Vector Boson Fusion
A powerful tool to discover new physics at the LHC

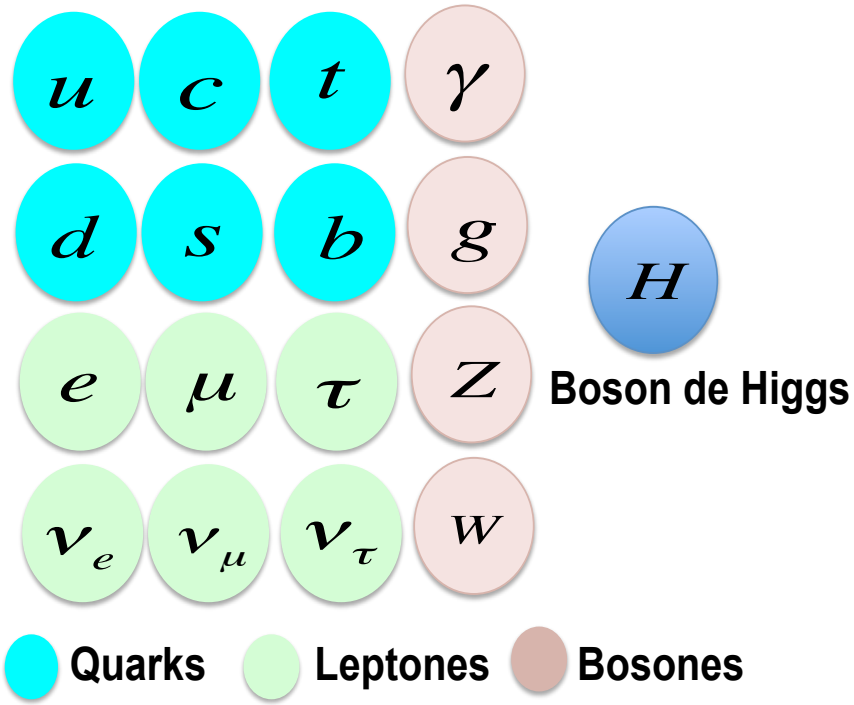
Andrés Flórez

July 31, 2018

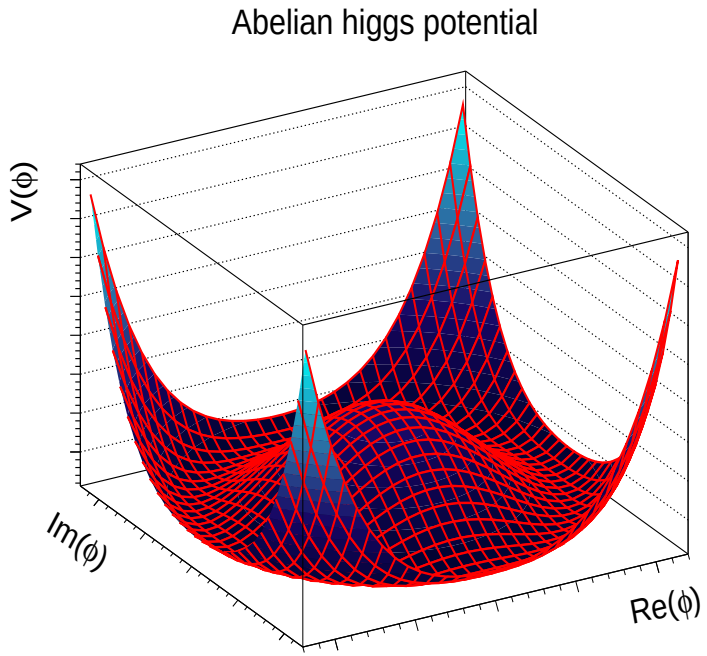
Generalities of the Standard Model (SM)

Fundamental particles and their interactions:

$$\mathbf{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y}, \qquad (1)$$



$$V(\phi) = -\mu^2\phi^\dagger(\phi) + \lambda(\phi^\dagger\phi)^2 \qquad (2)$$



$$|\langle 0|\phi|0\rangle|^2 = \frac{\nu^2}{2}, \text{with } \nu^2 = -\frac{\mu^2}{\lambda} \qquad (3)$$

The Large Hadron Collider (LHC)

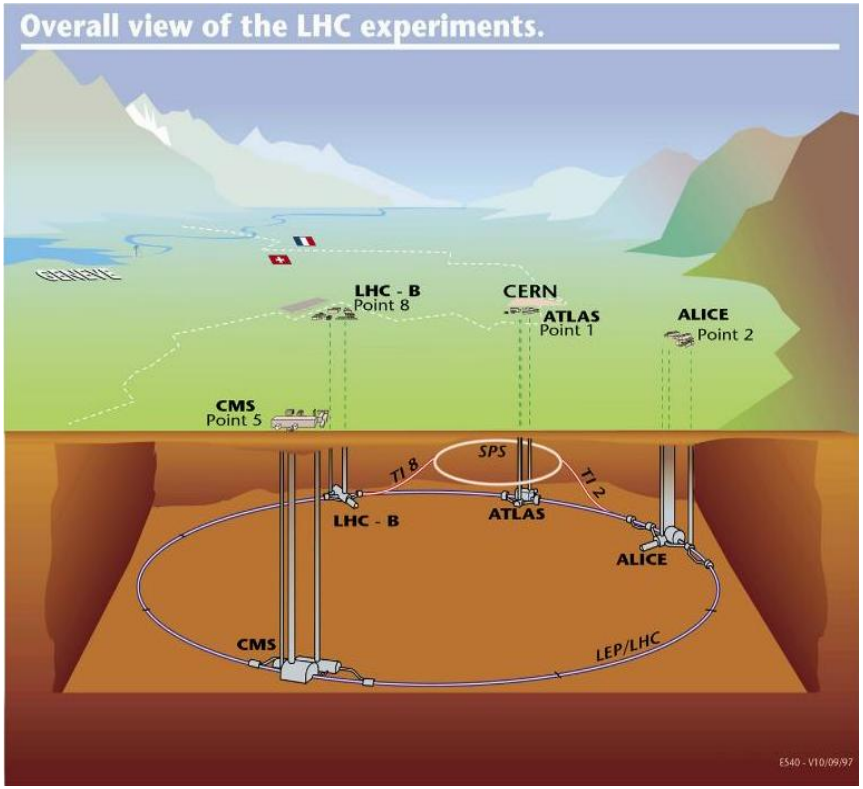


Figure: Sketch of the LHC. The main experiments are: CMS, ATLAS, ALICE and LHCb

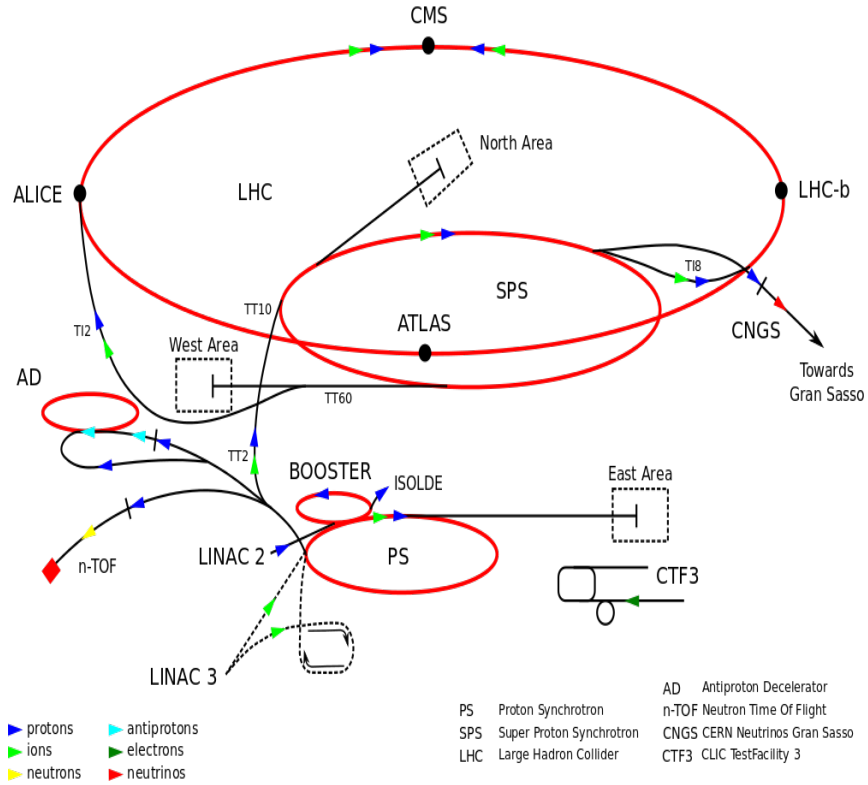
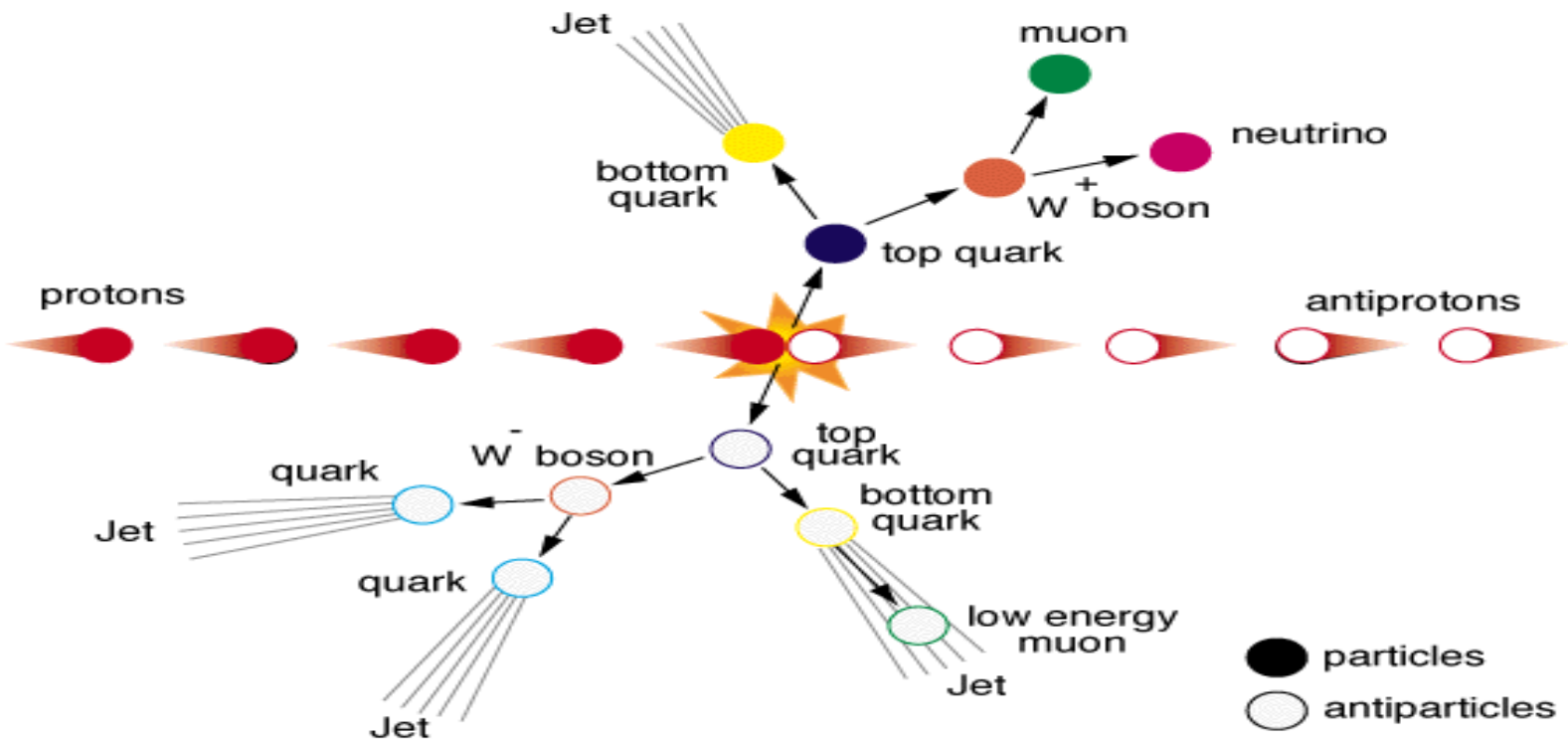


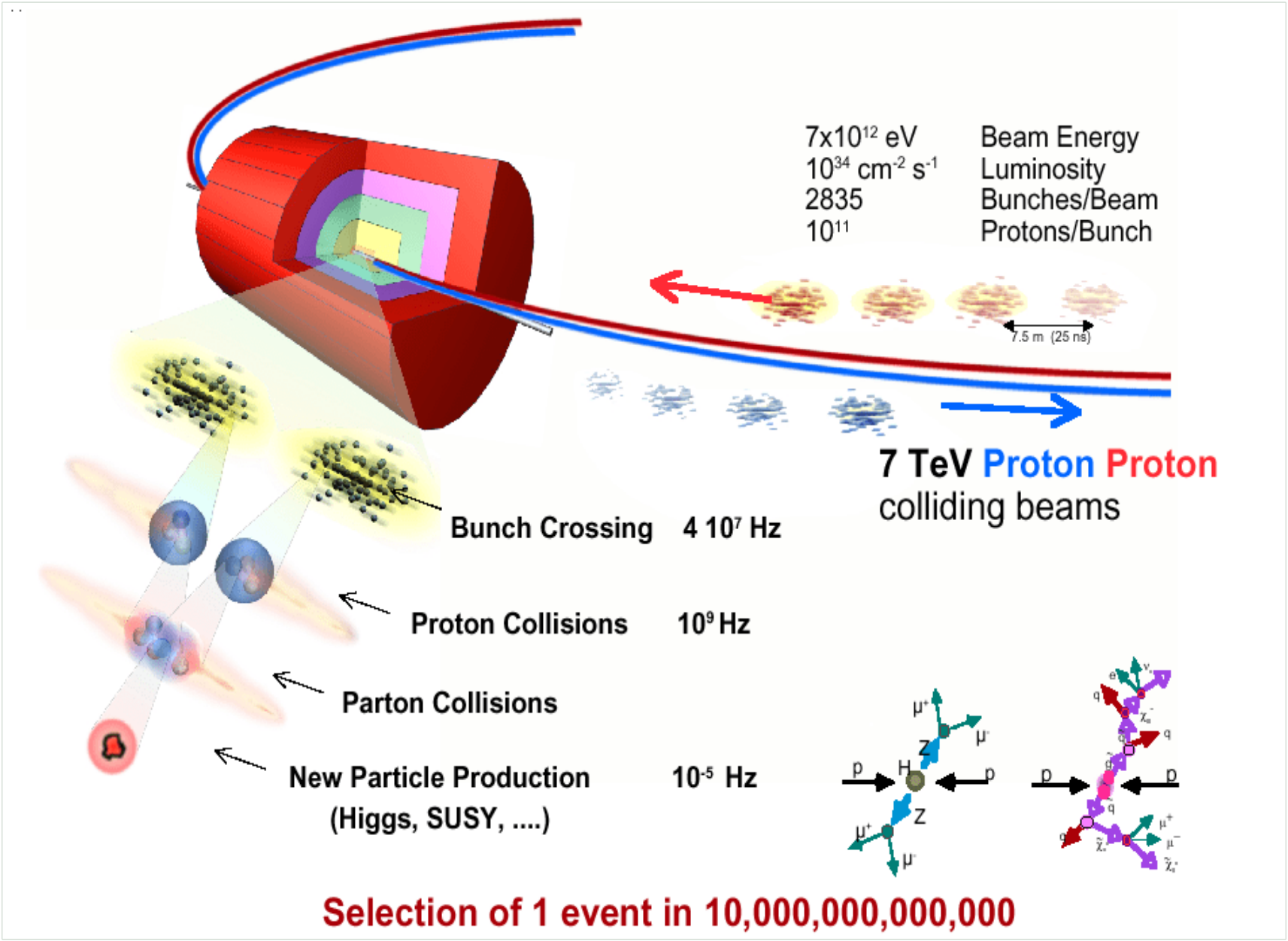
Figure: Sketch of the acceleration chain at the LHC

The Large Hadron Collider (LHC)

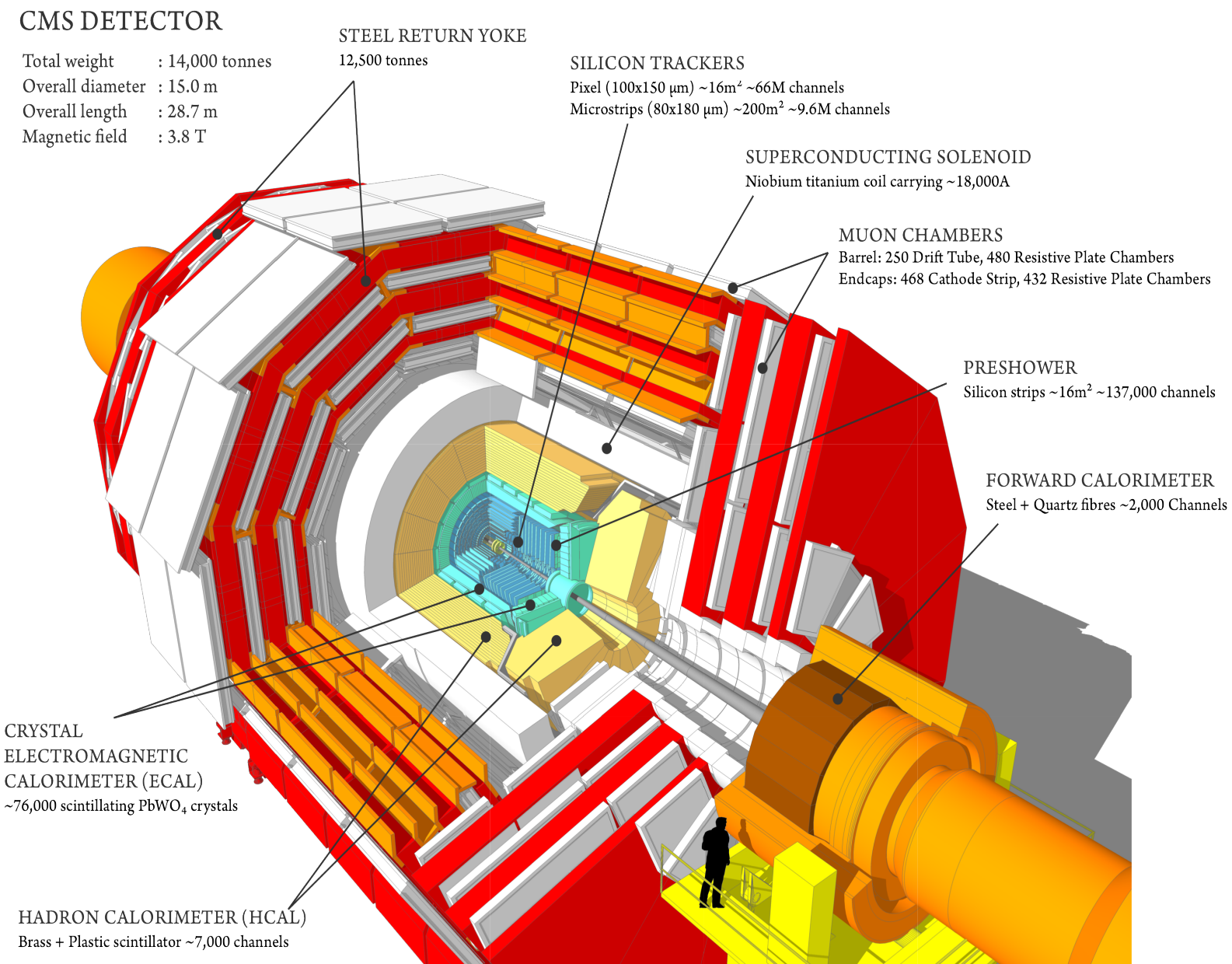


A Top Antitop Quark Event from the D-Zero Detector at Fermilab

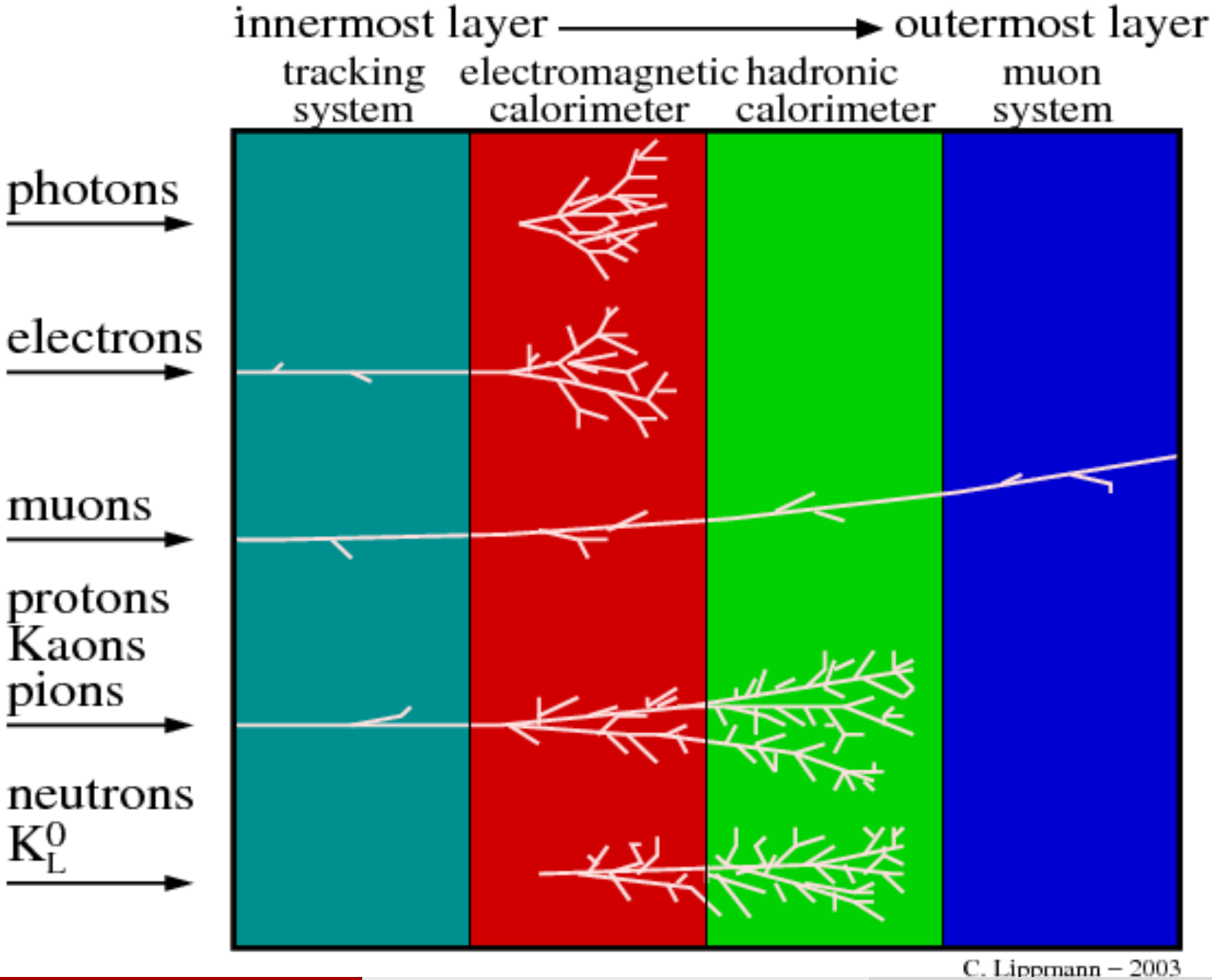
The Large Hadron Collider (LHC)



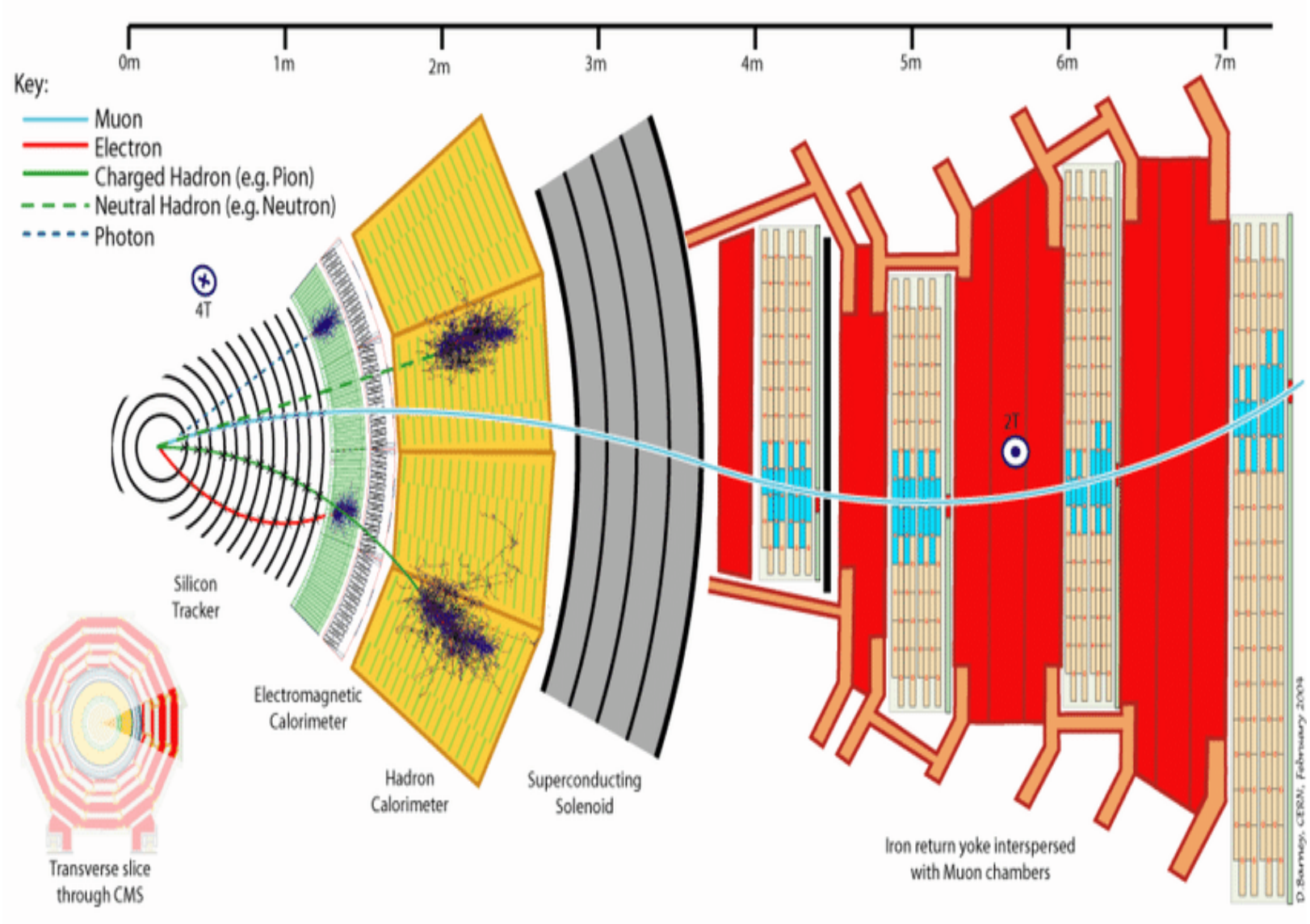
The CMS Detector



Detection of Particles



The CMS Detector



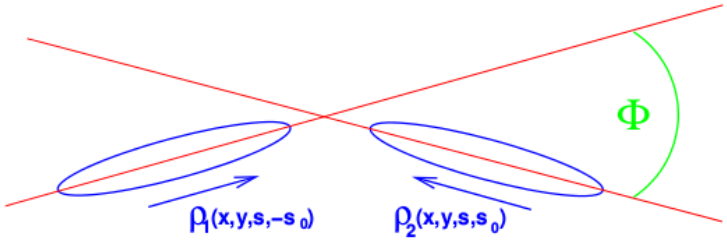
Some important concepts

1. Cross Section
2. Luminosity

In particle physics, a cross section (σ) represents the *probability of production* of a specific process. This quantity is related with the level of the interaction between the beam and the target, or between two beams, and it depends on the energy of collisions.

Some important concepts

1. Cross Section
2. Luminosity
3. Coordinate systems



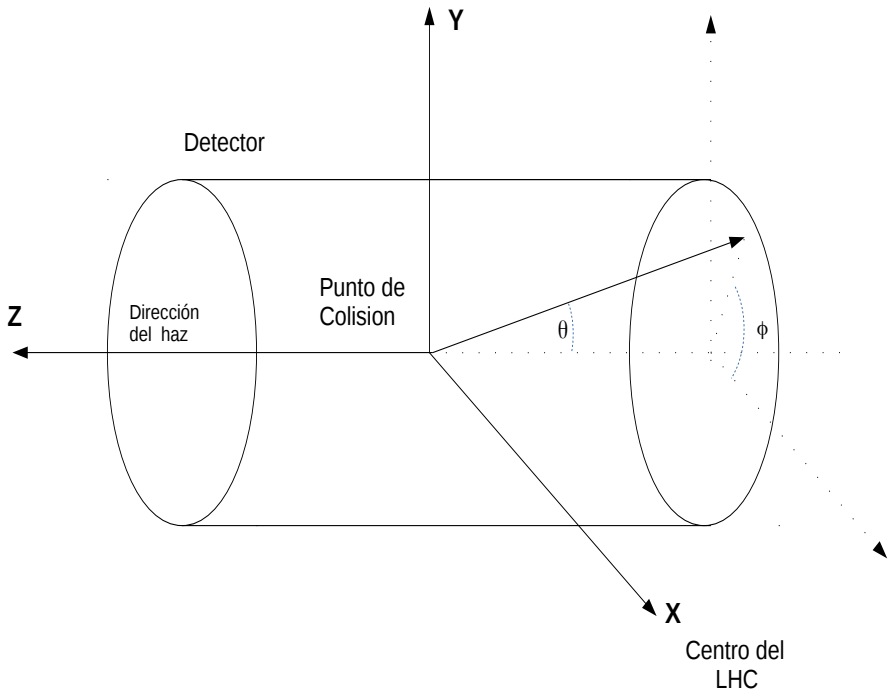
$$\mathcal{L} \sim \frac{N_A \times N_B \times f \times F}{4\pi(\sigma_A \times \sigma_B)} \tag{4}$$

$$L = \int \mathcal{L} dt \tag{5}$$

$$N_i = \sigma_i \times L \tag{6}$$

Some important concepts

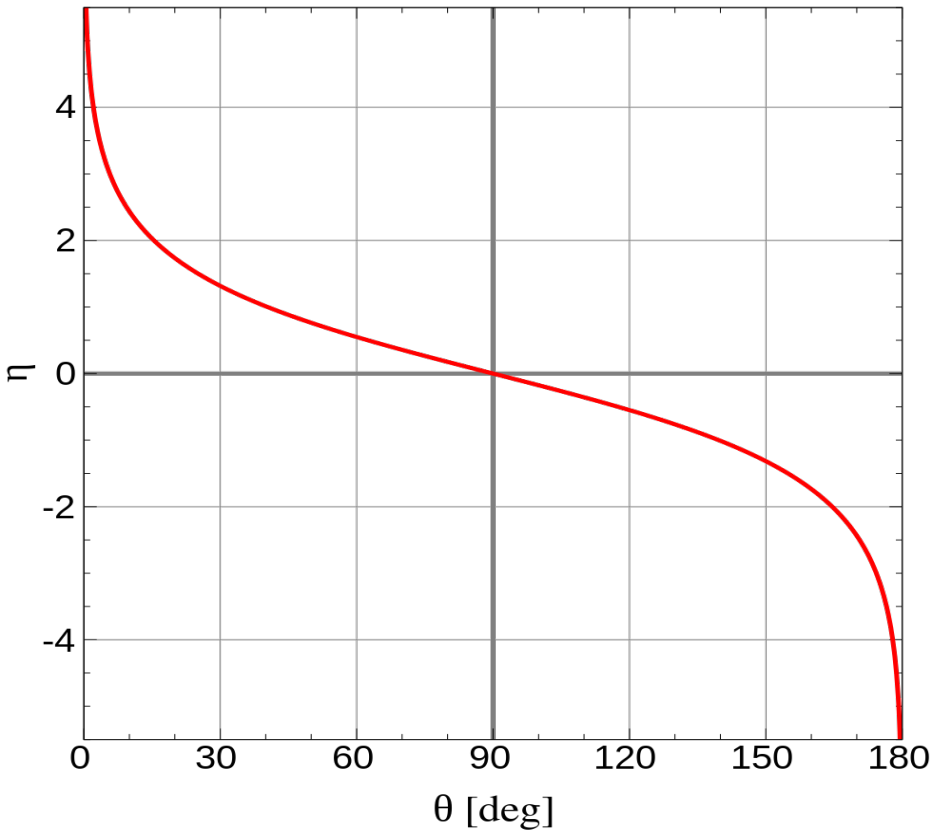
1. Cross Section
2. Luminosity
3. Coordinate systems
4. Pseudorapidity



Some important concepts

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

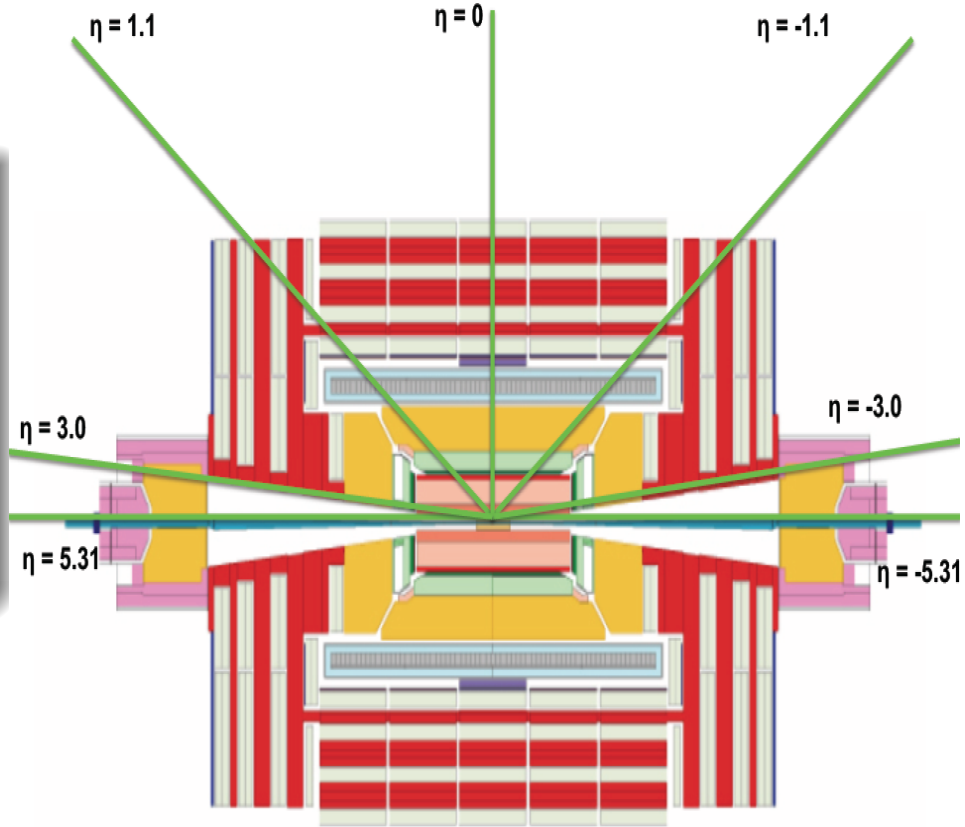
1. Cross Section
2. Luminosity
3. Coordinate systems
4. Pseudorapidity
5. η-gaps.



Some important concepts

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

1. Cross Section
2. Luminosity
3. Coordinate systems
4. Pseudorapidity
5. η-gaps.
6. Missing transverse momentum $\not{p}_T$



Some important concepts

1. Cross Section
2. Luminosity
3. Coordinate systems
4. Pseudorapidity
5. η-gaps.
6. Missing transverse momentum $\not{p}_T$

$$\sum_i \vec{p_i^T} = 0,$$

$$= \sum_j \vec{p_j^T}\,(visible) + \sum_k \vec{p_k^T}\,(invisible)$$

$$\sum_k \vec{p_k^T}\,(invisible) = -\sum_j \vec{p_j^T}\,(visible)$$

$$\not{p}_T = -\sum_j \vec{p_j^T}\,(visible) \qquad (4)$$

Particle Flow Algorithm - CMS

- The Particle Flow (PF) algorithm used by the CMS collaboration, has no precedent in the history of HEP.

Particle Flow Algorithm - CMS

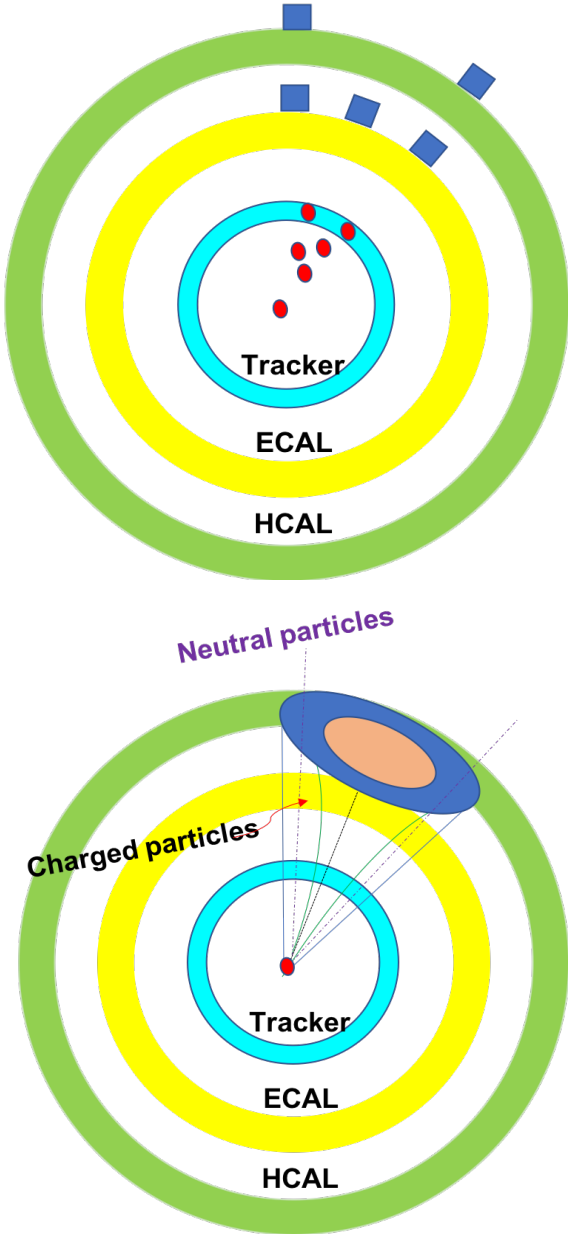
- The Particle Flow (PF) algorithm used by the CMS collaboration, has no precedent in the history of HEP.
- The algorithm uses the information from the different sub-detectors to reconstruct individual particle candidates: Muons, electrons, photons, charged and neutral hadrons.

Particle Flow Algorithm - CMS

- The Particle Flow (PF) algorithm used by the CMS collaboration, has no precedent in the history of HEP.
- The algorithm uses the information from the different sub-detectors to reconstruct individual particle candidates: Muons, electrons, photons, charged and neutral hadrons.
- The reconstructed particles are then used to reconstruct more complicated objets such as jets (see next) and hadronic taus (τ_h), and to also to measure the $\not{p}_T$ in the event.

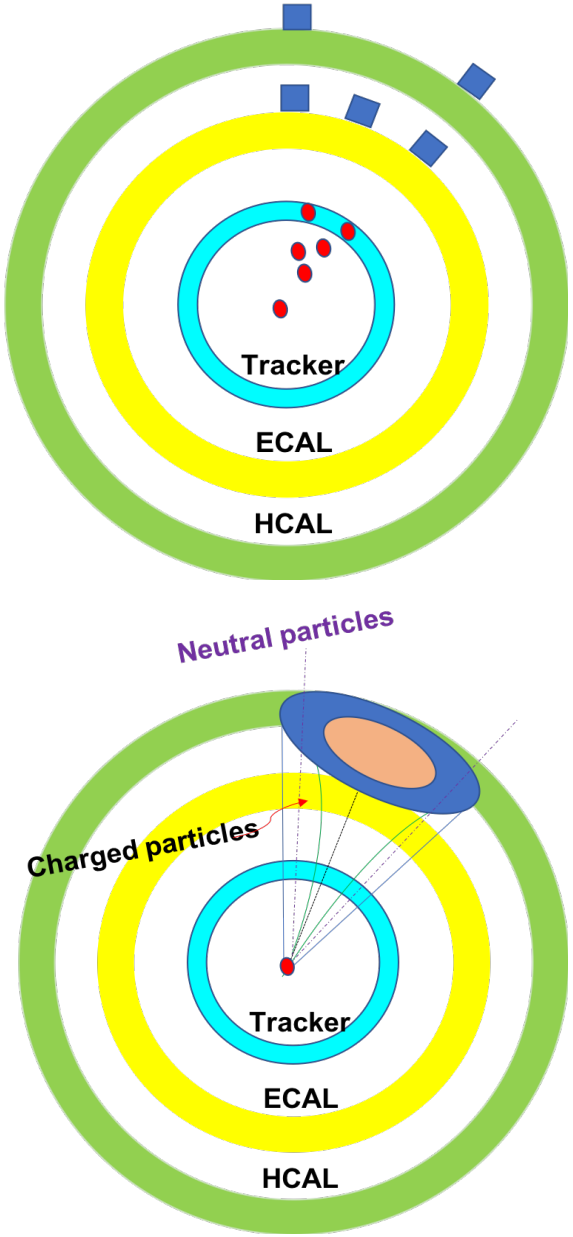
Particle Flow Algorithm - CMS

- The Particle Flow (PF) algorithm used by the CMS collaboration, has no precedent in the history of HEP.
- The algorithm uses the information from the different sub-detectors to reconstruct individual particle candidates: Muons, electrons, photons, charged and neutral hadrons.
- The reconstructed particles are then used to reconstruct more complicated objets such as jets (see next) and hadronic taus (τ_h), and to also to measure the $\not{p}_T$ in the event.



Particle Flow Algorithm - CMS

- The Particle Flow (PF) algorithm used by the CMS collaboration, has no precedent in the history of HEP.
- The algorithm uses the information from the different sub-detectors to reconstruct individual particle candidates: Muons, electrons, photons, charged and neutral hadrons.
- The reconstructed particles are then used to reconstruct more complicated objets such as jets (see next) and hadronic taus (τ_h), and to also to measure the $\not{p}_T$ in the event.

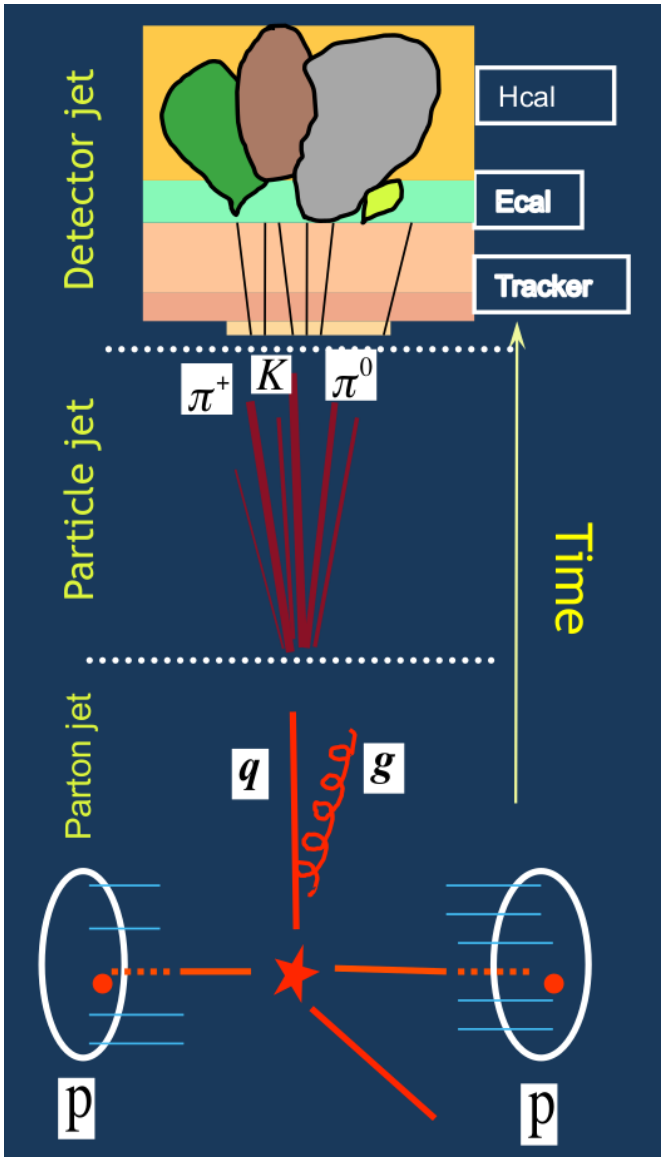


Some important concepts

1. Jet
    1. Partonic
    2. Hadronic
    3. Detector

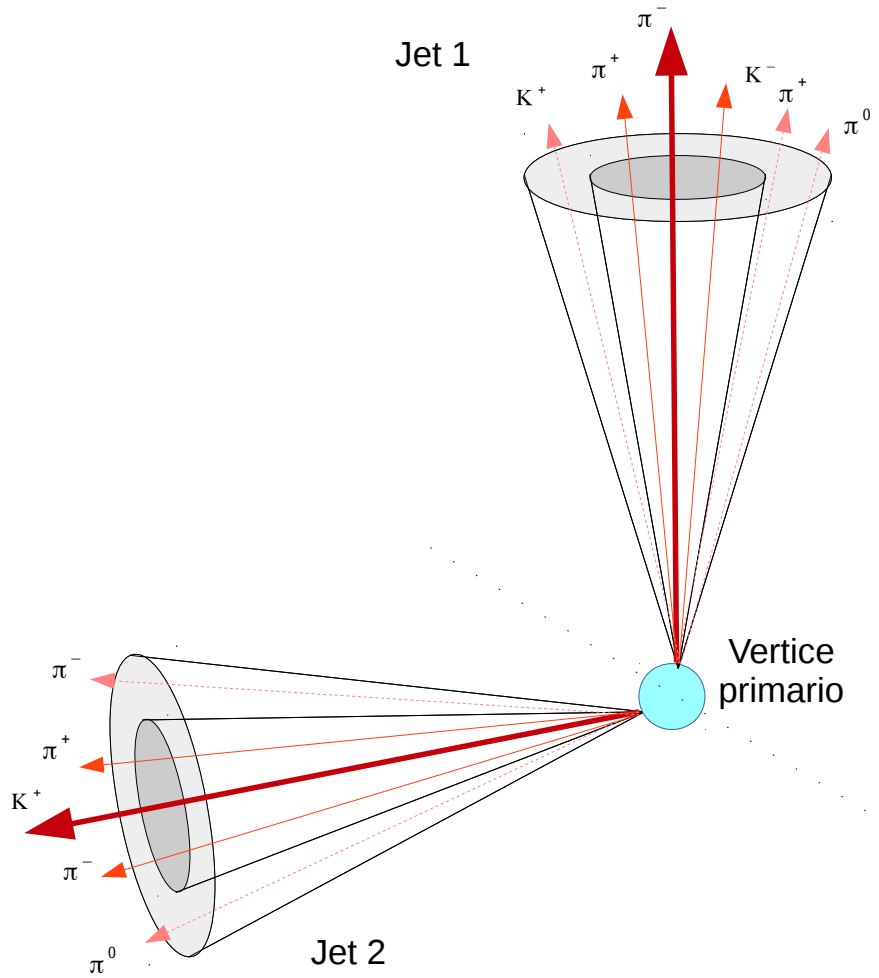
Some important concepts

1. Jet
   1. Partonic
   2. Hadronic
   3. Detector
2. Jet reconstruction



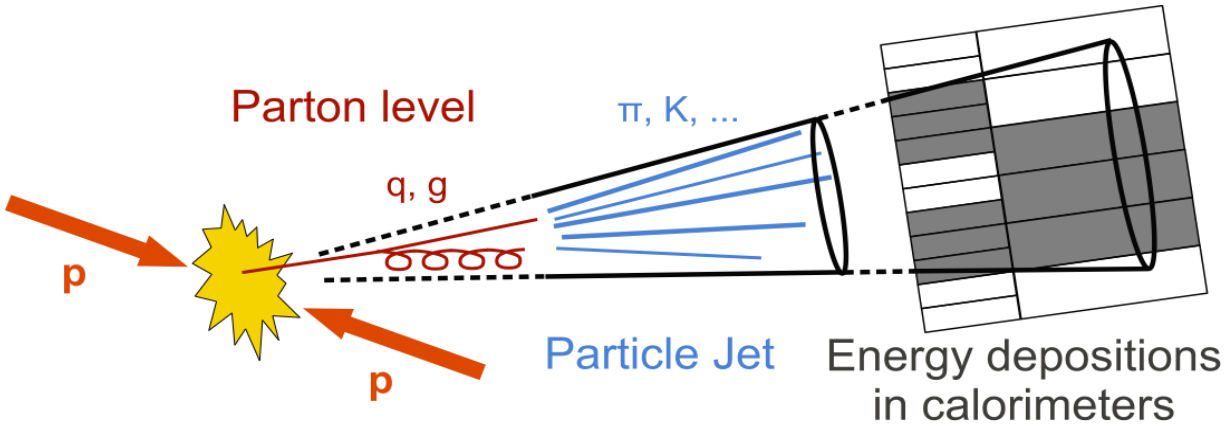
Some important concepts

1. Jet
   1. Partonic
   2. Hadronic
   3. Detector
2. Jet reconstruction



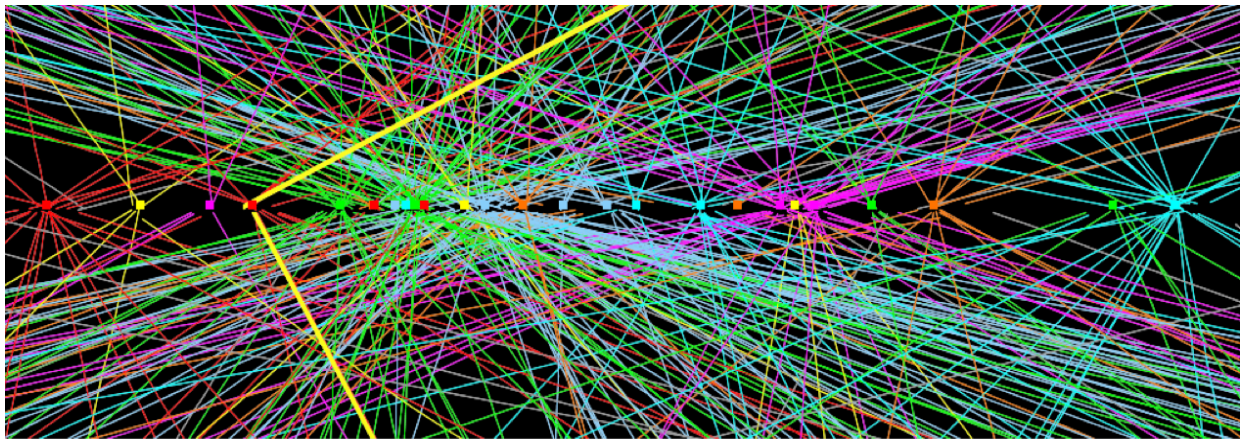
Jet Reconstruction Algorithms

- The identification of jets in collider experiments is very important.
- Cone-based reconstruction algorithms are of common use in particle physics.
- Determining the boundary of a cone for a reconstructed jet it is not a trivial problem, due to the repetitive branching nature of QCD radiation.
- There are two main classes of jet-reconstruction algorithms:
  1. The iterative cone.
  2. The sequential clustering, which includes the K_t and Anti$-K_t$ algorithms.



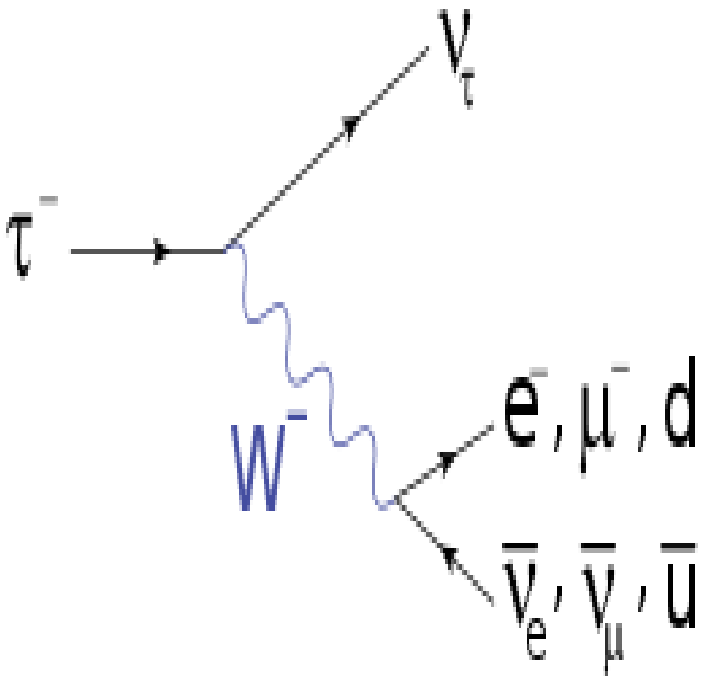
Important considerations

- There are to important aspects that any jet algorithm must consider: The jet size and if the algorithm is infra-red and collinear(IRC) safe.
- The area of the cone enclosing the jet determine how much soft radiation is allowed.
- When a large jet radius is set, it allows to include enough particles from the hadronization process. Therefore, there is a good accuracy when the jet mass and energy are estimated.
- Nevertheless, with large jet radius, the jet mass and energy can often be overestimated due to Underlying Event (UE) and Pile-Up (PU) effects.
- The UE and PU effect can be reduced with a smaller jet radius.



Reconstruction of Hadronic Tau Leptons

- Taus (τ) are the heaviest known leptons: Mass 1.777 GeV.
- Because of their large mass, taus can decay both leptonically and hadronically.

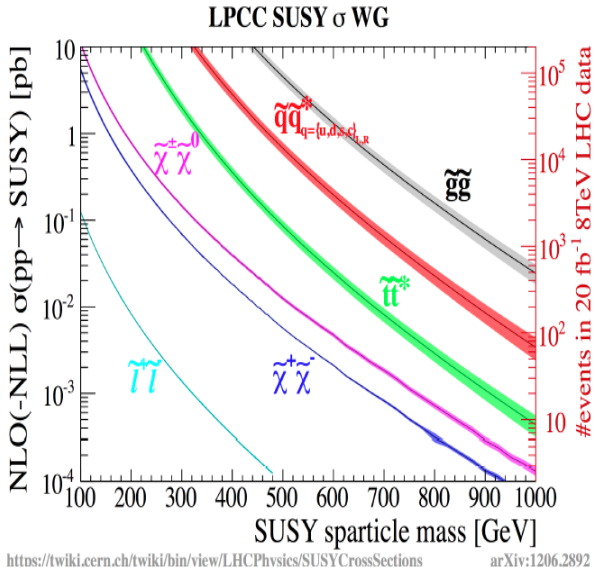


Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8

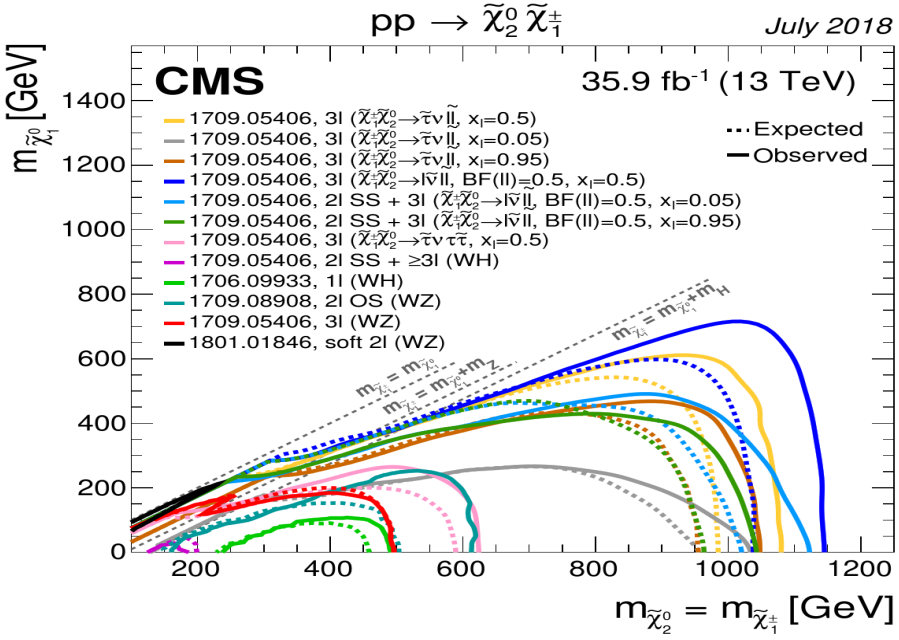
- The table shows the decay branching fraction for taus.
- Note that hadronic final states are the dominant decay modes : 64.8%.

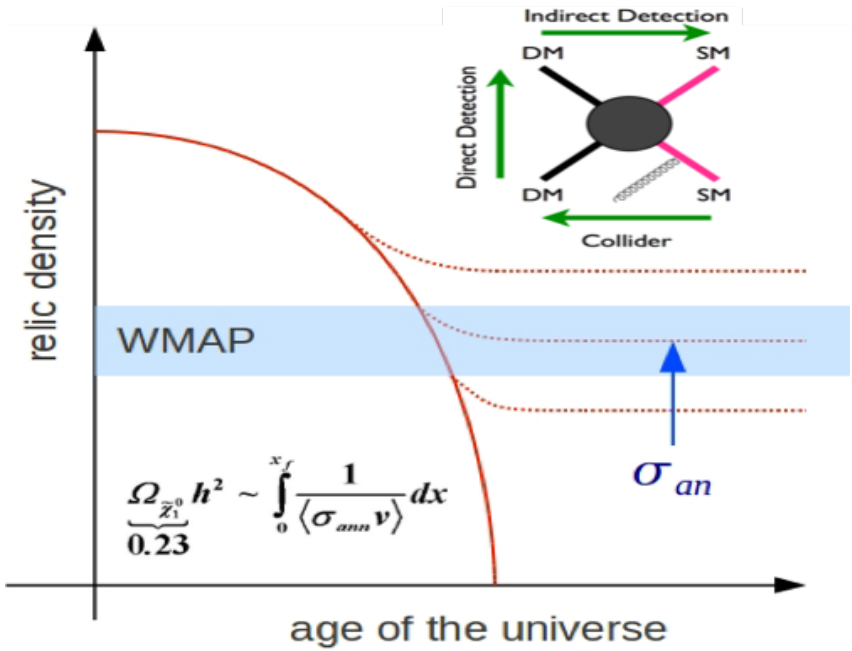
Electroweak SUSY Searches

- Searches in the color sector have not yield positive signs of SUSY until now.
- SUSY searches in the electroweak (EWK) sector open a different avenue to find new physics:
  - ✓ Smaller predicted cross sections but lower levels of hadronic activity.
  - ✓ Complements the color searches.



- **The discovery of the Higgs opened a new set of SUSY searches:**
  - ✓ Lightest neutral CP–even Higgs (h) expected to be SM–like, if others are heavy.
  - ✓ Would provide an indication for SUSY solution to hierarchy problem.
  - ✓ It can point to interesting models in compressed spectra scenarios.





R_x to Probe Ωh^2

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

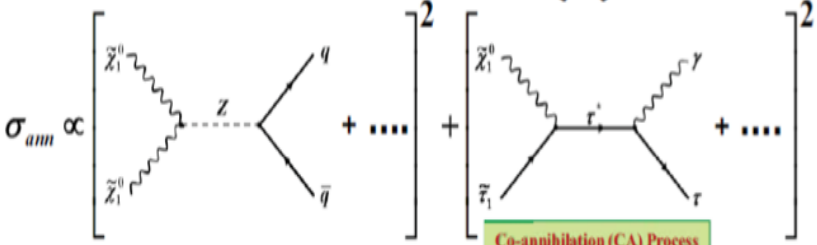
$$s_W = \sin(\theta_W) \quad c_W = \cos(\theta_W)$$

$$s_\beta = \sin(\beta) \quad c_\beta = \cos(\beta)$$

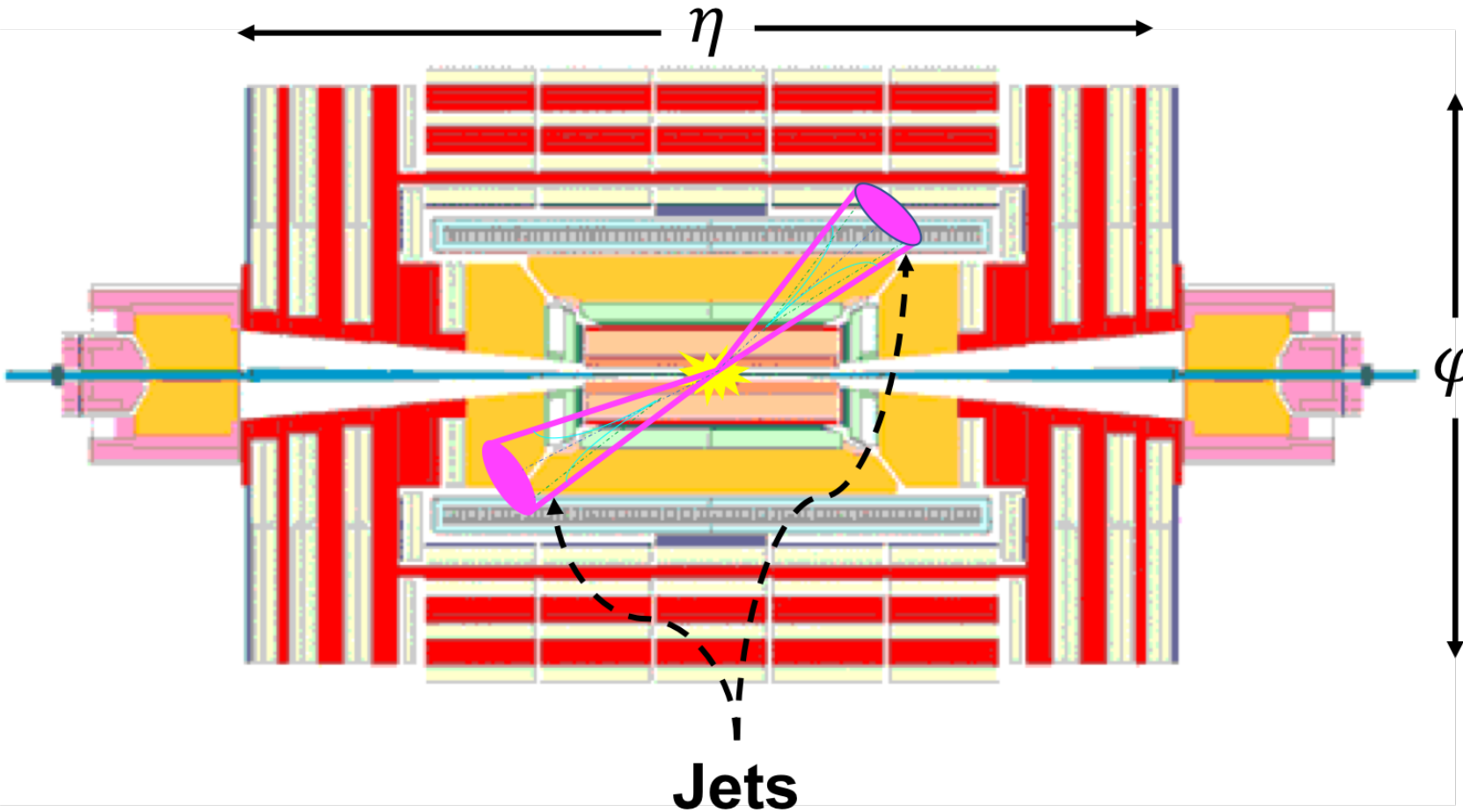
"Number" density (n) → Ω

$$\frac{dn}{dt} = -3Hn - \langle \sigma \cdot v \rangle \left(n^2 - n_{eq}^2 \right)$$

Cross section (σ)

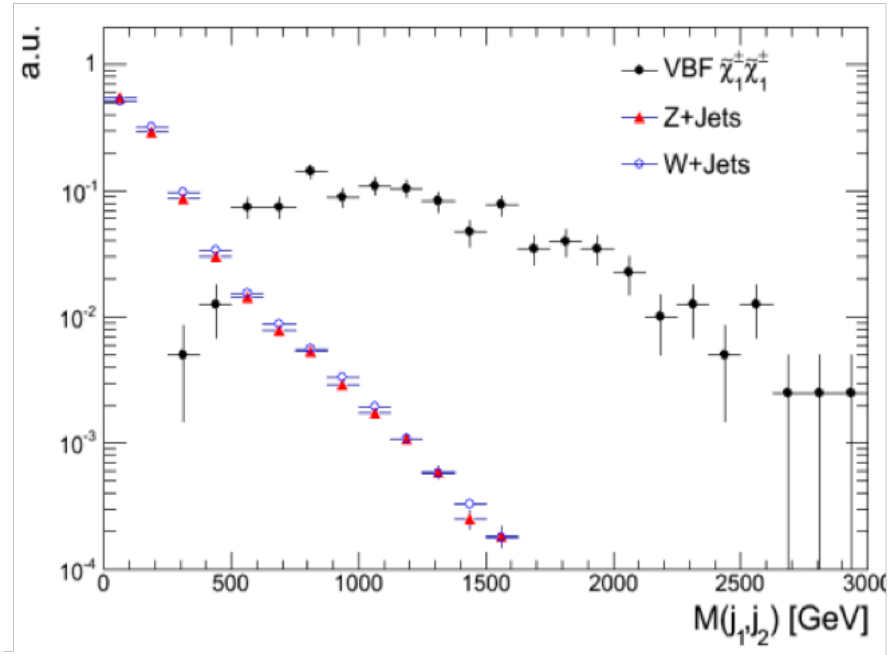


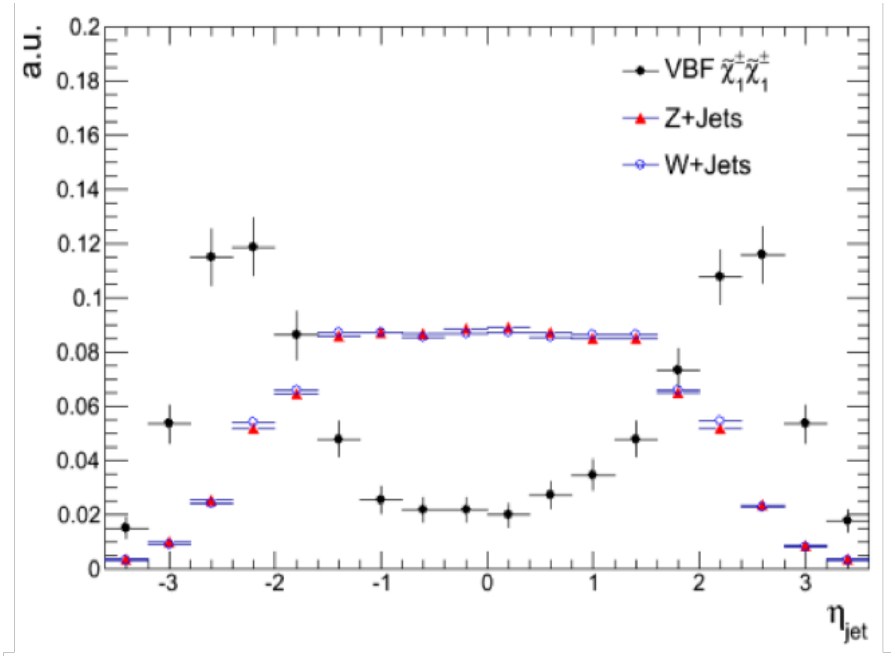
Vector Boson Fusion Topology

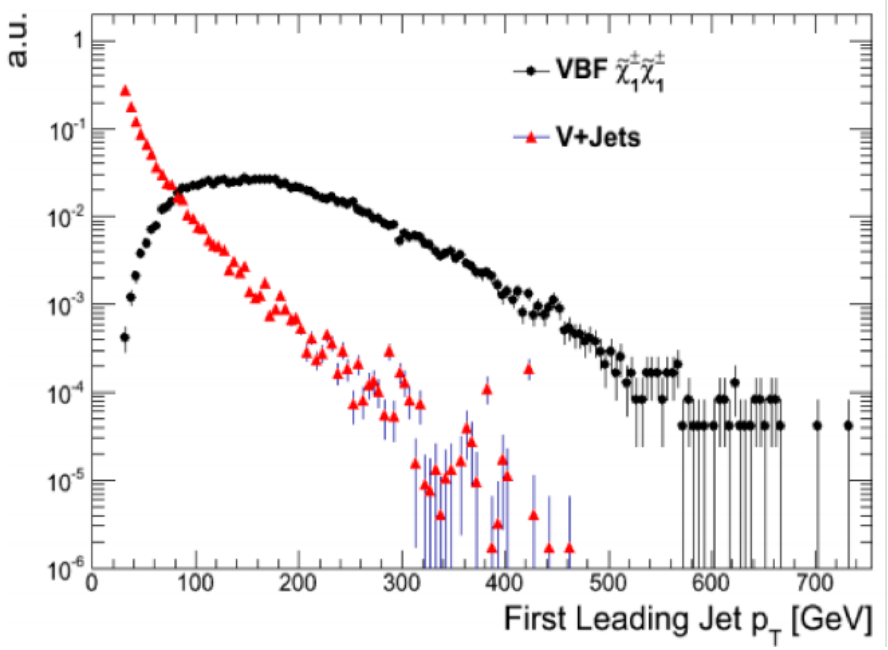


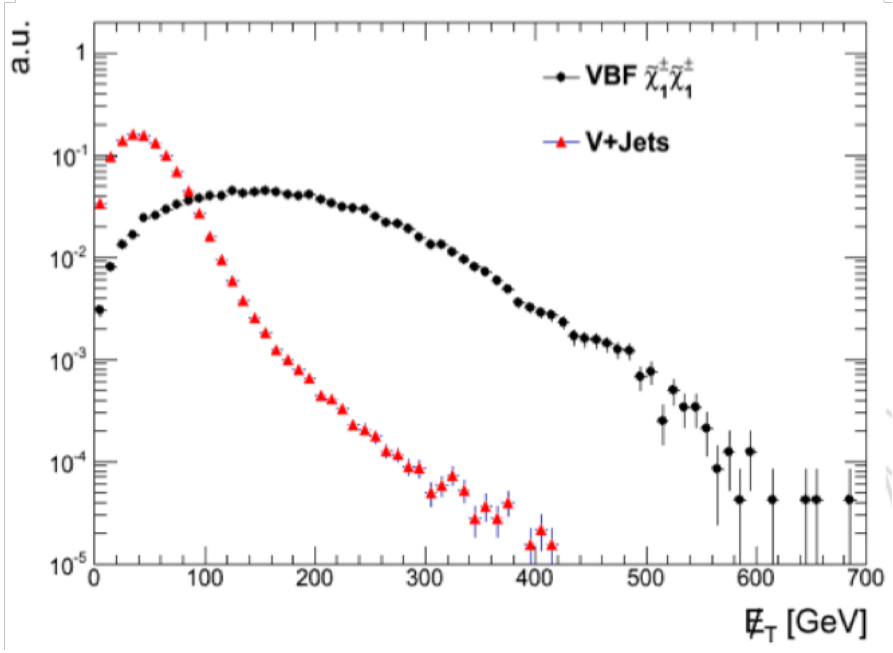
- The VBF topology is characterized by the presence of two highly energetic jets, with a large $\Delta\eta$ gap, located in oposite hemispheres of the detector, and with a large dijet reconstructed mass.

Vector Boson Fusion Topology



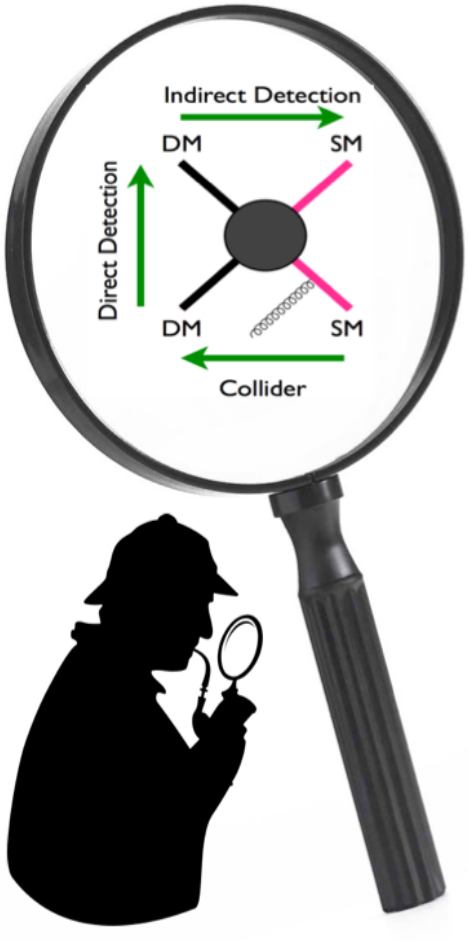


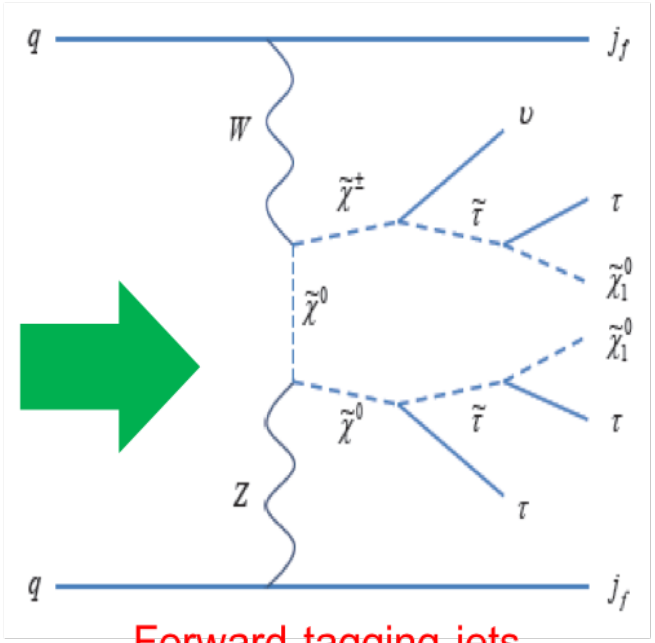


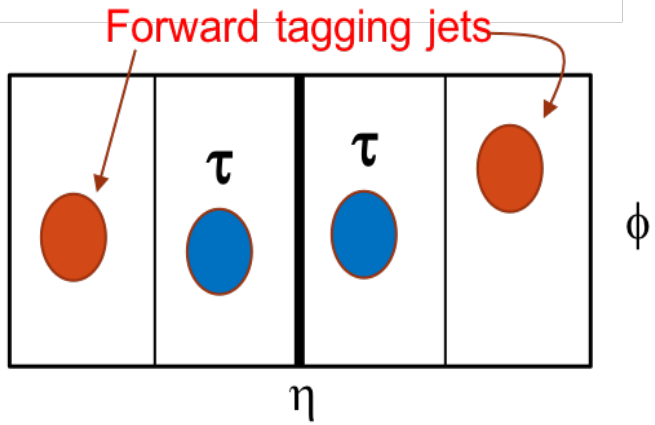


VBF SUSY at 8 TeV - **Published in JHEP 1511 (2015) 189**

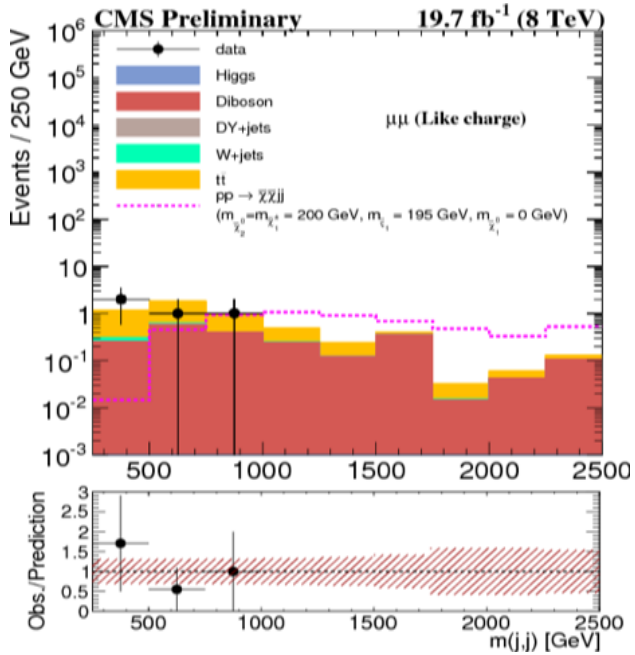
First VBF SUSY search (done w/ 8 TeV data)

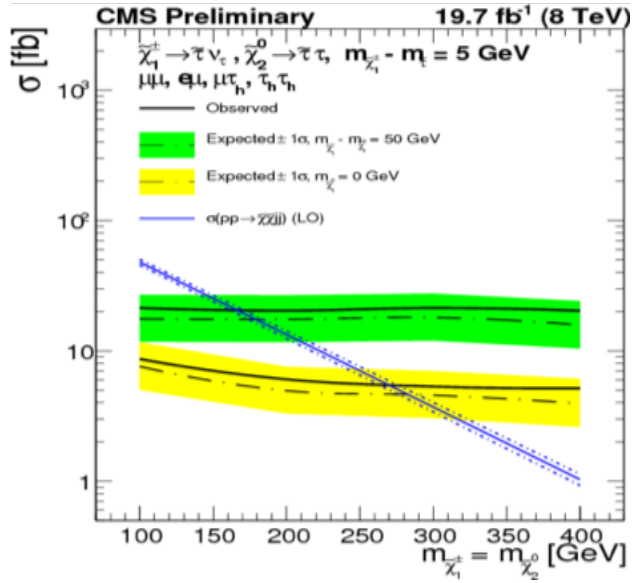






MET + ττ + leptons

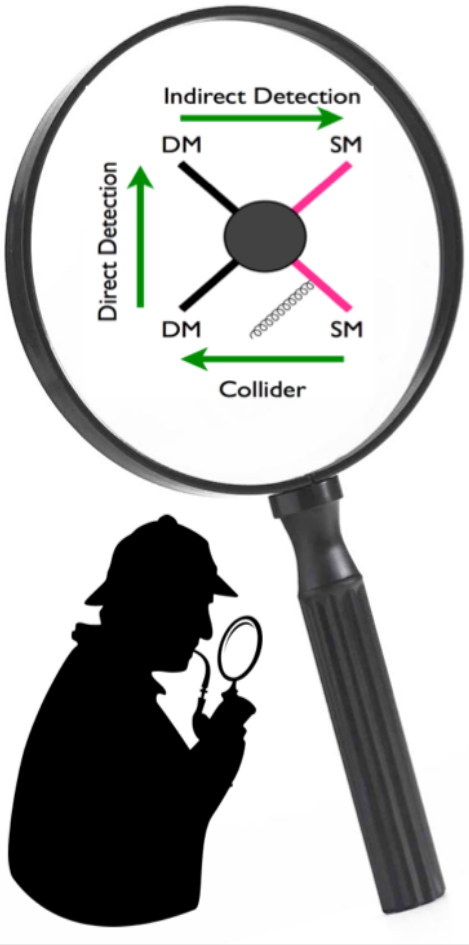


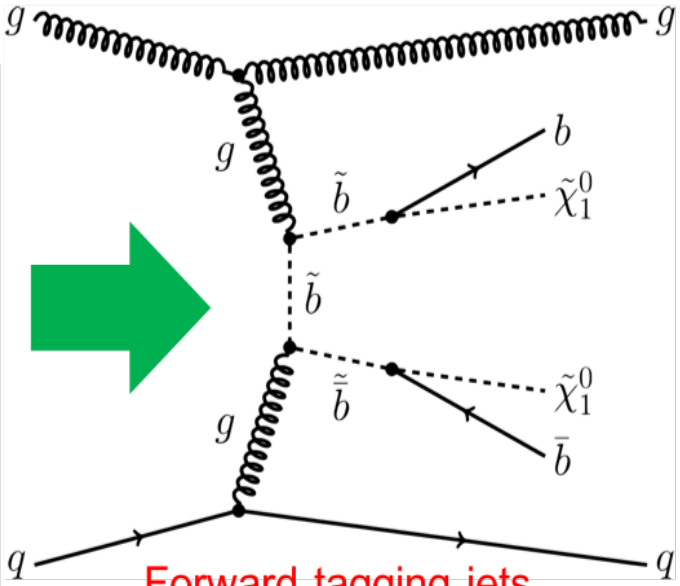


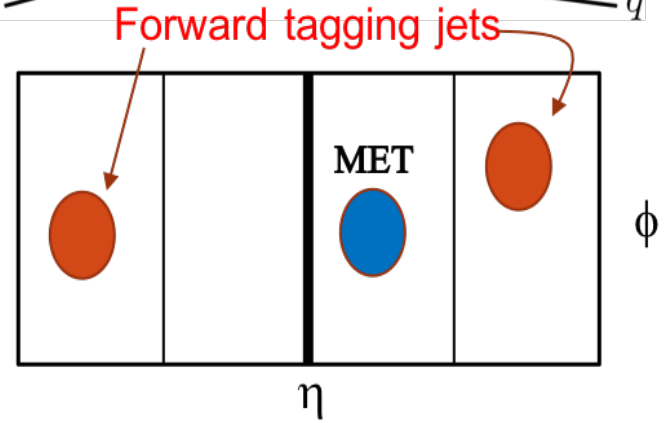
8 final states considered. Did not look at soft lepton channels.

VBF SUSY at 8 TeV - Published in PRL 118, 021802 (2017)

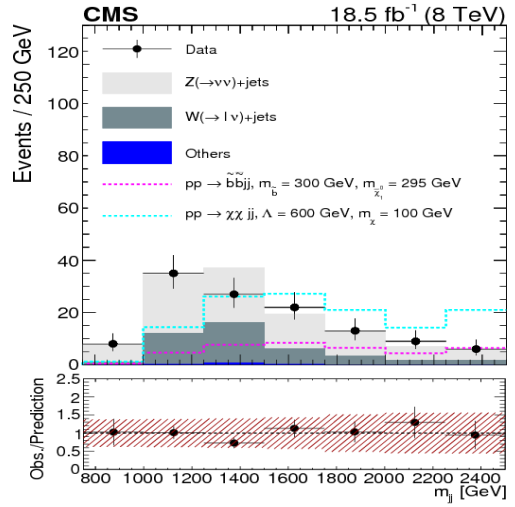
First VBF SUSY search (done w/ 8 TeV data)

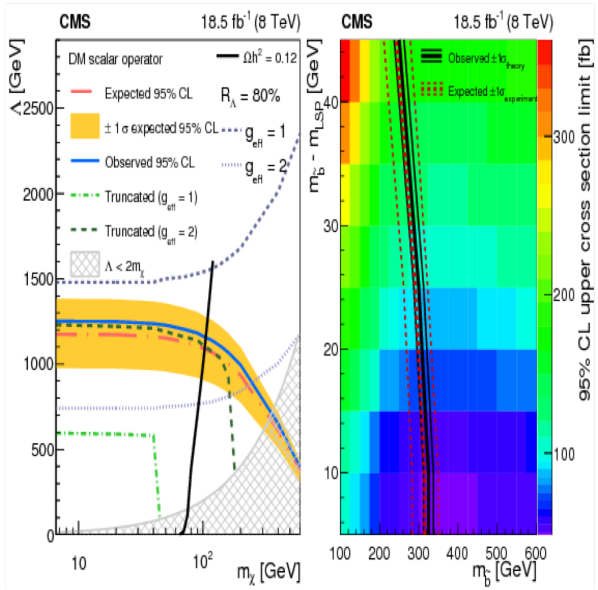






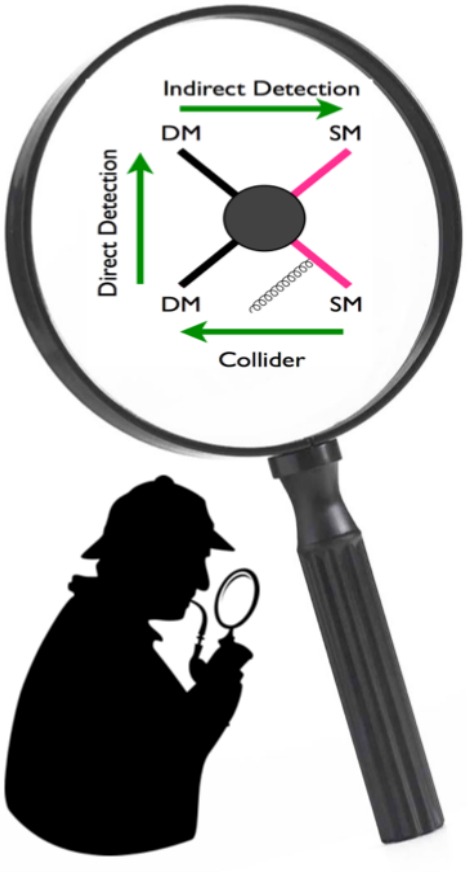
MET + ττ + leptons

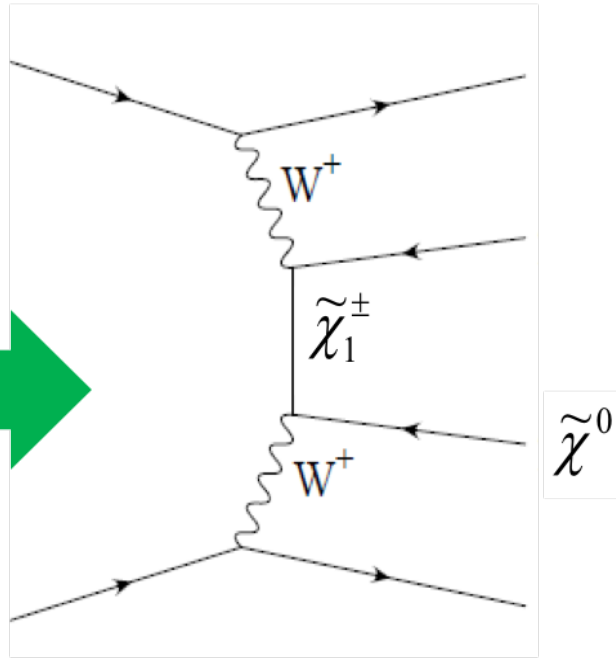


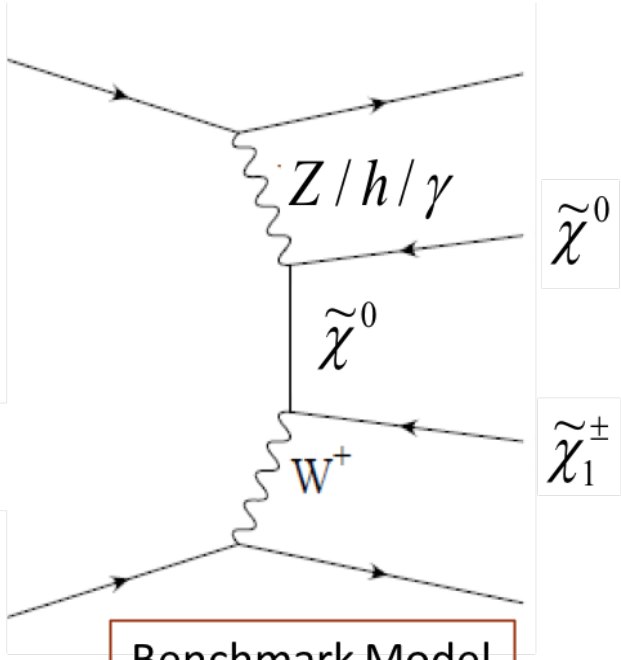


VBF SUSY at 13 TeV

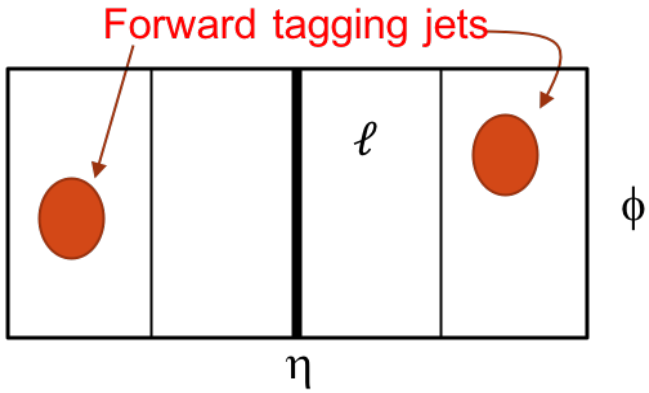
Improvements with 13 TeV!

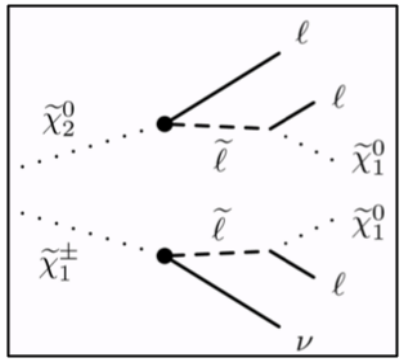






Benchmark Model





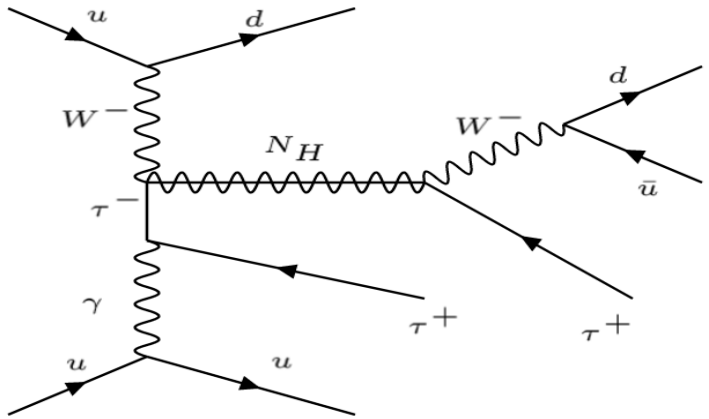
4 final states considered so far this year: μjj, ejj, $\tau_h$jj, and invisible VBF

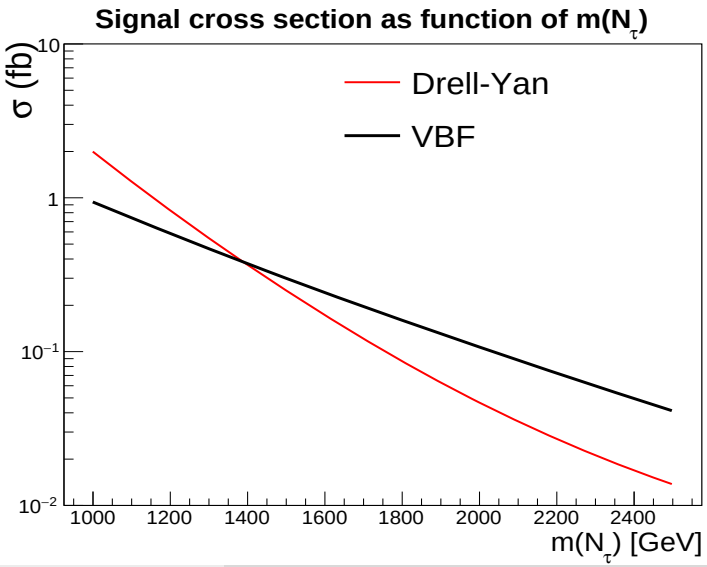
Focus on single soft-lepton channels since it's difficult to reconstruct multiple leptons in compressed spectra (higher acceptance/sensitivity than dilepton channels)

Pheno.: VBF Heavy Neutrino - **Phys.Lett. B778 (2018)**

- One of the open questions the SM fails to address is the non-zero mass of the three generations of neutrinos, which is implied by the observation of neutrino oscillations.
- It has been suggested that because neutrinos can be their own anti-particles (Majorana fermions), the non-zero mass of light neutrinos ν_ℓ could be generated by a see-saw mechanism.
- For example, in the left-right symmetric model (LRSM), originally introduced to explain the non-conservation of parity in weak interactions within the SM, the introduction of a $SU(2)_R$ group, the right-handed analogue of the SM $SU(2)_L$ group, produces three heavy right-handed neutrino states N_ℓ ($\ell = e, \mu, \tau$) and three gauge bosons, $V_R = \{W_R^\pm, Z'\}$.
- ATLAS and CMS have a strong program to search for N_ℓ.

- CMS and ATLAS searches assume that N_ℓ is lighter than V_R: $m_{N_\ell} < m_{W_R^\pm}$ and $m_{N_\ell} < 0.5 m_{Z'}$.

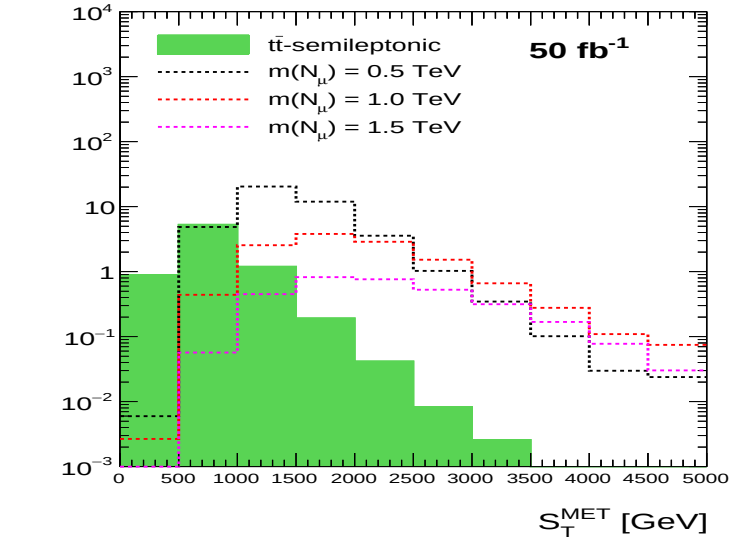


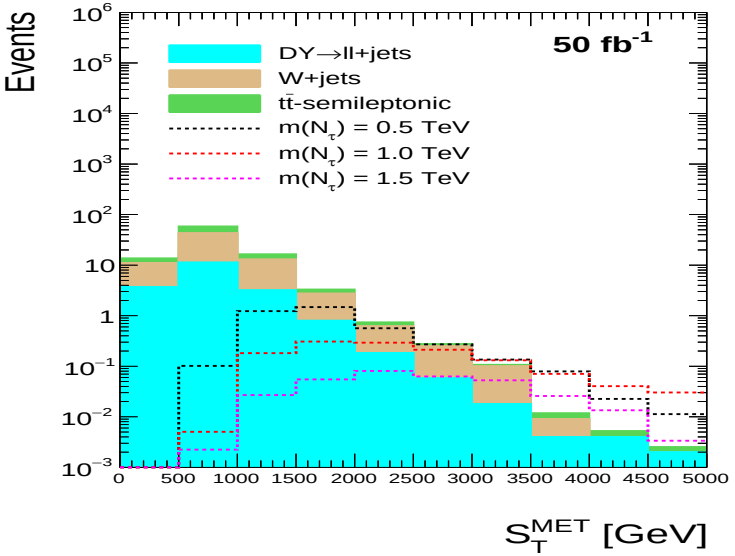


Phenomenology: VBF Heavy Neutrino

- The phenomenological analysis was performed using two final states: $\mu\mu jjj_f j_f$ and $\tau\tau jjj_f j_f$

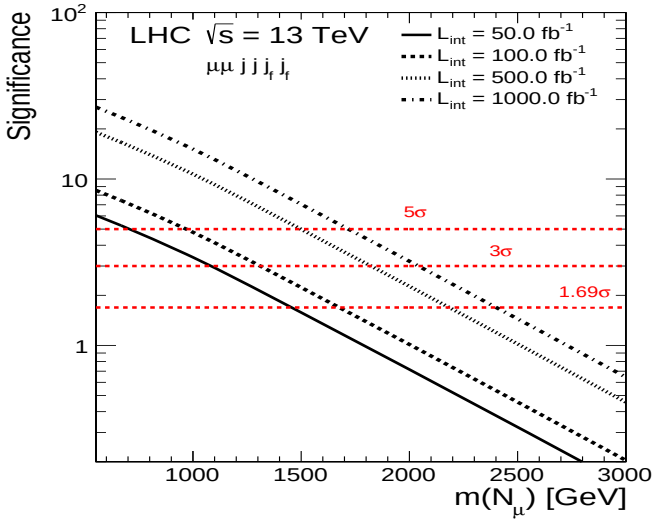
Criterion	$\tau_h\tau_h jjj_f j_f$	$\mu\mu jjj_f j_f$
Central Selections		
$\lvert\eta(\tau_h/\mu)\rvert$	< 2.1	< 2.5
$p_T^{lead}(\tau_h/\mu)$	> 50 GeV	> 50 GeV
$p_T^{slead}(\tau_h/\mu)$	> 20 GeV	> 8 GeV
$N(\tau_h/\mu)$	> 1	> 1
$\Delta R(\tau_{h1}/\mu_1, \tau_{h2}/\mu_2)$	> 0.3	> 0.3
$\lvert\Delta p_T(\tau_{h1}/\mu_1, \tau_{h2}/\mu_2)\rvert$	> 50 GeV	> 50 GeV
$Q(\tau_{h1}/\mu_1) \times Q(\tau_{h2}/\mu_2)$	> 0	> 0
N_{b-jets}	$= 0$	$= 0$
$p_T^{central}(j)$	30 GeV	30 GeV
$\lvert\eta^{central}(j)\rvert$	< 2.4	< 2.4
$N_{central}(j)$	$= 2$	$= 2$
$\Delta R(\tau_h/\mu, j)$	> 0.4	> 0.4
VBF Selections		
$p_T^{lead}(jet)$	30 GeV	30 GeV
$\lvert\eta^{lead}(jet)\rvert$	< 5.0	< 5.0
$p_T^{sub-lead}(jet)$	30 GeV	30 GeV
$\lvert\eta^{sub-lead}(jet)\rvert$	< 5.0	< 5.0
$\Delta R(\tau_h/\mu, jet)$	> 0.4	> 0.4
$\eta(j_1) \cdot \eta(j_2)$	< 0	< 0
$\lvert\Delta\eta(j_1, j_2)\rvert$	> 4.2	> 4.2
m_{jj}	> 750 GeV	> 750 GeV

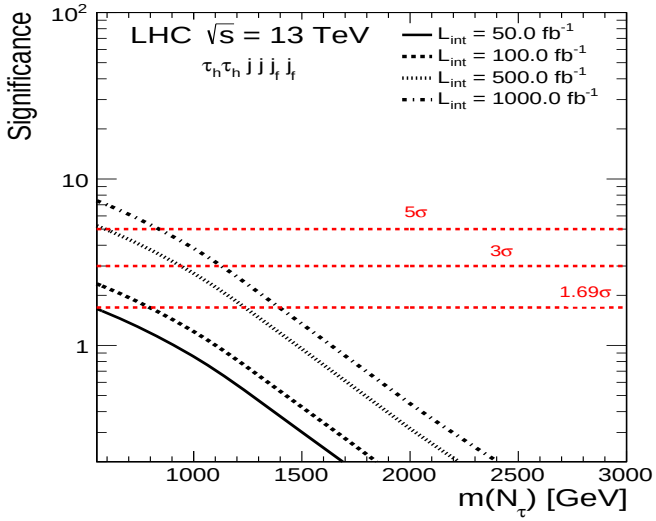




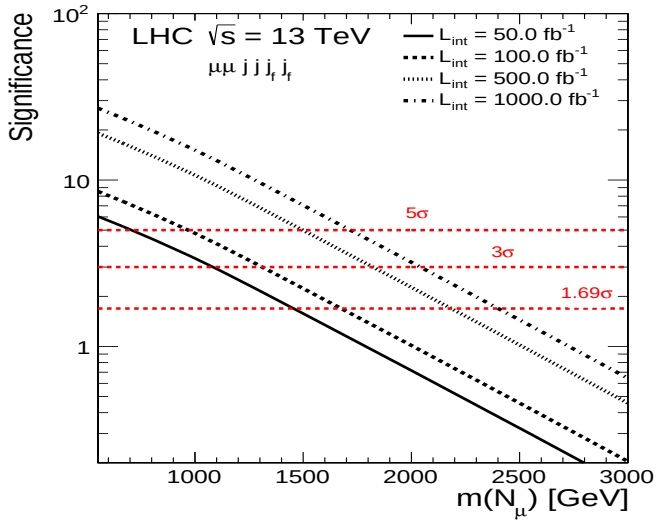
Phenomenology: VBF Heavy Neutrino

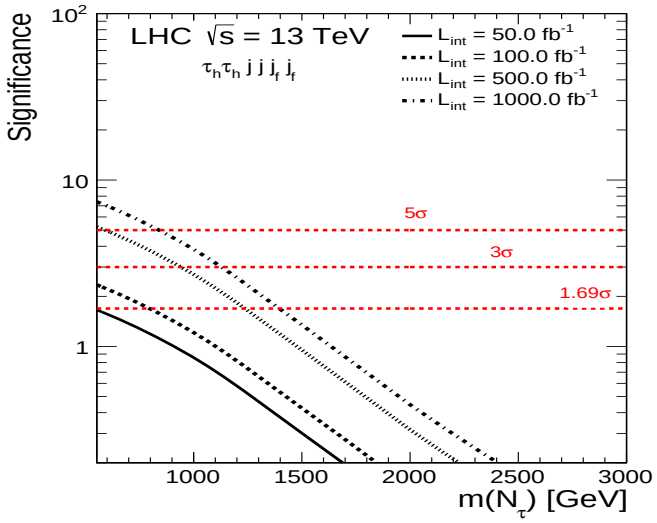
- The figures show the expected signal significance in the $\mu\mu jjj_f j_f$ and $\tau_h\tau_h jjj_f j_f$ channels, respectively, for integrated luminosities L_{int} = 50-1000 fb^{-1} and mixing $|V_{\ell N_\ell}|^2 = 1$.
- For $L_{int} = 100$ fb^{-1}, the expected 95% exclusion on m_{N_μ} using the $\mu\mu jjj_f j_f$ search channel is ~ 1.7 TeV, while the 3σ (5σ) reach is ~ 1.3 (1.0) TeV.
- Similarly, the expected 95% exclusion on m_{N_τ} using the $\tau_h\tau_h jjj_f j_f$ search channel is ~ 0.8 TeV at $L_{int} = 100$ fb^{-1}.

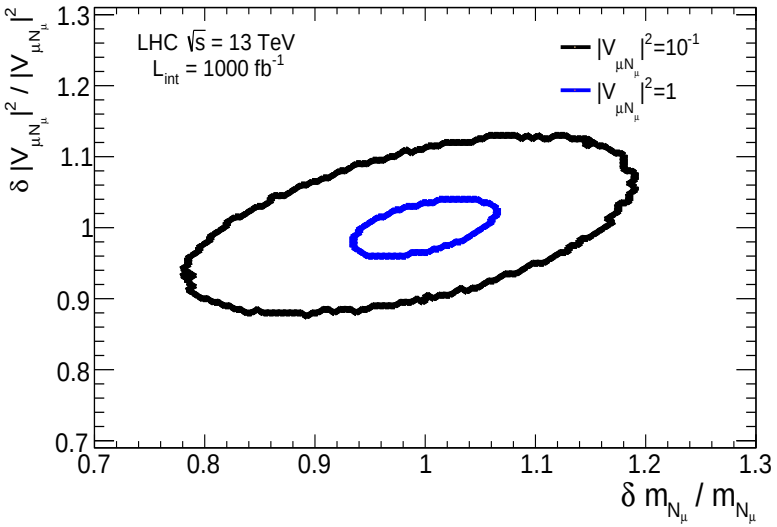


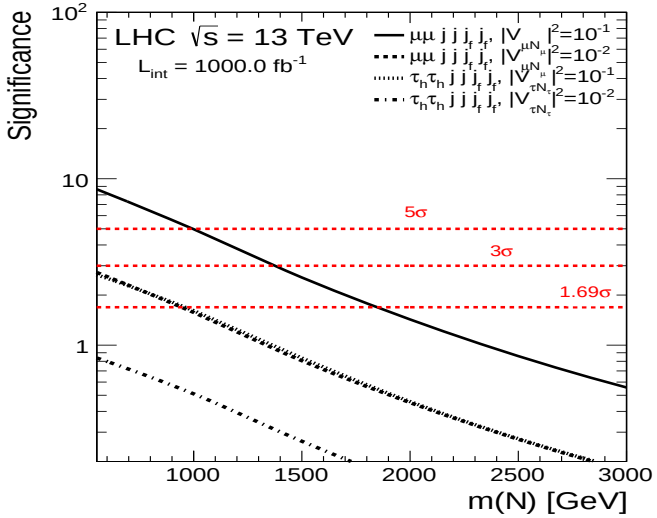


VBF Heavy Neutrino









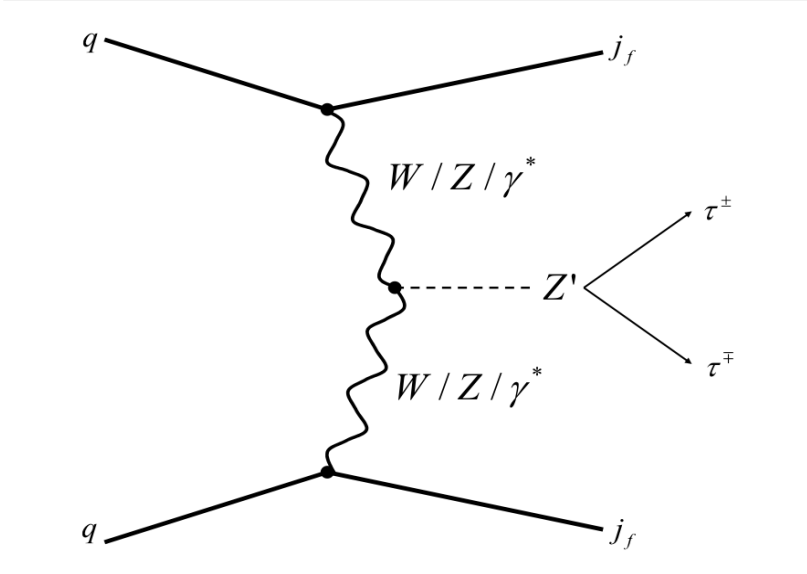
Pheno.: VBF Z' - **Phys.Lett. B767 (2017)**

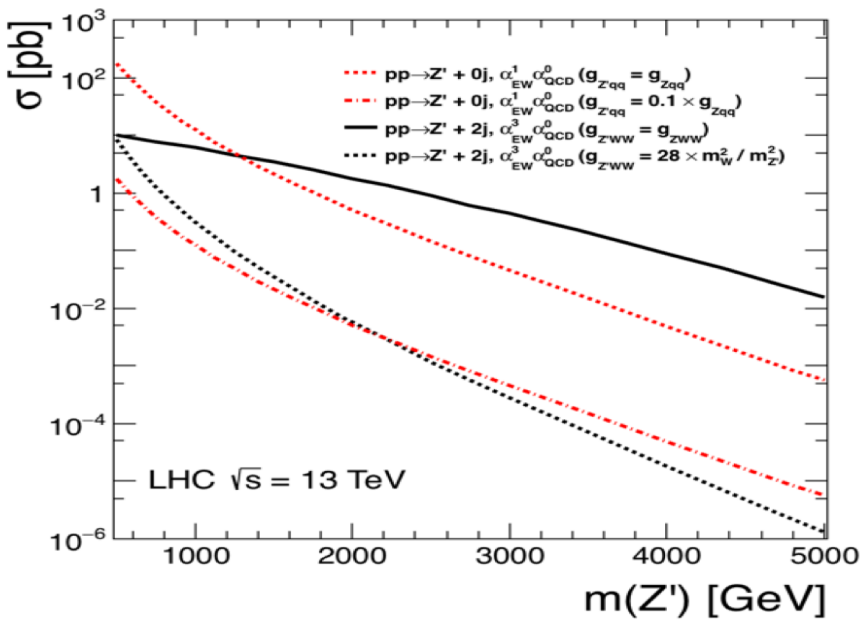
- Another interesting idea, is the search of Z' bosons through VBF production.
- So far, the LHC has search for Z', assuming DY production, and mainly assuming SSM scenarios.
- Nevertheless, what happens if this particle does not couple to the color sector?
- We have studied different scenarios, assuming the couplings go as:
  $g_{Z'qq} = k_q \times g_{Zqq}$, $g_{Z'vv} = k_v \times g_{Zvv}$
- If the Z' couples to vector bosons, its decay width is given by:

$$\frac{g_{Z'vv} cos\theta_\omega m^5_{Z'}}{192\pi m^4_W}$$

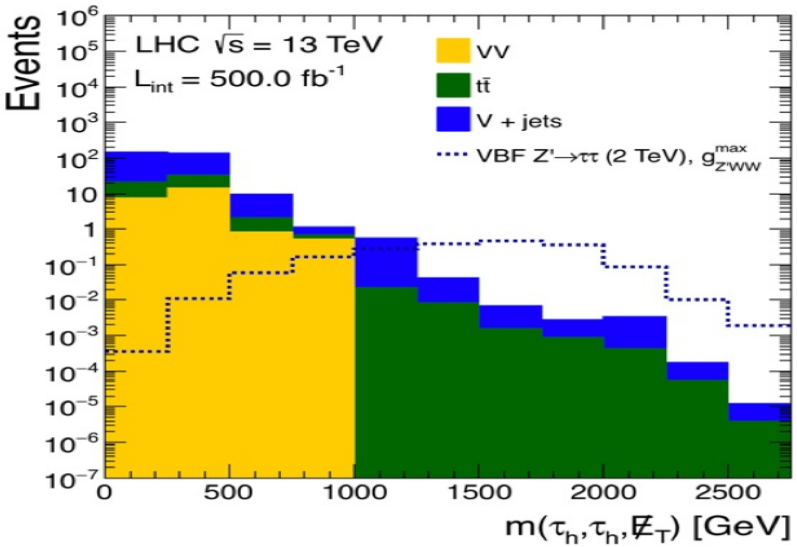
- The decay width can not be larger than the Z' mass:

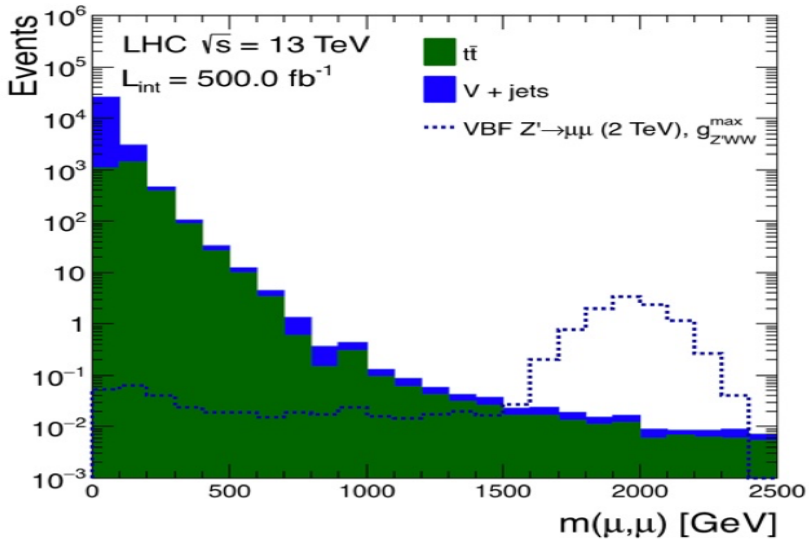
$$g^{max}_{Z'vv} = (5.3 \times m_W / mZ')^2$$

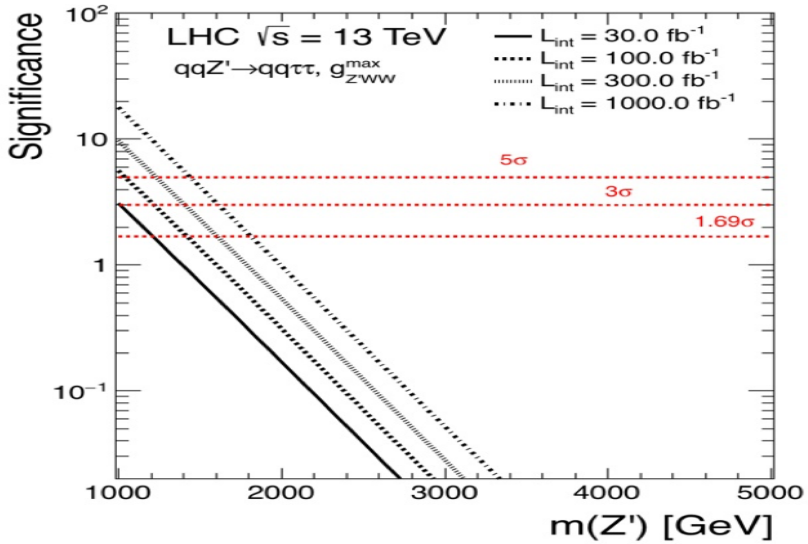


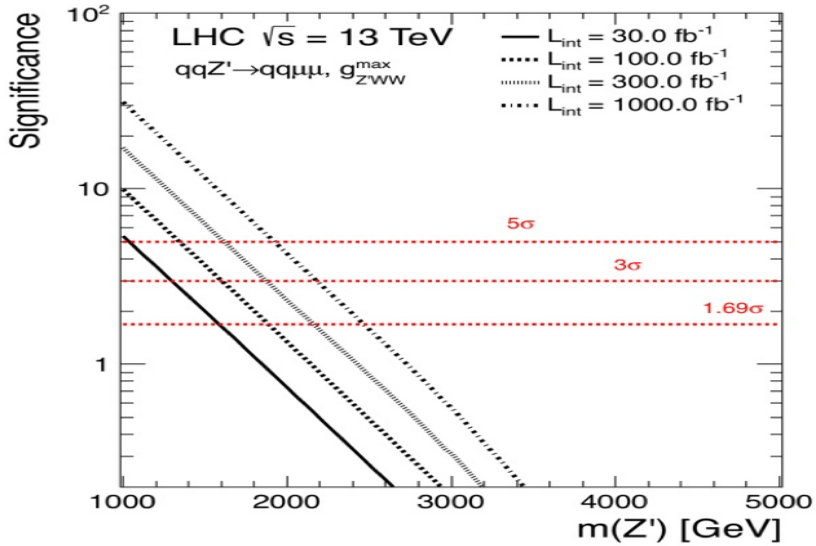


Phenomenology: VBF Z'









Summary

Introduction.

1. The VBF topology is a power tool to search for new physics at the LHC.
2. The particular topology allows to reduce QCD multi-jet BGs significantly, while keeping great signal acceptance

Summary

Introduction.

1. The VBF topology is a power tool to search for new physics at the LHC.
2. The particular topology allows to reduce QCD multi-jet BGs significantly, while keeping great signal acceptance
3. VBF is perhaps of the best way to explore very compressed spectra region with taus, in SUSY scenarios, which has a direct connection to DM.

Summary

Introduction.

1. The VBF topology is a power tool to search for new physics at the LHC.
2. The particular topology allows to reduce QCD multi-jet BGs significantly, while keeping great signal acceptance
3. VBF is perhaps of the best way to explore very compressed spectra region with taus, in SUSY scenarios, which has a direct connection to DM.
4. Other important applications of VBF have been proposed to search for heavy neutrinios of Z' at the LHC.

Summary

Introduction.

1. The VBF topology is a power tool to search for new physics at the LHC.
2. The particular topology allows to reduce QCD multi-jet BGs significantly, while keeping great signal acceptance
3. VBF is perhaps of the best way to explore very compressed spectra region with taus, in SUSY scenarios, which has a direct connection to DM.
4. Other important applications of VBF have been proposed to search for heavy neutrinios of Z' at the LHC.
5. **The group at Uniandes is one of the main leaders of VBF searches at CMS and also has participated proposing new ideas to be explored at the LHC, from the phenological side.**

Summary

Introduction.

1. The VBF topology is a power tool to search for new physics at the LHC.
2. The particular topology allows to reduce QCD multi-jet BGs significantly, while keeping great signal acceptance
3. VBF is perhaps of the best way to explore very compressed spectra region with taus, in SUSY scenarios, which has a direct connection to DM.
4. Other important applications of VBF have been proposed to search for heavy neutrinios of Z' at the LHC.
5. **The group at Uniandes is one of the main leaders of VBF searches at CMS and also has participated proposing new ideas to be explored at the LHC, from the phenological side.**

Thank you!

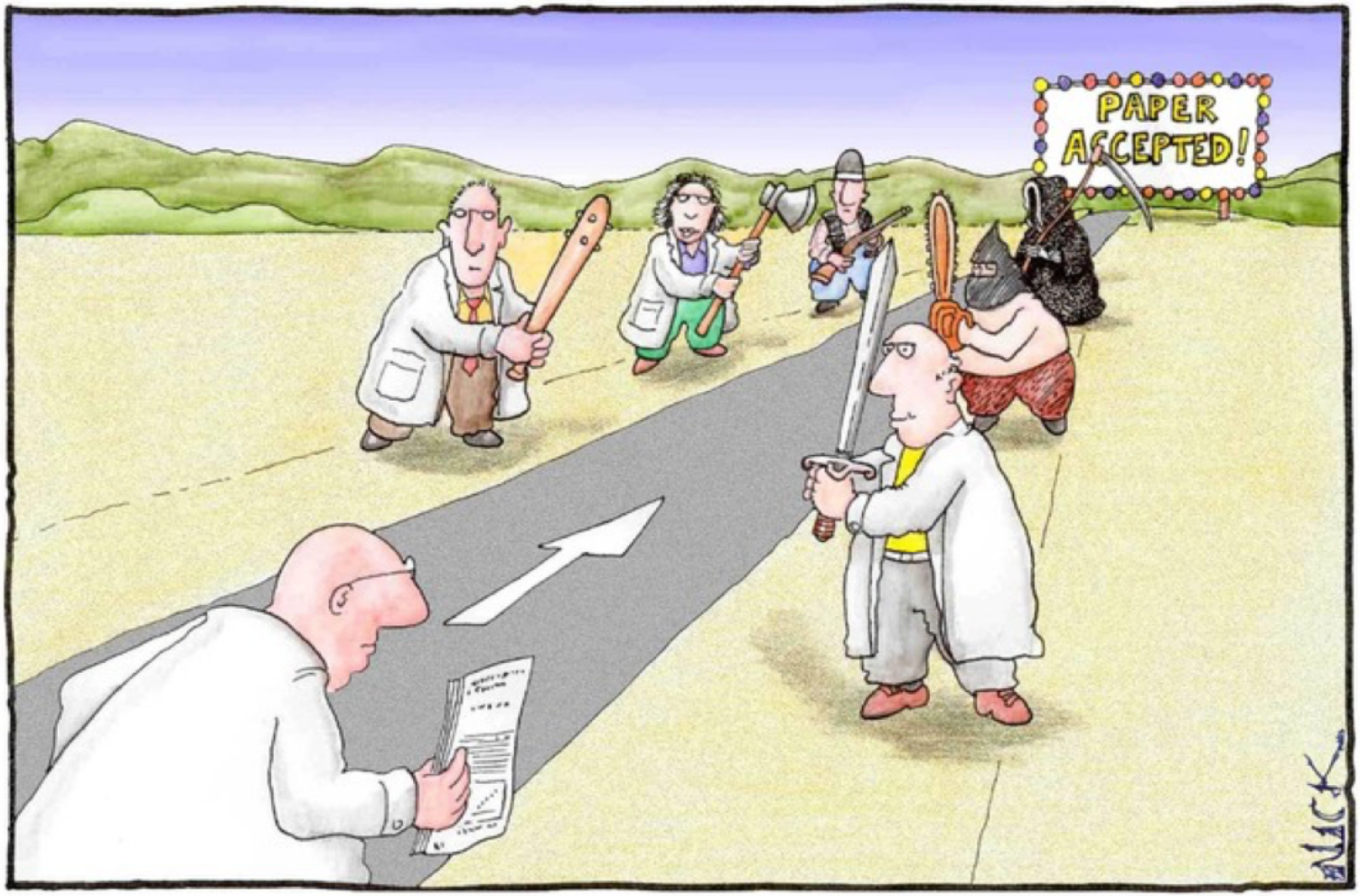
Summary

Introduction.

1. The VBF topology is a power tool to search for new physics at the LHC.
2. The particular topology allows to reduce QCD multi-jet BGs significantly, while keeping great signal acceptance
3. VBF is perhaps of the best way to explore very compressed spectra region with taus, in SUSY scenarios, which has a direct connection to DM.
4. Other important applications of VBF have been proposed to search for heavy neutrinios of Z' at the LHC.
5. **The group at Uniandes is one of the main leaders of VBF searches at CMS and also has participated proposing new ideas to be explored at the LHC, from the phenological side.**

Thank you!

Questions?



Sources

- http://iopscience.iop.org/article/10.1088/1748-0221/3/08/S08004/pdf
- http://cdsweb.cern.ch/record/1194487/files/PFT-09-001-pas.pdf
- http://iopscience.iop.org/article/10.1088/1742-6596/645/1/012008/pdf
- https://arxiv.org/pdf/1510.07488.pdf
- http://science.sciencemag.org/content/347/6226/1100/F1
- https://www.quantumdiaries.org/2011/06/01/anatomy-of-a-jet-in-cms/
- http://ed.fnal.gov/samplers/hsphys/old/activities%20old/top_quark_stud_old.html