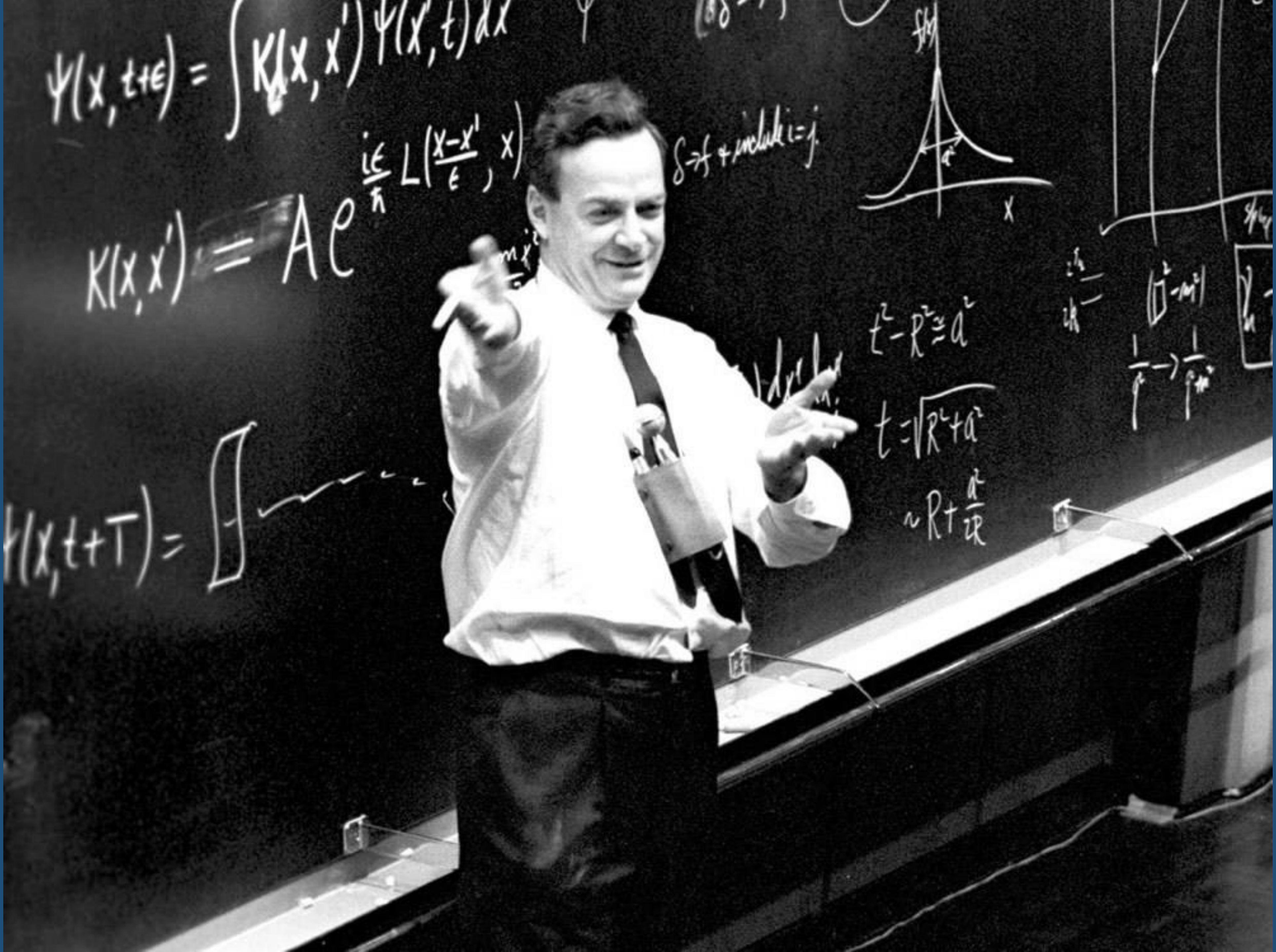
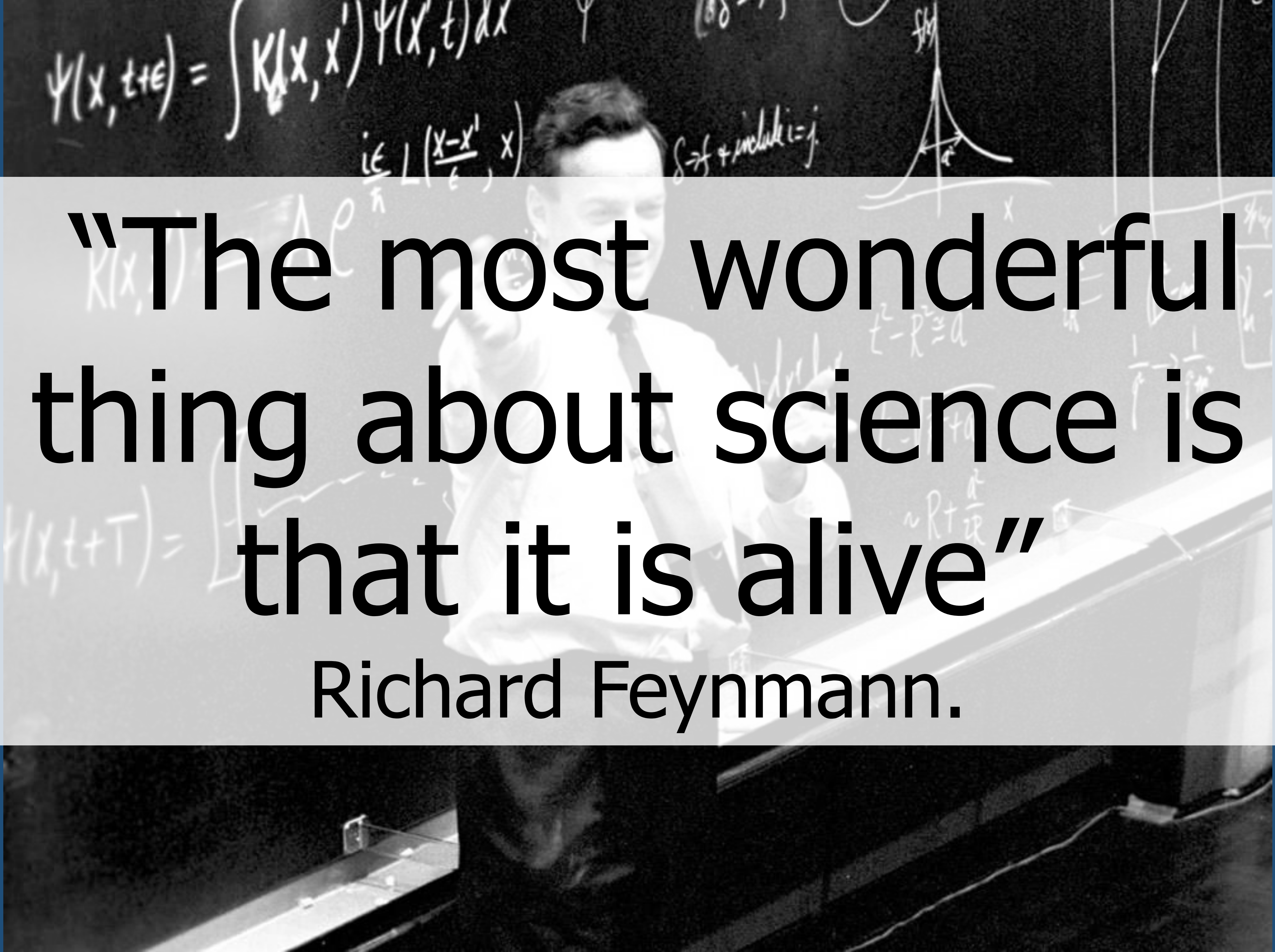
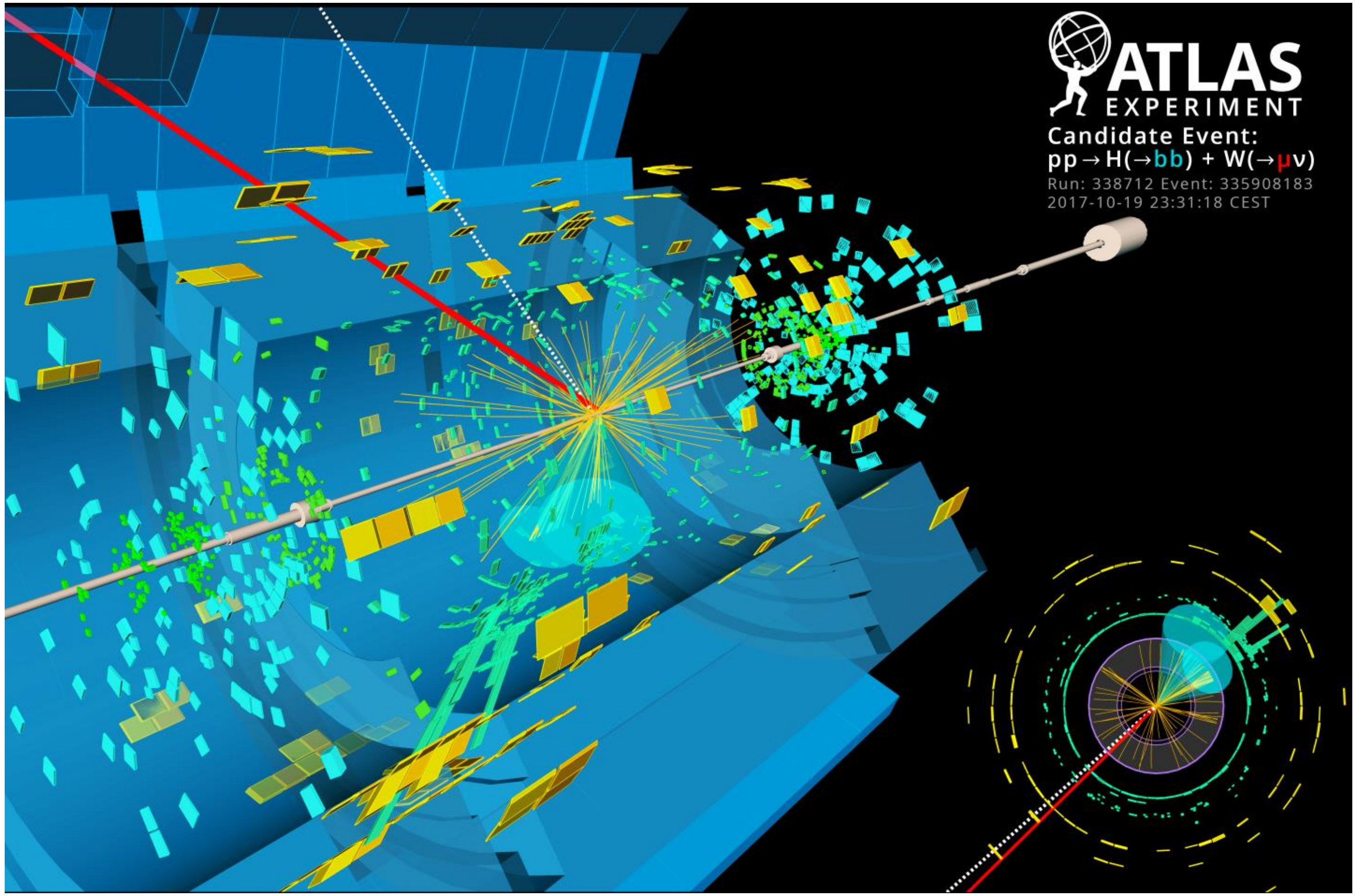


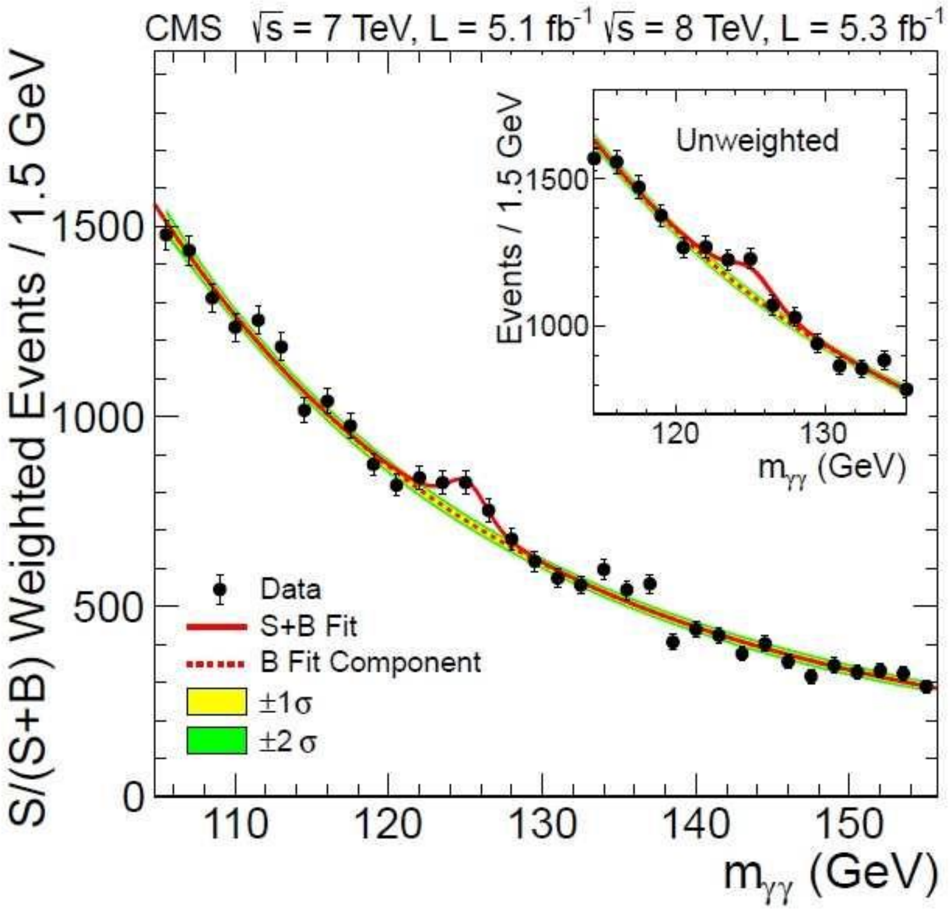


“The most wonderful thing about science is that it is alive”

Richard Feynmann.

Higgs observation at the LHC.



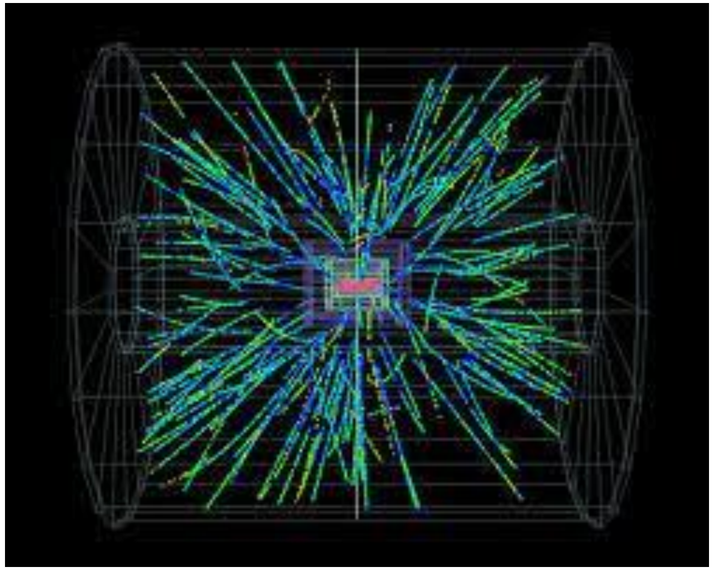


What is next?

Is there something beyond the Standard Model?

Are there any more Higgs?

Charged Higgs bosons at the LHC under the 2HDM



Victor Rodriguez Lorenzo

9 of December 2022

PHYS117: Project in Physics

Index:

- **Background**
  - Two Higgs Doublets Model
  - Production processes
  - Decay processes
- **Experimental procedure**
  - Conservation laws, energy-momentum relations and other relevant magnitudes
  - Reading Les Houches Events files
  - Events generation
- **Results**
  - Angular distributions
  - Generation of events
- **Discussion**
- **Conclusions**

Two Higgs Doublets Model

Two Higgs doublets

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

Potential

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^+ \Phi_1 + m_{22}^2 \Phi_2^+ \Phi_2$$

$$-m_{12}^2 (\Phi_1^+ \Phi_2 - \Phi_2^+ \Phi_1) + \frac{\lambda_1}{2} (\Phi_1^+ \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^+ \Phi_2)^2$$

$$+\lambda_3 \Phi_1^+ \Phi_1 \Phi_2^+ \Phi_2 + \lambda_4 \Phi_1^+ \Phi_1 \Phi_2^+ \Phi_2 + \frac{\lambda_5}{2} [(\Phi_1^+ \Phi_2)^2 + (\Phi_2^+ \Phi_1)^2]$$

$$+\frac{\lambda_5}{2} [(\Phi_1^+ \Phi_2)^2 + (\Phi_2^+ \Phi_1)^2]$$

Two Higgs Doublets Model

Vacuum expectation values for each of the doublets

$$< \Phi_1 >= \frac{v_1}{\sqrt{2}} \qquad < \Phi_2 >= \frac{v_2}{\sqrt{2}}$$

Linear combination of previous solutions:

$$\Phi_1' = \cos\beta\Phi_1 + \sin\beta\Phi_2$$
$$\Phi_2' = -\sin\beta\Phi_1 + \cos\beta\Phi_2$$

$$\tan\beta = \frac{v_2}{v_1}$$

Non-trivial vacuum expectation value for only one of the doublets:

$$< \Phi_1' >= \frac{v}{\sqrt{2}} \qquad < \Phi_2' >= 0$$

$$v = \sqrt{v_1^2 + v_2^2} = (246 \text{ GeV})^2.$$

Two Higgs Doublets Model

Yukawa coupling of the Higgs bosons to the quarks and leptons:

$$\mathcal{L}_{yuk} = -\sum_{f=u,d,l} \left(\frac{m_f}{v} \xi_h^f \bar{f} f h + \frac{m_f}{v} \xi_H^f \bar{f} f H - i \frac{m_f}{v} \xi_A^f \bar{f} \gamma_5 f A \right)$$

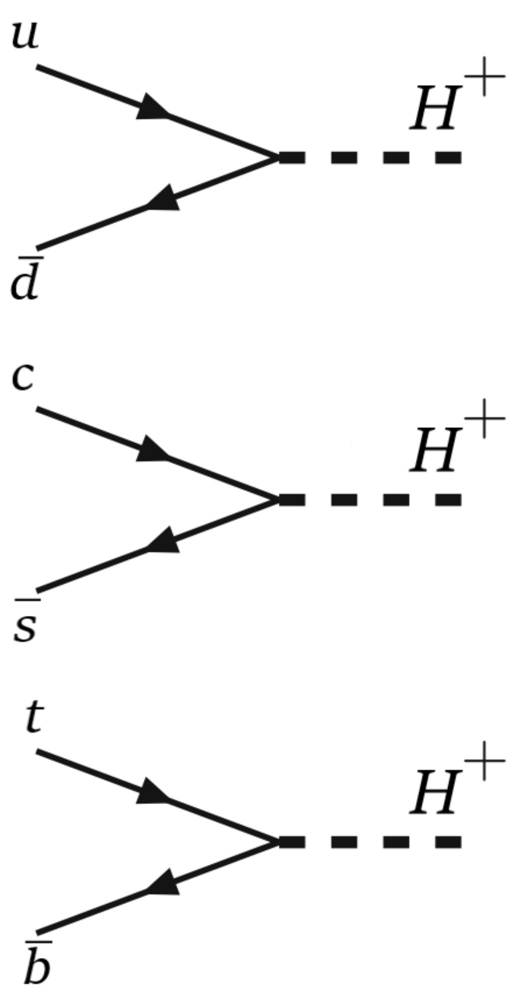
$$- \left[\frac{\sqrt{2} V_{ud}}{v} \bar{u} (m_u \xi_A^u P_L + m_d \xi_A^d P_R) d H^+ \right.$$

$$\left. + \frac{\sqrt{2} m_l \xi_A^l}{v} \bar{\nu_L} l_R H^+ + h.c. \right]$$

	Type I	Type II	Type X
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$
ξ_A^l	$-\cot\beta$	$\tan\beta$	$\tan\beta$

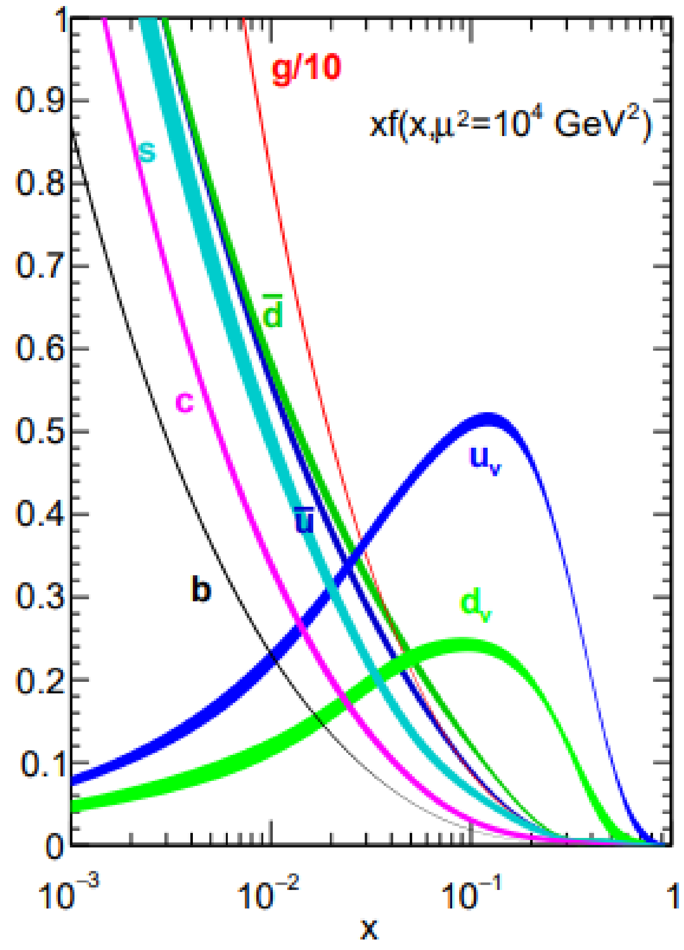
Production processes

Quark annihilation



Which is the most probable?

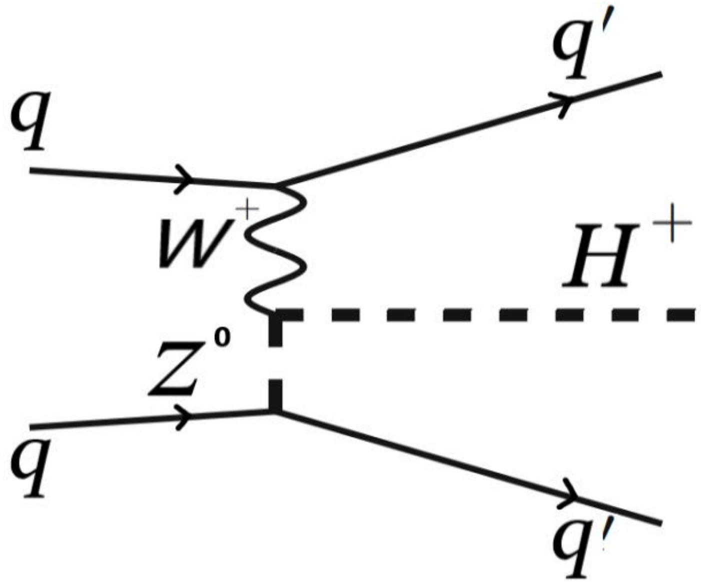
Parton Distribution Function of the proton



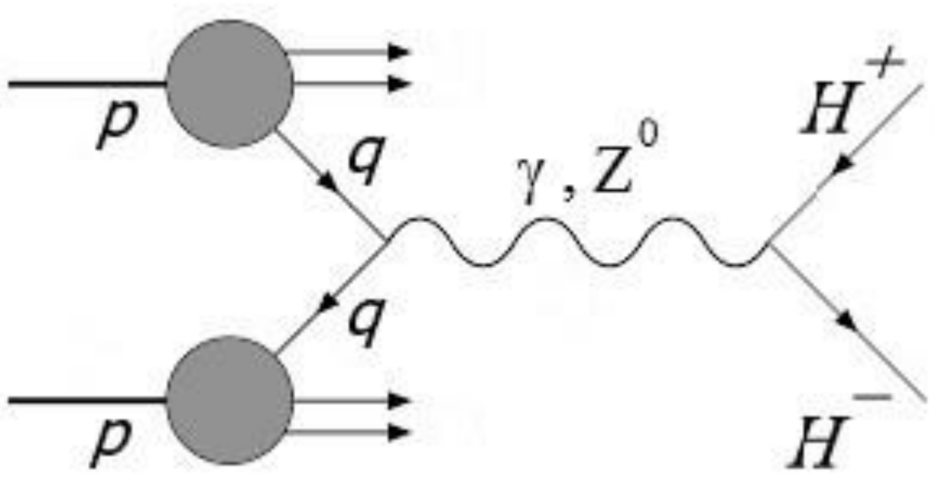
R. D. Ball, et al. "Parton distributions from high-precision collider data." *The European Physical Journal C*, 2017, vol. 77, no 10, pp. 1-75. [arXiv:1706.00428]

Production processes

Vector boson fusion



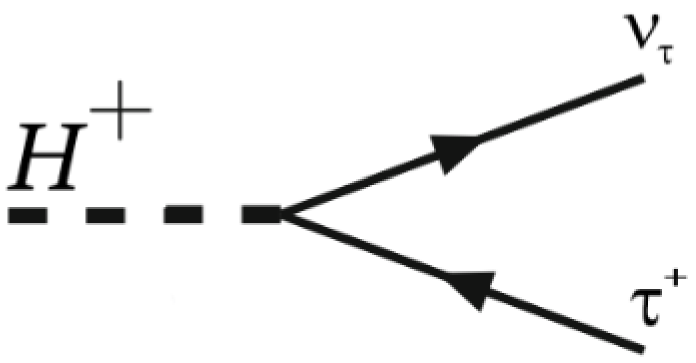
Drell Yang process



Decay processes

For a mass m_H=200 GeV and $\tan\beta = 35$

Lepton-antilepton decay



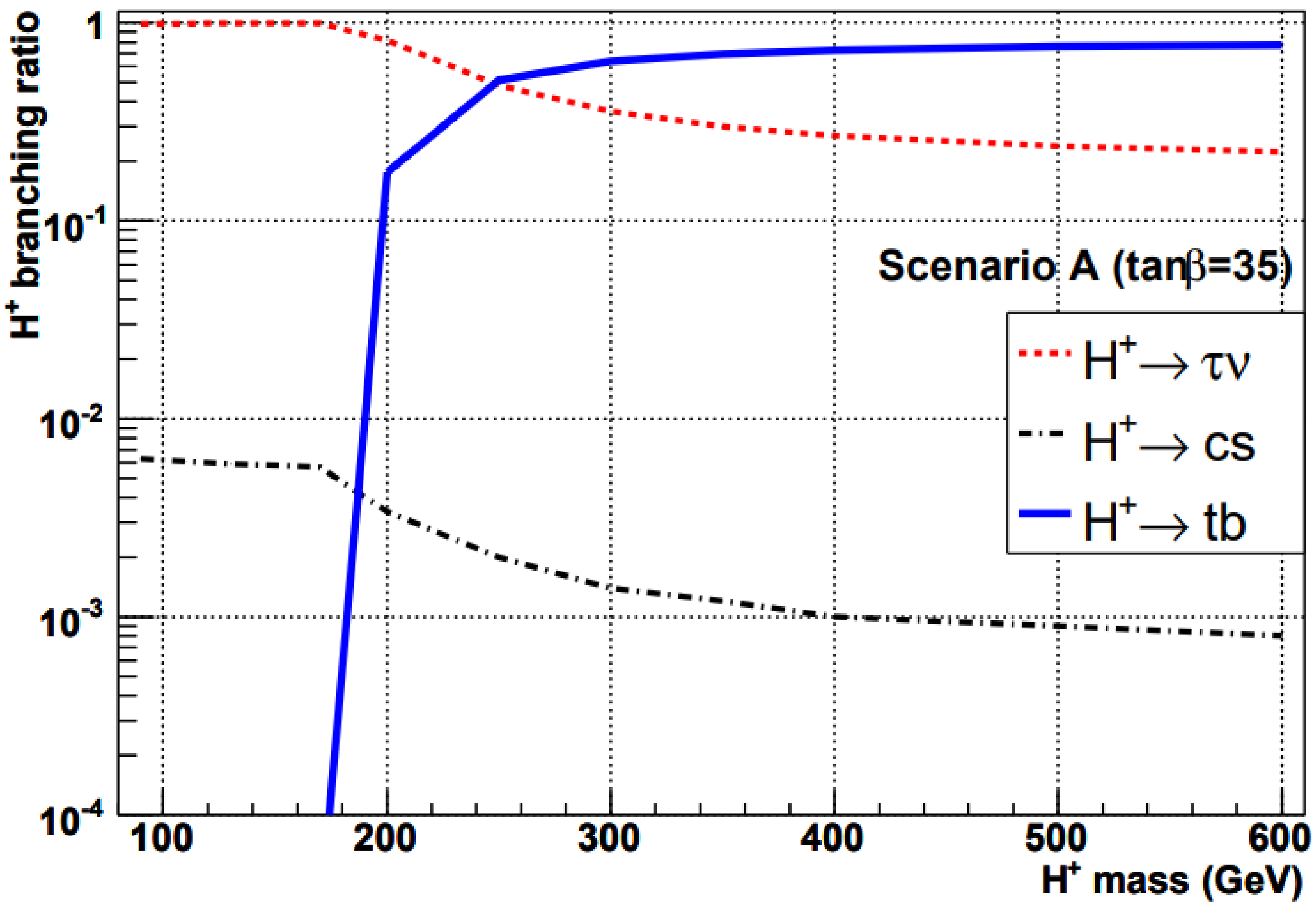
Processes involving quarks:

$$H^+ \to c\bar{s}$$
$$H^+ \to c\bar{b}$$
$$H^+ \to t\bar{b}$$

Processes involving vector bosons:

$$H^+ \to W^+\gamma$$
$$H^+ \to W^+Z$$

BR for the decay processes.



For $m_{H+} < m_t + m_b$

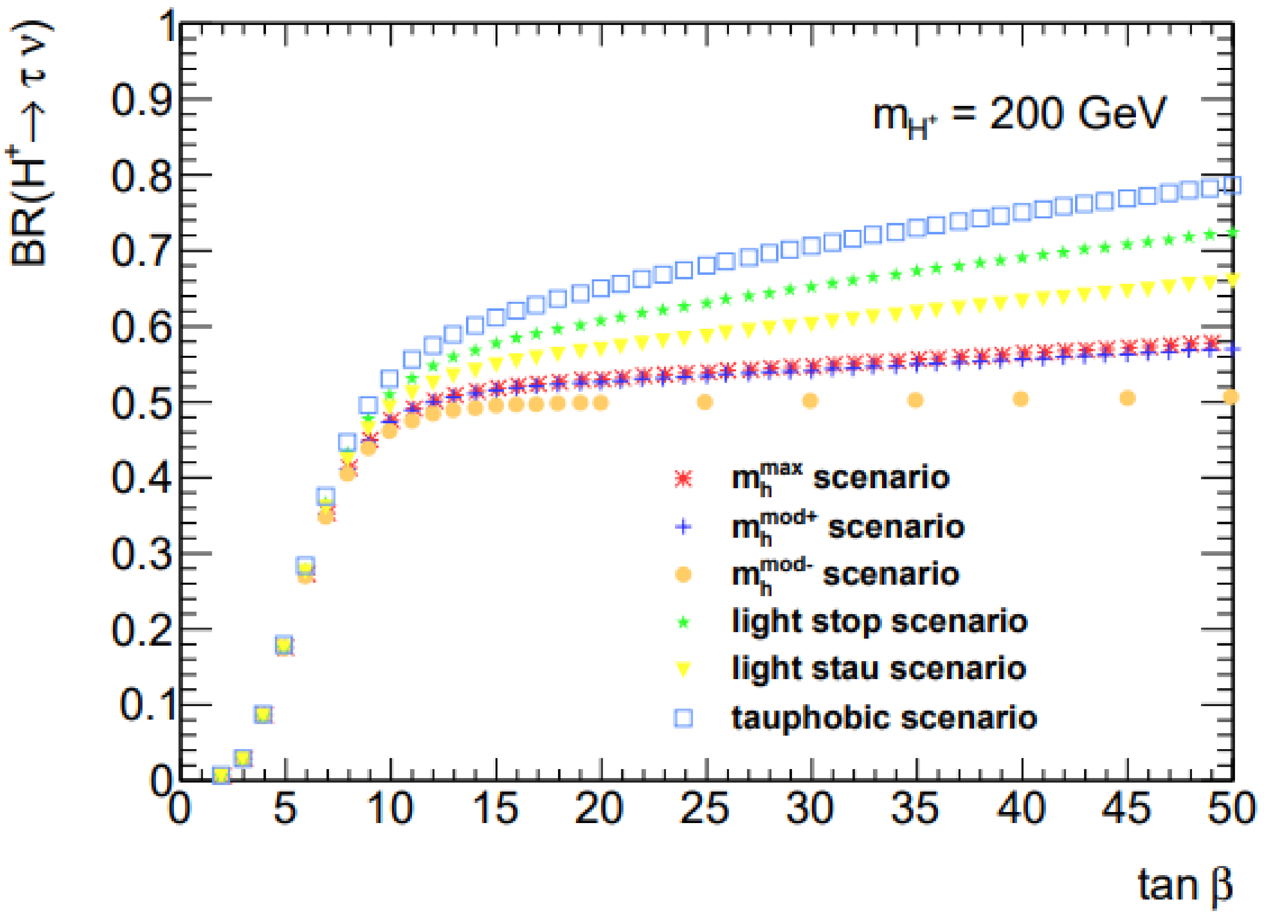
Antitau and tau neutrino as the most probable decay.

For $m_{H+} > m_t + m_b$

The top-bottom decay becomes increasingly more dominant.

A. Sopczak "Cross-sections and branching ratios for charged Higgs searches". *arXiv preprint*, 2009. [arXiv:0907.1498]

BR for the decay processes.



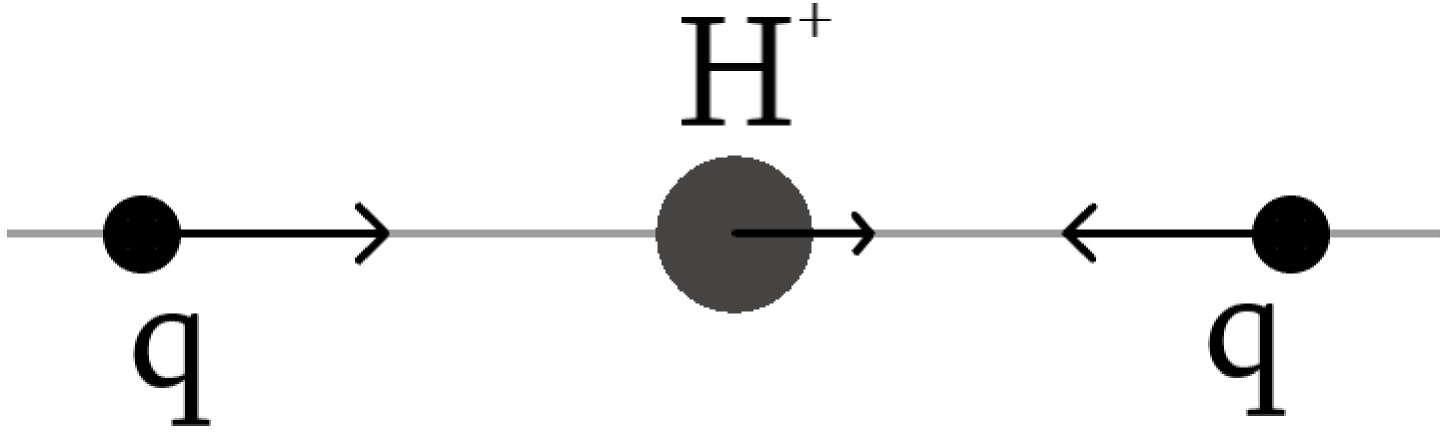
These branching ratios also change for different values of tan β

N. Bakhet; M. Yu Khlopov; T. Hussein. "Neural networks search for charged Higgs boson of two doublet Higgs model at the hadrons colliders". *arXiv preprint*. 2015 [arXiv:1507.06547]

Conservation laws.

- Linear momentum of the produced Higgs.

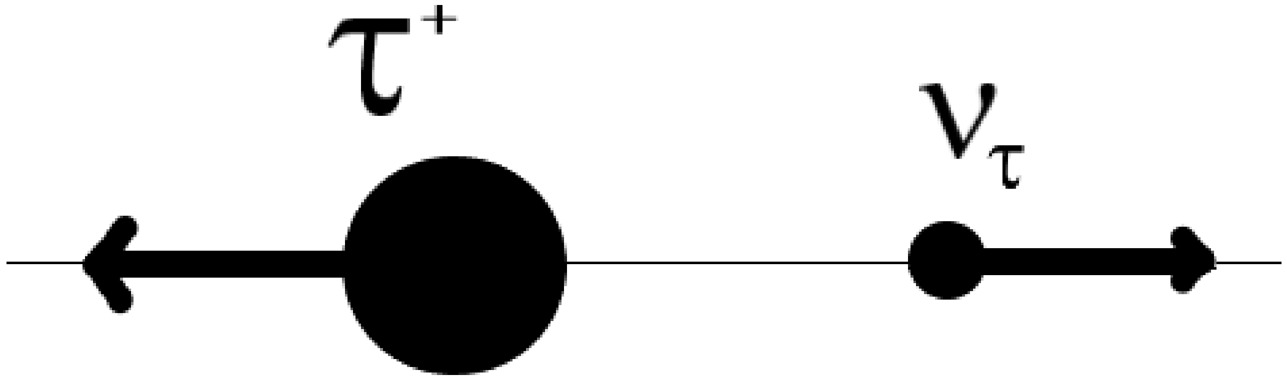
  Charged Higgs moving along the beam axis.



Conservation laws.

- Linear momentum of the decays.

$$\vec{p}_\tau = -\vec{p}_{\nu_\tau}$$



Conservation laws.

- Total angular momentum. $\vec{J} = \vec{L} + \vec{S}$

$$\vec{J}_H = \vec{J}_{\tau+\nu_\tau}$$

$$\left.\begin{aligned} \vec{J}_H &= \vec{L}_H + \vec{S}_H = 0 + 0 = 0 \\ \vec{J}_{\tau+\nu_\tau} &= \vec{L} + \vec{S}_\tau + \vec{S}_{\nu_\tau} \end{aligned}\right\}$$

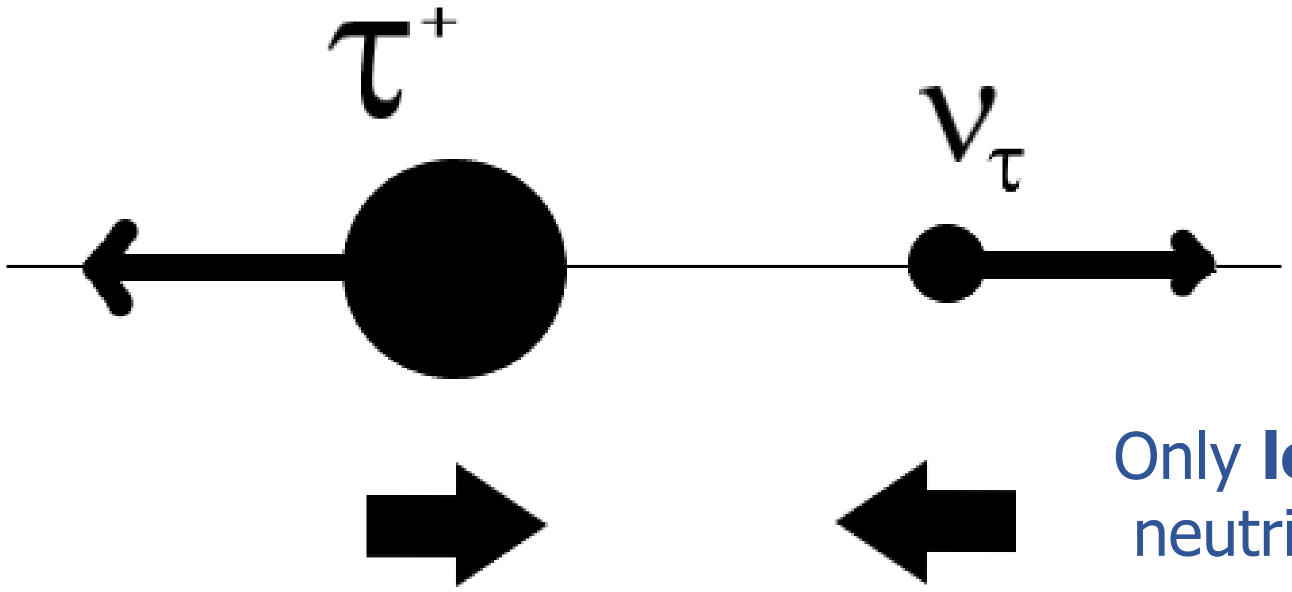
$\ell = 0, 1$

Looking at the configuration of the decay, which **cannot have a preferred orientation** for the decay, it must be

$$\boxed{\ell = 0}$$

Conservation laws.

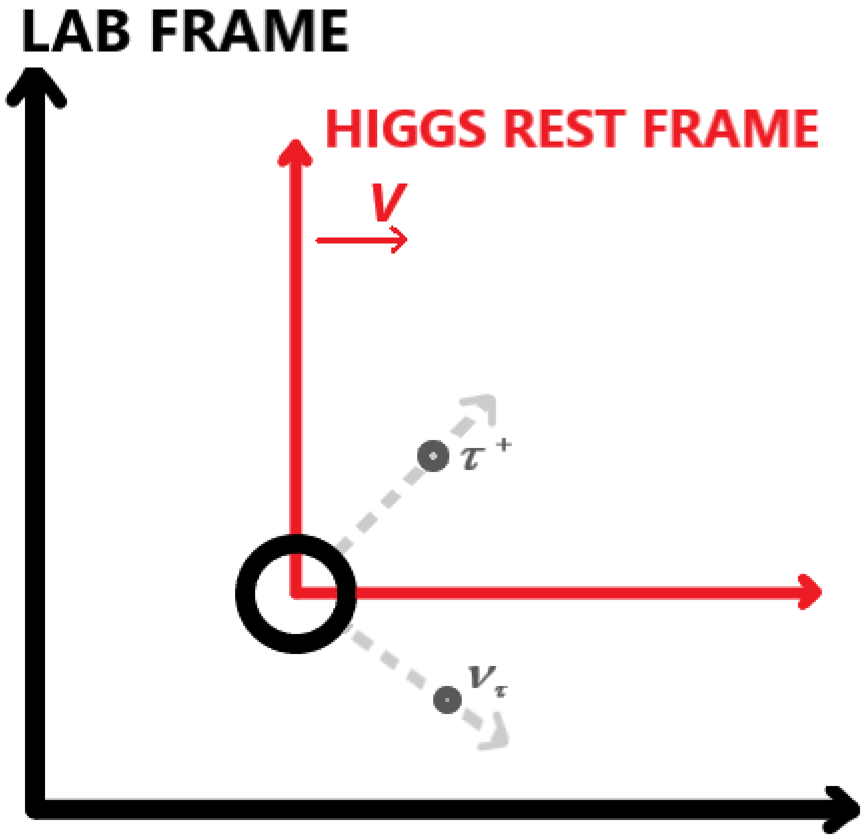
- Spin of the decays.



Only **left-handed** neutrinos exist in nature.

Energy and momentum relations.

- Energy of the tau in the Higgs rest frame.



$$(P_H^\mu - P_\tau^\mu)^2 = P_{\nu_\tau}^\mu P_{\nu_\tau}^\mu = M_{\nu_\tau}^2 = 0$$
$$P_H^\mu P_H^\mu + P_\tau^\mu P_\tau^\mu - 2P_H^\mu P_\tau^\mu = 0$$
$$M_H^2 + M_\tau^2 - 2(E_H^* E_\tau^* - \vec{p_H}\vec{p_\tau}) = 0$$
$$M_H^2 + M_\tau^2 - 2(M_H E_\tau^*) = 0$$

$$\Longrightarrow E_\tau^* = \frac{M_H^2 + M_\tau^2}{2M_H}$$

Energy and momentum relations.

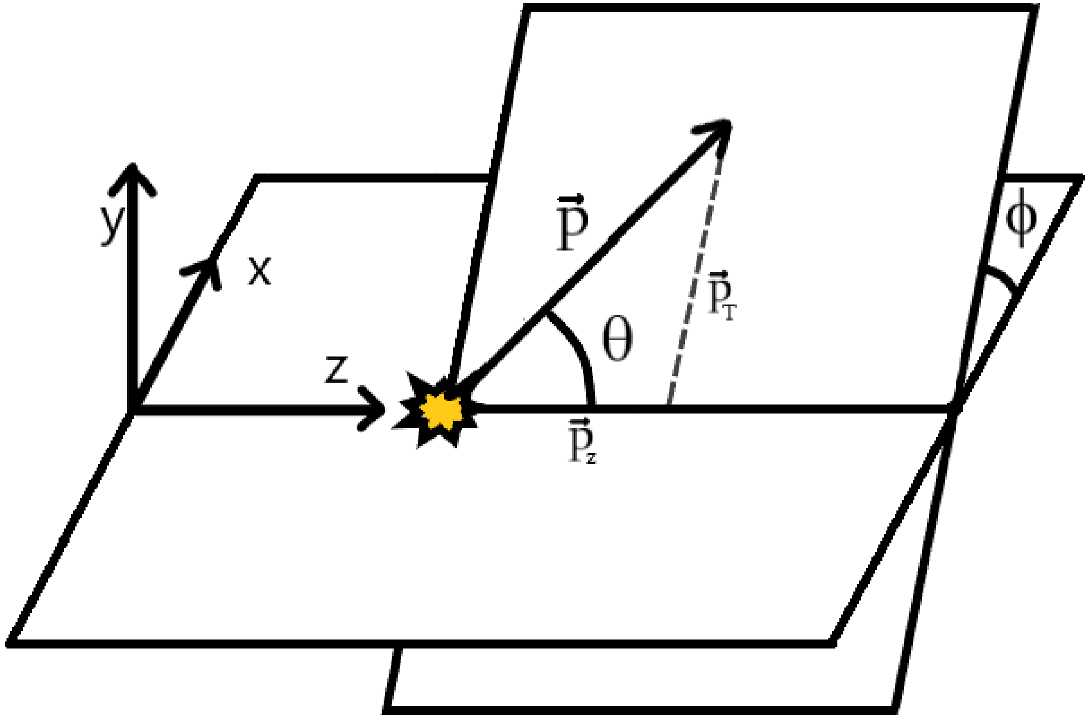
- Velocity coefficient.

$$E_\tau^* = \frac{E_\tau - v p_{\tau,z}}{\sqrt{1 - v^2/c^2}} = \frac{E_\tau - \beta c p_{\tau,z}}{\sqrt{1 - \beta^2}}$$

$$\beta = \frac{E_\tau c p_{\tau,z} \pm \sqrt{c^2 p_{\tau,z}^2 E_\tau^{*2} - E_\tau^{*2} E_\tau^2 + E_\tau^{*4}}}{(c^2 p_{\tau,z}^2 - E_\tau^{*2})}$$

Energy and momentum relations.

- Polar and azimuthal angles.



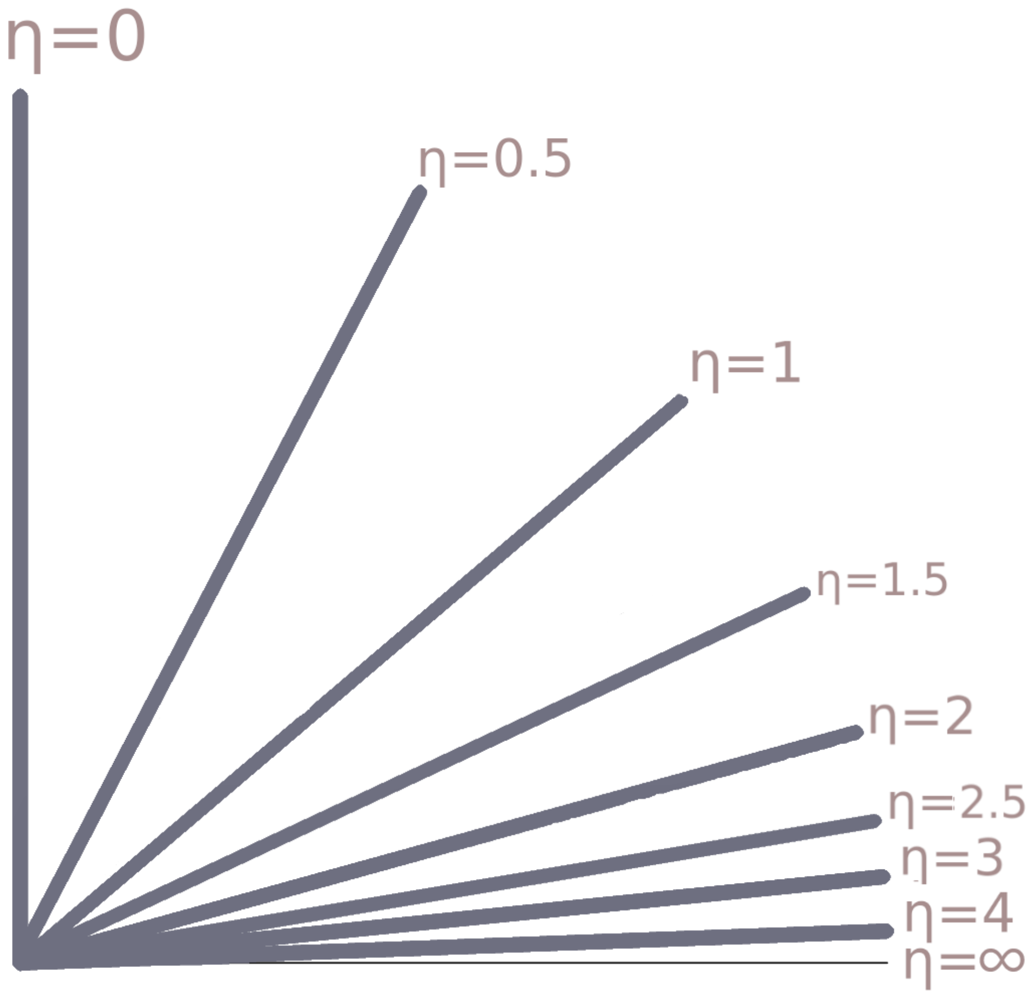
Polar angle: angle between the tau momentum and the beam axis

Azimuthal angle: angle around the beam axis

How do we get the polar angle from the measurements in the lab?

$$\tan(\theta^*) = \frac{p_\perp^*}{p_\parallel^*} = \frac{p_\tau \sin\theta}{\gamma(p_\tau \cos\theta - \beta E_\tau / c)}$$

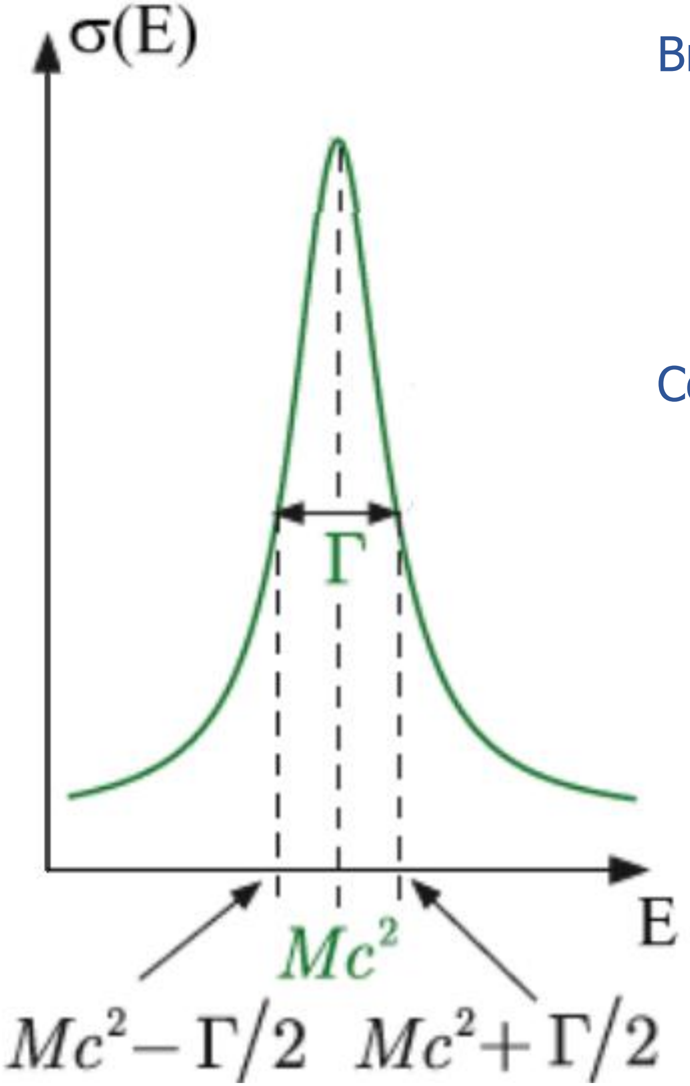
Pseudorapidity.



Describes the angle between the momentum of a particle and the beam axis.

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Decay widths.



Breit-Wigner distribution.

$$\Gamma_{H^+} = \Gamma_{H^+\to\tau^+\nu_\tau} + \Gamma_{H^+\to\mu^+\nu_m u} + \Gamma_{H^+\to t\bar{b}} + \Gamma_{H^+\to t\bar{s}} + \Gamma_{H^+\to t\bar{d}} + \Gamma_{H^+\to c\bar{b}} + \ldots$$

Consequence of the uncertainty principle

$$\Gamma = 2\Delta E = \frac{\hbar}{\tau}$$

Lifetime of the charged Higgs:

$$\tau_{H^+} = \frac{\hbar}{\Gamma_{H^+}} = 6.59 \cdot 10^{-25}\ \mathrm{s}$$

Reading Les Houches Events files.

Original LHE file

```
<event>
 5   0  0.1170000E-07  0.2007119E+03  0.7816531E-02  0.1149140E+00
       -3    -1     0     0     0  501  0.00000000000E+00  0.00000000000E+00  0.98858873129E+02  0.98858928890E+02  0.12500000000E+01 0.  1.
        4    -1     0     0   501    0  0.00000000000E+00  0.00000000000E+00 -0.10186786837E+03  0.10187553733E+03  0.10499999672E+00 0.  1.
       37     2     1     2     0    0  0.00000000000E+00  0.00000000000E+00 -0.30089952384E+01  0.20073446622E+03  0.20071191264E+03 0.  0.
      -15     1     3     3     0    0  0.20662917874E+02  0.83965590618E+02  0.49418318949E+02  0.99611769181E+02  0.17769999504E+01 0. -1.
       16     1     3     3     0    0 -0.20662917874E+02 -0.83965590618E+02 -0.52427314187E+02  0.10112269704E+03  0.00000000000E+00 0. -1.
</event>
```

Processed LHE file format.

```
EVENT NUMBER 9780
Particle(pdgid=-3, px=0.0, py=0.0, pz=98.858873129, energy=98.85892889, mass=1.25, spin=1, status=-1, vtau=0.0, parent=-1)
Particle(pdgid=4, px=0.0, py=0.0, pz=-101.86786837, energy=101.87553733, mass=0.10499999672, spin=1, status=-1, vtau=0.0, parent=-1)
Particle(pdgid=37, px=0.0, py=0.0, pz=-3.0089952384, energy=200.73446622, mass=200.71191264, spin=0, status=2, vtau=0.0, parent=0)
Particle(pdgid=-15, px=20.662917874, py=83.965590618, pz=49.418318949, energy=99.611769181, mass=1.7769999504, spin=-1, status=1, vtau=0.0, parent=2)
Particle(pdgid=16, px=-20.662917874, py=-83.965590618, pz=-52.427314187, energy=101.12269704, mass=0.0, spin=-1, status=1, vtau=0.0, parent=2)
```

→ Particle Data Group ID

→ Momentum components of each particle

→ Other information: energy, mass, spin…

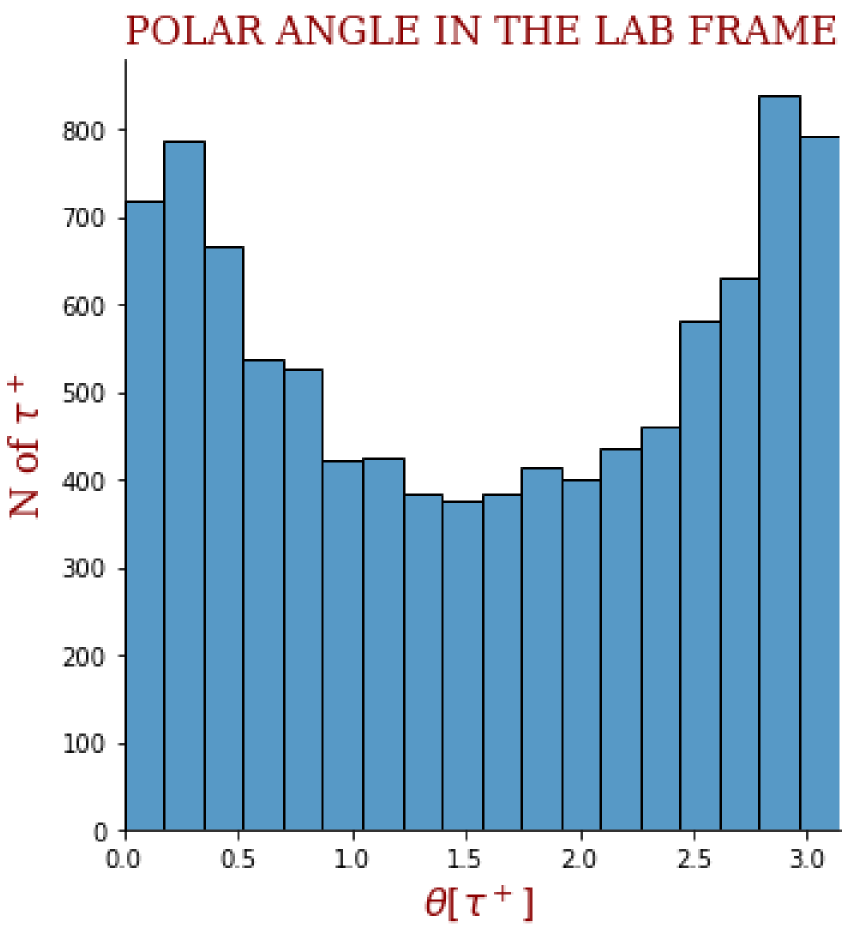
Events generation.

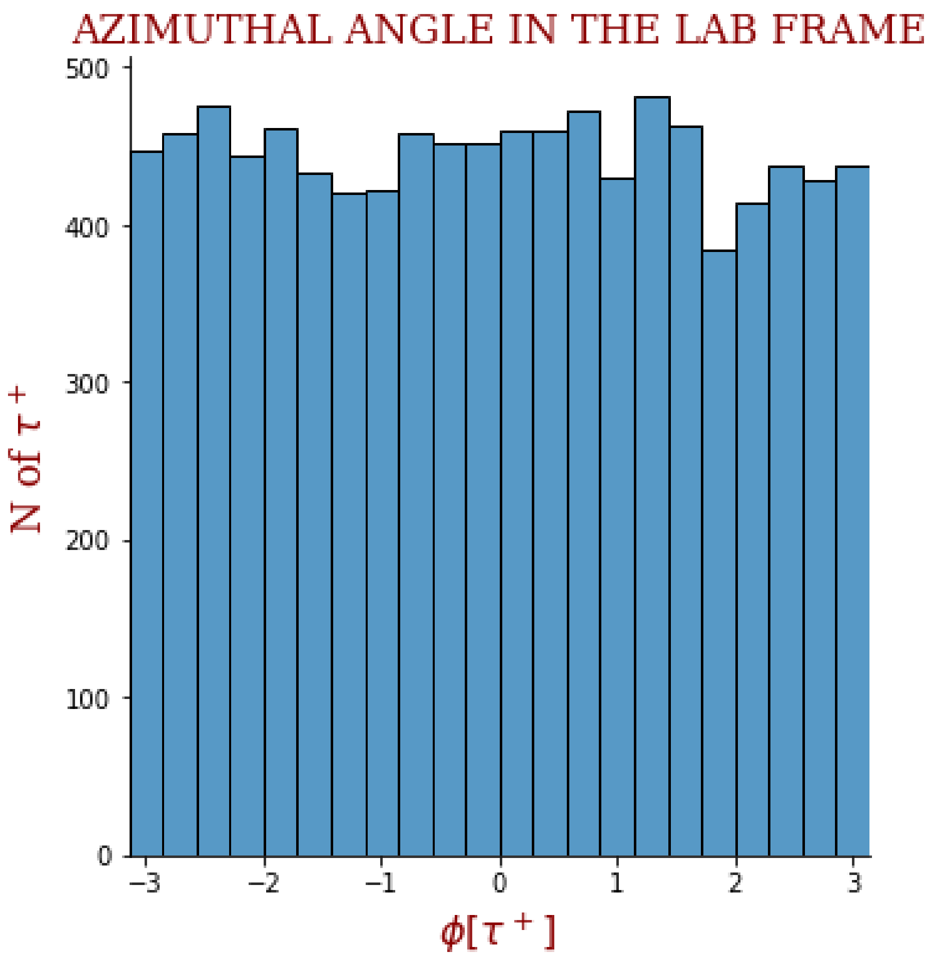
```
#************************************************************
#*                    MadGraph5_aMC@NLO                     *
#*                                                          *
#*                *                       *                 *
#*                  *        * *        *                   *
#*                    * * * * 5 * * * *                     *
#*                  *        * *        *                   *
#*                *                       *                 *
#*                                                          *
#*                                                          *
#*         VERSION 2.1.2                2014-07-03          *
#*                                                          *
#*    The MadGraph5_aMC@NLO Development Team - Find us at   *
#*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
#*                                                          *
#************************************************************
#*                                                          *
#*               Command File for MadGraph5_aMC@NLO         *
#*                                                          *
#*     run as ./bin/mg5_aMC  filename                       *
#*                                                          *
#************************************************************
import model 2HDM
define j = g u c d s u~ c~ d~ s~
define p = g u c d s u~ c~ d~ s~
define j = p
define l+ = e+ mu+
define l- = e- mu-
define vl = ve vm vt
define vl~ = ve~ vm~ vt~
generate  p p > h+ > ta+ vt
output madevent -f
</MG5ProcCard>
<MGProcCard>
```

Madgraph:

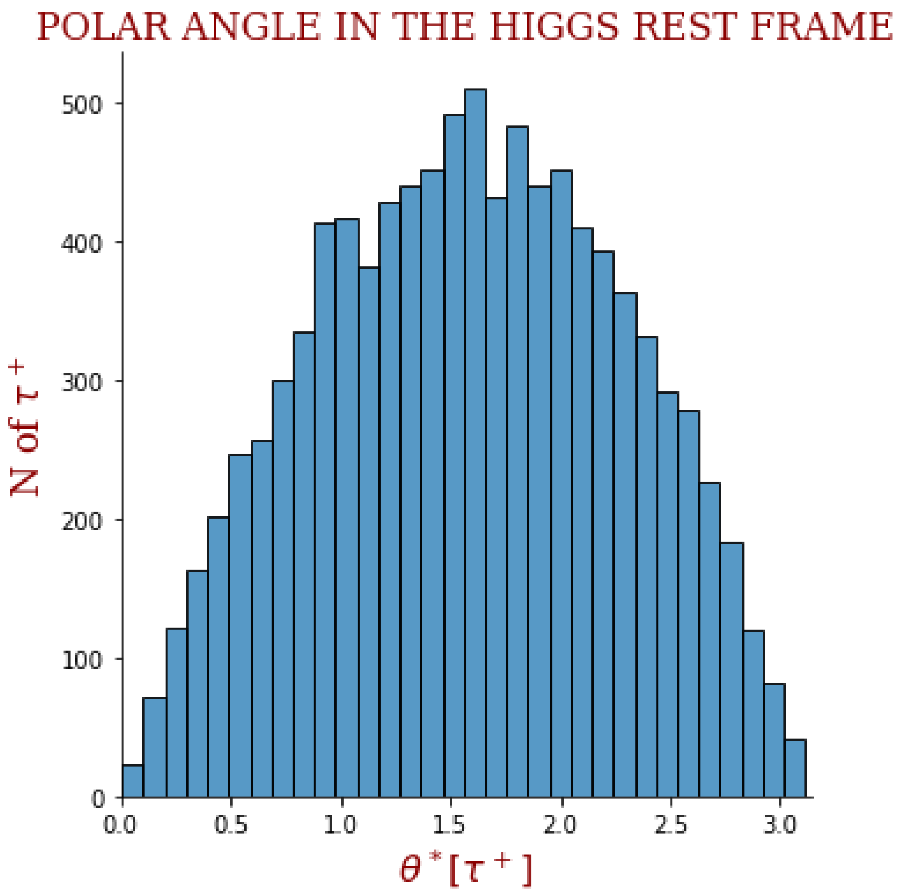
- Run ./bin/mg5_aMC
- Import the model you want to use.
  "import 2HDM"
- Specify the event you want to generate:
  "generate *p p > h+ > ta+ vt*"
- Finally generate the events using:
  "output ChargedHiggs"
  and launch it with:
  "launch ChargedHiggs"

Angular distributions.

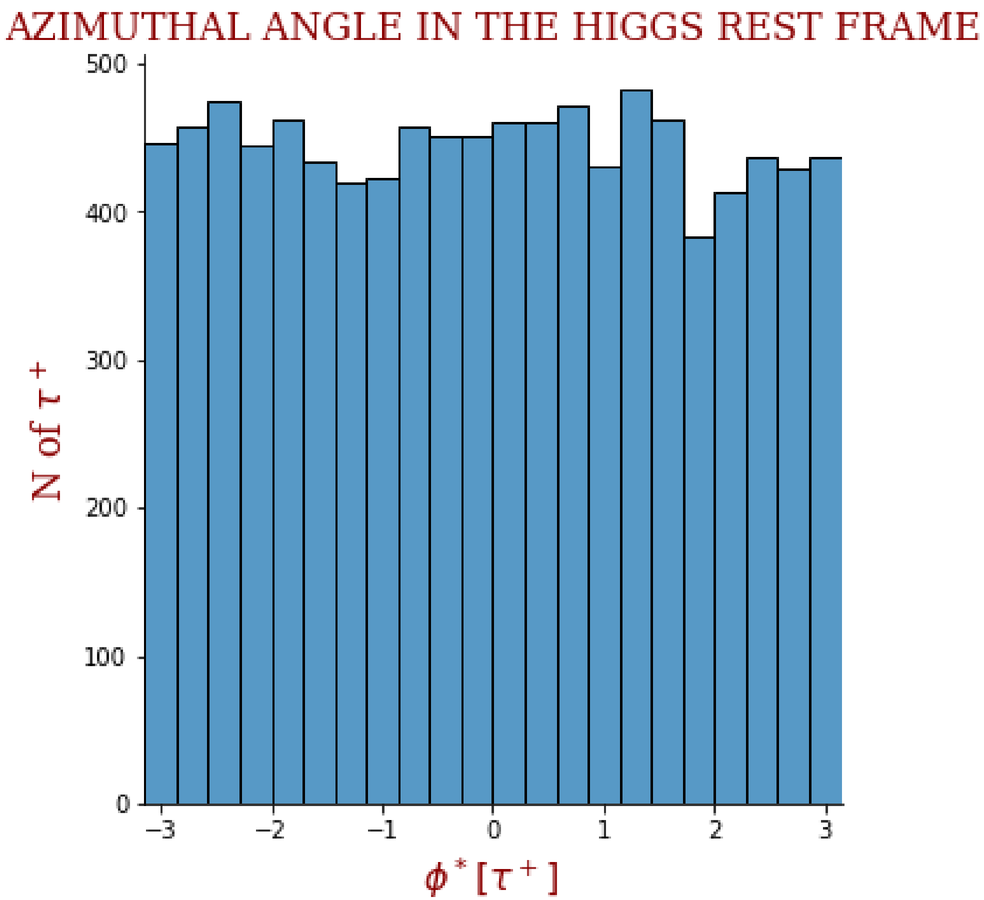




Angular distributions.

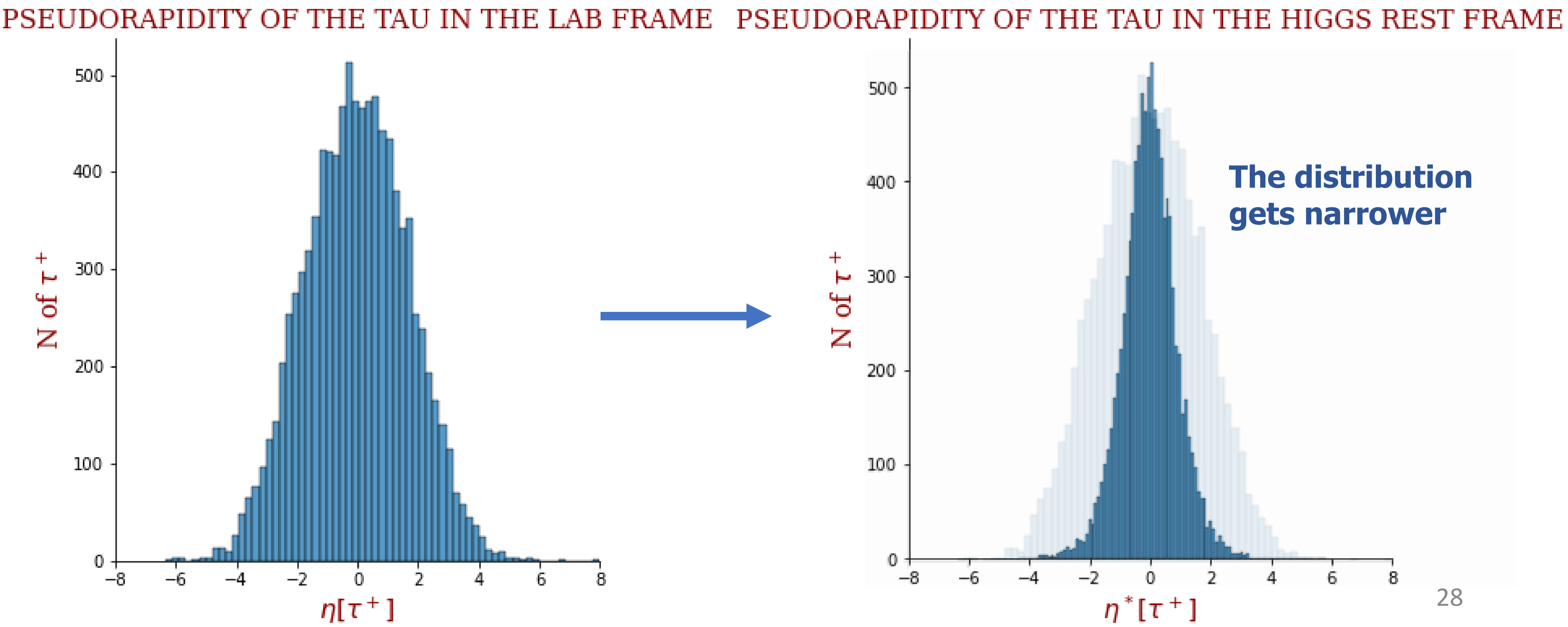


Similar to a **trigonometric** distribution



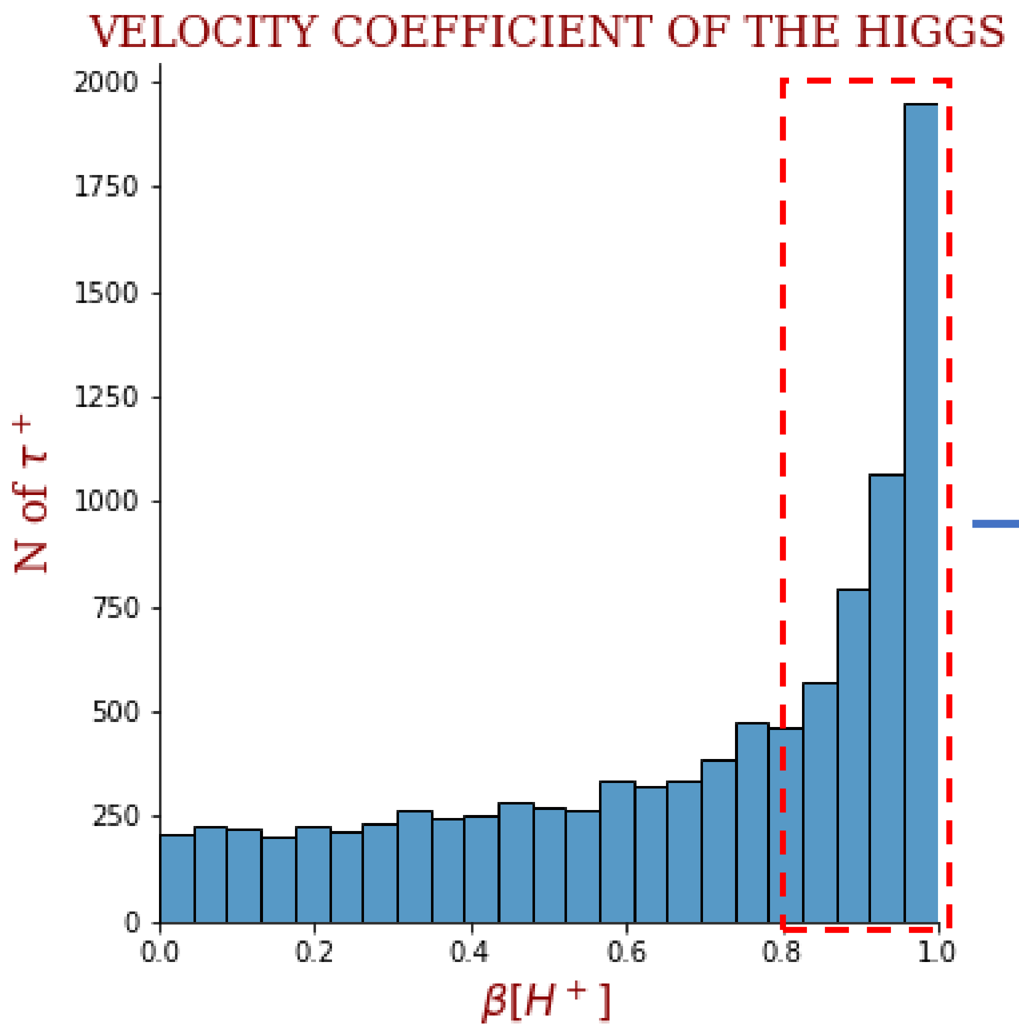
This distribution **does not** change

Pseudorapidities.



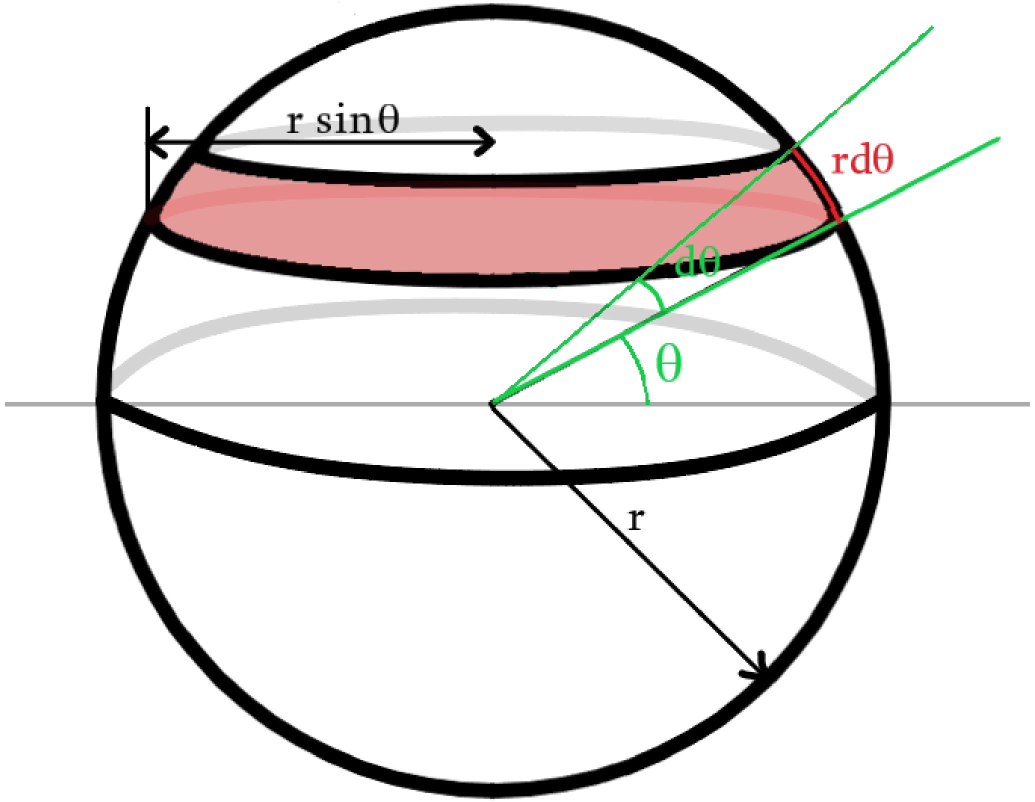
The distribution gets narrower

Velocity coefficient



Most of the taus carry relativistic velocities.

Discussion. Uniform distribution?

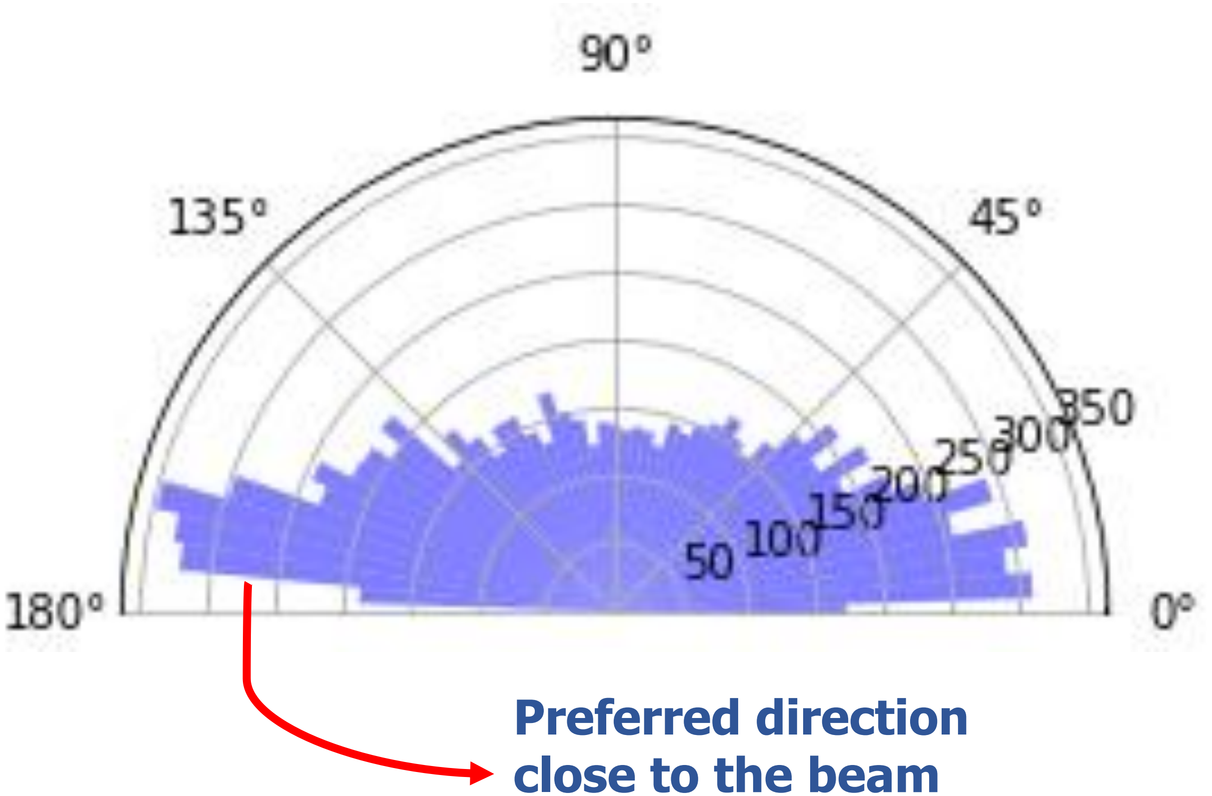


$$d\Omega = \frac{A_{ring}}{r^2} = \frac{2\pi(r\sin\theta)(rd\theta)}{r^2} =$$

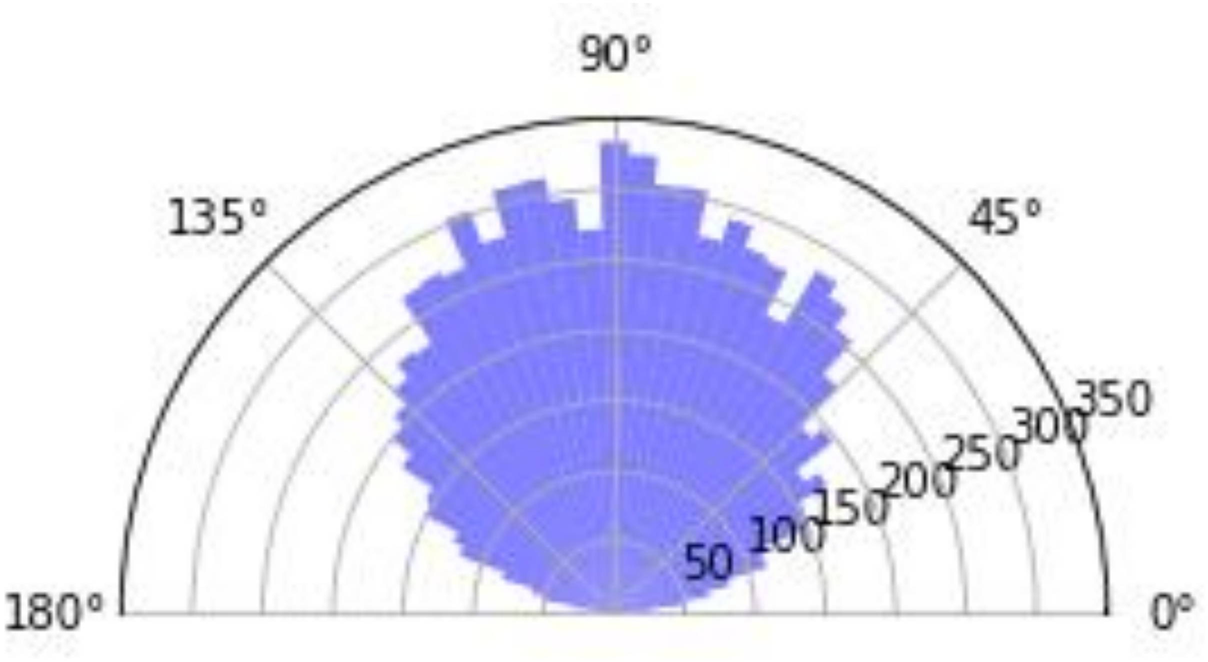
$$= 2\pi \sin\theta d\theta = -2\pi d(\cos\theta)$$

Discussion. Uniform distribution?

Laboratory frame.



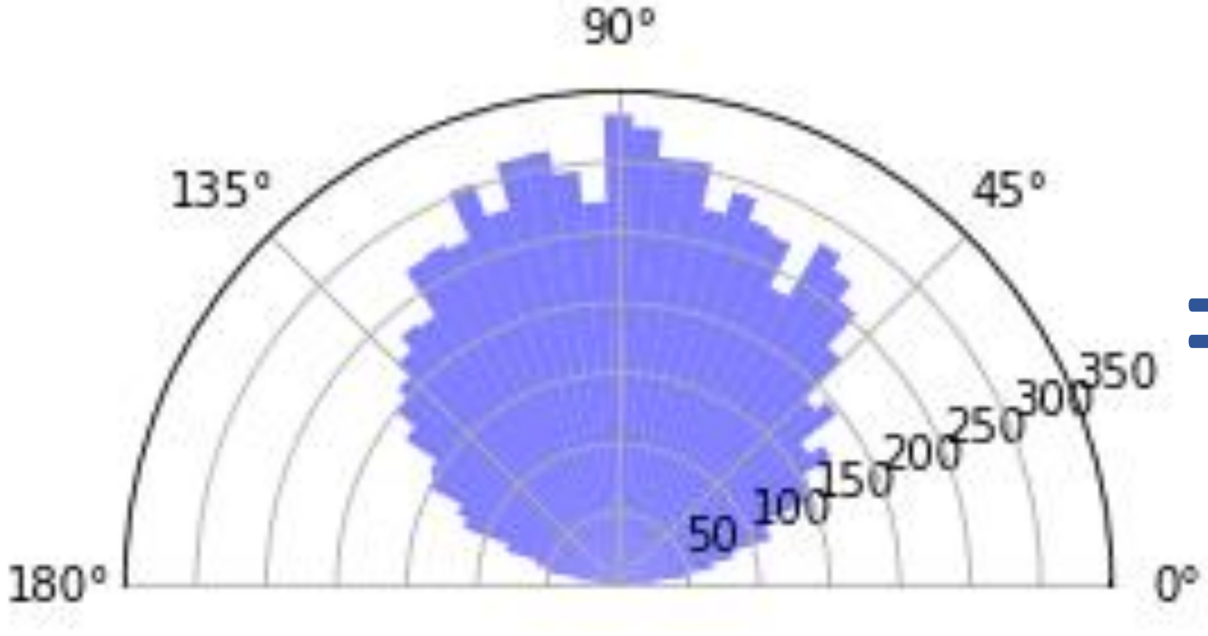
Higgs rest frame.



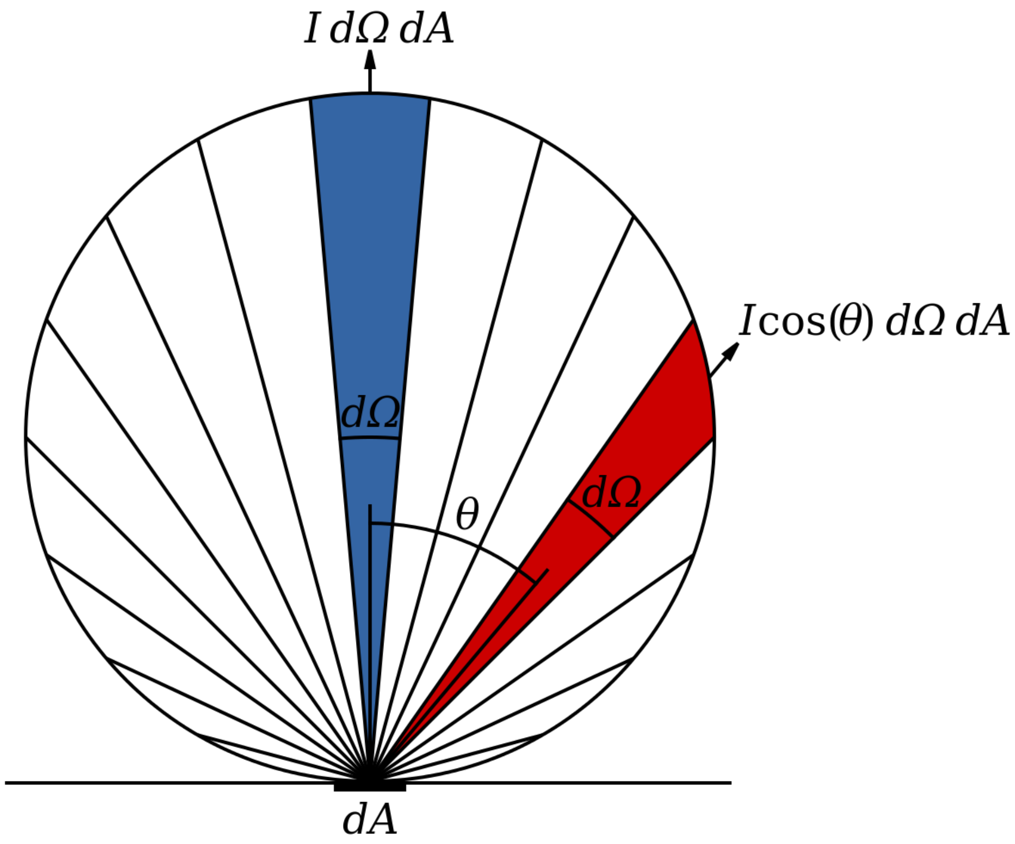
Preferred direction close to the beam axis.

Discussion. Uniform distribution?

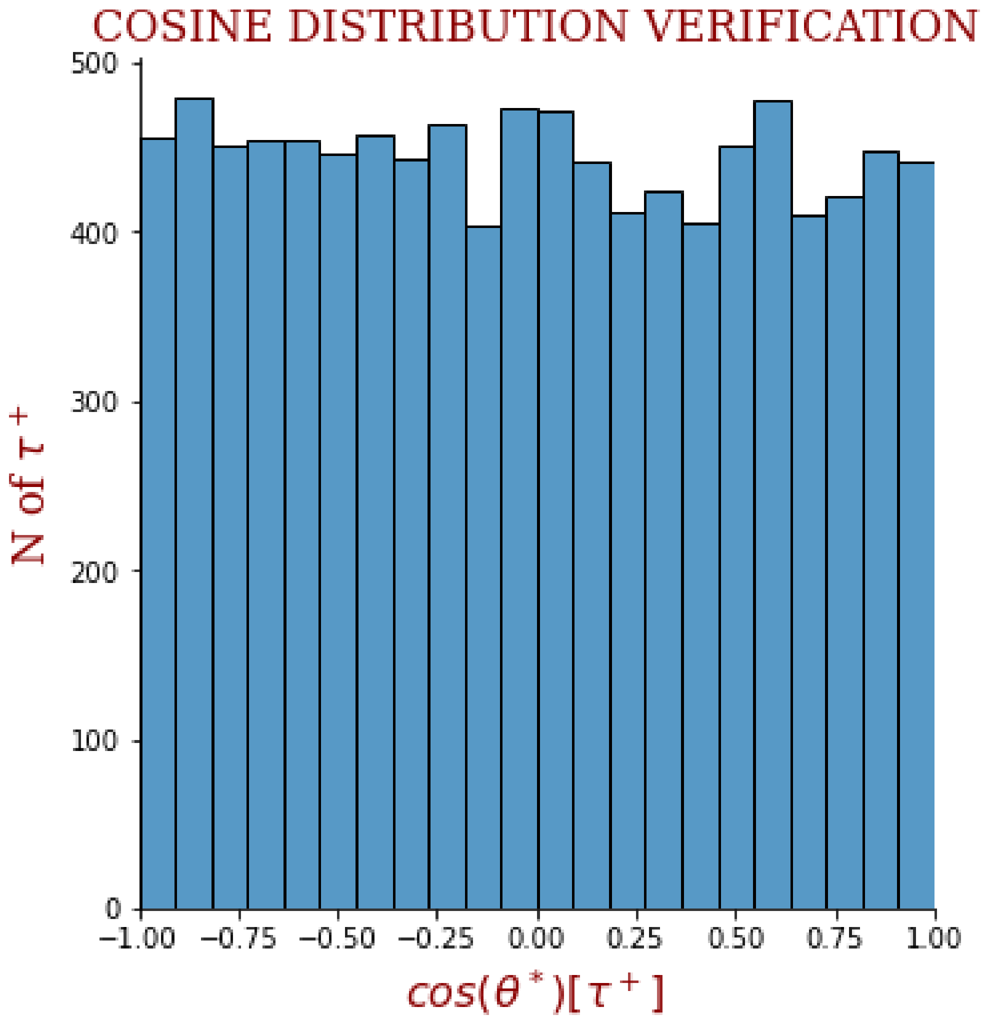
Similar to a perfect **Lambertian emmiter**



=

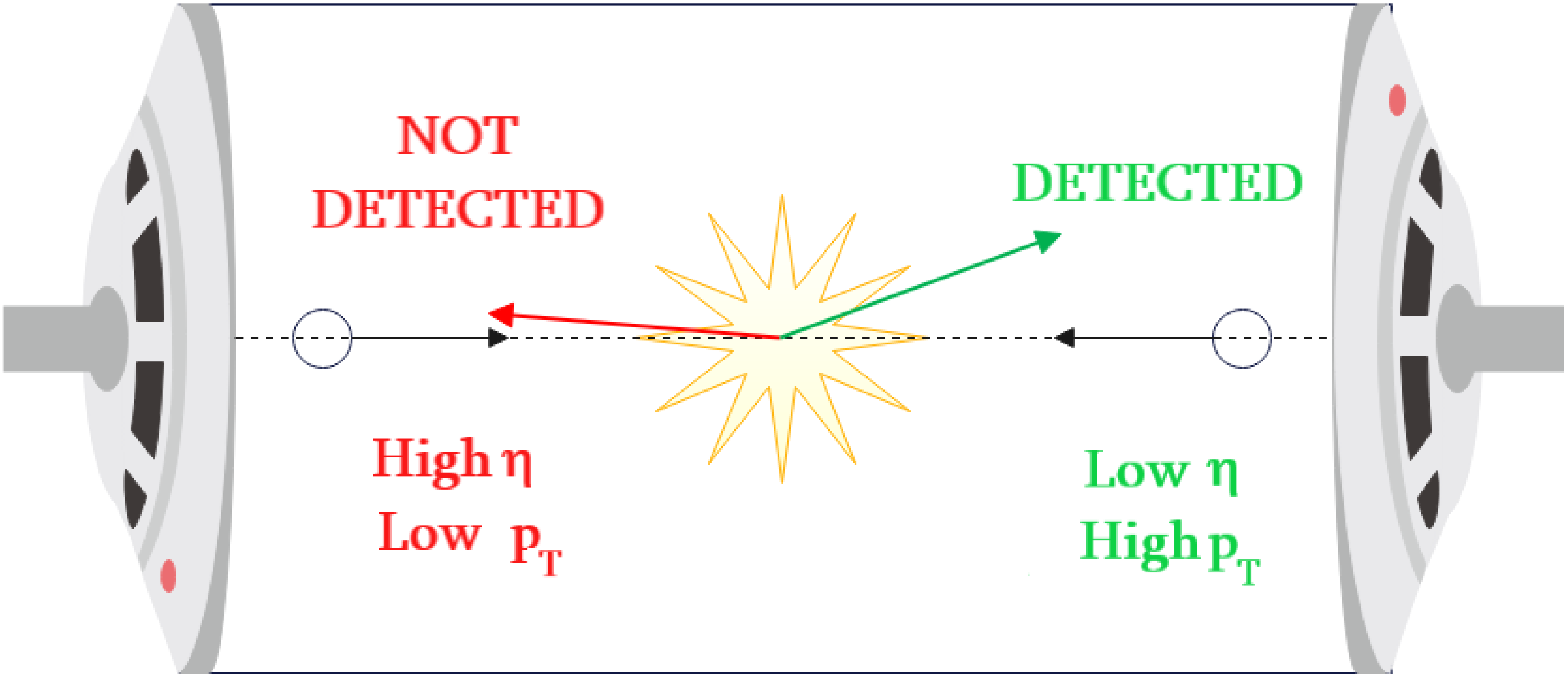


Discussion. Uniform distribution?



The isotropic distribution must be **regularly distributed** over the **cosine** of the polar angle.

Discussion. Geometry of the detector

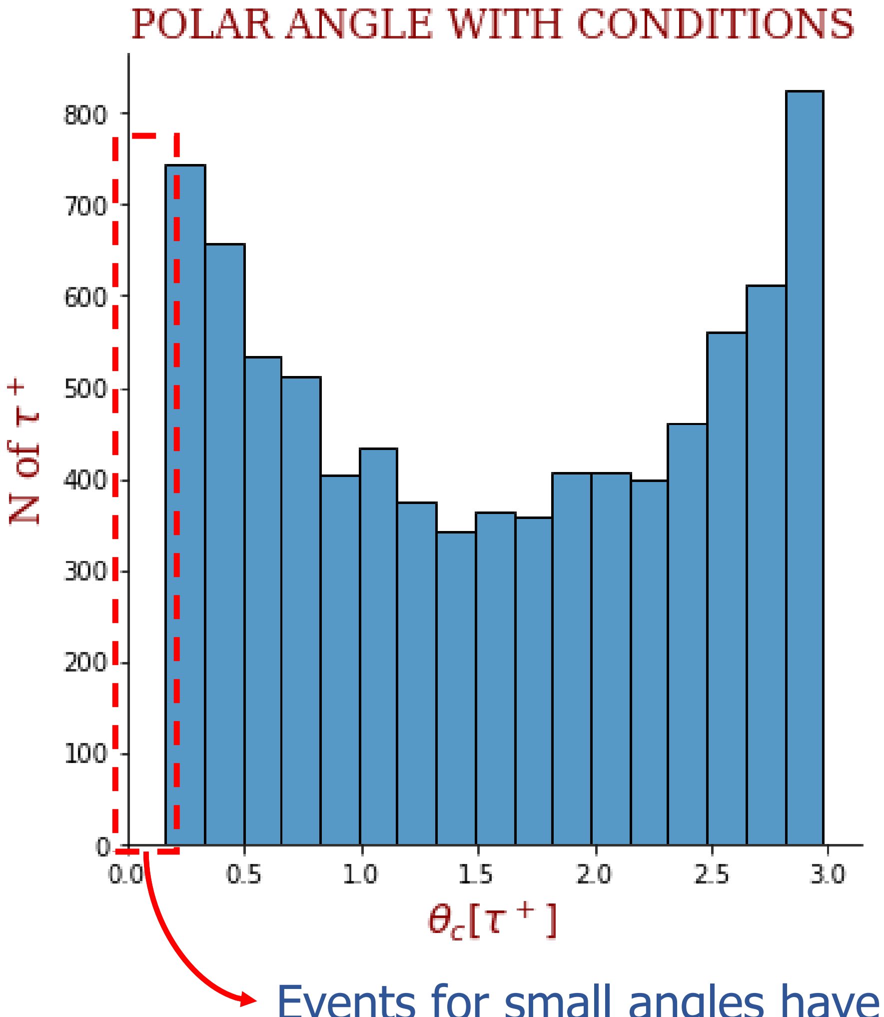


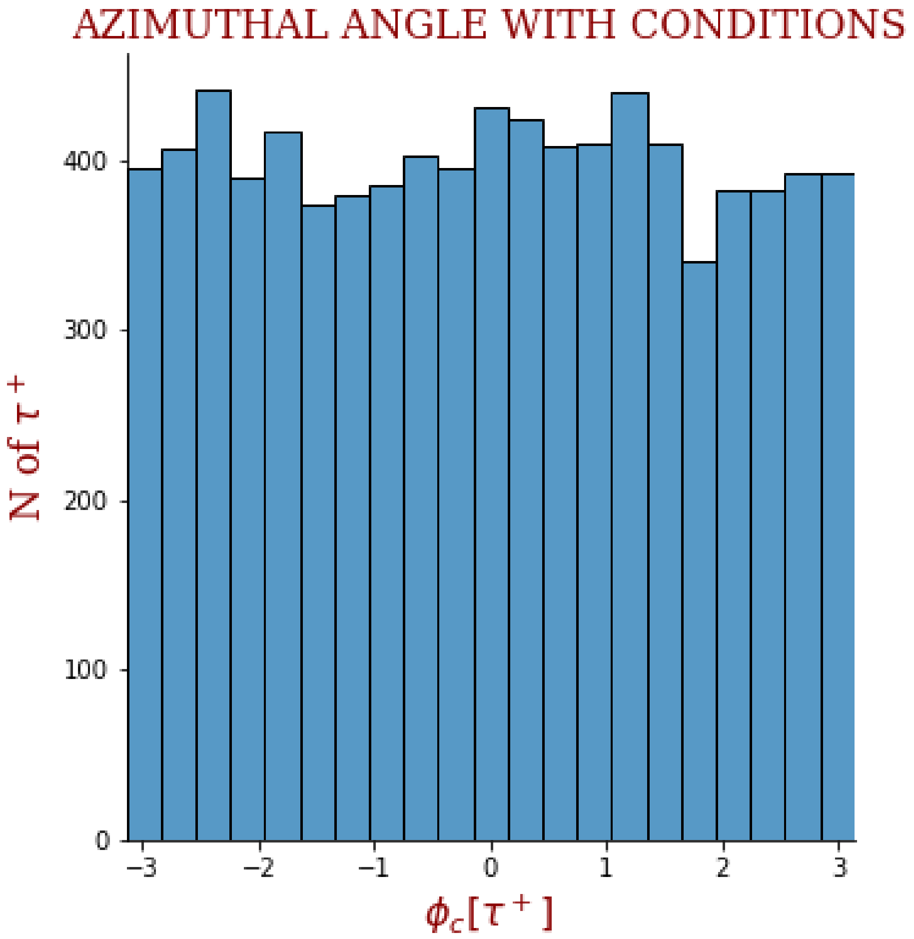
How do we solve this?

→ Applying **cuts** to the pseudorapidity and transverse momentum

Discussion. Geometry of the detector

Laboratory frame.

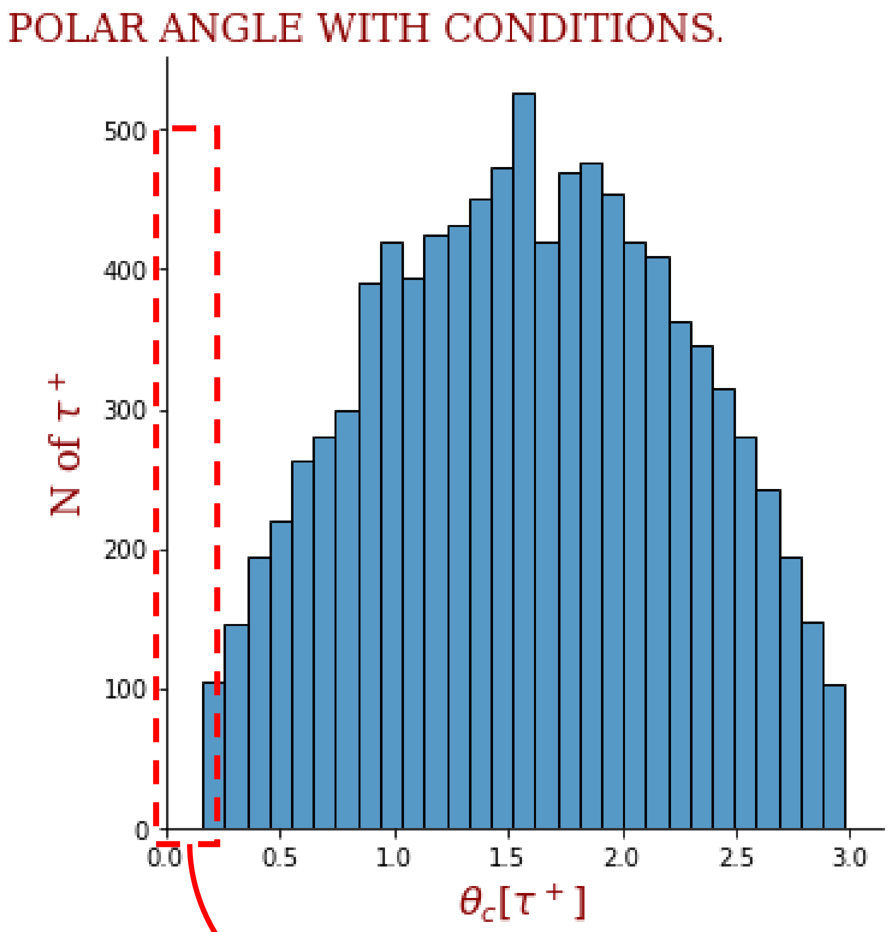


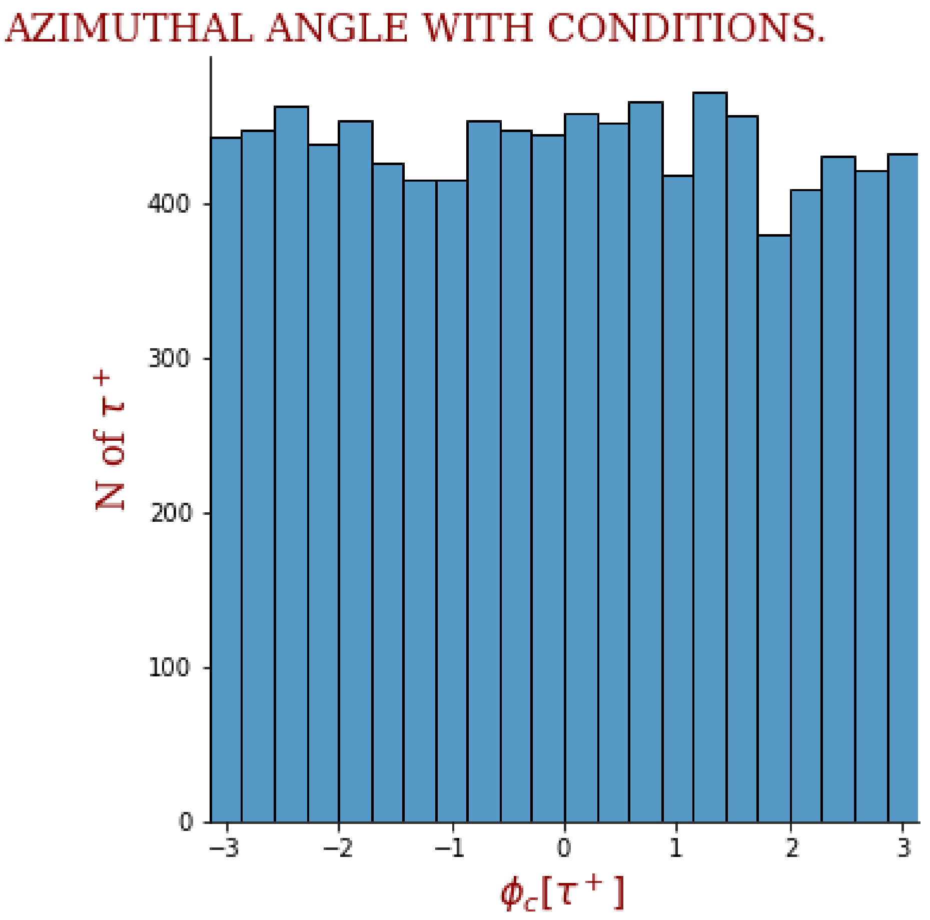


Events for small angles have been neglected.

Discussion. Geometry of the detector

Higgs rest frame.





Events for small angles have been neglected.

Generation of events

Number of events for different runs:

Quark pair	Number of events
$c\bar{s}$	1157
$u\bar{d}$	8843

$$\sigma_{N=10000}(pp \to H^+) = (2.571 \pm 0.003) \cdot 10^4 \text{ pb}$$

Quark pair	Number of events
$c\bar{s}$	56936
$u\bar{d}$	443064

$$\sigma_{N=500000}(pp \to H^+) = (2.57087 \pm 0.00012) \cdot 10^4 \text{ pb}$$

The ud annihilation has **higher** number of events

Cross sections for both quark annihilation processes:

Quark pair	σ [pb]
$c\bar{s}$	1476.0±1.1
$u\bar{d}$	11112±12

Discussion. Generation of events

$$R_1 = \frac{\sigma(c\bar{s} \to H^+)}{\sigma(u\bar{d} \to H^+)} \approx 0.1308 \text{ for N=10000 events}$$

$$R_2 = \frac{\sigma(c\bar{s} \to H^+)}{\sigma(u\bar{d} \to H^+)} \approx 0.1285 \text{ for N=500000 events}$$

As predicted with the PDF, the number of **ud annihilations is much higher**

$$\frac{\sigma(c\bar{s} \to H^+) + \sigma(u\bar{d} \to H^+)}{\sigma(pp \to H^+)} = 0.4896$$

Not even 50%, showing the importance of the **other production channels**

Generation of events

Particles	BR
$\tau^+ \nu_\tau$	0.468
$t\bar{b}$	0.325
$\mu^+ \nu_\mu$	0.068
$c\bar{s}$	0.065
$u\bar{d}$	0.049
$e^+\nu_e$	0.025

Almost **80%** of the decays

- Importance of the **Yukawa couplings**
- tb not the main channel due to phase space

Other channels still relevant

$$\Gamma_{H^+} = 61.5 \text{ GeV}$$

Certainly high

- For other massive particles like quark top: $\Gamma_t = 1.32 \text{ GeV}$

Discussion. Generation of events

Other decay channels:

Particles	$BR \cdot 10^4$
$u\bar{s}$	0.72
$c\bar{d}$	0.68
$u\bar{d}$	0.50
$c\bar{b}$	0.03
$e^+\nu_\tau$	0.06
$\mu^+\nu_\tau$	0.06
$e^+\nu_\mu$	0.06
$\tau^+\nu_\mu$	0.06
$\mu^+\nu_e$	0.06
$\tau^+\nu_e$	0.06
$t\bar{s}$	0.03
$t\bar{d}$	0.02

Why are these processes suppressed?

Difference in decay widths:

$$\frac{\Gamma(H^+ \to c\bar{d})}{\Gamma(H^+ \to c\bar{s})} \propto \frac{|V_{cd}|^2 m_d^2}{|V_{cs}|^2 m_s^2} = 3.35 \cdot 10^{-4}$$

Cabibbo suppressed

$$V_{CKM} = \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix},$$

Conclusions

The production and decay processes of the charged Higgs have been analysed

- ud annihilation as main production process
- tau and tau neutrino as main decay channel

The computation of the cross sections has shown how important other production processes are: VBF, Drell Yang, etc.