A FÍSICA DO LHC: Conceitos teóricos e principais resultados

5ª Aula

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Tópicos de Hoje

1. Física de Sabores e o LHCb
   - Resultados
2. ATLAS e CMS
   - Colisões pp no LHC: Aspectos Gerais
   - Colaborações e Detectores
   - Principais resultados: ATLAS e CMS

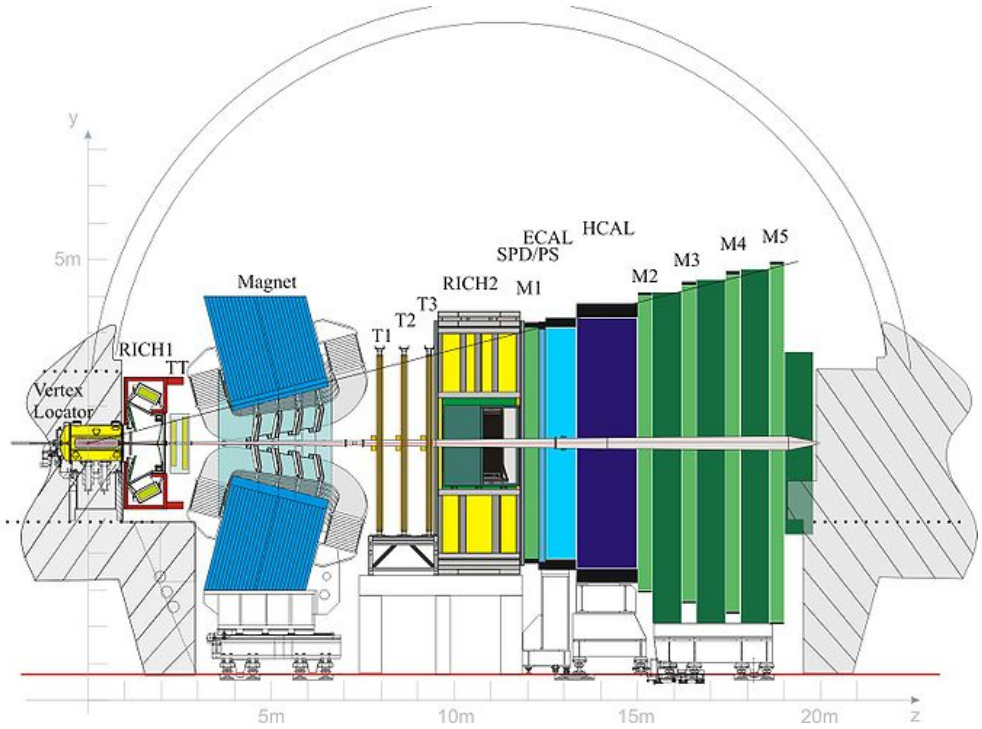
Física de Sabores e o LHCb

A Colaboração LHCb



O experimento LHCb

Dedicado ao estudo de hádrons contendo os quarks b e c - "Sabores Pesados'"



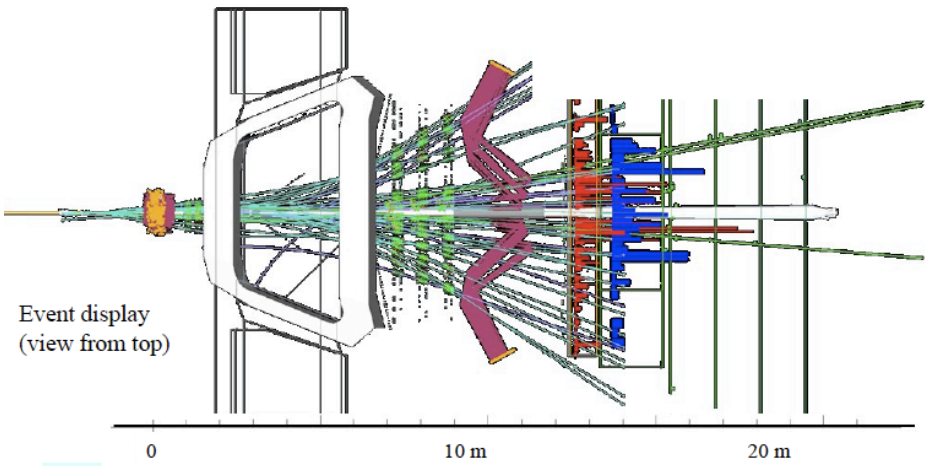
- explora característica de produção de b e c

  um detetor frontal
- excelente reconstrução dos pontos de interação e resolução de tempos de vida
- excelente identificação de partículas
- ótimas resoluções de momento e reconstrução de trajetórias

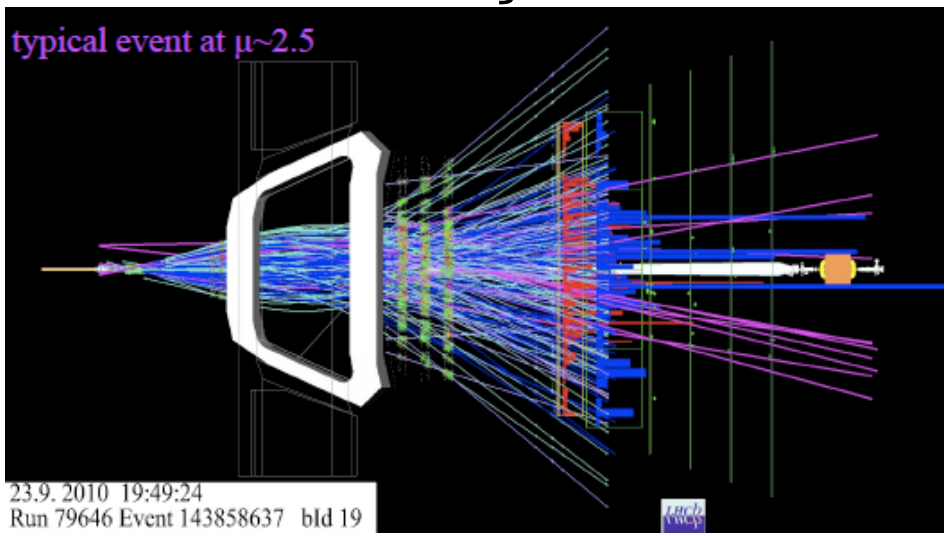
e um trigger muito eficiente

Eventos típicos ...

baixa taxa de interação



alta taxa de interação



Física de Sabores" como Fronteira de Precisão

Descobertas indiretas via Física de sabores incluem:

- pequena taxa de $K_S \to \mu^- \mu^+ \Rightarrow$ predição do charme (1970)
- oscilação de káons $\Rightarrow$ massa do charme (1974)
- violação de CP violation em káons $\Rightarrow$ 3^a família de quarks (1973)
- oscilação de B's $\Rightarrow$ massa do top (1987)



medidas em Física de Sabores na escala de GeV podem ser sensíveis a Nova Física a escala bem superior a TeV

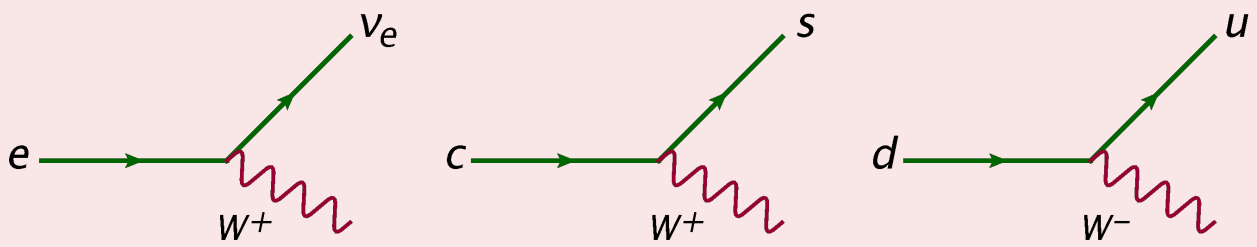
Atualmente não há ainda *observação* de desvios do MP, nem em medidas diretas nem de Física de Sabores

Mas ... Nova Física é esperada da escala $\approx$ TeV

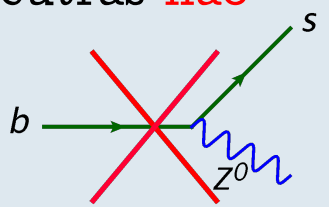
Física de Sabores deveria vê-la antes das medidas diretas!

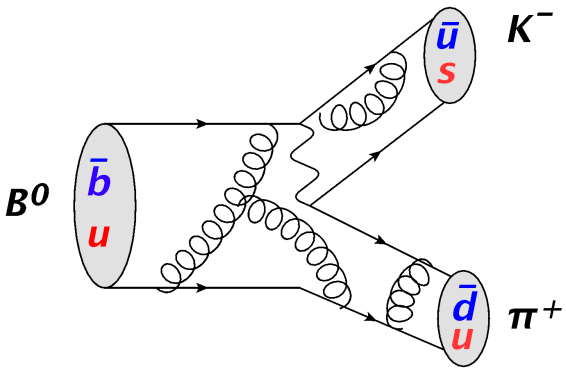
Física de sabores no setor de quarks ....

Correntes neutras carregadas promovem mudança de sabor



correntes neutras não





- hadronization é importantíssima: os hádrons são os estados observáveis!
- decaimento fraco acontecendo dentro de ambiente recheado de glúons
- QCD não -perturbativa!

- A Física de Sabores no LHCb – algumas das principais linhas:
  - Estudo abrangente de efeitos de violação de Carga-Paridade
  - Busca de decaimentos raros e proibidos pelo MP
  - Novos estados hadrônicos

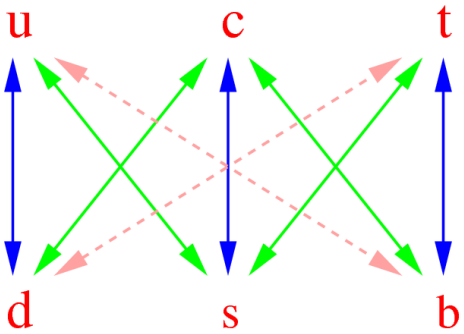
$\not{CP}$ no MP: a matriz de mistura dos quarks

Modelo Padrão $\Rightarrow$ Campo de Higgs quebra simetria eletrofraca

– todos os quarks adquirem massa –

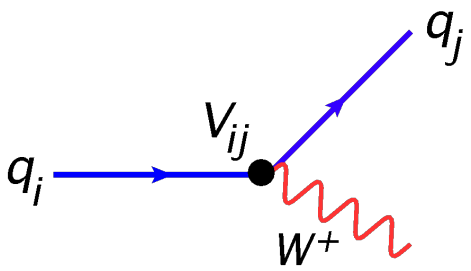
MAS: autoestados de massa não são os autoestados fracos

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$



$$\underbrace{\text{weak states}}_{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}} = \overbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}^{\text{CKM matrix}} \underbrace{\text{mass states}}_{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}$$

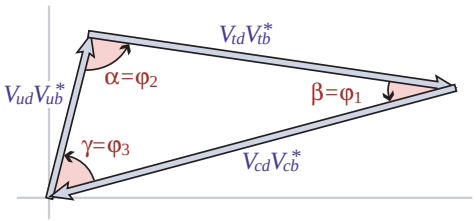
$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V_{ud}^* & V_{us}^* & V_{ub}^* \\ V_{cd}^* & V_{cs}^* & V_{cb}^* \\ V_{td}^* & V_{ts}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

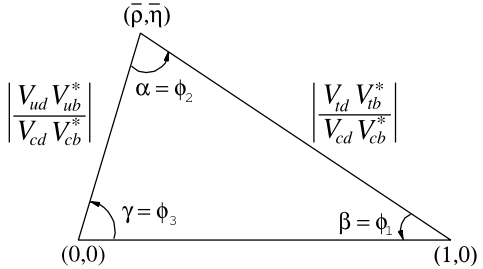


$C\not{P}$ no MP: a matriz de mistura dos quarks

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Unitariedade da matriz V_{CKM} impœas condições $\sum_i V_{ij} V_{ik}^* = 0$ se $j \neq k$ triângulos no plano complexo $\rho - eta$
- Lados dos triângulos dependem de potências de λ
- O único triângulo com lados de mesma ordem (λ^3) é





A determinação de α, β e γ e checar que somam 180° é um teste fundamental sobre o mecanismo de $C\not{P}$ predito pelo MP

Violação de CP e a evolução do triângulo unitário

⋆ 1964: Cronin & Fitch descobrem violação de CP em kaons neutros [1980]

⋆ 1973: Kobayashi & Maskawa [2008]

⋆ 2001: $C\!\!\!/P$ observada em mésons B^0 (BaBar & Belle)

⋆ 2013: $C\!\!\!/P$ observada em decaimentos de B_s (LHCb)

ainda não vista $C\!\!\!/P$ em decaimentos charmosos (baixíssima taxa no MP)

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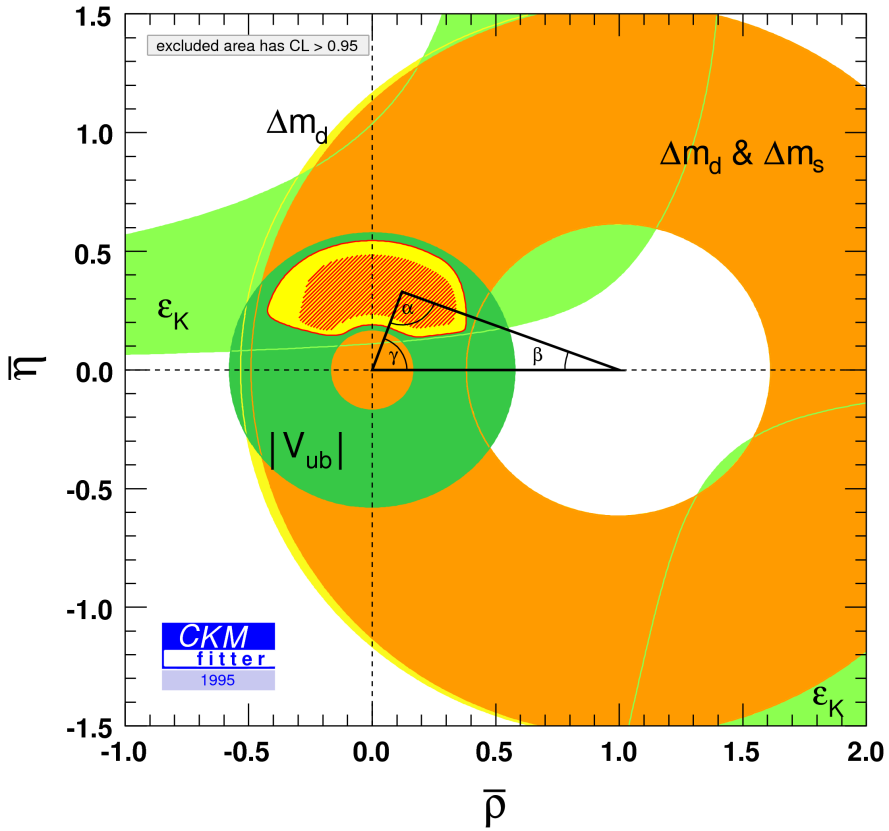
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1995



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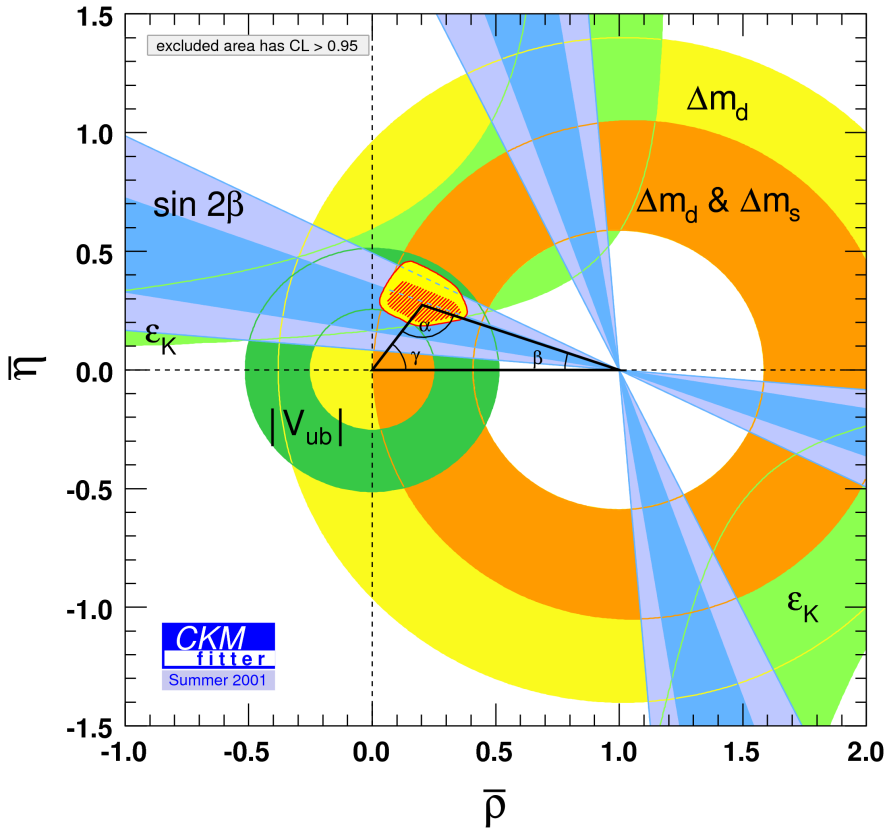
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2001



Violação de CP e a evolução do triângulo unitário

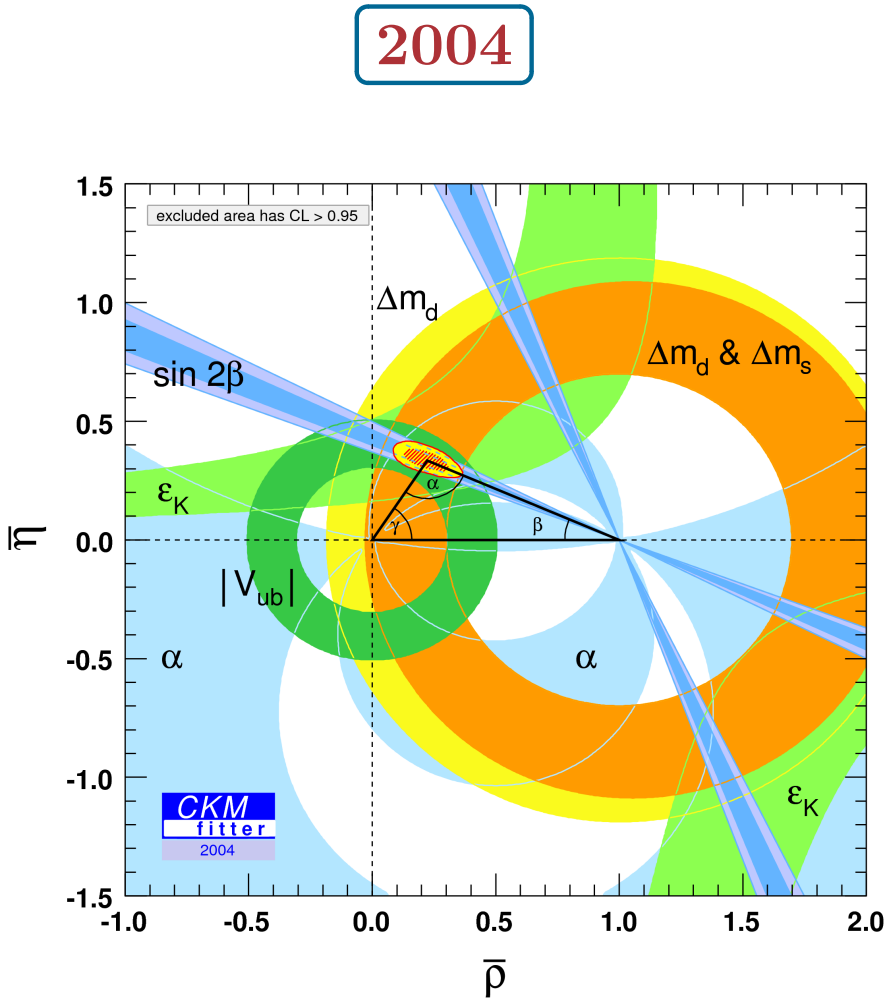
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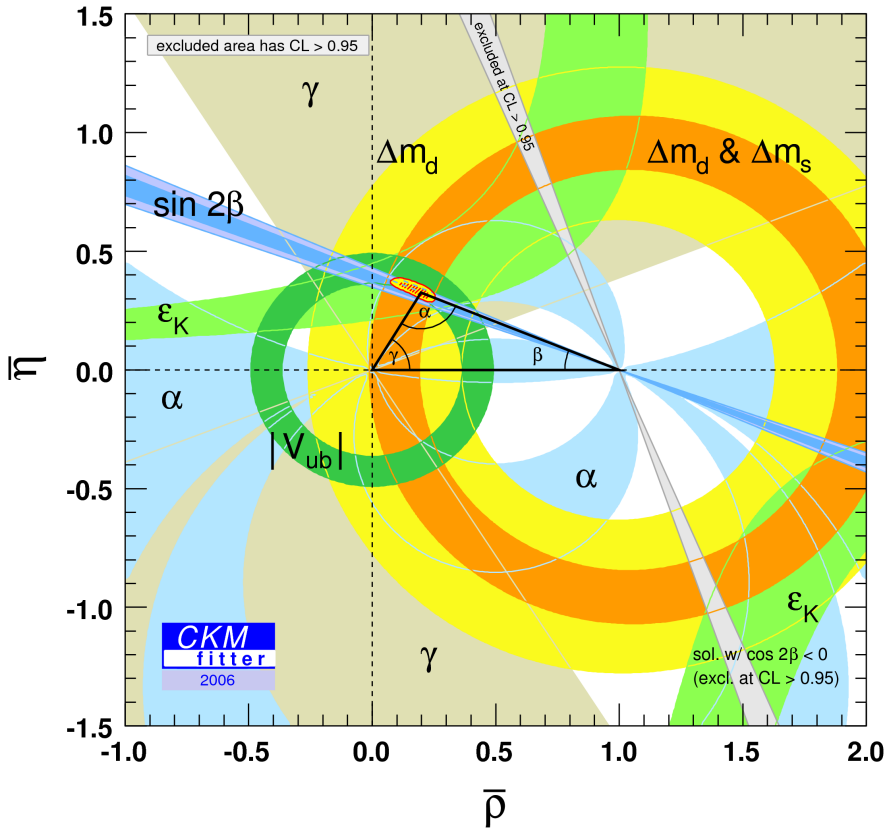
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2006



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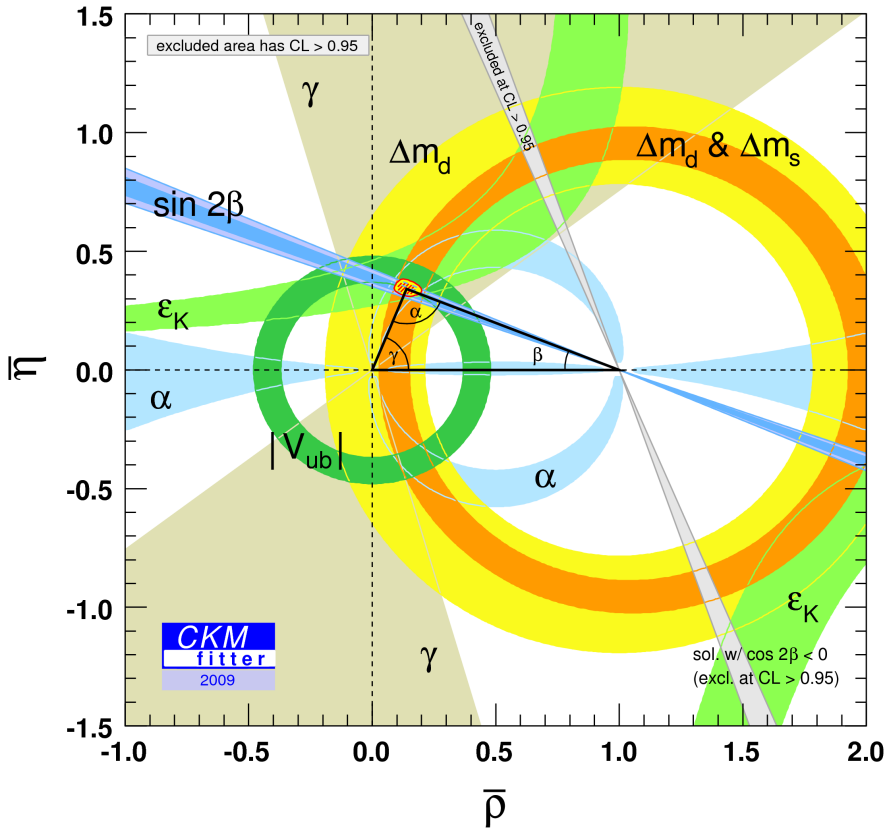
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2009



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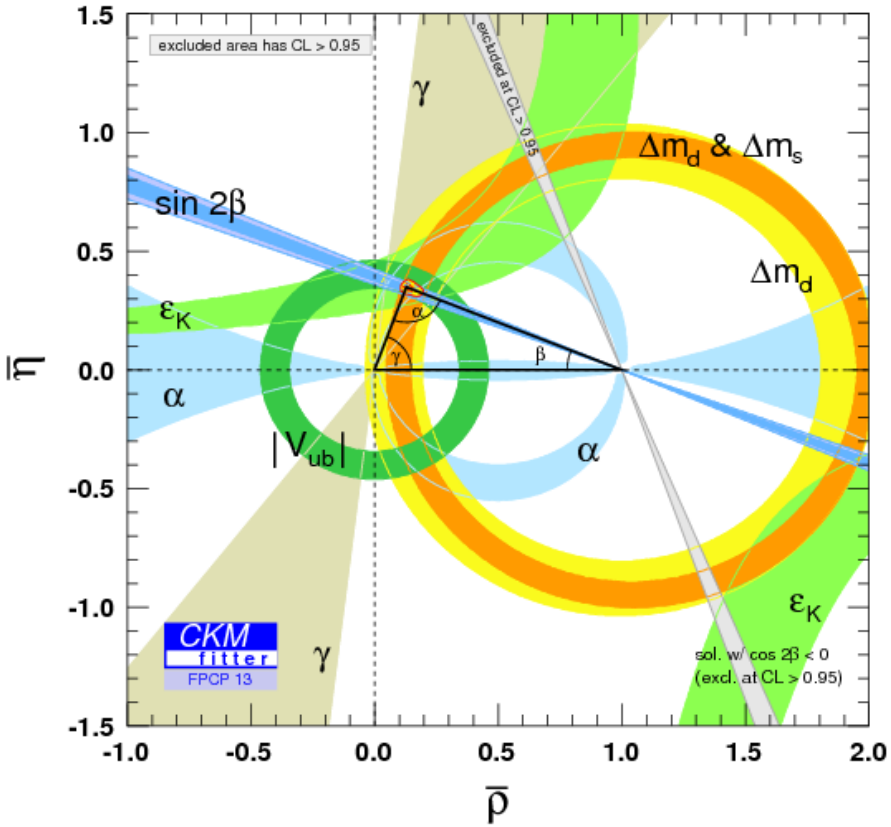
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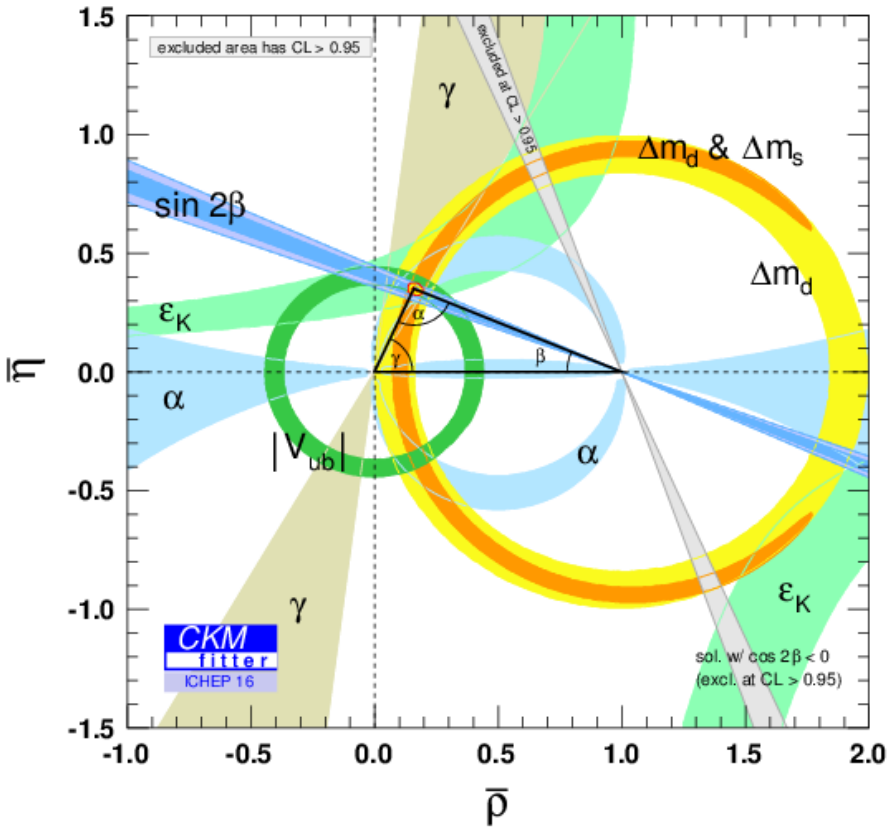
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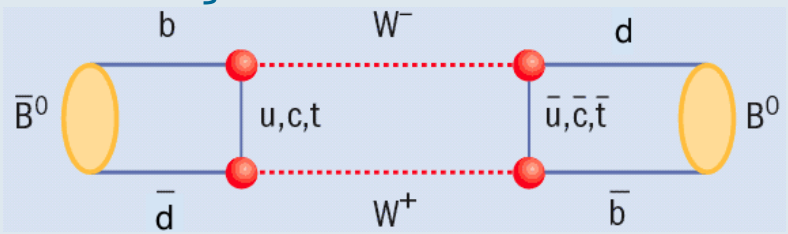
2016



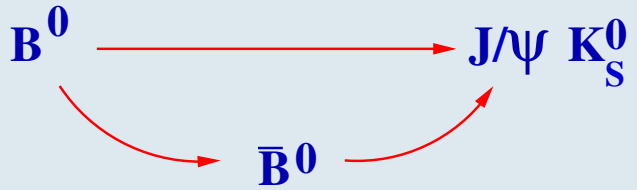
Resultados

O Decaimento de ouro: $B_d \to J/\psi K_S$

⋆ Oscilação $B^0 - \bar{B}^0$



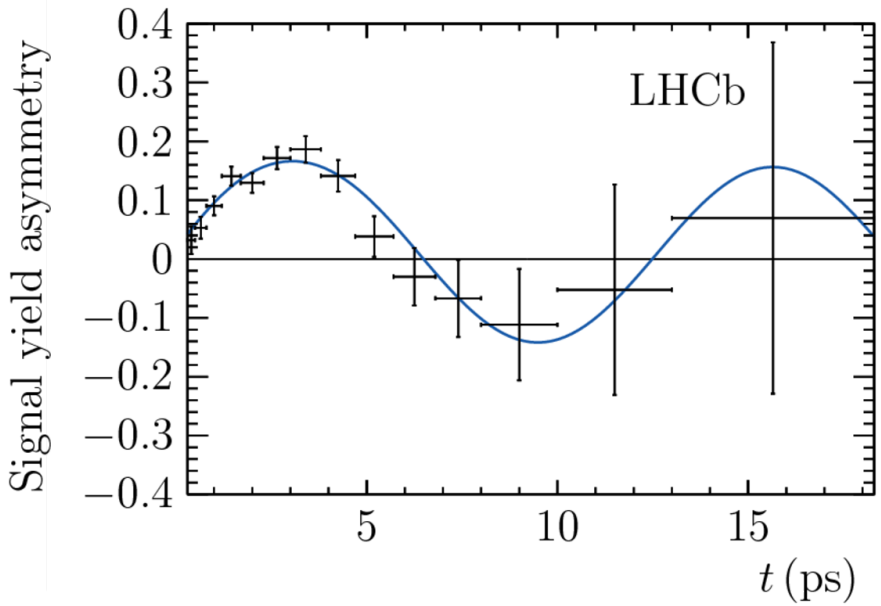
⋆ CP em $B^0 \to J/\psi K_S$:



$A_{CP} \propto \sin(2\beta)\sin(\Delta m\, t)$

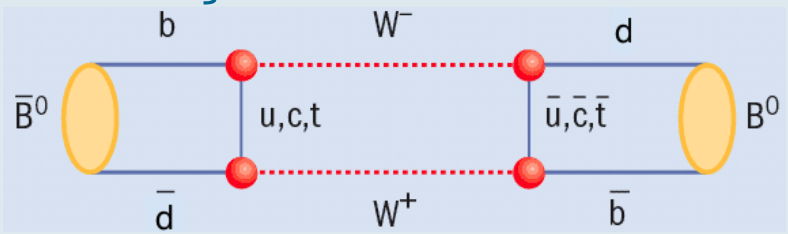
$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$

Média mundial $\sin 2\beta = 0.691 \pm 0.017$

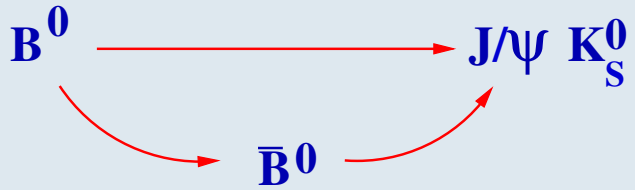


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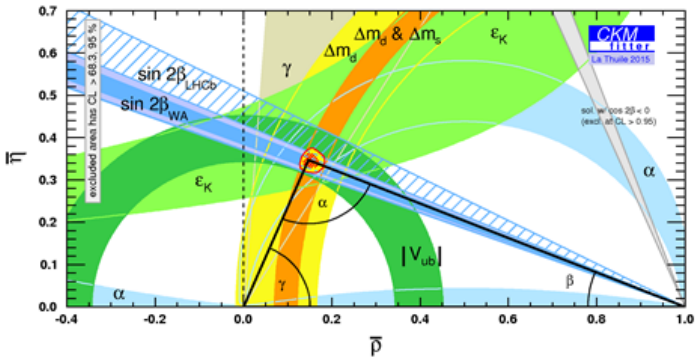
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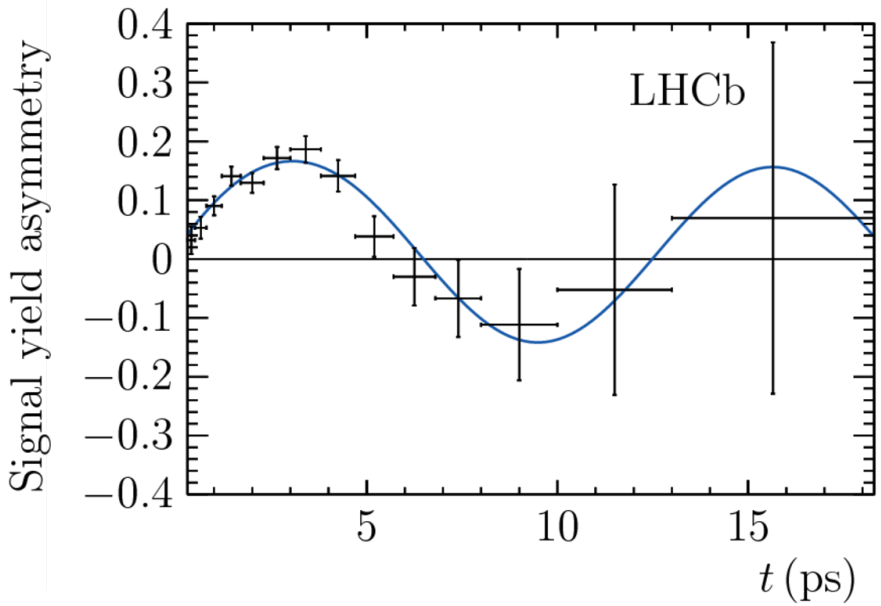


$$A_{CP} \propto \sin(2\beta)\sin(\Delta m\, t)$$

$$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$$

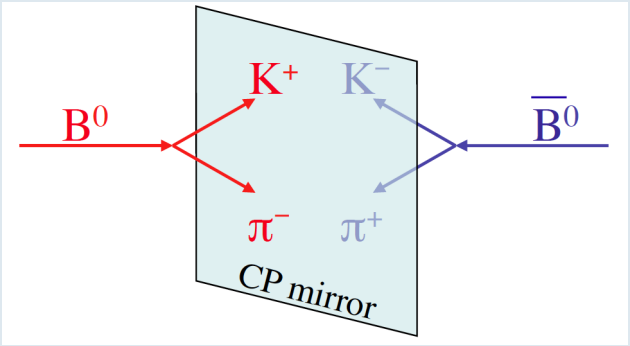
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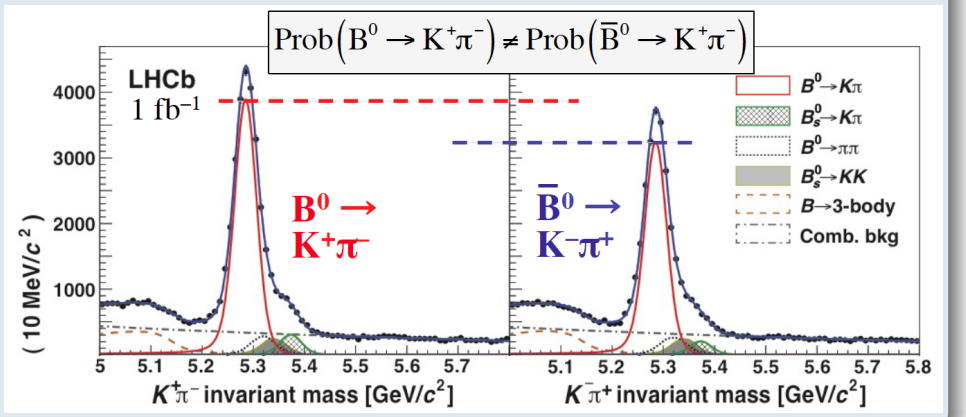




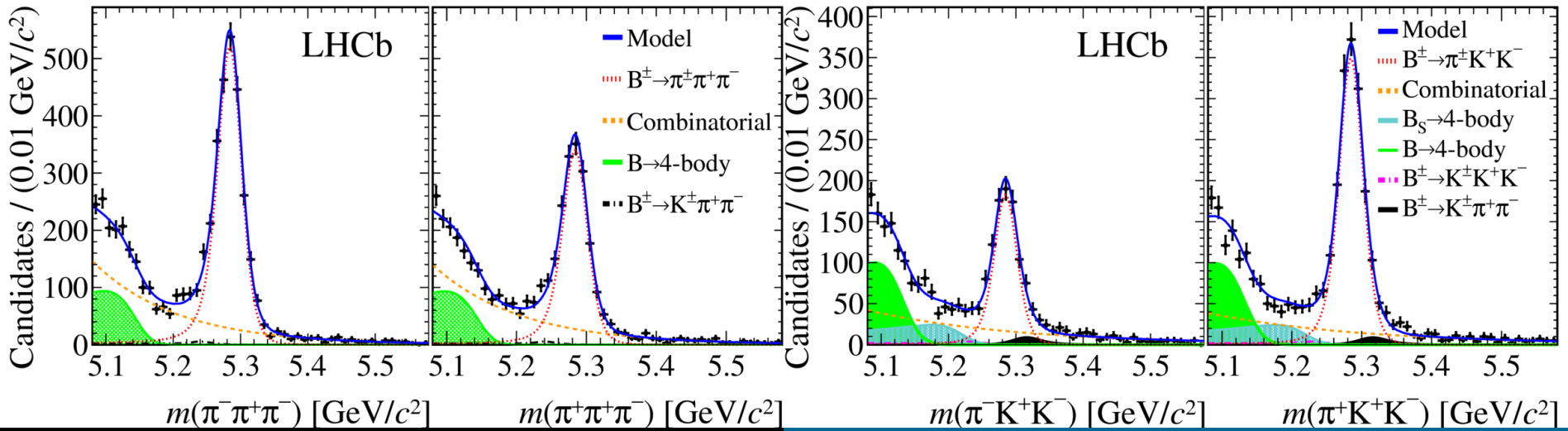
A assimetria matéria-antimatéria explícita...

$B^0 \to K^-\pi^+$



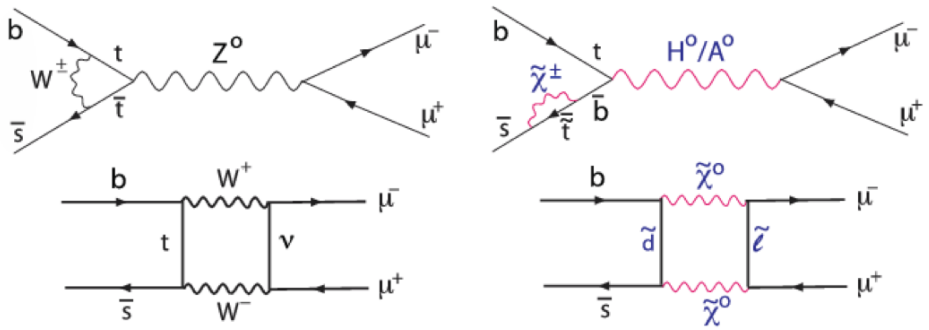


$B^\pm \to \pi^\pm\pi^+\pi^+$ vs $B^\pm \to \pi^\pm K^+ K^-$



Decaimento raro $B_s \to \mu^+\mu^-$

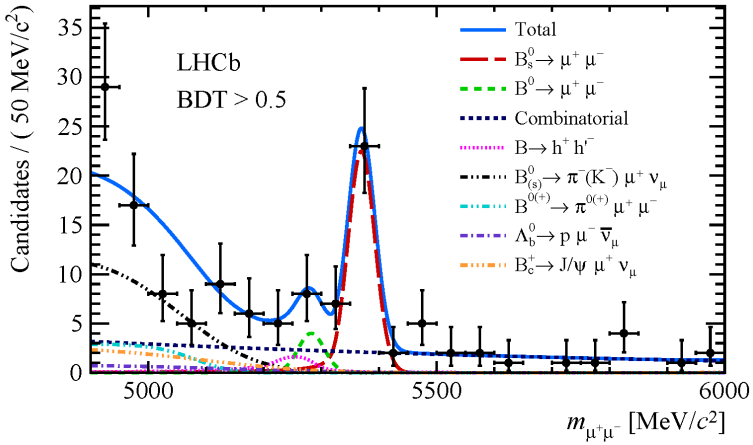
- canal de ouro na busca por efeitos de NF
- BR predito pelo MP muito pequeno $(3.66 \pm 0.23) \times 10^{-9}$
- NF (e.g. MSSM) aumentaria BR significativamente



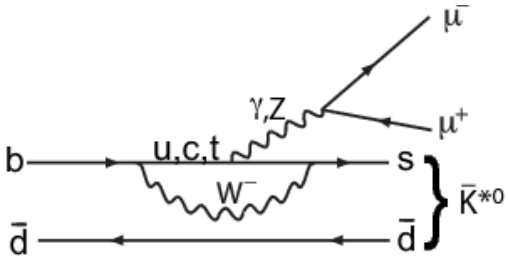
- LHCb e CMS combinados no run I medem $BR = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
- LHCb update incluindo parte do run II:

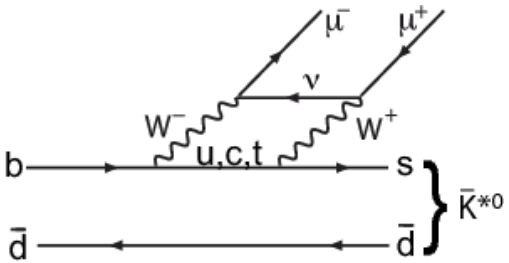
$$BR(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

Sinal confirmado com 7.8σ

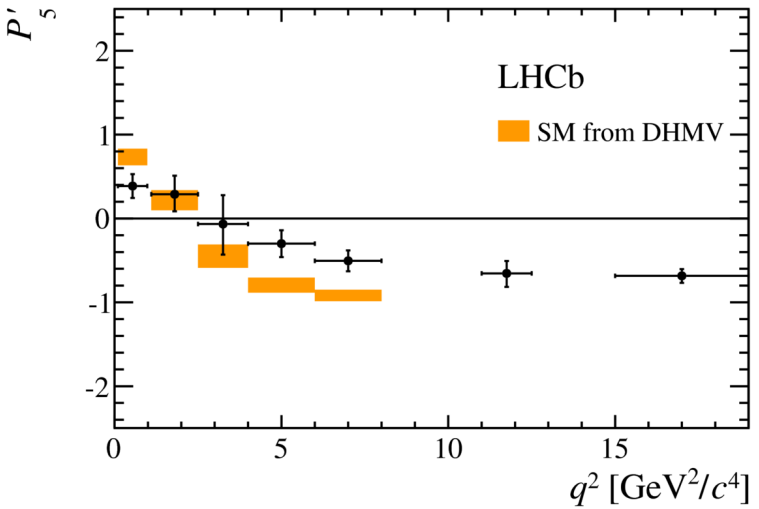


Decaimento raro $B^0 \to K^* \mu^+ \mu^-$





- processo via FCNC (troca de sabor por corrente neutra) efetiva
- ótima "sonda" para estrutura de helicidade em Nova Física (NF)
- em particular, assimetria *forward-backward* (AFB) do sistema de múons como função da massa invariante do par q^2
- um dos interessantes observáveis é P_5' - sensível a NF

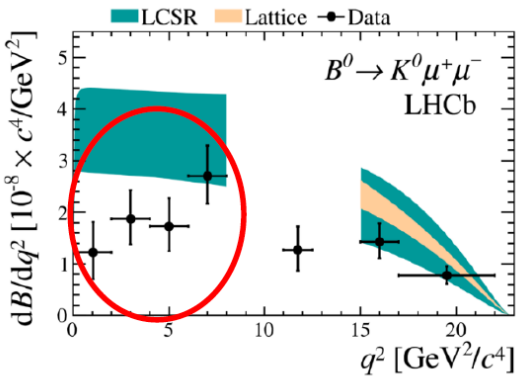


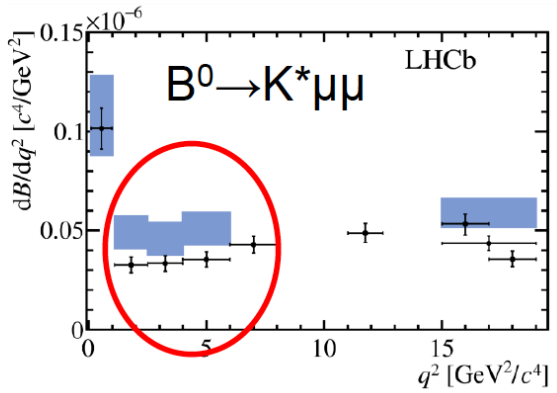
- **Desvio de 3.4σ em relação a predições do MP**

Alguns indícios de Nova Física? ...

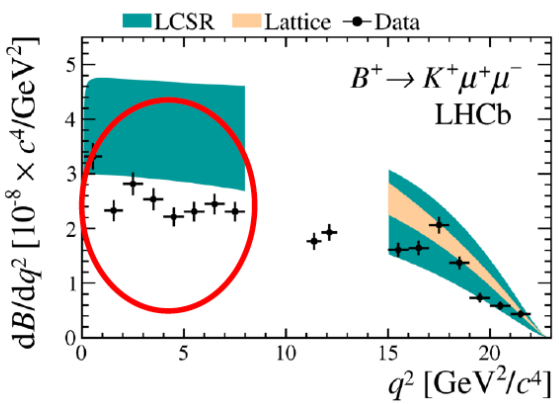
intrigantes padrões aparecendo também em outros membros da famiília $s \to b\ell\ell$ ..

[JHEP 06 (2014) 133]



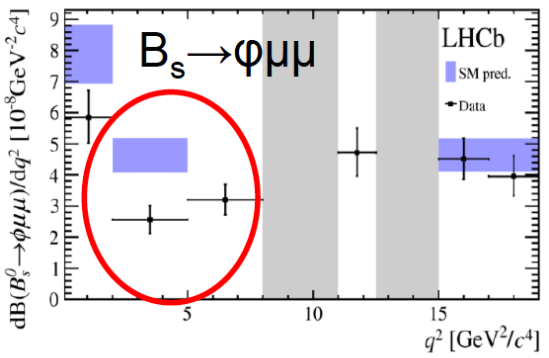


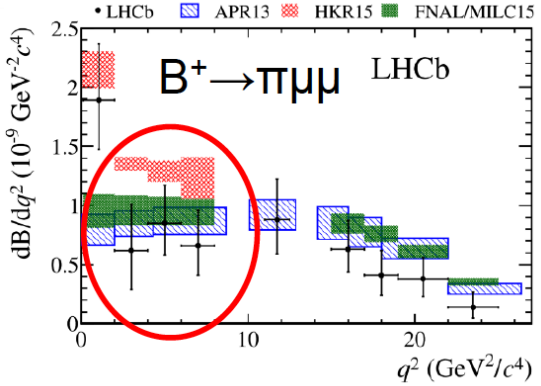
[JHEP 11 (2016) 047]



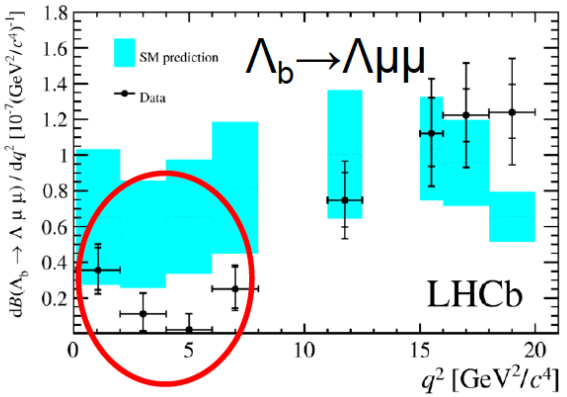
[JHEP 06 (2014) 133]

[JHEP 09 (2015) 179]





[JHEP 10 (2015) 034]



[JHEP 06 (2015) 009]

...mas, o ambiente é complicado: grandes incertezas hadrônicas

Universalidade Leptônica

Será que múons, elétrons e taus se comportam da mesma forma?

- A menos de sua massa, são cópias um do outro no MP $\Rightarrow$ "Lepton Universality" (LU)
  iguais acoplamentos de W e Z com e, μ, τ
- Amplitudes de processos envolvendo leptons em princípio devem apenas ser corrigidas pelos efeitos de massa
- Observação de violação de LU seria claro sinal de Nova Física

No setor hadrônico, podemos medir razões de taxas de decaimento semi-leptônicos, onde as incertezas teóricas hadrônicas se cancelam, por exemplo

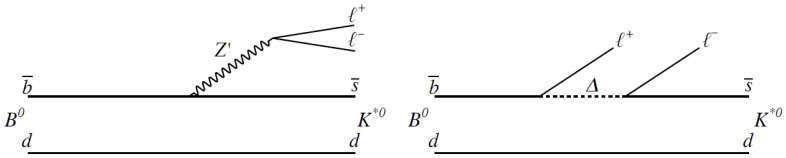
$$R_{K^{(*)}} = \frac{\mathcal{B}(B^0 \to K^{(*)}\mu\mu)}{\mathcal{B}(B^0 \to K^{(*)}ee)} \qquad R_{D^{(*)}} = \frac{\mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}$$

LU: $B \to K^{(*)}\ell^+\ell^-$

- Medindo a razão

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

- Deveria ser 1 no MP ...



$B^+ \to K^+\ell^+\ell^-$

PRL 113 (2014) 151601

LHCb mede:

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

2.6σ de desvio em relação ao MP

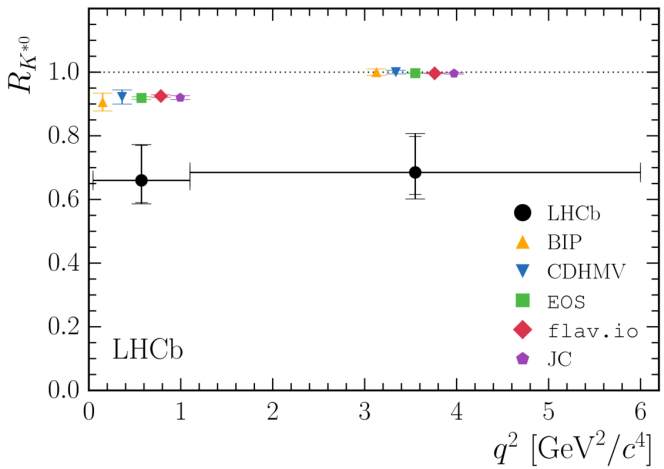
$B^0 \to K^*\ell^+\ell^-$

ArXiv:1705.05802

	low- q^2	central- q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$

q^2 baixo: $2.2 - 2.4\sigma$

q^2 central: $2.4 - 2.5\sigma$

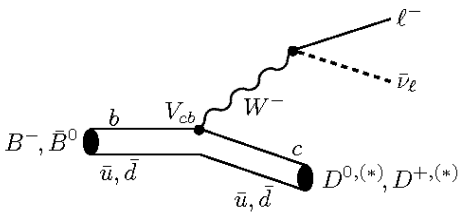


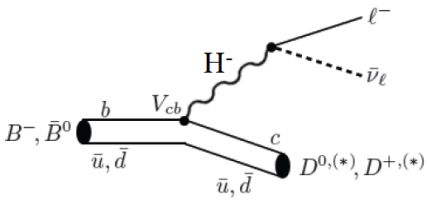
LU: $B^0 \to D^{(*)-}\ell^+\nu_\ell$

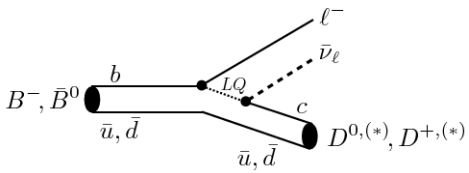
- $B^0 \to D^{*-}\tau^+\nu_\tau$ é um canal abundante
- Predição do MP: R_{D^*} conhecido com precisão melhor que 2%

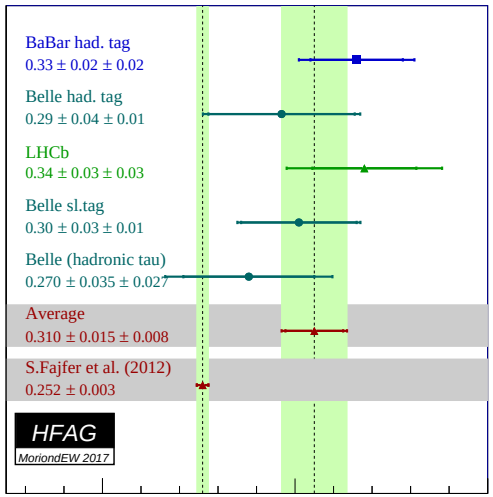
$$R_{D^{(*)}} = \frac{\mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}$$

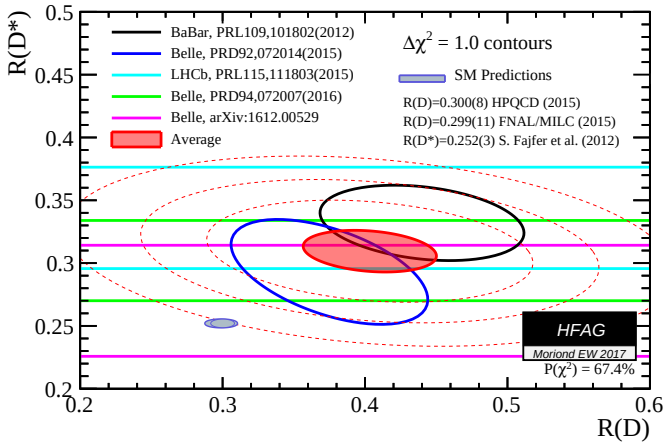
- sensível a efeitos de Nova Física: Higgs carregado, leptoquarks







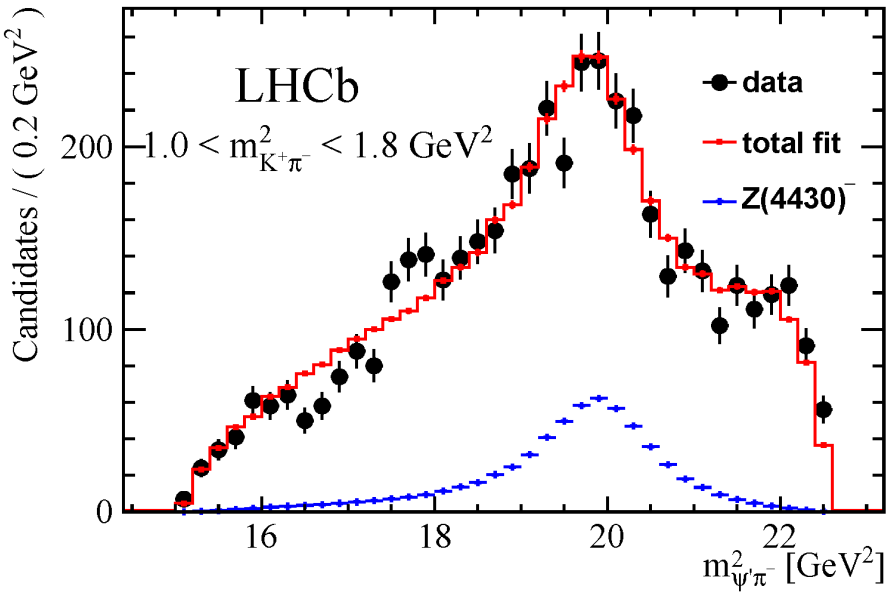


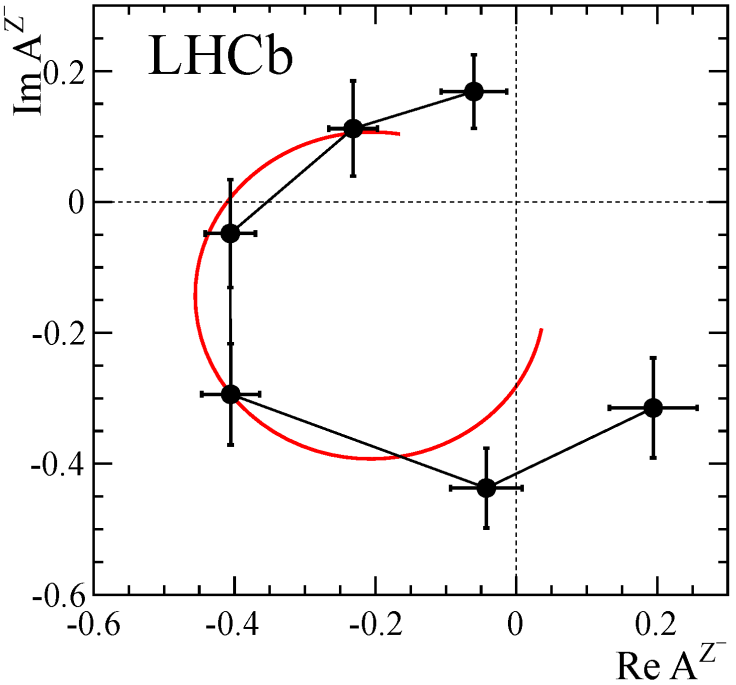


Resultados combinados $R_{D^{(*)}}$ discrepância global de 3.9σ com relação ao MP !!

Exóticos: Tetraquark

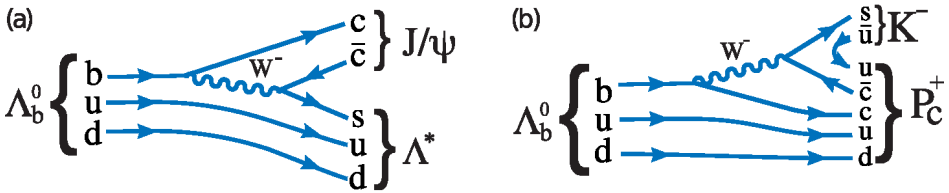
- Partícula exótica $Z(4430)^-$ observada pela primeira vez pelo Belle (2008)
- LHCb confirmou sua existência em processos $B^0 \to \psi' K^+ \pi^-$ comprovando sua natureza ressonante



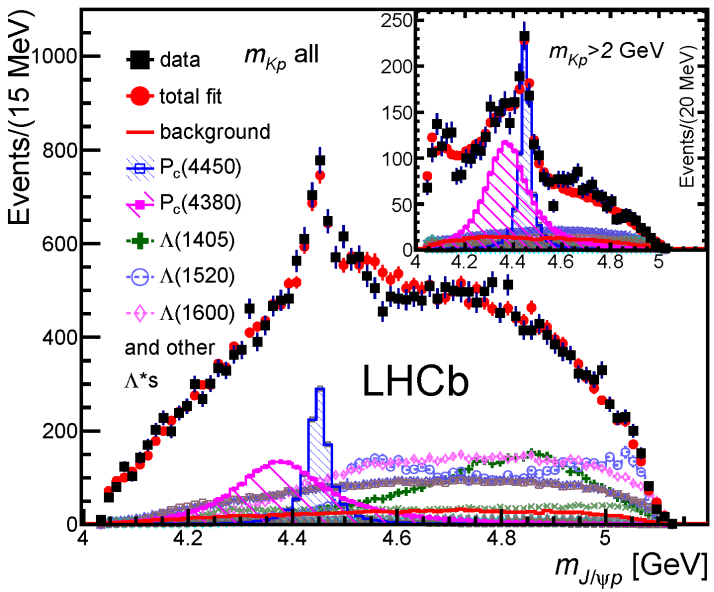


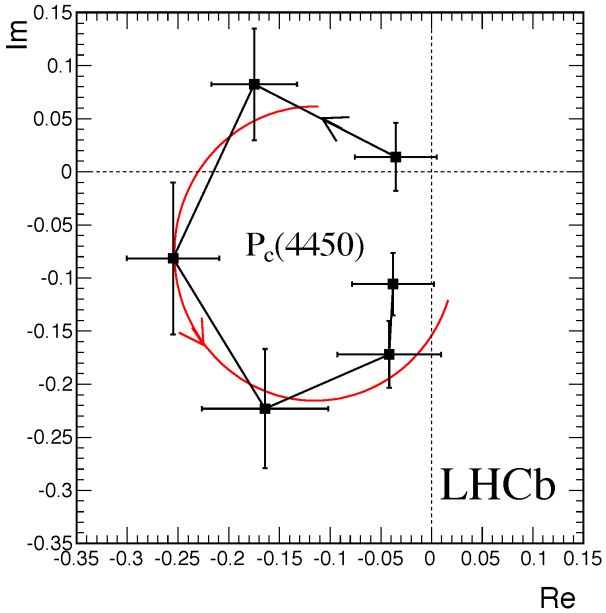
Composição $c\bar{c}d\bar{u}$

Exóticos: Pentaquark



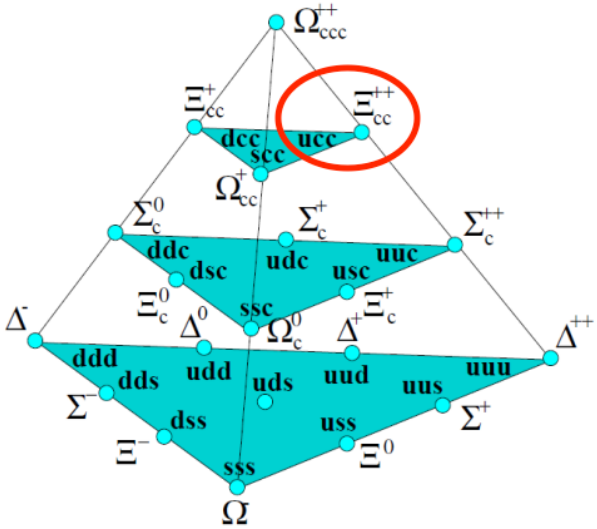
- Dados não podem ser explicados sem a inclusão de pentaquarks
- dois estados são observados $P_c^+(4450)$ e $P_c^+(4380)$





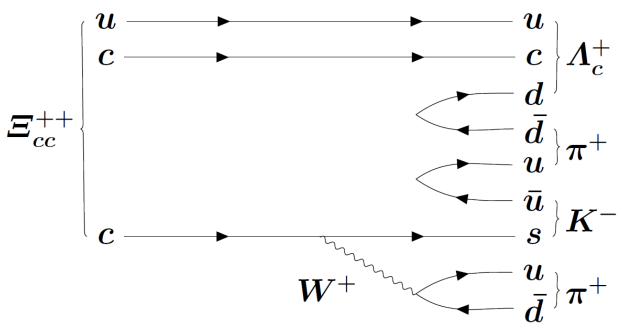
Composição $c\bar{c}uud$

... e o novo super charmoso Ξ_{cc}^{++} !

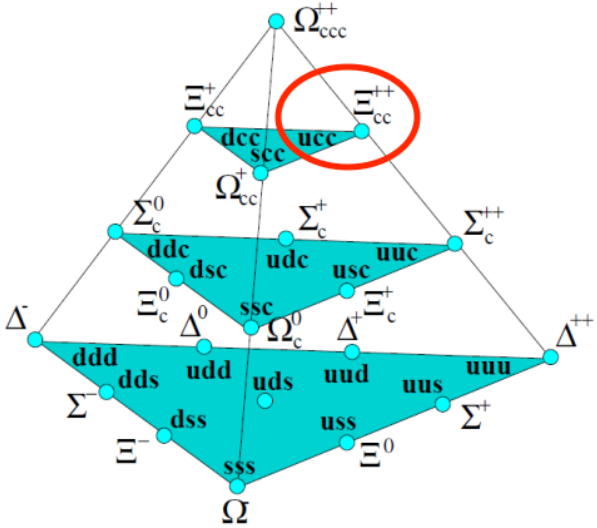


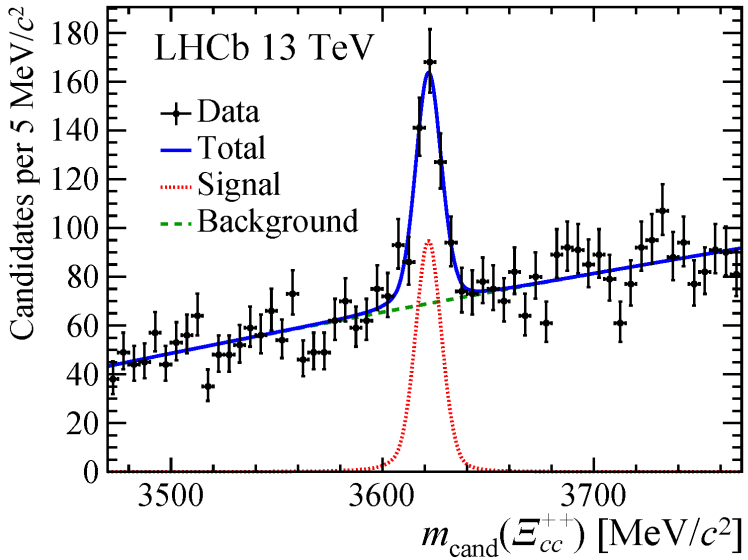
$\Rightarrow$ LHCb procurou por Ξ_{cc}^{++} através do canal

$$\Xi_{cc}^{++}(ccu) \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$$



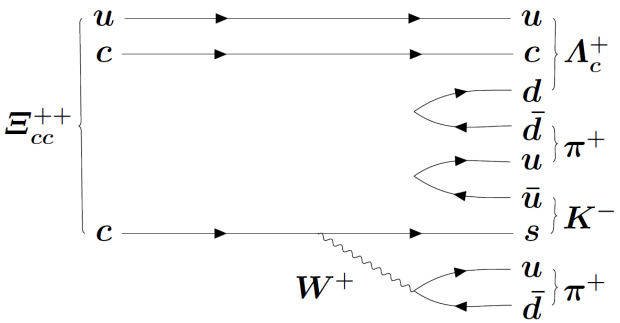
... e o novo super charmoso Ξ_{cc}^{++} !

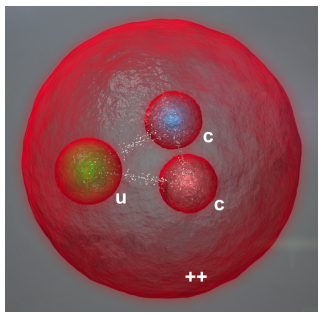




$\Rightarrow$ LHCb procurou por Ξ_{cc}^{++} através do canal

$$\Xi_{cc}^{++}(ccu) \to \Lambda_c^+ K^- \pi^+ \pi^+$$





$$m(\Xi_{cc}^{++}) =$$
$$3621.40 \pm 0.72 \pm 0.27 \pm 0.14\,\text{MeV}/c^2$$

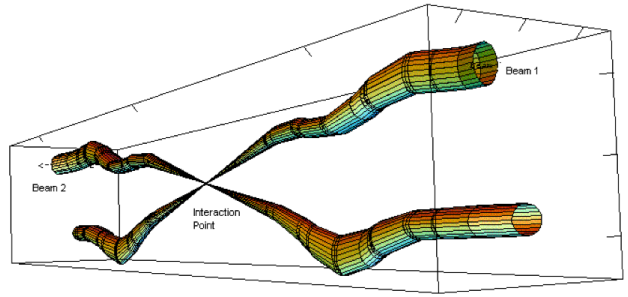
ATLAS e CMS

Colisões pp no LHC: Aspectos Gerais

As colisões próton-próton

Alguns números atuais: (tomada de dados de 2011/2012)

- Energia de cada feixe 3.5/4.0 TeV
  => energia de 7/8 TeV no CM
- Pacotes com 10^{11} prótons
- 1300 pacotes simultaneamente no túnel



Relative beam sizes around IP1 (Atlas) in collision

A partir da colisão próton-próton, quais os atributos dos detectores?

- antes de mais nada, perceber que houve uma colisão e "armar o gatilho" para coletar as informações dos detectores
  sistema de trigger
- ser capaz de detectar as partículas produzidas na colisão
  energia: **calorímetros hadrônico e eletromagnético**
  trajetória e momento: **sistema de tracking**

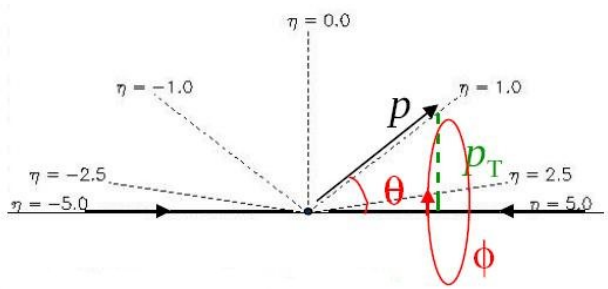
ATLAS e CMS - Principais objetivos

- Os principais objetivos do ATLAS e CMS são os mesmos dois desenhos para a mesma física
- Principais tópicos de seu programa de Física:
  - Busca do Higgs
  - Busca de partículas super-simétricas
  - candidatos a matéria escura e dimensões extra
- para qualquer suposta descoberta de um, deve haver contra–cheque do outro
- maior diferença está no campo magnético para os múons

ATLAS e CMS desenhados para serem espectrômetros de precisão para múons

Variáveis importante para colisões pp

- momentum transverso $p_T = p \sin\theta$ (plano $\perp$ ao feixe)
- pseudorapidez $\eta = -\ln\tan\theta/2$
- ângulo azimutal ϕ



♣ Produção de objeto de alta massa (W, Z, H ou partículas de nova física (NF)) requer grande fração de momento para os "pártons" (quarks, glúons) $\Rightarrow$ produzido centralmente

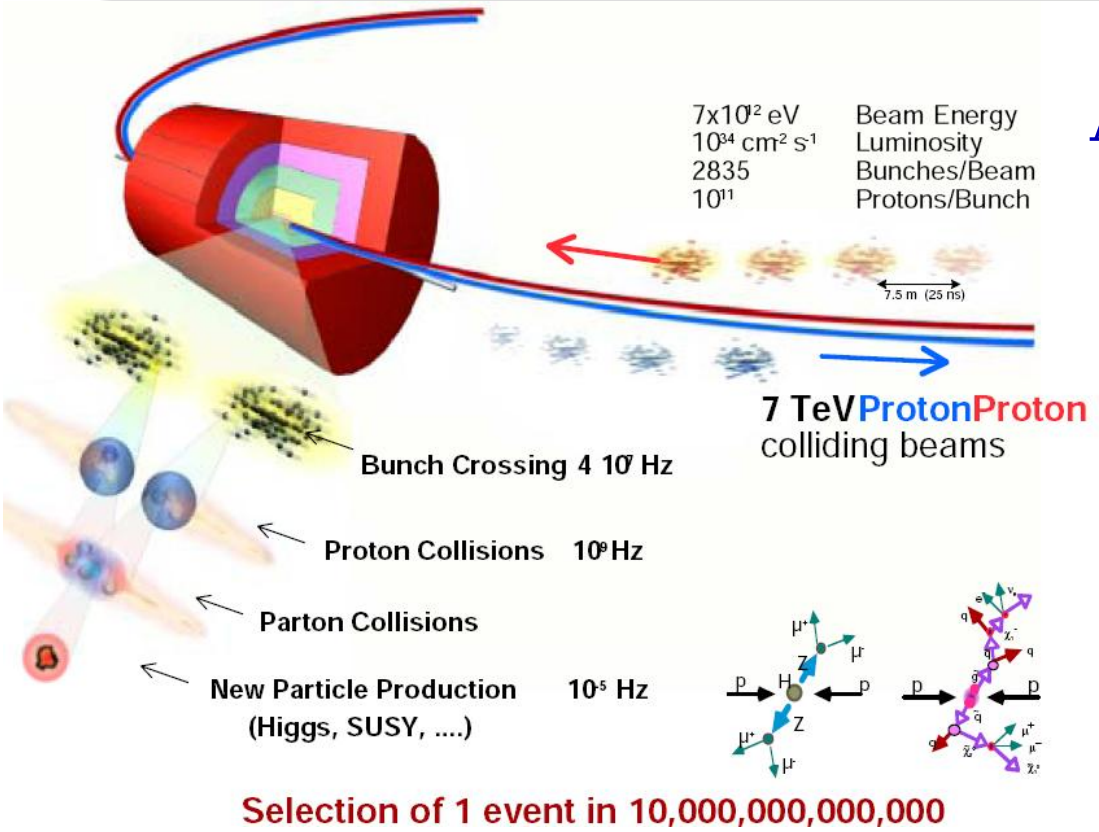
- por outro lado, a esmagadora maioria de interações pp baixo momento transferido:
  - partículas no estado final tem grande momento mas pequeno p_T ($\overline{p_T} \sim 500\text{MeV}$)
  - distribuídas uniformemente em ϕ, alto η

♣ ATLAS e CMS desenhados para $|\eta| < 3$

O que buscar?

⋆ espalhamento quark–quark comum tem múltiplos jets no estado final mas não léptons ou fótons

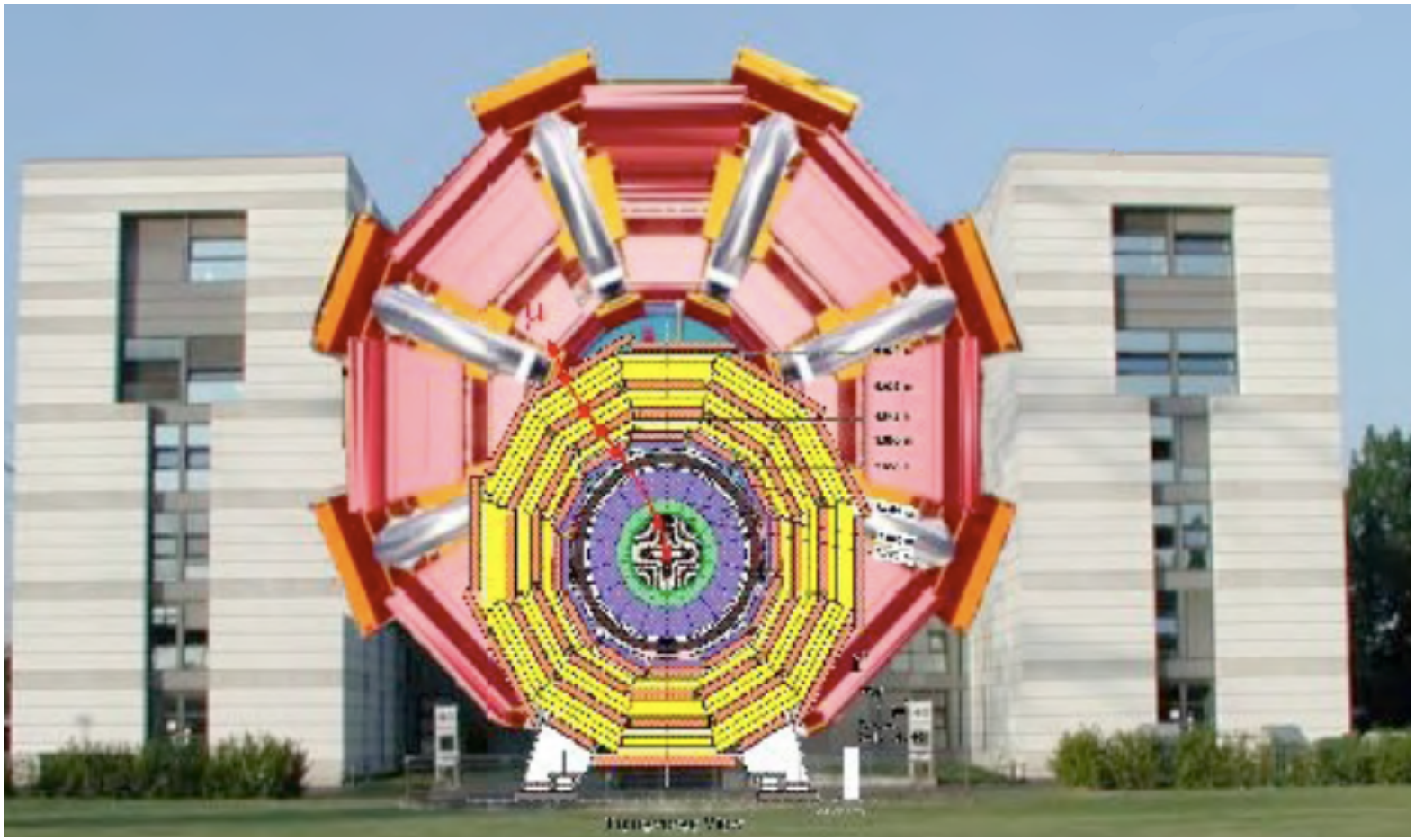
⋆ física interessante acontece quando jatos de alto p_T jets, léptons & photons são observados



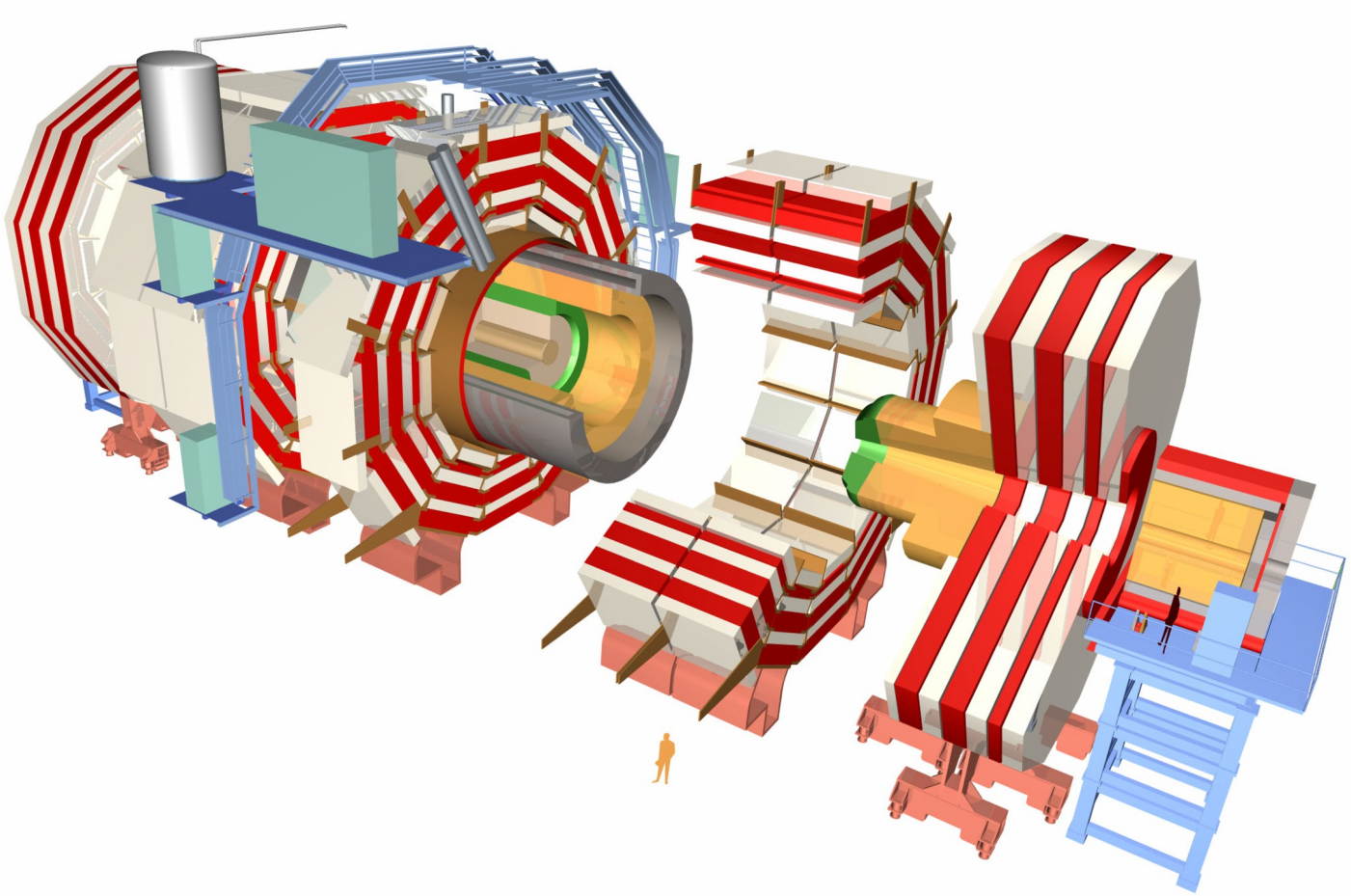
Assinaturas:

- léptons isolados ou de alto p_T
- presença de jatos com alto p_T
- p_T, E_T faltante (neutrinos e partículas NF que escapam)
- quarks b e léptons tau

Colaborações e Detectores



O Experimento CMS



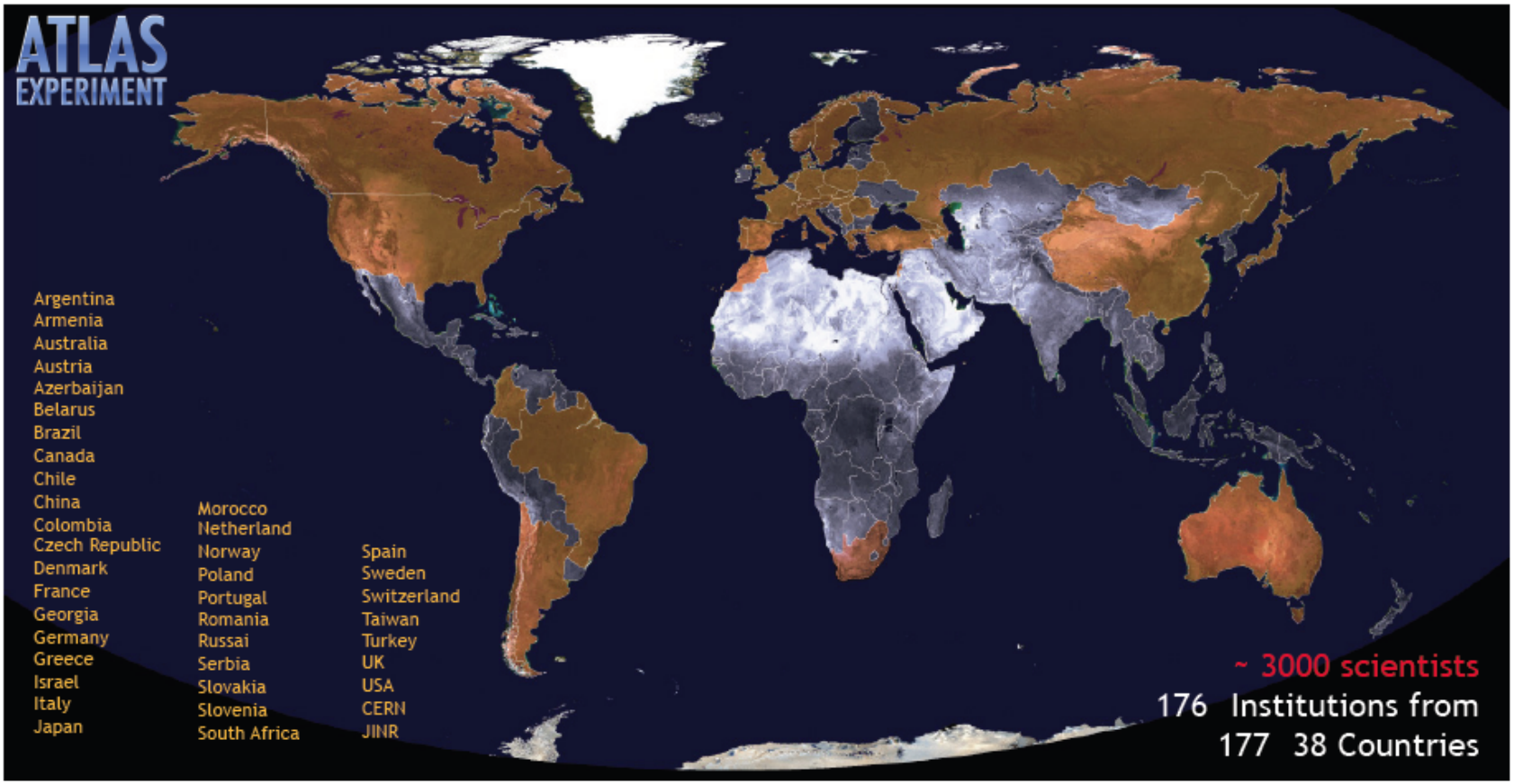
3275 físicos (1535 estudantes), 790 engenheiros e técnicos

179 institutos, 41 países

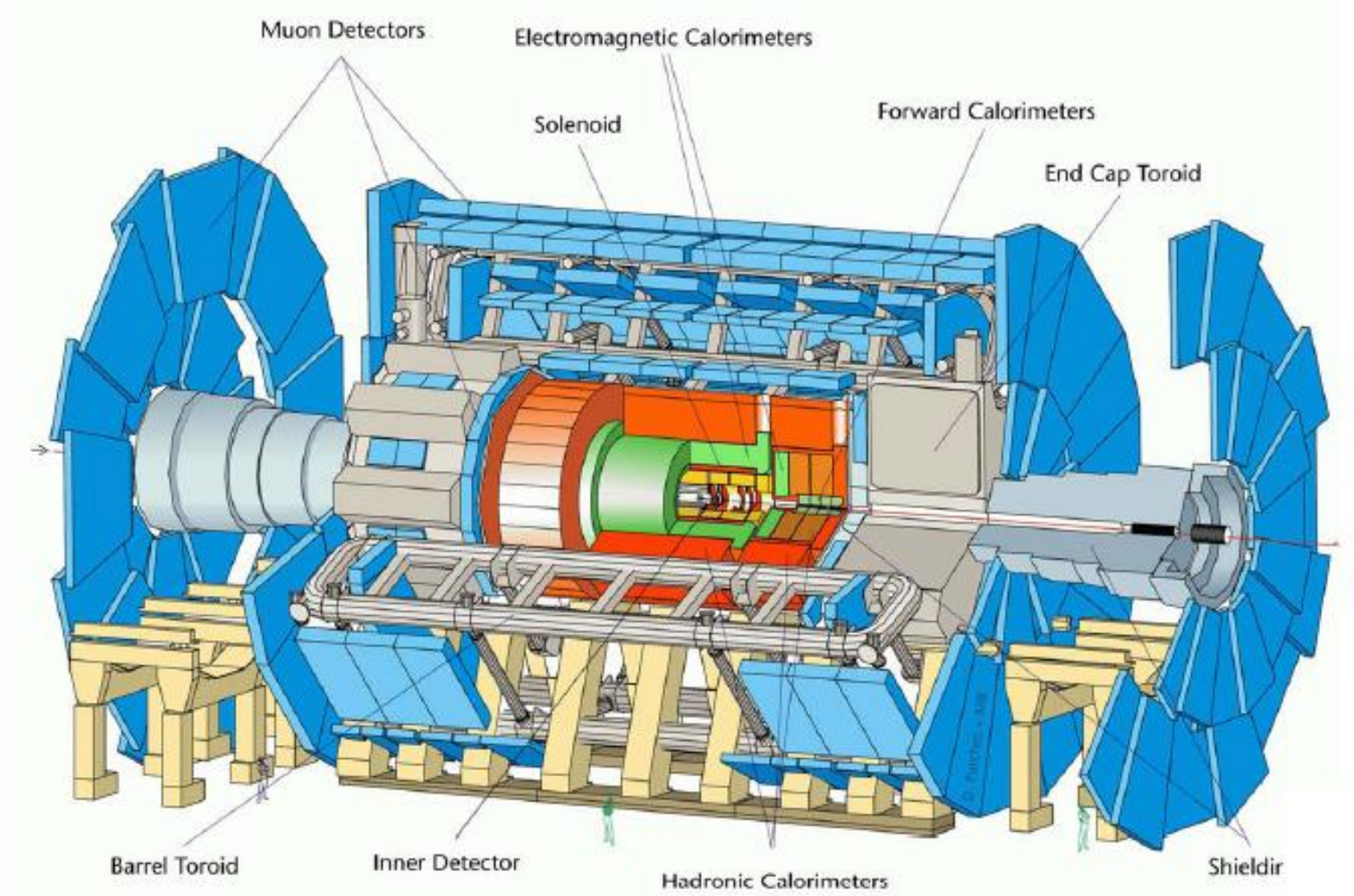
O Detector CMS



O Experimento ATLAS

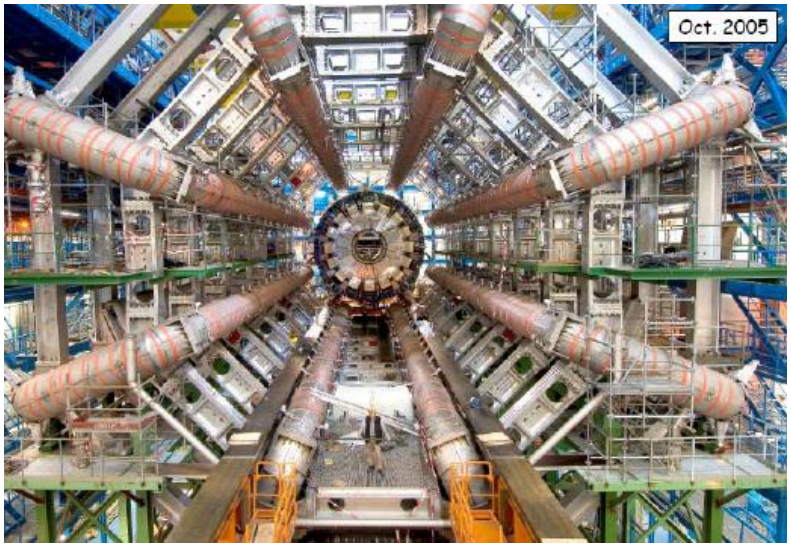


O Experimento ATLAS



Os Detectores ATLAS





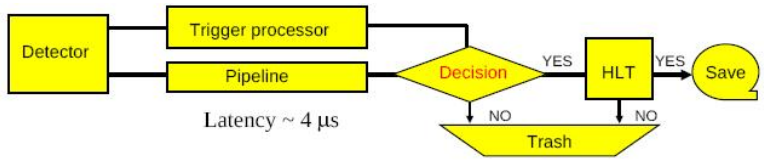


Trigger e Análise de Dados @ ATLAS e CMS

- pode-se gravar $\sim$ 100 eventos/s ($\sim$ 1 MB/evento) $\Leftrightarrow$ 10^9 MB/year (petabyte de dados!)
- taxa de interação $\sim 10^9$ eventos/s $\Rightarrow$ deve-se rejeitar $\sim 10^7$ eventos/s

$\Rightarrow$ sistema de trigger

- decisão do trigger leva poucos μs: muito mais que os 25 ns da taxa de bunch crossing
- deve-se guardar enorme quantidade de dados momentanemente para que processadores especiais de trigger façam cálculos em parte dos dados



- reconstrução dos dados involve reconhecimento de padrões e ajustes $\Rightarrow$ alto poder computacional
- Análise usa poder computacional e armazenamento distribuído em todo o mundo (GRID)

Principais resultados: ATLAS e CMS

A evolução do pile-up



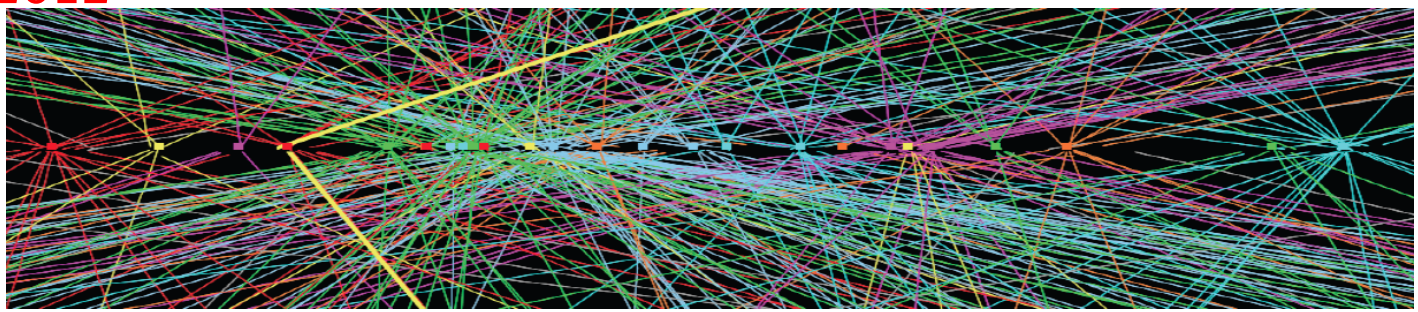
2010

2011

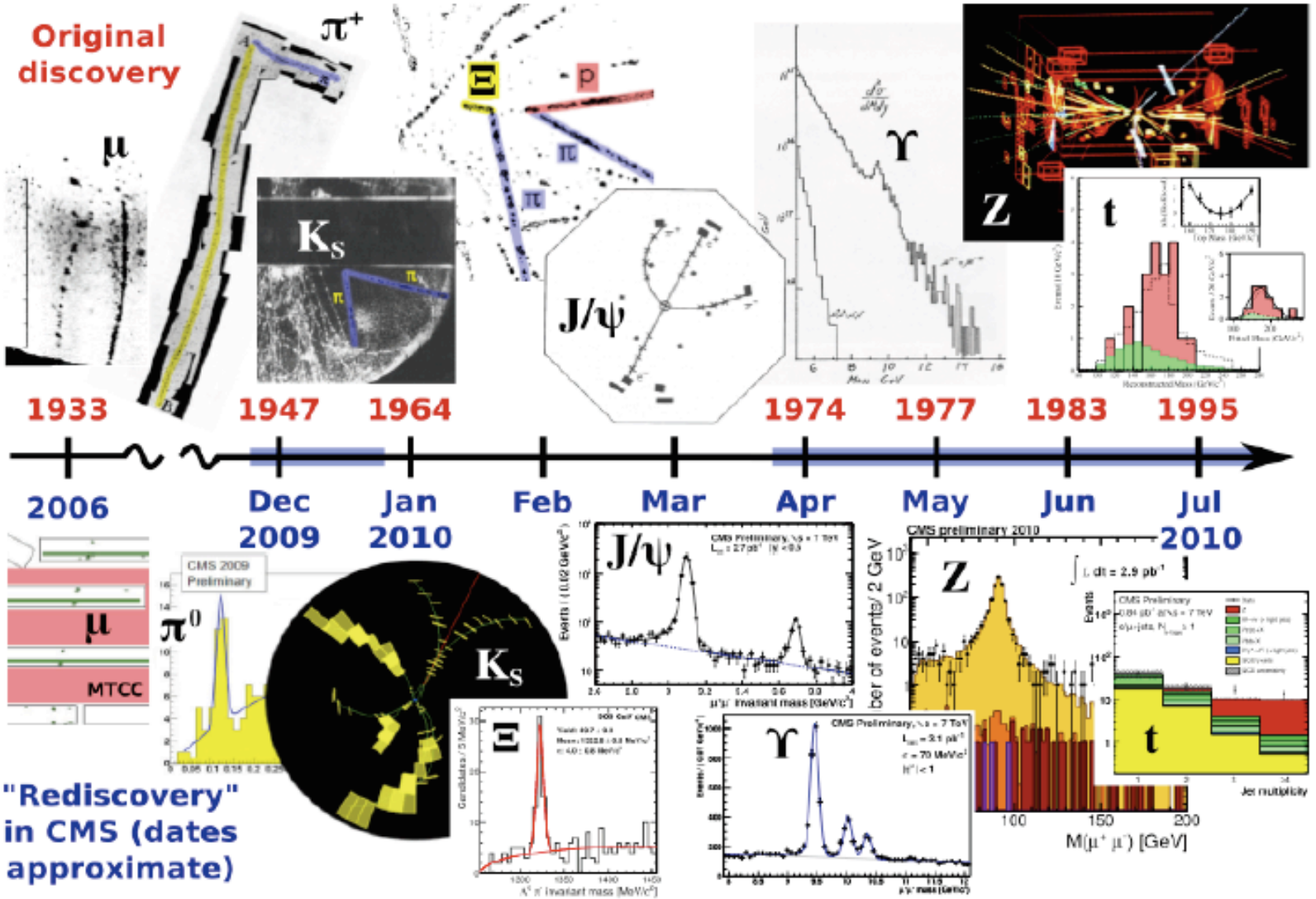
2012

⋆ a taxa de interações pp inelásticas "normais" ($\sigma = 0.1$barn) para a luminosidade nominal $\mathcal{L}$ do LHC é
$\mathcal{L} \cdot \sigma = 10^{34}\text{cm}^{-2}s^{-1} \cdot 0.1b = 10^{9}\,Hz$

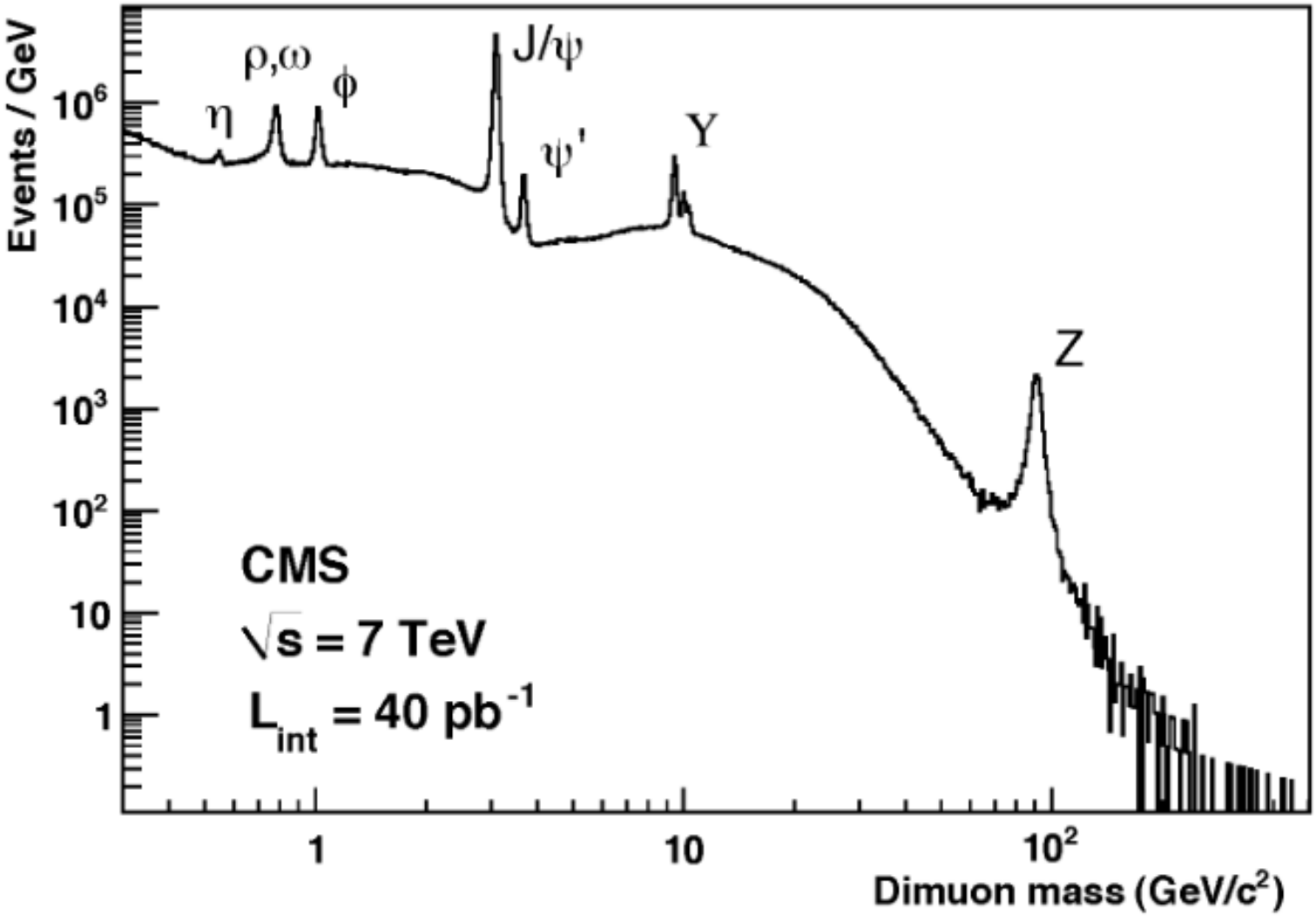
⋆ p.e., com uma taxa de "bunch crossing" de 40 MHz (um bunch a cada 25 ns) pode haver 25 colisões pp ineláticas por bunch cross! $\Rightarrow$ pile-up (empilhamento)



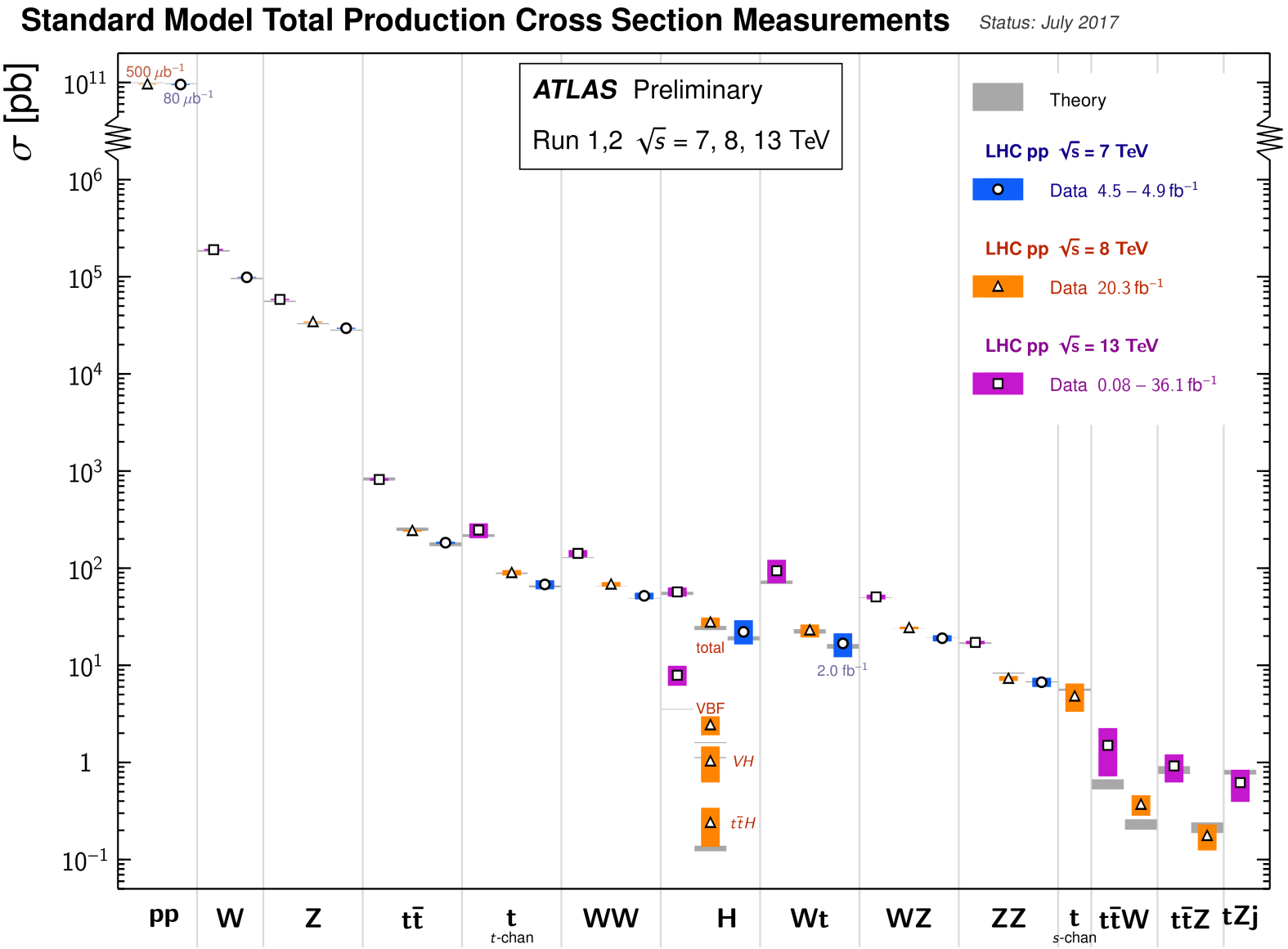
Redescobrindo o Modelo Padrão



O especto de massa $\mu^-\mu^+$ - colisões a 7 TeV

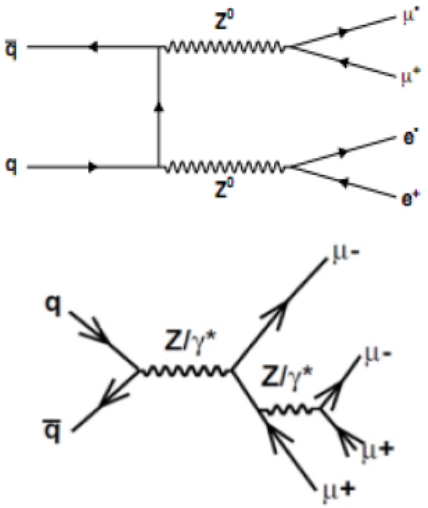


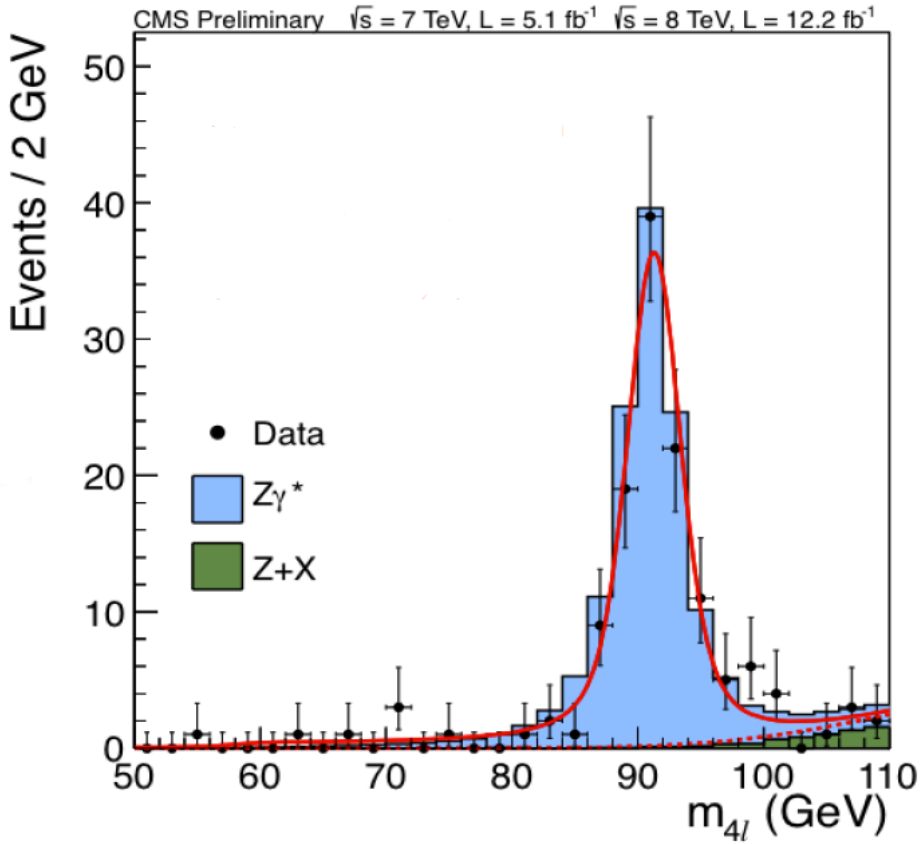
Física de Modelo Padrão - Seções de choque



Física de Modelo Padrão

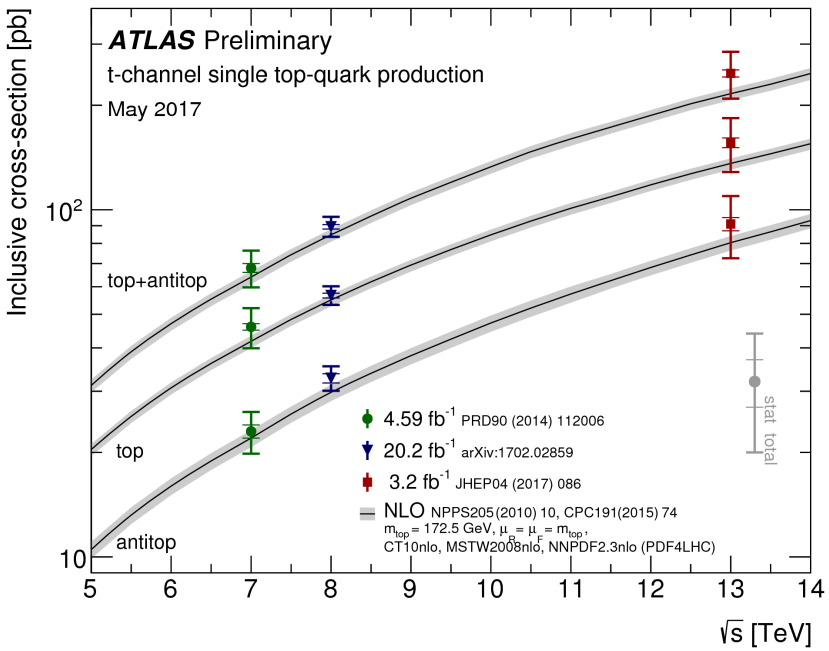
Um canal importante: $ZZ, Z\gamma^* \to 4\ell$

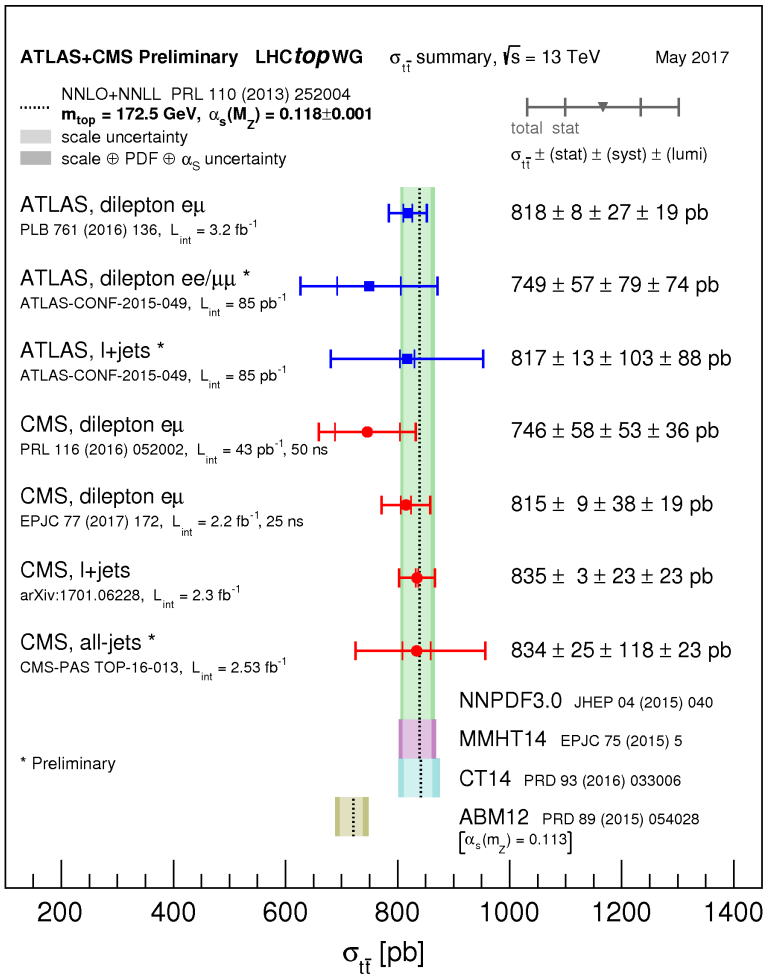




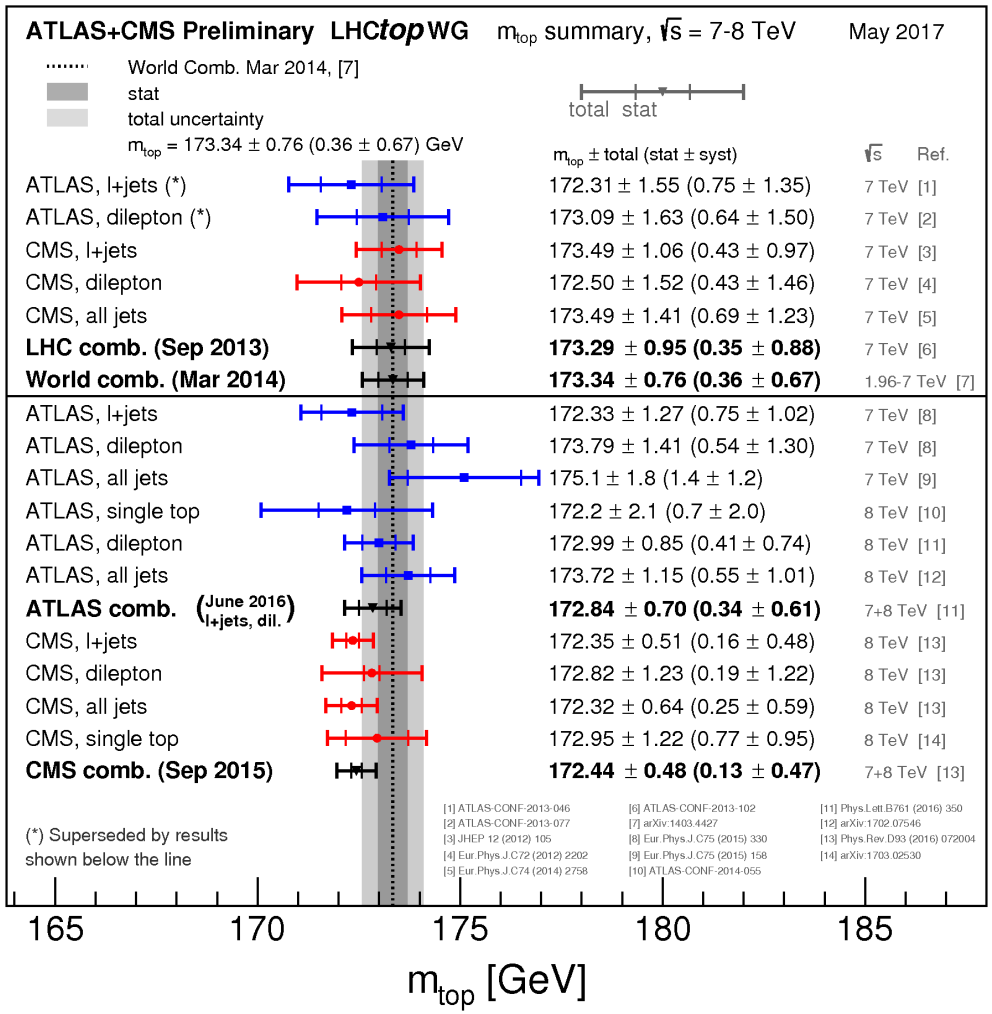
- o canal $H \to ZZ^*, Z\gamma^* \to 4\ell$ é um dos principais na busca do Higgs!

Física de Top – Seção de choque



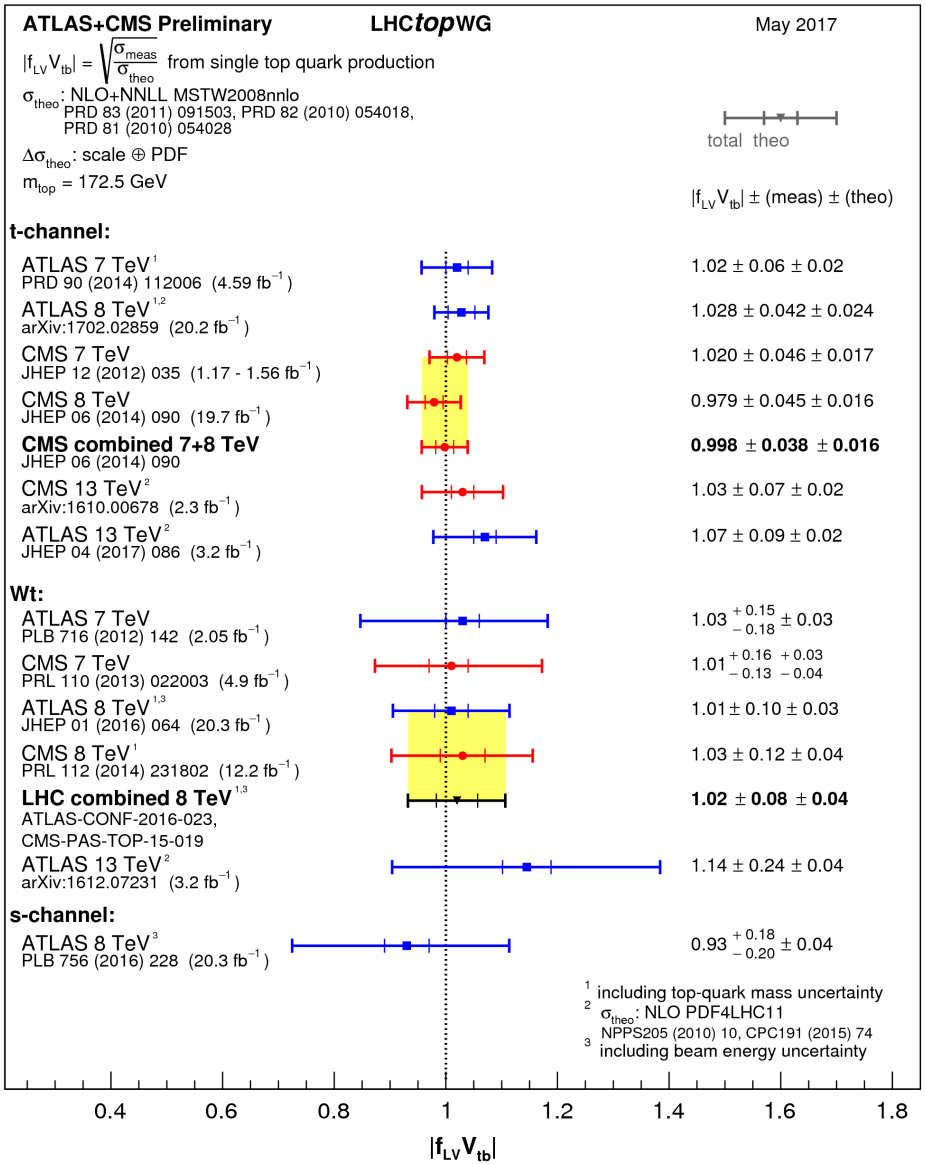


Física de Top - Massa



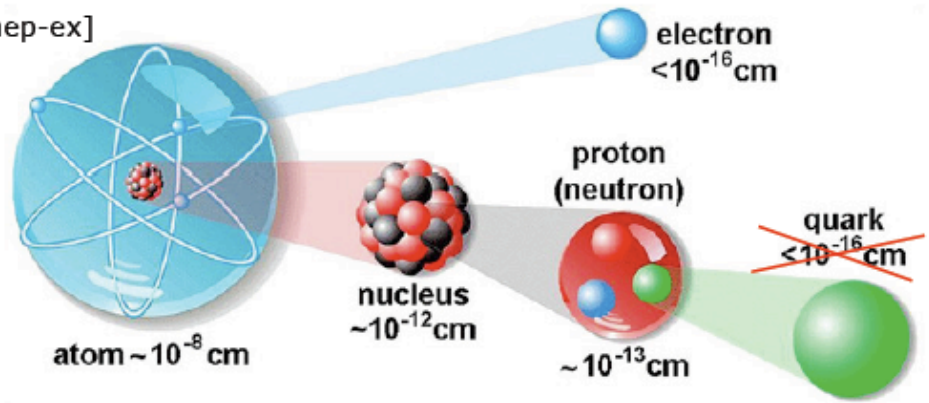
Física de Top - Matrix de CKM

V_{tb}



Busca por composição de quark

Accepted by PRL
arXiv:1010.4439 [hep-ex]

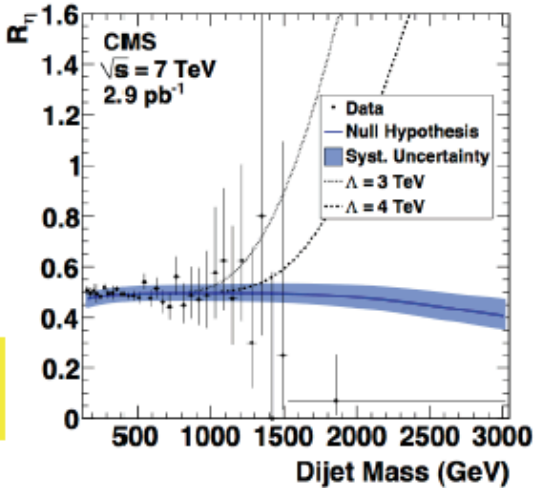


< 5x10^{-18} cm

Dijet Centrality Ratio

Ratio of number of events with two leading jets within $|\eta|$ <0.7 to the number with both leading jets within 0.7<$|\eta|$ <1.3

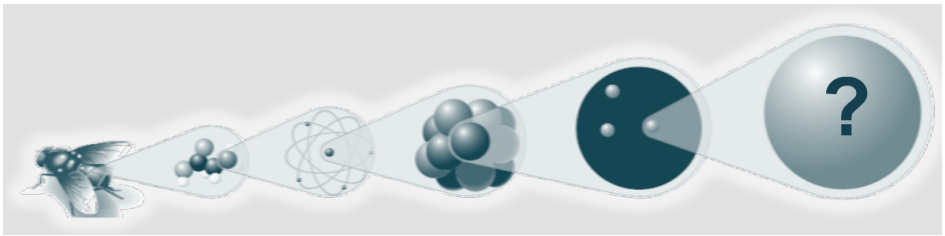
Sensitive to Quark Sub-Structure

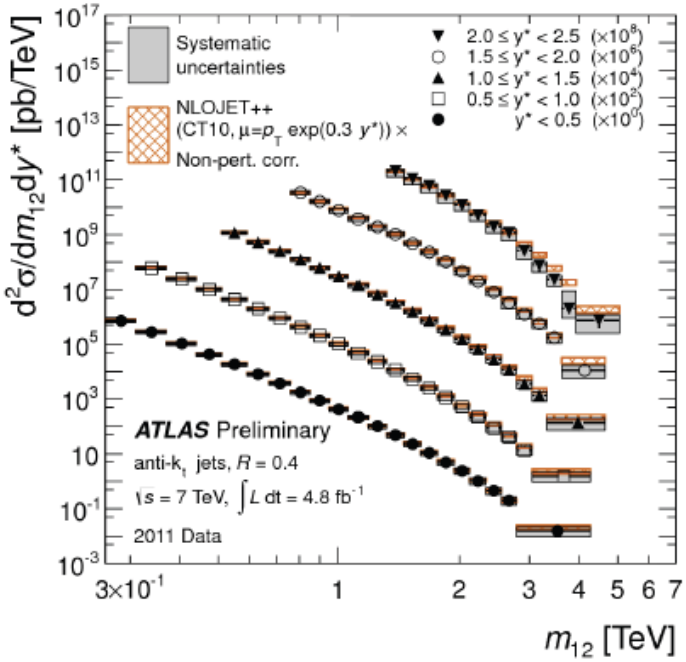


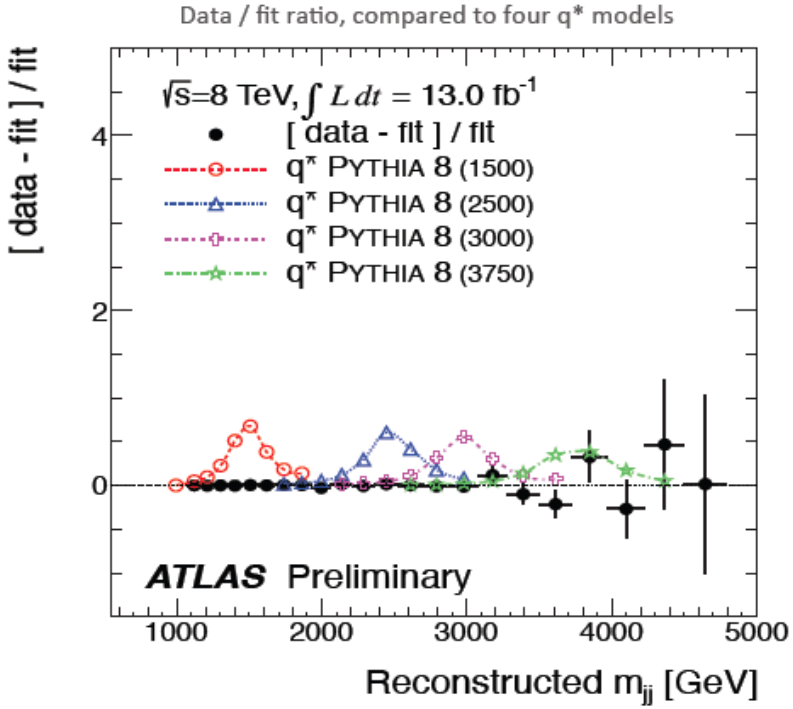
exclude quark compositeness at energy scales of Λ<4.0TeV at the 95%CL

Buscas por Ressonâncias Di-Jatos

existência de estados excitados de quarks: estrutura?



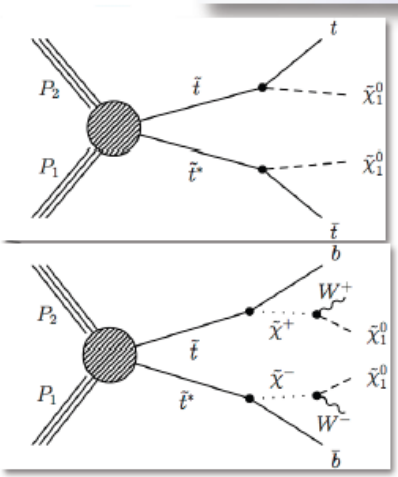


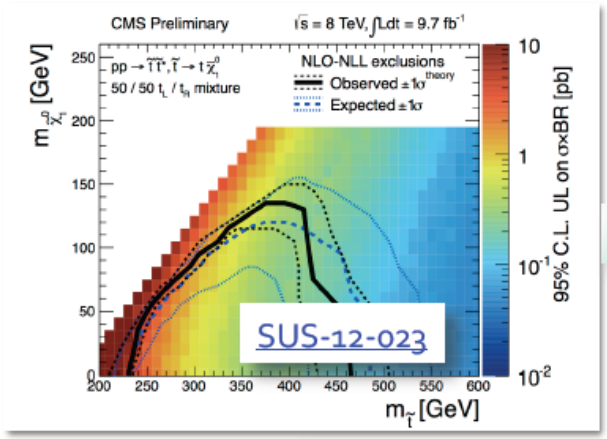


- $m(q^*) > 3.84\,\mathrm{GeV}/c^2$

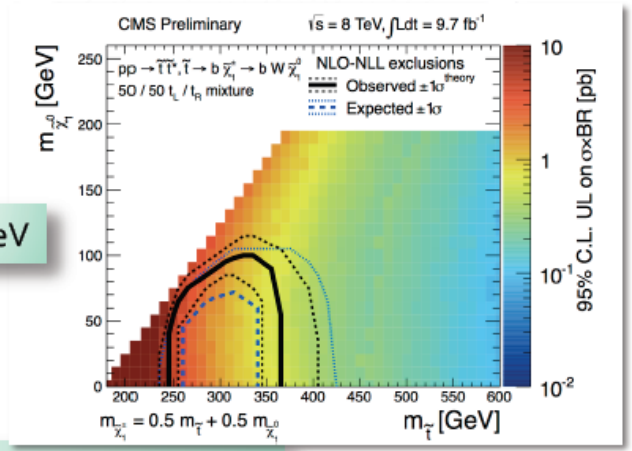
Busca por SUSY no CMS - exemplos

Search for direct top squark pair production



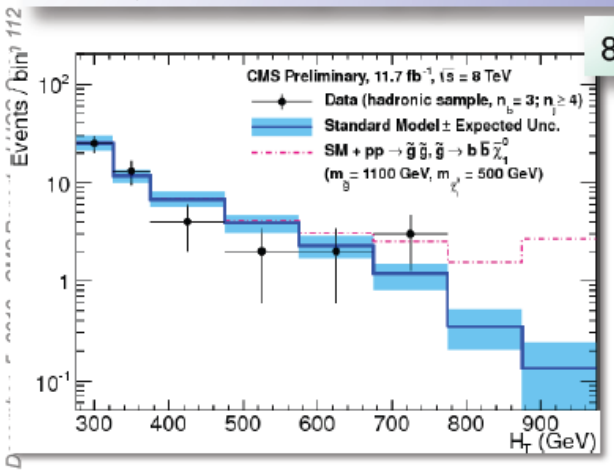


8 TeV

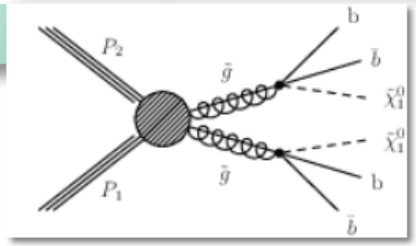


Search for supersymmetry in final state with E_T and 0,1,2,3, >= 4 b jets

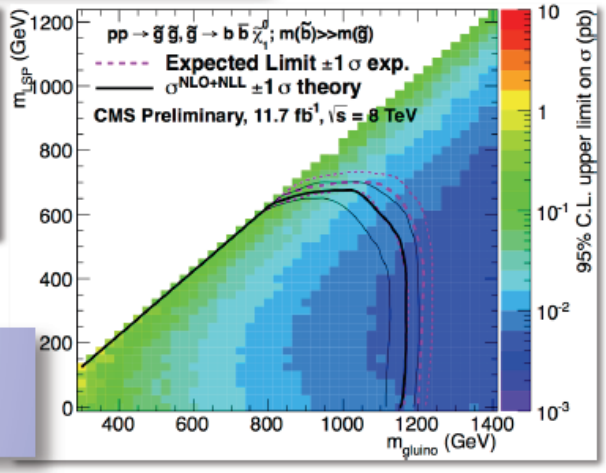
No excess in data observed above expected SM background.



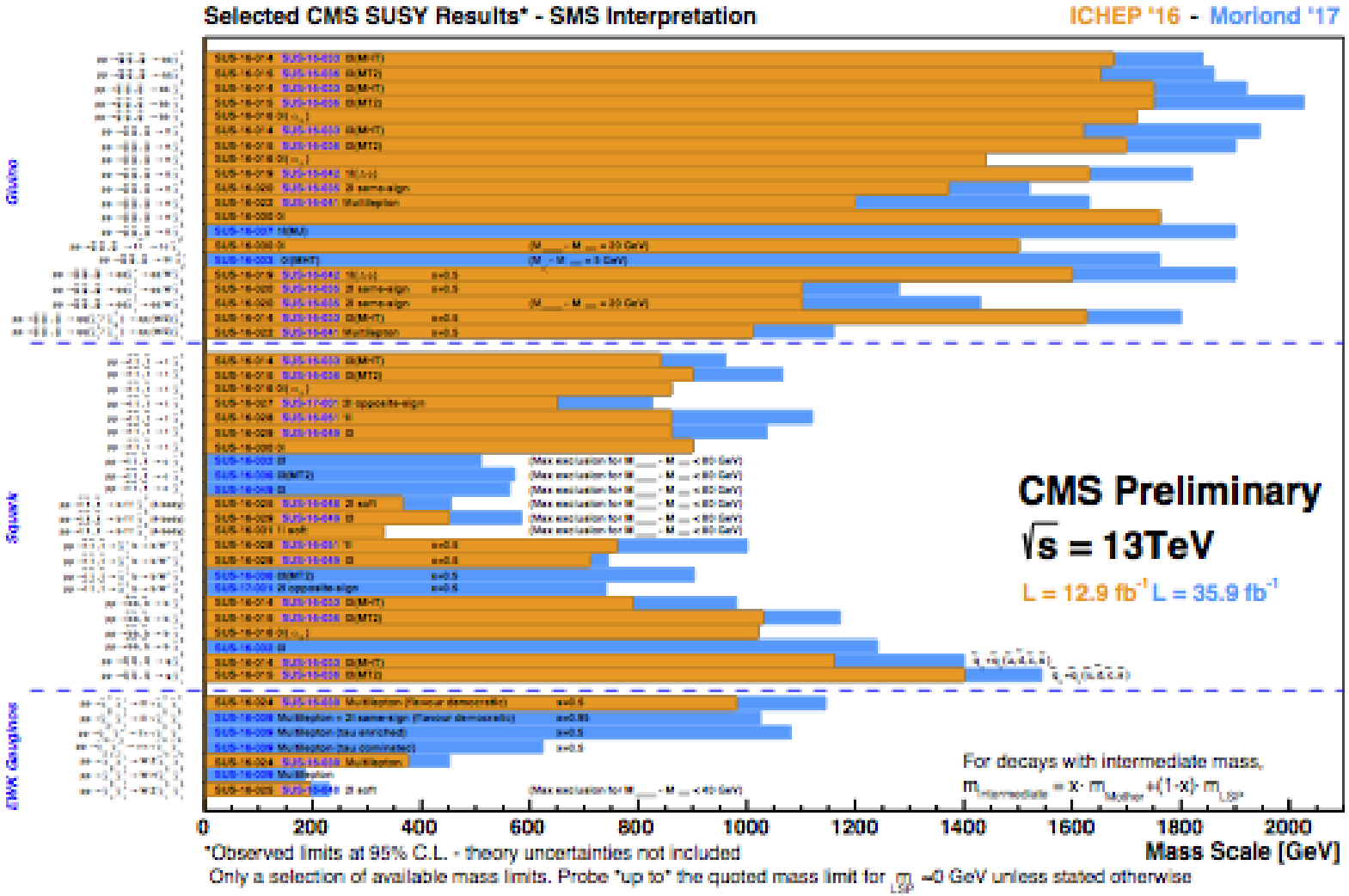
8 TeV



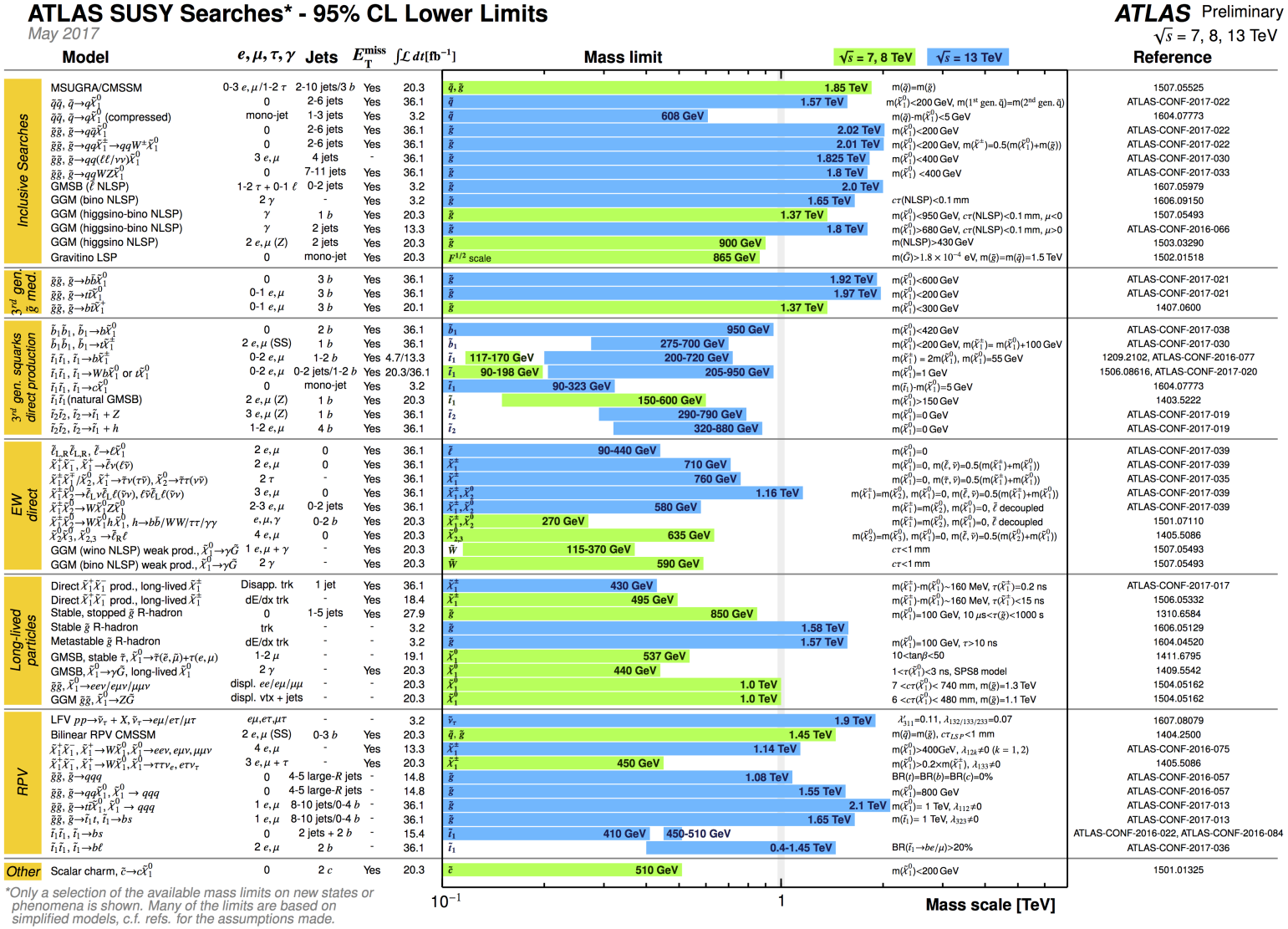
SUS-12-028



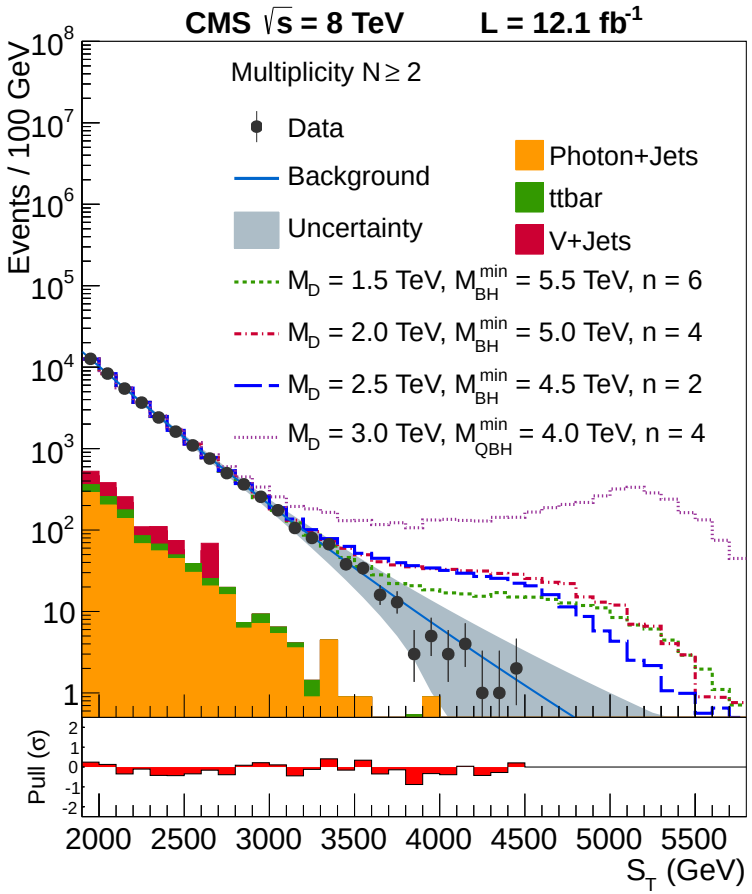
Exclusion for pair-produced gluinos, each decaying to a bottom quark-antiquark pair and a neutralino LSP.

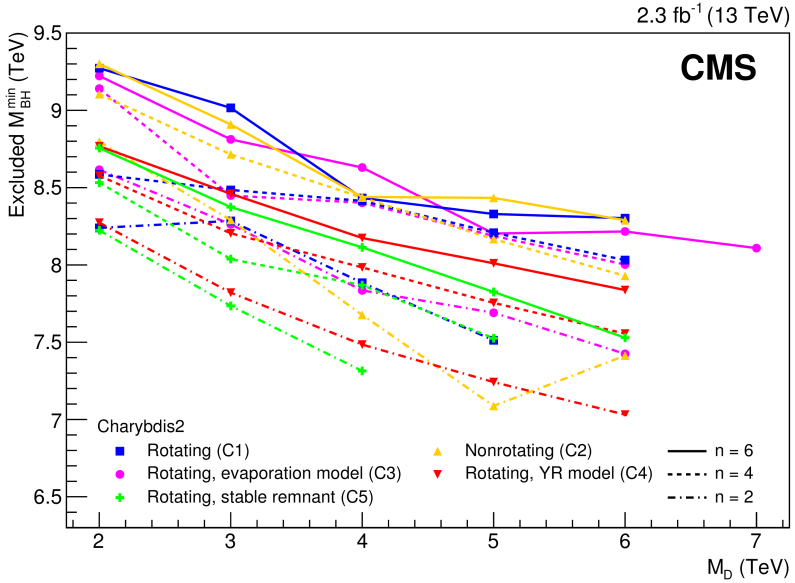

Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb-1 L = 35.9 fb-1
For decays with intermediate mass,
m_intermediate = x· m_Mother +(1-x)· m_LSP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe "up to" the quoted mass limit for m_LSP =0 GeV unless stated otherwise

Busca por SUSY no ATLAS

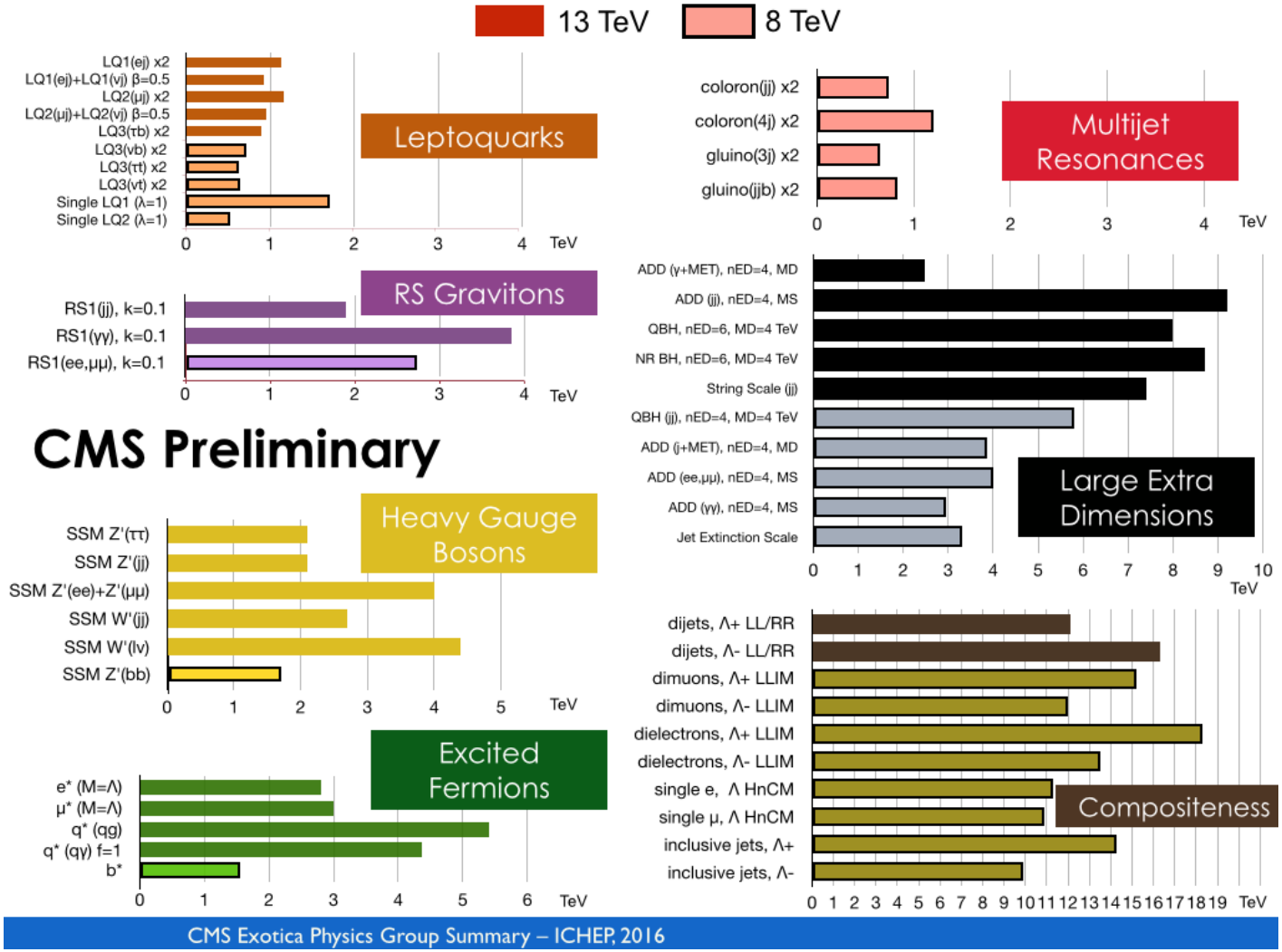


Busca por Mini Buracos Negros no CMS

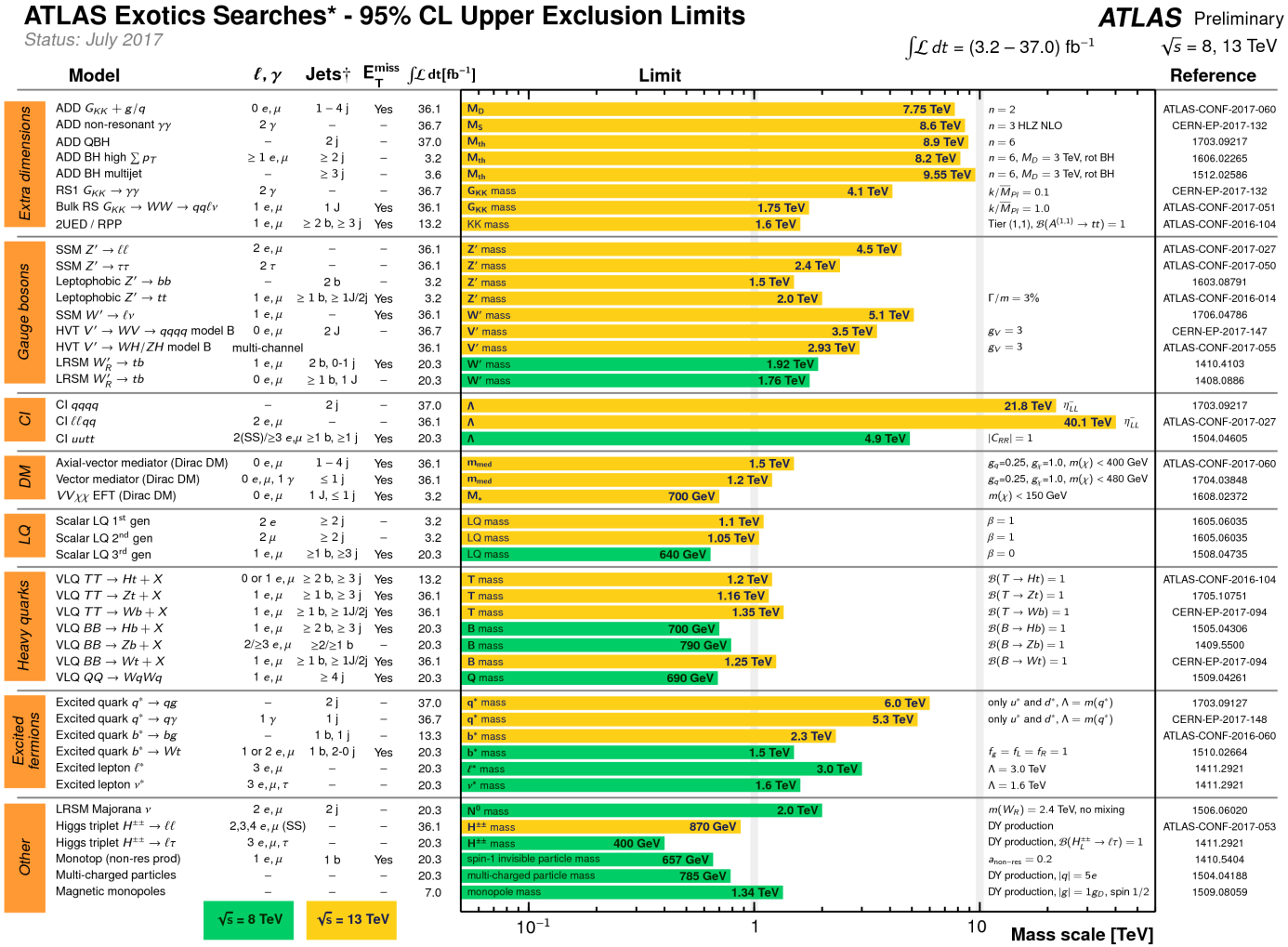




Resumo: Busca de Nova Física CMS



Resumo: Busca de Nova Física ATLAS

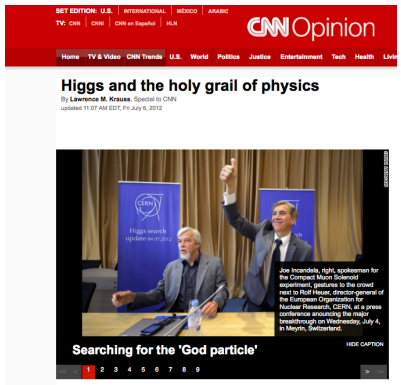


*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

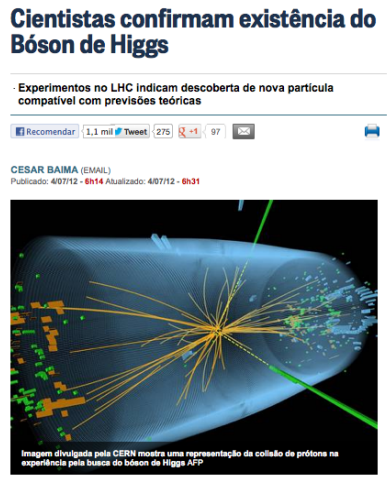
Higgs ... finalmente

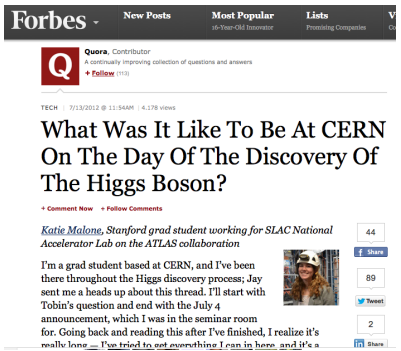








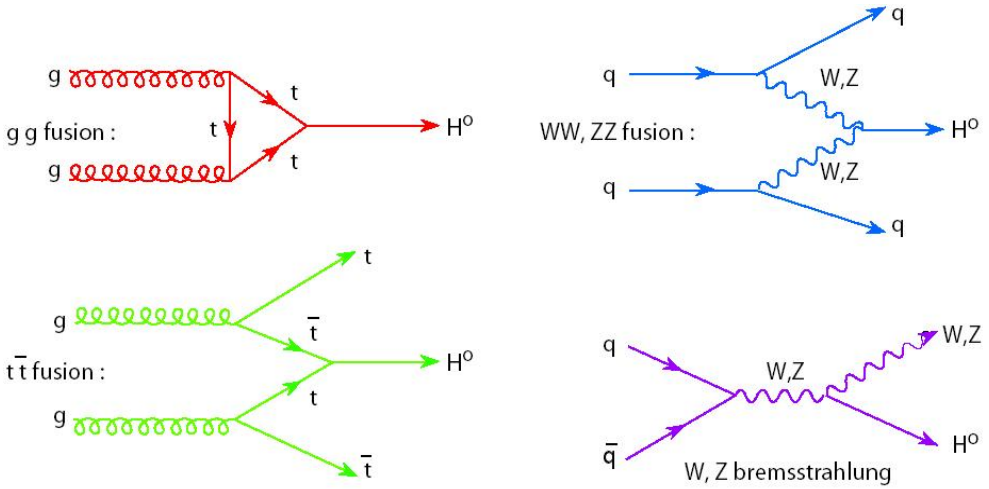


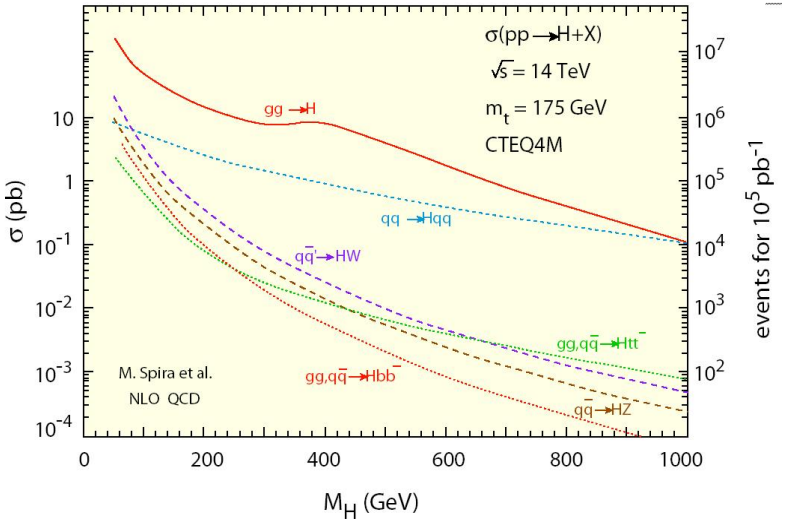




Produção e decaimentos do Higgs

Sabemos em que tipos de processos ele pode ser formado ...



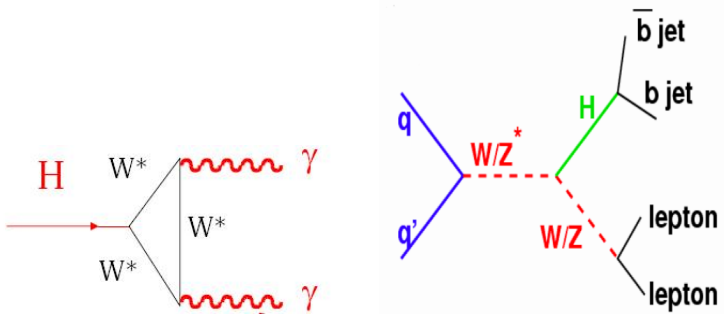


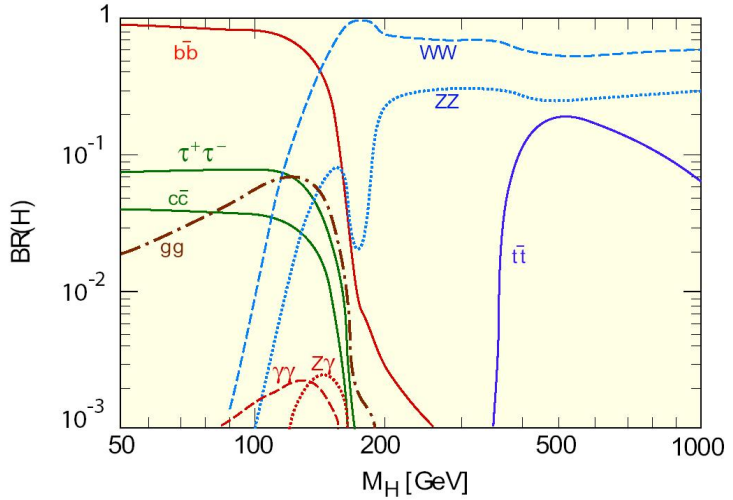
E como ele pode decair...

$H \to \gamma\gamma$; $H \to \tau\tau$

$H \to WW^* \to \ell\nu\ell\nu$; $H \to WW \to \ell\nu q\bar{q}$

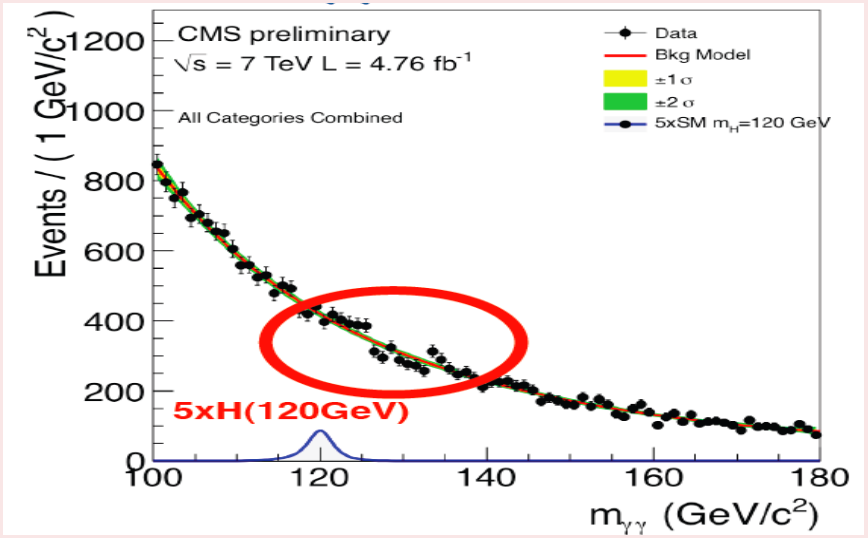
$H \to ZZ \to \ell\ell\nu\nu$; $H \to ZZ^* \to \ell\ell\ell\ell$

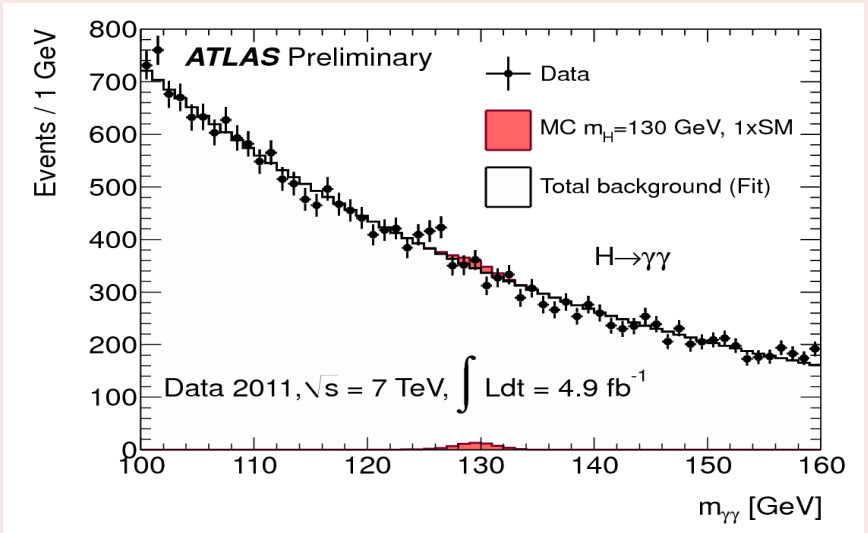




Primeiros Resultados ... $H \to \gamma\gamma$

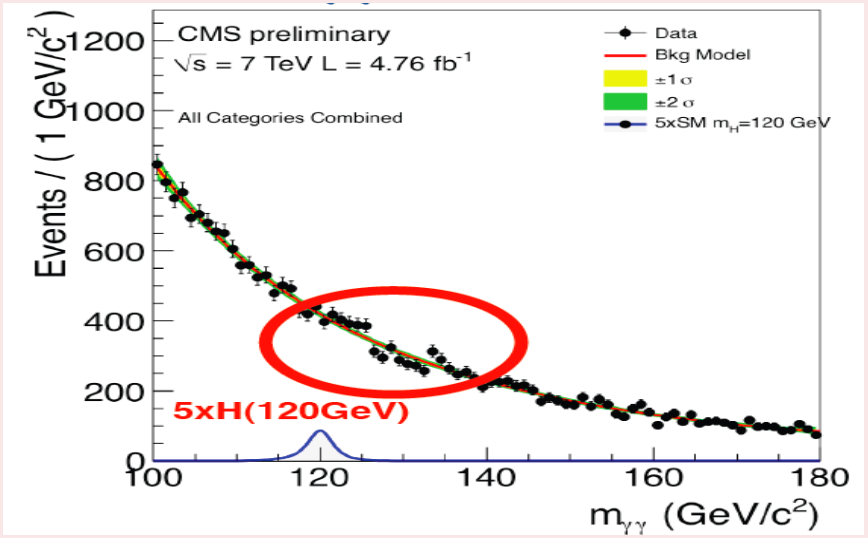
Pré-Descoberta - Dez'11

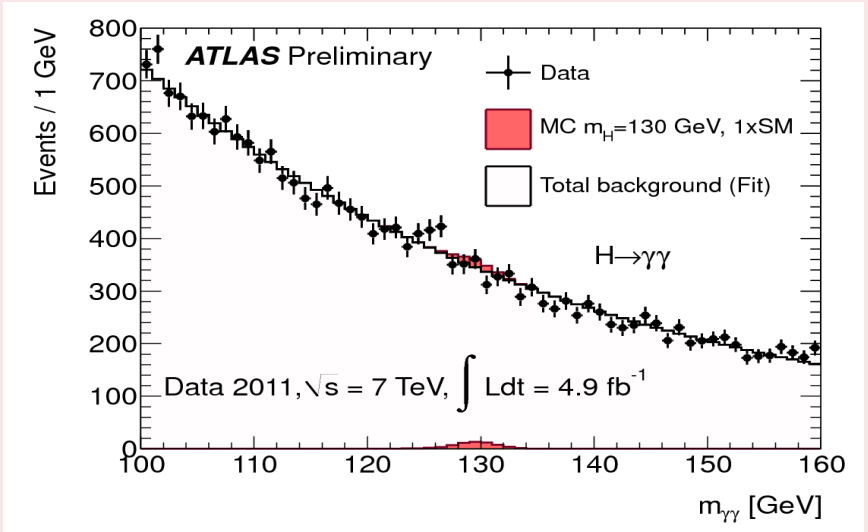




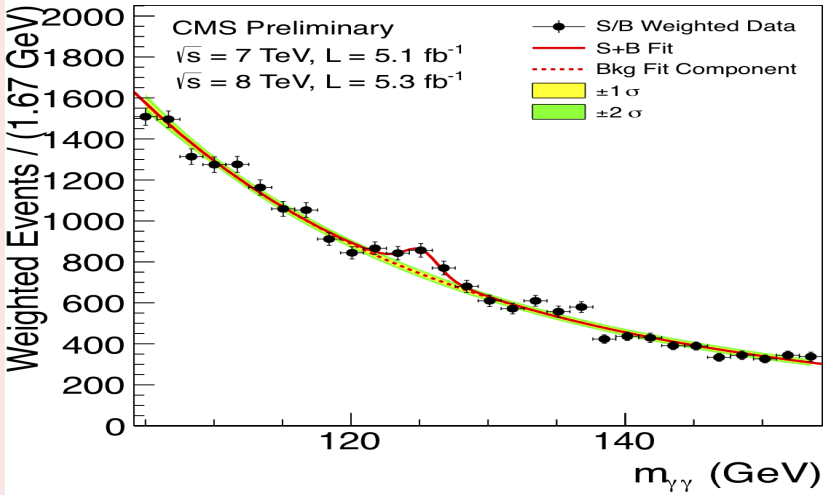
Primeiros Resultados ... $H \to \gamma\gamma$

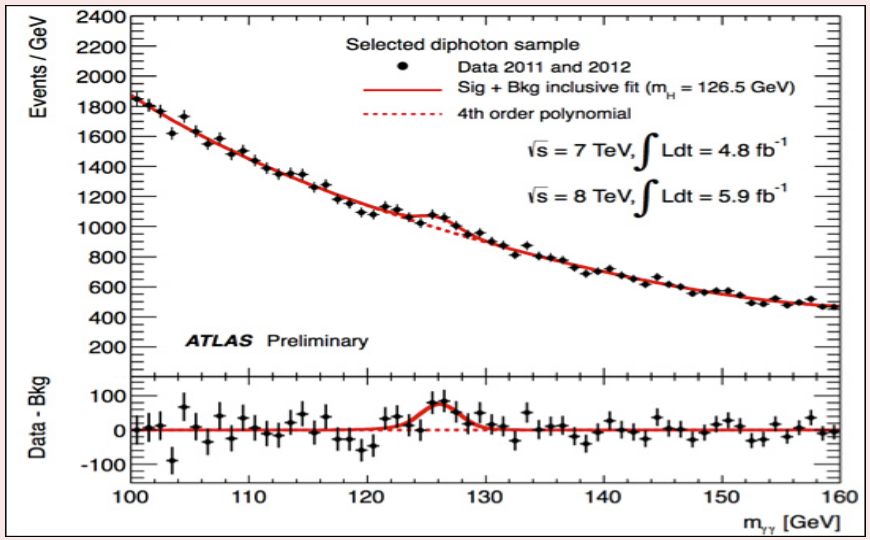
Pré-Descoberta - Dez'11





Descoberta - Jul'12





Entendendo o "Brazil plot"

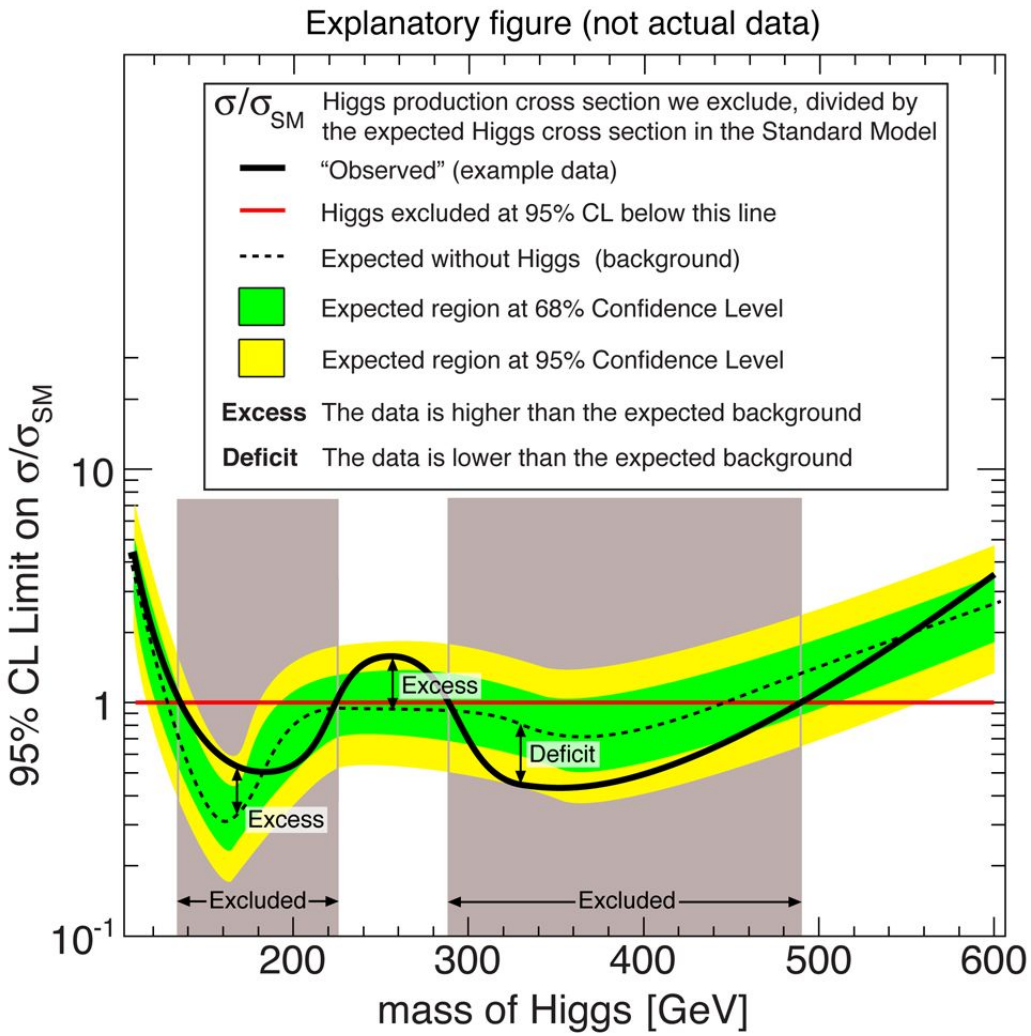
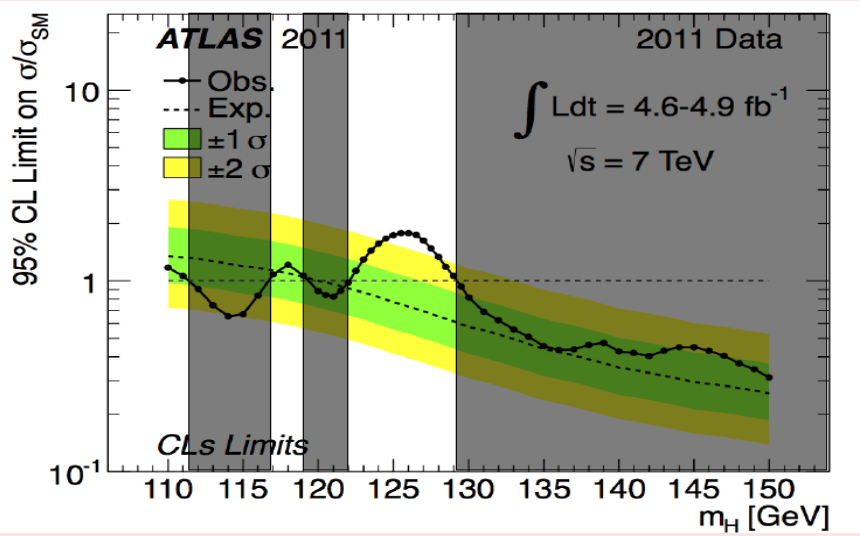
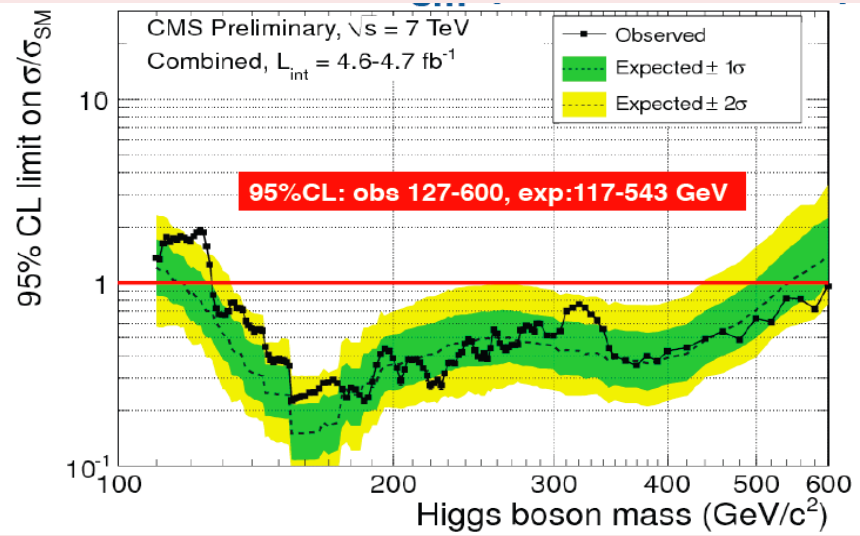


Figure A

Primeiros Resultados - Combinação

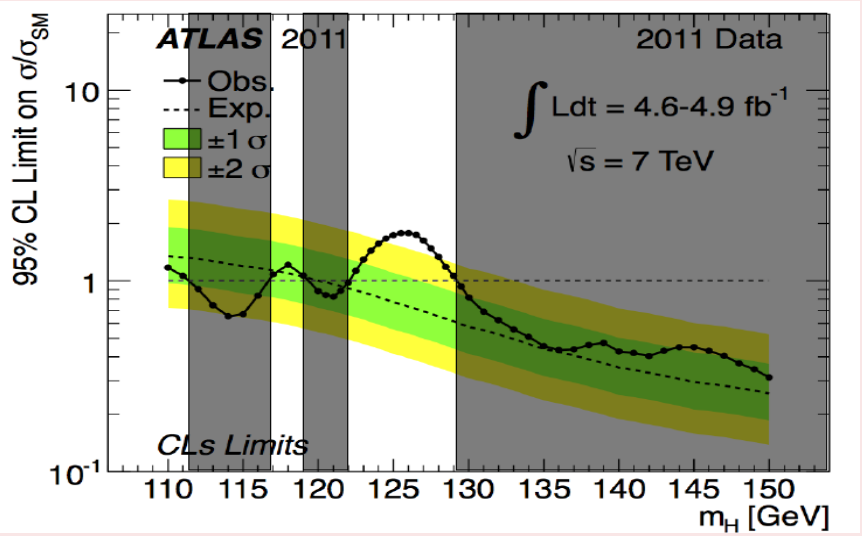
Pré-Descoberta - Dez'11

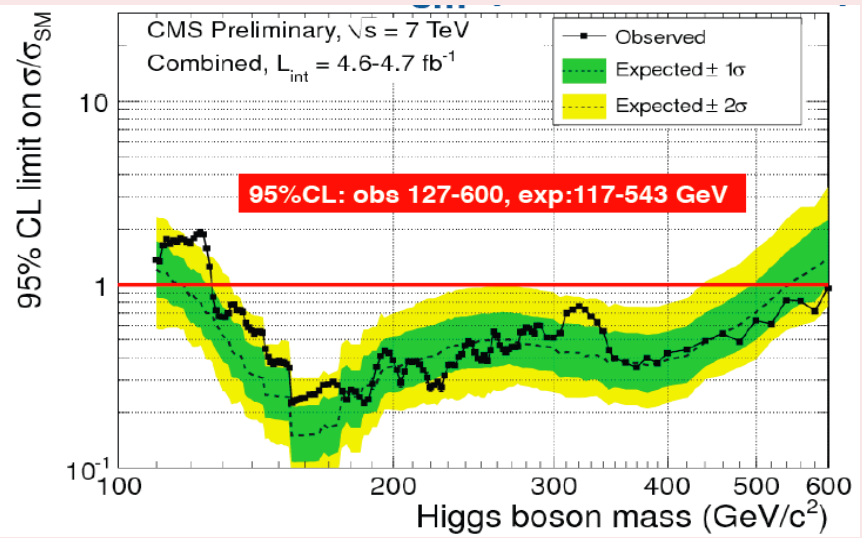




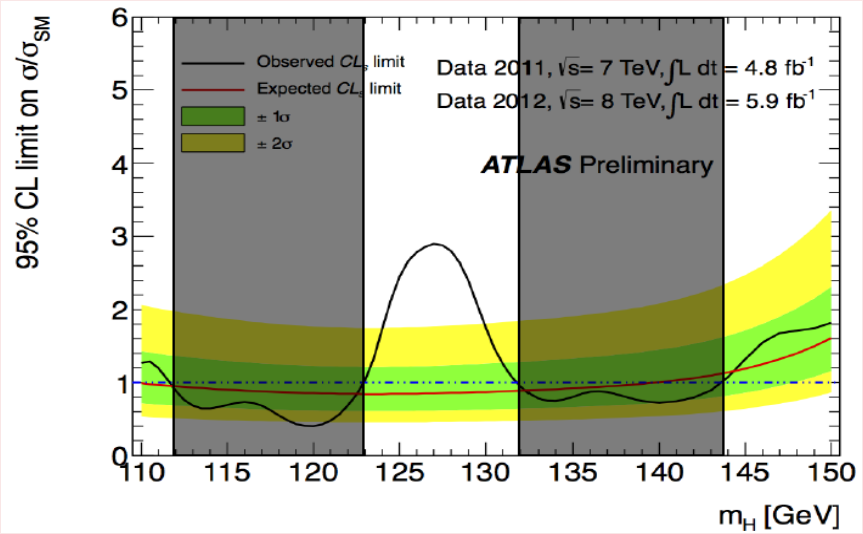
Primeiros Resultados - Combinação

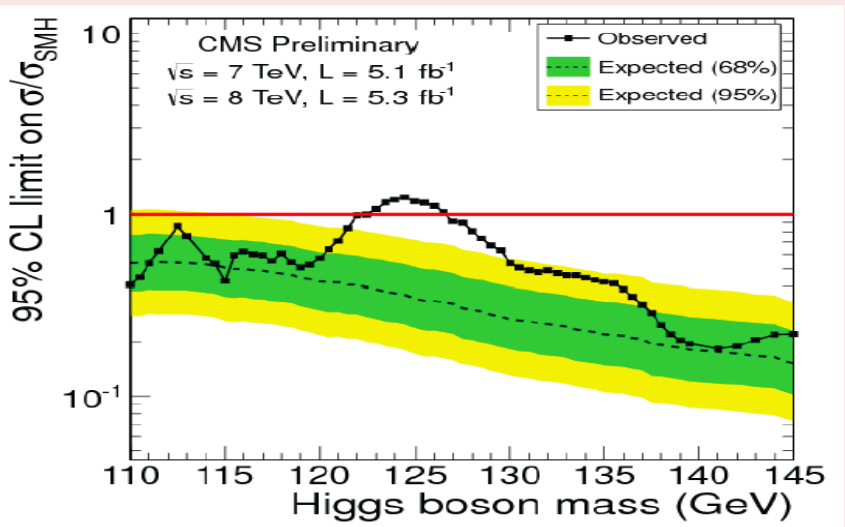
Pré-Descoberta - Dez'11





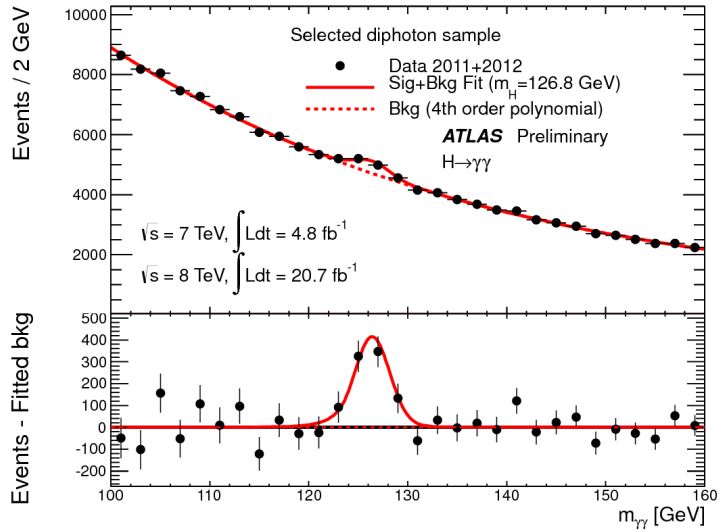
Descoberta - Jul'12

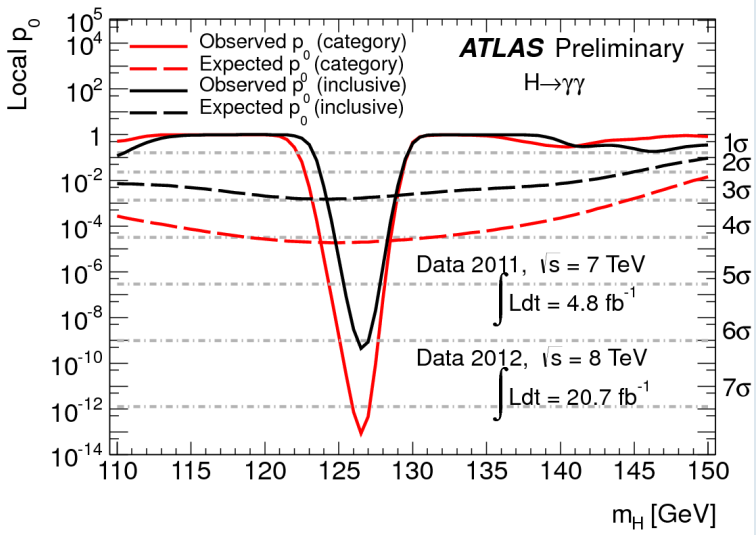




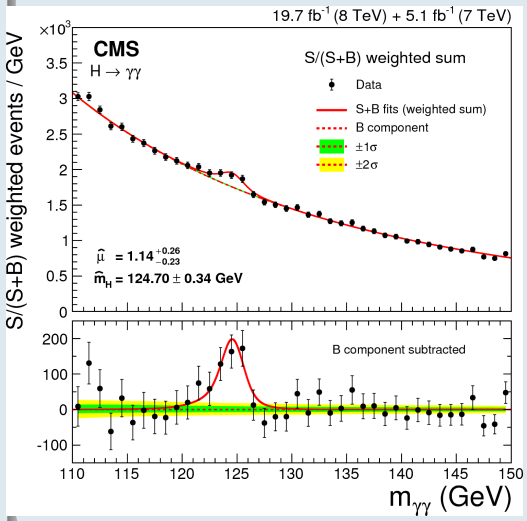
$H \to \gamma\gamma$ - run I

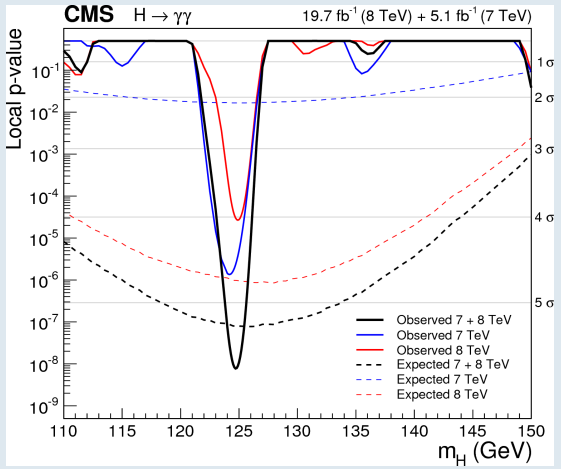
ATLAS





CMS

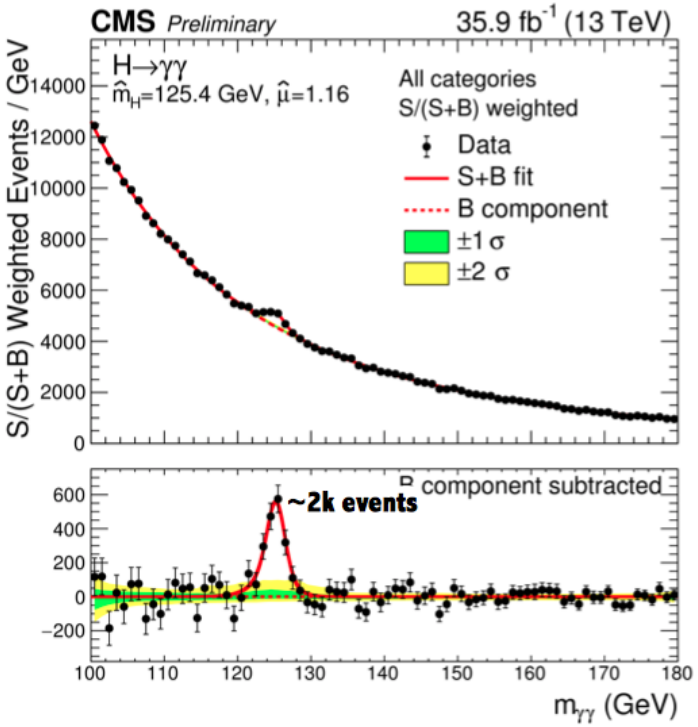




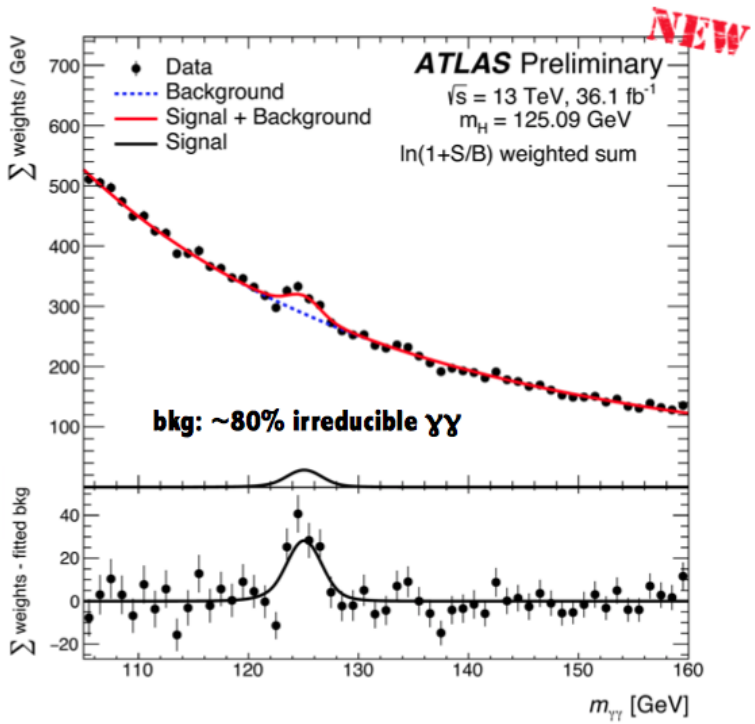
ATLAS:

- Medida com significância de 7.4σ em um único canal!
- massa $126.8 \pm 0.2 \pm 0.7 \mathrm{GeV}/c^2$

$H \to \gamma\gamma$ - run II



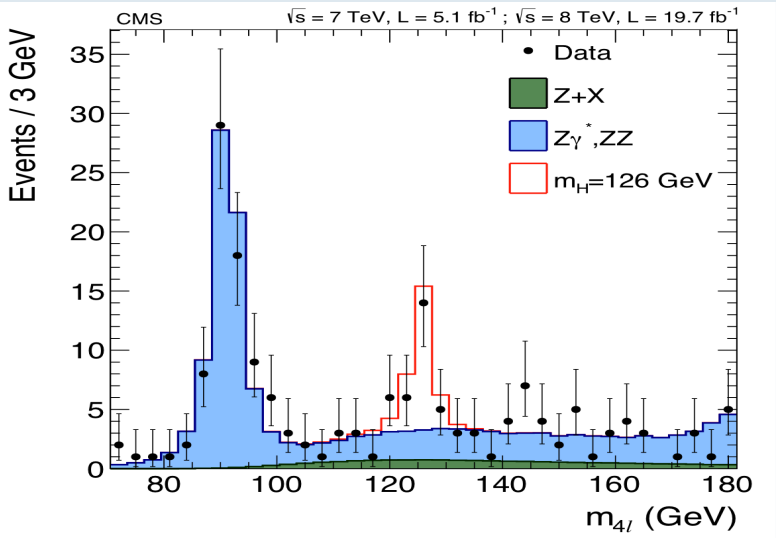
$$\mu = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}(\text{stat})^{+0.09}_{-0.08}(\text{exp})^{+0.06}_{-0.05}(\text{theo})$$

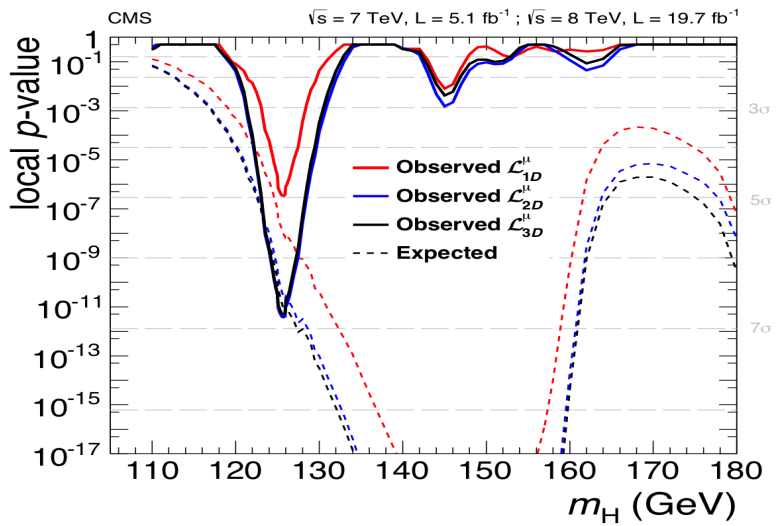


$$\mu = 0.99\ ^{+0.14}_{-0.14} = 0.99\ ^{+0.12}_{-0.11}\,(\text{stat.})\ ^{+0.06}_{-0.05}\,(\text{exp.})\ ^{+0.06}_{-0.05}\,(\text{theory})$$

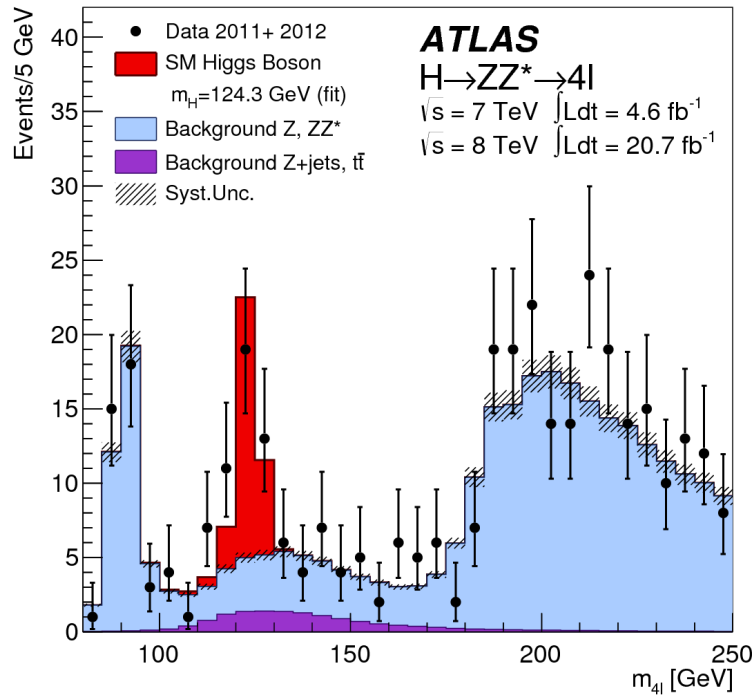
$H \to ZZ^* \to 4\ell^{\pm}$

CMS

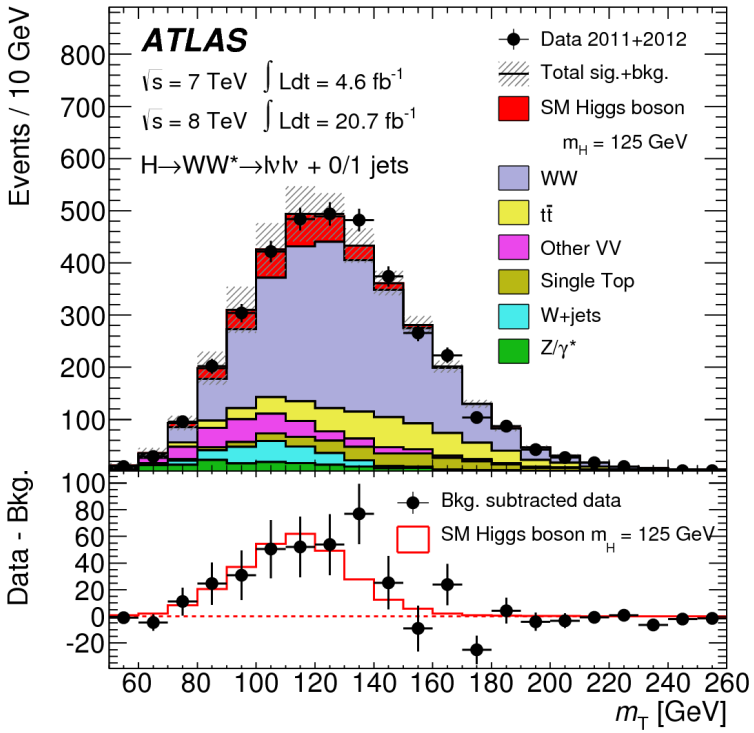


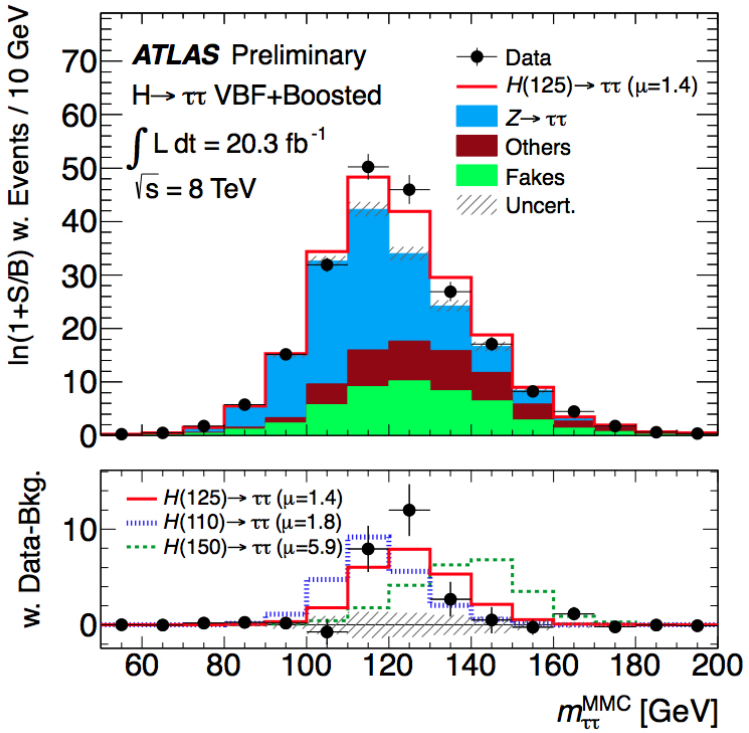


ATLAS



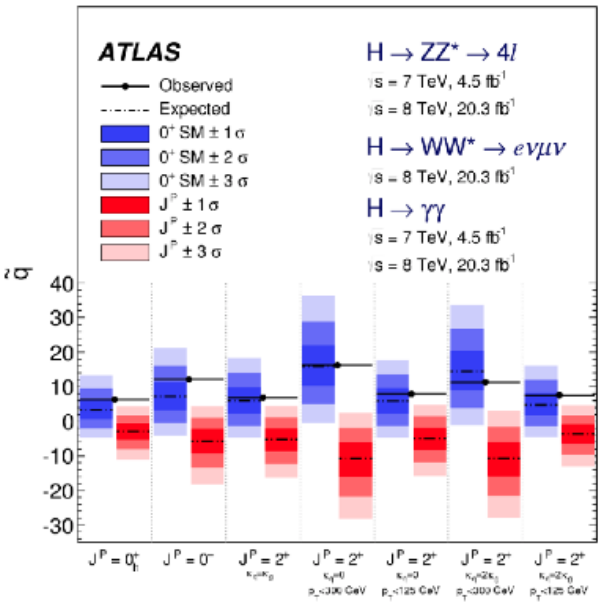
Outros canais ...

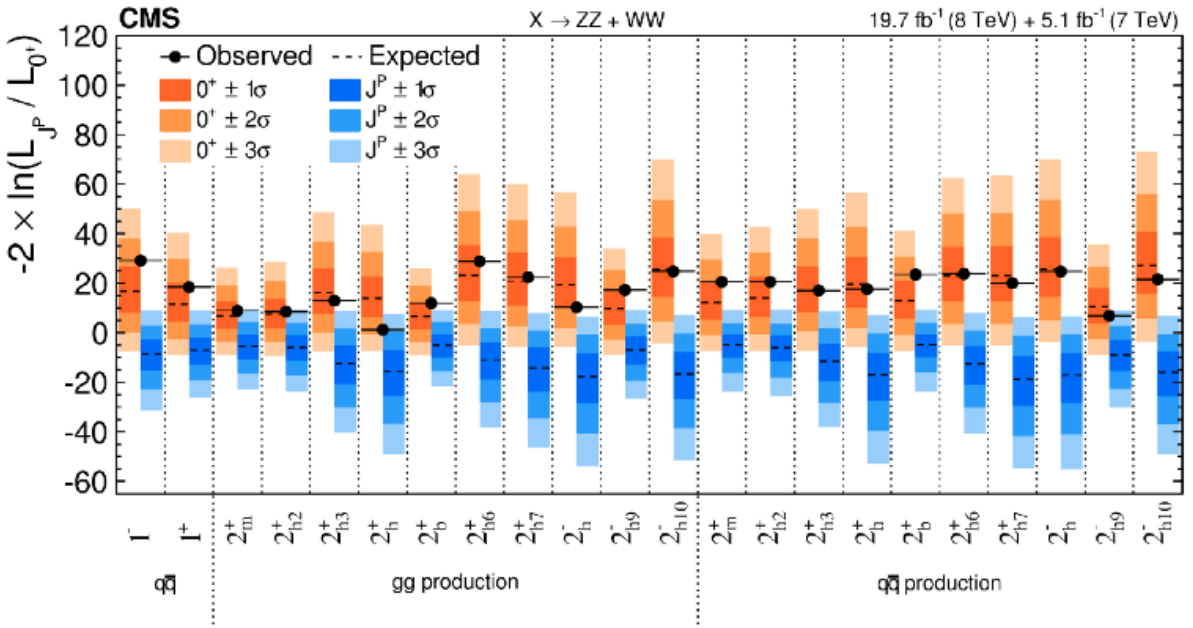




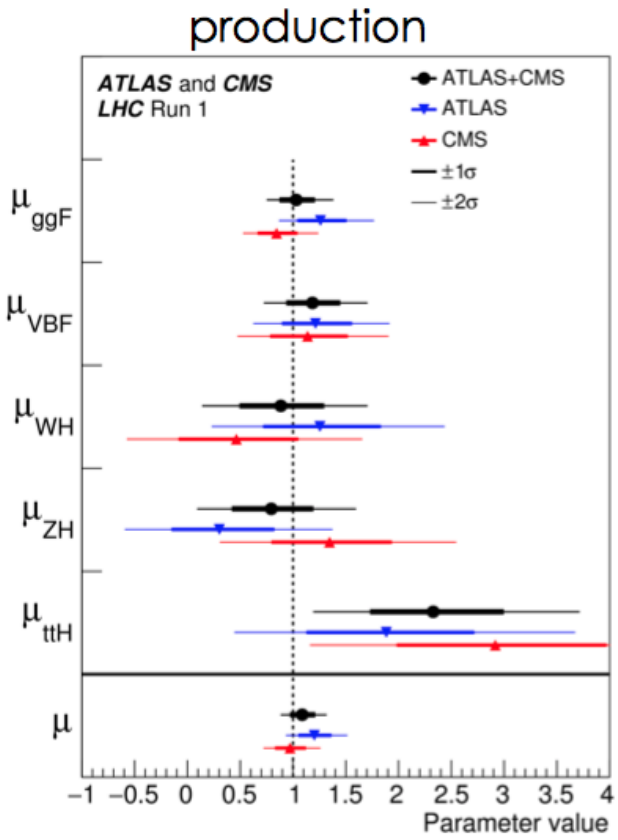
Spin e Paridade do Higgs ...

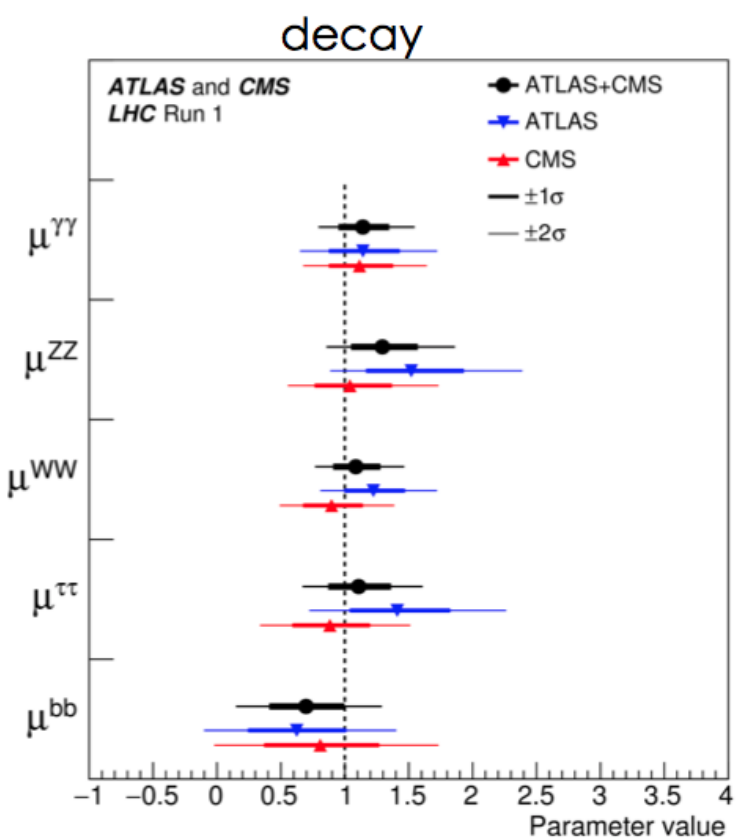
- O Higgs do MP é um bóson de spin 0, com números quânticos do vácuo $J^P = 0^+$ (escalar!)





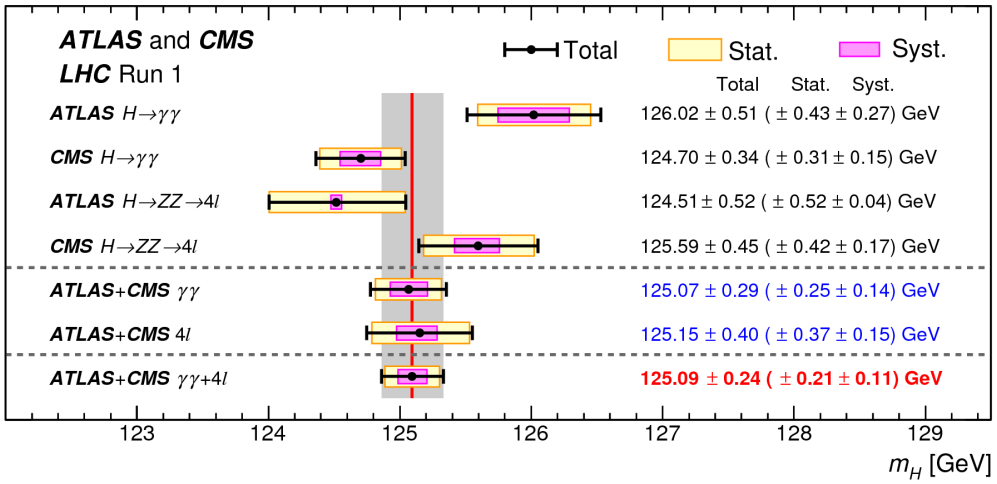
Acoplamentos



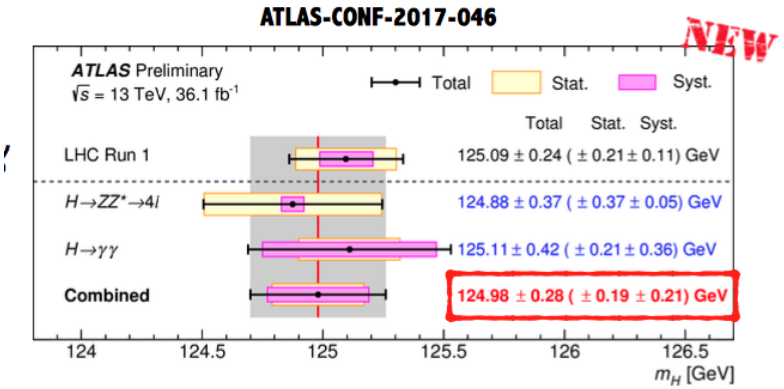


Medida de massa combinada

Run I - resultado final



Run II - primeiros resultados



CMS arXiv:1706.09936

$$m_H = 125.26 \pm 0.20(\text{stat}) \pm 0.08(\text{syst}) \text{ GeV}$$

Conclusões

- Física de Partículas sempre se baseou em nesses dois paradigmas complementares

  Fronteira de Energia e Fronteira de Precisão

- Até agora, buscas diretas (Fronteira de Energia) no LHC não mostraram nenhuma indicação de "Nova Física"

  De fato, Modelo Padrão vem se mostrando incrível !!!

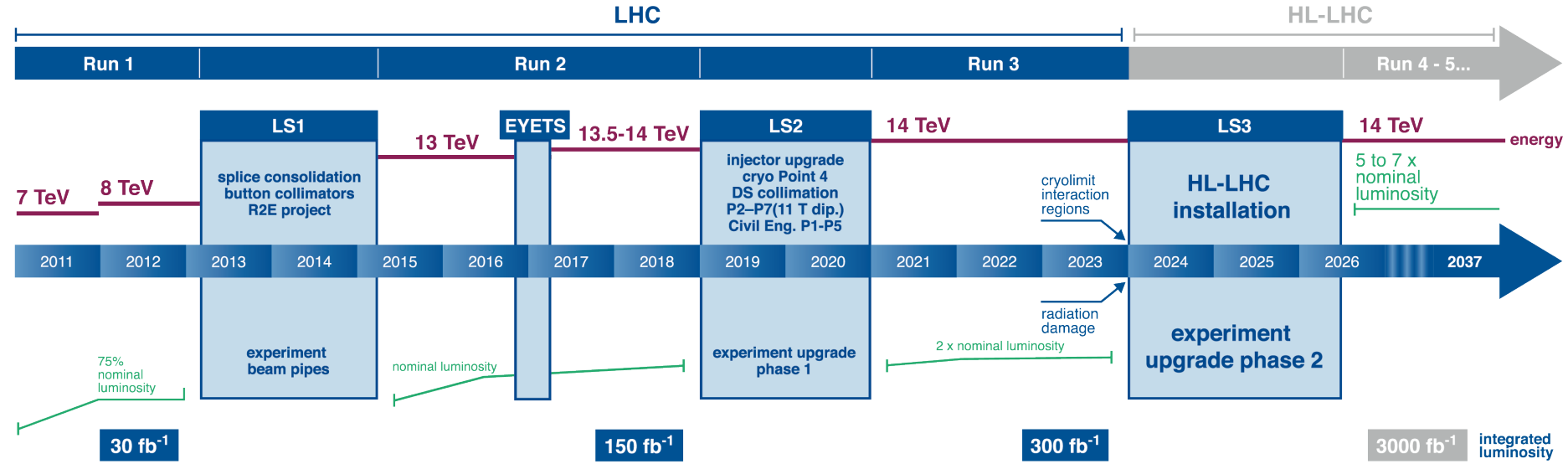
- Porém, alguns interessantes sinais com efeitos de $2 - 4\sigma$ vêm aparecento a partir de buscas indiretas (Fronteira de Precisão) em Física de Sabores

  mas... por que de fato ainda não apareceu claramente? Escalas acima de 100 TeV?

- De qualquer forma, próximos anos serão excitantes! Esperamos!

OBRIGADA

Futuro do LHC



Referências

Introdutórios:

- F. Close, "Particle Physics: A Very Short Introduction", Oxford University Press (2004).
- B. Martin, "Particle Physics: A Beginner's Guide", Oneworld Publications (2011).

Mais avançados:

- M. Thomson, "Modern Particle Physics", Cambridge University Press (2013).
- G. Kane, "Modern Elementary Particle Physics: Exploring and Extending the Standard Model", 2nd Ed., Cambridge University Press (2017).
- D. Griffiths, "Introduction to Elementary Particles", 2nd Ed., Wiley-VCH (2008).
- F. Halzen, A. Martin. "Quarks & Leptons: An Introductory Course in Modern Particle Physics", John Wiley & Sons (1984).

Páginas dos experimentos LHC:

- ATLAS: https://atlas.cern/
- CMS: https://cms.cern/
- ALICE: http://aliceinfo.cern.ch/Public/Welcome.html
- LHCb: http://lhcb-public.web.cern.ch/lhcb-public/

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