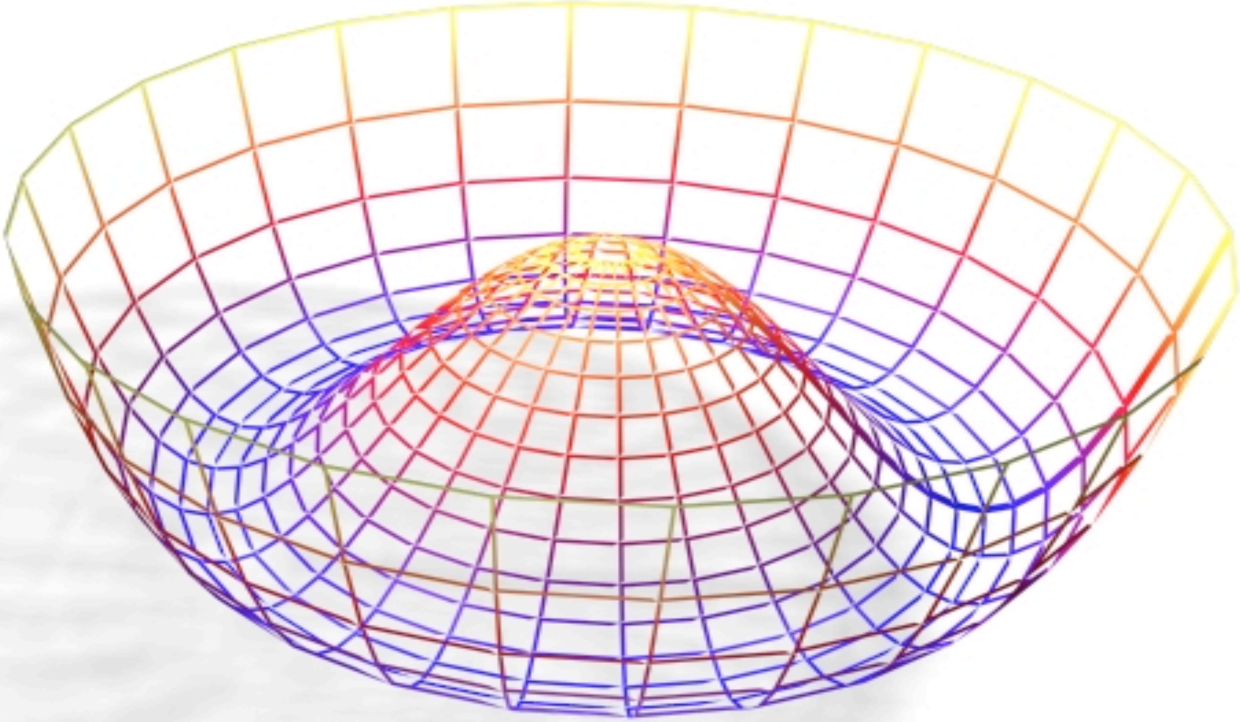
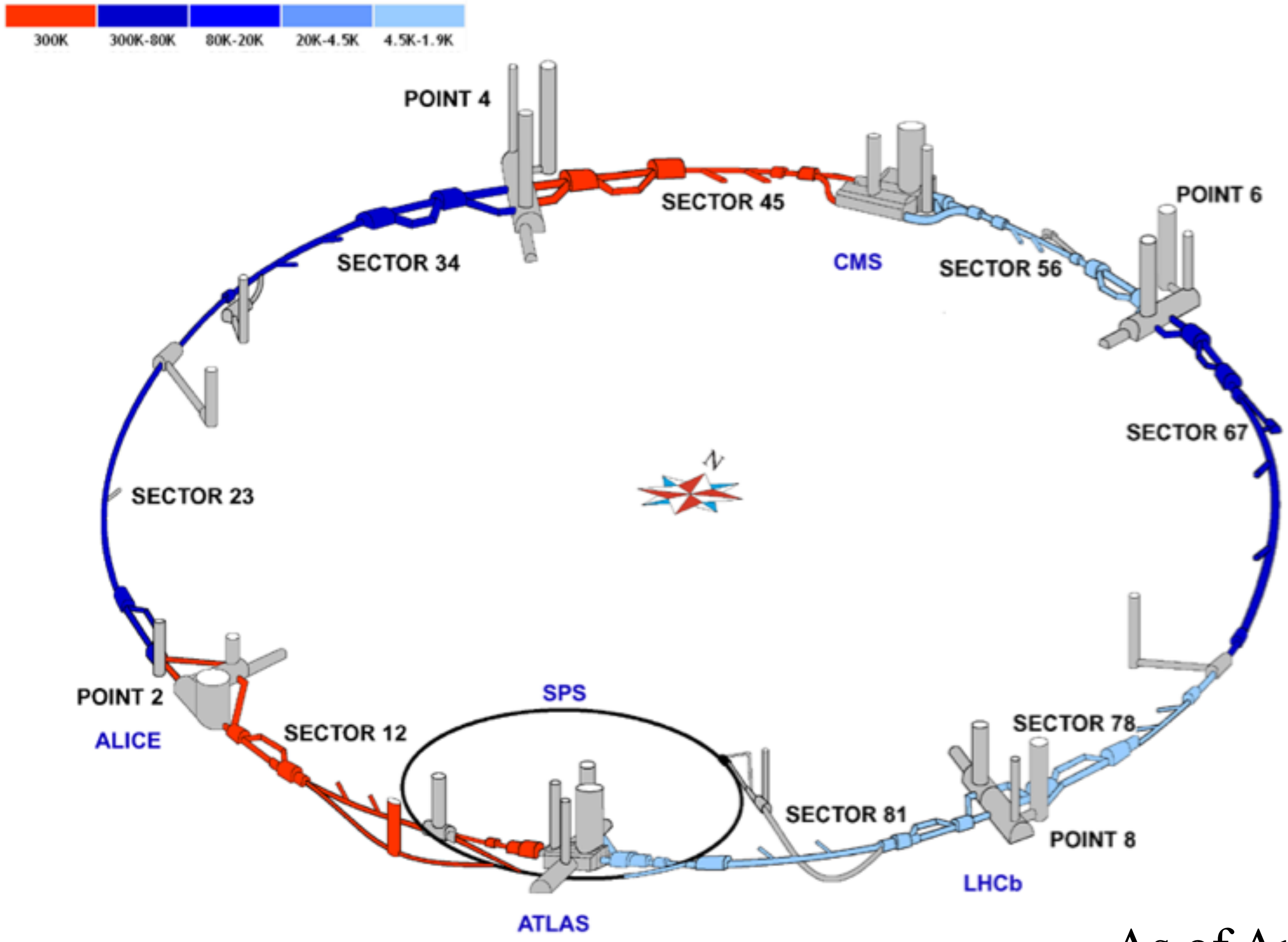
LHC: The Early Phase



Kyle Cranmer
New York University

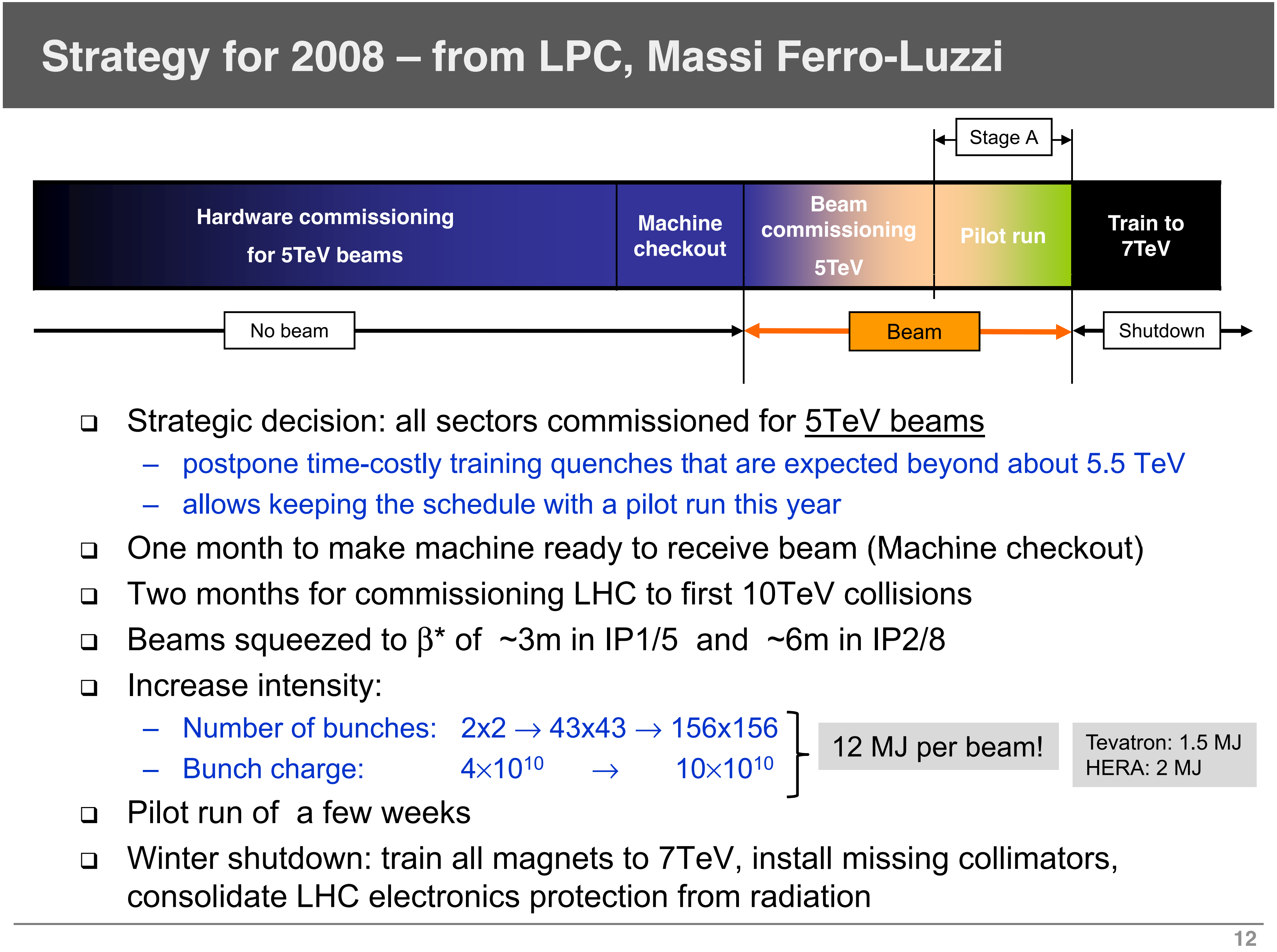
LHC cool down

LHC magnets must be cooled down to 1.9 K, which takes several weeks per sector. Expected to be cold by mid June.



As of April 29

The Party Line



Strategy for 2008 – from LPC, Massi Ferro-Luzzi

Stage A

Hardware commissioning for 5TeV beams | Machine checkout | Beam commissioning 5TeV | Pilot run | Train to 7TeV

No beam | Beam | Shutdown

- ❑ Strategic decision: all sectors commissioned for <u>5TeV beams</u>
  - – postpone time-costly training quenches that are expected beyond about 5.5 TeV
  - – allows keeping the schedule with a pilot run this year
- ❑ One month to make machine ready to receive beam (Machine checkout)
- ❑ Two months for commissioning LHC to first 10TeV collisions
- ❑ Beams squeezed to β^* of ~3m in IP1/5 and ~6m in IP2/8
- ❑ Increase intensity:
  - – Number of bunches: 2x2 → 43x43 → 156x156
  - – Bunch charge: 4×10^{10} → 10×10^{10}

12 MJ per beam!

Tevatron: 1.5 MJ
HERA: 2 MJ

- ❑ Pilot run of a few weeks
- ❑ Winter shutdown: train all magnets to 7TeV, install missing collimators, consolidate LHC electronics protection from radiation

Further details

Start "Physics" with first 10 TeV collisions

  2x2, i.e. 2 bunches on 2 bunches, each experiment sees 1 colliding pair

Optics squeezed as much as efficiently possible

  about 3m in IP1 and IP5

  about 6m in IP2 and IP8 (due to missing TCTVB collimators)

Interleave "Physics" with machine developments to increase luminosity

  push bunch charges: 4 10^{10} 10^{11} protons/bunch

  push number of bunches: 43x43, then 156x156

zero external crossing angle

Target luminosities (for 10^{11} protons per bunch):

Scheme	Lumi at IP1 and IP5
2x2	4.2 10^{29} cm^{-2} s^{-1}
43x43	1.8 10^{31}
156x156	6.6 10^{31}

← Pileup could be relevant

If time allows, interleave "Physics" periods with machine "explorations" for 2009

  crossing angle, 25 to 75 ns bunch spacing

The near future

Very difficult to say anything definitive about what might happen this year (both accelerator and detectors)

LHC is a proton (no anti-protons) machine, so several luminosity problems are not an issue

I am cautiously optimistic

Detectors at Startup

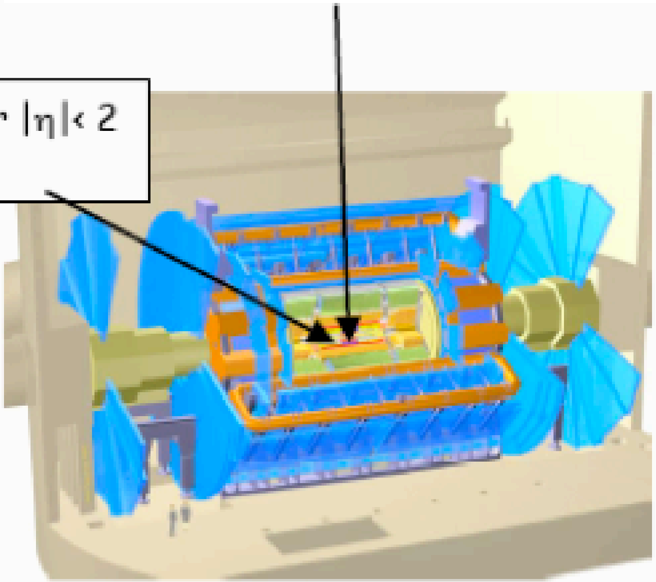
❷ Which detectors the first year ?

RPC over $|\eta|<1.6$ (instead of $|\eta|< 2.1$)
4th layer of end-cap chambers missing

Pixels and end-cap ECAL
installed during first shut-down

Detectors progressing well and
will be fairly complete at start-up

TRT acceptance over $|\eta|< 2$
(instead of $|\eta|< 2.4$)



Both experiments:
deferrals of high-level Trigger/DAQ processors
→ LVL1 output rate limited to
~ 50 kHz CMS (instead of 100 kHz)
~ 40 kHz ATLAS (instead of 75 kHz)

De Roeck, Wine & Cheese

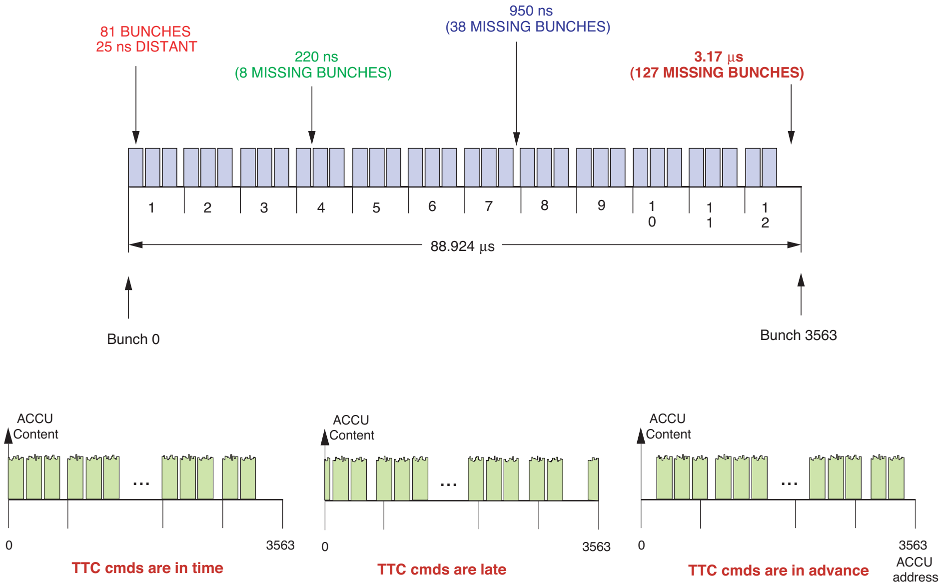
“Timing-in” detectors & Triggers

The detectors have complex and independent paths for data coming from various subsystems

- the subsystems and trigger must be synchronized with each other and with the LHC clock

Even though the luminosity is low, both ATLAS and CMS will take data at full capacity (~100-200 Hz) immediately

- Level2 and Level3 triggers in “pass through” mode
- boot strap from Random->Anything->electrons/muons/jets



Commissioning the trigger will be a major achievement.

Difficulty in achieving a reasonable data taking efficiency is one of the biggest threats to the early physics program

Early Detector Performance

Most detector subsystems have some level of built in calibration and alignment (eg. lasers, calibration pulses, etc)

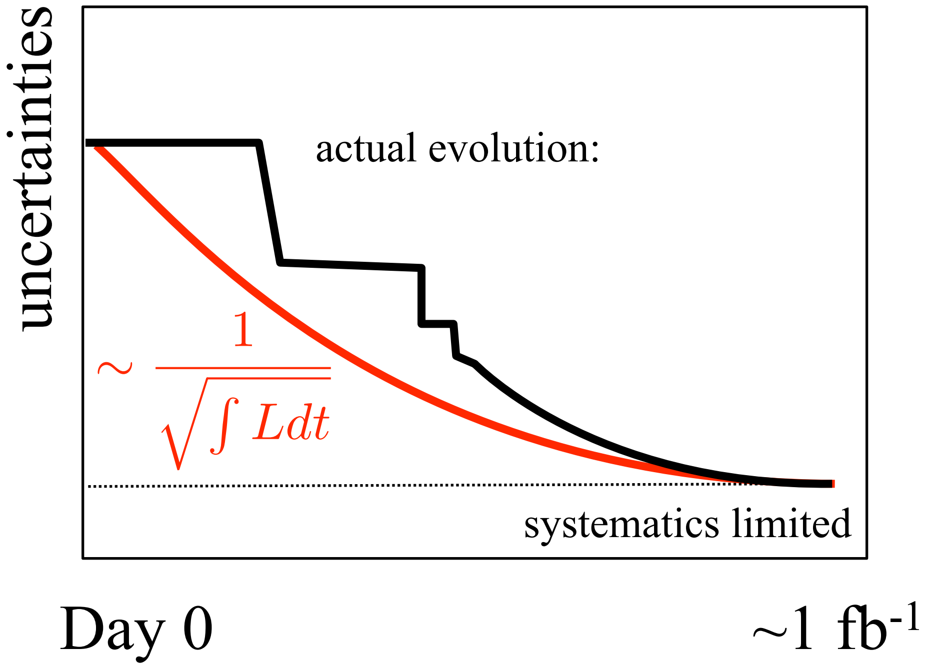
In addition to test beams studies, cosmic ray muons already being used, beam gas interactions are anohter early handle

In situ calibration is an iterative procedure:

- technically complex requires practice to be efficient

	Expected Day 0	Goals for Physics
ECAL uniformity	~ 1% ATLAS ~ 4% CMS	< 1%
Lepton energy scale	0.5—2%	0.1%
HCAL uniformity	2—3%	< 1%
Jet energy scale	<10%	1%
Tracker alignment	20—200 μm in Rϕ	$\mathcal{O}$(10 μm)

De Roeck, Wine & Cheese



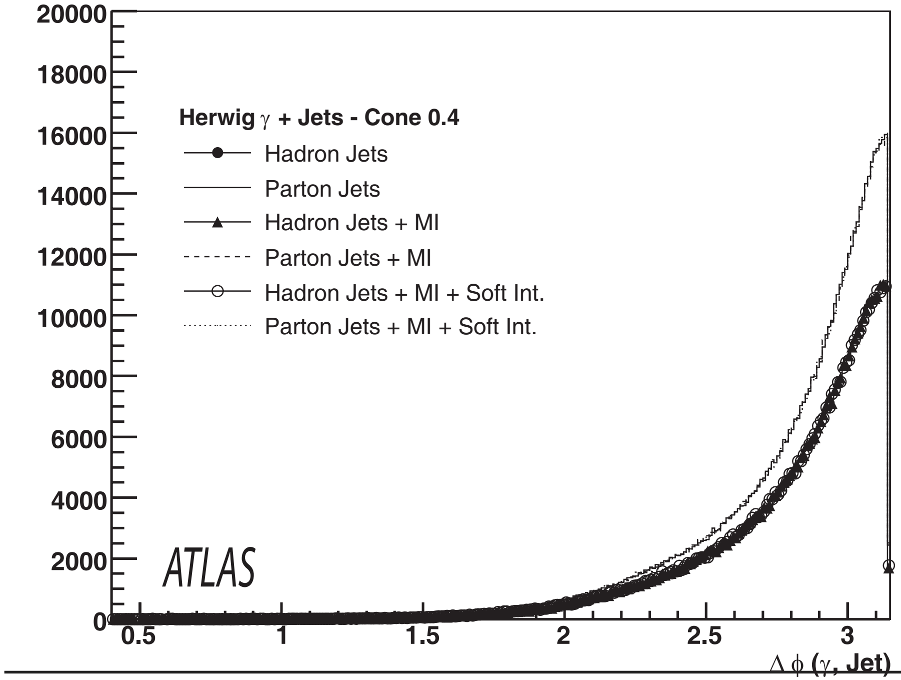
Calibration

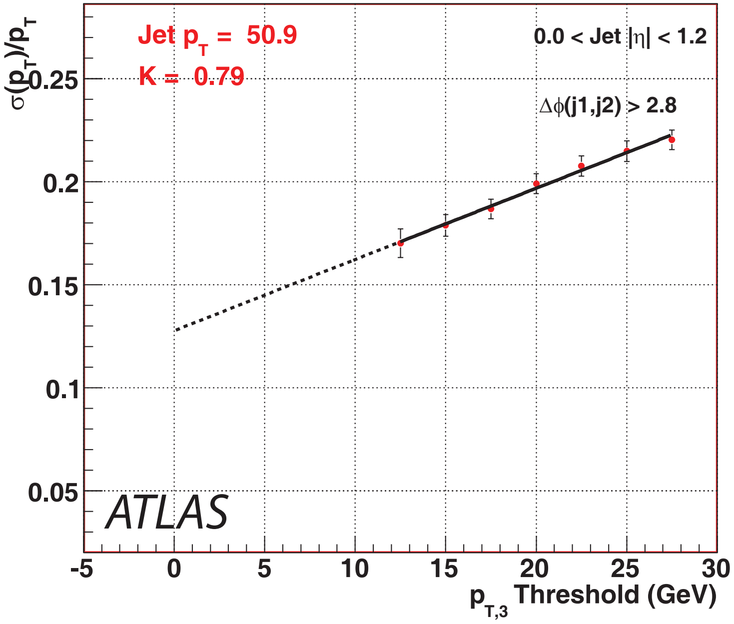
Electromagnetic calorimeter

- Using $Z \rightarrow e^+e^-$ and coorelating two electrons it is possible to "inter-calibrate" the electromagnetic calorimeter

In-situ Hadronic Calibration

- Single hadron response from test beam validated in situ using min bias
- jet energy scale:
  - uniformity via dijet balance (sensitive to soft radiation)
  - scale from Z+jet and γ+jet balance (also limited by theoretical uncertainties)
  - beyond 500 GeV more difficult to get jet energy scale

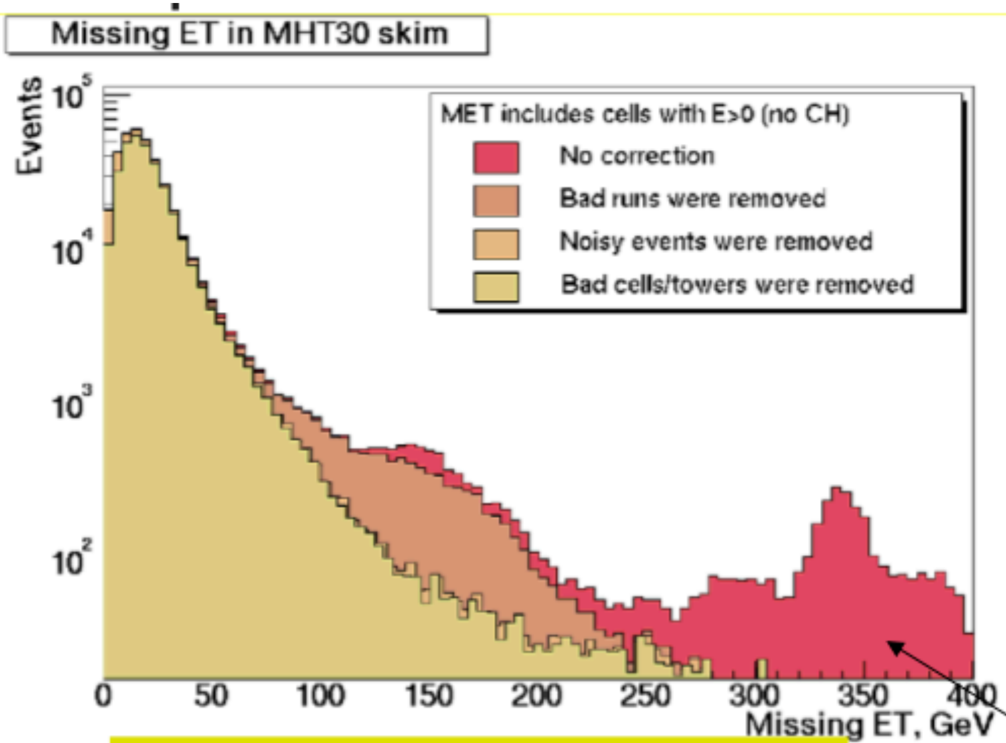




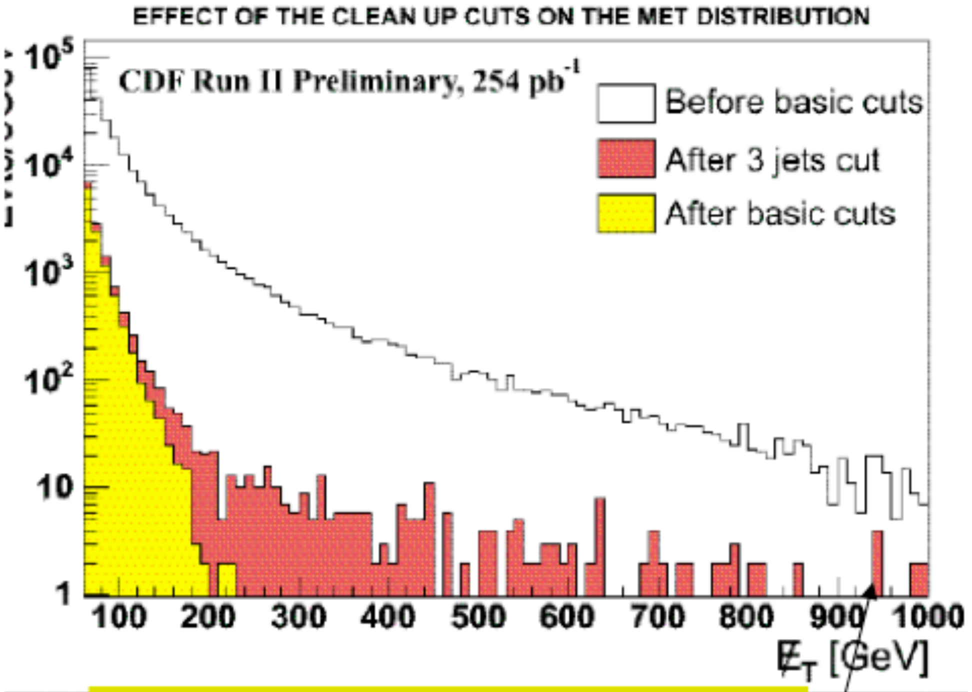
Beam & Instrumental Backgrounds

We expect a variety of beam and instrumental backgrounds will occur. What kinds, how severe?

Early running will be largely focused on understanding these kinds of effects: where do they come from, how do we identify them, how do we remove them

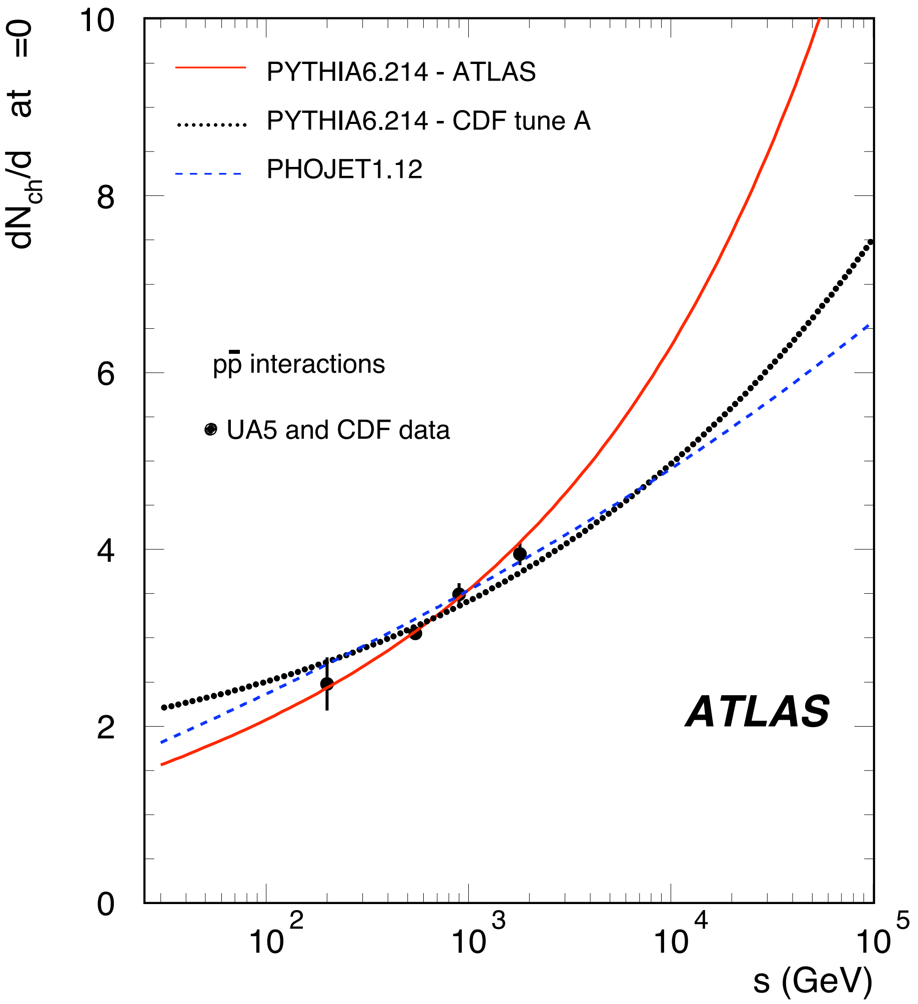


MET, before corrections (Do)



MET, after corrections (CDF)

Minimum Bias & Underlying Event

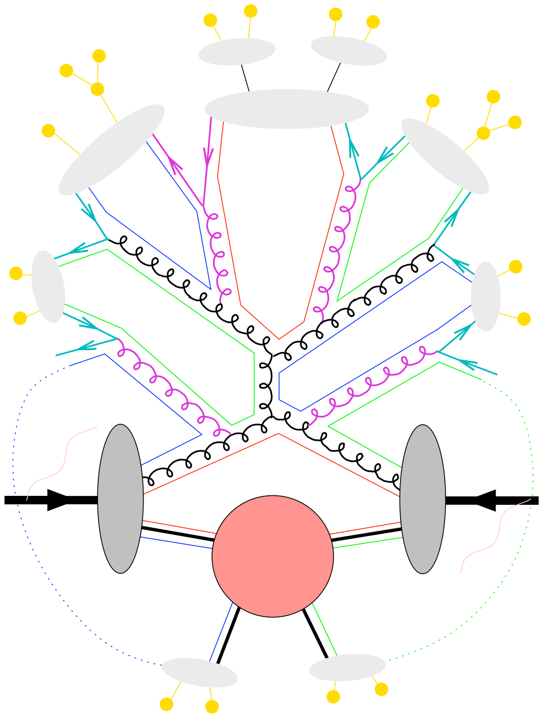


Modeling of the underlying event has very large uncertainty when extrapolated to LHC energies

Understanding “minimum bias” will be one of the first measurements at the LHC

Process	Cross-section (mb)	
	PHOJET	PYTHIA
non-diff.	69	55
single diff.	11	14
double diff.	4	10
central diff.	1	-
total inelastic	85	79
elastic	35	23
total	120	102

A pp event at the LHC: dijet production via $gg \to gg$

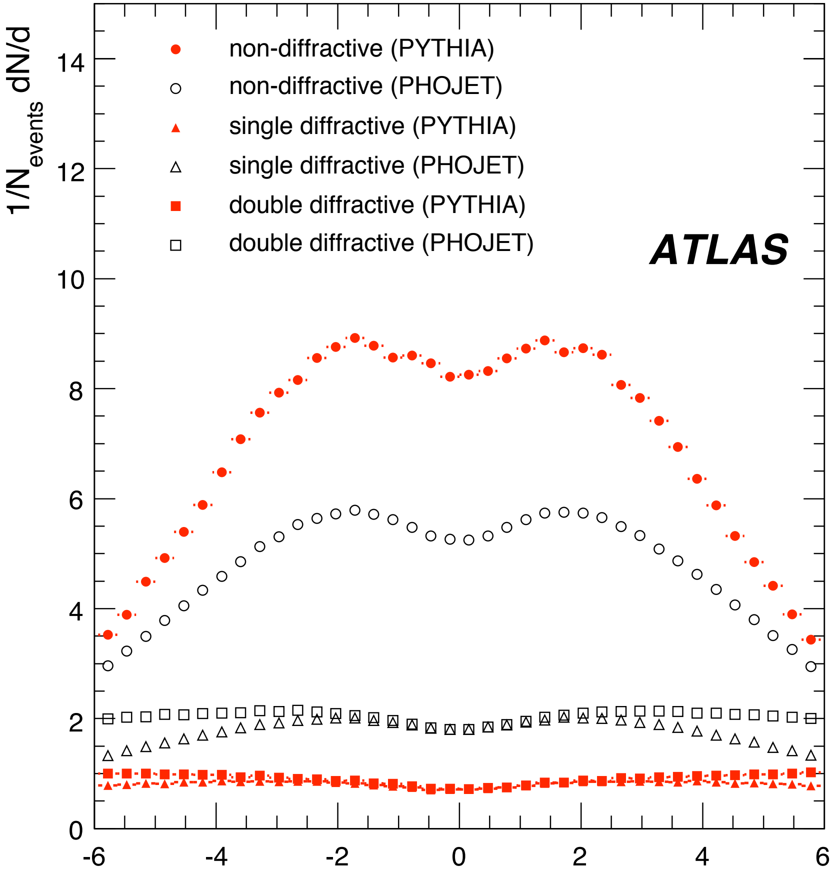


- hard scattering
- (QED) initial/final state radiation
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

and in addition

- + backward parton evolution
- + soft (possibly not–so–soft) underlying event

Minimum Bias & Underlying Event



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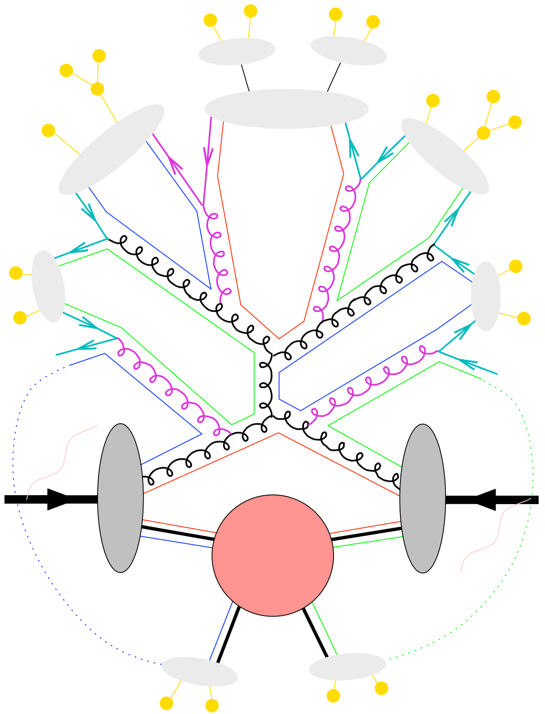

- ● hard scattering
- ● (QED) initial/final state radiation
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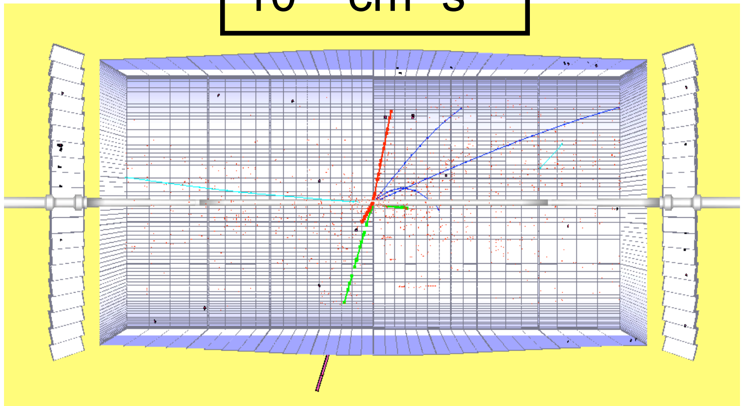
and in addition

- + backward parton evolution
- + soft (possibly not–so–soft) underlying event

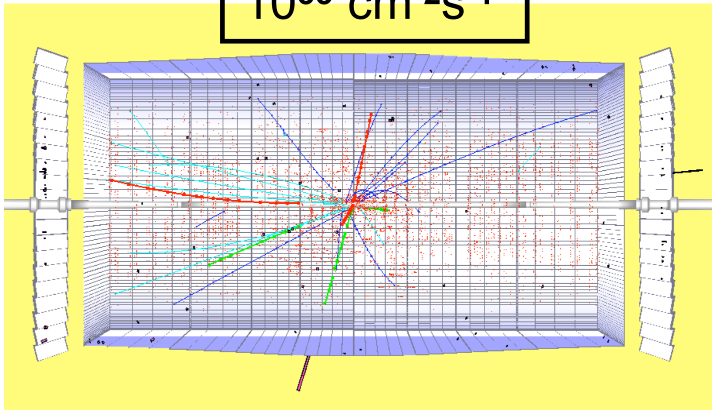
"Pile-Up"

Despite the low initial luminosity, there will only be a small number of bunches (156 of the 2808), which enhances the number of interactions per bunch crossing: eg. pileup

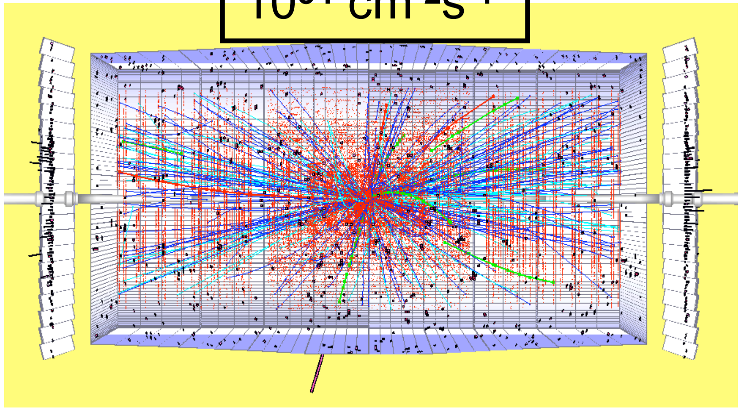
Having some early experience with pileup will be useful



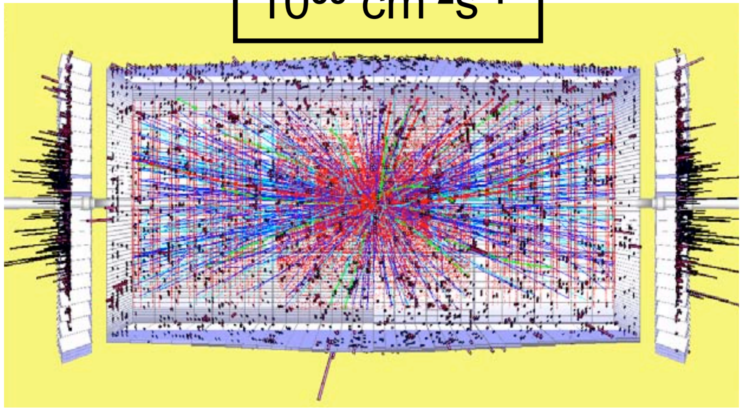
10^{32} cm^{-2}s^{-1}



10^{33} cm^{-2}s^{-1}



10^{34} cm^{-2}s^{-1}



10^{35} cm^{-2}s^{-1}

The 2008 Physics Run

With the first physics run in 2008 ($\sqrt{s}$ = 14 TeV) ....

1 fb^{-1} (100 pb^{-1}) ≡ 6 months (few days) at L= 10^{32} $cm^{-2}s^{-1}$
with 50% data-taking efficiency
→

Channels (examples ...)	Events to tape for 100 pb^{-1} (per expt: ATLAS, CMS)	Total statistics from some of previous Colliders
$W \rightarrow \mu\nu$	~ 10^6	~ 10^4 LEP, ~ 10^6 Tevatron
$Z \rightarrow \mu\mu$	~ 10^5	~ 10^6 LEP, ~ 10^5 Tevatron
$tt \rightarrow W b W b \rightarrow \mu\nu + X$	~ 10^4	~ 10^4 Tevatron
QCD jets $p_T > 1$ TeV	> 10^3	---
$\tilde{g}\tilde{g}$ m = 1 TeV	~ 50	---

With these data:

- Understand and calibrate detectors *in situ* using well-known physics samples
  e.g. - $Z \rightarrow ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $tt \rightarrow bl\nu\, bjj$ jet scale from $W \rightarrow jj$, b-tag performance, etc.

- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, QCD jets ...
  (also because omnipresent backgrounds to New Physics)

[F. Gianotti, ICHEP 06]

ATLAS CSC & CMS PTDR

CMS “Physics Technical Design Report” [CERN/LHCC 2006-001]

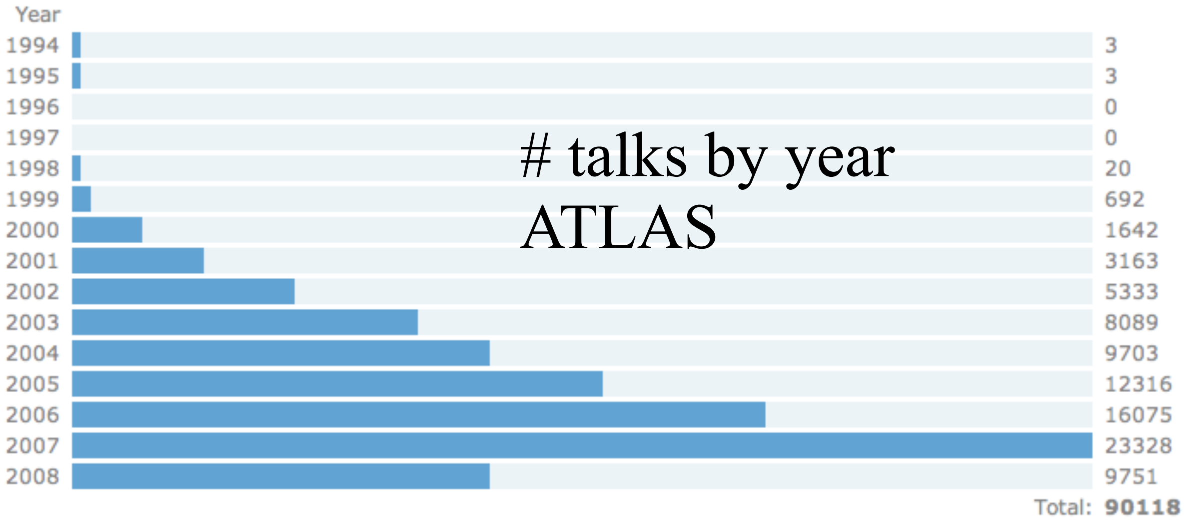
- ~1200 page update to physics potential

ATLAS had a similar “CSC” exercise that lasted ~1.5 years over almost all aspects of our Physics (still converging....)

- focused on “early physics” 1-30 fb^{-1}
- about 90 notes of ~30 pages each
- using fully simulated events with realistic misalignments and distorted material
- some studies with pileup
- development of data-driven background estimation

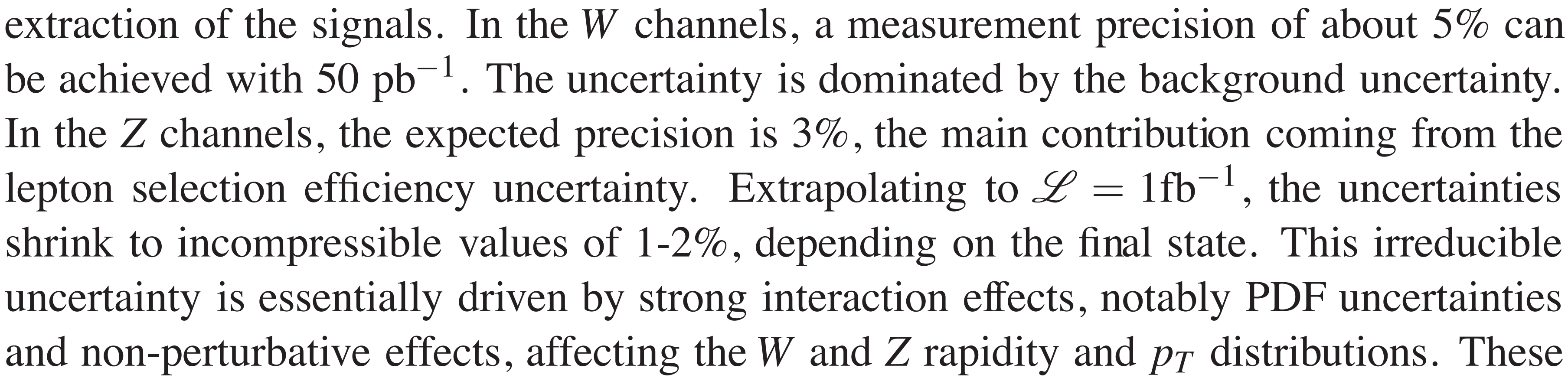
A lot of new material will be available this summer

- happy reading!

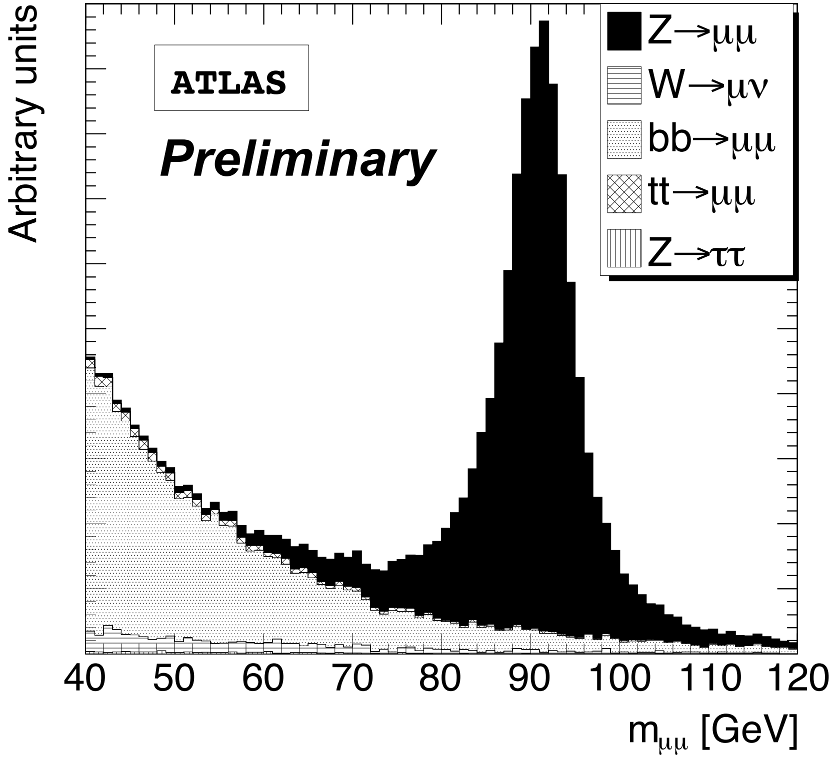


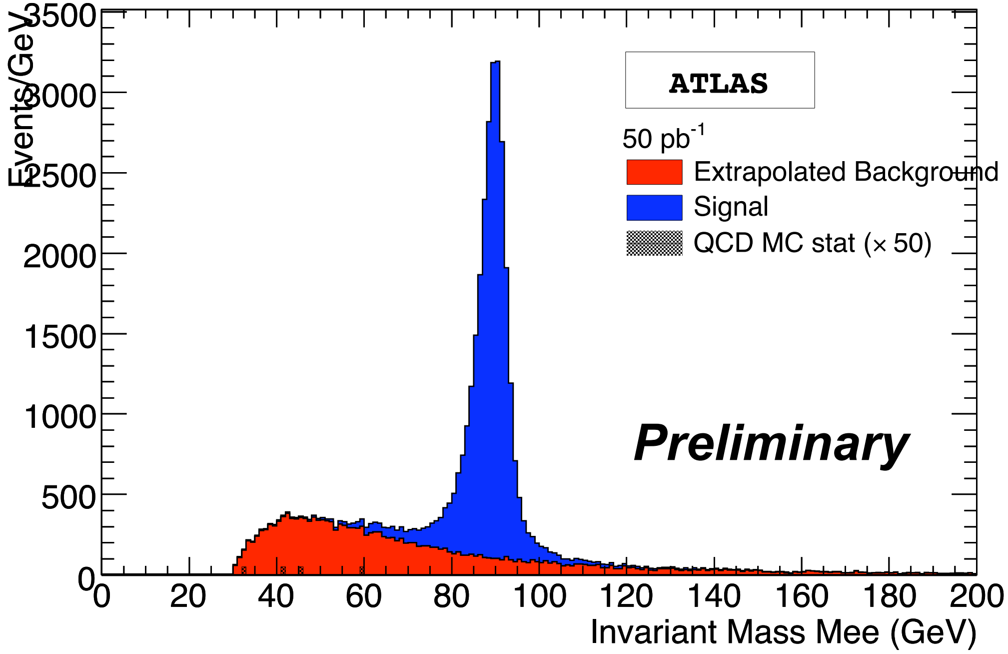
Z decaying to leptons in 50 pb^{-1}

We can see the Z very early

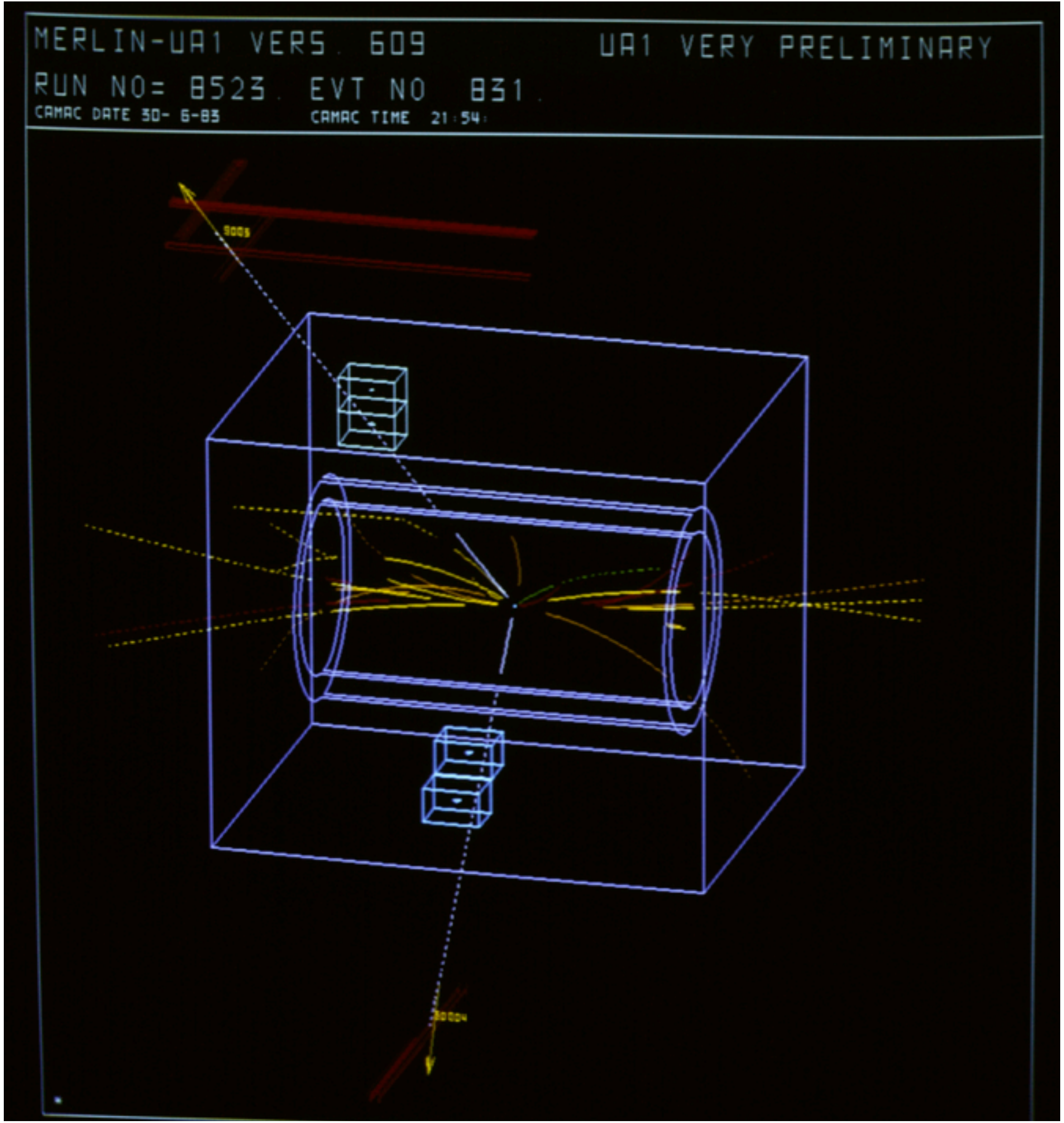


extraction of the signals. In the W channels, a measurement precision of about 5% can be achieved with 50 pb^{-1}. The uncertainty is dominated by the background uncertainty. In the Z channels, the expected precision is 3%, the main contribution coming from the lepton selection efficiency uncertainty. Extrapolating to $\mathscr{L} = 1\mathrm{fb}^{-1}$, the uncertainties shrink to incompressible values of 1-2%, depending on the final state. This irreducible uncertainty is essentially driven by strong interaction effects, notably PDF uncertainties and non-perturbative effects, affecting the W and Z rapidity and p_T distributions. These





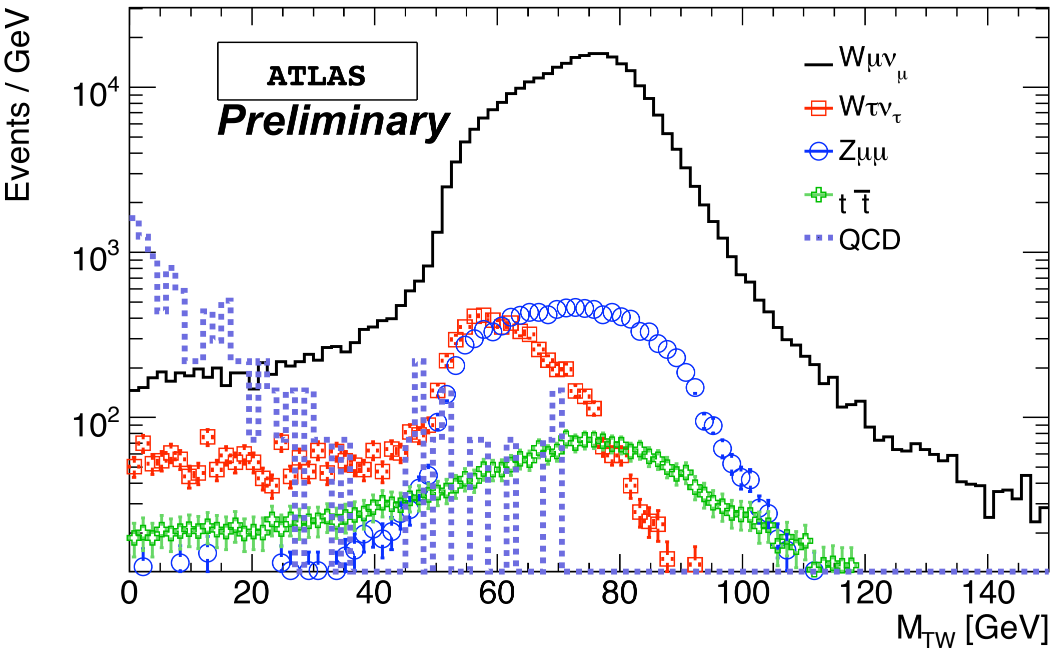
25 years later, still “VERY PRELIMINARY”

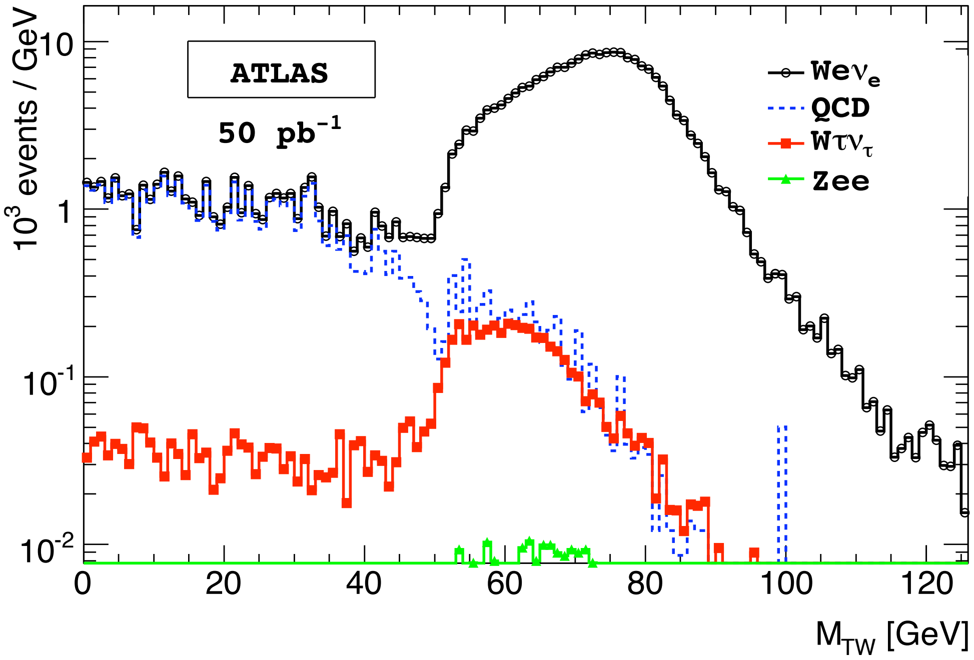


W decaying to leptonically in 50 pb^{-1}

And the W too...

extraction of the signals. In the W channels, a measurement precision of about 5% can be achieved with 50 pb^{-1}. The uncertainty is dominated by the background uncertainty. In the Z channels, the expected precision is 3%, the main contribution coming from the lepton selection efficiency uncertainty. Extrapolating to $\mathscr{L} = 1\text{fb}^{-1}$, the uncertainties shrink to incompressible values of 1-2%, depending on the final state. This irreducible uncertainty is essentially driven by strong interaction effects, notably PDF uncertainties and non-perturbative effects, affecting the W and Z rapidity and p_T distributions. These





Top With Very Early Data

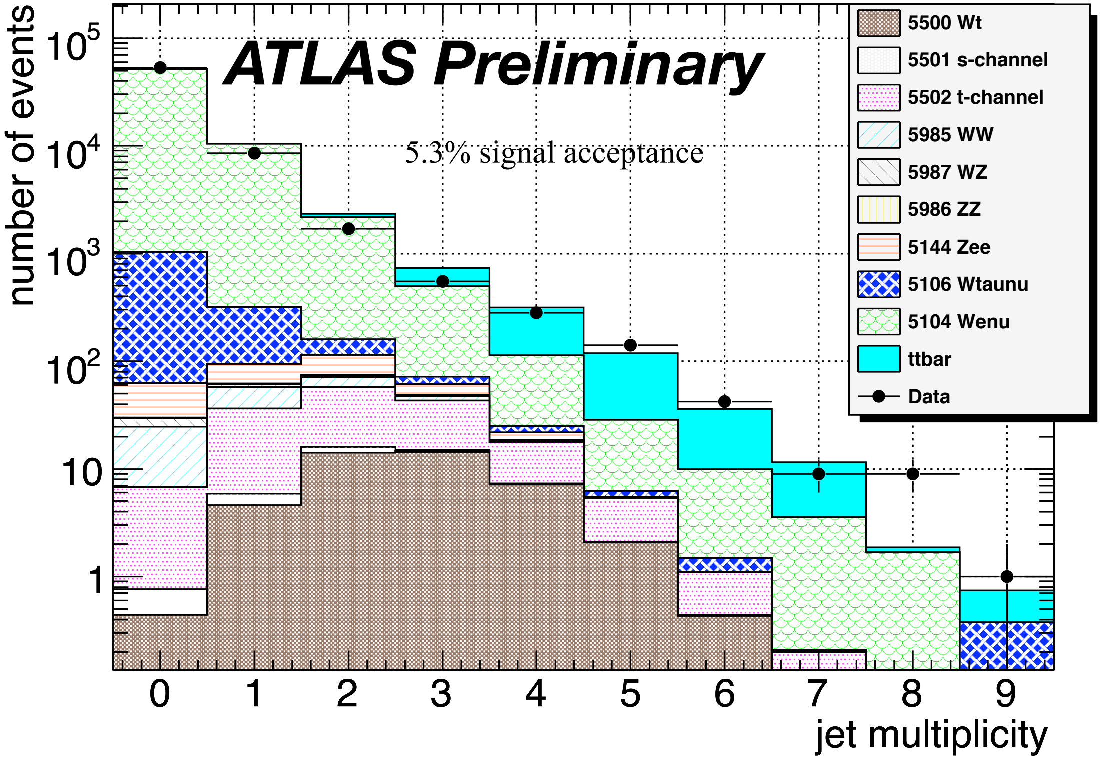
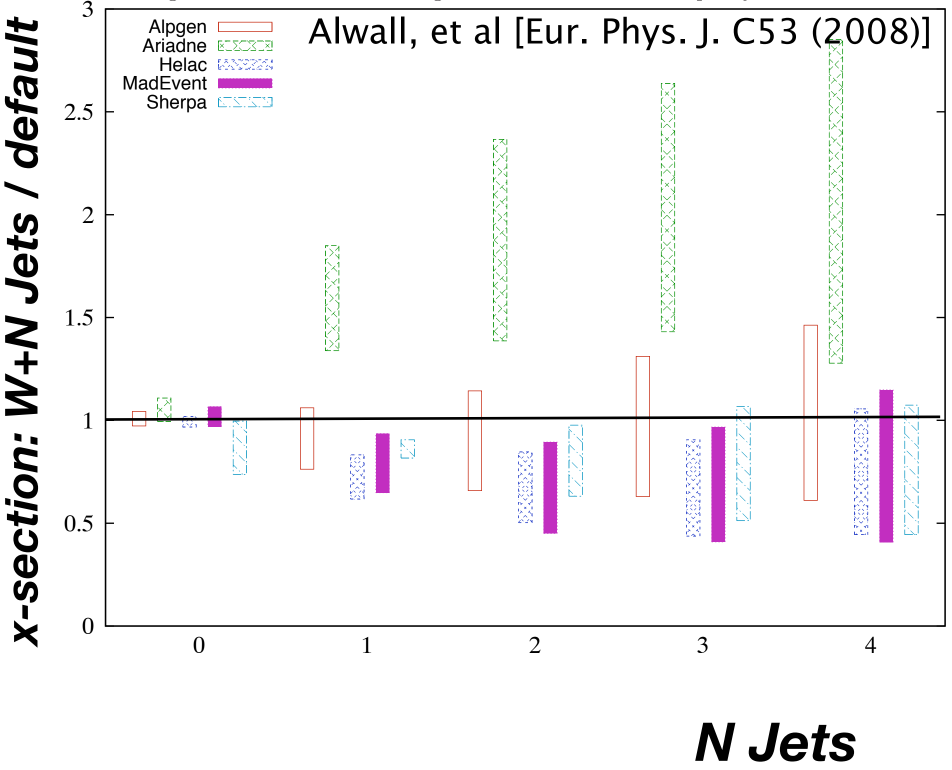


Figure 7: Range of variation for the LHC cross-section rates of the five codes, normalized to the average value of the default settings for all codes in each multiplicity bin.



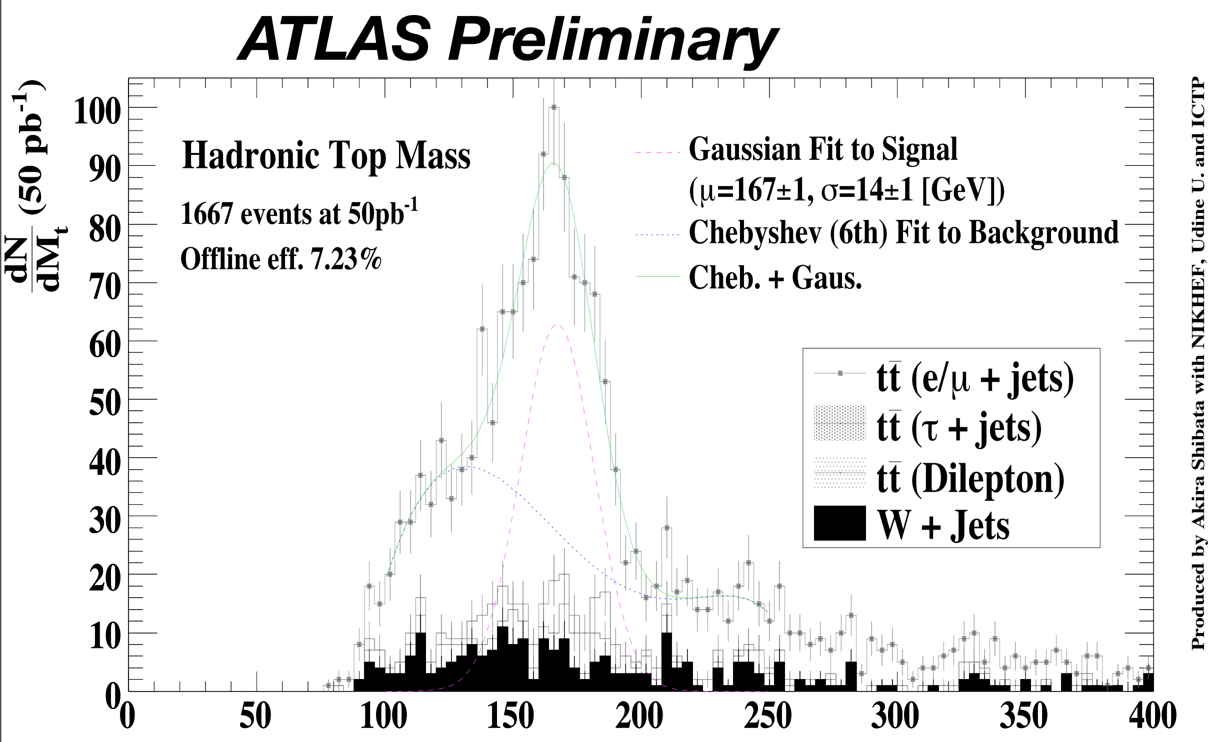
In the very early days (~15 pb^{-1}) possible to use simply the jet multiplicity in events with 1 electron + and Missing ET to see evidence of top and even make a rough measurement of ttbar cross-section

Clearly, sensitive to uncertainty in jet multiplicity (can be large)

Use Z+jets to constrain / inform W+Jets background

Being exercised using realistic “stream test” Monte Carlo samples

Top With Early Data



Typical selection in the lepton+jets channel for “commissioning analysis”

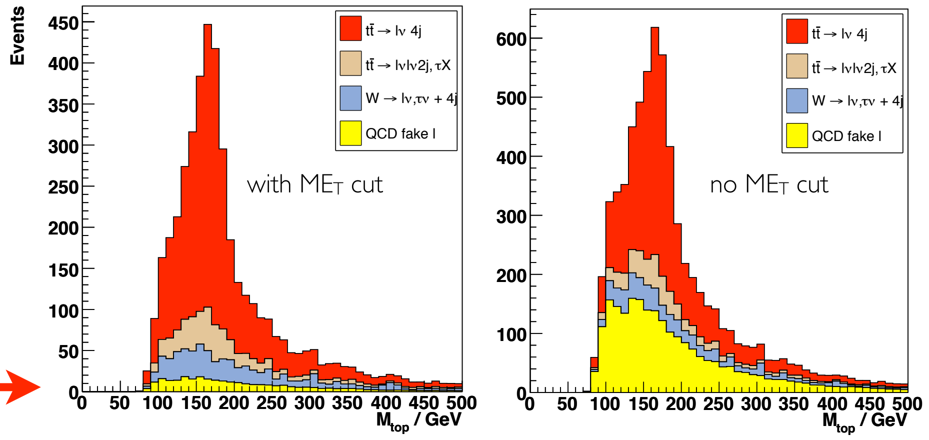
- 1 high-pT lepton > 20 GeV/c
- at least 3 high-pT jets > 40 GeV/c
- 1 high-pT jet > 20 GeV/c
- ET miss>20 GeV
- |eta(lepton)|<2.4, |eta(jet)|<2.5
- top is reconstructed as the 3-jet combination with the highest PT sum
- cut |mjj-MW|<10 GeV

With a simple algorithm, we can clearly reconstruct a top mass peak and background found from fit.

No b-tagging in early analysis! Irreducible background due to combinatorics.

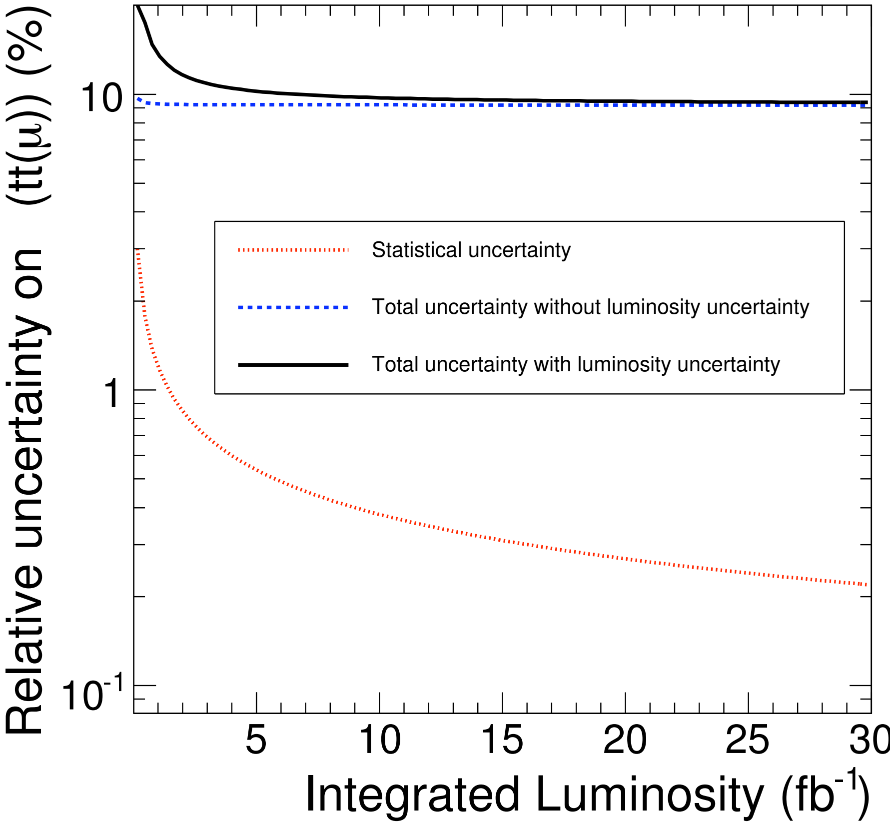
Plot at 50 pb^{-1} with W+Jets background only.

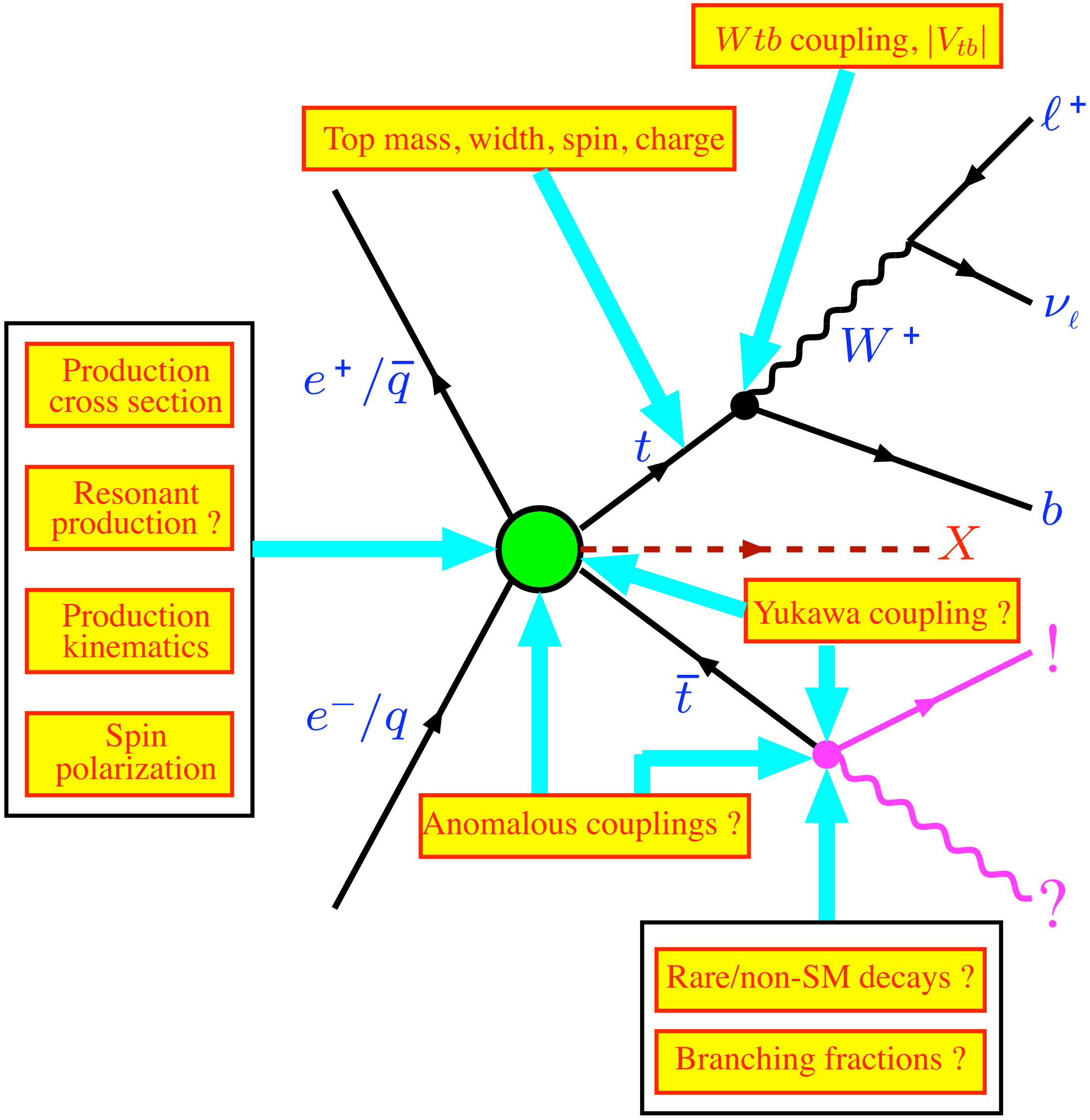
Now studying situation with and w/o MET cut



Top Quark

The LHC will be a “top factory”, many opportunities to study this very interesting particle!





Wtb coupling, $|V_{tb}|$

Top mass, width, spin, charge

Production cross section

Resonant production ?

Production kinematics

Spin polarization

Yukawa coupling ?

Anomalous couplings ?

Rare/non-SM decays ?

Branching fractions ?

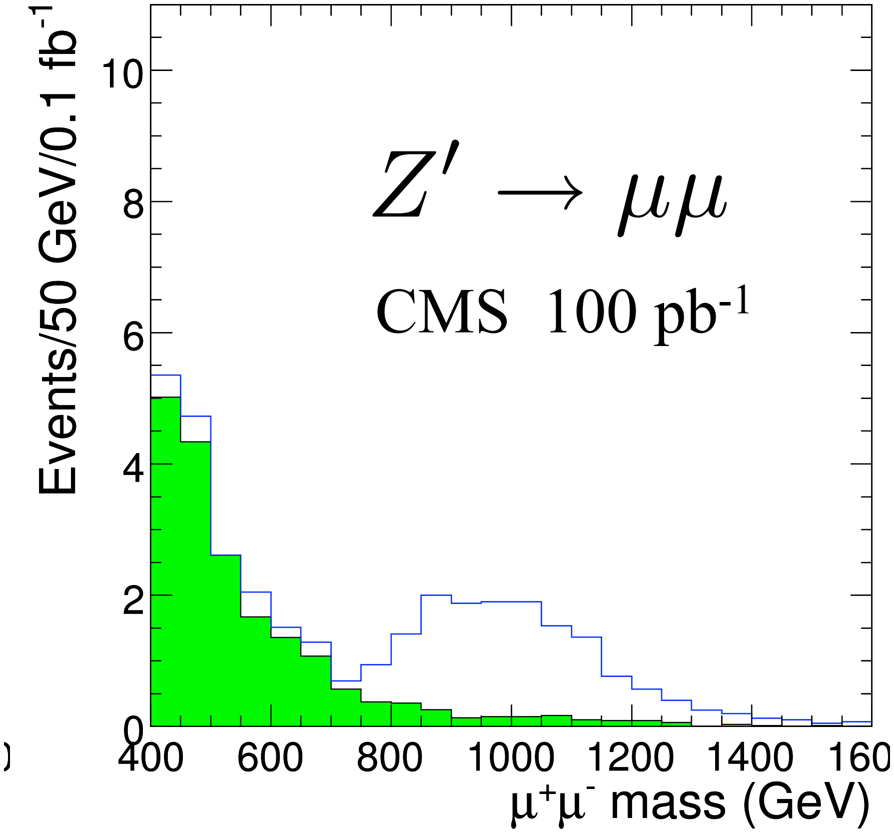
Dhiman Chakraborty

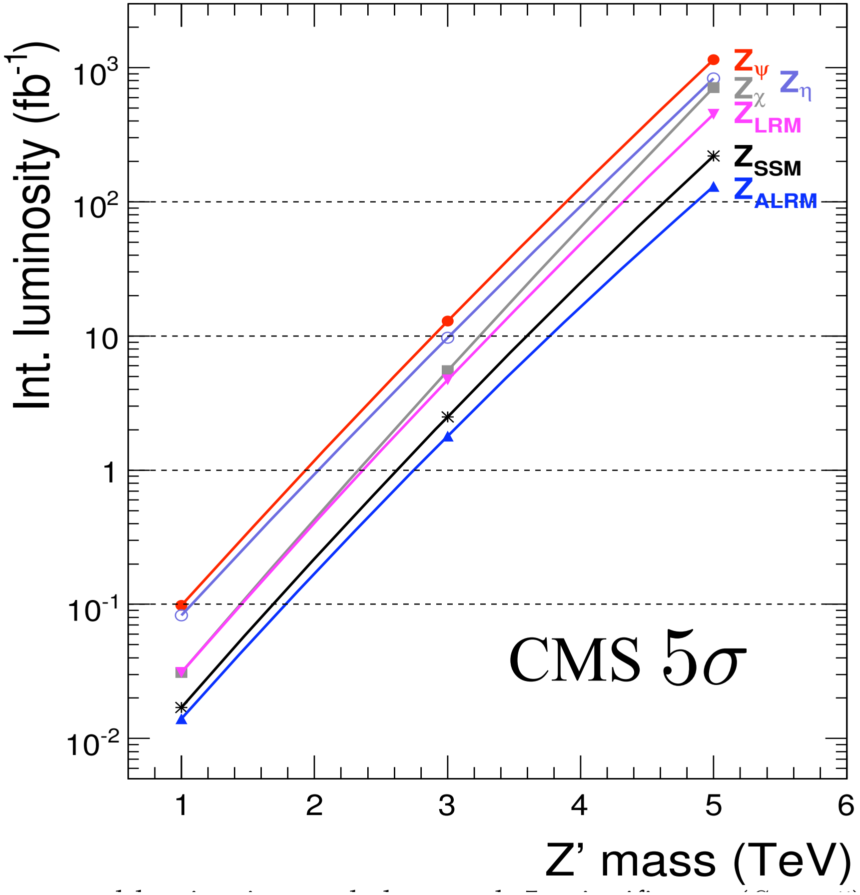
Lucky scenarios

There are some signatures to new physics that may show up very early if we are lucky

- eg. a relatively light Z’ resonance to muons

No time to go through the long list of possibilities



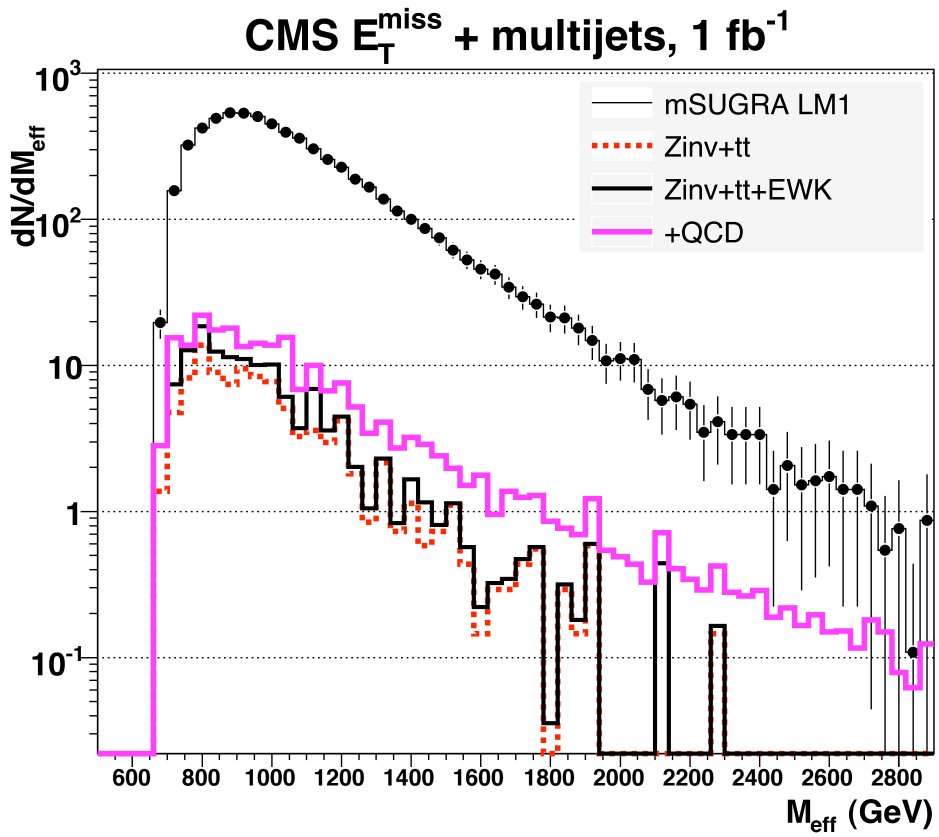


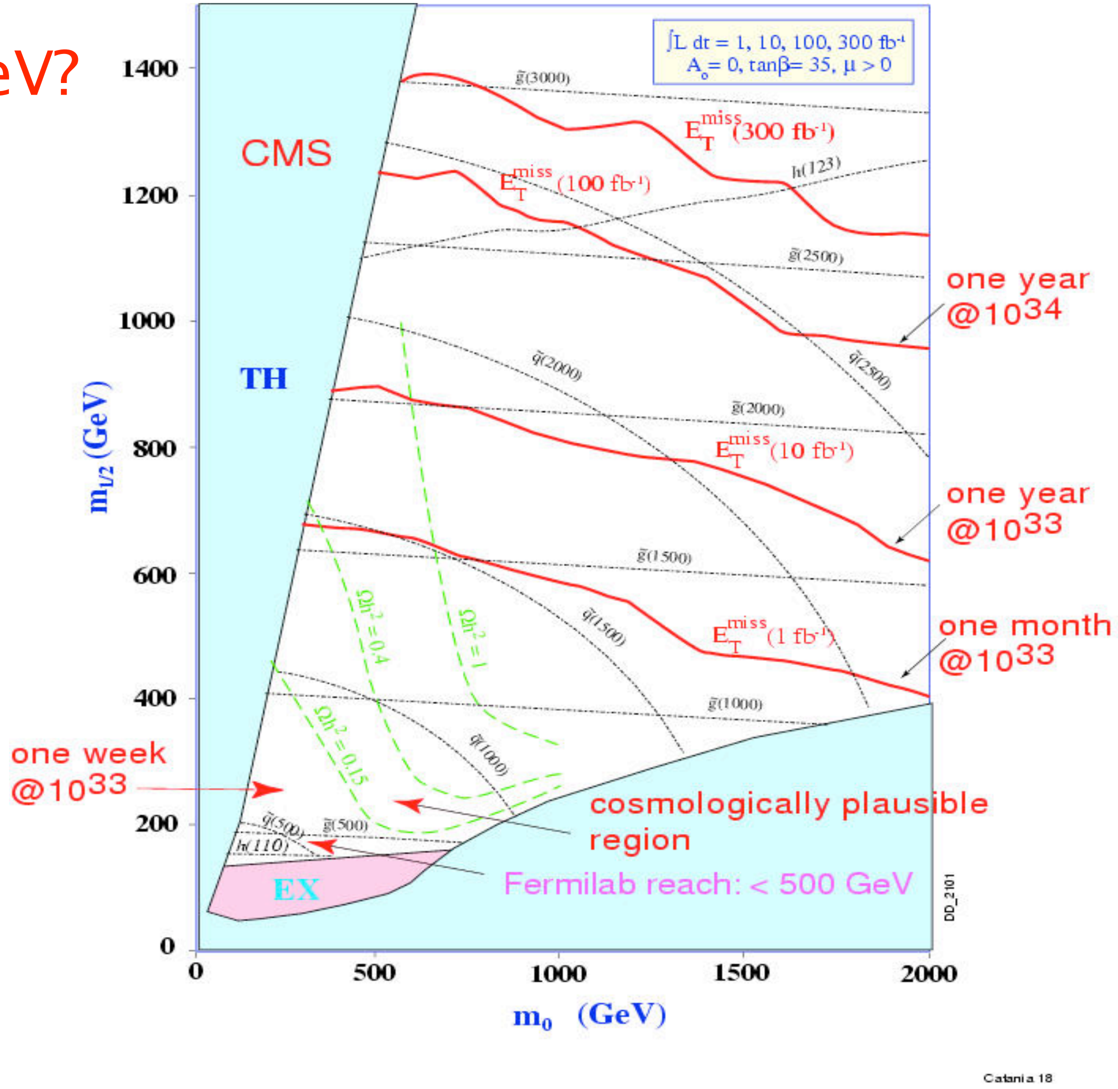
SUSY Reach

Fairly robust search for SUSY based on inclusive observables:

$$M_{eff} = E_T^{miss} + \sum_{i=1}^{4} E_T$$

How will this change with 10 TeV?





one year @10^{34}

one year @10^{33}

one month @10^{33}

one week @10^{33}

cosmologically plausible region

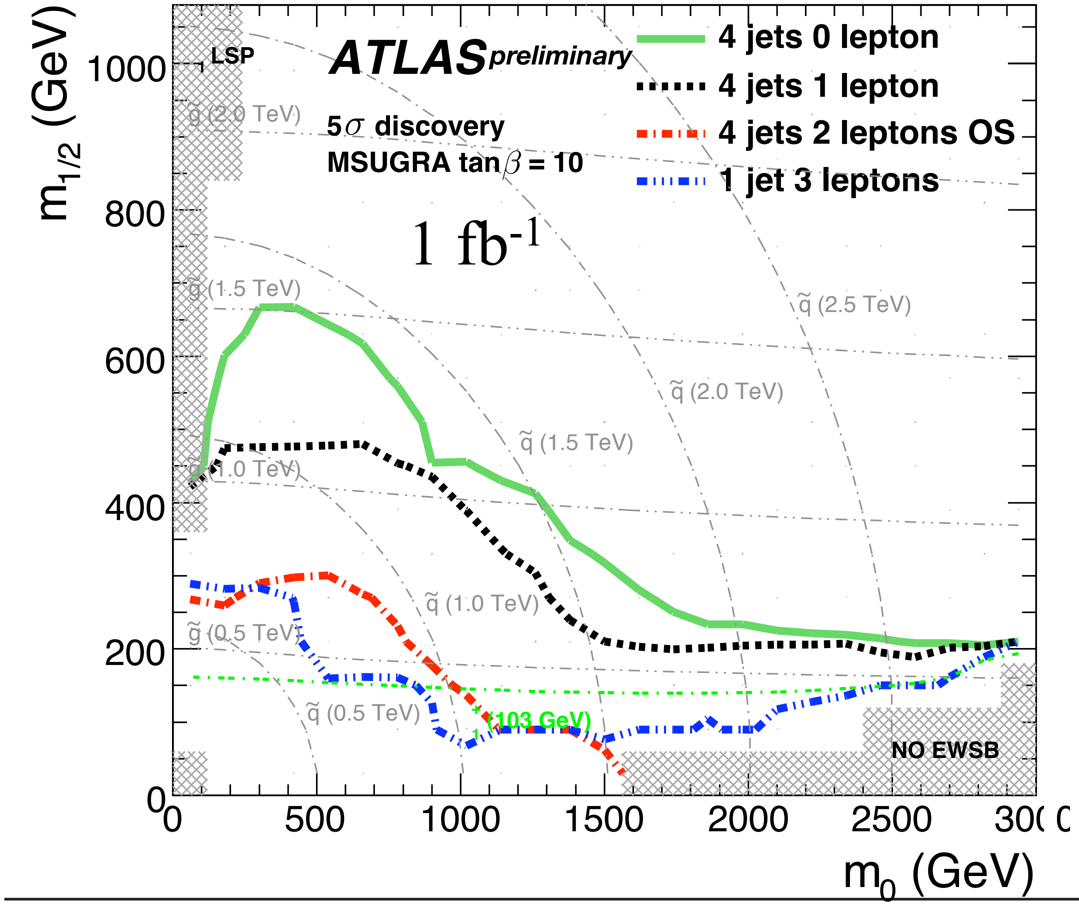
Fermilab reach: < 500 GeV

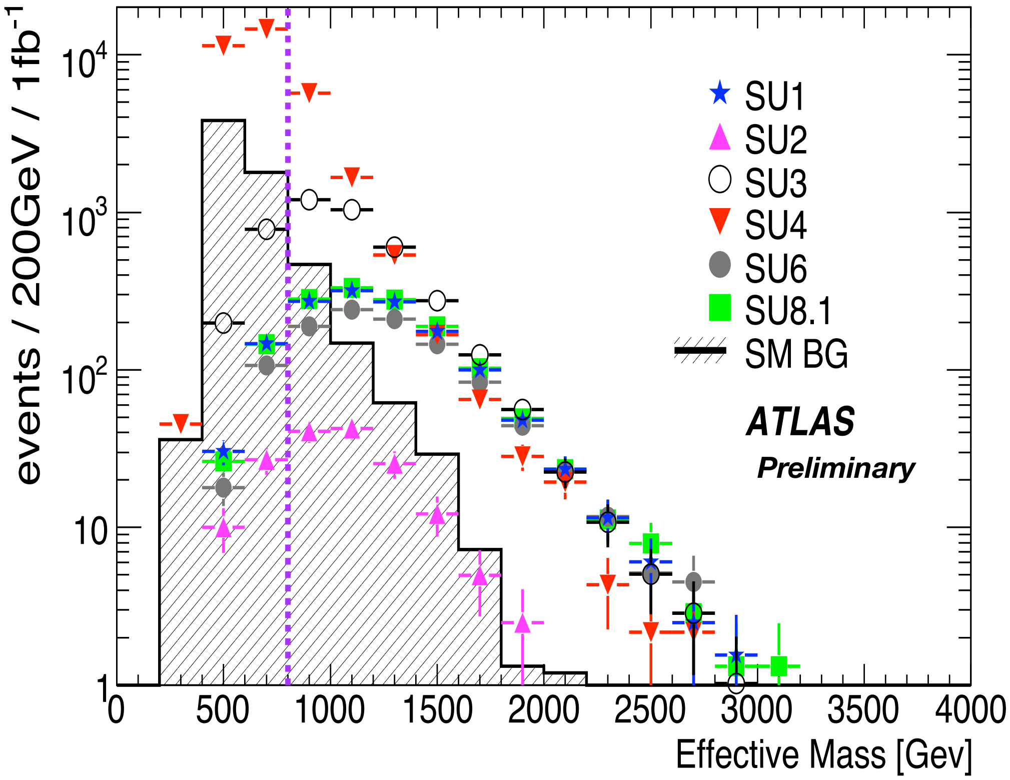
Catania 18

SUSY Reach

Preliminary ATLAS result including full simulation of the detector and trigger

Also consider 1 lepton mode, more robust signature





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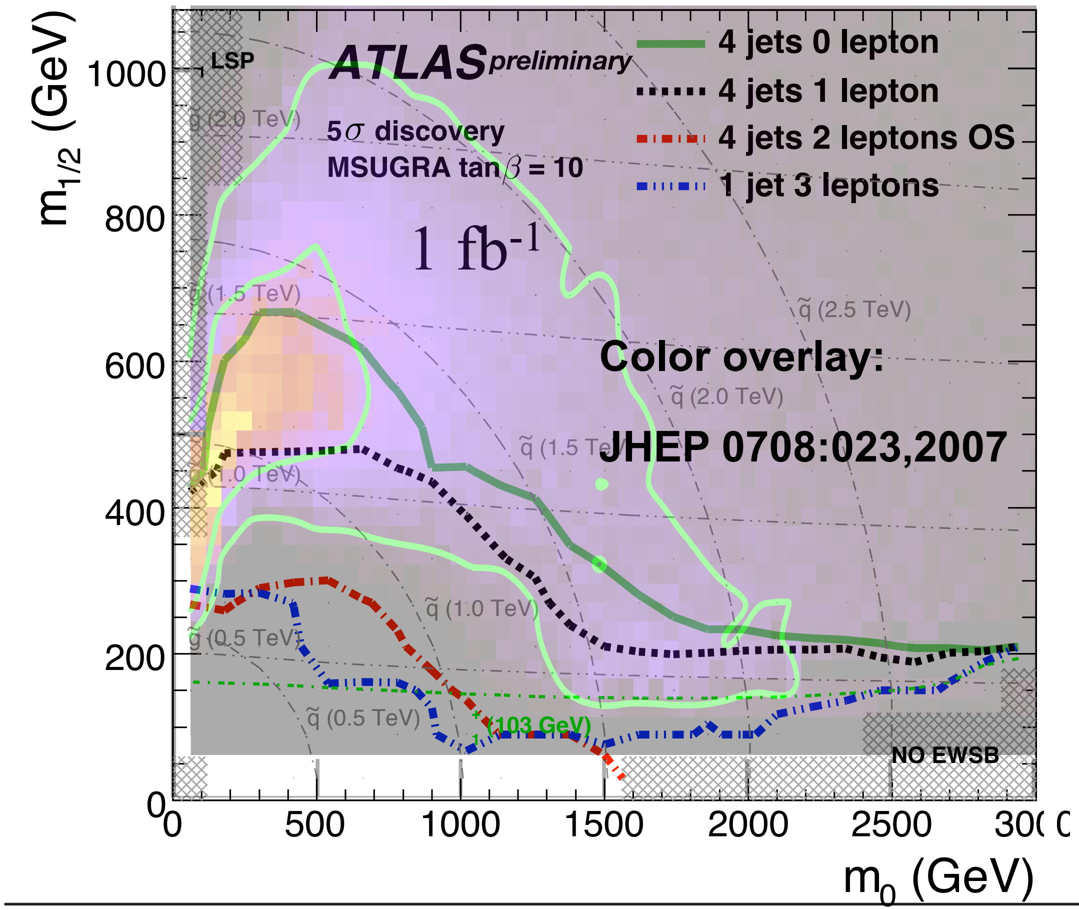
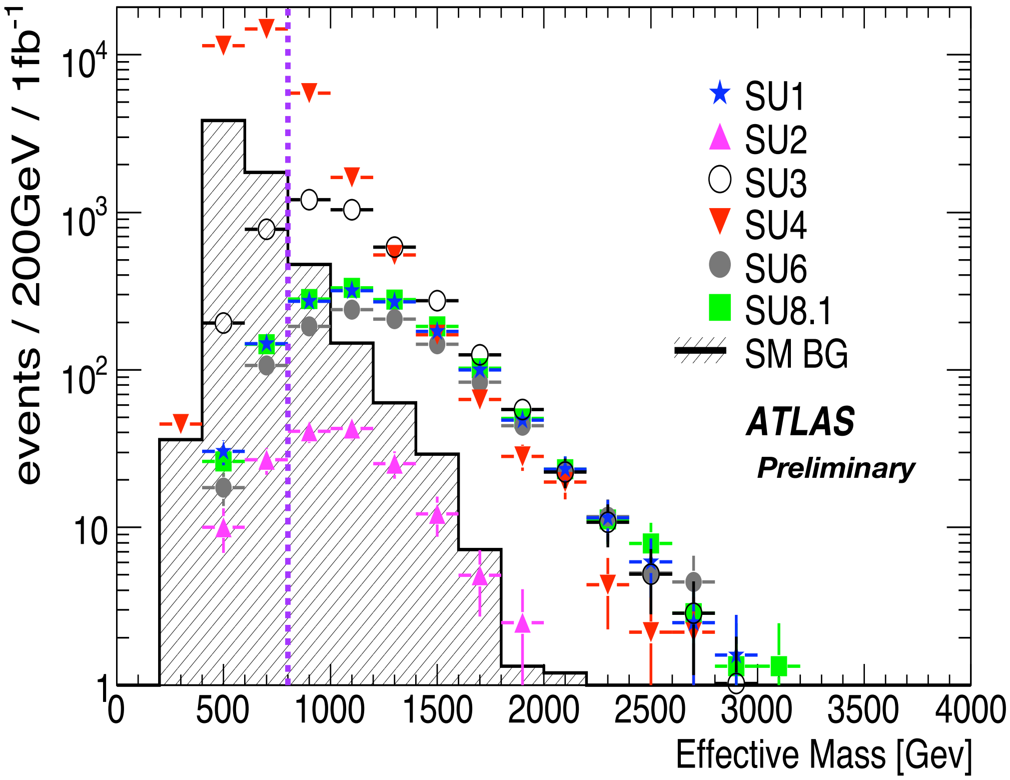


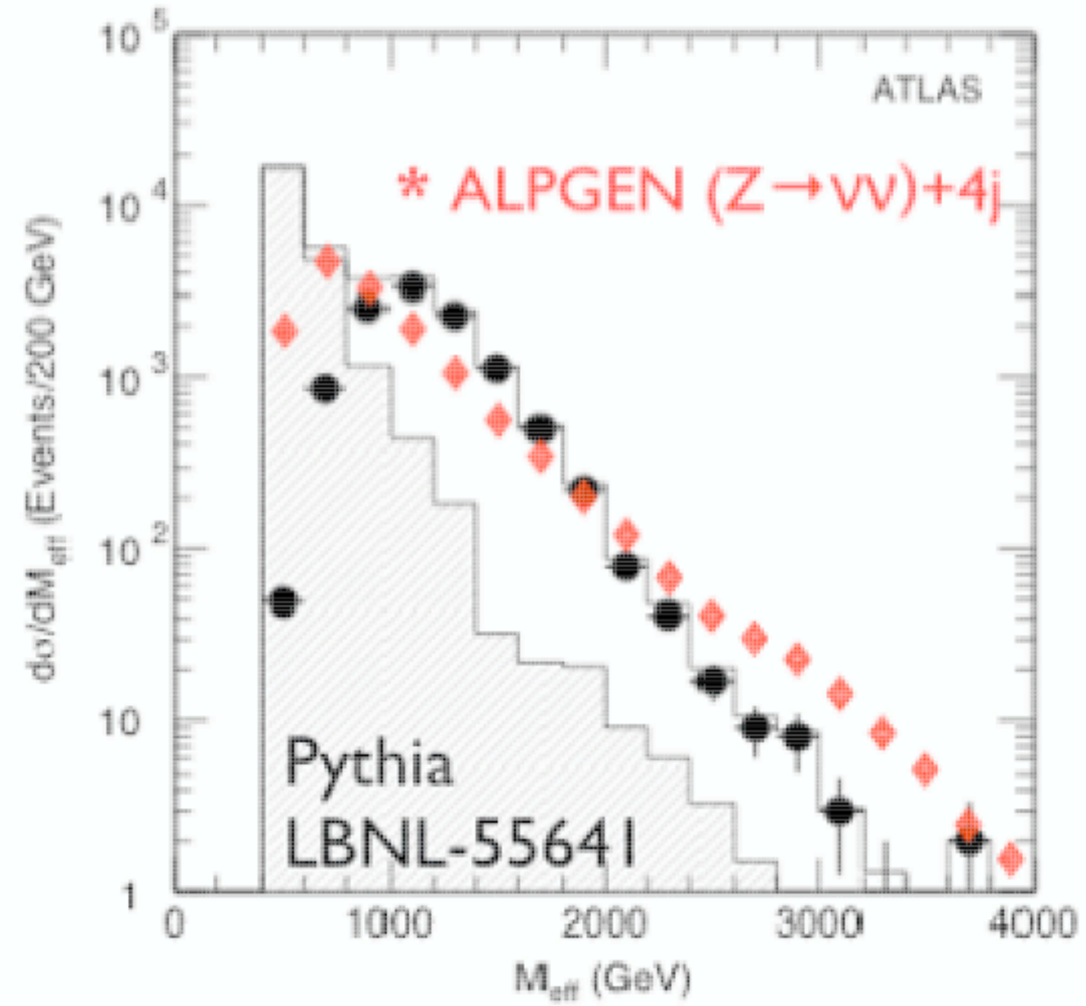
Color overlay:

JHEP 0708:023,2007



Impact of Matrix Element Calculations

The earliest SUSY studies within ATLAS and CMS relied on the parton shower to produce the jet activity



The background predictions in many searches changed drastically once higher-order tree-level matrix element calculations were introduced

Motivates background estimates derived directly from the data, eg:

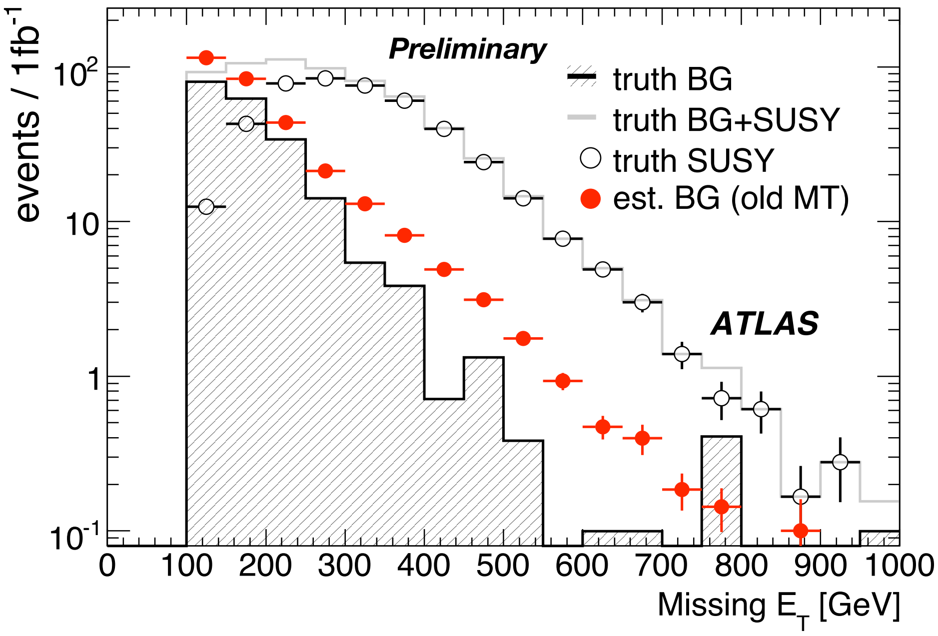
$$Z \rightarrow \mu\mu + jets \Rightarrow Z \rightarrow \nu\nu + jets$$

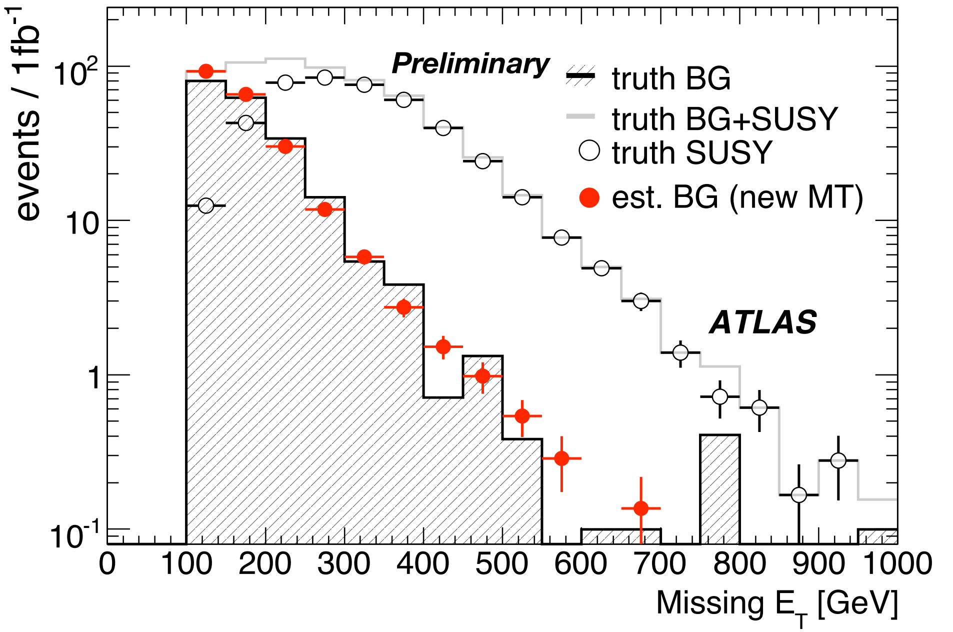
SUSY as background

Another technique for estimating background relies on inverting one of the selection cuts: eg. M_T in the 1-lepton mode

The difficulty with these approaches is that SUSY contaminates the control region, and one can “fit away” evidence of the signal

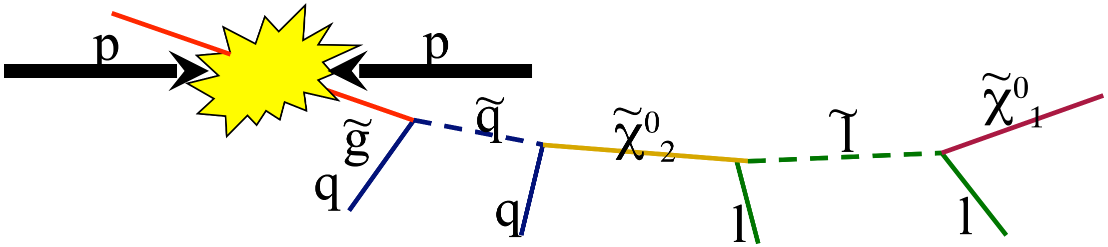
To some extent this can be corrected for by assuming something about the possible SUSY signal





Masses from edges

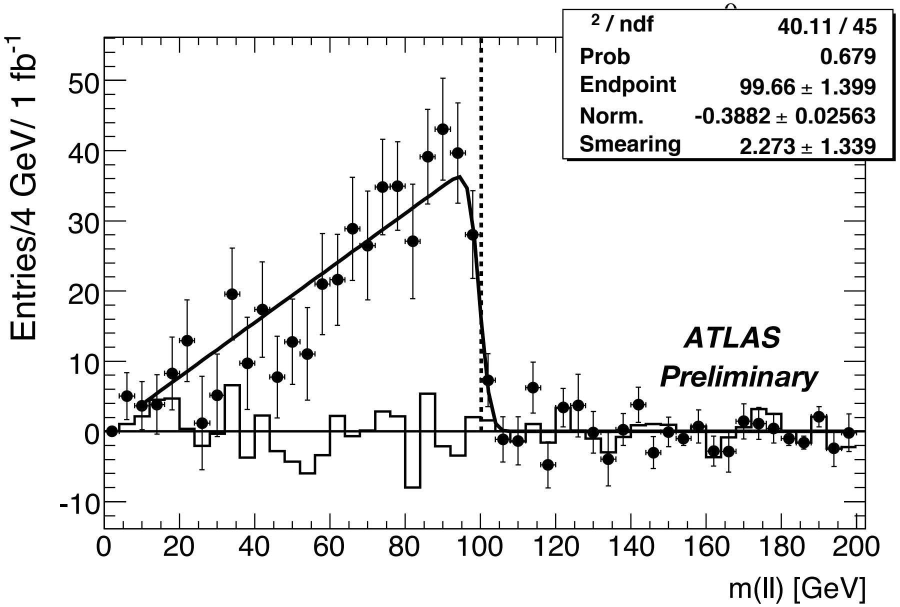
Many presentations this week about measuring masses of SUSY particles



For example di-lepton edges

$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$

Expect signal in same-flavor, opposite-sign. Understand background via “flavor subtraction”.



What happens with lepton flavor violation?

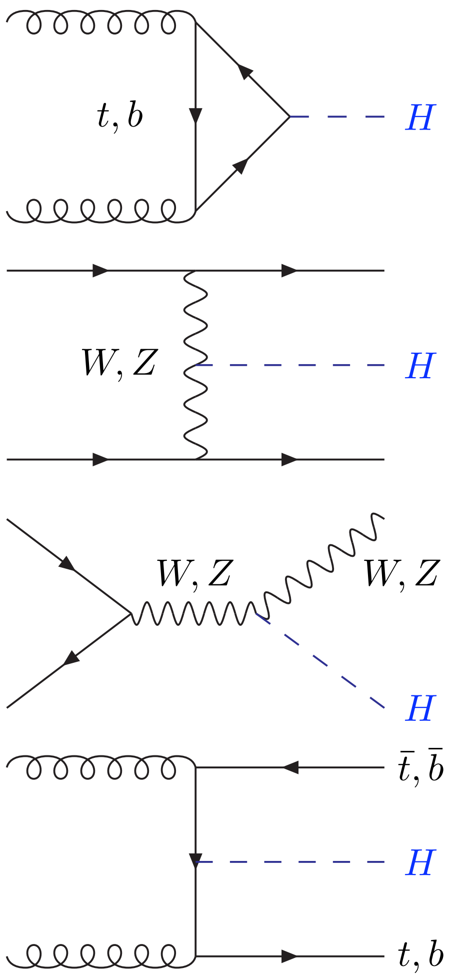
- eg. R-symmetry scenario

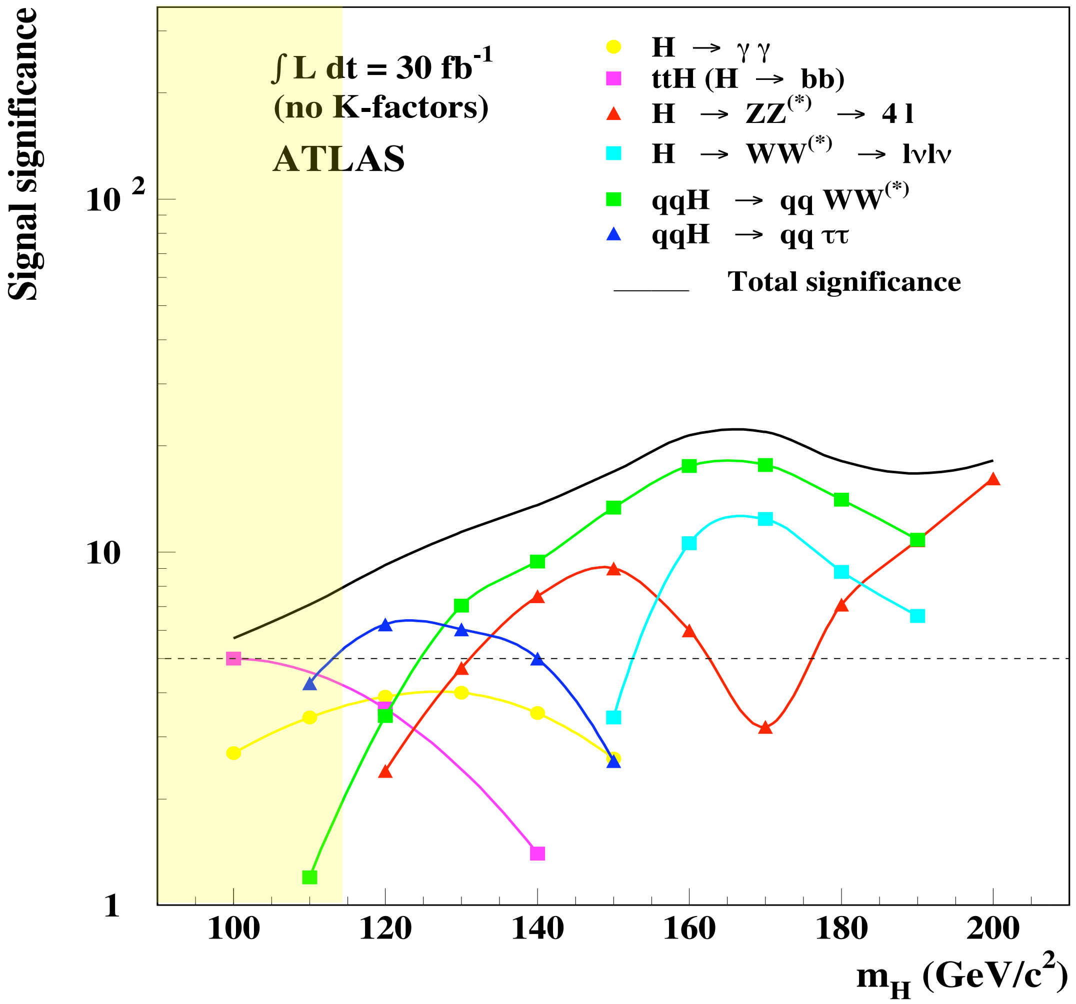
Kribs, Poppitz, Weiner [arXiv:0712.2039]

Higgs Discovery

If the Standard Model Higgs exists, we will find it at the LHC

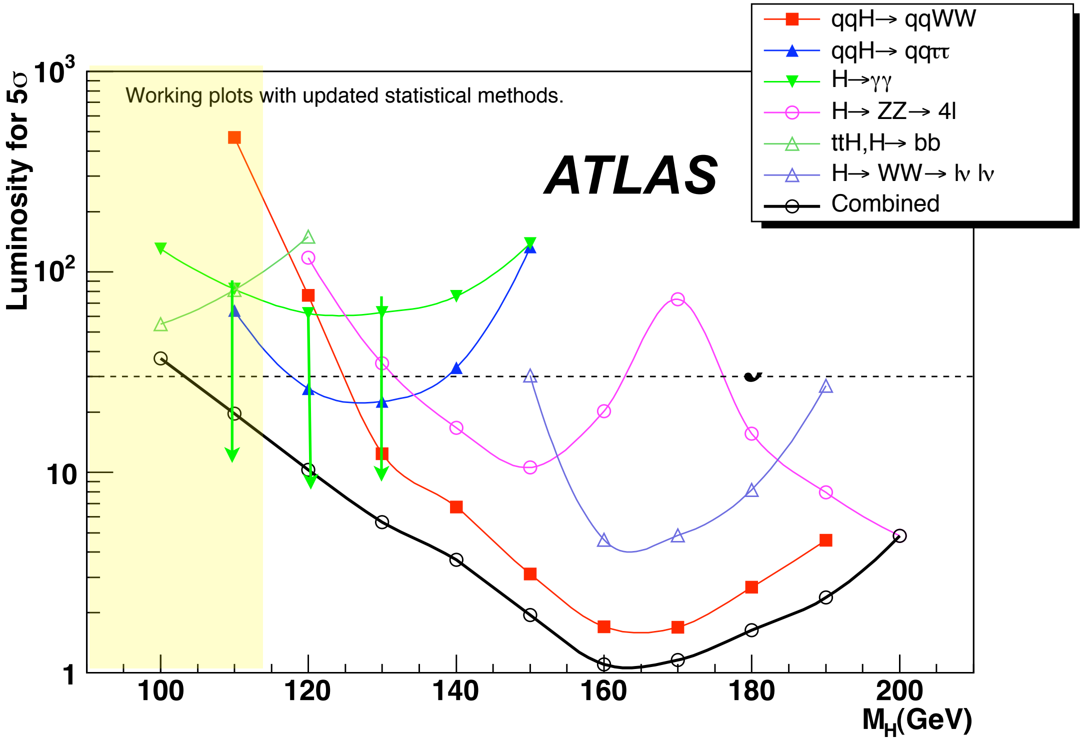
- How do we know if what we see is really the Higgs?
  - Multiple production and decay modes provides an opportunity to study several of the Higgs's properties (not early physics)

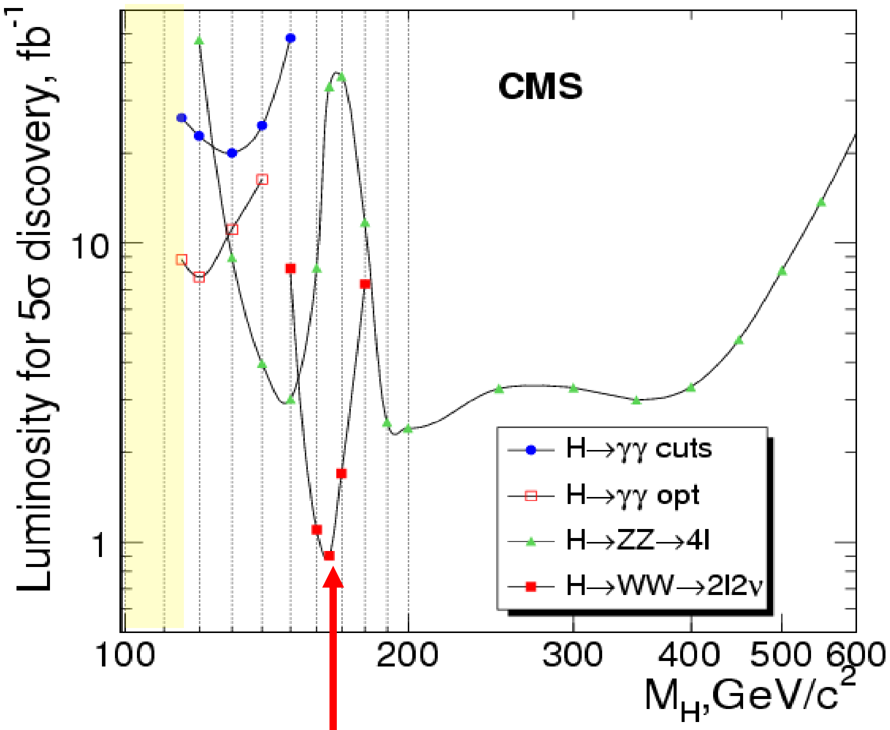




In an Ideal World....

Even including our (naive?) estimates of systematics, the standard model Higgs can be discovered with 1-15 fb^{-1} of data





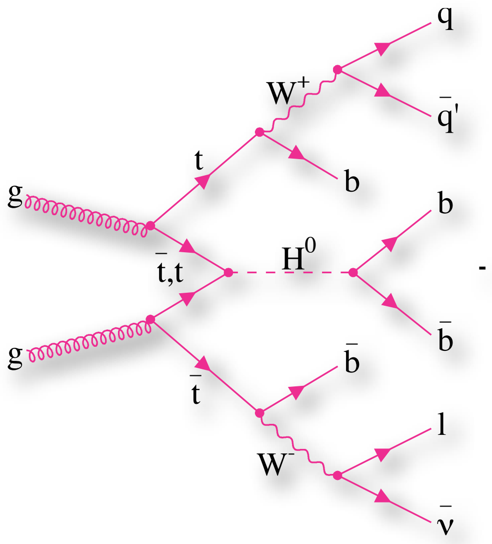
Discovery with ~1 fb^{-1}

Of course, that's well understood

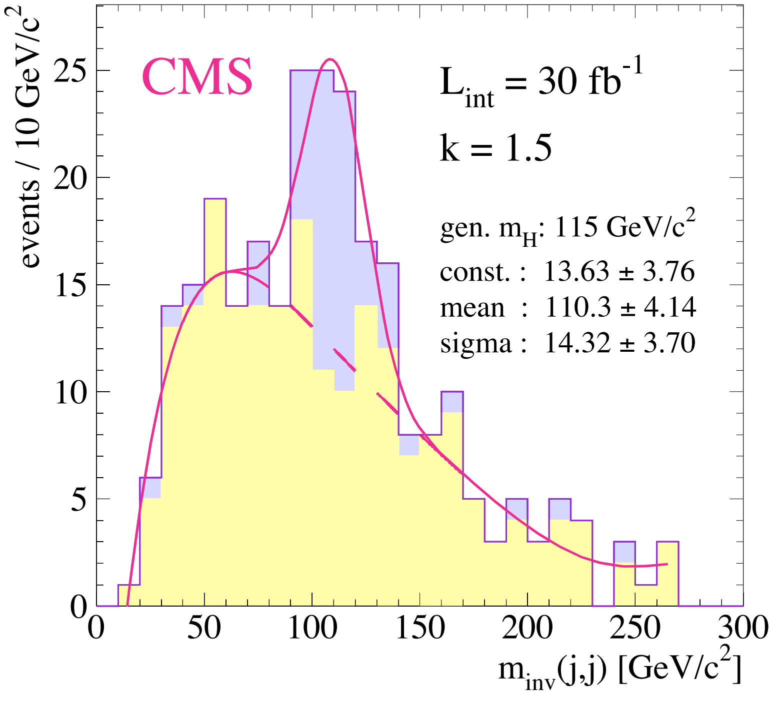
- How long will that take?

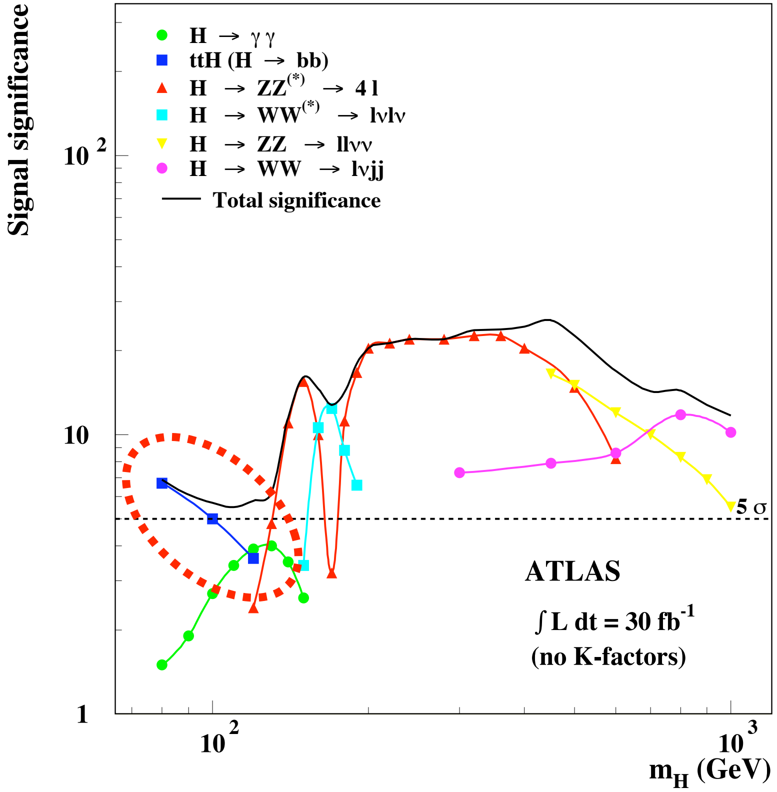
The Rise and Fall of ttH, H→bb

Initially, both ATLAS and CMS indicated ttH with H bb would be a powerful discovery channel near the LEP limit.



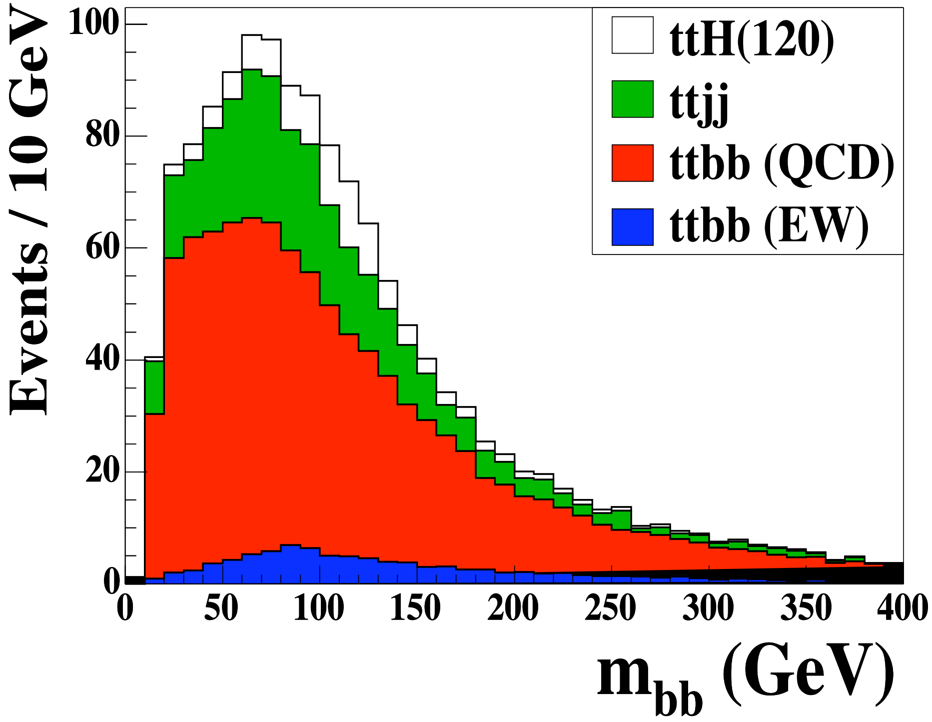
Improved Monte Carlo tools and treatment of systematics now show only marginal sensitivity





ttH (H→bb)

J. Cammin & M. Schumacher, ATL-PHYS-2003-024 (nice thesis by J. Cammin)



Combinatorial background is challenging with $4b$-jets and ≥ 6 jets total

Signal efficiency goes like ϵ_b^4

Signal & bkgnd. have similar shape

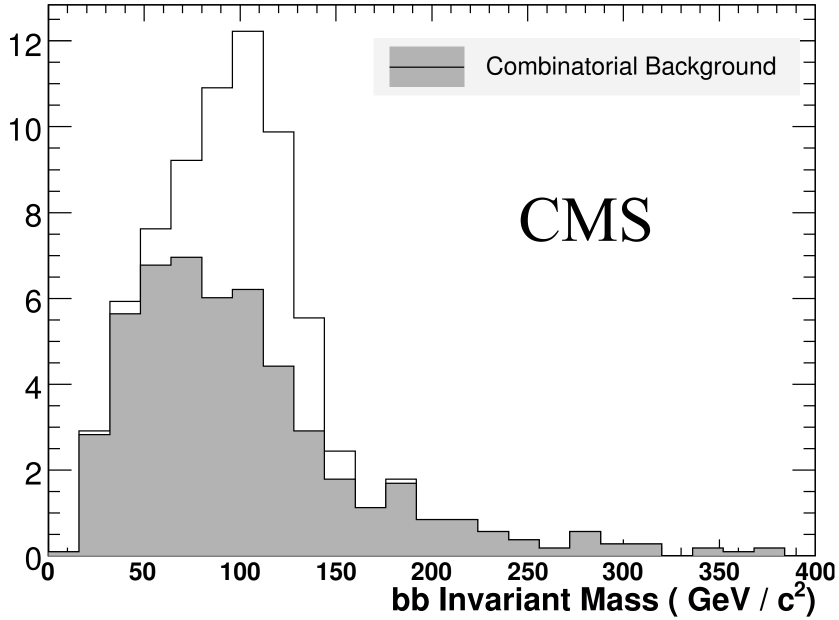
Estimating $ttjj$ and $ttbb$ background from data difficult, large systematics

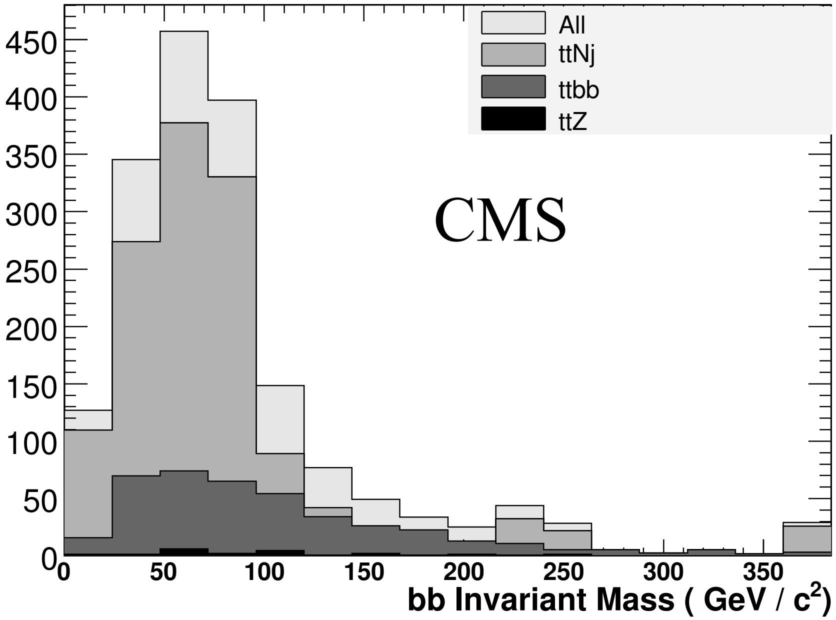
- This is (was) one of the few powerful channels near the LEP limit

It's not clear if this channel will ever reach 5σ

ttH ($H \rightarrow bb$)

ttH (H→bb)

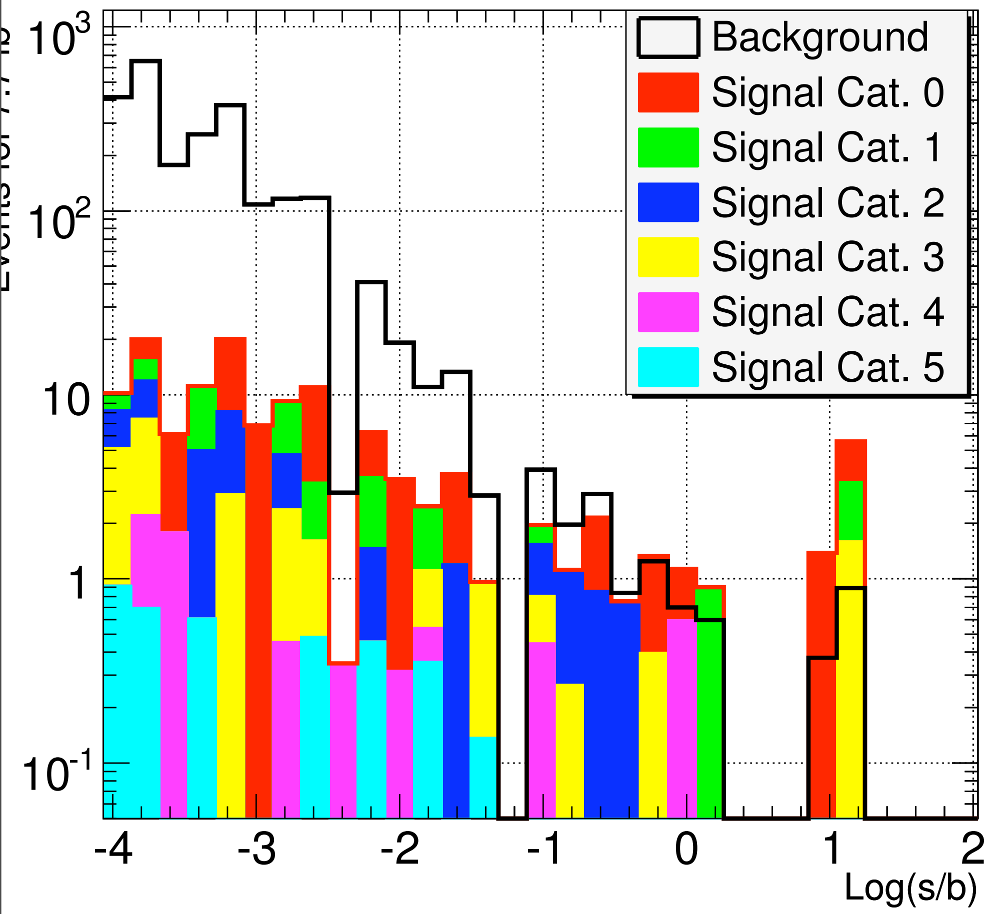

Combinatorial Background
CMS
0
2
4
6
8
10
12
0
50
100
150
200
250
300
350
400
bb Invariant Mass (GeV / c^2)

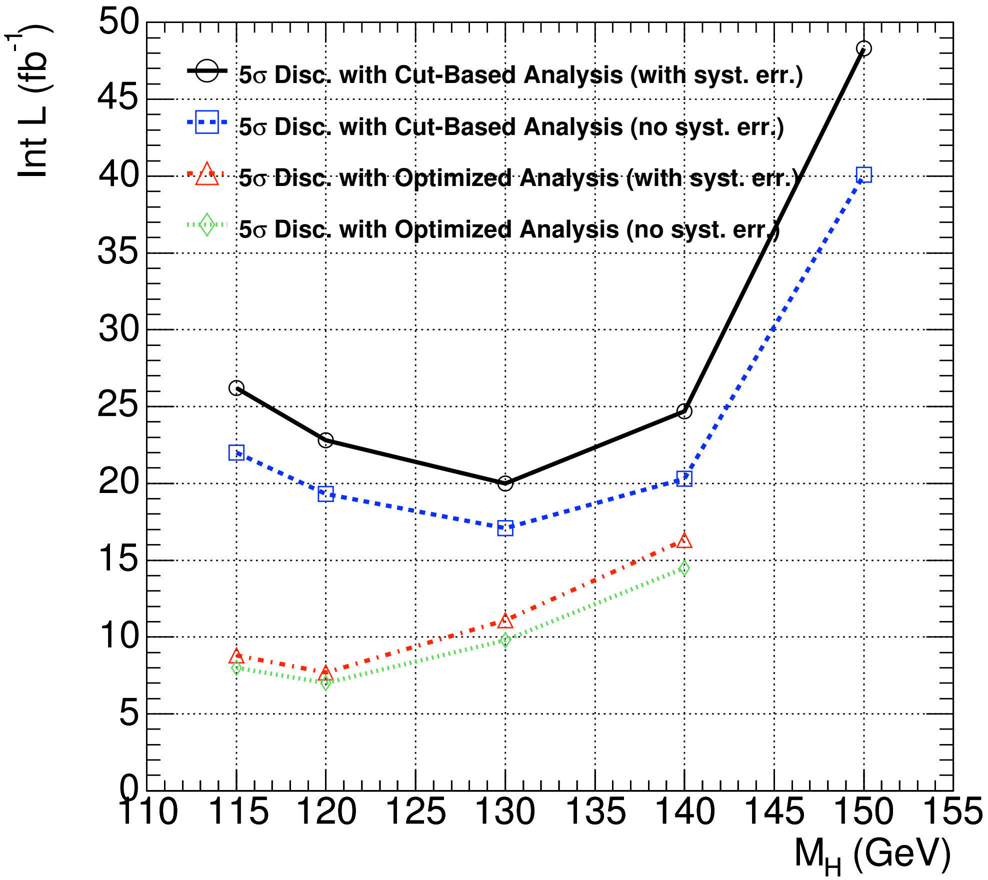

All
ttNj
ttbb
ttZ
CMS
0
50
100
150
200
250
300
350
400
450
0
50
100
150
200
250
300
350
bb Invariant Mass (GeV / c^2)

$H \rightarrow \gamma\gamma$ *Analysis Improvements*

The CMS “optimized analysis” divides events into categories with different s/b

This takes more advantage of “golden events” and improves the power of the analysis



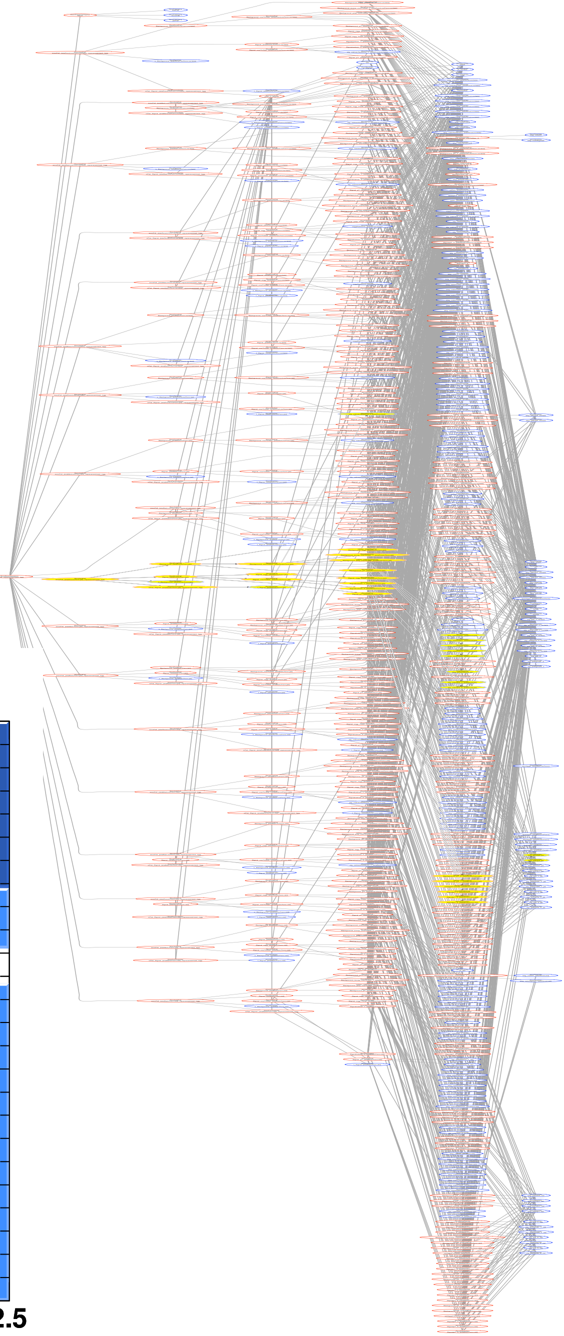


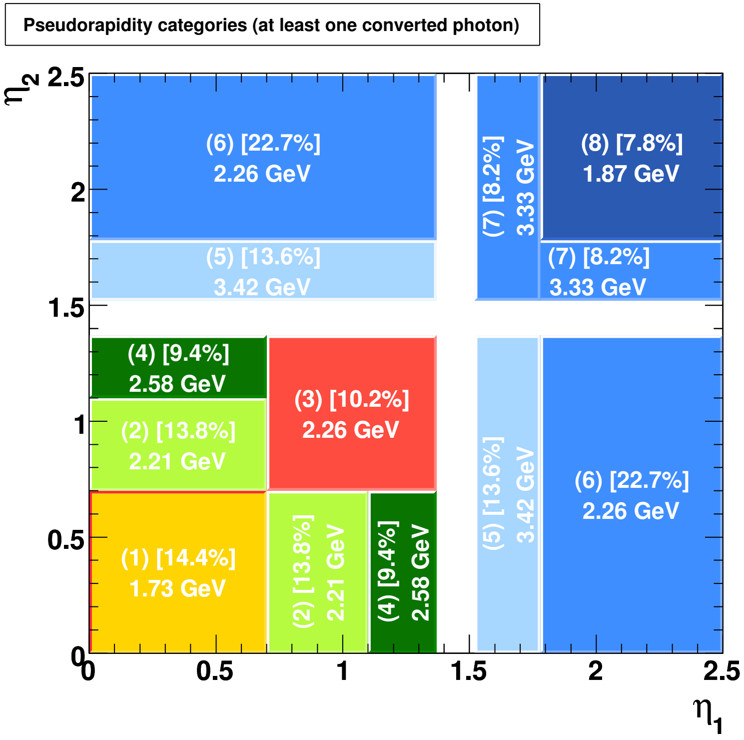
$H \to \gamma\gamma$ Analysis Improvements

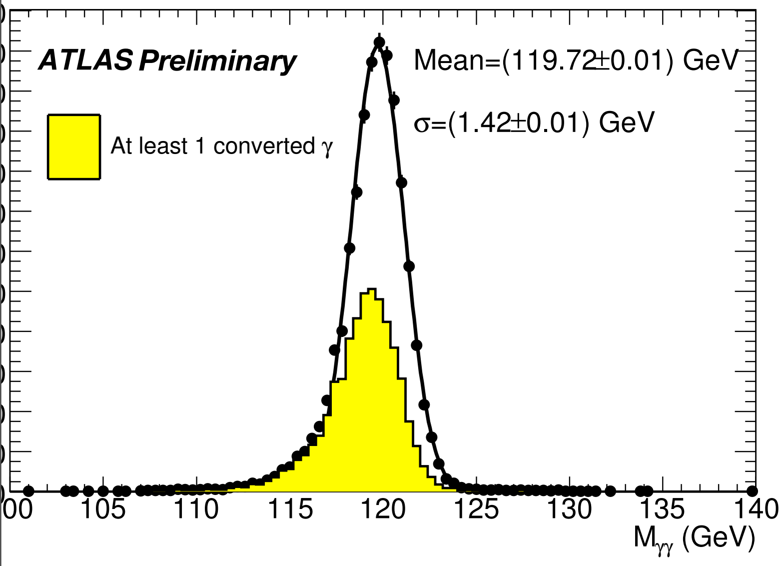
Similarly, ATLAS fits to the $M_{\gamma\gamma}$ spectrum are categorized by the number of jets x conversion status x rapidity region

Similar sensitivity as CMS result

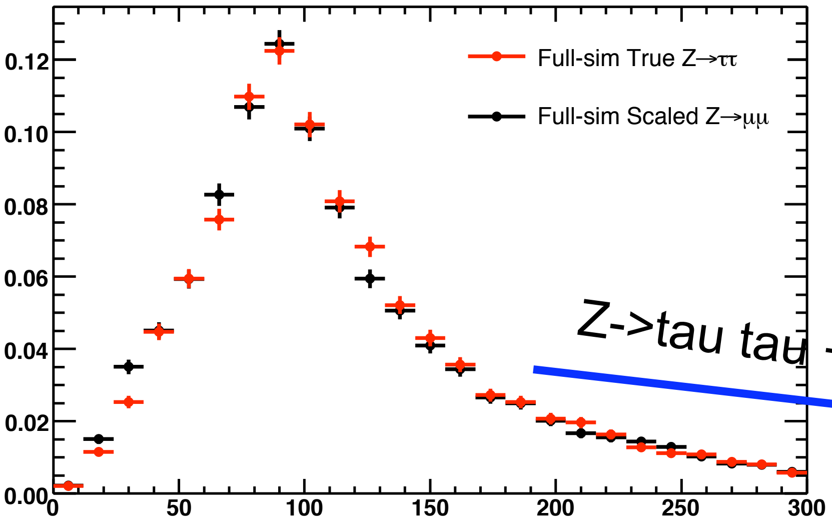
Complex fit represented by this graph



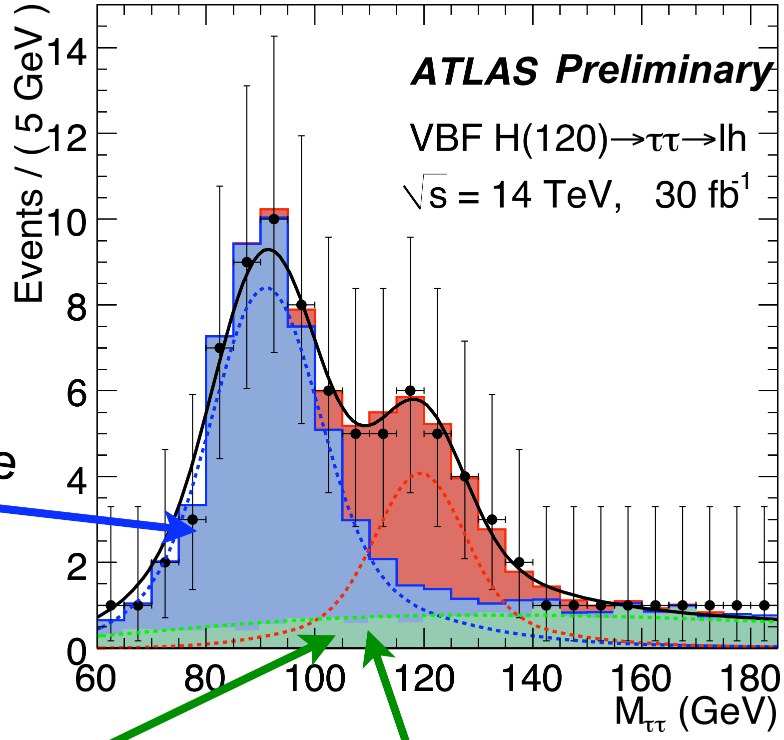


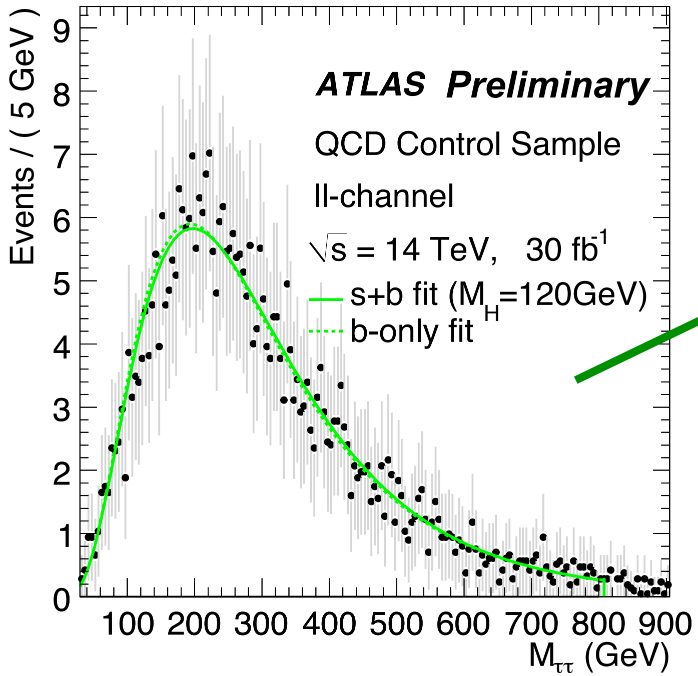


Data-driven background estimation

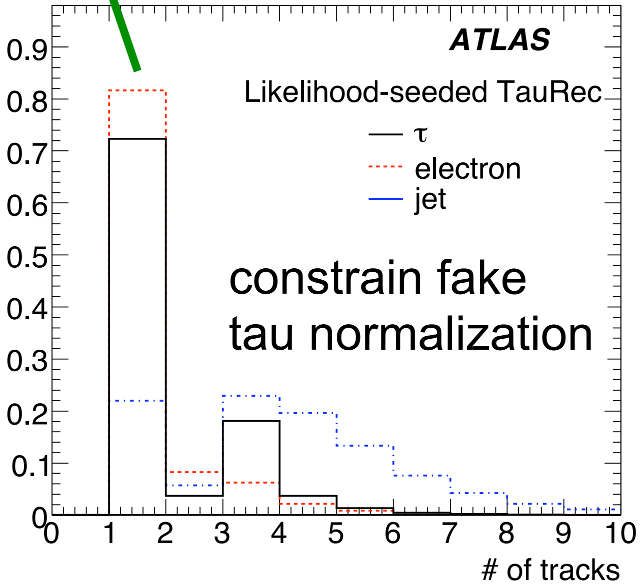


Z->tau tau + jets shape





tt,W+jets, QCD shape



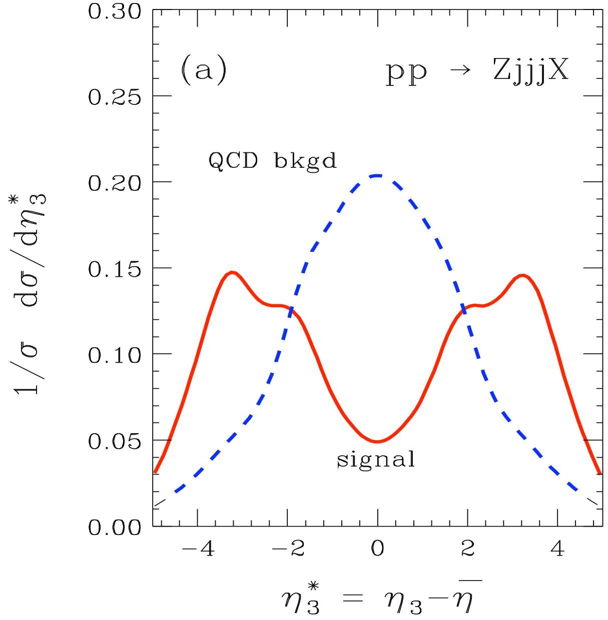
constrain fake tau normalization

Assumed Uncertainties

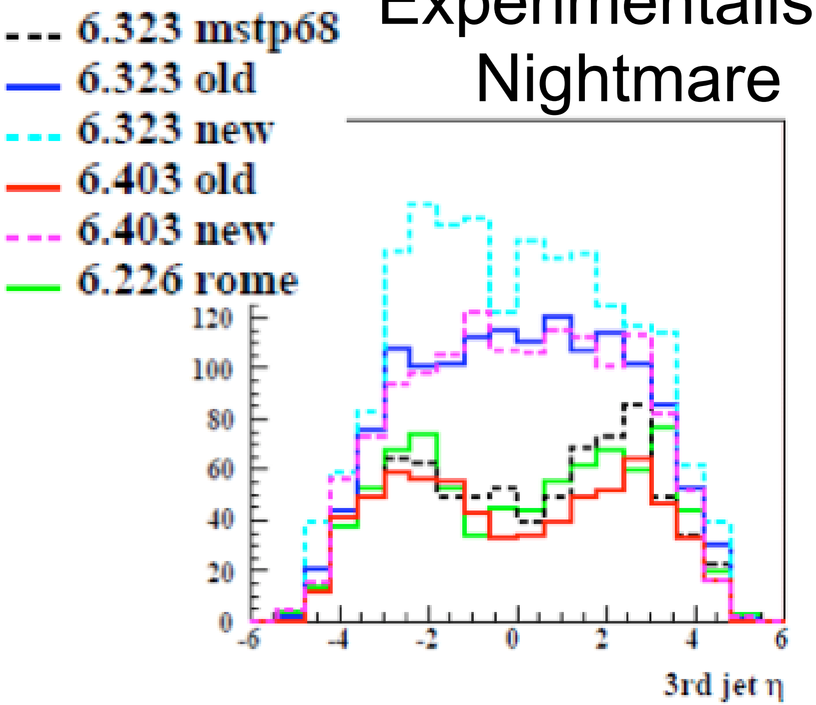
Assumed systematic uncertainties in the coupling measurements

L	5%	Measurement of luminosity
ϵ_D	2%	Detector efficiency
ϵ_L	2%	Lepton reconstruction efficiency
ϵ_γ	2%	Photon reconstruction efficiency
ϵ_b	3%	b-tagging efficiency
ϵ_τ	3%	hadronic τ-tagging efficiency
ϵ_{Tag}	5%	WBF tag-jets / jet-veto efficiency
ϵ_{Iso}	3%	Lepton isolation ($H \to ZZ \to 4\ell$)

Theorist's Dream



Experimentalist's Nightmare



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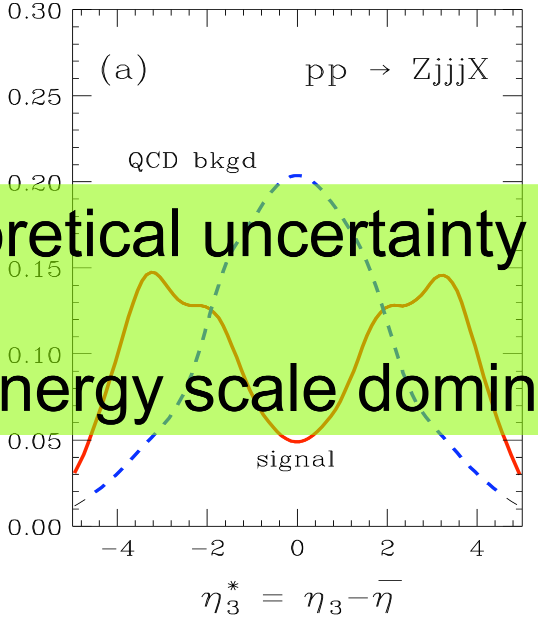
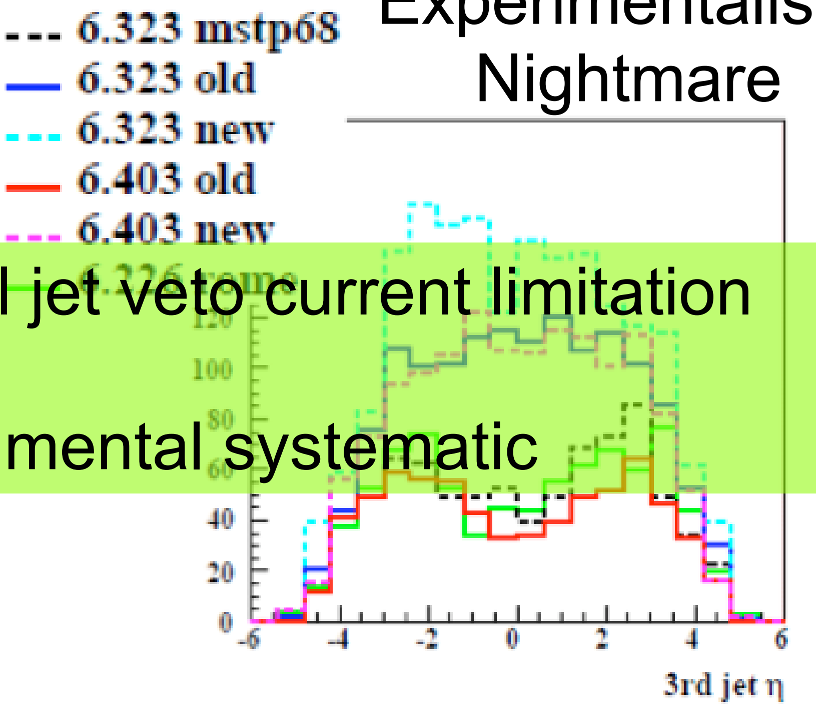


Experimentalist’s Nightmare



Theoretical uncertainty on central jet veto current limitation

Jet energy scale dominant experimental systematic

Comment on systematics

For the last several years focus in Monte Carlo community was on improving modeling of backgrounds

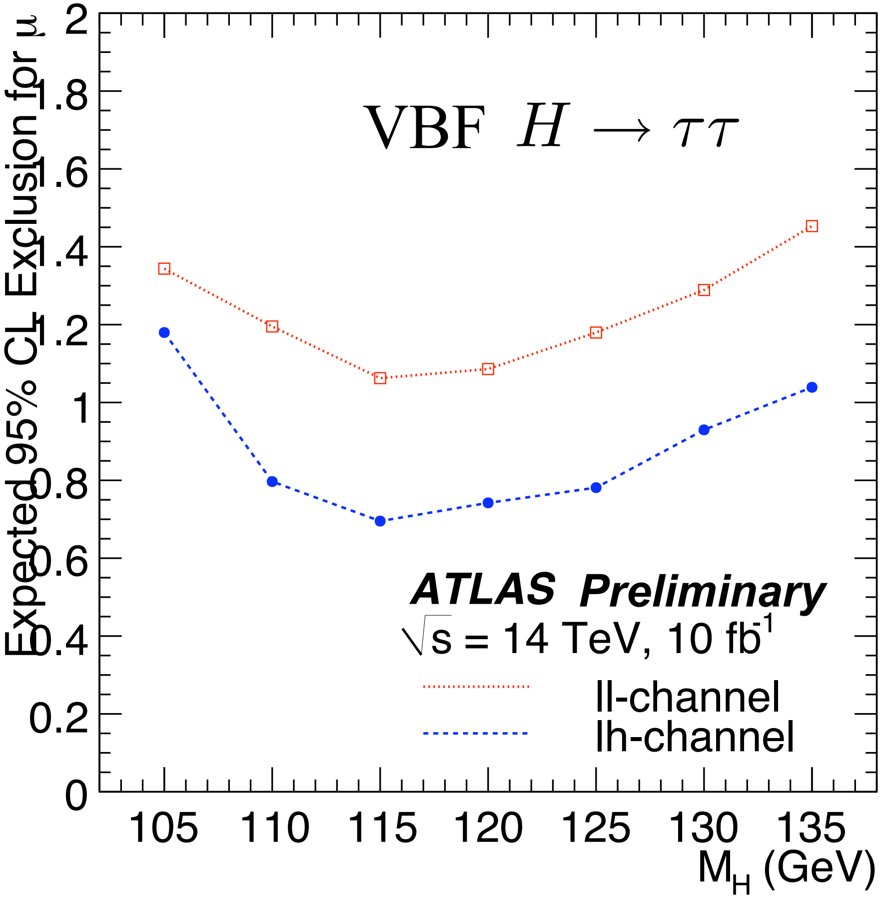
- "The signal is easy"

That was the right strategy for understanding our physics potential

As we move into data-taking period, we are focusing on data-driven background estimation

Monte Carlo is used to inform parametrizations and occasionally for extrapolation

Monte Carlo is crucial for understanding signal, and theoretical uncertainties in the signal limit several measurements

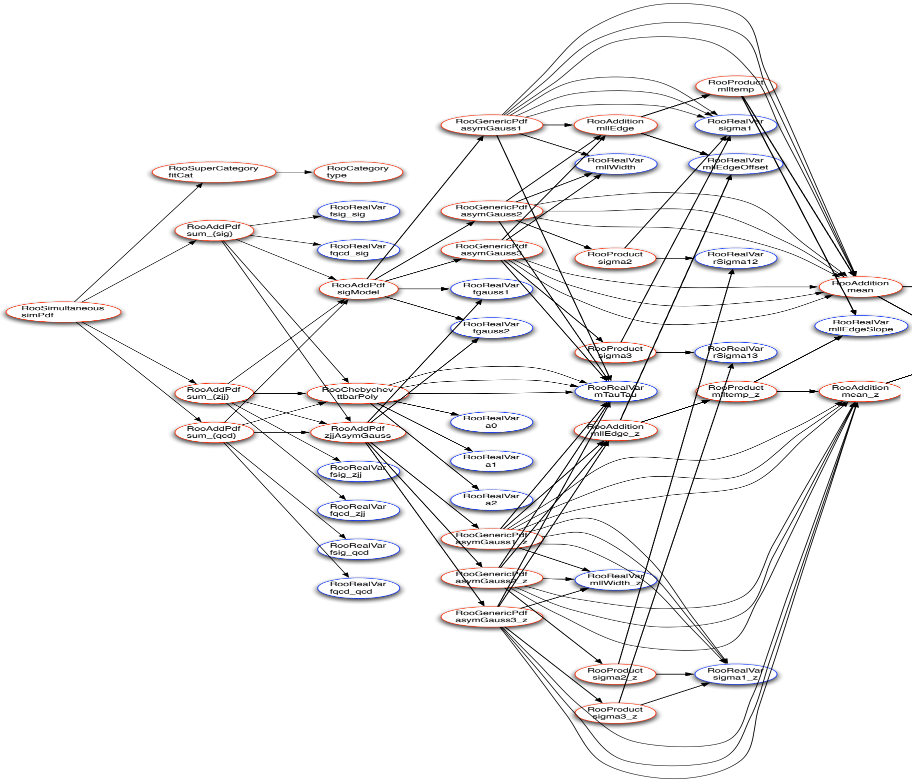


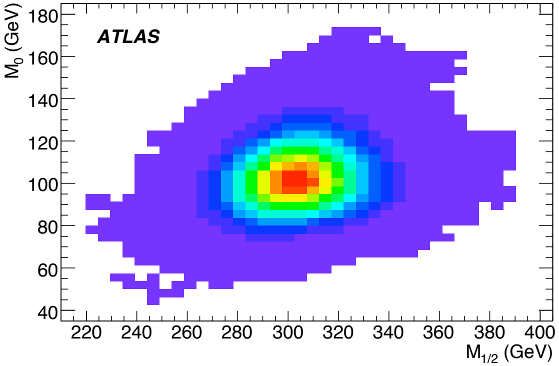
Digital Publishing

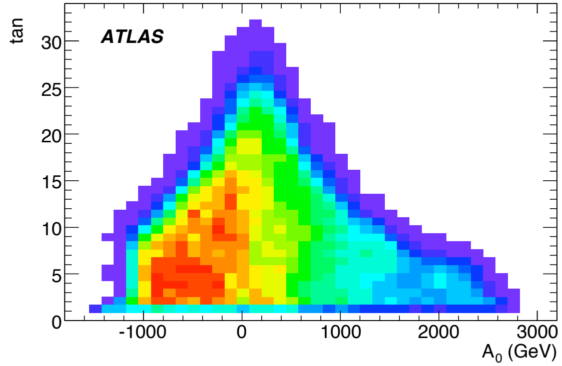
In order to combine channels within an experiment or to combine ATLAS and CMS results, we are developing the technology to package the full likelihood function that relates observables to measured physics quantities

My hope is that we will move from publishing 2-d contours in a plot to publishing full likelihood maps of the parameter space. That is now technically possible.

This opens up a discussion on what is the ideal model-neutral and model-relevant parametrization







Conclusions

After a long wait, the LHC is just around the corner!

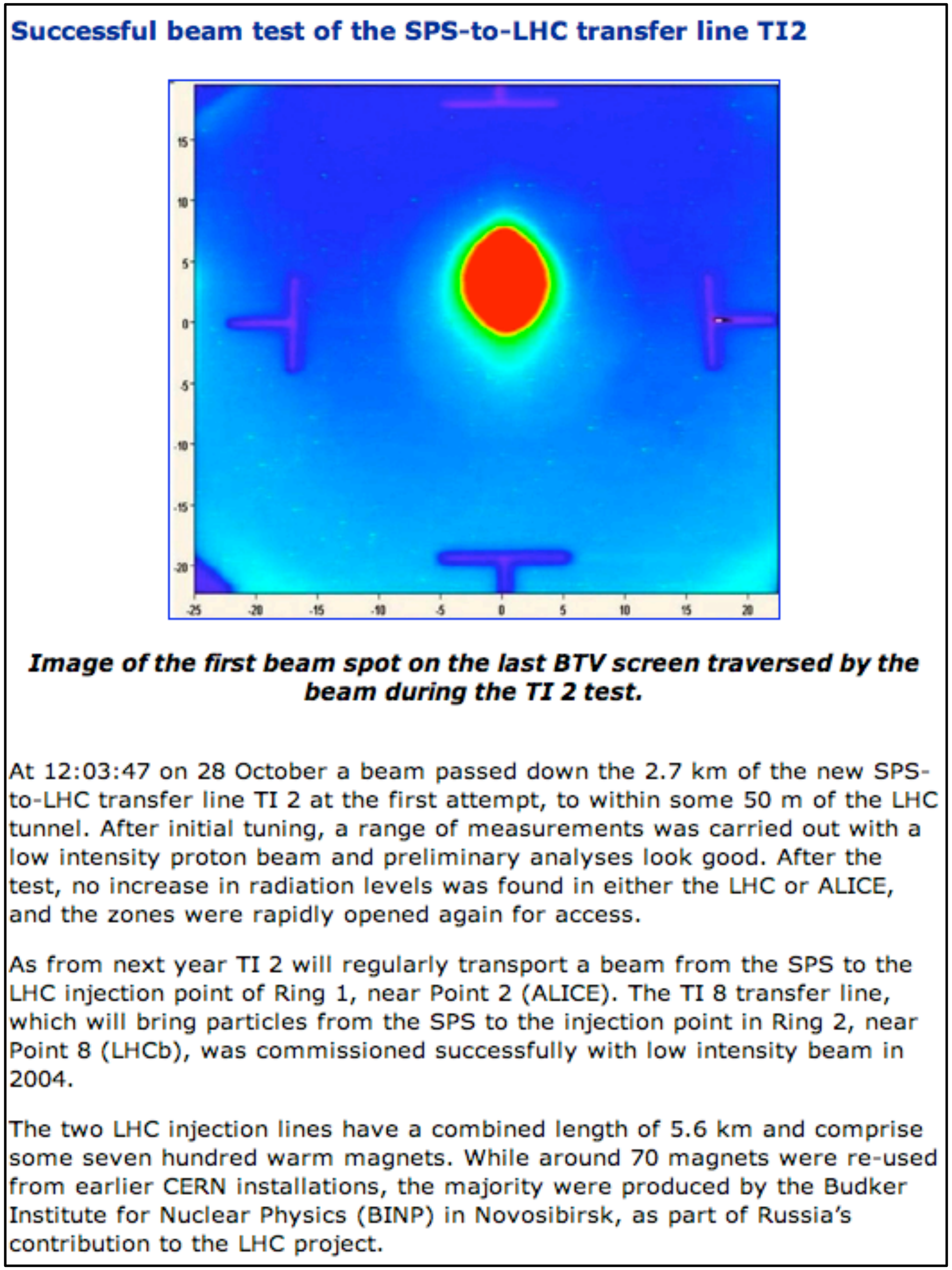
- We expect to see beam this summer and collisions in the fall!

The first year will mainly be a learning experience and any physics will probably be “re-discovering the standard model”

As we enter the data taking period, the role and interaction of theory, phenomenology, and experiment will evolve.

Wish us luck!

Successful beam tests



Successful beam test of the SPS-to-LHC transfer line TI2

Image of the first beam spot on the last BTV screen traversed by the beam during the TI 2 test.

At 12:03:47 on 28 October a beam passed down the 2.7 km of the new SPS-to-LHC transfer line TI 2 at the first attempt, to within some 50 m of the LHC tunnel. After initial tuning, a range of measurements was carried out with a low intensity proton beam and preliminary analyses look good. After the test, no increase in radiation levels was found in either the LHC or ALICE, and the zones were rapidly opened again for access.

As from next year TI 2 will regularly transport a beam from the SPS to the LHC injection point of Ring 1, near Point 2 (ALICE). The TI 8 transfer line, which will bring particles from the SPS to the injection point in Ring 2, near Point 8 (LHCb), was commissioned successfully with low intensity beam in 2004.

The two LHC injection lines have a combined length of 5.6 km and comprise some seven hundred warm magnets. While around 70 magnets were re-used from earlier CERN installations, the majority were produced by the Budker Institute for Nuclear Physics (BINP) in Novosibirsk, as part of Russia's contribution to the LHC project.