Highlights from EPS HEP 2015

Dieter Zeppenfeld

Karlsruhe Institute of Technology

Karlsruhe Institute of Technology

Excellent conference with many beautiful results presented in talks and posters

- 41 plenary talks
- 425 talks in 36 parallel session
- 194 posters

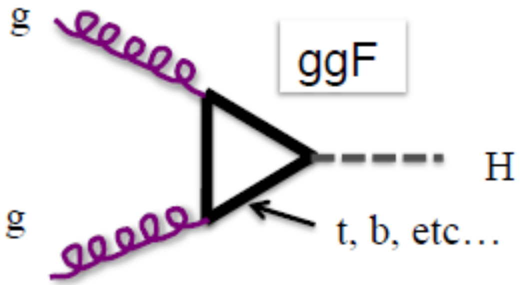
Selection of some highlights cannot do justice to all the great physics discussed during the past week

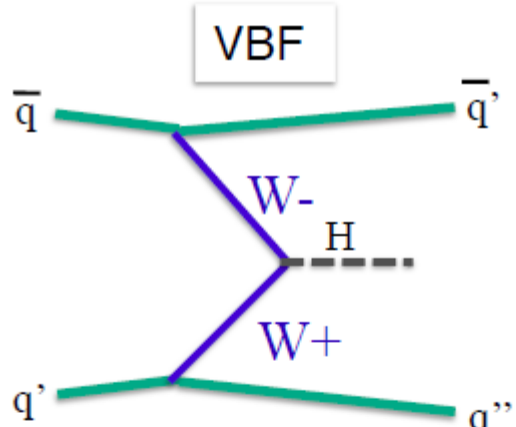
Outline

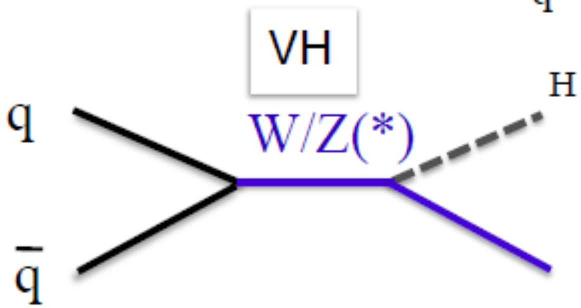
- The Higgs and its friends
- Resonance searches
- First results from run 2 of the LHC
- The ridge
- NLO and the NNLO revolution
- Cosmology
- Heavy flavors
- … and more

Pierre Savard

Higgs Production at the LHC

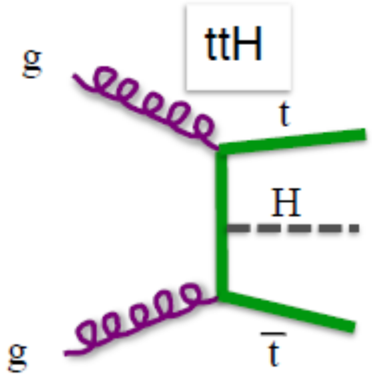


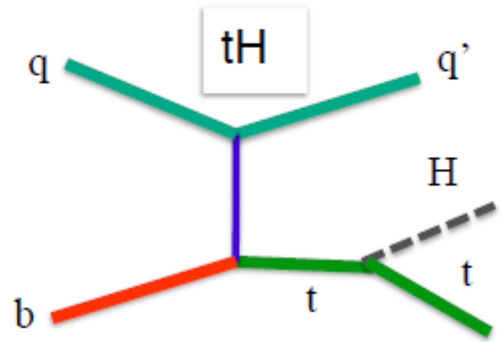




	process	8 TeV	13 TeV
ggF	gluon-gluon fusion	19 pb	44 pb
VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
ttH	associated production	0.13 pb	0.51 pb
tH	Associated production	~20 fb	~90 fb

SM Production Modes
(M_H = 125 GeV)





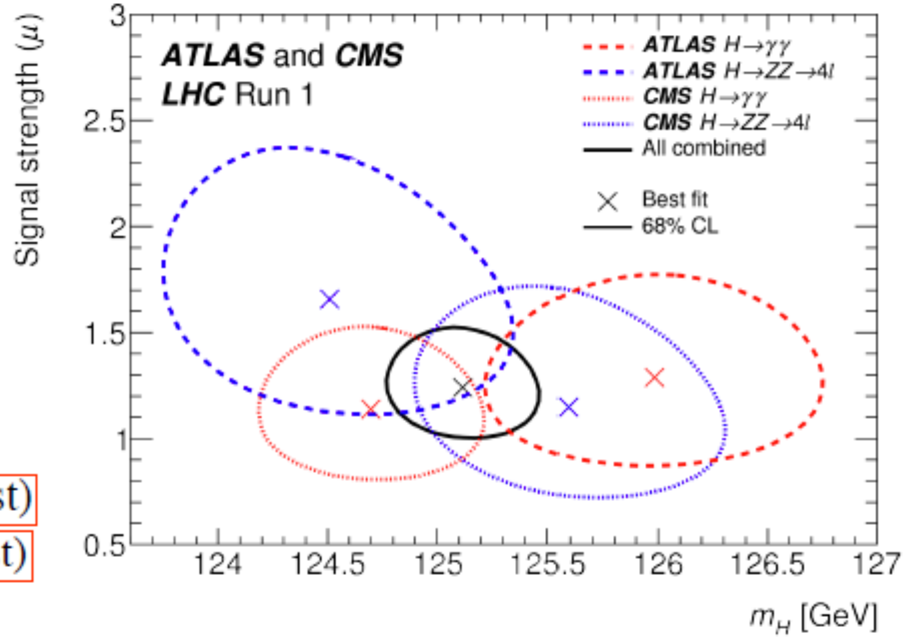
Higgs Mass

The SM does not predict the Higgs boson mass: we need to measure it

Given a mass, we can make predictions* for the production cross section and decay rates

Higgs mass measurements (GeV):

ATLAS: 125.36 ± 0.37 (stat) ± 0.18 (syst)
CMS: 125.02 ± 0.27 (stat) ± 0.15 (syst)



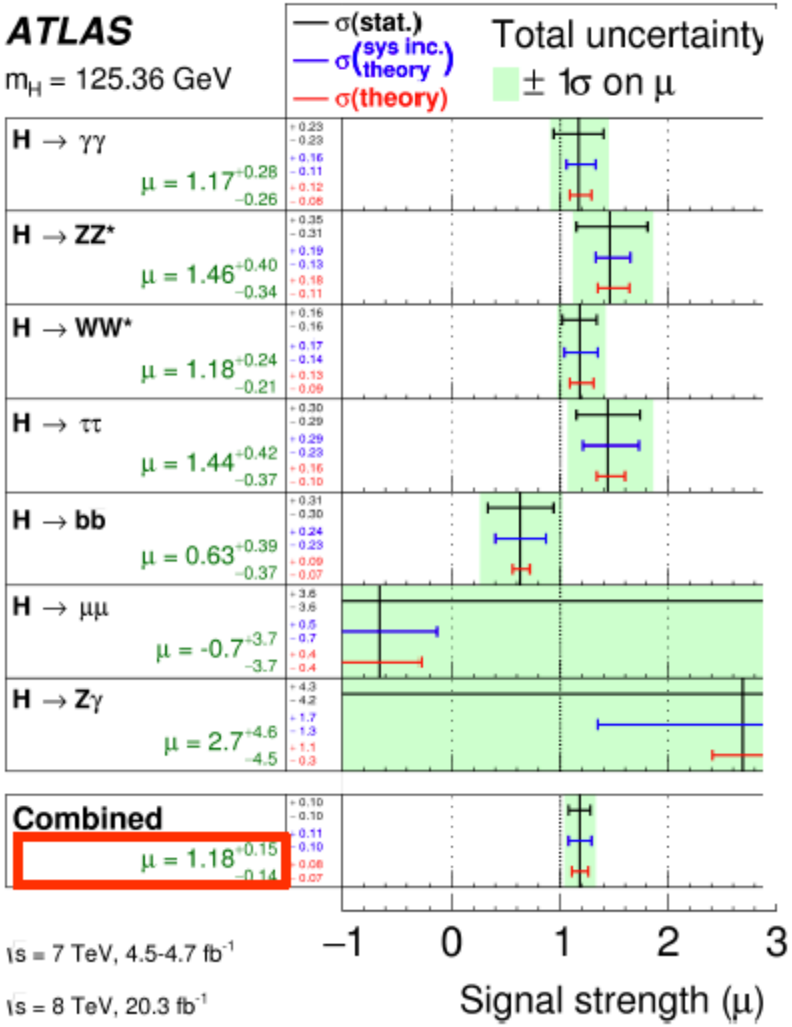
LHC combination:
125.09 ± 0.21 (stat) ± 0.11 (syst)

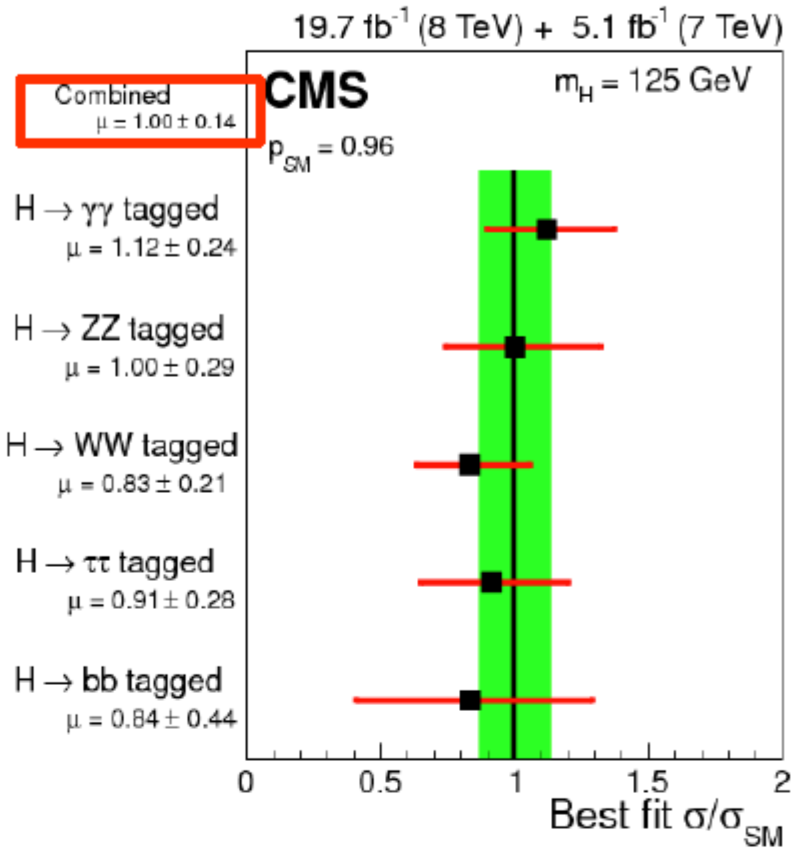
Precision measurement: <0.2%

*a lot of progress by theory community, LHCXSWG. Improvements continue…

Pierre Savard

Signal Strength for Decay Modes





ATLAS: individual μ values from combination of channels
CMS: individual μ values from tagged analyses

Pierre Savard

Status of SM Rare Decays

Searches for rare decays performed in various channels

Observation of these decays in Run 1 would signal BSM physics

Non-universal coupling of Higgs to leptons:

- $\mu\mu$ signal would be 280 times larger than SM if μ coupling was equal to that of τ

Process	limit (times SM)
$\mu\mu$ (ATLAS)	7.0
$\mu\mu$ (CMS)	7.4
$Z\gamma$ (ATLAS)	11
$Z\gamma$ (CMS)	9
$\gamma\gamma^*$ (CMS)	7.7
$J/\psi\gamma$ (ATLAS)	540
$J/\psi\gamma$ (CMS)	540
ee(CMS)	10^5

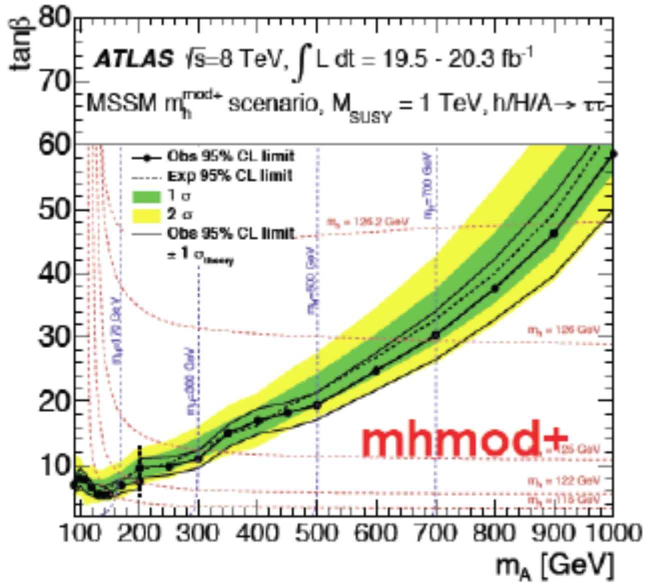
A->ττ (Low/High Mass)

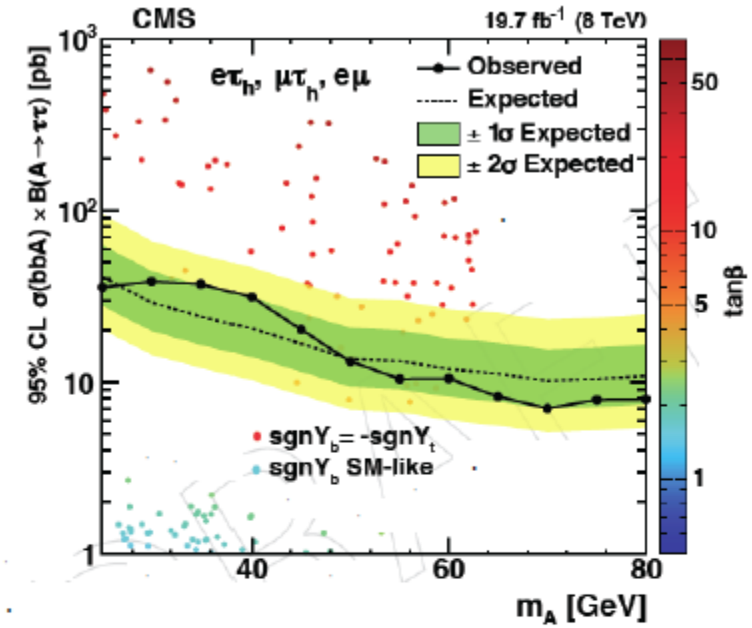
Search for pseudoscalar (A) boson decaying to τ leptons

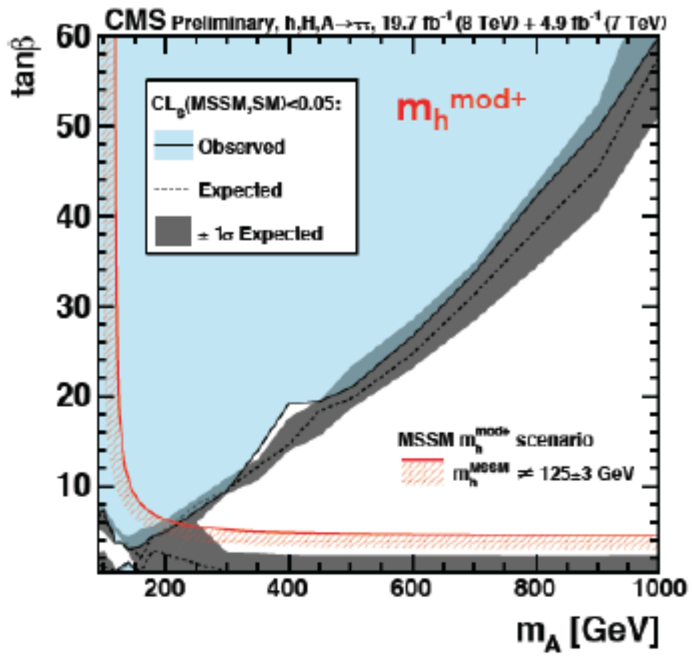
- Sensitive in high tan(β) regime

Searches performed at high and low mass

Results interpreted in the context of SUSY scenarios. Limits given on σ x BR







Search for heavy, narrow resonances

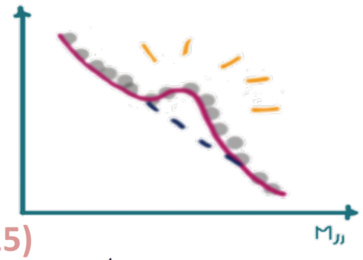
Many channels

- Dijets
- Photon pairs
- Lepton Pairs
- Pairs of heavy bosons

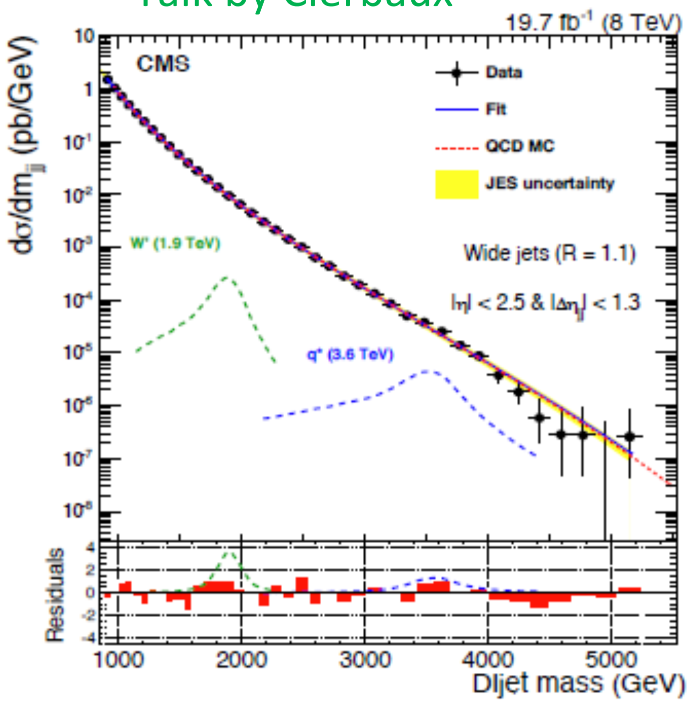
Mikulec

Di-jets

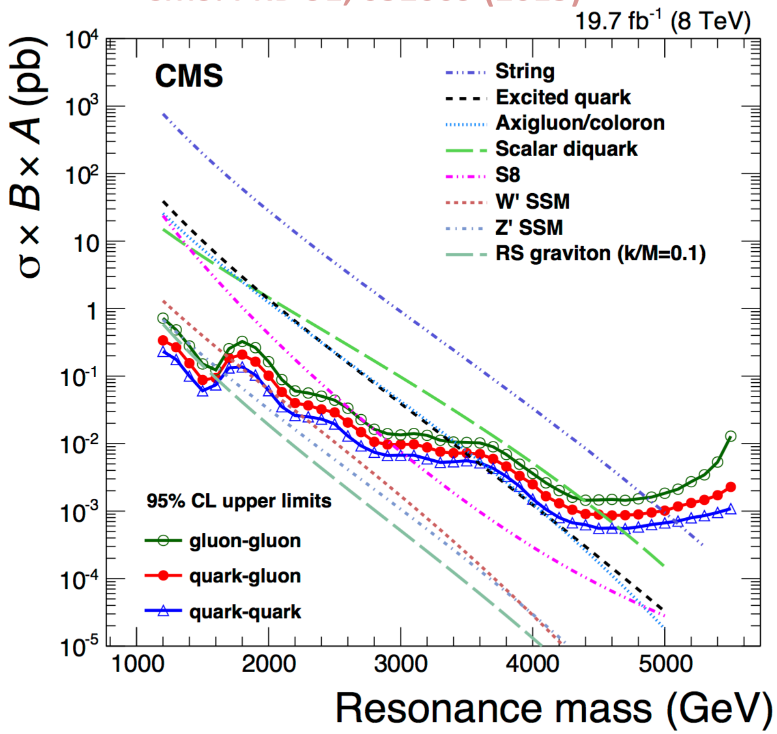
- Classical bump search – narrow resonance: up to widths 20-30% of the mass
- Simple – Data-driven, background parameterized by smooth function
- Powerful – generic search, many interpretations, high mass reach



Talk by Clerbaux



CMS: PRD 91, 052009 (2015)

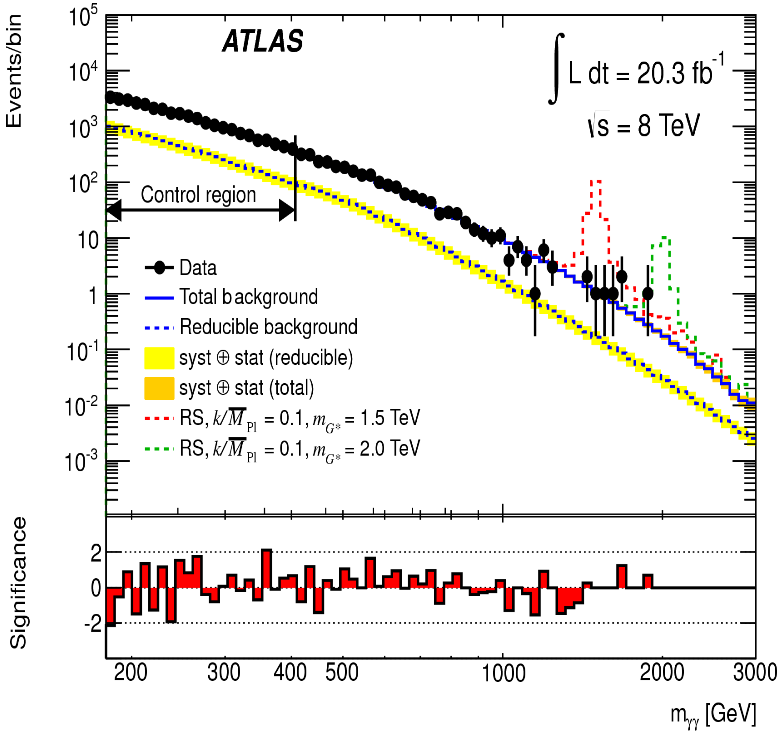


- **Excluded resonances with masses of 2 – 5 TeV depending on model**

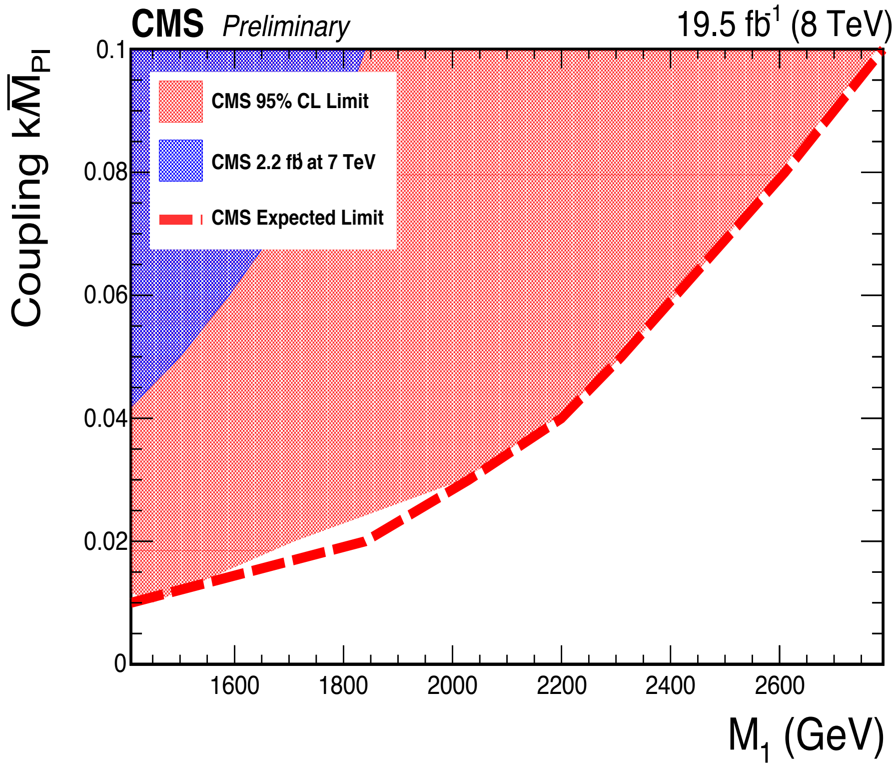
Di-photons

- Sensitive to spin 2 (RS graviton) or spin 0 (heavy Higgs) resonances
- Clean topology with well understood SM γγ background (Higgs searches)
- Challenge is the photon reconstruction and ID at high energies

ATLAS: arXiv 1504.05511



CMS: PAS EXO-12-045



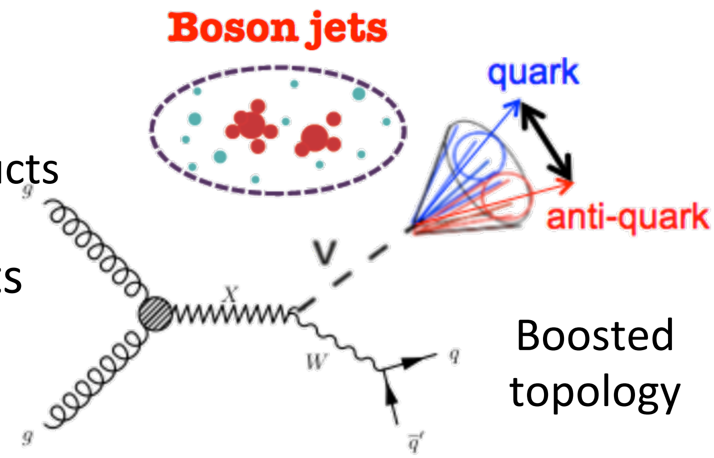
- **Limits on RS graviton mass 1- 2.7 TeV (sensitivity similar to di-lepton)**

Mikulec

Mikulec

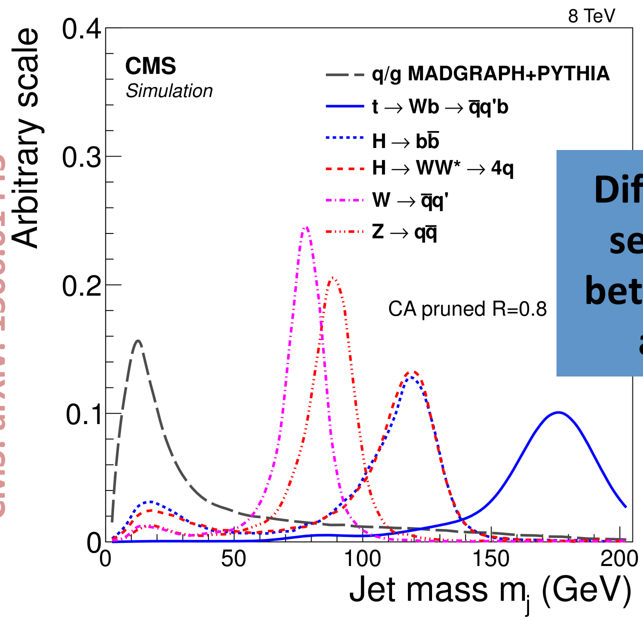
Di-bosons

- Search for resonance decaying to pairs of W, Z, H
- Challenging topology:
  - At resonance masses above 1 TeV the decay products of bosons overlap due to strong boost
- Needs dedicated techniques to reconstruct objects
  - Specific lepton isolation
  - Grooming techniques (cleaning pileup and noise)
  - Boson tagging (jet substructure, jet mass)



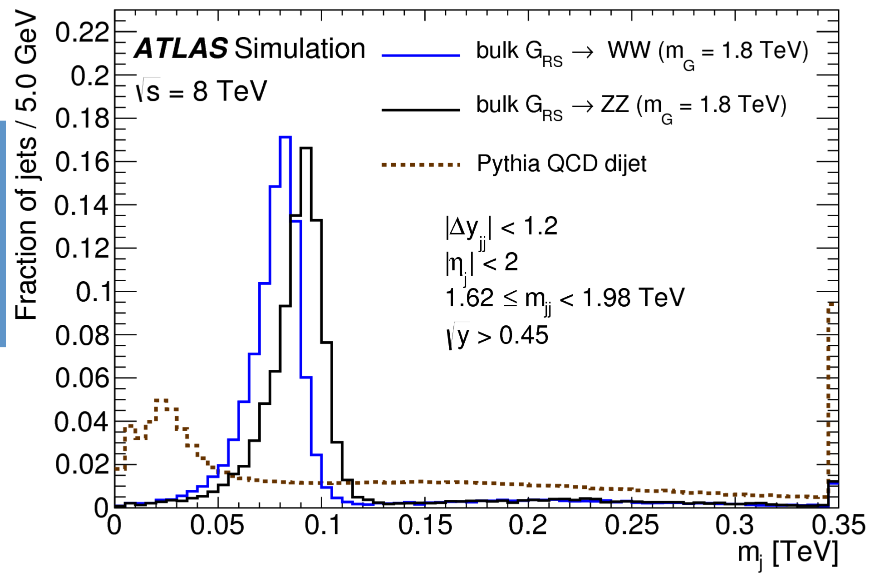
Boosted topology

CMS: arXiv: 1506.01443



Difficult to separate between W and Z

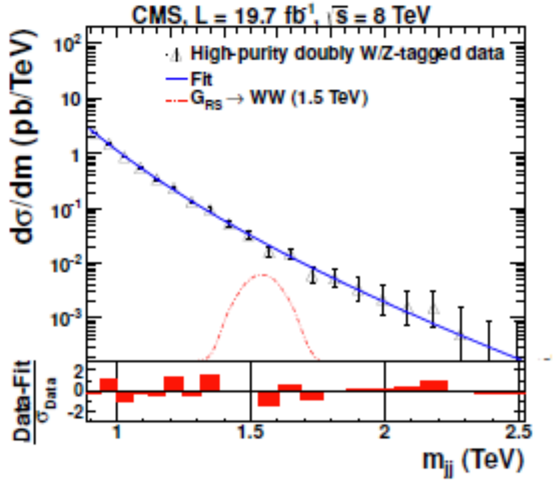
ATLAS: arXiv 1506.00962



VV->qqqq

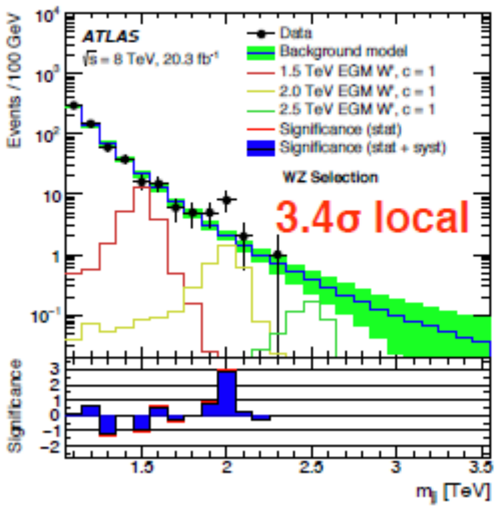
CMS: arxiv:1405.1994

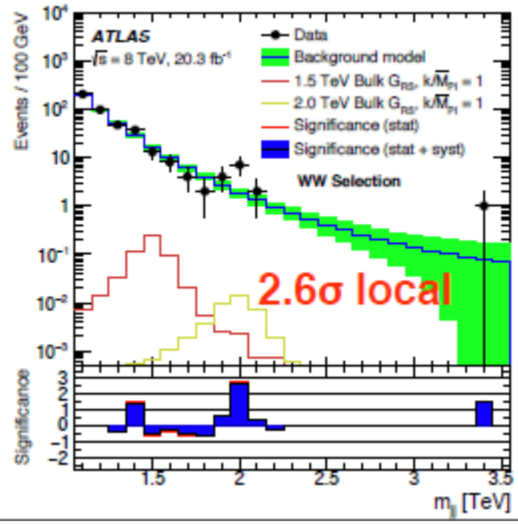
- ATLAS: Trigger on a jet with pt>360 GeV CMS: Trigger on HT
- Only boosted region considered (low mass QCD dominated)
- Select events with Mj within the W/Z mass window
  - ATLAS: $|y_1\text{-}y_2|< 1.2$, Pt Asymmetry <0.15 to reject events where one of the jets is poorly measured
  - 3 overlapping signal regions/non statistically independent
- Additional cuts to reduce QCD (ntrk, nsubjettiness...)
- The background is estimated by fitting the data

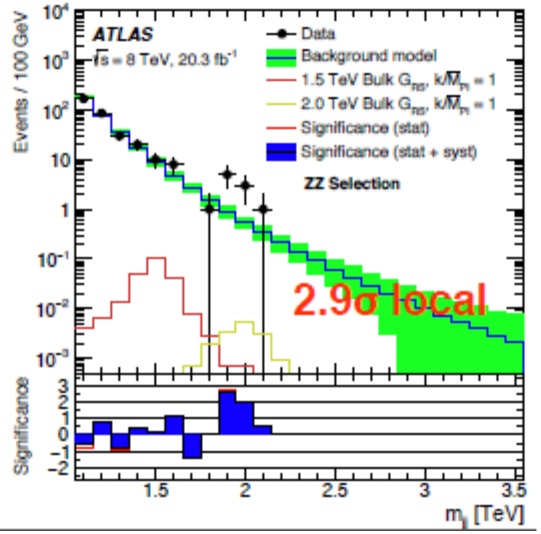


ATLAS: arxiv:1506.00962

$$\frac{dn}{dx} = p_1(1-x)^{p_2-\xi p_3} x^{p_3},$$



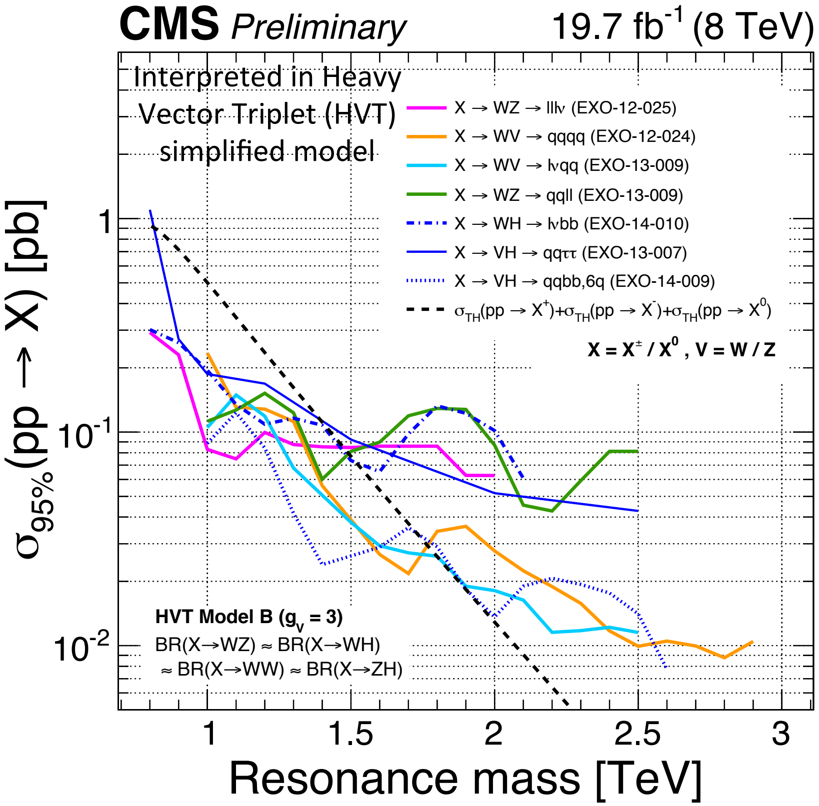




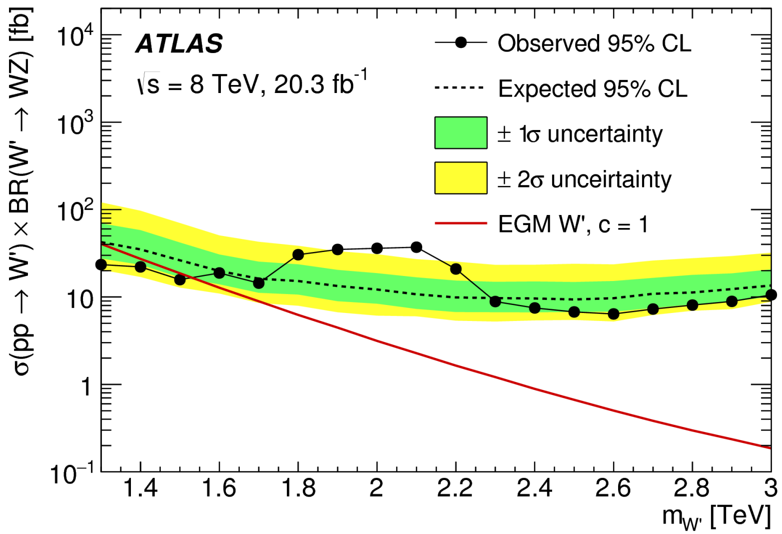
Di-bosons – excess?

- Moderate excesses observed in some channels around 1.8 – 2 TeV
  - Global significance 2 – 2.5 σ
  - Small excesses also in di-jets…
- Excesses of 2σ not unusual, but ATLAS + CMS at similar place = excitement

CMS: PAS EXO-14-010

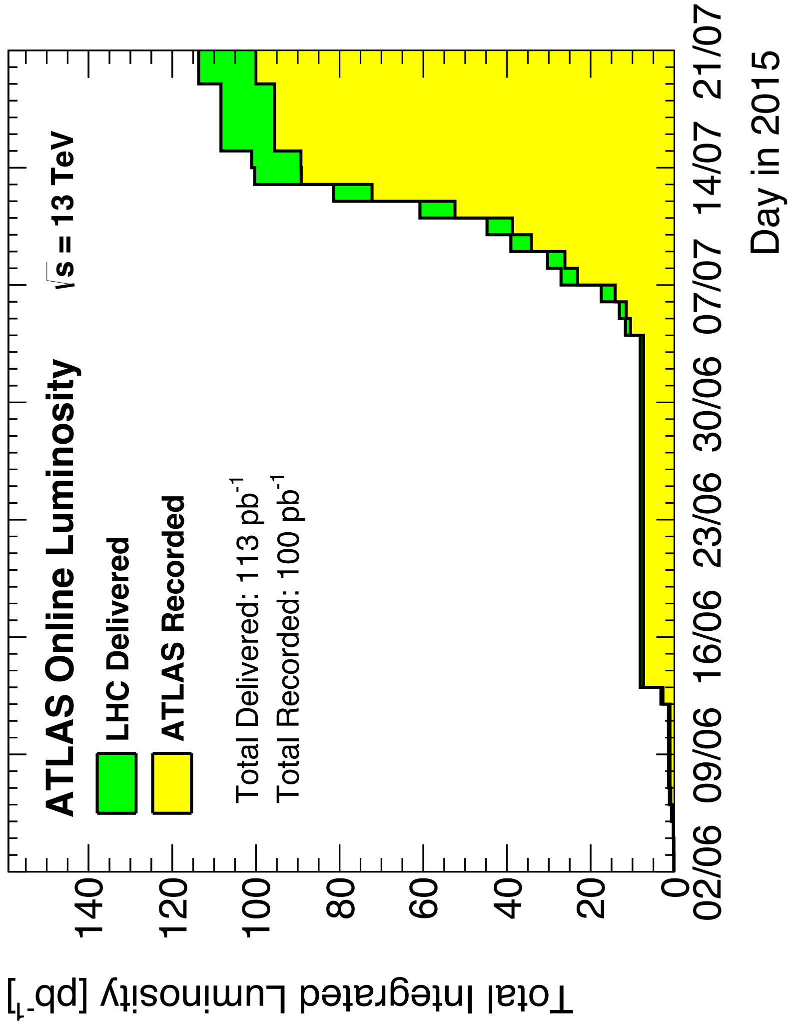


ATLAS: arXiv 1506.00962



- **Not in all channels…**
- **Will know more after a few first fb^{-1} of Run 2 data**

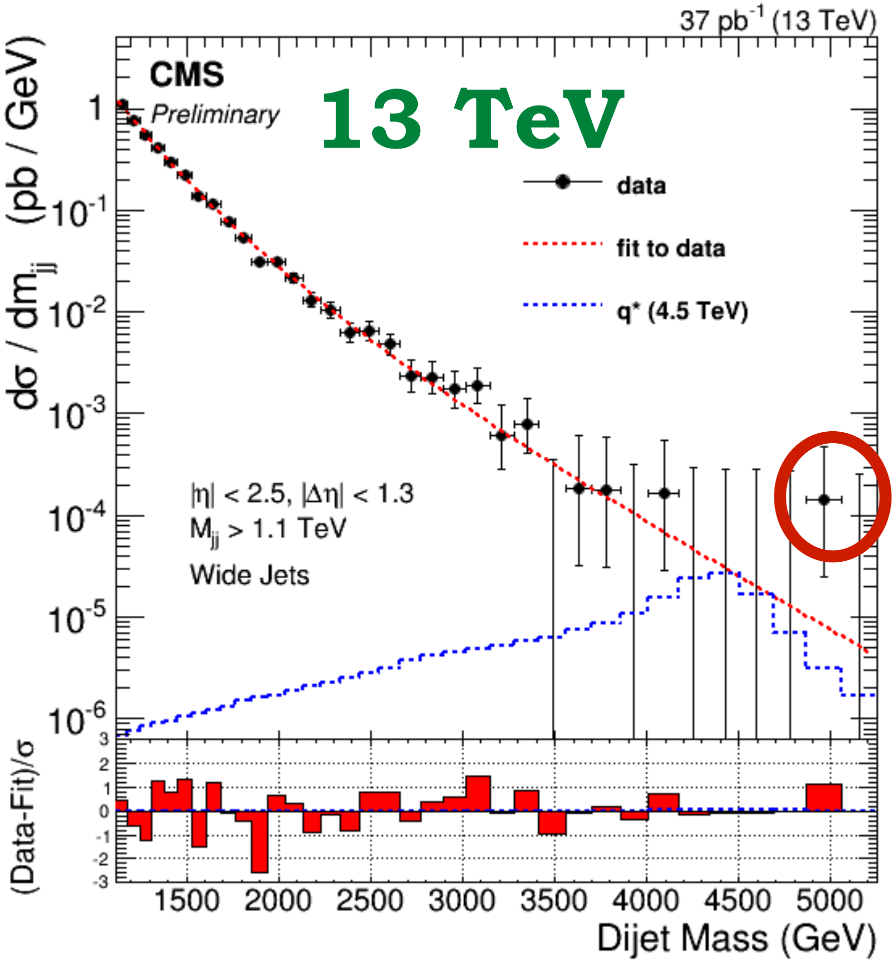
LHC has started run 2 and is delivering

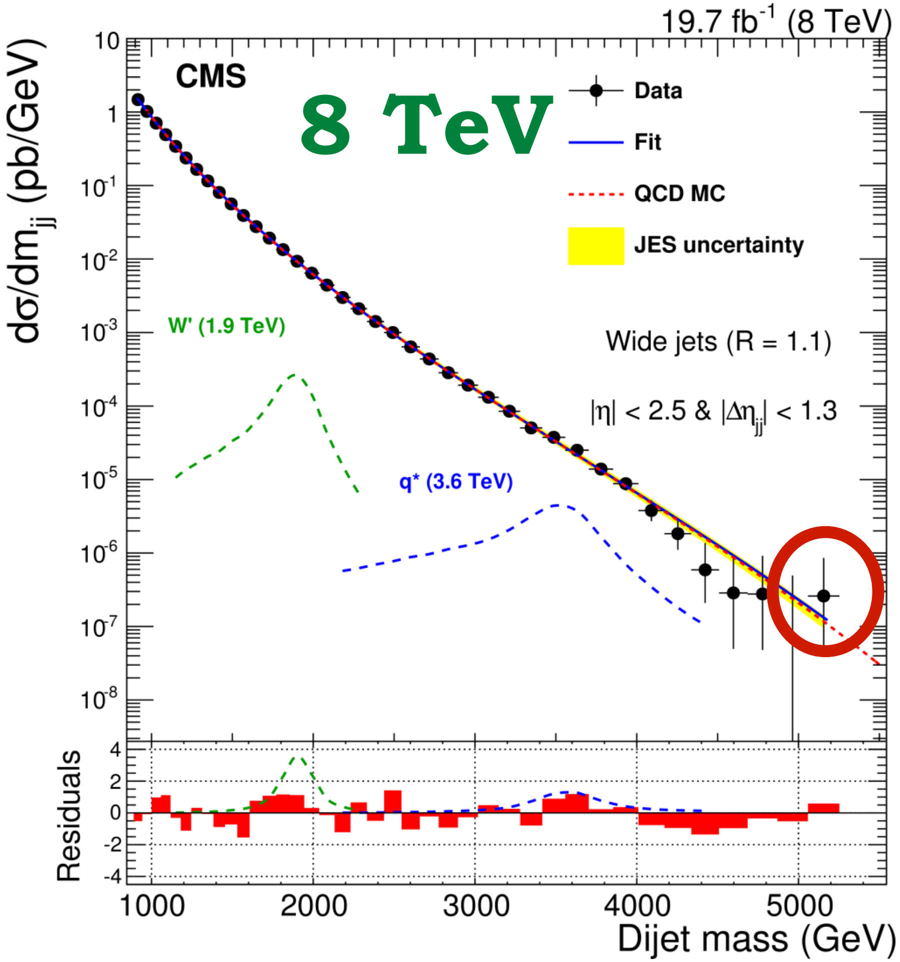


Luminosities @ CMS

- **Total delivered: 106/pb**
- **Total recorded: 83.5/pb**
- **Total recorded @ 3.8T: 61.8/pb**
- **Results @ EPS presented up to 43/pb**

Di-Jet Mass Spectra 13 TeV ↔ 8 TeV

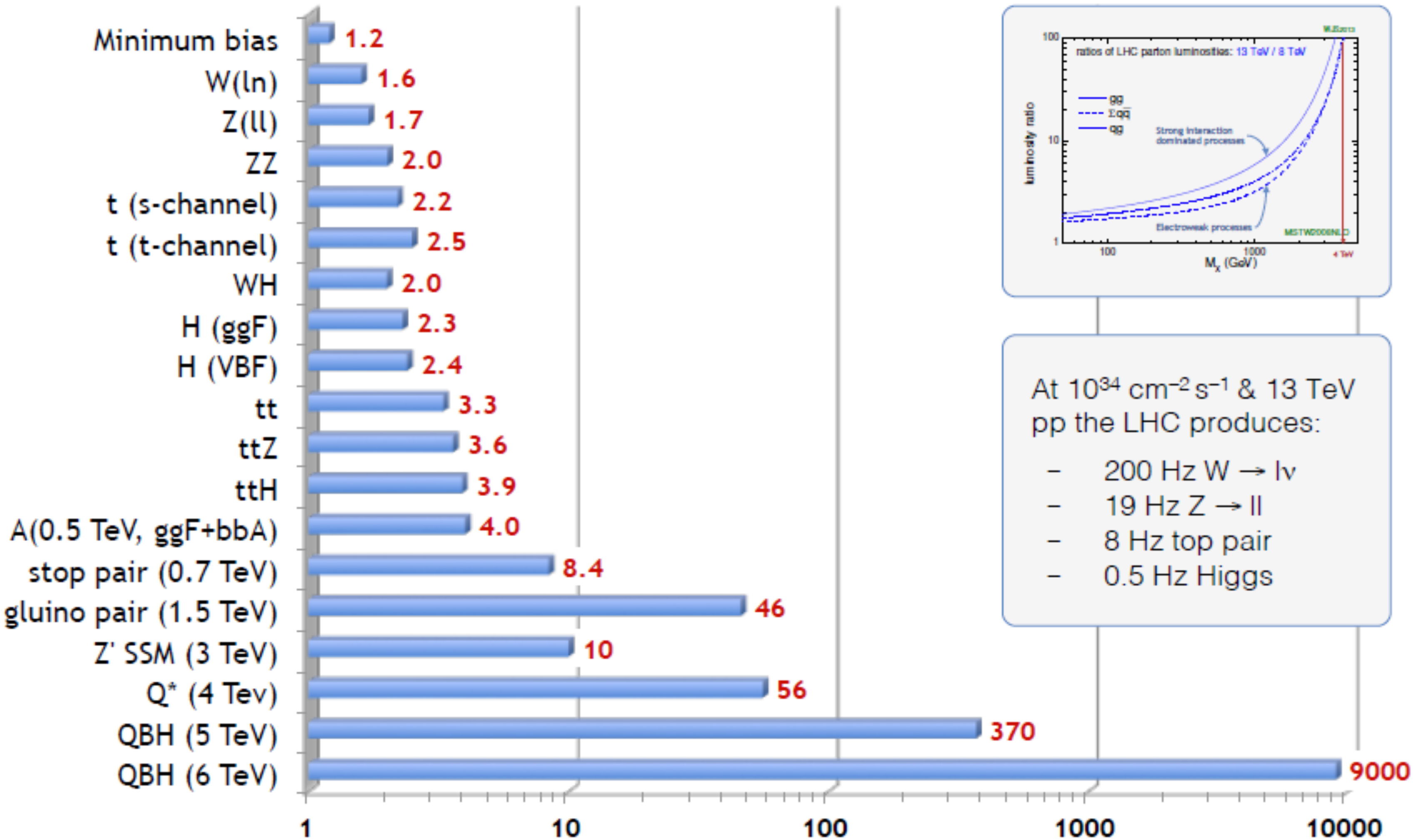




- **13 TeV: 37 pb-1, Mjj ≤ 5 TeV, 8 TeV:19.7 fb-1, Mjj ≤ 5.15 TeV**
- **Close to Run 1 limit ➔ interesting times ahead of us ☺**

Hoecker

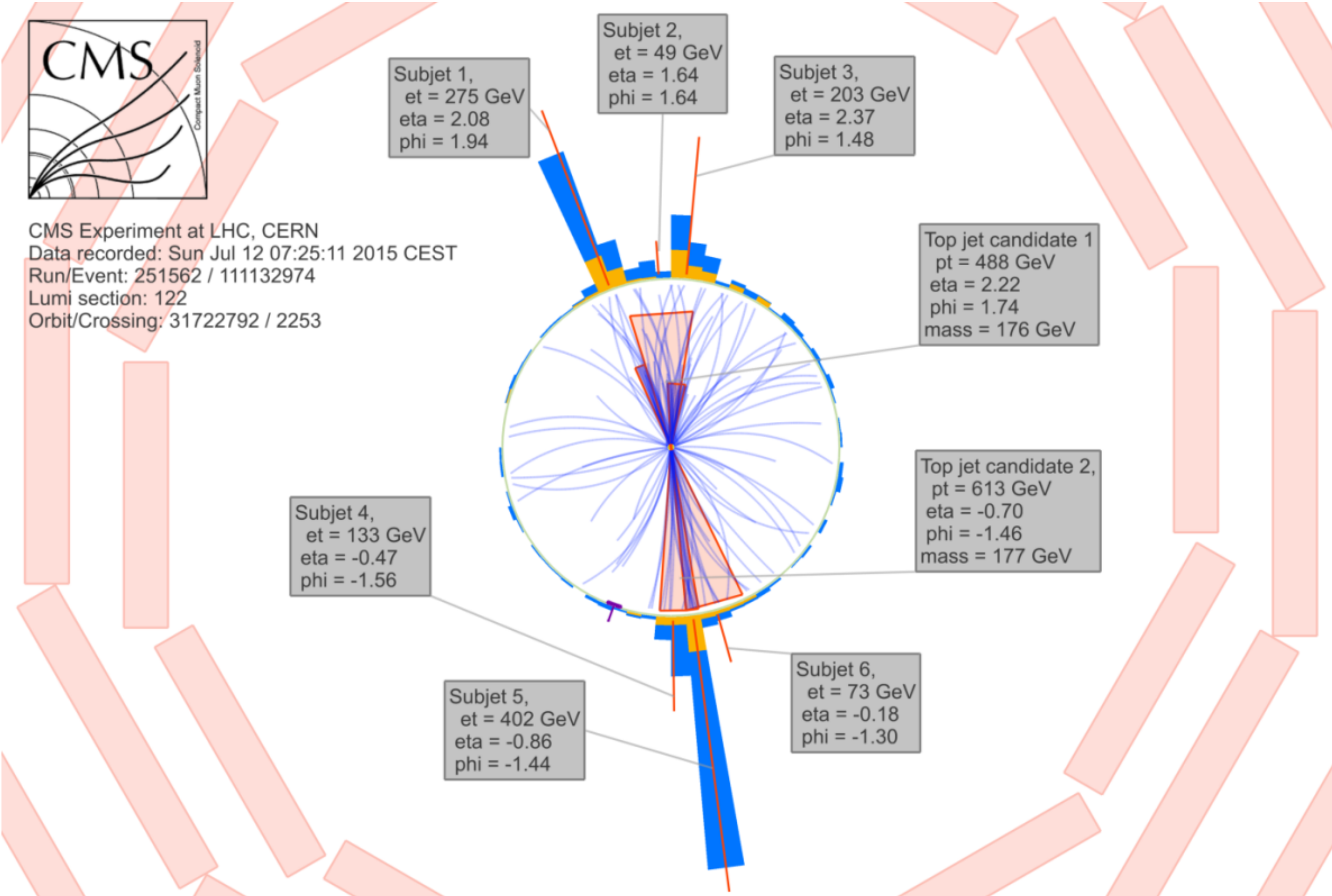
13 TeV / 8 TeV inclusive pp cross-section ratio



At 10^{34} cm^{-2} s^{-1} & 13 TeV pp the LHC produces:

- 200 Hz W → lν
- 19 Hz Z → ll
- 8 Hz top pair
- 0.5 Hz Higgs

Reach very high mass ttbar pairs



Borras

- **Top – jet 1:**
  - m =177 GeV, p_T =613 GeV
- **Top – jet 2:**
  - m =176 GeV , p_T = 488 GeV
- **Di-top jet Mass: 2491 GeV**

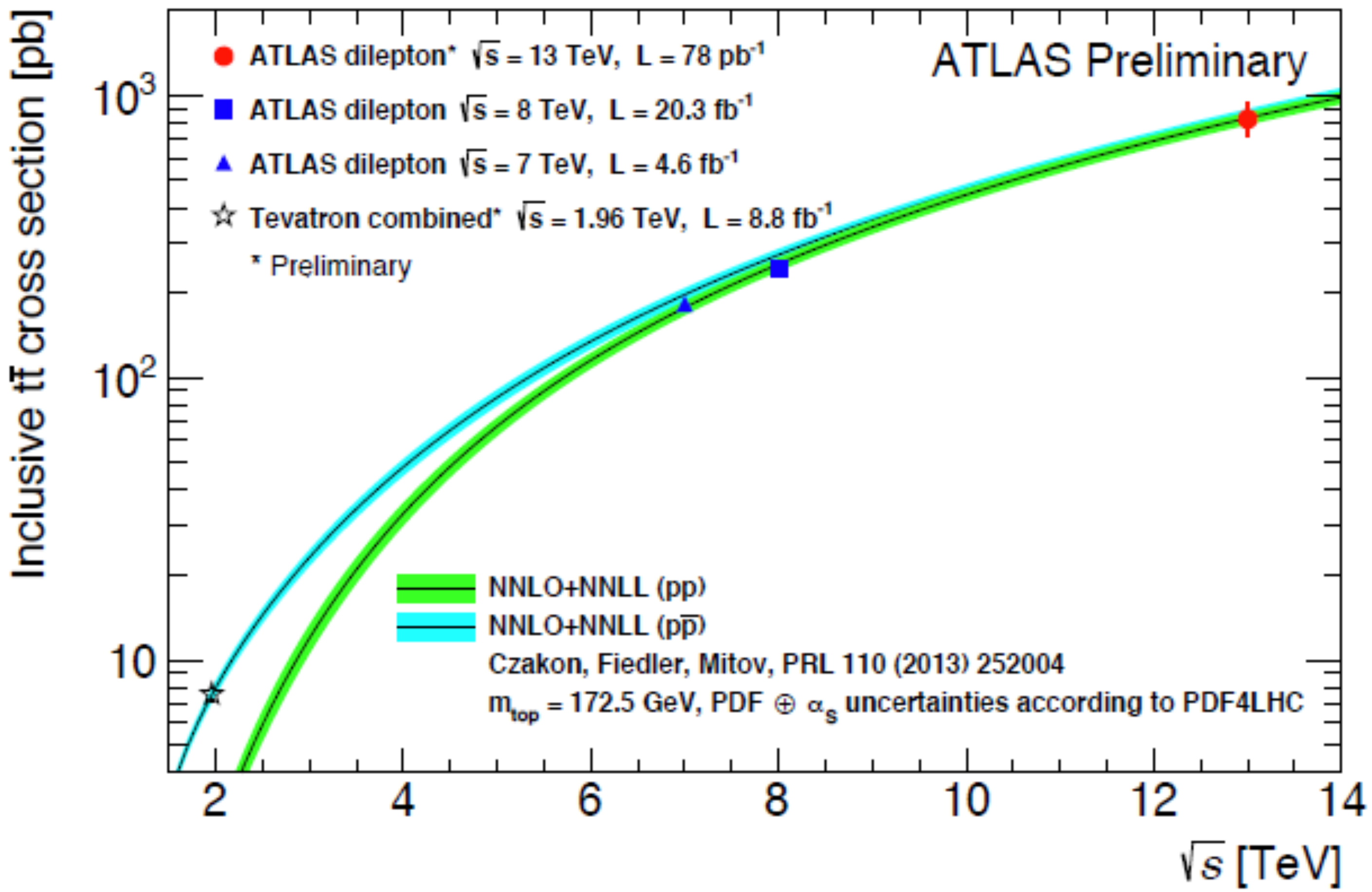
Top-antitop production at 13 TeV

Hoecker

Extraction of top-pair cross section

[ATLAS-CONF-2015-033]

$\sigma_{t\bar{t}}$ (13 TeV) = 825 ± 49 (stat) ± 60 (syst) ± 83 (lumi) pb

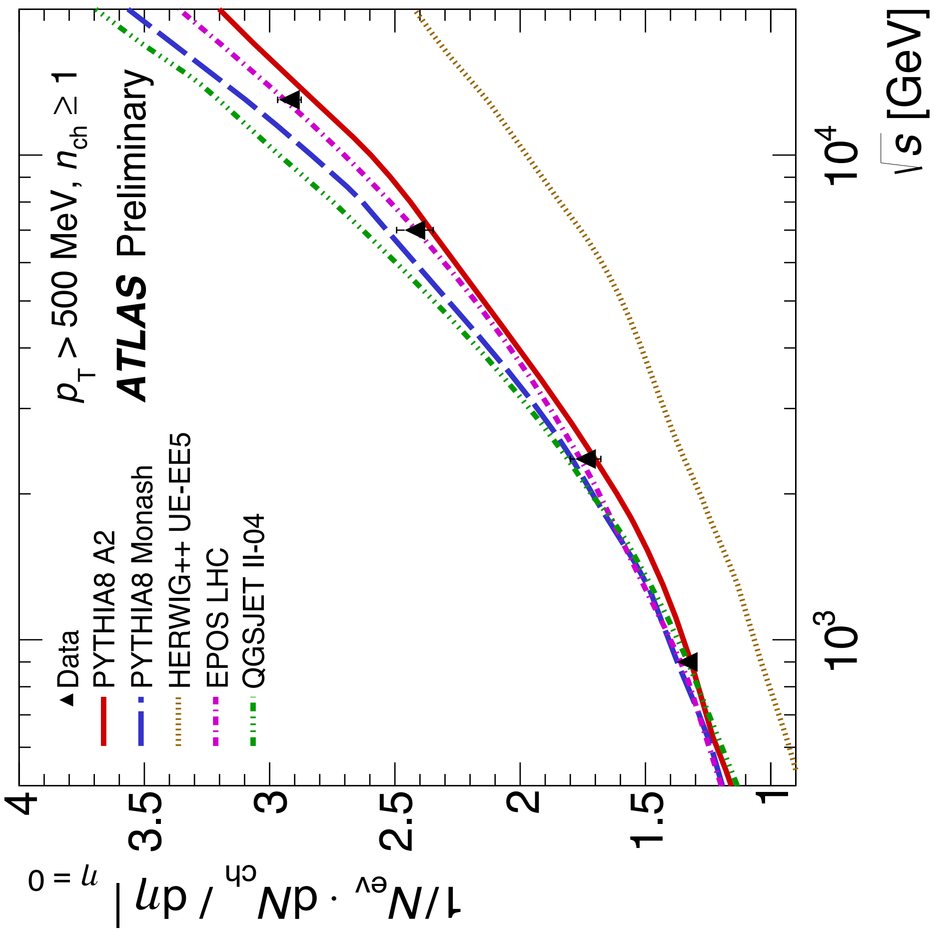


Properties of inelastic pp collisions at 13 TeV

Key input to pileup and underlying event modelling, uses low-μ data

[ATLAS-CONF-2015-028]

Average charged-particle multiplicity per unit of rapidity for η = 0 vs CM energy



For comparison, the strange baryon contribution is included at 13 TeV (1.5% correction factor)

Hoecker

Two-charged-particle correlations

In high-multiplicity pp collisions using low-μ data

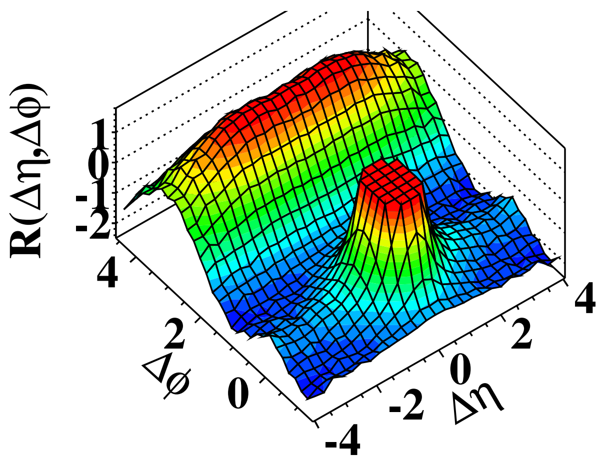
Hoecker
(see also Bielcikova talk)

[ATLAS-CONF-2015-027]

Near-side ($\Delta\phi \sim 0$) "ridge" shape in $\Delta\eta$–$\Delta\phi$ seen in pp, pPb and PbPb collisions

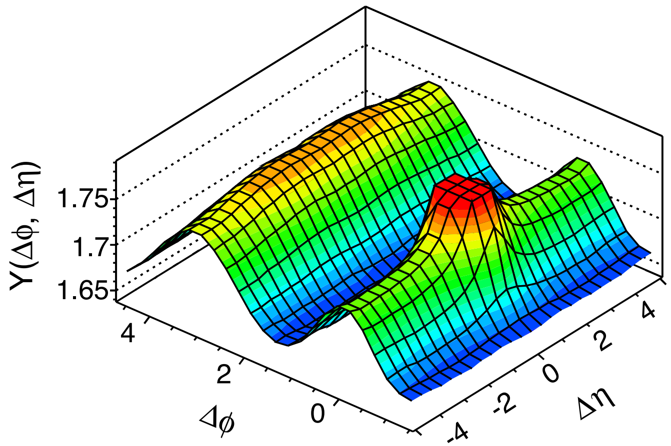
Unexpected effect of collective dynamics. Increases with particle multiplicity and moderate p_T

CMS, pp at 7 TeV:
$N_{ch} > 110$, $1.0 < p_T < 3.0$ GeV



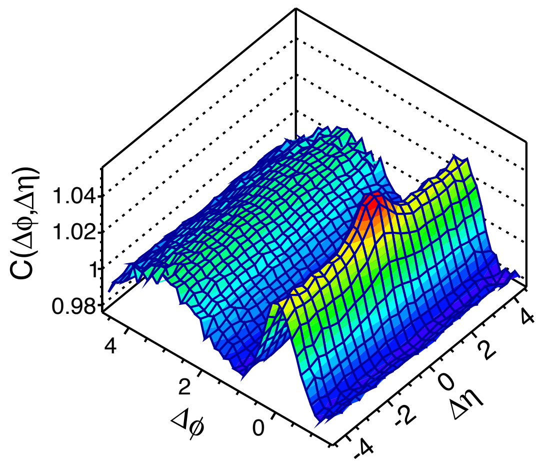
[CMS, 1009.4122]

ATLAS, pPb at 5.02 TeV:
$N_{ch} > 220$, $1.0 < p_T < 3.0$ GeV



[ATLAS, 1212.5198]

ATLAS, PbPb at 2.76 TeV:
Centrality 0–5%, largest 10% q_2



[ATLAS, 1504.01289]

[Enhancement found to be also present at $\Delta\phi \sim \pi$, when subtracting hard scattering contributions]

Two-charged-particle correlations in 13 TeV

Hoecker

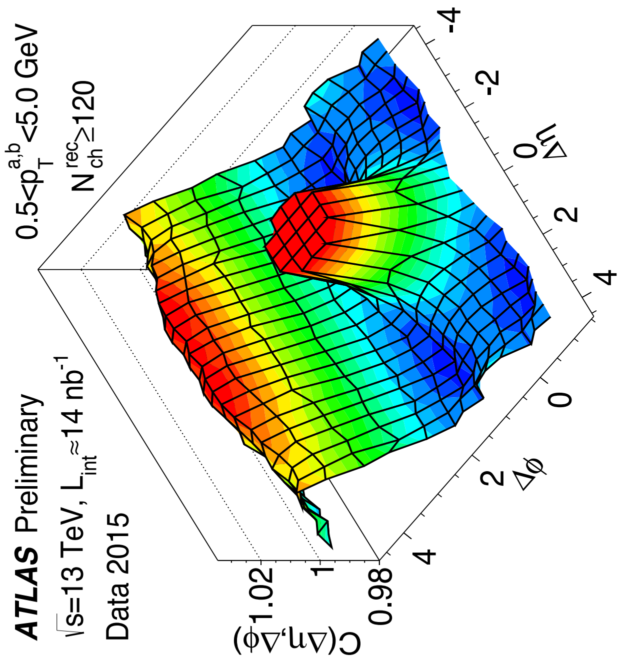
In high-multiplicity pp collisions using low-μ data

[ATLAS-CONF-2015-027]

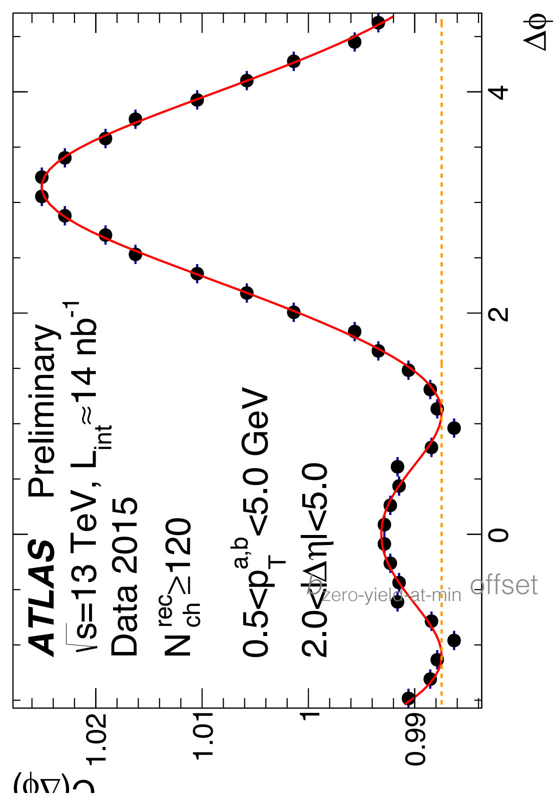
How does the pp ridge evolve with CM energy ?

- Trigger on MBTS (97M events) & high charged multiplicity (9.5M)
- Exploit work on tracking systematics from minimum bias analysis
- Unfold to particle level
- Extract two-particle correlation function $C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)}$
- Background from mixed data events

High charged multiplicity



Integrate: $2 < |\eta| < 5$



Higher order calculations [Grazzini]

The NLO automation

- Unitarity and on-shell methods

MadGraph5_aMC@NLO   BlackHat+Sherpa   NJet

GoSam+Sherpa   Helac-NLO

- Numerical off-shell methods

Combine efficiency of the numerically stable tensor-integral reduction with the automation made possible by a completely recursive approach

OpenLoops+Sherpa   Recola

see also Van Hameren (2009)

The final goal is really automatic NLO calculations

Specify process (input card), define cuts/distributions ➡ run and get the results

The problem is "in principle" solved

The NNLO revolution

Grazzini

NNLO calculations important for:

1) Benchmark processes measured with high accuracy

- ✅ $e^+e^- \to 3$ jets
- ✅ $pp \to W, Z$
- ✅ $pp \to t\bar{t}$bar and single top
- (✅) $pp \to 2$ jets
  - ➘ towards completion

2) Processes with large NLO corrections

- ✅ $pp \to H$
  - ➘ even N3LO known now
- ✅ $pp \to H$+jet
- ✅ $pp \to HH$

3) Important backgrounds for Higgs and NP searches

- ✅ $pp \to \gamma\gamma$
- ✅ $pp \to W\gamma, Z\gamma$
- ✅ $pp \to WW$
- ✅ $pp \to ZZ$
- ❌ $pp \to WZ$
- ✅ $pp \to W(Z)$+jet

It is essential to provide fiducial cross sections and distributions with which the data can be directly compared

(for more processes see also Les Houches 2013 NNLO wish list)

Comparison to measured WW cross section

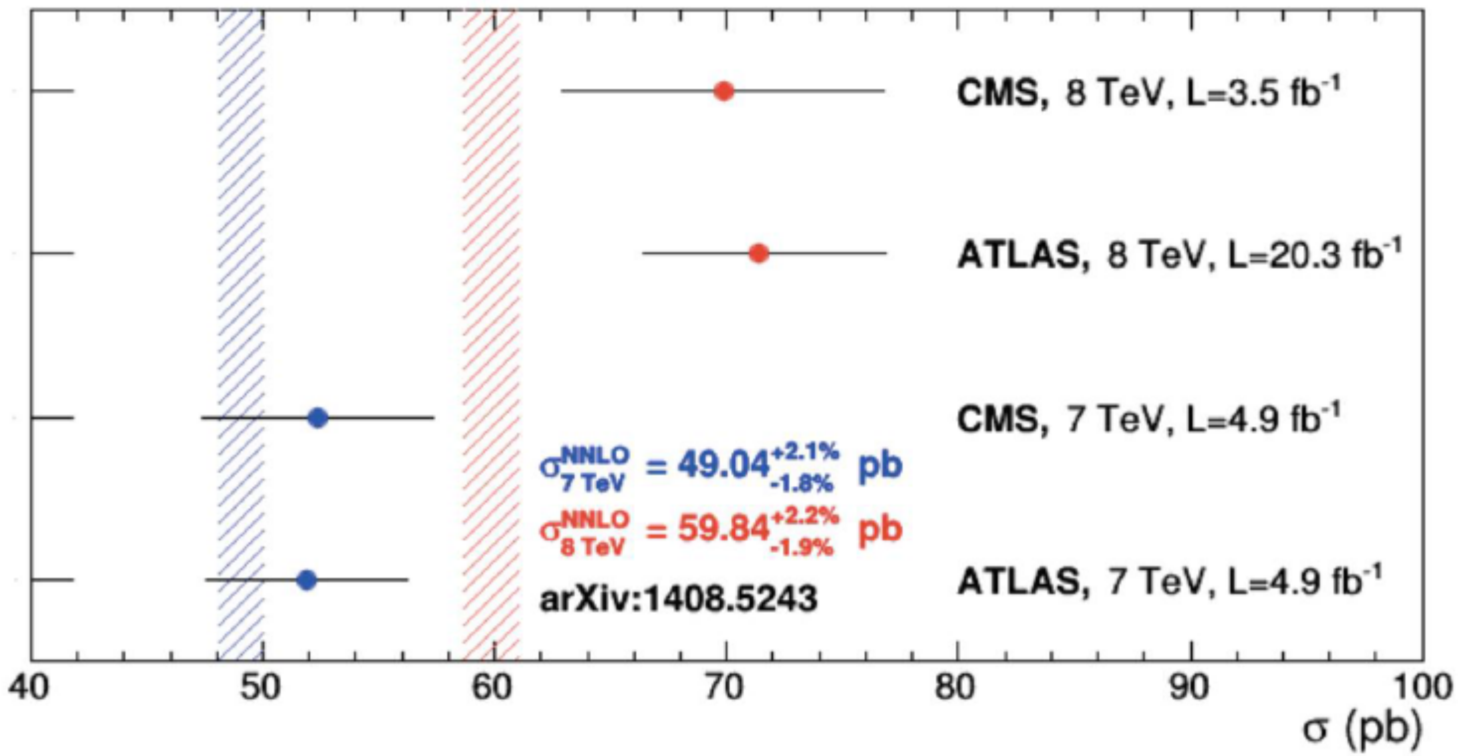
Signature

$e^+e^-, \mu^+\mu^-,$ or $e^\pm\mu^\mp$ + 0,1 jets + MET

Previous Measurements

CMS-PAS-SMP-12-013

- 8 TeV, 3.5 fb^{-1}, found $\sigma(WW \to 2\ell 2\nu)$ = (22±13)% higher than NLO prediction



Reanalysis of WW cross section by CMS

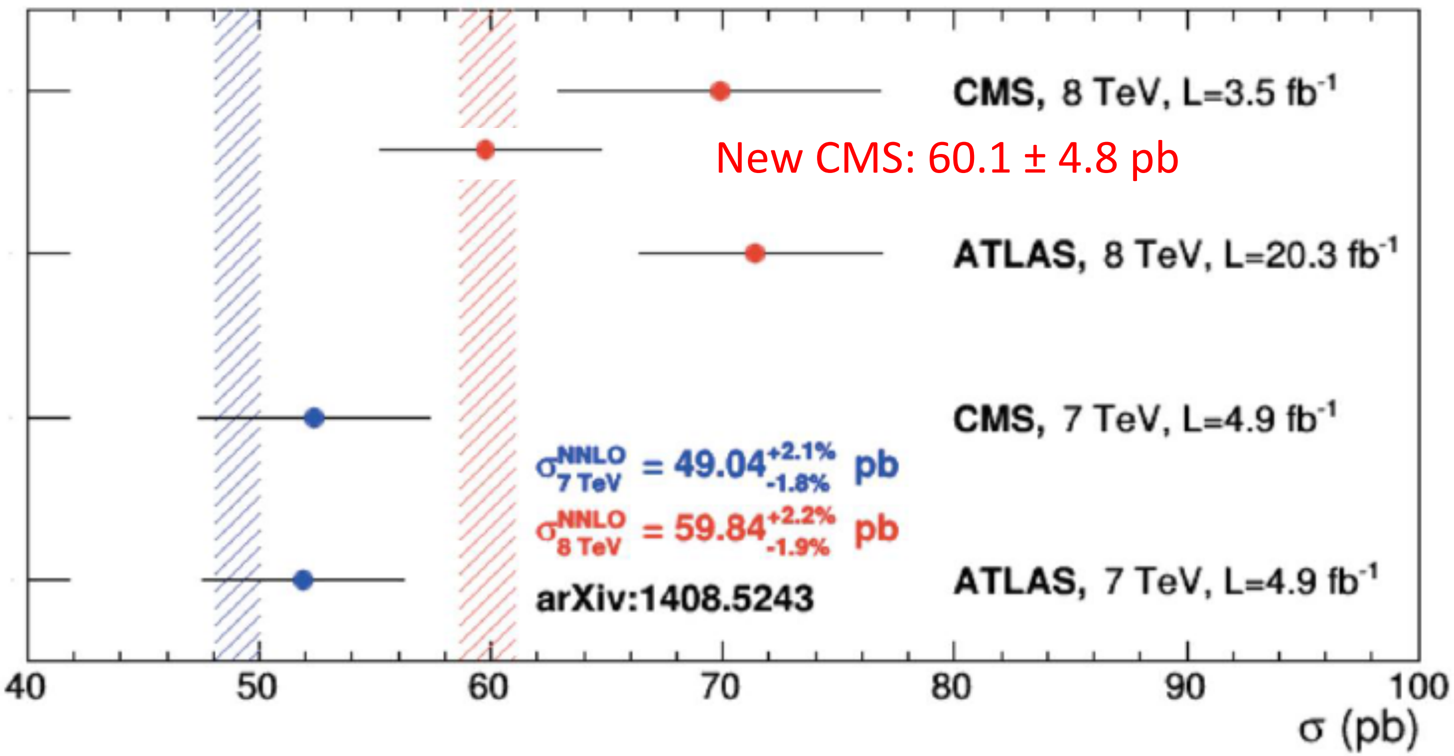
Signature

$e^+e^-, \mu^+\mu^-,$ or $e^\pm\mu^\mp$ + 0,1 jets + MET

Previous Measurements

CMS-PAS-SMP-12-013

- 8 TeV, 3.5 fb^{-1}, found $\sigma(WW \rightarrow 2\ell 2\nu)$ = (22±13)% higher than NLO prediction



Cosmology, dark matter and cosmic rays

- Many nice talks in parallel sessions
- Great reviews on Tuesday morning

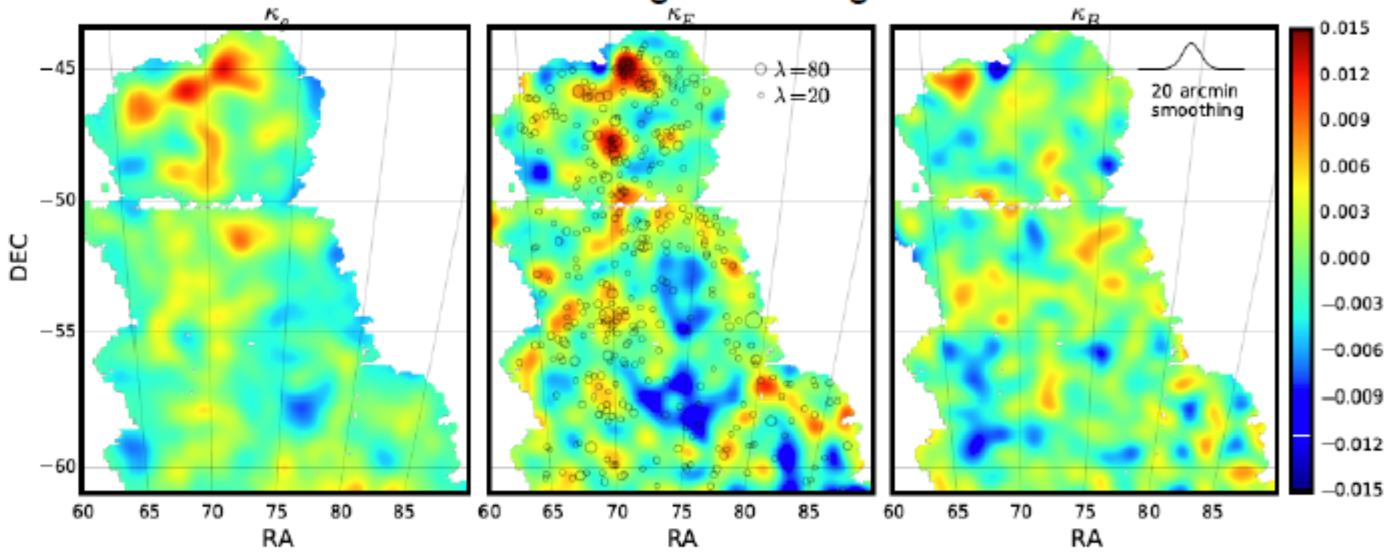
  Volansky, Monroe, Hoffmann, Halzen, Ganga, Lahav, Binetruy

Dark Energy Survey (DES) (talk by Ofer Lahav)

Goal: weak lensing effects on 300 million galaxies provide dark matter map

SV area 139 sq deg (only 3% of final DES)
Cross correlation signal: 5-7 sigma

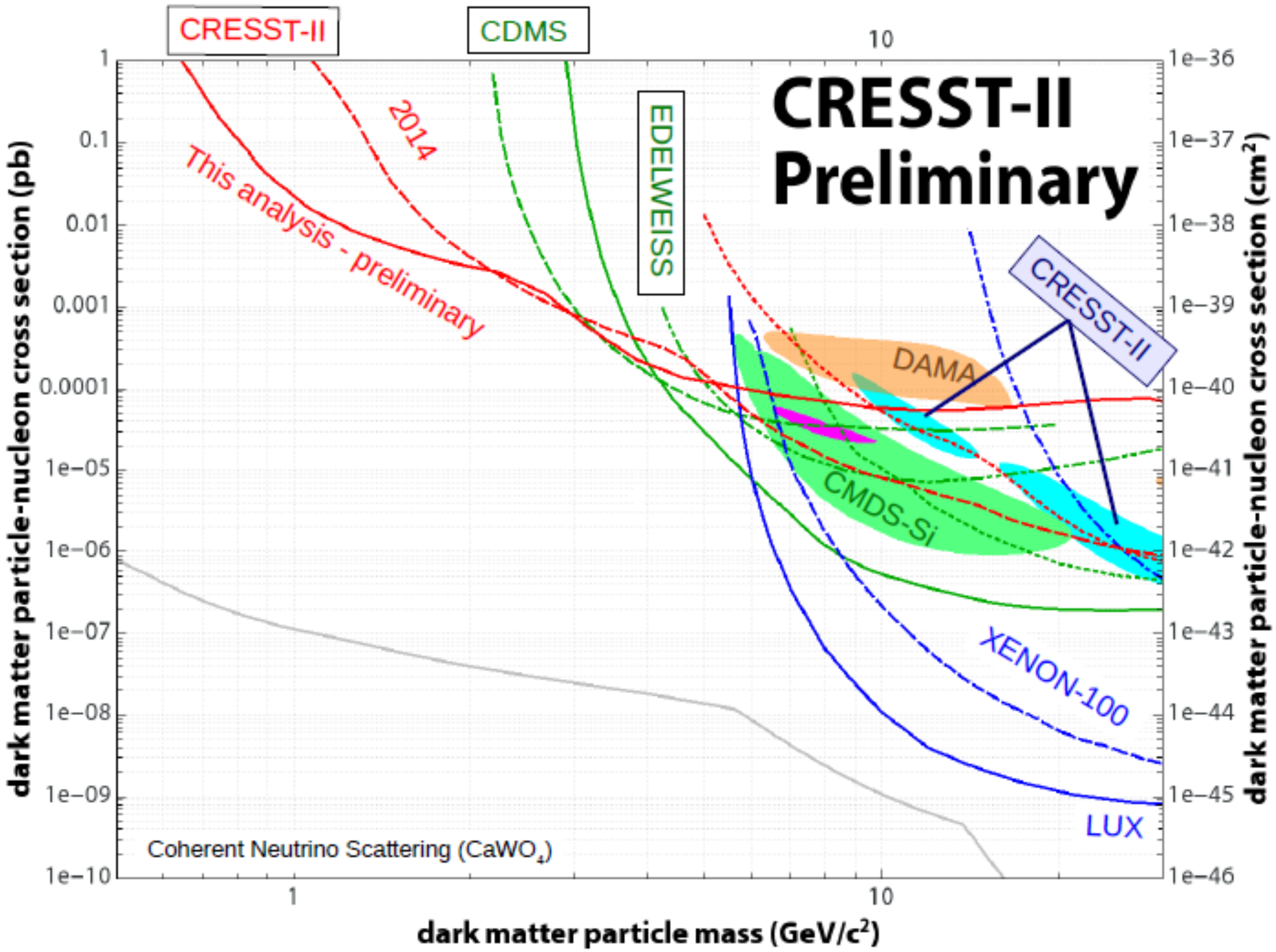
Lahav



Chang, Vikram, Jain et al. (PRL) 1M Background sources @ z ~0.8
Vikram, Chang, Jain et al. (PRD) 1M Foreground lenses @ z ~ 0.3

DM distribution (center) tracks luminous matter distribution of galaxies (left)

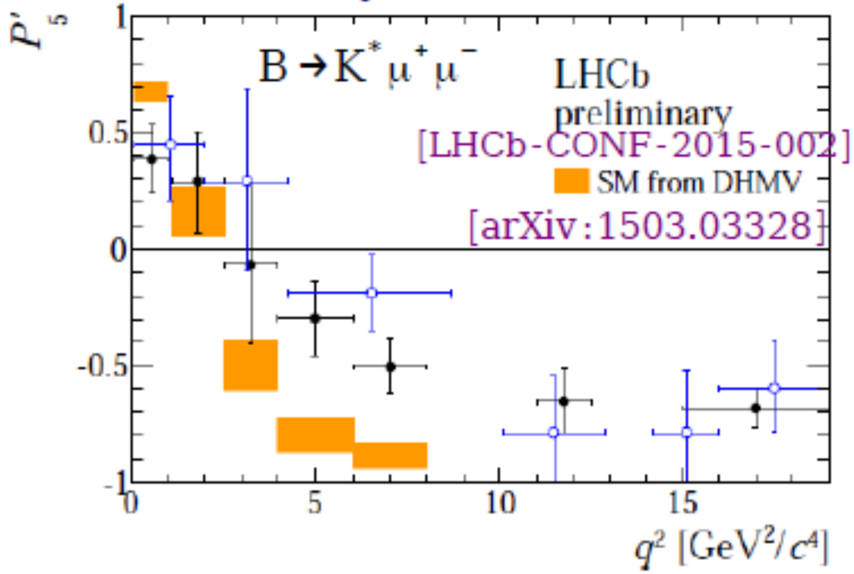
Improved low mass WIMP bounds by CRESST



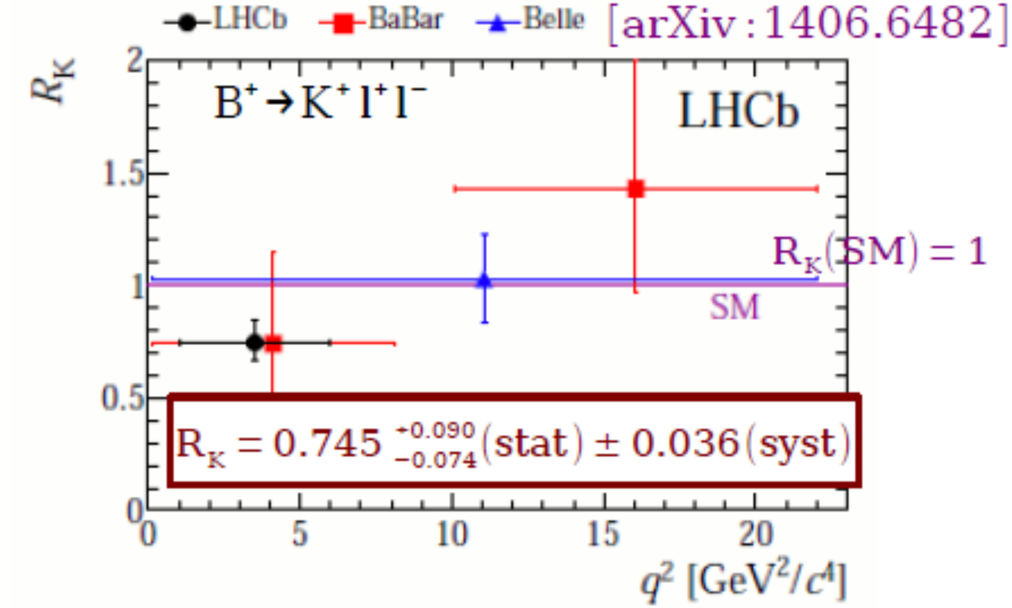
Talk Reindl

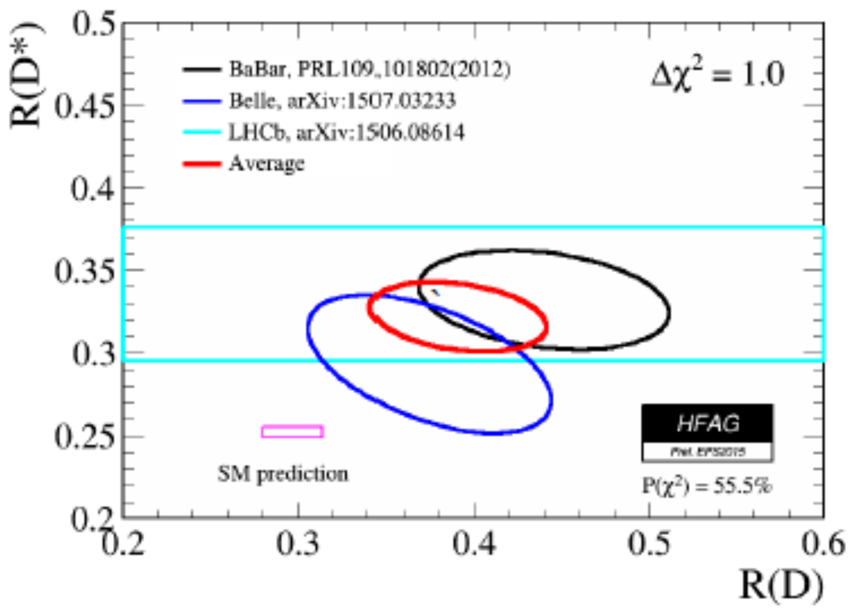
Few anomalies in B sector

⇒ Tension in P'_5 is confirmed with $3fb^{-1}$



Test of lepton universality using $B^+ \rightarrow K^+ l^+ l^-$ decays





Summary for $B \rightarrow D^{(*)} \tau \nu$

BaBar
$R(D) = 0.440 \pm 0.058 \pm 0.042$
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle
$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

LHCb
$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

average

$R(D) = 0.391 \pm 0.041 \pm 0.028$
$R(D^*) = 0.322 \pm 0.018 \pm 0.012$

⇒ difference with SM predictions is at **3.9σ** level

New anomaly in ε'/ε: direct CPV in $K_L \rightarrow \pi\pi$

- Highly BSM-sensitive observable, precisely measured

  $(\varepsilon'/\varepsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$ world average (KTeV & NA48)

- Major driver of flavour theory in 1990's

  Buras-Buchalla-Lautenbacher; Buras-Jamin-Lautenbacher-Weisz; Bosch-Buras-Gorbahn-Jaeger-Jamin-Lautenbacher-Silvestrini; Bertolini et al; Ciuchini et al; Pallante-Pich; Cirigliano et al; ...

  situation murky due to uncertain hadronic matrix elements (nonperturbative)

- @ EPS 2015: first complete lattice calculation (tour de force; evaluation of 20 hadronic matrix elements in isospin limit)

  $(\varepsilon'/\varepsilon)_{\rm SM} = (1.4 \pm 7.0) \times 10^{-4}$

  RBC-UKQCD collaboration [Z Bai et al]; talk A Soni at this conference

- @ EPS 2015: impose Delta I=1/2 to reduce number of independent hadronic matrix elements; isospin and NNLO corrections; corroborate lattice with new large-N relations (and vice versa)

  $\varepsilon'/\varepsilon = (2.2 \pm 3.7) \times 10^{-4}$ $3.3\,\sigma$ from expt

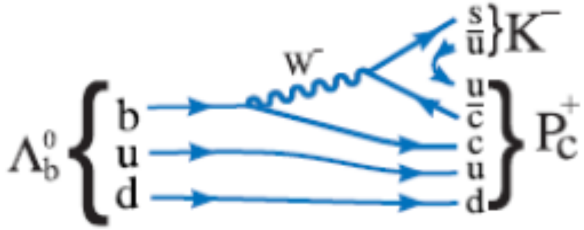
  Buras, Gorbahn, Jaeger, Jamin; Buras and Gerard; talk A Buras at this conference

Excellent prospects as BSM probe if theory errors are confirmed/further reduced

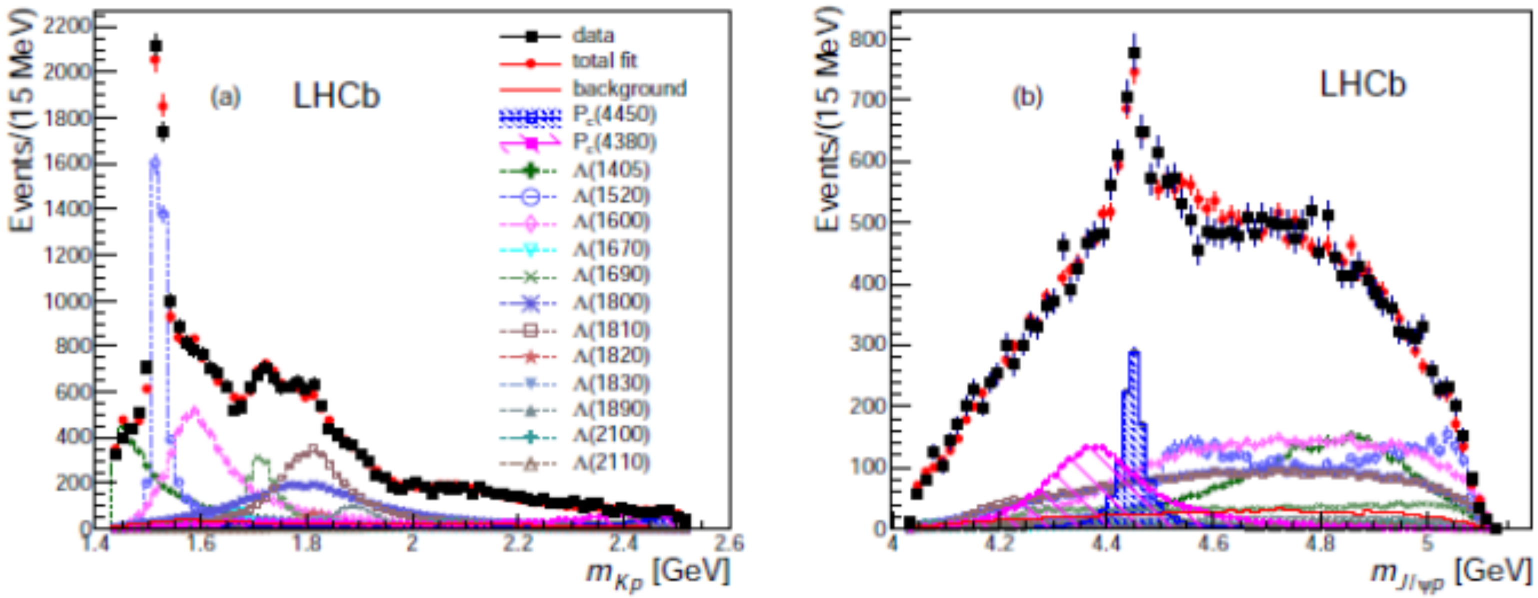
Big improvements on hadronic matrix elements for B-physics , talk R. van de Water

Observation of J/ψ p resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

[arXiv:1507.03414]



Best fit with $J^P = (3/2^-, 5/2^+)$
(also $(3/2^+, 5/2^-)$ and $((5/2^+, 3/2^-))$)



Mass (MeV)	Width (MeV)	fit fraction (%)	Significance
4380±8±29	205±18±86	8.4±0.7±4.2	9σ
4449.8±1.7±2.5	39±5±19	4.1±0.5±1.1	12σ

…and another real highlight of the conference

A big thank you to the organizers for making this a great conference!