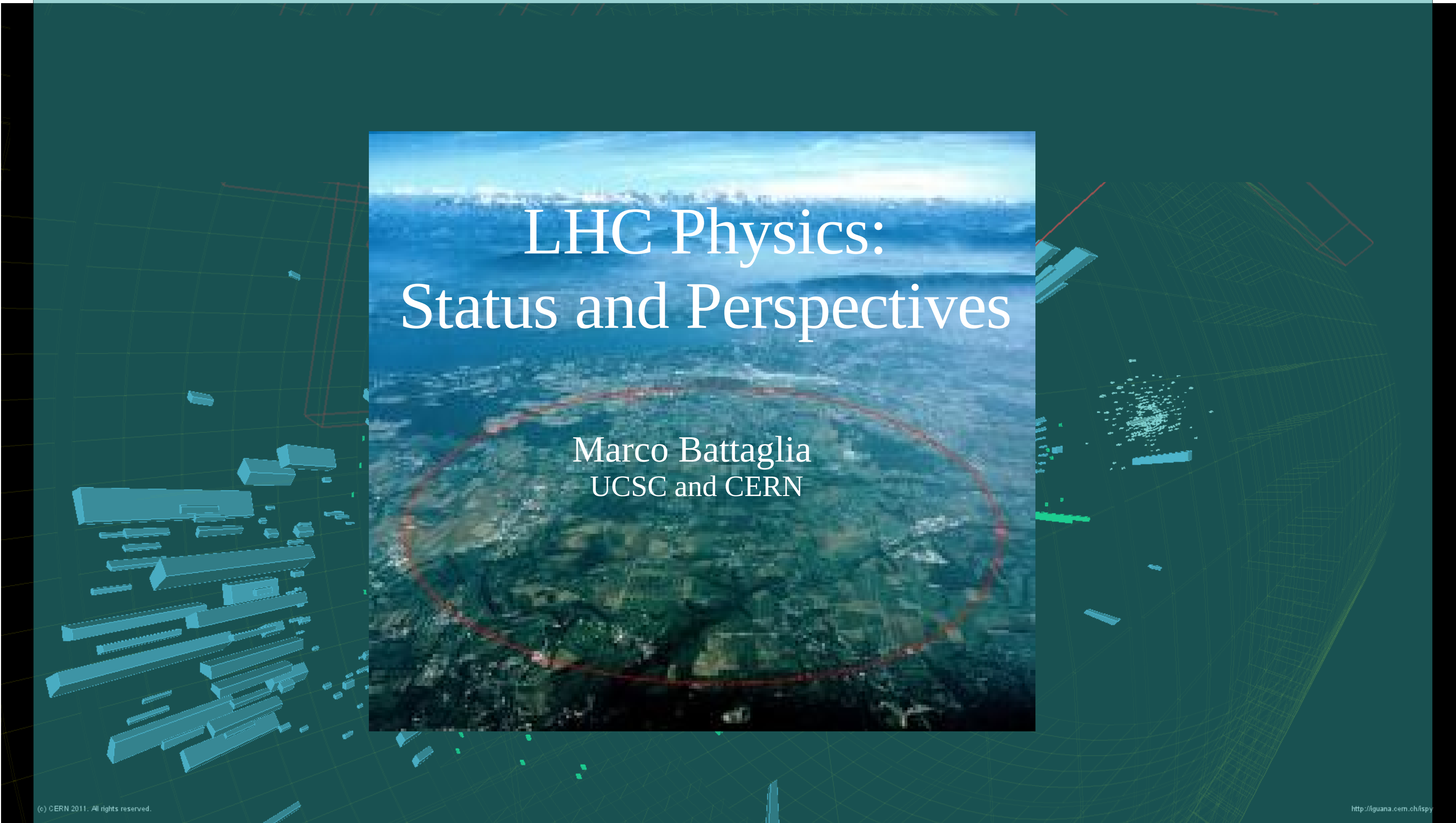


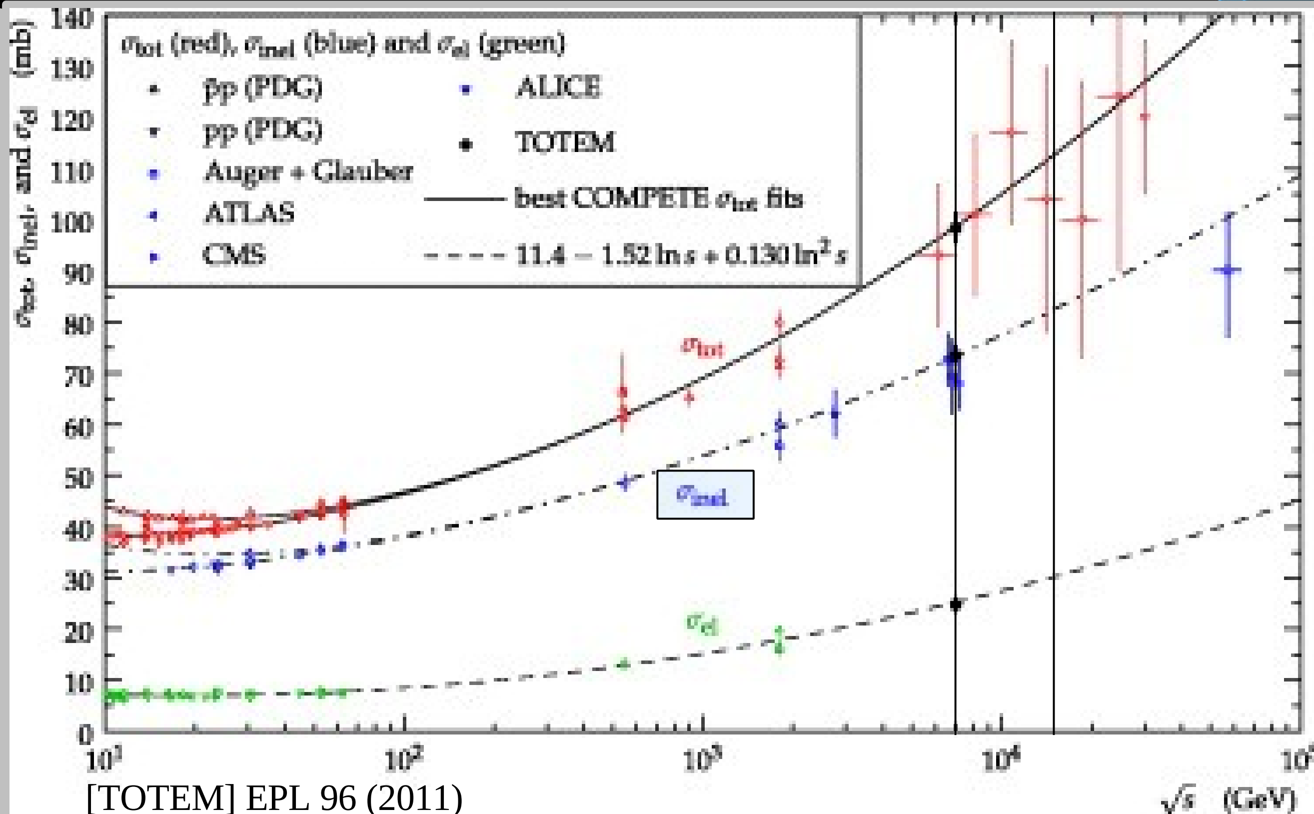
LHC Physics: Status and Perspectives

Marco Battaglia
UCSC and CERN

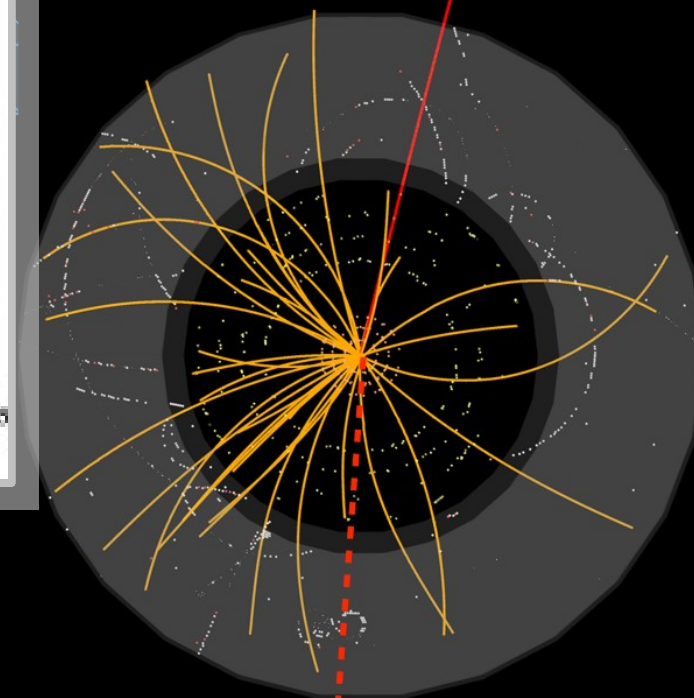
CERN Winter School on Supergravity, Strings, and Gauge Theory
CERN, 3-7 February 2014

Event Rates from LHC Collisions

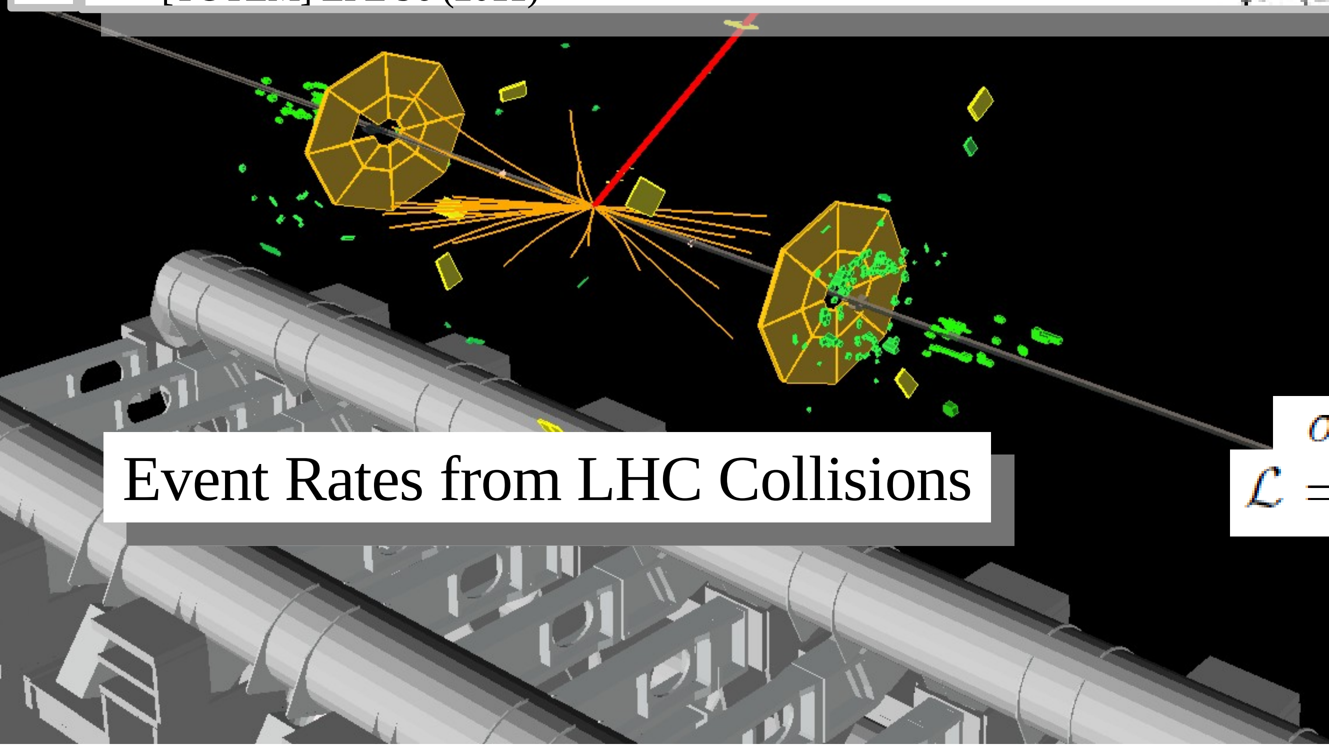
σ = production cross section



[TOTEM] EPL 96 (2011)

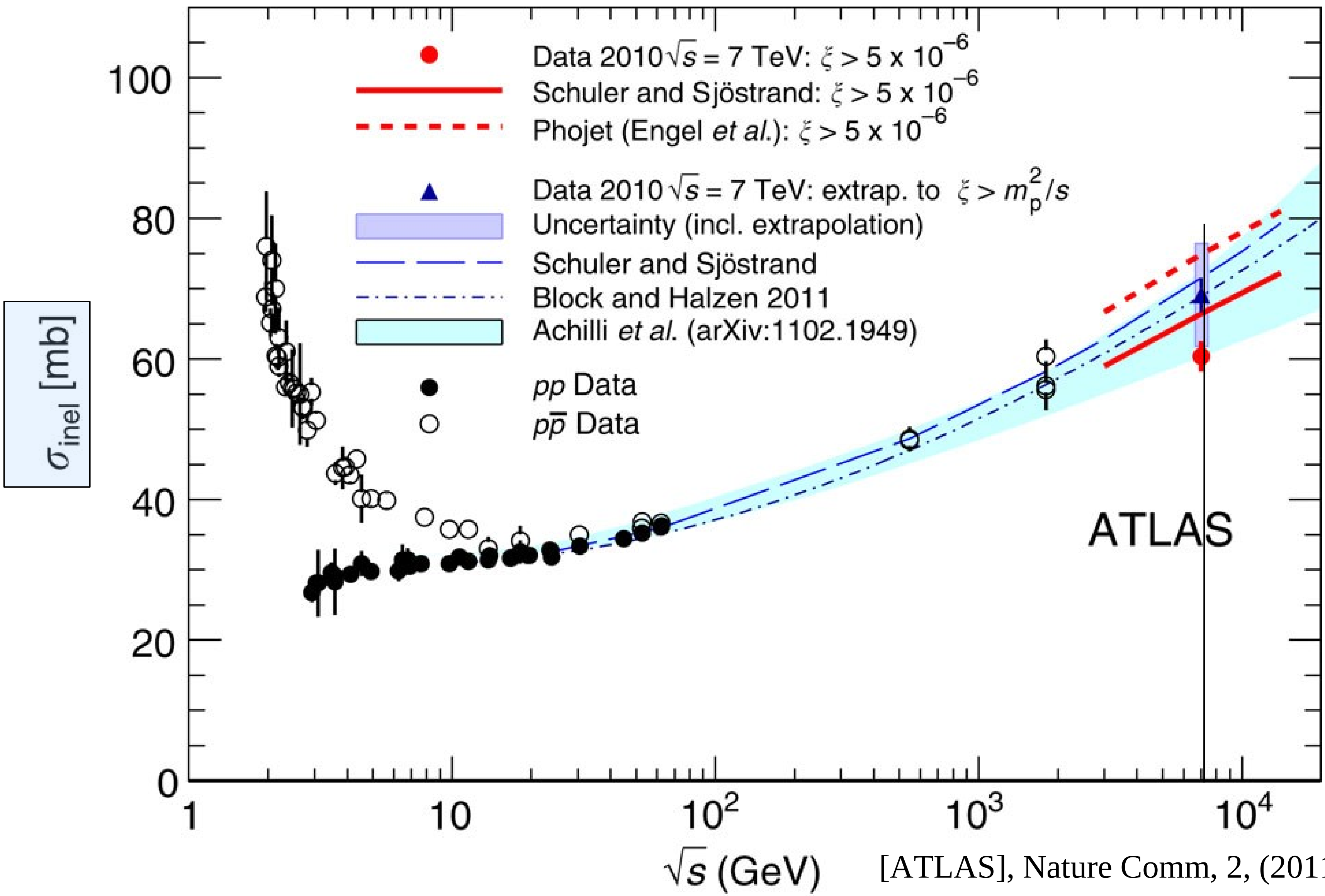


$p_T(\mu+) = 29$ GeV
$\eta(\mu+) = 0.66$
$E_T^{miss} = 24$ GeV
$M_T = 53$ GeV



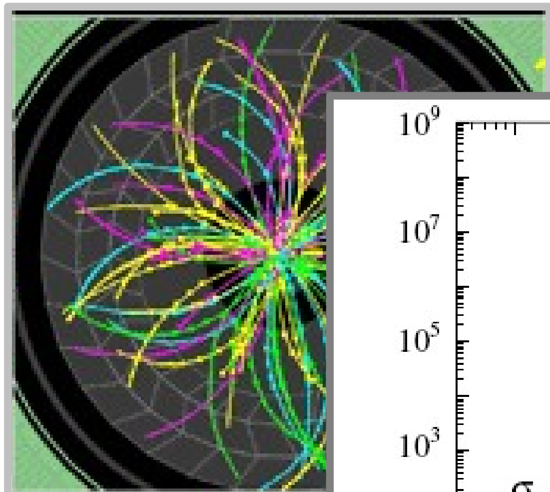
$$N_{events} = \sigma \times \mathcal{L}$$

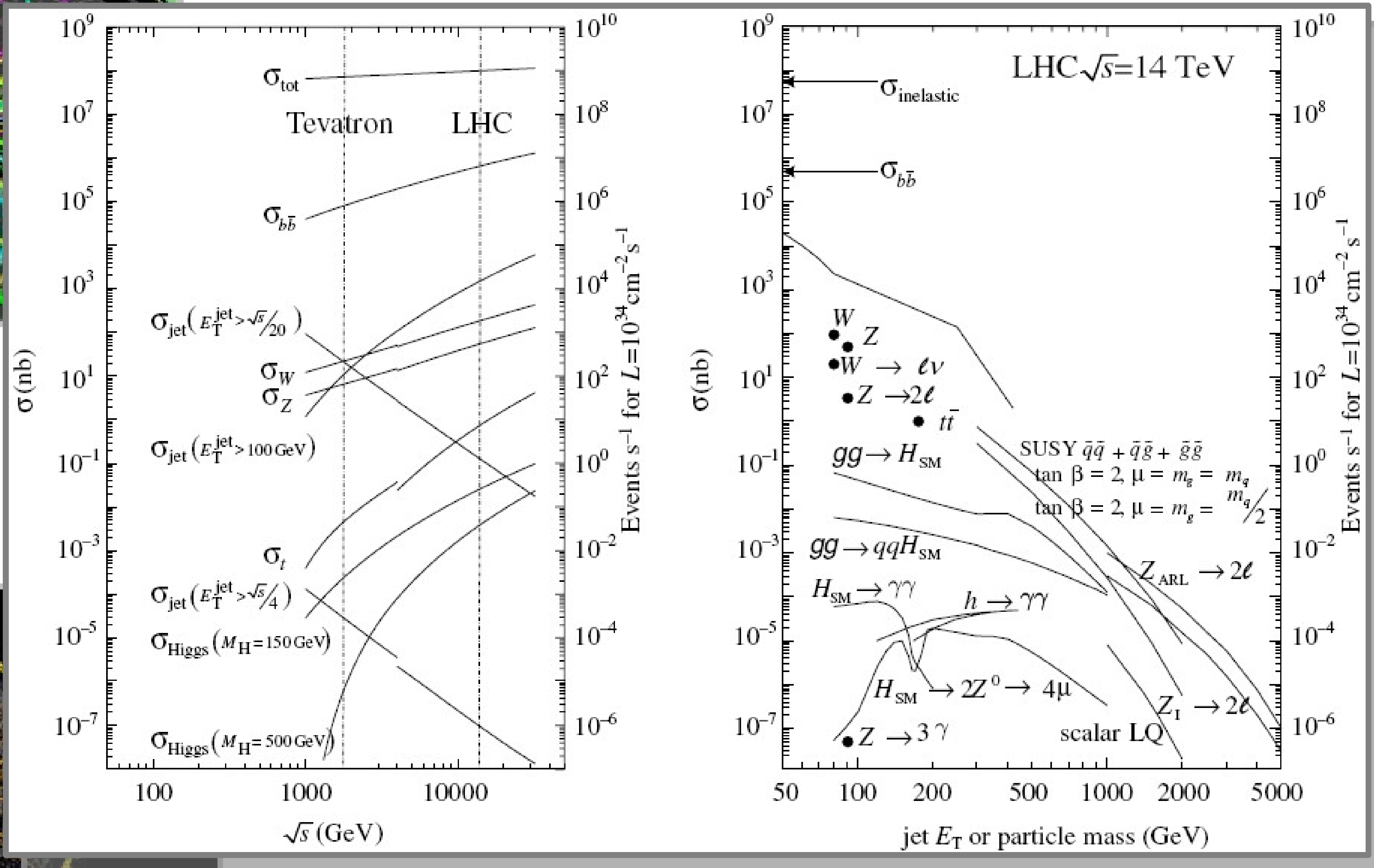
σ = production cross section
$\mathcal{L}$ = integrated collider luminosity

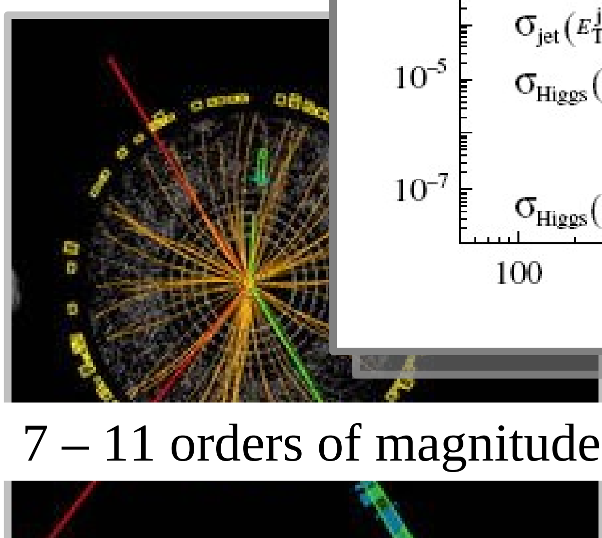


[ATLAS], Nature Comm, 2, (2011)

From "Events" to "Signal Events"







7 – 11 orders of magnitude between inelastic and "interesting" - "discovery" physics event rate

Event Trigger

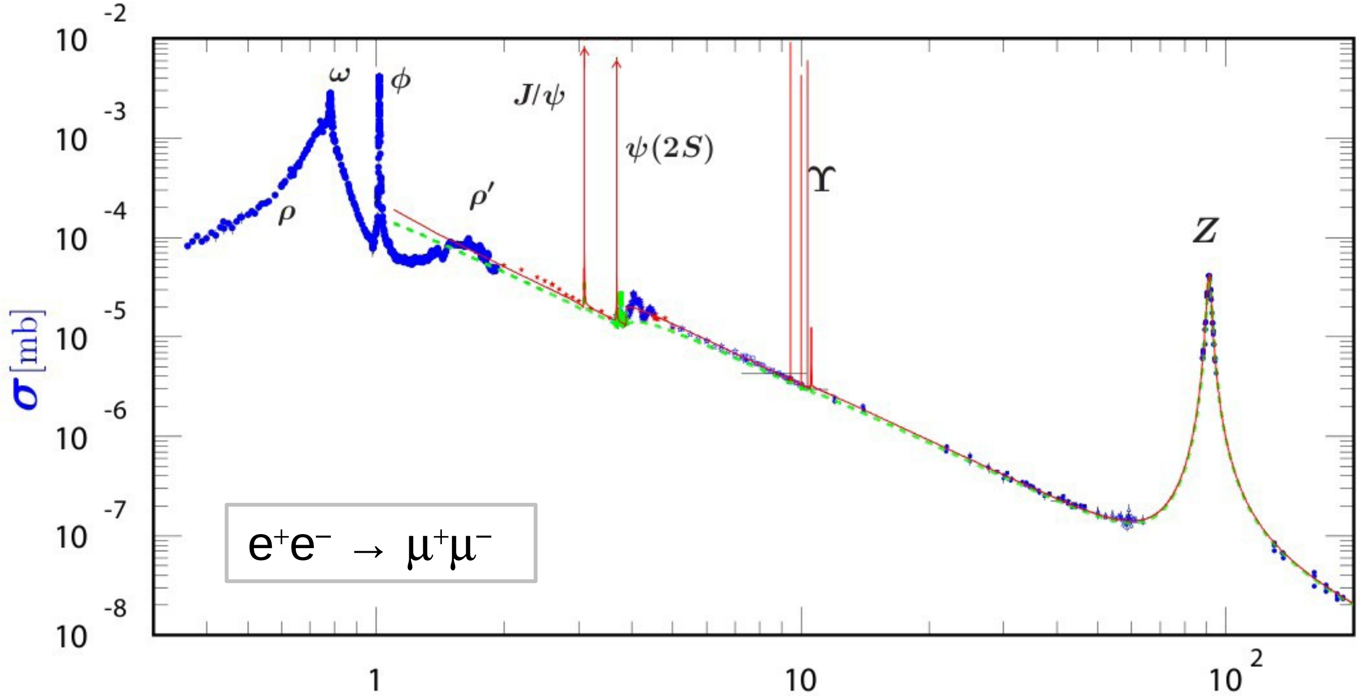
LHC interaction rate compels use of fast online event filter before full data collection and storage

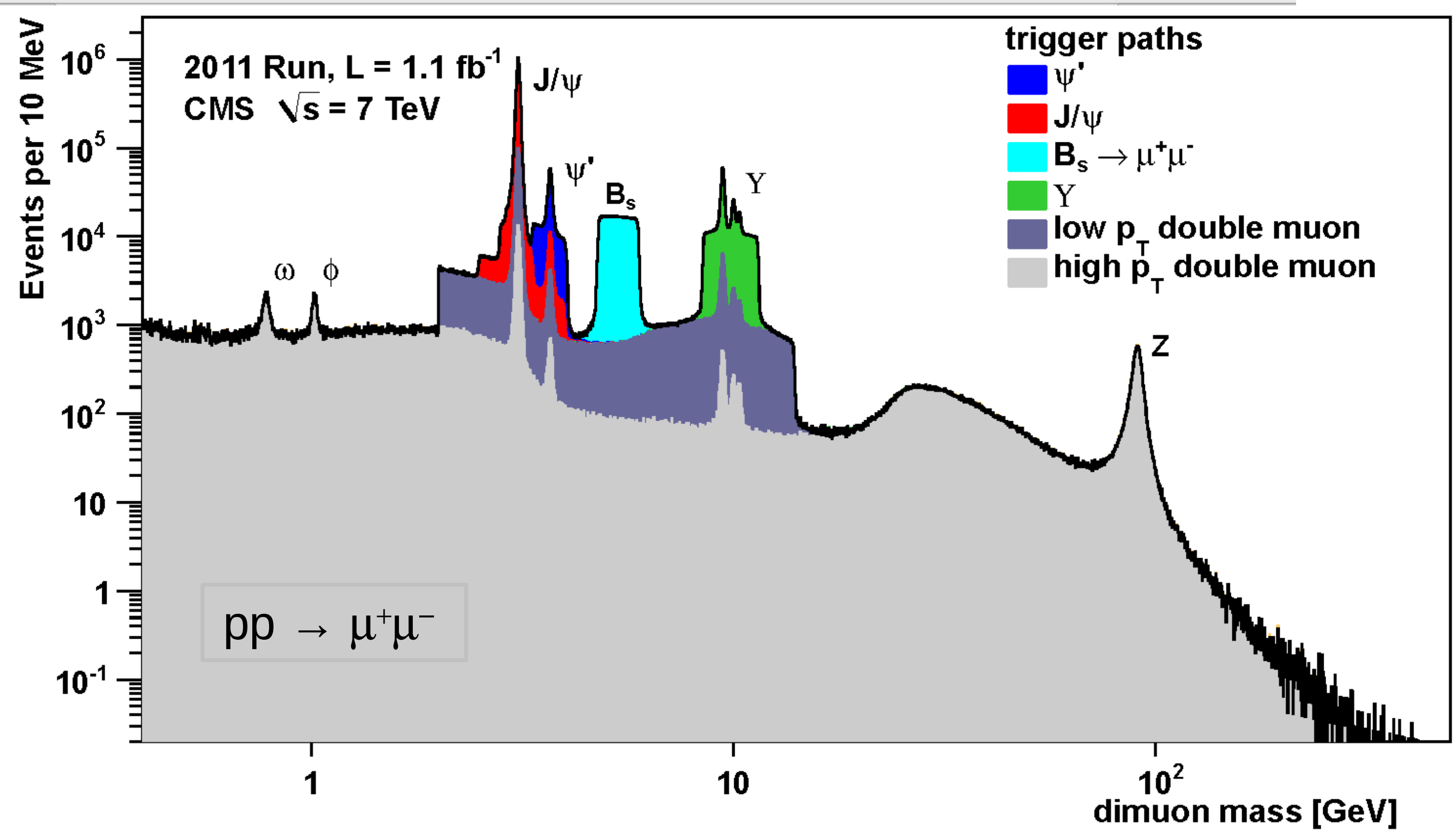
Process	Evt Rate (Hz)
Inelastic	10^9
$b\bar{b}$	5×10^6
$W \to \ell\nu$	150
$t\bar{t}$	10
SUSY	O(0.5)

Analyse and save/reject events with fast processing, high rejection factors & high efficiency for physics;

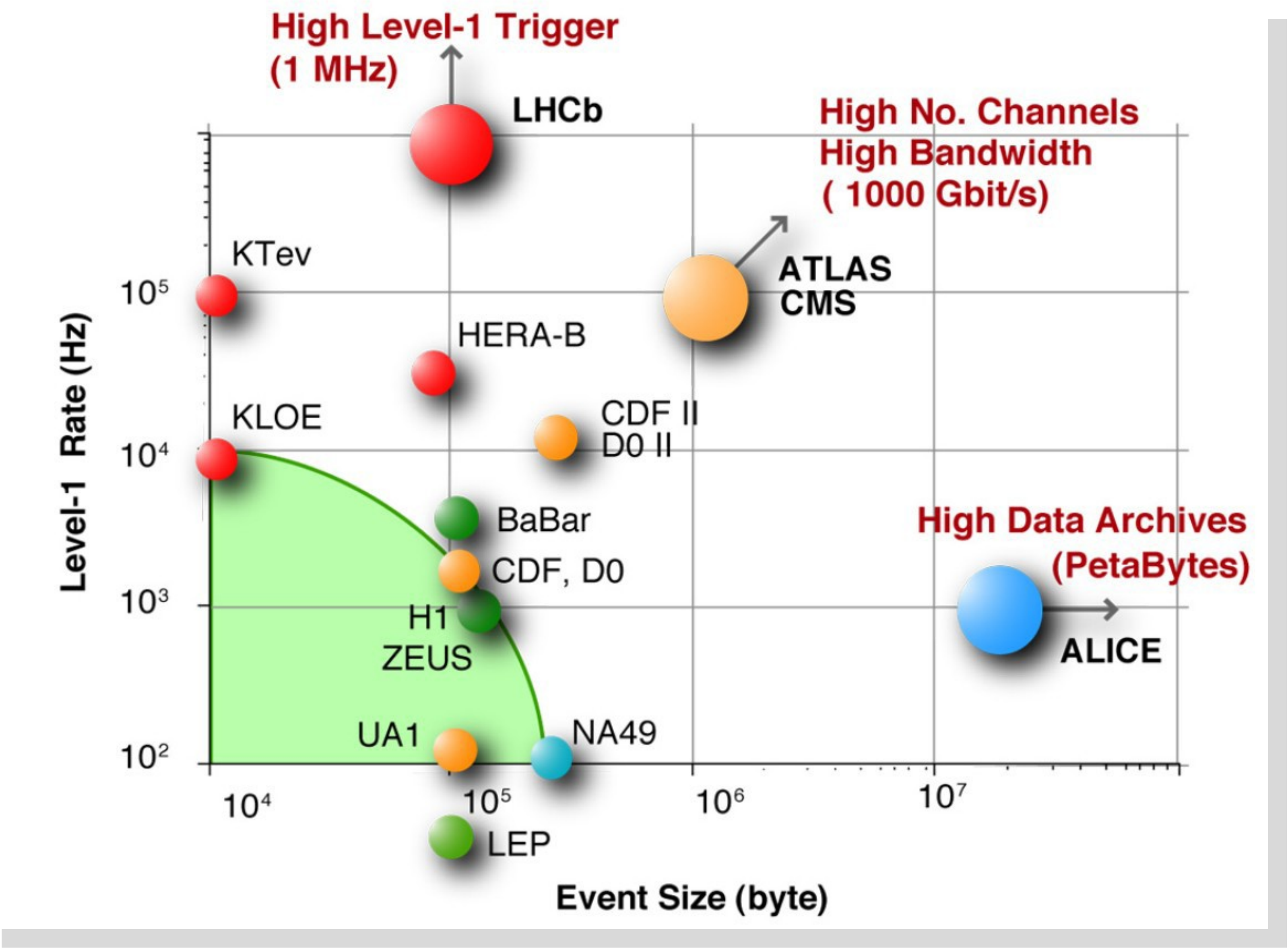
From 40(20)MHz to ~100Hz in stages (HW+SW);

Use redundant trigger (Muon & Calo at L1 + HLT)



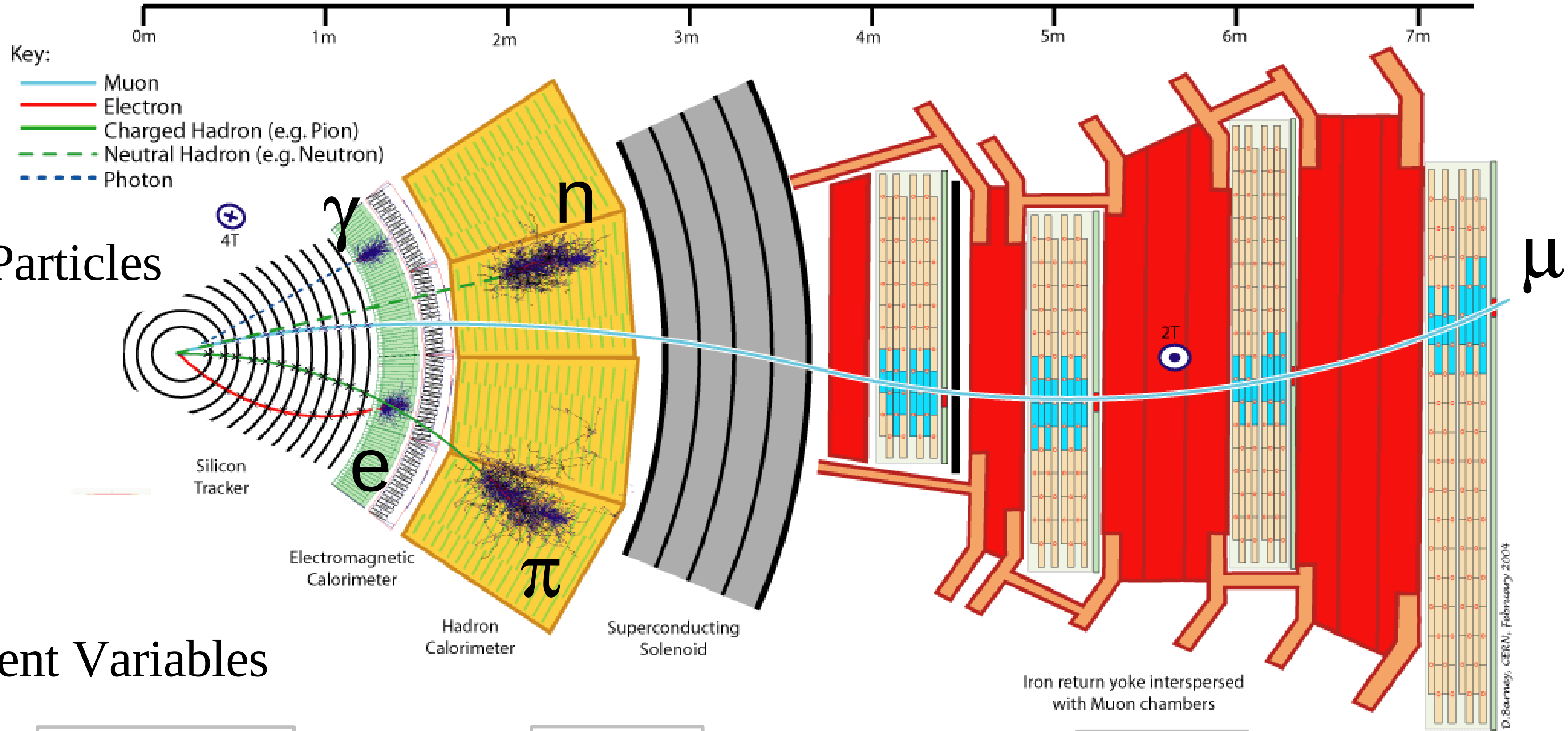


Trigger Rate and Event Size depends on Physics



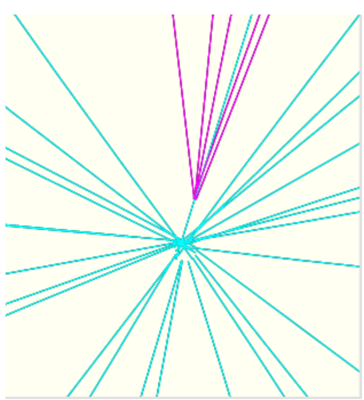
Reconstruction of Physics Objects

from Particles

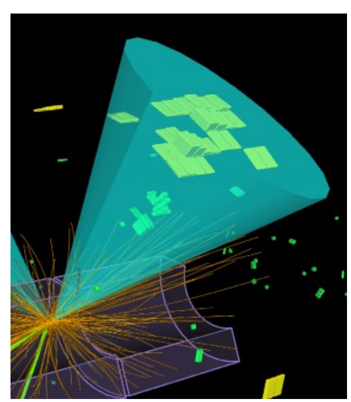


to Event Variables

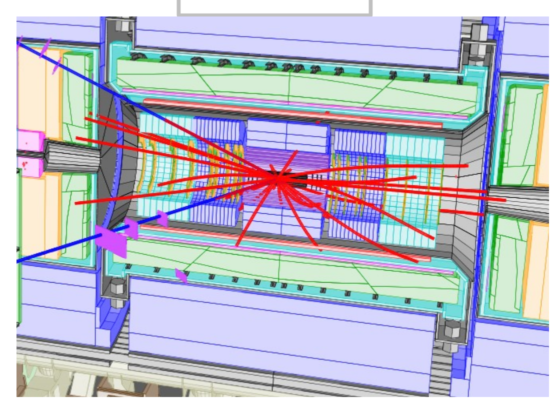
Sec Vtx

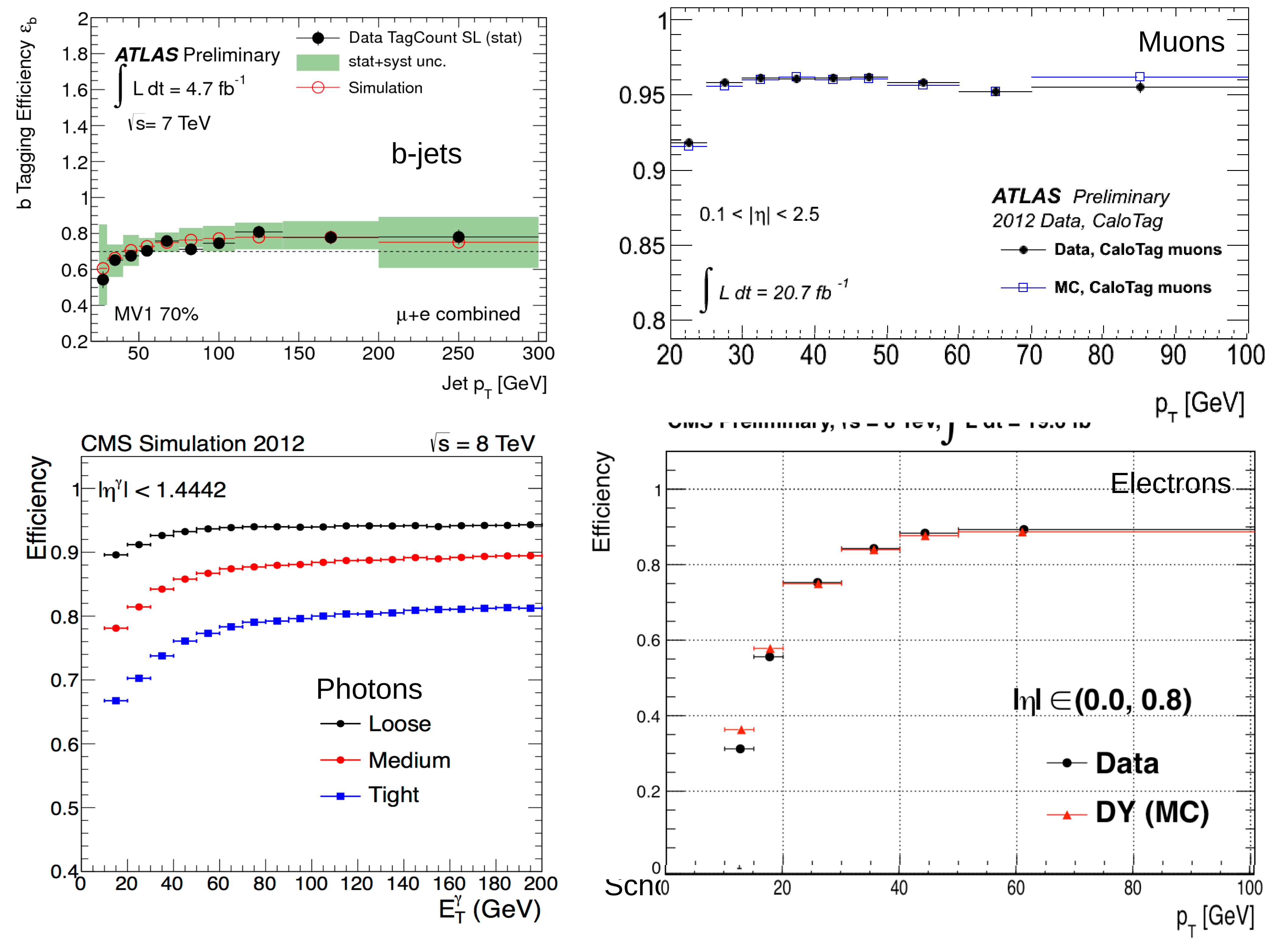


Jets



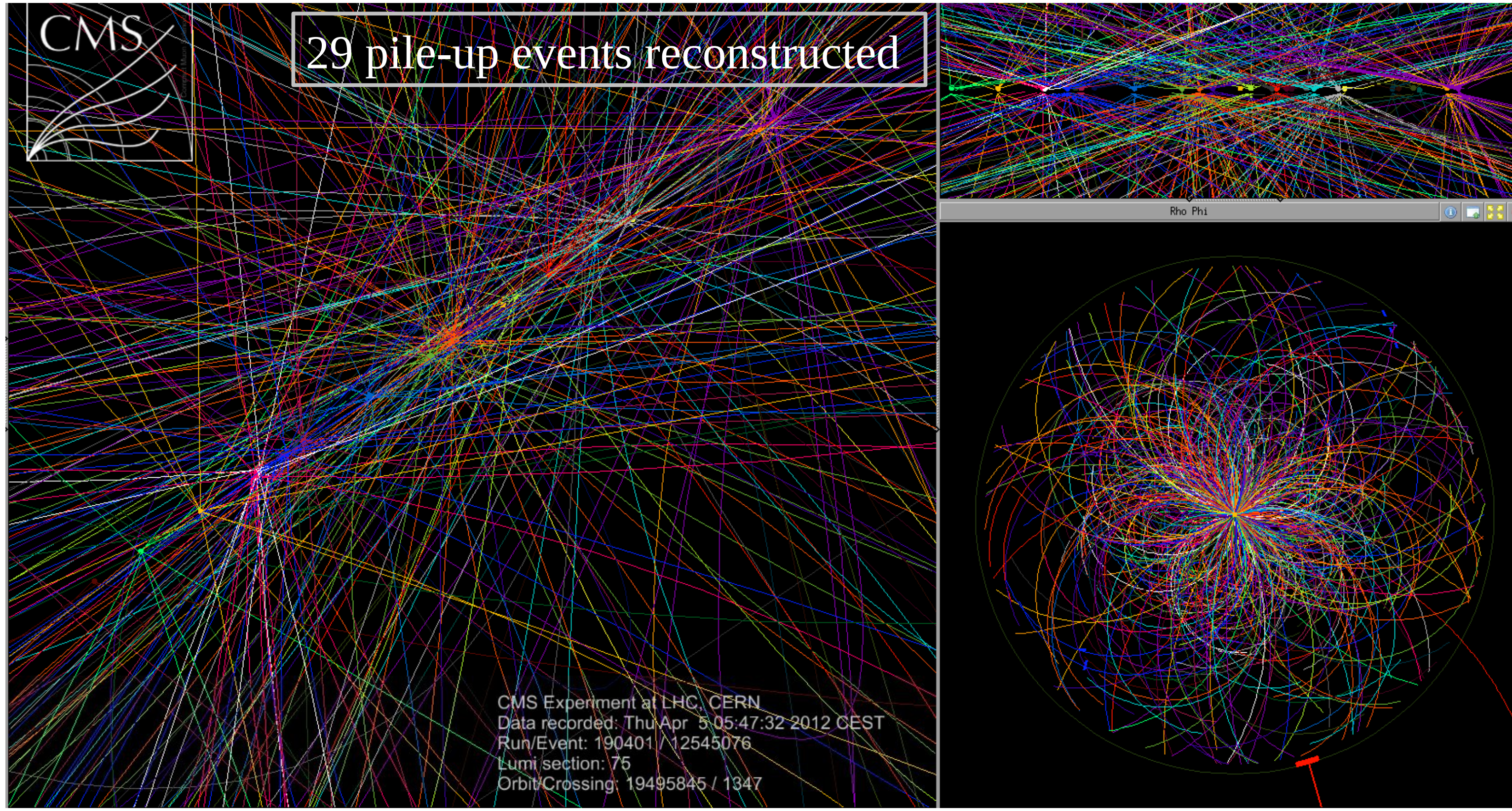
MET





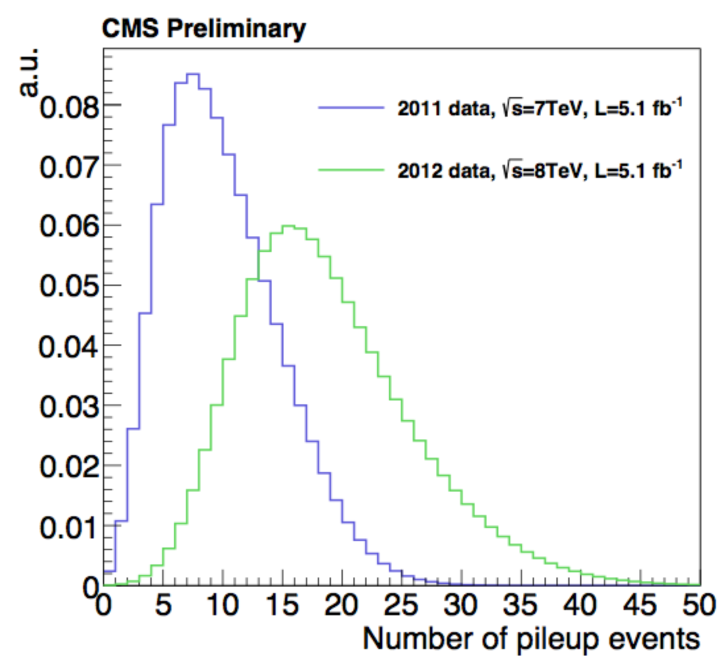
b Tagging Efficiency ε_b
ATLAS Preliminary
∫ L dt = 4.7 fb^-1
√s= 7 TeV
Data TagCount SL (stat)
stat+syst unc.
Simulation
b-jets
MV1 70%
μ+e combined
Jet p_T [GeV]
Muons
0.1 < |η| < 2.5
ATLAS Preliminary
2012 Data, CaloTag
Data, CaloTag muons
MC, CaloTag muons
∫ L dt = 20.7 fb^-1
p_T [GeV]
CMS Simulation 2012
√s = 8 TeV
Efficiency
|η^γ| < 1.4442
Photons
Loose
Medium
Tight
E_T^γ (GeV)
Efficiency
Electrons
|η| ∈(0.0, 0.8)
Data
DY (MC)
p_T [GeV]

Event Pile-up



High interaction rate (to attain luminosity) and large inelastic cross section make minimum bias event pile-up on “physics event” important and must be dealt with in event reconstruction (jet clustering, MET, …)

Long bunch spreads events origin along beam axis.



Signal Topologies

Trigger pre-selection & severe hadronic backgrounds make essential the identification of well-defined signal topologies for signal-bkg event discrimination;

Theories & models being tested typically depend on many parameters which often change the way signal event look like in the detectors;

Topologies are driven by physics and by available triggers on physics objects (leptons, jets, photons, MET, ...);

- Di-Jet/lepton/photons Resonances
- (b) Jet(s)+Lepton(s) +MET
- Multi-(b) jets +MET
- Photon(s) +MET
- Multi-leptons +MET
- …

Studies and searches by signal topologies make LHC results available for re-interpretation for other theories and models than those originally aimed at;

Whenever developing a new theory ask yourself whether the LHC may not have already something to say about it.

LHC result re-interpretation

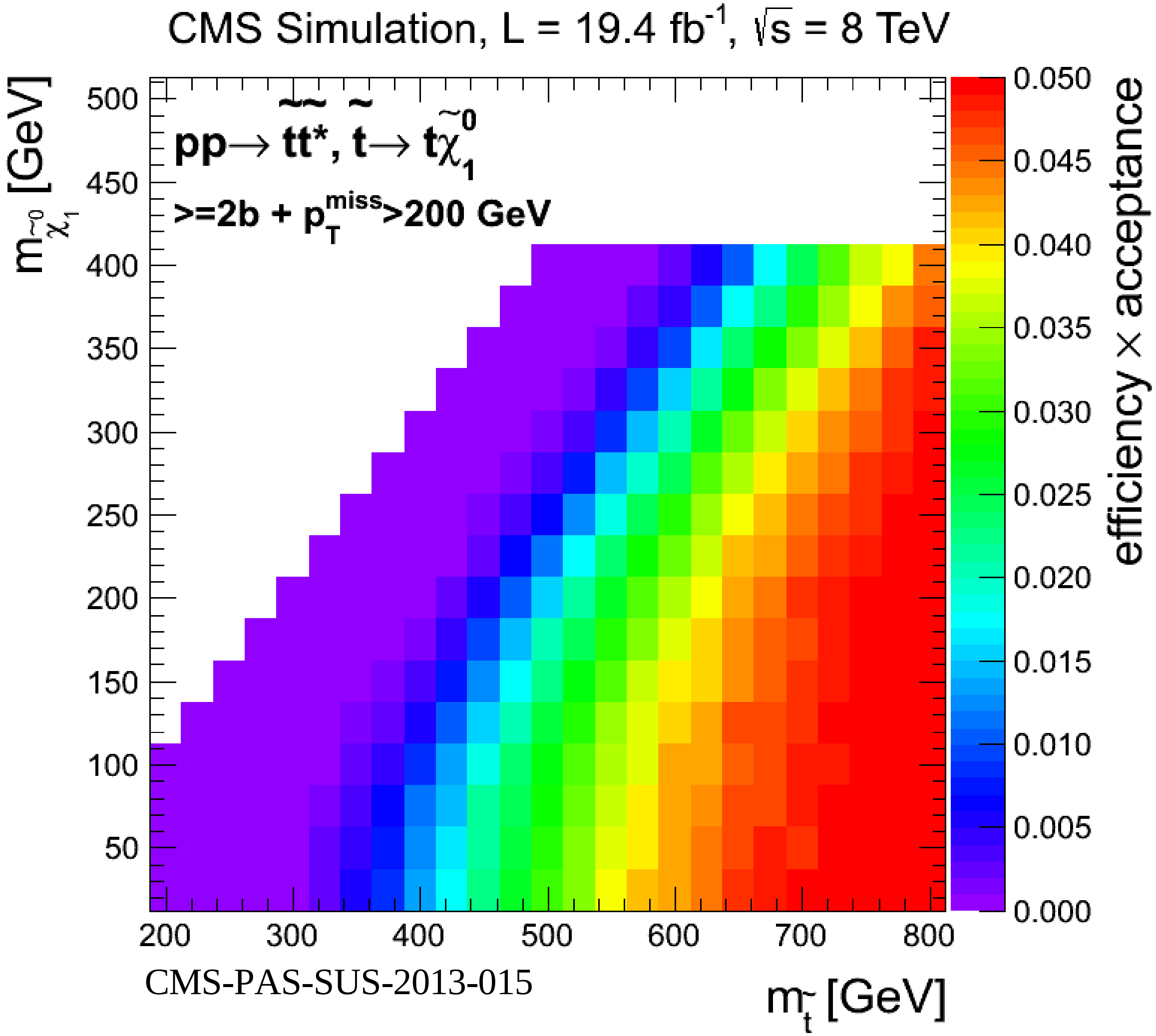
Results of LHC searches are upper limits (signal strength determinations) for given topology and acceptance x efficiency of selection: these can be re-interpreted for different physics signals once the acceptance x efficiency matrix for the new process can be determined:

LHC cross section upper limits;

Generation of new process;

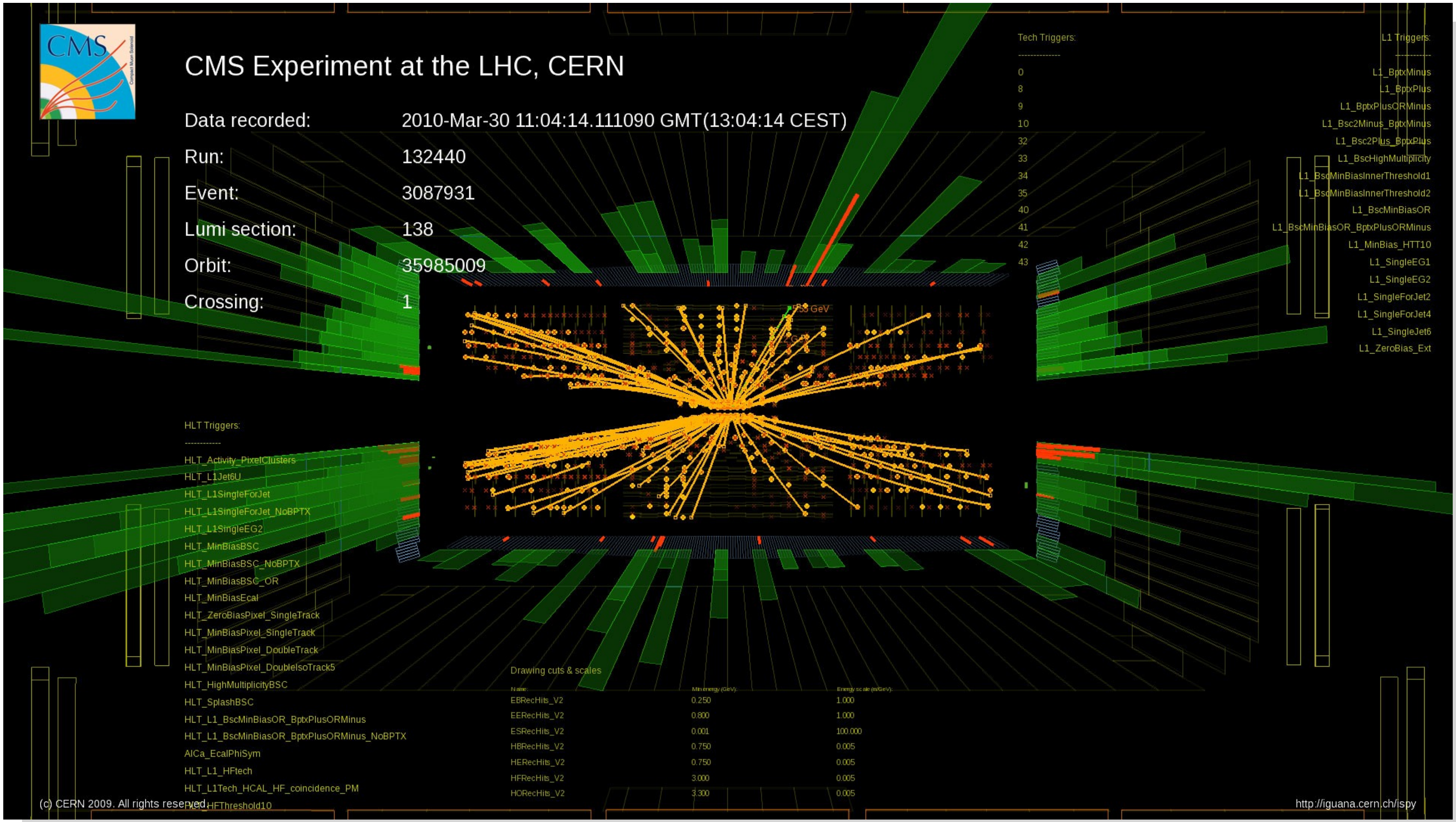
Efficiency x acceptance matrix of trigger + selection cuts (validated fast parametric simulation)

Extraction of upper limits for new process

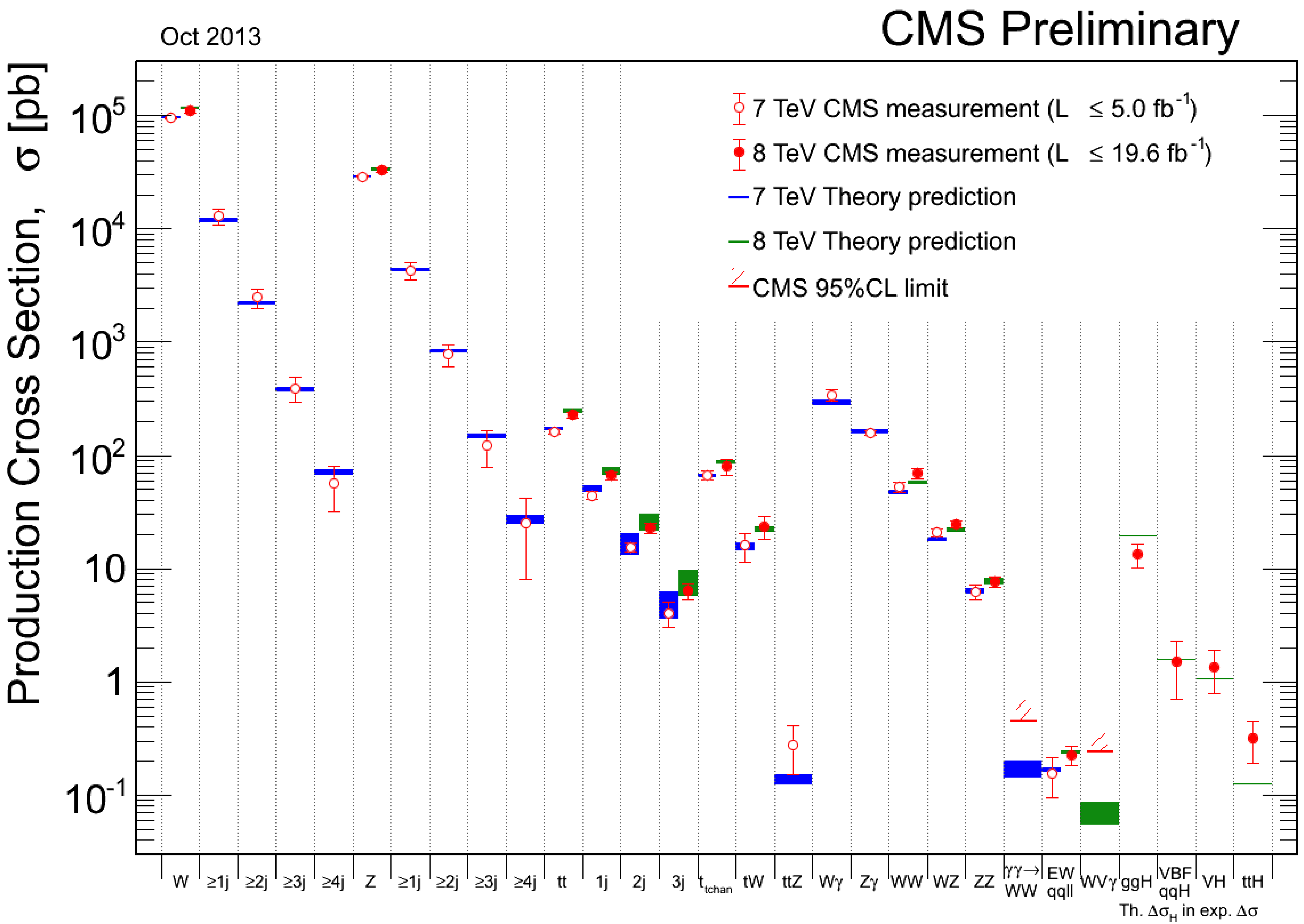


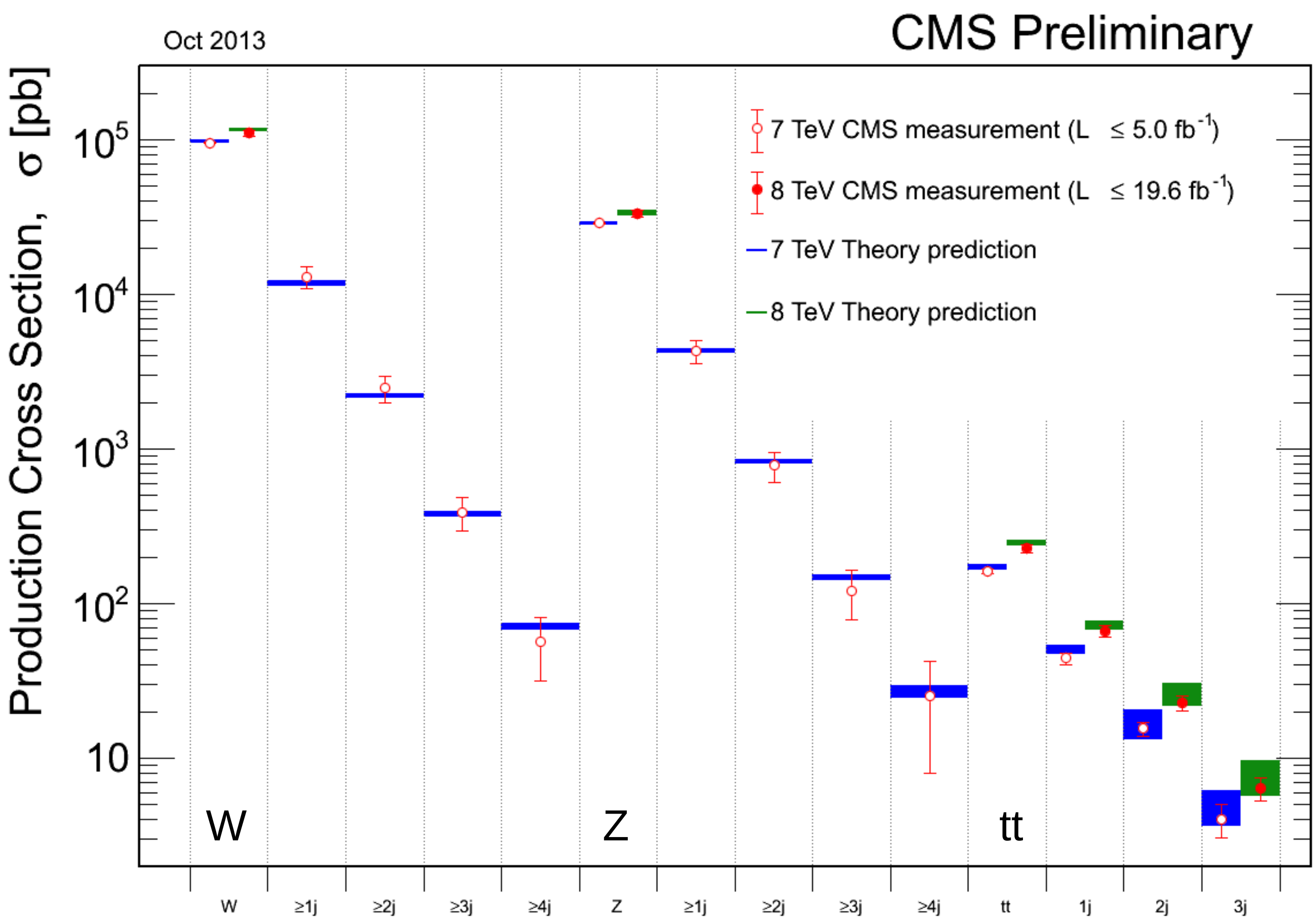
CMS-PAS-SUS-2013-015

LHC and the “SM Rediscovery”



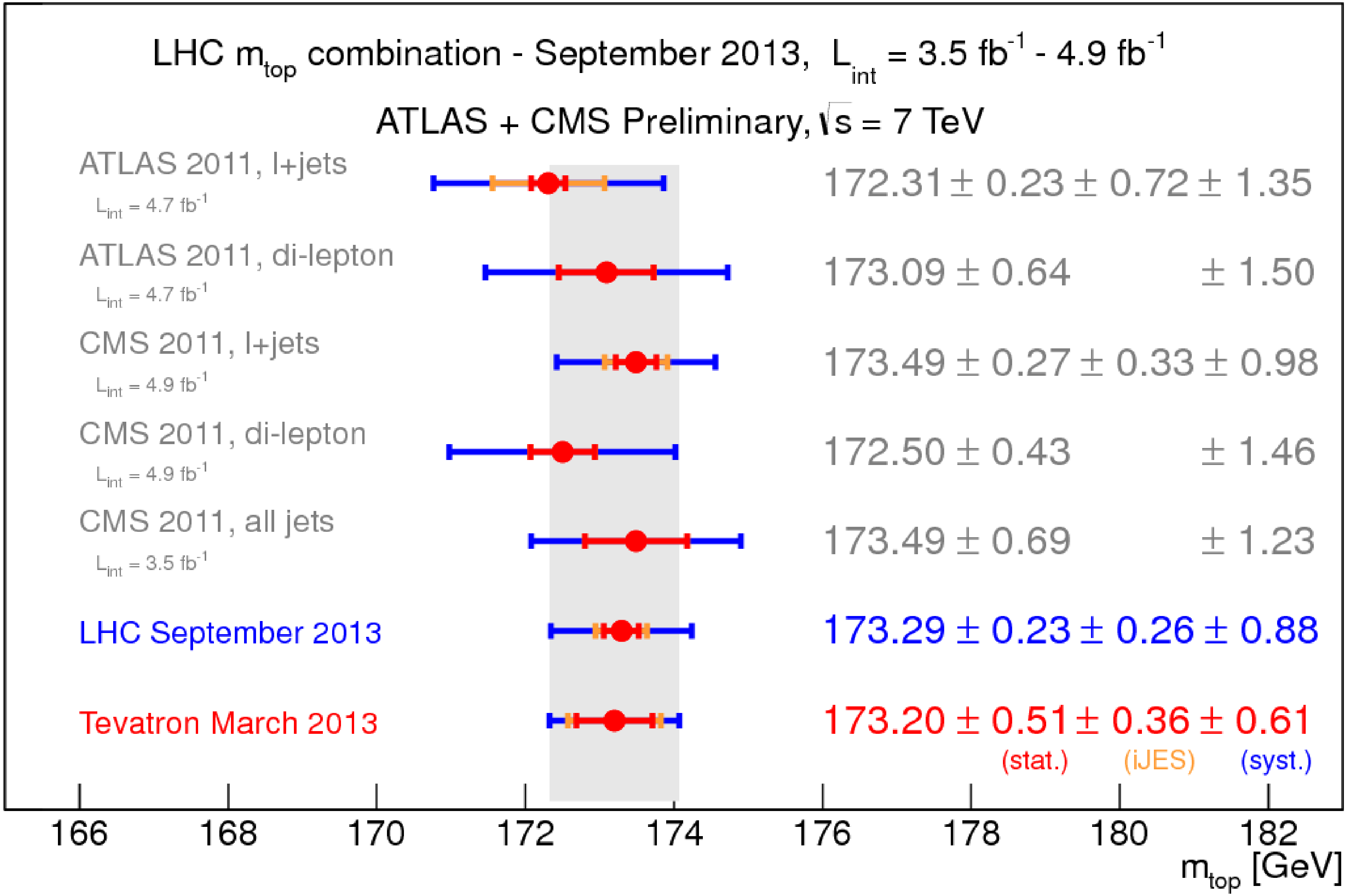
SM Cross Sections:
LHC Measurements and Theory Predictions





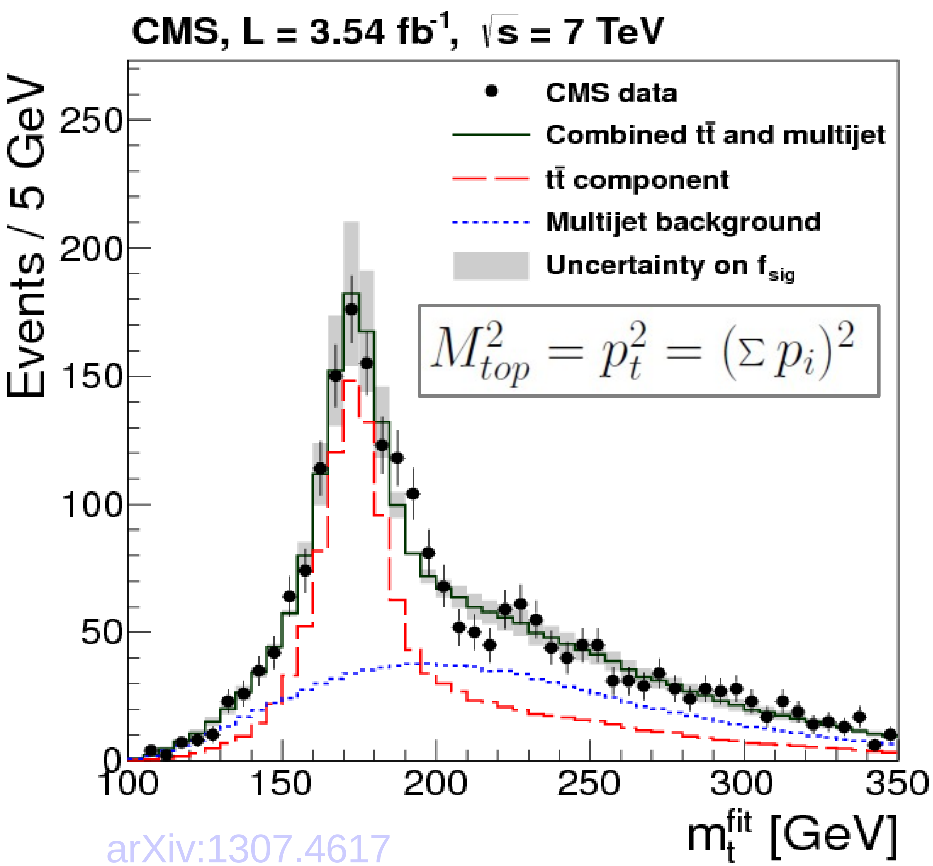
Beyond proof of accuracy achieved in reconstructing complex hadronic final states, these results are essential for new physics searches, which explore the same topologies

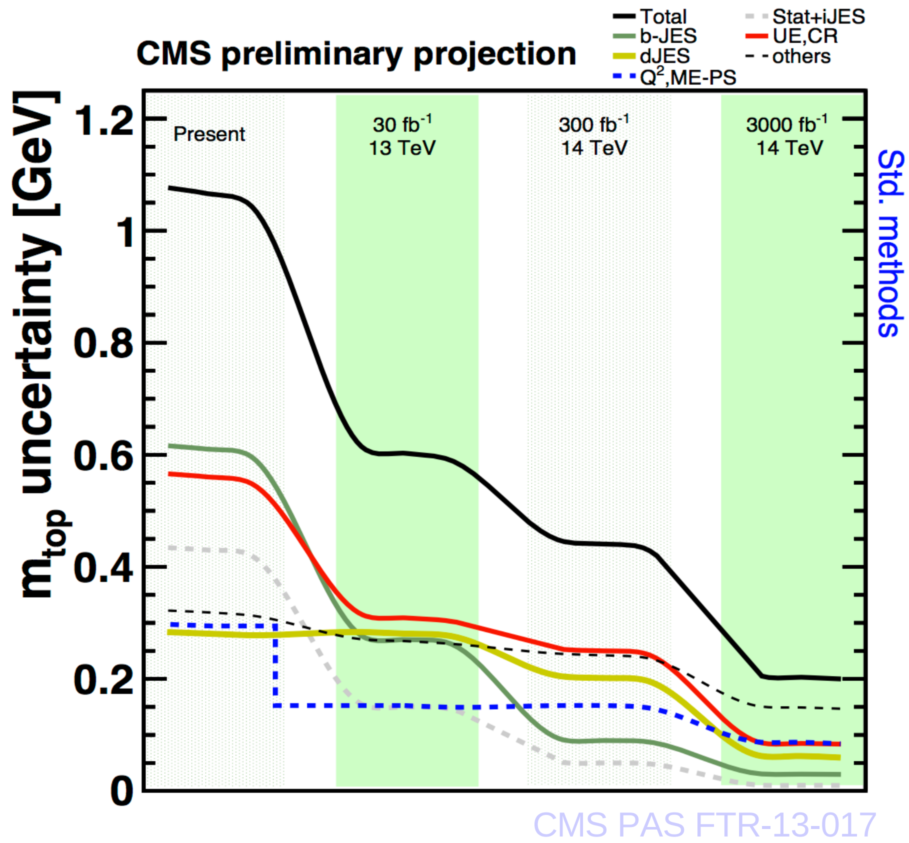
Top Mass Determination



Top quark mass key input to tests of the SM from flavour physics to Higgs sector

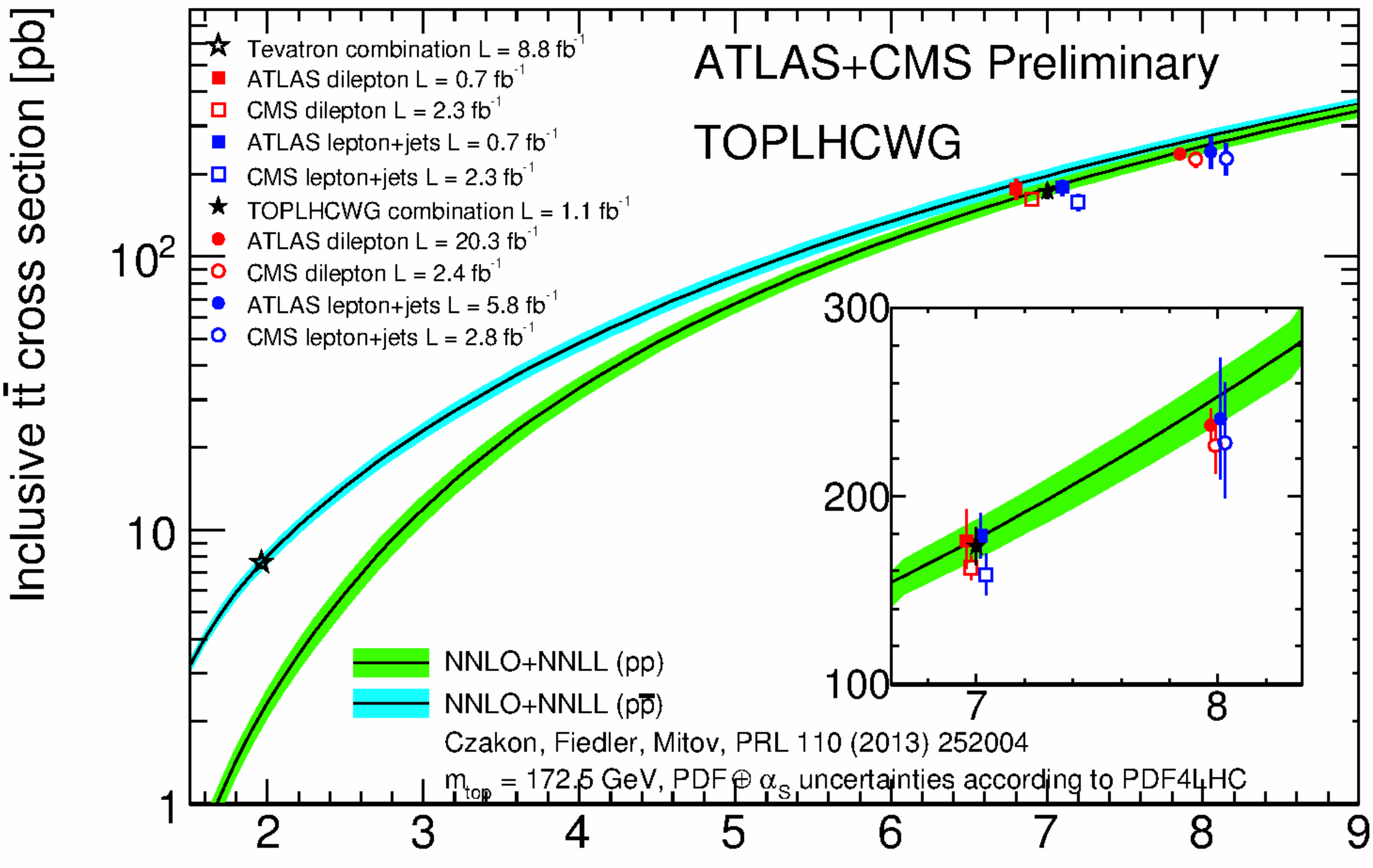
Top Mass Definition and Expected Accuracy





With syst accuracy falling below 1 GeV, it is relevant to ask ourselves which mass is Measured and which is its relation to the masses appearing in the theory expressions; Fit to invariant mass of jets effectively measures a generator mass (M_{top}^{Pythia}) which is a short-distance mass and can be related to the Msbar mass: theory effort needed to fully profit of progress in M_{top} accuracy from LHC measurements (Hoang & Stewart, NP 185 (2008)).

Top production cross section

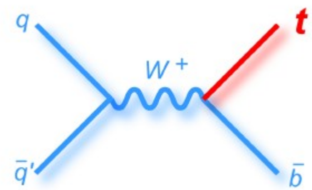


Contrary to Tevatron, gg production dominates at LHC.
tt cross section can be used to extract M_{top} in well-defined renormalization scheme and thus with better control of theory uncertainties, stat accuracy not yet competitive

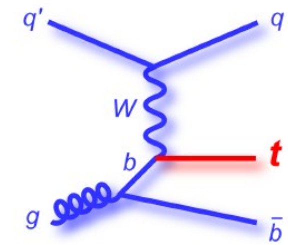
Single top cross section

EW production of t quark sensitive to $|V_{tb}|$:

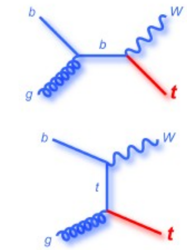
s-channel
$\sigma \sim 4.6$ pb

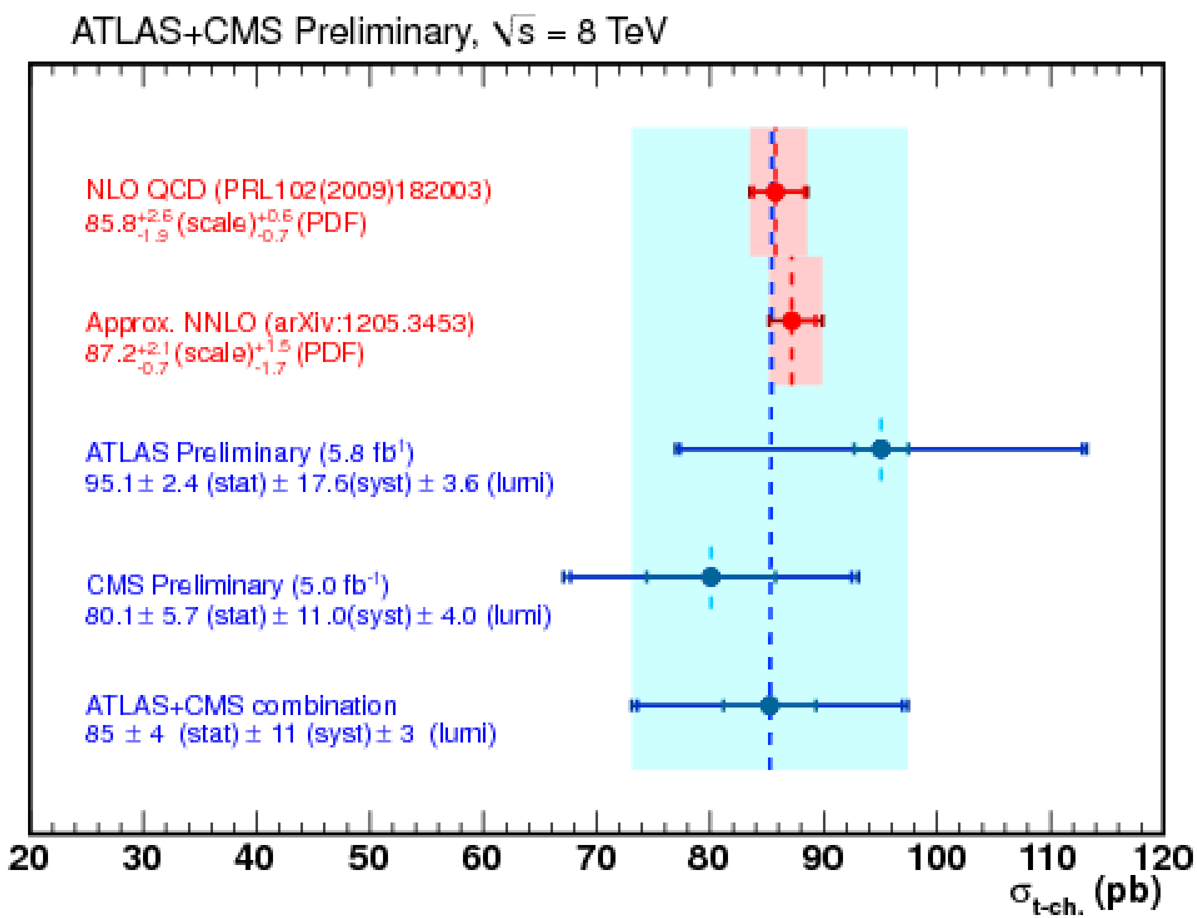


t-channel
$\sigma \sim 64$ pb



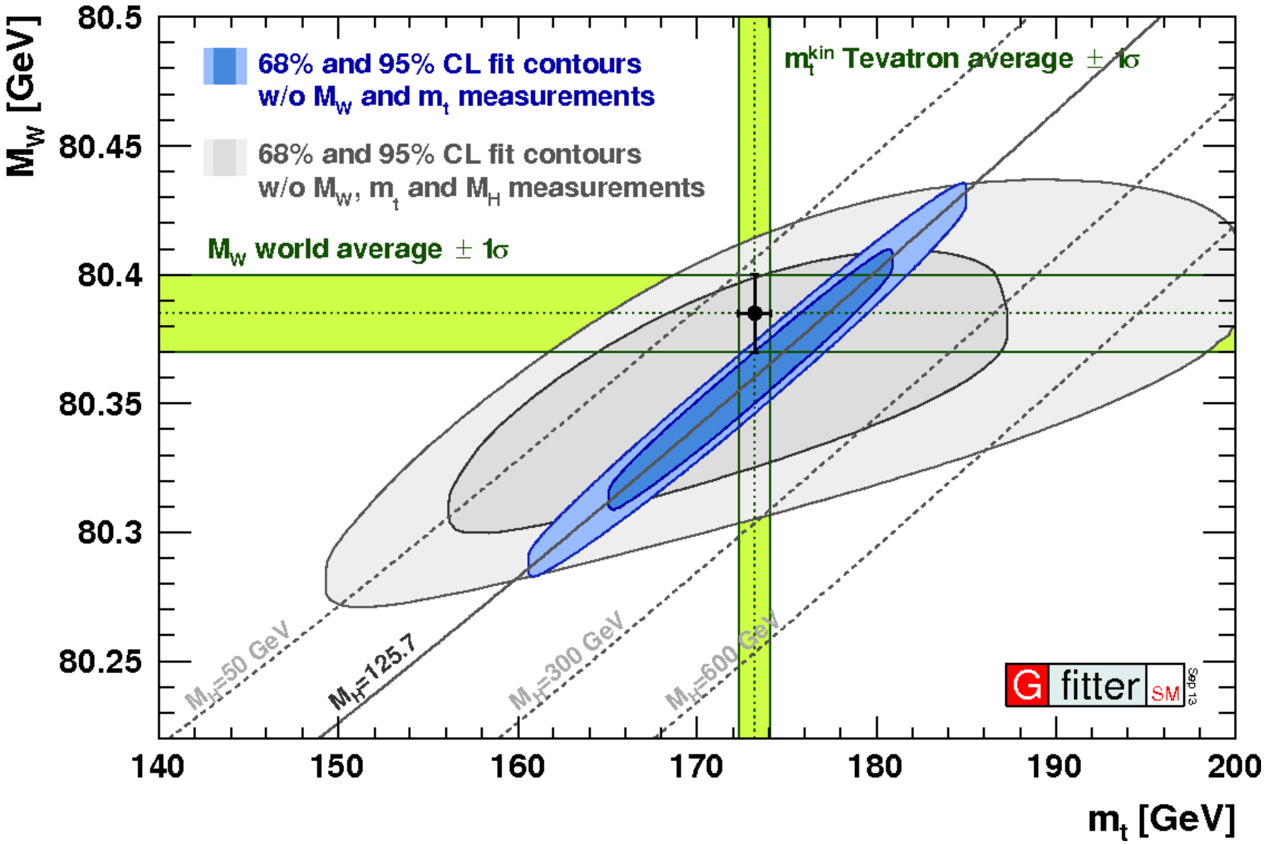
Wt-channel
$\sigma \sim 15.6$ pb

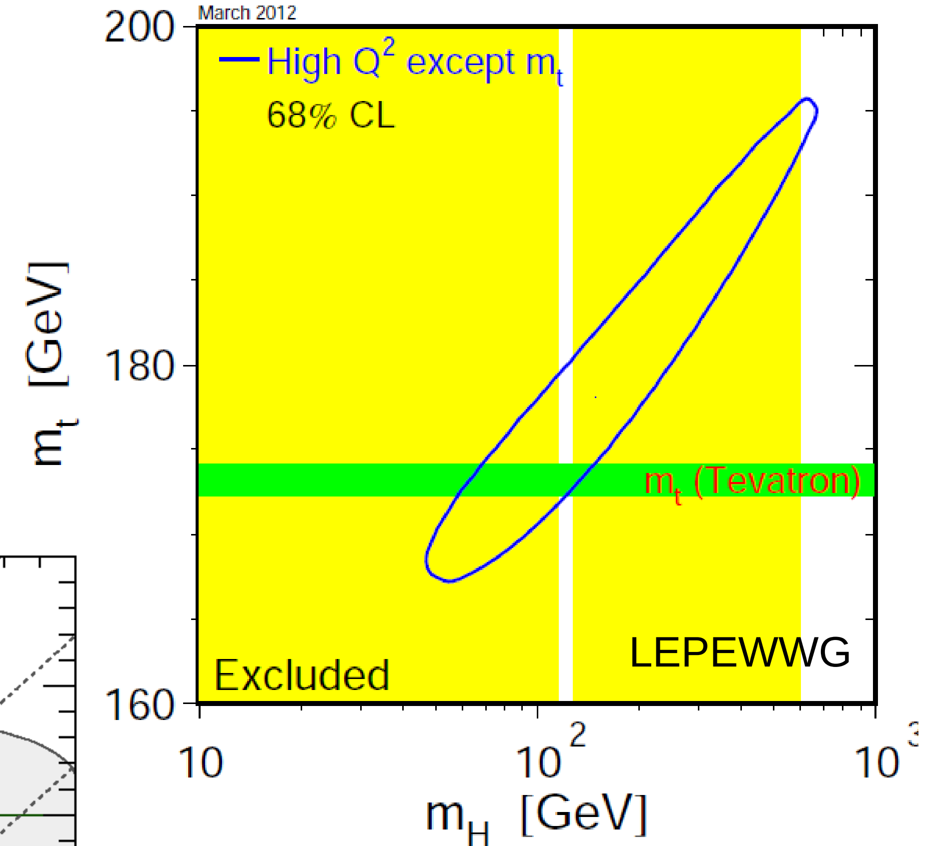




LPCC Top WG
ATLAS-CONF-2013-098
CMS PAS TOP-12-002

Top quark mass, EW constraints and the Higgs

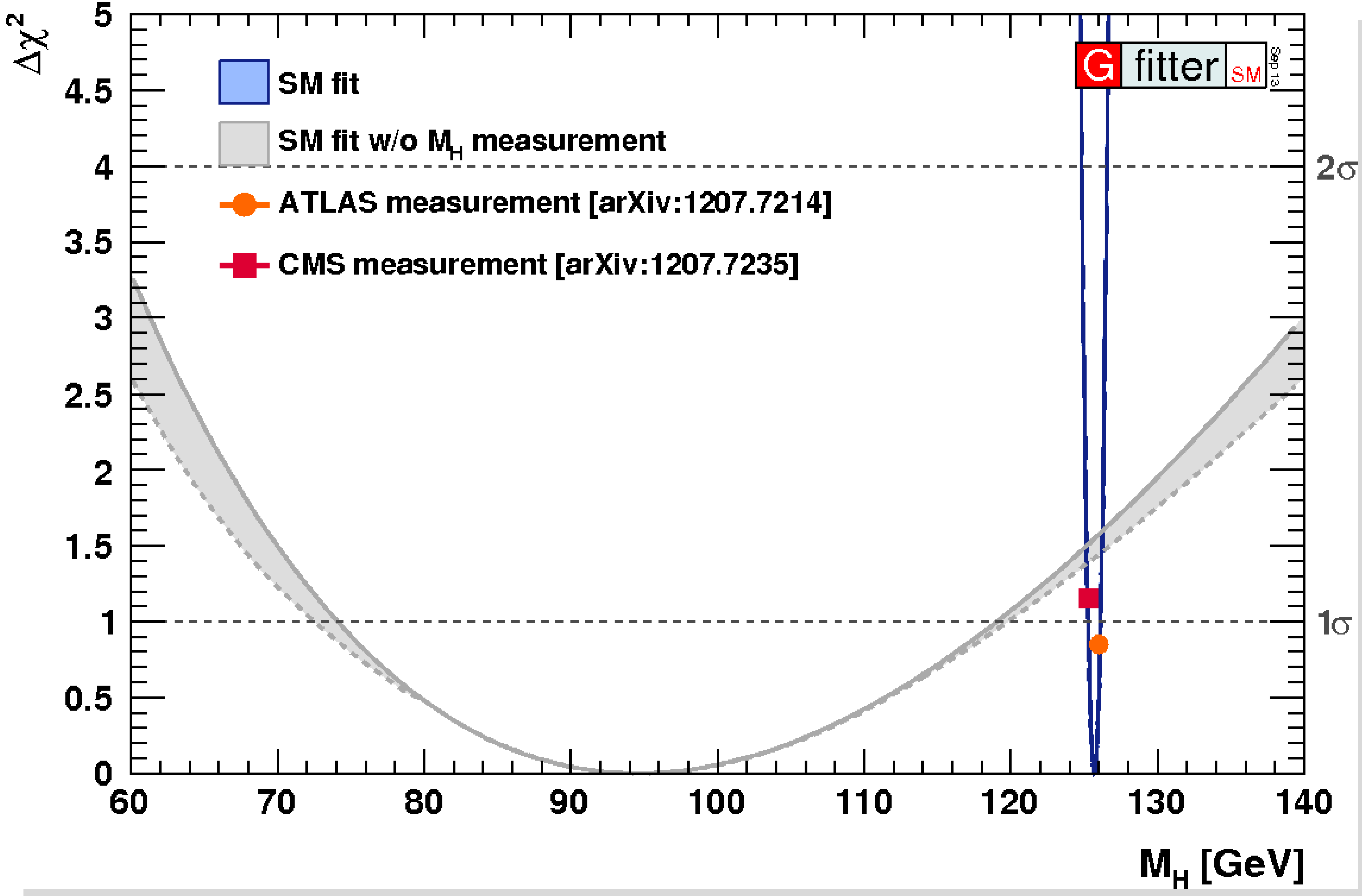




Two-loop EW corrections grow as

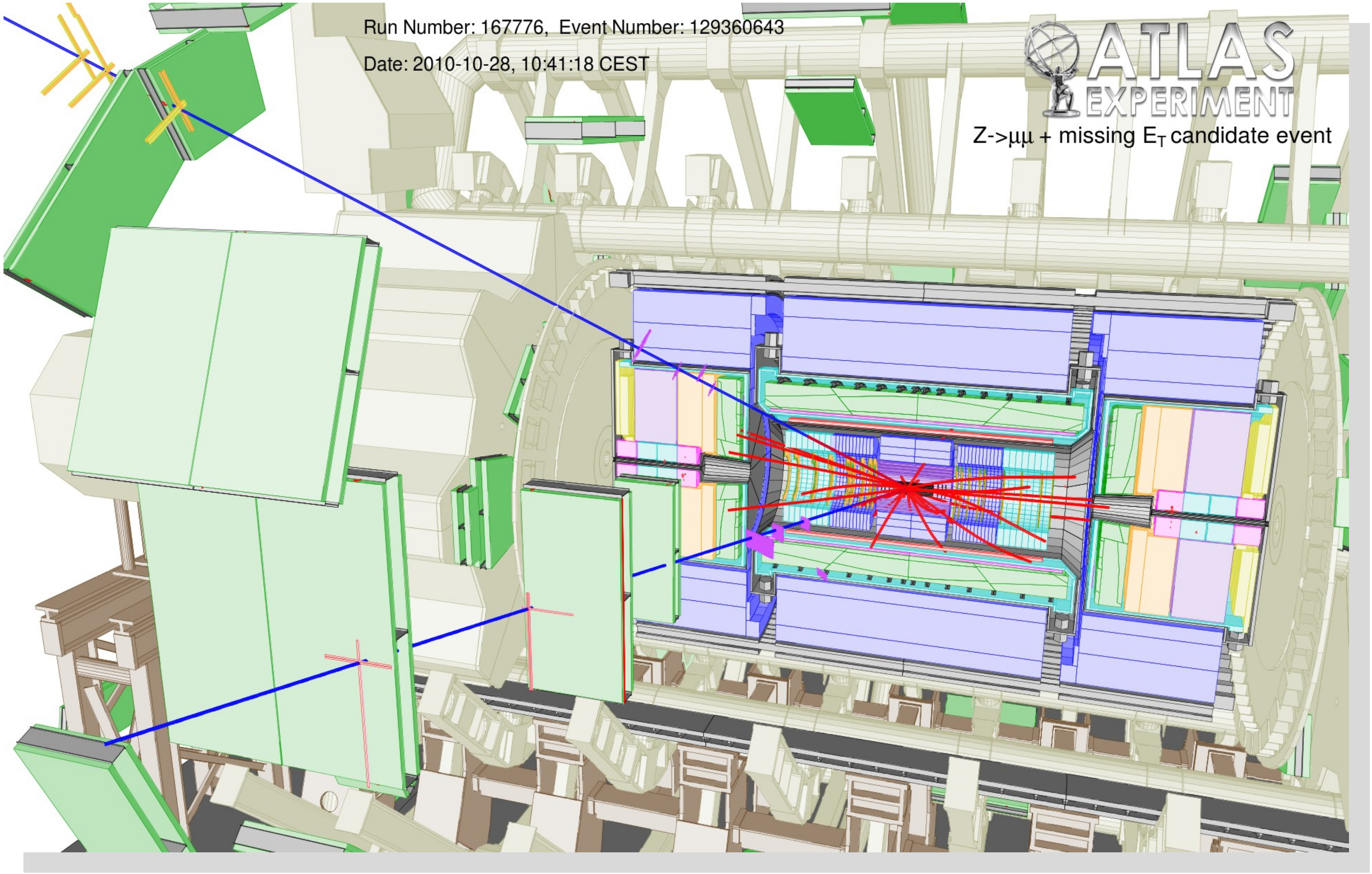
$$G_\mu^2 M_{top}^4,\ G_\mu^2 M_{top}^2 M_Z^2$$

2 GeV uncertainty on M_{top}
→ 8% change in M_H



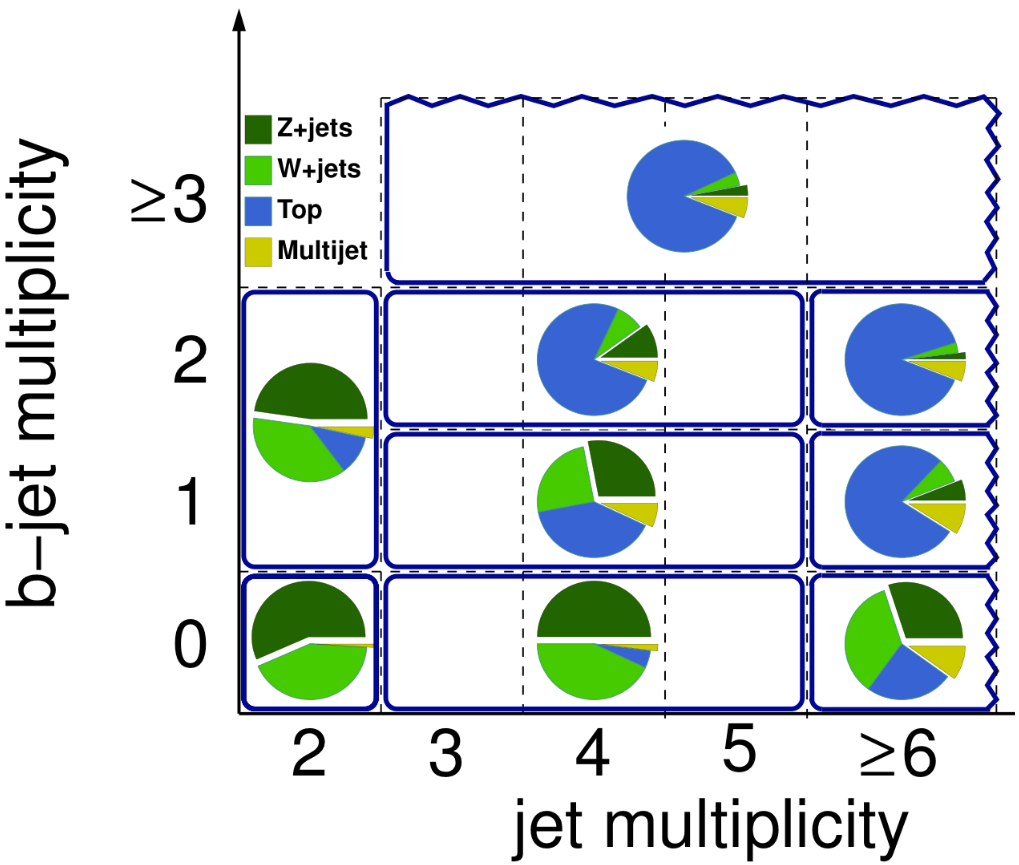
$\Delta\chi^2$
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
SM fit
SM fit w/o M_H measurement
ATLAS measurement [arXiv:1207.7214]
CMS measurement [arXiv:1207.7235]
G fitter SM
Sep 13
2σ
1σ
60
70
80
90
100
110
120
130
140
M_H [GeV]

LHC, SUSY and Dark Matter: WIMP Searches

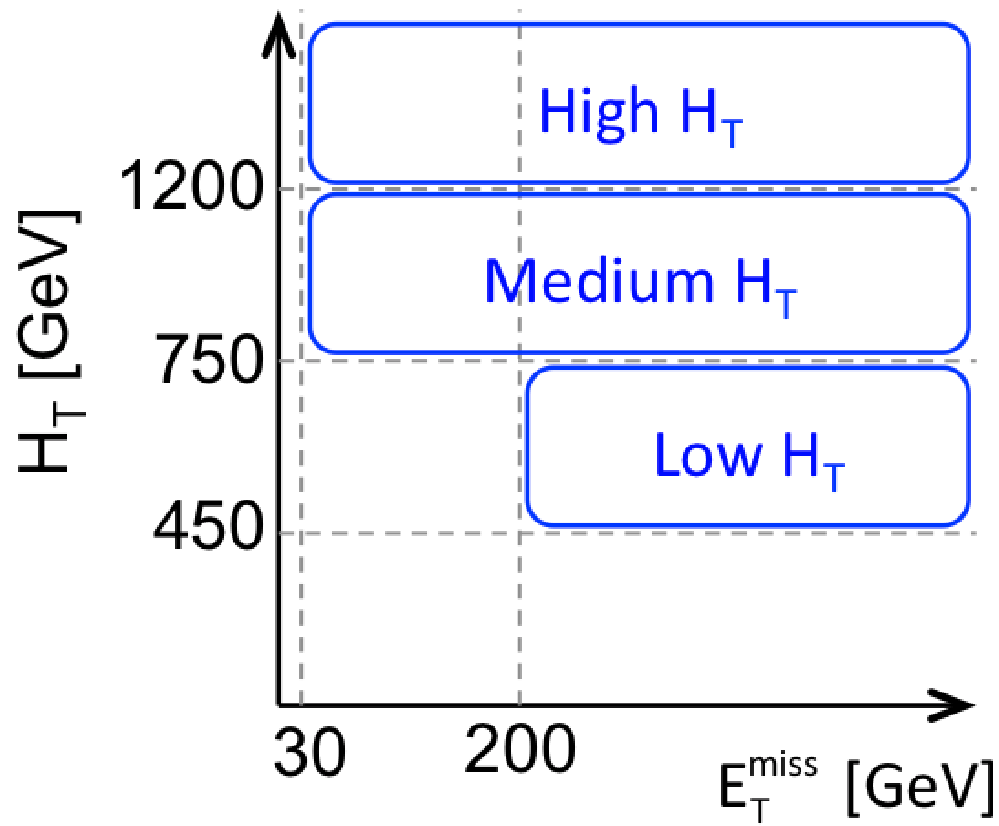


SUSY searches sensitive to WIMPs through decay chains as MET:
Broad sensitivity over sparticle mass range but less efficient at small ΔM

Event Topology

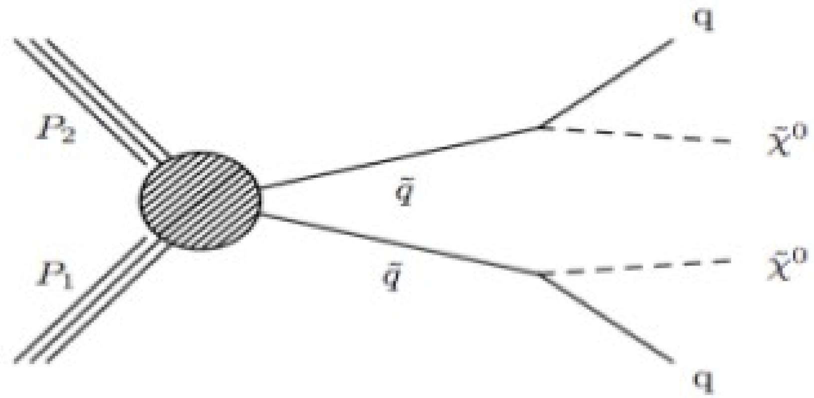


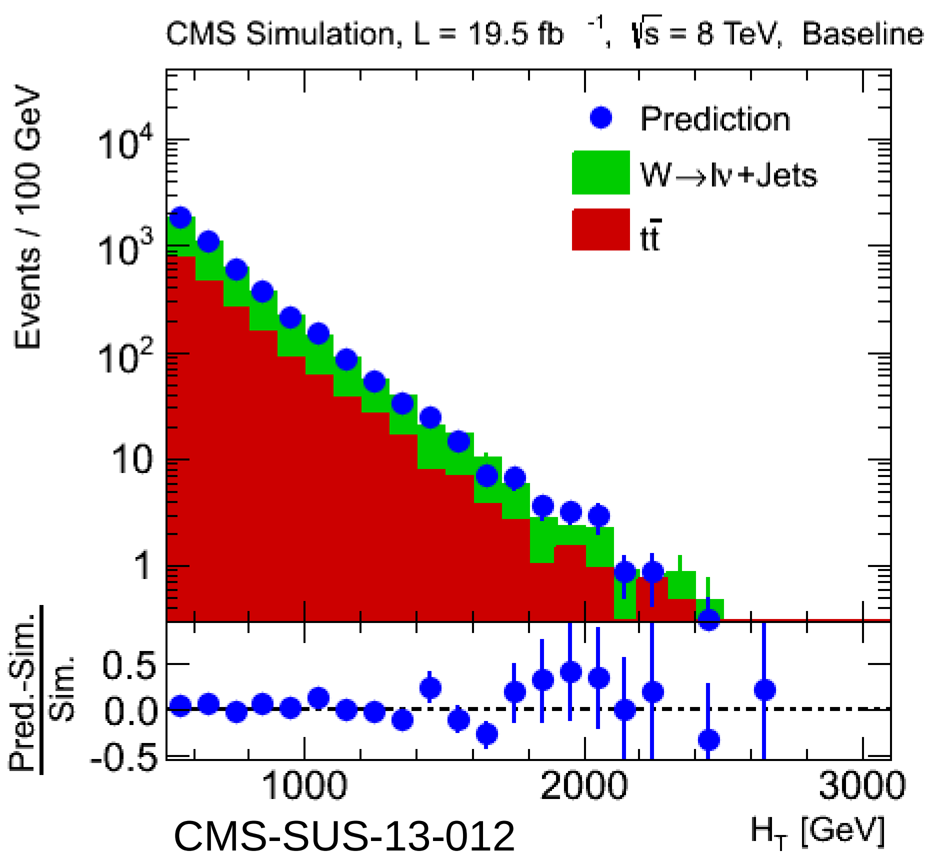
Correlation of Discriminating Variables



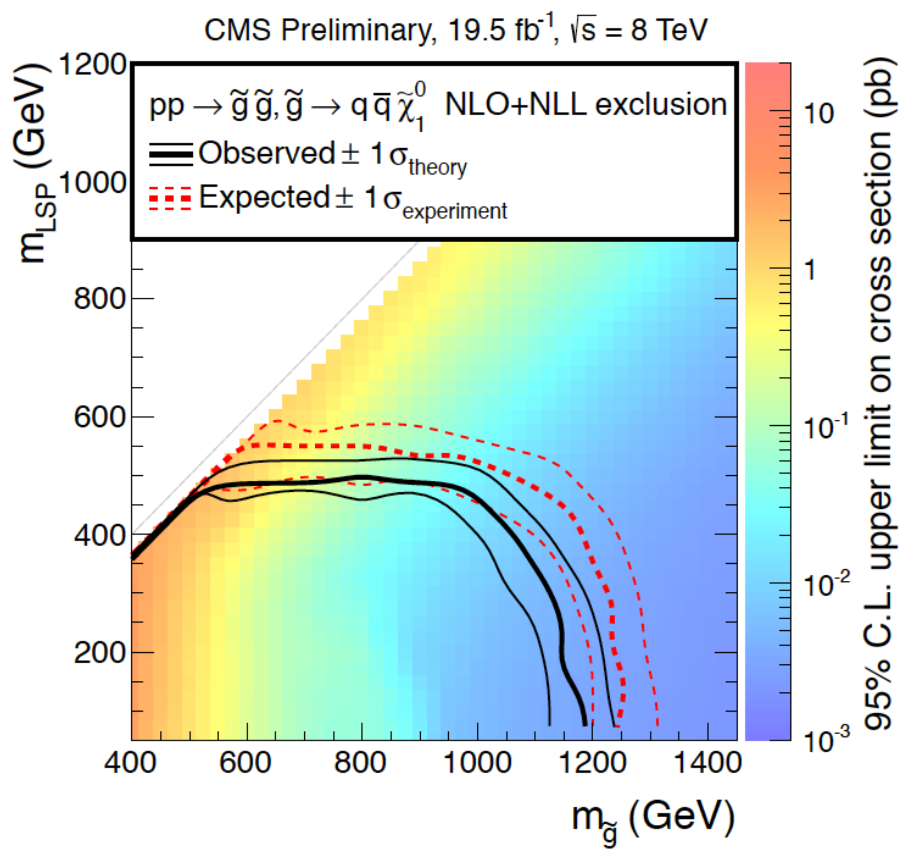
CMS-PAS-SUS-13-009

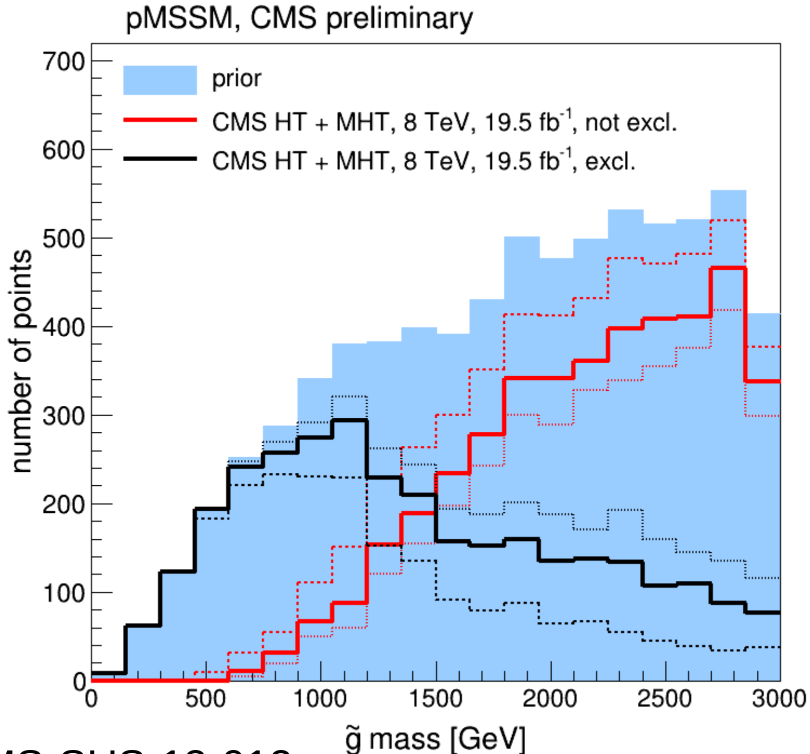
Strongly-interacting SUSY particles

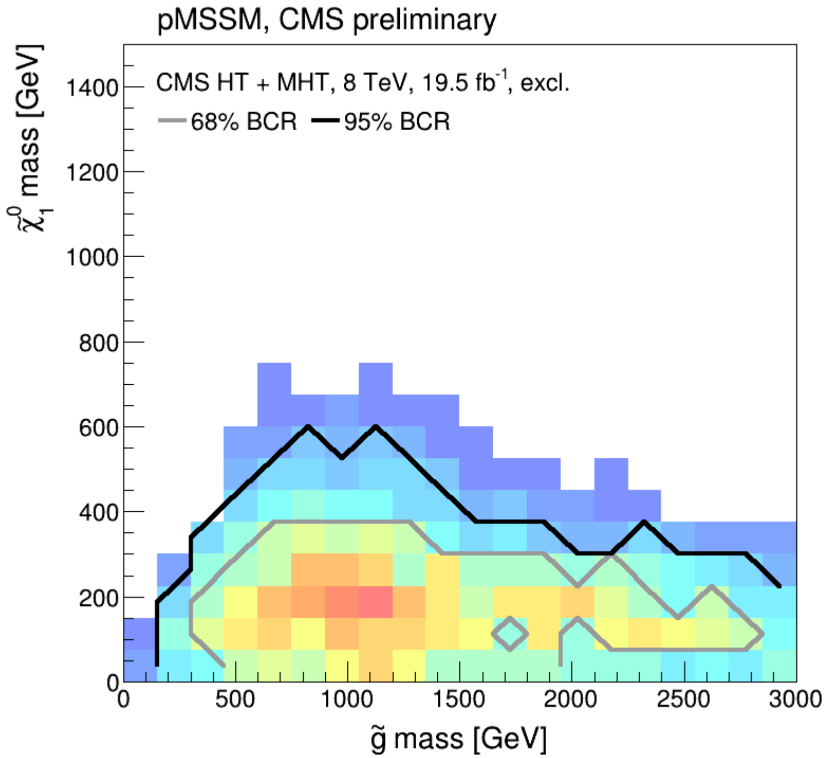




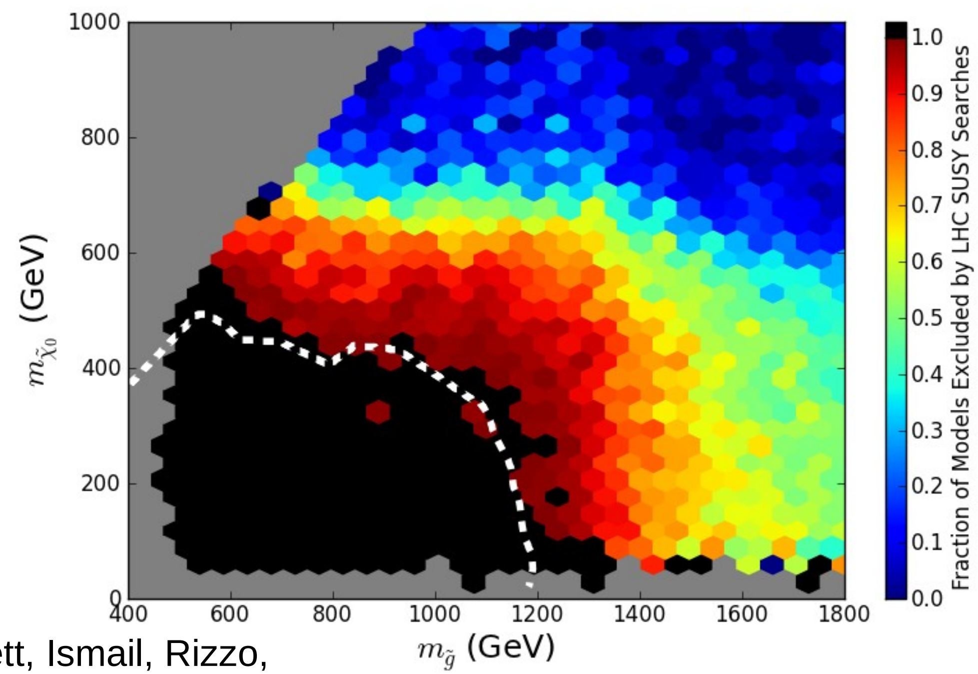
CMS-SUS-13-012





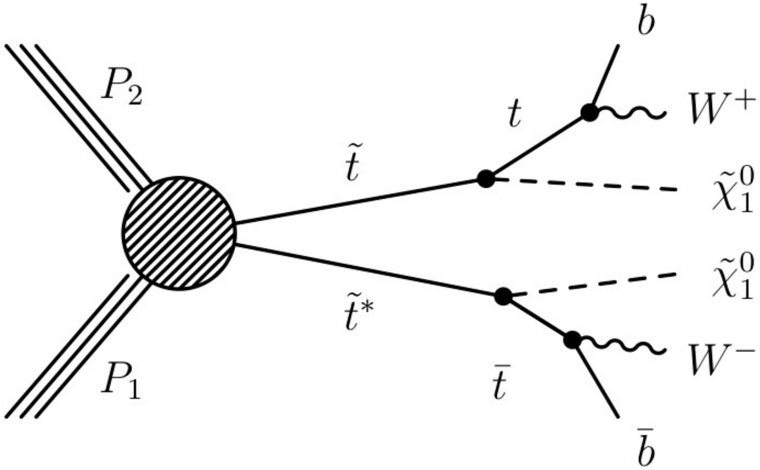


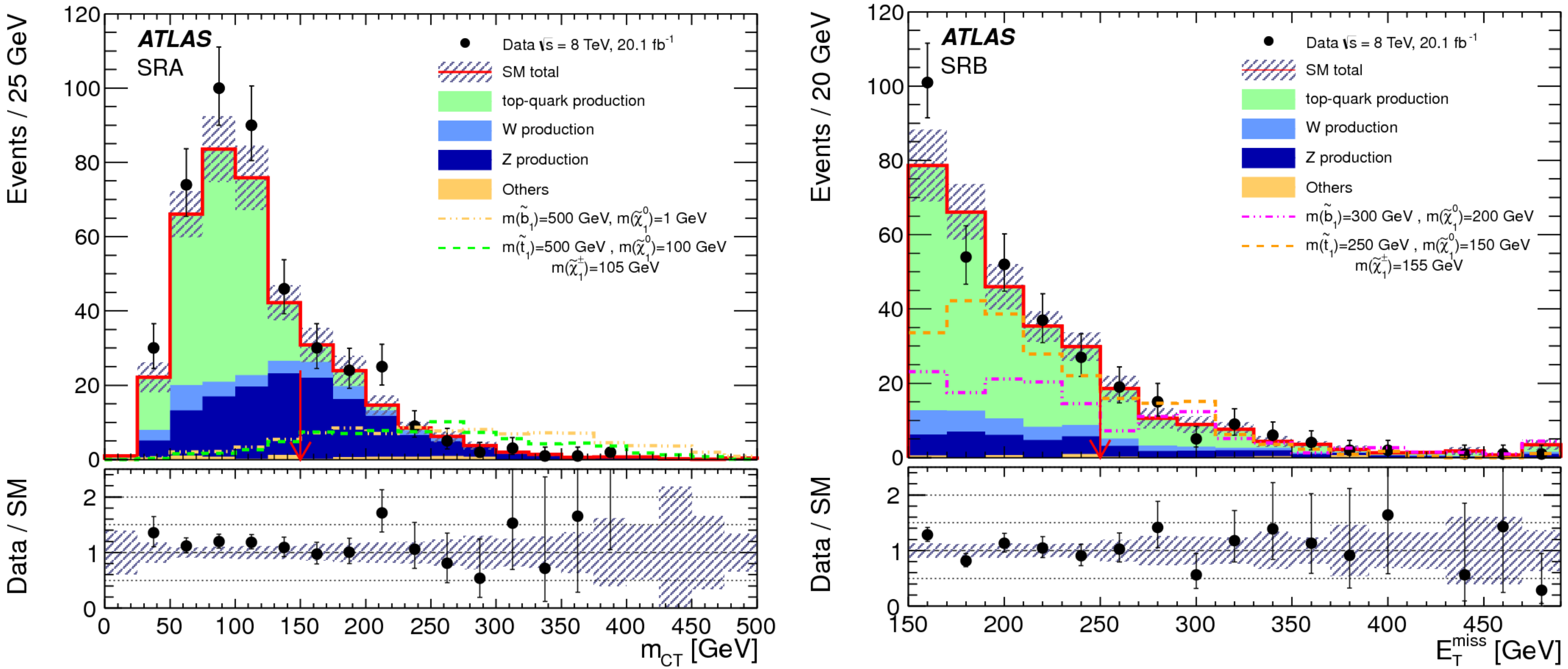
CMS-SUS-13-012



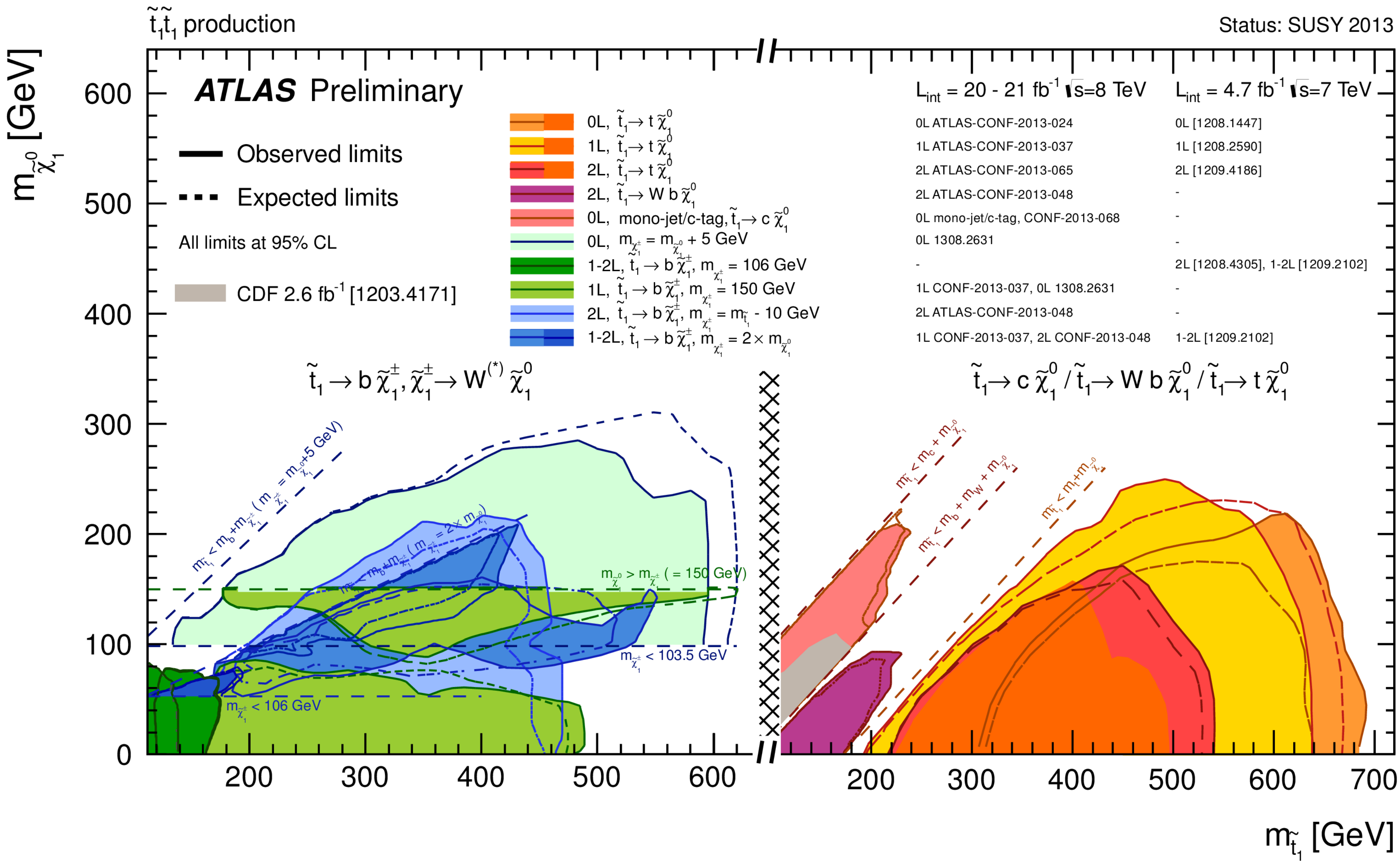
Cahill-Rowley, Hewett, Ismail, Rizzo,
arXiv:1307.8444

Weakly-interacting SUSY particles
Scalar top and bottom



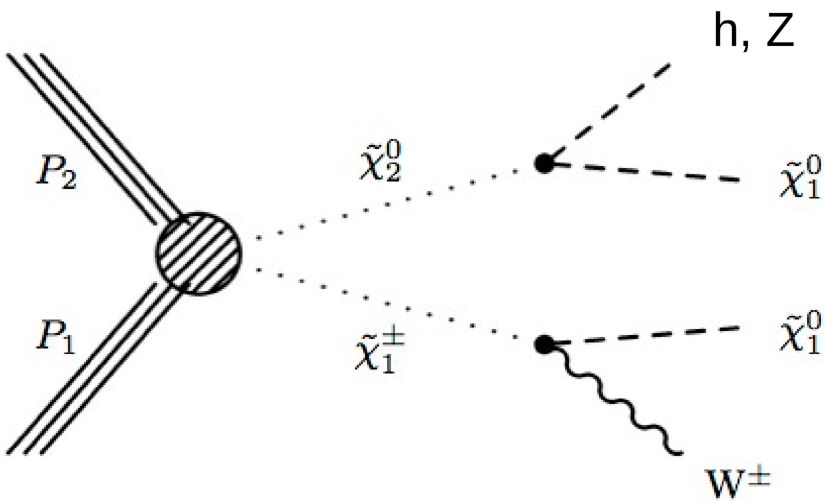


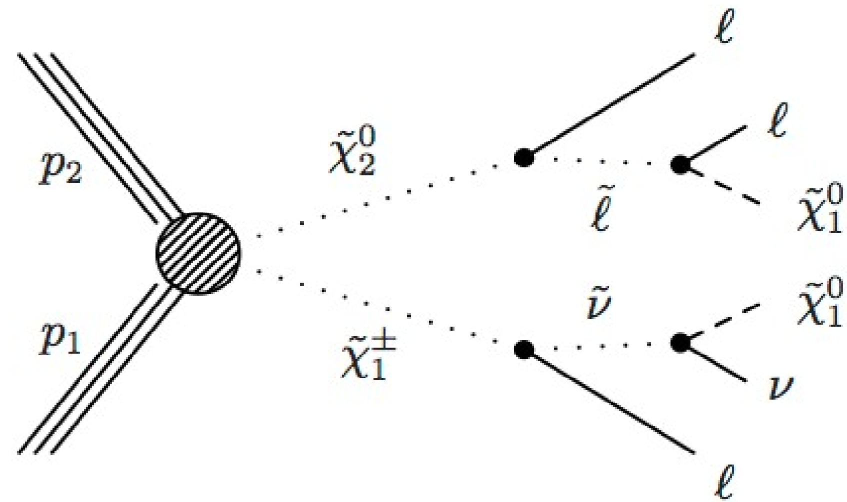
[ATLAS], JHEP 10 (2013) 189

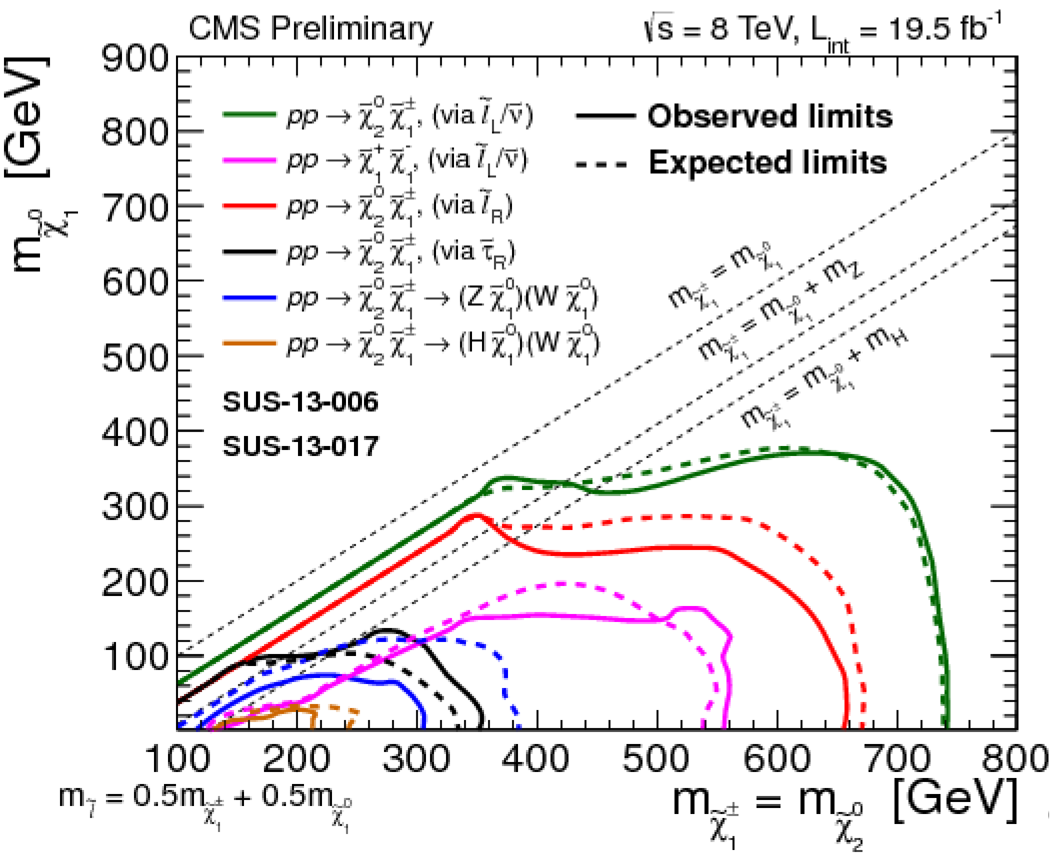


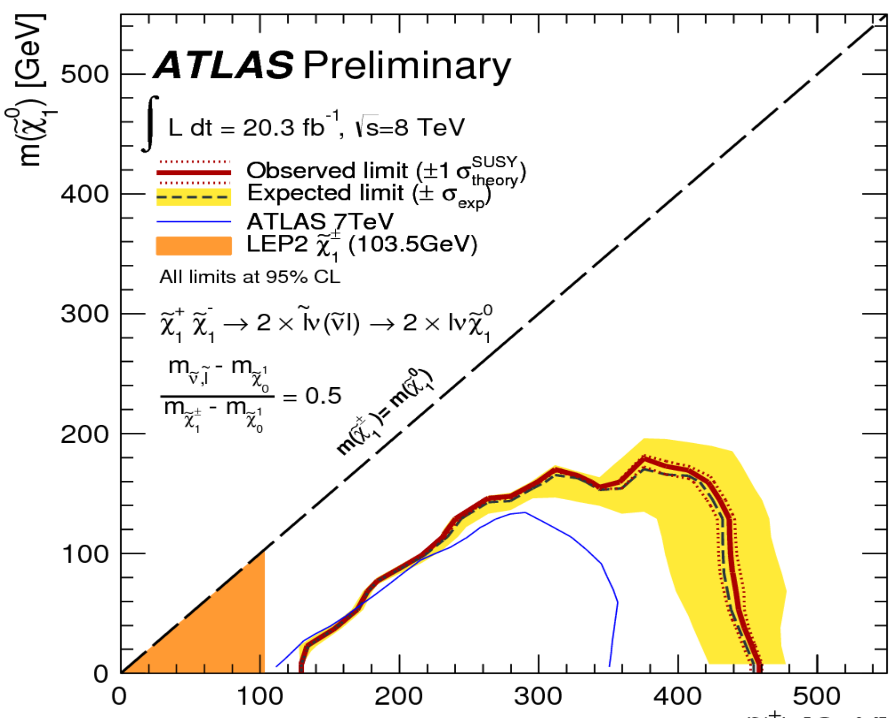
t̃₁t̃₁ production
Status: SUSY 2013
ATLAS Preliminary
Observed limits
Expected limits
All limits at 95% CL
CDF 2.6 fb-1 [1203.4171]
L_int = 20 - 21 fb-1 √s=8 TeV
L_int = 4.7 fb-1 √s=7 TeV
0L ATLAS-CONF-2013-024
0L [1208.1447]
1L ATLAS-CONF-2013-037
1L [1208.2590]
2L ATLAS-CONF-2013-065
2L [1209.4186]
2L ATLAS-CONF-2013-048
0L mono-jet/c-tag, CONF-2013-068
0L 1308.2631
2L [1208.4305], 1-2L [1209.2102]
1L CONF-2013-037, 0L 1308.2631
2L ATLAS-CONF-2013-048
1L CONF-2013-037, 2L CONF-2013-048
1-2L [1209.2102]
m_t̃1 [GeV]
m_χ̃01 [GeV]

Weakly-interacting SUSY particles



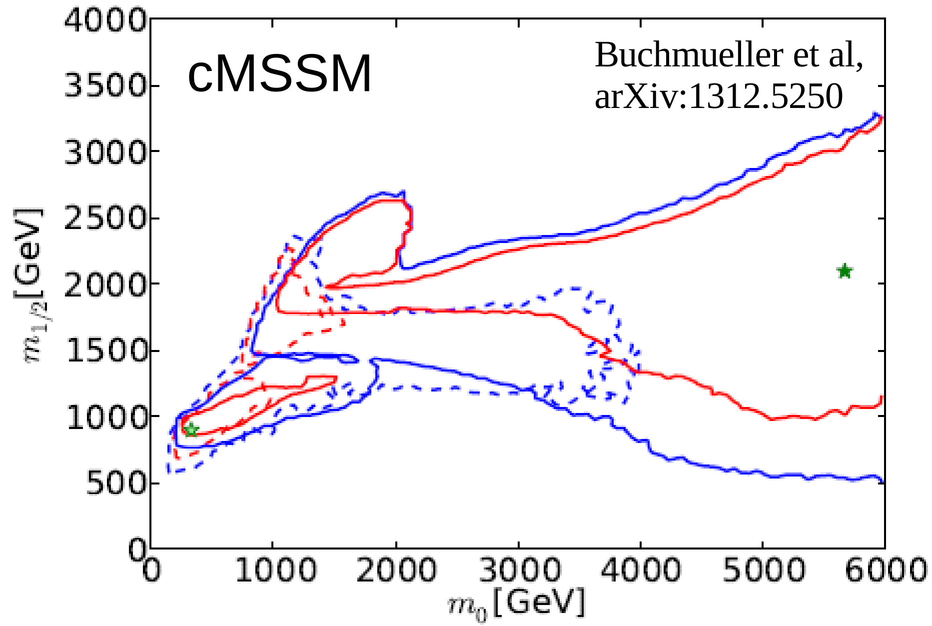




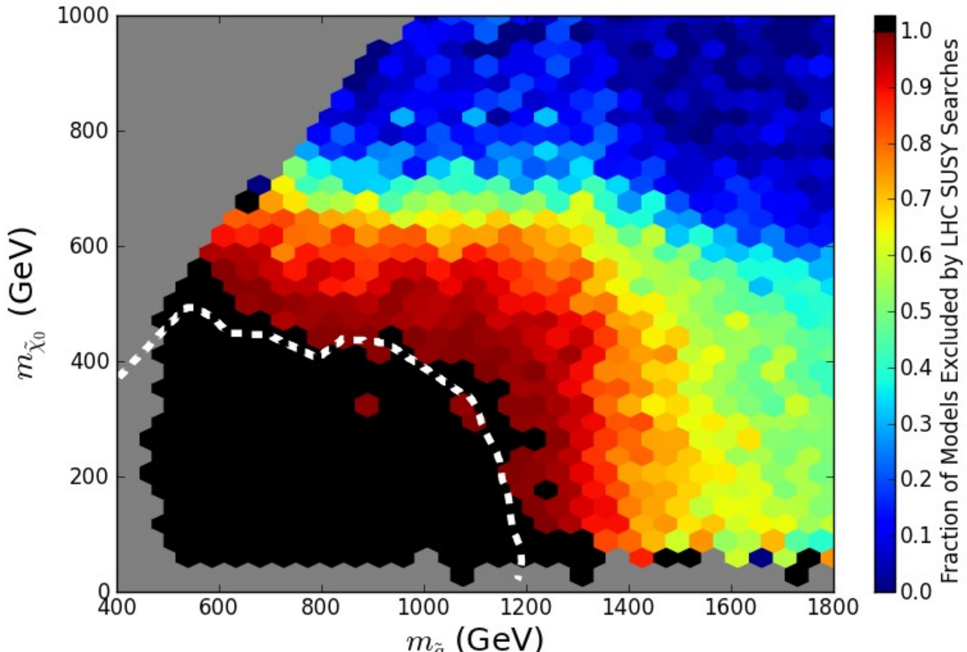


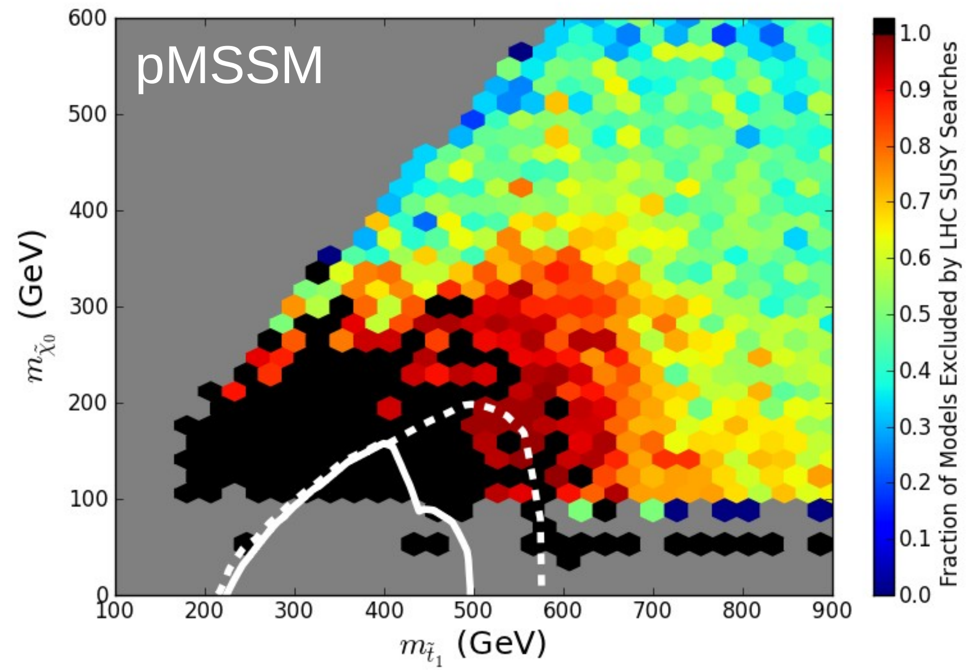
ATLAS-CONF-2013-049

How much of SUSY has been excluded by the LHC 7+8 TeV Data ?



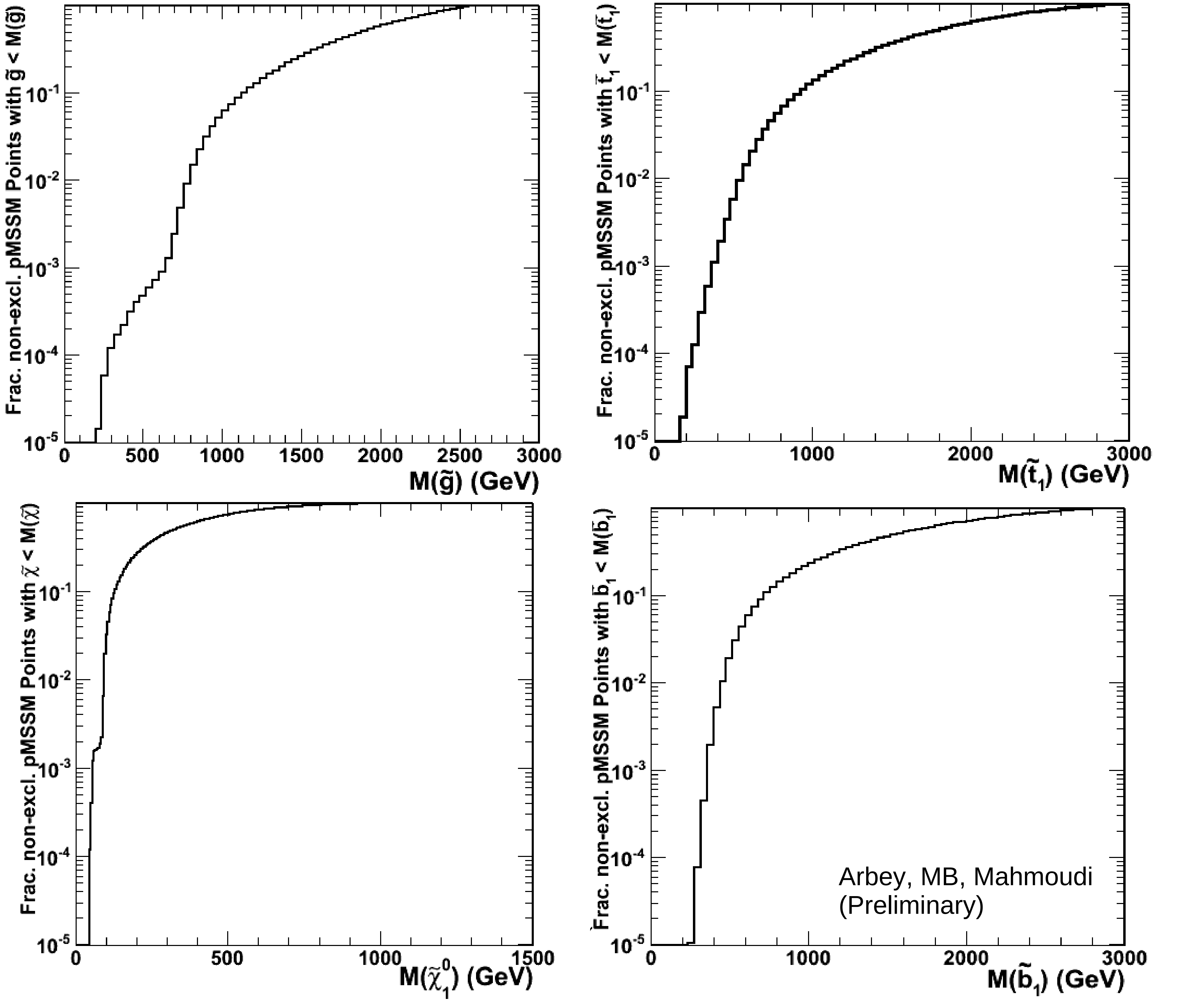
constrained vs unconstrained SUSY models:



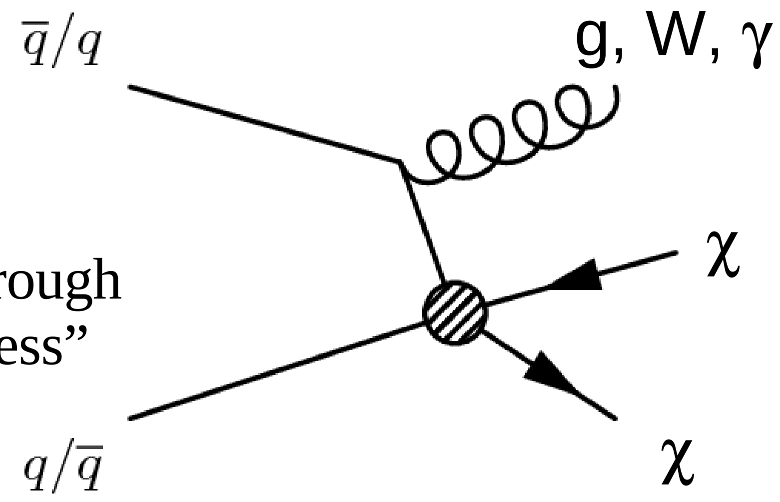


Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1307.8444

Non-excluded points in pMSSM scenarios



Model-independent WIMP searches: mono-jet, mono-photon, mono-W/Z, mono-lepton



LHC collision can search for WIMP production through processes with large MET and one parton as "witness" of interaction;

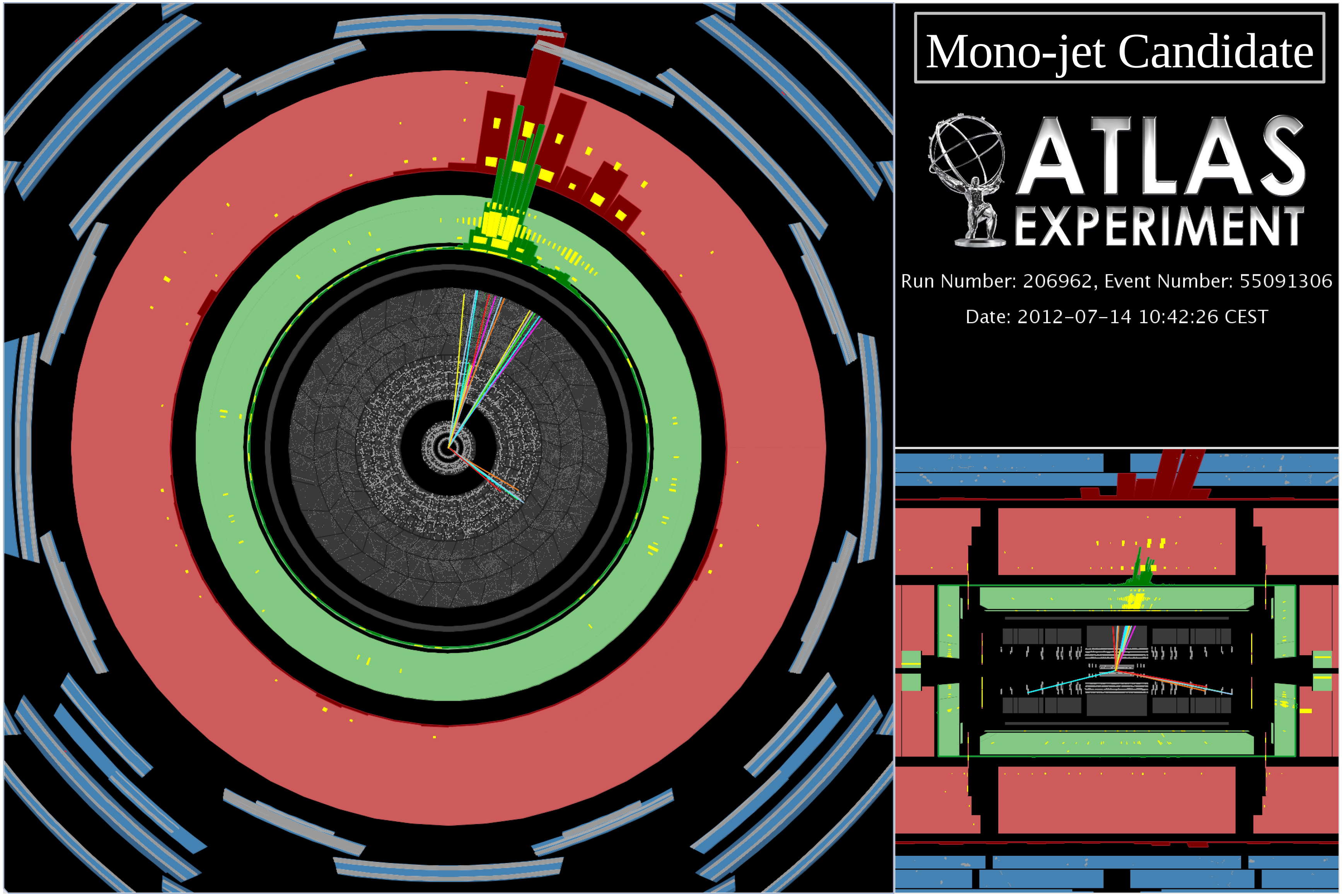
Sensitivity can be estimated using EFT or actual models (SUSY, …);

Results can be interpreted as limits on $\Lambda \equiv M/\sqrt{g_\chi g_q}$ related to limits on

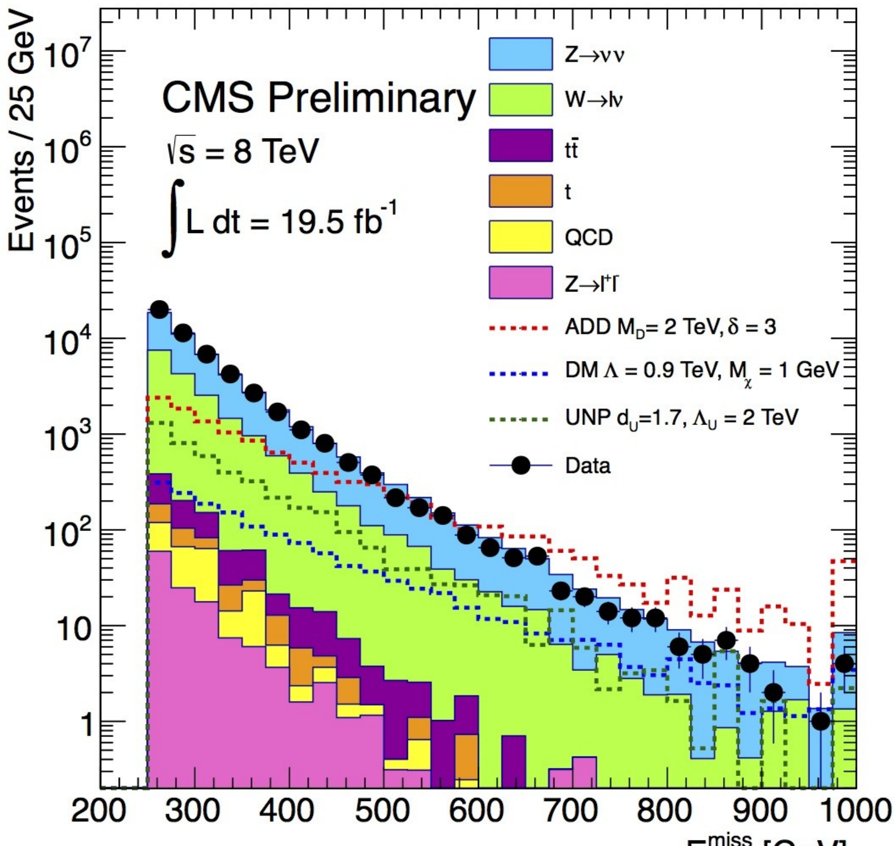
WIMP scattering cross section on nucleons $\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$ to compare

with results of DM direct detection experiments.

Bai, Fox, Harnik, JHEP 1012 (2010) 048
Goodman et al, PRD 82 (2010) 116010
Goodman et al, PLB 695 (2011) 185

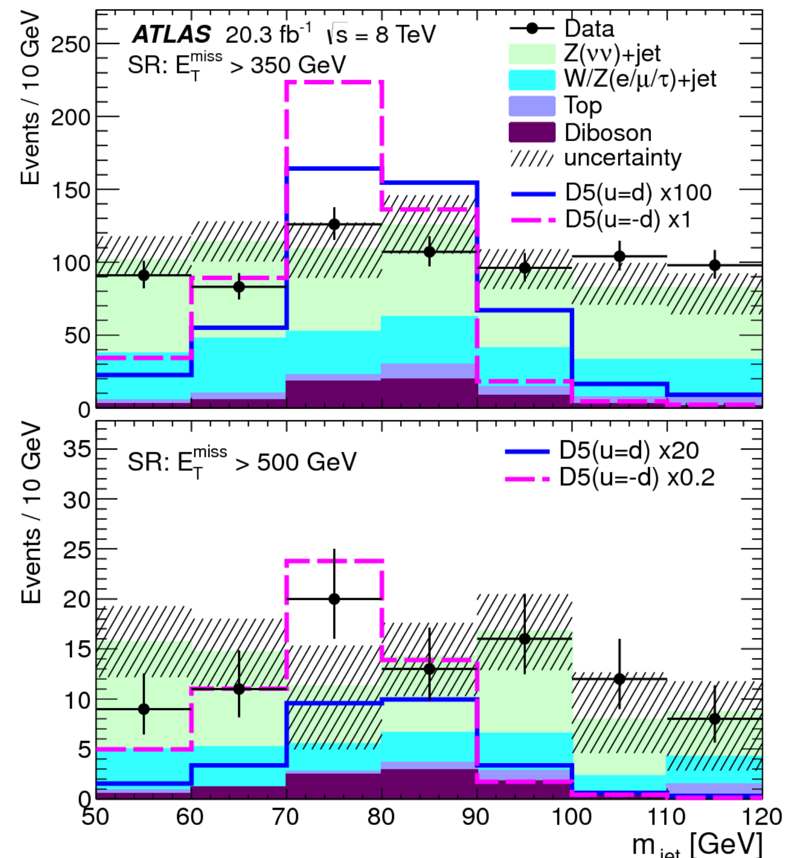

Mono-jet Candidate
ATLAS
EXPERIMENT
Run Number: 206962, Event Number: 55091306
Date: 2012-07-14 10:42:26 CEST

Mono-jet



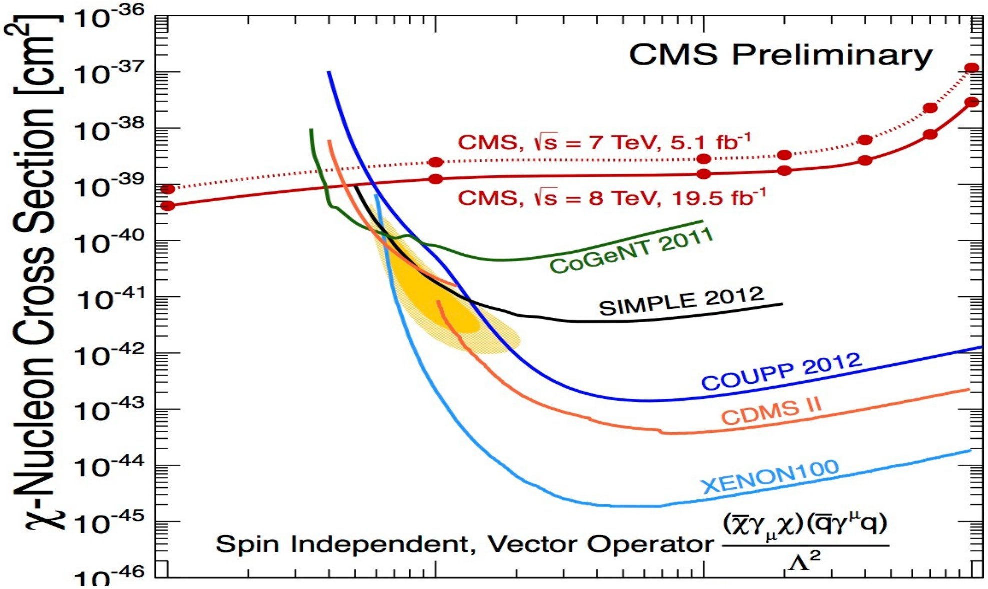
CMS-PAS-EXO-12-048

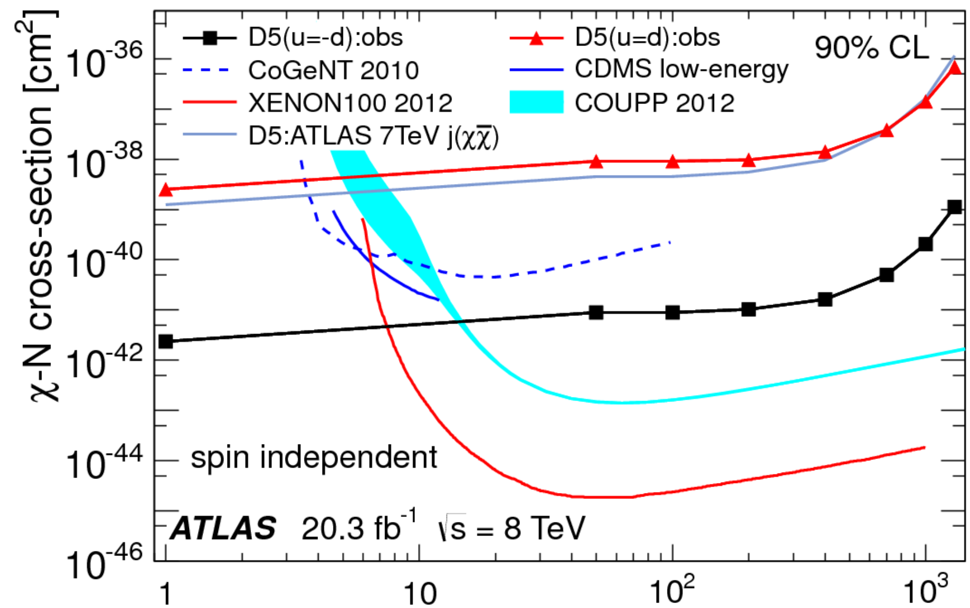
Mono W/Z

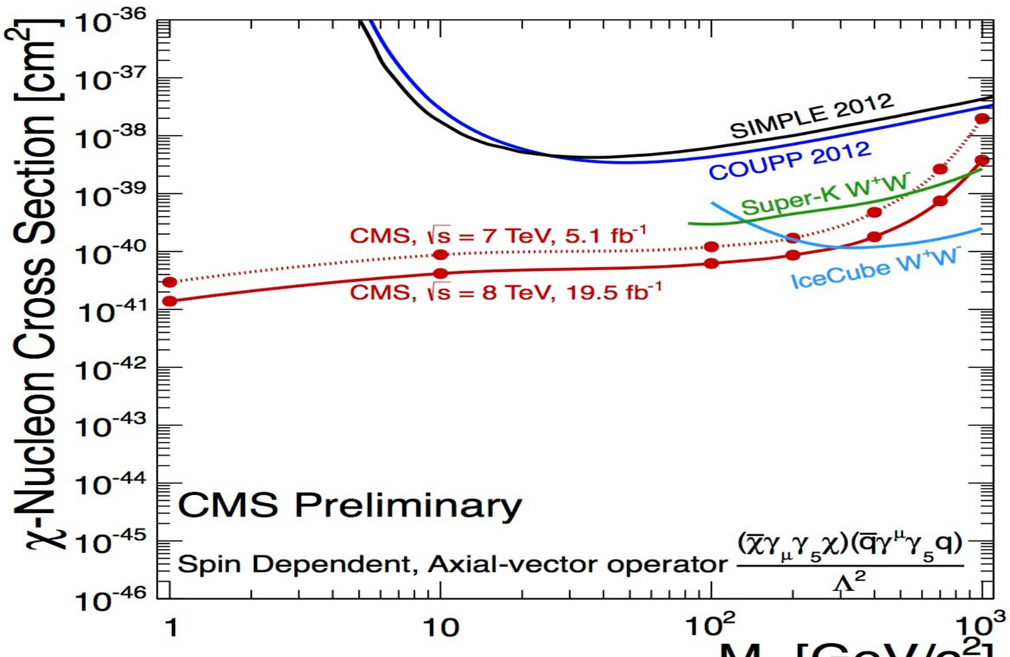


arXiv:1309.4017

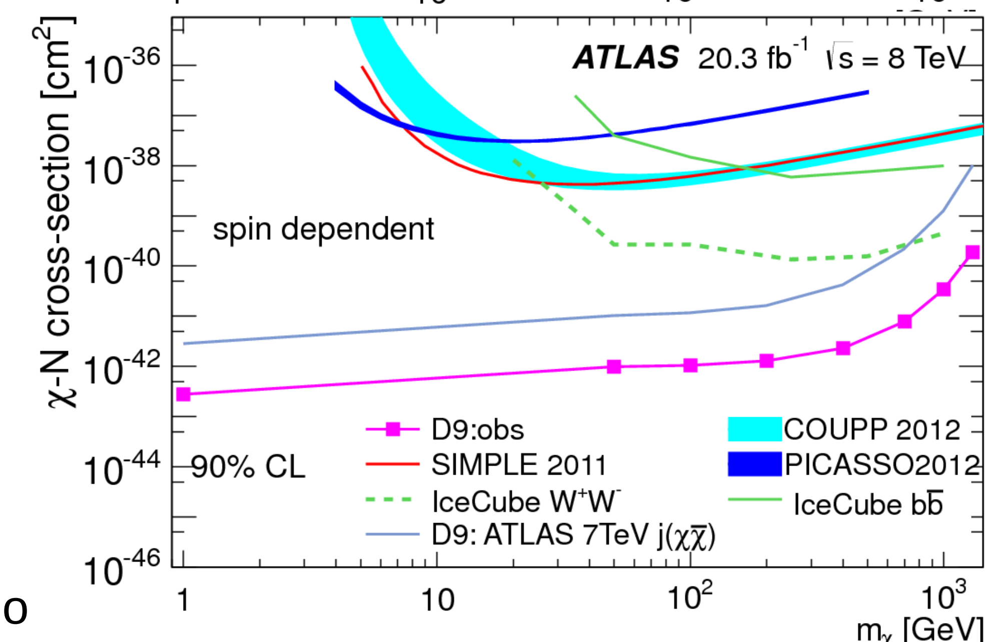
Correlating LHC searches and WIMP DM direct searches







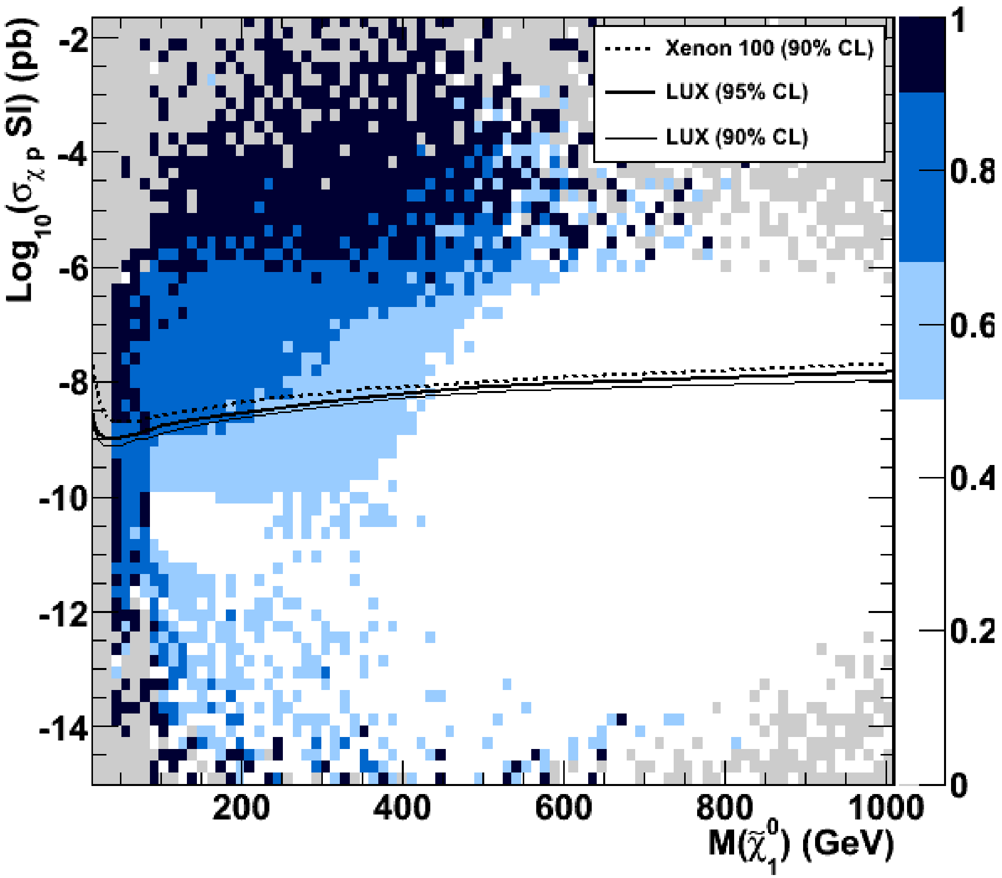
CMS-PAS-EXO-12-048

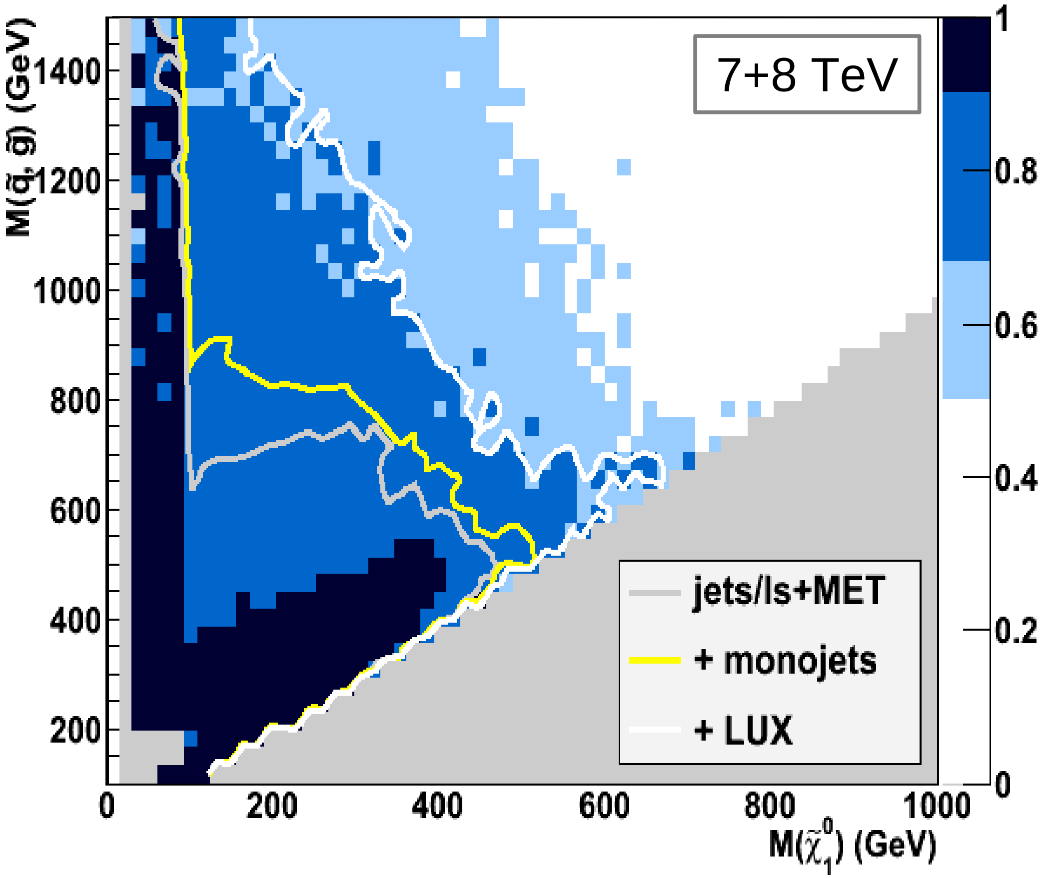


arXiv:1309.4017 to appear on PRL

The Case of the MSSM

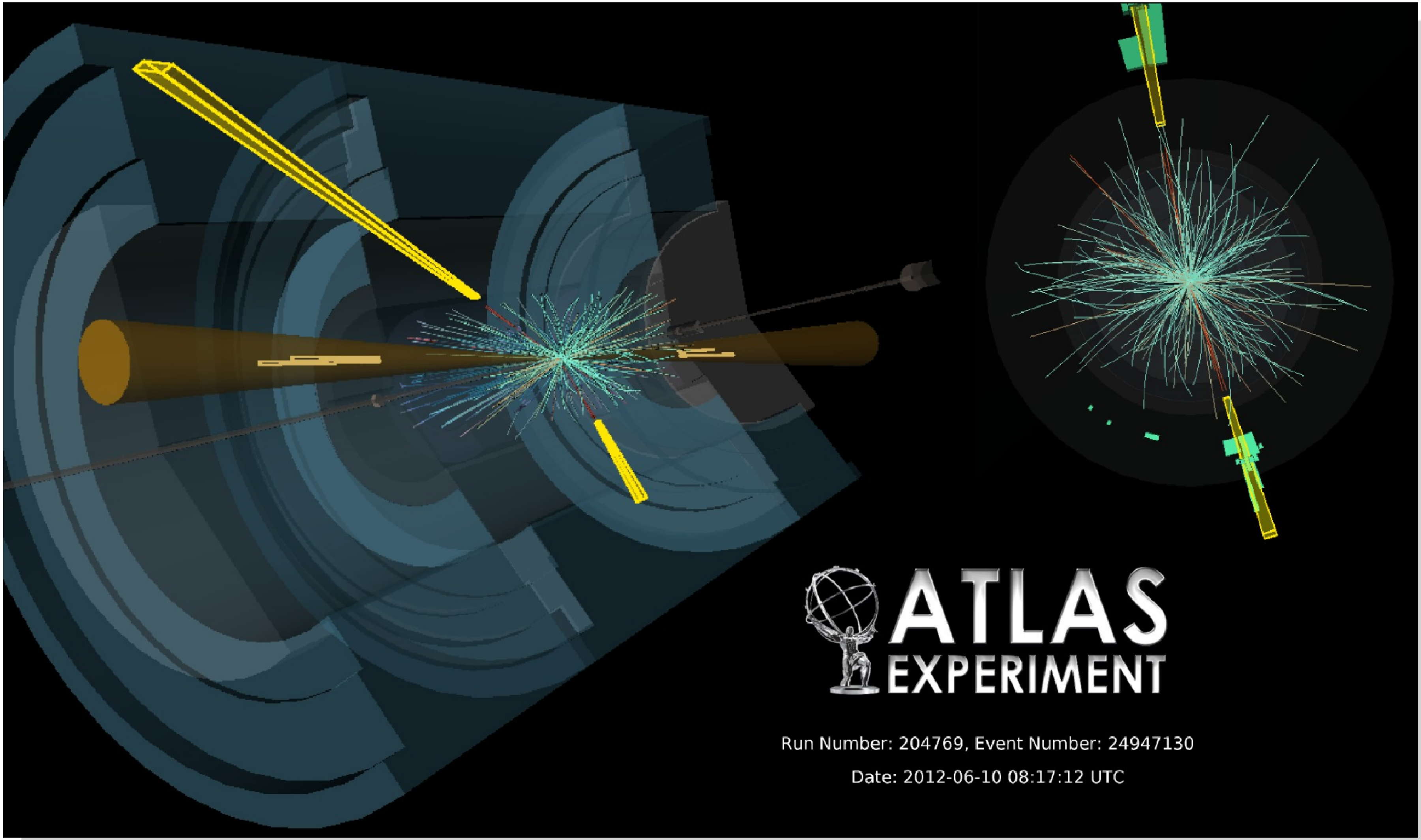
In a more complex case as a SUSY χ^0_1 WIMP, the results are affected by the availability of multiple propagators and the presence of other particles at small mass splitting, still mono-jets add to the LHC sensitivity, notably in the kinematically difficult small DM region;



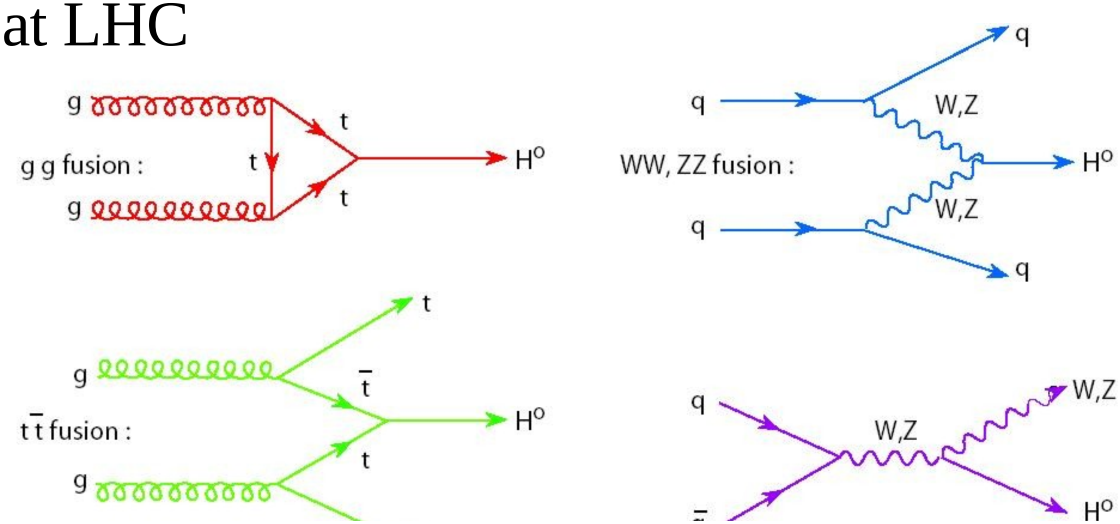


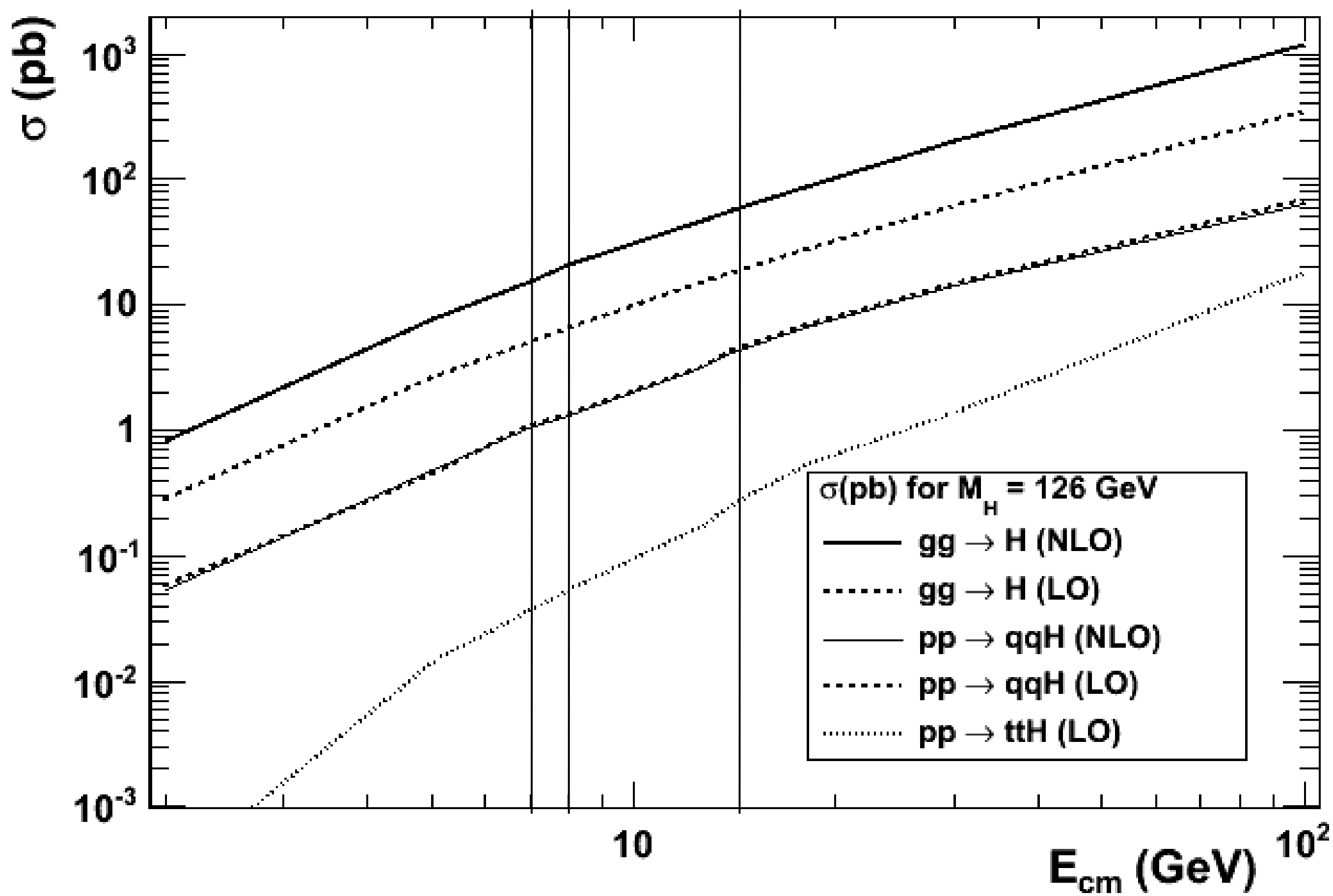
Arbey, MB, Mahmoudi, arXiv:1311.7641

Higgs Physics at LHC

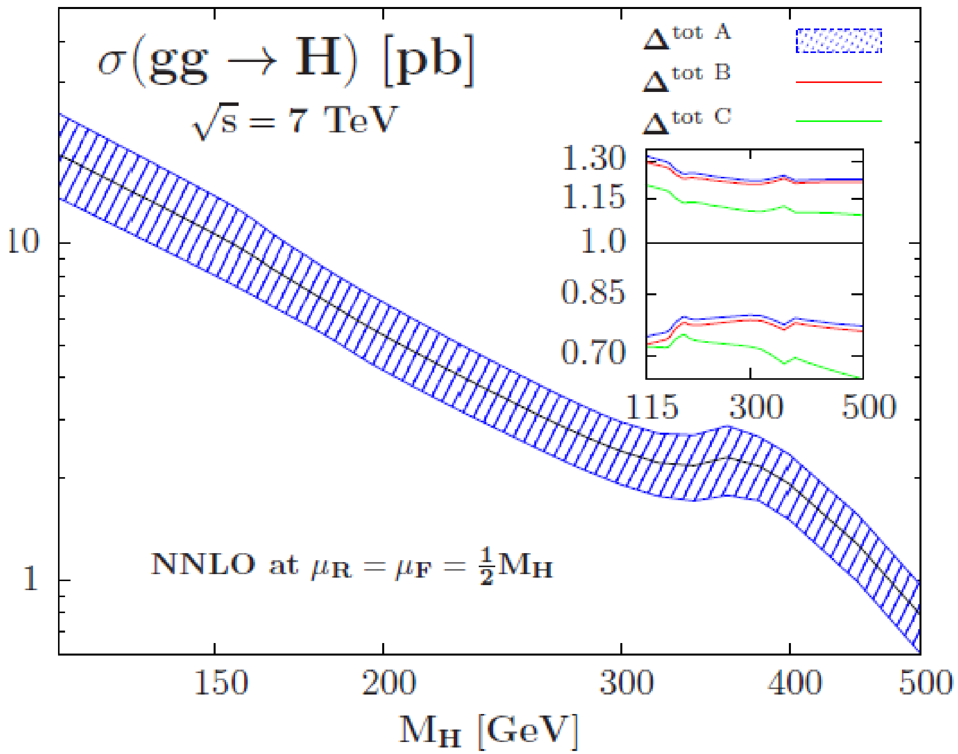


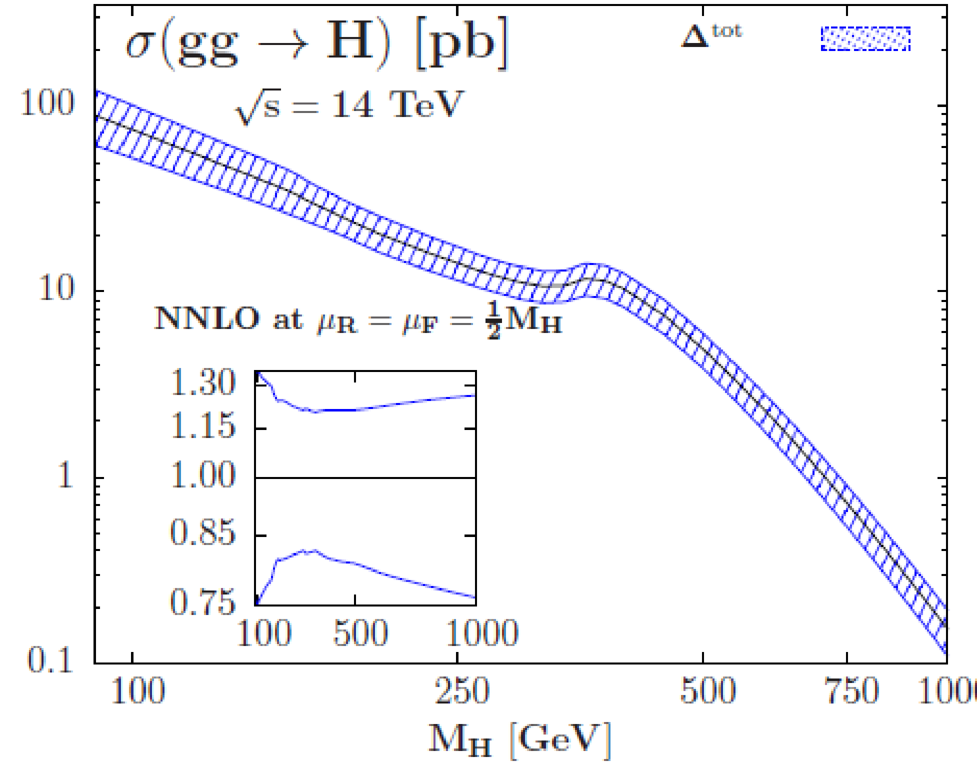
Higgs Production at LHC





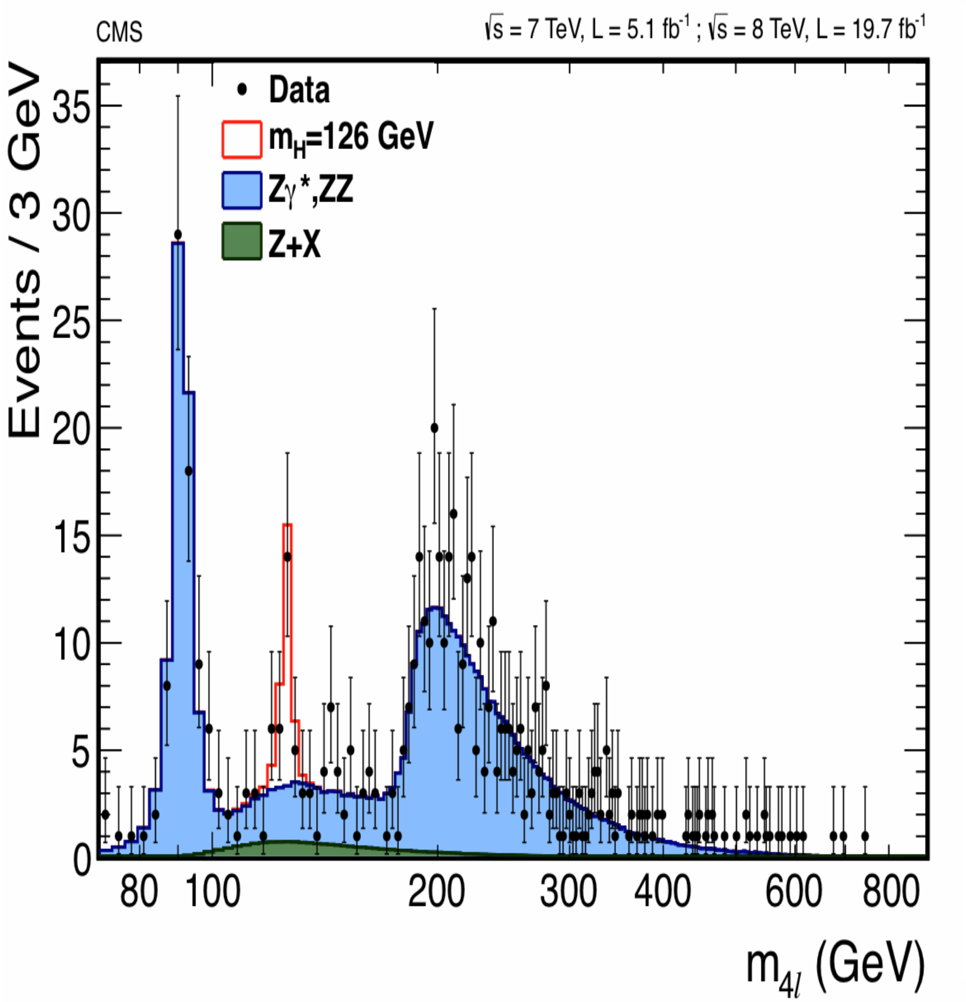
Higgs Production at LHC: Theory Uncertainties

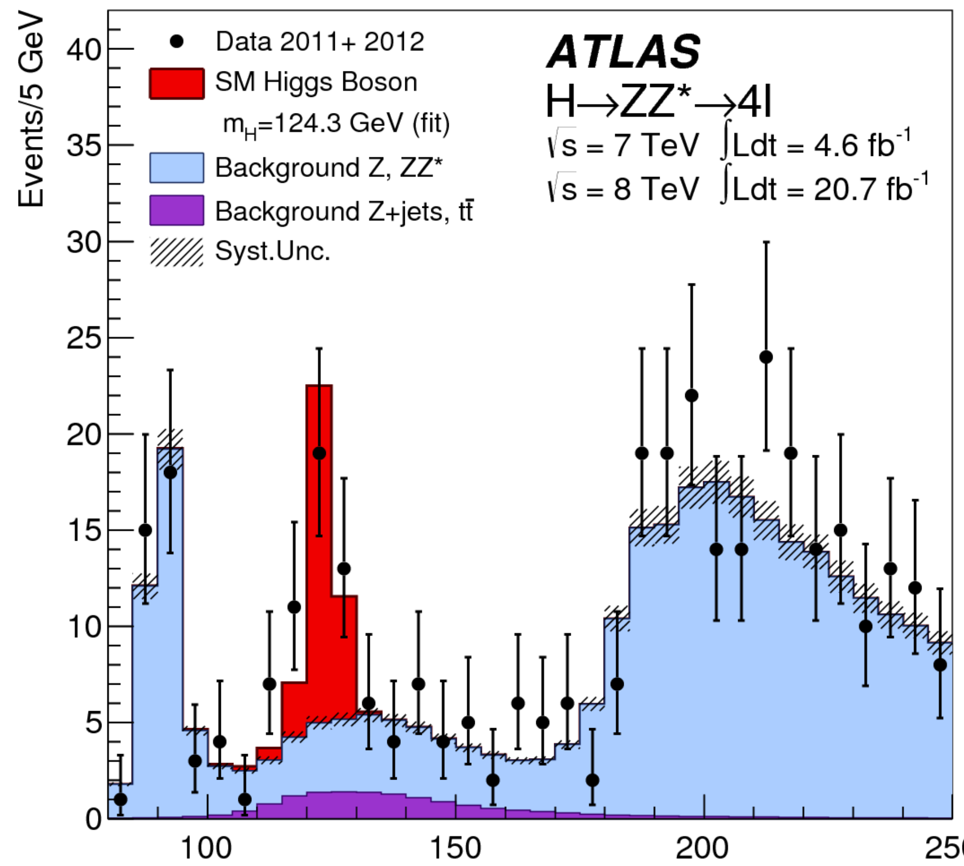




$$\sigma(gg \to H(125))(\text{NNLO})(7\ \text{TeV})(\text{pb}) =$$
$$15.51^{+8.8\%}_{-9.9\%}(\text{scale})^{+9.1\%}_{-8.8\%}(\text{PDF} + \alpha_s) \pm 7.2\%(\text{EFT})$$
$$\sigma(gg \to H(125))(\text{NNLO})(14\ \text{TeV})(\text{pb}) =$$
$$51.45^{+9.0\%}_{-11.6\%}(\text{scale})^{+8.5\%}_{-8.4\%}(\text{PDF} + \alpha_s) \pm 7.6\%(\text{EFT})$$

Baglio, Djouadi, JHEP 1103 (2011)





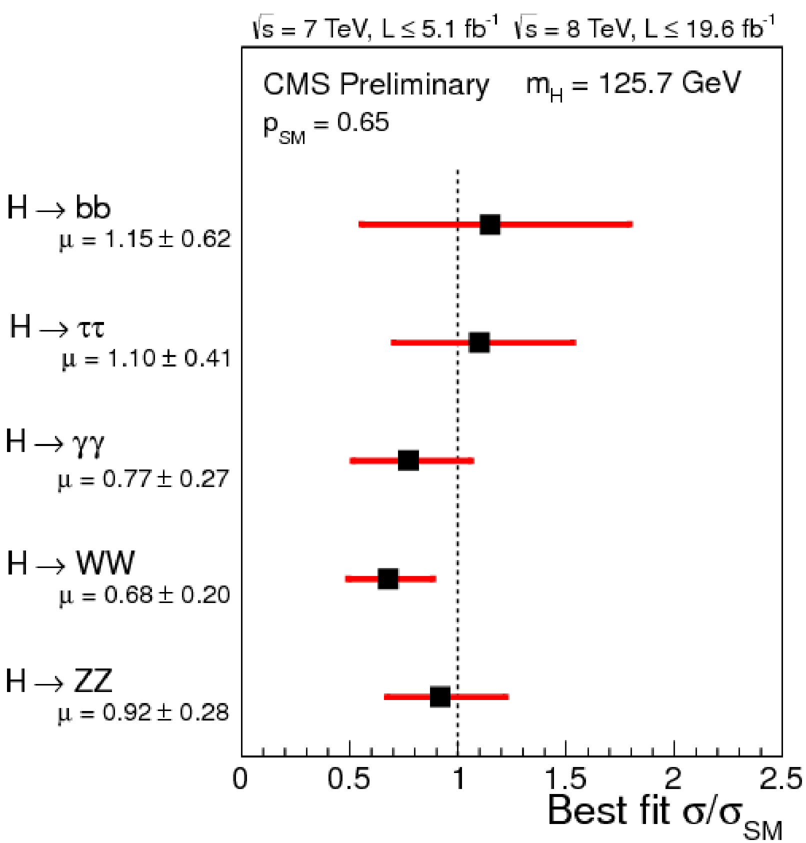
Phys. Lett. B 726 (2013), pp. 88-119

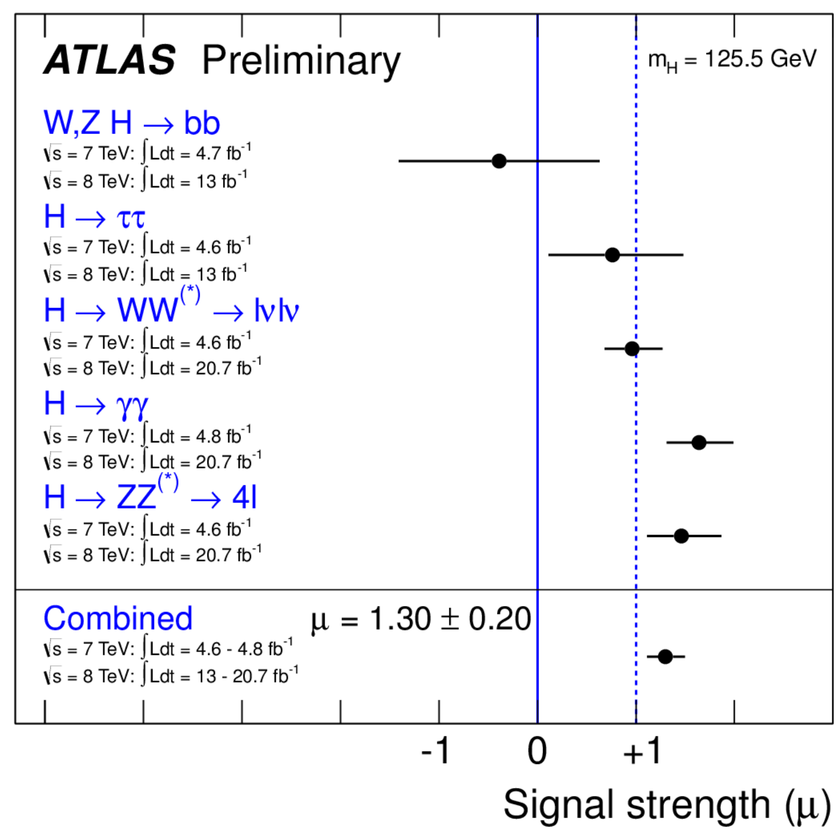
ATLAS	$M_H = (125.5 \pm 0.2\ (\text{stat.})\ ^{+0.5}_{-0.6}\ (\text{syst.}))$ GeV
CMS	$M_H = (125.7 \pm 0.3\ (\text{stat.})\ \pm 0.3\ (\text{syst.}))$ GeV

Signal Strengths $\mu = \frac{\sigma \times \mathrm{BR}}{\sigma \times \mathrm{BR}|_{\mathrm{SM}}}$

Experiment measures “signal” rates in given final state defined by analysis criteria;

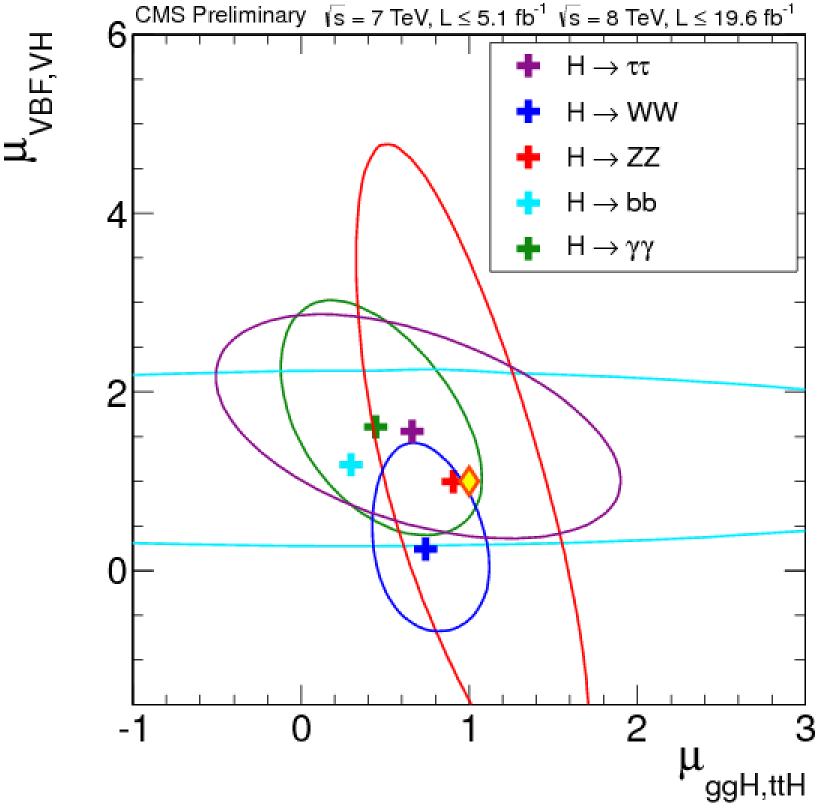
No model independent way to extract Higgs branching fractions (contrary to e^+e^- colliders)
Conversion of LHC signal strengths to Higgs couplings requires additional assumptions:

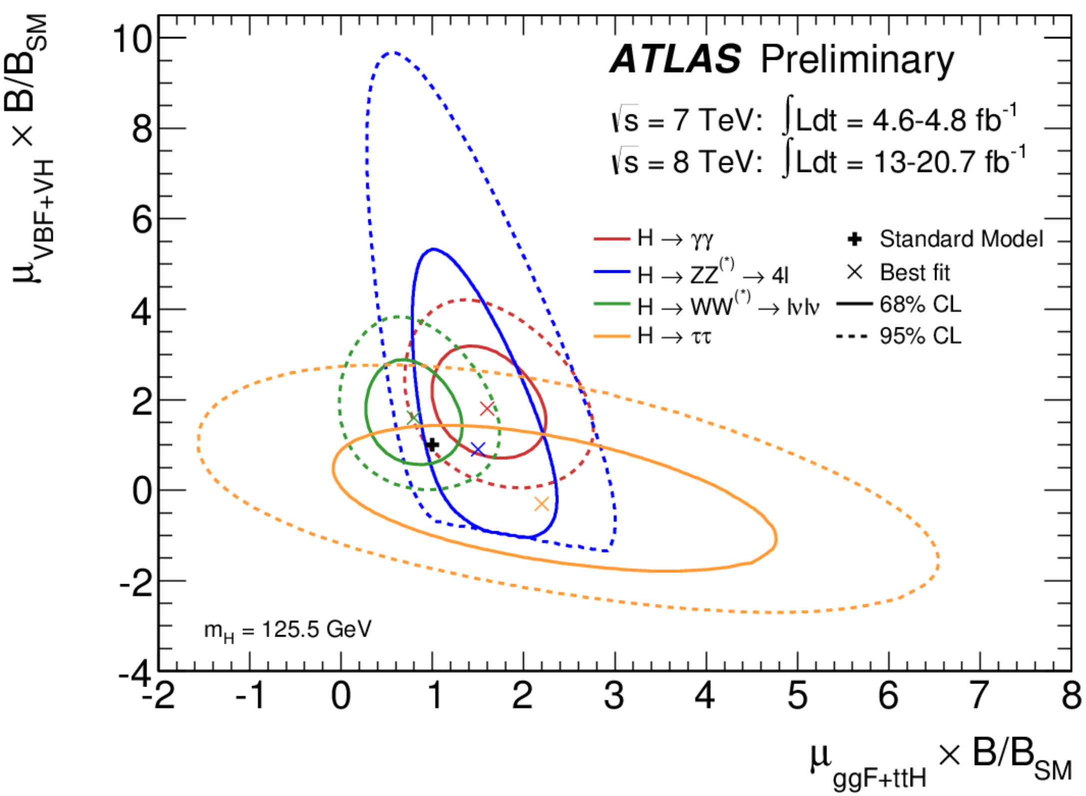




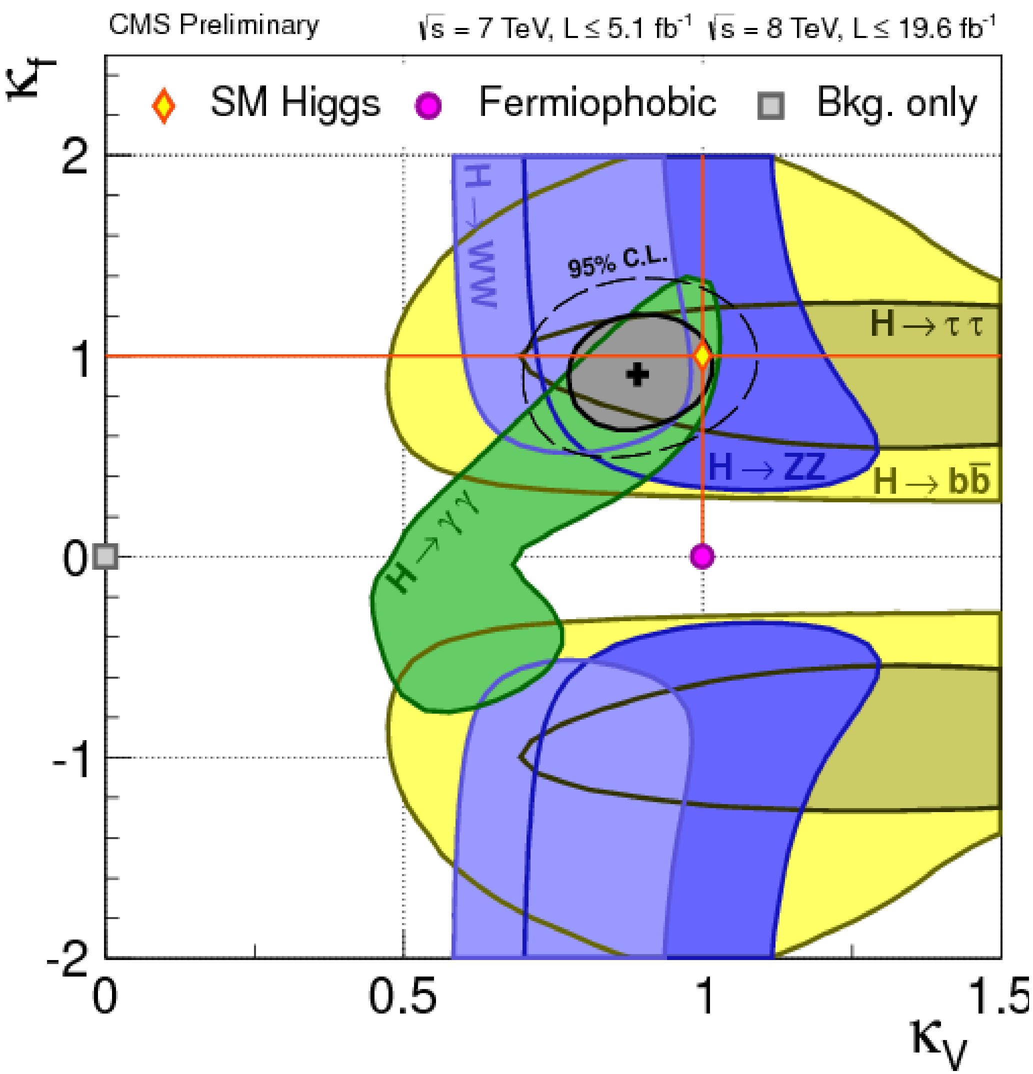
Signal Strengths and Production Process

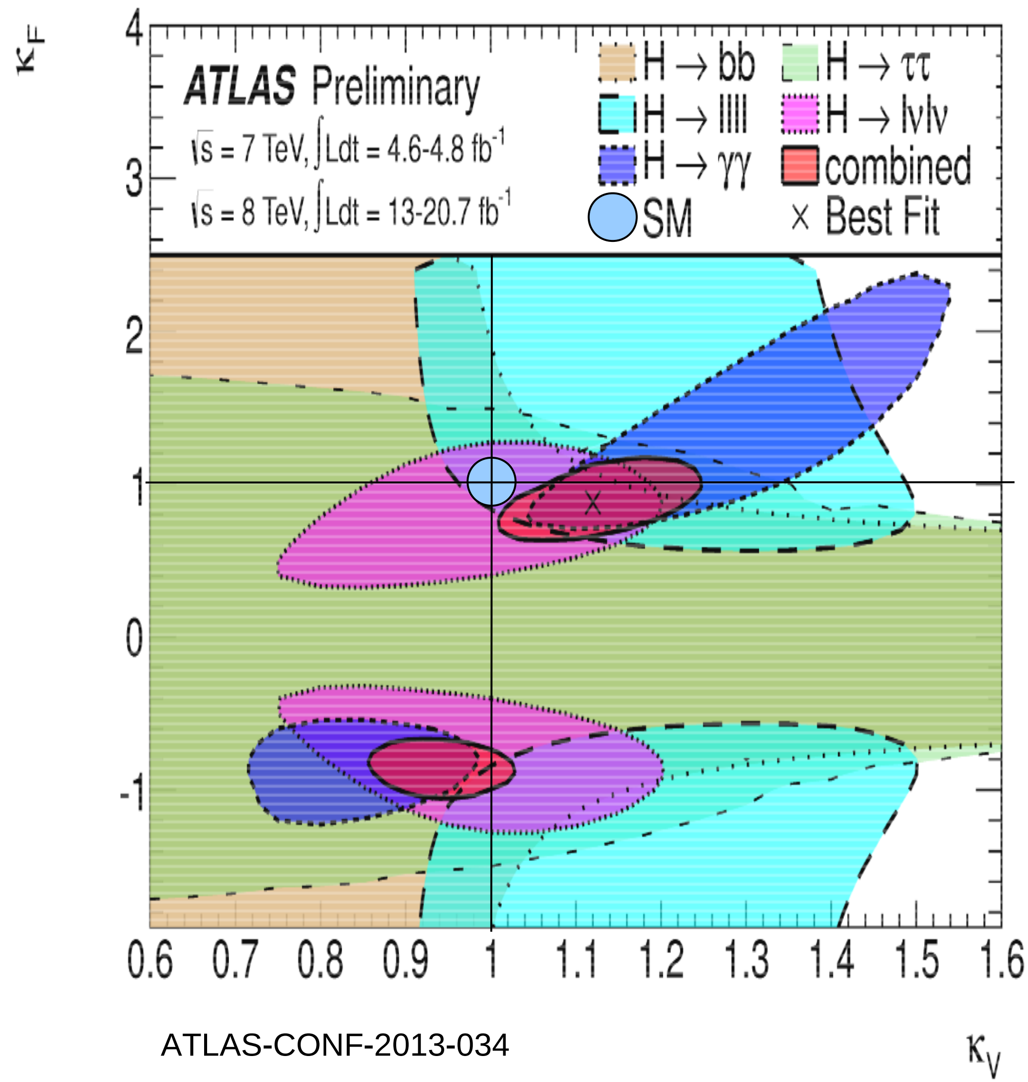
Several production processes at LHC, analysis criteria modify their contribution to signal giving access to Higgs couplings to vector bosons in production;



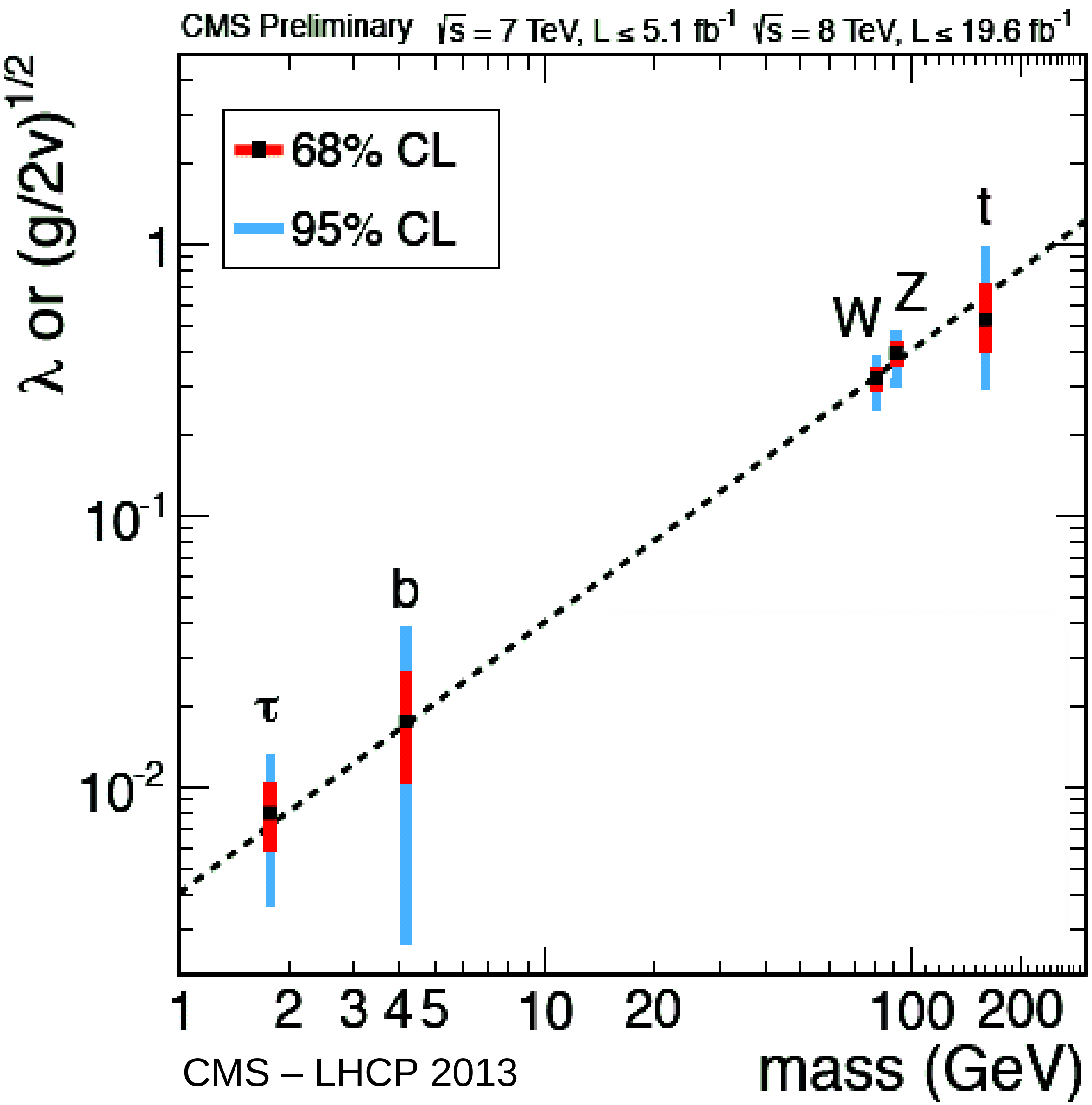


Fermion and Vector couplings





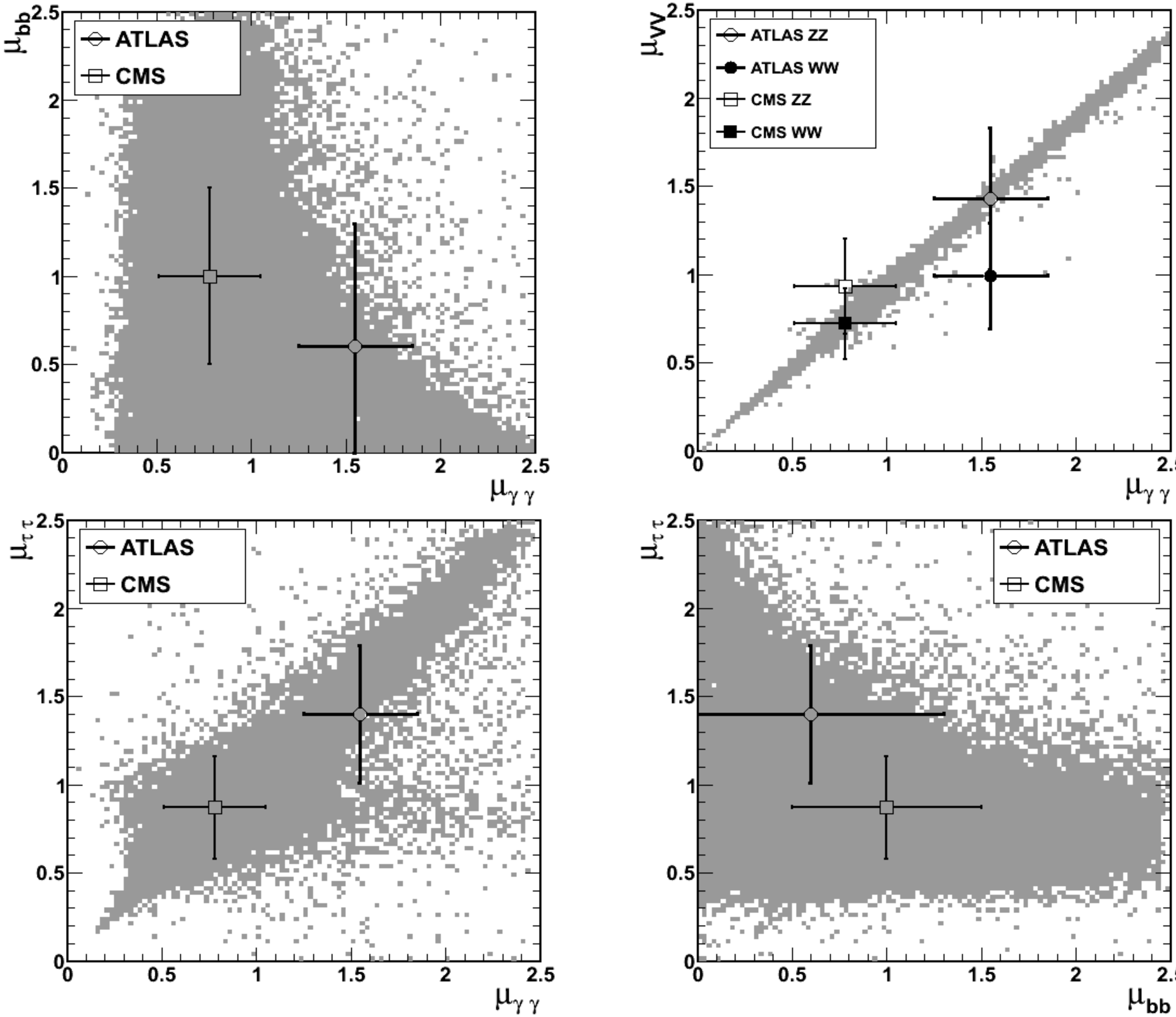
ATLAS-CONF-2013-034



CMS – LHCP 2013

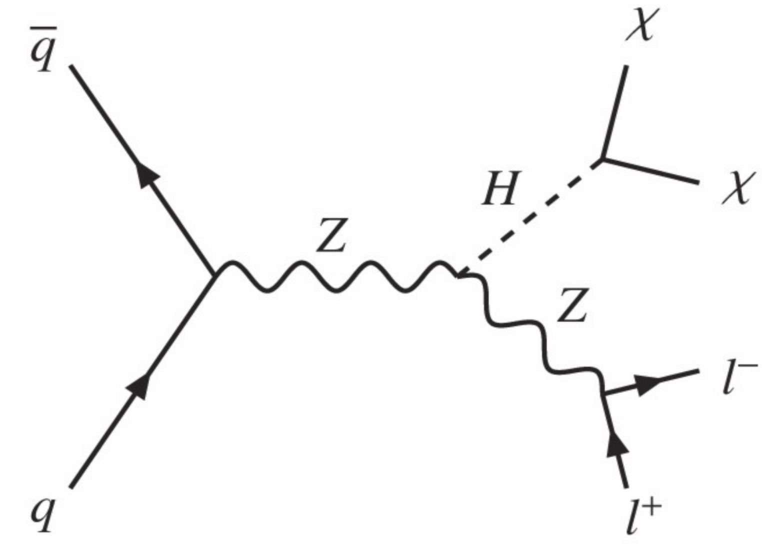
Higgs Signal Strenghts and the MSSM

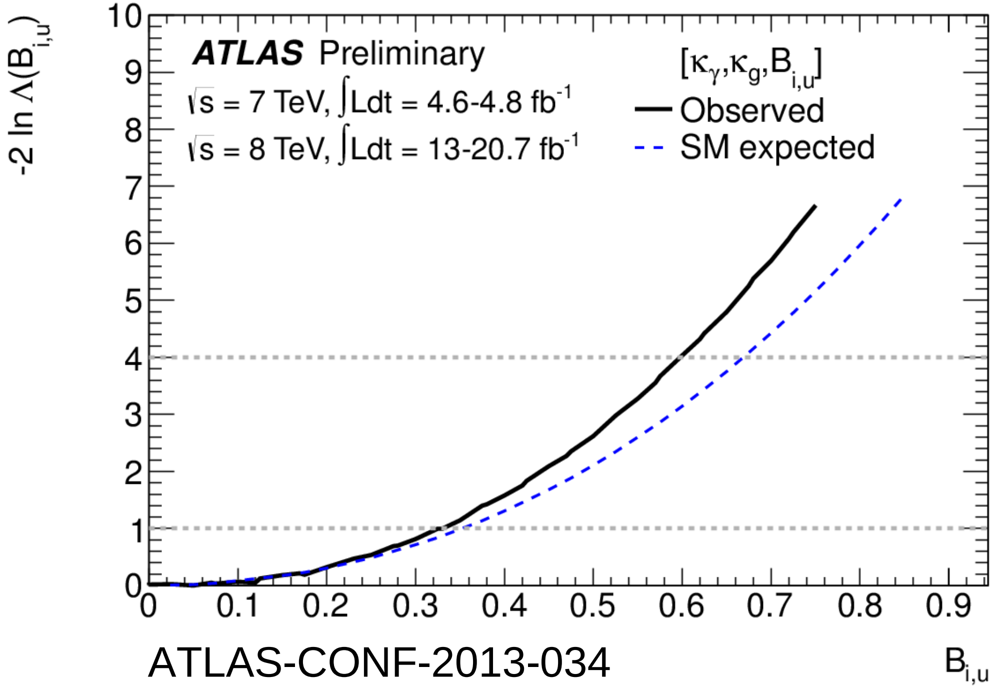
Compare LHC results for signal strengths to predictions of BSM models (here SUSY MSSM from 19-par scans): too early to decide between H^0_{SM} and h^0



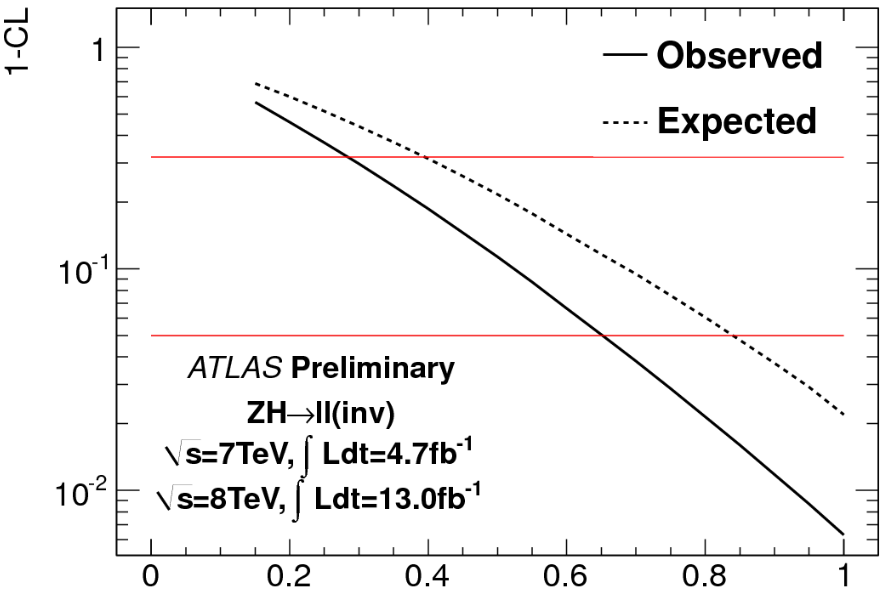
Updated from Arbey, MB, Djoaudi, Mahmoudi, PLB 720 (2013) 153

Invisible Higgs Decays



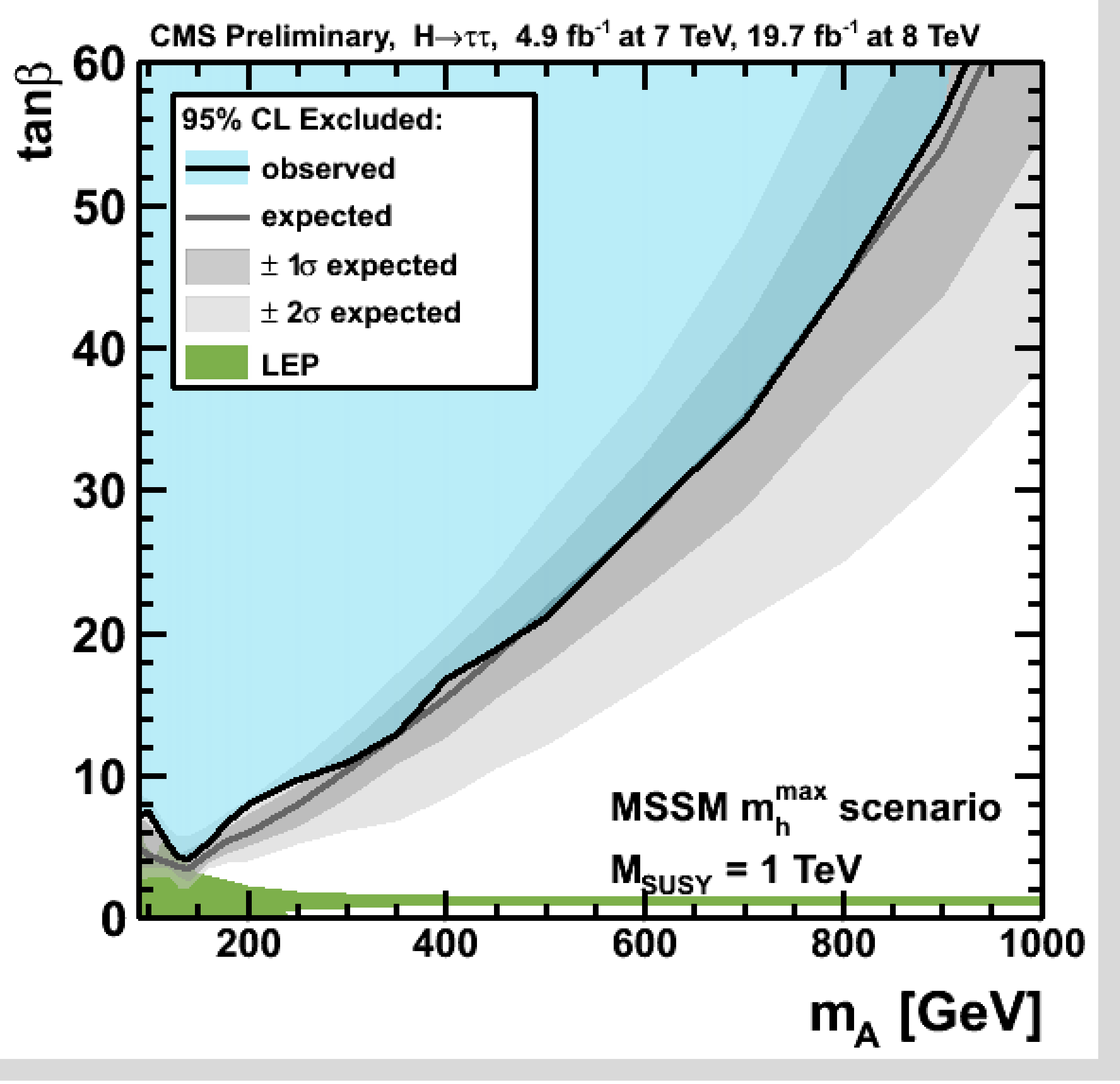


ATLAS-CONF-2013-034

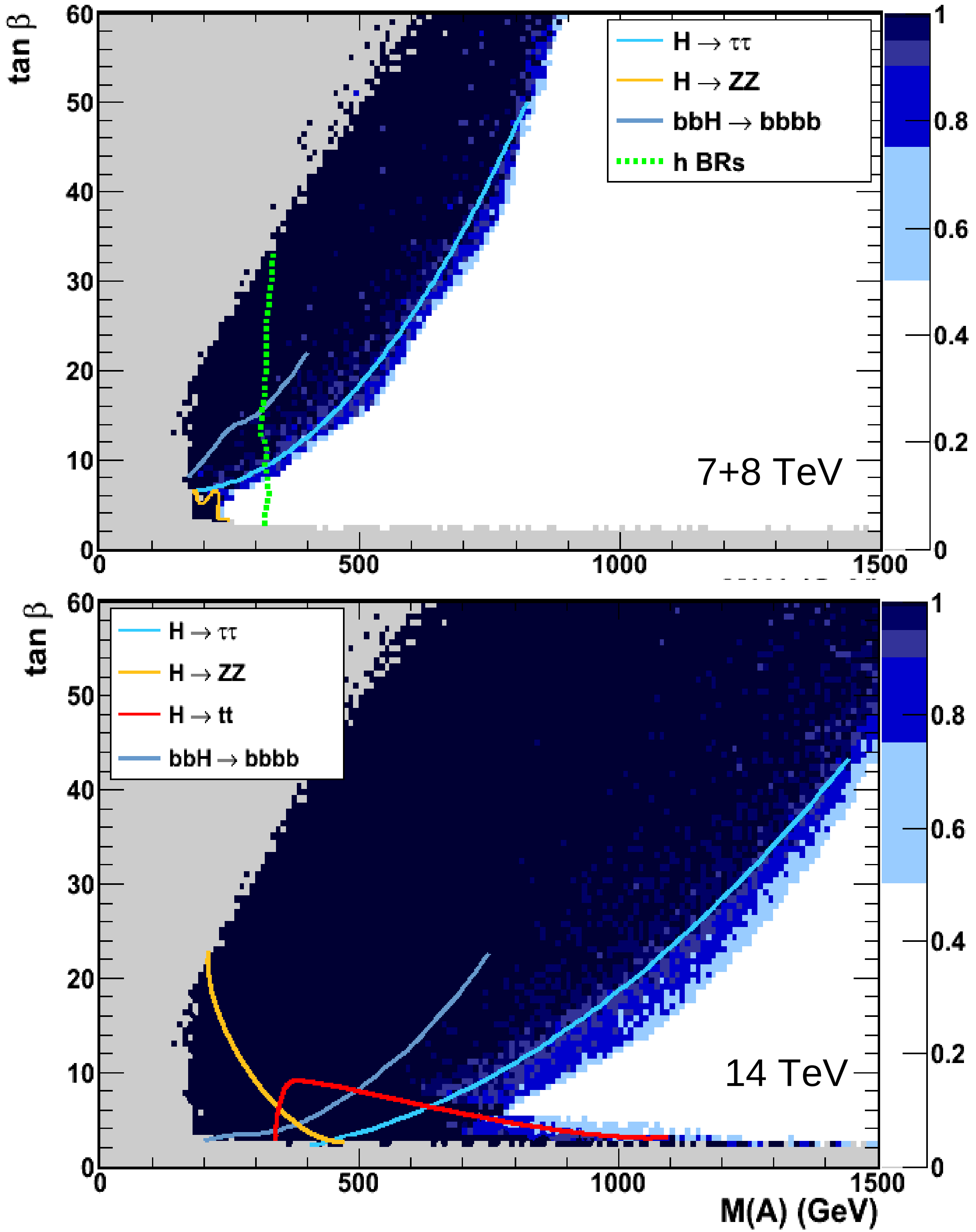


ATLAS-CONF-2013-011

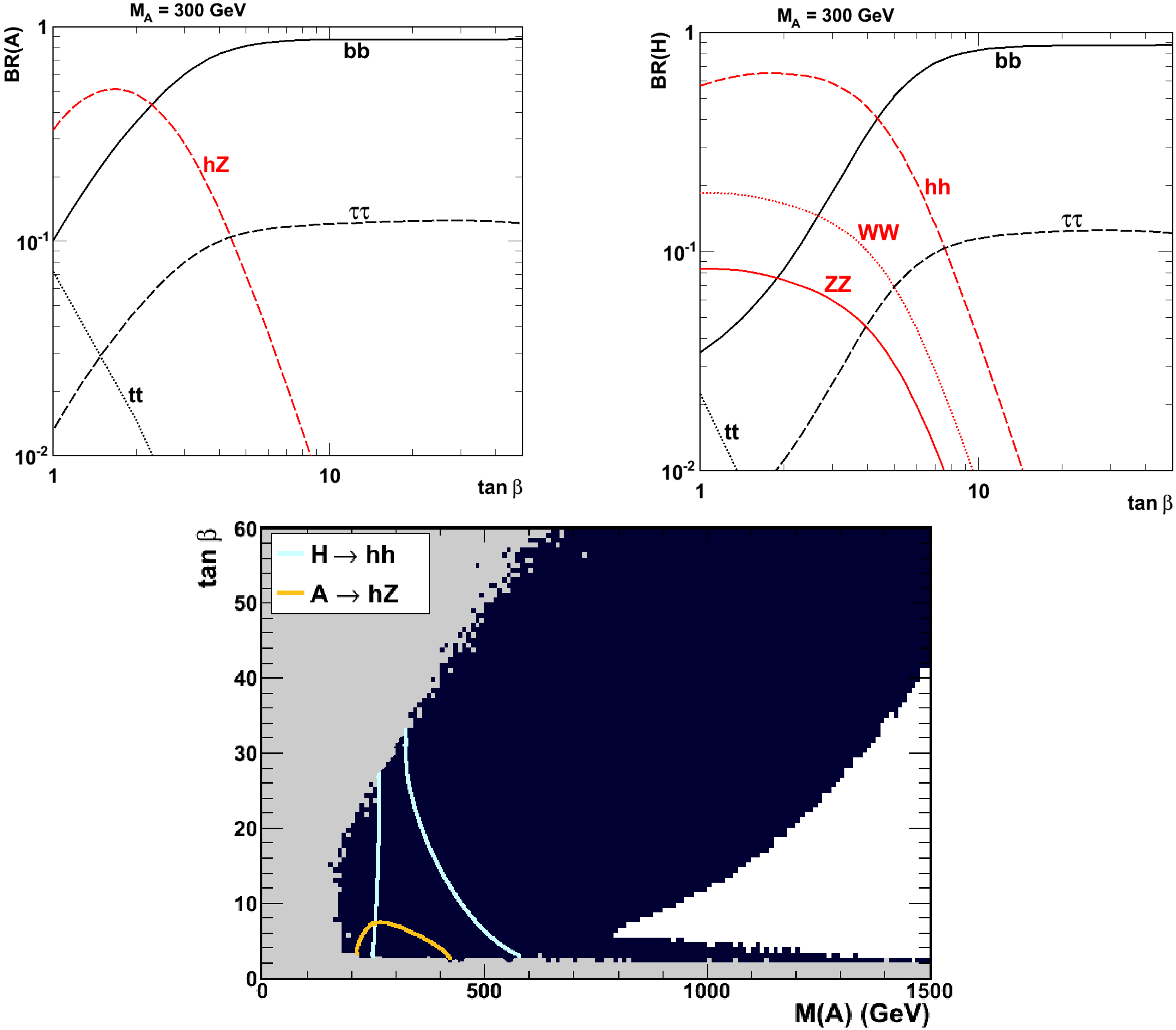
Beyond minimal Higgs Sector:
Heavy Higgs bosons in SUSY and 2HDM models



CMS-PAS-HIG-13-021

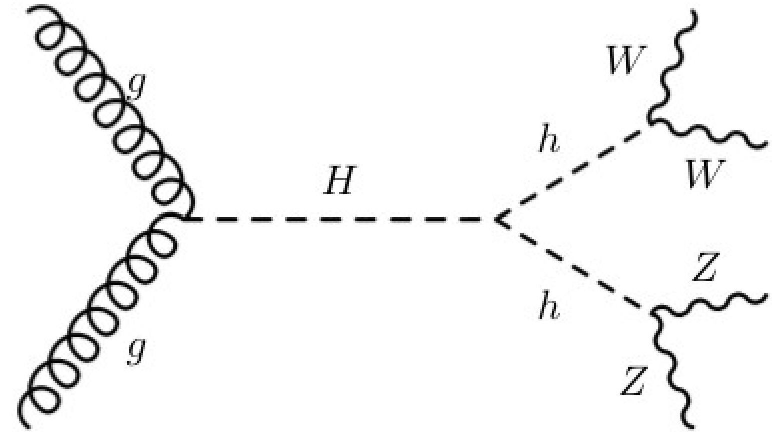


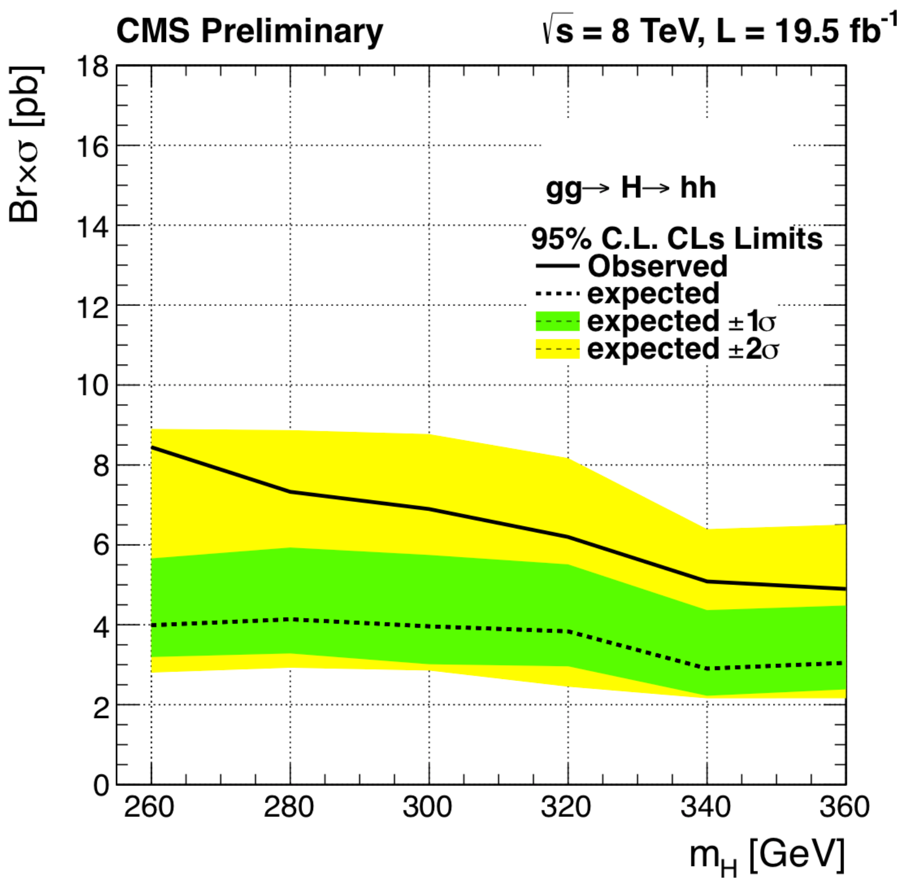
Arbey, MB, Mahmoudi,
PRD 88 (2013) 015007



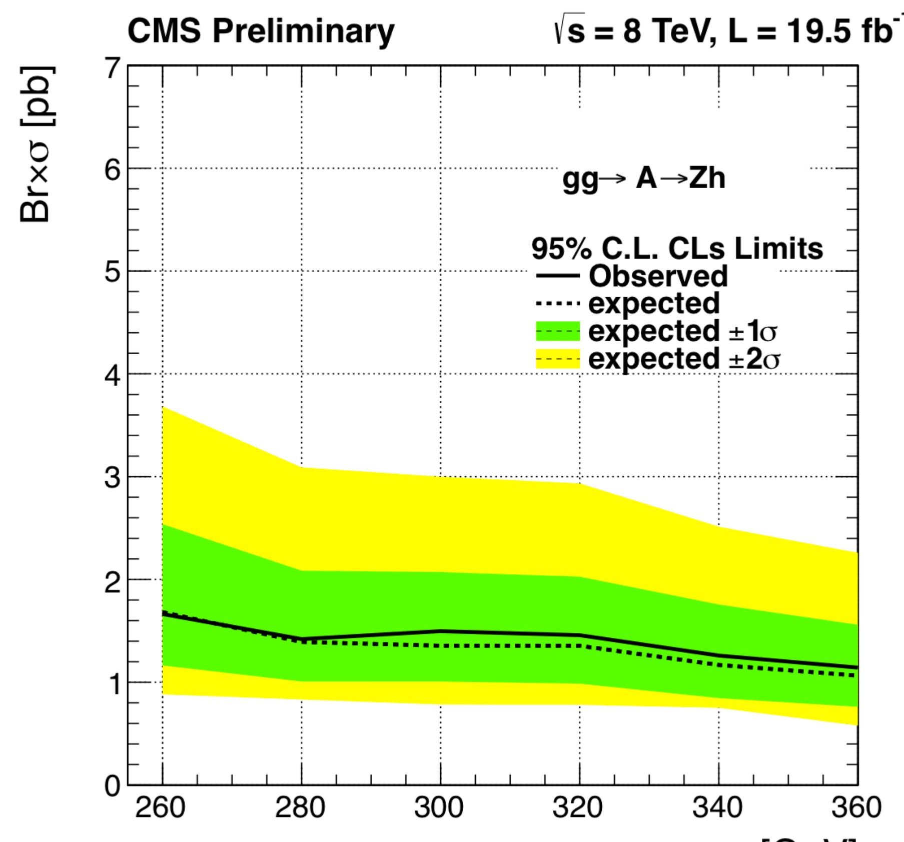
M_A = 300 GeV
BR(A)
bb
hZ
ττ
tt
tan β
M_A = 300 GeV
BR(H)
bb
hh
WW
ZZ
ττ
tt
tan β
tan β
H → hh
A → hZ
M(A) (GeV)

First look at H → hh and A → Zh



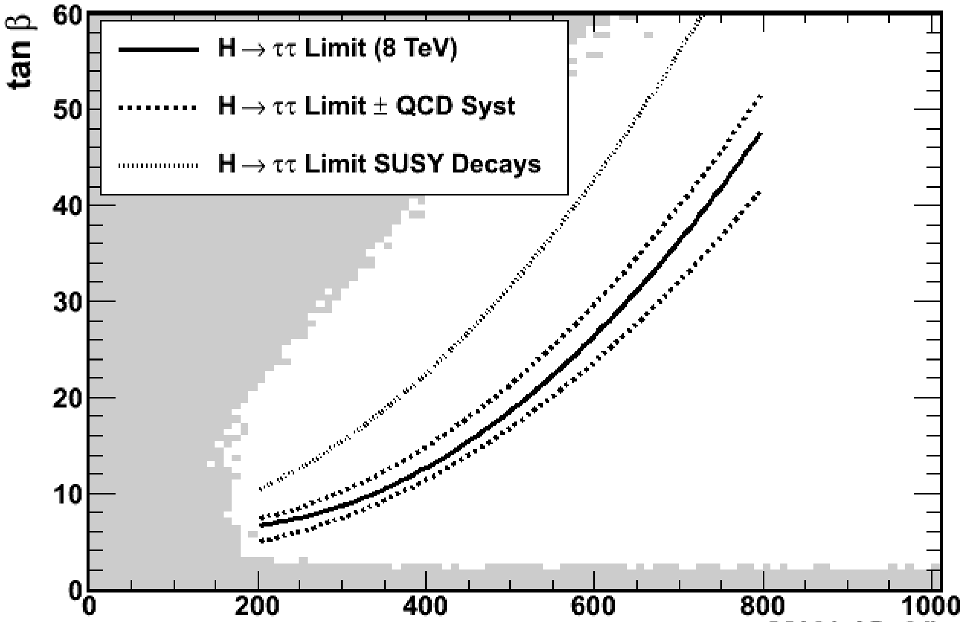


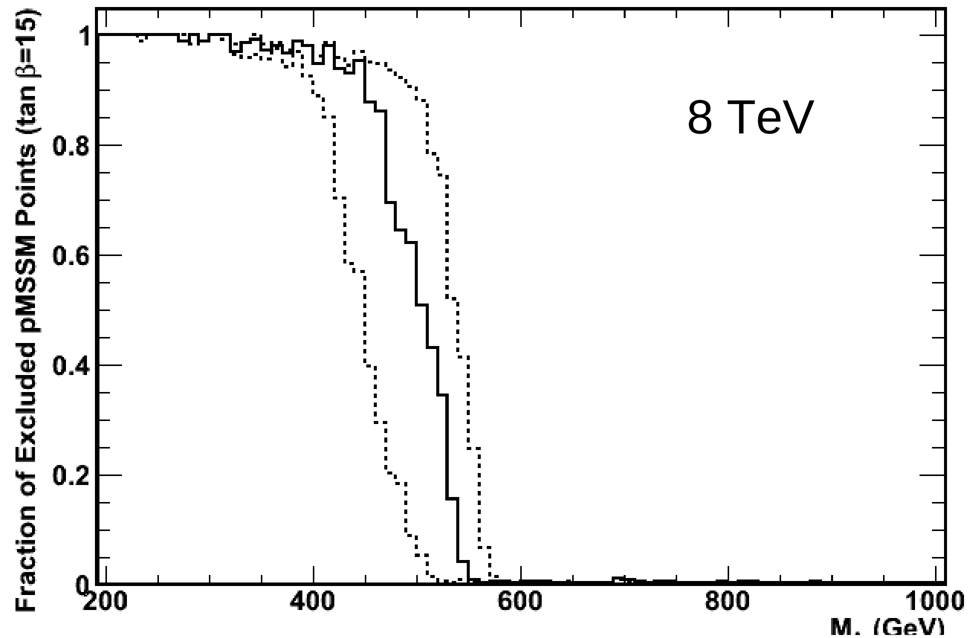
Sch

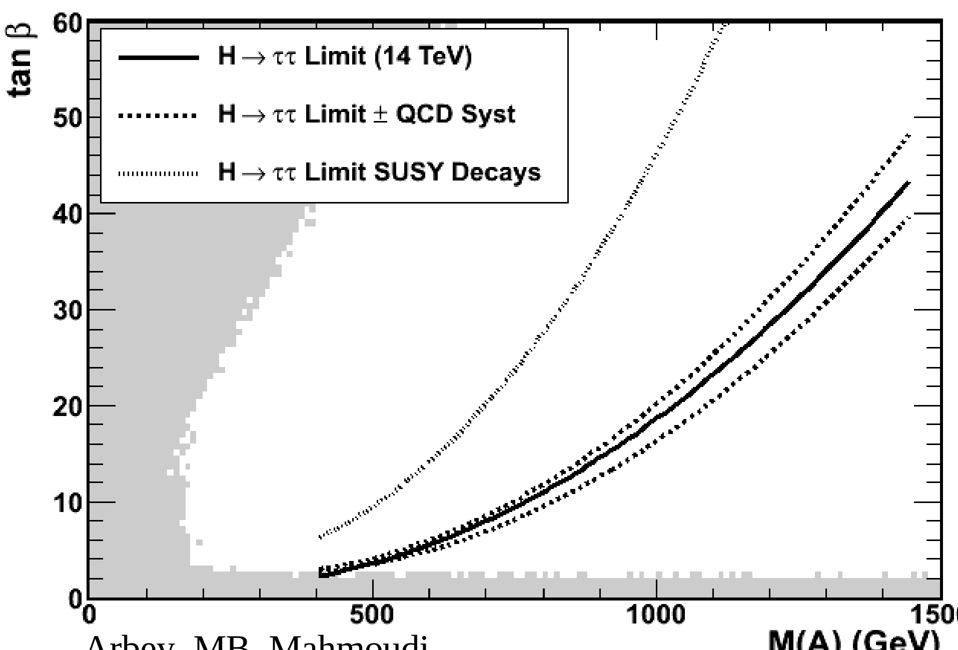


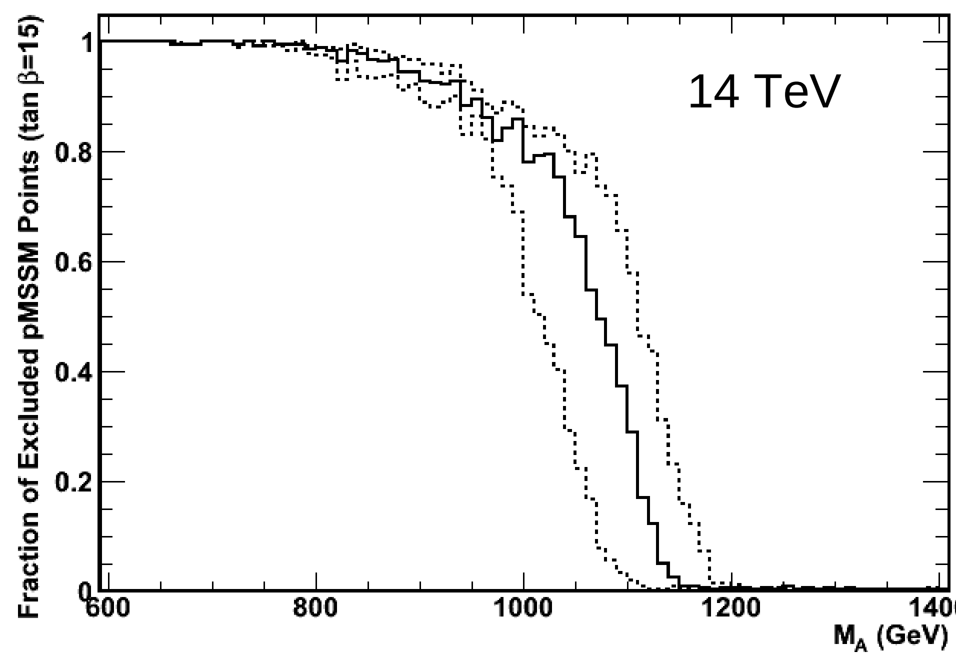
CMS-PAS-HIG-13-025

Impact of model & syst uncertainties in LHC limit interpretation



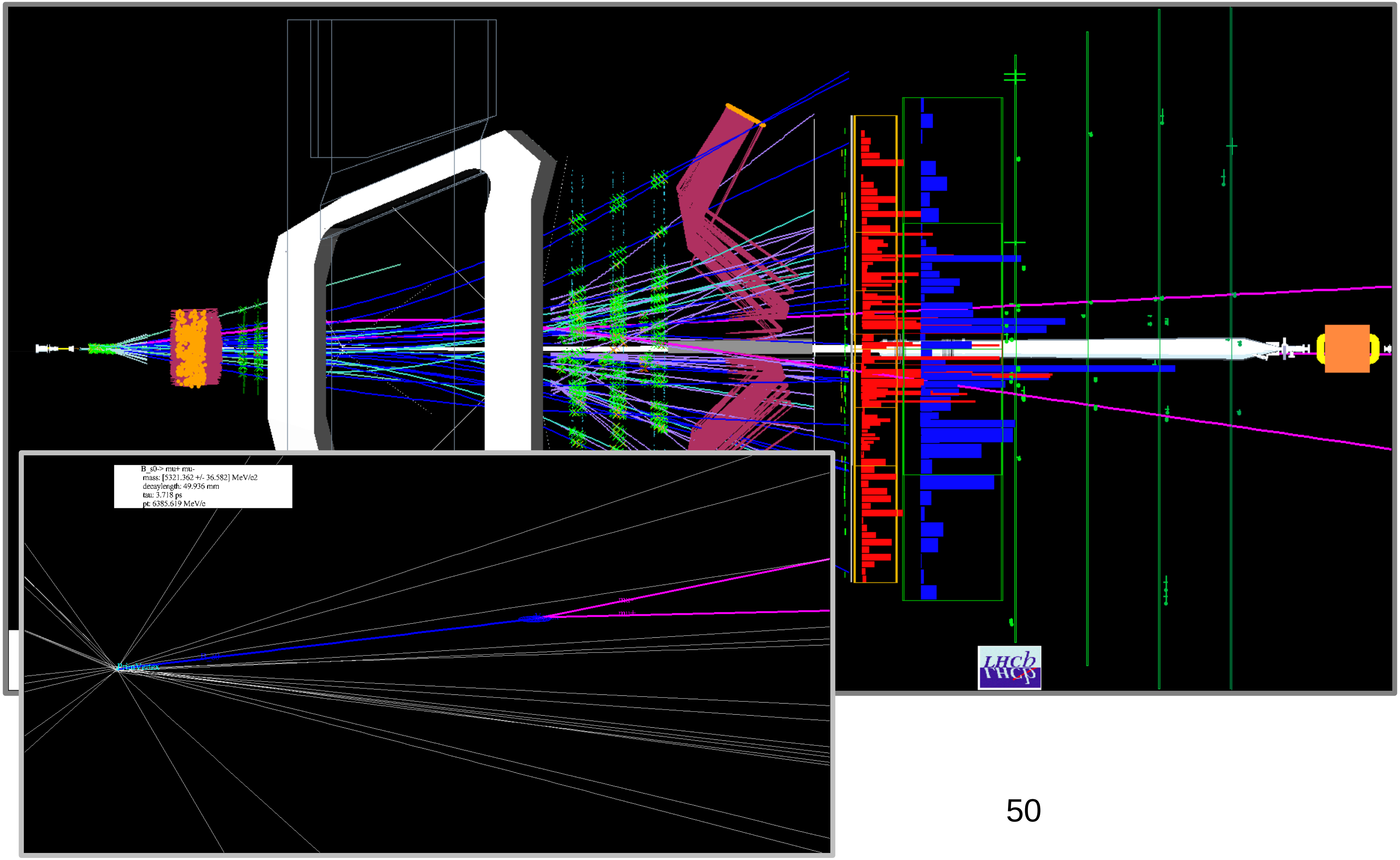




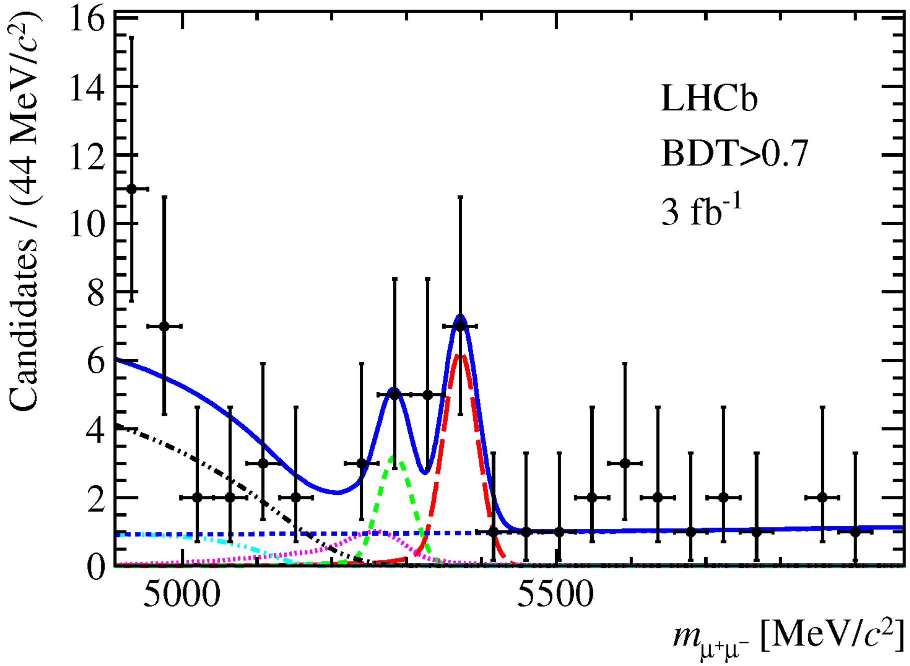


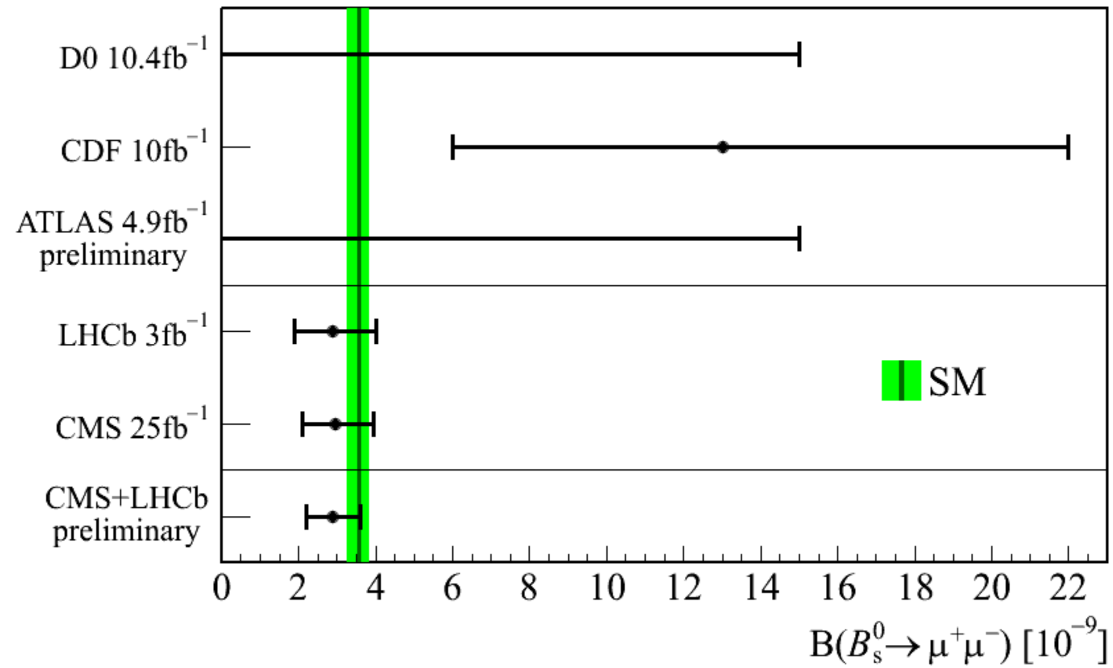
Arbey, MB, Mahmoudi,
PRD 88 (2013) 015007

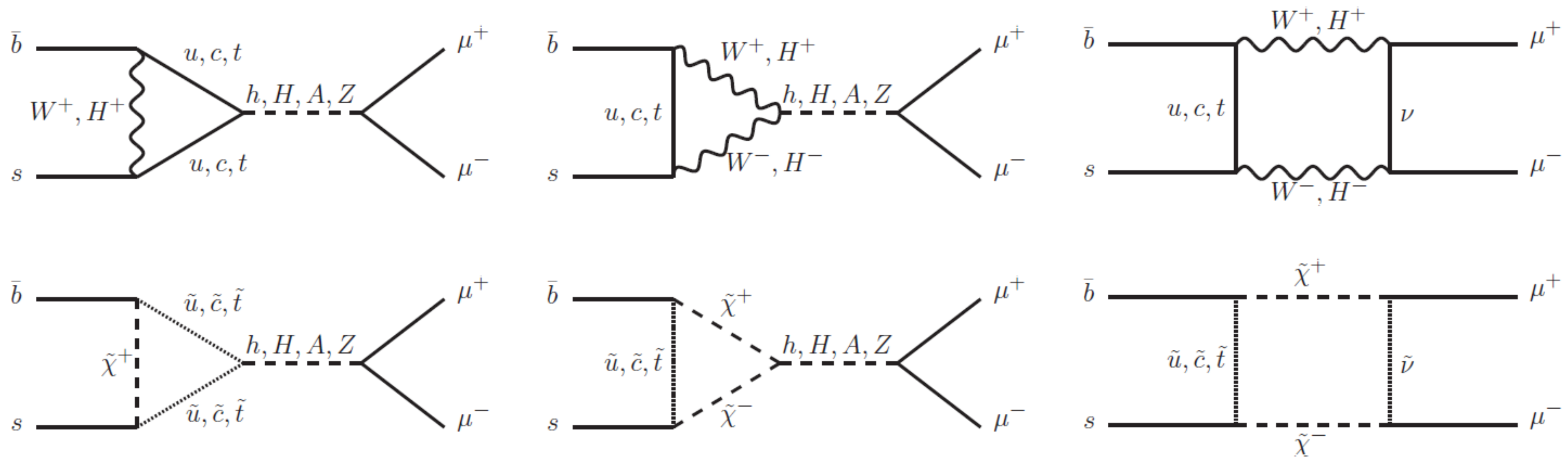
Rare Decays and New Physics



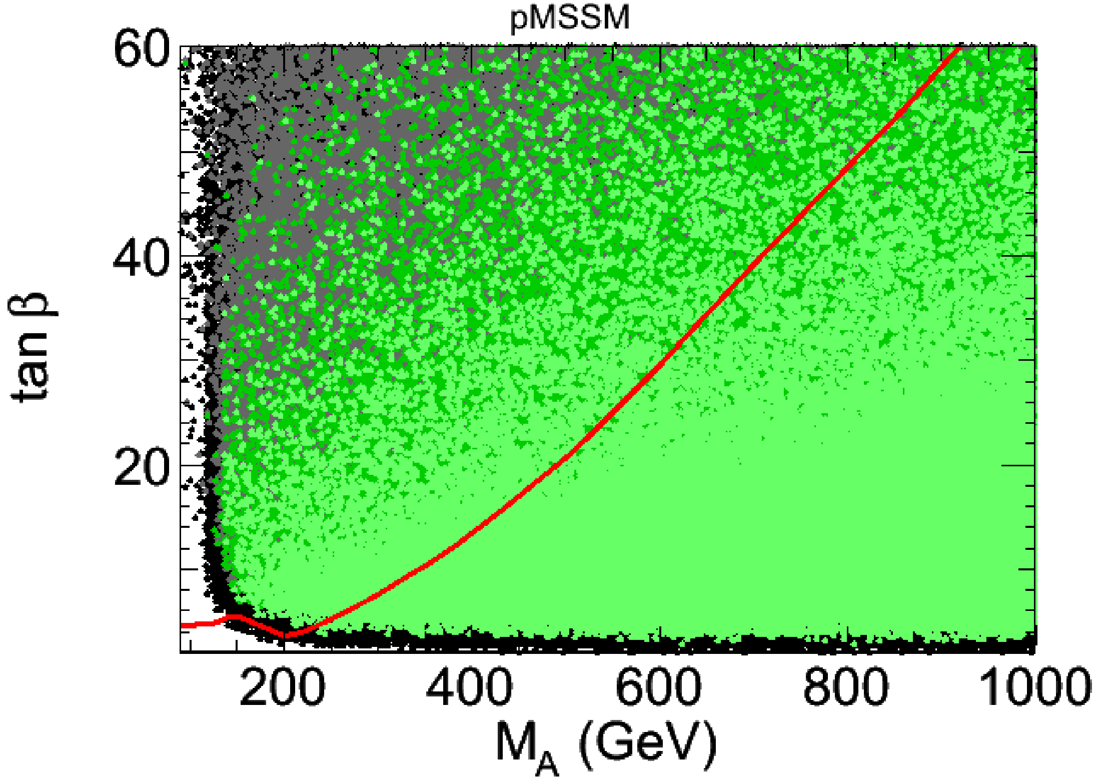
$B_s \rightarrow \mu\mu$

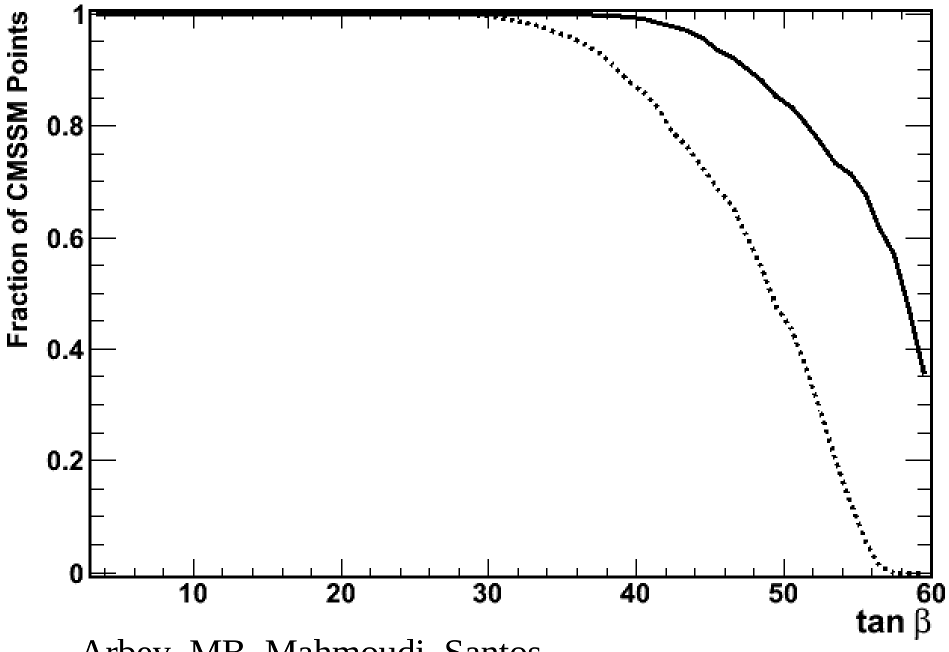


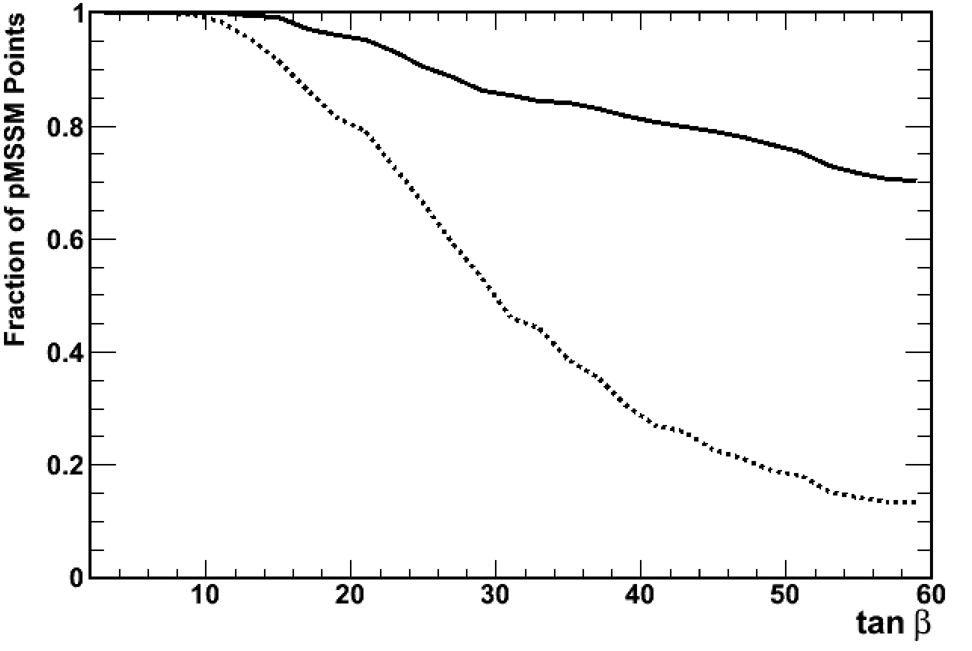




$B_s \to \mu\mu$ and the MSSM

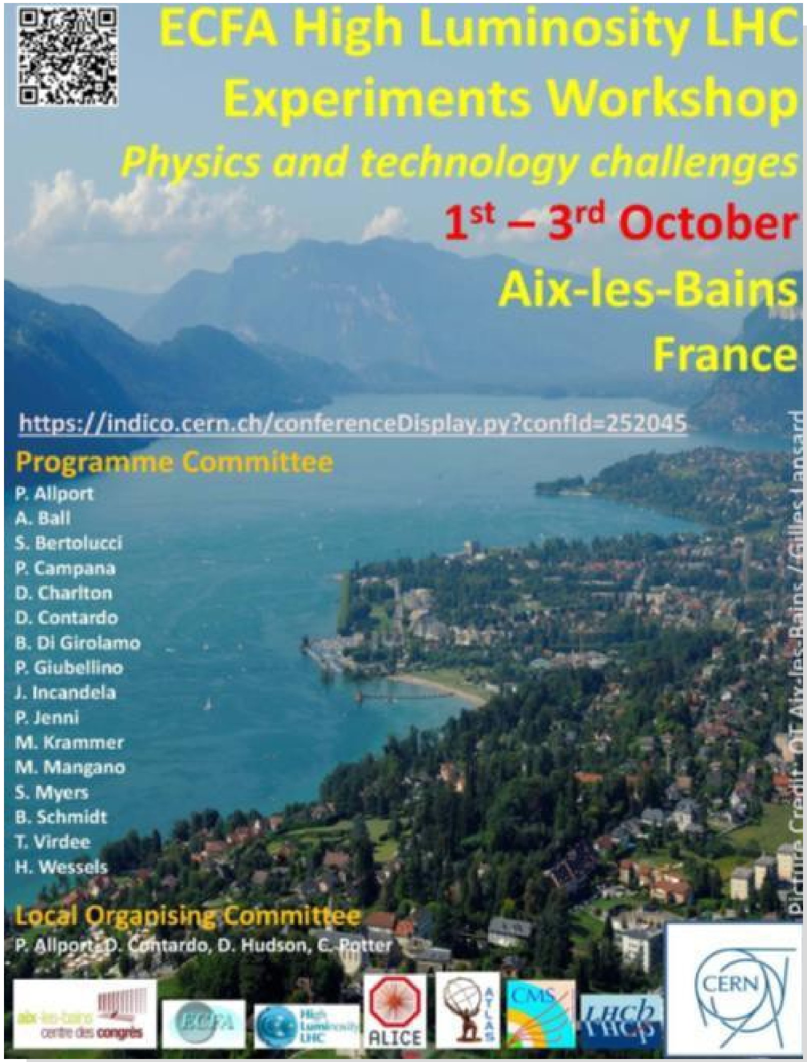






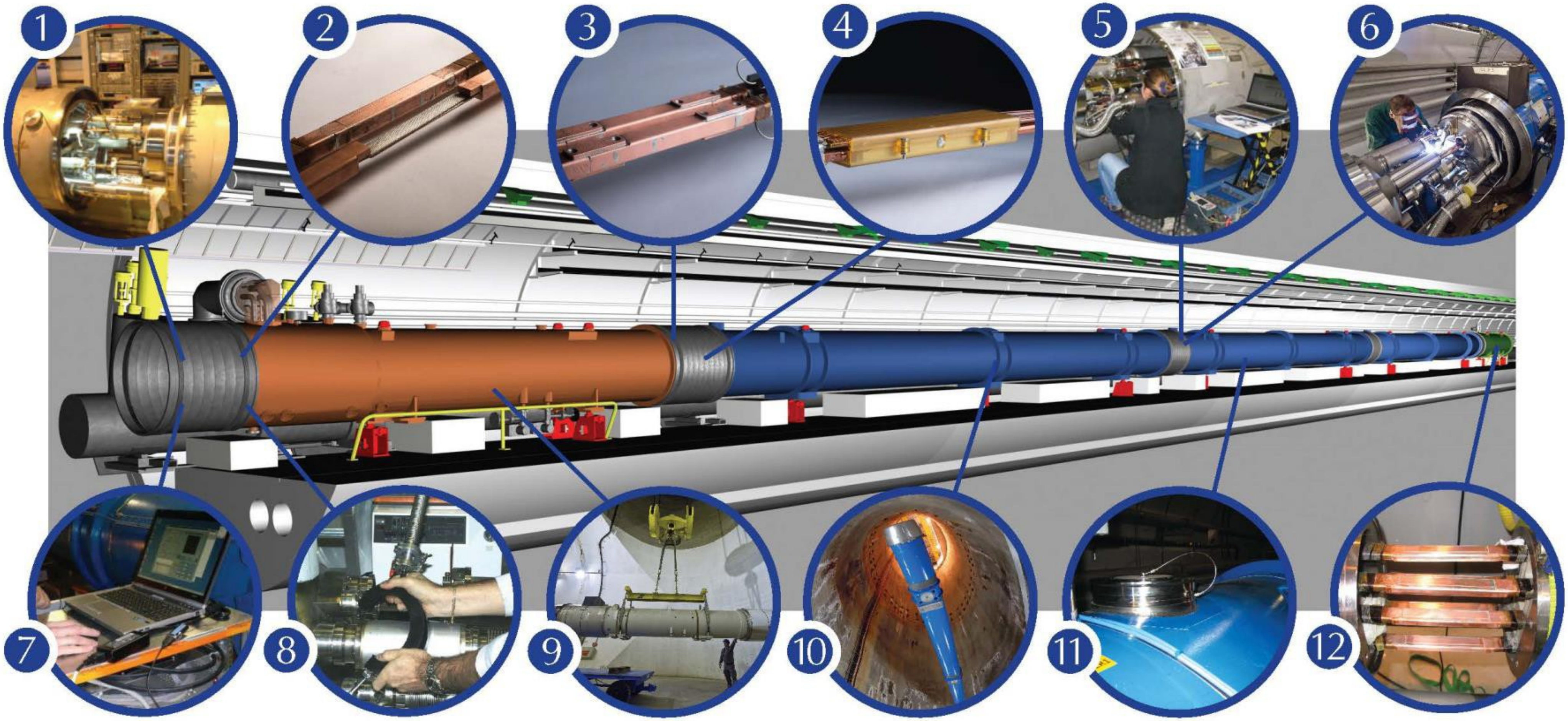
Arbey, MB, Mahmoudi, Santos,
PRD 87 (2013) 035026

Towards Nominal Energy
and
the Machine Luminosity Upgrade

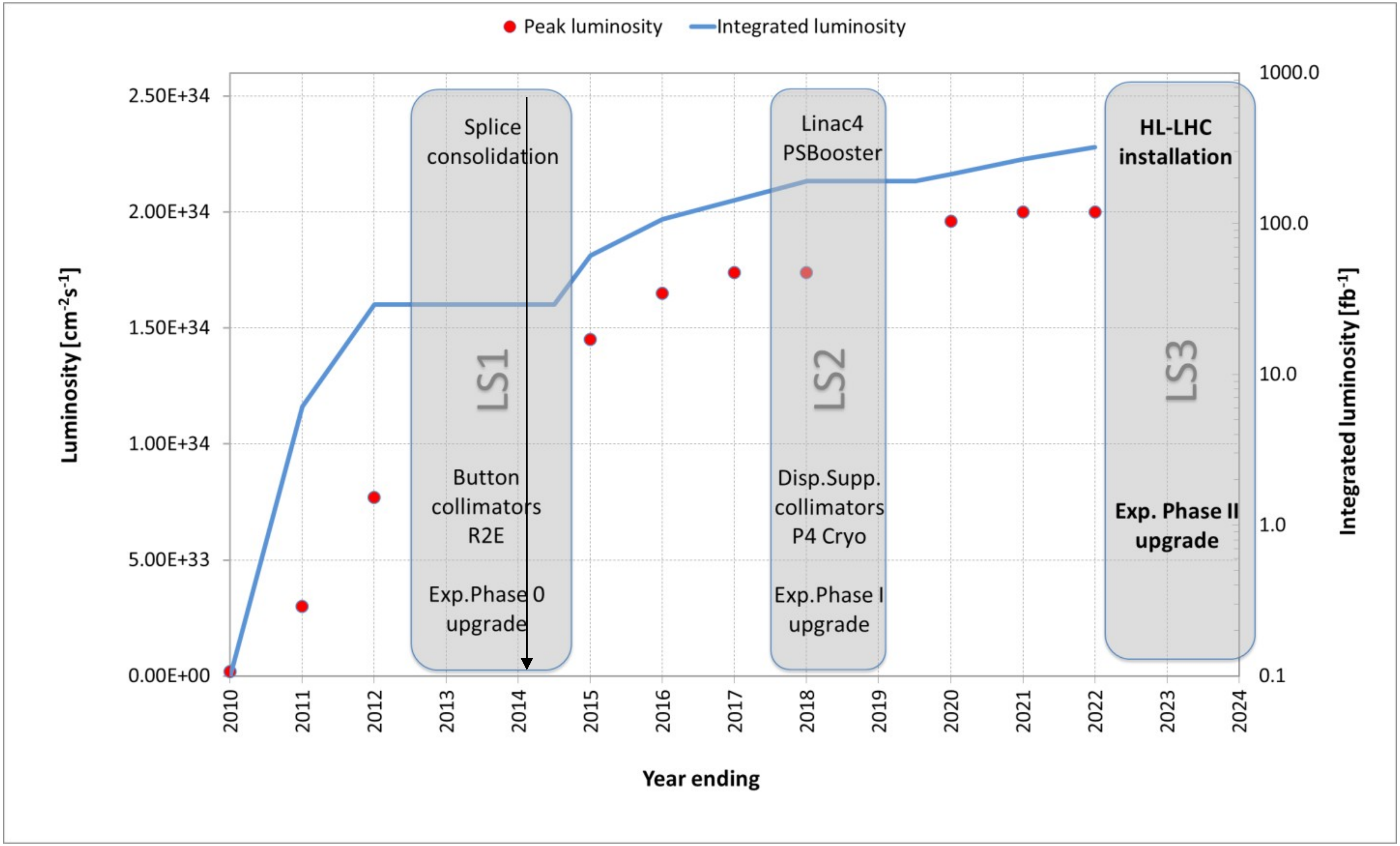


The main 2013-14 LHC consolidations

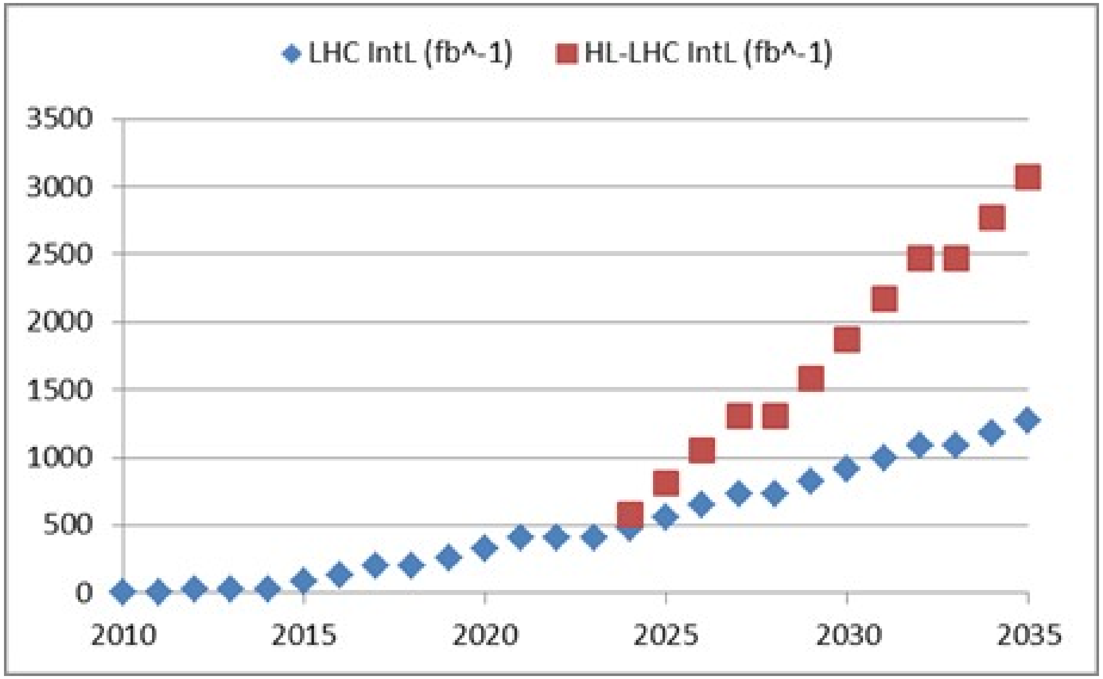
1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines



7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 4 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes



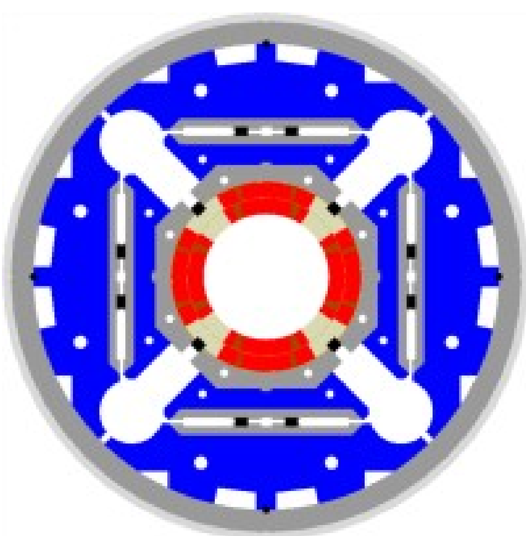
Peak luminosity
Integrated luminosity
Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
Year ending
2.50E+34
2.00E+34
1.50E+34
1.00E+34
5.00E+33
0.00E+00
1000.0
100.0
10.0
1.0
0.1
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
Splice consolidation
LS1
Button collimators R2E
Exp.Phase 0 upgrade
Linac4 PSBooster
LS2
Disp.Supp. collimators P4 Cryo
Exp.Phase I upgrade
HL-LHC installation
LS3
Exp. Phase II upgrade



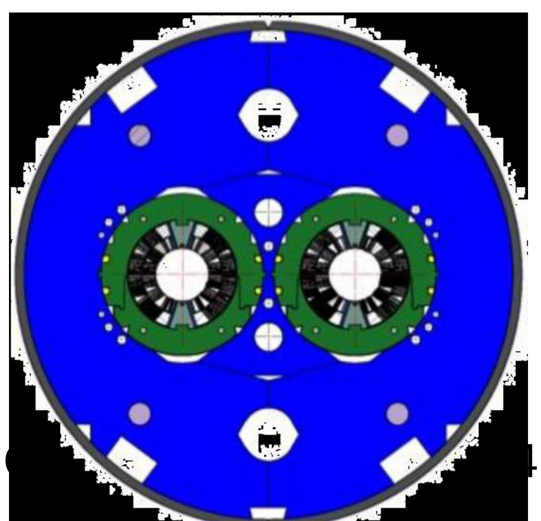
3000 fb^{-1}

300 fb^{-1}

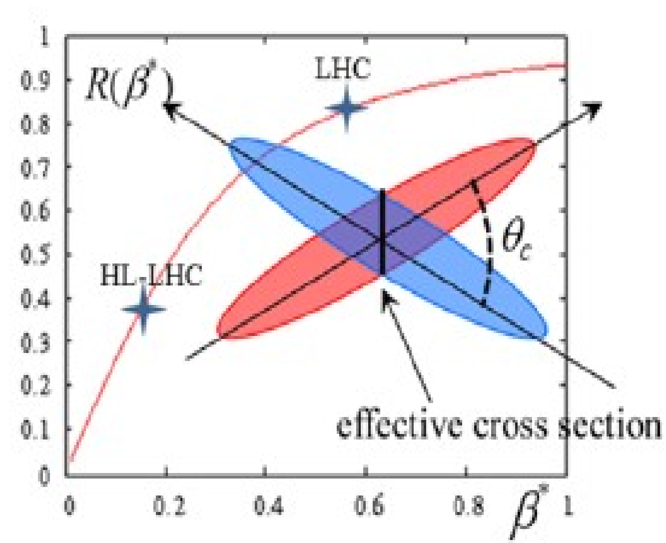
New IR Quads
Larger Aperture, Higher B Field

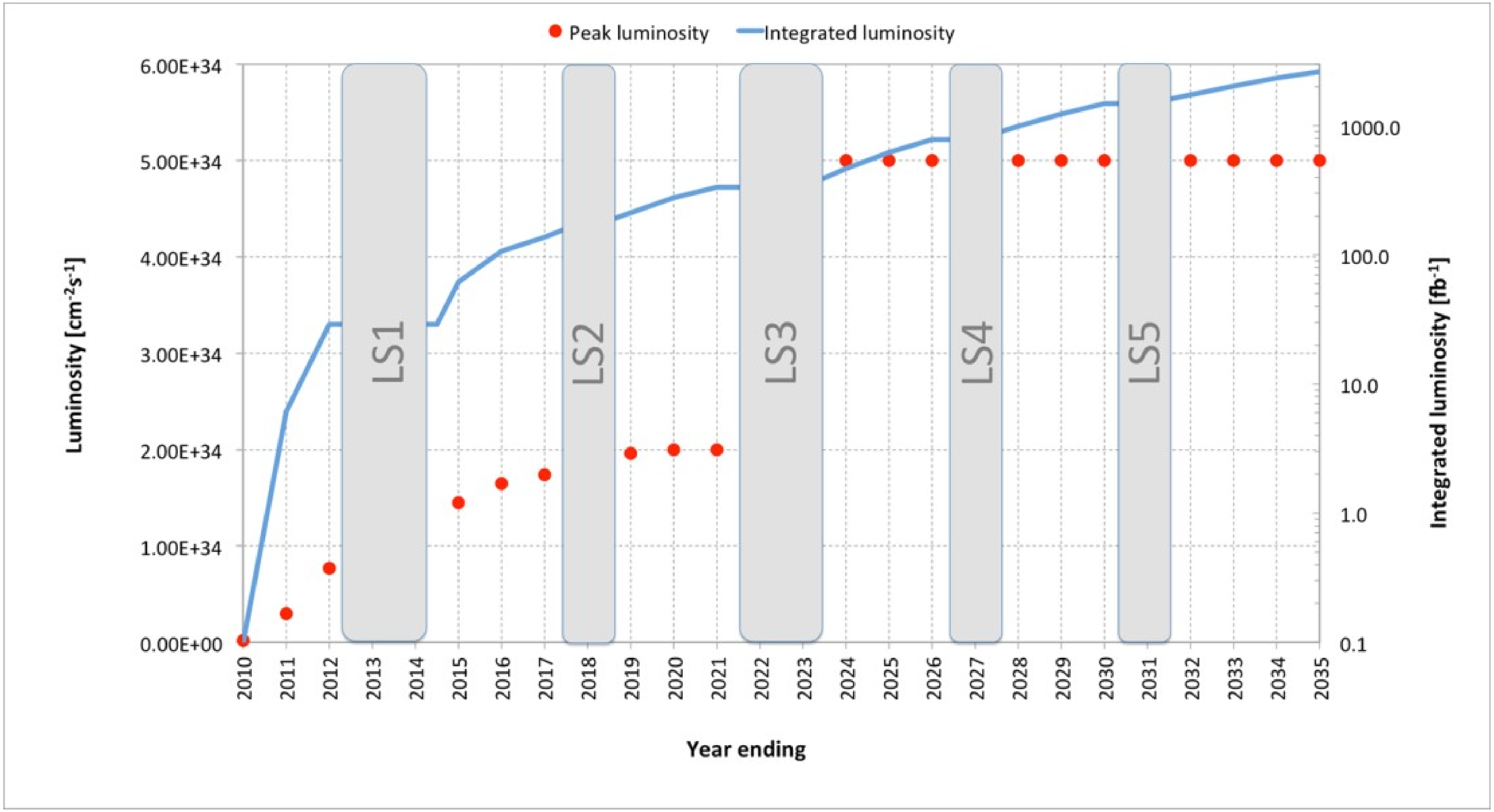


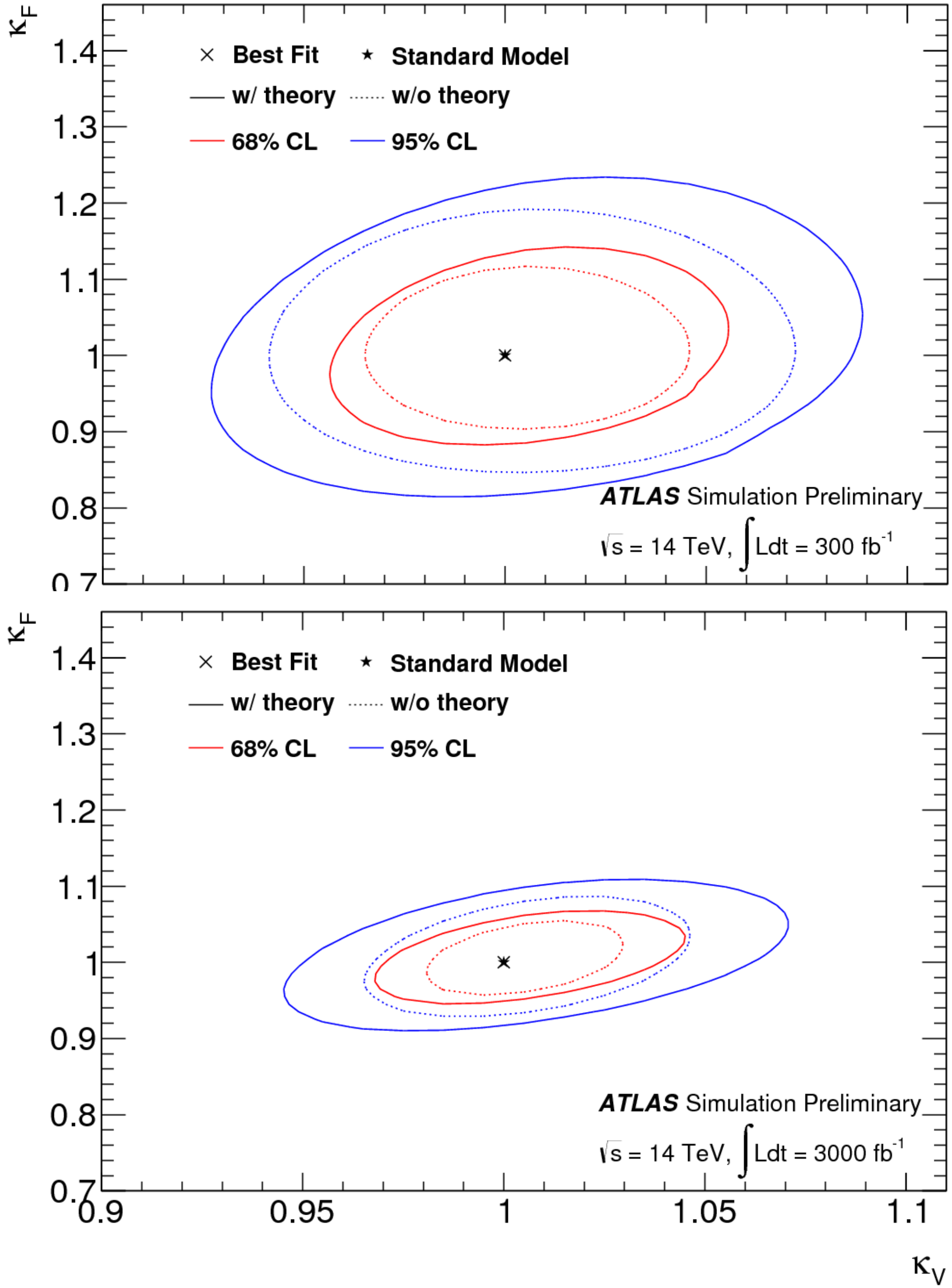
New 11 T Dipoles
for collimation upgrade



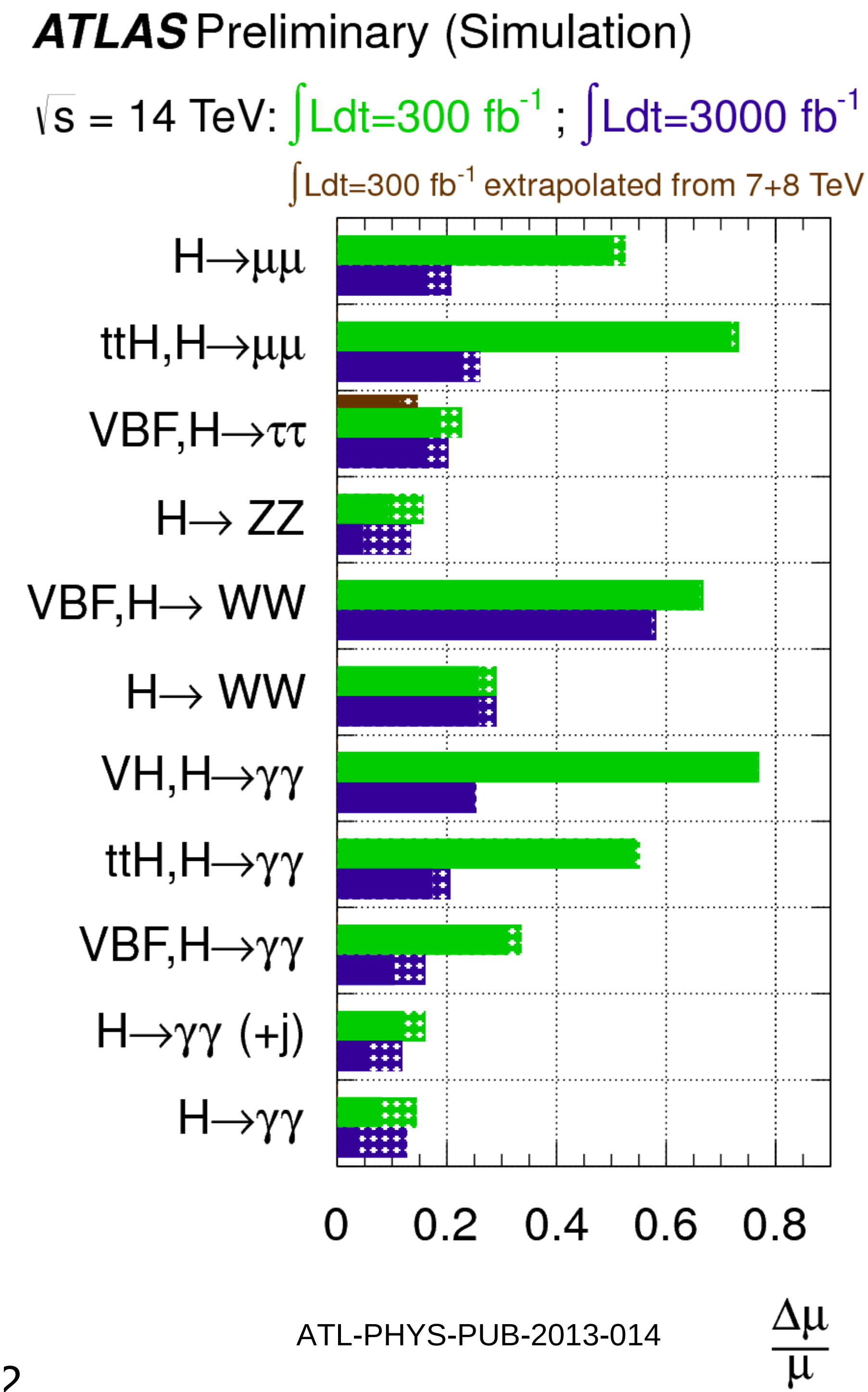
Crab crossing




Peak luminosity
Integrated luminosity
6.00E+34
5.00E+34
4.00E+34
3.00E+34
2.00E+34
1.00E+34
0.00E+00
Luminosity [cm-2s-1]
1000.0
100.0
10.0
1.0
0.1
Integrated luminosity [fb-1]
LS1
LS2
LS3
LS4
LS5
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
Year ending

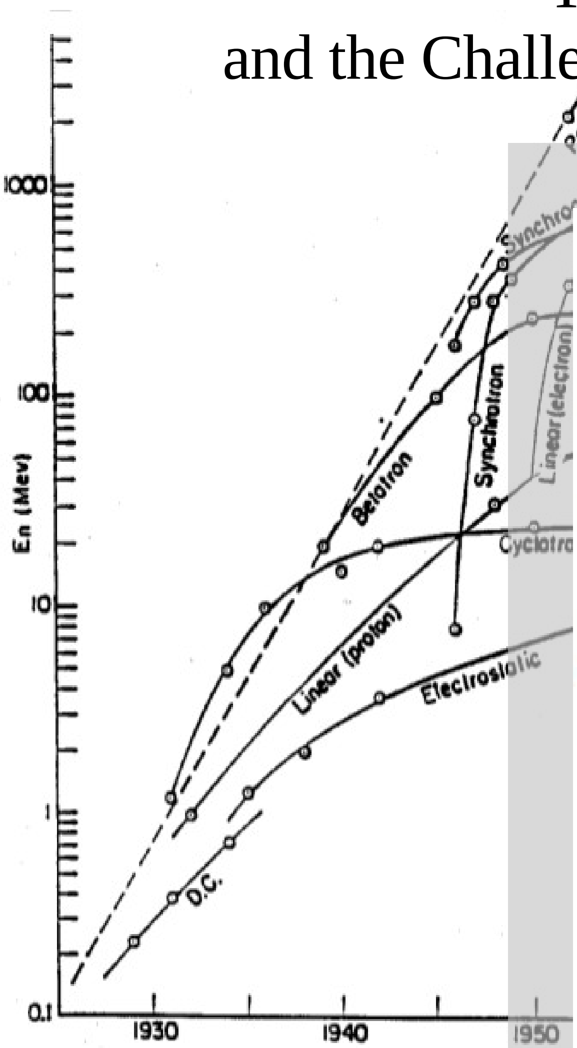


Best Fit
Standard Model
w/ theory
w/o theory
68% CL
95% CL
ATLAS Simulation Preliminary
$\sqrt{s}$ = 14 TeV, $\int Ldt$ = 300 fb^{-1}
$\sqrt{s}$ = 14 TeV, $\int Ldt$ = 3000 fb^{-1}
κ_F
κ_V

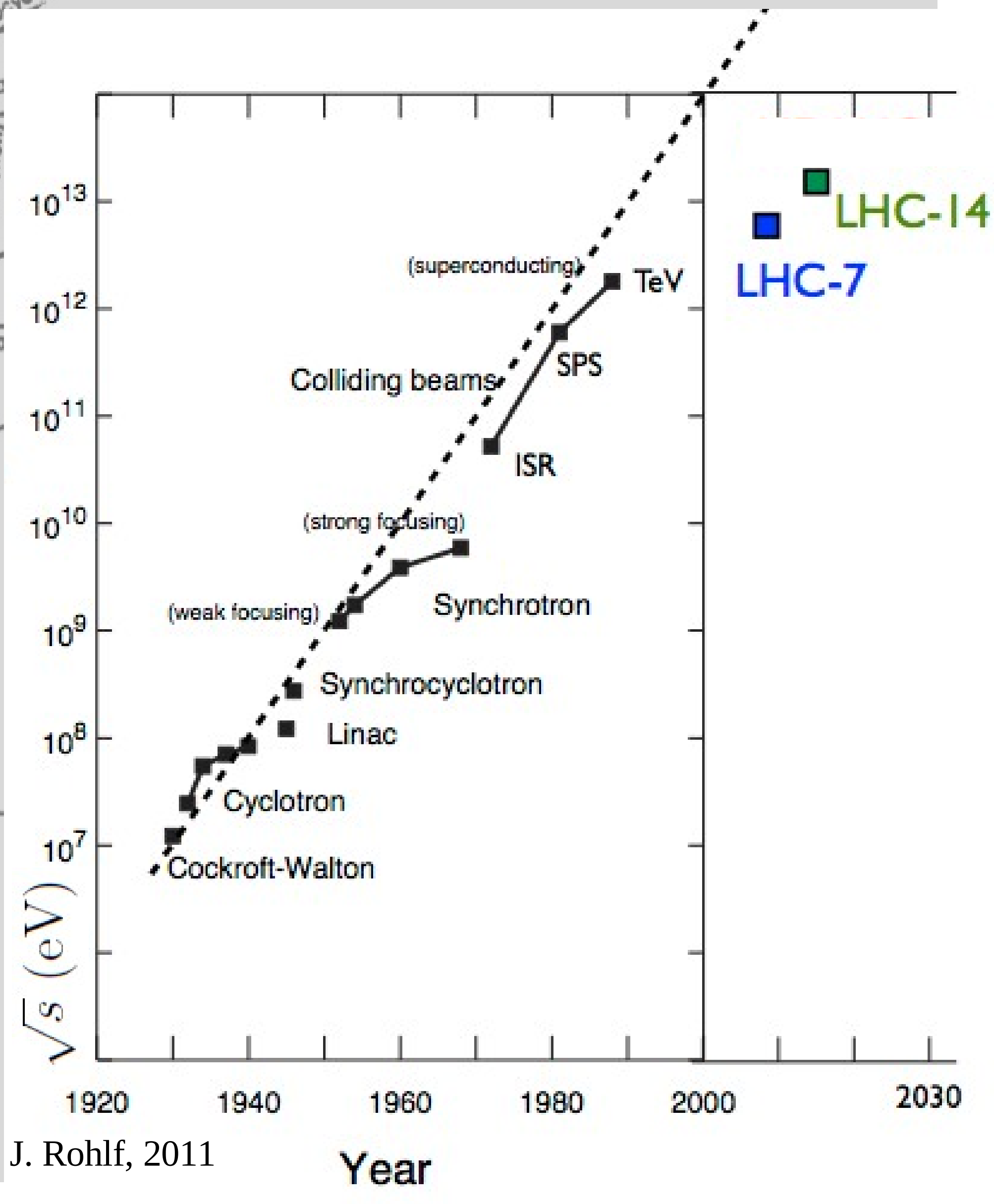


ATLAS Preliminary (Simulation)
$\sqrt{s}$ = 14 TeV: $\int Ldt$=300 fb^{-1} ; $\int Ldt$=3000 fb^{-1}
$\int Ldt$=300 fb^{-1} extrapolated from 7+8 TeV
$H\rightarrow\mu\mu$
ttH,$H\rightarrow\mu\mu$
VBF,$H\rightarrow\tau\tau$
$H\rightarrow$ ZZ
VBF,$H\rightarrow$ WW
$H\rightarrow$ WW
VH,$H\rightarrow\gamma\gamma$
ttH,$H\rightarrow\gamma\gamma$
VBF,$H\rightarrow\gamma\gamma$
$H\rightarrow\gamma\gamma$ (+j)
$H\rightarrow\gamma\gamma$
$\frac{\Delta\mu}{\mu}$
ATL-PHYS-PUB-2013-014

The Livingston Curve
and the Challenges of High(er) Energy Colliders



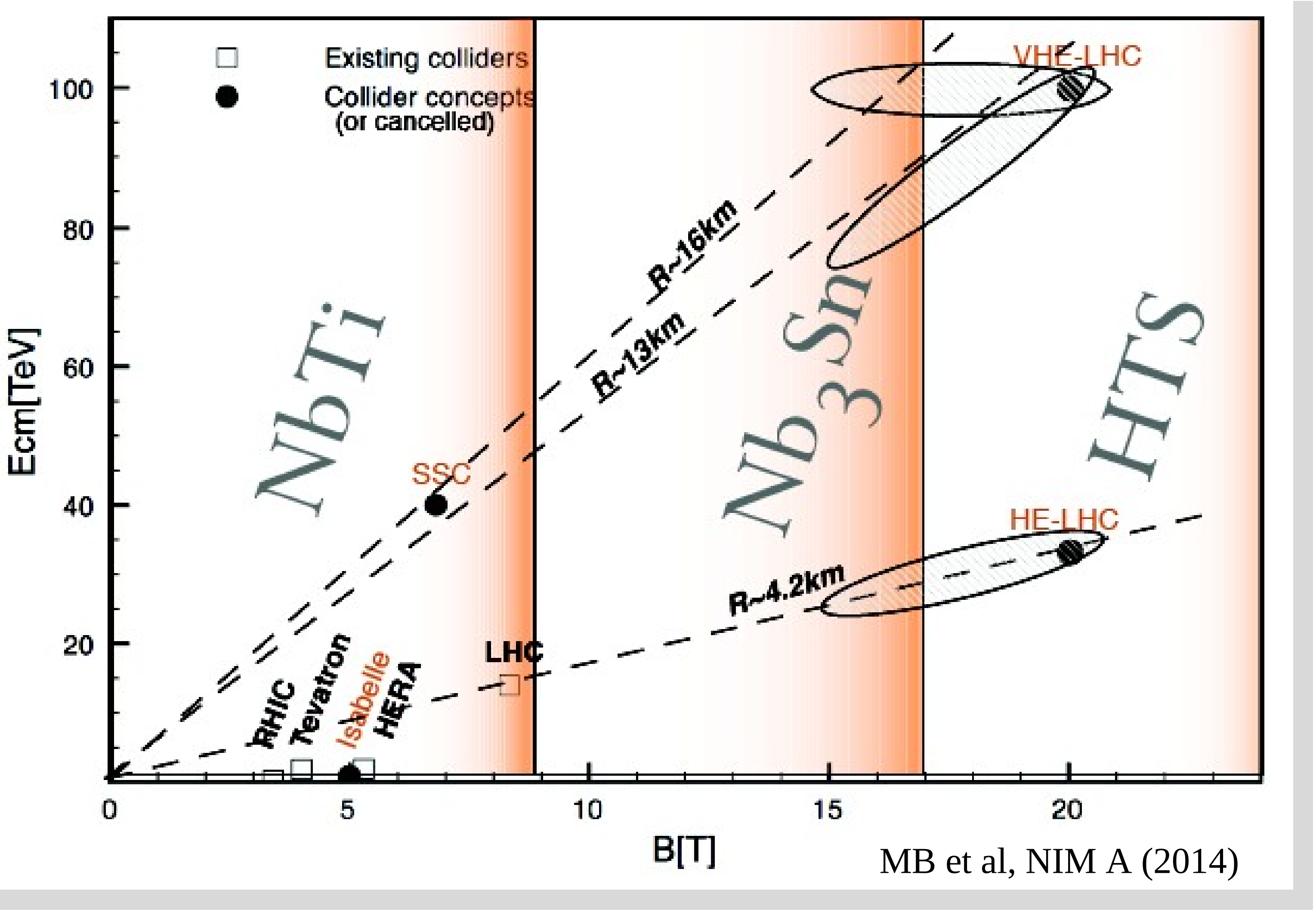
M.S. Livingston 1954



J. Rohlf, 2011

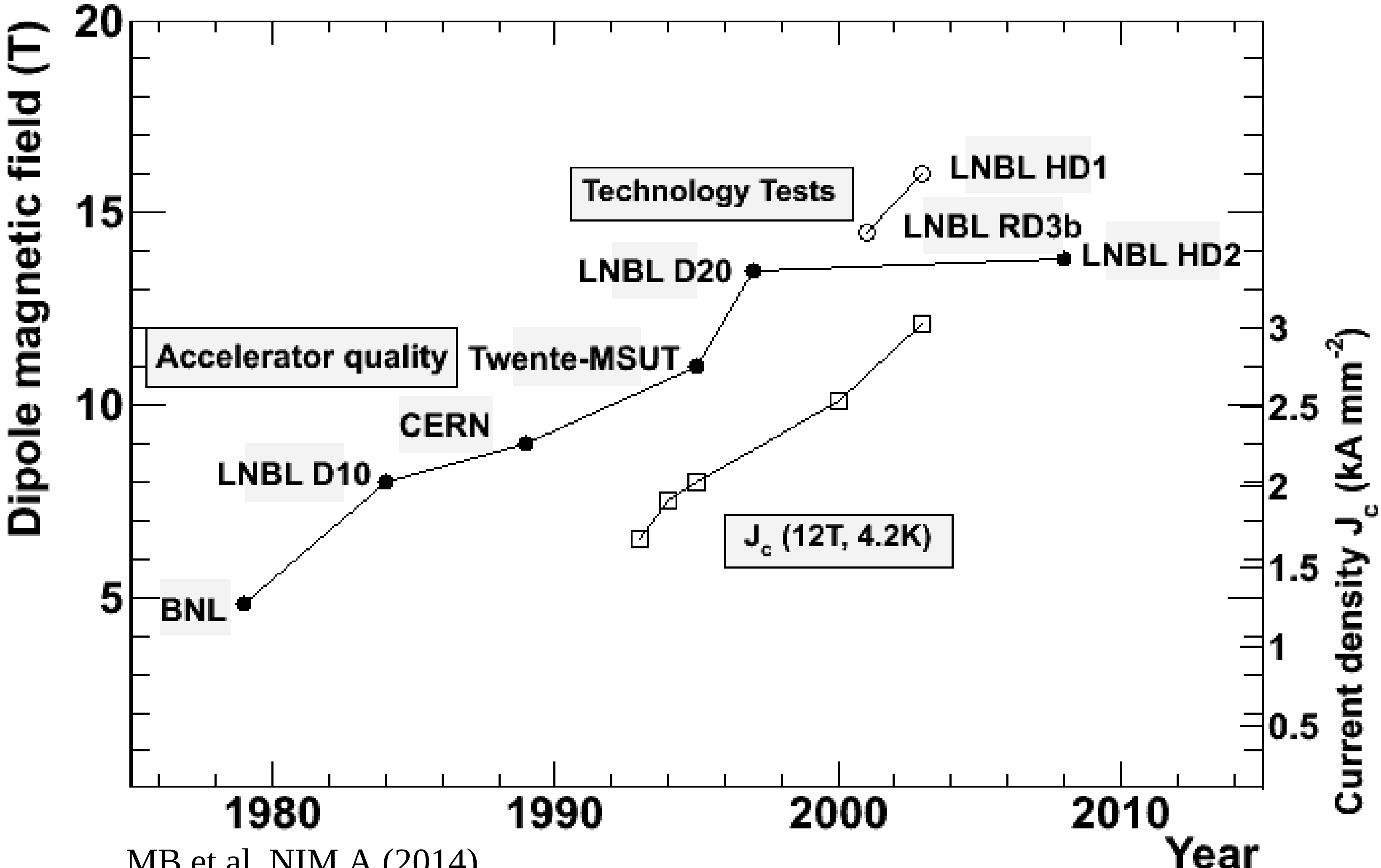
Collider Energy and Dipole Magnetic Field Strength

$$E = 0.3B(\mathrm{T})R(\mathrm{km})$$

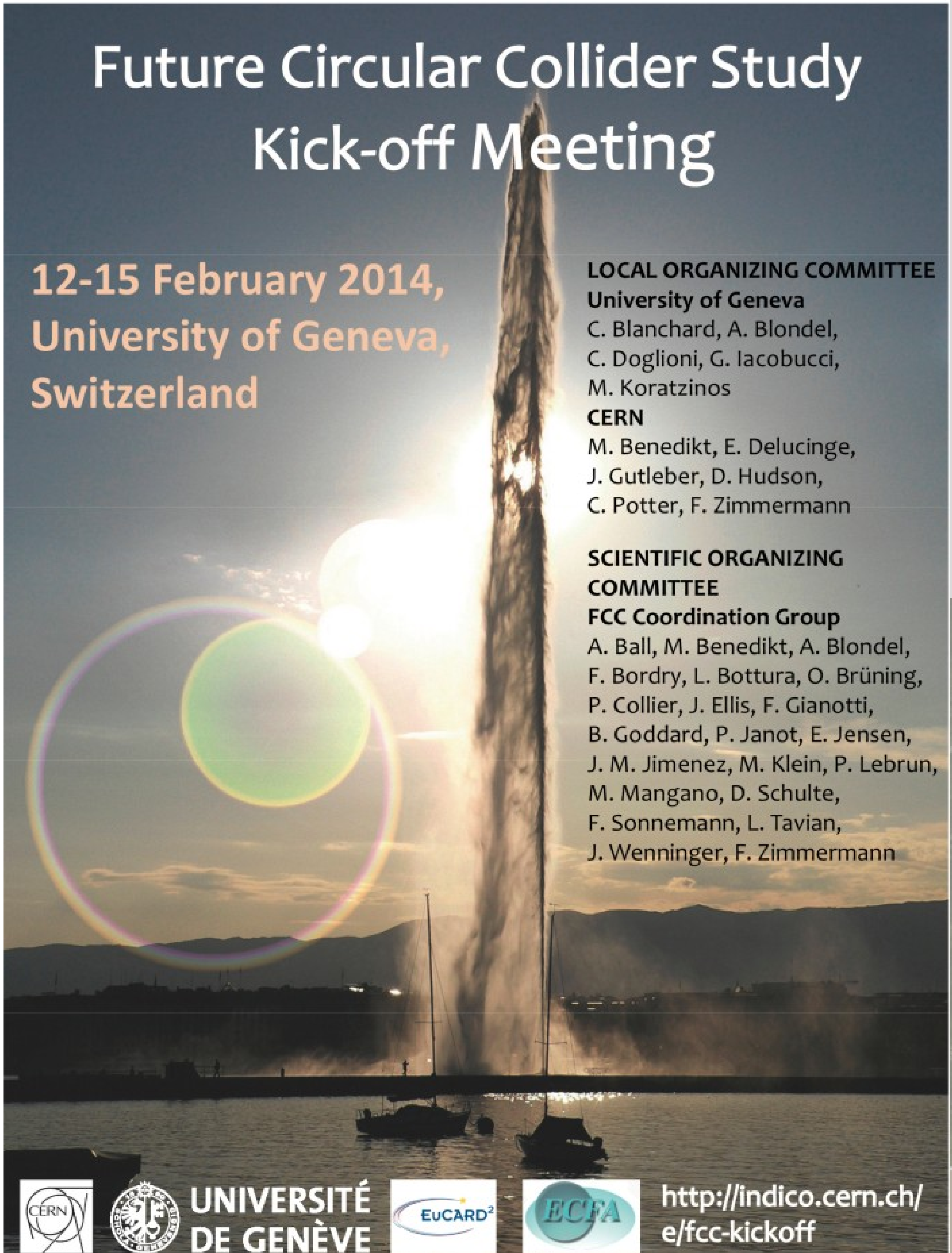


MB et al, NIM A (2014)

Progress with Superconducting Magnetic Field



MB et al, NIM A (2014)



Start of a 5-year study for a 100 TeV hadron collider in a 80-100 km tunnel