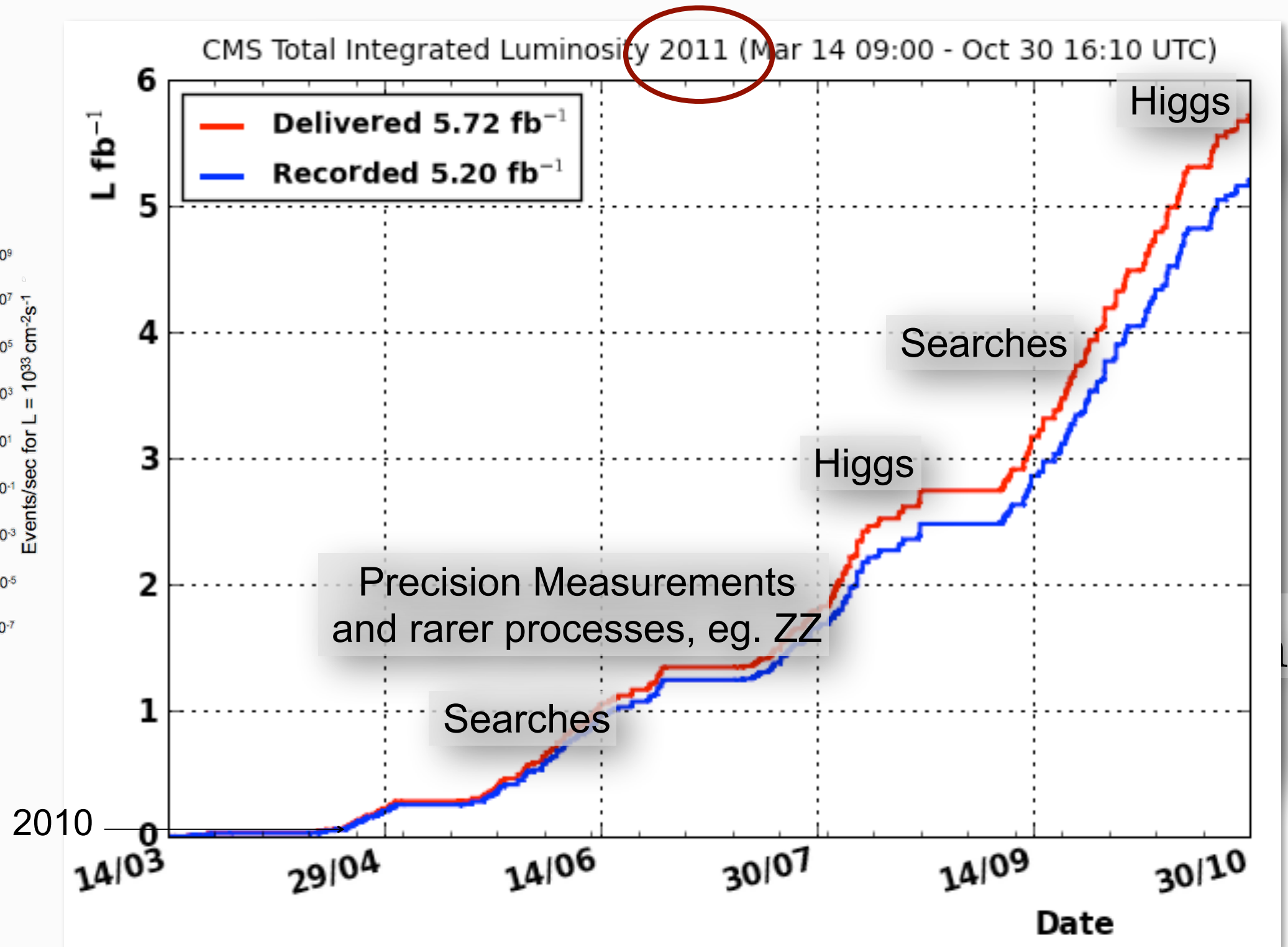
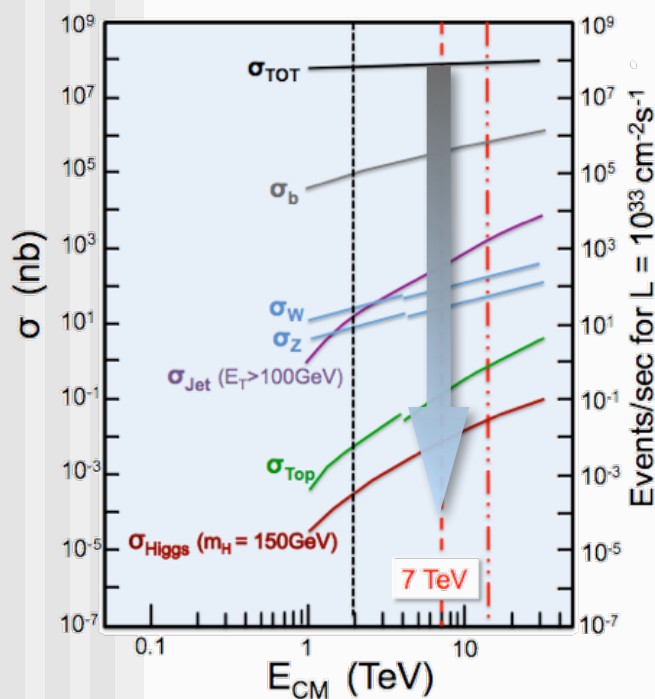


Our milestones:

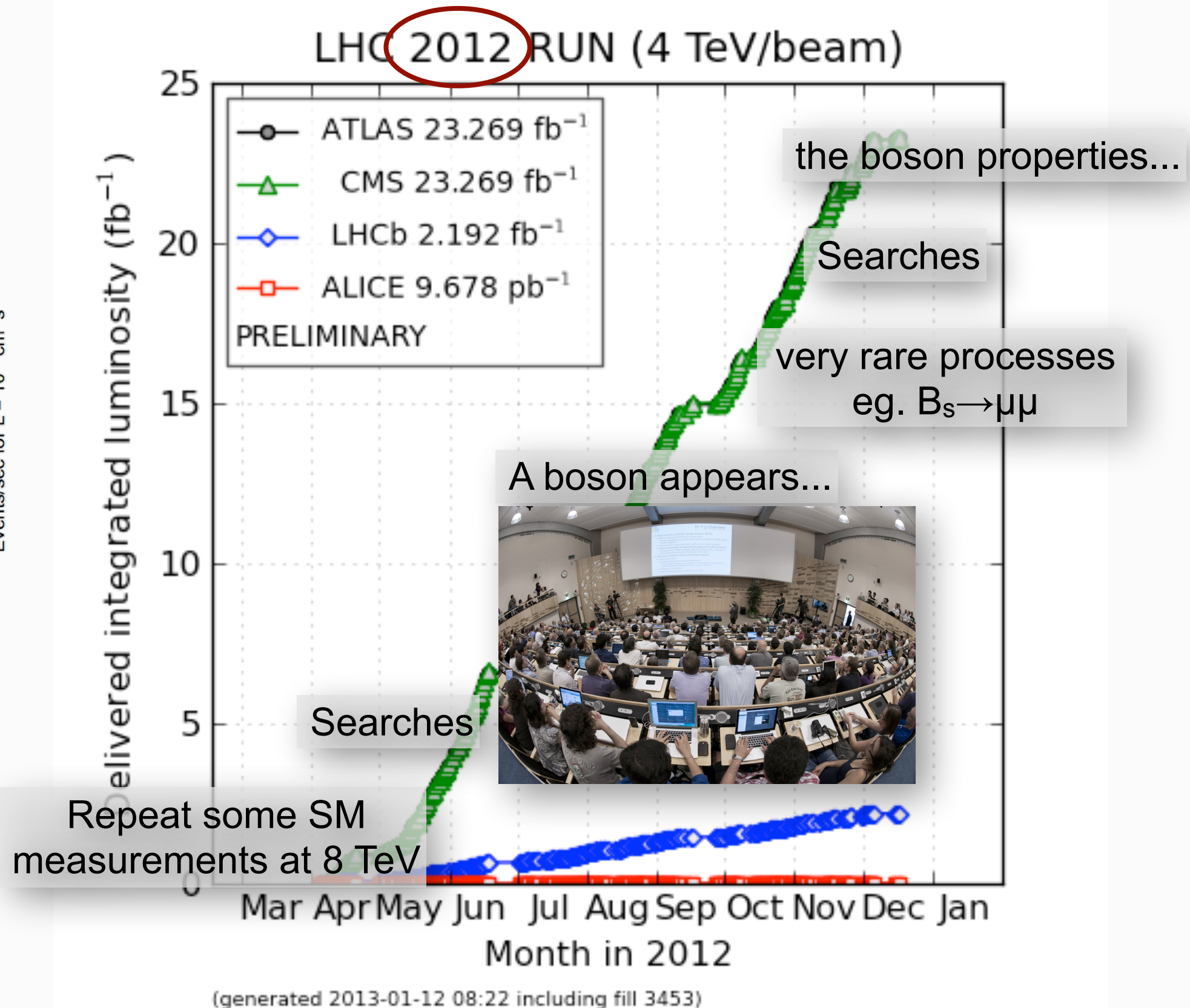
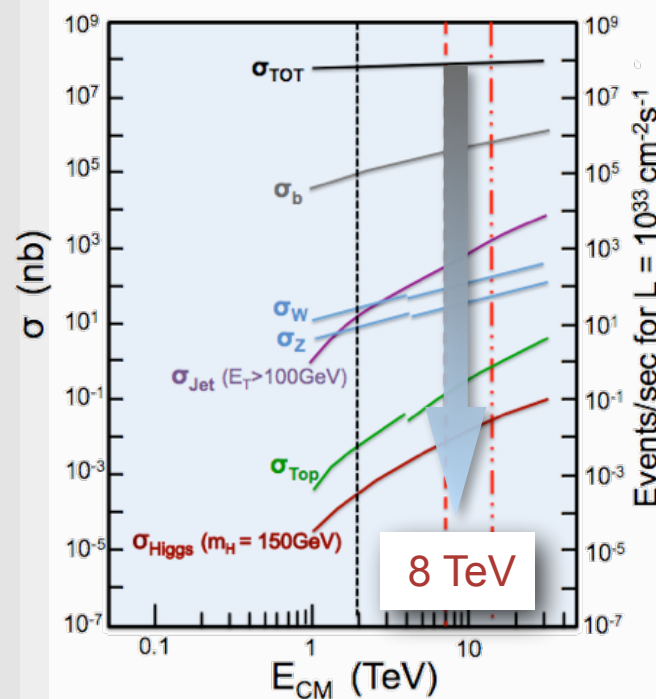
1. Why do ATLAS and CMS look like they look like today?
2. Tools used in the analyses
- 3. Some highlights, and comments:
achievements, physics highlights,
why your calculations are/will be
important**
4. What next?

The speed, at which things appeared....



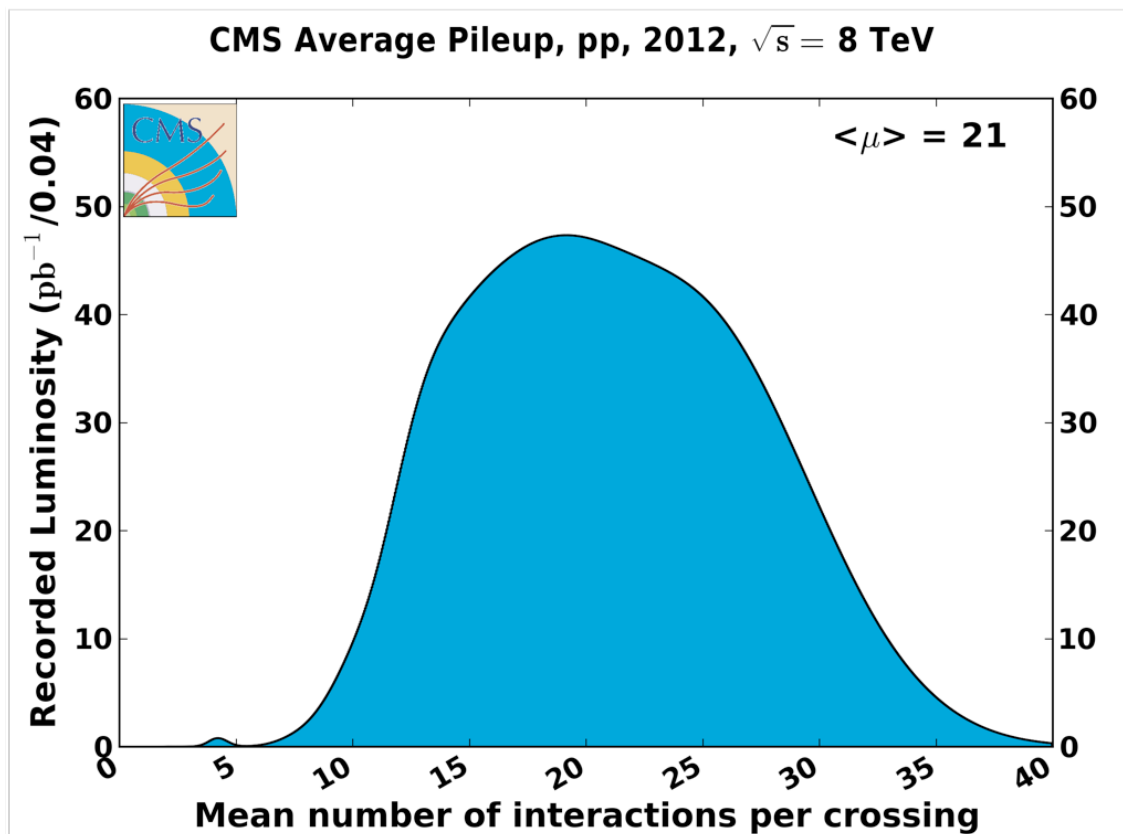
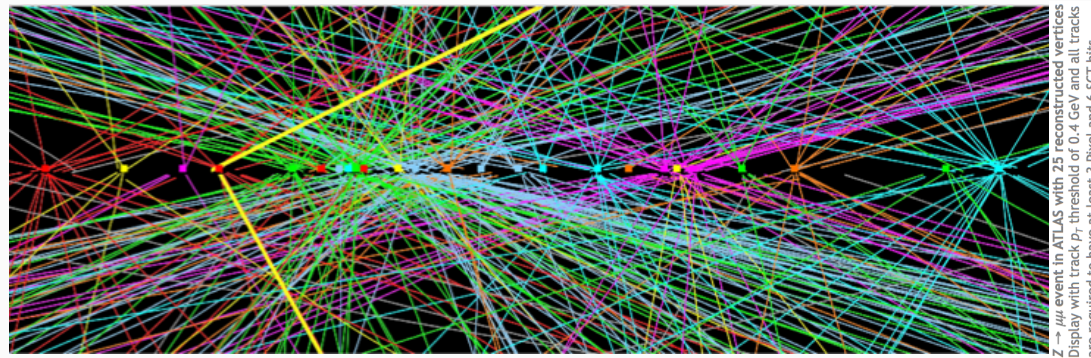
2010

The speed, at which things appeared....



The environment...

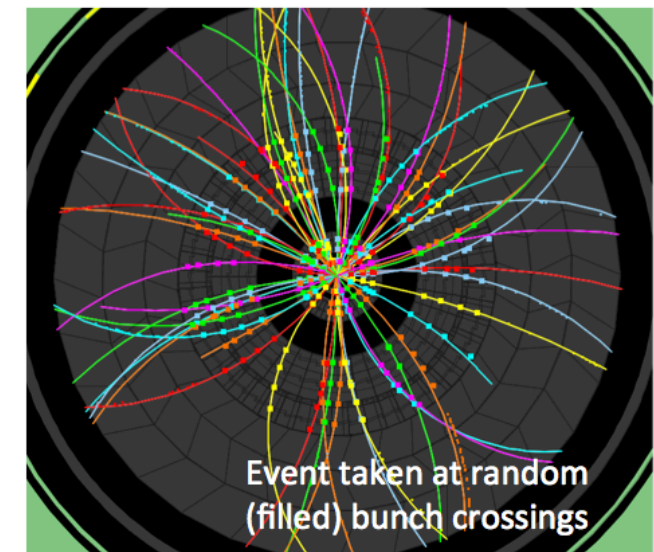
A. Hoecker, Dec 2012



Data taking efficiencies ~94%
At or above 90% used for physics.
Kept the performance, despite high PU!

2010
O(2) Pile-up events

150 ns inter-bunch spacing



2011
O(10) Pile-up events

50 ns inter-bunch spacing



2012
O(20) Pile-up events

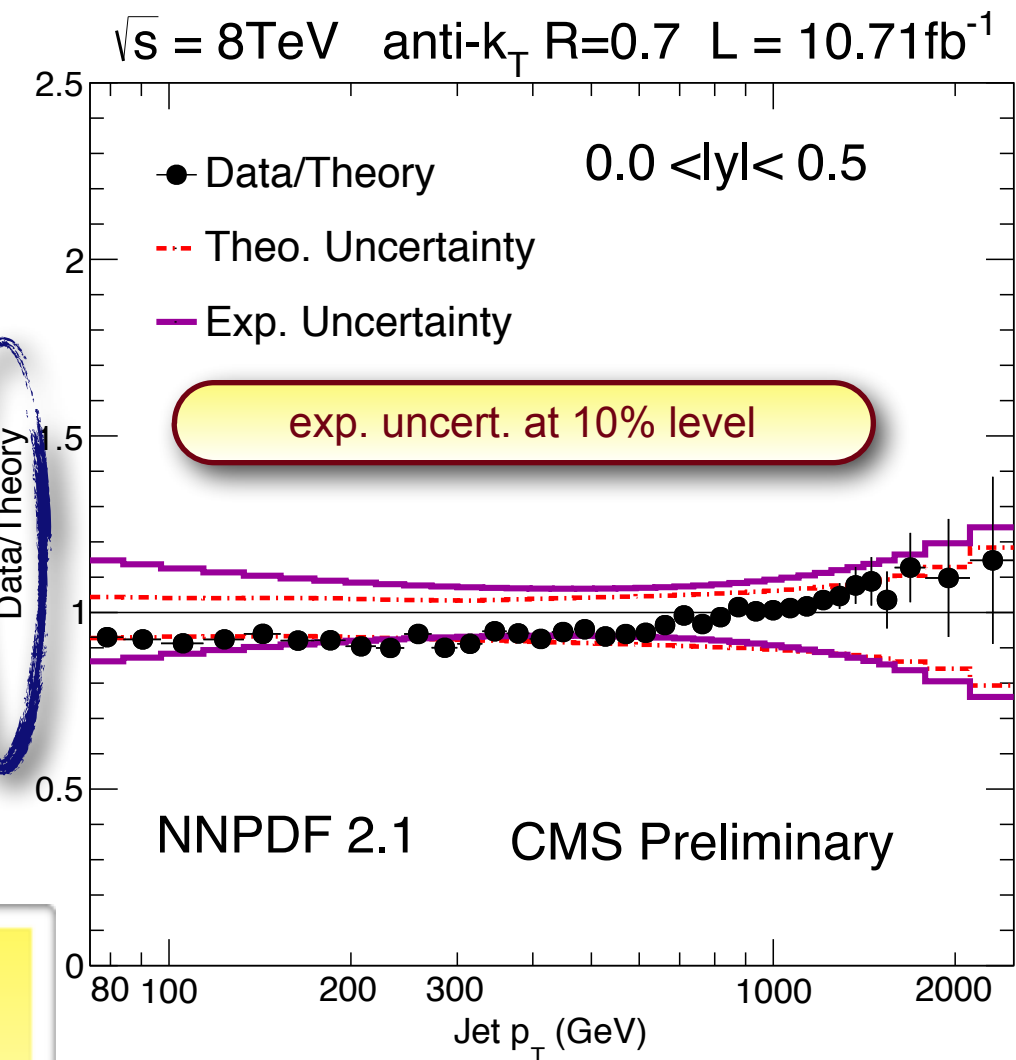
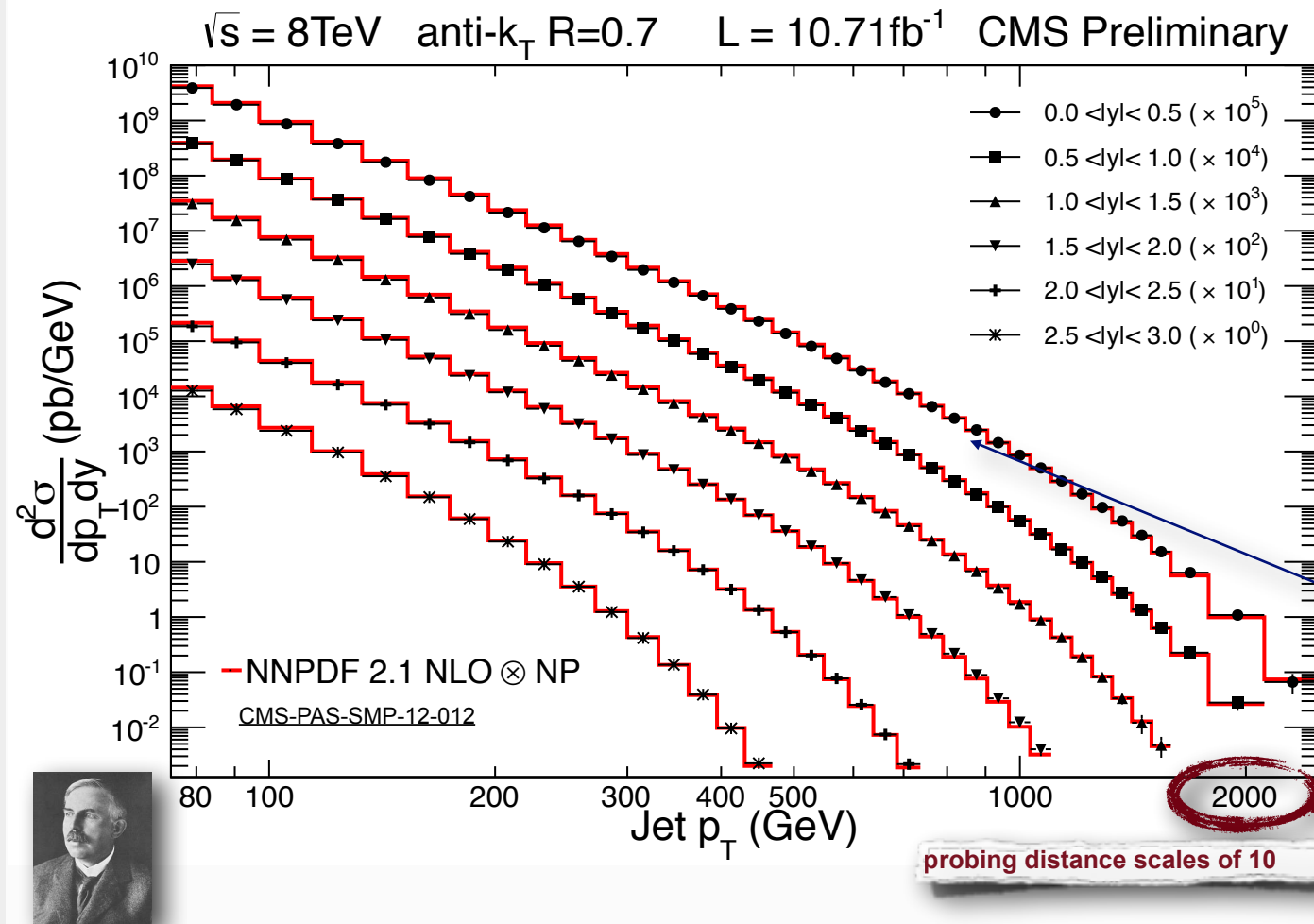
50 ns inter-bunch spacing



Marumi Kado, Dec 2012

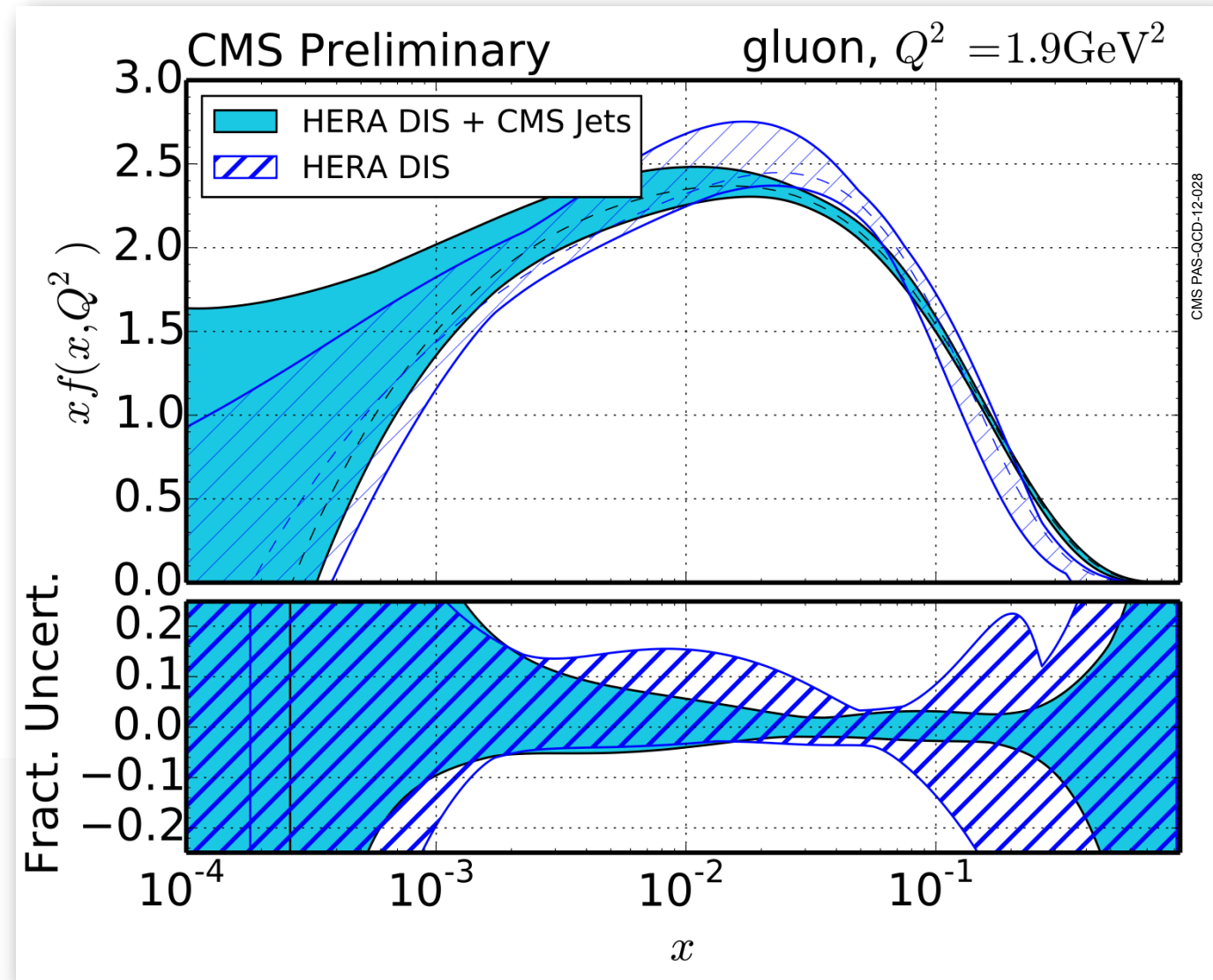
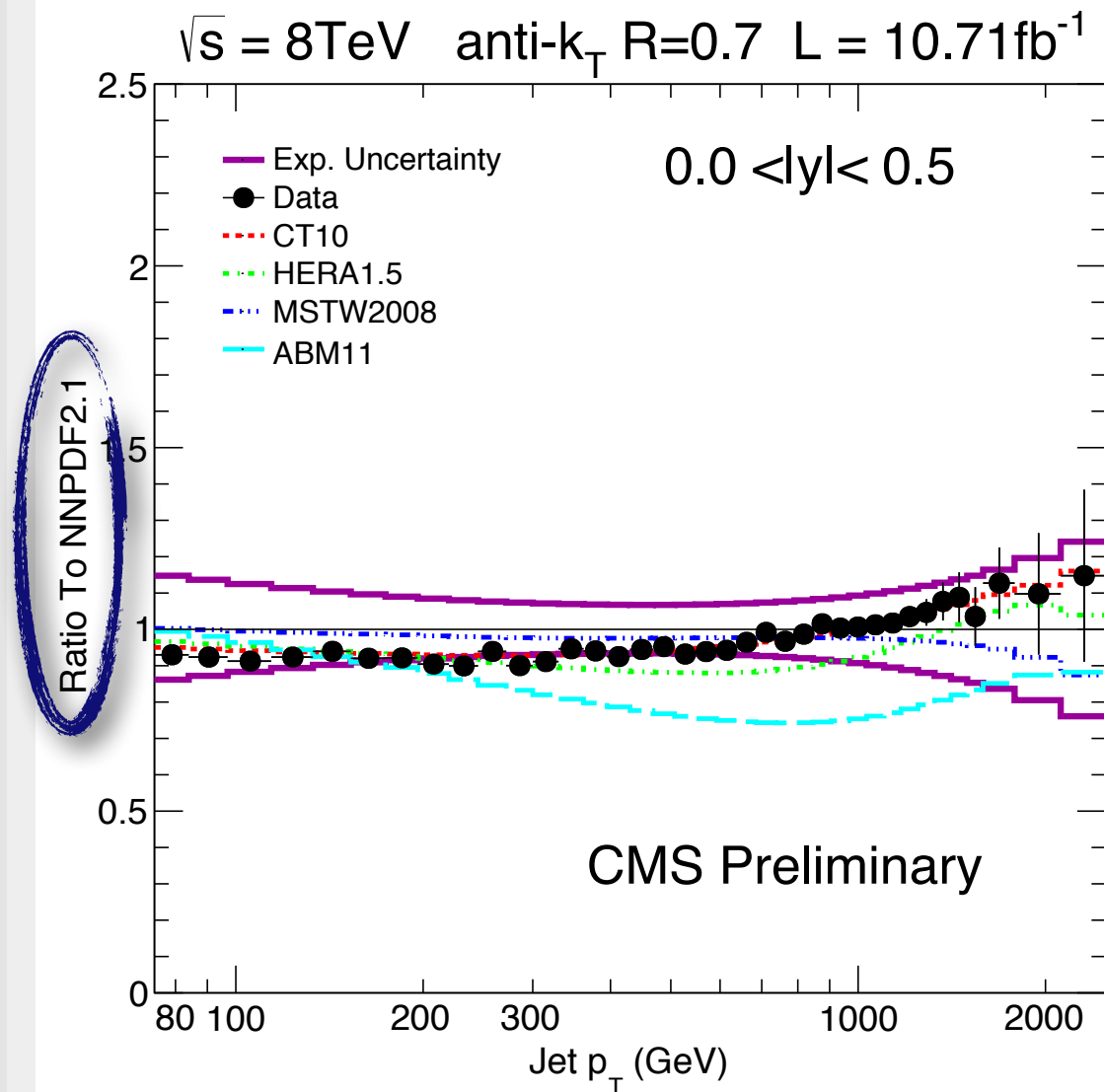
Good performance leads to good results

example: inclusive jet production



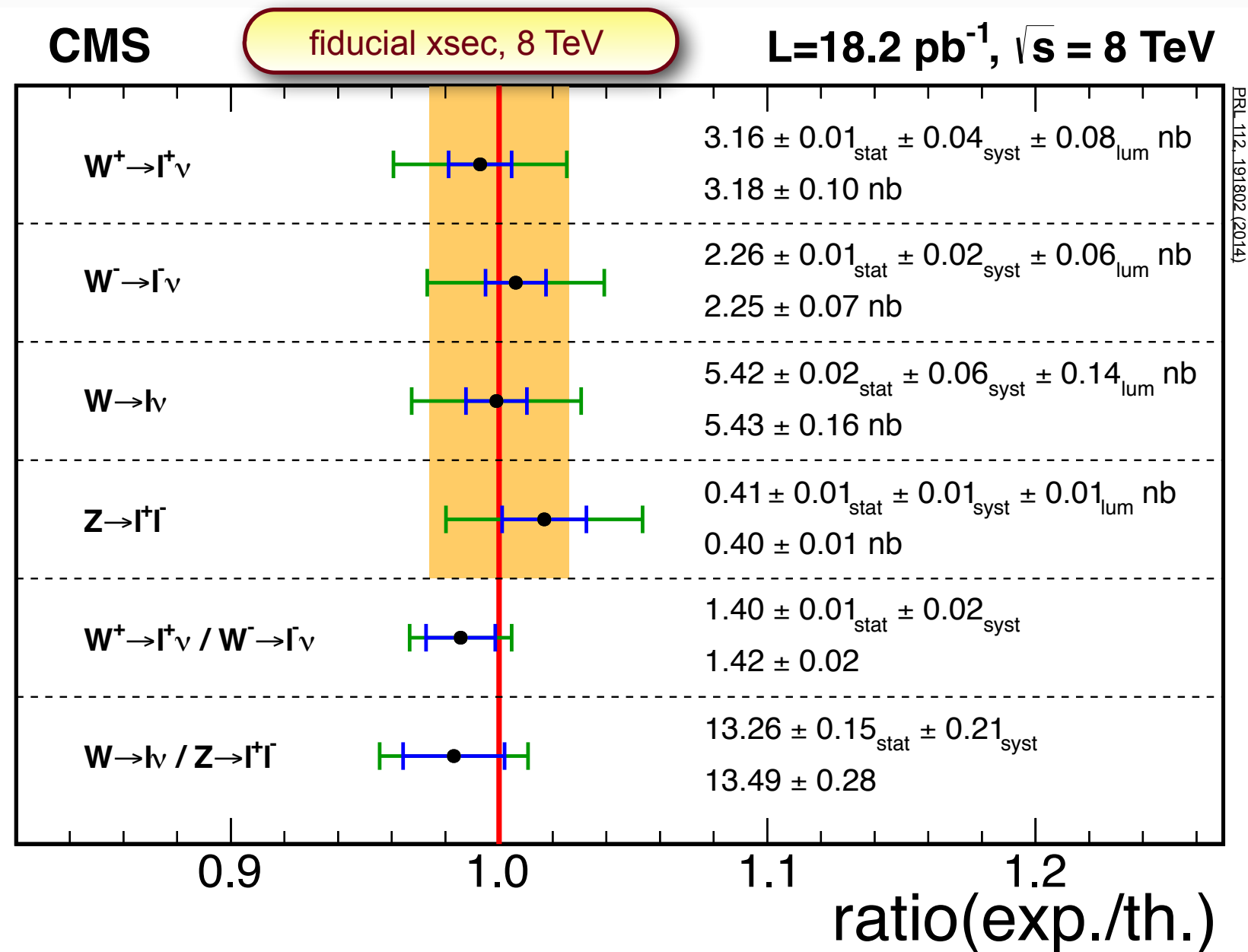
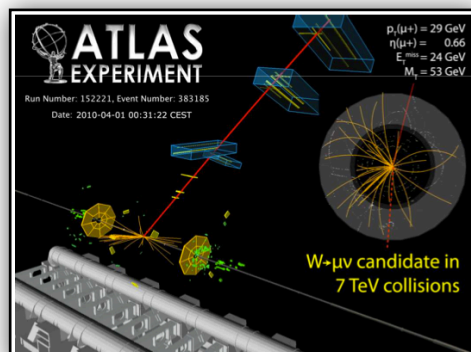
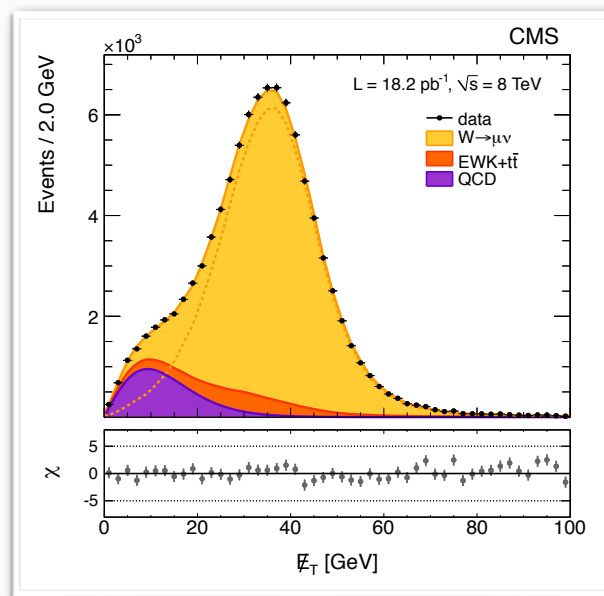
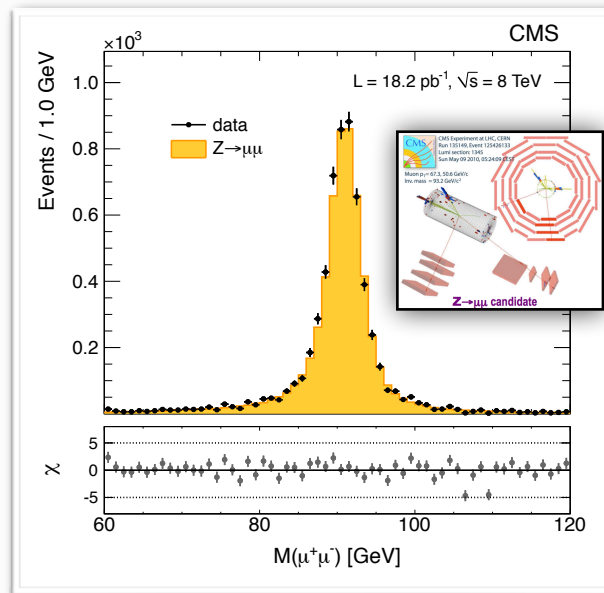
- jet energy scale uncertainties at the 1-2% level ==>
- for central rapidities: similar exp. and theo. uncertainties, 5 - 10%
- inclusive jet data :
NLO QCD describes data over ~10 orders of magnitude!
==> starts to be important tool for constraining PDFs

Incl. Jet Production seen before



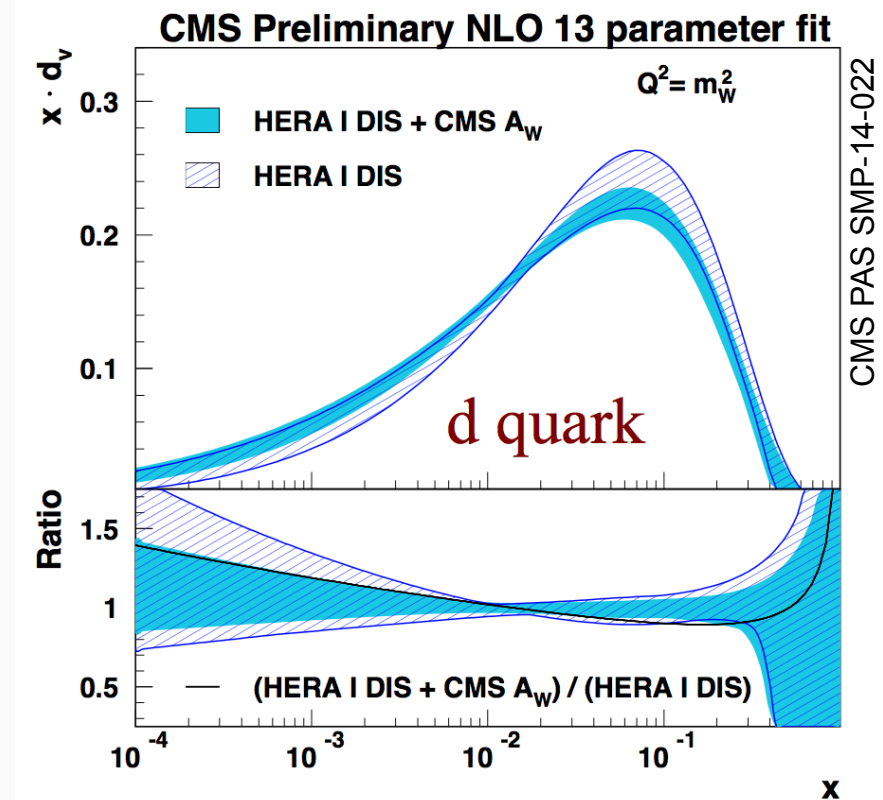
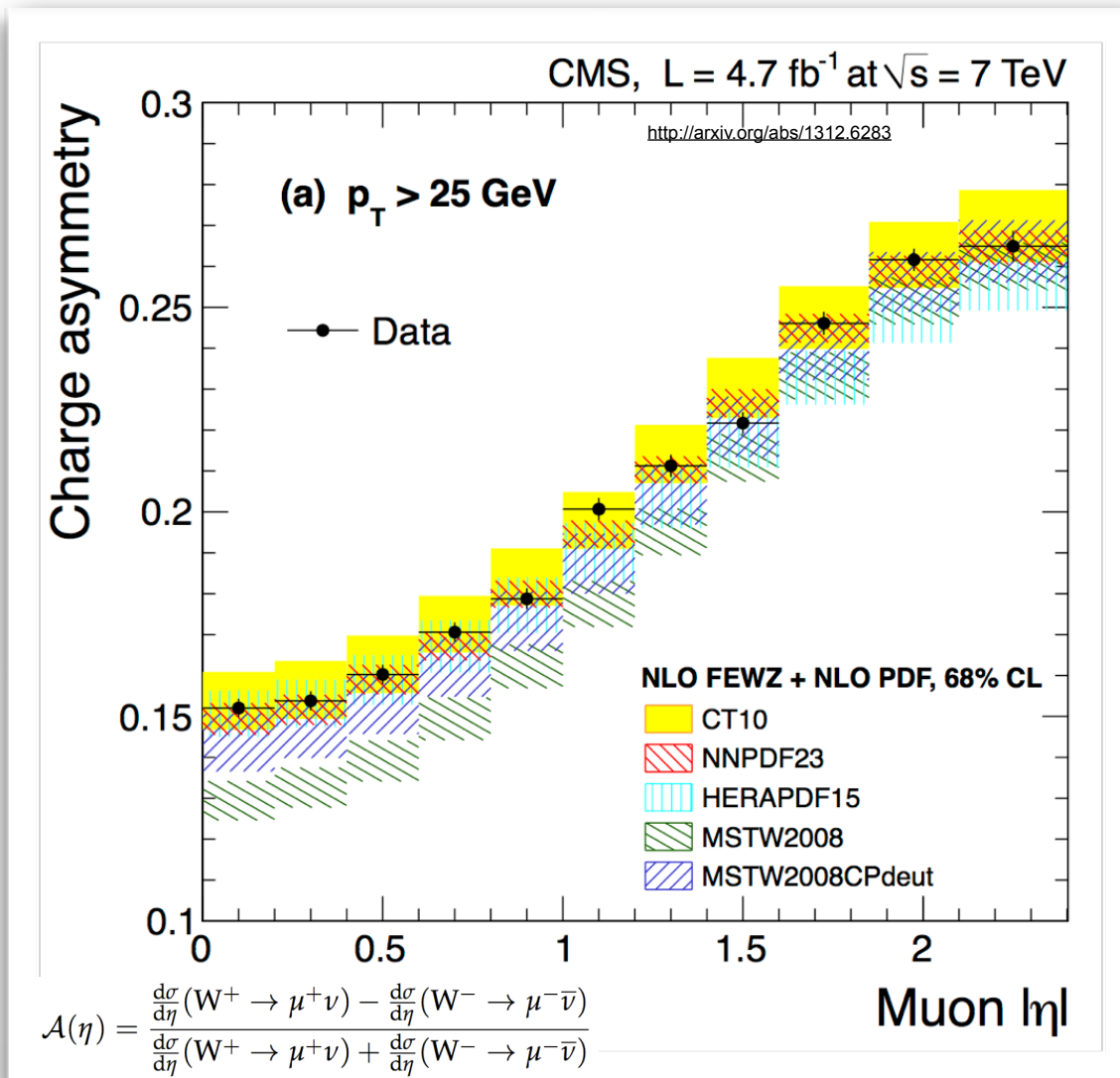
- 📌 inclusive jet data : starts to be important tool for constraining PDFs
- 📌 future NNLO calculation for dijet prod. will have a further impact!

Good performance leads to good results

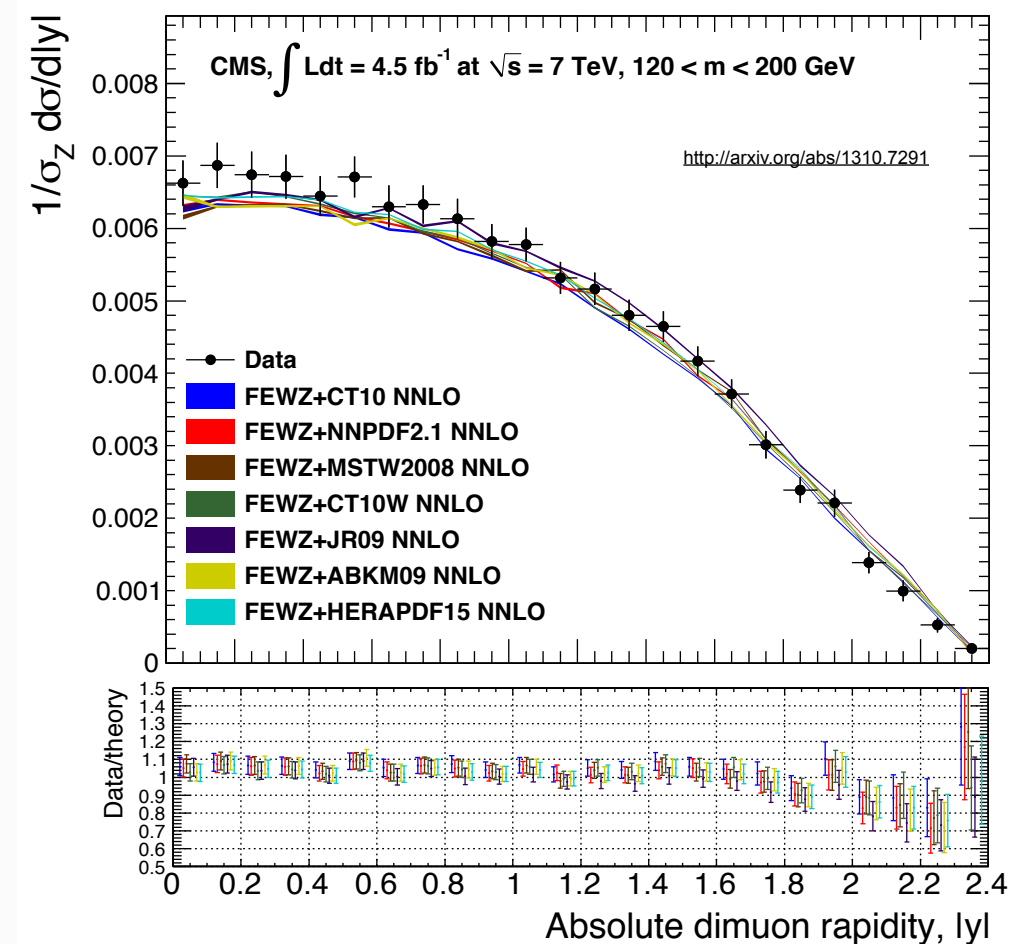
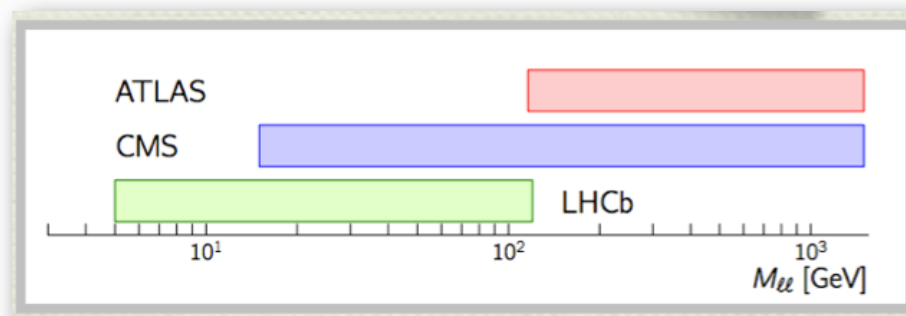


Amazing precision reached (~1% experimental !)
Also fiducial xsecs measured (no acceptance uncert. !)
 Important test of and constraints on theory (NNLO, PDFs)

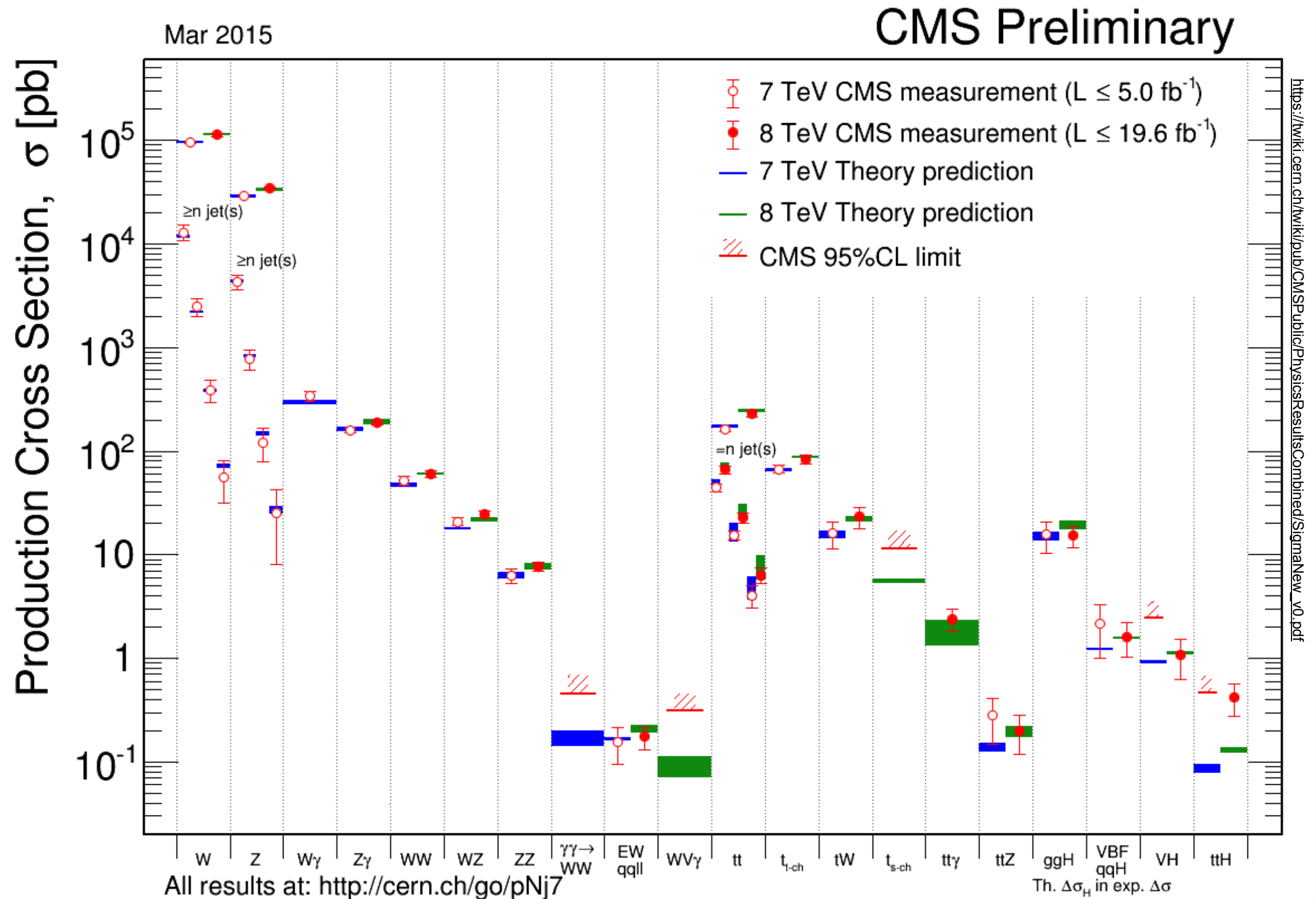
More on W/Z production



extremely rich and precise data set at hand, covering a very large phase space....

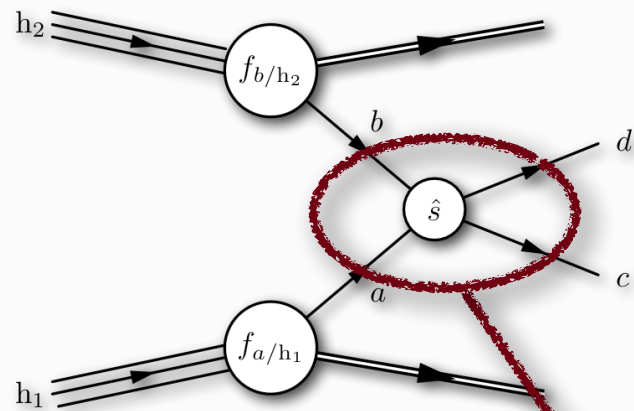


Good performance leads to good results

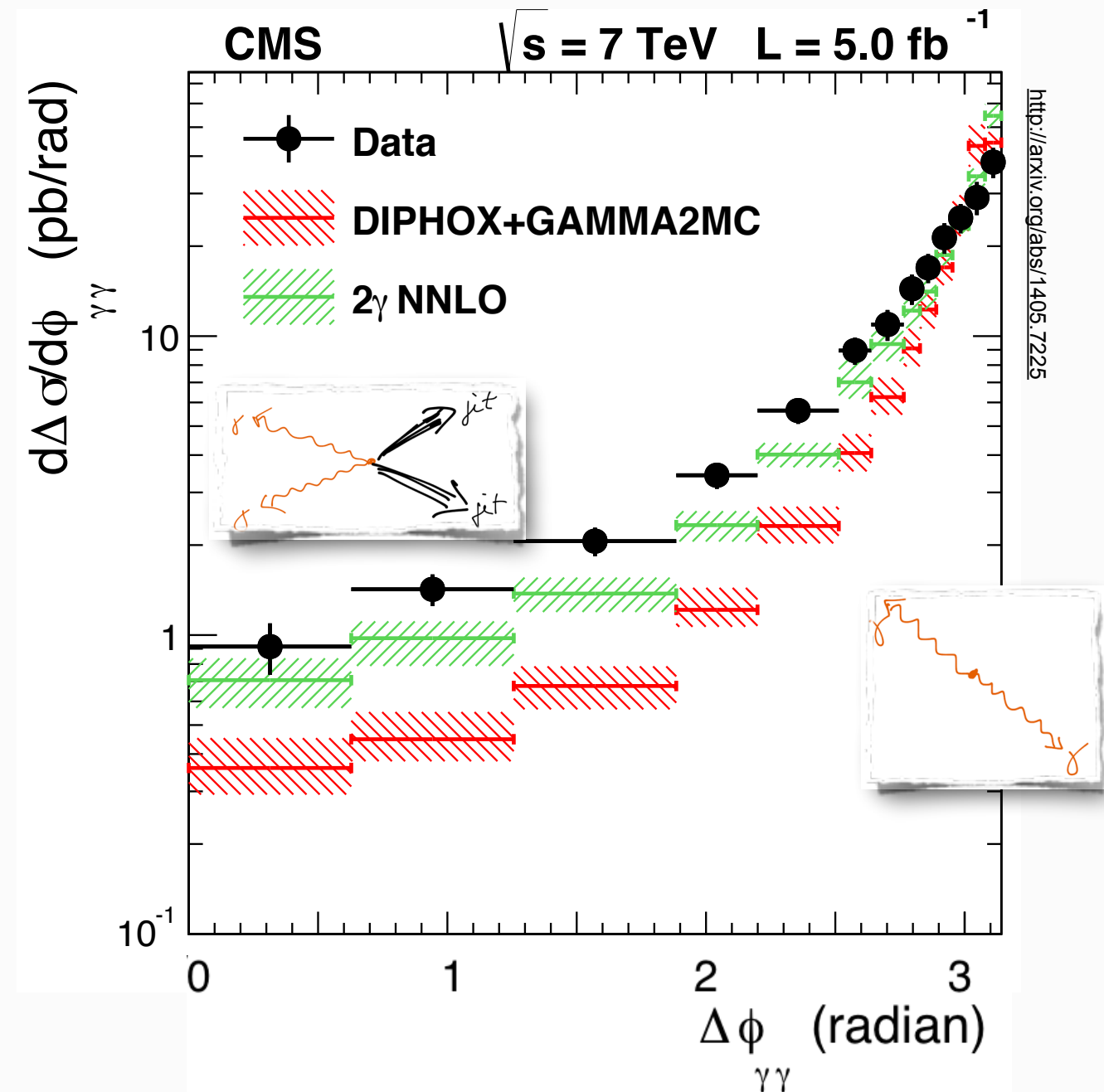
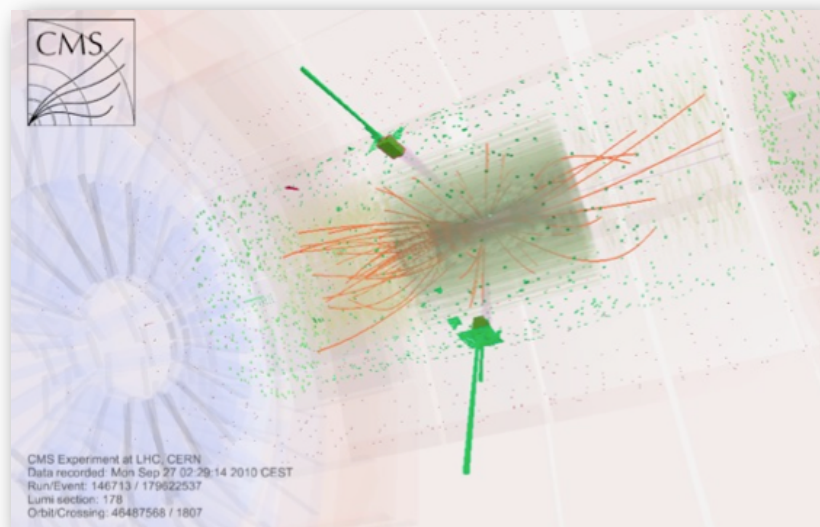
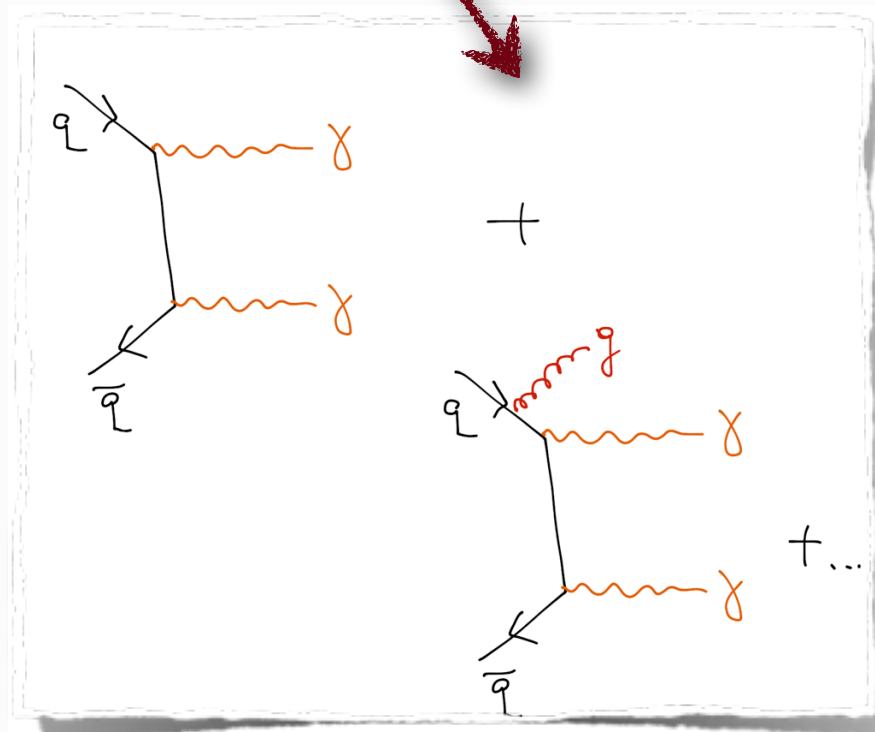


The impact of new (N)NLO (+PS) calculations

Usage of new NNLO calculations

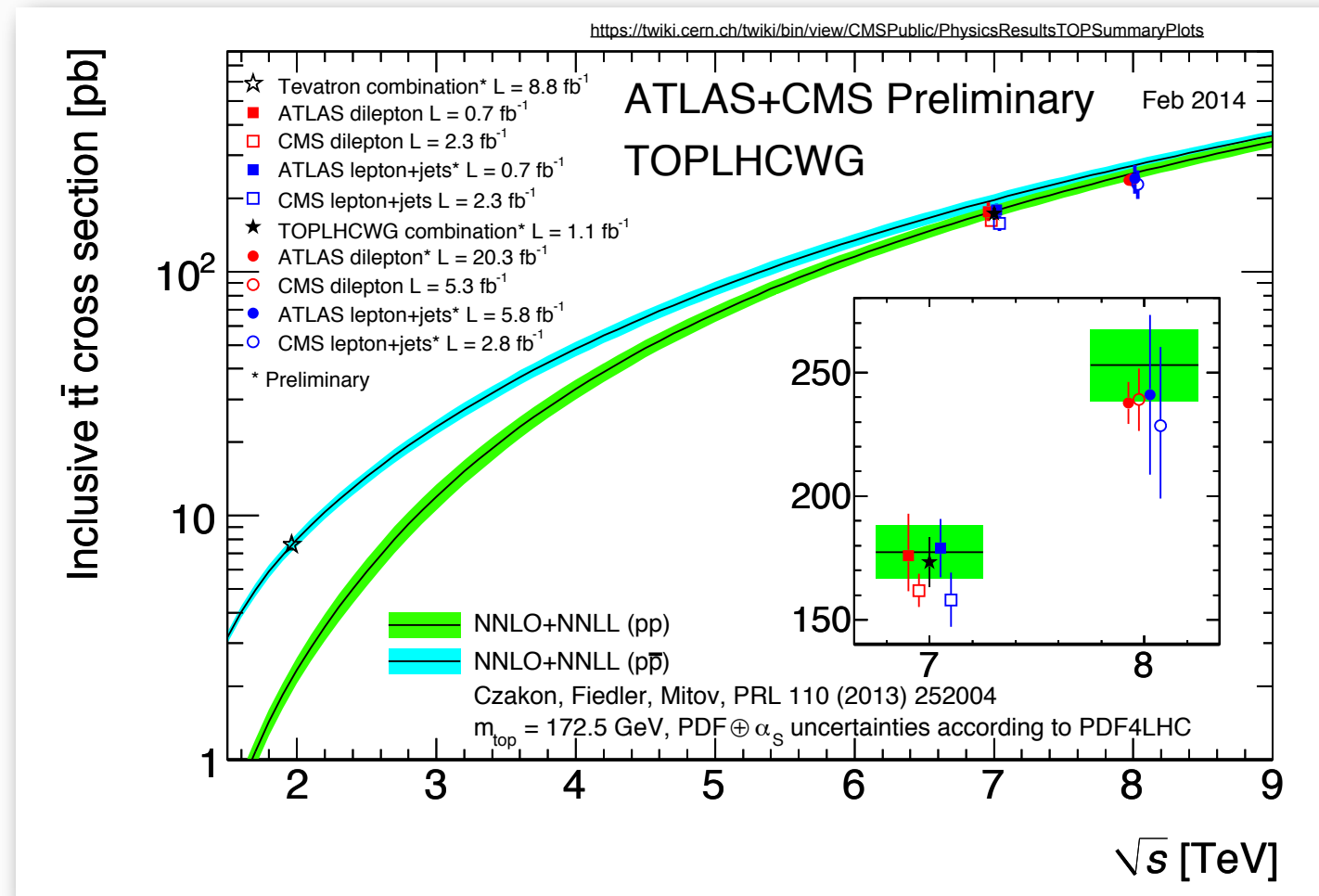
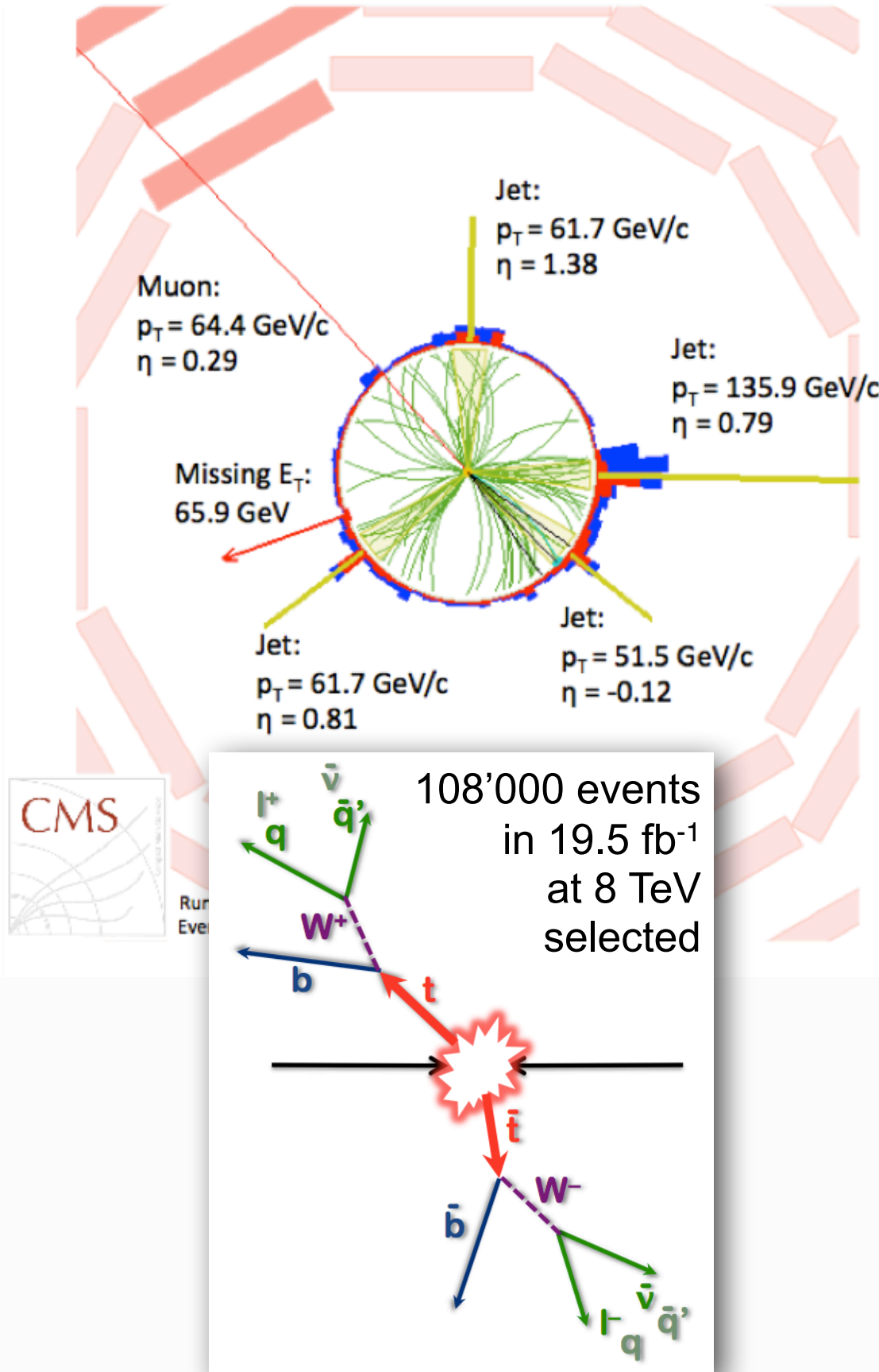


besides incl. W/Z prod. mentioned already, and besides the Higgs sector:



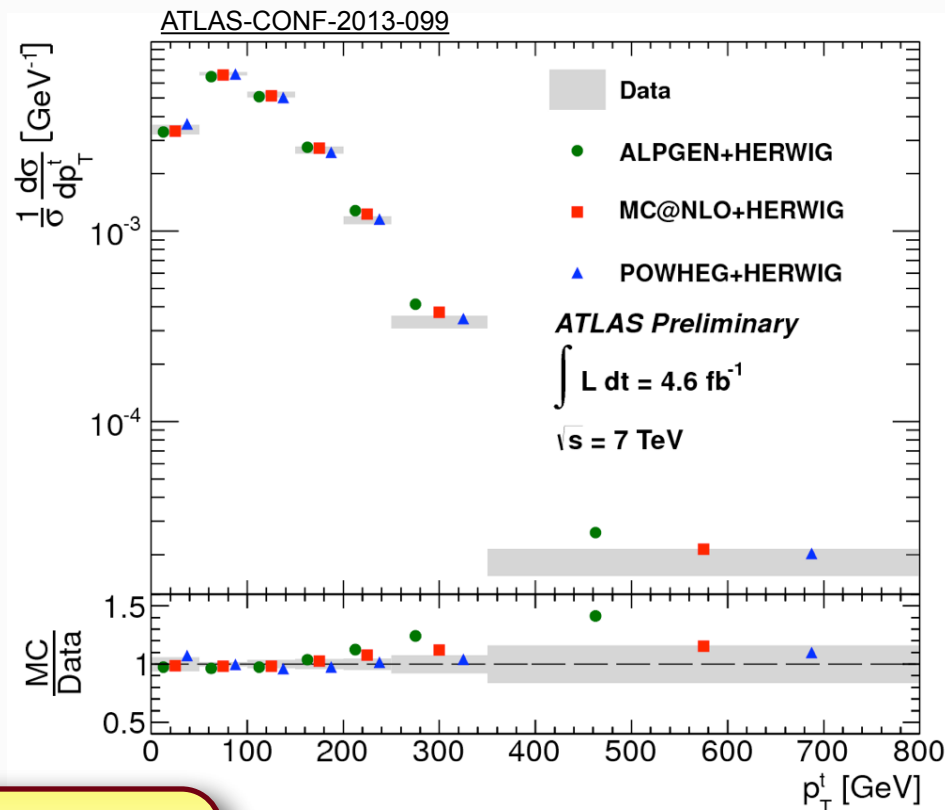
- diphoton production:** exp. uncert. at the 10% level
- For small angular separation: NLO calculation off by factors 2 - 3 !
- Need **at least** recent NNLO calculation for appropriate description!

Usage of new NNLO calculations



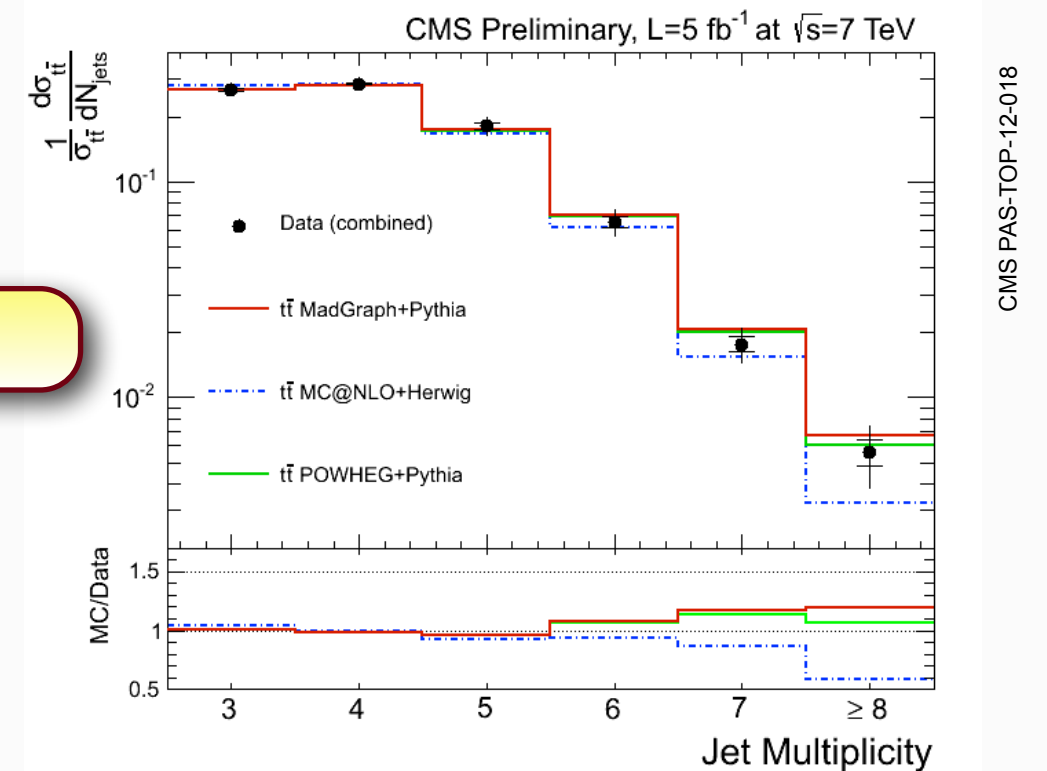
- incl. $t\bar{t}$ production cross sections:
- Recent total experimental uncertainty (including lumi uncert) at the **4-5 % level!**
- similar or better than theor. uncertainty (scales + PDF)
- see more about the usage of this NNLO xsec later.....

Probing the TOP: going differential and rare

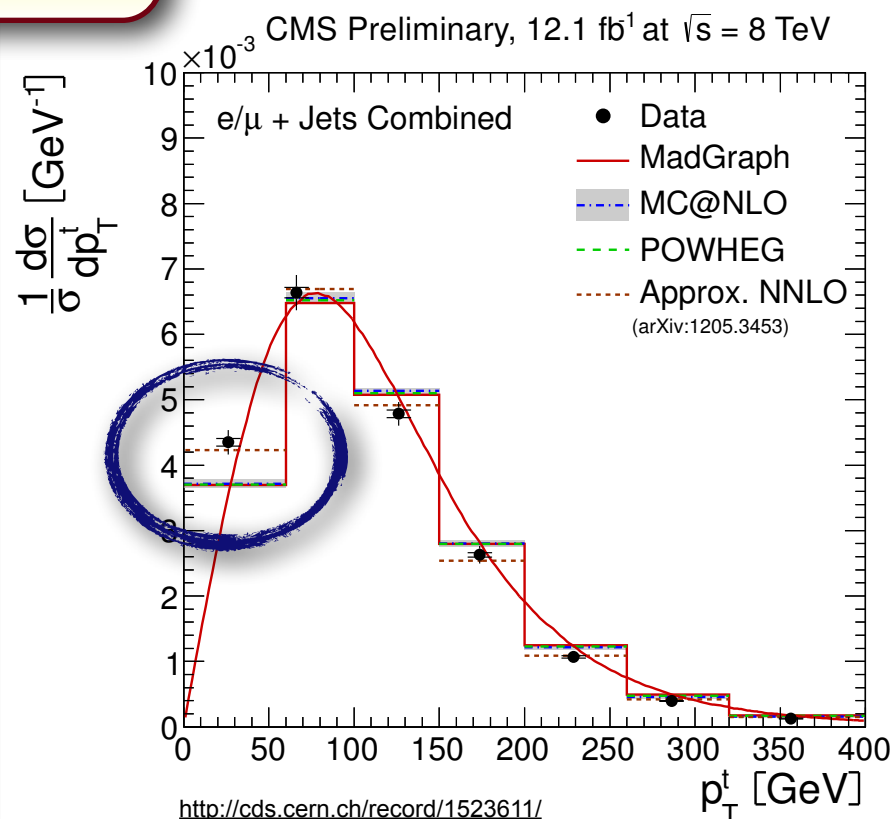


p_T^{top}

jet mult.



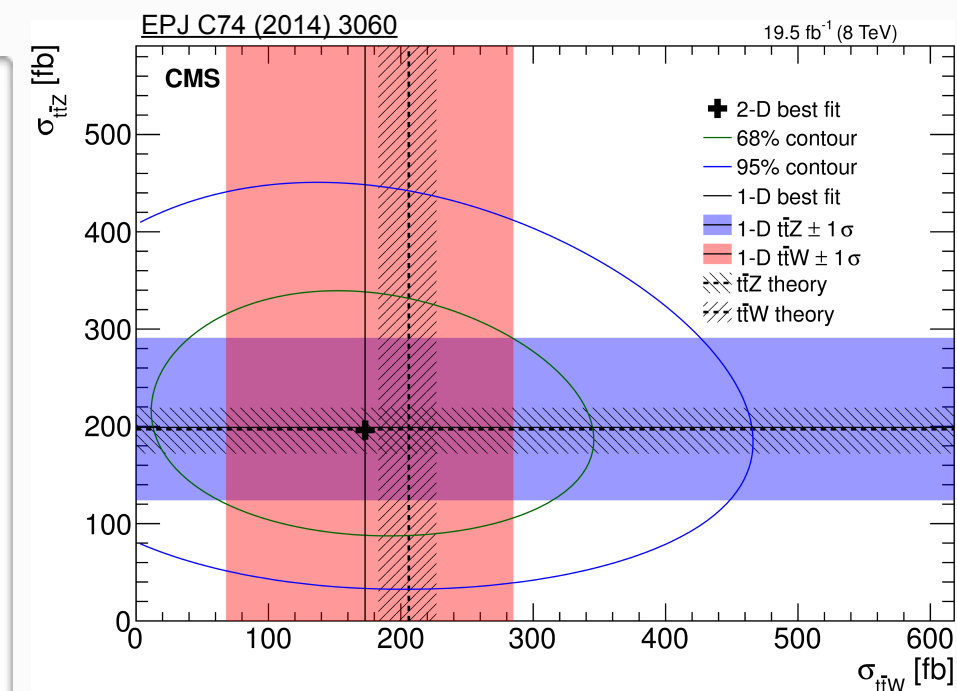
CMS PAS-TOP-12-018



<http://cds.cern.ch/record/1523611/>

see also <http://arxiv.org/pdf/1505.04480v1.pdf>

- many properties tested, with high exp. precision
- also: $t\bar{t}$ +MET, $t\bar{t}$ +photon, $(t\bar{t}+b\bar{b})/(t\bar{t}+\text{jets})$
- TOPLHCWG studying differences between ATLAS and CMS, eg. in top p_T dist.



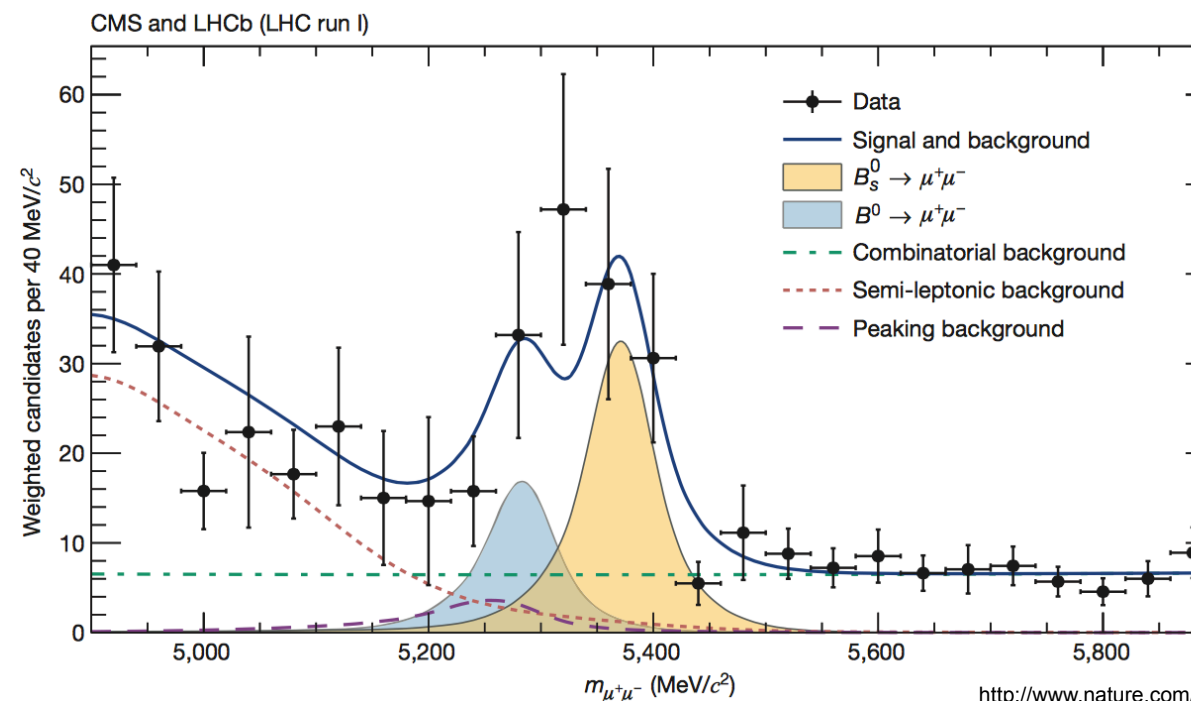
very rare processes / couplings:
 $t\bar{t}W$ and $t\bar{t}Z$ prod, sub-pb regime

By the way...

- ... talking about rare processes....



$$B^0_{(s)} \rightarrow \mu^+ \mu^-$$



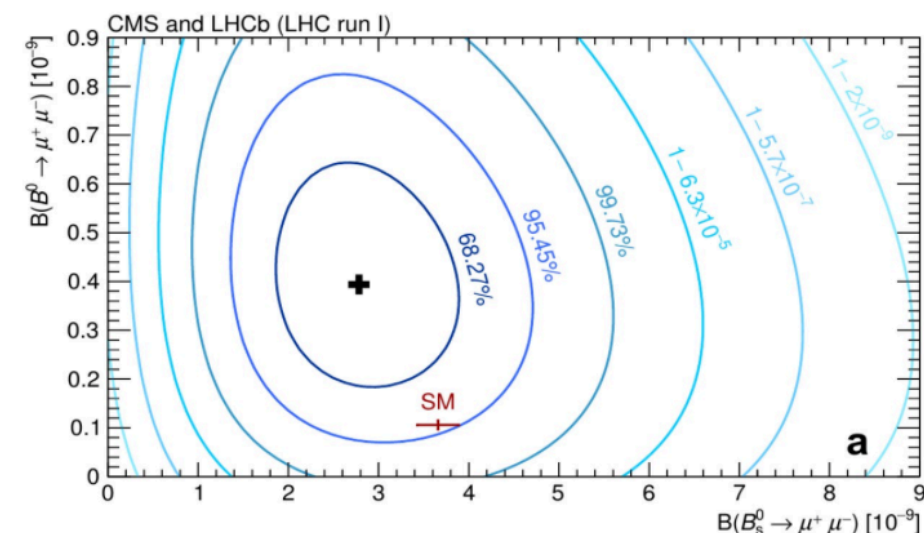
- combination with CMS measurement

$$BF(B^0_s \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$BF(B^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

[arXiv:1411.4413]

- $B^0_s \rightarrow \mu^+\mu^-$ agrees with Standard Model
- $B^0 \rightarrow \mu^+\mu^-$ 2.2 σ above Standard Model



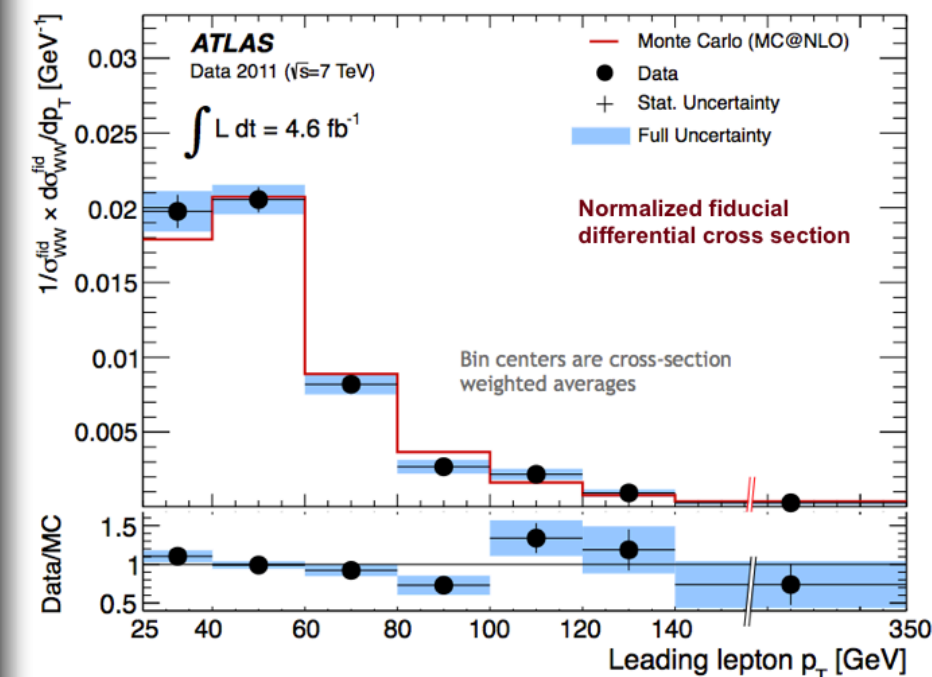
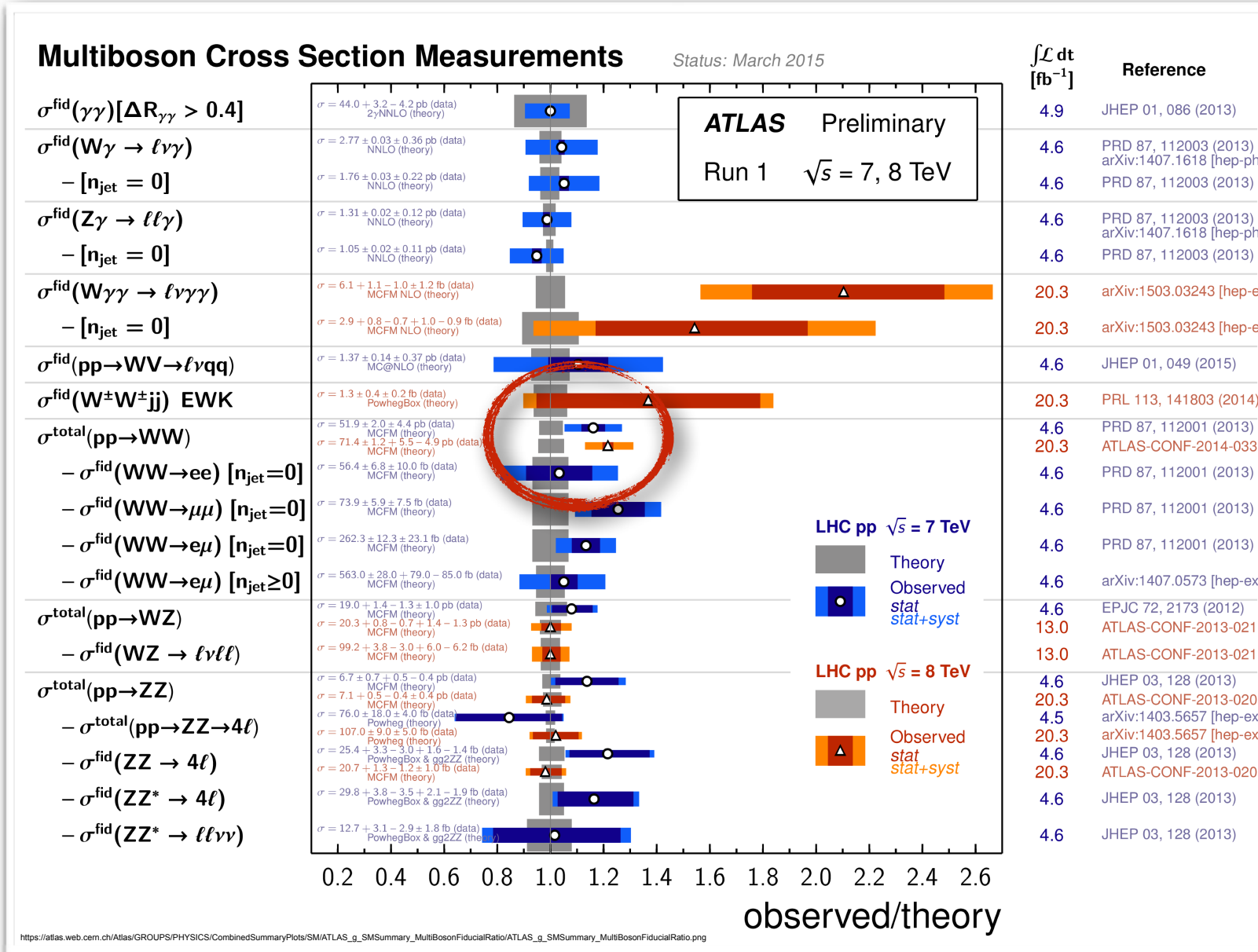
13.05.2015

Particle Physics Seminar Bern (38/64)

O. Steinkamp

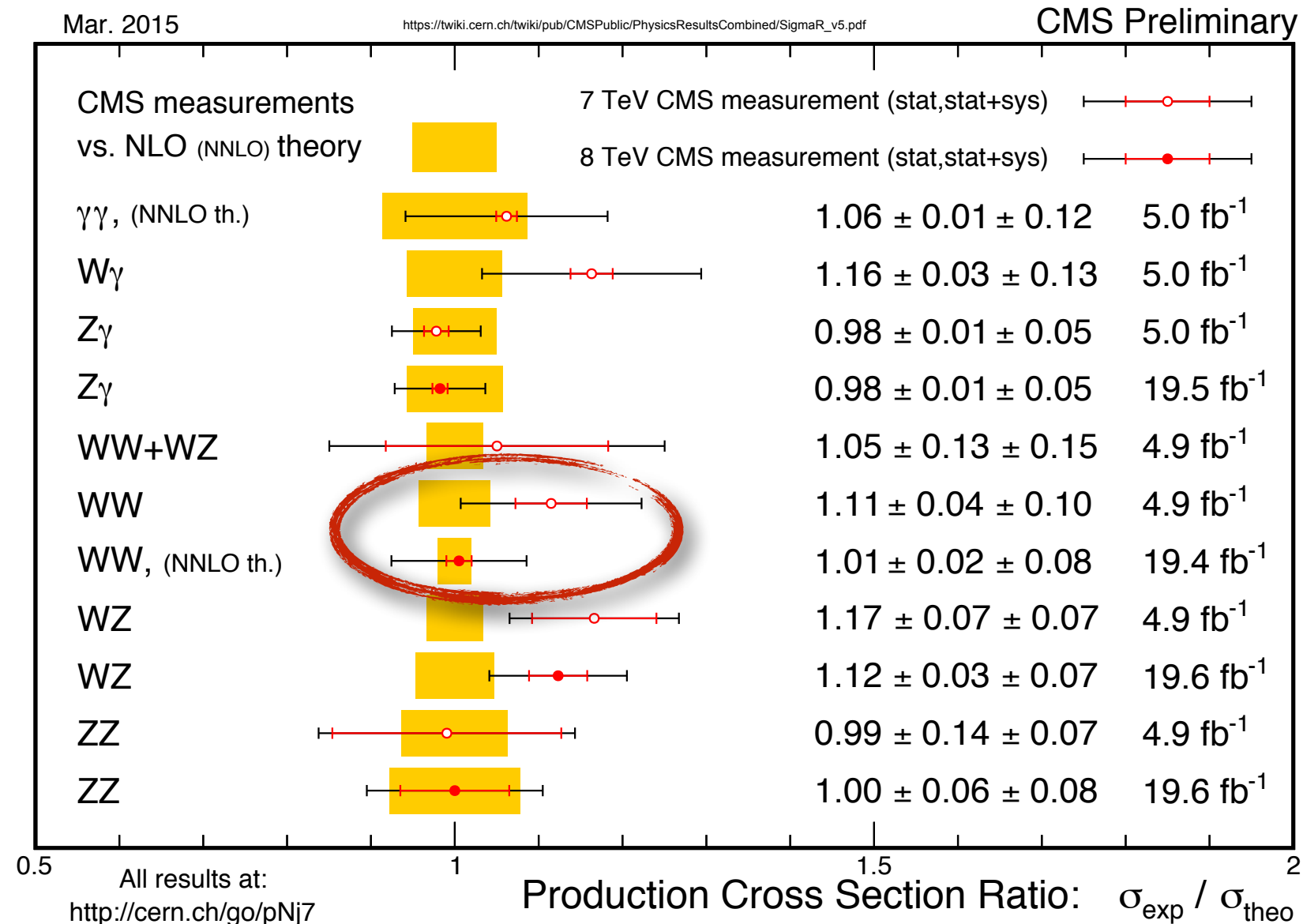
NNLO: A very recent example....

- Are we sure we understand “normal” WW production?
- Was definitely wanted: NNLO pred. for WW prod.



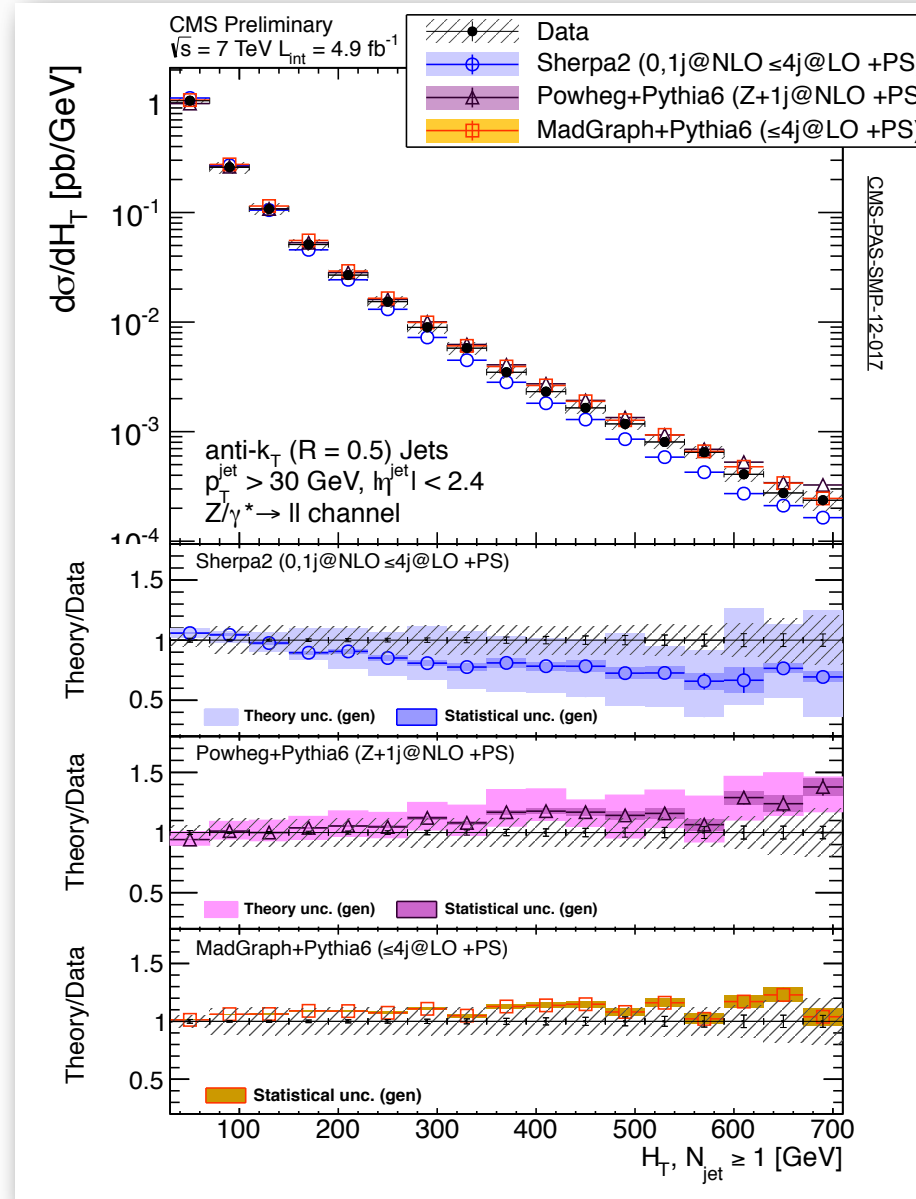
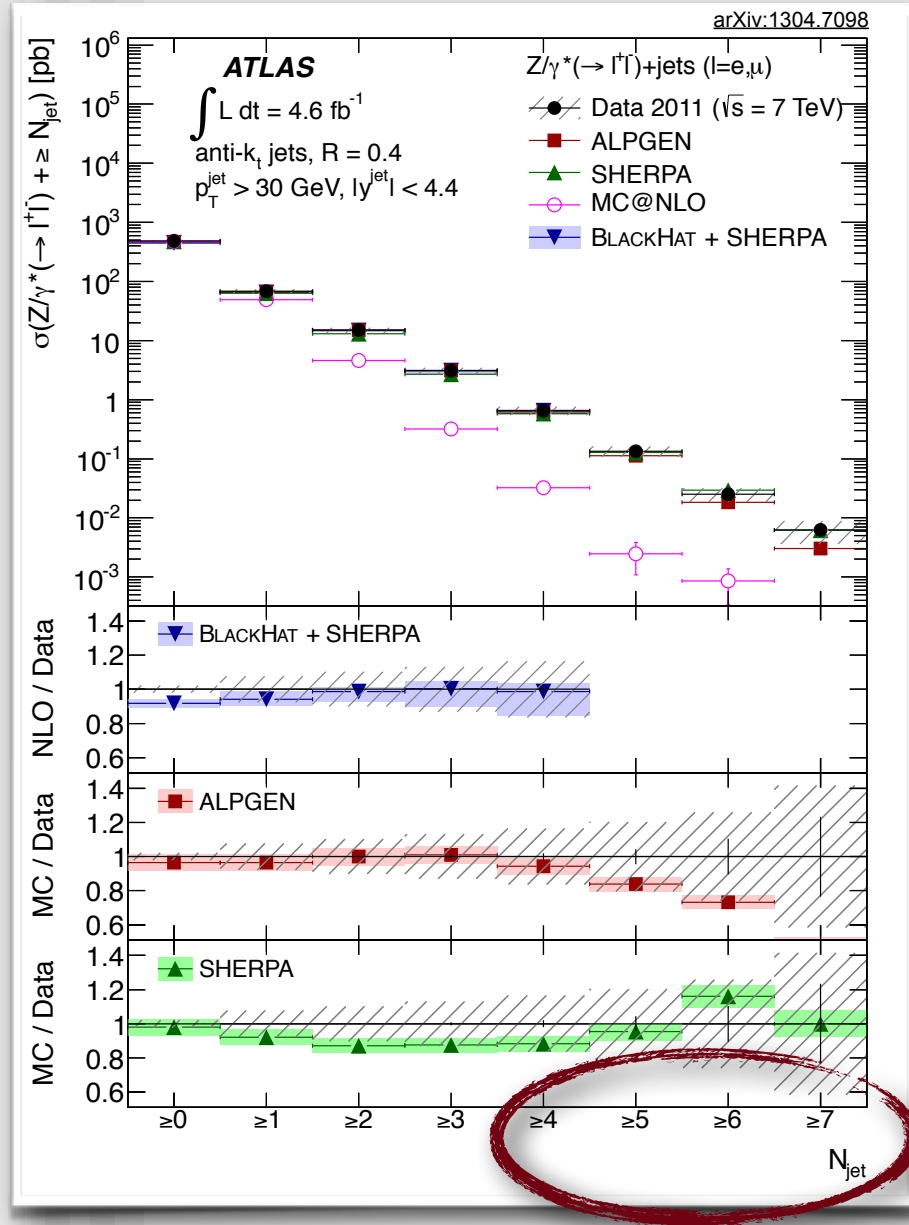
- measured WW xsecs in fully leptonic channel slightly above NLO pred. (by 10-20%, 1-2 sigma)
- differential distributions appear ~ok; similar in CMS...
- is it a significant deviation? some NNLO effect?

A very recent example....

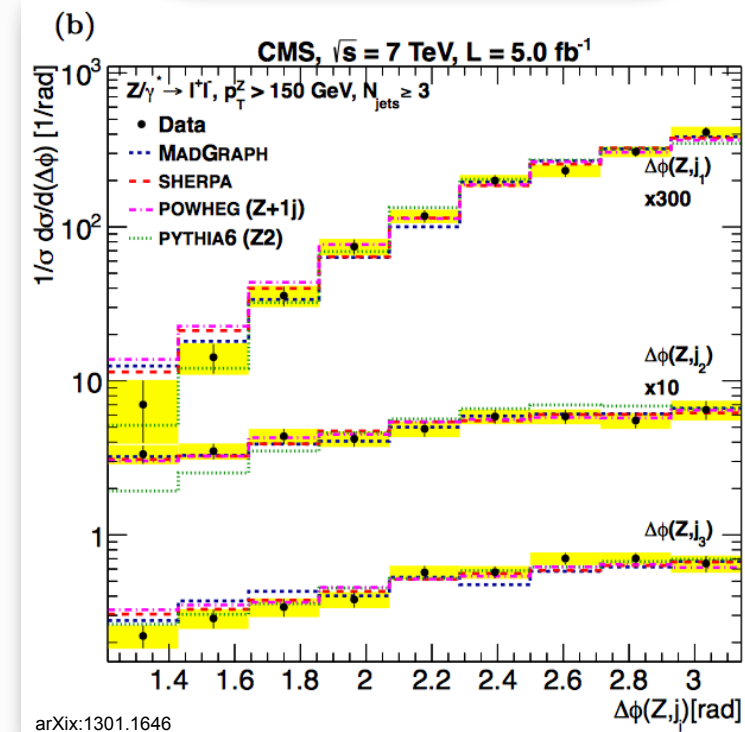


- measured WW xsecs in fully leptonic channel slightly above NLO pred. (by 10-20%, 1-2 sigma)
- differential distributions appear ~ok
- is it a significant deviation? some NNLO effect?
- Very new: recent new CMS measurement, and first NNLO calc. by Gehrmann et al:**
10% increase from NNLO, thus SM ok..... :-)

V + jet production



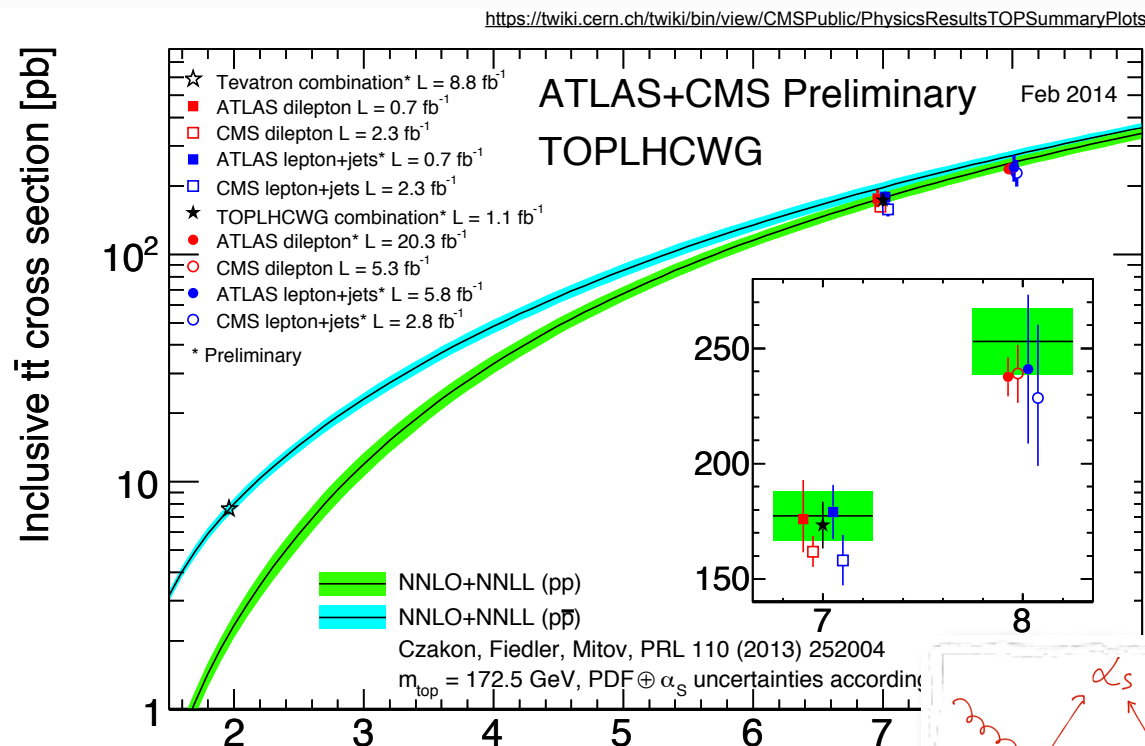
for $Z P_T > 150 \text{ GeV}$



- more and more probing a large phase space, with exp. uncertainties between ~ 5 and 20%
- multiplicities, jet p_T distributions, H_T distributions, angular correlations, incl. or for boosted bosons
- Quite a large playground for testing : fixed-order calculations, LO+PS, NLO+PS, as implemented in different MCs

Determination of fundamental parameters

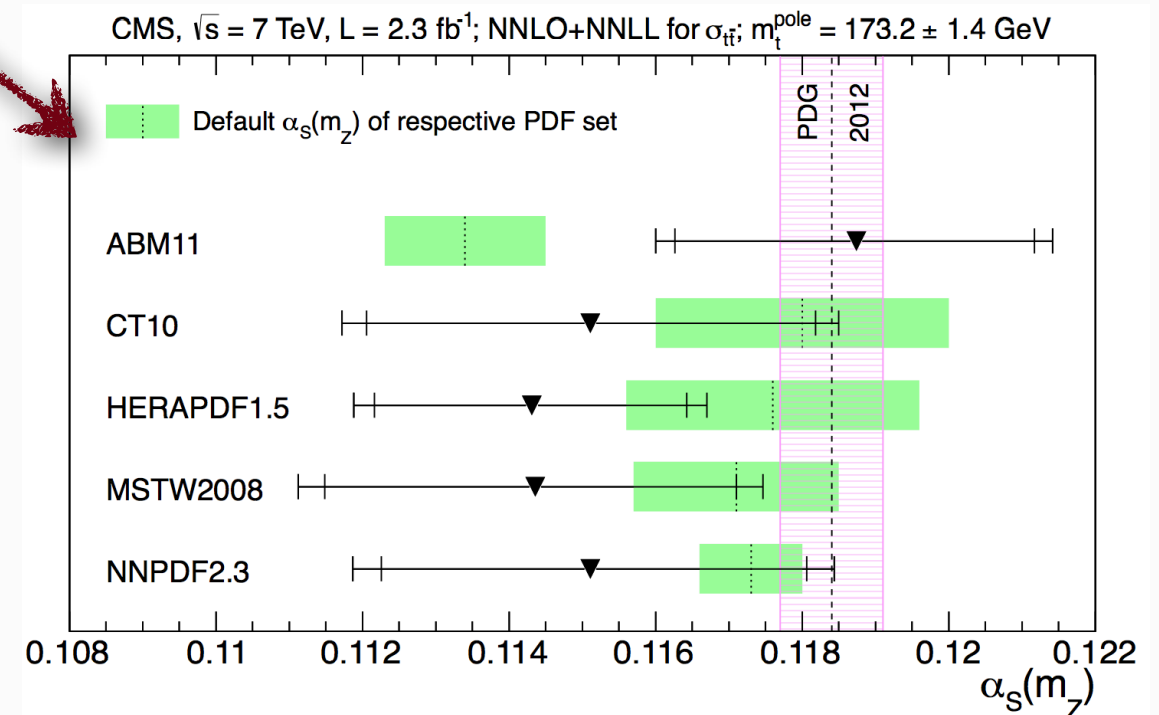
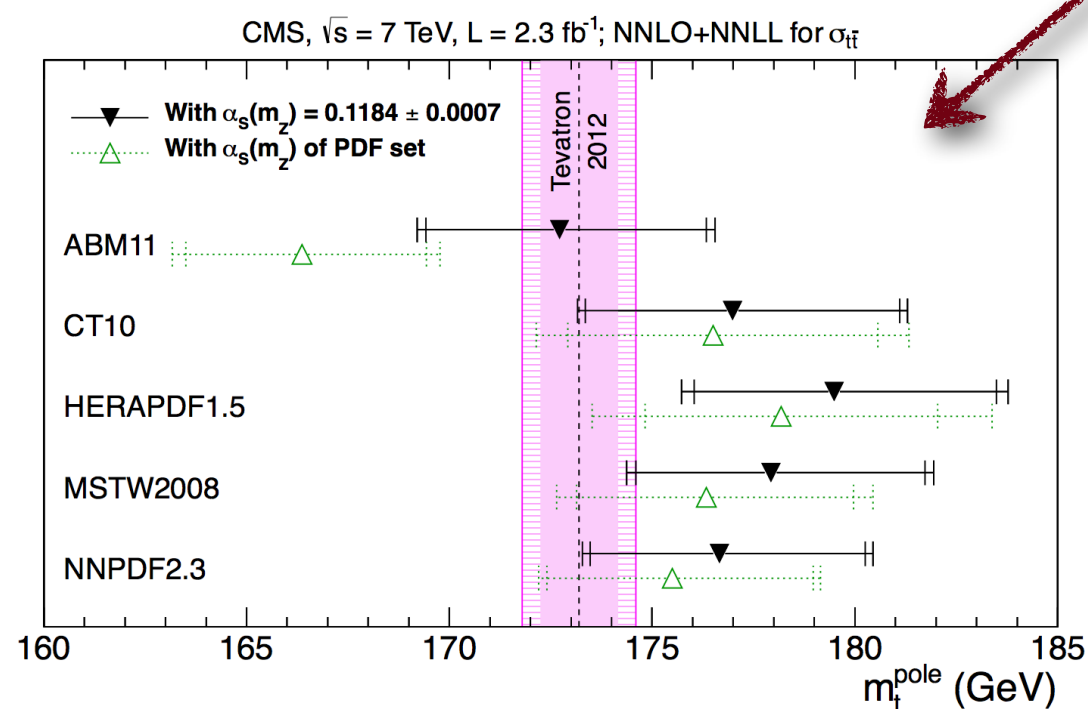
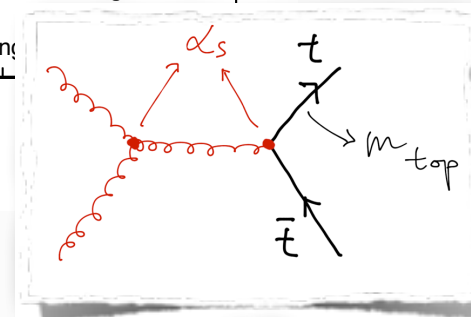
Top pair xsec: strong coupling and m_{top}



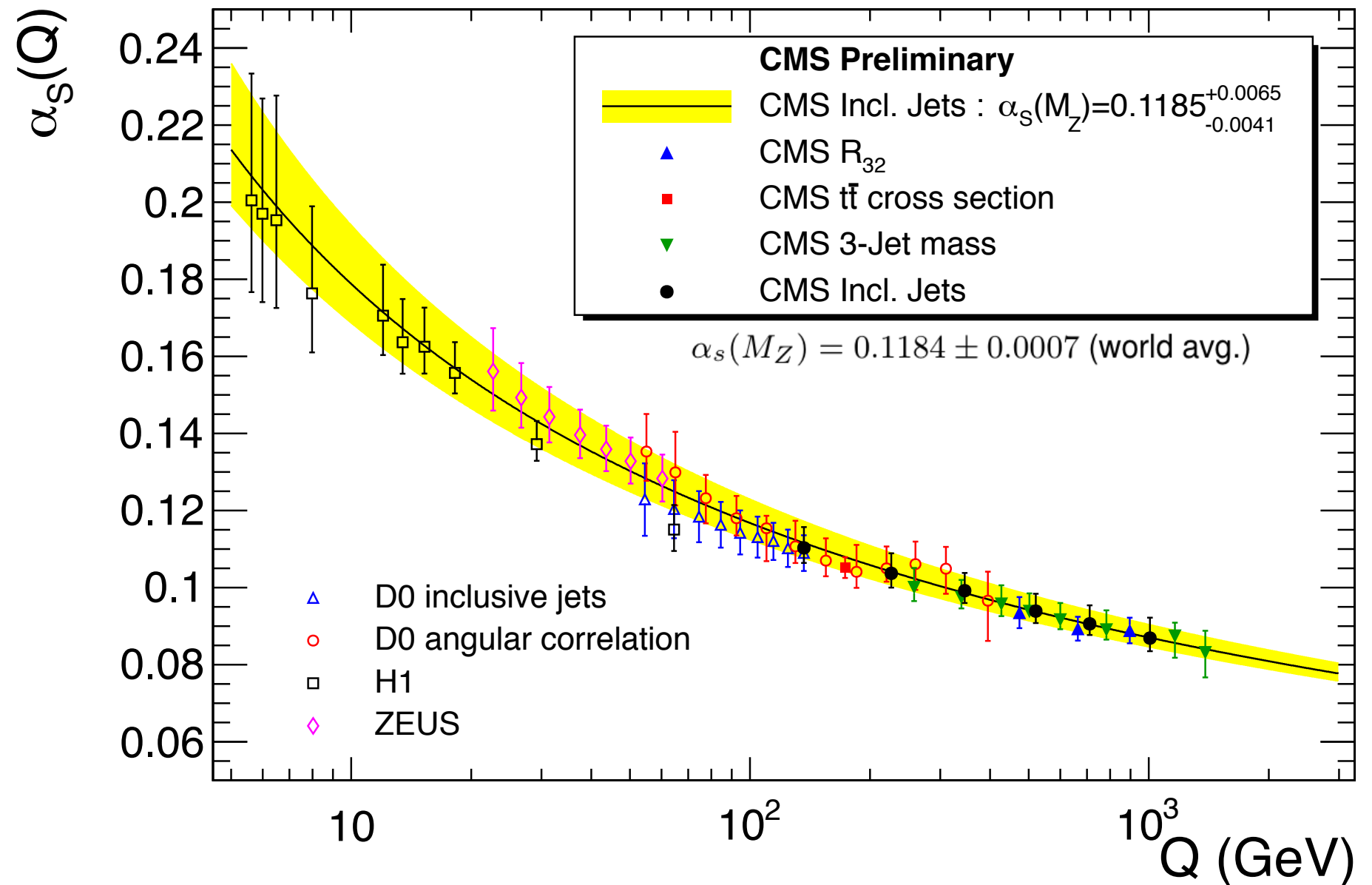
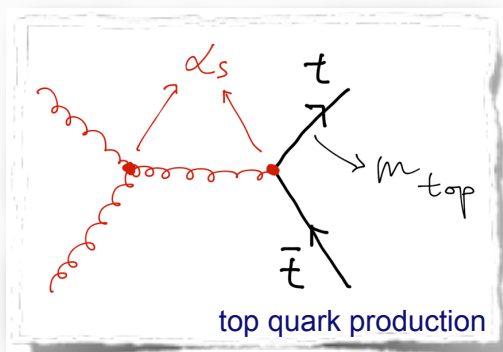
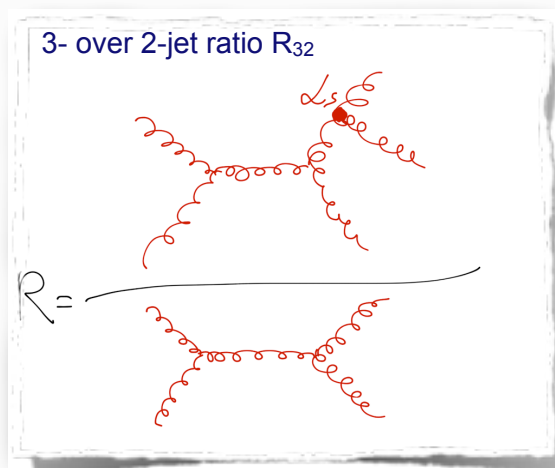
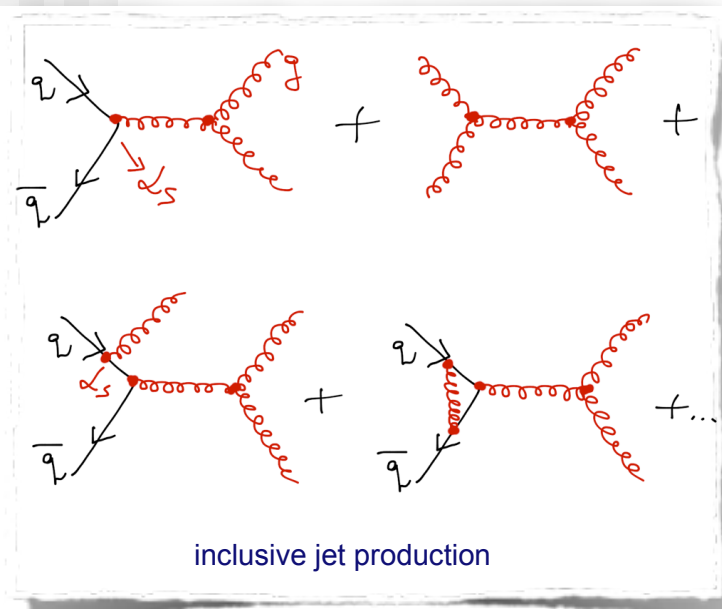
CMS and ATLAS have used very recent NNLO QCD prediction for the top-pair cross section to extract a **precise measurement of** the strong coupling constant (**rel. error 2.6%**) and the top quark pole mass (**abs. error $\sim 2.5 - 3.5 \text{ GeV}$**)

CMS: <http://arxiv.org/abs/arXiv:1307.1907>
 ATLAS: [arXiv:1406.5375](http://arxiv.org/abs/arXiv:1406.5375)

interesting discussion in this context: how and how precisely can one relate this measurement to those from the direct mass determinations (the "MC mass"). See eg. S. Moch at LHCP2014



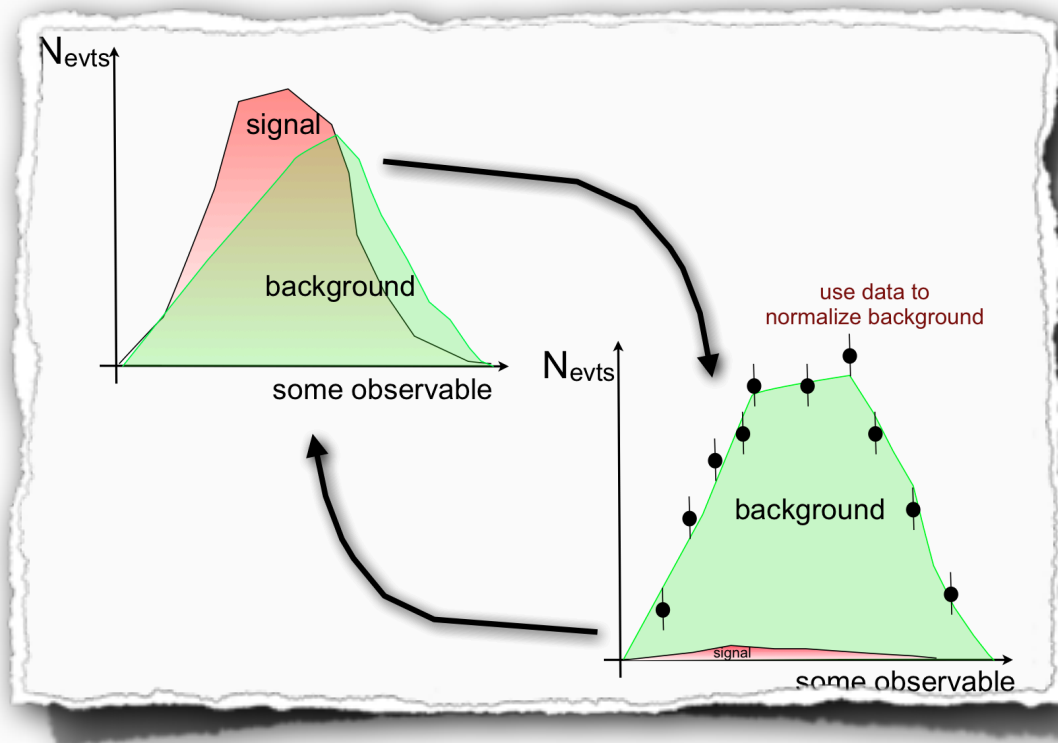
The strong coupling constant



- Quite impressive precision attained already, of similar order than for jets and event shapes at LEP and HERA !
- Future higher-order calculations for two-jet and three-jet production will have an impact....

The case for (clever) ratios

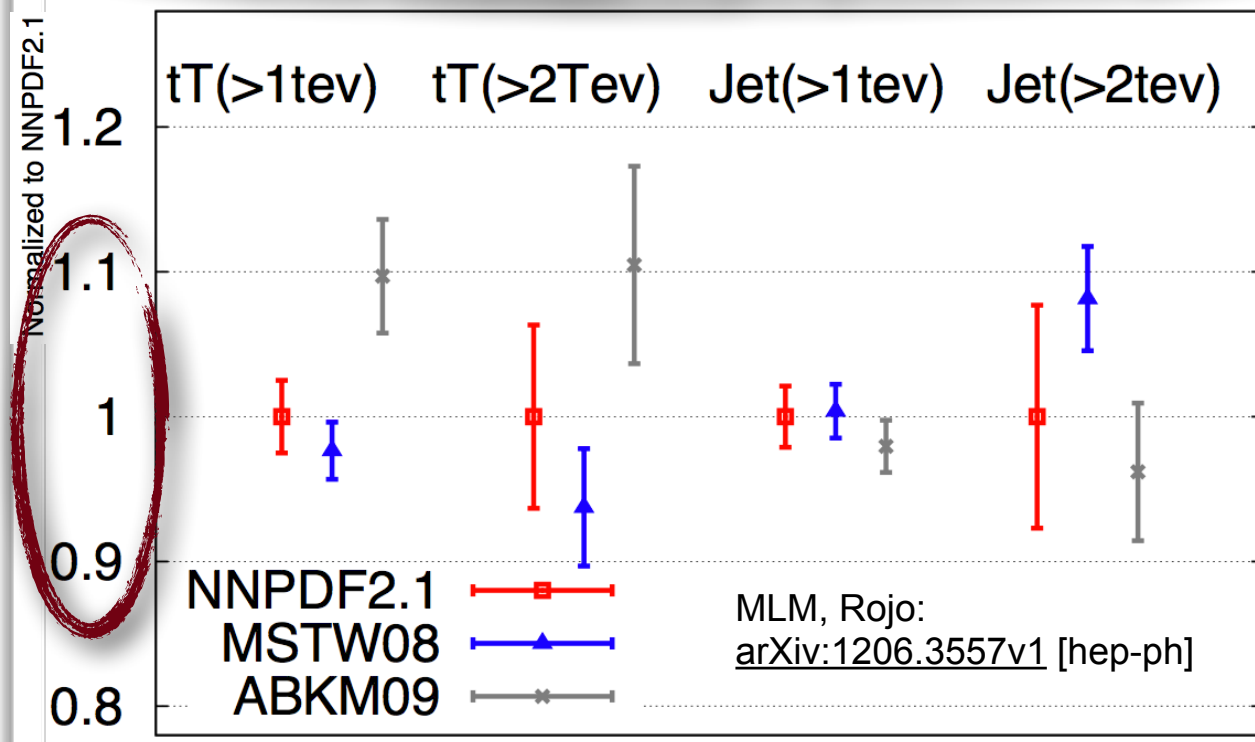
Examples



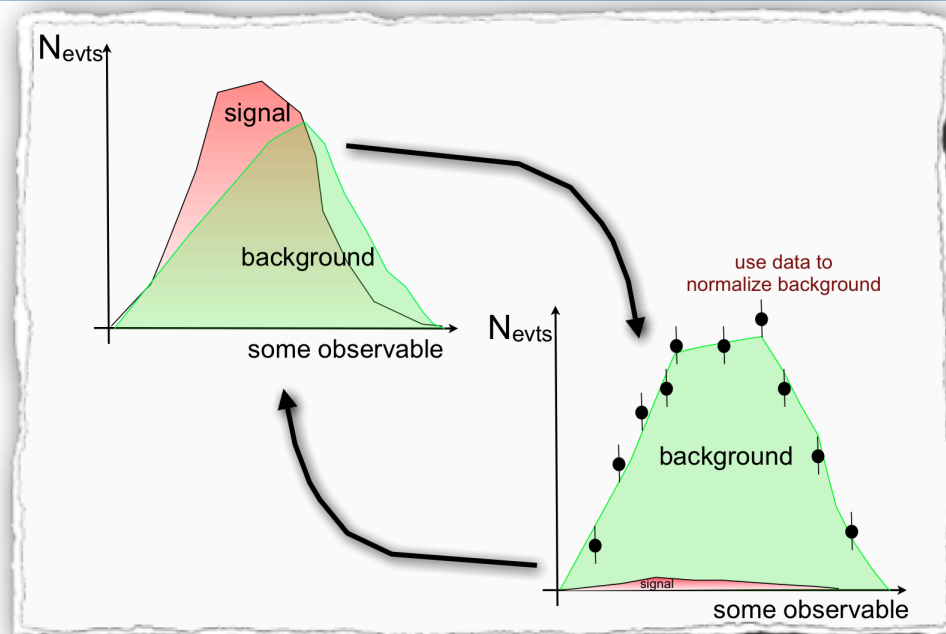
remember this picture?

- eg. 7 and 8 TeV data set as a "gigantic" control region?
- but: the transport by theory from one energy to the next, ie. via a ratio, should be as precise as possible

Cross section Ratios between 14 and 8 TeV



- great potential in ratio observables:**
 - either to obtain %-level (or better) theory predictions, or to constrain PDFs to the % level, over large x-range

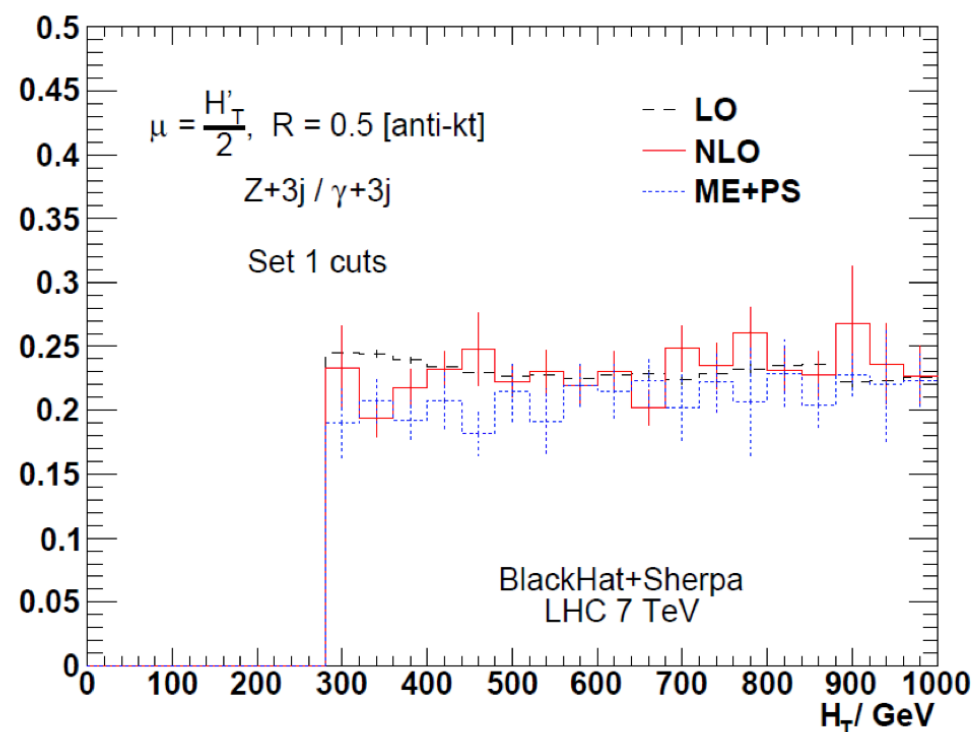


remember this picture?

- eg. in SUSY searches: final states with large jet multiplicities, leptons, MET
- Z+jets, Z to neutrinos, an example of a background
- find signal-free control regions, see below
- but: the transport by theory from one region to the other, ie. via a ratio, should be as precise as possible

The CMS search did **not** estimate Z+jets bkgd from NLO. Instead used

$$\frac{d\sigma^{Z+jets}}{dH_T} = \left(\frac{d\sigma^{\gamma+jets}}{dH_T} \right)_{data} \times \left(\frac{d\sigma^{Z+jets}}{dH_T} / \frac{d\sigma^{\gamma+jets}}{dH_T} \right)_{NLO}$$



Example of widely used **data-driven** bkgd estimates

Combine best of theory knowledge with best of experimental knowledge.

Example from a CMS all-hadronic SUSY search, based on the MT2 variable

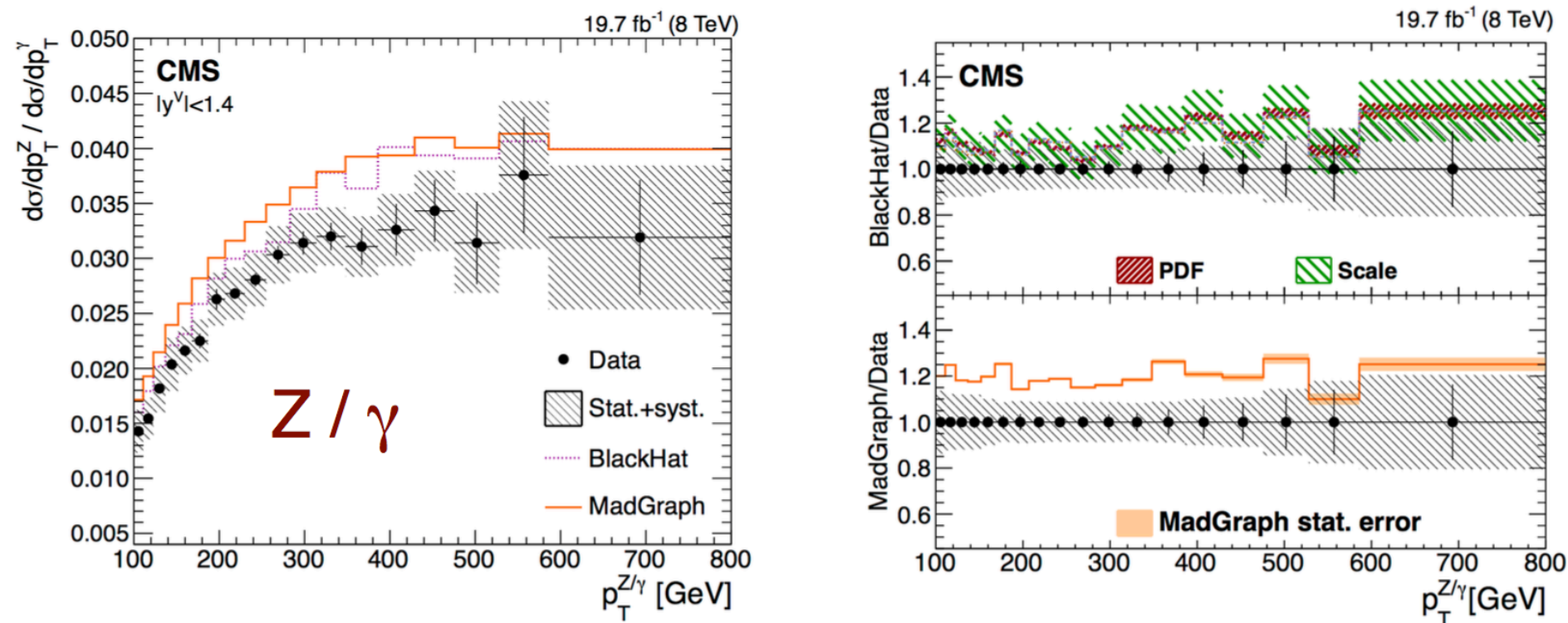
- used photon+jets data to estimate the Z+jets background ([JHEP 10 \(2012\) 018](#))
- and now the Z+jet / photon +jet ratios has also been measured for the first time, by CMS...

Example of a measured ratio

Z+jets/ γ +jets

LO predictions for the ratio vs data off by 20% but flat!

BH prediction (NLO for both processes) are also $\sim 10\%$ larger than data



from V. Ciulli, Les Houches 2015

see [arXiv:1505.06520](https://arxiv.org/abs/1505.06520)

currently being discussed: **importance of EWK corrections?**

And some further examples...

- ratios of W^+/W^- , W/Z , WW/Z cross sections
- 3/2 jet ratio (for measurements of α_s)
- ratios of incl. jet cross sections with different jet sizes
- ratios of incl. jet cross sections at different centre-of-mass energies (eg. used by ATLAS to constrain pdfs)
- I hope you can come up with new, clever, ideas....

The Higgs sector

see more in lectures by Grojean, Stroynowski and Pich

The Higgs sector

Grant overview by M. Klute, LHCP2014

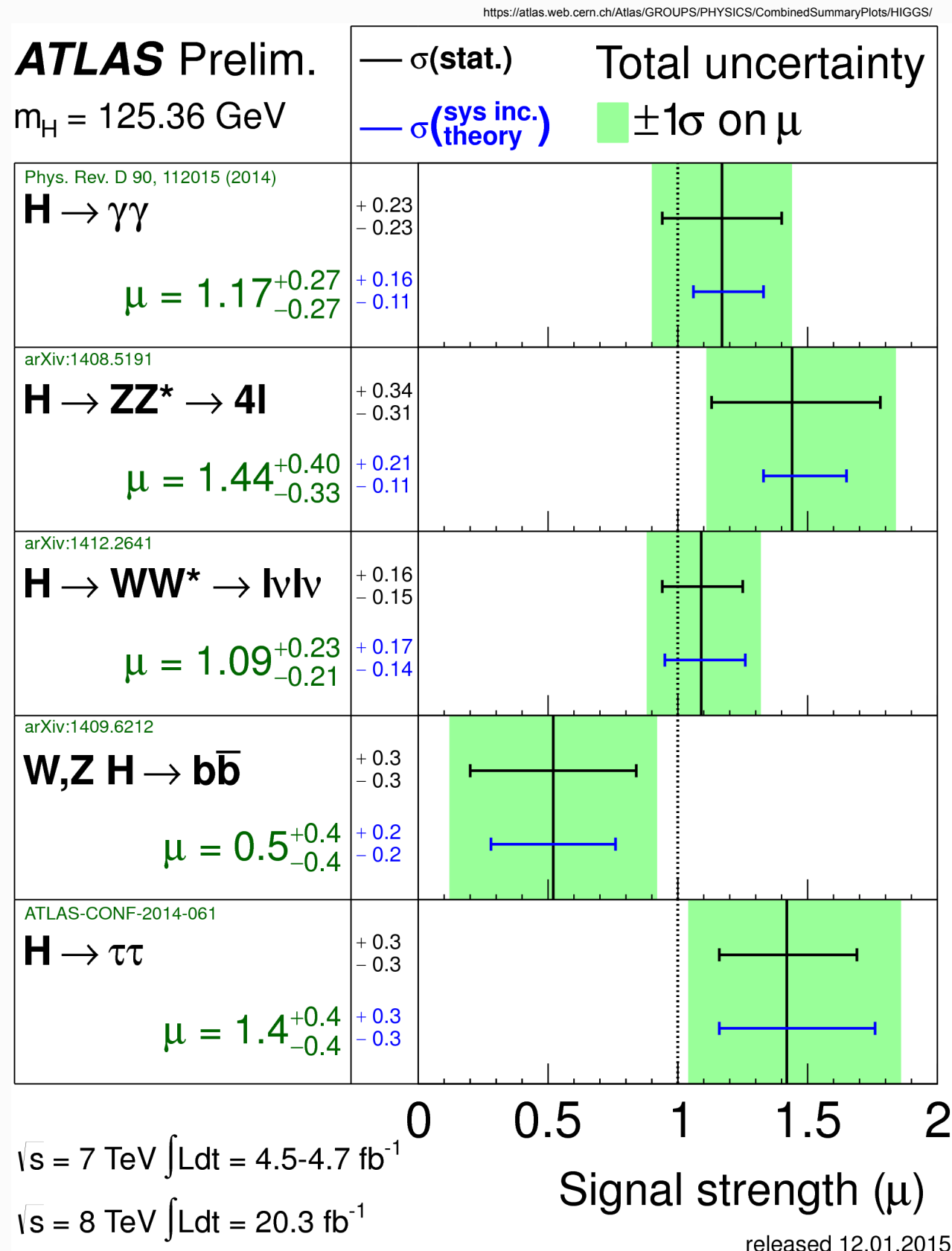
Channel	ATLAS Lumi [1/fb]	CMS Lumi [1/fb]	Specialty	Inclusive signature	σ Obs. (Exp.)	mass [GeV]	Signal Strength μ	Spin/ Parity
$H \rightarrow ZZ \rightarrow 4l$	4.6+20.7 ATLAS-CONF-2013-012	5.1+19.6 arXiv: 1312.5353	mass, discovery , spin/parity	4 leptons	6.6 (4.4) 6.8 (6.7)	124.5 ± 0.5 125.6 ± 0.4 (stat) ± 0.2 (sys)	1.7+0.5-0.4 0.93+0.29-0.25	$\checkmark$ $\checkmark$
$H \rightarrow WW \rightarrow 2l2\nu$	4.6+20.7 ATLAS-CONF-2013-030	4.9+19.5 arXiv: 1312.1129	cross section, coupling	2 leptons, MET	3.8 (3.7) 4.3 (5.8)	consistent 125 ± 4	1.01 ± 0.31 0.72+0.20-0.18	$\checkmark$ $\checkmark$
$H \rightarrow \gamma\gamma$	4.8+20.7 ATLAS-CONF-2013-012	5.1+19.6 CMS-PAS- HIG-13-001	mass, discovery , couplings	two photons	7.4 (4.3) 3.2 (4.2)	126.0 ± 0.5 125.4 ± 0.5 (stat) ± 0.6 (sys)	1.65+0.33-0.28 0.78+0.28-0.26	$\checkmark$ $\checkmark$
$H \rightarrow b\bar{b}$	4.7+20.3 ATLAS-CONF-2013-079	5.0+18.9 arXiv: 1310.3687	total width, coupling to fermions	two b-jets	- 2.1 (2.1)	consistent consistent	0.2 ± 0.7 1.0 ± 0.5	- -
$H \rightarrow \tau\tau$	20.3 ATLAS-CONF-2013-108	4.9+19.4 arXiv: 1401.5041	couplings to leptons	hadronic taus, leptons, MET	4.1 (3.2) 3.4 (3.6)	- 122 ± 7	1.4 + 0.5 - 0.4 0.78 ± 0.27	- -

Signal strengths in individual channels : **30-50% precision**, including **stat**, **exp. syst.** and **theo. syst.**

mass known with precision of **0.2 %** ! 125.09 ± 0.24 ($\pm 0.21 \pm 0.11$) GeV

Let's have closer look, and what about in the future?

Higgs parameters: current precision



Thus, very roughly speaking:

- Stat. uncert ~ exp. uncert. ~ theo. uncert.
- each component ~ 10-20% ,
for better known channels
- Theory: ~ 7-8 % PDF and α_s ; ~ 7-8 % scale

General statement:

precision needed for both background and signal processes. However, while a discovery typically doesn't rely on signal predictions, the later extraction of model parameters, and possible disentangling of models or model classes (ie. not only in the Higgs sector, but for BSM in general) will very much rely also on the precision of signal predictions!

Summary by M. Donega

The first big chunk of work is completed.
We learnt a lot and we got a lot of fun

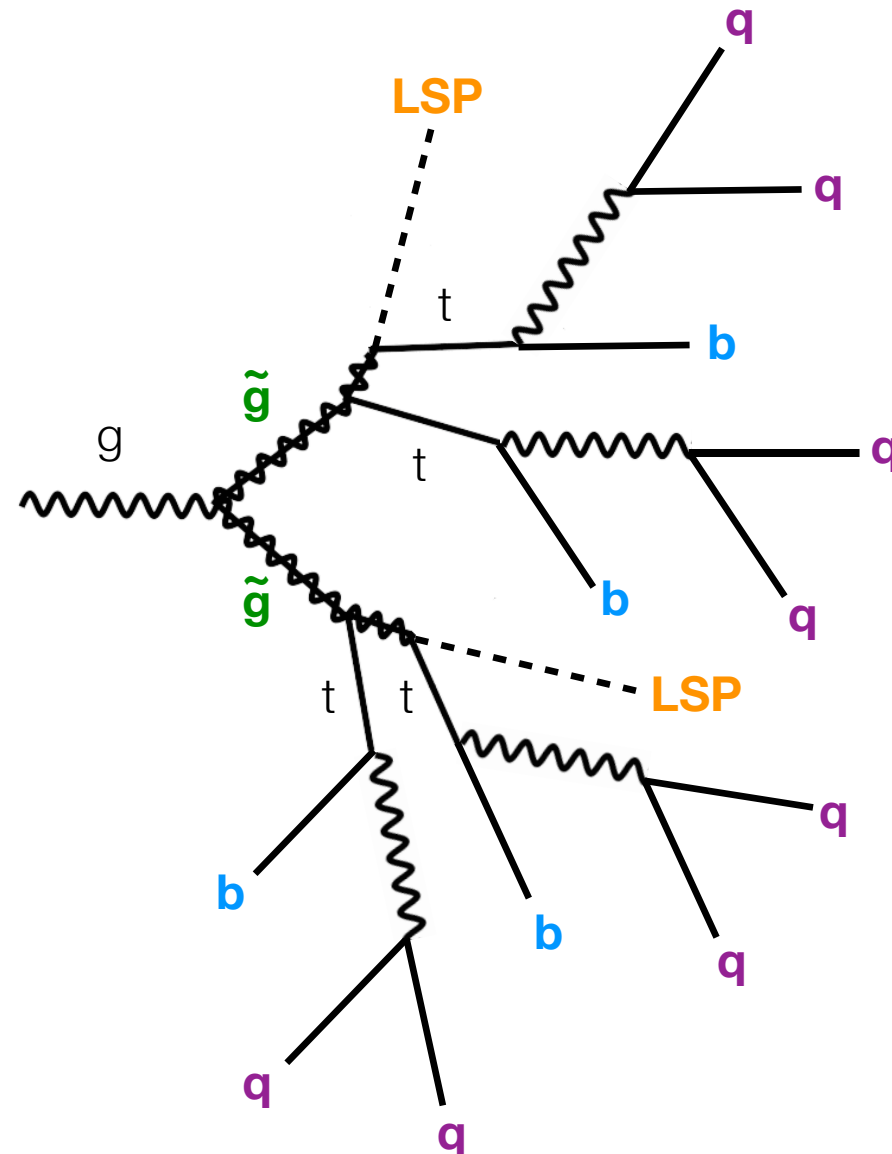
We discovered a new boson and its properties are very close to
what we expect from the SM Higgs boson...

...but sometimes things are not what they look like



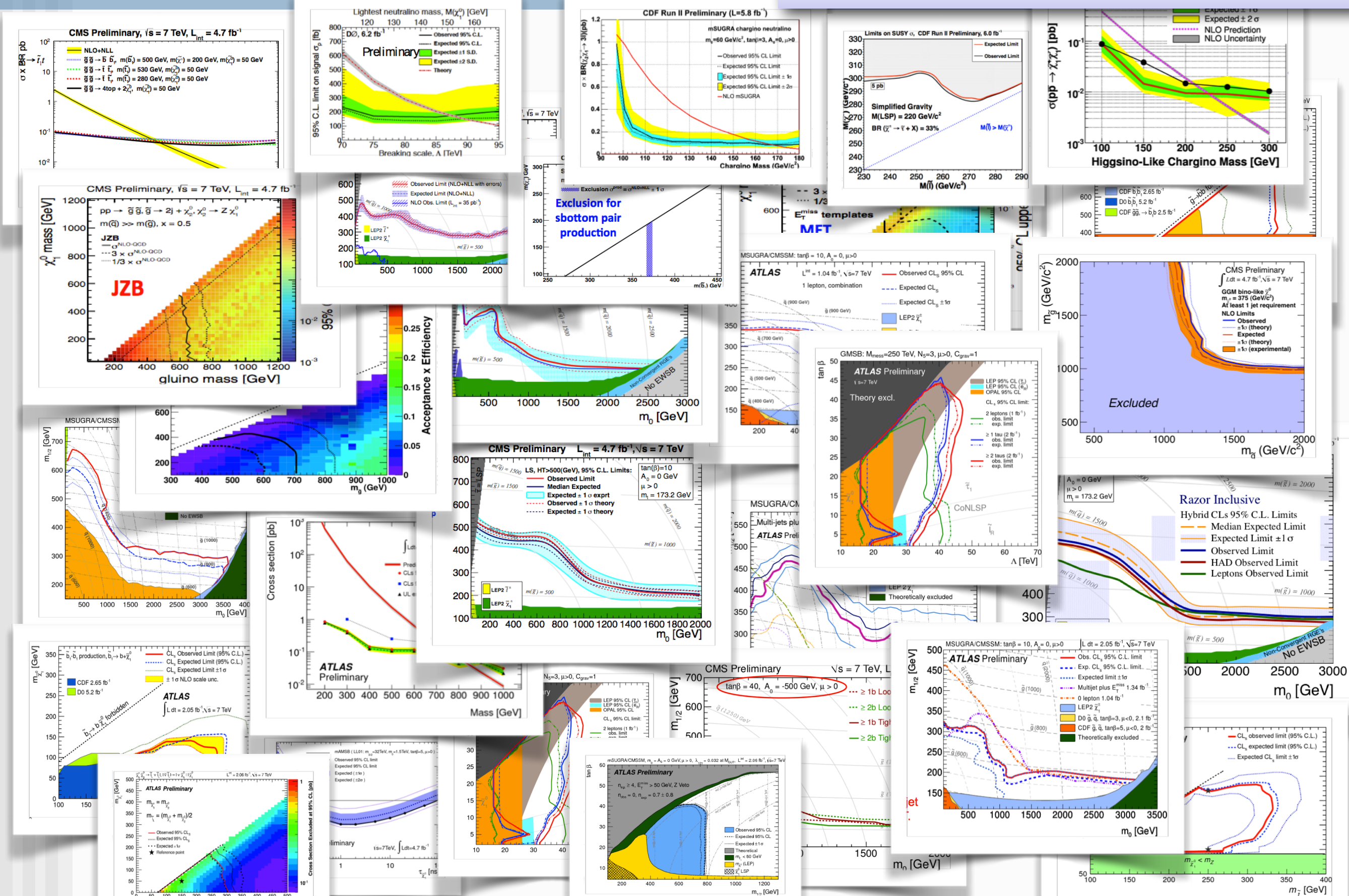
What about searches?

see more in the lectures by Grojean and Kalinowski



ETH Institute for
Particle Physics

eg. exclusions plots shown at Moriond QCD 2012....



This plot really depresses me...

inclusive searches

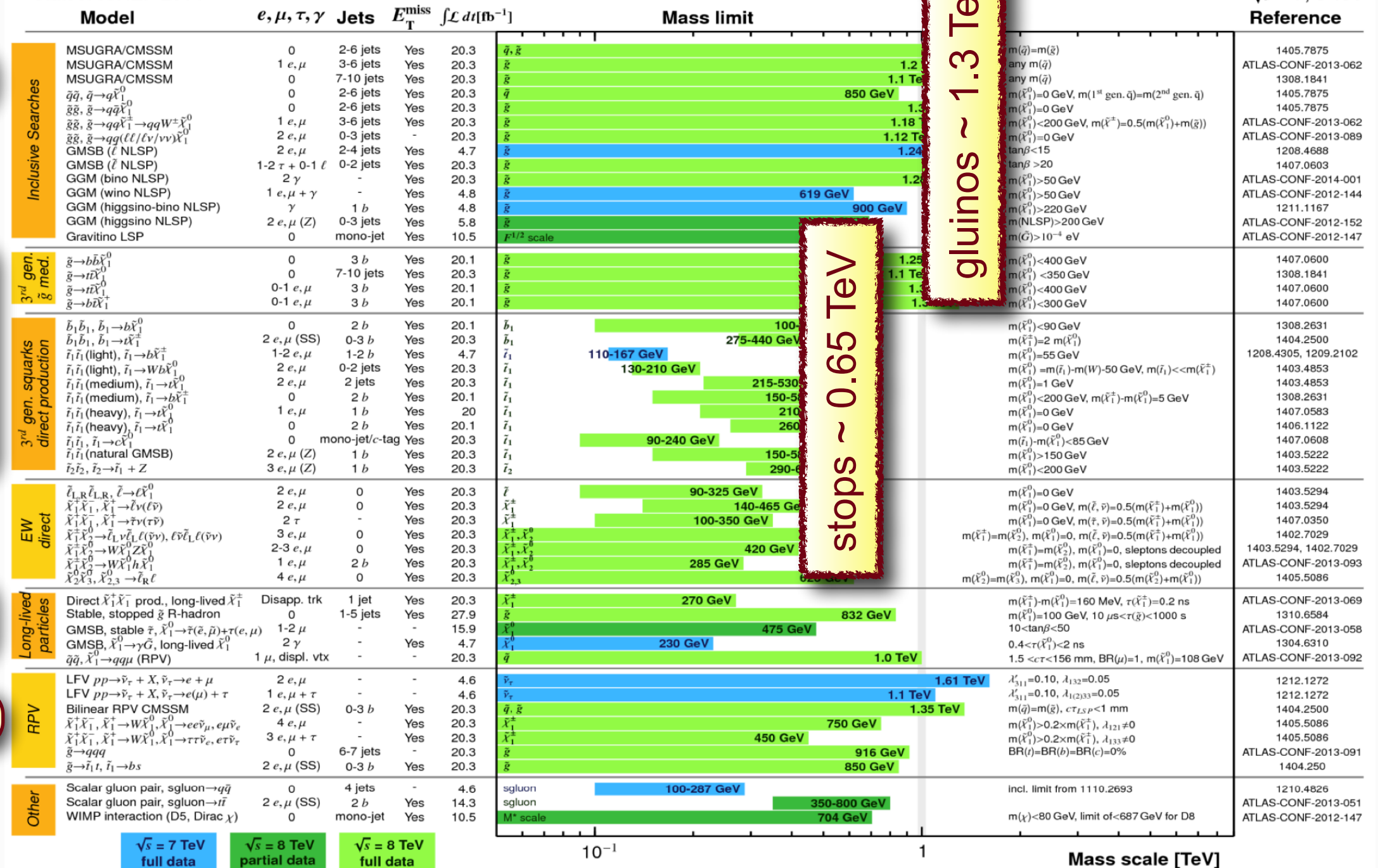
Natural SUSY

long-lived particles, eg. split SUSY

RPV

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

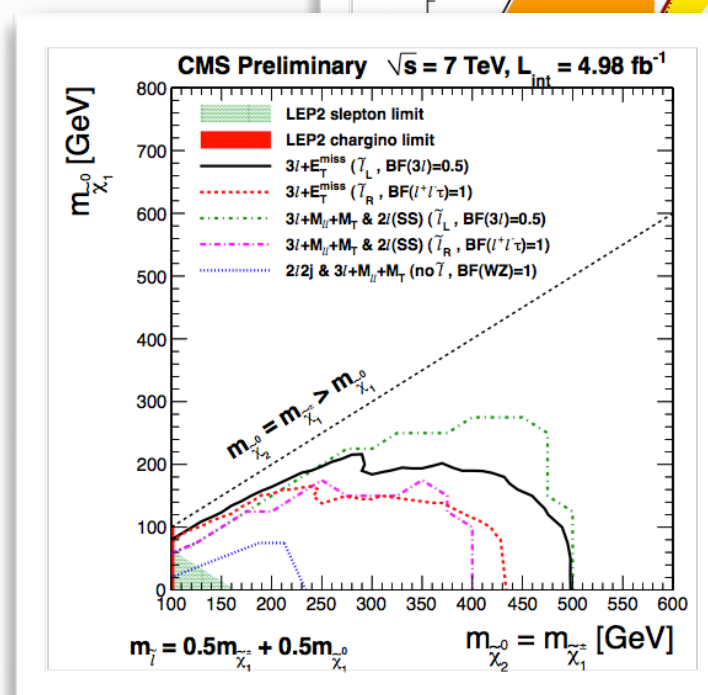
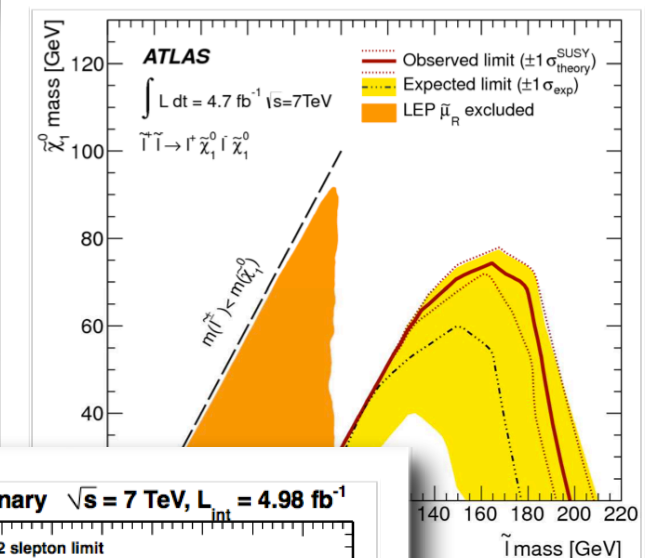
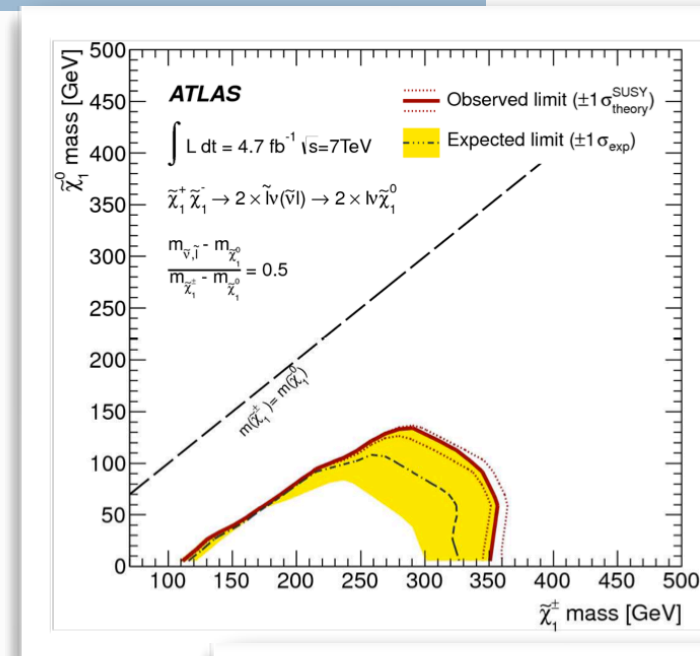


*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

- impressive list, similar plethora of results from CMS
- but: read the fine-print !!
- most of the time, limits are based on (many) assumptions, simplified models

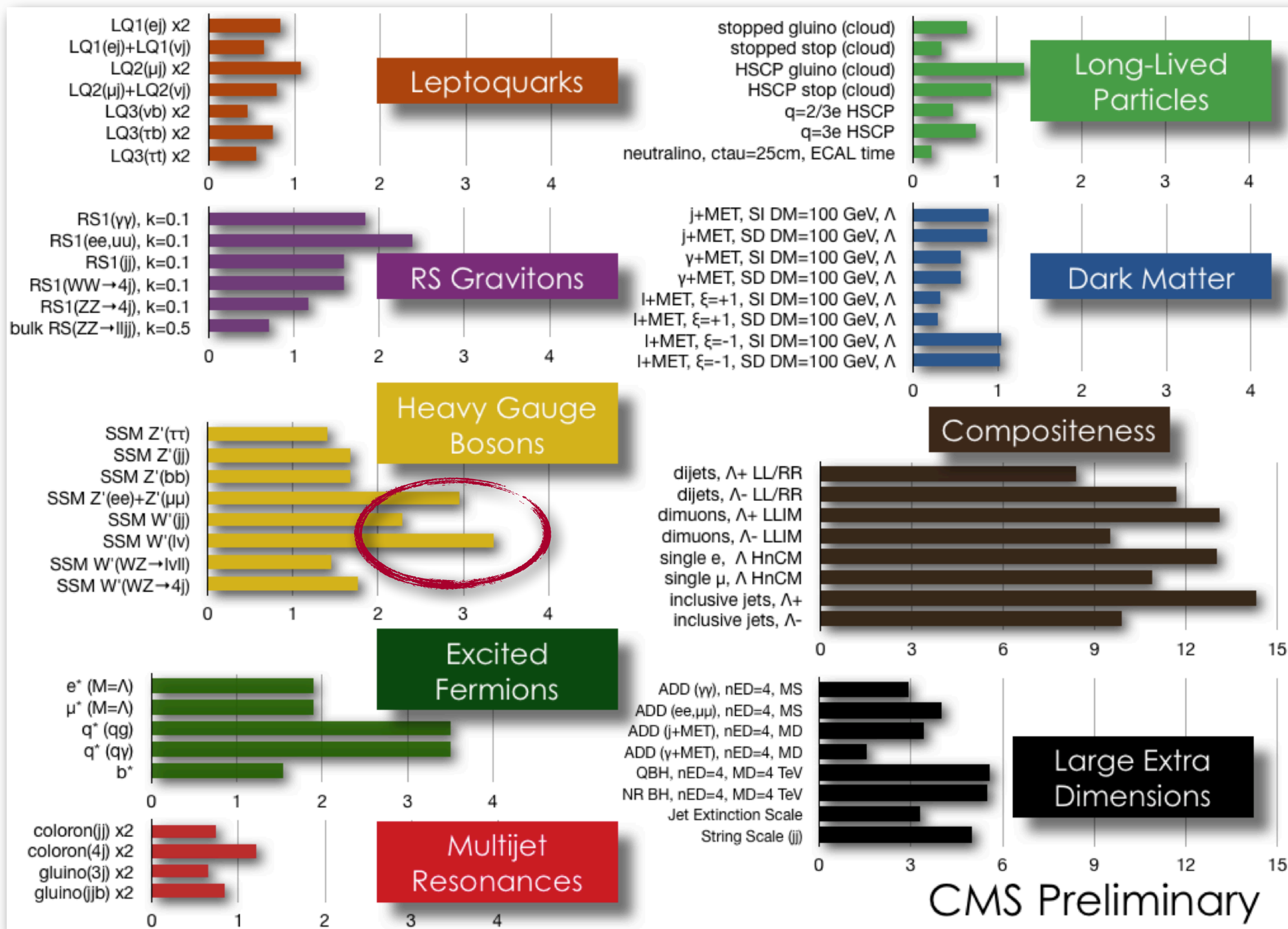
The “IF” files (ie. the fine-print)

- The experiments have already explored a very vast range of masses and parameters
- Though, too early to declare SUSY's death, since there remain important parameter regions to be explored, and because
 - Difficult or impossible to give “absolute” limits, since basically always assumptions involved
 - limits quickly degrade or disappear when raising $m(\text{LSP})$ beyond several hundreds of GeV
 - inclusive searches often assume degenerate 1st and 2nd generation squarks. Limits decrease (by several hundreds of GeV) if this is given up
 - simplified models make strong assumptions on branching ratios, masses of intermediate states
 - theory uncertainties (cross sections/scales/pdfs, initial state radiation)



Exotica: Executive summary

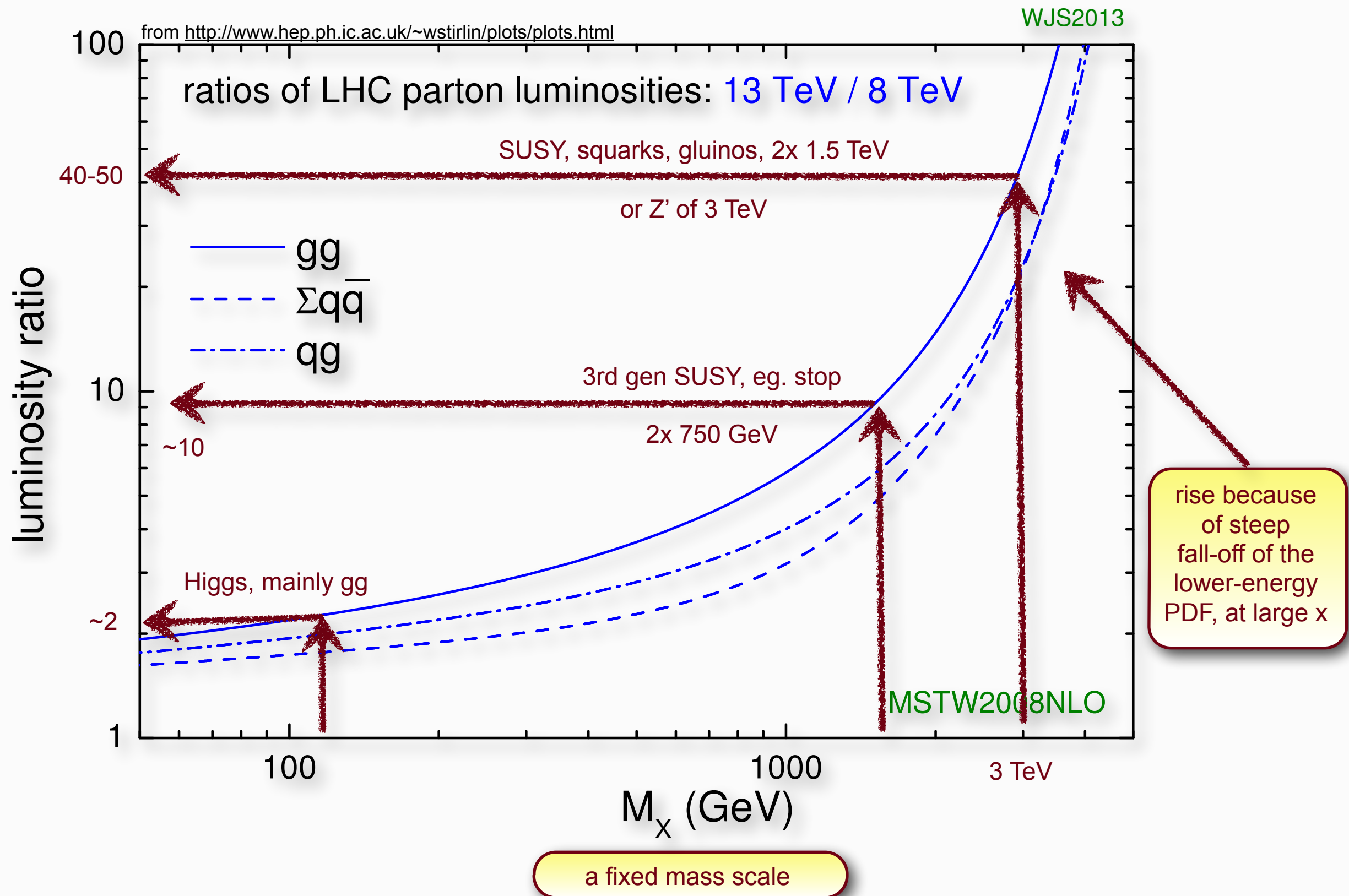
also this plot depresses me...



Our milestones:

1. Why do ATLAS and CMS look like they look like today?
2. Tools used in the analyses
3. Some highlights, and comments
- 4. What next?**

Parton luminosities



Well, this is another possibility

- We all hope for “easy” smoking-gun discoveries during Run 2.
- BSM constraints obtained in run 1 will be washed out within a few fb^{-1} , opening the road for possible 5σ discoveries by late 2015 or 2016.
- If that doesn't happen, after that it'll be blood and sweat, and discoveries will rely more and more on the detailed modeling of the dynamics of pp collisions (see e.g. the Higgs observation at the tevatron)
- So, if no quick discovery in run 2, the rest of the programme will have to focus on precision

(M.L. Mangano CMS Week Dec'13)

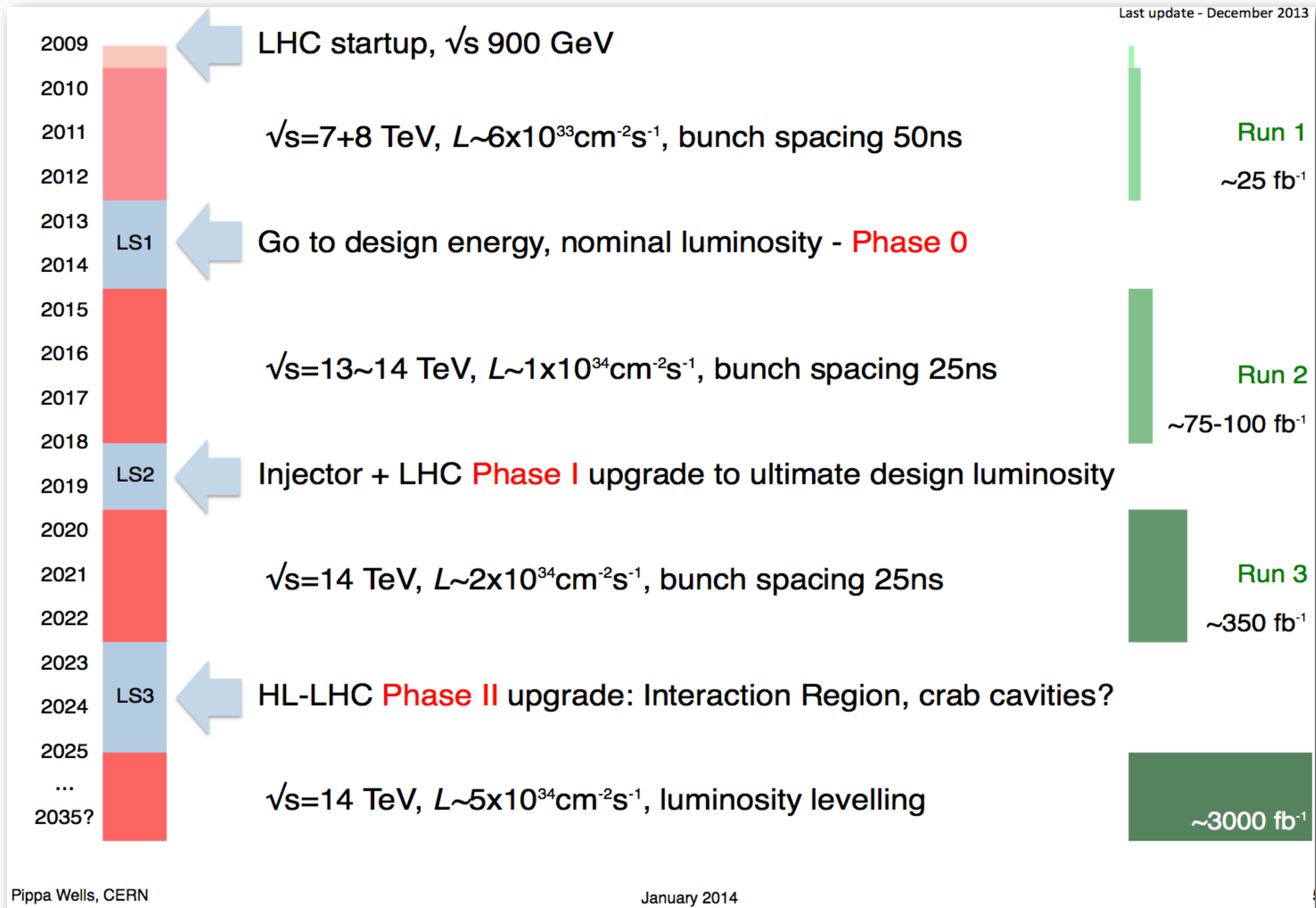


Oswaldo Guayasamín "Lágrimas de sangre" (1973)

"In football as in watchmaking, talent and elegance mean nothing without rigour and precision."
particle theory
[Lionel Messi]

The future

So far: only ~1% (?) of the foreseen data registered and analyzed....



Conclusion

LHC Page1

Fill: 3819

E: 6500 GeV

t(SB): 00:12:50

03-06-15 10:53:23

PROTON PHYSICS: STABLE BEAMS

Energy:

6500 GeV

I(B1):

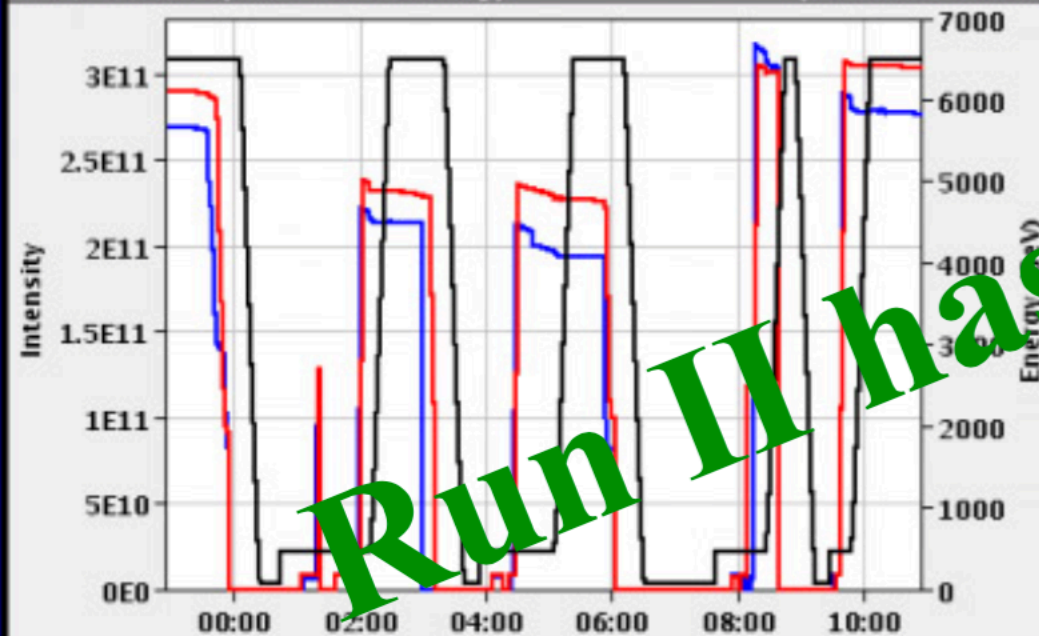
2.94e+11

I(B2):

2.94e+11

FBCT Intensity and Beam Energy

Updated: 10:53:22



Instantaneous Luminosity

Updated: 10:53:20



BIS status and SMP flags

B1

B2

Comments (03-Jun-2015 10:48:25)

the LHC is back in business!
(all IPs optimized)

Link Status of Beam Permits

false

false

Global Beam Permit

true

true

Setup Beam

false

false

Beam Presence

true

true

Moveable Devices Allowed In

true

true

Stable Beams

true

true

AFS: Single_3b_2_2_2_with_nc_probes

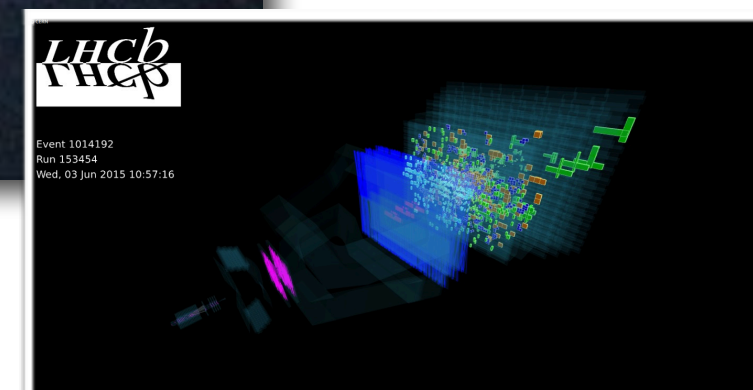
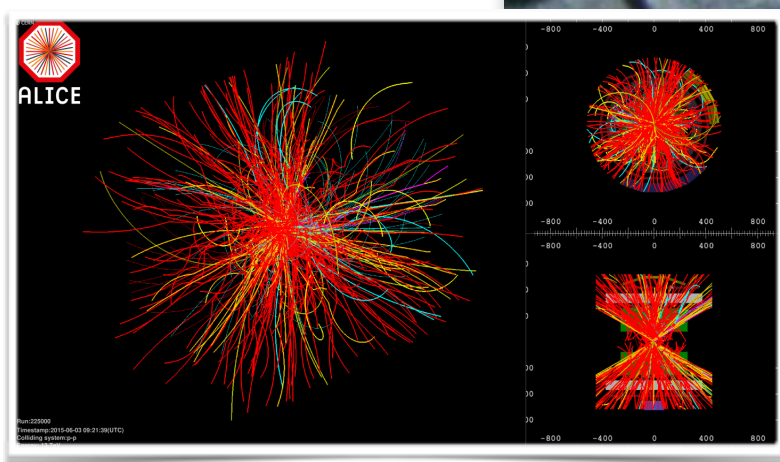
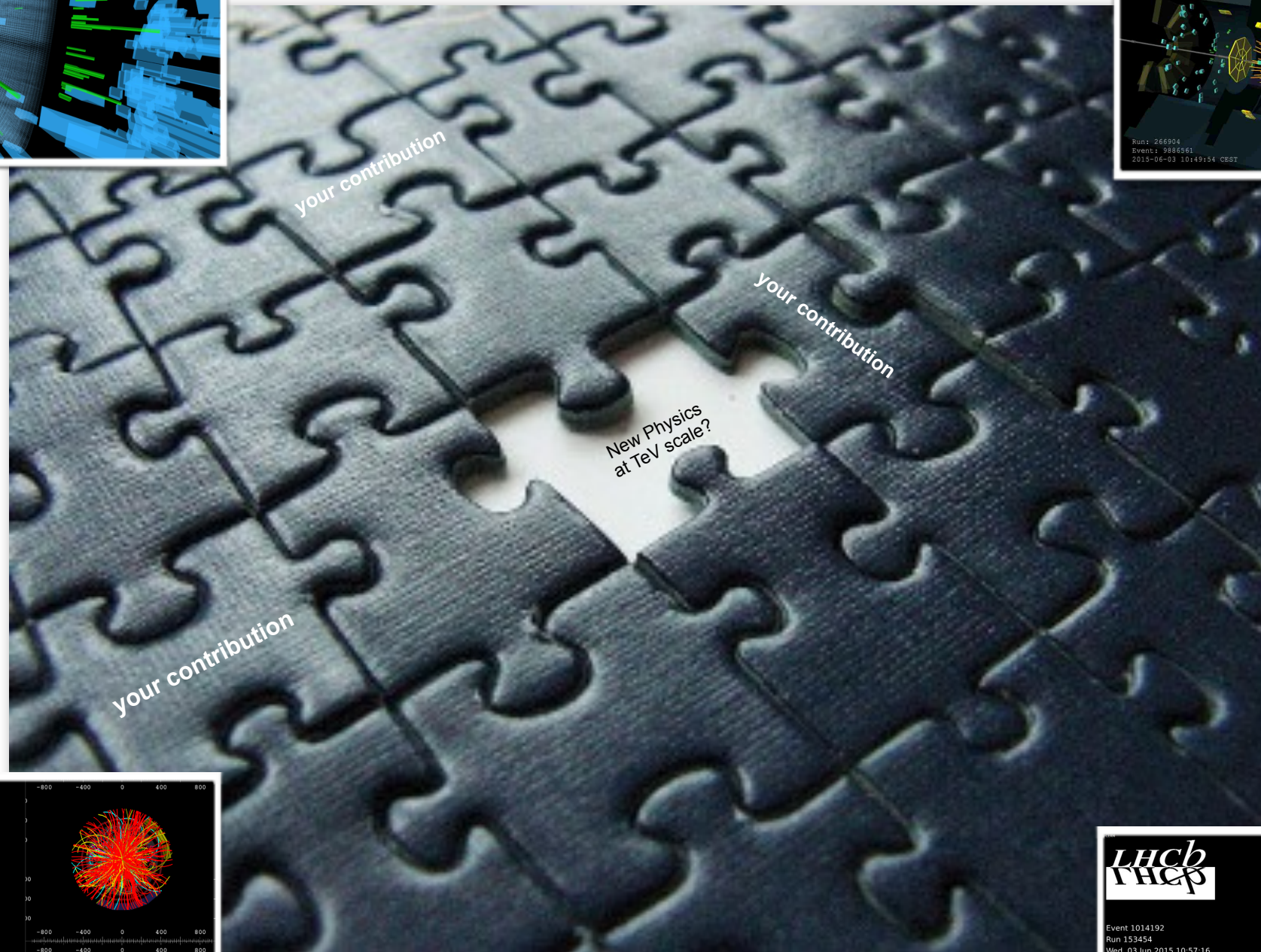
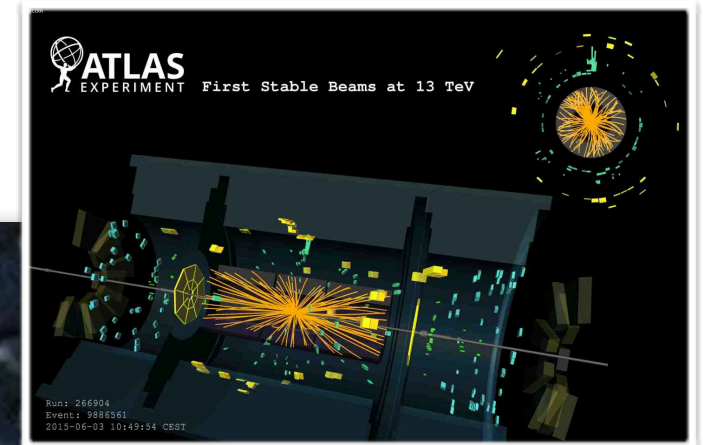
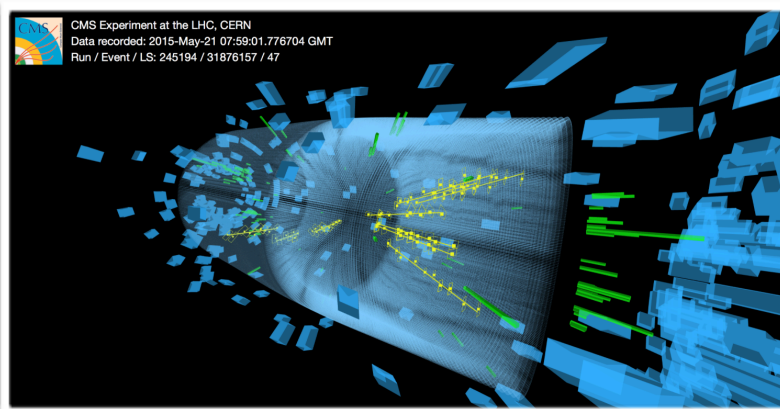
PM Status B1

ENABLED

PM Status B2

ENABLED

Summary



Doing something ordinary is a waste of time.

Madonna

Where to look....

Recent (big) conferences:

- ICHEP2014 : <http://ichep2014.es>
- LHCP 2014 : <http://www.bnl.gov/lhcp2014/>
- Physics at the LHC and beyond, Vietnam, 2014:
<http://events.lal.in2p3.fr/Physics-LHC-2014/>
- Rencontres de Moriond in 2015: <http://moriond.in2p3.fr>
- or the upcoming big confs (EPS-HEP, Lepton-Photon)

Of course, the experiment's websites:

- <https://twiki.cern.ch/twiki/bin/view/AtlasPublic>
- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>
- <http://lhcb.web.cern.ch/lhcb/Physics-Results/LHCb-Physics-Results.html>
- <https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults>

Review articles, such as

- Dissertori, *LHC detectors and early physics*, <http://inspirehep.net/record/848687?ln=en>
- Butterworth, Dissertori, Salam, Hard Processes in pp collisions at the LHC, <http://inspirehep.net/record/1087377?ln=en>
- J. Ellis, *Theory Summary and prospects*, <http://inspirehep.net/record/1312173?ln=en>
- D. Froidevaux, P. Sphicas, Ann. Rev. Nucl. Part. Sci. 56 (2006) 375
- T. Carli, K. Rabbertz, S. Schumann, *Studies of QCD at the LHC*, [arXiv:1506.03239](https://arxiv.org/abs/1506.03239)
- P. Bechtle, T. Plehn, C. Sander, The Status of Supersymmetry after the LHC Run 1, [arXiv:1506.03091](https://arxiv.org/abs/1506.03091)
- of course, there are many more on the market....