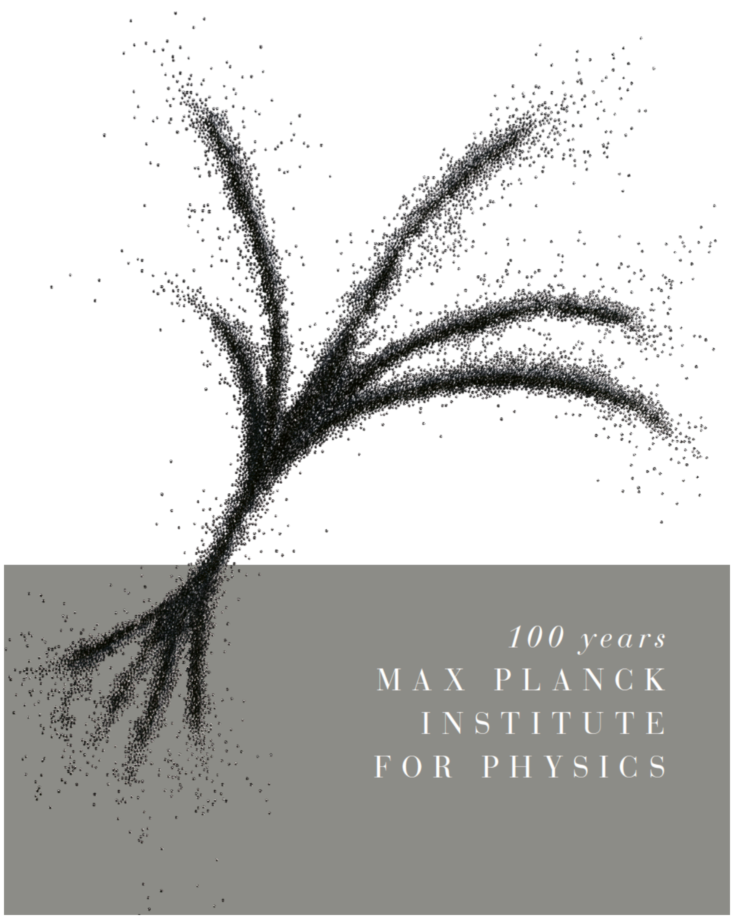
MPI 100 Year Anniversary

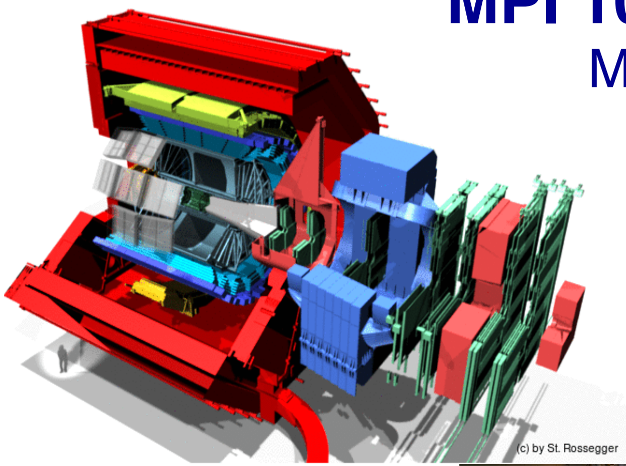


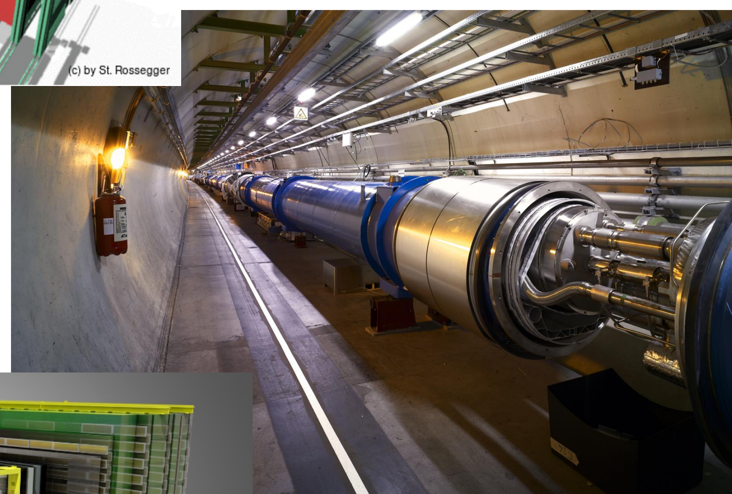
Imperial College London

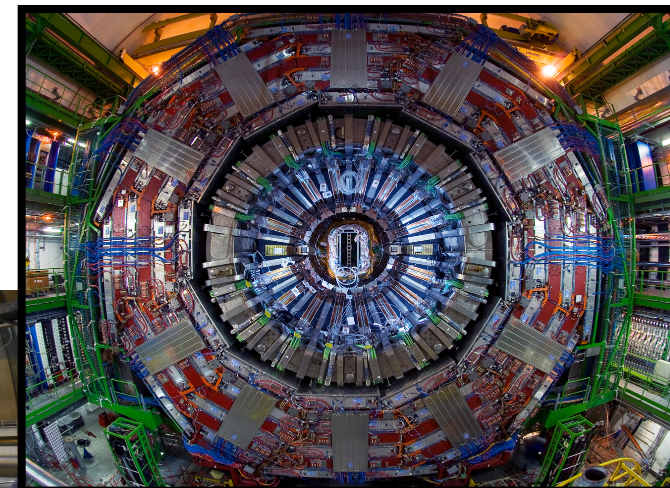
The LHC – perspectives for discovery

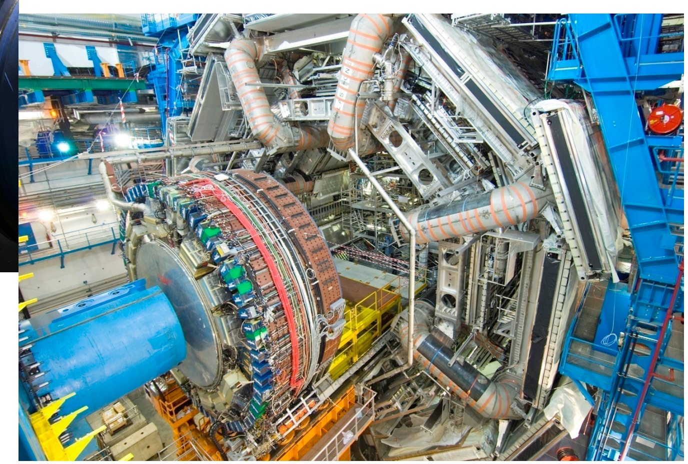
MPI 100 Year Anniversary

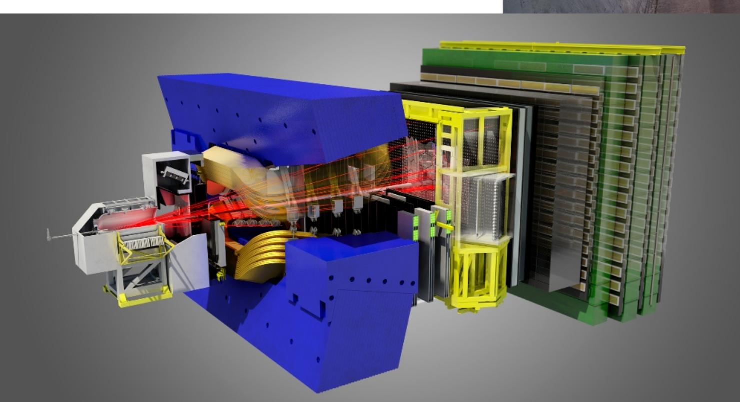
Munich 10-12 Oct'17





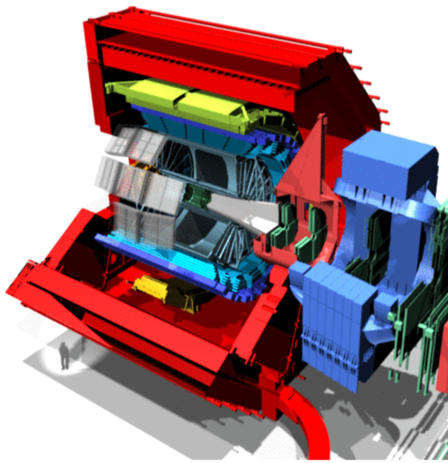


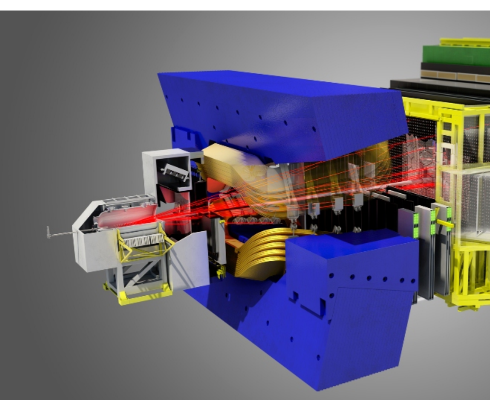


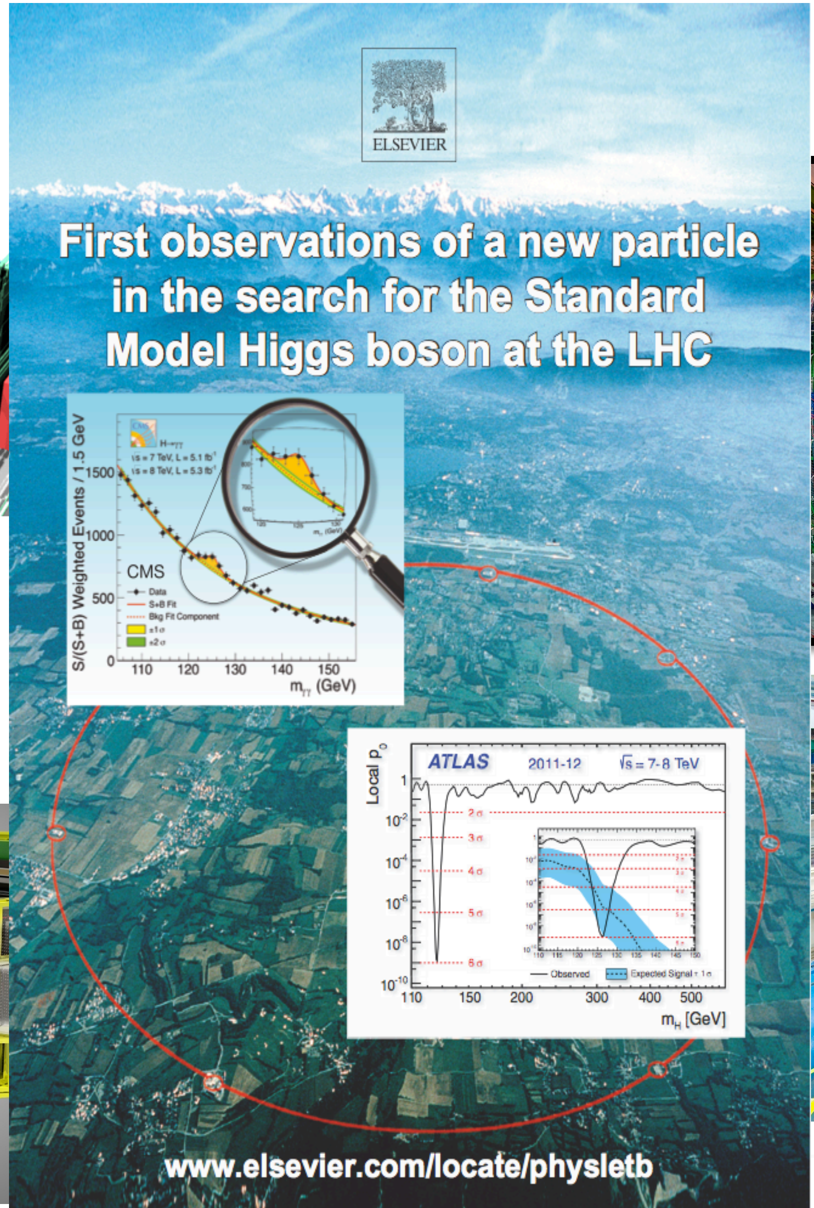


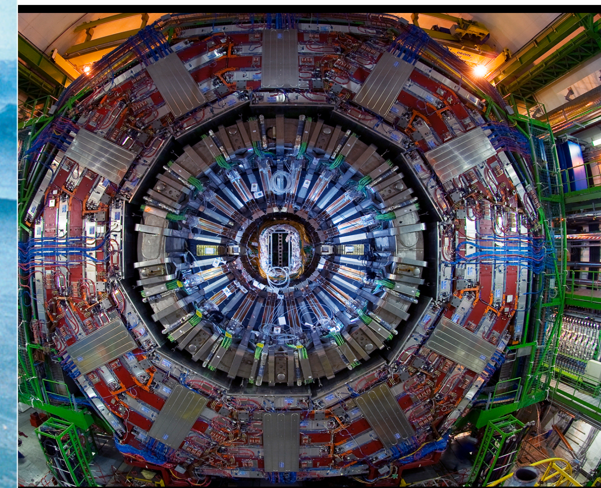
Tejinder S Virdee, Imperial College

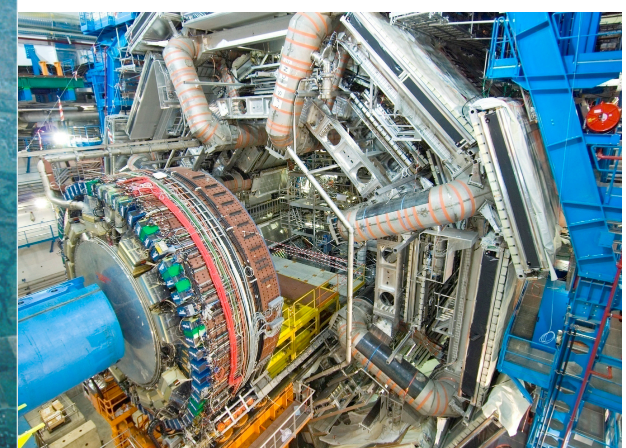
The LHC – perspectives for discovery



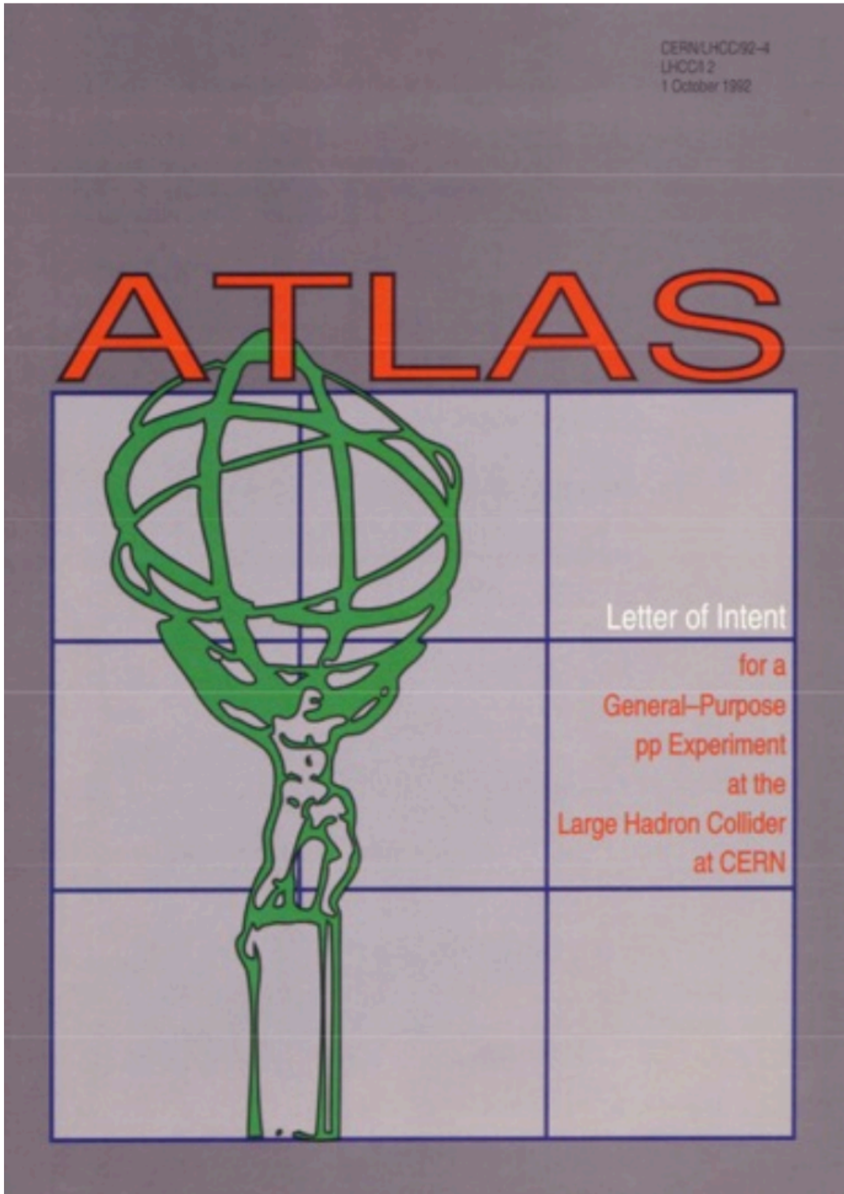


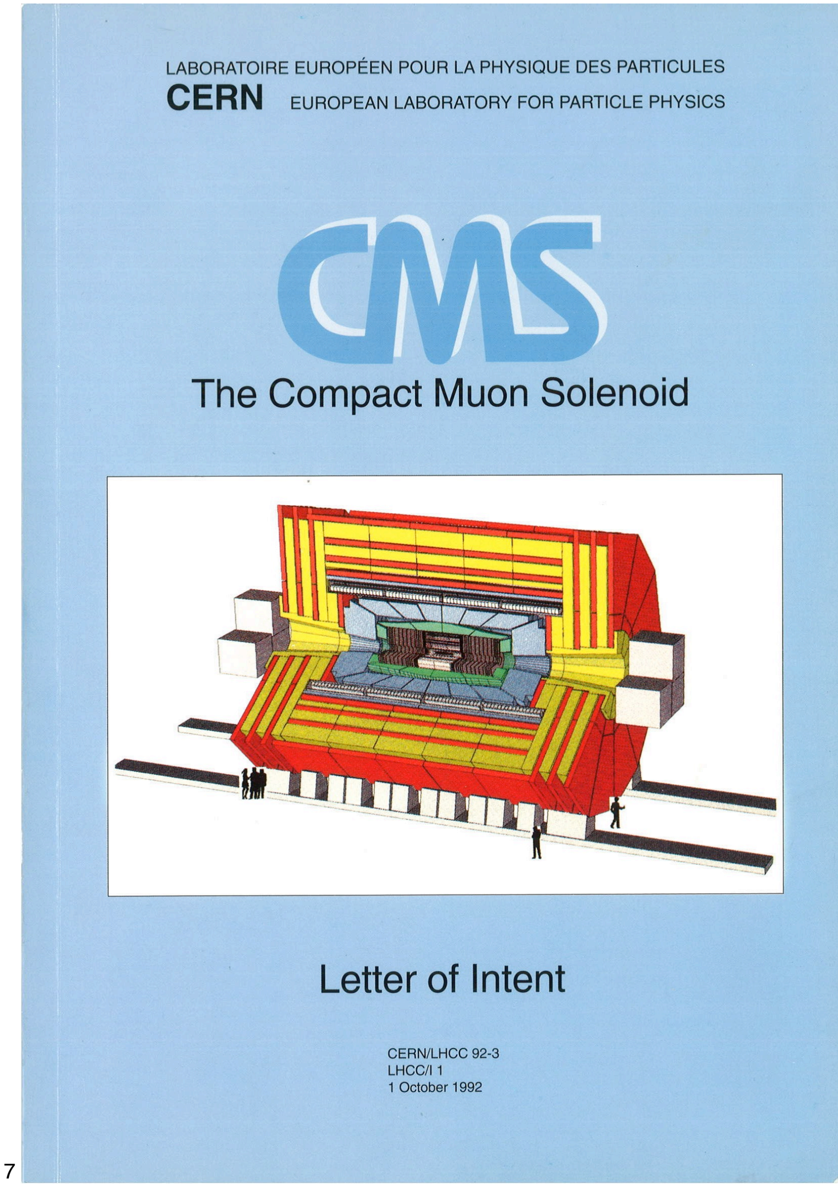






ATLAS and CMS – 25 Year Anniversary of LoI





Outline of the Talk

LHC

Where do we stand today (LHC and Experiments)?

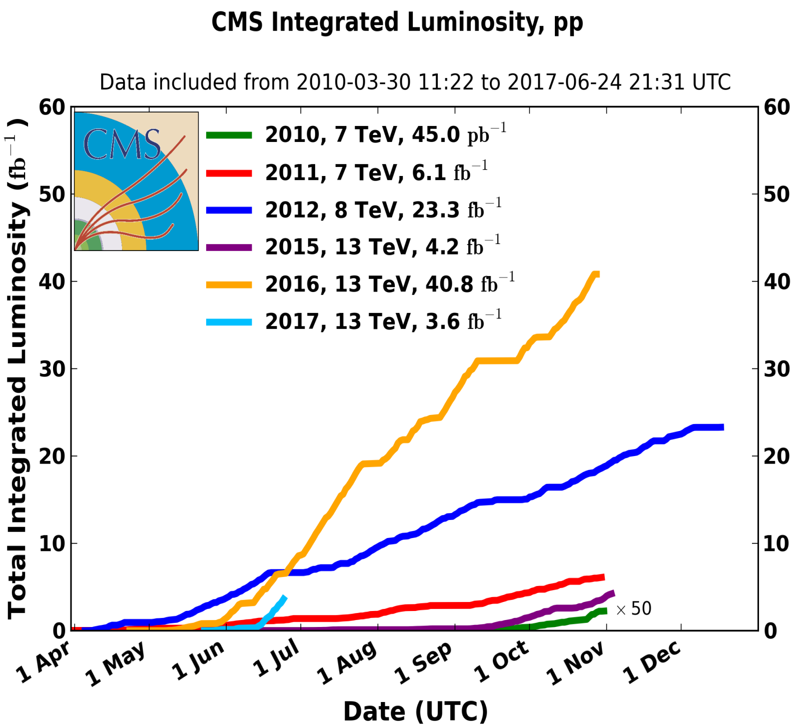
What are the expectations for an integrated luminosity of 300 fb^{-1} (original design goal)?

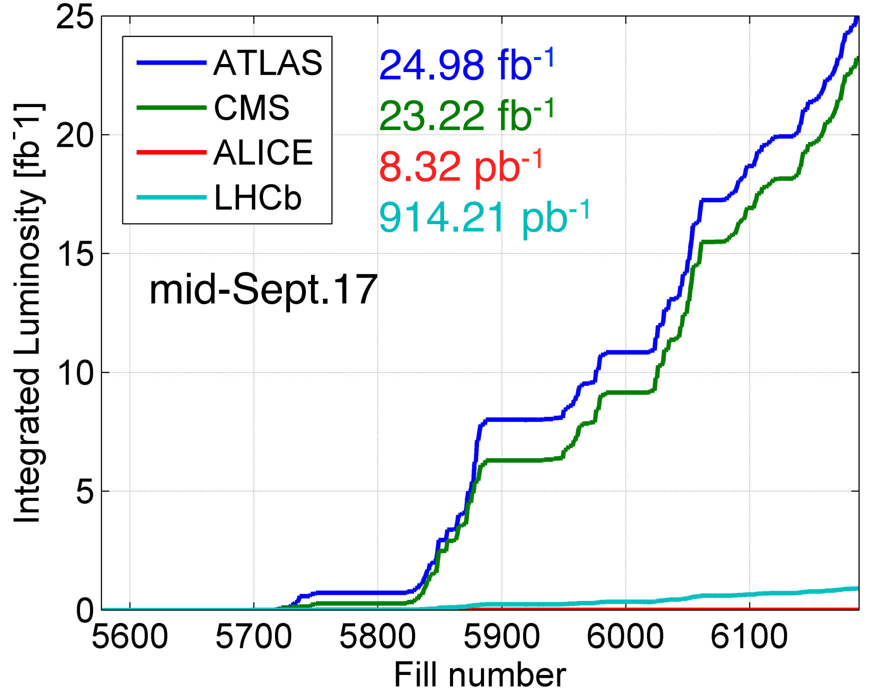
HL-LHC

What are the upgrades to the experiments?

What are the expectations for an integrated luminosity 3000 fb^{-1}(HL-LHC design goal)?

The LHC Accelerator is Operating Superbly





Much progress has been made in the recent years

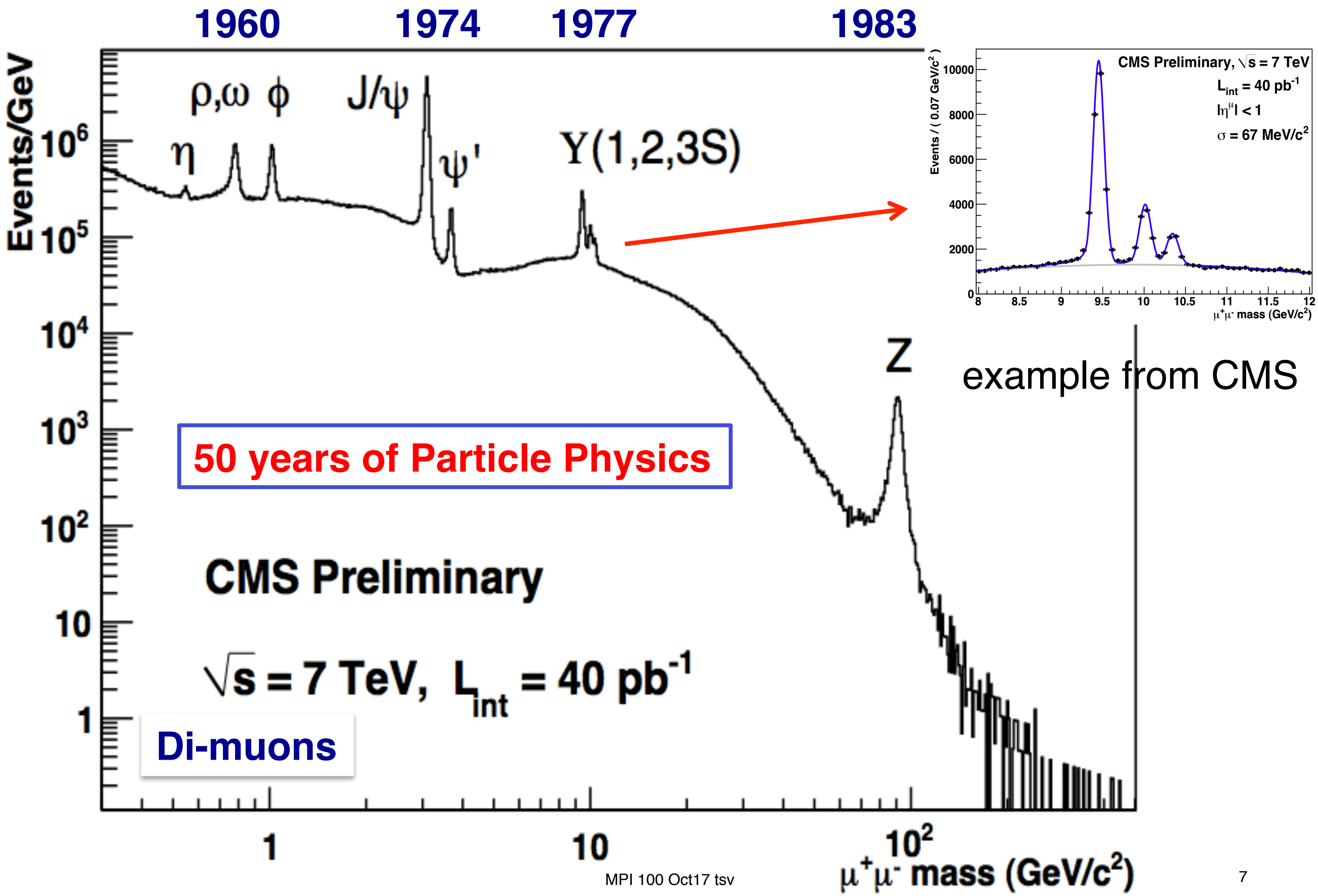
High machine availability (up to ~ 50%)

High luminosity lifetime

High peak luminosity (reached >1.7 10^{34} $cm^{-2}s^{-1}$)

More bunches, higher bunch intensity, stronger focussing

So are the experiments .....

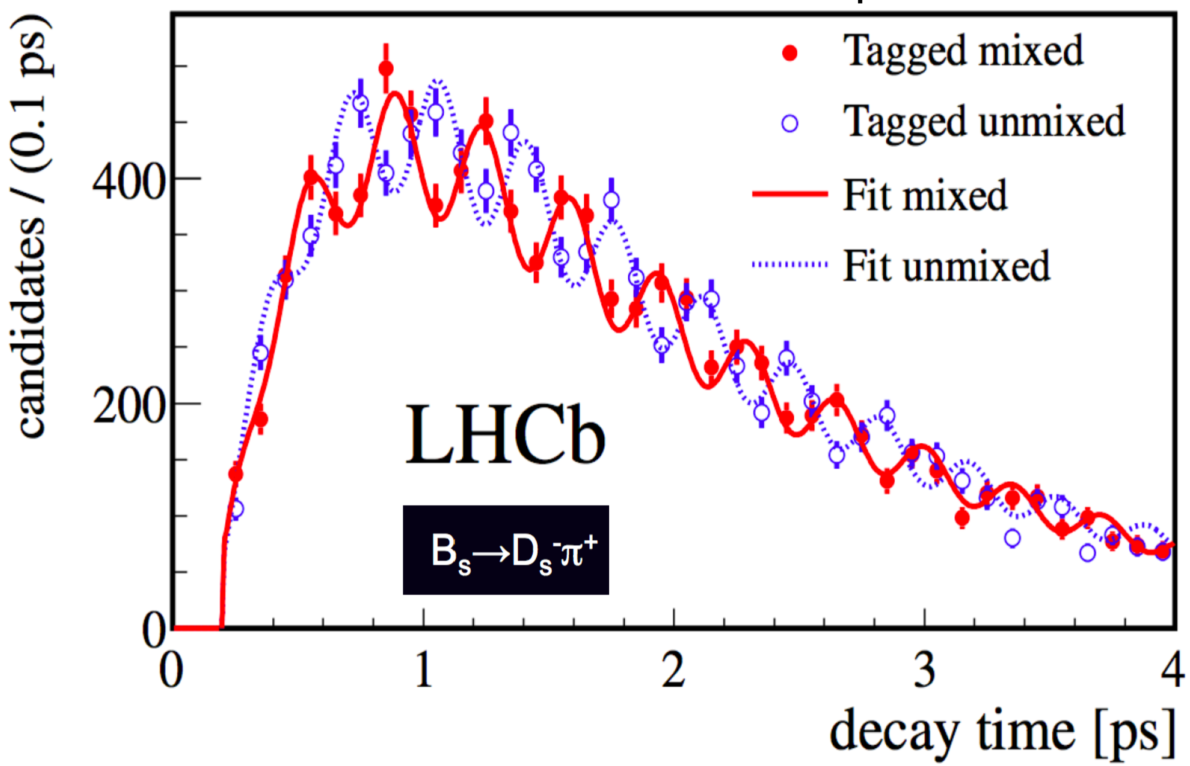


example from CMS

So are the experiments …

- Precision measurement of the B_S^0–B_S^0 Oscillation frequency (equivalent to mass difference Δm_S of the B_S^0 mass eigenstates).
- Using 34k $B_s \rightarrow D_S^- \pi^+$ decays

example from LHCb

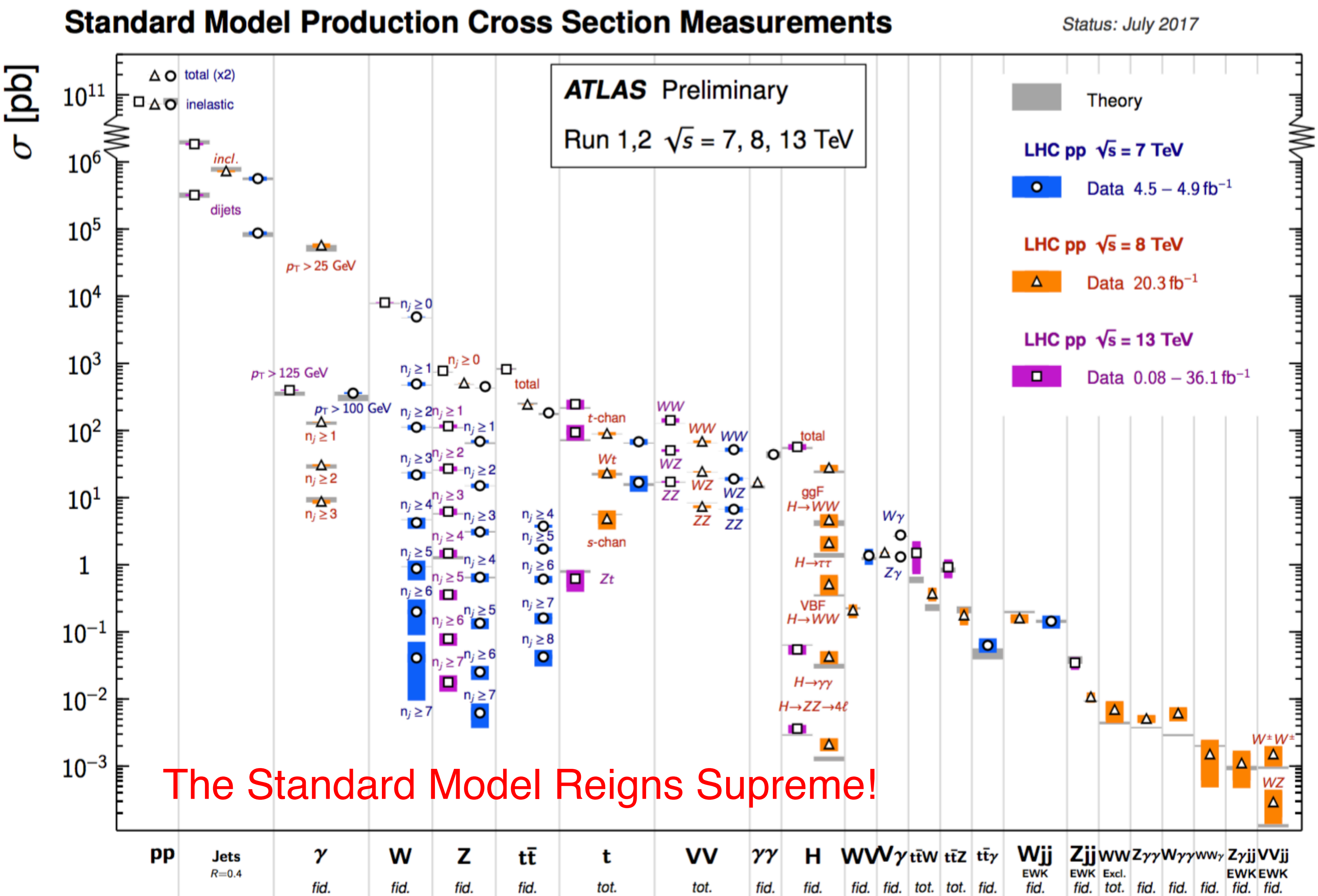


Δm_S = 17.768±0.023(stat)±0.006(syst) ps^{-1}

LHCb: NJP 15(2013)053021

Imperial College London

And making superb measurements (1)

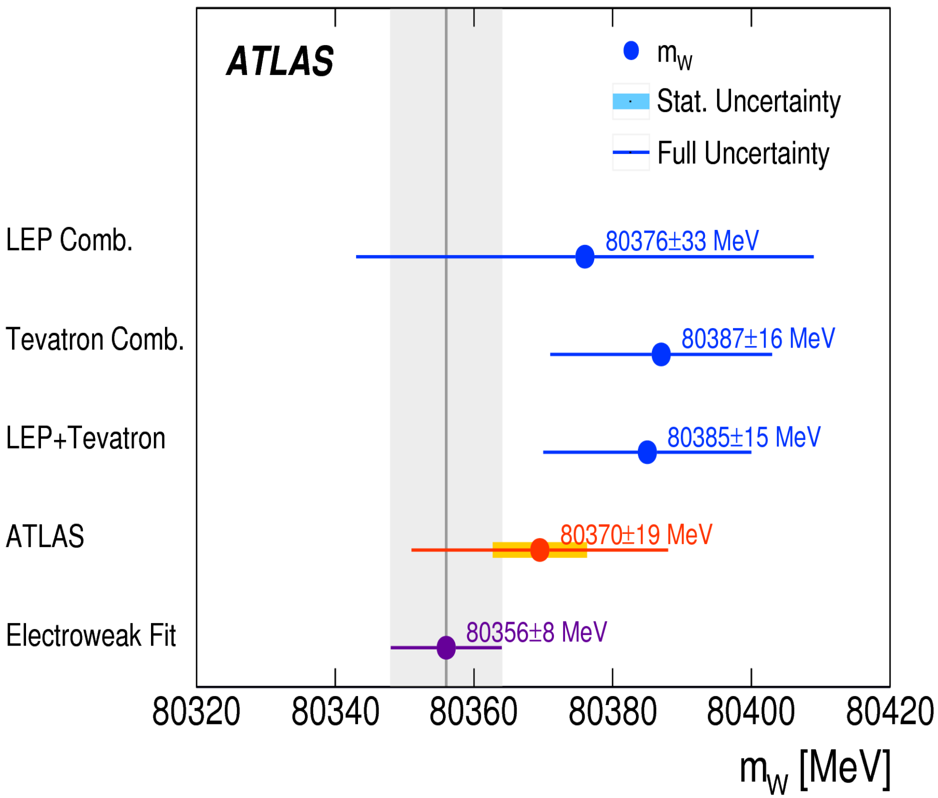


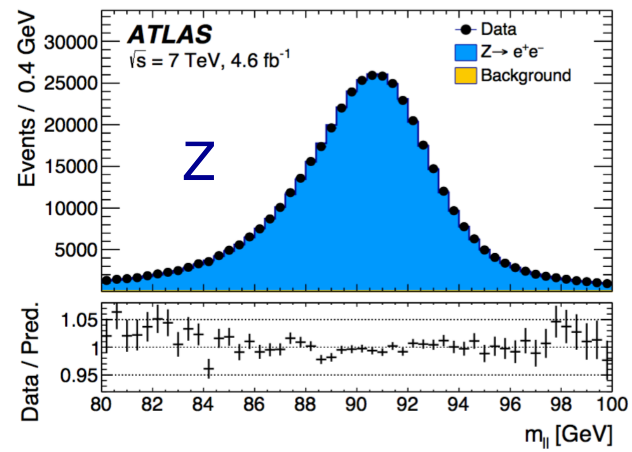
And making superb measurements (2)

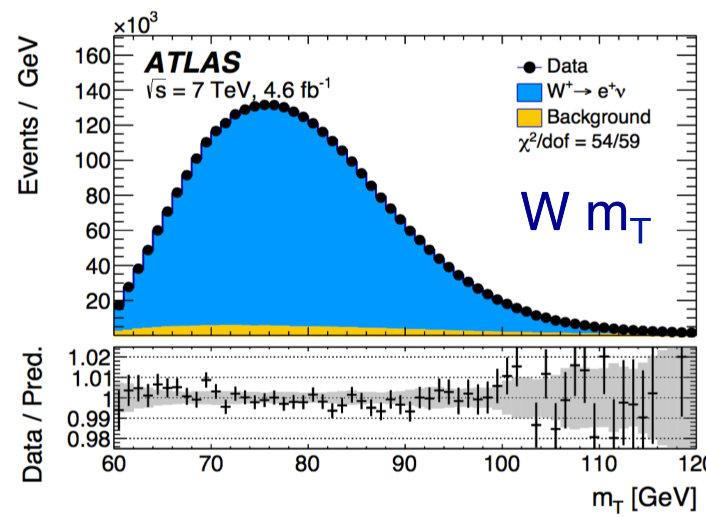
m_W

Electroweak Fit

$M_W = 80.358 \pm 0.008$ GeV



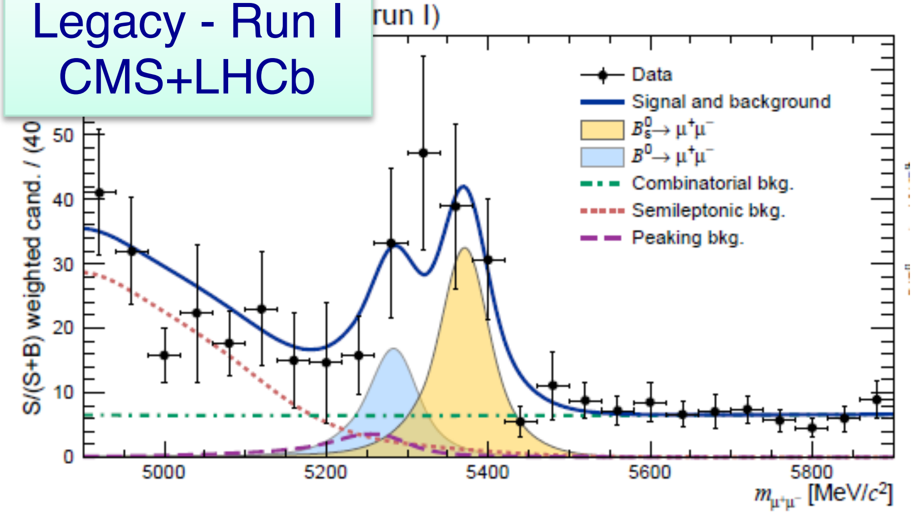




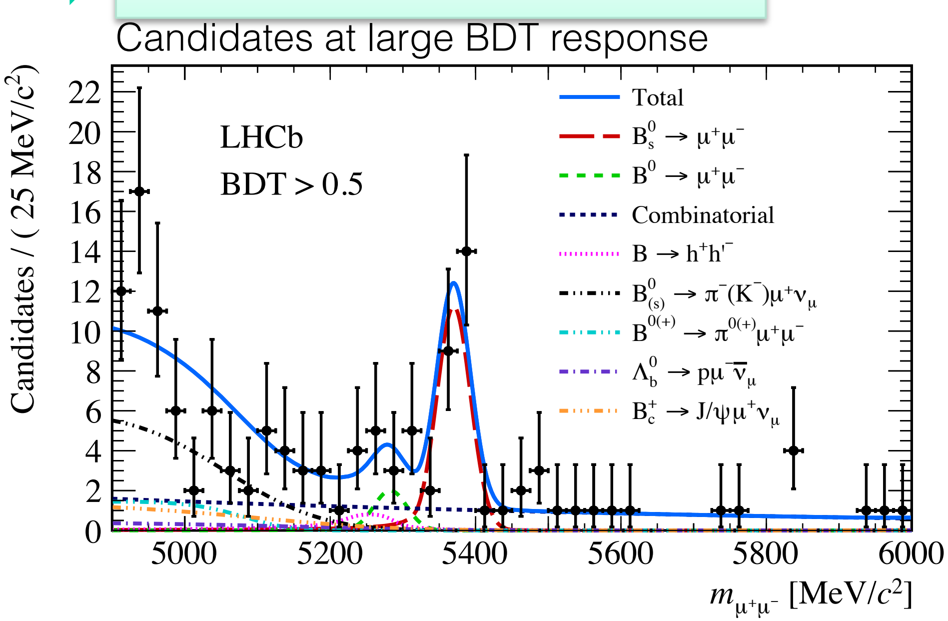
$$
\begin{aligned}
m_W &= 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV} \\
&= 80370 \pm 19\ \text{MeV},
\end{aligned}
$$

And making superb measurements (3)

Legacy - Run I CMS+LHCb

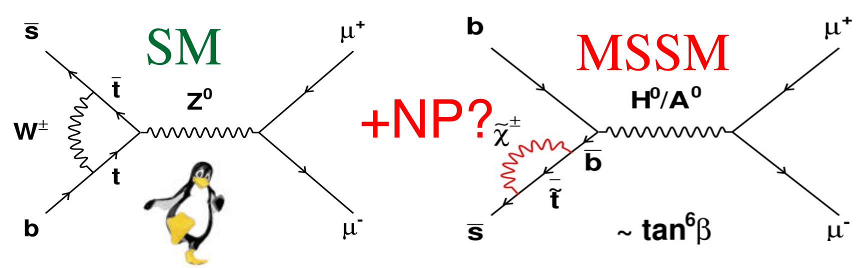


LHCb alone: >7σ

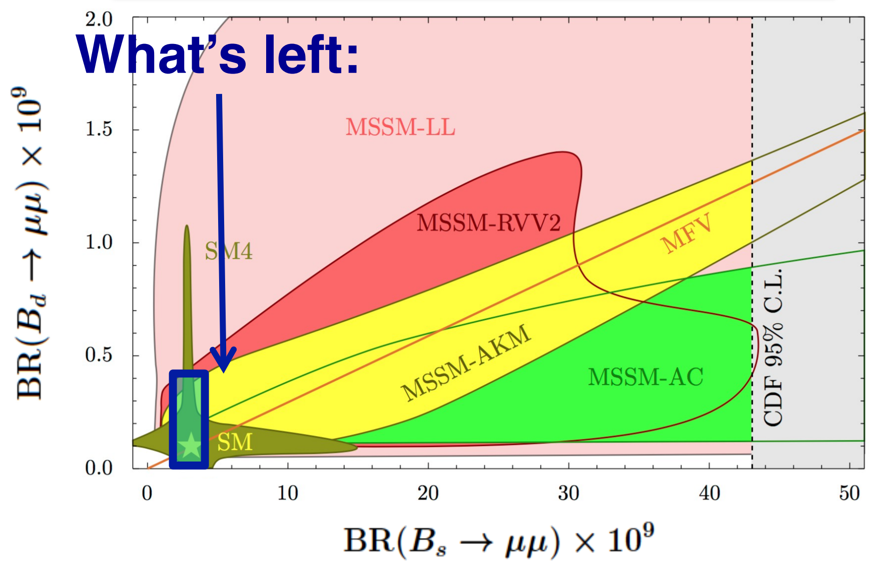


ct17 tsv

Flavor Physics: rare processes



… and did away with many hopes for signs of NewPhys

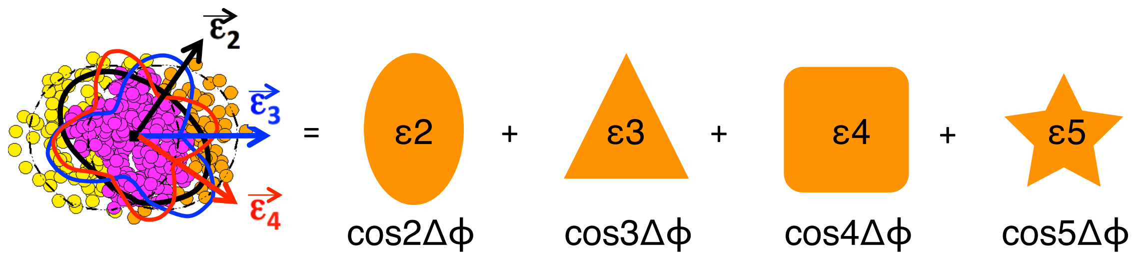


And making superb measurements (4)

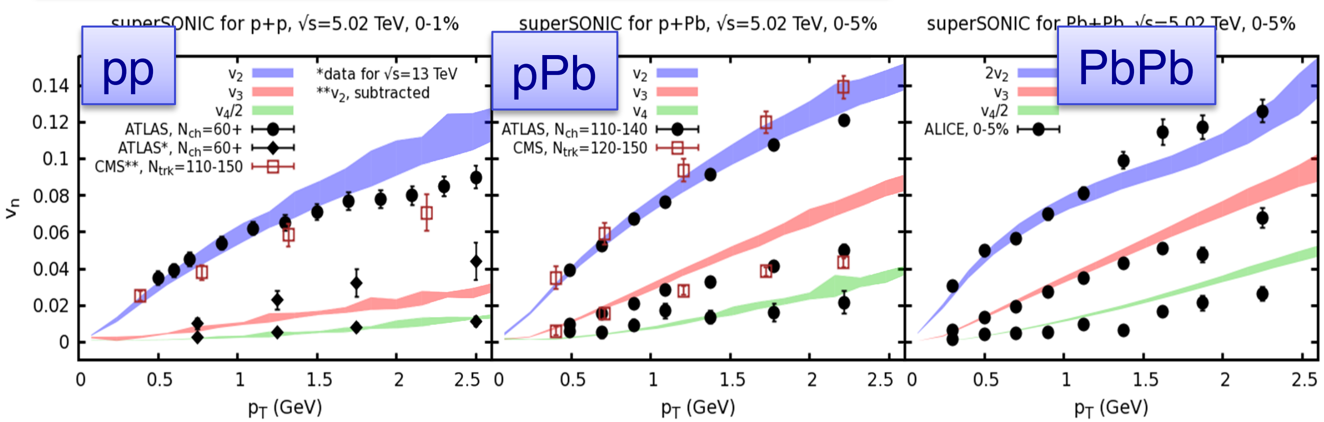
Heavy Ions: collectivity (flows)

Multipole expansion

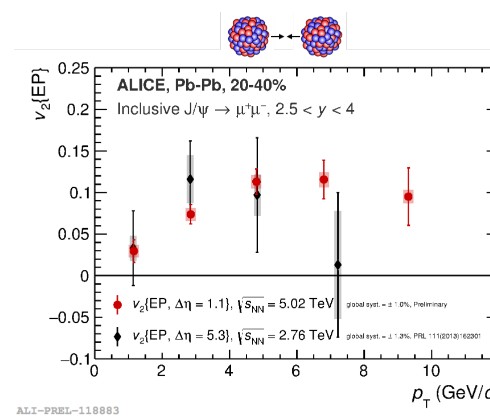
$$\frac{d^3N}{dyd^2p_T} = \frac{d^2N}{dydp_T^2}\left[1+2\sum_{n=1}^{\infty} v_n(p_T)\cos(\phi-\psi_n)\right] \qquad \psi_n = \frac{1}{n}\arctan\left(\frac{\langle p_T \sin n\phi\rangle}{\langle p_T \cos n\phi\rangle}\right)$$



"One fluid to rule them all"



Charm flows too

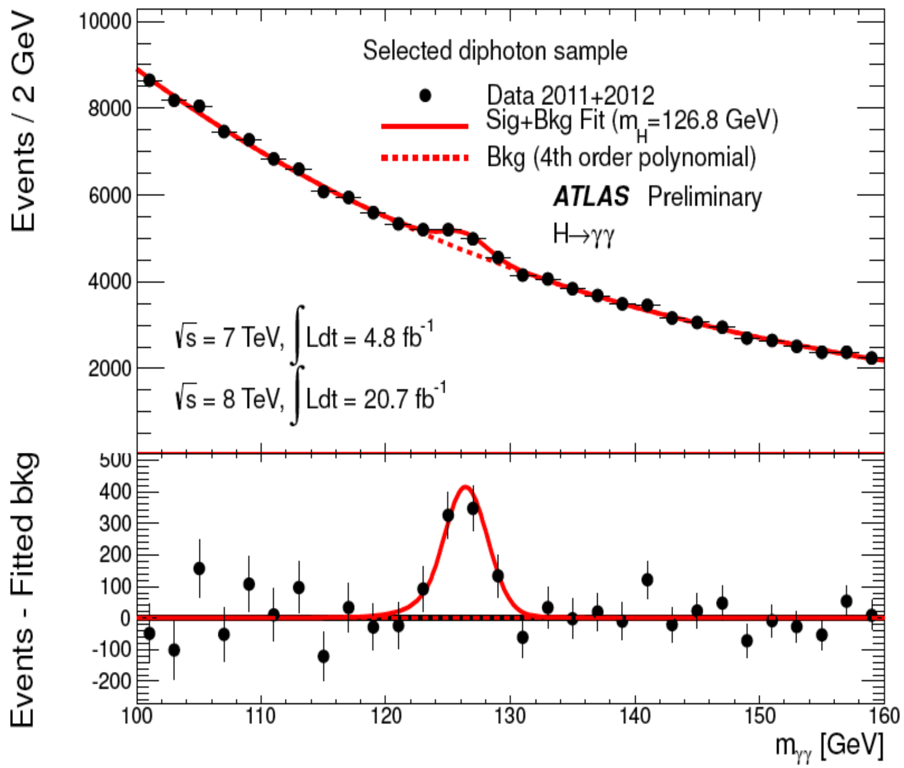


Imperial College London

Making Discoveries: Run 1 Legacy Results: H → bosons

ATLAS: H→ 2γ Channel

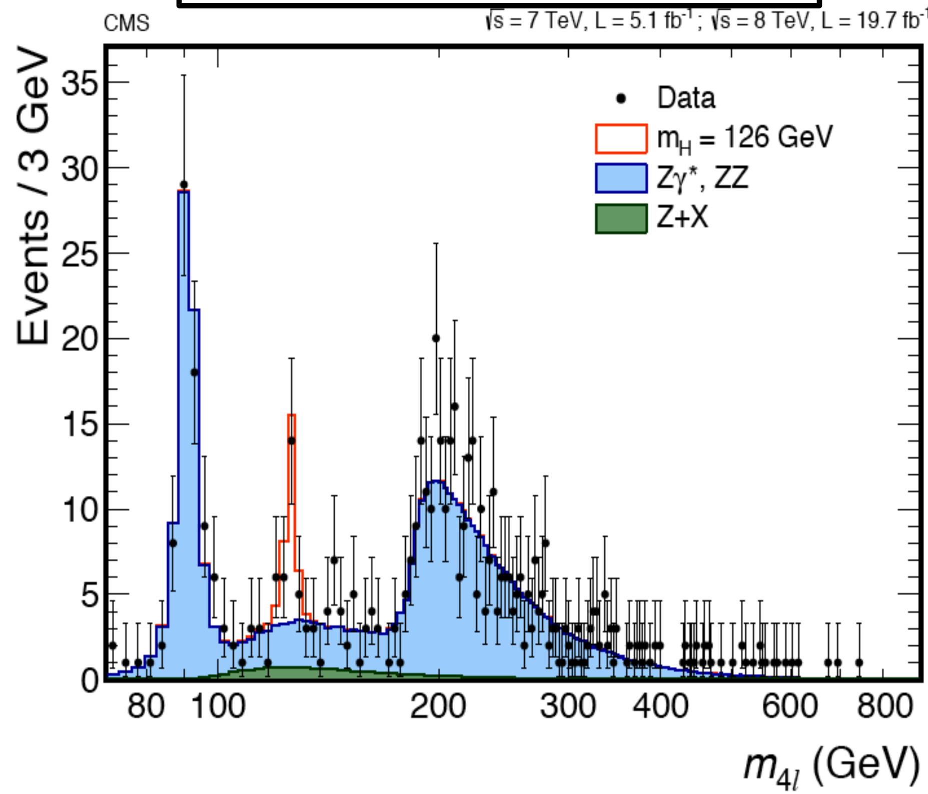
Phys. Rev. D90 (2014) 112015.



Sign/Exp	Exp	Obs
ATLAS	4.6 σ	5.2 σ
CMS	5.3 σ	5.6 σ

CMS: H→Z→4*l* Channel

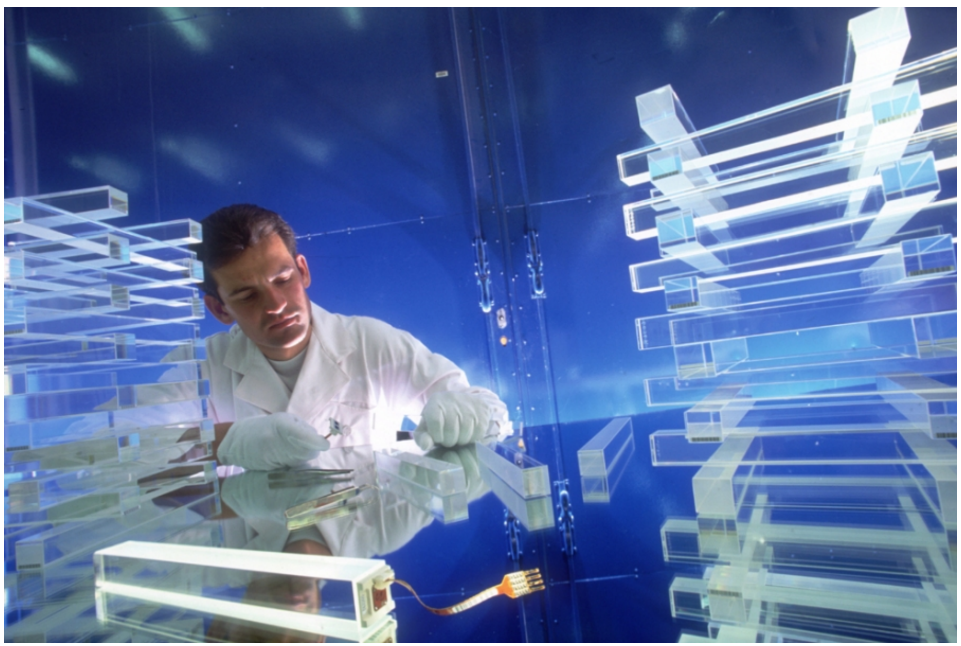
Phys. Rev. D89 (2014) 092007



Sign/Exp	Exp	Obs
ATLAS	6.2 σ	8.1 σ
CMS	6.3 σ	6.5 σ

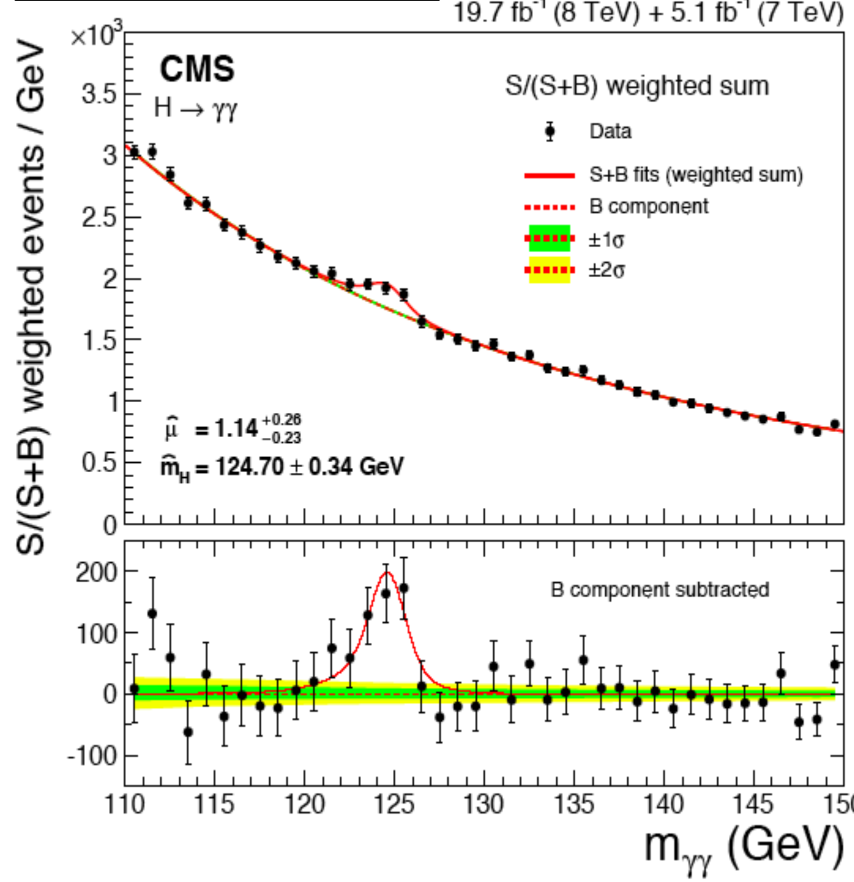
Making Discoveries: Run 1 Legacy Results: H → bosons

Paper on Avalanche Photodiodes
E. Lorentz et al.,
Max Planck Institute, Munich
MPI-PHE-93-23 (1993)



CMS: H→ 2γ Channel

EPJC (2014) 74:3076



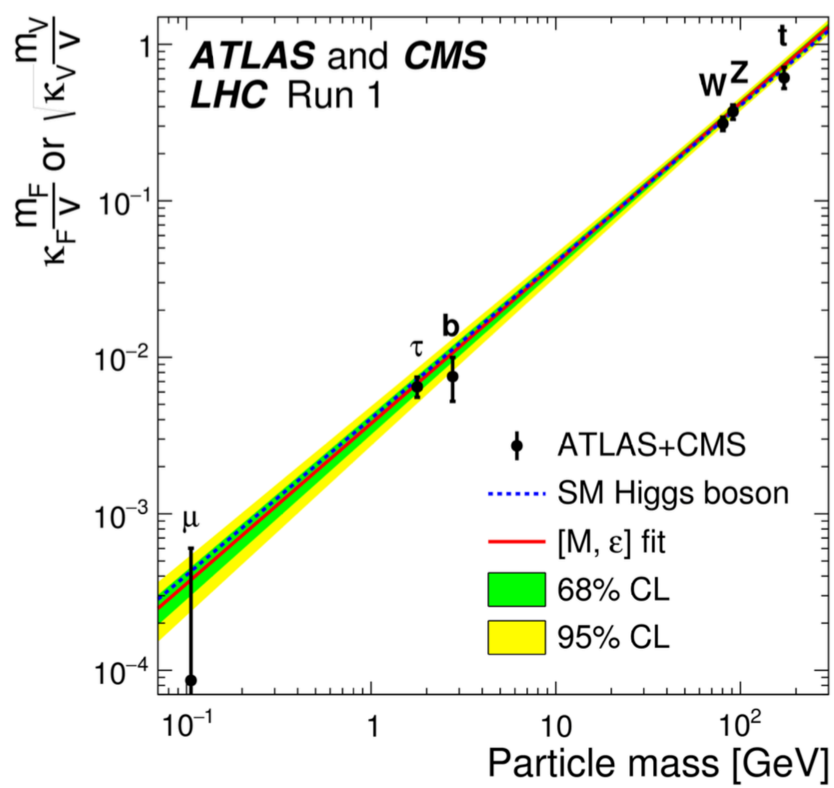
Higgs boson: Legacy Measurements

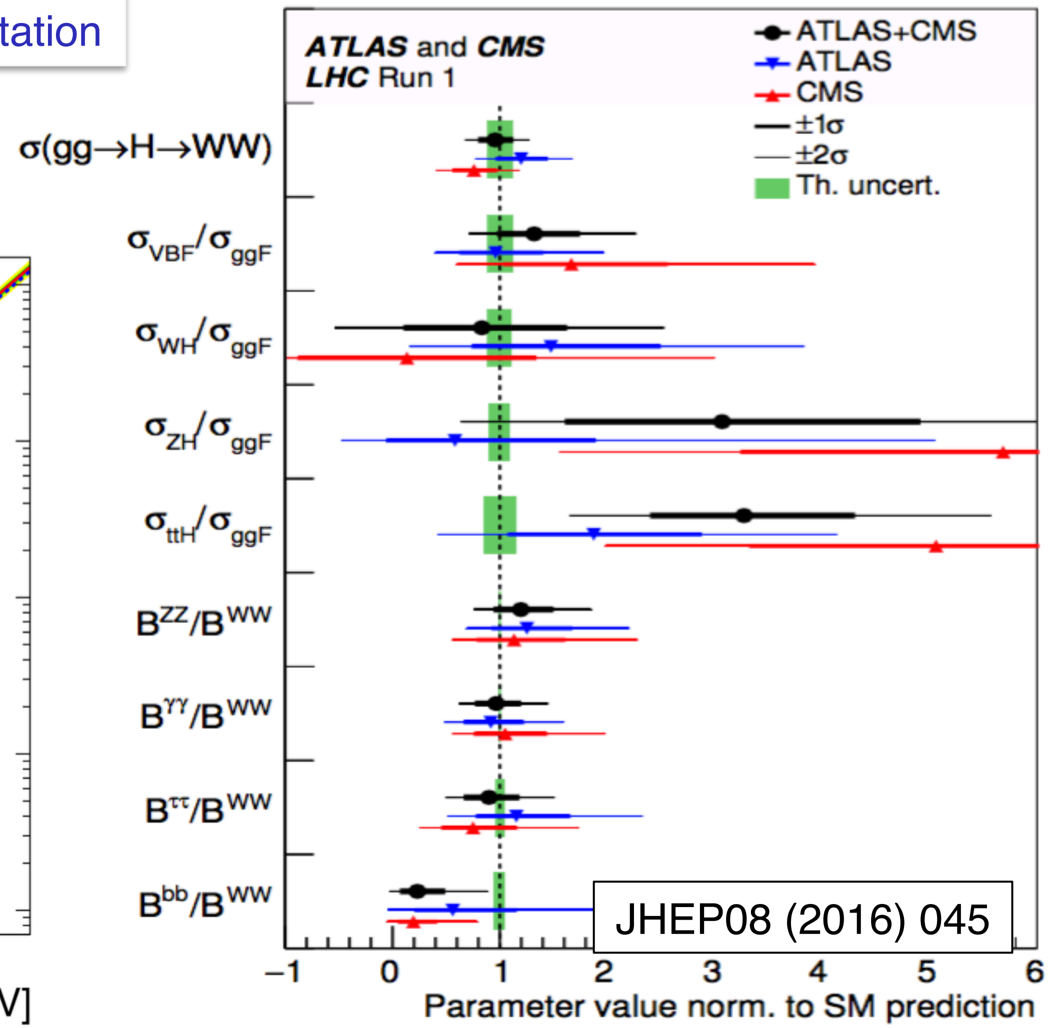
Signal Strength

Ratio of measured rate and the SM expectation

ATLAS+CMS

Ratio = 1.09 ± 0.11





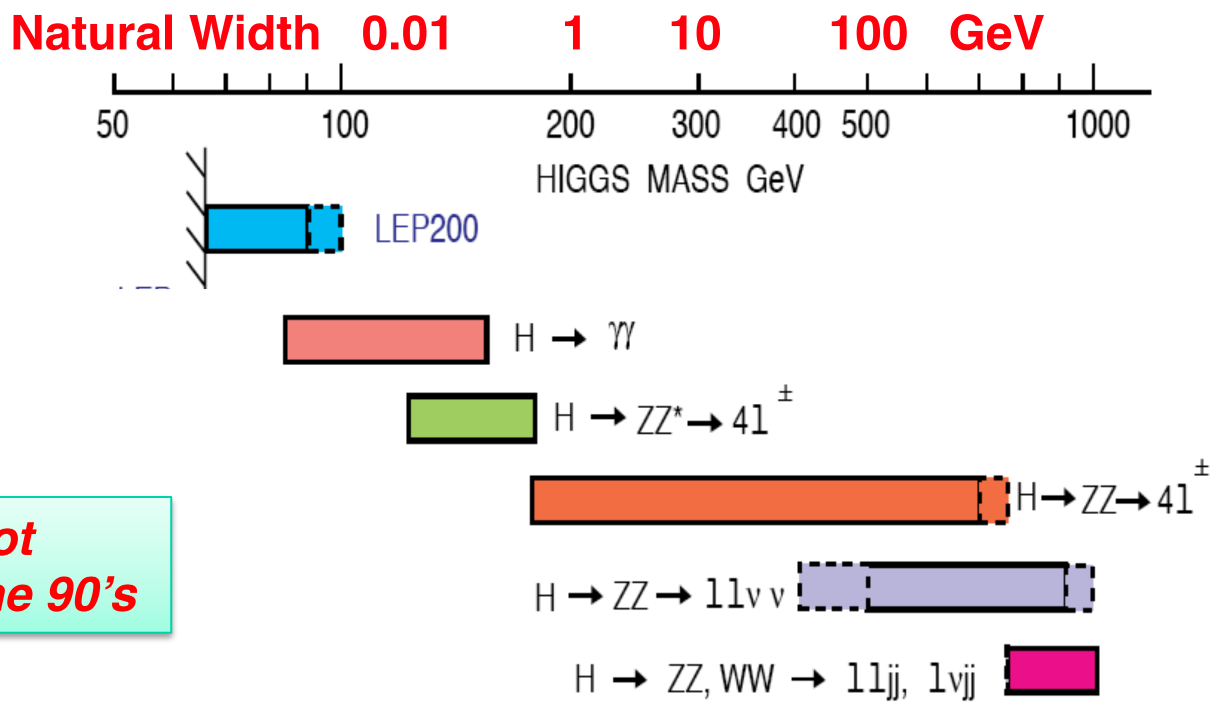
JHEP08 (2016) 045

Within errors the found Higgs boson looks very much like the SM one

Imperial College London

Search for the Standard Model Higgs Boson and LHC Experiment Design

The possibility of detection of the SM Higgs boson over the wide mass range, and its diverse manifestations, played a crucial role in the conceptual design of the ATLAS and CMS experiments



Natural width
$\Gamma \sim h/\tau$

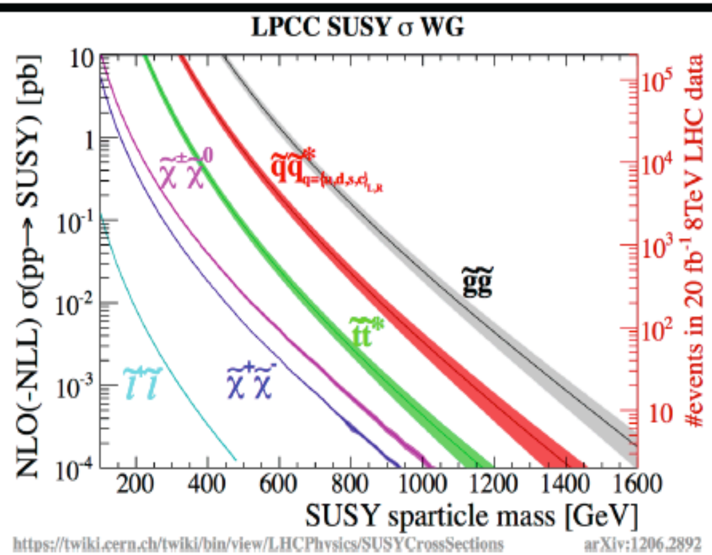
Plot from the 90's

Search for a low mass Higgs boson (e.g. H→γγ, H→ZZ→4*l*) **placed stringent performance requirements on ATLAS and CMS** detectors (especially Tracker momentum and ECAL energy resolution).

SUSY Searches at the LHC

Searches split by production process

- **Strong SUSY production**
  - "Natural" gluinos are "light" (<~2TeV).
- **Third generation production**
  - "Natural" $\tilde{b}$ and $\tilde{t}$ are light (<~1TeV).
- **Electroweak production**
  - "Natural" Higgsinos are light (~0.1TeV).



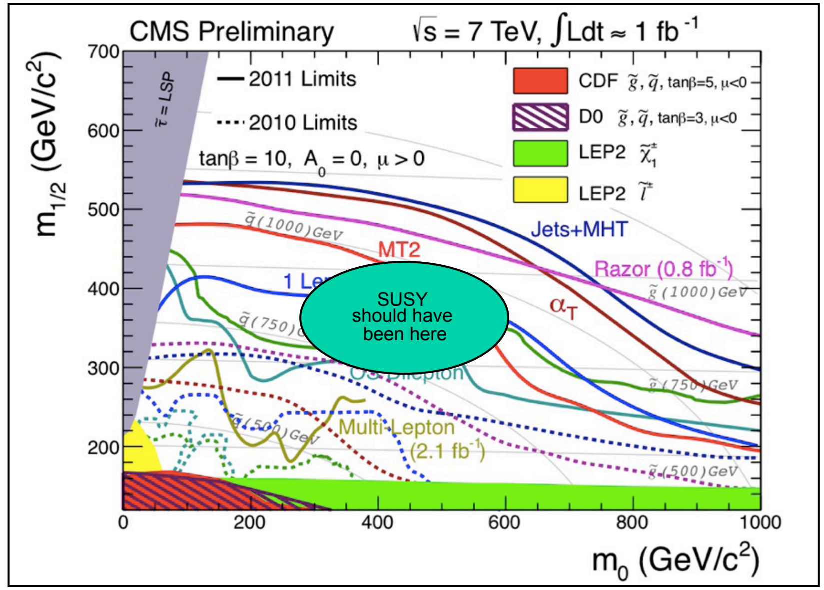
...and by final state characteristics

- **R-parity Conserving (RPC) SUSY.**
  - The LSP is stable becoming a possible dark matter candidate.
  - Searches are largely MET-based.
- **R-parity violating (RPV) SUSY.**
  - The LSP decays into SM particles.
  - Searches are typically associated with large object multiplicity.
- **Long-Lived particles, within RPC and RPV.**
  - Searches use the distinct signatures of particles with lifetime.

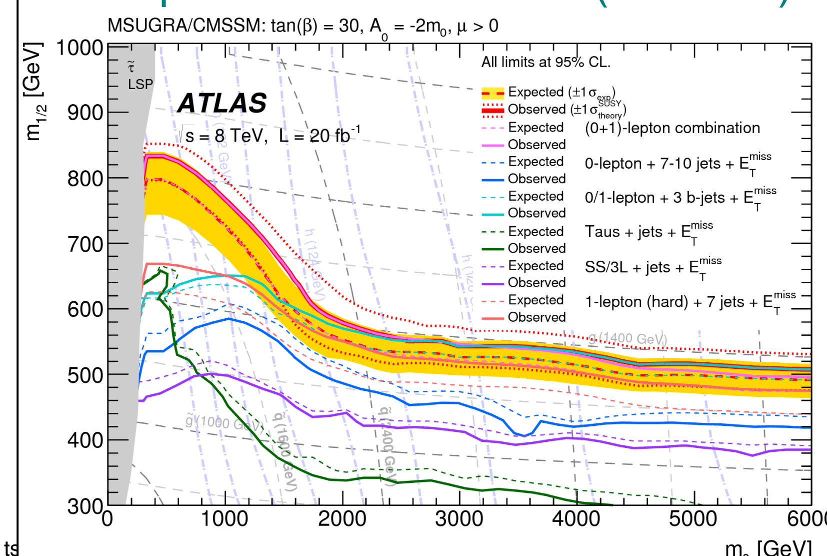
Not yet discovering: Supersymmetry

SUSY Summary

- SUSY discovery (should be) easy and fast
  - Expect very large yield of events in clean signatures (dilepton, diphoton).
    - Establishing mass scale is also easy (M_{eff})
- Squarks and gluinos can be discovered over very large range in SUGRA space (M_0,$M_{1/2}$)~(2,1)TeV
  - Discovery of charginos/neutralinos depends on model
  - Sleptons difficult if mass > 300 GeV
  - Evaluation of new benchmarks (given LEP, cosmology etc) in progress
- Measurements: mass differences from edges, squark and gluino masses from combinatorics
- Can extract SYSY parameters with ~(1-10)% accuracy



Specific SUSY Models (CMSSM)



In 2012, we found a Higgs boson at 125 GeV…

P. Sphicas EPS 2017

Imperial College London

Alas – SUSY has not turned up yet …

Inclusive Searches

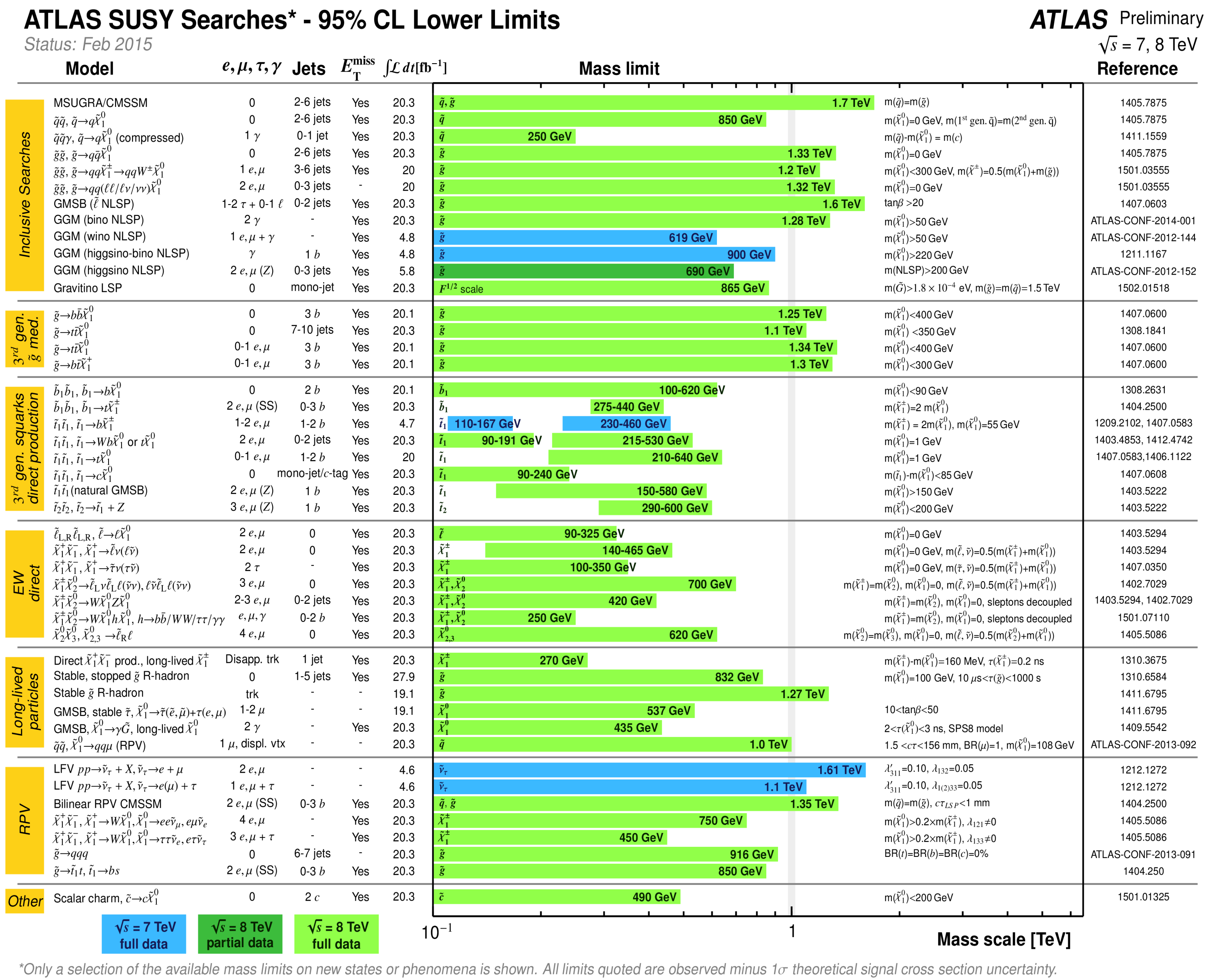
3rd Gen gluino med.

3rd Gen Direct

EW Direct

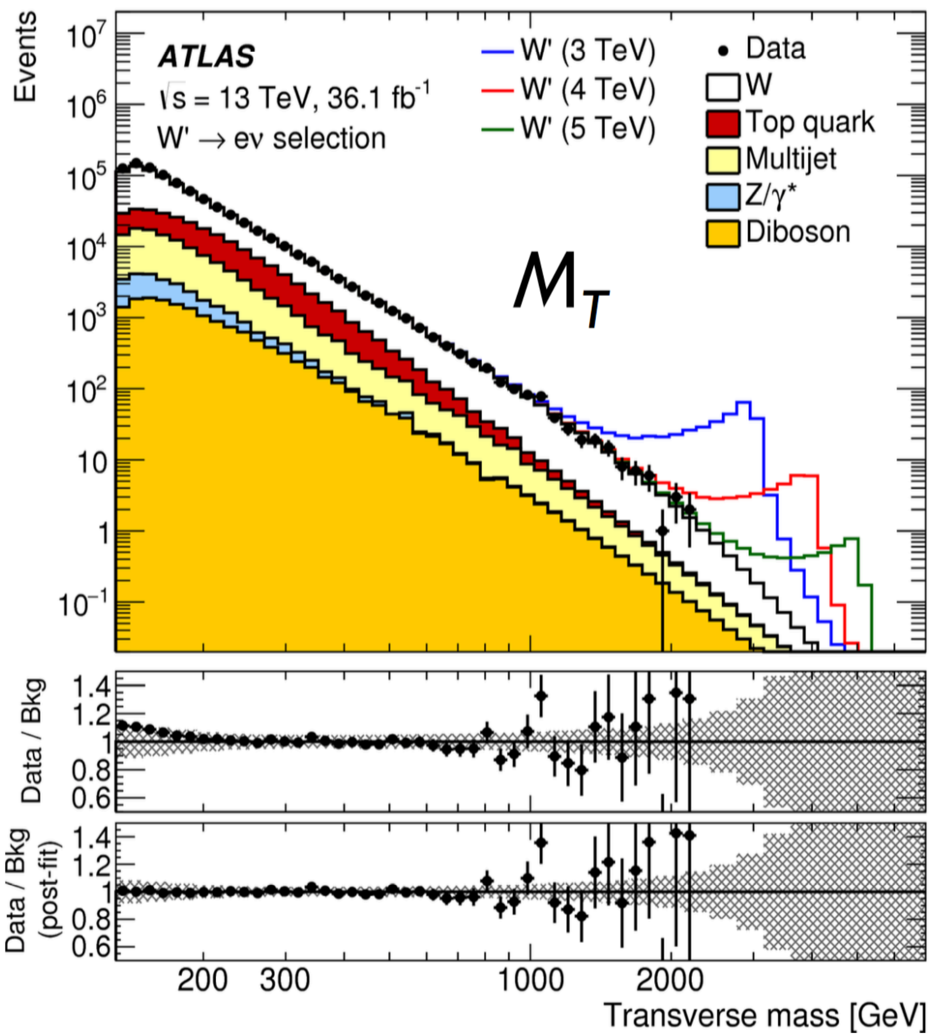
Long-lived

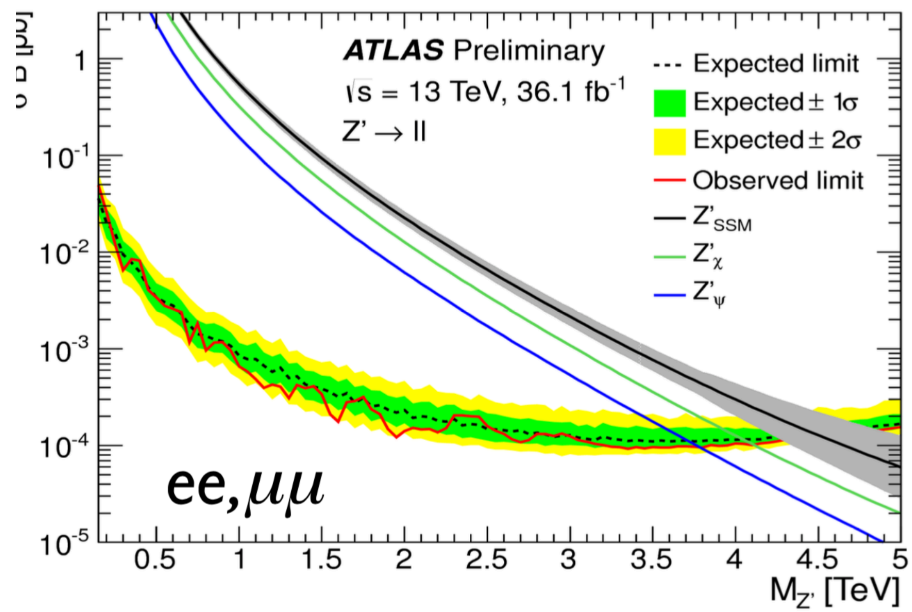
RPV



Imperial College London

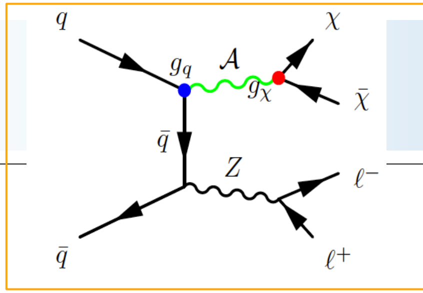
Search for Heavy (Z') bosons at the LHC



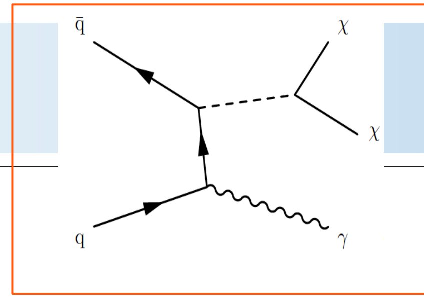


No evidence for BSM physics has been found so far.

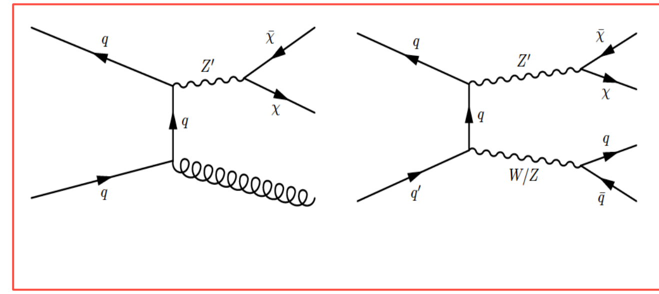
Imperial College London



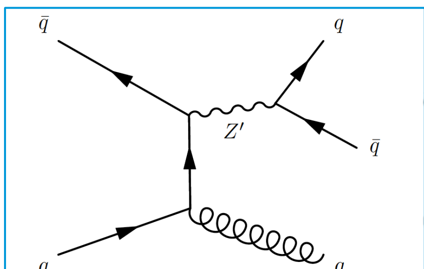
Mono-Z(ll)



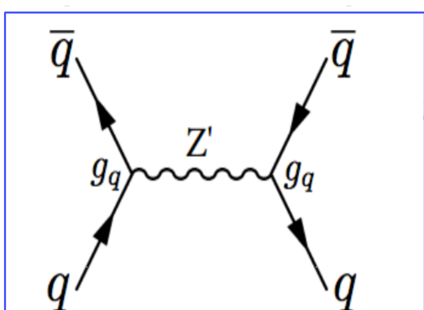
Mono-Photon



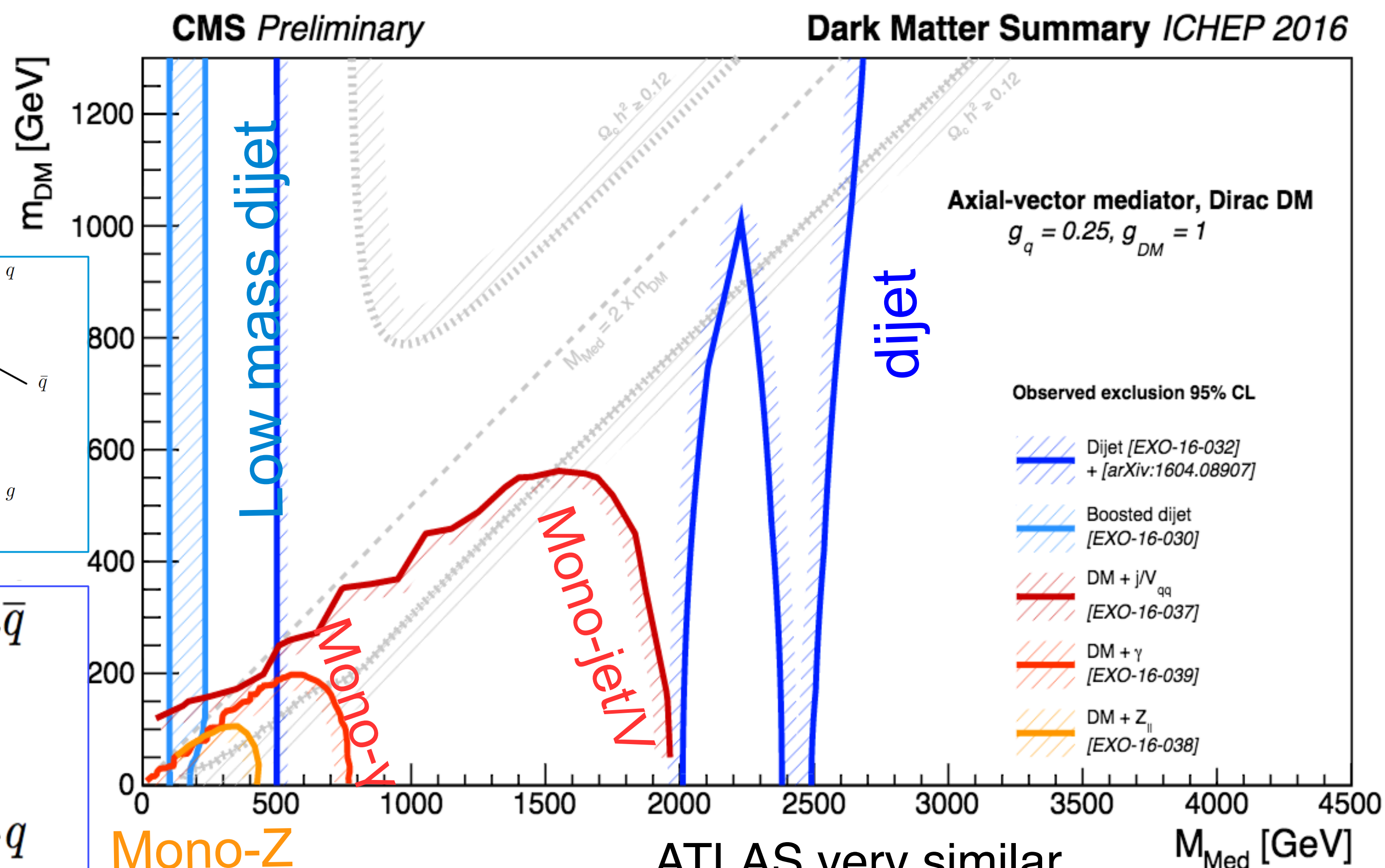
Mono-jet/Mono-V



Z'→(jj)+j



Z'→j+j

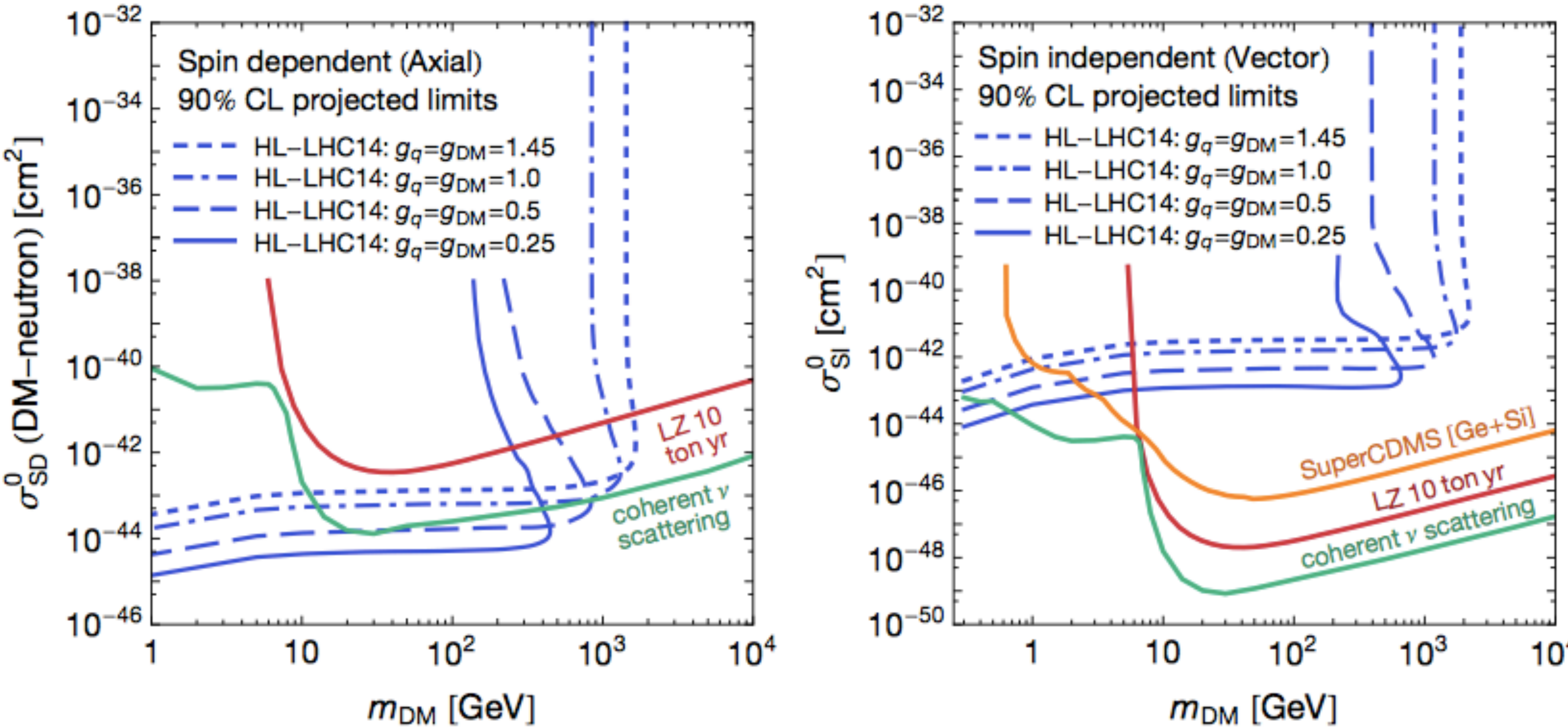


Mono-Z

ATLAS very similar

Projections for Future Experiments: σ vs M_{DM}

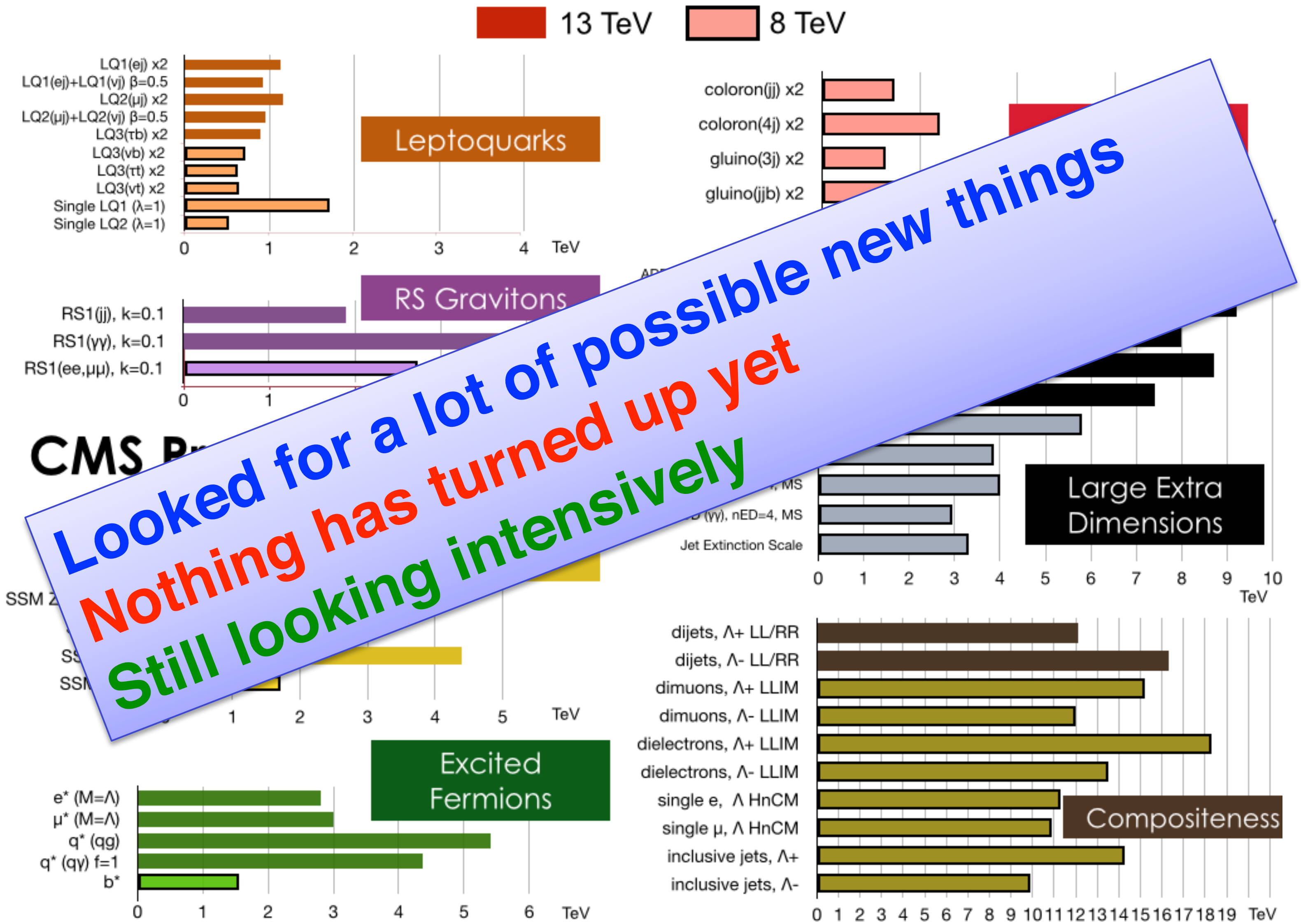
Can be also shown in the σ vs M_{DM} plane …



Direct Detection experiments and collider are complementary!
They probe different regions of the relevant parameter space!

Imperial College London

Non-SUSY BSM: vast, simply vast ….



Looked for a lot of possible new things

Nothing has turned up yet

Still looking intensively

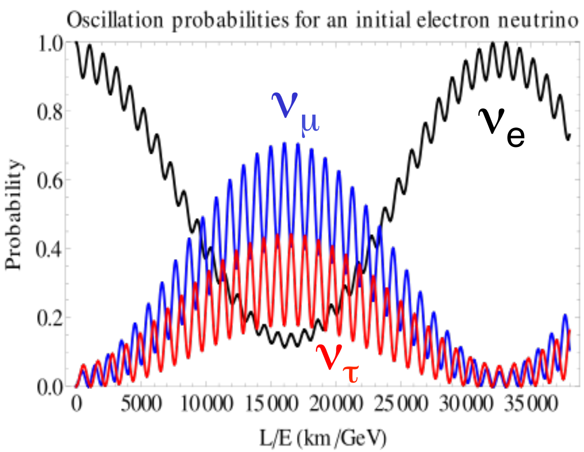
Moving Forward
Should we really expect new physics?

Moving Forward
Should we really expect new physics ?

Ample observational evidence for physics Beyond the SM

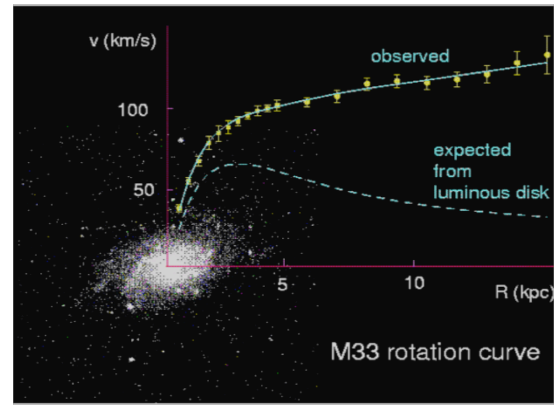
Neutrino mass (oscillations)

a QM phenomenon

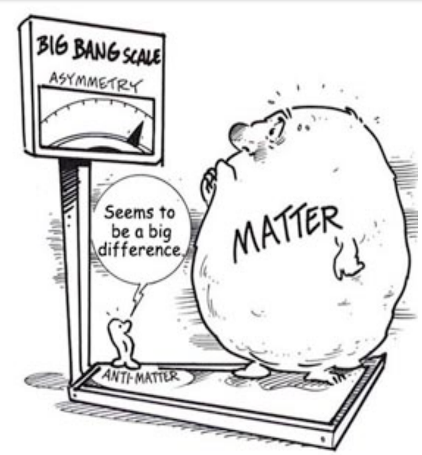


2015

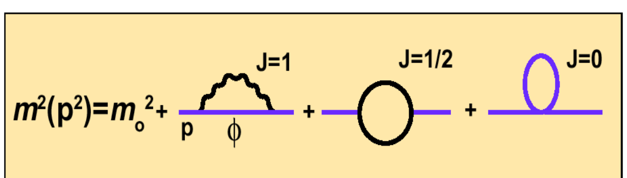
Dark Matter



Matter-antimatter asymmetry



The lightness of the Higgs boson?



Physics Outlook: Questions for the LHC

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

✓ **2. Clarify the e-w symmetry breaking sector**

SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, M_Z ~ 100,000 MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found all is not completely well with SM alone: next question is "Why is (Higgs) mass so low"?

*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV)**

5. Search for new physics at the TeV scale

SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

What makes it worthwhile to continue physics exploitation of an accelerator?

1. **Higher centre-of-mass Energy**
   LHC is now running at 13 TeV (~ twice the energy of Run 1)

2. **Higher Integrated Luminosity**
   From mid-2020s LHC will examine 10 times the number of p-p collisions previously examined.

3. **Qualitatively better detectors**

World's Topmost Priority in Particle Physics

exploitation of the full potential of the LHC

High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

“SLHC” Started a Long Time Ago

Jan 2001

Detector Issues

EP-TH Faculty Meeting

Challenges for pp GPDs
- LHC design luminosity,
- L ~ 10^{35} cm^{-2}s^{-1},
- Higher c.o.m energy

Implications for Detector R&D
- LHC design energy and luminosity - Upgrades (~ 2009)
- L ~ 10^{35} cm^{-2}s^{-1} - Major Upgrades (~ 2012)
- Higher energy – next generation of detectors (20??)

Conclusions

EP-TH Faculty 17 Jan 01 T. S. Virdee

Apr 2002

CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]
Contributors: S. Abdullin [4], G. Azuelos [5], A. Ball [1], D. Barberis [6], A. Belyaev [7], P. Bloch [1], M. Bosman [8], L. Casagrande [1], D. Cavalli [9], P. Chumney [10], S. Cittolin [1], S.Dasu [10], A. De Roeck [1], N. Ellis [1], P. Farthouat [1], D. Fournier [11], J.-B. Hansen [1], I. Hinchliffe [12], M. Hohlfeld [13], M. Huhtinen [1], K. Jakobs [13], C. Joram [1], F. Mazzucato [14], G.Mikenberg [15], A. Miagkov[16], M. Moretti[17], S. Moretti [2,18], T. Niinikoski [1], A. Nikitenko[3,†], A. Nisati [19], F. Paige[20], S. Palestini [1], C.G. Papadopoulos[21], F. Piccinini[2,‡], R. Pittau[22], G. Polesello [23], E. Richter-Was[24], P. Sharp [1], S.R. Slabospitsky[16], W.H. Smith [10], S. Stapnes [25], G. Tonelli [26], E. Tsesmelis [1], Z. Usubov[27,28], L. Vacavant [12], J. van der Bij[29], A. Watson [30], M. Wielers [31]

EPJC39 (2005) 293

Physics Thrust for HL-LHC: Energy Frontier

S. Cittolin

Physics should drive technical choices

1. Higgs boson and EWSB physics

- Experimentally → make precision (aka sensitive) measurements of the properties (couplings etc.) and self couplings **in a new sector**
- Theoretically → are precise predictions (~1%) possible

2. Search for physics beyond the SM

- Extend mass reach for possible high mas objects predicted by BSM
- Dark matter & weakly interacting BSM phenomena
- Ensure coverage and sensitivity to elusive signatures

3. Precision (sensitive) SM measurements

- Look for (significant) deviation from SM predictions
- Intrinsic value of knowledge acquired independent of discovery

Physics Thrust for HL-LHC: Flavour

LHCb : Searching for new physics via precision measurements

Also contributions from ATLAS and CMS

CP violation

- Reduce uncertainty on Unitarity Triangle angle γ to ~1^{o}
- Probe B_s sector ever more precisely, in particular phase φ_s in $B_s \to J/\Psi\varphi$ etc. (analogue of $\sin 2\beta$ in B^0 system), down to <0.01 rad
- Intensify search for CPV in charm

Rare decays and friends

- Increase precision on BR($B_s \to \mu\mu$) and aim to observe $B^0 \to \mu\mu$
- Full exploration of rich wealth of observables in electroweak Penguins (*e.g.* $B^0 \to K^*\mu\mu$). Elucidation of many puzzles in this area (P_5', R_K, R_{K^*} etc.)
- Continue to explore Lepton Universality Violation in $B \to D^*\tau\nu$ etc. (current tension with SM ~ 4 sigma). Remarkably, prospects *at least* as good as Belle II.

Continue to explore frontiers of spectroscopy (pentaquarks, doubly heavy baryons…)

Guy Wilkinson

Physics Thrust for HL-LHC: Extreme Matter

Heavy quark interaction in QCD medium

heavy flavour dynamics and hadronisation at low p_T

high precision measurement of R_{AA} and v_n of charm and beauty

Charmonium regeneration in QGP

charmonium down to zero p_T

Chiral symmetry restoration and QGP radiation

vector mesons and virtual thermal photons (di-leptons)

Production of nuclei in QGP

high-precision measurement of light nuclei and exotic states

Deconfinement

charmonium and bottomium spectroscopy

Energy loss of parton in QGP

jet quenching, high p_T spectra, open charm and beauty

Tapan Nayak

Guidance for HL-LHC: Energy Frontier

Instantaneous Luminosity x 5 (much higher pileup !!!)

Integrated Luminosity x 10 (higher radiation levels!!!)

1. **Higgs boson and EWSB physics**
2. **Search for physics beyond the SM**
3. **Precision (sensitive) SM measurements**

The guidance implies the following:

Preserve (and possibly improve), at today's values,

trigger thresholds

reconstruction and identification efficiencies (granularity)

energy/momentum/mass resolutions

All at factor of 5 larger pileup !

Translation to Detector Design

New higher granularity more radiation hard inner trackers

ATLAS & CMS – factor ~10 more channels with sensors and electronics that can withstand doses of up to 500 Mrad and fluences of 10^{16} n/cm^2

LHCb – new Velo with pixels, new SciFi tracker

ALICE - new pixels detector and new (lower deadtime) readout for TPC

Replacement of components affected by radiation

ATLAS/CMS – endcap calorimeters (CMS' needs replacement)

Higher bandwidth L1 triggers and DAQ

Introduce Track Triggers in L1

Higher L1 output rate [e.g. ATLAS/CMS 100→750kHz and latency (>10μs)] – new trigger processors (ASICs → FPGAs).

DAQ recording rate 1000→10k evts/s

Replacement of front-end electronics

Deal with higher rates, longer pipelines (e.g. ATLAS/CMS >10 us),

LHCb – deal with 40MHz L1 trigger

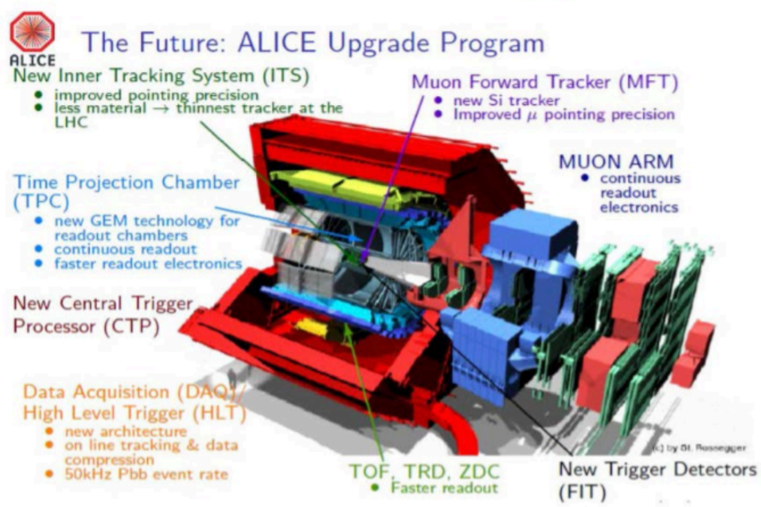
Introduction of precision timing

Vertex localization and pileup suppression

Detector Upgrades for the HL-LHC Programme

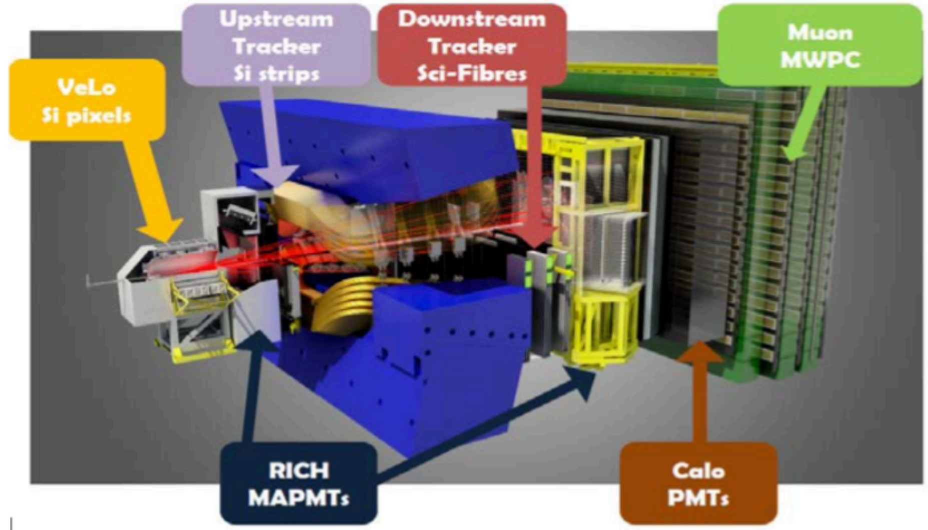
P. Allport EPS 2017

ALICE: Phase-I Upgrades



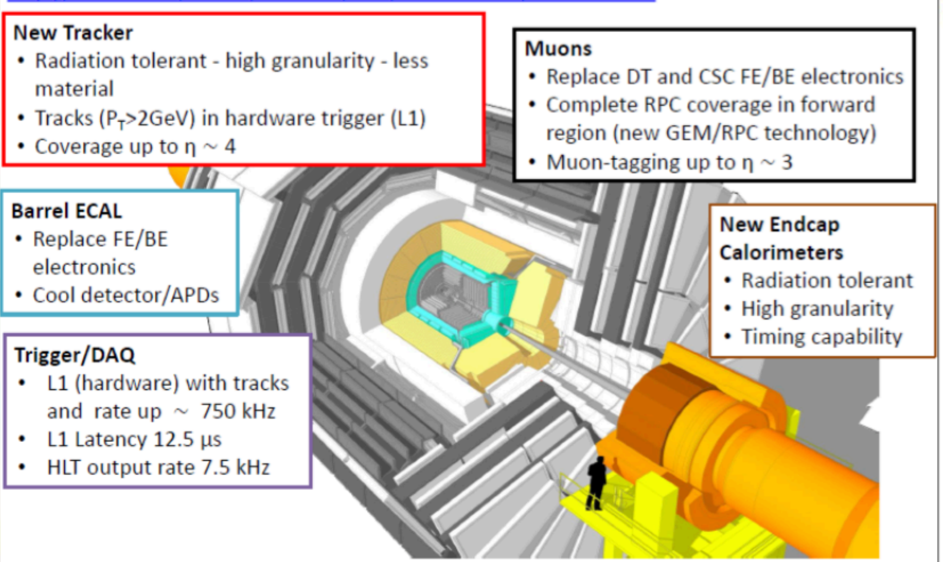
https://indico.cern.ch/category/4863/

LHCb: Phase-I Upgrades



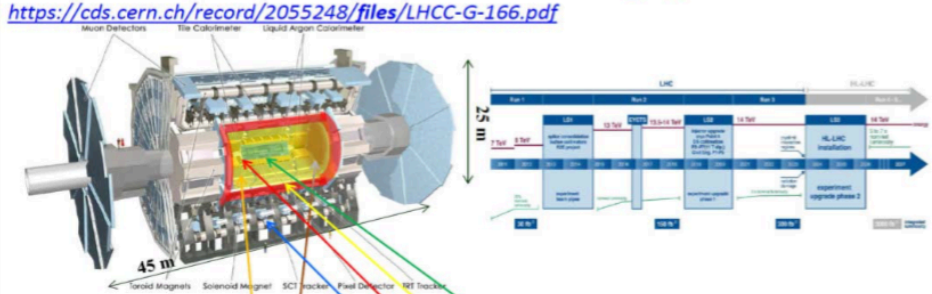
CMS: Phase-II Upgrades

http://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf?version=4



ATLAS: Phase-II Upgrades

https://cds.cern.ch/record/2055248/files/LHCC-G-166.pdf



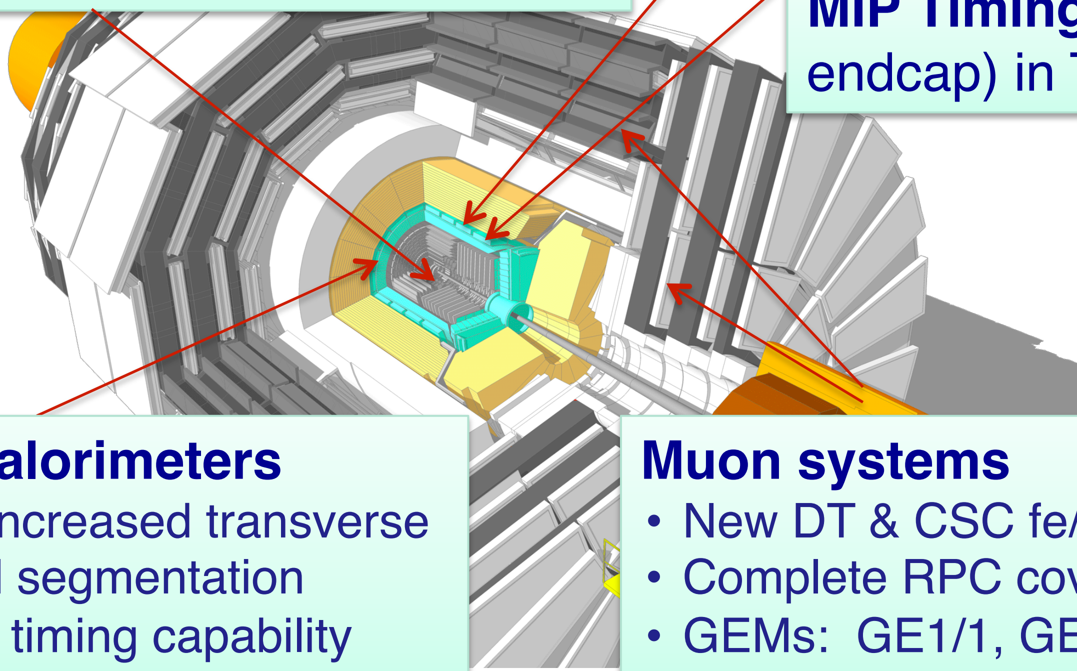
Phase-1 Upgrade	Phase-2 Upgrade
L = 2e34 (μ~60) int L = 200 fb^{-1}	L = 7.5e34 (μ~200) int L = 3000 fb^{-1}
• New Muon Small Wheel (NSW) • Fast Track Trigger (FTK) • TDAQ Phase-1 • LAr Calorimeter Electronics • ATLAS Forward Protons (AFP)	• All new Tracking Inner Detector (ITk-Strip/Pixel) • Calorimeter Electronics Upgrade • Forward Timing Detector Muon System Upgrade • TDAQ Phase-2

Example: CMS Upgrades for Phase II

New Tracker
- Rad. tolerant - increased granularity - lighter
- Tracks ($p_T \geq 2$ GeV) in hardware trigger (L1)
- Extended coverage to $\eta \simeq 4$

Barrel EM calorimeter
- New FE/BE electronics
- Lower operating temperature (8°C)

MIP Timing Layer (barrel & endcap) in TP stage



New Endcap Calorimeters
- Rad. tolerant - increased transverse and longitudinal segmentation
- intrinsic precise timing capability

Muon systems
- New DT & CSC fe/be electronics
- Complete RPC coverage $1.5 < \eta < 2.4$
- GEMs: GE1/1, GE2/1, ME0

Trigger/HLT/DAQ
- Tracks ($p_T \geq 2$ GeV) in hardware trigger (L1)
- Trigger latency 12.5 μs, output rate 750 kHz
- HLT output 7.5 kHz

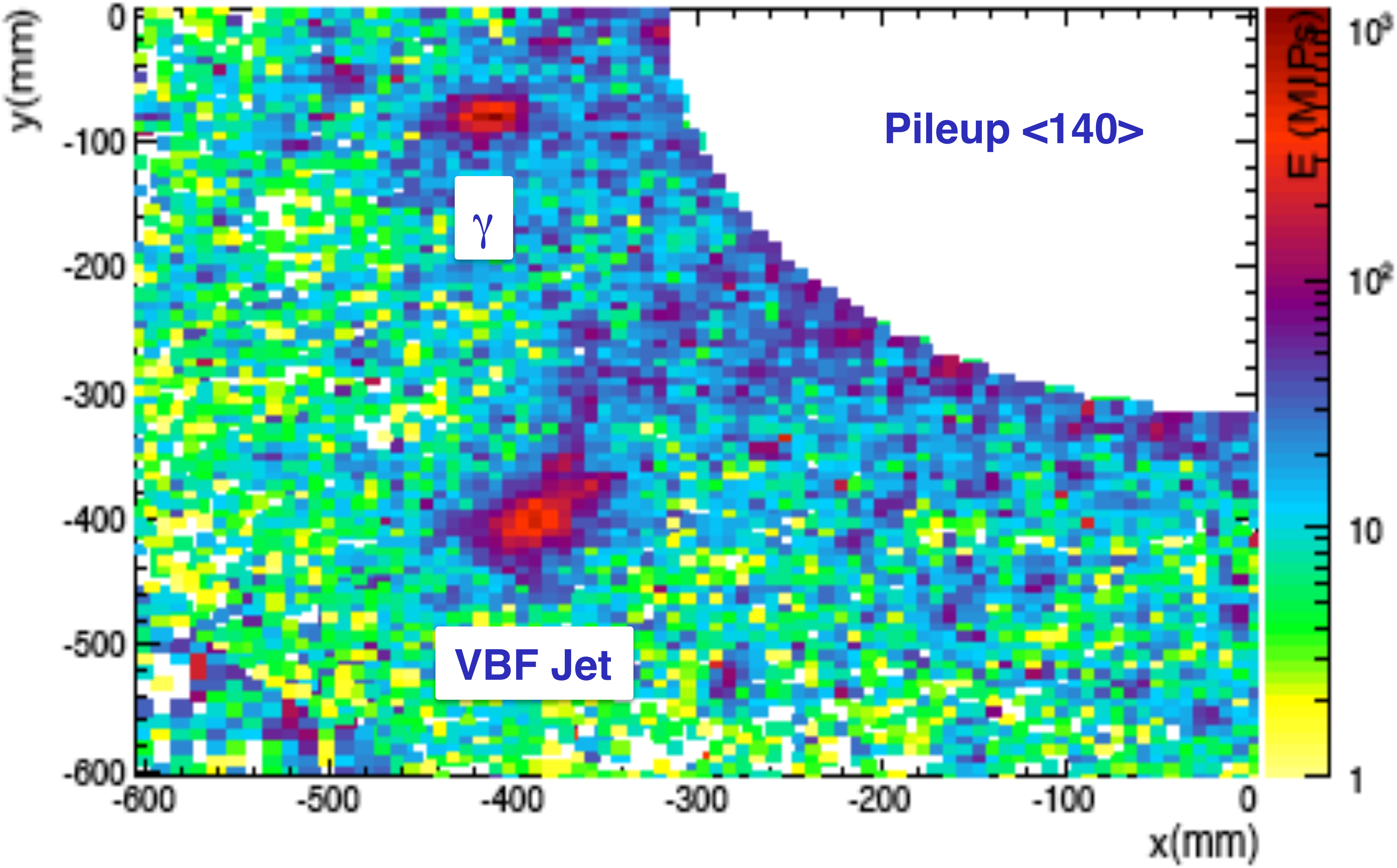
Beam radiation and luminosity
Common systems &infrastructure

Example Event: VBF H→γγ – a VBF Jet

VBFH evt 5 characteristics

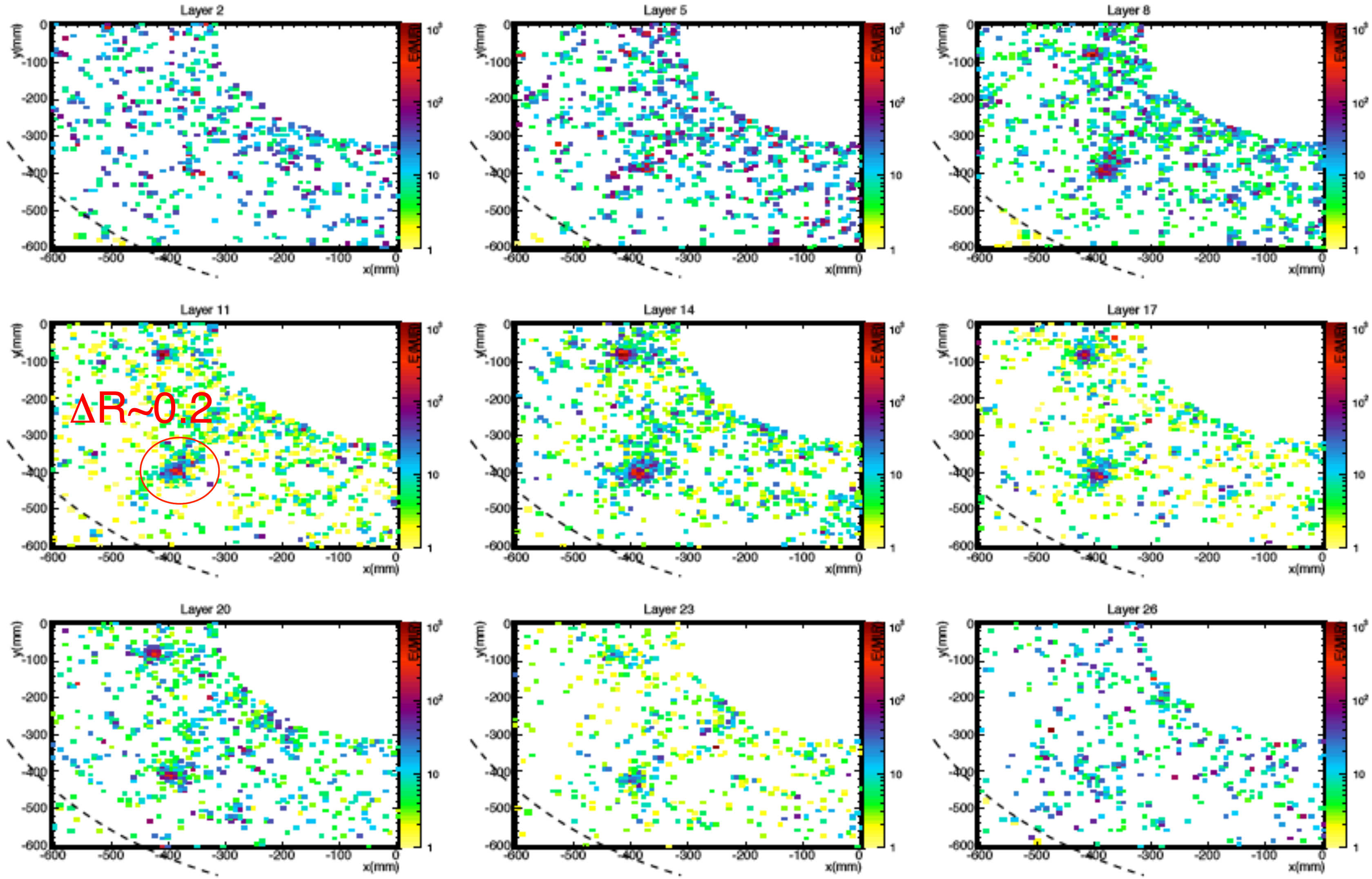
vtx	pId	pdg	status	E (GeV)	pT (GeV)	η	ϕ	xFF	yFF
5	3	25	3	267.234	62.6023	2.00296	1.36729	176.108	853.37
6	1	22	3	176.836	21.8914	2.77842	-2.9555	-388.644	-73.1711
5	1	1	3	717.497	117.849	2.4927	-2.35589	-373.128	-373.353
60	4	321	1	7.29636	1.25235	2.44572	1.83431	-144.198	534.494
60	10	-211	1	1.78182	0.462846	2.02064	-1.83334	-222.04	-826.214
60	12	-211	1	11.7788	1.69217	2.62817	-2.51502	-372.791	-269.858
60	17	-211	1	247.168	40.4587	2.49616	-2.34136	-366.375	-377.406
92	1	-321	1	4.30936	1.00983	2.12334	-1.78458	-163.255	-751.959
138	1	-211	1	2.32255	0.588201	2.0482	1.23511	273.902	785.074
139	1	-211	1	2.23853	0.474176	2.23174	-3.08816	-687.496	-36.7692
140	1	-321	1	5.55465	0.560226	2.98066	-0.105339	320.857	-33.9245
142	1	-211	1	1.65867	0.336068	2.27555	-0.812546	452.696	-477.968
144	1	211	1	19.5236	2.40514	2.78332	-2.8646	-378.524	-107.614
146	1	-321	1	15.5038	2.39386	2.5548	-2.83058	-471.88	-151.683
148	1	211	1	252.986	41.7544	2.4878	-2.32486	-363.165	-386.666
229	1	130	1	3.76919	0.928466	2.06963	-2.57243	-685.065	-438.296
269	1	22	1	0.756801	0.129004	2.45506	2.9175	-534.673	121.86
271	2	22	1	1.38013	0.248237	2.4005	0.25498	560.887	146.197
272	2	22	1	1.94457	0.454496	2.13281	-2.78818	-714.922	-263.736
273	1	310	1	47.4983	7.83109	2.48882	-2.30261	-354.104	-394.243
274	1	22	1	17.8013	2.73597	2.55998	-2.38144	-357.343	-339.741
274	2	22	1	19.7095	3.03037	2.5596	-2.33456	-341.159	-356.25
275	1	22	1	68.3848	11.2397	2.49203	-2.35071	-371.44	-375.539
275	2	22	1	10.3692	1.6526	2.52322	-2.34794	-358.873	-364.848

Event Display (VBF H→γγ)



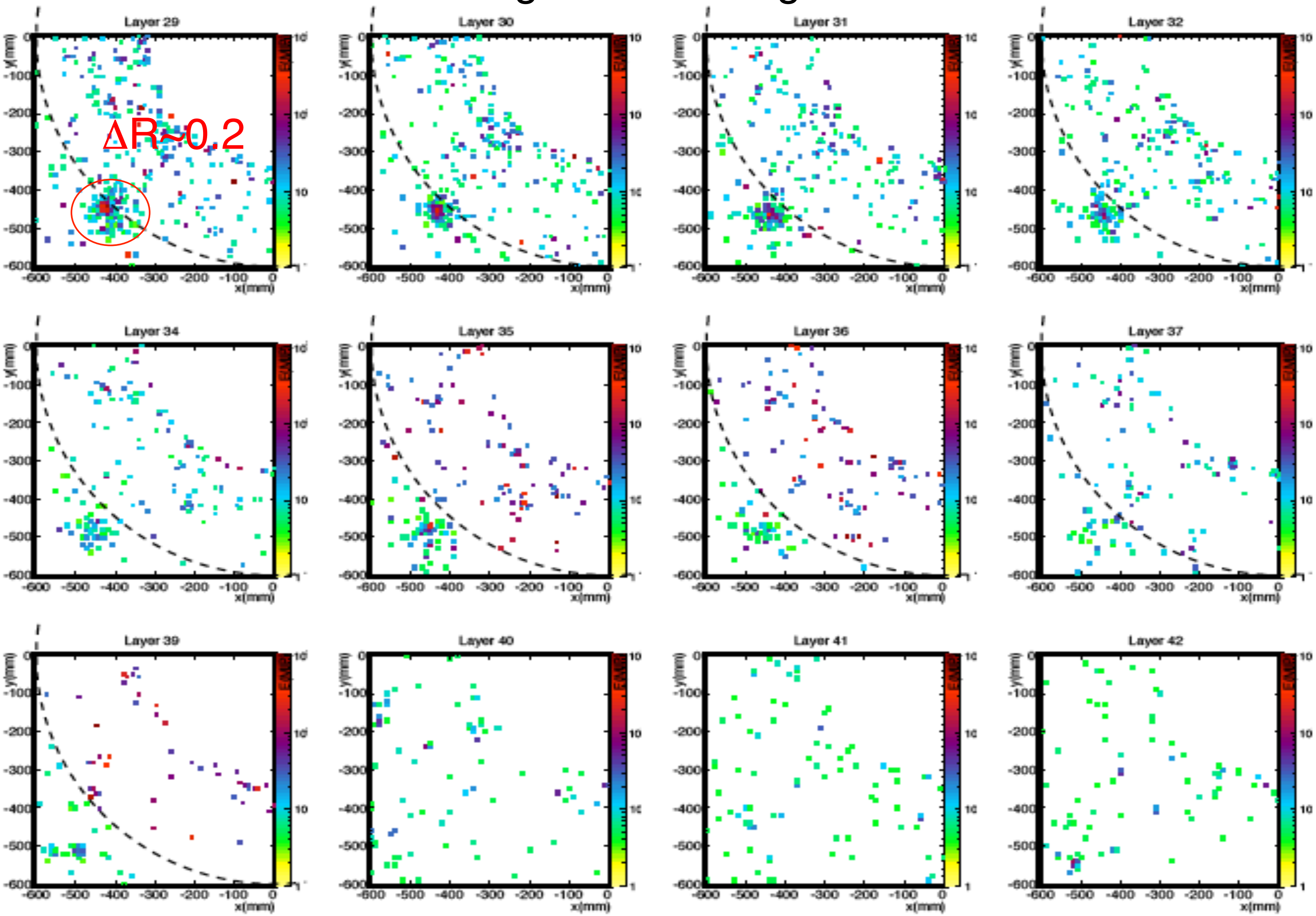
Event Display of VBF Jets (VBF H→γγ)

Standalone simulation: Taking Slices through ECAL section



Event Display of VBF Jets (VBF H→γγ)

Standalone simulation: Taking Slices through Si- HCAL section

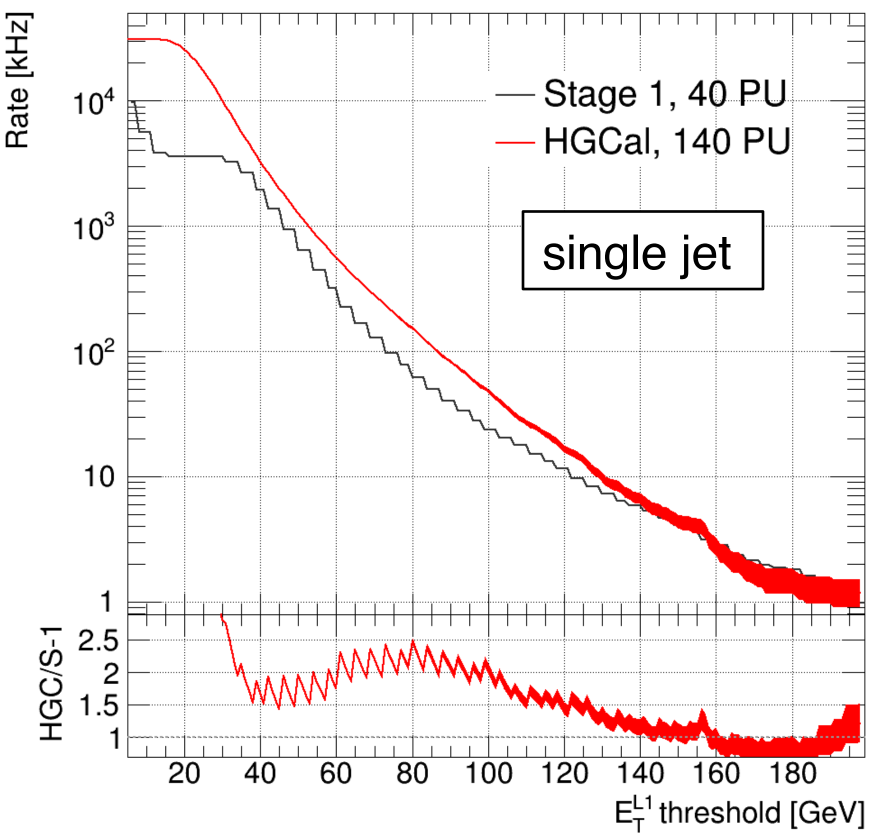


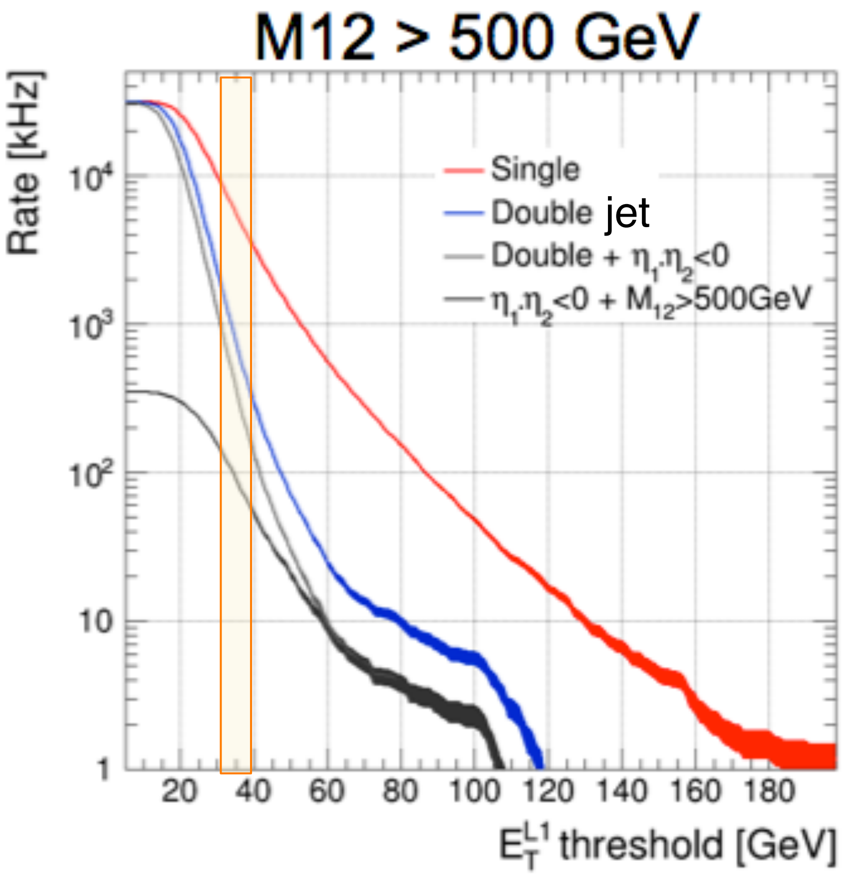
Imperial College London

Performance: Level-1 Trigger

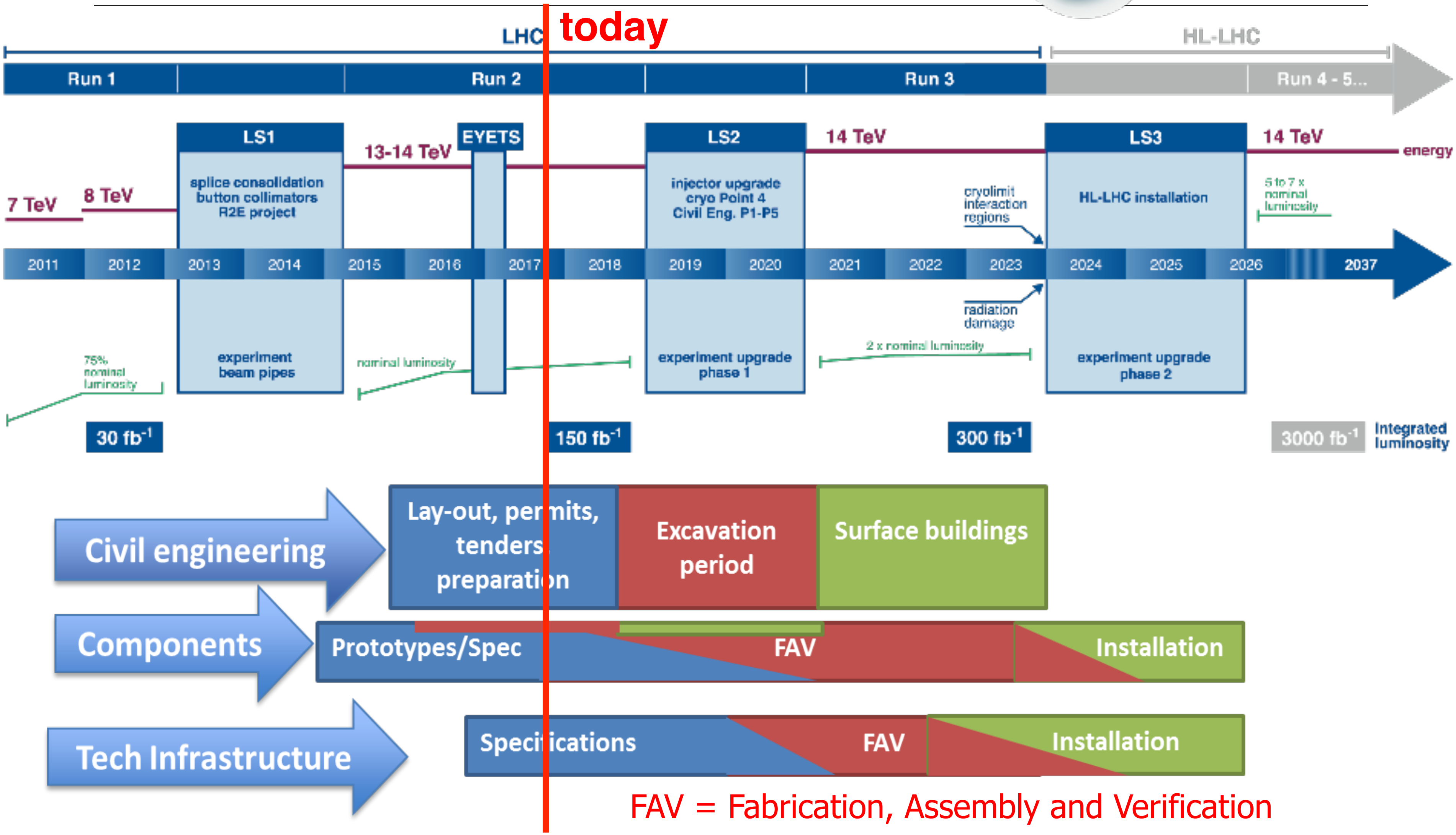
Jet-Trigger Endcap region

Considerable power lies in the selection of events with difficult signatures e.g. selection at L1 of VBF topologies without any requirement in the central region.





LHC / HL-LHC Plan



Imperial College London

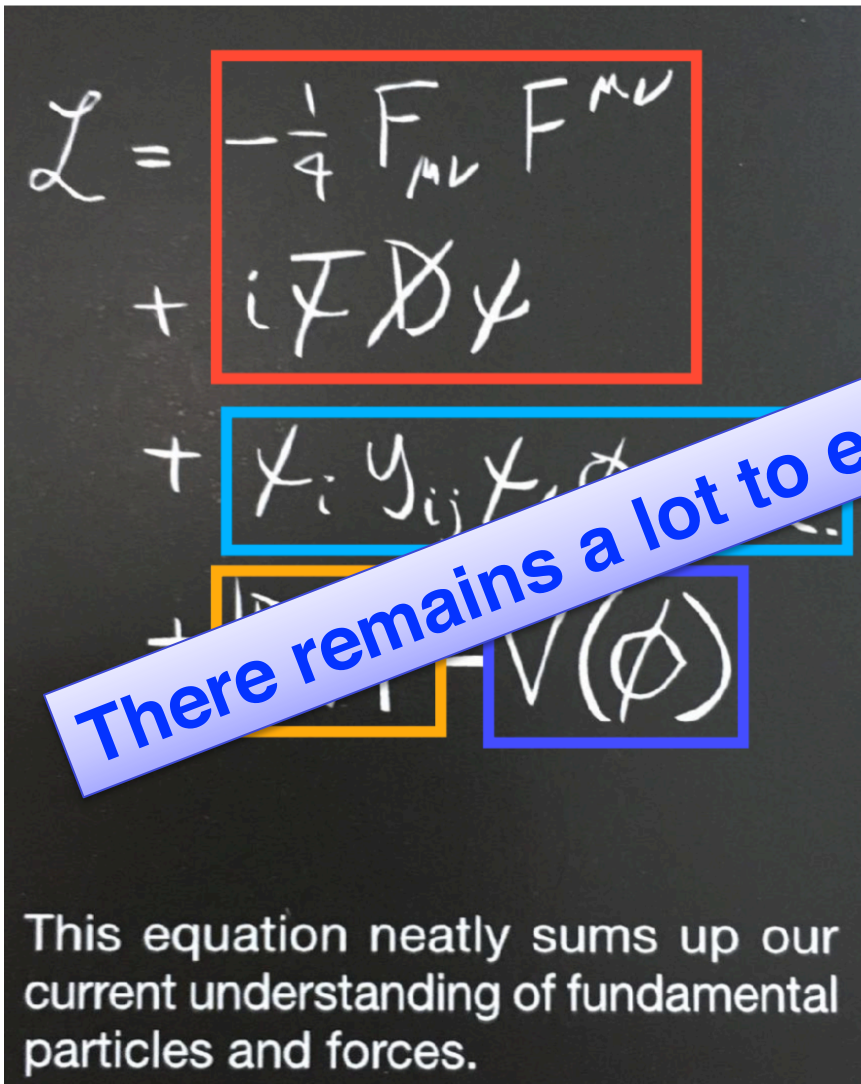
From Today to End of HL-LHC

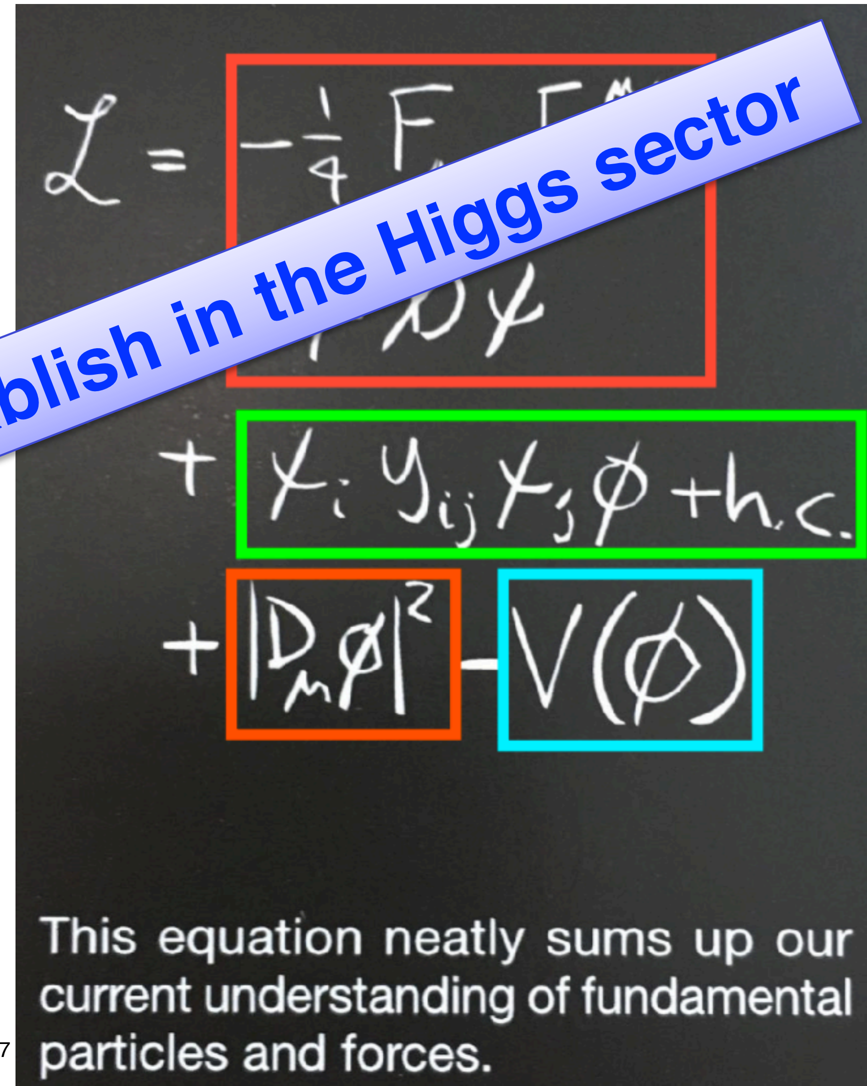
G. Salam

Today

ASSUMPTION

KNOWLEDGE





There remains a lot to establish in the Higgs sector

What will the LHC (and HL-LHC) Bring?

P. Meridiani EPS 2017

No direct sign of new physics @ LHC from searches

Higgs couplings can provide indirect access to BSM:

- SUSY (tanβ=5): $$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$
- Composite Higgs: $$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$
- Top partners: $$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$$

Higgs boson Events in Numbers

Numbers of events at $\sqrt{s}$=14 TeV for 3000 fb^{-1}

Process	**No. Evts (M)**
gg→ H	145
VBF	13
WH	5
ZH	2.5
ttH	1.8

- Higher statistics allows categorization (selection) of signal regions with higher S/B, regions where the systematics are better controlled,
- The balance between statistical and systematic errors changed

- The precision of theoretical calculations/prediction need improving.
- Are 1% theoretical predictions possible at a hadron collider?

Calculations: Great progress in recent years

GLUON-FUSION (13 TEV)

G. Salam

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

$$48.58\,\text{pb} \pm 1.89\,\text{pb}\,(3.9\%)\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

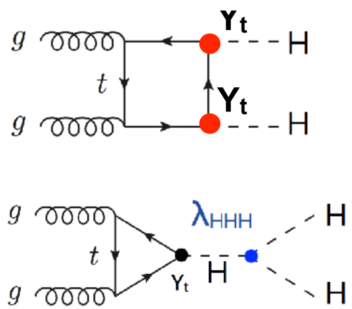
Imperial College London

What will the LHC (and HL-LHC) Bring?

HH : within factor 20 of SM→HL-LHC

H→μμ: same

Rare decays…

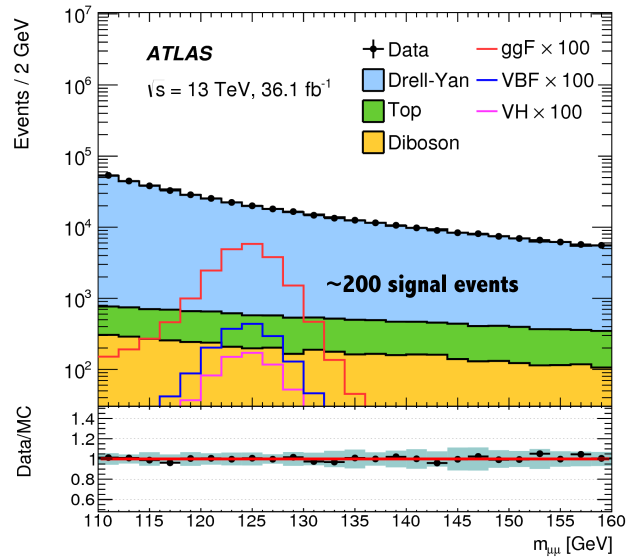


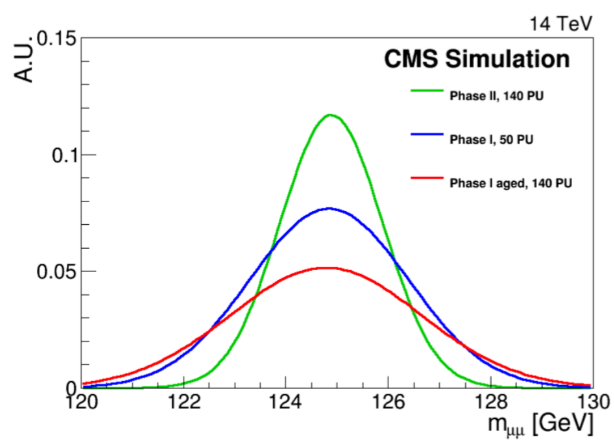
Run 2 Obs. (exp) 95% CL limits on σ/σ_{SM}

	ATLAS	CMS
bbbb	29 (38)	342 (308)
bbWW		79 (89)
bbττ		28 (25)
bbγγ	117 (161)	19 (17) NEW
WWγγ	747 (386)	

3 fb^{-1} 13 fb^{-1} 36 fb^{-1}

ATLAS arXiv:1705.04582





Process	σ/σ_{SM} (95% CL)
H→Zγ (ATLAS) 36fb^{-1}@ 13 TeV	<6.6
H→Zγ (CMS) Run1	<9
H→γ*γ (CMS) Run1	<7.7
H→J/Ψγ (ATLAS) Run1	<540
H→J/Ψγ (CMS) Run1	<540
H→ργ (ATLAS) 36 fb-1 @ 13 TeV	<52
H→φγ (ATLAS) 36 fb-1 @ 13 TeV	<208
H→ee (CMS) Run1	<~10^5

Run1
Run2 36 fb^{-1}

CMS projections

$\sigma(m)_{\mu\mu}$: 40% better

$\varepsilon_{\mu\mu}$: 20% better

5% $H_{\mu\mu}$ coupling

P. Sphicas EPS 2017

What will the LHC (and HL-LHC) Bring?

G. Salam

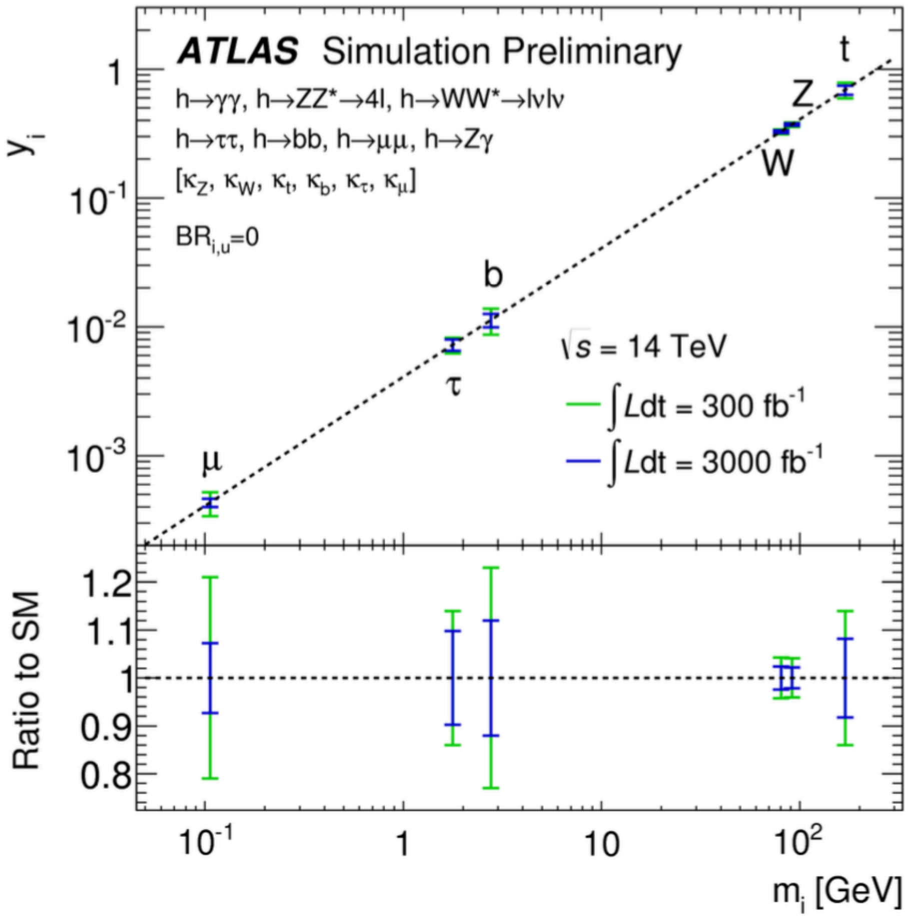
- Run 2: observation of $H \to bb$ (Yukawa)
- Run 2/3: observation of ttH (Yukawa)
- HL-LHC: observation of $H \to \mu\mu$ (2nd gen Yukawa)

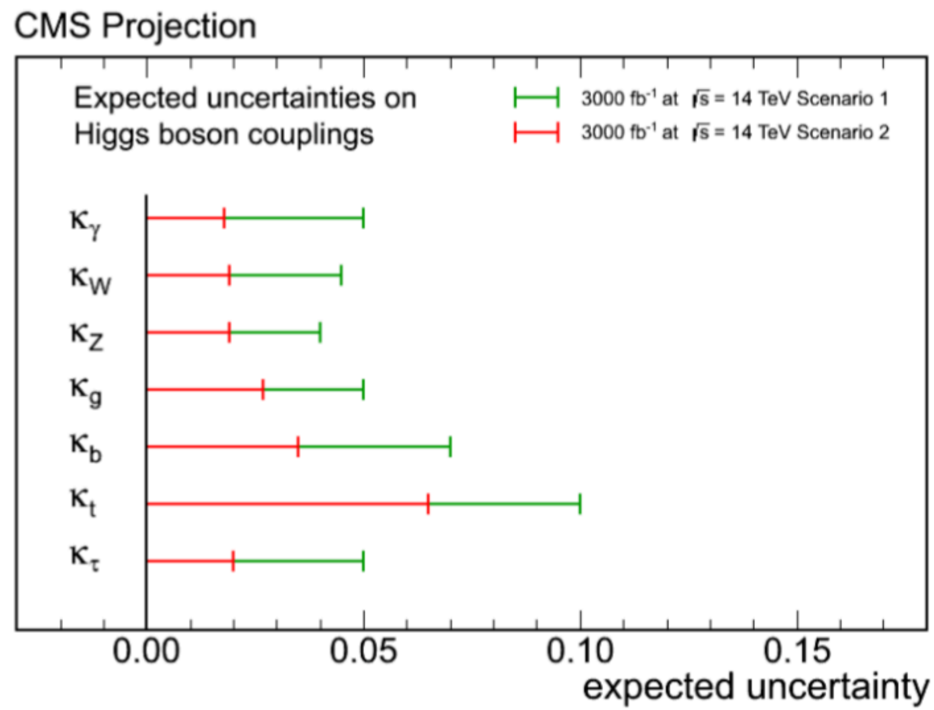
- HL-LHC: Higgs width $\to$ SM \pm 50% (BSM constraint)
- HL-LHC: $H \to$ invisible $< 10\%$ (BSM constraint)

- HL-LHC: $gg \to HH$? (Higgs potential)
- HL-LHC: Hcc coupling? (2nd gen Yukawa)

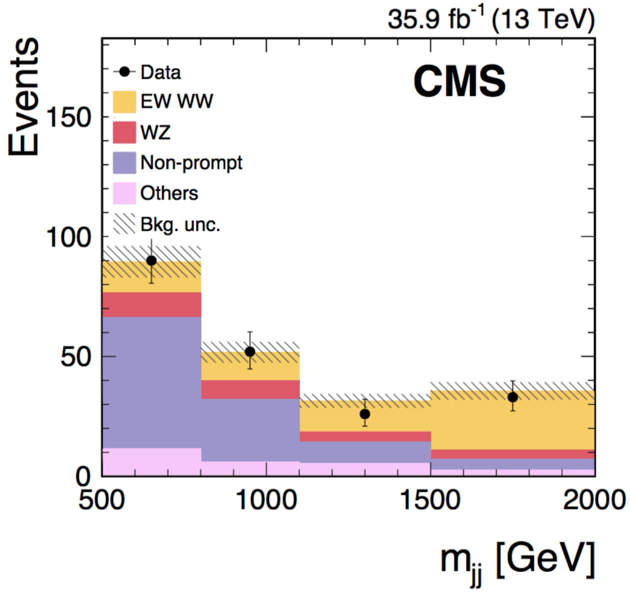
Imperial College London

What will the LHC (and HL-LHC) Bring?

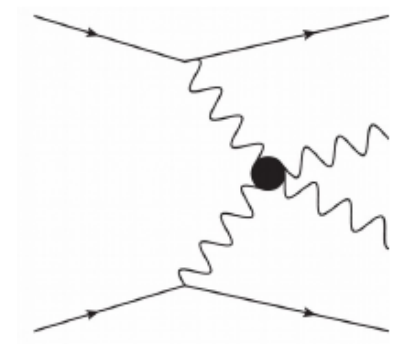


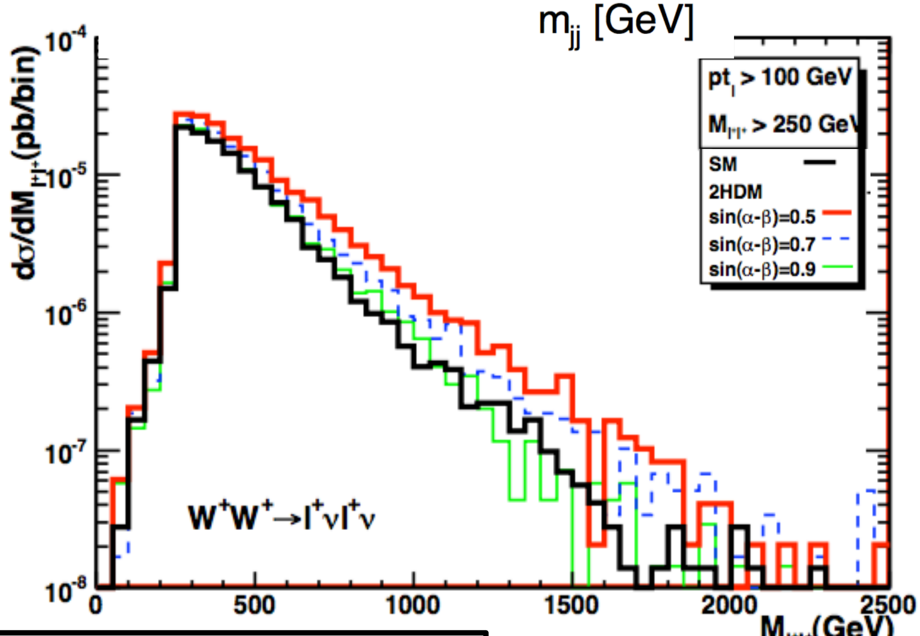


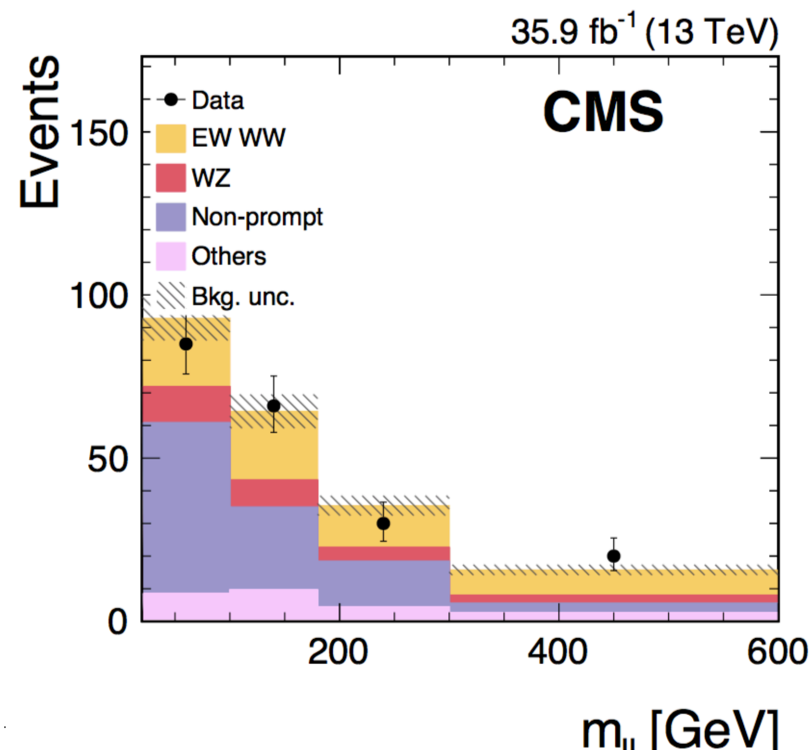
What will the LHC (and HL-LHC) Bring?



$W^{\pm}W^{\pm}$! 5.3σ!







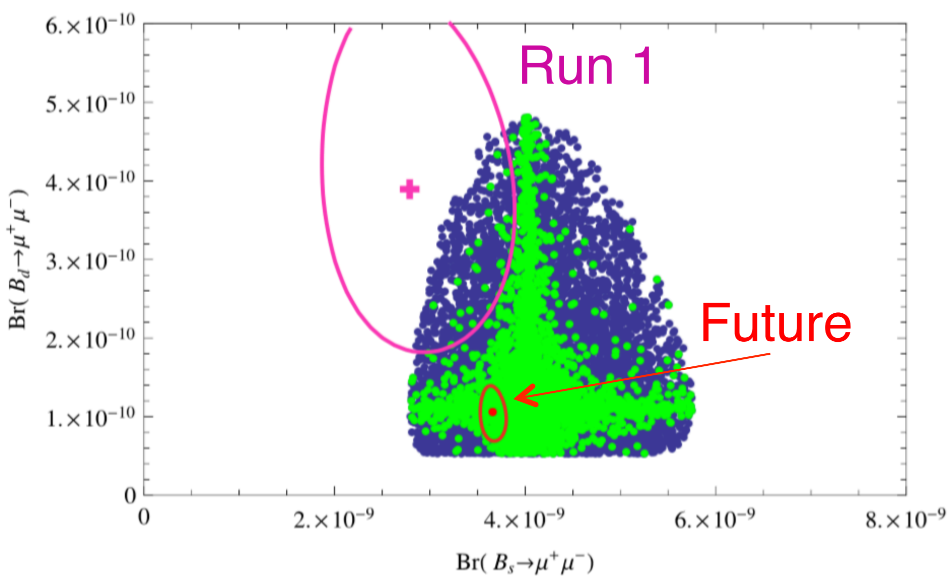
J.Chang et al arXiv 1303.6335

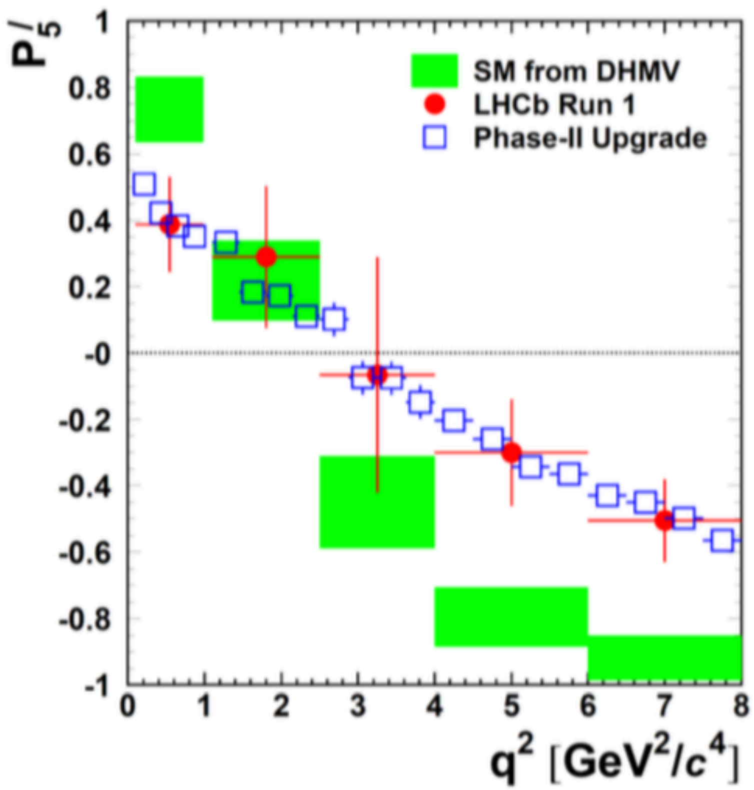
Imperial College London

Physics Thrust for HL-LHC: Flavour

	LHC Run	Period of data taking	Maximum $\mathcal{L}$ [$cm^{-2}s^{-1}$]	Cumulative $\int \mathcal{L}\, dt$ [fb^{-1}]
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8
Phase-I Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50
Phase-II Upgrade	5 →	2031–2033, 2035 →	2×10^{34}	300

LHCb *Selected* performance plots



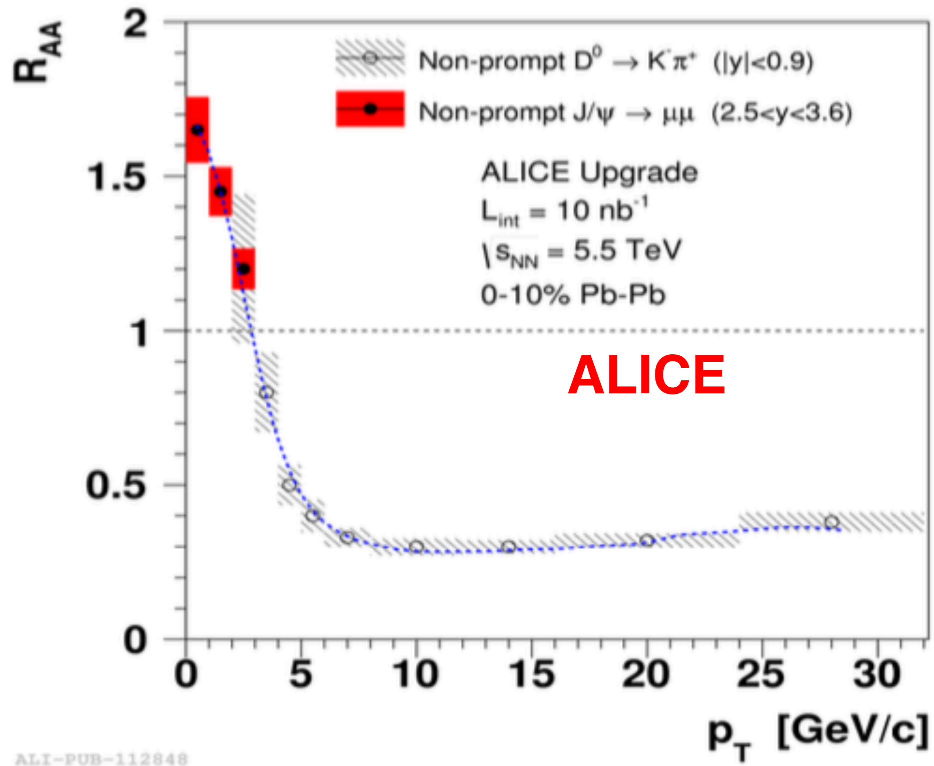


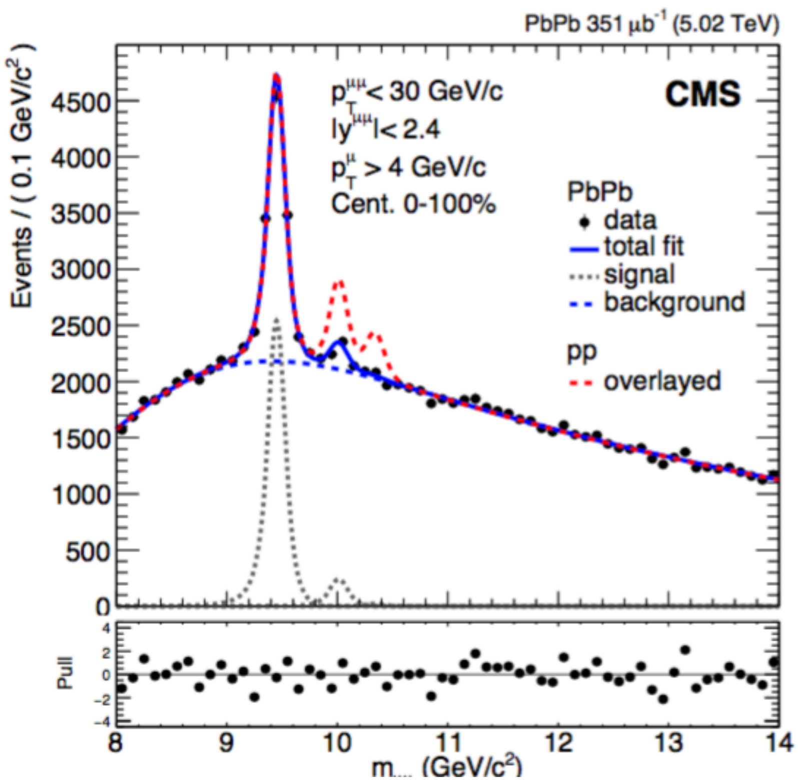
Imperial College London

Physics Thrust for HL-LHC: Extreme Matter

ALICE: Pb-Pb integrated luminosities

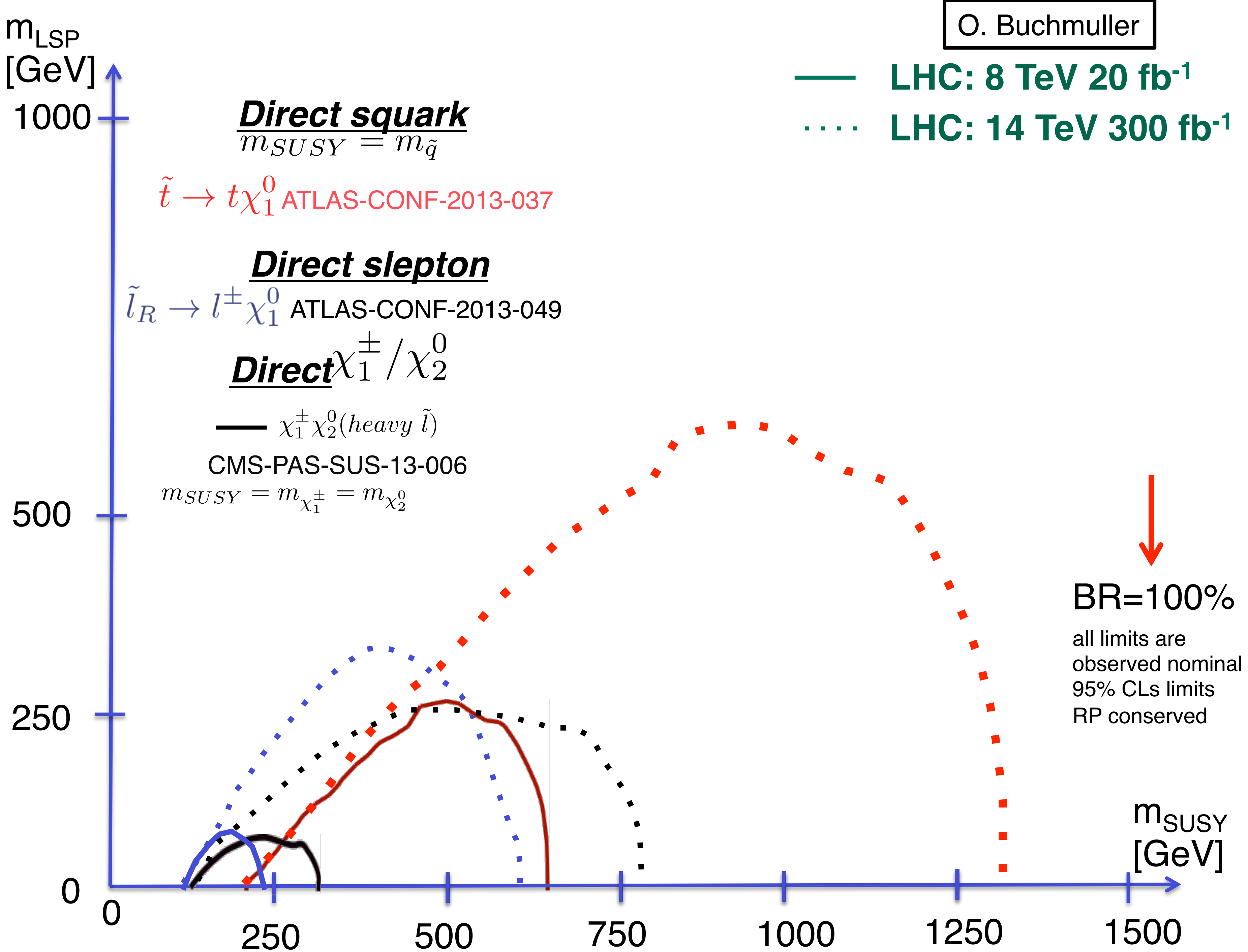
Run1+2	Up to 2018:	1 nb^{-1}
Run 3	2012-2023:	6 nb^{-1}
Run 4	2026-2029	7 nb^{-1}



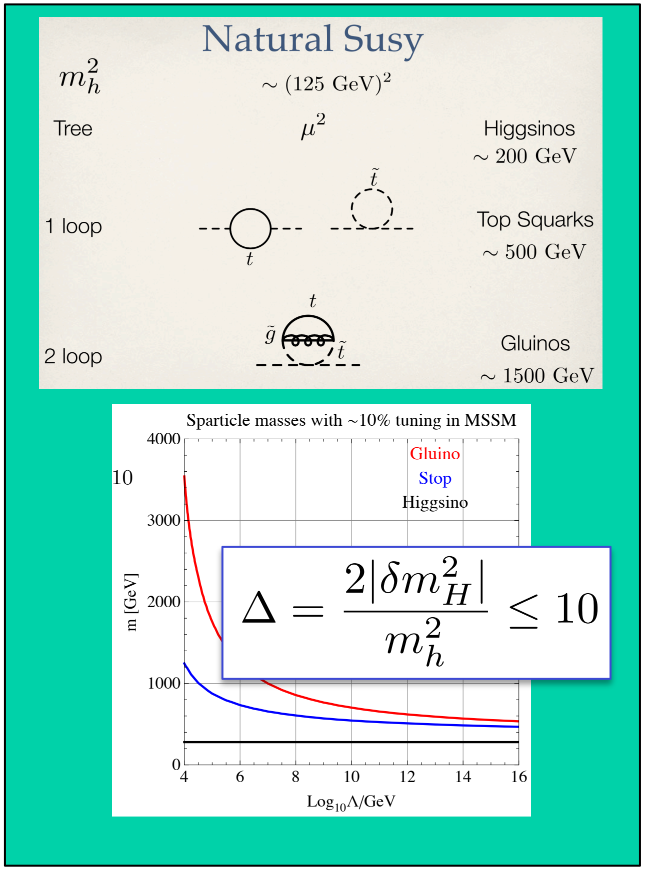


High p_T probes

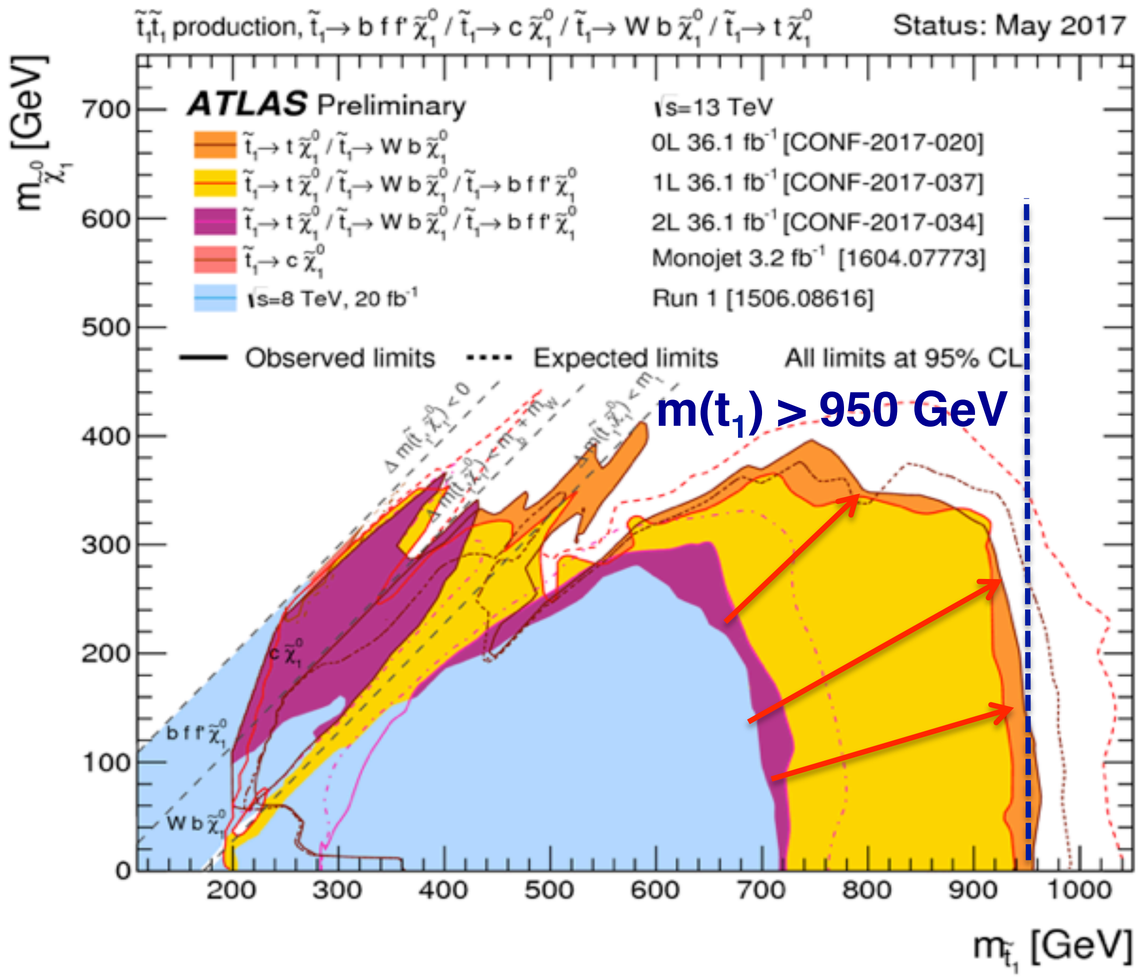
- Upsilon suppression
- γ, Z jet quenching, fragmentation


O. Buchmuller
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
1000
500
250
0
0
250
500
750
1000
1250
1500

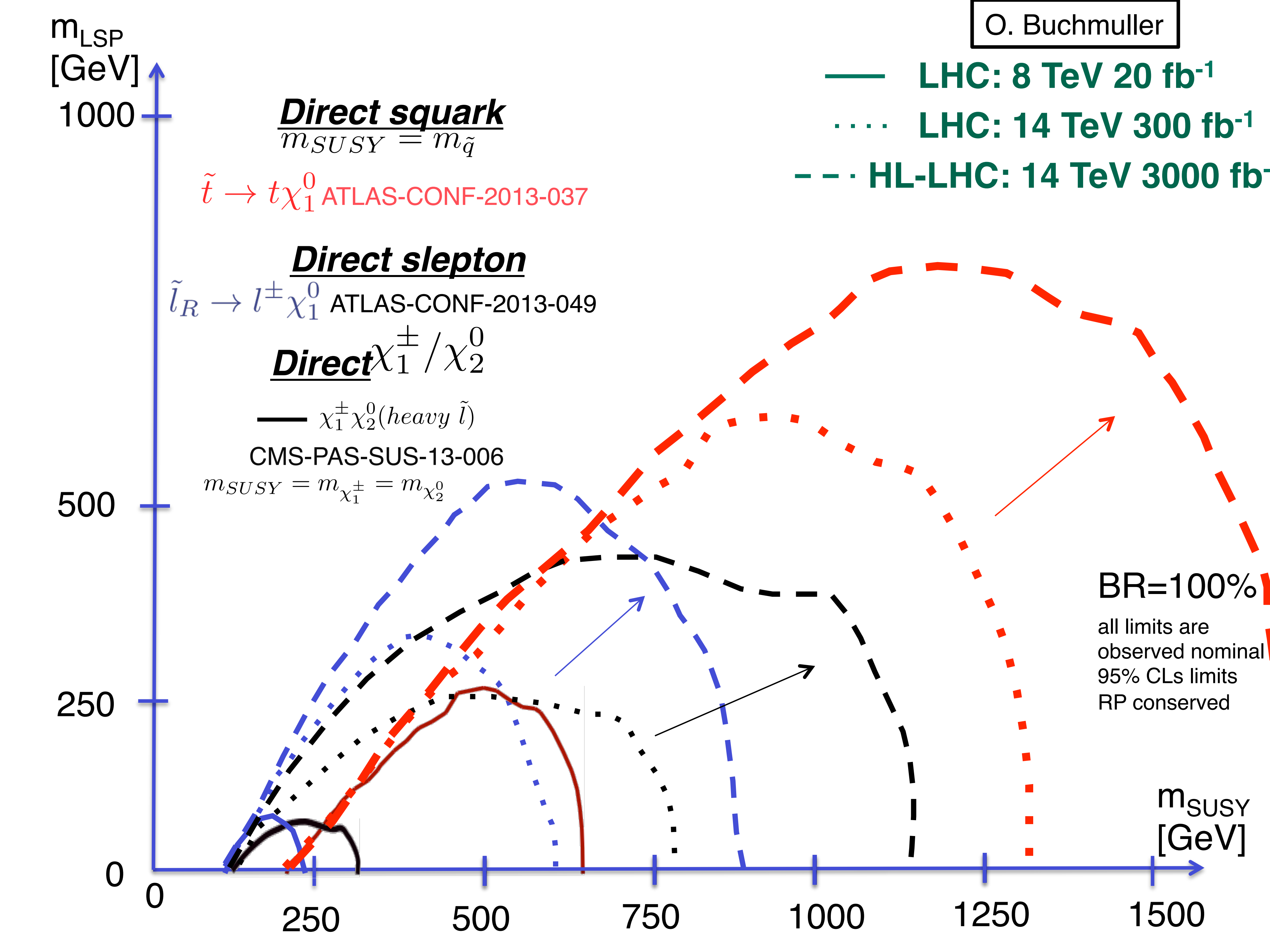
Not yet discovering: Supersymmetry



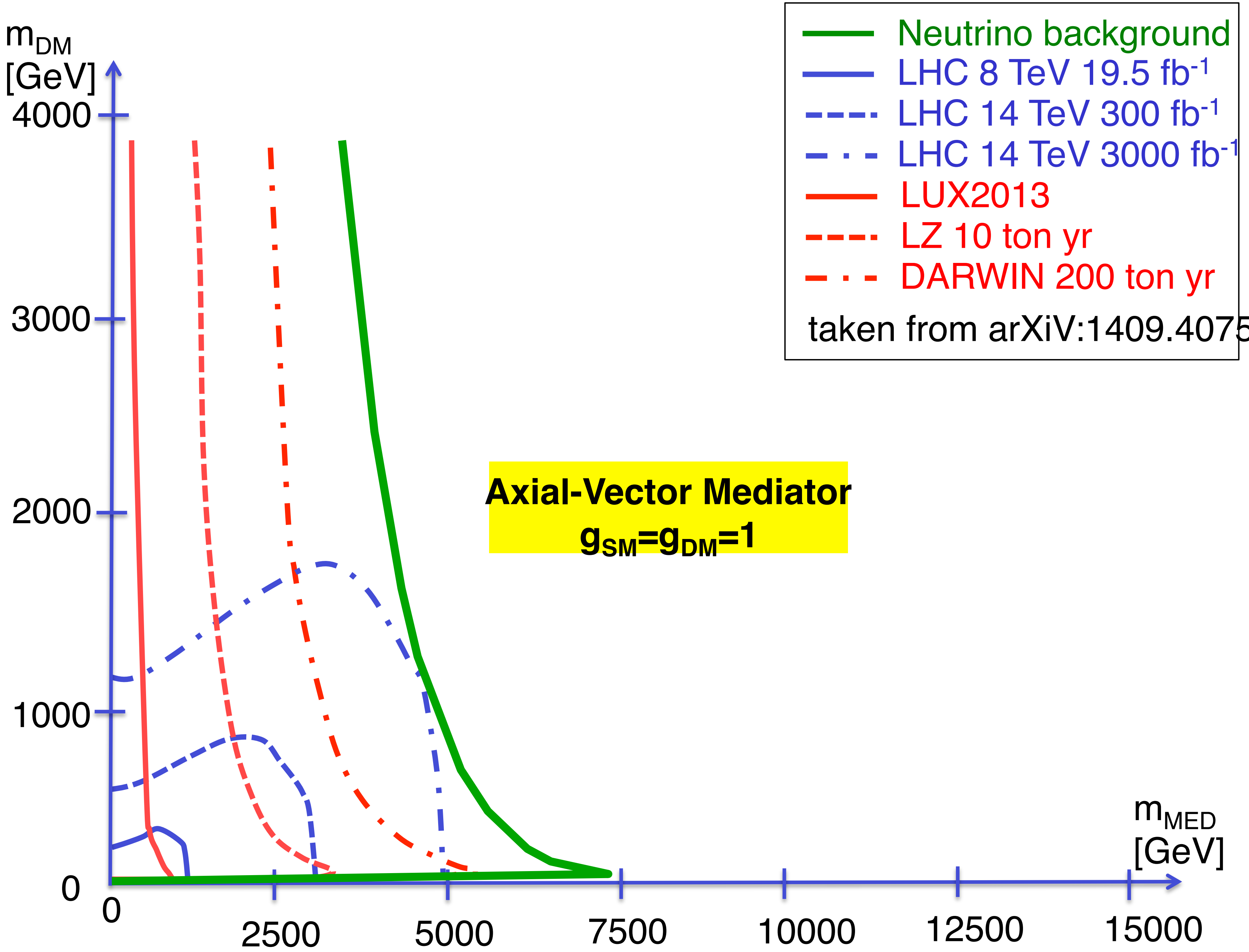
$$\Delta = \frac{2|\delta m_H^2|}{m_h^2} \leq 10$$



P. Sphicas EPS 2017

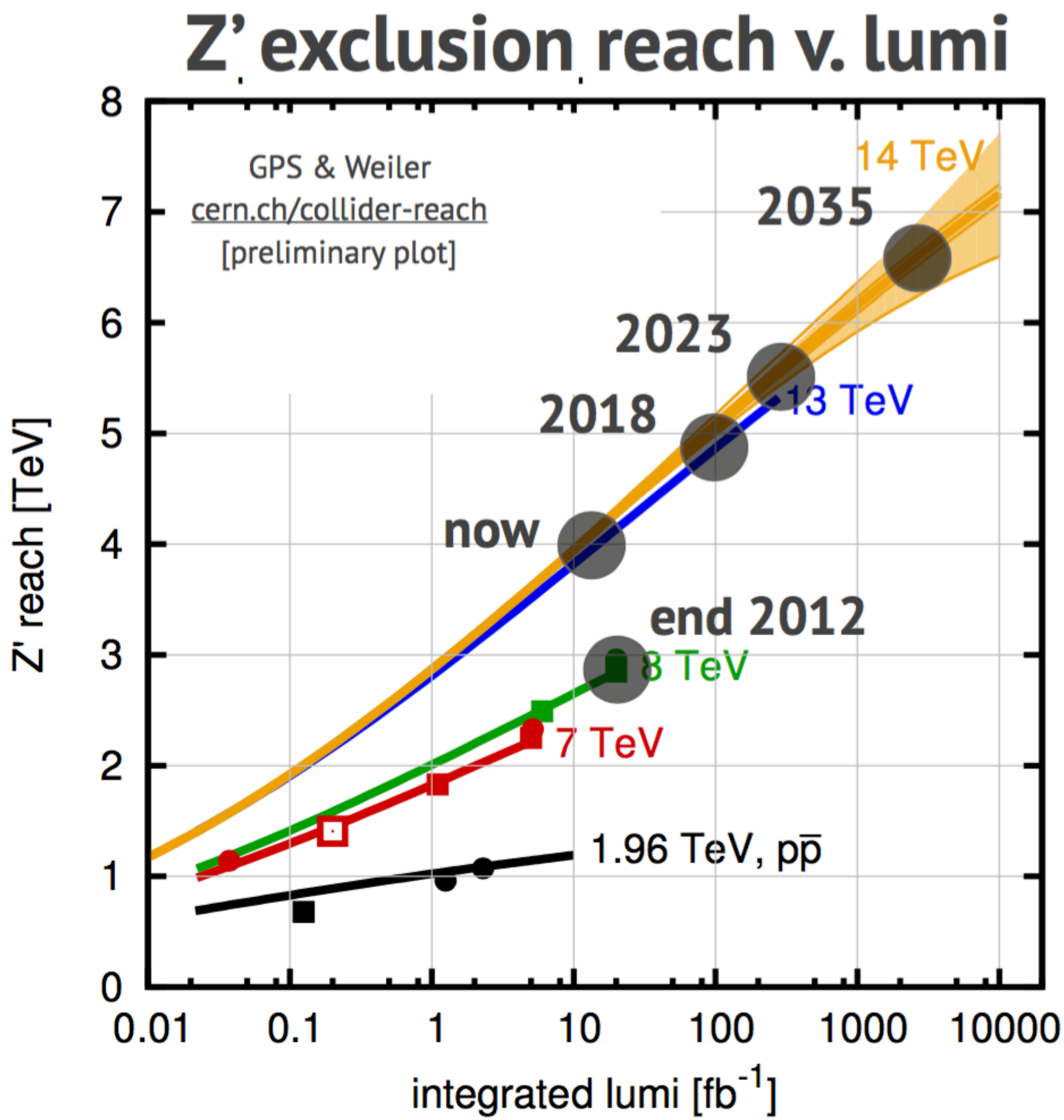


O. Buchmuller
LHC: 8 TeV 20 fb-1
LHC: 14 TeV 300 fb-1
HL-LHC: 14 TeV 3000 fb
mLSP [GeV]
1000
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
mSUSY [GeV]
0
250
500
750
1000
1250
1500



m_DM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_MED [GeV]
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LHC 14 TeV 3000 fb-1
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
g_SM=g_DM=1

Heavy Objects: Mass Reach



Summary

- **The LHC Accelerator and its Experiments are "Marvels of Technology"**
- **At the LHC a "massive" discovery of the Higgs boson has been made.** The boson appears just to be the one predicted by the SM. Its properties are now being studied in great detail.
- Superb measurement from all LHC experiments.
- **No evidence found yet of physics BSM.** The Standard Model with a single "elementary" scalar doublet seems to work well (too well).

- Discovery of Higgs boson is just the start of the exploration of the Terascale.
- LHC is the only frontier accelerator we have. So incumbent upon us to exploit its full potential. To do so the accelerator and the detectors are being upgraded for the HL-LHC phase (to give a factor ten increase in the integrated luminosity over the original design).
- The detectors are likely to be more powerful than ever.
- **Ahead is a suite of precision measurements (in the Higgs sector, SM), and the search for new physics.**
- **What further discoveries await us?**