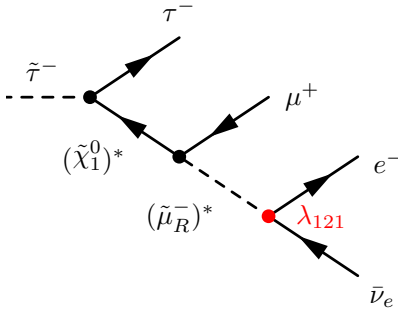



17th October 2011
Promotionskolloquium



# Overview
## Setting the scene

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Theory
Experiment
Tau ID
SUSY
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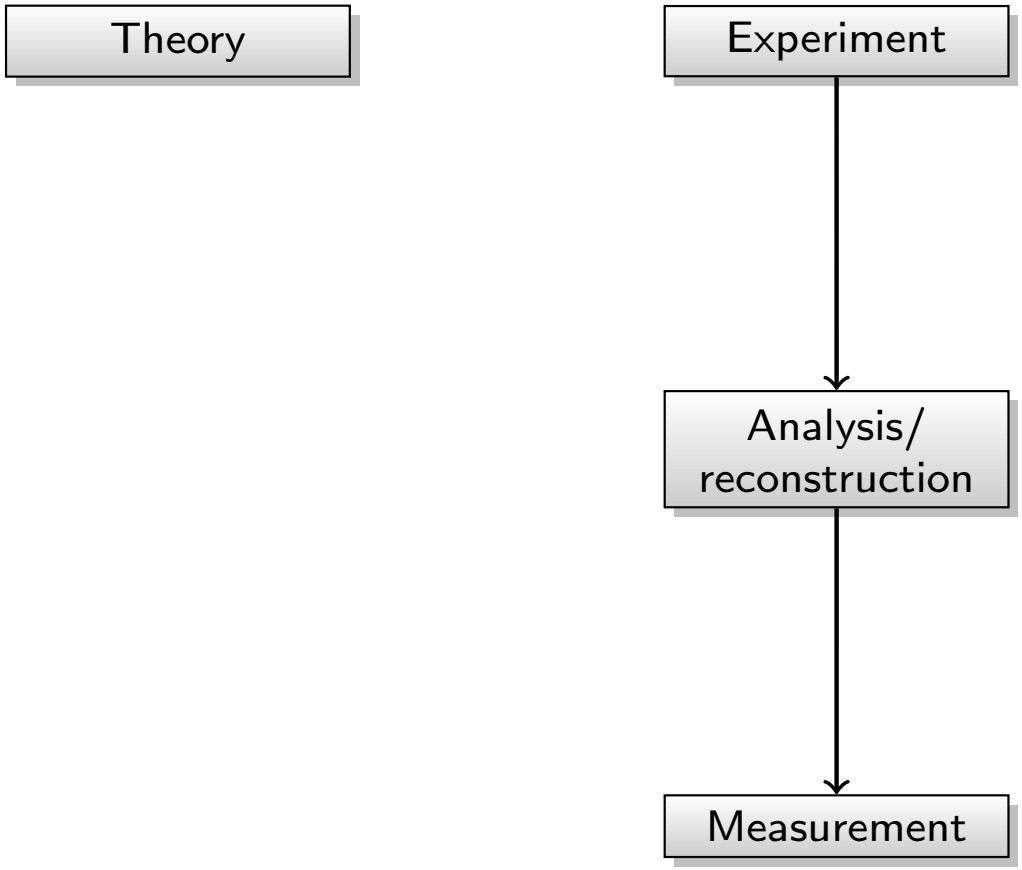

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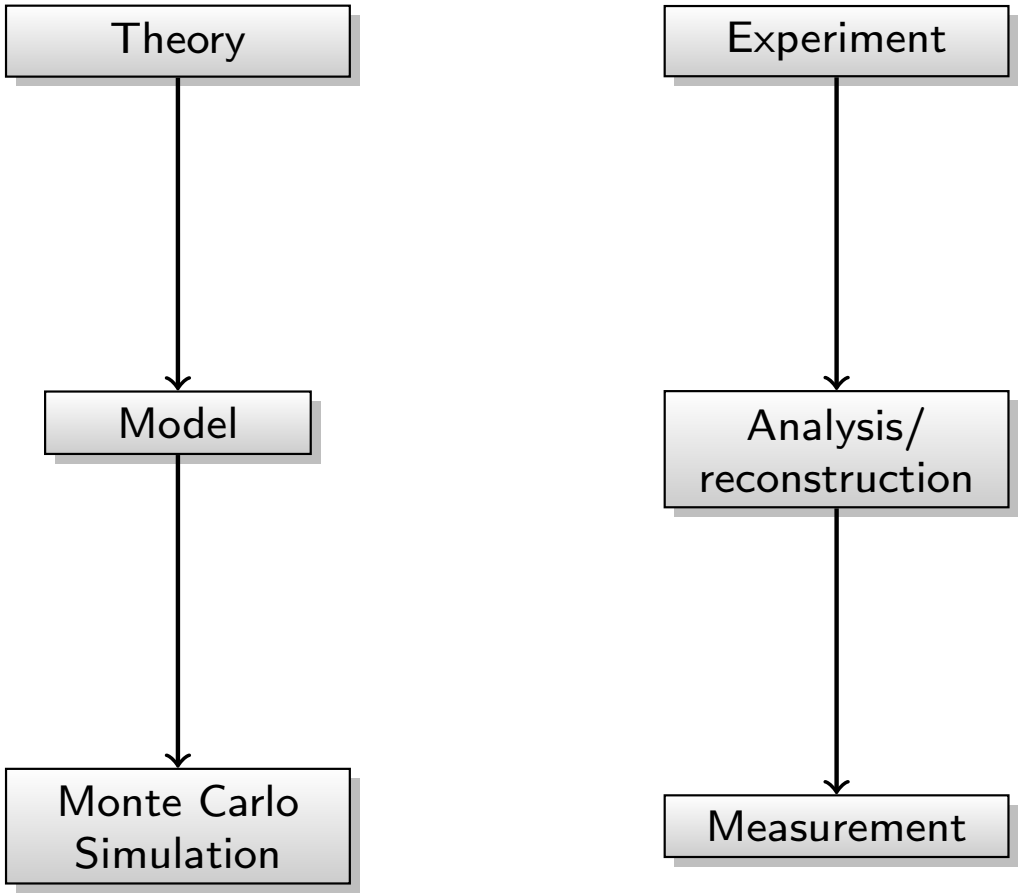

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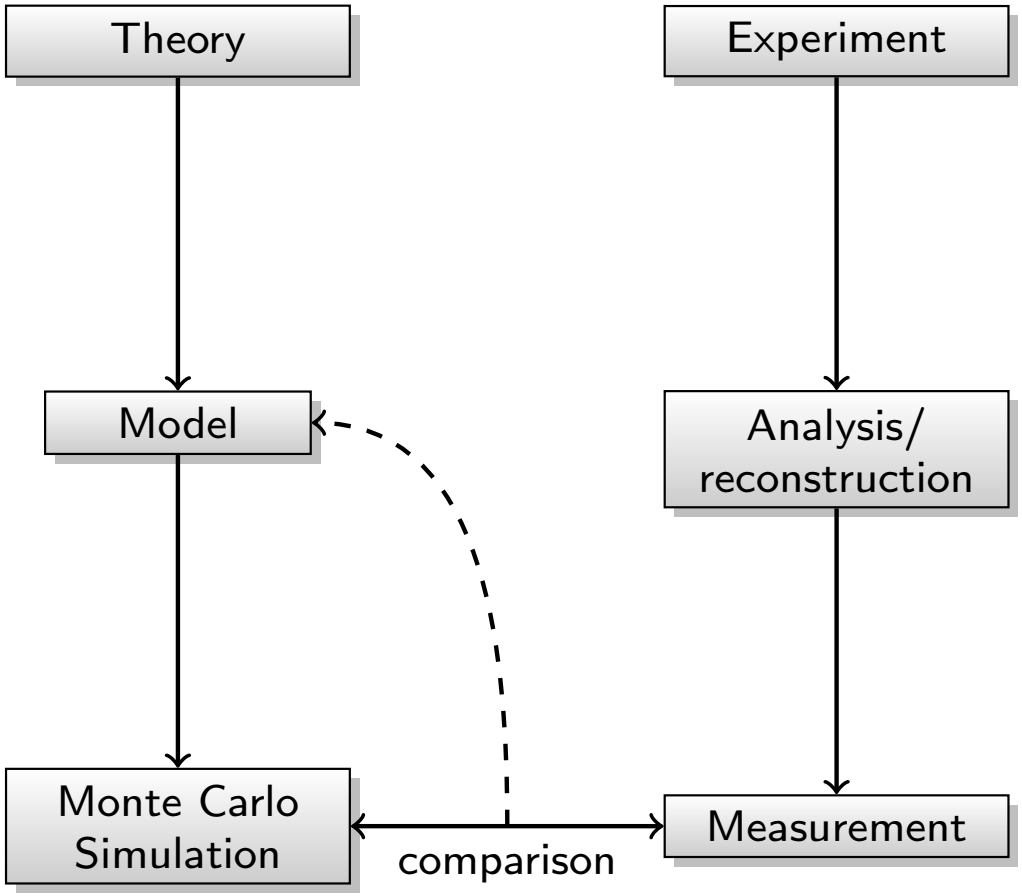

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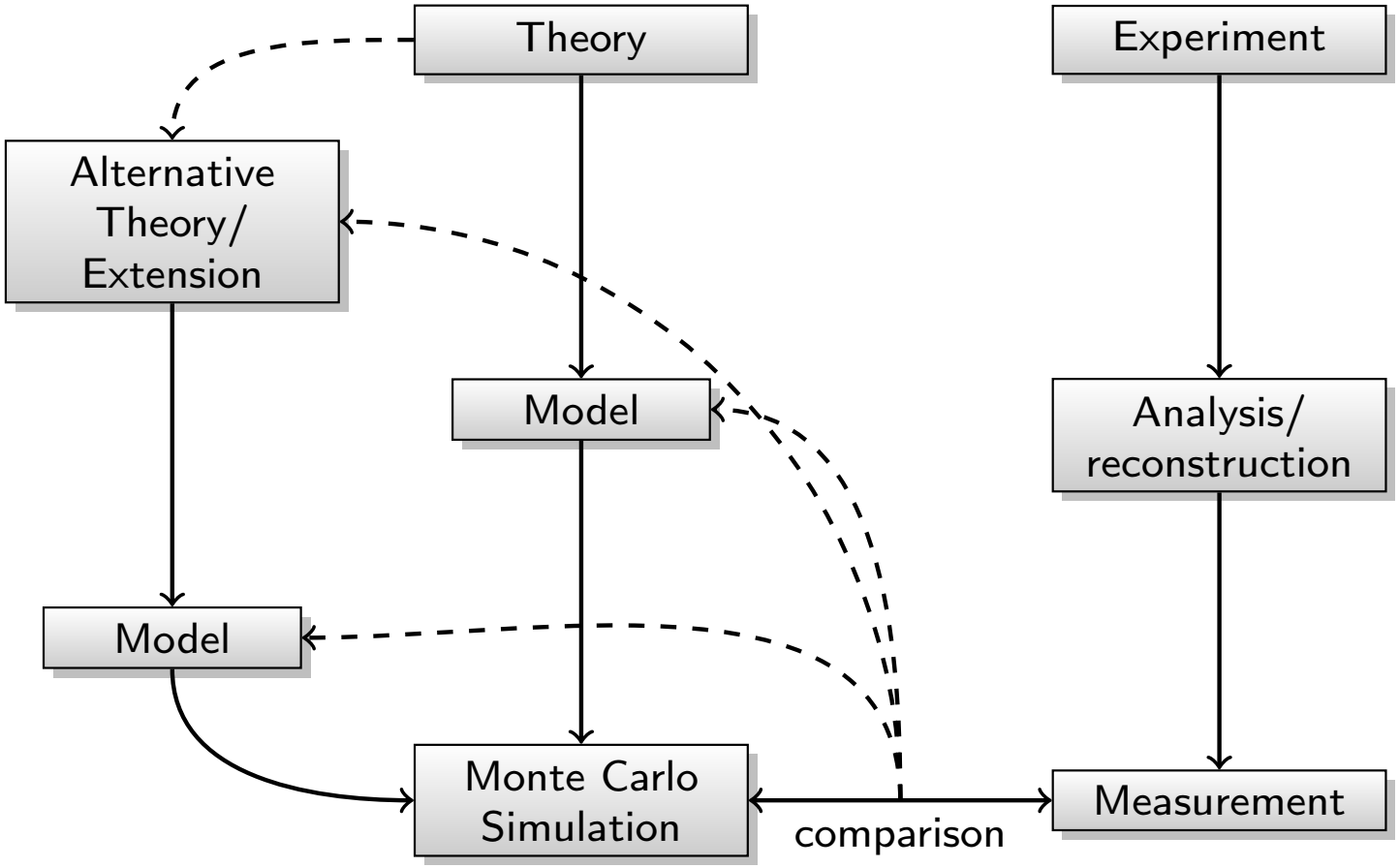

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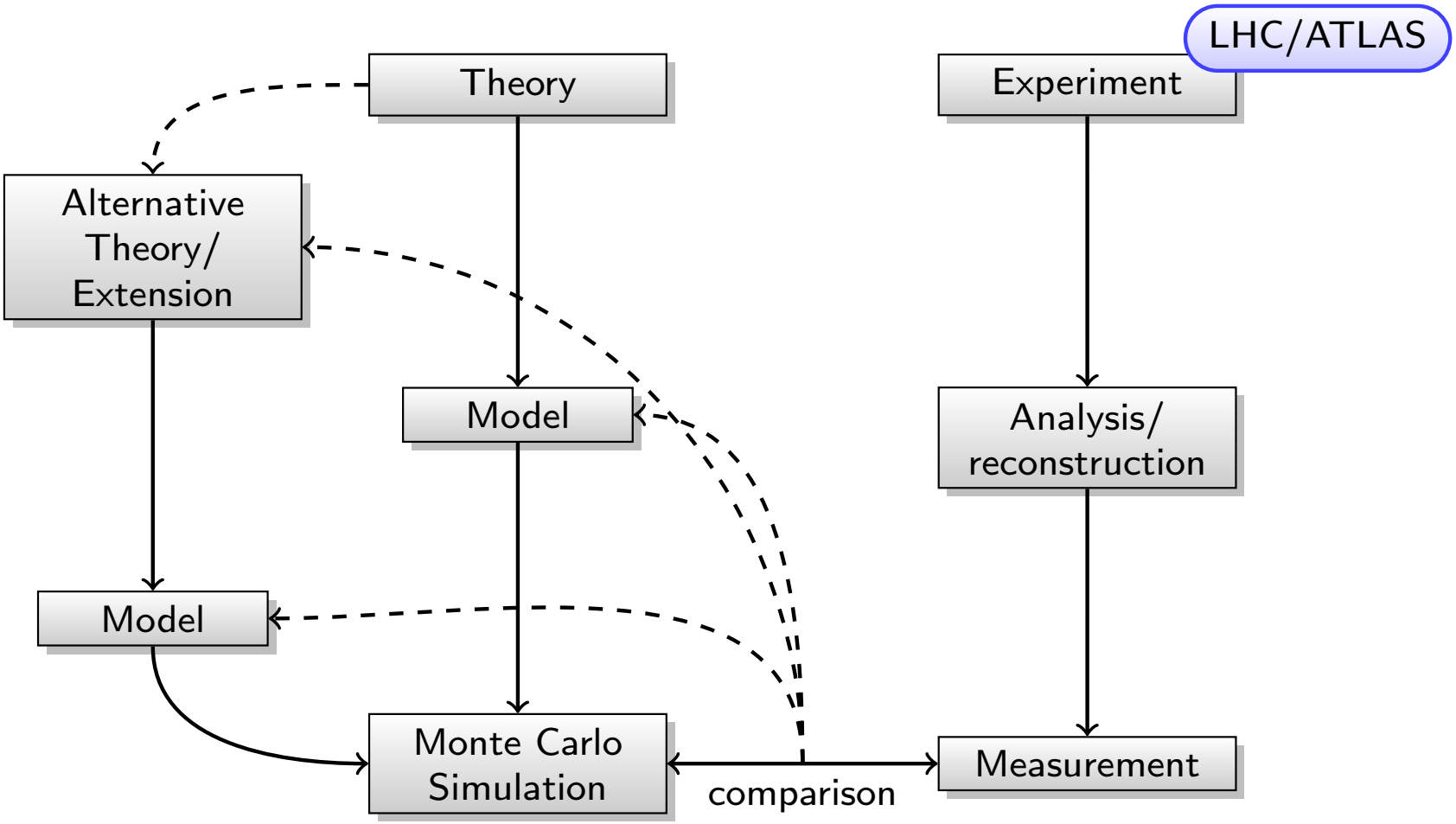

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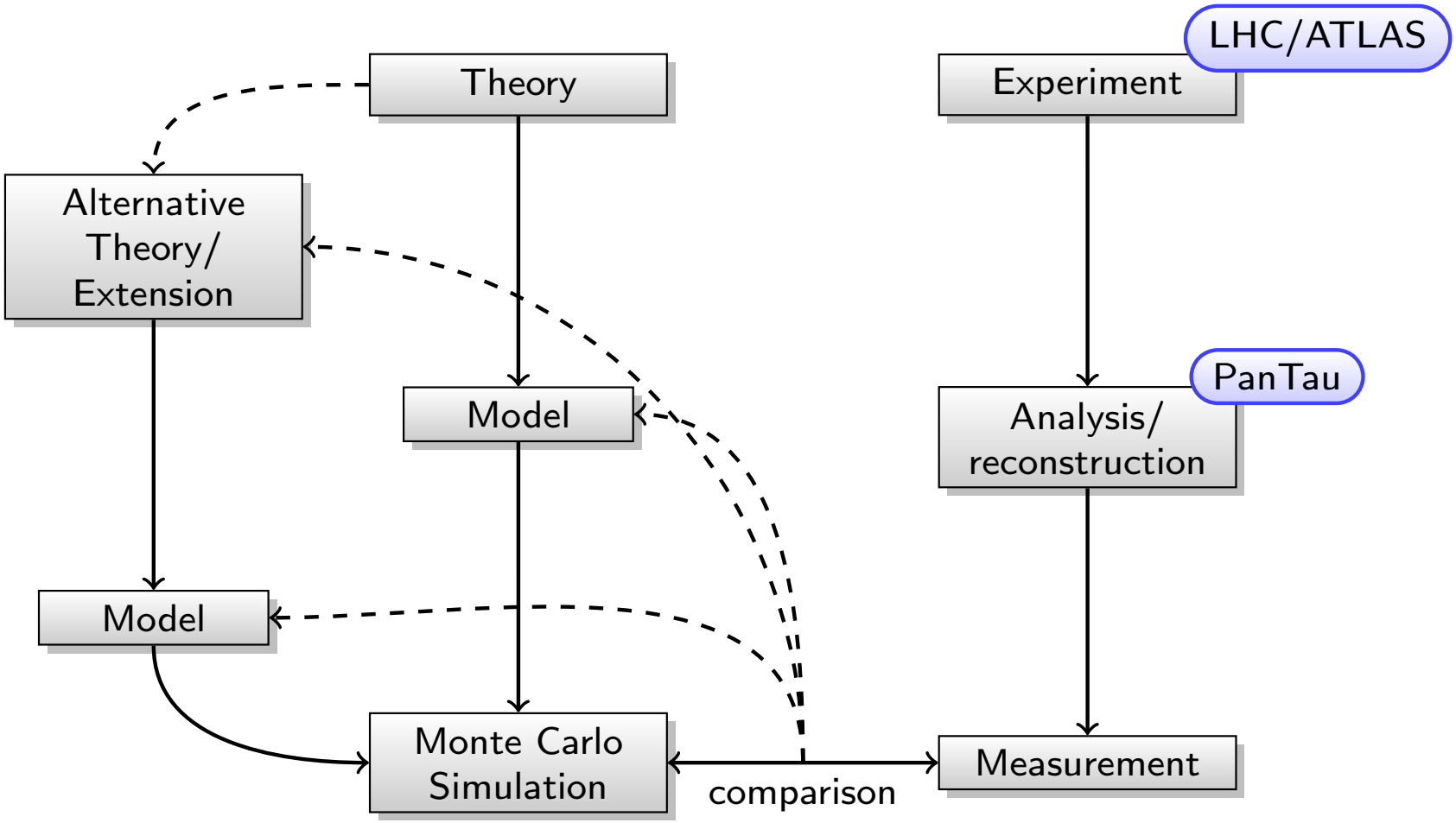

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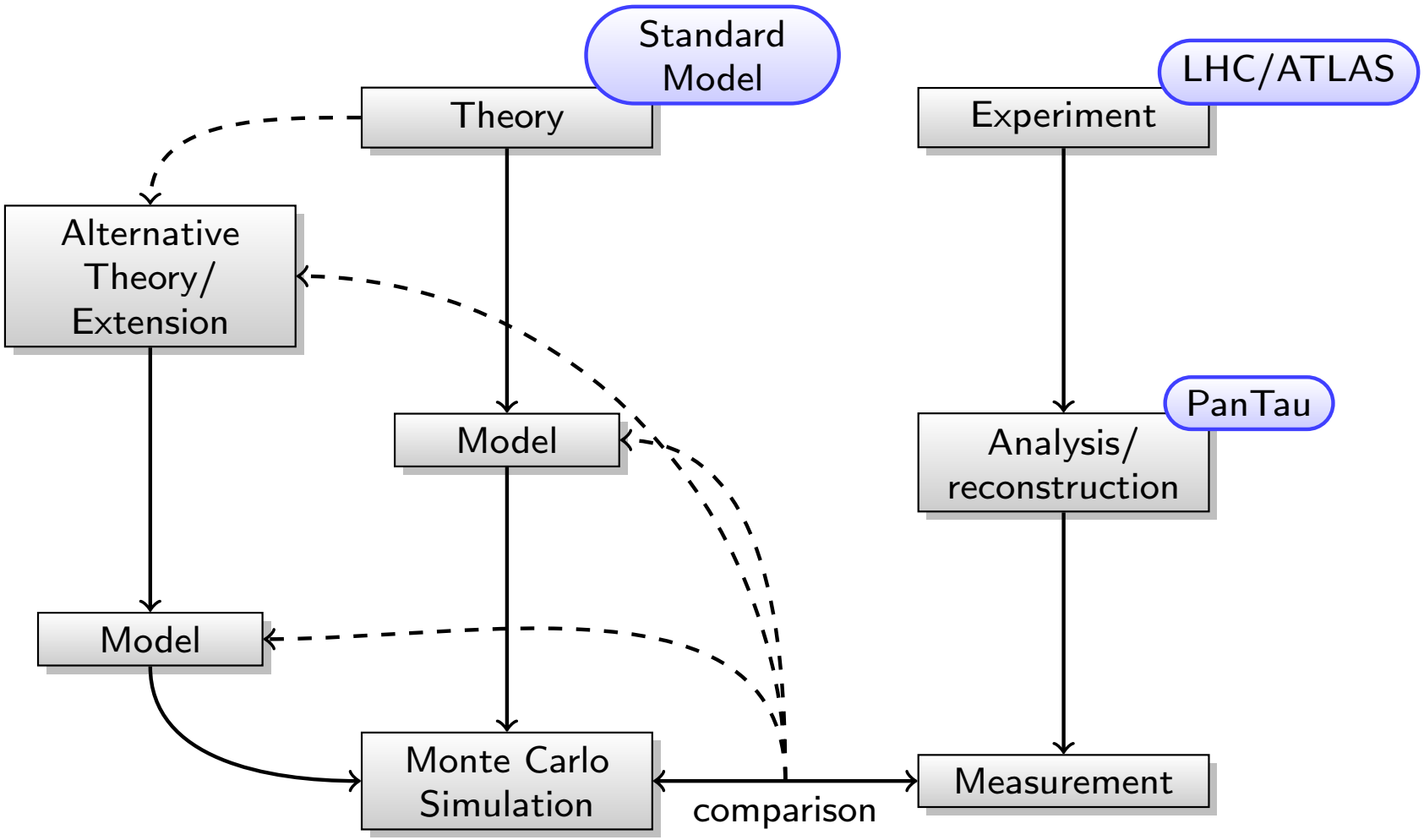

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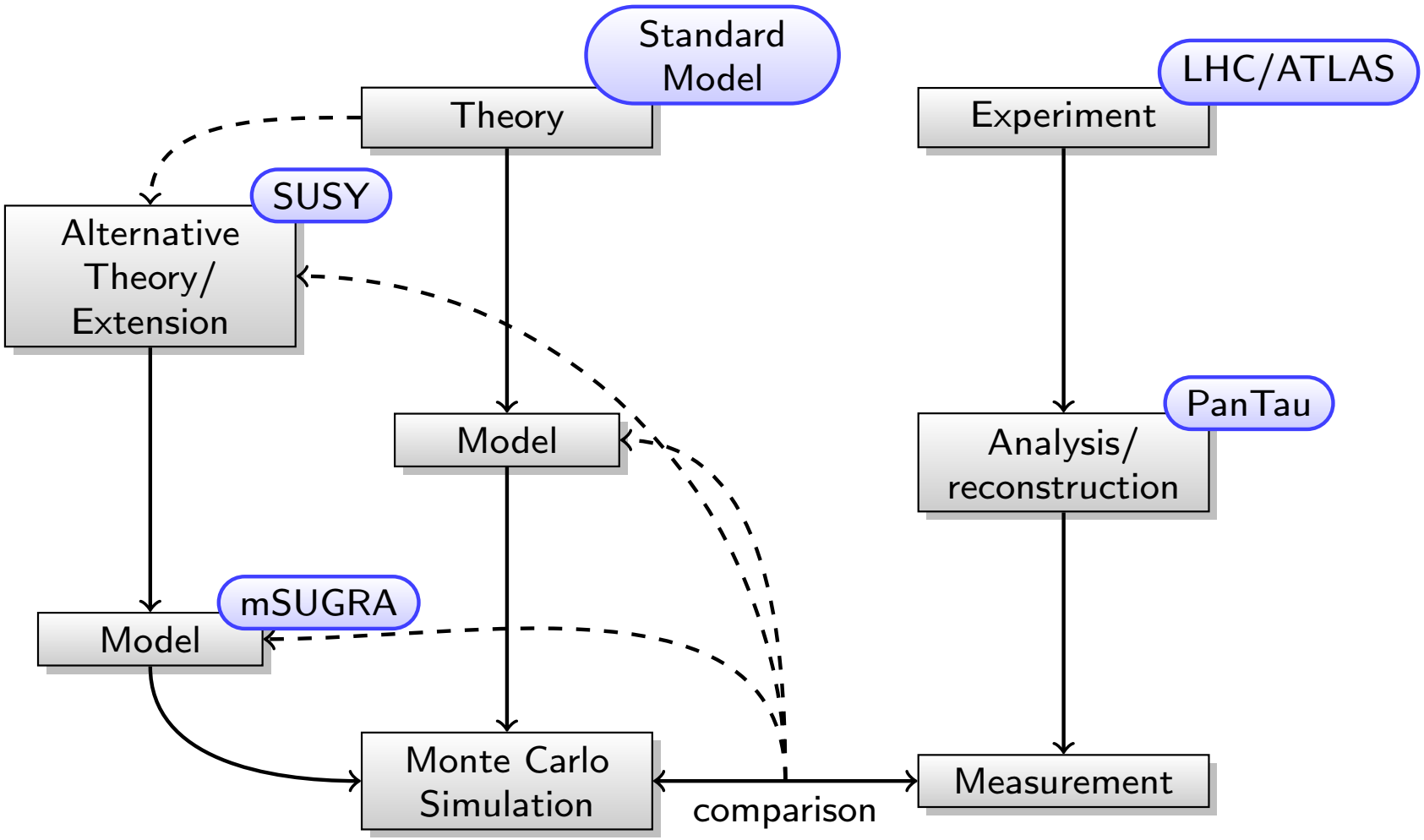

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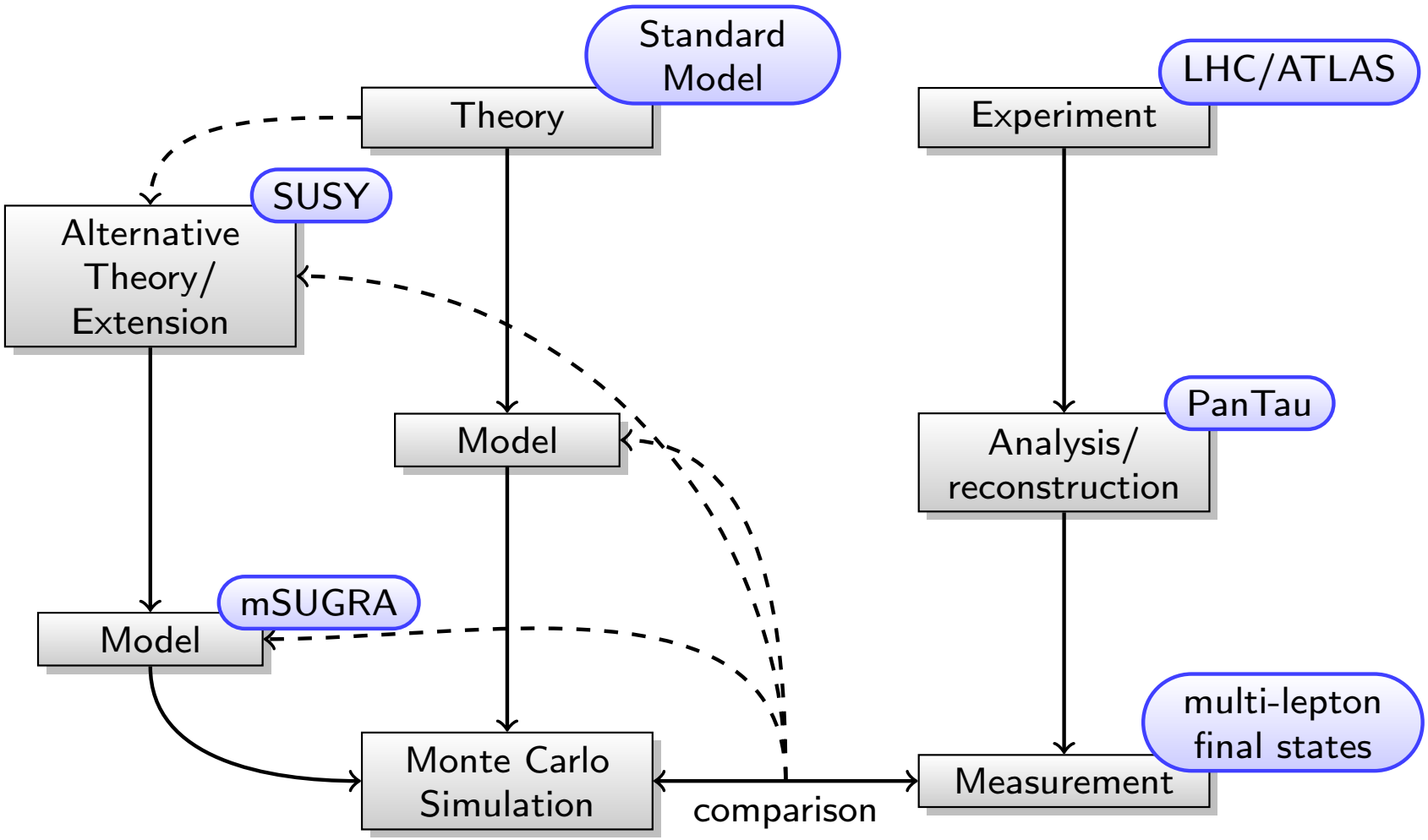

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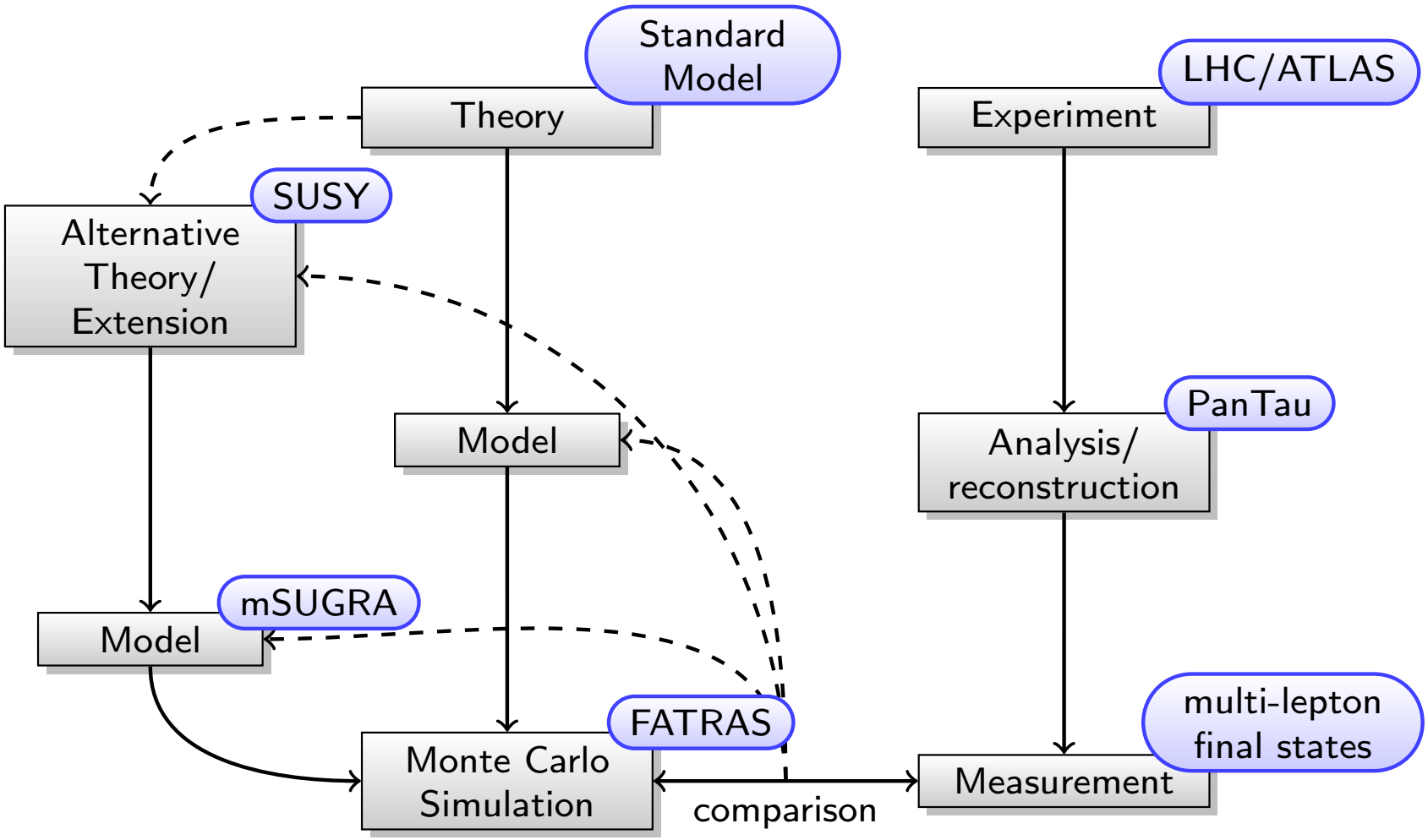

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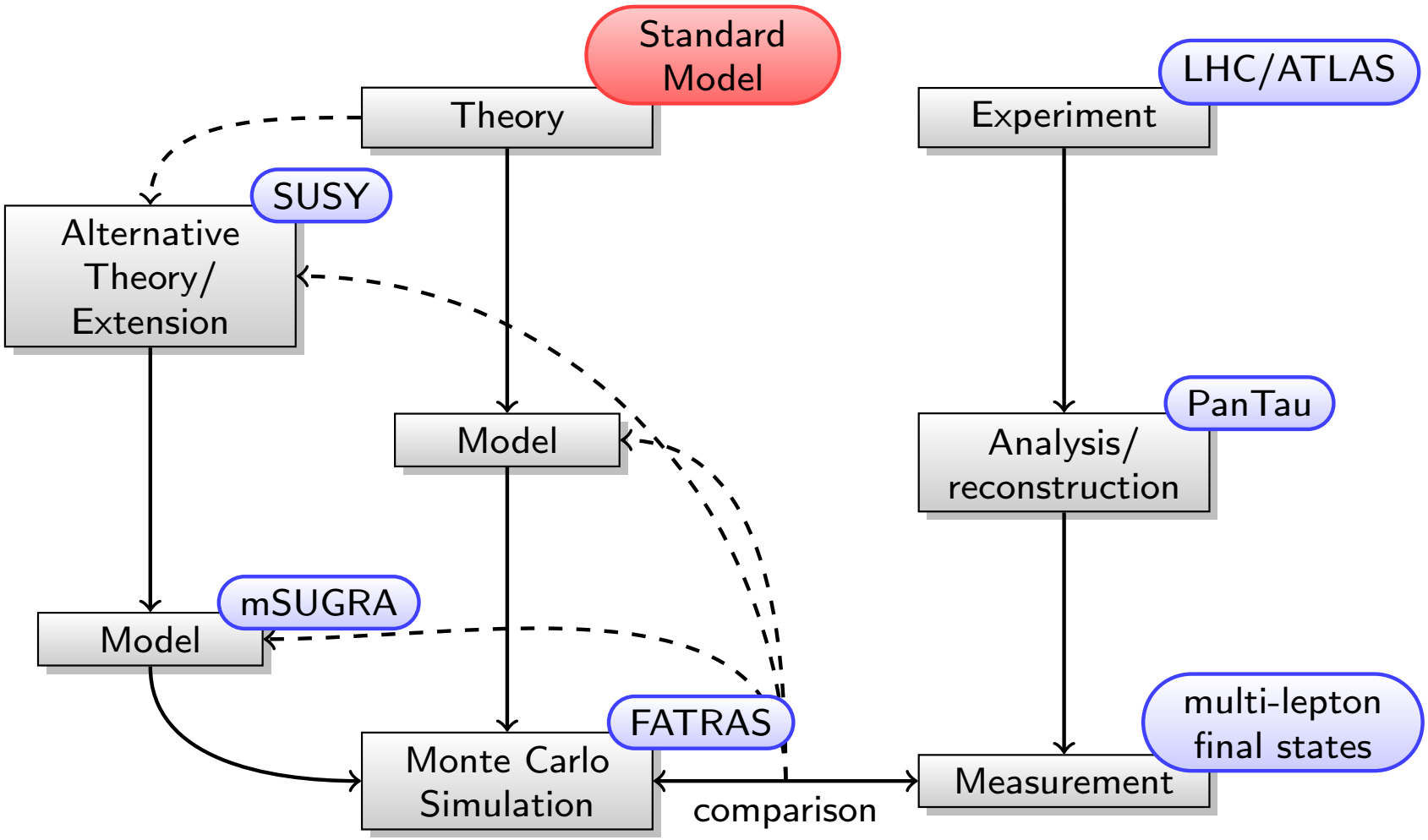
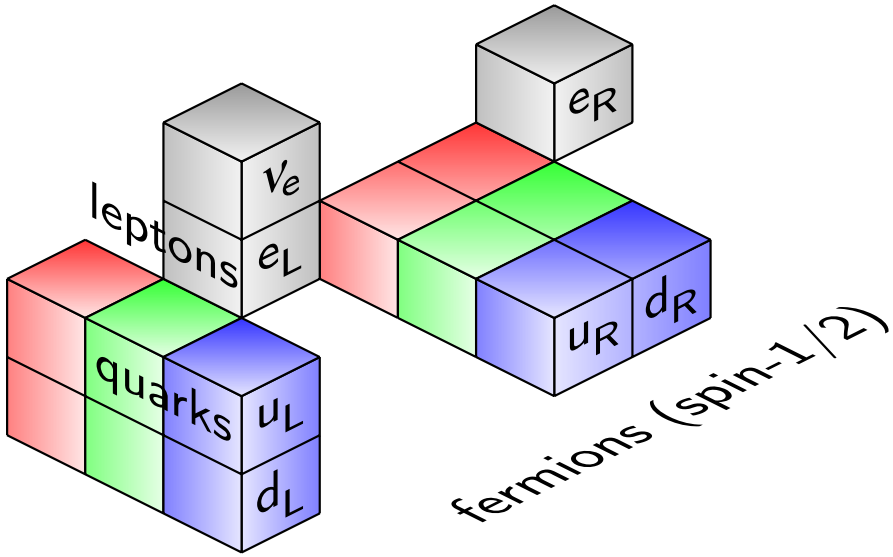


# The Standard Model of Particle Physics





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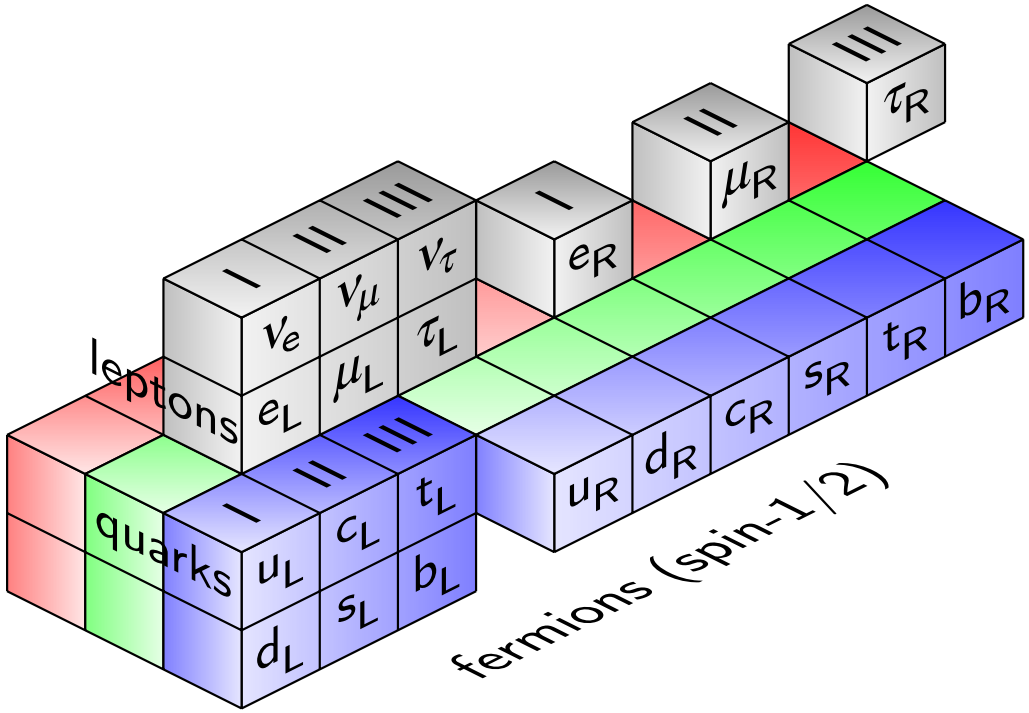

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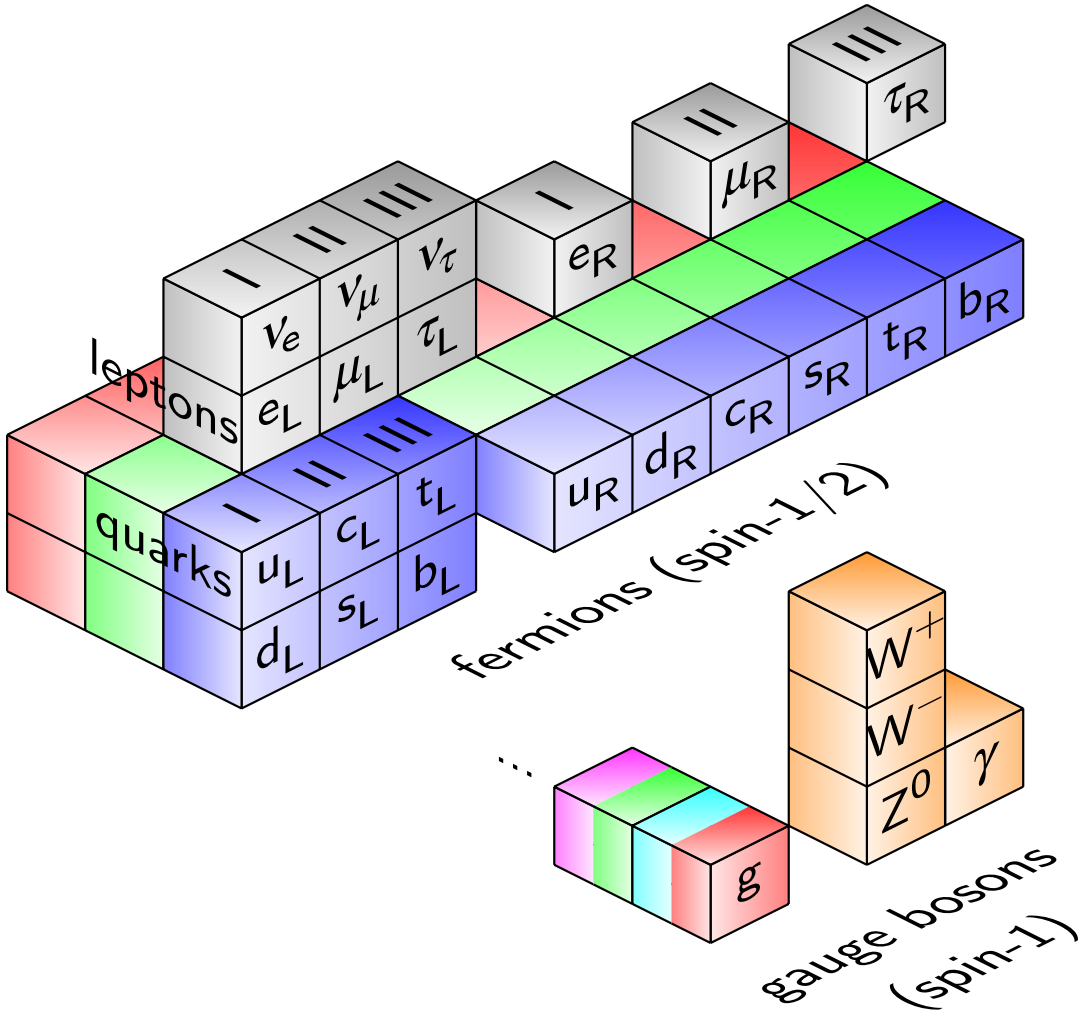




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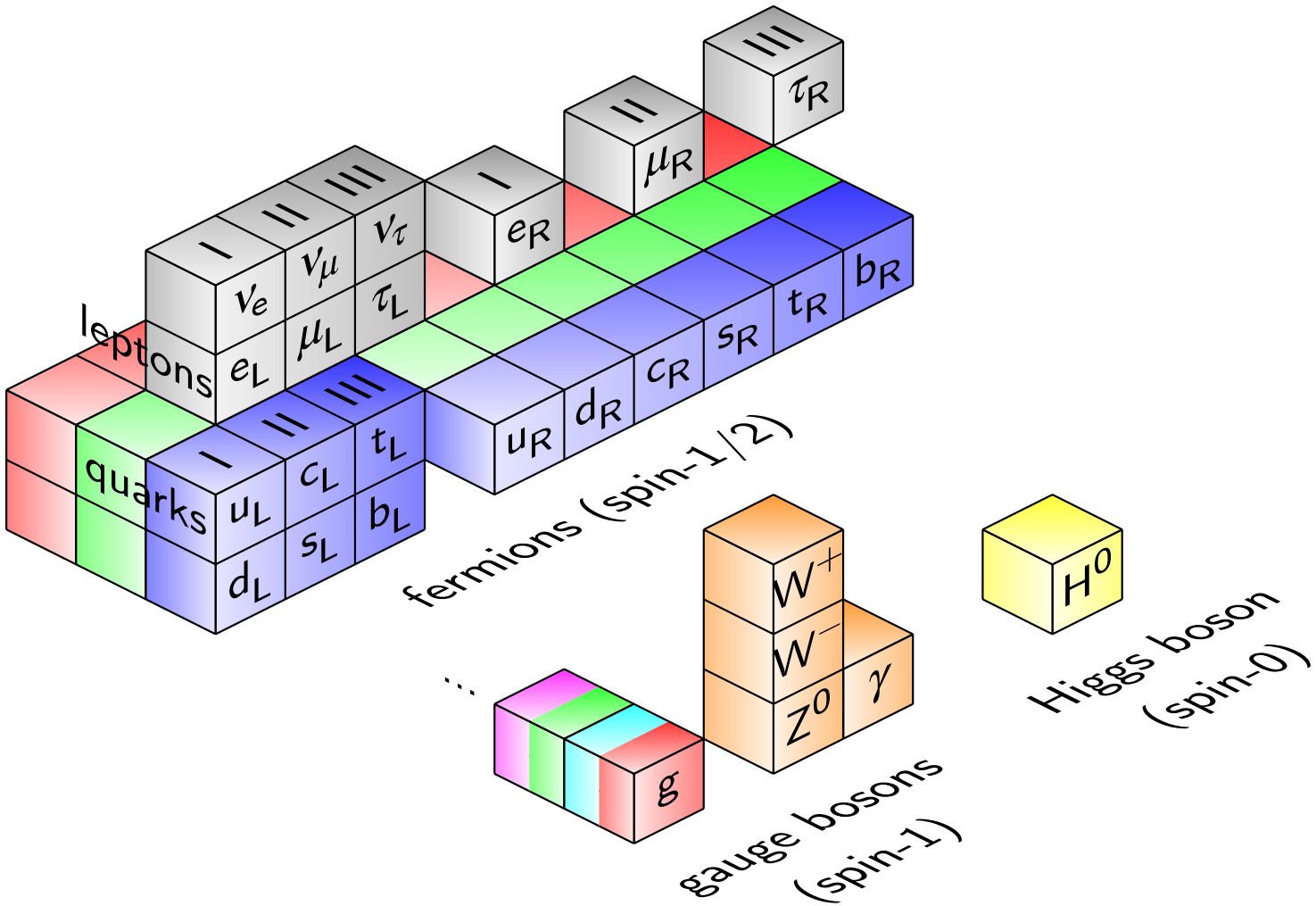




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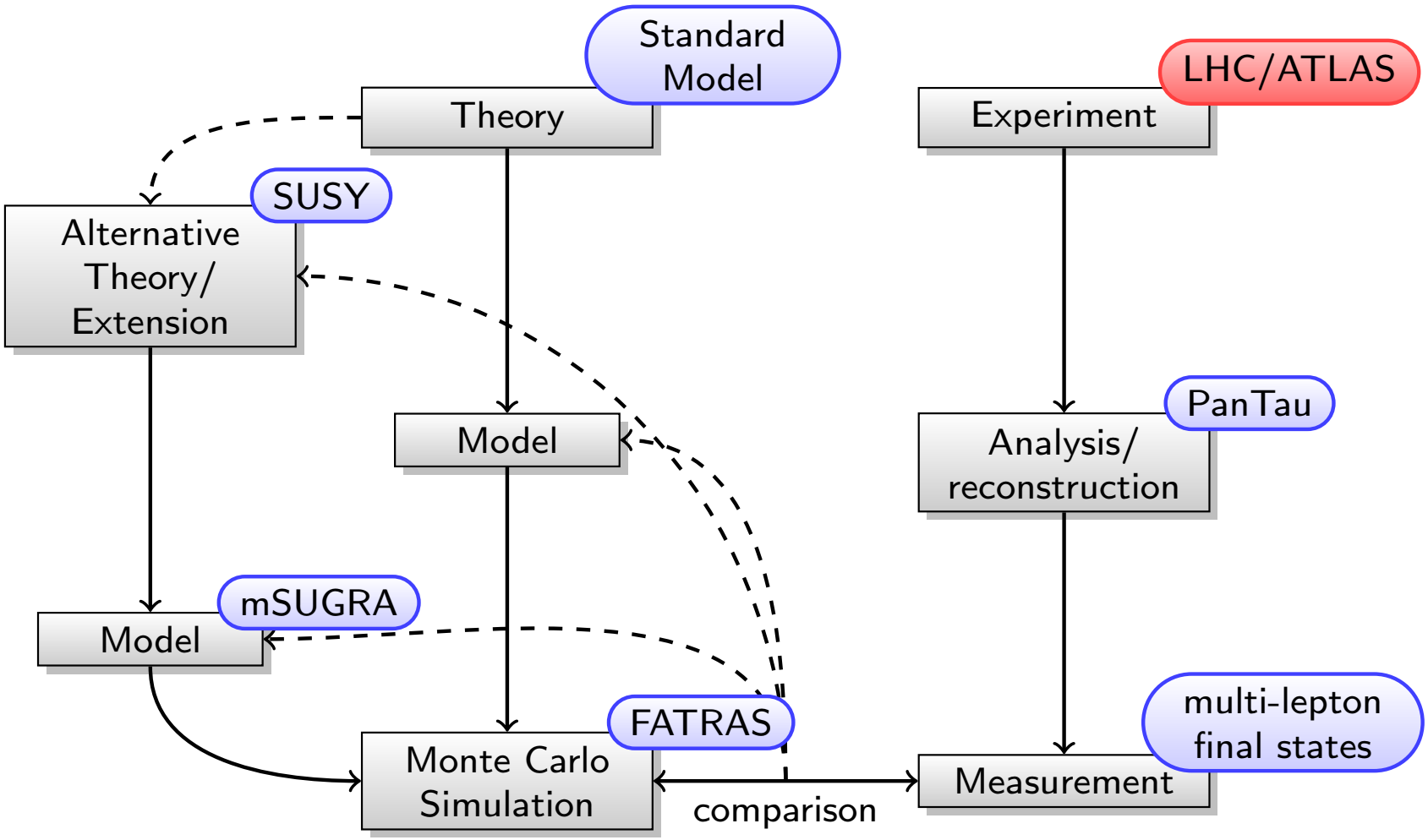



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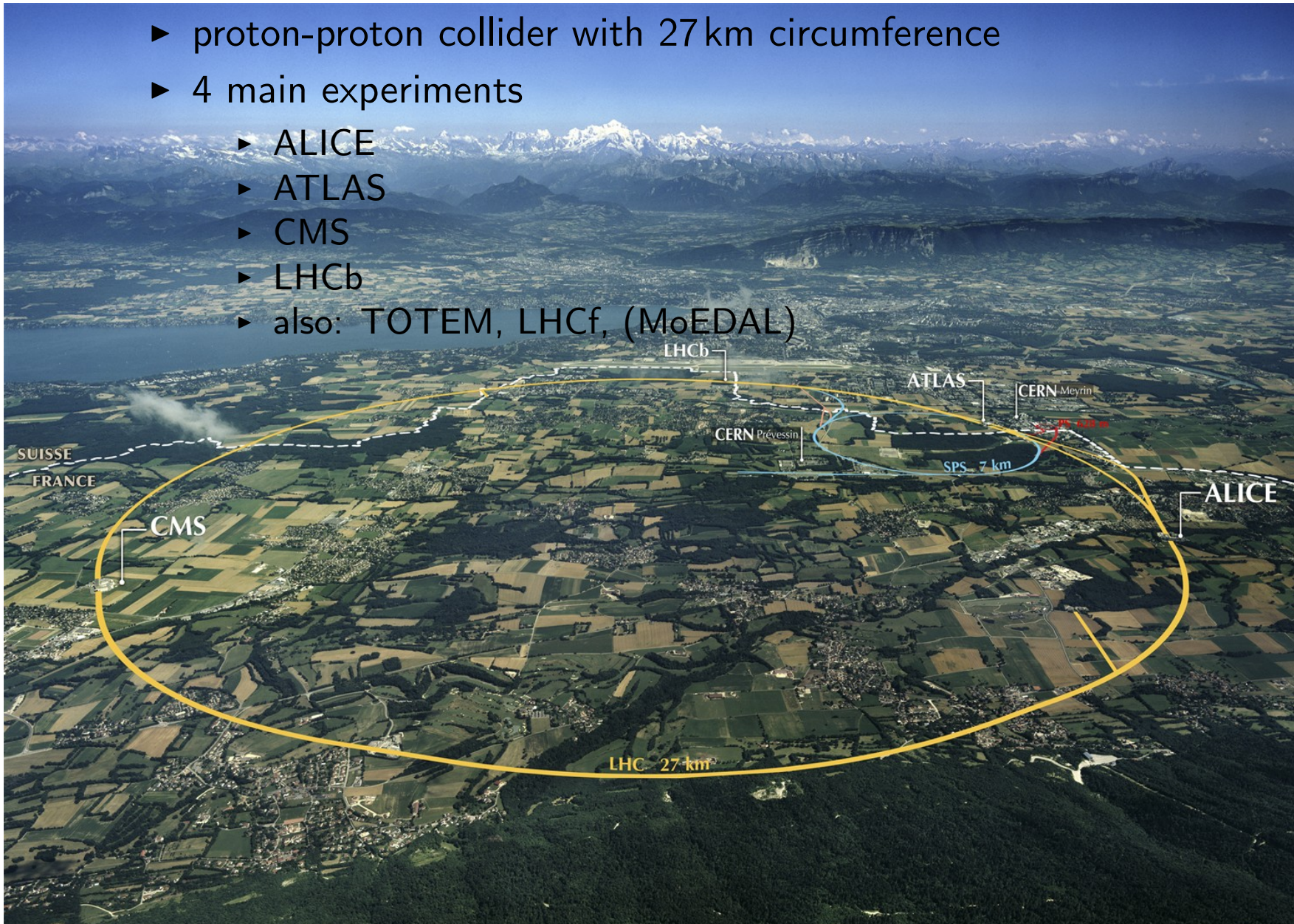
# Introduction
## The Large Hadron Collider (LHC)



- proton-proton collider with 27 km circumference
- 4 main experiments
  - ALICE
  - ATLAS
  - CMS
  - LHCb
  - also: TOTEM, LHCf, (MoEDAL)



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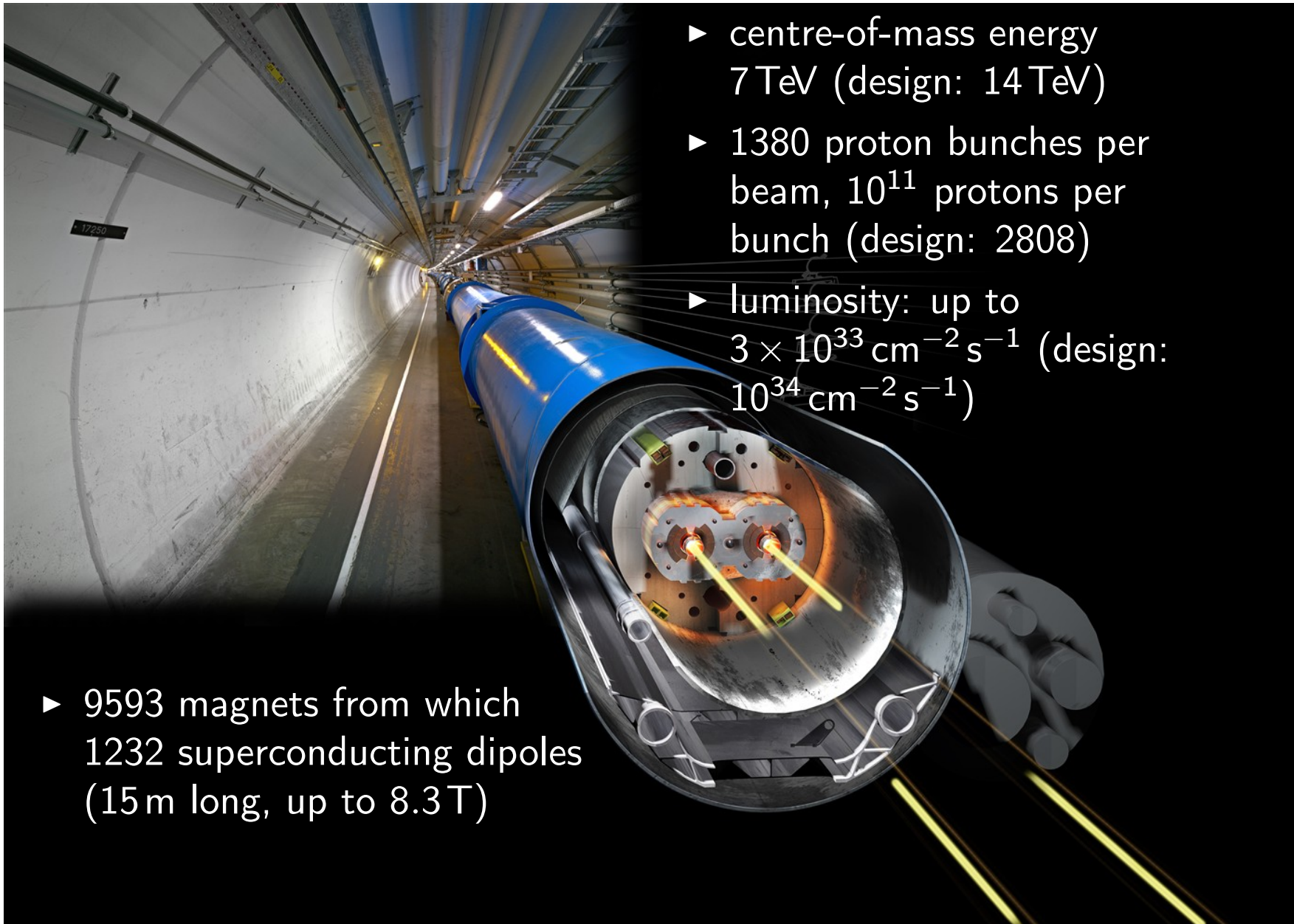

- centre-of-mass energy 7 TeV (design: 14 TeV)
- 1380 proton bunches per beam, $10^{11}$ protons per bunch (design: 2808)
- luminosity: up to $3 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (design: $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)
- 9593 magnets from which 1232 superconducting dipoles (15 m long, up to 8.3 T)


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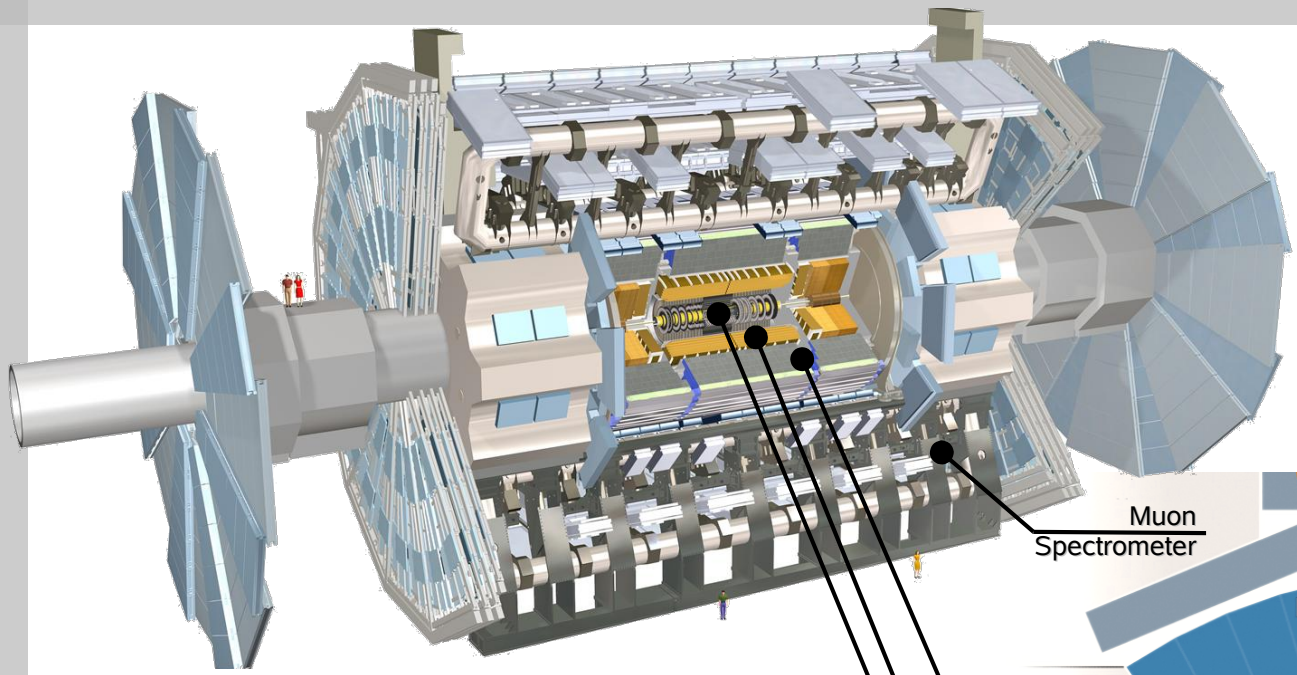
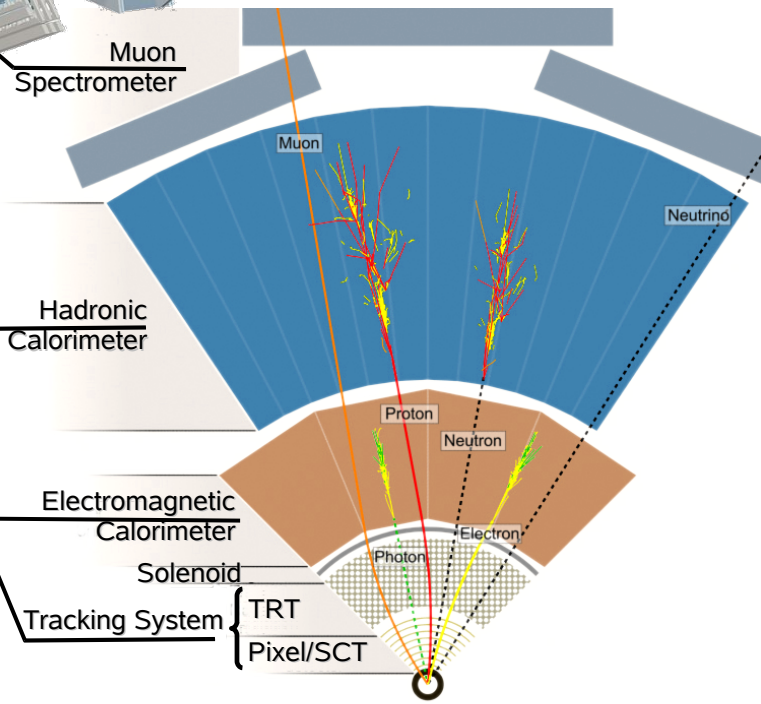
# The ATLAS detector







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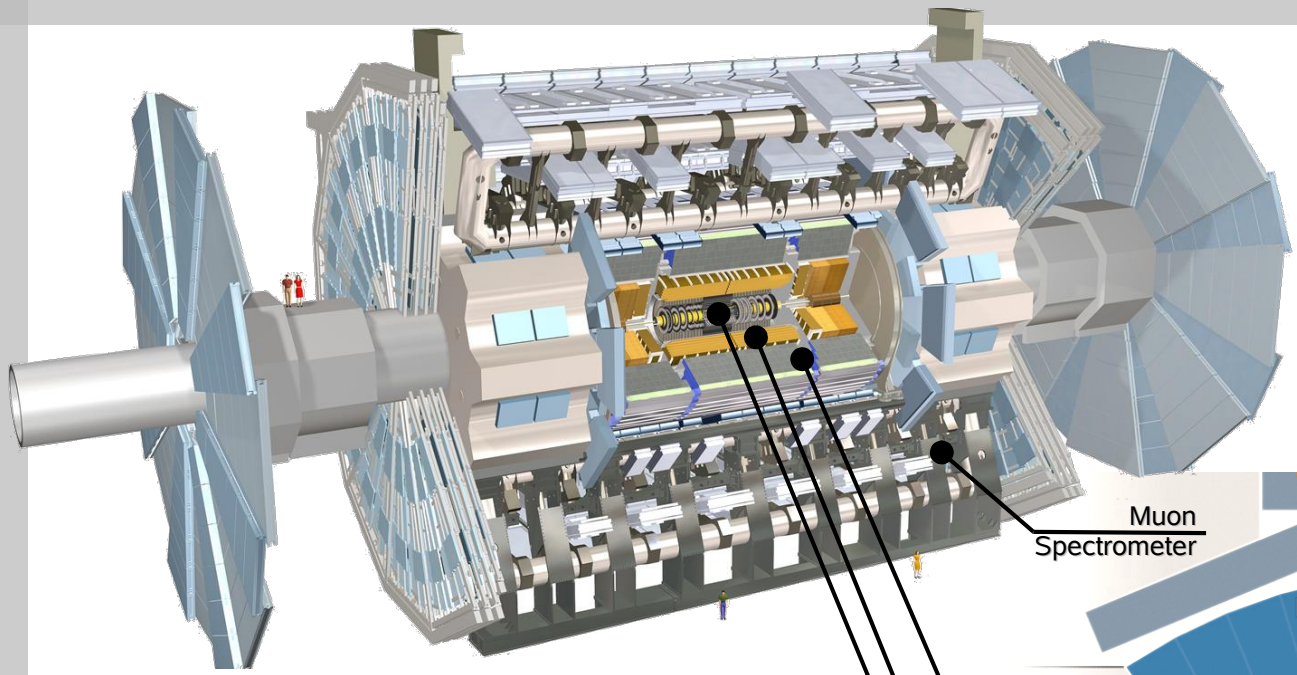
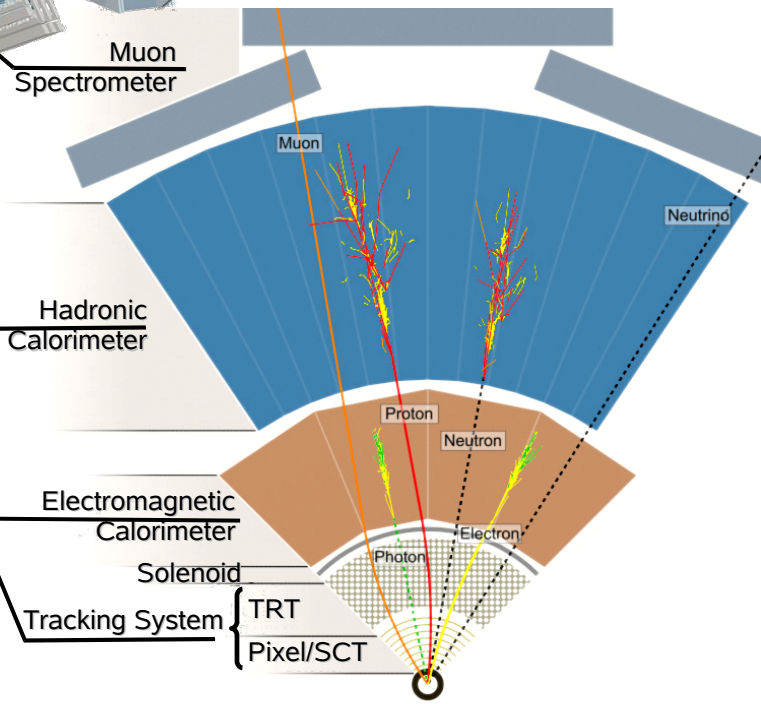
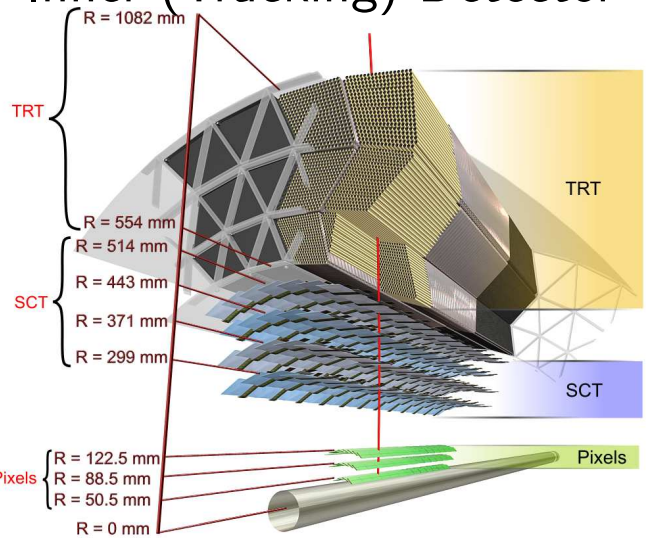





## Inner (Tracking) Detector



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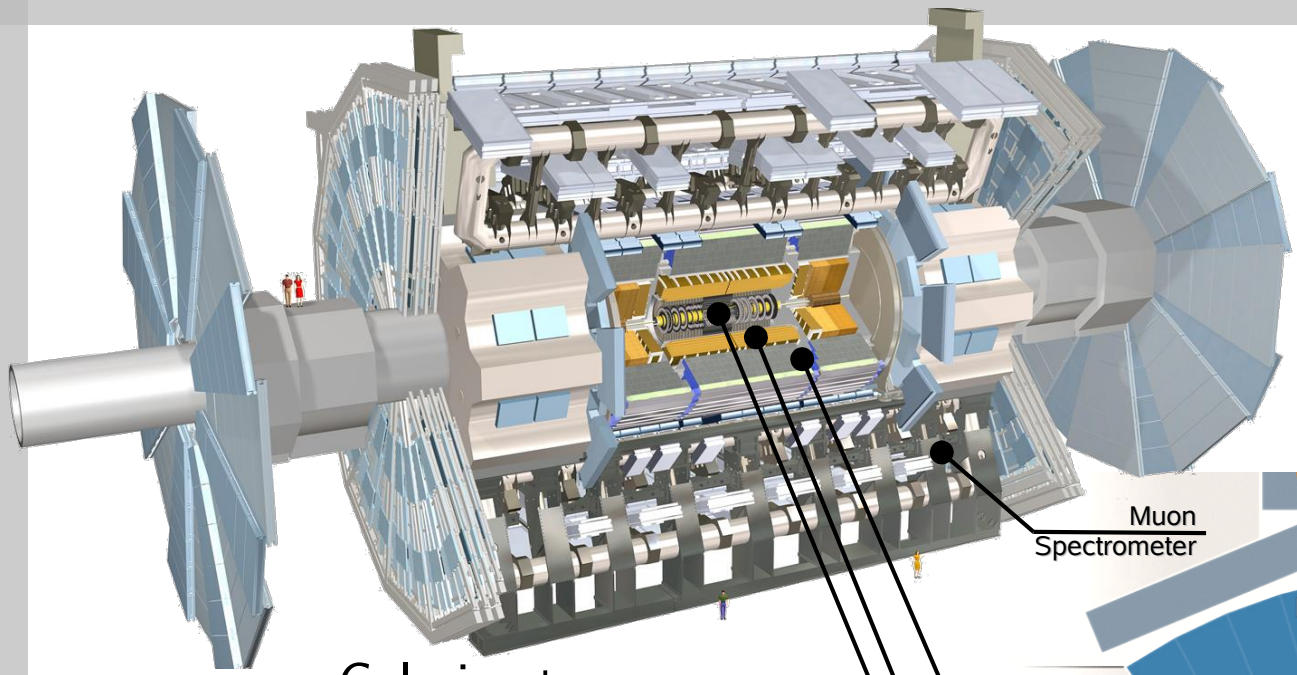
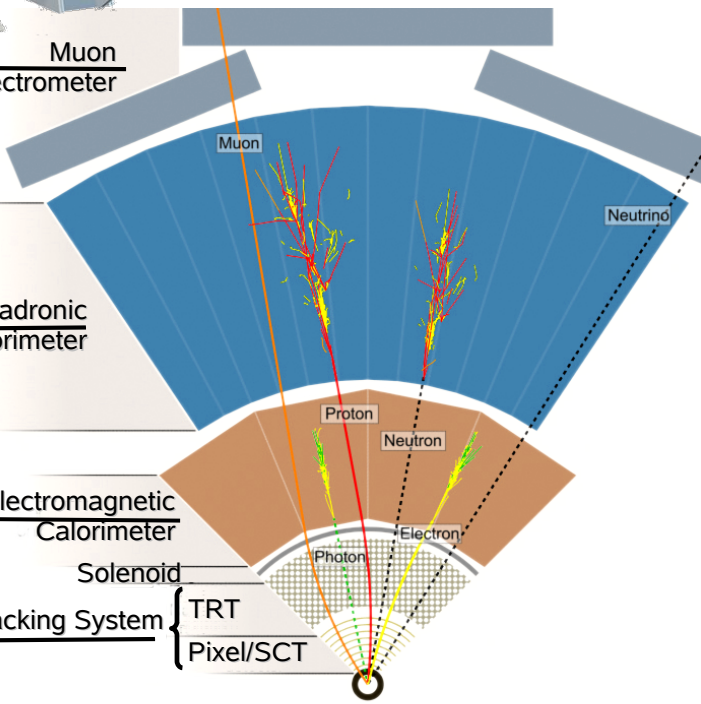
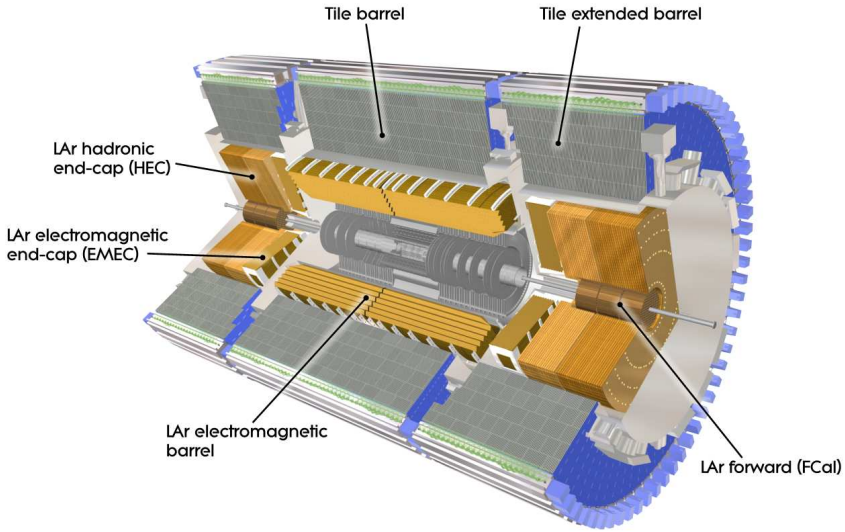





## Calorimetry



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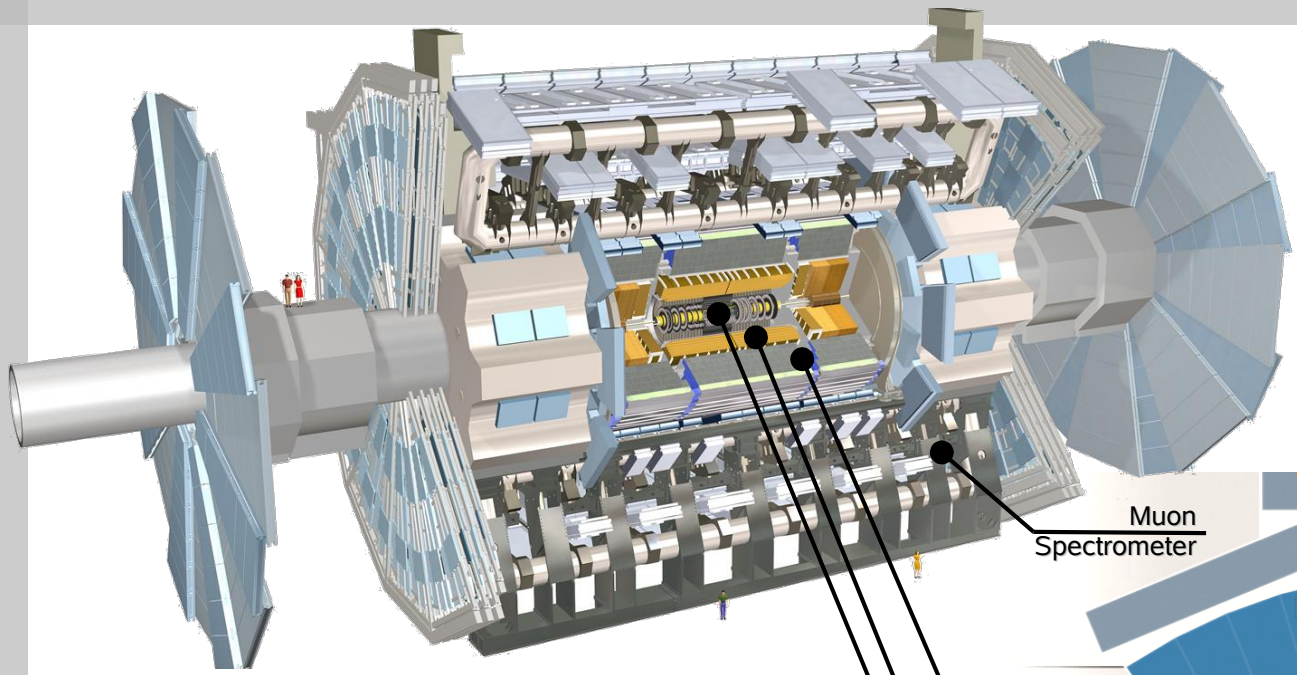
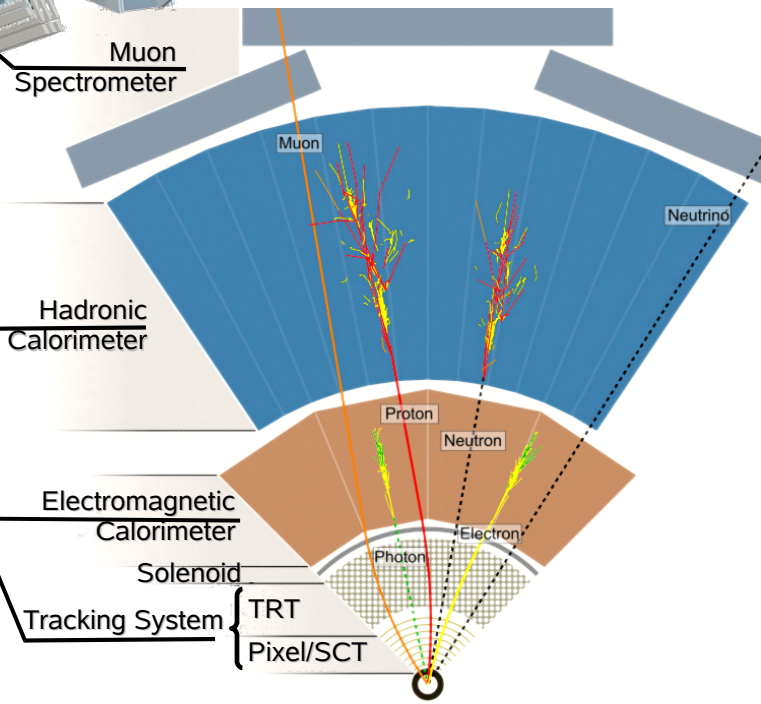
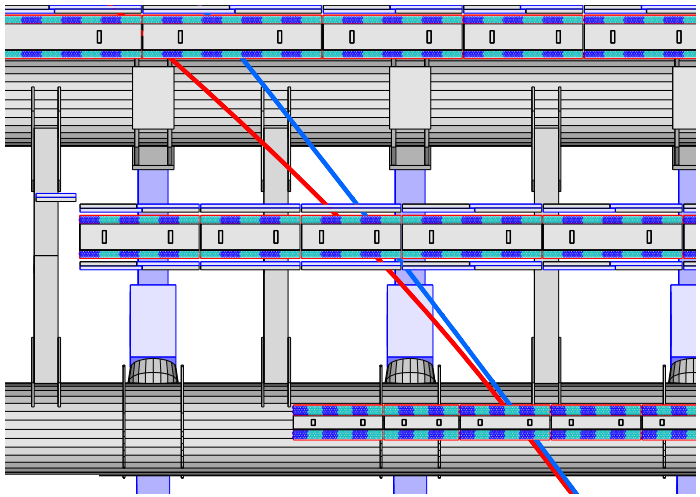





## Muon Spectrometer





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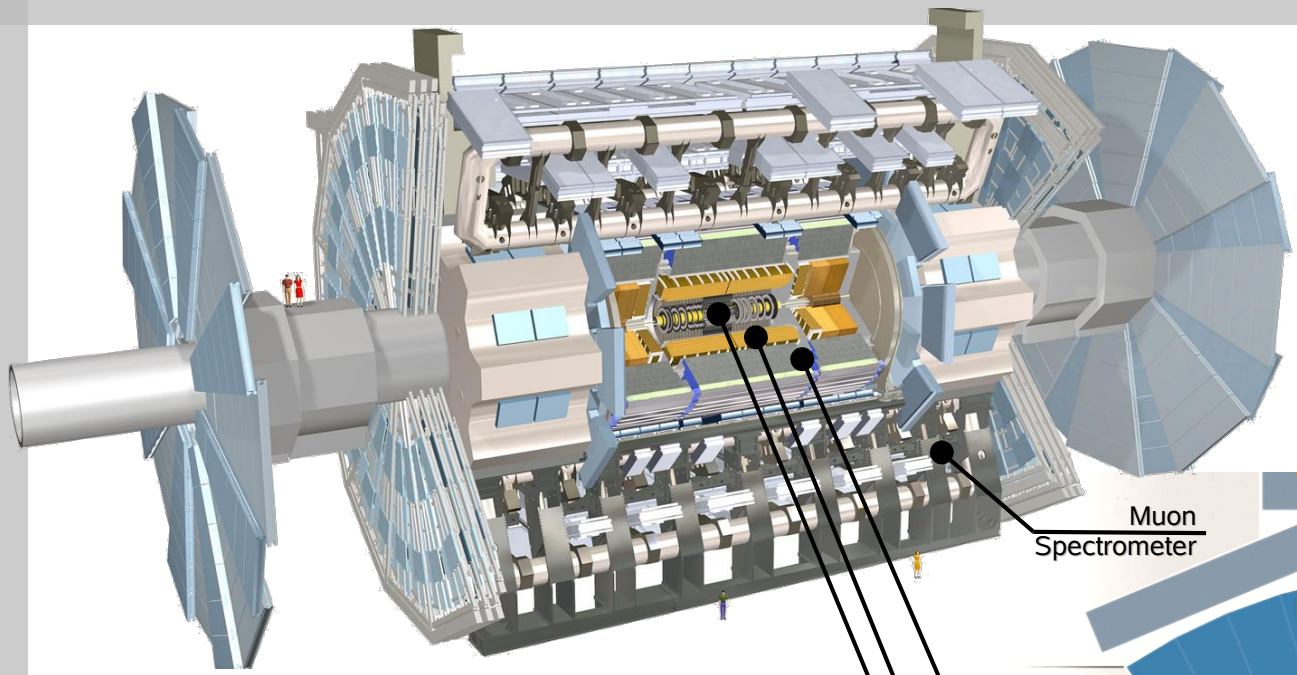
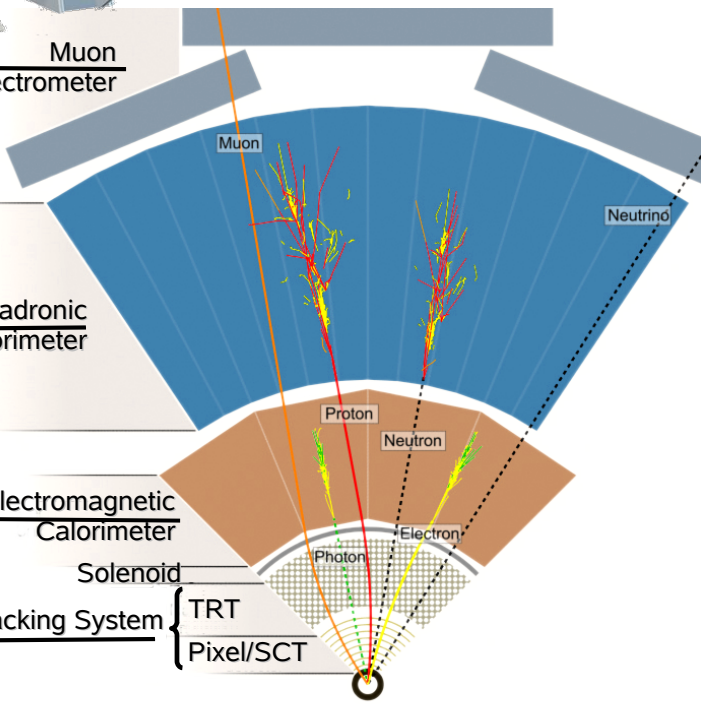
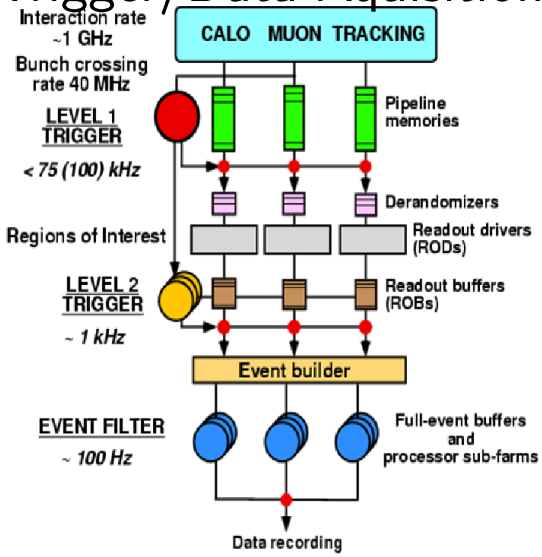





## Trigger/Data Aquisition



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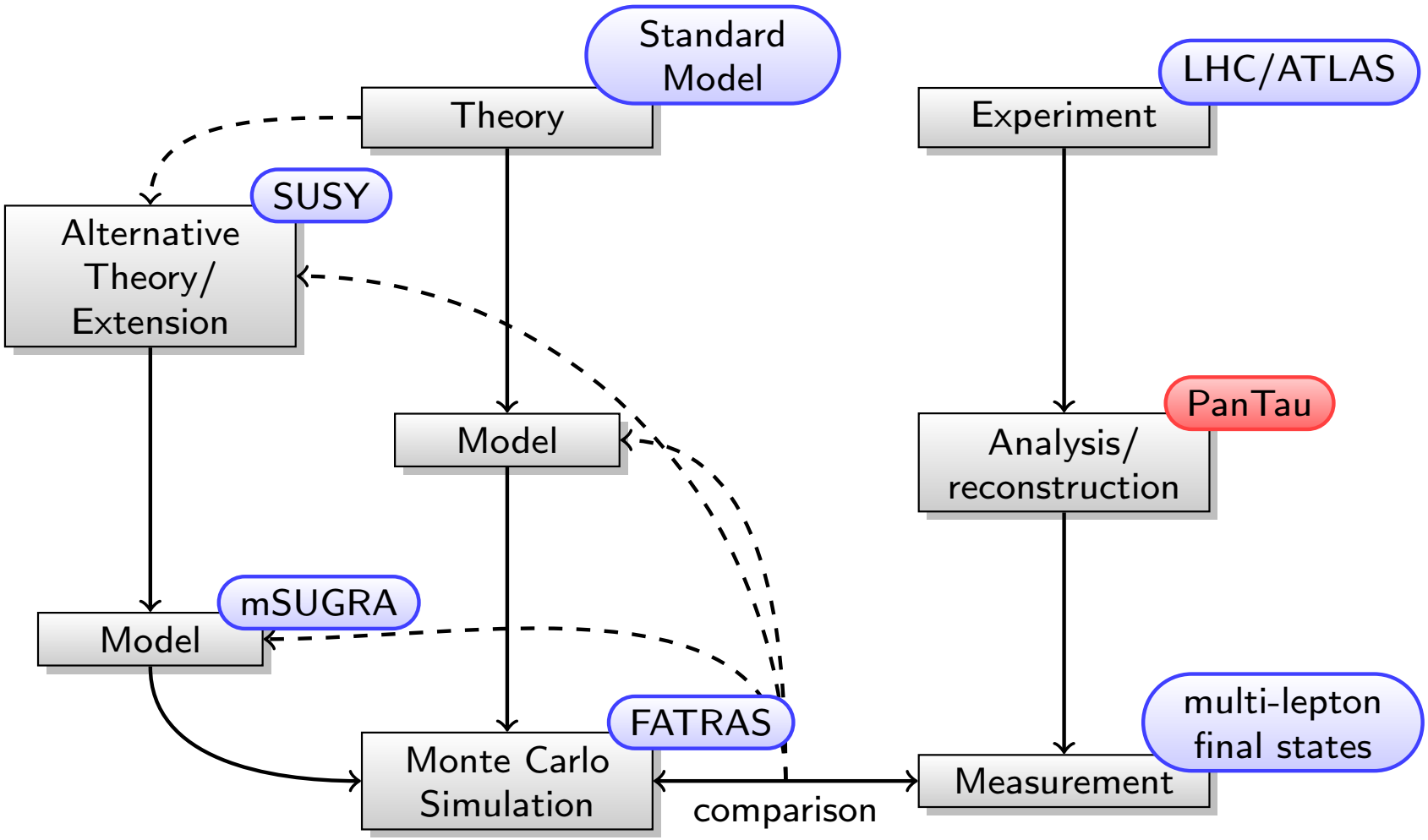
# Reconstruction of tau leptons





# General properties of $\tau$ leptons

- 3rd family "brother" of electron and muon

| | $e^{\pm}$ | $\mu^{\pm}$ | $\tau^{\pm}$ |
|---|---|---|---|
| mass $m$ (MeV) | 0.511 | 105.7 | 1777 |
| lifetime $\tau$ (s) | stable | $2.2 \cdot 10^{-6}$ | $2.9 \cdot 10^{-13}$ |
| $c \cdot \tau$ | | 659m | 87.1$\mu$m |

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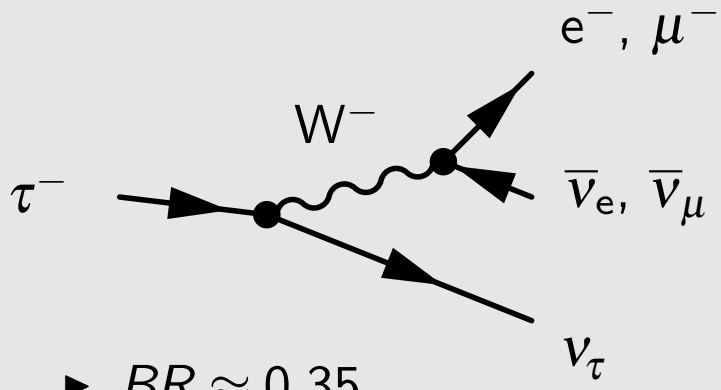
## Leptonic decays




- $BR \approx 0.35$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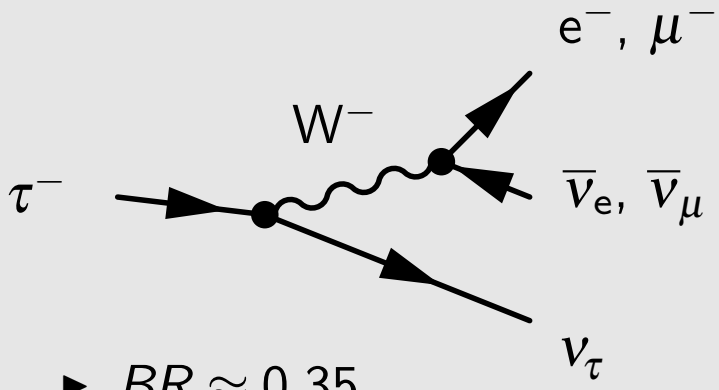


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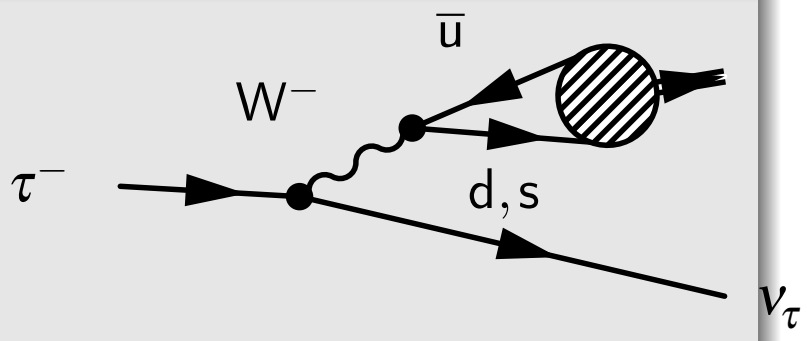
## Hadronic decays

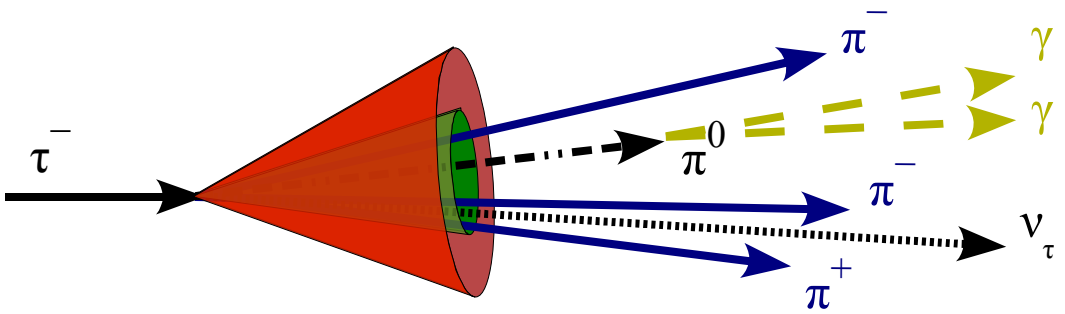



- decay via resonances ($\rho$, $a_1$, $K$, ...) into $\pi^{\pm}$ and $\pi^0$
- $BR \approx 0.65$

# Reconstruction of $\tau$ leptons



- Only hadronic $\tau$ decays are considered in this context



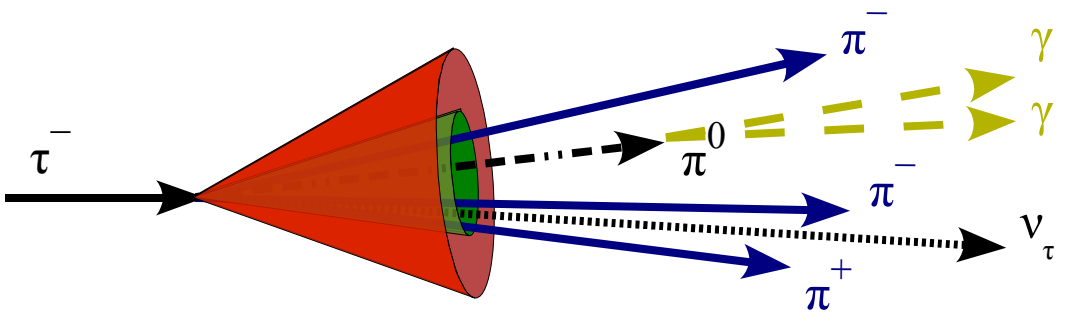
# Reconstruction of $\tau$ leptons



- Only hadronic $\tau$ decays are considered in this context

## (Inner Detector) Tracking

- Tracks from $\pi^{\pm}$
  - low multiplicity (1 or 3)
  - collimated
  - isolation from other tracks
- Secondary vertex



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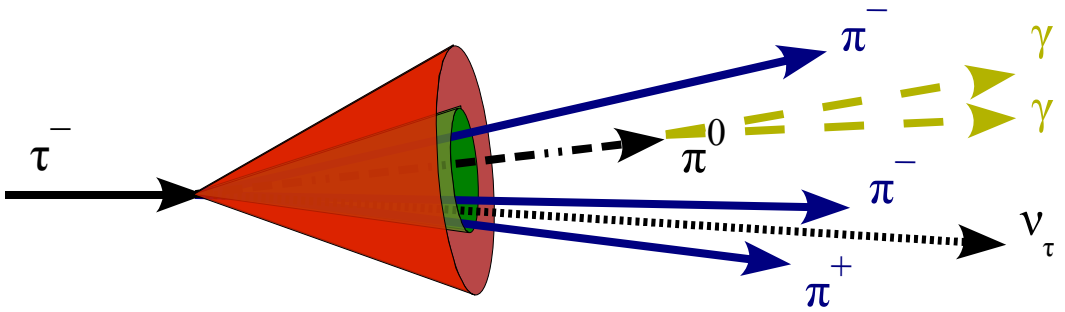
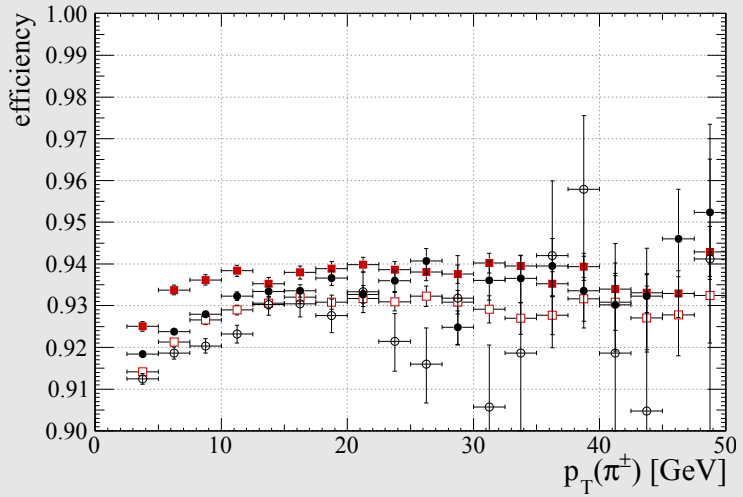
## Calorimetry

- Collimated energy deposit
- EM and HAD component
  - strong EM component for 1-prong
  - identify $\pi^0$ subclusters
- Isolation

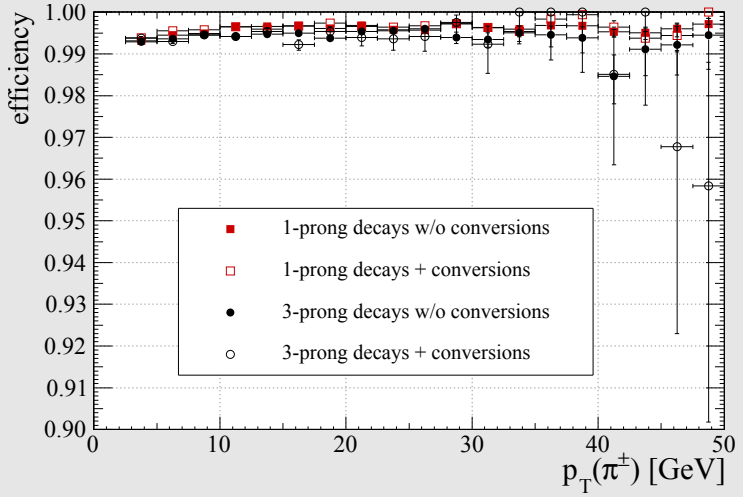


# Track reconstruction efficiency

- High track reconstruction efficiency for $\pi^{\pm}$ from $\tau$ decays is needed for
  - Reliable charge reconstruction
  - $\tau$ decay mode identification




including hadronic interactions



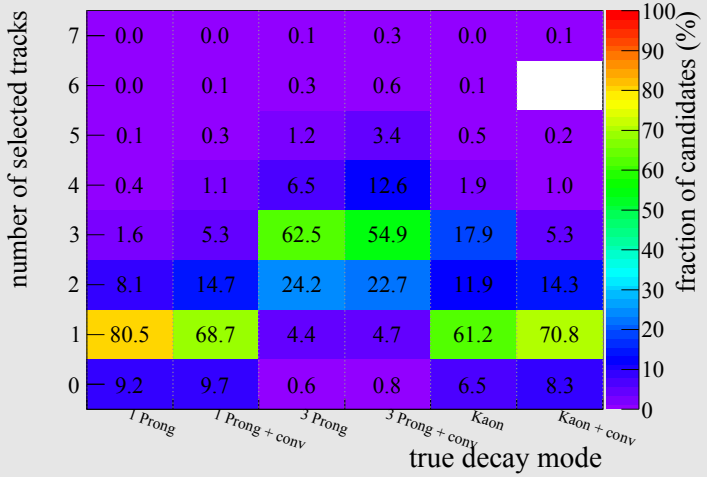

w/o hadronic interactions

- missing tracks mainly due to hadronic interactions in the Inner Detector
- Problem: Additional tracks due to converted $\gamma$ from $\pi^0 \rightarrow \gamma\gamma$: Needs track selection cuts

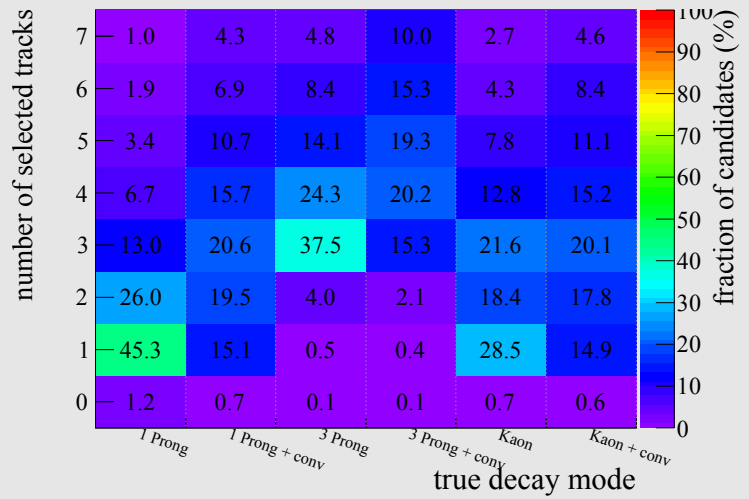
# Track selection criteria

## Number of selected tracks versus tau decay mode ($Z \to \tau\tau$)

### PanTau qualified selection

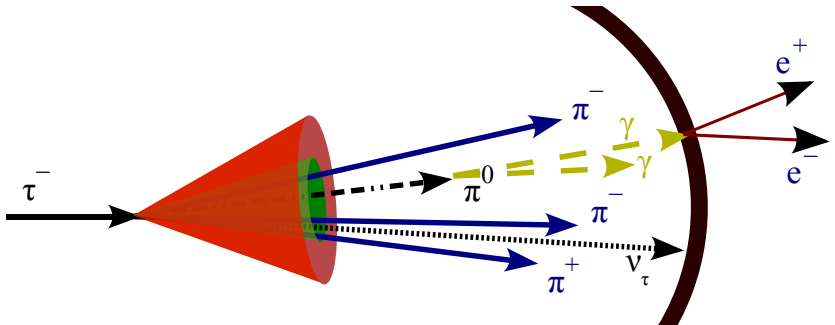



### all reconstructed tracks




| selection criteria | PanTau qualified |
|---|---|
| $p_T^{\text{min}}$ (GeV) | 1.0 |
| $\lvert d_0 \rvert$ (mm) | 2.0 |
| $\lvert z_0 \cdot \sin\theta \rvert$ (mm) | 10.0 |
| min. b-layer hits | 0 |
| min. Pixel hits | 2 |
| min. SCT hits | 0 |
| min. silicon hits | 7 |
| min. TRT hits | 0 |

- Track selection to reject fake tracks and photon conversions ($\gamma \to e^- e^+$)



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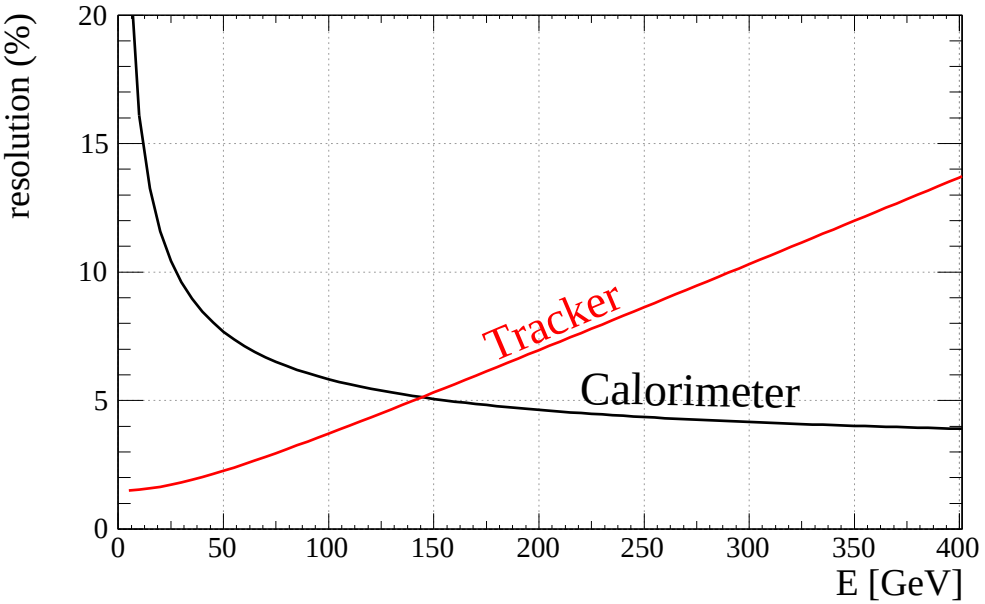
# Why Energy Flow Algorithms?

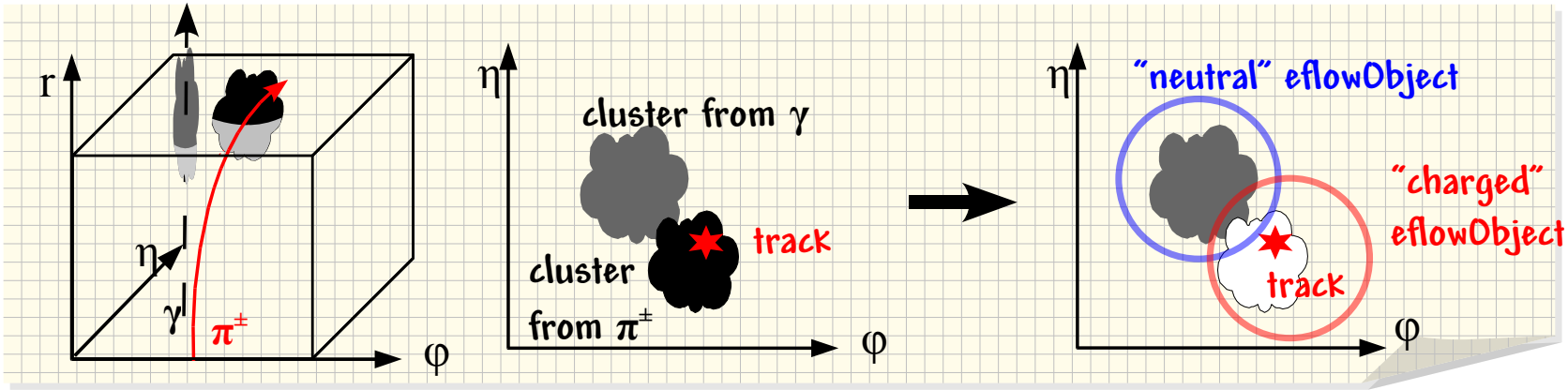



- Up to moderate $\pi^{\pm}$ momenta the energy resolution of the tracker is better than the calorimetry
- Try to combine both measurements

# Energy Flow Algorithms



- Physics motivated approach to combine tracking and calorimetry
- Use tracking data for charged particles and calorimeter data only for neutrals
- Therefore: Subtract energy deposition of charged particles from calo clusters
- (Main-) error: "Double counting" of energy deposits due to wrong assignments



# Tau identification with PanTau



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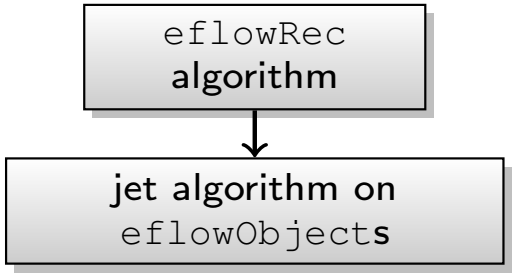

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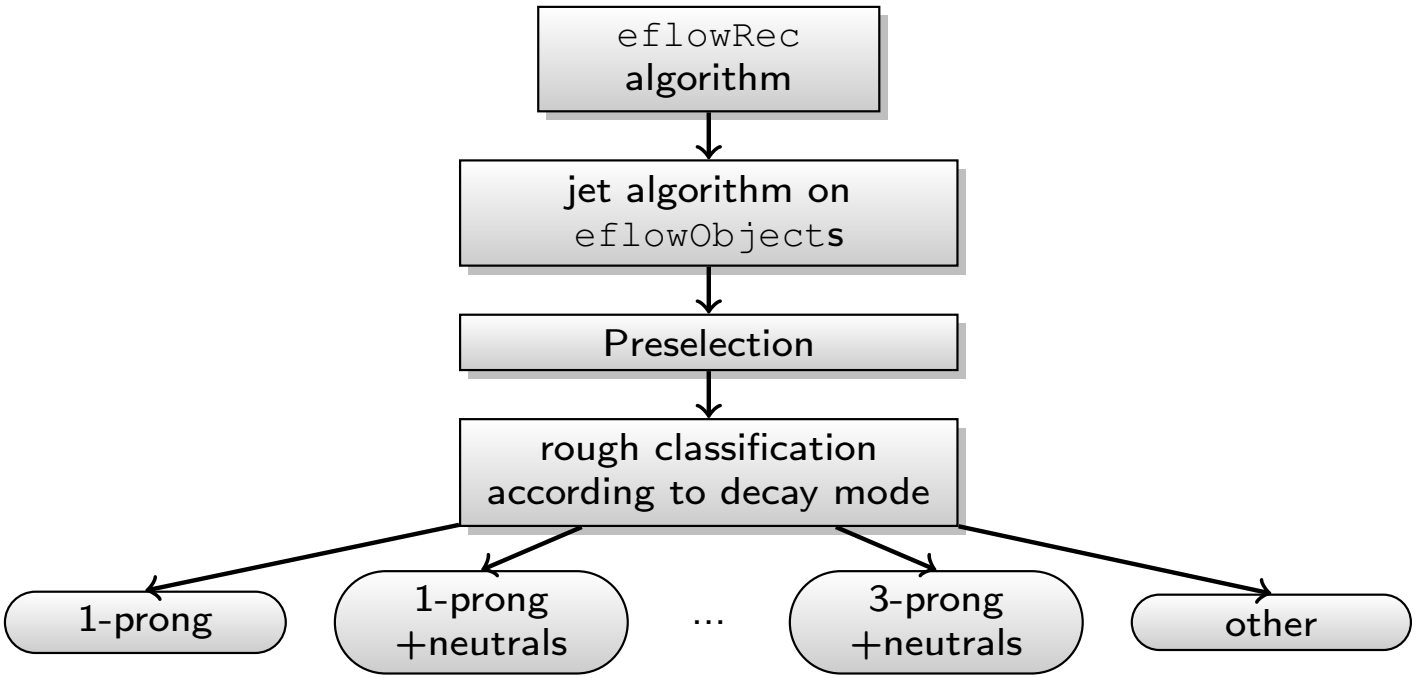

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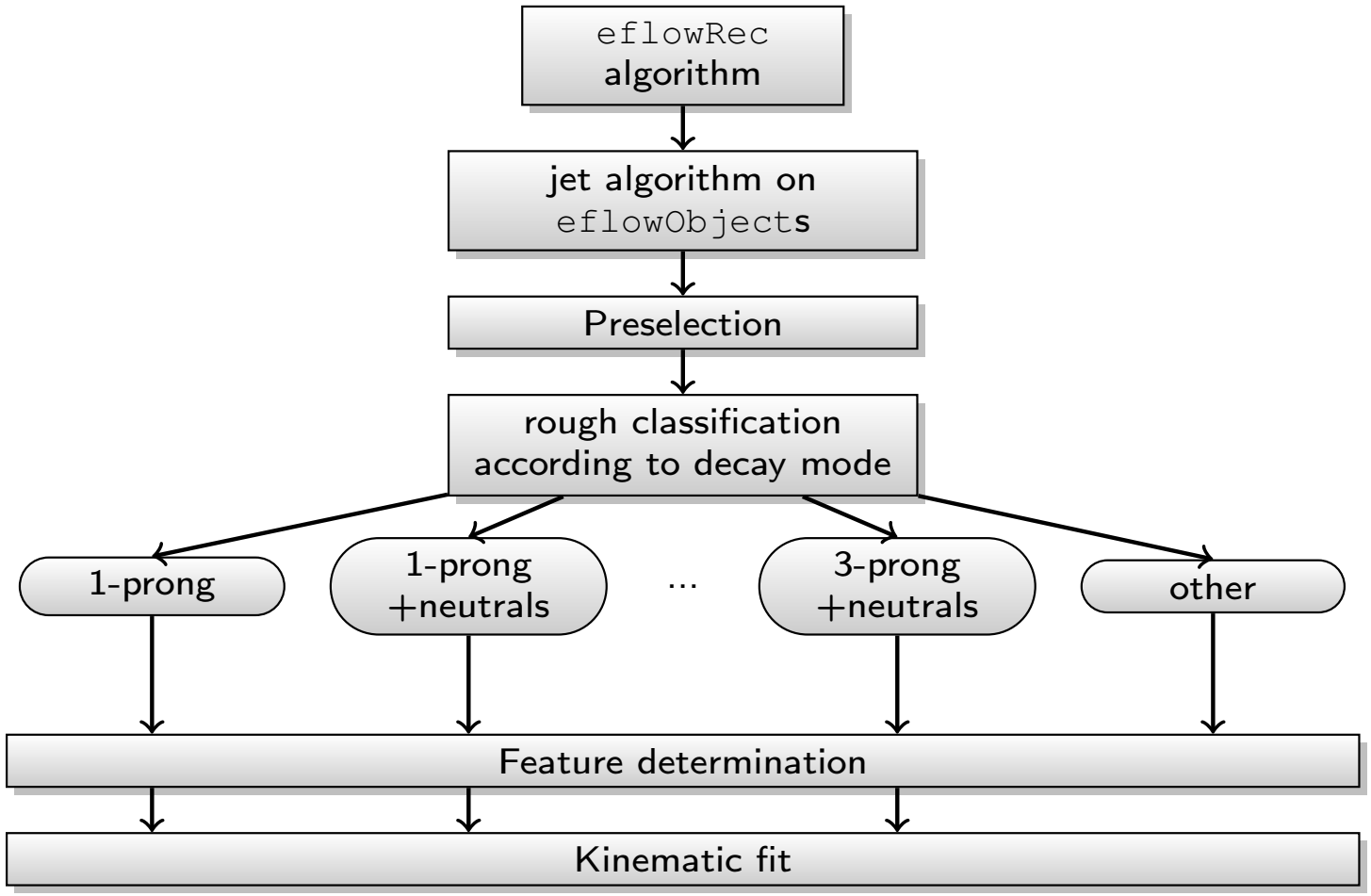

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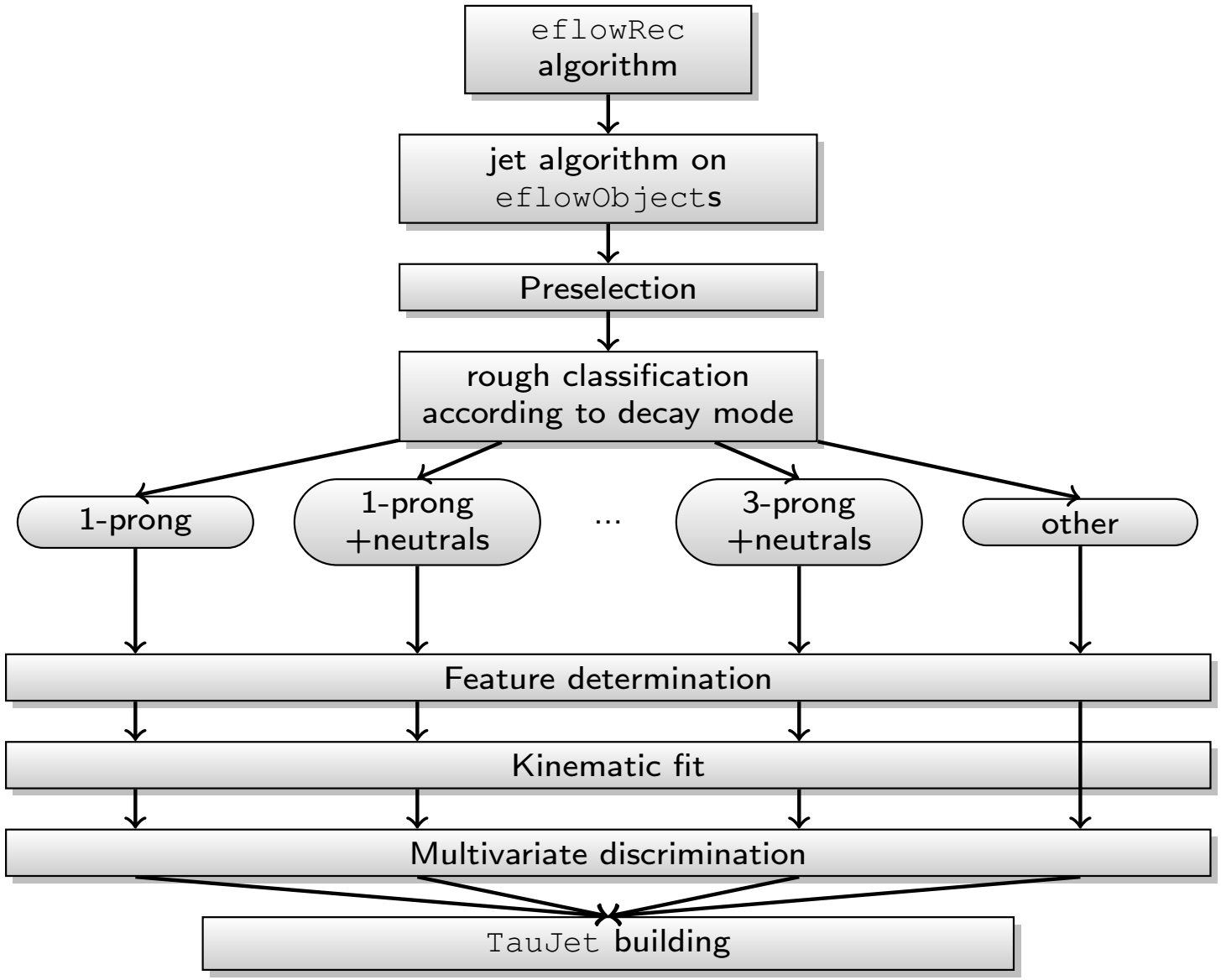
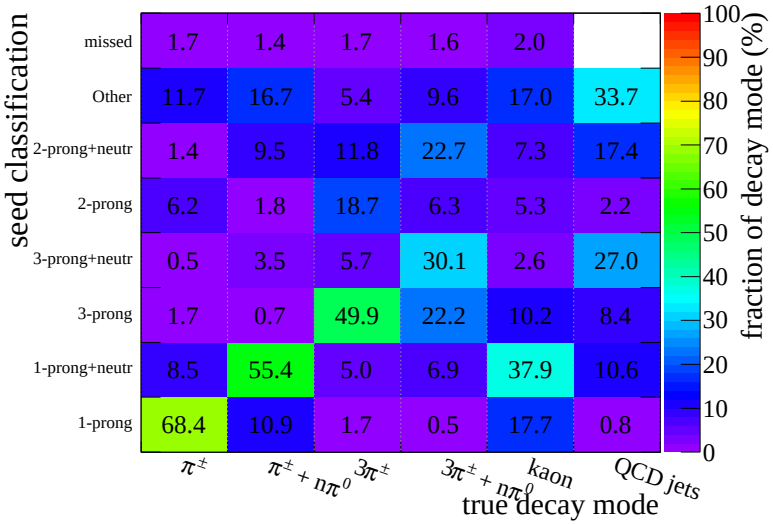
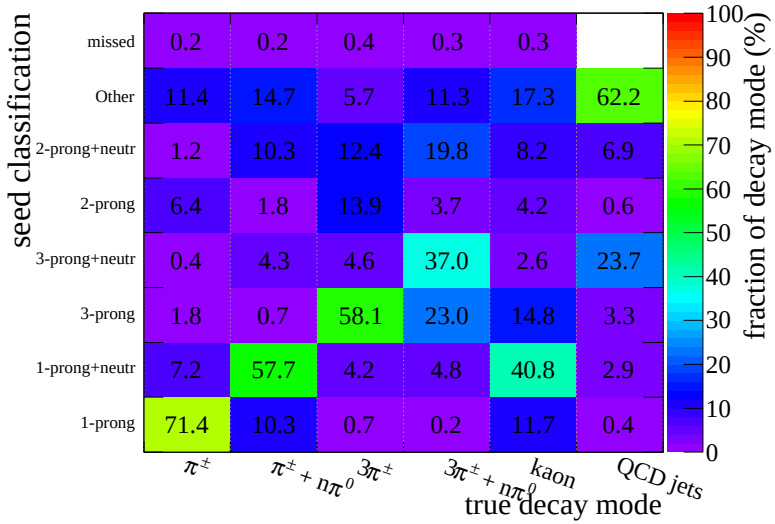


# Decay mode estimation



- One aim of PanTau was a good identification of the tau decay mode
- Feature extraction, ID, etc. is done decay mode specific




$10\,\text{GeV} < p_T^{\text{vis}} < 25\,\text{GeV}$ $25\,\text{GeV} < p_T^{\text{vis}} < 100\,\text{GeV}$

PanTau candidates in $W \to \tau\nu$ and $Z \to \tau\tau$ (resp. QCD) events with $|\eta^{\text{vis}}| < 2.0$



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# Tau identification variables in PanTau

## Variable: Energy spread of all energy flow objects

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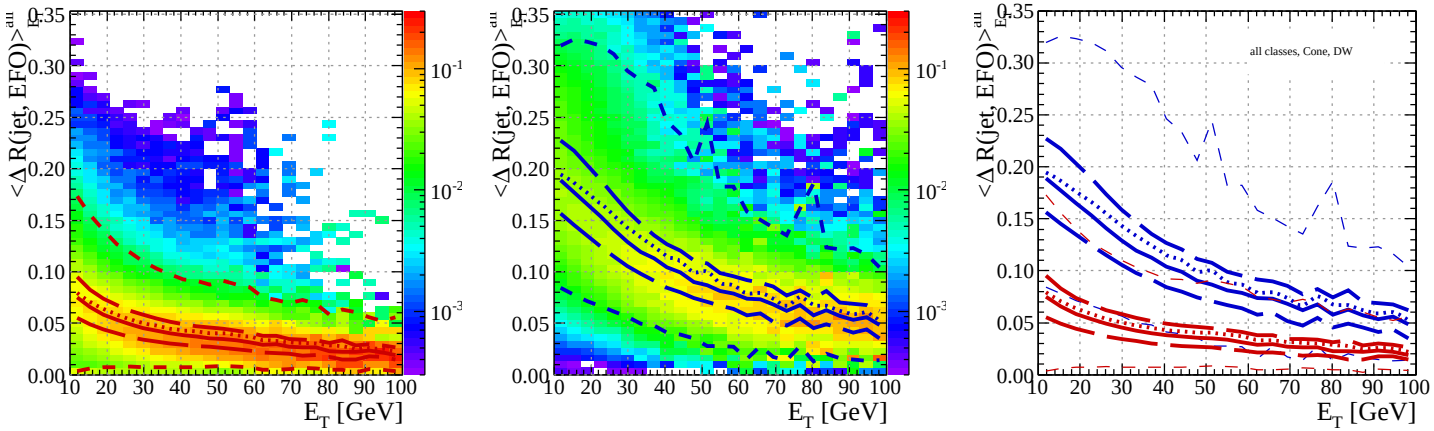
Define energy weighted mean distance of all energy flow objects in the jet as

$$\langle \Delta R(\text{jet}, \text{EFO}) \rangle^{\text{all}}_{E_T} = \frac{1}{\sum_{\text{EFO}} E_T^{\text{EFO}}} \sum_{\text{EFO}} E_T^{\text{EFO}} \cdot \Delta R(\text{jet}, \text{EFO})$$

- Different energy dependency of this variable for true taus (left, red) and QCD jets (middle, blue)




distribution normalised in $E_T$ bins, lines show mean, median and contours of 95%, 68.3%, 31.7% and 5% of entries per $E_T$ bin

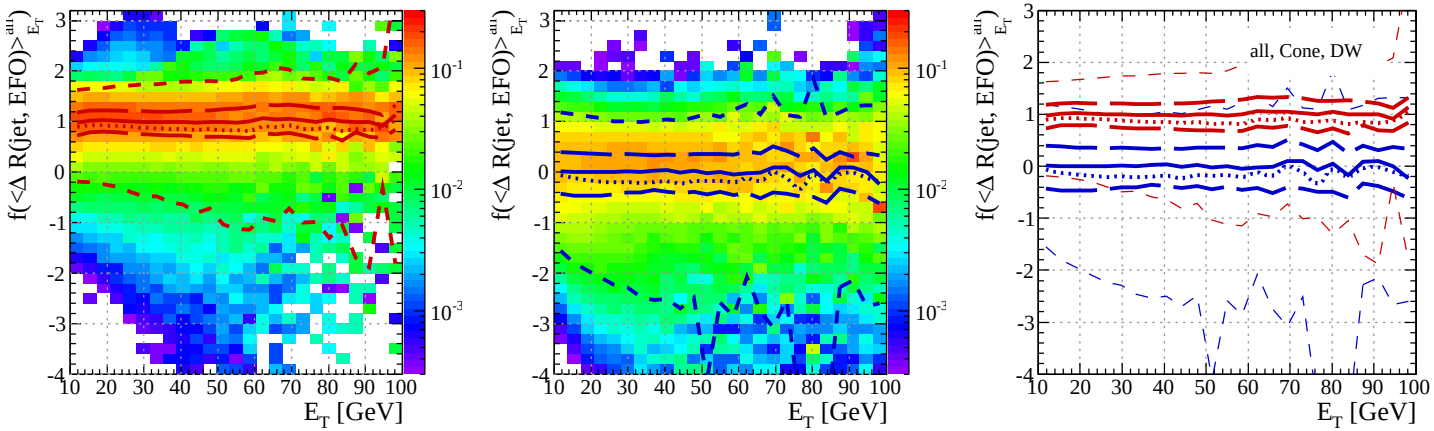
# Tau identification variables in PanTau

## Energy dependency and flattening

Flatten distribution by

$$x' = f(x) = \frac{x - B(E_T)}{S(E_T) - B(E_T)} = \frac{x - \sum_{n=0}^{4} b_n E_T^n}{\sum_{n=0}^{4} (s_n - b_n) E_T^n}$$

where the median of the tau ($S(E_T)$) and QCD jet ($B(E_T)$) distribution has been fitted with a fourth order polynomial




- Median and mean of resulting distribution flat in $E_T$, but still some dependency in width



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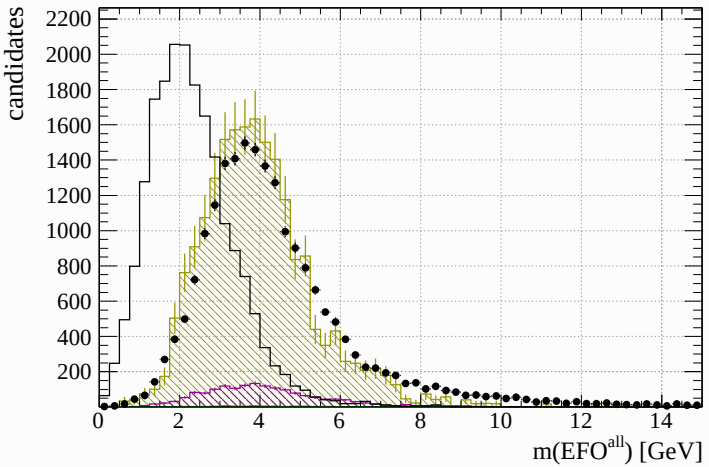
# Tau identification variables in PanTau

## Monte Carlo simulation and reality



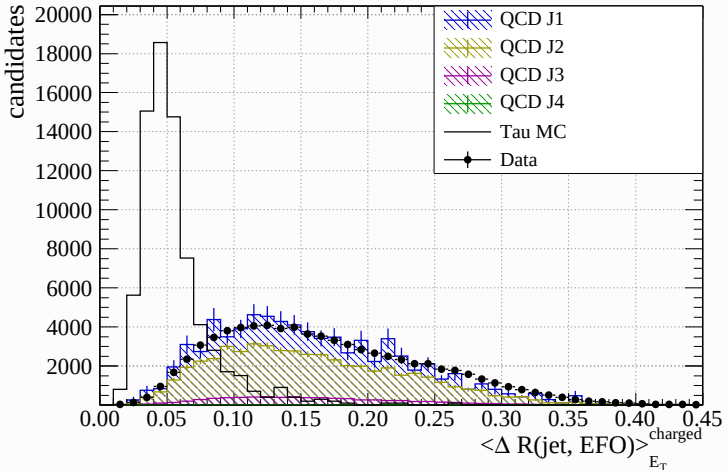
- ID variables fully based on energy flow objects (no direct usage of cells or clusters)
- Mostly reasonable agreement between data and Pythia Monte Carlo

### Invariant mass of energy flow objects (1-prong+neutral category)

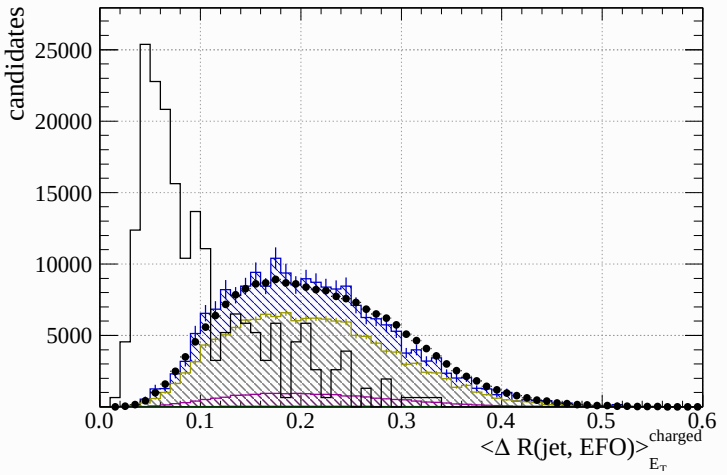



### $E_T$ weighted spread of charged EFOs

3-prong category




3-prong+neutral category



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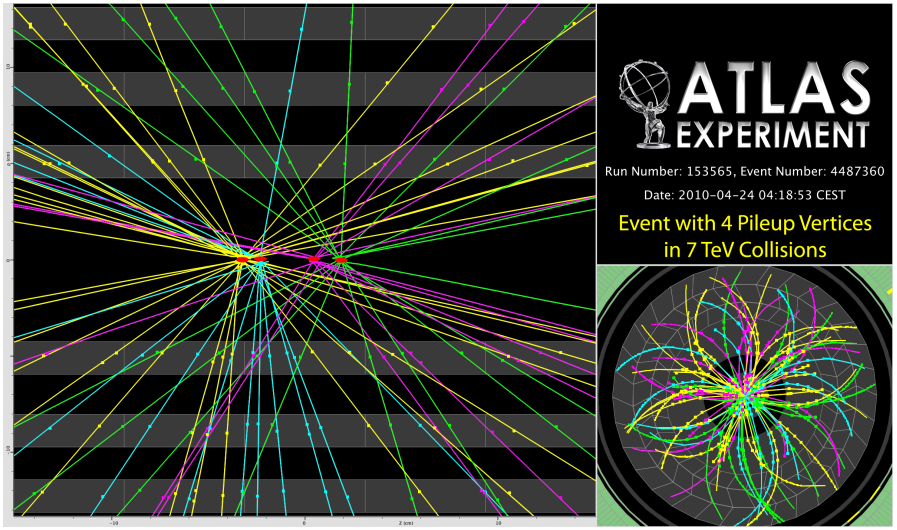
# Tau identification variables in PanTau

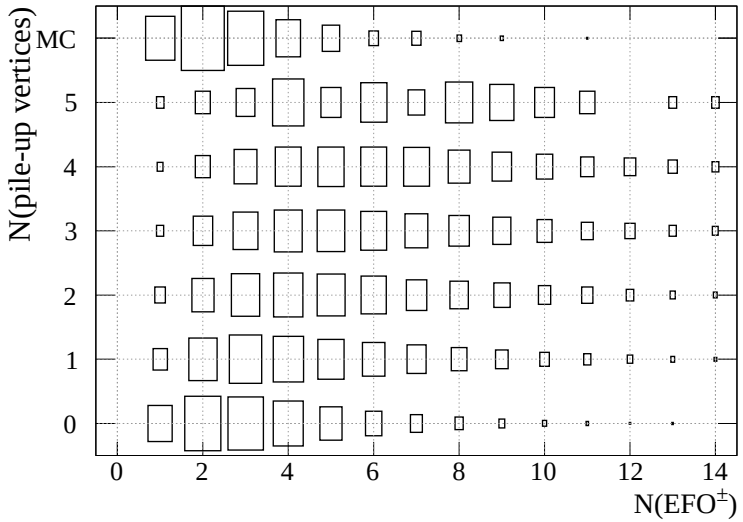
## Pile-up dependency

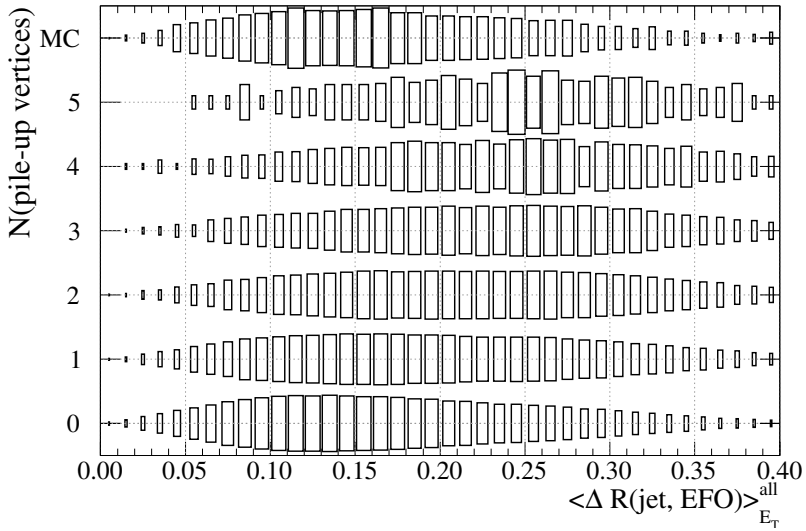


More than one proton-proton reaction may occur per bunch collision: "pile-up"

- Discrepancies between MC and data mainly due to pile-up
- PanTau variables can be made more "pile-up proof" by harder track selection



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# Performance of the tau identification

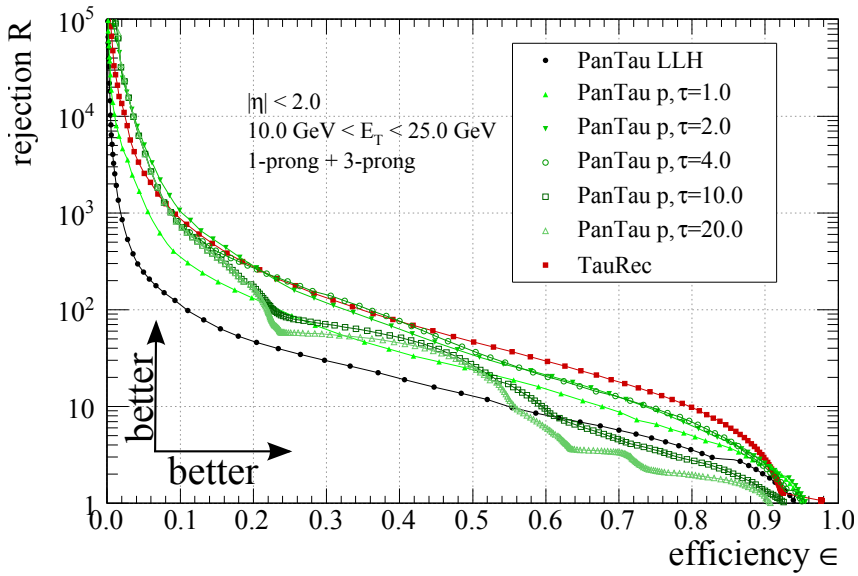
- Performance to identify hadronic tau decays given by tau efficiency and jet rejection

efficiency $\varepsilon_\tau = N(\text{tagged candidates w/ truth match})/N(\text{true candidates})$,

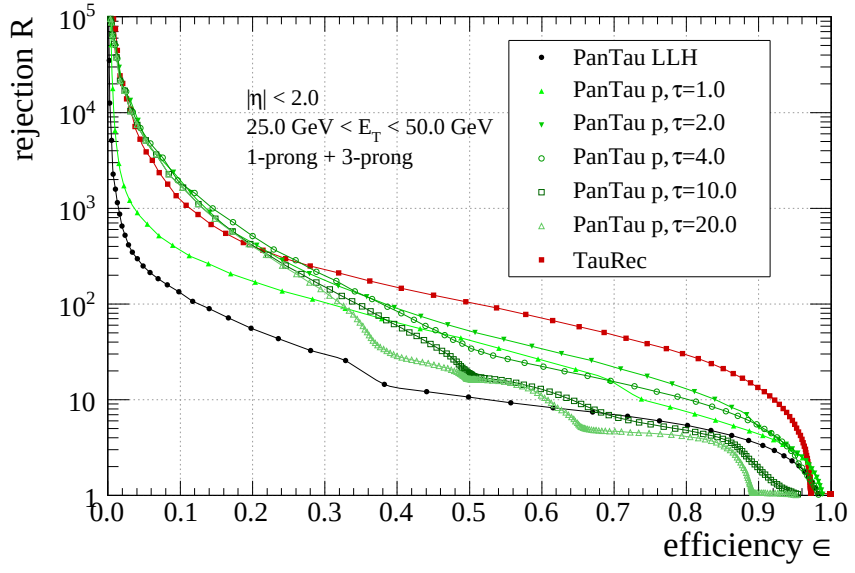
jet rejection $R = 1/\varepsilon_{\text{jet}} - 1$ with $\varepsilon_{\text{jet}} = N(\text{tagged w/o match})/N(\text{truth jets})$

- Combination of decay mode categories crucial to obtain good results

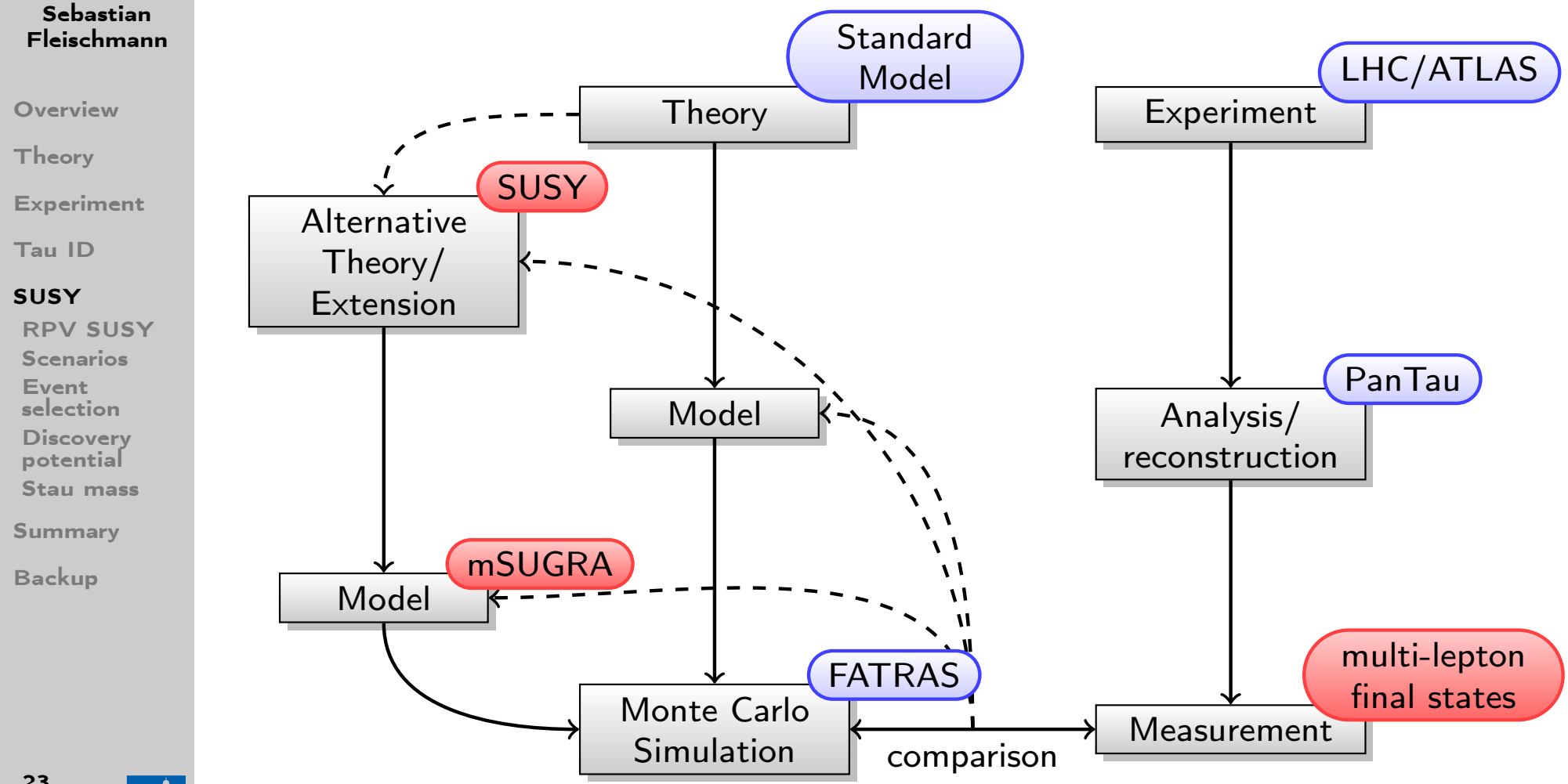
$10\,\text{GeV} < E_T < 25\,\text{GeV}$




$25\,\text{GeV} < E_T < 50\,\text{GeV}$



# Supersymmetry



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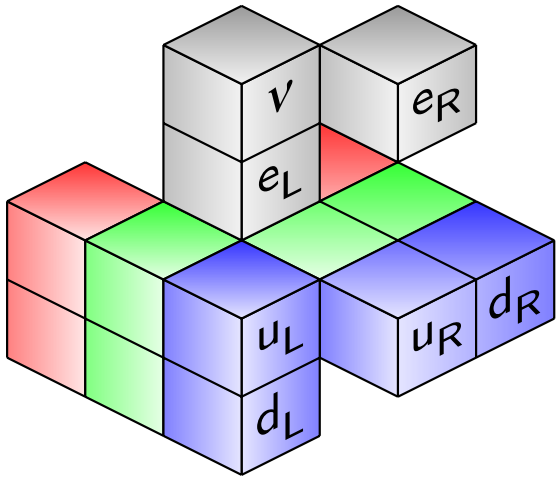
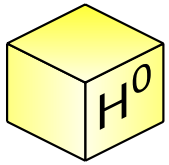
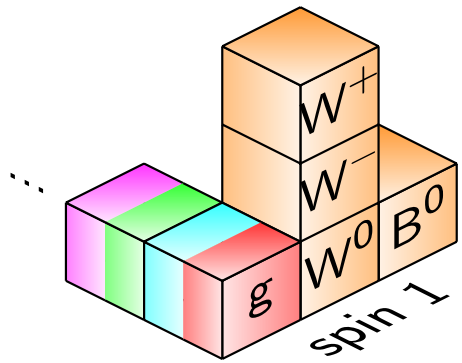
# The Standard Model of Particle Physics

... and its supersymmetric extension




spin 1/2

spin 0



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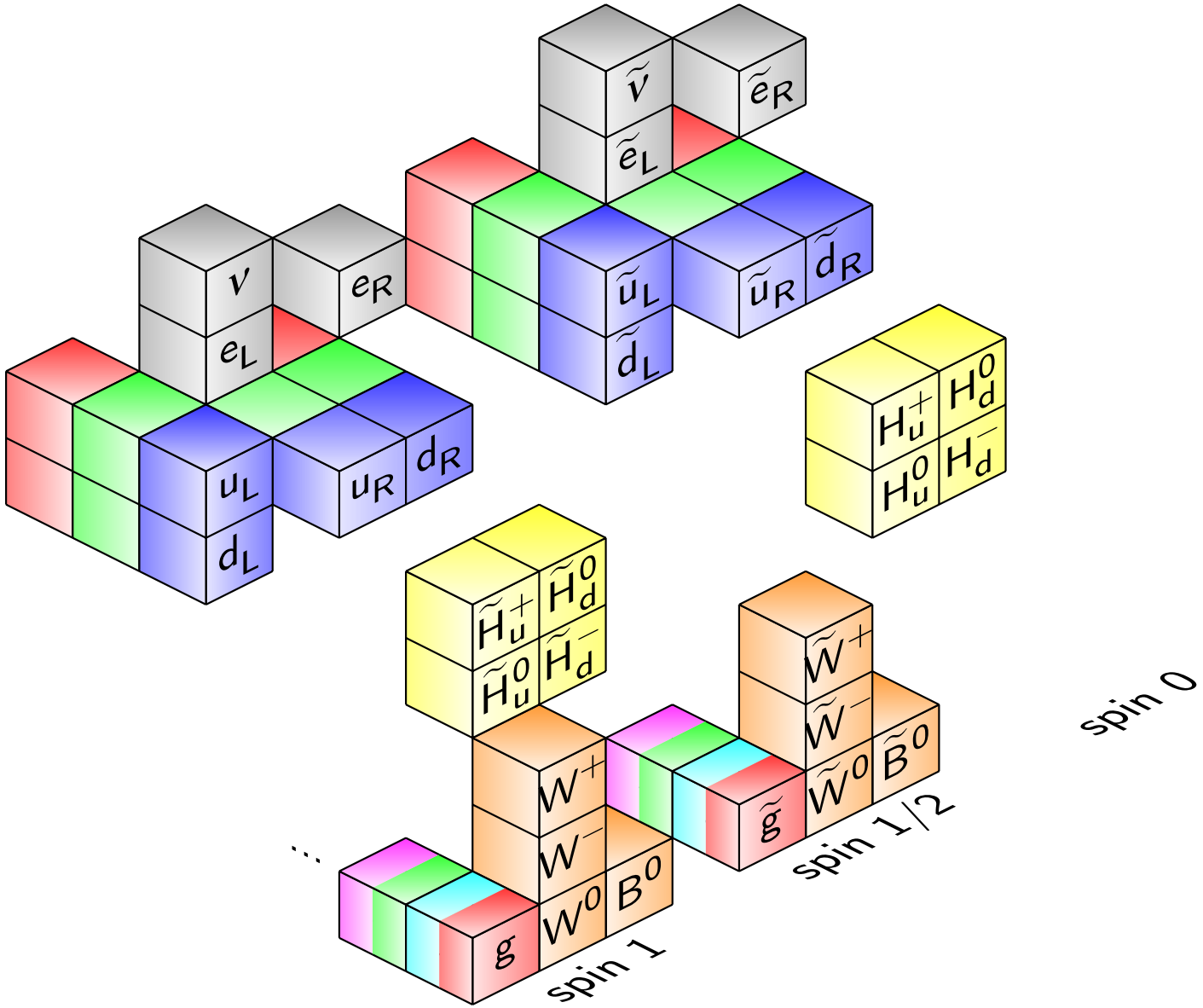




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Promotions-kolloquium

Sebastian Fleischmann

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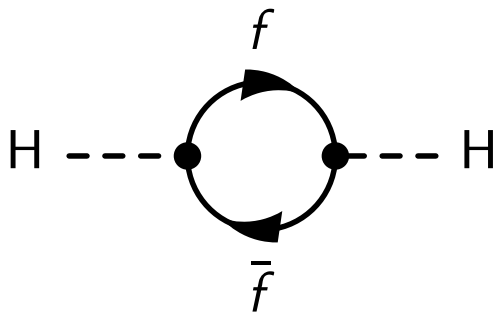
Supersymmetry (SUSY): Fundamental symmetry between fermions and bosons

- Solves hierarchy problem of the Higgs-mass by cancellation of fermion and boson loop contributions



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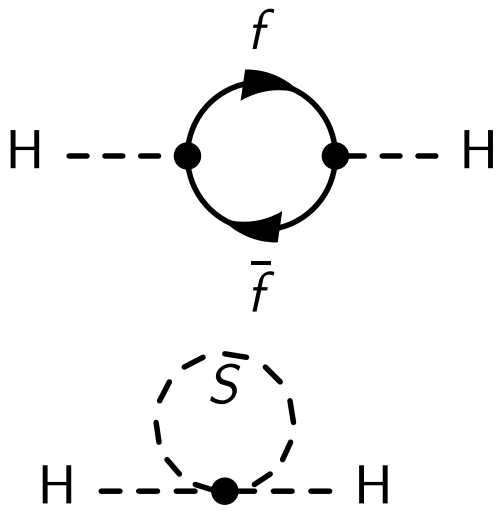

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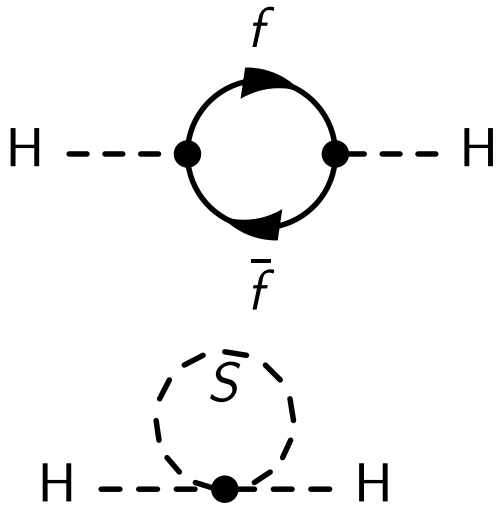
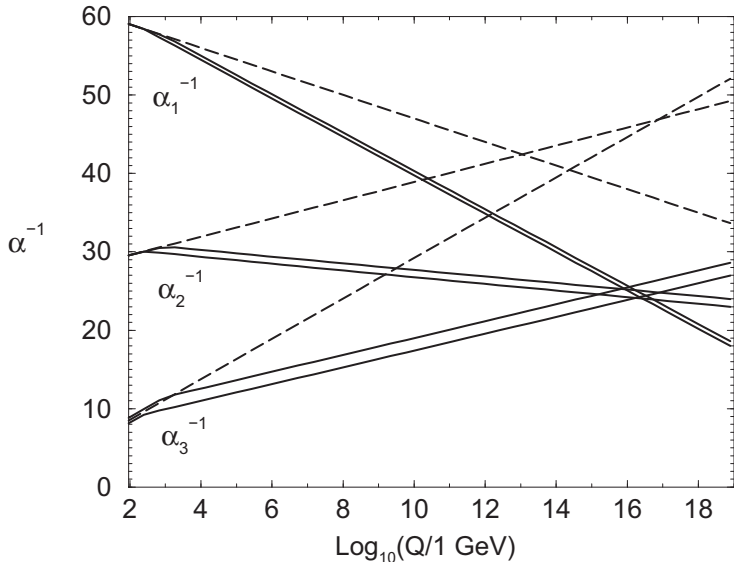


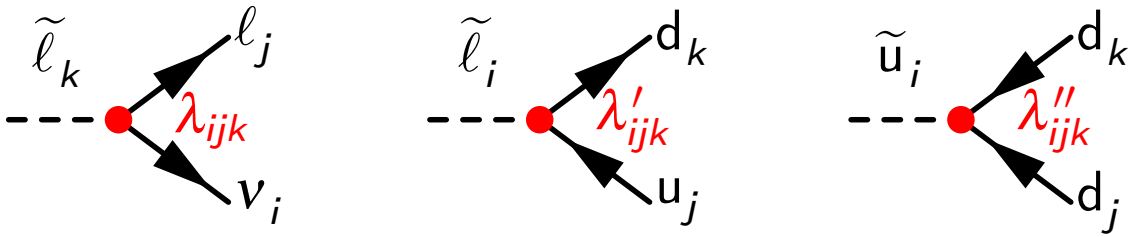

- Yields unification of gauge couplings at $M_X \approx 10^{16}$ GeV in its simplest model: First step towards Grand Unified Theory

# Proton decay, $R$-parity and its consequences

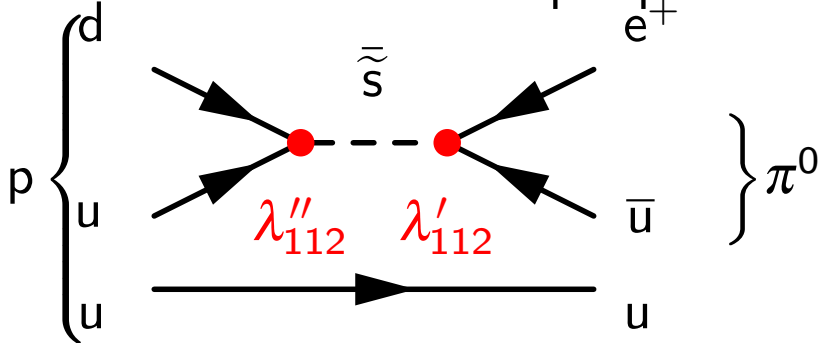
Most general interaction terms give baryon ($B$) and lepton number ($L$) violating couplings

$$W_{R_p} = (\mathbf{Y}_E)_{ij}\, L_i H_1 \bar{E}_j + (\mathbf{Y}_D)_{ij}\, Q_i H_1 \bar{D}_j + (\mathbf{Y}_U)_{ij}\, Q_i H_2 \bar{U}_j + \mu H_1 H_2$$

$$W_{\not{R}_p} = \frac{1}{2}\underbrace{\lambda_{ijk} L_i L_j \bar{E}_k}_{\text{violates } L} + \underbrace{\lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{violates } L} + \frac{1}{2}\underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{violates } B} - \underbrace{\kappa^i L_i H_2}_{\text{violates } L}$$




- $\Delta B$ *and* $\Delta L$ leads to rapid proton decay, *e.g.*



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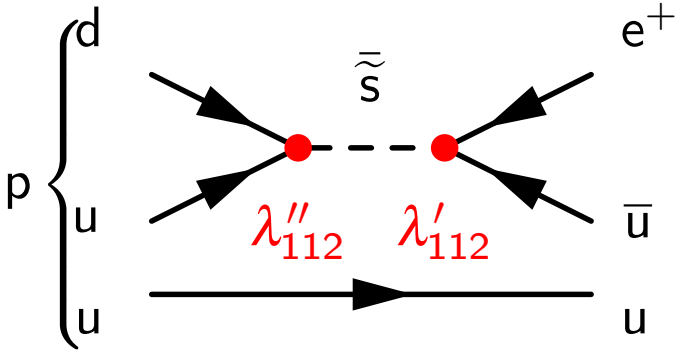
# $R$-parity and its consequences



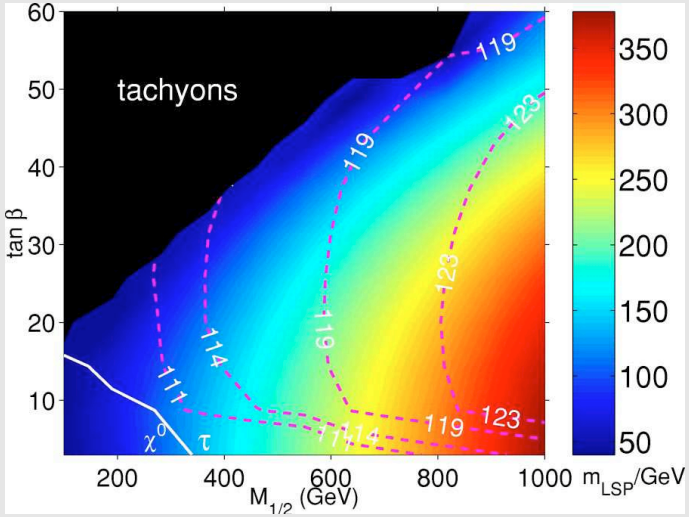

- Common solution: $R$-parity ($R = (-1)^{3(B-L)+2s}$)
  - Lightest Supersymmetric Particle (LSP) stable $\Rightarrow$ needs to be neutral by cosmological constraints $\Rightarrow \not{E}_T$ signature in collider experiments
  - Sparticles pair produced in collider experiments
- Sufficient to avoid $\Delta L \neq 0$ and $\Delta B \neq 0$ at the same time, to keep proton stable $\Rightarrow$ $R$-parity violation
  - Lightest Supersymmetric Particle (LSP) no longer stable
    - LSP may be charged
  - Depending on RPV couplings very different signatures in collider experiments
    - Long-lived massive particles
    - Exotic bound states ($R$-hadrons)
    - Prompt decays

# Benchmark scenarios in $\not{R}_p$ mSUGRA



- $\widetilde{\tau}$ (superpartner of $\tau$ lepton) is LSP in wide range of mSUGRA parameter space
  - With conserved $R$-parity: excluded because of charge

## LSP in no-scale mSUGRA




Allanach, Dedes, Dreiner, Phys. Rev. D69 115002

mass and type of LSP in "no-scale mSUGRA"

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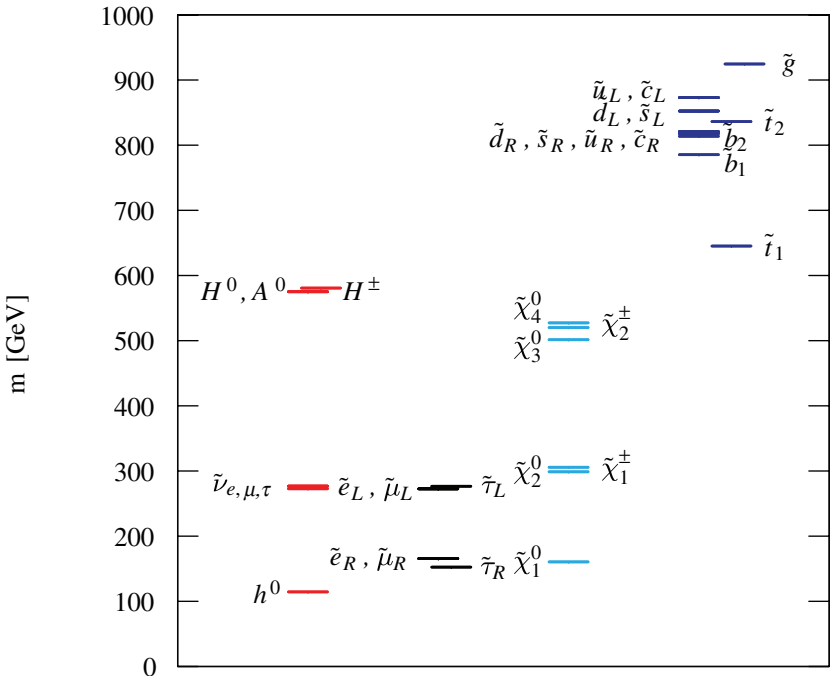
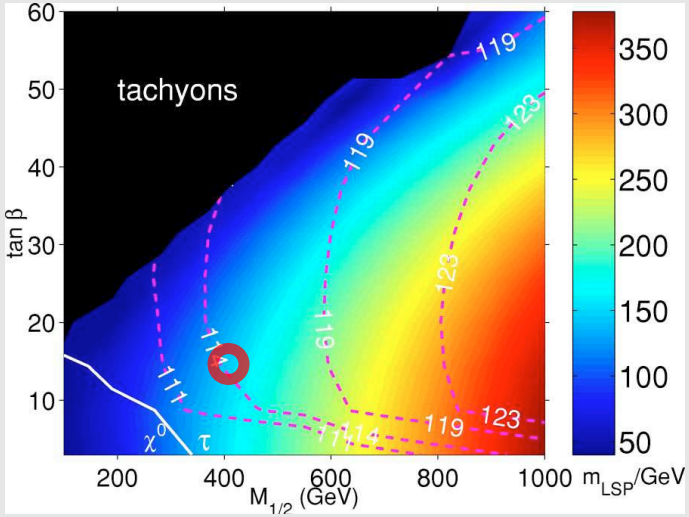



Allanach et al., Phys. Rev. D75 (2007) 035002

## LSP in no-scale mSUGRA




Allanach, Dedes, Dreiner, Phys. Rev. D69 115002

mass and type of LSP in "no-scale mSUGRA"



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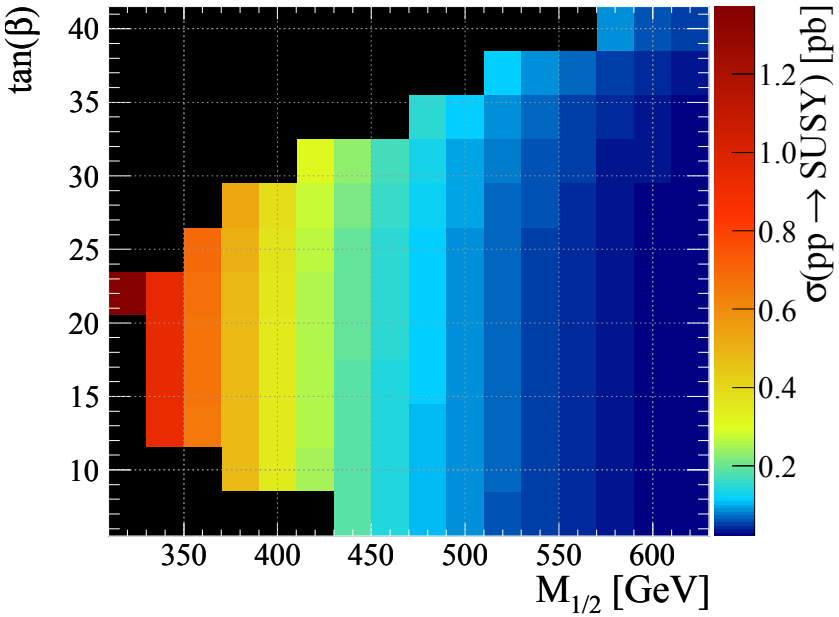
# Benchmark scenarios in $\not{R}_p$ mSUGRA



- $\tilde{\tau}$ (superpartner of $\tau$ lepton) is LSP in wide range of mSUGRA parameter space
  - With conserved $R$-parity: excluded because of charge
- cross section at LHC @$\sqrt{s} = 7\,\text{TeV}$: $\sigma = 0.28\,\text{pb}$ (comparison: $\sigma_{t\bar{t}} = 160\,\text{pb}$)

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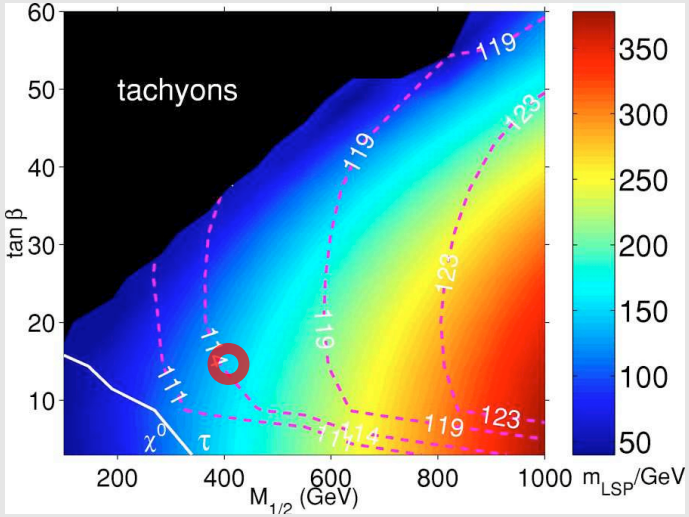
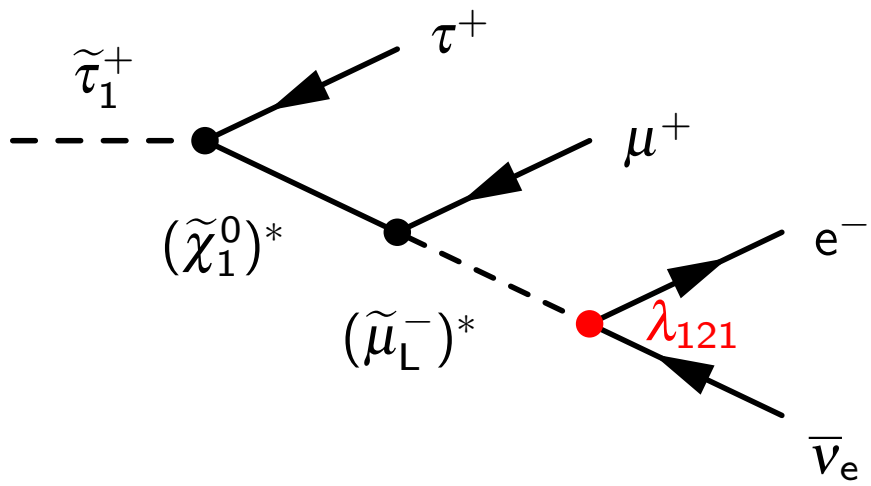



Allanach, Dedes, Dreiner, Phys. Rev. D69 115002

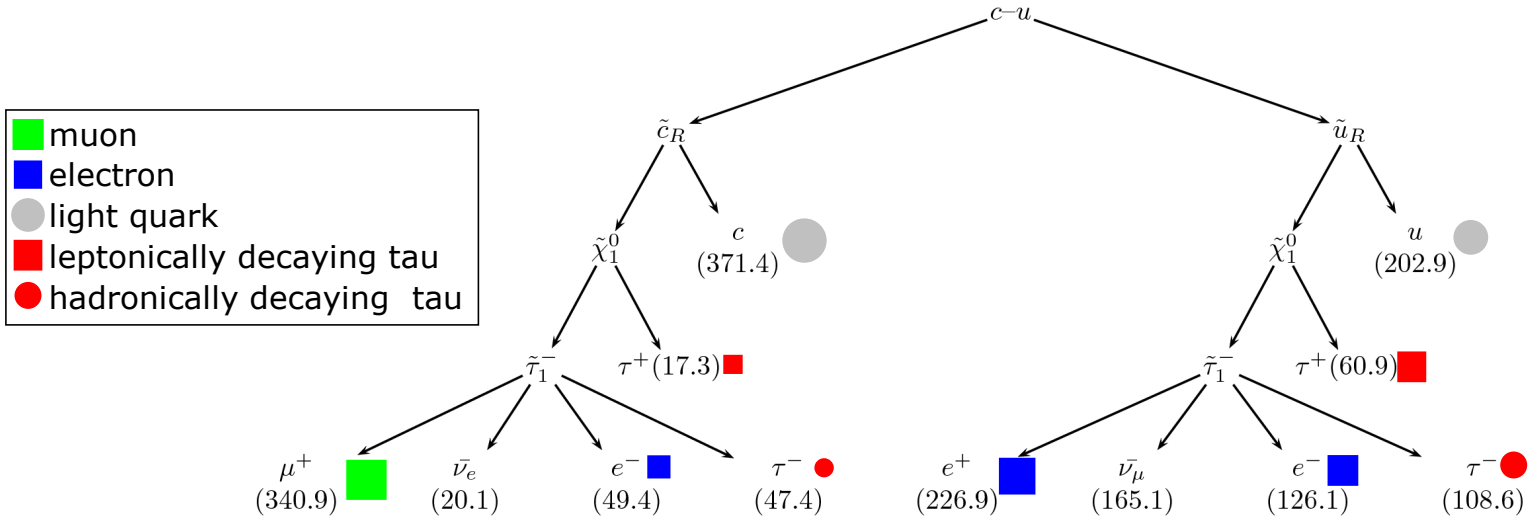
mass and type of LSP in "no-scale mSUGRA"

# RPV mSUGRA scenario BC 1

- $\lambda_{121}(M_{GUT}) = 0.032$ ($L_1 L_2 \bar{E}_1$ coupling)
- yields 4-body decay of $\widetilde{\tau}$-LSP: $\widetilde{\tau}_1^{\pm} \rightarrow \tau^{\pm}\ell^{\mp}\ell'^{\pm}\nu$




- Example event:





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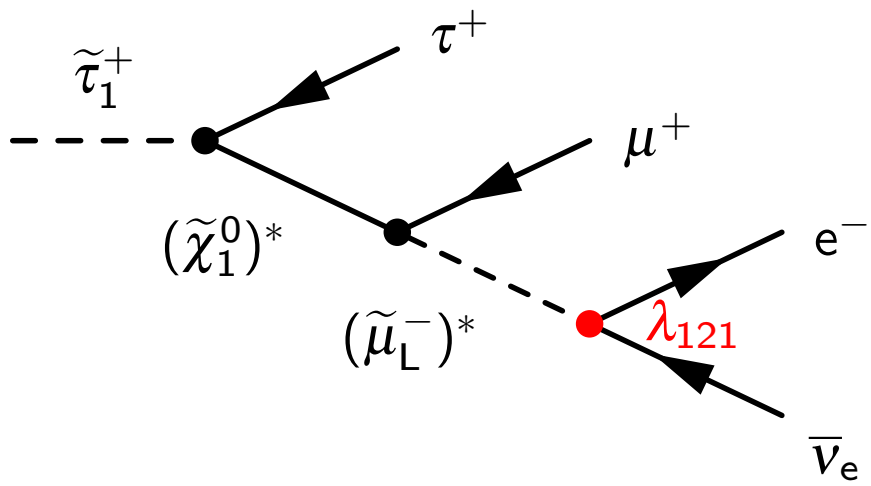


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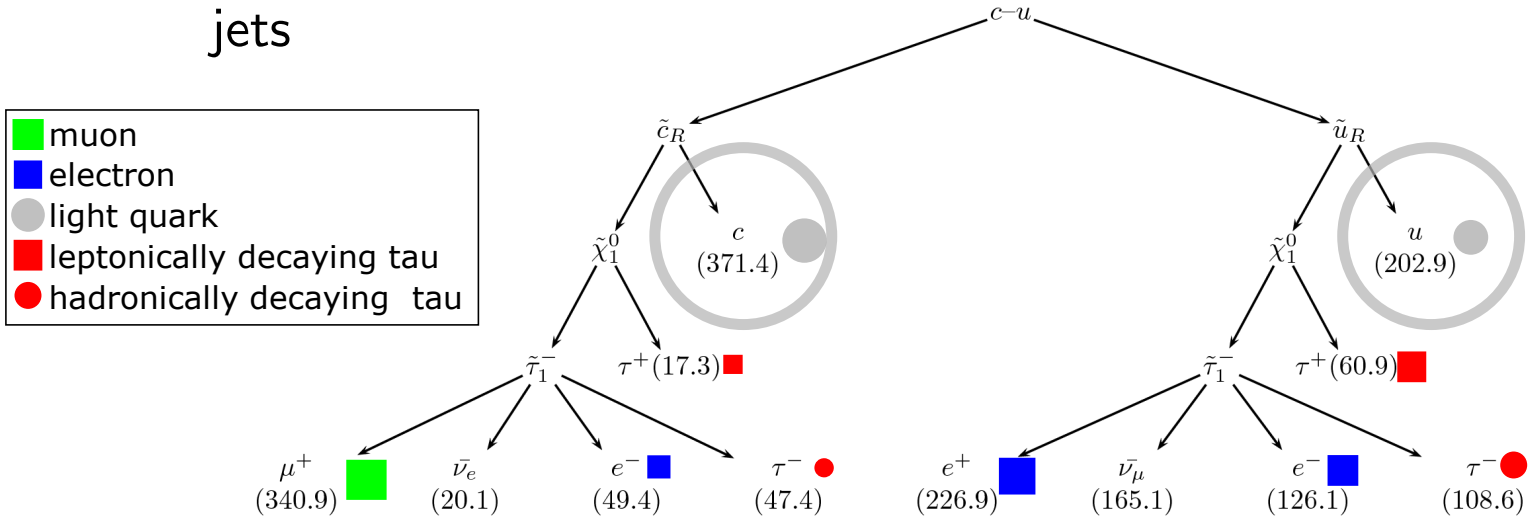



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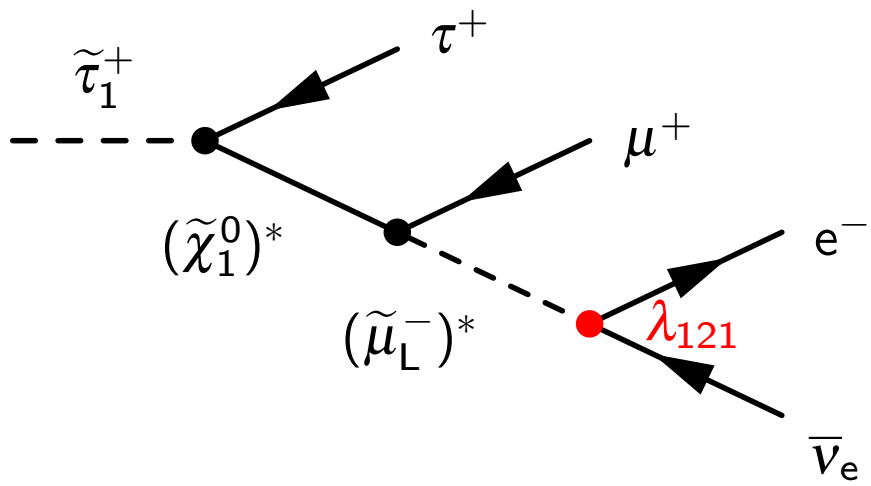
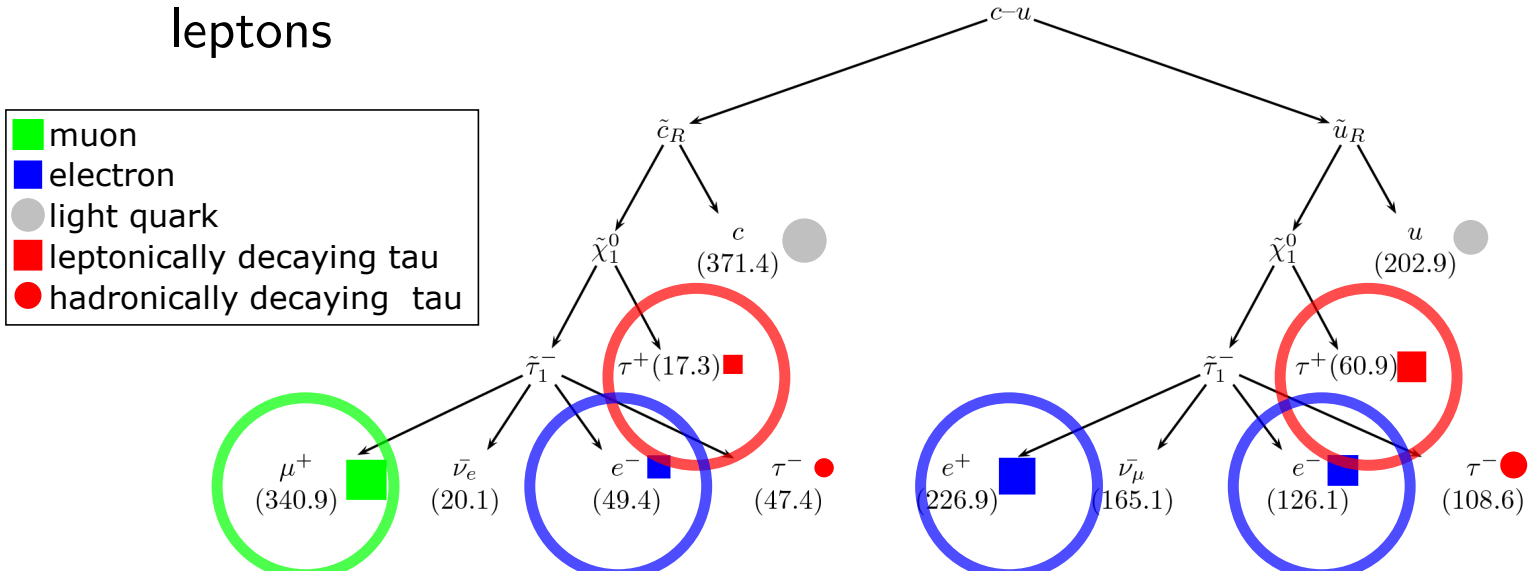



- Example event:

leptons



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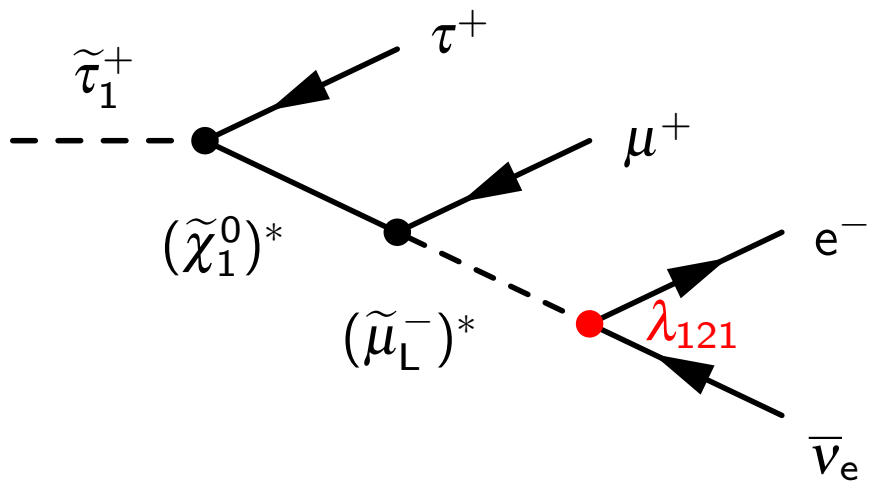
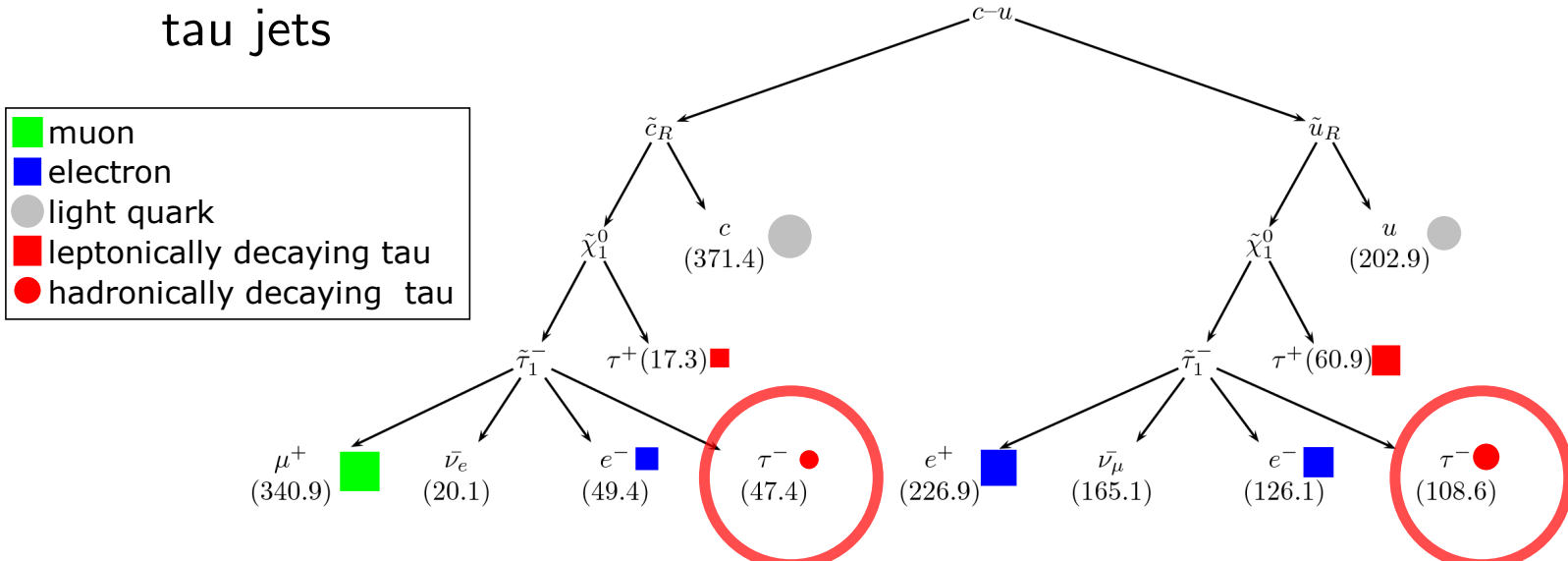
# RPV mSUGRA scenario BC 1

- $\lambda_{121}(M_{GUT}) = 0.032$ ($L_1 L_2 \bar{E}_1$ coupling)
- yields 4-body decay of $\widetilde{\tau}$-LSP: $\widetilde{\tau}_1^{\pm} \rightarrow \tau^{\pm}\ell^{\mp}\ell'^{\pm}\nu$




- Example event:

tau jets





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# RPV mSUGRA scenario BC 1



- $\lambda_{121}(M_{GUT}) = 0.032$ ($L_1 L_2 \bar{E}_1$ coupling)
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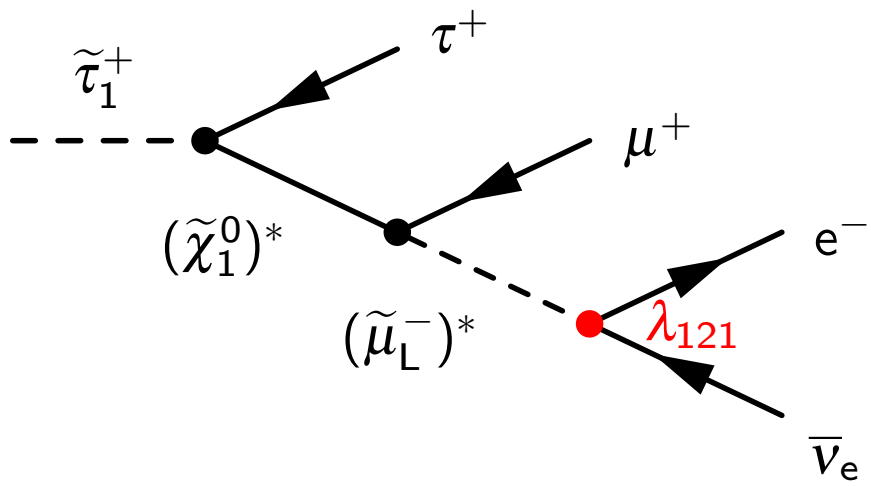
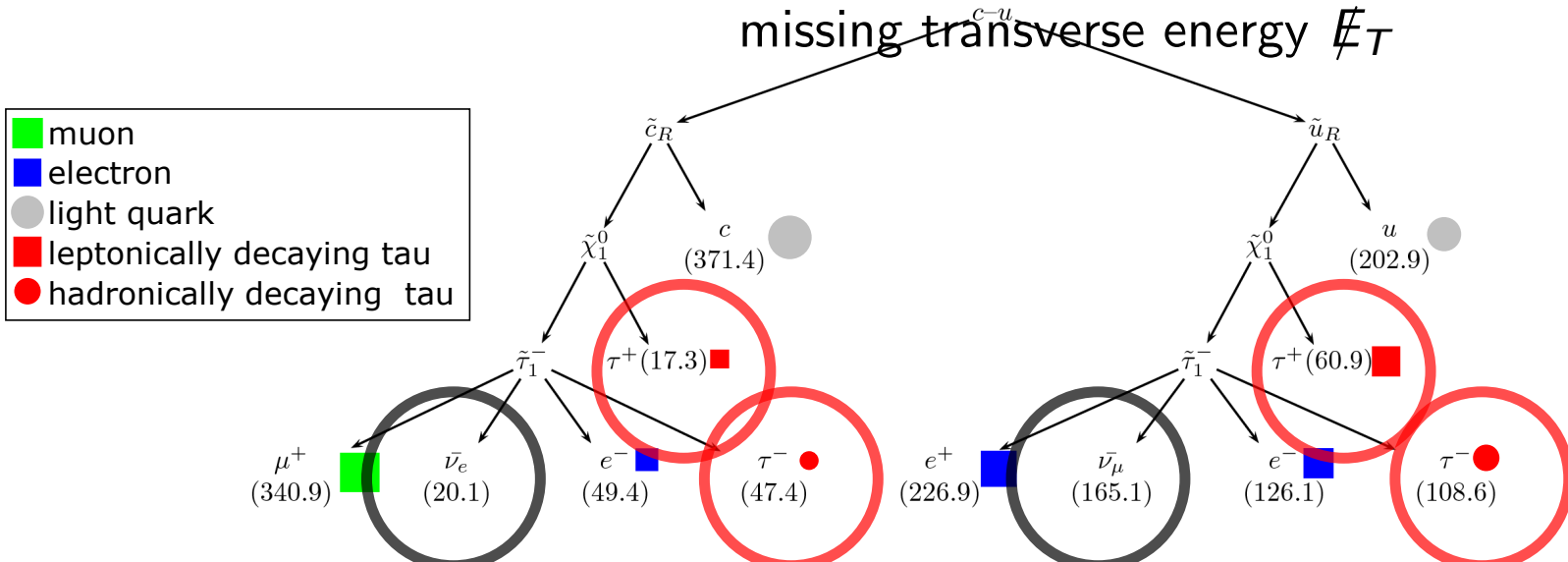



- Example event:



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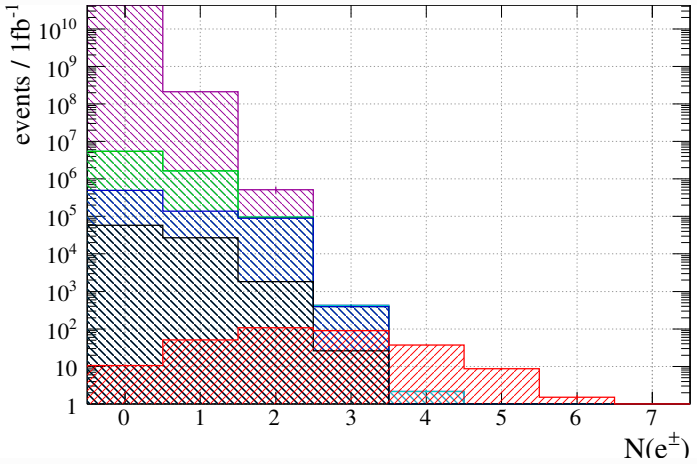
# BC 1: Number of reconstructed objects per event

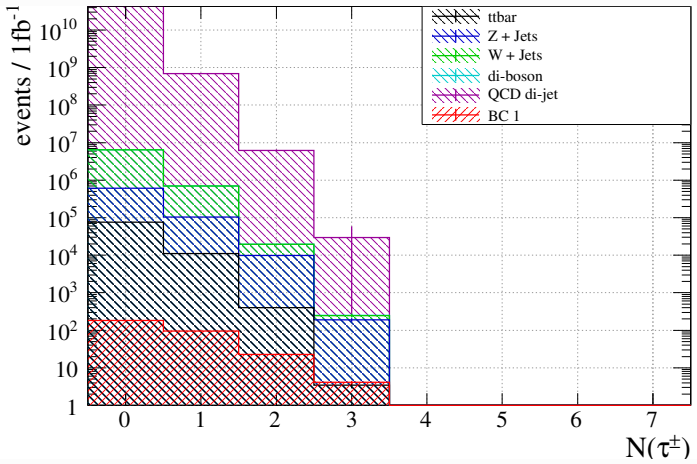
after ATLAS default object selection and overlap removal, $\sqrt{s} = 7\,\text{TeV}$



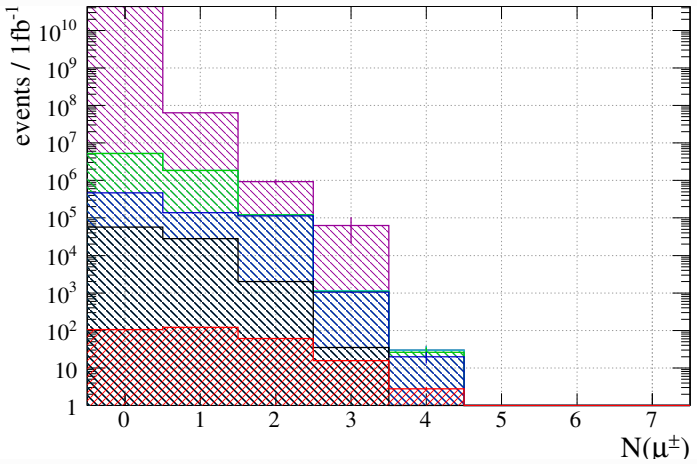
## electrons



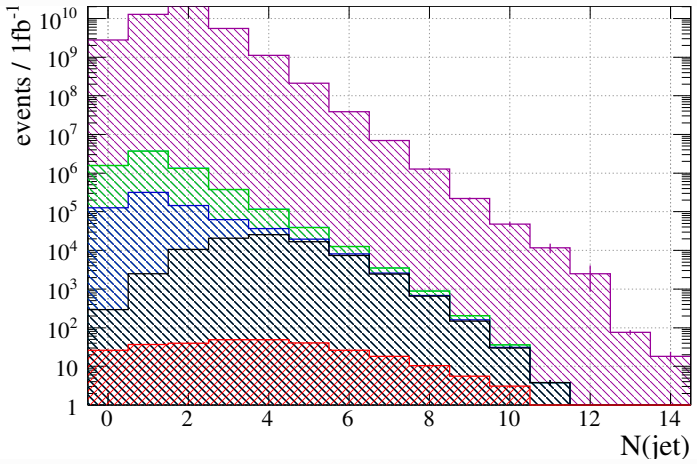

## hadronic decays of tau leptons




## muons




## jets

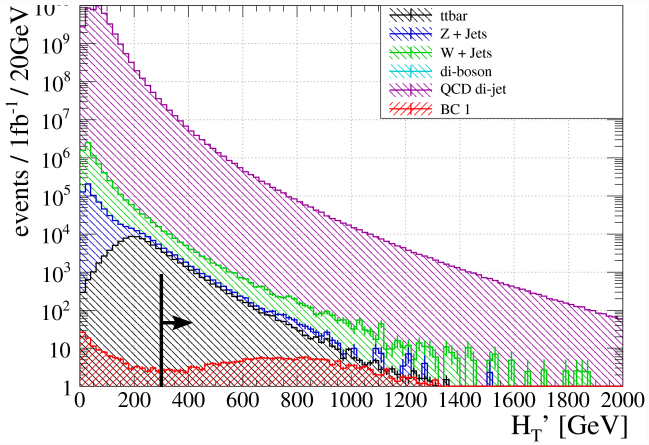


# BC 1: Jet and lepton momenta

scaled to $\int L dt = 1\,\mathrm{fb}^{-1}$, $\sqrt{s} = 7\,\mathrm{TeV}$

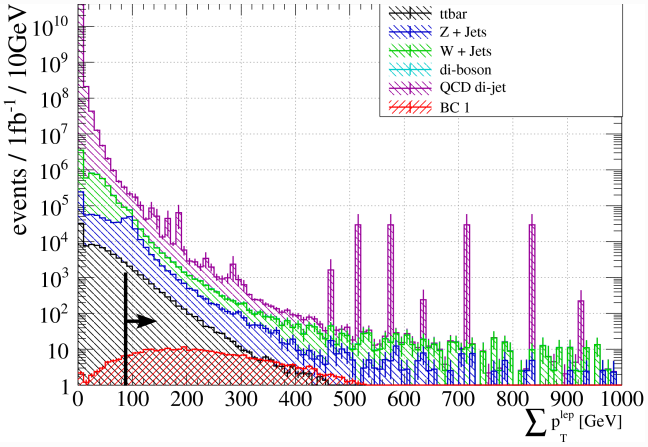
## Scalar sum of jet momenta

$H_T' = \sum_{\mathrm{jet1-4}} p_T$



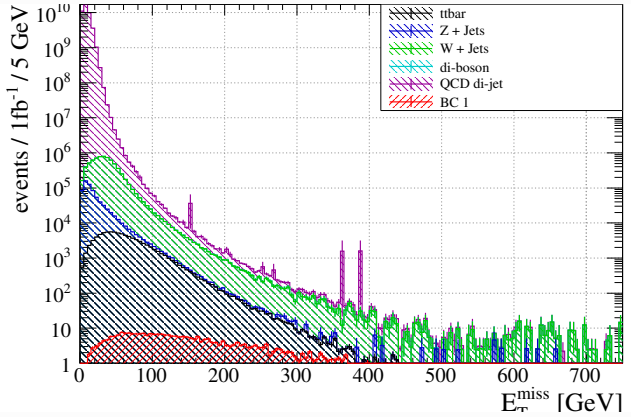

## Scalar sum of lepton momenta

$\sum p_T^{\ell} = \sum p_T^{\mu^{\pm}} + \sum p_T^{e^{\pm}}$




- amount of hadronic energy in BC1 differs for production mode
- large amount of leptonic energy
- even in RPV SUSY: $\not{E}_T$ significant (but not used as event selection cut!)

## Missing transverse energy $\not{E}_T$



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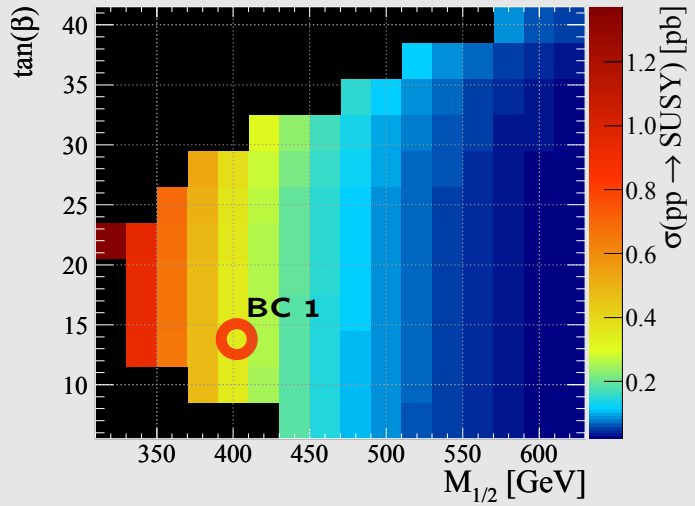
# Parameter scan around BC 1

Delphes fast detector simulation, $\int L dt = 500\,\text{pb}^{-1}$, $\sqrt{s} = 7\,\text{TeV}$

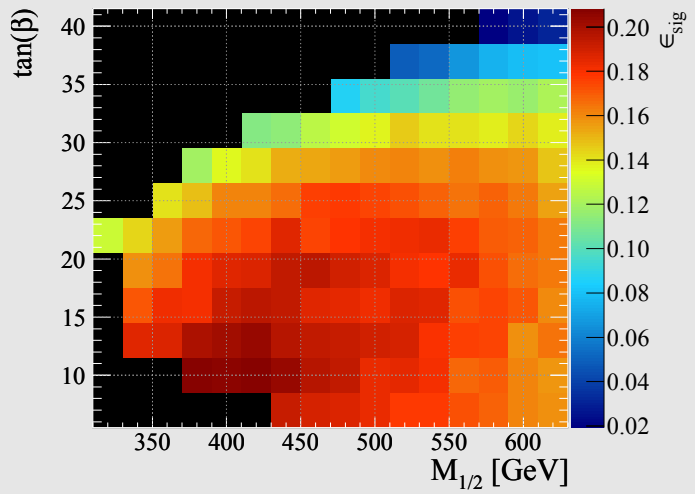


## Cross section

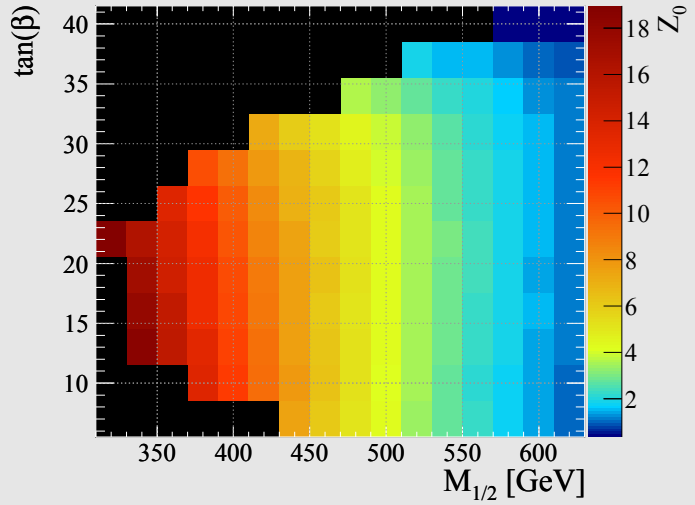



- High signal efficiency in wide range of parameters
- Decrease at high $\tan(\beta)$ because of low mass difference between $\widetilde{\chi}_1^0$ and $\widetilde{\tau}$

## Efficiency of event selection




## Significance $Z_0$, 25 % systematic uncertainty



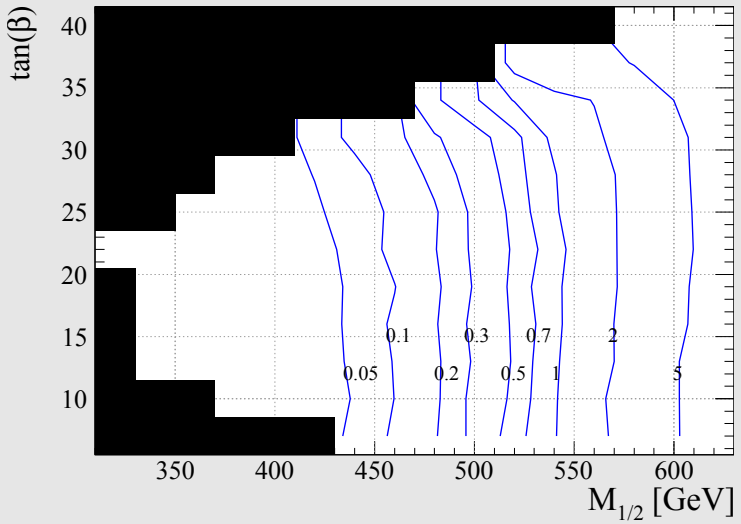
Overview
Theory
Experiment
Tau ID
SUSY
RPV SUSY
Scenarios
Event selection
Discovery potential
Stau mass
Summary
Backup

# Discovery potential at the LHC

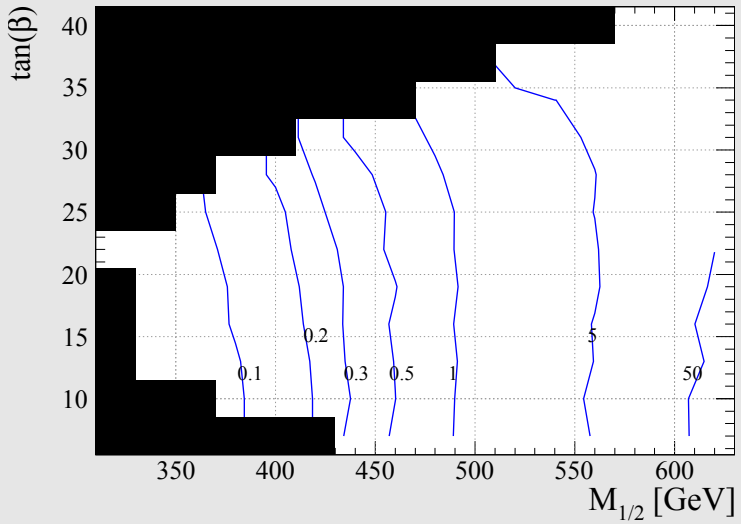
Expected integrated luminosity for $5\sigma$ discovery
Delphes fast simulation, $\sqrt{s} = 7\,\text{TeV}$

- Estimate of integrated luminosity needed for discovery depends strongly on systematic uncertainty of the estimated SM background

$S/\sqrt{B}$




Binomial significance $Z_0$,
25% systematic uncertainty

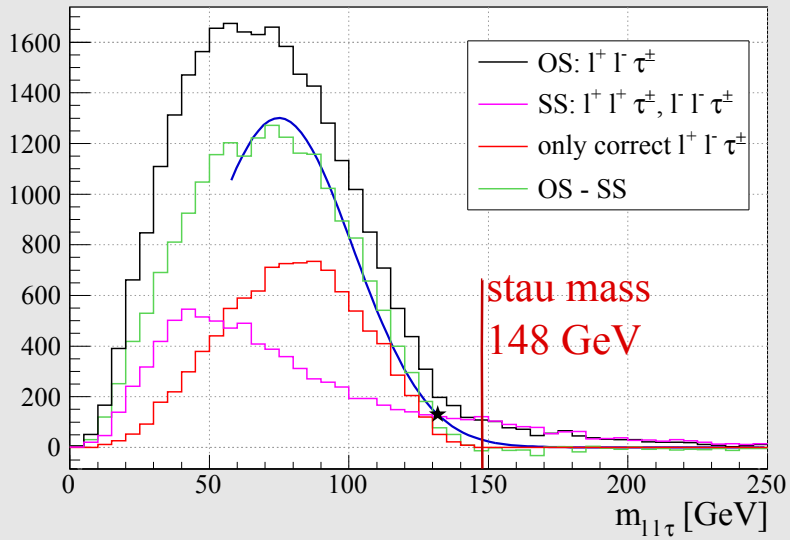


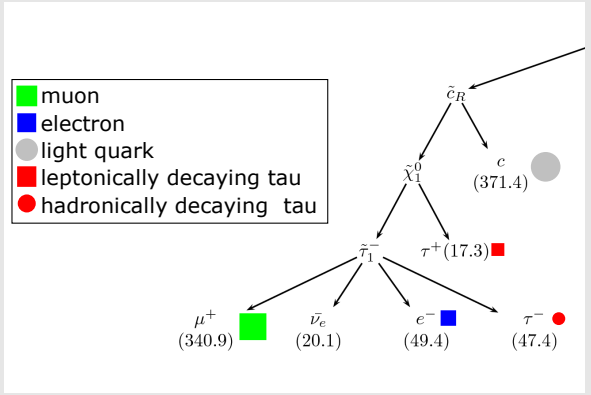

- Estimate of systematic uncertainties from full detector simulation and data-driven techniques
- Discovery possible with $\sim 1\text{fb}^{-1}$!

# Study feasibility of stau mass determination

## $\widetilde{\tau}$ mass at generator level in BC 1

### What to do after a discovery?




Expect no mass peak but endpoint in spectrum at simulated $\widetilde{\tau}$ mass (148 GeV), because of $\nu$

- Combinatorial background, because two $\widetilde{\tau}$ decays per event: Which leptons belong to which decay?
  - (Statistical) reduction by "opposite sign − same sign" subtraction

# Study feasibility of stau mass determination

## Calibration and expected resolution

Overview
Theory
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Discovery potential
Stau mass
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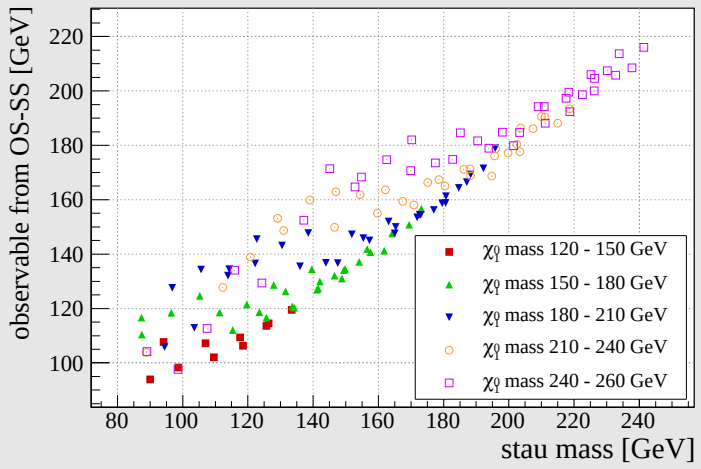
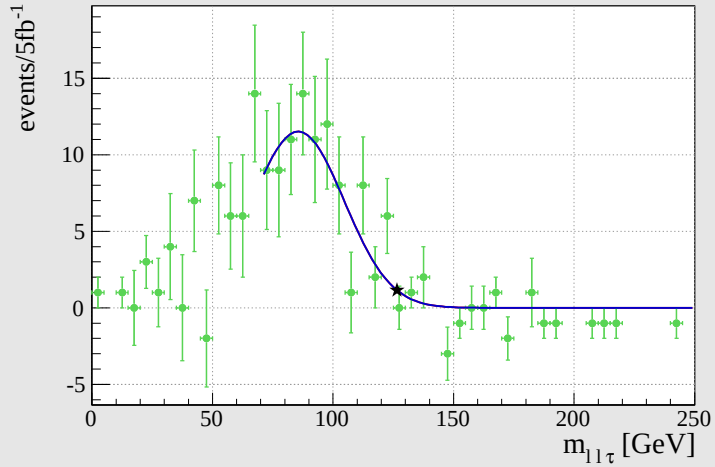
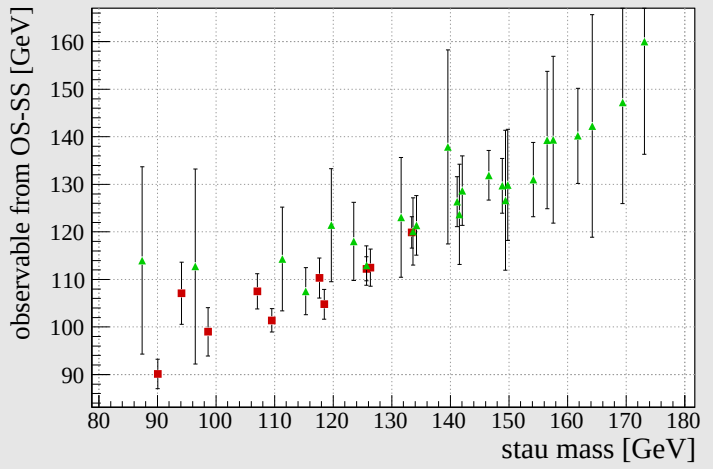
- Use points of parameter scan
- Calibration curve to determine $\widetilde{\tau}$ mass from observable (10 % value of Gaussian fit)

### Calibration curve (full statistics)




### Expectation for $5\,\mathrm{fb}^{-1}$, including event selection



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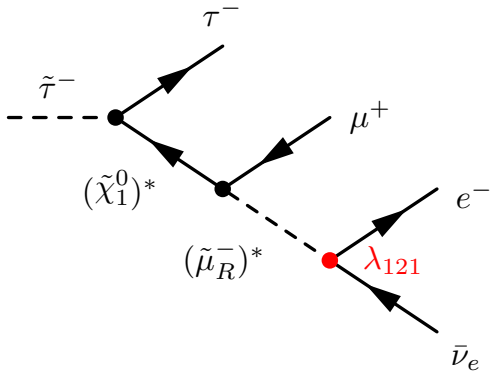
# Summary

- Identification of tau leptons important for many searches of new physics at the ATLAS experiment
- Studies on track reconstruction of $\pi^{\pm}$ from $\tau$ decays (track selection, detector misalignments)
- PanTau: Novel algorithm for tau ID in ATLAS, based on energy flow
  - Disentangle detector effects (clusterisation, conversions, ...) from tau ID
  - Categorisation according to decay modes
  - Improves energy resolution
  - Comparisons of PanTau variables between first data and Monte Carlo show reasonable agreement
  - Will (hopefully) be used soon by wider analyses in the ATLAS collaboration

# Summary

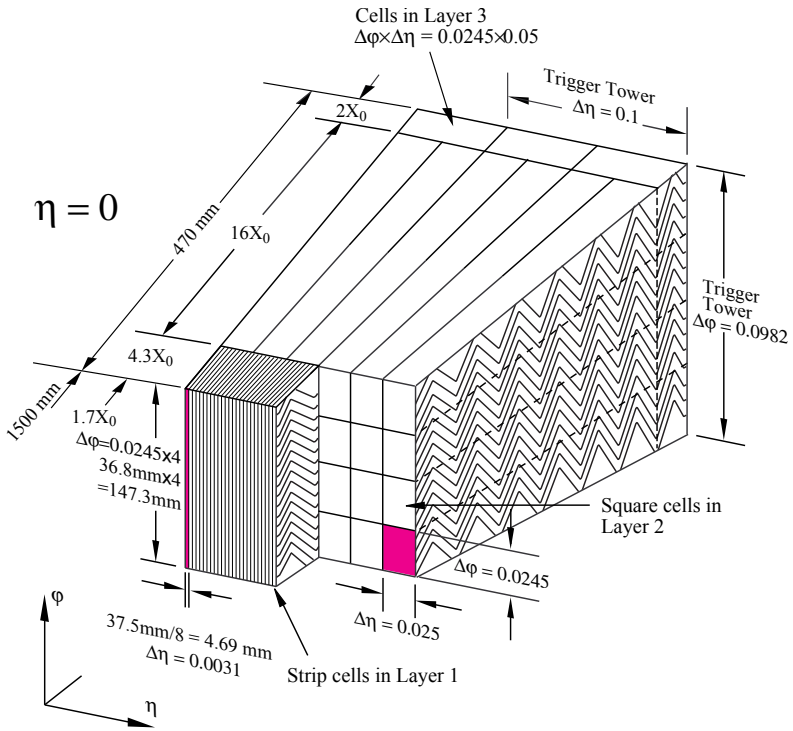
- *R*-parity violating supersymmetry is appealing extension of the Standard Model
  - Complementary phenomenology compared to commonly studied *R*-parity conserving SUSY models
  - High discovery potential for models with $\widetilde{\tau}$-LSP (depends on $\widetilde{\tau}$ decay, i.e. RPV couplings) in ATLAS
  - Estimation of $\widetilde{\tau}$-LSP mass possible with early data even in presence of neutrinos in $\widetilde{\tau}$ decay
  - Unfortunately no signatures of new physics in ATLAS yet, RPV searches are ongoing
- New fast simulation of ATLAS tracking detector (FATRAS) shows good performance and is used for large statistics Monte Carlo samples by the ATLAS collaboration

# Backup



# $\tau$ leptons in the ATLAS calorimeter

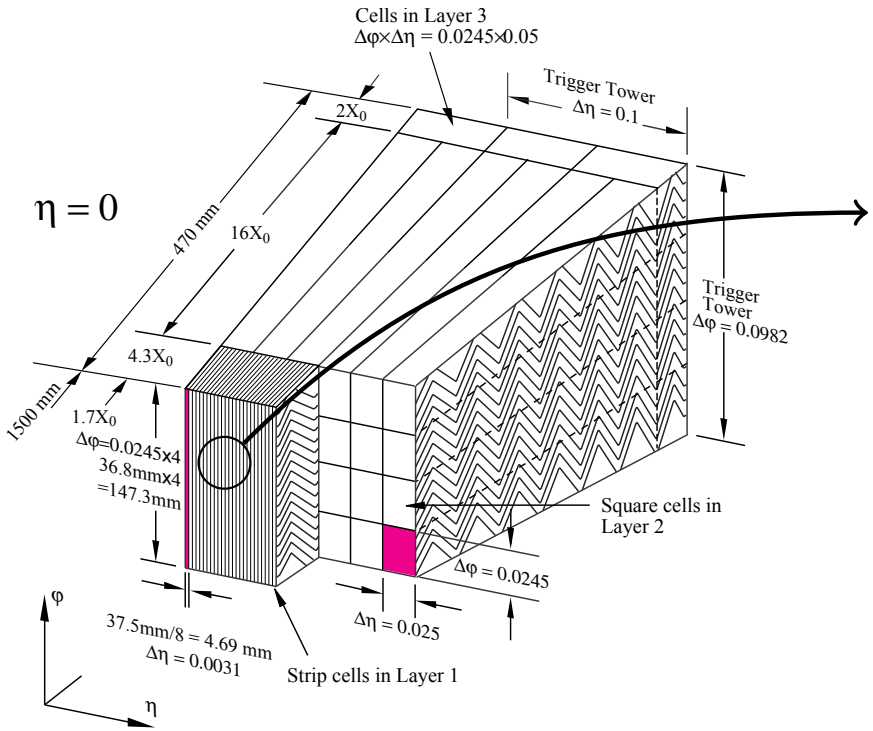


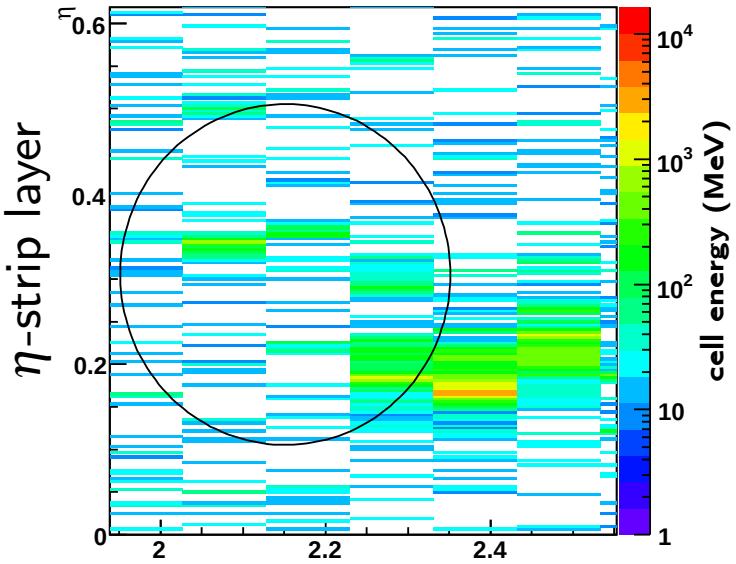



- The ATLAS Liquid Argon Calorimeter
  - high granularity allows to extract many features of $\tau$ jets

# $\tau$ leptons in the ATLAS calorimeter





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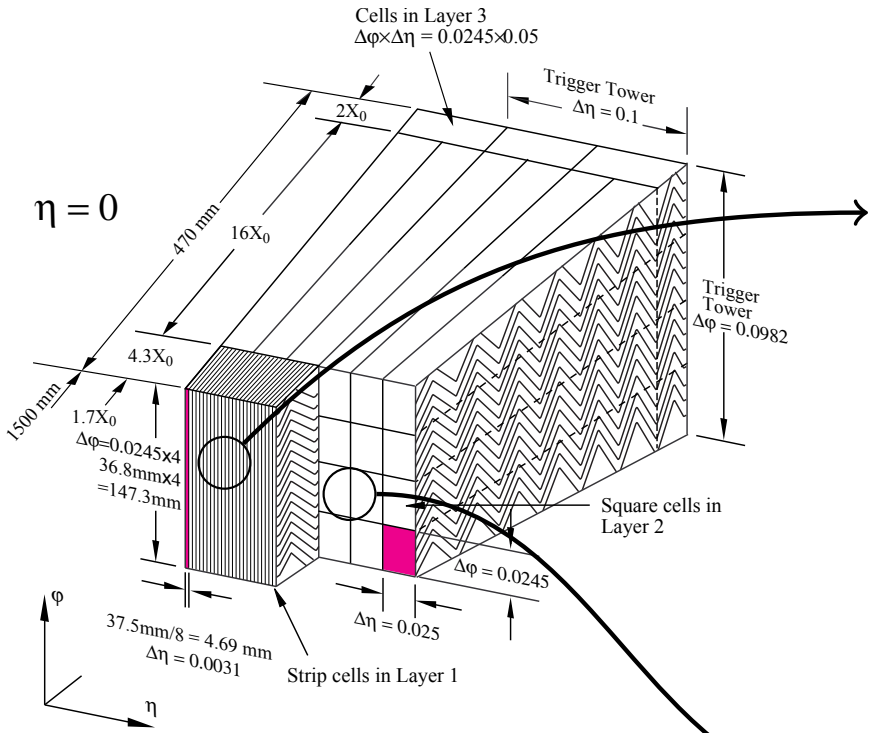
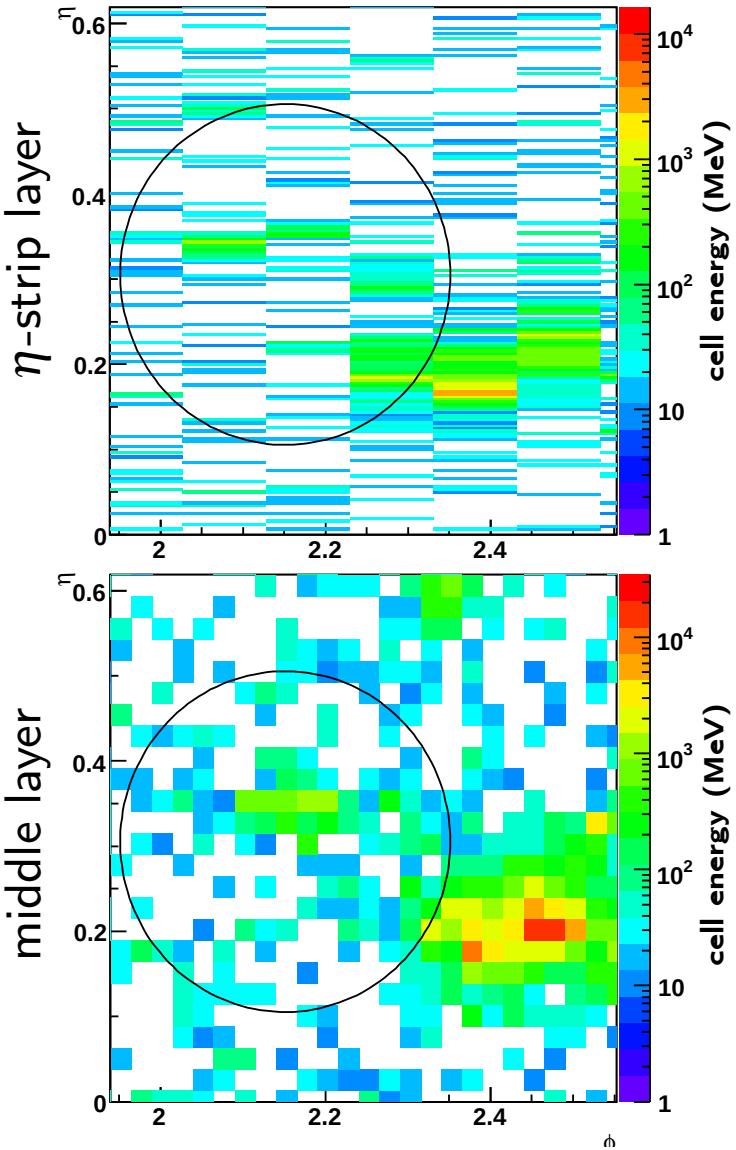
# $\tau$ leptons in the ATLAS calorimeter





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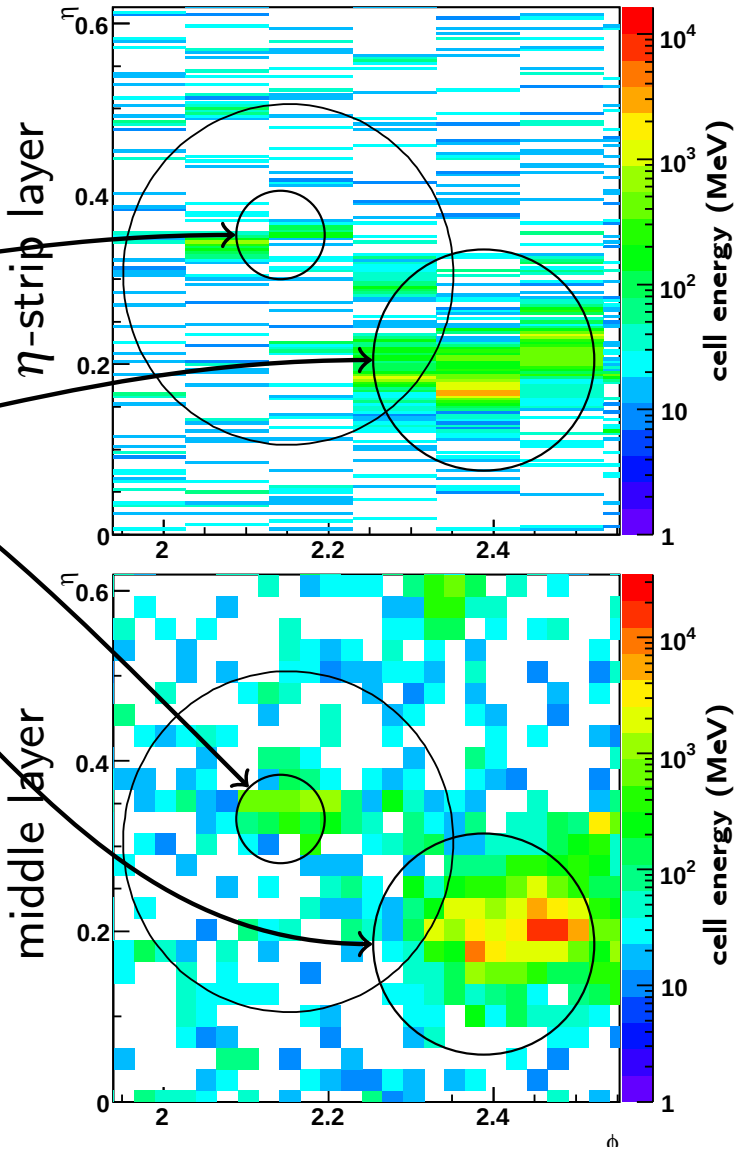
# $\tau$ leptons in the ATLAS calorimeter



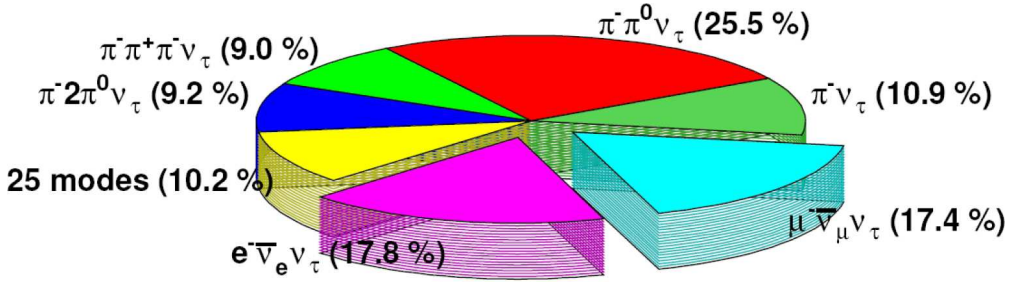
- $\tau$ jet
  - collimated
- quark jet
  - broad profile already in $\eta$-strip layer



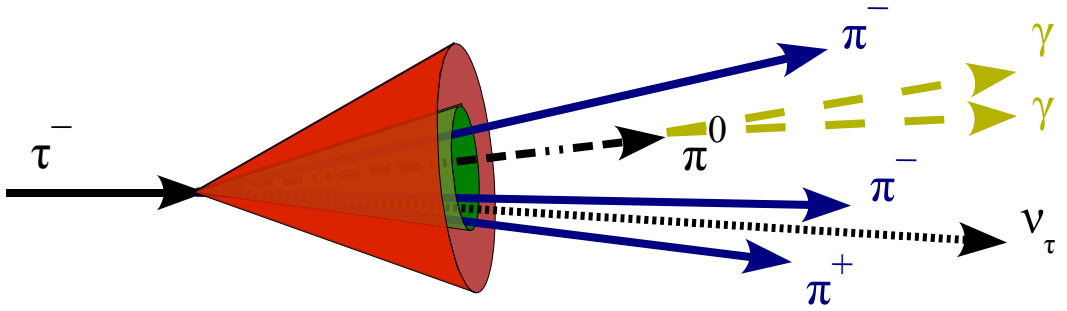
# Hadronic $\tau$ decays



- 65% of all decays into hadrons




- decay via resonances ($\rho$, $a_1$, K, ...) into $\pi^\pm$ and $\pi^0$
  - $\pi^0 \to \gamma\gamma$ ($BR = 99.8\%$) with $\tau_{\pi^0} \approx 8 \cdot 10^{-17}$s
- low charged multiplicity:
  - 1 $\pi^\pm$ ("1-prong"): $\pi^\pm$, $\rho^\pm \to \pi^\pm\pi^0$, $a_1^\pm \to \pi^\pm\pi^0\pi^0$, ...
  - 3 $\pi^\pm$ ("3-prong"): $a_1^\pm \to \pi^\pm\pi^\pm\pi^\mp$, ...
  - very small fraction (0.1%) of 5-prong decays
- strongly collimated jet



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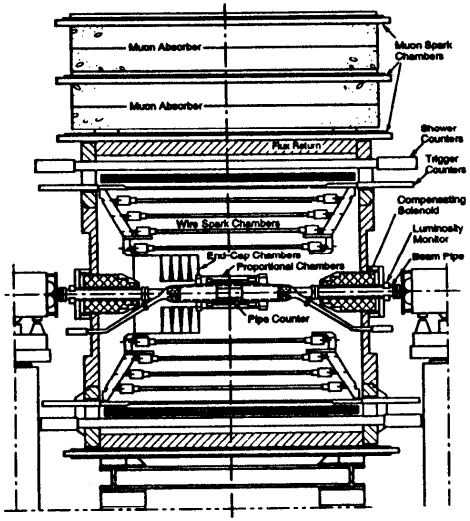
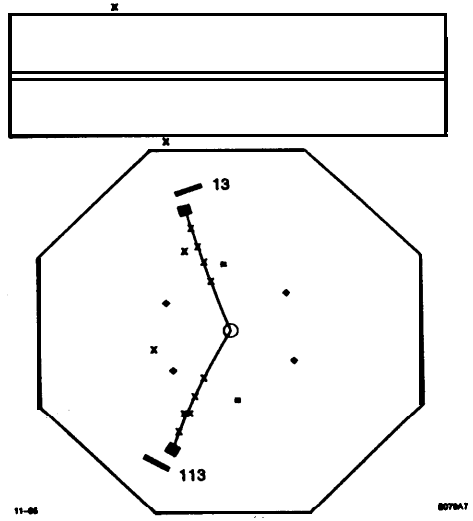
# Discovery of the $\tau$ lepton

- Discovery in 1975 with the MARK I detector at the SPEAR collider at SLAC



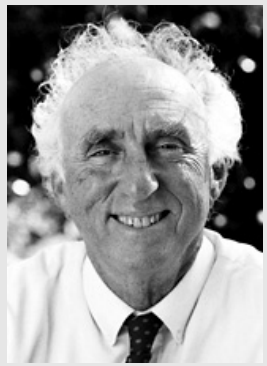

M. Perl, Nobel lecture




M. Perl, Nobel lecture

- $e^+e^- \to \tau^+\tau^- \to \mu^+\nu_\mu\bar{\nu}_\tau \;\; e^-\bar{\nu}_e\nu_\tau$
- they claimed to have found $e\mu$ events with at least 2 undetected particles

## Martin L. Perl



nobelprize.org

Nobelprice in Physics 1995, "for the discovery of the tau lepton"



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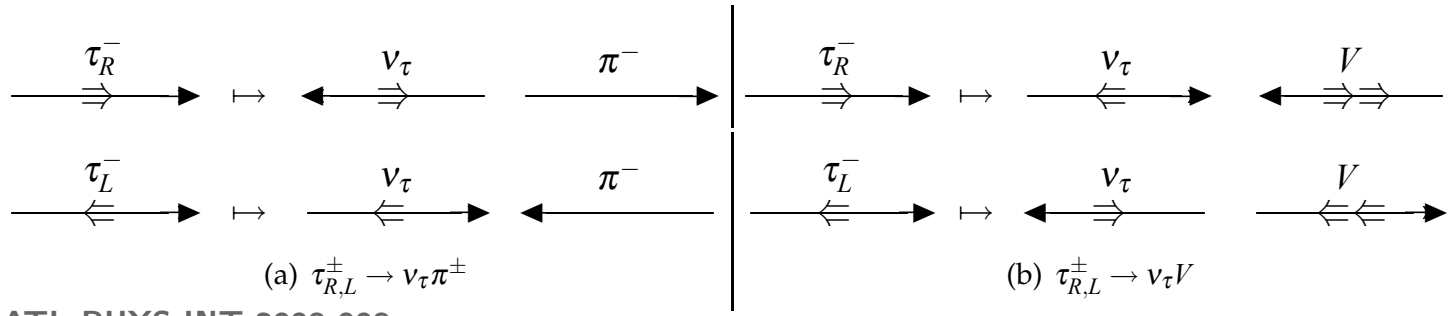
# Influence of the $\tau$ polarisation on visible momentum

- By angular momentum conservation and neutrino helicity: $\nu_\tau$ direction along or opposite $\tau$ momentum depending on the $\tau$ polarisation




(a) $\tau^\pm_{R,L} \to \nu_\tau \pi^\pm$ (b) $\tau^\pm_{R,L} \to \nu_\tau V$

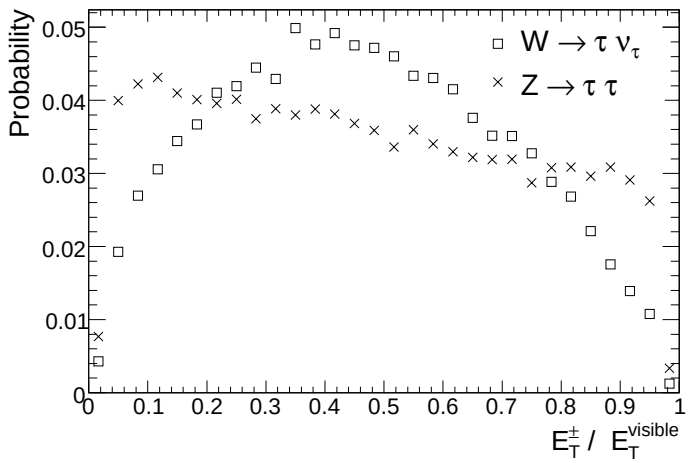
ATL-PHYS-INT-2008-008

- Results in softer or harder $p_T$ spectrum of $\pi^\pm$ or transverse vector meson $V$
- Leads to shape dependence of the invariant mass spectrum $m_{\tau^{\text{vis}}\tau^{\text{vis}}}$ e.g. in $Z \to \tau\tau$

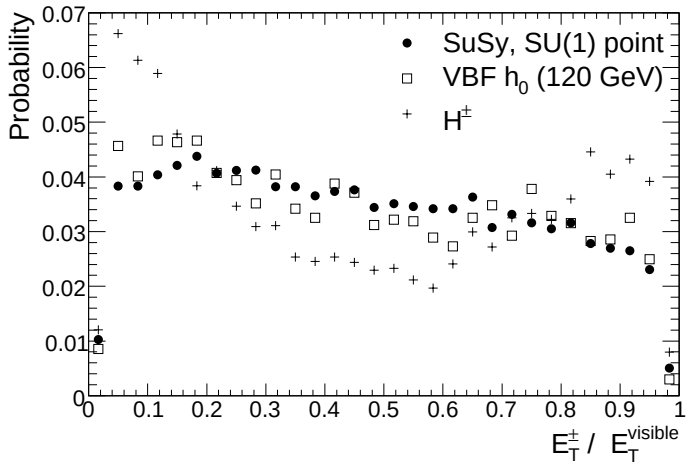
# Influence of the $\tau$ polarisation



- The $\tau$ polarisation affects the splitting of energy into charged and neutral components
  - The ration $R = \frac{E^{\text{charged}}}{E^{\text{visible}}}$ can be used to measure $\tau$ polarisation event-by-event




ATL-PHYS-INT-2008-003




ATL-PHYS-INT-2008-003

Figure: $R$ for single prong decays ($\tau^{\pm} \to \pi^{\pm} n\pi^0 \nu$). $\tau$s from $W \to \tau\nu$ are 100% polarised ($P_{\tau^{\pm}} = -1$), $H^{\pm} \to \tau\nu$ as well ($P_{\tau^{\pm}} = +1$)



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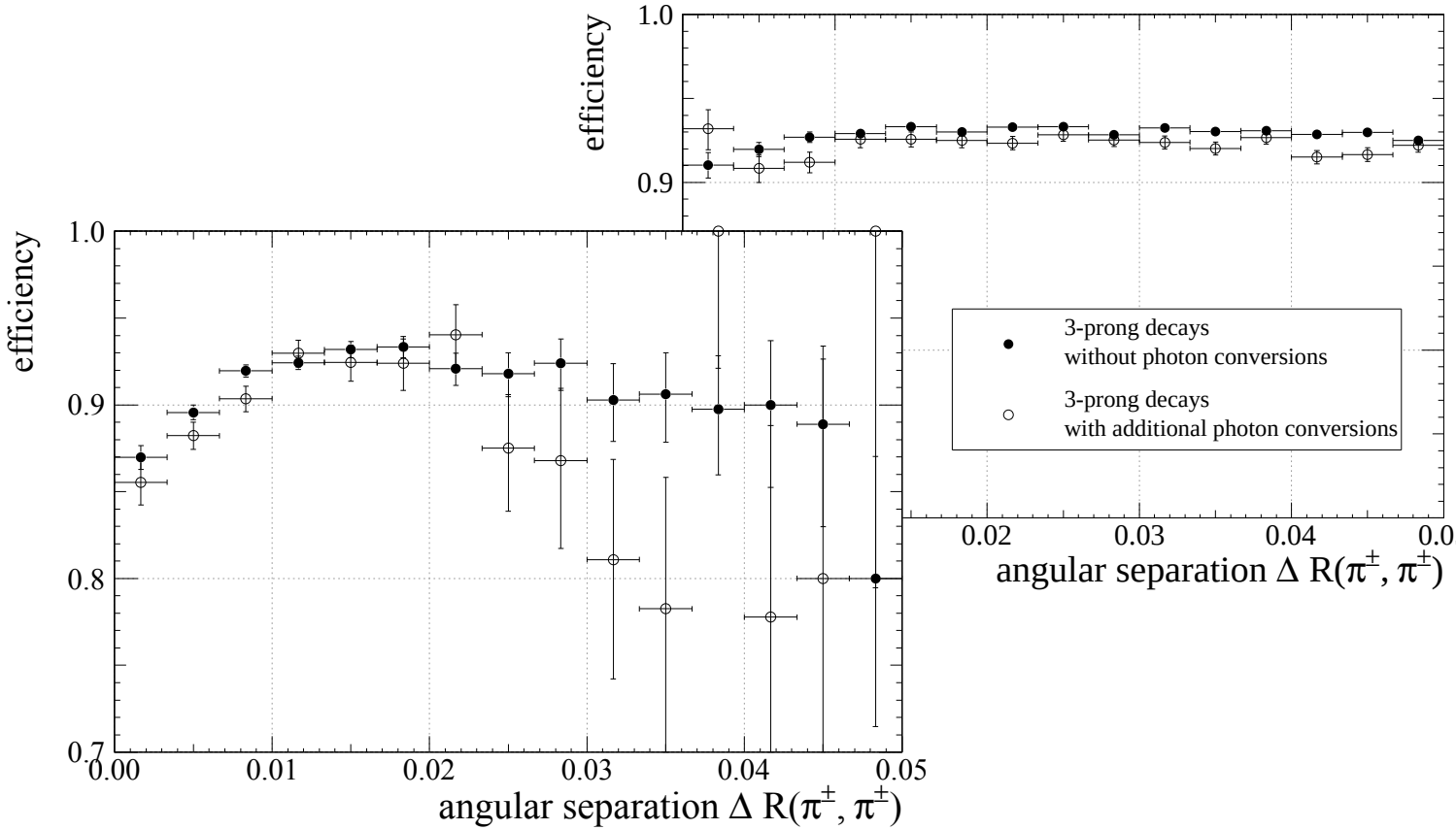
# Track reconstruction efficiency

## Problems with collimated tracks

- Track efficiency degrades for high momentum 3-prong decays due to overlapping tracks




- effect only visible for high momentum $\tau$s (not in $Z \rightarrow \tau\tau$)



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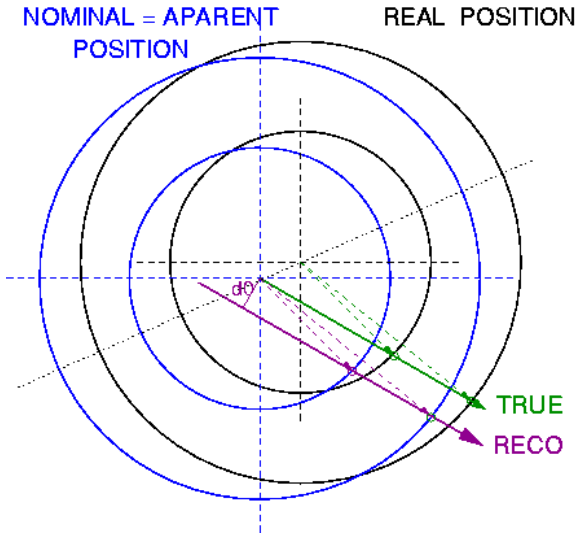
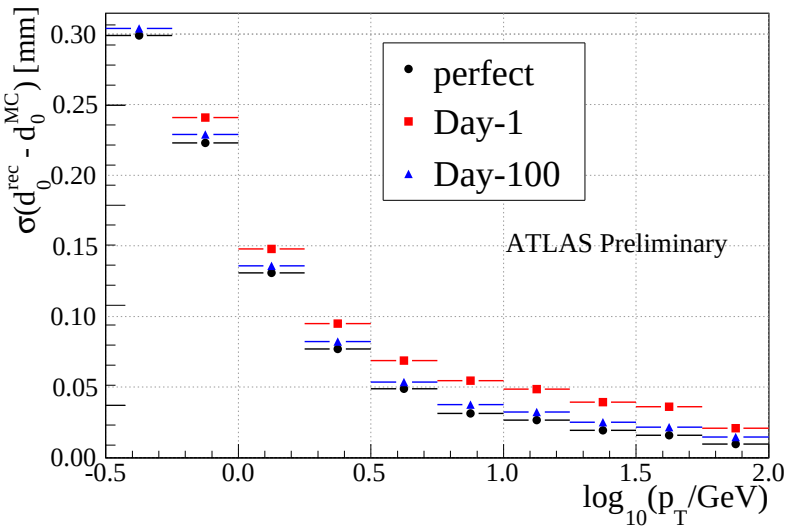
# Quality of the track reconstruction

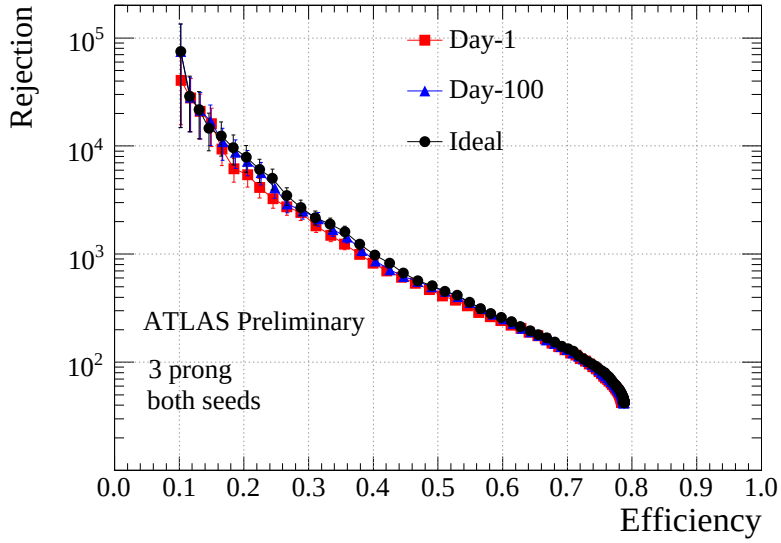
## Impact of detector misalignments

Uncertainties in the positioning of the detector modules affects quality of the track reconstruction

- Study effect of different levels of random misalignments on tracks from tau decays
- Small effect on track reconstruction efficiency and impact parameter resolution
- Almost negligible effect on tau identification



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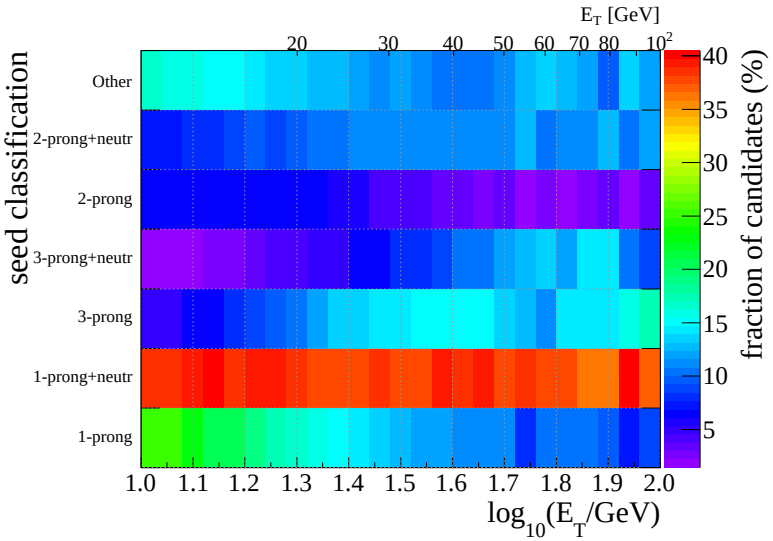
# Decay mode estimation

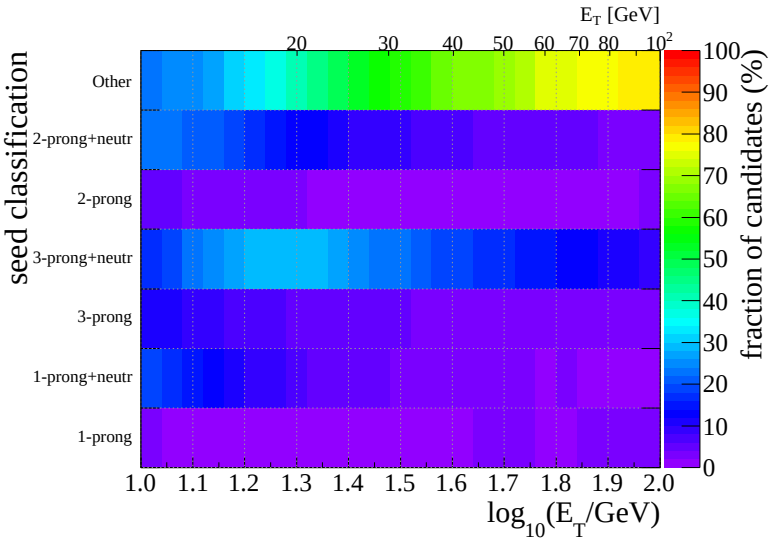
## Energy dependency

Purity (before identification step) very different in the categories

- Strong energy dependency due to jet kinematics and tracking efficiency




true taus




QCD jets

Fraction of PanTau candidates in $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$ (resp. QCD) events with $|\eta^{vis}| < 2.0$ (normalised in $E_T$ bins)



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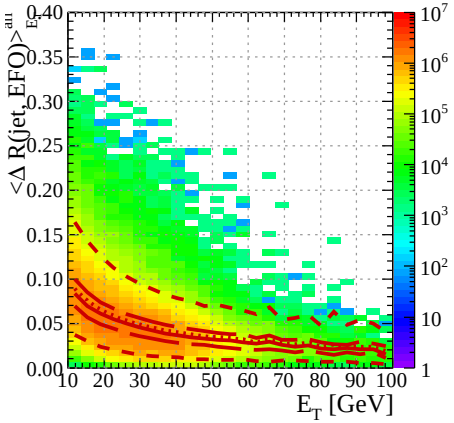
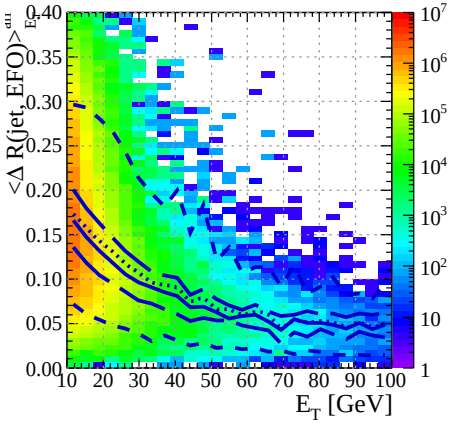
# Energy dependency and flattening

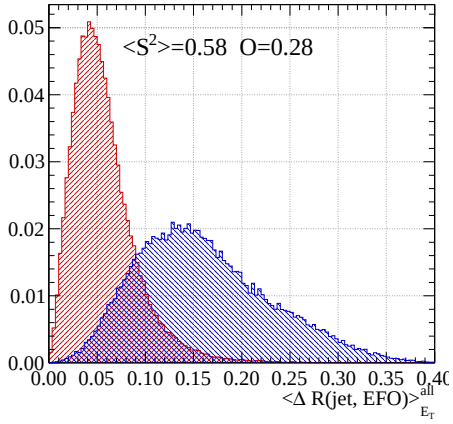
## Separation of signal and background in flattened variable

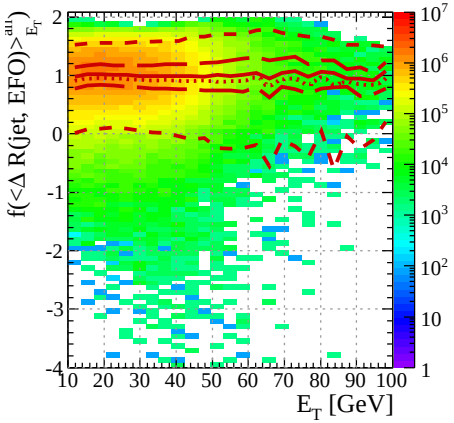
$E_T$ dependency

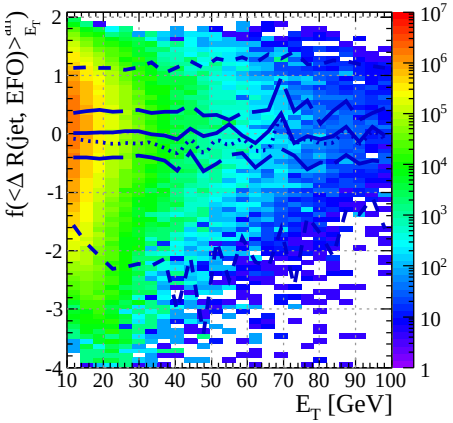


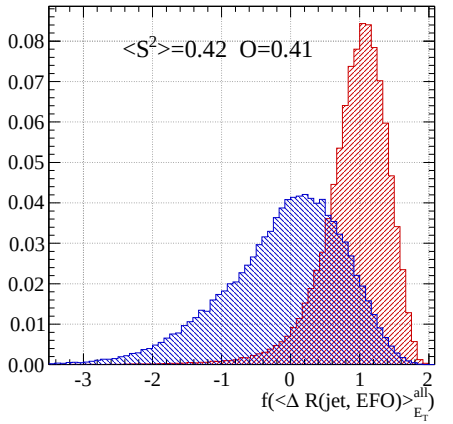




$10\,\text{GeV} < E_T < 100\,\text{GeV}$




- Overlap between signal (true $\tau$) and background (QCD) larger (worse) after flattening
- Effect of different $E_T$ composition of tau and QCD sample



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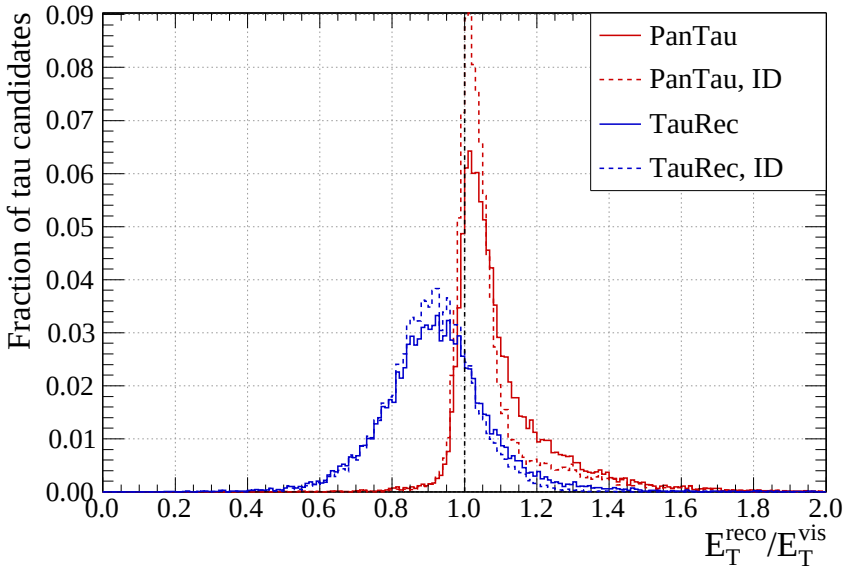
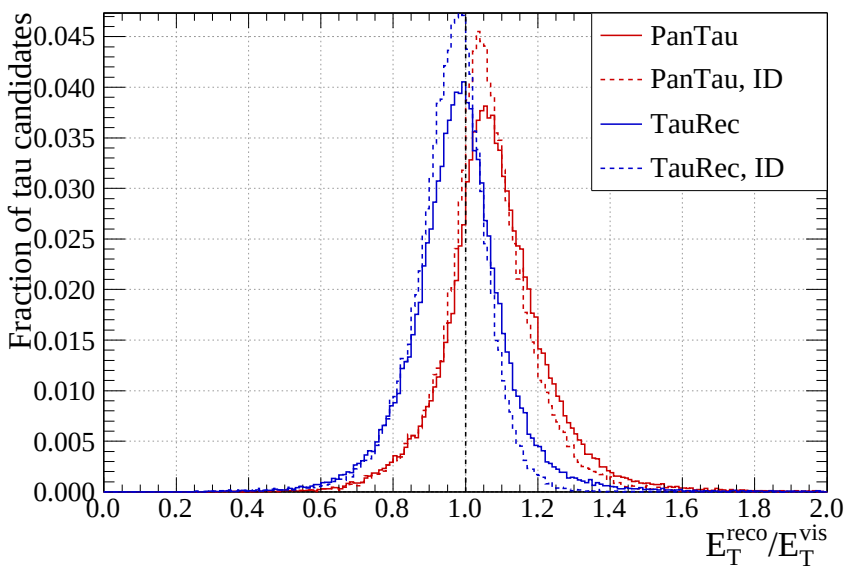
# Energy resolution

true 1-prong decays
without neutral particles




true 1-prong decays
with neutral particles

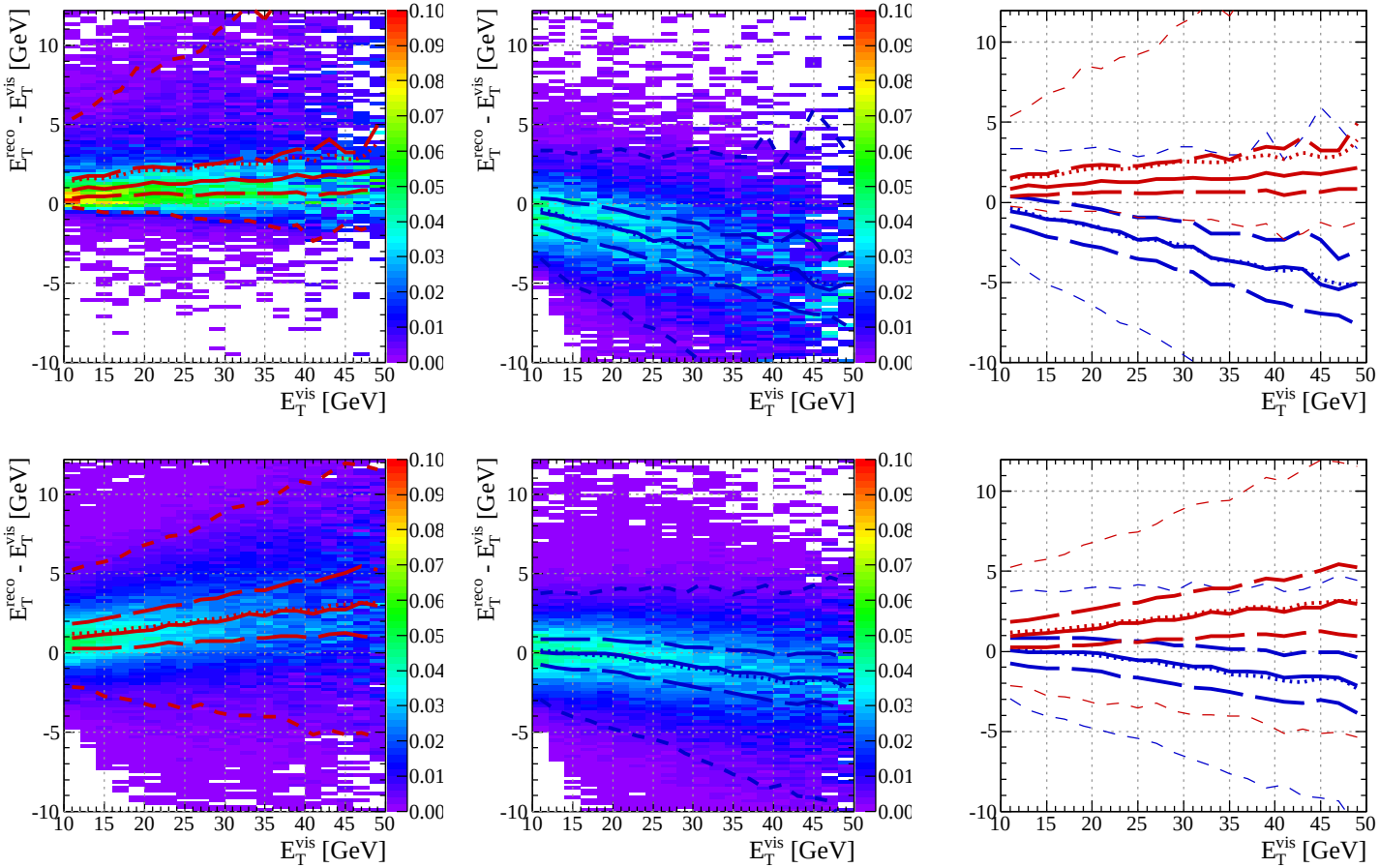



- Relative energy resolution of PanTau in the energy range $10\,\text{GeV} < E_T^{\text{vis}} < 50\,\text{GeV}$
- Dashed line: After identification using LLH with $\varepsilon^{\tau\text{had}} \approx 50\,\%$
- Using only reconstructed candidates with corresponding number of prongs

# Energy resolution

## Linearity of the reconstructed energy






- Linearity of the energy response better for PanTau than for TauRec



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# Combining different reco classes

TMVA output of likelihood classifier:

$$y = \frac{L_S}{L_S + L_B}$$

where

$$L_C = \prod_k p_{C\,k}(x_k), C = S, B \text{ and } \int_{-\infty}^{\infty} p_{C\,k}(x_k) dx_k = 1$$

i.e. signal and background reference distributions are normalised individually. Remark: $\ln\left(\frac{L_S}{L_B}\right) = -\ln\left(\frac{1}{y} - 1\right) \equiv \text{logit}(y)$

Probability for being signal including the a priori probability of the signal class (according to Bayes):

$$p = \frac{aL_S}{aL_S + bL_B} = \frac{aL_S}{aL_S + (1-a)L_B}$$

where $a$ is the a priori probability of the signal class and $b = 1 - a$ the a priori probability of background.

$$\text{logit}(p) = \ln\left(\frac{a}{1-a}\frac{L_S}{L_B}\right) = \ln\left(\frac{a}{1-a}\right) + \ln\left(\frac{L_S}{L_B}\right)$$

# BC 1: Event selection

scaled to $\int L\,dt = 0.5\,\text{fb}^{-1}$, $\sqrt{s} = 7\,\text{TeV}$

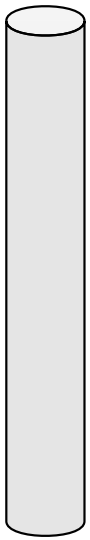
| cut | $t\bar{t}$ | all SM | BC 1 | $Z_0$ |
|---|---|---|---|---|
| pre-selection | 80 854 ±138 | $2.161(2) \times 10^{10}$ | 153.4±1.7 | — |
| $p_T(1\text{st}\ \mu^{\pm}) > 30\,\text{GeV}$ | 10 225 ±29 | $1.72(12) \times 10^{6}$ | 78.5±1.2 | — |
| $p_T(1\text{st}\ e^{\pm}) > 30\,\text{GeV}$ | 697 ± 7 | 1 508 ± 33 | 67.9±1.1 | — |
| $p_T(2\text{nd}\ e^{\pm}) > 10\,\text{GeV}$ | 10.6± 0.9 | 27.4± 2.0 | 56.4±1.0 | 4.3 |
| $\sum p_T^{\ell} > 85\,\text{GeV}$ | 10.3± 0.9 | 26.8± 2.0 | 56.3±1.0 | 4.4 |
| $m_{\text{T}}^{l} > 200\,\text{GeV}$ | 1.7± 0.3 | 2.0± 0.4 | 35.8±0.8 | 9.5 |
| $m_{\text{T}}^{l} > 300\,\text{GeV}$ | 0.7± 0.2 | 0.8± 0.2 | 33.2±0.8 | 10.8 |
| $m_{\text{T}}^{l} > 465\,\text{GeV}$ | 0.1± 0.1 | 0.1± 0.1 | 28.7±0.7 | 12.1 |

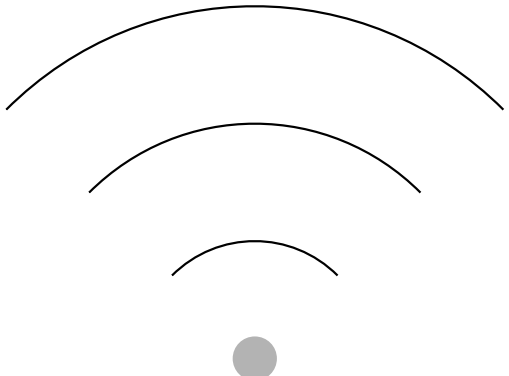
- At $\sqrt{s} = 7\,\text{TeV}$ (nearly) background free samples can be selected with high signal efficiency
- QCD expected to be very low
- Main background: $t\bar{t}$

# Track simulation in FATRAS



MC Event Generator





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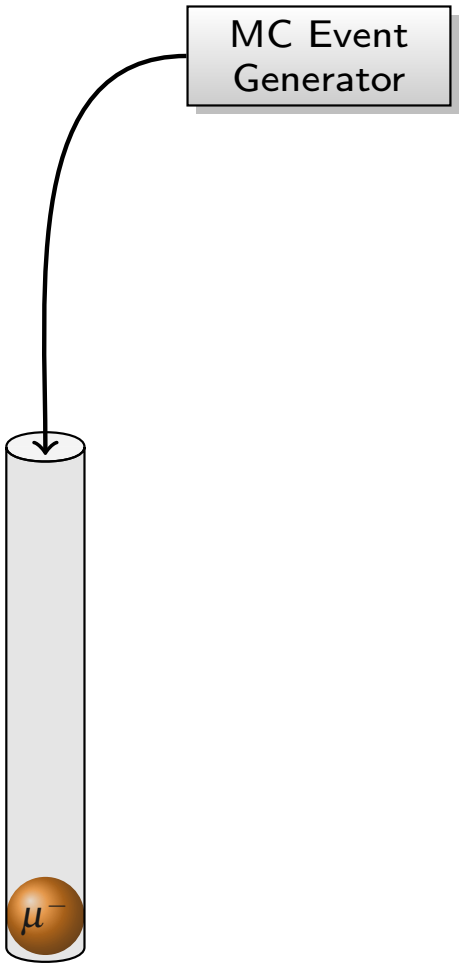


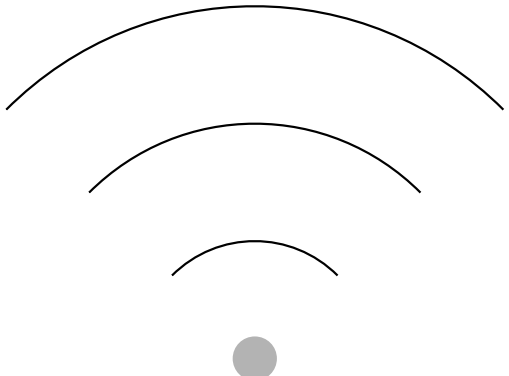

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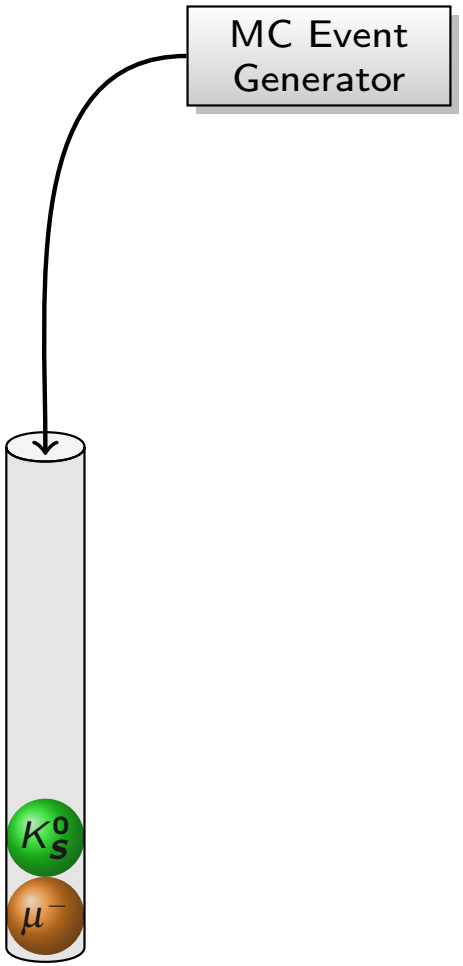
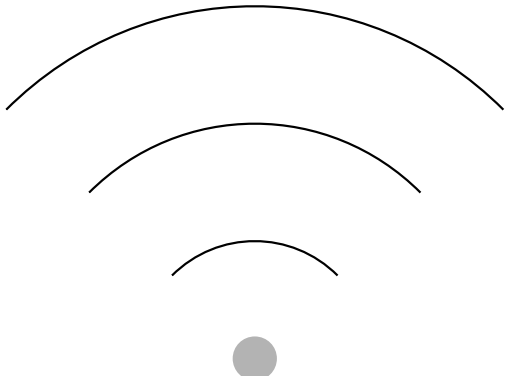
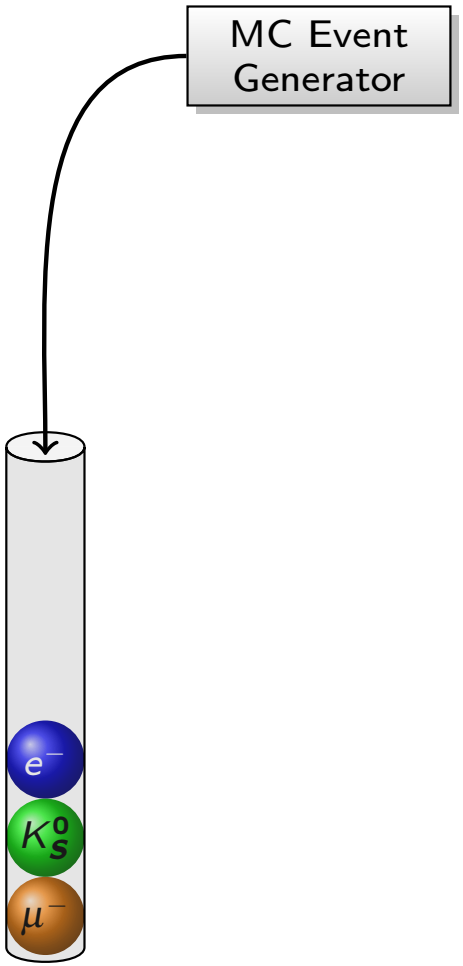


# Track simulation in FATRAS



Overview
Theory
Experiment
Tau ID
SUSY
Summary
Backup
Tau ID
RPV SUSY
FATRAS



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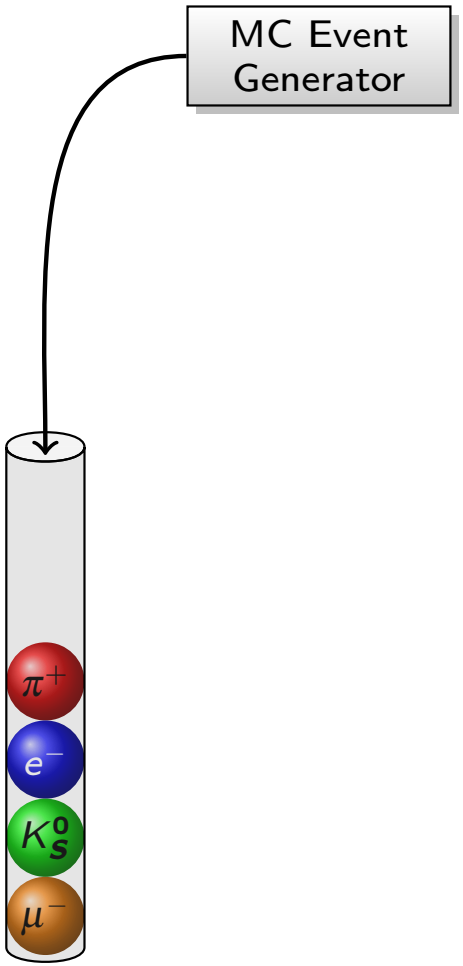


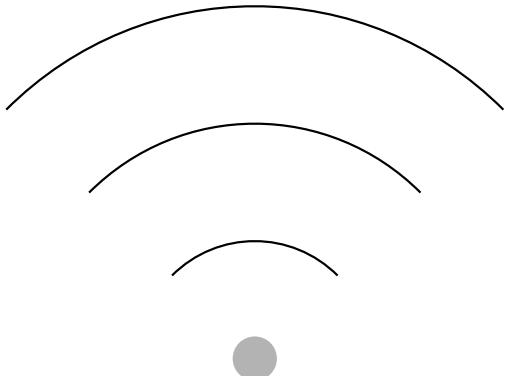

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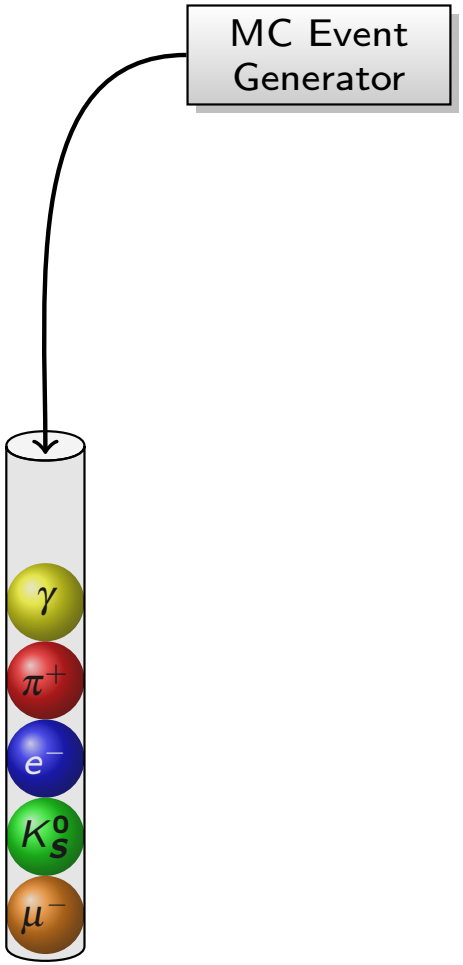


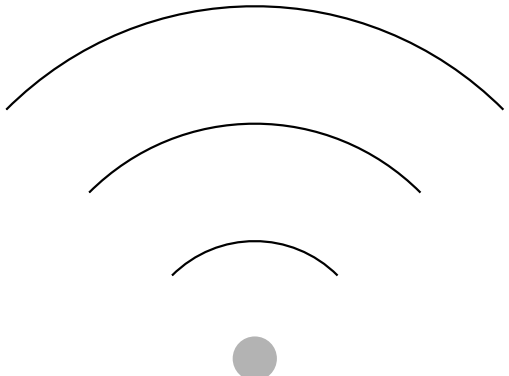

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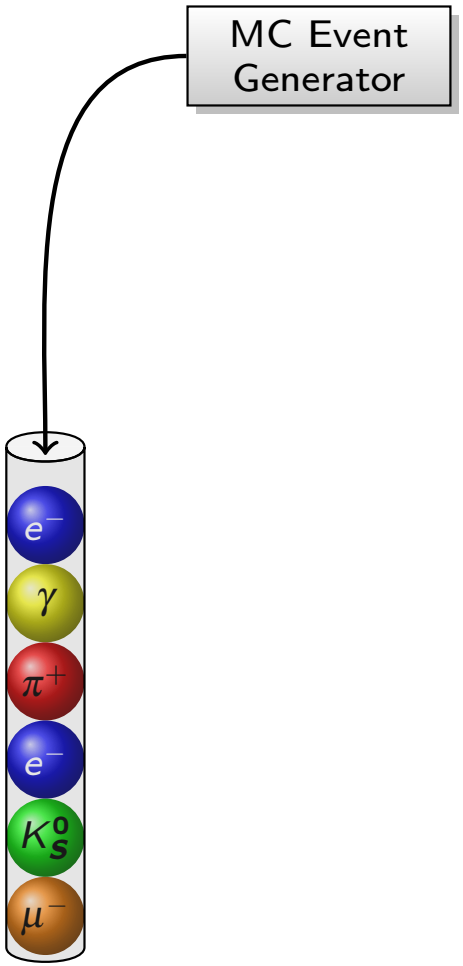
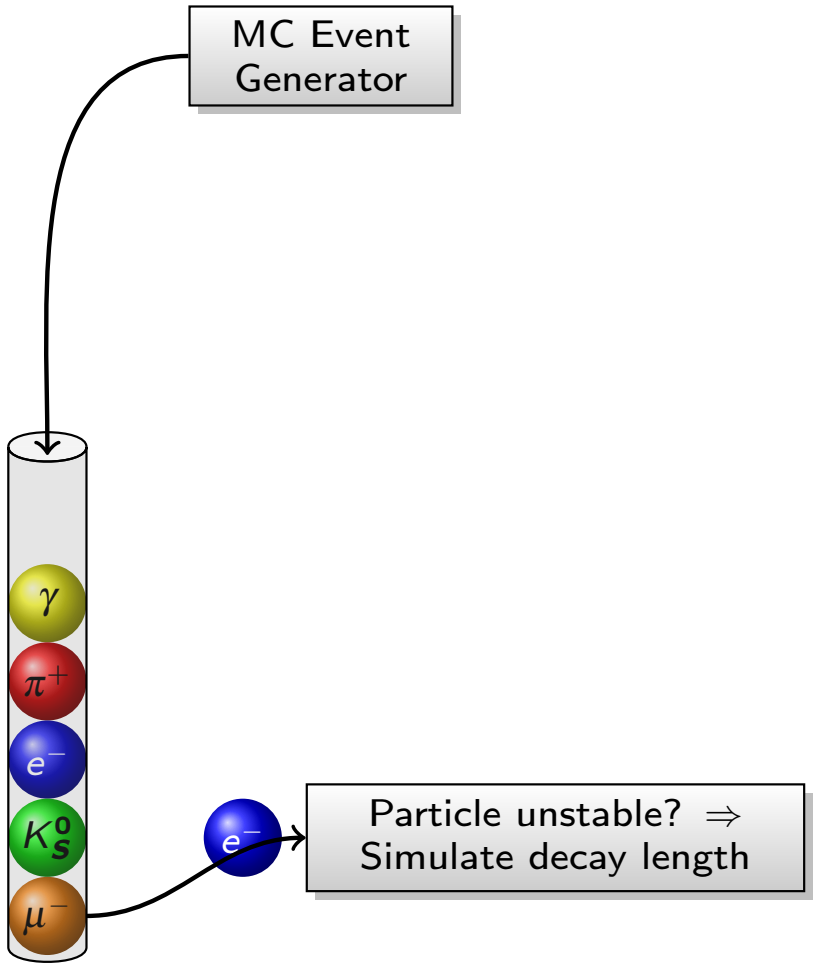


# Track simulation in FATRAS





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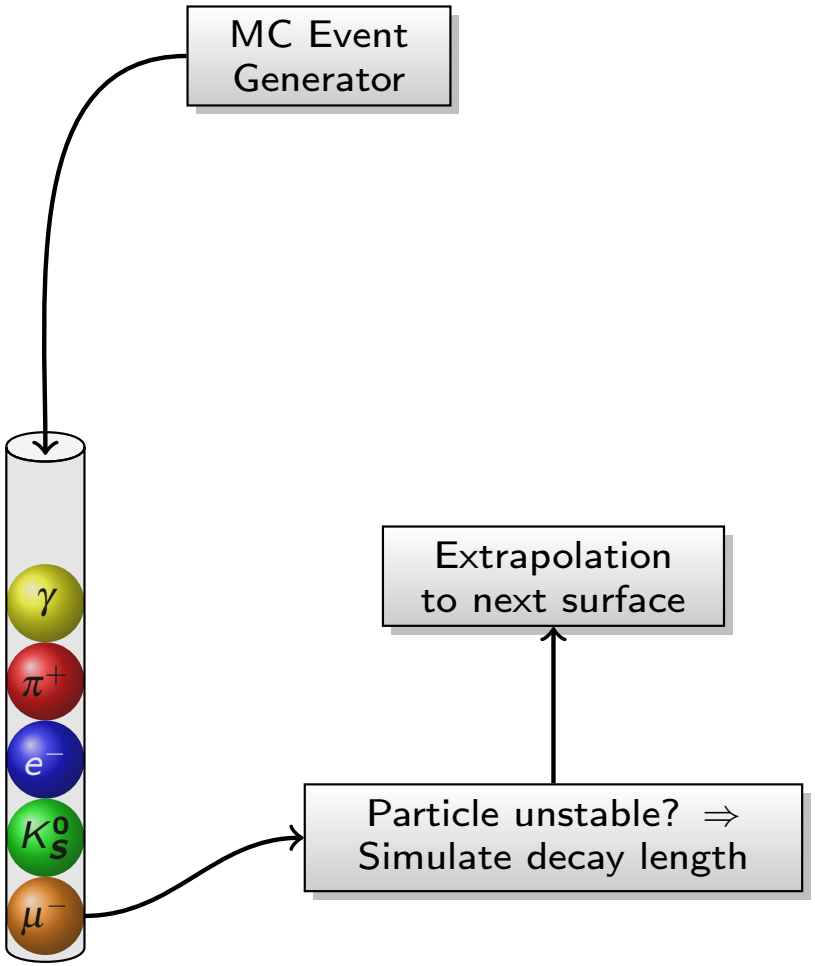


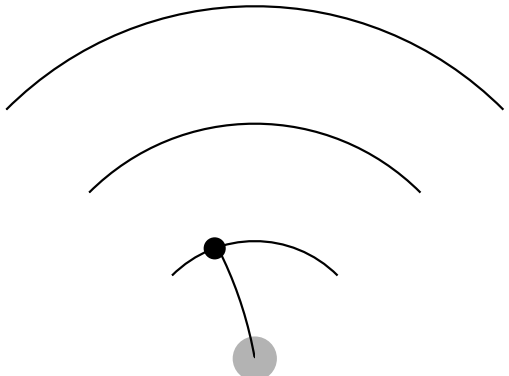

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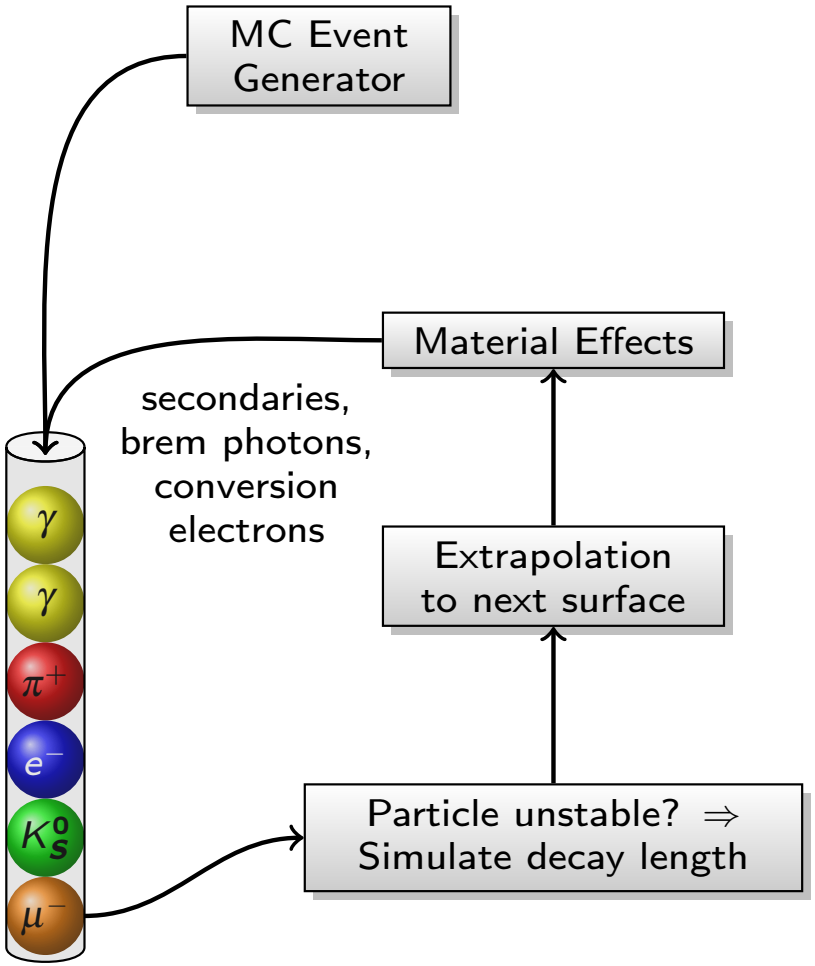


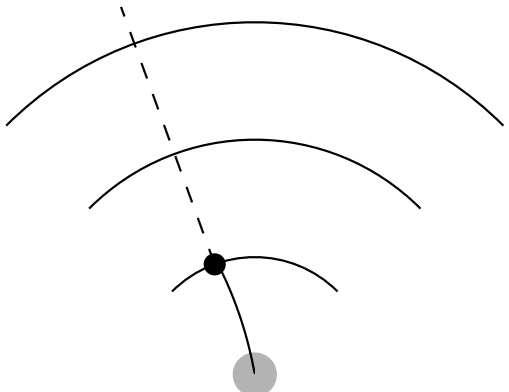

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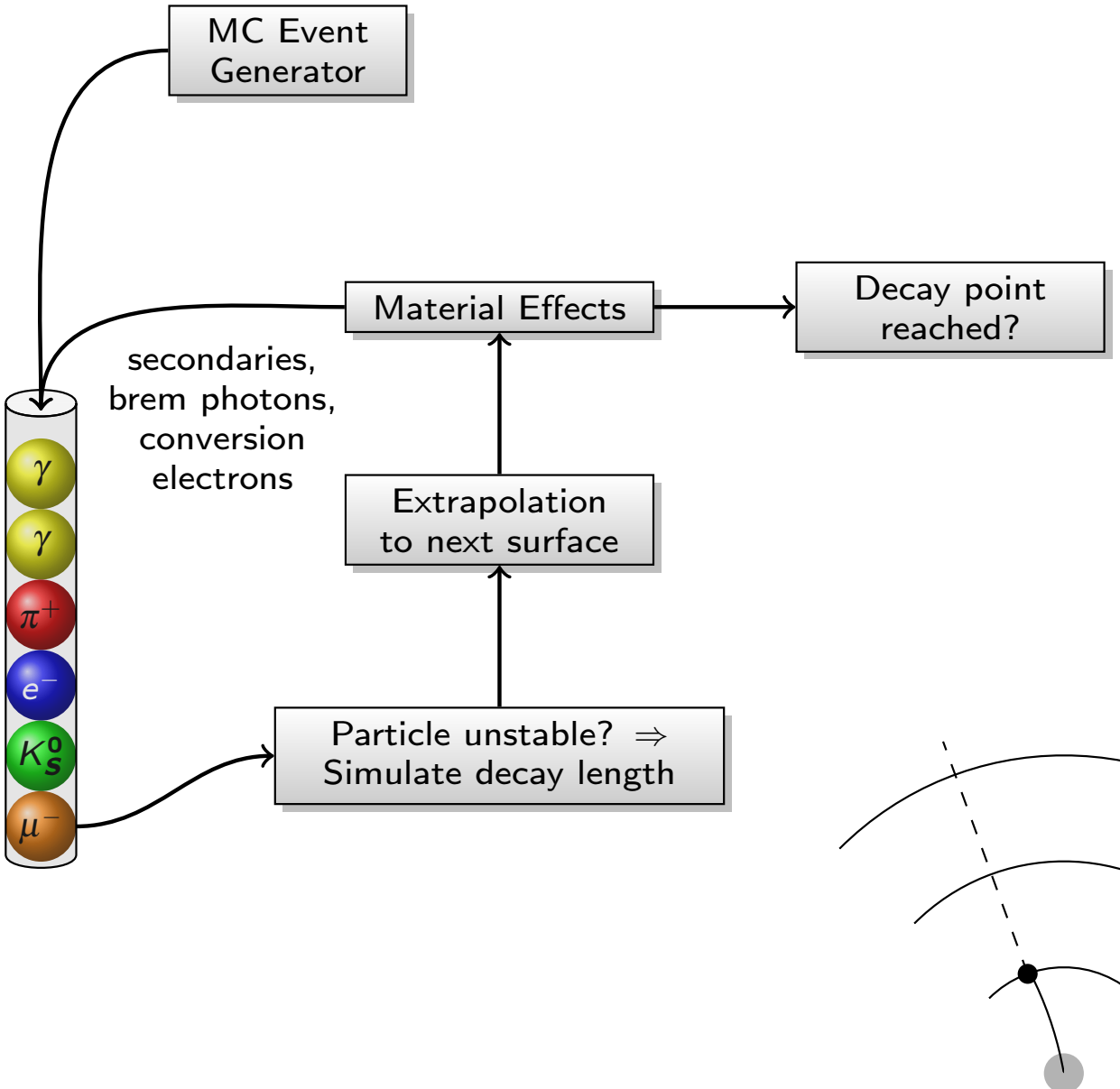

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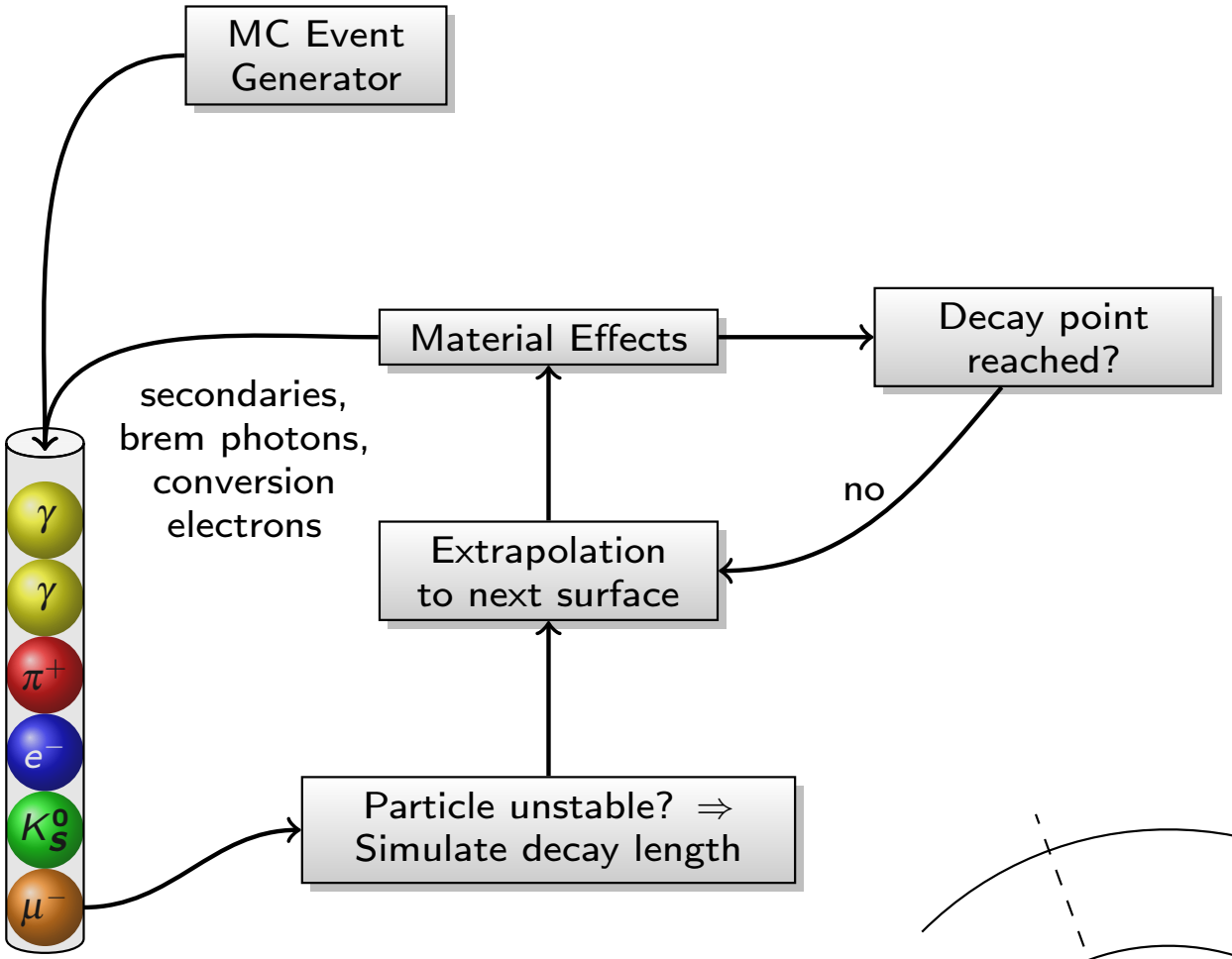


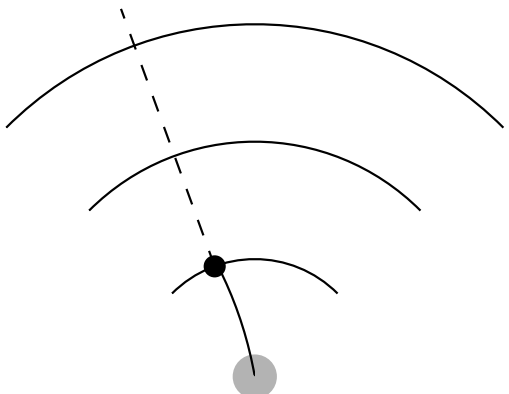

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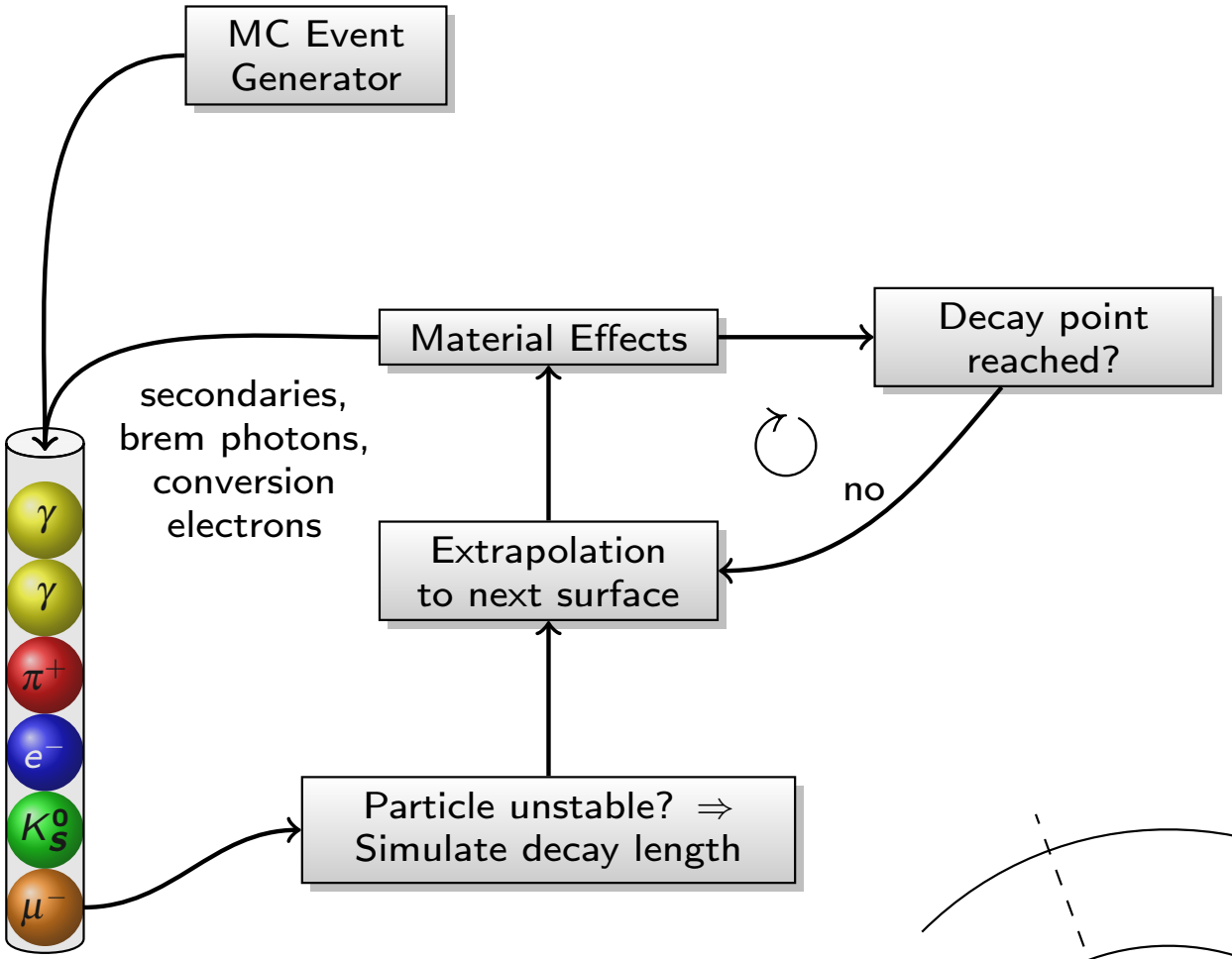


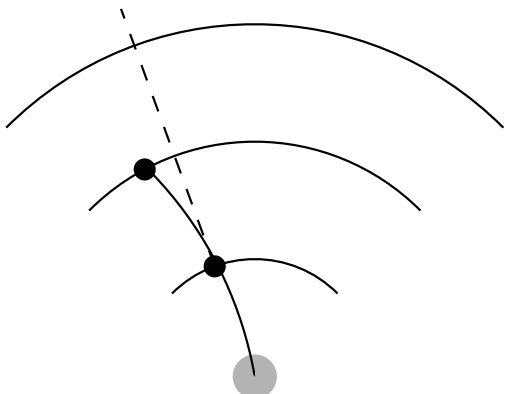

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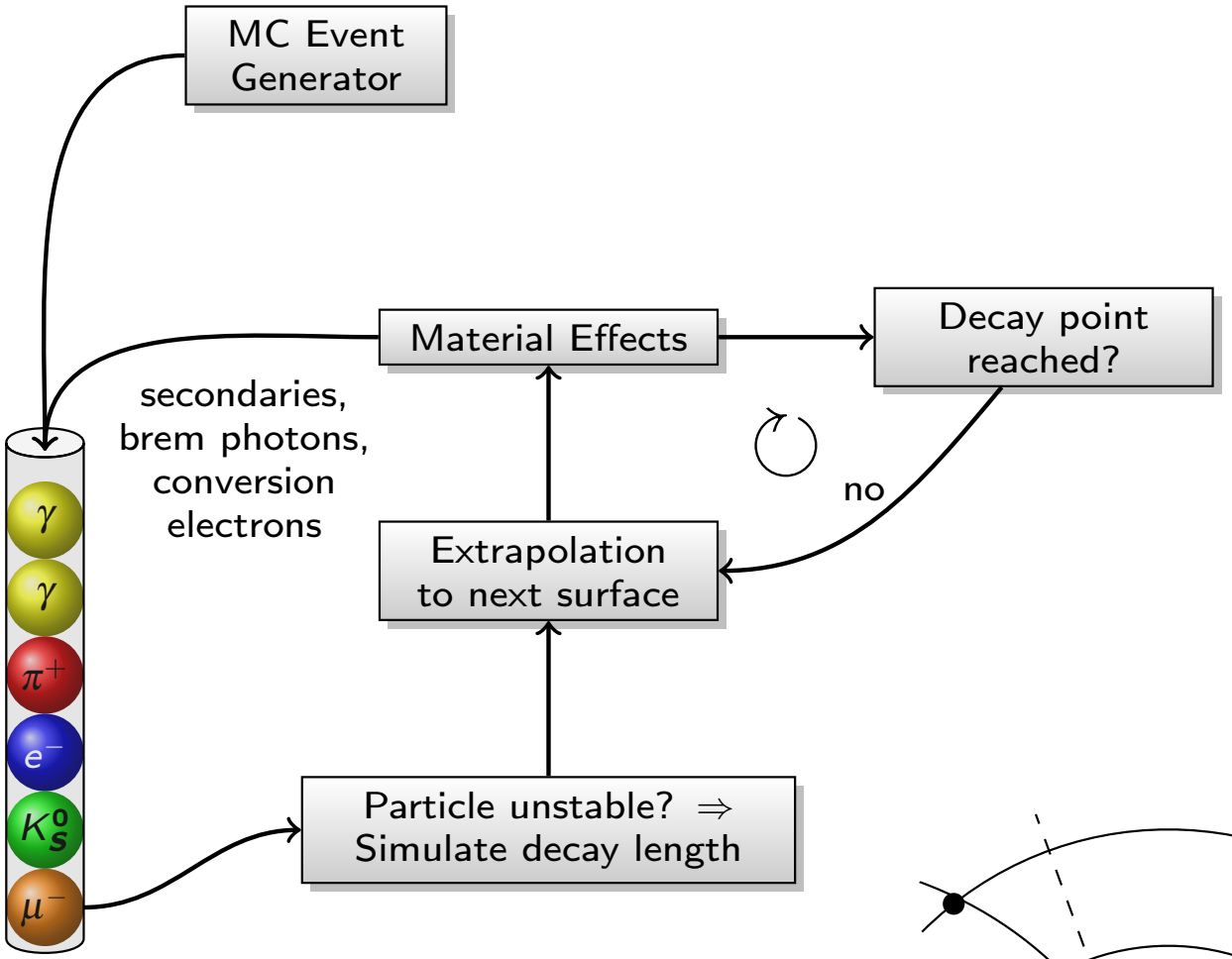


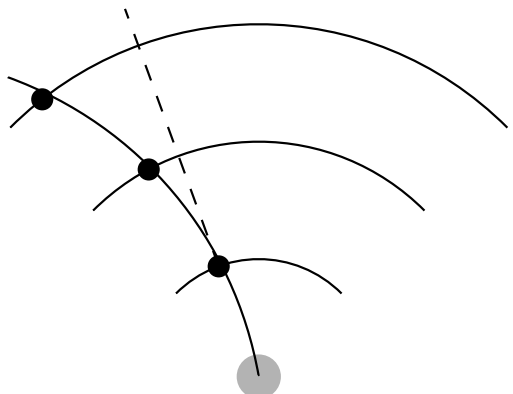

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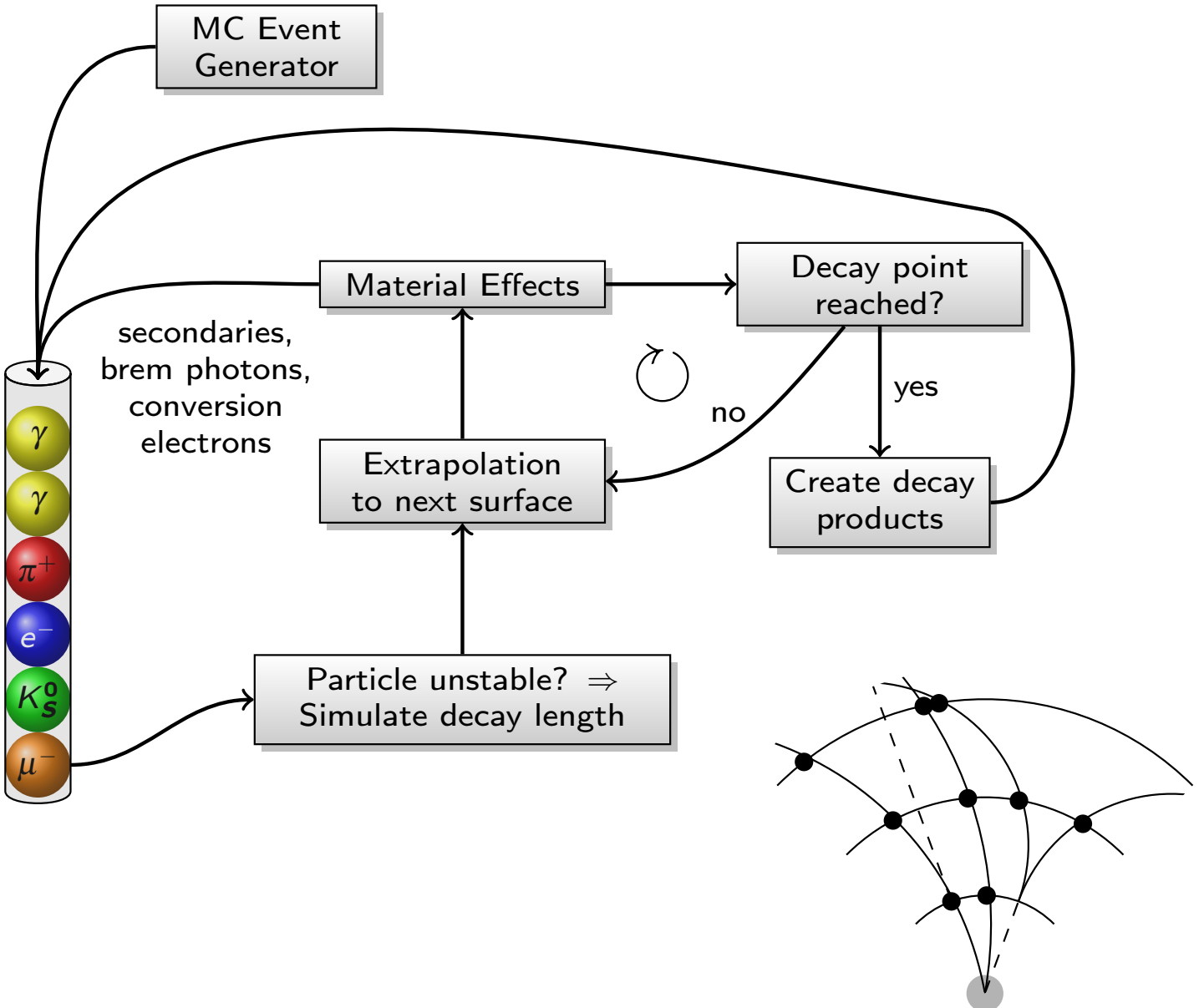
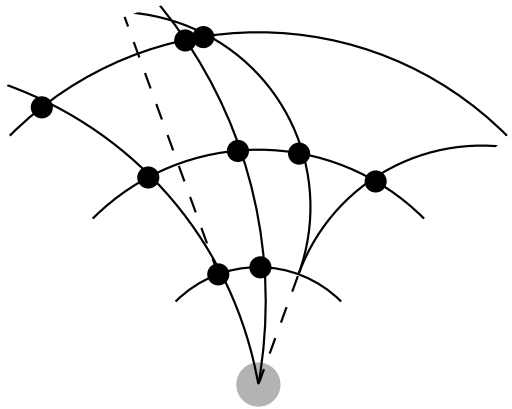


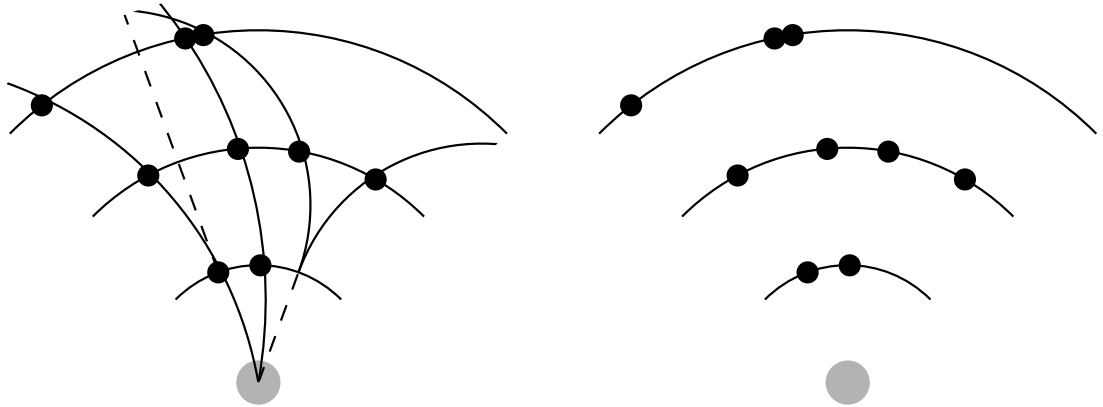
# Track simulation in FATRAS

## Postprocessing



# Track simulation in FATRAS

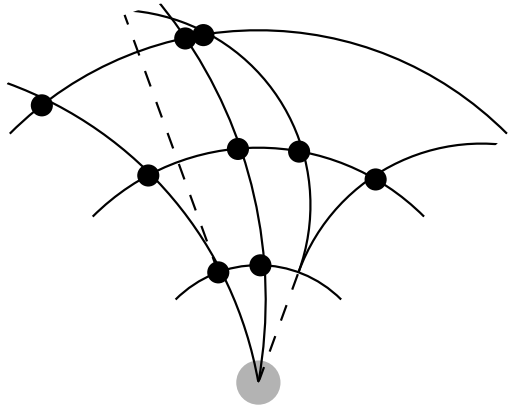
## Postprocessing

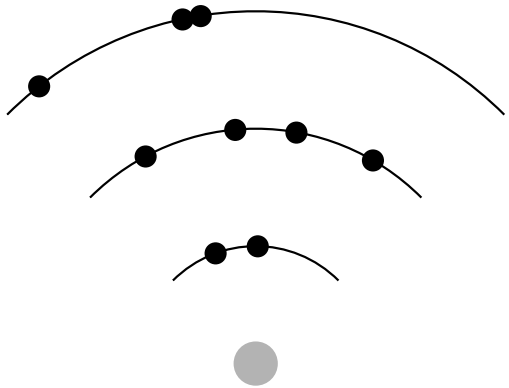


Extract measurements from simulated tracks

# Track simulation in FATRAS

## Postprocessing





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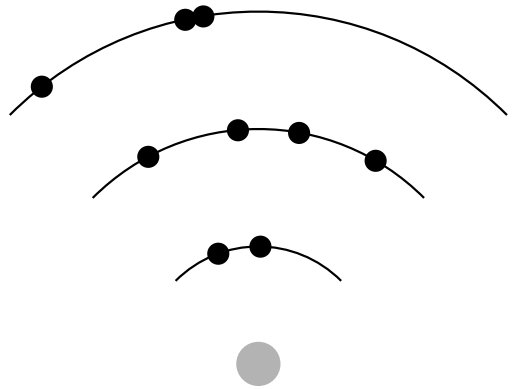

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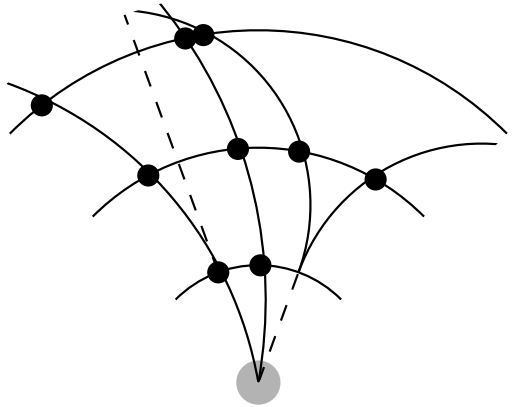
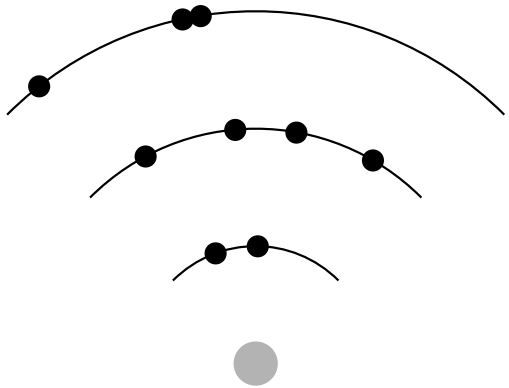
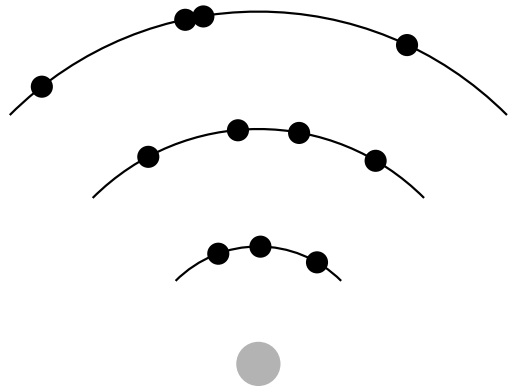
## Postprocessing





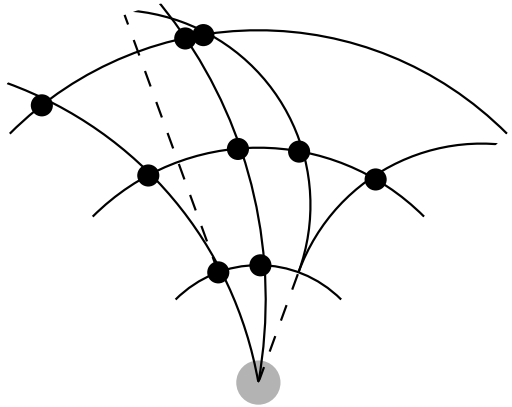
Extract measurements from simulated tracks

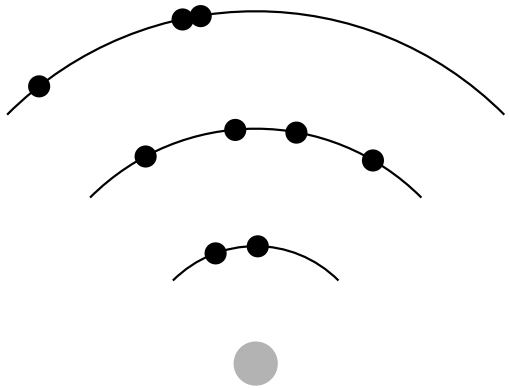


Add noise

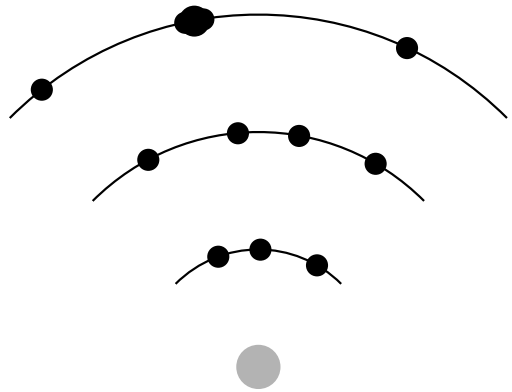
# Track simulation in FATRAS

## Postprocessing





Extract measurements from simulated tracks

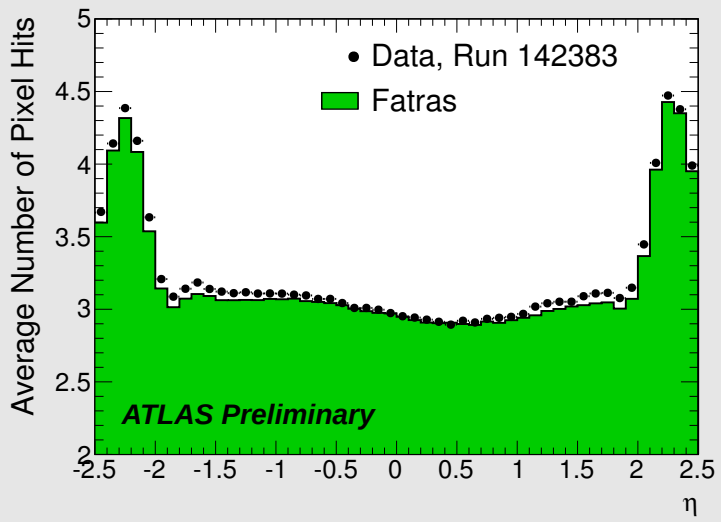


Add noise and merge clusters

# Reconstructed tracks in minimum bias events

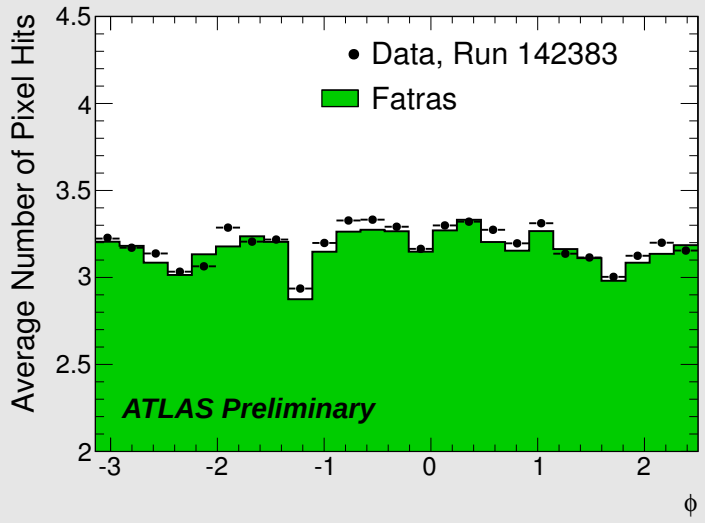
## Average number of Pixels hits per track

### Pixels hits / track vs $\eta$




"sinoidal structure" due to inactive Pixels modules in b-layer folded with the $z$-position of the primary vertex

### Pixels hits / track vs $\phi$

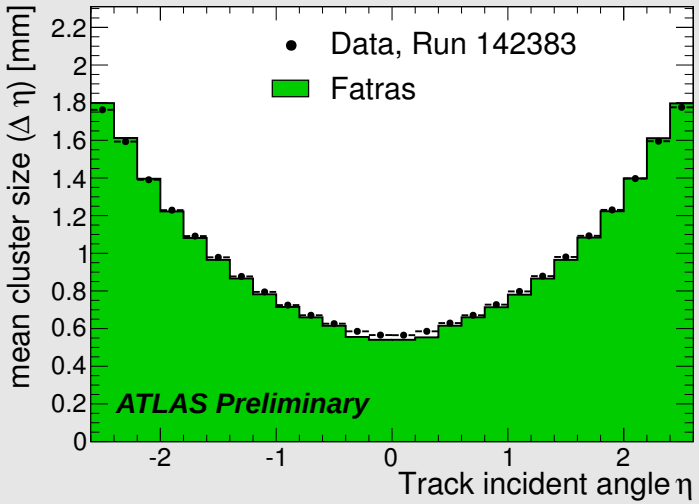



- Detector conditions like inactive modules automatically taken into account in FATRAS
- Precise description of the detector geometry

# Reconstructed tracks in minimum bias events at $\sqrt{s} = 900\text{GeV}$



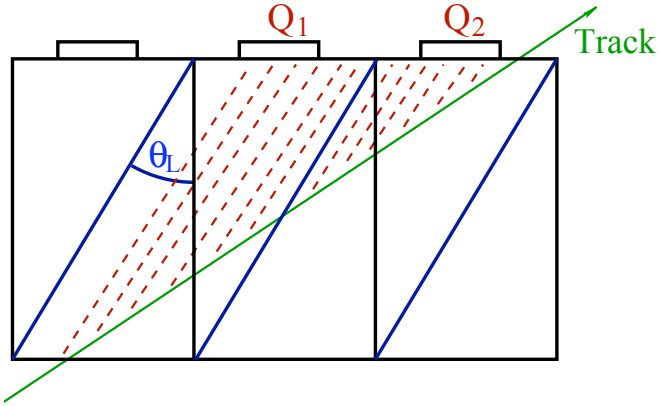
## Pixel cluster size




Mean cluster size (in $\eta$ direction) vs incident angle ($\eta$) on the Pixel module

- Cluster size depends on incident angle, because of sensor thickness

With Lorentz angle:




- Very sensitive test of the clusterisation model



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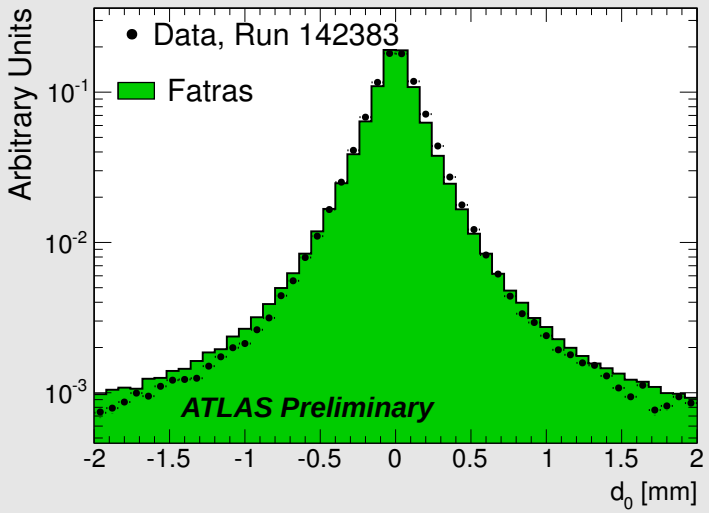
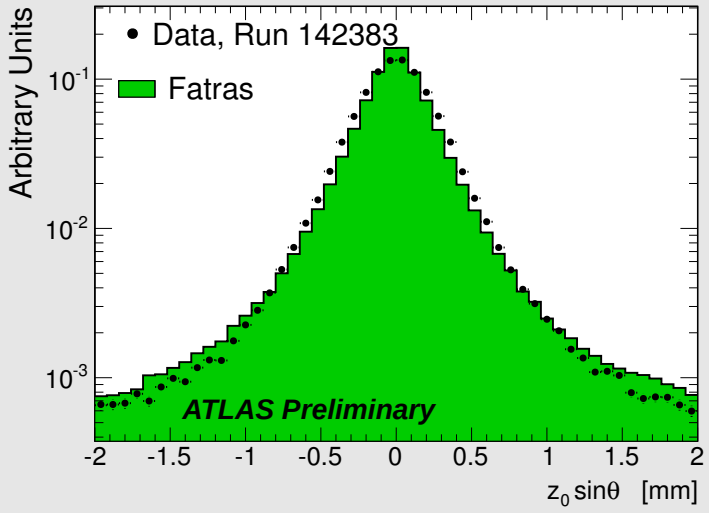
# Reconstructed tracks in minimum bias events at $\sqrt{s} = 900\text{GeV}$



## Transverse impact parameter wrt. primary vertex




## Longitudinal impact parameter




- Position and size of the beam spot in the simulation taken from detector conditions data base