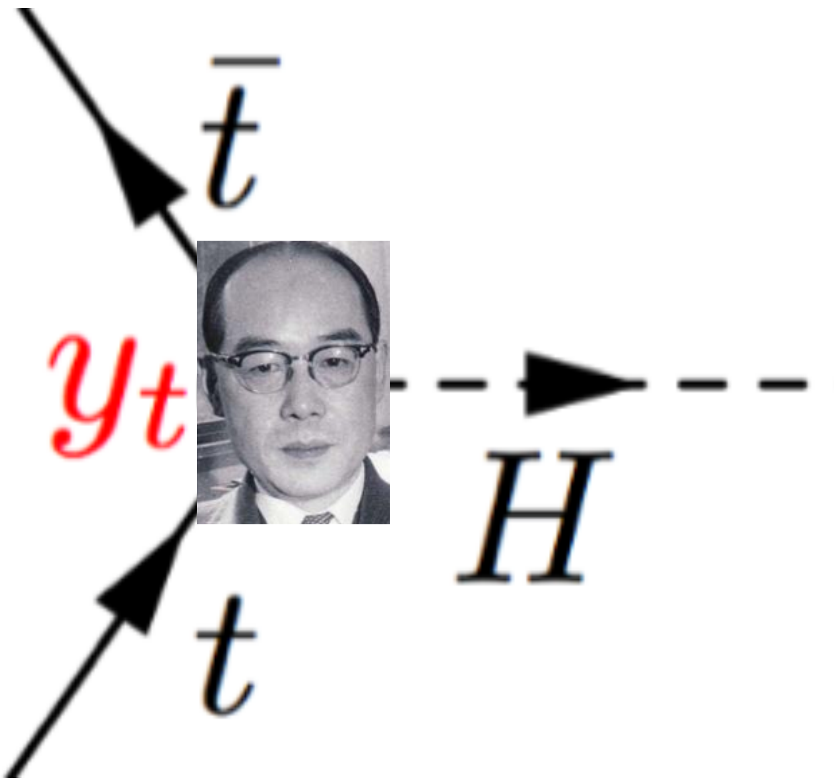
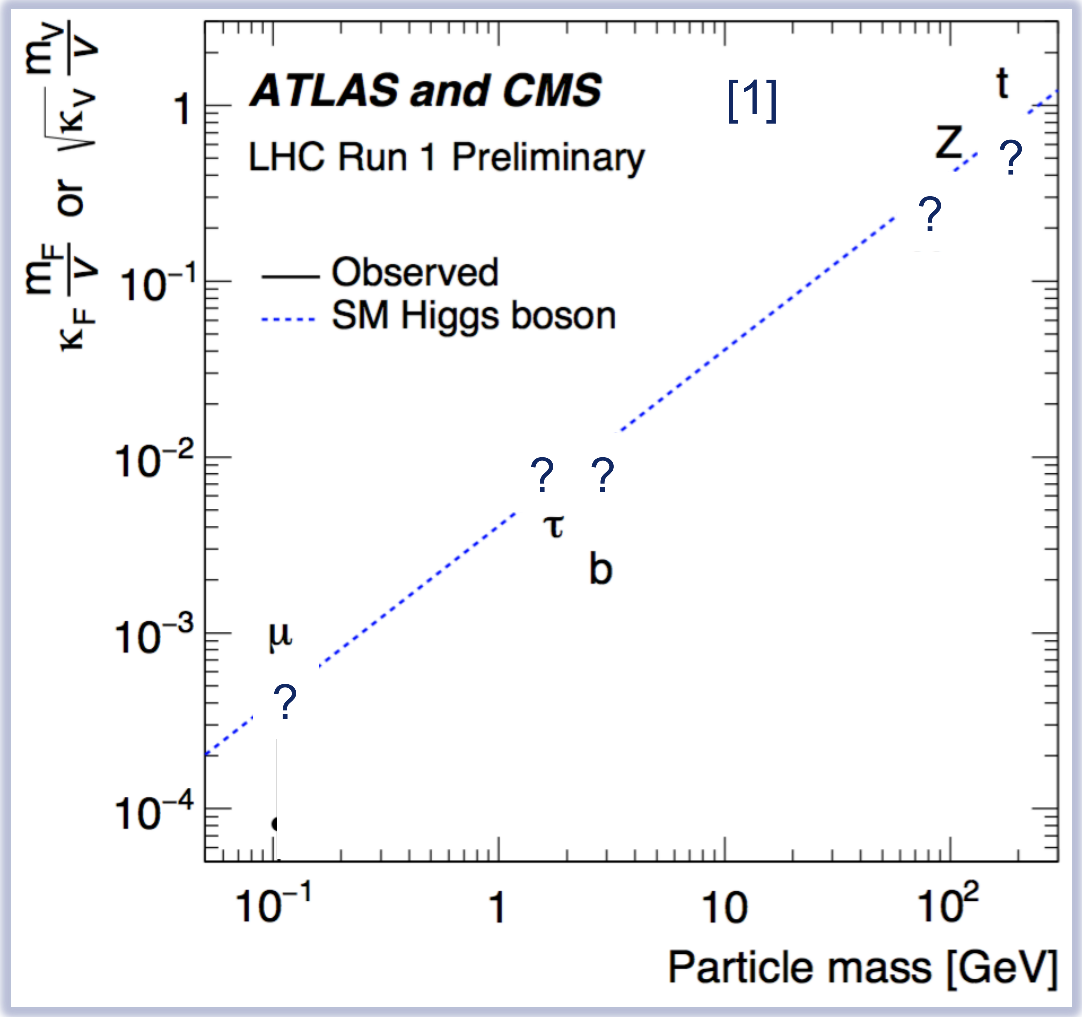
Top Yukawa -- motivation



Is it THE SM Higgs?

- Fundamental prediction for Higgs coupling to fermions in the SM:
  - $y_{f,\mathrm{SM}} = \sqrt{2}/v \cdot m_f$
- Experimental check imperative!
- Ansatz:
  - Mass m_f measured with "conventional methods"
    - Will talk about it in a minute
  - Measure the Yukawa coupling y_f through measurement of Higgs production and decay!

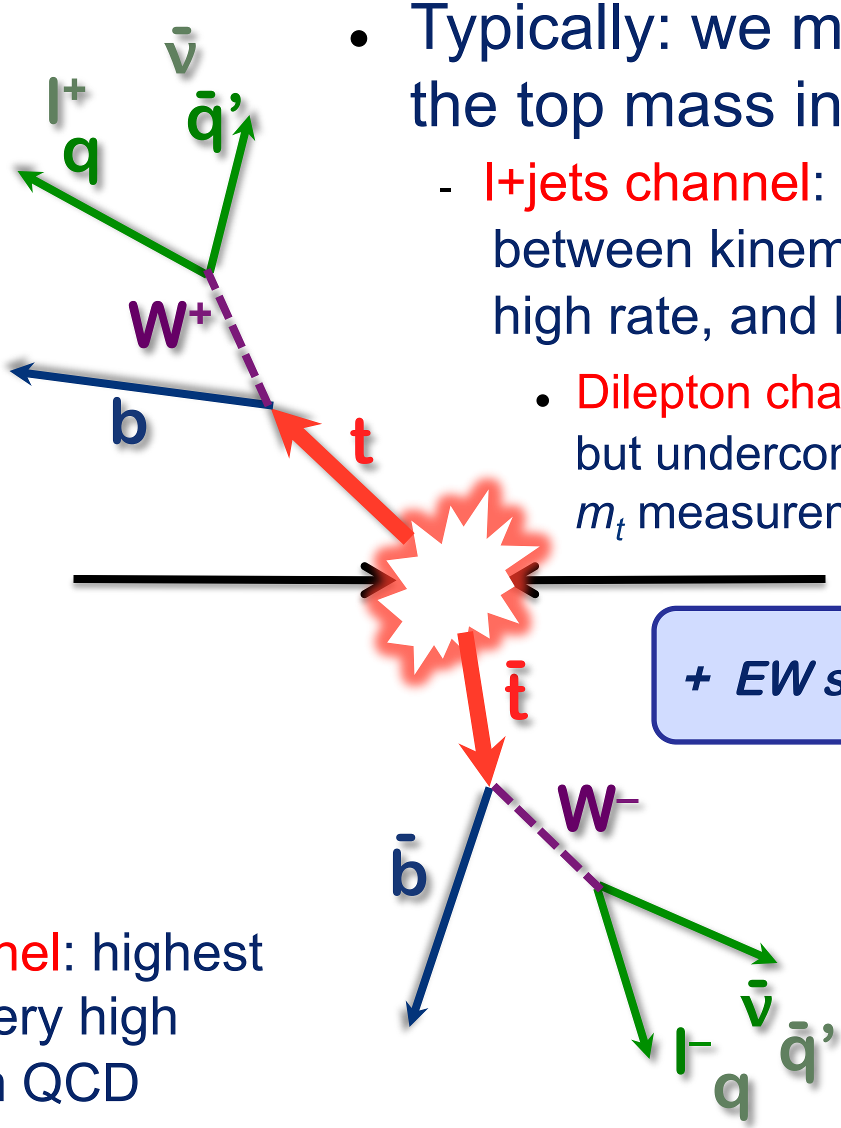


[1] ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002

Top quark mass (m_t) measurement

- due to very high m_t the Yukawa coupling is very large in the SM:
  - **$y_{t,SM}$ = 0.996** for m_t = 173.2 GeV (world average)
- → use this as an experimental consistency check of the SM!
  - → measure y_t experimentally and compare against $y_{t,SM}$
- But first we need to measure m_t itself to determine $y_{t,SM}$:)
  - → subject of next section

Top quark mass (m_t) measurement



- Typically: we measure the top mass in $t\bar{t}$ events:
  - l+jets channel: good compromise between kinematic reconstruction, high rate, and backgrounds
    - Dilepton channel: low backgrounds, but underconstrained kinematics for m_t measurement and low rate

+ *EW single top production*

– All-hadronic channel: highest branching ratio, very high backgrounds from QCD multijet production

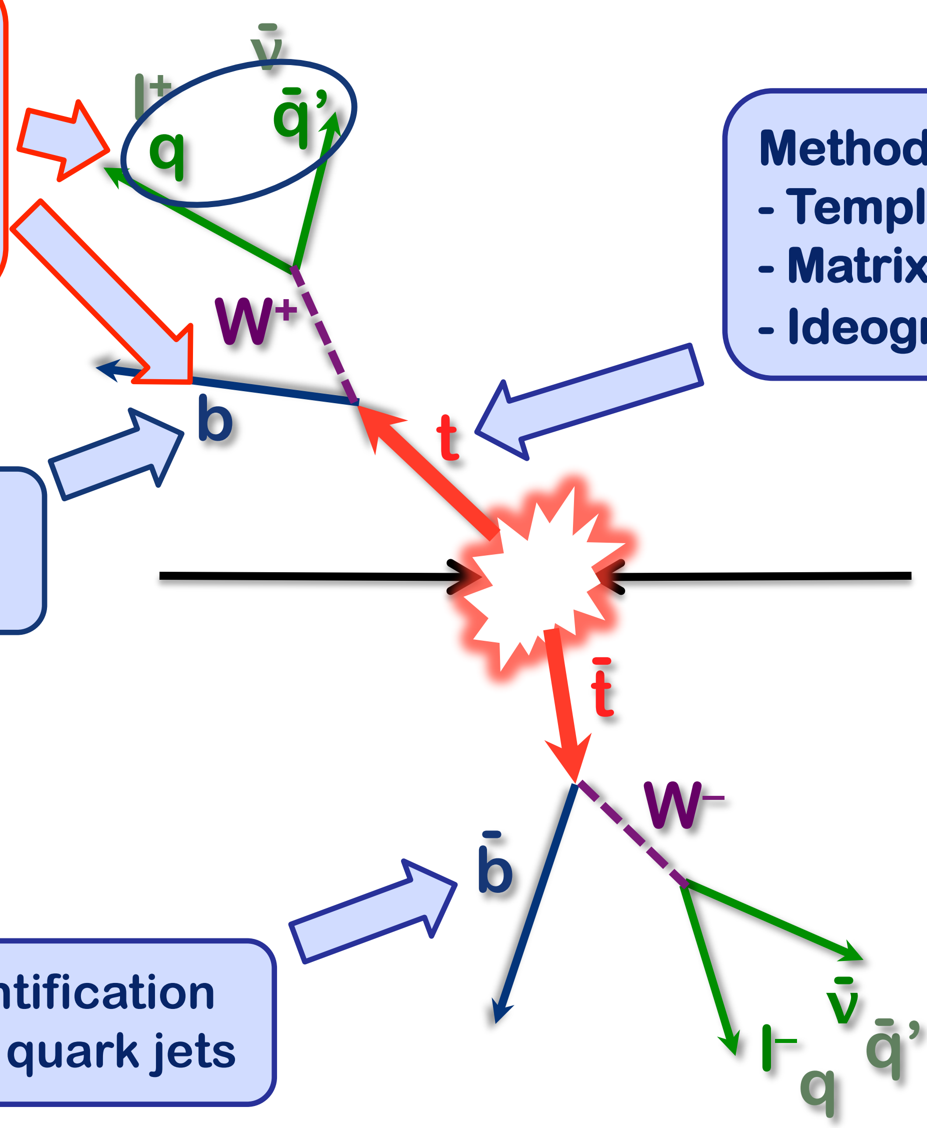
Key ingredients to m_t measurements

Measurement of jets and calibration of the jet energy scale (JES)

Methods to extract m_t:
- Template method
- Matrix element method
- Ideogram method

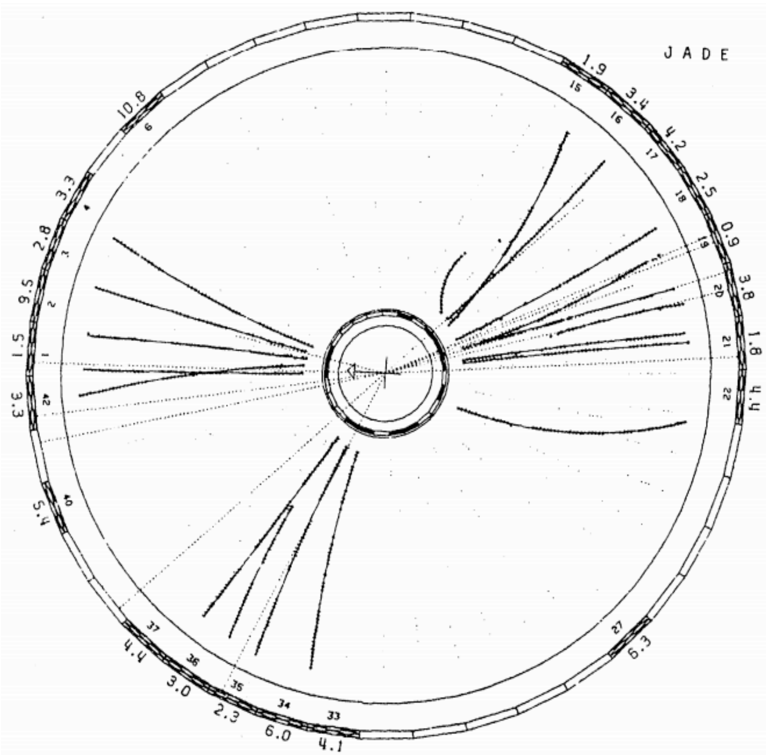
Calibration of *b* quark JES

Identification of *b* quark jets

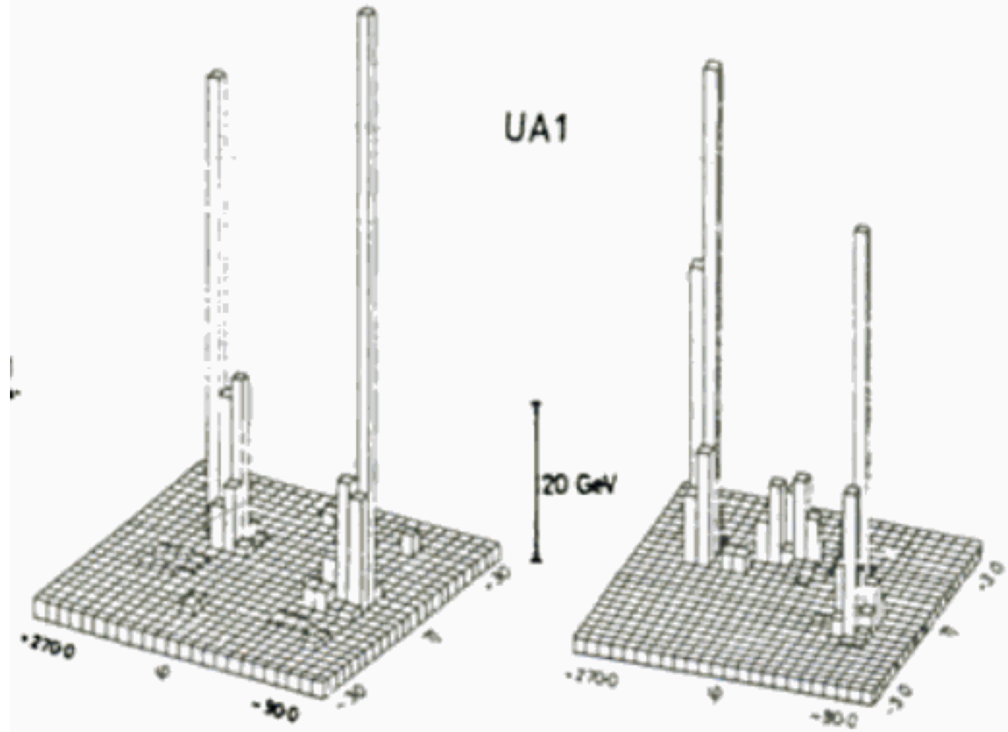


- **What are jets** and how do we measure them?
  - Jets are collimated sprays of hadrons:

See also lecture by Caterina today & Tuesday

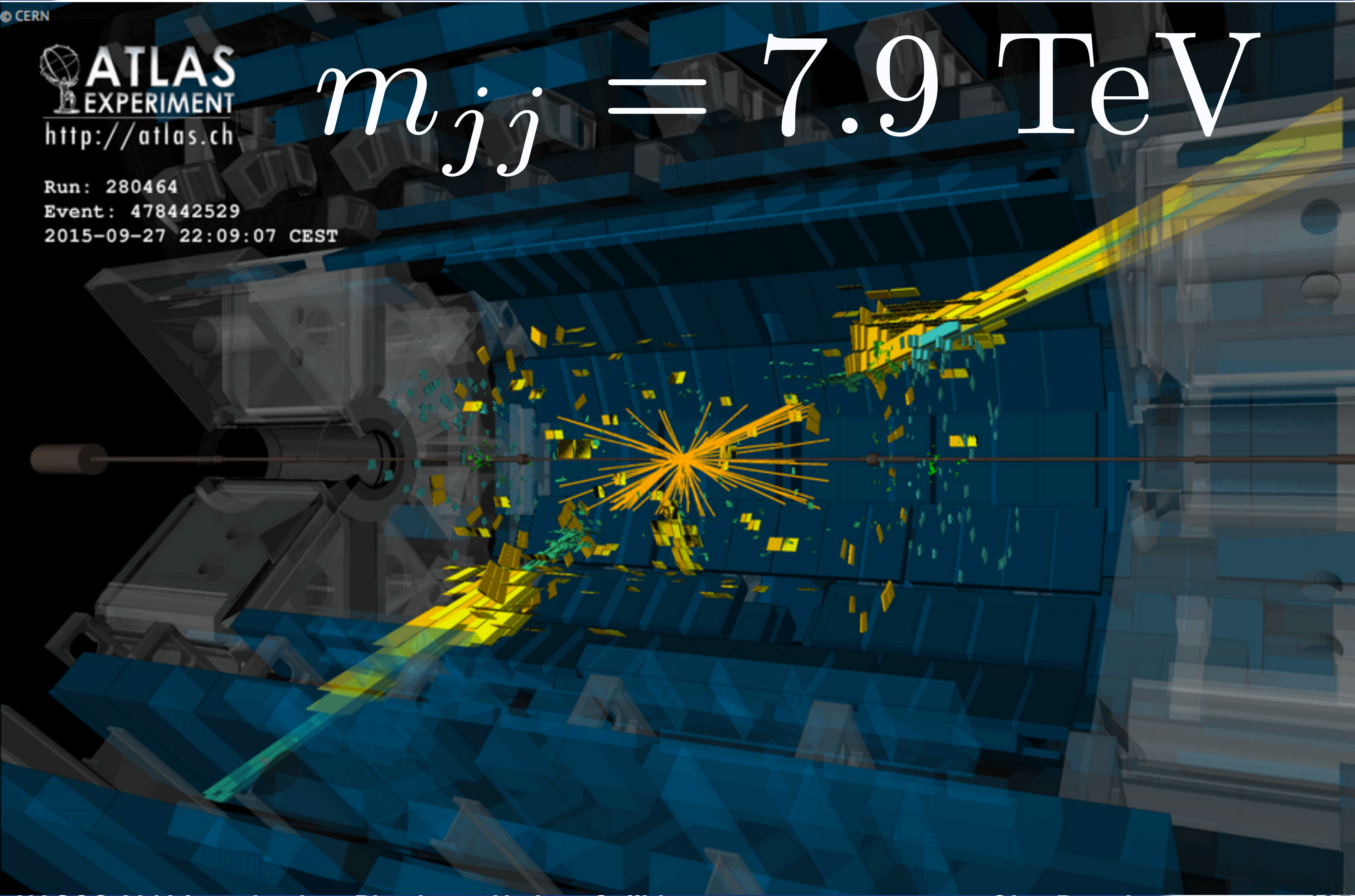


One of first trijet events at JADE (PETRA e^+e^- collider, ‘79)



Energetic dijet events from UA1 ISR pp collider, (‘82)

What are jets?



$$m_{jj} = 7.9\,\text{TeV}$$

- **Jets:**
  - remnants of the parton showering process after hadronisation!
- Experimental signature:
  - Several charged hadron tracks with similar $(\boldsymbol{\eta},\boldsymbol{\varphi})$ from the same primary vertex
  - Energy deposits in several neighbouring calorimeter cells

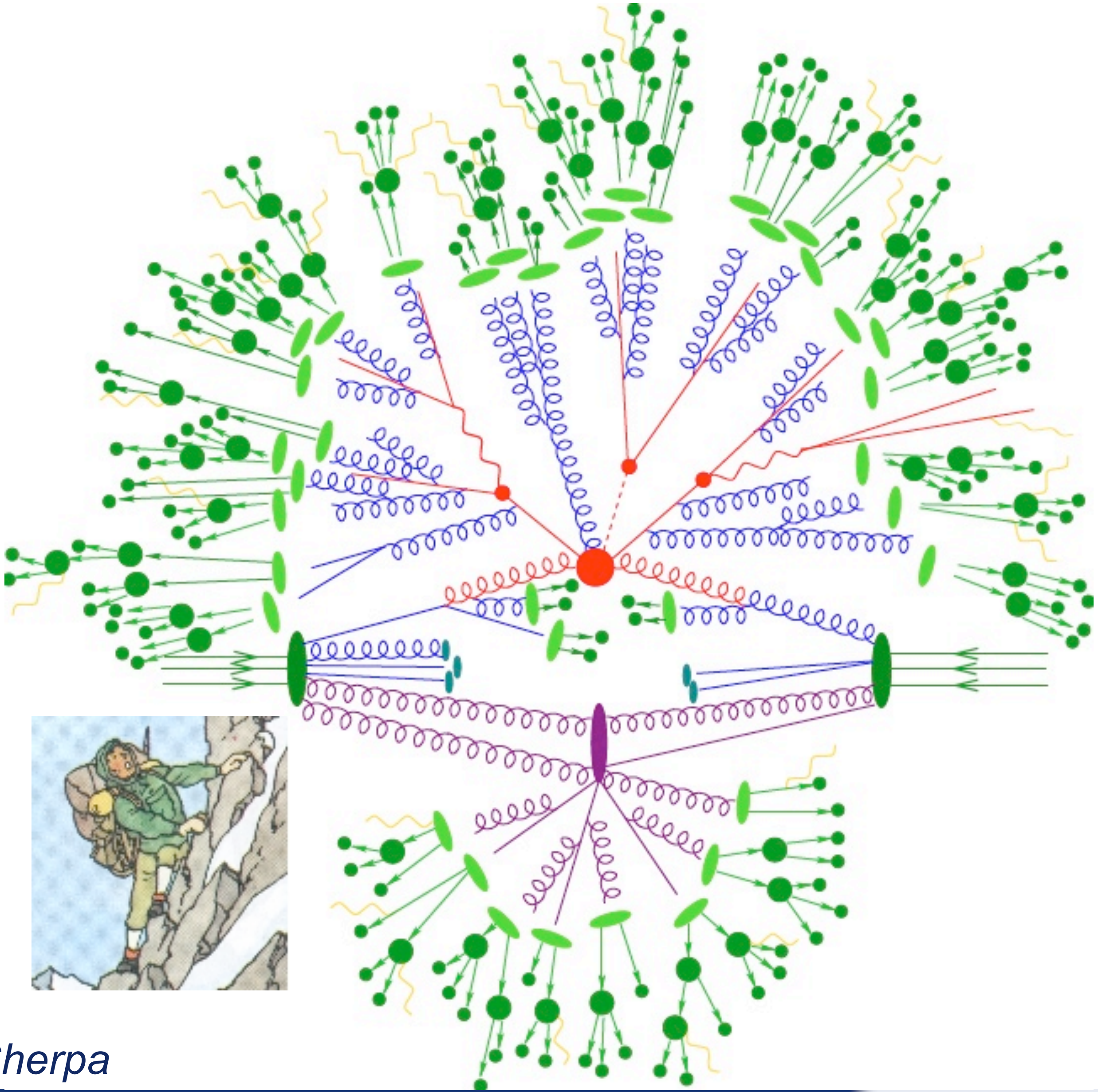


Illustration: $t\bar{t}H(b\bar{b})$ *event in Sherpa*

What are jets?

- **Jets:**
  - remnants of the parton showering process after hadronisation!
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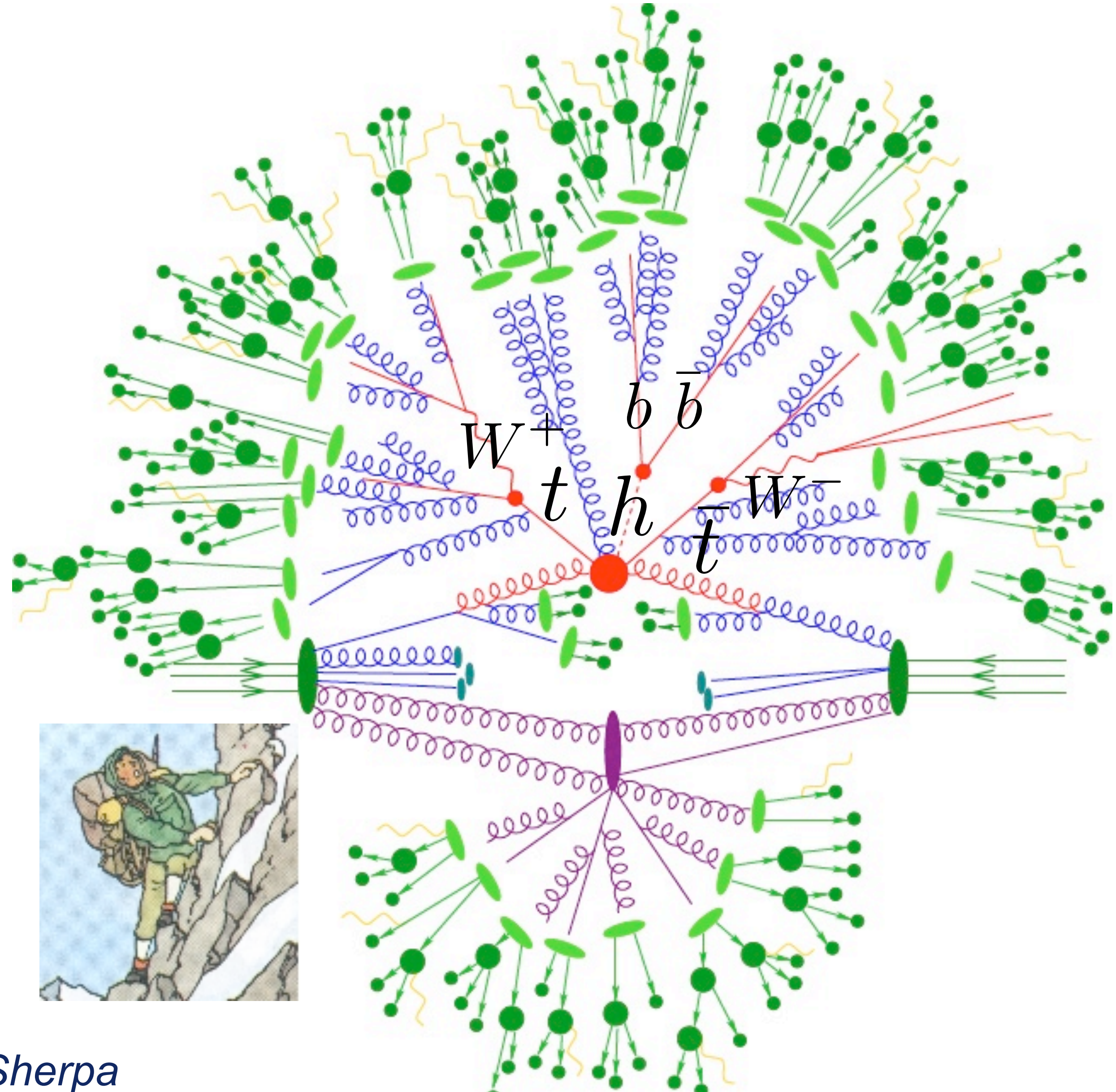


Illustration: $t\bar{t}H(b\bar{b})$ *event in Sherpa*

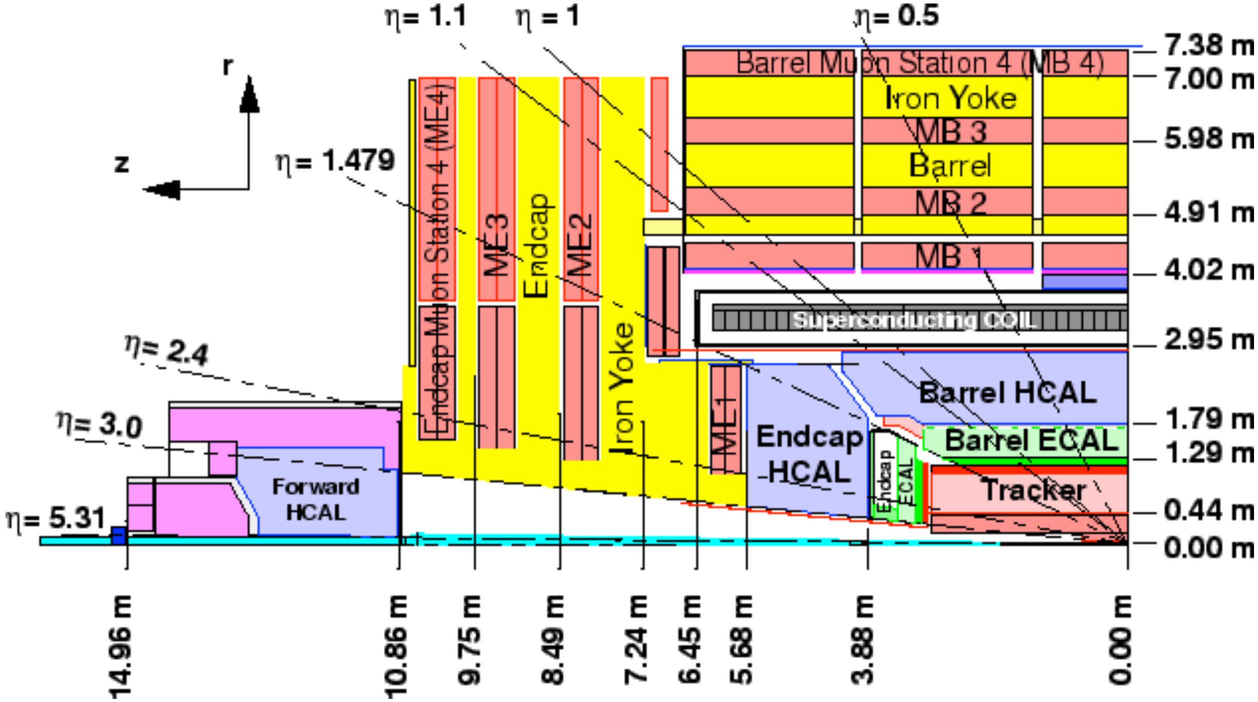
Pseudorapidity (η)

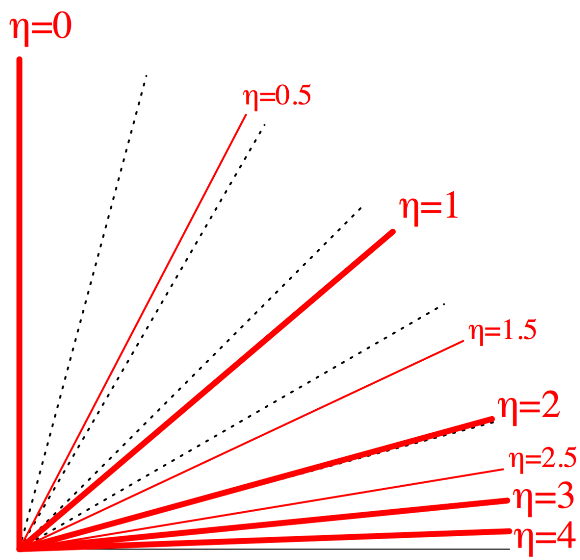
- **Definition:**

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

- Advantage:
  - flux of particles from QCD processes is invariant in $\Delta\eta$ intervals

Cross-section through a quadrant of CMS





What are jets?

- **MC event simulation steps:**
  - Hard scattering → partonic decays → parton shower → non-perturbative splitting → clusters → hadrons → hadronic decays

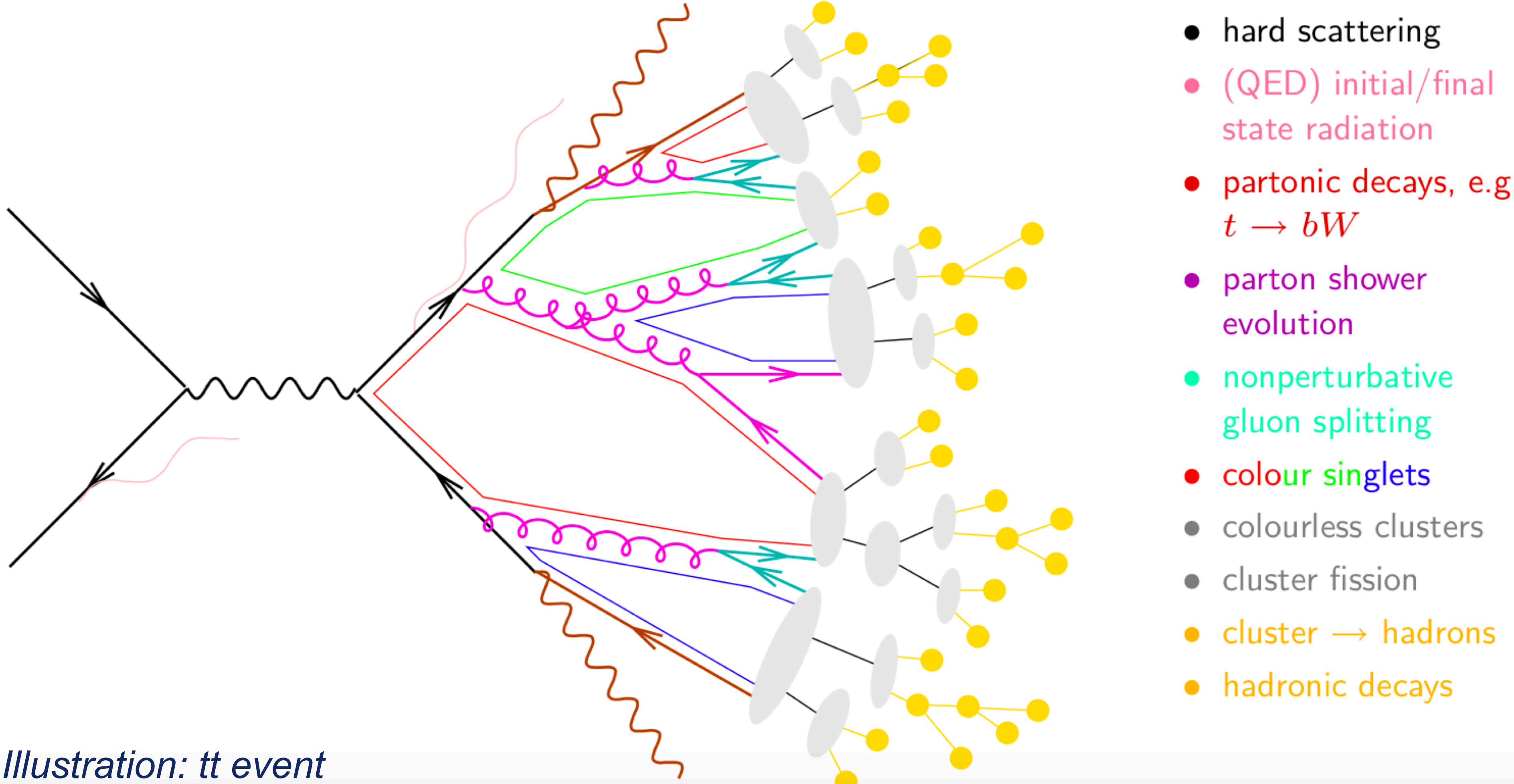


Illustration: tt event

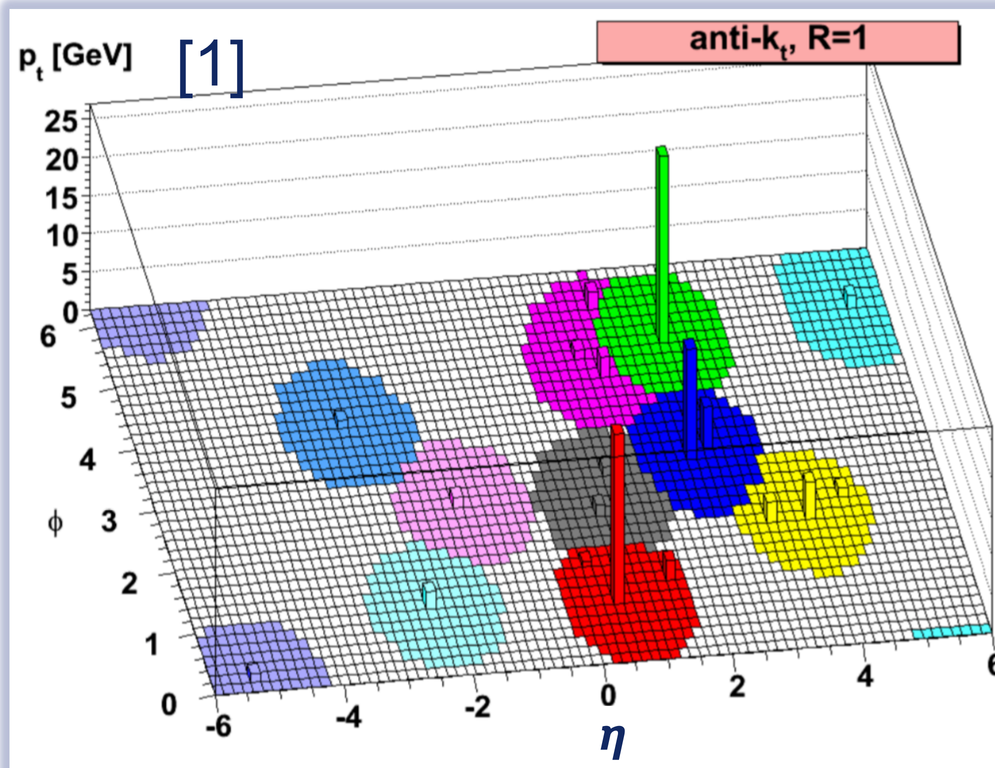
- **Jet reconstruction [1]:**
  - Cluster cells with energy deposits:
    - 1) Find entities i,j with smallest d_{ij}
    - 2) add four-momenta p_i and p_j
    - 3) if smallest d_{ij} is d_{iB}, entity i is a jet
    - With R "radius parameter"
  - ATLAS (CMS) use the anti-k_T algorithm with R=0.4 (0.5) by default
    - Circular-shaped jets
    - Easy to calibrate
    - [Also other jet algorithms are used → will talk about it later]

$$d_{ij} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right)\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = \frac{1}{p_{T,i}^2}$$

anti-k_T algorithm

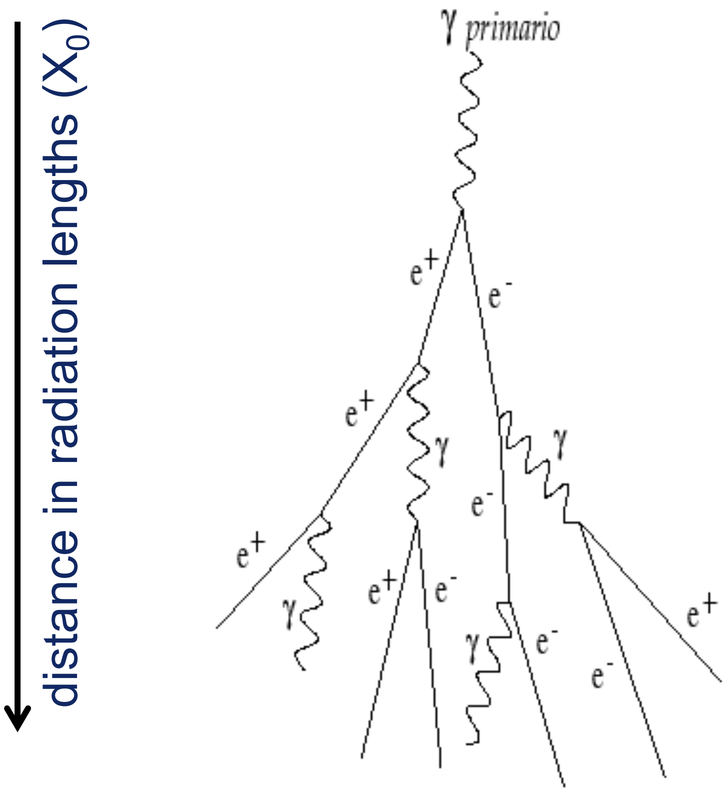
$$\Delta_{ij} \equiv \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$



[1] JHEP 04 (2008) 063

Parton showers vs EM-showers

EM shower

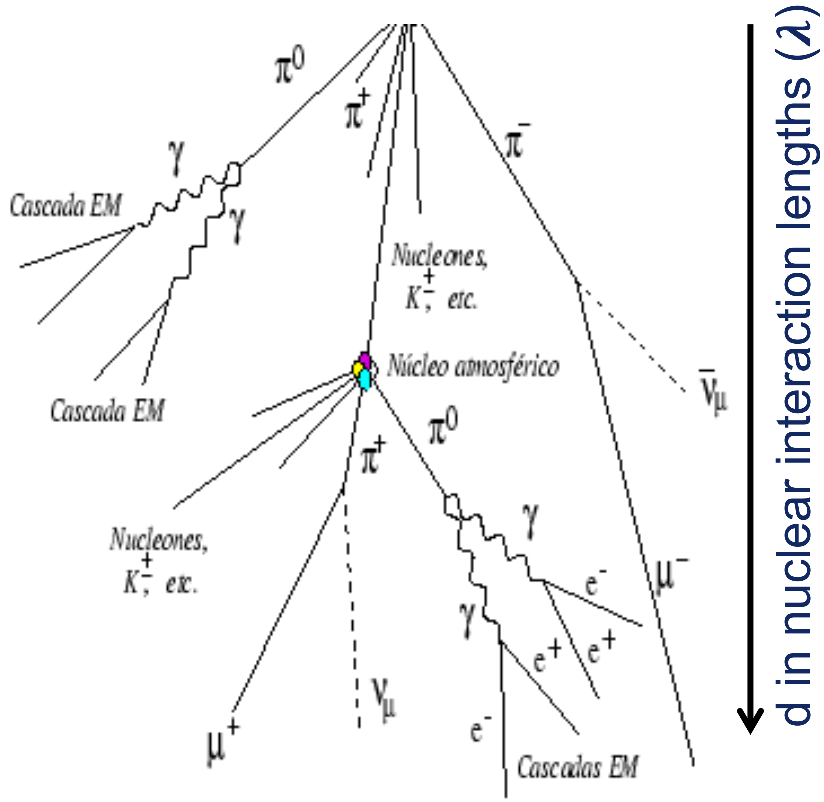


- Radiation length
  - $X_0^{Ar} = 14$ cm
  - $X_0^{Fe} = 1.7$ cm
  - $X_0^{Pb} = 0.6$ cm

Examples for atmospheric showers applicable to calorimeter showers too

$\lambda \gg X_0$!!!

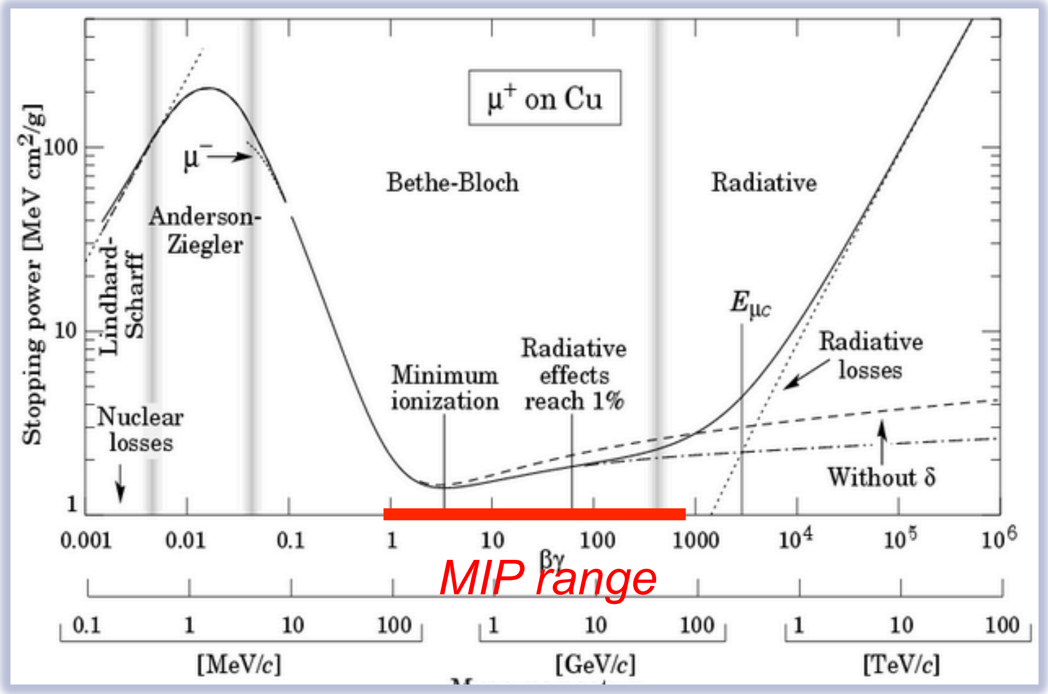
Parton shower



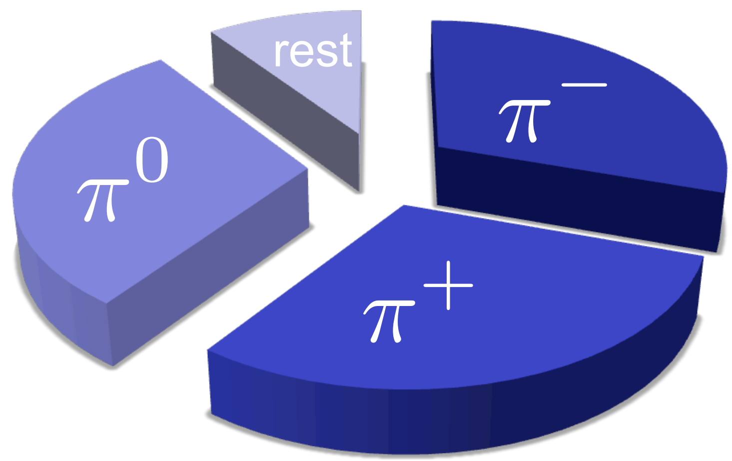
- Nuclear interaction length
  - $\lambda^{Ar} = 86$ cm
  - $\lambda^{Fe} = 17$ cm
  - $\lambda^{Pb} = 18$ cm

Hadronic calorimeters

- → **Need deep calorimeters for parton showers (jets)!**
  - Large volume, choose cheap technology!
  - Except strong interaction, $\pi^{\pm}$ hadrons behave just like muons:



Typical jet composition

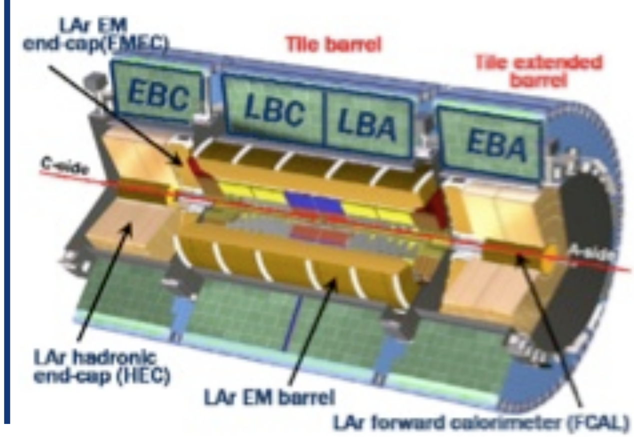


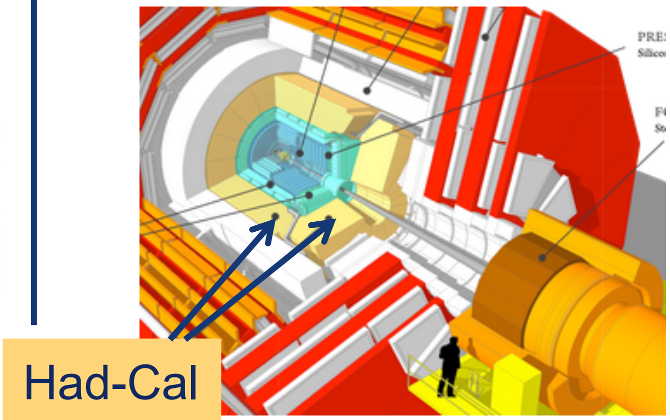
  - Use again sandwich calorimeter principle
    - Faster hadronic shower development
  - Hadronic showers more spread (transversely+longitudinally)

Hadronic calorimeters

- → **Need deep calorimeters for parton showers (jets)!**
  - Large volume, choose cheap technology!

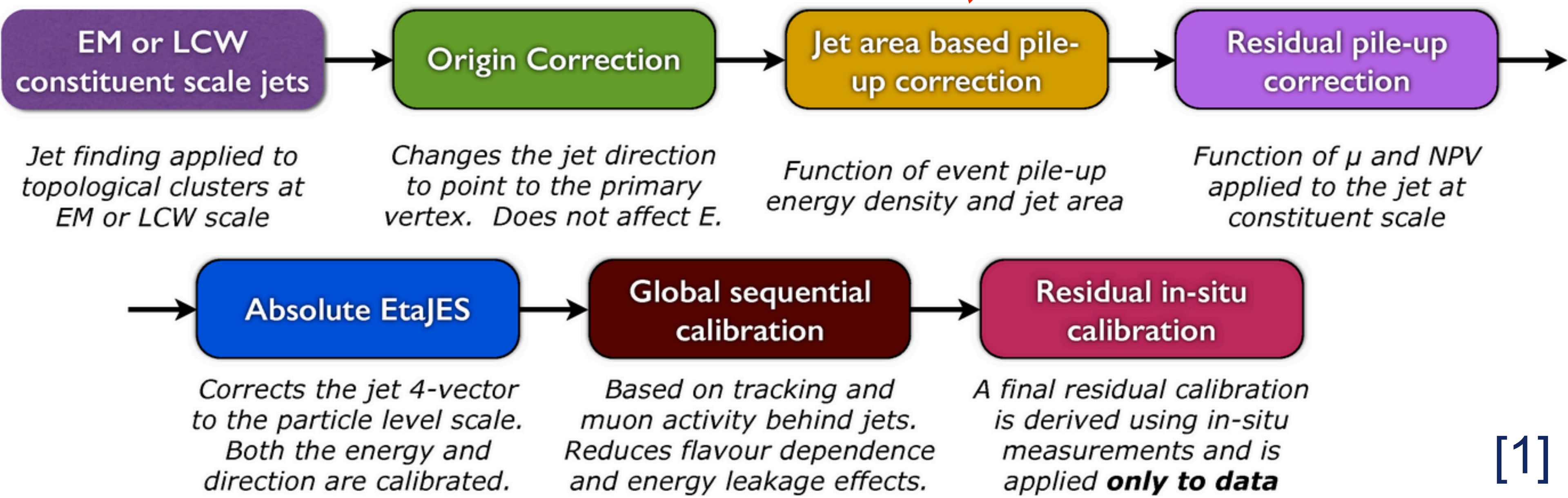
	ATLAS	CMS
Active material	Plastic scintillator / (LAr forward)	Plastic scintillator
Absorber	Fe / (Cu forward)	Brass
Depth	10 λ	7 λ
Energy resolution	$\frac{\sigma}{E} \approx \frac{50\%}{\sqrt{E}} + 0.03\text{GeV}$	$\frac{\sigma}{E} \approx \frac{100\%}{\sqrt{E}} + 0.05\ \text{GeV}$





Jet energy scale (JES) calibration

Particular challenge at the LHC
→ discuss in the following

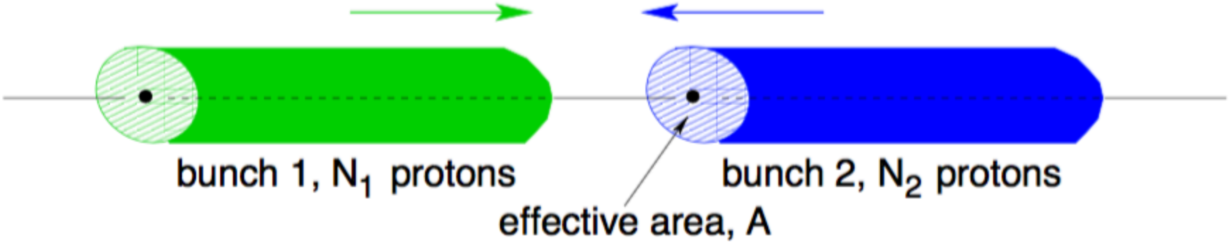


[1]

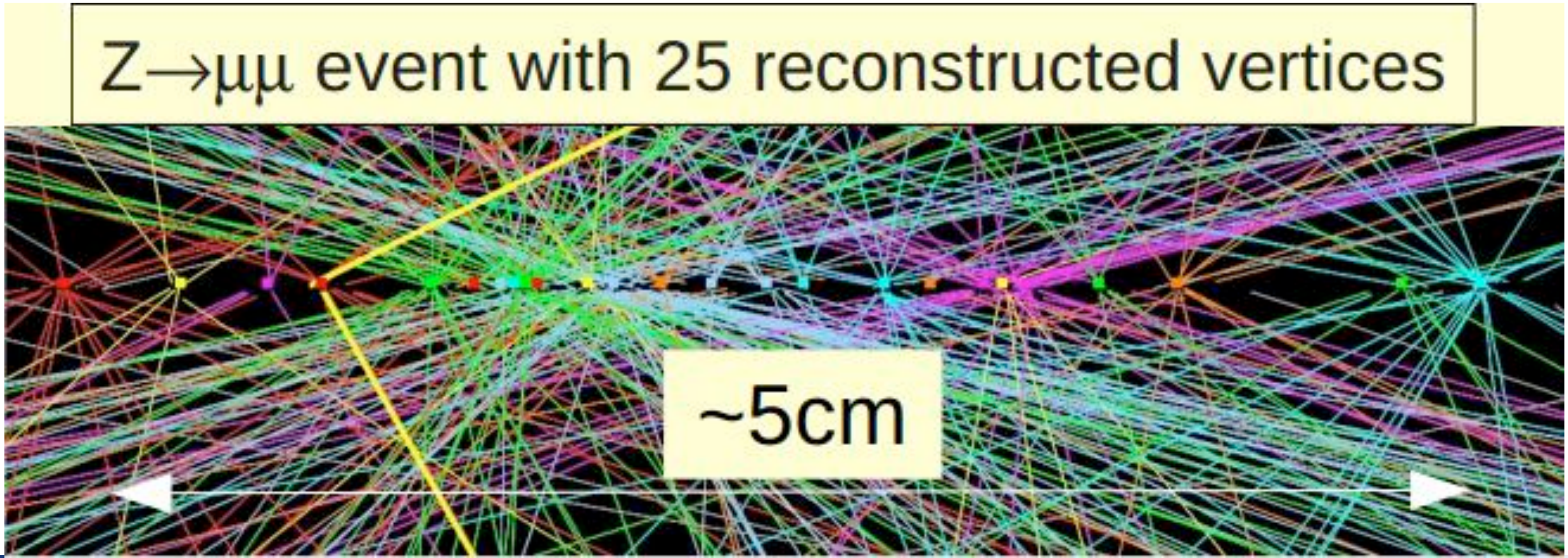
[1] ATLAS-CONF-2015-037

- **Pile-up:**
  - Additional low-p_T pp interactions in the same bunch crossing
    - The price to pay for large luminosity and many Higgs events!

LHC: $N_1 \approx 10^{11}$ protons / bunch x 2808 bunches



$$\mathcal{L} = \frac{N_1 \cdot N_2 \cdot f}{A}$$

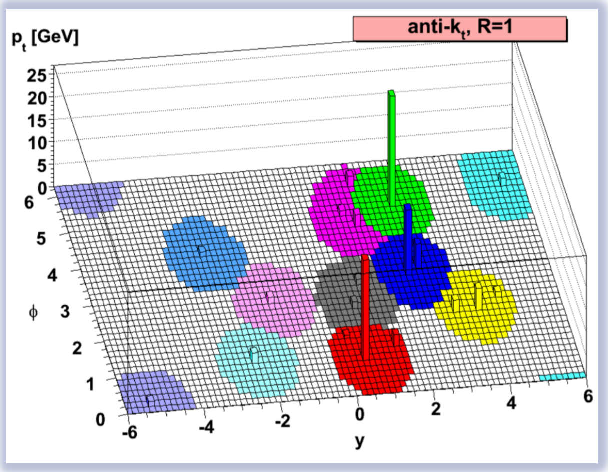


JES Calibration

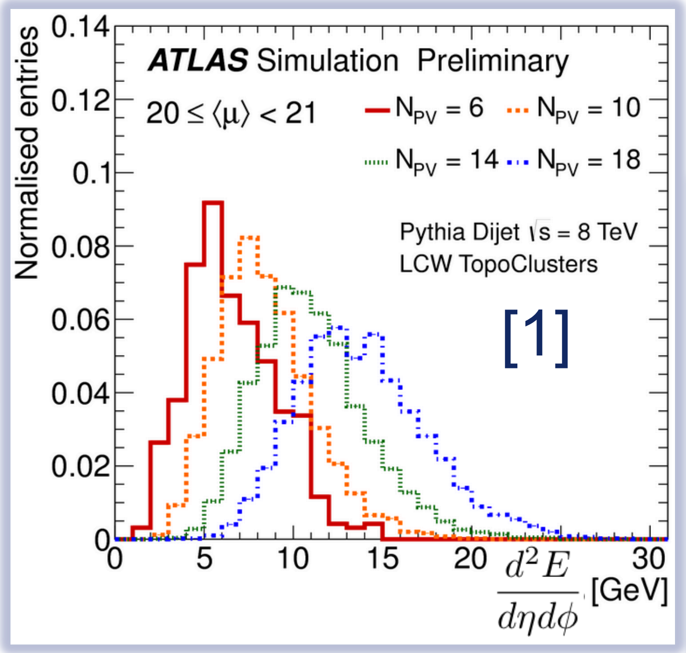
- **Correct for pile-up by by subtracting:**

$$E_{\text{jet}} \to E_{\text{jet}} - \int_{\text{jet area}} \frac{d^2 E}{d\eta d\phi} d\eta d\phi$$

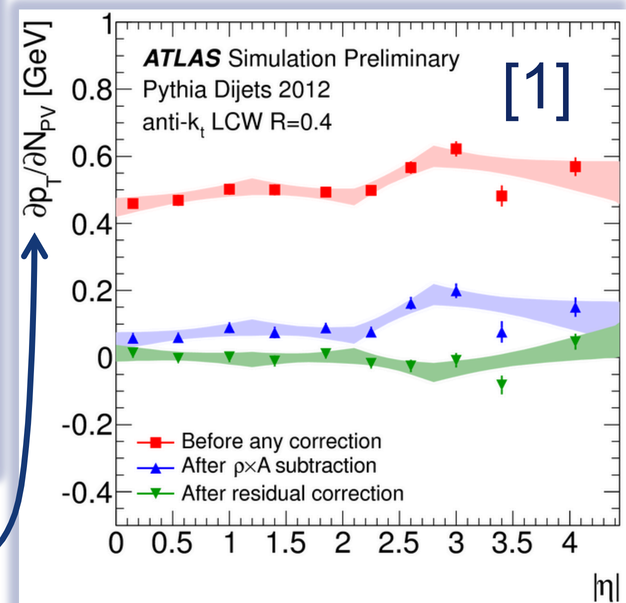
1) Determine jet area



2) Find average correction



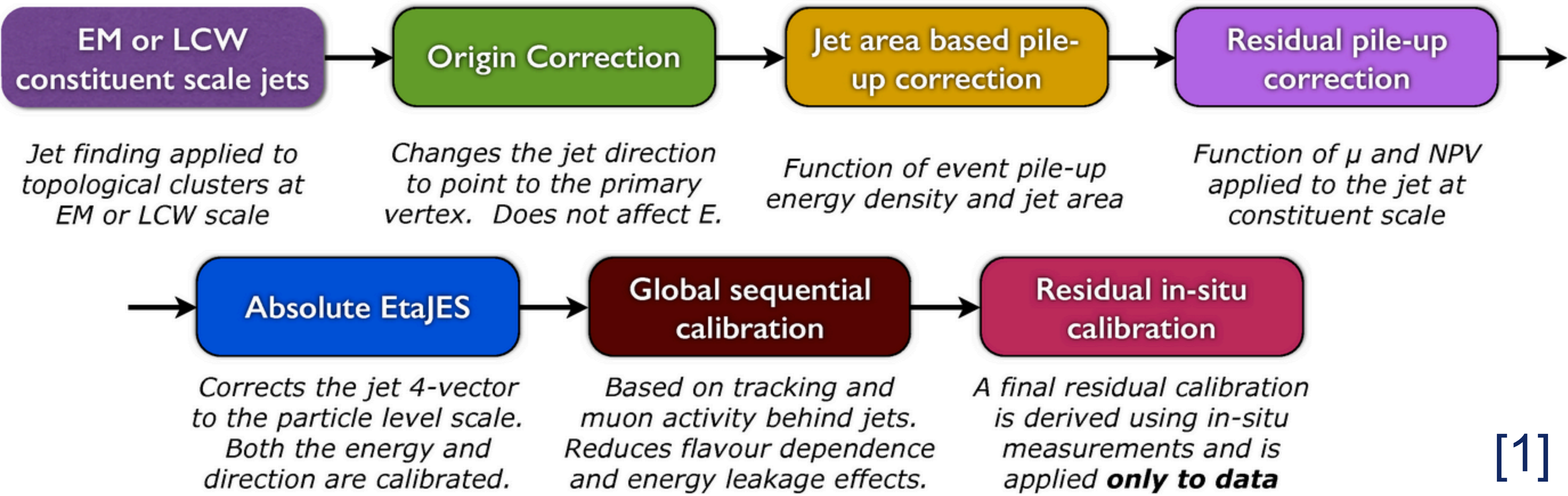
3) Apply correction & correct for residual biases



Dependence of jet p_T on # of primary vertices N_{PV}

[1] ATLAS-CONF-2015-037

JES Calibration



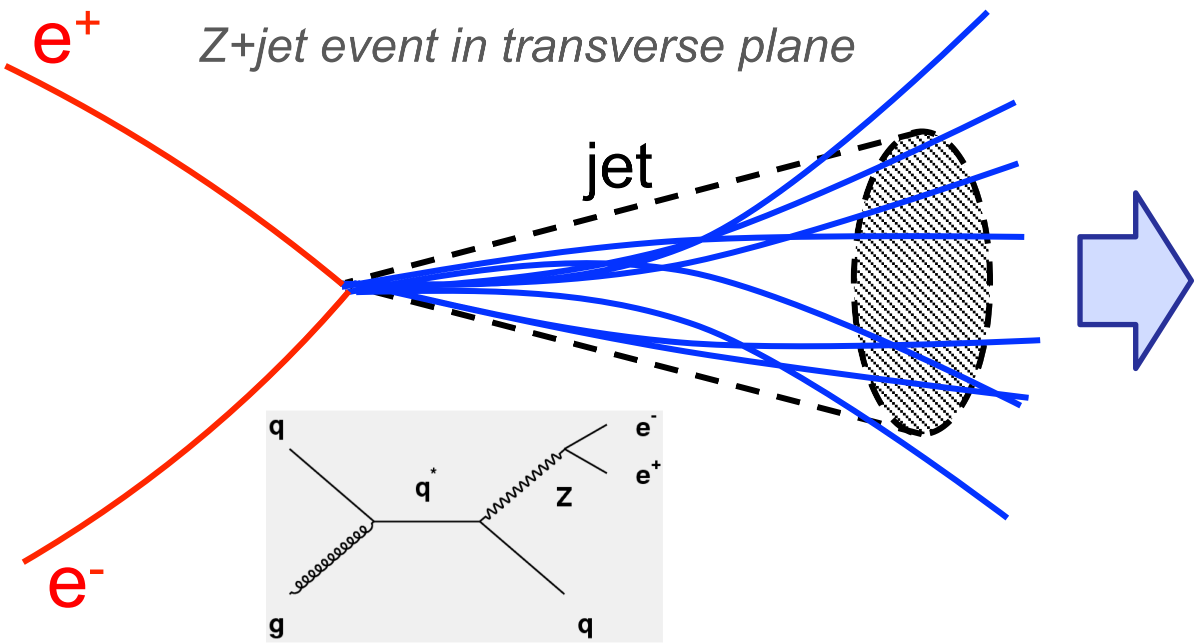
[1]

the heart of the calibration
→ discuss in the following

[1] ATLAS-CONF-2015-037

JES Calibration

- Generic procedure to calibrate jet energies:
  - 1) Calibrate EM energy scale with SM candles, i.e. $Z \rightarrow e^+e^-$
    - Central (well instrumented) region for absolute calibration
  - 2) Z+jet events to calibrate major JES components
    - Basic idea: momentum balance in transverse plane

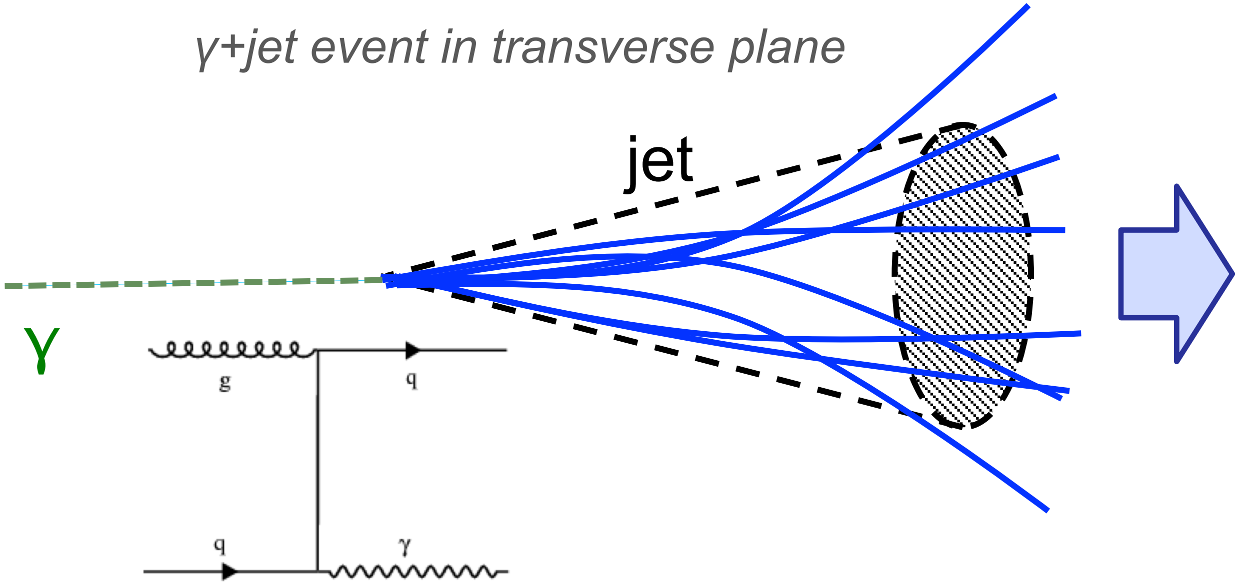


$$E^{\rm ptcl} = \frac{E^{\rm meas} - E_{\rm O}}{R \cdot S}$$

  - 3) Use γ+jet, Z+jet, and dijets to extend calibration in p_T,η

- Generic procedure to calibrate jet energies:
  - 1) Calibrate EM energy scale with SM candles, i.e. $Z \rightarrow e^+e^-$
    - Central (well instrumented) region for absolute calibration
  - 2a) Correct EM energy scale for e to that of γ
  - 2b) γ+jet events to calibrate major JES components
    - Basic idea: momentum balance in transverse plane

γ+jet event in transverse plane



$$E^{\mathrm{ptcl}} = \frac{E^{\mathrm{meas}} - E_{\mathrm{O}}}{R \cdot S}$$

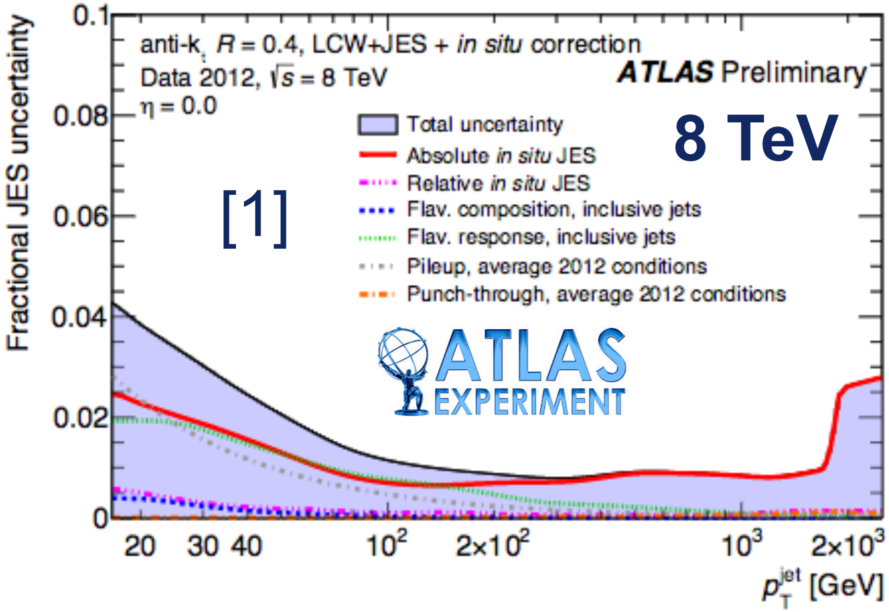
  - 3) Use γ+jet, Z+jet, and dijets to extend calibration in p_T,η

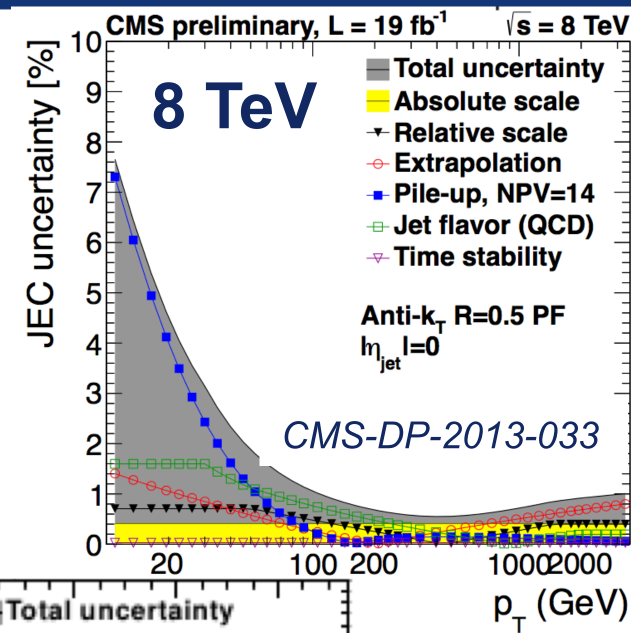
JES Calibration

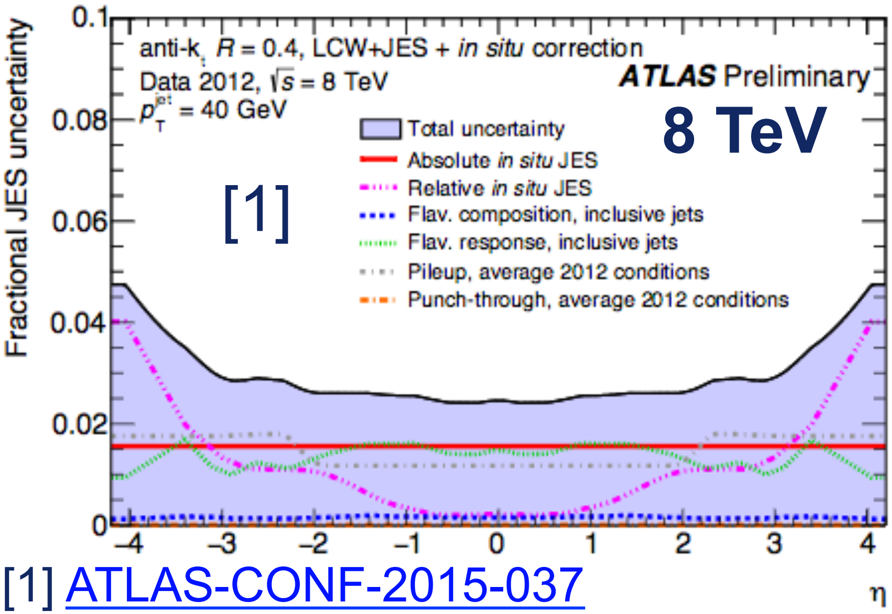
- Typically, JES uncertainty Δ_{JES} is dominant or next-to-dominant
  - Pronounced dependence of JES uncertainty on η:
    - Better instrumentation for central η, $\Delta_{JES} \approx 1.5\%$
    - Upstream material & pile up for forward η, $\Delta_{JES} \approx 3\%$-5%
  - Pronounced dependence of JES uncertainty on p_T
    - Noise and pile up relevant for small p_T, $\Delta_{JES} \approx 5\%$
    - Extrapolation to $p_T > 1.5$ TeV $\Delta_{JES} \approx 3\%$
    - Best resolution for:
      - 100 GeV < p_T < 1000 GeV, $\Delta_{JES} \approx 1.5\%$

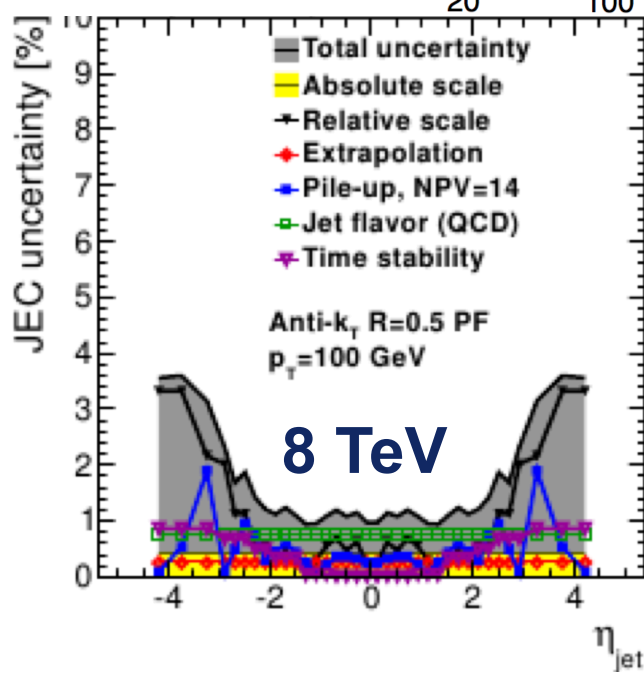
To get an idea: Δm_t is almost directly proportional to Δ_{JES}

JES Calibration (III)



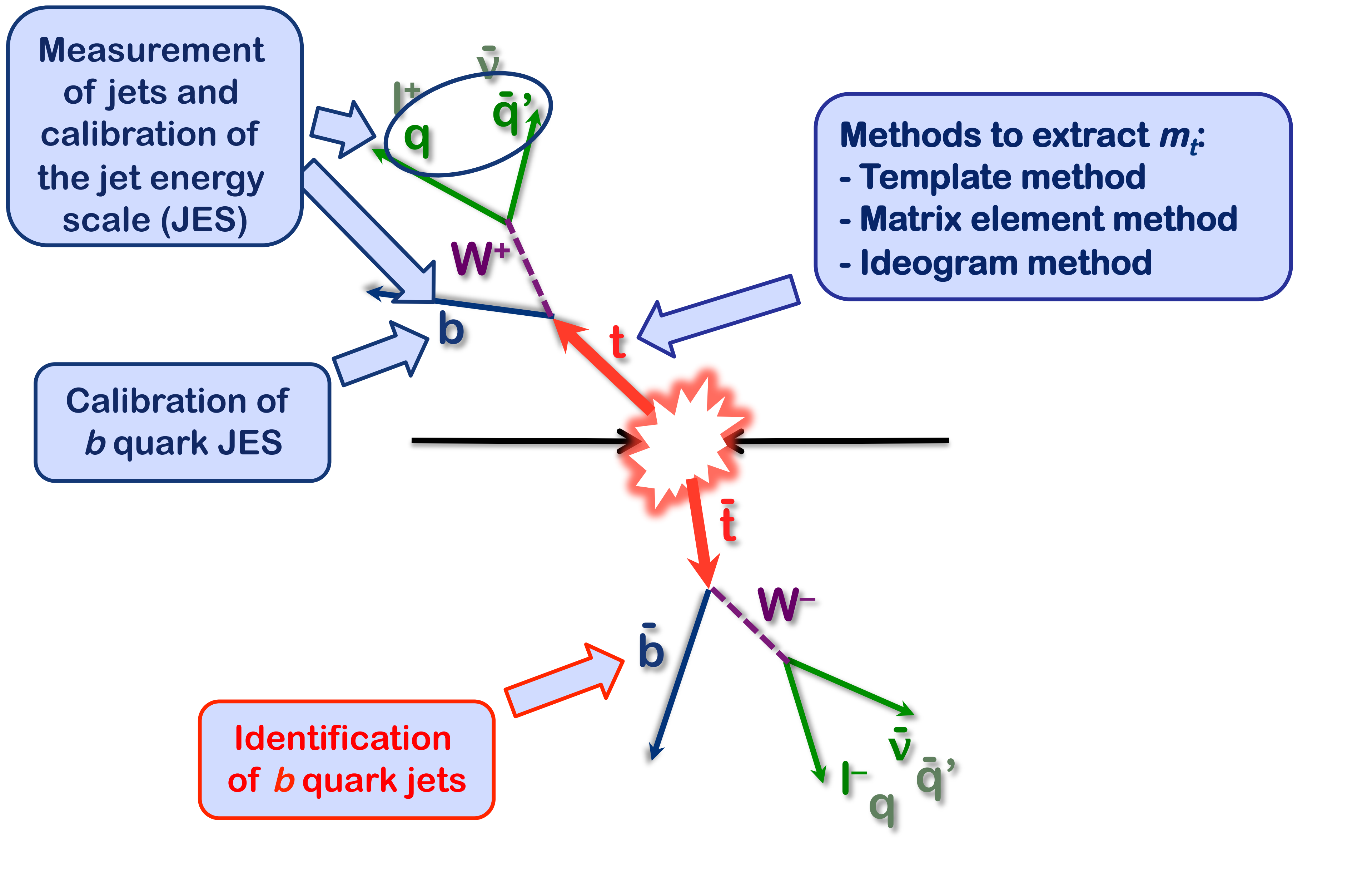






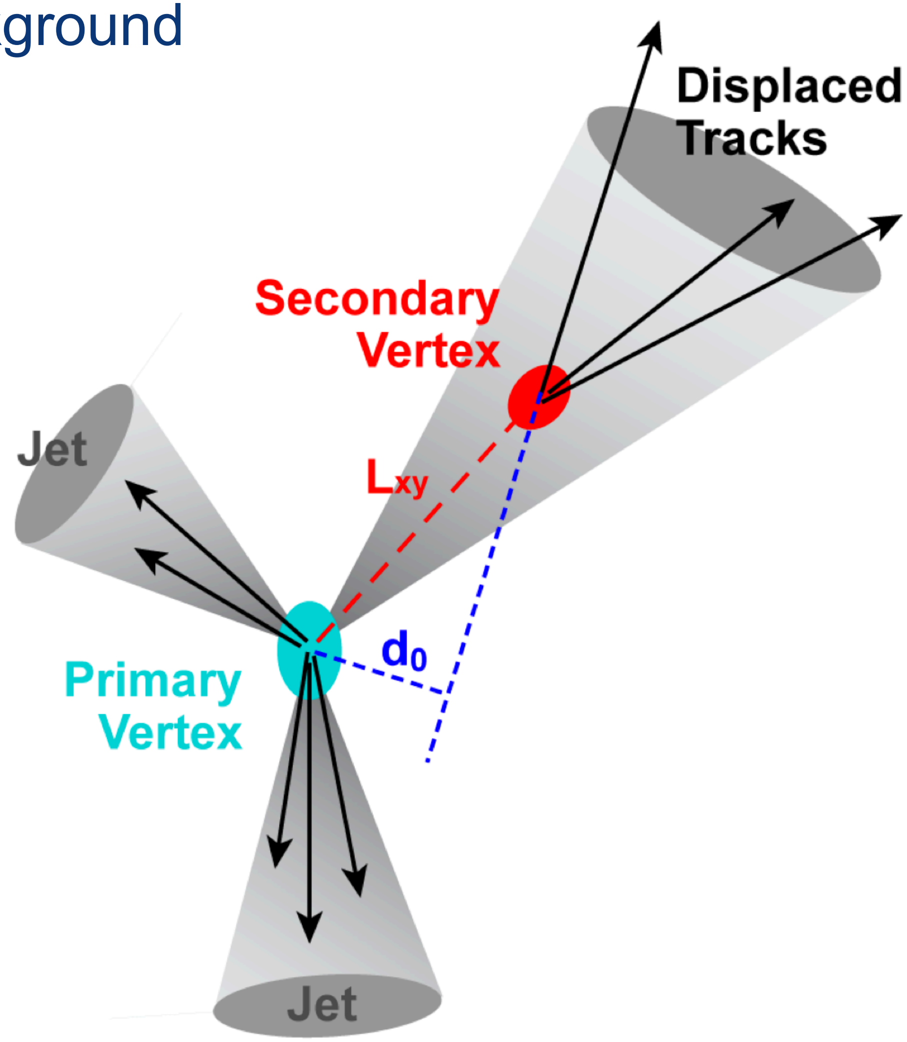
[1] ATLAS-CONF-2015-037

Key ingredients to m_t measurements



b–tagging in top analyses

- 2 *b* quark jets in each $t\bar{t}$ event at Born level
  - → Separate signal from background
- Identify *b* quark jets:
  - Existence of a displaced secondary vertex
  - Impact parameters d_0 of tracks associated with the secondary vertex
  - Mass of the secondary vertex
  - Etc.



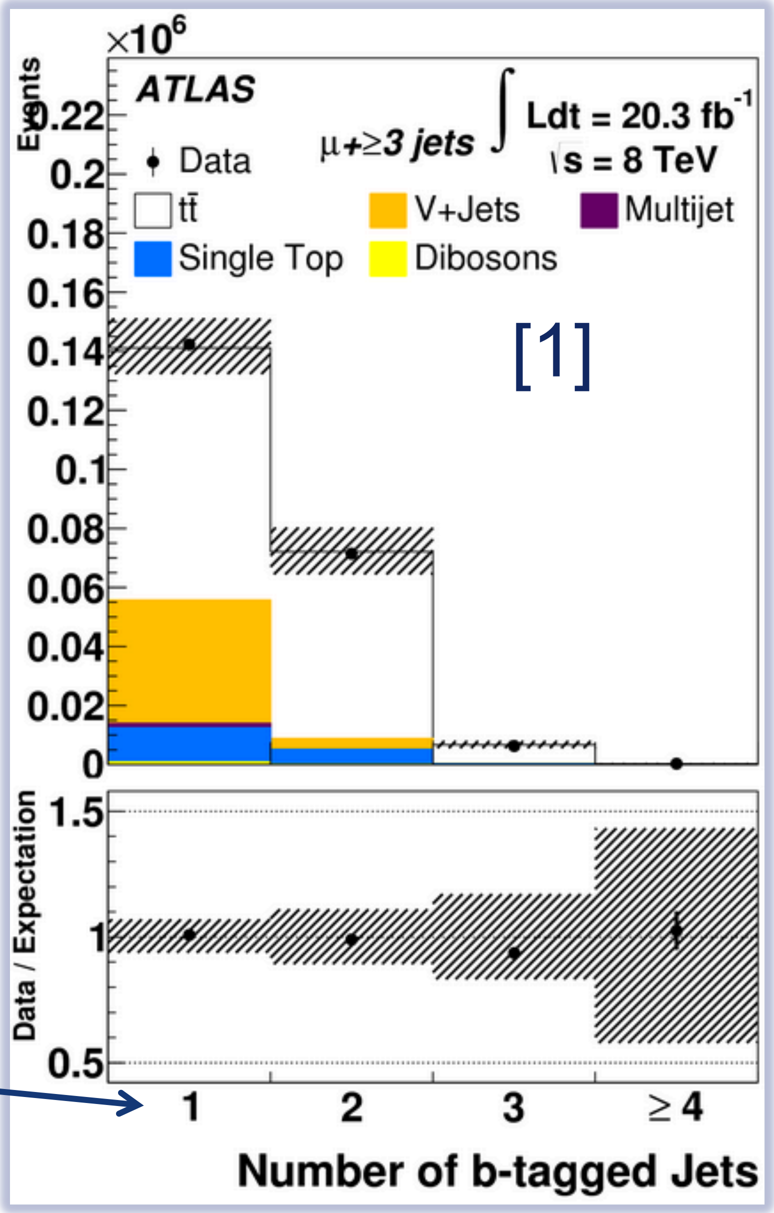
b–tagging in m_t analyses

- Typical operation points:

	ATLAS	CMS
$\varepsilon_{\text{b quark}}$	70%	≈ 70%
$\varepsilon_{\text{light quark}}$	≈ 1%	1%

- Uncertainties dependent on p_T and η
  - Pronounced impact on shape-sensitive analyses

Bin of 0 b-tags not even shown!

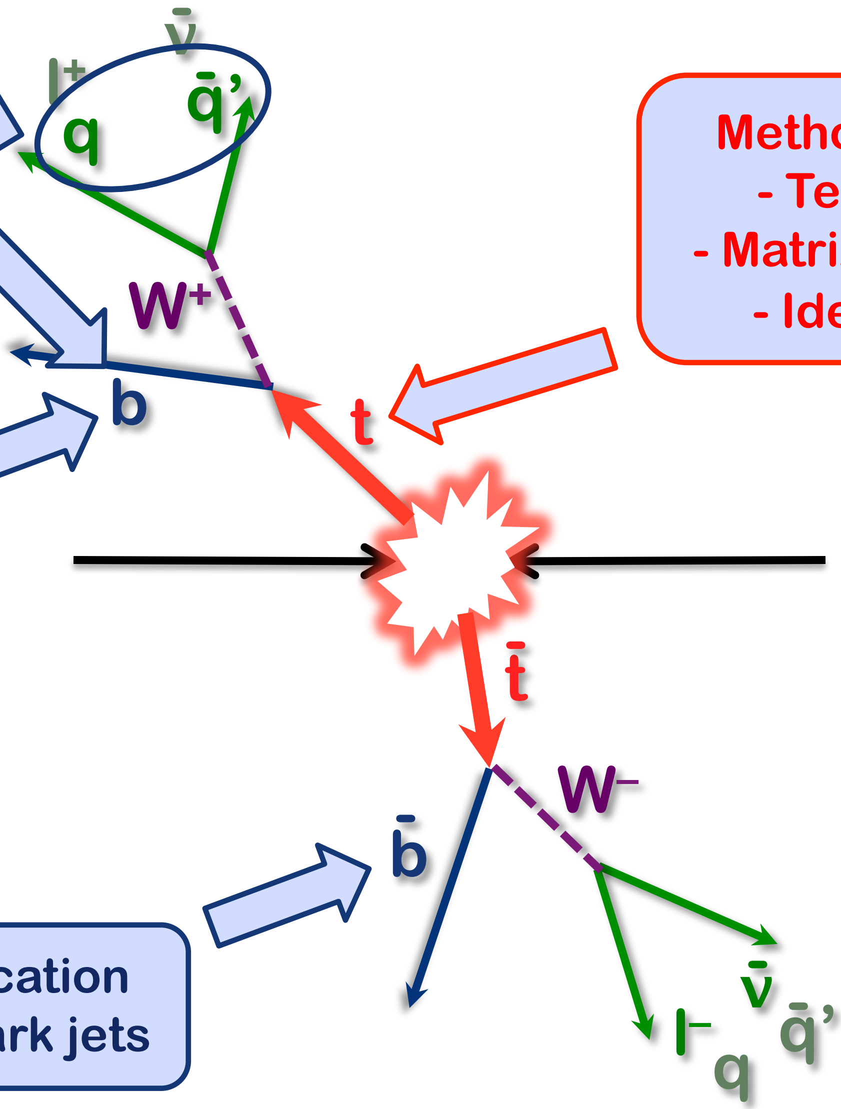


[1] ATLAS-CONF-2016-005

Key ingredients to m_t measurements

Measurement of jets and calibration of the jet energy scale (JES)

Methods to extract m_t:
- Template method
- Matrix element method
- Ideogram method



Calibration of *b* quark JES

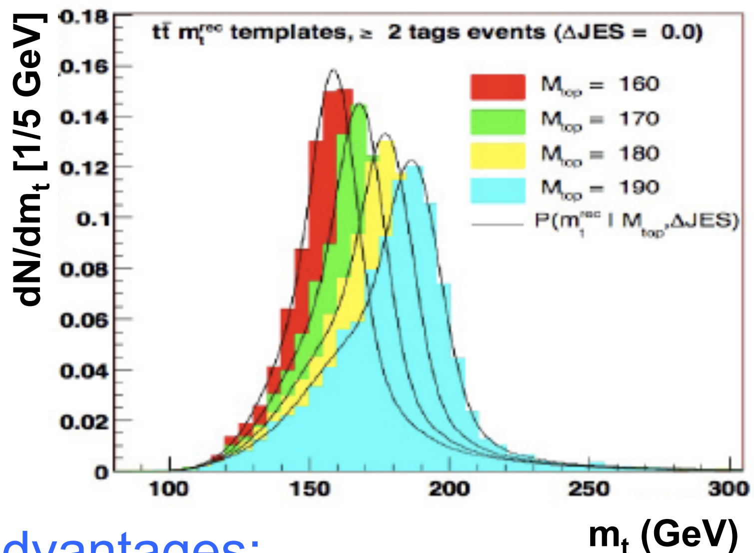
Identification of b quark jets

m_t measurements and methods

Analysis methods

Template method:

- Exploit dependence of m_t on kinematic observables
  - Form templates using MC
  - Maximise consistency of templates with data given m_t



- Advantages:
  - Robust and straight-forward
- Drawback:
  - Sub-optimal sensitivity

Matrix element (ME) method:

- Directly calculate event probability

$$P_{\rm evt}(m_{\rm top}) \propto f P_{\rm sig}(m_{\rm top}) + (1-f) P_{\rm bgr}$$

$$P_{\rm sig}(m_{\rm top}) \propto \int ... d\sigma_{t\bar{t}}(m_{\rm top})$$

$$d\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2 (m_{\rm top})$$

- Advantages:
  - Highest possible sensitivity according to the Neyman-Pearson lemma
  - Theory assumptions
- Drawback:
  - Computationally intensive
  - Theory assumptions

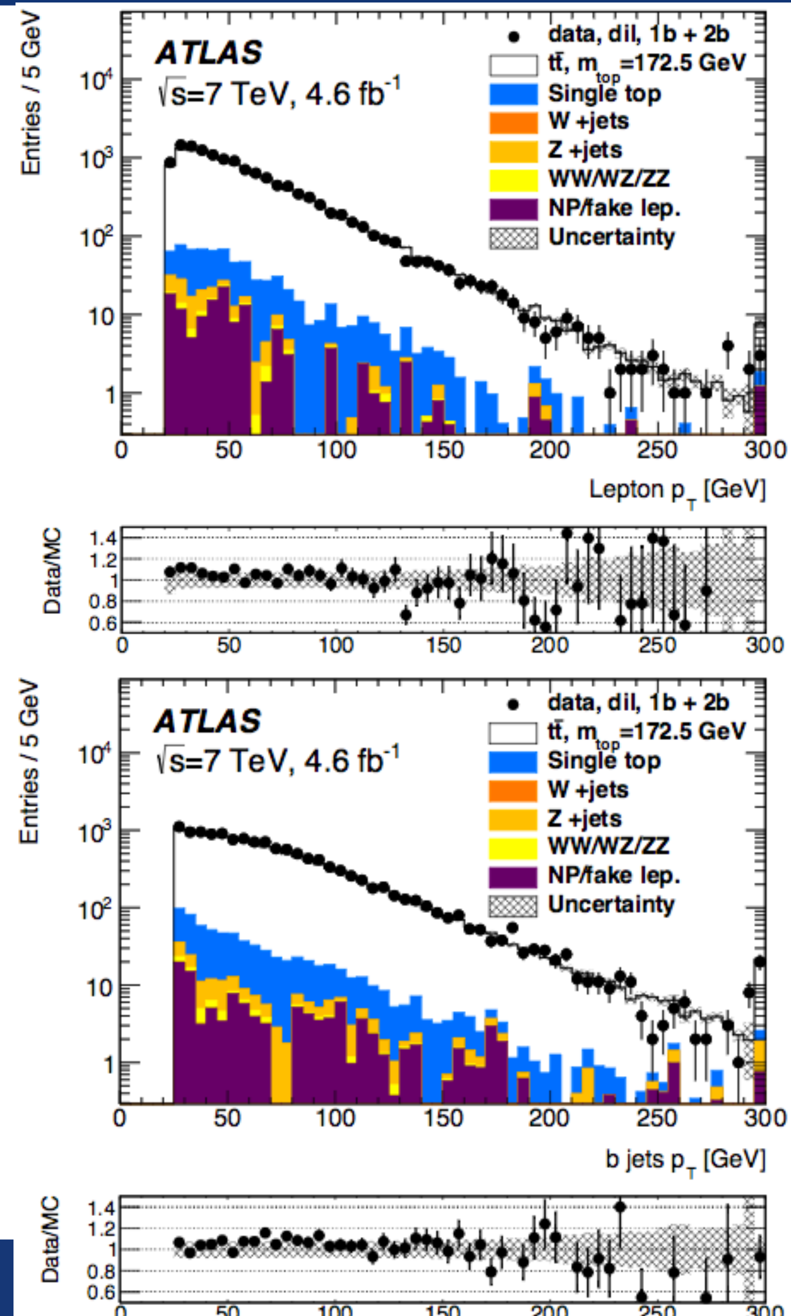
Ideogram method:

- In-between the two

Template method

m_t with template method in $\ell\ell$ channel (I)

- **Template method:**
  - m_t in dilepton channel (ATLAS, 7 TeV) [1]
    - Very clean final state
    - Statistics not an issue at LHC
  - Preselection:
    - 2 high-p_T ℓ (*e or* $\boldsymbol{\mu}$)
    - high E_t^{miss} (2 $\boldsymbol{\nu}$)
    - ≥2 High-p_T jets $|\eta| < 2.5$
    - 1 or 2 *b*-tags
  - Purity 94%

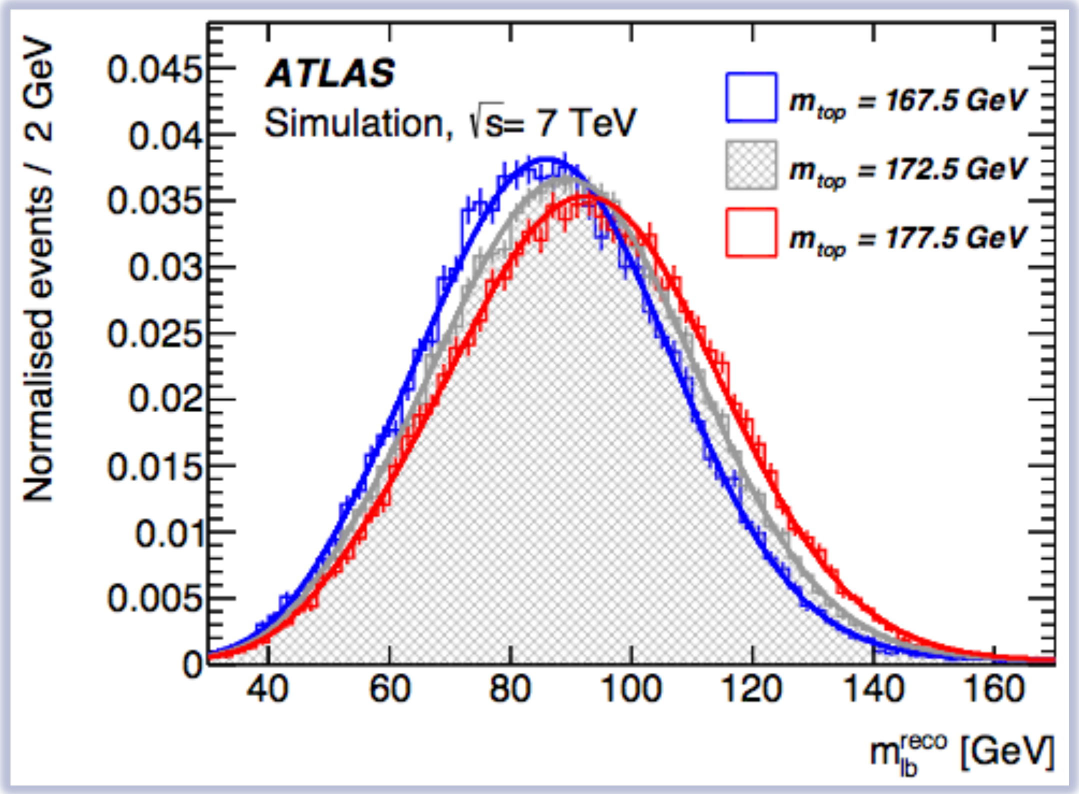


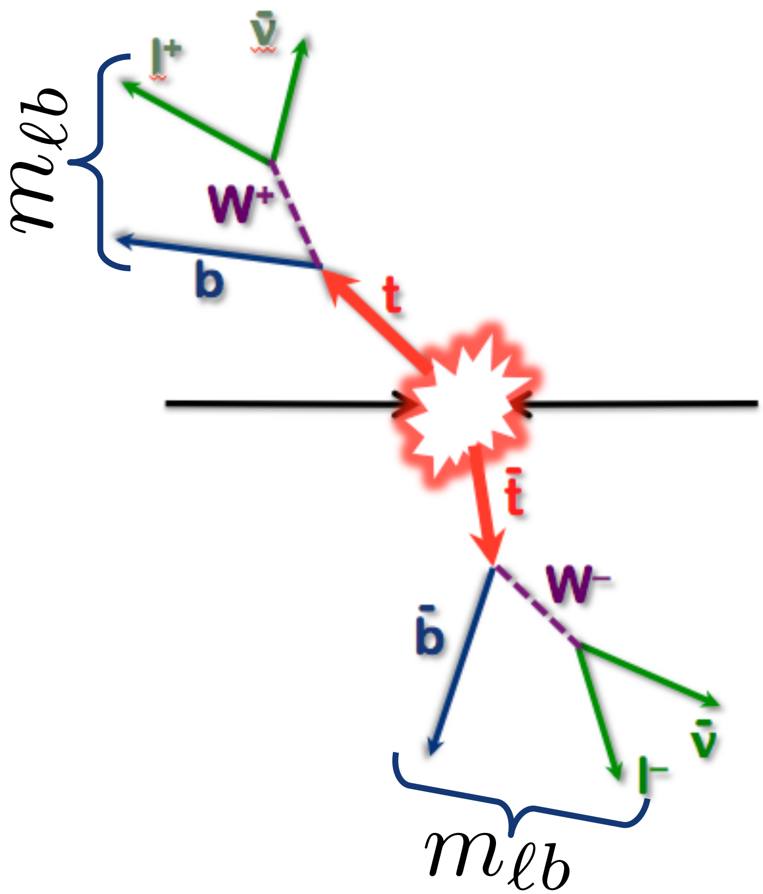
[1] Eur. Phys. J. C (2015) 75:330

m_t with template method in $\ell\ell$ channel (II)

- Apply template method to observable $m_{\ell b}$ [1]:
  - Invariant mass of ℓ+b system
  - → reduced sensitivity to systematic uncertainties [2]

[1] Eur. Phys. J. C (2015) 75:330
[2] *W. Bernreuther, priv. comm. (2013)*

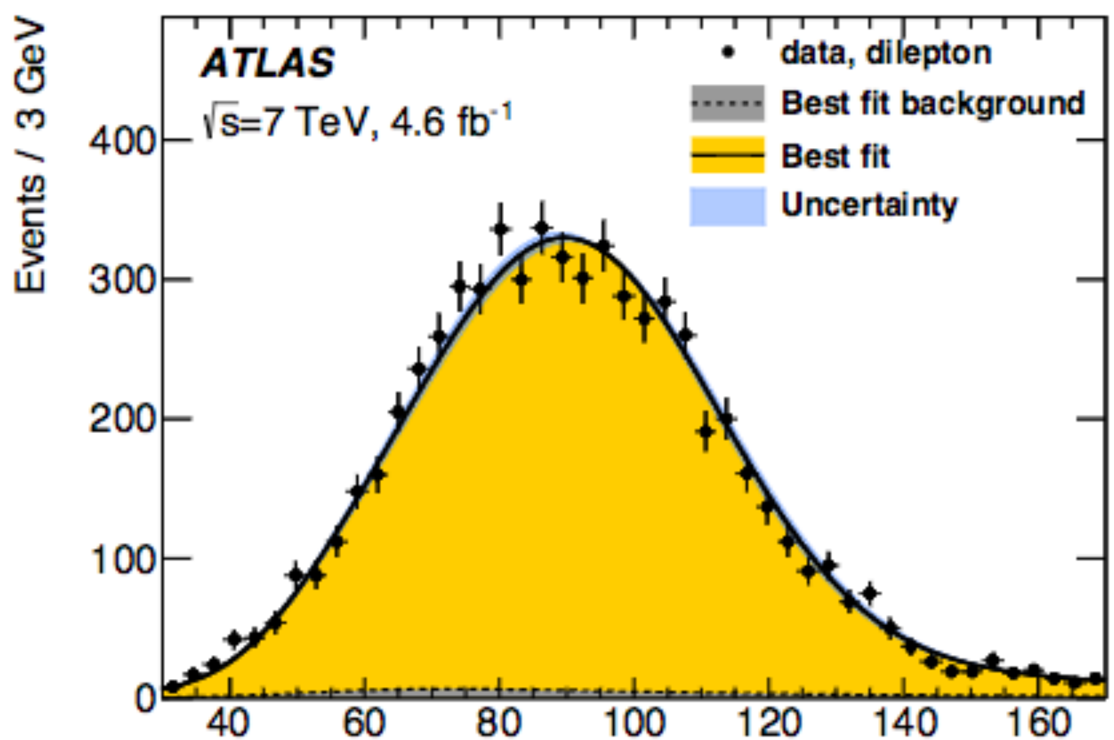




m_t with template method in $\ell\ell$ channel (III)

- Extract m_t by maximising the likelihood in m_t

$$\mathcal{L}^{\text{dilepton}}_{\text{shape}}(m_{\text{top}}, f_{\text{bkg}}) = \prod_{i=1}^{N} \left[(1 - f_{\text{bkg}}) \cdot P^{\text{sig}}_{\text{top}}(m^{\text{reco},i}_{\ell b} \,|\, m_{\text{top}}) + f_{\text{bkg}} \cdot P^{\text{bkg}}_{\text{top}}(m^{\text{reco},i}_{\ell b}) \right]$$



[1] Eur. Phys. J. C (2015) 75:330

Dominant systematic uncertainties:

- Detector calibration:
  - JES (0.8 GeV)
  - b quark JES (0.7 GeV)
- Signal modelling:
  - Hadronisation (0.5 GeV)
  - Initial/final state radiation (0.5 GeV)

JES uncertainty negligible after constraint from ℓ+jets!

$$m^{\text{dil}}_{\text{top}} = 173.79 \pm 0.54\,(\text{stat}) \pm 1.30\,(\text{syst})\ \text{GeV}.$$

0.8% precision!

Matrix element method

ME method (I)

DØ, l+jets channel, √s=1.96 TeV, 9.7 fb^{-1} [1]

(Tevatron's most precise single measurement)

b **tagging-based weight to identify relevant jet-parton assignments**

Integration over phase space (10 dim)

$$P_{\rm sig} = \frac{1}{\sigma_{\rm obs}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int \overbrace{d\rho\, dm_1^2 dM_1^2 dm_2^2 dM_2^2 d\rho_\ell dq_1^x dq_1^y dq_2^x dq_2^y}$$

$$\sum_{\rm flavors,\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{(\eta_{\alpha\beta}q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\rm JES})$$

LO matrix element
PRD 53, 4886 (1996)
PLB 411, 173 (1997)

Phase space factor

Transfer functions to map parton level quantities *y* to reco level quantities *x*

[1] *PRL* ***113*** *032002 (2014)*

ME method (II)

DØ, l+jets channel, $t\bar{t}$ events, $\sqrt{s}$=1.96 TeV, 9.7 fb^{-1} [1]

Normalisation by observed cross section using the same LO ME

Sum over all 24 possible jet-parton assignments

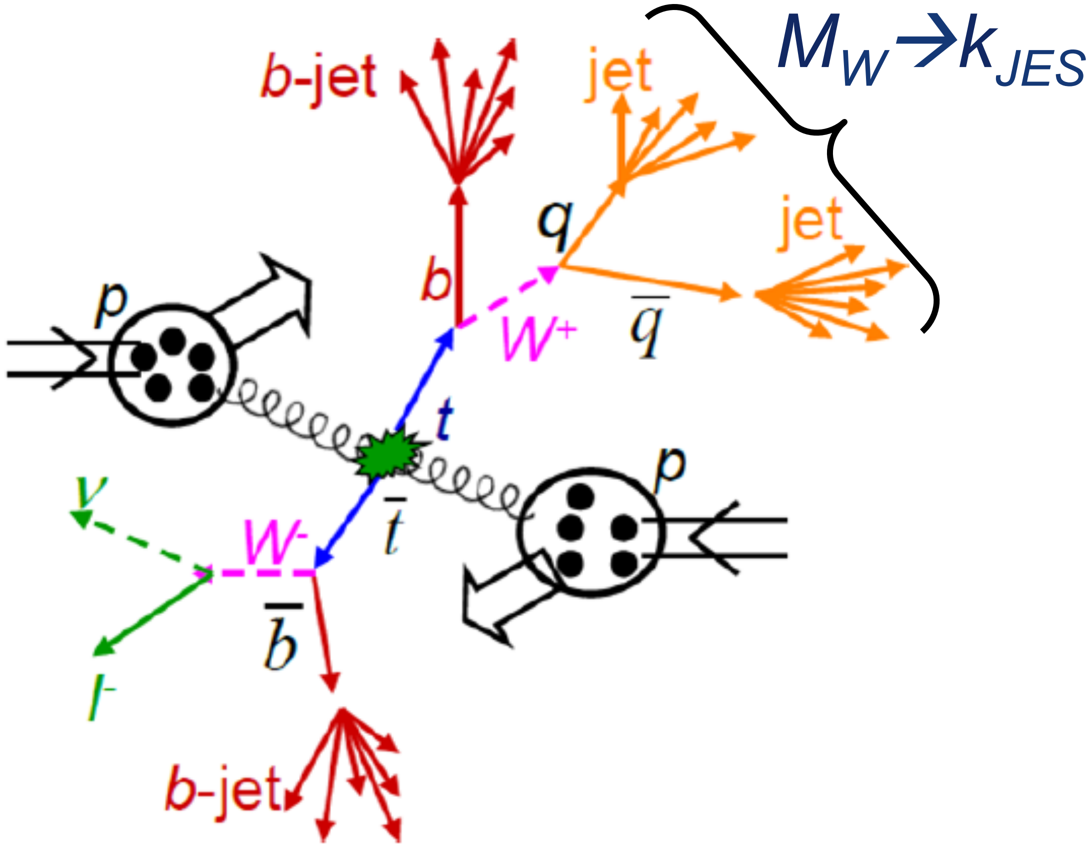
$$P_{\rm sig} = \frac{1}{\sigma_{\rm obs}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int d\rho\, dm_1^2\, dM_1^2\, dm_2^2\, dM_2^2\, d\rho_\ell\, dq_1^x\, dq_1^y\, dq_2^x\, dq_2^y \sum_{\rm flavors,\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1) f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\rm JES})$$

Sum over incoming parton flavours and all neutrino p_z solutions

PDFs for Björken-*x* and PD for transverse momenta of incoming partons

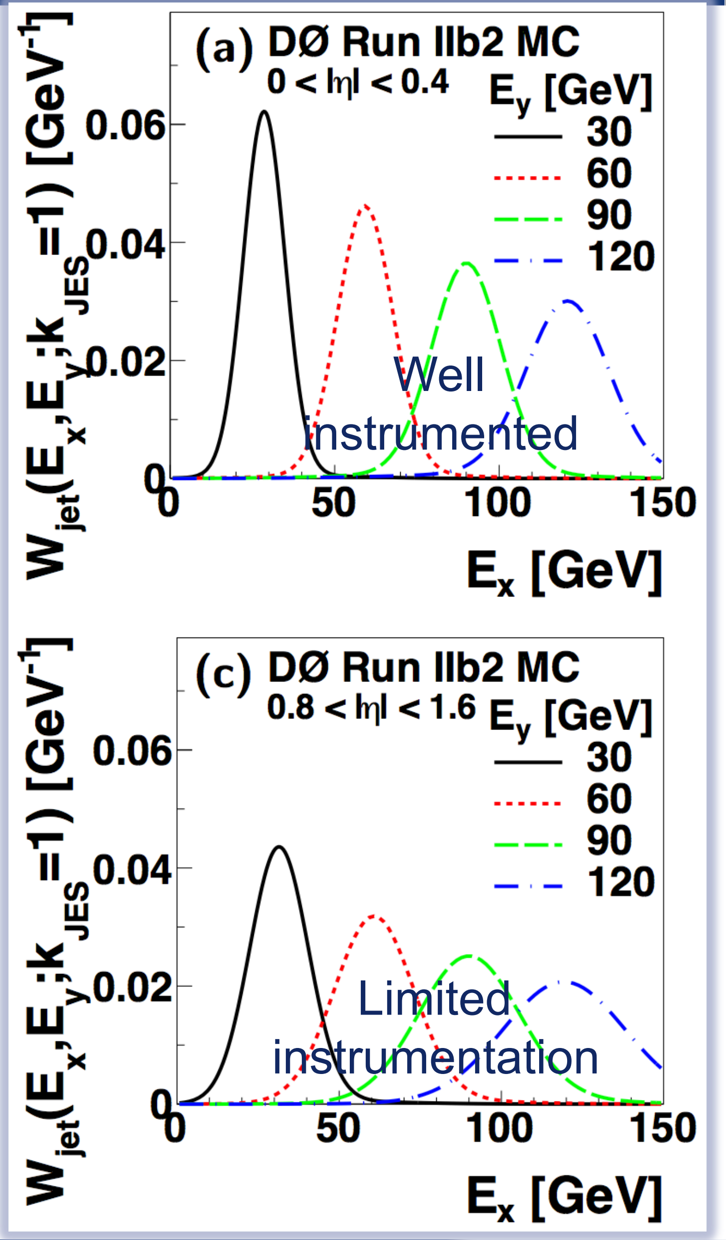
[1] *PRL* ***113*** *032002 (2014)*

Calibrate jet energy scale k_{JES} in-situ



ME method (III)

- The Transfer Functions $W(x,y;k_{JES})$ relate parton-level quantities *y* to detector-level ones *x*
  - Two Gaussians:
    - One for the core of the distribution
    - One for the tails
  - Direction of jets and leptons in (η,ϕ) well-measured



ME method (VI)

This measurement

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
Initial/final state radiation*	0.09
Hadronization & UE*	0.26
Color reconnection*	0.10
Multiple $p\bar{p}$ interactions	0.06
Heavy flavor scale factor	0.06
b-jet modeling	0.09
PDF uncertainty	0.11
Detector modeling:	
Residual jet energy scale	0.21
Data-MC jet response difference	0.16
b-tagging	0.10
Trigger	0.01
Lepton momentum scale	0.01
Jet energy resolution	0.07
Jet ID efficiency	0.01
Method:	
Modeling of multijet events	0.04
Signal fraction	0.08
MC calibration	0.07
Total systematic uncertainty	0.49
Total statistical uncertainty	
Total uncertainty	

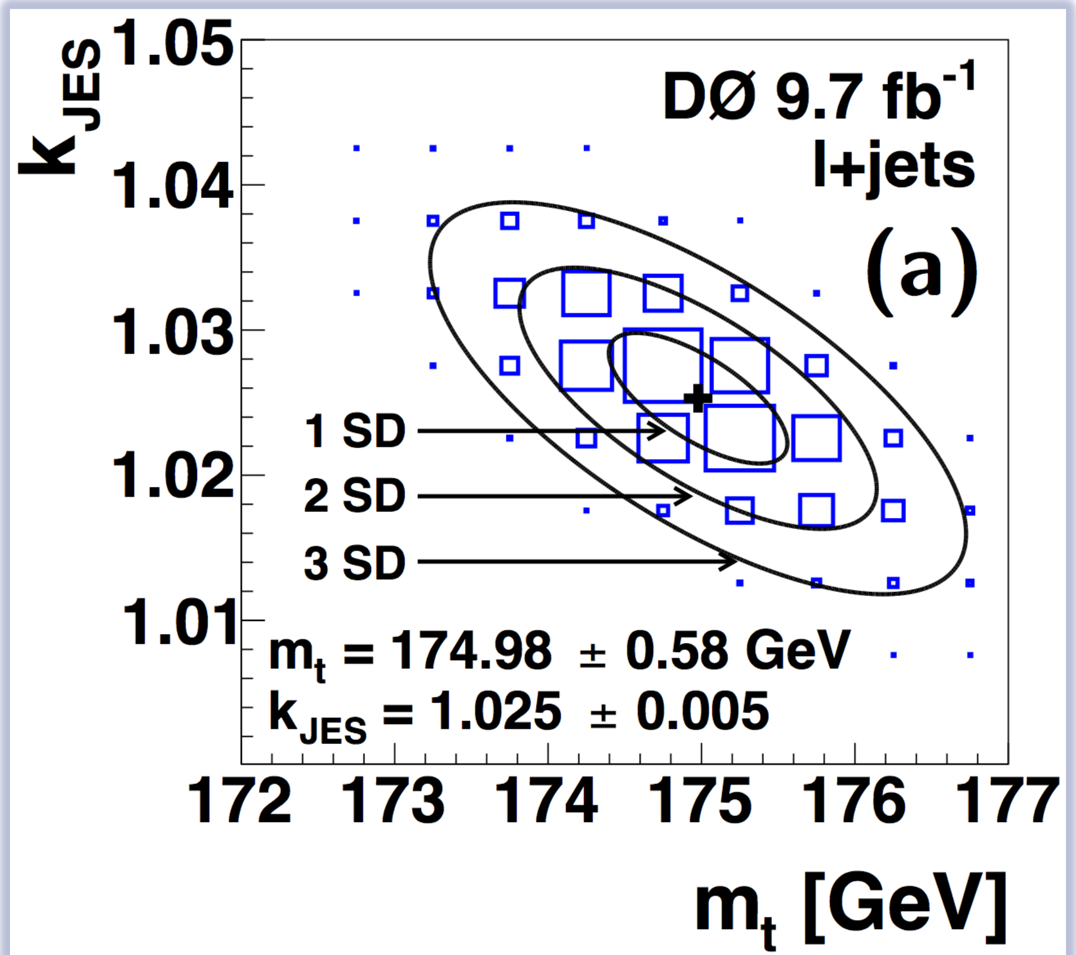
0.49 GeV

1.02 GeV

*Previous DØ result: PRD **84**, 032004 (2011)*

Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color reconnection	±0.28
Multiple $p\bar{p}$ interactions	±0.07
Modeling of background	±0.16
W+jets heavy-flavor scale factor	±0.07
Modeling of b jets	±0.09
Choice of PDF	±0.24
Modeling of detector:	
Residual jet energy scale	±0.21
Data-MC jet response difference	±0.28
b-tagging efficiency	±0.08
Trigger efficiency	±0.01
Lepton momentum scale	±0.17
Jet energy resolution	±0.32
Jet ID efficiency	±0.26
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

ME method (VII)



relative uncertainty ***0.43%!***

PRL **113**, 032002 (2014)

Physics spotlight
Synopsis:
Top Quark Mass Gets an Update

Featured in
nature
Nature, **514**, 174 (2014)
Particle physics: the mass of a top

Detailed (40 pages!) paper:
PRD ***91****, 112003 (2015)*

$$m_t = 174.98 \pm 0.58\,(\text{stat} + \text{JES}) \pm 0.49\,(\text{syst})\ \text{GeV}$$


Is it THE Higgs?
(i.e. the SM Higgs)

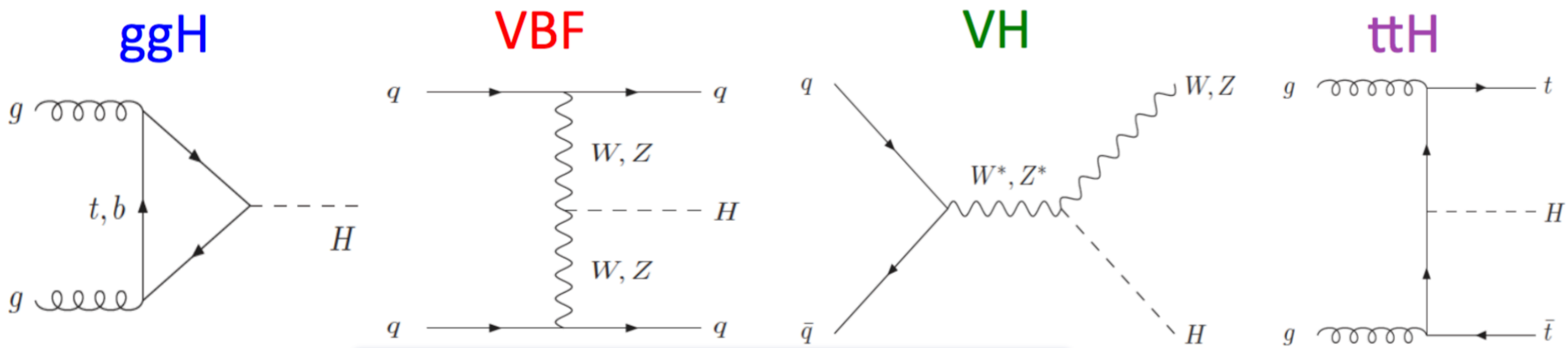
Coupling strength measurements

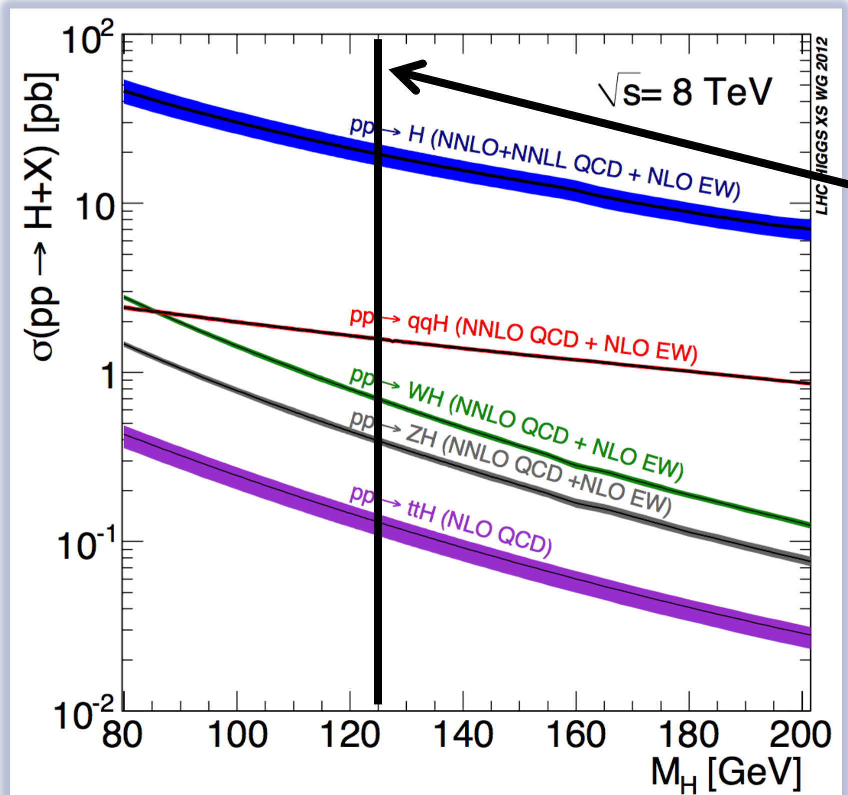
We've come a long way since the discovery:
→ coupling strength $\mu = \sigma_{obs} / \sigma_{SM}$ measured in all discovery channels with high precision

→ Sensitivity to New Physics!

Higgs production (reminder)

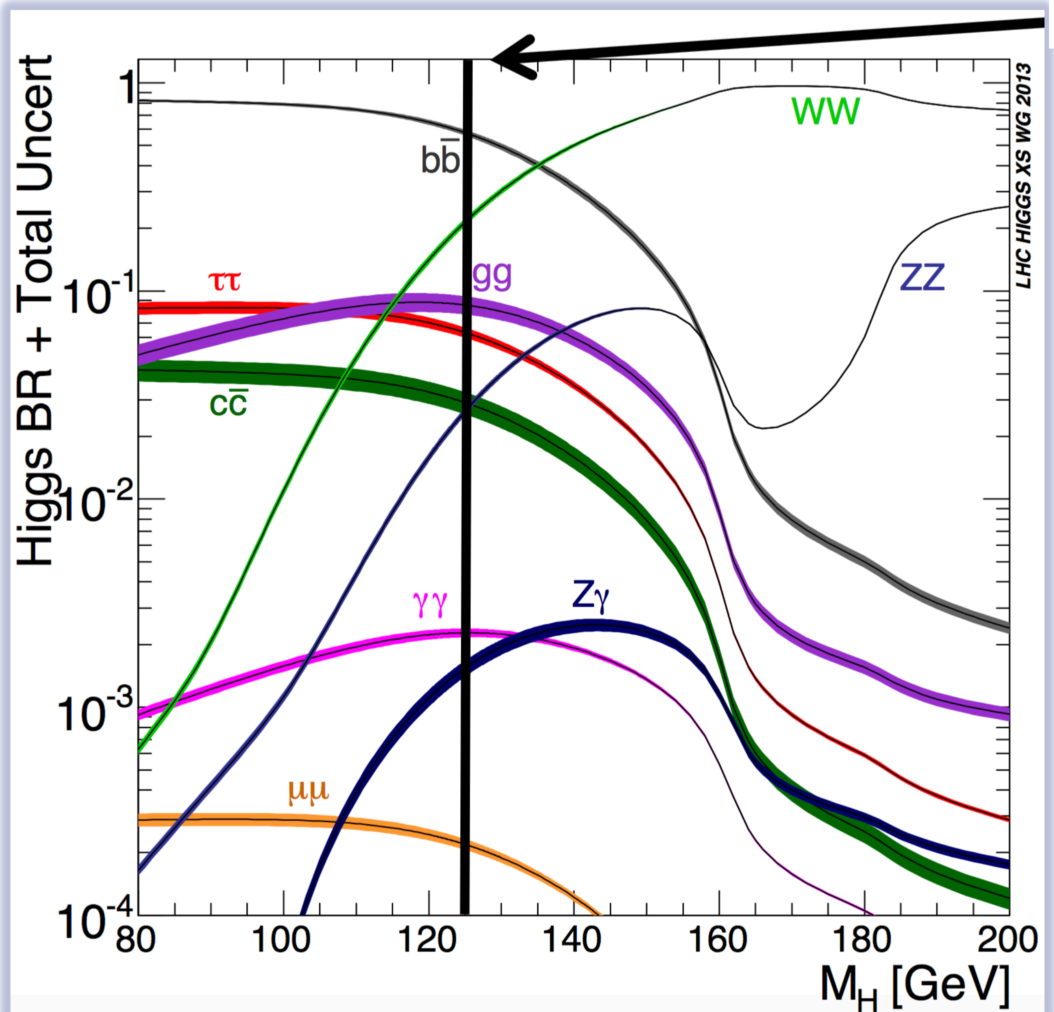
ggH VBF VH ttH





m_H=125.09 GeV

Higgs decay (reminder)



m_H=125.09 GeV

Higgs boson decay width Γ_H negligible in SM (4.1 MeV) relative to experimental resolution (~1 GeV)

Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Run 1 Higgs coupling combo (Sept 2015)

- Focus on Run 1 ATLAS+CMS Higgs coupling combo [1]
  - Gain √2 in precision
    - Measurements (or dominant systematics) statistically limited
  - Combined channels:

Decay / Production	Untagged	VBF	VH	ttH
H→γγ	■	■	■	■
H→ZZ→4l	■	■	■	■
H→WW→2l2ν	■	■	■	■
H→ττ	■	■	■	■
H→bb			■	■
H→μμ	■	■		

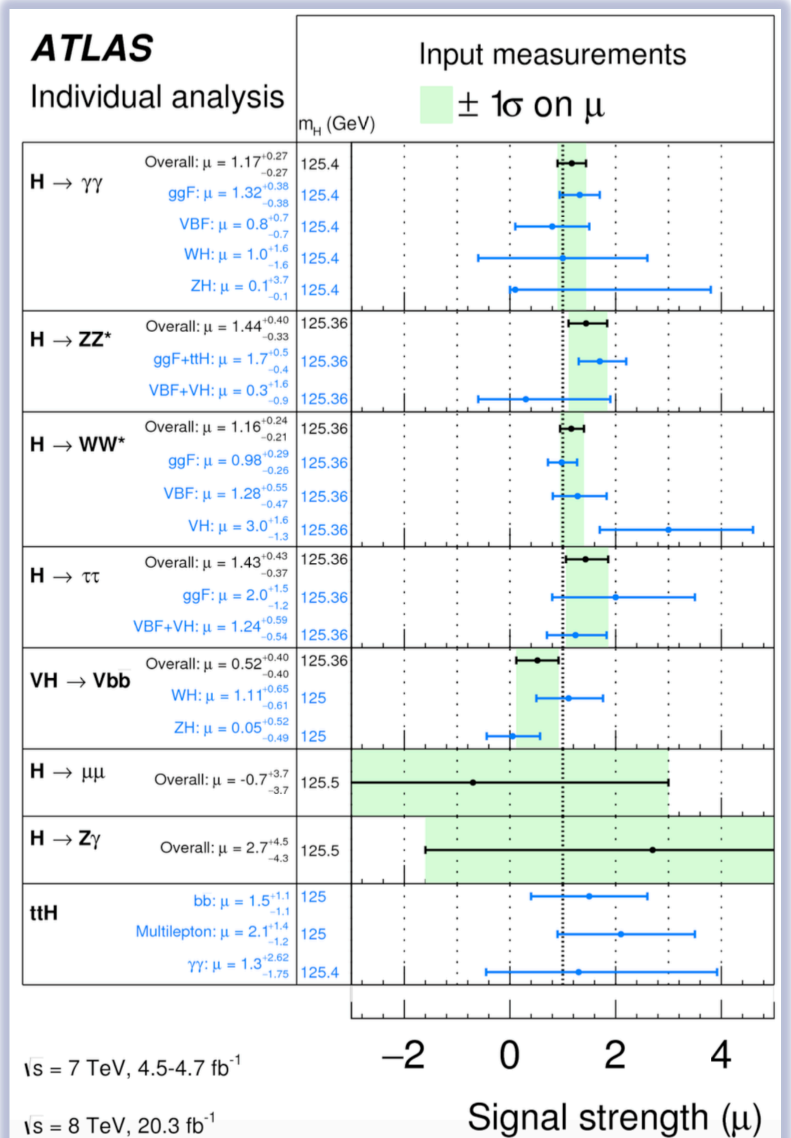
  - Directly sensitive to Higgs couplings to
    - W, Z bosons
    - τ, b and t fermions
  - Indirectly sensitive to gluons, photons, and t quarks

Fresh off the press!

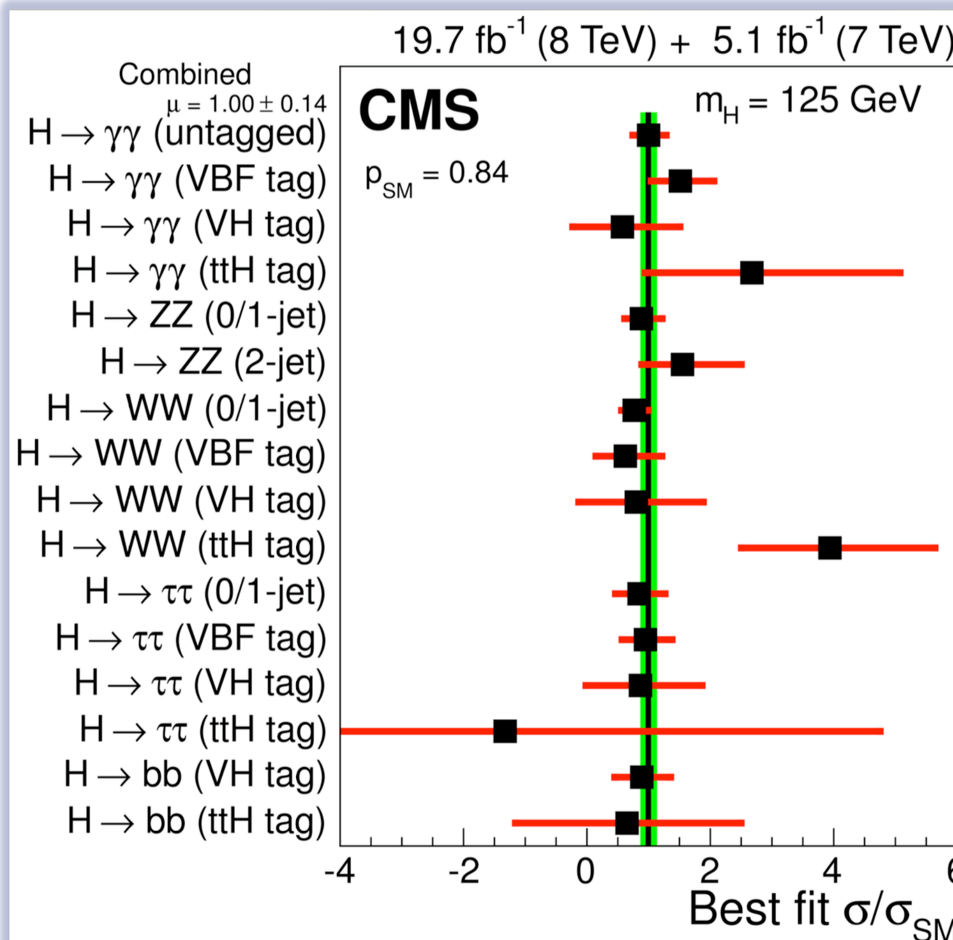
[1] *ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002*

Inputs to Higgs coupling combo

ATLAS [1]



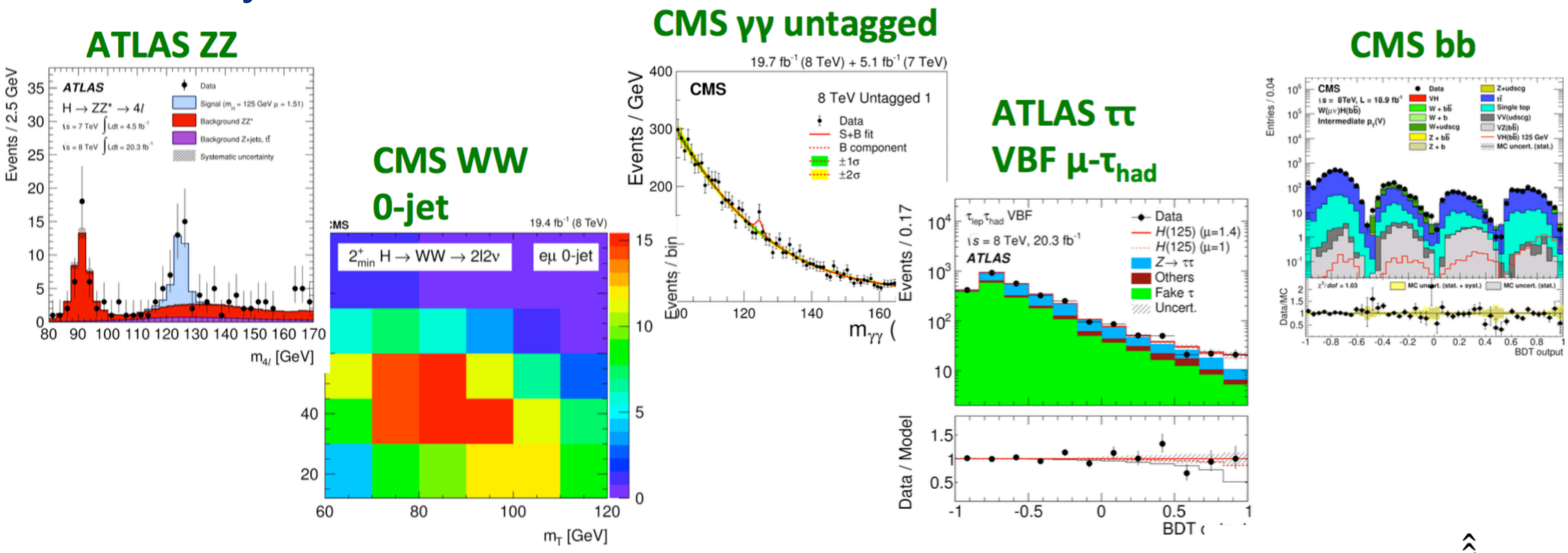
CMS [2]



[1] arXiv:1507.04548
[2] Eur. Phys. J. C 75 (2015) 212

Inputs & statistical treatment

- Many different final discriminant distributions combined



- Include systematics via nuisance parameters: $\Lambda(\vec{\alpha}) = \dfrac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$
  - About 4200 nuisance parameters!
    - MC statistics, signal theory σ, background theory σ, etc.
    - Most systematics considered uncorrelated
    - Theory input (calculations, PDFs, etc.) fully correlated

Signal strength μ

- Measure signal strength μ in units of SM expectation:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}. \qquad \mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

  - i = initial state, f = final state

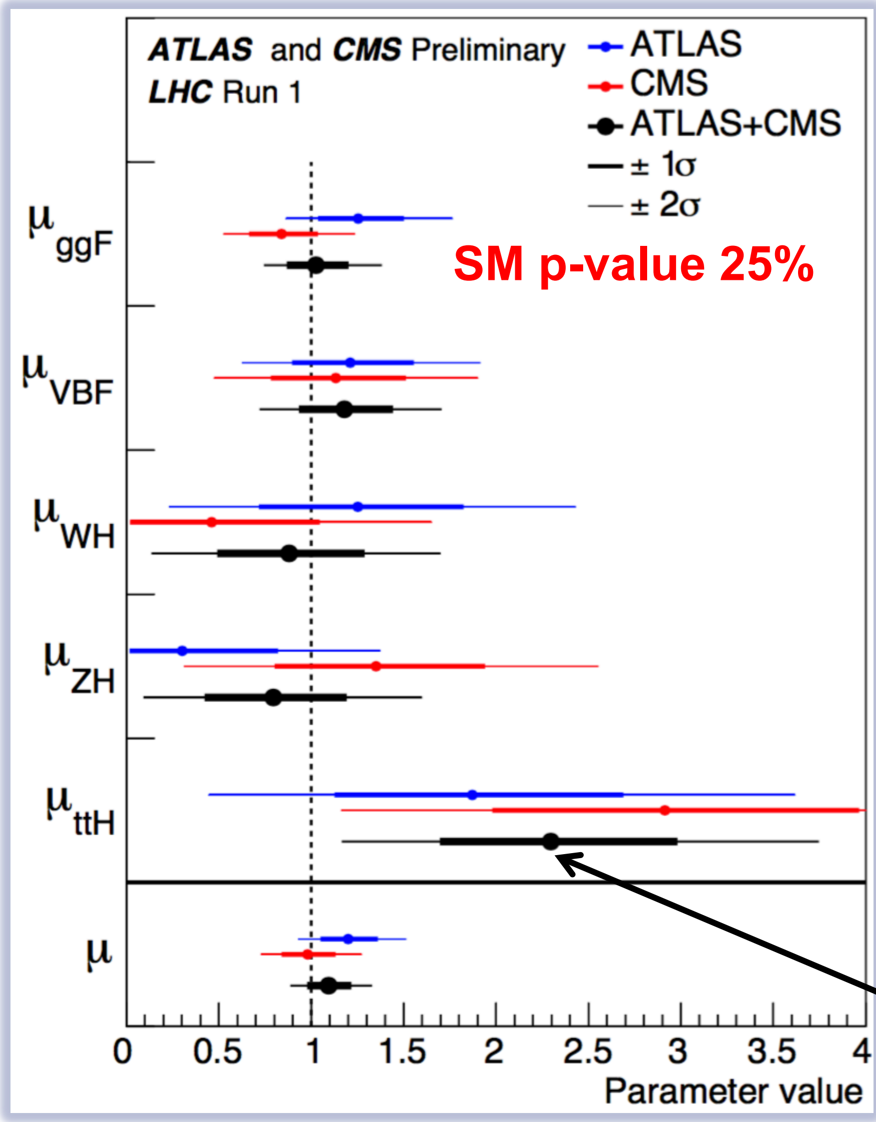
- Most constrained fit of μ:

$$\mu = 1.09^{+0.11}_{-0.10} \quad = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

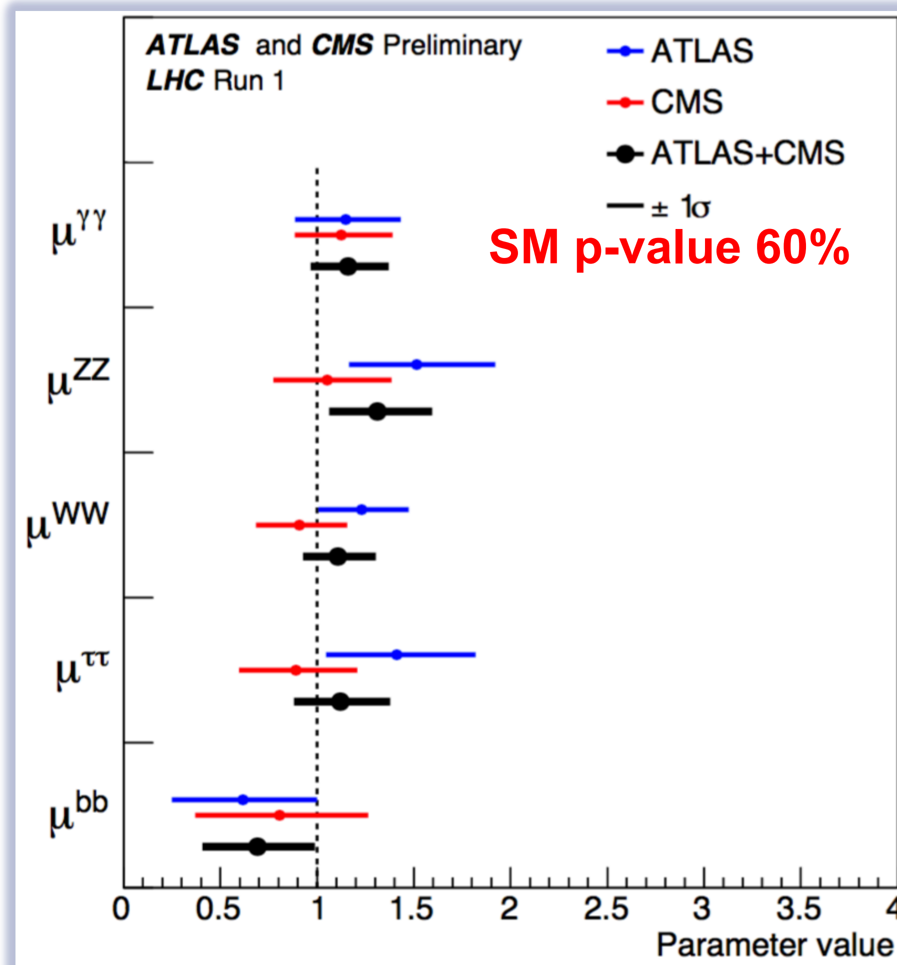
  - The only not statistically limited coupling measurement
  - QCD scale and PDF dominate theory signal uncertainty

Signal strength μ

SM decay assumed



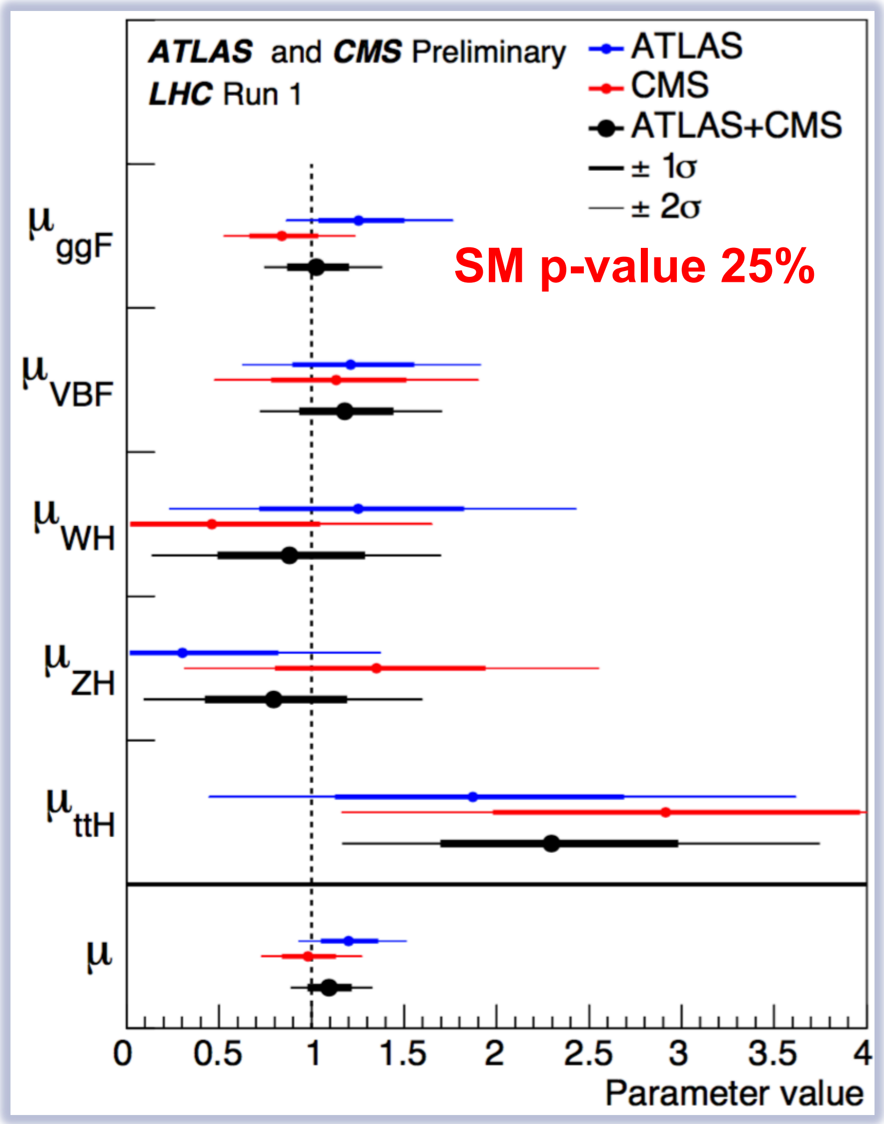
SM production assumed



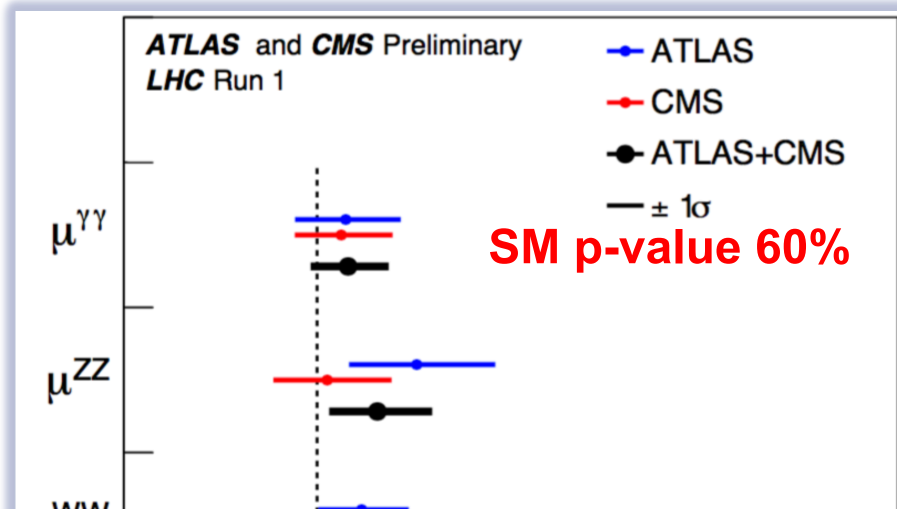
Largest difference: ttH (2.3σ excess)
→ will talk about it in a second

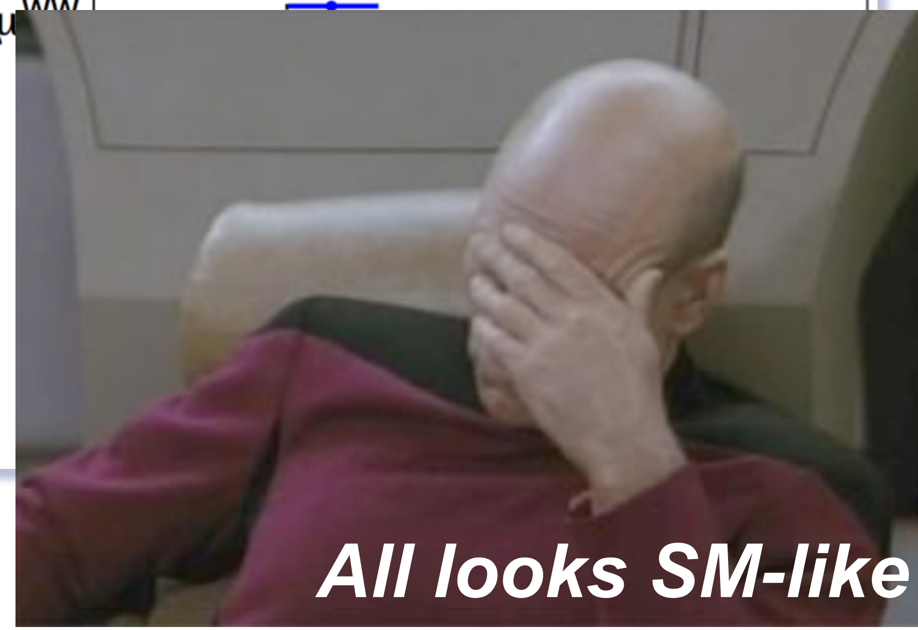
Signal strength μ

SM decay assumed



SM production assumed



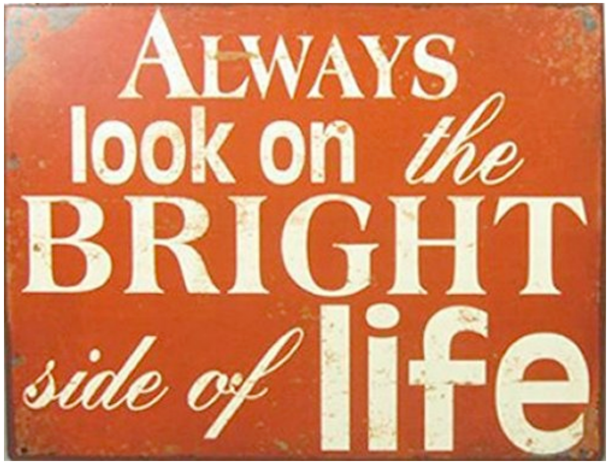


Significance per channel

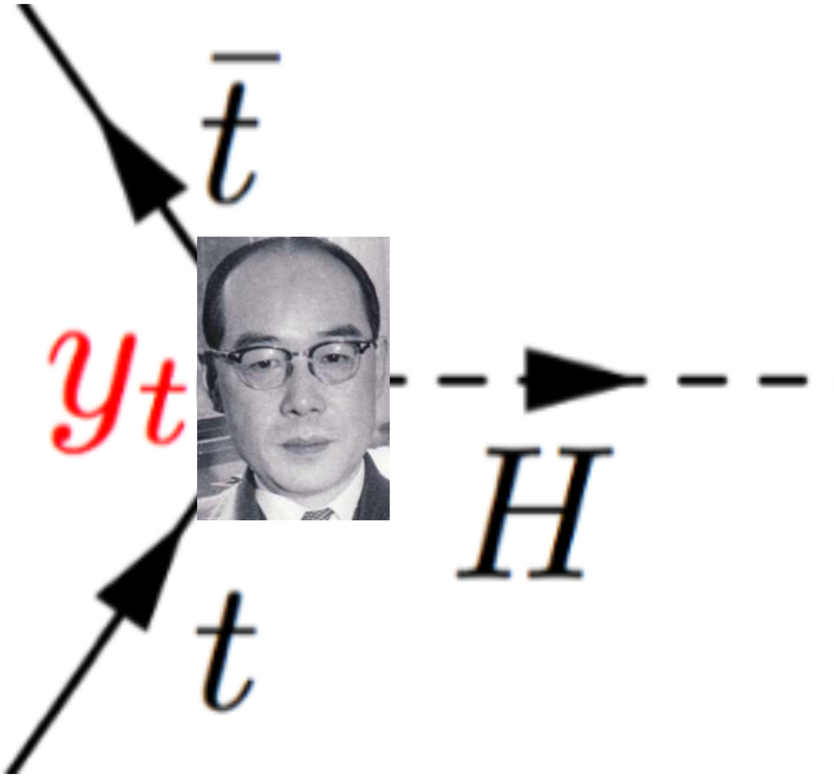
- Compare μ per channel with H_0 (μ_i=μ_f=0):

Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	**4.7**
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	**5.0**
H→bb	2.6	3.7

- VBF and H→$\tau\tau$ observed in combo (>5σ)!
- ggF, $H \rightarrow ZZ^*, \gamma\gamma, WW^*$ observed in each experiment independently!

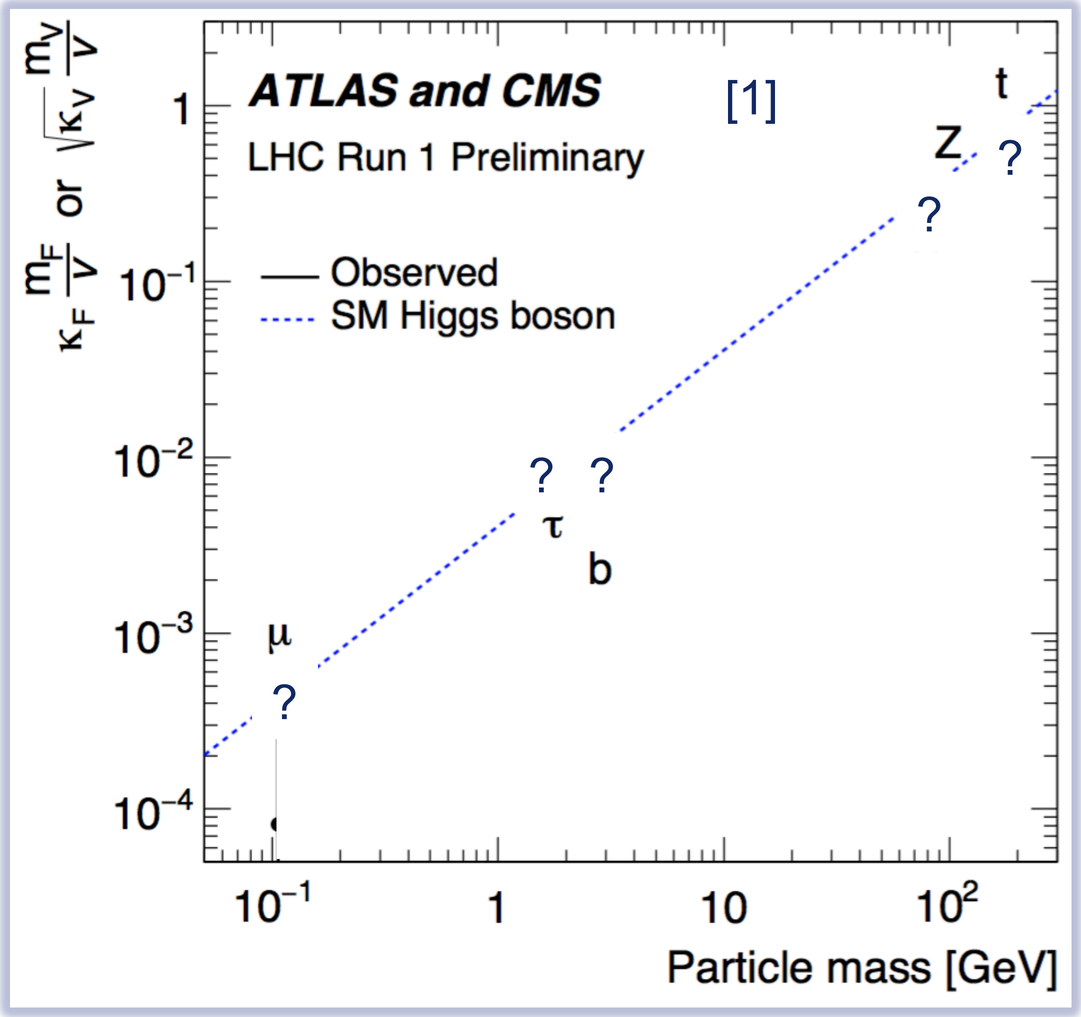


Top Yukawa coupling measurement



Is it THE SM Higgs?

- Fundamental prediction for Higgs coupling to fermions in the SM:
  - $y_{f,\mathrm{SM}} = \sqrt{2}/v \cdot m_f$
- Experimental check imperative!
- Ansatz:
  - Mass m_f measured with "conventional methods"
  - Measure the Yukawa coupling y_f through measurement of Higgs production and decay!



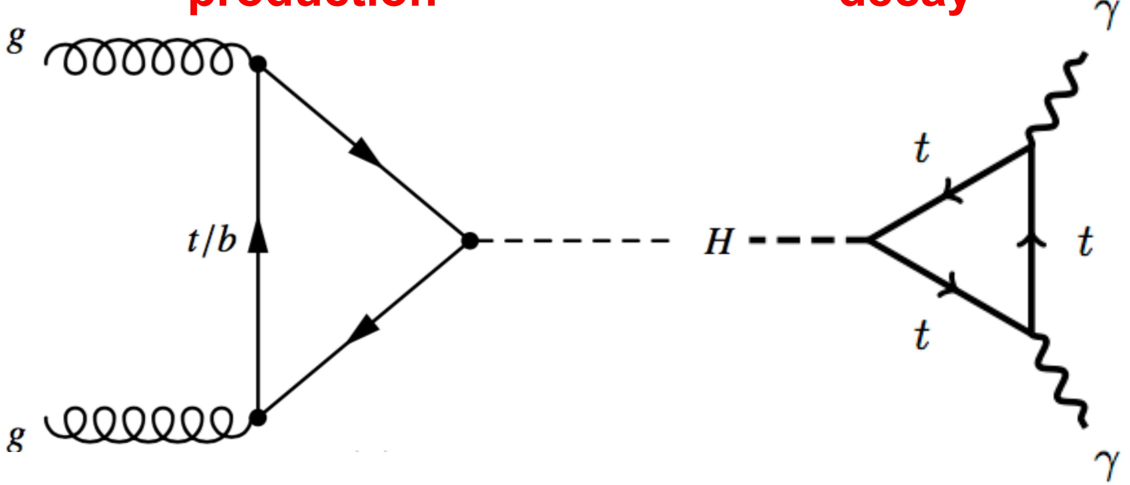
[1] *ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002*

Is it THE SM Higgs?

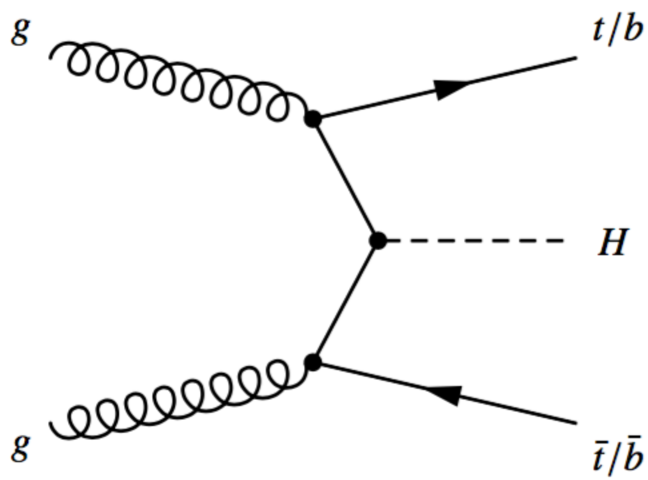
- Particularly interesting to check if $y_{f,\mathrm{SM}} = \sqrt{2}/v \cdot m_f$?
  - The top quark is the most massive fermion
  - In the SM, y_t = 0.996 (using world average m_t)
  - Any deviations from SM most likely to show up in y_t
- Challenge:
  - The y_t coupling enters in different places, e.g.:

Indirectly

production **decay**



Directly



Indirect y_t: the κ coupling framework [1]

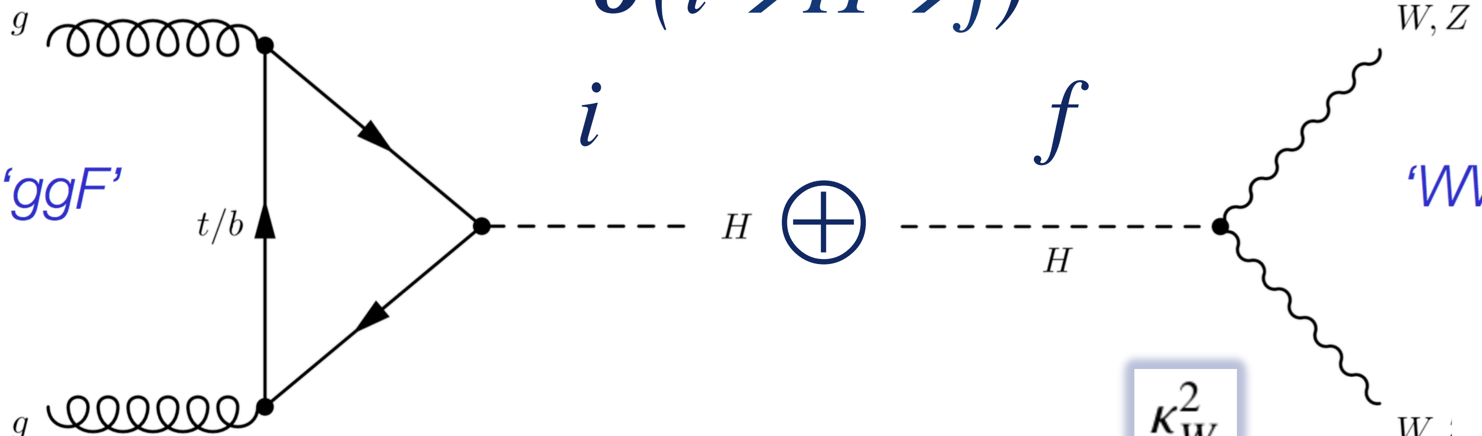
- Interpretation in terms of Higgs boson coupling strenghts?
- Narrow Width Approximation allows factorisation of $\boldsymbol{\sigma}$:

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

(Γ_H = 4.1 MeV in SM)

- Parametrise $\boldsymbol{\sigma}_i$ and Γ_f in terms of couplings strengths $\boldsymbol{\kappa}_i$ relative to SM couplings in LO approximation, e.g.

$\boldsymbol{\sigma}(i \to H \to f)$



$$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$$

$$\kappa_W^2 \quad \kappa_Z^2$$

[1] ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002

Indirect y_t: the κ coupling framework [1]

- Assumptions (cannot extract $\boldsymbol{\sigma}$ and *BR* model-indepently):
  - Narrow width approximation (ditto)
  - $J^P = 0^+$ (all non-SM excluded at CL >99% [2], not in this lecture)
  - Assume no invisible decays
  - Take SM Γ_H since not measured with meaningful precision

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\boxed{\Gamma_H(\kappa_j)}}$$

  - Adjust Γ_H by measured $\boldsymbol{\kappa}$'s:

$$\Gamma_H(\kappa_j) = \kappa_H^2(\kappa_j) \cdot \Gamma_H^{\text{SM}}$$

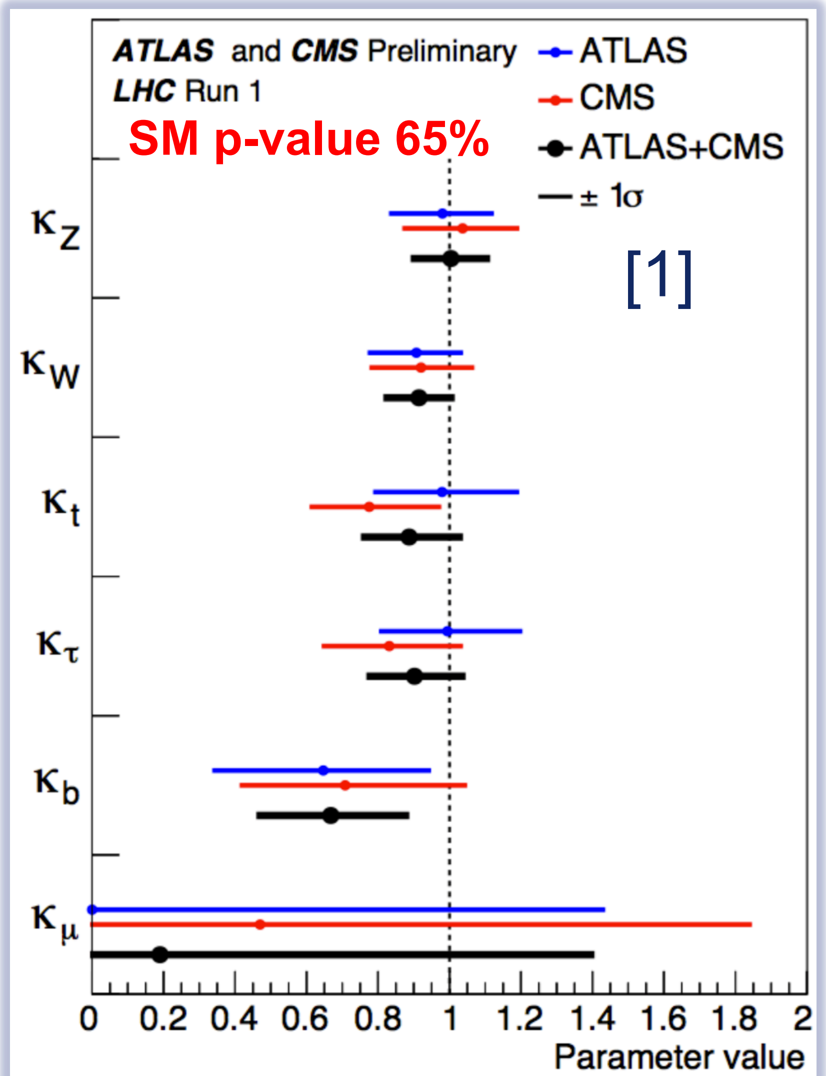
$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

- → Results rigorous for small deviations from SM
- But also large deviations would show up!

[1] *ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002*
[2] *EPJ C75 (2015), arXiv:1506.05669 [hep-ex], PRD 92 (2015), EPCJ C74 (2014)*

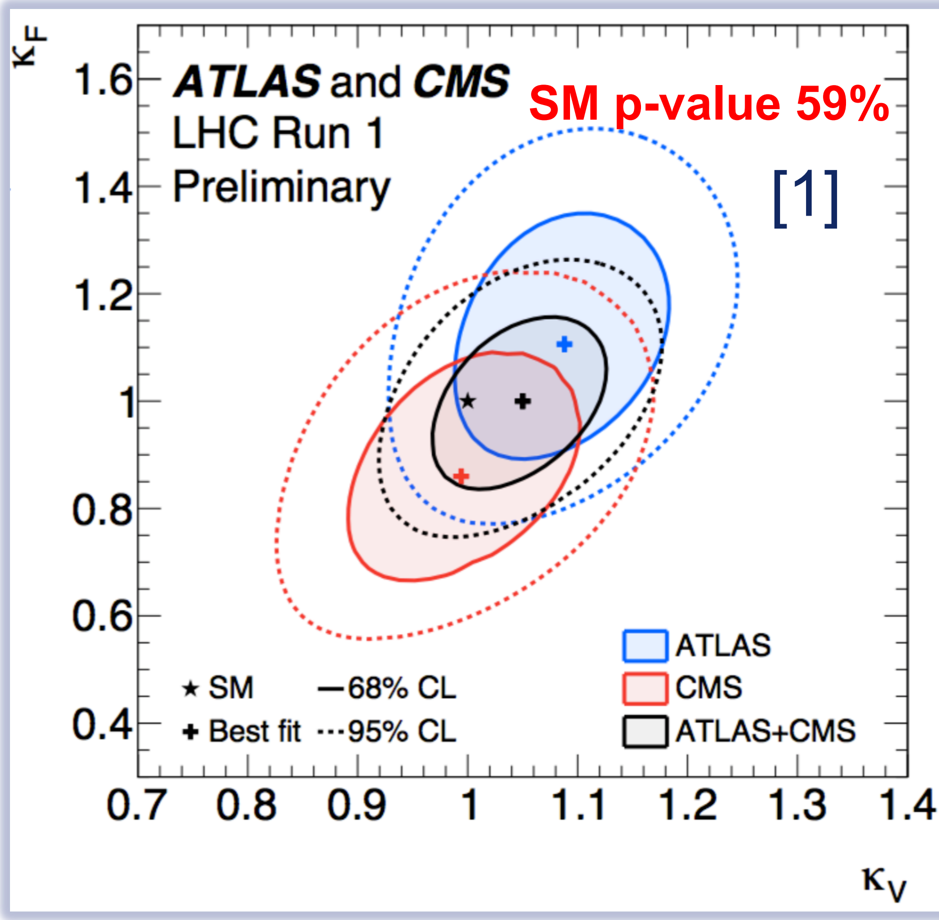
Indirect y_t: results in κ coupling framework

Run 1: probe six tree-level couplings to *W* and *Z* bosons and up/down fermions



Increase stat. sensitivity by

- $\kappa_V = \kappa_W = \kappa_Z$
- $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$



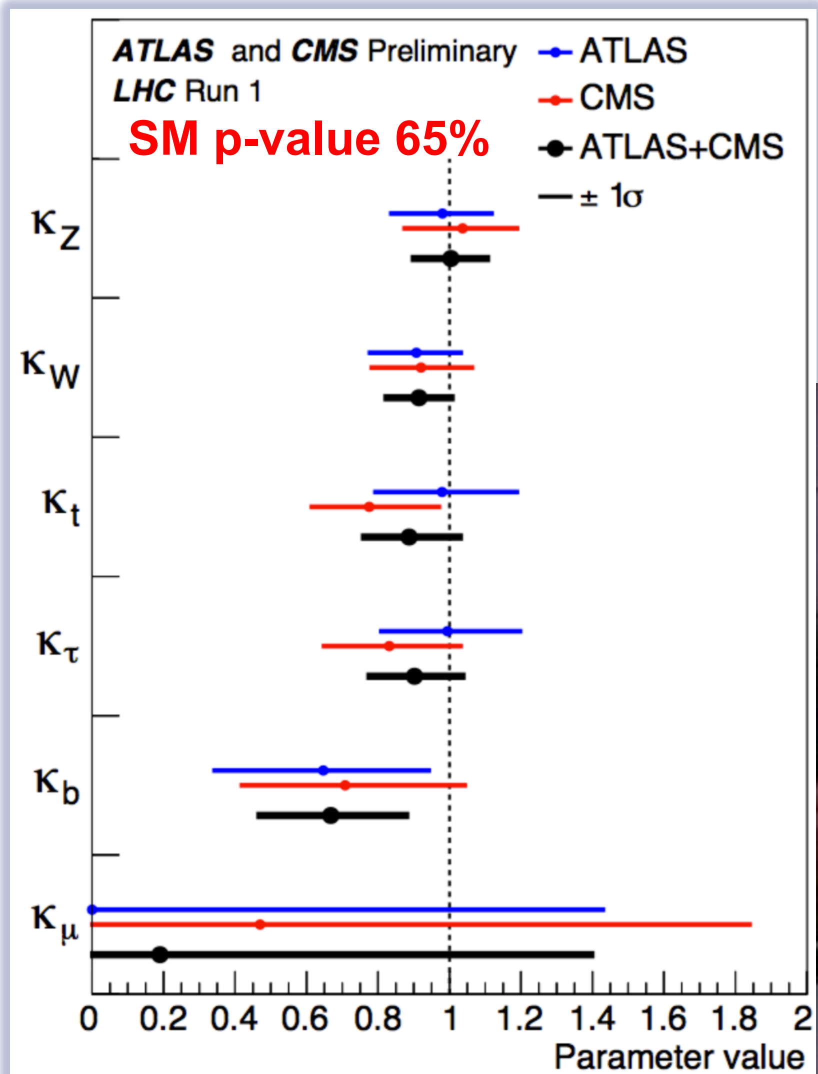
[1] *ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002*

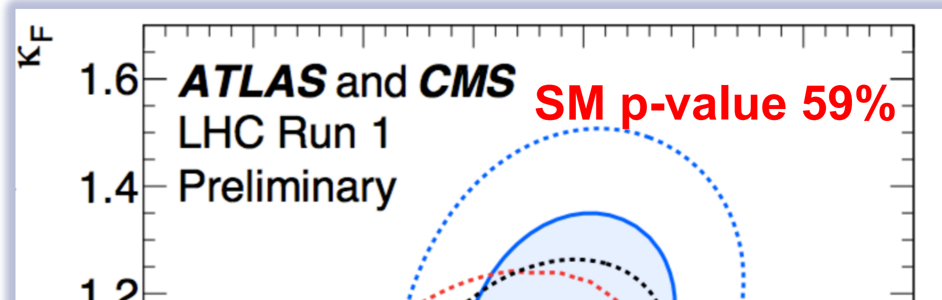
Indirect y_t: results in κ coupling framework

Run 1: probe six tree-level couplings to *W* and *Z* bosons and up/down fermions

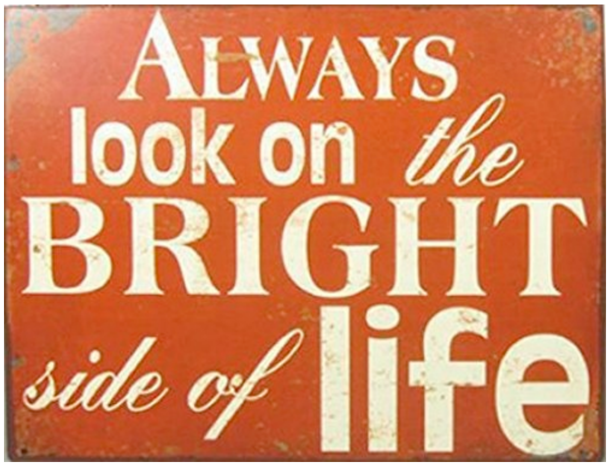
Increase stat. sensitivity by

- $\kappa_V = \kappa_W = \kappa_Z$
- $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$

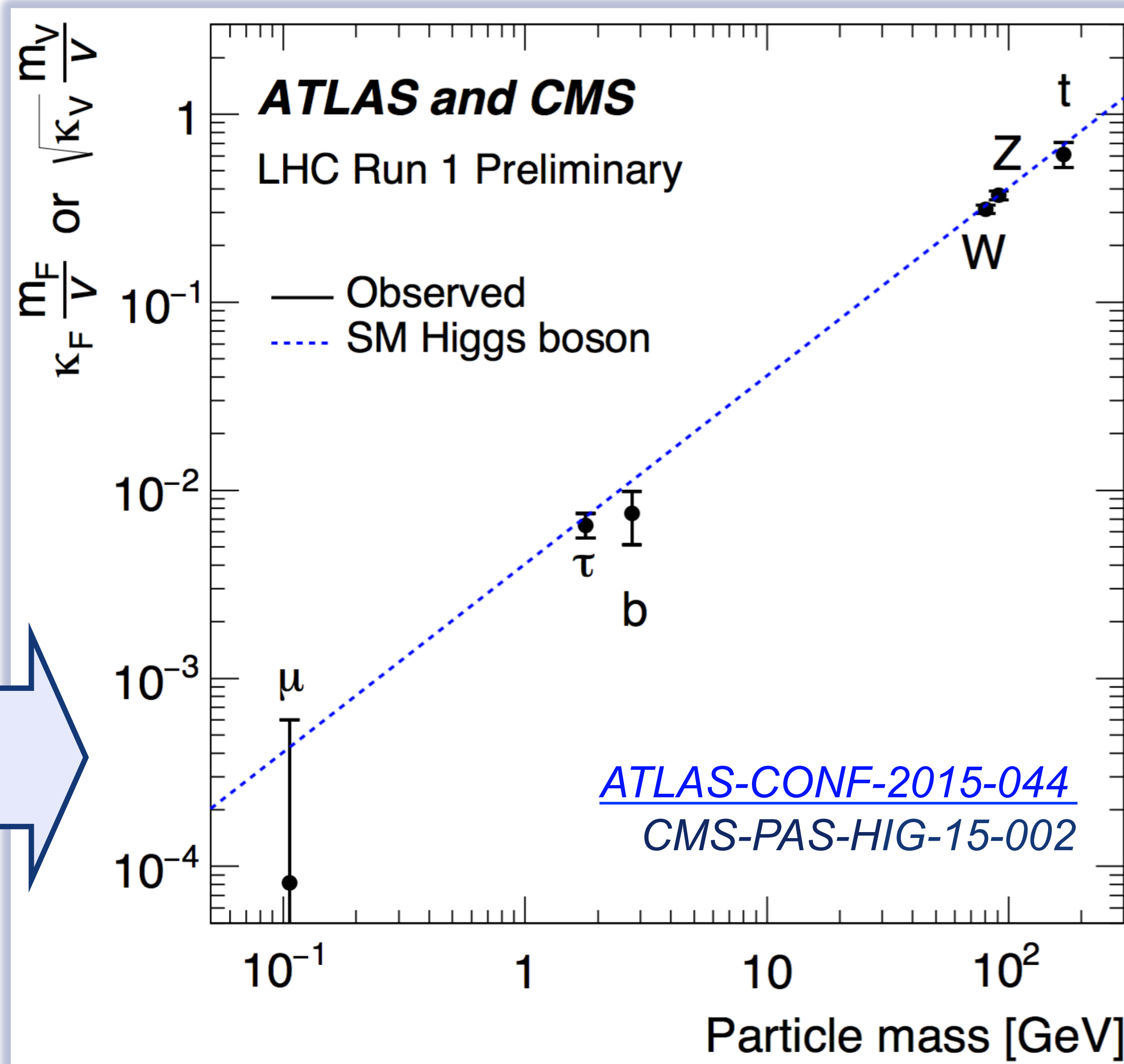




Indirect y_t: results in κ coupling framework

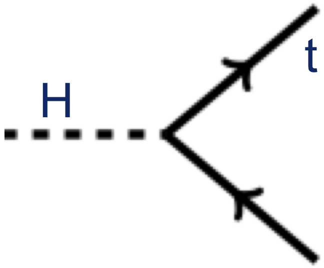


Now we can make nice looking plots!

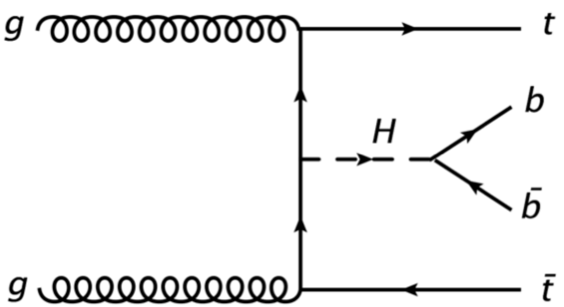


Direct y_t: motivation for ttH(bb)

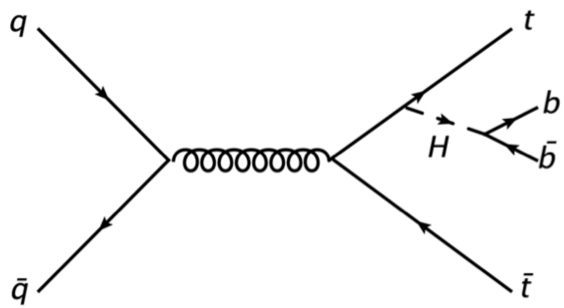
- Reminder:
  - *In SM:* $y_t = 0.996$ for $m_t = 173.2$ GeV (world average)
  - Any deviations from SM Yukawa couplings would be first seen for large y_t!
    - → Measure directly the *ttH* vertex!



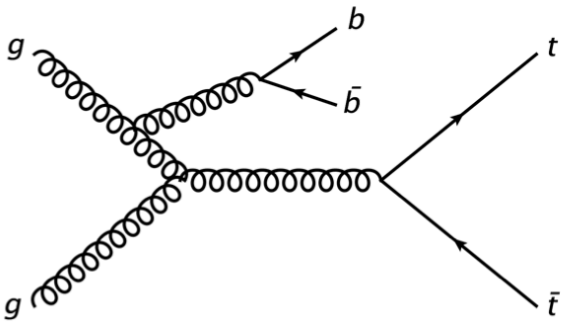
- We look for:



Signal



Signal

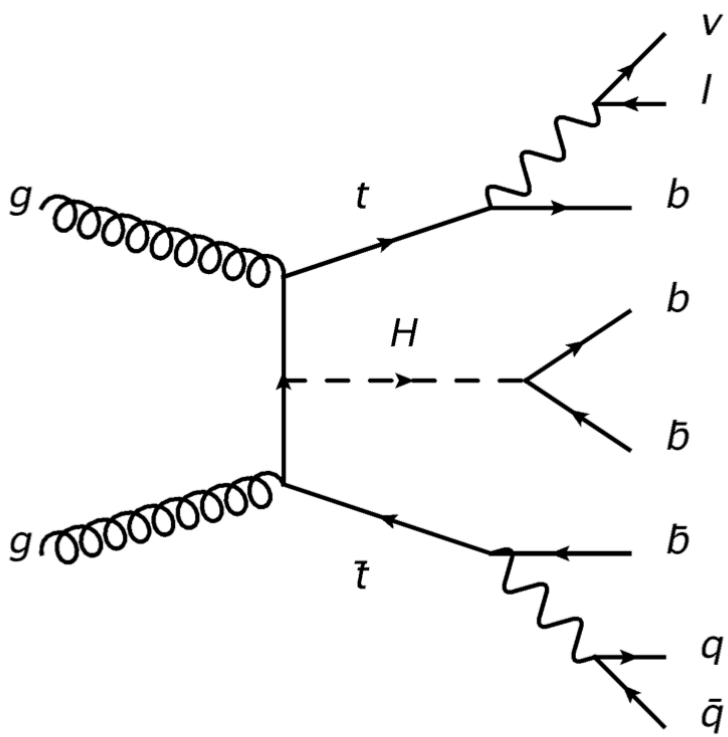


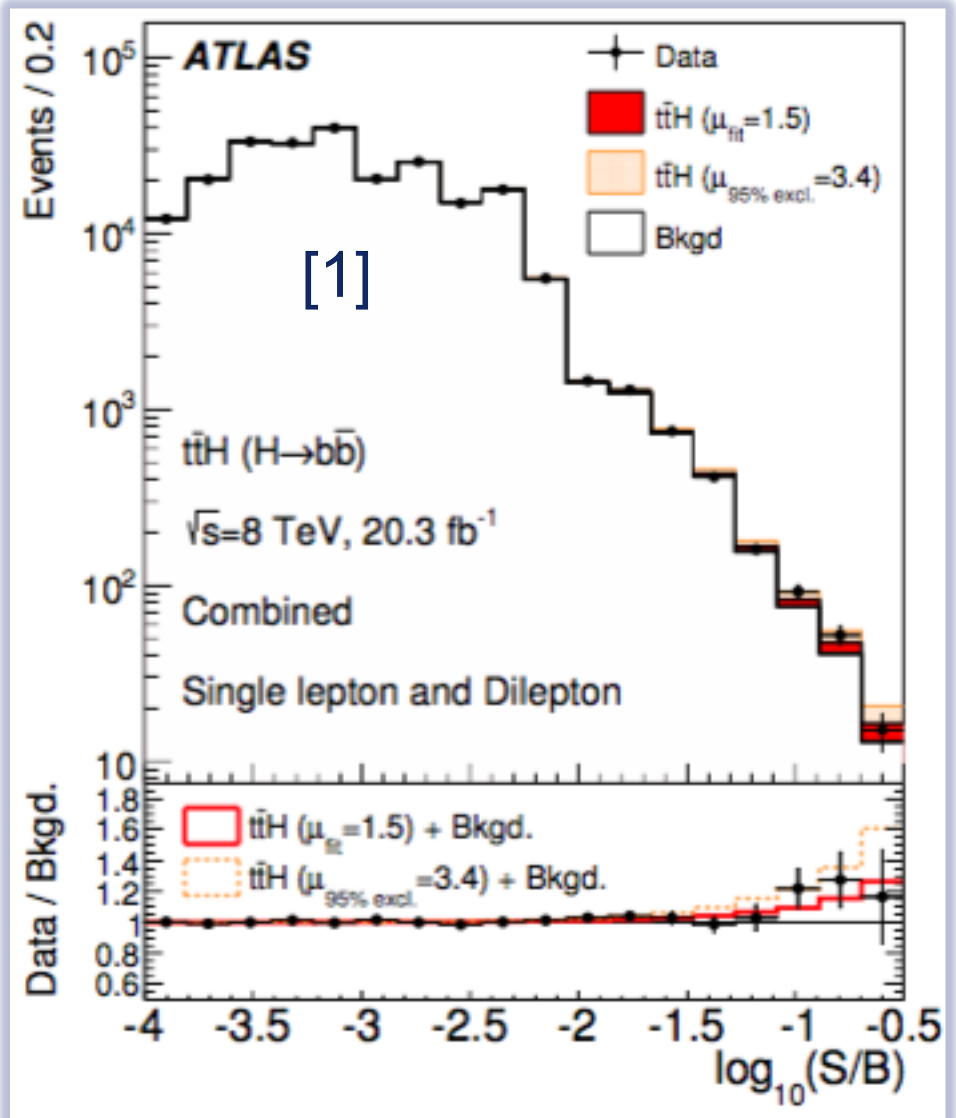
Background

- Nota bene:
  - *H→bb* is NOT the main motivation of *ttH* search
  - Additional motivation: we do it because we can do it!

Direct y_t: motivation for ttH(bb)

- Challenge:
  - σ_{ttH} ≈ 0.1 pb (very small!)
  - Notorious irreducible ($t\bar{t} + b\bar{b}$) + instrumental backgrounds
- Focus on ℓ+jets final states:

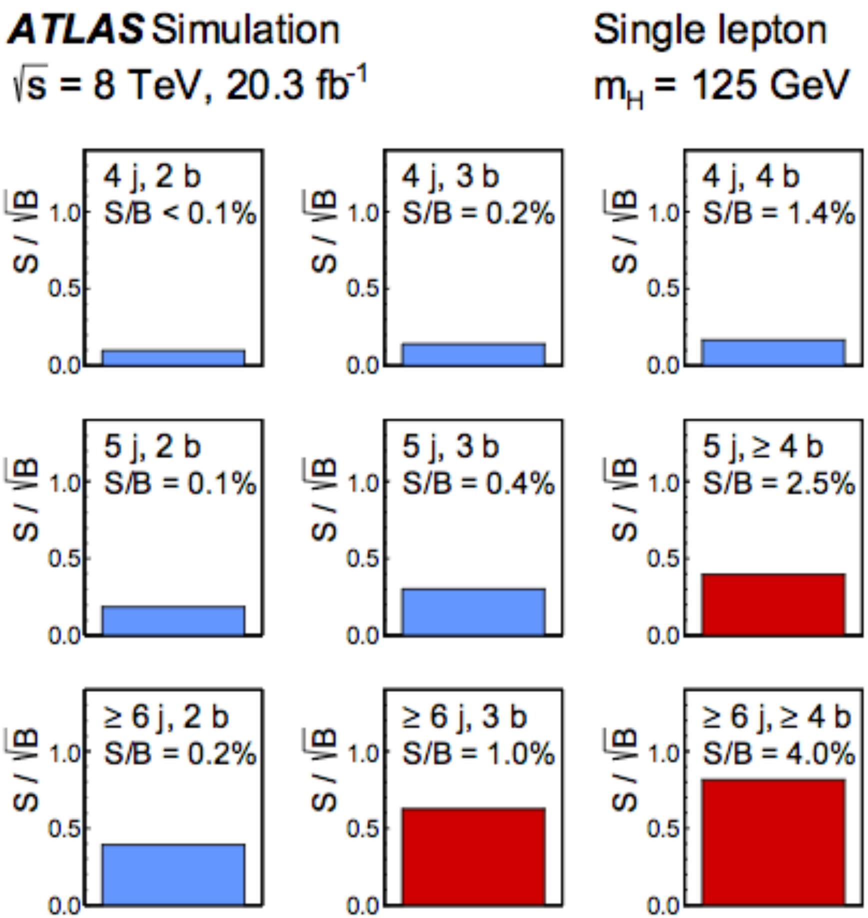




[1] EPJC (2015) 75:349

Direct y_t: analysis strategy

- Maximise sensitivity by splitting into different regions
  - Different S/B → constrain backgrounds in respective regions



[1] EPJC (2015) 75:349

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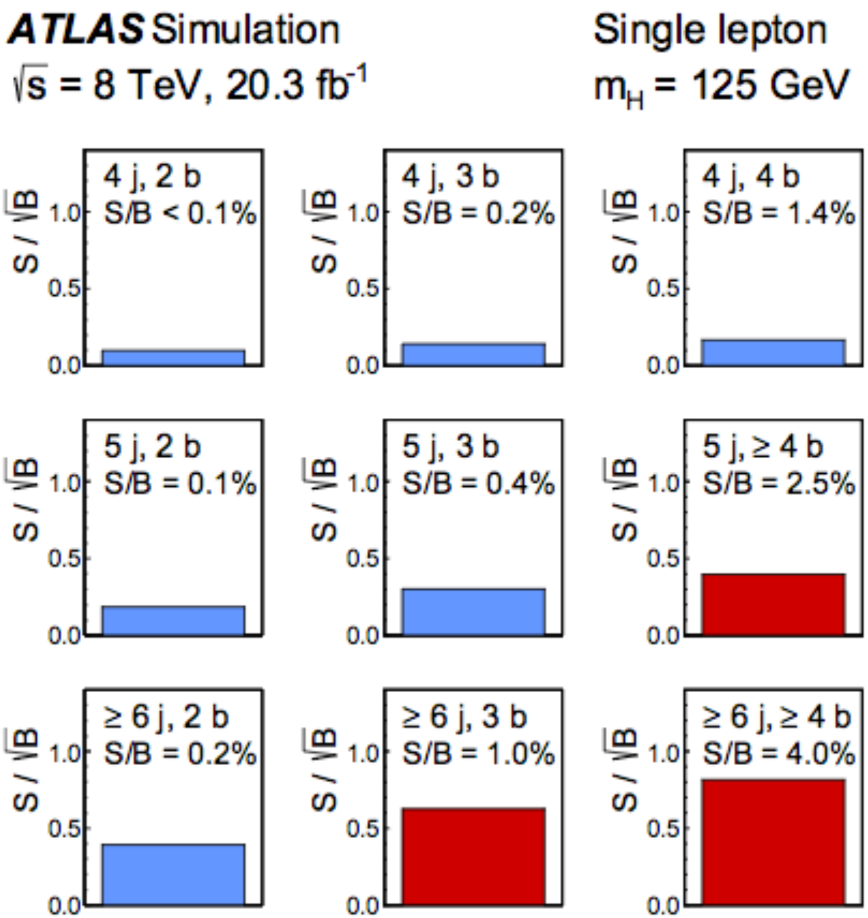
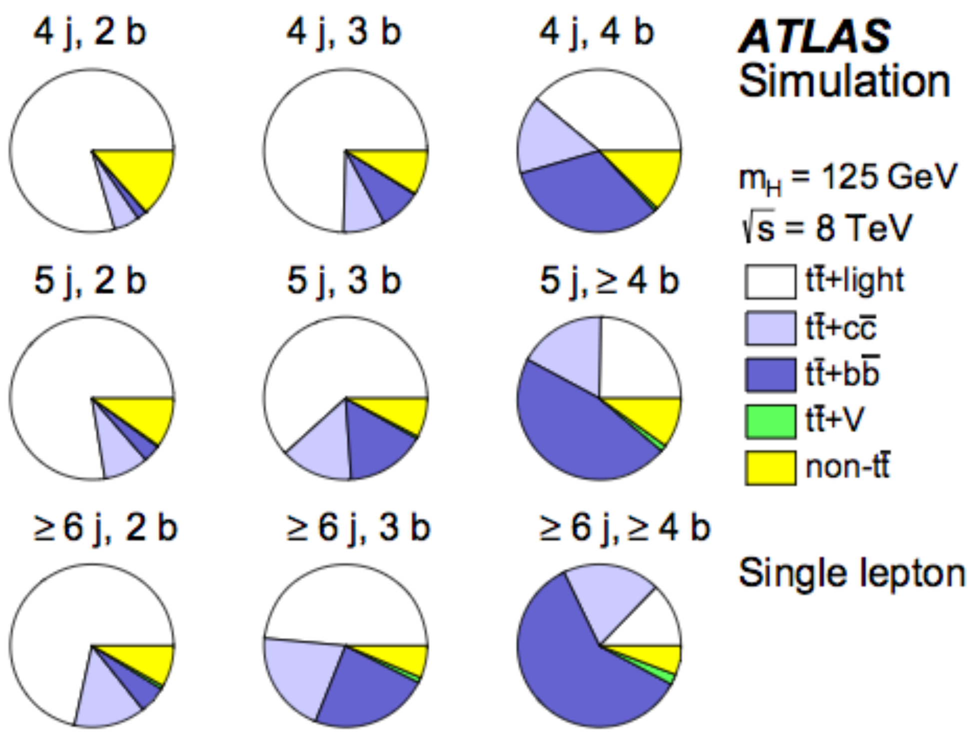


Most important backgrounds:

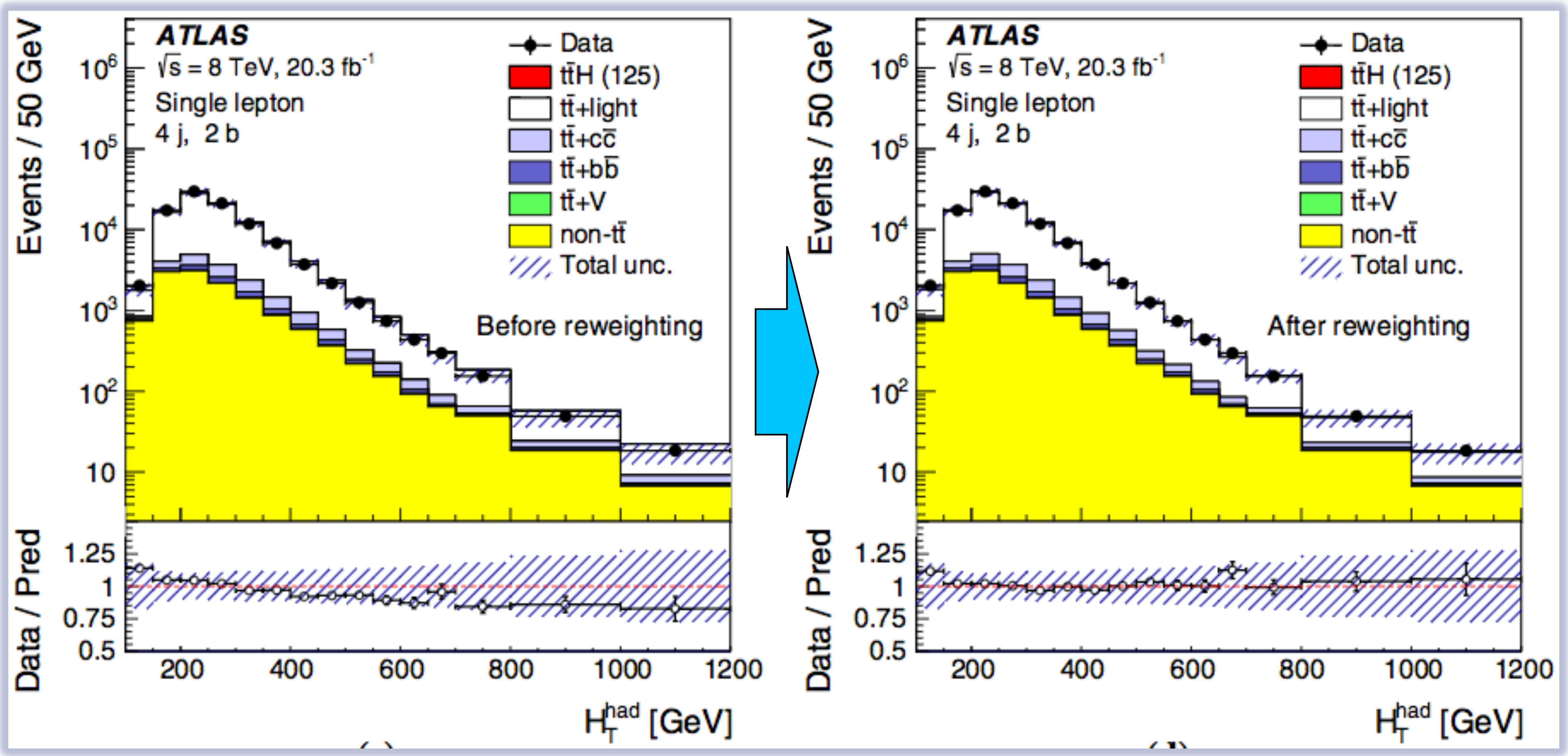
- $t\bar{t} + \mathrm{light}$ (large $\boldsymbol{\sigma}$)
- $t\bar{t} + b\bar{b}$ (irreducible)



[1] EPJC (2015) 75:349

Direct y_t: analysis strategy

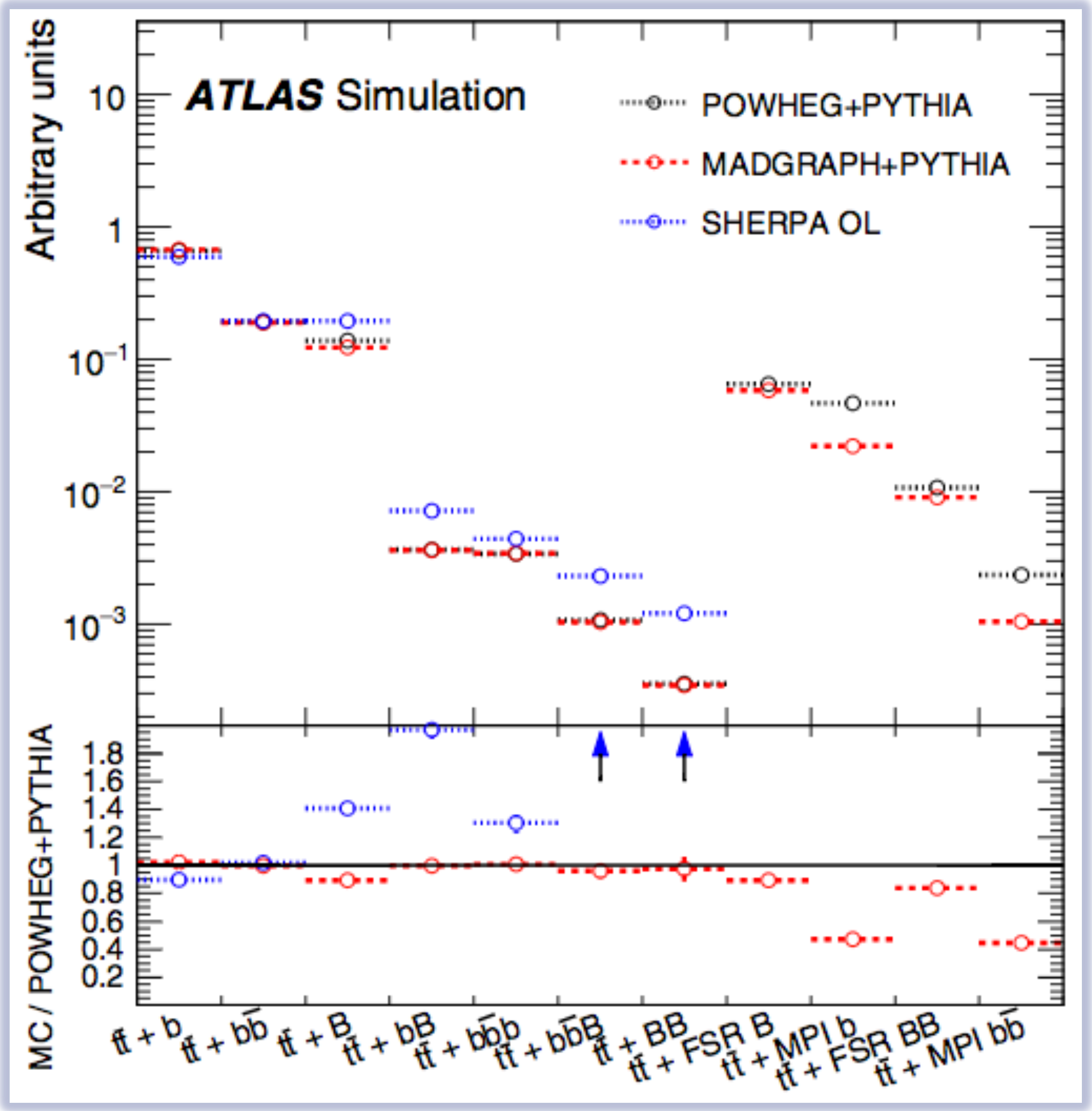
- Reweight $t\bar{t} + \text{light}$ in p_T(top) & p_T(tT)
  - (known modelling issues)



[1] EPJC (2015) 75:349

Direct y_t: analysis strategy

- In most signal-enriched region (6 jets, 4 b-tags):
  - only 4% *ttH*
  - 85% $t\bar{t} + b\bar{b}$
- → Modelling of $t\bar{t} + b\bar{b}$ crucial!
- Reweight $t\bar{t} + b\bar{b}$ to first NLO calculation
  - Kinematic variables like
    - $\Delta R_{\min}(b, \bar{b})$
    - $p_T(t\bar{t})$
  - Flavour composition! →

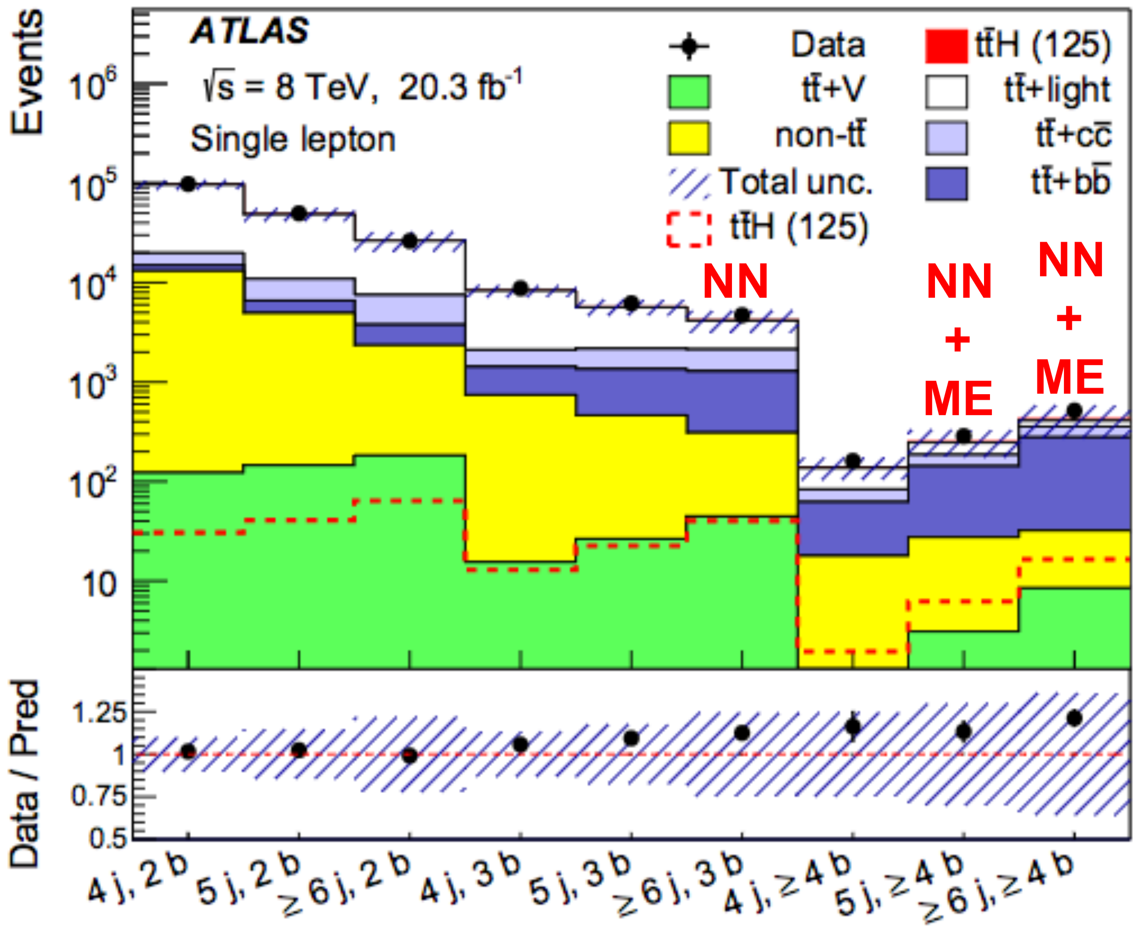


[1] EPJC (2015) 75:349

Direct y_t: analysis strategy

- First look: hopeless!
- Improve sensitivity:
  - Constrain $t\bar{t} + \text{light}$ (yield & shape) in signal-depleted regions with a simultaneous fit
  - Profile systematics
  - Neural Network in 3 signal-enriched regions
  - Discriminate against the irreducible $t\bar{t} + b\bar{b}$ background in signal-enriched regions (6j, 4b) and (5j,4b) using Matrix Element method

Before fit to data

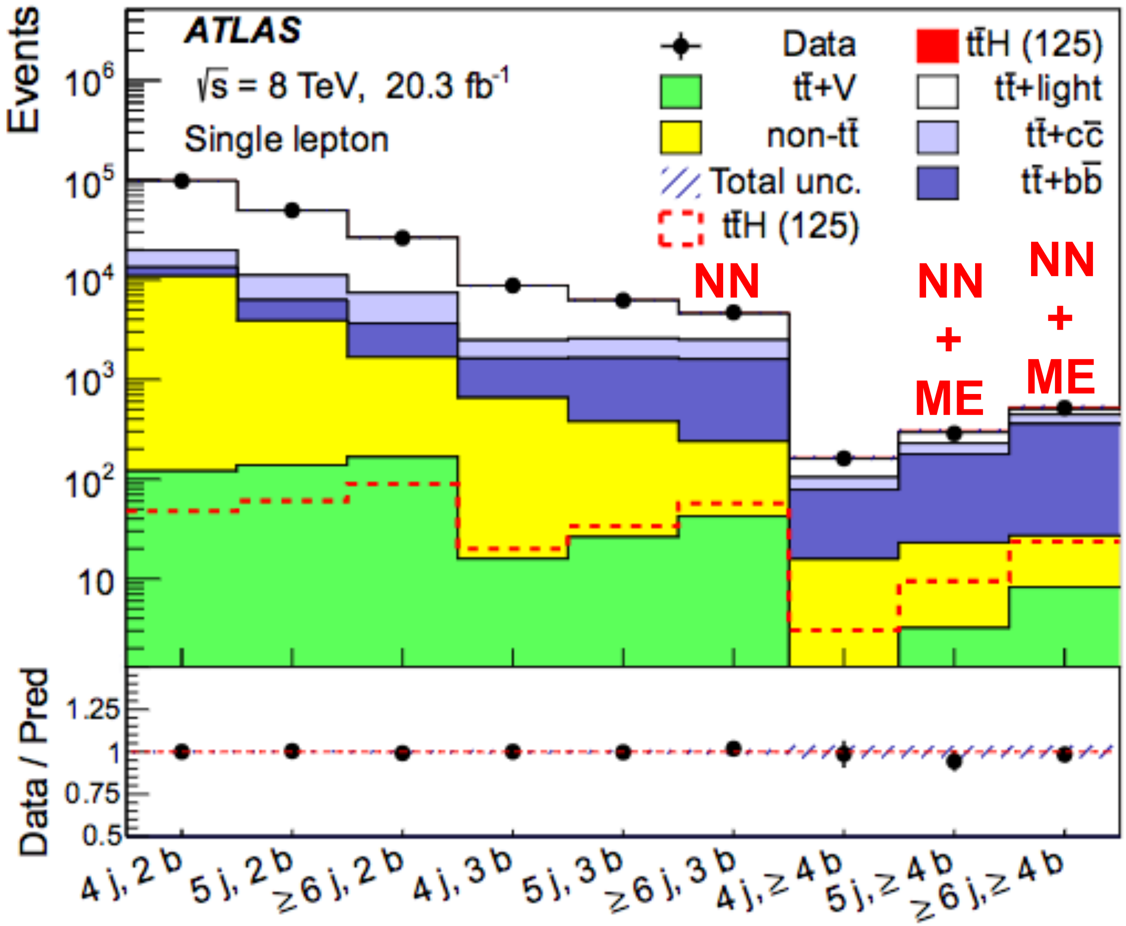


[1] EPJC (2015) 75:349

Direct y_t: analysis strategy

- First look: hopeless!
- Improve sensitivity:
  - Constrain $t\bar{t} + \text{light}$ (yield & shape) in signal-depleted regions with a simultaneous fit
  - Profile systematics
  - Neural Network in 3 signal-enriched regions
  - Discriminate against the irreducible $t\bar{t} + b\bar{b}$ background in signal-enriched regions (6j, 4b) and (5j,4b) using Matrix Element method

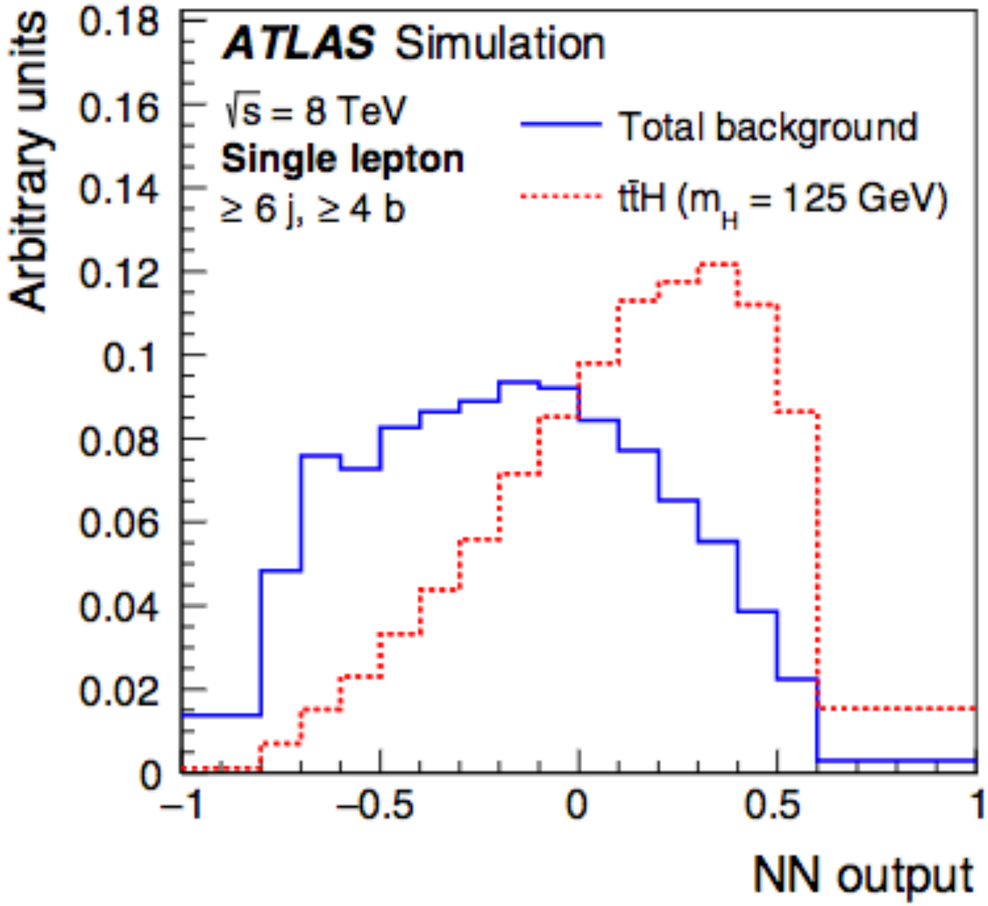
After fit to data



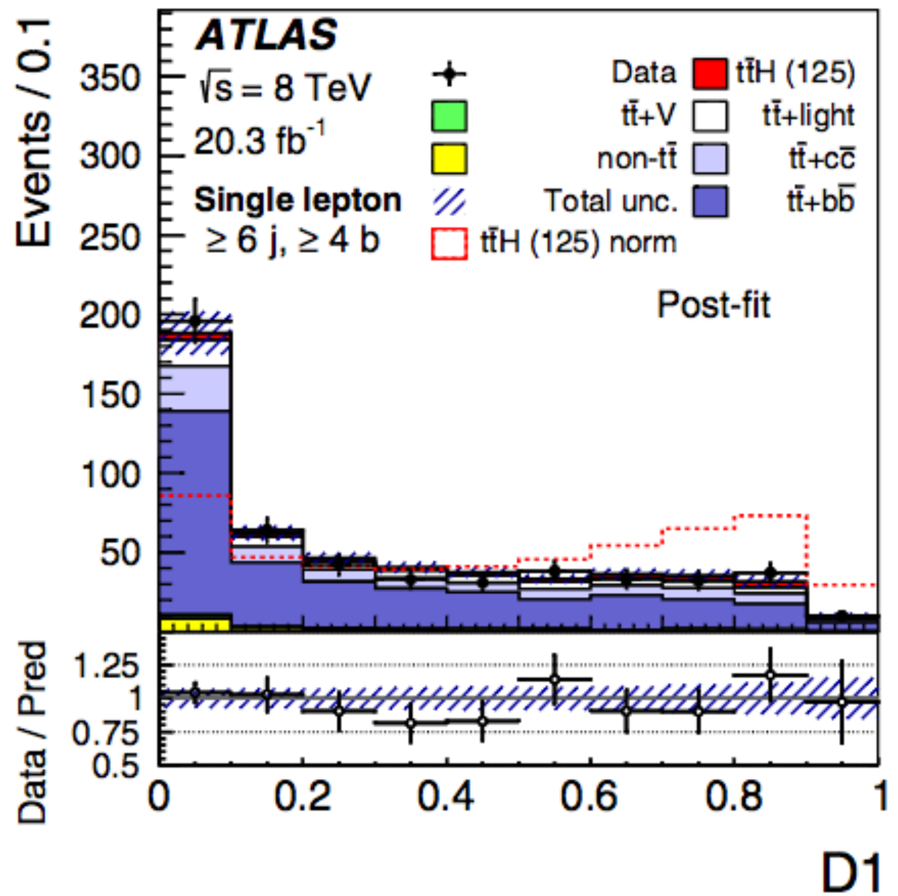
[1] EPJC (2015) 75:349

Direct y_t: analysis strategy

Powerful NN discrimination

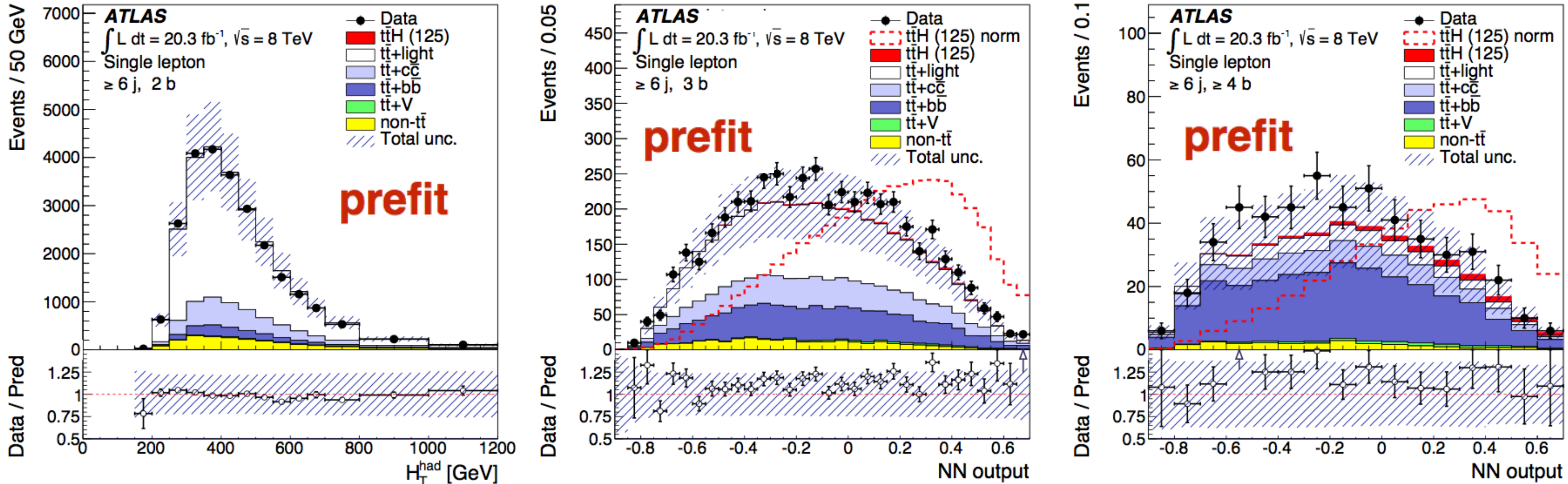


Most discriminant variable in NN: from matrix element

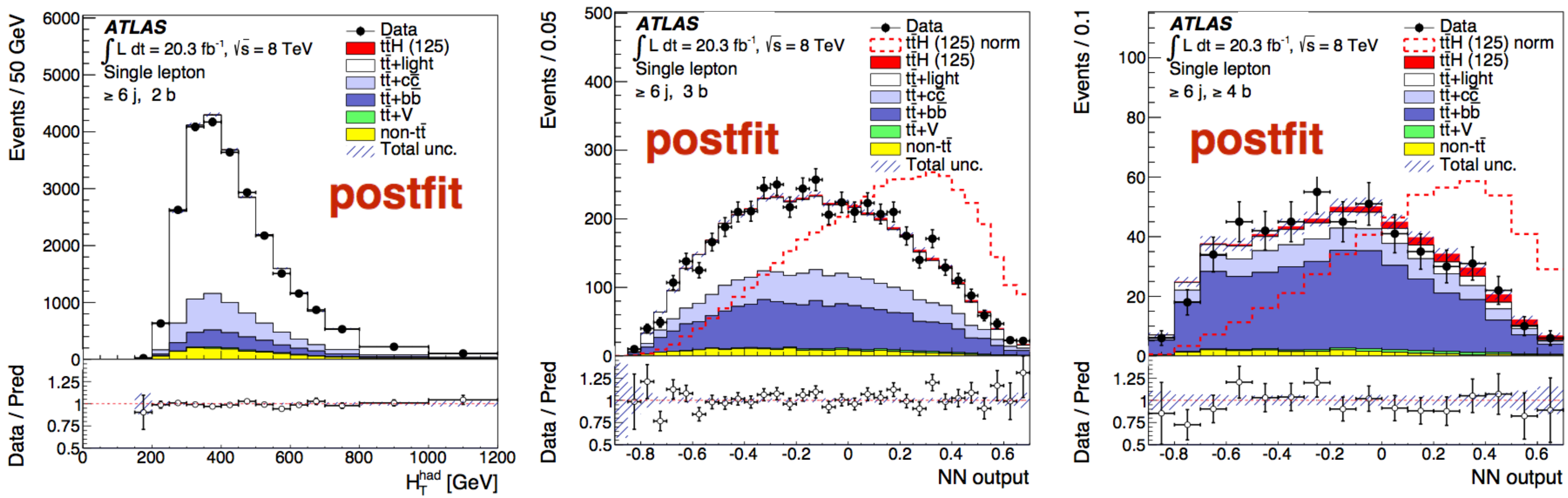


[1] EPJC (2015) 75:349

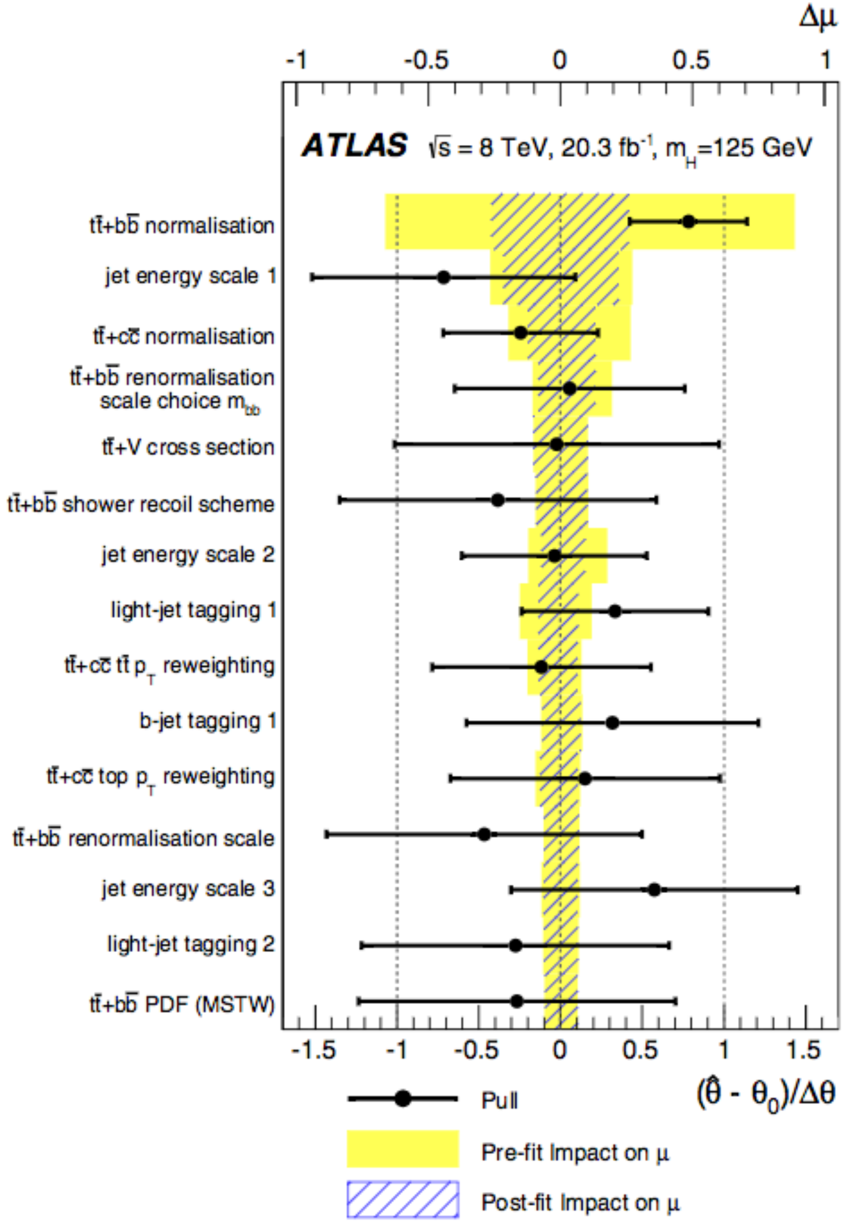
Direct y_t: results for ttH(bb)



EPJC (2015) 75:349

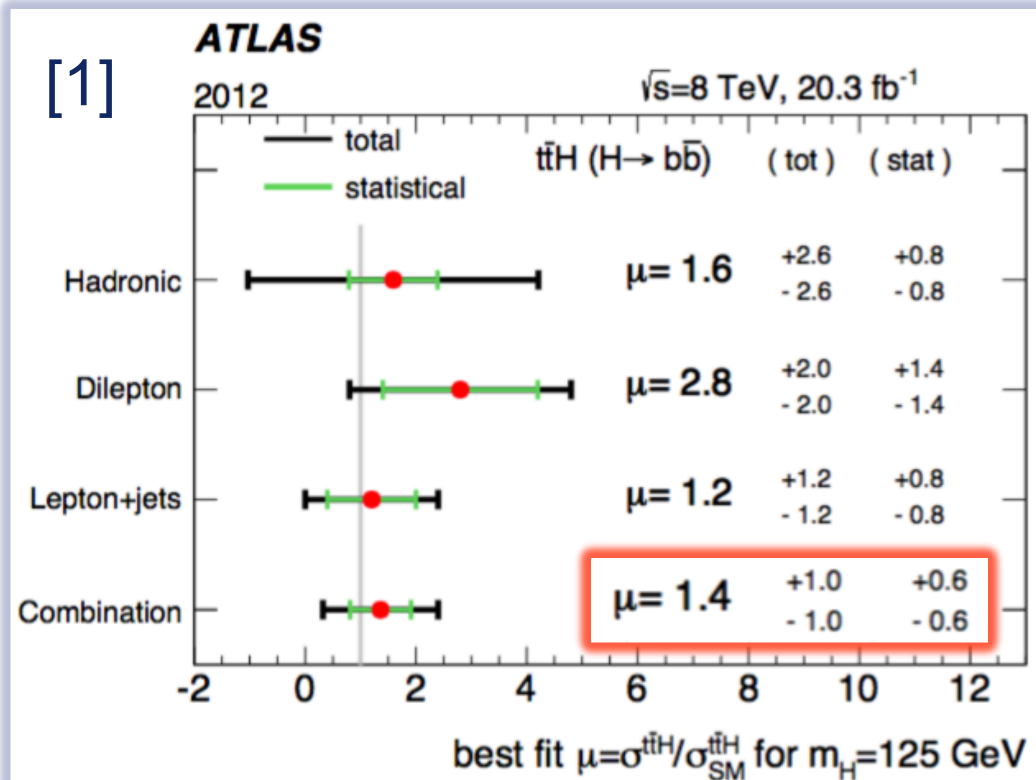


Direct y_t: results for ttH(bb)



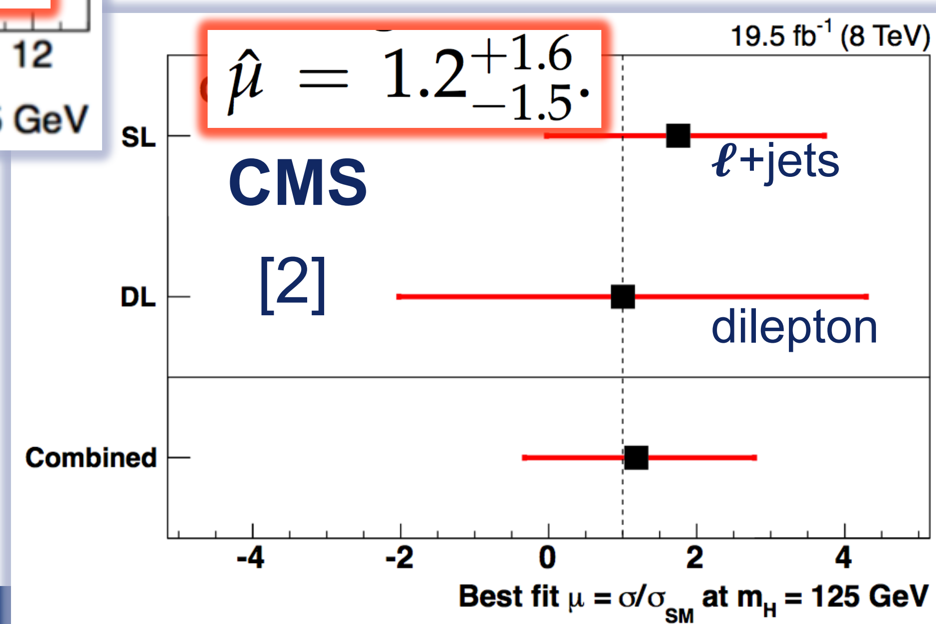
[1] EPJC (2015) 75:349

Direct y_t: results for ttH(bb)



- Did not have time to talk about:
  - Dilepton channel:
    - combined in same analysis
  - Fully hadronic channel:
    - challenging due to QCD bgr
    - in review

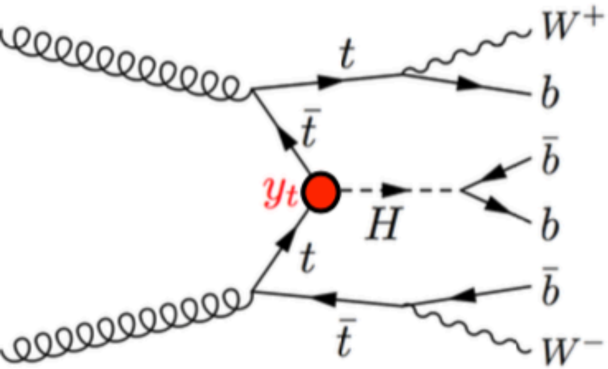
Results with the matrix element method only

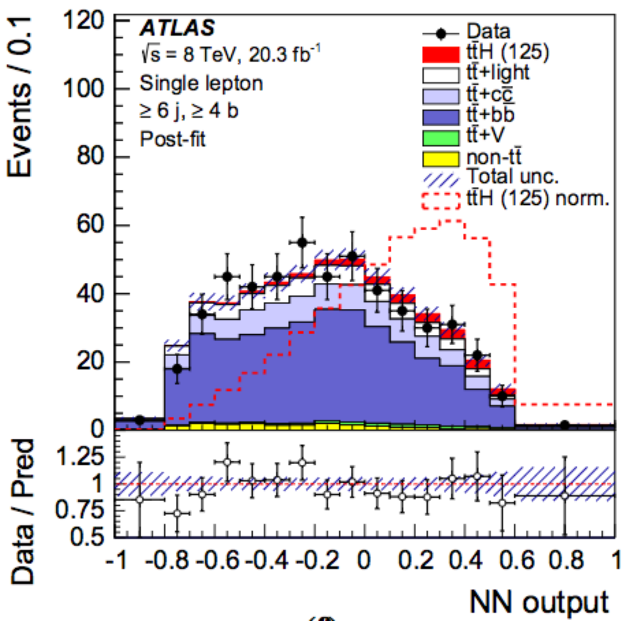


[1] EPJC (2015) 75:349
[2] EPJC (2015) 75:251

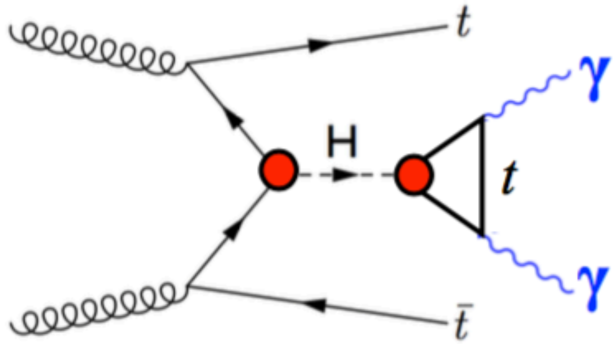
Direct y_t: results for ttH (ATLAS)

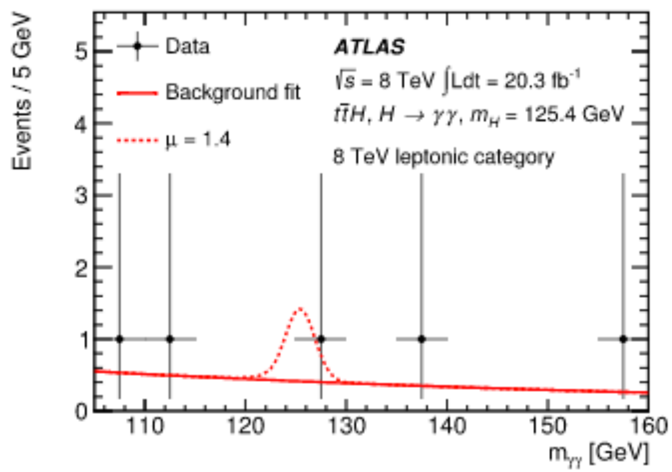
H→bb



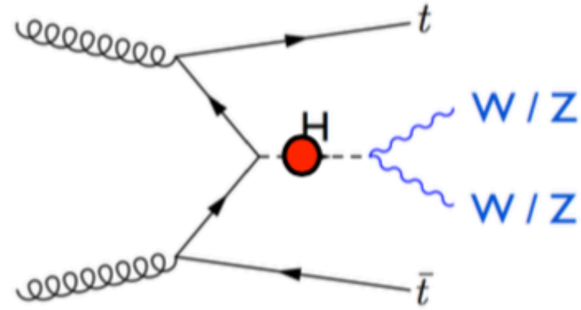


H→γγ

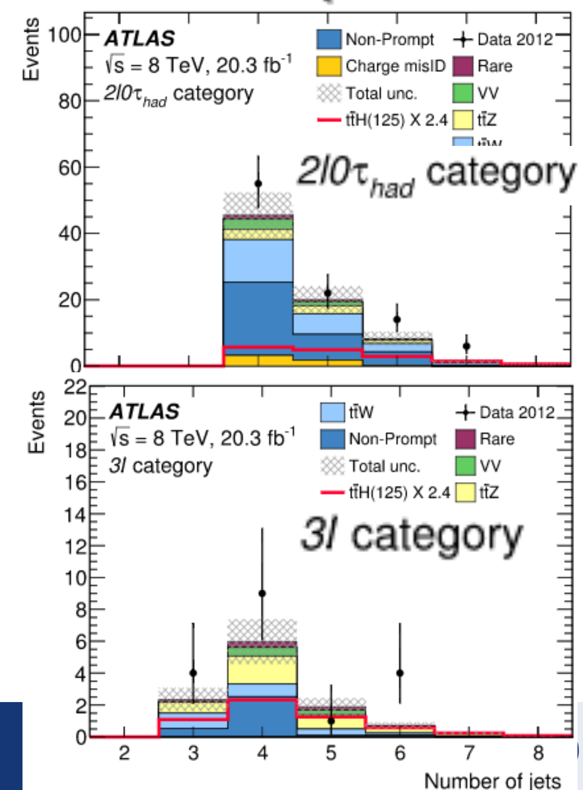




H→WW, ZZ

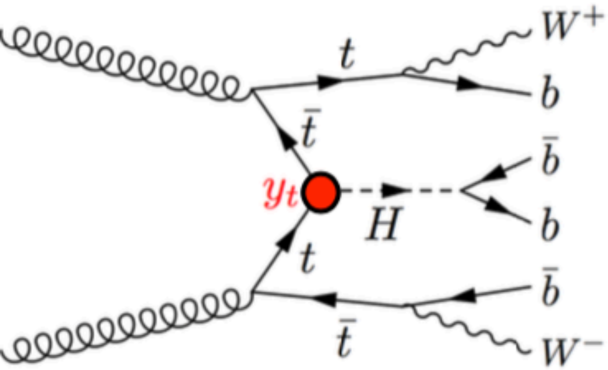


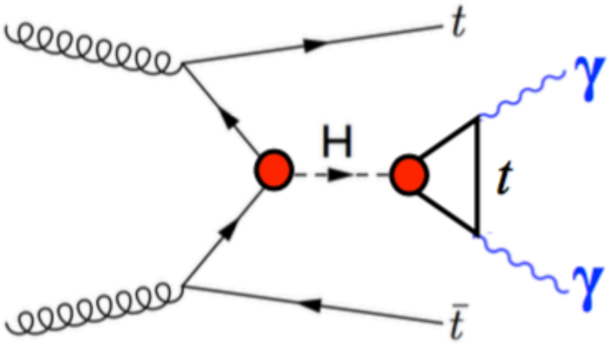
multi-leptons

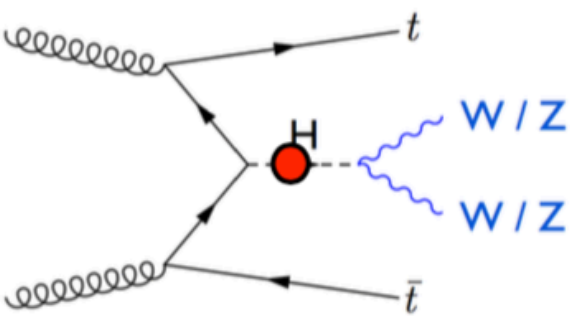


Direct y_t: results for ttH (ATLAS)

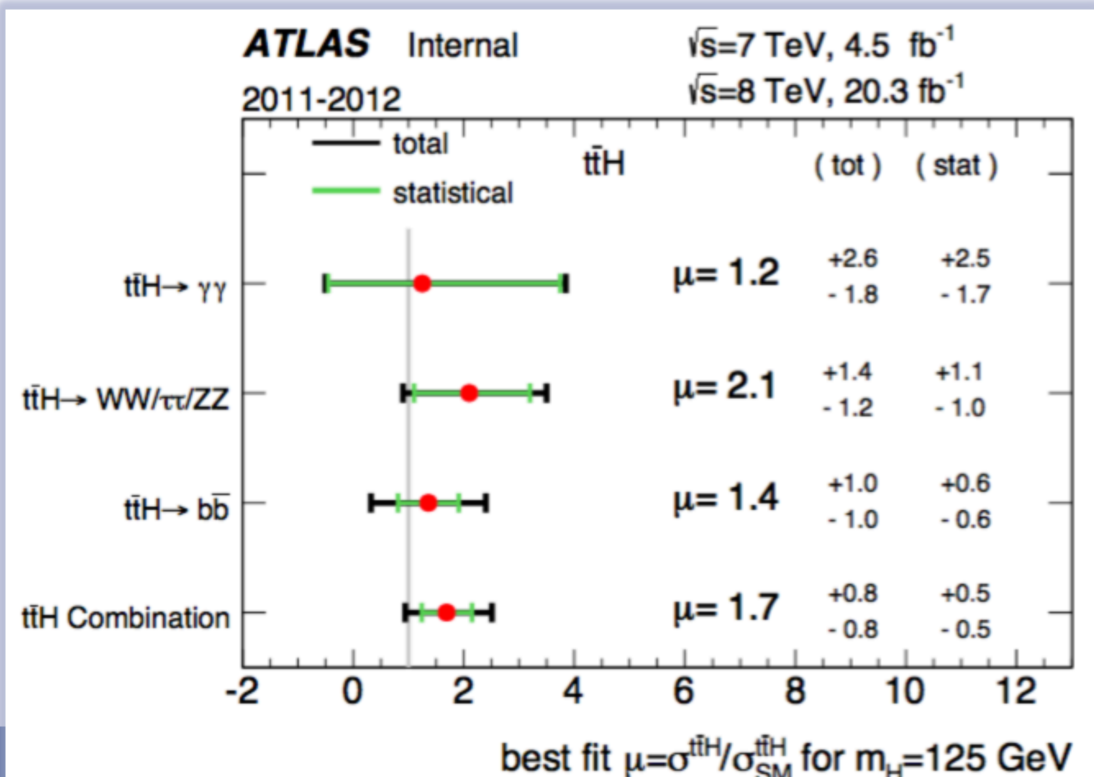
H→bb | **H→γγ** | **H→WW, ZZ**







multi-leptons



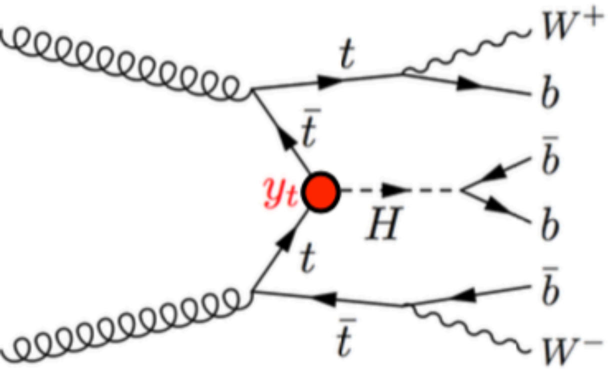
$\mu_{ttH} = 1.4 \pm 0.9$

Consistent with the SM

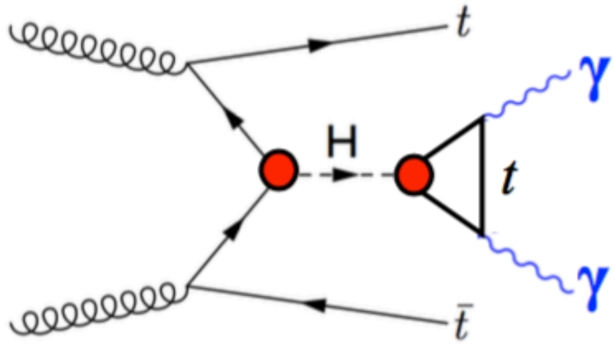
[1] EPJC (2015) 75:349

Direct y_t: results for ttH (CMS)

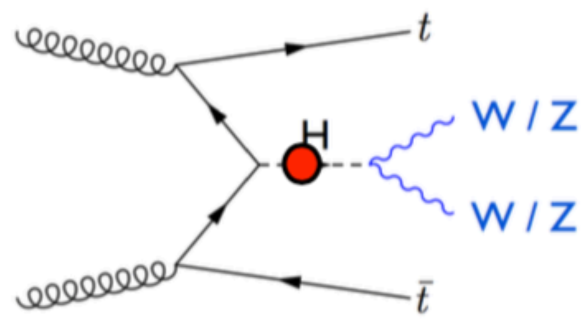
H→bb



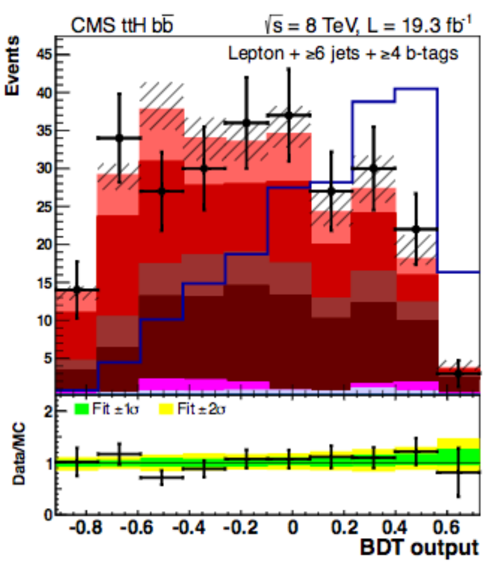
H→γγ

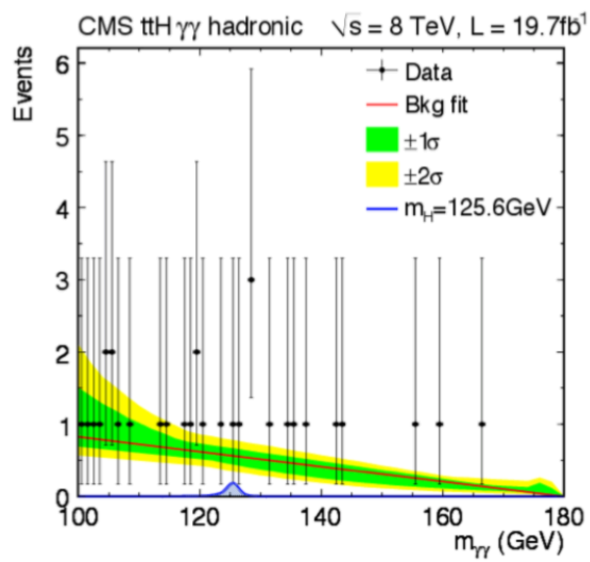


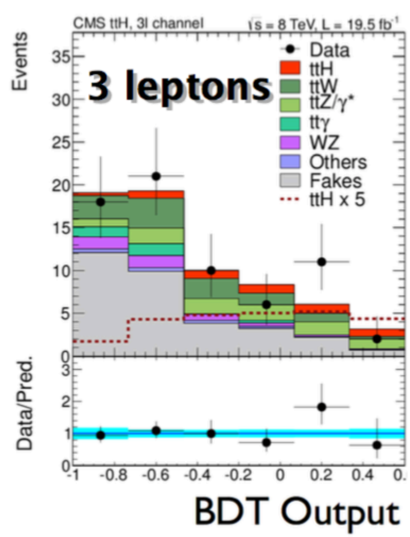
H→WW, ZZ

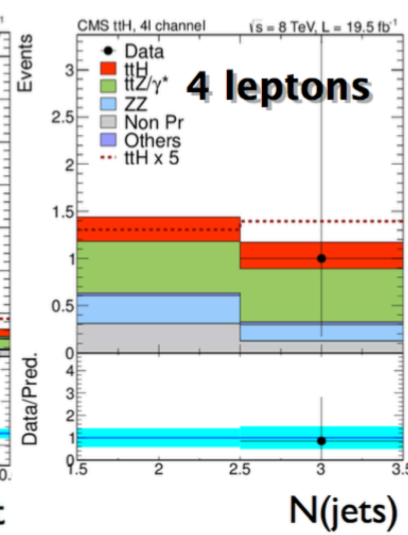


multi-leptons



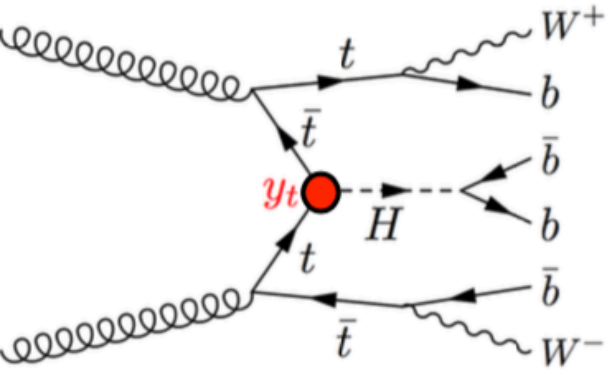




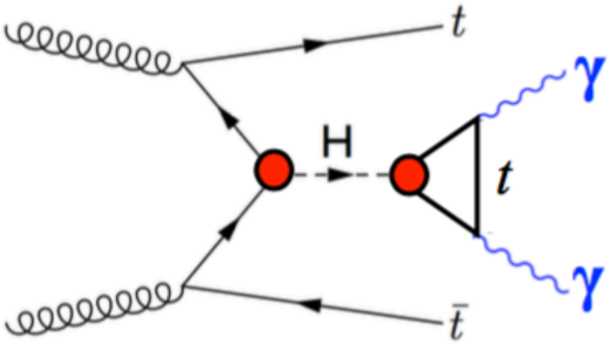


Direct y_t: results for ttH (CMS)

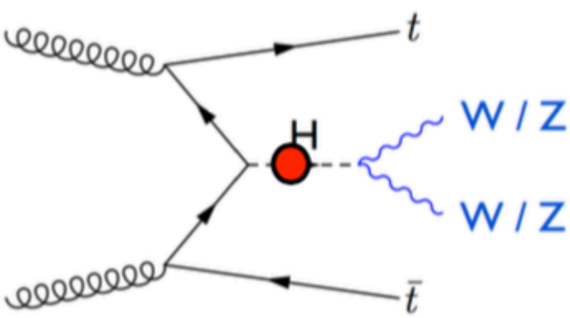
H→bb



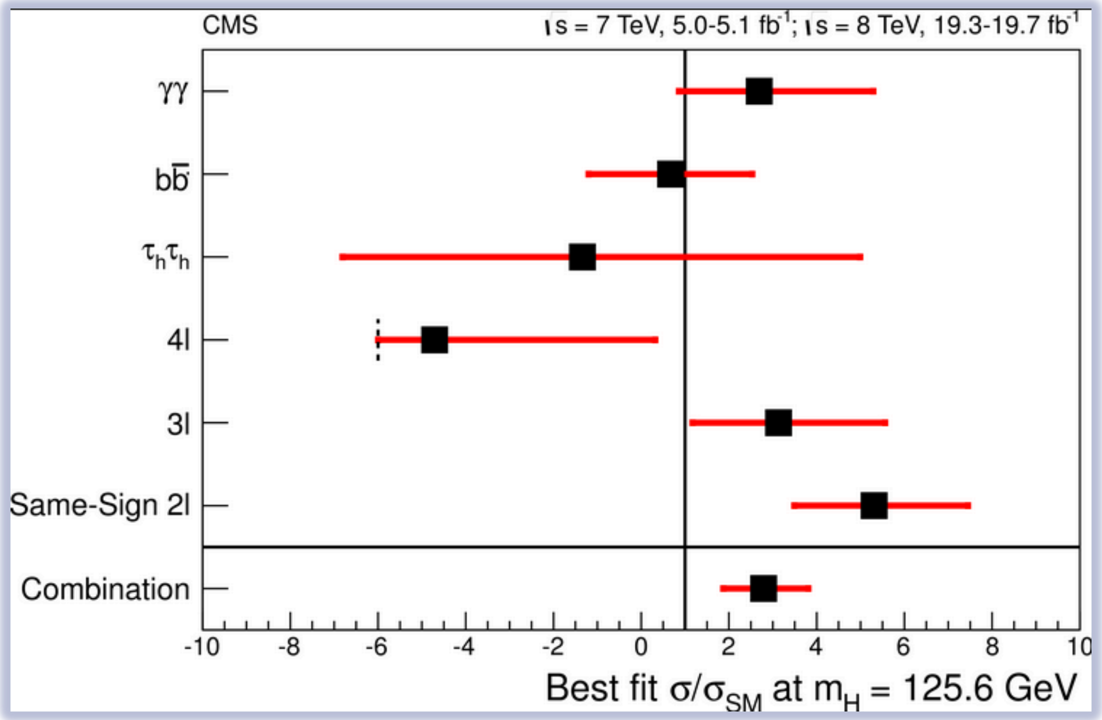
H→γγ



H→WW, ZZ



multi-leptons



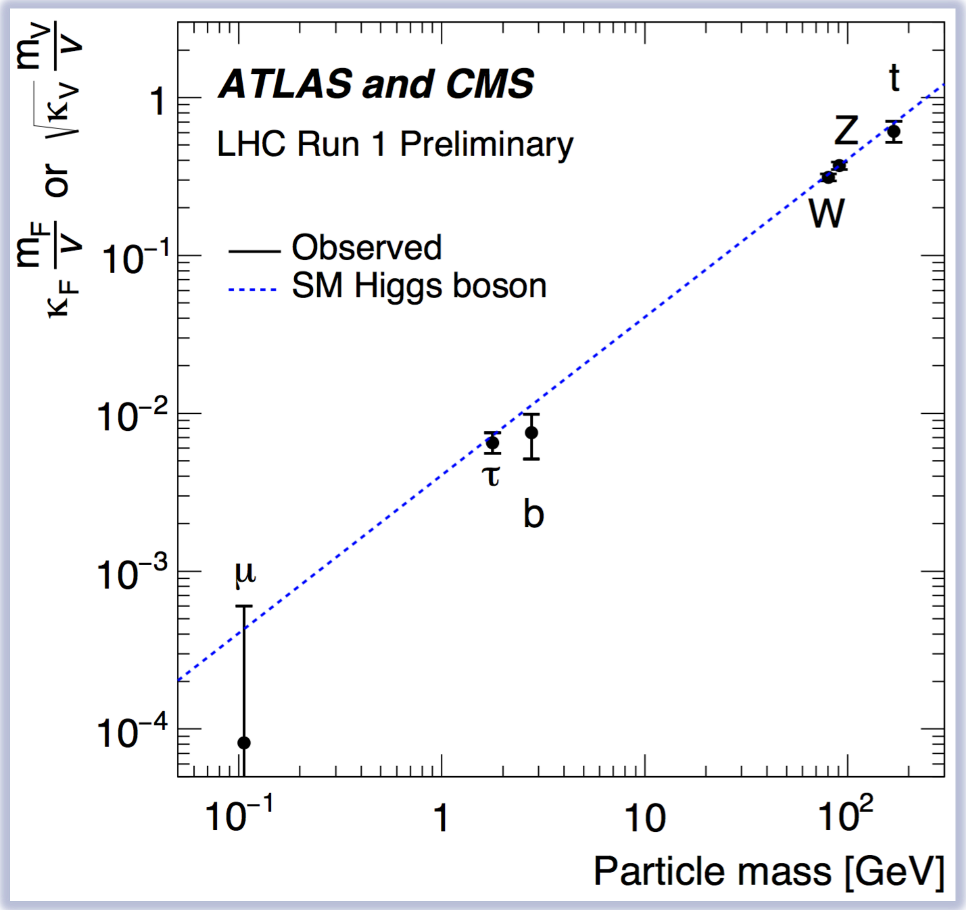
$\mu_{ttH} = 2.8 \pm 1.0$

Still consistent with the SM, but a little bit of tension…

[1] JHEP 09 (2014) 087

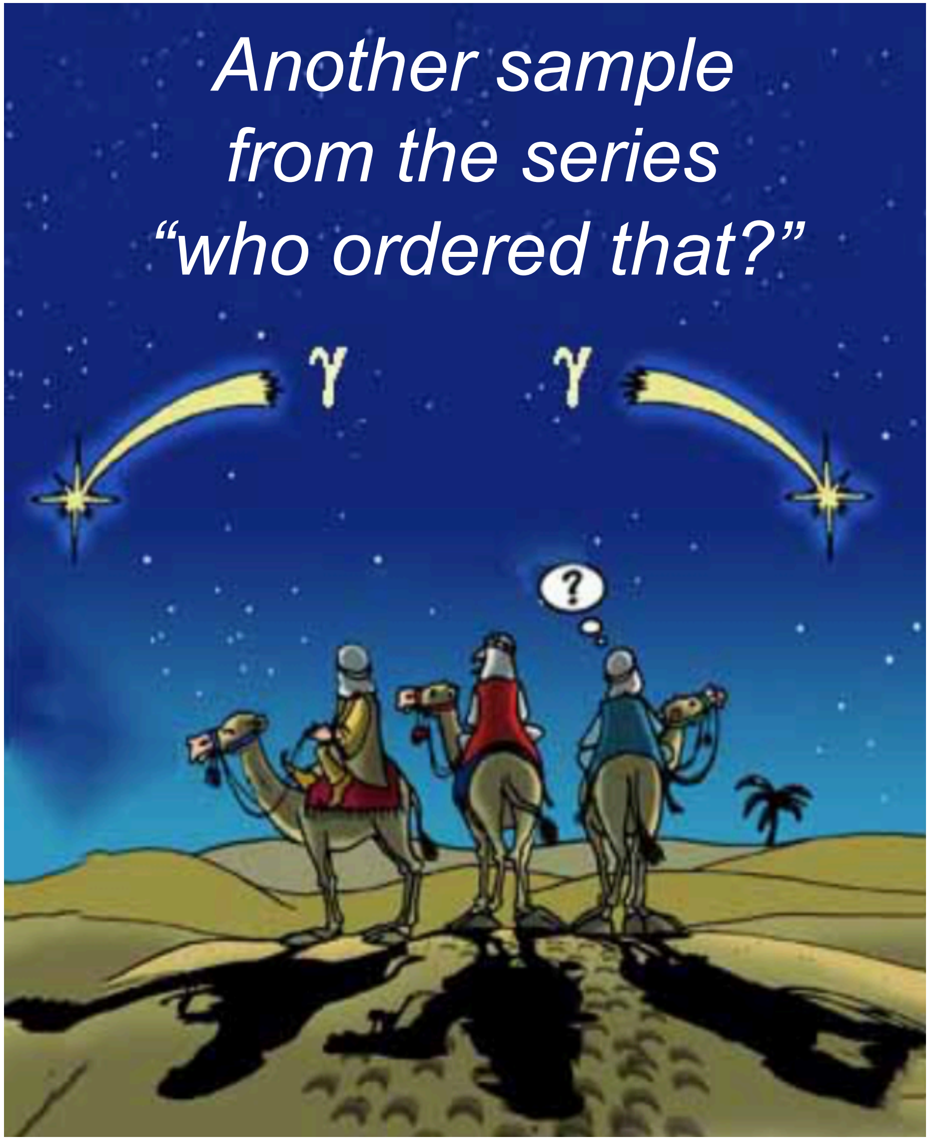
Direct and indirect y_t: summary & outlook

- We came a long way since the Higgs discovery:
  - Higgs couplings measured with unprecedented precision
  - Consistency with SM at the current level of precision
    - Coupling measurements statistically limited
- The SM is a resilient beast!
  - → Lots of work ahead of us in Run 2!




And now for something completely different

Diphoton excess at 750 GeV



ATLAS NOTE

ATLAS-CONF-2015-081

December 15, 2015

Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This note describes a search for new resonances decaying to two photons, with invariant mass larger than 200 GeV. The search is optimized for scalars such as those expected, for example, in models with an extended Higgs sector. The dataset consists of 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV recorded with the ATLAS detector at the Large Hadron Collider. The data are consistent with the expected background in most of the mass range. The most significant deviation in the observed diphoton invariant mass spectrum is found around 750 GeV, with a global significance of about 2 standard deviations. A limit is reported on the fiducial production cross section of a narrow scalar boson times its decay branching ratio into two photons, for masses ranging from 200 GeV to 1.7 TeV.

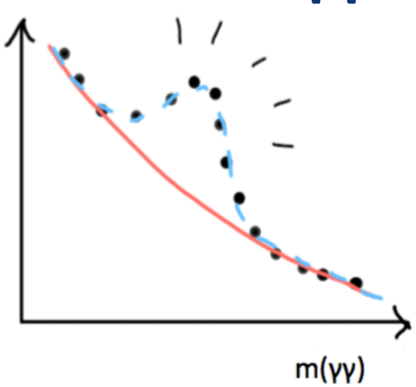
ATLAS-CONF-2015-081
15 December 2015

See also lecture by Mario on Thursday

[1] ATLAS-CONF-2015-081 (13 TeV search)

Diphoton excess at 750 GeV

- **Analysis strategy [1]:**
  - Require 2 photons
    - High-p_T (35 and 25 GeV)
      - Reduce QCD multijet bkg.
    - Isolated
      - Reduce QCD multijet bkg.
  - Bump-hunt in $m_{\gamma\gamma}$ distribution
    - Remake of 8 TeV search [2]
  - (similar to SM $h \rightarrow \gamma\gamma$ search)



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ATLAS-CONF-2015-081 15 December 2015

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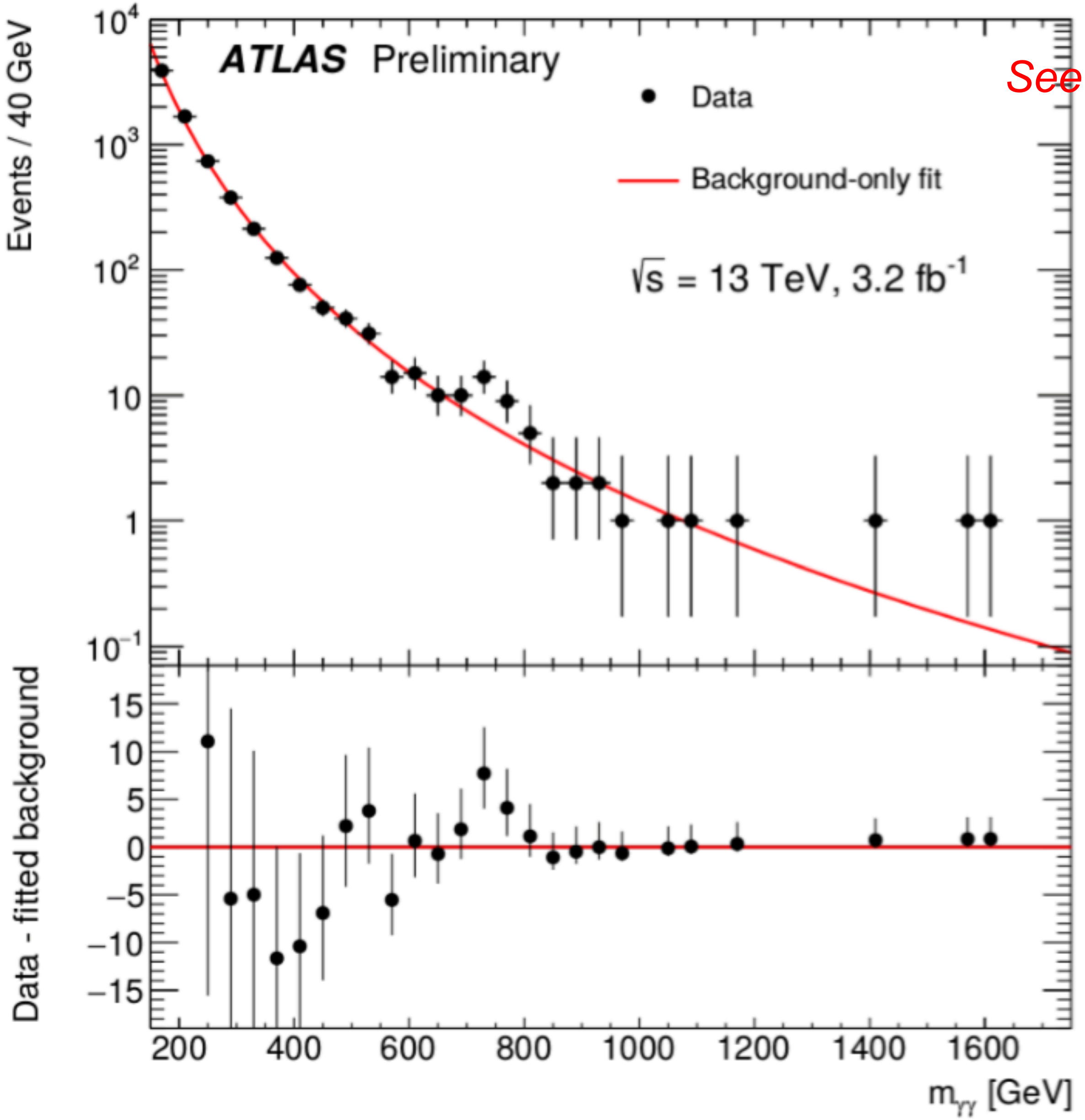
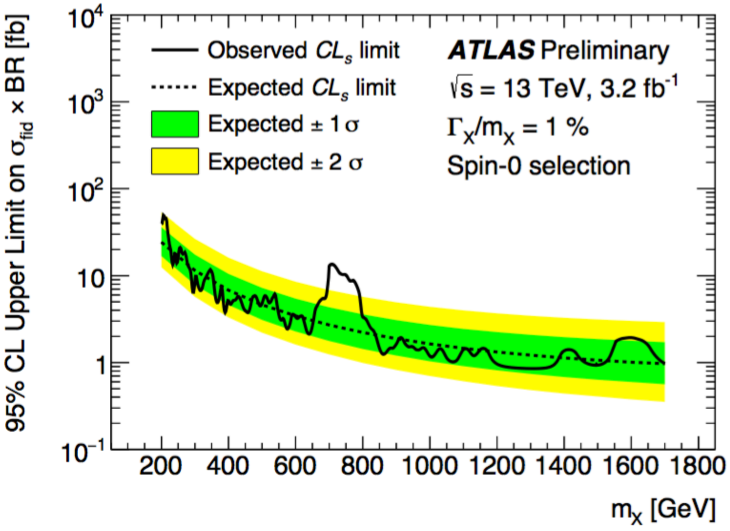
[1] ATLAS-CONF-2015-081 (13 TeV search)
[2] PRL 113, 171801 (2014) (8 TeV search, up to $m_{\gamma\gamma}$ < 600 GeV)

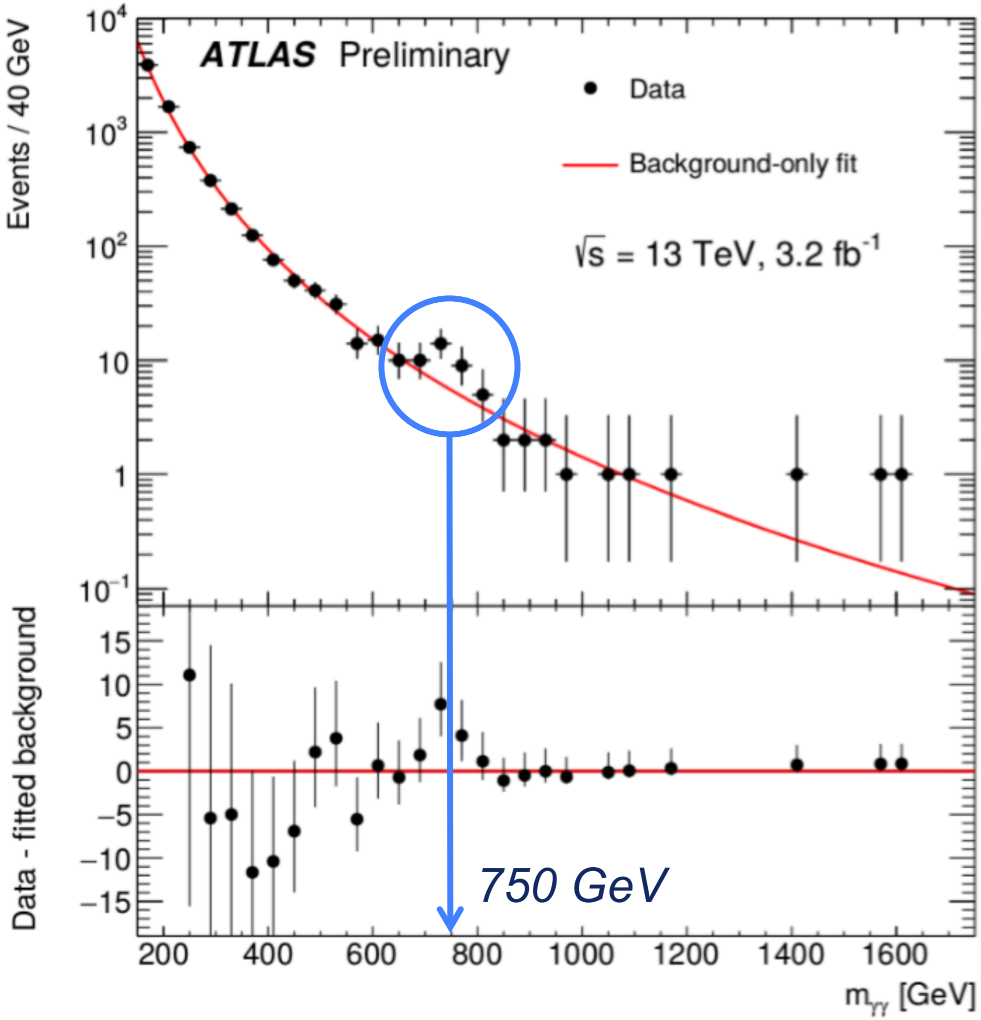
Diphoton excess at 750 GeV

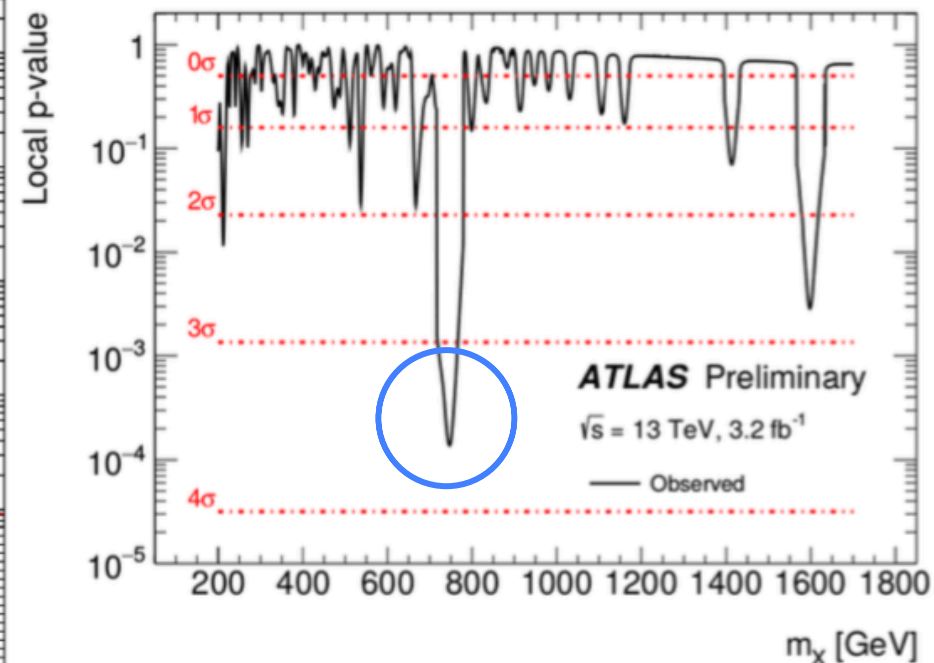


See also lecture by Sigve on Tuesday



Diphoton excess at 750 GeV





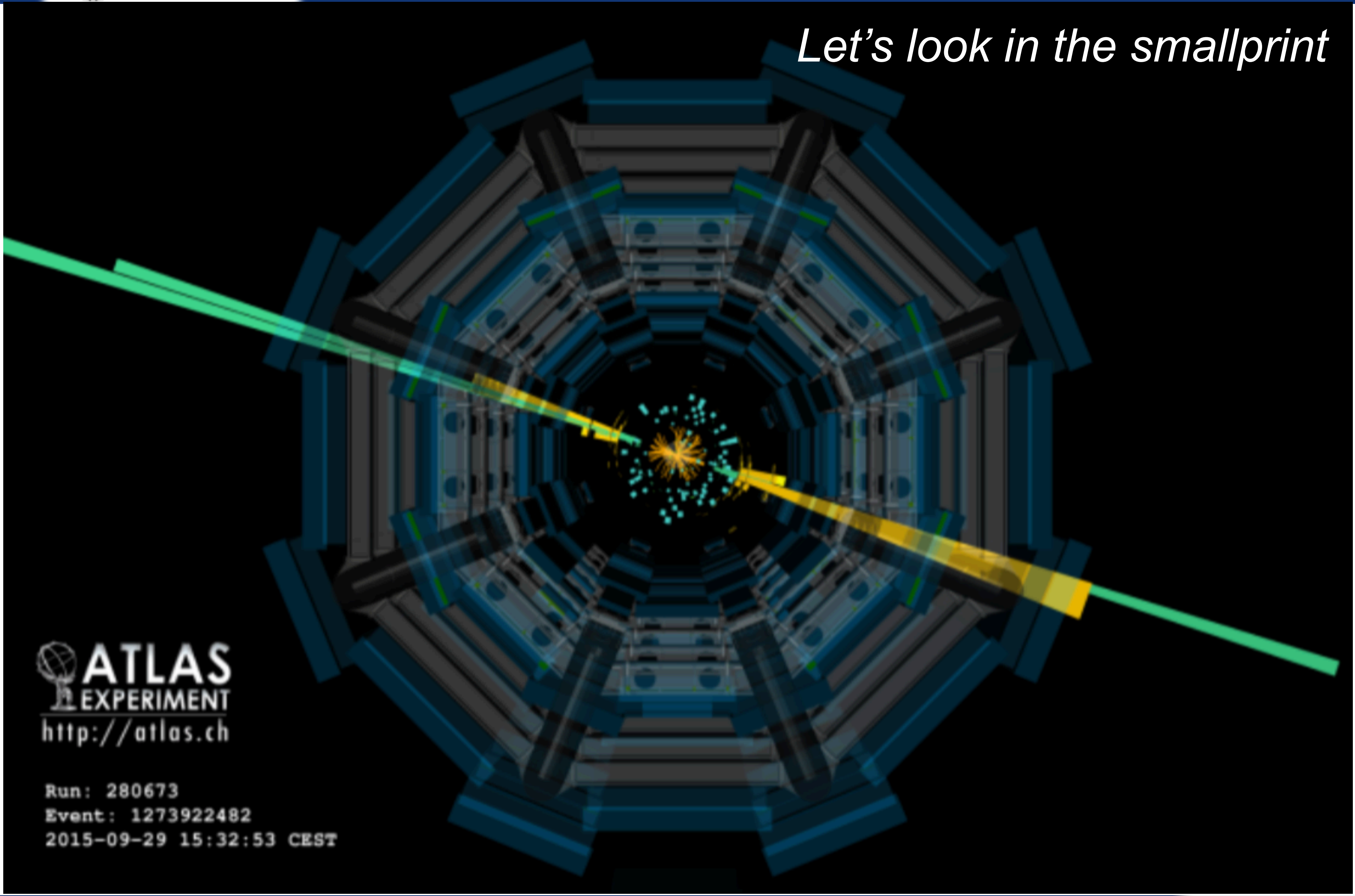
3.6 σ local significance

2.3 σ global significance

More details on the analysis in the following…

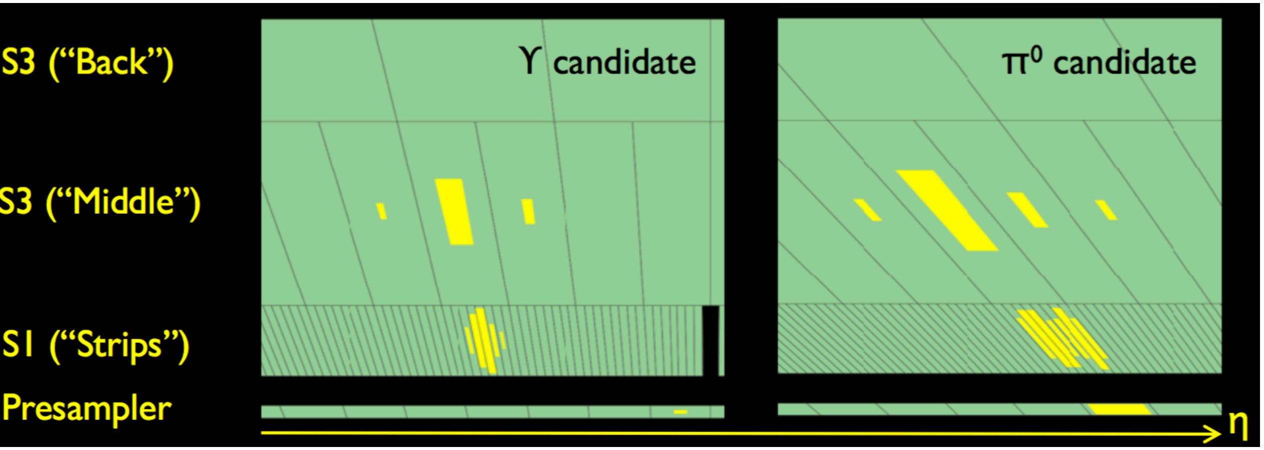
Diphoton excess at 750 GeV

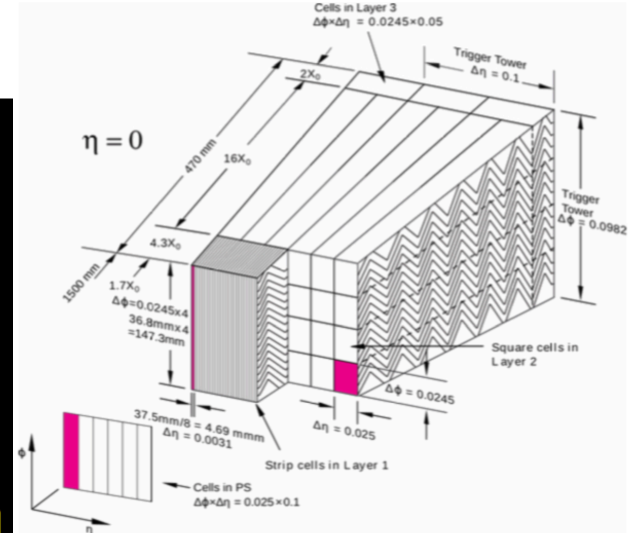
Let's look in the smallprint



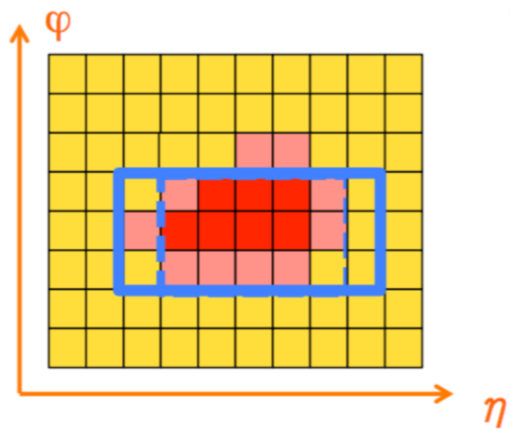
Diphoton excess at 750 GeV

- **Photon reconstruction in a nutshell:**

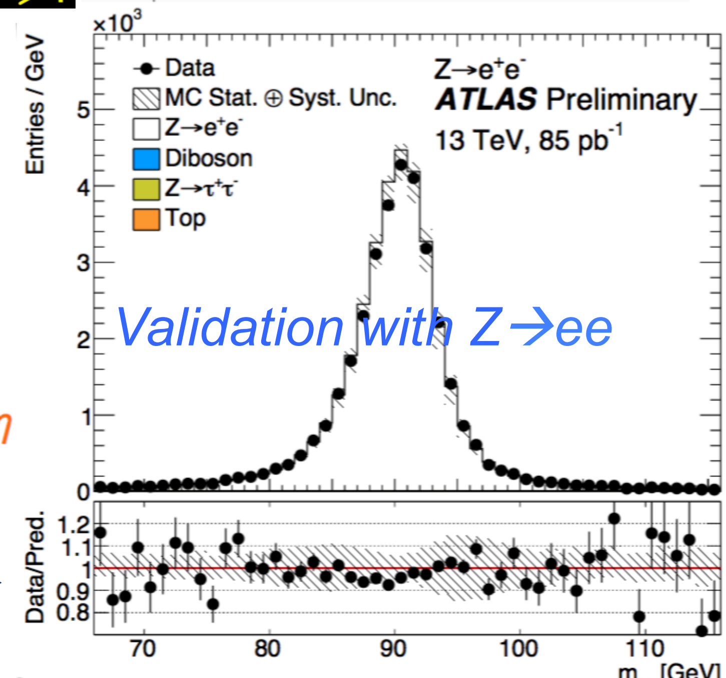




Cluster reconstruction using fixed cone size algorithm, central: $\Delta\eta\times\Delta\varphi=0.075\times0.175$
Size:
compromise between energy leakage and noise



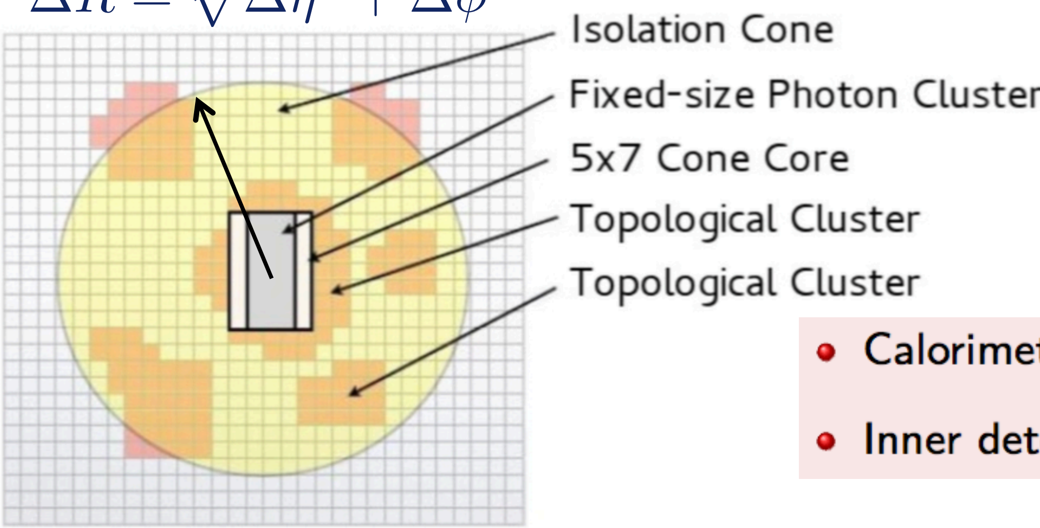
- Use multivariate regression to calibrate photon cluster energy [1] ⟶



[1] EPJC 74 (2014) 3071

Diphoton excess at 750 GeV

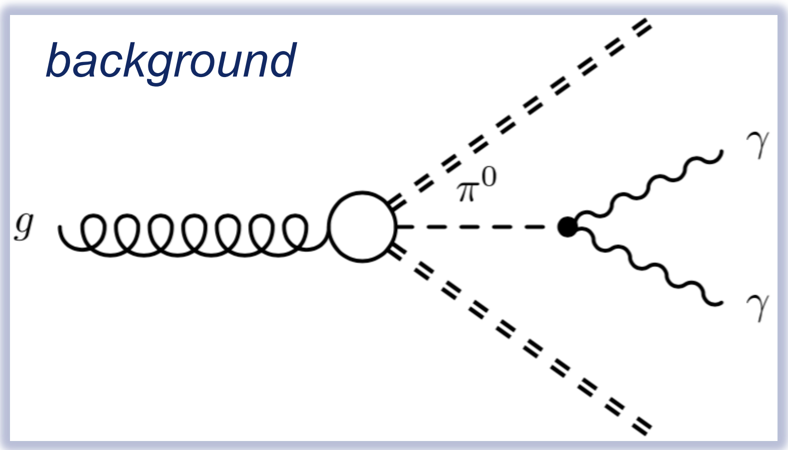
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



- **Isolated photons:**
  - Little activity in tracker/calo in a ΔR cone around the γ
  - Reduces background from jets which mimic γ

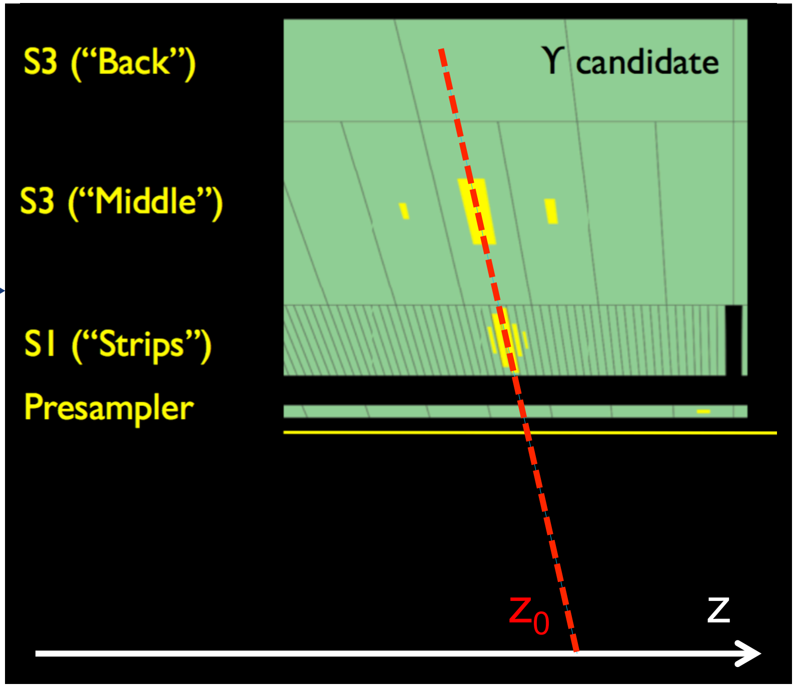
- Calorimeter: $E_T^{iso} < 2.45 + 0.022 \cdot E_T^{\gamma}$ in $\Delta R < 0.4$
- Inner detector: $p_T^{iso} < 0.05 \cdot E_T^{\gamma}$ in $\Delta R < 0.2$

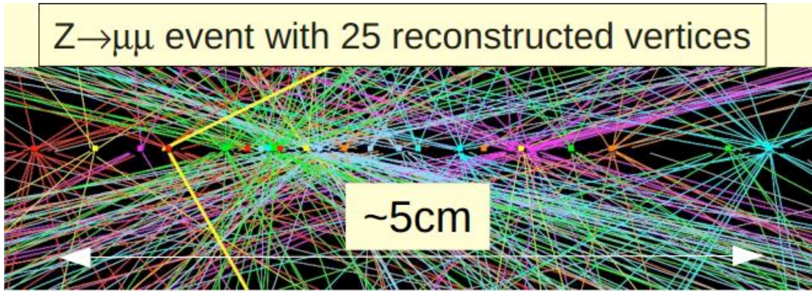
- **Challenge:**
  - Determine γ trajectory to:
  - → calculate isolation
  - → calculate $m_{\gamma\gamma}$
    - Which primary vertex did the γ come from?
      - How to select primary vertex for γ w/o tracks in the tracker?

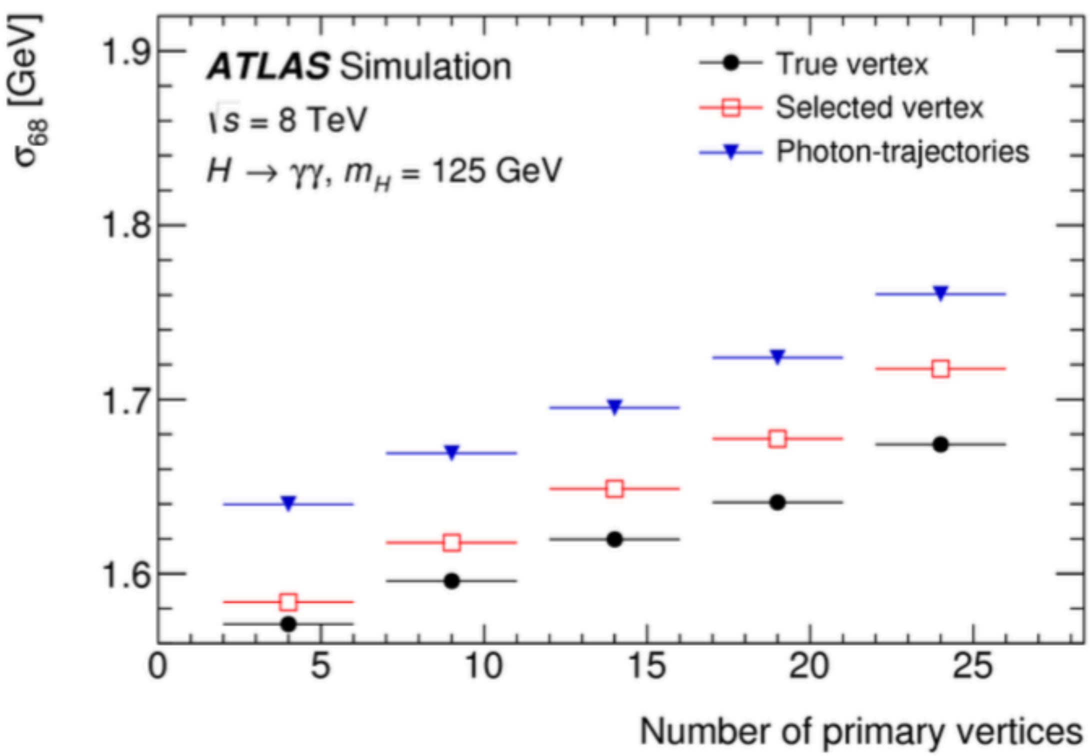


Diphoton excess at 750 GeV

- Exploit longitudinal segmentation of the EM calorimeter
  - Select primary vertex using:
    - Extrapolated z_0 coordinate
    - $\Sigma_{\text{PV tracks}} p_T^2$, $\Sigma_{\text{PV tracks}} p_T$
    - $\Delta\phi(\vec{p}_{T,\gamma\gamma}, \sum_{\text{PV tracks}} \vec{p}_T)$



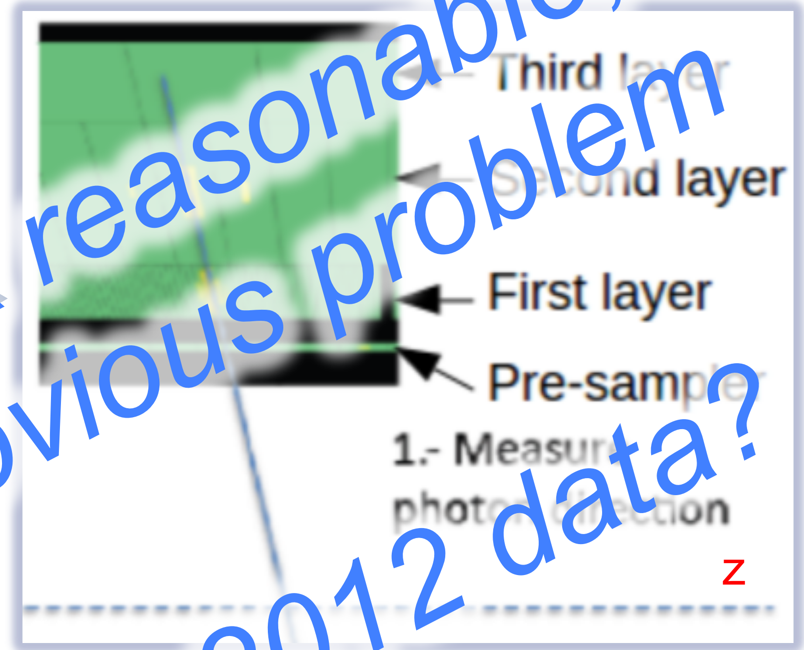


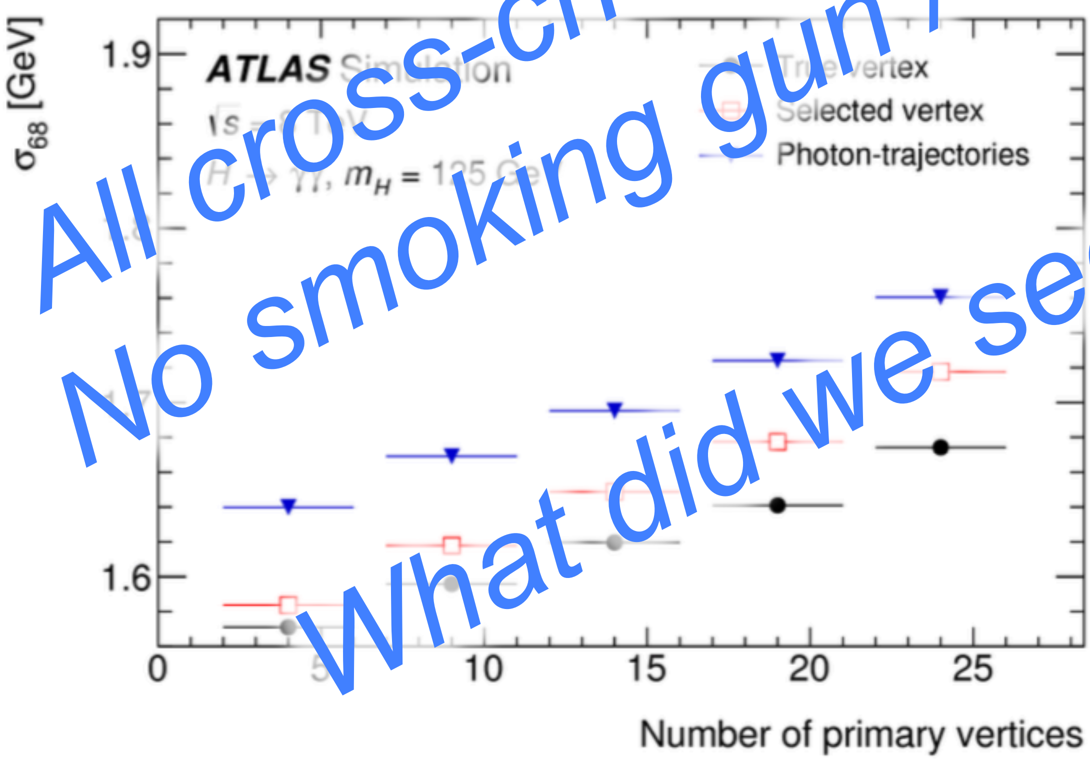


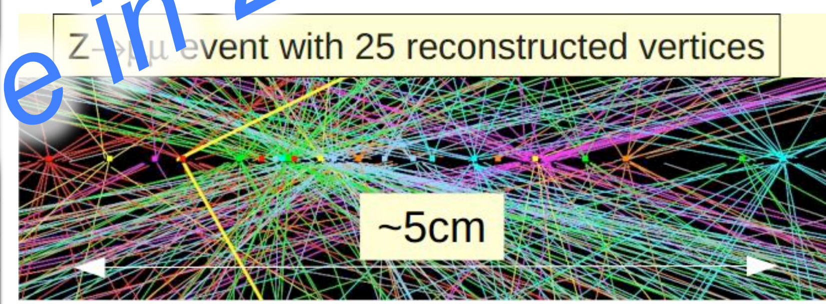
+ other quality and kinematic requirements

Diphoton excess at 750 GeV

- Exploit longitudinal segmentation of the EM calorimeter
  - Select primary vertex using:
    - Extrapolated z coordinate
    - $\Sigma_{\text{PV tracks}} p_T^2$, $\Sigma_{\text{PV tracks}} p_T$
    - $\Delta\phi(\vec{p}_{T,\gamma\gamma}, \sum_{\text{PV tracks}} \vec{p}_T)$



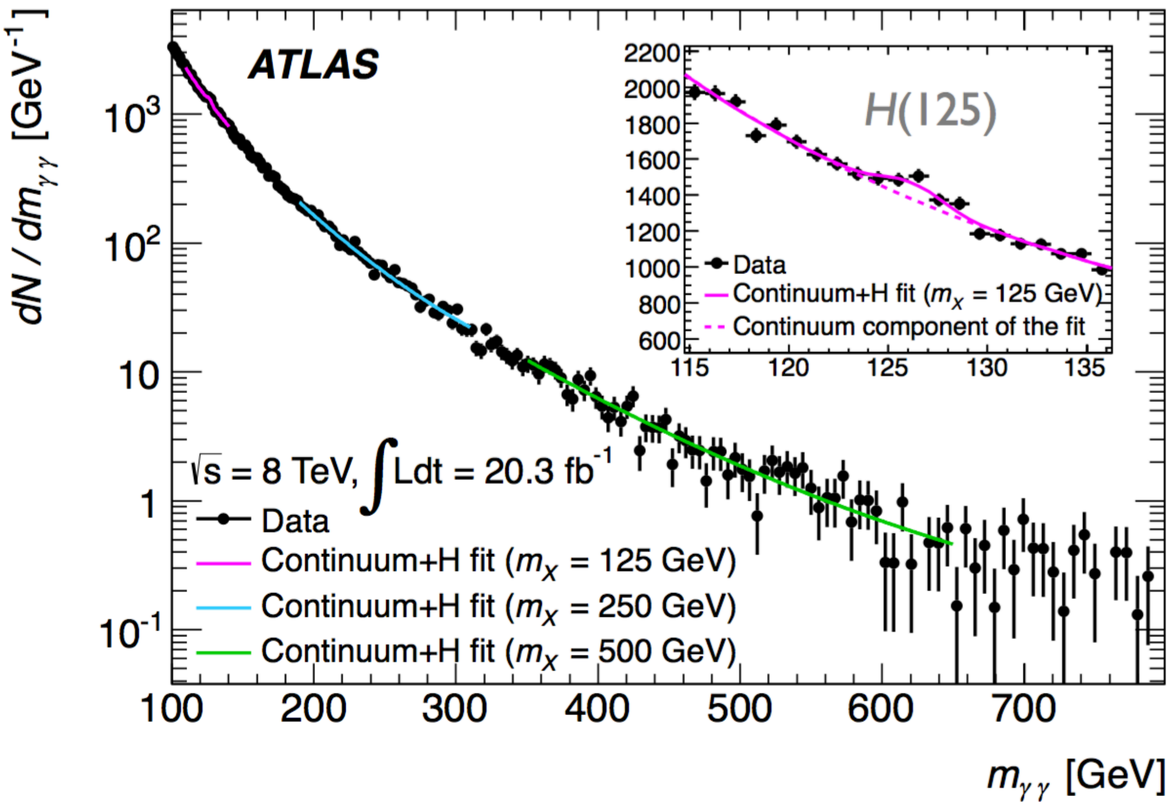


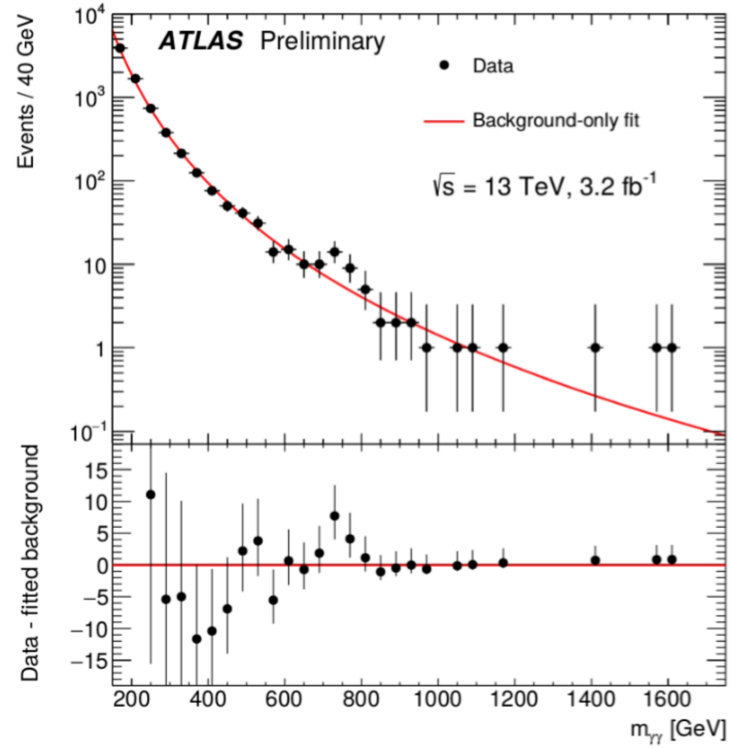


+ *other quality and kinematic requirements*

All cross-checks look reasonable,
No smoking gun / obvious problem
What did we see in 2012 data?

Diphoton excess at 750 GeV



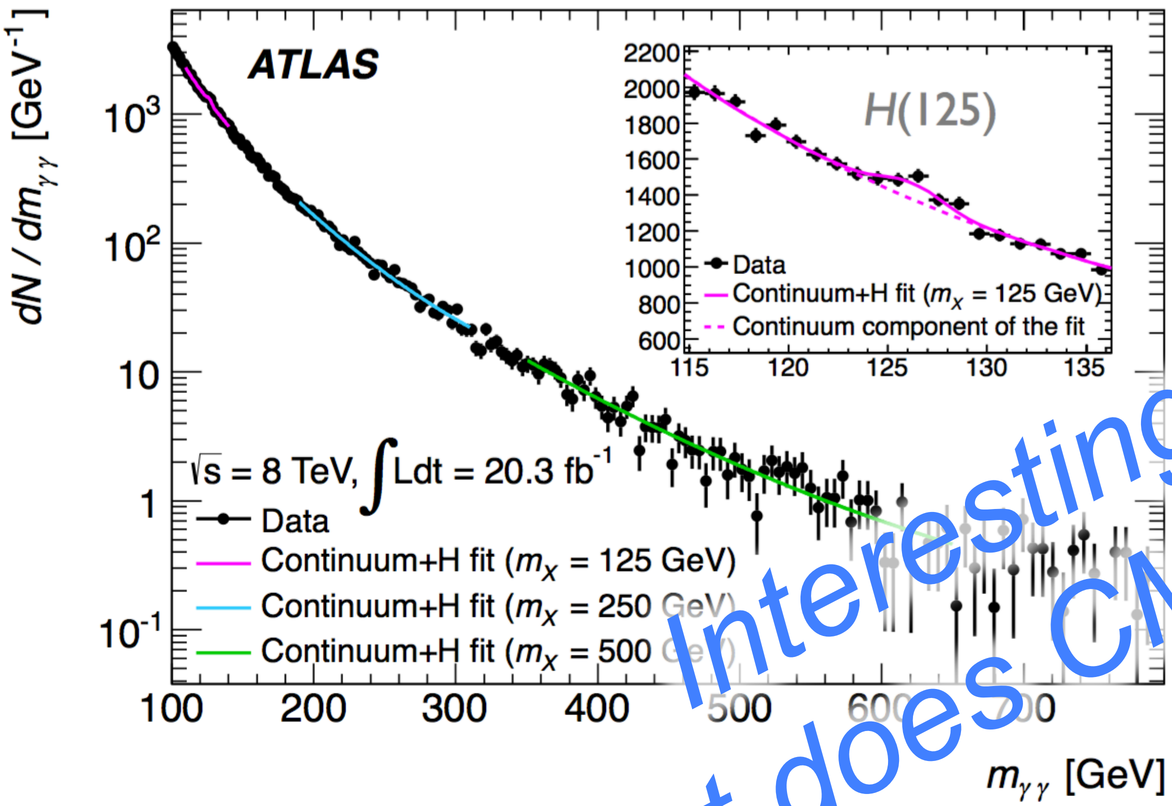


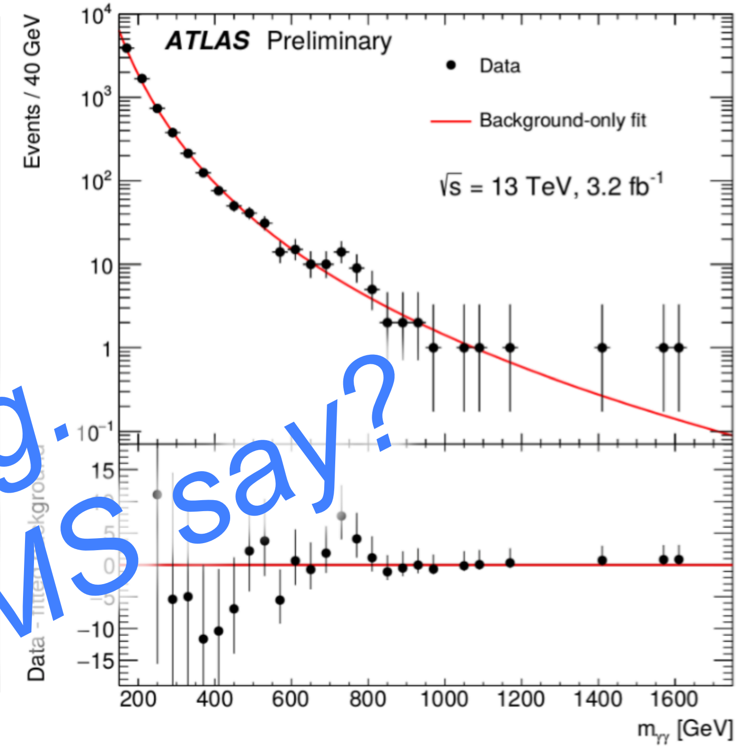
- Extend Run 1 X→$\gamma\gamma$ search above 600 GeV
  - Use the same fit model as originally (otherwise bias!)
  - No excess in 2012 data
  - 2015 and 2012 results compatible

Ratio of cross sections for s-channel resonance produced in gg fusion:

$$\sigma_{13\ TeV} / \sigma_{8\ TeV} = 4.5$$

Diphoton excess at 750 GeV





Interesting.
What does CMS say?

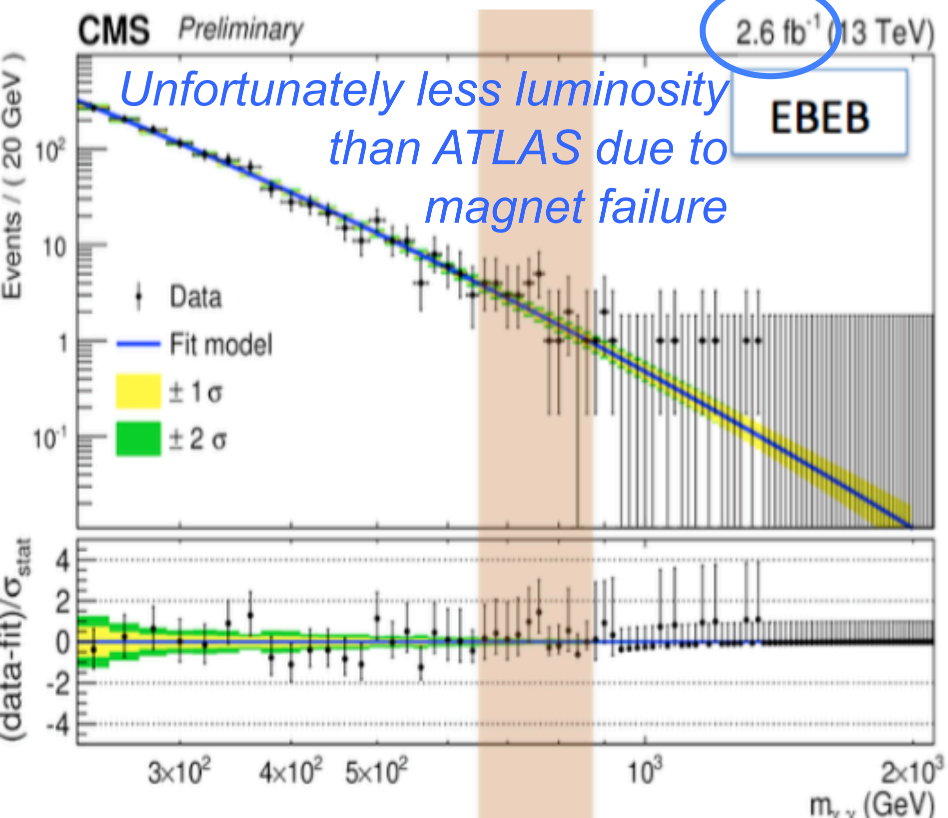
- Extend Run 1 X→$\gamma\gamma$ search above 600 GeV
  - Use the same fit model as originally (otherwise bias!)
  - No excess in 2012 data
  - 2015 and 2012 results compatible

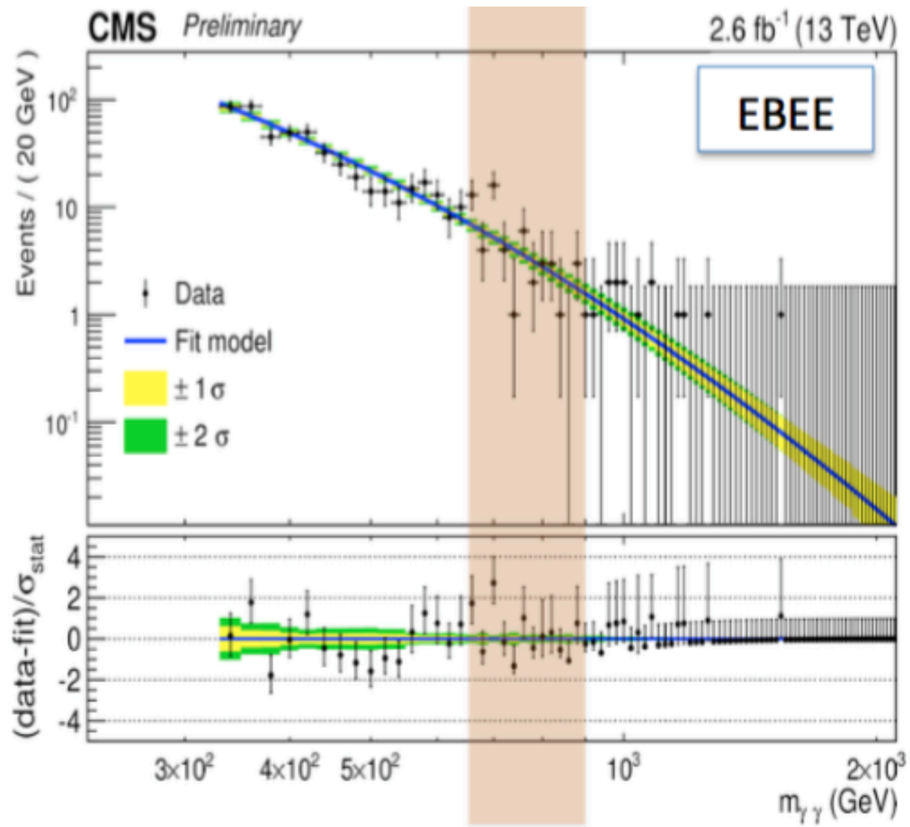
Ratio of cross sections for s-channel resonance produced in gg fusion:

$$\sigma_{13\ TeV} / \sigma_{8\ TeV} = 4.5$$

Diphoton excess at 750 GeV

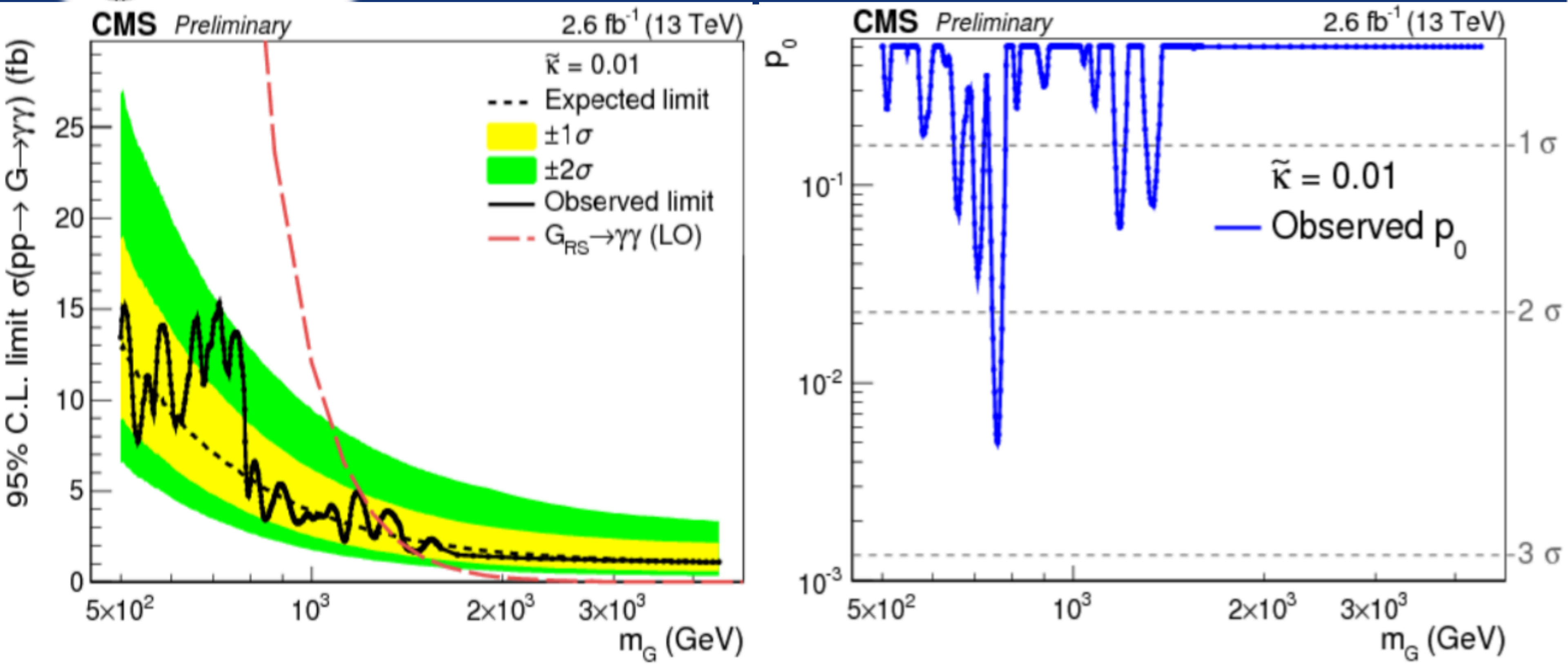
- **CMS performed a similar search at 13 TeV**
  - Two event categories
    - Both γ in barrel calorimeter (EBEB) → best resolution
    - One γ in barrel, one in endcap calorimeter (EBEC) → OK resolution





[1] CMS-PAS-EXO-15-004

Diphoton excess at 750 GeV

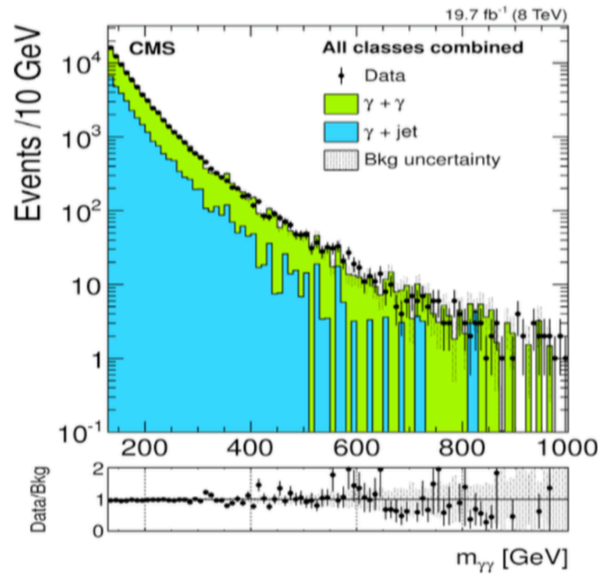


- **Largest excess:**
  - $m_{\gamma\gamma}$=760 GeV in the narrow width hypothesis
    - Local significance 2.6σ
    - Global significance 1.2σ

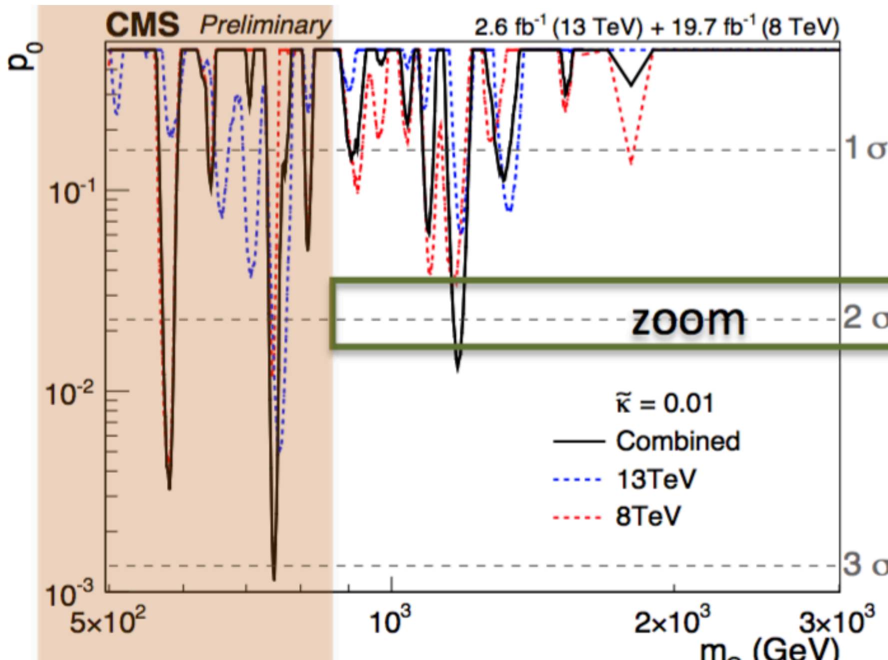
[1] CMS-PAS-EXO-15-004

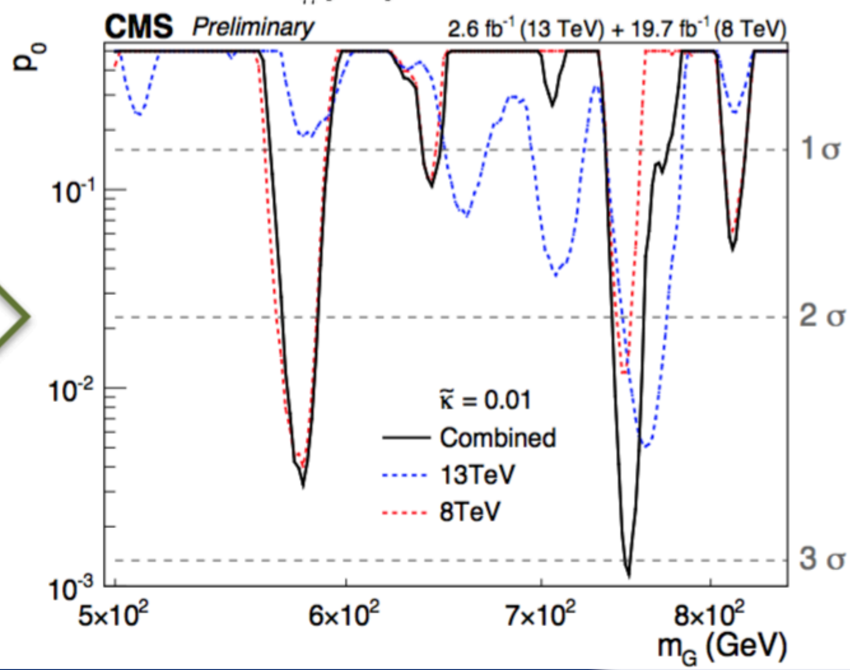
Diphoton excess at 750 GeV

- For CMS, 13 and 8 TeV results more compatible

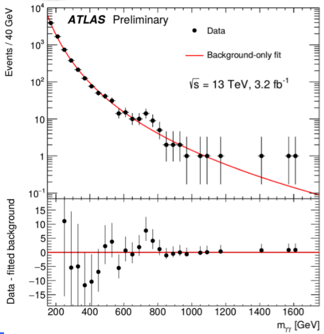


[1] CMS-PAS-EXO-15-004

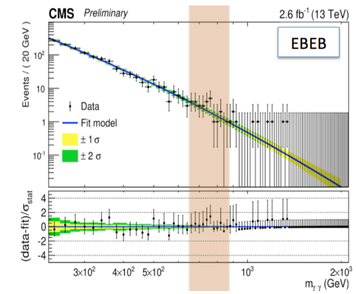




Diphoton excess at 750 GeV



It looks like a fluke.



But what if this is the beginning of