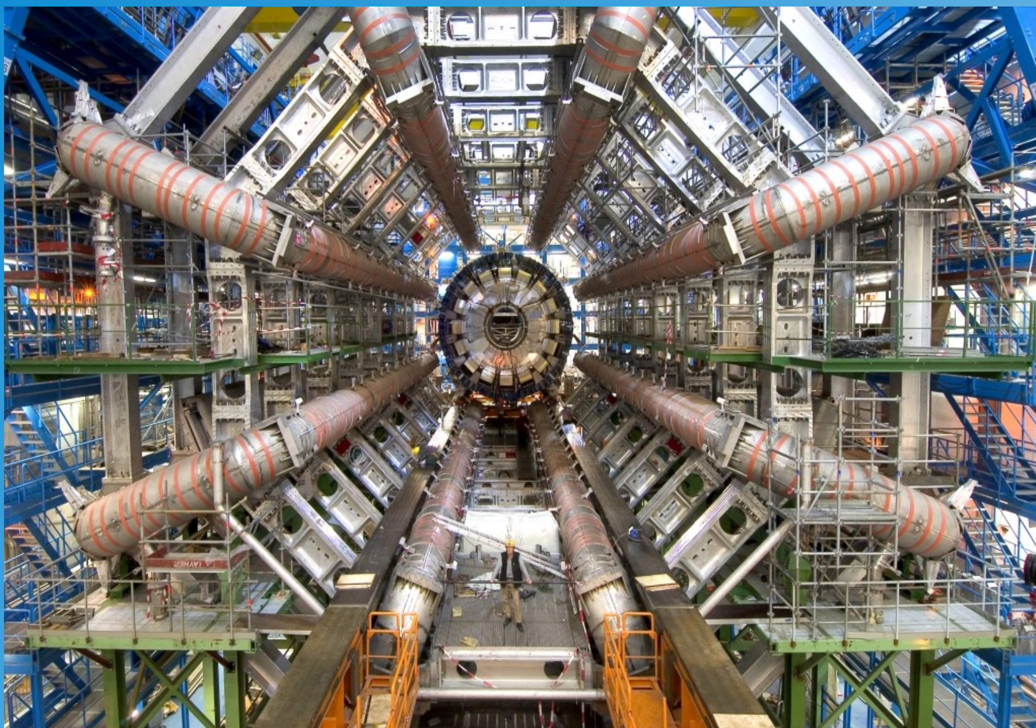
High Energy Frontier - Recent Results from the LHC

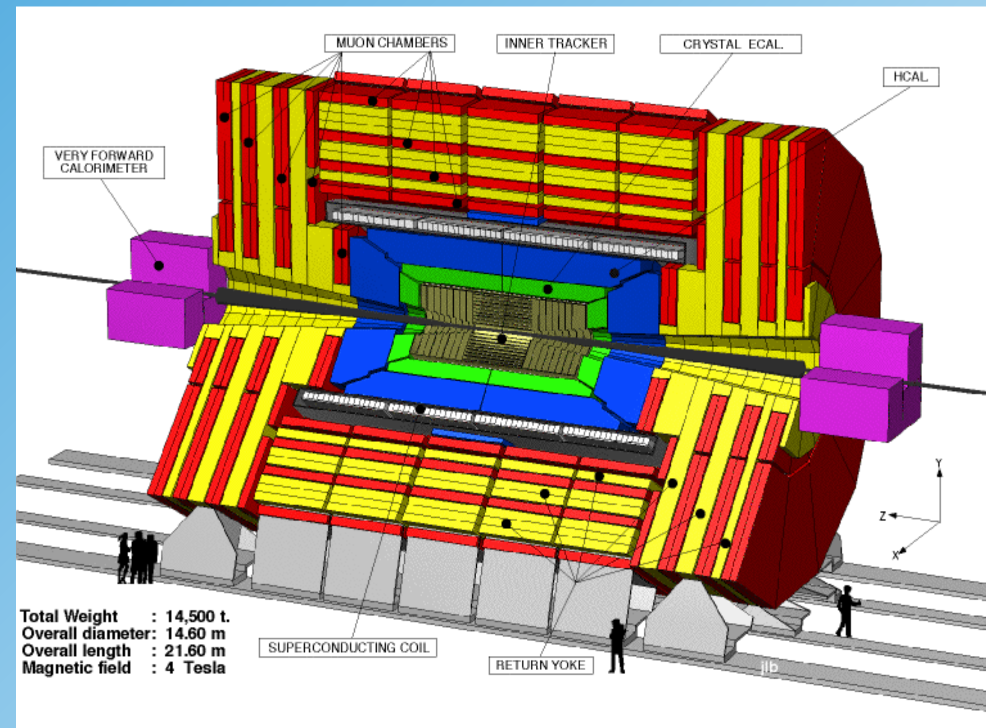
University of Heidelberg WS 2012/13

Lecture 2

LHC-Searches I

LHC: The Energy Frontiere





ATLAS = An ToroidaL ApparatuS

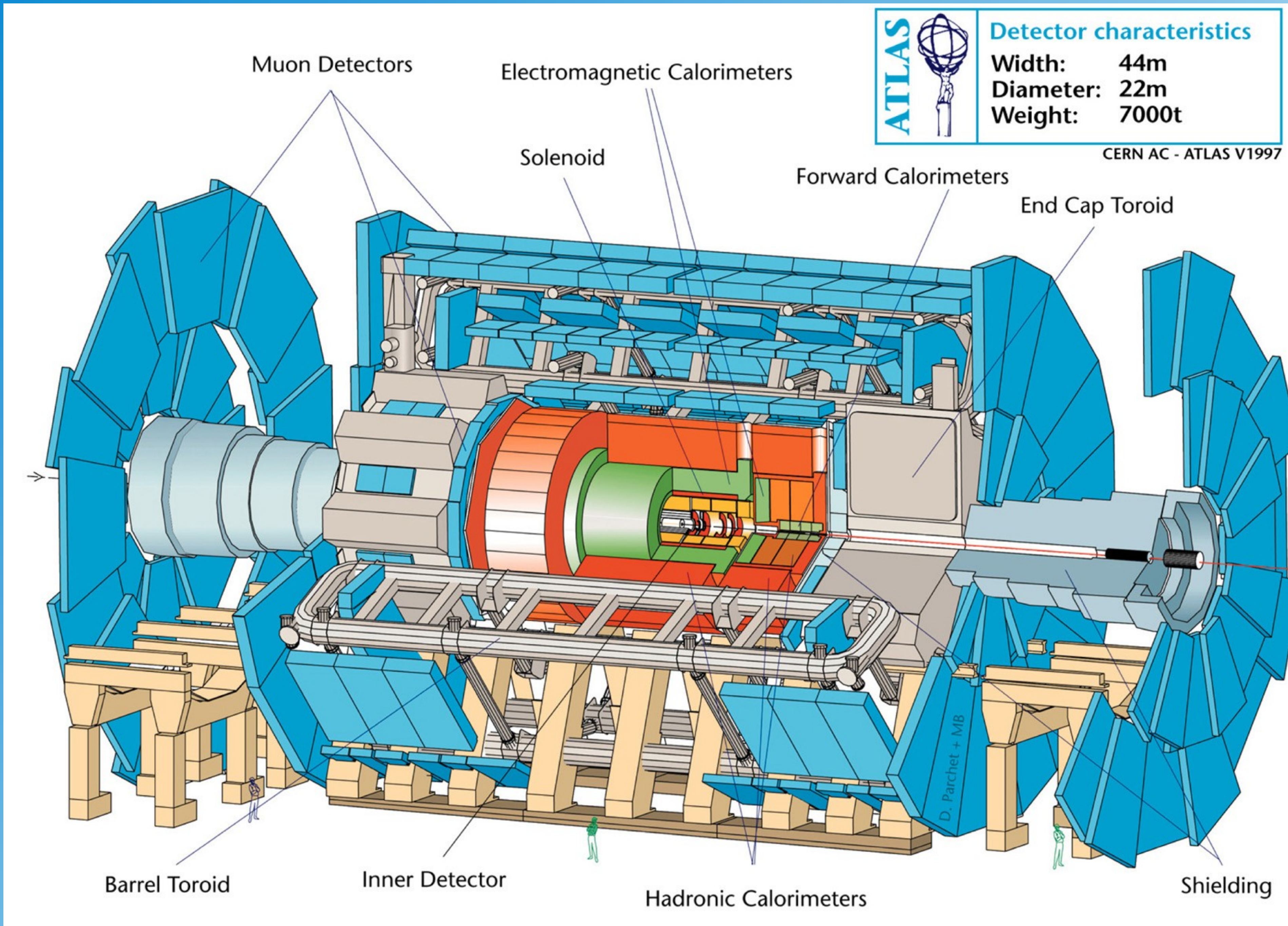
~ 2900 authors

CMS = Compact Muon Solenoid

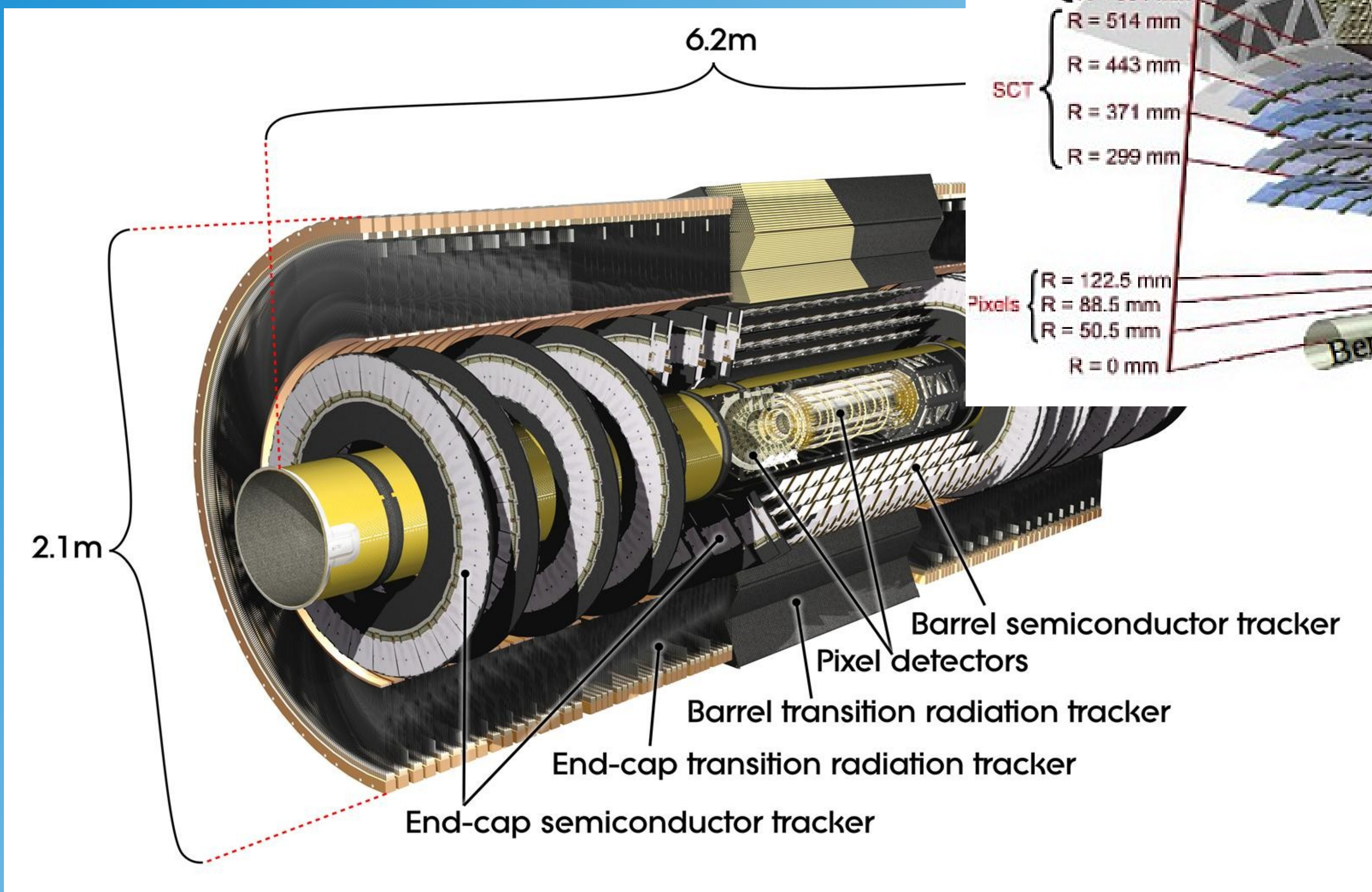
~ 2200 authors

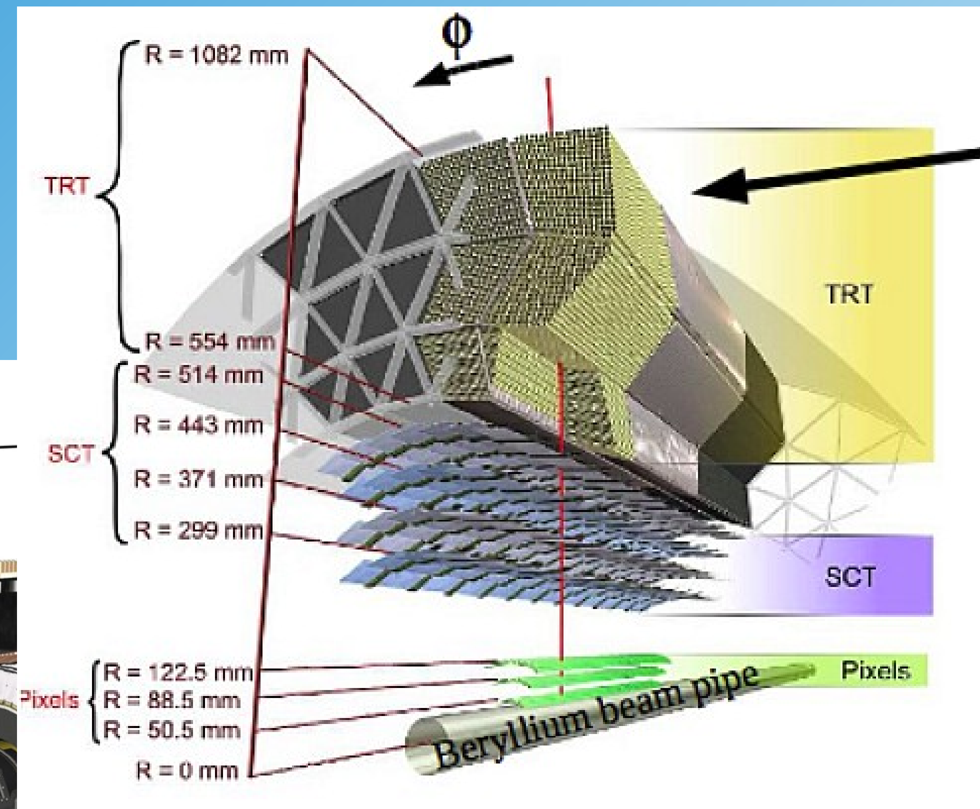
about 350 publication in last two years!
most are Searches for New Phyisics

ATLAS Detector

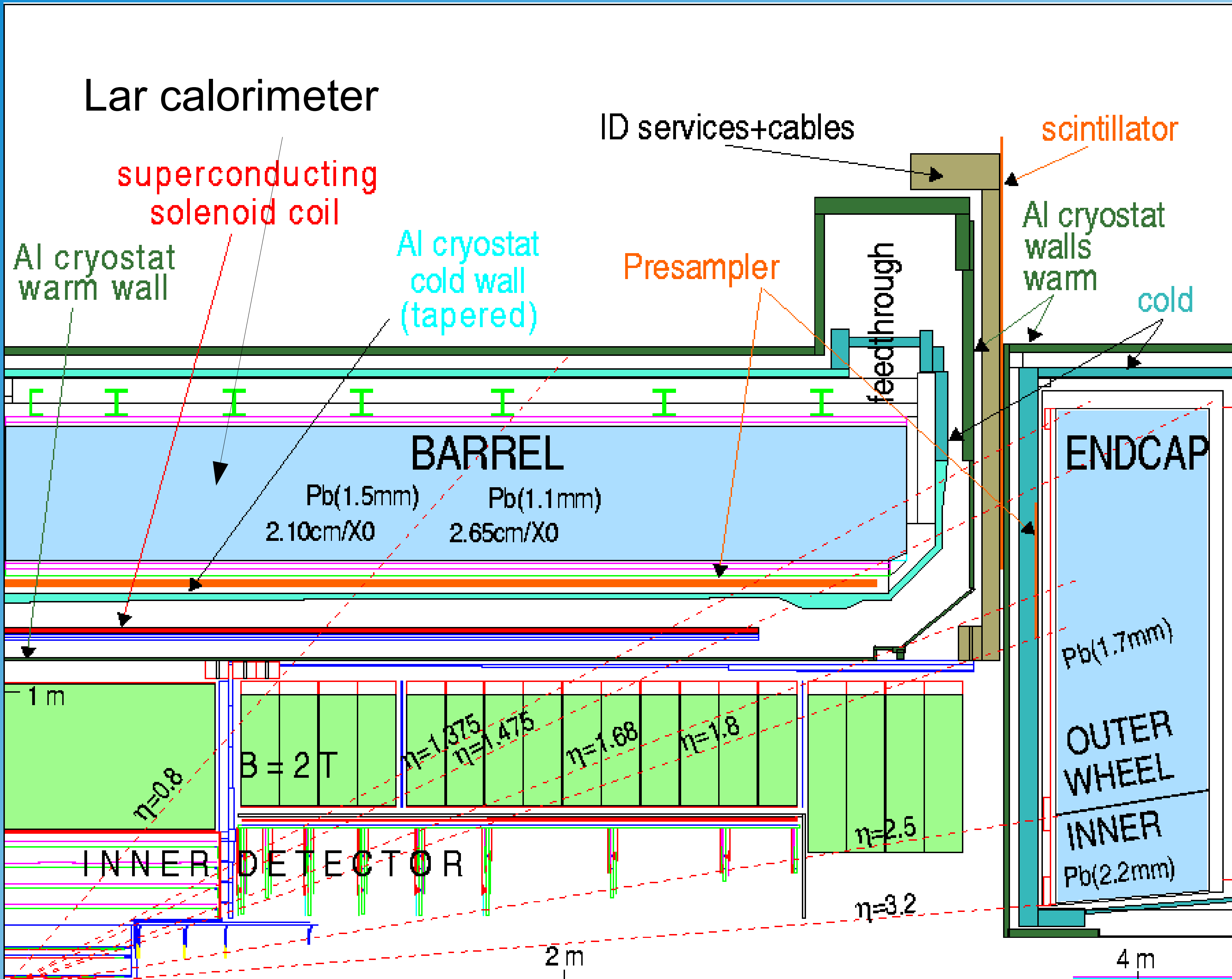


ATLAS Inner Detector

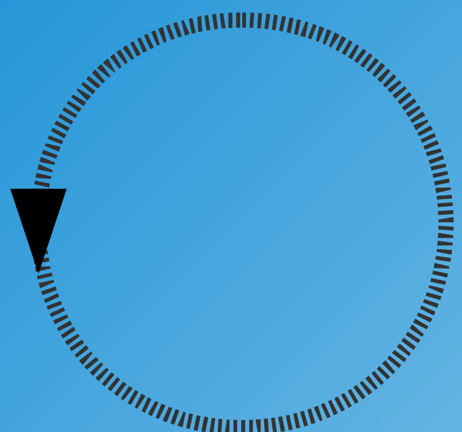


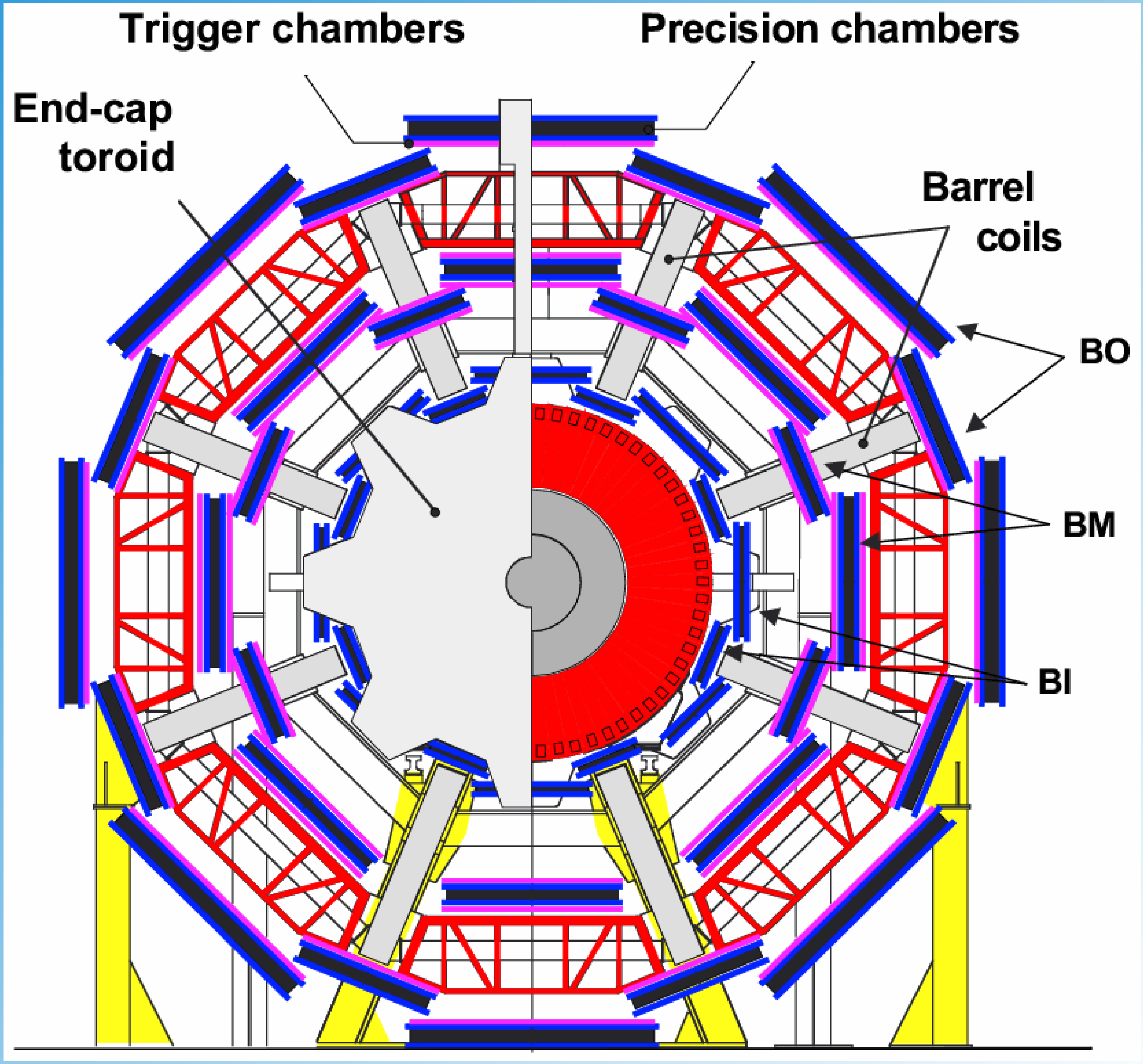


ATLAS Detector

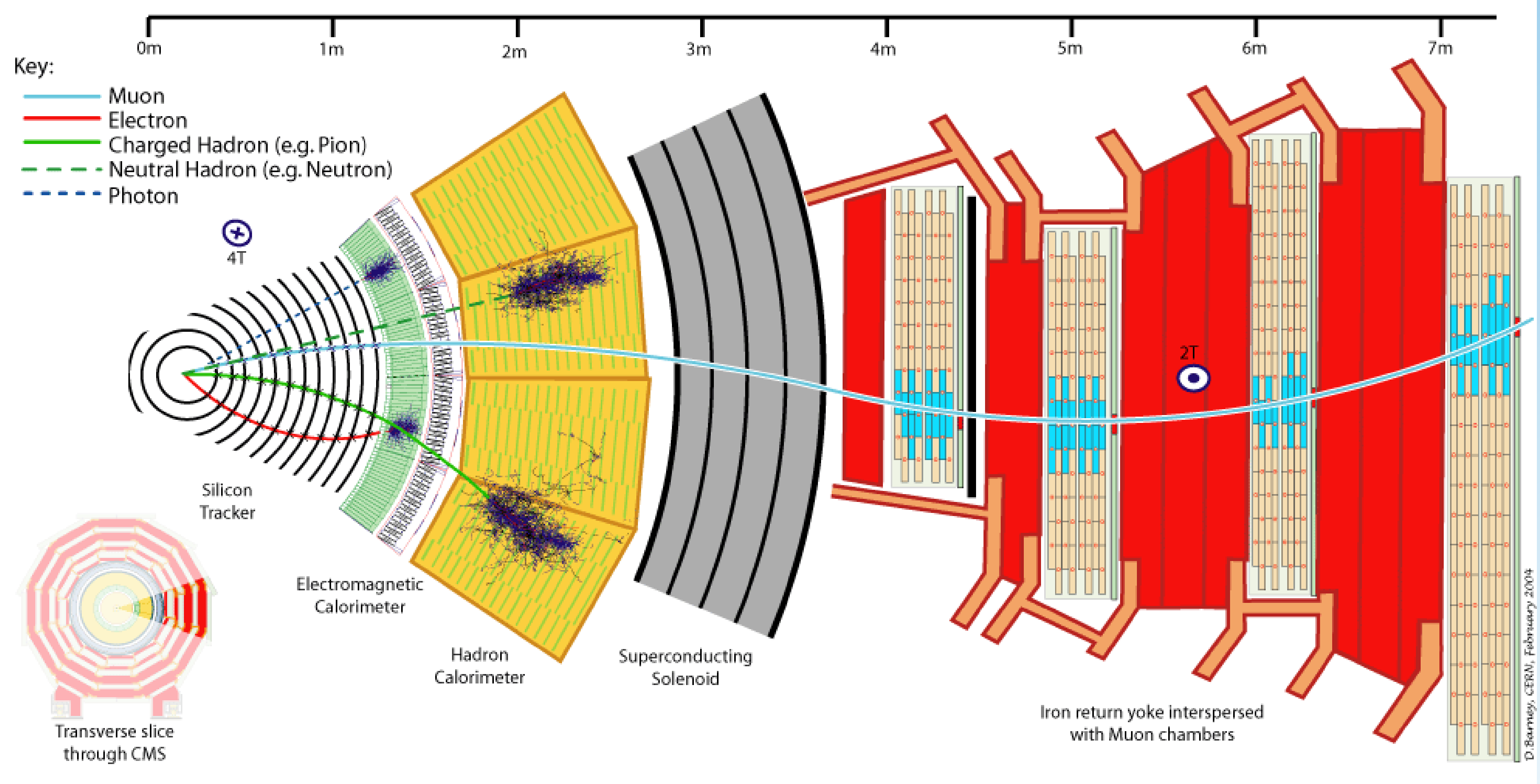


ATLAS Muon Detector



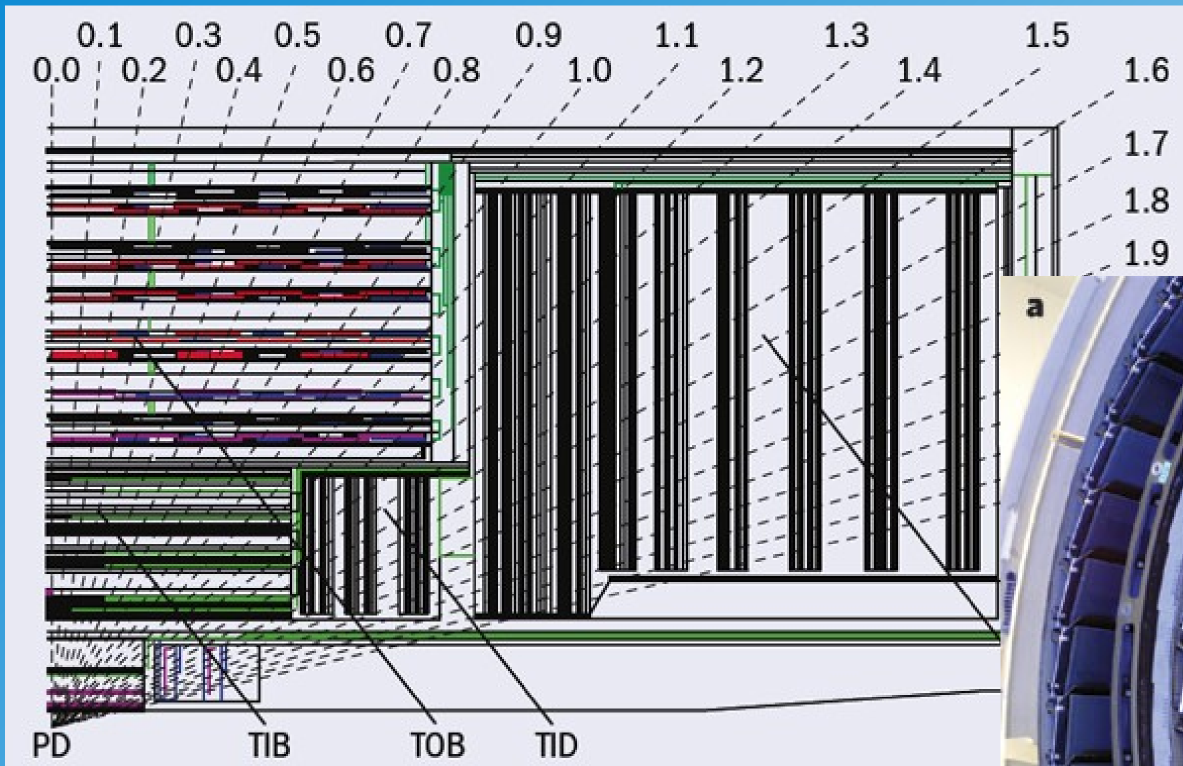


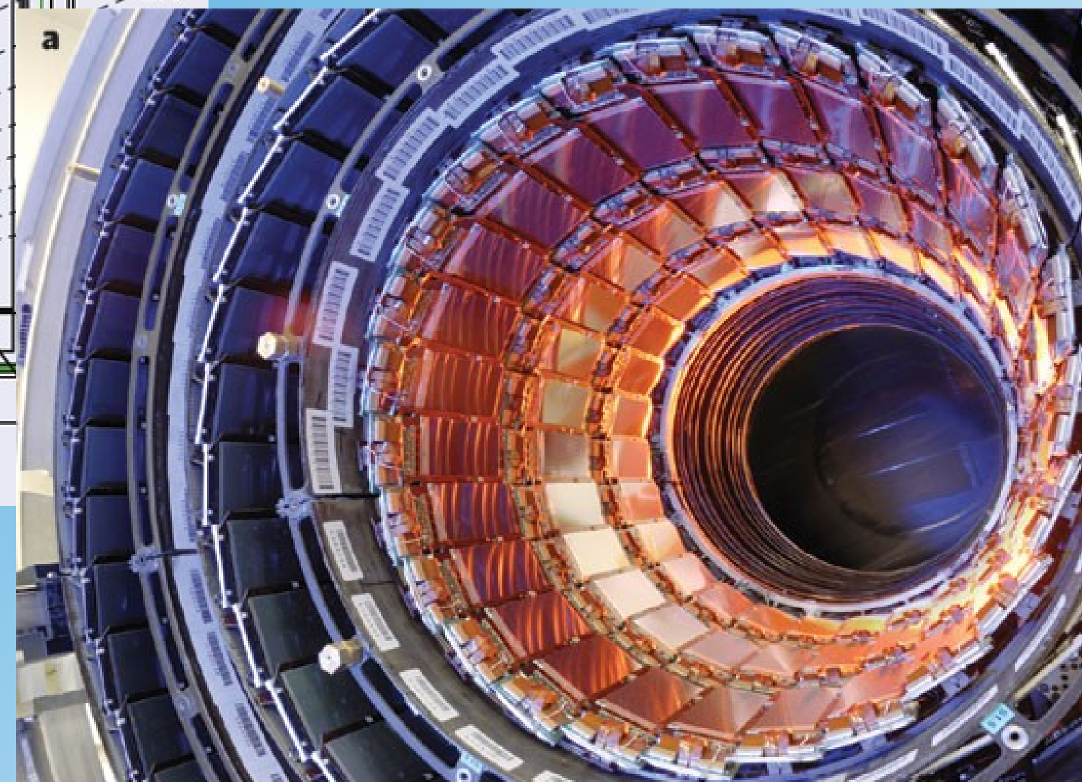
CMS Detector



B_{magn} ~ 4 Tesla (inner), 2 Tesla (outer)

CMS Silicon Detector

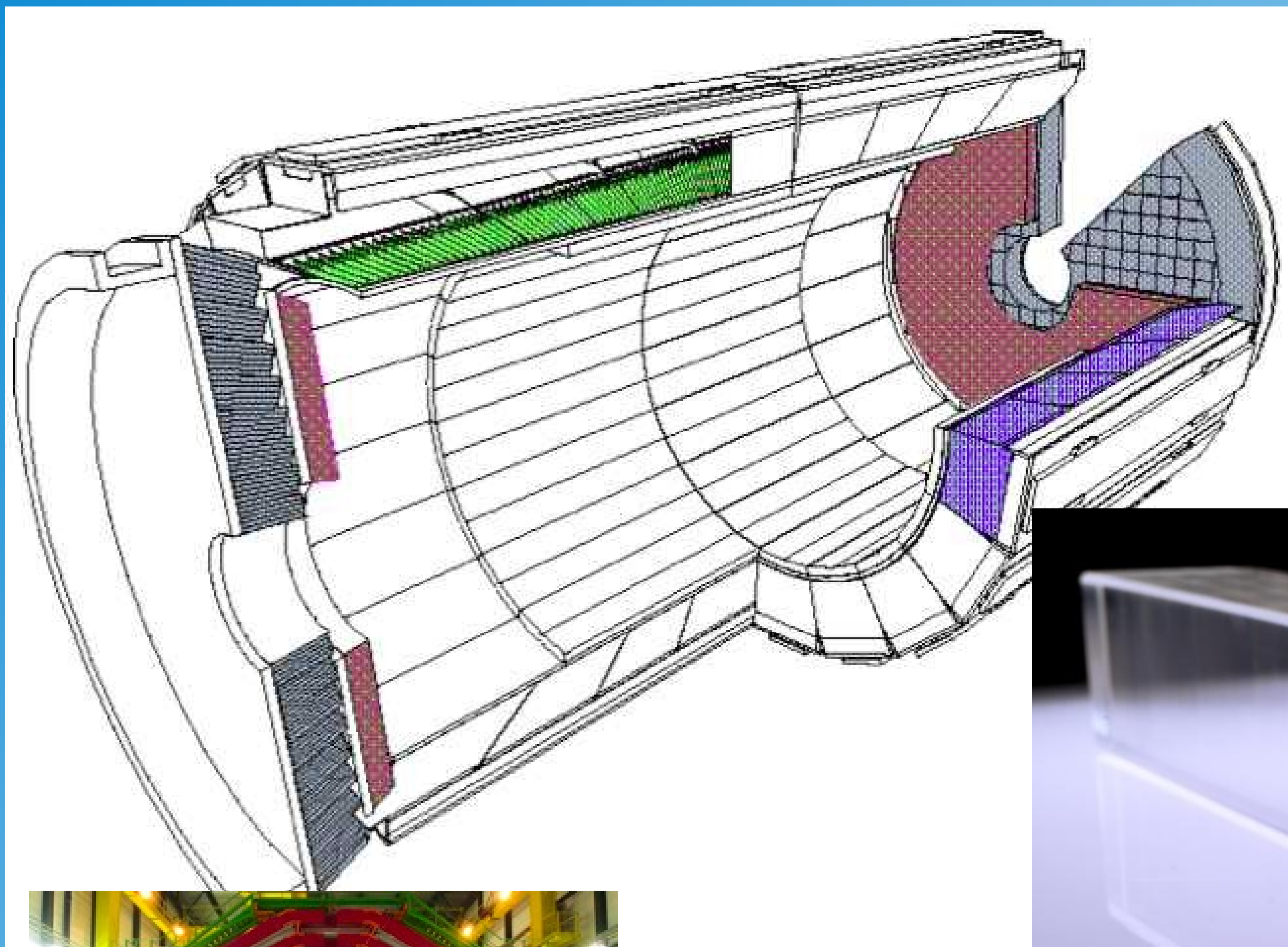


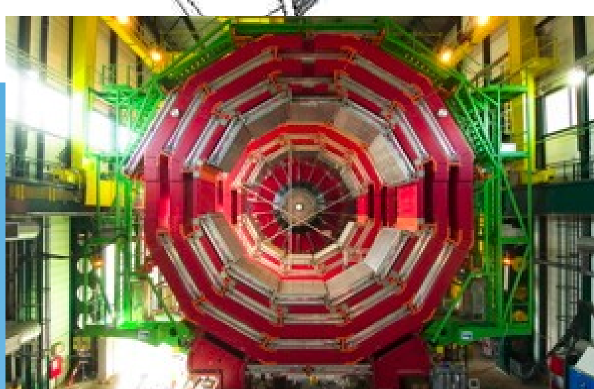


Tracker Inner Barrel (TIB)

Pixel Detector (PD)

CMS ECAL (PWO)





low light yield and
not very radiation hard
but very good resolution

$$\frac{\sigma_E}{E} \sim \frac{0.03}{\sqrt{E/GeV}}$$

First Collisions: November 23rd 2009

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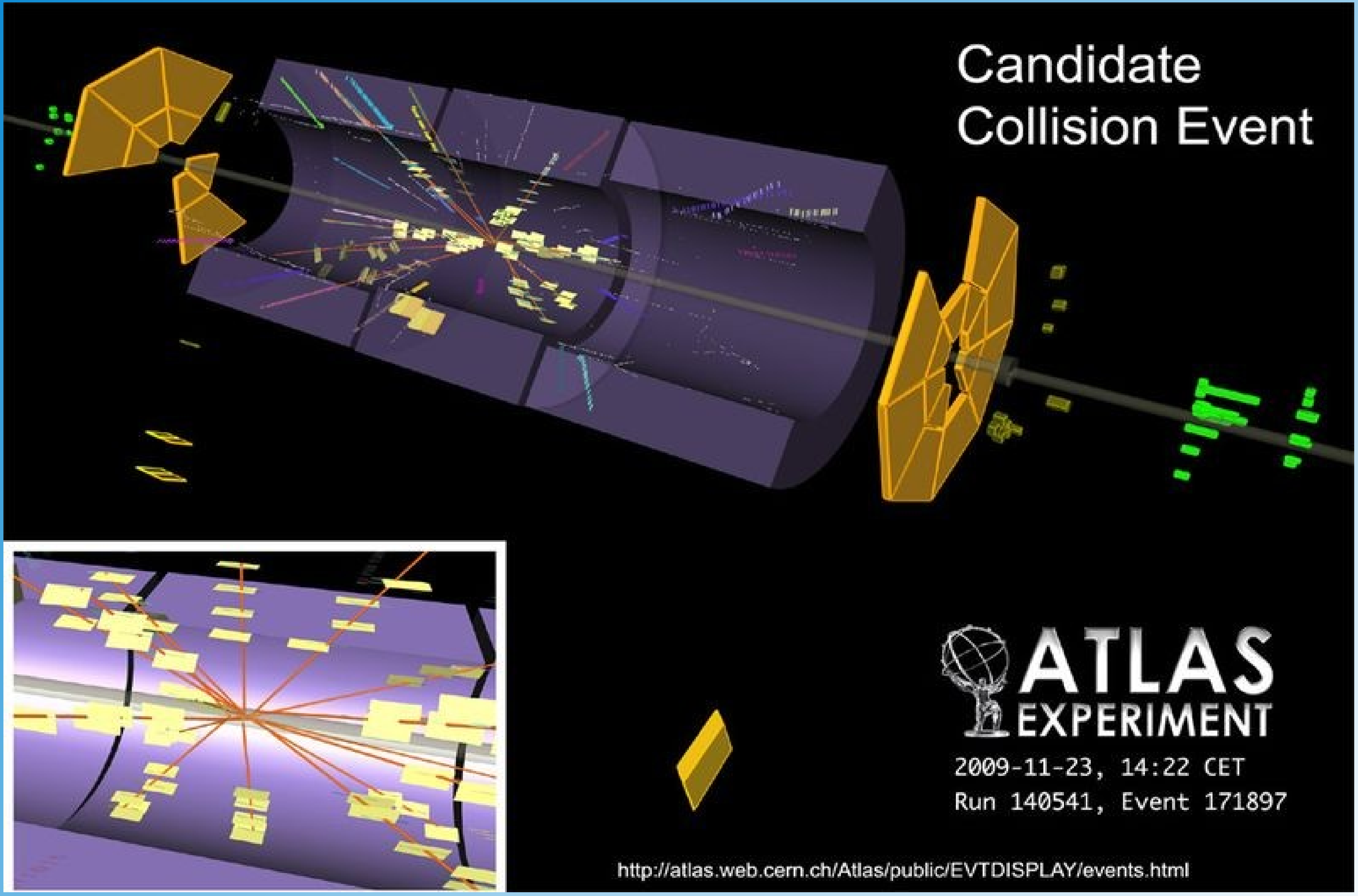


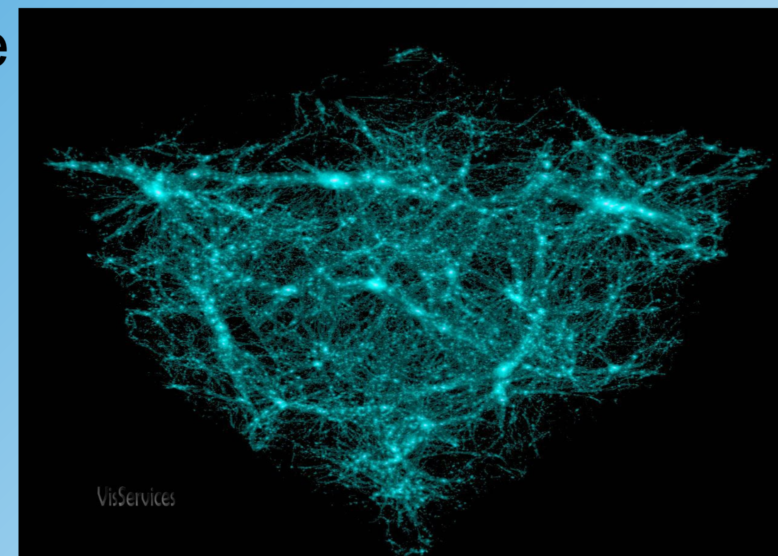
Motivation for New Physics Searches

- **Hints from astroparticle physics**
- **Hints from experimental particle physics**
- **Theoretical arguments**

The SM and Astro- Particle Physics

- Matter-Antimatter Asymmetry in Universe
(problem of CP violation)

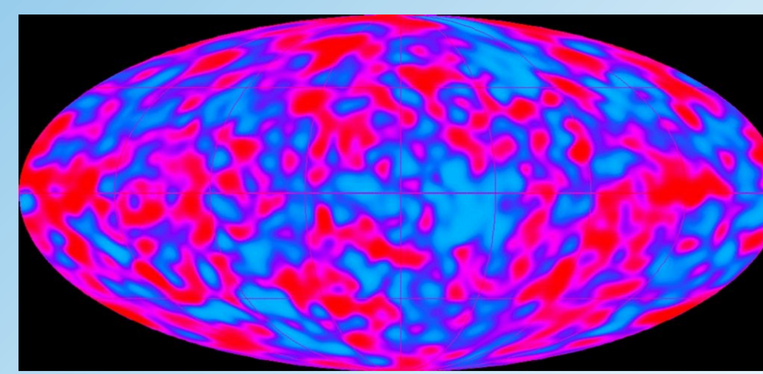
$$\frac{N(B)}{N(\gamma)} \quad 10^{-9}$$



- Dark Matter Problem (25% of total energy):

(rotation curves, formation of galaxies and structures in the universe)

- Dark energy (70% of energy)
(from microwave back-ground anisotropy)
- Big-Bang (inflation)
- Nucleosynthesis constraints



requires new physics (at high energies?)

Experimental Hints for New Physics

- Weinberg Angle Discrepancy

NuTev: $\sin^2\theta_W = 0.2277 \pm 0.0015$ (2003)

SM prediction (LEP): $\sin^2\theta_W = 0.22280 \pm 0.00035$ (2004)

about 3 sigma discrepancy

- Muon g-2

$\mu = g\mu_B J$ $\mu_B = \frac{e\hbar}{2m}$

$a = (g-2)/2$

$$a(\mu) = 1.16592080(53) \times 10^{-3}$$
$$a(\mu)_{theor} = 1.16591773(63) \times 10^{-3}$$

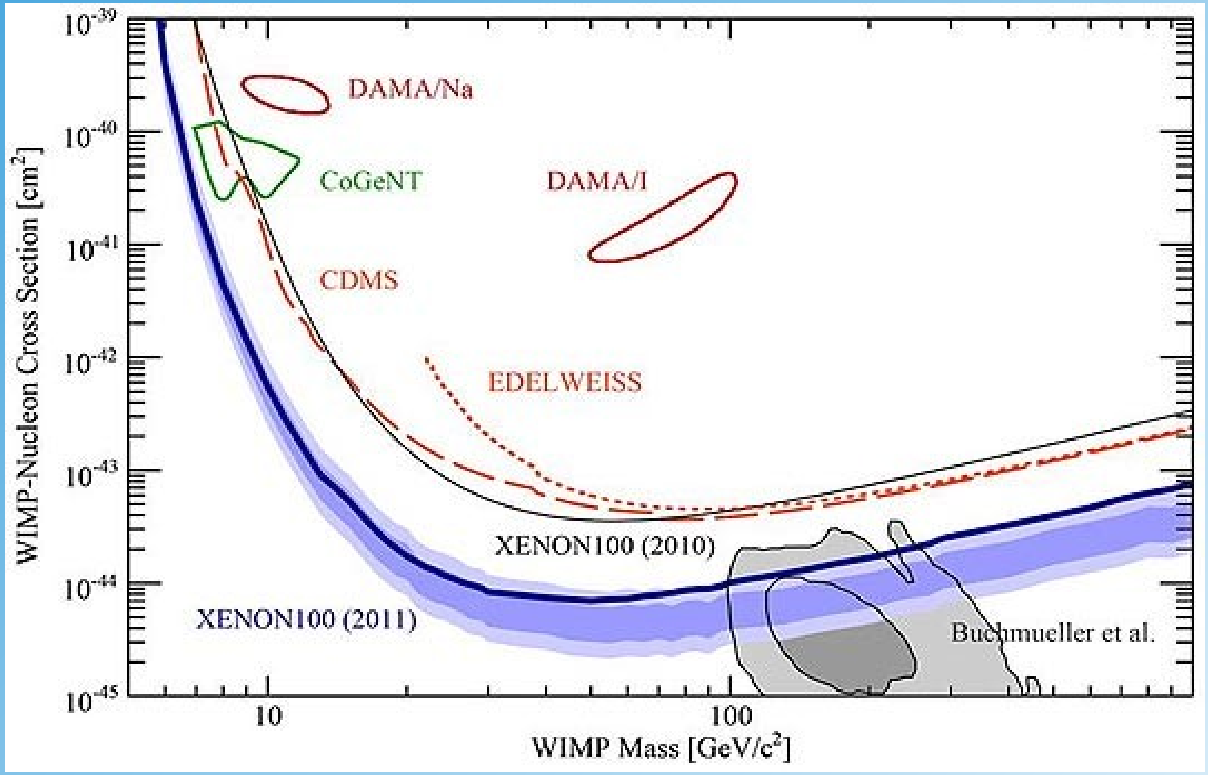
3.7 sigma discrepancy

- DAMA oscillations → next page

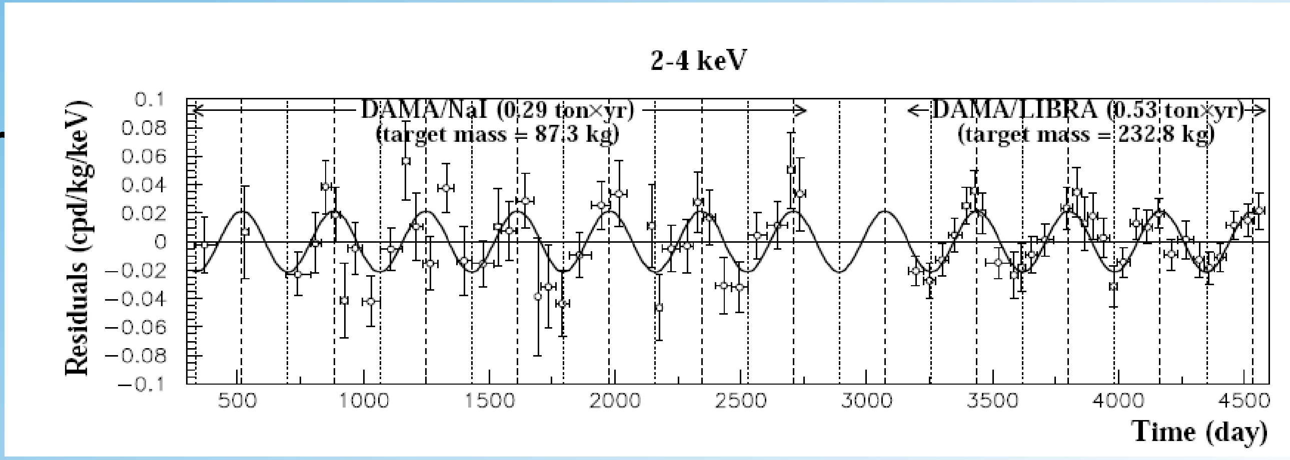
Search for Dark Matter

Several Search Experiments for Dark Matter

WIMP =
weakly interacting massive particle



DAMA Collaboration reported 8.2 sigma evidence for dark matter candidate based on an annual modulation signature



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3.7 sigma discrepancy

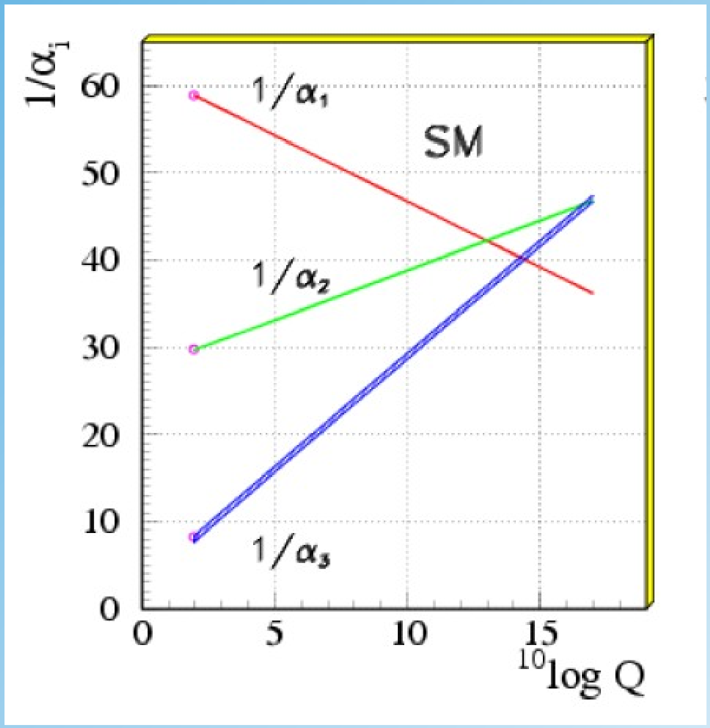
- DAMA oscillations ⟶ next page

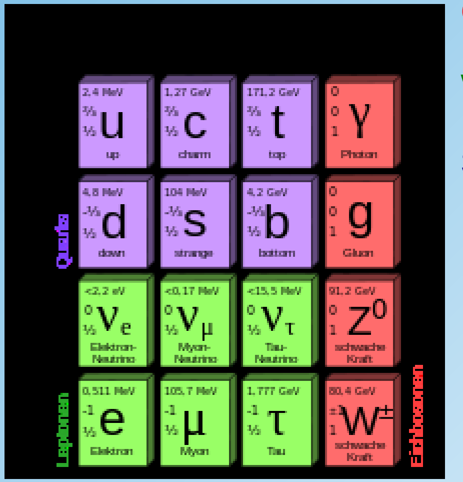
No strong sign for new physics ye!t

But Situation would be COMPLETELY different if no Higgs candidate found at LHC, recently!

Theory Arguments for New Physics

- (Too) many parameters (25)!
- Why three generations?
- Why so different masses (Yukawa couplings)
- Grand Unification (GUT) → couplings?
- Fine Tuning and Naturalness Problem of the Higgs Mass ($M_H < M_{planck}$)
- Ultraviolet catastrophe at high energies
- Unification with Gravitation?
- Mechanism of CP violation?



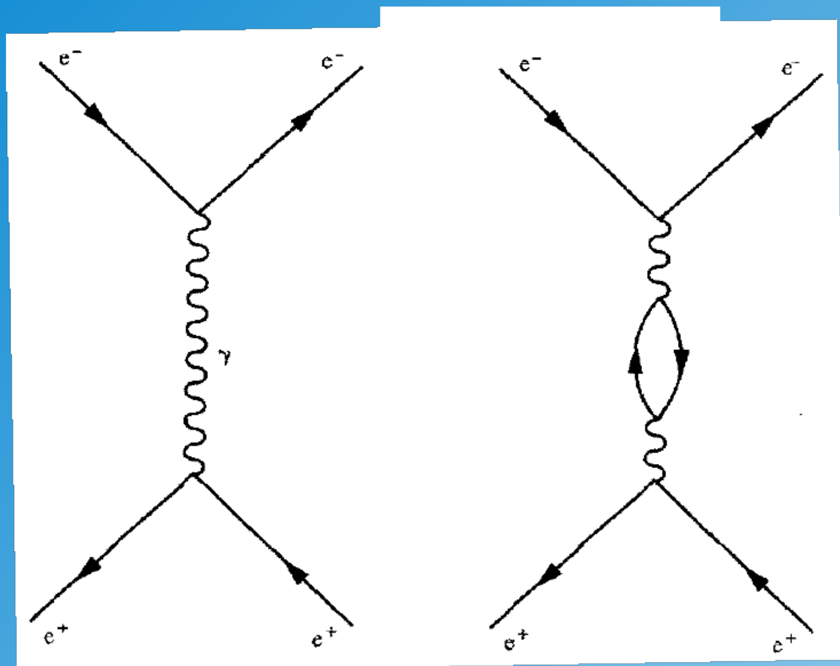


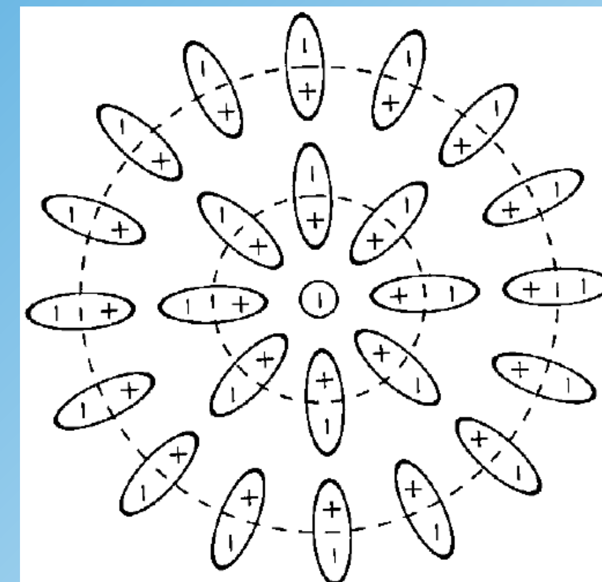
electromagnetic (γ) $\alpha_1 \sim 1/137$

weak IA (W, Z) $\alpha_2 \sim 1/29$

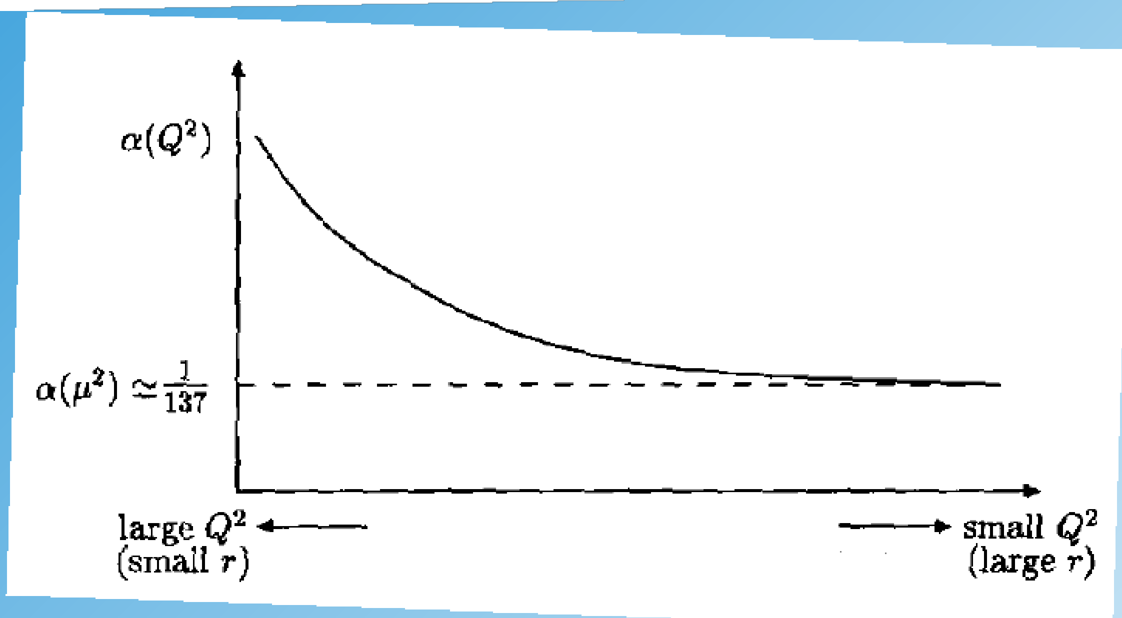
strong IA (gluon) $\alpha_3 \sim 1/10$

Vacuum Polarisation





classical picture



$$e^2(q^2) = e^2\left(1 + \frac{e^2}{12\pi^2}\ln\frac{|q^2|}{m^2}\right)$$

e=bare charge

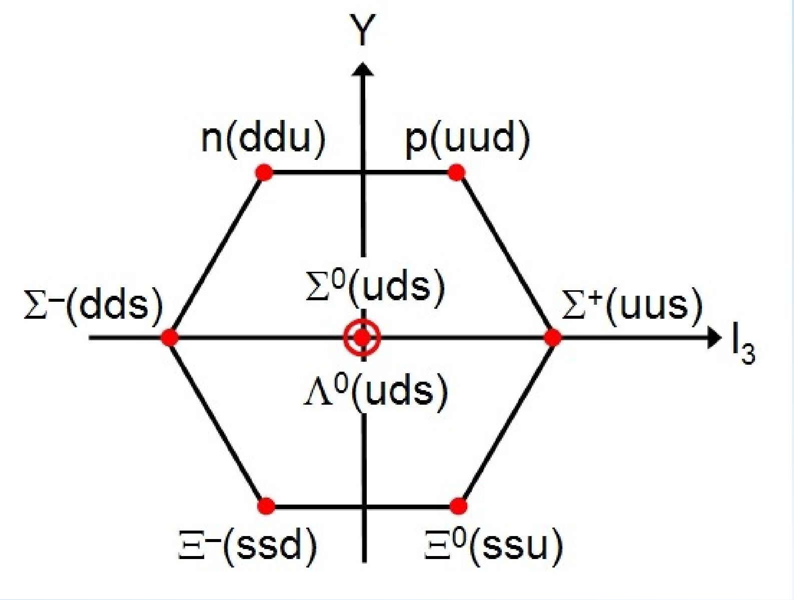
How can New Physics be tested?

Concepts:

- **Look for new or hidden symmetries** (model driven)
- **Look for deviations from the Standard model** (curiosity of experimentalists)

Examples for Symmetries

- QCD: “color” SU(3) symmetry → gluons
- Number of generations (quarks + leptons)
- Quark Flavor: isospin SU(3) symmetry of light quarks → hadrons
- Weak Interaction: SU(2) symmetry → W,Z boson
- Higgs → spontaneous symmetry breaking
- Periodic system of elements → p,n



Searches for New Symmetries at LHC

- **Fourth generation quarks** (extension of the three generations)
- **Heavy** new vector **bosons** (W´, Z´) → Left-Right Symmetric Models
- Search for large **extra dimensions** (extension of 3D+1 space-time)
- Search for **supersymmetry**: → fermion-boson symmetry
- and many more models (symmetries) …
- and many variants ...

Search for Heavy Quarks

Heavy Top Quark partners **t'** or Bottom Quark partners **b'**

Production:

$g \rightarrow t' \bar{t}'$, $b' \bar{b}'$ (strong coupling)

$W^{+} \rightarrow t' \bar{b}$, $b' \bar{t}$ (weak coupling)

Decays:

$t' \rightarrow b' W^{+}$, $t Z$

$b' \rightarrow t W^{-}$, $b Z$

(flavor changing CC and NC decays)

$t' \rightarrow t H$

$b' \rightarrow b H$

Higgs decay channels

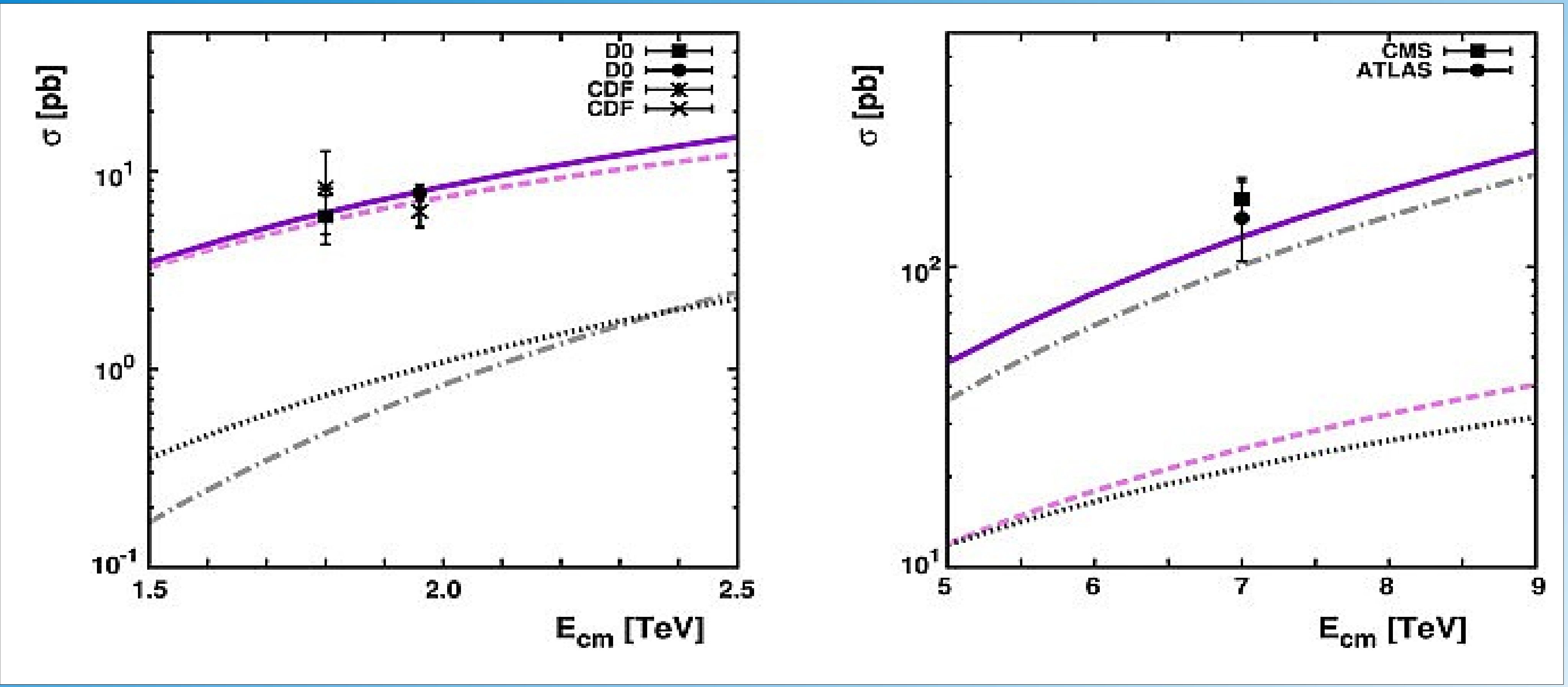
Experimental Observables:

- higher rate of b-quarks
(too high SM background)
- higher rate of top-quarks
(inclusive measurement)
- specific final state topologies:
bbWW, ttWW, ttZZ, bbZZ, …
ttW, bbW, tbZ, …

Backgrounds:
Top-pair production,
QCD multijets,
W-production + jets,
Z-production+jets

Important tools are
b-tagging and top-tagging!

Top Pair Production Cross Section



First Inclusive Measurement Counting all Tops!

(limited sensitivity)

Search for pair production of heavy top-like quarks decaying to a high-p_T W boson and a b quark in the lepton plus jets final state at $\sqrt{s} = 7$ TeV with the ATLAS detector

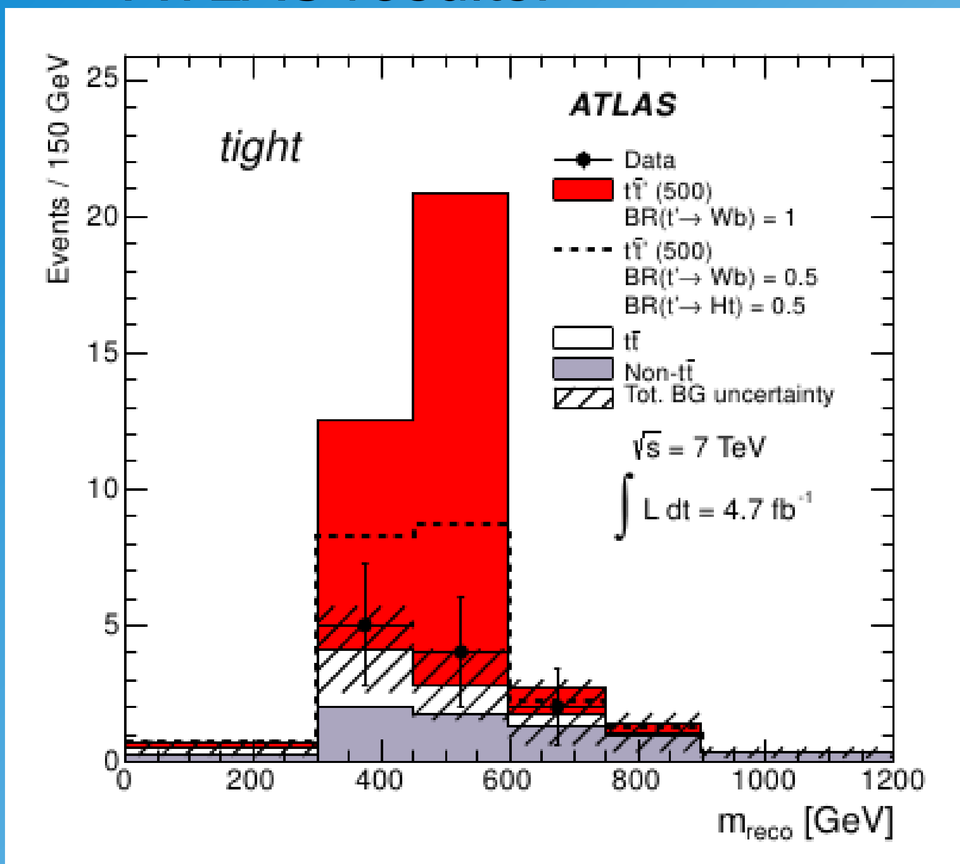
CERN-PH-EP-2012-258

	loose selection	*tight* selection
$t\bar{t}$	94 ± 26	4.2 ± 2.9
W+jets	5.4 ± 4.2	2.0 ± 1.4
Z+jets	0.5 ± 0.4	0.2 ± 0.2
Single top	7.2 ± 1.7	1.1 ± 0.5
Dibosons	0.1 ± 0.1	0.04 ± 0.04
Multi-jet	5.9 ± 8.4	3.8 ± 3.2
Total background	113 ± 30	11.3 ± 4.8
Data	122	11
$t'\bar{t}'$(500 GeV)		
$Wb : Zt : Ht = 1.0 : 0.0 : 0.0$	47.4 ± 6.3	28.2 ± 3.6
$Wb : Zt : Ht = 0.5 : 0.0 : 0.5$	25.4 ± 3.6	11.2 ± 1.5

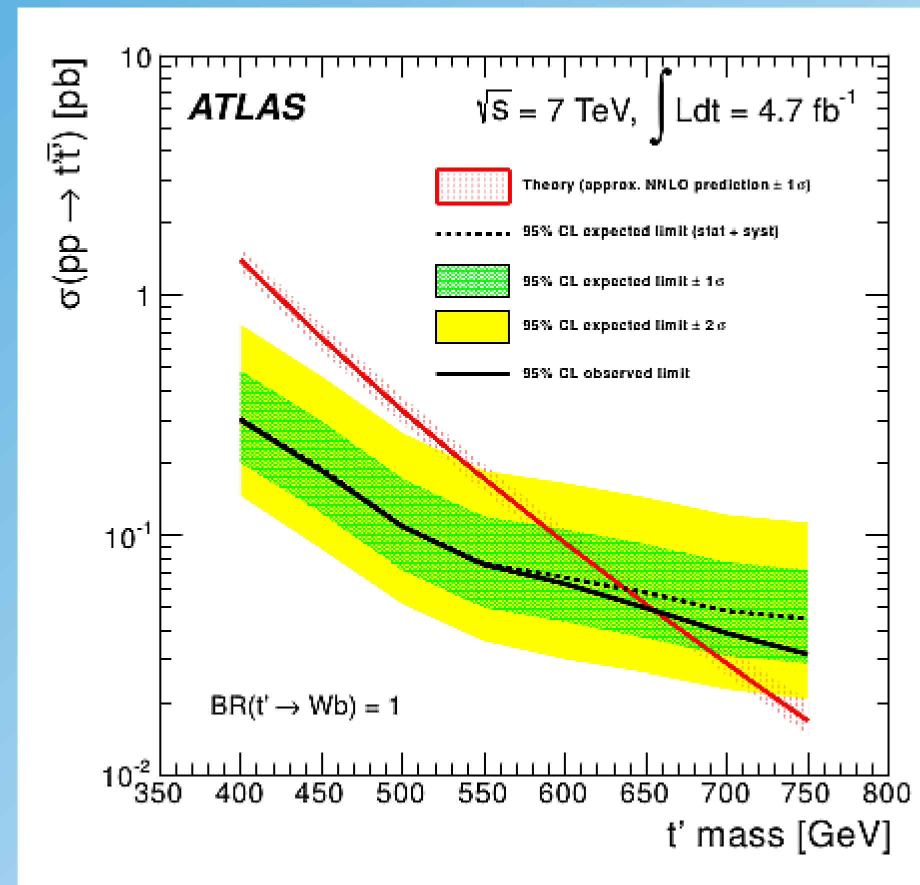
Table 1: Number of observed events, integrated over the whole mass spectrum, compared to the SM expectation for the combined e+jets and μ+jets channels after the *loose* and *tight* selections. The expected signal yields assuming $m_{t'} = 500$ GeV for different values of $BR(t' \to Wb)$, $BR(t' \to Zt)$ and $BR(t' \to Ht)$ are also shown. The case of $BR(t' \to Wb) = 1$ corresponds to a fourth-generation t' quark. The quoted uncertainties include both statistical and systematic contributions.

Search for Heavy Top Decays

ATLAS results:



mass distribution



t' mass limit

Statistics and Limit Setting

chi² fit:

$$\chi^2 = \sum_i \frac{(y_i - \mu_i)^2}{\sigma_i^2}$$

y_i measurement
μ_i model prediction (nuisance parameter)
σ_i uncertainty (statistical and systematical)

chi² fit with correlated errors:

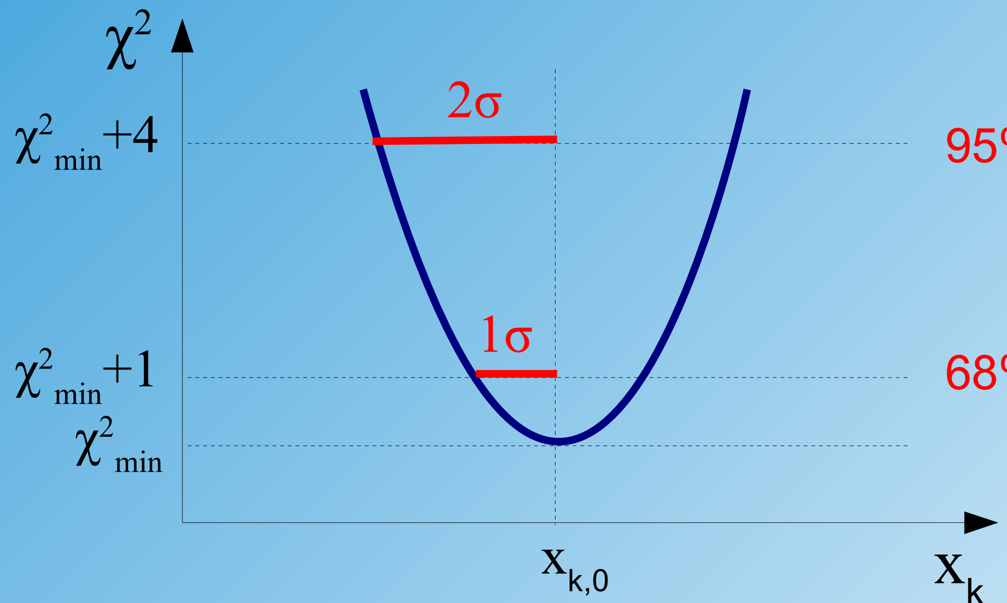
$$\chi^2 = \sum_i \sum_j (y_i - \mu_i) cov_{ij}^{-1} (y_j - \mu_j)$$

cov_{ij} covariance (error) matrix

Parameter Fit:

$$\mu_i = \mu_i(x_{1,} x_{2,} \ldots, x_n)$$

x_k model parameter



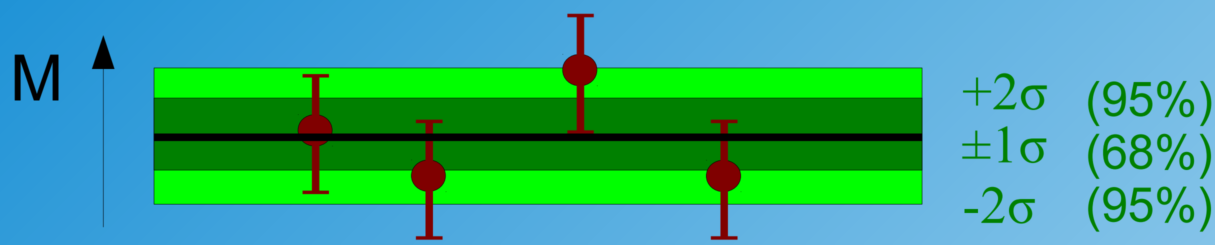
95% confidence level

68% confidence level

good fit if:
χ^2_{min} / degrees of freedom ~ 1

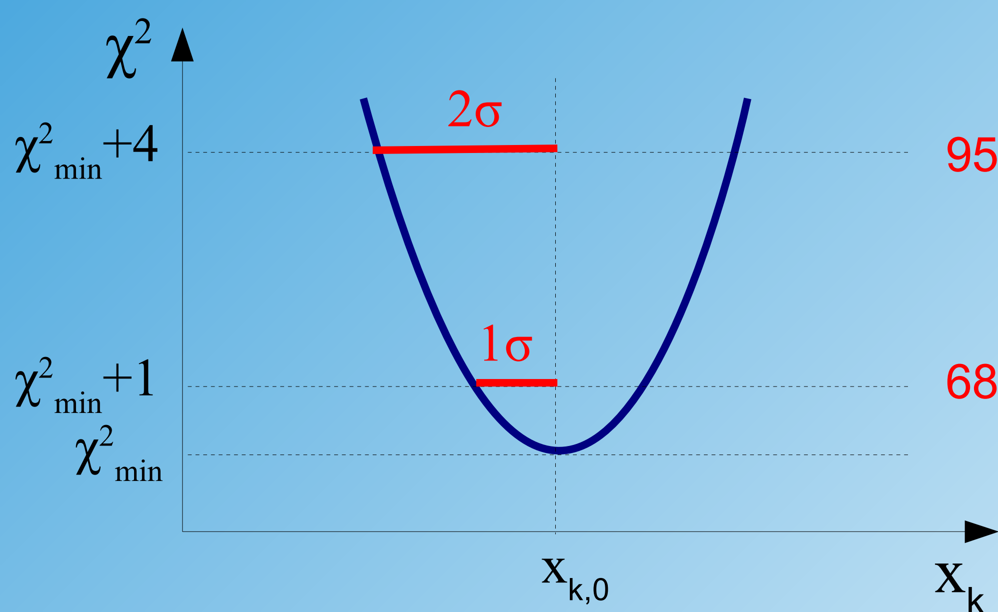
Example Fit

Measurement of some mass (1-Parameter fit) from 4 experiments:



confidence level bands

(could also be a cross section)



95% confidence level

68% confidence level

good fit if:

χ^2_{min} / degrees of freedom ~ 1

Probability Densities

for the above example a Gaussian probability density was used

<u>Gaussian (normal)distribution:</u>

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad \rightarrow \quad P(a<x<b) = \int_a^b f(x)\,dx$$

- used for systematic uncertainties (symmetric)

<u>Poisson distribution:</u>

$$P(N) = \frac{e^{-\mu}\mu^N}{N!}$$

- used for statistical uncertainties

Note, Poisson distribution approaches Gaussian distribution for large μ

Limit Setting Philosophies

Bayesian Method:

- based on the experiment posterior, exclusion limits are calculated
- low probability models are excluded
- probabilities are assigned to models using a prior

"natural method" but choose of prior is arbitrary

Frequentist Method:

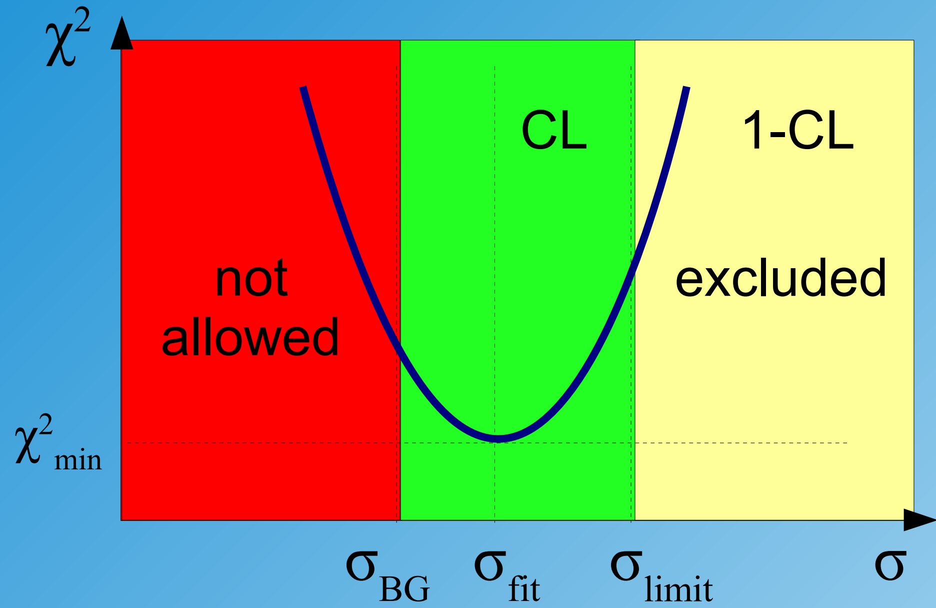
- based on Monte Carlo toy experiments probabilities are assigned to all possible experimental outcomes
- exclusion limit is set by that model which excludes this experimental outcome with certain confidence interval

computationally expensive and might give unphysical results
(e.g. negative cross sections)

Bayesian Method

Model: $N = N_{BG} + N_{Sig}$ (background + signal)

$\sigma = \sigma_{BG} + \sigma_{Sig} = N/L$ choose cross section as “prior”



Probability:

$$P \propto e^{-\frac{1}{2}\left(\chi^2(\sigma) - \chi^2_{fit}\right)}$$

additional constraint:

$\sigma \geq \sigma_{BG}$ because $\sigma_{Sig} \geq 0$

$$CL = \frac{\int_{\sigma > \sigma_{BG}}^{\sigma_{CL}} P(\sigma)\, d\sigma}{\int_{\sigma > \sigma_{BG}}^{\infty} P(\sigma)\, d\sigma}$$

CL = confidence level

Choice of Prior

- Cross sections depend on couplings
- Alternatively, choose coupling as prior

$$\sigma_{Sig} = \sigma_0\, \alpha^2$$

$$\frac{d\sigma}{d\alpha} = \frac{d\sigma_{Sig}}{d\alpha} = 2\sigma_0\, \alpha$$

$$CL = \frac{\int_{\alpha>0}^{\alpha_{CL}} P(\alpha)\, d\alpha}{\int_{\alpha>0}^{\infty} P(\alpha)\, d\alpha} = \frac{\int_{\alpha>0}^{\alpha_{CL}} P(\alpha)/\alpha\, d\sigma}{\int_{\alpha>0}^{\infty} P(\alpha)/\alpha\, d\sigma} \neq \frac{\int_{\sigma_{Sig}>0}^{\sigma_{CL}} P(\sigma)\, d\sigma}{\int_{\sigma_{Sig}>0}^{\infty} P(\sigma)\, d\sigma}$$

Results depends on choice of prior!

Frequentist Method

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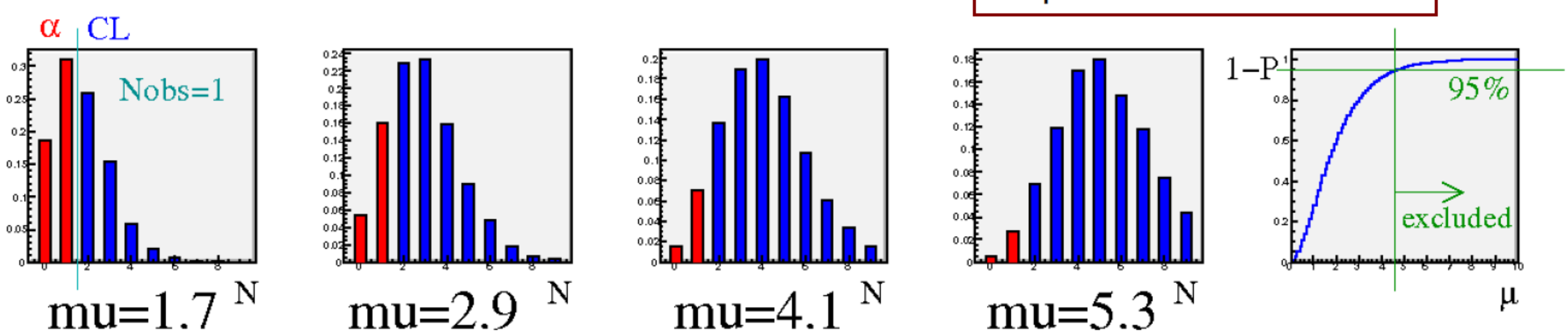
- Frequentist limit: exclude all theories which produce the data at small probability α less than 1-CL (typically: CL=0.95)

$$\alpha = P_{\mu}(N \le N_{\mathrm{obs}}) < 1 - \mathrm{CL}$$

α: also called p-value

Frequentist limit:
sum (integrate)
over observations
up to N_{obs}
Repeat for each model



➔ set limit with 95% confidence level for mu=4.6
➔ experiment has a 5% probability to happen

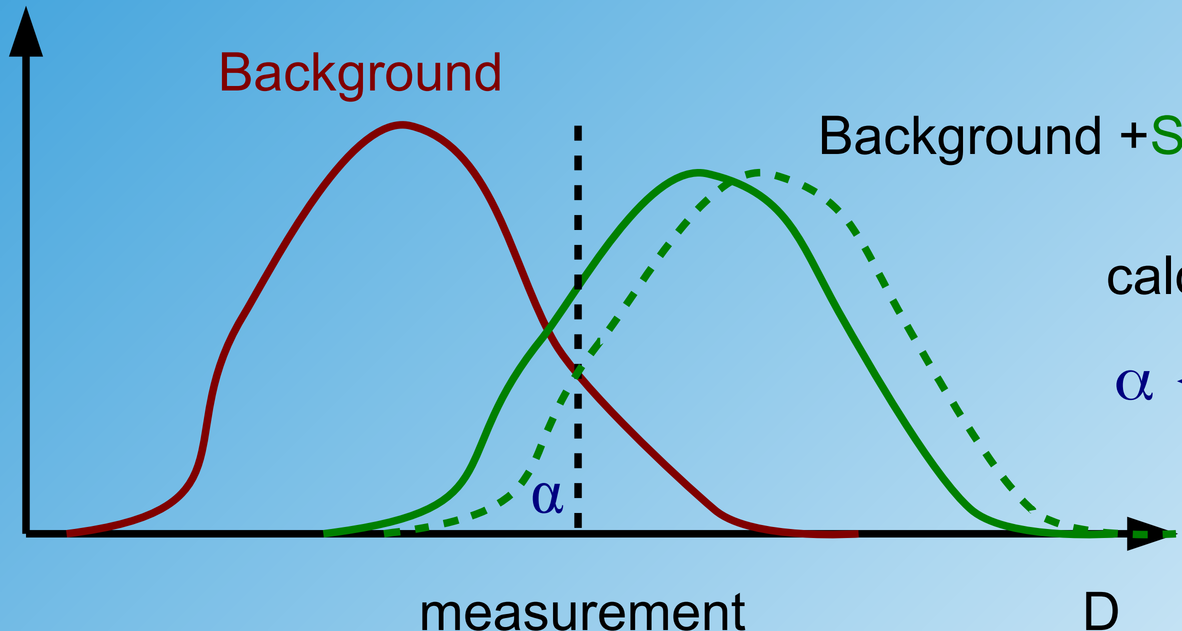
Frequentist Method

In case of many observables x_k a combined discriminator variable is often defined:

$$D = D(x_{1,} x_{2,} x_{3,} \ldots X_k)$$

- large discriminator means high probability
- small discriminator means low probability

Often, the output from artificial neural nets or other multivariate methods is used as discriminator variable



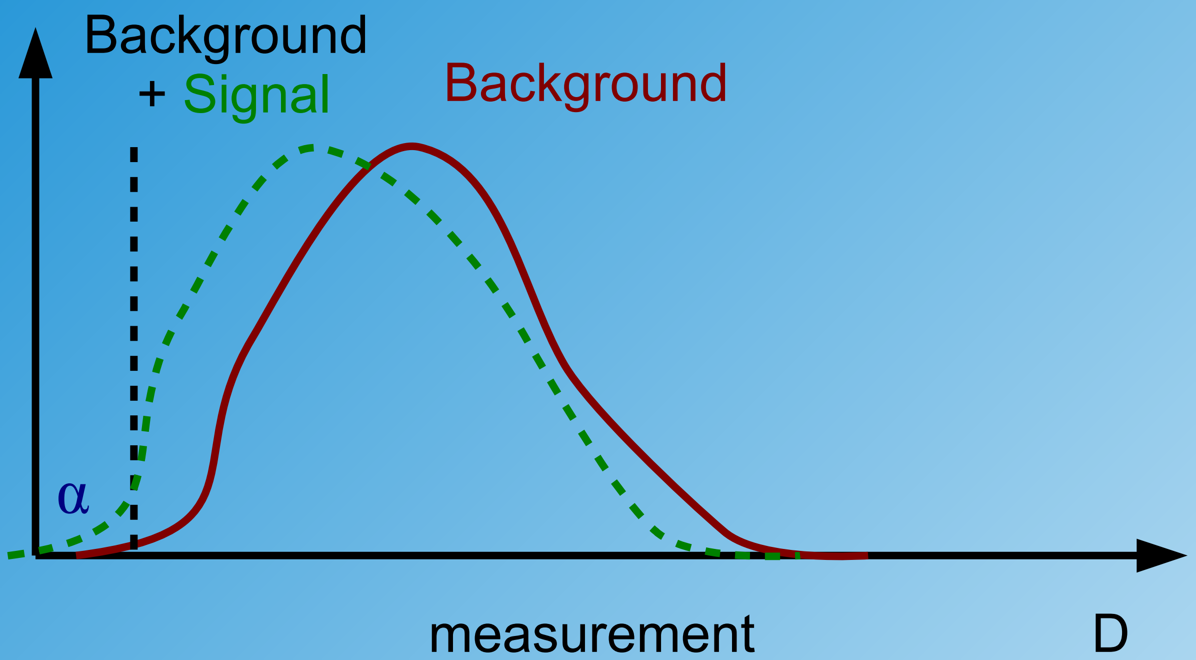
calculate smallest signal with:

$$\alpha < 1 - CL$$

Problem with Frequentist Method

Problem in case of a very small measurement value with P(BG)< (1-CL)

- would require a negative signal cross section:



unphysical solution!

CL_S Method

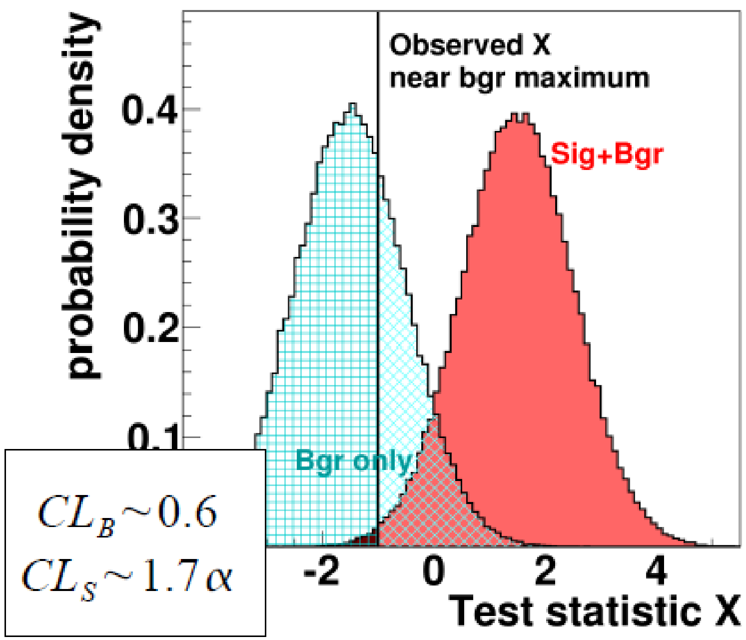
- Use ratio of two probabilities CL_S instead of α to test against CL

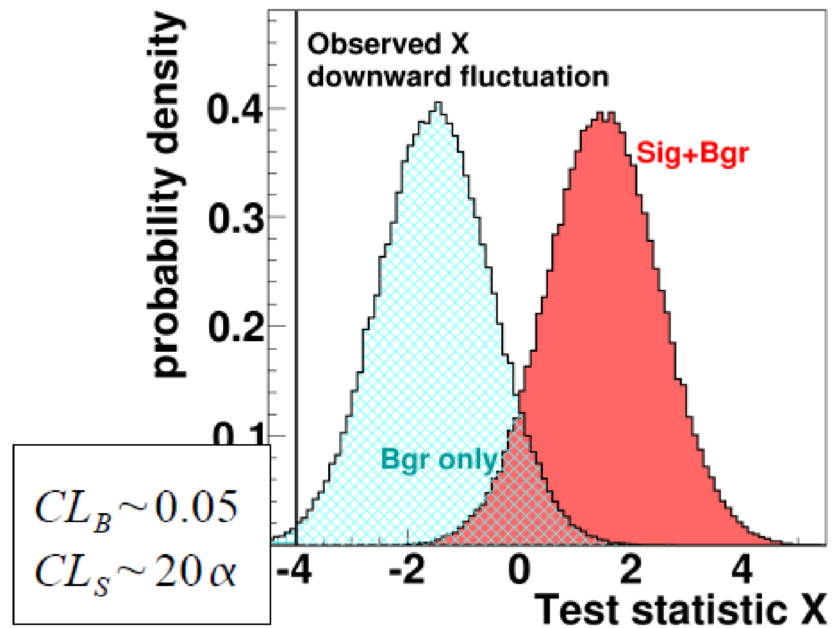
$$CL_{SB} = \alpha = \int_{X<X_{obs}} P(X|\text{signal}+\text{bgr})\,dX$$

$$CL_B = \int_{X<X_{obs}} P(X|\text{bgr})\,dX$$

$$CL_S = \frac{CL_{SB}}{CL_B}$$

- Standard model has CL_S=1 and is never excluded





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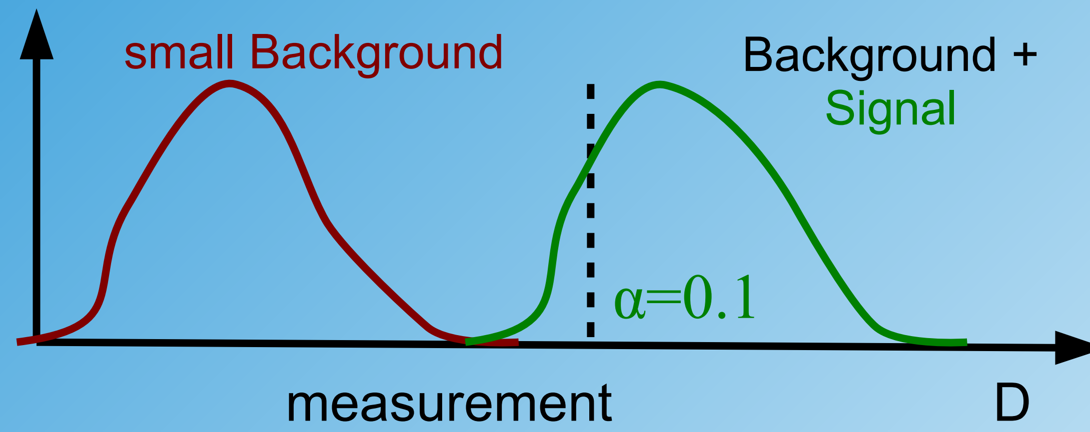
CL_S > CL_{SB} by definition!

Another Example CL_s Method

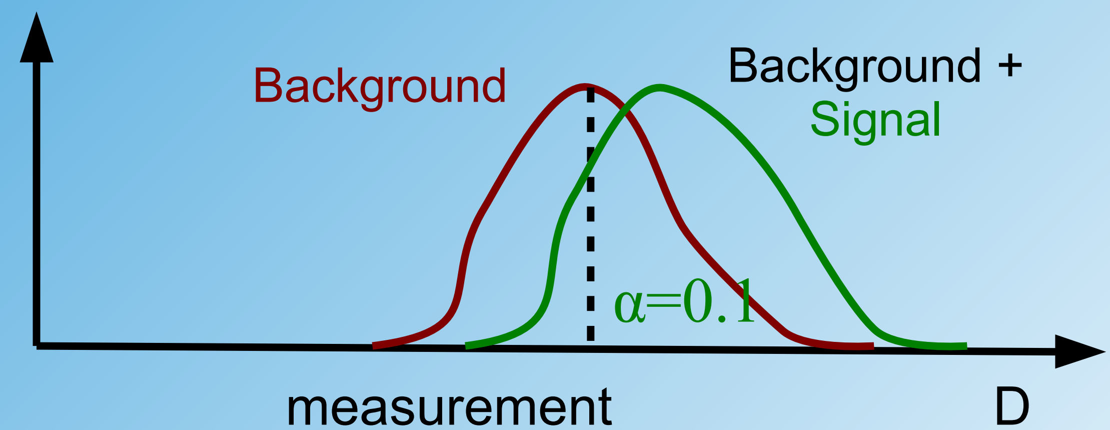
Definition:

$$CL_s = \frac{CL_{SB}}{CL_B}$$

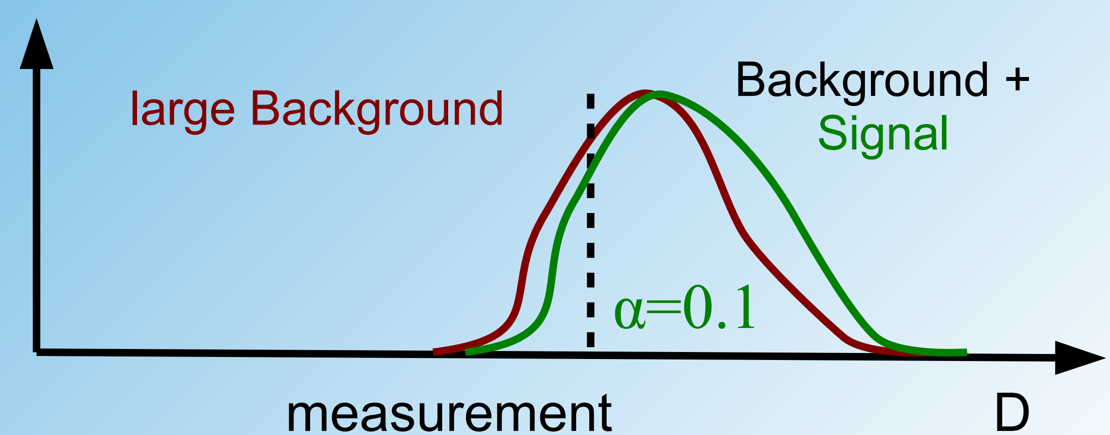
$$0.1 = \frac{0.1}{1.0}$$



$$0.2 = \frac{0.1}{0.5}$$



$$0.5 = \frac{0.1}{0.2}$$



Another Example CL_S Method

Definition:

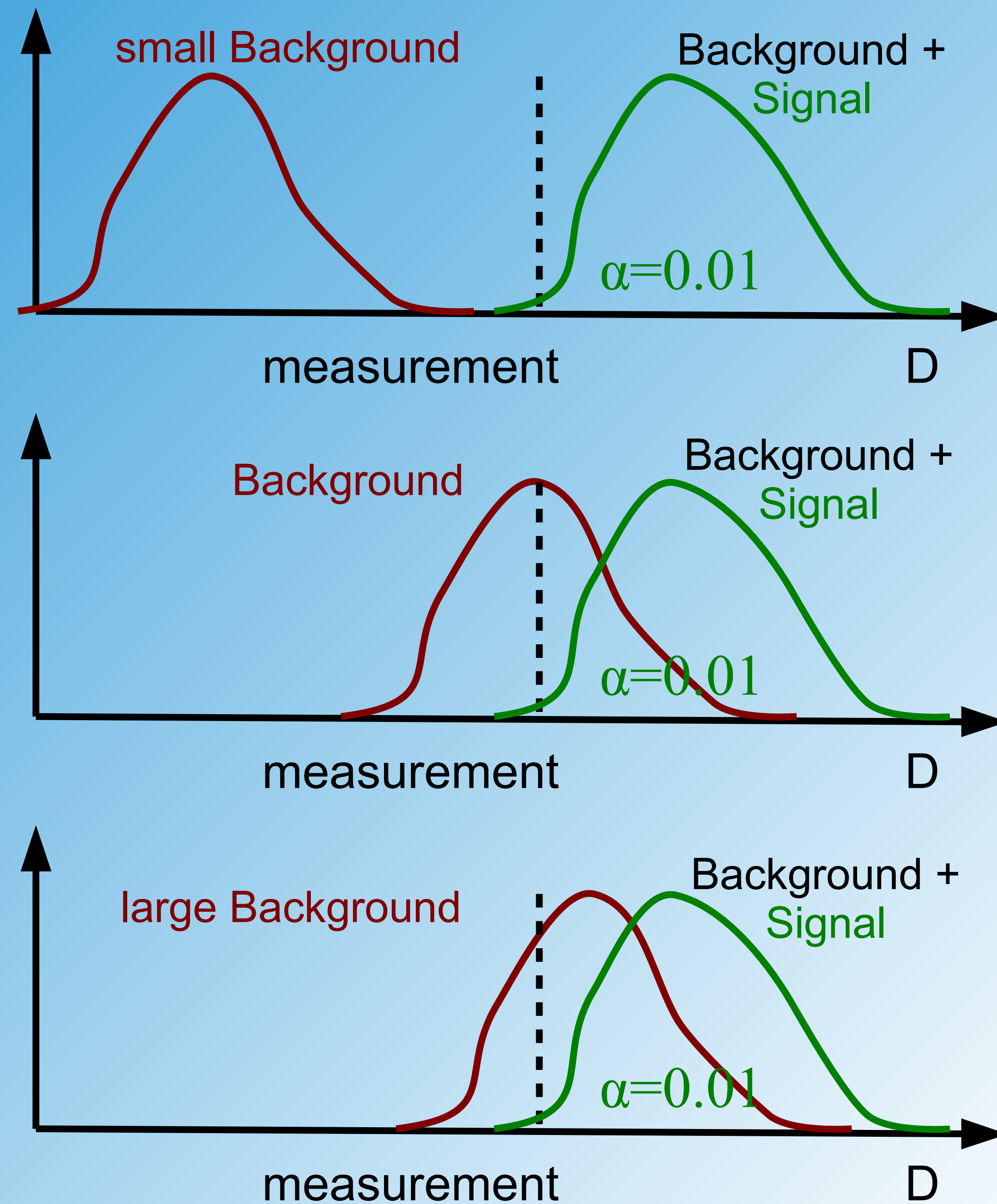
$$CL_S = \frac{CL_{SB}}{CL_B}$$

$$0.01 = \frac{0.01}{1.0}$$

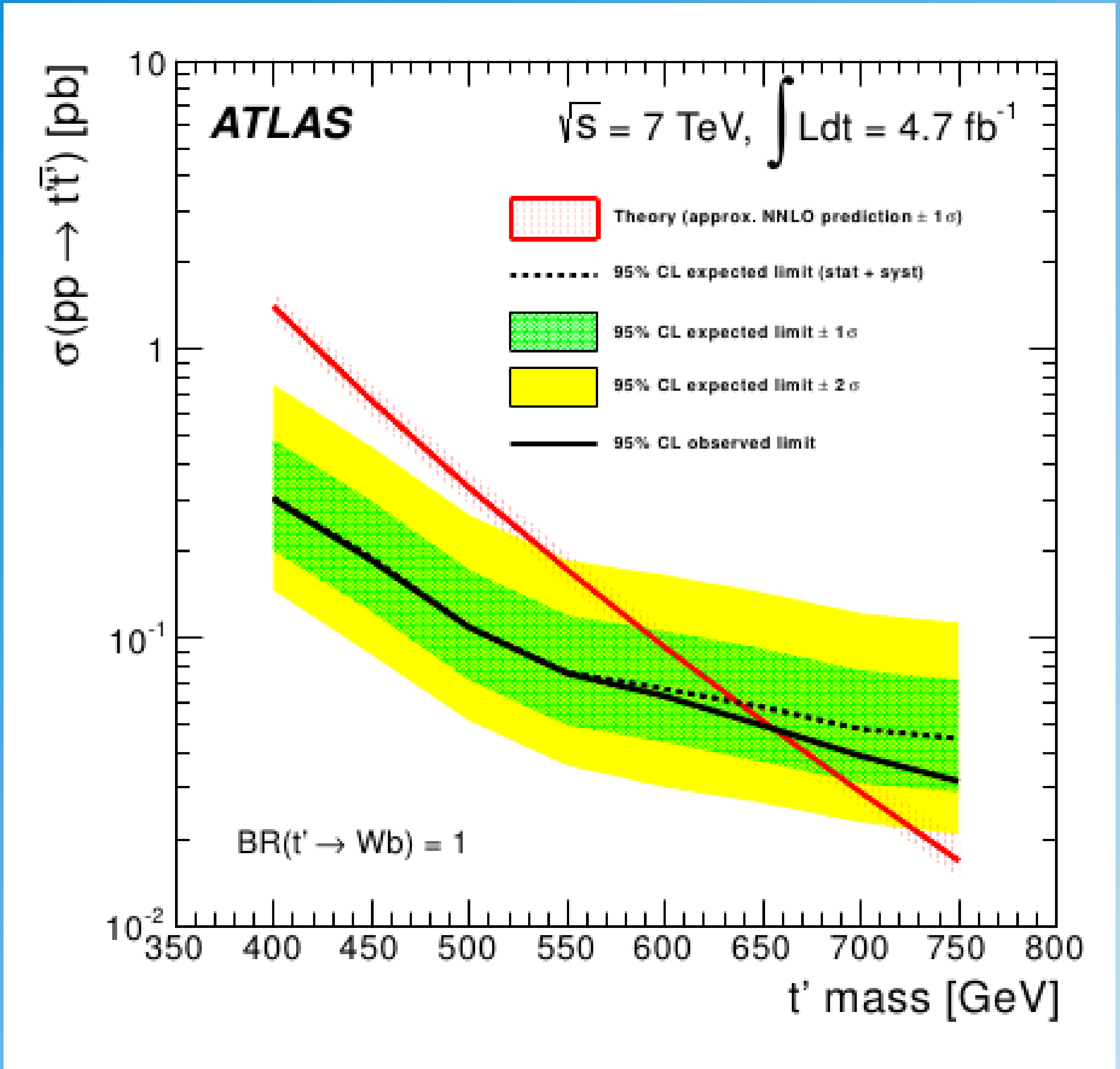
$$0.02 = \frac{0.01}{0.5}$$

$$0.05 = \frac{0.01}{0.2}$$

excluded at 95% CL



Search for Heavy Top Decays



Frequentists CL_S method used

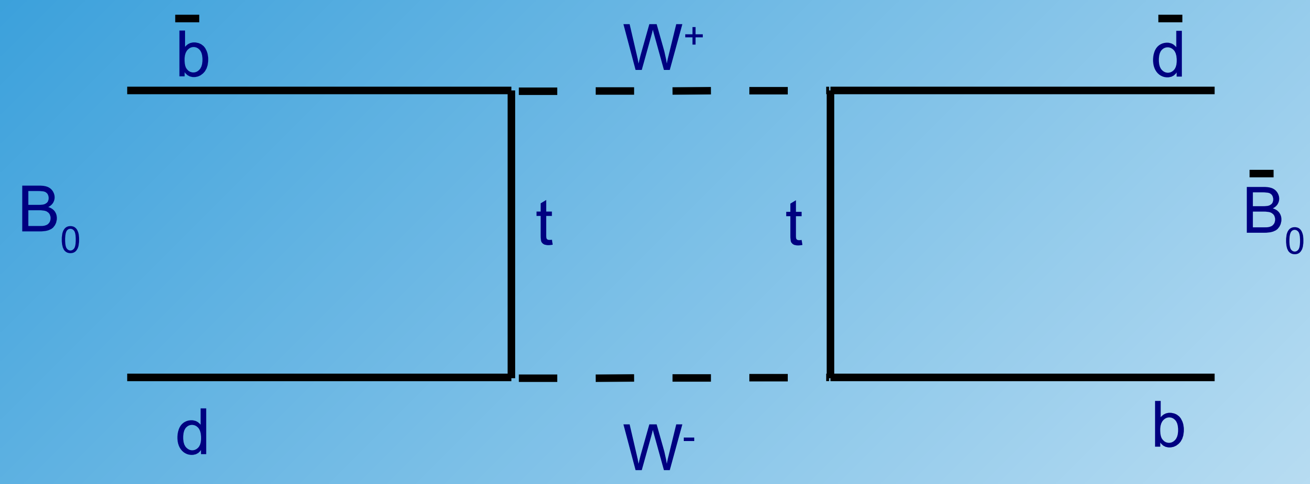
to be compared to indirect limit from e.g. mixing:

$$\frac{\Lambda}{\lambda_{ij}} > 500\, TeV$$

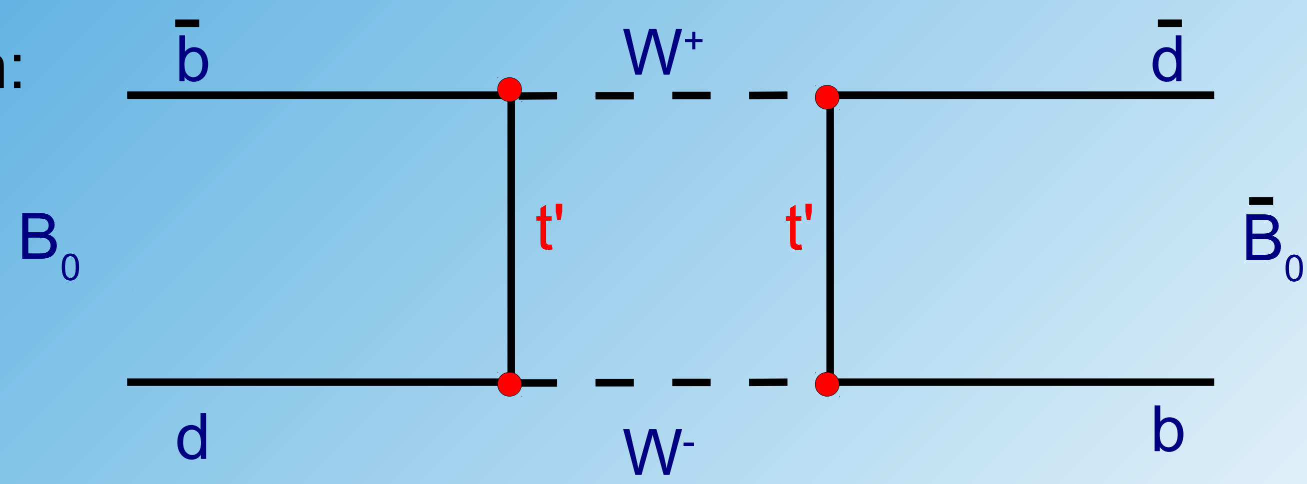
(B-mixing)

B-mixing

SM:



Fourth Generation:



unknown couplings!

- **Change of oscillation amplitude**

Reminder Electroweak Symmetry Breaking

$$\begin{pmatrix} Z \\ A \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W_3 \\ B \end{pmatrix}$$

$$L_{ew} = g\, j_L^3 W_3 + \frac{1}{2} g' j^Y B$$

↓ symmetry breaking

$$L_{elm} = g\, j_L^3 \sin\theta_W A + \frac{1}{2} g' j^Y \cos\theta_W A$$

$$L_{NC} = g\, j_L^3 \cos\theta_W Z - \frac{1}{2} g' j^Y \sin\theta_W Z$$

- The Lagrangian can be extended by right handed VBs
- Couplings to SM fermions a priori unknown!

Extending the Electroweak Sector

$$L_{ew} = g\, j_L^3 W_3 + \frac{1}{2} g' j^Y B + g'' j_R^3 W_3'$$

↓ symmetry breaking

$$L_{elm} = g\, j_L^3 \sin\theta_W A + \frac{1}{2} g' j^Y \cos\theta_W A$$

$$L_{NC} = g\, j_L^3 \cos\theta_W Z - \frac{1}{2} g' j^Y \sin\theta_W Z + g'' j_R^3 Z'$$

- The Lagrangian can be extended by right handed VBs
- Couplings to SM fermions a priori unknown!

Search for Z'

Partner of the well known Z-boson

Production:

$q\bar{q} \rightarrow Z'$ (weak coupling)

Decays:

$Z' \rightarrow$ jet jet ($q\bar{q}$) (light quarks)

$Z' \rightarrow b\bar{b}$

$Z' \rightarrow t\,\bar{t}$

$Z' \rightarrow l^+ l^-$

$Z' \rightarrow \nu\,\nu$ not visible

Experimental Observables:

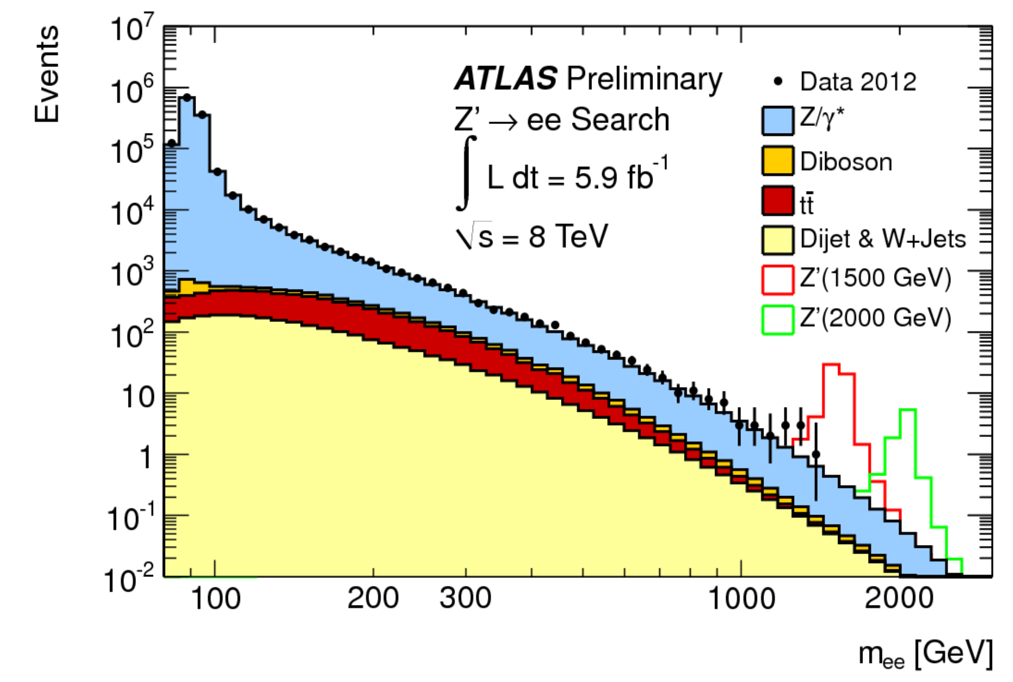
- higher cross section for two-fermion processes ($m_{Z'} > s^{1/2}$)
- resonance peak in two fermion (two jets) invariant mass ($m_{Z'} < s^{1/2}$)

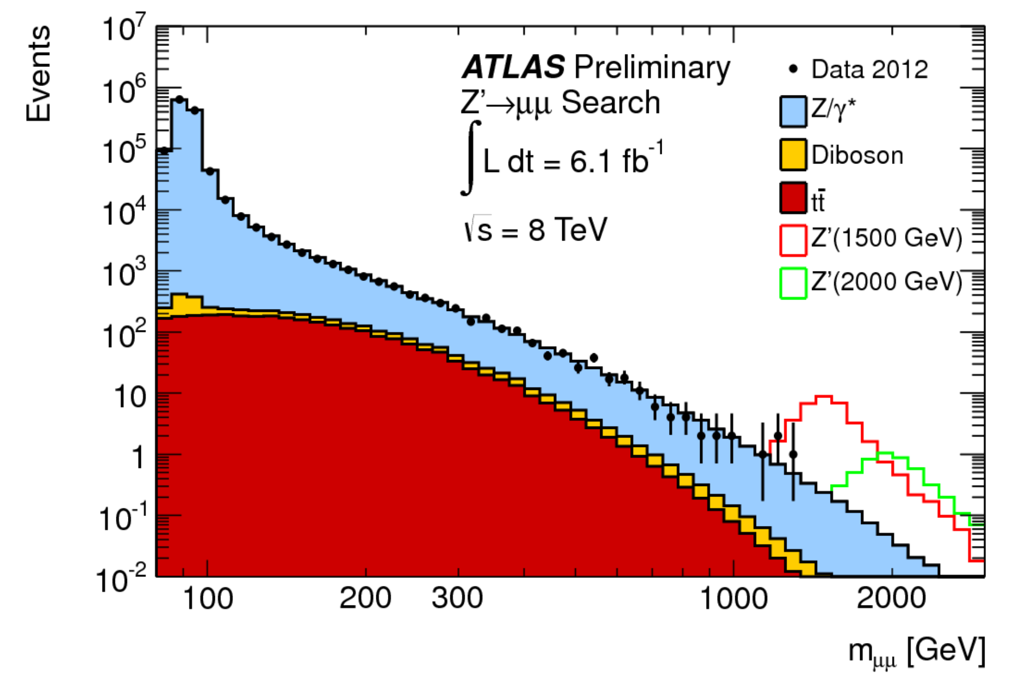
Backgrounds:

- QCD two-jets
- B-pair production
- Top-pair production
- Lepton-Pair production
- (Drell-Yan)

Important tools are b-tagging and top-tagging!

ATLAS Seach for Z' → Lepton-Pair



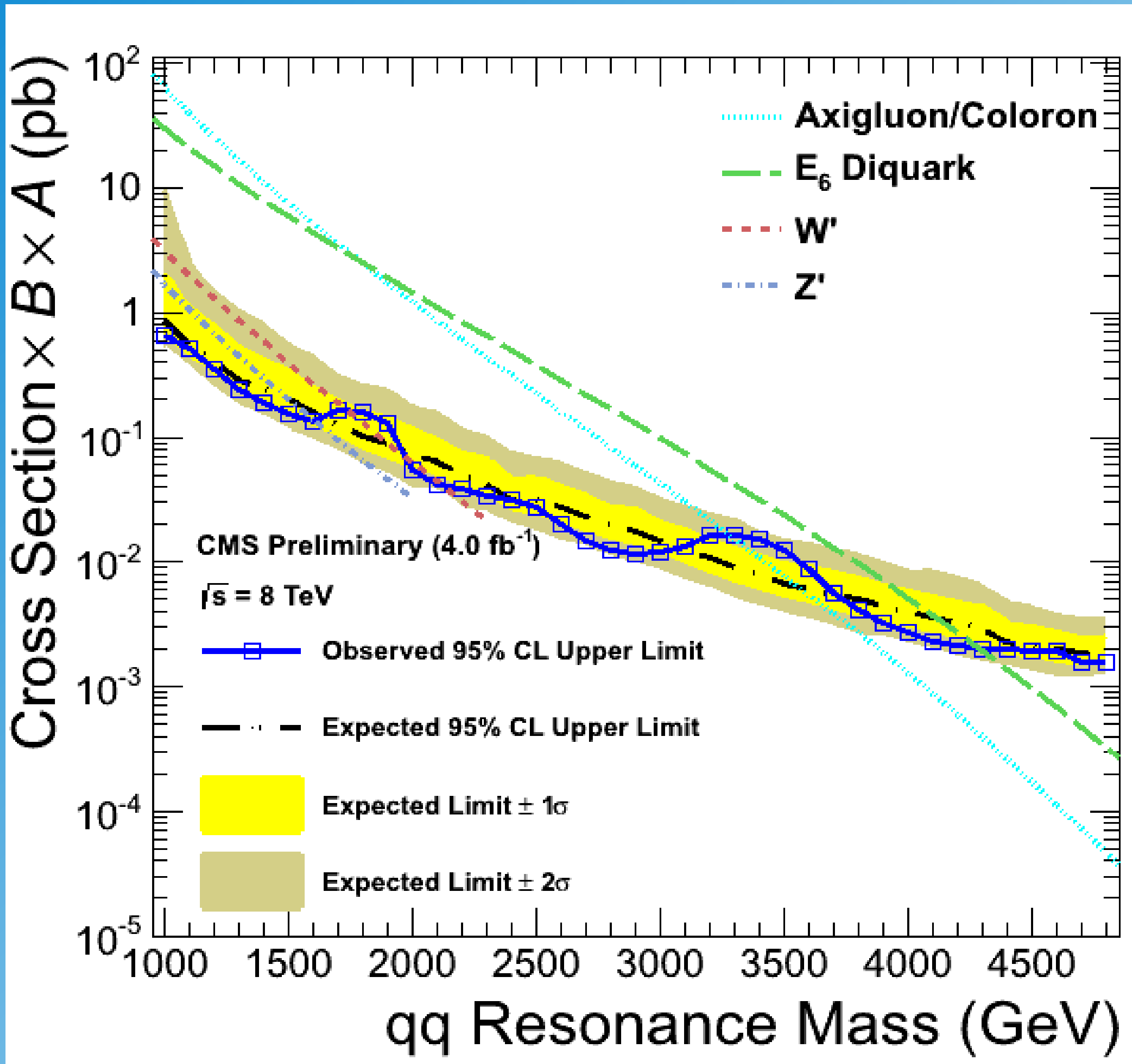


di-electron channel

di-muon channel

No sign for new physics up to ~ 1 TeV!

CMS Dijet Search



$G_{axi} \rightarrow q\, q$

$Q_{E6} \rightarrow q\, q$

$W' \rightarrow q\, \bar{q}$

$Z' \rightarrow q\, \bar{q}$

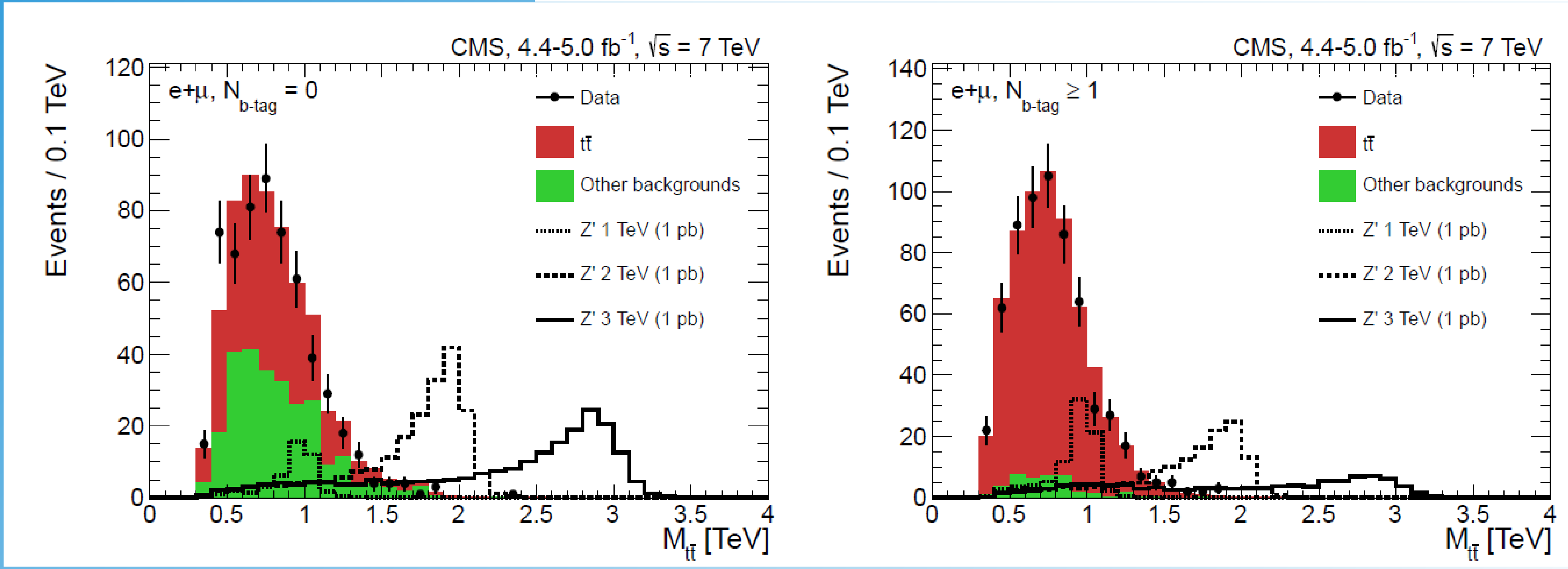
limit (Z') ~ 1.5 TeV

Search for ttbar resonance with 1 lepton at CMS

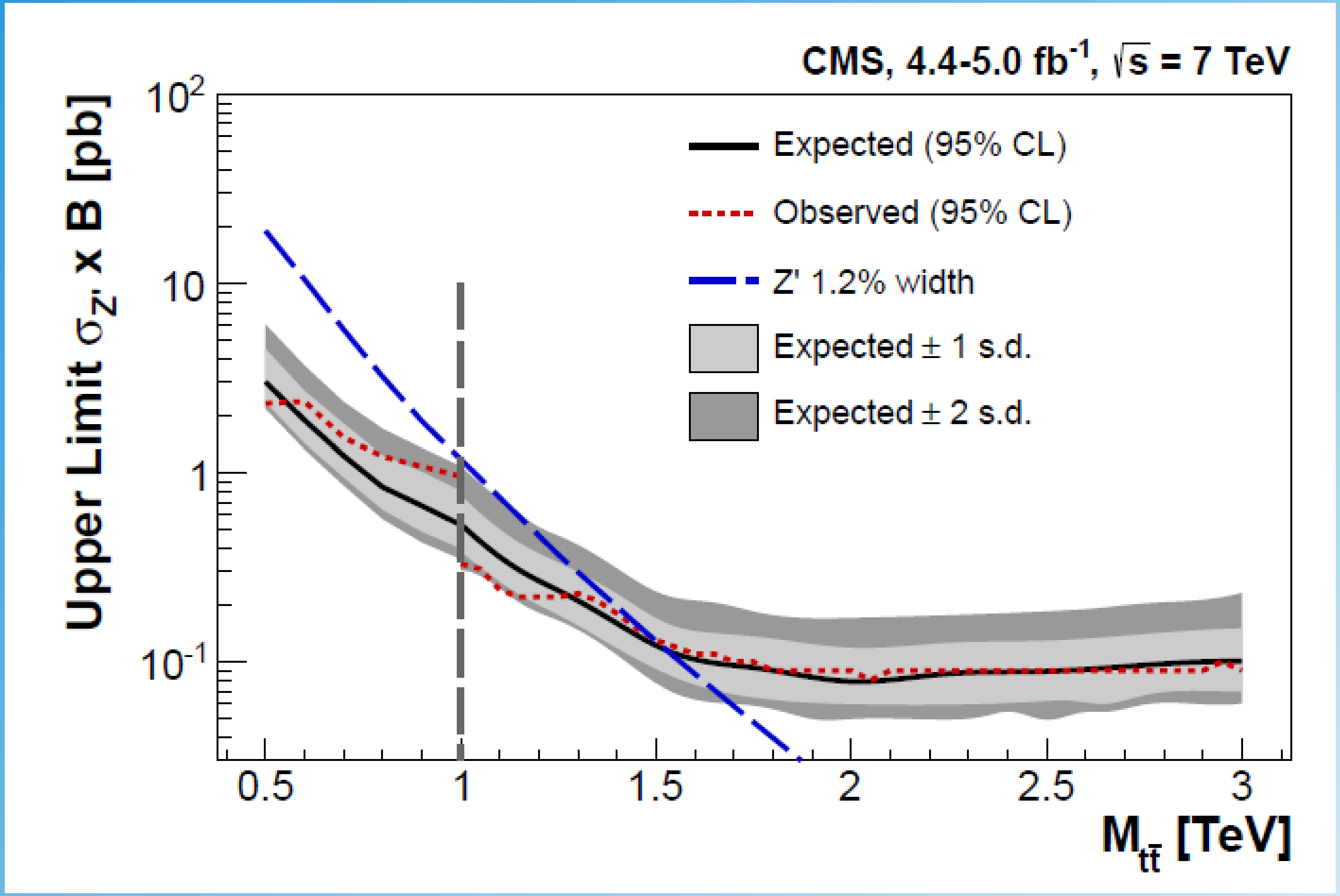
$t \rightarrow W\,b \rightarrow l\,\nu\,b$

$t \rightarrow W\,b \rightarrow j\,j\,b$

Boosted analyses	Electron channel		Muon channel	
Sample	$N_{\text{b-tag}} = 0$	$N_{\text{b-tag}} \geq 1$	$N_{\text{b-tag}} = 0$	$N_{\text{b-tag}} \geq 1$
Z′ (M= 1 TeV)	17.1	36.5	27.8	48.3
Z′ (M= 1.5 TeV)	44.7	55.4	95.9	94.4
Z′ (M= 2 TeV)	62.1	52.8	146.3	94.1
Z′ (M= 3 TeV)	57.2	36.9	155.2	69.0
$t\bar{t}$	172	336	157	262
W/Z+jets	95	6	149	9
Single top	9.3	15	8.1	11
Total background	276 ± 58	357 ± 50	314 ± 72	282 ± 34
Data	277	354	300	269



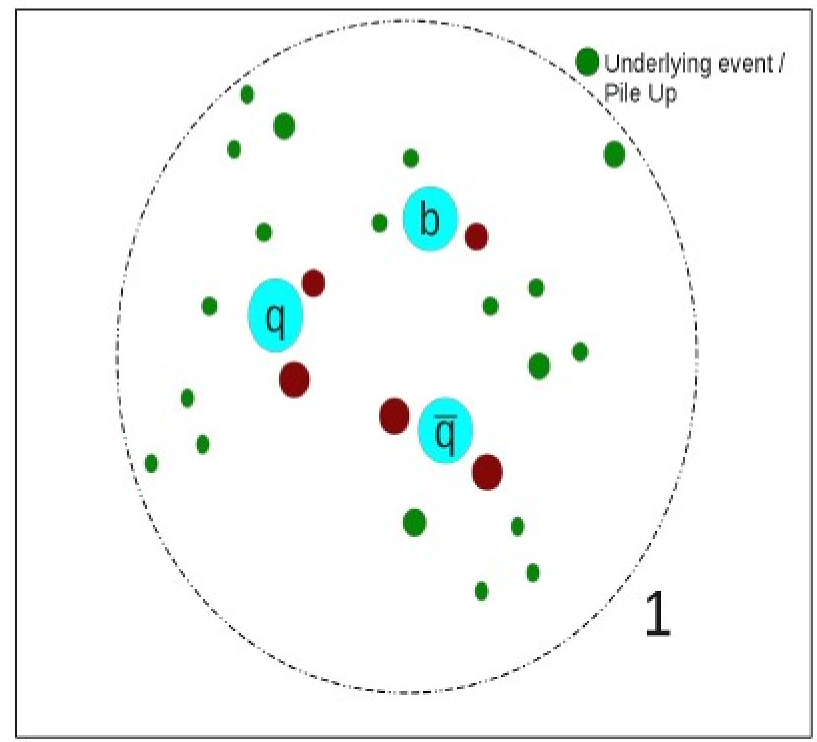
CMS ttbar Resonance Limit



- Unknown branching ratio included in limit
- Assumption on resonance width 1.2%
- use “boosted top finder” at high mass

Boosted Top Quark

- For new heavy states decaying into top quarks, the top quark is highly Lorentz boosted
- The Top quark is identified by a jet finder as one jet



Fat jet clustered with $R_{fatjet} = 1.5$

from D.Sosa

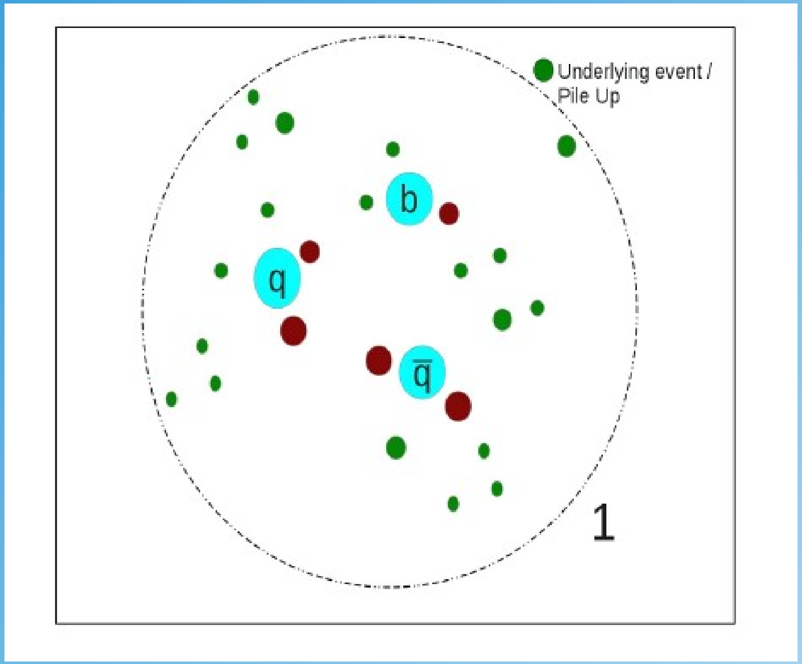
HEPTopTagger

- Developed by Plehn et al. [arXiv1006.2833] and used by ATLAS group in Heidelberg
- Allows reconstruction of hadronic decaying tops

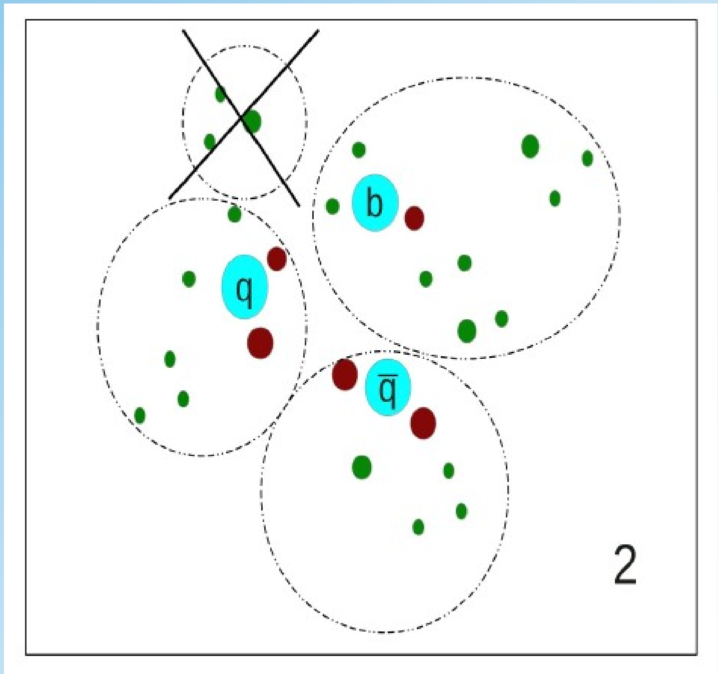
$t \rightarrow W^{+}\, b \rightarrow j\, j\, b$

$\bar{t} \rightarrow W^{-}\, \bar{b} \rightarrow j\, j\, \bar{b}$

no lepton tag!

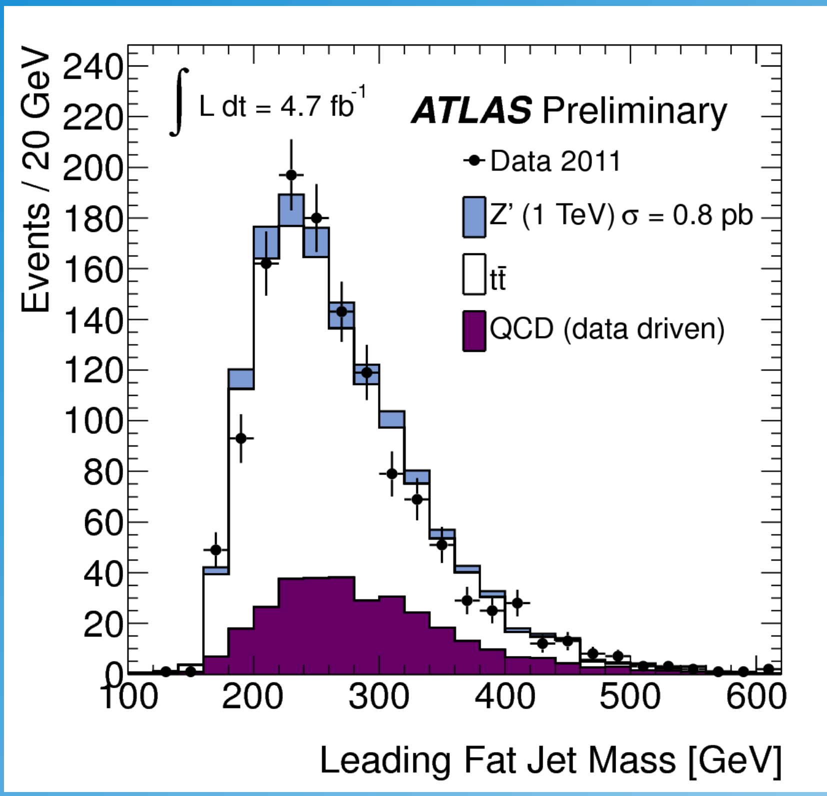


filtering + substructure →

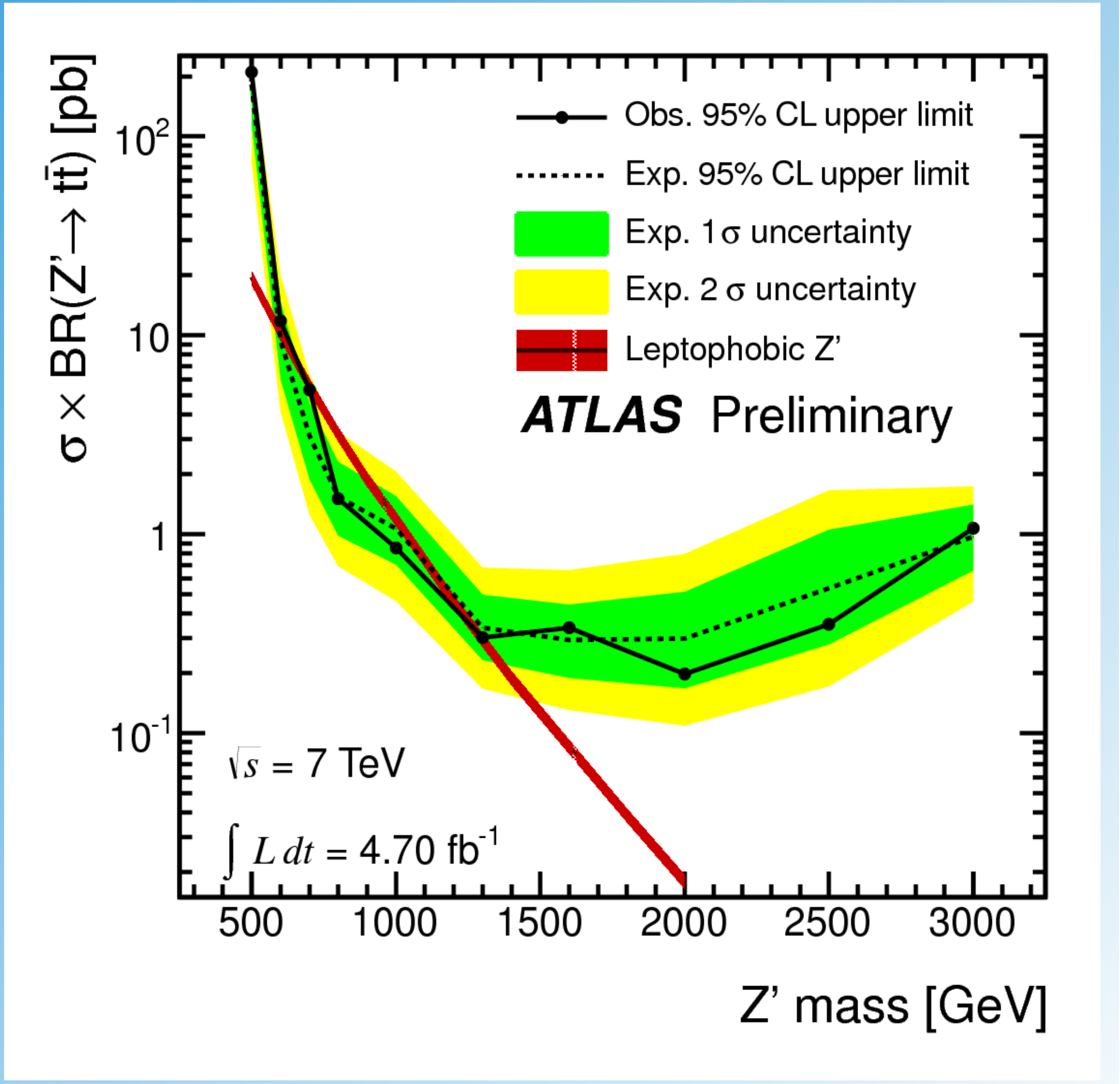


from D.Sosa

ttbar Resonance Search with HEPTopTagger



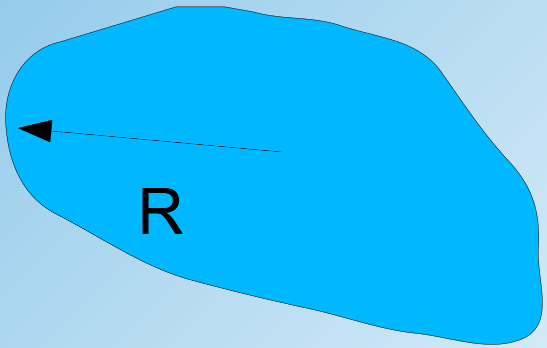
fat jet mass



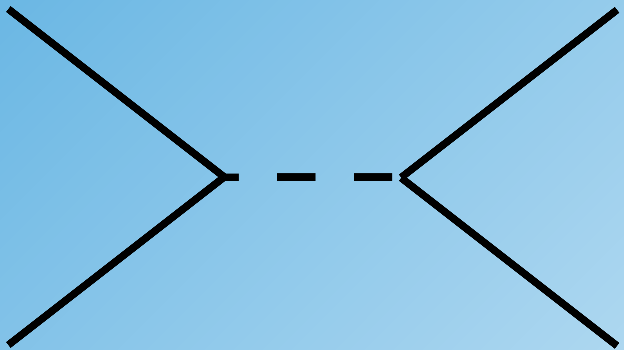
Z' decaying only into quarks

Search for Large Extra Dimensions

- There might be more than 3+1 dimensions
- Higher dimensions compactified (might explain weakness of gravity)
- Compactification radius R
- Introduce new mass scale M_s replacing the Planck Scale
- Higher modes can be excited in compactified extra dimensions (Kaluzza, Klein)

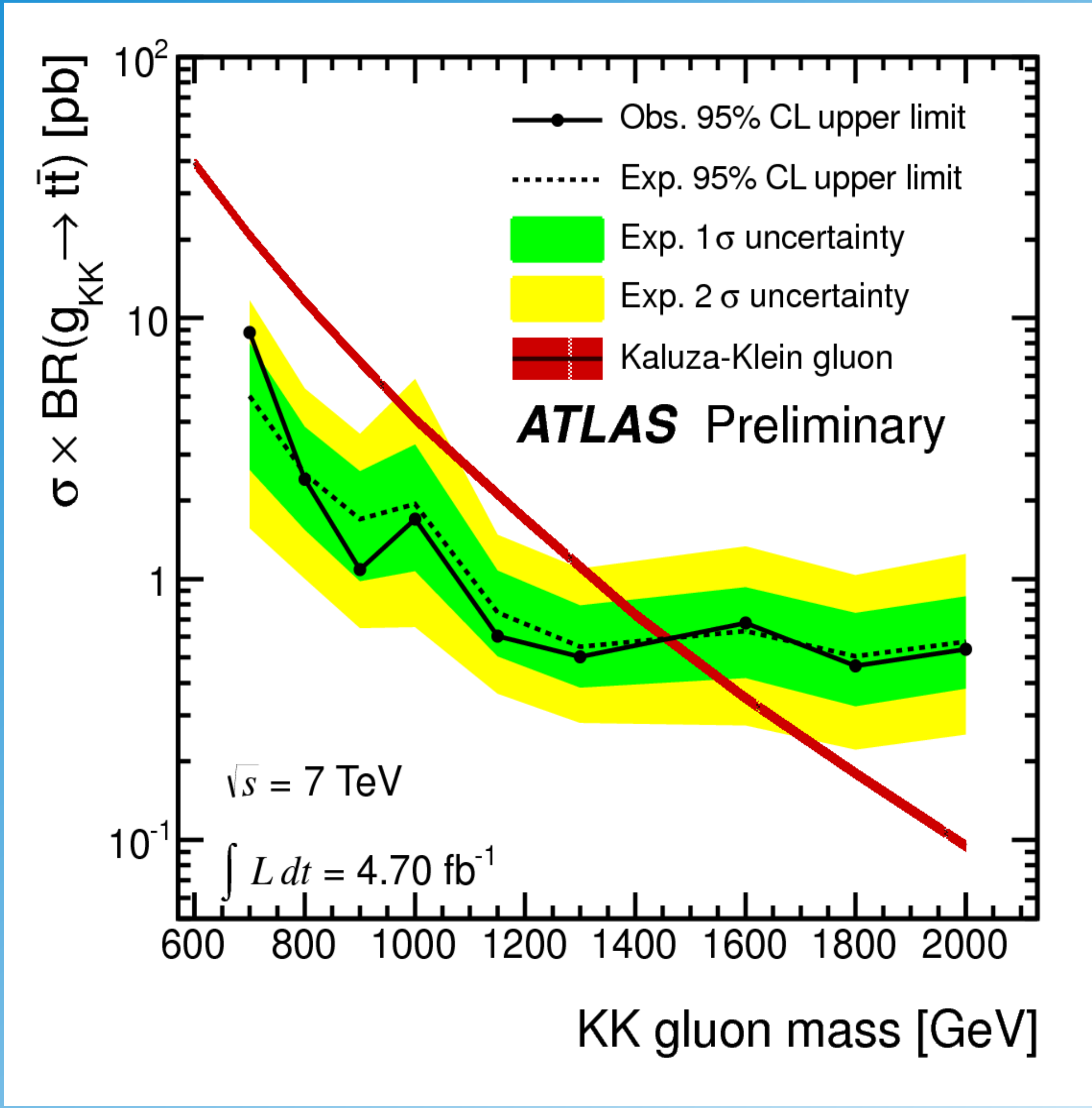


- Tower of excited Kaluza-Klein states mediate new interactions



- looks like Z'
- Kaluza-Klein Gluons (strong)

Kaluza-Klein Gluons



even stronger limits