Challenges for early discovery in ATLAS and CMS

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NIKHEF Amsterdam

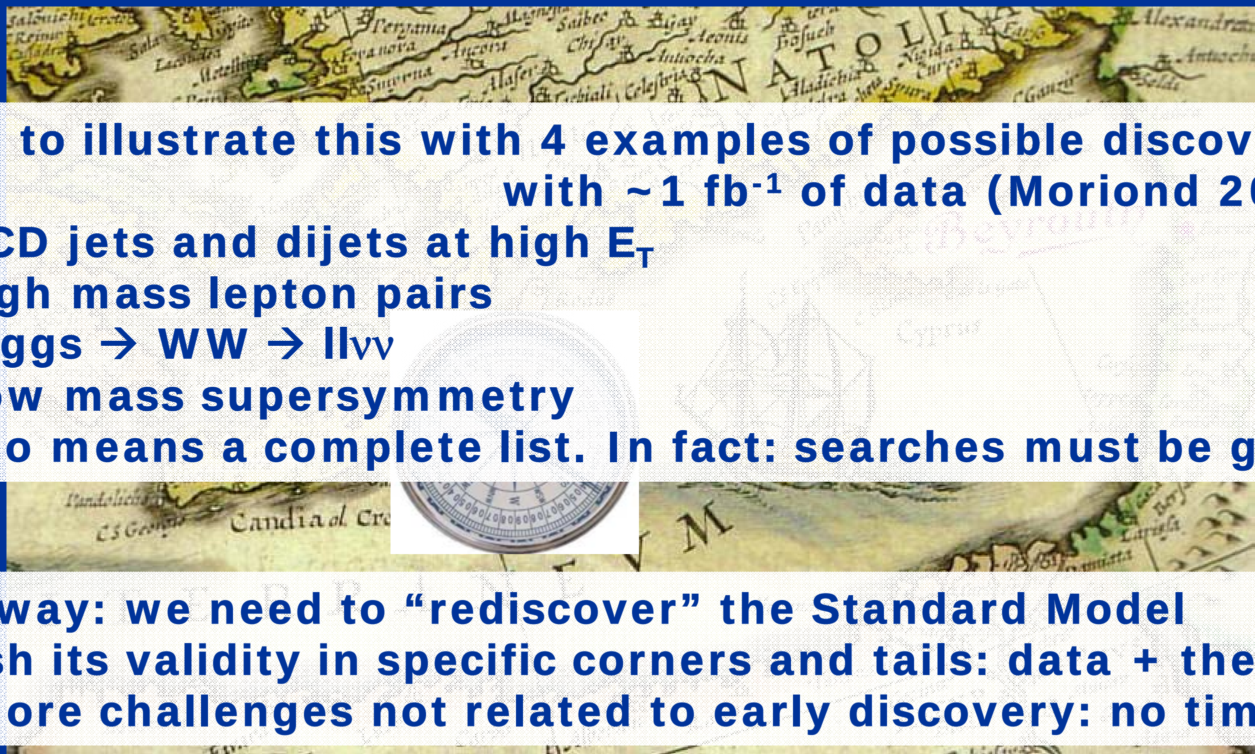
Rencontres de Moriond 2007
Electroweak interactions and Unified theories

Outline

Often remarked: LHC can make discoveries with one month of data.

Maybe correct. But not the first month of data…

pp at 14 TeV, ATLAS and CMS: new territory.
Need to find the north, make a map, firm ground under our feet.



Plan to illustrate this with 4 examples of possible discoveries with ~1 fb^{-1} of data (Moriond 2009?):

- QCD jets and dijets at high E_T
- high mass lepton pairs
- Higgs → WW → $ll\nu\nu$
- Low mass supersymmetry

By no means a complete list. In fact: searches must be general

On the way: we need to “rediscover” the Standard Model
Establish its validity in specific corners and tails: data + theory
Many more challenges not related to early discovery: no time to cover

First challenge: get the LHC operational

Still on course for engineering run fall 2007:
- system commissioning
- single beam operations at 450 GeV
- collisions at 450 x 450 GeV, no ramp, no squeeze
  - → low luminosity: ATLAS/CMS commissioning

First collisions at 14 TeV: June 2008 ?
- after system and beam commissioning
  - 26 weeks of proton-proton physics run in 2008
- phase 1: 43 bunches, $L \sim 5 \times 10^{30}$
- phase 2: 75 ns, $L \sim 2.5 \times 10^{31}$ → 1×10^{32}
- phase 3: 25 ns, $L \sim 4 \times 10^{32}$ → 1×10^{33} $cm^{-2}s^{-1}$

Integrated luminosity end of 2008: 0.5 - 1 fb^{-1} ?
(e.g.: 1 fb^{-1} = 120 effective days @ 10^{32} $cm^{-2}s^{-1}$)

And the experiments too: huge challenge

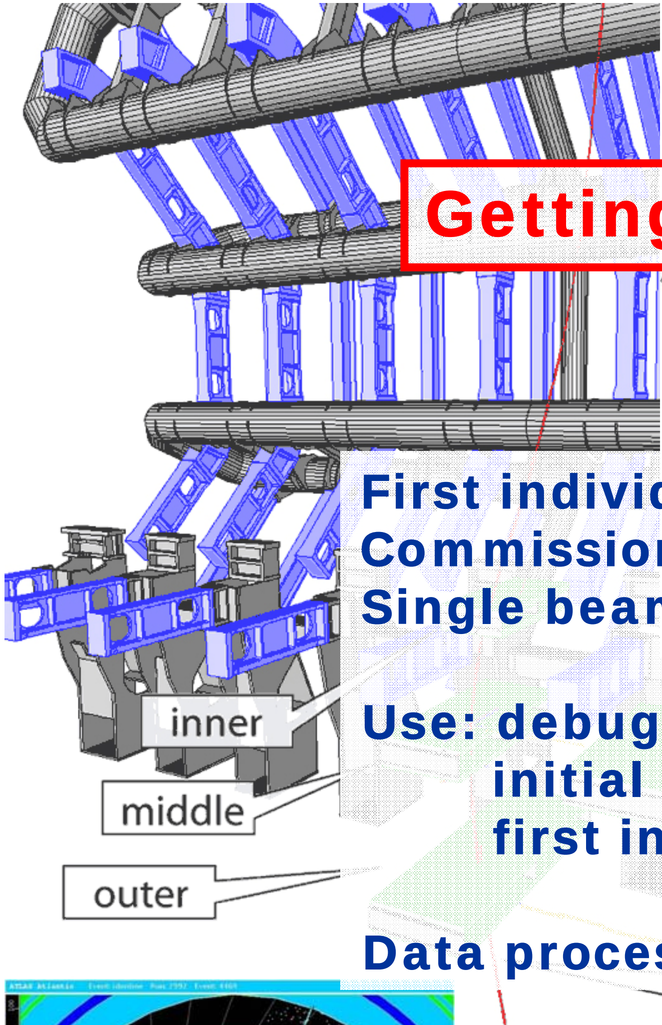
Getting the subdetectors built, tested and installed.
Power and signal cables, detector control and monitoring
Cooling pipes, cryogenic installations, magnets...

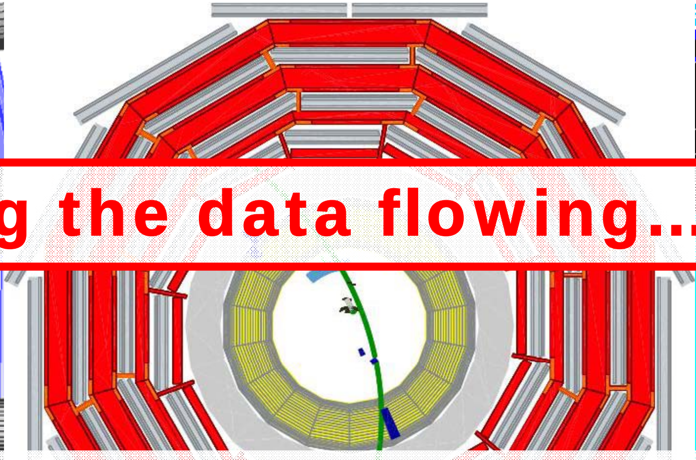
CMS: lowered central part (YB0) February 28th , rest soon
will run in 2007 without ECAL endcap and pixels
rest going well

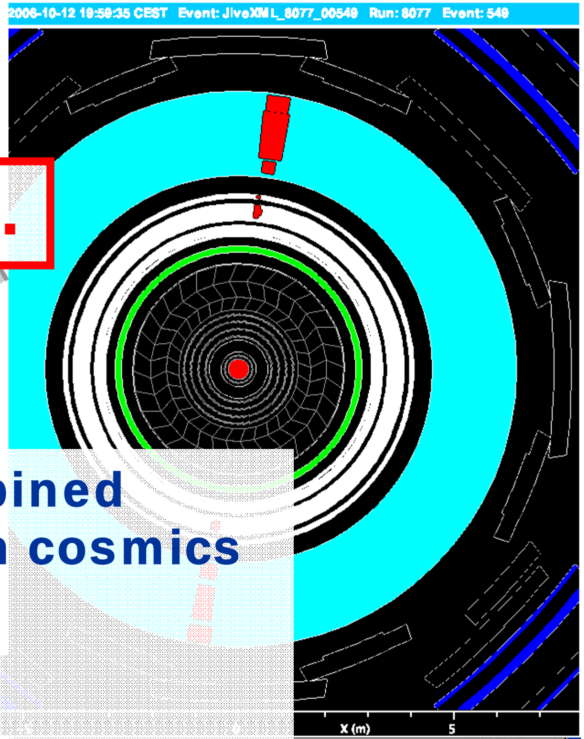
ATLAS: on a tight schedule to run almost complete in 2007
No TRT at high $|\eta|$, some muon chambers missing

Both will have reduced trigger/DAQ capabilities initially

Getting the data flowing…



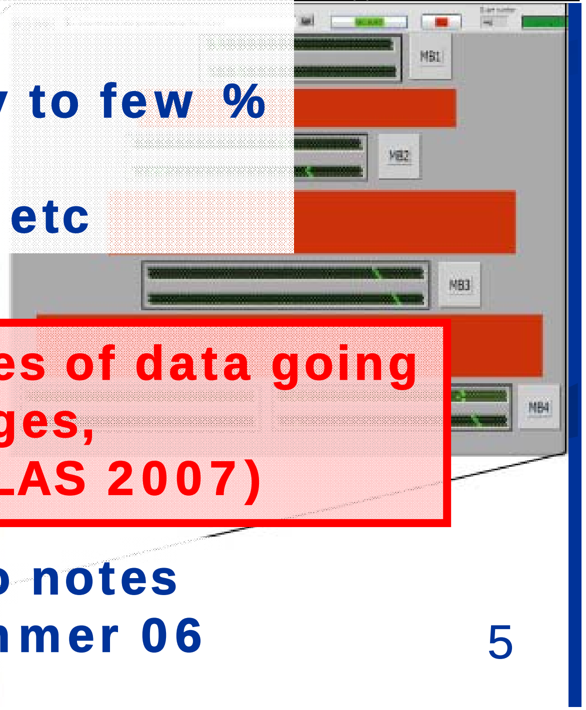


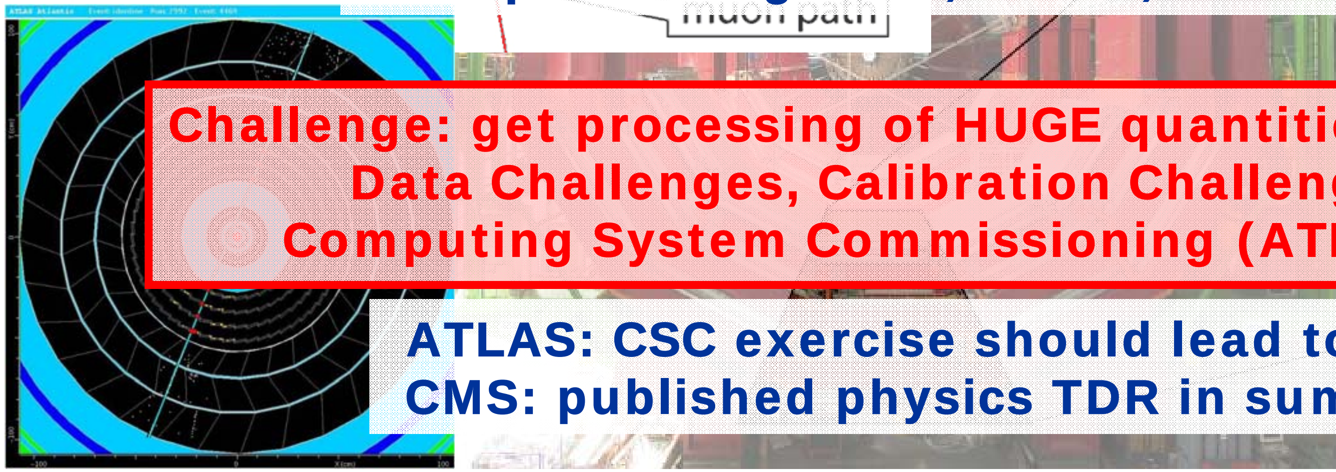


First individual detectors, then combined
Commissioning the DAQ system with cosmics
Single beam in LHC: beam halo

Use: debug cabling errors
initial alignment
first intercalibration: uniformity to few %

Data processing: Grid, Tier-1, Tier-2 etc





Challenge: get processing of HUGE quantities of data going
Data Challenges, Calibration Challenges,
Computing System Commissioning (ATLAS 2007)

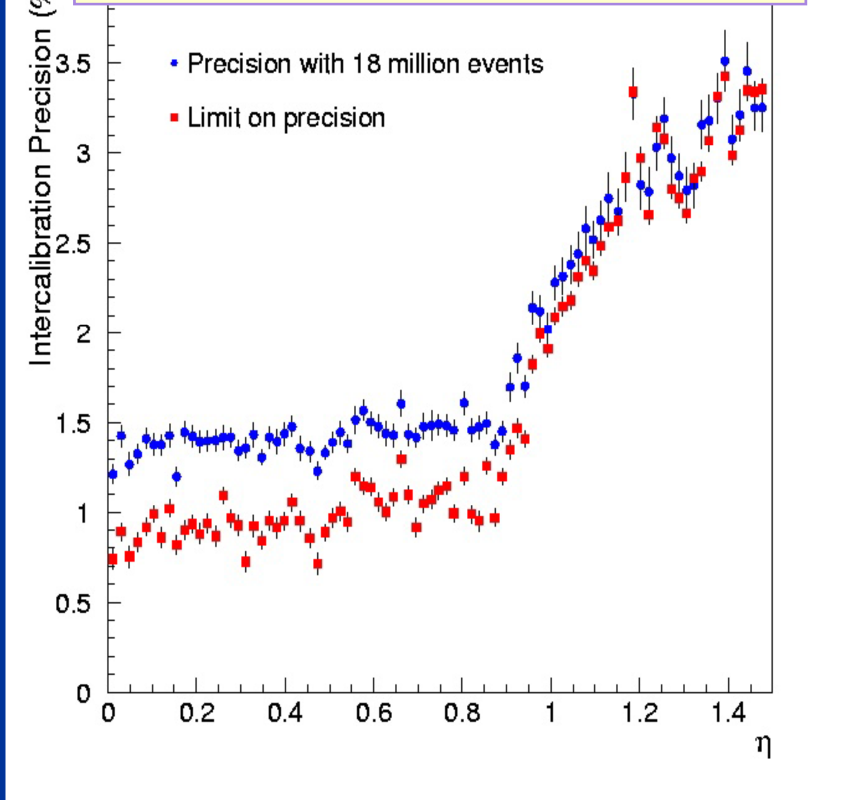
ATLAS: CSC exercise should lead to notes
CMS: published physics TDR in summer 06

Use of 2007 data (at 900 GeV)

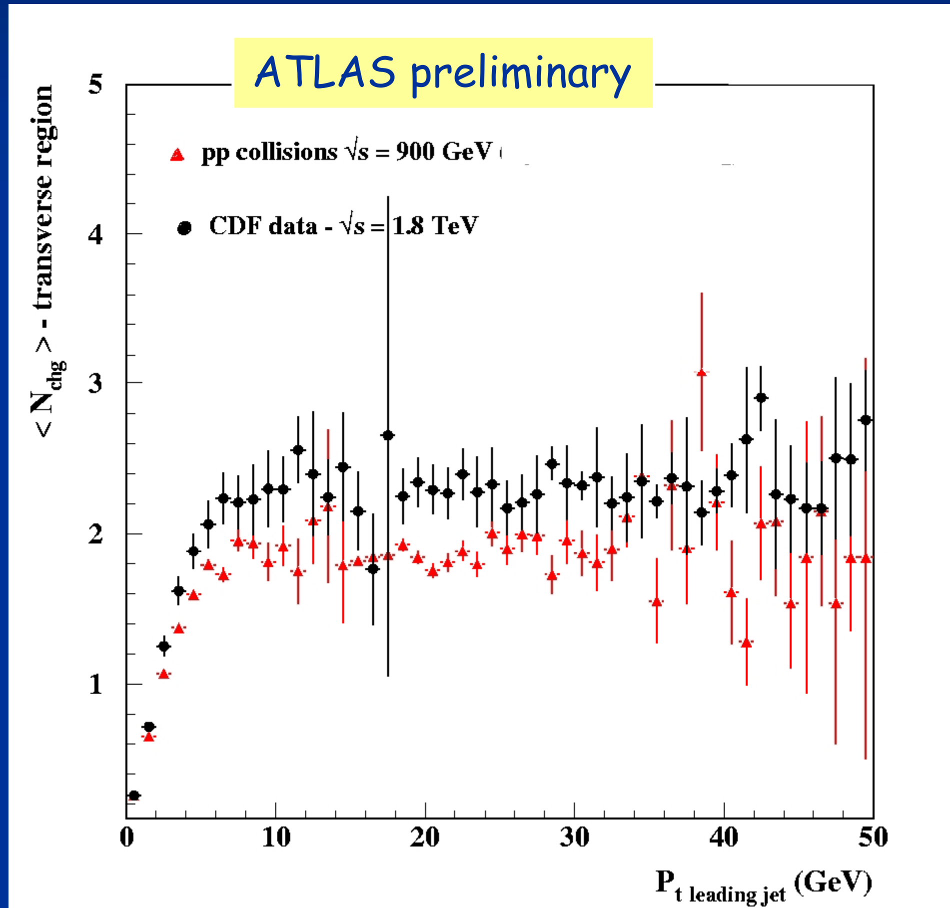
100 nb^{-1} ? No W,Z; few J/ψ; mostly minimum bias, some jets

CMS ECAL intercalibration:

~ 1.5% calibration uniformity achievable in central barrel with 18 million minimum-bias (few days of data taking in 2007)



Commissioning of tracking:



~ 15 days of data taking in 2007 enough to cover up to p_T(leading jet) ~ 40 GeV

What do we expect to see at 14 TeV?

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

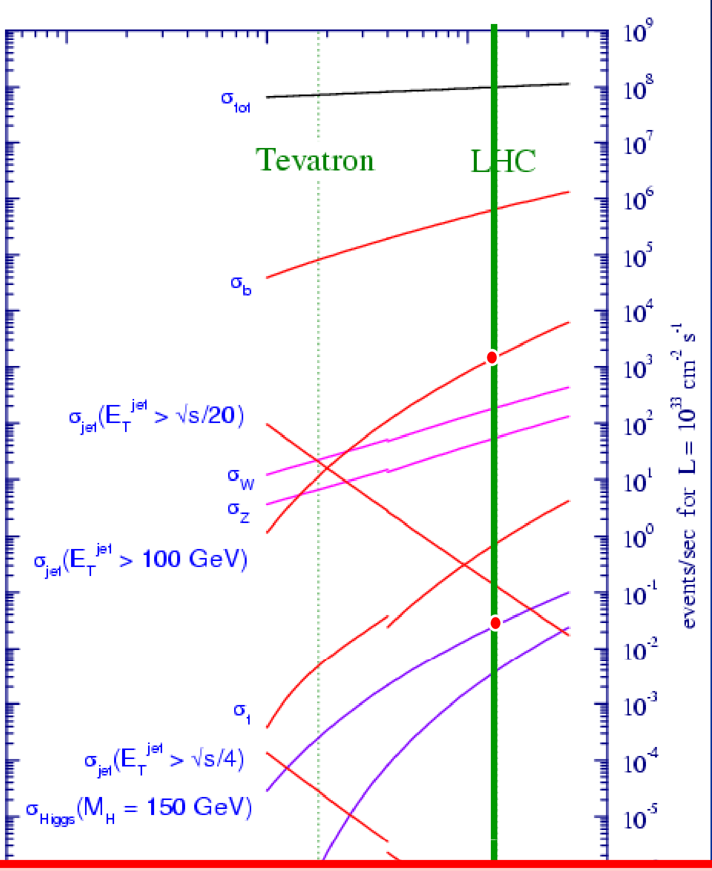
10^6 / s

10^3 / s

1 / s

1 / hr

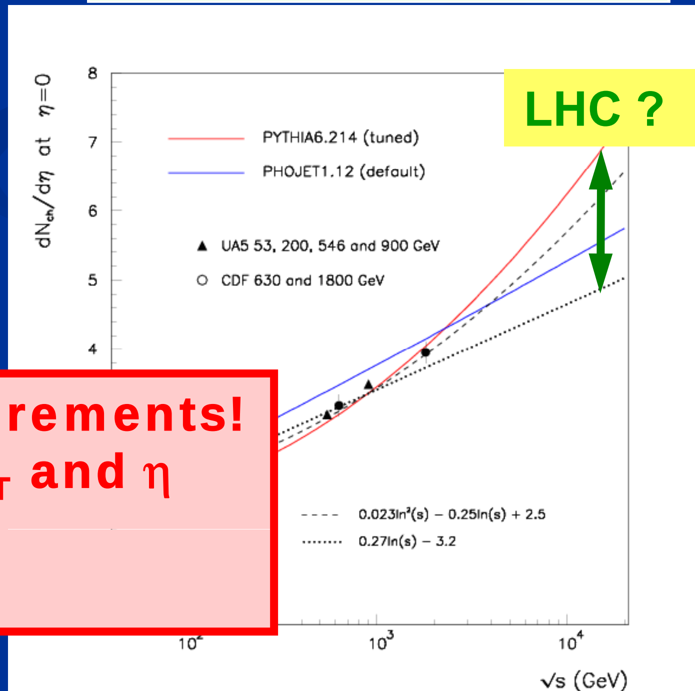
1 / day



Low p_T hadronic events ("minimum bias")

Modeled in various generators, but big uncertainties

$\langle N_{ch} \rangle$ at η =0 for generic pp collisions (minimum bias)



Probably the first CMS / ATLAS measurements!
Charged particle multiplicities vs p_T and η
Particles away from jet regions
(No time to cover here)

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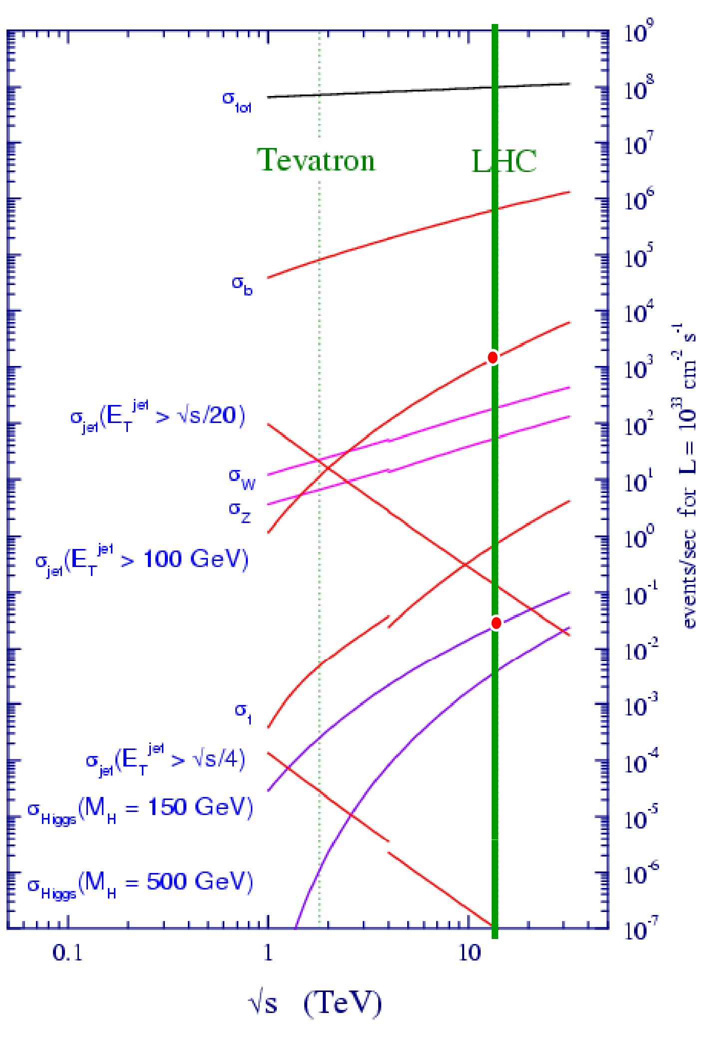
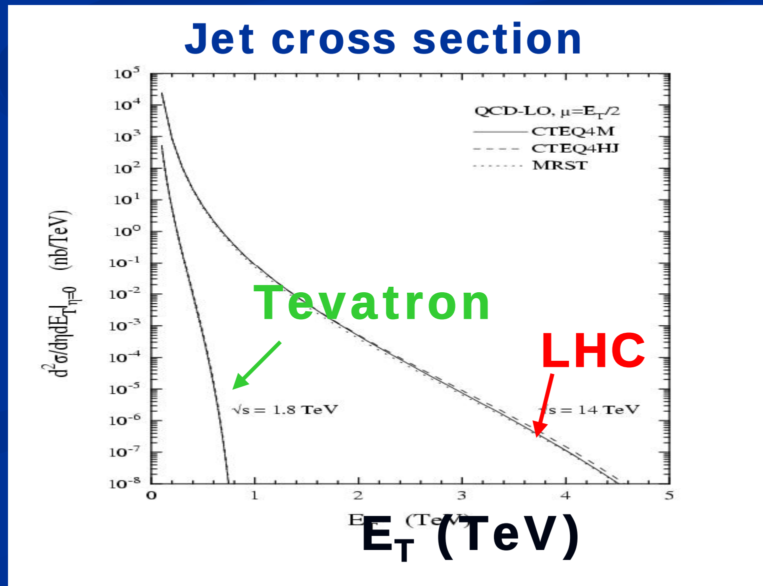


QCD jets, jets and more jets

Standard candles: W, Z, top

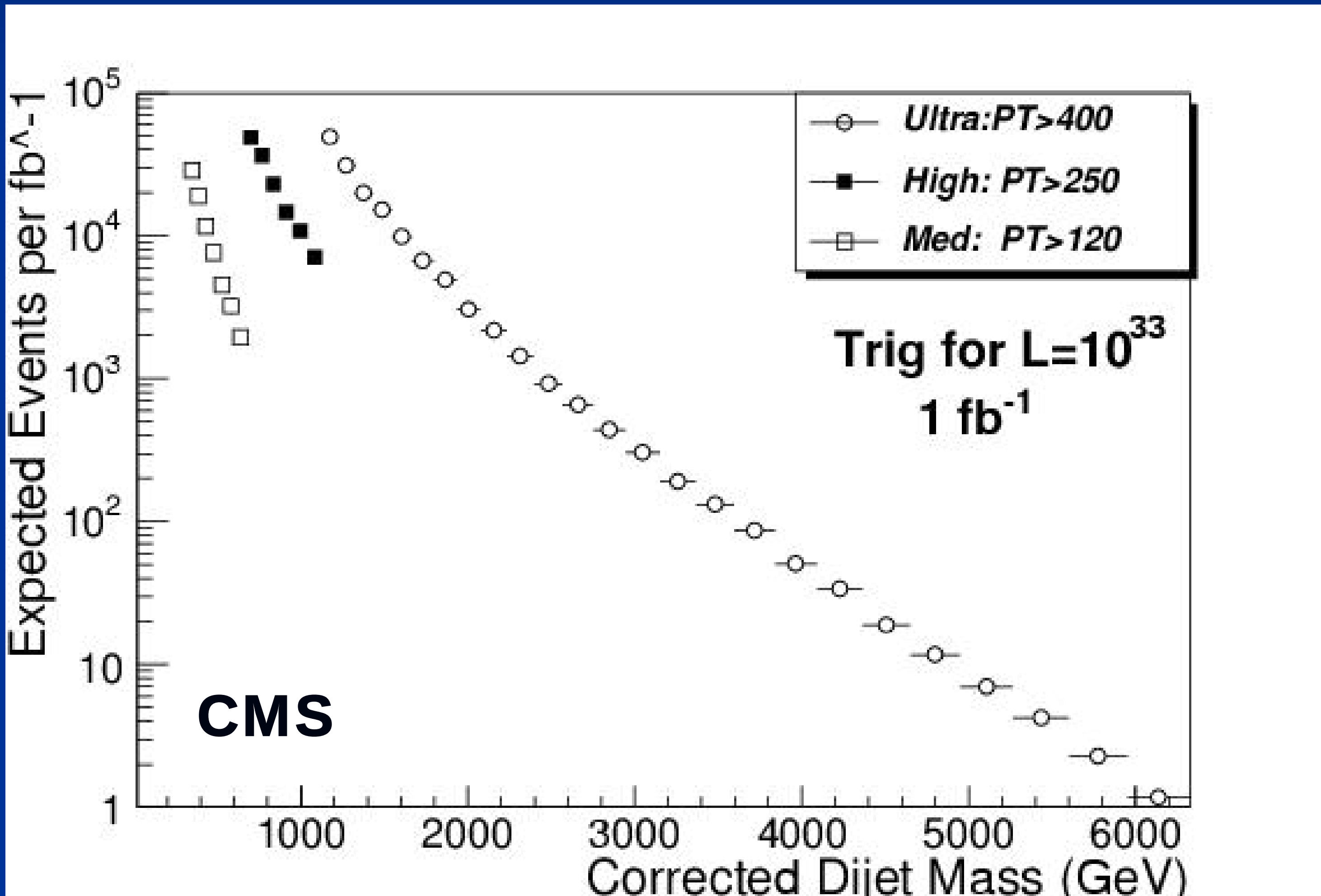
SM Higgs

Perhaps new physics



Example 1 of possible early discovery: anomalies in high E_T QCD jets, di-jet masses

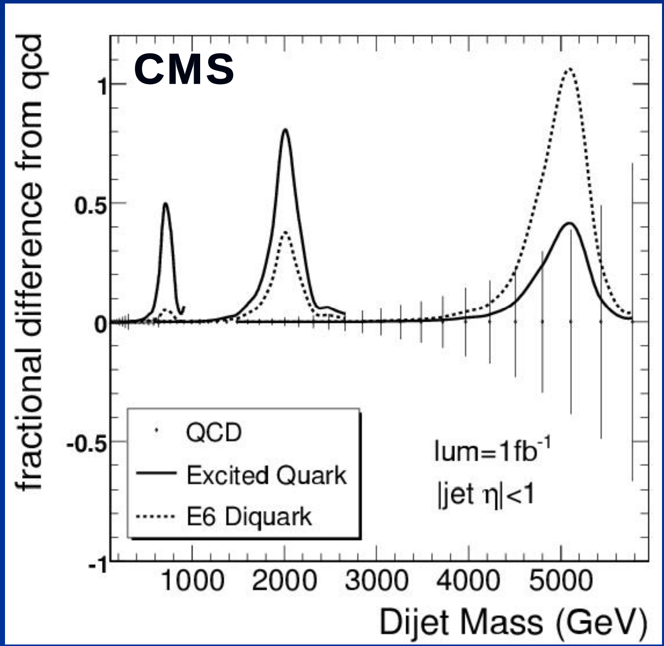
1 fb^{-1} : jets up to 3-3.5 TeV, di-jet masses up to 6 TeV: **new territory!**

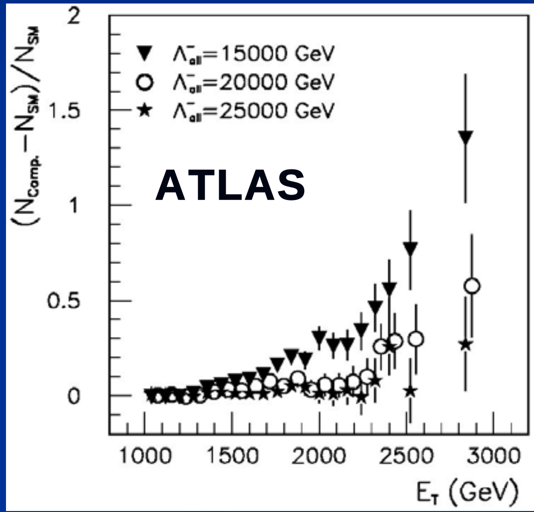


Example 1 of possible early discovery: anomalies in high E_T QCD jets, di-jet masses

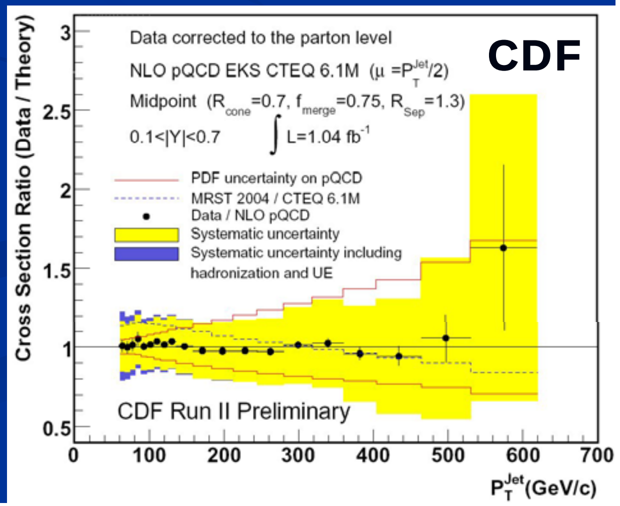
1 fb^{-1} : jets up to 3-3.5 TeV, di-jet masses up to 6 TeV: new territory!

Sensitive to substructure, contact interactions, high mass resonances





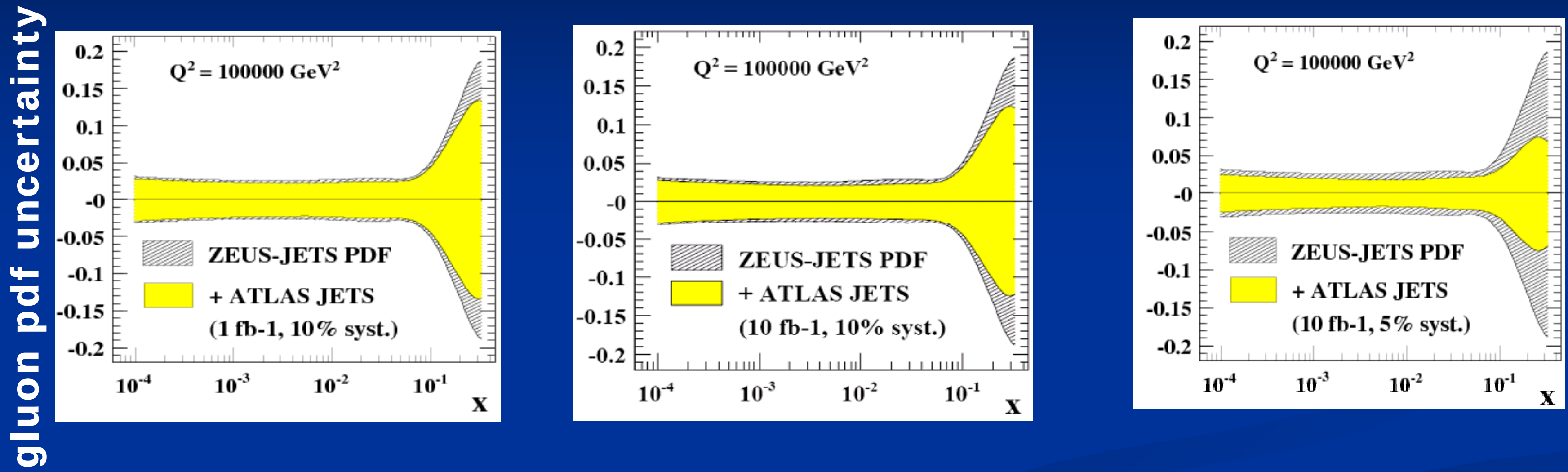
Deviations from SM for various compositeness scales, 30 fb^{-1}



Challenges: Jet energy scale,
Parton density functions (PDF)
(notably: gluon at high x),
underlying event, trigger,
scale variation, hadronization

Challenge: Parton Density Function uncertainties

Uncertainty on the gluon pdf, and can LHC jet data help?:



Further pdf information from W, Z production: no info on high x gluon pdf information from γ+ jet does help.

Does PDF fitting sweep new physics under the rug? Measure over large kinematic range: new physics central, PDF everywhere

Beyond 1 fb^{-1} : needs reduction of systematics: jet energy scale

Challenge: Jet energy scale

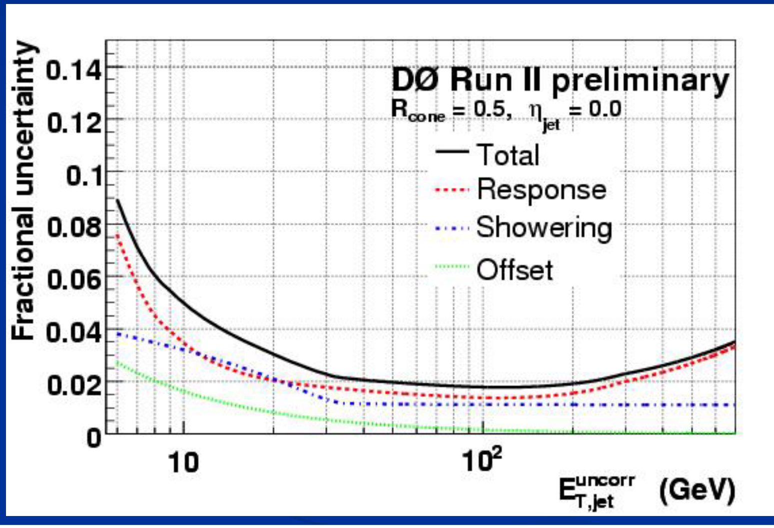
Validation of the energy of a jet is a <u>BIG challenge</u>

Startup: uncertainty ~10% , from test beam, calibration, cosmics
First data: embark on data-driven JES derivation

e.g. D0: 5 years of run II data:

$$E_{cor} = \frac{E_{raw} - offset}{F_{\eta} \bullet response \bullet showering}$$

Using γ+jet and dijet events

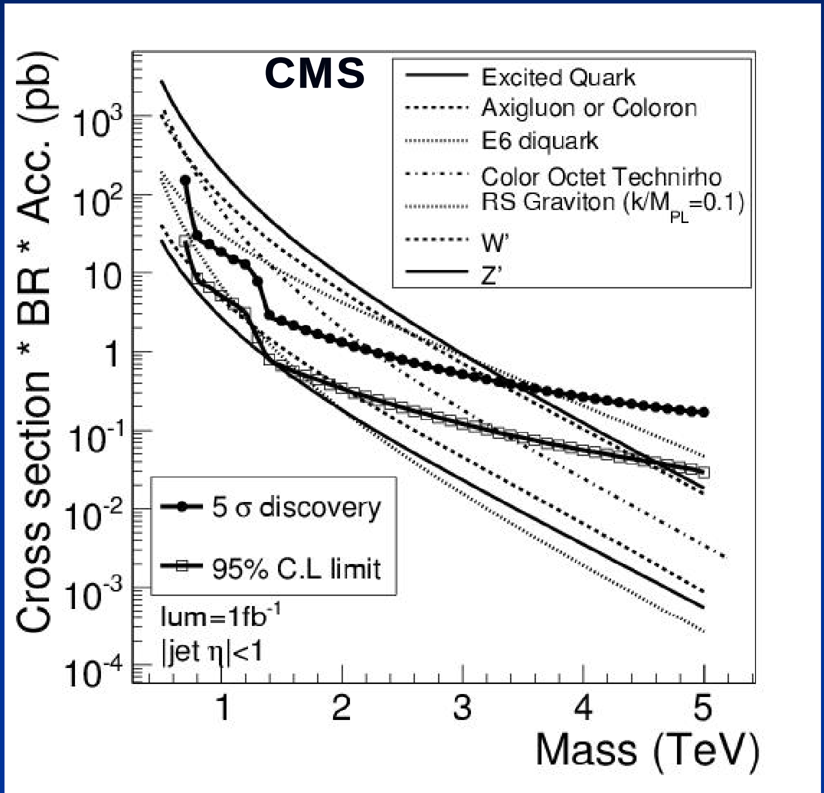


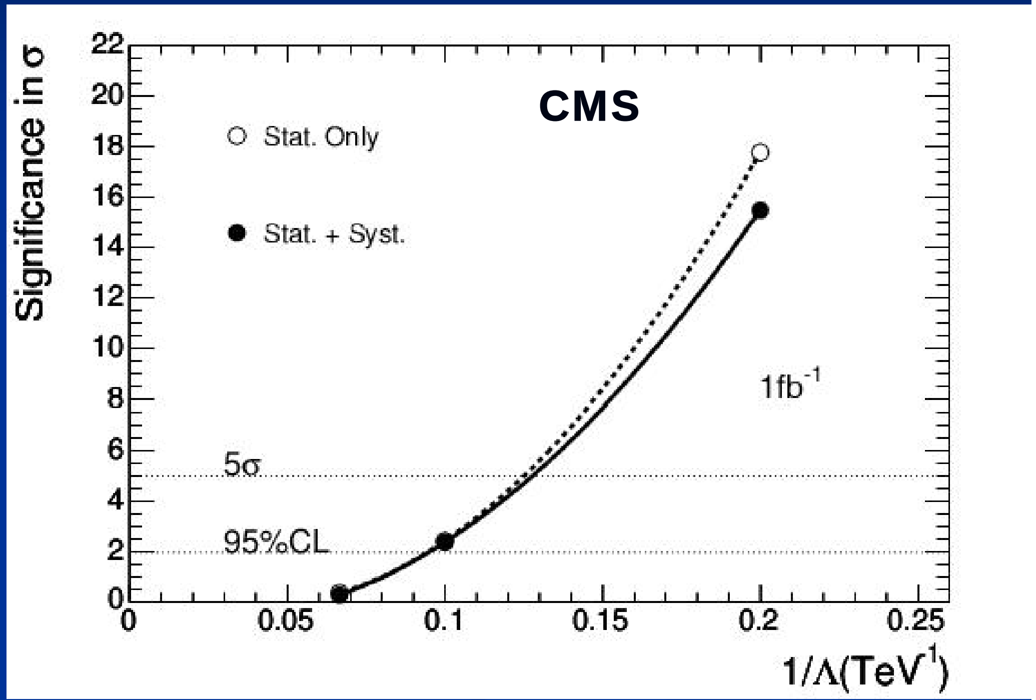
CMS and ATLAS: 10% initially → 2-3% above 20 GeV after 1-10 fb^{-1} and 1% eventually? <u>Ambitious!</u>

Using: γ+ jet events
Z + jet events } Needs EM scale first
top-pair events: 2 jets from W

light jets and b-jets !

Expected sensitivity for new physics:





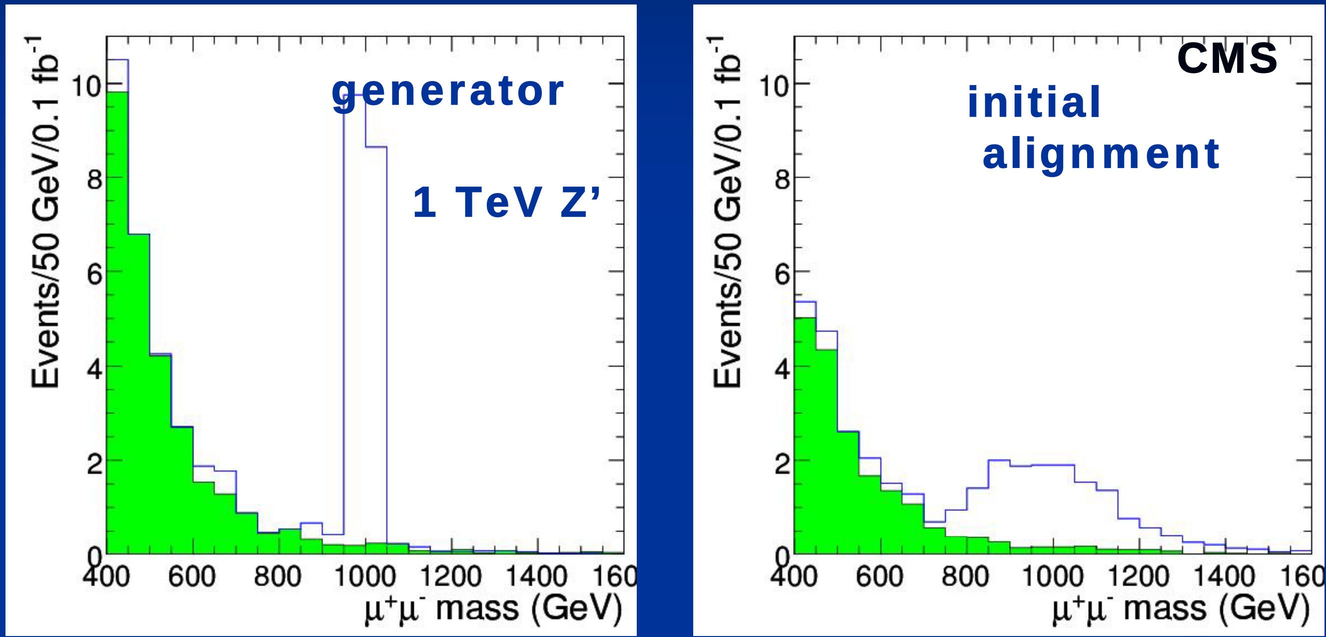
Discovery potential with 1 fb^{-1}: excited quarks up to 3.4 TeV

E_6 diquarks up to 3.7 TeV

Contact interactions scale 7.7 TeV

Example 2: high mass di-lepton pairs

High mass: sensitive to Z', graviton resonances, etc.
Also: large extra dimensions: deviations from SM spectrum



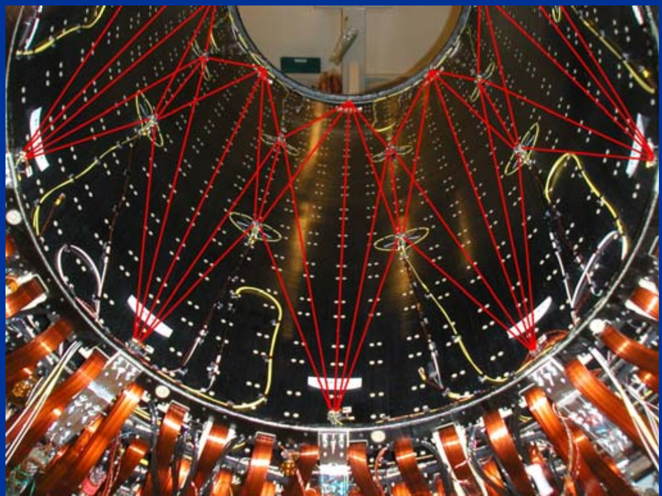
Challenges: lepton momentum scale: alignment, calibration
knowledge of efficiencies, fakes, misreconstruction
SM predictions at high mass, K-factors
MC generators for new physics

Challenge: tracker alignment

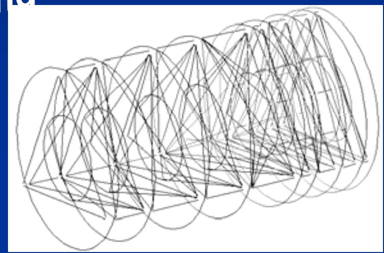
At start-up: hardware based-alignment, plus cosmics

→ 20-200 μm accuracy at startup

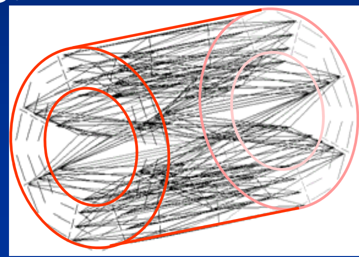
e.g. ATLAS: frequency scanning interferometry in silicon strip detector

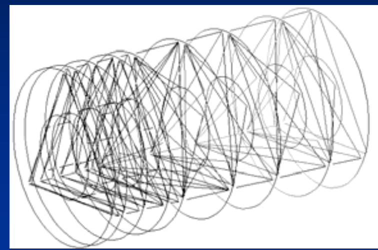


End-cap SCT grid (165)



Barrel SCT grid (512)





End-cap SCT grid (165)

842 grid line lengths measured precisely
→ measures structure shapes, not sensors
→ monitor movements over ~hours

CMS: laser alignment

"robust" local vs big matrix inversion

Track-based alignment using minimum bias, Z→ee, μμ

Few days of data taking: sufficient statistics.

Challenge: <10 μm precision, 120000 parameters (CMS)
36000 parameters (ATLAS)

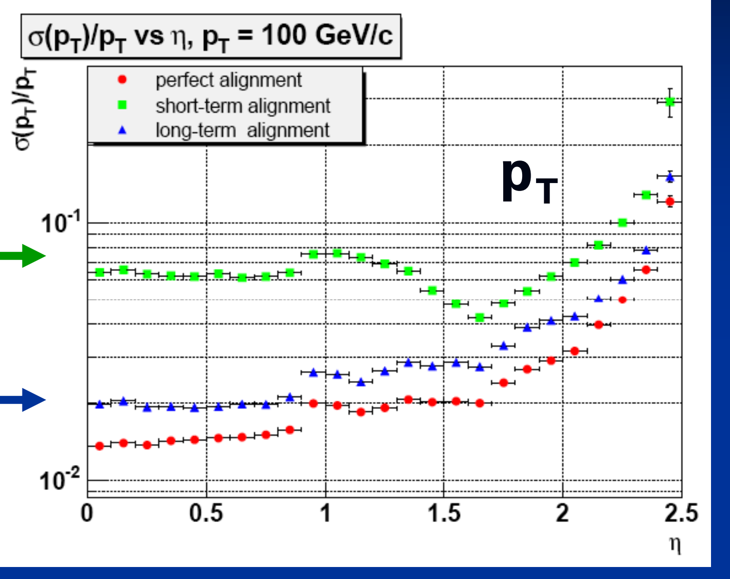
Challenge: tracker alignment

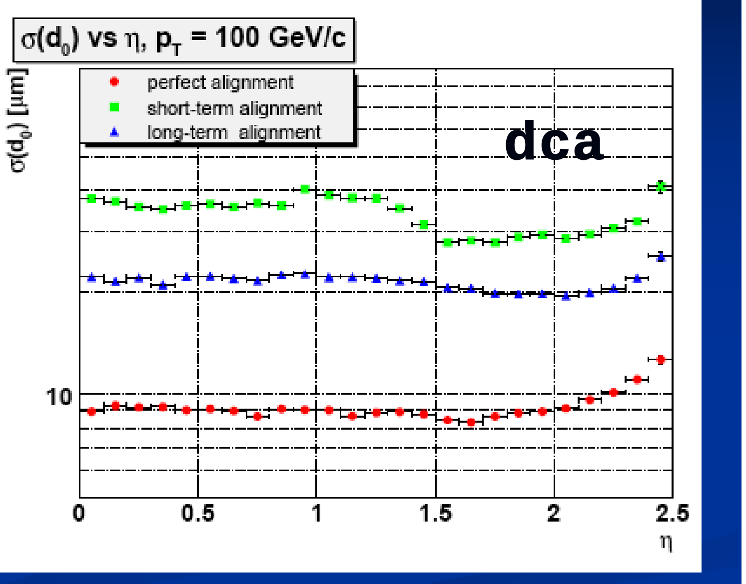
CMS plots:

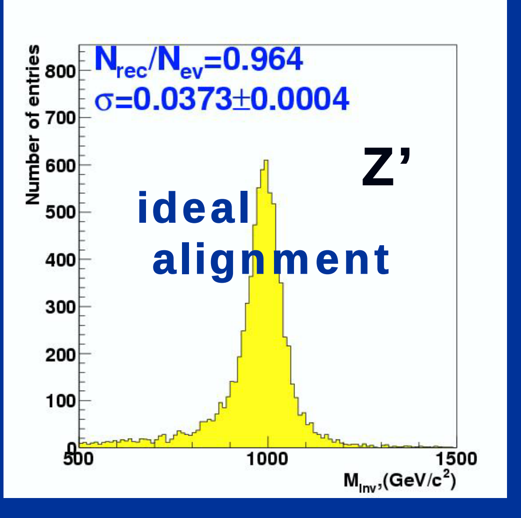
Track-based alignment using minimum bias, Z→ee, μμ

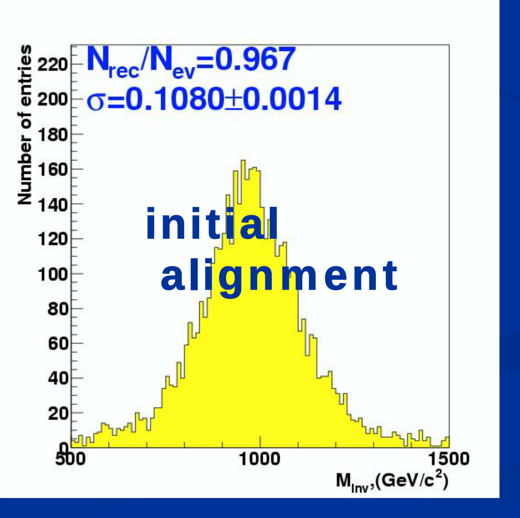
initial:

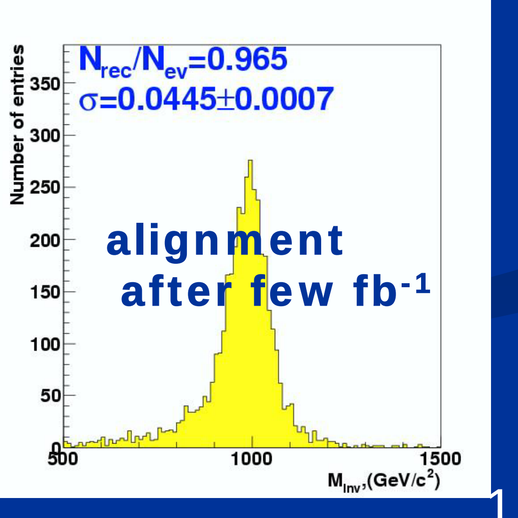
after few fb^{-1}



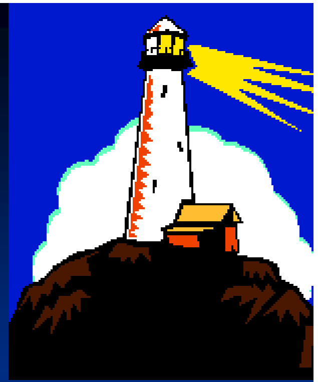








Lepton energy / momentum scale calibration



Electrons: Z → ee

CMS: intercalibration with single electrons, min bias
uniformity 0.4 – 2.0% (from 4% at day-1)
absolute scale from Z: 0.05 – 0.1%

ATLAS: uniformity 1.0 → 0.4%, scale < 0.1%

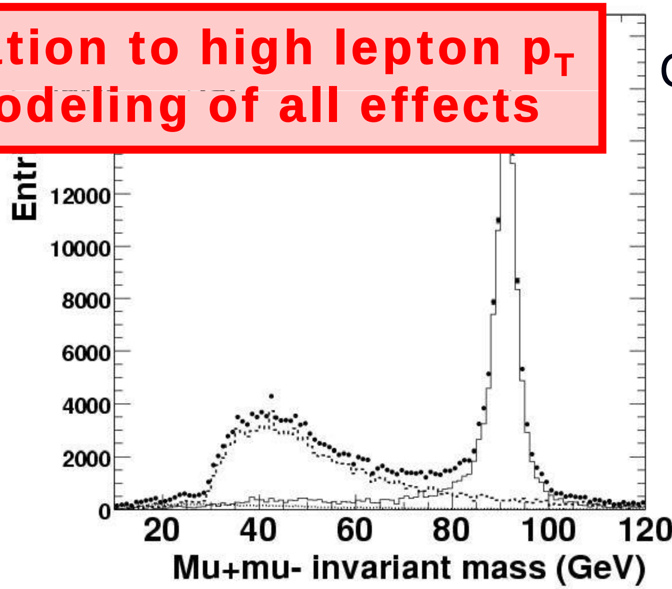
Challenge: disentangle many effects with Z sample:
B-field, material, non-uniformity, alignment, response…
(so: also need top, J/ψ, Υ, minimum bias,…)

Challenge: extrapolate Z calibration to high lepton p_T
Need accurate MC modeling of all effects

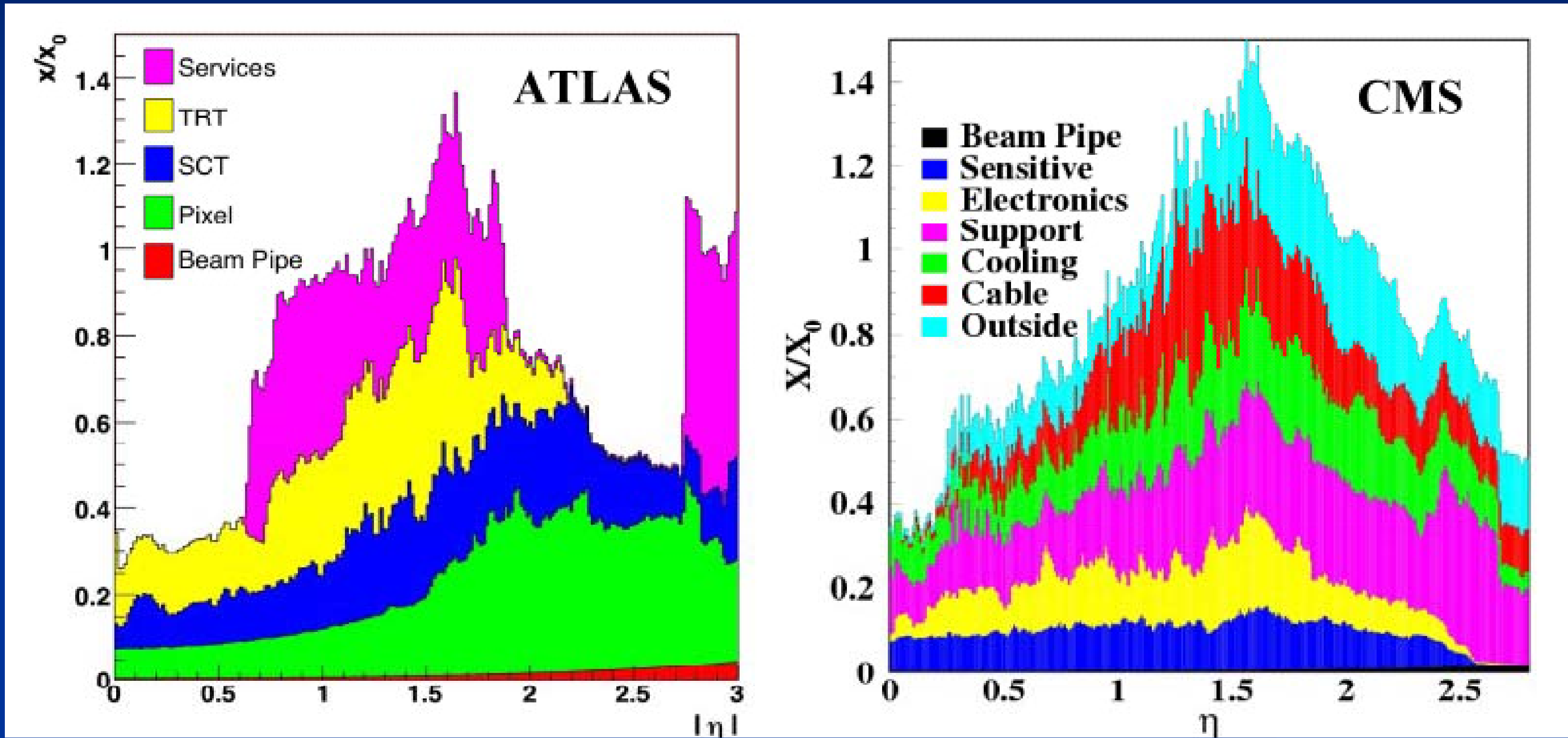
Muons: Z → μμ

3 days of data taking at 10^{33}
(or 1 month at 10^{32}):
$>10^5$ muon pairs

Momentum scale < 0.1%



Mystery of dark matter in the universe solved: it's in front of CMS / ATLAS ECAL…



Affects electrons and photons: energy loss, conversions

Some more challenges

Challenge: reconstruction and trigger efficiency, fakes

Cannot rely on MC
Use data: redundant triggers
prescaled triggers
redundant reconstruction methods
e.g. muons in inner detector, calorimeter, muon system
build up confidence that an object is what it seems to be
expect muons to be easier than electrons

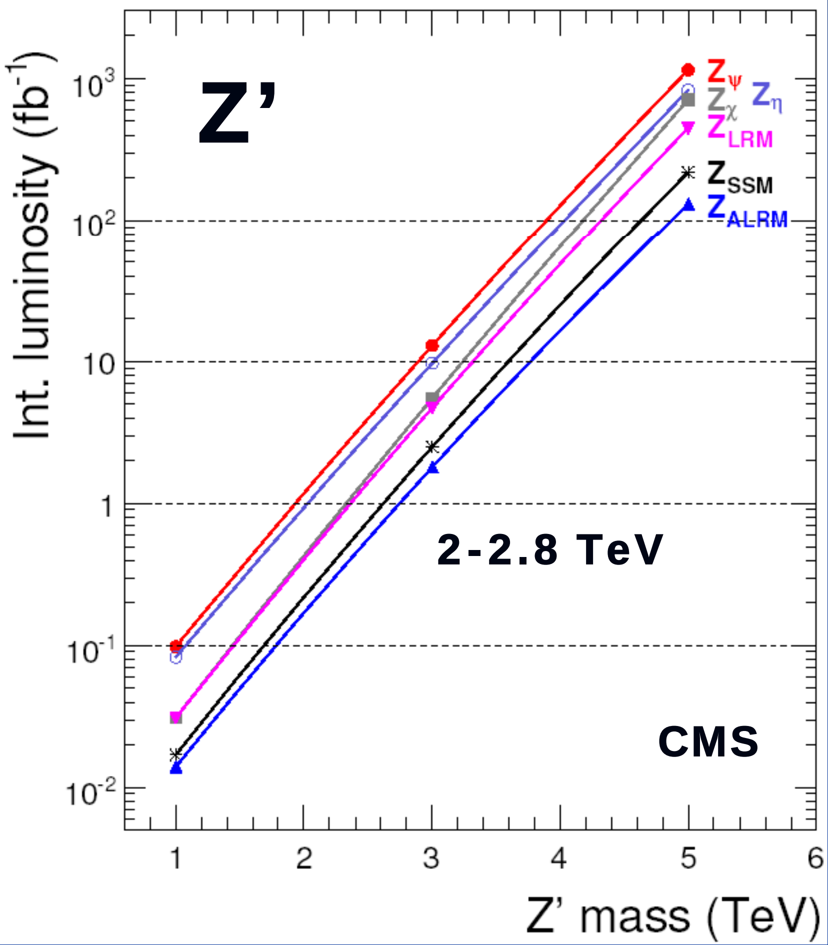
W,Z cross sections
→ Juan Alcaraz talk

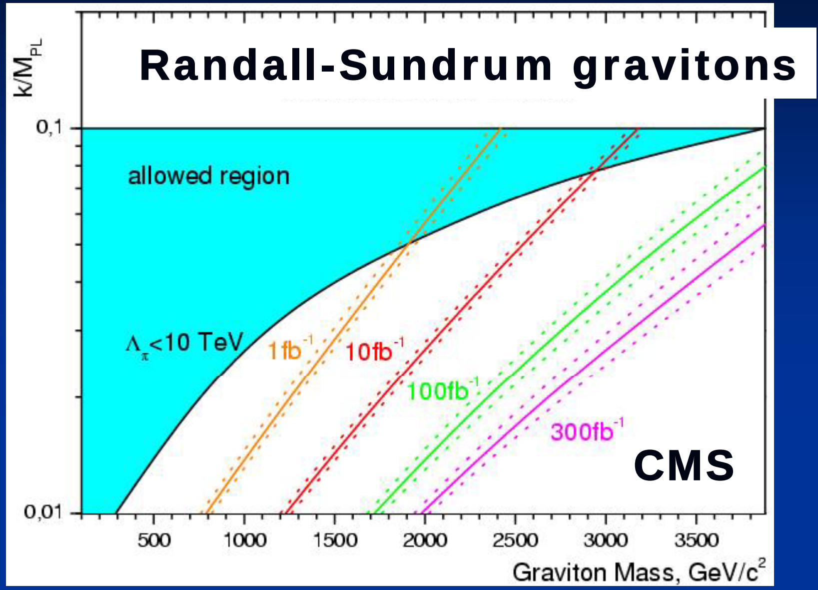
Challenge: uncertainties in SM prediction: scale, pdf
EW corrections?
corners of phase space

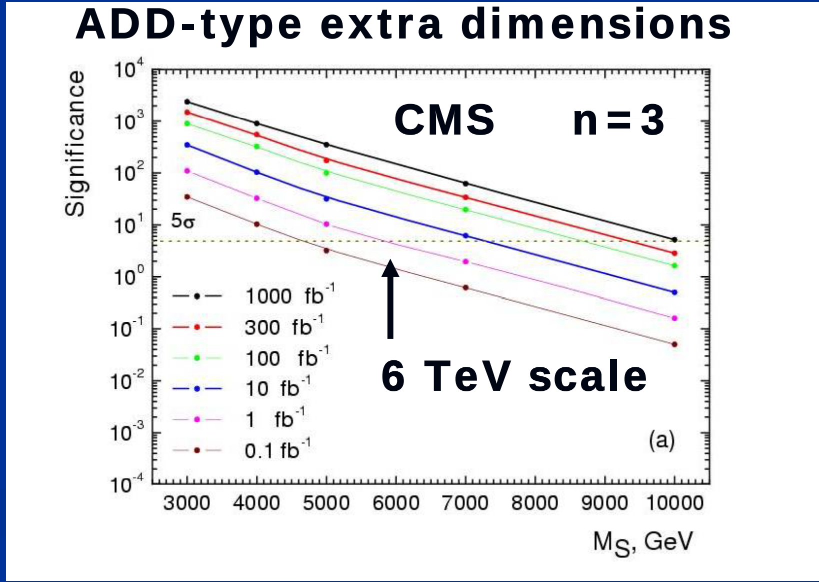
Use control samples in data
But cannot always cover tails, corners of phase space

→ MC remains important, must describe data control samples
Still NLO calculations needed: see wishlist hep-ph/0611148
(tt+jets, ttbb, W/Z+3jets, WW/WZ/ZZ+jet(s), WWbb)

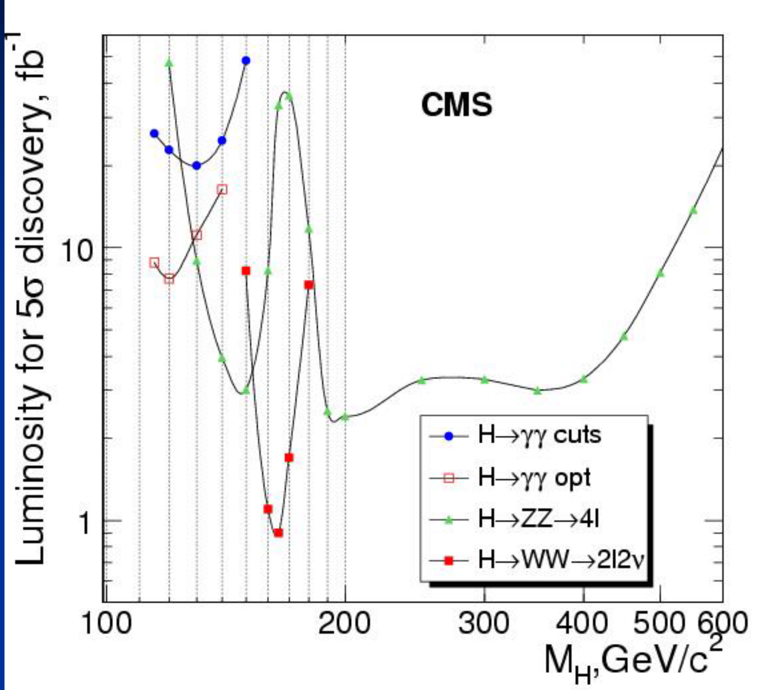
Sensitivities for various new physics models







Example 3: a SM Higgs boson with a mass of 165 GeV



H → WW → llνν
(see talk Alexey Drozdetskiy)

No mass peak: counting experiment

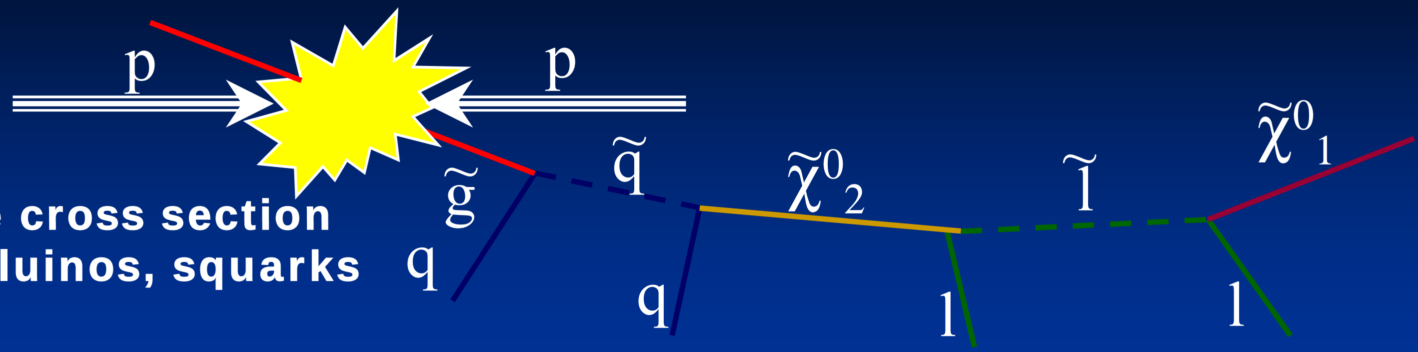
Challenge: extremely good knowledge of background needed

Backgrounds: qq→WW, gg→WW, tt→WWbb, tWb→WWb(b),
ZW→lll, ZZ→ll,νν

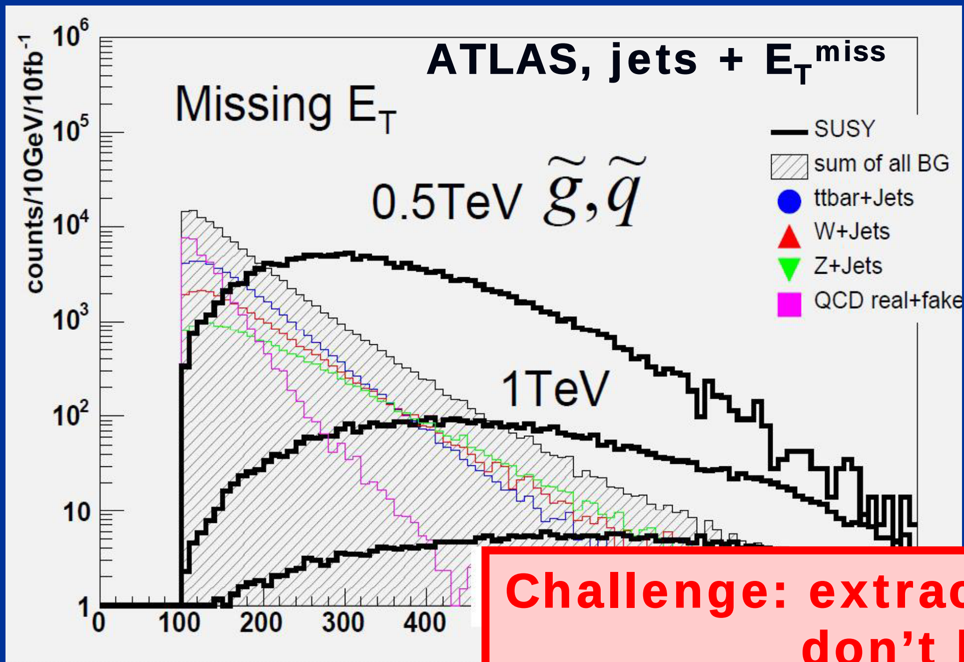
Get background from data itself: control samples: tt, WW, WZ

Challenge: understanding of control samples
control of systematics
keep theory uncertainties small

Final example: SUSY in (lepton+)jets+E_T^{miss} final state



Large cross section for gluinos, squarks



Inclusive searches:

- high p_T jets
- large E_T^{miss}
- optional: high p_T lepton(s) (QCD)

SUSY could show up in:

- E_T^{miss}
- H_T "fat" events
- M_{eff}

Challenge: extract backgrounds from data
don't be fooled by detector mishaps
be generic, yet efficient
busy events: reconstruction affected

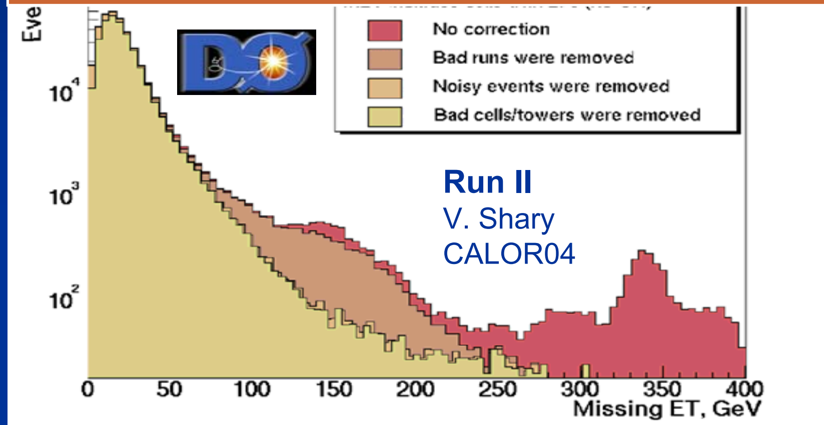
Backgrounds: QCD, top-pair, W, Z production

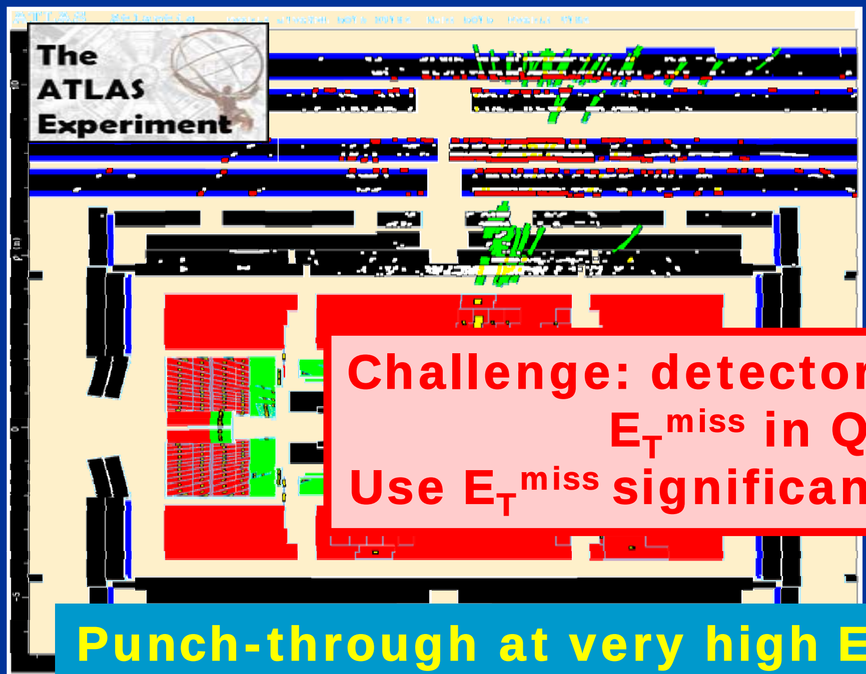
Missing transverse energy: E_T^{miss}

Escaping particles: momentum balance upset
But: - detector effects (holes, noise…)
- finite resolution
- QCD jets can have real E_T^{miss}

Difficult!
Day-1: poor resolution
Data-driven calibration needed

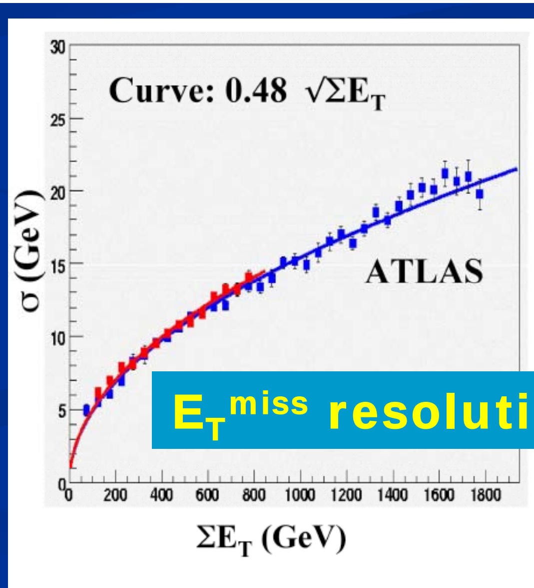
E_T^{miss} spectrum contaminated by cosmics, beam-halo, machine/detector problems, etc.





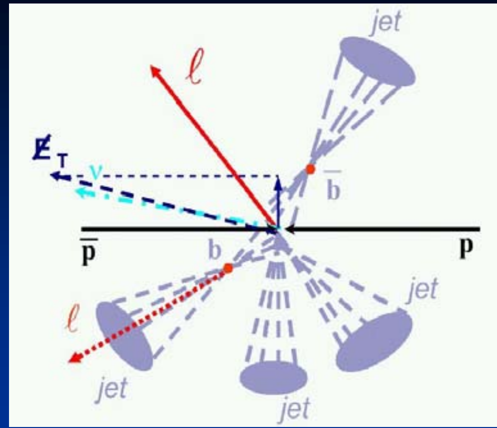
Challenge: detector effects
E_T^{miss} in QCD events
Use E_T^{miss} significance

Punch-through at very high E_T



E_T^{miss} resolution

Object reconstruction in busy events,
Samples of b-jets
E_T^{miss} calibration
Jet energy scale calibration



Top-pair events!

Observe with 30 pb^{-1}
$\sigma(tt)$ to 20%: 100 pb^{-1}
M(t) to 7-10 GeV

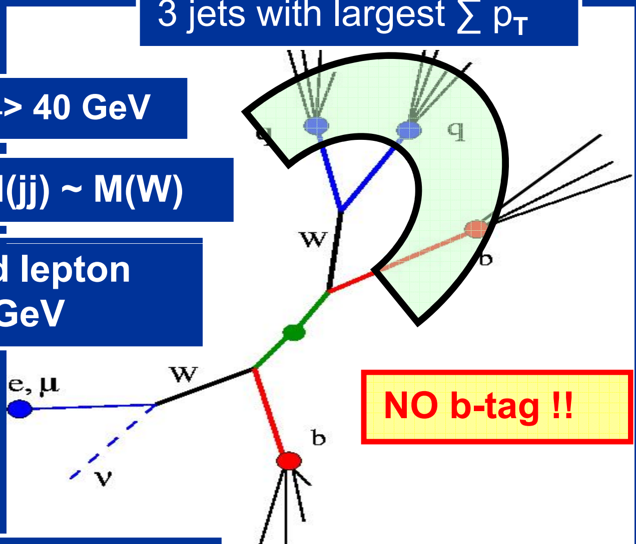
ATLAS: try early sample without b-tagging:

3 jets with largest $\sum p_T$

4 jets p_T> 40 GeV

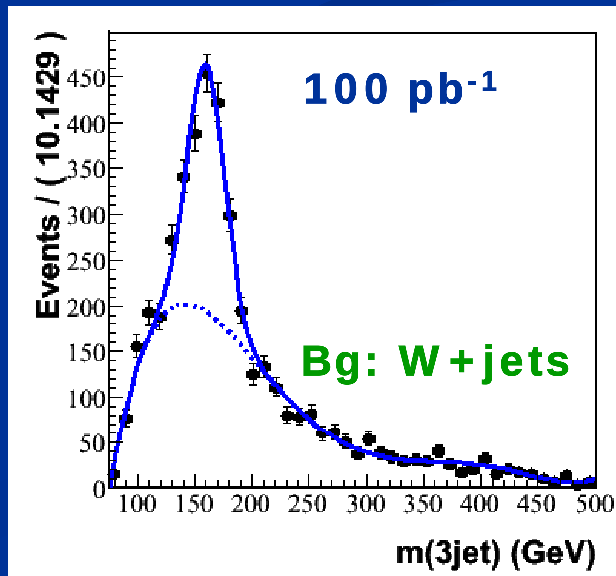
2 jets M(jj) ~ M(W)

Isolated lepton
p_T> 20 GeV



NO b-tag !!

E_T^{miss} > 20 GeV



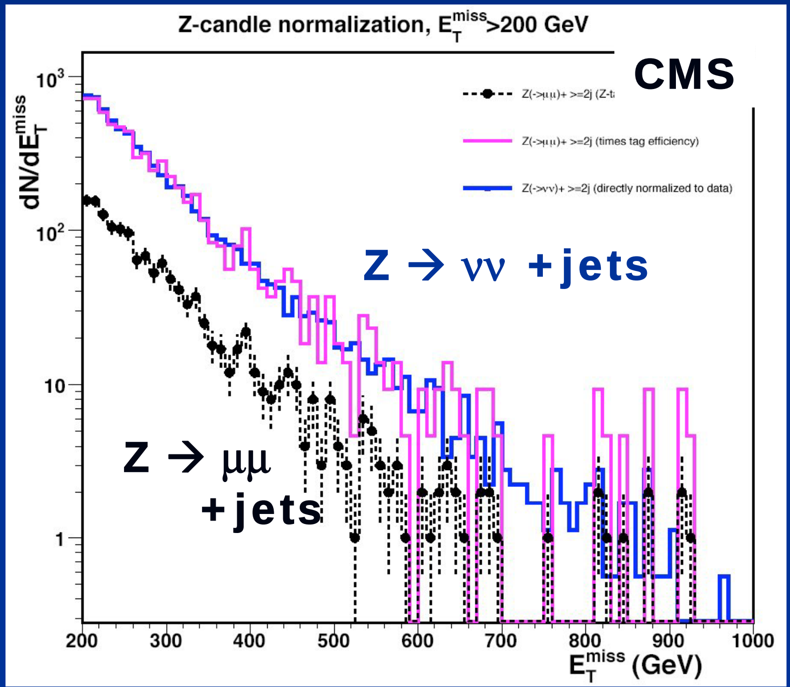
-b jets
-E_T^{miss} calibration
-Hadronic W's
-p_T (top) studies

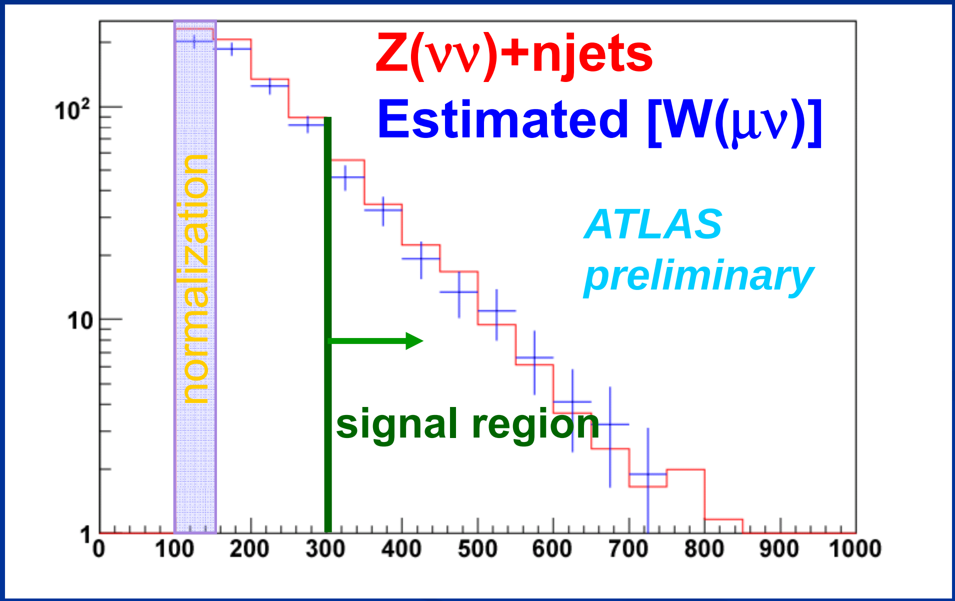
If b-tag works,
cleaner selection

Background estimation: as much as possible from data

Main sources: Z+jets, W+jets, top-pair production

Can select control samples: $Z \rightarrow \mu\mu$, $W \rightarrow \mu\nu$, semileptonic top pairs





E_T^{miss} (GeV)

Top: can select clean control sample with mass reconstruction normalize at low E_T^{miss}

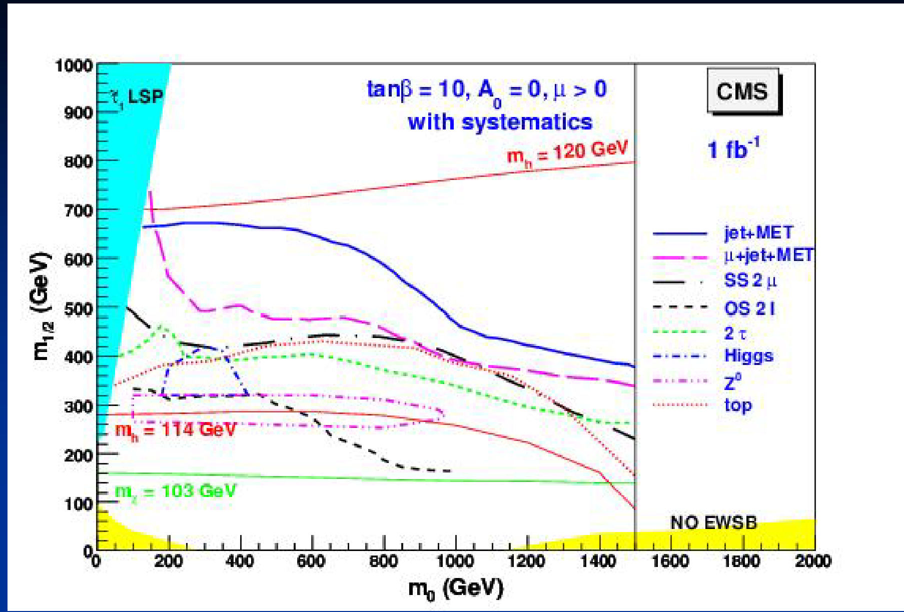
Major activity now: control samples:
- **robust, also in early data**
- **selection close to signal selection**
- **clean, good statistics**
- **theoretically reliable**

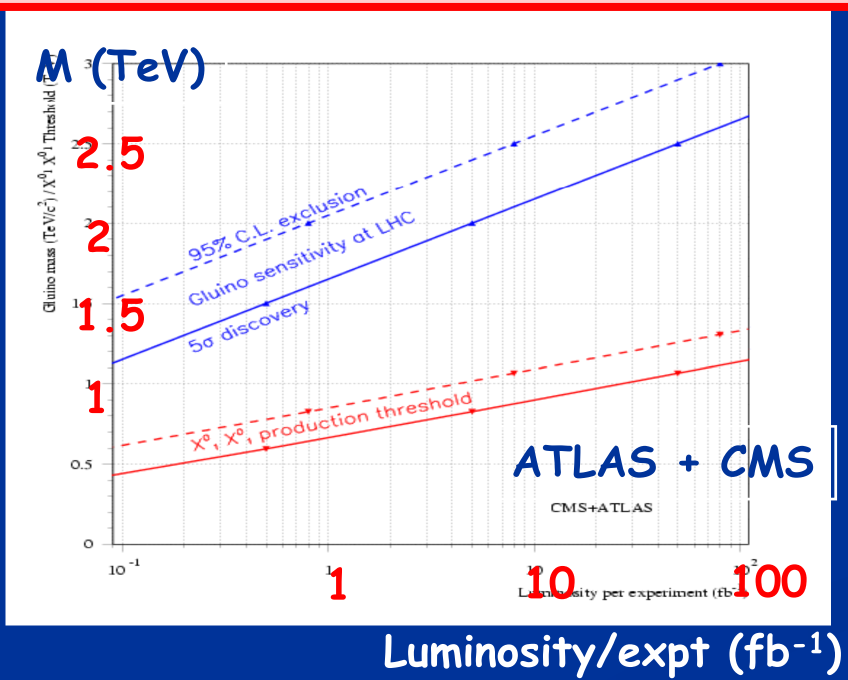
mSUGRA reach

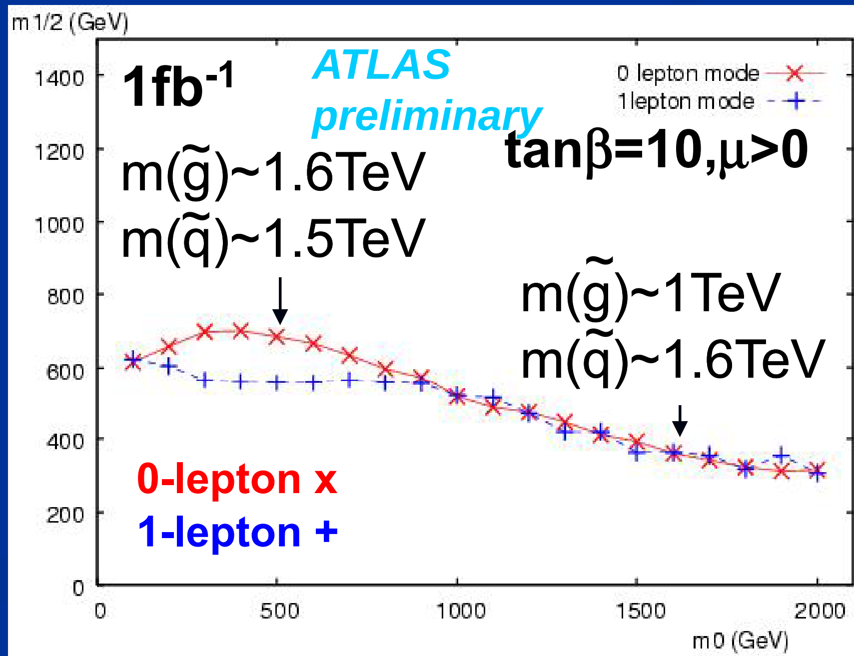
Fairly robust discovery potential with 1 fb^{-1}

More general searches also performed

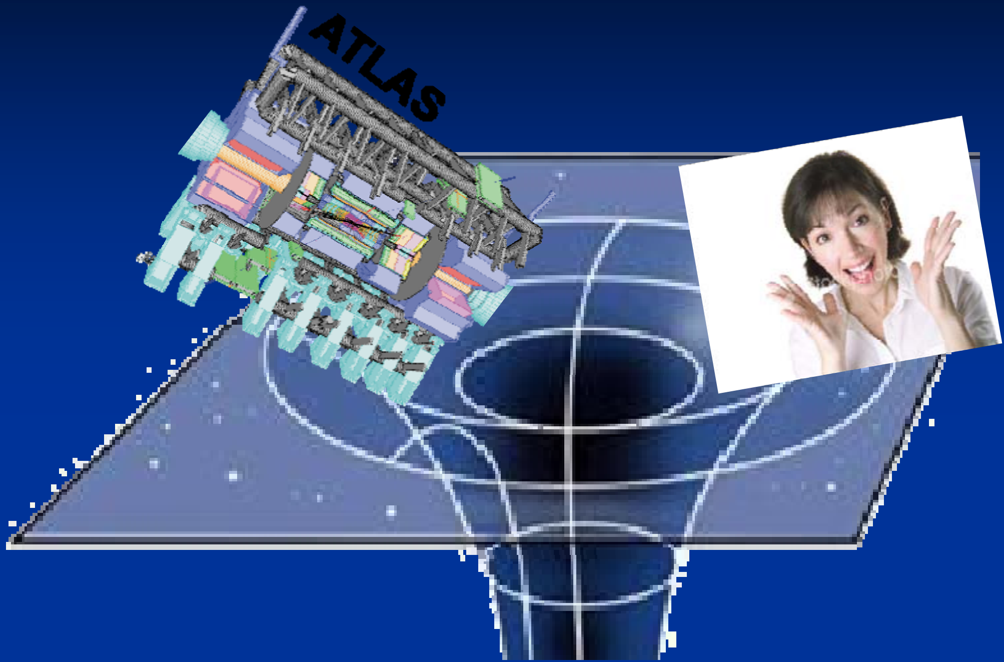
Challenge: if we see something: what is it? (“inverse problem”)







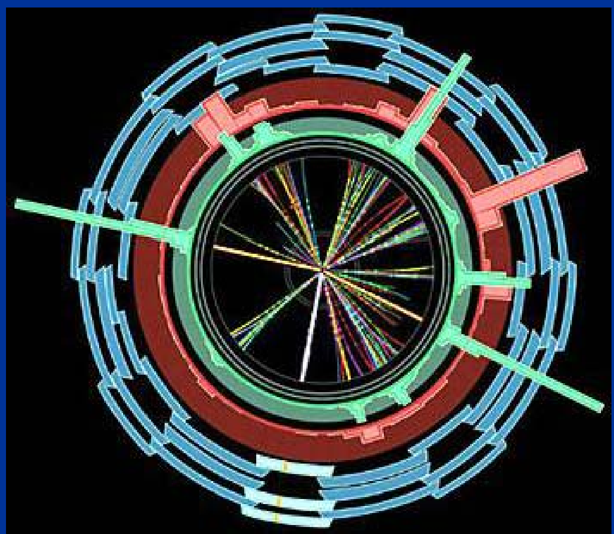
Maybe nature has some REAL SURPRISES in store…



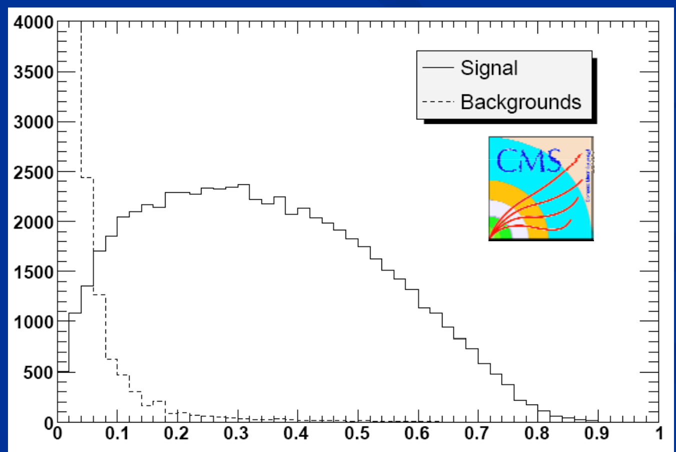
Large extra dimensions, Planck scale ~ EW scale

Possible micro black hole production; decay via Hawking radiation into photons, leptons, jets…

CMS and ATLAS might see this with 1-100 pb^{-1} !



Black hole event in ATLAS



sphericity

Some final thoughts and general challenges

LHC eagerly awaited by large community, theorists…
Pressure for early results
Strong internal competition
→ But must not compromise quality!

Blind analyses: desirable, but practical?

Look at 10^7 bins, see three 5σ peaks even if no new physics!

Learn from the Tevatron. Still lots to be learned on W,Z production, particularly with associated jets, b-quarks…
Understanding the detectors will be a MAJOR task.

The end. Fin. Ende. Fine. Einde.

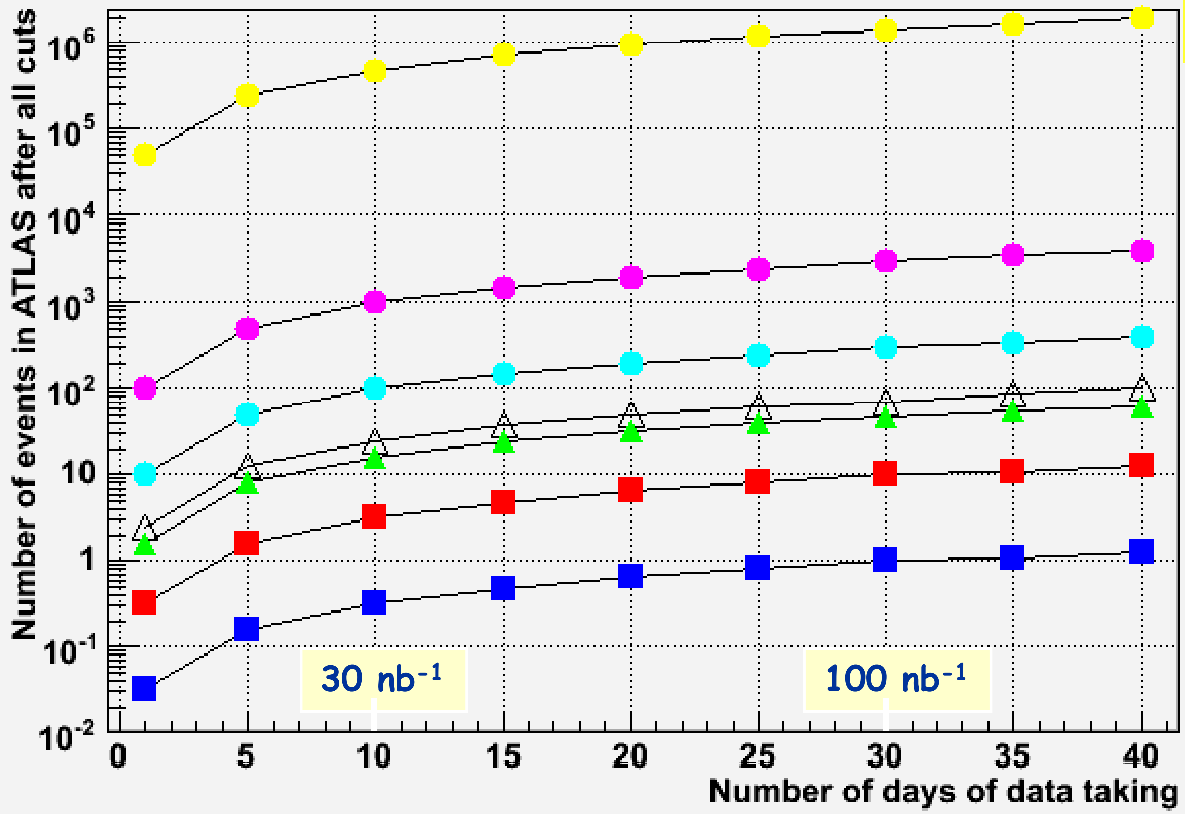
Backup

What data samples in 2007 ?

30% data taking efficiency included (machine plus detector)
Trigger and analysis efficiencies included

ATLAS preliminary

$\sqrt{s}$ =900 GeV, L = 10^{29} cm^{-2} s^{-1}



Jets p_T > 15 GeV

Jets p_T > 50 GeV

Jets p_T > 70 GeV

$\Upsilon \to \mu\mu$

$J/\psi \to \mu\mu$

W $\to$ eν, $\mu\nu$

Z $\to$ ee, $\mu\mu$

+ 1 million minimum-bias/day

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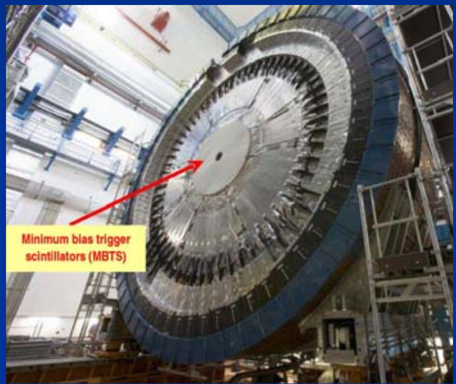
- Start to commission triggers and detectors with collision data (minimum bias, jets, ..) in real LHC environment
- Maybe first physics measurements (minimum-bias, underlying event, QCD jets, …) ?
- Observe a few W$\to$ lν, $\Upsilon \to \mu\mu$, $J/\psi \to \mu\mu$?

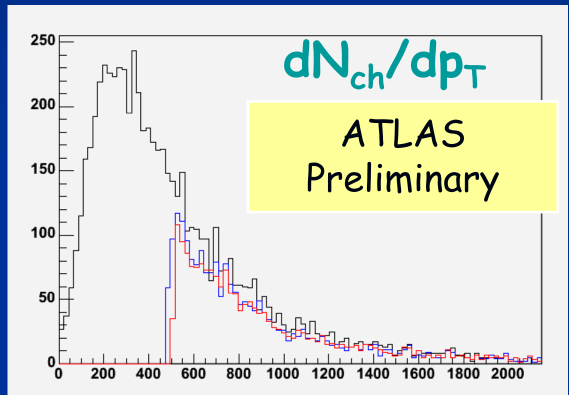
The inevitable first measurements: soft hadronic stuff

- Your average inelastic collision: “minimum bias”
- The “rest of the event” for a hard scattering: underlying event

Probably very first measurement in 14 TeV (and 900 GeV) data:

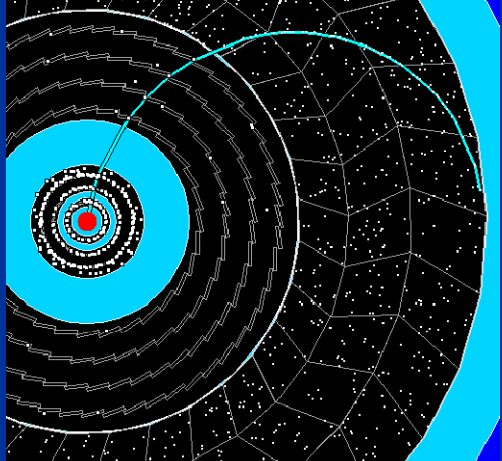
- central charged particle multiplicity
- “transverse” charged particle density in di-jet, DY events

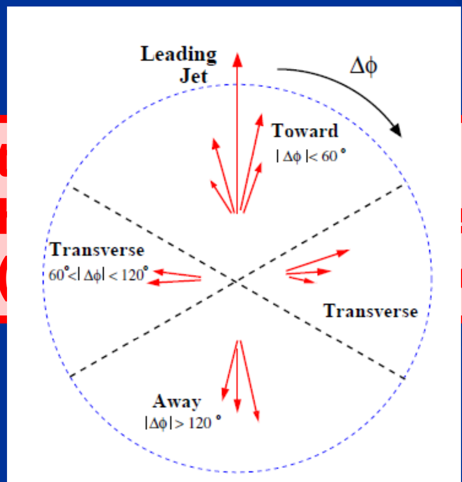


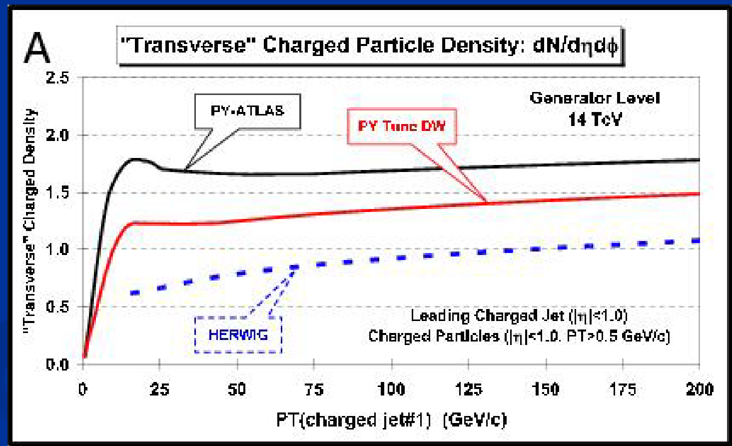


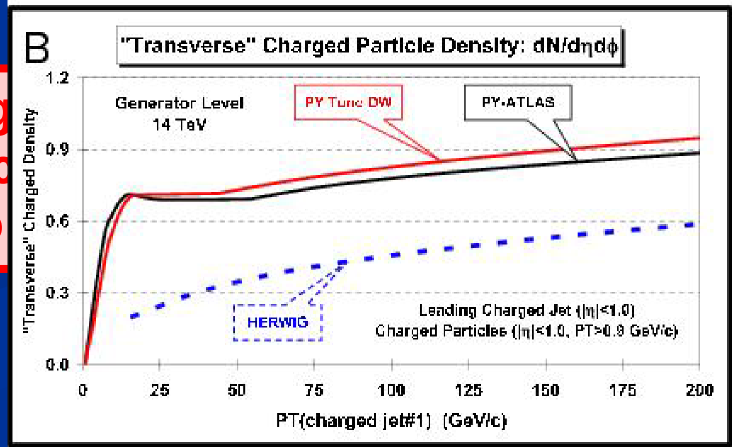
p_T (MeV)

400 MeV tracks: reach end of TRT









With the first collision data (1-100 pb^{-1}) at 14 TeV

Understand detector performance in situ in the LHC environment, and perform first physics measurements:

- **Measure particle multiplicity in minimum bias (a few hours of data taking …)**
- **Measure QCD jet cross-section to ~ 30% ?**
  (Expect >10^3 events with E_T (j) > 1 TeV with 100 pb^{-1})
- **Measure W, Z cross-sections to 10% with 100 pb^{-1}?**
- **Observe a top signal with ~ 30 pb^{-1}**
- **Measure tt cross-section to 20% and m(top) to 7-10 GeV with 100 pb^{-1} ?**
- **Improve knowledge of PDF (low-x gluons !) with W/Z with O(100) pb^{-1} ?**
- **First tuning of MC (minimum-bias, underlying event, tt, W/Z+jets, QCD jets,…)**

And, more ambitiously:

- **Discover SUSY up to gluino masses of ~ 1.3 TeV ?**
- **Discover a Z' up to masses of ~ 1.3 TeV ?**
- **Surprises ?**

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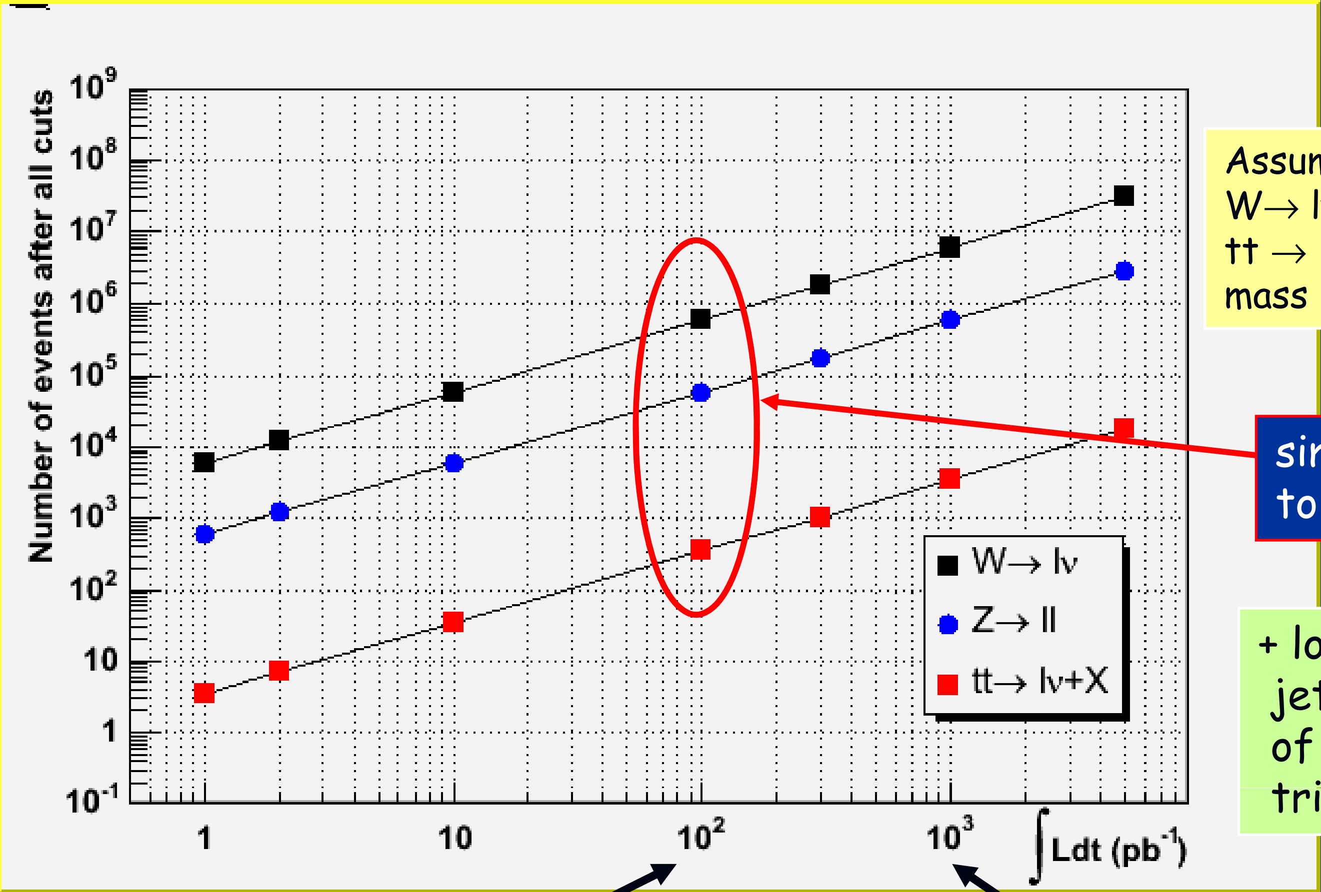
How many events per experiment at the beginning ?



l ≡ e or μ

Assumed selection efficiency:
W→ lν, Z→ ll : 20%
tt → lν+X : 1.5% (no b-tag, inside mass bin)

similar statistics to CDF, D0 today

+ lots of minimum-bias and jets (10^7 events in 2 weeks of data taking if 20% of trigger bandwidth allocated)

100 pb^{-1} ≡ few days at 10^{32} , ε=50%

1 fb^{-1} ≡ 6 month at 10^{32}, ε=50%

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Compact Muon Solenoid (CMS) DETECTOR

EM Calorimeter,

$\sigma/E \approx 3\%/\sqrt{E(GeV)} \oplus 0.5\%$

CALORIMETERS

Scintillating PbWO4 crystals

ECAL

HCAL

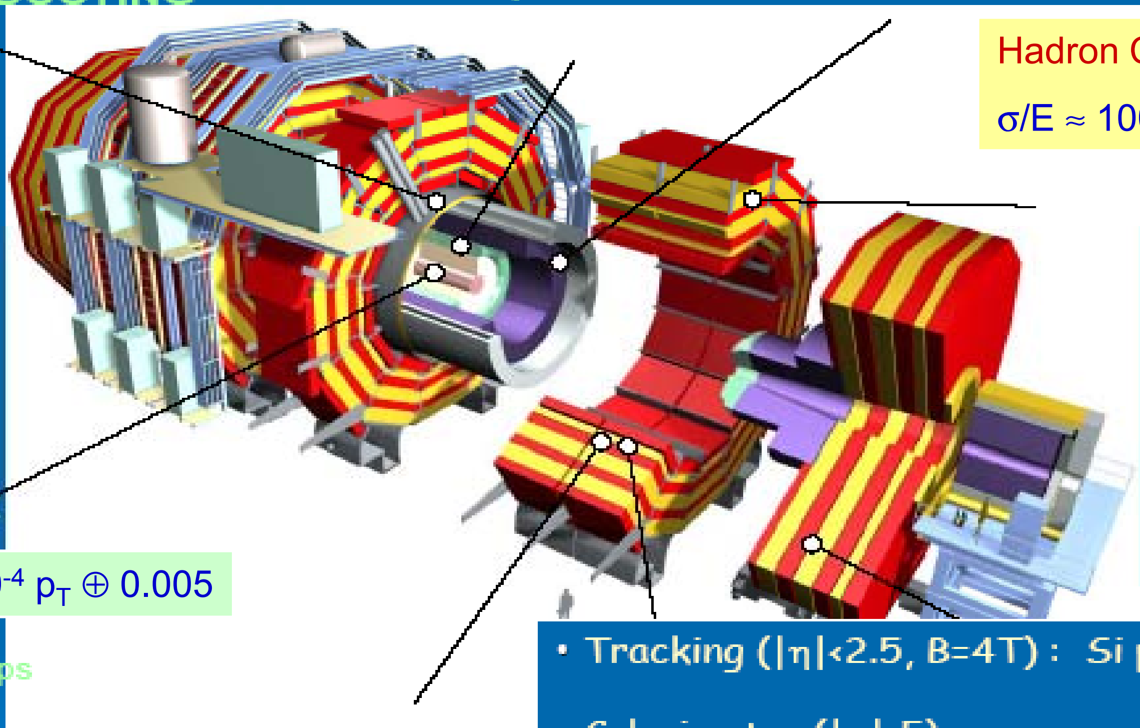
Plastic scintillator/brass sandwich

SUPERCONDUCTING COIL

Hadron Calorimeter,

$\sigma/E \approx 100\% / \sqrt{E(GeV)} \oplus 5\%$

IRON YOKE



TRACKER

$\sigma/p_T \approx 1.5 \times 10^{-4}\, p_T \oplus 0.005$

Silicon Microstrips
Pixels

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

MUON E

Drift Tube Chambers

- Tracking ($|\eta|<2.5$, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|<5$) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass-scintillator (central+ end-cap), Fe-Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers

Muon Spectrometer,

$\sigma/p_T \approx 5\%$ at 1 TeV/c (from Tracker)

A Toroidal LHC AppartuS (ATLAS) DETECTOR

EM Calorimeters, $\sigma/E \approx 10\%/\sqrt{E(\mathrm{GeV})} \oplus 0.7\%$

excellent electron/photon identification

Good *E* resolution (e.g., $H \rightarrow \gamma\gamma$)

Precision Muon Spectrometer,

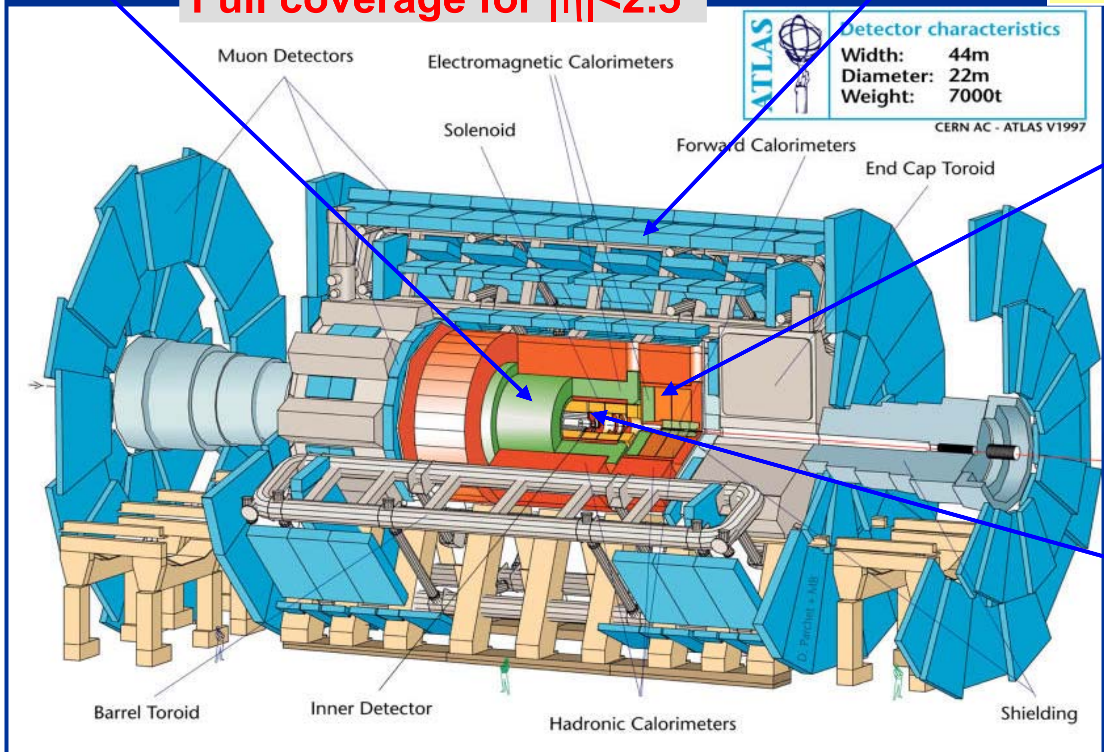
$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution

(e.g., $A/Z' \rightarrow \mu\mu$, $H \rightarrow 4\mu$)

Full coverage for $|\eta|<2.5$



Hadron Calorimeters,

$\sigma/E \approx 50\% / \sqrt{E(\mathrm{GeV})} \oplus 3\%$

Good jet and E_T miss performance

(e.g., $H \rightarrow \tau\tau$)

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

Good impact parameter res.

$\sigma(d_0)=15\mu m @ 20 GeV$ (e.g. $H \rightarrow bb$)

Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T

Selected figure-of-merit	ATLAS	CMS
Rec. Eff. Muons with pT=1GeV	97%	97%
Rec. Eff. Pions p_T=1GeV	84%	80%
Rec. Eff. El. pT=5GeV	90%	85%
σp_T for p_T=1GeV η=0	1.3%	0.7%
σp_T for p_T=100GeV η=0	3.8%	1.5%
Transverse σi.p. for p_T=1GeV	75μm	90μm
Longitunal σi.p. for p_T=1GeV	150μm	125μm

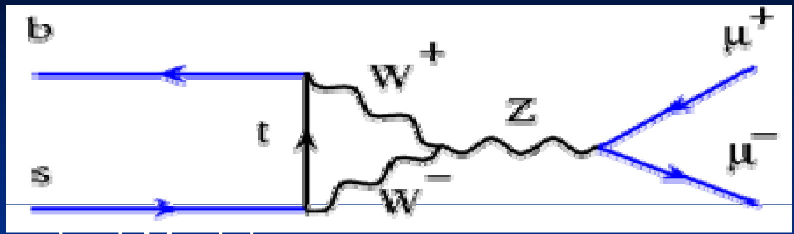
- CMS tracker has better momentum resolution (larger field and lever arm)
- However impact of material on efficiencies
- Similar impact parameter resolution

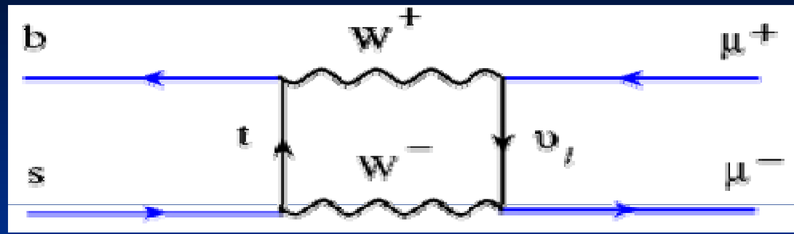
*These numbers as many others and some plots extracted from: D. Froidevaux, P. Sphicas (CERN) General-purpose detectors for the Large Hadron Collider. Ann.Rev.Nucl.Part.Sci.56:375-440,2006.

Trigger type	ATLAS (GeV) Threshold	CMS (GeV) Threshold
Inclusive isolated e/γ	25	29
Two electrons/Two photons	15	17
Inclusive isolated muon	20	14
Two muons	6	3
Inclusive τ-jet	-	86
Two τ-jet	-	59
τ-jet and E^T_{miss}	25 and 30	-
1-jet, 3-jets, 4-jets	200,90,65	177,86,70
Jet and E^T_{miss}	60 and 60	
Electron and Jet		21 and 45
Electron-Muon	15*10	-
+calibration, monitoring, etc…		

	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)

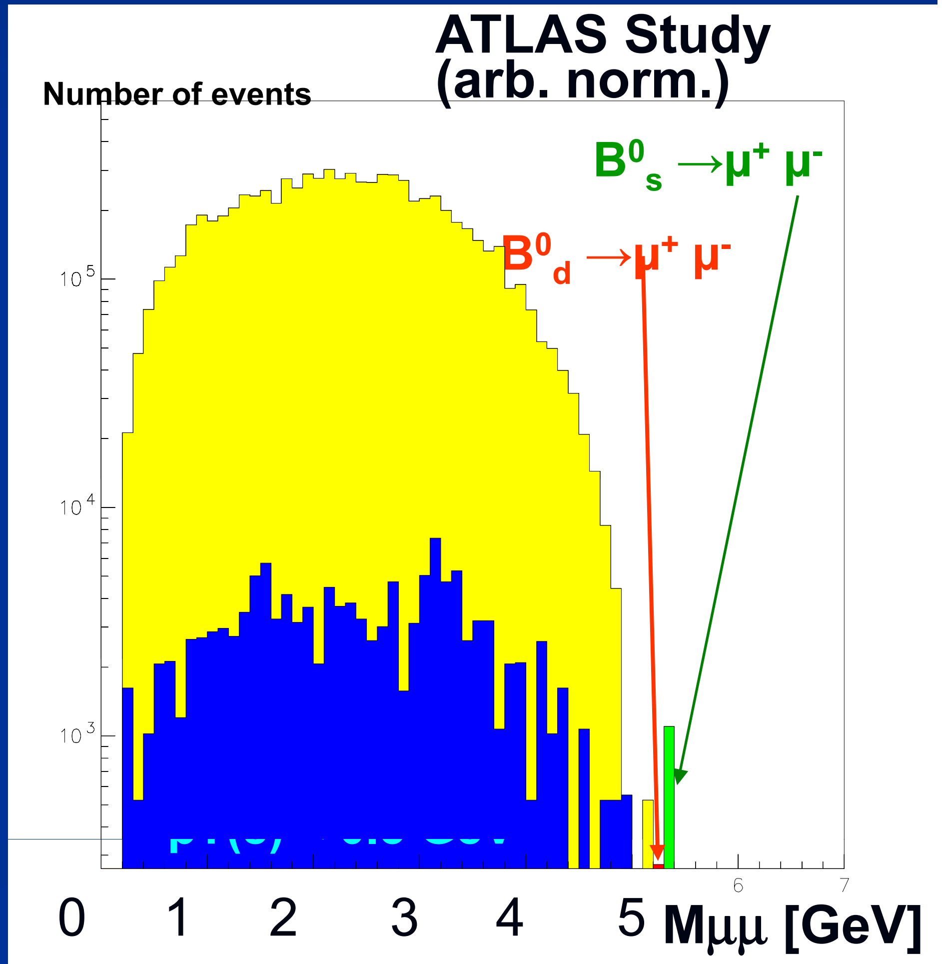
$B_{s,d} \to \mu\mu$





- Standard Model
  - $Br(B^0_s \to \mu^+ \mu^-) \approx 3.5 \times 10^{-9}$
  - $Br(B^0_d \to \mu^+ \mu^-) \approx 10^{-10}$
- *Eg:* ATLAS (yes, "staged" ATLAS for early running)
  - Trigger: $P_T(\mu) > 6$ GeV for $|\eta(\mu)|<2.5$
  - Analysis optimized for $S/\sqrt{B}$
  - $\sigma(B\to\mu\mu) \approx 80$ MeV

Integral LHC Luminosity	ATLAS upper limit at 90% CL
100 pb^{-1}	$< 1.0\times10^{-7}$
1 fb^{-1}	$< 1.5\times10^{-8}$
10 fb^{-1}	$< 5.5\times10^{-9}$



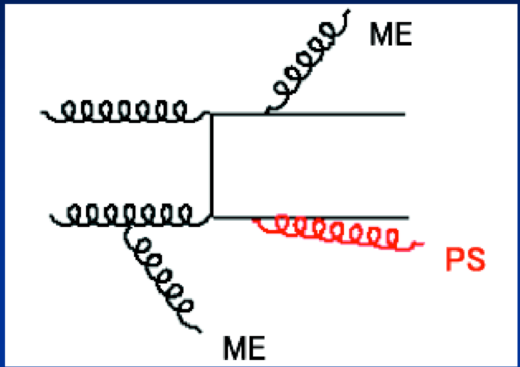
NLO wishlist

process ($V \in \{Z, W, \gamma\}$)	relevant for	
1. $pp \to V\,V + \text{jet}$	$t\bar{t}H$, new physics	
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)	(done)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$	
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$	
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics	
6. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$	
7. $pp \to V + 3$ jets	various new physics signatures	
8. $pp \to V\,V\,V$	SUSY trilepton searches	

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

(from Campbell, Huston and Stirling, hep-ph/0611148)

Challenge: W / Z / top + jets backgrounds

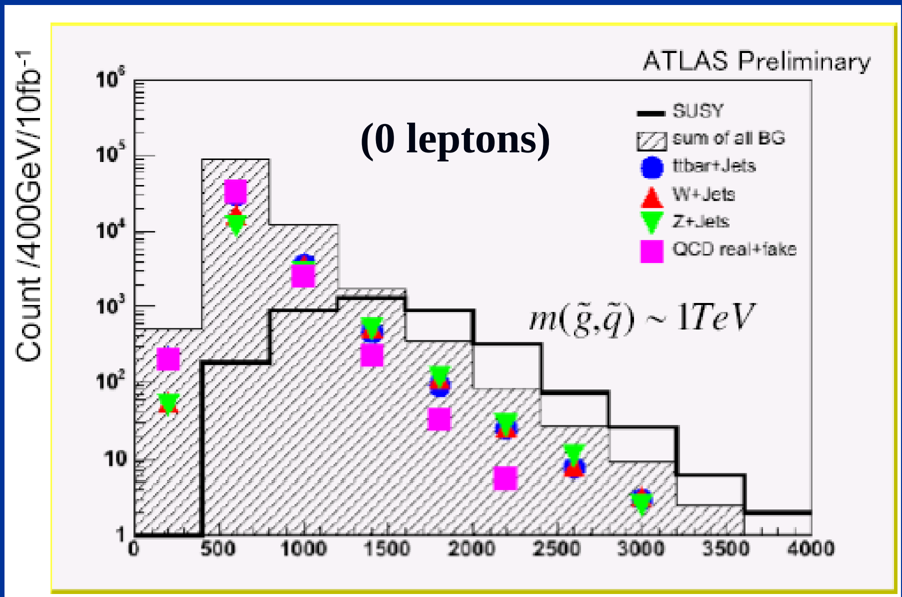


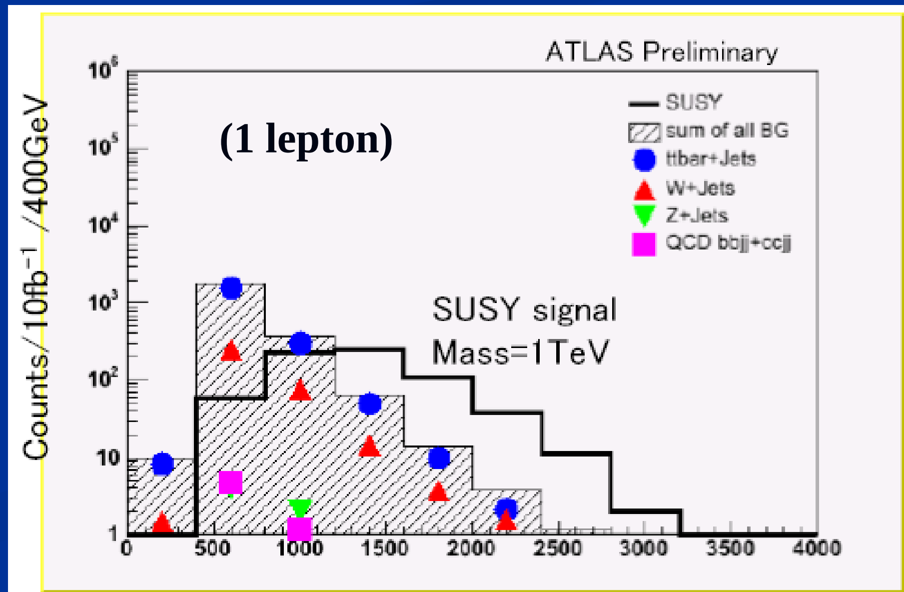
Large cross sections

Difficult to model:
match ME and PS
in generators

- tt(→bblνlν) + Njets
- tt(→bblνqq) + Njets
- W(→lν) + Njets
- Z(→νν) + Njets
- Z(→ττ) + Njets
- QCD QQ+Njets (Q=b,c semileptonic decay)
- QCD multijets (light flavor)

no-lepton vs one-lepton searches:





M_{eff} (GeV) M_{eff} (GeV)