Challenges for early discovery in ATLAS and CMS

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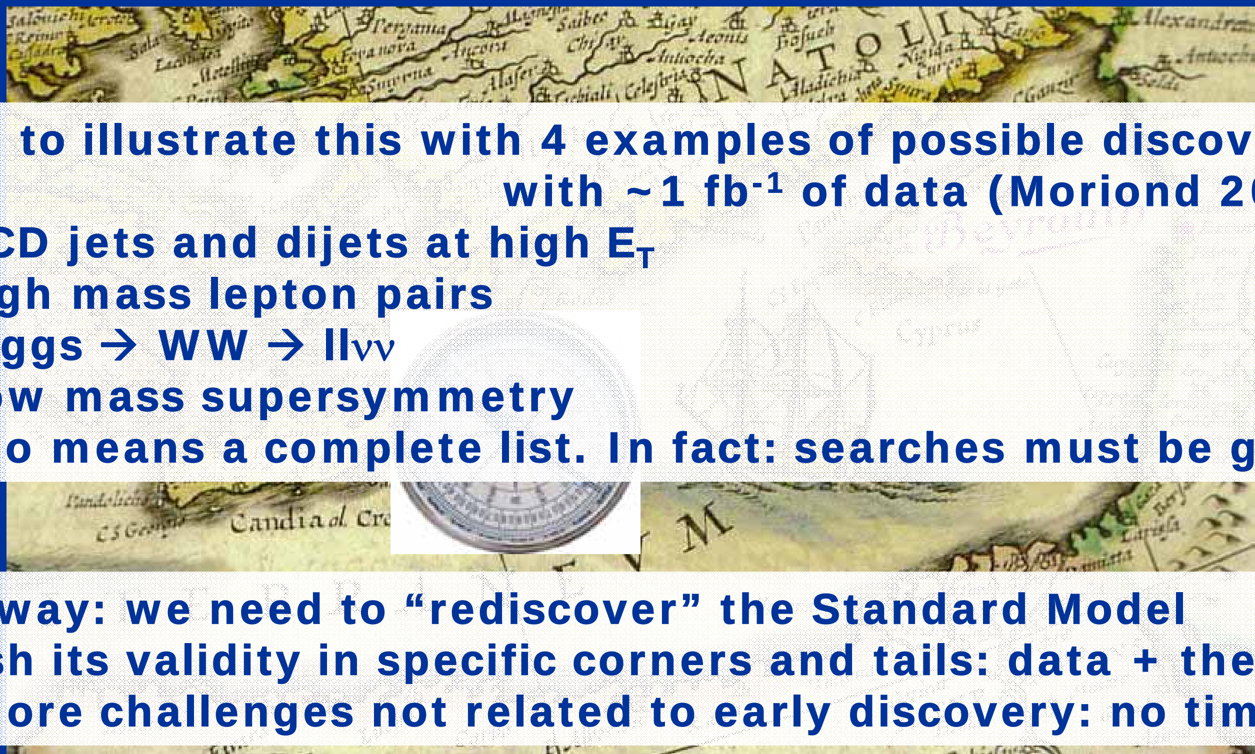
Rencontres de Moriond 2007
Electroweak interactions and Unified theories

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, $L \sim 2.5 \times 10^{31} \rightarrow 1 \times 10^{32}$
- phase 3: 25 ns, $L \sim 4 \times 10^{32} \rightarrow 1 \times 10^{33}\ cm^{-2}s^{-1}$

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

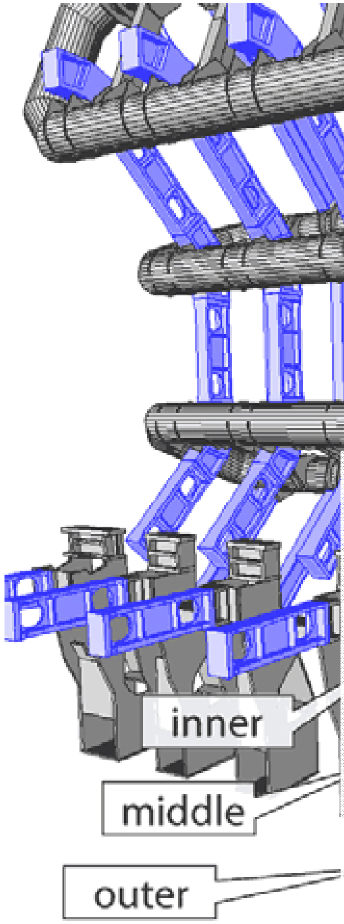
Getting the subdetectors built, tested and installed.
Power and signal cables, detector control and monitoring
Cooling pipes, cryogenic installations, magnets…

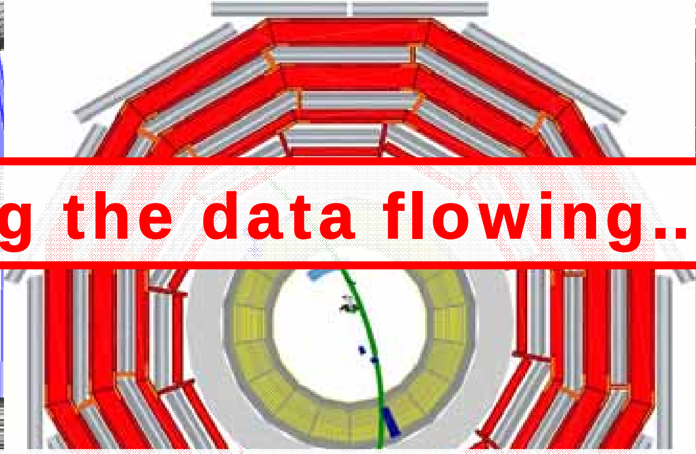
CMS: lowered central part (YB0) February 28th , rest soon
will run in 2007 without ECAL endcap and pixels
rest going well

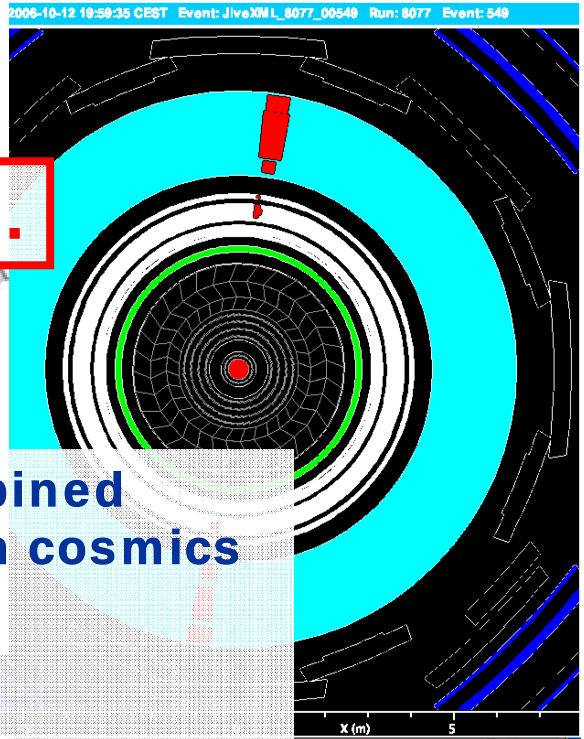
ATLAS: on a tight schedule to run almost complete in 2007
No TRT at high $|\eta|$, some muon chambers missing

Both will have reduced trigger / DAQ capabilities initially

Getting the data flowing…



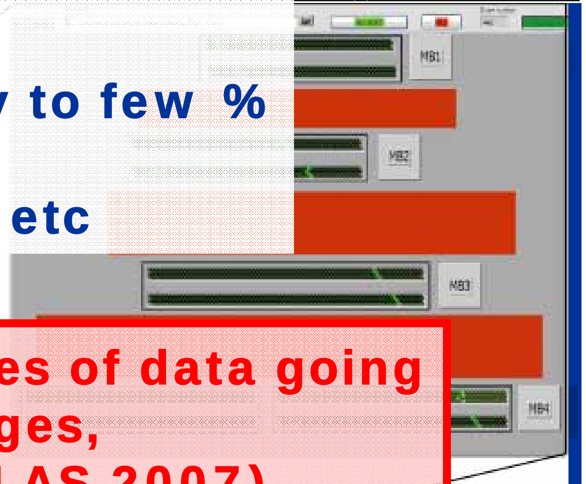


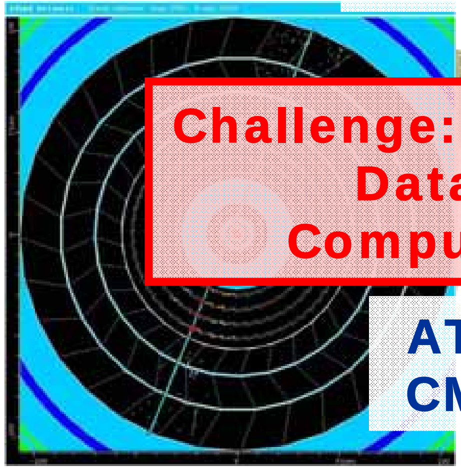


First individual detectors, then combined
Commissioning the DAQ system with cosmics
Single beam in LHC: beam halo

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)

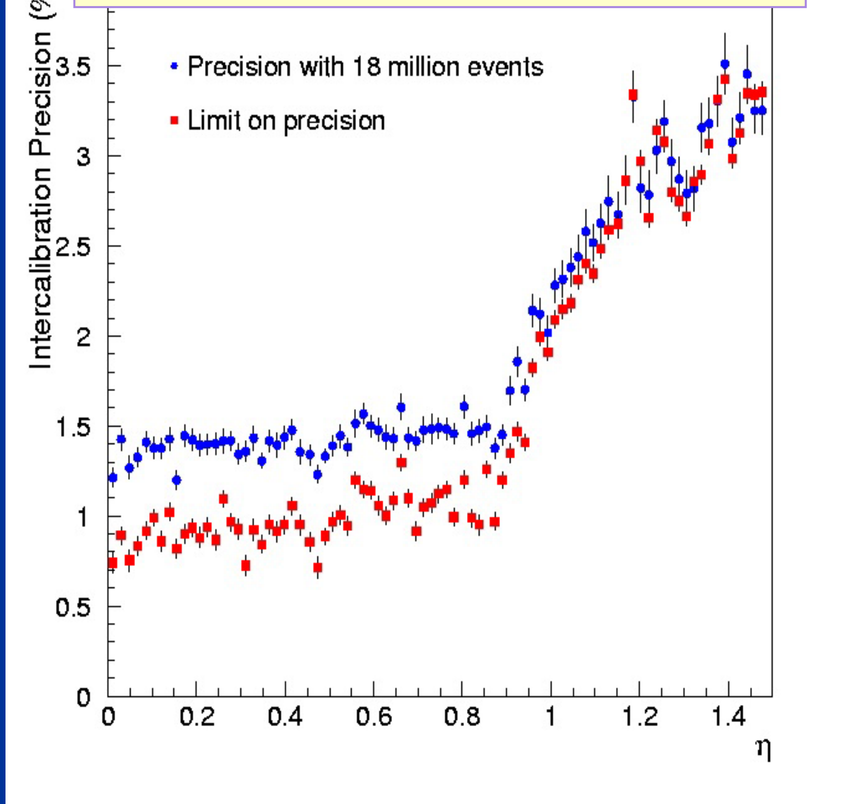
ATLAS: CSC exercise should lead to notes
CMS: published physics TDR in summer 06

Use of 2007 data (at 900 GeV)

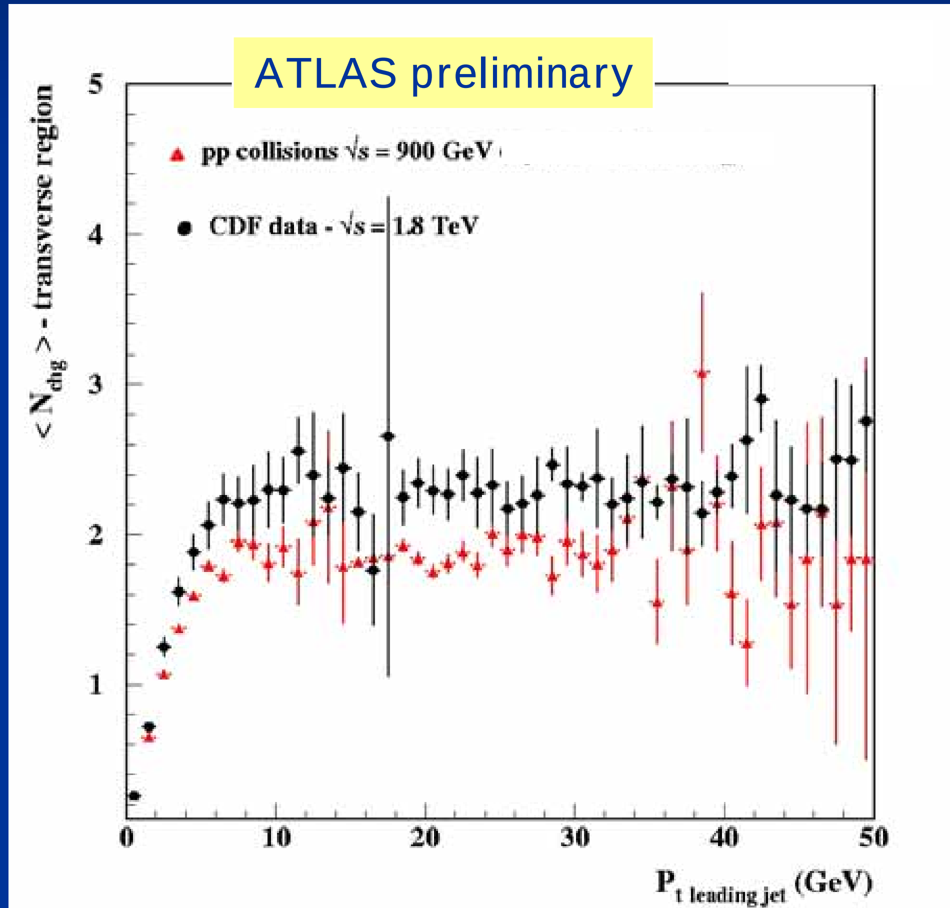
100 nb^{-1} ? No W,Z; few J/ψ; mostly minimum bias, some jets

CMS ECAL intercalibration:

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



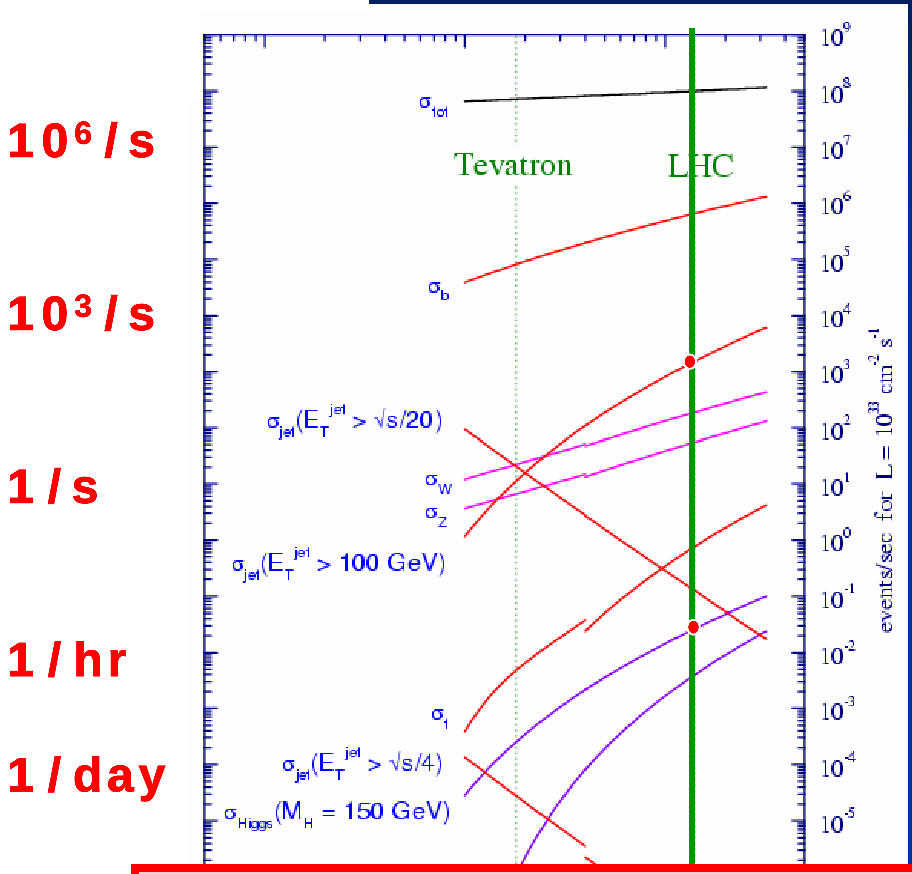
Commissioning of tracking:



~ 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?

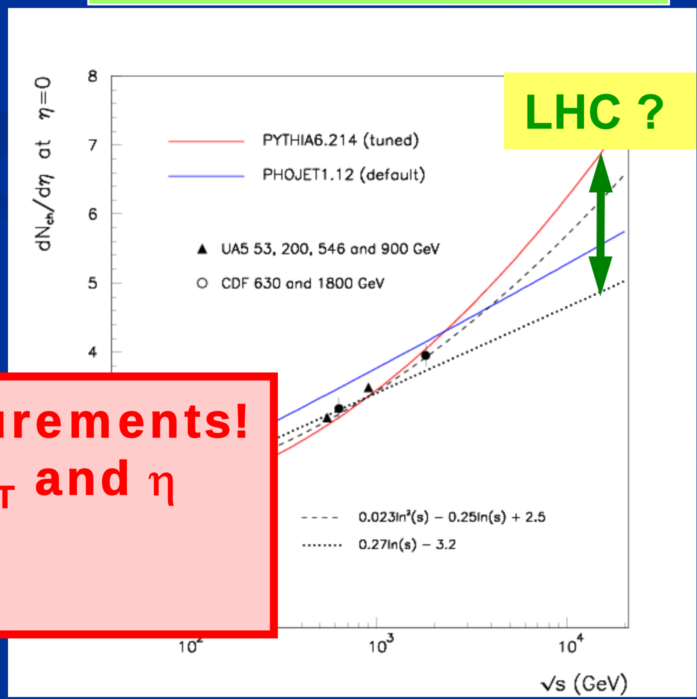
@10^{32} $cm^{-2}s^{-1}$



Low p_T hadronic events ("minimum bias")

Modeled in various generators, but big uncertainties

$\langle N_{ch} \rangle$ at $\eta = 0$ 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)

What do we expect to see at 14 TeV?

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

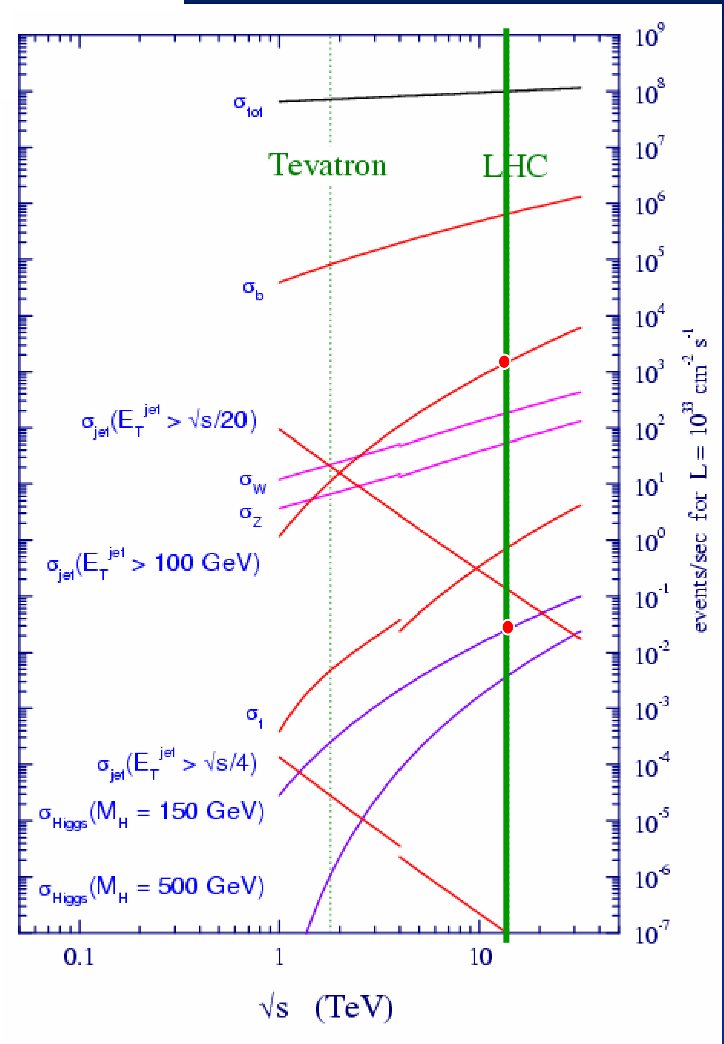
10^6 / s

10^3 / s

1 / s

1 / hr

1 / day

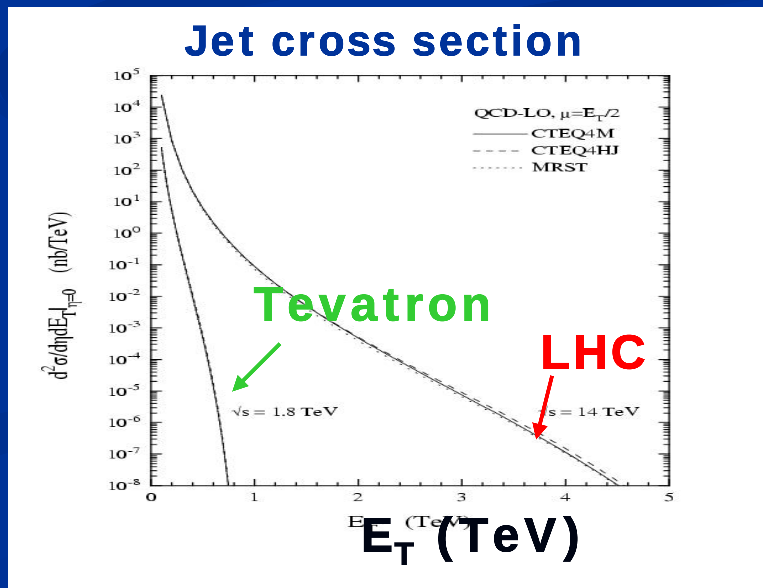


QCD jets, jets and more jets

Standard candles: W, Z, top

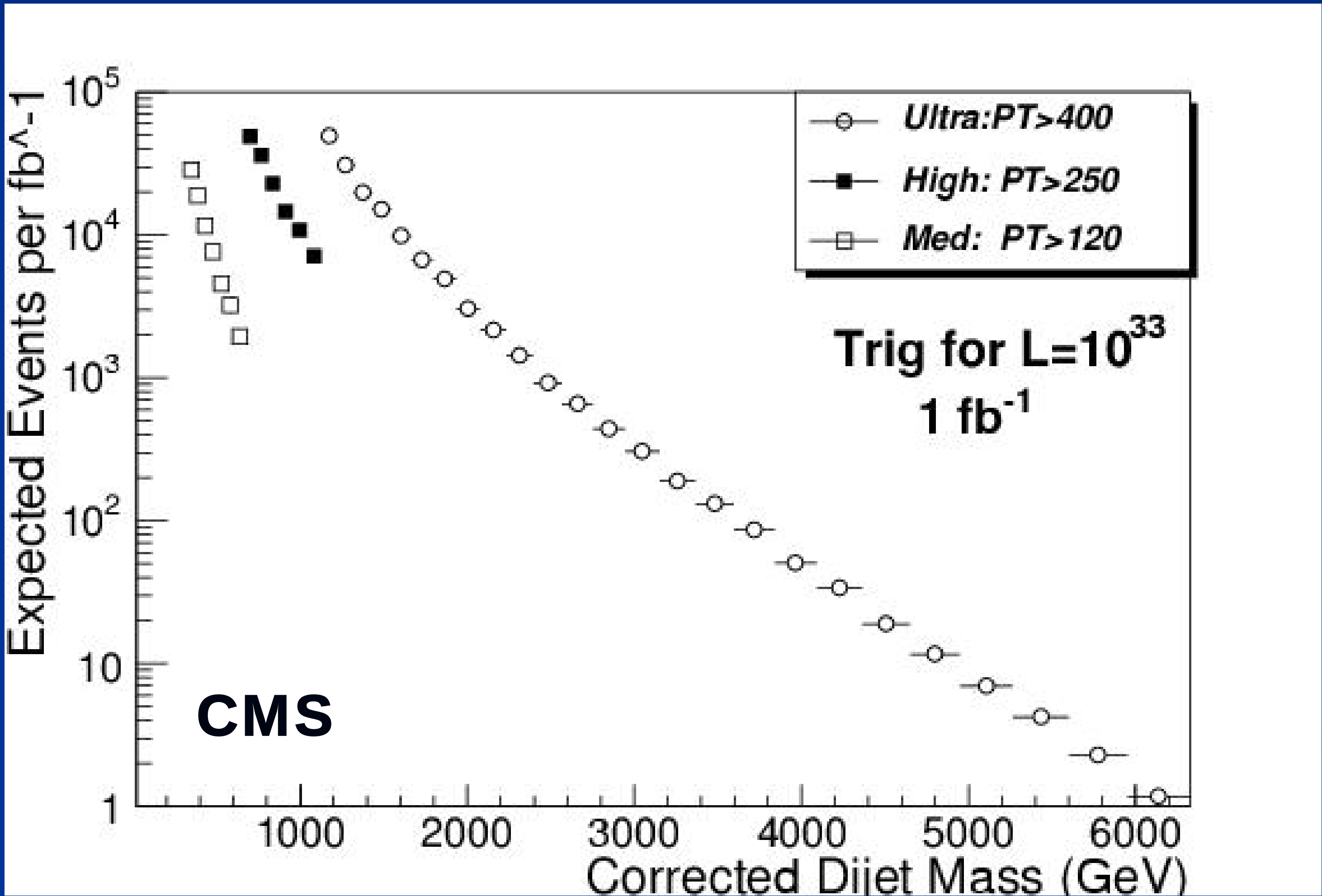
SM Higgs

Perhaps new physics



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

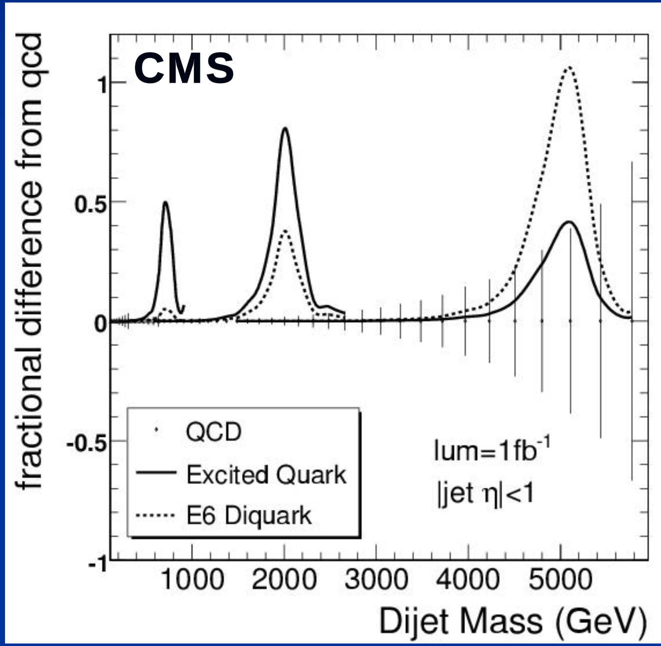
1 fb^{-1} : jets up to 3-3.5 TeV, di-jet masses up to 6 TeV: **new territory!**

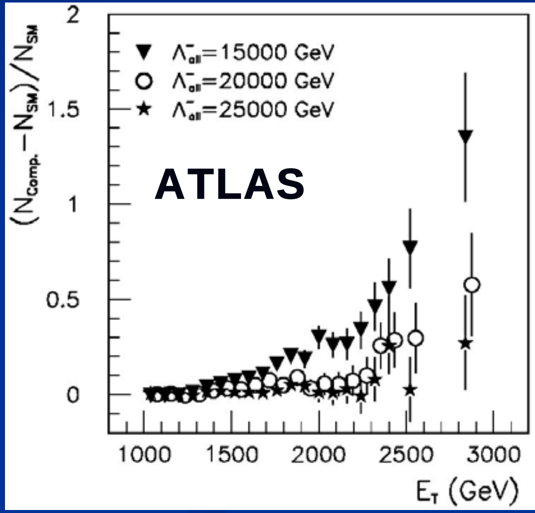


Example 1 of possible early discovery: anomalies in high E_T QCD jets, di-jet masses

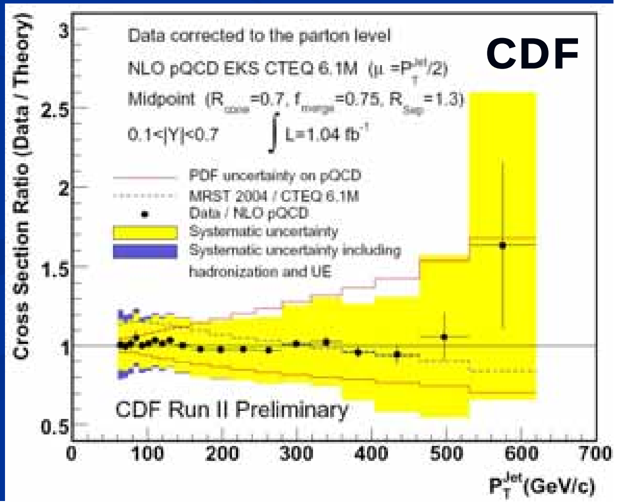
1 fb^{-1} : jets up to 3-3.5 TeV, di-jet masses up to 6 TeV: new territory!

Sensitive to substructure, contact interactions, high mass resonances





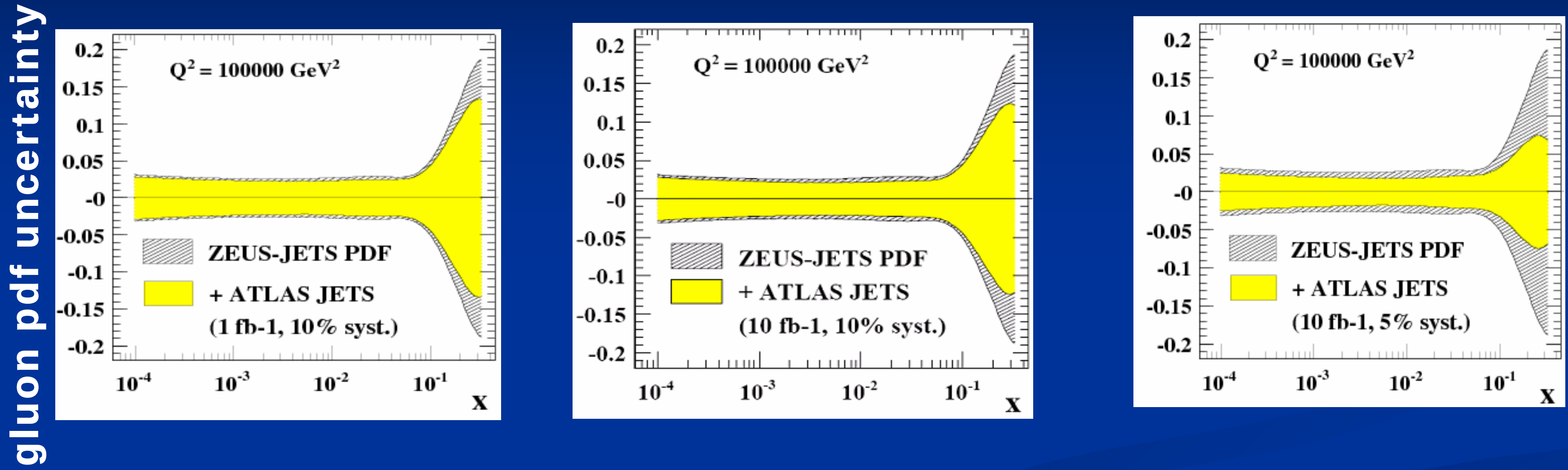
Deviations from SM for various compositeness scales, 30 fb^{-1}



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

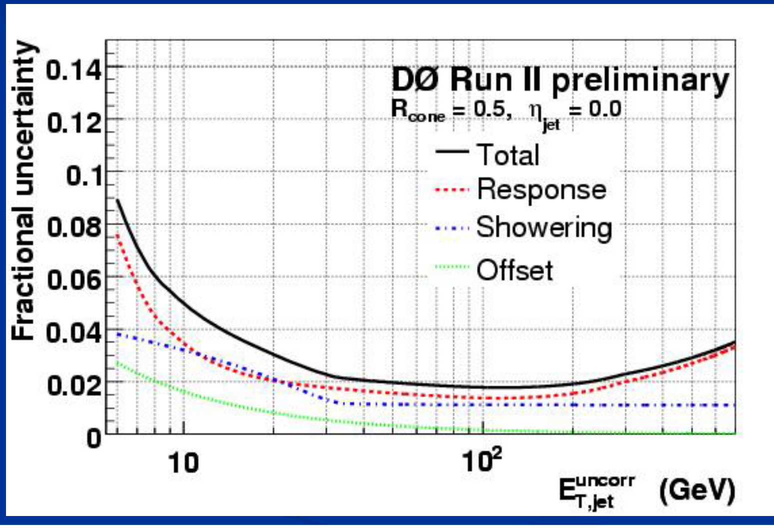
Validation of the energy of a jet is a <u>BIG challenge</u>

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



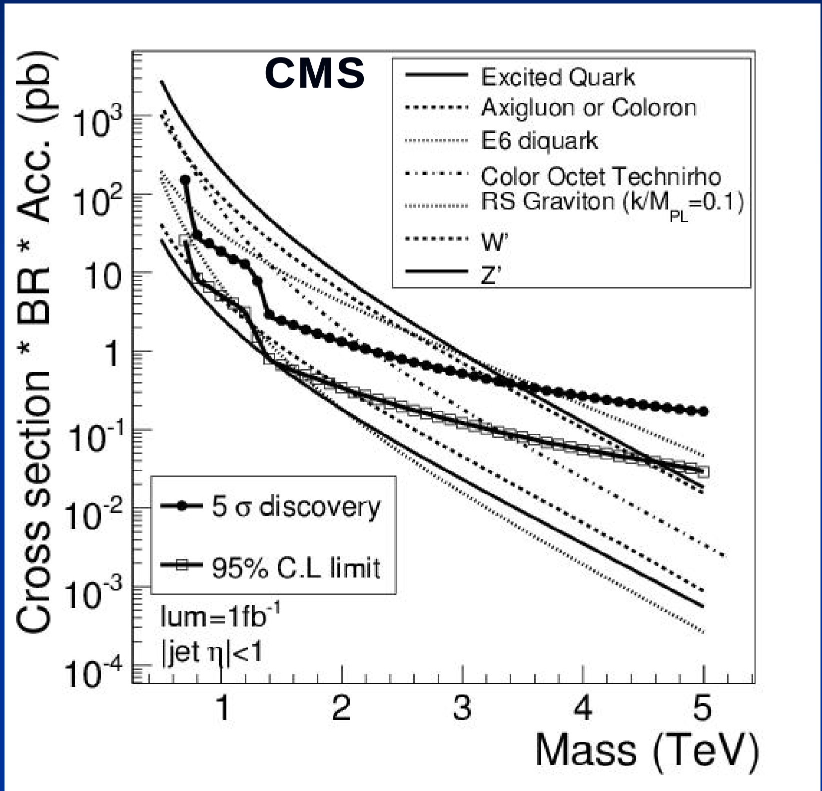
CMS and ATLAS: 10% initially → 2-3% above 20 GeV after 1-10 fb^{-1} and 1% eventually? <u>Ambitious!</u>

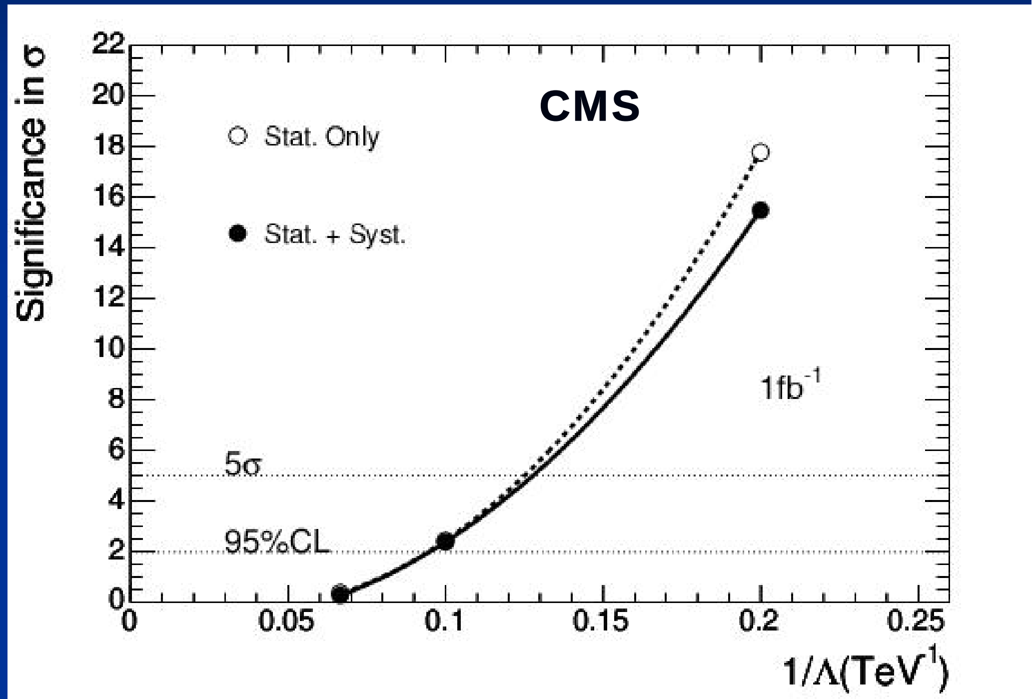
Using: γ+ jet events
Z + jet events
} Needs EM scale first

top-pair events: 2 jets from W

light jets and b-jets !

Expected sensitivity for new physics:





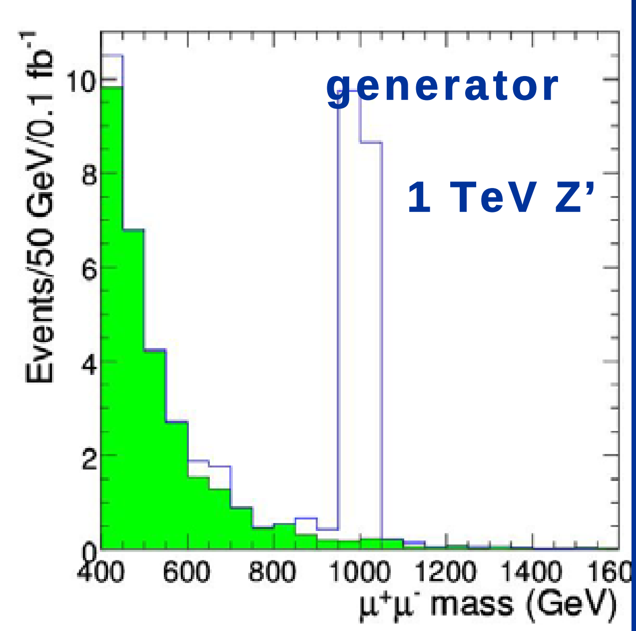
Discovery potential with 1 fb^{-1}: excited quarks up to 3.4 TeV

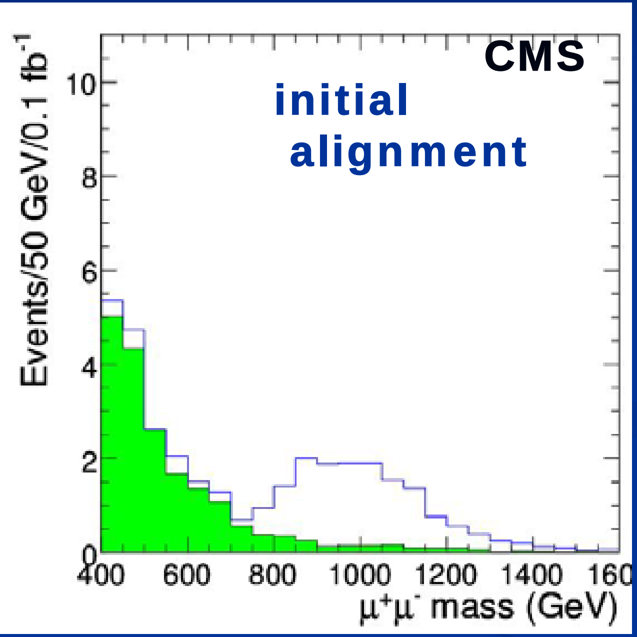
E_6 diquarks up to 3.7 TeV

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





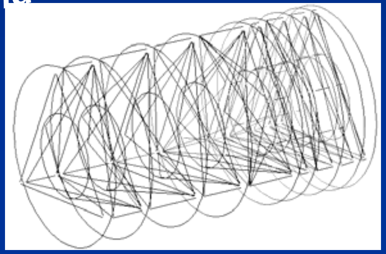
Challenges: lepton momentum scale: alignment, calibration
knowledge of efficiencies, fakes, misreconstruction
SM predictions at high mass, K-factors
MC generators for new physics

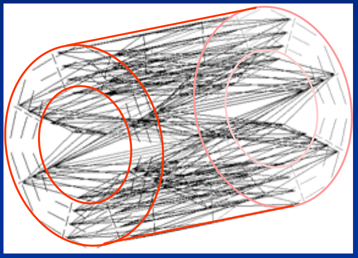
Challenge: tracker alignment

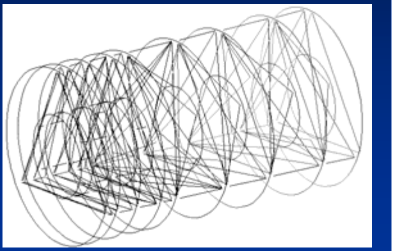
At start-up: hardware based-alignment, plus cosmics

→ 20-200 μm accuracy at startup

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







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

CMS: laser alignment

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)

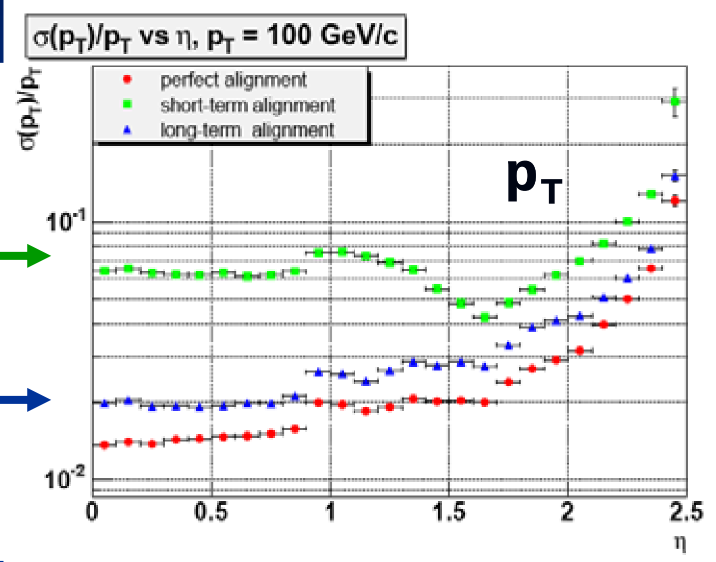
Challenge: tracker alignment

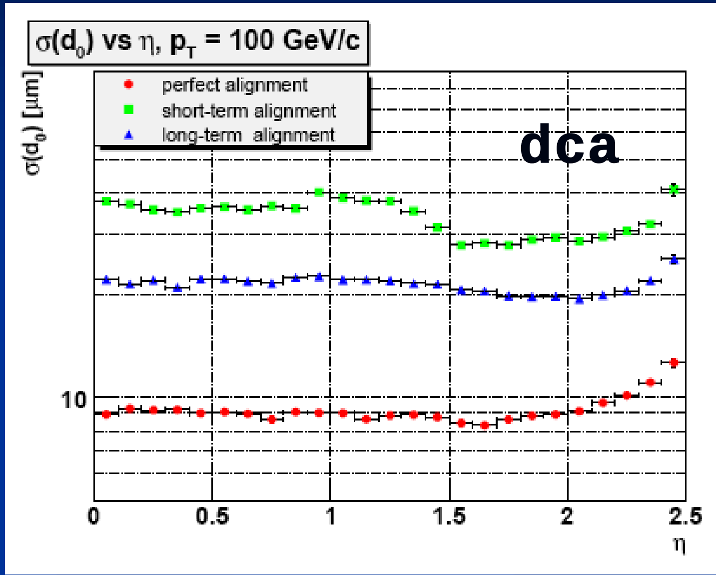
CMS plots:

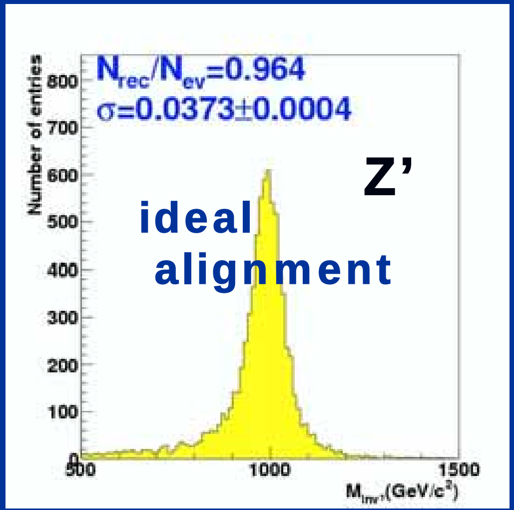
Track-based alignment using minimum bias, Z→ee, μμ

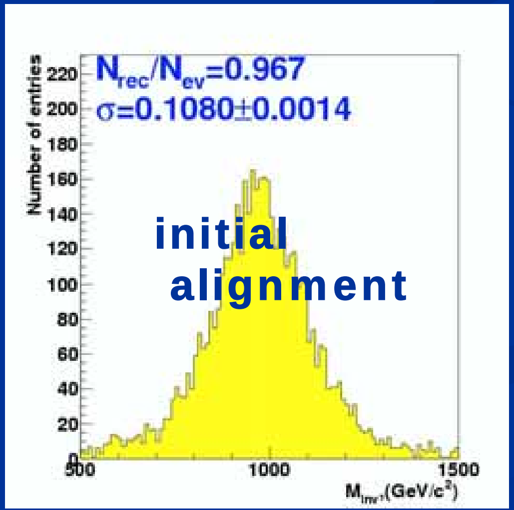
initial:

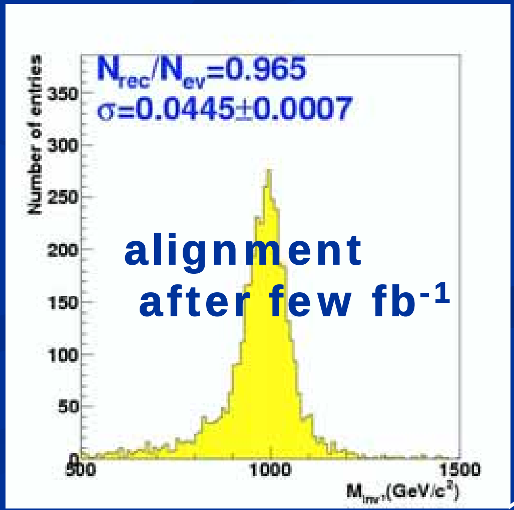
after few fb^{-1}



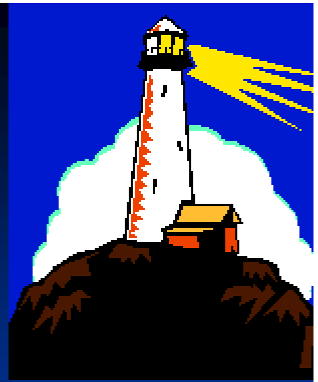








Lepton energy / momentum scale calibration



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%

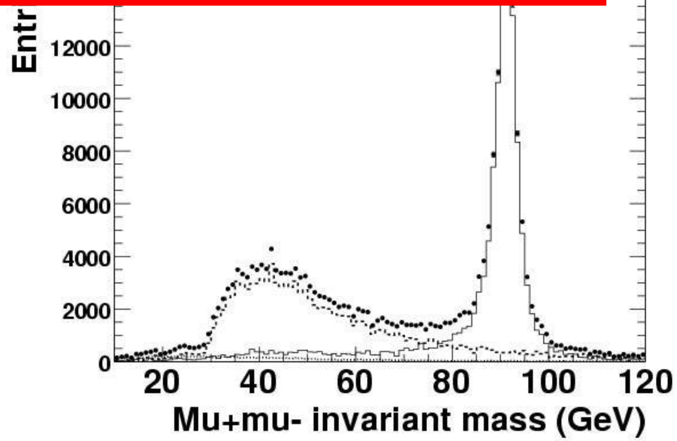
Challenge: disentangle many effects with Z sample:
B-field, material, non-uniformity, alignment, response…
(so: also need top, J/ψ, ϒ, minimum bias,…)

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

CMS

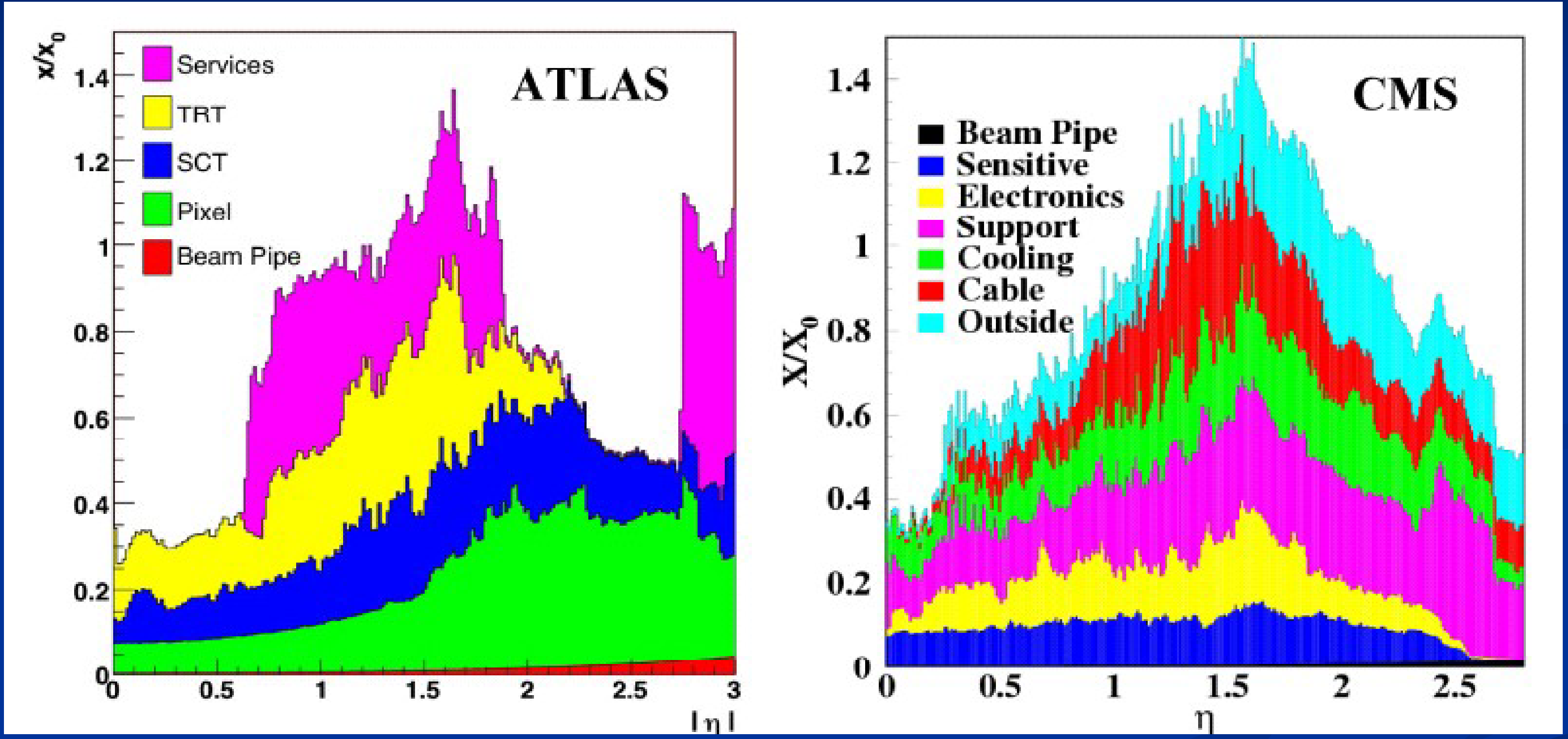
Muons: Z → μμ

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: selection and trigger efficiency

Cannot rely on MC
Use data: redundant triggers
prescaled triggers

W,Z cross sections
→ Juan Alcaraz talk

redundant reconstruction methods
e.g. muons in inner detector, calorimeter, muon system

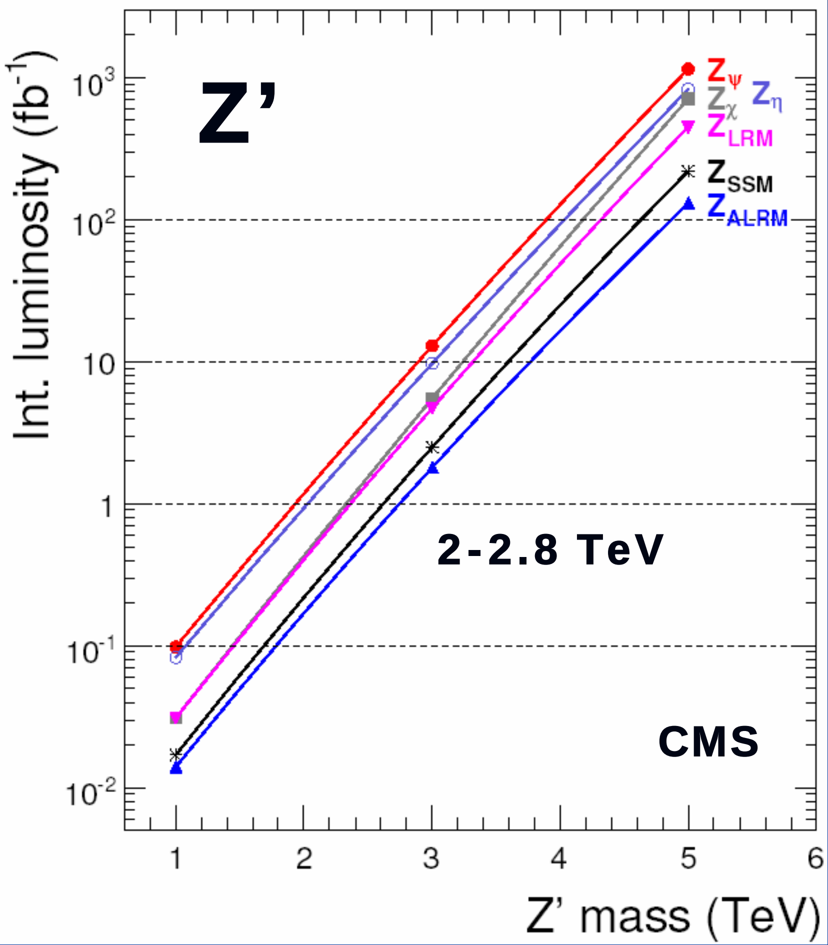
tag-and-probe: $Z \rightarrow \mu\mu$ one μ tight, look at other

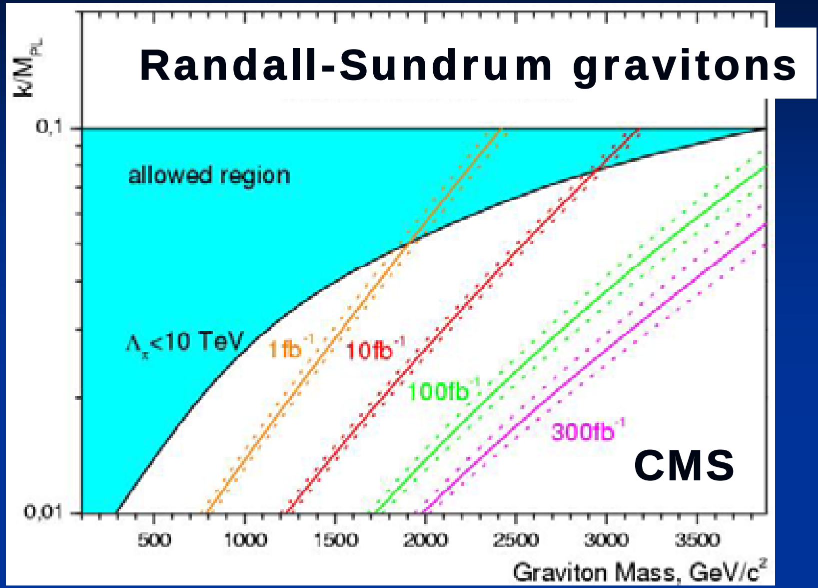
Challenge: uncertainties in SM prediction: scale, pdf
EW corrections?
corners of phase space

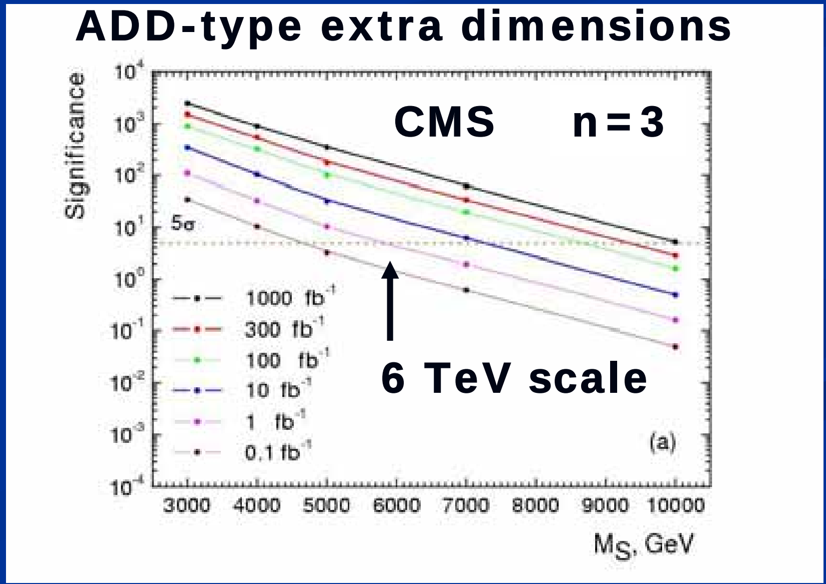
Use control samples in data
But cannot always cover tails, corners of phase space

→ MC remains important, must describe data control samples

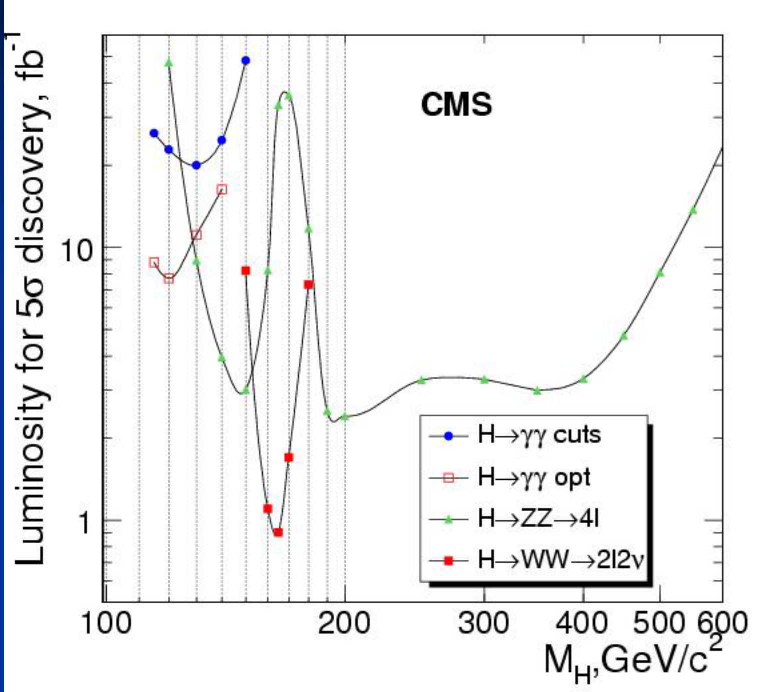
Sensitivities for various new physics models







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



H → WW → llνν
(see talk Alexey Drozdetskiy)

No mass peak: counting experiment

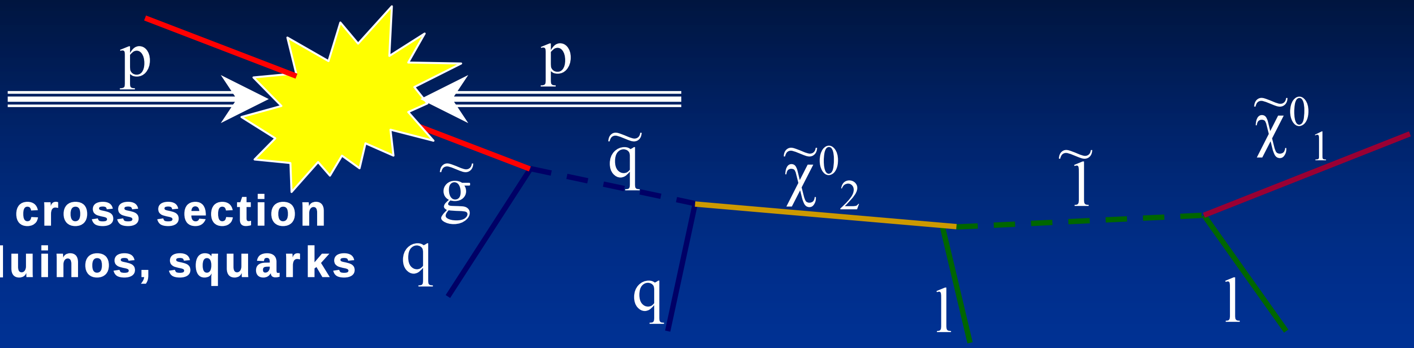
Challenge: extremely good knowledge of background needed

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

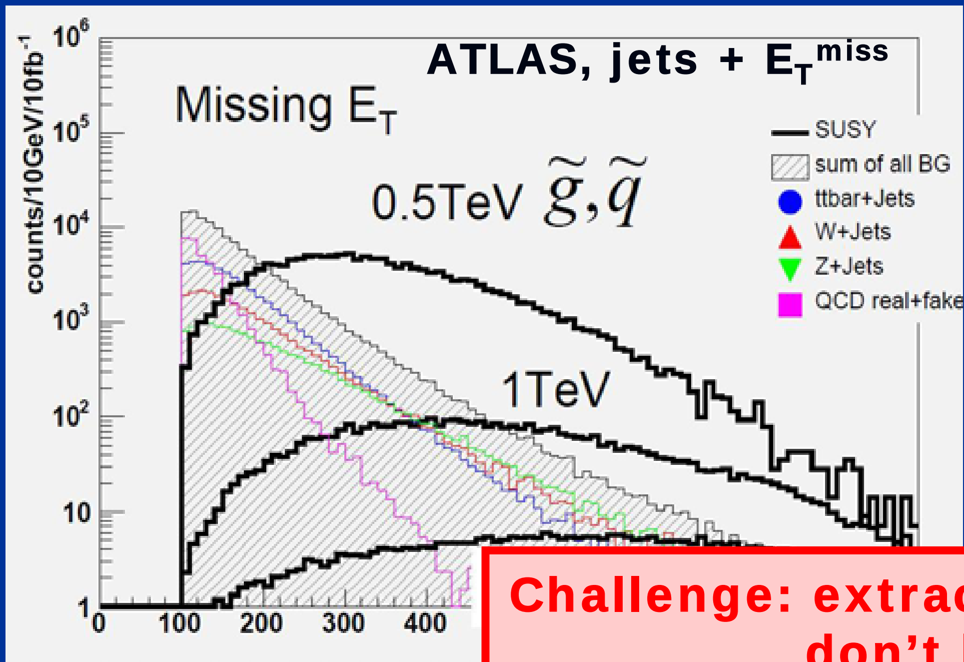
Get background from data itself: control samples: tt, WW, WZ

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)

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

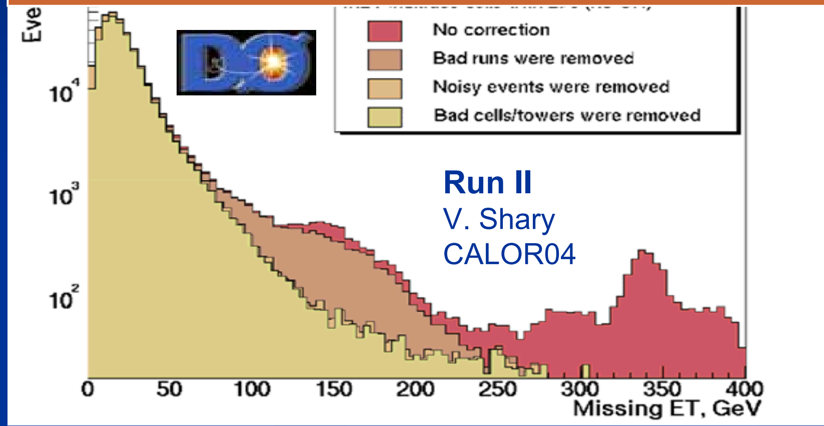
Missing transverse energy: E_T^{miss}

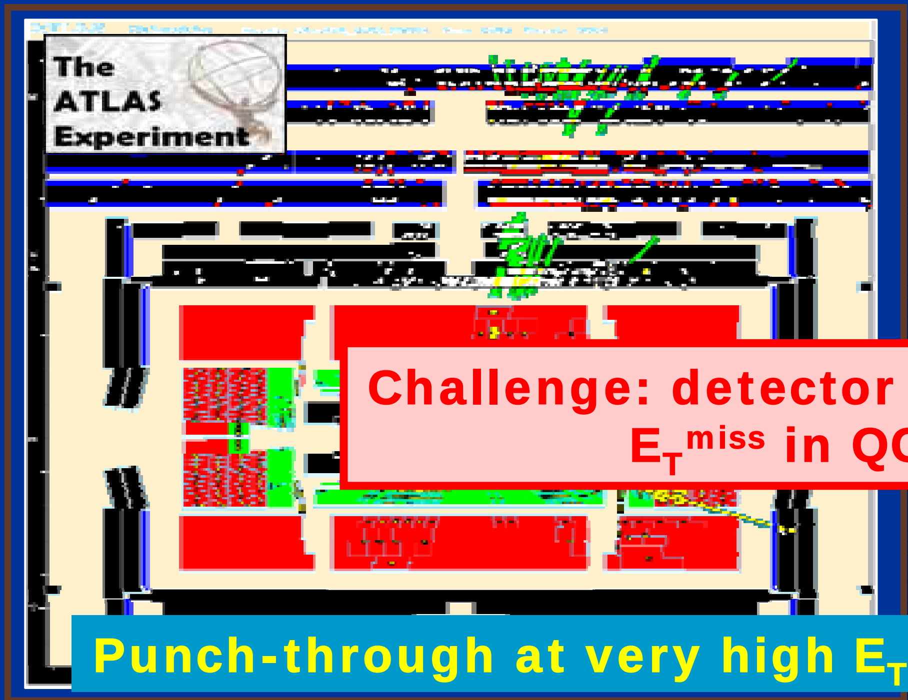
Escaping particles: momentum balance upset

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

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

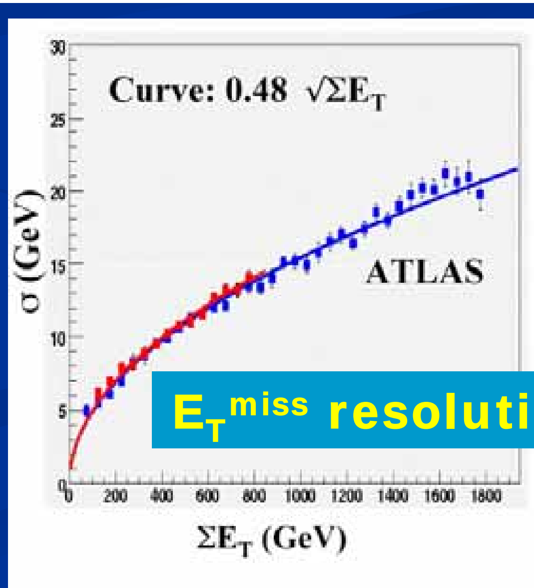
E_T^{miss} spectrum contaminated by cosmics, beam-halo, machine/detector problems, etc.





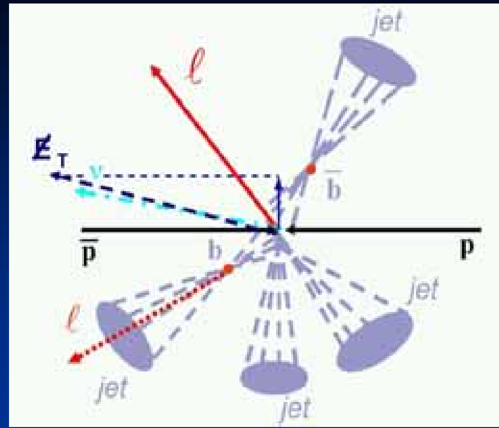
Challenge: detector effects
E_T^{miss} in QCD events

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:

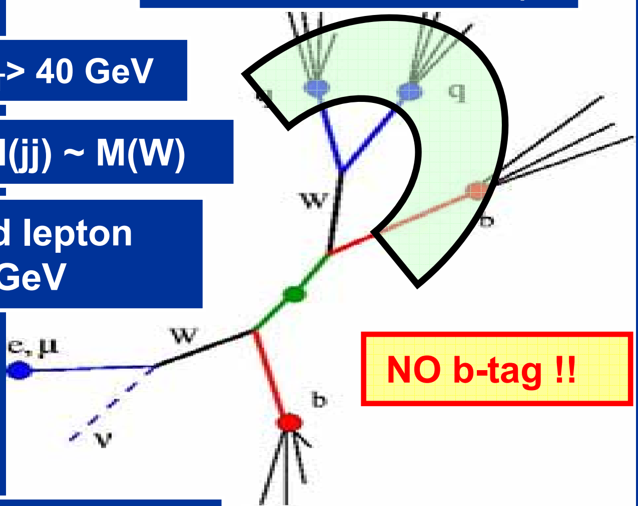
3 jets with largest $\sum p_T$

4 jets p_T> 40 GeV

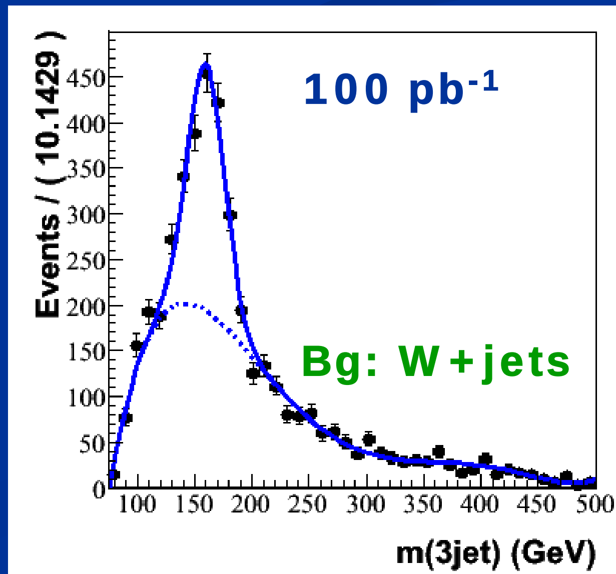
2 jets M(jj) ~ M(W)

Isolated lepton
p_T> 20 GeV

E_T^{miss} > 20 GeV



NO b-tag !!



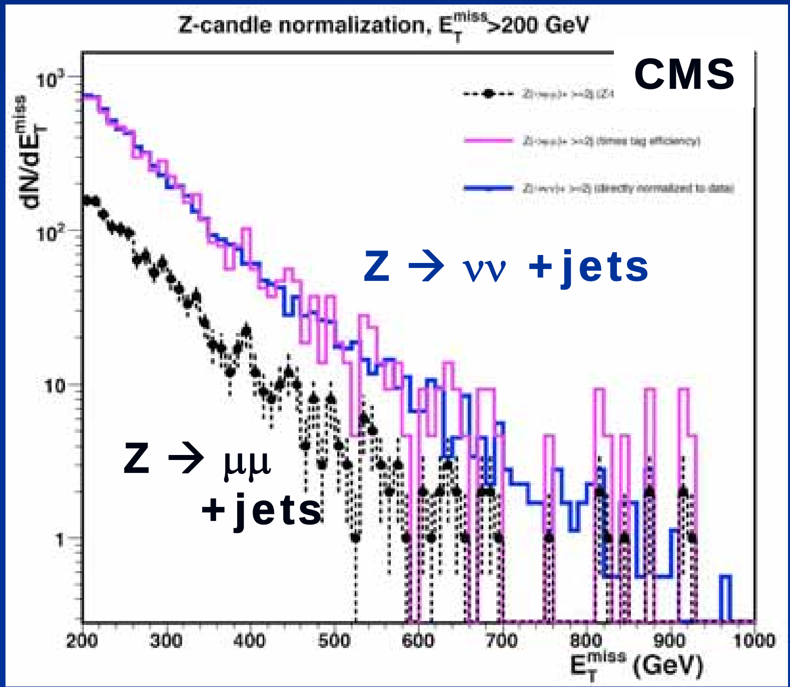
- -b jets
- -E_T^{miss} calibration
- -Hadronic W's
- -p_T (top) studies

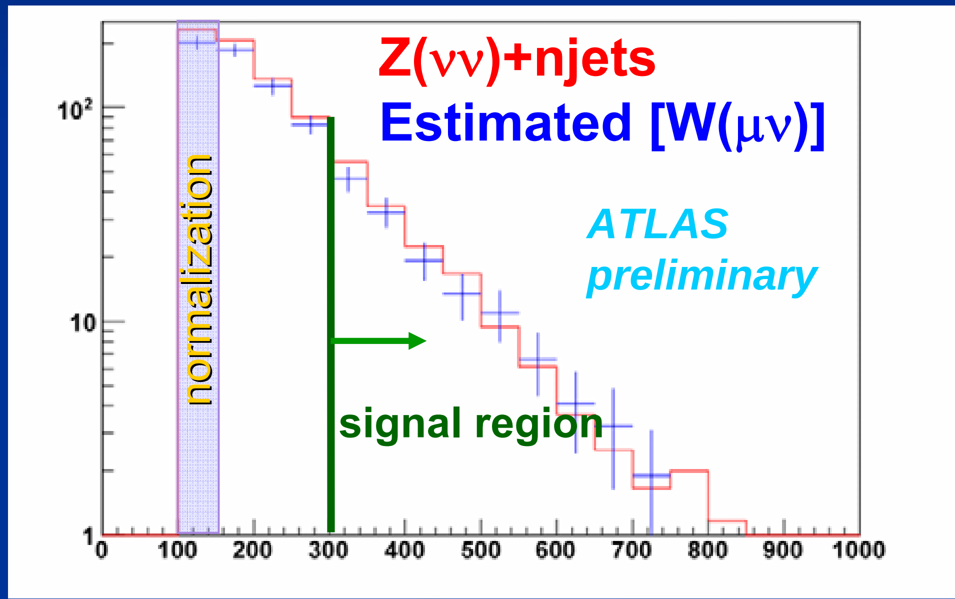
If b-tag works,
cleaner selection

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)

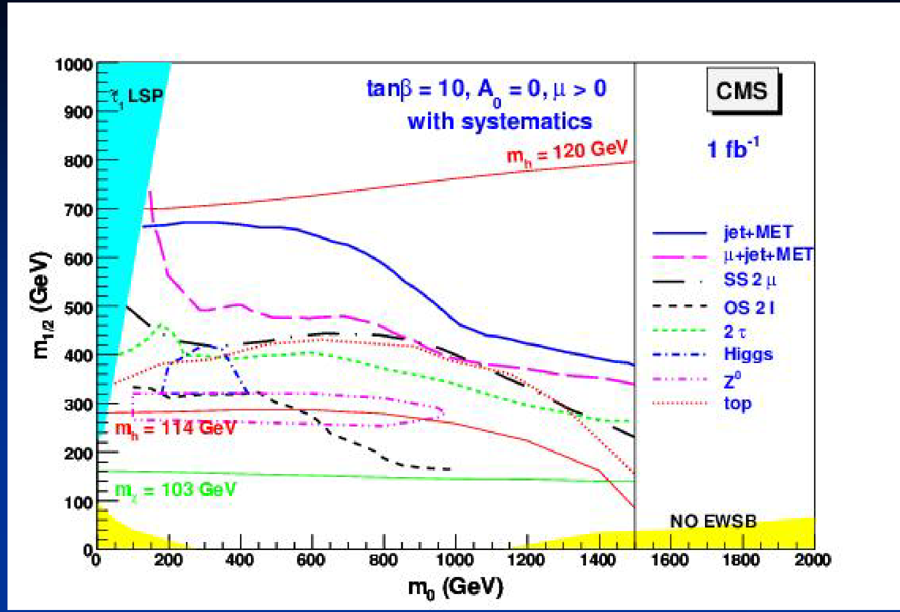
Top: can select clean control sample with mass reconstruction
normalize at low E_T^{miss}, extrapolate to SUSY signal region

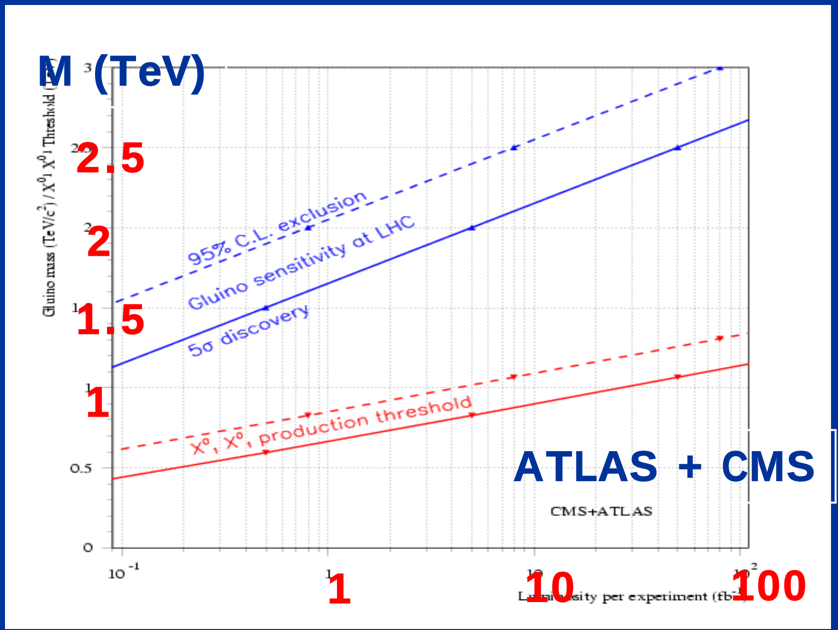
mSUGRA reach

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

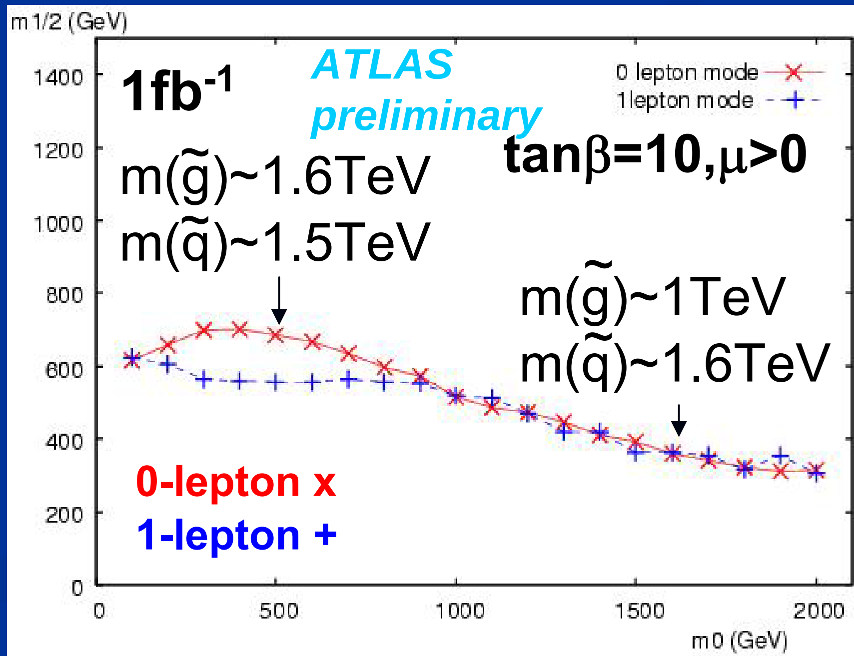
More general searches also performed

Challenge: if we see something: what is it?

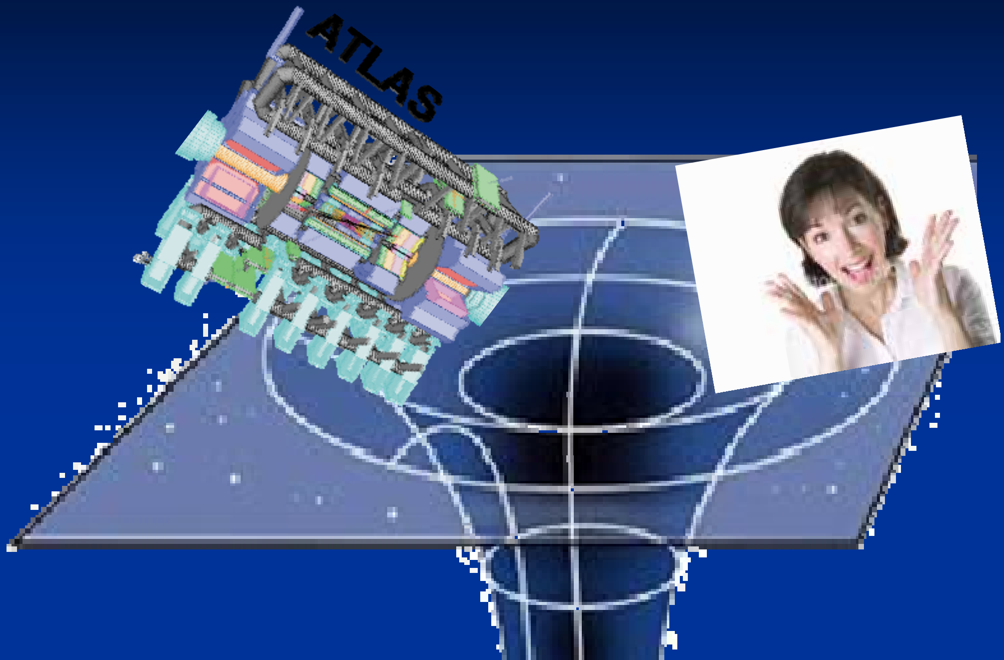




Luminosity/expt (fb^{-1})



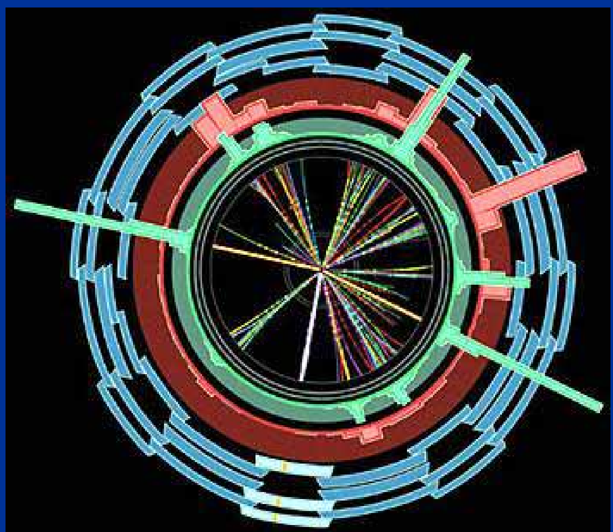
Maybe nature has some REAL SURPRISES in store…



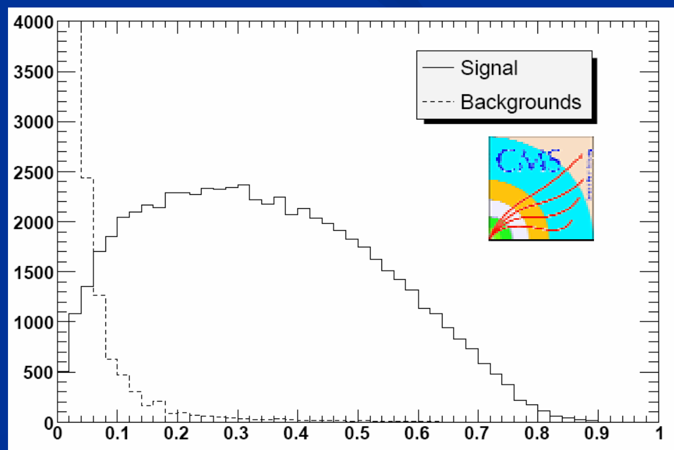
Large extra dimensions, Planck scale ~ EW scale

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
→ But must not compromise quality!

Blind analyses: desirable, but practical?

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

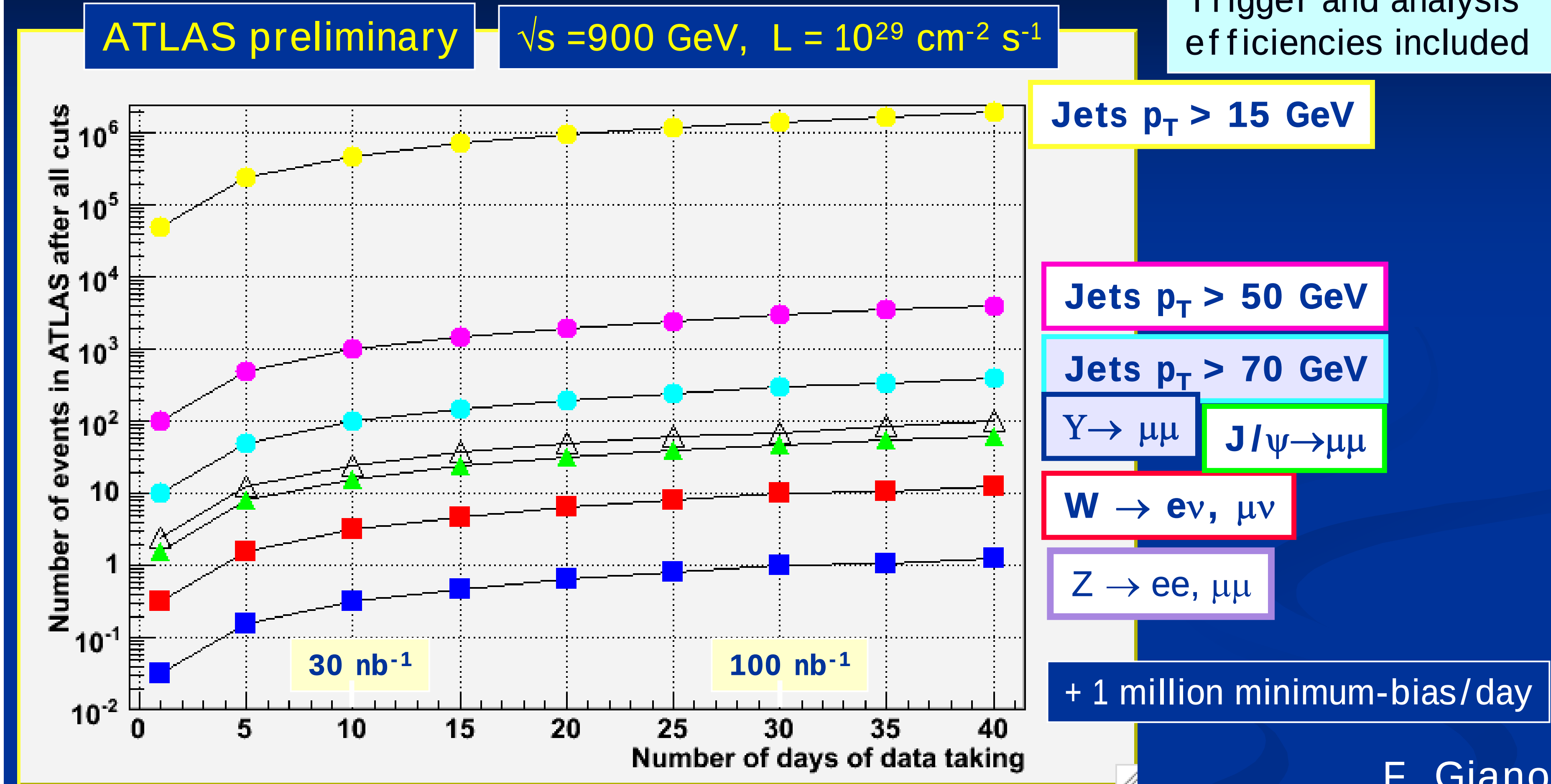
Learn from the Tevatron. Still lots to be learned on W,Z production, particularly with associated jets, b-quarks…
Understanding the detectors will be a MAJOR task.

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



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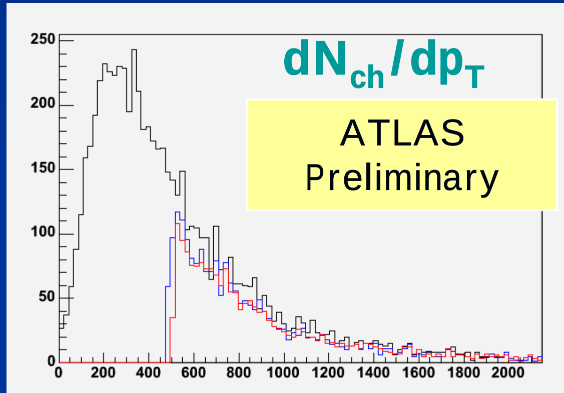
- Start to commission triggers and detectors with collision data (minimum bias, jets, ..) in real LHC environment
- Maybe first physics measurements (minimum-bias, underlying event, QCD jets, ...) ?
- Observe a few $W \to l\nu$, $\Upsilon \to \mu\mu$, $J/\psi \to \mu\mu$?

The inevitable first measurements: soft hadronic stuff

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

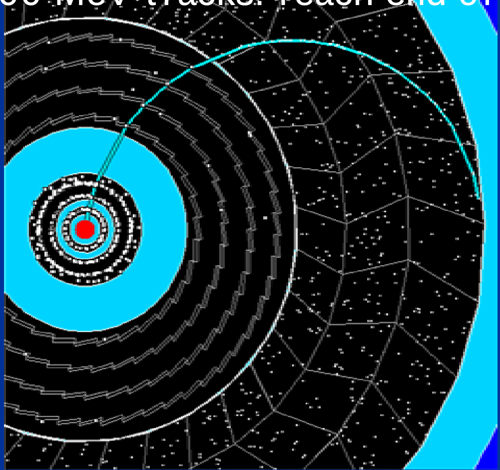
Probably very first measurement in 14 TeV (and 900 GeV) data:

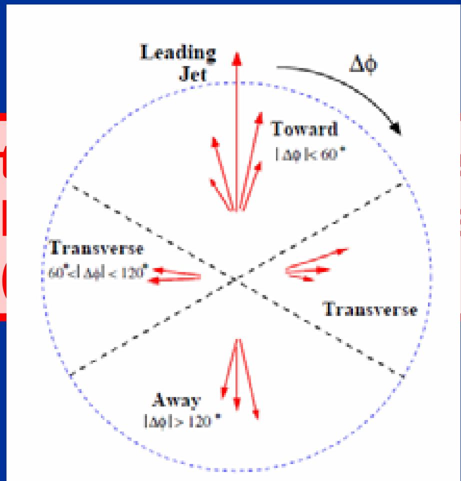
- central charged particle multiplicity
- “transverse” charged particle density in di-jet, DY events

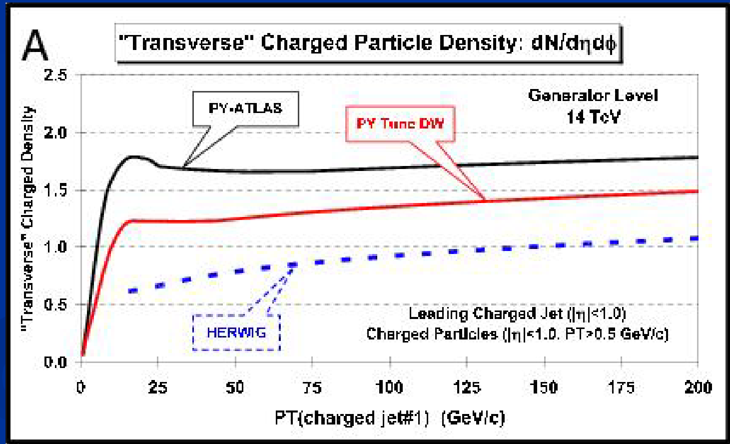


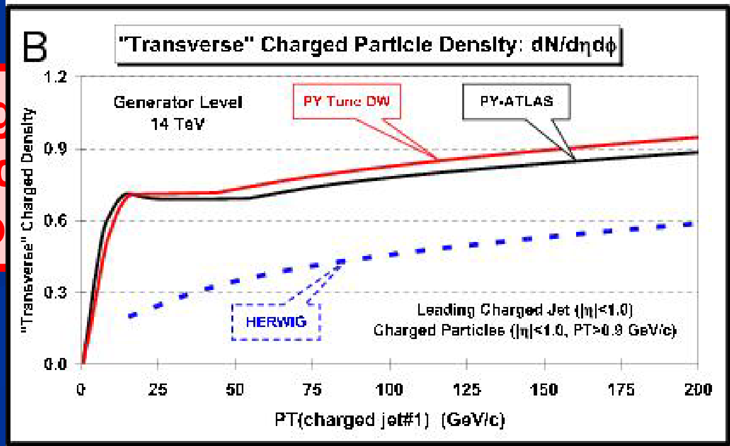
p_T (MeV)

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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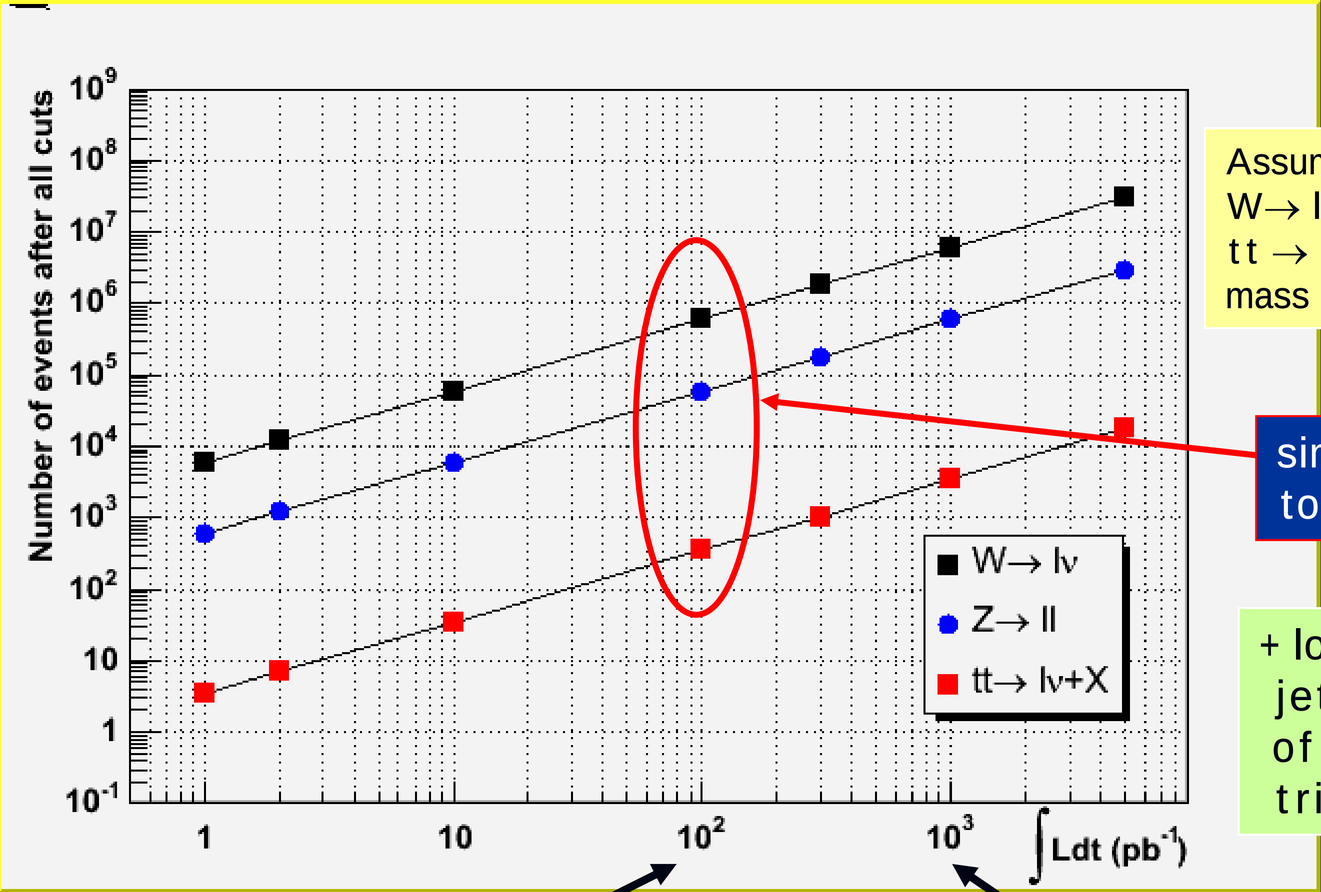
How many events per experiment at the beginning ?



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

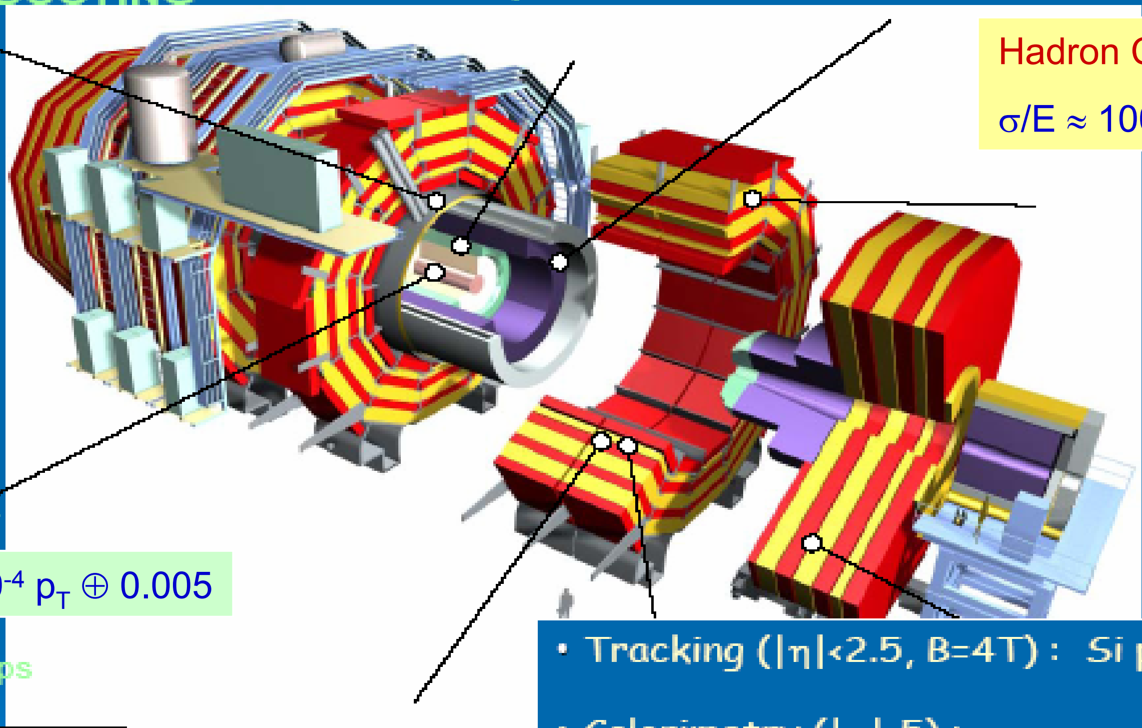
Plastic scintillator/brass sandwich

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 B

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 ApparatuS (ATLAS) DETECTOR

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

excellent electron/photon identification

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

Precision Muon Spectrometer,

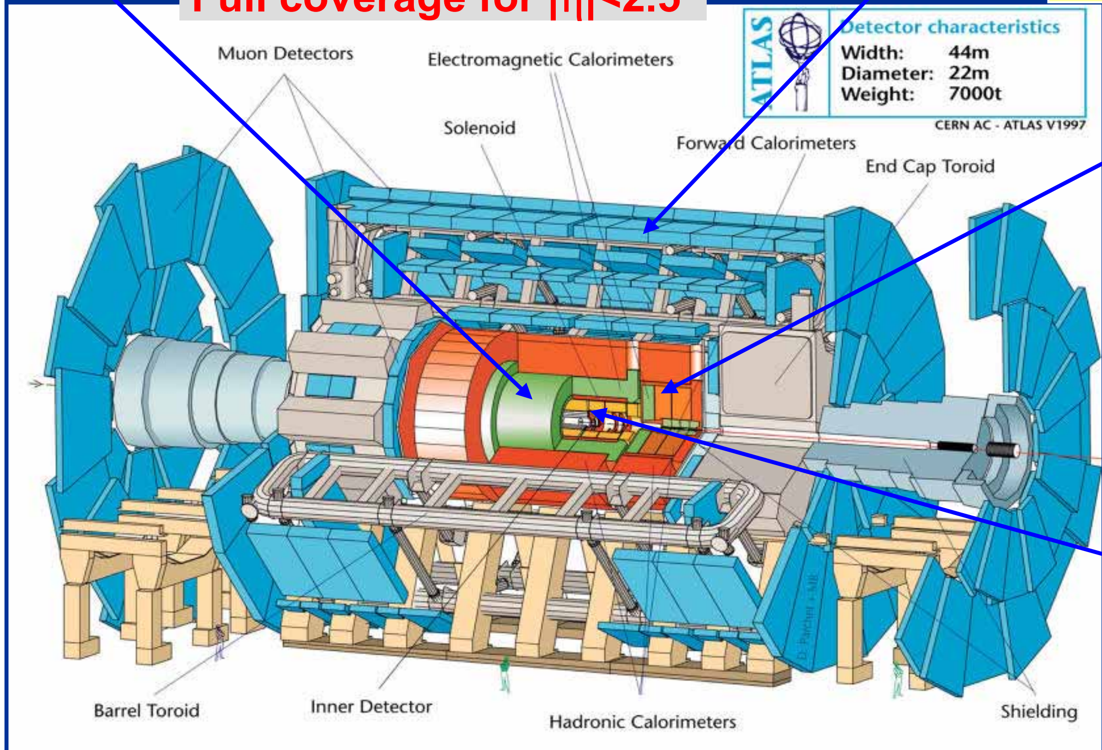
$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution

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

Full coverage for $|\eta|<2.5$



Hadron Calorimeters,

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

Good jet and E_T miss performance

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

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.

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

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

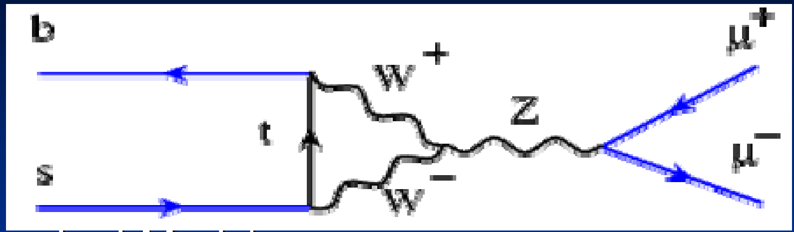
- CMS tracker has better momentum resolution (larger field and lever arm)
- However impact of material on efficiencies
- Similar impact parameter resolution

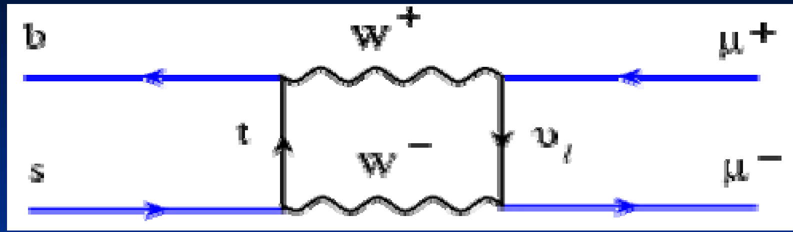
*These numbers as many others and some plots extracted from: D. Froidevaux, P. Sphicas (CERN) General-purpose detectors for the Large Hadron Collider. Ann.Rev.Nucl.Part.Sci.56:375-440,2006.

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	**O**(10 μm)

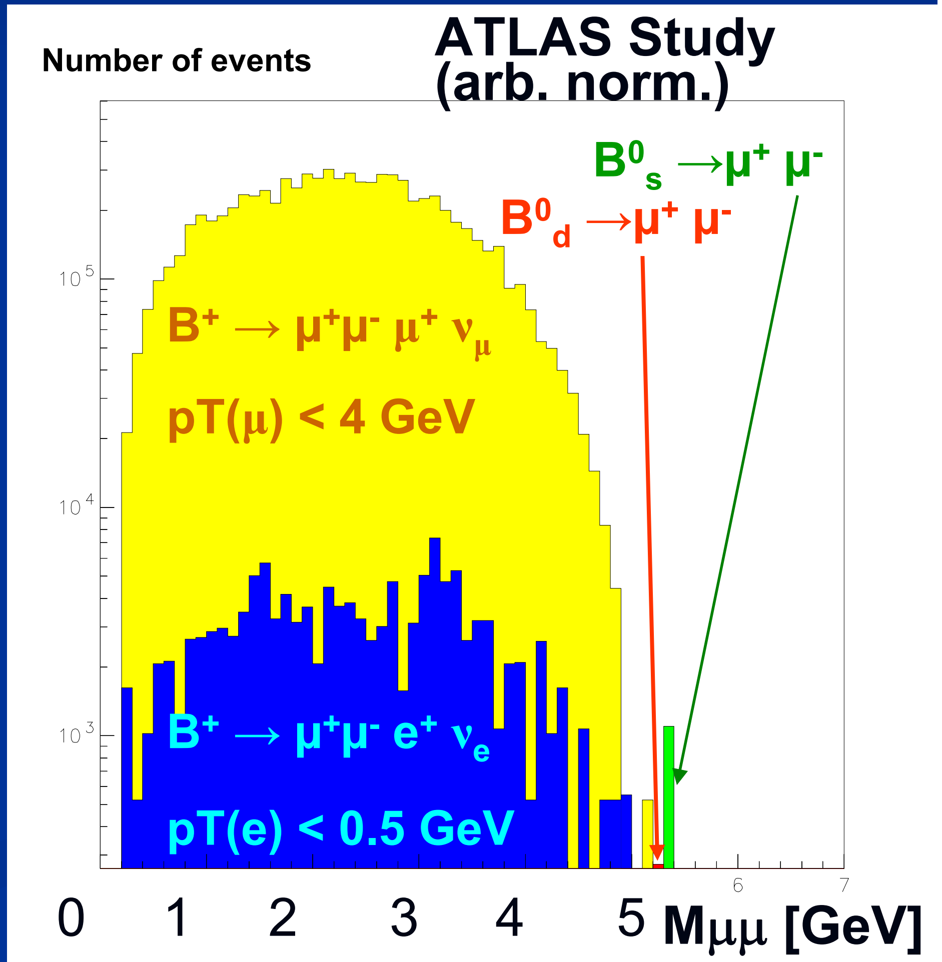
$B_{s,d} \rightarrow \mu\mu$





- Standard Model
  - $Br(B^0_s \rightarrow \mu^+ \mu^-) \approx 3.5 \times 10^{-9}$
  - $Br(B^0_d \rightarrow \mu^+ \mu^-) \approx 10^{-10}$
- *Eg*: ATLAS (yes, "staged" ATLAS for early running)
  - Trigger: $P_T(\mu) > 6$ GeV for $|\eta(\mu)|<2.5$
  - Analysis optimized for $S/\sqrt{B}$
  - $\sigma(B\rightarrow\mu\mu) \approx 80$ 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}	$< 5.5\times10^{-9}$



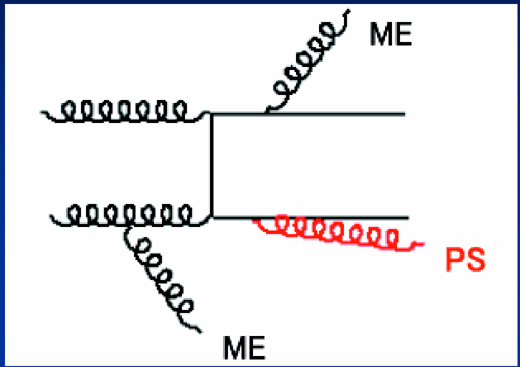
NLO wishlist

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

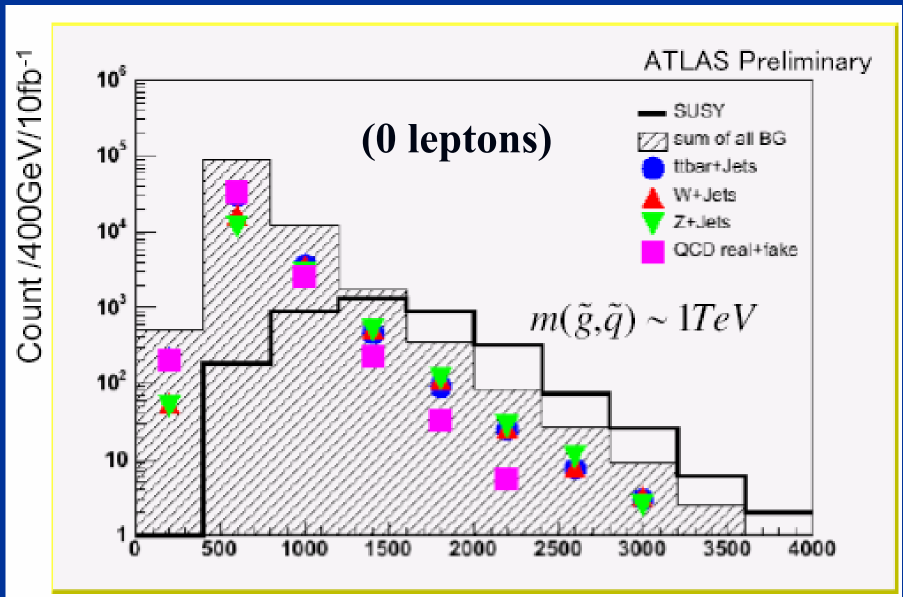


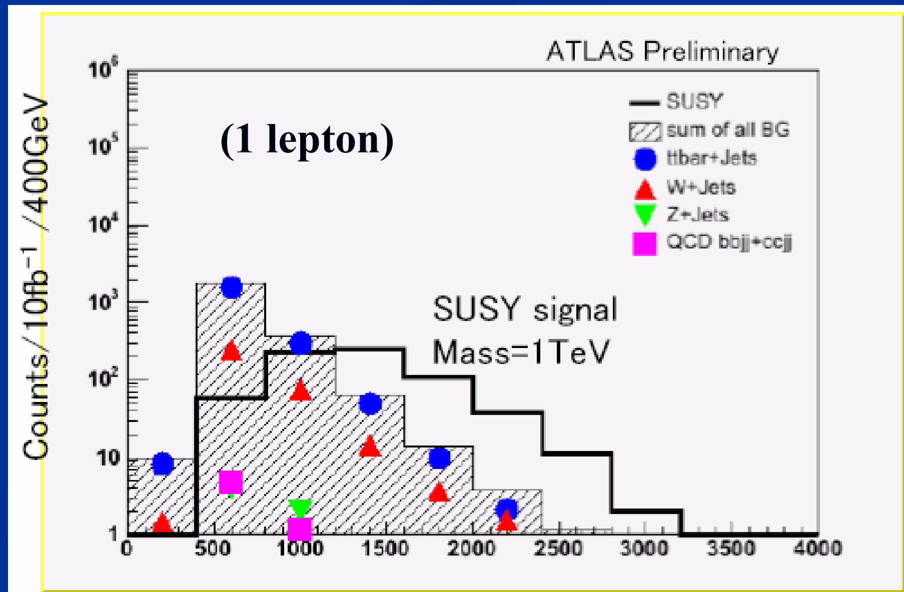
Large cross sections

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)