LHC physics with early data

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DESY Theory Workshop
"Collider Phenomenology"

Hamburg
Sep. 29th - Oct. 2nd 2009

Contents

- Motivation
- LHC & ATLAS and CMS
- "Rediscovery" of Standard Model

  → … and more
- New physics beyond SM
- Summary

LHC motivation / expectation

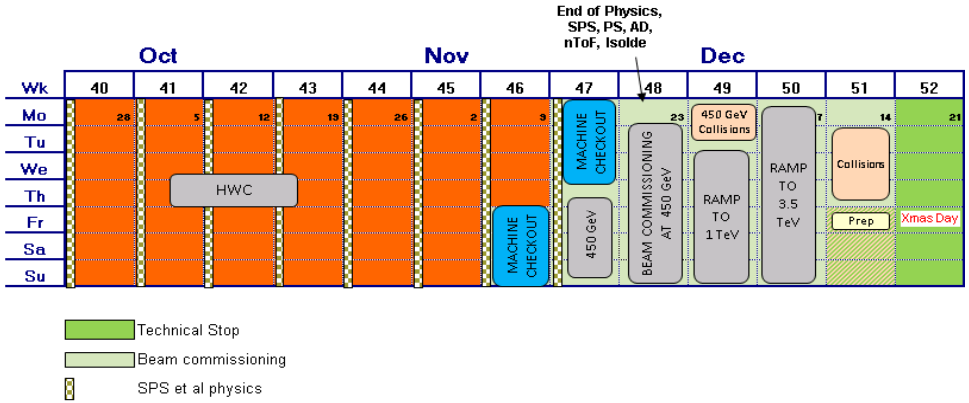
- as discussed during the workshop already …

LHC & ATLAS and CMS

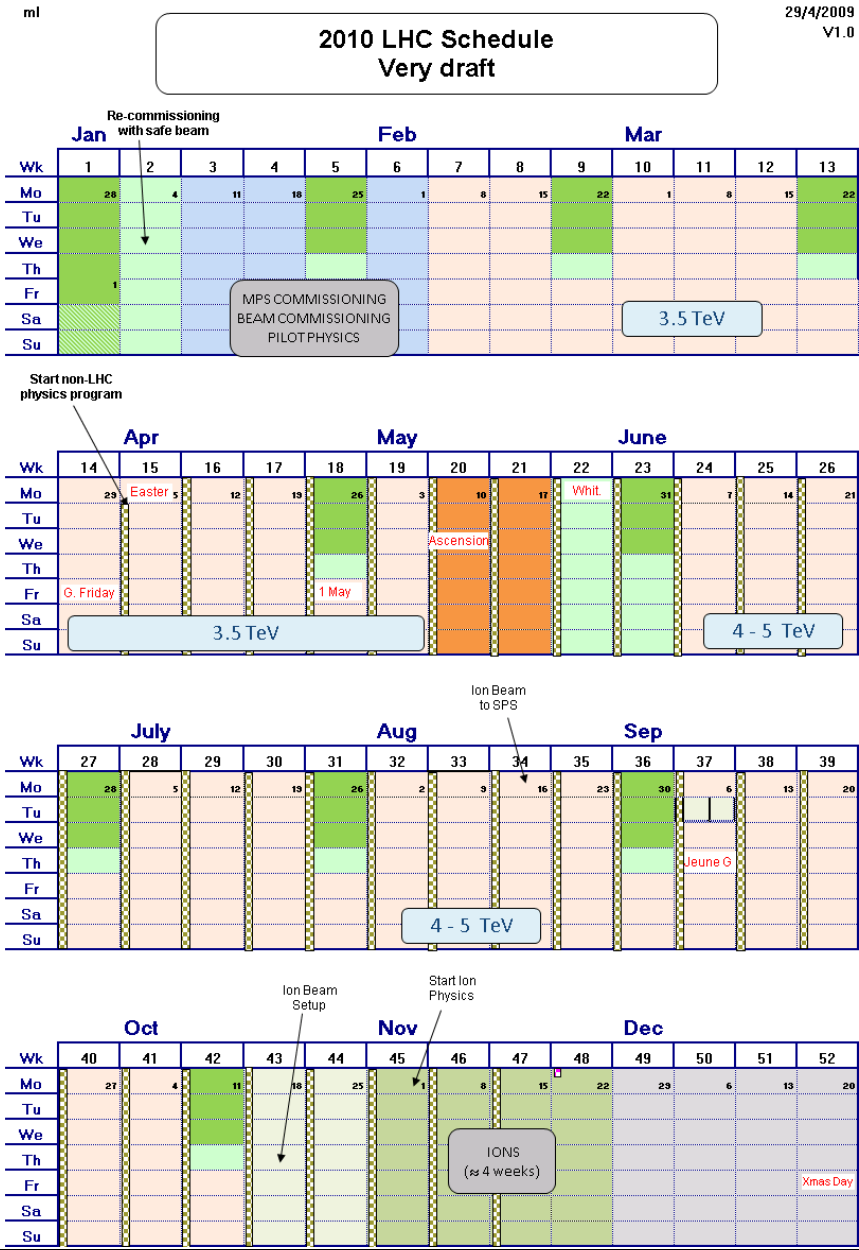
Expectation for 2009/2010

→ all numbers shown have uncertainties

- start-up end of 2009
  - 1 month commissioning



Mike Lamont (August 2009)



- physics run through 2010
  - 1 month commissioning / pilot run

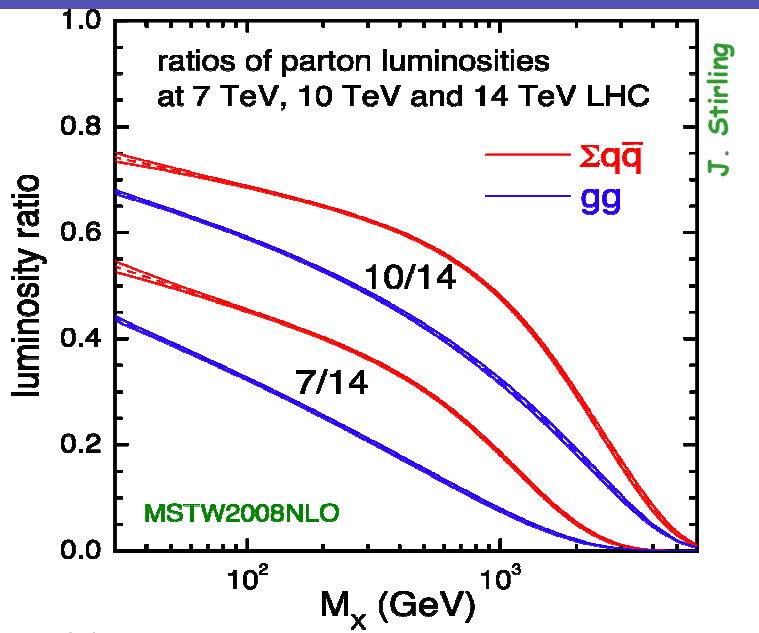
→ 3 months at $\sqrt{s}$ = 7 TeV
  - 1 month 'step-up'

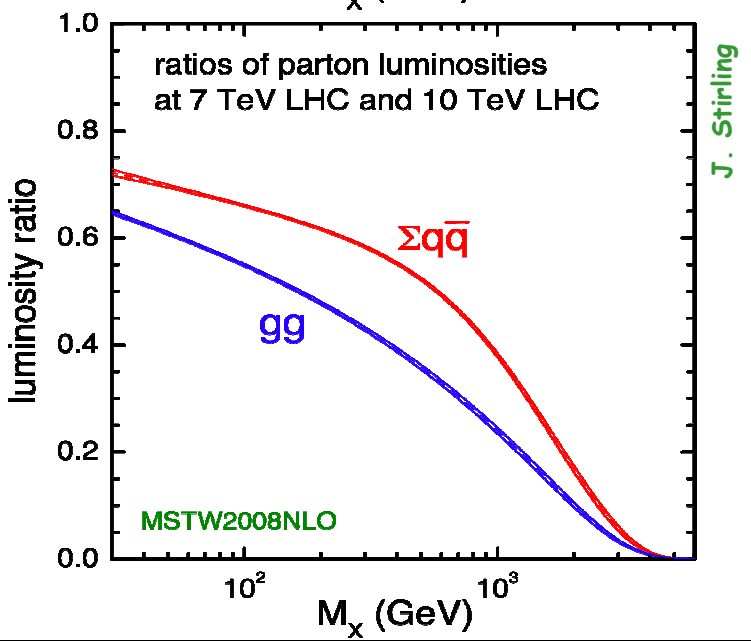
→ 5 months at $\sqrt{s}$ = 8-10 TeV

→ 1 month heavy ions

Expectation for 2009/2010 (cont'd)

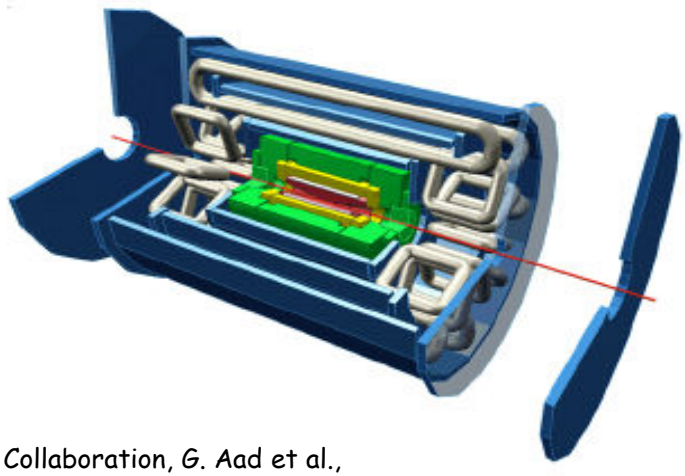
- instantaneous luminosity of up to $1\text{-}2*10^{32}\ cm^{-2}\ s^{-1}$
  - → at most 2-3 inelastic events per crossing (on average)
- integrated luminosity (delivered by LHC)
  - → up to 200-300 pb^{-1}
  - → possibly shared between two c.m.s. energies
    - 7 TeV and 8-10 TeV
- impact of reduced c.m.s. energy on cross-sections compared to design
  - → M_X = 100 GeV
    - 0.3-0.5 resp. 0.6-0.7 (7 resp. 10 TeV)
  - → M_X = 1 TeV
    - 0.1-0.2 resp. 0.3-0.5 (7 resp. 10 TeV)



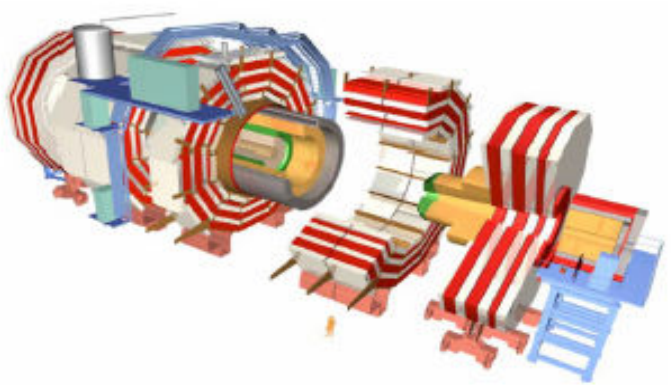


ATLAS and CMS

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\times10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\times10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass+scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID +MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (DT/CSC+Tracker)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)

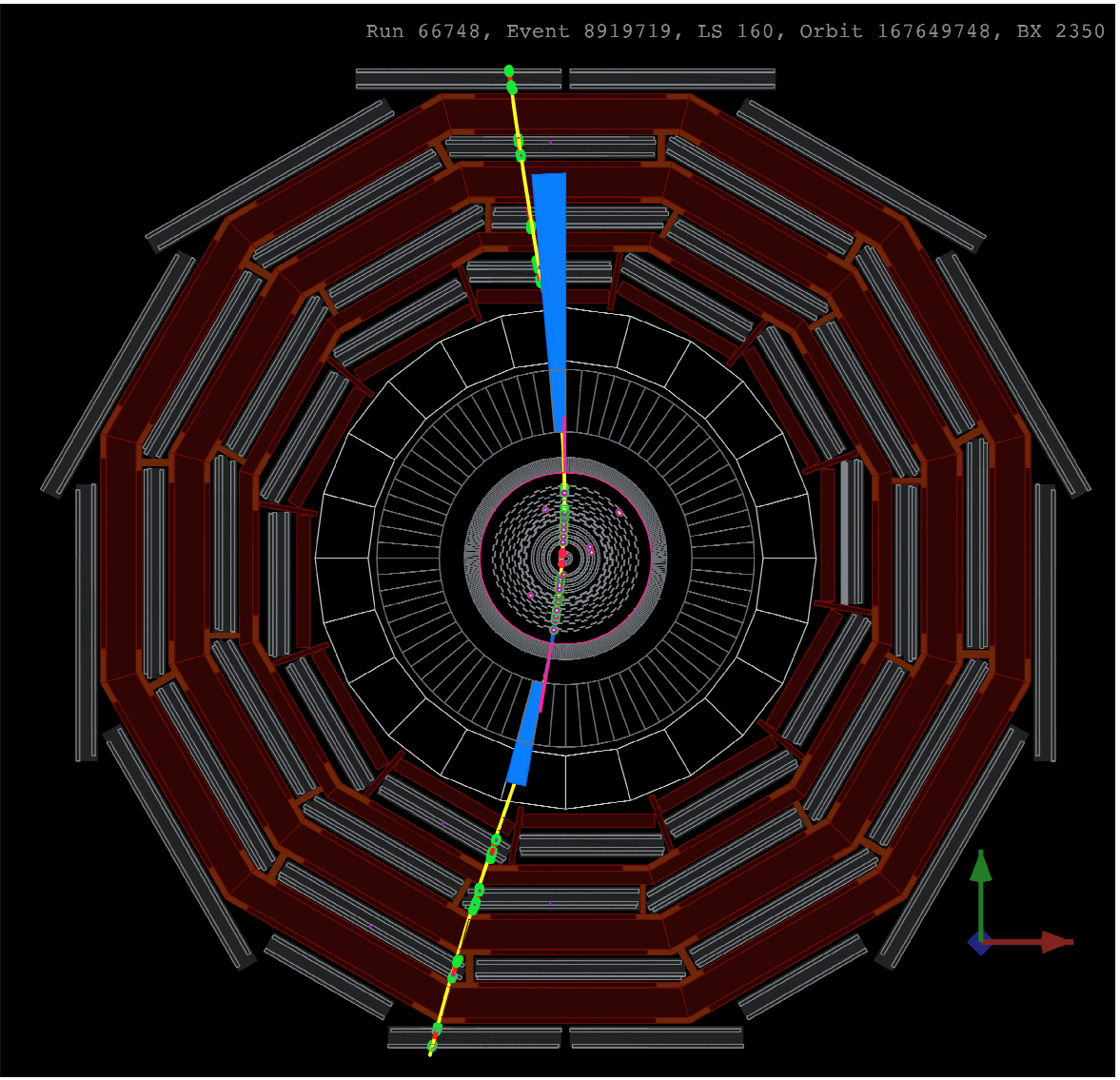


The ATLAS Collaboration, G. Aad et al.,
The ATLAS Experiment at the CERN Large Hadron Collider,
JINST 3 (2008) S08003.

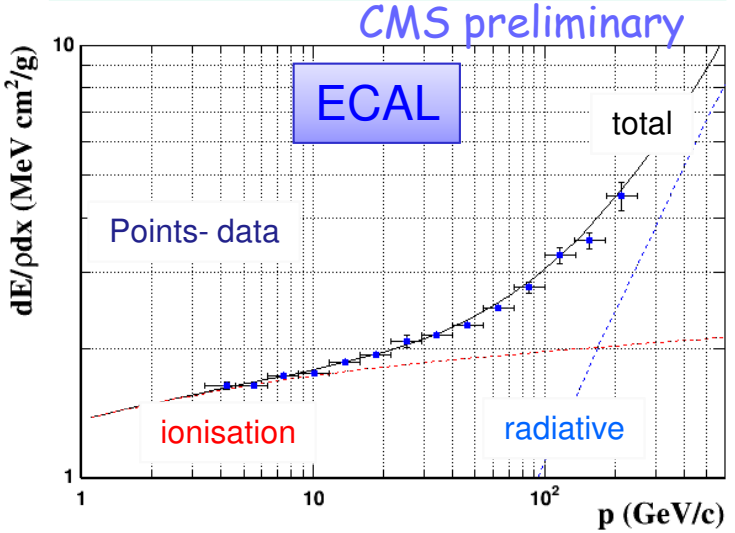


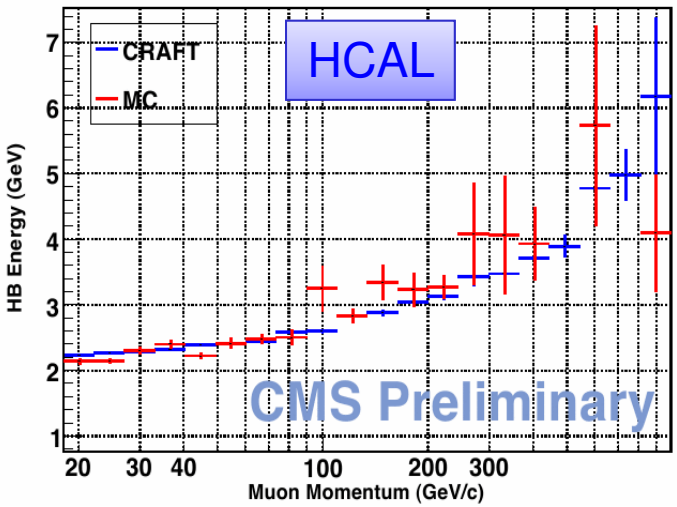
The CMS Collaboration, S. Chatrchyan et al.,
The CMS Experiment at the CERN Large Hadron Collider,
JINST 3 (2008) S08004.

Commissioning with cosmic muons

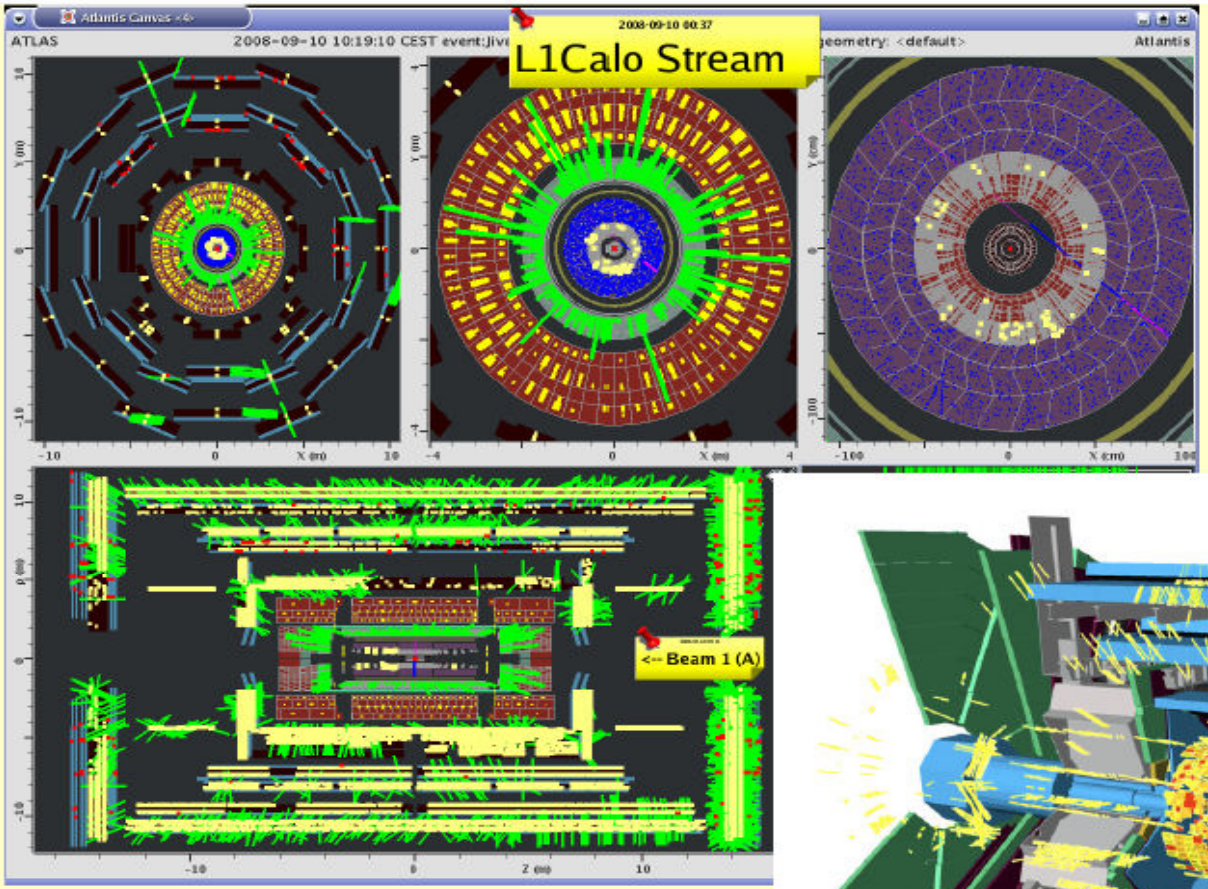


Energy deposited by muons

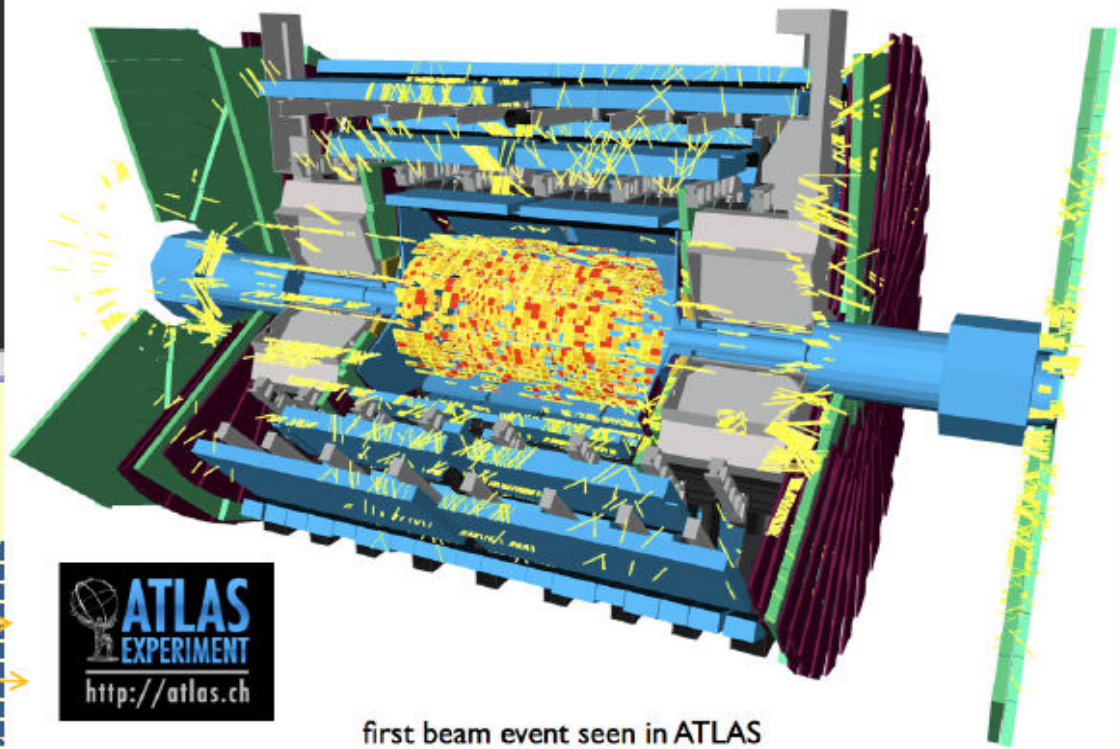


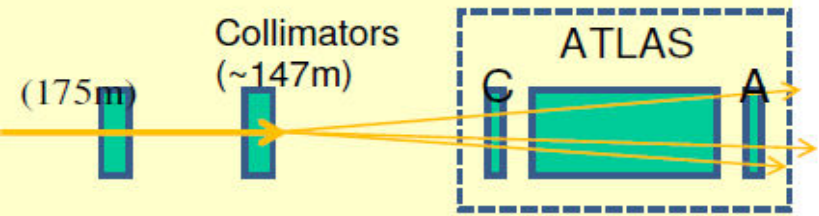


Experiments are functioning



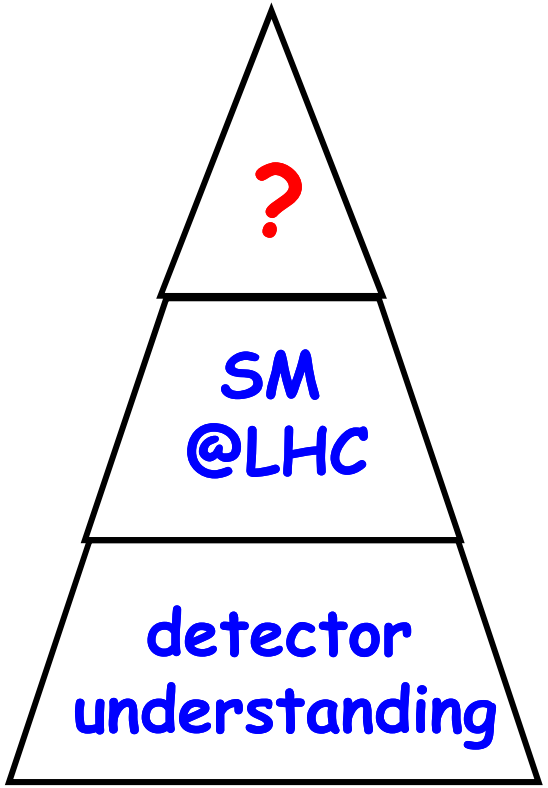
The very first beam-splash event from the LHC in ATLAS on 10th September 2008, 10:19



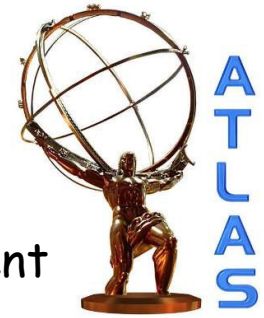


Start-up of LHC physics

- threefold approach (not fully sequentially)
  1. detector (and reconstruction) understanding with collision data
     - beyond extensive commissioning with cosmic muons
  2. "re-discovery" of Standard Model
     - establish how pp collisions really look like at LHC
     - followed later on by precision measurements
  3. search for new physics beyond the SM
     - and (precision) measurements of its properties



References

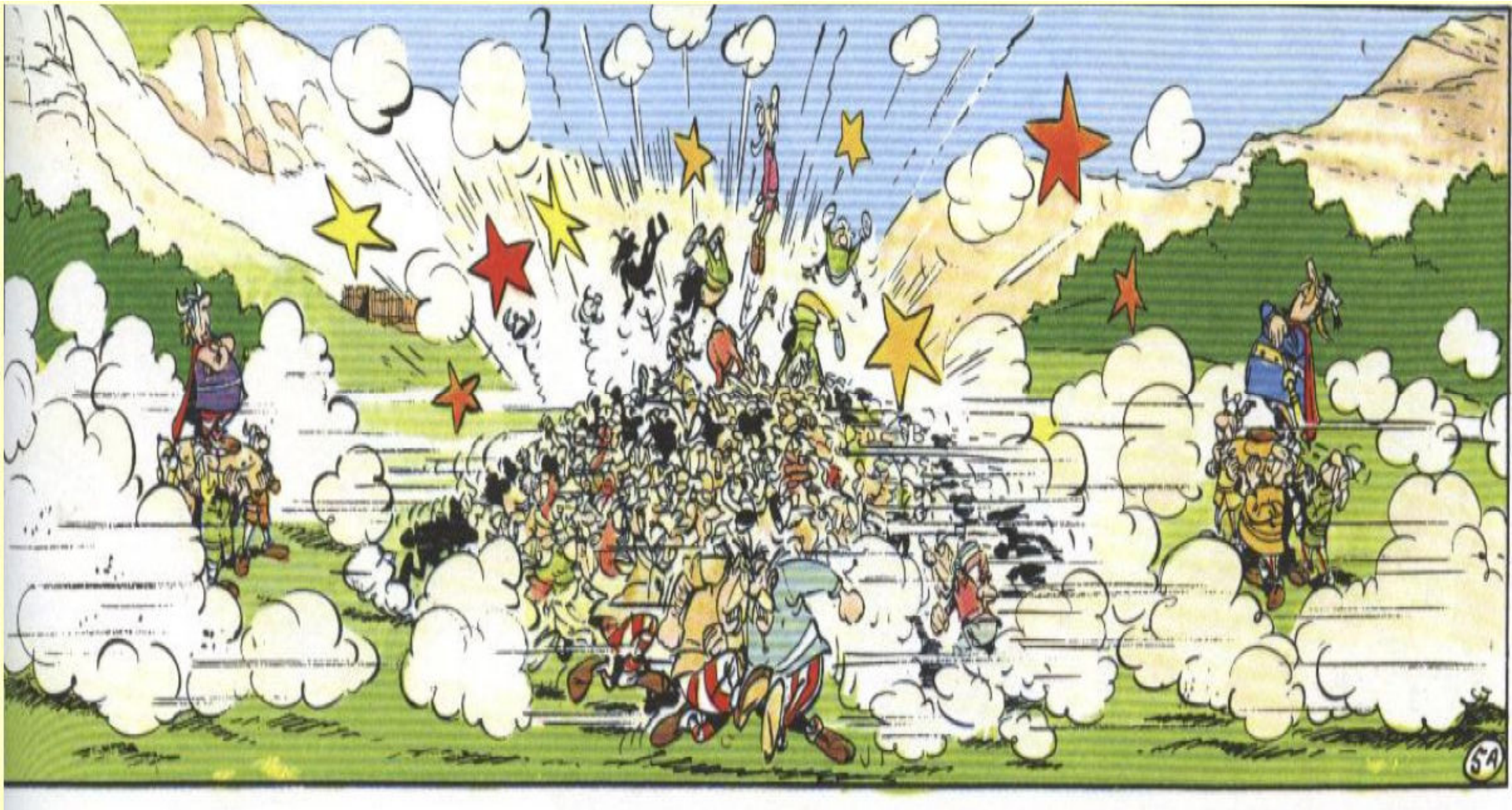


- ATLAS: Expected Performance of the ATLAS Experiment
  - CERN-OPEN-2008-020 or arXiv 0901.0512
- ATLAS: further public results
  - https://atlas-physco.web.cern.ch/atlas-physco/ATLASPubNotes.html
  - https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults
- CMS: "Physics TDR"
  - CERN-LHCC-2006-001 or J.Phys. G 34 (2007) 995-1579
- CMS: "Post Physics TDR" Results
  - https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults

- most (simulation) studies done for $\sqrt{s}$ = 14 TeV
  - → recently studies 'published' for $\sqrt{s}$ = 10 TeV as well

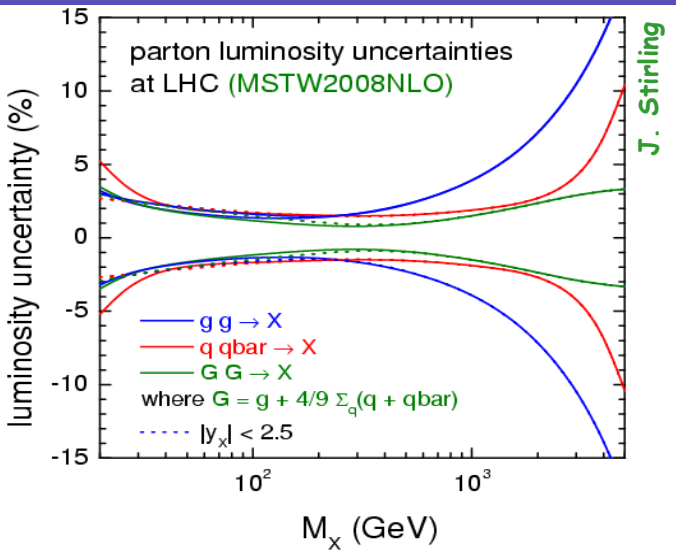
"re-discovery" of Standard Model (and more...)

The complexity of pp at LHC



- Pile-up included or not yet ?

Schema of pp collision

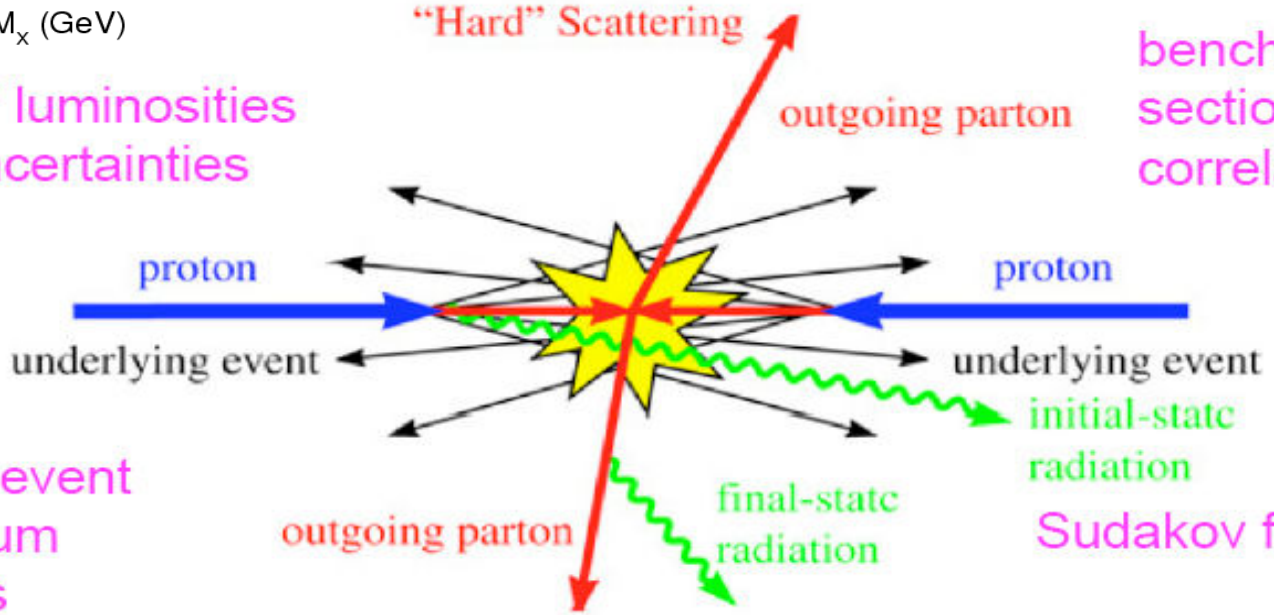


- interesting part: the hard scatter
  - → but it does not come alone

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations



underlying event and minimum bias events

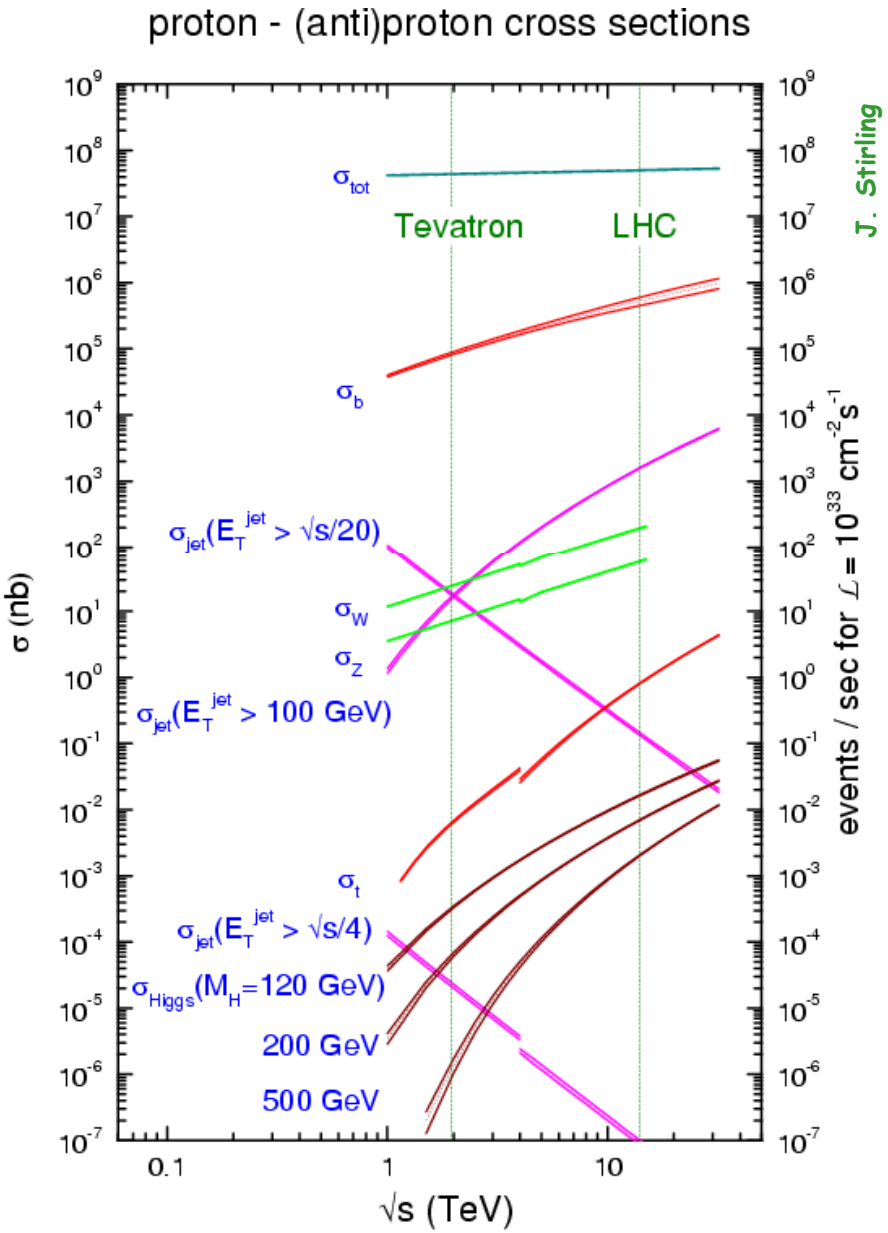
Sudakov form factors

jet algorithms and jet reconstruction

R. Field, Acta Phys. Pol. B39 (2008) Vol. 10, 2611

The SM menu (sort of)

- minimum bias properties
- underlying event
- jet production
  - → cross-section, di-jet mass and angular distribution, shapes
- direct photon production
- W/Z production
  - → incl. in association with jets
- Drell-Yan lepton pair production
  - → incl. low mass resonances
- di-boson production
  - → gauge boson self coupling
- top quark production



„Roadmap" for first data

- 1-10 pb^{-1}: calibration and alignment with collision data, first measurements ("minimum bias", …)

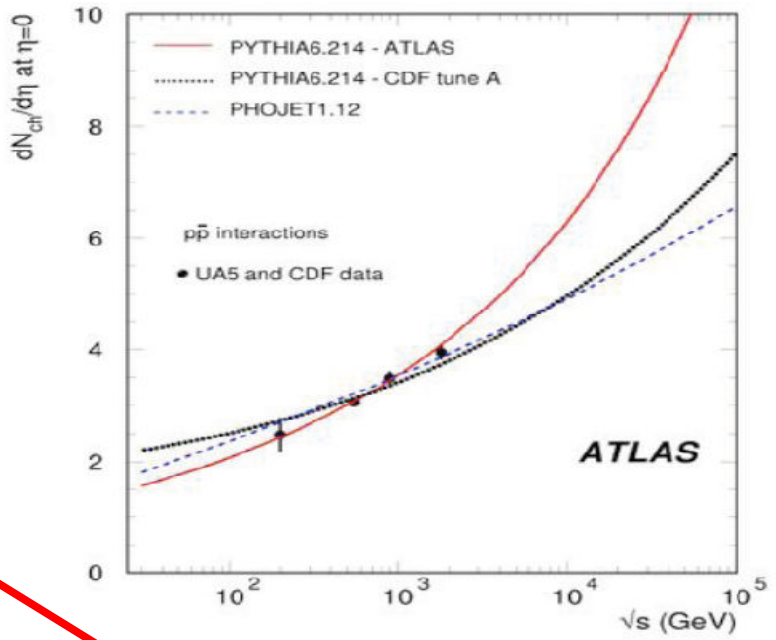
- ~100 pb^{-1}: refinement of calibration and alignment, re-discovery and measurement of SM processes, first serious sensitivity for new physics
  - expected statistics, scaled to 10 TeV (and 100 pb^{-1})

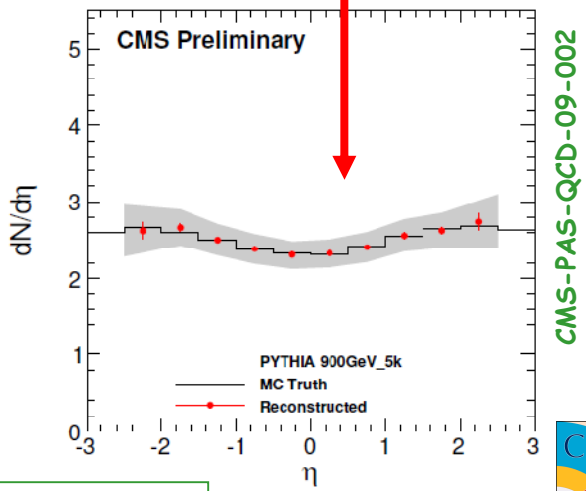
$>5*10^6$	"minimum bias" events (after trigger)
10^8	jet events (after Trigger)
$5*10^6$	direct photon events
$2.5*10^5$	$W \rightarrow l\nu$ events
$2.5*10^4$	$Z \rightarrow ll$ events
$>10^4$	Drell-Yan events (small invariant masses)

- ~1 fb^{-1}: sensitivity for Higgs boson discovery, supersymmetry, new resonances (O(TeV))

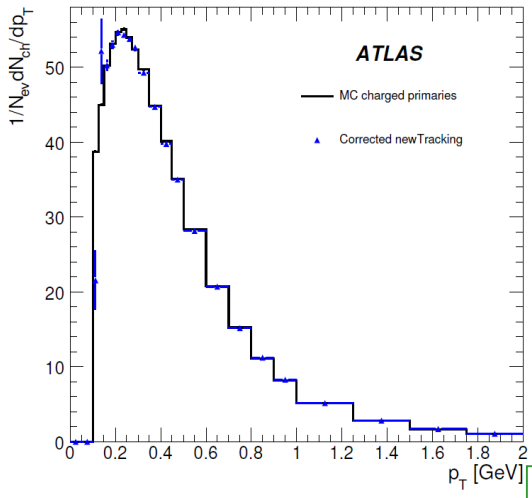
Minimum bias event properties

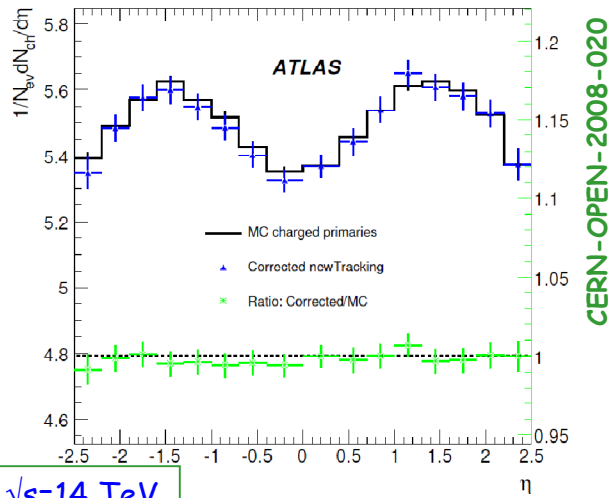
- experimental definition of minimum bias events necessary
  - → usually related to trigger (bias)
- several methods to determine charged particle multiplicity
  - → track reconstruction
    - challenge: access to low p_T
  - → hit counting (pixel detector)
    - determination of secondaries
  - → tracklet reconstruction
    - pairs (triplets) of pixel hits





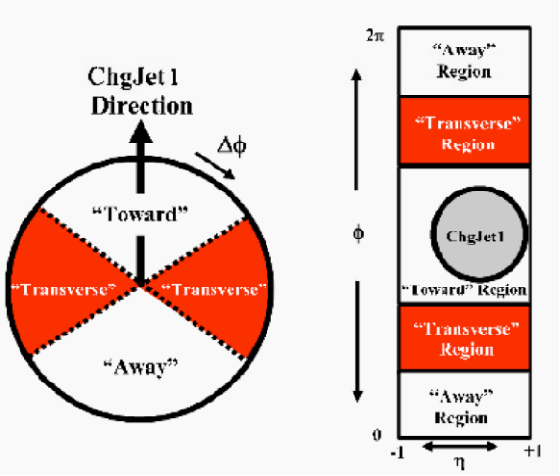
√s=900 GeV

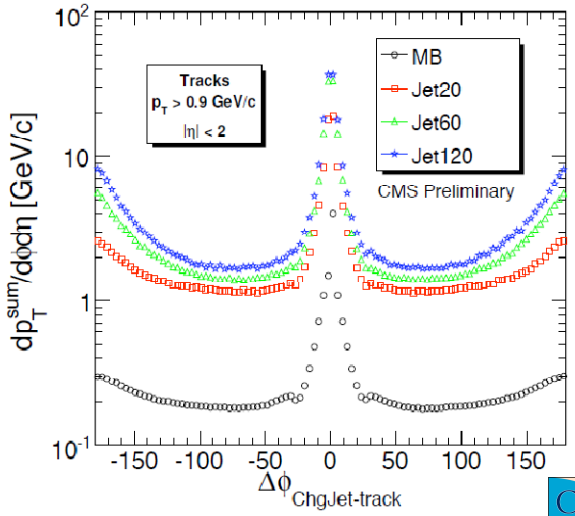


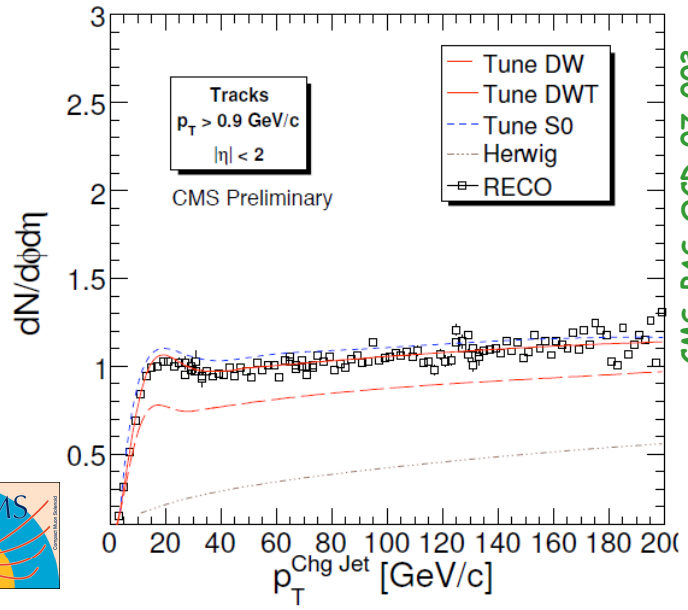


√s=14 TeV

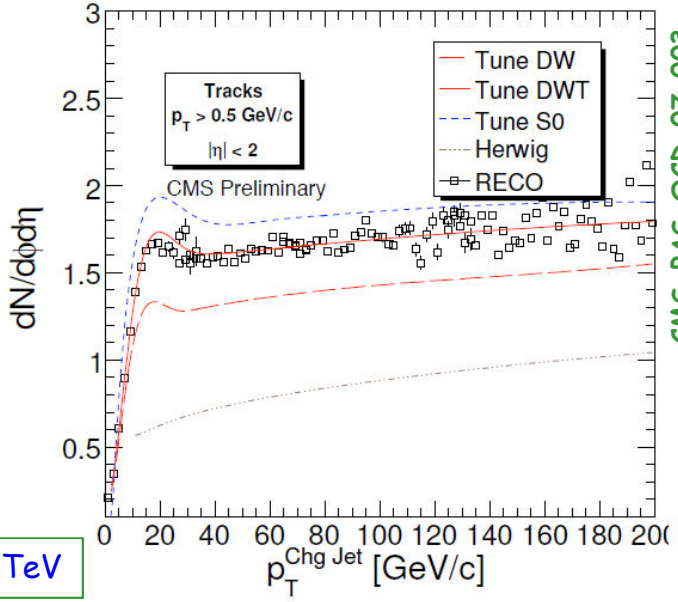
Underlying event structure





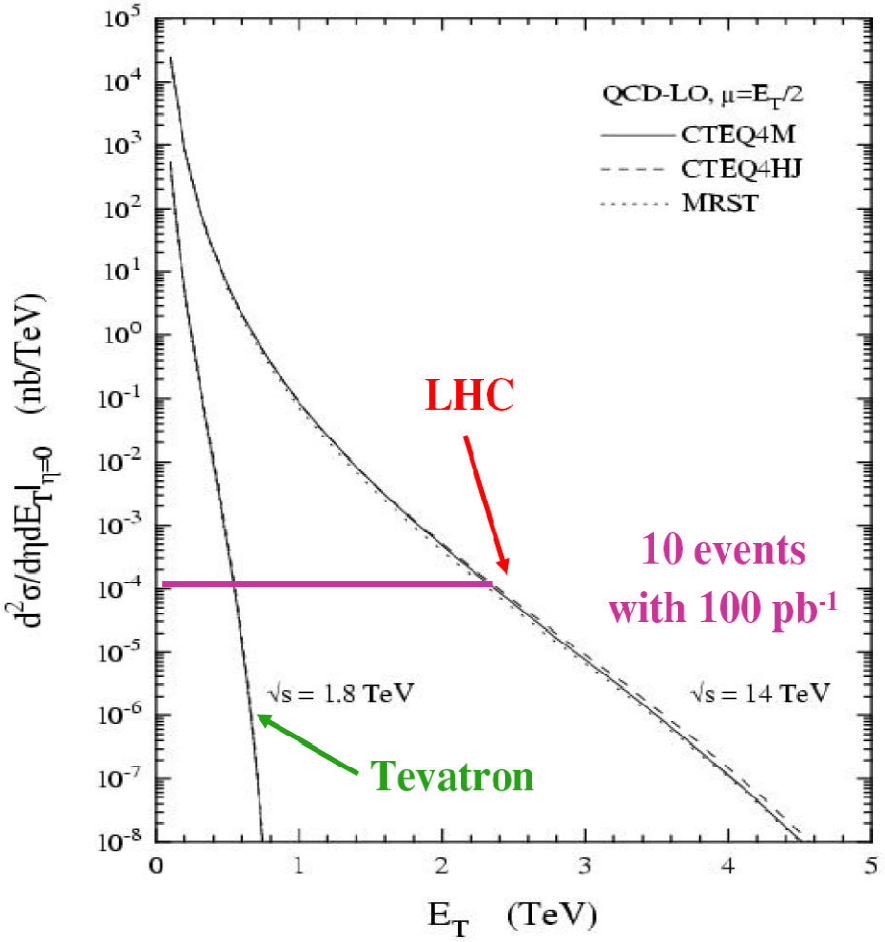


- underlying event (UE) definition
  - → all particle production accompanying the hard scatter
  - → importance → contribution from multi-parton interaction to UE
- measurement in transverse region
  - → relative to jets (or Drell-Yan pair)
    - distributions shown for 100 pb^{-1}
- importance of minimum track p_T

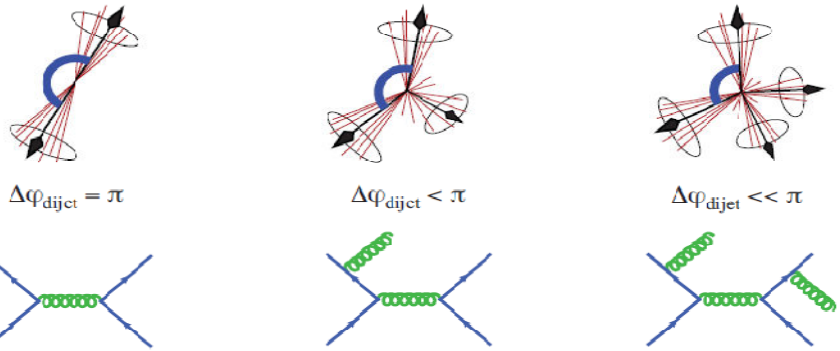


√s=14TeV

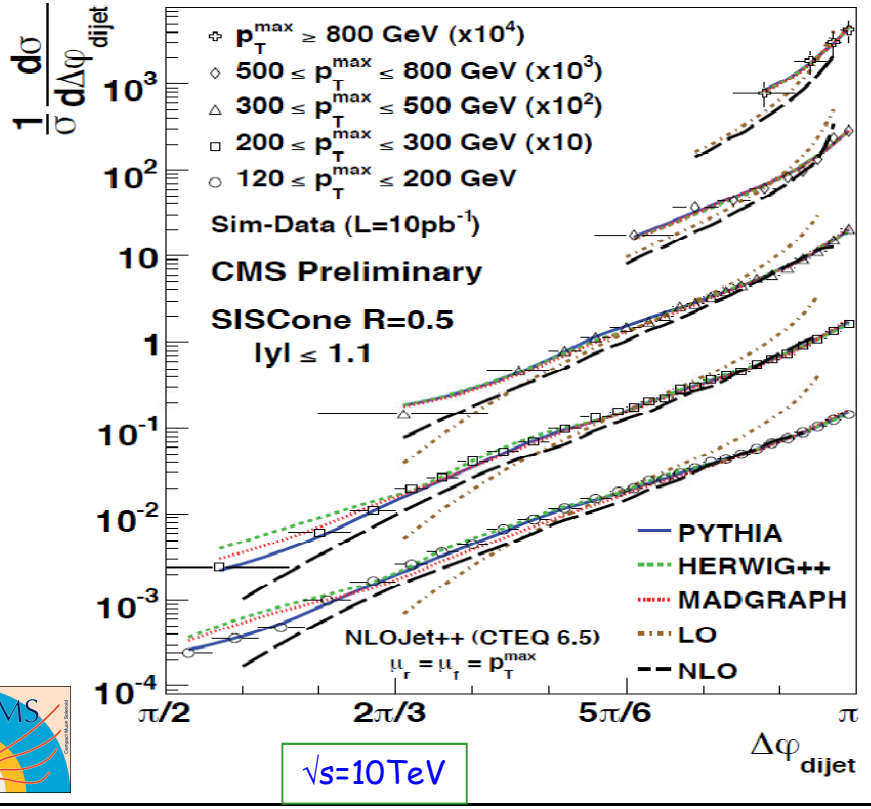
Dijet azimuthal decorrelation



- need to define what a jet is
  → jet algorithm
- challenge: jet energy scale determination



- sensitivity to modeling of radiation



CMS-PAS-QCD-09-003

√s=10TeV

Jet shape measurements

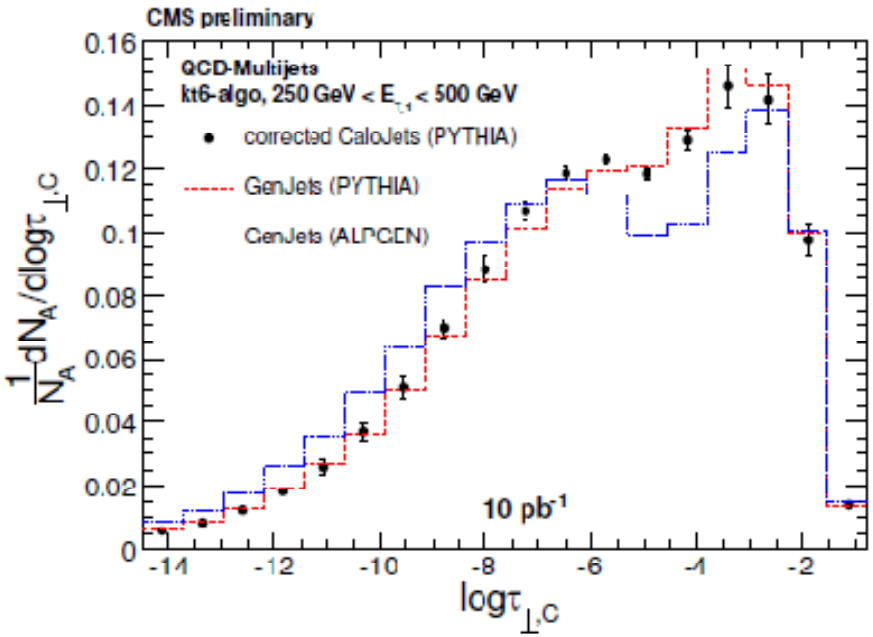
- global transverse thrust
  - → ½ for homogenous event

$$T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T}{\sum_i p_{\perp,i}} \qquad \tau_{\perp,g} \equiv 1 - T_{\perp,g}.$$

global thrust minor

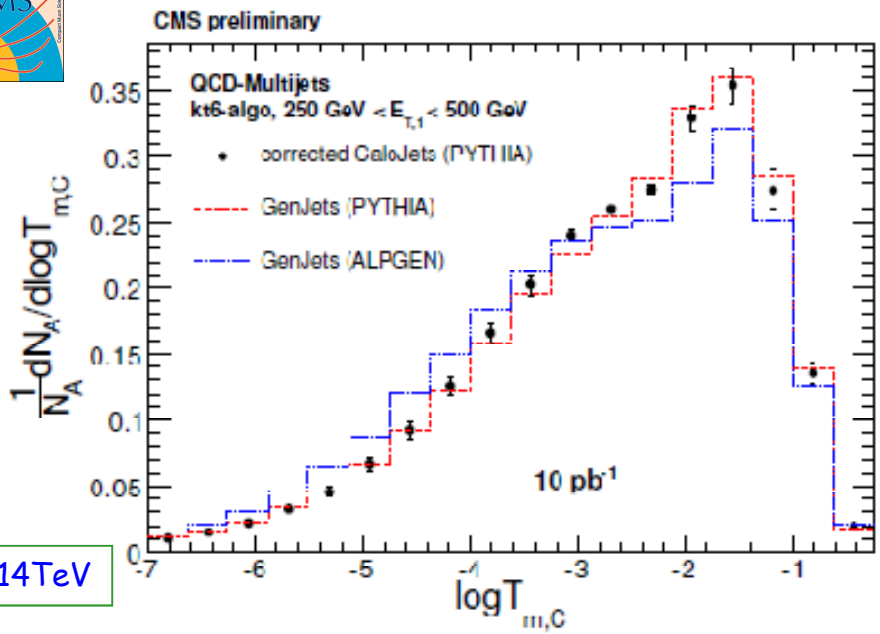
deviation from thrust axis

$$T_{m,g} \equiv \frac{\sum_i |p_{x,i}|}{\sum_i p_{\perp,i}} = \frac{\sum_i |(\vec{p} \times \vec{n}_B) \times \vec{n}_T|}{\sum_i p_{\perp,i}}.$$



CMS-PAS-QCD-08-003

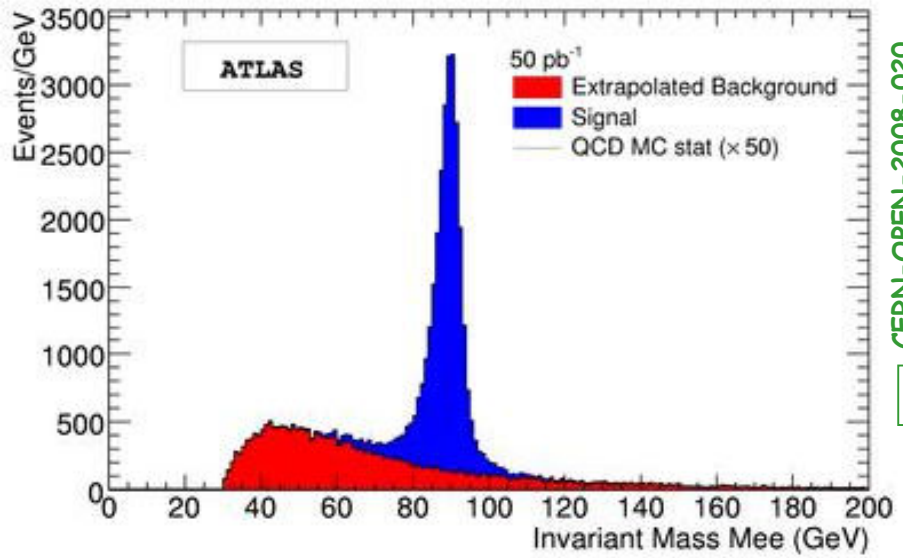
√s=14TeV



- sensitivity to modeling of multi-jet events
  - → insensitive to jet algorithm and energy scale corrections
  - → input for MC tuning

Z(ee) production

- efficiency determination
  - → "tag & probe" method (data)



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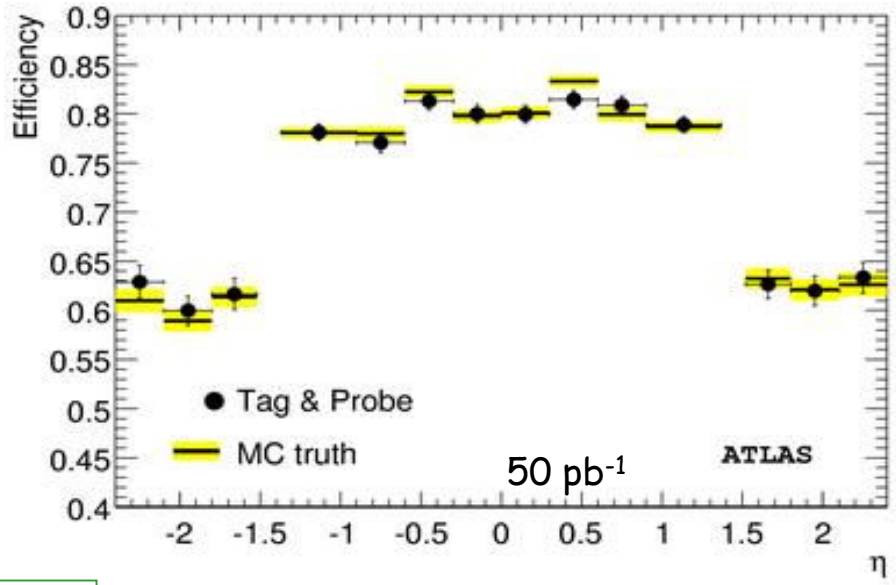

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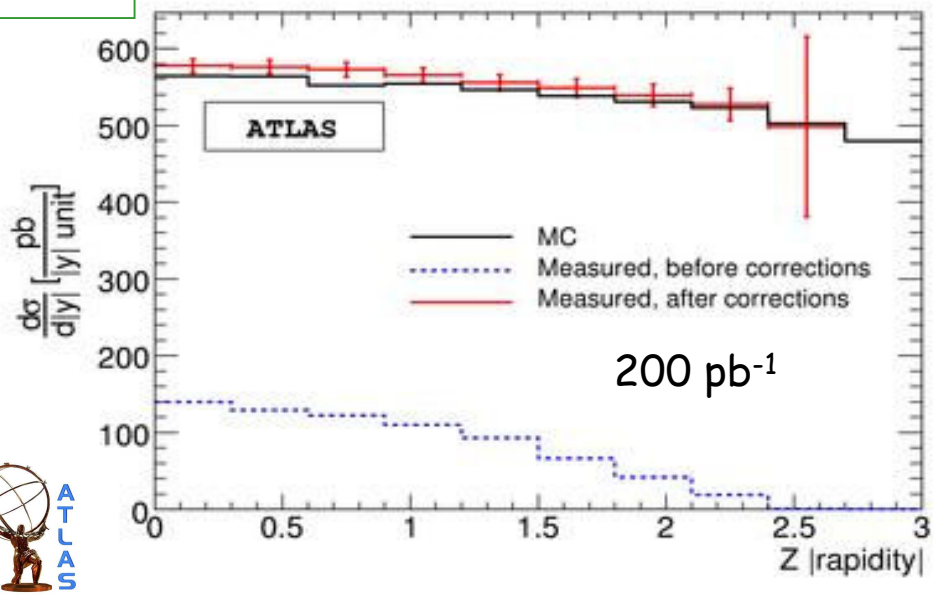
√s=14TeV

- Z → ee signal in 50 pb^{-1}
  - → selection via
    - 2 electrons E_T>15 GeV
    - soft identification criteria
  - → accuracy on inclusive cross-section (no luminosity uncert.)
    - 2-4% (stat) and 2-4% (syst.)



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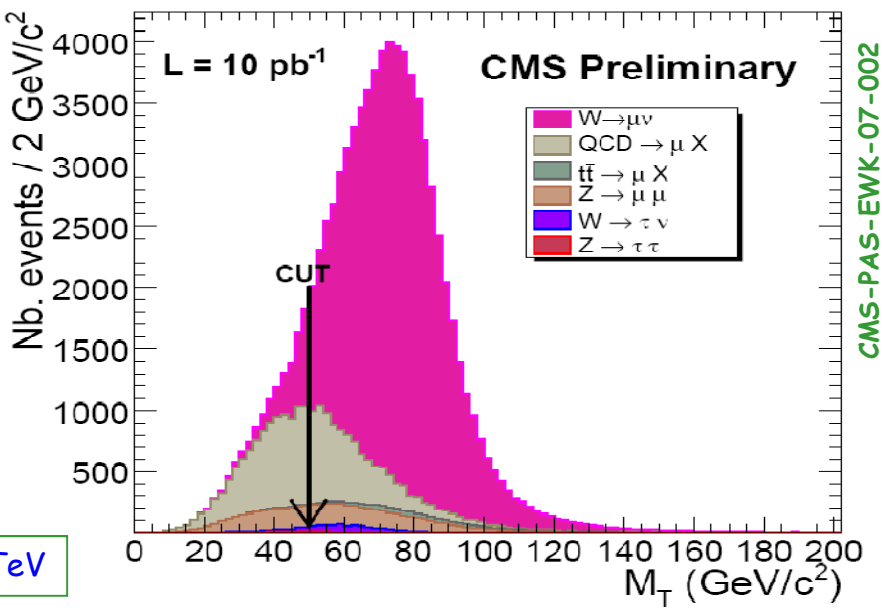
W(μν) production

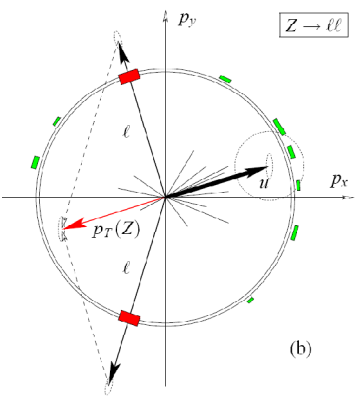
- W selection
  - → single muon with p_T>25 GeV and $|\eta|$<2
    - as well as isolation
- background suppression by cut on m_T:

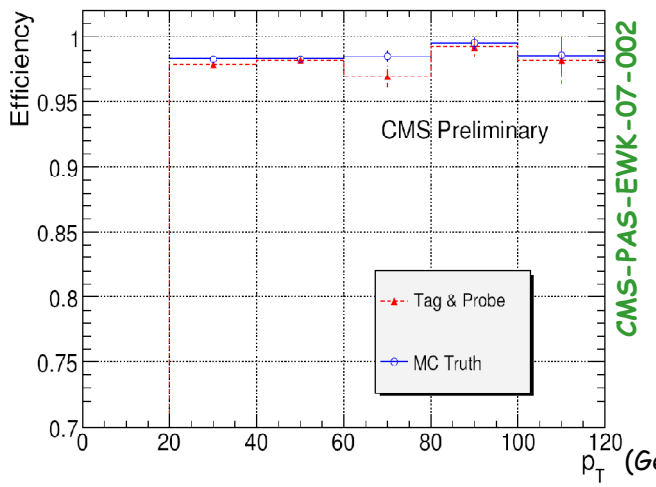
$$m_T^W = \sqrt{2 p_T^l p_T^\nu (1 - \cos\Delta\phi)}$$

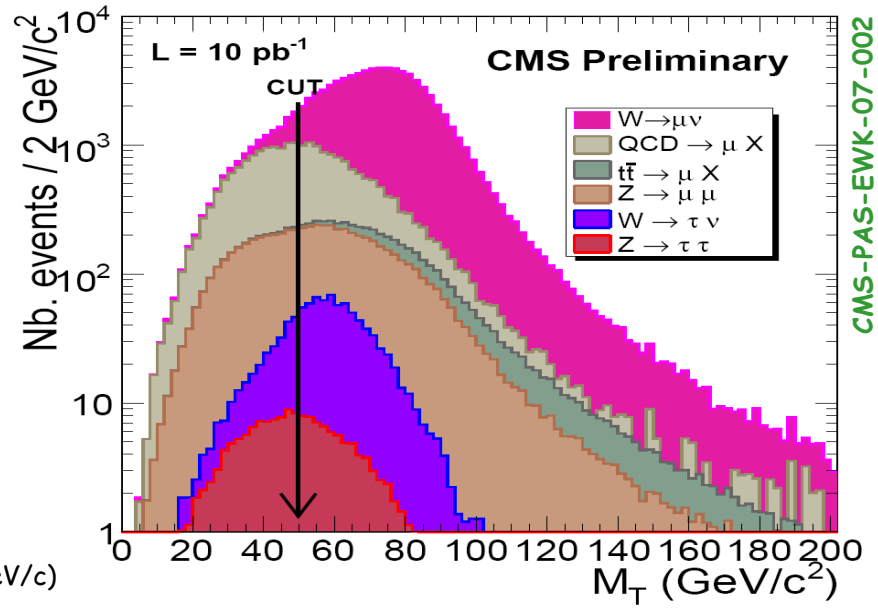
- reconstruction efficiency via "tag & probe" also for muons



√s=14TeV



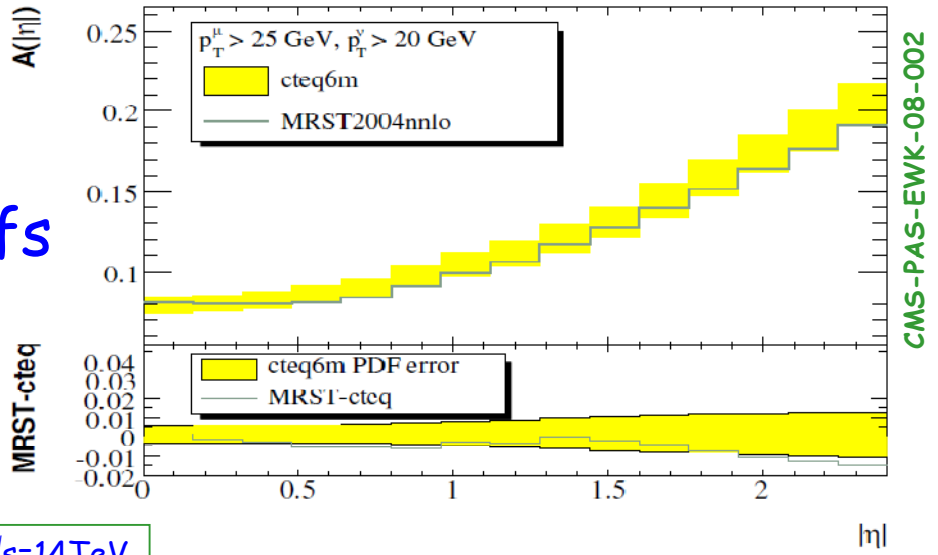




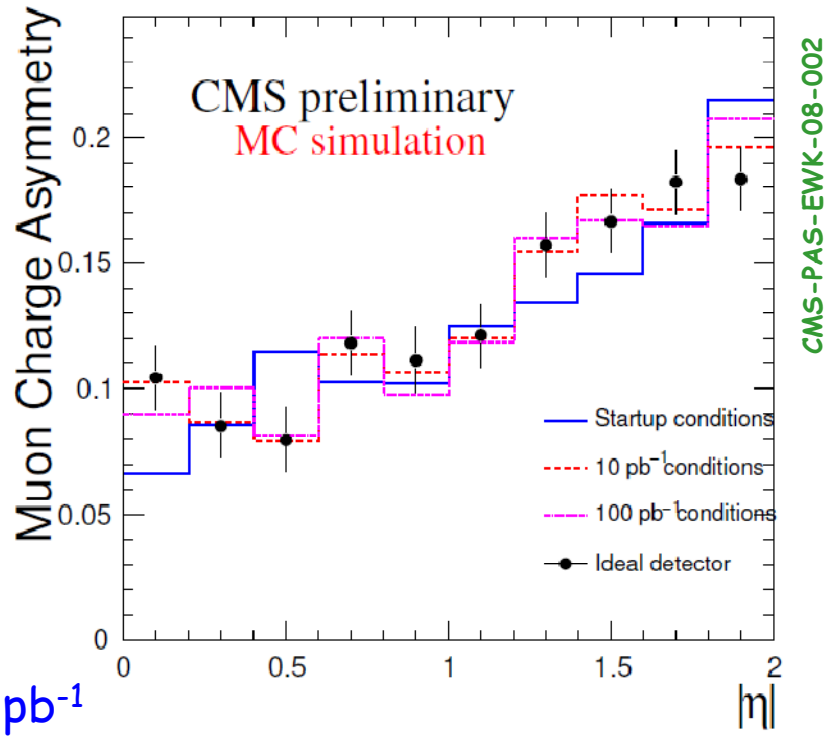
Measurement of μ charge asymmetry

$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\bar{\nu}_\mu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\nu_\mu)}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\bar{\nu}_\mu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\nu_\mu)}$$

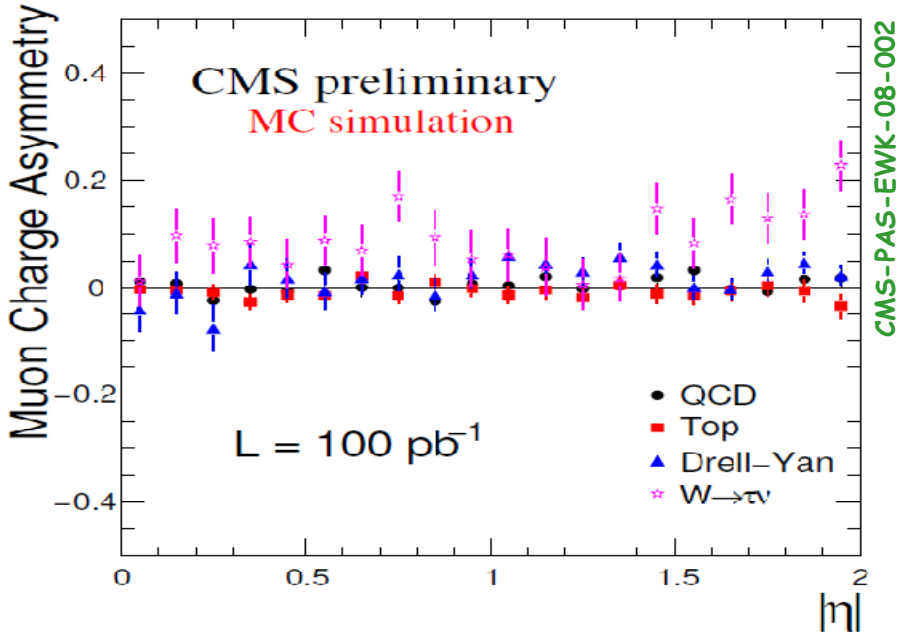
- sensitive to u and d quark pdfs
- only few systematic uncertainties



√s=14TeV



10 pb^{-1}

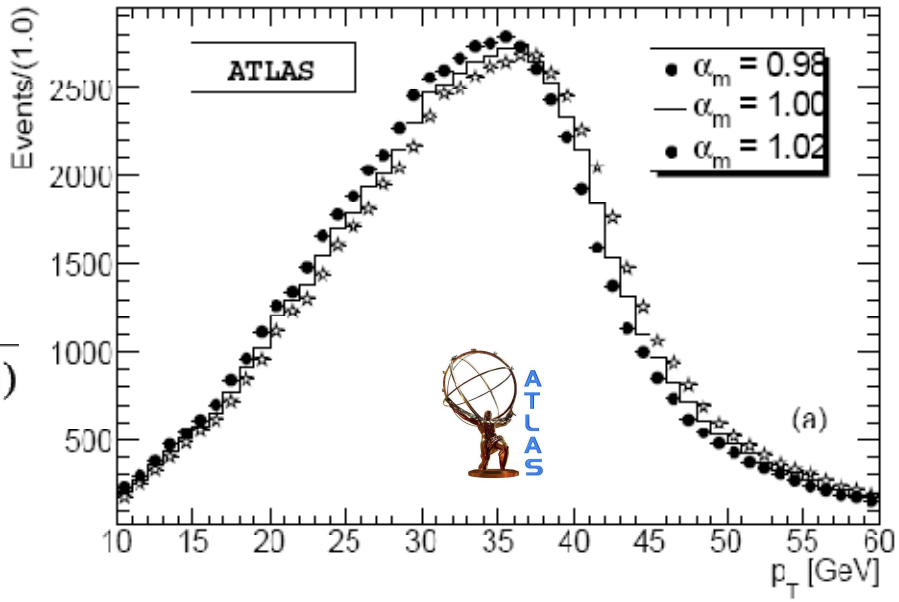


W mass determination

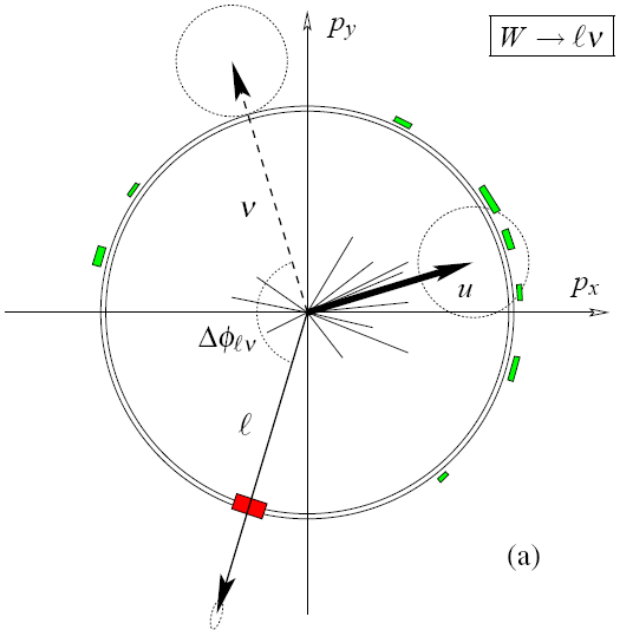
- with initial data (only 15 pb^{-1})
  - → $p_T(e)$: 120 ⊕ 117 MeV
    - ➔ energy scale dominates
  - → $M_T(\mu)$: 57 ⊕ 231 MeV
    - ➔ recoil modeling dominates

$$m_T^W = \sqrt{2 p_T^l p_T^\nu (1 - \cos\Delta\phi)}$$

- precision measurement: with higher integrated luminosity



CERN-OPEN-2008-020



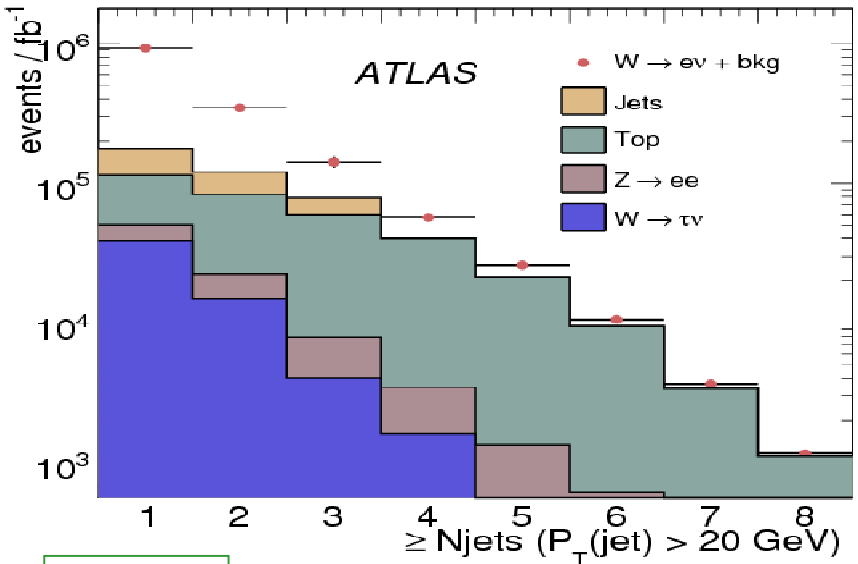
Method	$p_T(e)$ [MeV]	$p_T(\mu)$ [MeV]	$M_T(e)$ [MeV]	$M_T(\mu)$ [MeV]
δm_W (stat)	120	106	61	57
δm_W (α_E)	110	110	110	110
δm_W (σ_E)	5	5	5	5
δm_W (tails)	28	< 28	28	< 28
δm_W (ε)	14	–	14	–
δm_W (recoil)	–	–	200	200
δm_W (bkg)	3	3	3	3
δm_W (exp)	114	114	230	230
δm_W (PDF)	25	25	25	25
Total	167	158	239	238

√s=14TeV

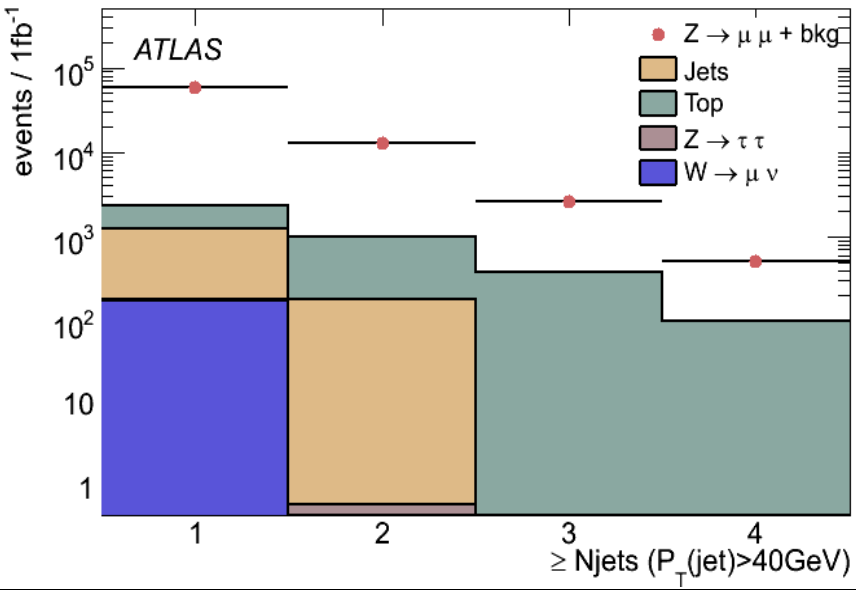
(estimates shown for 15 pb^{-1})

CERN-OPEN-2008-020

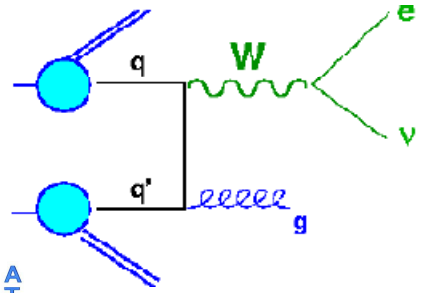
W/Z+jet production

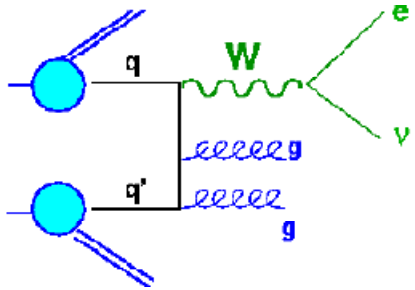


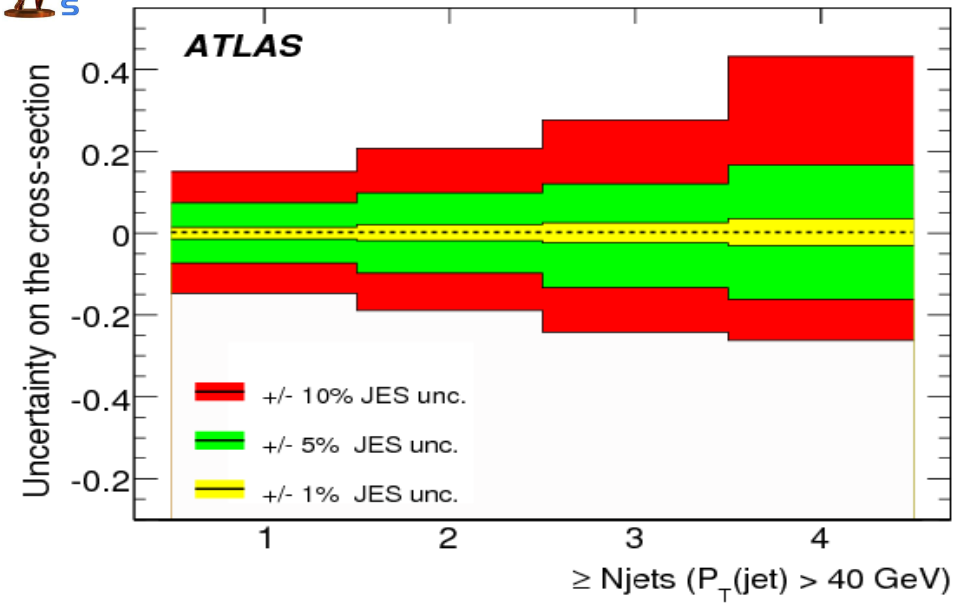
√s=14TeV



- important background for many other physics processes
  - → top production, SUSY searches, …

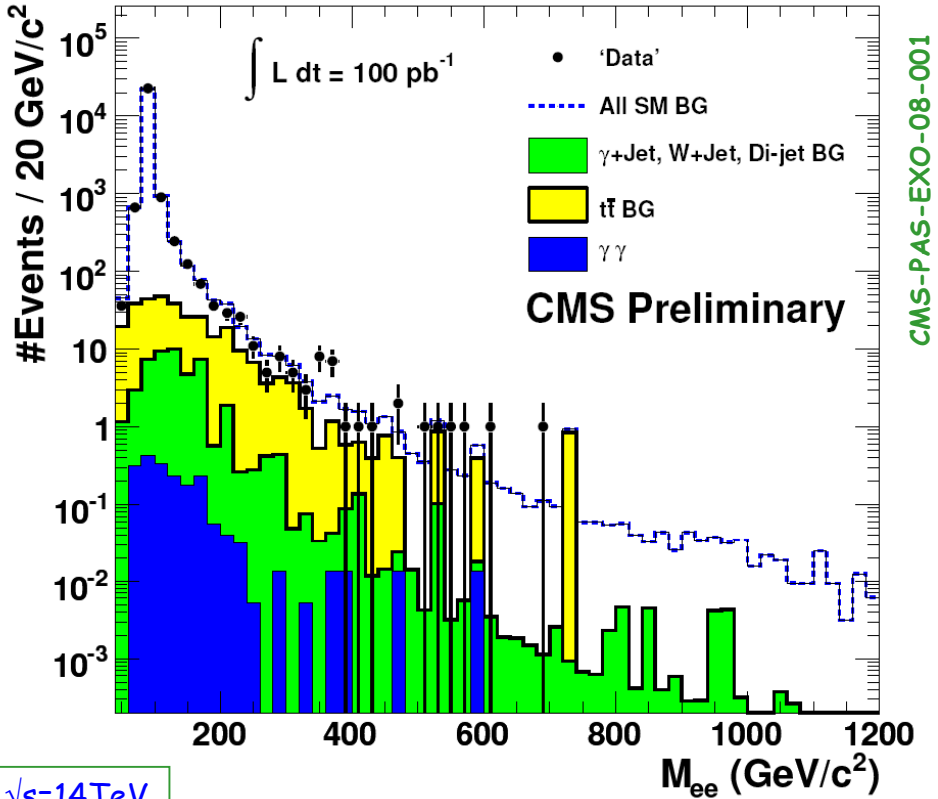




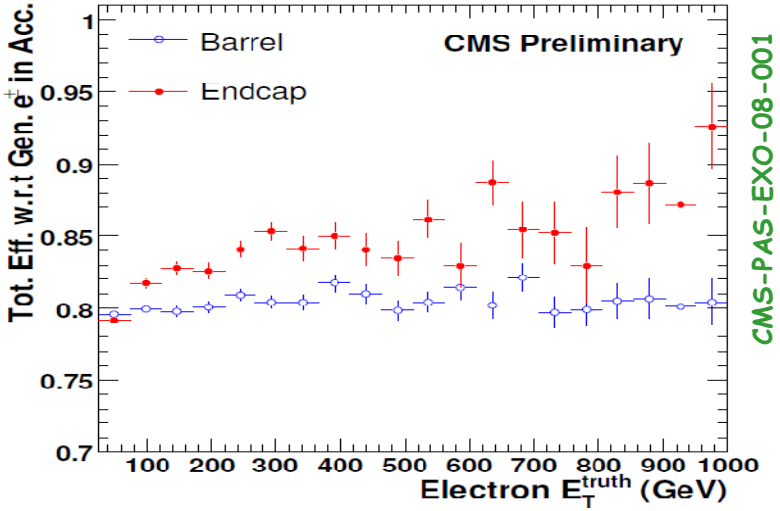


https://twiki.cern.ch/twiki/bin/view/Atlas/StandardModelFurtherResultsWZJets

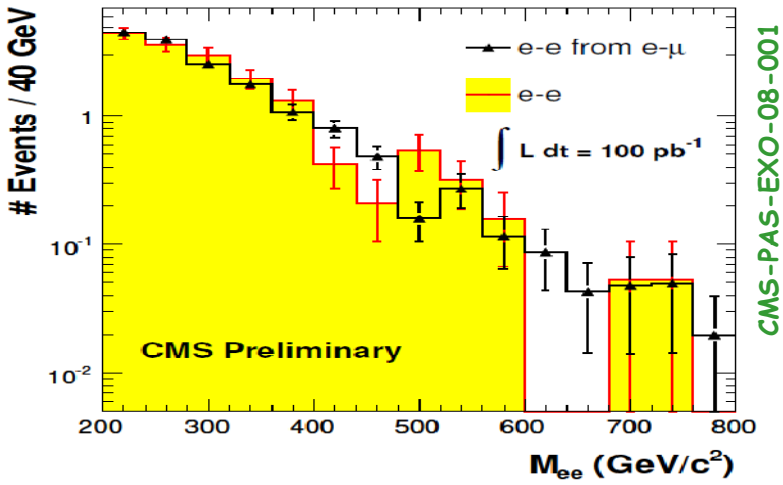
Drell-Yan lepton pair production



√s=14TeV

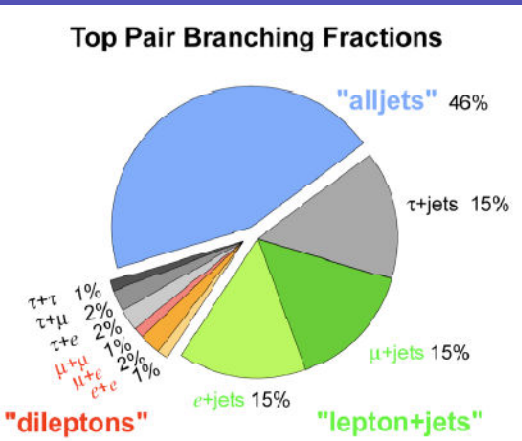


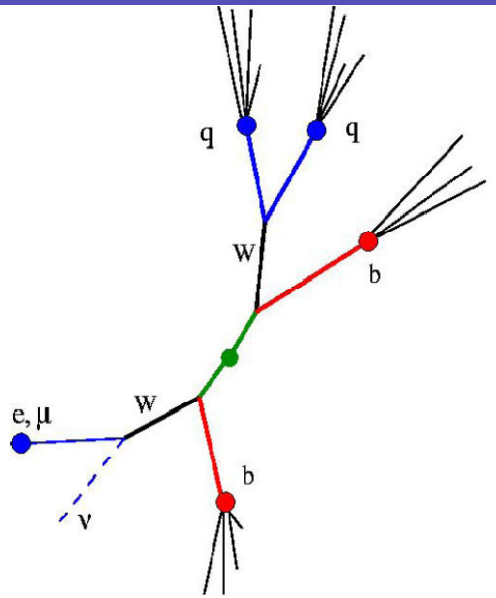
- top pair background determination
  - → from data using eμ events



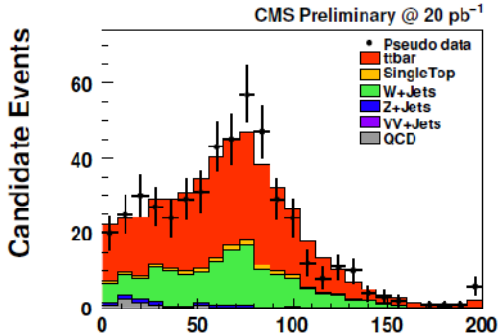
- two electrons with $E_T > 30$ GeV and $|\eta| < 2.5$
  - → with identification criteria
  - → not required: opposite charges

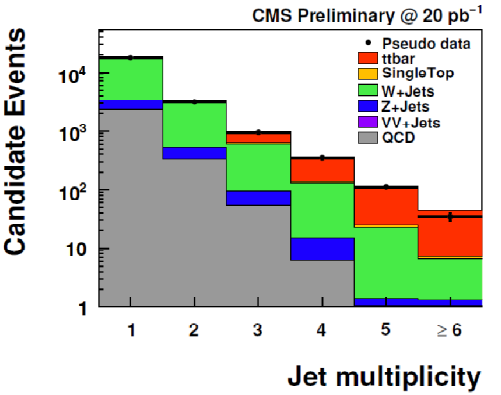
Rediscovery of top quark

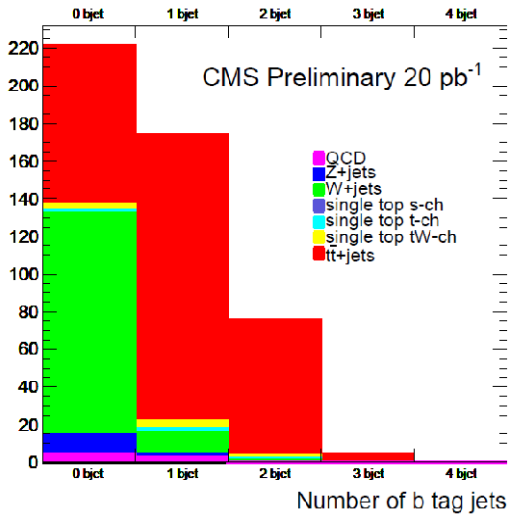


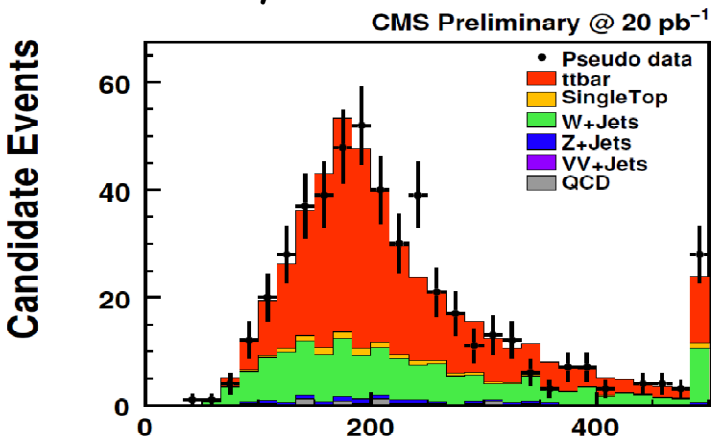


- robust selection criteria
  - → one isolated muon, p_T > 20 GeV
    - veto on events with further muons
  - → ≥4 jets, E_T > 30 GeV
    - SISCone, R=0.5
    - no b-tagging used
- highest vectorially summed transverse momentum of three jets
  - → candidate hadronic top decay







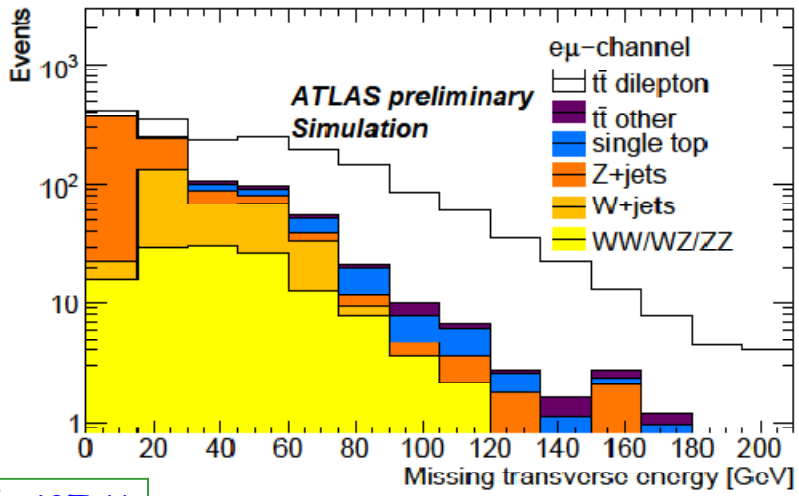


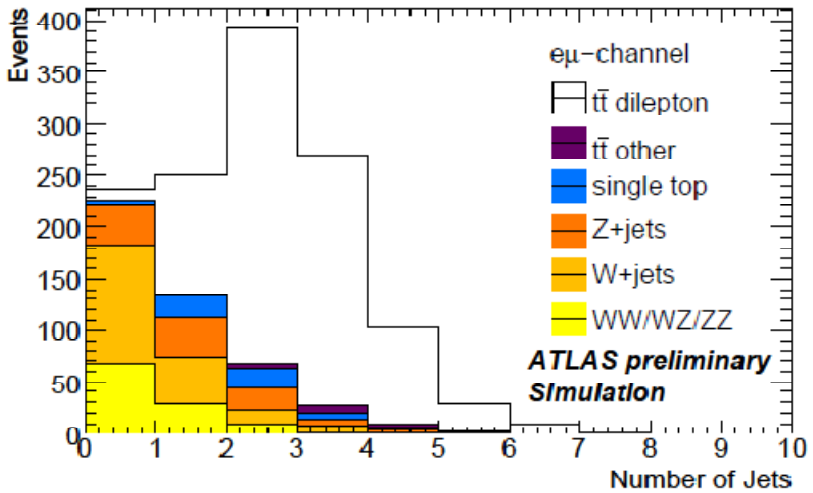
- ➢ next step cross-section measurement

CMS-PAS-TOP-09-003

CMS-PAS-TOP-09-003

Top quark cross-section





ATL-PHYS-PUB-2009-086

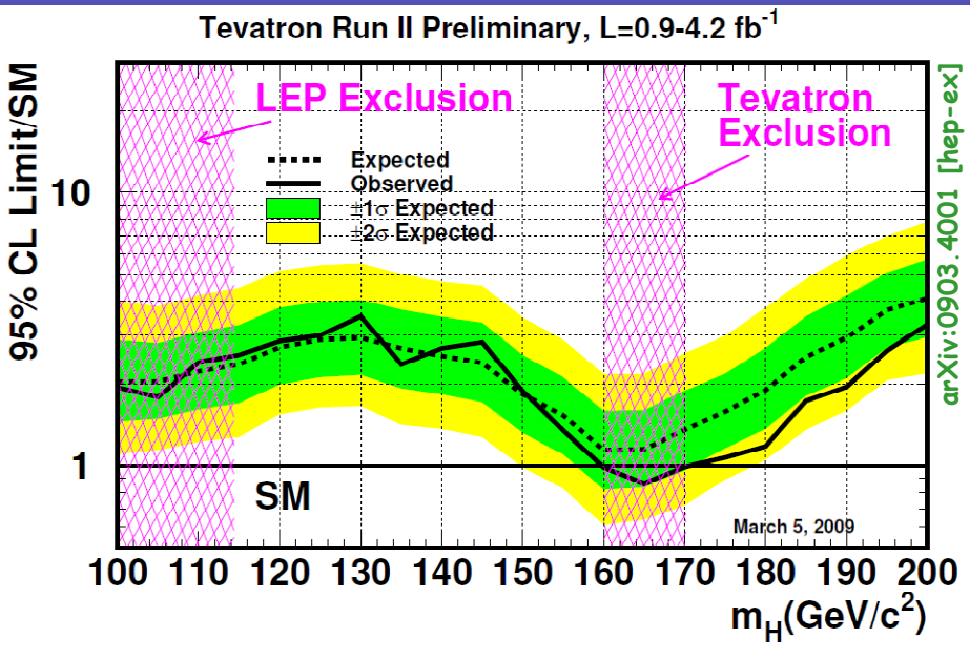
√s=10TeV

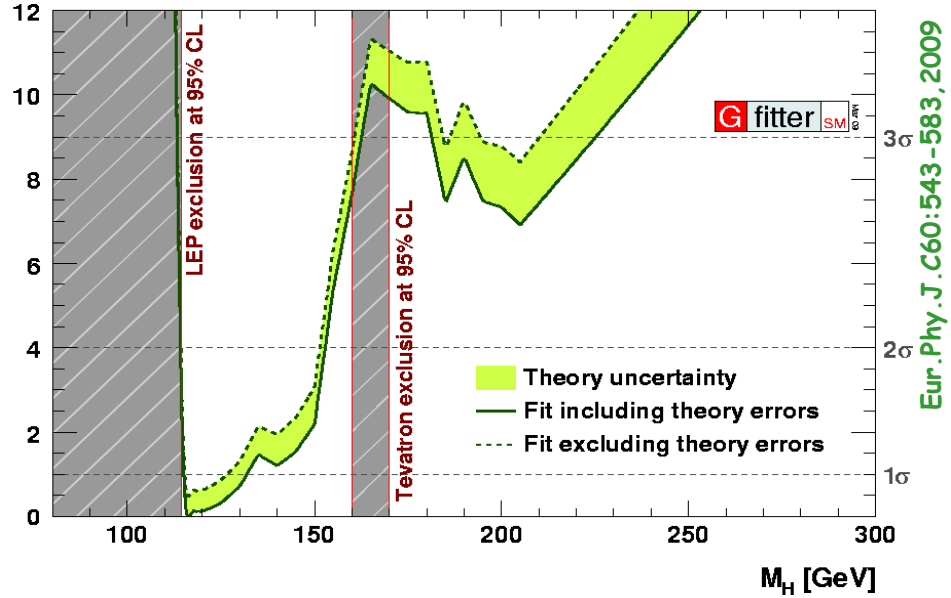
- dilepton channel
  - → integr. lumin. 200 pb^{-1}
- simple object and event selection
  - → leptons (e,μ) E_T > 20 GeV
    - isolation required
  - → jets (Cone 0.4) E_T > 20 GeV
  - → E_T^{miss} > 20 GeV
- data driven background determination
- signal-to-background ratio between 3.8 (μμ) and 5.5 (eμ)

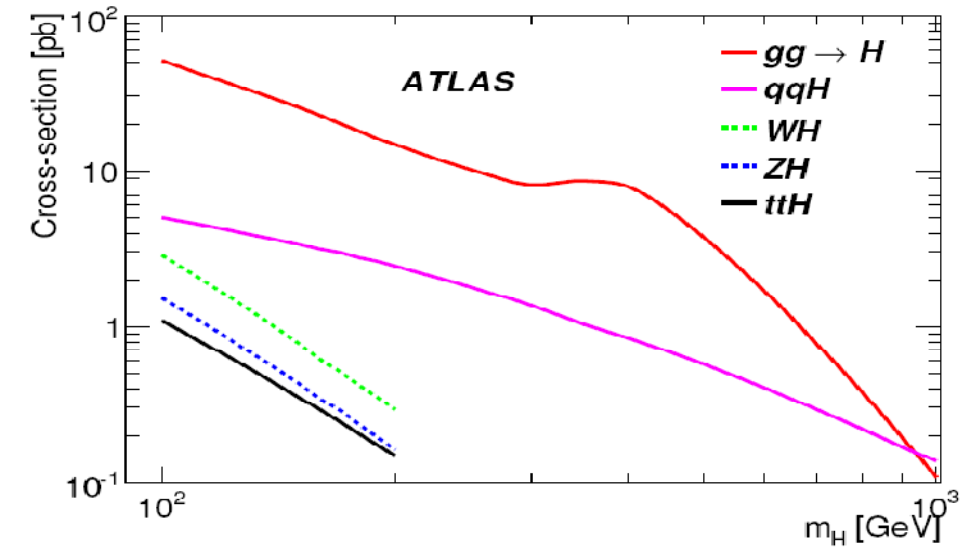
$\Delta\sigma/\sigma$ (%)	ee channel	$\mu\mu$ channel	$e\mu$ channel	combined
Stat only	-7.5 / 7.8	-6.0 / 6.2	-4.0 / 4.1	-3.1 / 3.1
Luminosity	-17.3 / 26.3	-17.4 / 26.2	-17.4 / 26.2	-17.4 / 26.2
Electron Efficiency	-4.5 / 5.0	0.0 / 0.0	-2.2 / 2.4	-1.9 / 1.9
Muon Efficiency	0.0 / 0.0	-4.6 / 5.2	-2.1 / 2.2	-2.2 / 2.3
Lepton Energy Scale	-0.3 / 1.6	-2.4 / 2.0	-0.5 / 0.5	-0.8 / 0.8
Jet Energy Scale	-3.4 / 3.2	-3.0 / 4.5	-2.5 / 2.5	-2.8 / 3.0
PDF	-2.1 / 2.3	-1.4 / 1.6	-1.6 / 1.8	-1.7 / 1.8
ISR FSR	-4.0 / 4.2	-3.6 / 3.7	-3.5 / 3.5	-3.6 / 3.7
Signal Generator	-4.7 / 5.4	-4.6 / 5.4	-4.7 / 5.3	-4.7 / 5.3
Cross-Sections	-0.3 / 0.3	-0.3 / 0.3	-0.3 / 0.3	-0.3 / 0.3
Drell Yan	-1.4 / 1.3	-2.2 / 2.2	-0.5 / 0.5	-0.8 / 0.9
Fake Rate	-9.7 / 9.5	-1.1 / 1.1	-6.2 / 6.2	-4.0 / 4.0
All syst but Luminosity	-12.7 / 13.9	-8.9 / 10.2	-9.4 / 10.2	-8.7 / 9.6
All systematics	-21.0 / 30.3	-19.3 / 28.3	-19.5 / 28.5	-19.3 / 28.1
Stat + Syst	-22.3 / 31.3	-20.2 / 29.0	-19.9 / 28.8	-19.5 / 28.3

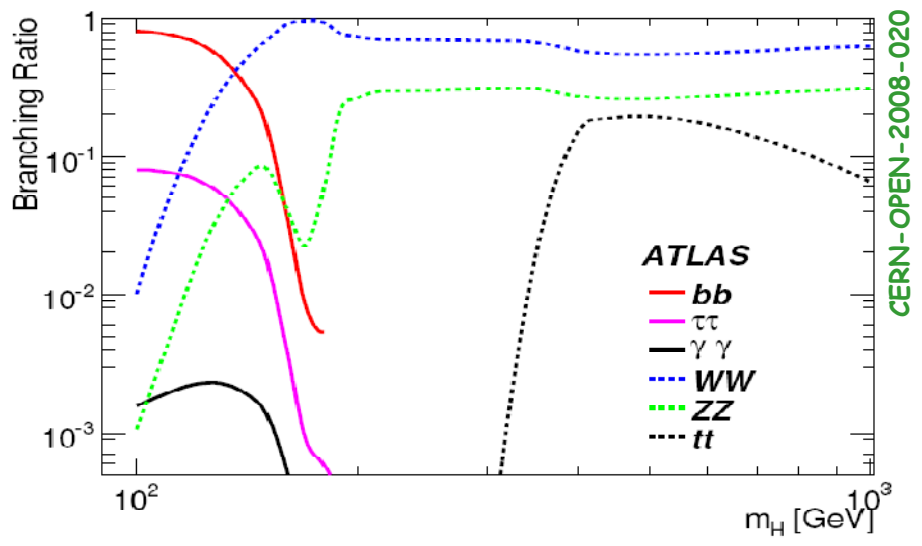
"re-discovery" of Standard Model (and more...)

Search for the Higgs boson at LHC



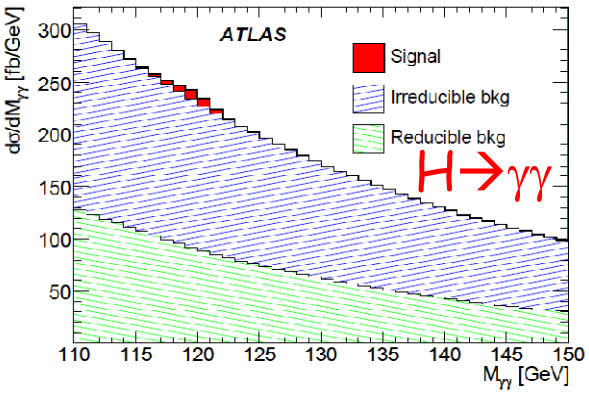


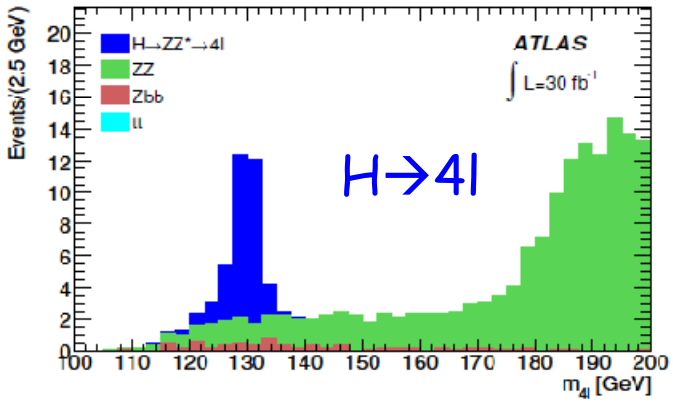


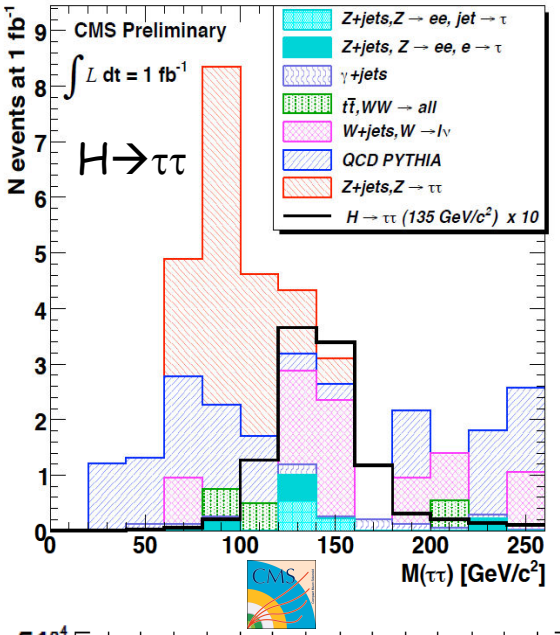


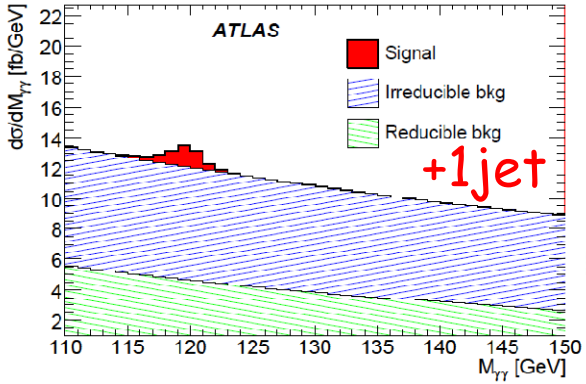
Examples of Higgs signals

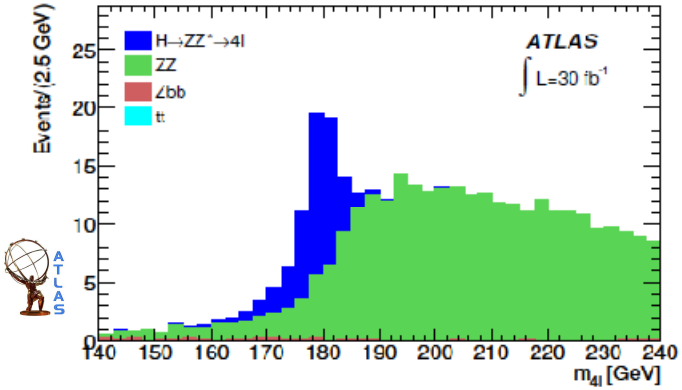
CERN-OPEN-2008-020

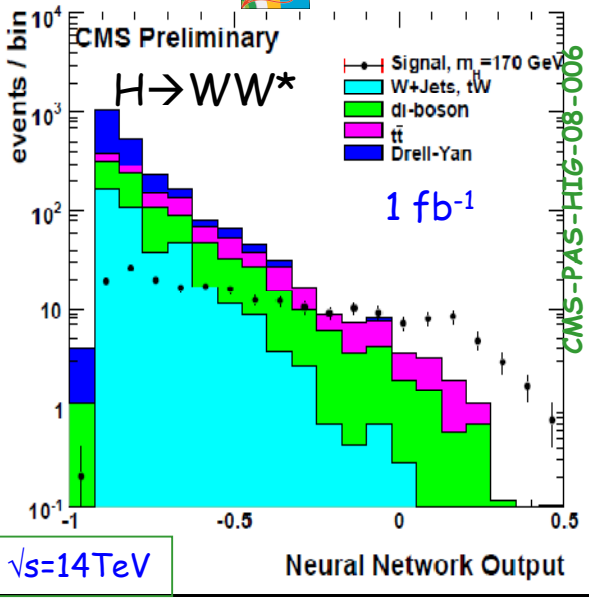


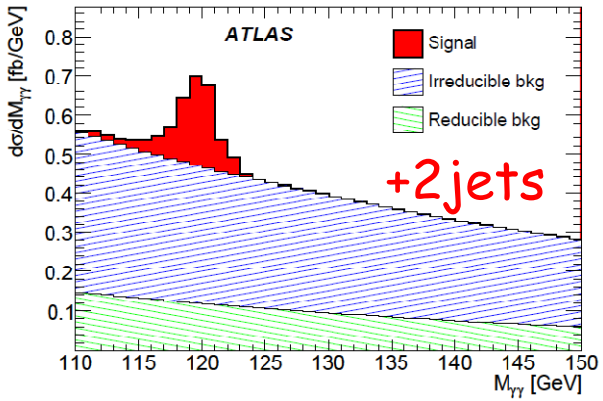


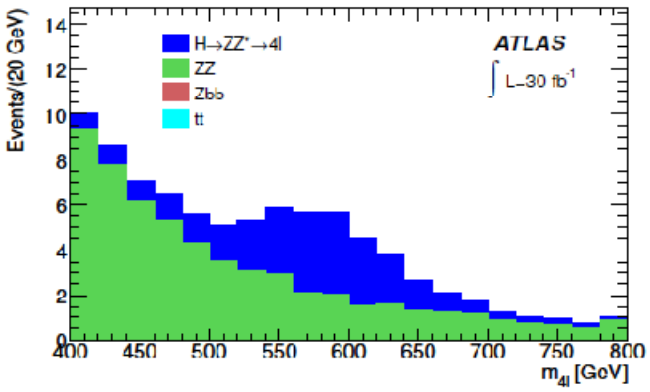






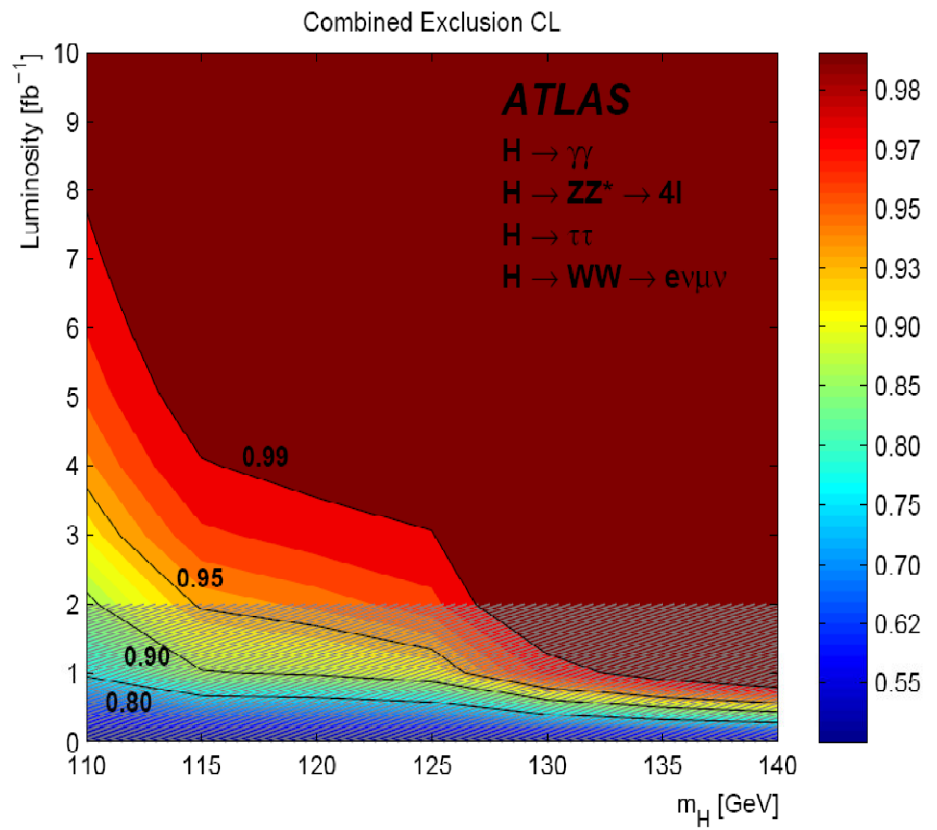


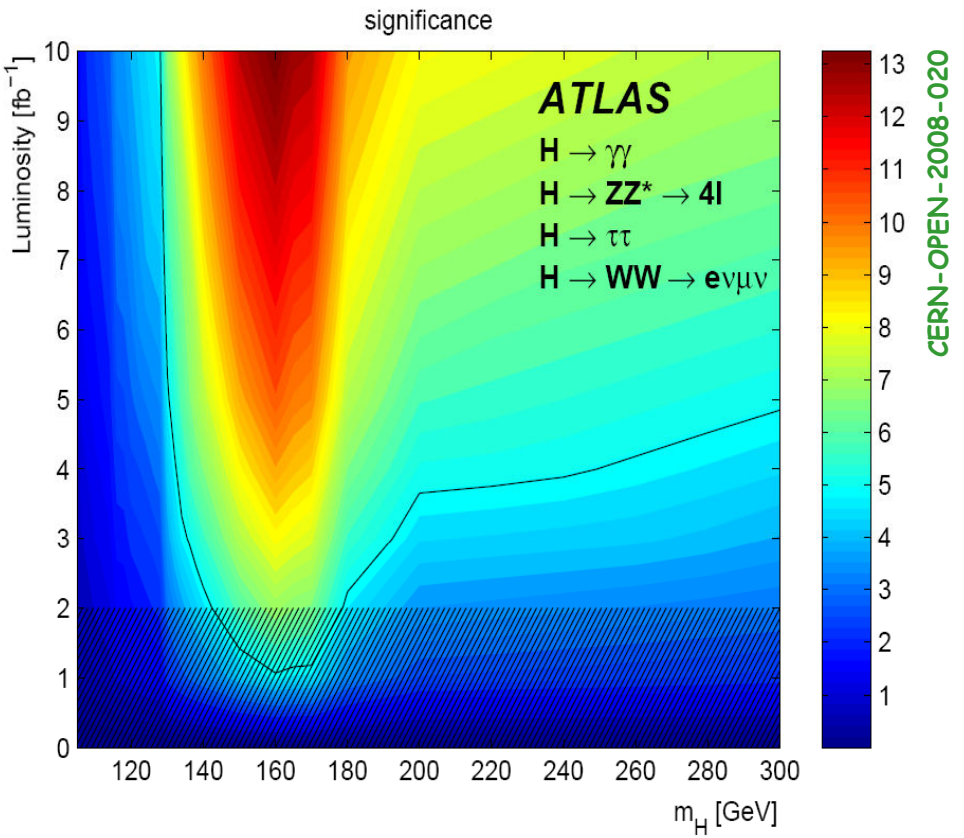




√s=14TeV

Discovery potential Higgs boson





- for an integrated luminosity of 2 fb^{-1} ($\sqrt{s}$=14 TeV)
  - → 5σ sensitivity for discovery: 143 GeV < M_H < 179 GeV
  - → expected range of exclusion (95% C.L.)on M_H: 115 to 460 GeV
    - studies valid only for $L \geq 2$ fb^{-1}
    - not all relevant channels have been included

$\sqrt{s}$=14TeV

search for new physics beyond the Standard Model

On the way to Terra Incognita …

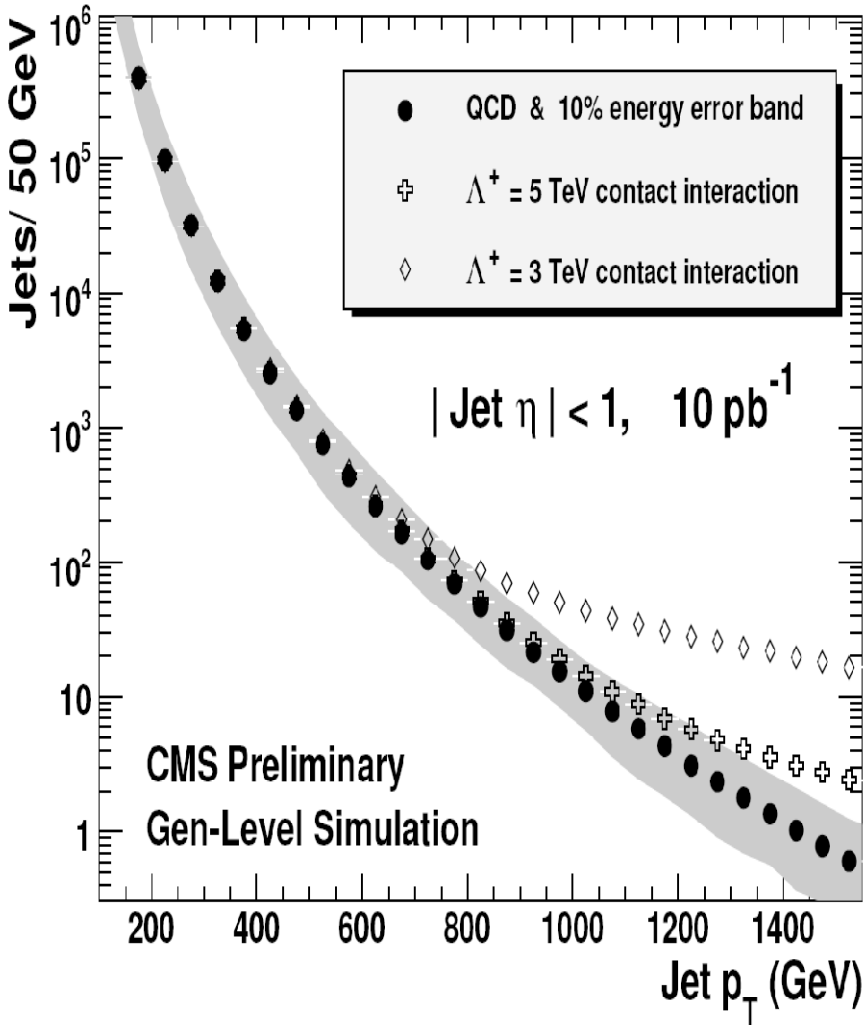
- http://www.interactions.org/imagebank/search_detail.php?image_no=OT0103

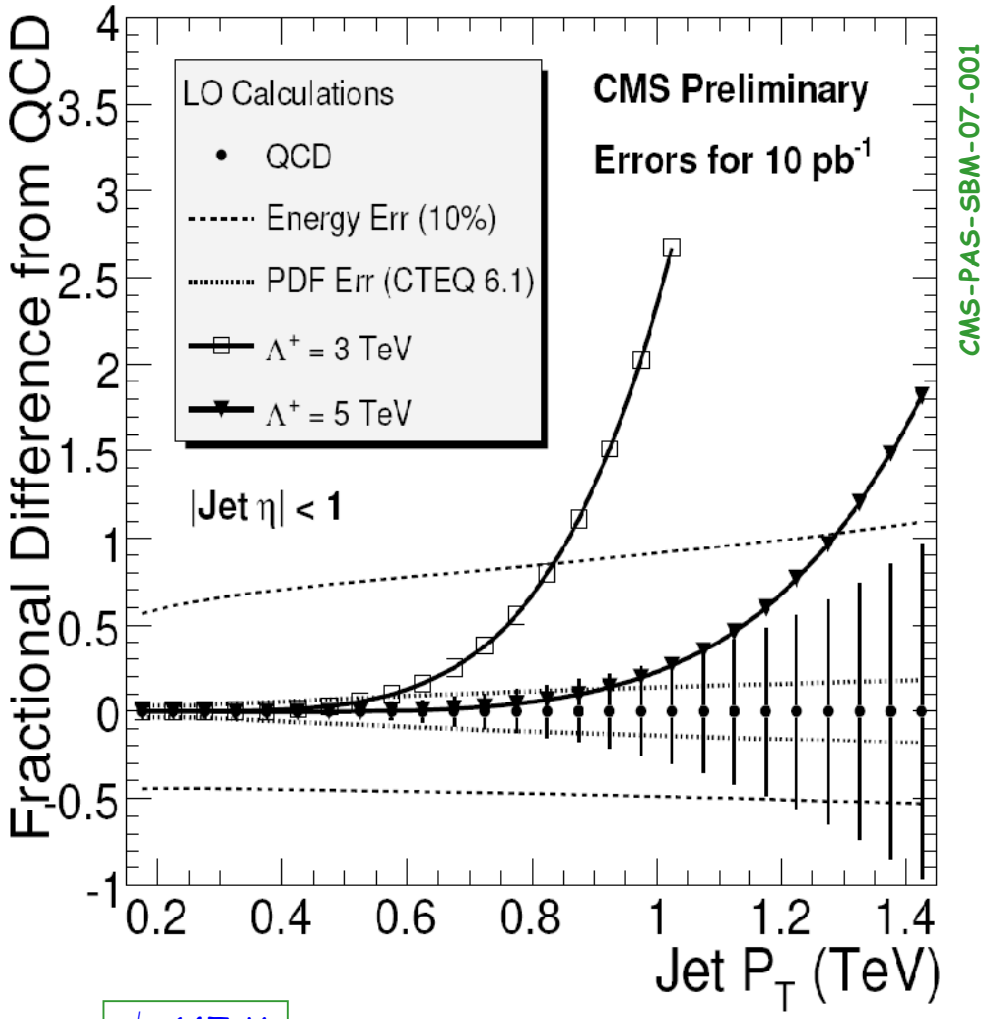
Recipe (checklist) for discoveries

- to find a deviation is easy …
  - → to prove that it stems from new physics is harder
  - → simple-minded recipe
    - find variable(s) discriminating between signal and background
    - cut away most background (maximing signal significance)
    - estimate remaining background events → look at yield …
- need to care/worry about
  - → is the detector behavior really understood ?
    - efficiencies, fake rates, energy/momentum scales, non-Gaussian resolution, …
      - ➔ try to obtain as much information as possible from data
  - → is the SM prediction really understood ?
    - cross-section, kinematic distributions, underlying event, …
      - ➔ must know sources for uncertainties on these

Compositeness

- present exclusion limit (Tevatron) Λ^+: ~2.7 TeV

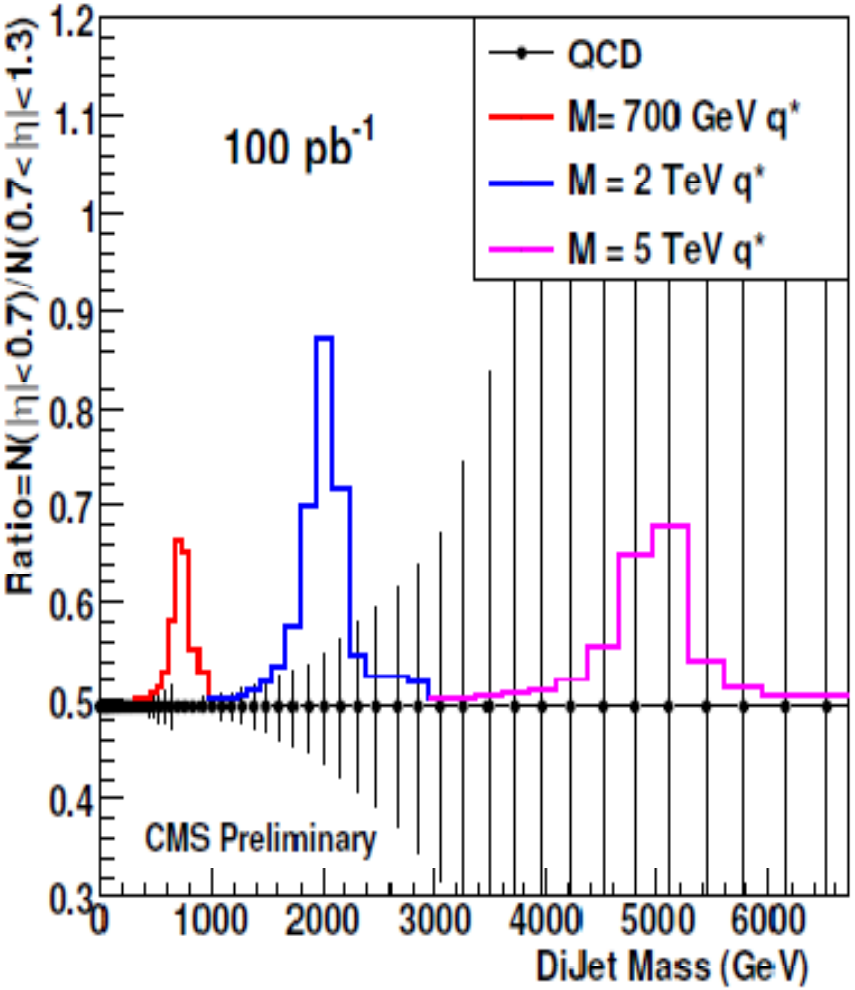


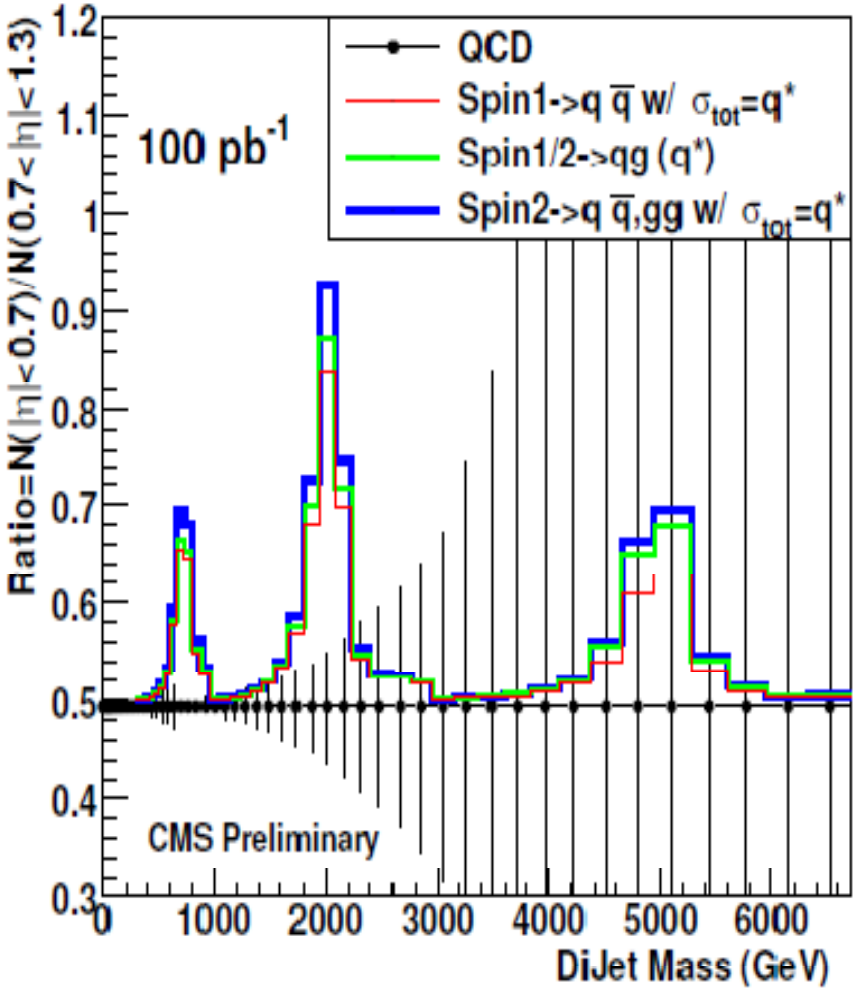


√s=14TeV

Resonances in dijets

- present exclusion limit (Tevatron) dijet mass: ~ 0.8 TeV

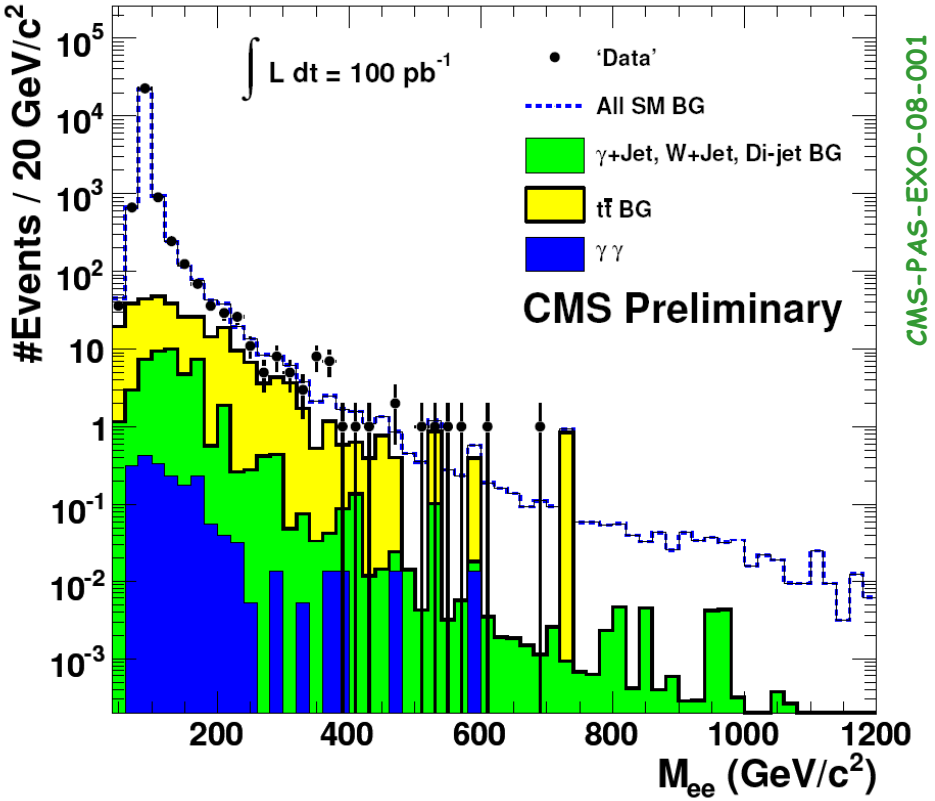




CMS-PAS-SBM-07-001

√s=14TeV

Drell-Yan lepton pair production

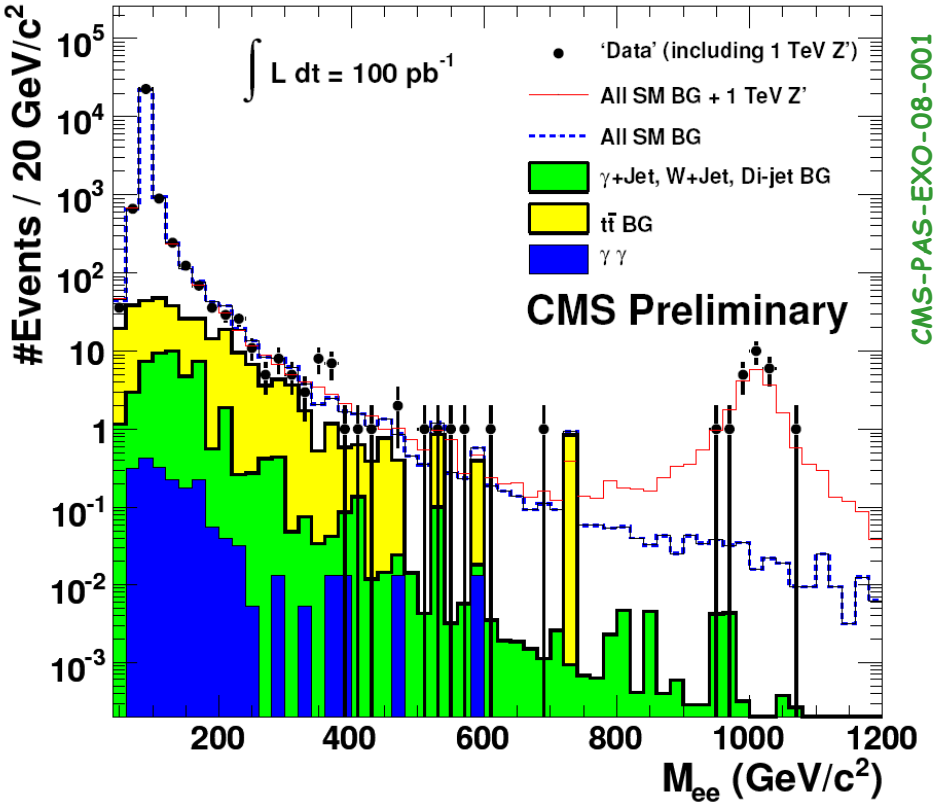


Standard Model

- two electrons with $E_T > 30$ GeV and $|\eta| < 2.5$
  - → with identification criteria
  - → not required: opposite charges

√s=14TeV

Search for new gauge bosons: Z'



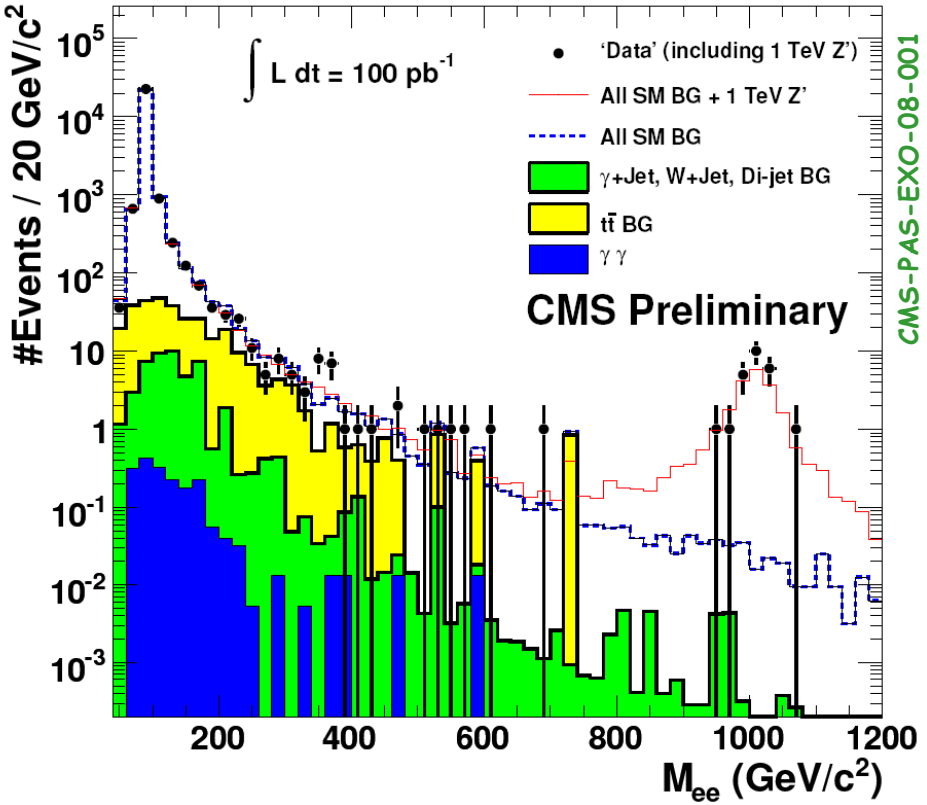
Standard Model

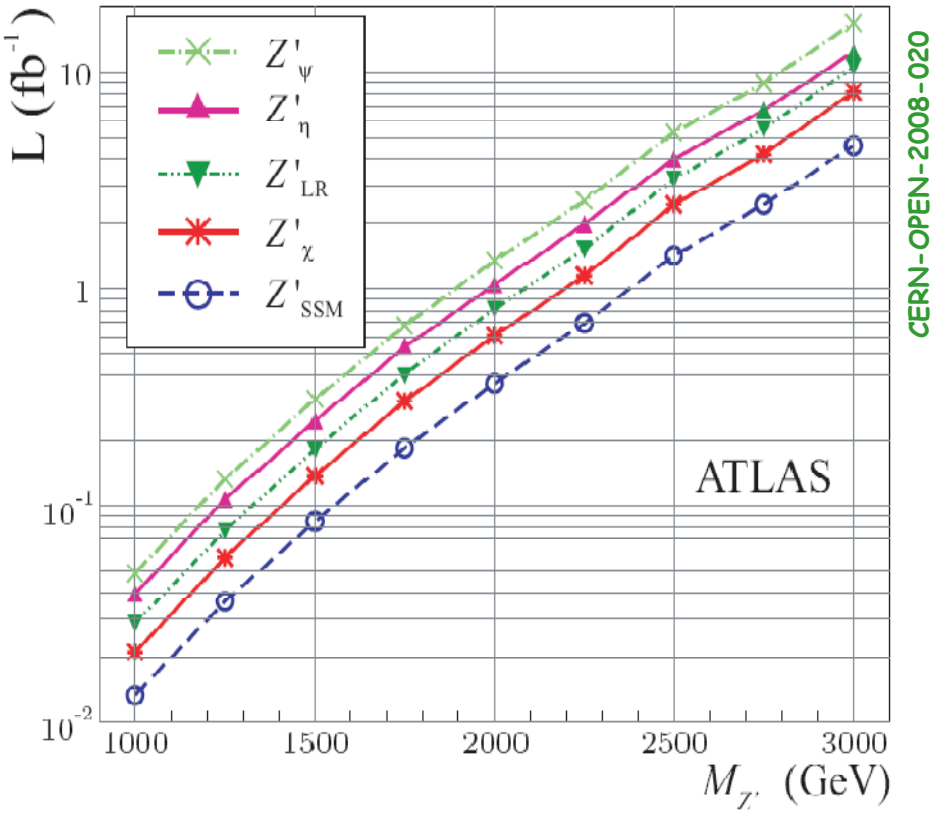
... and more

- two electrons with $E_T > 30$ GeV and $|\eta| < 2.5$
  - → with identification criteria
  - → not required: opposite charges

√s=14TeV

Search for new gauge bosons: Z'



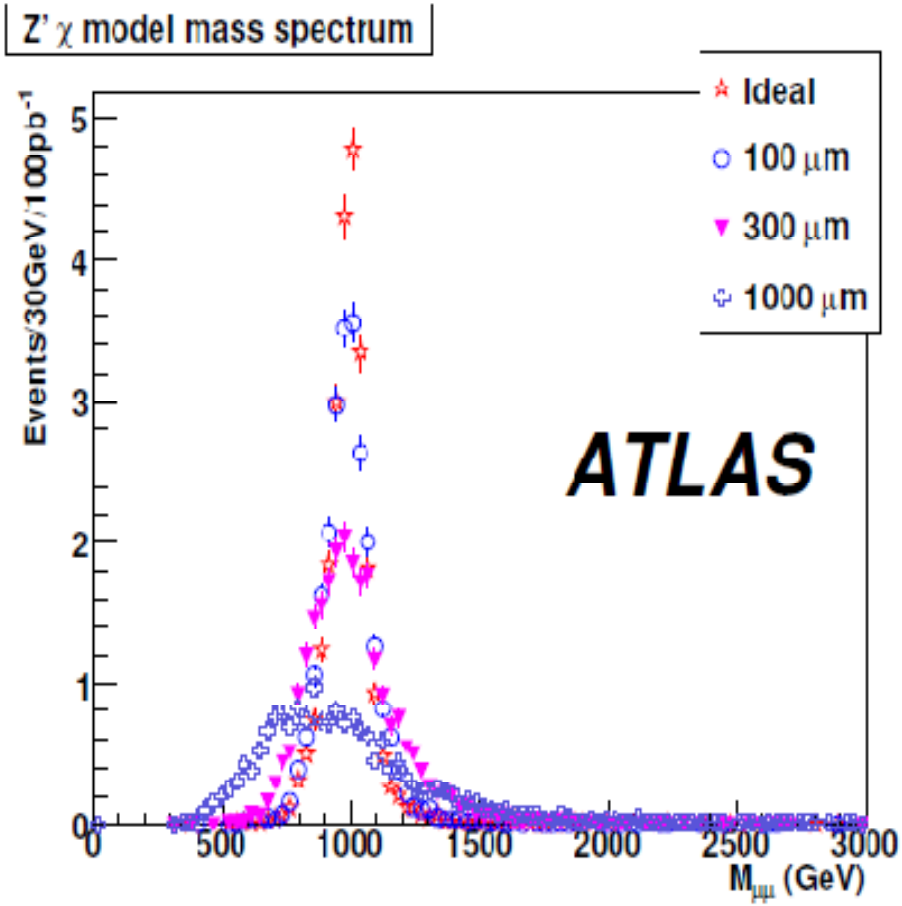


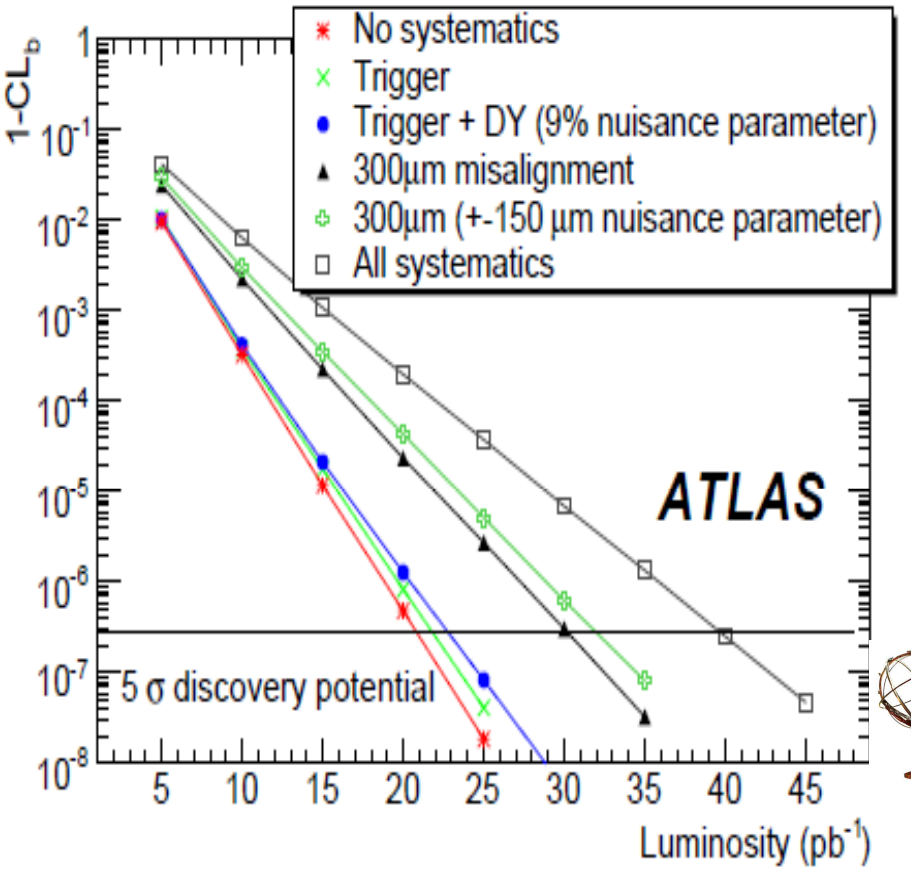
- two electrons with $E_T > 30$ GeV and $|\eta| < 2.5$
  - → with identification criteria
  - → not required: opposite charges

- Z' discovery potential
  - 2 electrons ($p_T > 65$ GeV)
  - → exclusion limit (95% C.L.) ~ 1 TeV by Tevatron

√s=14TeV

Misalignment and discovery potential



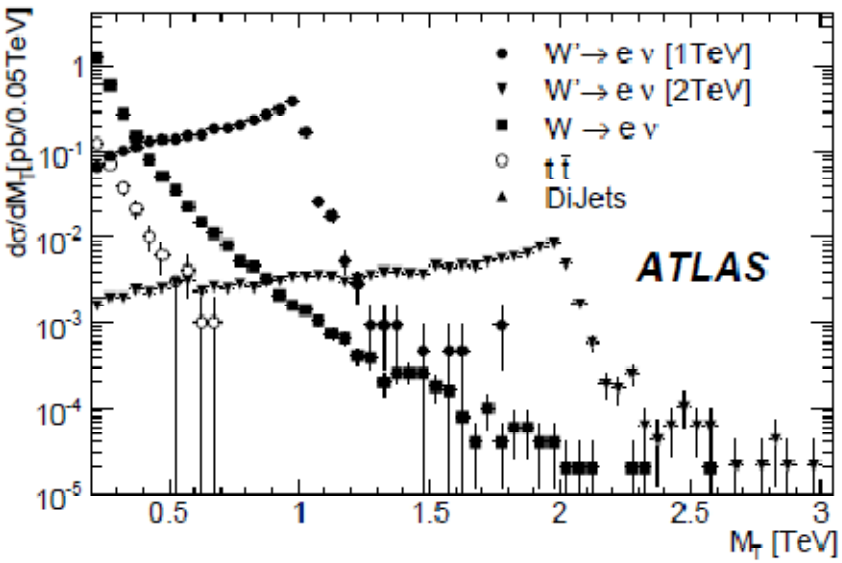


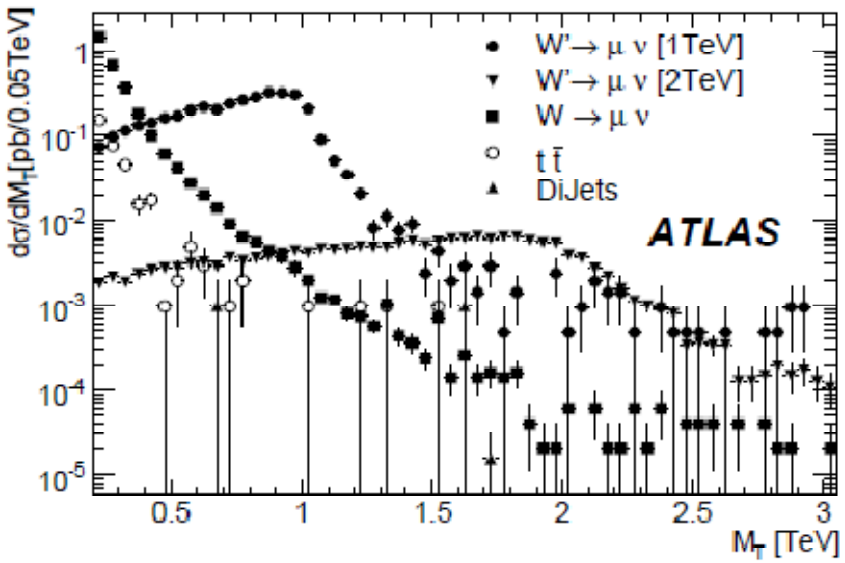
- invariant μμ mass distribution for several misalignment scenarios
  - Z'_χ model

- $1\text{-}CL_b$ value vs. integrated luminosity
  - for Z'_χ model

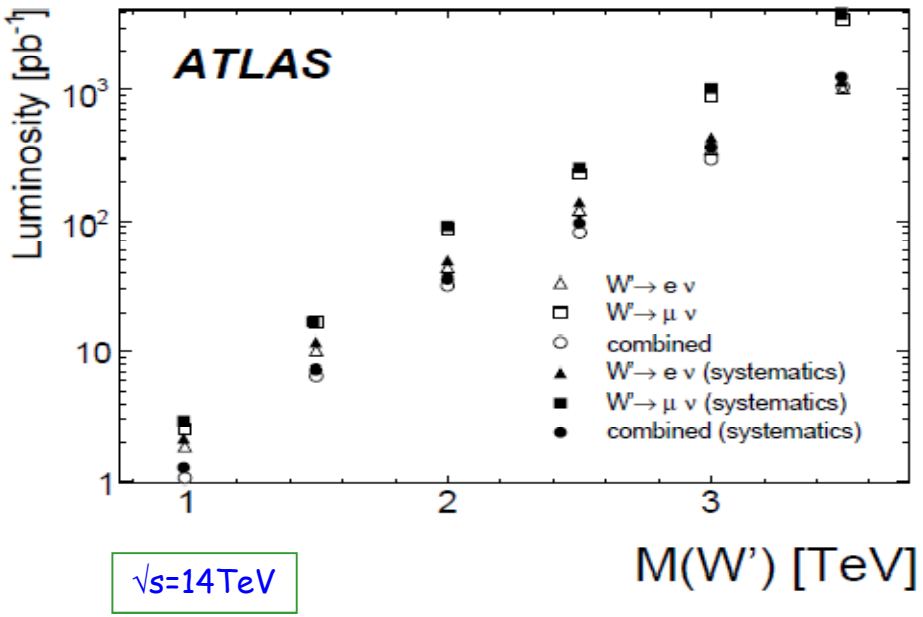
√s=14TeV

Discovery potential for W'





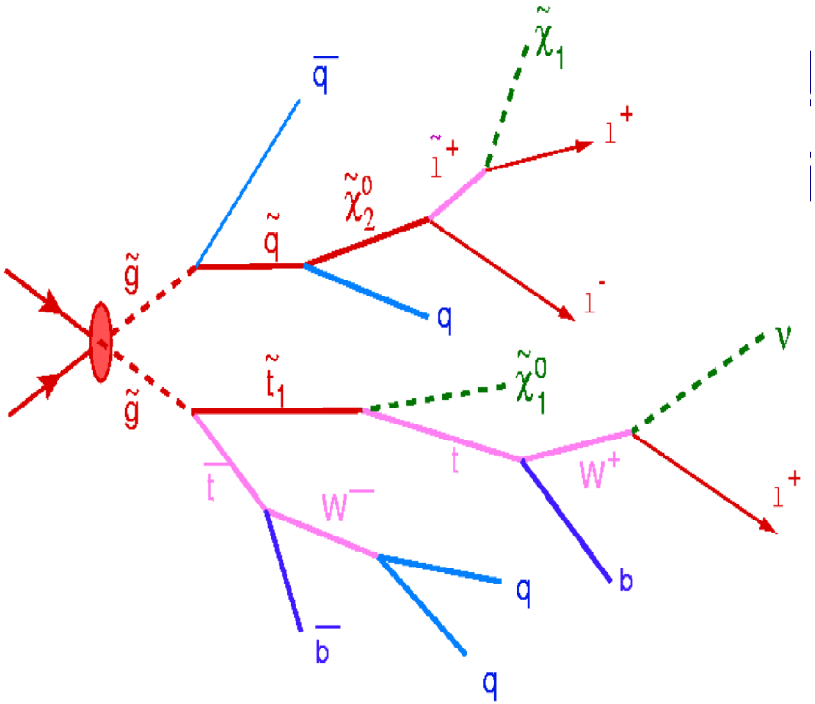
- 5σ discovery potential
  - → systematics considered
    - generator (higher orders, pdf)
    - instrumental (energy scale and resolution of lepton and jet, impact on missing E_T)

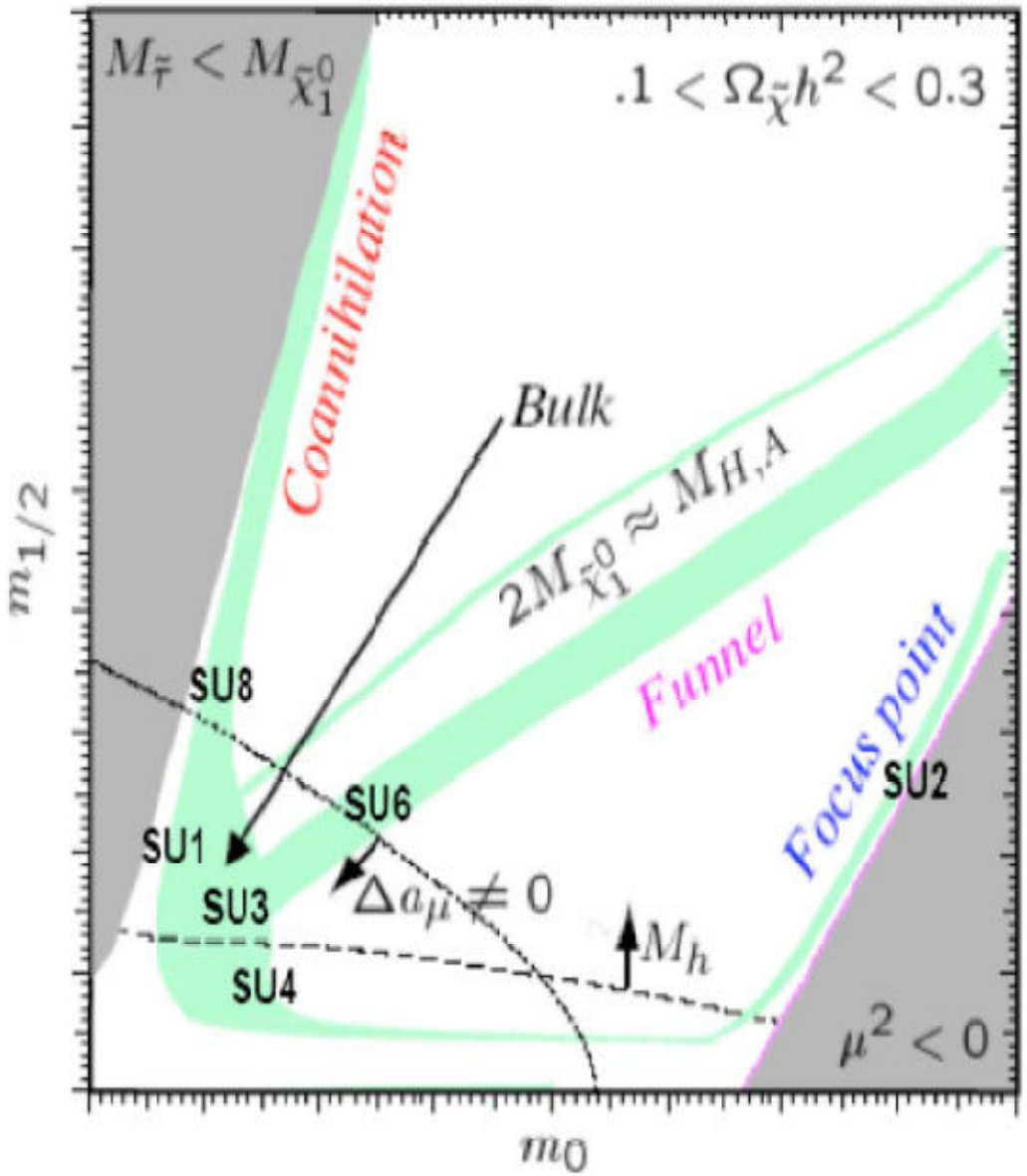


√s=14TeV

Supersymmetry

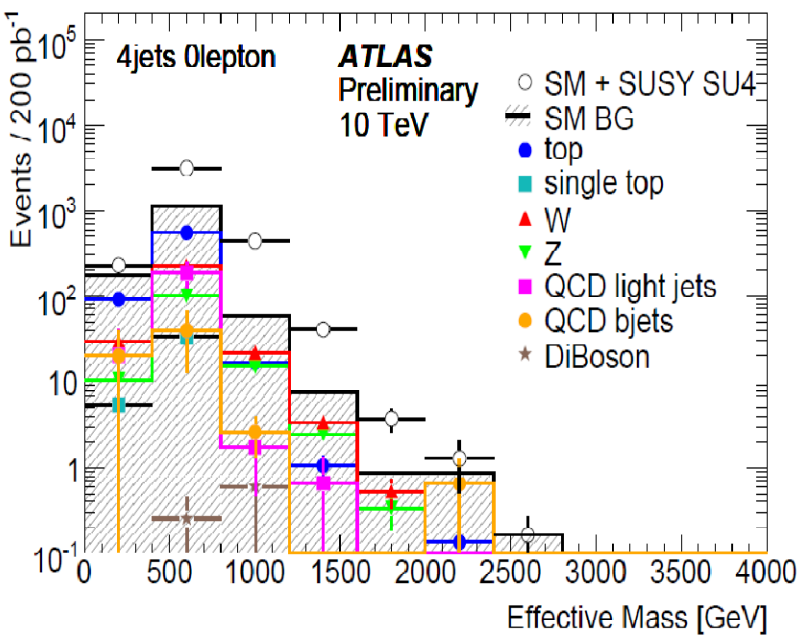
- mSUGRA
  - → one model for the symmetry breaking
  - → defines benchmark points

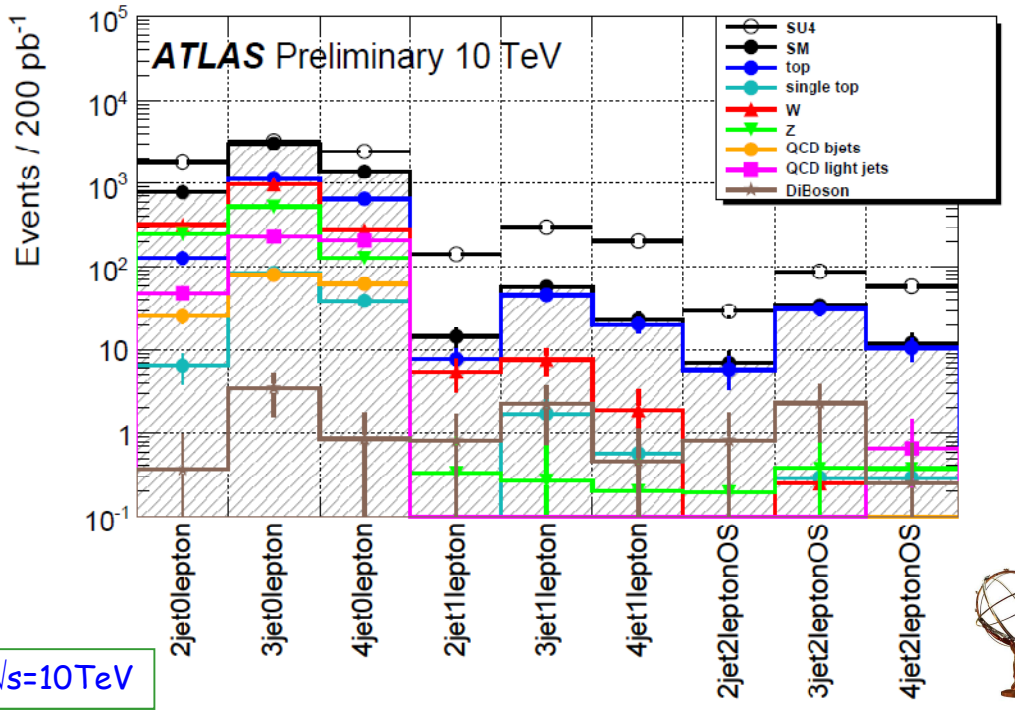




Inclusive SUSY search

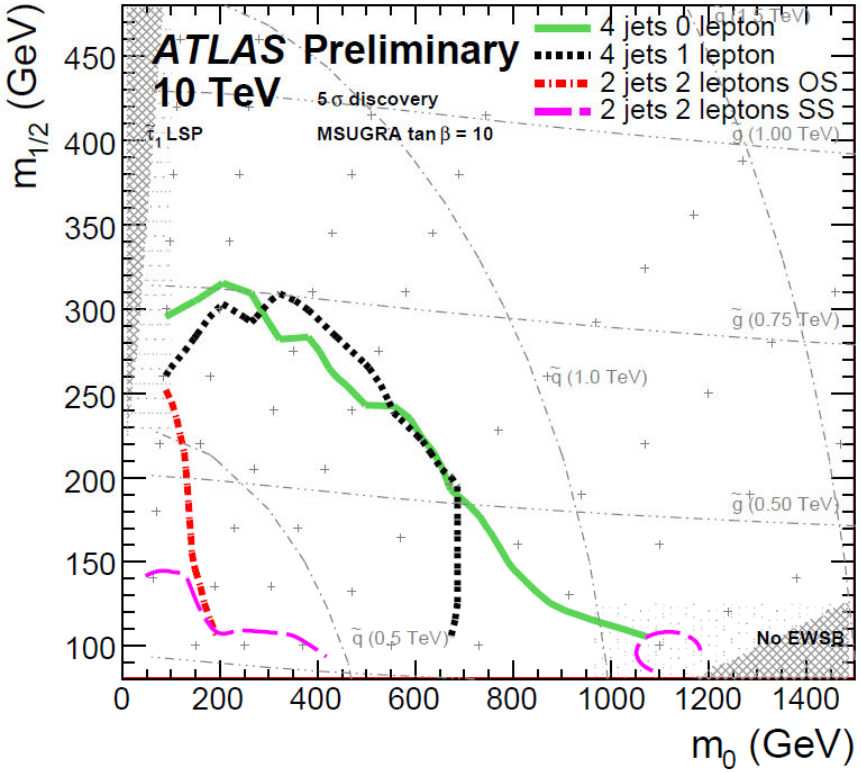
- event selection
  - → lepton(s): electron or muon ($|\eta|<2.5$ and $p_T > 10$ GeV)
  - → jets: cone algorithm (R=0.4, $|\eta|<2.5$ and $E_T > 20$ GeV)
  - → E_T^{miss}: using calorimeter cells, adding muon contribution

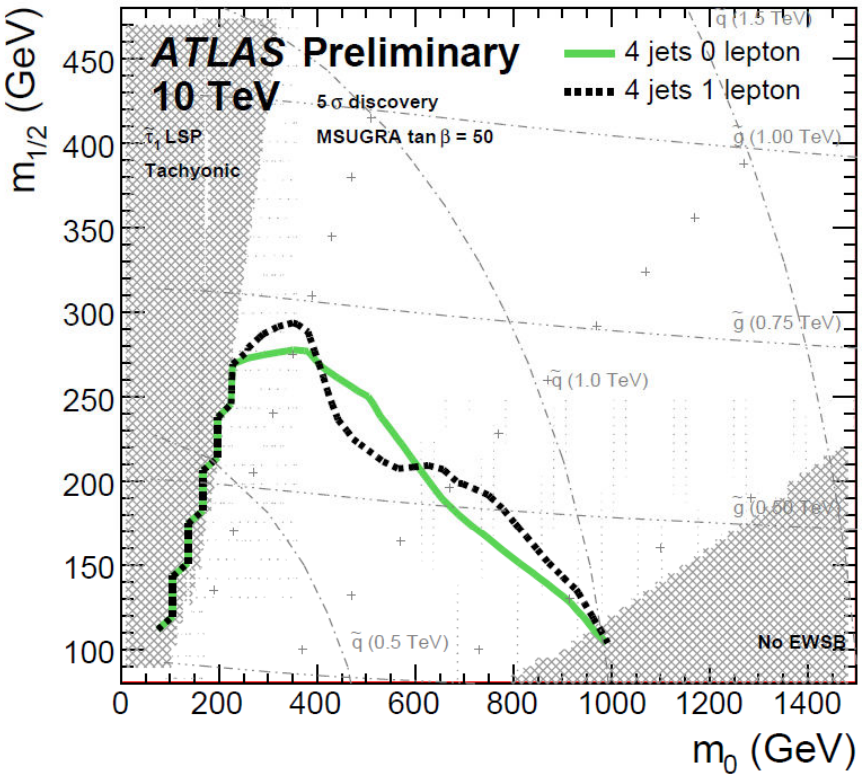




√s=10TeV

Discovery reach for SUSY





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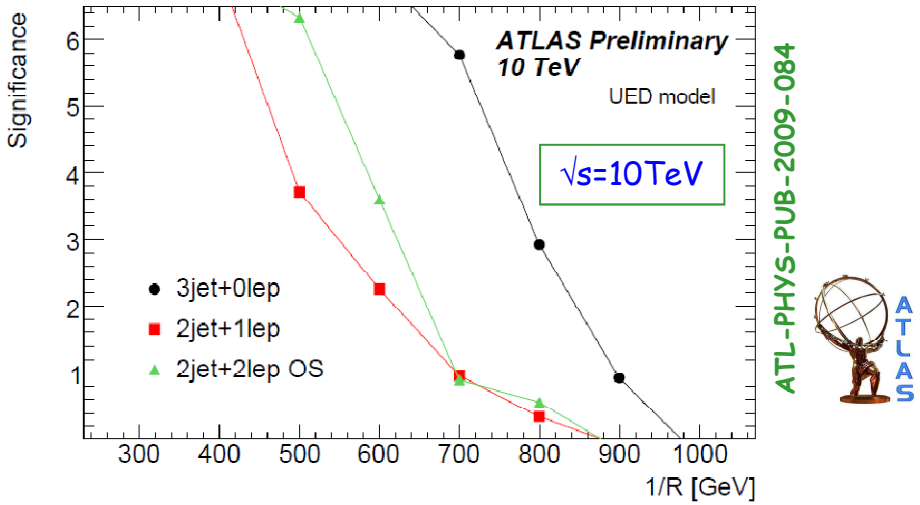
- inclusive search ($\sqrt{s}$ = 10TeV and 200 pb^{-1})
  - → using 0,1 or 2 leptons and up to 4 jets
  - → discovery of squarks and gluinos with masses up to 600-700 GeV possible (case of R-parity conservation)

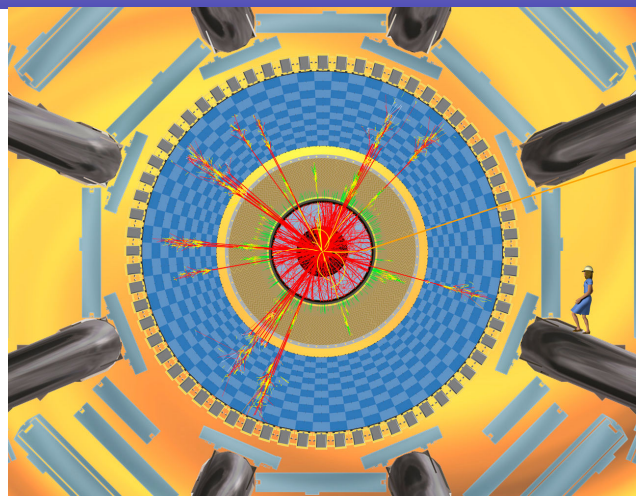
$\sqrt{s}$=10TeV

Extra dimensions / mini black holes

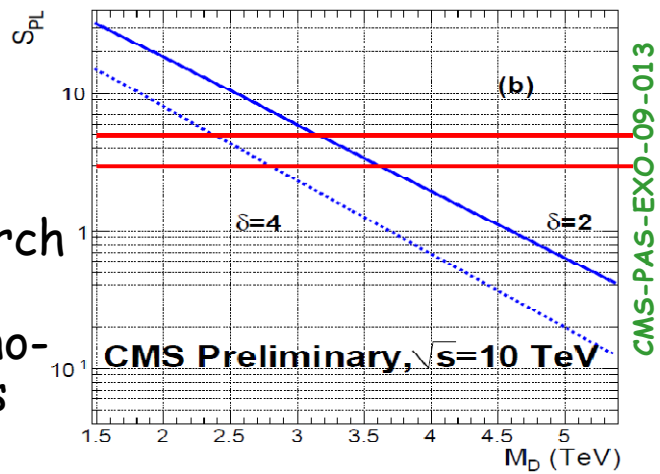
- Universal extra dimensions
  - → analysis similar to inclusive supersymmetry search



- mini black holes: spectacular signatures possible
  - → selection
    - $\Sigma|p_T| > 2.5$ TeV
    - ≥ 1 lepton with $p_T > 50$ GeV
  - → 5σ discovery potential

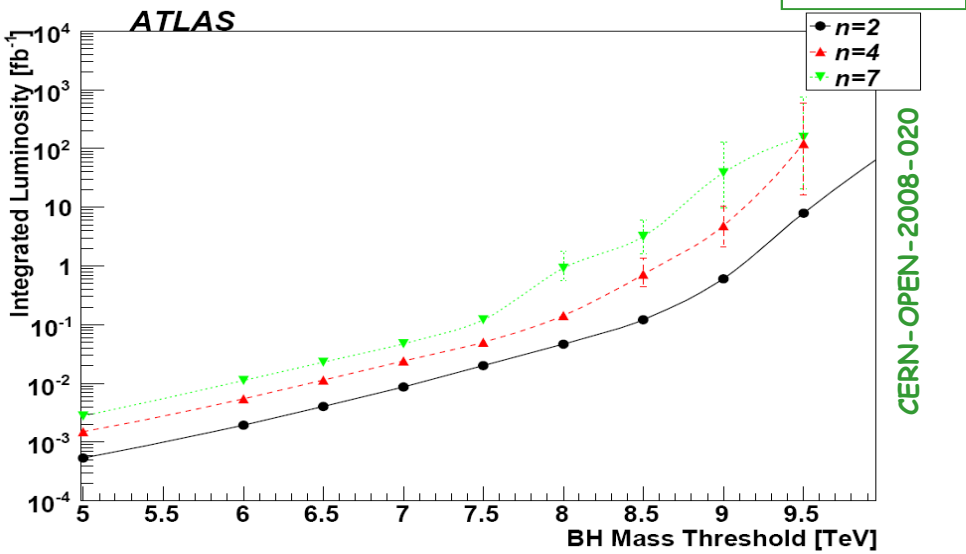


- ADD extra dimensions
  - → search for mono-jets

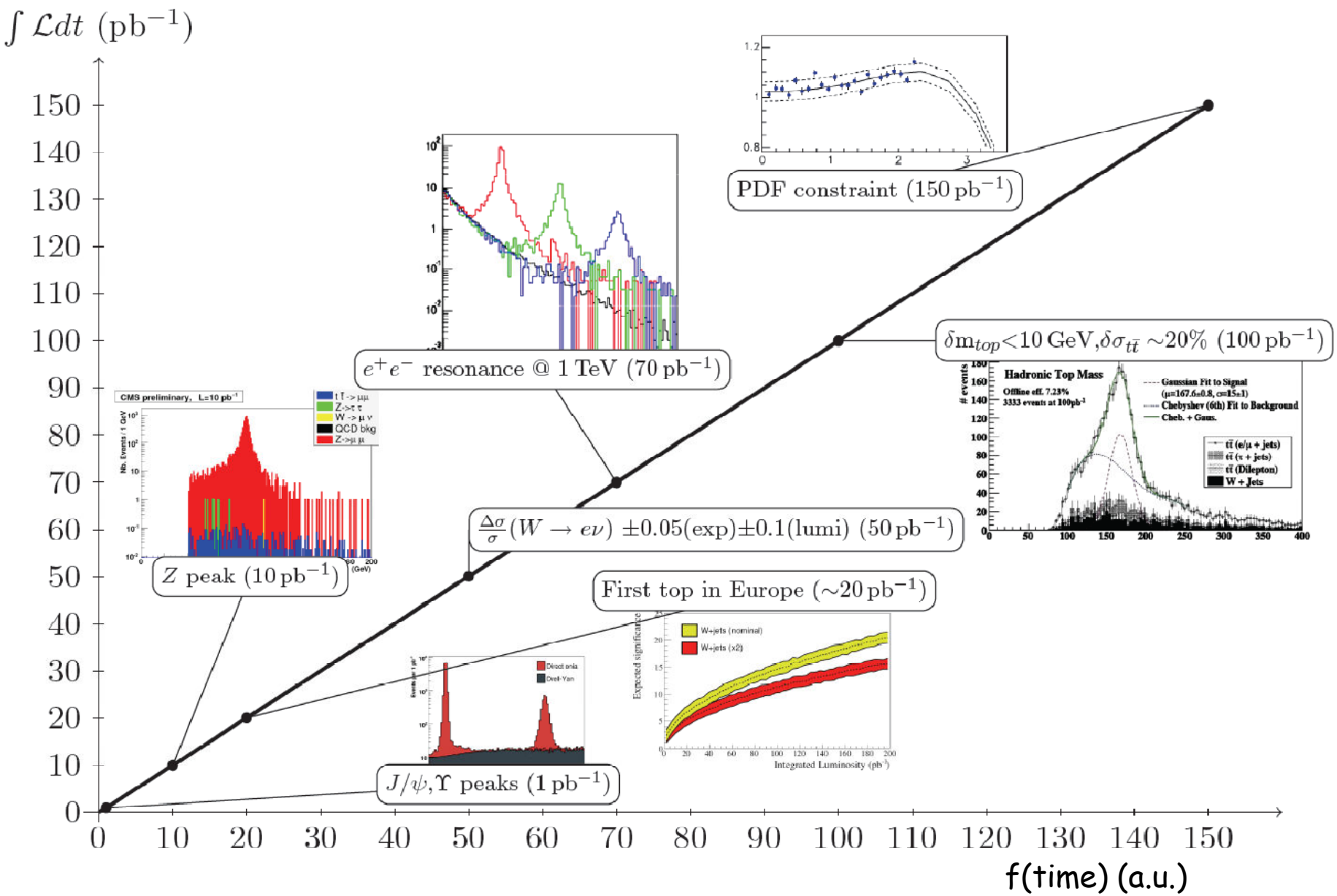


√s=10TeV

√s=14TeV



A vision towards initial results …



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Summary and outlook

- first LHC physics run in 2010
  - → $\sqrt{s}$ = 7 TeV (with possible step-up to 8-10 TeV)
  - → integrated luminosity of 200 – 300 pb^{-1}
- ATLAS and CMS are ready and well prepared to exploit this initial data
  - → extensive commissioning (e.g. muons from cosmic rays)
- threefold approach to initial data taking
  - → refine detector understanding with collision data
  - → establish properties of pp collisions at 7 TeV and beyond
    - 're-discovery' of the Standard Model
  - → search for new phenomena and surprises
    - first possibility to move beyond Tevatron sensitivity

The very final slide

- hope to be soon in a situation where we know that there are a lot of unknowns to be explored