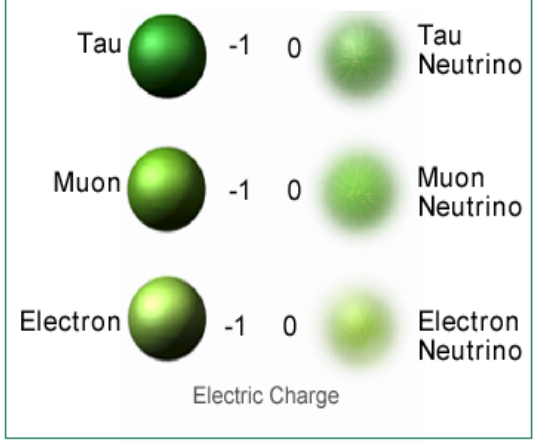
LHC
Higgs, etc.

Gilvan A. Alves
Lafex/CBPF

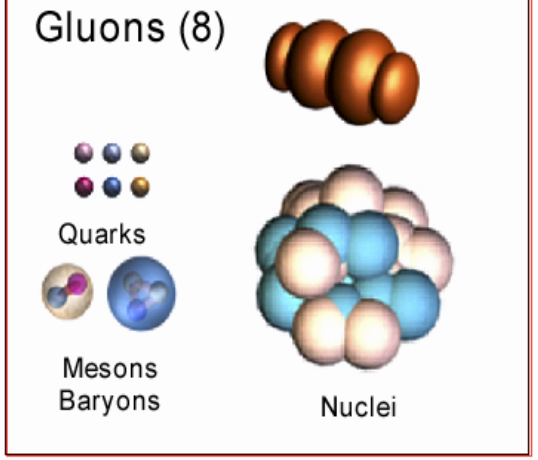


O que sabemos sobre a matéria

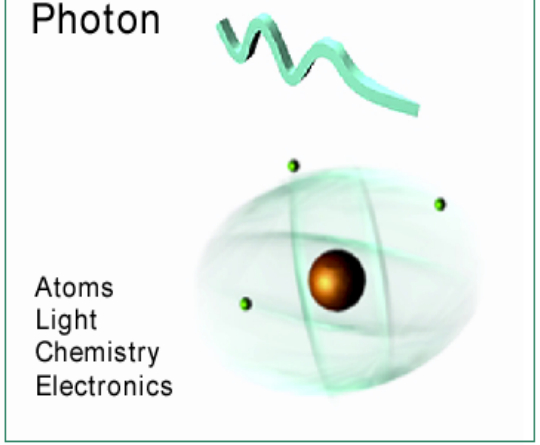
Leptons



Strong



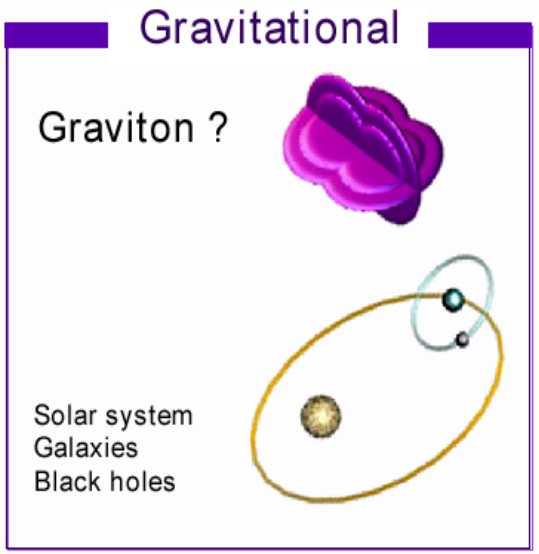
Electromagnetic



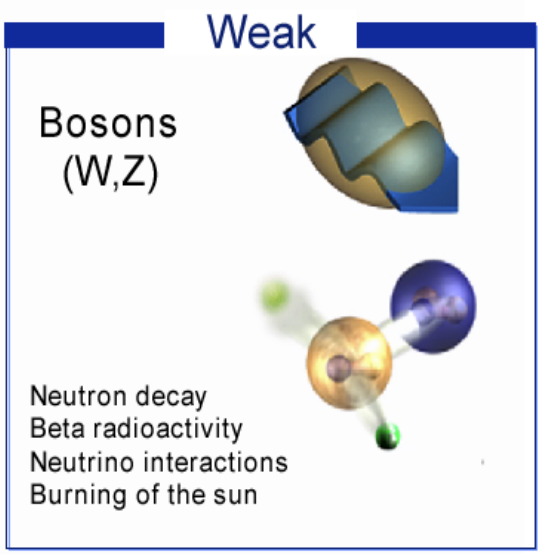
Quarks



Gravitational



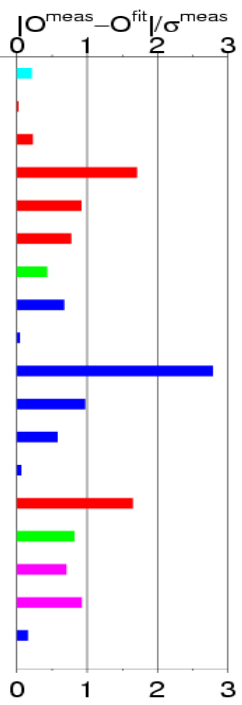
Weak

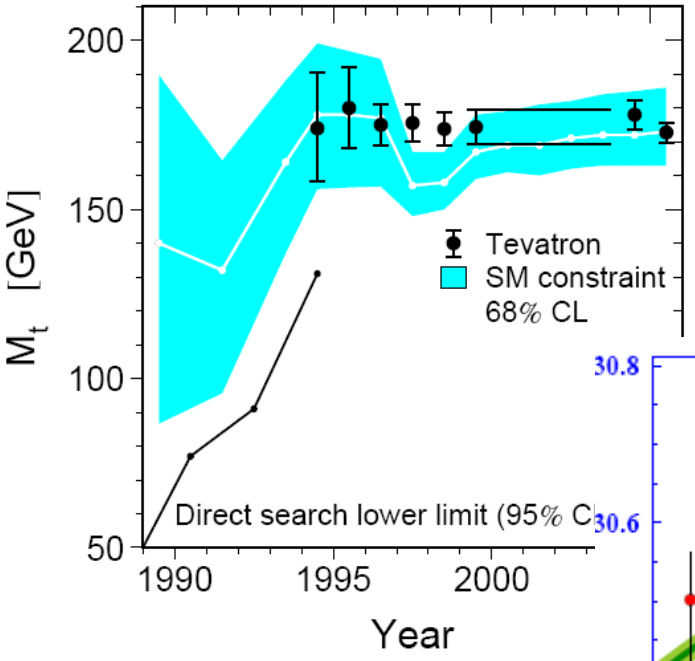


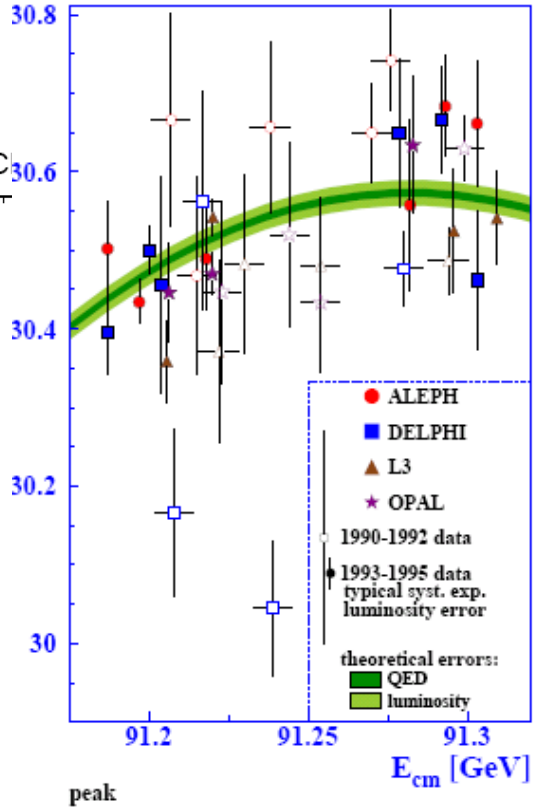
O Modelo Padrão é um marco da Física Moderna

- Impressionante acordo com dezenas de medidas experimentais
  - Incluindo a massa do top
  - Produção de quarks pesados
  - Jatos
  - Assimetrias W, Z
  - ...

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7





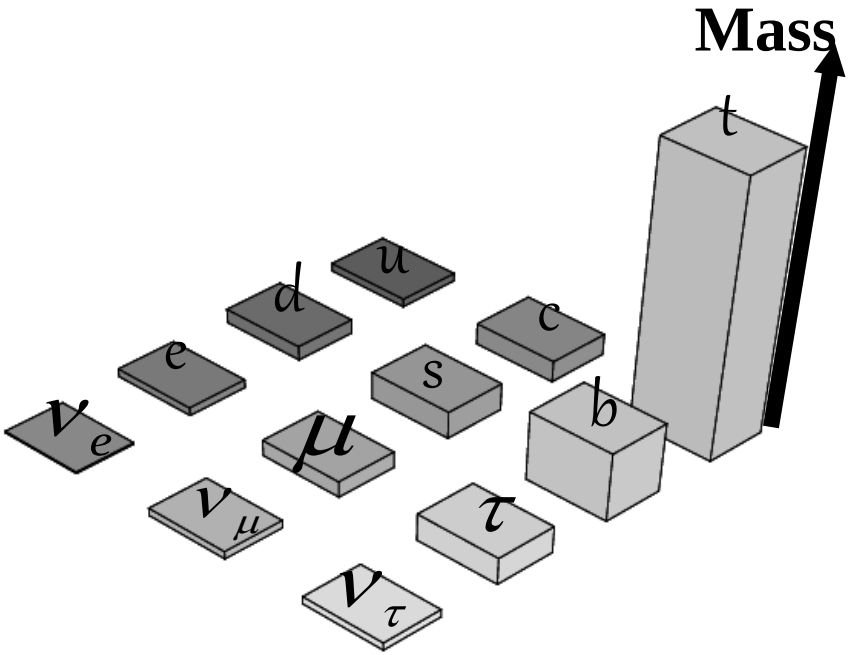


Mas as partículas não teriam massa...

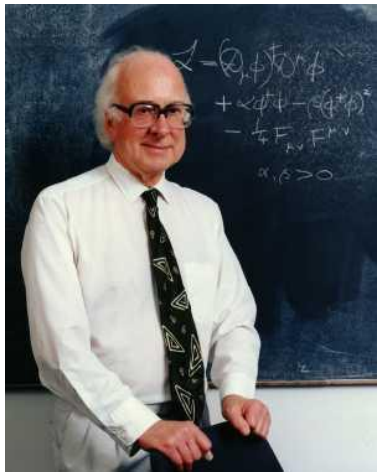
Fundamental para previnir anomalias.

Como o fóton (sem massa) e o bóson W (~80 GeV) mediam a interação eletrofraca?
Solução mais simples (Higgs, Brout, Englert & Kibble)
Novo campo escalar permeia o universo ←→ partículas interagem com este campo





O Mecanismo de Higgs



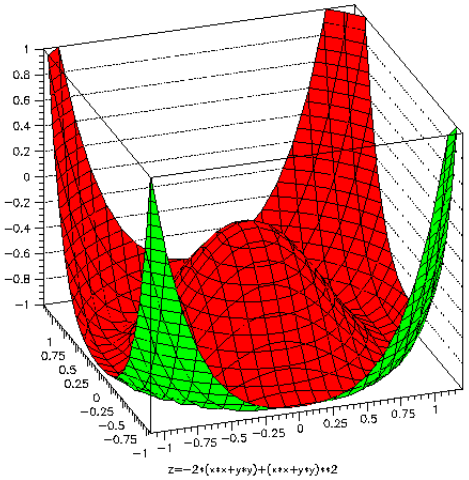
No Modelo Padrão as partículas adquirem massa pela interação com o campo de Higgs (do físico britânico Peter Higgs). Excitações do campo → bóson de Higgs.

O que é o bóson de Higgs? Cartoon baseado na explicação de David Miller ao Ministro de Ciência britânico em 1993.



Por que não estamos satisfeitos?

- **Simetria Interna (calibre): previne anomalias**
- Qualquer massa quebra a simetria



$$\underbrace{SU(3)_C}_{\text{CDQ}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{Eletrofraca}}$$

Quebra espontânea → Mecanismo de Higgs
EDQ + Fraca

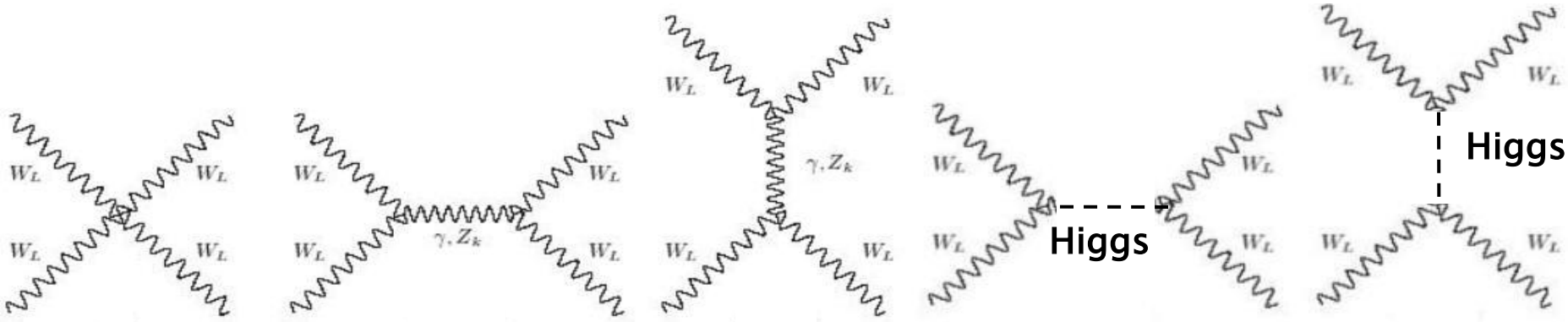
Solução mais econômica

$V(\phi) = \mu^2\phi^2/2 + \lambda\phi^4/4$ (vev≠0)

- Um único escalar com massa = $\sqrt{2}\,\lambda v$
- Termos de massa para $W^{\pm}$, Z (α v)
- Interação com férmions ➔ massa (α v)

Mas...

- **Artificial: forma do potencial, acoplamento, etc.**
- Massas não determinadas.
  - Massa do Higgs < 1 TeV para evitar anomalias

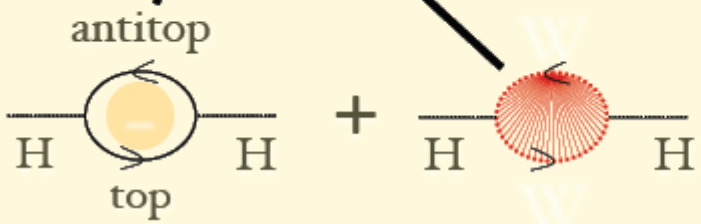


Violação da unitaridade
$\sigma \sim E^2$

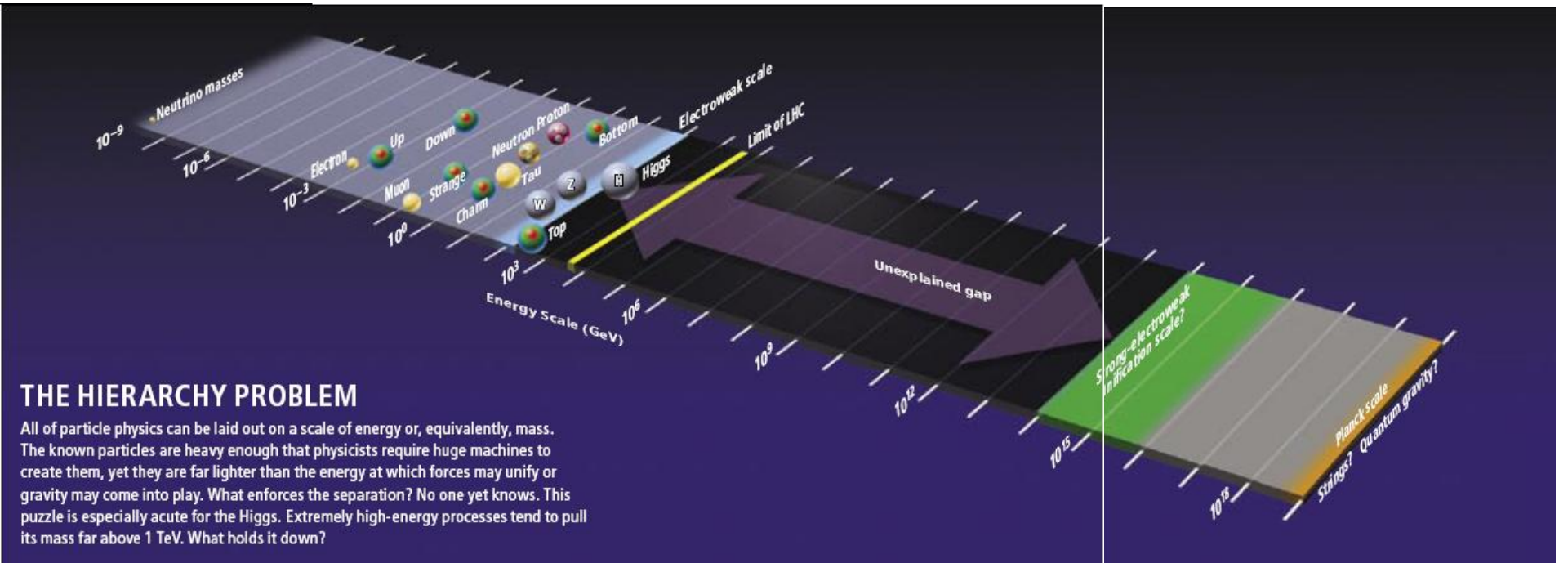
Restaura a unitaridade

- Massa do Higgs sofre correções por sua interação
- $m_H < 1$TeV exige ajuste preciso (artificial) $\Lambda \approx 10^{19}$ GeV
  - Problema da hierarquia

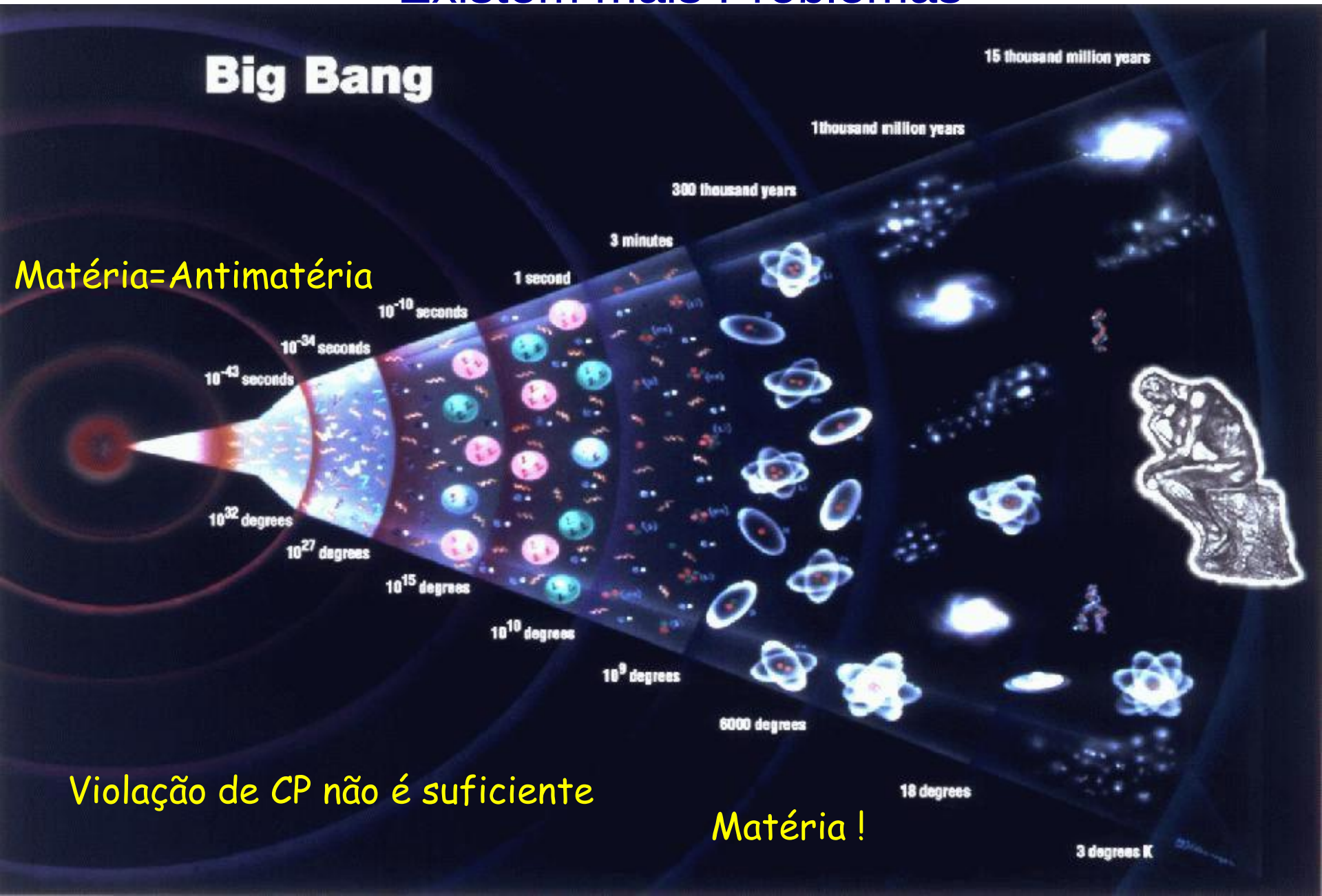
$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim m_0^2 - (115\text{GeV})^2\left(\frac{\Lambda}{400\text{GeV}}\right)^2$$



Λ= scale up to which the SM is valid



Existem mais Problemas



Matéria=Antimatéria

Violação de CP não é suficiente

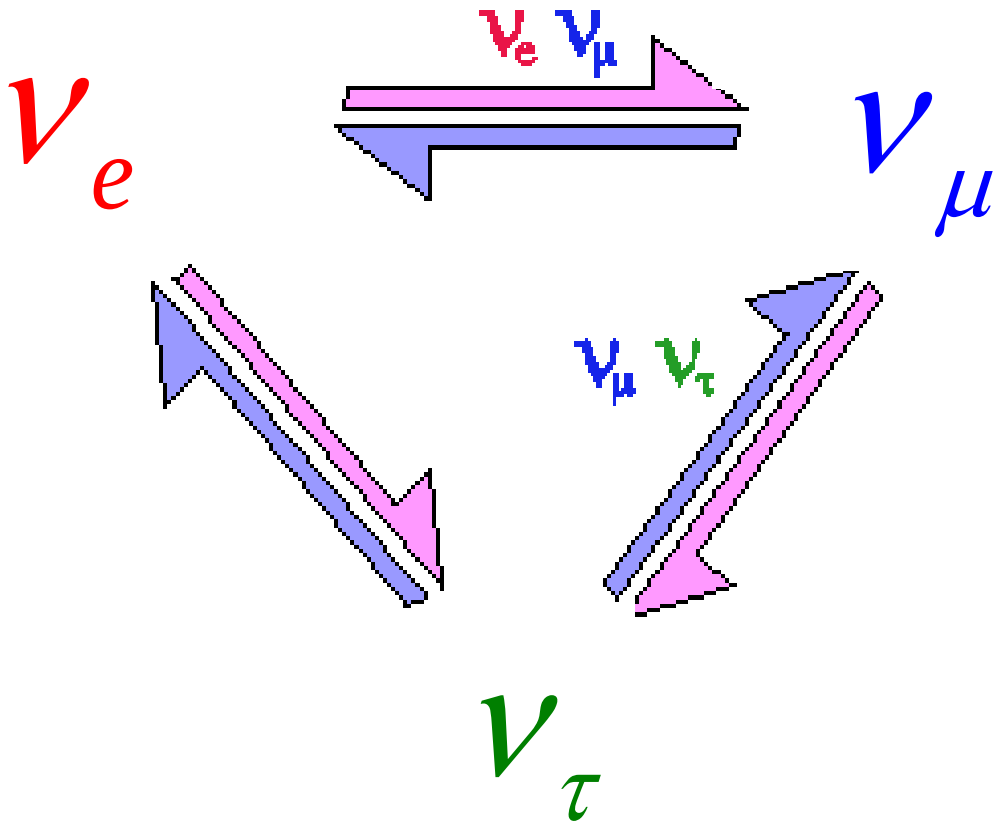
Matéria !

Matéria Escura

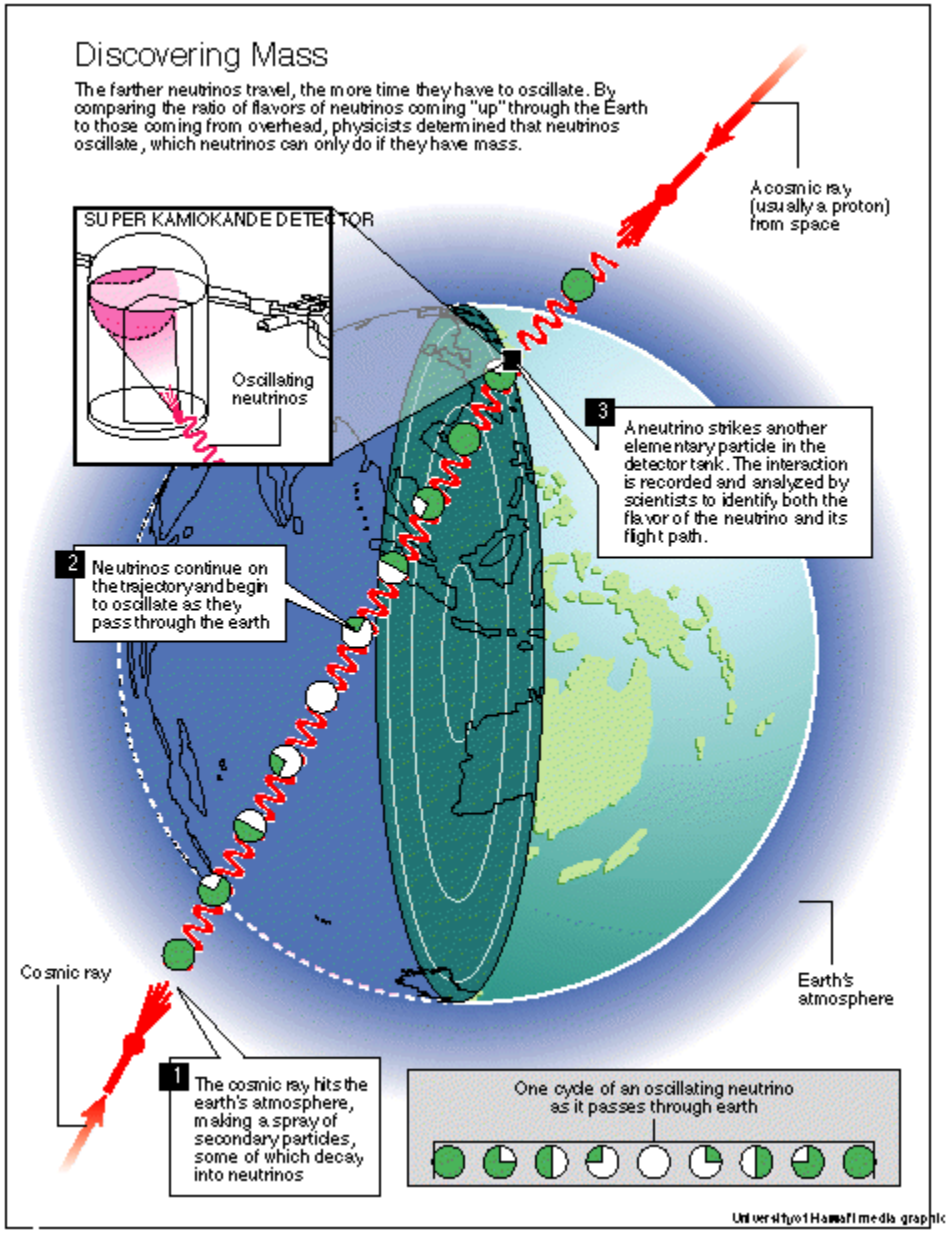


Oscilação de Neutrinos

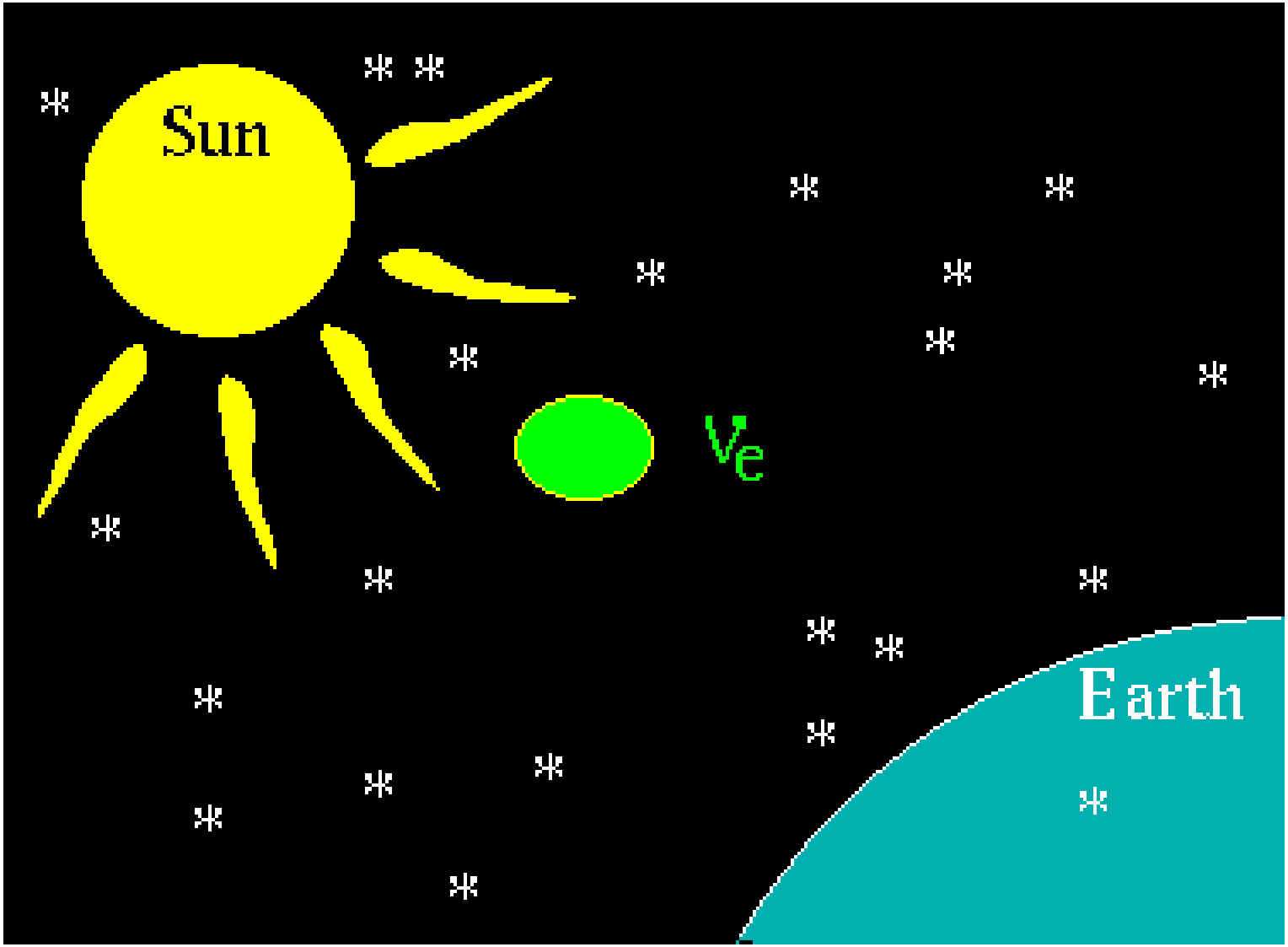
(Neutrinos precisam ter massa)



Oscilações $\nu_\mu \rightarrow \nu_\tau$ são observadas na atmosfera

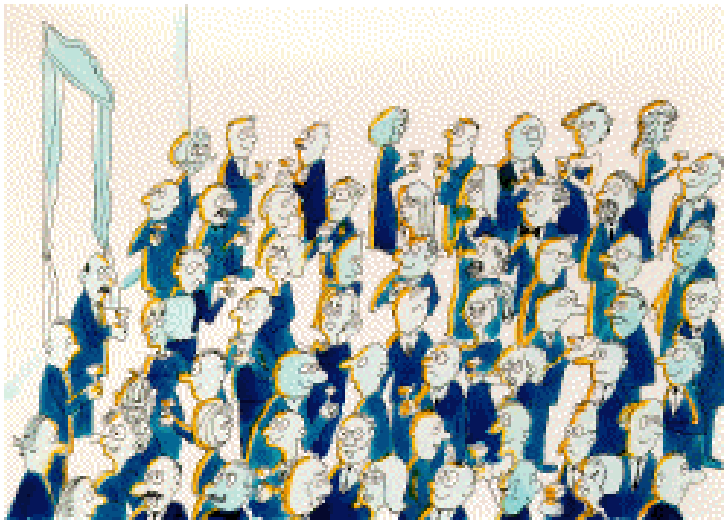


Oscilacões $\nu_e \rightarrow \nu_\mu + \nu_\tau$ vindos do Sol



A observação de oscilação (portanto massa) em neutrinos é uma das maiores descobertas da física de partículas dos últimos tempos (comparável com a dos W e Z)

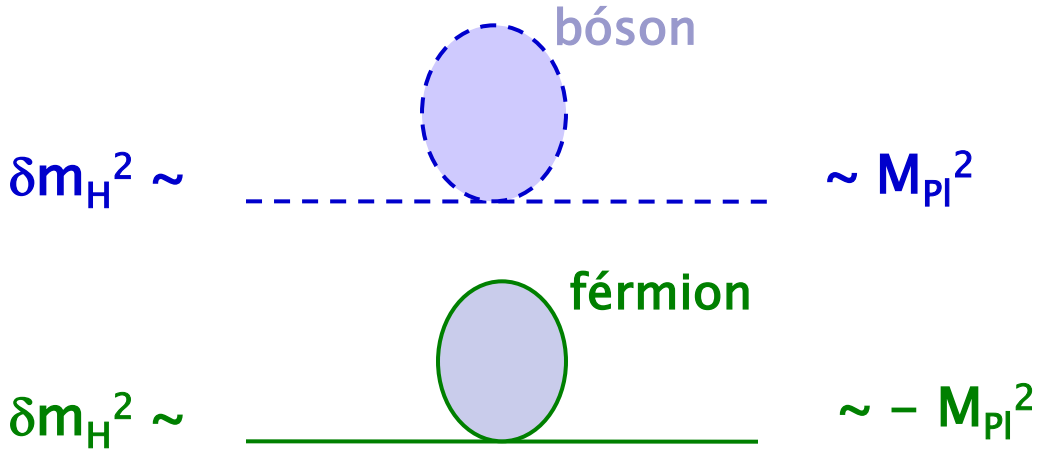
No modelo padrão neutrinos são sempre levógiros, não interagindo com o campo de Higgs.

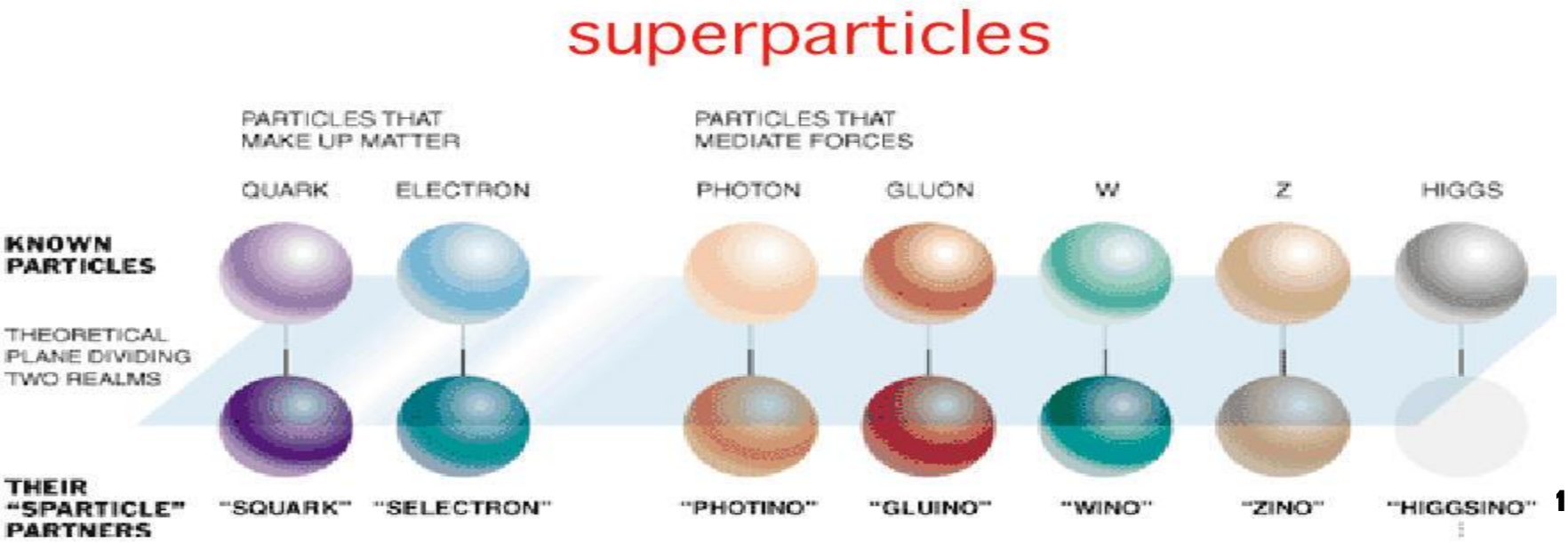


Isso implica necessariamente **Física Além do Modelo Padrão**!

Como resolver esses problemas???

- Supersimetria
  - Perfeita simetria
    - férmions e bósons
    - cancelamento
  - Novas partículas

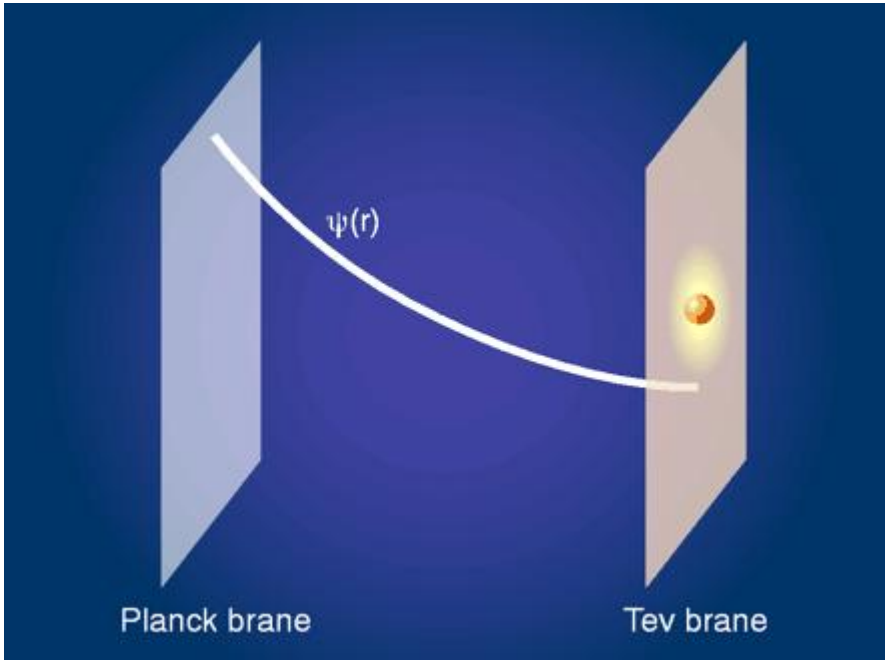




Dimensões extras

- Motivação - Supercordas
  - Gravitação⇔D.E.
- Escala de unificação == Eletrofraca

- Muitos modelos
  - Muitos efeitos
  - Ressonâncias KK
    - Cordas
    - Gráviton
  - Mini-buracos negros
  - Energia perdida
  - ...



Parece confuso??

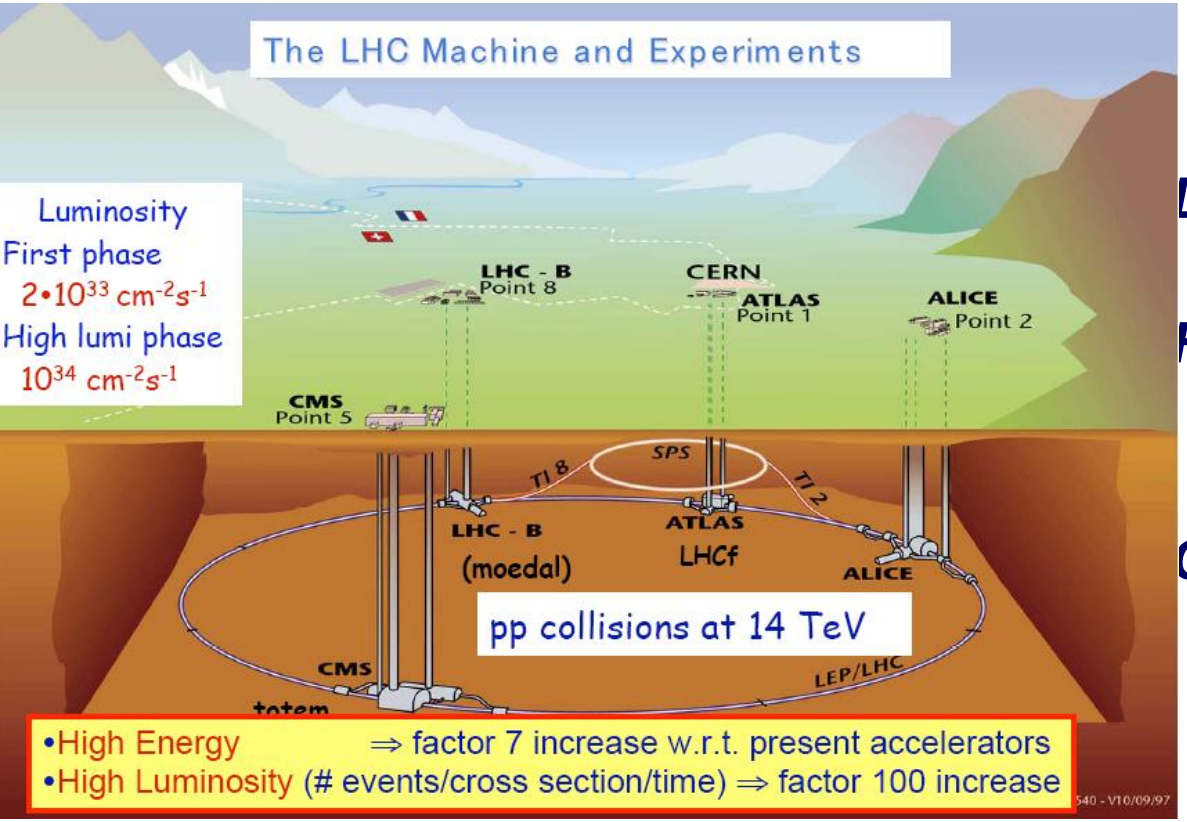
Qual a solução??

- Estudar a escala de energia TeV
- LHC



"Whatever happened to *elegant* solutions?"

O LHC (Large Hadron Collider)



Large
- 27 km de circunferência

Hadron
- prótons
- ions

Collider
- ~ 7 x mais energia
- ~ 100 x mais luminosidade
- Comparado ao Tevatron

Próton - Próton
a **$\sqrt{s}$ = 14 TeV**

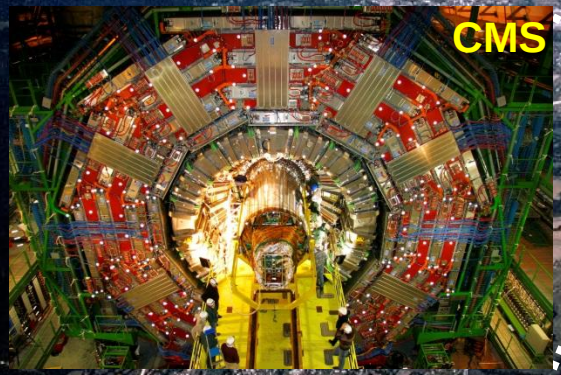
Luminosidade ~
~100 fb^{-1} / expt / Ano

Porque O LHC é Importante?

- ***Escala de energia quebra de simetria ≈1TeV***
  - Higgs ou outro mecanismo
- ***Massa do Higgs ≤1TeV***
  - Unitaridade
  - Outro processo cancela anomalias
- ***Partículas Supersimétricas***
  - Massas ***≈TeV***
    - h ?
- ***Estudo sistemático da violação de CP***
- ***Potenciais candidatos a Matéria Escura***
- ***Massa dos neutrinos***
- ***Buracos negros, dimensões extras….***

Os Experimentos do LHC

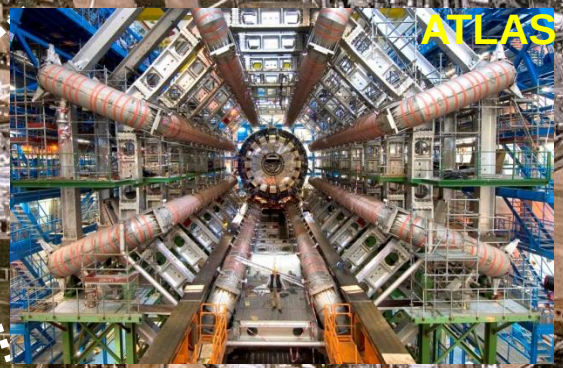
Os experimentos do LHC formam um conjunto de projetos científicos globais, um dos maiores empreendimentos da física atual.



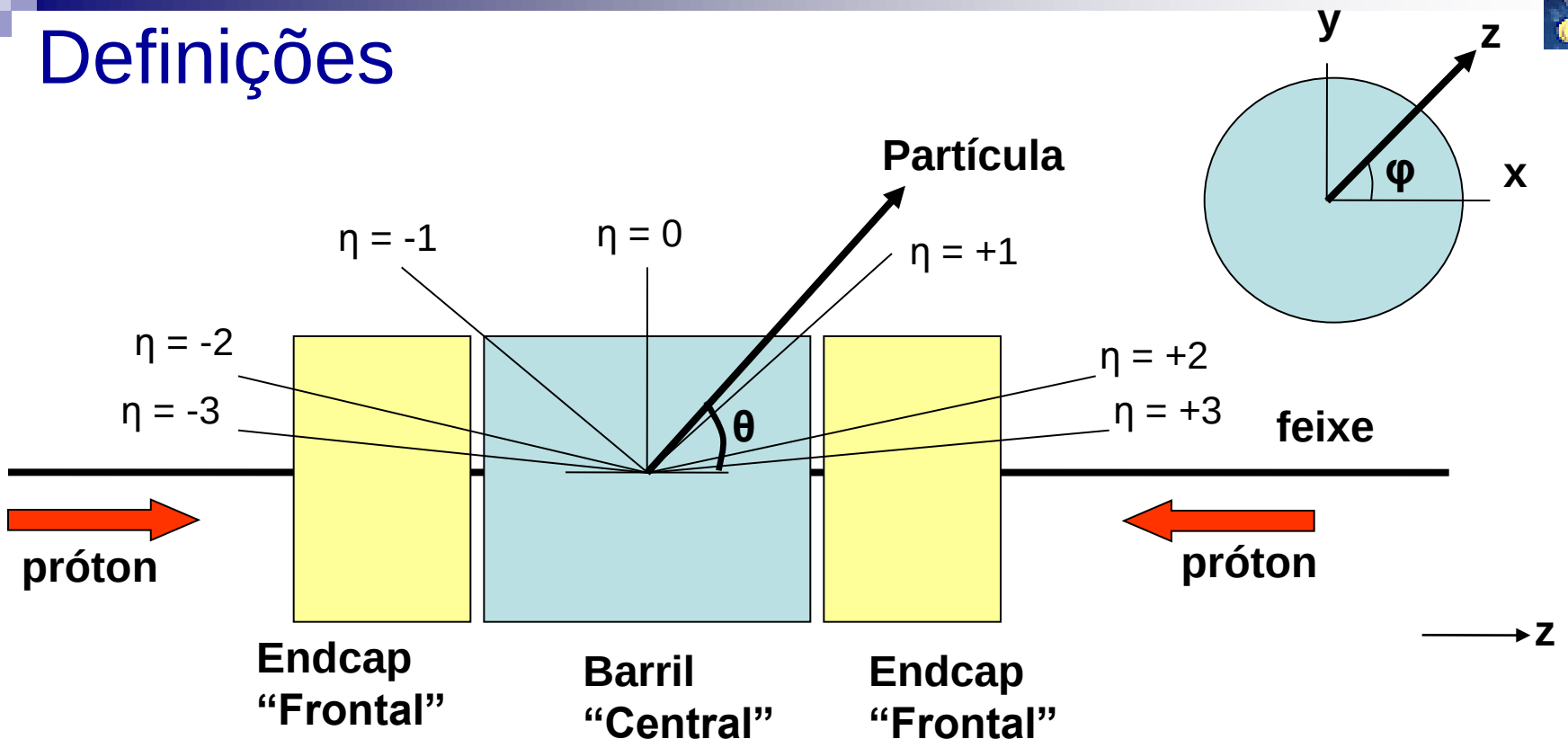








Definições

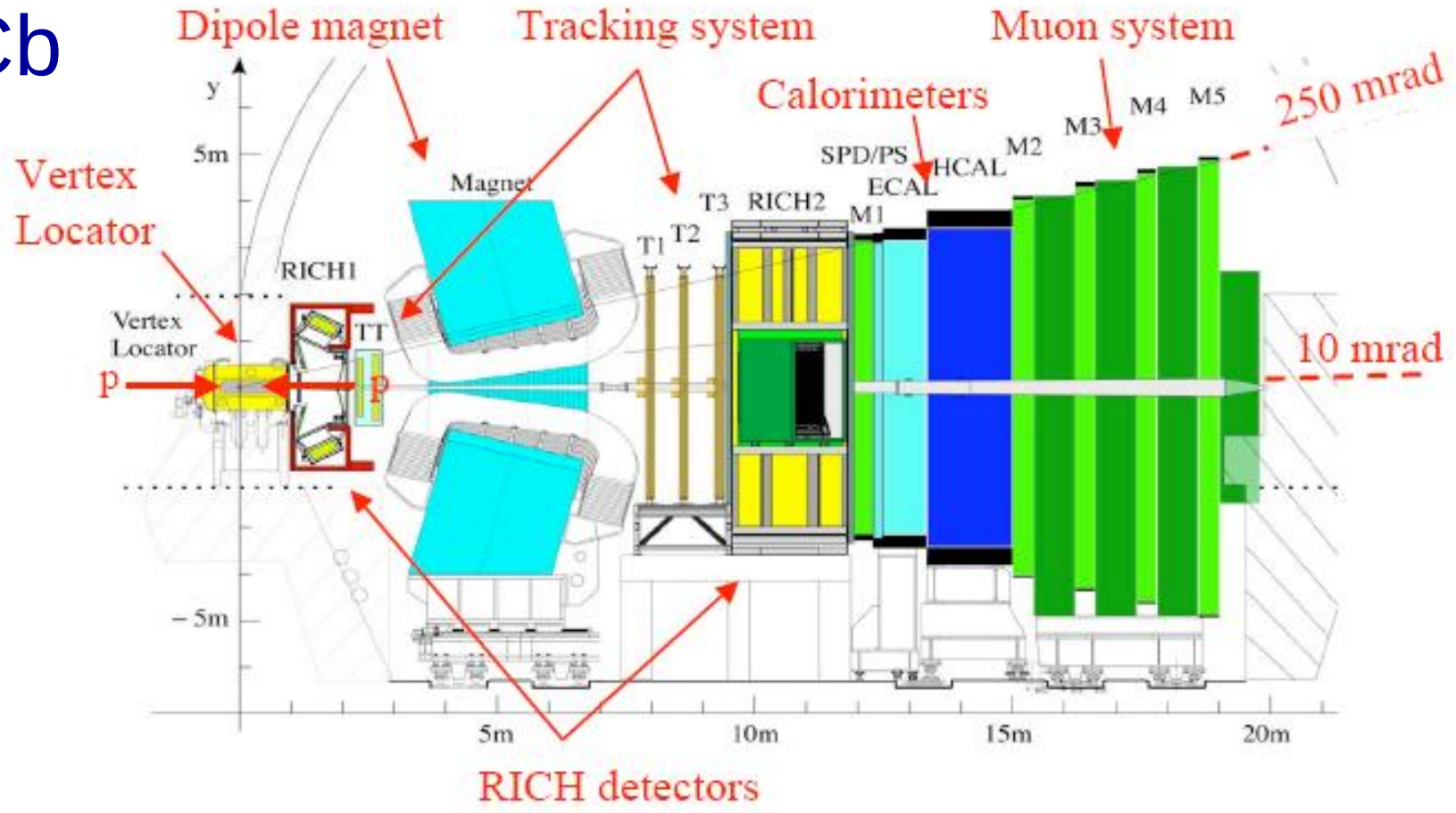


Rapidez: $y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}$ **Diferenças em rapididez são conservadas numa transf. de Lorentz na direção z** *

Pseudorapidez: $\eta = -\ln[\tan(\theta/2)]$ **Boa aproximação da rapididez se E>>m** *

"Momentum Transverso" $\mathbf{p}_T = (p_x, p_y)$ $|\mathbf{p}_T| = \sqrt{(p_x^2, p_y^2)}$

LHCb

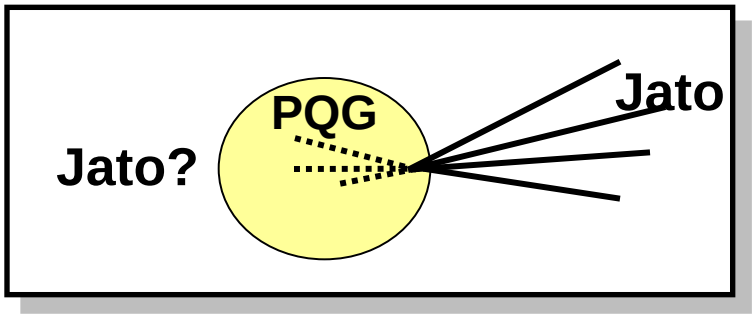


- Detector assimétrico para a física de mesons B
- Violação de CP

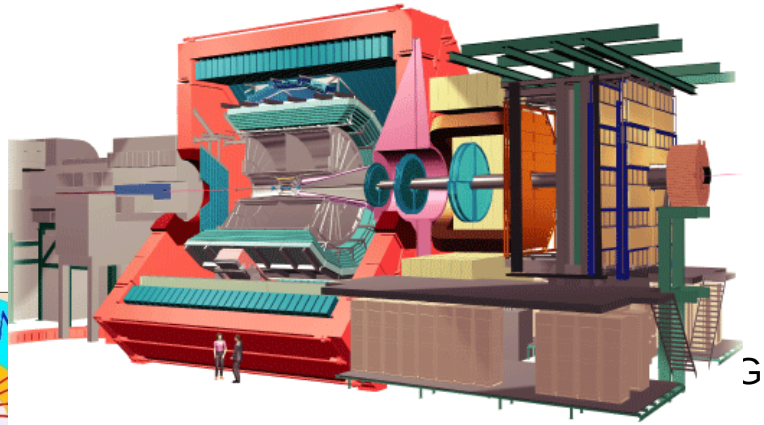
ALICE

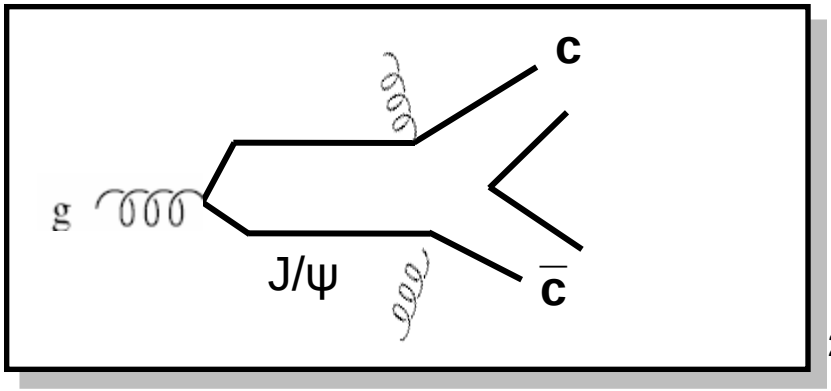
- Desenhado para estudar colisões de **ions pesados** (e.g. Pb-Pb ou Au-Au)
- Produção de um novo estado da matéria – o plasma de quarks-gluons
- Quarks não mais **confinados** no interior de hádrons sem cor

- Sinais de PQG:
  - Supressão de Jatos

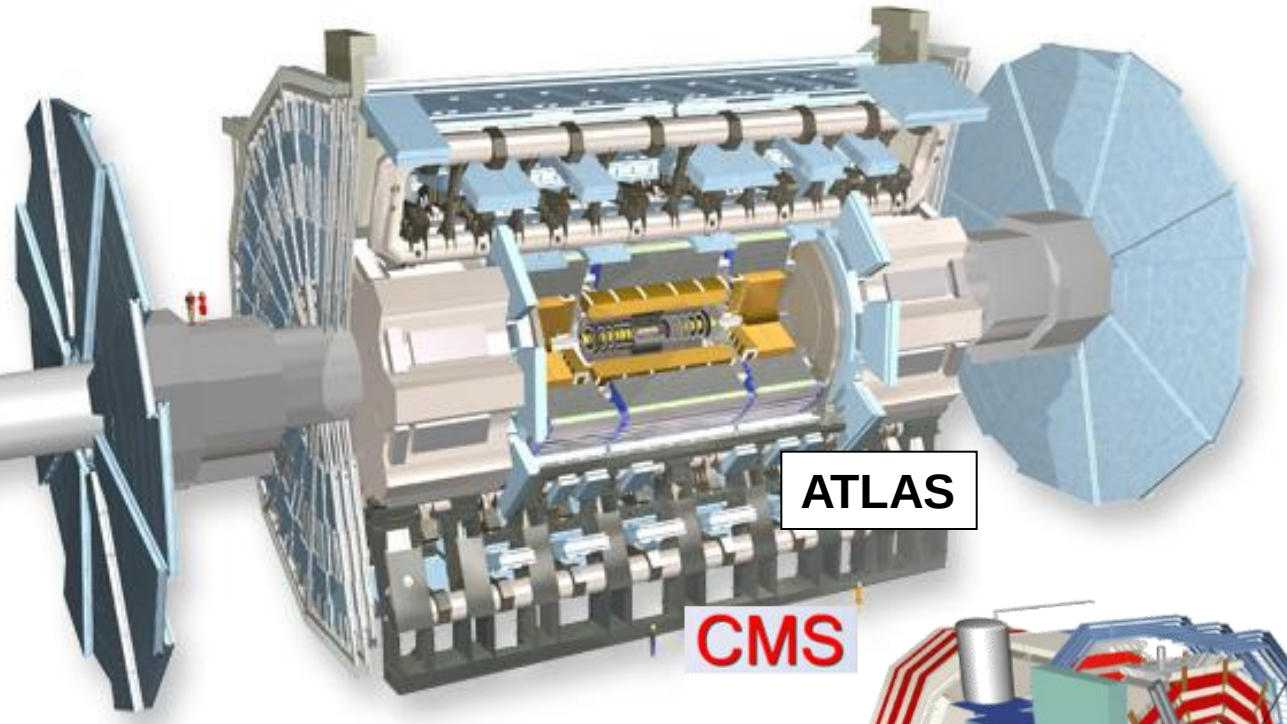


  - **Supressão de** Quarkônio (e.g. J/ψ) (“estados ligados ”)

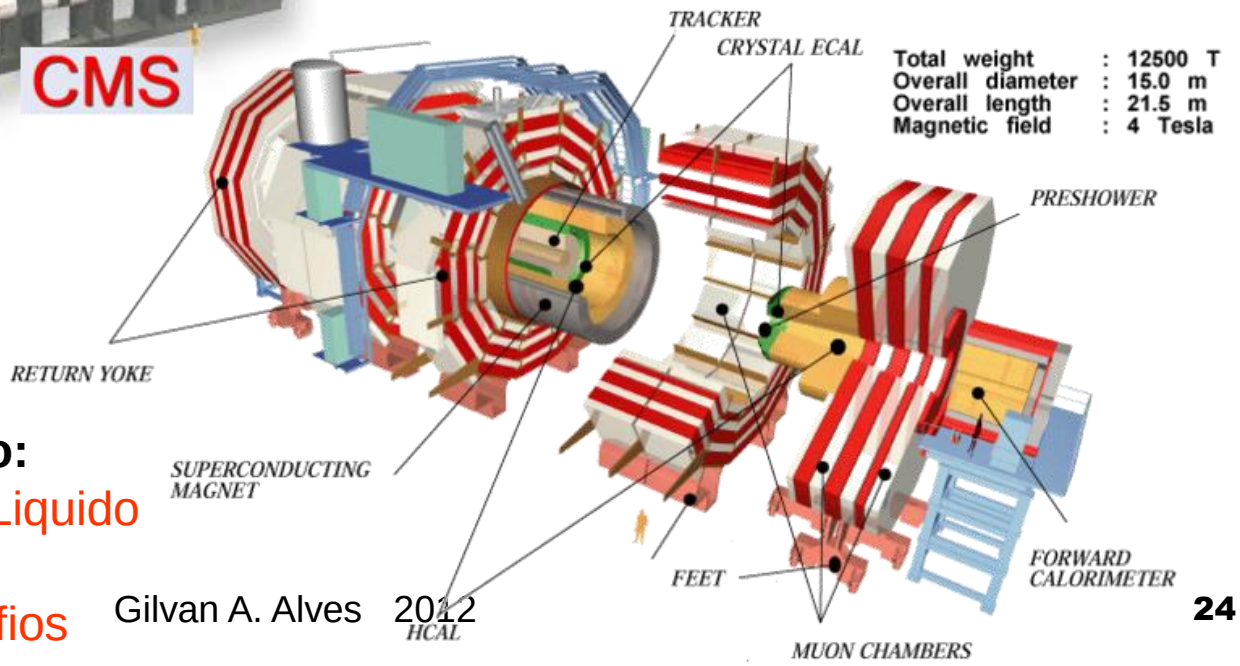




Detectores Gerais

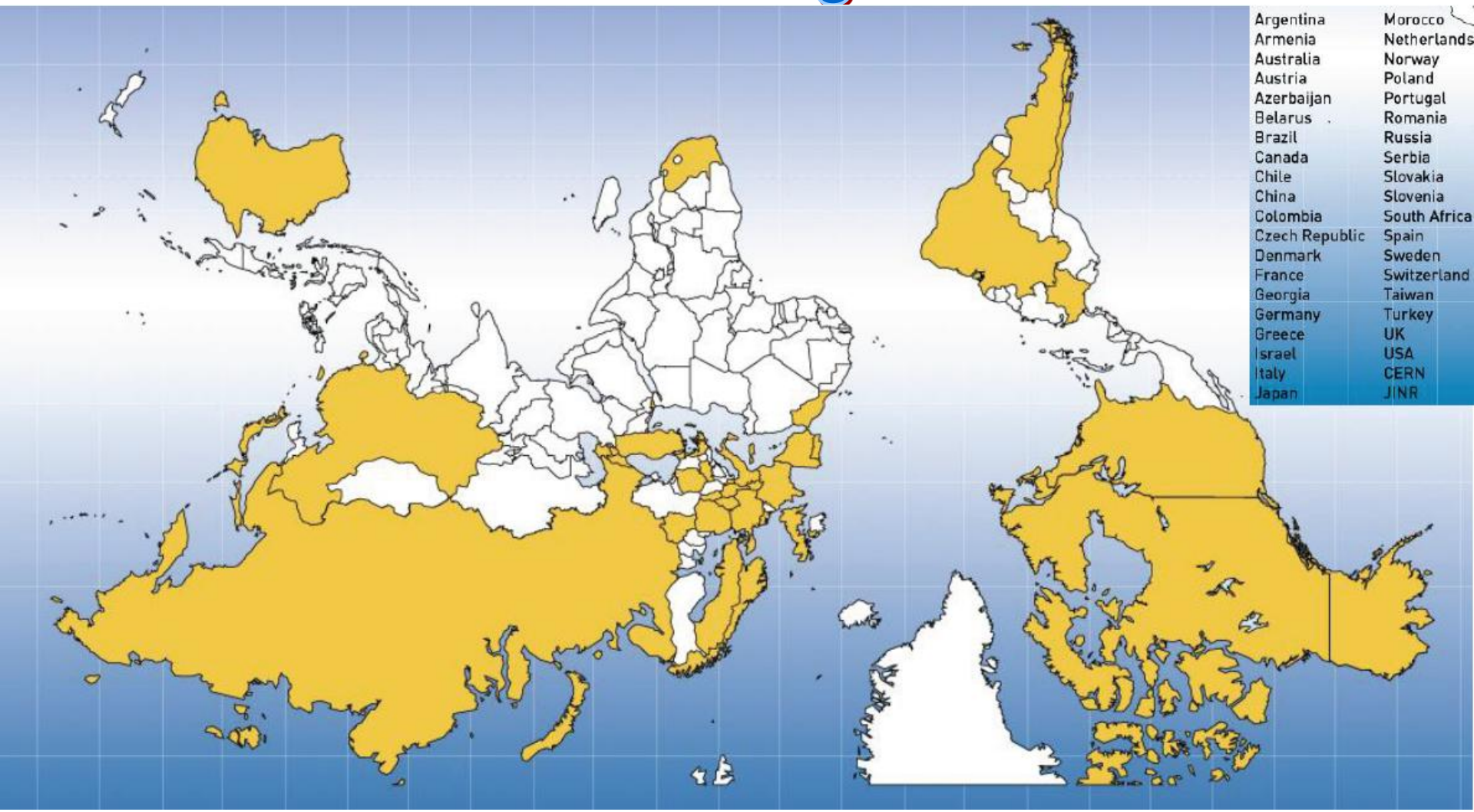


Semelhanças:
1- Det. Posição
2- Calorímetros
3- Câmaras de Muon



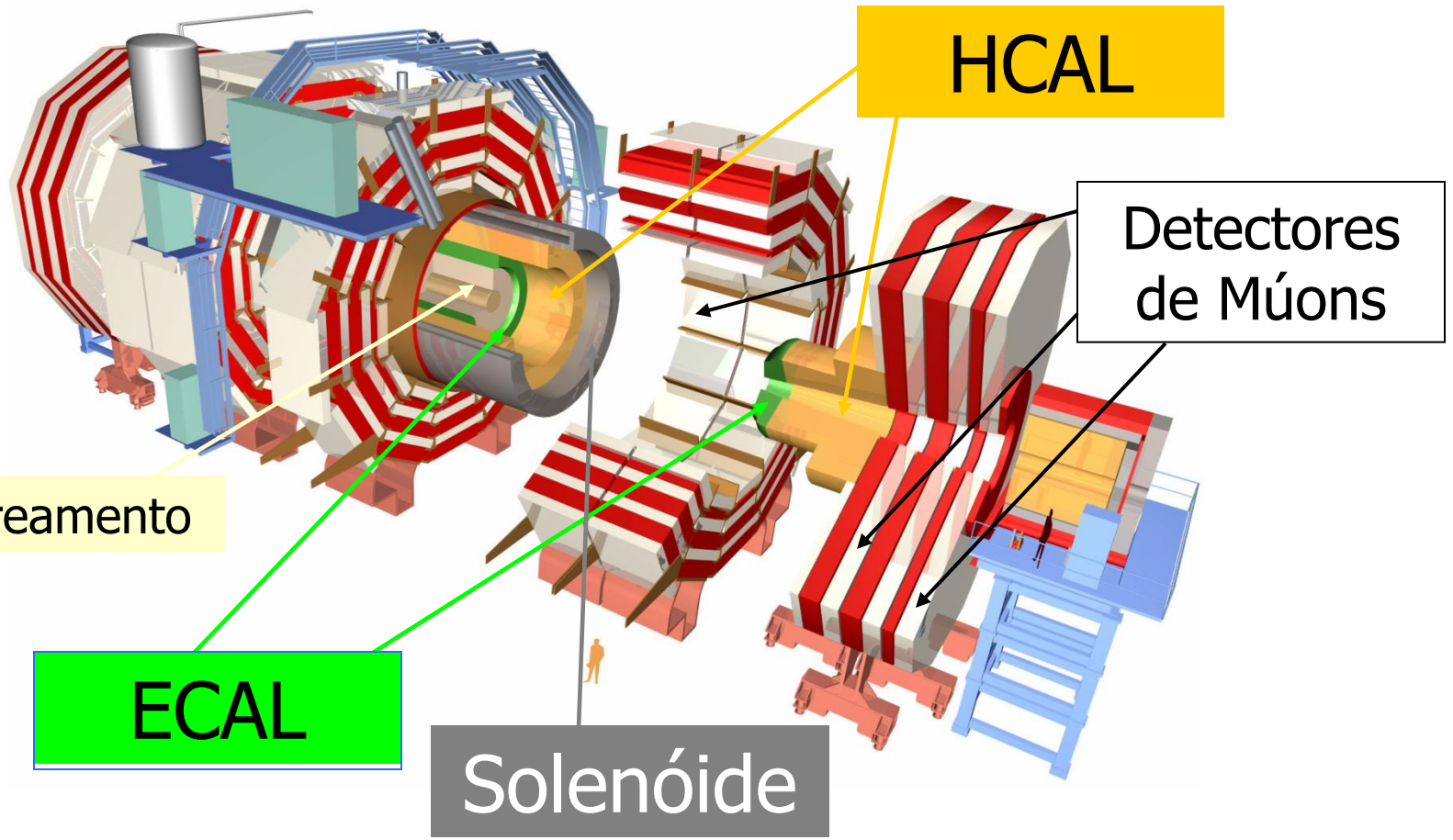
Diferenças:
Tamanho : CMS “compacto”
Campo Magnético
ATLAS tem um toróide
Calorímetro Eletromagnético:
CMS cristais. ATLAS Argônio Liquido
Det. De posição externos
CMS silício. ATLAS câmara a fios

A Colaboração CMS

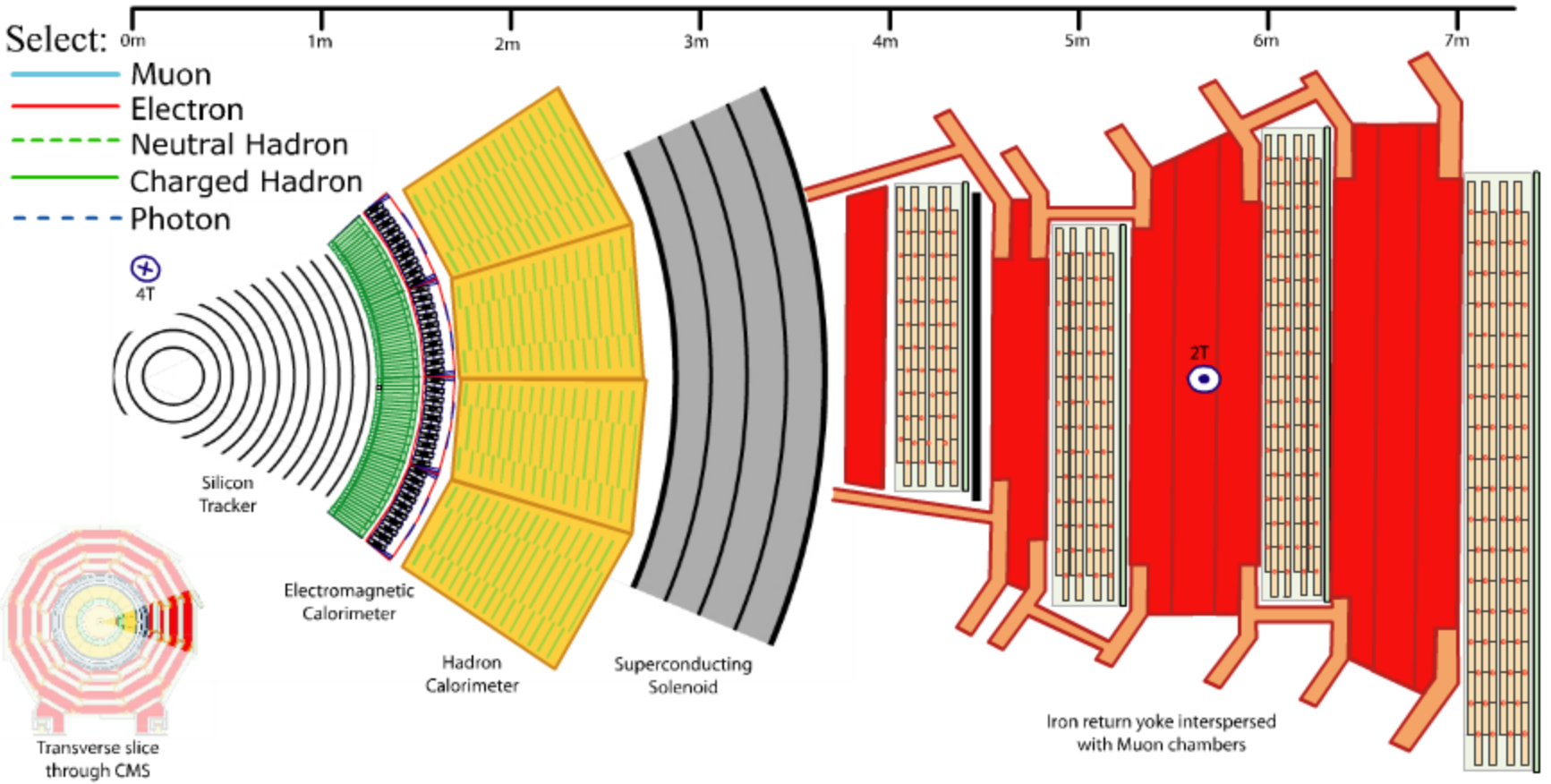


Gilvan A. Alves 2012

O Detector CMS



Corte Transversal do Detector



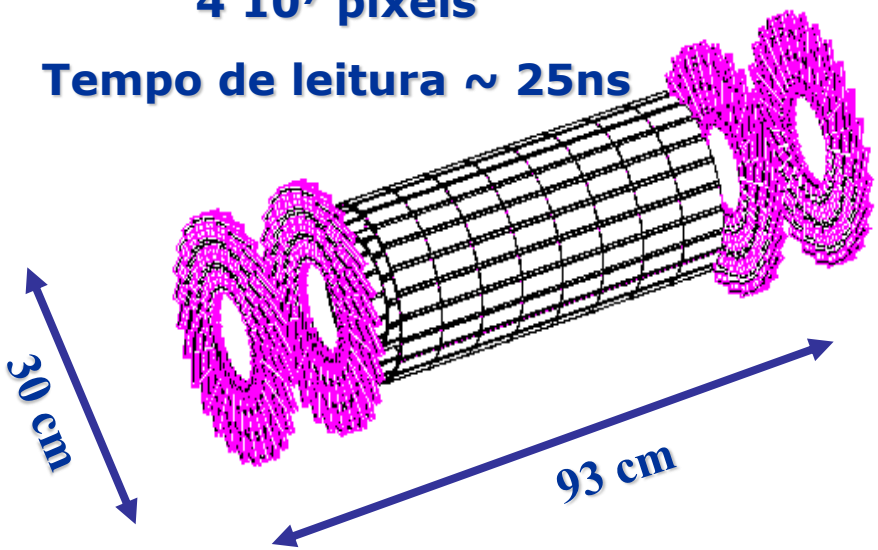
O Detector de Vértices do CMS

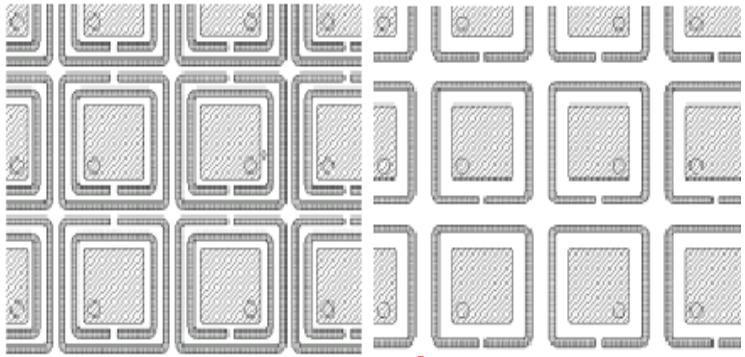
A região mais próxima da colisão é intrumentada com detectores de pixel

Cada pixel ~ 150 * 150 μm^2

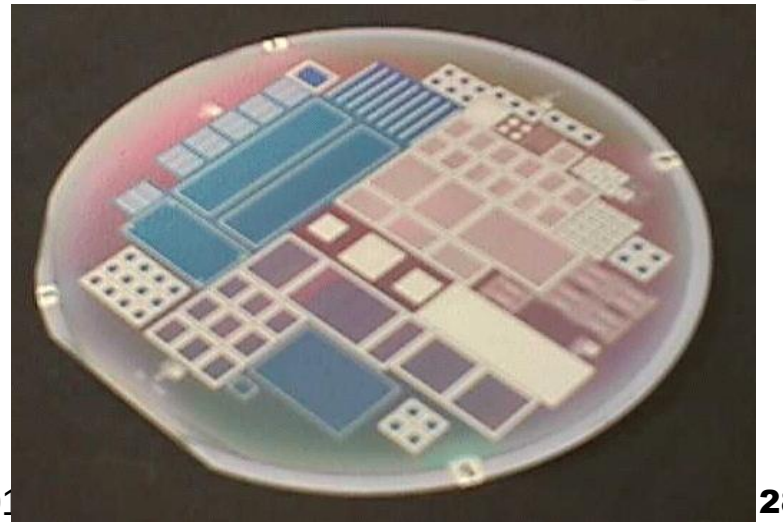
$4\ 10^7$ pixeis

Tempo de leitura ~ 25ns

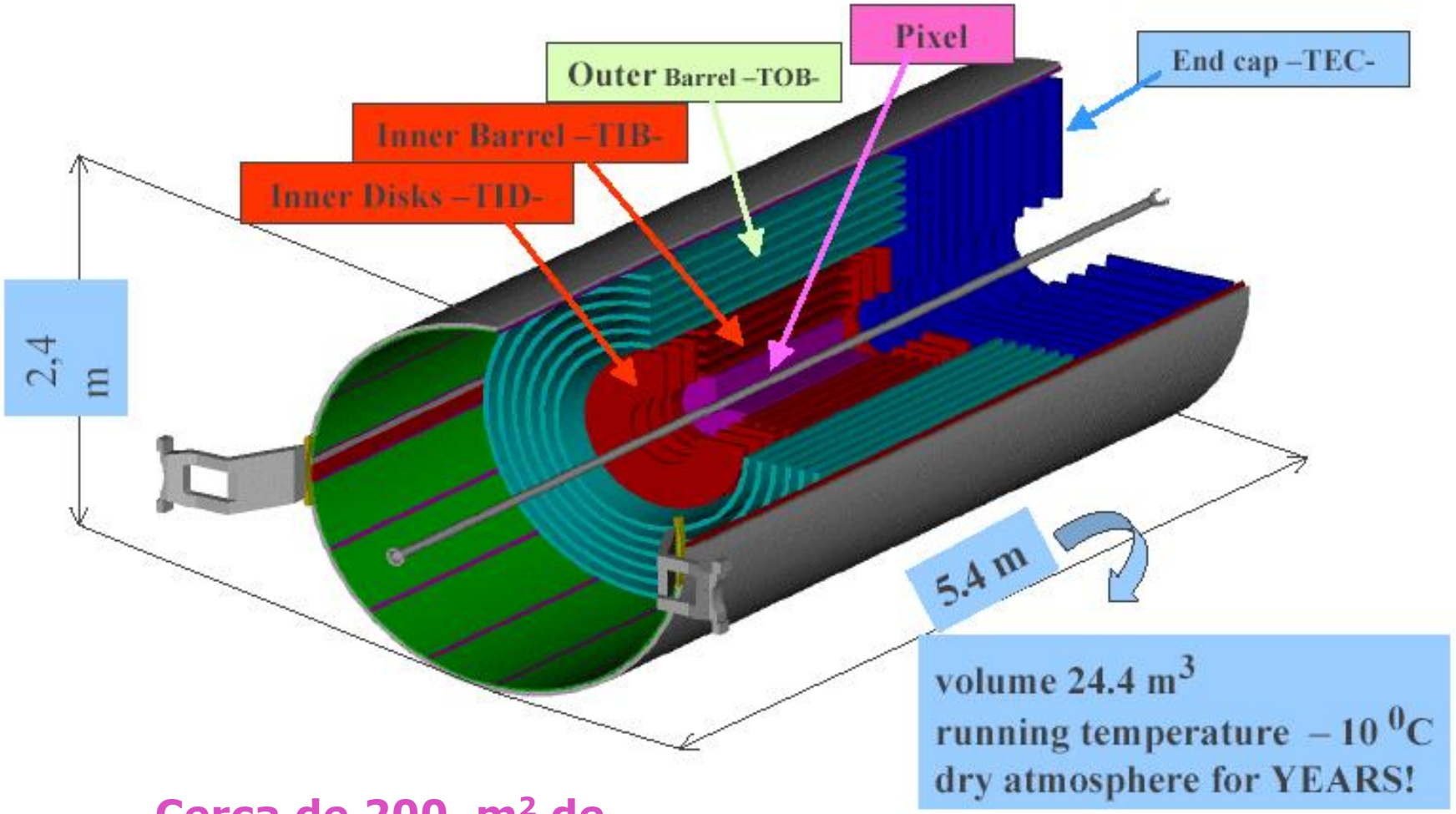




Semelhante a sua câmera digital

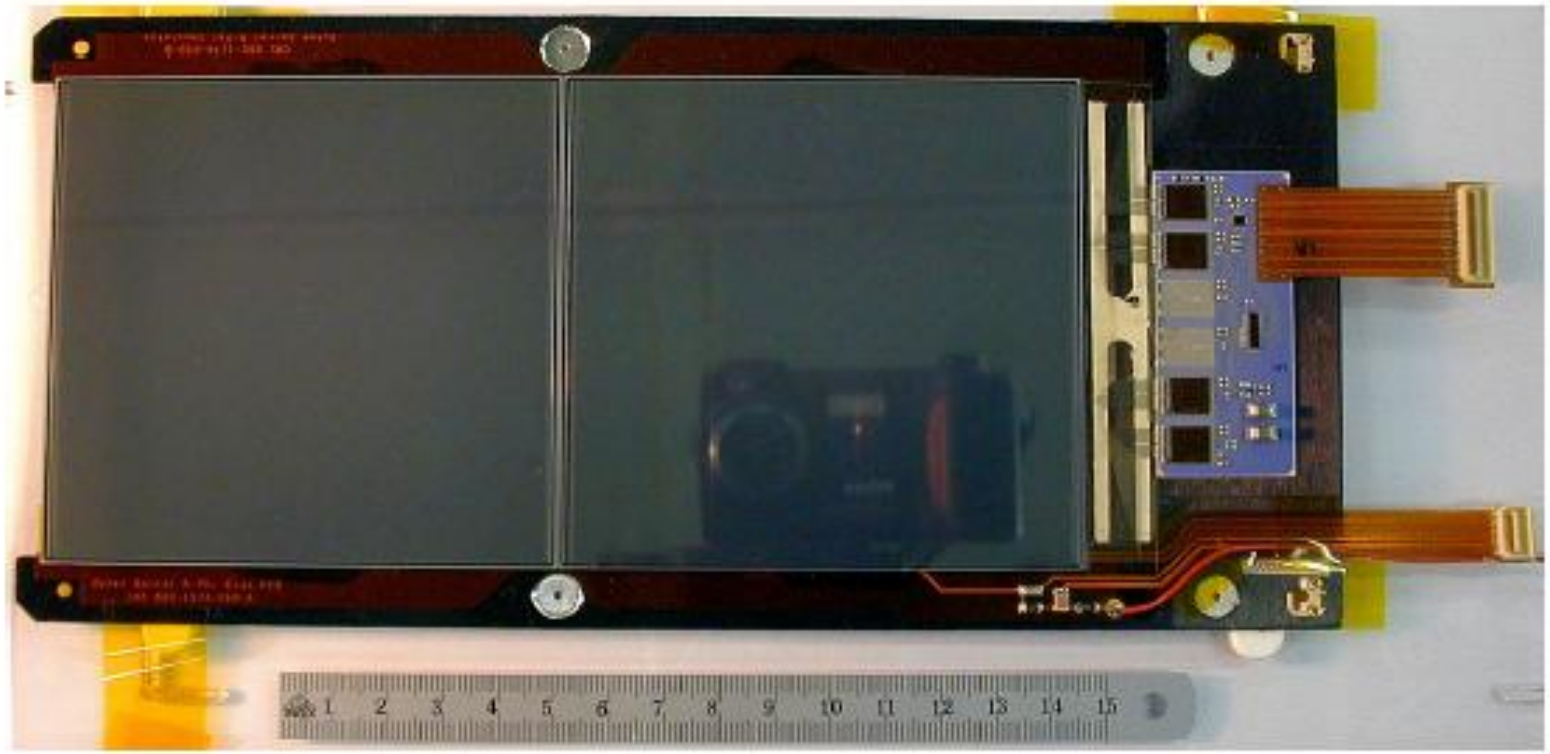


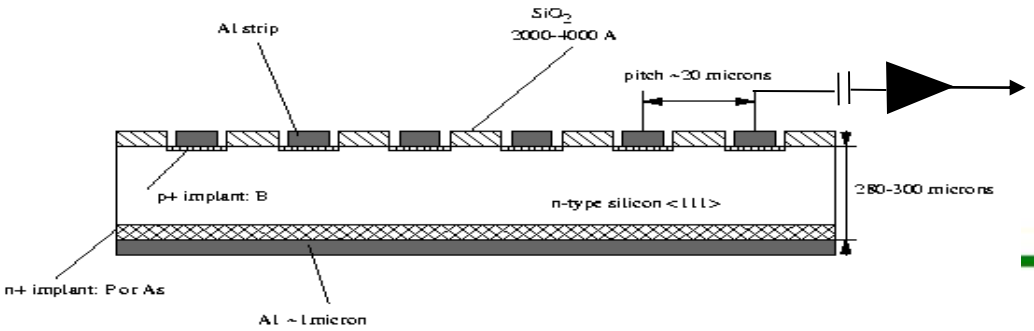
Sistema de Rastreamento do CMS



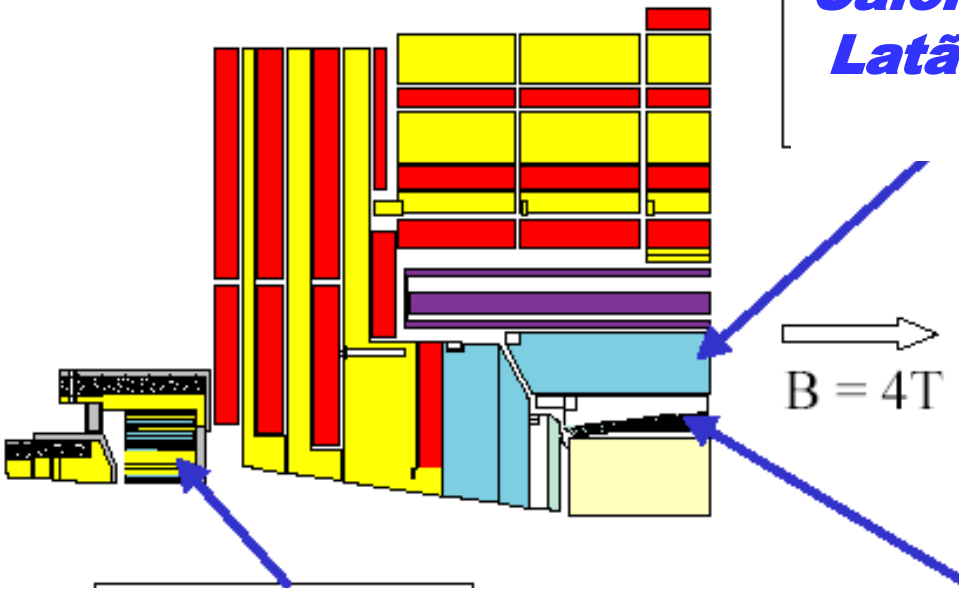
Cerca de 200 m^2 de Detectores de Si

Detectores de micro-tiras de Silício





Os Calorímetros do CMS

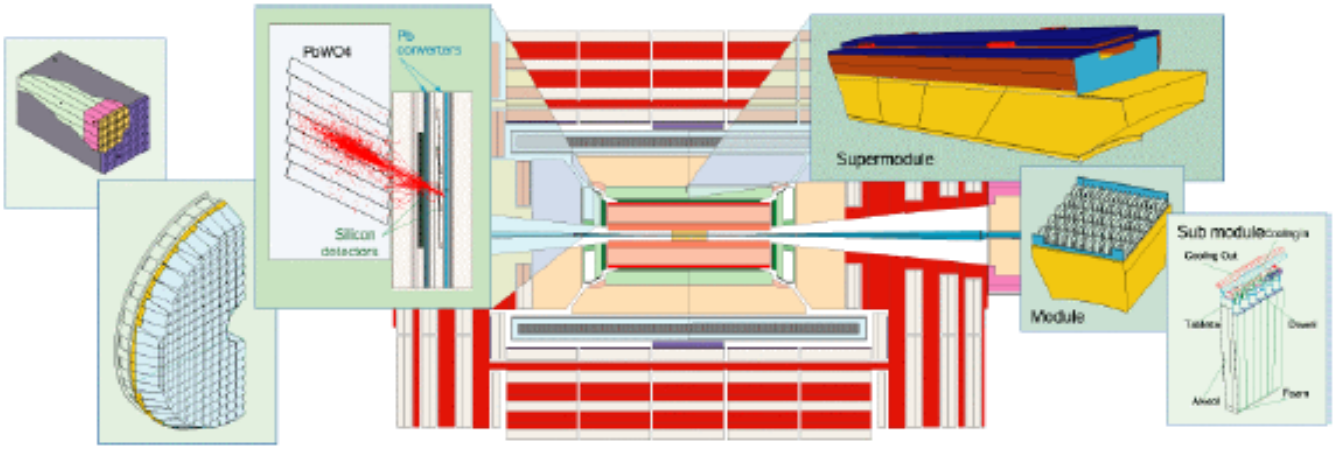


Calorímetro Hadrônico
Latão+Cintilador Plástico

Castor
Cristais de Quartzo

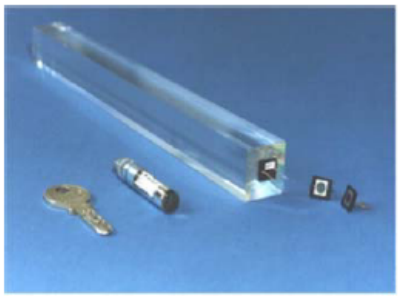
Calorímetro EM
Cristais de $PbWO_4$

O Calorímetro EM do CMS



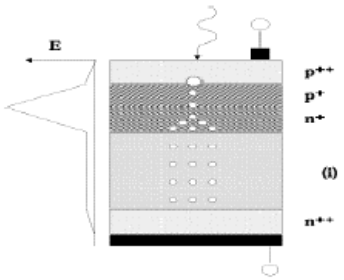
- 80,000 lead-tungstate ($PbWO_4$)
  - 22x22x230 mm^3 (barrel) $\Leftrightarrow$ 1
  - 30x30x220 mm3 (end cap)
- magnetic field of 4T
- radiation dose of ~ 1-2 kGy/yea

PWO crystals and avalanche photodiodes



Zeff	73
Density	8.28 g/cm^3
X_0	0.9 cm
RM	2.1 cm
Refraction index	2.2
lmax	450 nm
Decay time	10 ns
Light output	200 photons/MeV

Signal: > 4 photoel./ MeV ×(gain=50)



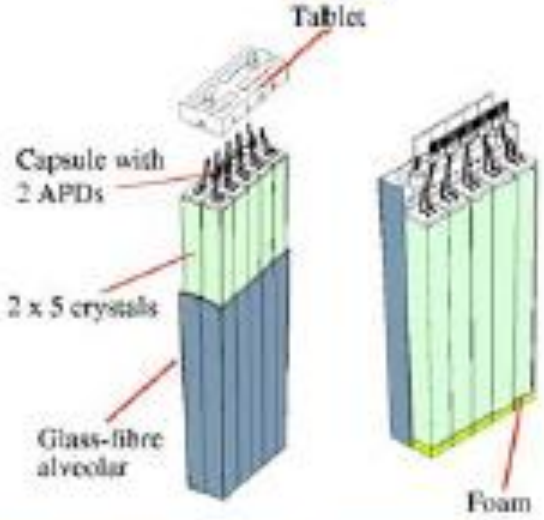
- available size:5x5 mm^2 x 2/per cr.
- C ~ 100pF @ U_W ~ 300V
- Gain ~ 50
- ENF ~ 2
- High rad.tolerance
- Low nuclear counter effect

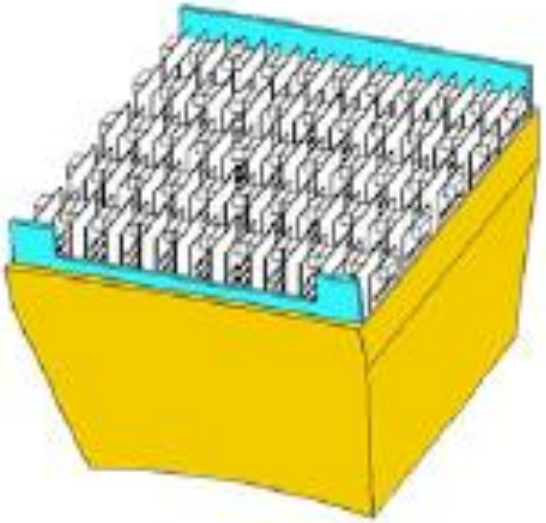
Gi

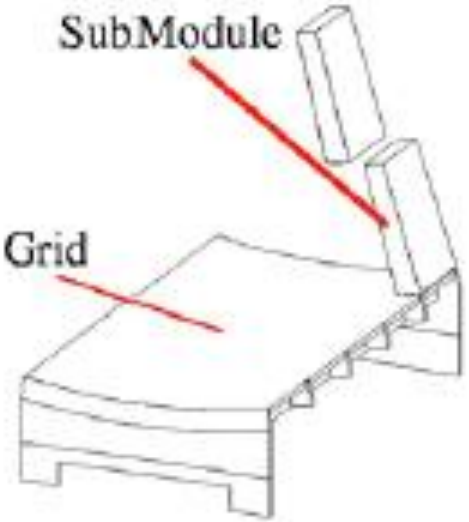
Construção do Calorímetro EM

Submodule: 2x5 Xtals with APD and FE electronics in 200μm glass fibre alveola

Module: 10x4 or 10x5 submodules mounted on a 'Grid', inside a 'basket'

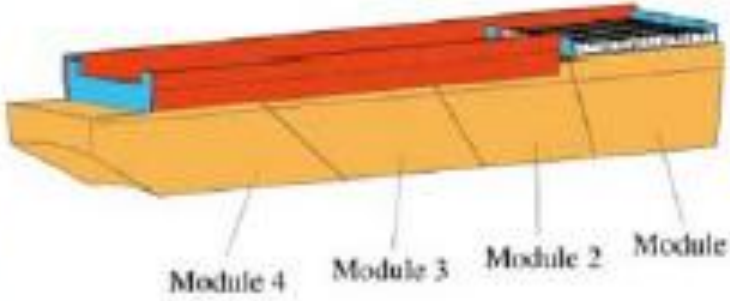








Assembled Submodules



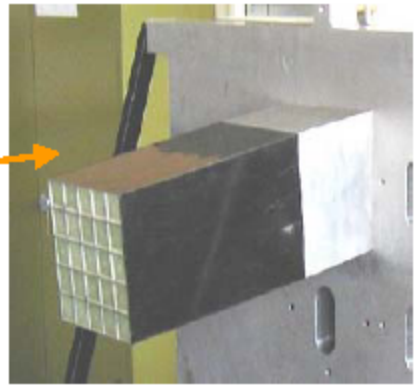
Supermodule: 4 Modules (1700 Xtals)

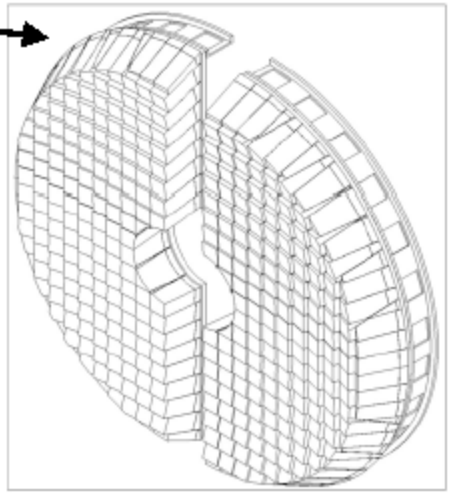
Barrel = 36 Supermodules

Construção da parte Frontal

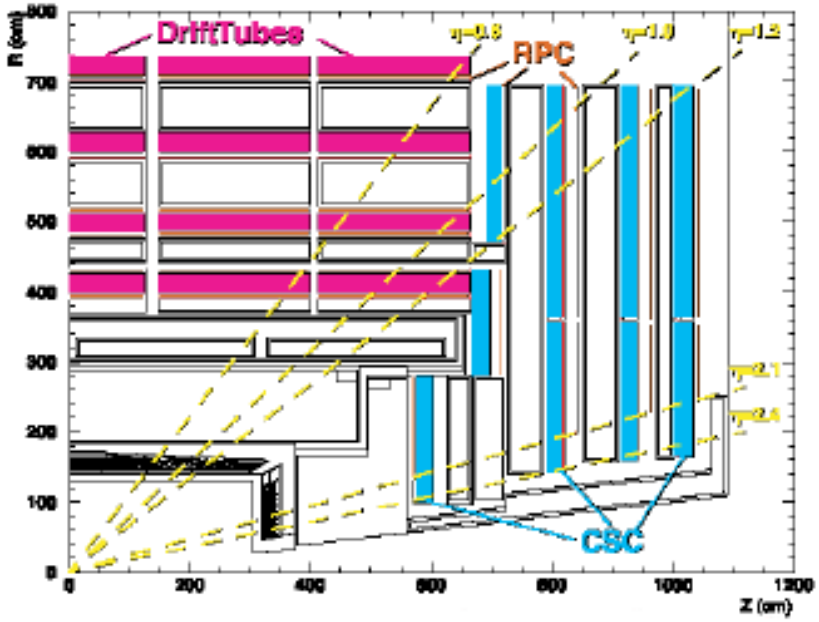
'**Supercrystal**': carbon-fibre alveola containing 5x5 tapered crystals + VPTs + HV filter

- 156 Supercrystals per **Dee**
- All crystals have identical dimensions
- All Supercrystals are identical (apart from inner and outer circumference)

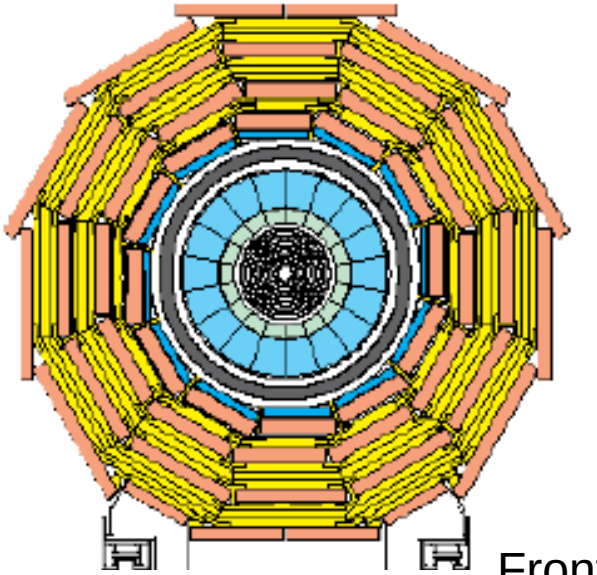




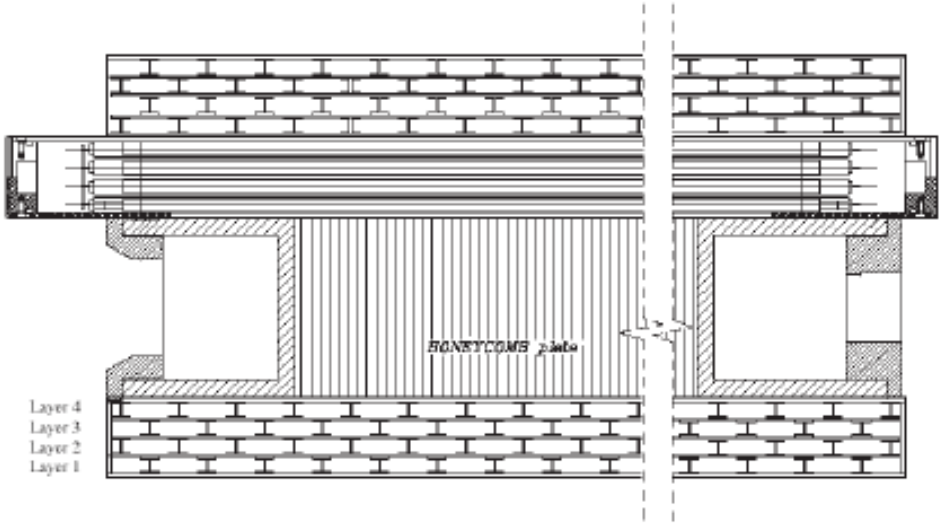
O Sistema de detecção de Múons do CMS



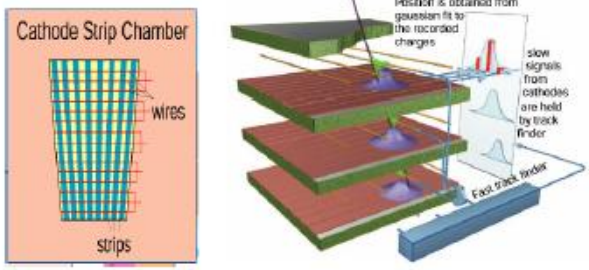
Central – Câmaras de Arraste



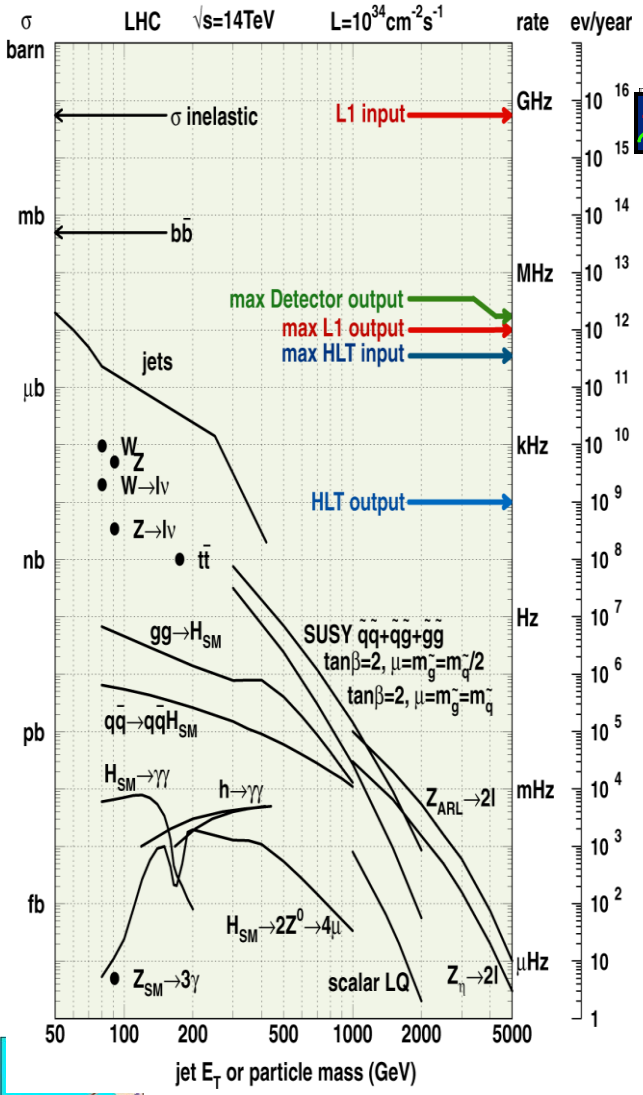
Frontal







Seleção de eventos interessantes



ON-line

OFF-line

LEVEL-1 Trigger
Hardwired processors (ASIC, FPGA)
Pipelined massive parallel

HIGH LEVEL Triggers
Farms of processors

Reconstruction&ANALYSIS
TIER0/1/2 Centers

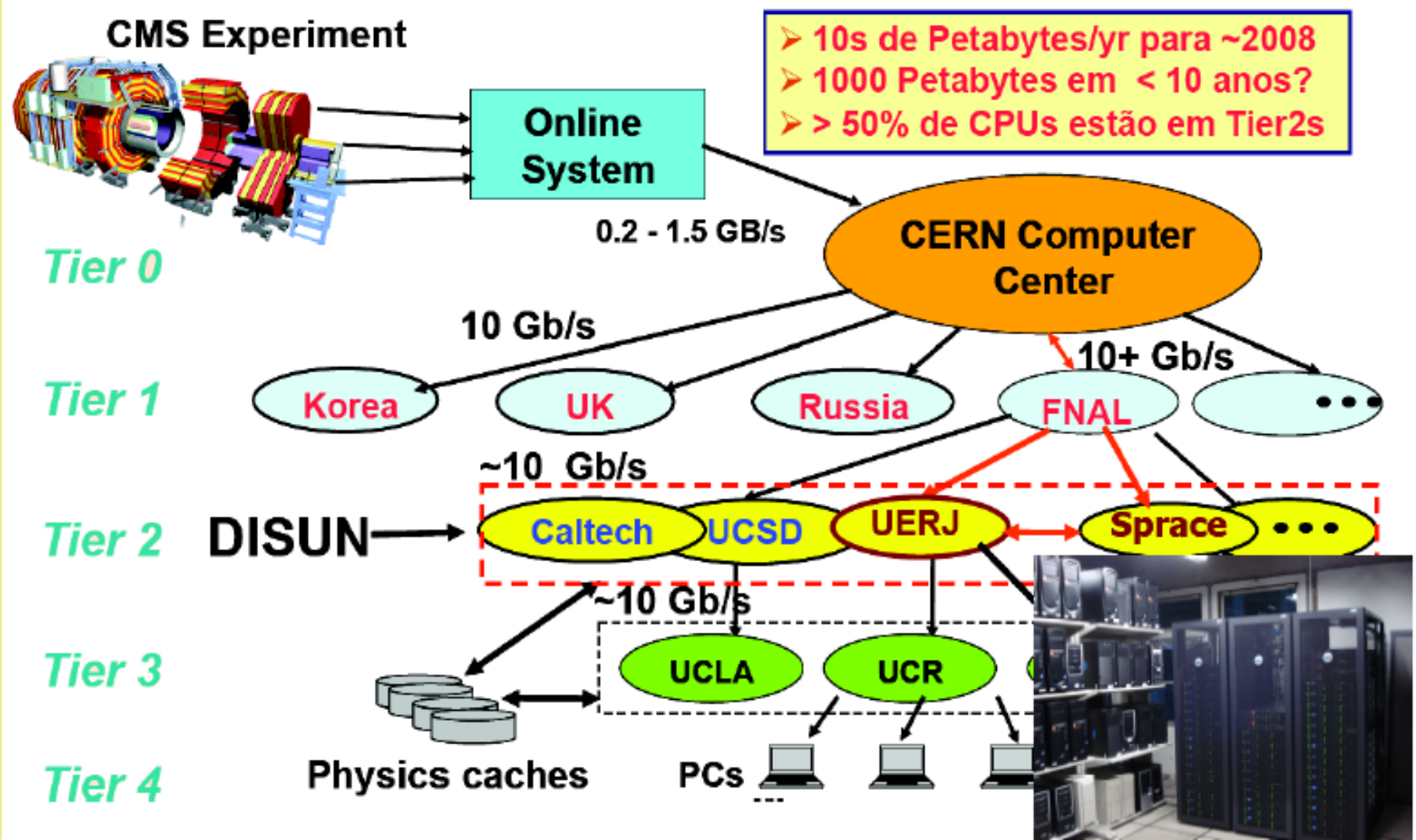
25ns 3μs ms sec hour year

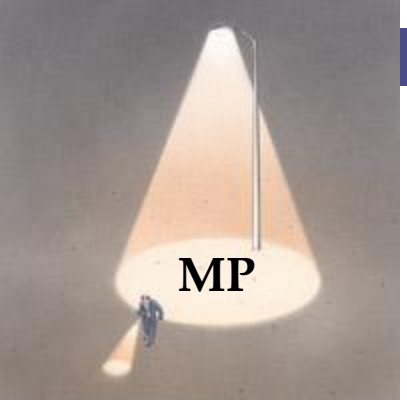
10^{-9} 10^{-6} 10^{-3} 10^{-0} 10^{3}

Giga Tera Petabit

Gilvan A. Alves 2012

Uma GRID mundial de computação
Análise dos dados de cada experimento

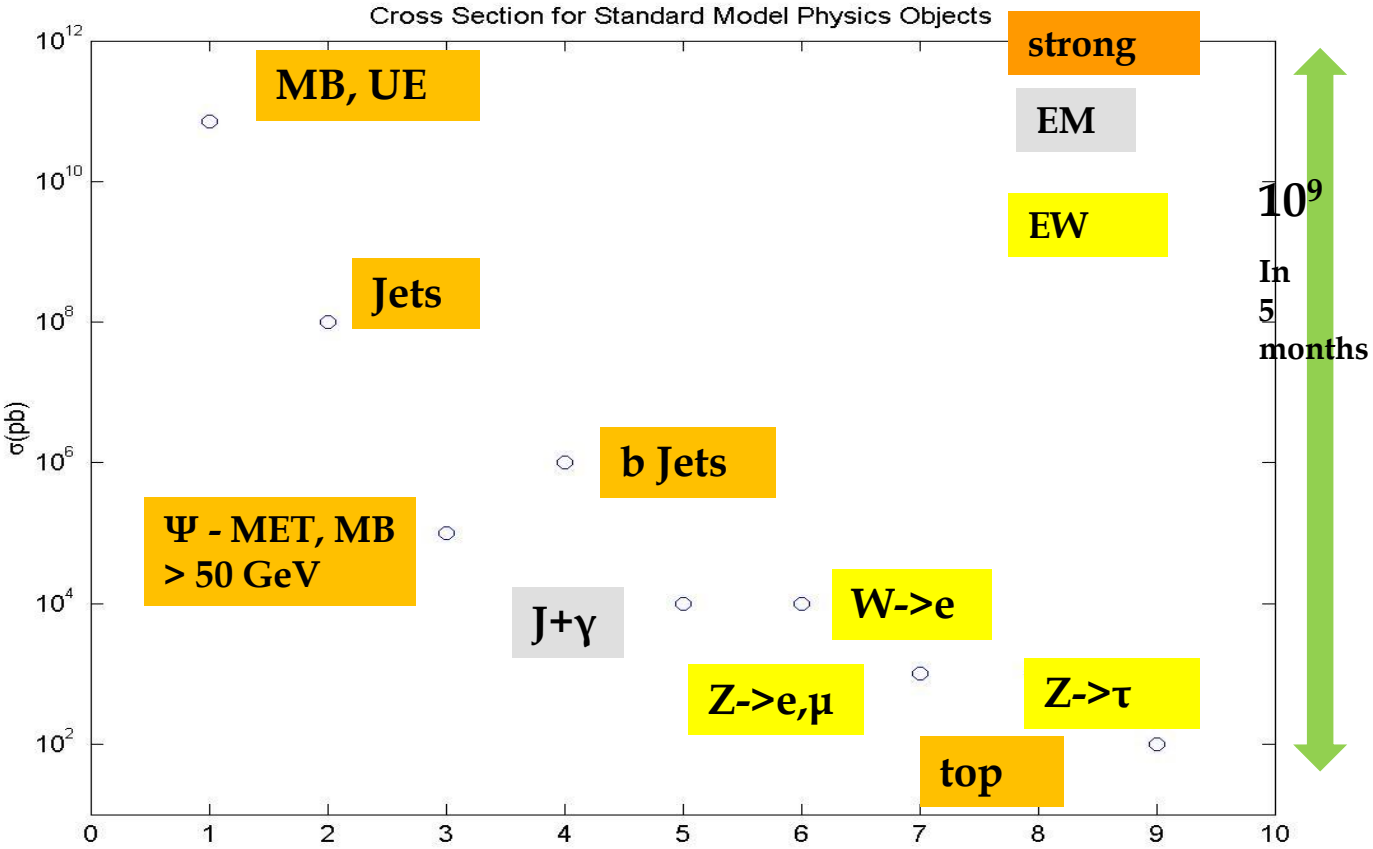




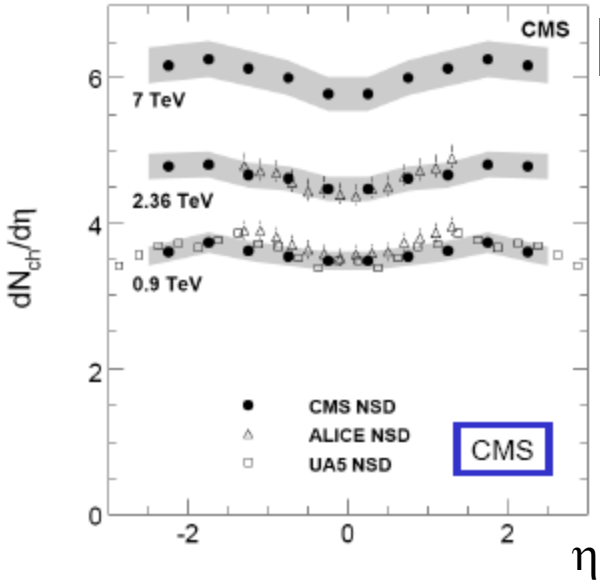
Novo acelerador, novos detectores, nova faixa de energia

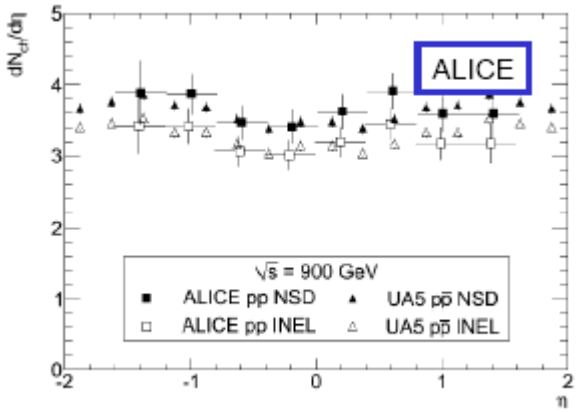
Redescoberta do MP

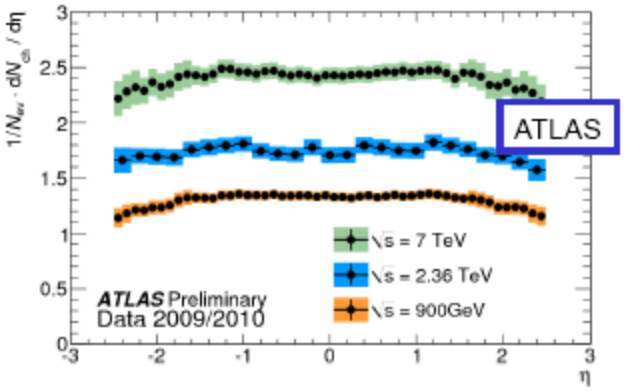
$\sigma(pb)$

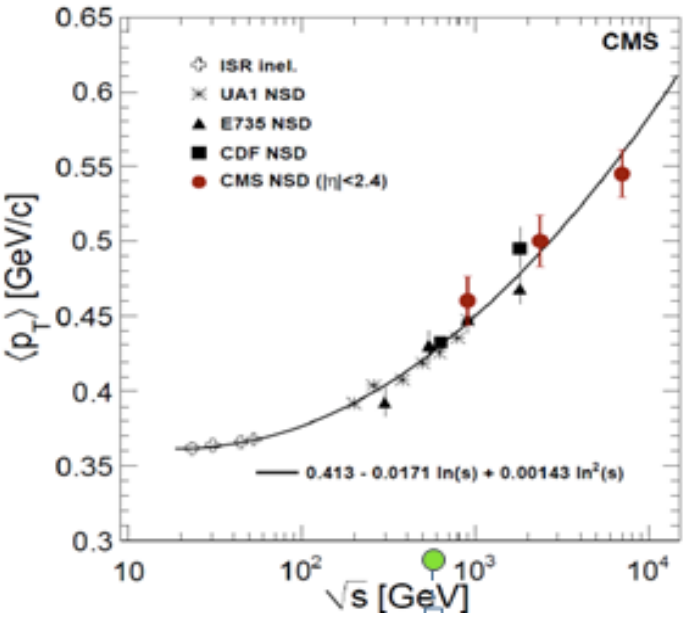


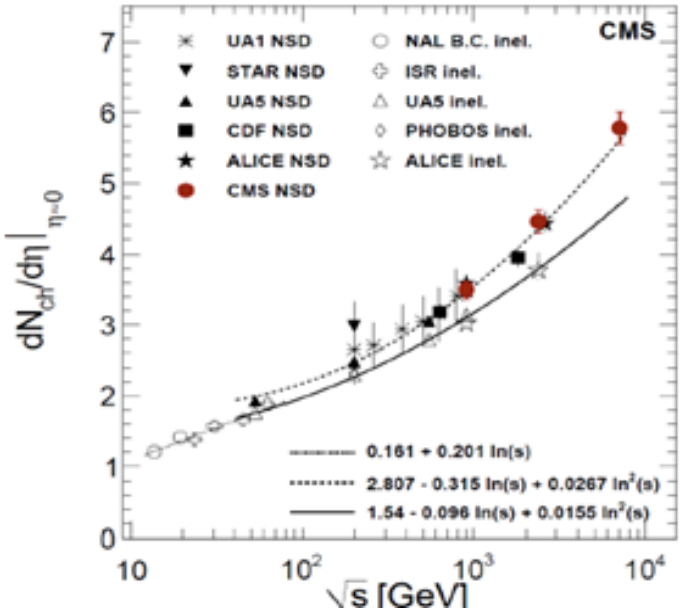
Multiplicidade de partículas no LHC





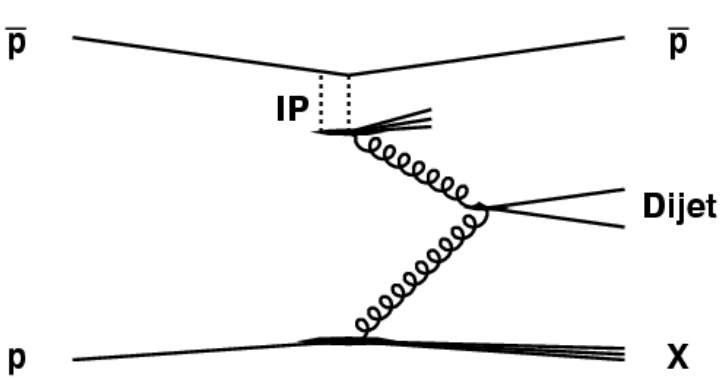


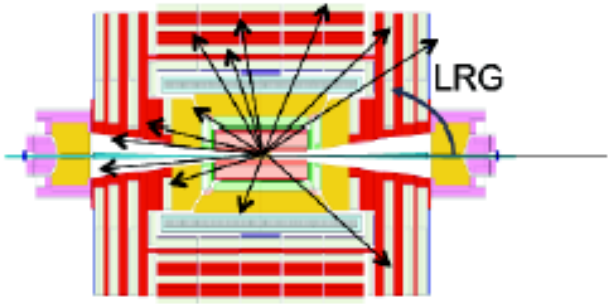




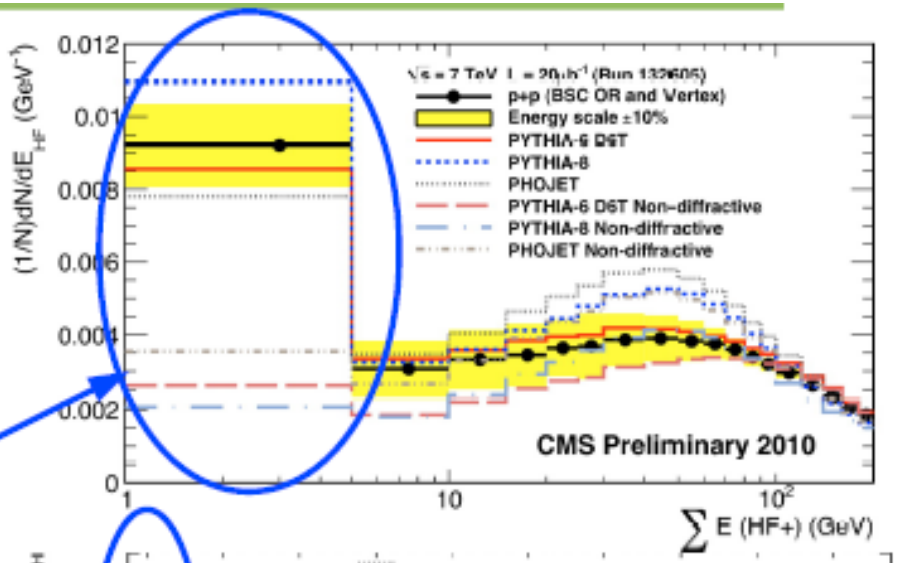
Importante para ajustar modelos teóricos utilizados nas simulações. Dados coletados para energias de centro de massa √s = 0.9, 2.36 e 7 TeV

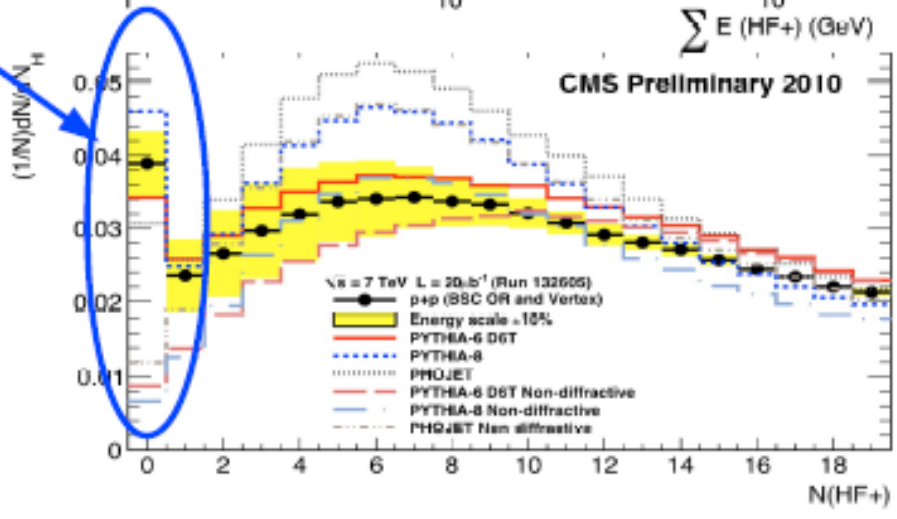
Eventos Difrativos





LRG – Grande Lacuna de Rapidez no HF

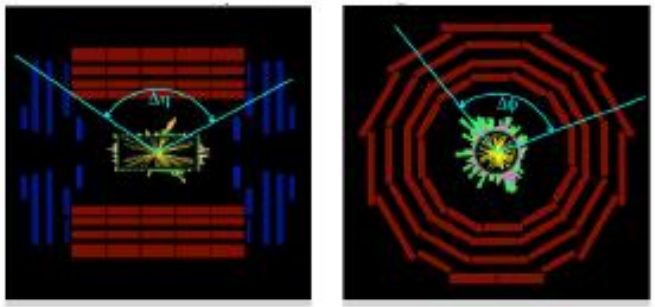


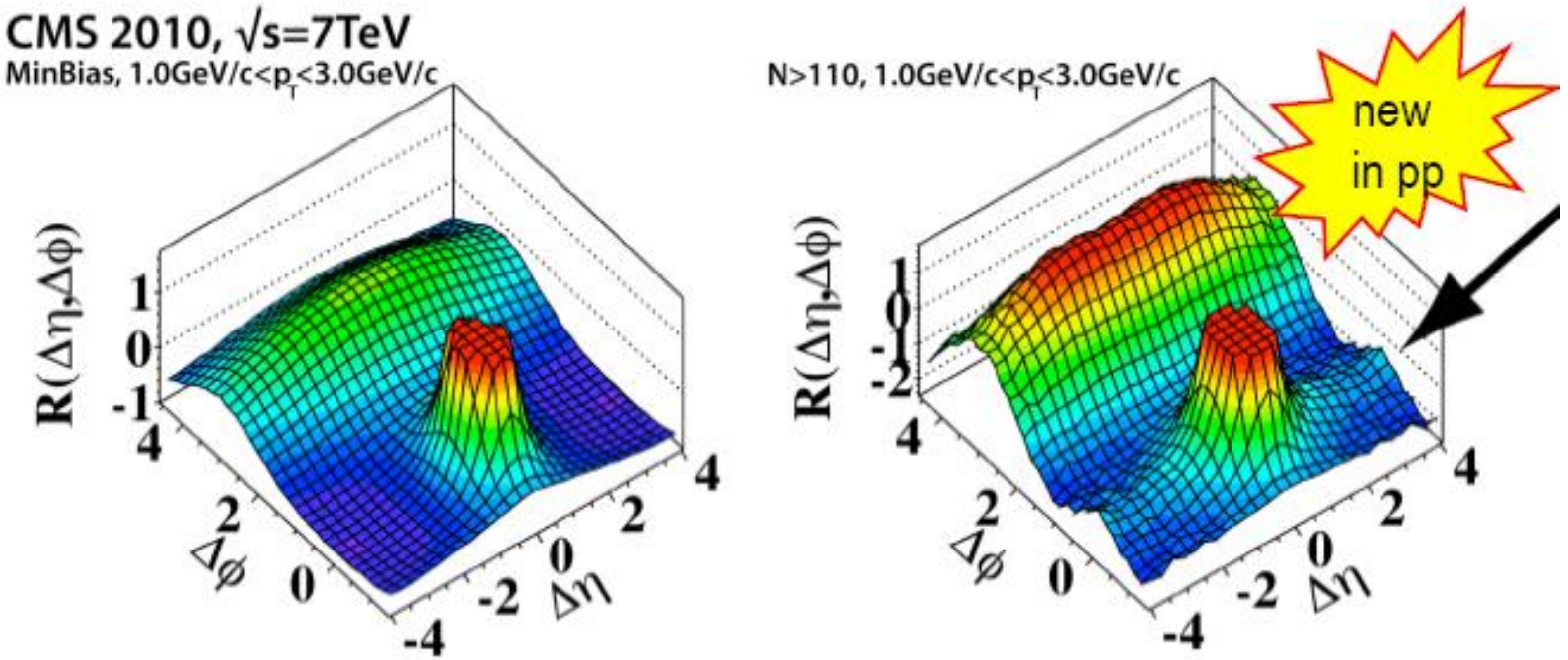


Eventos difrativos – Um dos prótons (pelo menos) sobrevive intacto.
Característica Experimental - LRG
Visível nos calorímetros frontais

1º Resultado Inesperado

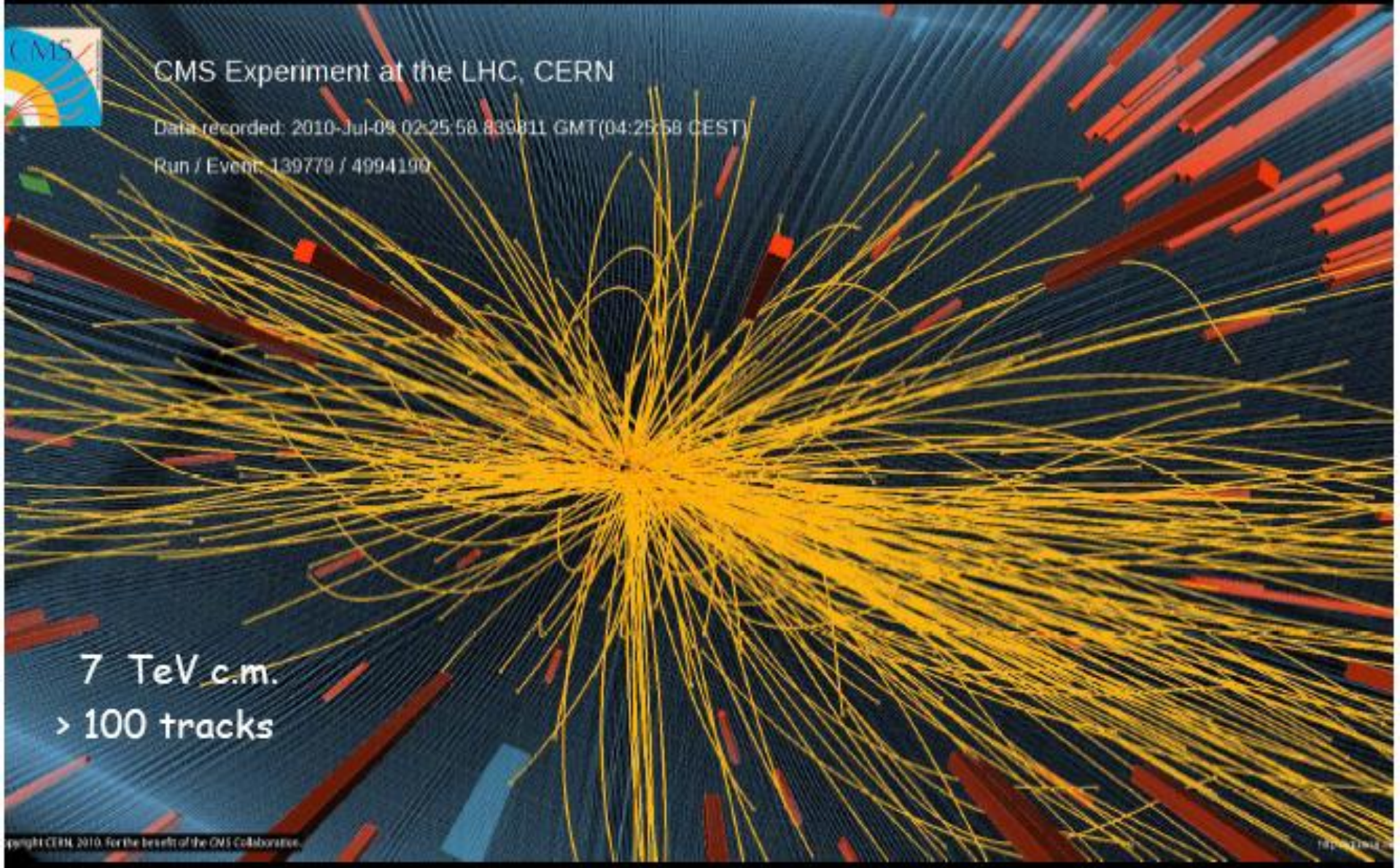
Particle correlations in multi hadron events



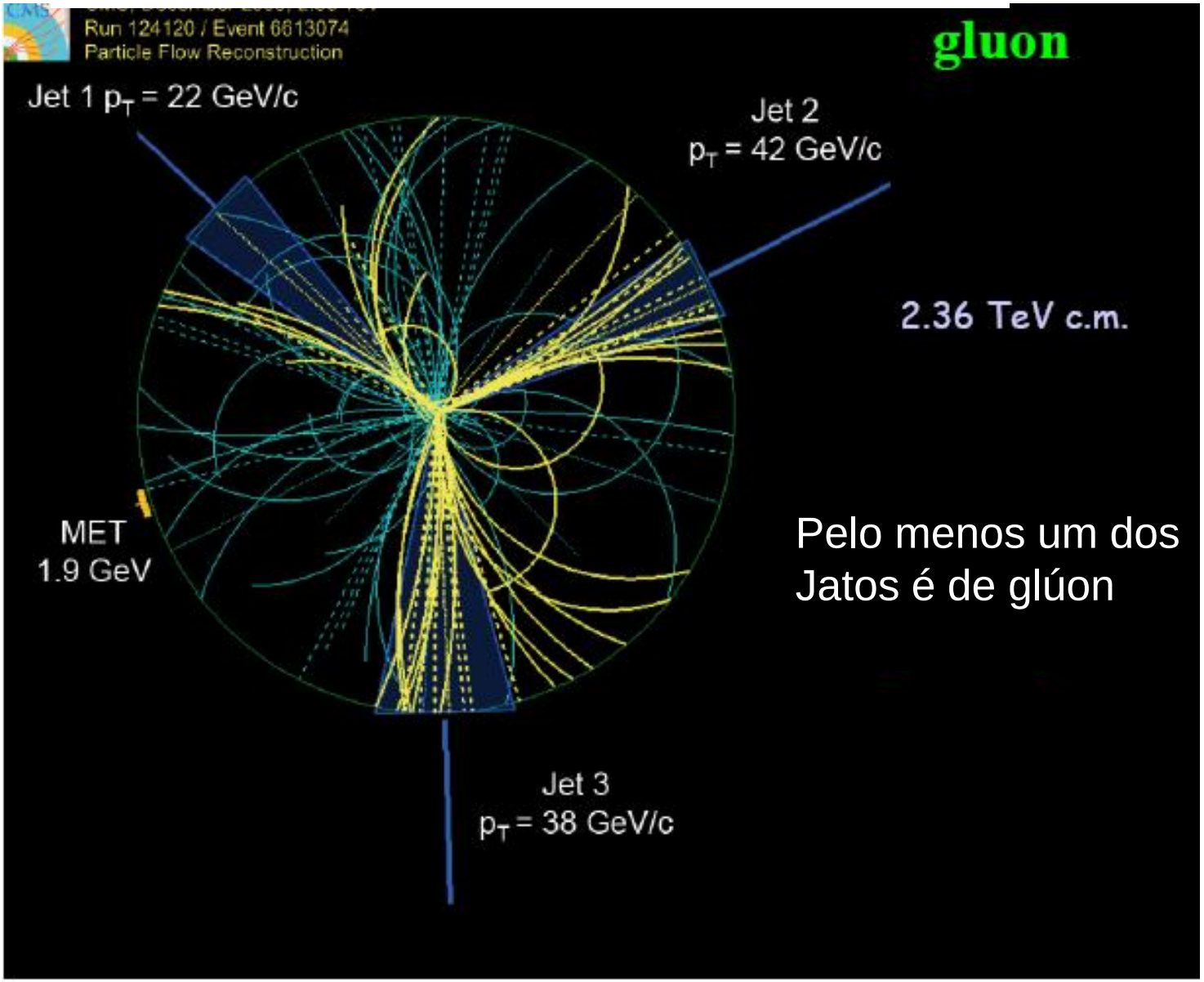


Multi hadron production

dedicated trigger !

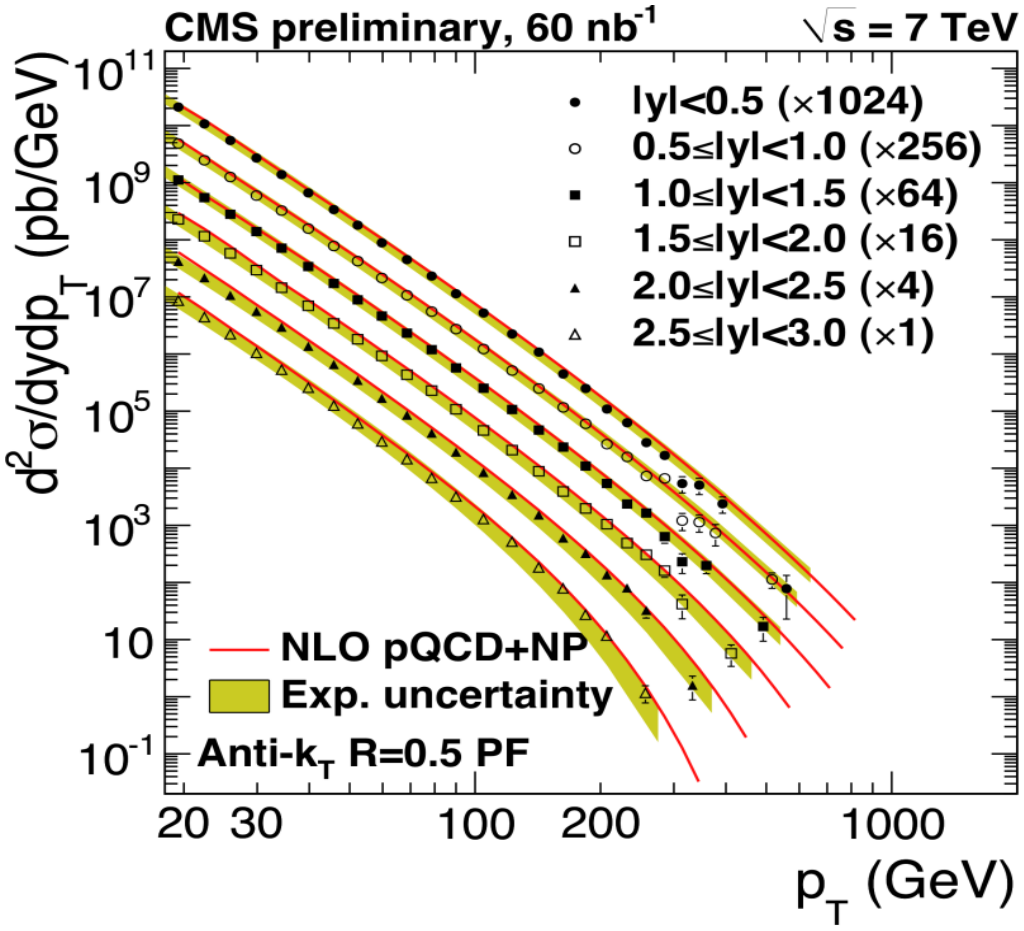


Jatos de quarks e glúons



Pelo menos um dos Jatos é de glúon

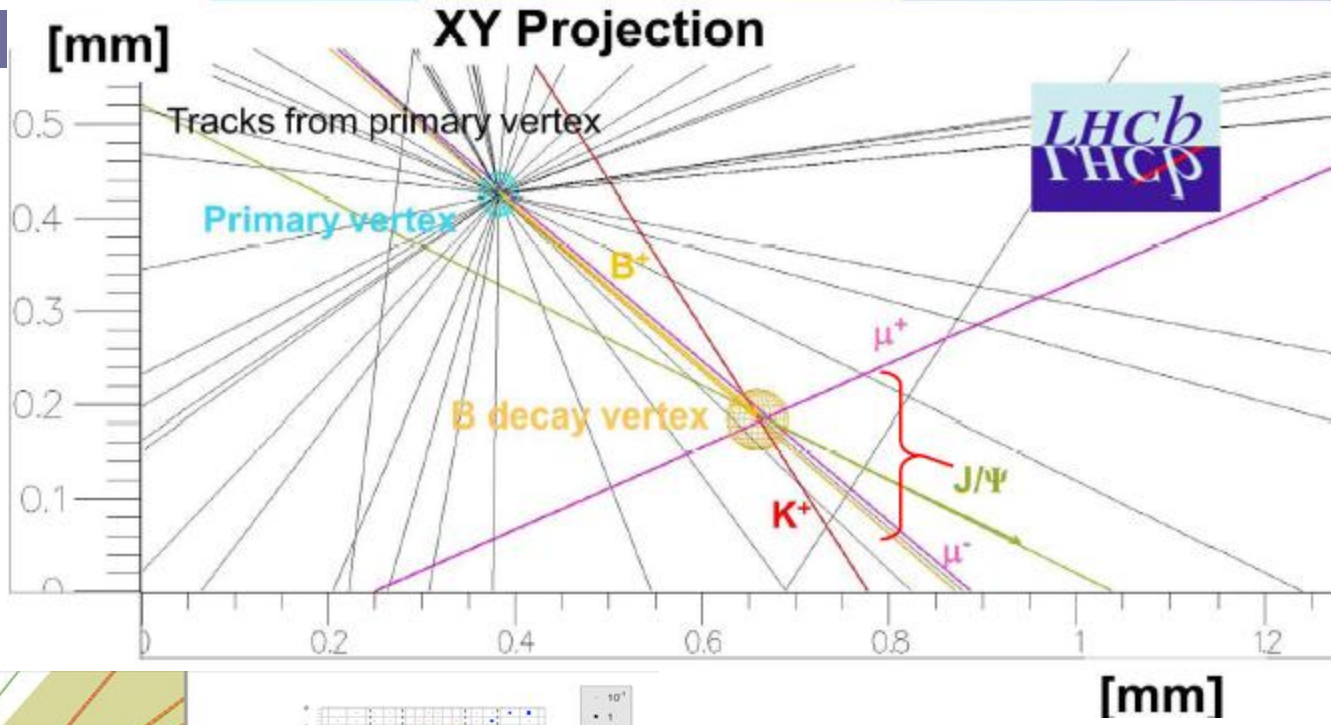
Jatos - Seção de Choque

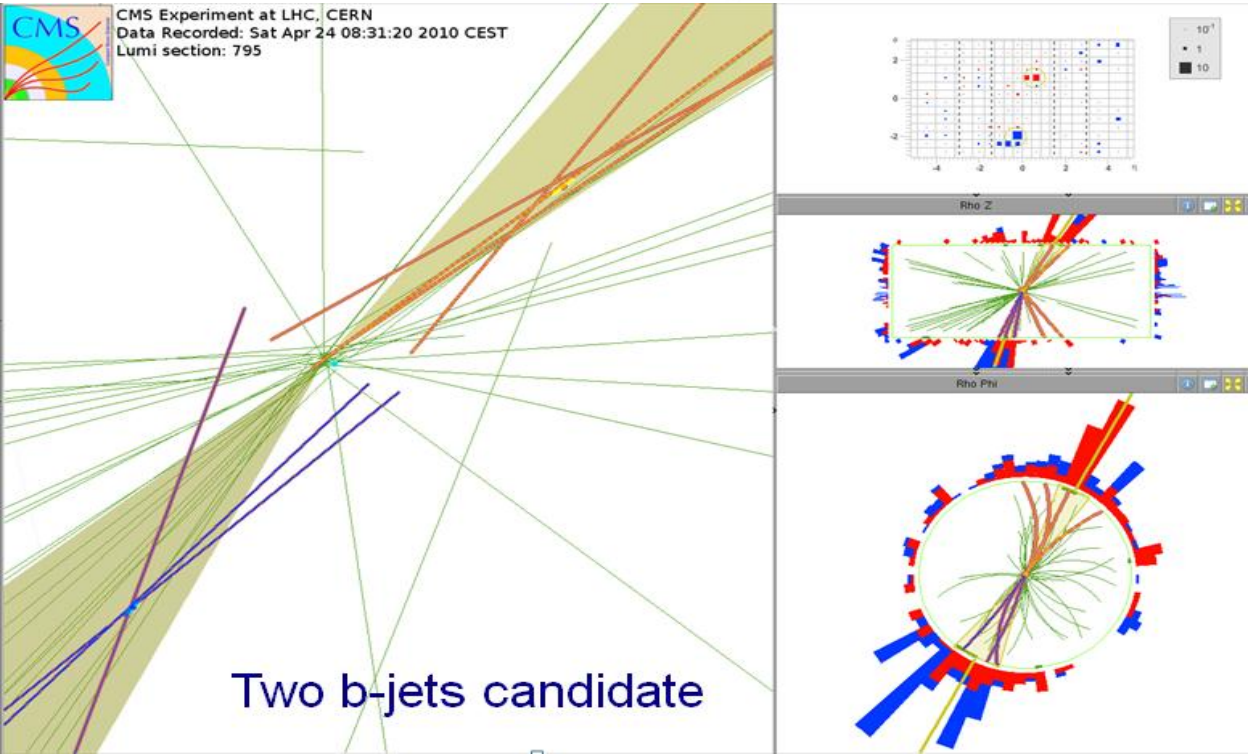


Importante teste da QCD perturbativa. Primeiro passo para procura de novos fenômenos.

Quarks Pesados – b

$B^+ \rightarrow J/\Psi\ K^+$



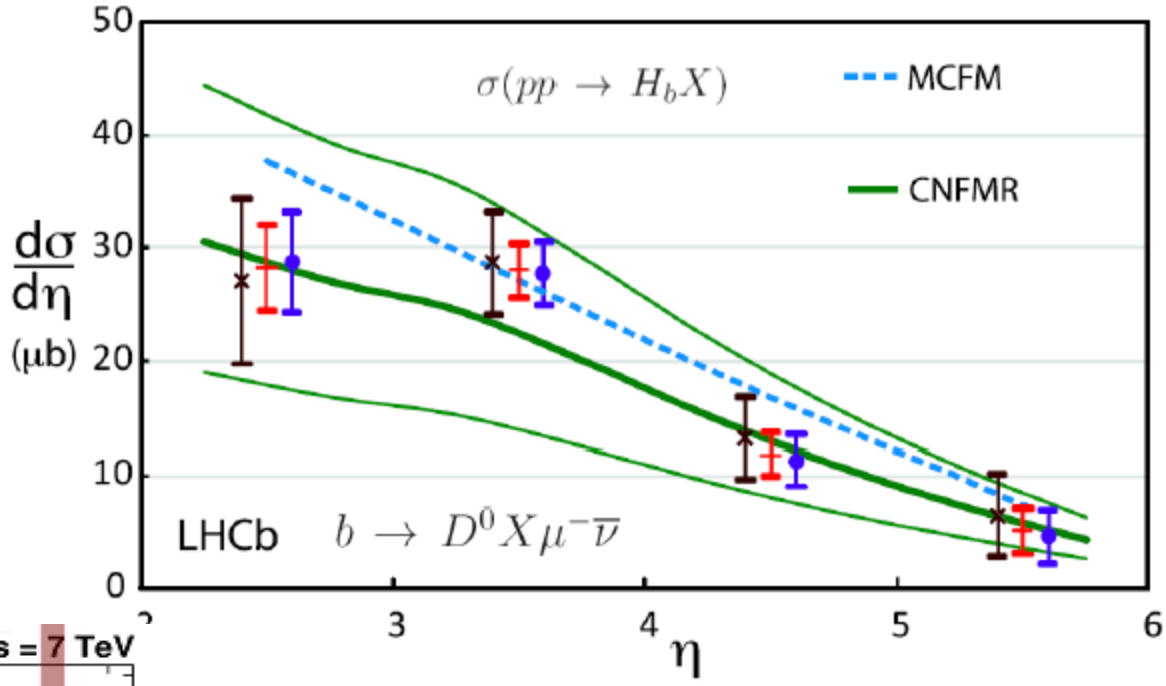


Detectores de vértice fundamentais na identificação dos decaimentos

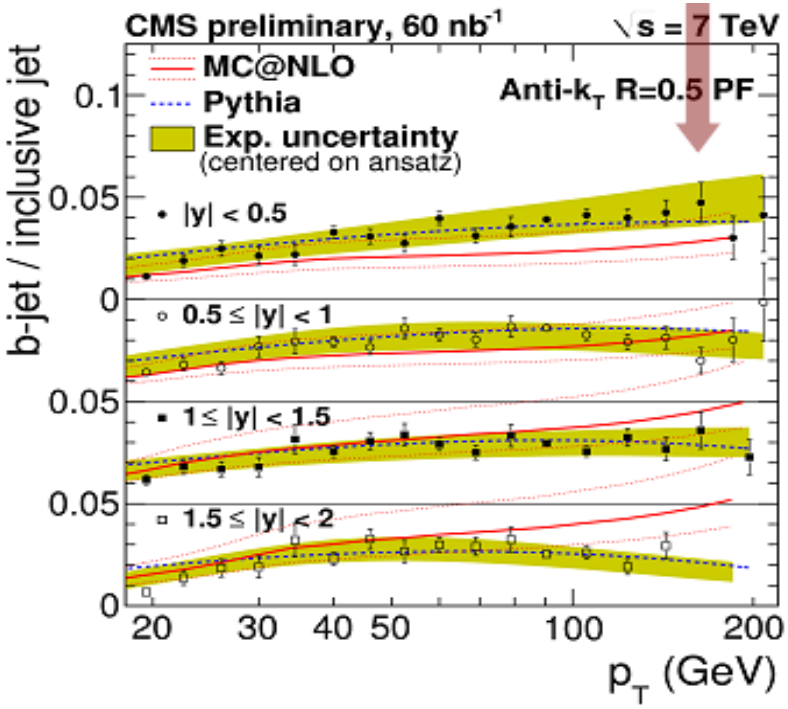
Quarks Pesados – b

Inclusive b-hadron production

T.Hebbeker

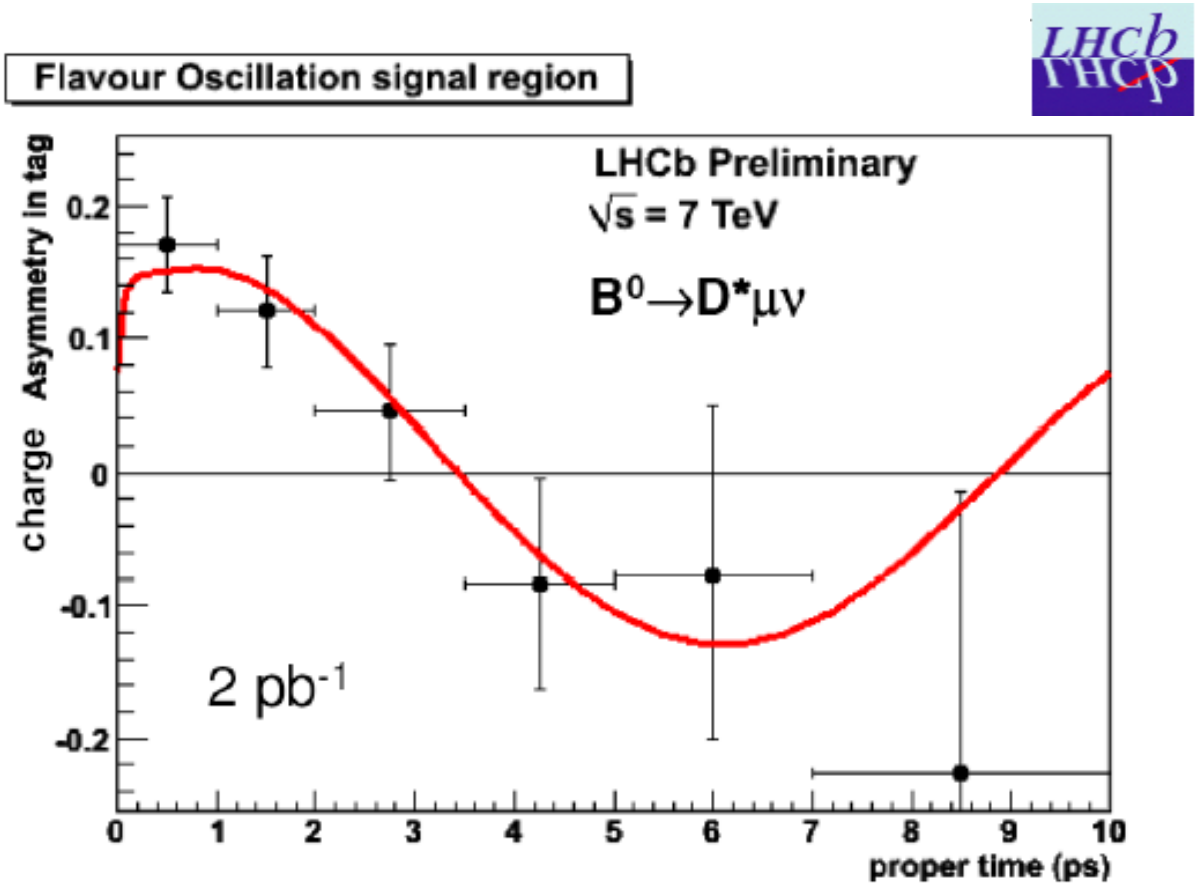


$\sigma(pp \to H_b X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$ $\quad 2 < \eta < 6$

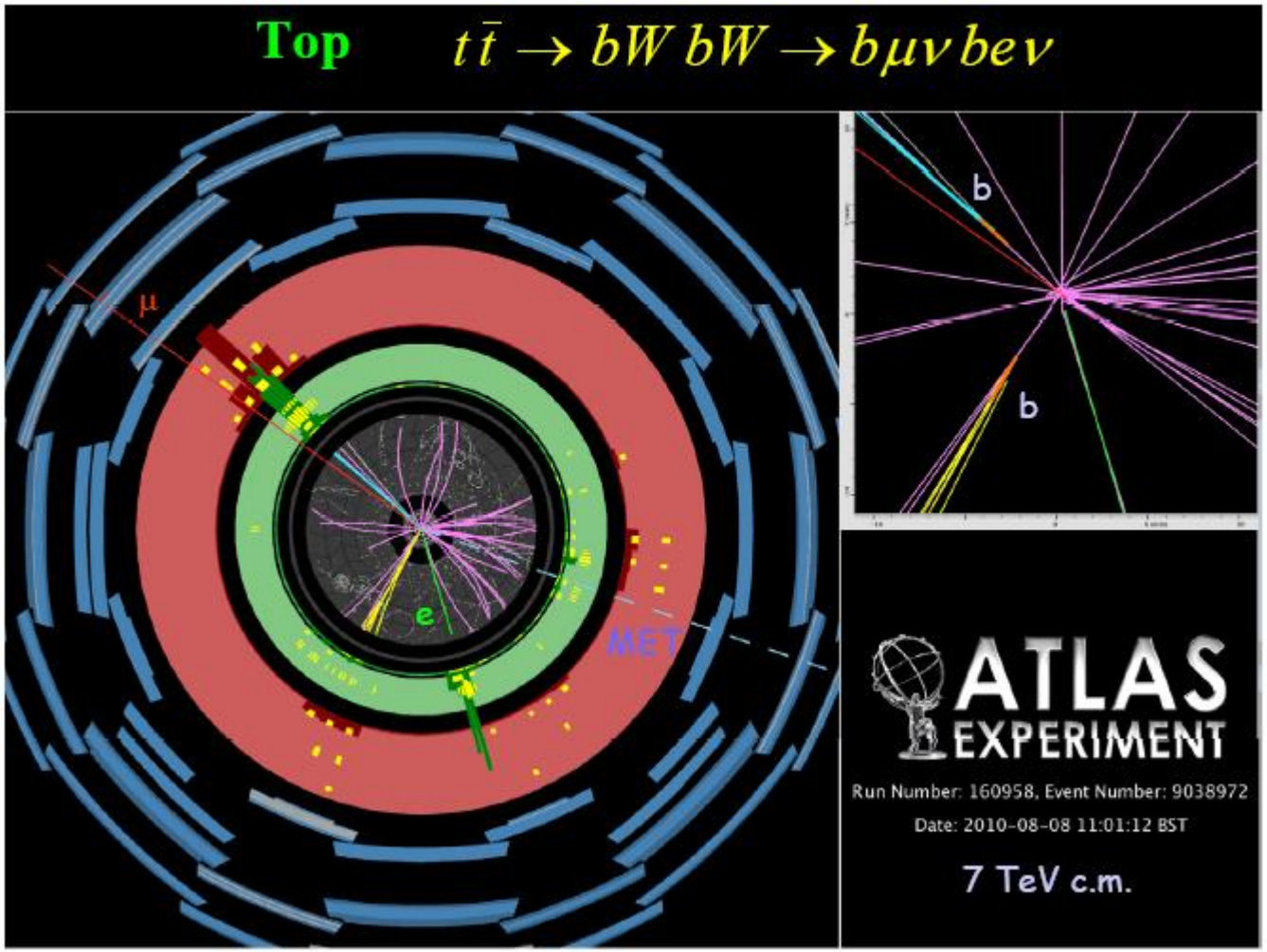


Alta seção de choque
Bom acordo com previsões teóricas

Quarks Pesados – Primeiro sinal de oscilação

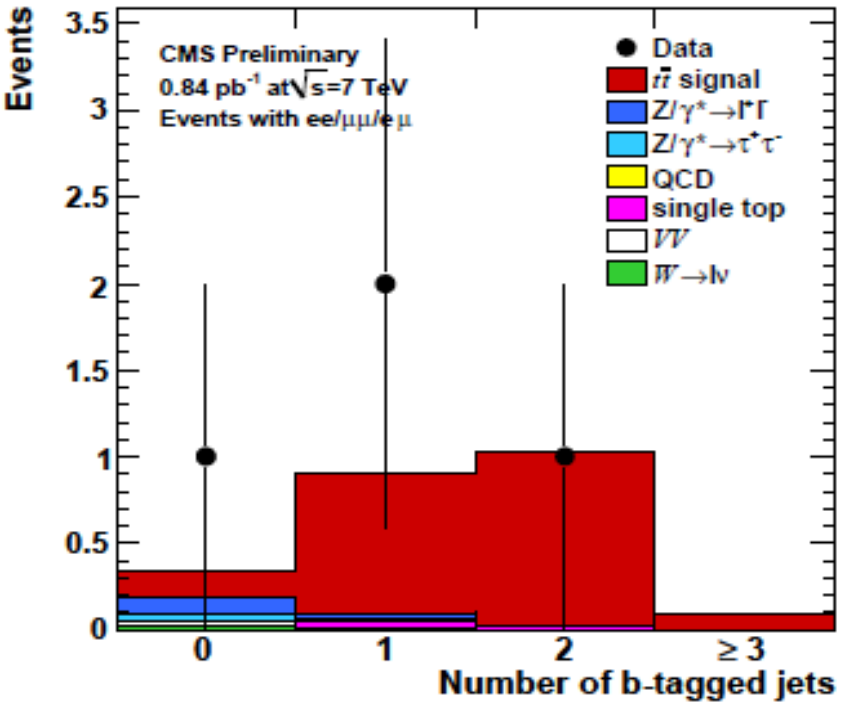


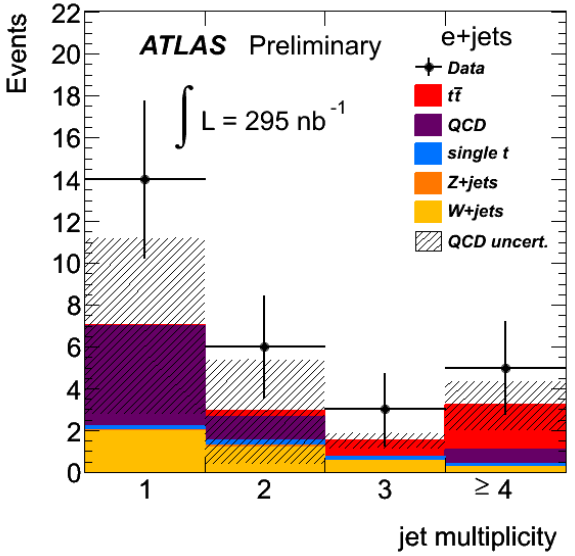
Quarks Pesados – top

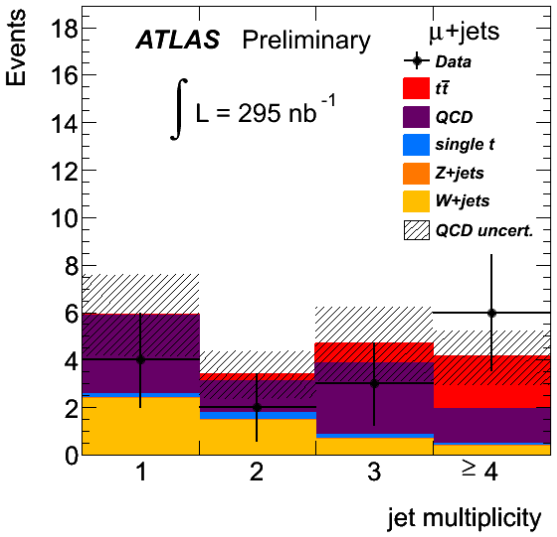


Quarks Pesados – top

ATLAS e CMS confirmam a observação do quark top com alta precisão.

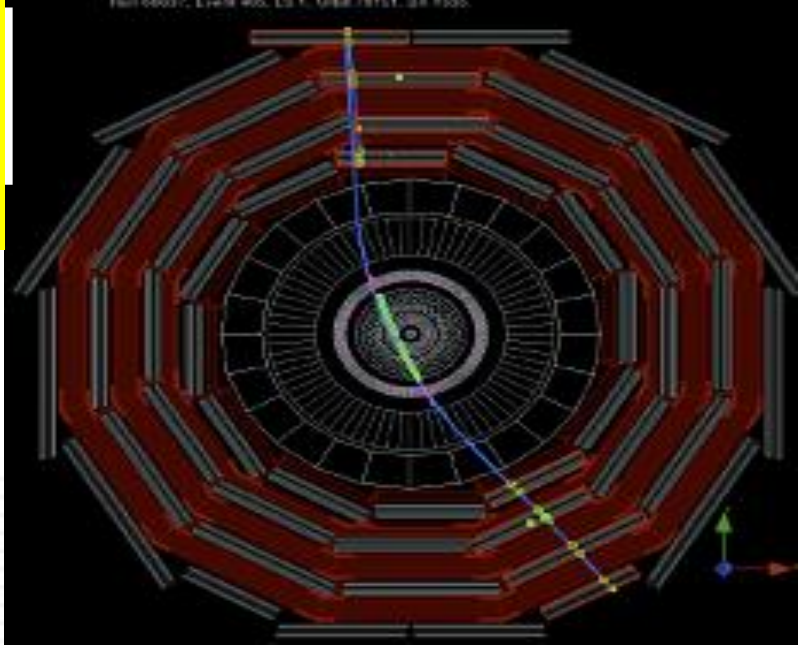


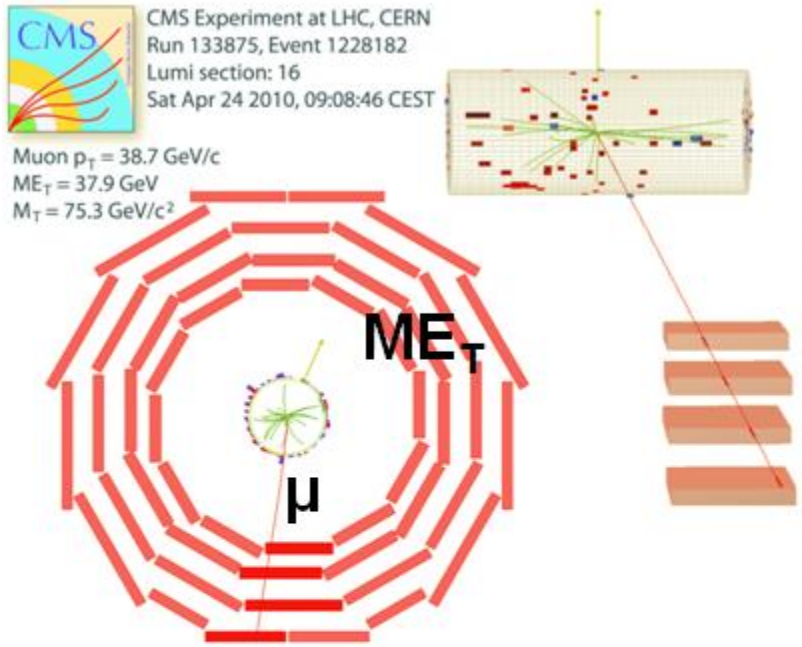


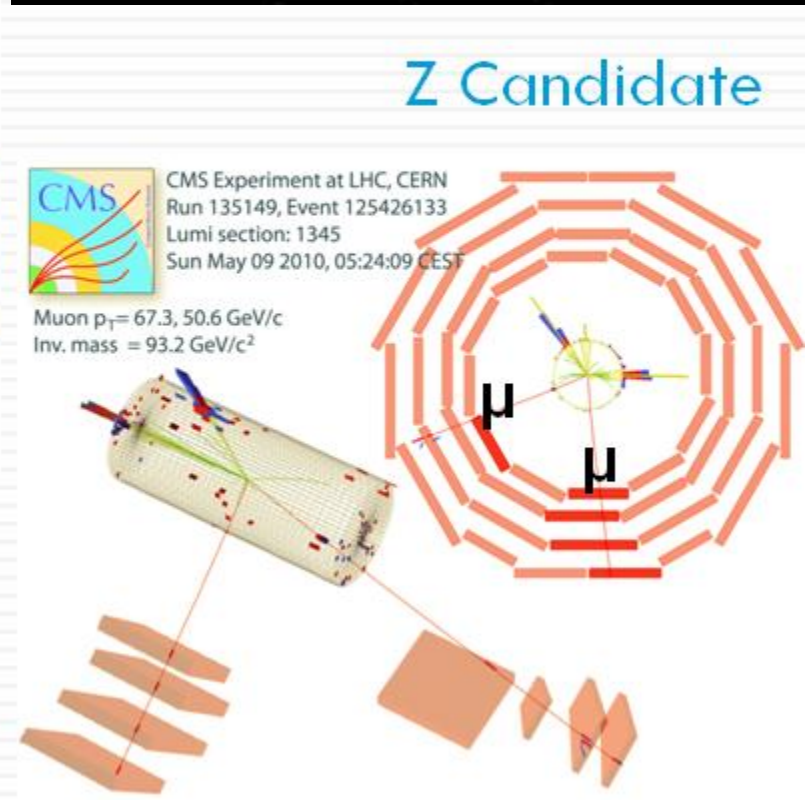


Muons

Identificação precisa. Fundamental para novas descobertas – Estado final em diversos decaimentos.

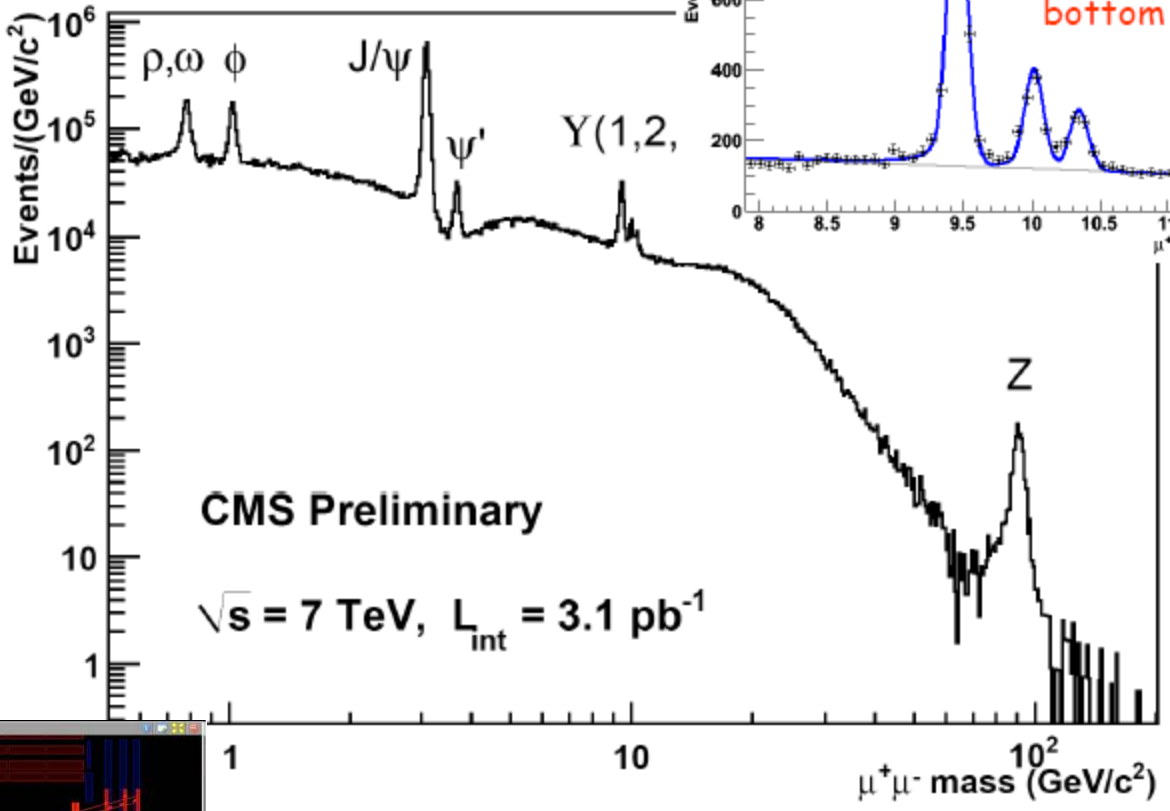


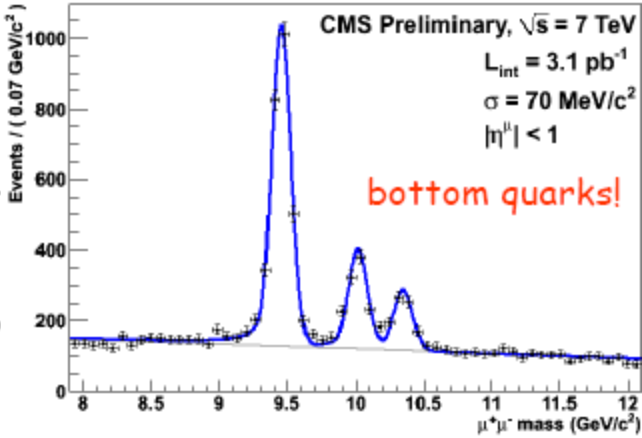


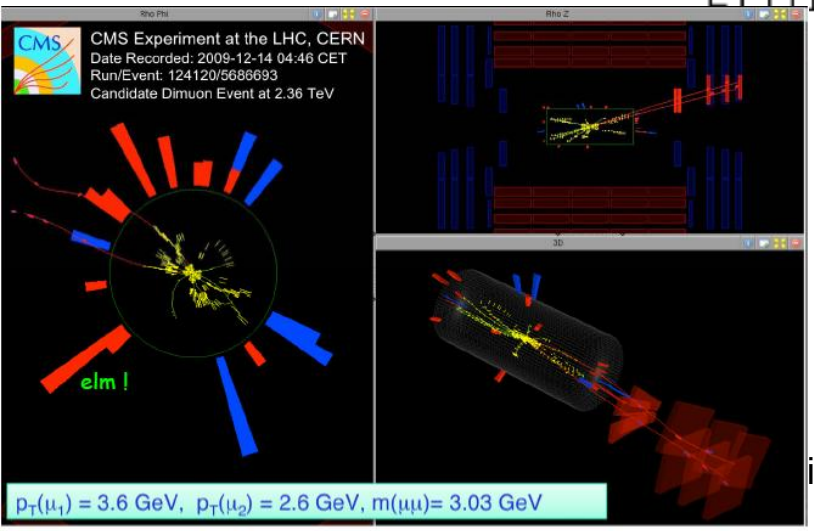


Muons - Um século em semanas

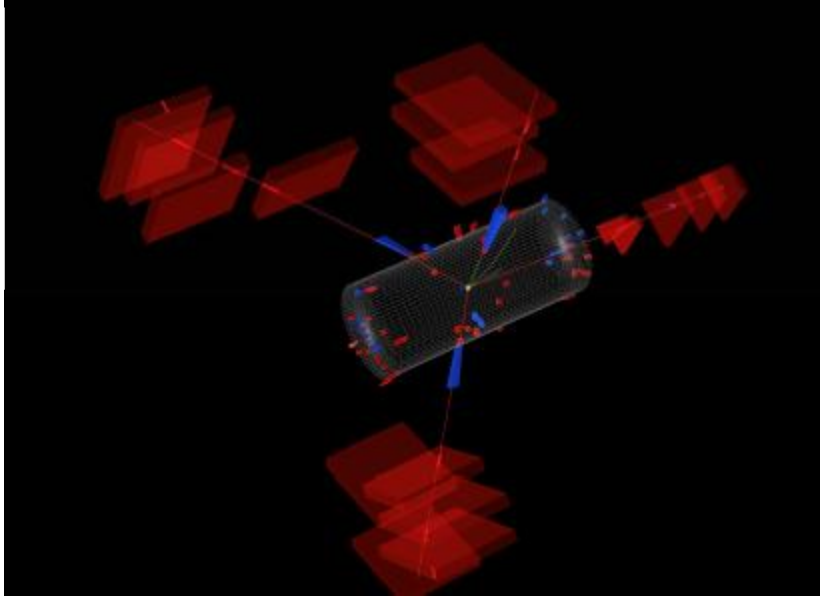
Dimuon resonances

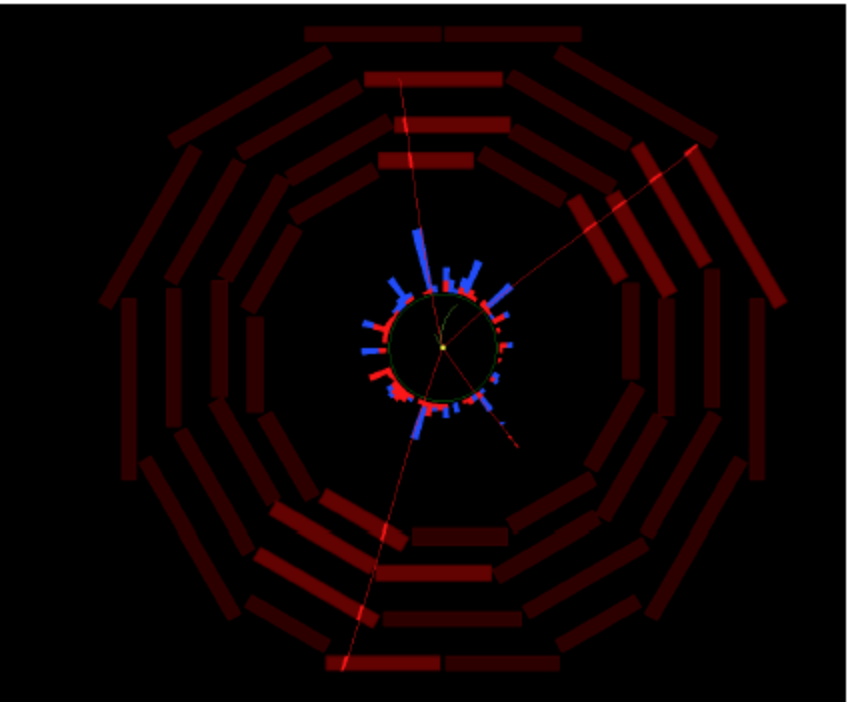






Muons – primeiro evento ZZ→μμμμ





Muons (pt, eta, phi)

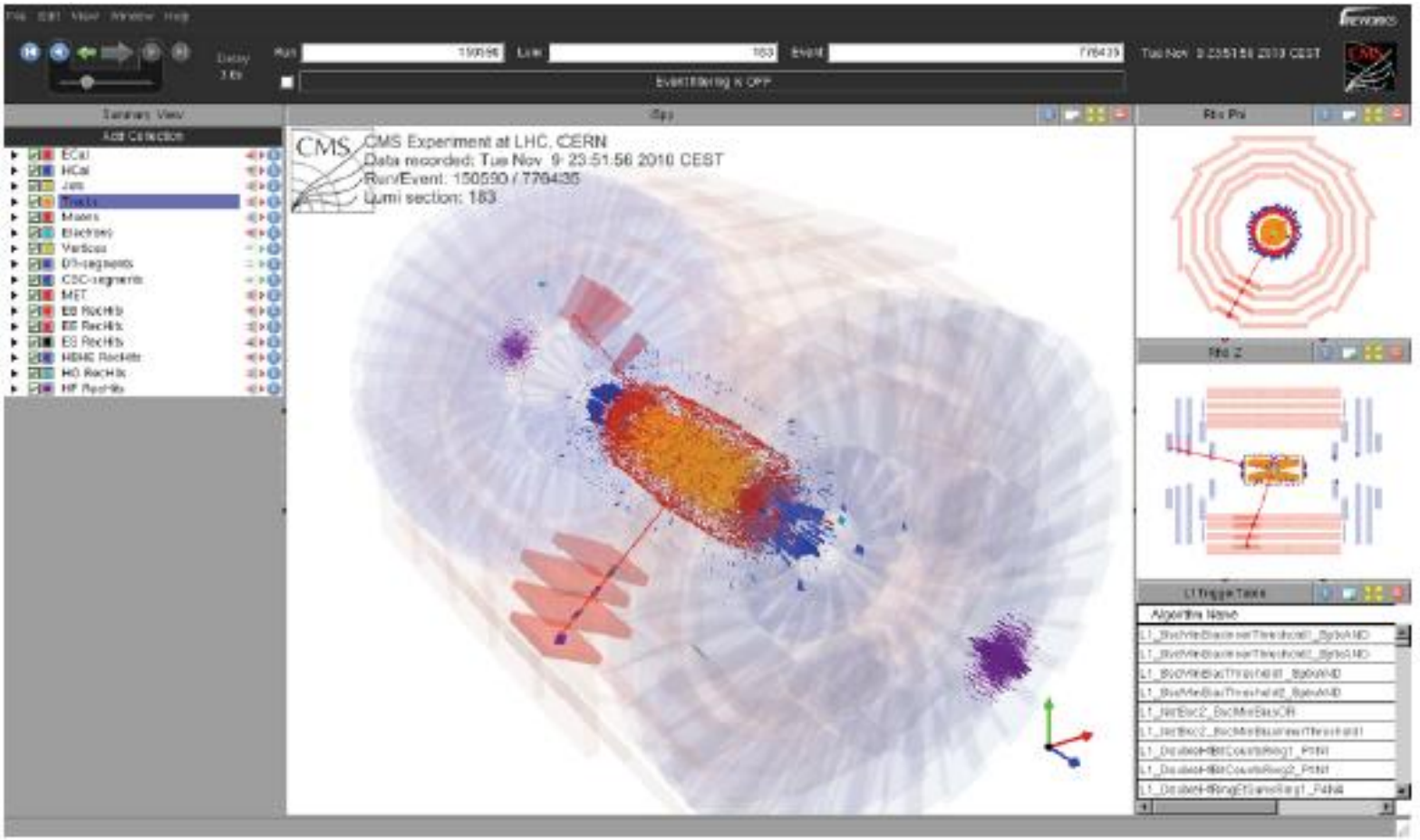
μ_0^-(48.1422, -0.412532,-1.92555)
μ_1^+(43.4421, 0.204654, 1.79493)
μ_2^+(25.8769, -0.782084, 0.774588)
μ_3^-(19.5646, 2.01112, -0.980597)

Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

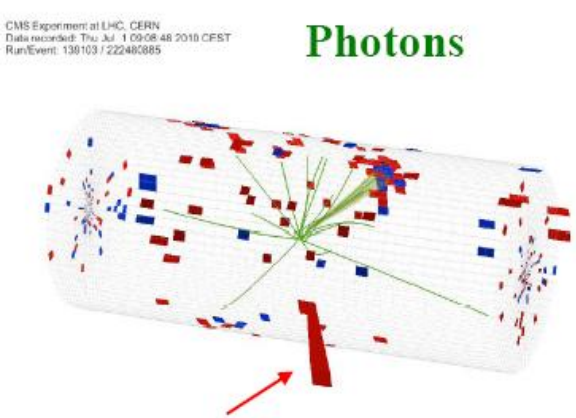
Invariant Mass of 4μ: 201 GeV

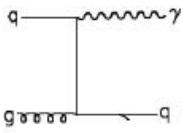
Muons em Pb-Pb – primeiro evento $Z \rightarrow \mu\mu$

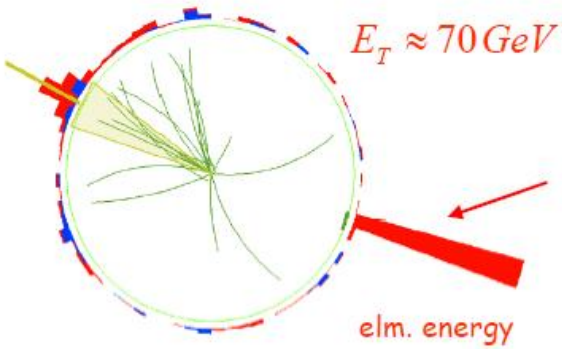


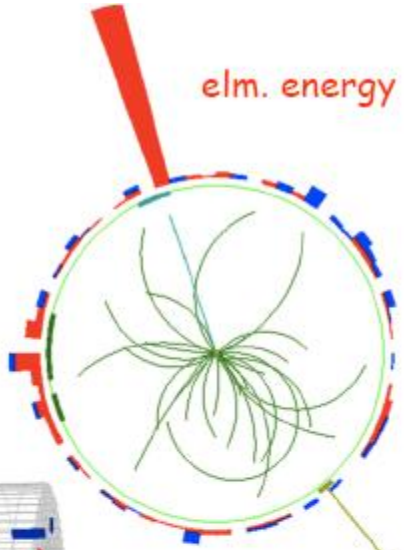
Z^0 candidate (1 glb/glb candidate in 800k events)
Maybe the first Z0 ever seen in nucleus-nucleus collision

Elétrons e Fótons





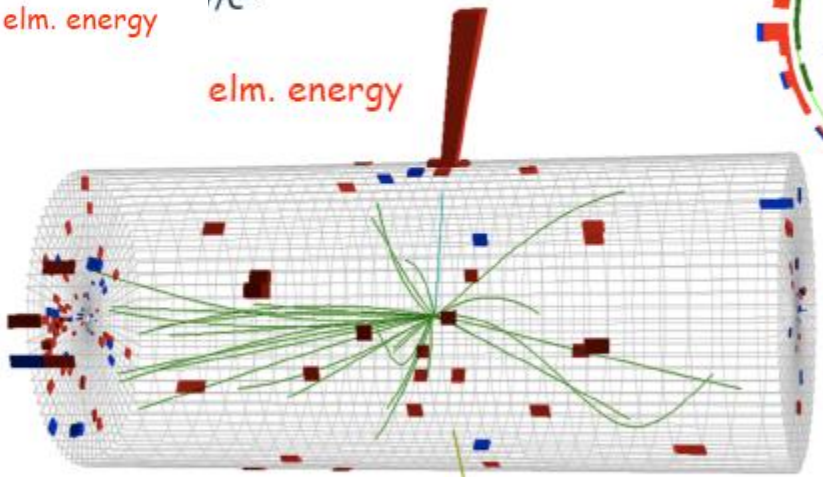




Fundamentais para calibração da Energia medida nos calorímetros.

Estado final em diversos decaimentos.

H→γγ

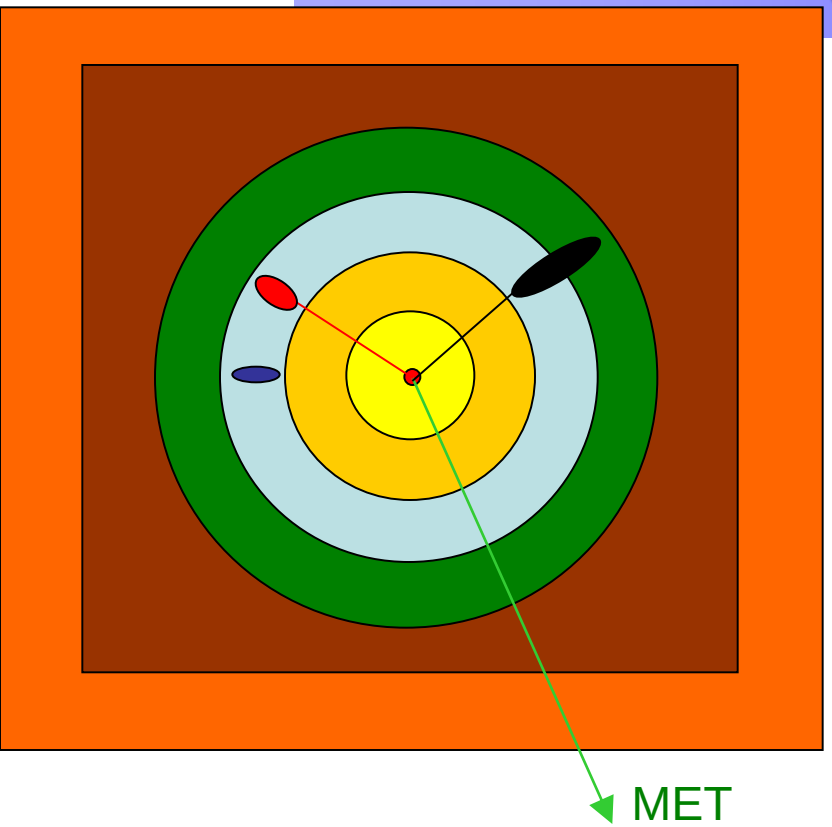


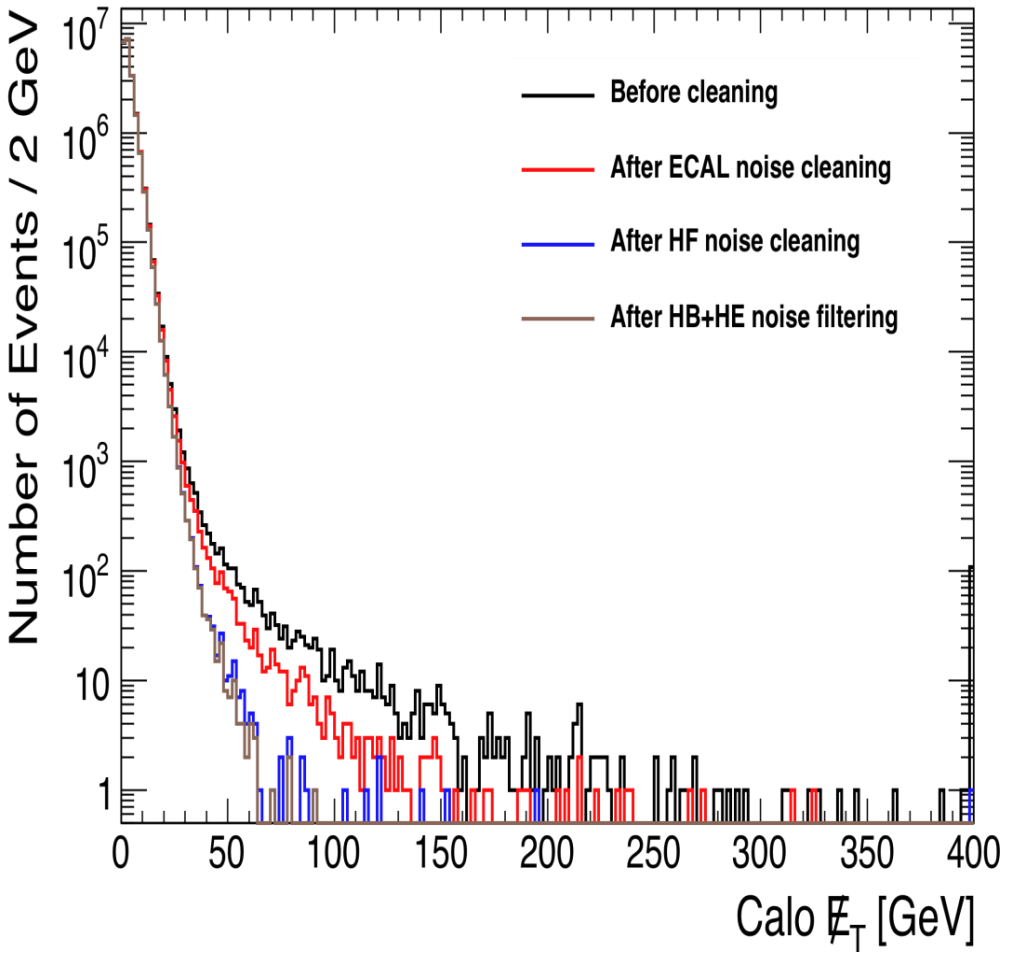
$W \rightarrow e\nu_e$

7 TeV c.m.

Missing E_T = neutrino !

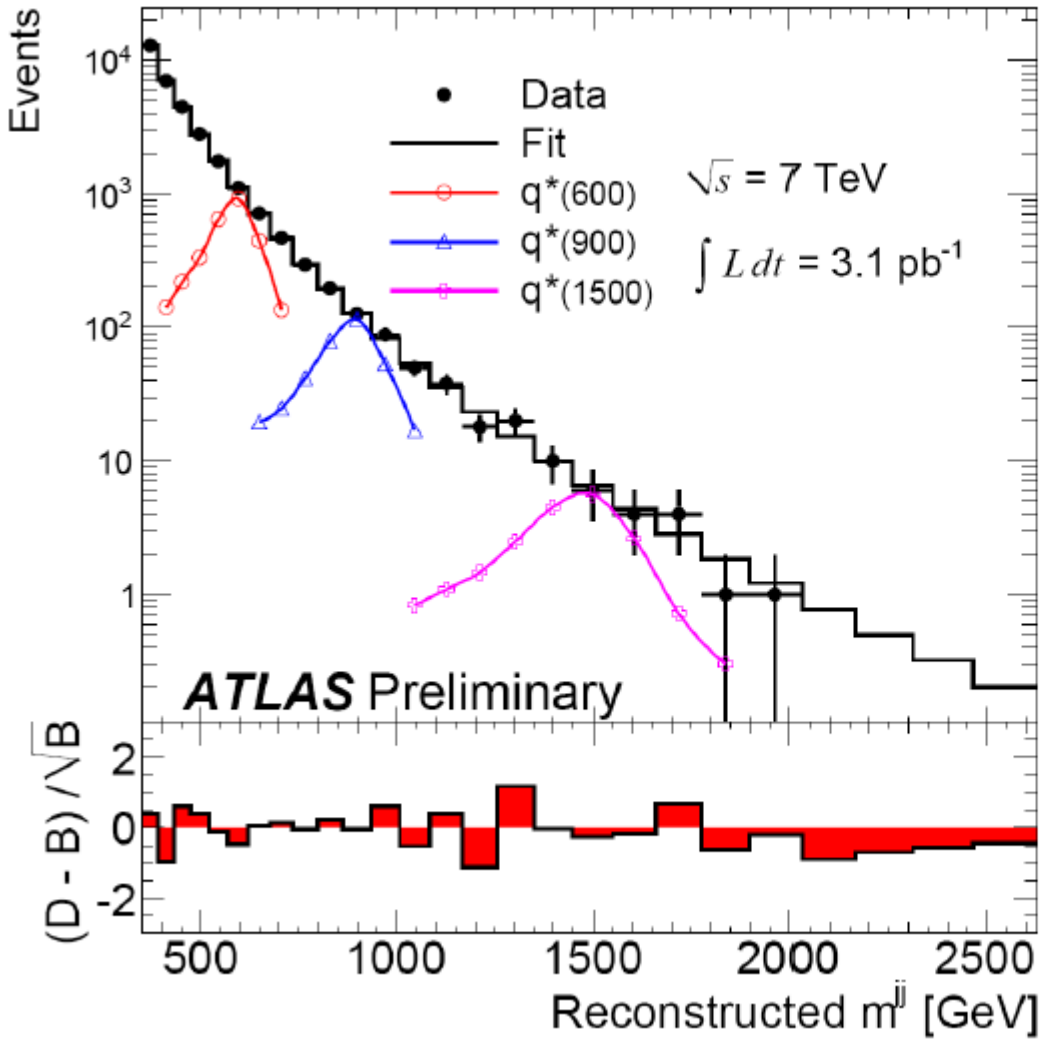
MET – Energia Perdida





Calibração dos calorímetros é fundamental – falsas fontes
Divesas fontes físicas
MP - υ
EMP - SUSY

Buscas por fenômenos além do MP



compositeness:

$$q^* \rightarrow q\,g \rightarrow 2\,jets$$

compositeness scale

$$\Lambda = m(q^*)$$

excited quarks excluded up to a mass of

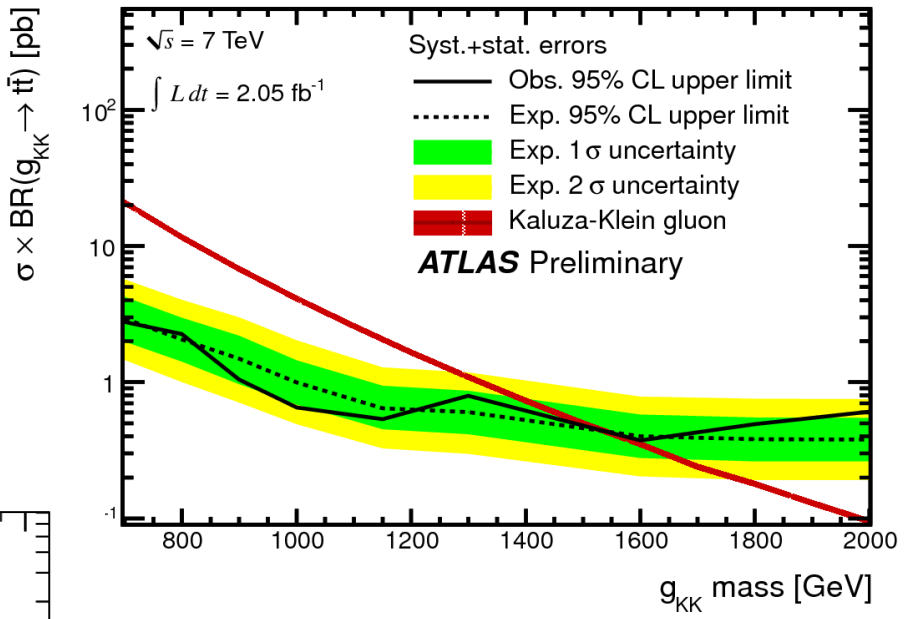
1.53TeV (95%)

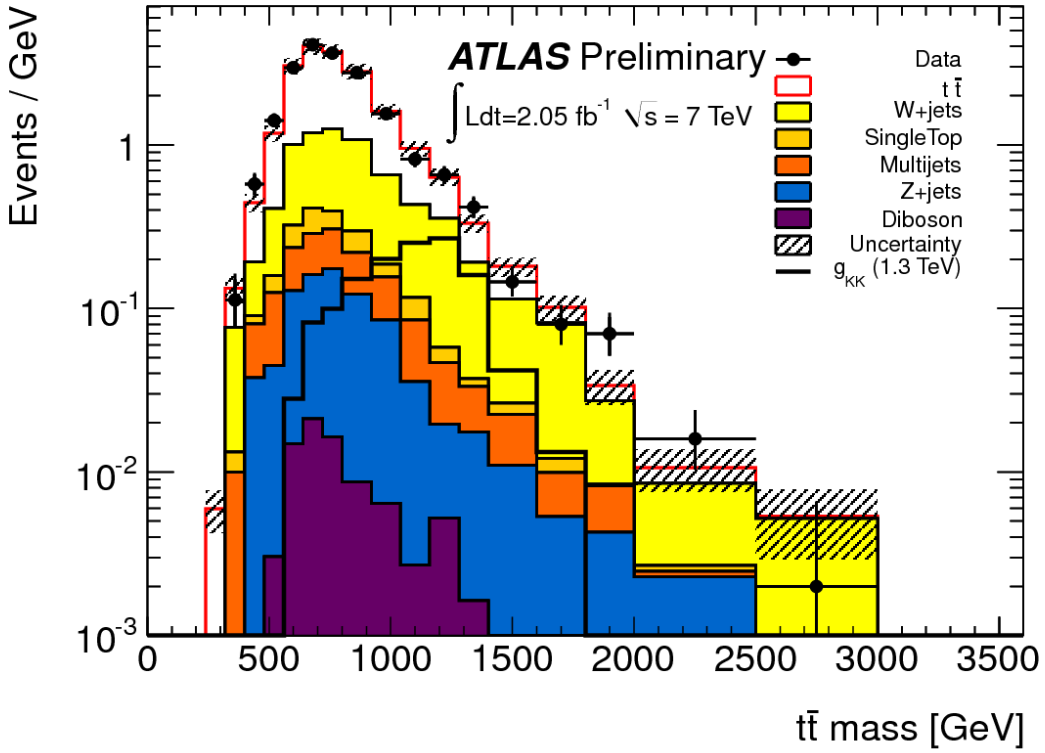
world record !

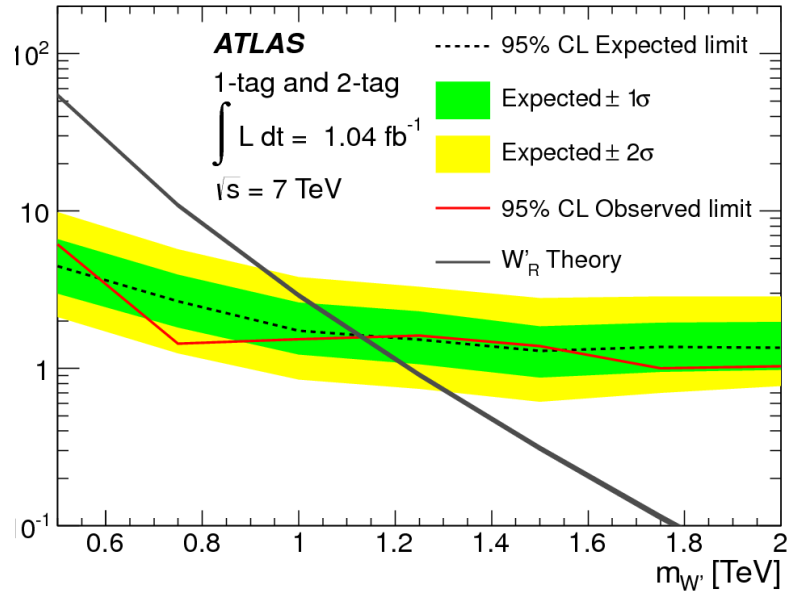
(Tevatron limit: 870 GeV)

Buscas por fenômenos além do MP

Resonâncias tb and tt





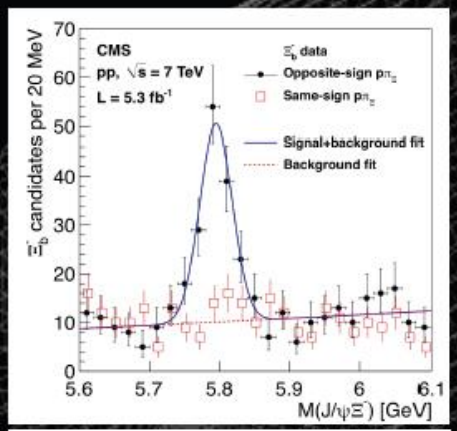


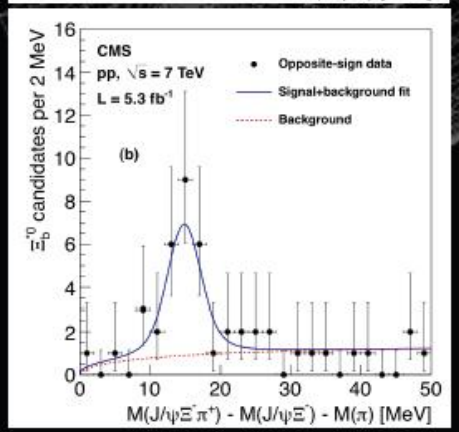
Nova Partícula (não é o Higgs)

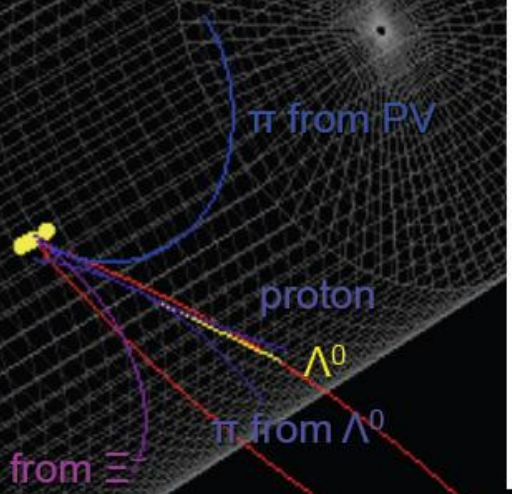
Candidate event display

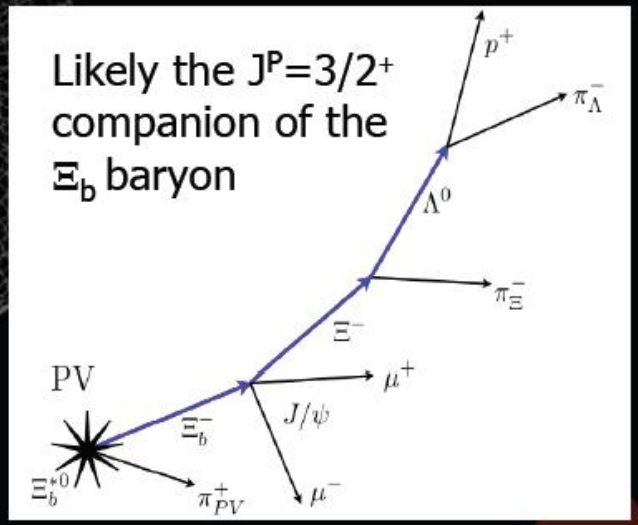
New Particle Discovery

garnered a lot of media attention







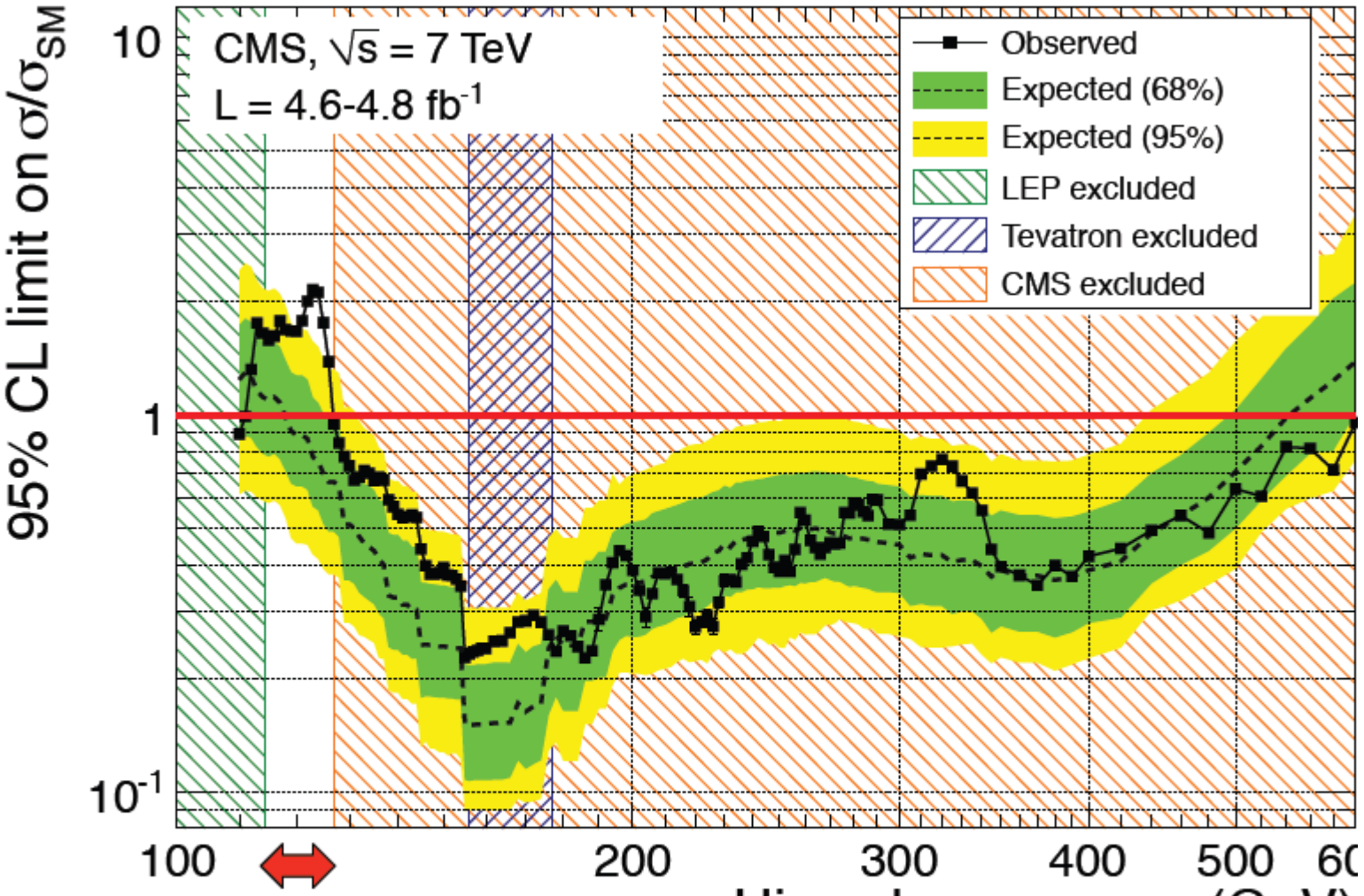


$$M(p^+\pi^-) = 1116.7\ MeV$$
$$M(\Lambda^0\pi^-) = 1315.5\ MeV$$
$$M(\mu^+\mu^-) = 3117.1\ MeV$$
$$M(J/\psi\Xi^-) = 5787.8\ MeV$$
$$Q(J/\psi\Xi^-\pi^+) = 15.7\ MeV$$

Ξ_b^0 (5945 MEV) $\rightarrow \Xi_b^- \pi^+ \rightarrow \Xi^- J/\psi\, \pi^+ \rightarrow \Lambda\pi^-\mu^+\mu^-\pi^+ \rightarrow p^+\pi^-\pi^-\mu^+\mu^-\pi^+$

CMS-BPH-12-001 arXiv:1204.5955

Procura pelo Higgs: até 4 de julho



114,4 – 127,0 GeV/c²

Allowed M_H range for the SM Higgs Boson

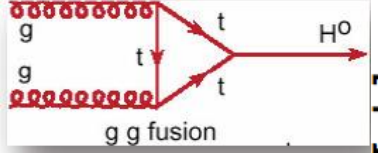
Observação do Higgs no CMS!!

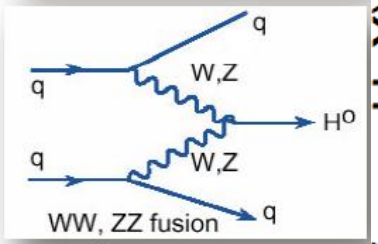


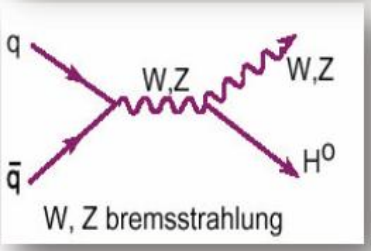
Gilvan A. Alves 2012

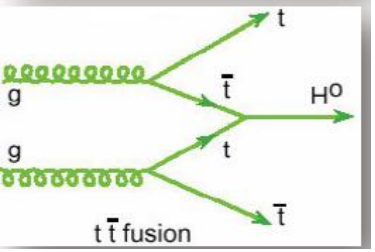
Procura pelo Higgs no LHC

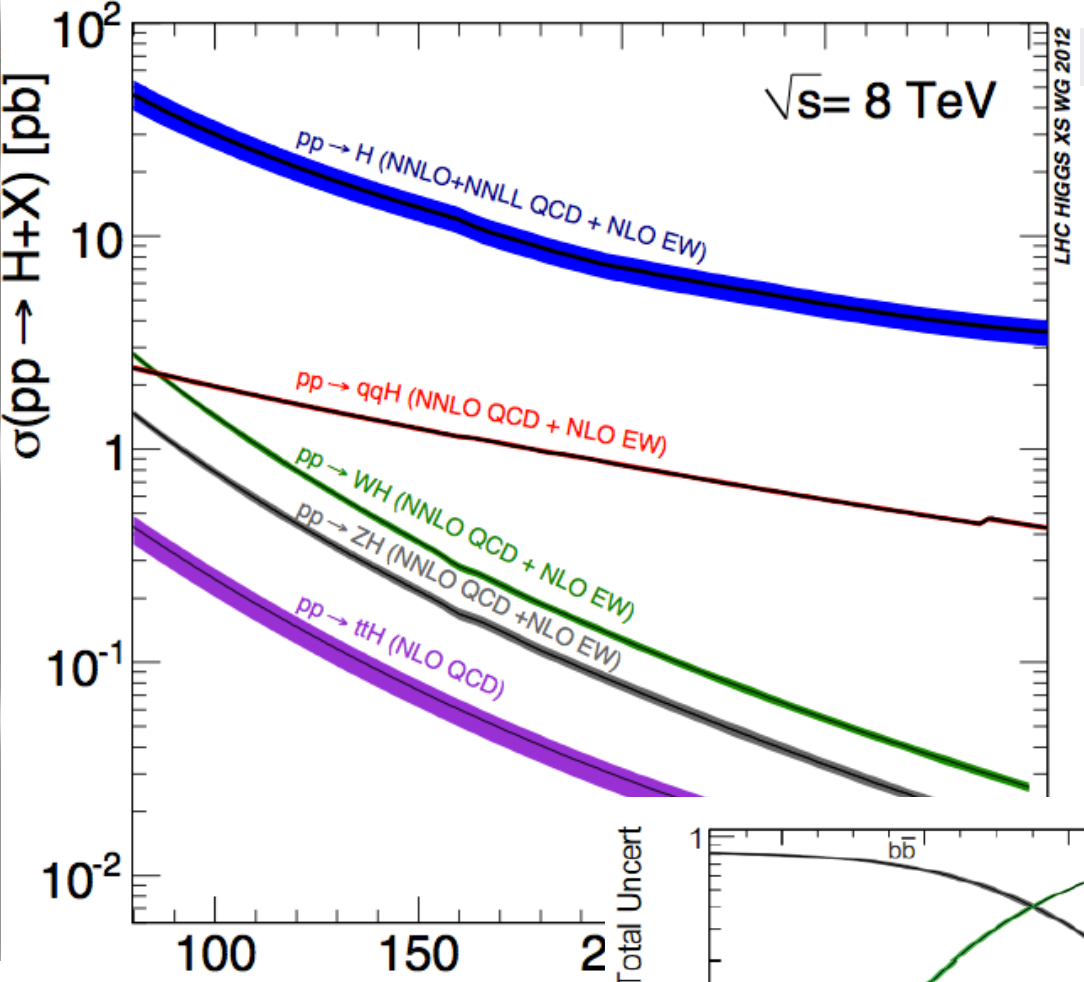
- Algumas dificuldades
  - Não sabemos a massa do Higgs
    - Entre 114-127 GeV ou 600-1000 GeV
    - Deteção depende da massa
  - O LHC produz 10^9 interações p-p /s
    - … mas só algumas centenas de Higgs/ano
  - LHC é um colisor próton-próton
    - Não é um ambiente como o LEP

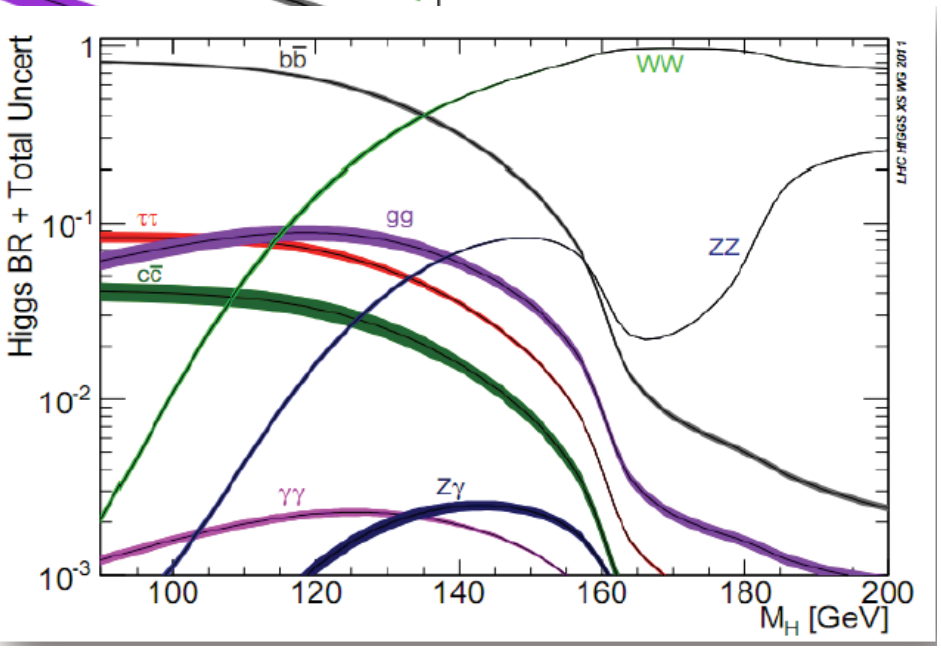








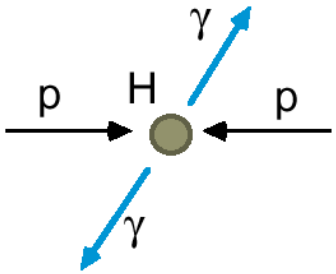


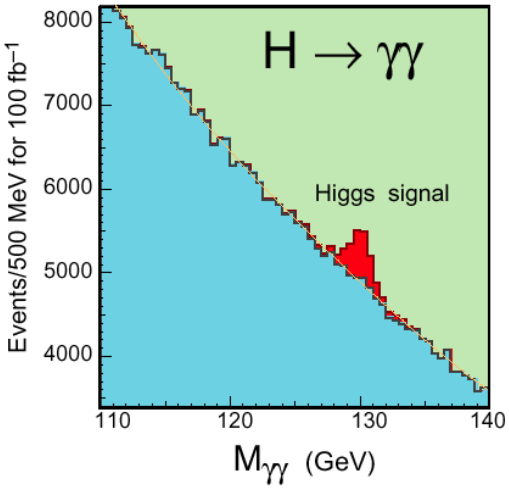


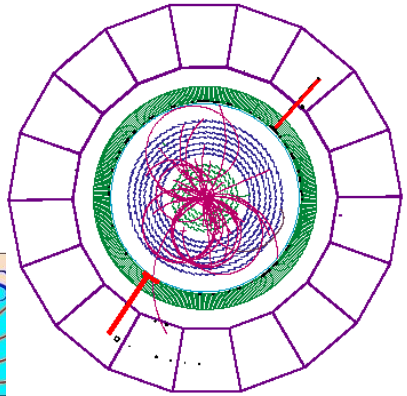
Como procurar pelo Higgs?

Como procurar pelo Higgs?

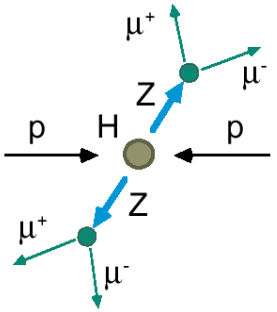
M_H < 140 GeV

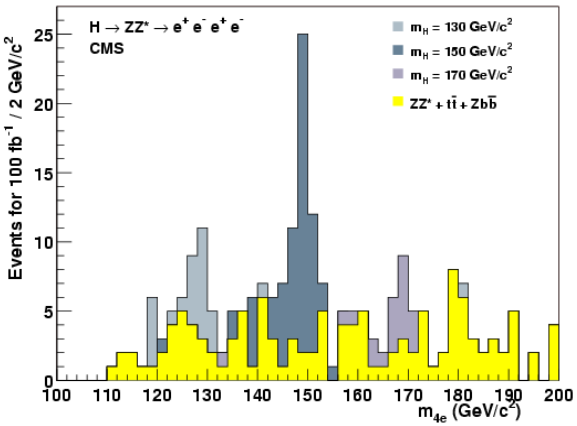


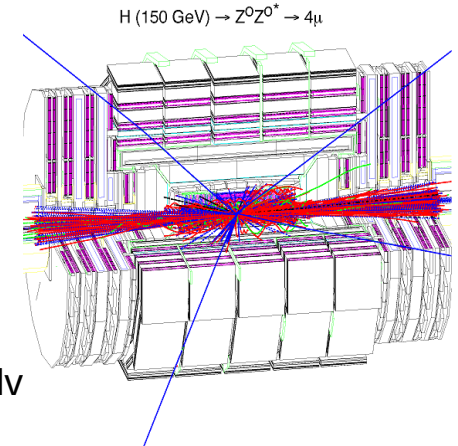




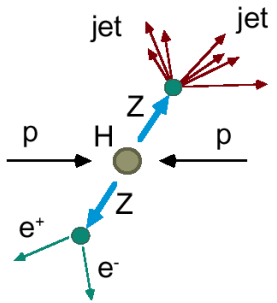
130<M_H<500 GeV

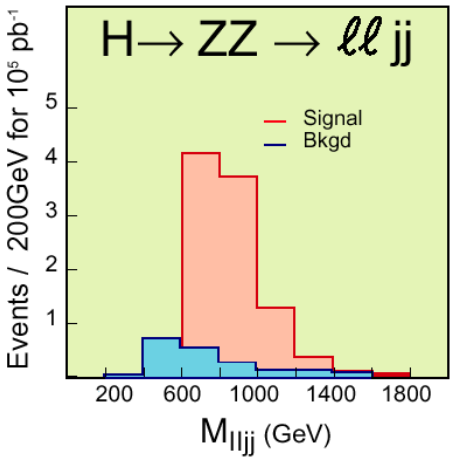


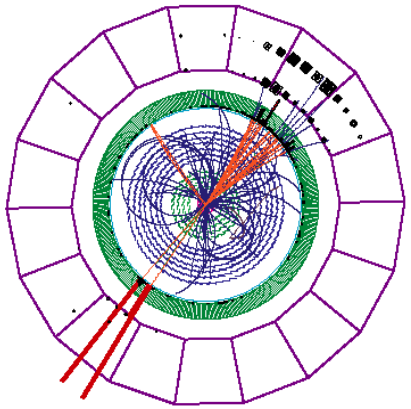




M_H > ~500 GeV







Gilv

Nossa análise

5 modos de decaimento

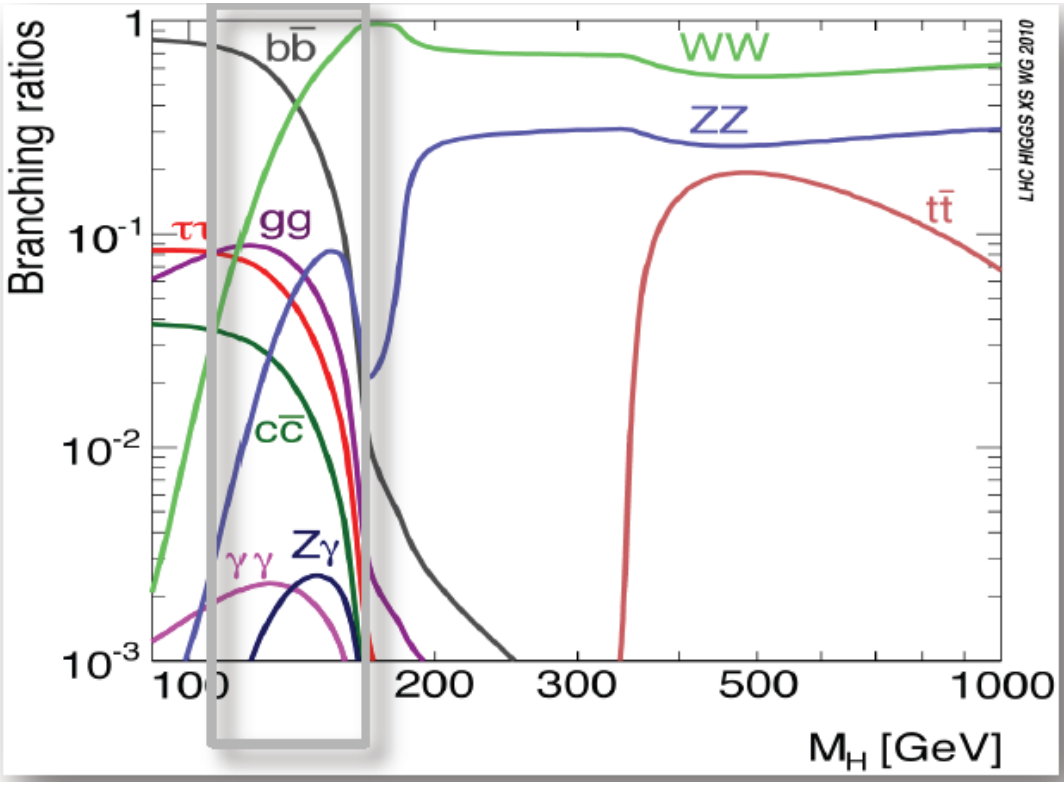
- $b\bar{b}$, $\tau\tau$, WW, ZZ, $\gamma\gamma$

Região de baixa massa: m_H = 114-127 GeV

Dificil devido ao enorme fundo (QCD, EW)

Canais com boa resolução em massa: ~1%

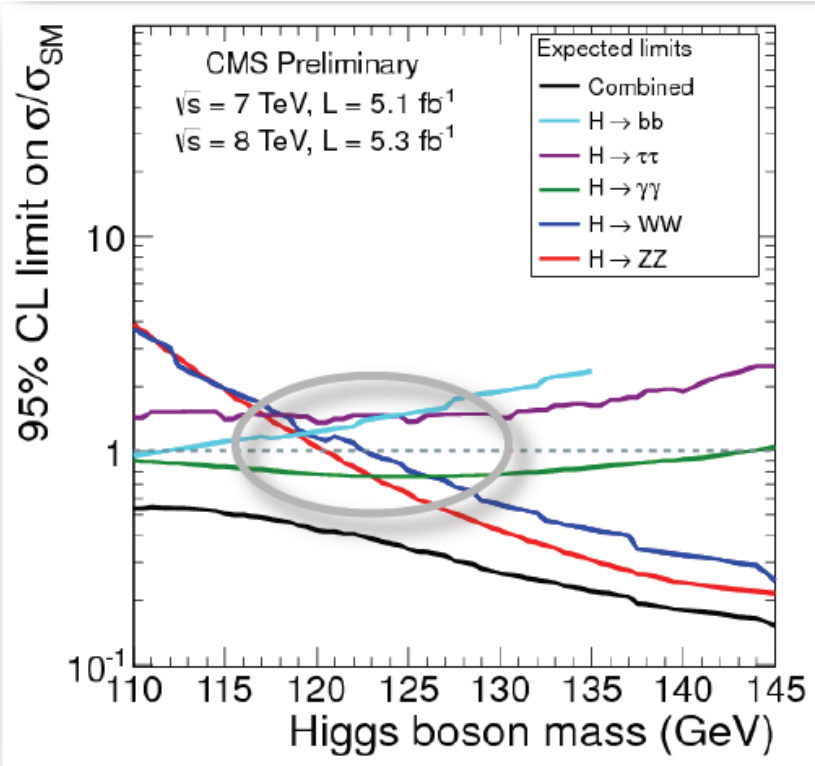
$H \rightarrow \gamma\gamma$ $H \rightarrow ZZ \rightarrow 4l$

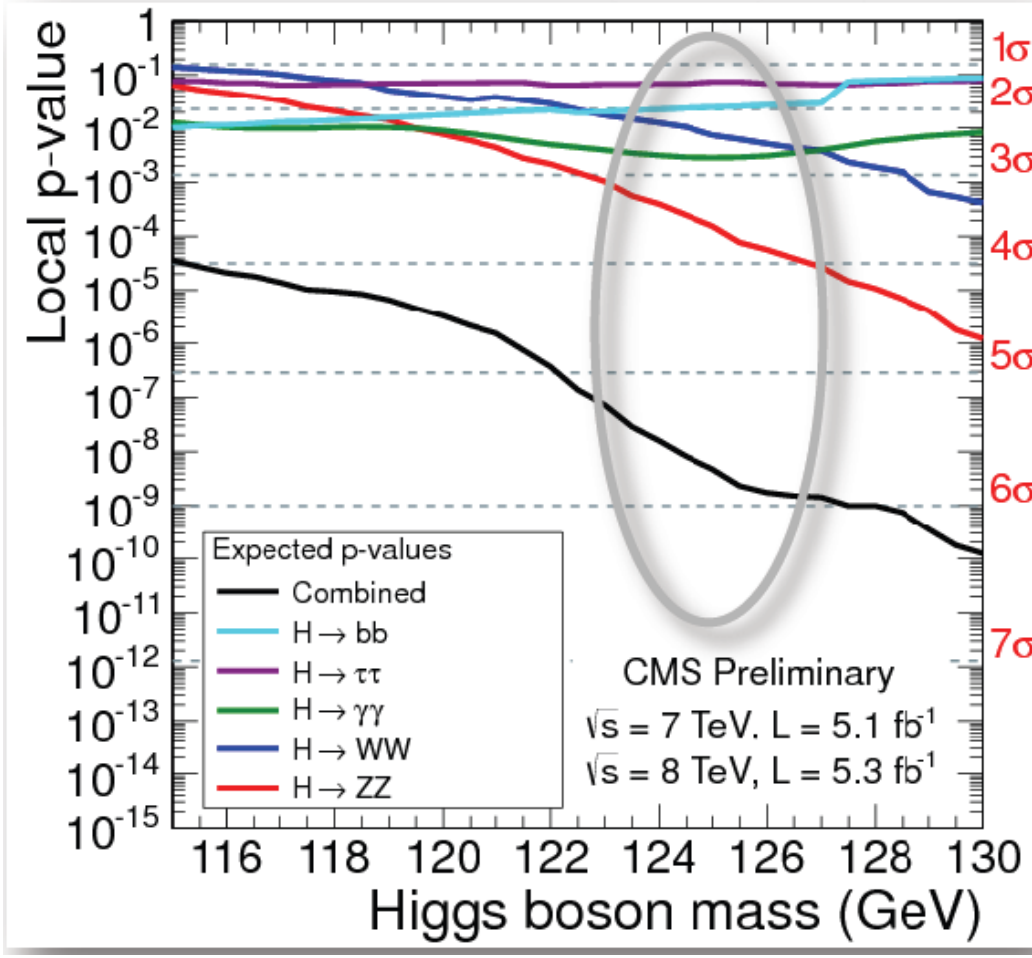


Potencial do CMS

Na região de baixa massa ~[115-130]GeV

A combinação dos 5 canais permite excluir ou observar o Higgs em todo o intervalo

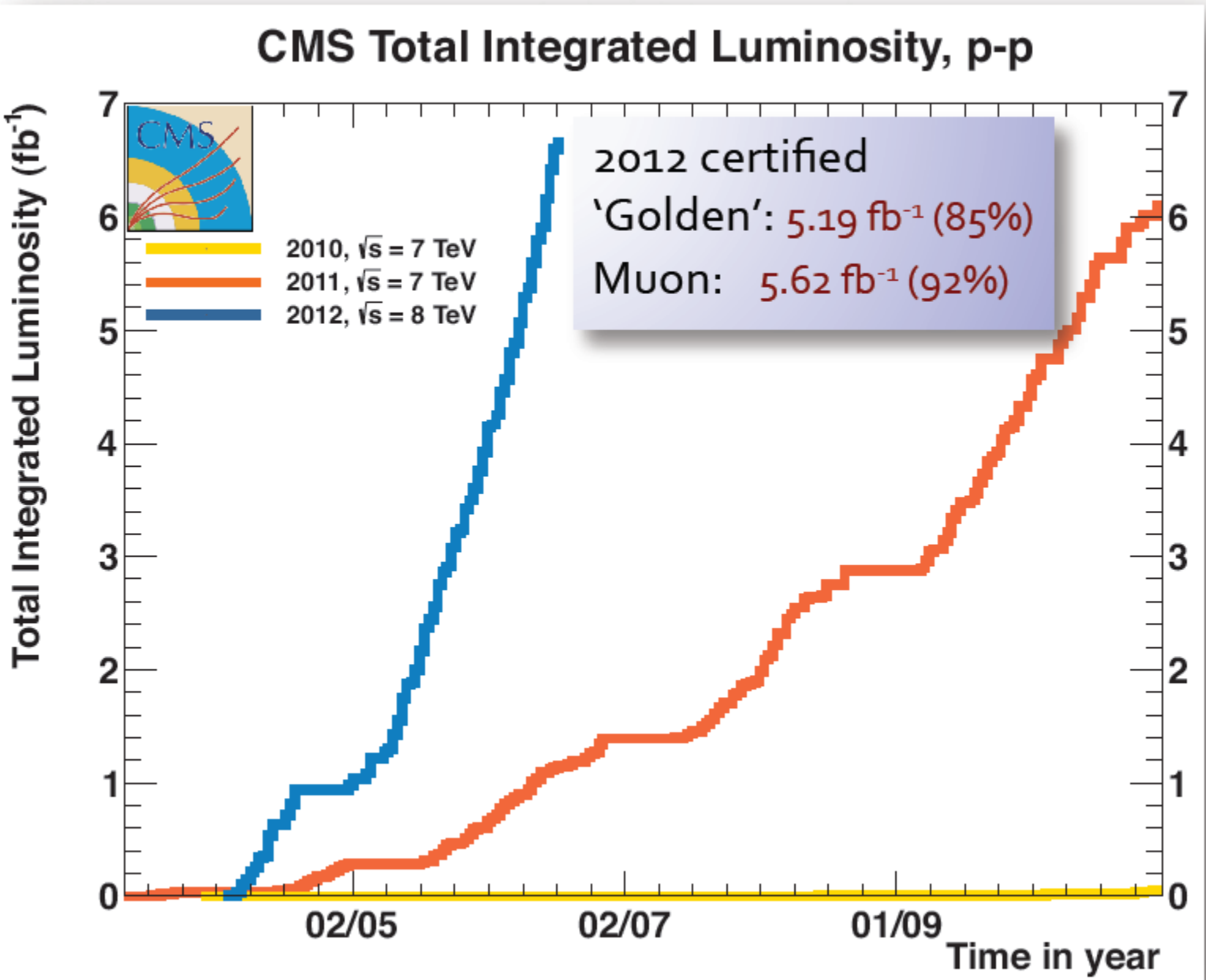




p-values

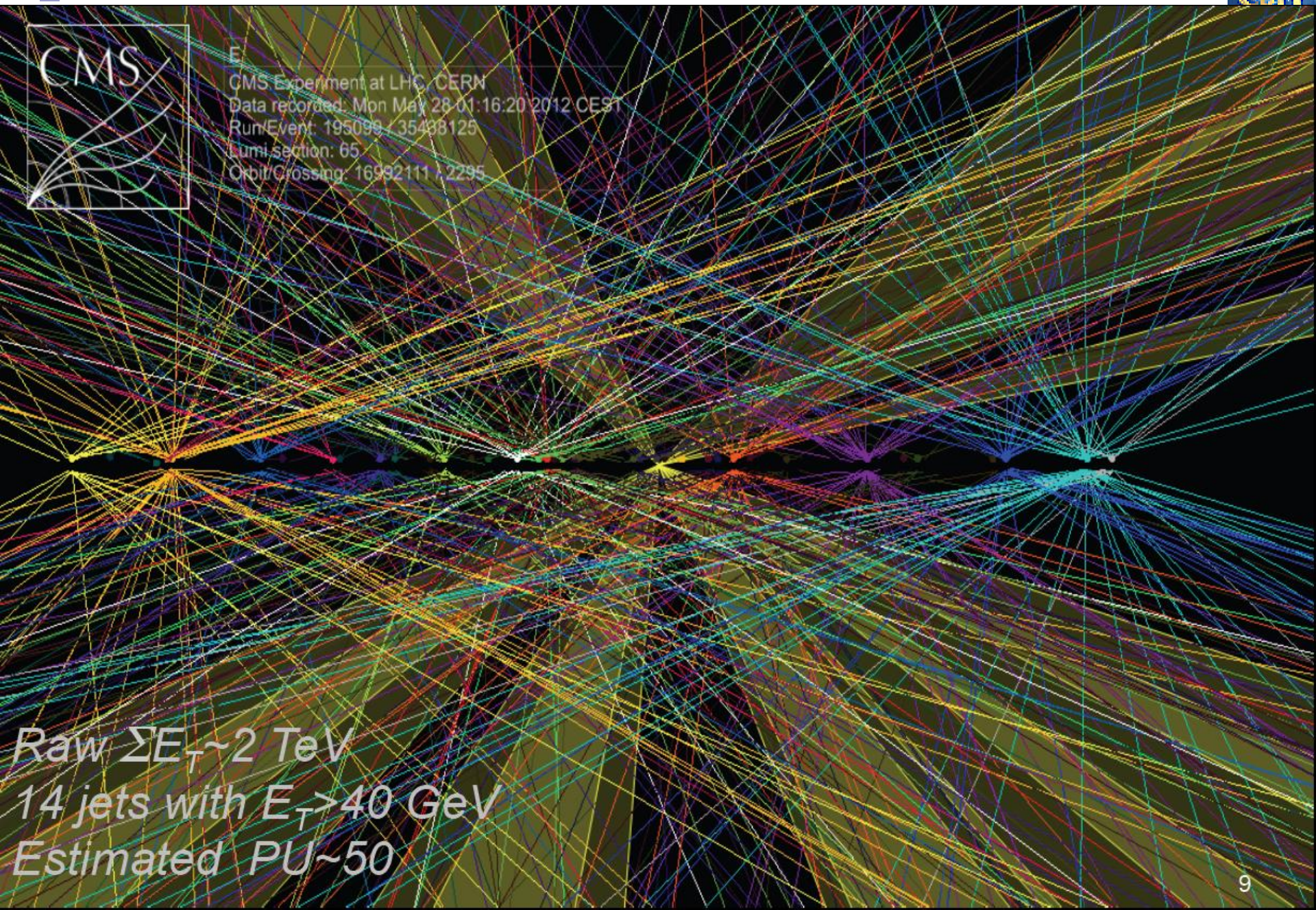
- Probabilidade de que uma flutuação do background cause um excesso como observado no sinal.

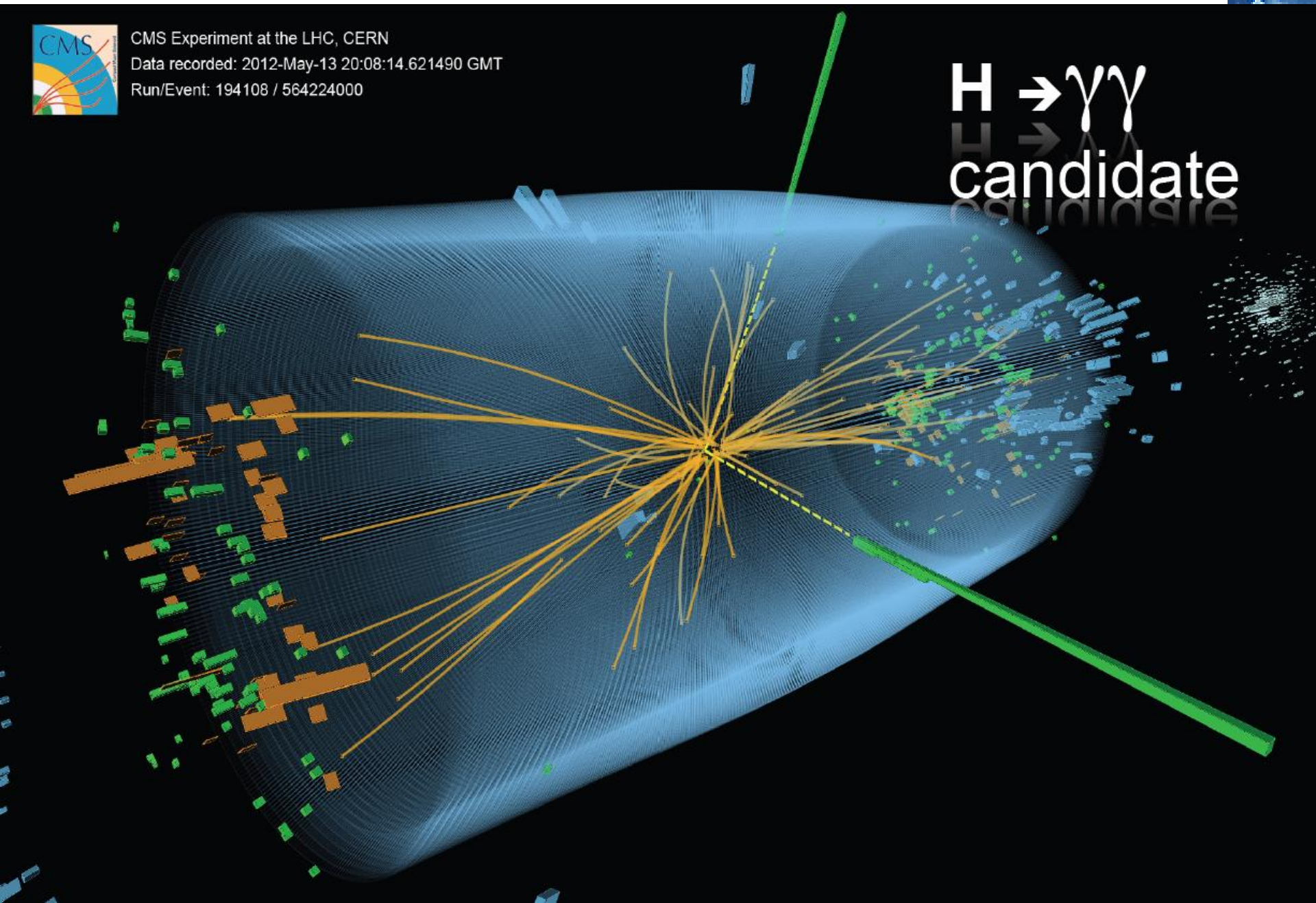
Como é possível?

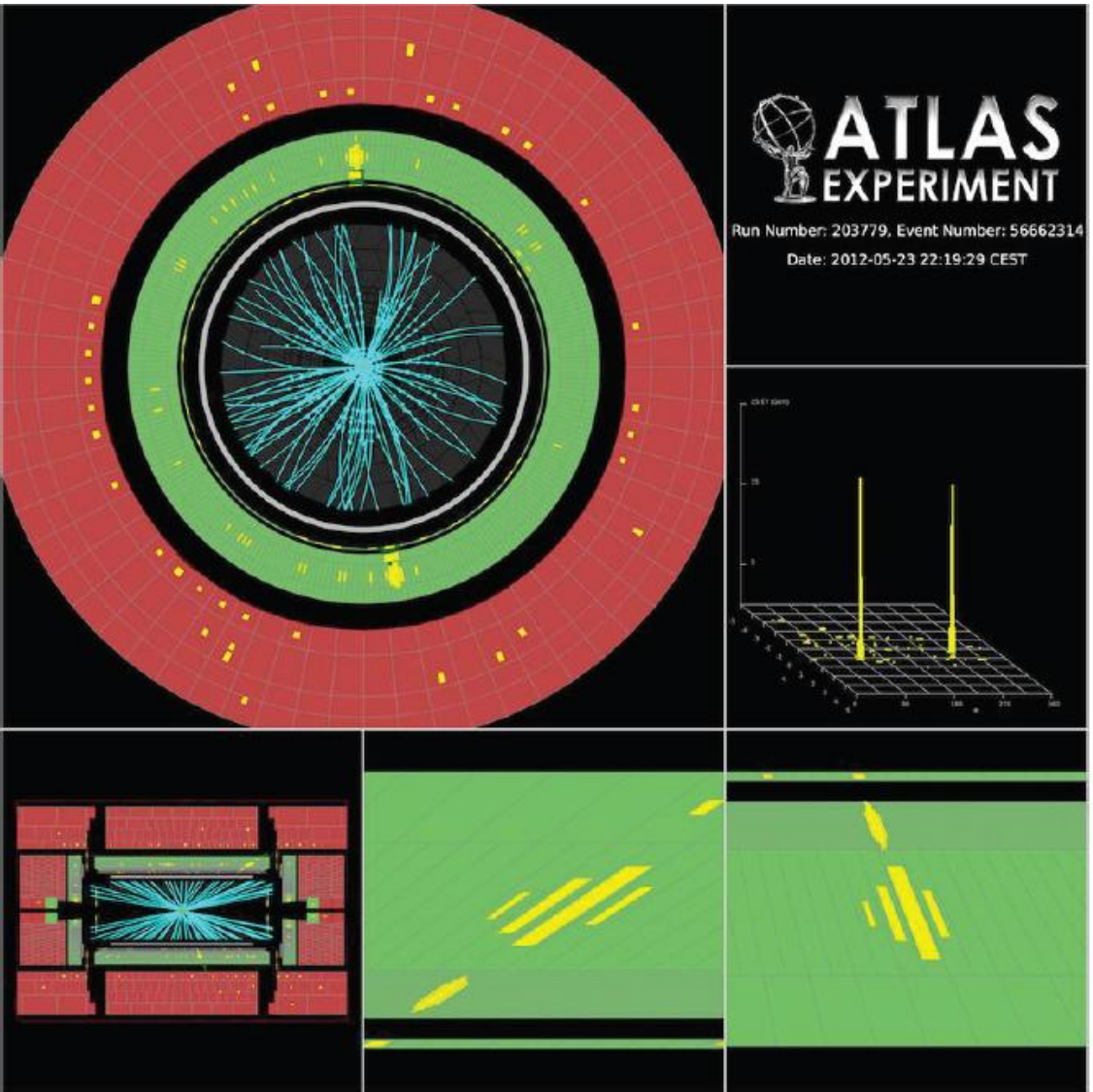


O Desempenho excepcional do LHC permite a investigação de processos físicos raros.

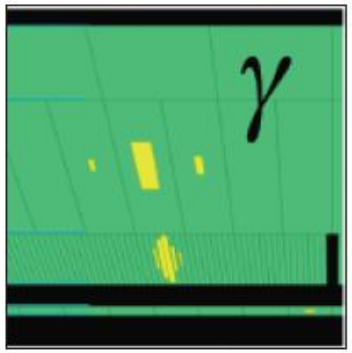
Mas paga-se um preço por isso…

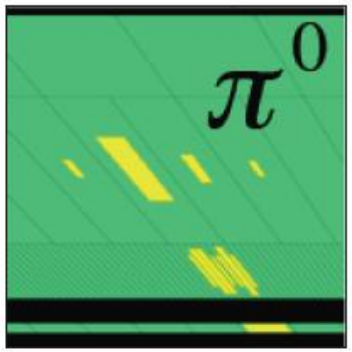

CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
Raw ΣE$_T$~2 TeV
14 jets with E$_T$>40 GeV
Estimated PU~50


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
candidate



- Separation of γ and π^0 in LAr calorimeter
  - Photon 'pointing' to locate primary vertex

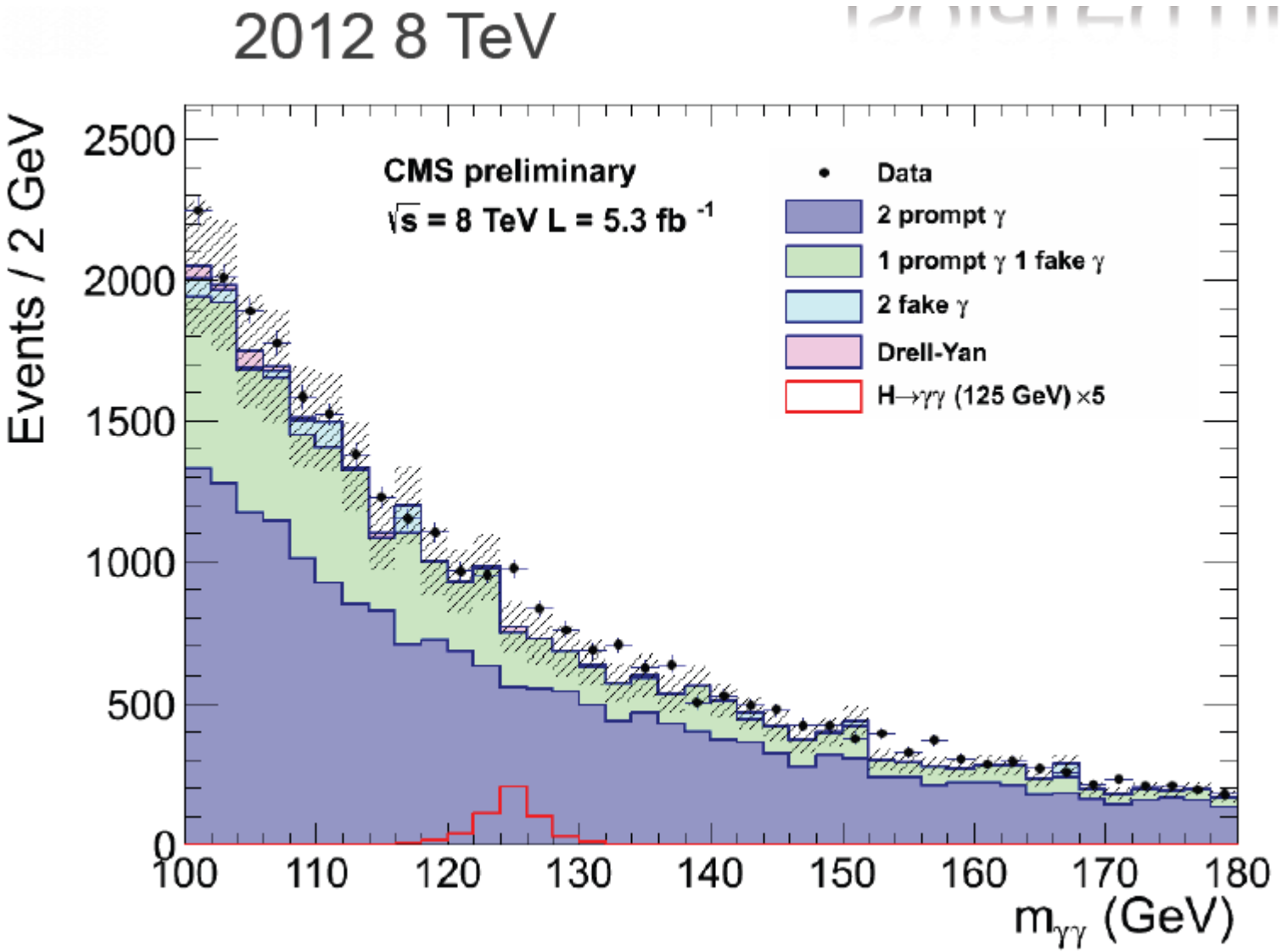




- Composition of γγ sample:
  - 75-80% QCD γγ production
  - 20-25% γ-jet or jet-jet, jet mis-ID e.g. due to hard π^0

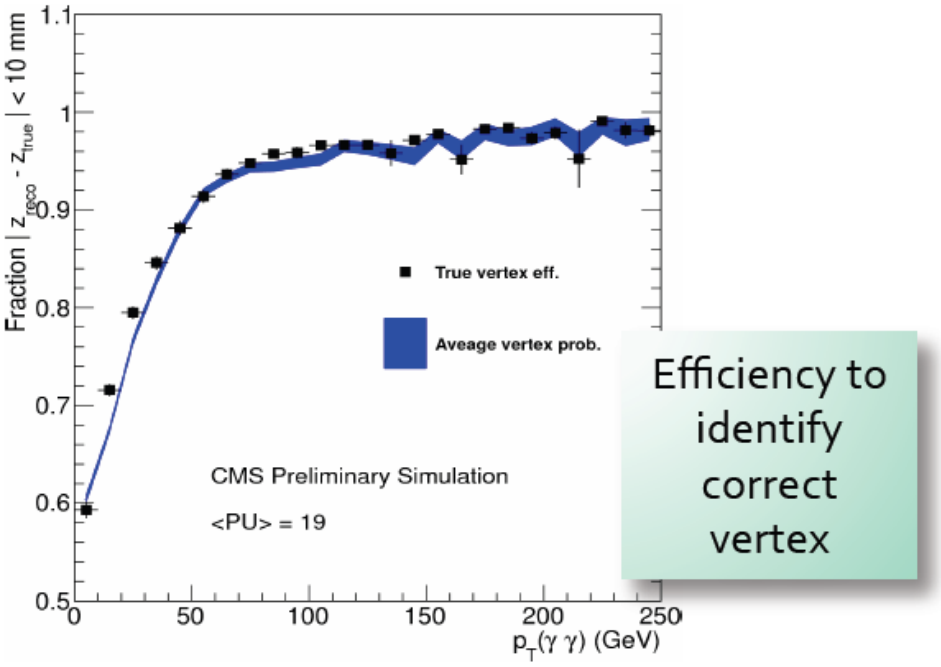
O sinal do Higgs aparece como um excesso em uma região de massa bem definida

Eficiências para sinal/background extraidas de dados Z → e+e-

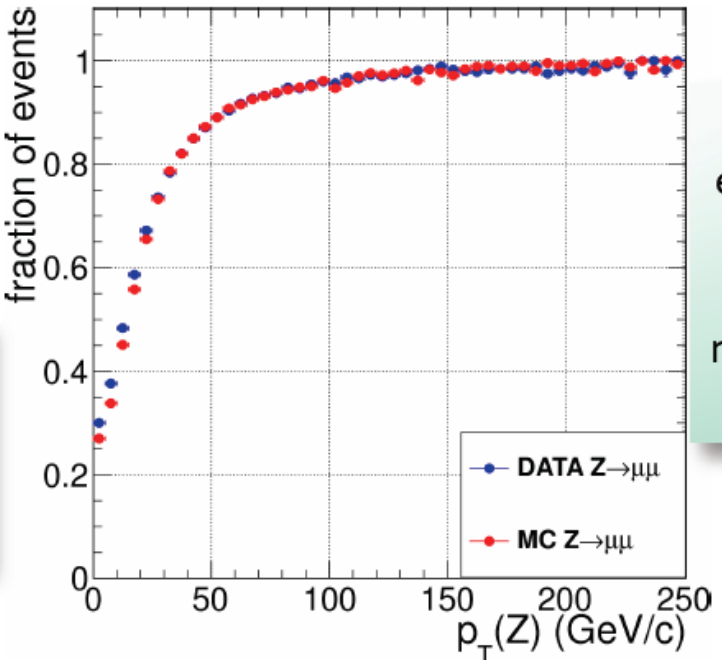


A maior dificuldade é identificar corretamente o vértice de produção

83% em 2011 <PU> ~10; 80% em 2012 <PU> ~ 19



Efficiency to identify correct vertex

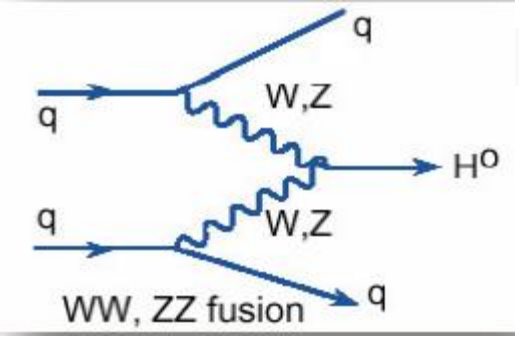


Data-MC efficiency for Z->μμ After removing the μ tracks

Seleção especial para eventos com topologia VBF.

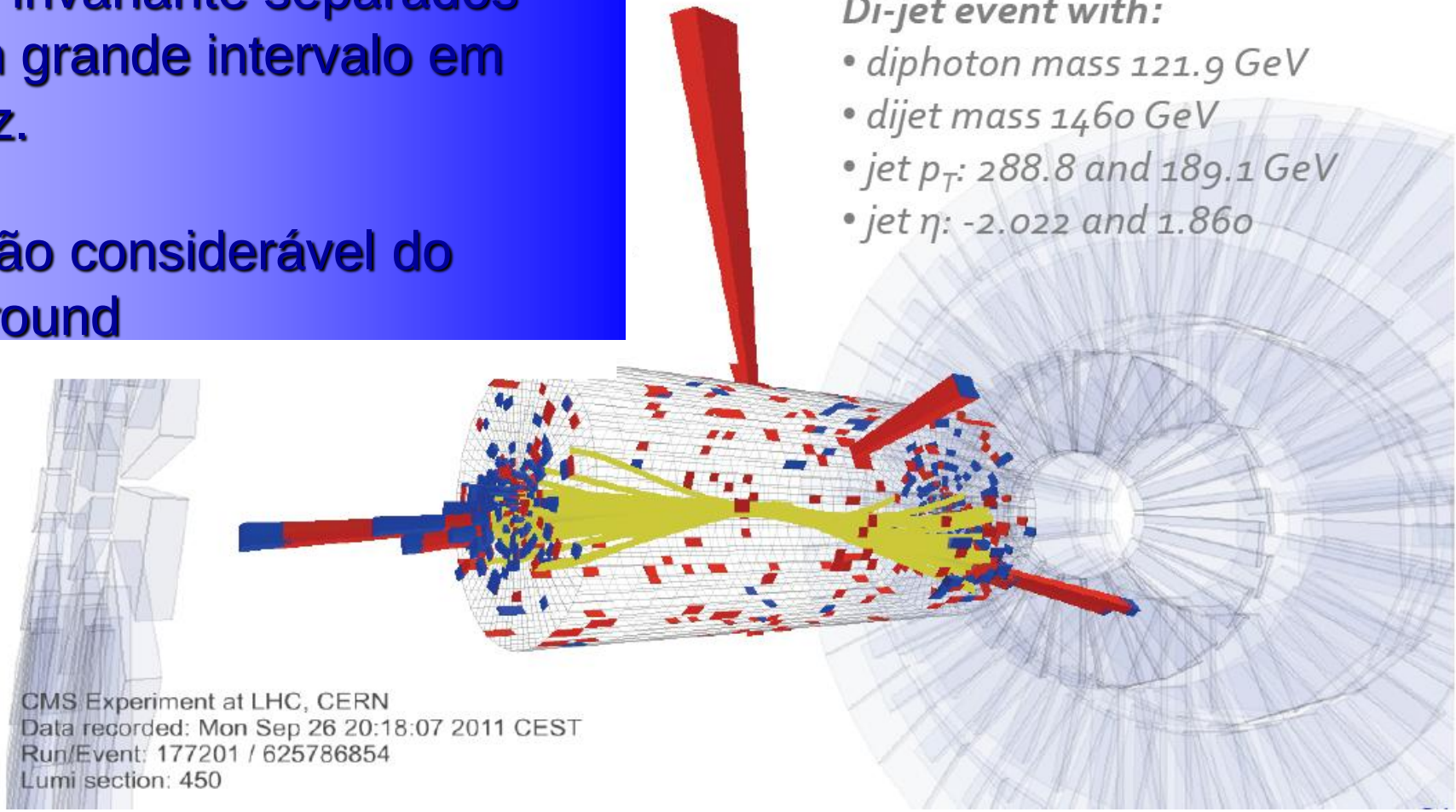
Dois jatos de alta energia e massa invariante separados por um grande intervalo em rapidez.

Redução considerável do background

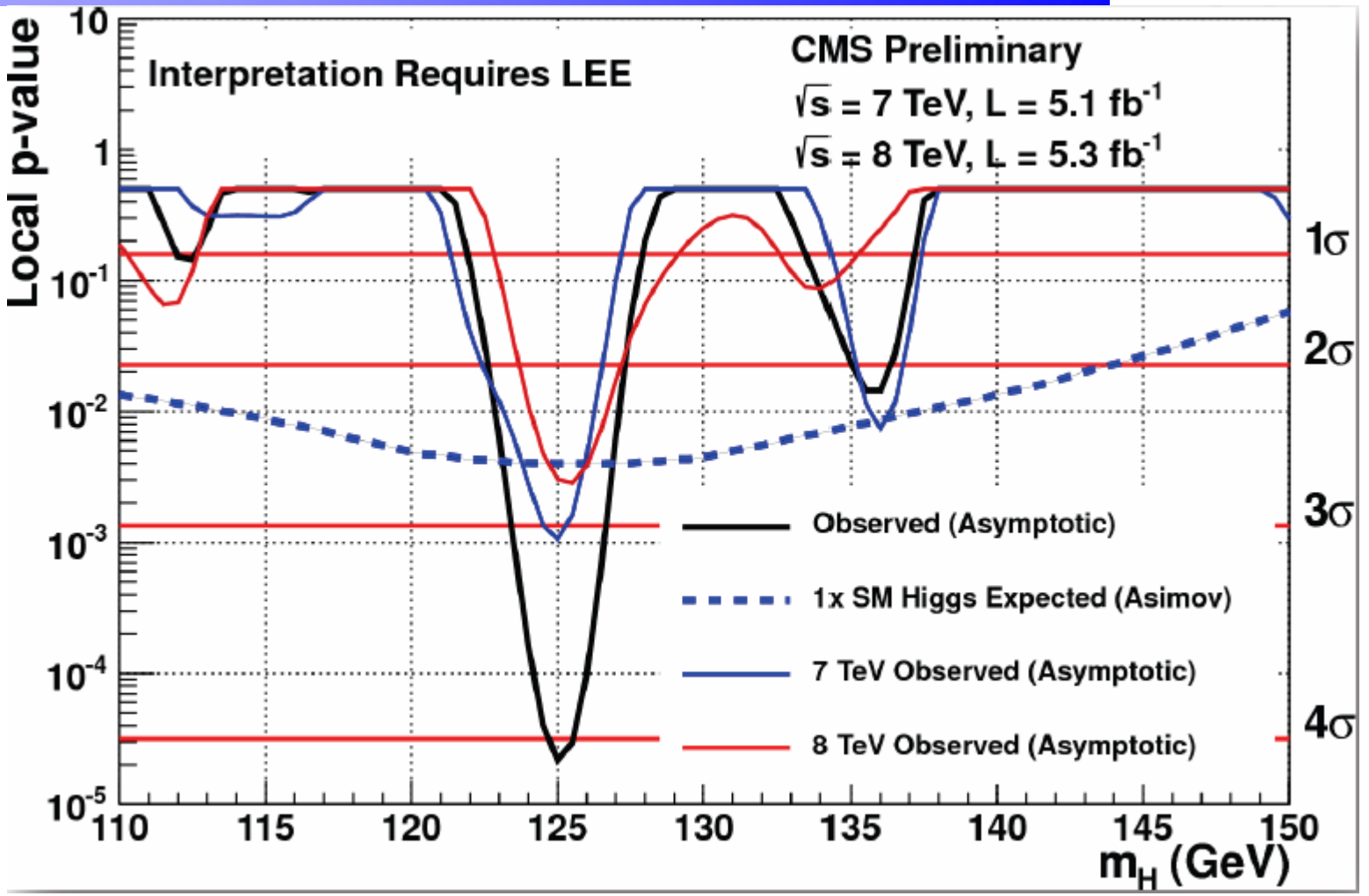


Di-jet event with:

- *diphoton mass 121.9 GeV*
- *dijet mass 1460 GeV*
- *jet p_T: 288.8 and 189.1 GeV*
- *jet η: -2.022 and 1.860*



P-values (probabilidade de flutuação do bck)



Compatibilidade entre dados de 2011- 2012

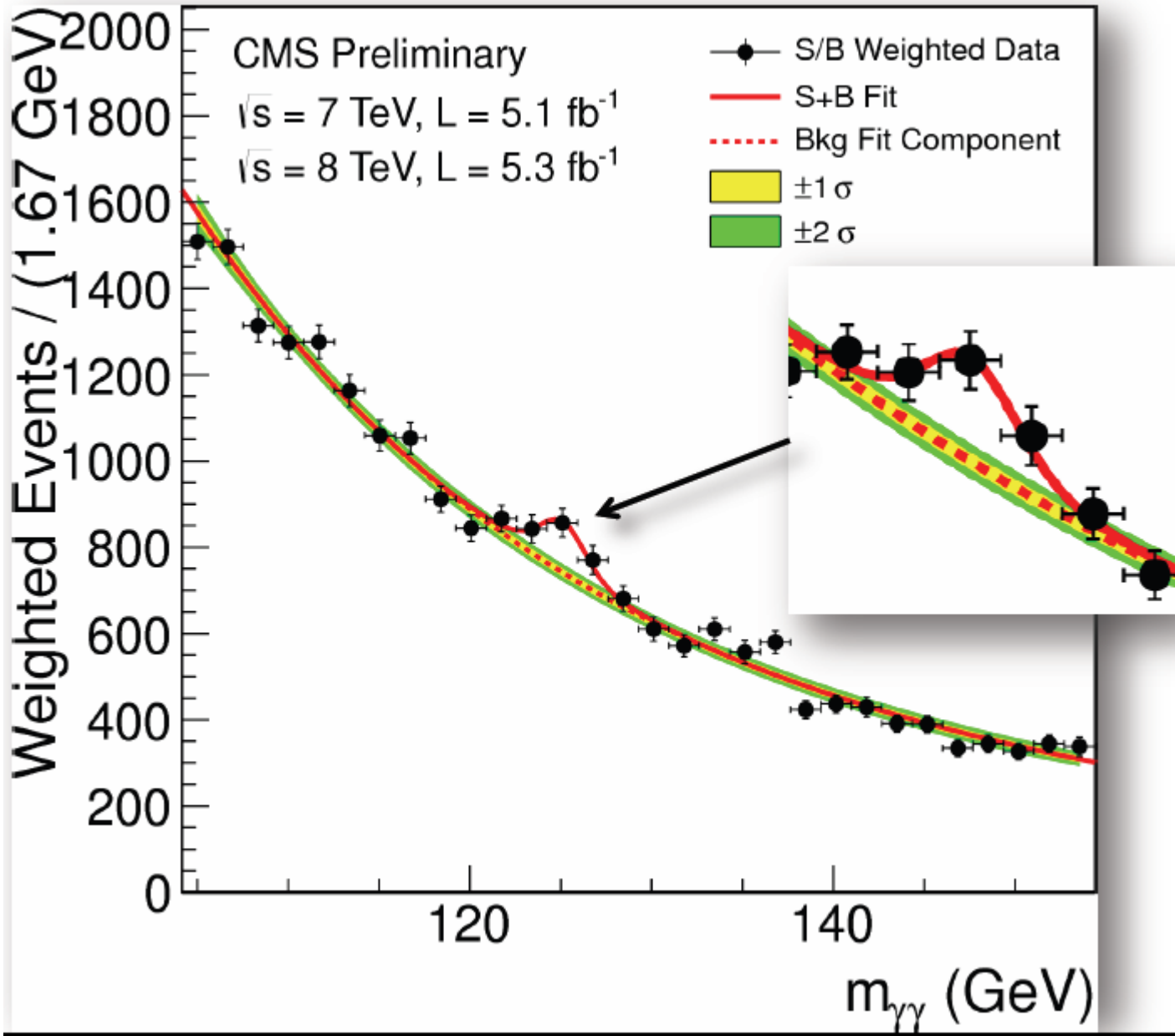
Análises independentes produzem mesmos resultados

Massa invariante H → γγ

Distribuição de massa ponderada pela razão S/B.

Não usada no cálculo da probabilidade.

Reflete o resultado do cálculo.



H → ZZ* with FSR recovery

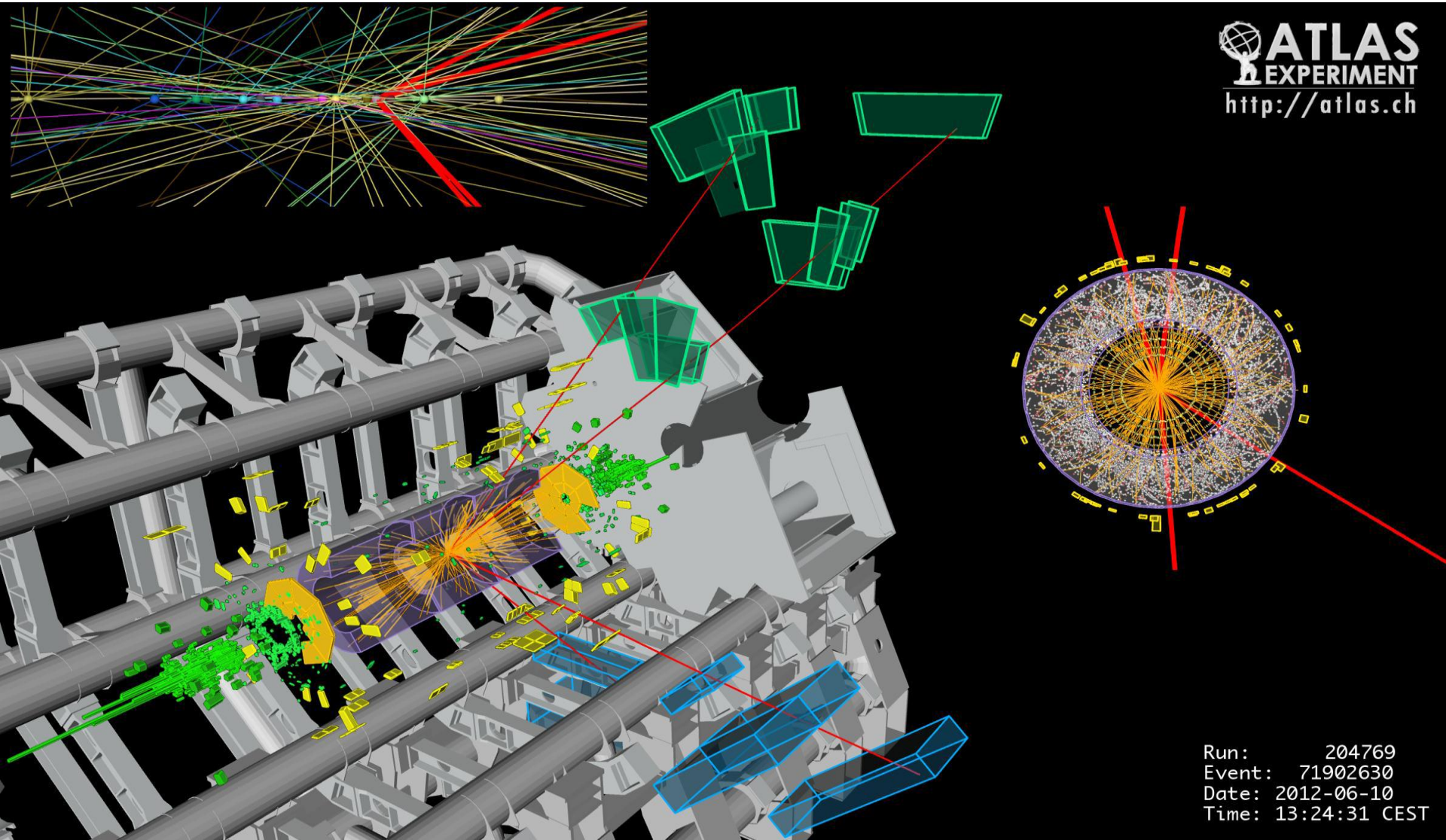
CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86



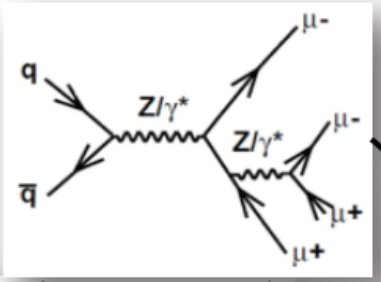
7 TeV DATA

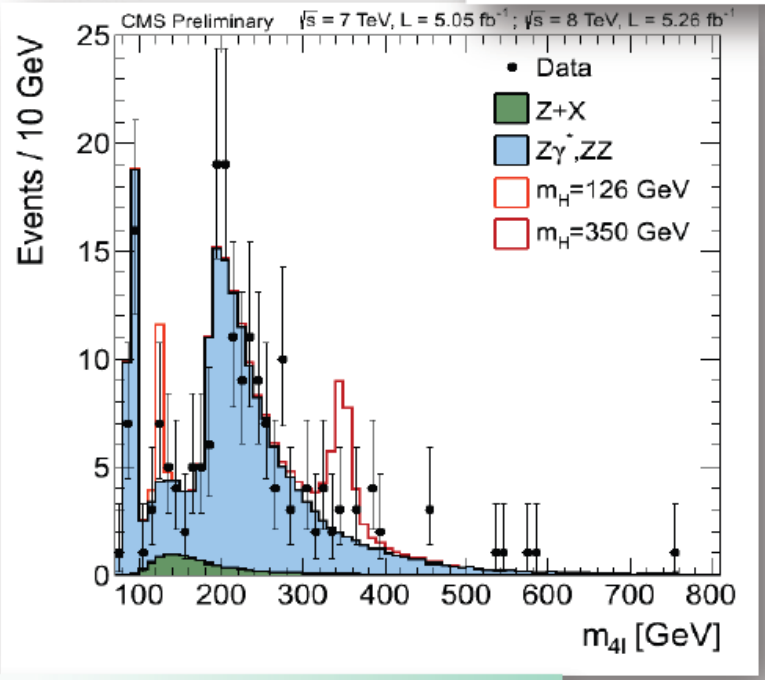
4μ+γ Mass : 126.1 GeV

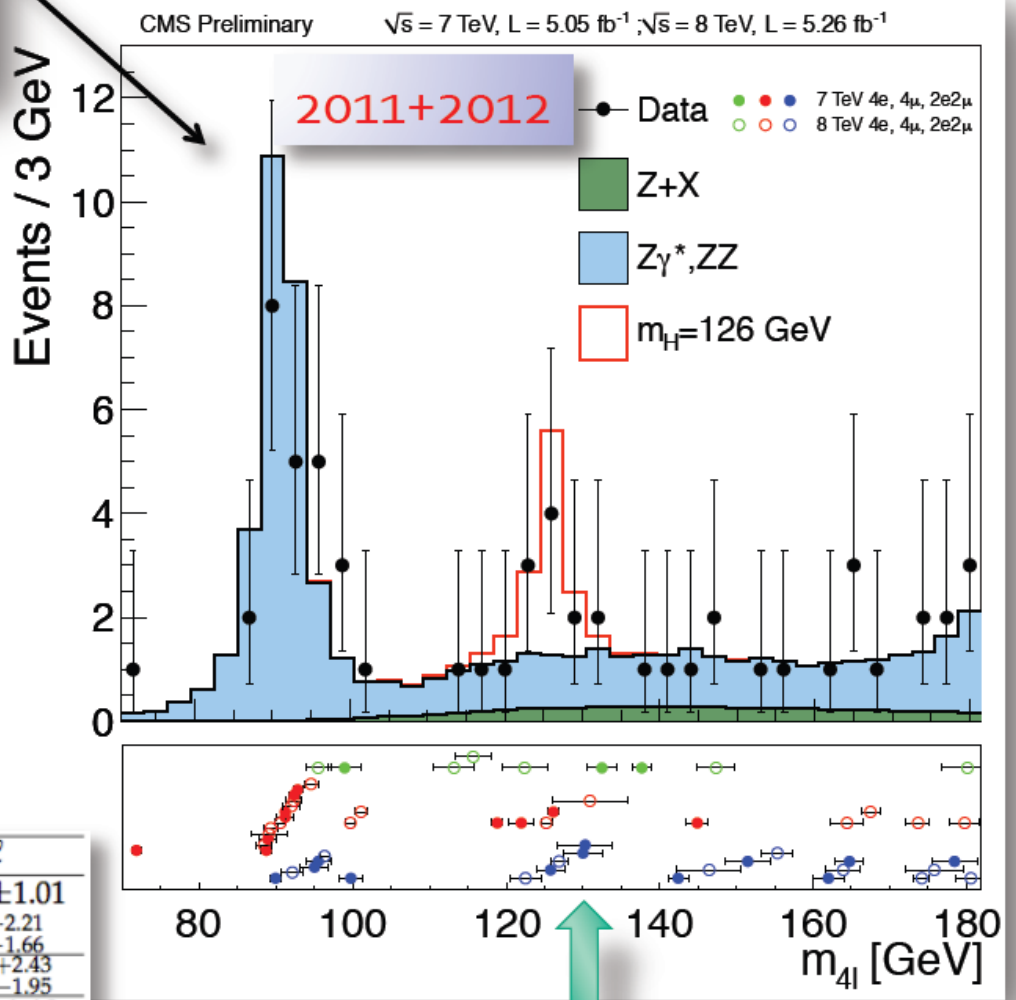
H → ZZ* → 4l


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Massa invariante 4l







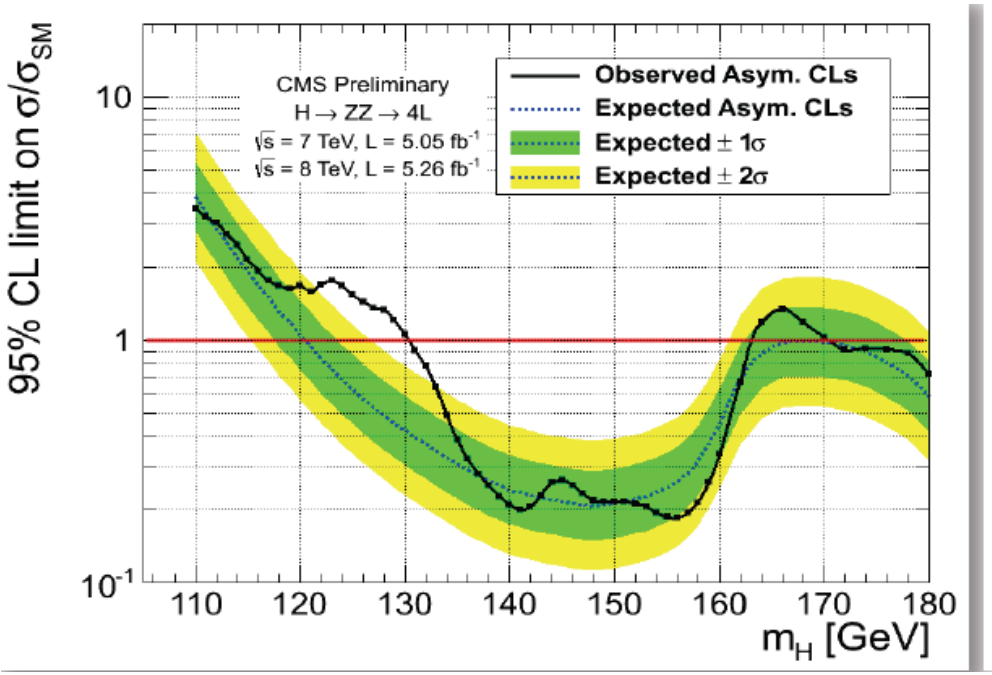
Yields for m(4l)=110..160 GeV

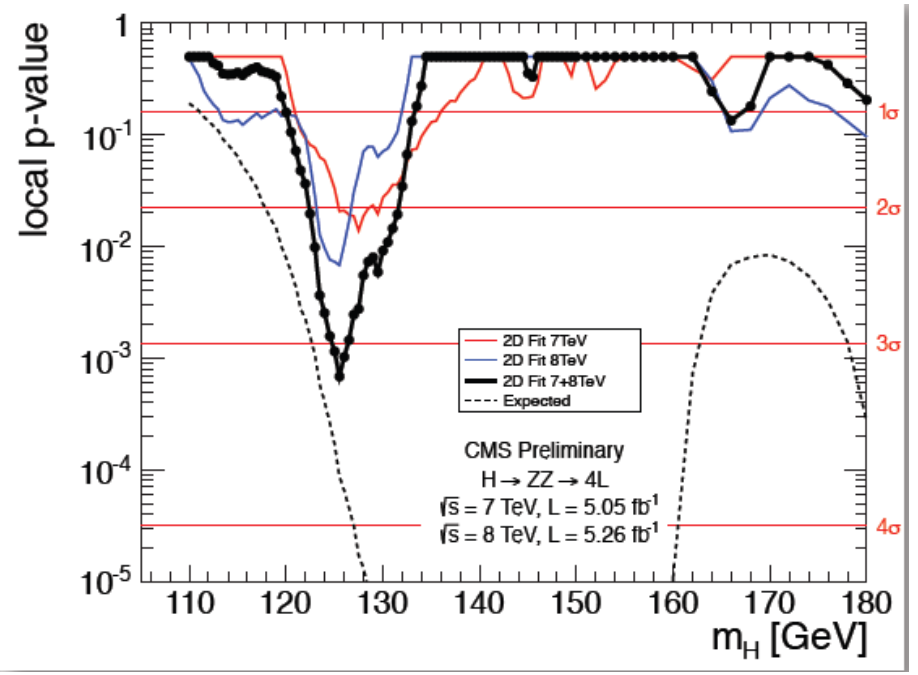
Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 $\pm$0.31	5.65 $\pm$0.59	7.17 $\pm$0.76	15.48 $\pm$1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 $\pm$0.48	2.99 $\pm$0.60	3.81 $\pm$0.89	8.31 $\pm$1.18

164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

Event-by-event errors

Limites e p-value



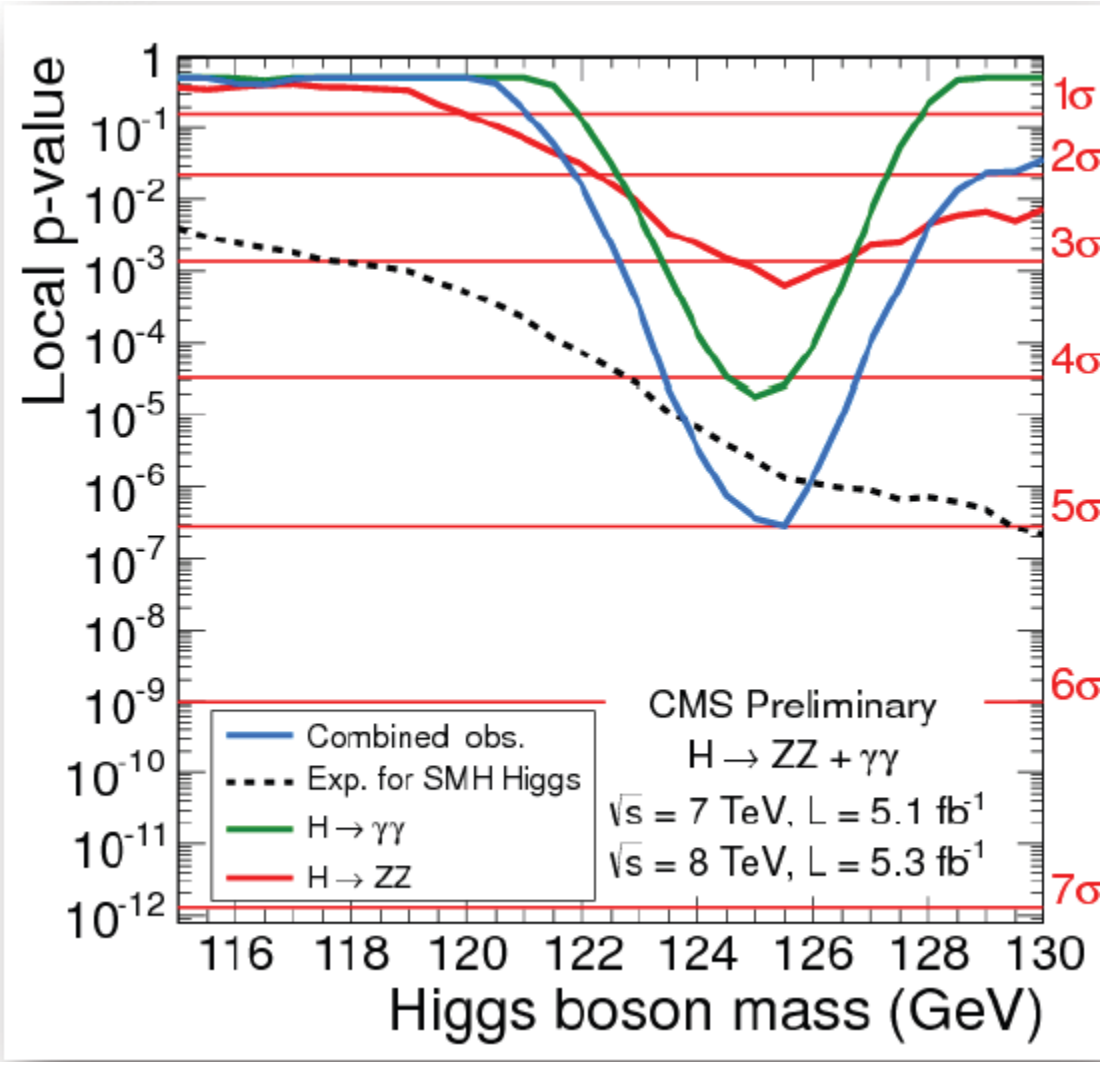


Massas entre 131-162 GeV e 172-530 GeV

Excluídas com 95% de confiança

P-value correspondente a 3,2σ para massa de 125,5 GeV

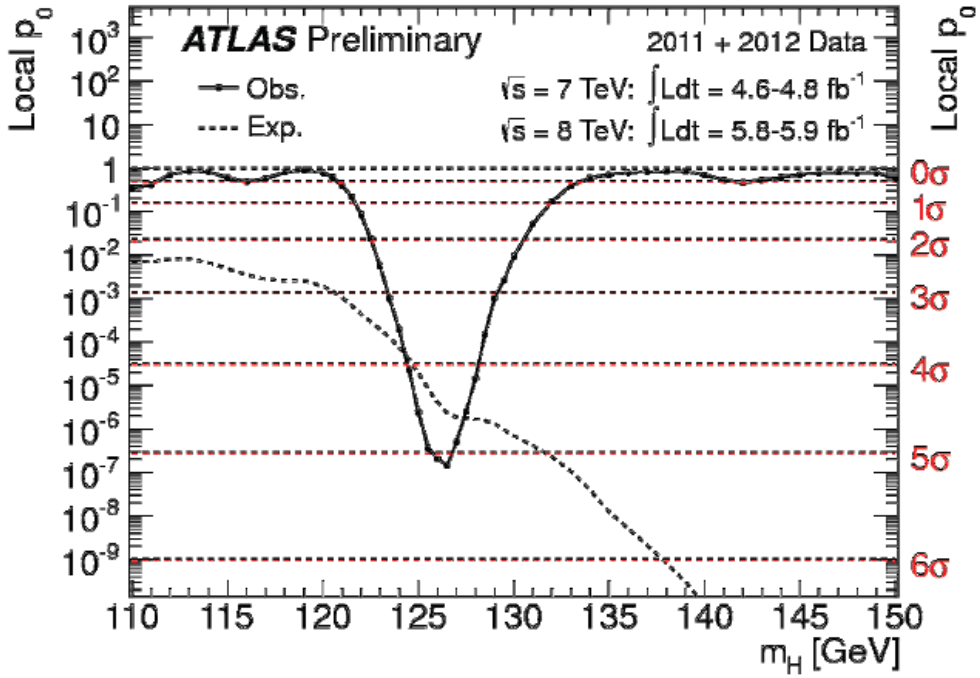
Combinação H→γγ + H→ZZ*

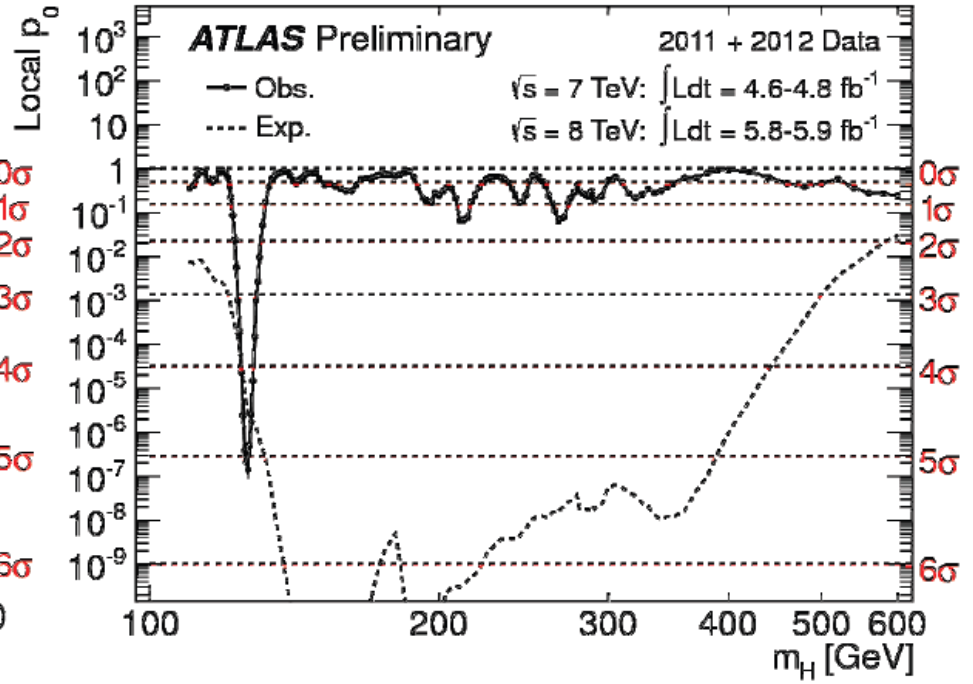


P-value correspondente a 5,0σ para massa de 125,5 GeV

P-value para 125,5 GeV segundo o MP → 4,7σ

Combinação H→γγ + H→ZZ* (ATLAS)





P-value correspondente a 5,1σ para massa de 126,5 GeV

P-value para 126,5 GeV segundo o MP → 4,6σ

Outros modos de decaimento H→WW*(CMS)

CMS Experiment at LHC, CERN
Data recorded: Sat Apr 14 18:18:05 2012 CEST
Run/Event: 191247 / 398701455
Lumi section: 272

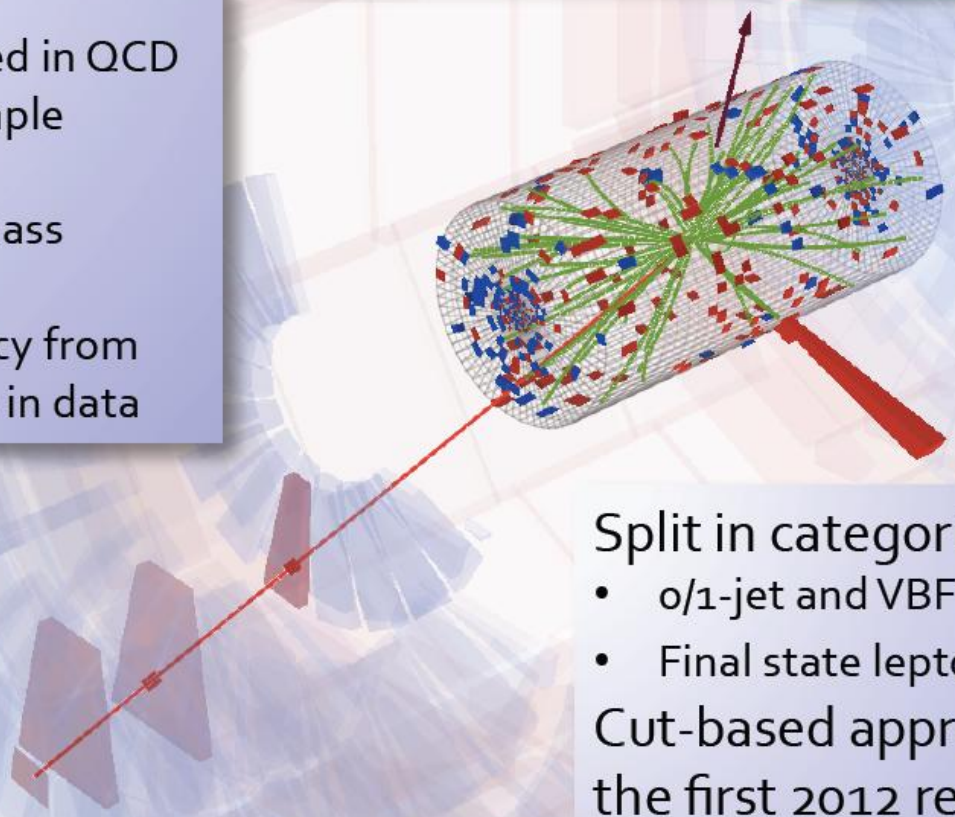
Analysis Strategies

Irreducible Background
- qq→WW + gg→WW

Data-driven estimates
- W+jets
  - Fake rate measured in QCD enriched data sample
- Z/γ*
  - Normalised in Z mass
- Top
  - b-tagging efficiency from top control region in data

Signature:
2 high p_T leptons
large missing E_T

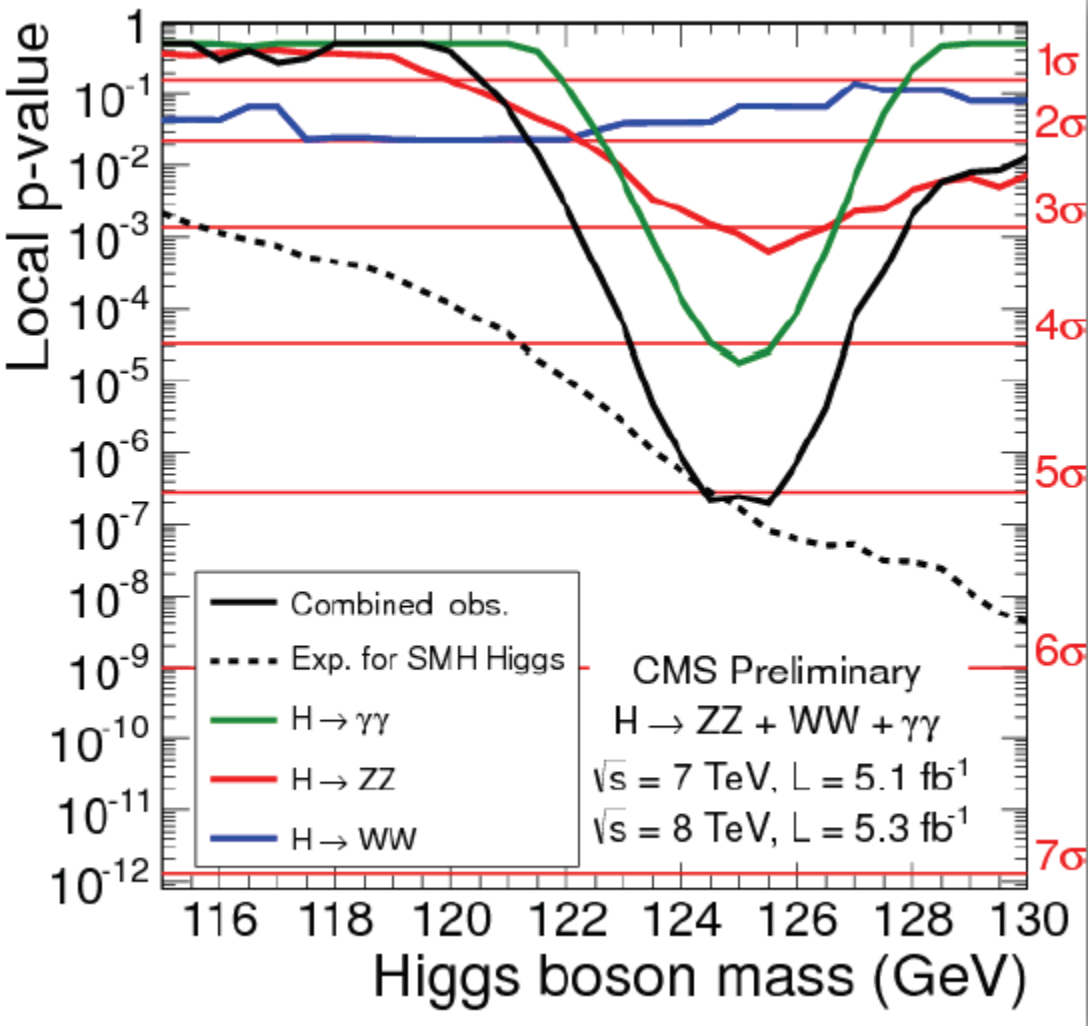
H→WW
- Large BR
- Small $\Delta\phi(ll)$



Split in categories
- 0/1-jet and VBF
- Final state lepton flavors

Cut-based approach for the first 2012 result

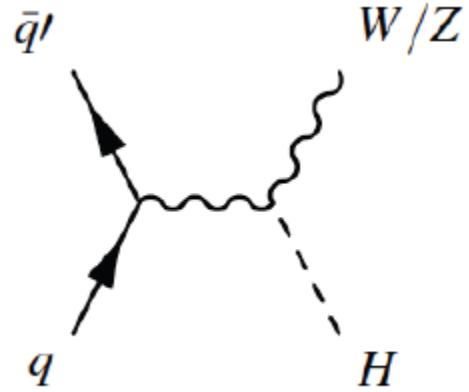
Combinação H→γγ + H→ZZ* + H→WW*



Não permite determinar a massa
Apenas excesso em um intervalo

P-value correspondente a 5,1σ
para massa de 125,5 GeV

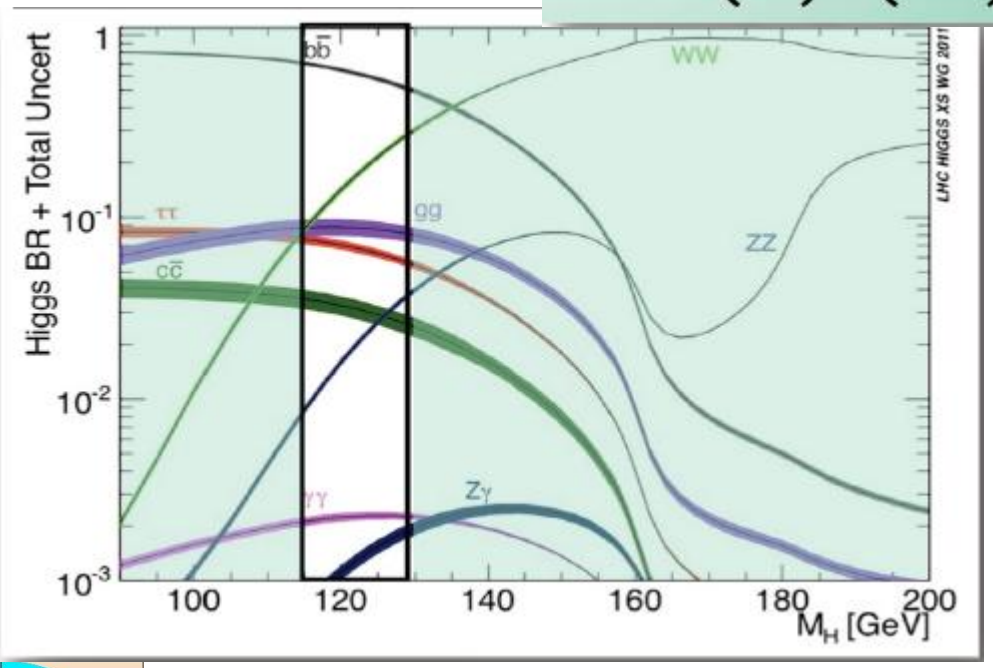
VH→Vbb – V→ll, lυ, υυ (CMS)

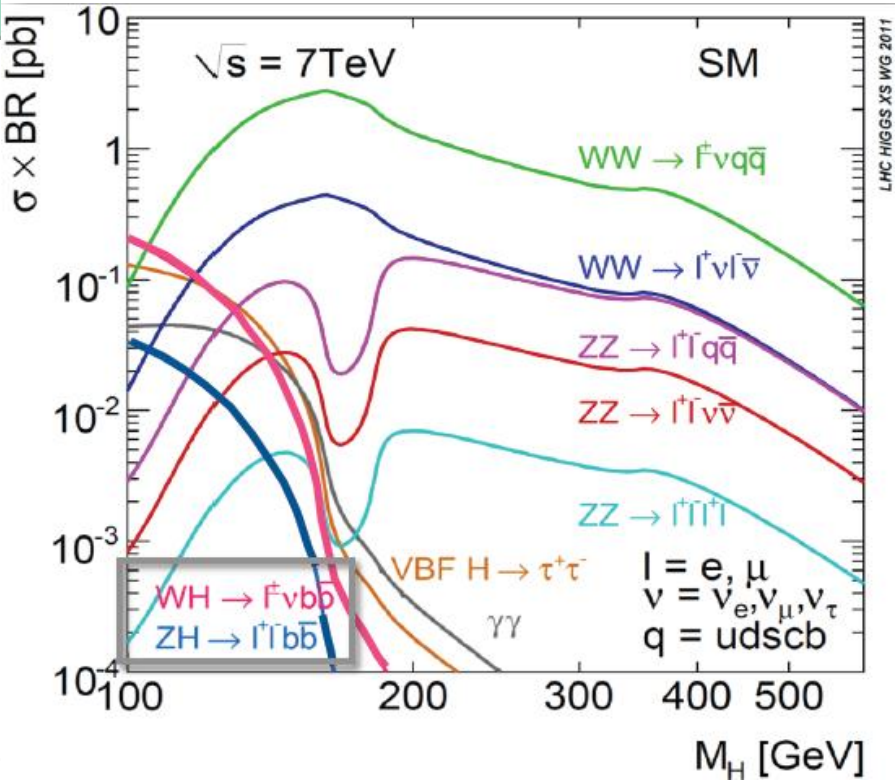


$\sigma_{b\bar{b}}(QCD) \sim 10^7\ \sigma x BR(H \to b\bar{b})!$

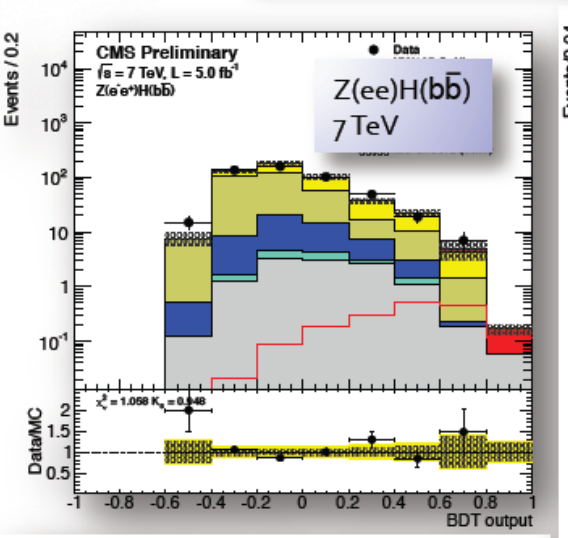
5 channels

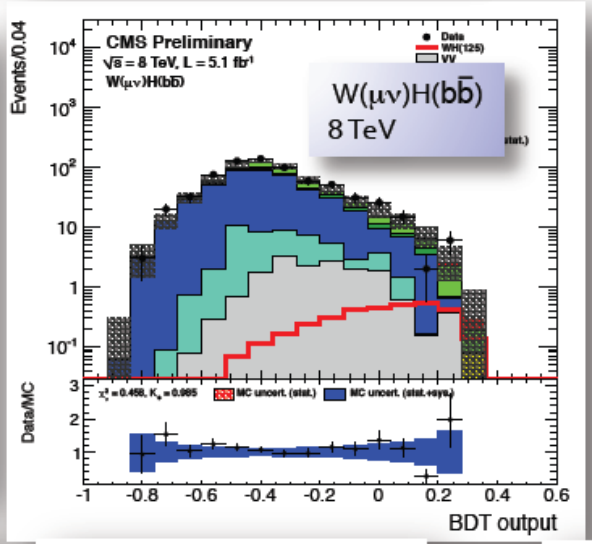
- Z(ll)H(bb)
- Z(νν)H(bb)
- W(lν)H(bb)



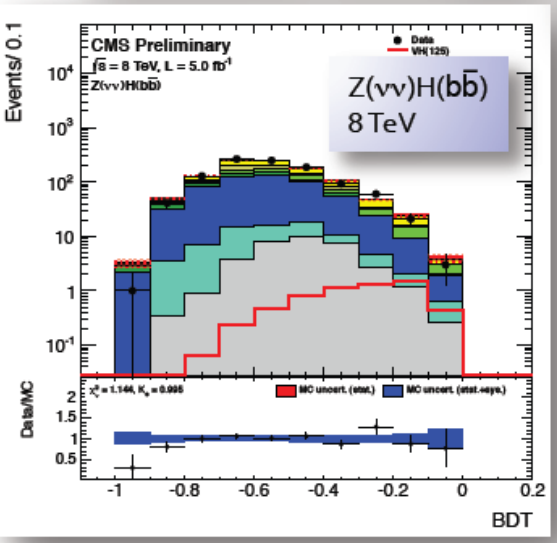


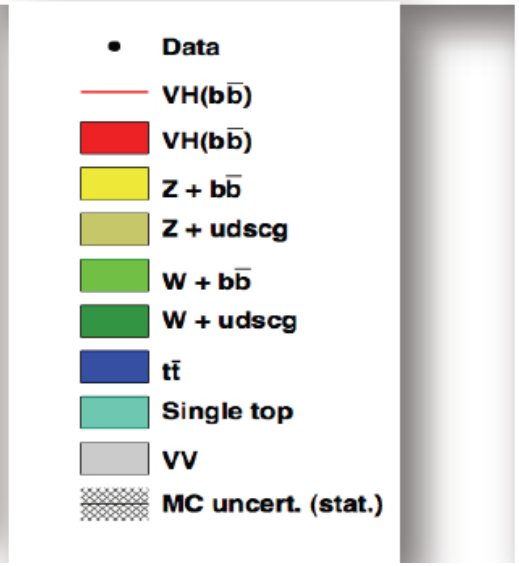
VH→Vbb – V→ll, lυ, υυ (CMS)

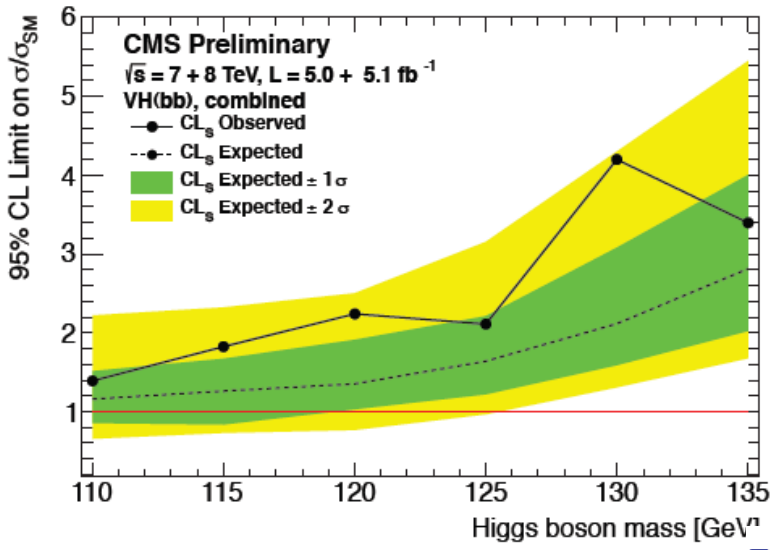




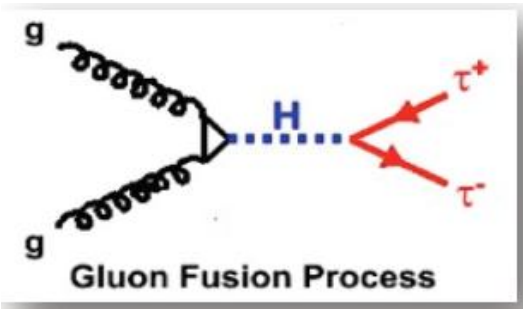
Imenso background
Observação compatível com puro bck. Ou pequeno excesso.

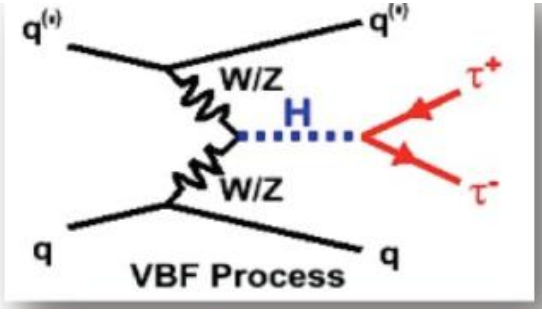


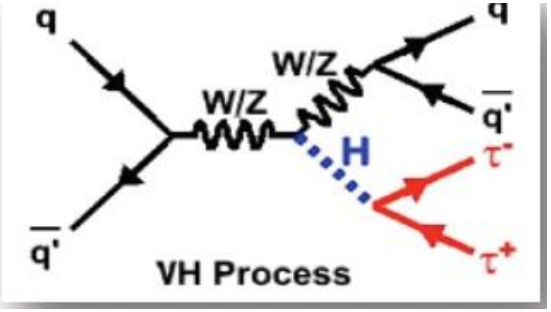




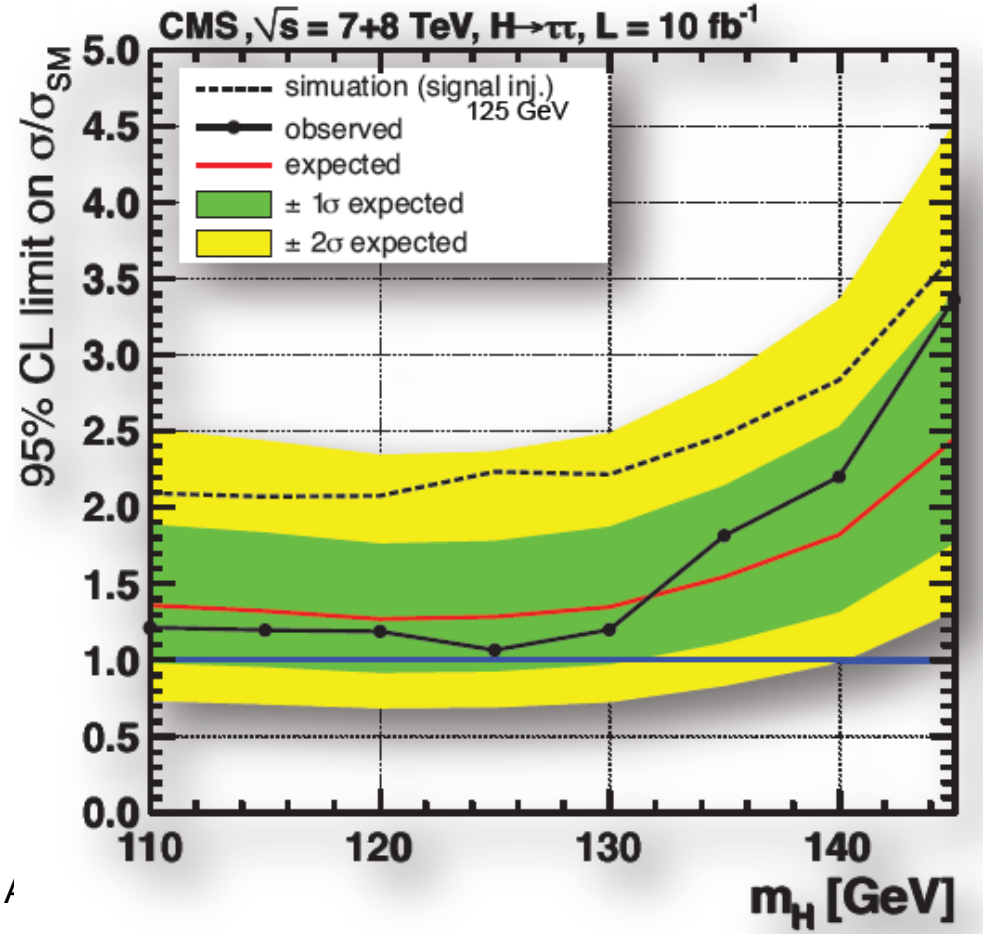
H→ τ+τ- (CMS)



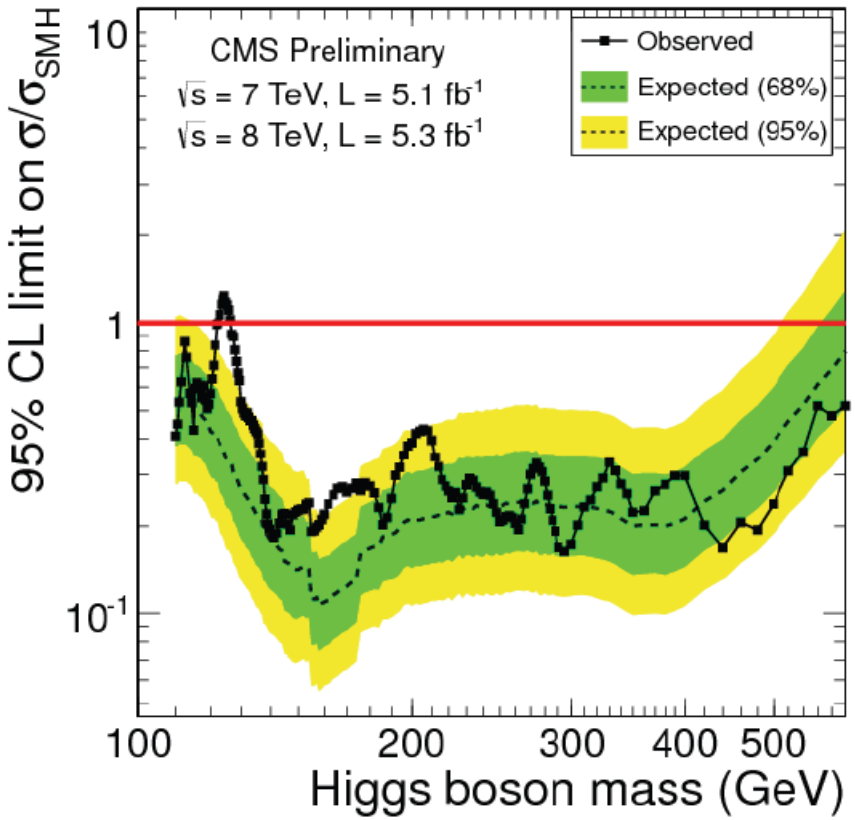


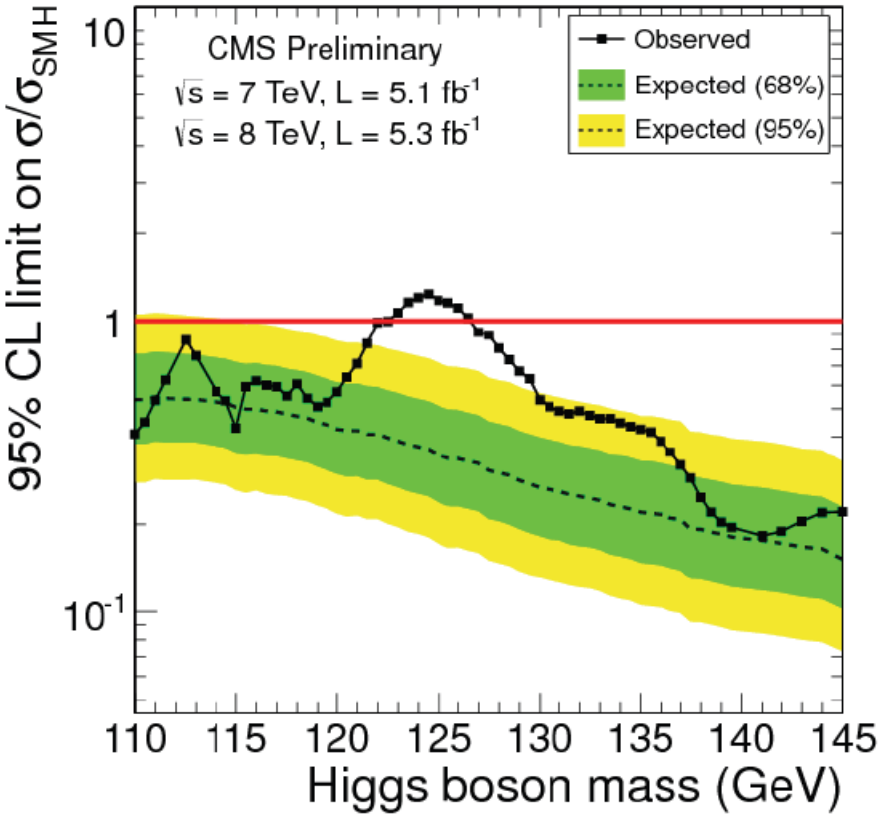


Grande background
Observação compatível com puro background



Combinação Final

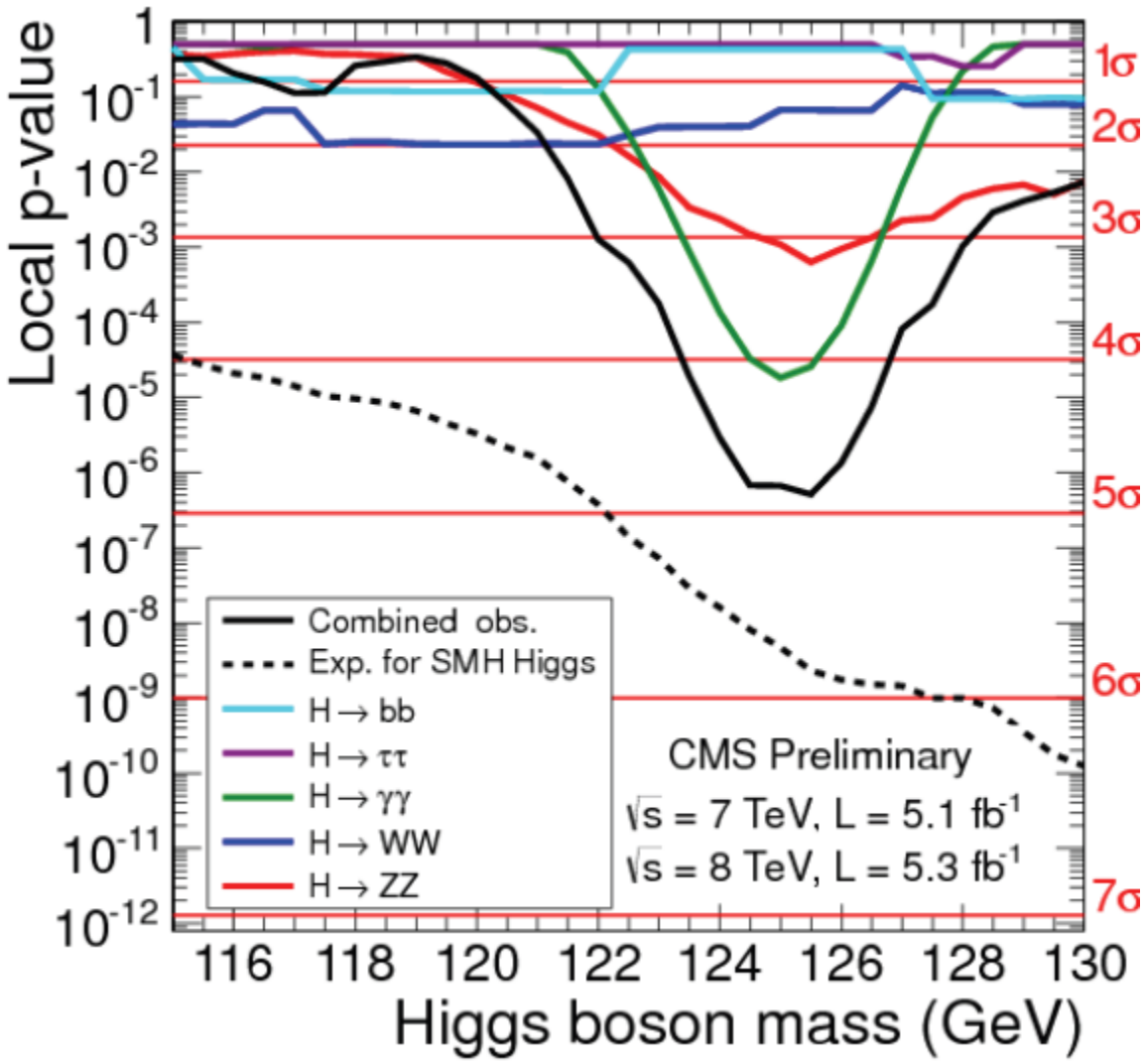




Exclusão entre 127-600 GeV

Excesso em torno de 125 GeV

Combinação Final

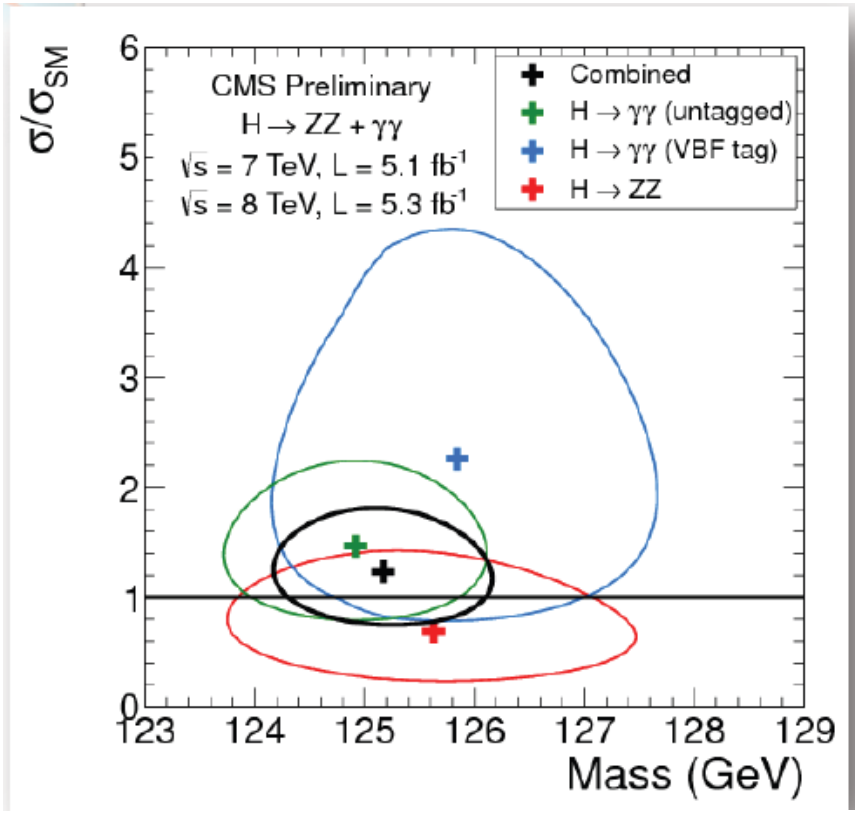


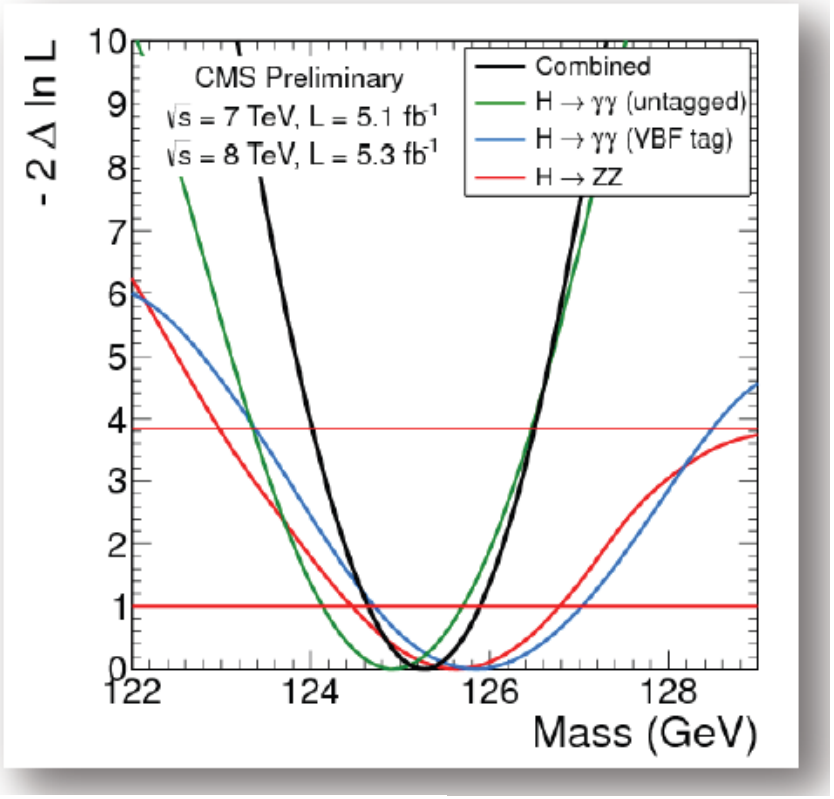
P-value correspondente a 4,9σ para massa de 125,5 GeV

Ausência de sinal nos canais com maior background VH→Vbb , H→ττ

Massa do sistema

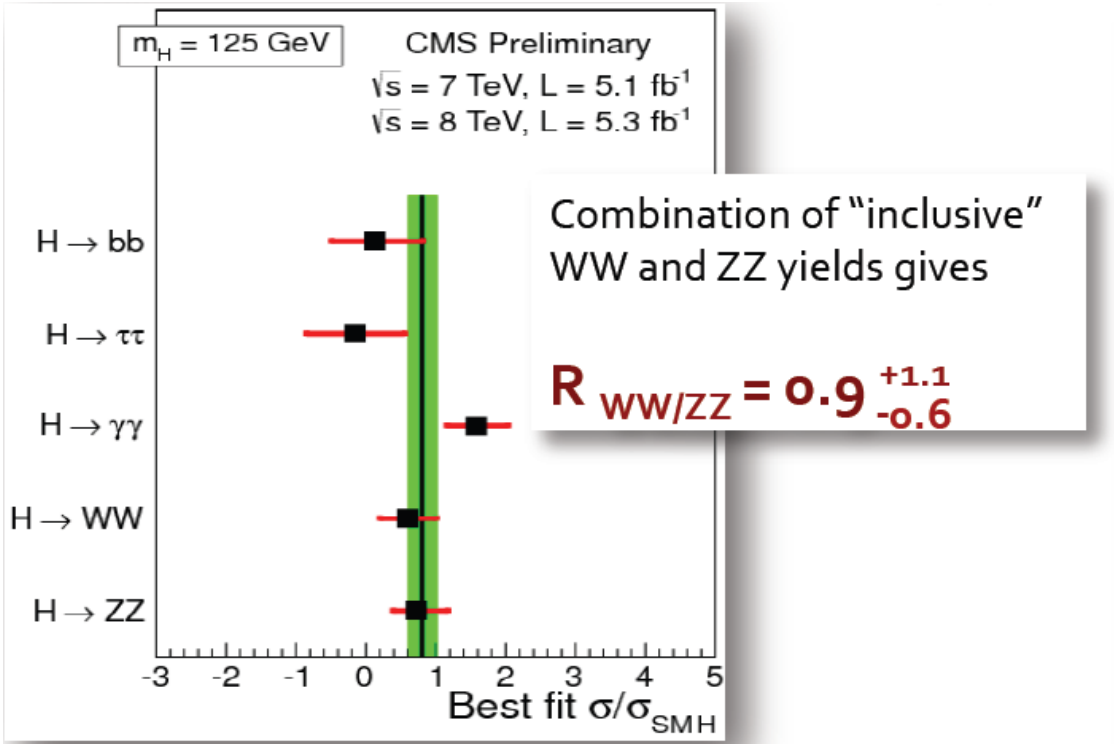
Utilizando os canais com boa resolução em massa e baixo background
H→γγ , H→ZZ*





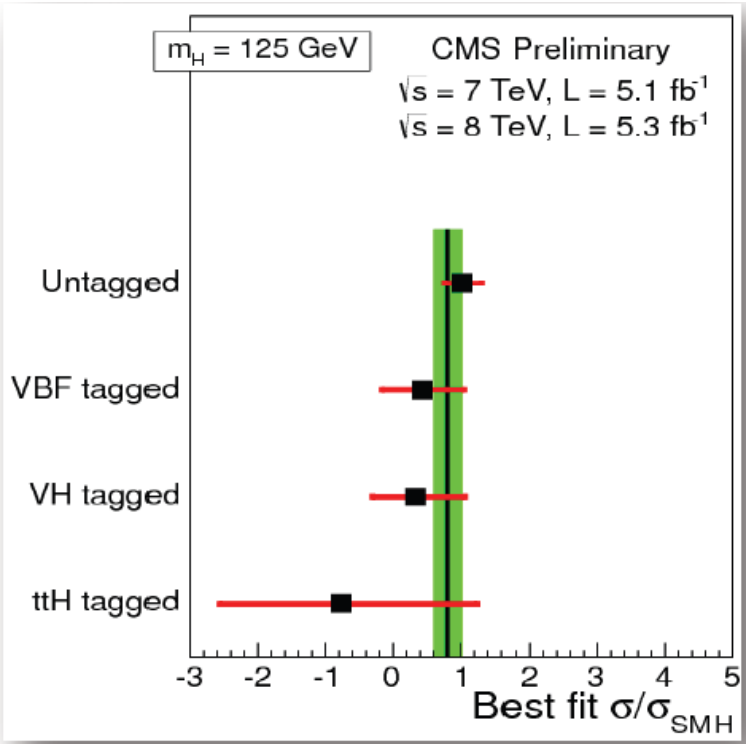
$$m = 125.3 \pm 0.4\,(stat) \pm 0.5\,(syst)$$

Compatibilidade com o Modelo Padrão



Combination of "inclusive" WW and ZZ yields gives

$R_{WW/ZZ} = 0.9^{+1.1}_{-0.6}$

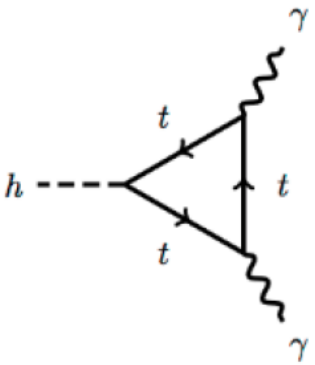


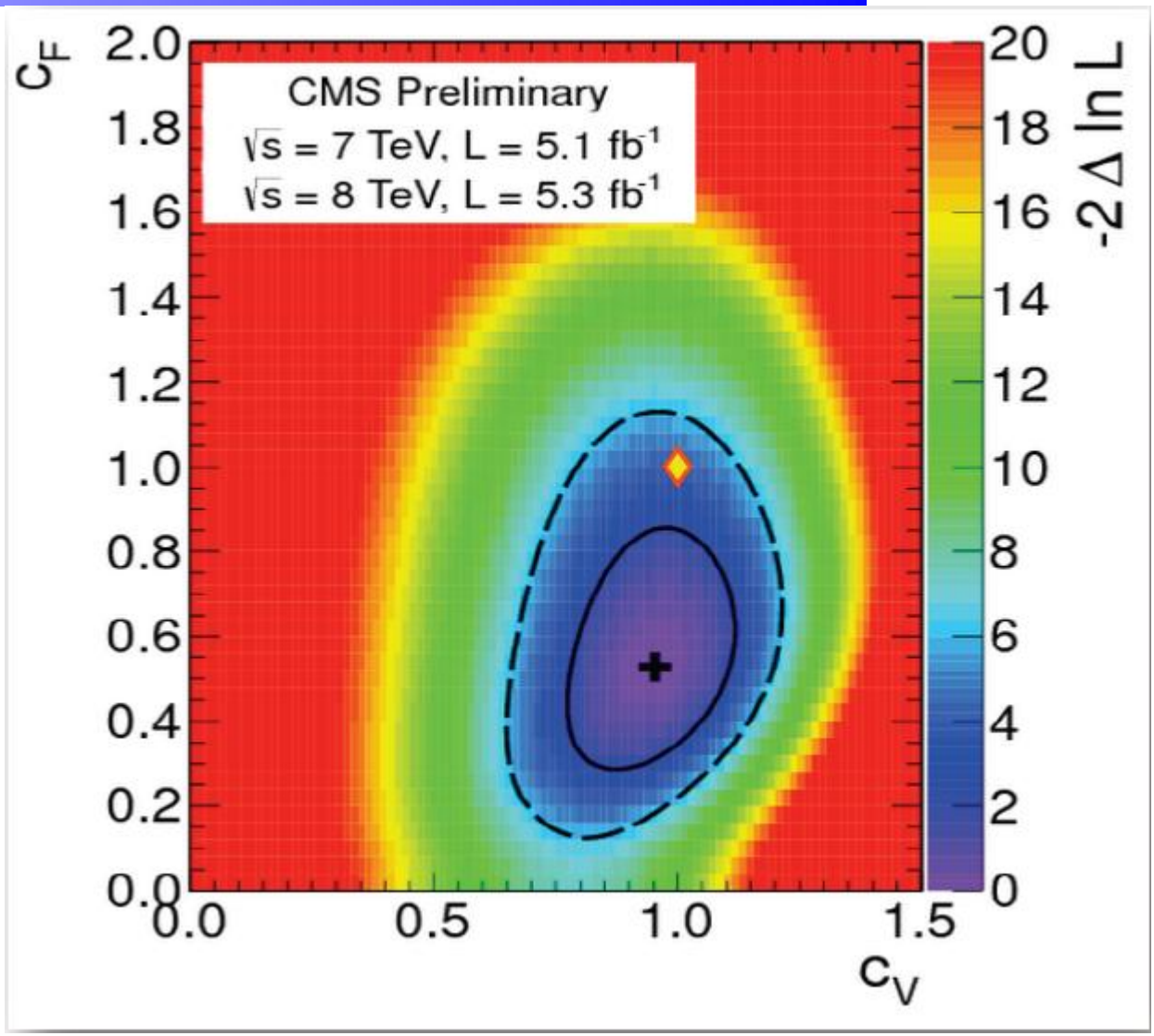
Compatível com o Modelo Padrão em relação aos modos de decaimento e diferentes topologias.

Compatibilidade com o Modelo Padrão

Acoplamento com Bósons Vetoriais (C_V) e Férmions (C_F), Utilizando os decaimentos do tipo $H \rightarrow \gamma\gamma$ e $H \rightarrow ZZ^*$

Acordo com o MP dentro da margem de erro (2σ)





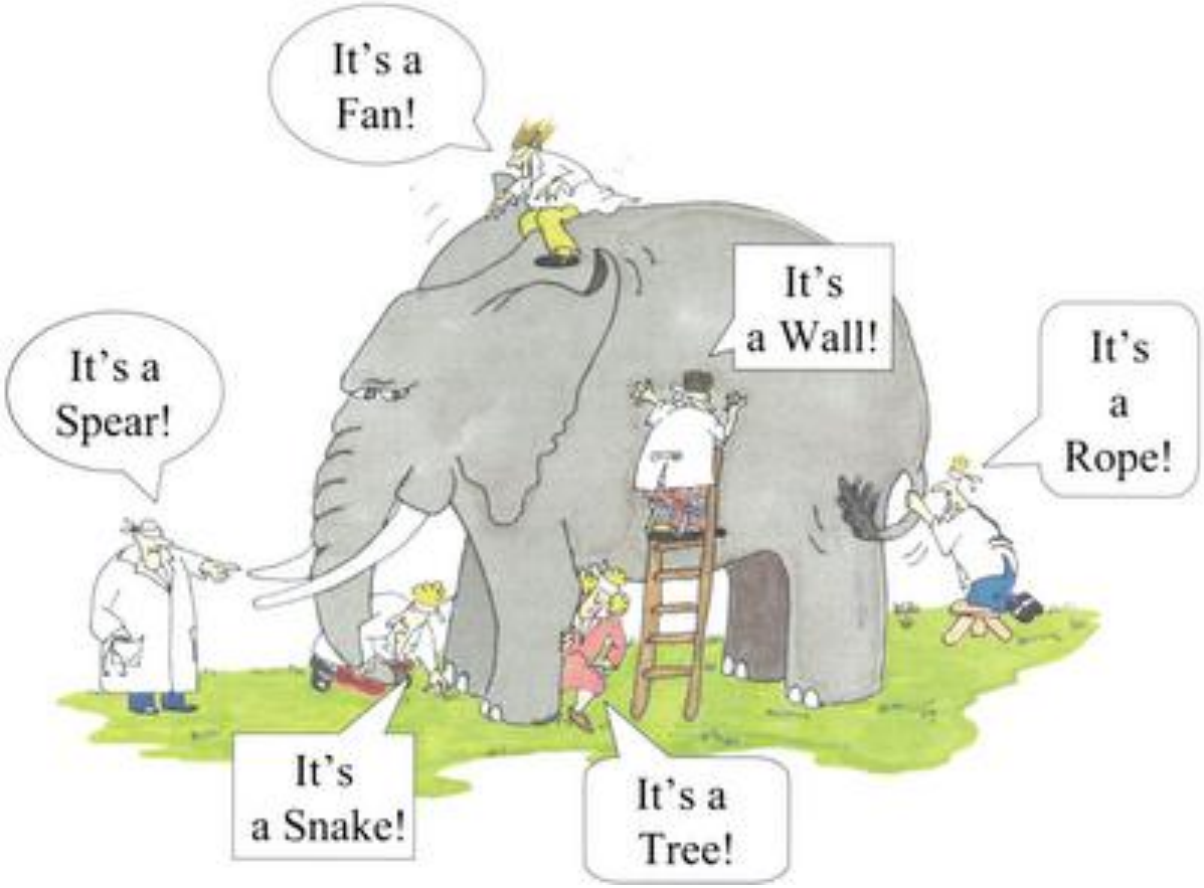
Conclusões

- **Estamos vivendo uma época fantástica**
  - **Grandes descobertas foram feitas**
  - **O Modelo Padrão é uma façanha impressionante**
  - **Muitas questões ainda em aberto**

  Estas questões levaram a um grande desenvolvimento teórico e experimental

- **LHC**
  - **O LHC representa a nossa melhor ferramenta experimental para atacar estes problemas**
  - **O LHC está funcionando de forma excepcional, dobrando o número de eventos até o fim do ano**
  - **A observação de uma partícula com as características do bóson de Higgs é uma das maiores descobertas dos últimos tempos**

Será realmente o Higgs



Other exciting possibilities for naturalness

If the Higgs boson is discovered and Super-symmetry does not manifest itself in the TeV region again we have to find other mechanisms to fight against the radiative corrections to the Higgs mass.

$$M_H^2 \rightarrow M_H^2\,(o) + c\,\Lambda^2$$

Λ is the scale of the theory. If $\Lambda \sim M_{GUT} \sim 10^{15}$ GeV an incredible, un-natural fine tuning would be needed to allow for a "light" Higgs

Two major sets of possibilities to save naturalness:

Protected by other new forces/particles? (Z', W', technicolor).

Protected by (compactified) extra dimensions?

….

New signatures of new physics.

… and if no Higgs boson will be found

Several dynamical mechanisms have been proposed for the symmetry breaking.

QCD inspired

W_L and Z_L could be sort of 'pions' of a new interaction
rescale f_π to $1/\sqrt{G_F}$ leading to strong interaction in TeV range
V_L- V_L scattering analog of π - π scattering

Technicolour

The Higgs-less SM is saved by a techni-ρ
Whole family of new states predicted

Strong breaking of E-W symmetry

No Higgs boson but a triplet of massive bound states - vector bosons V^0, $V^{\pm}$ (similar to techni-ρ)

New particles and new signatures.