Aspen Winter Institute 2016
Experimental Summary – Highlights - Outlook

ASPEN CENTER FOR PHYSICS

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Marumi Kado

Laboratoire de l'Accélérateur Linéaire

Forward and Disclaimers

- This conference gave a very complete overview of the field with a strong emphasis on experimental results and the crucial interaction of experiment and theory.
- Most talks were Reviews and typically of a large number of results.
- 53 talks altogether
- 33 Experimental Talks Covering most recent progress in:
  - High energy collider physics (LHC)
  - Neutrino physics
  - Particle Astrophysics (Multi-messenger)
  - Cosmology
- Congratulations and thanks to all the speakers for the exceptional quality of their talks.
- Summary of these Review talks: a personal choice of selected Highlights and Comments will be presented. It will hopefully represent the full (fascinating) picture.
- Michael covered the Particle Astrophysics and Cosmology experiment, the Collider and Neutrino physics will be covered here.

Retrospective

- Let's look back on the past 5-10 years at the landscape of particle physics since the Aspen winter Institute (Same organization – same conference tittle!)
- Aspen Winter Institute 2006:
  - The TeVatron Run II was the Energy Frontier at 1.96 TeV: the TeVatron Higgs searches where ramping up already many channels available!
  - The Precision frontier was dominated by B-factories (LEP already belonged to the past decade): The triangle closes!
  - In neutrino physics, Miniboone was ready to open the box and MINOS showed its first results. Reactor projects for θ_{13} were flourishing and T2K and NOvA where already pointed at to give answers to the mass hierarchy!
  - Particle Astrophysics: Auger is seeing events beyond the GZK cutoff and HESS to start pinning down the cosmic ray acceleration mechanism!
  - Dark Matter: Direct detection progress and challenges
  - Cosmology: Still mapping the morphology of Dark Energy and high hopes in Planck data and to learn about tensor perturbations from inflation.
  - Indication of a new QCD phase at high temperature: measurements of v2 in Heavy Ion collisions and jet quenching at RHIC
  - Prospects where focused mainly on the imminent advent of the LHC

Recent Landmarks and Evolutions
(Relevant for this Summary)

- A word on colliders:
  - Many large machines have stopped operations:
    - Hera in 2007
    - PEP-II and CLEO-c in 2008
    - TeVatron in 2011
  - Super KEKb is starting
  - The LHC has started in 2009
  - RHIC running with polarized pp collisions (probing spin structure of protons)

- Landmark Results that have changed the overall picture in the past five years
  - The discovery of the Higgs boson in 2012 (ATLAS and CMS)
  - The measurement of a fairly large θ_{13} in 2012
  - The release of the Planck data in 2013

Particle Physics at the Verge of another Discovery?

This summary will focus on the observed anomalies to try to address the main question of the conference

The Standard Model of EW Interactions: can it be it?

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

The essentially elegant gauge sector but… for the strong CP problem

The less elegant Higgs sector:

- Gauge Hierarchy (and Naturalness
- Flavor hierarchy
- Neutrino masses

For neutrinos: Masses imply right handed neutrino, why should a Majorana term not be present? Is the LN a fundamental symmetry?

- Evidence for Dark Matter: is there a Dark sector?
- Significant theoretical motivations (Naturalness, Stong CP problem, Neutrino masses, Flavor Hierarchy, Grand Unification, Explanation of Baryon Asymmetry (through Leptogenensis?) …)
- Celebrated but elusive SUSY

The Standard Model of EW Interactions: can it be it?

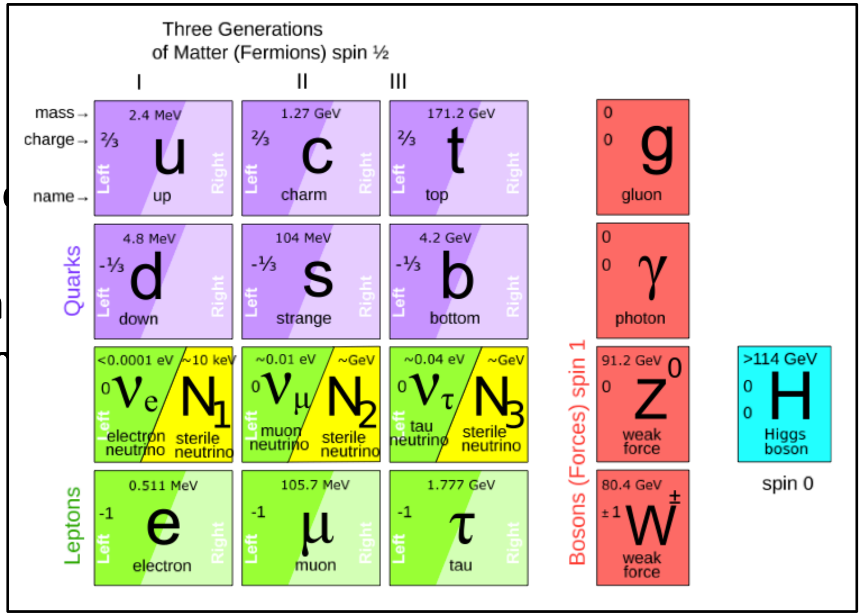
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

The essentially elegant gauge sector but… for the strong CP problem

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

The less elegant Higgs sector:

- Gauge Hierarchy (and Naturalness
- Flavor hierarchy
- Neutrino masses



- Evidence for Dark Matter: is there a Dark s

- Significant theoretical motivations (Natura
  Flavor Hierarchy, Grand Unification, Explan
  Leptogenensis?) …)

- No discussion of the νMSM?
  SHiP experiment proposal

ν Neutrino Physics Status and main questions

Silvia Pascoli

1. What is the nature of neutrinos? Addressed by neutrinoless double beta decay experiments:
   - Low density trackers: Super NEMO (82Se) and Next (136Xe)
   - Liquid Scintillators: KamLAND-Zen (136Xe) and SNO+ 130Te
   - Crystals: Majorana and Gerda (Ge76), CUPID (130Te, 82Se, 100Mo), CUORE
   - Liquid TPC: nEXO (Lxe)

   No signal observed yet, but vast and very active number of experiments covering a large variety of tehniques and isotopes!
   - But also search for LNV at accelerators (SS 2l signatures)

   Giorgio Gratta

2. What are the values of the masses? Absolute scale (KATRIN, ...?) and the ordering?

3. Is there CP-violation?

   Marc Messier

   Karsten Heeger

4. What are the precise values of mixing angles?

5. Is the standard picture correct? Sterile neutrinos? Other effects?

   Karsten Heeger

Overview of Consolidated Status Neutrino Physics

$$U=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}=\begin{pmatrix}0.8 & 0.5 & U_{e3}\\ 0.4 & 0.6 & 0.7\\ 0.4 & 0.6 & 0.7\end{pmatrix}=\underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\text{atmospheric, K2K}}\times\underbrace{\begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}}_{\text{reactor and accelerator}}\times\underbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{SNO, solar SK, KamLAND}}\times\underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha/2} & 0\\ 0 & 0 & e^{i\alpha/2+i\beta}\end{pmatrix}}_{0\nu\beta\beta}$$

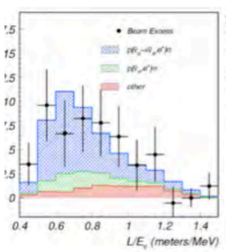
	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$

Includes: SK, MINOS, T2K, Chlorine, Gallex, SAGE, SNO, Borexino, Double Chooz, Daya Bay, RENO, KamLAND

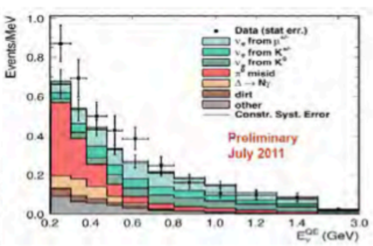
Impressive precision on θ_{13} !

Silvia Pascoli

LSND



MiniBoone



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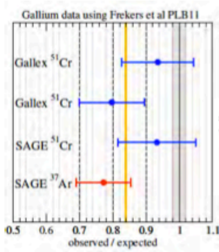
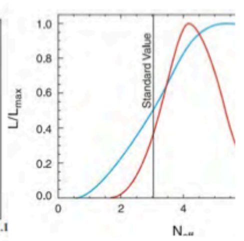
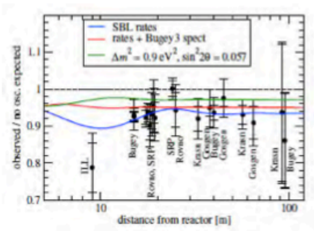


Cosmology (WMAP)



Reactor



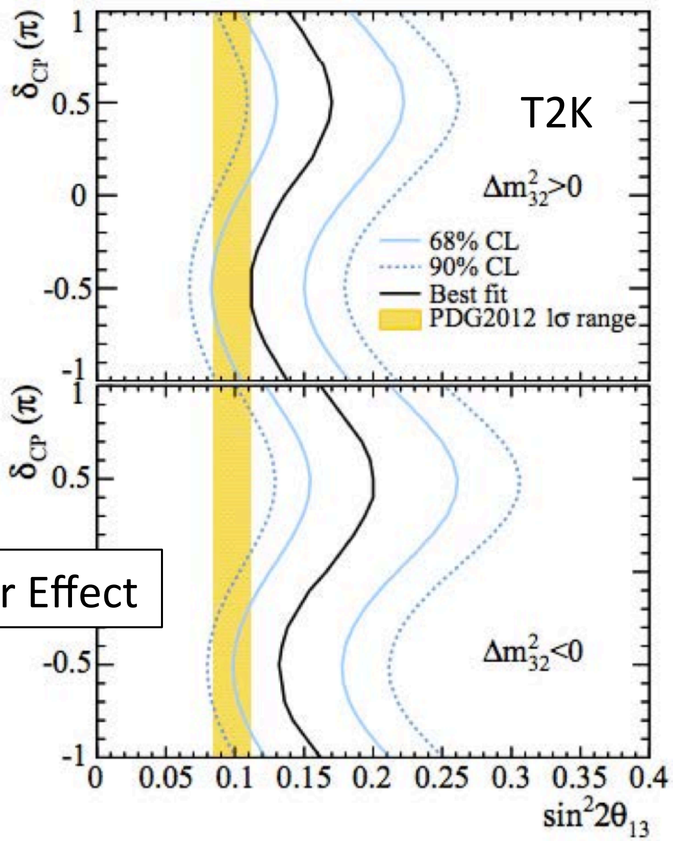
Anomalies:
Picture not fully consistent

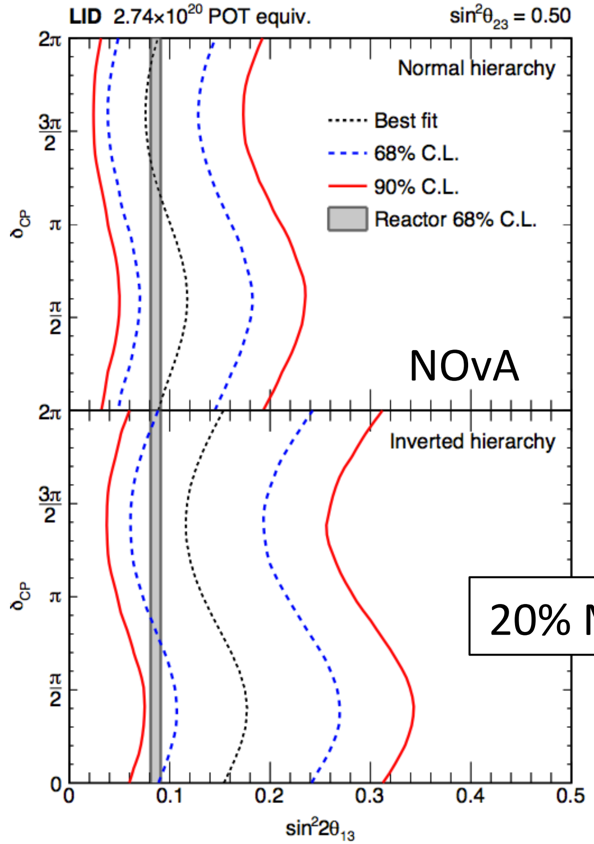
Karsten Heeger

ν Neutrino Recent Progress

From electron neutrino appearance

Marc Messier





10% Matter Effect

20% Matter Effect

- Atmospheric and long baseline give a very consistent picture
- Electron appearance in LBL exciting hints:
  - δCP roughly 3π/2
  - Normal Hierarchy

ν

Future Projects

Large number of projects, two most prominent towards Intense Neutrino Beams to settle δCP and the mass hierarchy with very long baselines:

- LBNF ad JPARC beamlines (40% matter effect) to be completed in 2026
- DUNE (Lar TPC), T2K extended and Hyper-K : Also sensitive to proton decay and super nova neutrinos.

Jelena Maricic

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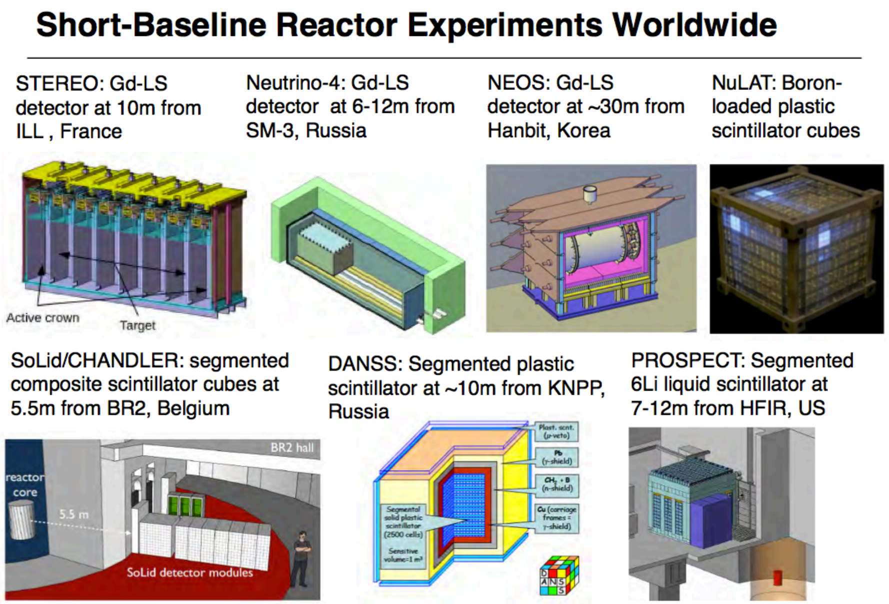
Large number of projects, to settle on anomalies



Solid Experiment

Jonathan Link

Prospect Experiment

Karsten Heeger

MicroBoone
(check MiniBoone excess)

Taritree Wongjirad

ν

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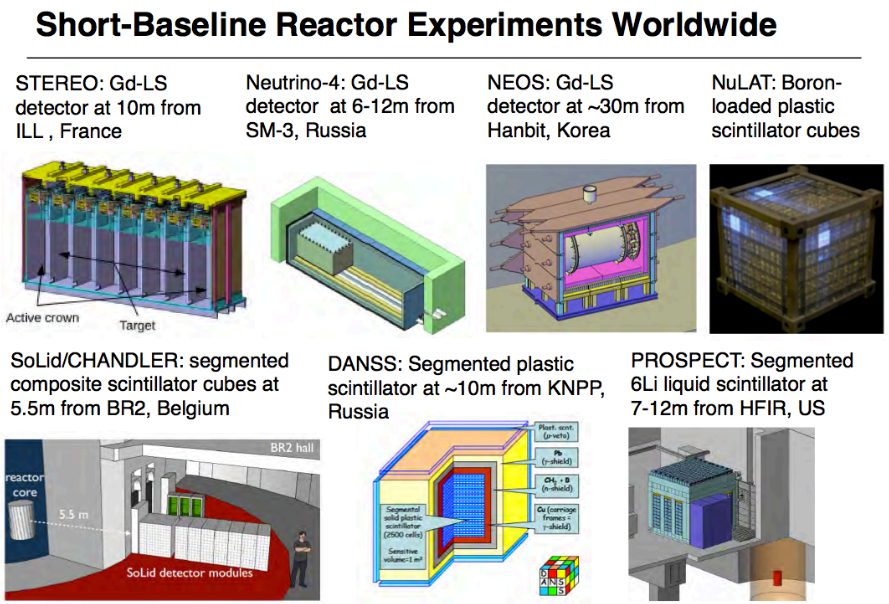

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(check MiniBoone excess)

Taritree Wongjirad

Measurement of Coherent Neutrino-Nucleus Scattering (COHERENT)
(Background to direct DM detection experiment)

Phil Barbeau

Key SM Parameters (I)

Guillaume Unal

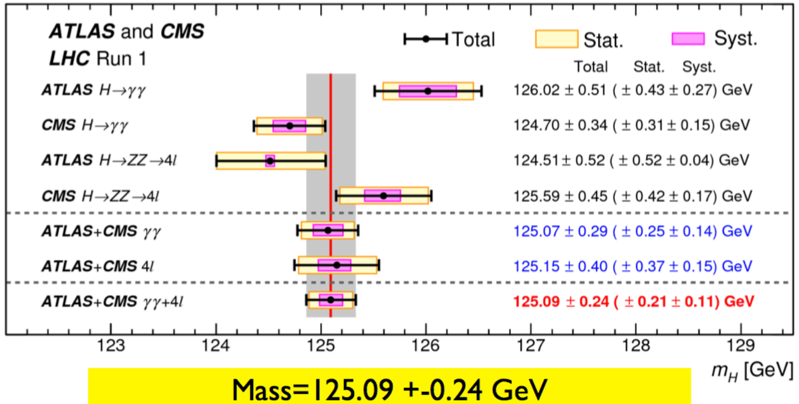
- The Higgs boson mass:
  - Measured at the 0.2% level
  - One of the most precise measurements at the LHC
  - Dominated by statistics (calibration uncertainties not negligible)
- Top mass
  - Traditional MC mass measurements at 0.3% level
  - Uncertainty on MC mass definition w.r.t. Pole mass at least of the order of Λ_{QCD}

Fabrizio Caola

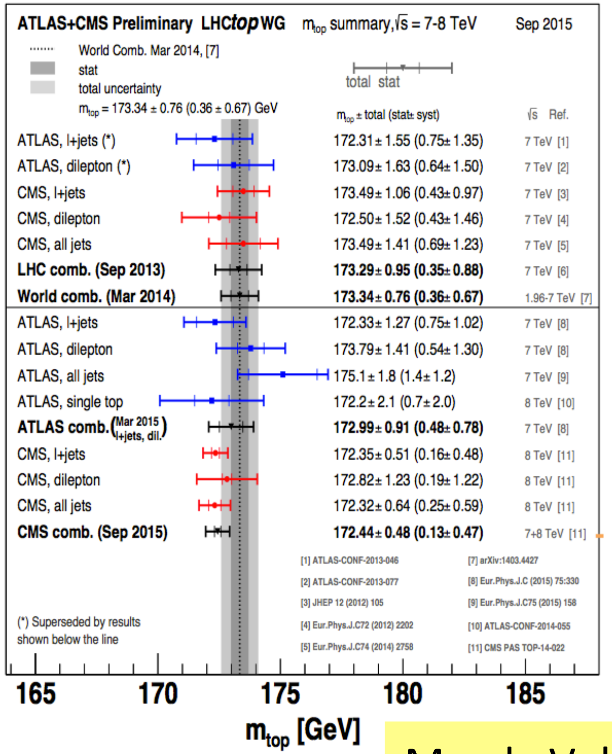
Congratulations for prize win and for splendid work on TH top physics developments

  - Pole Mass measurements from cross sections (inclusive and tt-1-jet) at the level of 1.2% (also sensitive to hadronization uncertainties)
  - Future challenge: How will we reach the 200 MeV level?
  - An experimental as well as TH challenge

ATLAS-CMS PRL 114 (2015) 191803



Mass=125.09 +-0.24 GeV
Accuracy < 0.2% (main uncertainty is statistical)



Mayda Velasco

Key SM Parameters (II)

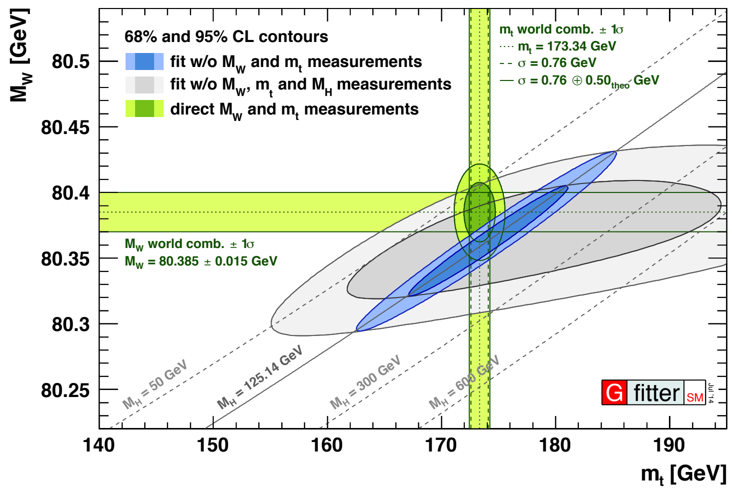
Doreen Wackeroth

- The W boson mass:
  - Current precision (mostly TeVatron): 16 MeV i.e. 0.002% (Still improvements expected)
  - At LHC expected uncertainty: 15 MeV extremely challenging (PDF uncertainties are dominant).

ΔM_W [MeV]	present	CDF	D0	combined	LHC		
$\mathcal{L}$[fb]	7.6	10	10	20	20 (8 TeV)	300	3000
PDF	10	5	5	5	10	5	3
QED rad.	4	4	3	3	4	3	2
$p_T(W)$ model	2	2	2	2	2	1	1
other systematics	9	4	11	4	10	5	3
W statistics	9	6	8	5	1	0.2	0
Total	16	10	15	9	15	8	5

- Status of the EW fit
  - Important to constrain $\Delta\alpha_5$
  - TH uncertainty due to missing 3-loop corrections

	ΔM_W [MeV]		$\Delta \sin^2 \theta^l_{\text{eff}} [10^{-5}]$	
	present	future	present	future
$\Delta m_t = 0.9; 0.5(0.1)$ GeV	5.4	3.0(0.6)	2.8	1.6(0.3)
$\Delta(\Delta\alpha_{\text{had}}) = 1.38(1.0); 0.5 \cdot 10^{-4}$	2.5(1.8)	1.0	4.8(3.5)	1.8
$\Delta M_Z = 2.1$ MeV	2.6	2.6	1.5	1.5
missing h.o.	4.0	1.0	4.5	1.0
total	7.6(7.4)	4.2(3.0)	7.3(6.5)	3.0(2.6)



A Run 1 Legacy: The *Standard Model* Higgs Boson

Guillaume Unal

$$(\sigma_i.BR_j)=\sigma(gg\to H\to ZZ)\ \frac{\sigma_i}{\sigma_{ggF}}\ \frac{BR^j}{BR^{ZZ}}$$

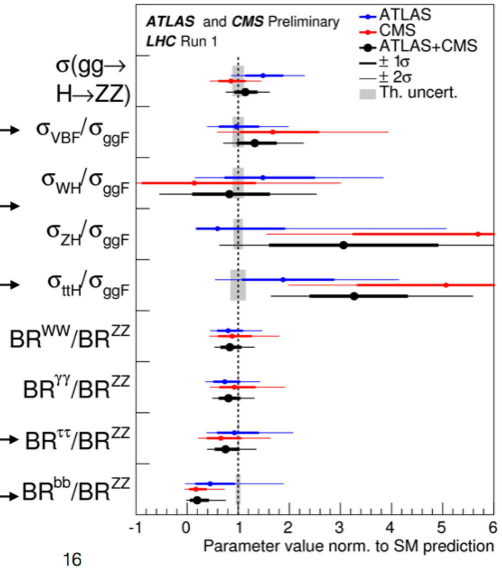
Observed with 5.4 σ significance (exp 4.7)

3.5 σ for combined WH+ZH production (exp. 4.2)

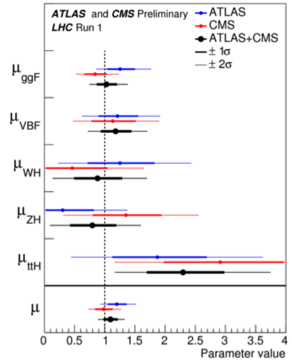
~2.4 σ excess over SM prediction for ttH (4.4 observed, 2.0 expected)

Observed with 5.5 σ significance (exp. 5.0)

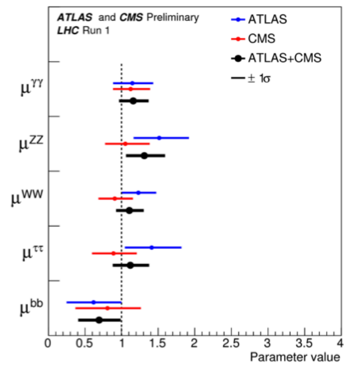
Driven low by "excess" in ZH and ttH production modes in other decay channels than bb



Cross-section per production mode (assuming SM BR) compared to theory prediction



Branching ratio per decay mode (assuming SM cross-section) compared to theory prediction



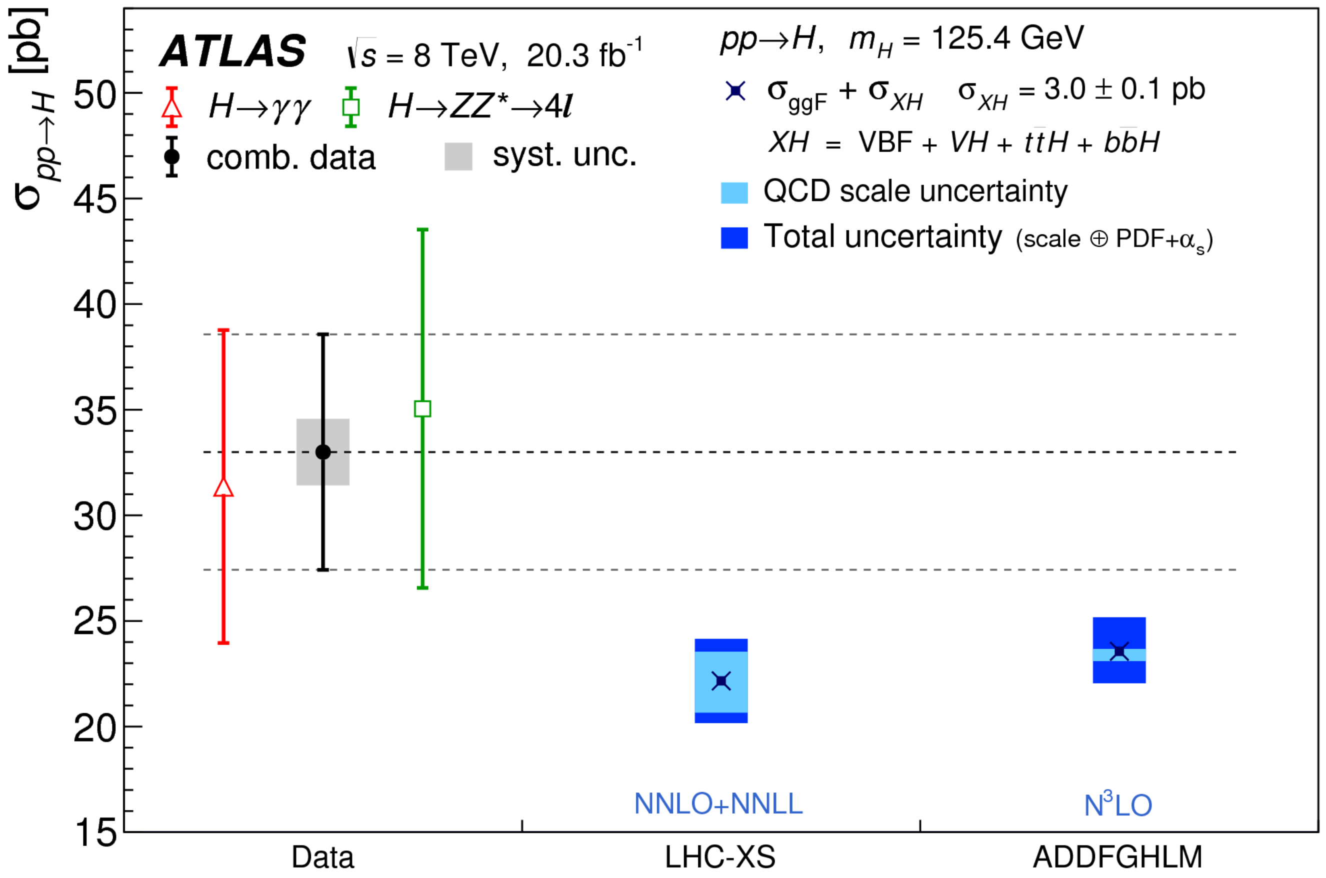
Global signal strength assuming SM ratio for all production and decay (~10% accuracy):

$\mu = 1.09 \pm 0.07_{\text{stat}} \pm 0.04_{\text{exp syst.}} \pm 0.03_{\text{th. bkg}}\ {}^{+0.07}_{-0.06}{}_{\text{th. sigma}}$

ATLAS and CMS coupling properties combination: an impressive host of interesting results:

- Gluon Fusion and VBF production modes observed at more than 5σ
- WW, ZZ, γγ,and ττ decay modes observed at more than 5σ
- Accuracy on couplings (with assumptions) 10% - 20%
- The ttH production mode a little high (to be followed up at Run 2 in high priority)
- Extremely important input from TH both for the signal and for the background

Breakthrough !!



$$\sigma(\mathrm{Data}, pp \to H) = 33.0 \pm 5.3\ (\mathrm{stat}) \pm 1.6\ (\mathrm{syst})\ \mathrm{pb}$$

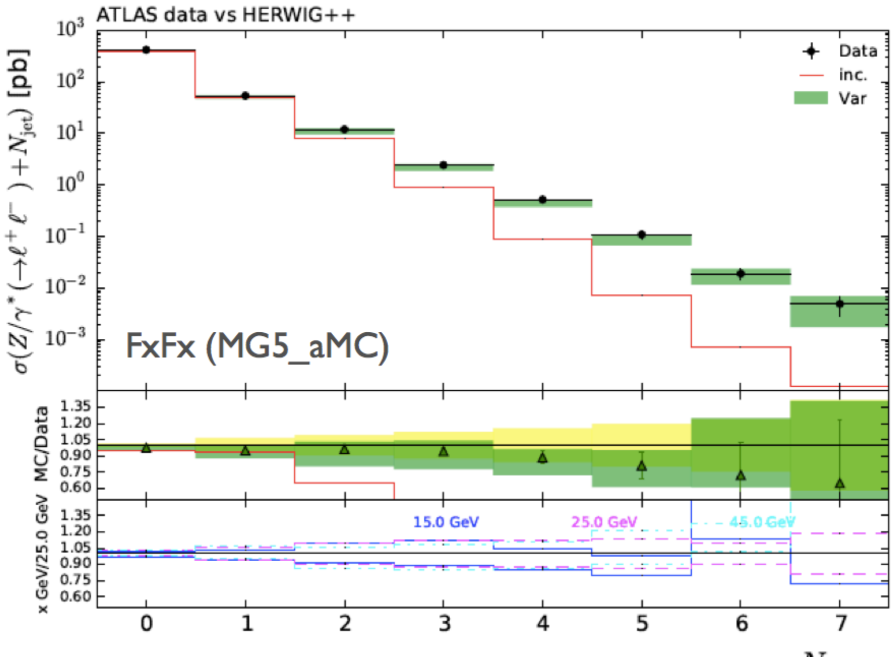
$$\sigma(\mathrm{Data}, gg \to H) = 30.0 \pm 5.5\ \mathrm{pb}$$

$$\sigma(\mathrm{LHC\ Higgs\ XS\ WG}, gg \to H) = 19.1 \pm 2.0\ \mathrm{pb}$$

Next Challenges in (SM) Higgs Physics at Run 2

- Direct measurement of Hbb (in VH production)
- Direct measurement of Htt (in ttH production)

These measurement will require a high level of precision in the simulation of intricate background processes such as the V+jets and tt: at Run 2 experiments have migrated to State of the Art MC



In Fabio's words: The LHC demands an unprecedented level of precision

Fabio Maltoni

H^0

Higgs Physics Overall Summary *Landscape redefined*

Guillaume Unal

More Precision

- Quantum numbers (Spin, CP) - input to couplings
- Coupling properties precision of 10% - 20%
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays

- Zγ, γγ*
- Muons μμ
- LFV μτ, eτ
- J/Ψγ, ZY, WD etc…

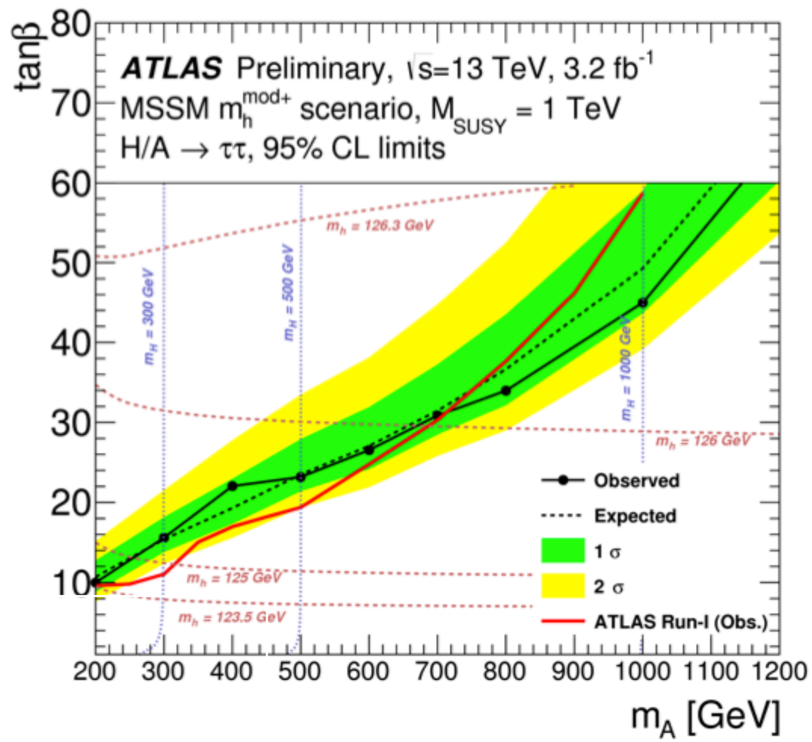
Is the SM minimal?

- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

…and More!

- FCNC top decays
- Di-Higgs production
- Trilinear couplings prospects

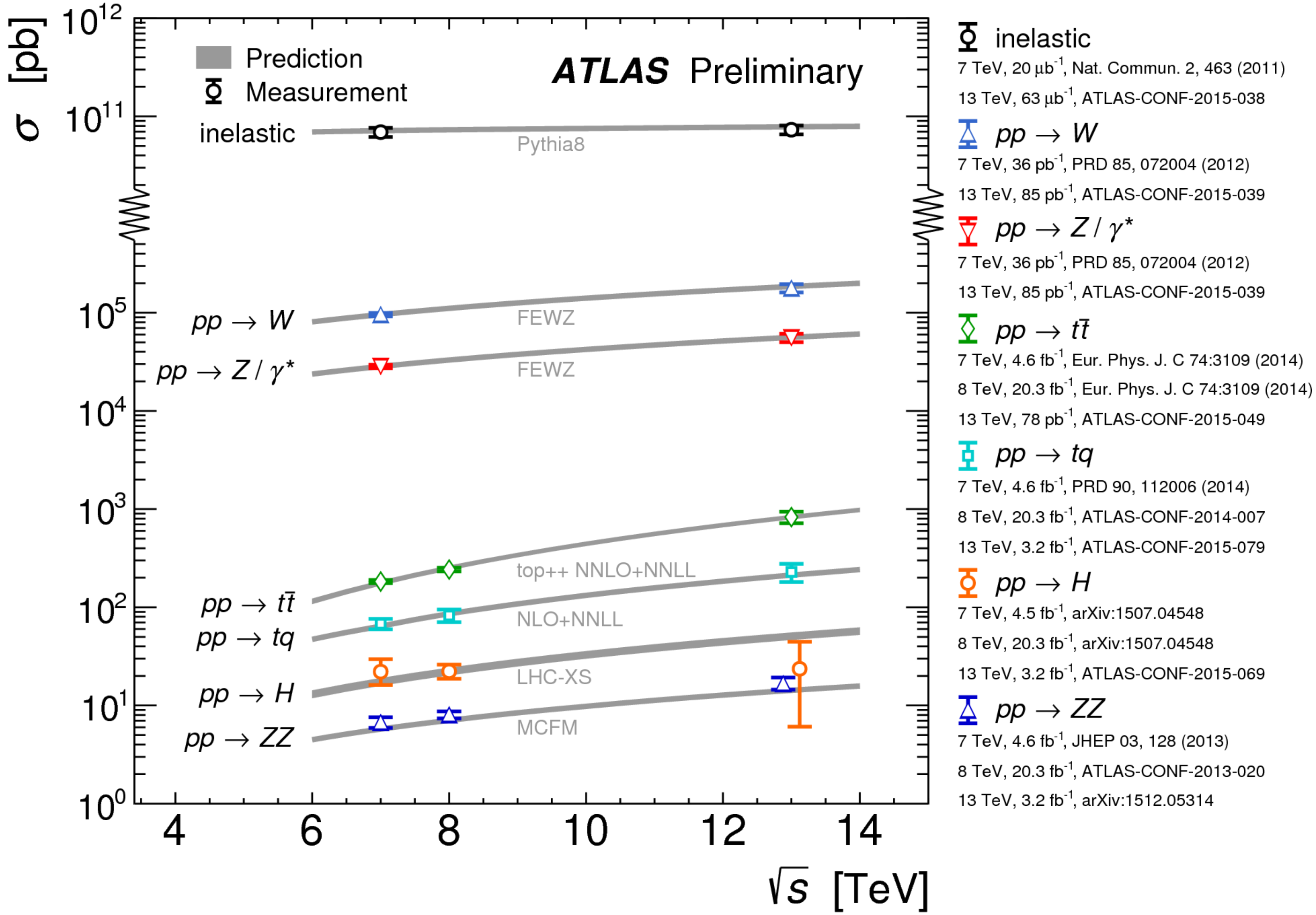
ATLAS-CONF-2015-061



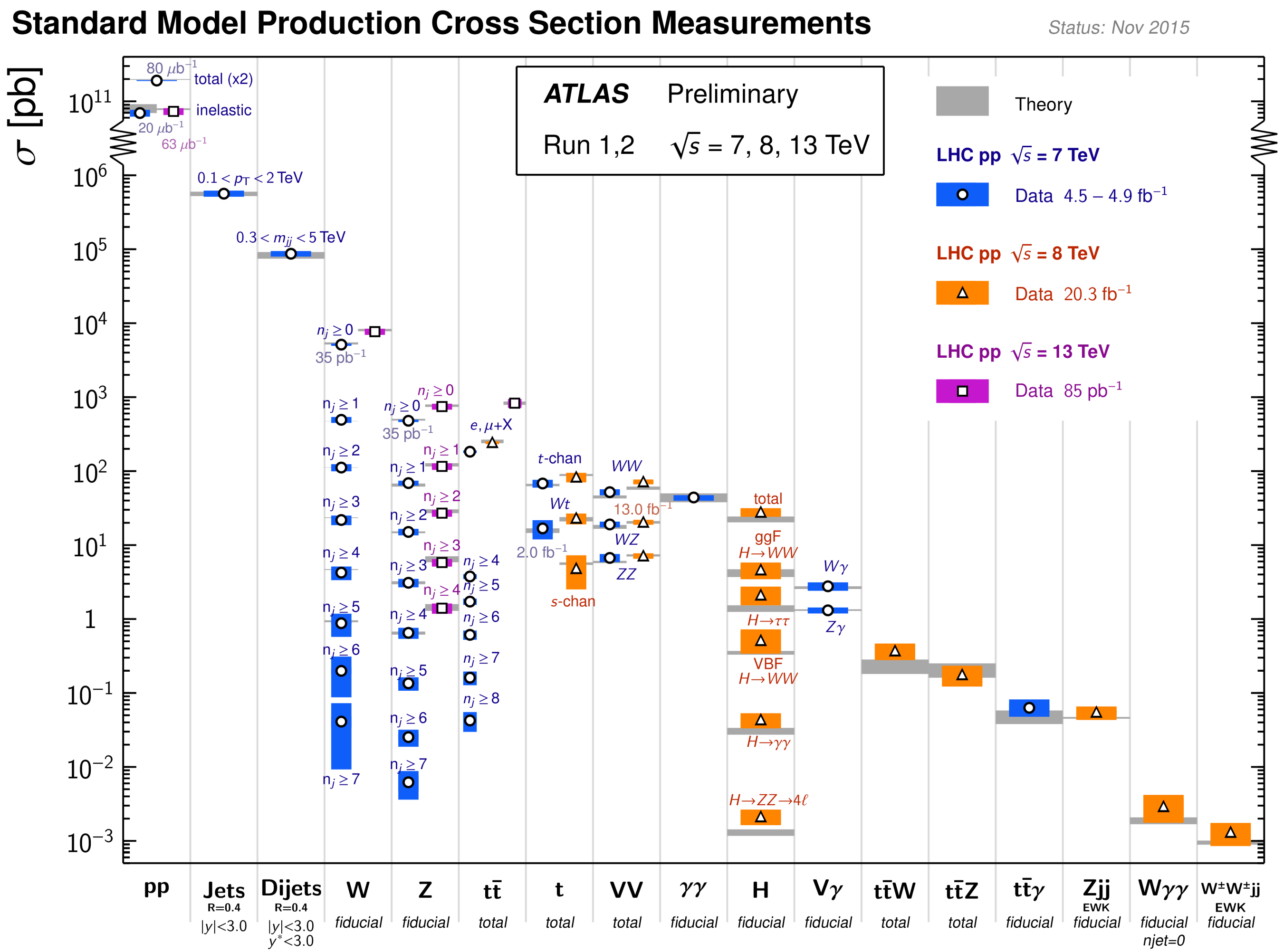
Current limits exceed Run 1 sensitivity at high mass

Measurements of SM Rates

Already well advanced at Run 2!



A broad (but Very Incomplete) View



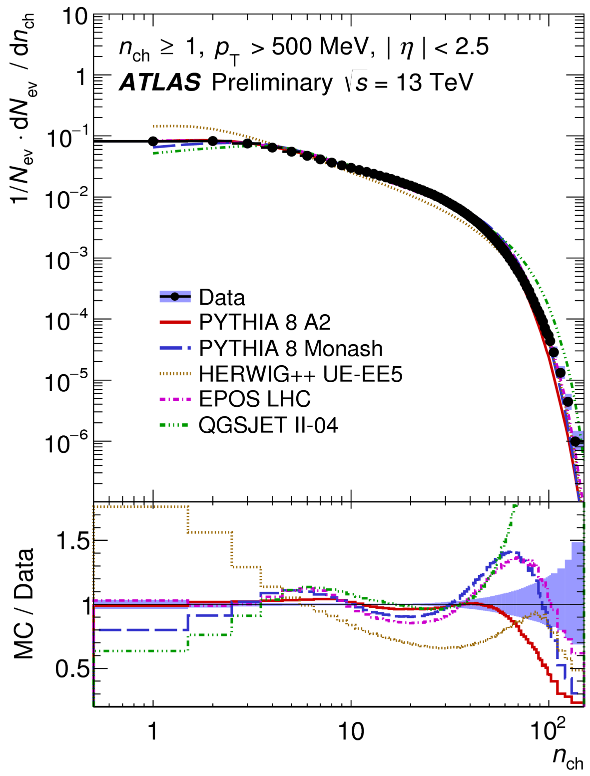
4 Key Aspects

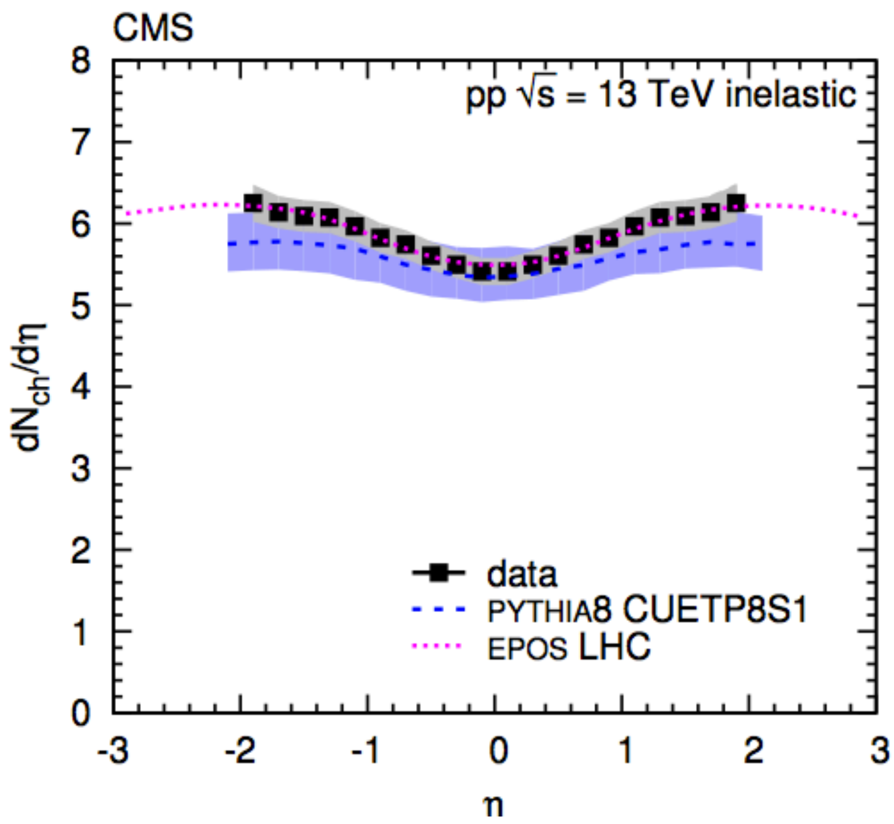
- A incredible harvest of results (made usefully public through **Fiducial** Cross Section **HEPData** and **Rivet Routines**)
- NLO and NNLO predictions, PDFs
- **NLO Monte Carlos**
- **IR and Collinear safe Fast Jet**

… There is more in Jet physics developments

Doug Schouten | David d'Enterria | Louis Hellary

Progress and Importance of Soft QCD Measurements

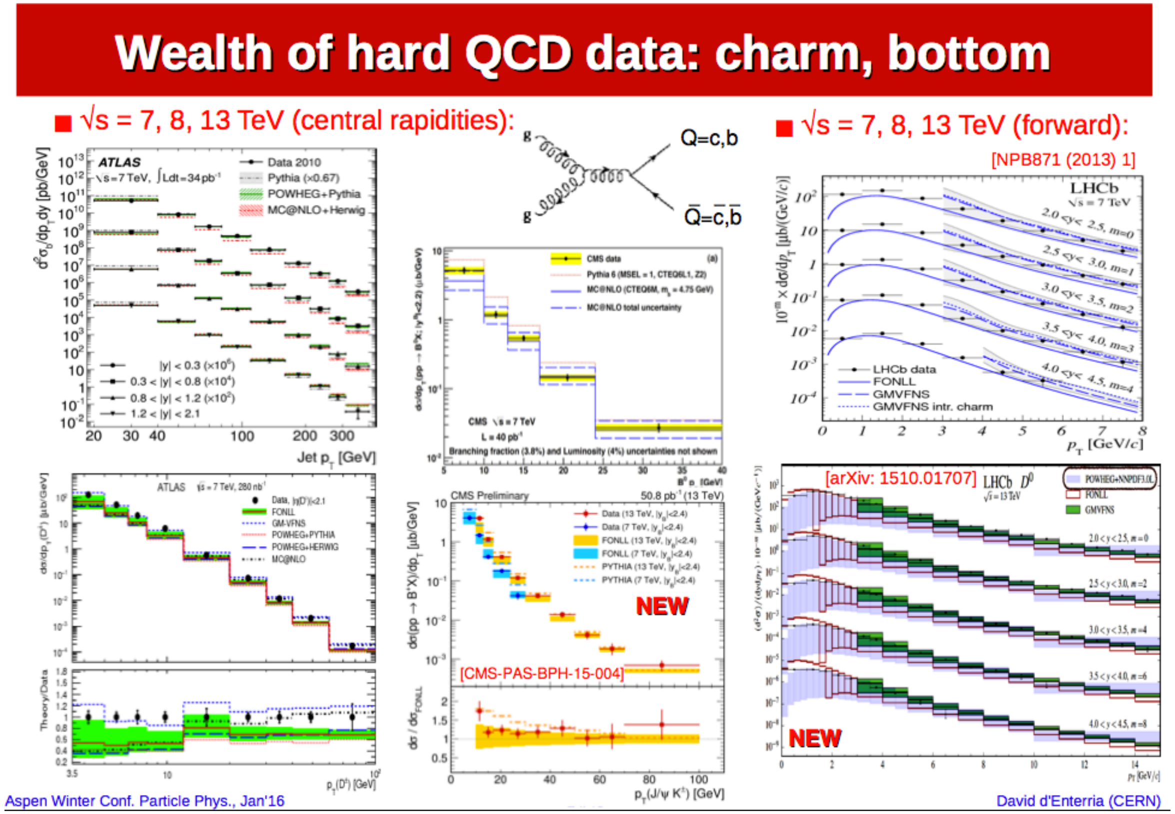




These measurements are essential to tune the Underlying Event and Minimum Bias modeling (as well as probing tracking and the detector geometry)

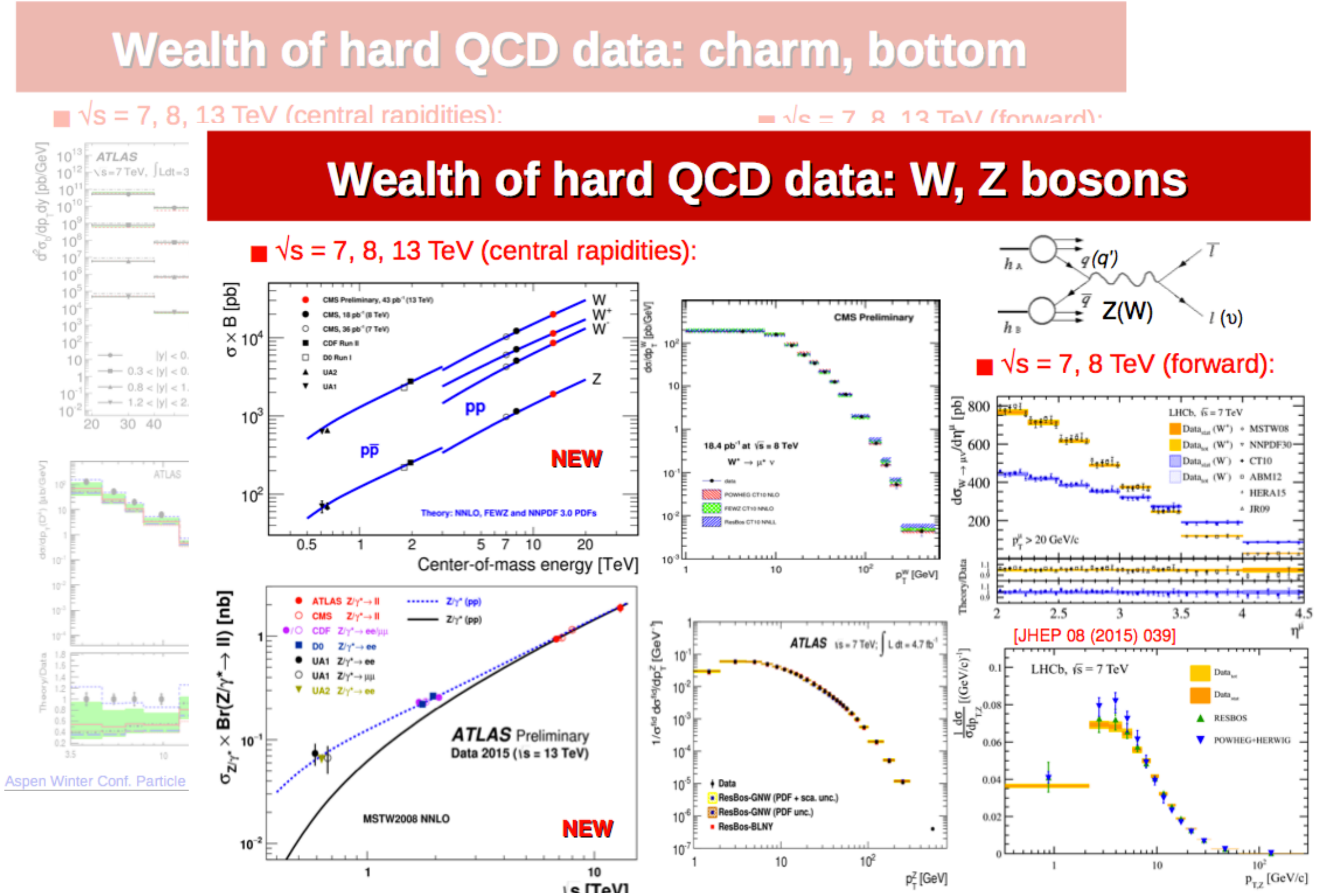
Doug Schouten

Progress in Hard QCD Measurements



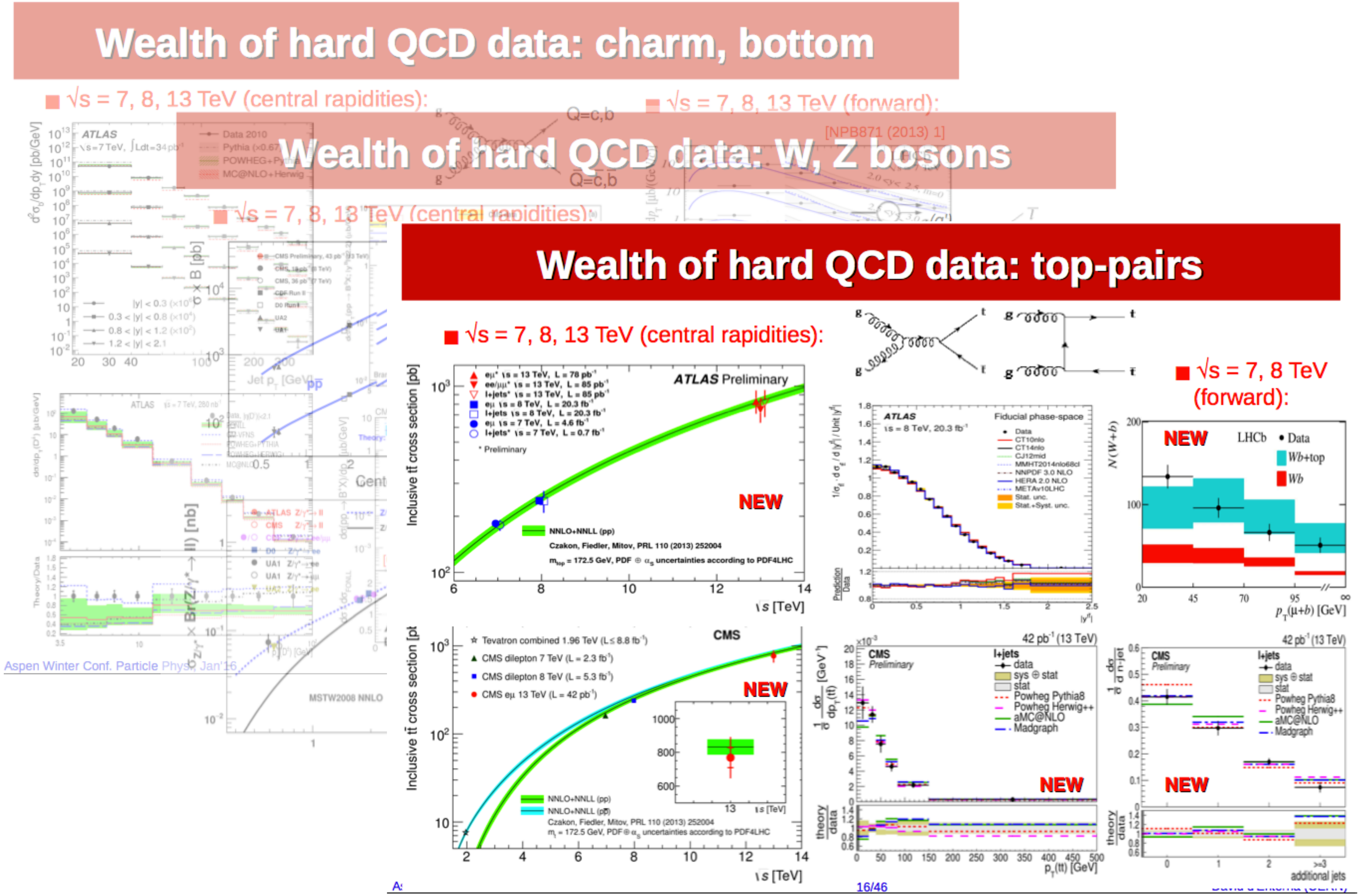
David d'Enterria

Progress in Hard QCD Measurements



David d’Enterria

Progress in Hard QCD Measurements



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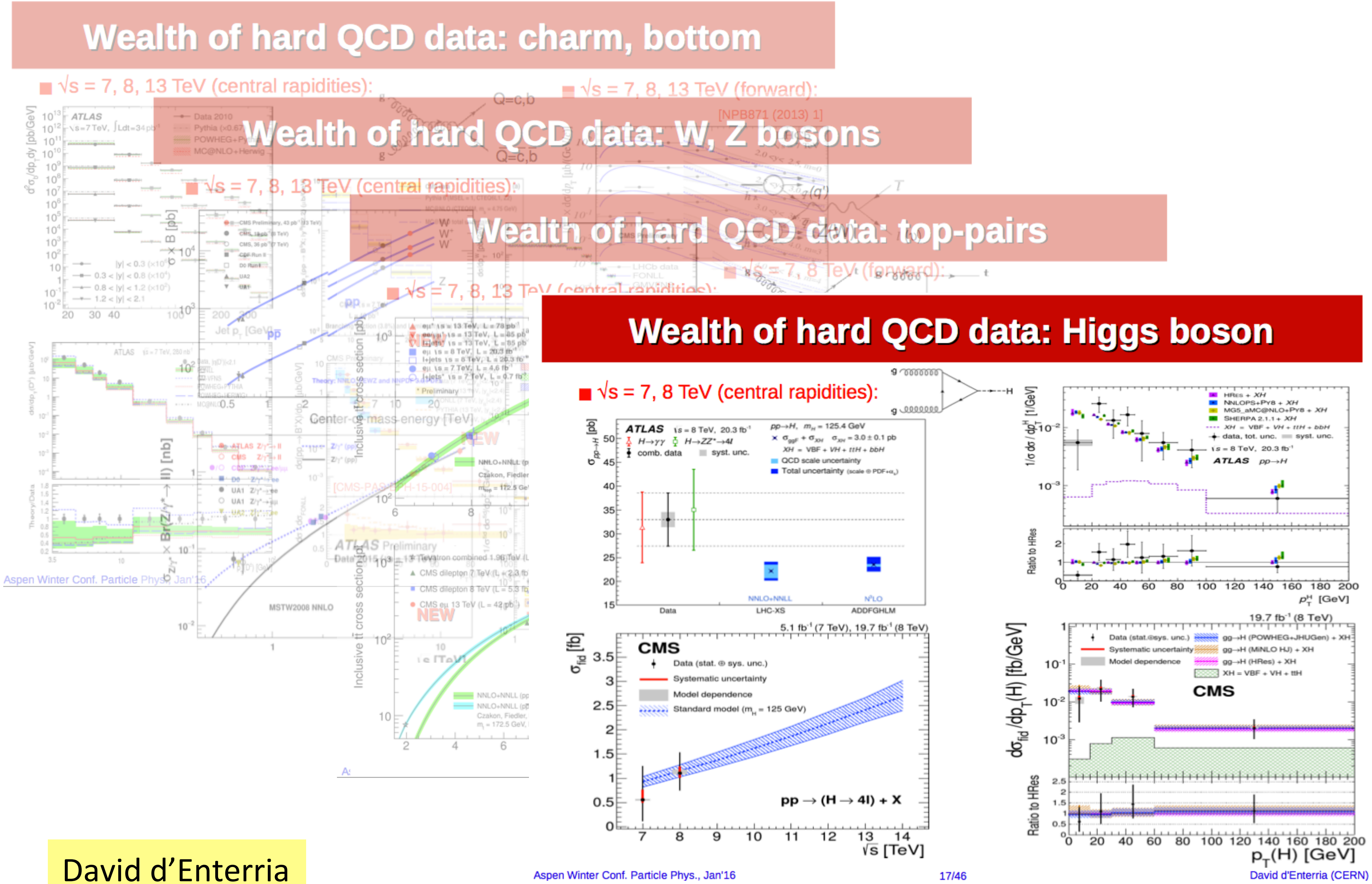

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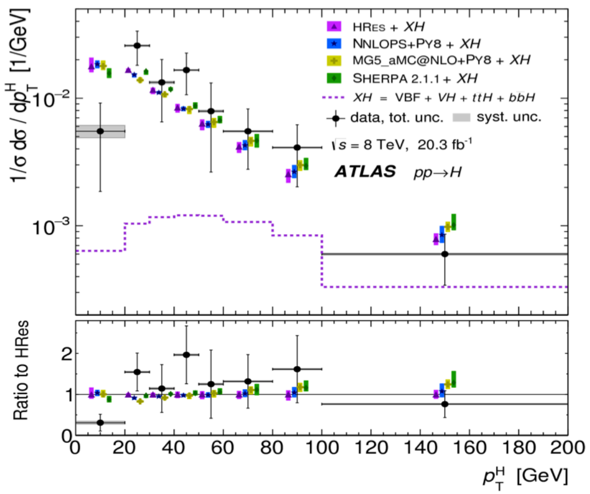
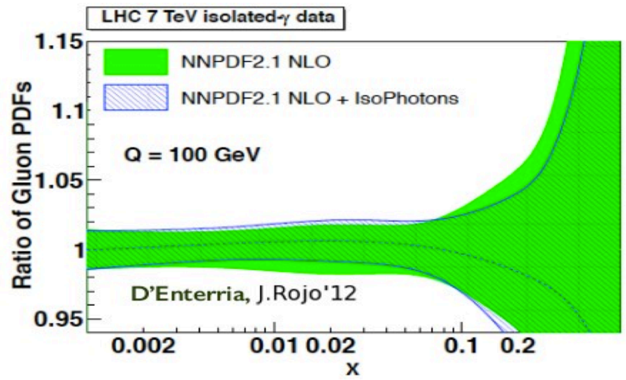
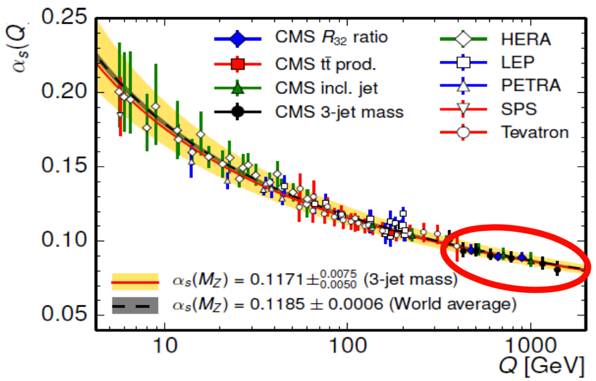






3 Key points:

- A wealth of measurements, including the Higgs (which has the only N3LO estimate available so far)

- Still work to be done to include more interesting data and improve N(N)LO PDFs

- Measuring α_s at LHC with increasing precision (Test asymptotic freedom up to 2 TeV)

David d'Enterria

Impressive Achievement (and summary)

- NNLO is a necessary level of precision for many analyses.
- Ability to compute NNLO QCD increased dramatically.
- EW Corrections are alsoessential for many analyses.

Processes currently known through NNLO

dijets	O(3%)	gluon-gluon, gluon-quark	PDFs, strong couplings, BSM
H+0 jet	O(3-5 %)	fully inclusive (N3LO)	Higgs couplings
H+1 jet	O(7%)	fully exclusive; Higgs decays, infinite mass tops	Higgs couplings, Higgs p_t, structure for the ggH vertex.
tT pair	O(4%)	fully exclusive, stable tops	top cross section, mass, p_t, FB asymmetry, PDFs, BSM
single top	O(1%)	fully exclusive, stable tops, t-channel	V_{tb}, width, PDFs
WBF	O(1%)	exclusive, VBF cuts	Higgs couplings
W+j	O(1%)	fully exclusive, decays	PDFs
Z+j	O(1-3%)	decays, off-shell effects	PDFs
ZH	O(3-5 %)	decays to bb at NLO	Higgs couplings (H-> bb)
ZZ	O(4%)	fully exclusive	Trilinear gauge couplings, BSM
WW	O(3%)	fully inclusive	Trilinear gauge couplings, BSM
top decay	O(1-2 %)	exclusive	Top couplings
H -> bb	O(1-2 %)	exclusive, massless	Higgs couplings, boosted

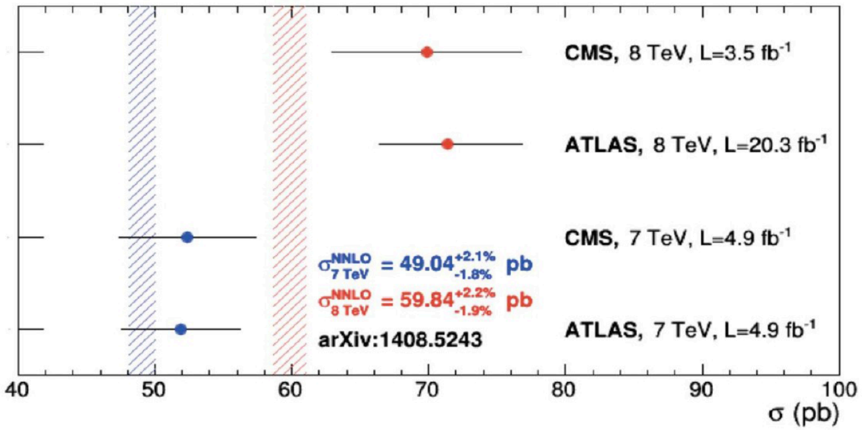
Kirill Melnikov

One important example…

Example of Resolved Anomaly

The WW Cross Section

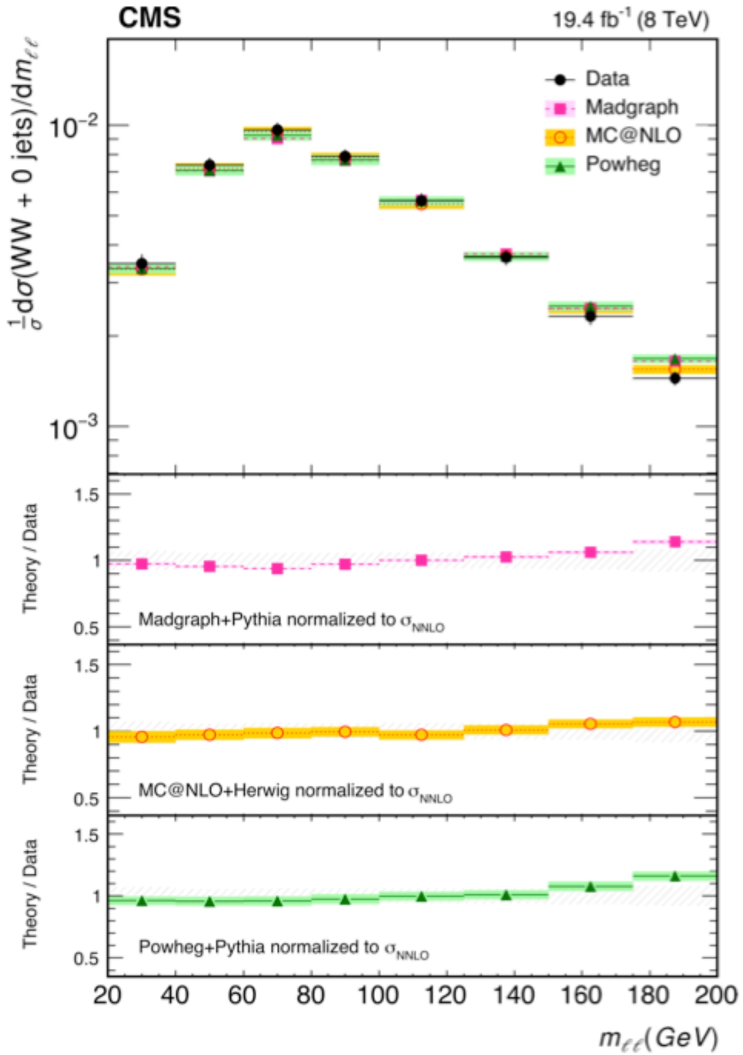
The WW excess at 8 TeV



Recent CMS measurement at 8 TeV in perfect agreement with NNLO prediction

$$\sigma_{tot} = 60.1 \pm 4.8 \text{ pb}$$
$$\sigma_{NNLO} = 59.8^{+1.3}_{-1.1} \text{ pb}$$

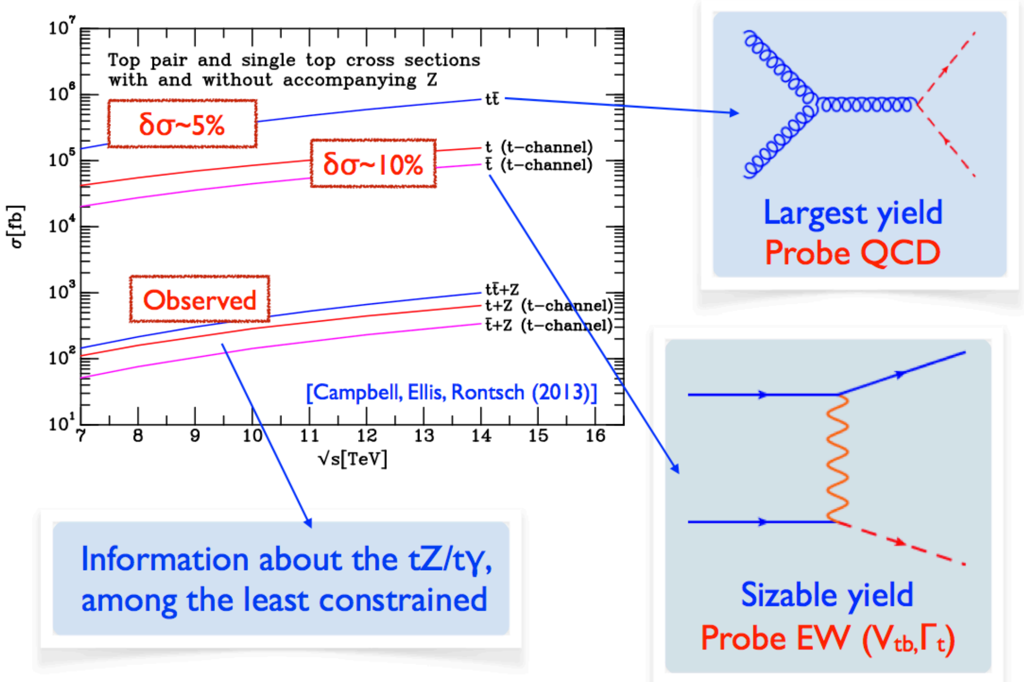
Also produced Differential cross sections



Louis Hellary

Top Physics Highlights

LHC is a top factory



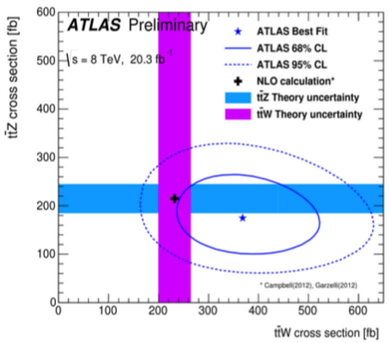
- Cross Sections now at the percent level precision.
- Single top: s-channel, t-channel and Wt observed (extraction of Vtb)!
- FCNC top decays investigated in tqZ, tqγ, tqg ad tqH No deviation obsereved!
- Differential cross sections (unfolded and fiducial – extremely important to tune our MC)

Measured cross sections:

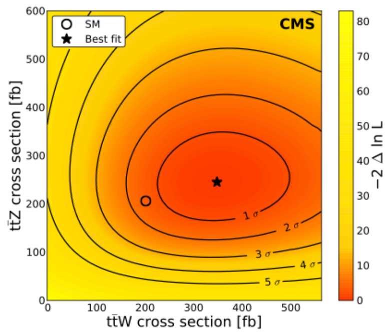
$$\sigma_{t\bar{t}W} = 369^{+86}_{-79}\ (\text{stat}) \pm 44\ (\text{syst})\ \text{fb}$$

$$\sigma_{t\bar{t}Z} = 176^{+52}_{-48}\ (\text{stat}) \pm 24\ (\text{syst})\ \text{fb}$$

The observed (expected) significance of:
- ttW is 5.0σ (3.2σ)
- ttZ is 4.2σ (4.5σ)



ATLAS-CONF-2015-032



CMS-PAS-TOP-14-021

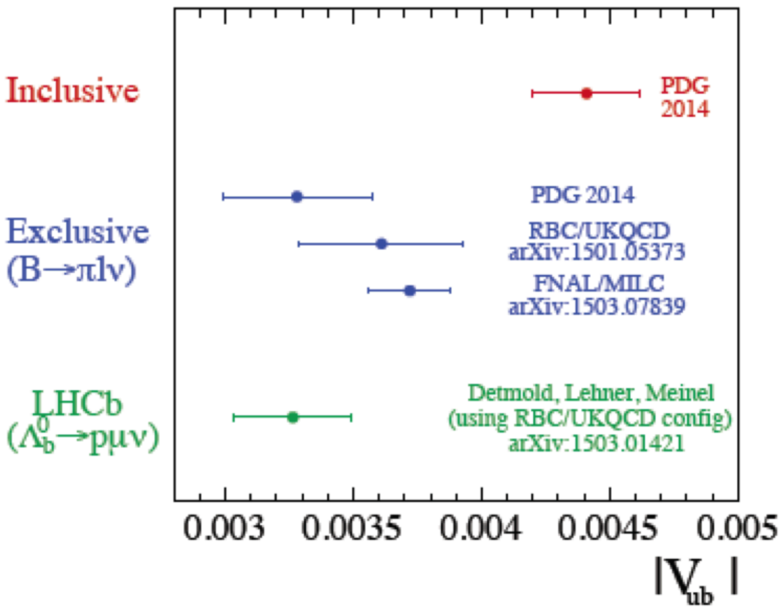
ttV Measurement very important in the determination of ttH (similarly tt-HF is also very important see Mayda's slides)

Fabrizio Caola

Mayda Velasco

Flavor Physics

Highlighting 2 Anomalies



- World average V_{ub} determined by PDG 2014
  - **Inclusive: $b \to u\ell\nu$: $|V_{ub}|=[4.41\pm0.15^{+0.15}_{-0.17}]\ 10^{-3}$**
  - **Exclusive: $B \to \pi\ell\nu$: $|V_{ub}|=[3.28\pm0.29]\ 10^{-3}$**

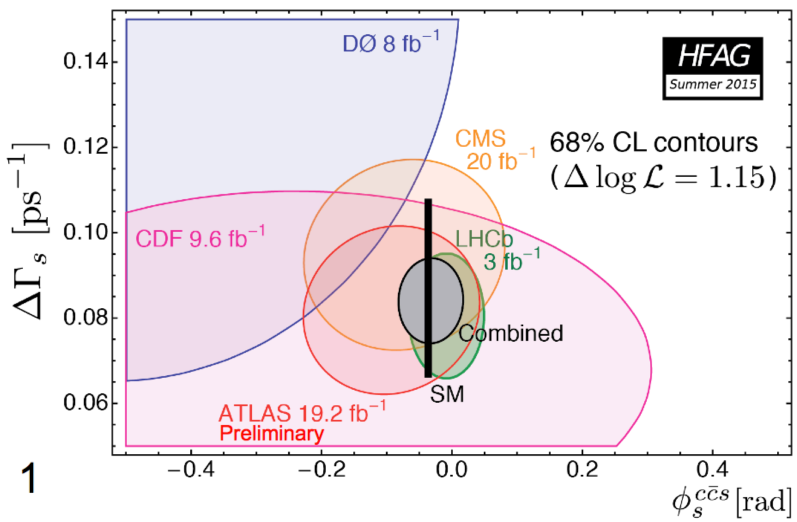
3σ discrepancy

Measurement of $|V_{ub}|$ on of $\Lambda^0_b \to p\mu^- \bar{\nu}_\mu$

- Using the world average $|V_{cb}|=[39.5\pm0.8]\ 10^{-3}$ by exclusive decays

  $|V_{ub}|=[3.27\pm0.15_{(exp)}\pm0.16_{(LQCD)}+0.06_{(norm)}]10^{-3}$
- Confirms **discrepancy** between inclusive and exclusive

Essentially resolved: Measurement of the weak phase in B_s to $J/\psi\phi$



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Silvia Borghi

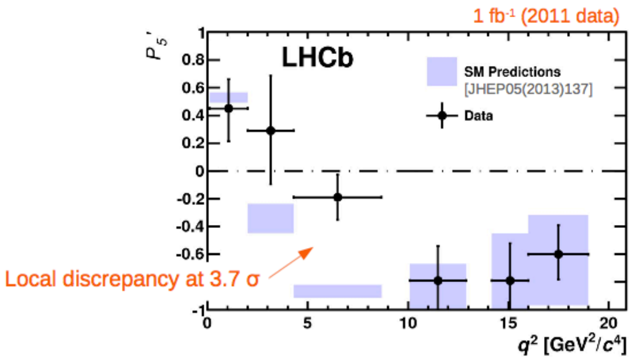
Flavor Physics (Rare Decays)

Highlighting 3 Anomalies

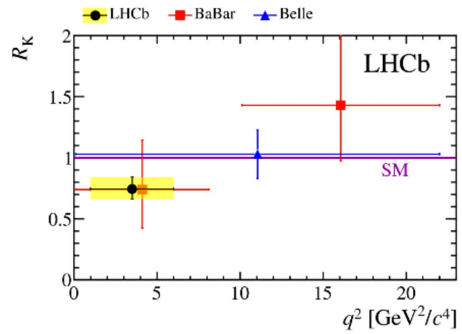
Angular analysis of a b to sγ transition in B^0 to $K^*\mu\mu$ from LHCb

Set of optimised variables where the leading form factor uncertainties cancel

→ ex : $P_5' = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$



$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$



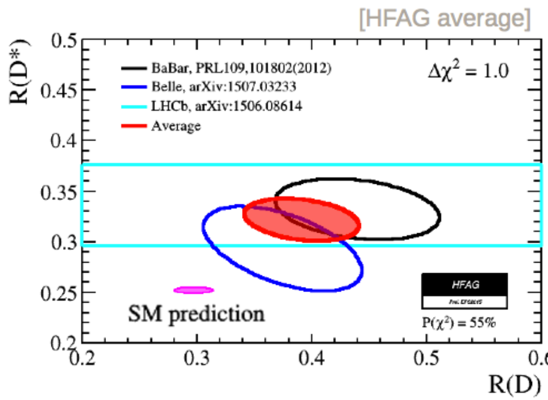
- 2.6 σ from SM
- electron mode is in agreement with SM
- deficit of muon mode again

From BaBar, Belle and LHCb data

$$R(D) = \frac{B(B^0 \to D^+\tau^-\nu)}{B(B^0 \to D^+\mu^-\nu)}$$

$$R(D^*) = \frac{B(B^0 \to D^{*+}\tau^-\nu)}{B(B^0 \to D^{*+}\mu^-\nu)}$$

↘ Average is 3.9 σ away from SM



Julien Cogan

Flavor Physics Anomalies

$\sim 3.5\sigma$	$(g-2)_\mu$ anomaly
$\sim 3.5\sigma$	non-standard like-sign dimuon charge asymmetry
$\sim 3.5\sigma$	enhanced $B \to D^{(*)}\tau\nu$ rates
$\sim 3.5\sigma$	suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{ub}\rvert$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$
$2-3\sigma$	anomaly in $B \to K^*\mu^+\mu^-$ angular distributions
$2-3\sigma$	SM prediction for ϵ'/ϵ below experimental result
$\sim 2.5\sigma$	lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$
$\sim 2.5\sigma$	non-zero $h \to \tau\mu$

Large number of modest tensions in large number of data!

Wolfgang Altmannshofer

Flavor Physics Anomalies

$\sim 3.5\sigma$ $(g-2)_\mu$ anomaly

$\sim 3.5\sigma$ non-standard like-sign dimuon charge asymmetry

$\sim 3.5\sigma$ enhanced $B \to D^{(*)}\tau\nu$ rates

$\sim 3.5\sigma$ suppressed branching rati

$\sim 3\sigma$ tension between inclusive

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$2-3\sigma$ anomaly in $B \to K^* \mu^+ \mu^-$

$2-3\sigma$ SM prediction for ϵ'/ϵ belo

$\sim 2.5\sigma$ lepton flavor non-universa

$\sim 2.5\sigma$ non-zero $h \to \tau\mu$

Large number of modest tensior

	branching ratios	angular observables	LFU ratios
millisecond pulsars?	?	?	?
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

Wolfgang Altmannshofer

Flavor Physics Anomalies

$\sim 3.5\sigma$ $(g-2)_\mu$ anomaly

$\sim 3.5\sigma$ non-standard like-sign dimuon charge asymmetry

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$\sim 3.5\sigma$ suppress

$\sim 3\sigma$ tension b

$\sim 3\sigma$ tension b

$2-3\sigma$ anomaly

$2-3\sigma$ SM predi

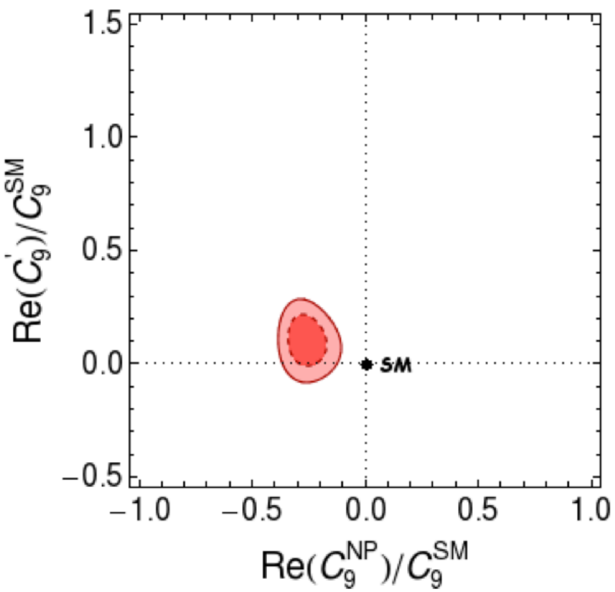
$\sim 2.5\sigma$ lepton fla

$\sim 2.5\sigma$ non-zero

Large number of measurements gives large trial factor

Global p-value

- $\Delta\chi^2 = 15.2$
- p-value: 12.4% (2.1% in the SM)



Large number o

Interesting model(s) with Lμ-Lτ gauged symmetry

Wolfgang Altmannshofer

Flavor Physics Anomalies

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$2-3\sigma$ SM prediction for ϵ'/ϵ below experimental result

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Interesting model(s) with Lμ-Lτ gauged symmetry
..and extended Higgs sector

Andreas Crivellin

Flavor Physics Anomalies

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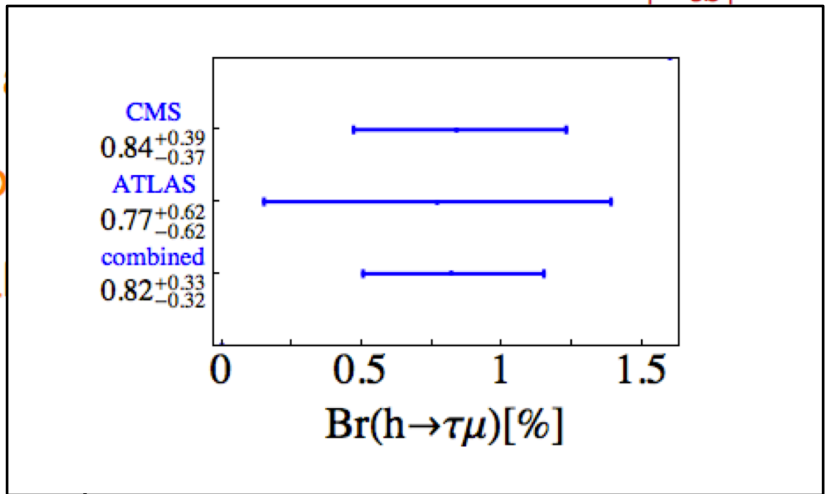
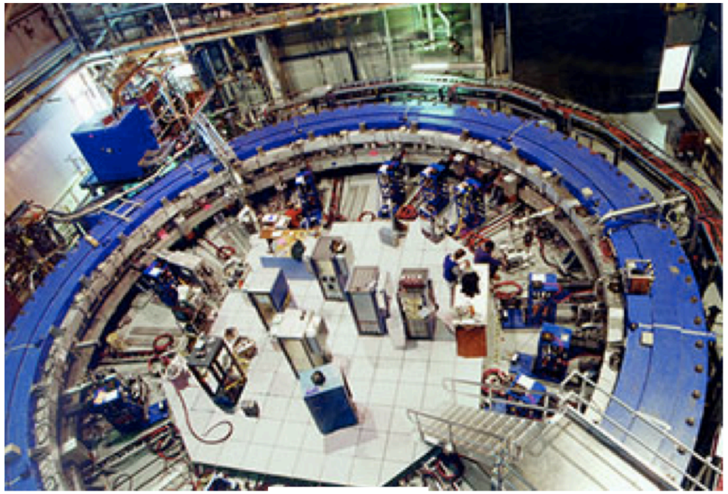


Interesting model(s) with Lμ-Lτ gauged symmetry
..and extended Higgs sector

Andreas Crivellin

Anomalous Magnetic Moment

2 New Experiments : FNAL and
JPARC (longer timescale)

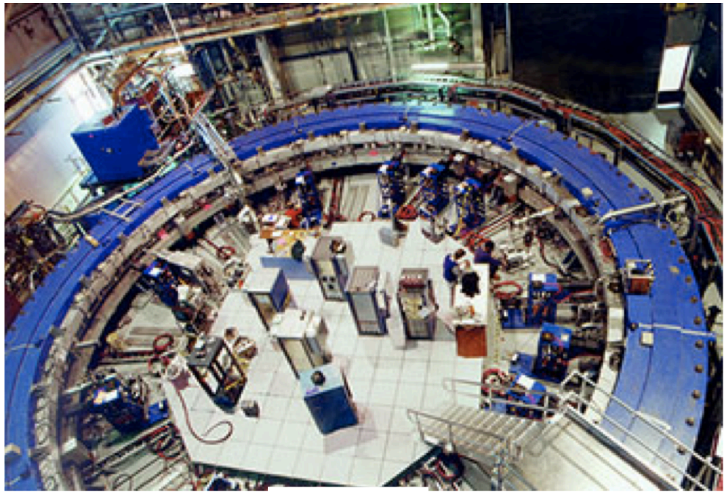


- Magnet reassembly has been completed! Detector installatino this summer and data one ~year after
- BNL Level results in 2018
- Bulk of the data in 2018-2019 for 21 x BNL statistics

Brendan Casey

Anomalous Magnetic Moment

2 New Experiments : FNAL and JPARC (longer timescale)



- Magnet reassembly has been completed! Detector installatino this summer and data one ~year after
- BNL Level results in 2018
- Bulk of the data in 2018-2019 for 21 x BNL statistics

Brendan Casey

Improving the Prediction:

SM Contribution	Value $\pm$ Error ($\times 10^{11}$)	Ref
QED (5 loops)	116584718.951 ± 0.080	[Aoyama et al., 2012]
HVP LO	6923 ± 42	[Davier et al., 2011]
	6949 ± 43	[Hagiwara et al., 2011]
HVP NLO	-98.4 ± 0.7	[Hagiwara et al., 2011]
		[Kurz et al., 2014]
HVP NNLO	12.4 ± 0.1	[Kurz et al., 2014]
HLbL	105 ± 26	[Prades et al., 2009]
HLbL (NLO)	3 ± 2	[Colangelo et al., 2014b]
Weak (2 loops)	153.6 ± 1.0	[Gnendiger et al., 2013]
SM Tot (0.42 ppm)	116591802 ± 49	[Davier et al., 2011]
(0.43 ppm)	116591828 ± 50	[Hagiwara et al., 2011]
(0.51 ppm)	116591840 ± 59	[Aoyama et al., 2012]
Exp (0.54 ppm)	116592089 ± 63	[Bennett et al., 2006]
Diff (Exp – SM)	287 ± 80	[Davier et al., 2011]
	261 ± 78	[Hagiwara et al., 2011]
	249 ± 87	[Aoyama et al., 2012]

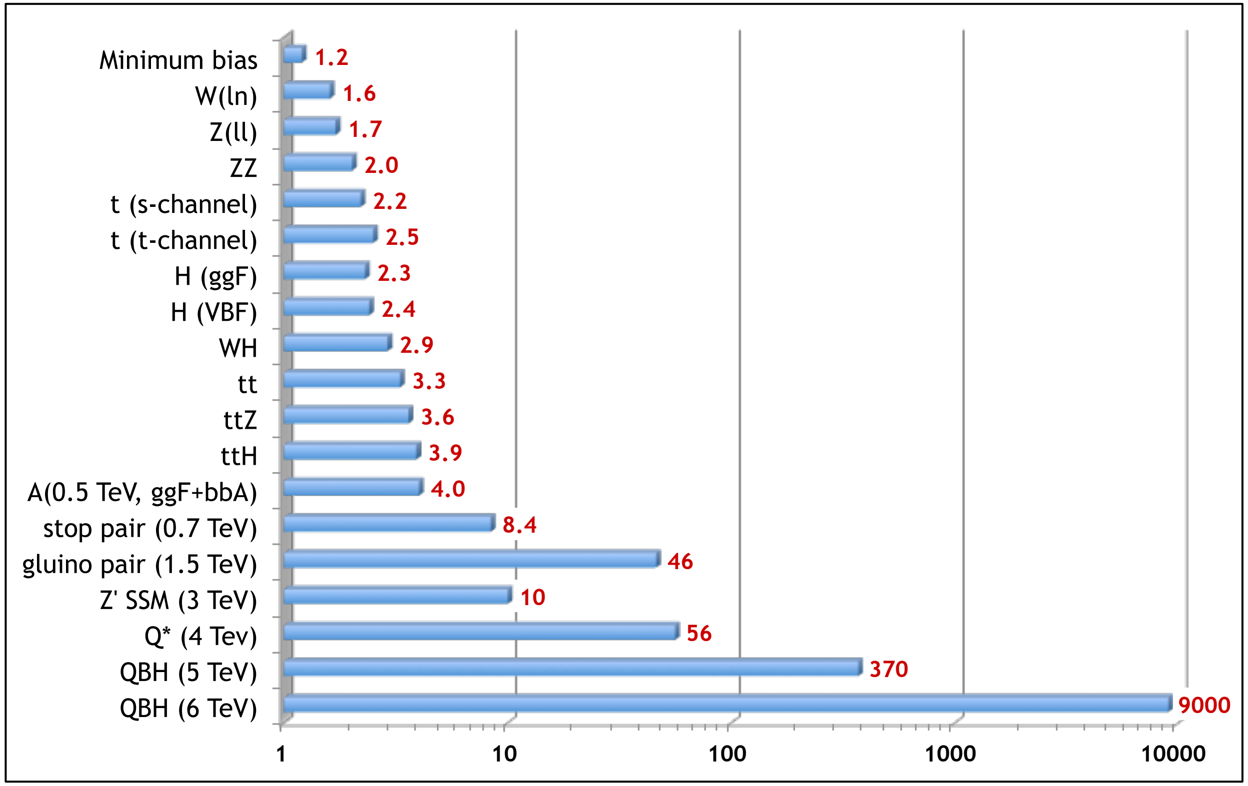
- Fermilab E989 early 2017, aims for 0.14 ppm
- J-PARC E34 late 2010's, aims for 0.3-0.4 ppm
- Today $a_\mu(\text{Expt})$-$a_\mu(\text{SM}) \approx 2.9 - 3.6\sigma$
- If both central values stay the same,
  - E989 ($\sim 4\times$ smaller error) $\rightarrow \sim 5\sigma$
  - E989+new HLBL theory (models+lattice, 10%) $\rightarrow \sim 6\sigma$
  - E989+new HLBL +new HVP (50% reduction) $\rightarrow \sim 8\sigma$
- Good for discriminating models if discovery of BSM at LHC [Stckinger, 2013]
- Lattice calculations important to trust theory errors

Tom Blum

Searches for BSM Physics at the LHC

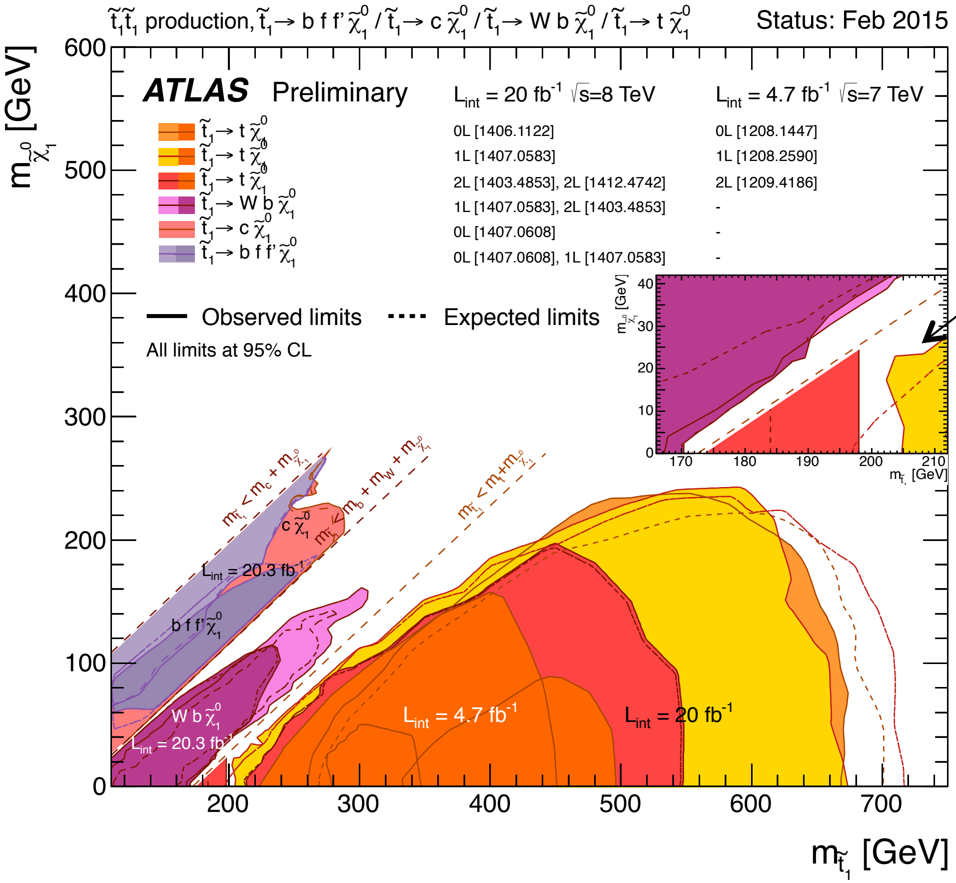
and the Energy Frontier

This is a unique moment for a potentially Spectacular Discovery!



Chris West

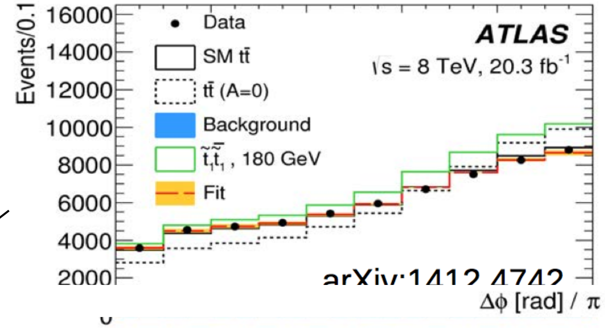
Searches for SUSY at LHC (I)



Splendid (very thorough) achievement to survey the impact of all analyses…
Also probed efficiency of Simplified Models

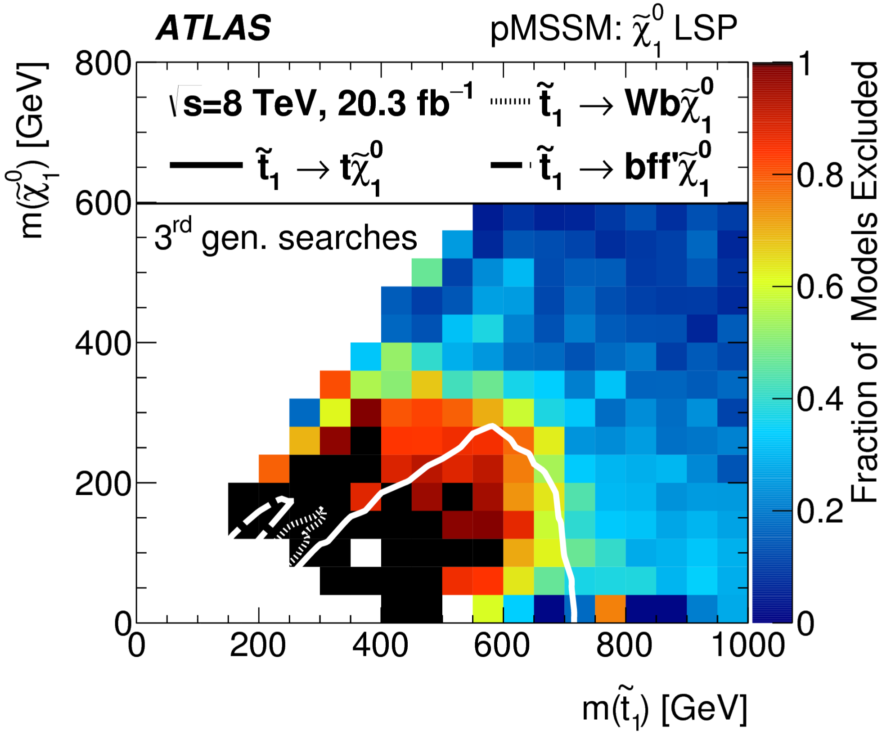
Leaving no stone unturned

Spin correlations in tt production

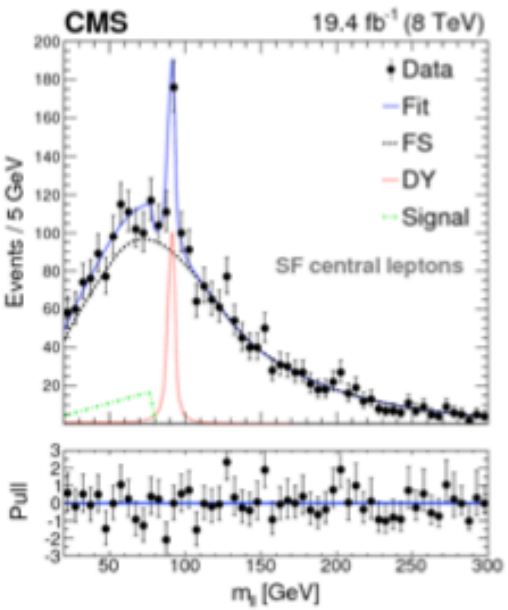


pMSSM Survey

(300 kmodels and 30 Gevt)



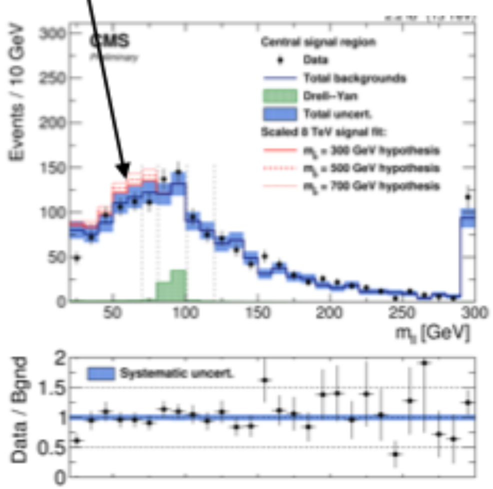
Searches for SUSY at LHC (II)

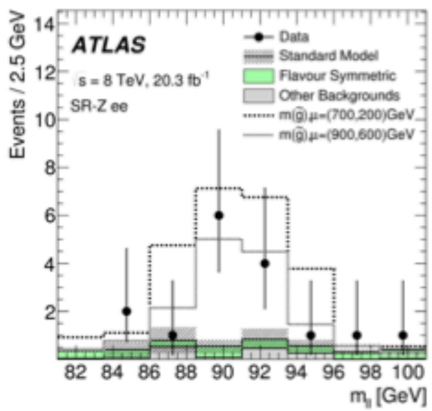


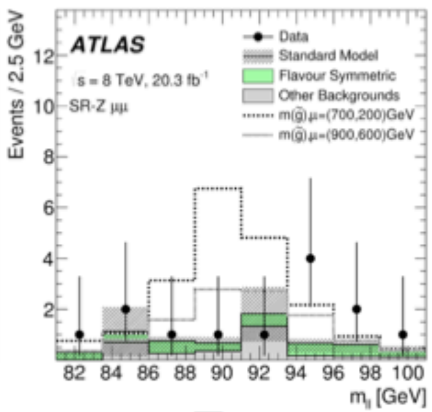
2.6σ excess below Z, enriched in b-jets (seen only by CMS)

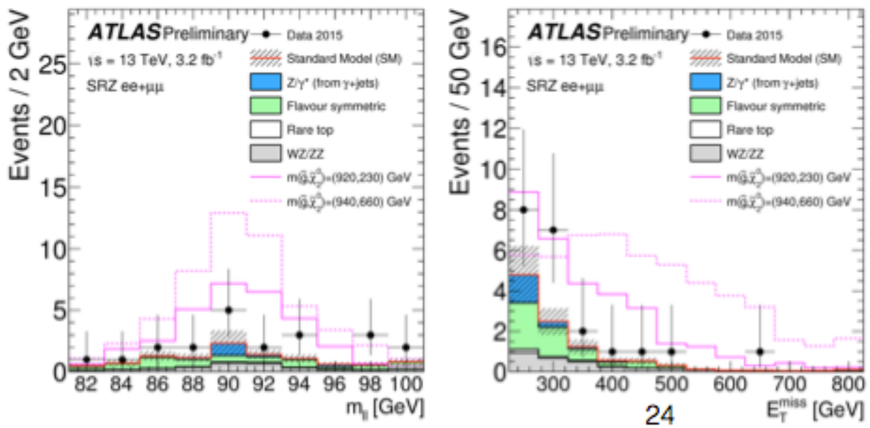
Scaled 8 TeV signal hypothesis

Edge









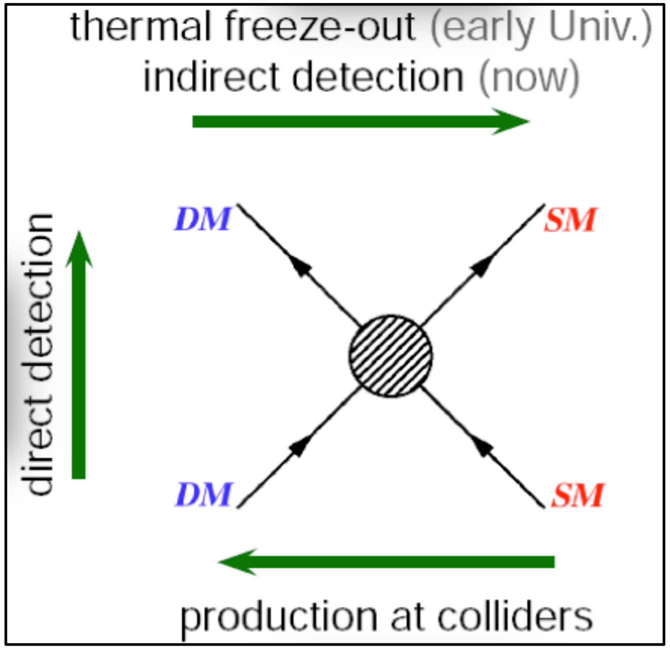
24

On-Z

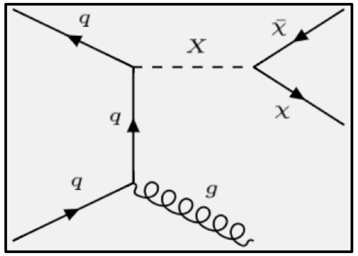
3.0σ excess on Z (seen only by ATLAS)

10 Events expected 20 observed 2.2σ

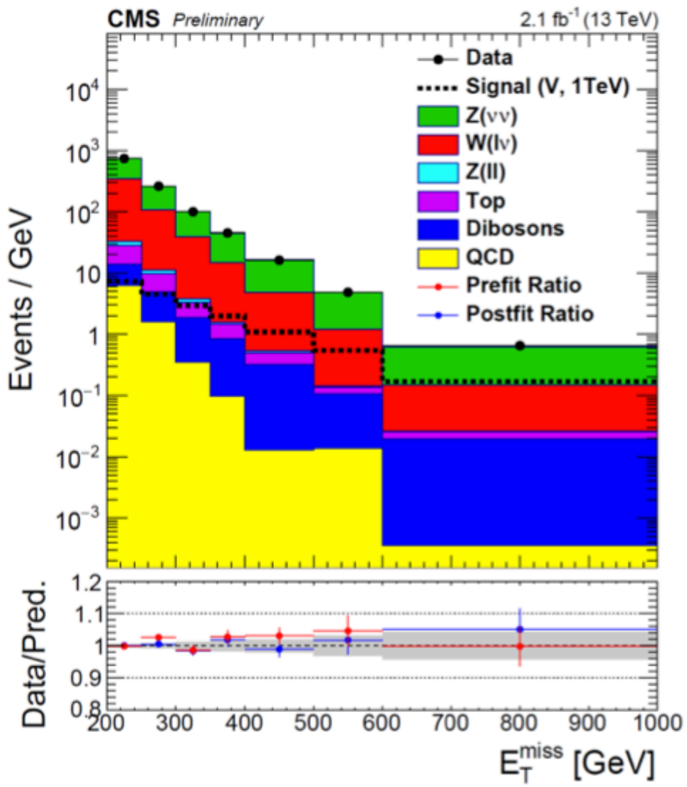
Searches for DM at the LHC in a Nutshell



One 13 TeV example



Mono jet analysis



A wealth of analyses to sarch for DM at the LHC:

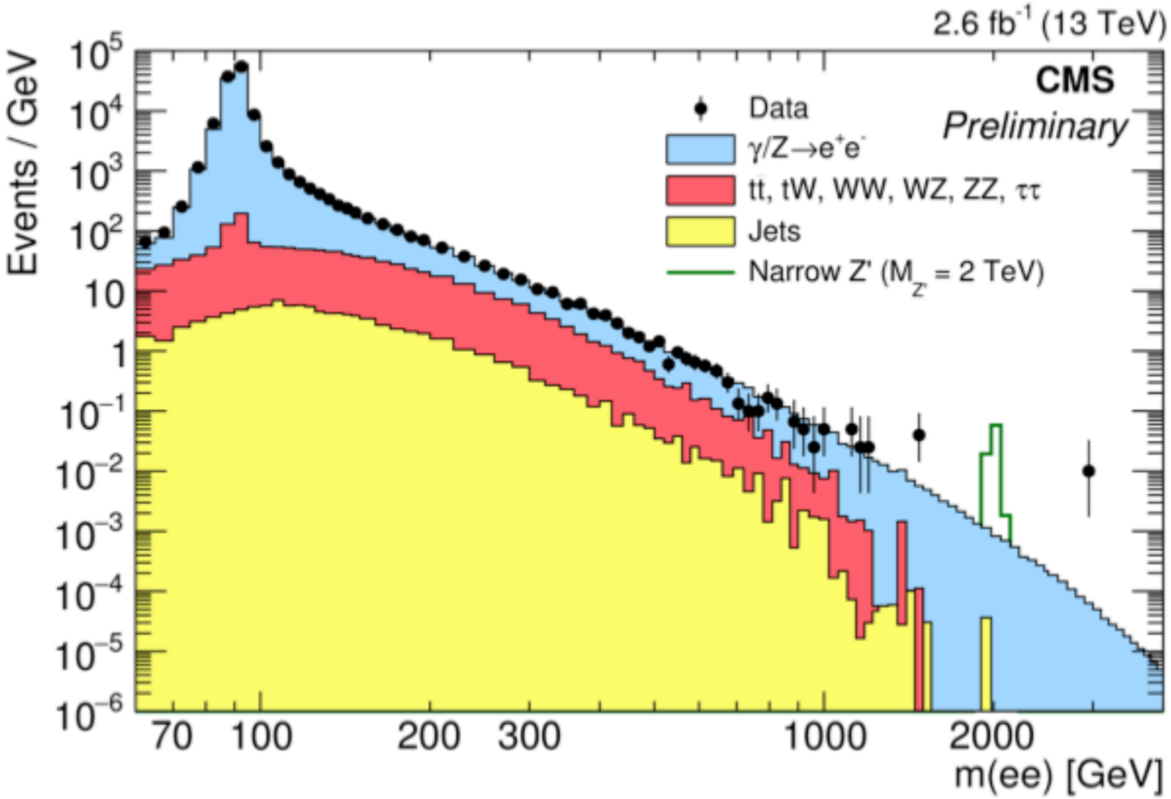
- Mono-jet
- Mono-V (leptonic and hadronic boosted)
- Mono-Higgs
- Mono-photon
- Invisible Higgs decays in VH and VBF production (ttH also possible)

No excess seen so far

Keti Kaadze

Searches for Exotic NP at the LHC

A one event (resolved) anomaly

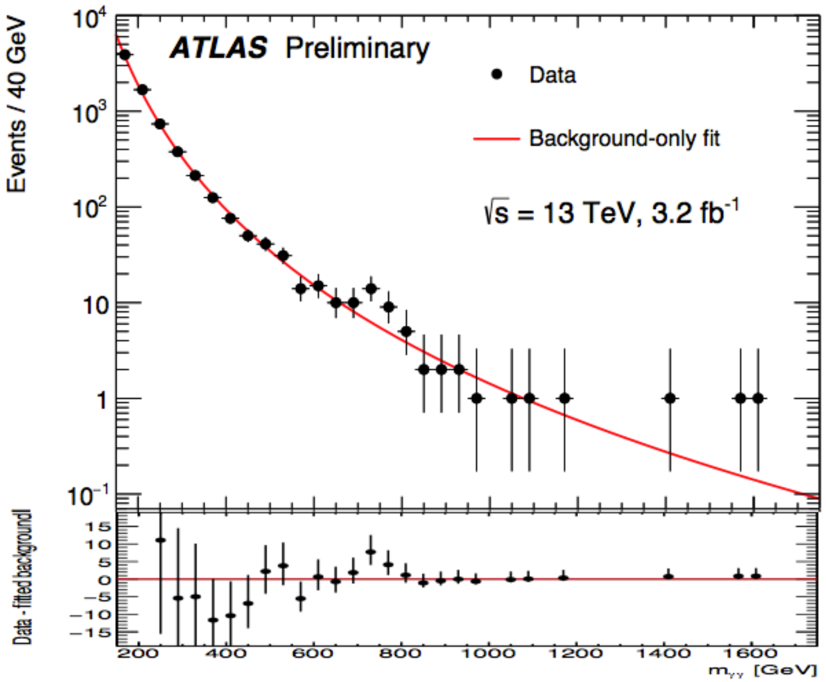


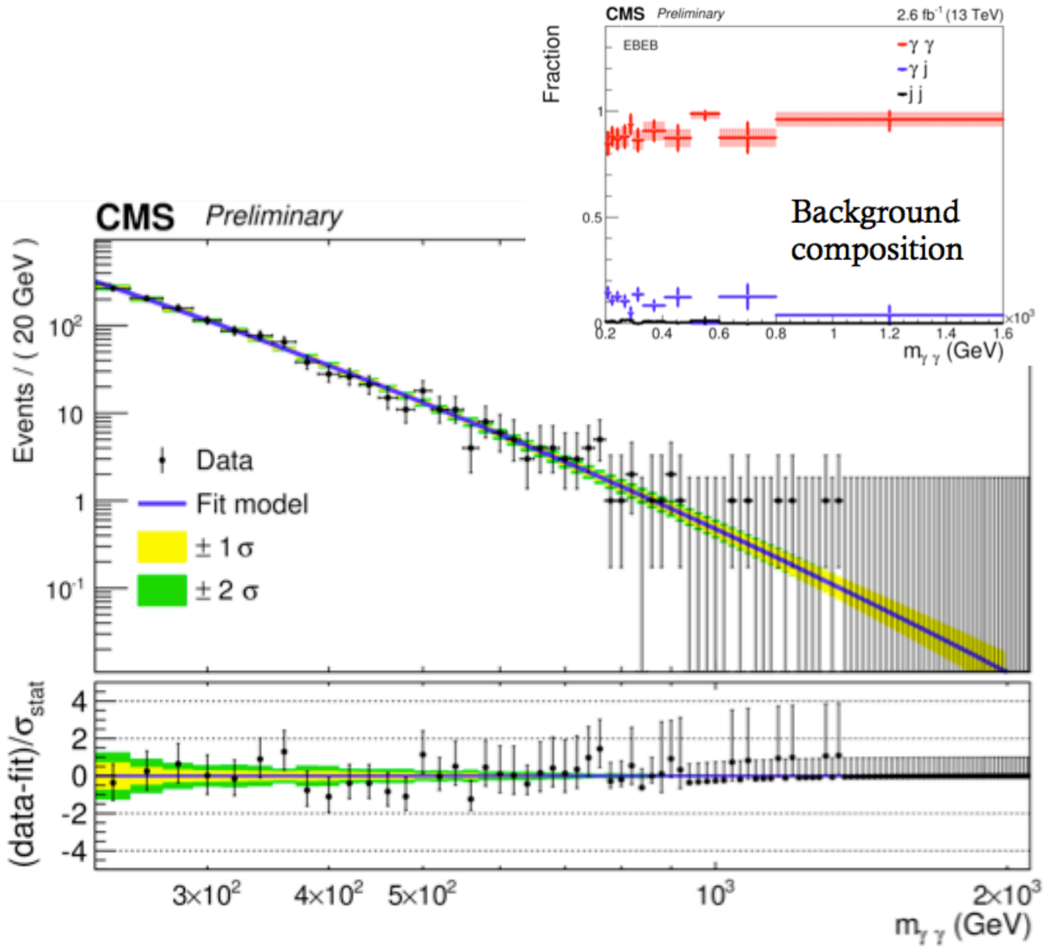
At LHCP in September 1 event observed at 3 TeV in electrons with 0.002 events expected above 2.5 TeV

Keti Kaadze

Searches for Exotic NP at the LHC

The 750 GeV (modest) Excess



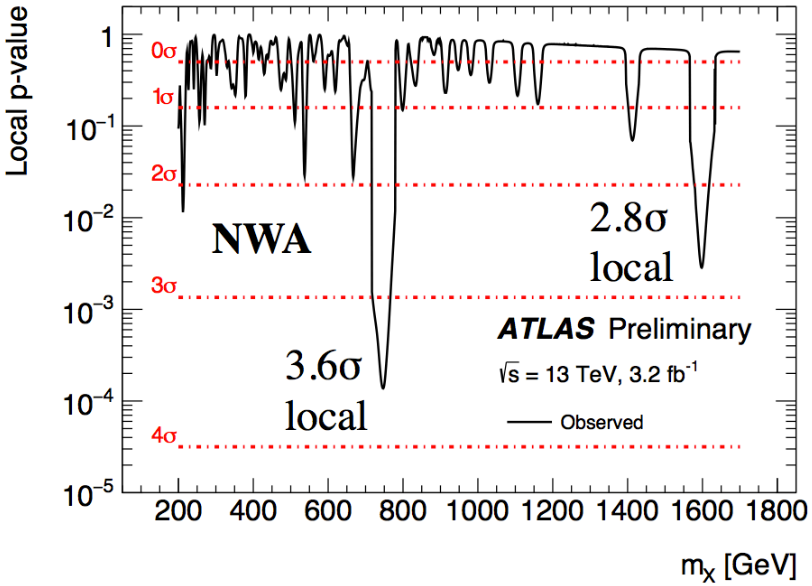


Haichen Wang

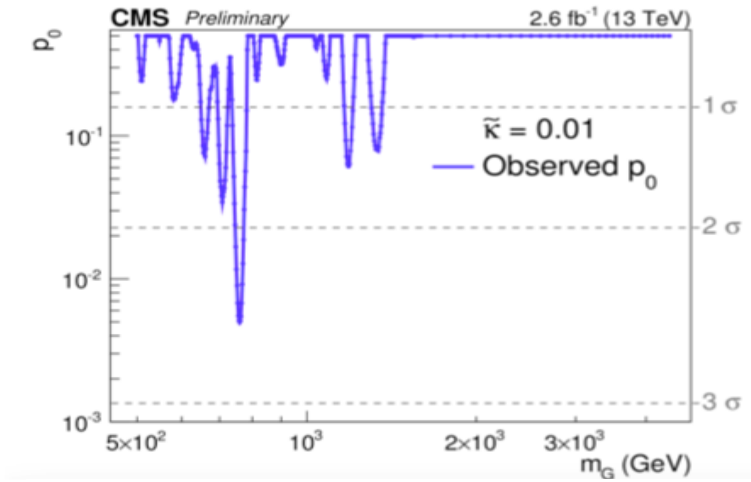
Keti Kaadze

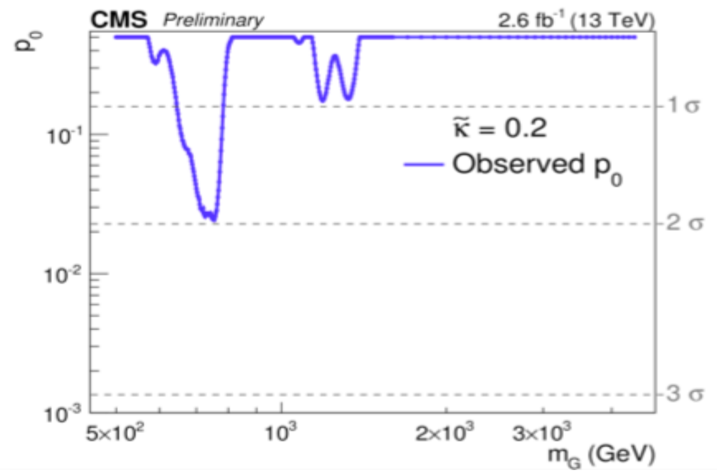
Searches for Exotic NP at the LHC

The 750 GeV (modest) Excess



Excess at 750 GeV		
	Local	Global
NWA	3.6σ	2.0σ
Γ ~ 45 GeV	3.9σ	2.3σ





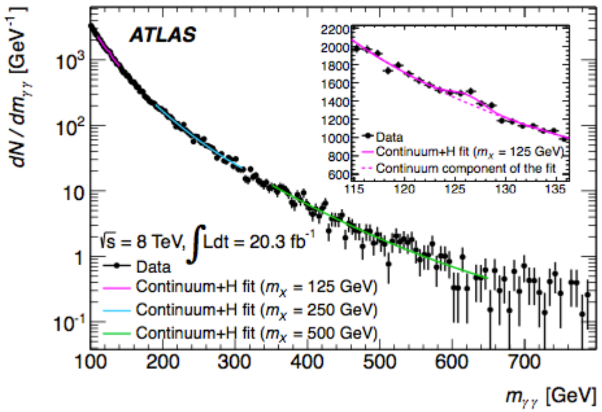
Haichen Wang

Keti Kaadze

Searches for Exotic NP at the LHC

The 750 GeV (modest) Excess

- Property of events in the excess region is found to be consistent with that outside the region.



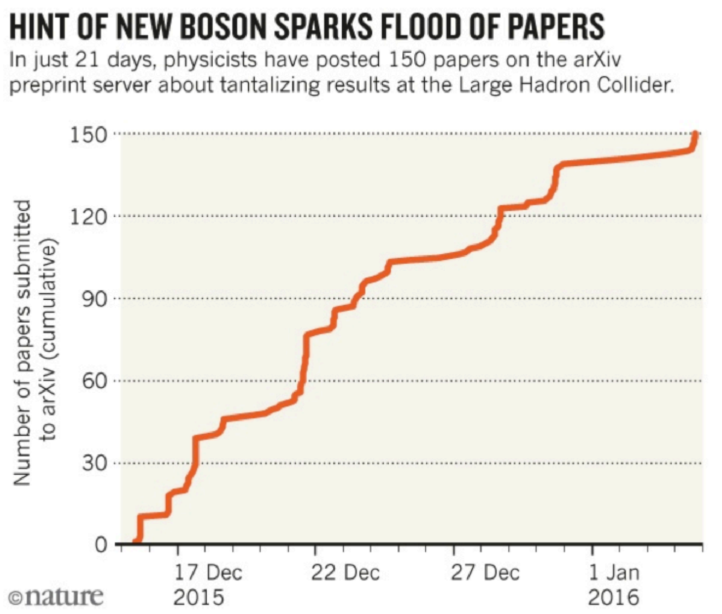
- Run-2 excess is compatible with Run-1 observation at 1.4 σ level for the Γ~45 TeV interpretation, 2.2 σ for the NWA.

Haichen Wang

CMS has shown full compatibility with Run 1 data

Keti Kaadze

The indications are not strong enough to make any claim whatsoever



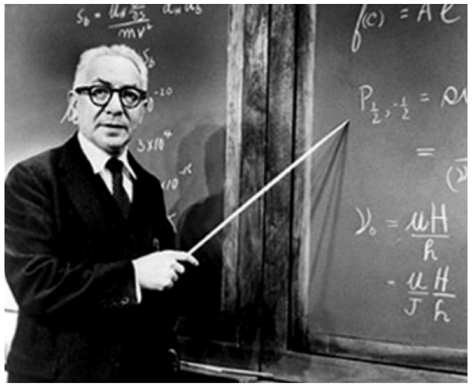
The 750 GeV Excess

* Definitely most interesting + likely LHC anomaly – Exciting!

[* Run 1 vs Run 2 tension, "other channels look elsewhere", width issue; also big co-incidence that $S/B \sim$ few with $\mathcal{O}(10)$ events (but just where syst/background fluct. hurt!)]

* I give it a ~10% chance of being real (= betting odds)

- If it is a new state: it has very weak couplings
- In particular to the Higgs
- Paraphrasing I. Rabi if this is real: "who ordered that"? (1934)



Nima Arkani-Ahmed

Searches for NP at the LHC

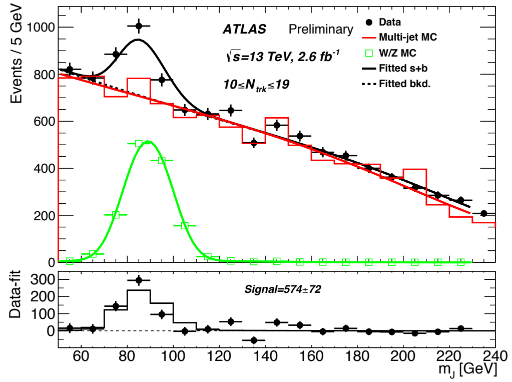
- This talk does not do justice to the very large number of searches performed at the LHC

- Performing these searches is essential in probing NP beyond the SM

- The large number also means that even the global p-value does not reflect a correct estimate of a background fluctuation probability

- Concerning the (interesting) anomalies: we are in the very fortunate situation that we are just at the start of the LHC data taking, so any statistically

Searches for NP using Substructure Techniques

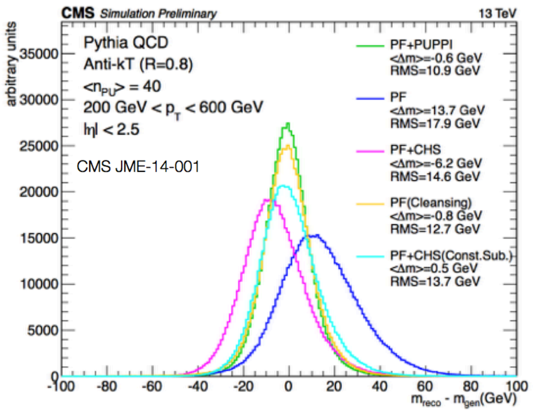


Very succesfull techniques which are providing extremely important gains in sensitivity in searches for boosted and relatively massive objects

Brilliant explanation and justification of Algorithms… (in particular of ATLAS)

Jesse Thaler

W jets

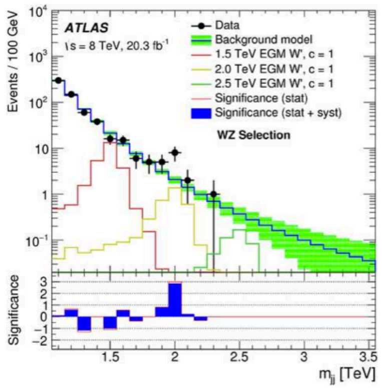


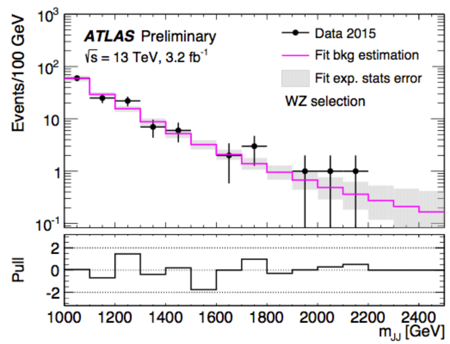
Brilliant explanation of algorithms and the importance of PU supression…

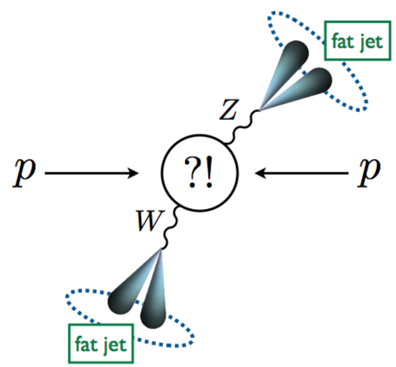
James Dolen

At work… on yet another anomaly

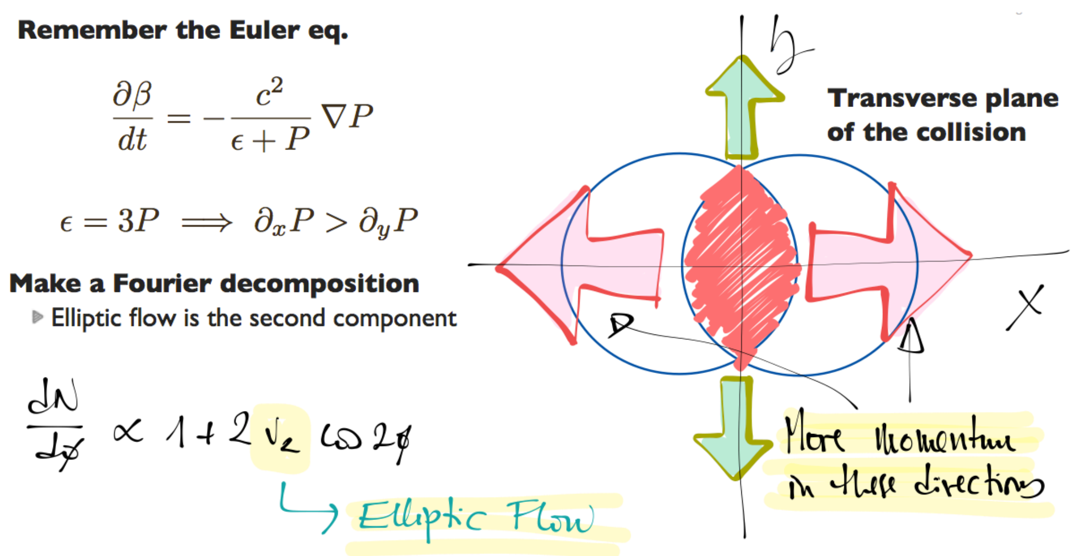
Of coruse many other examples





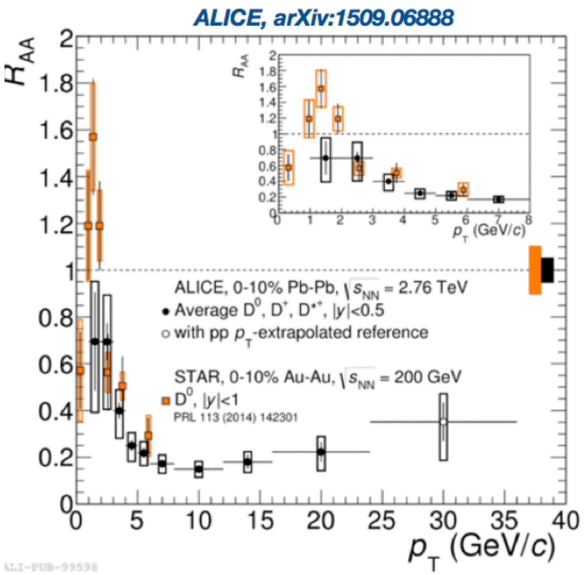


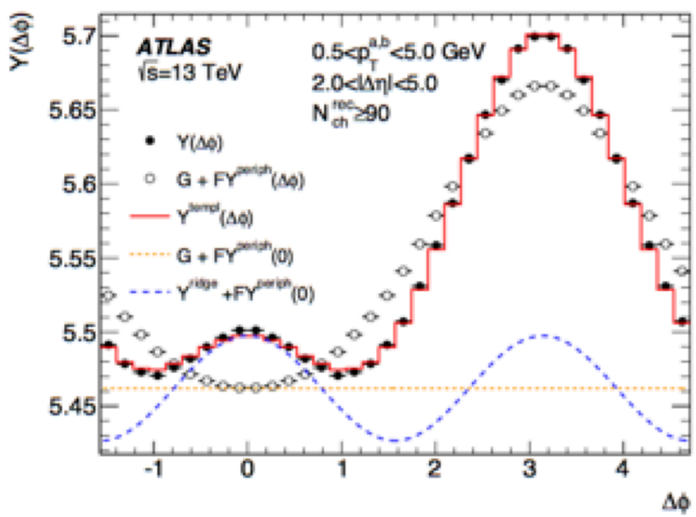
Heavy Ions (nano) Summary



Carlos Salgado

Splendid pedagogical TH introduction





Flow in small systems:
Is it due to collective flow as in PbPb?

Grazia Luparello

Brian Cole

Few Words on Future at Colliders

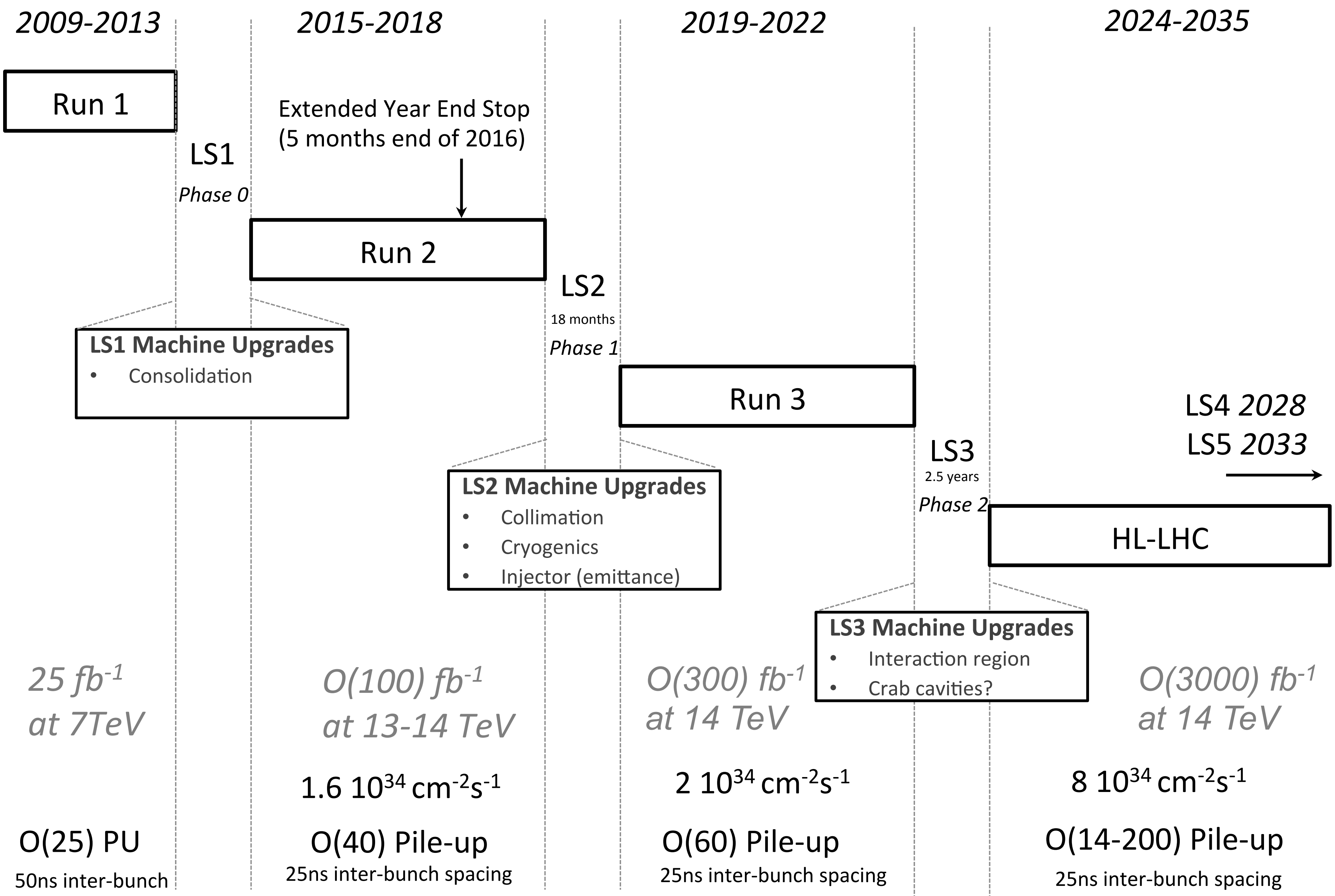
- FCC-ee, CepC, ILC see Michael's Summary
- Very near future for the LHC:
  - pp Stable Beams collision data (b* of 40cm) foreseen for April 25.
  - What to expect for ICHEP 2016 (Chicago) 4-8 fb-1
  - Full 2016 dataset: 23 fb-1 (reappraised estimate) with a Pile Up of 25 (in average).
- Near future at SuperKEKb starting (and should reach 40x Lumi of KEKb) and Belle-II to start next year (without vertex detector)
- HL-LHC (see next slide)

Milind Purohit

- FCC-hh:
  - Very strong Physics Program
    - Probing Naturalness
    - Probing the Higgs potential (tri-linear, quartic nearly impossible)
  - Extremely challenging machine (splendid review of FCC-hh machine)
  - Extreme challenges for the experiment
  - As Michael commented: "We are not entitled a new machine"

Daniel Schulte

The LHC: *Only ~1% of the total so far*



Conclusions

- A remarkable number of results and novel ideas have been discussed (in talks of exceptional quality) covering all aspects of our field
- Impressive progress in all fields, well beyond anticipations
- Fairly large number of modest anomalies (are uncertainties underestimated?)
- Are we on the verge of a another discovery?
  - TH does Suggest BSM physics (how strongly?)
  - Experimental data shows many modest anomalies but no strong deviations from the SM
  - No emerging clear and coherent picture between the modest tensions

Incredibly exciting times with a strong Program of Experiments at the **new energy frontier** and pushing actively the limits of the precision frontier to Leave no tones unturned!

Ackowledgements

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And local organizing staff

Patty Fox, Jane Kelly, and Paula Johnson