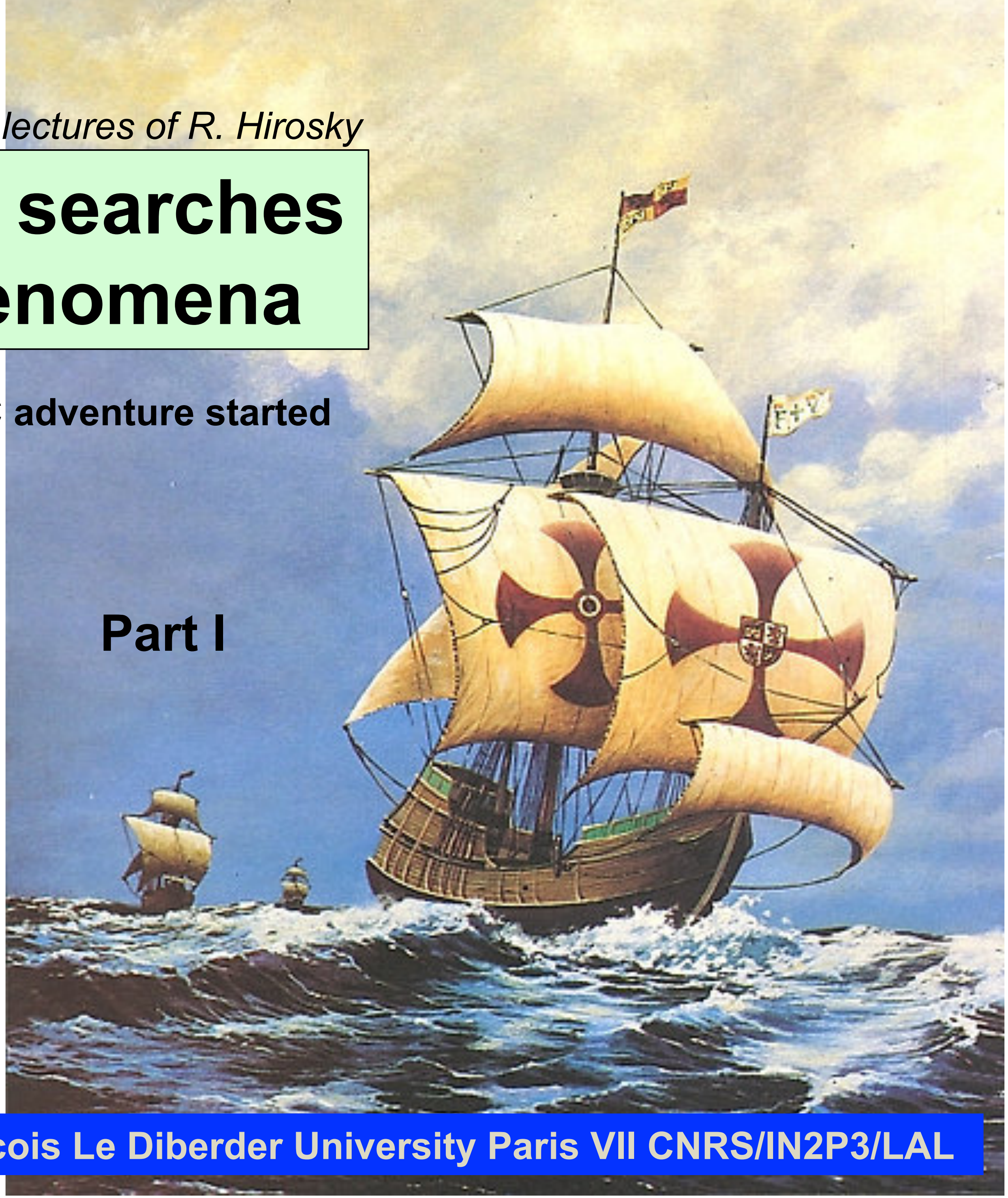
Follow up of this morning lectures of R. Hirosky

LHC : Early searches for new phenomena

The great LHC adventure started

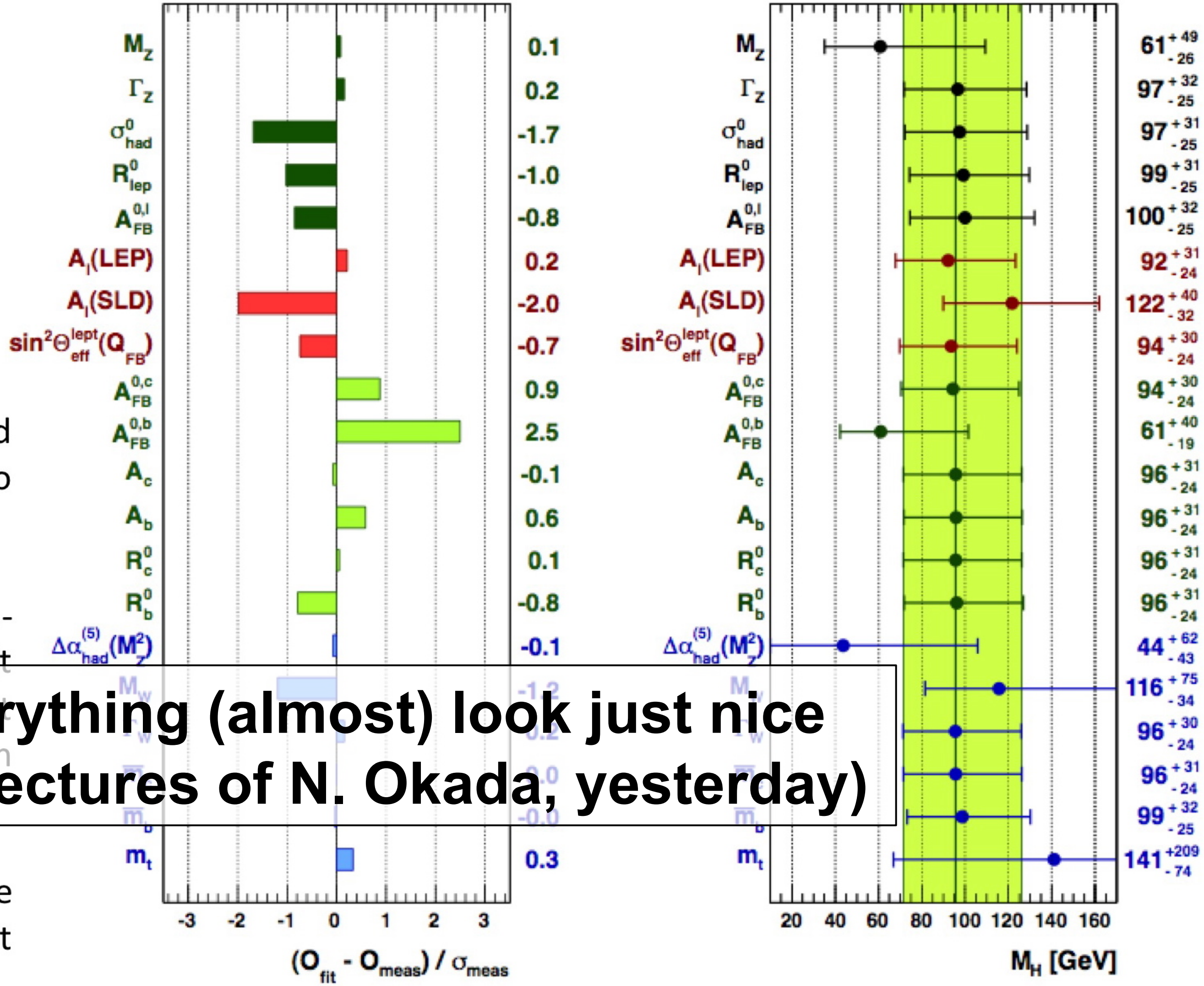


Part I

BCVSPIN July 2011: Francois Le Diberder University Paris VII CNRS/IN2P3/LAL

Gfitter Standard Model Fit Results

- Standard Fit Results
  - χ^2_{min} = 16.7
  - 13 degrees of freedom
  - Prob(χ^2_{min},13) = 0.21
- Complete Fit Results
  - χ^2_{min} = 17.6
  - 14 degrees of freedom
  - Prob(χ^2_{min},14) = 0.23
- Probabilities confirmed by pseudo Monte Carlo experiments
- Improvement in the p-value of the complete fit due to increased best fit value of the Higgs mass in the standard fit
- new result reduces the tension with the direct Higgs boson searches



Everything (almost) look just nice (cf. lectures of N. Okada, yesterday)

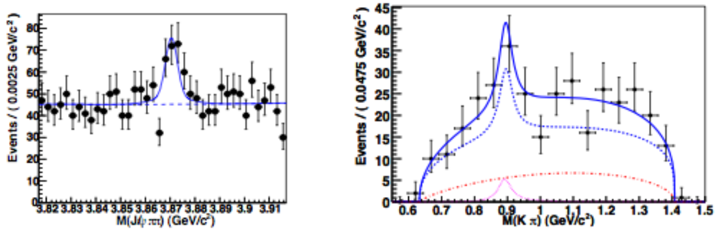
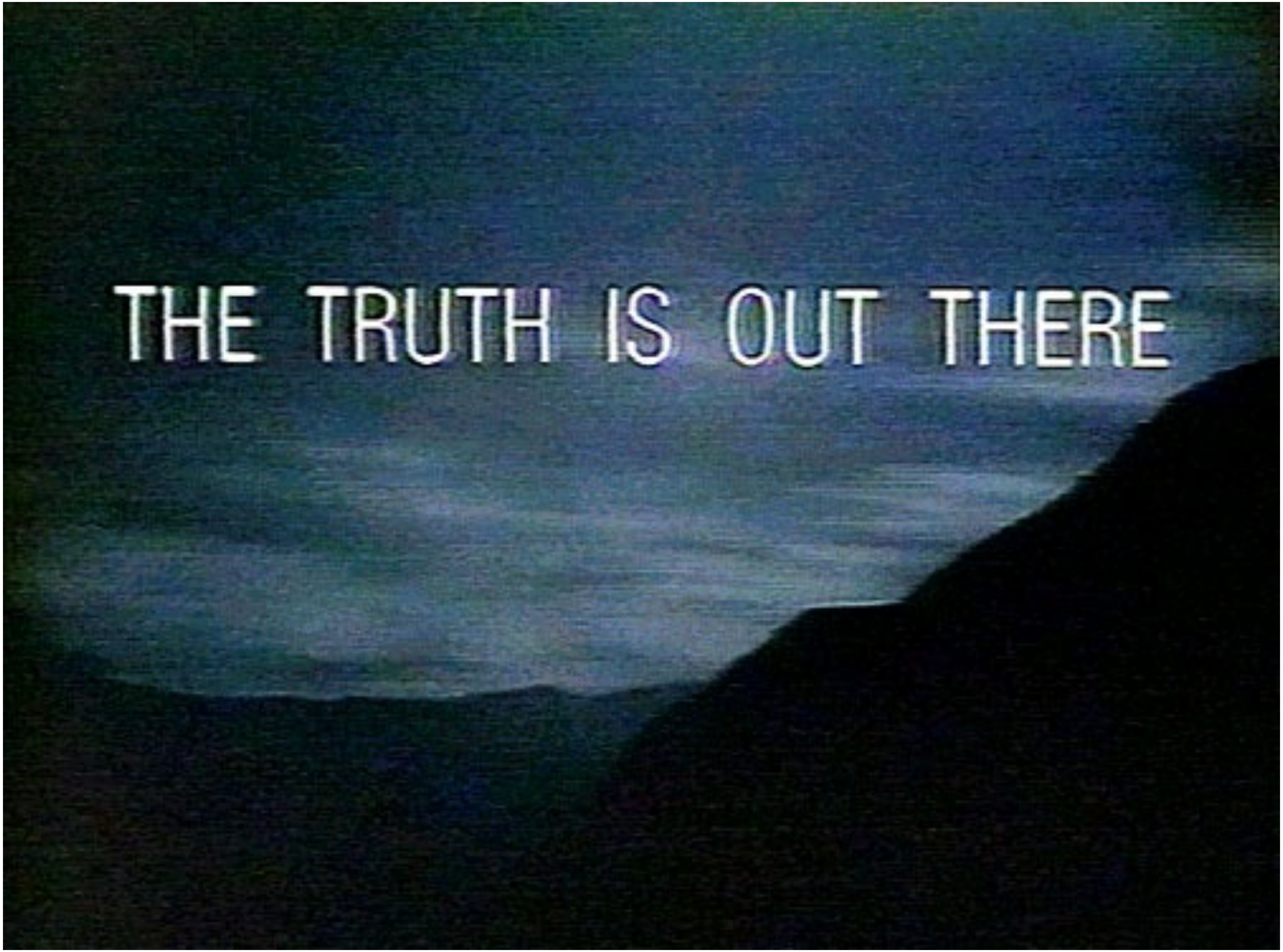


Figure 1: The $J/\psi\pi^+\pi^-$ invariant mass distribution (left) and $K^+\pi^-$ invariant mass distribution (right) for $B^0 \to J/\psi\pi^+\pi^-K^+\pi^-$ from Belle. In the $K^+\pi^-$ distribution only events in $X(3872)$ region are used. The full line shows the fit projection, the dashed blue line represents background, the dashed-dotted shows non-resonant decays with $X(3872)$ signal and the dotted curve shows resonance decays with $X(3872)$ signal.

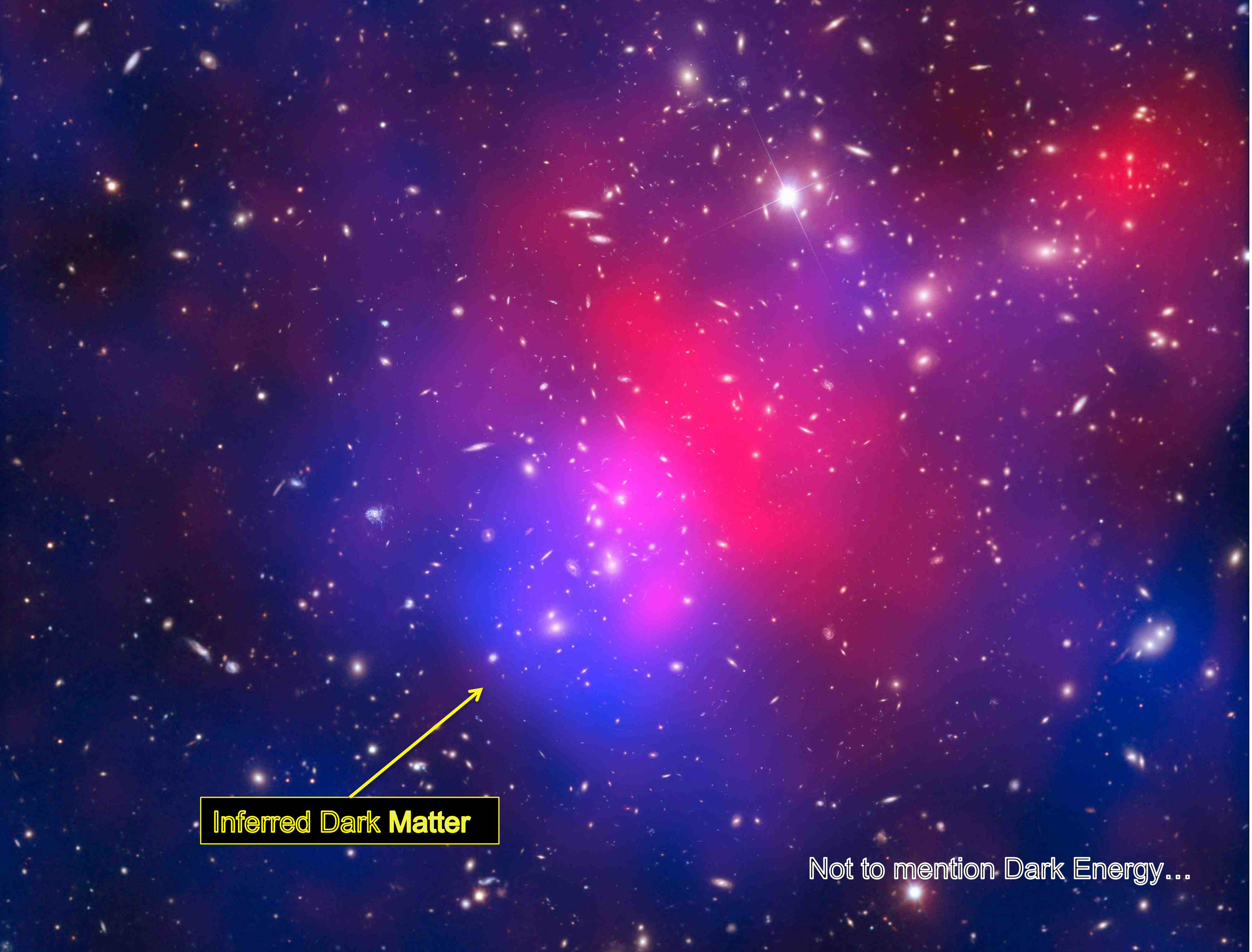
Time to time one stumbles
on a nice discovery, like
a new animal species
(left X(3872) resonance)

Similarly, the recent discovery of a large Gibbon colony in Vietnam does not change our understanding of the world (although it is very nice news)


THE TRUTH IS OUT THERE

We know, for sure, that the Standard Model cannot be the end of the Story

We need a reliable compass to find our way towards the new world


Inferred Dark Matter
Not to mention Dark Energy…

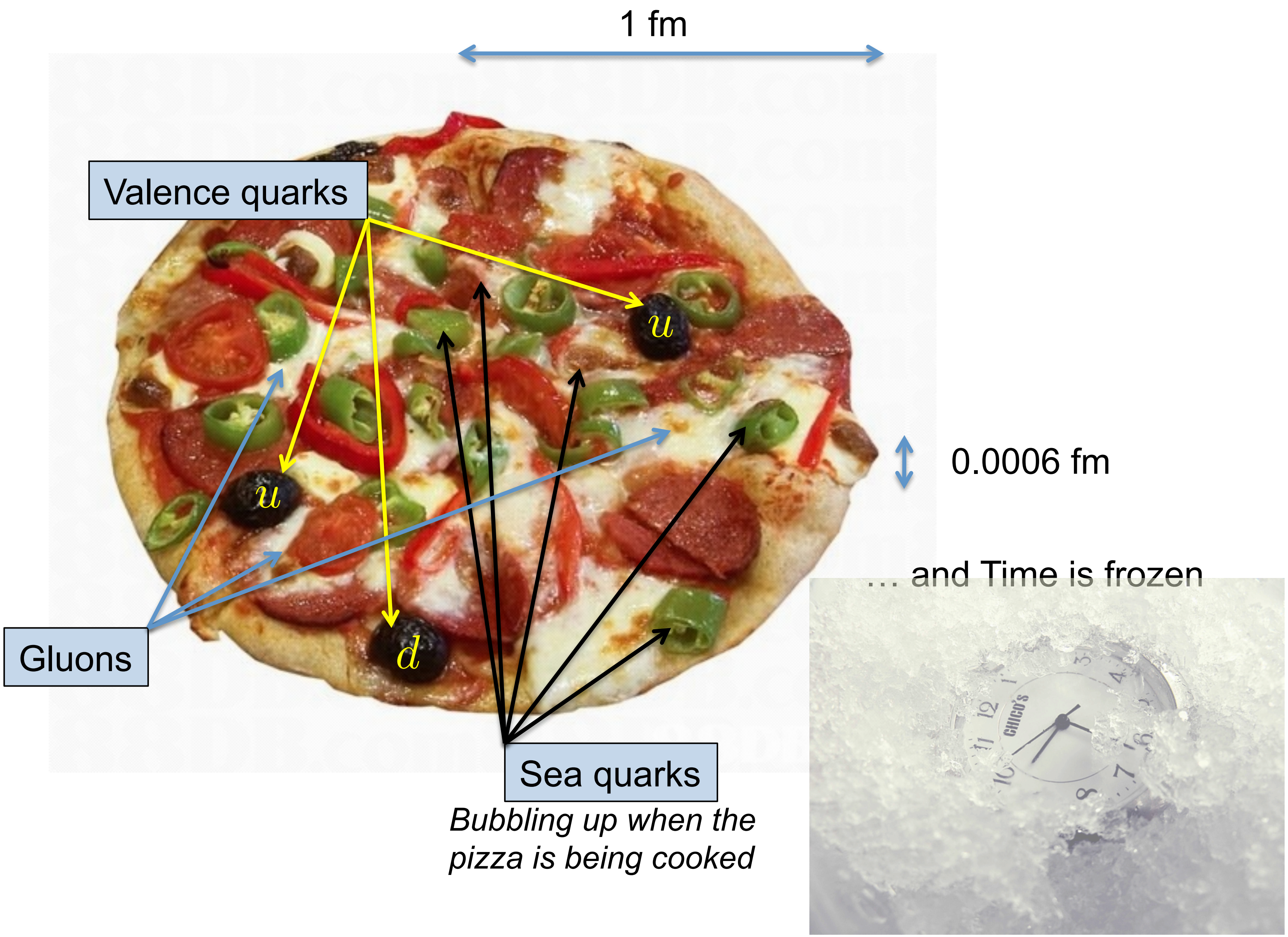
Searching for new phenomena at the LHC
Implies dealing with several issues:

1) **Underlying event**
2) **Pile-up events**
3) **Standard Model backgrounds**

Underlying event

My personal contribution to
Quantum Field Theory

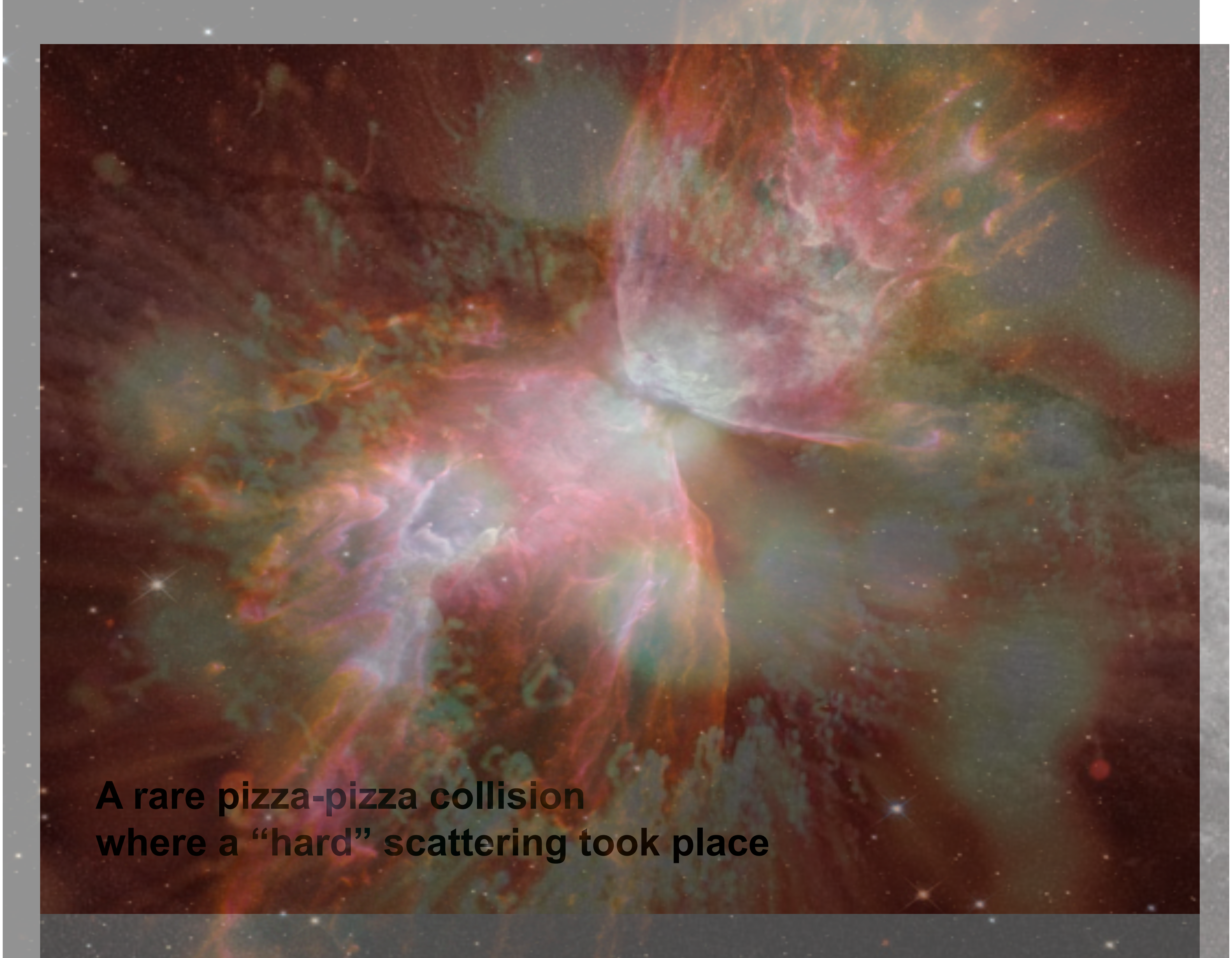
Proton in the LHC at 7 TeV CoM *Is a Quantum Mechanics Frozen Pizza*



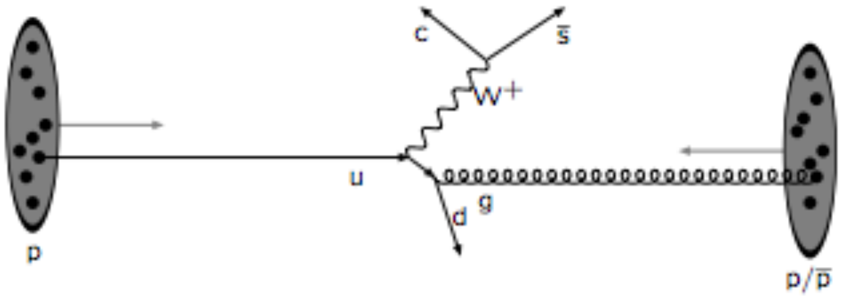

Pizza Pizza collisions


The Gluon field
Strong Interaction is Strong

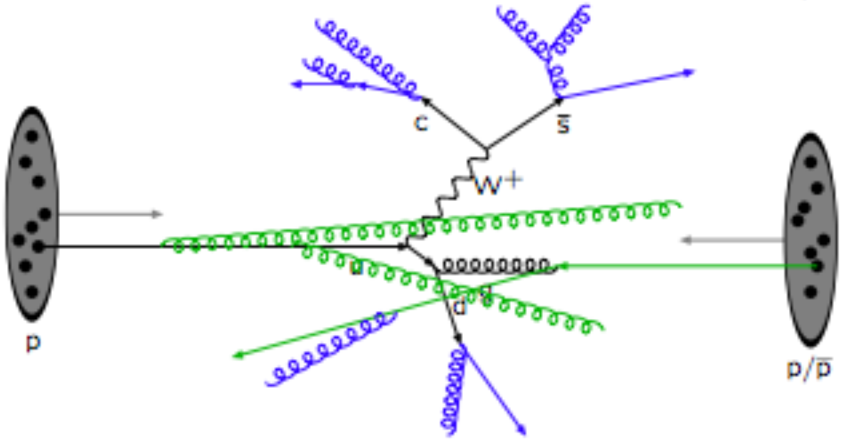
A typical Pizza-Pizza collision


A rare pizza-pizza collision
where a “hard” scattering took place

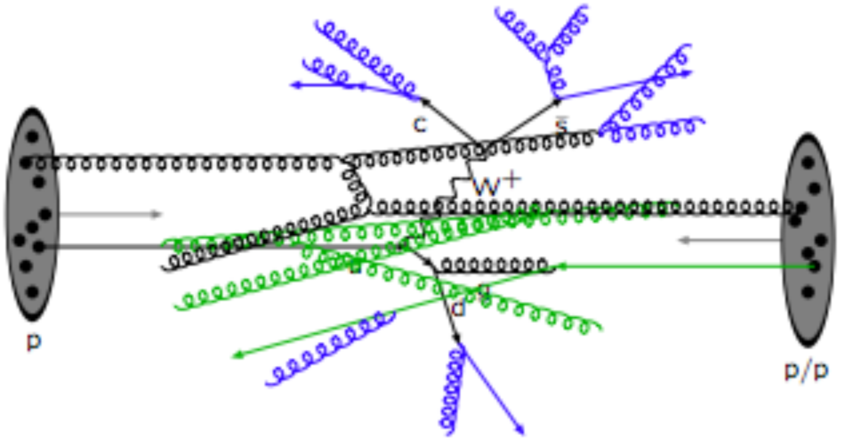

A Pizza-Pizza collision with an example of new physics



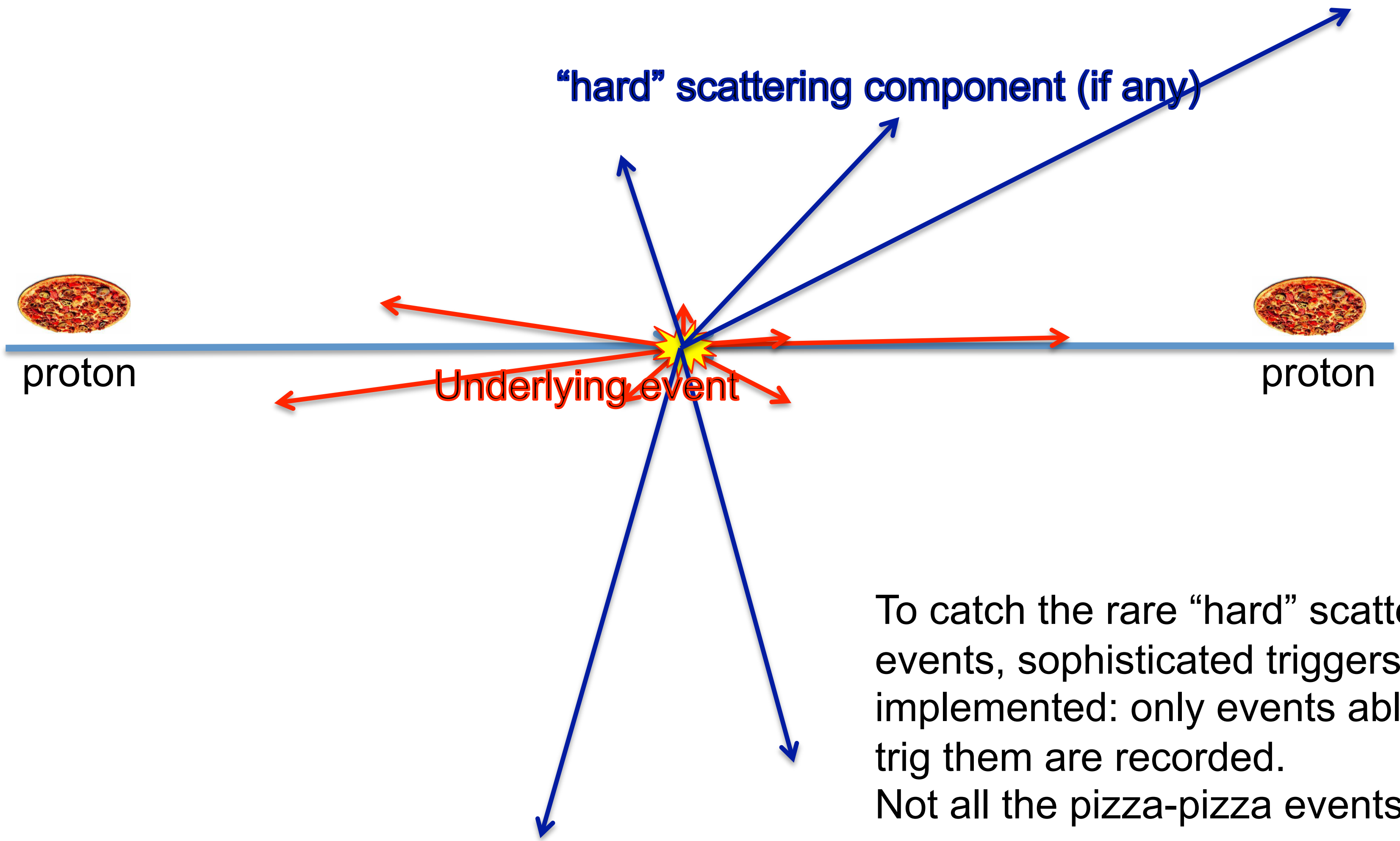
Example of interesting process



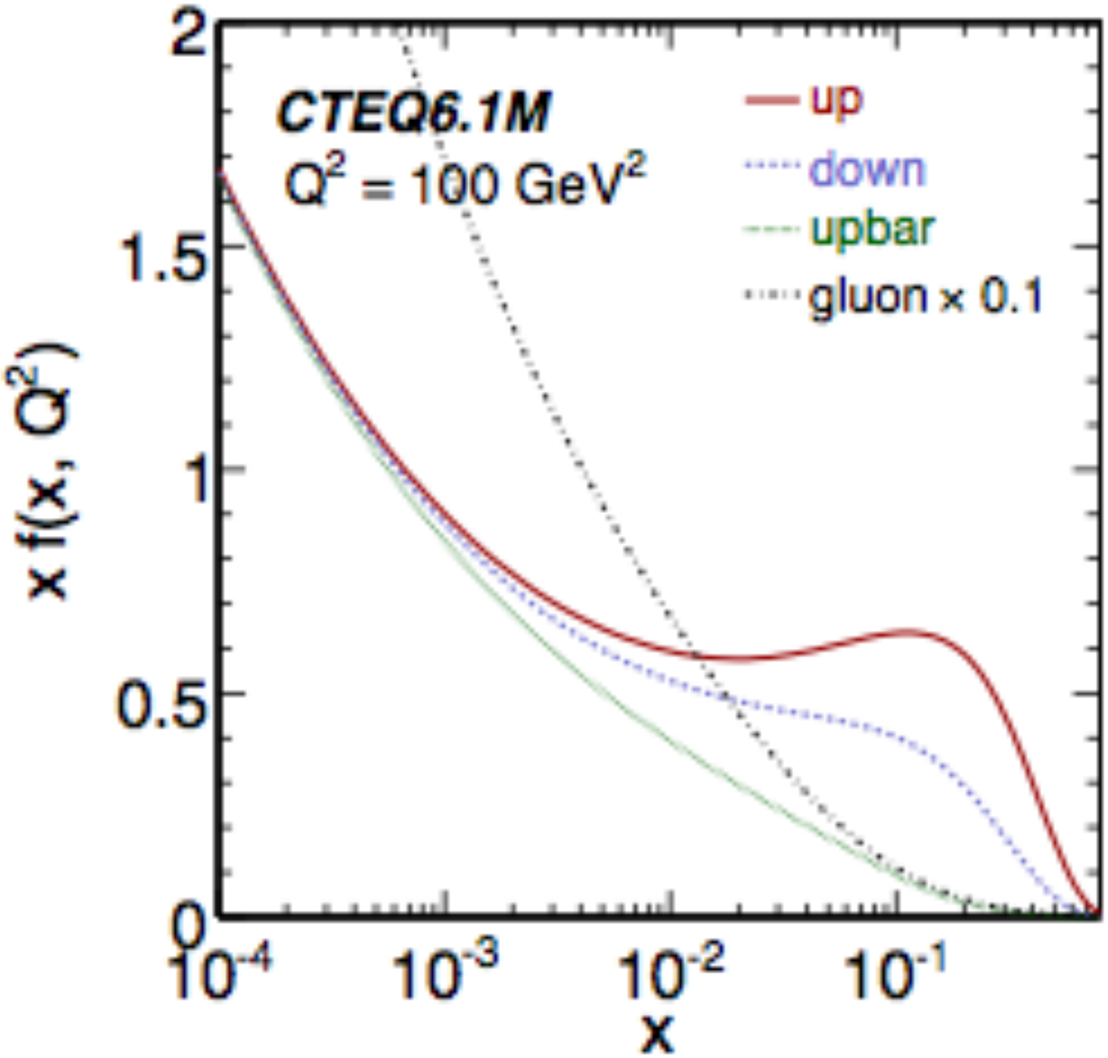
Next-to-Next-to-Next… QCD



Underlying event (pizza-pizza)



To catch the rare "hard" scattering events, sophisticated triggers are implemented: only events able to trig them are recorded.
Not all the pizza-pizza events !!!

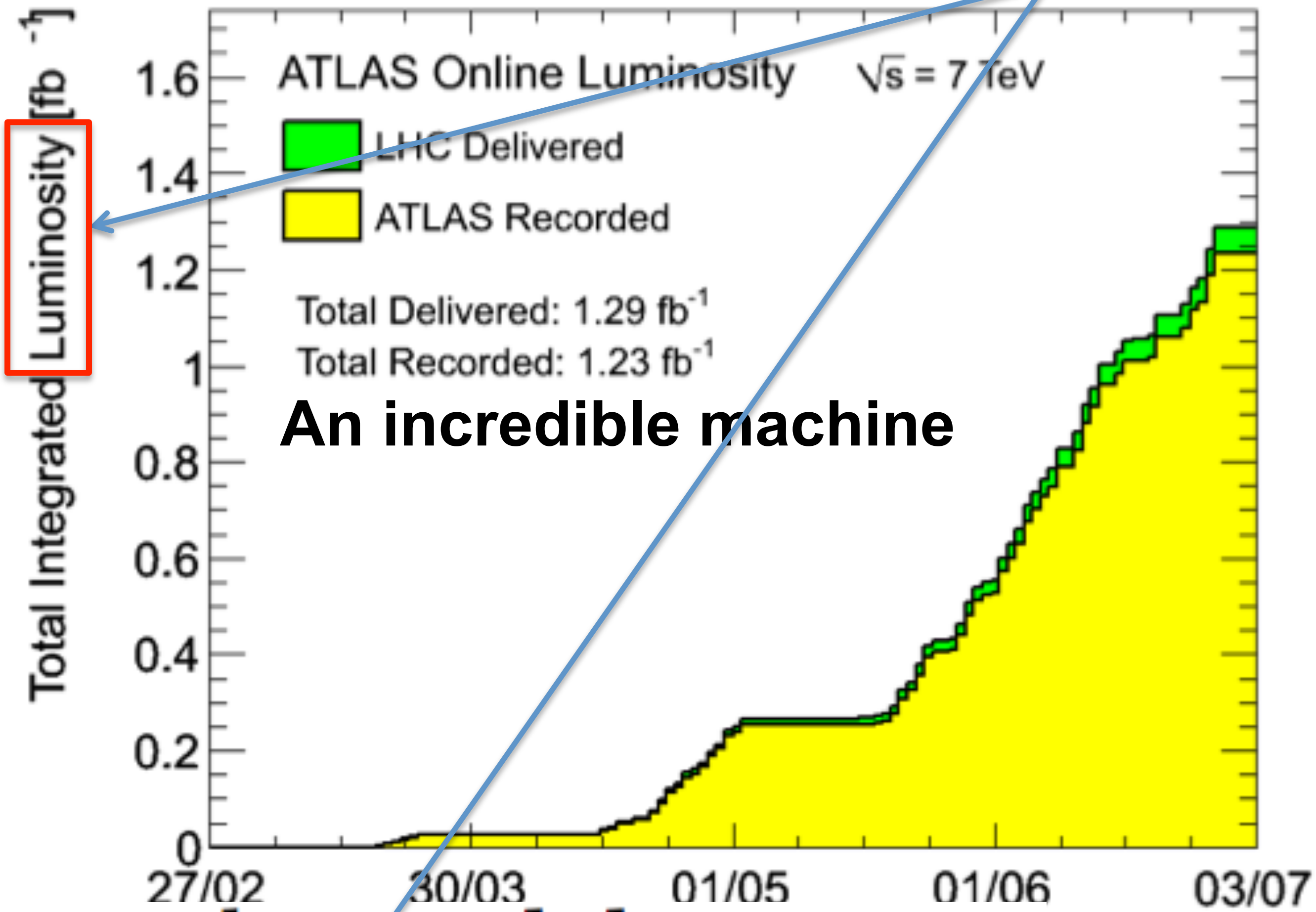


The interesting ("hard") process is driven by the probability (PDF) that such and such parton (i.e.quarks or gluon) is carrying a fraction x of the proton, when the pizza-pizza collision occurs.

A very-very long story, with quite numerous dedicated experiments, amongst which the two of DESY did fantastic.

Pile-up events

Number of events produced are proportional to the "Luminosity" of the machine



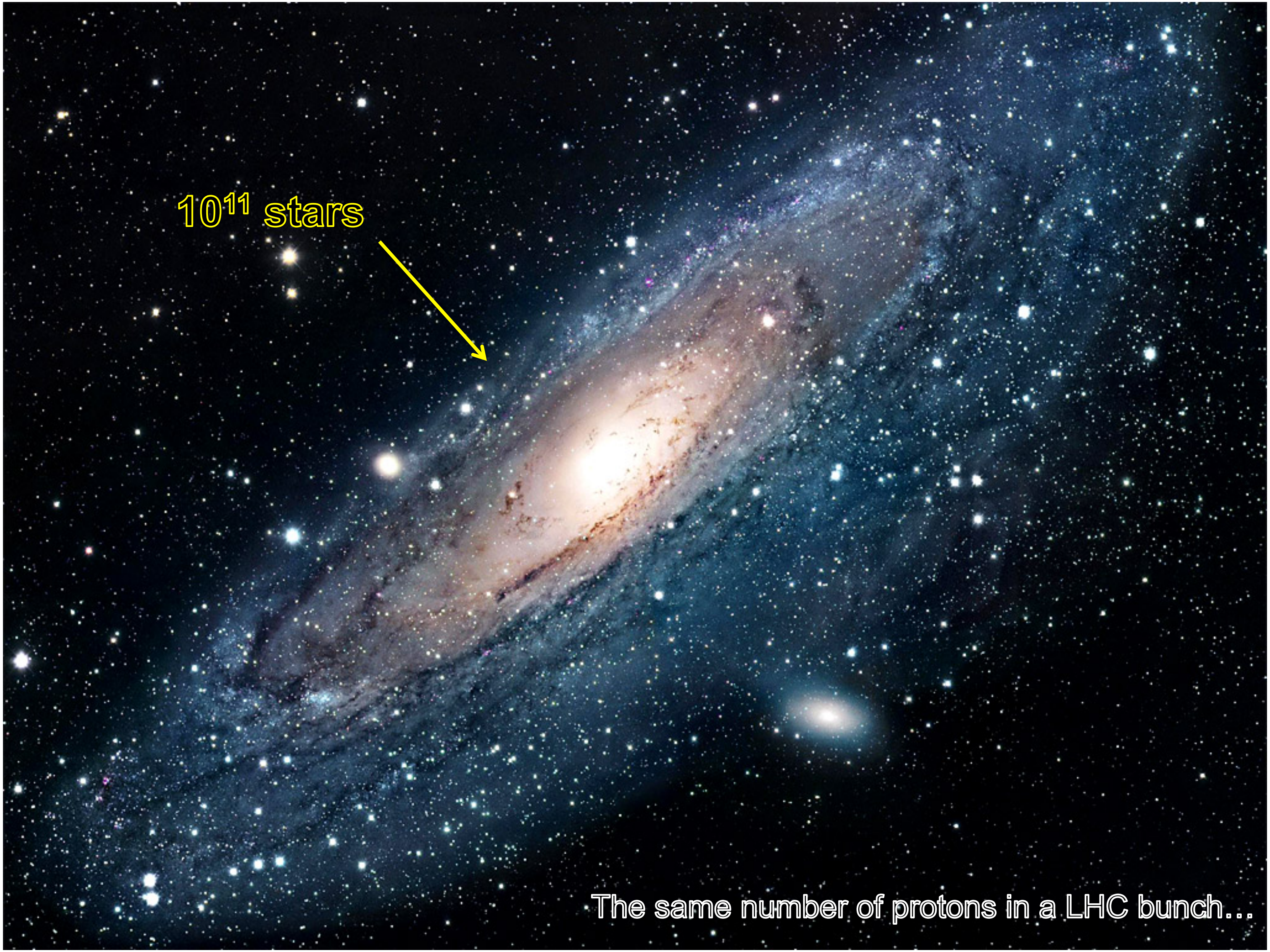
An incredible machine

2010: 45pb^{-1} recorded

2011 (till 1/07): 1.23fb^{-1} recorded

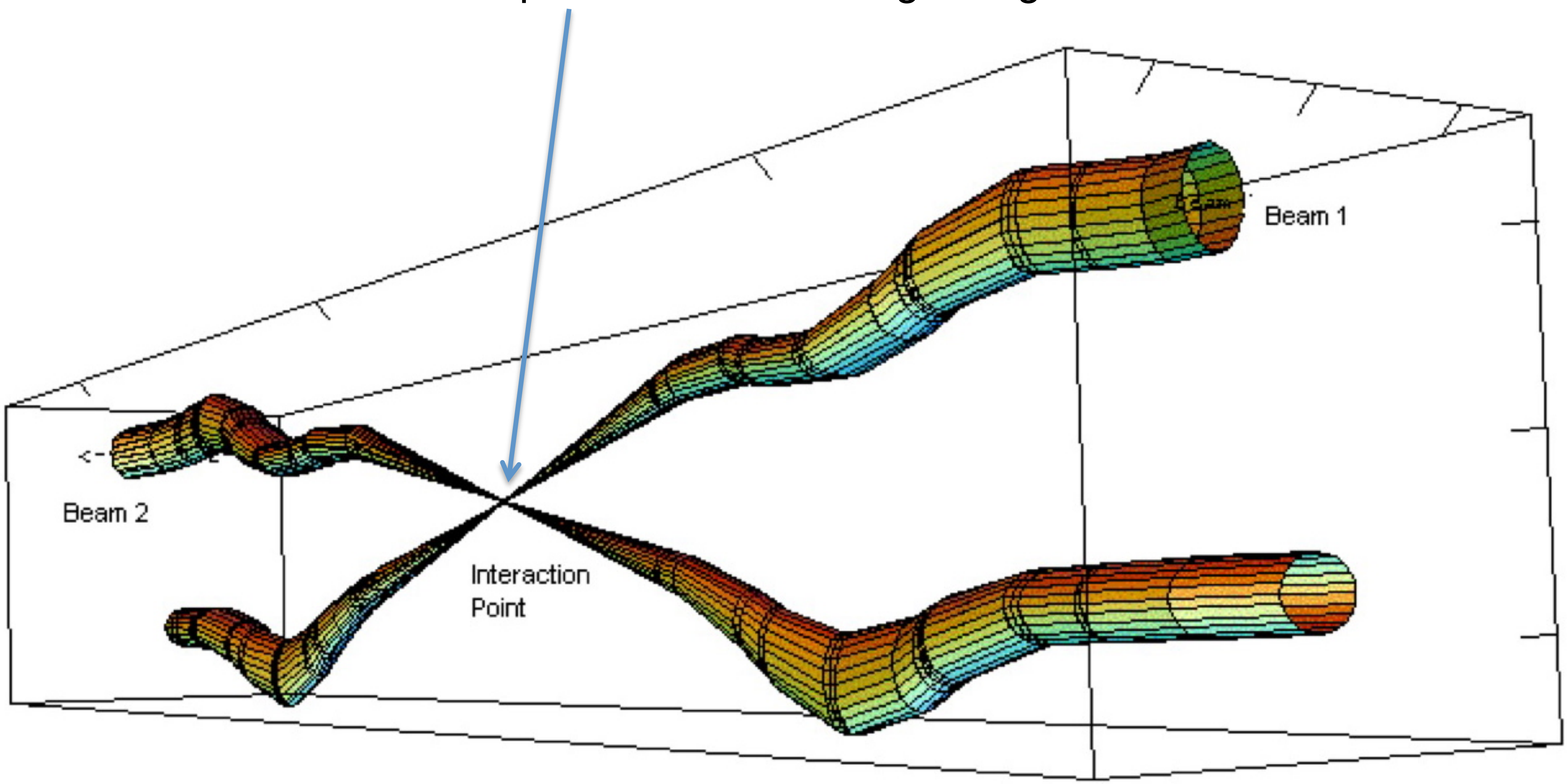
Peak Lumi of 1.26×10^{33} $cm^{-2}s^{-1}$

6 interactions per BC on average → **Pile-up events**


10^{11} stars
The same number of protons in a LHC bunch…


Galaxy collisions are not that frequent….
Bunch bunch collisions are in the ten-MegaHerz range at LHC…

and the bunches are squeezed before being brought into collision



Relative beam sizes around IP1 (Atlas) in collision

The probability P for a given proton to experience a collision in a bunch-bunch crossing is the ratio of two surfaces

1) The effective surface σ occupied by one proton of one beam (call it the target beam)

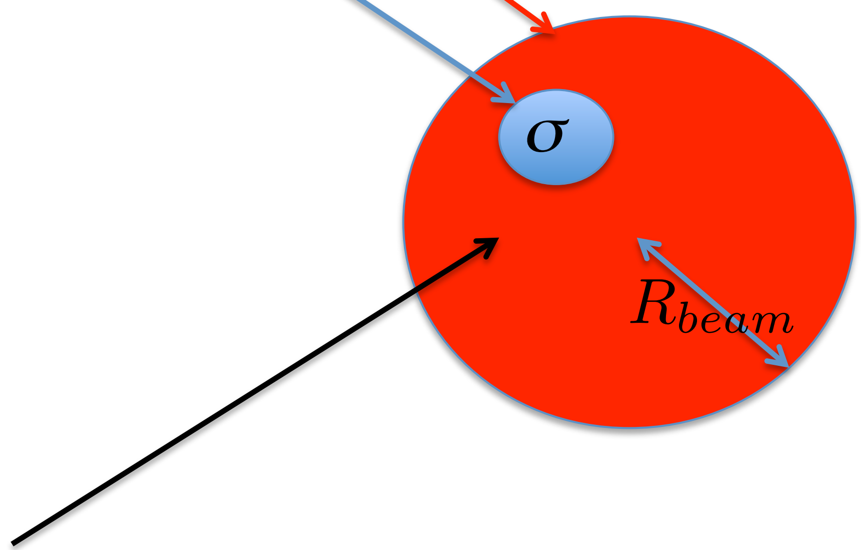
divided by

2) the effective surface of the colliding beams $S_{beam} = \pi R_{beam}^2$

mulipied by

3) N : the number of protons in the (target) beam

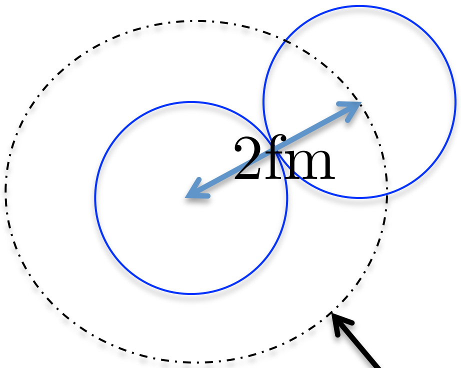
$$P = \frac{\sigma}{S_{beam}} N$$



proton incoming onto the target beam

Let's compute $P = \frac{\sigma}{S_{beam}} N$

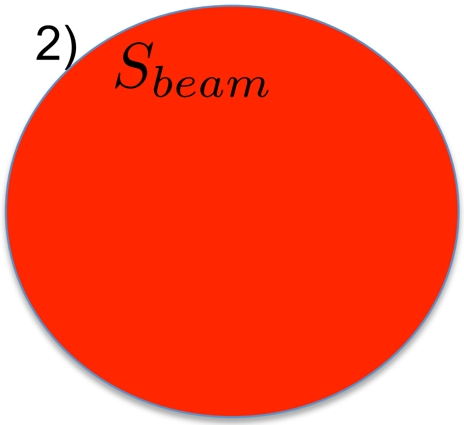
1) σ



The strong interaction is so strong that whenever two protons touch they do interact.
Thus, the effective radius is twice the radius of one proton, about $2\mathrm{fm} = 2 \;\; 10^{-15}\mathrm{m}$

$$\sigma = \pi(2\mathrm{fm})^2 \simeq 120\mathrm{mbarn}$$

2)



The beam density is a double Gaussian of widths $\sigma_x^* \simeq \sigma_y^* \simeq 20\mu\mathrm{m}$

Not obvious, it needs proof…

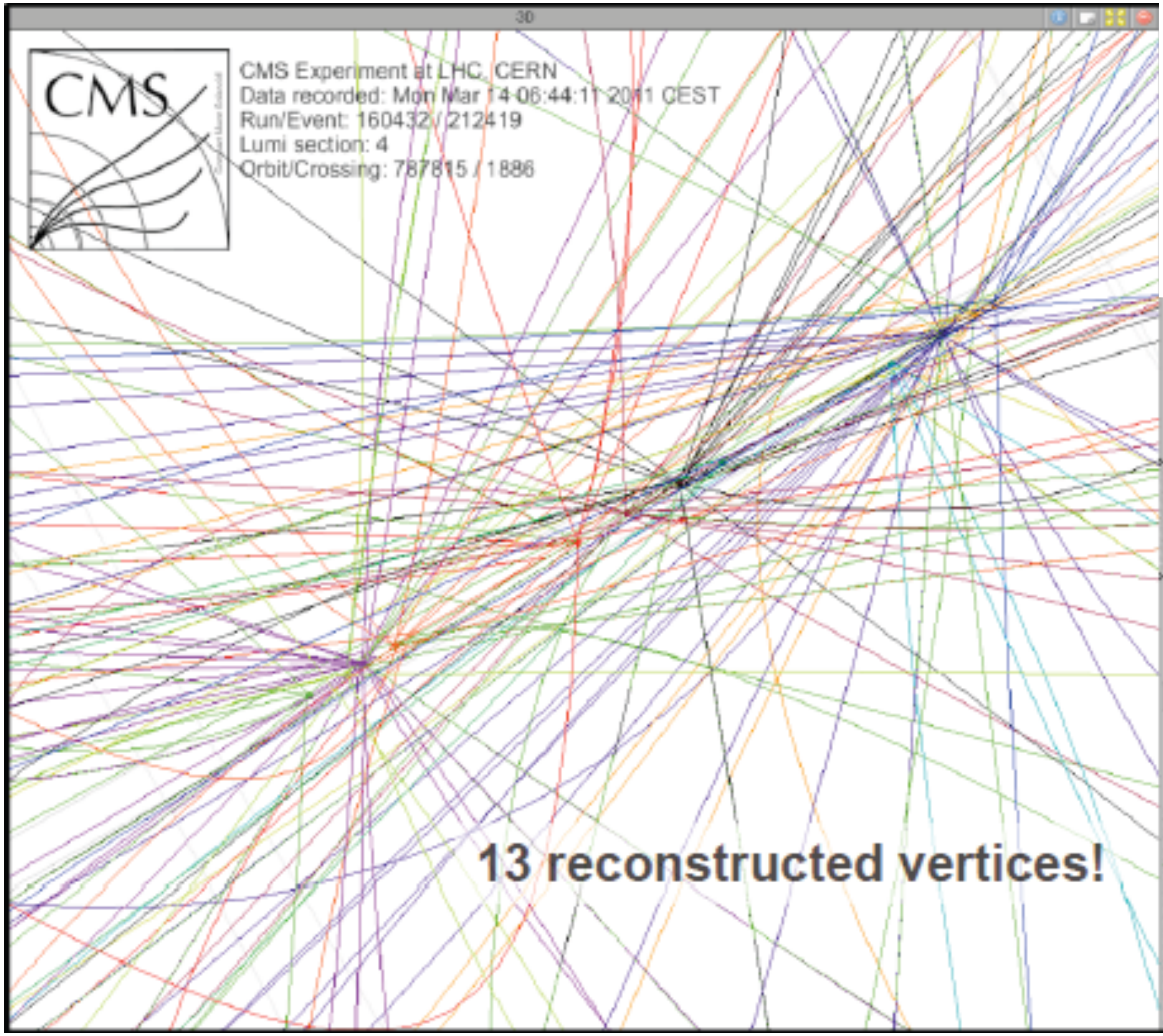
$$R_{beam} = 2\sigma_{x,y}^*$$

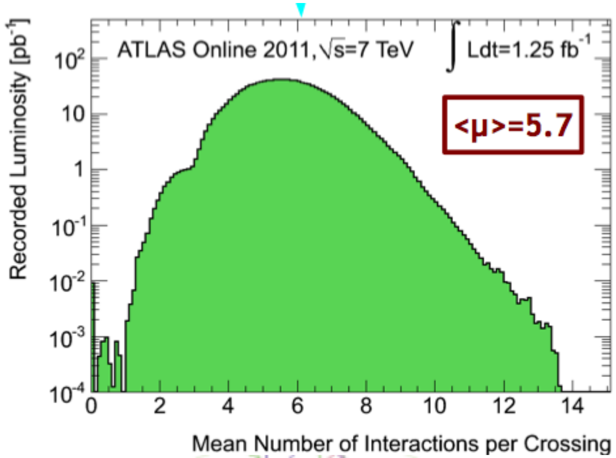
$$S_{beam} = \pi R_{beam}^2 = 4\pi\sigma_x^*\sigma_y^* = 5 \; 10^{-9} m^2$$

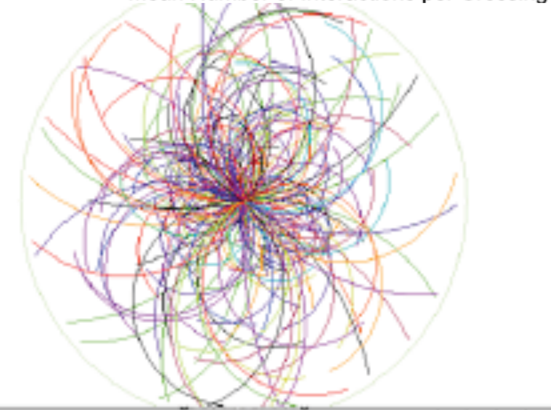
1+2) $P \simeq 10^{-10}$

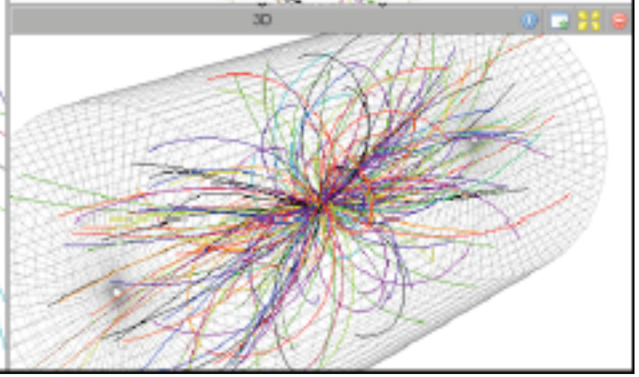
But there are 10^{11} incoming protons !!!

Presently, close to 6 pizza-pizza collisions per bunch crossing





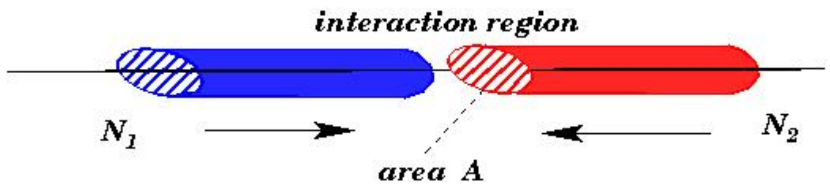




So-called pile-up events, superimposed onto the interesting events

The event rate N for a physics process with cross-section σ is proprotional to the collider Luminosity L:

$$N = L\sigma_{\epsilon}$$

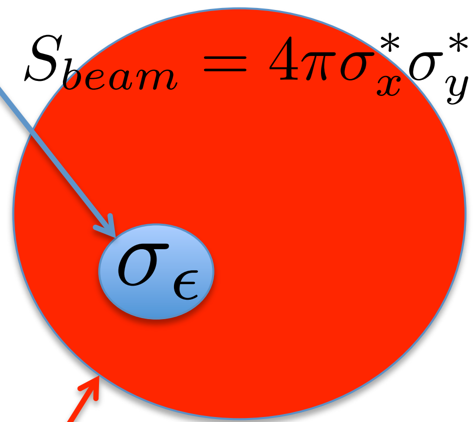


Design

k = number of bunches = 2808
N = no. protons per bunch = 1.15×10^{11}
f = revolution frequency = 11.25 kHz
σ^*_x, σ^*_y = beam sizes at collision point (hor./vert.) = 16 μm

To maximize L:

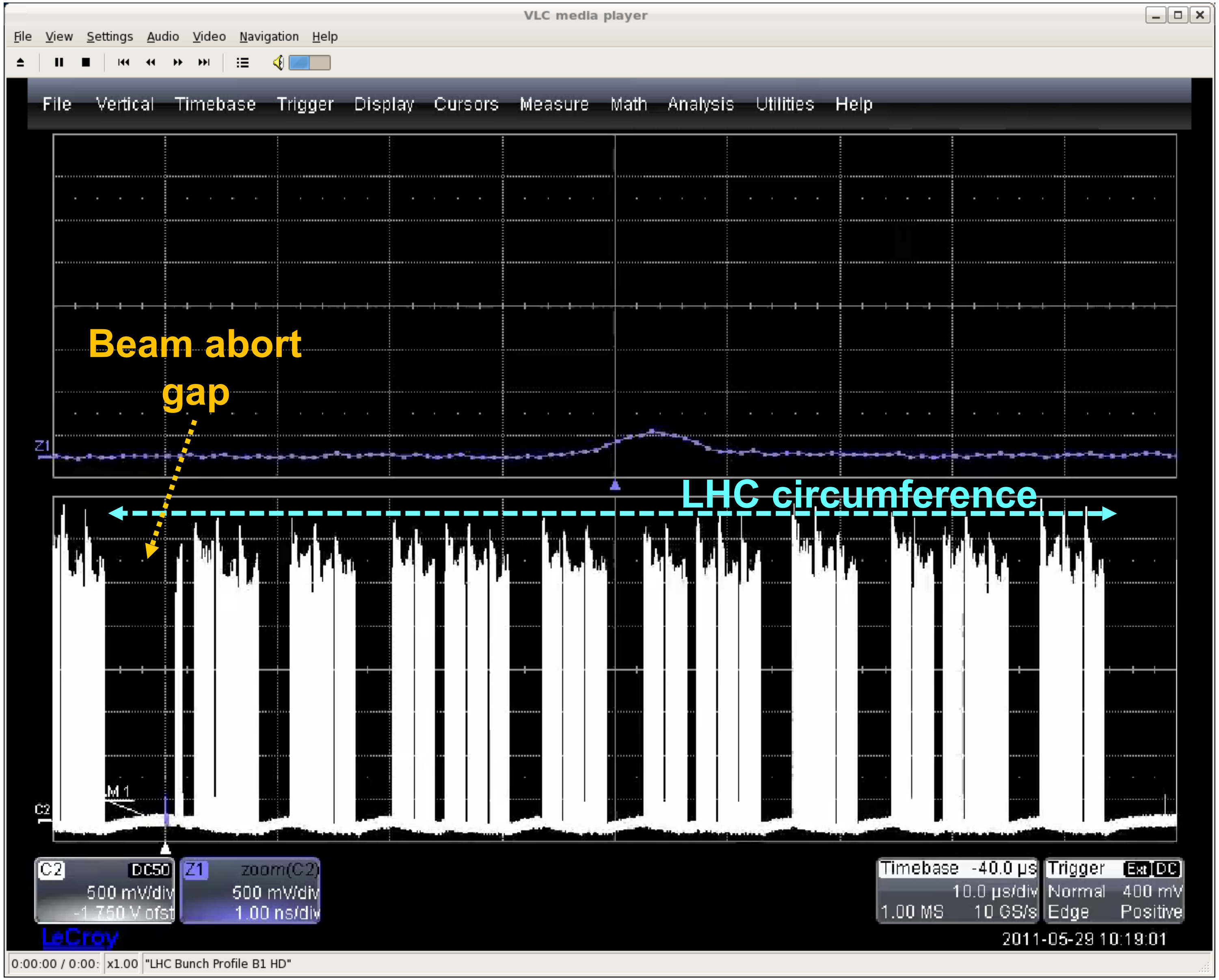
- **Many bunches (*k*)**
- **Many protons per bunch (*N*)**
- **Small beam sizes $\sigma^*_{x,y}$**



$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

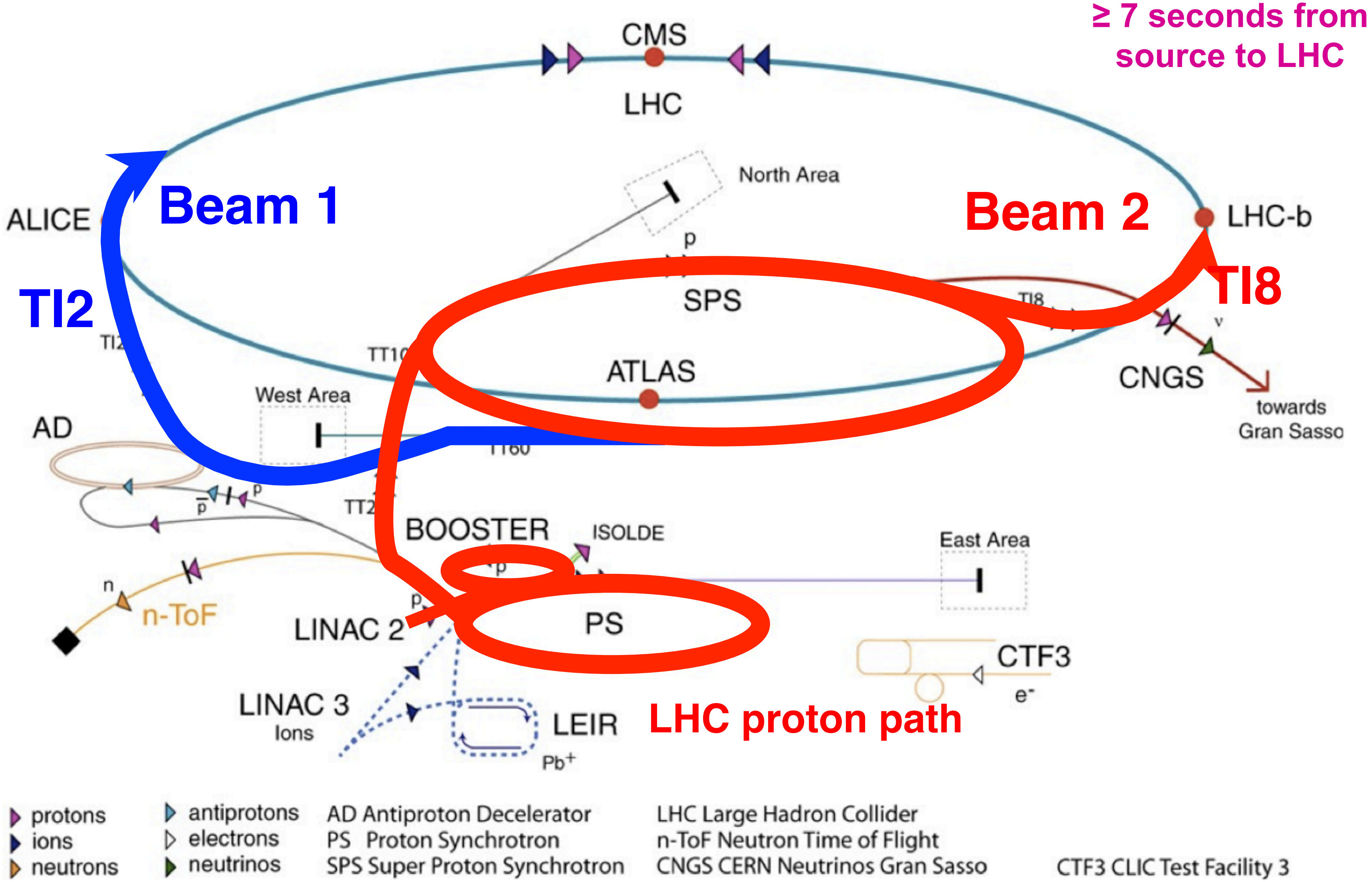
L is the effective area^{-1} of the beam, times N, times N (again), times k, times f

1380 bunches with 50 ns spacing



LHC accelerator complex

≥ 7 seconds from source to LHC



The LHC needs most of the CERN accelerators...


A few cm long groove in a SPS vacuum chamber after the impact of ~1% of a nominal LHC beam (2 MJ) during an ‘incident’

Standard Model events

Ignoring factorization scale and renormalization scale subtleties…

$$\sigma_{[ij\to X]} = \int \mathrm{d}x_i f_i(x_i) \int \mathrm{d}x_j f_j(x_j)\ \hat{\sigma}_{[ij\to X]}$$

Parton Density Function (PDF)

See also lecture-2 of N. Okada

For a given X invariant mass $m_X^2 = x_i x_j S$ one gets:

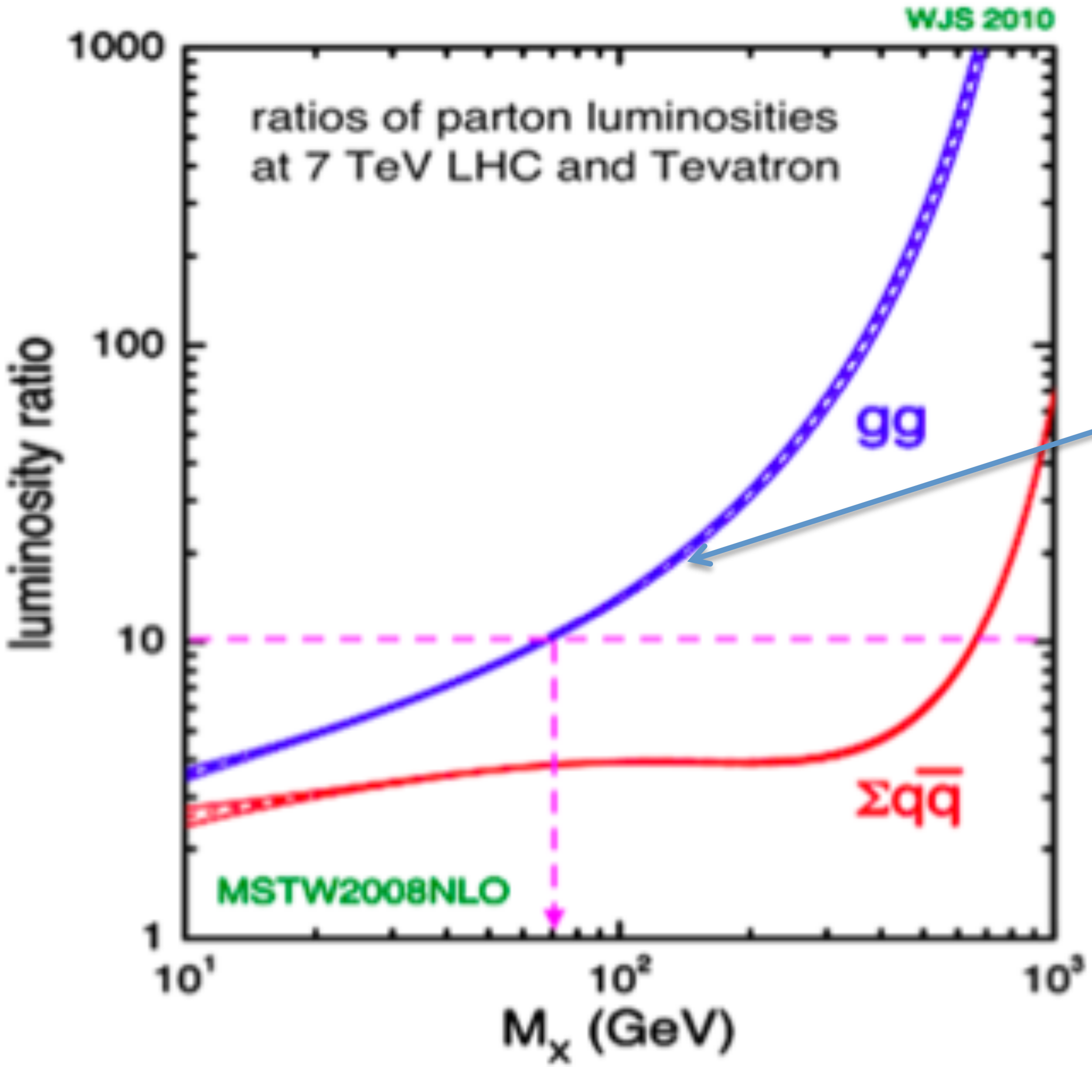
$$\frac{\mathrm{d}\sigma_{[ij\to X]}}{\mathrm{d}m_X^2} = \frac{\mathrm{d}\mathcal{L}_{ij}}{\mathrm{d}m_X^2}\quad \hat{\sigma}_{[ij\to X]}(m_X^2)$$

Where the so-called “parton luminosity function” is:

$$\frac{\mathrm{d}\mathcal{L}_{ij}}{\mathrm{d}m_X^2} = \frac{1}{S}\int_{m_X^2/S}^{1} \frac{\mathrm{d}x_i}{x_i} f_i(x_i) f_j(x_j = m_X^2/(x_i S))$$

Just need to know the Dirac delta function to get it

Parton luminosity functions



A factor of about 20 for Higgs production If

$m_{Higgs} = 150\text{GeV}$

between LHC and Tevatron, if the two Luminosities of the machines were the same …

Rapidity

$$y \equiv \frac{1}{2} \ln[\frac{E+Pz}{E-Pz}]$$

$$\eta \equiv y_{m \ll E} = -\ln\tan(\theta/2)$$

Interesting because :

- Distributions of events are rather flat in terms of rapidity
- The difference between two rapidities

$$y_1 - y_2 = \Delta y_{12}$$

is z-Lorentz invariant : LHC(lab) $\simeq$ CoM(colliding parton)

Easy to demonstrate, please do it.

An example of a cross section : quark pair production

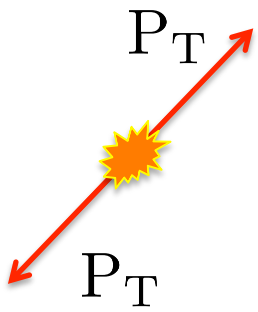
(The differential form is more interesting than the integrated one)

$$\frac{\mathrm{d}^3\sigma_{[ij\to q\bar{q}]}}{\mathrm{dP}_\mathrm{T}^2\mathrm{d}y\mathrm{d}\bar{y}} = \frac{1}{32\pi}\frac{x_i f(x_i) x_j f(x_j)\Sigma_{ij}(y-\bar{y},\mathrm{P}_\mathrm{T}^2)}{\left((m_q^2+\mathrm{P}_\mathrm{T}^2)(1+\cosh(y-\bar{y}))\right)^2}$$

y = rapidity of quark

$\bar{y}$ = rapidity of antiquark

P_T = transverse momentum of quark/antiquark
(*the same value in LHC(lab) and CoM)*



An example of a cross section : quark pair production

Just the PDF of partons i and j

$$\frac{\mathrm{d}^3\sigma_{[ij\to q\bar{q}]}}{\mathrm{dP_T^2}\mathrm{d}y\mathrm{d}\bar{y}} = \frac{1}{32\pi}\frac{x_i f(x_i) x_j f(x_j)\Sigma_{ij}(y-\bar{y},\mathrm{P_T^2})}{\left((m_q^2+\mathrm{P_T^2})(1+\cosh(y-\bar{y}))\right)^2}$$

Just the invariant mass[4] of the quark pair, but expressed in terms of $\mathrm{P_T}, y, \bar{y}$

With:

$$x_{i,j} = \sqrt{\frac{m_q^2+\mathrm{P}_T^2}{S}}\left(e^{\pm y}+e^{\pm\bar{y}}\right)$$

Check that you can obtain this

An example of a cross section : quark pair production

The tough one: Feynam Diagrams

$$\frac{d^3\sigma_{[ij\to q\bar{q}]}}{dP_T^2\,dy\,d\bar{y}} = \frac{1}{32\pi}\frac{x_i f(x_i) x_j f(x_j)\Sigma_{ij}(y-\bar{y}, P_T^2)}{\left((m_q^2+P_T^2)(1+\cosh(y-\bar{y}))\right)^2}$$

$$\frac{d^3\sigma_{[ij\to q\bar{q}]}}{dP_T^2\,dy\,d\bar{y}} = \frac{1}{32\pi m_q^4}\frac{r^2}{(1+c)^2}(x_i f(x_i) x_j f(x_j))\Sigma_{ij}$$

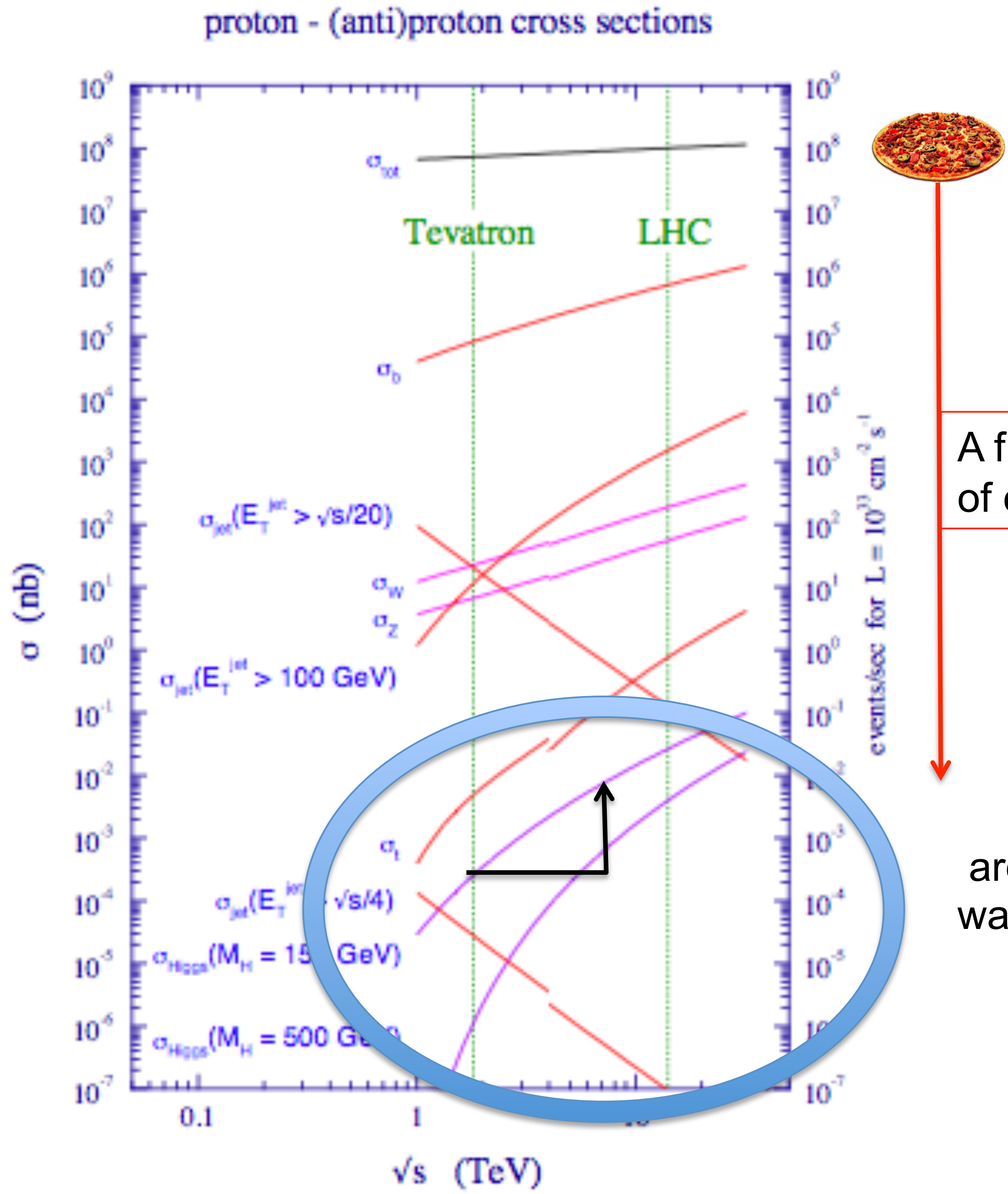
$$\Sigma_{gg} = \frac{1}{24}\frac{8c-1}{1+c}(c+2r(1-r))$$

$$\Sigma_{q\bar{q}} = \frac{4}{9}(c+r)$$

$$c \equiv \cosh(y-\bar{y})$$

$$r \equiv m_q^2/(m_q^2+P_T^2)$$

Quite challenging (for me) : do not try it home!

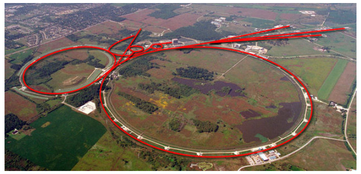


A frightening number of order of magnitude

Most of the new phenomena are expected with cross-sections way below the known phenomena

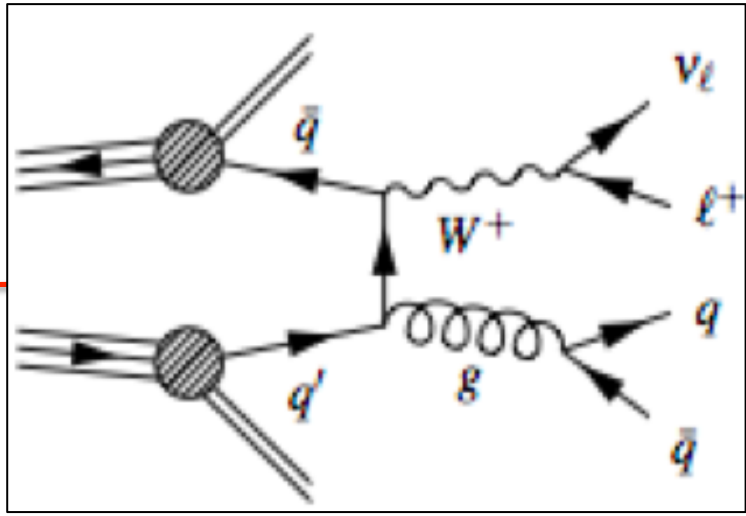
Ultra-Rare events

Tevatron



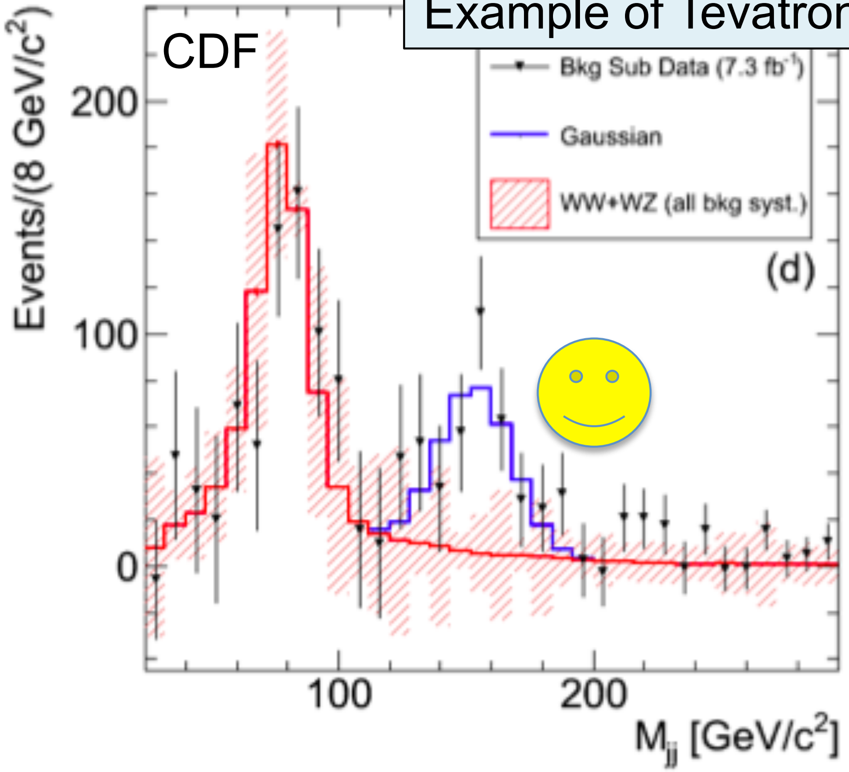
LHC

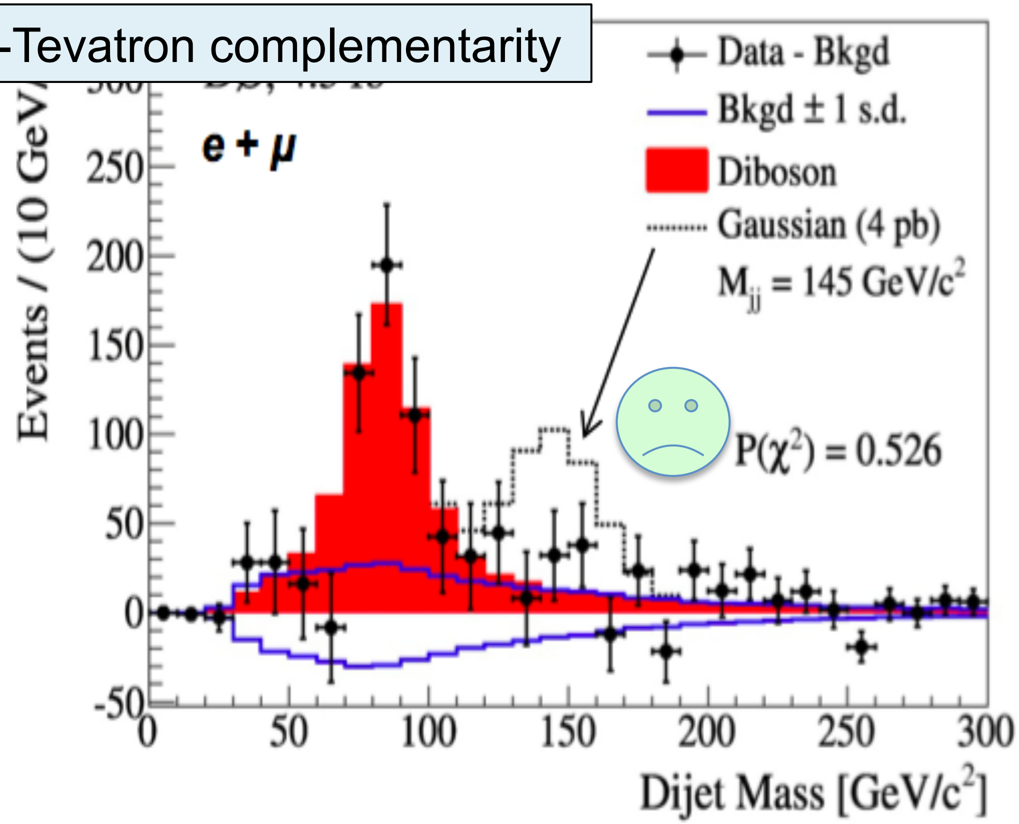
Competion



For the sake of Science

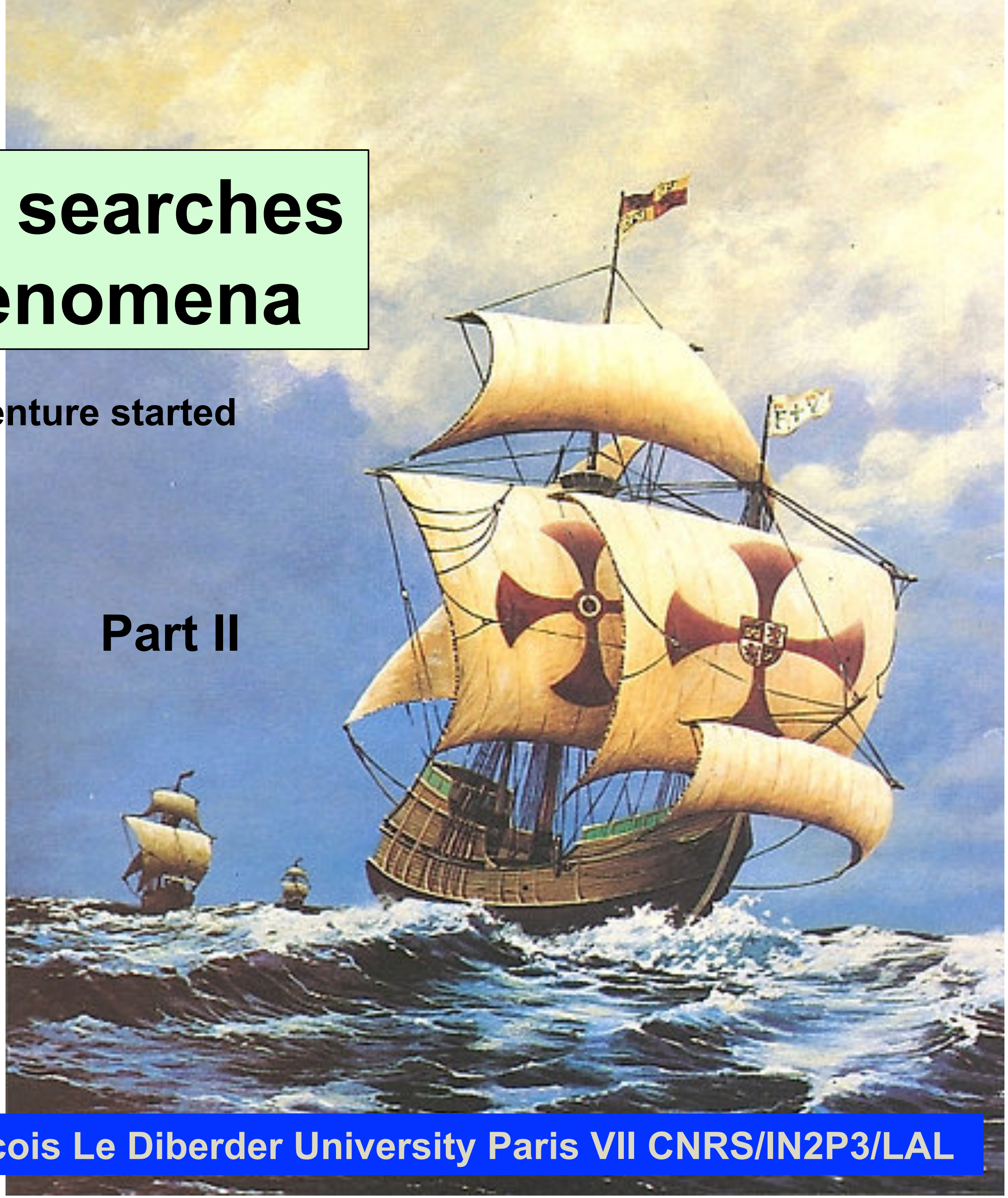
Example of Tevatron-Tevatron complementarity





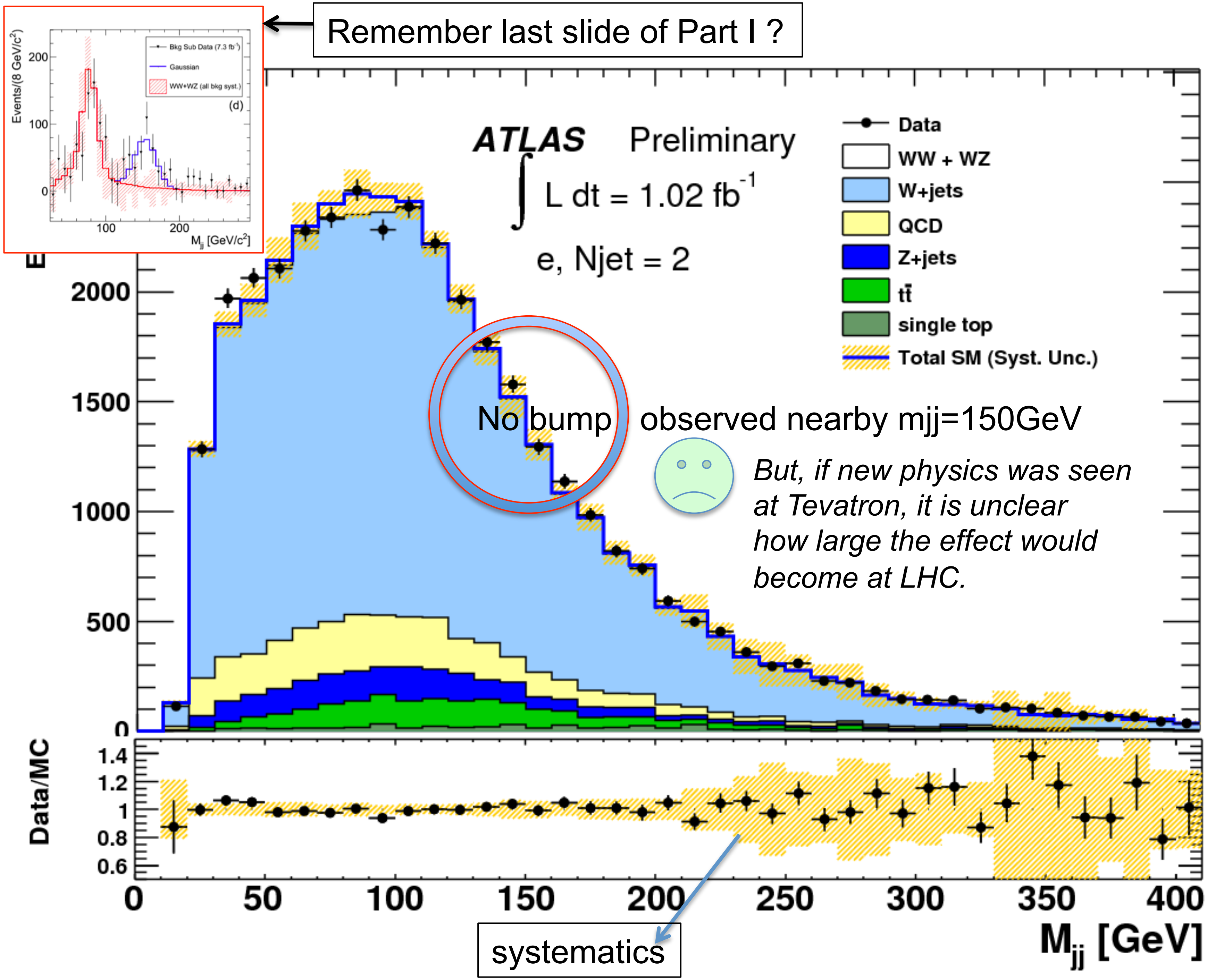
LHC : Early searches for new phenomena

The great adventure started



Part II

Remember last slide of Part I ?



No bump observed nearby mjj=150GeV

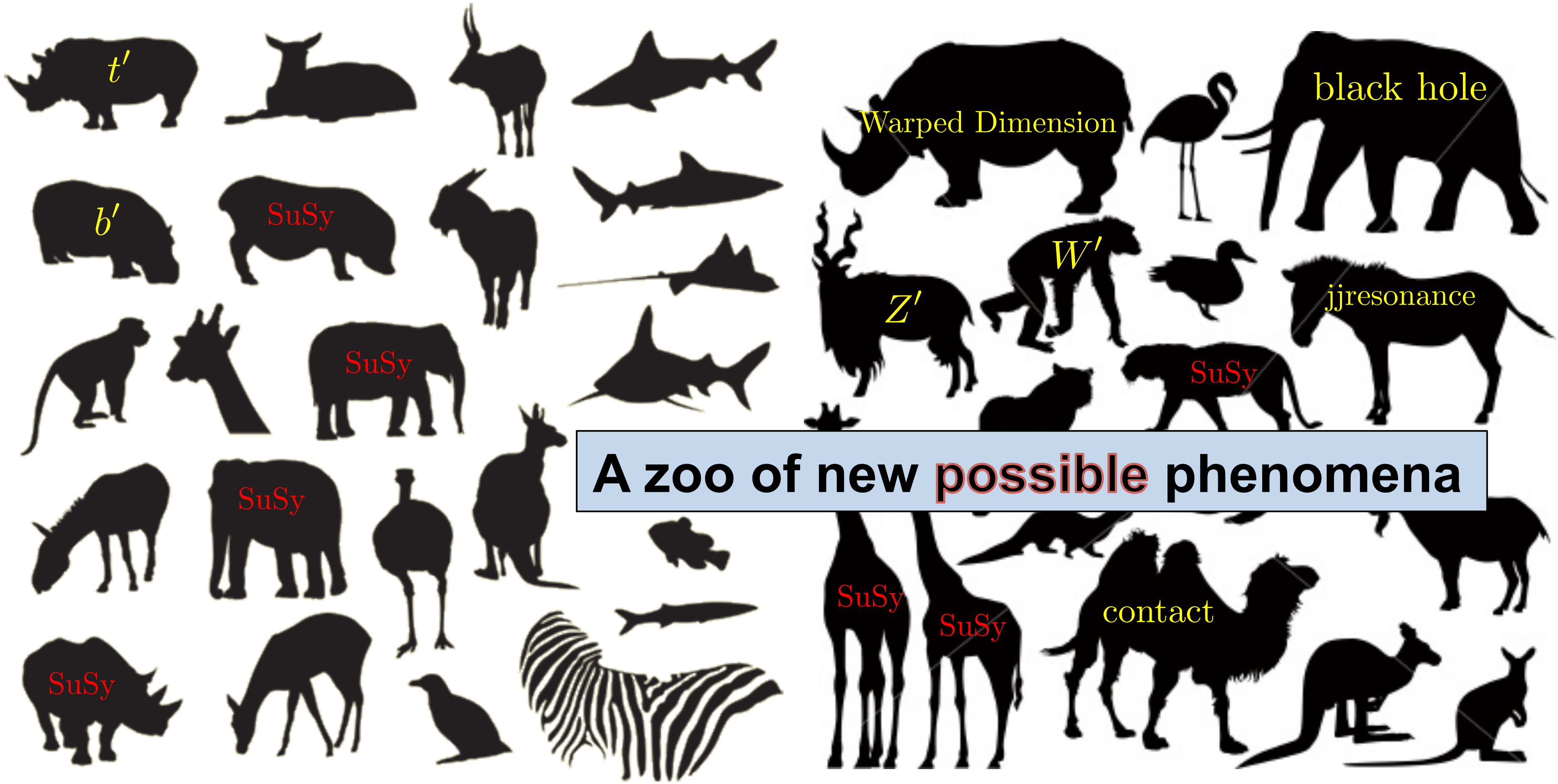
But, if new physics was seen at Tevatron, it is unclear how large the effect would become at LHC.

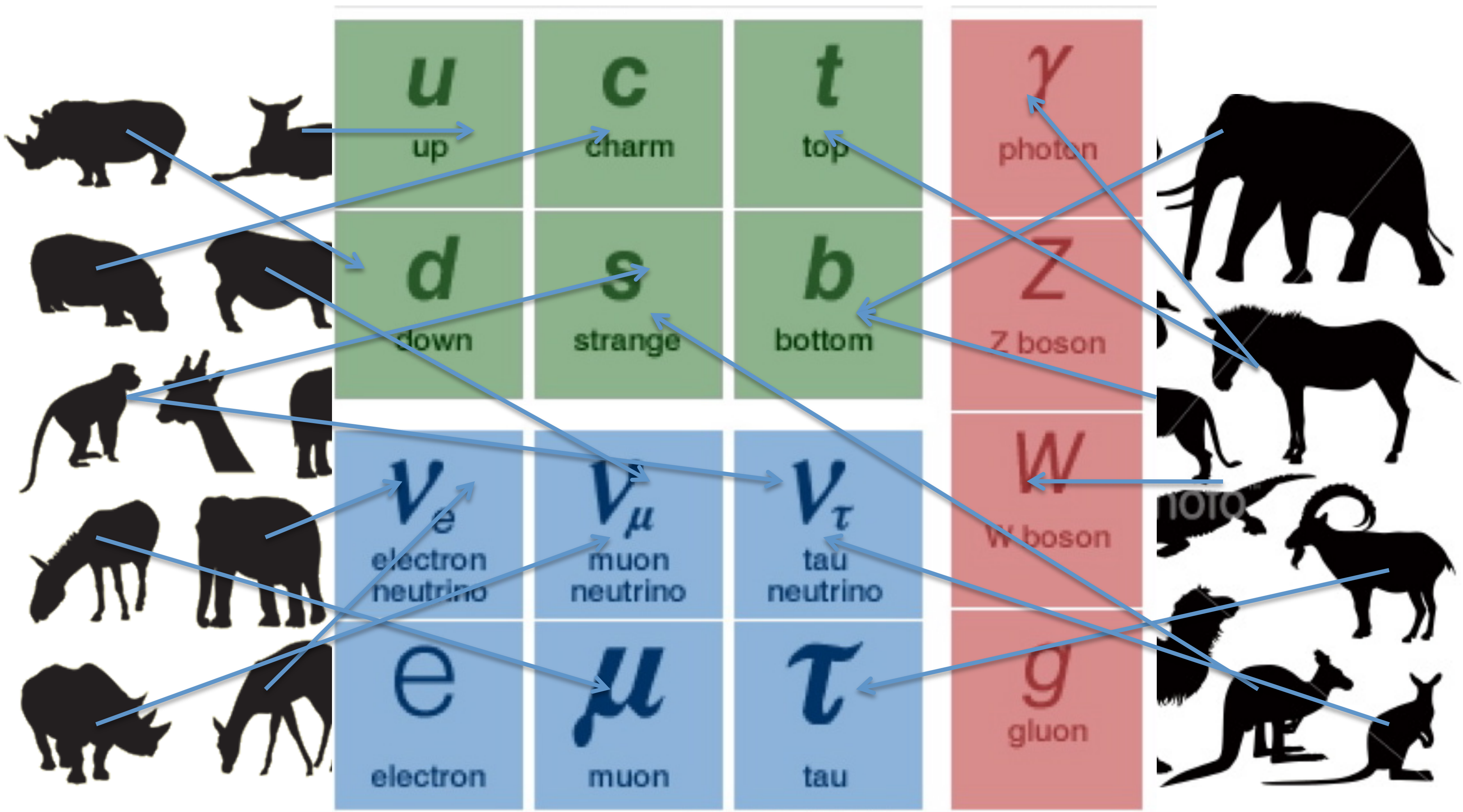
systematics


ATLAS
CMS
LHCb

Many compasses on the market …

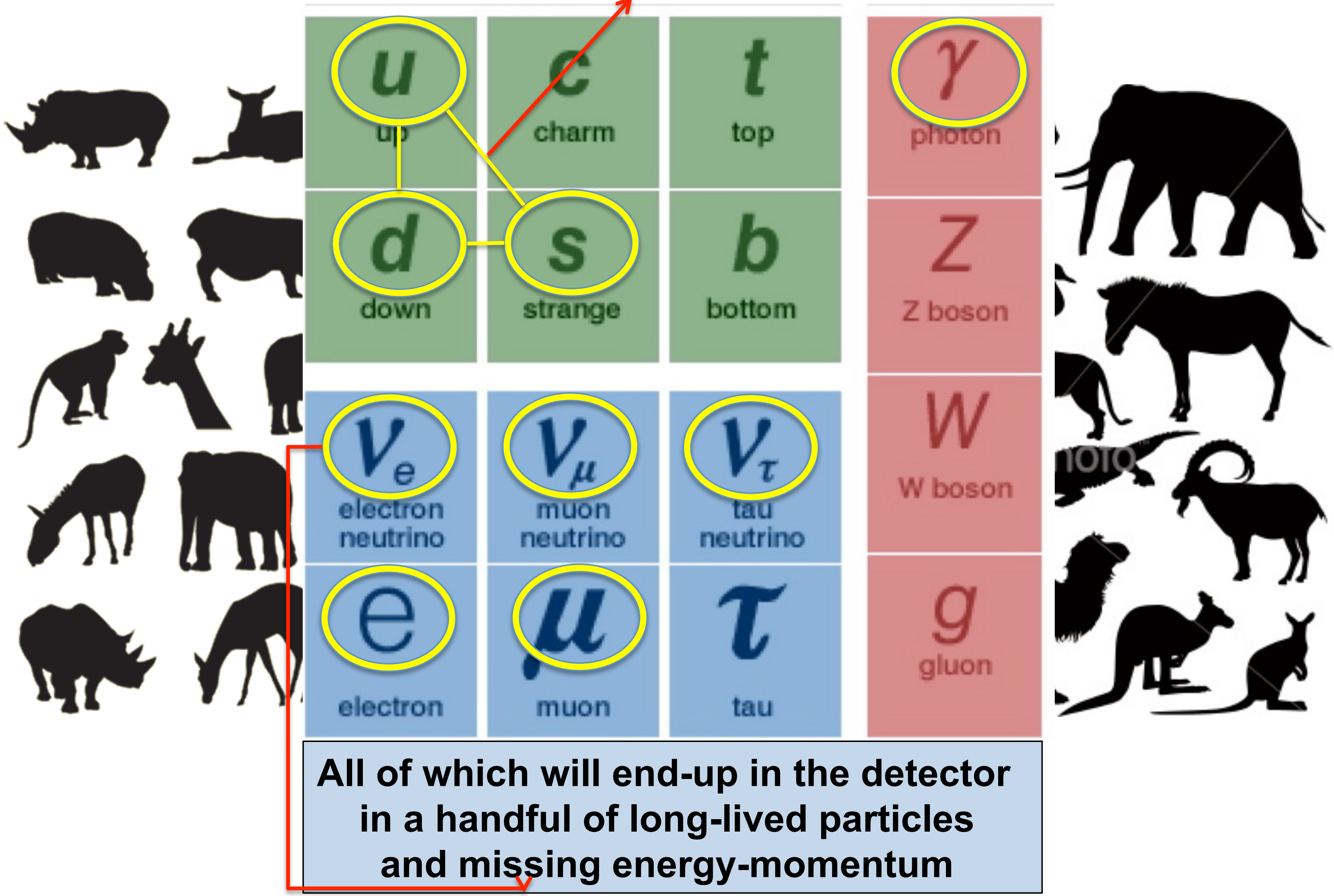
Theorists are creative !


t'
b'
SuSy
SuSy
SuSy
SuSy
Warped Dimension
black hole
W'
Z'
jjresonance
SuSy
A zoo of new possible phenomena
SuSy
SuSy
contact



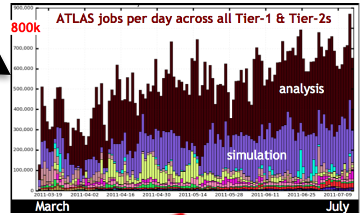
All of which will manifest through the decays into Standard Model particles

$$\pi^{\pm}, \pi^0(\to \gamma\gamma), K^{\pm}, K^0_s(\to \pi^+\pi^-), K^0_L, p, n)$$

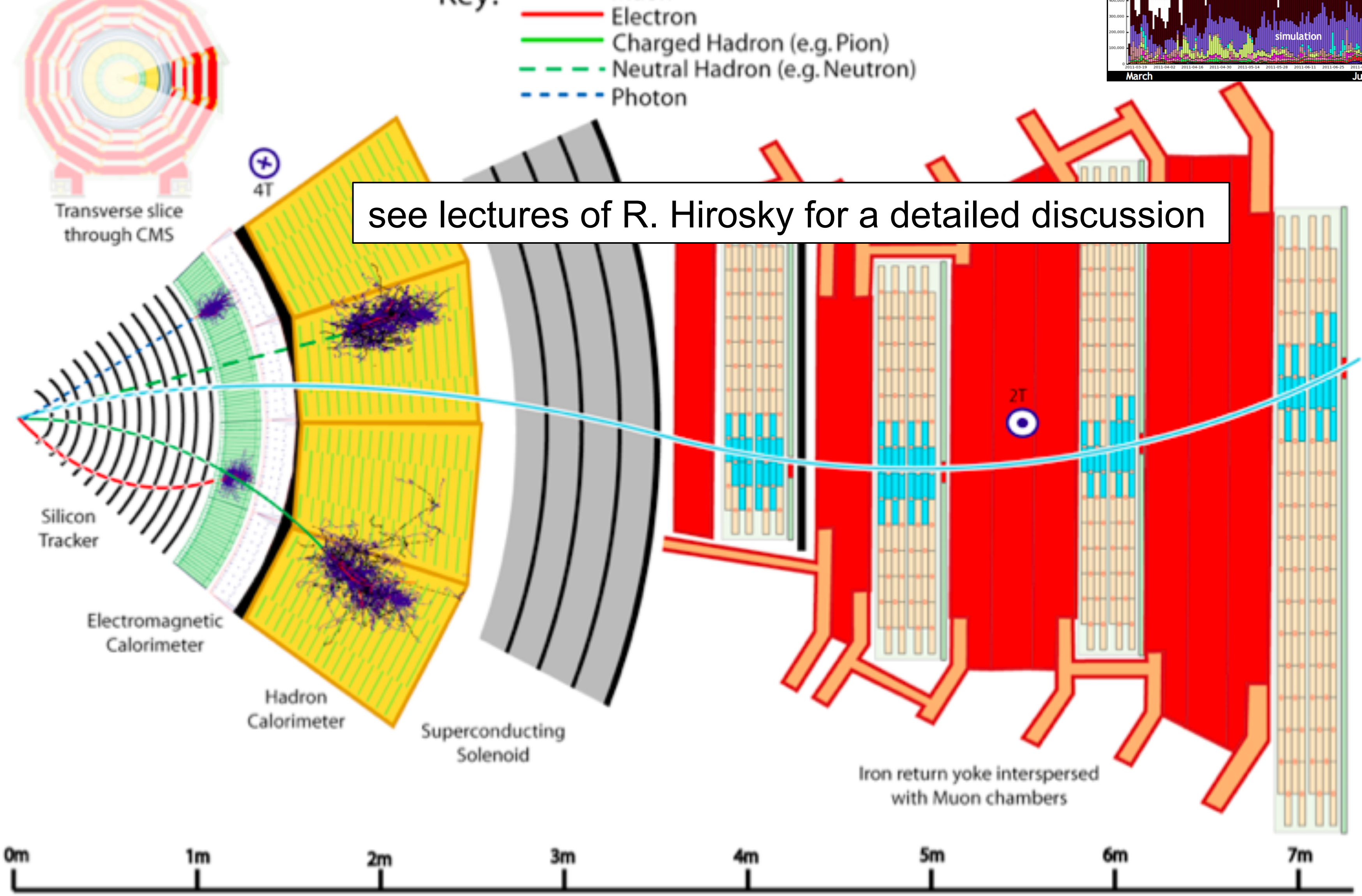


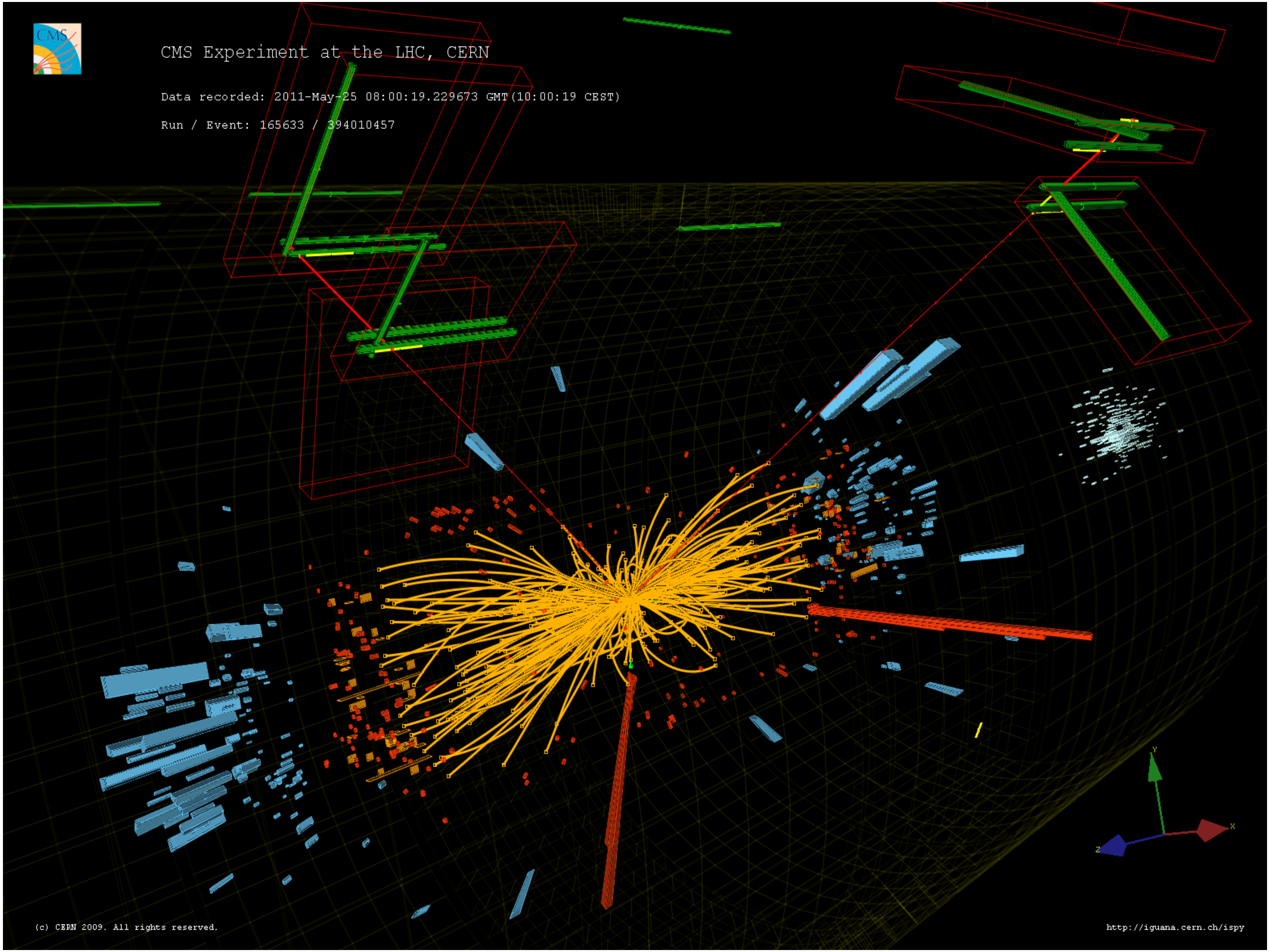
All of which will end-up in the detector in a handful of long-lived particles and missing energy-momentum

And none of these standard particles is really seen: what we detect are electronic impulses on a large variety of dedicated detectors, followed by sophisticated softwares running on huge computers within the LHC world-wide Grid.



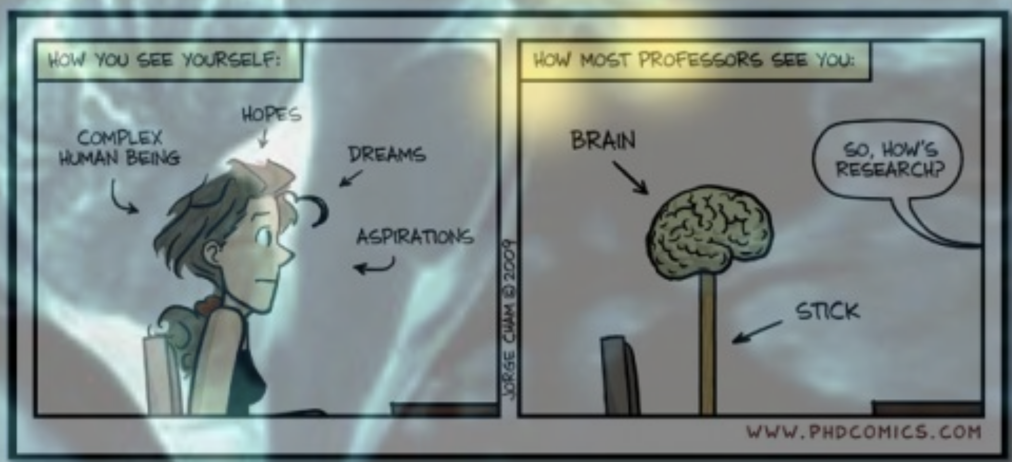
see lectures of R. Hirosky for a detailed discussion




CMS
CMS Experiment at the LHC, CERN
Data recorded: 2011-May-25 08:00:19.229673 GMT(10:00:19 CEST)
Run / Event: 165633 / 394010457
(c) CERN 2009. All rights reserved.
http://iguana.cern.ch/ispy
Y
X
Z

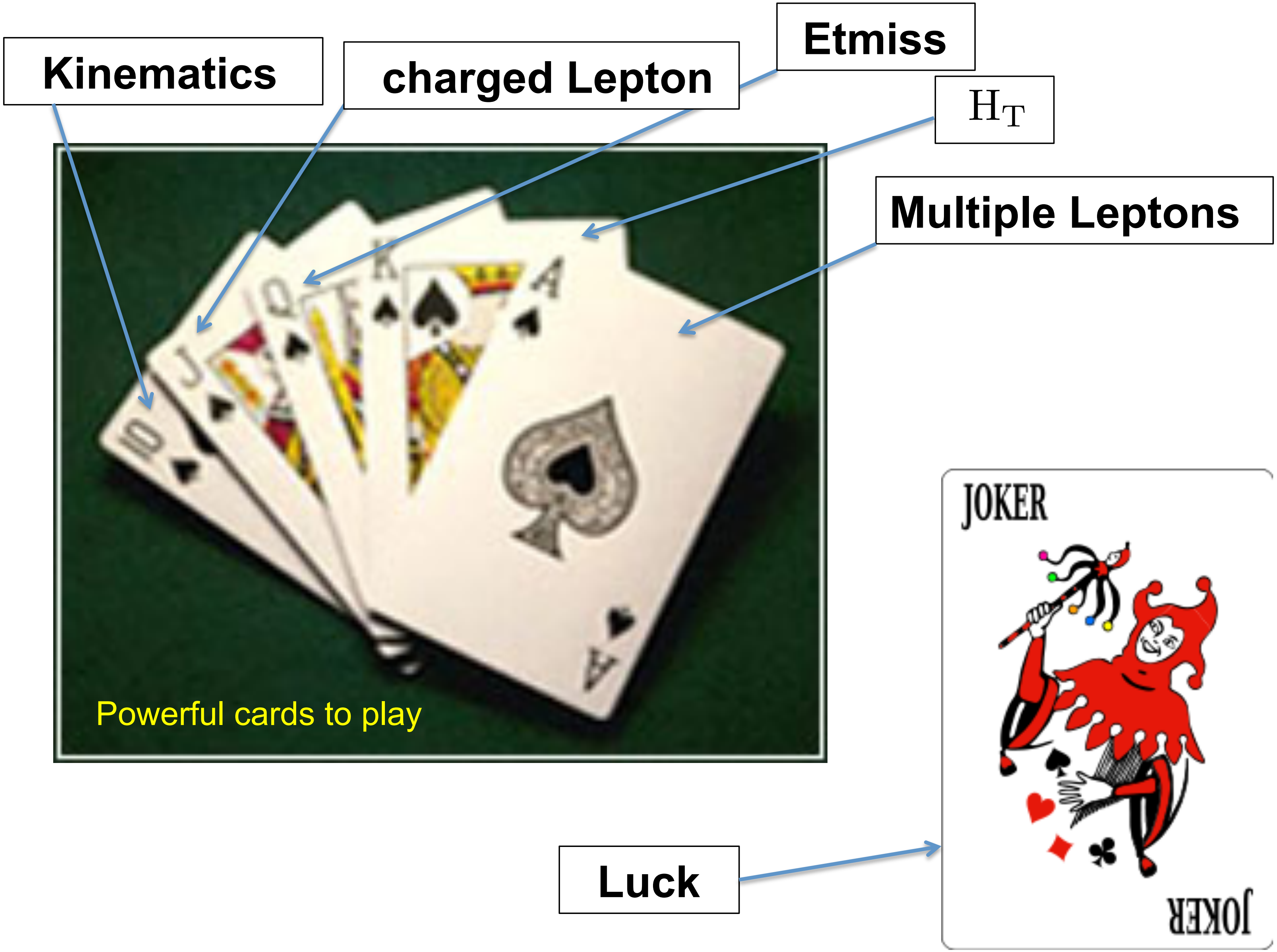
The analyses themselves needs lot of thinking. The most clever wins (usually). Creativity is welcome!

A detailed account was given for the most important of all : the Higgs search in the previous lectures of R. Hirosky.



And was further illustrated in H. Nguyen’s talk

About 3000 people, working/competing together in teams of 10 to 100


Kinematics
charged Lepton
Etmiss
H_T
Multiple Leptons
Powerful cards to play
JOKER
Luck

Et miss

If neutrinos are present in the final state, they will not be detected, but they can be inferred from a lack of balance of the transverse(*) momentum.

$$\vec{\mathrm{Pt}}_{\mathrm{miss}} = -\sum_{jets} \vec{\mathrm{Pt}}_{jets} \qquad \mathrm{Et}_{miss} = \|\vec{\mathrm{Pt}}_{\mathrm{miss}}\|$$

Etmiss is a neutrino's smoking gun.

(Or any weakly interacting particle, like some in SuSy (etc.))

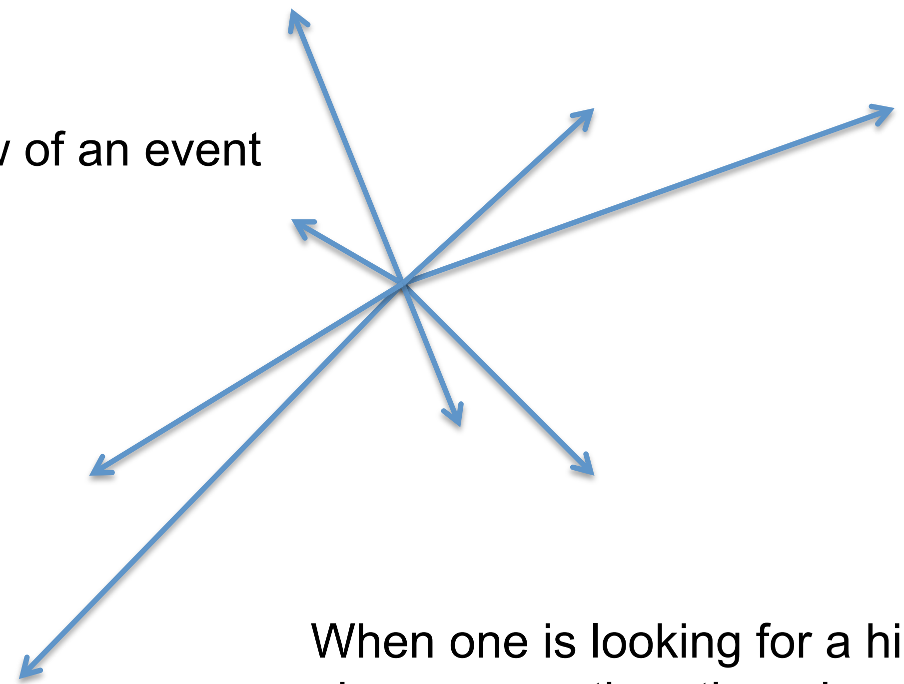
If one assumes that an event contains a W decay, and if one has a detected lepton, then one can compute Pz_{miss} :

$$m_W^2 = \left(E_l + \sqrt{\mathrm{Et}_{miss}^2 + \mathrm{Pz}_{miss}^2}\right)^2 - \left((\vec{\mathrm{Pt}}_l + \vec{\mathrm{Pt}}_{miss})^2 + (\mathrm{Pz}_l + \mathrm{Pz}_{miss})^2\right)$$

(*) Only the transverse momentum is considered, since the underlying event takes off a large fraction of the momentum z-component of the two colliding protons

Ht

Transverse view of an event

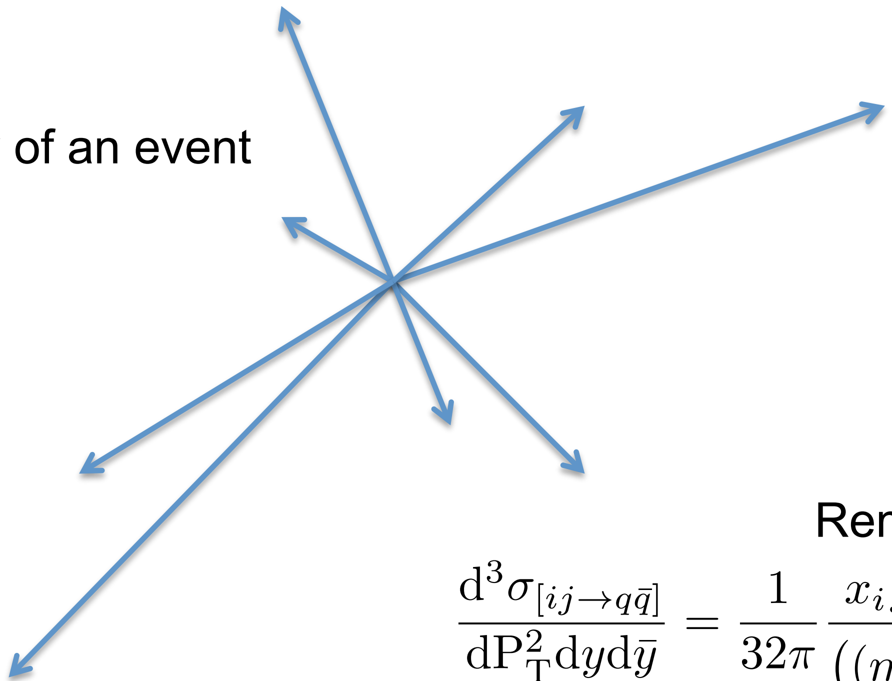


When one is looking for a high energy phenomena, then there is a simple variable which helps a lot to isolate it: $\mathrm{H_T}$
the sum of the $\|\vec{\mathrm{P}}_{\mathrm{T}}\|$ of the “objects” (jets, etc.)

Ht

Example of the heavy quark production

Transverse view of an event



Remember?

$$\frac{d^3\sigma_{[ij\to q\bar{q}]}}{dP_T^2 dy d\bar{y}} = \frac{1}{32\pi}\frac{x_i f(x_i) x_j f(x_j)\Sigma_{ij}(y-\bar{y}, P_T^2)}{\left((m_q^2+P_T^2)(1+\cosh(y-\bar{y}))\right)^2}$$

It implies that large P_T are OK provided that
They stay comparable to m_q
Thus, if P_T is large, then H_T can be easily very large because it benefits the double effect:

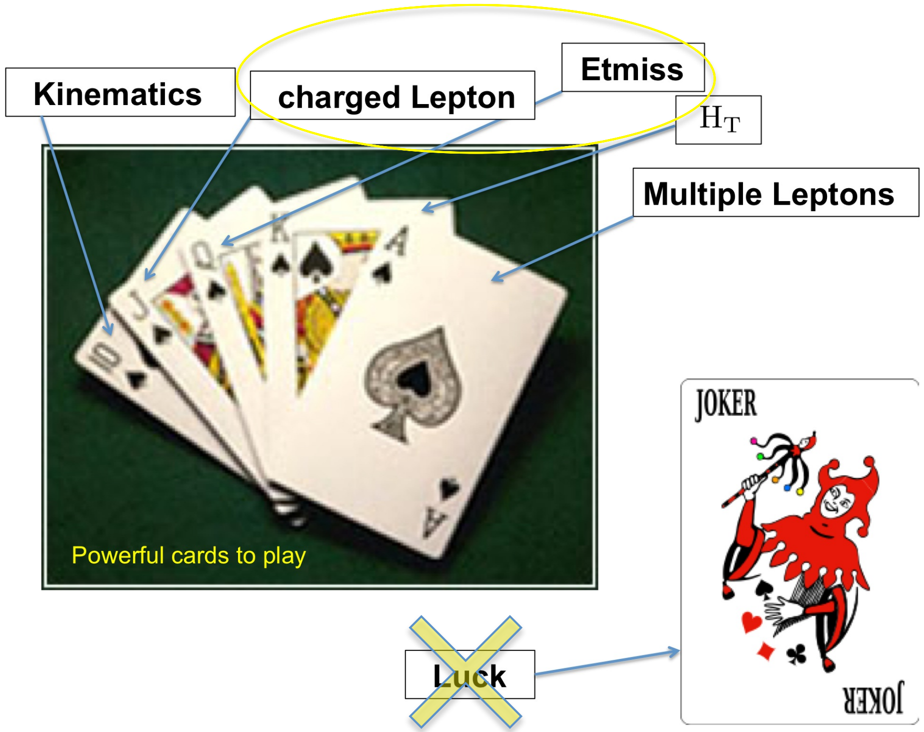
- Large intrinsic P_T
- Large $m_q \to \text{large energy} \to \text{large } H_T$

Systematics

Reflect uncertainties on the detector responses,
the backgrounds, and … the signal itself.
Such uncertainties can shatter the analysis power.

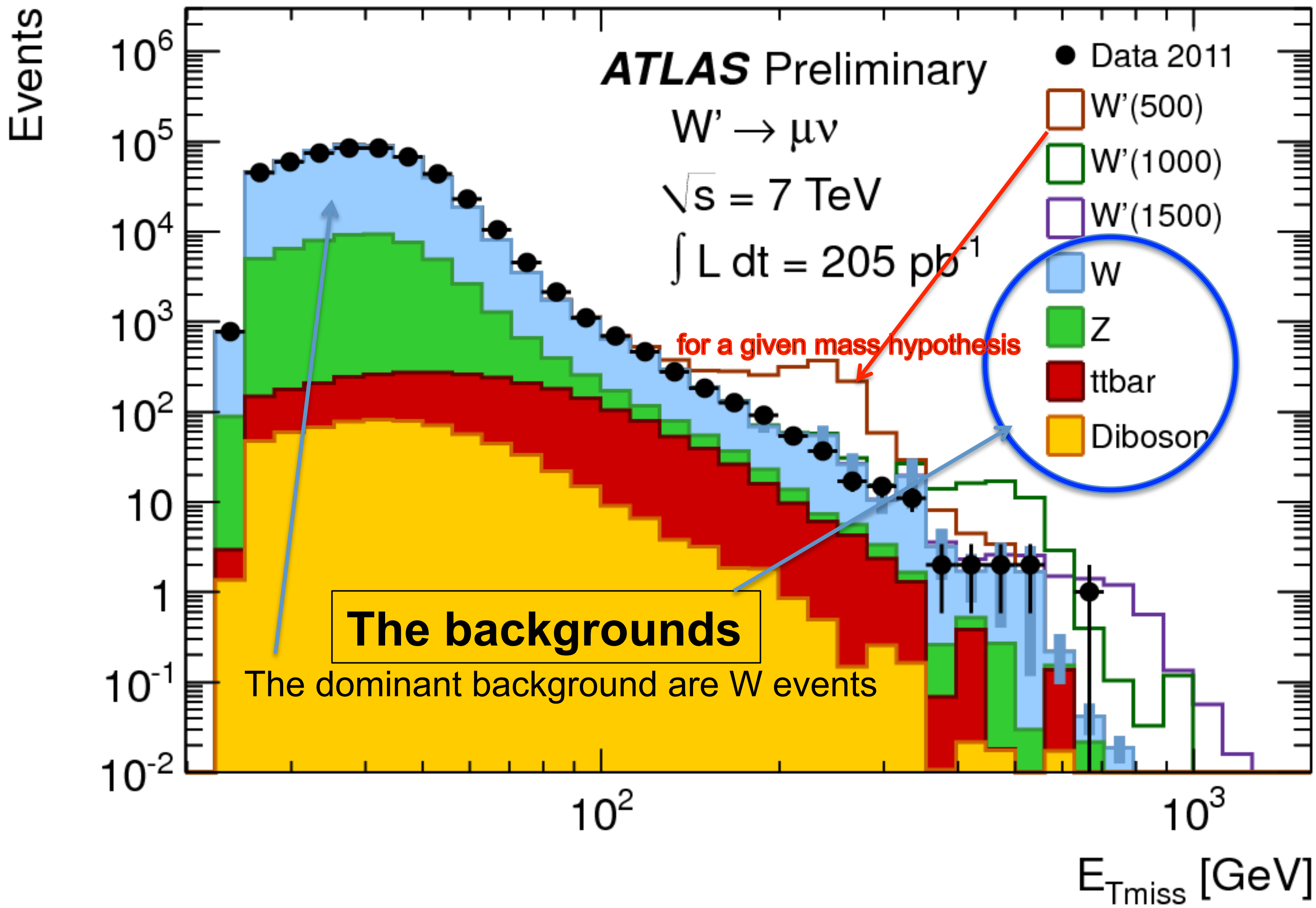
It is a tough and very technical subject, rather boring, but extremely important in practice

W' duplicate of the Standard Model W



Copy cat of W production

Request a lepton (electron or muon) and EtMiss



No anomaly is observed, thus one sets limits…

From the data (cf. previous plot) one can compute the probability for a given $m_{W'}$ hypothesis that there was a given number of signal events, on average.

$$\mathcal{P}(N_{\text{events}}; m_{W'})$$

A matter of convention, nothing to understand
… and CL means Confidence Level

Then, one looks for the number

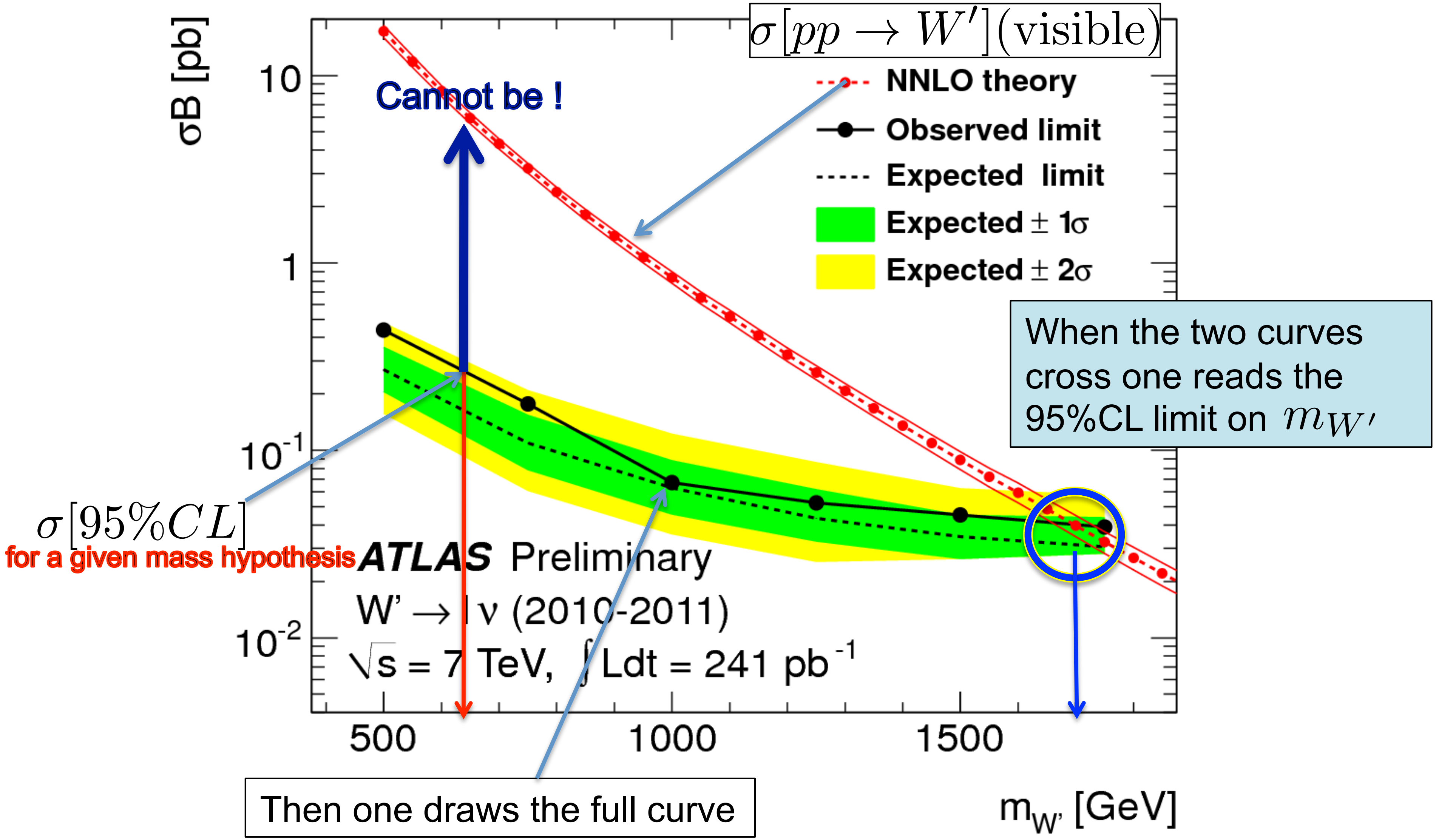
$$N_{\text{events}}[95\%CL]$$

For which

$$\mathcal{P}(N_{\text{events}}[95\%CL]; m_{W'}) = 0.05$$

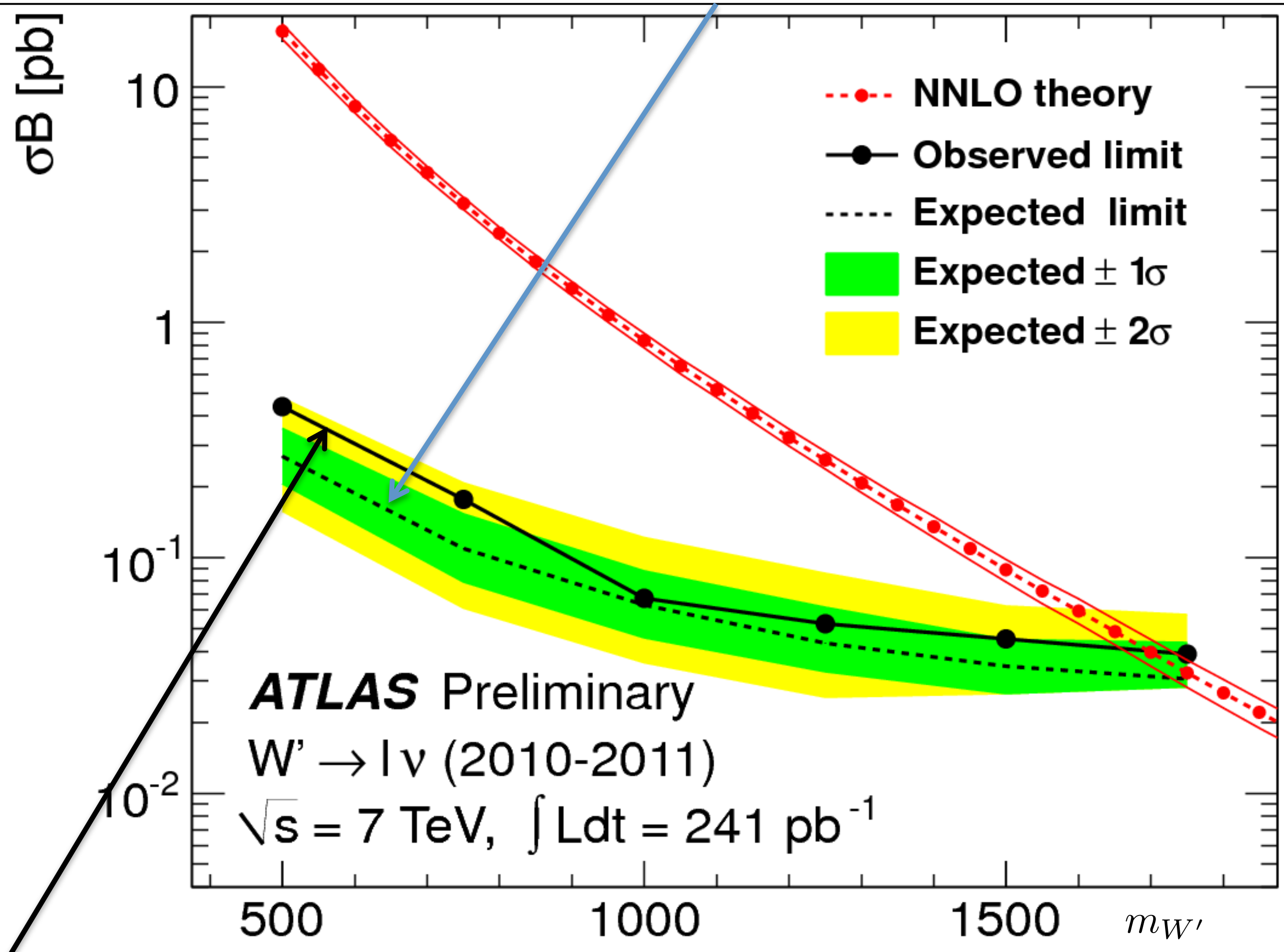
Dividing by the Luminosity, one obtains the limit on the cross-section for a given mass hypothesis

$$\sigma[95\%CL] = N_{\text{events}}[95\%CL]/\mathcal{L}$$



$\sigma[pp \to W'](\text{visible})$
σB [pb]
10
1
10^{-1}
10^{-2}
500
1000
1500
$m_{W'}$ [GeV]
Cannot be !
NNLO theory
Observed limit
Expected limit
Expected ± 1σ
Expected ± 2σ
When the two curves cross one reads the 95%CL limit on $m_{W'}$
$\sigma[95\%CL]$
for a given mass hypothesis
ATLAS Preliminary
W' → l ν (2010-2011)
$\sqrt{s}$ = 7 TeV, ∫Ldt = 241 pb^{-1}
Then one draws the full curve

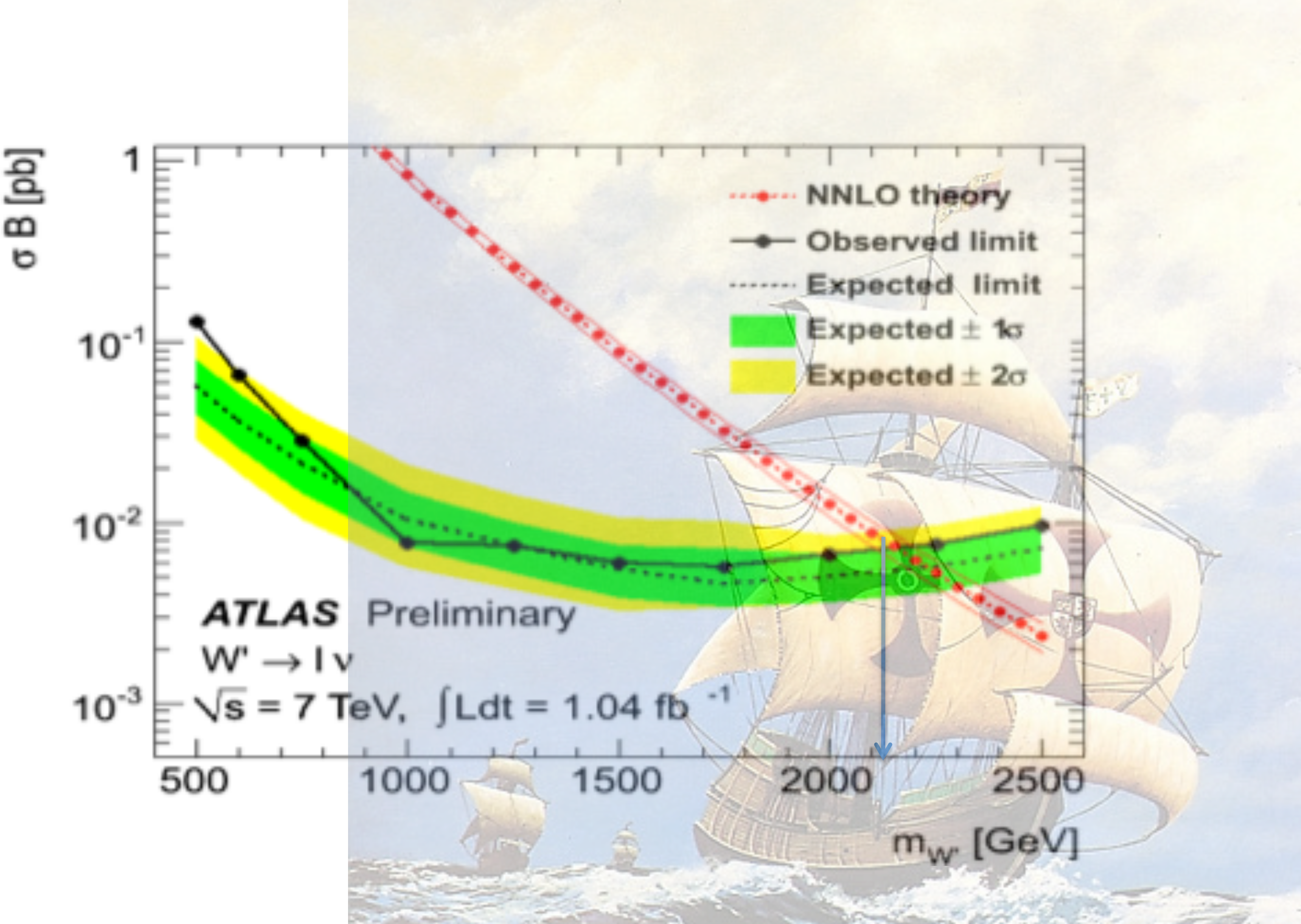
Remains to explain what are this dot line and green/yellow bands



$\sigma[95\%CL]$

(Assuming No signal)

Being the result of a given experiment (here ATLAS) is subject to statistical fluctuations. One can compute its distribution, using Monte Carlo simulation. If the measured $\sigma[95\%CL]$ lies outside the Yellow band, one should be suspicious that something is not right.



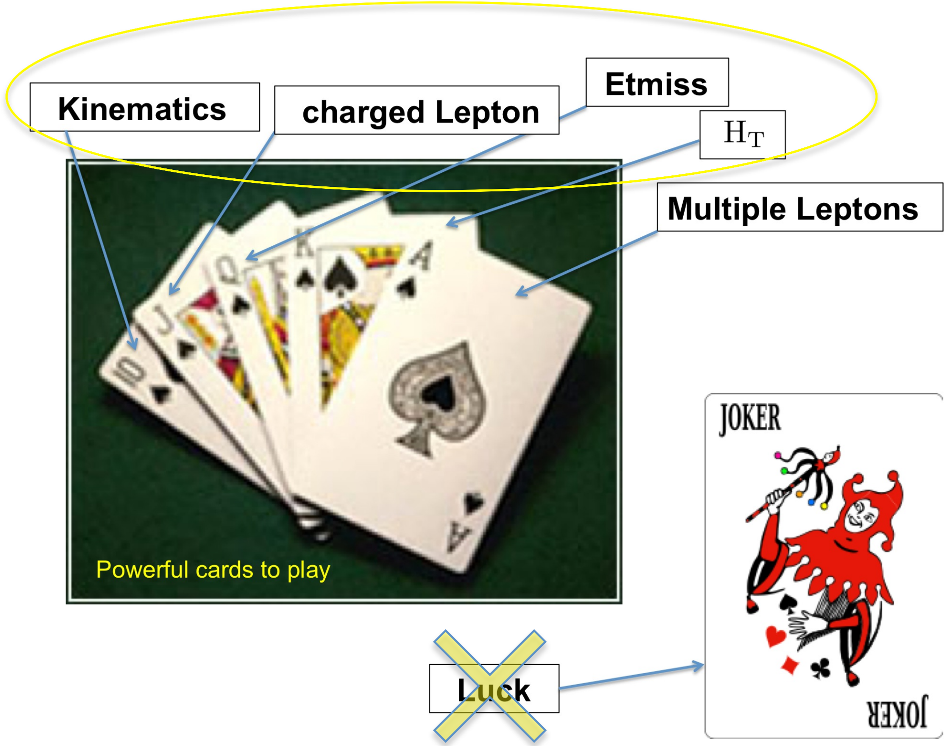
Update from last week : 2.1 TeV (and 2.3 TeV from CMS)

Similarly a search for a heavy copy-cat of the Z yields : 1.8 TeV (1.9 TeV CMS)

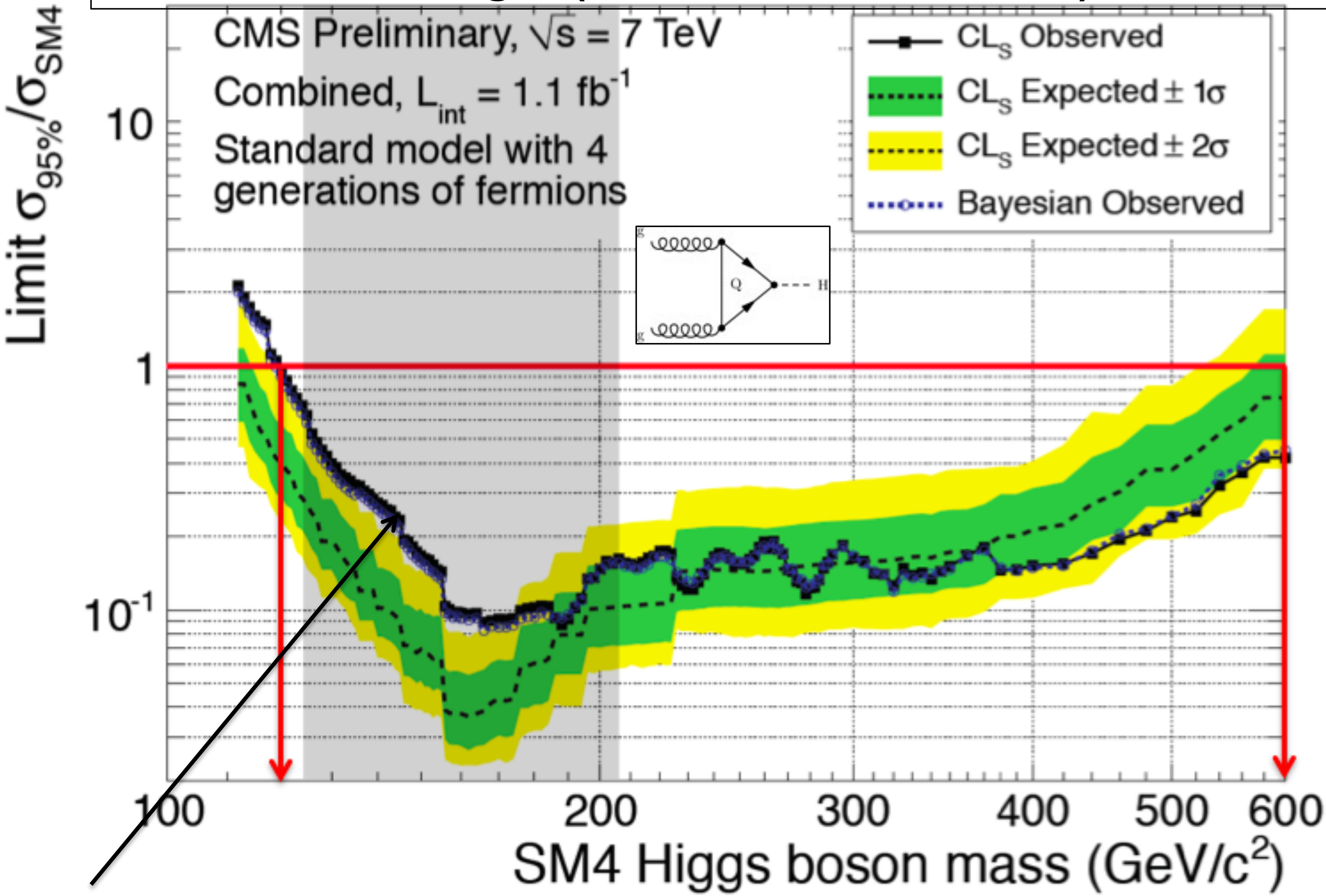
The ships are moving very fast, beware!

4th generation top, pair production

4^{th} Generation of the Standard Model (cf. Lectures of P.Q. Hung)

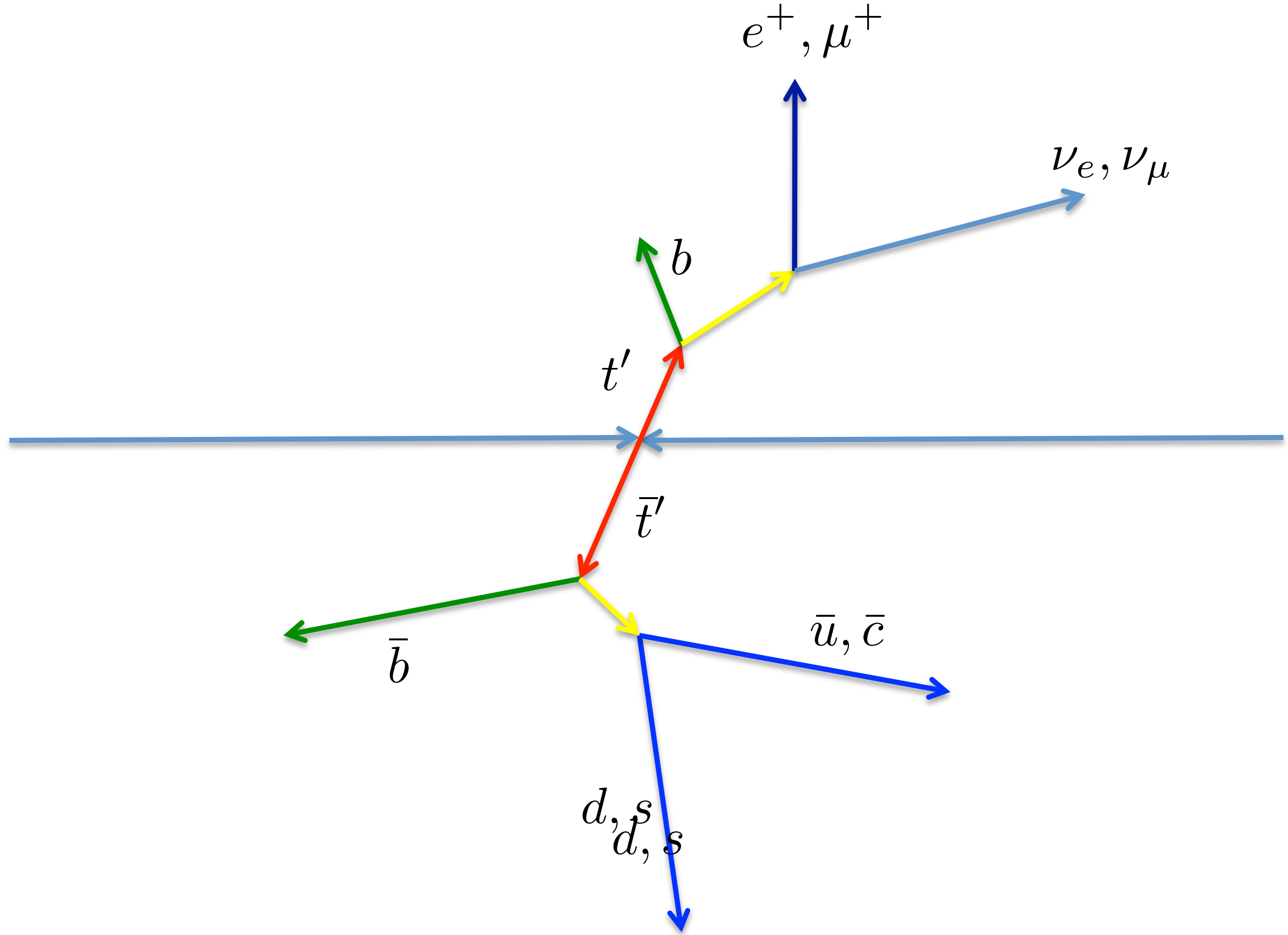


If the 4^{th} generation exists, and if the Higgs is unique, then it must be light (CDF, D0, CMS, ATLAS)

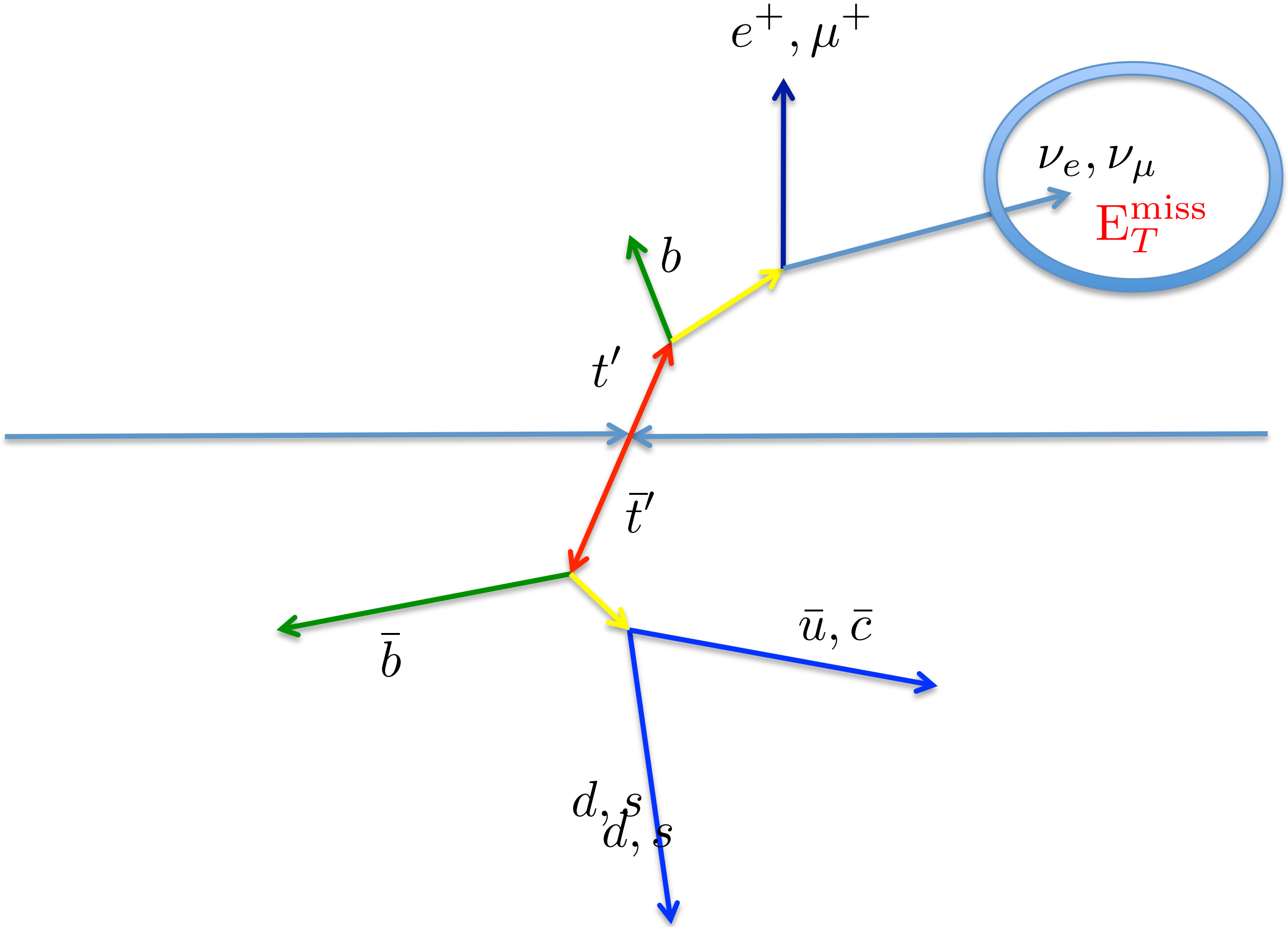


Note that the line is NOT within the Yellow band, and a same trend is reported by ATLAS…

Kinematics : event should be compatible with a t' $\bar{t}'$ pair production both decaying into bW, one of the W's leptonically, the other hadronically

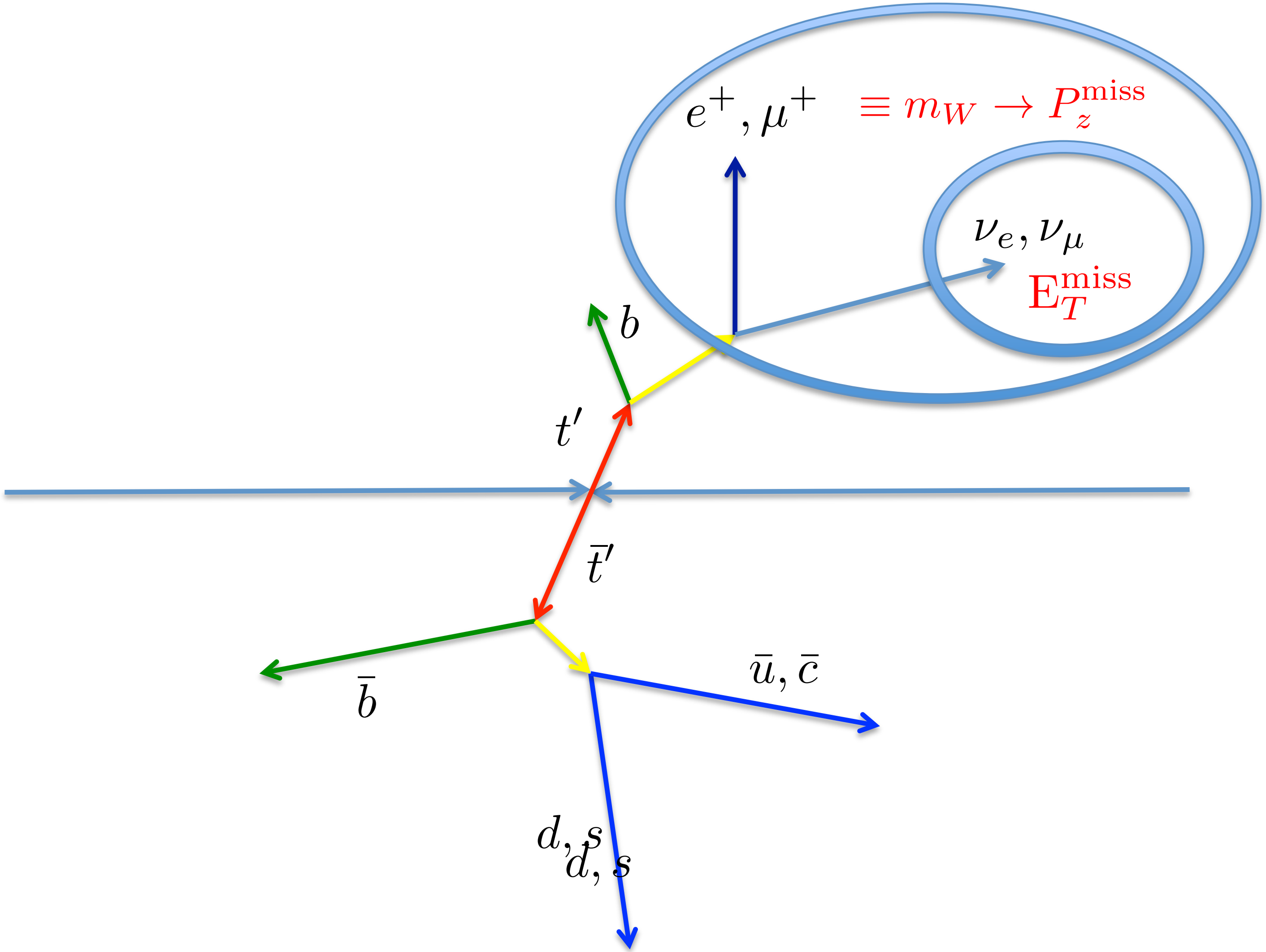


Kinematics : event should be compatible with a $t'\bar{t}'$ pair production



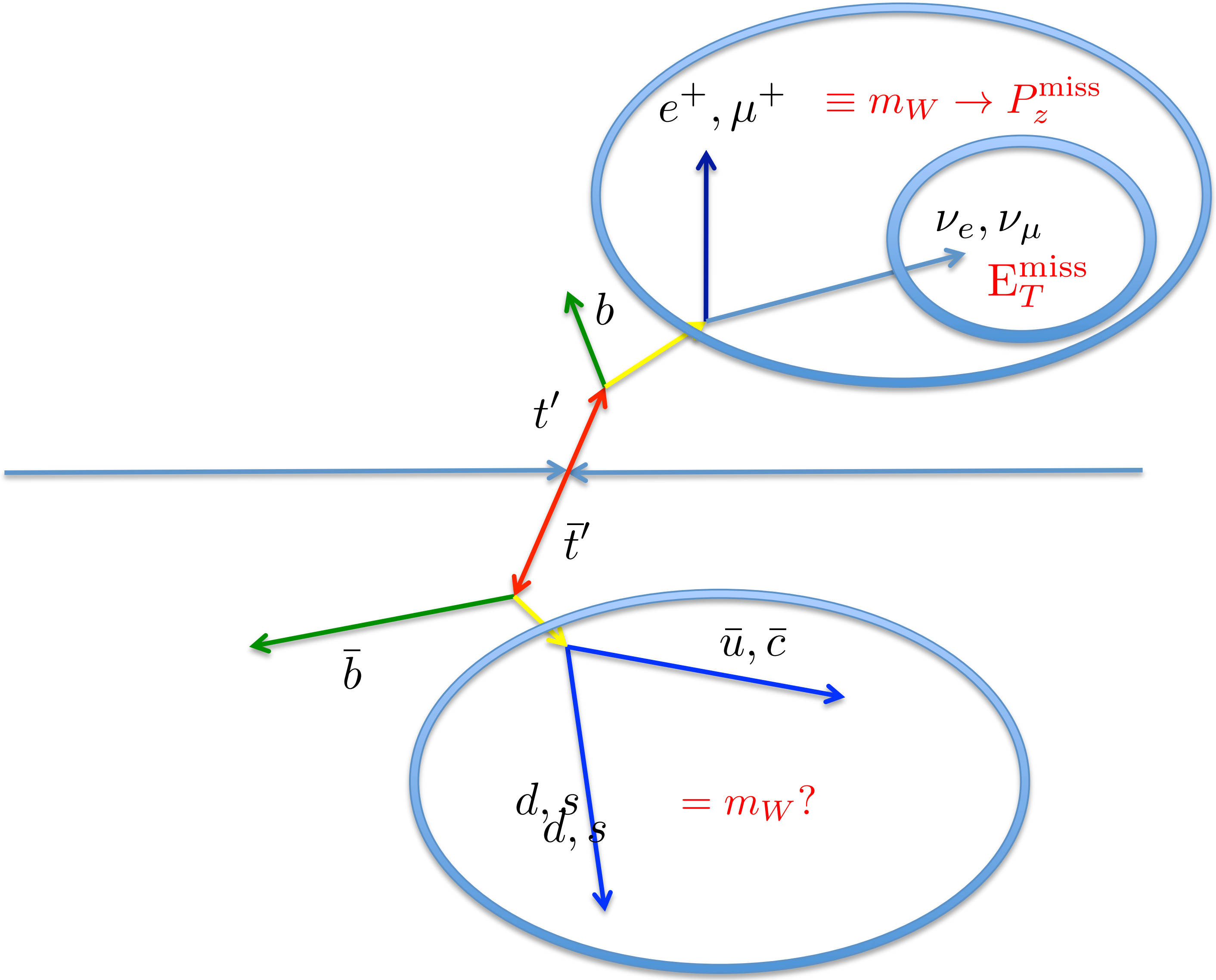
1)
2)
3)
4)
5)

Kinematics : event should be compatible with a $t'\bar{t}'$ pair production



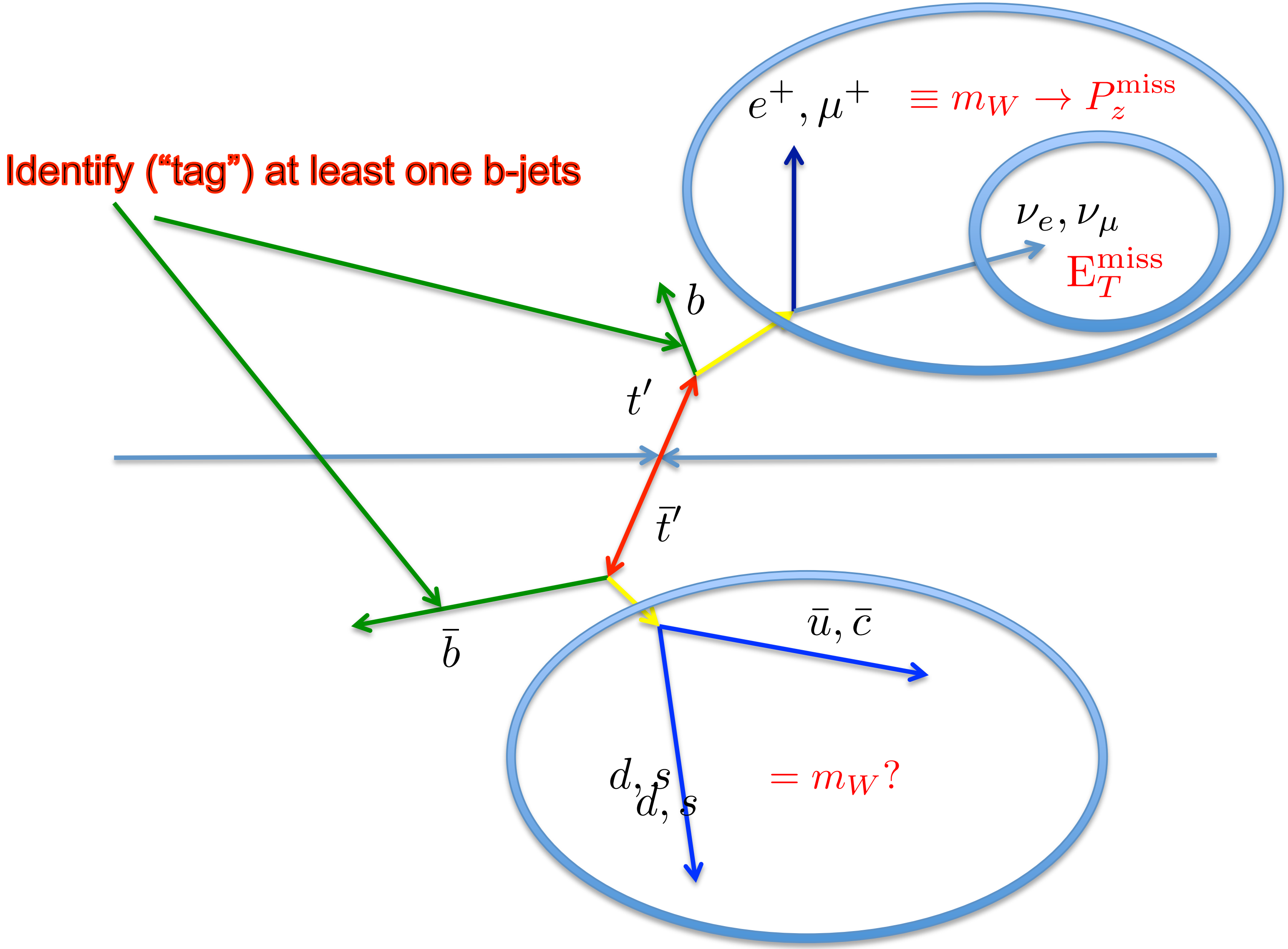
1)
2)
3)
4)
5)

Kinematics : event should be compatible with a $t'\bar{t}'$ pair production



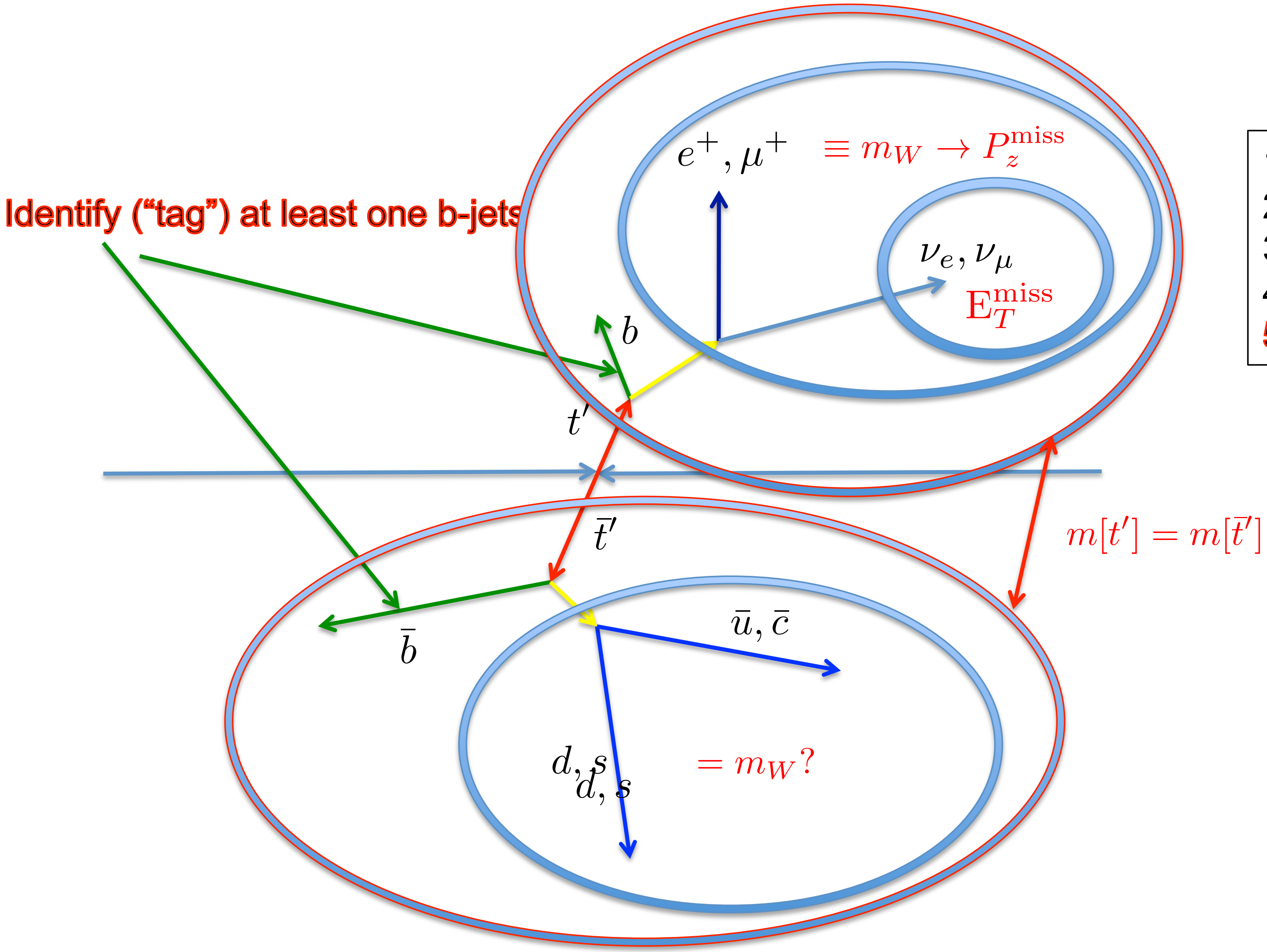
1)
2)
3)
4)
5)

Kinematics : event should be compatible with a $t'\bar{t}'$ pair production



1)
2)
3)
4)
5)

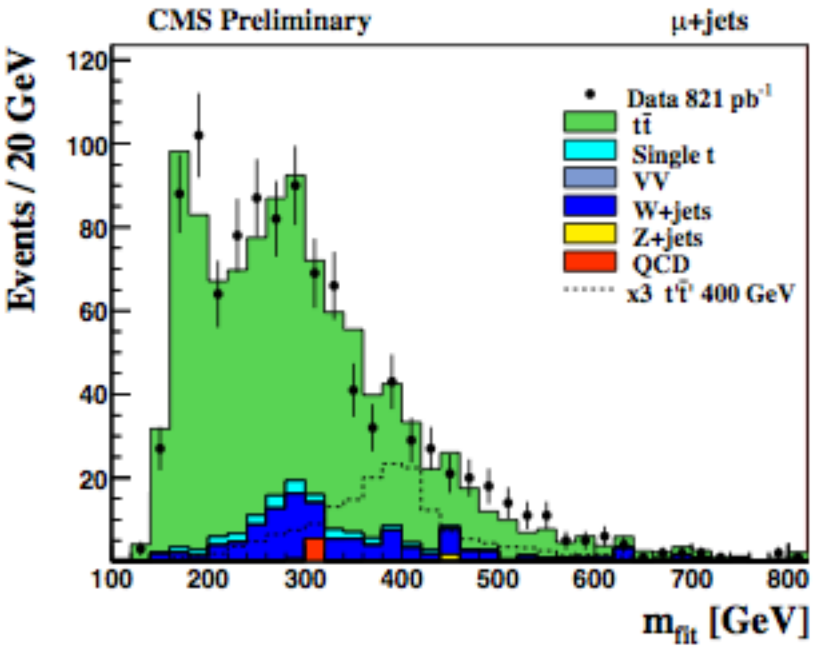
Kinematics : event should be compatible with a $t'\bar{t}'$ pair production

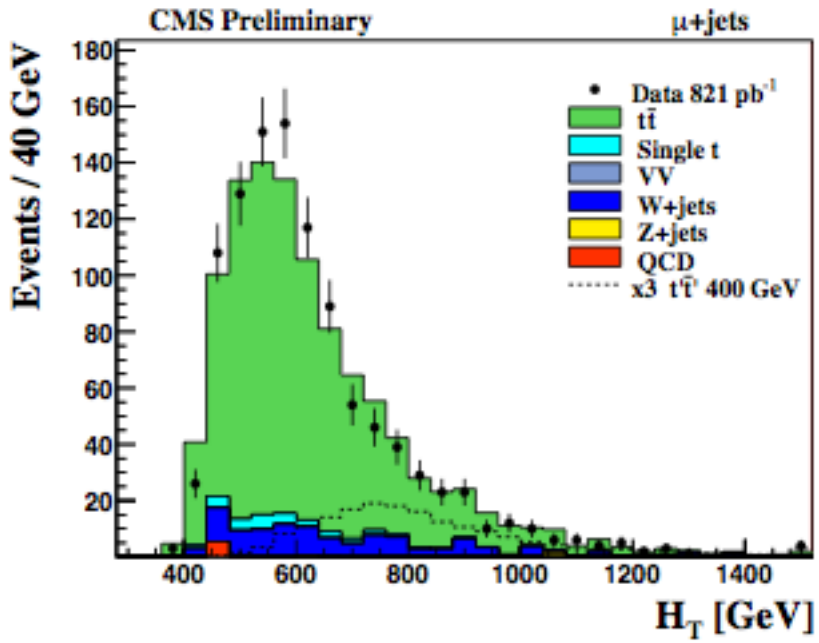


1)
2)
3)
4)
5)

In practice, one does a kinematics fit to obtain : $m_{\mathrm{fit}} \equiv m_{t'} = m_{\bar{t}'}$

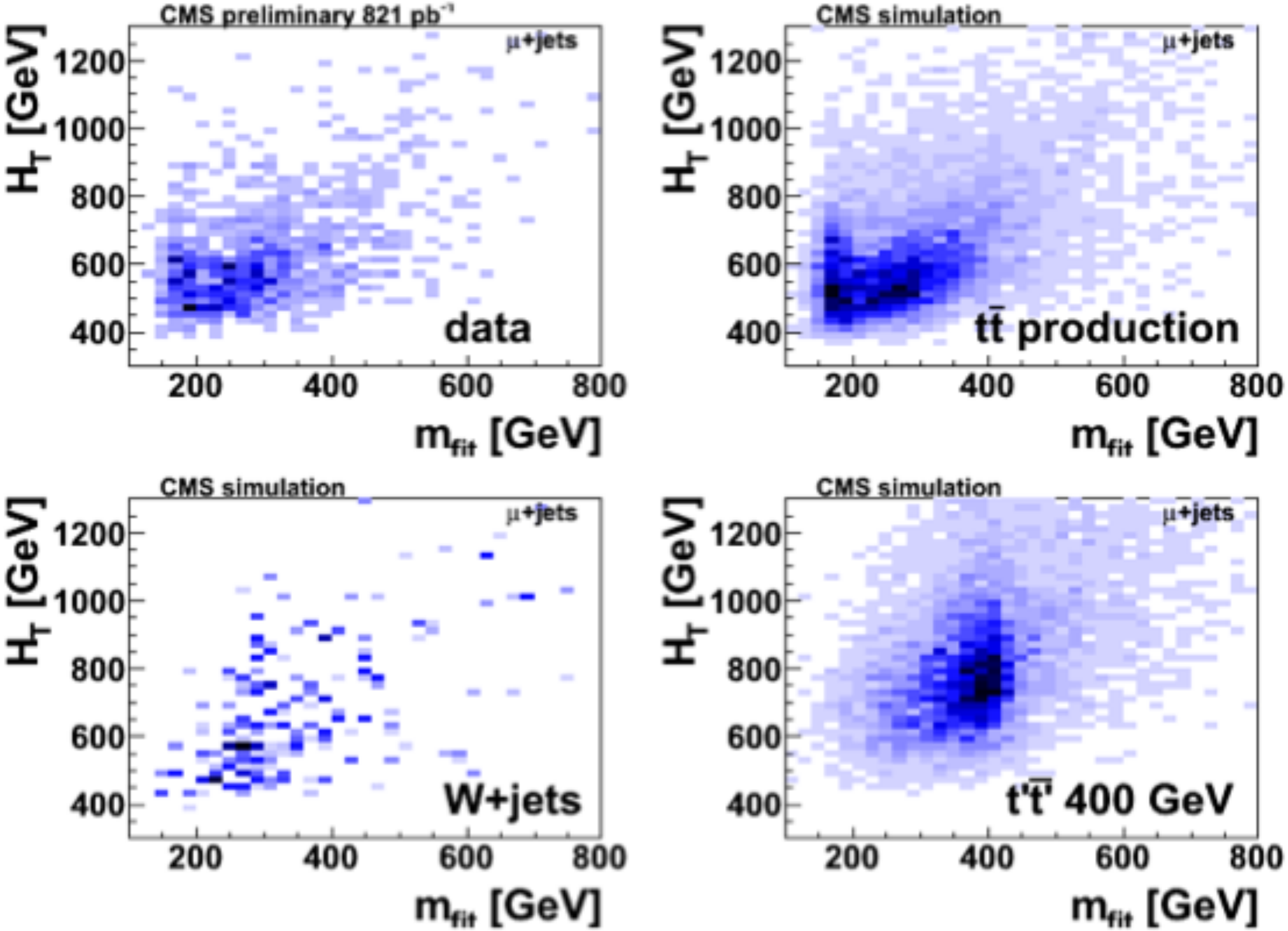
Another handle to fight against The backgrounds is $\mathrm{H_T}$





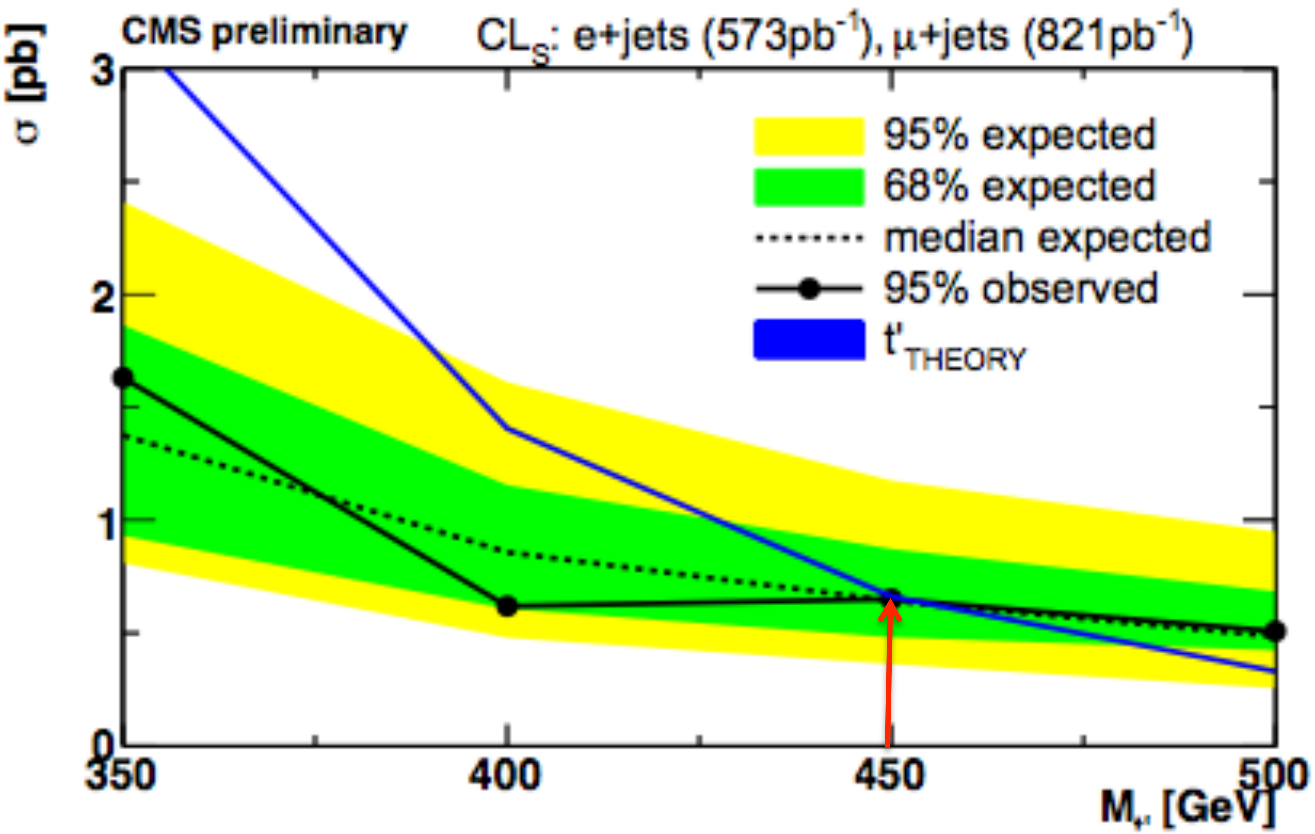
The bulk of the background is coming from misreconstructed $t\bar{t}$ pairs

Then one builds the two-dimensional $(m_{\rm fit}, \rm H_T)$ plot



… to conclude that data do not show any hint of $t'\bar{t}'$ production and one should just set limits…

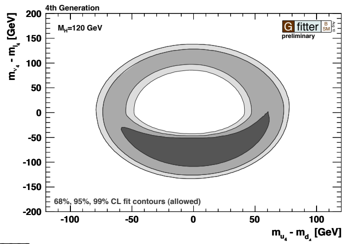
Top of 4th Generation must be heavier than 450 GeV

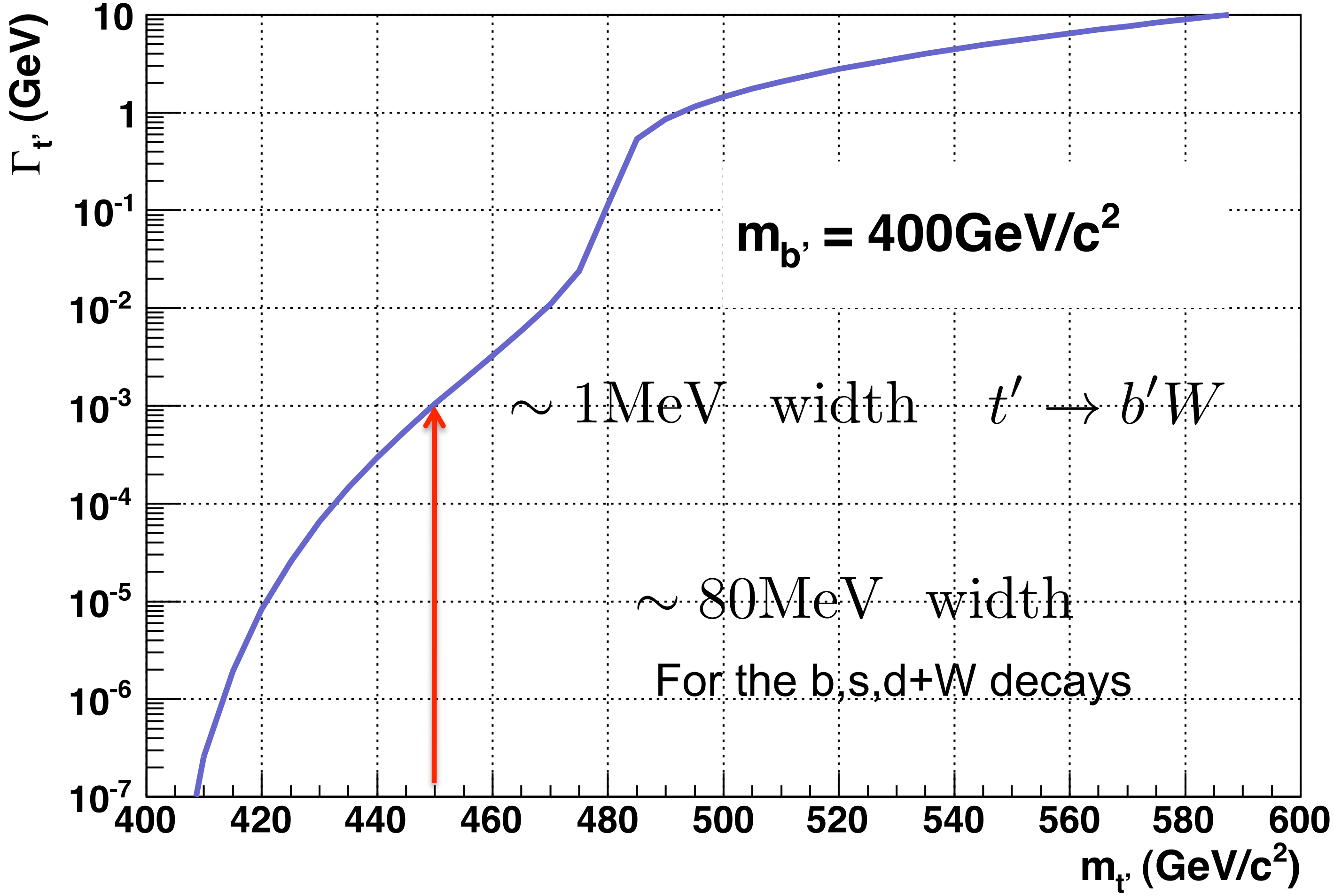


If it exists, and if it decays mostly through bW

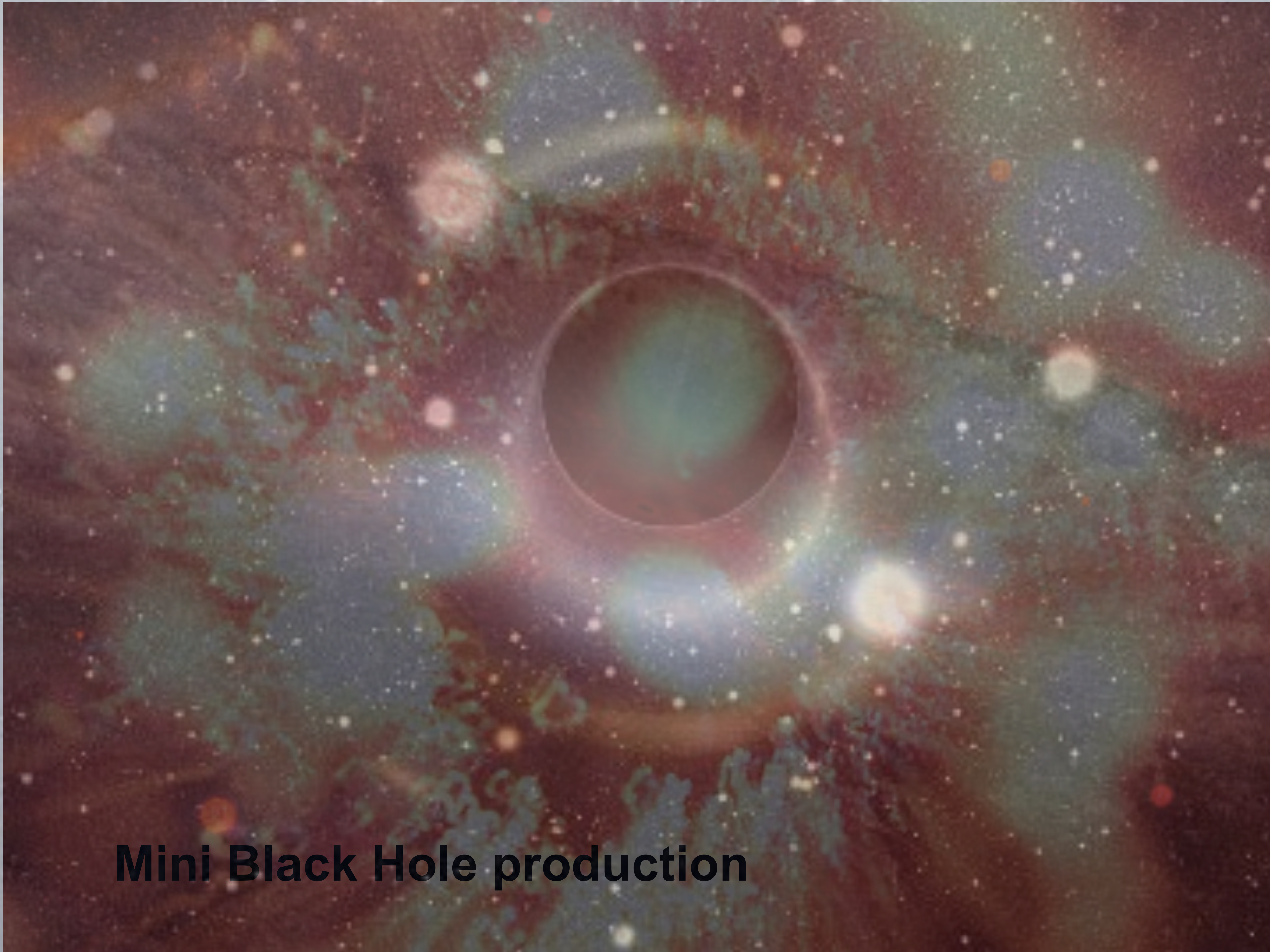
From CKM precise measurements, one expects $V_{t'b} = 0.04 \pm 0.06$

But high-energy precise measurements (mentioned in lecture of N. Okada) suggest that $\| m_{t'} - m_{b'} \| \sim 50\mathrm{GeV}$ if the Higgs is light, thus practically freezing the (CKM favored) decay $t' \to b'W$





Mini Black Hole production

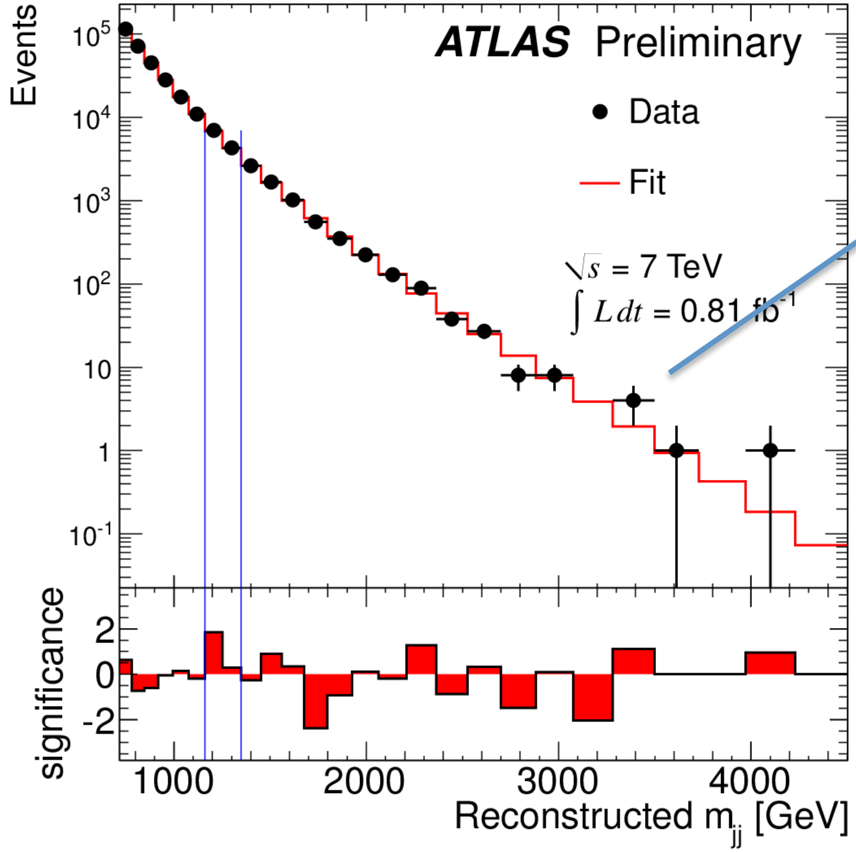


Mini Black Hole production

Can decay in multi-leptons final state: none seen…

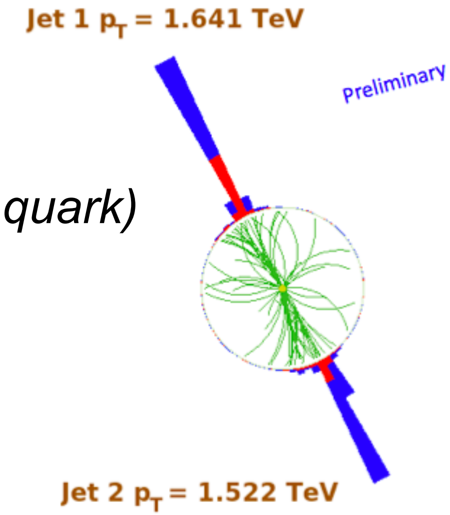
di-Jets resonances ?

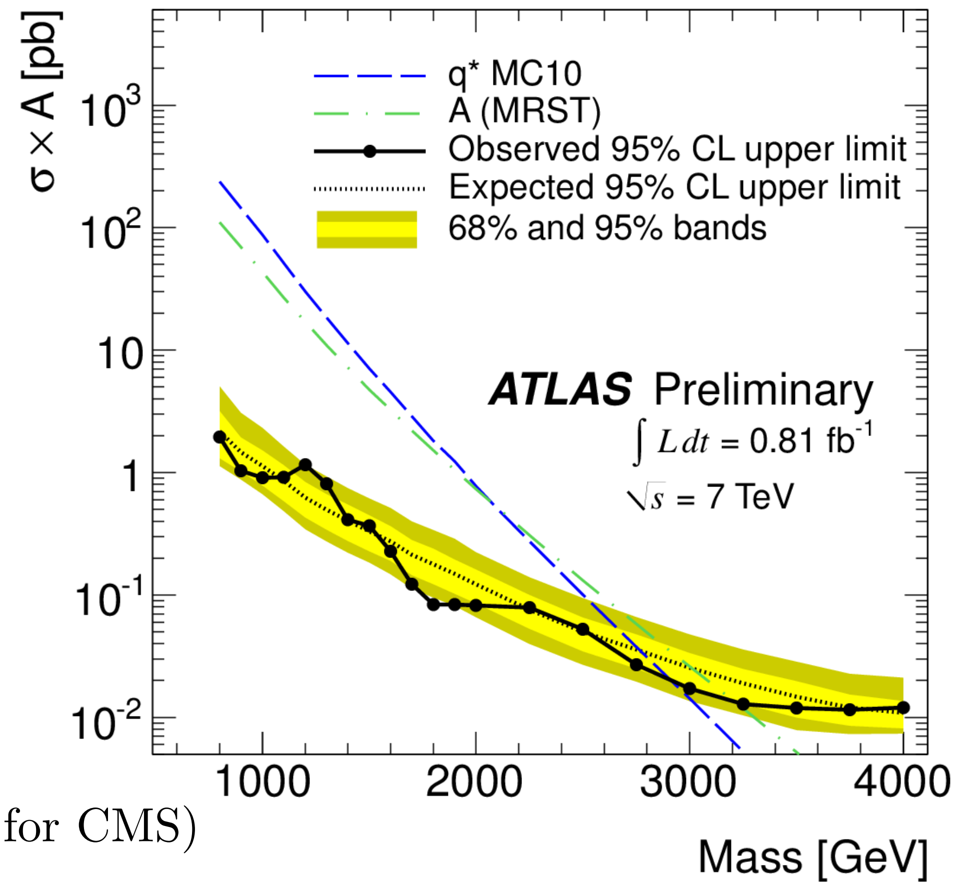
(e.g. excited heavy quark)



Nope…

Limits!



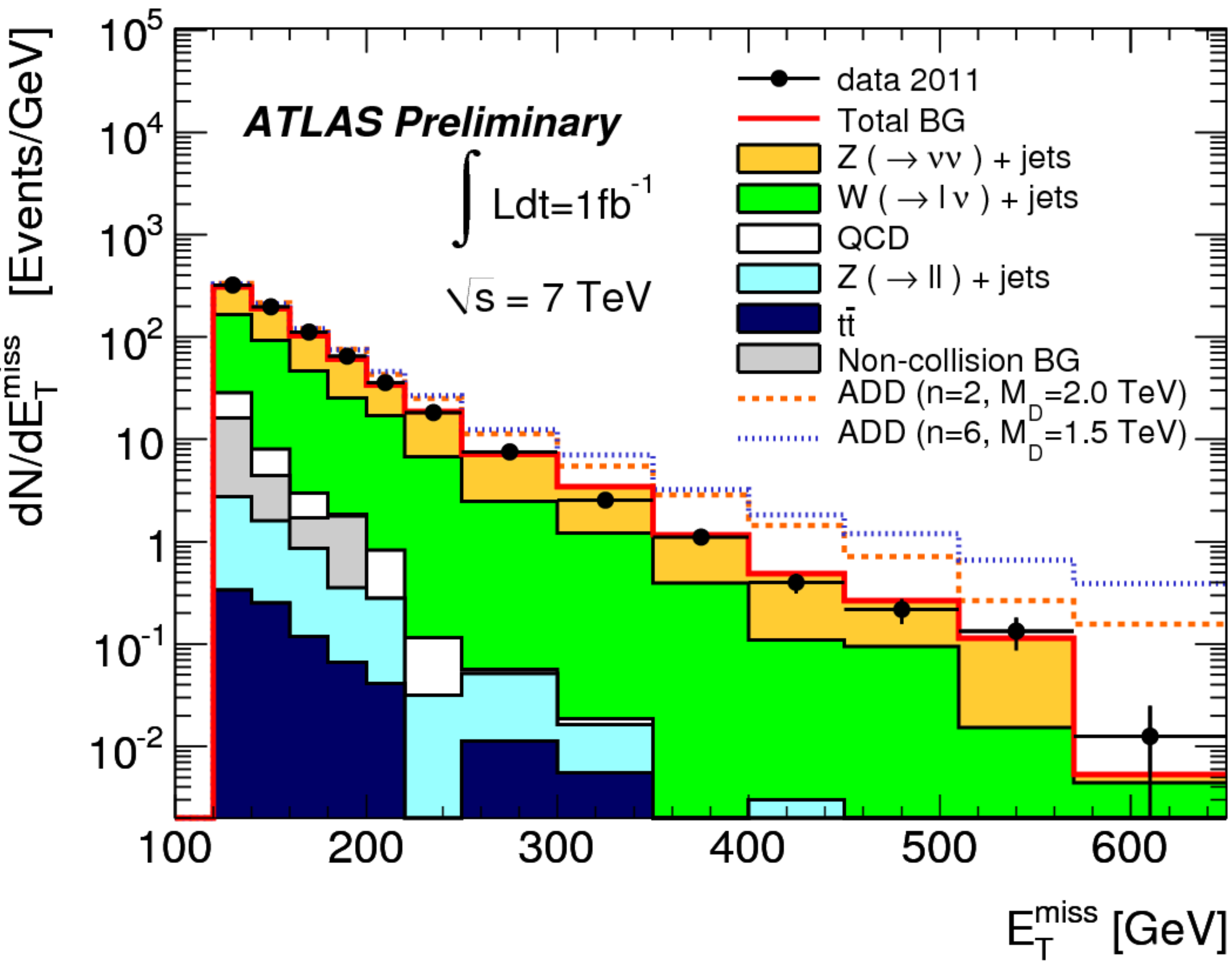


$$m_{q^*} > 2.9\ \text{TeV(ATLAS, and 2.7 TeV for CMS)}$$

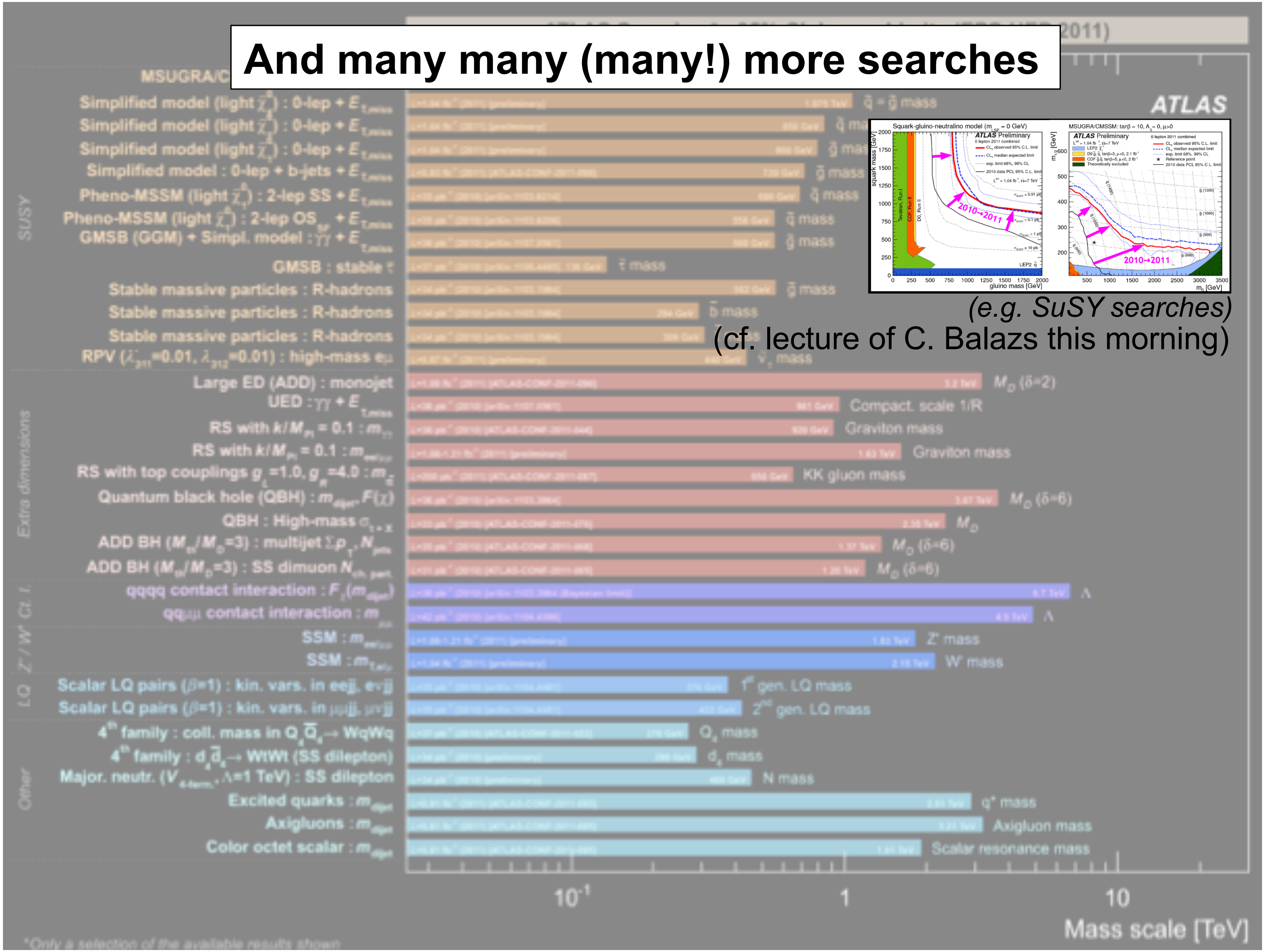
Mono-jets with ETmiss

(e.g. large extra dimensions)

$q\bar{q} \rightarrow g\mathrm{Graviton}$



And many many (many!) more searches



(e.g. SuSY searches)

(cf. lecture of C. Balazs this morning)

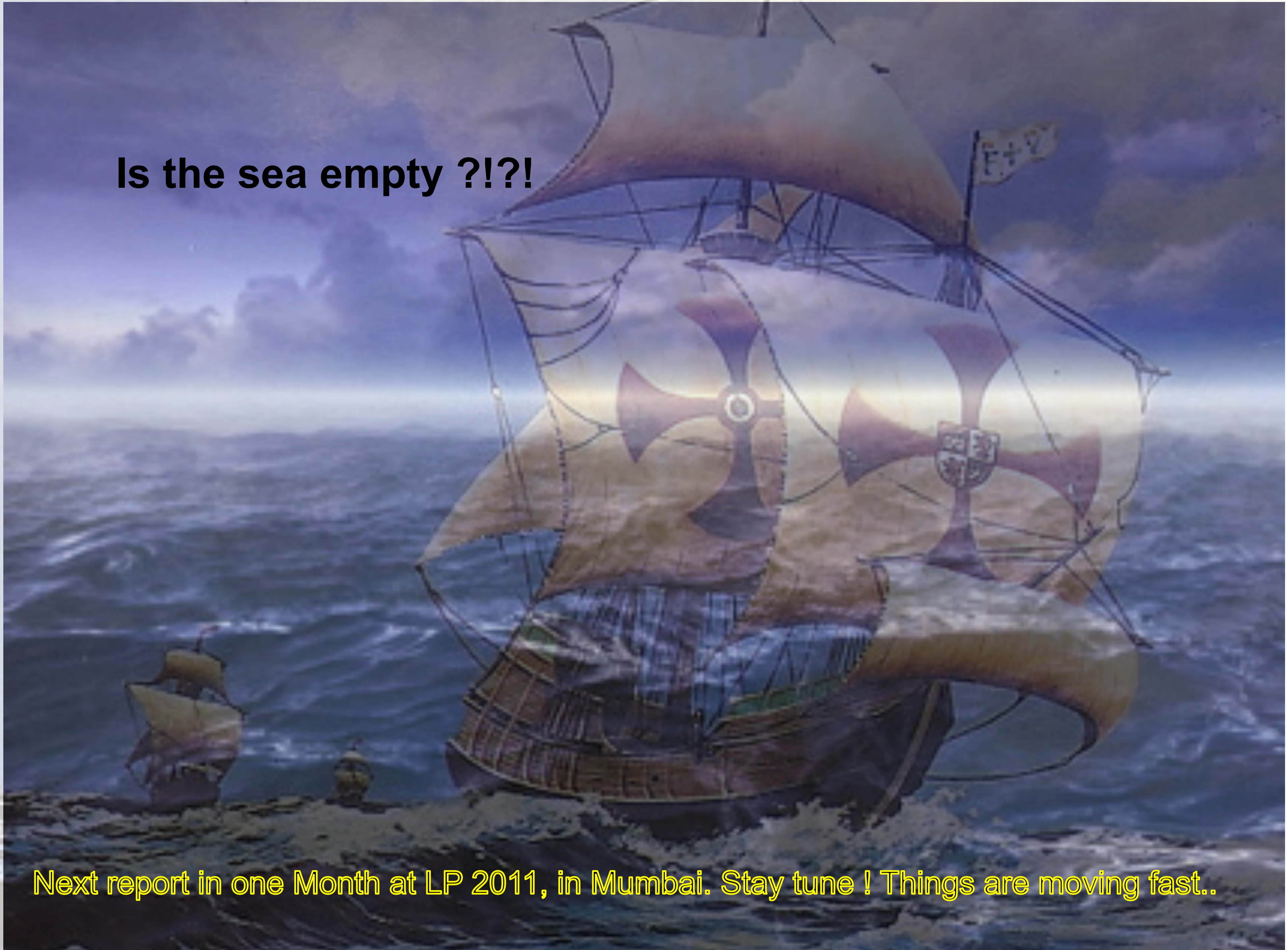
But, in Summary :

No luck yet ...

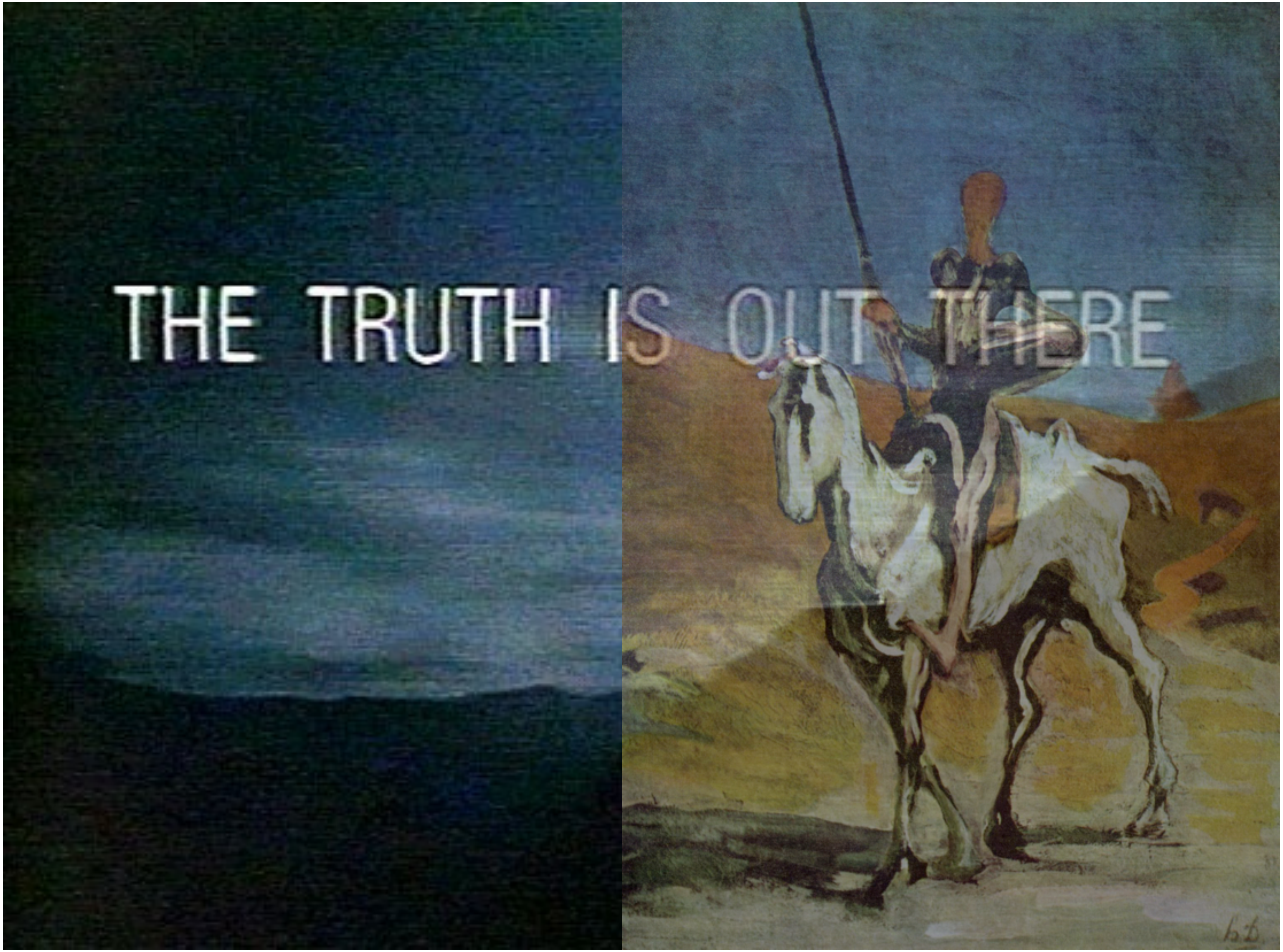
Many compasses on the market …

Although it is only the beginning
of the LHC journey

Quite many are already on (cheap) sell!


Is the sea empty ?!?!
Next report in one Month at LP 2011, in Mumbai. Stay tune ! Things are moving fast..


So far no discovery
But we know there is SuperNew physics somewhere


THE TRUTH IS OUT THERE