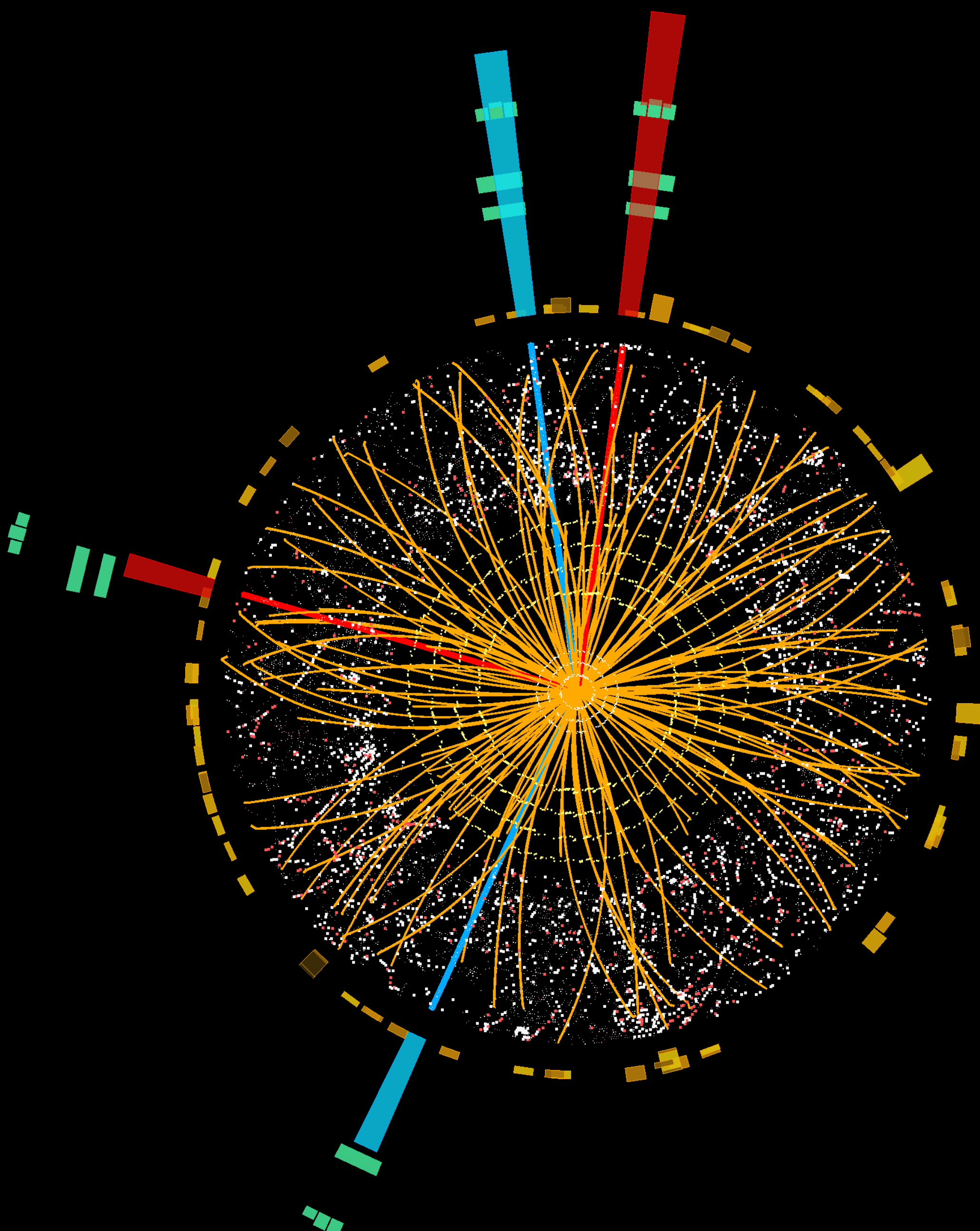


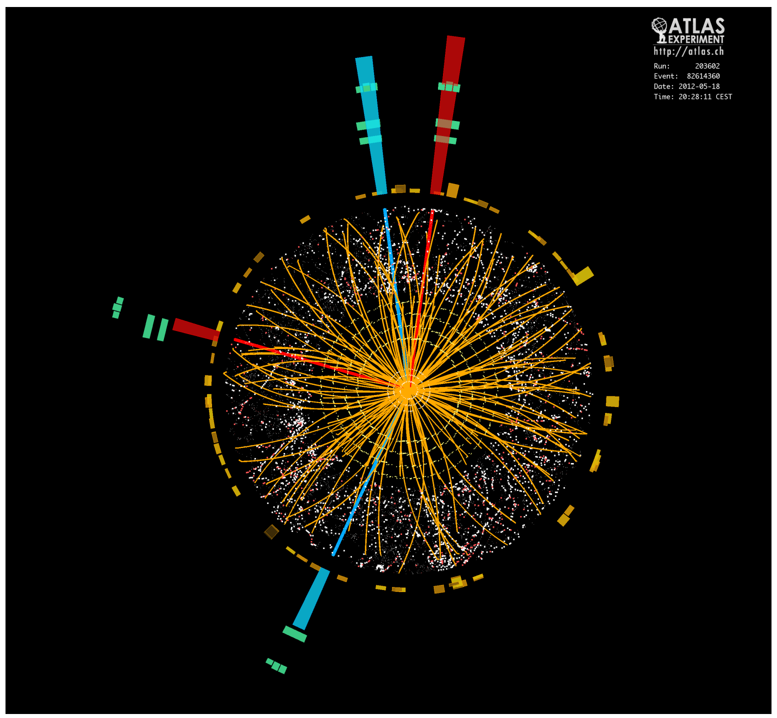
From hits to the Higgs

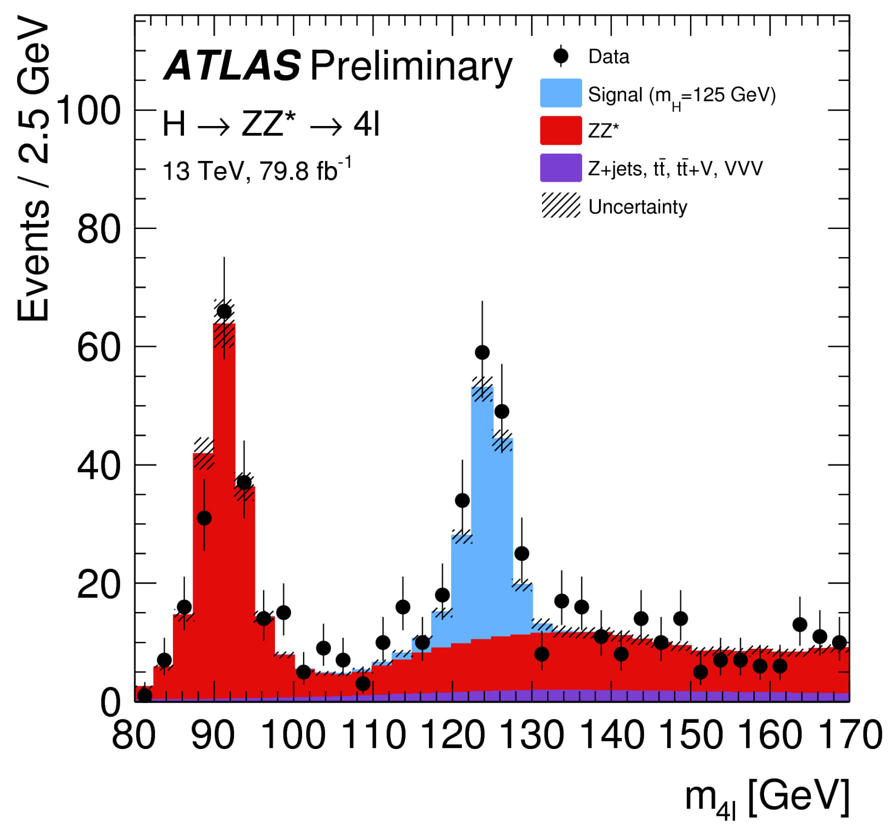
Sarah Heim

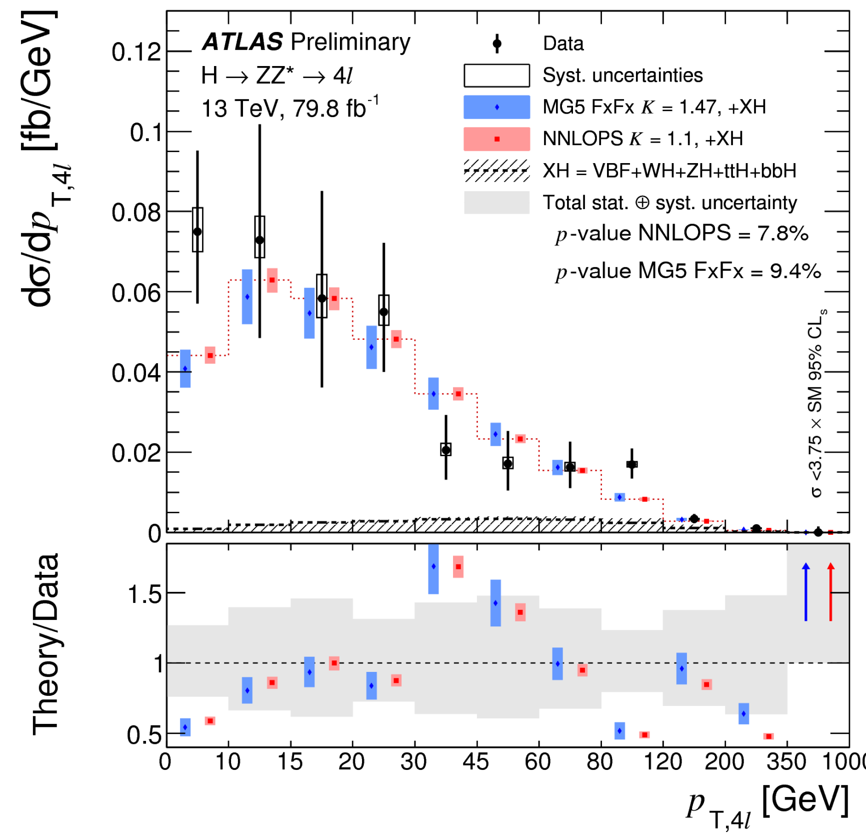
DESY Colloquium, May 28/29th, 2019

DESY. UHH HELMHOLTZ Young Investigators ATLAS EXPERIMENT

From hits to the Higgs







Higgs mechanism

- postulated to explain masses of elementary particles in the Standard Model through electroweak symmetry breaking
- consequence: Higgs boson
- SM predictions:

Spin and CP
scalar: spin 0, CP even

Width
- Depends on the mass
- Very short life-time!

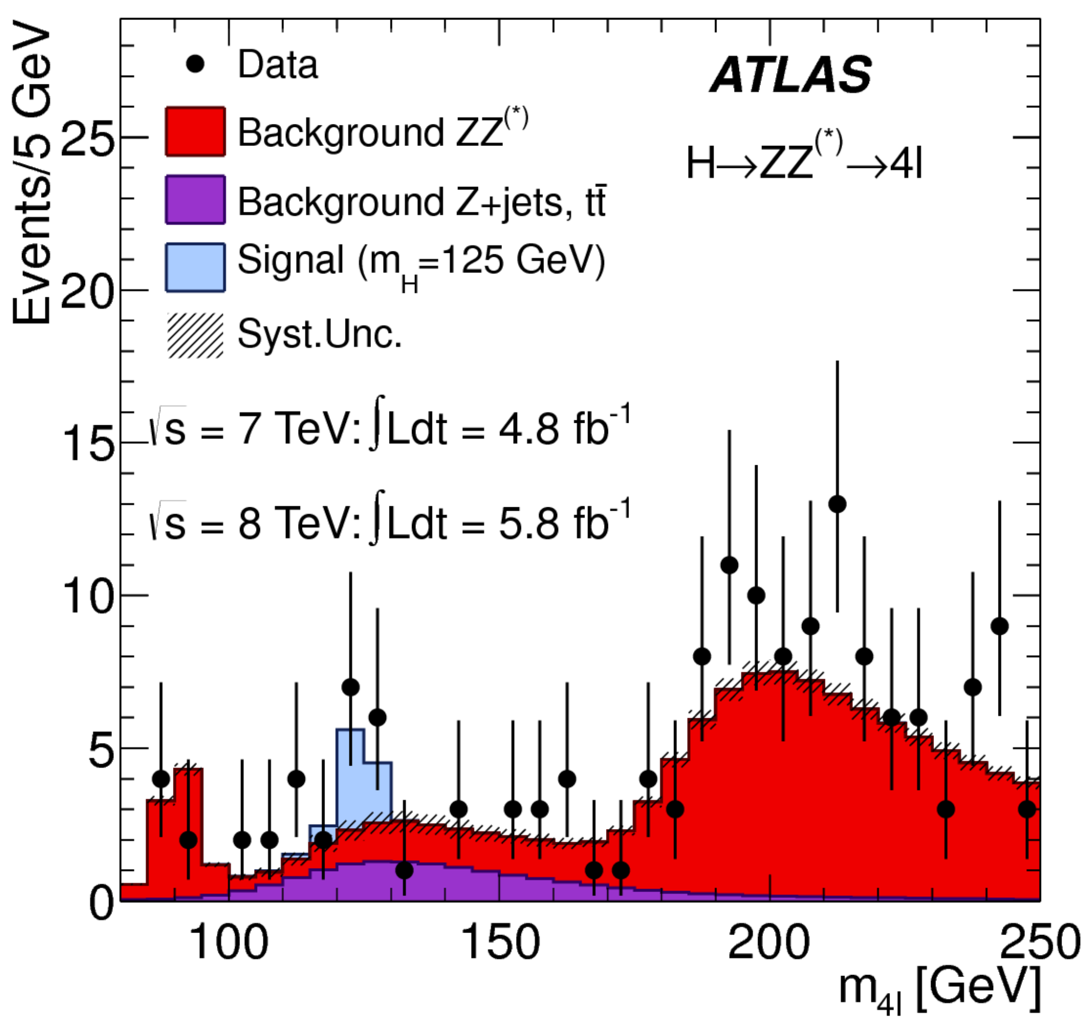
Couplings
Higgs-fermion couplings ~ fermion mass
Higgs-boson couplings ~ boson mass²

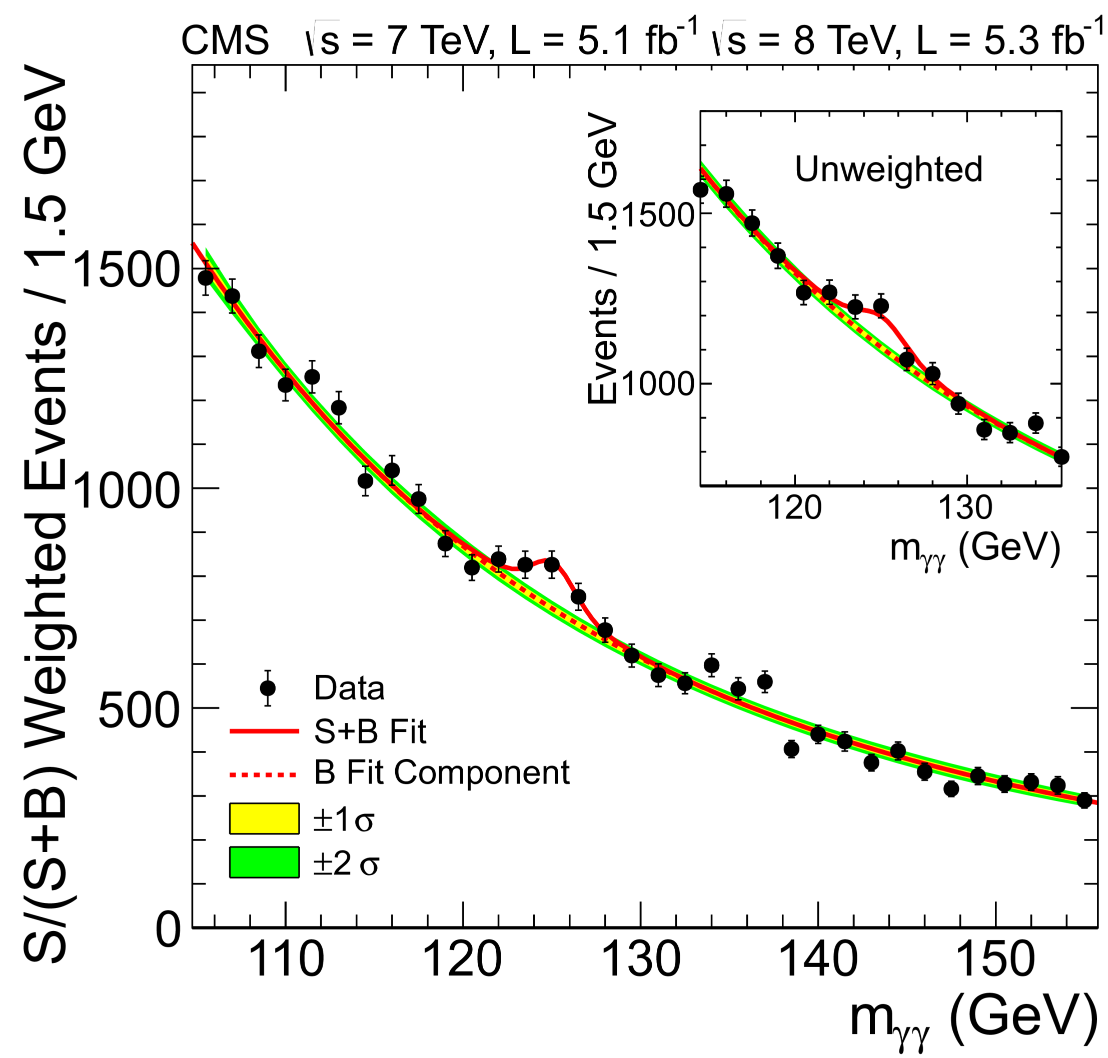
=> SM Higgs sector is overall very predictive:

Knowing the fermion masses, only free parameter is m_H

Higgs discovery

The Higgs boson was discovered in 2012 by the ATLAS and CMS collaborations with a mass of ~125 GeV

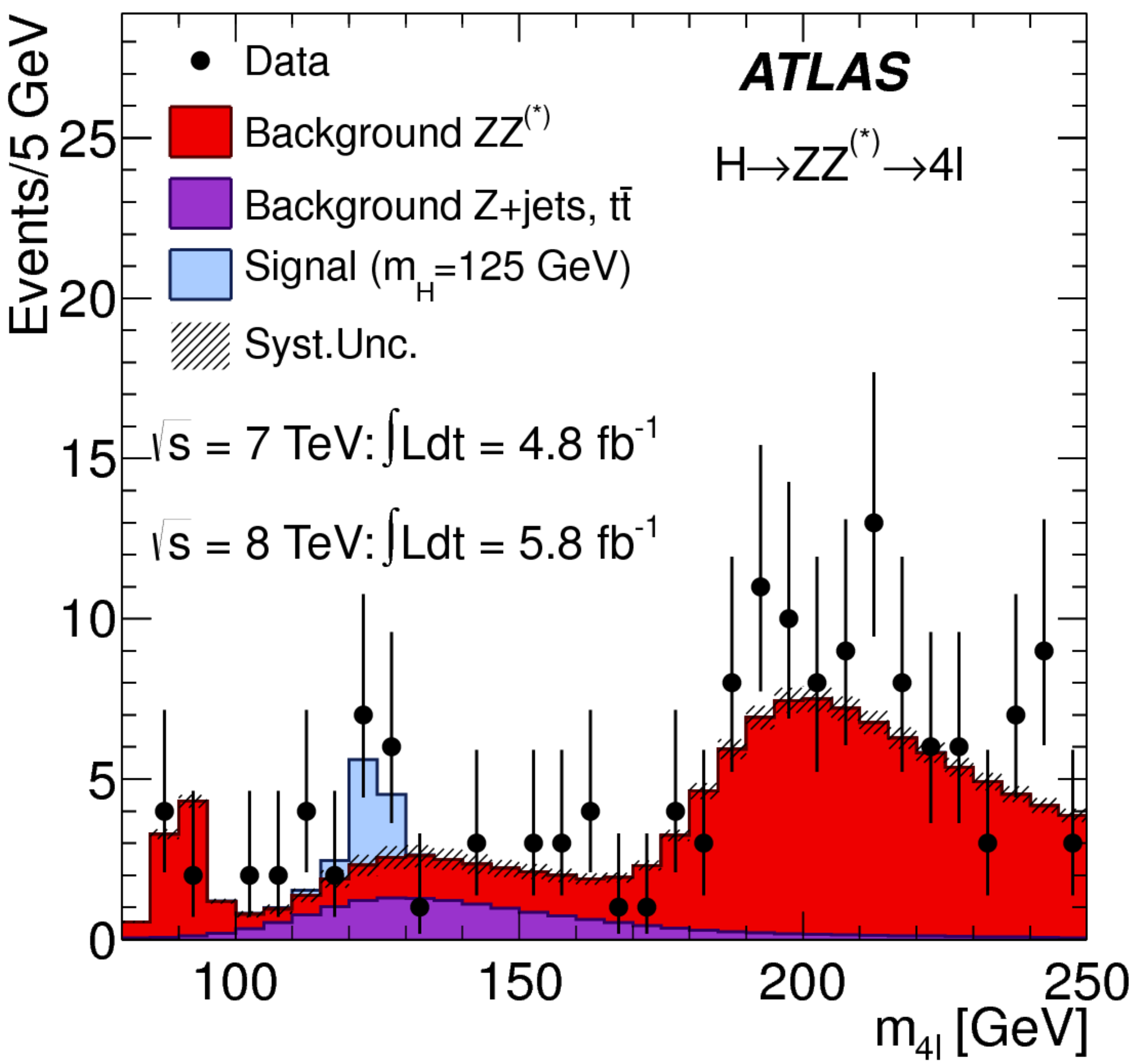




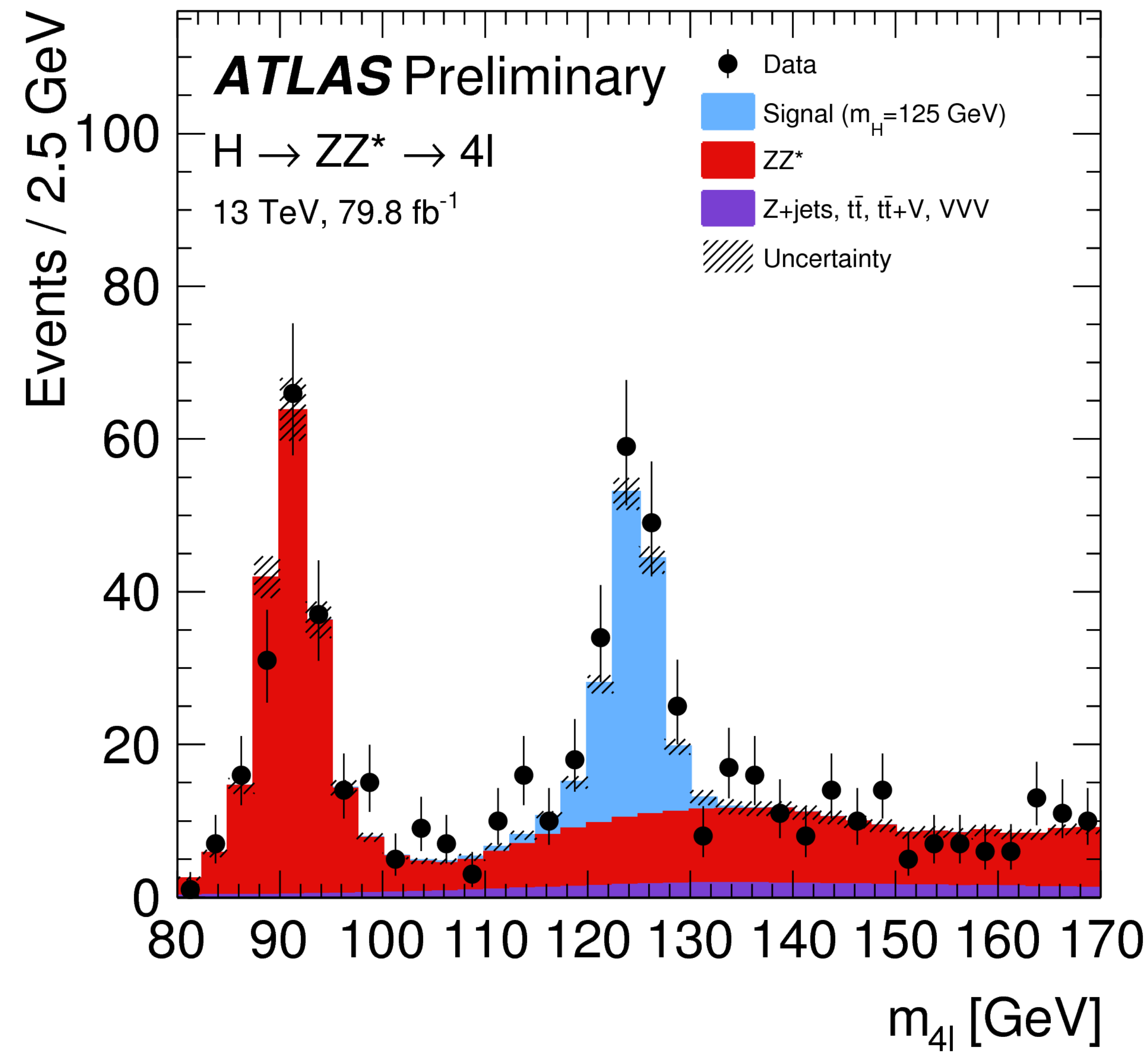
We live in exciting times

…from discovery to property measurements

2012



2017



Is it the Higgs boson the SM predicts?

Examples of non-SM Higgs mechanisms/extensions

- SUSY Higgs sector (h, H, A, H+/-)
- Composite Higgs
- Couplings to new particles, like dark matter

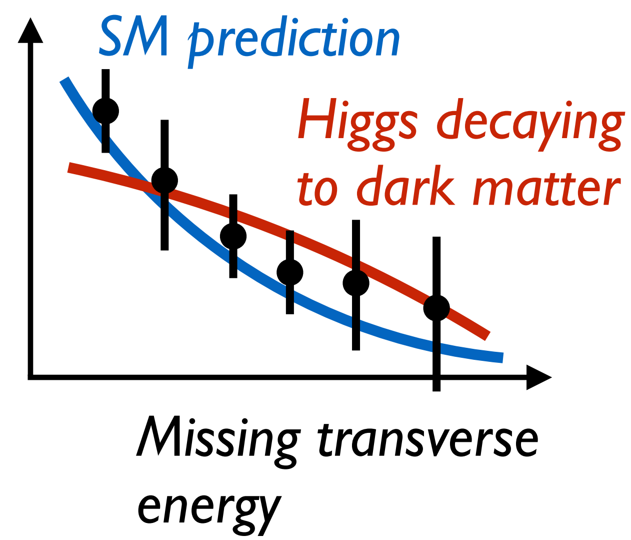
=> use the Higgs boson as a tool to search for physics beyond the SM

Is it the Higgs boson the SM predicts?

Two ways of searching:

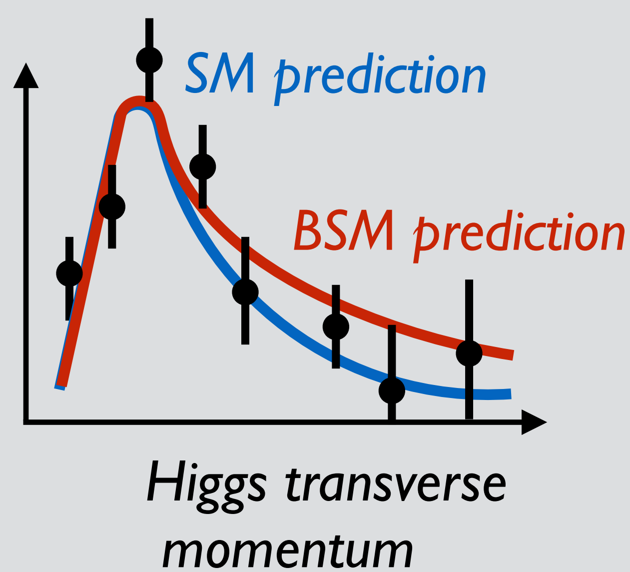
1. Direct search:

   Search for new phenomena directly, like additional Higgs bosons or dark matter decays of the Higgs boson



2. Indirect search:

   Measure Higgs boson properties, compare to predictions of the Standard Model



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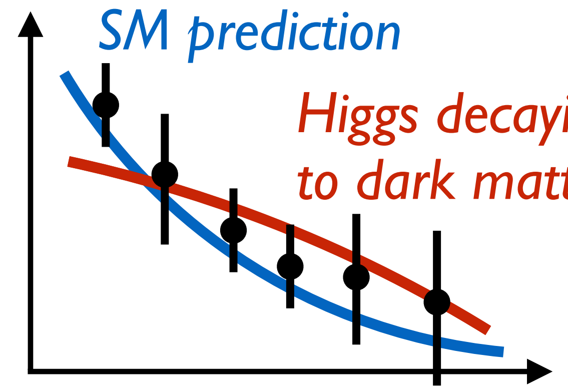


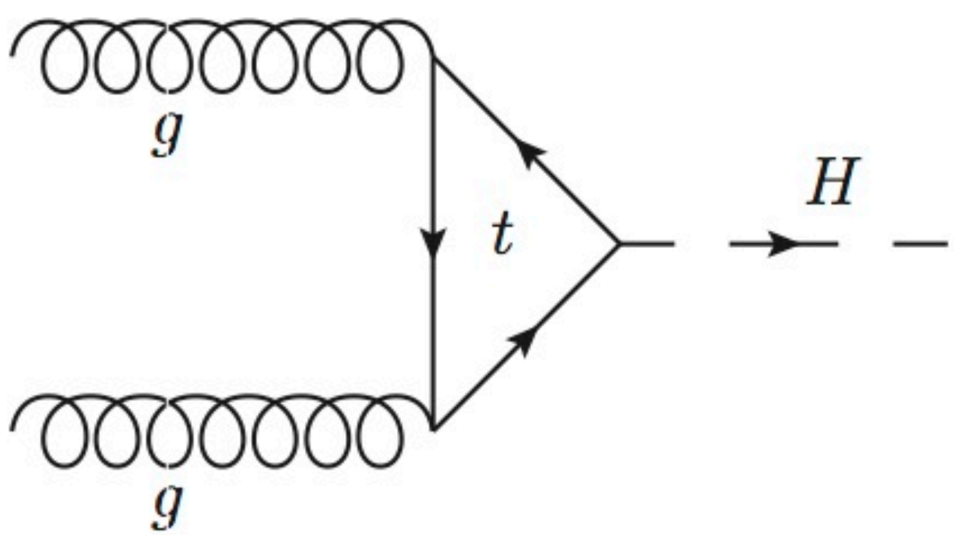
If new physics is at 1 TeV:

Snowmass 2013 (1310.8361)

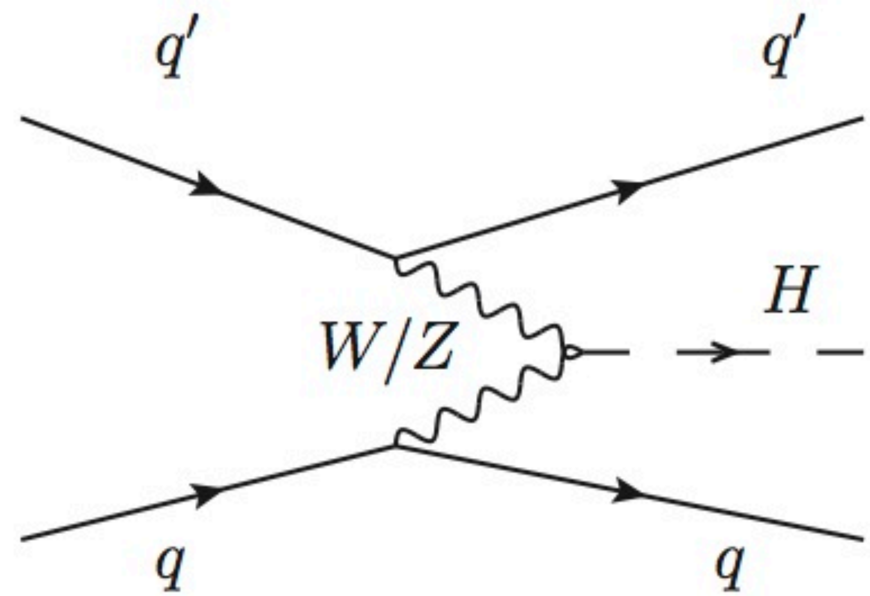
	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	~6%	~6%	~6%
2HDM	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

Higgs production at the LHC

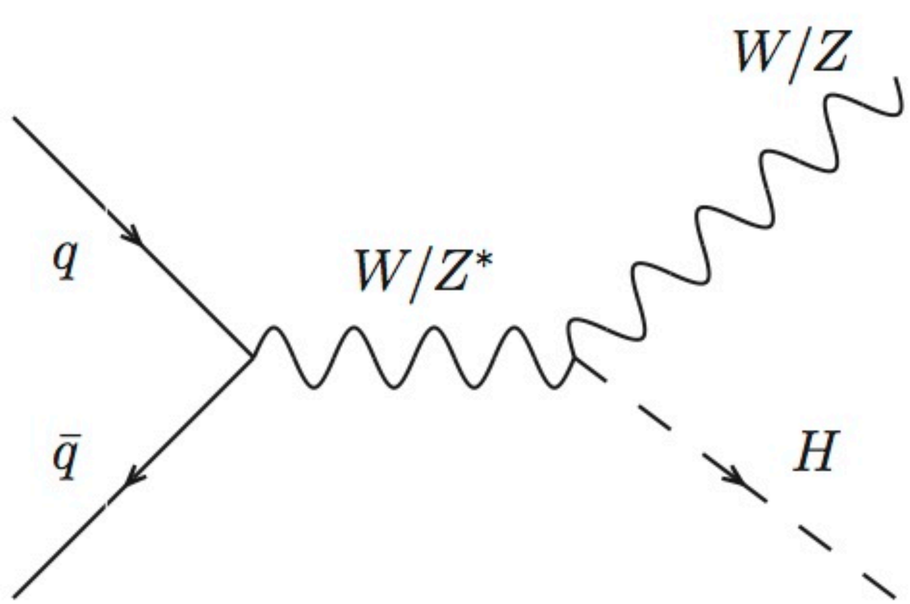
…as predicted by the Standard Model at 13 TeV



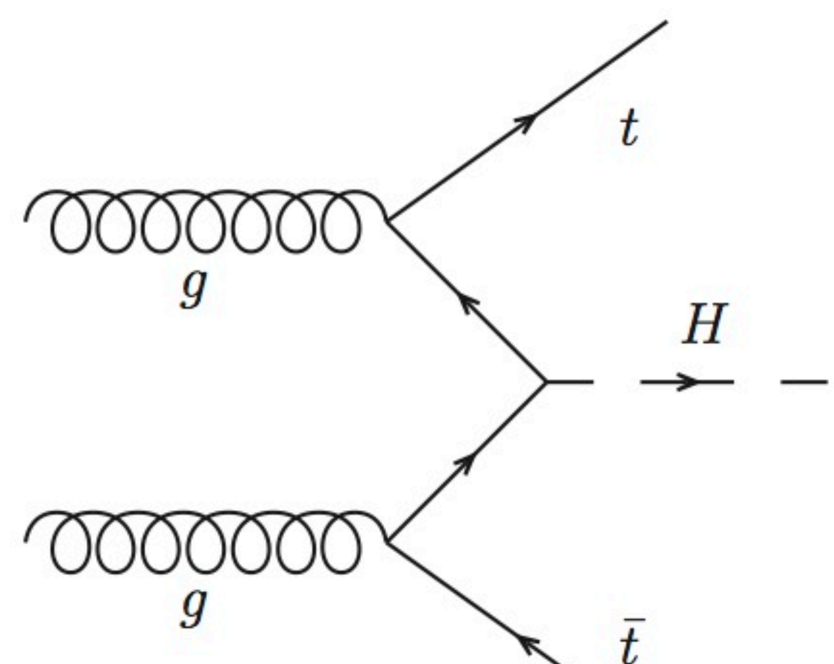
ggF: 87.2%



VBF: 6.8%



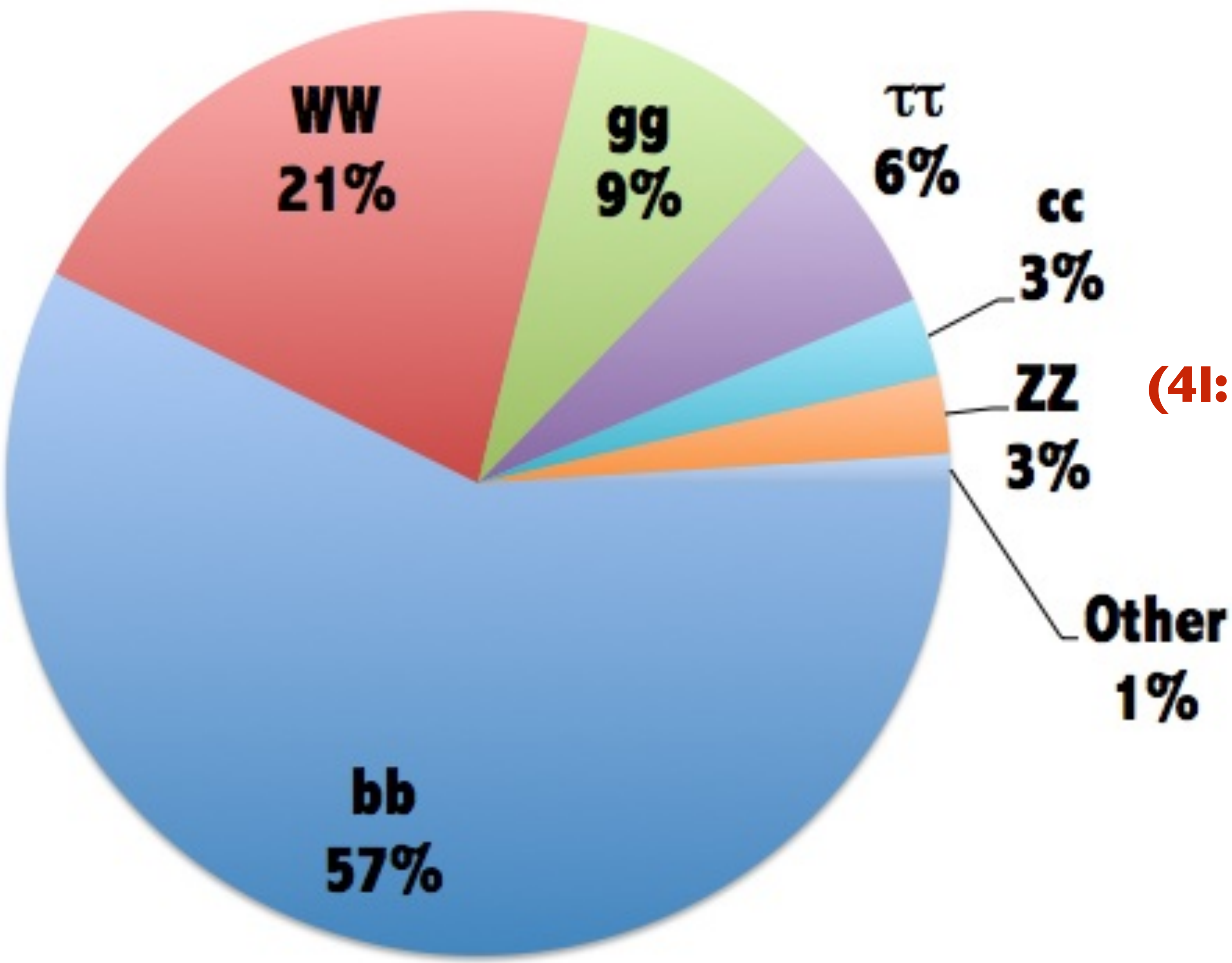
VH: 4.1%



ttH: 1.9%

Higgs decays

…as predicted by the Standard Model



(4l: 0.0125%)

$\gamma\gamma$: 0.2%
Zγ: 0.2%
$\mu\mu$: 0.02%

Higgs decays

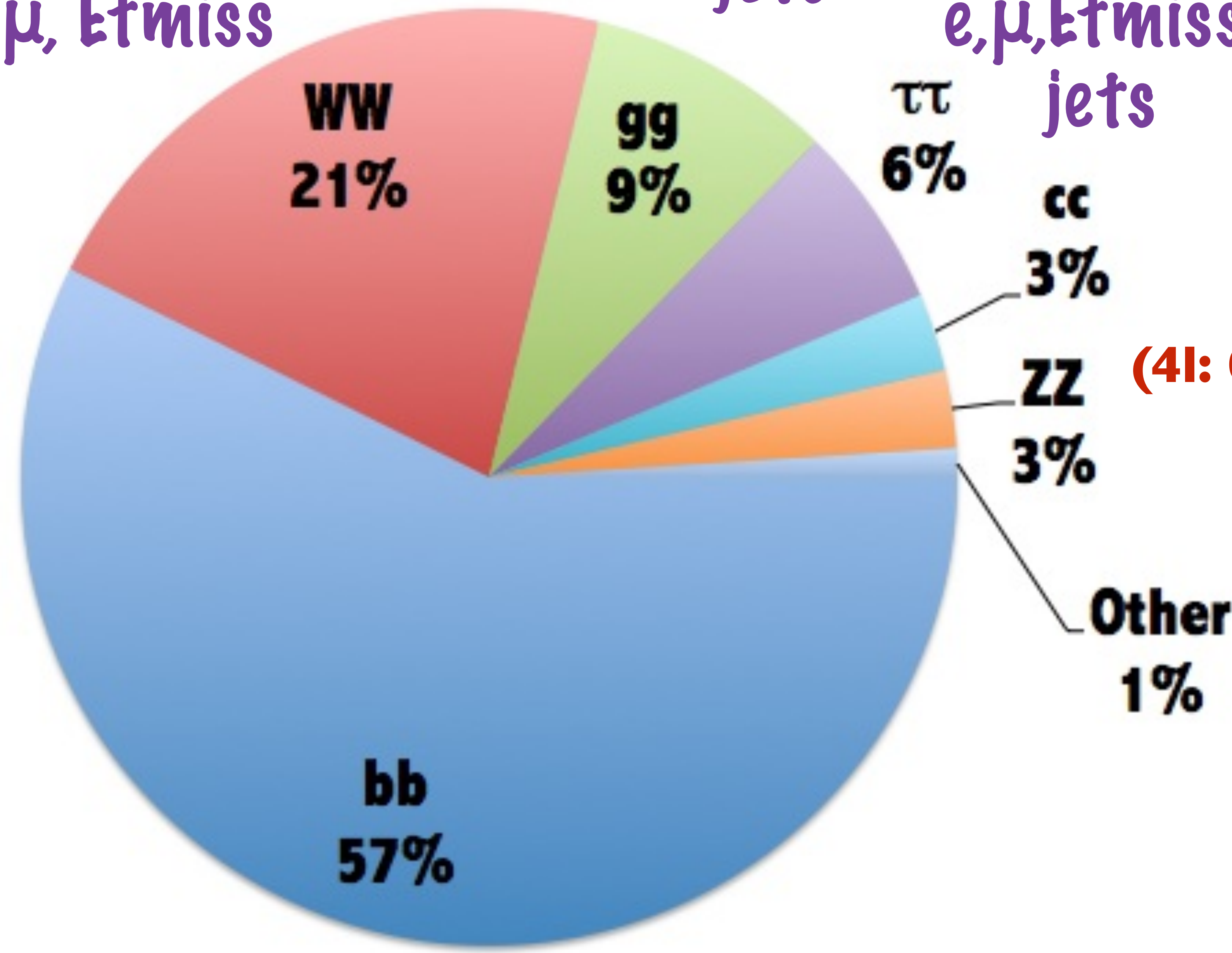
…as predicted by the Standard Model

(lvlv: 1%)

e,μ, Etmiss

jets

e,μ,Etmiss,
jets



(4l: 0.0125%) e,μ

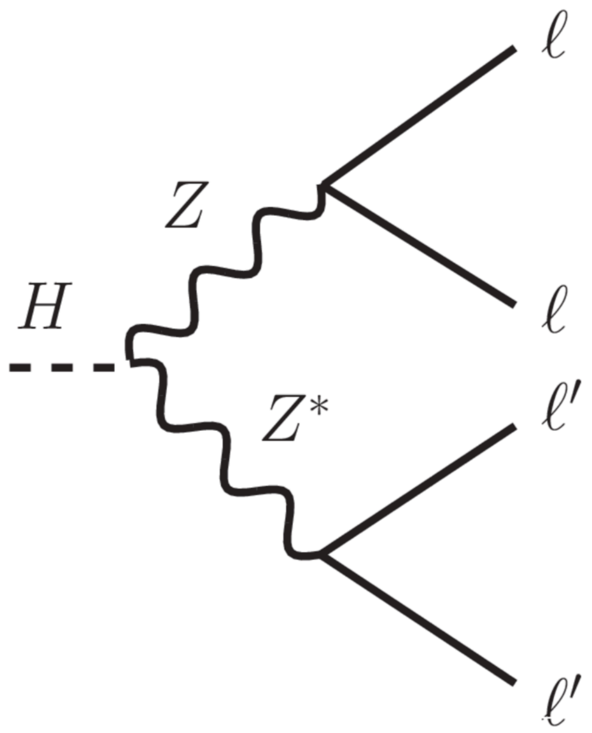
$\gamma\gamma$: 0.2%
Zγ: 0.2%
$\mu\mu$: 0.02%

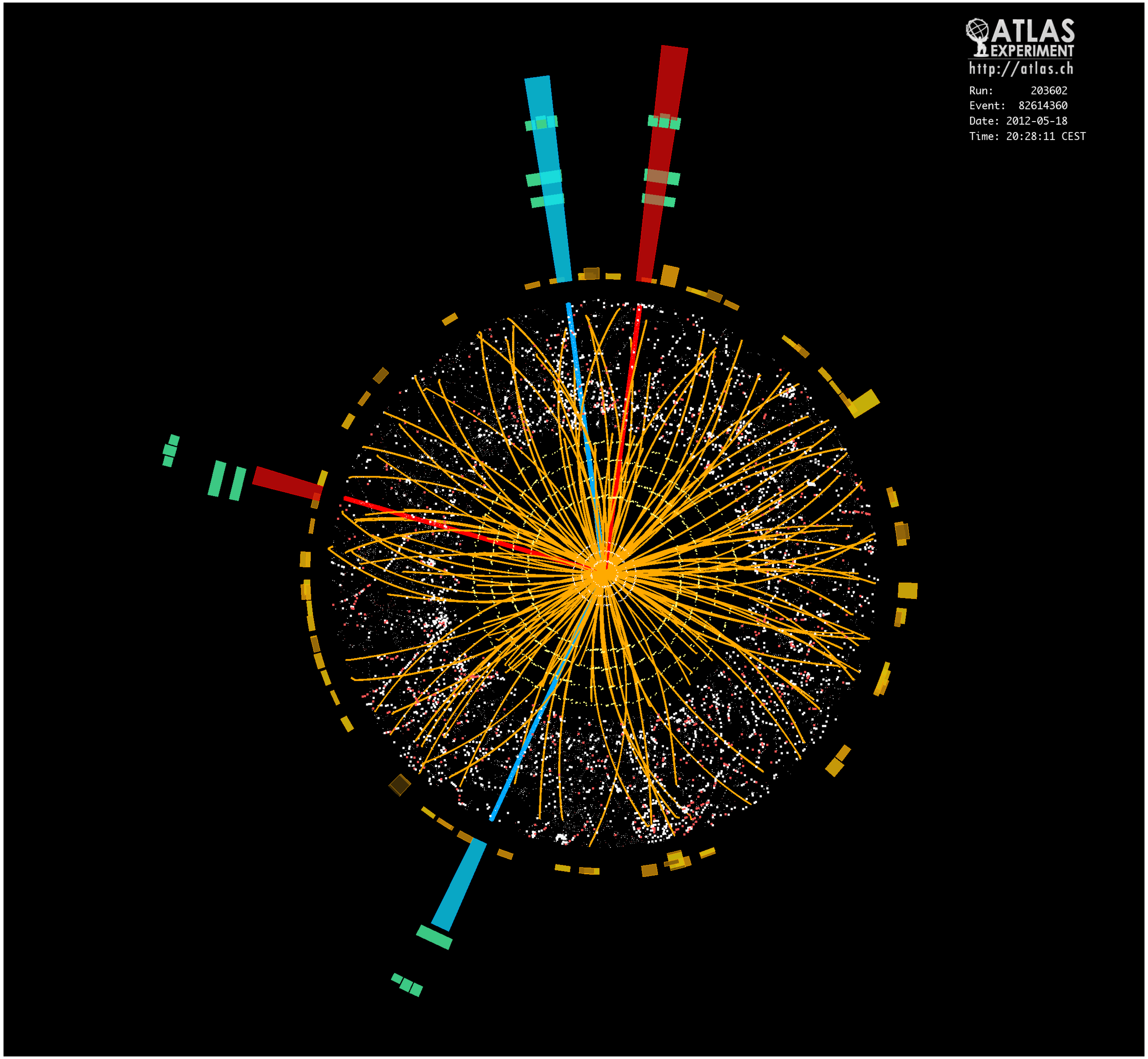
e,μ,γ

b-jets

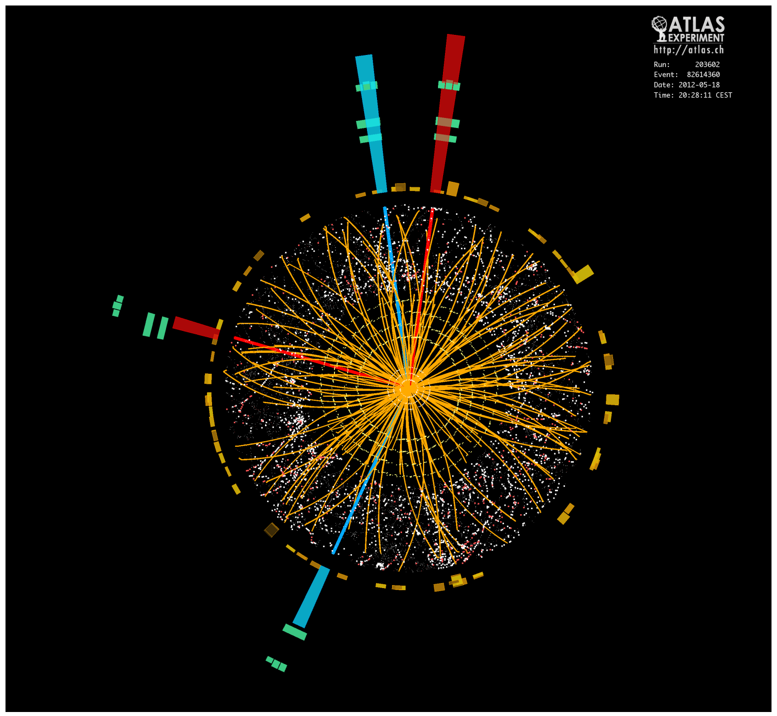
+ jets in VBF, b-jets in top quarks…

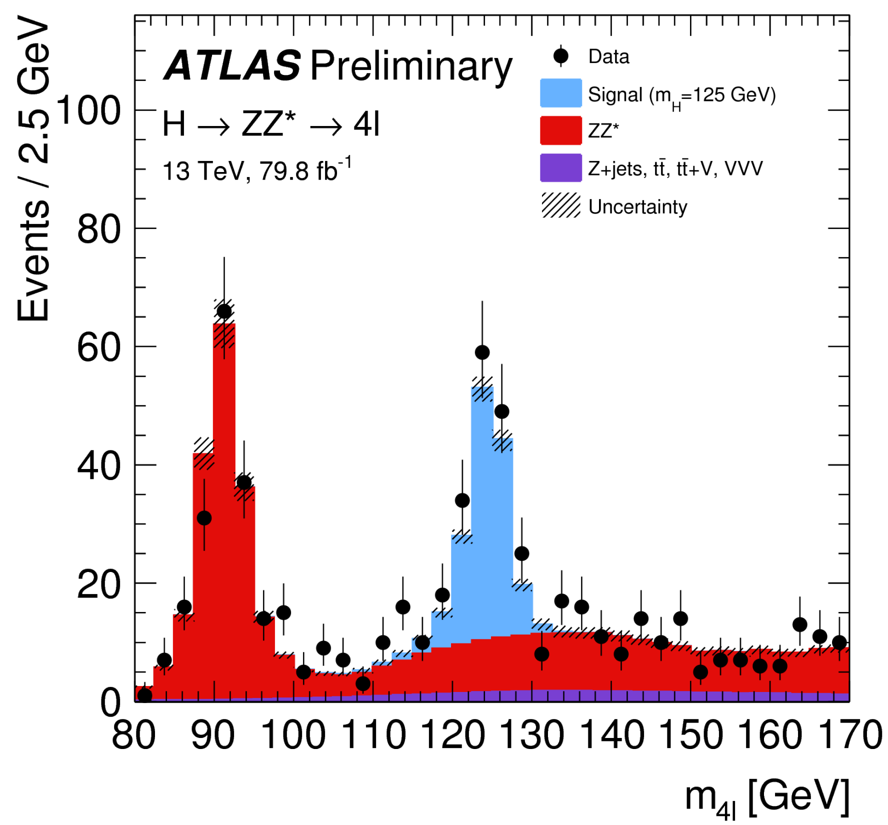
The H →4l channel

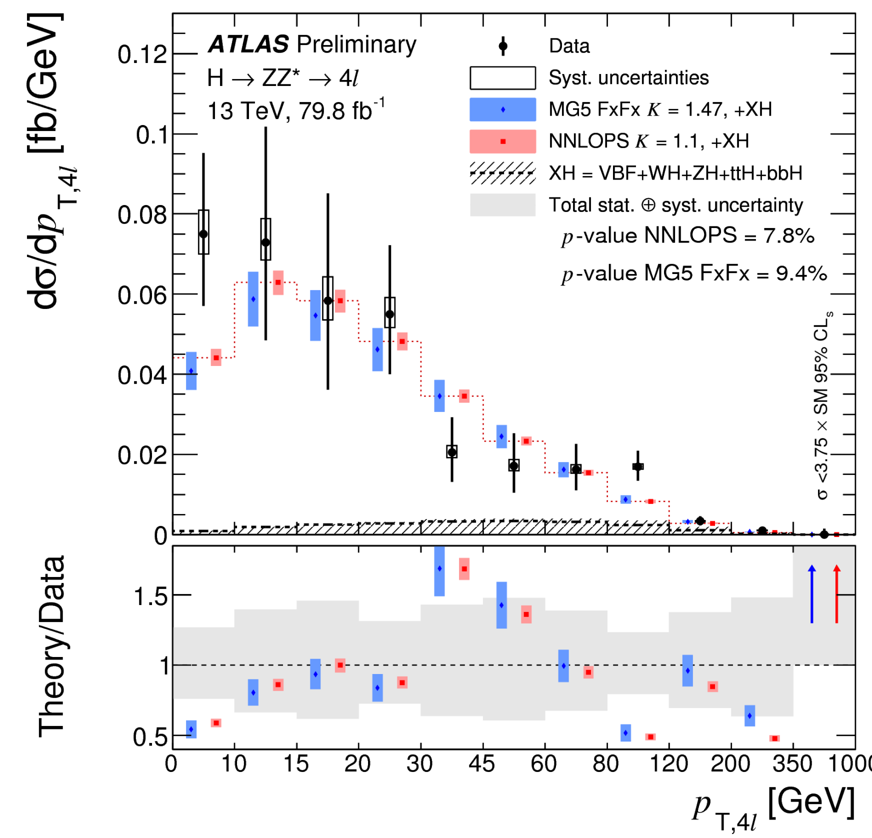


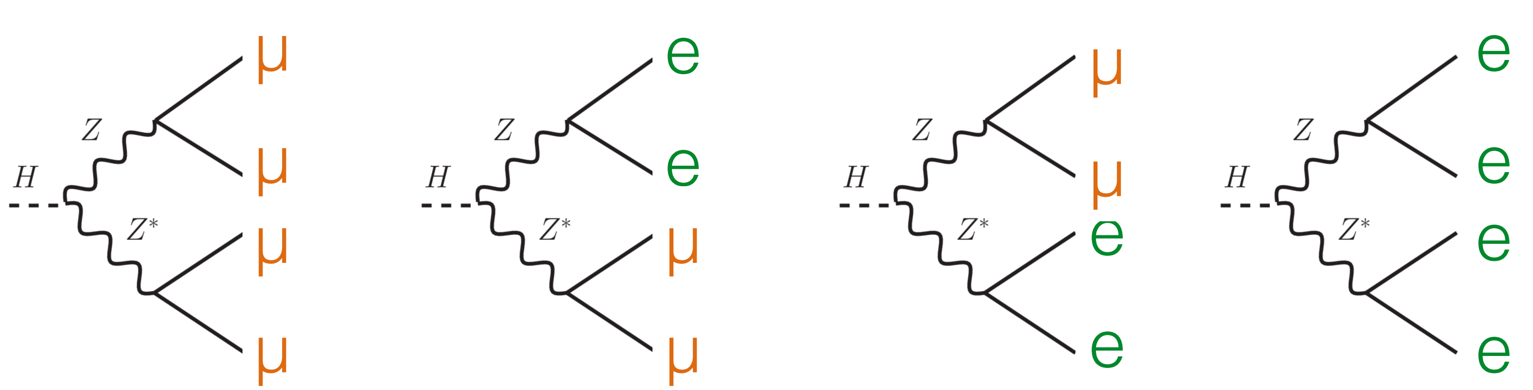


Differential cross section measurements

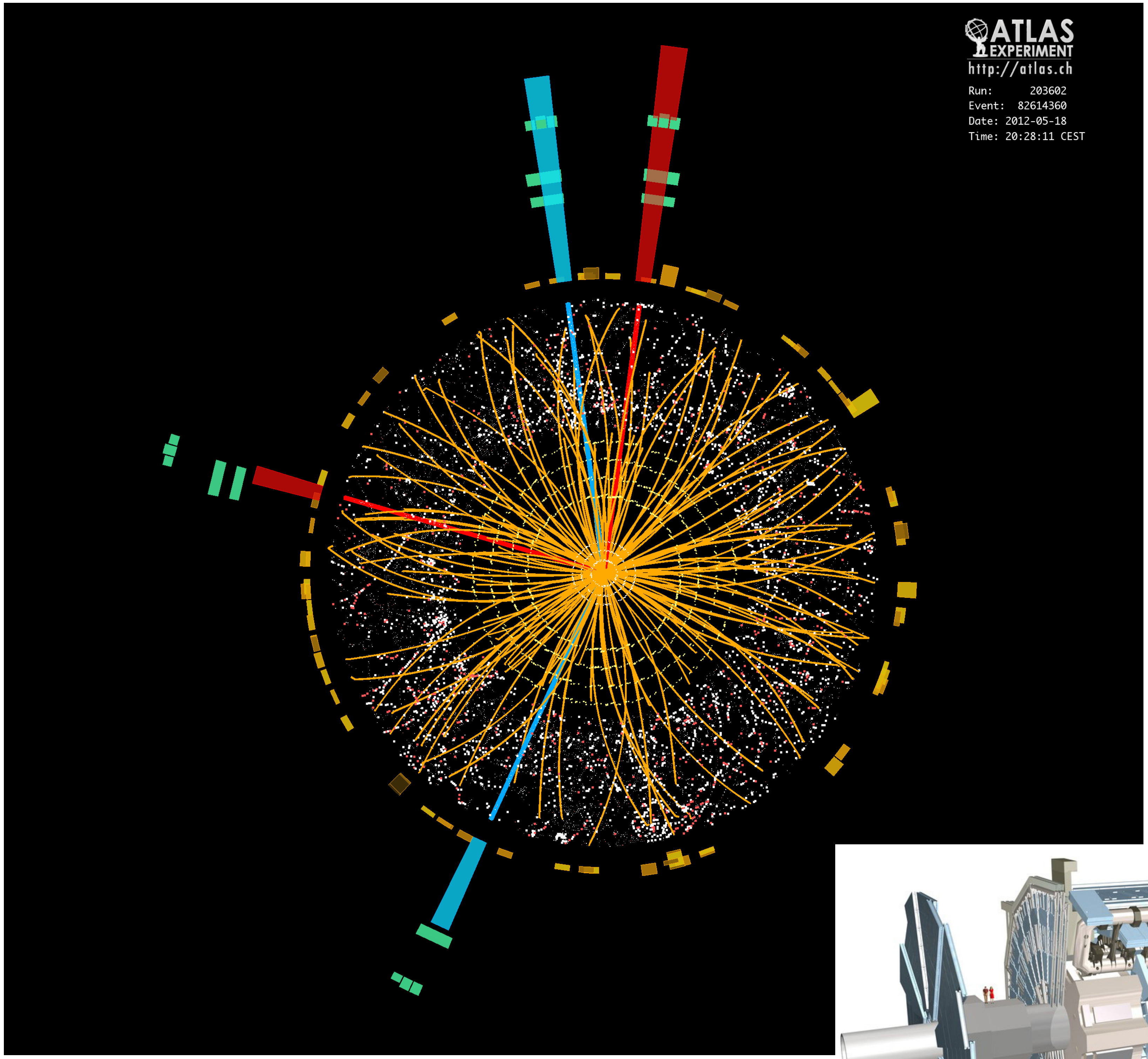


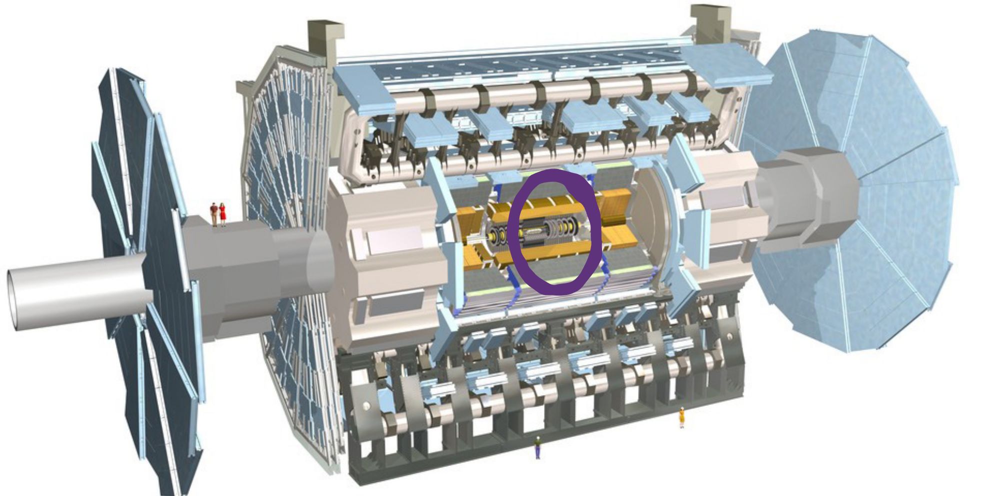






4 electrons


ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST



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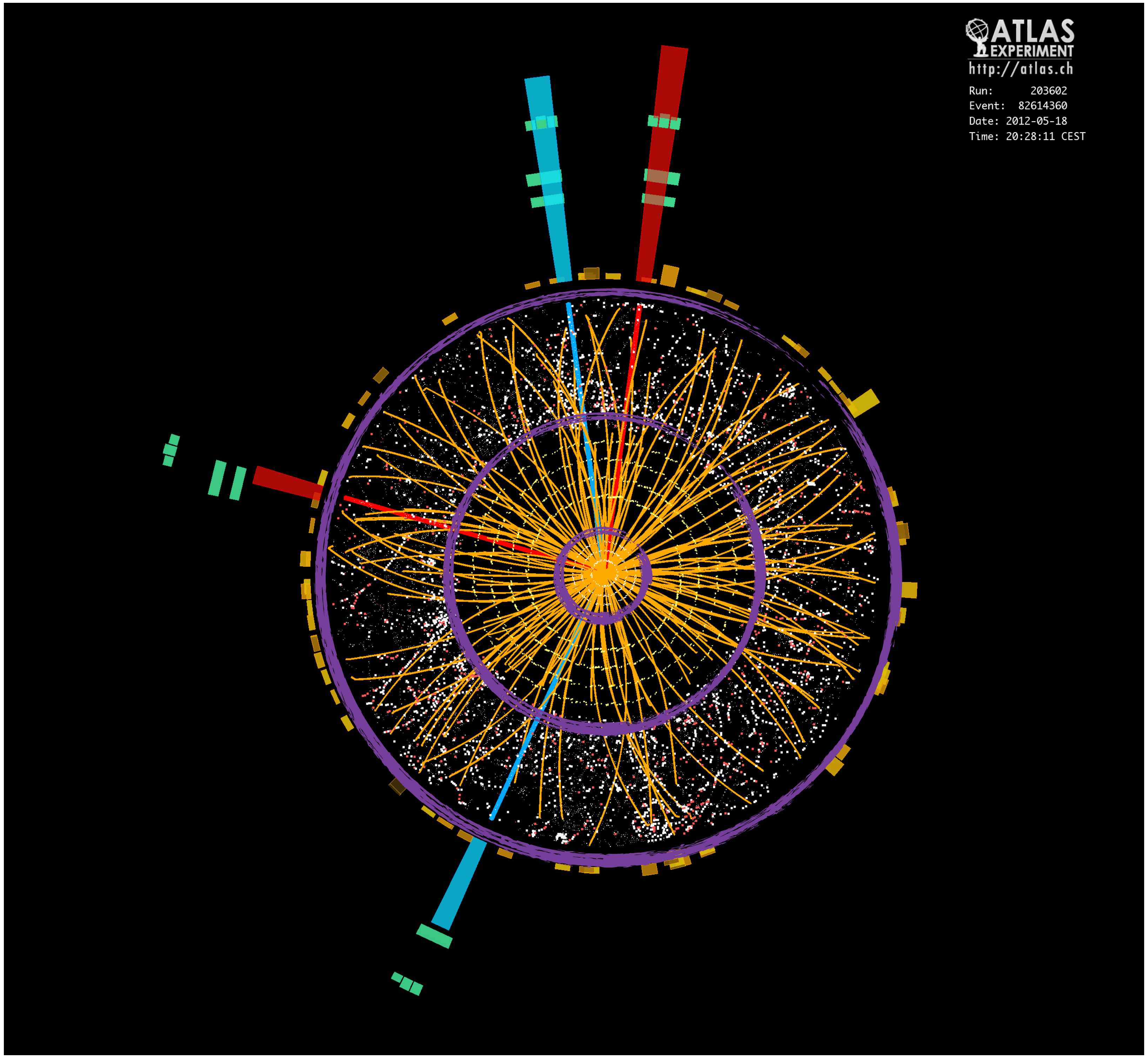


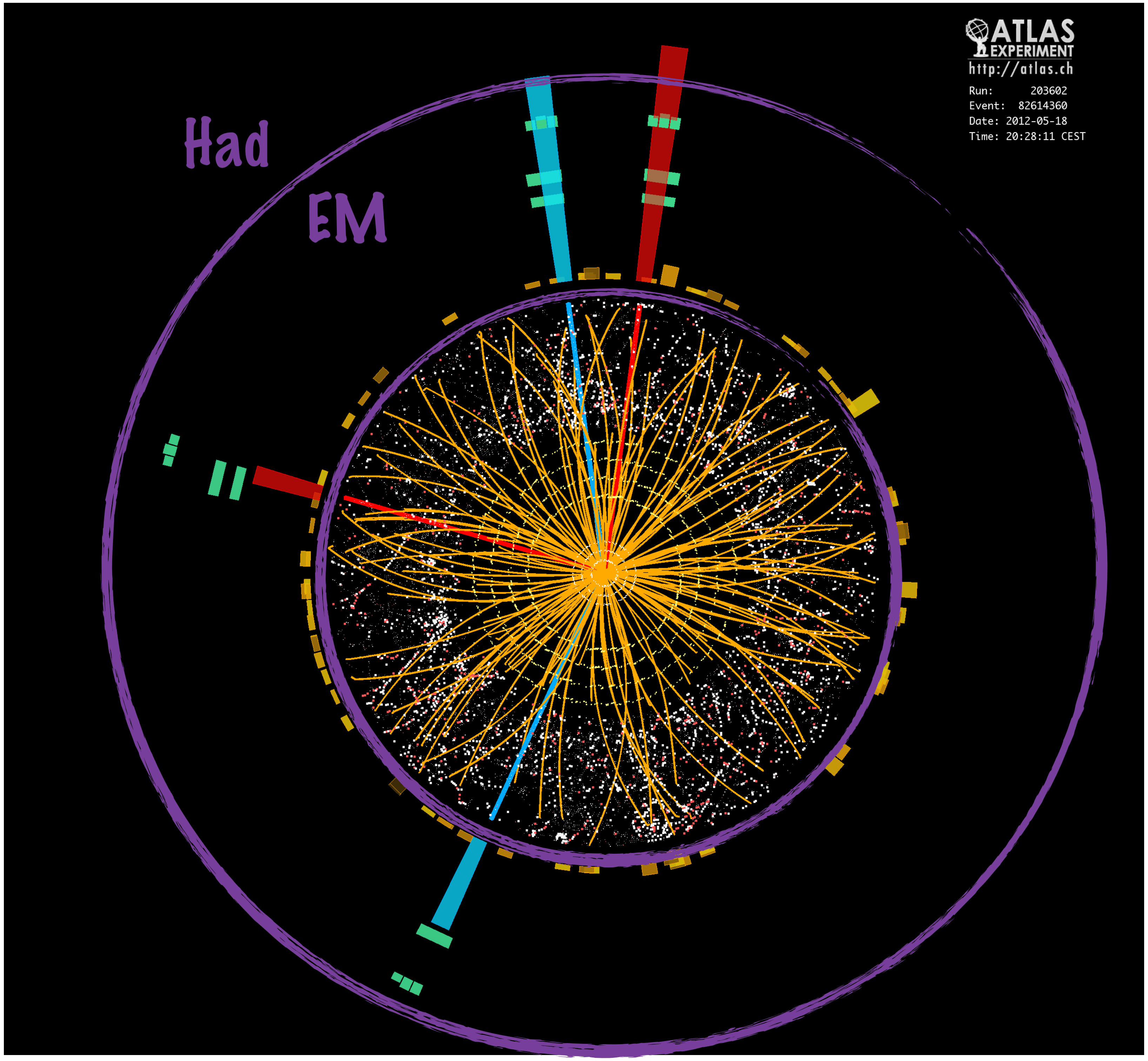
<u>Tracking</u>

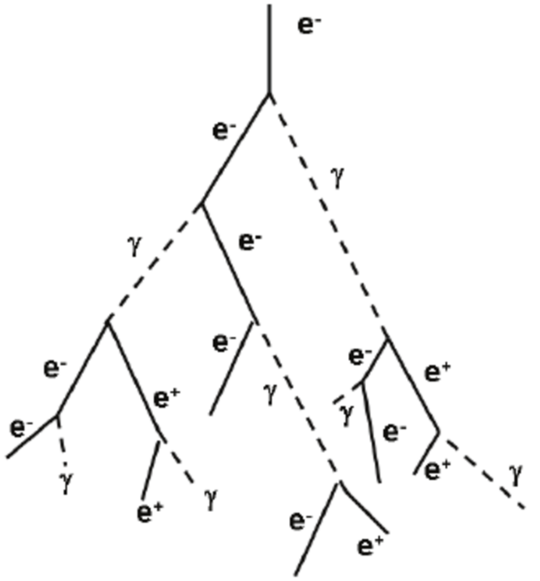
Pixel

Strips

TRT

4 electrons





EM Calorimeter: 3 layers

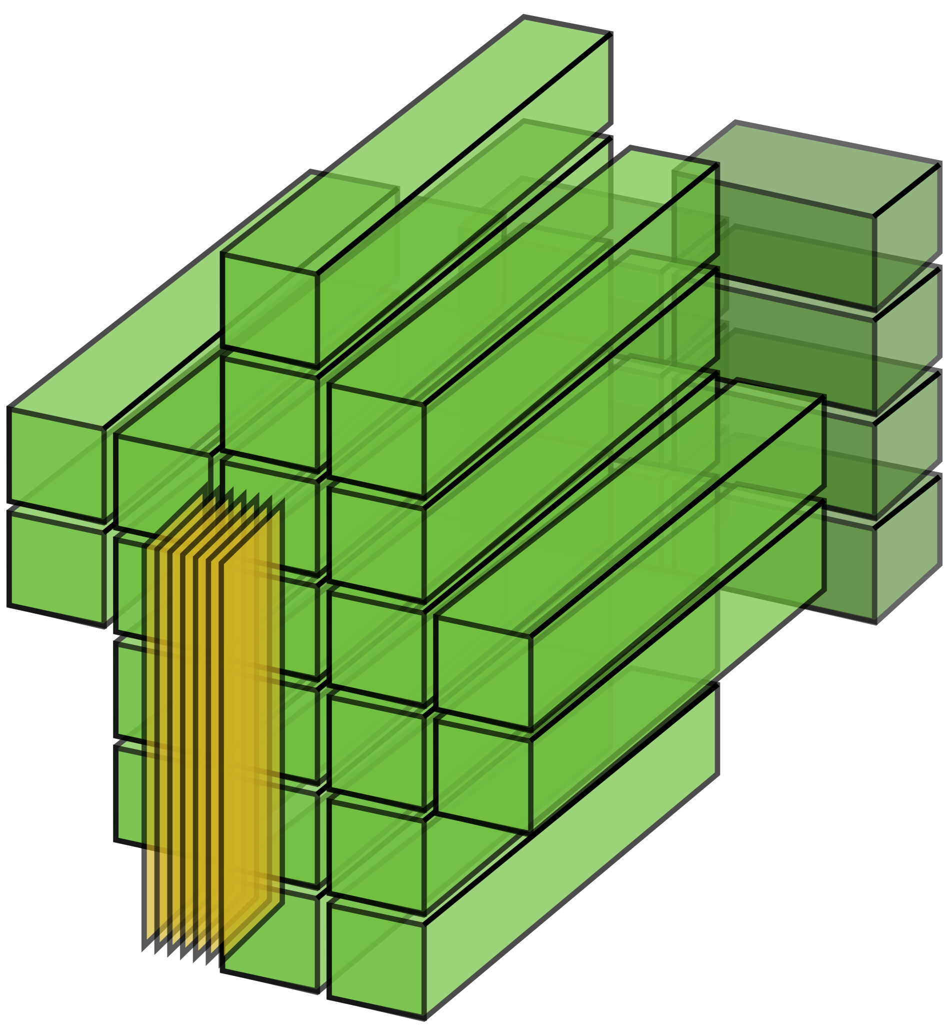
Hadronic Calorimeter

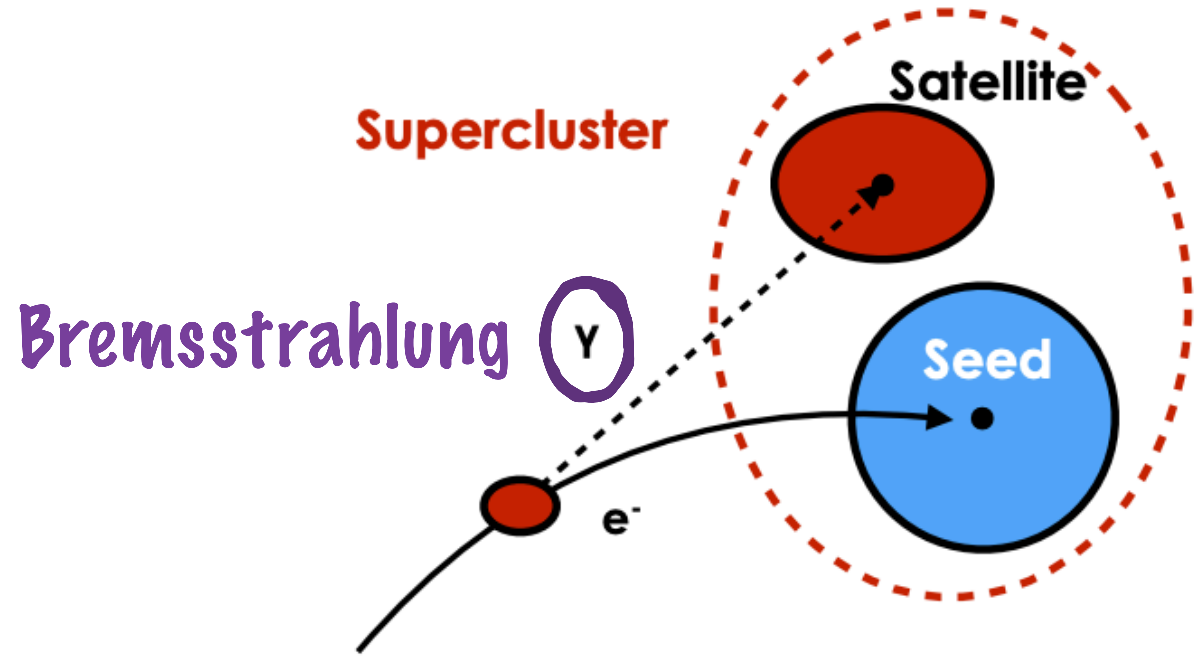
Electron reconstruction: Energy cluster

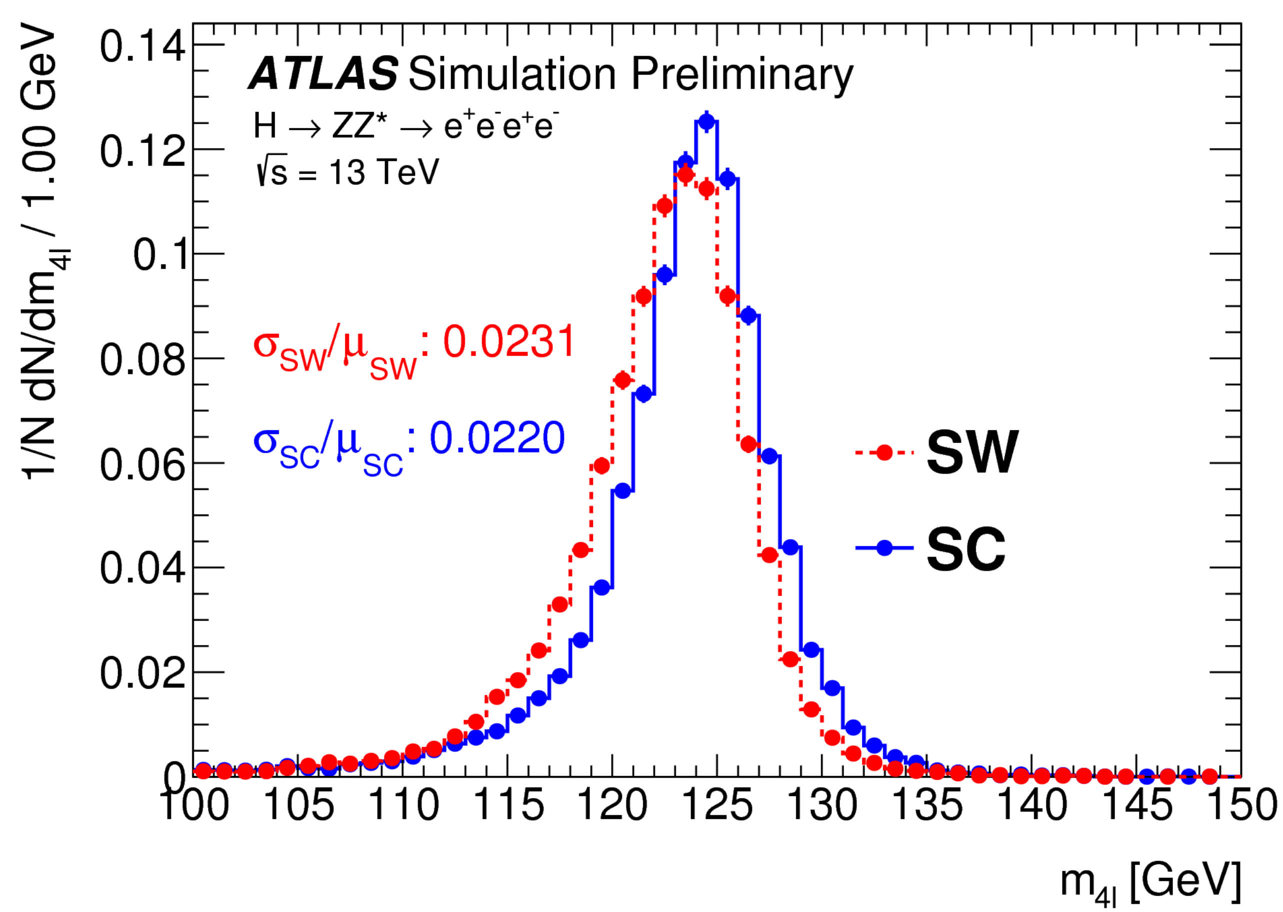
Topological clusters (3D)

Formed from cells

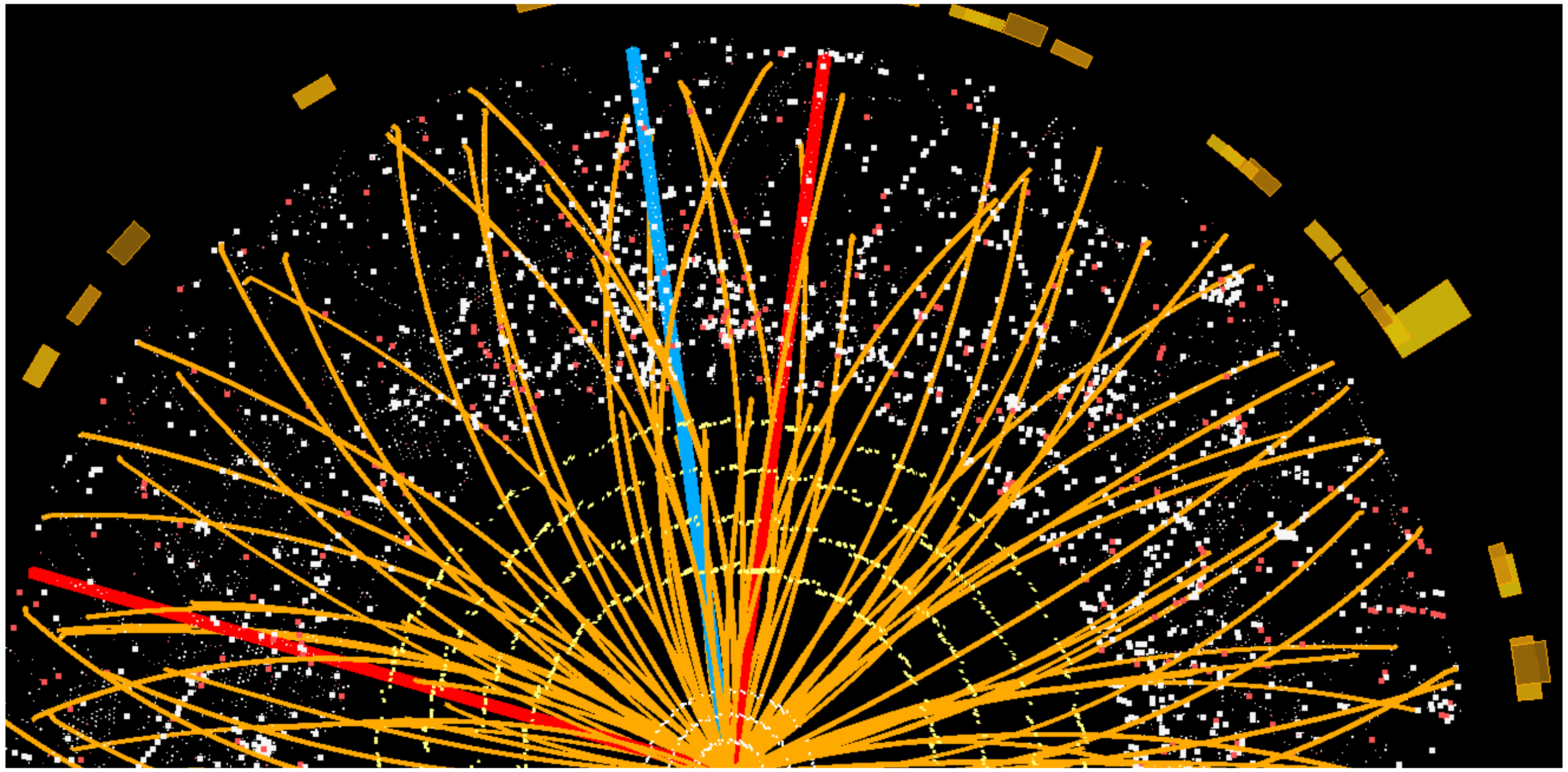
in EM calorimeters







Electron reconstruction: Track

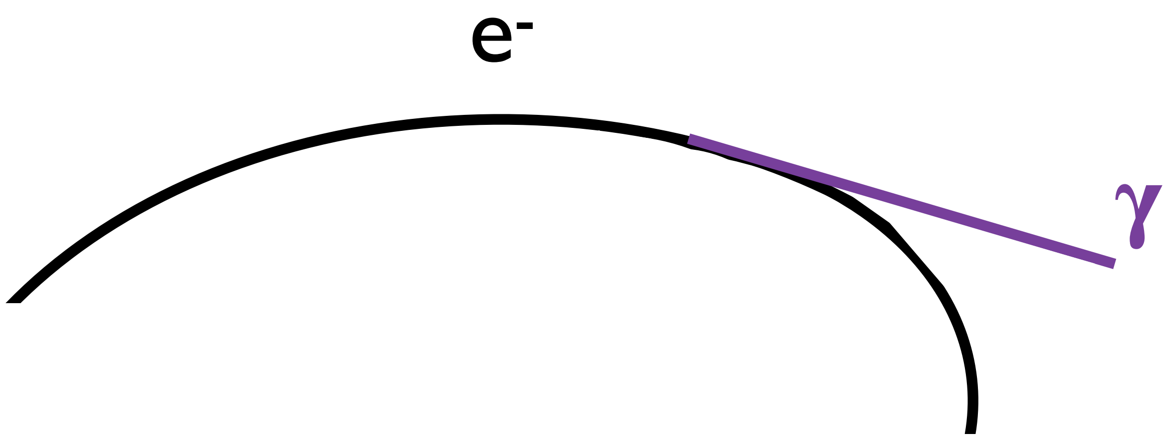


Seeds - pattern recognition - track fit

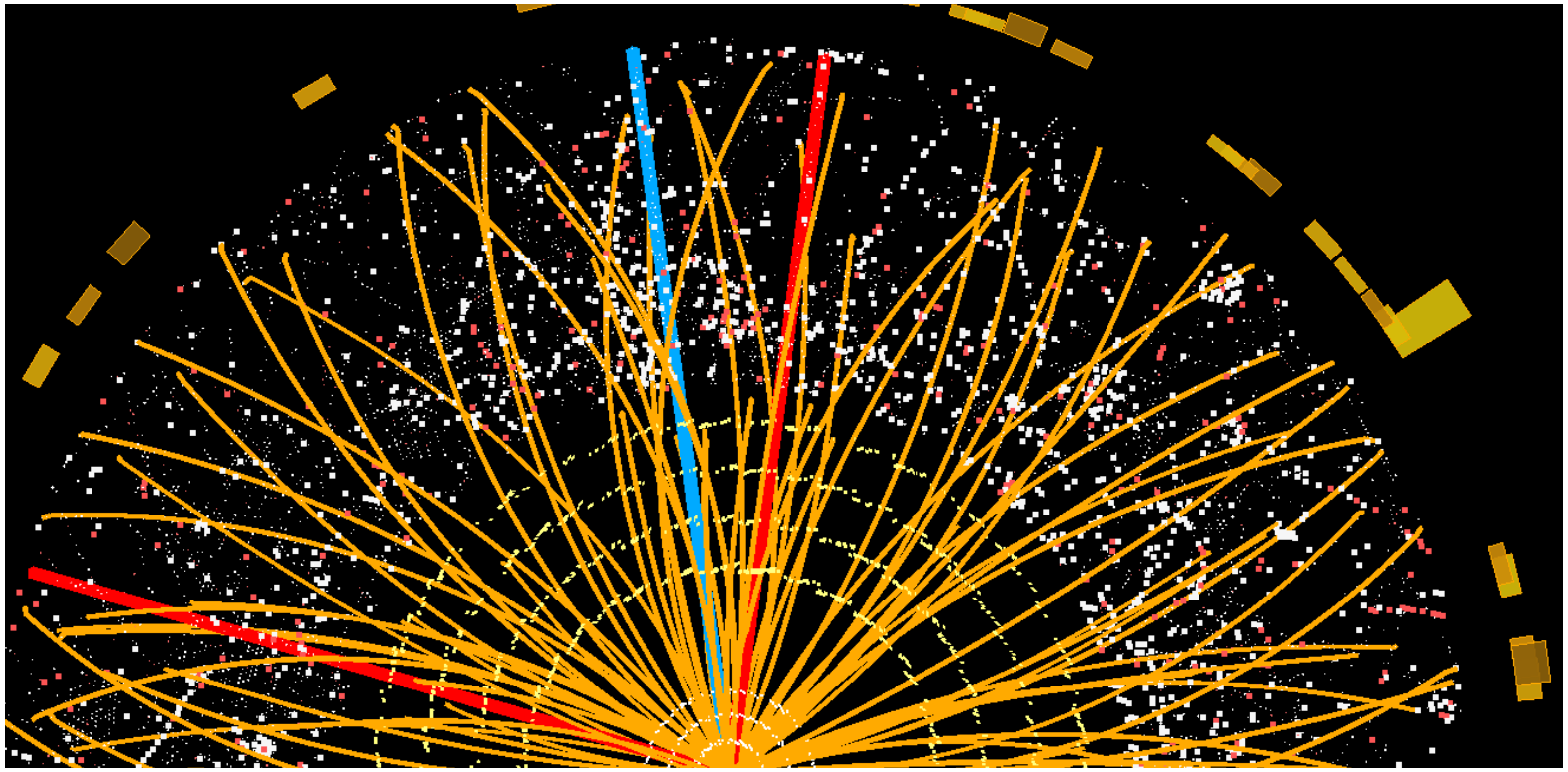
Standard tracking is optimized for pions

But electrons undergo Bremsstrahlung

>> Allow for energy loss in material
during the tracking reconstruction



Electron reconstruction: Track



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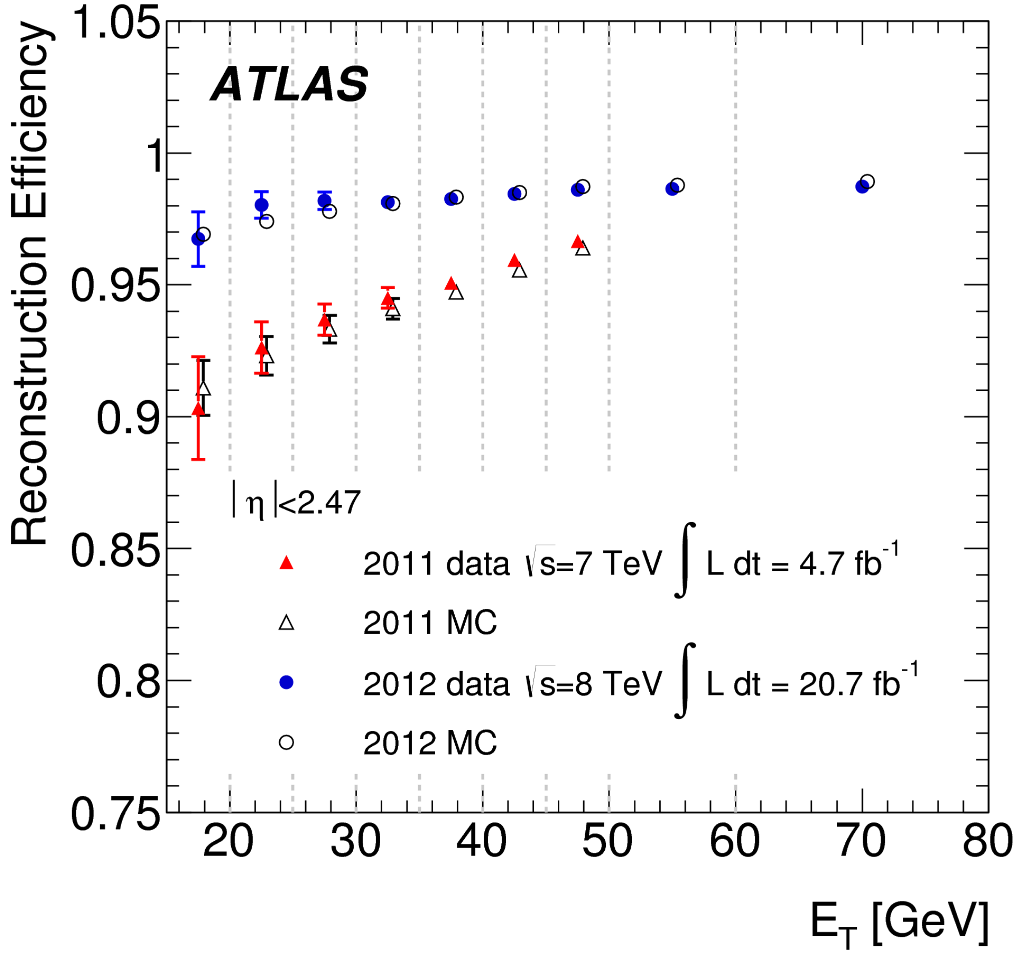


Electron identification

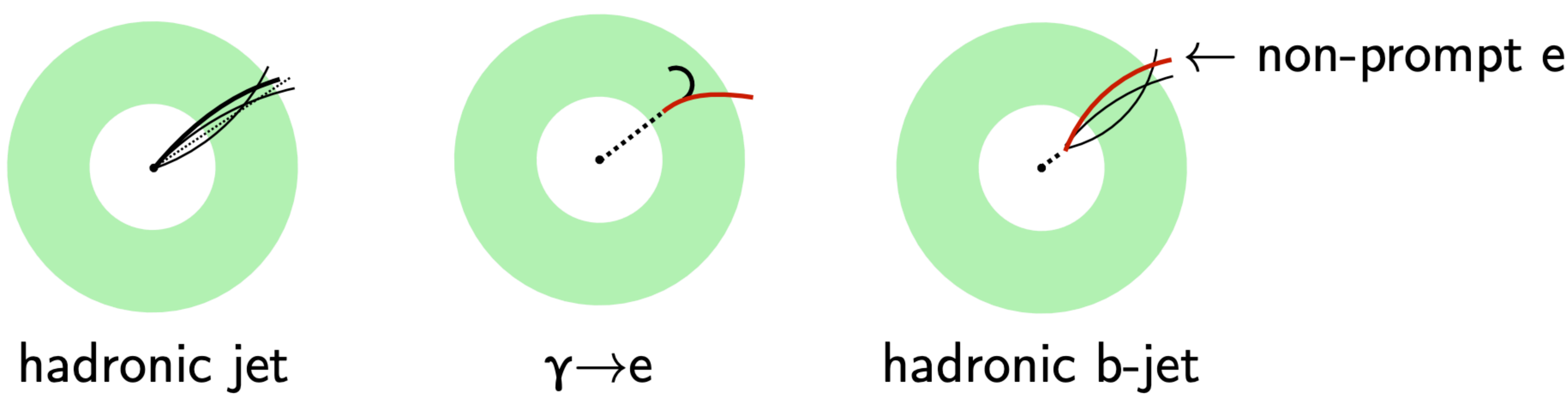
So is every track+cluster combination an electron from the interaction point?

Electron identification

So is every track+cluster combination an electron from the interaction point?

No!

Electrons can be "faked" by

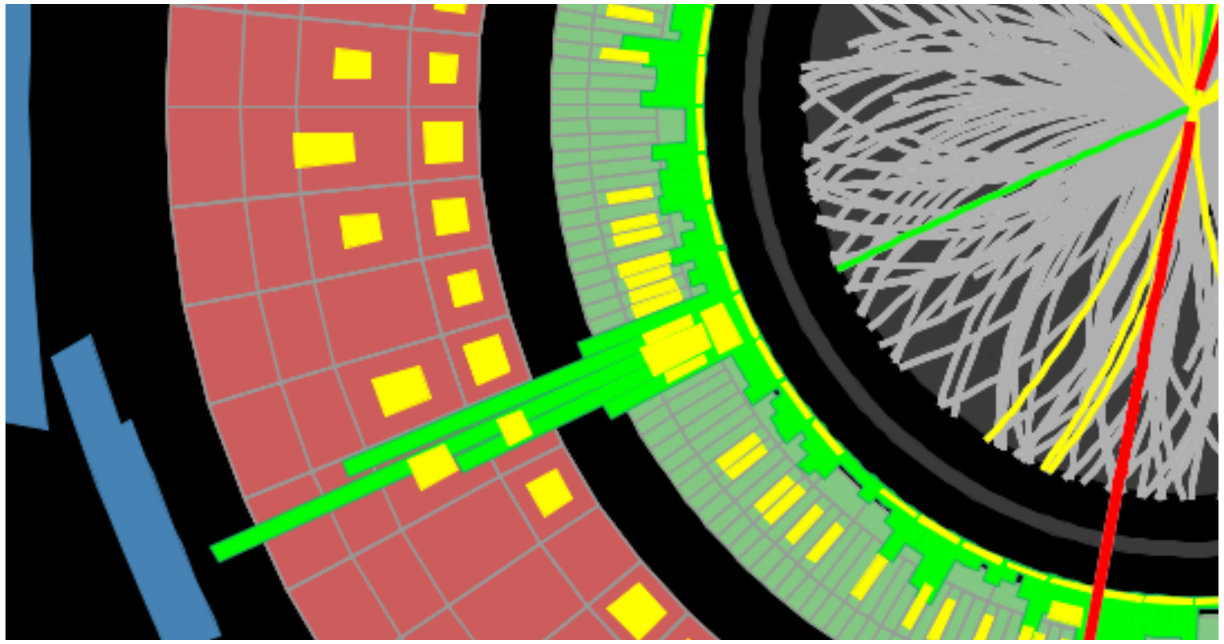


Electron identification

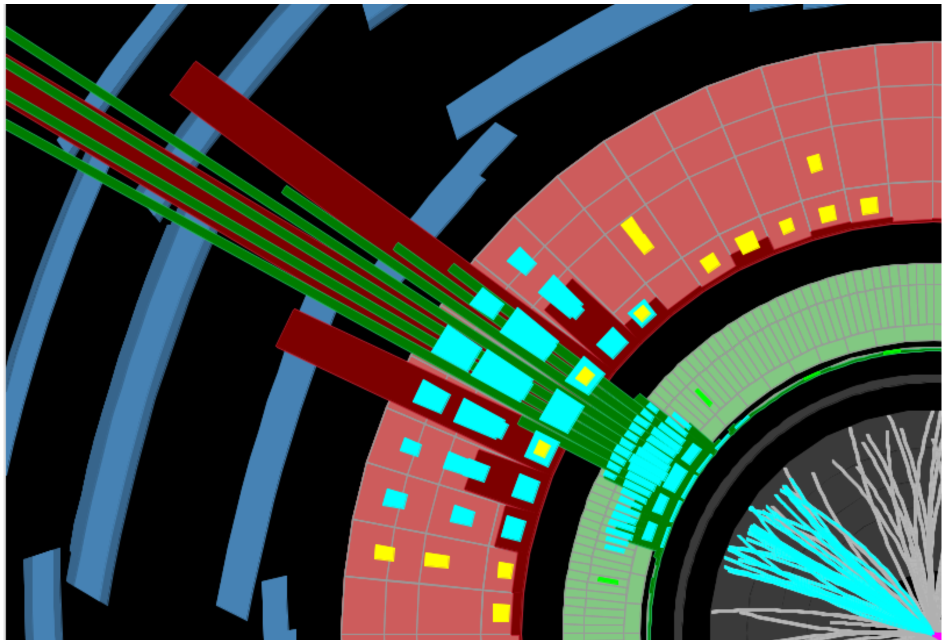
We want to select electrons from the interaction point only

How do we reject fakes?

We use properties of the tracks and clusters, p.ex.



electron

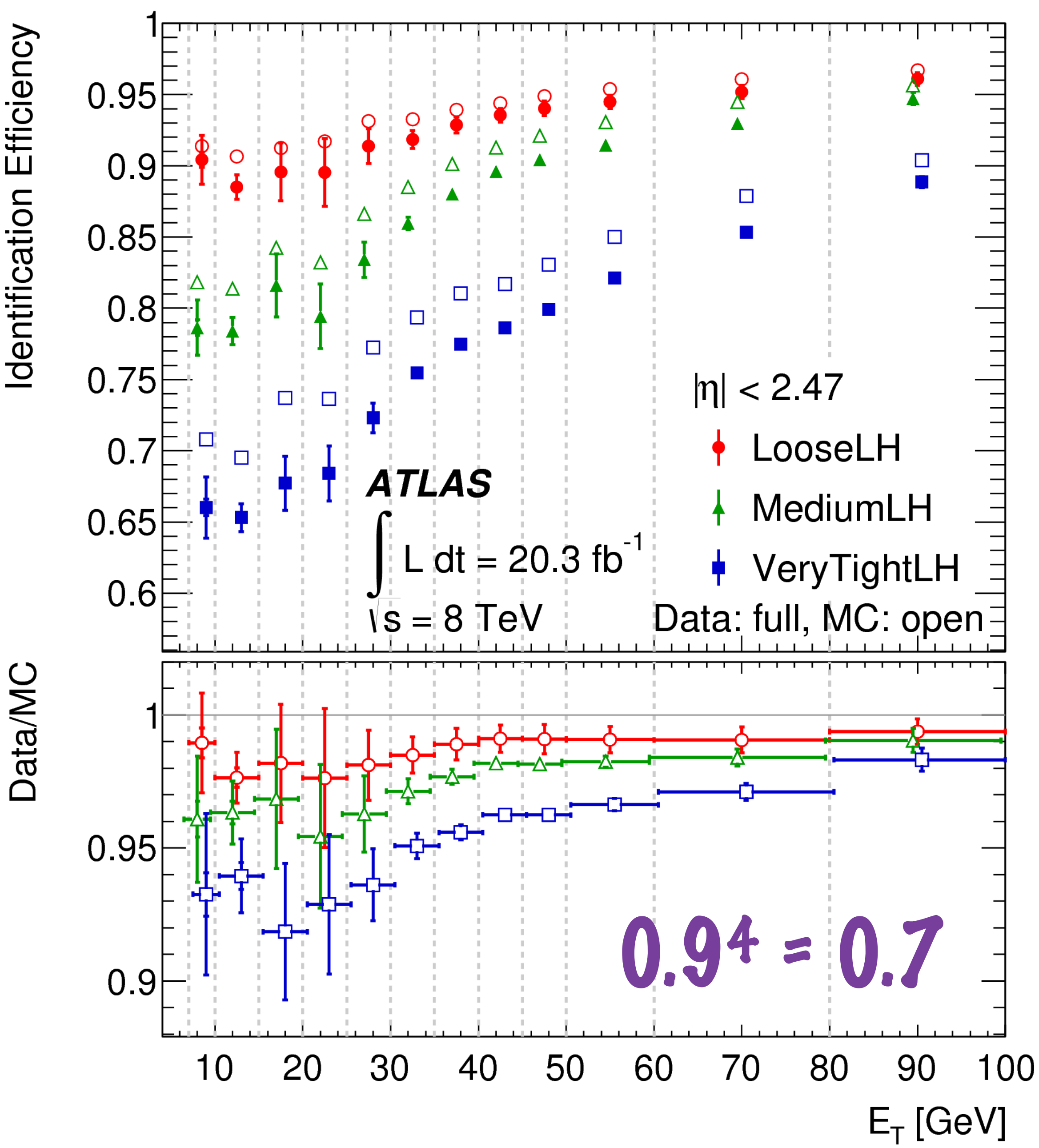


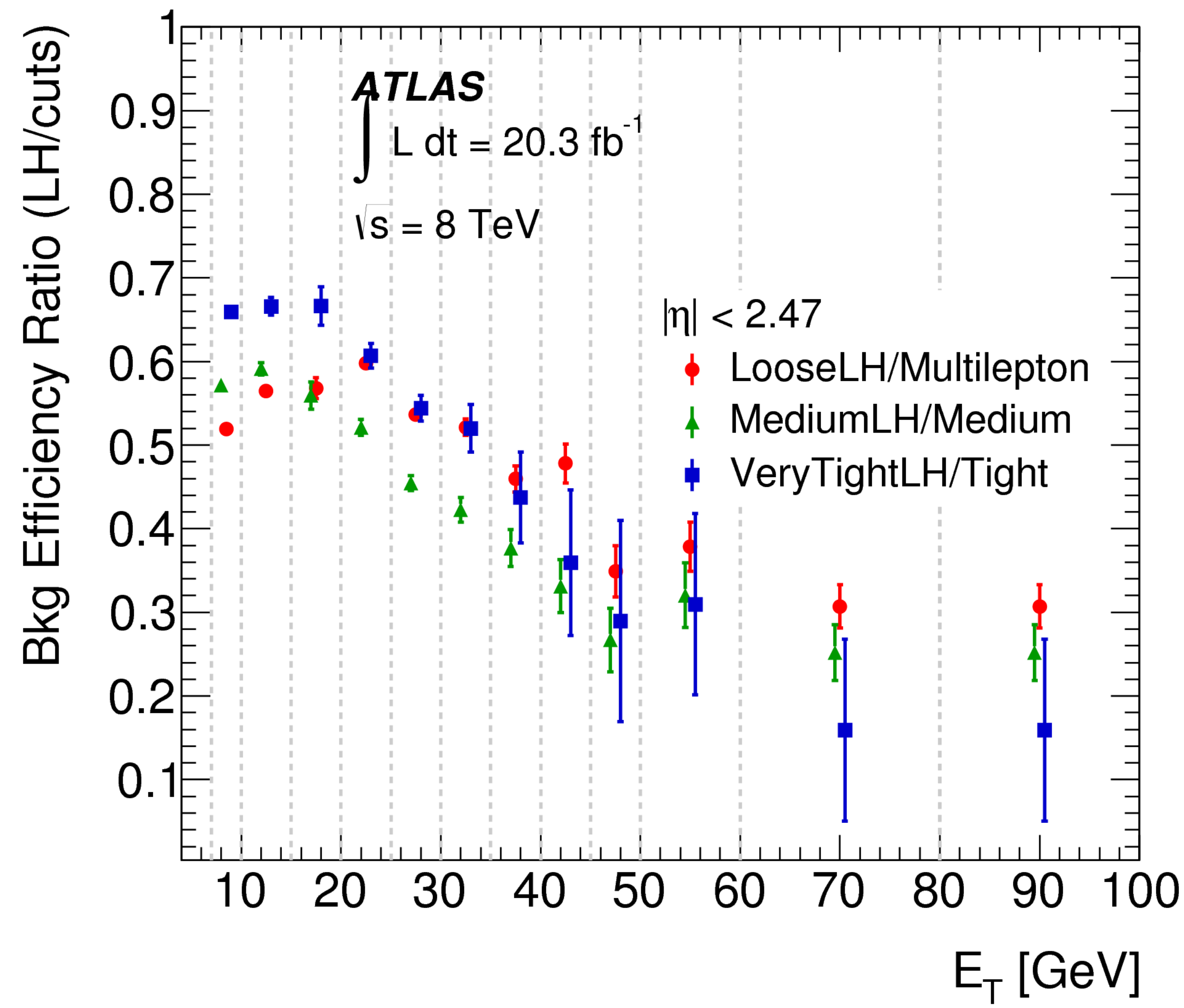
hadronic jet

Electron identification

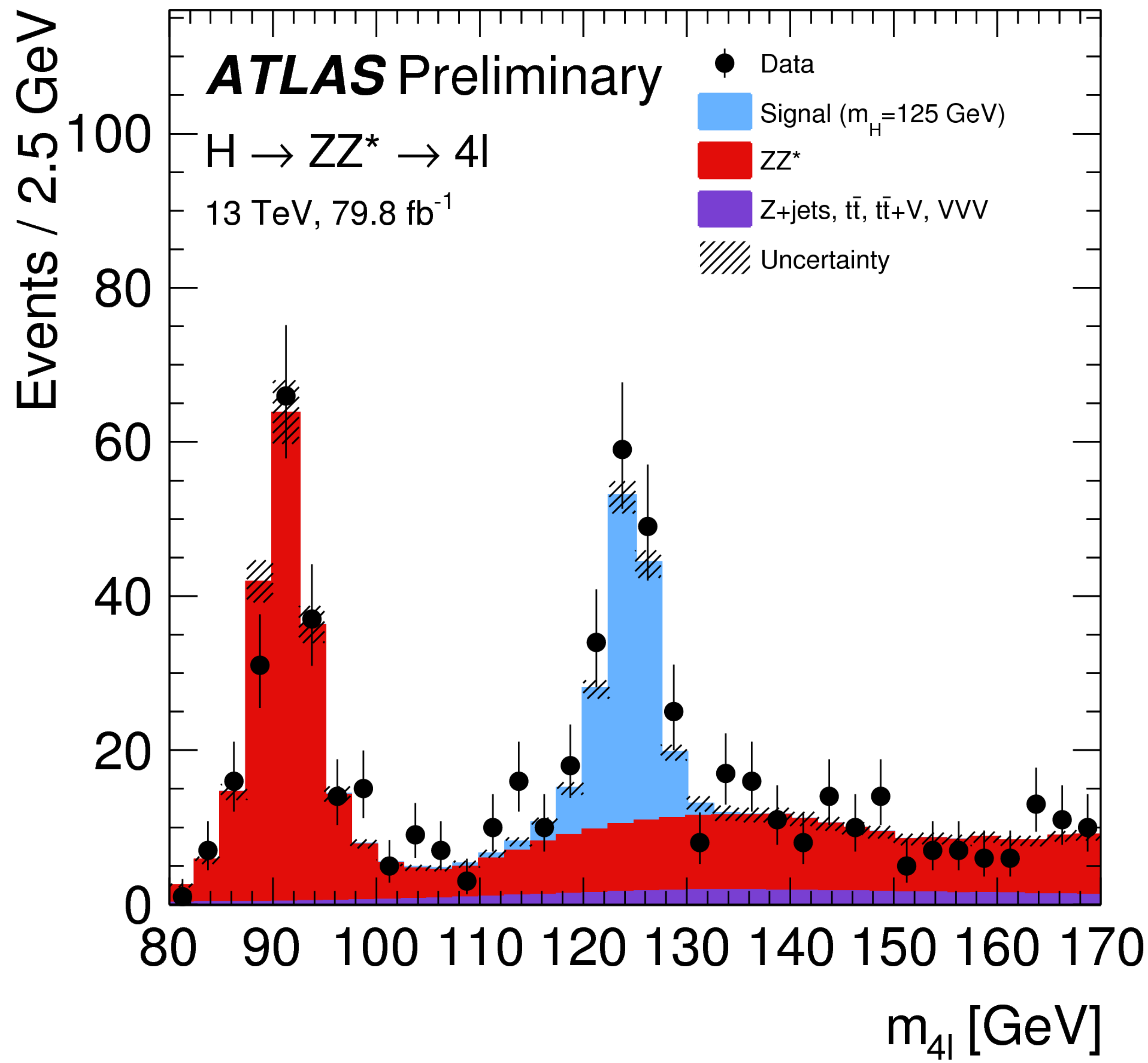
Goal: High signal efficiency, good background rejection

=> stick discriminating variables into a multivariate likelihood





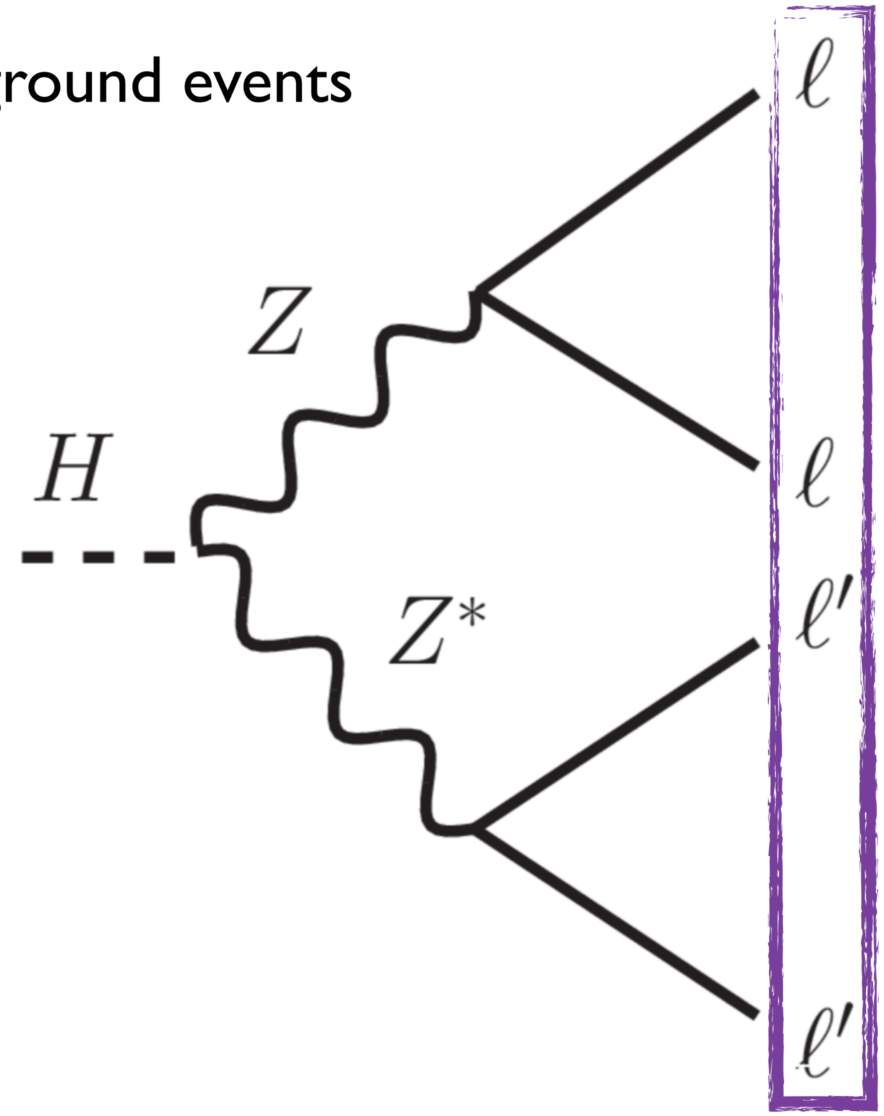
Making a Higgs peak



Event selection

Purpose of event selection:

- select signal events
- reject background events



Select 4 leptons

Backgrounds are small and efficiency important

=> loose criteria on identification and isolation

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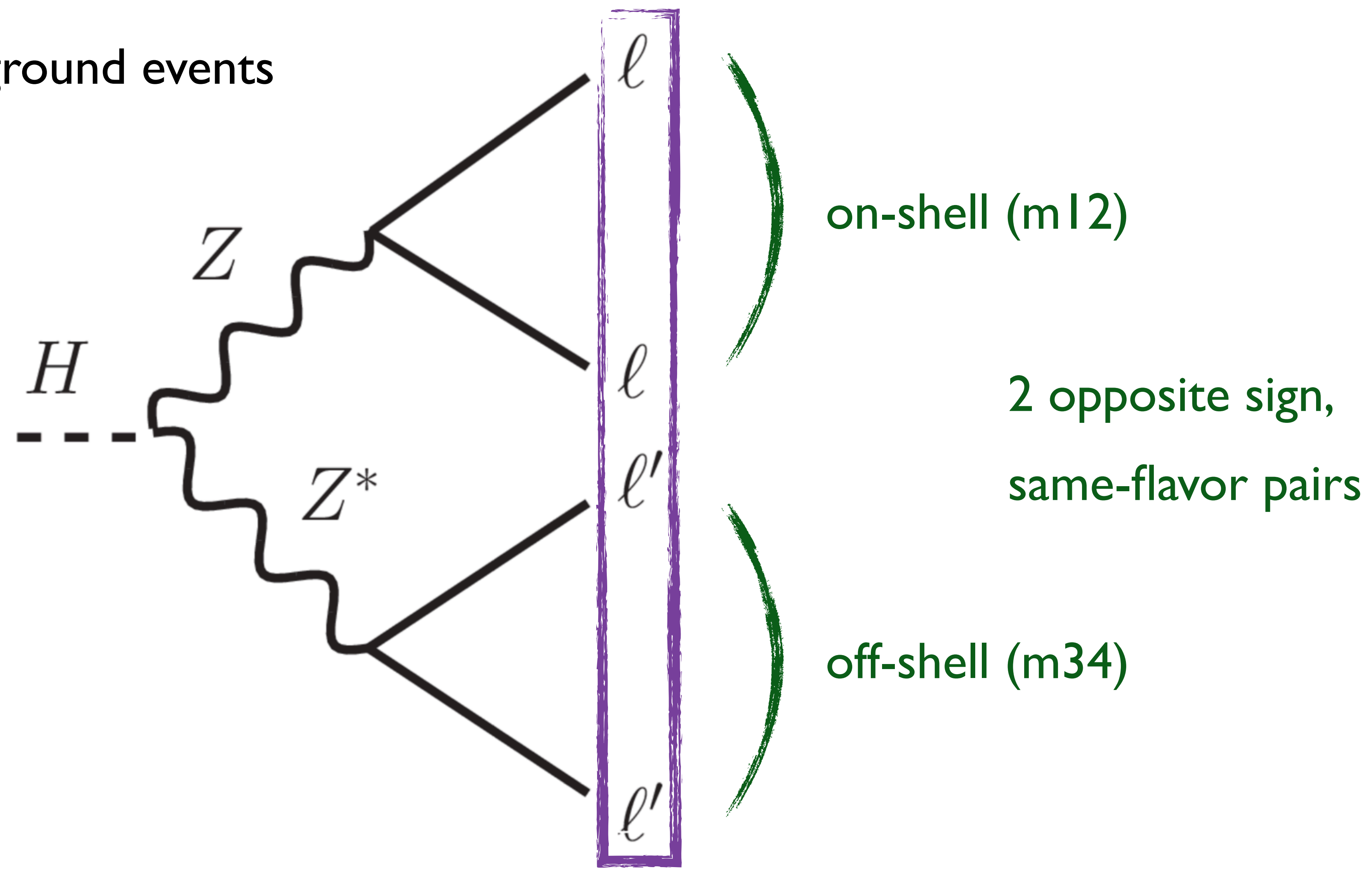

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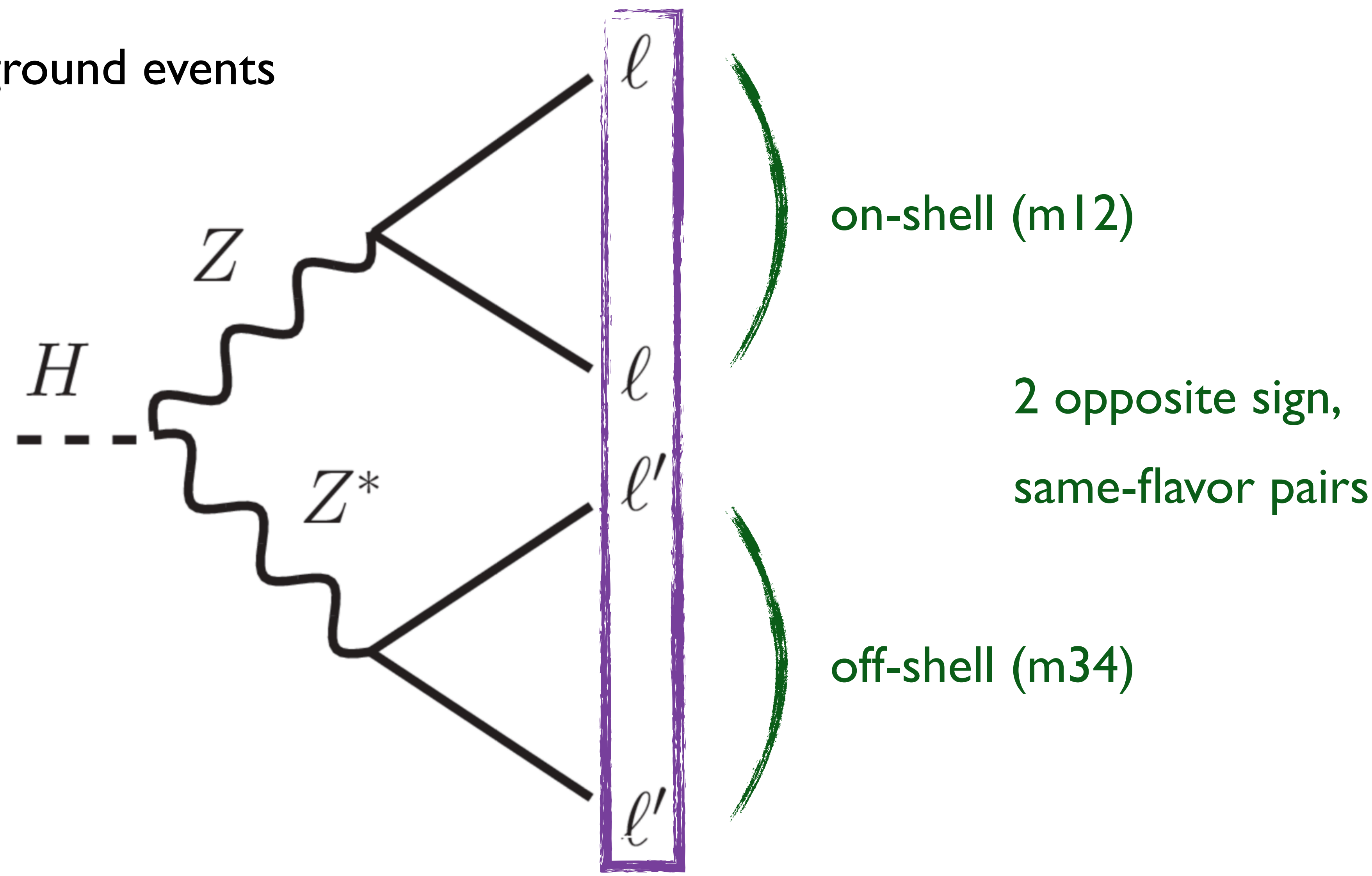
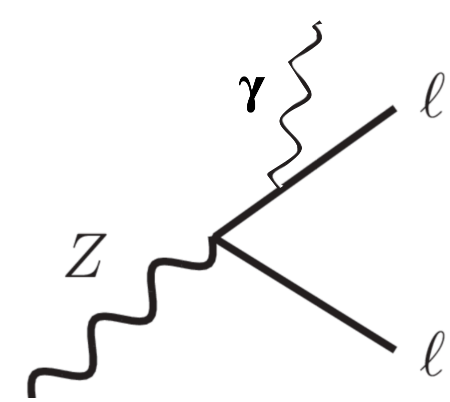




Recover final state radiation to improve peak position and resolution

(important for muons!)

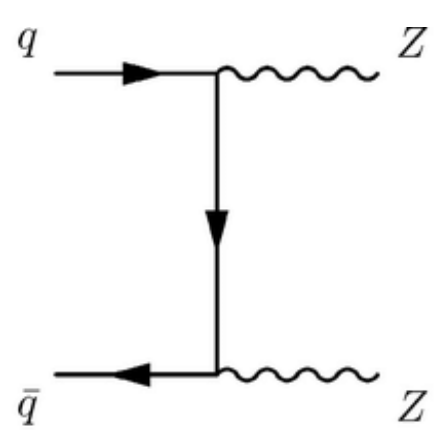
Background estimate

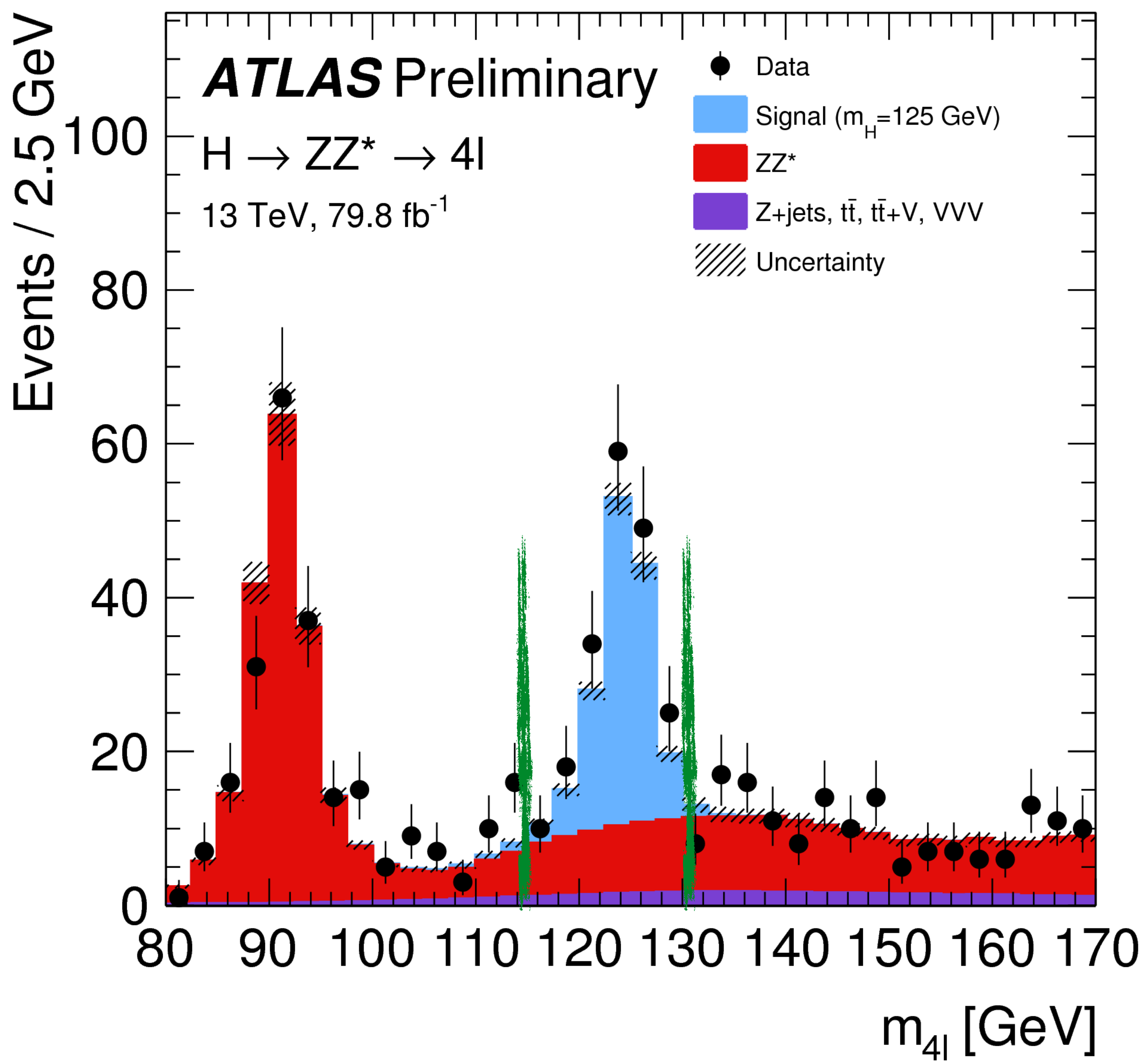
Small backgrounds: Z+jets, ttbar

- difficult to model, estimated from data
- profit from our understanding of lepton fakes

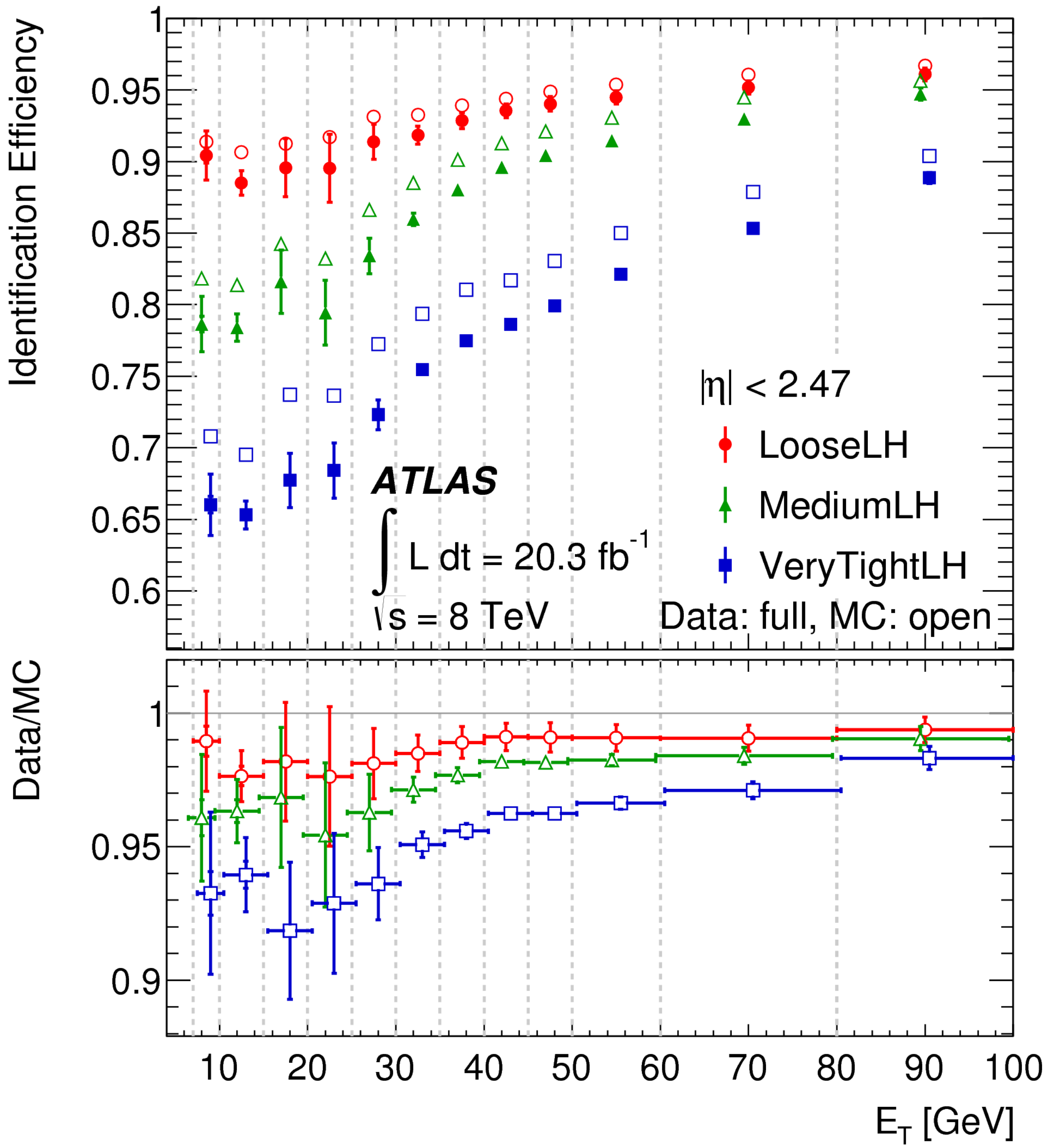
ZZ from MC simulation

(validated using the mass sidebands)





Correction to lepton efficiencies



Lepton efficiency in simulation is not the same as data

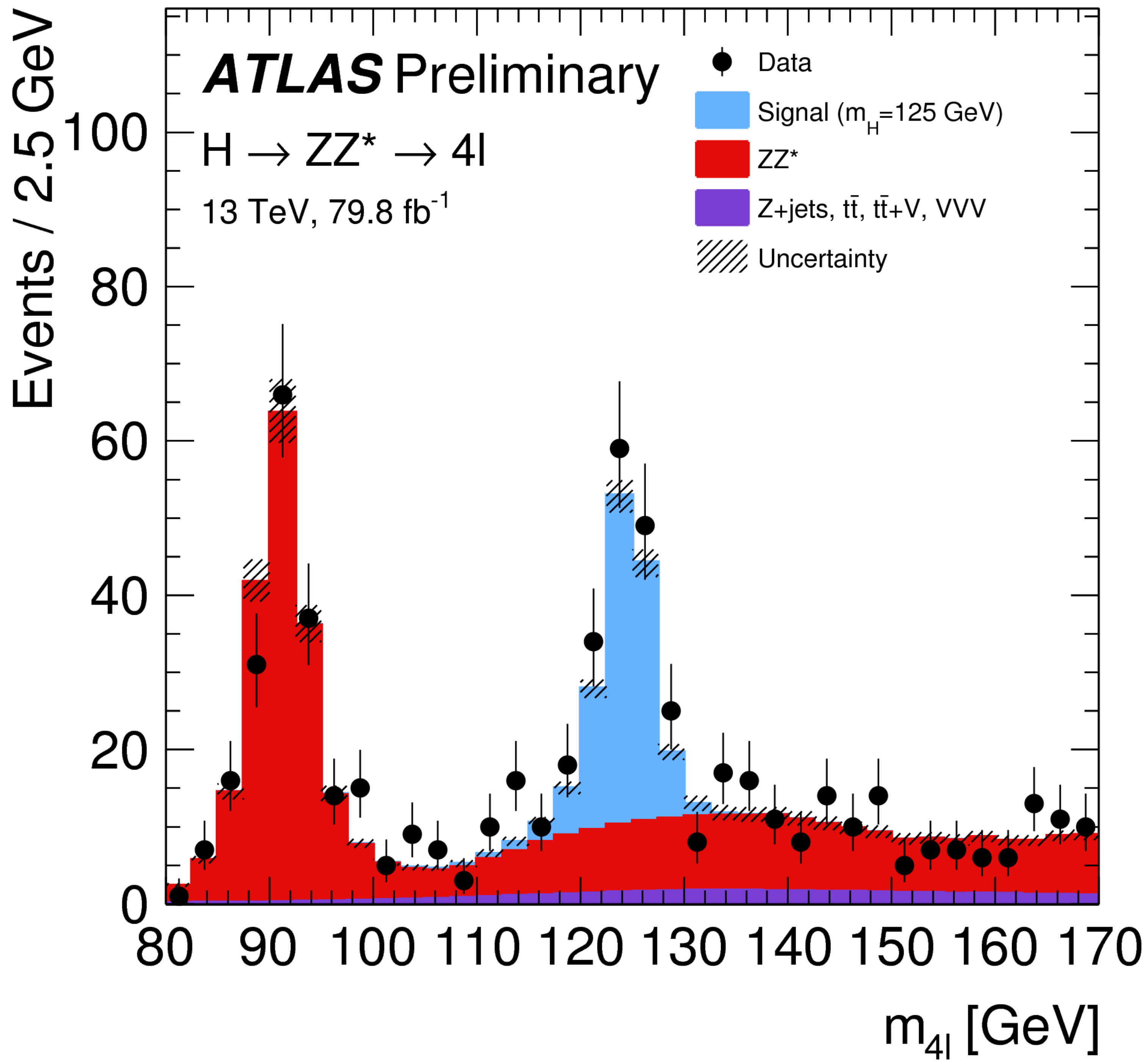
=> simulation needs to be corrected

For both muons and electrons:

- data/MC correction factors obtained from Z and J/Psi resonances (Tag & Probe)
- percent-level uncertainties

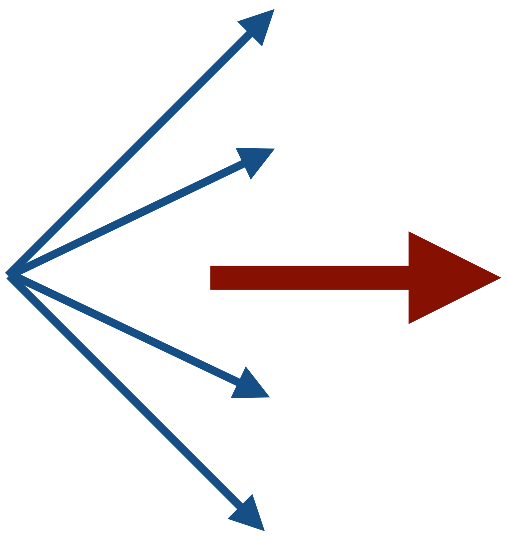
Similar: Correction also for energy scale/resolution

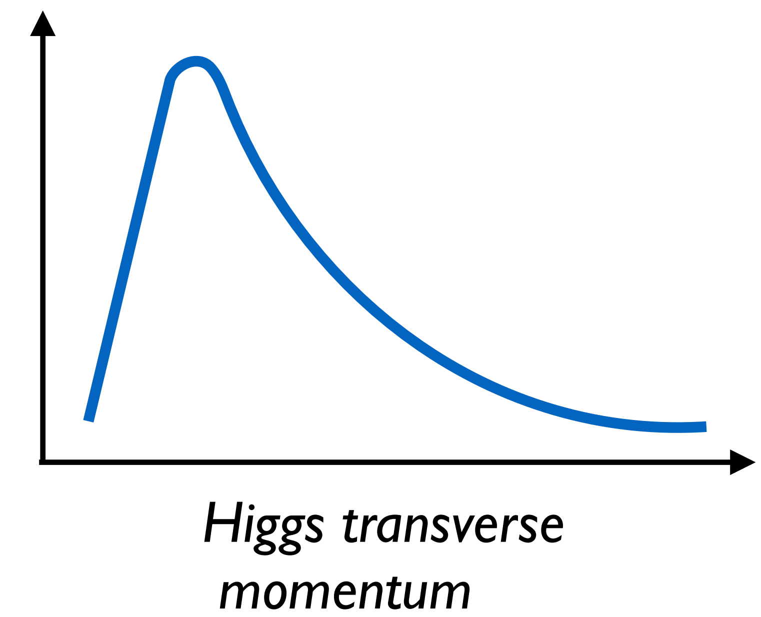
The peak


ATLAS Preliminary
H → ZZ* → 4l
13 TeV, 79.8 fb-1
Data
Signal (mH=125 GeV)
ZZ*
Z+jets, tt̄, tt̄+V, VVV
Uncertainty
Events / 2.5 GeV
0
20
40
60
80
100
80
90
100
110
120
130
140
150
160
170
m4l [GeV]

Differential cross sections

- What are differential cross sections?
  - cross sections in bins of an observable, examples
    - Higgs transverse momentum, reconstructed from the transverse momentum of the 4 leptons
    - number of jets produced together with the Higgs
  - cross sections: no detector simulation necessary to compare models
  - fiducial: attempt to be as model independent as possible





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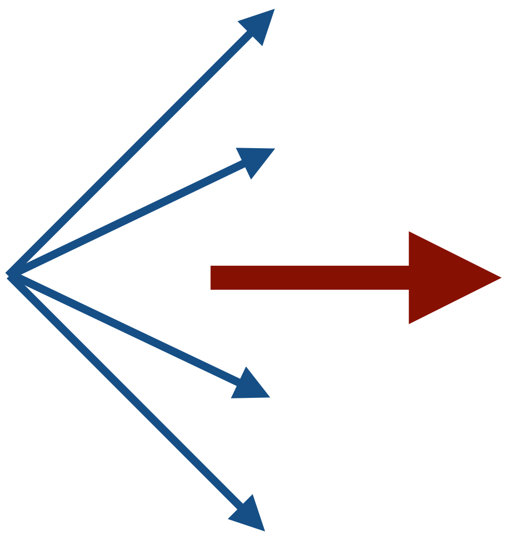
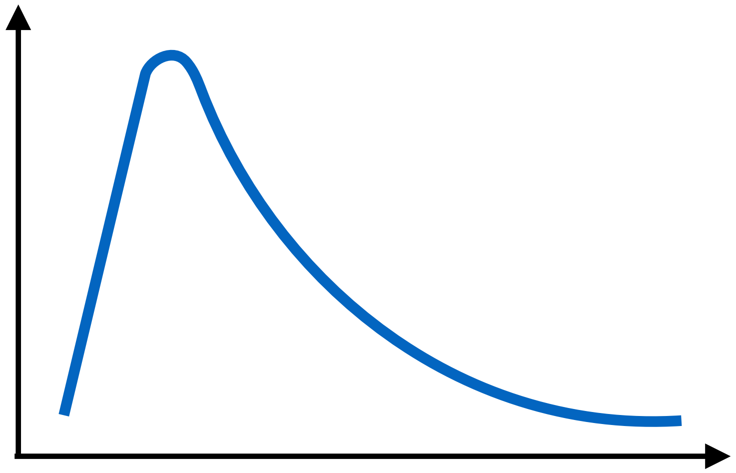
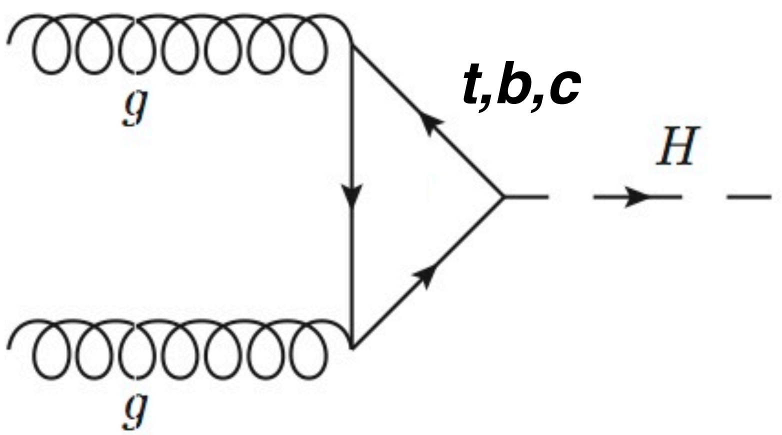


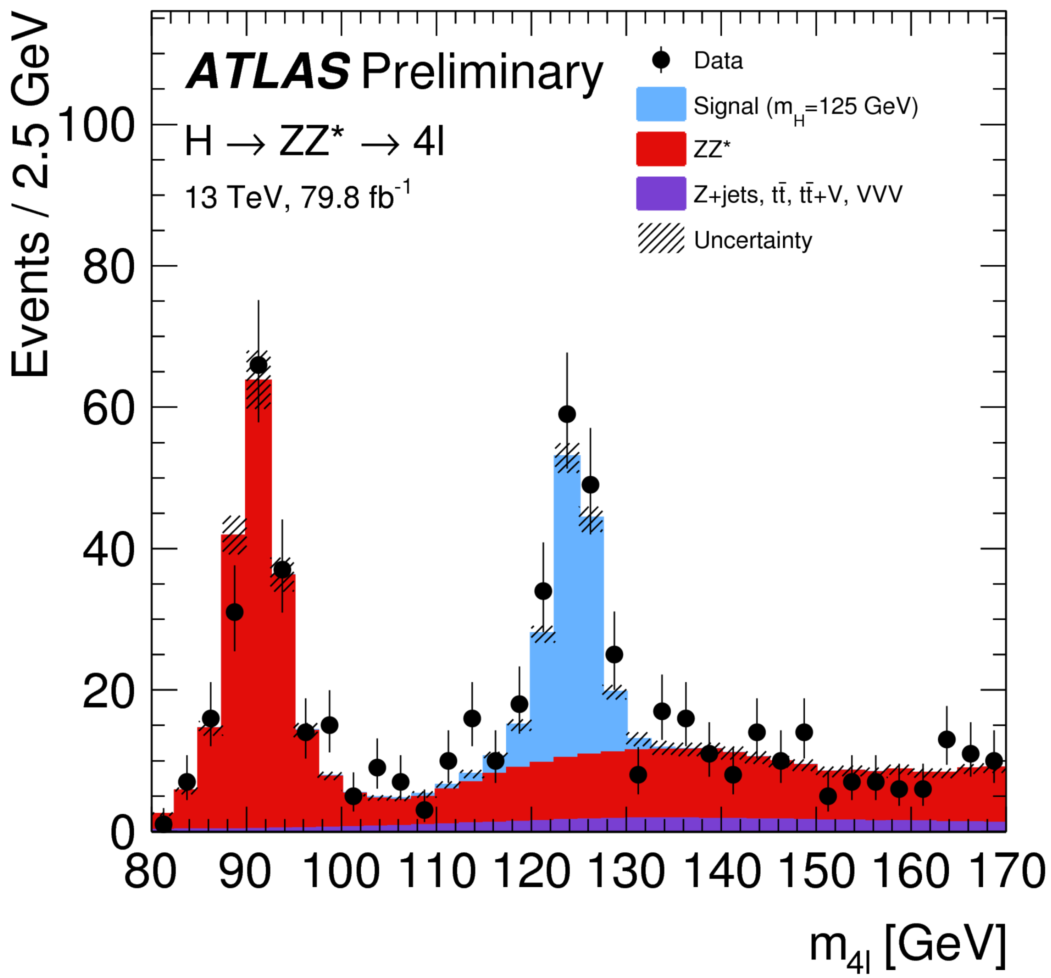


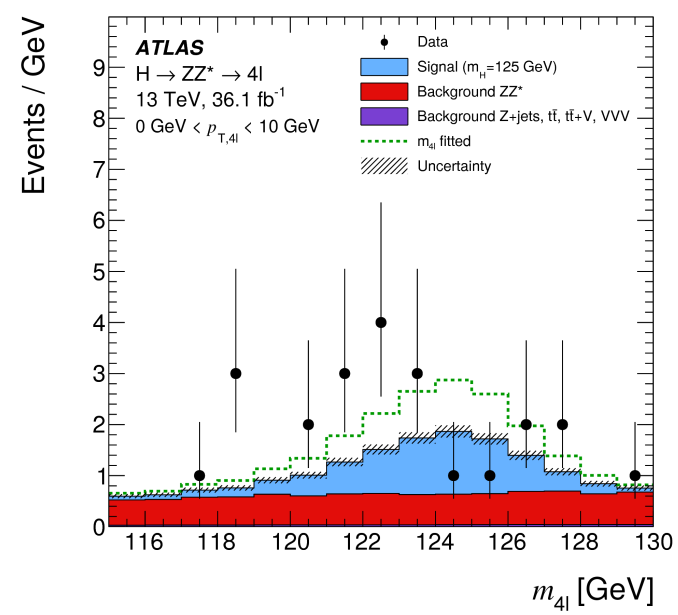
Higgs transverse momentum

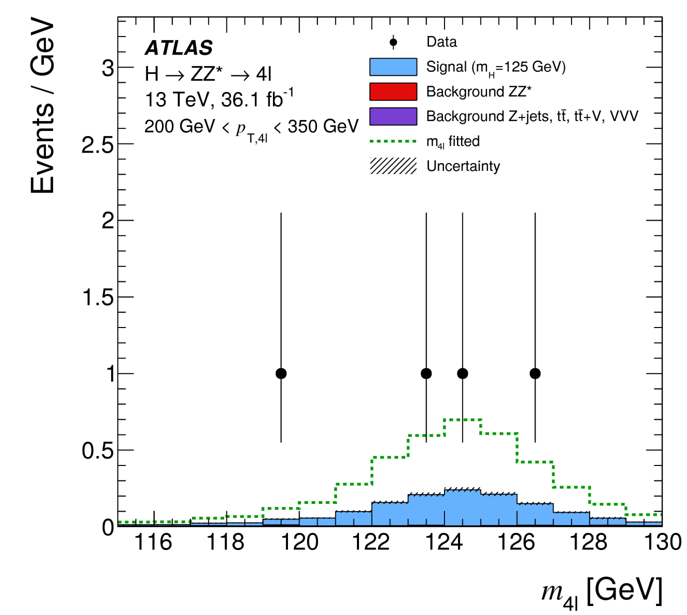
- Why measure them?
  - properties Higgs boson production and decay
  - Higgs transverse momentum
    - search for heavy particles in the ggF loop
    - checks of quark couplings



The peak





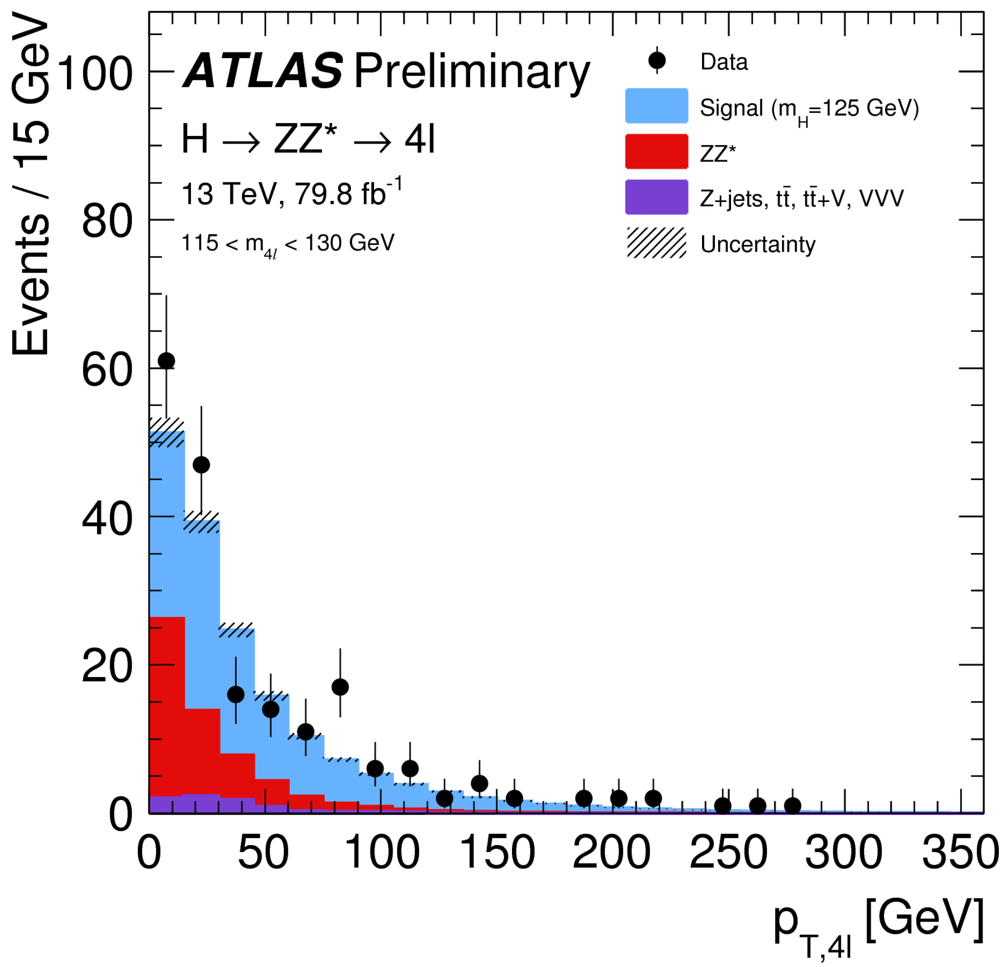


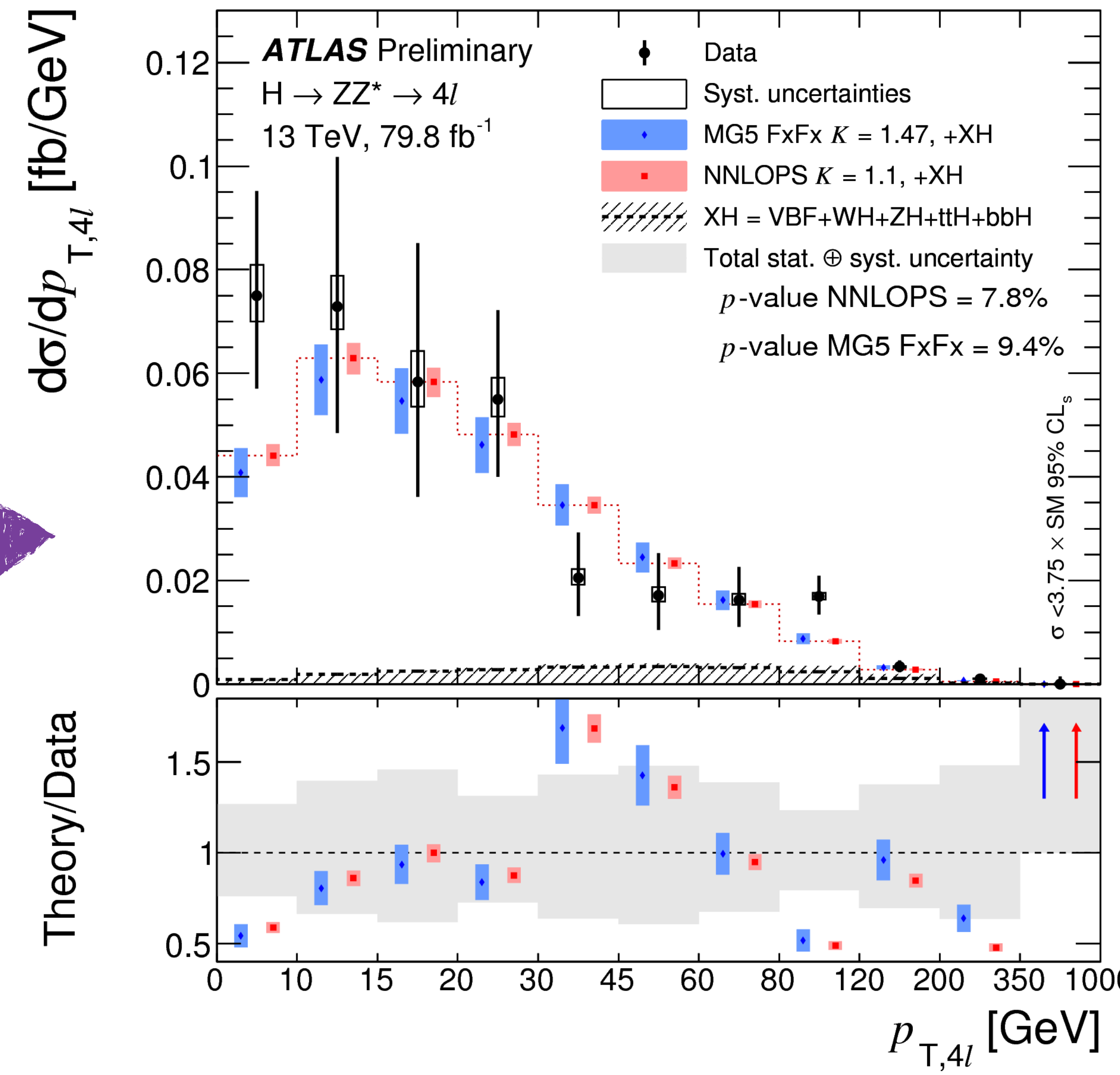
pT < 10 GeV

200 GeV< pt < 350 GeV

- differential: do template fit in every bin

Differential cross sections





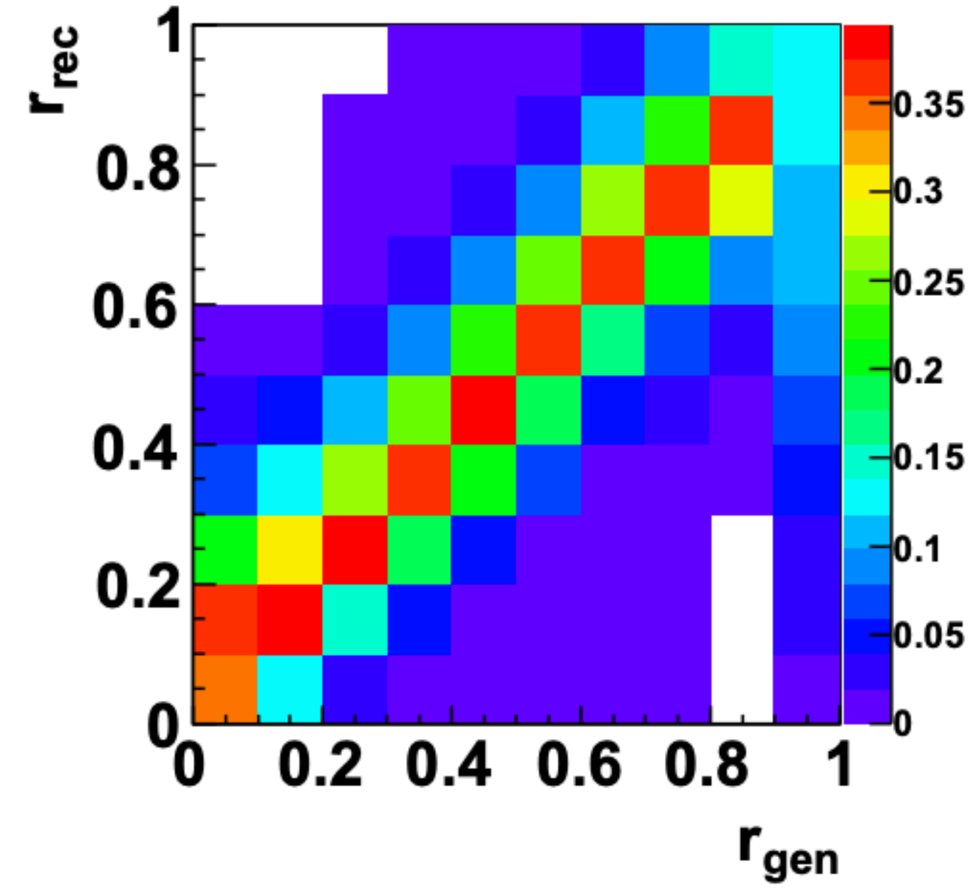
Correction for

- luminosity
- detector effects, like lepton efficiency and energy resolution

Correction for detector effects

Need to go from measured to truth distribution

Detector response matrix A



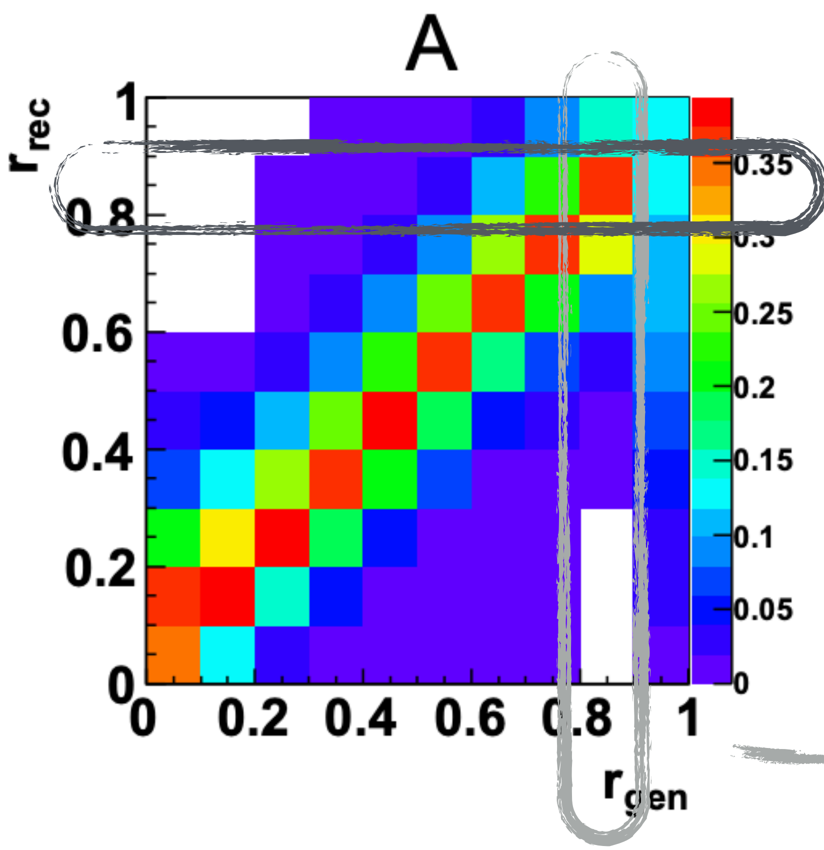
$$\mu_i = \sum A_{ij} x_j^{\text{truth}}$$

=> to get truth, invert matrix

Problems: creates large negative off-diagonals
→ statistical fluctuations of the data are amplified

>> Regularization
>> Used here: Bin-by-bin correction

Correction factors



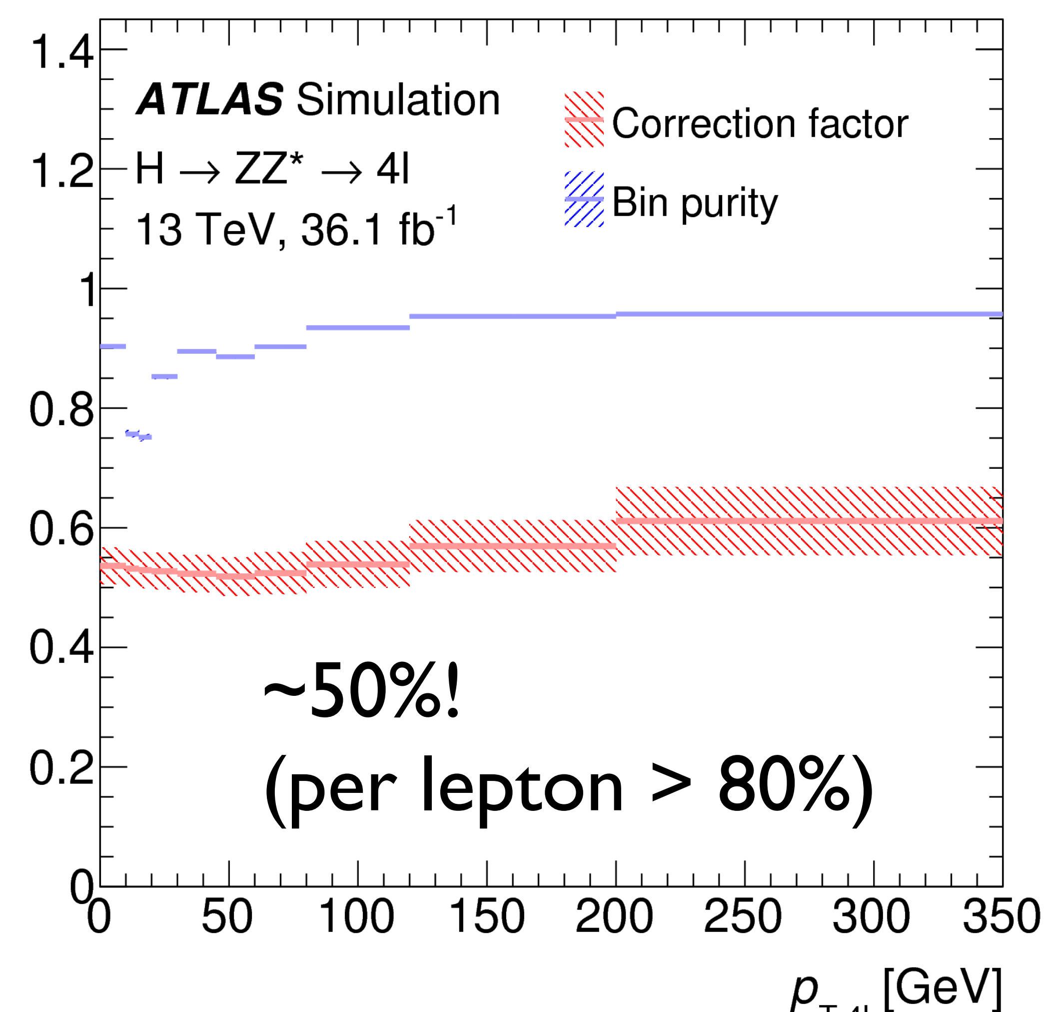
$$\epsilon^i = \frac{N^i_{\mathrm{reco}}}{N^i_{\mathrm{true}}}$$

$$\sigma^i_{fid} = \frac{N^i_{sig}}{L \cdot \epsilon^i}$$

Simplest correction for detector effects

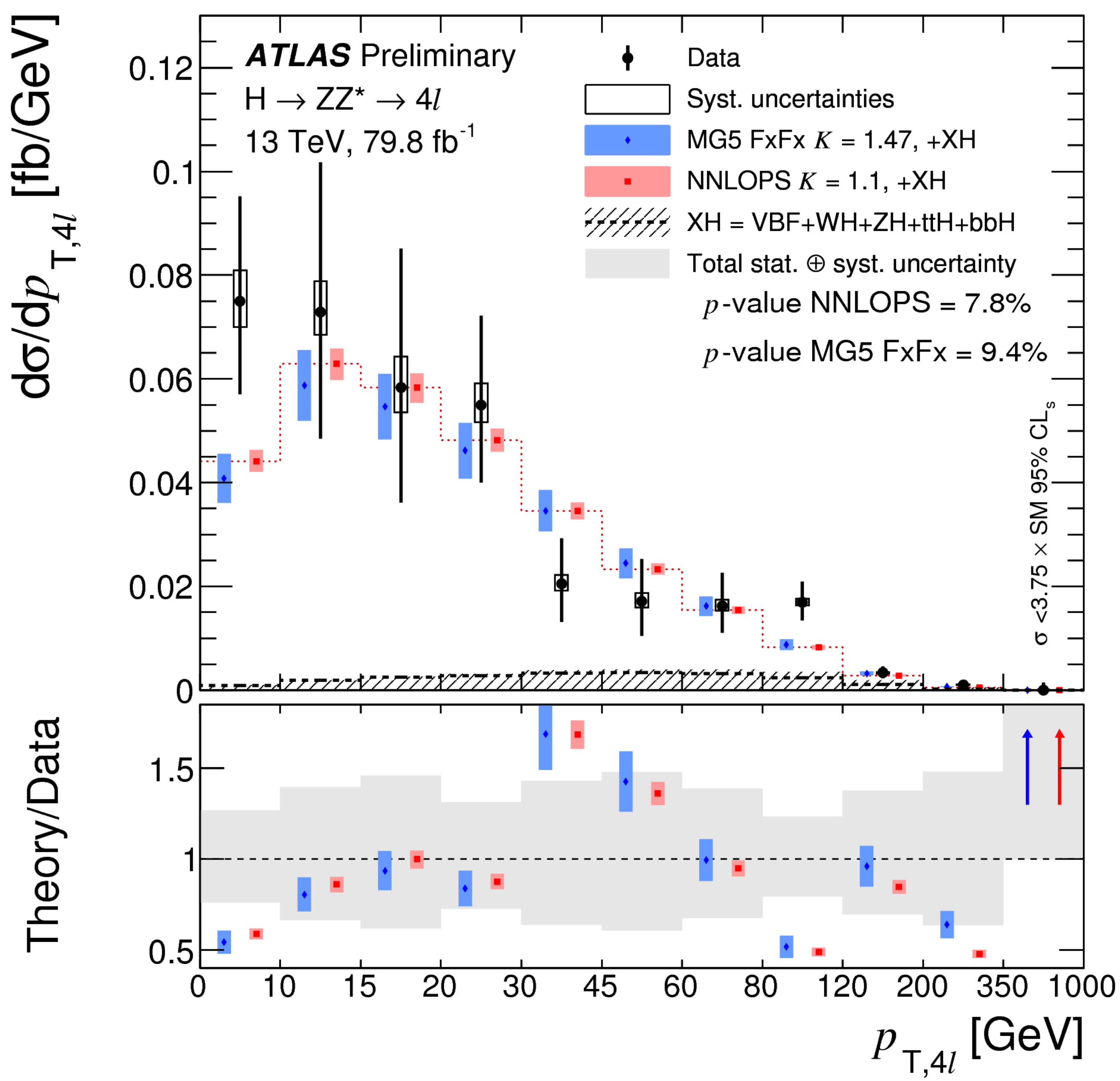
=> careful evaluation of possible biases

=> currently much smaller than statistical uncertainties

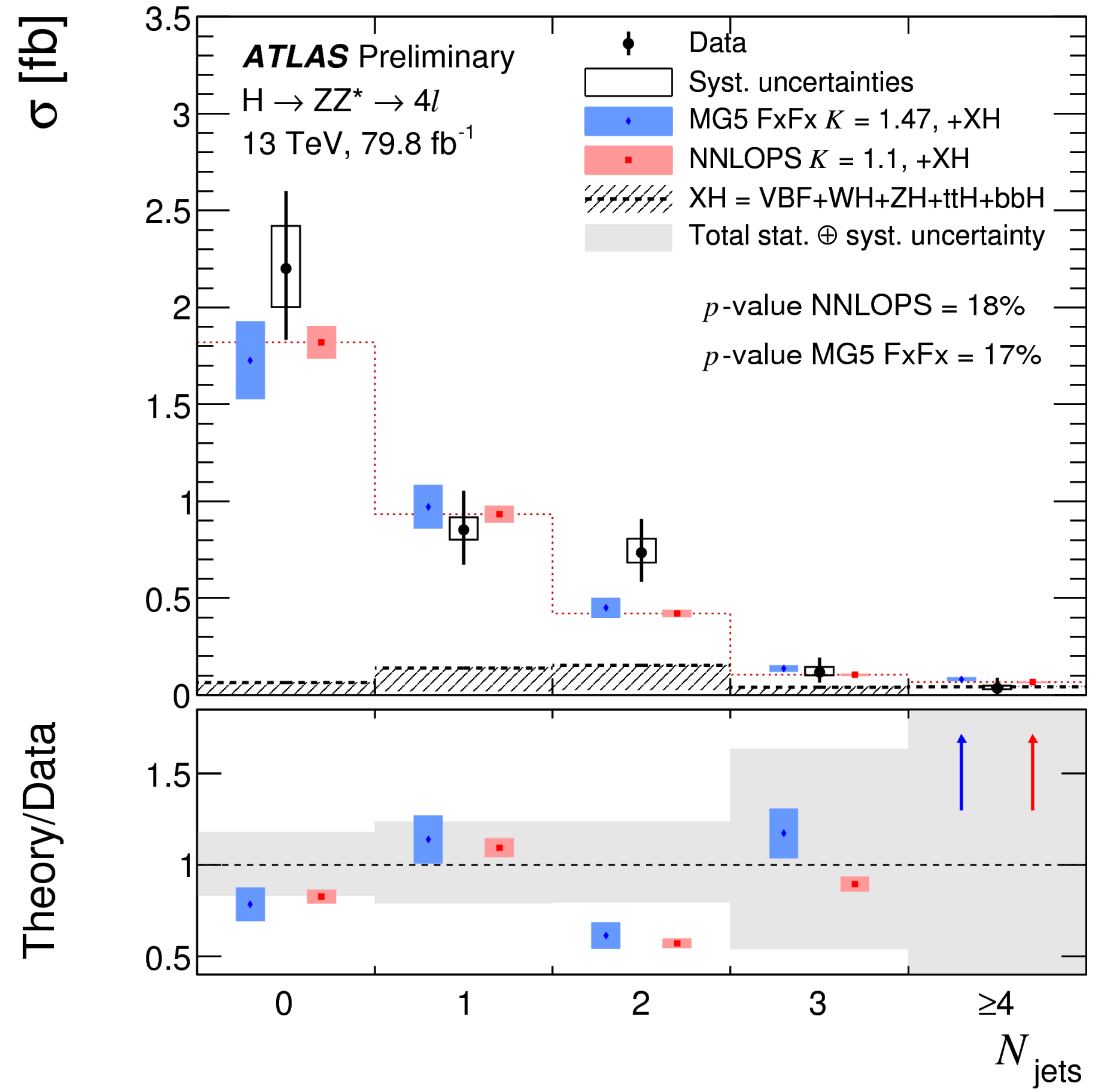


Differential cross sections results

Higgs transverse momentum



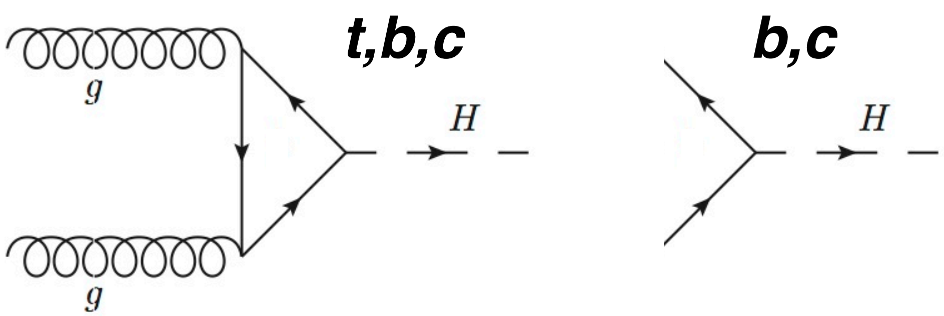
Number of jets

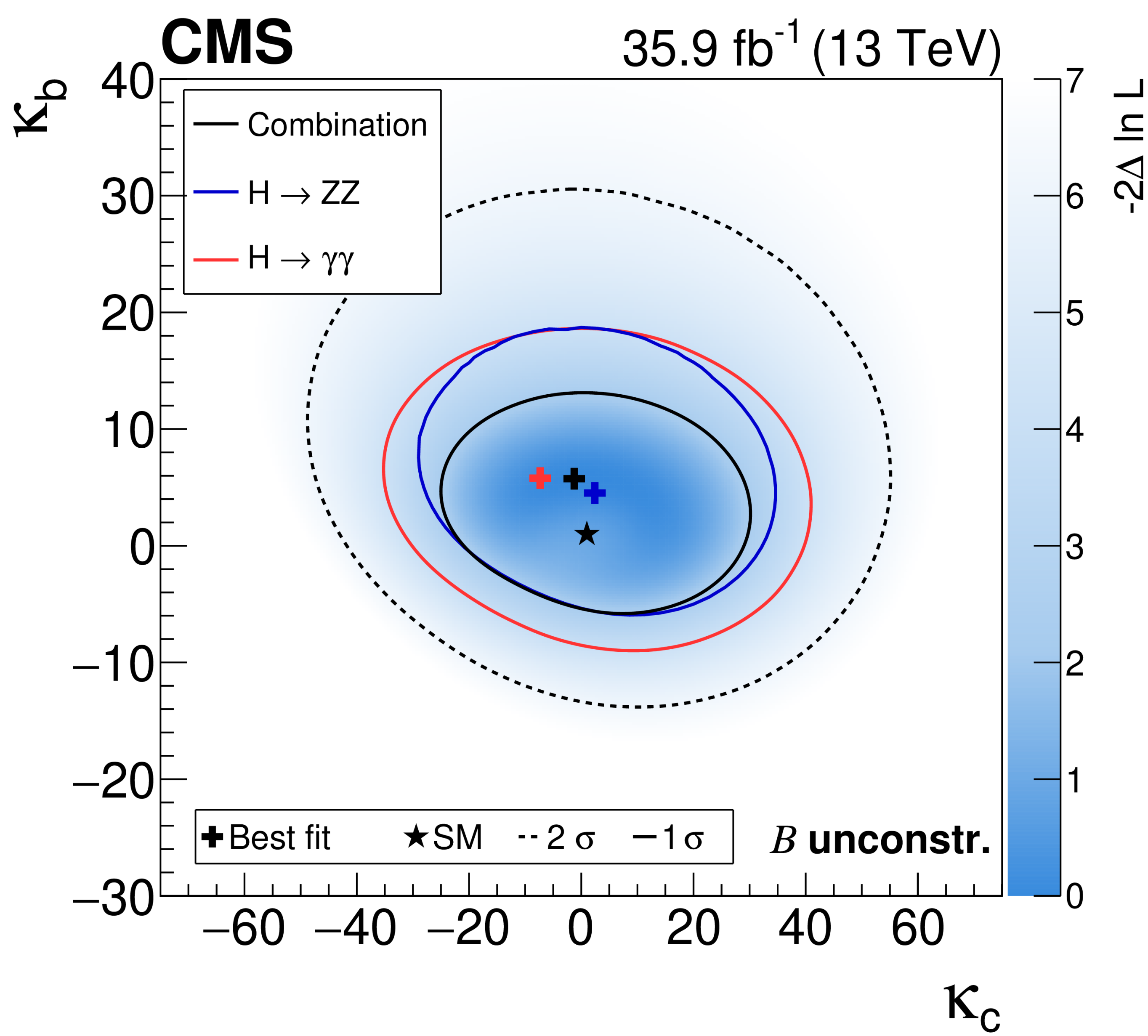


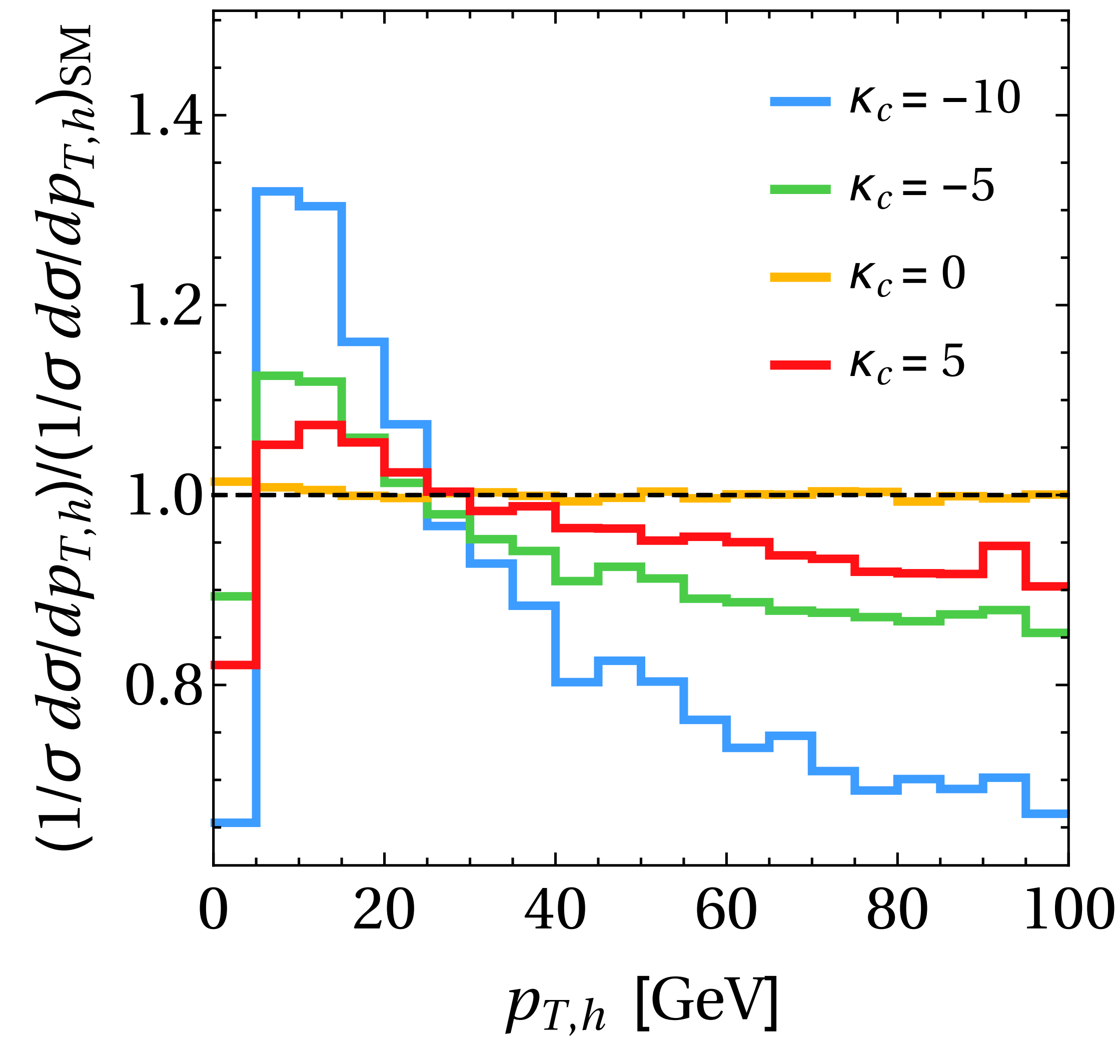
Interpretations of differential cross sections

Checks of quark couplings

PRL 118, 121801 (2017)







κ: scaling factors to SM couplings

$$\kappa_c = \frac{y_c}{y_c^{\mathrm{SM}}}$$

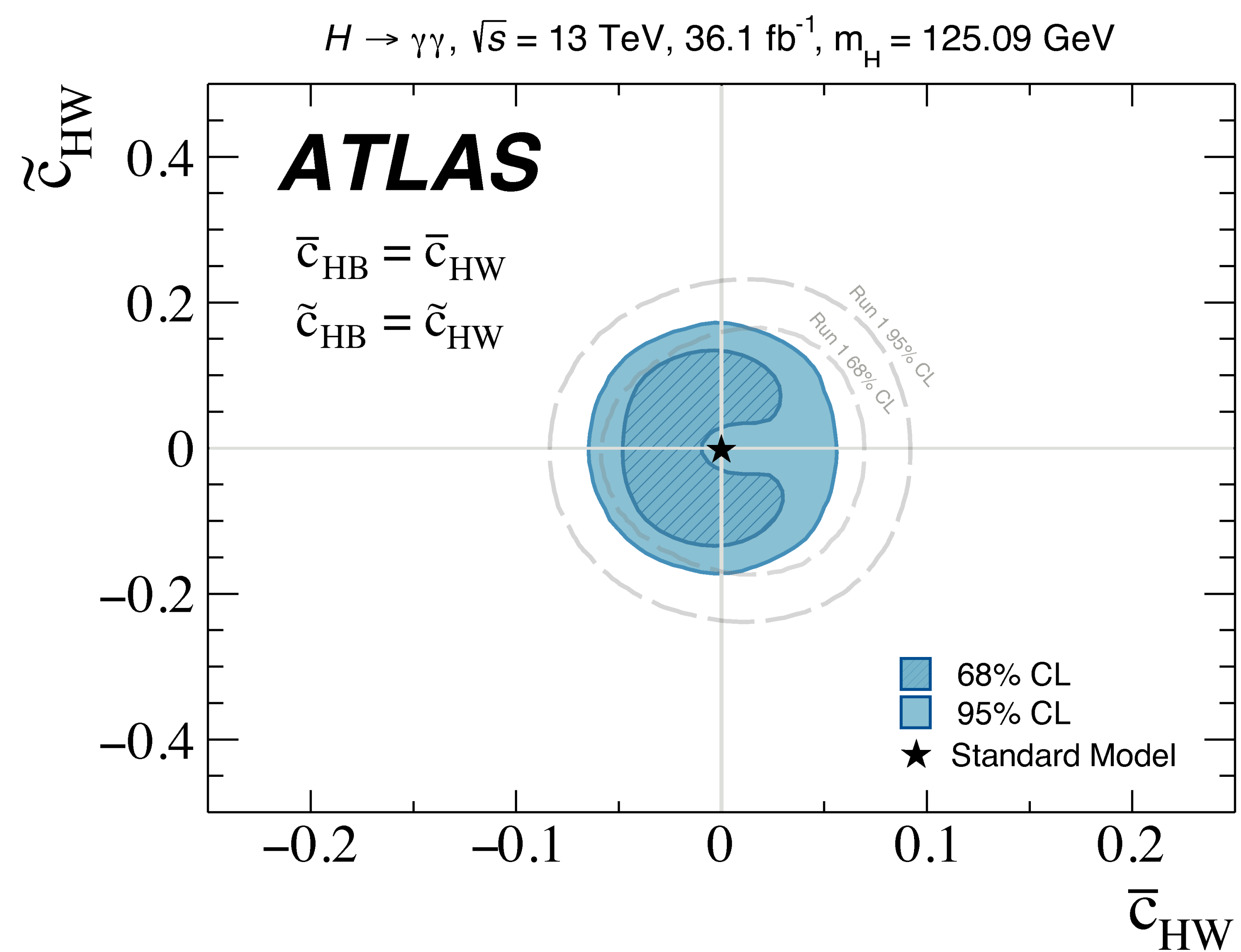
Interpretations of differential cross sections

EFT: Way to search for deviations in the Higgs Lagrangian without knowing exact new physics model

Introduce additional operators, with coefficients $\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$ (c_i = $\frac{f_i}{\Lambda^2}$)

H →γγ

>> fit differential cross sections for Wilson coefficients (0 in SM) in the SILH basis



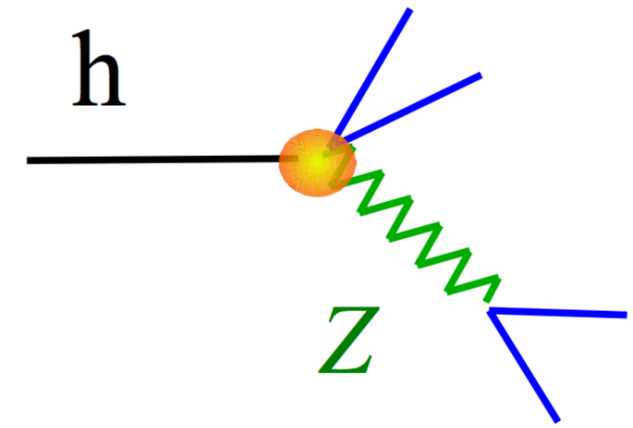
Interpretations of differential cross sections

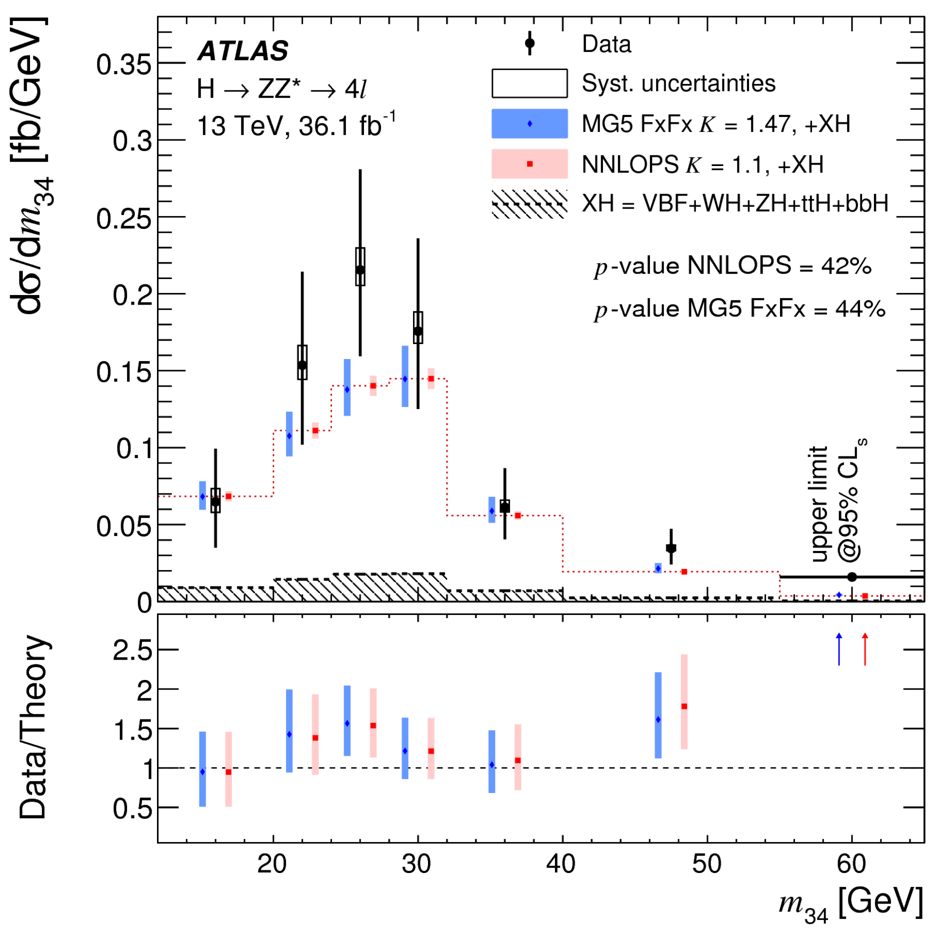
Eur.Phys.J. C75 (2015) 128

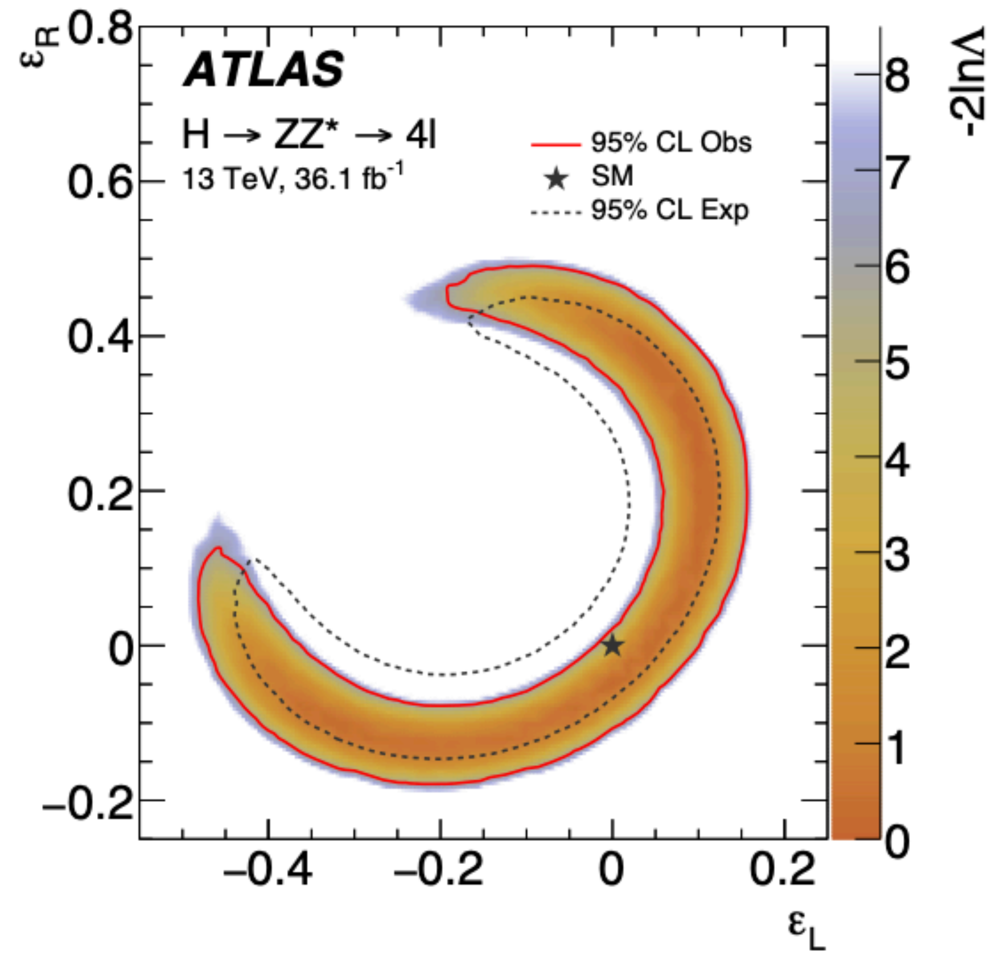
Search for contact interactions

Introduce an effective coupling (pseudo-observable) for left and right handed leptons

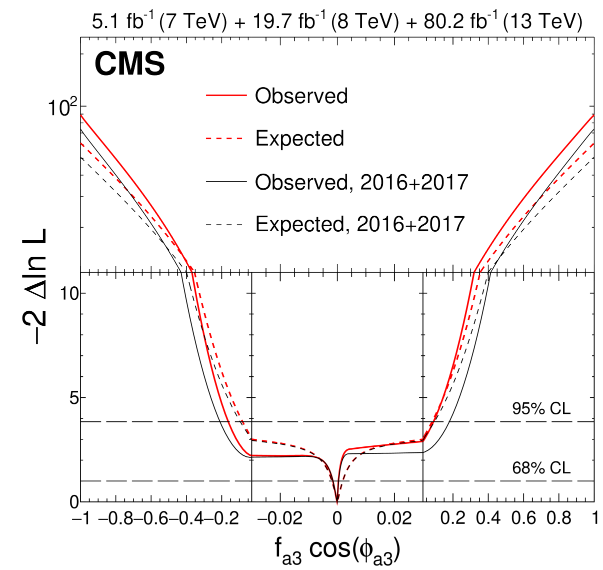
→ would modify BR, and the m12, m34 distributions



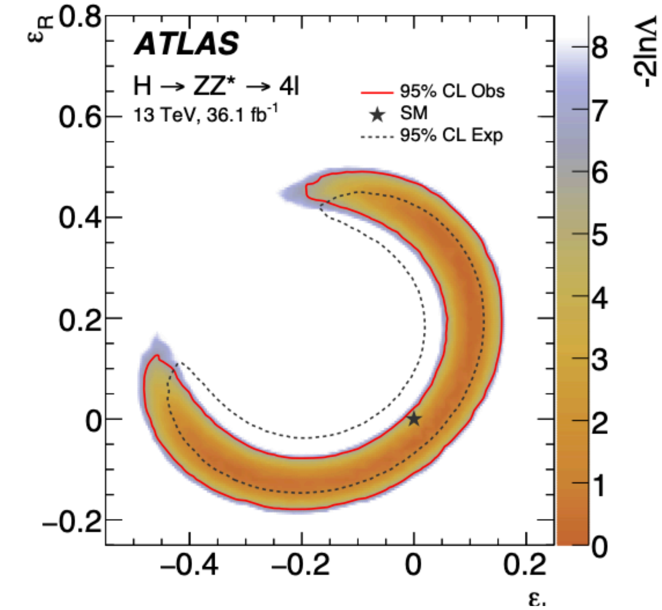




H → 4l channel



Spin and CP

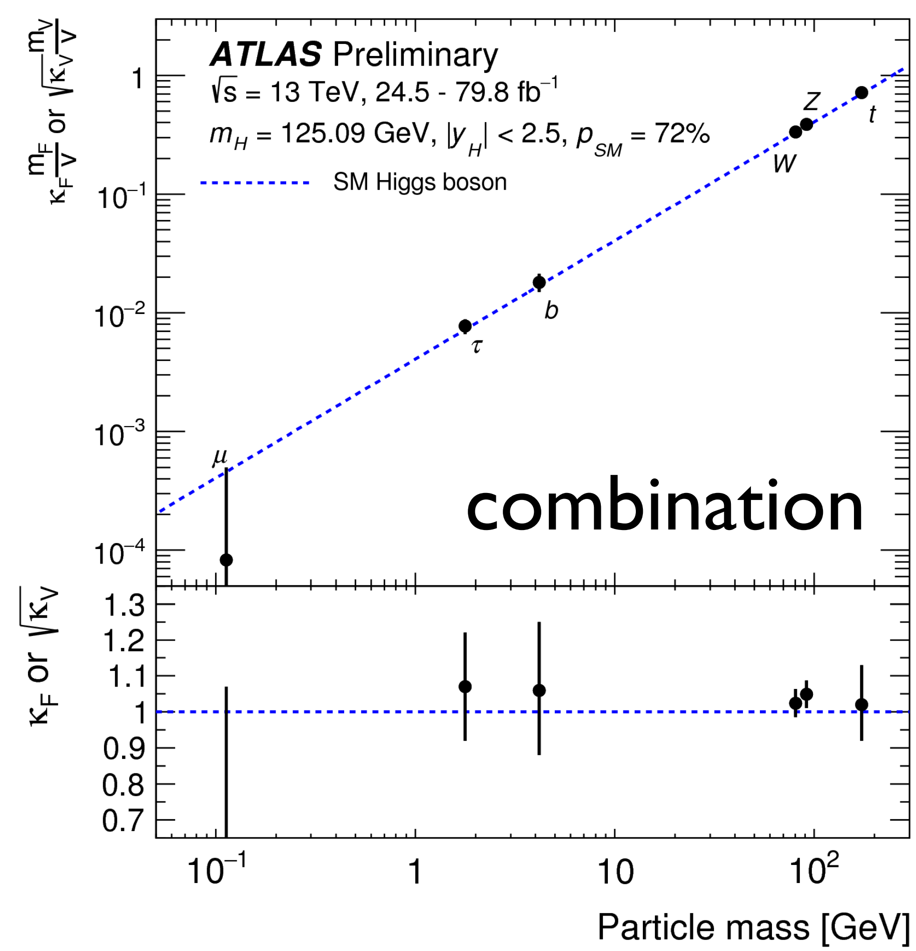


Width

From off-shell signal strength

limit: ~2-3 * SM

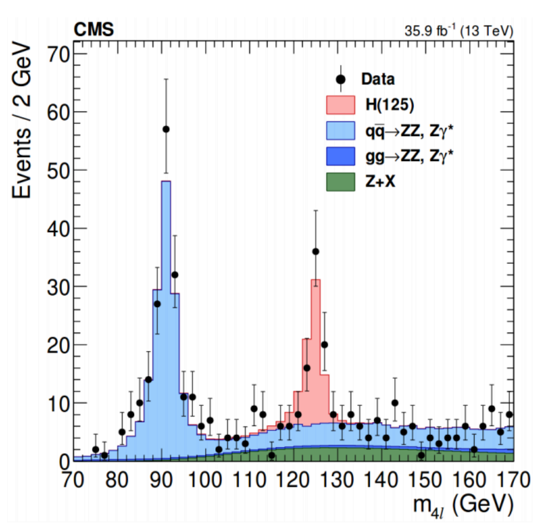
Couplings



combination

Mass

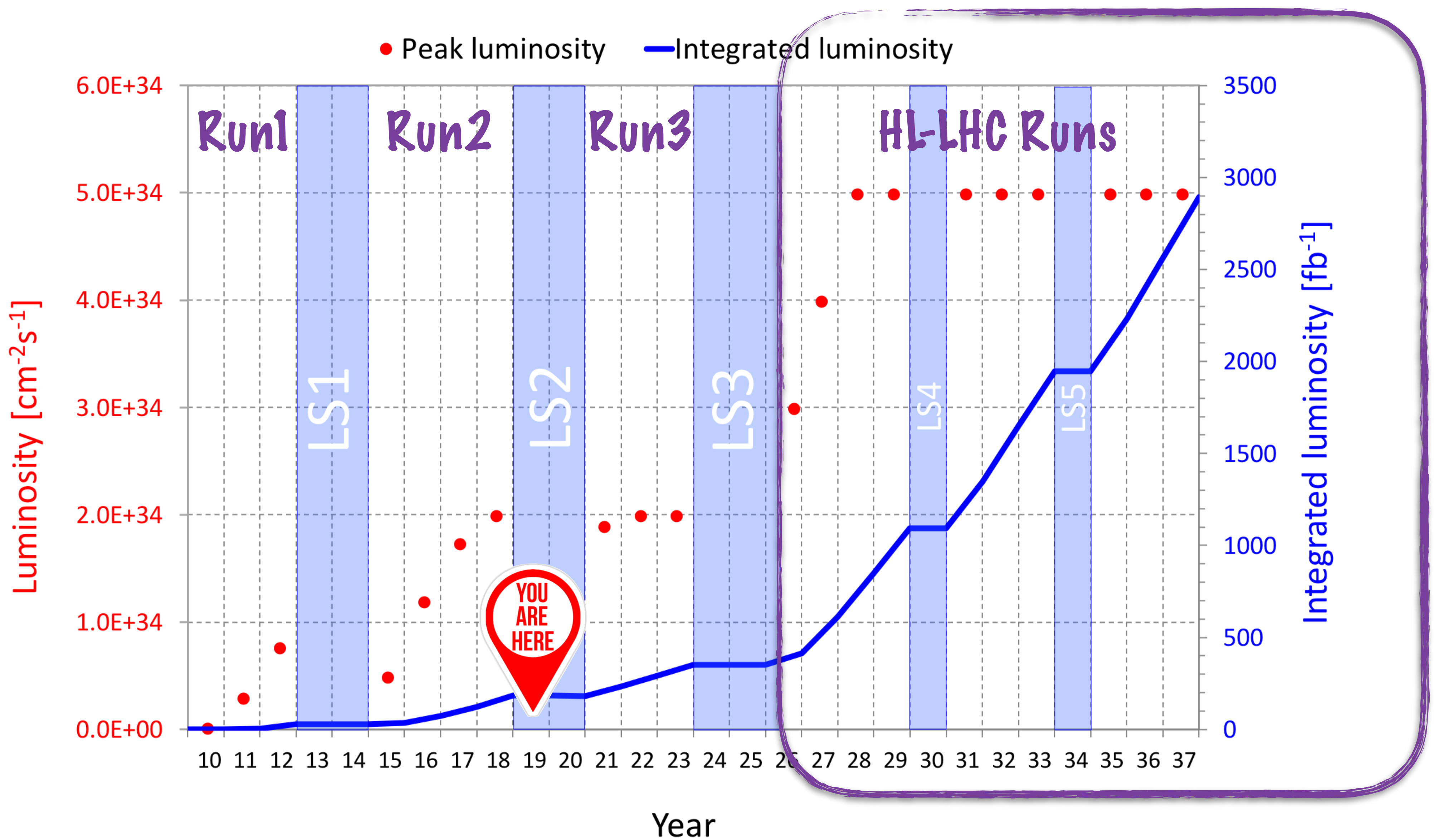
2 permille accuracy!



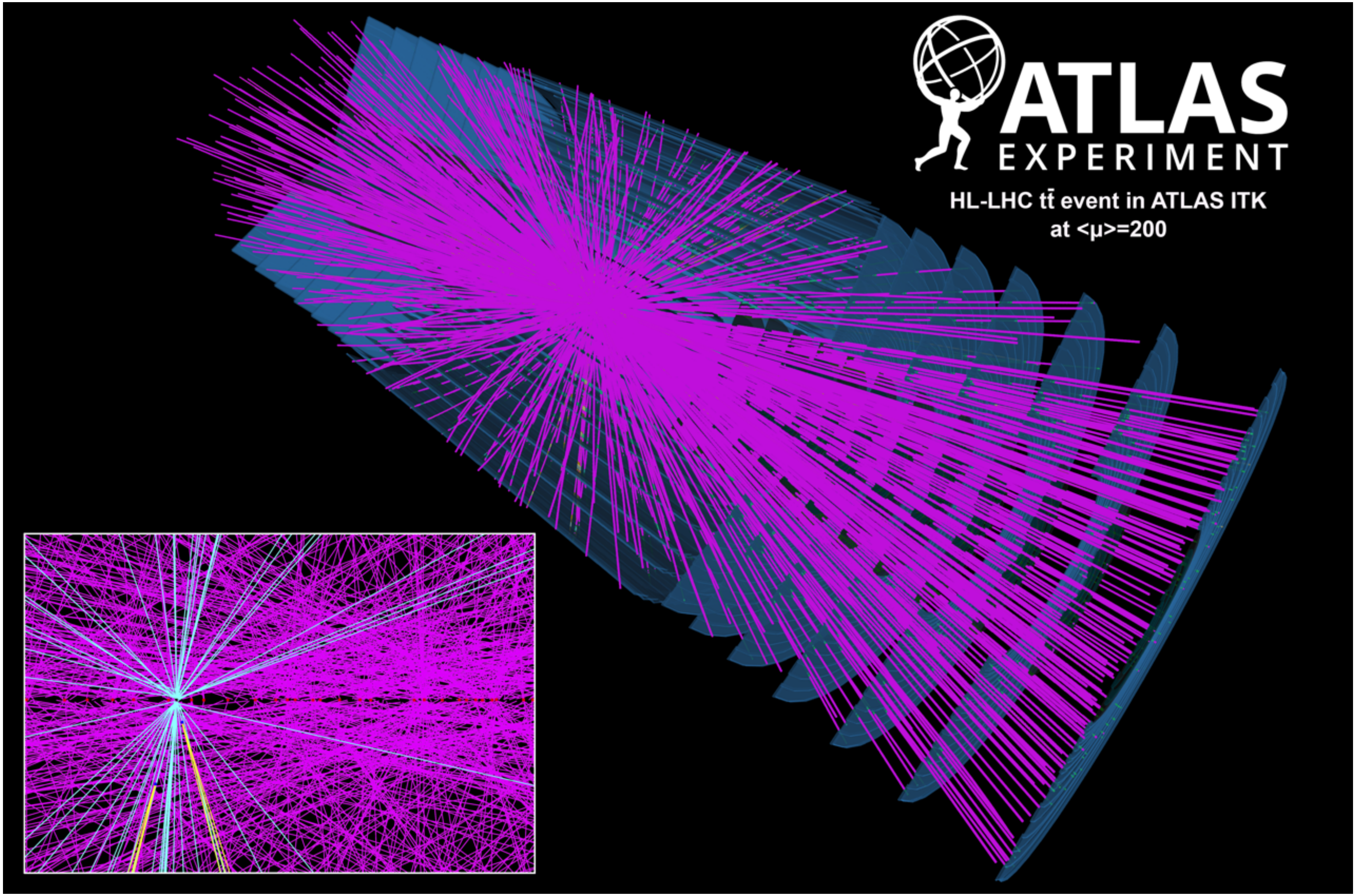
Future

- many Higgs measurements limited by low statistics
- H → 4l is a good example

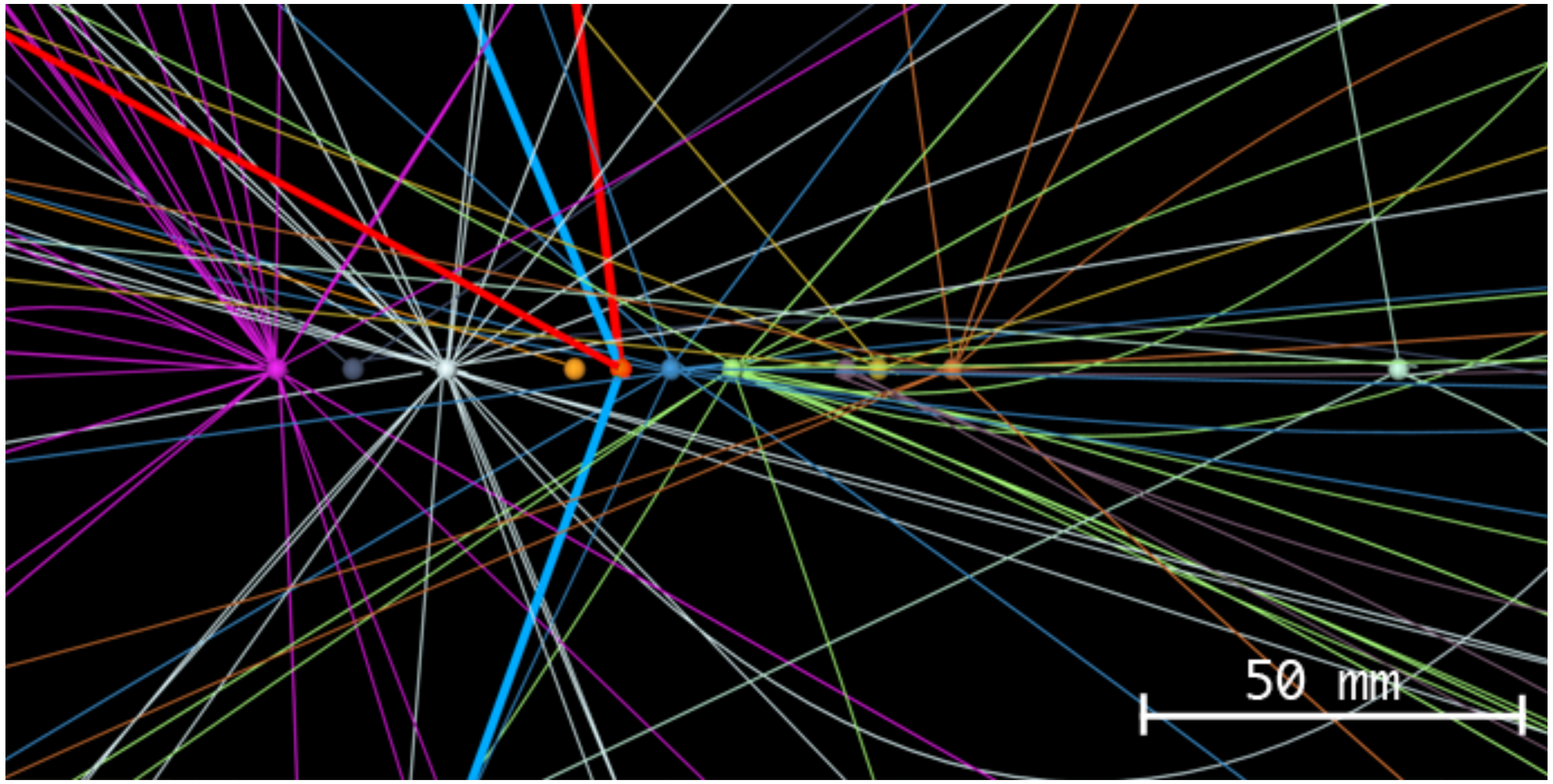
=> looking forward to more data, amazing opportunity



Challenge: up to 200 interactions per bunch-crossing



Challenge: up to 200 interactions per bunch crossing

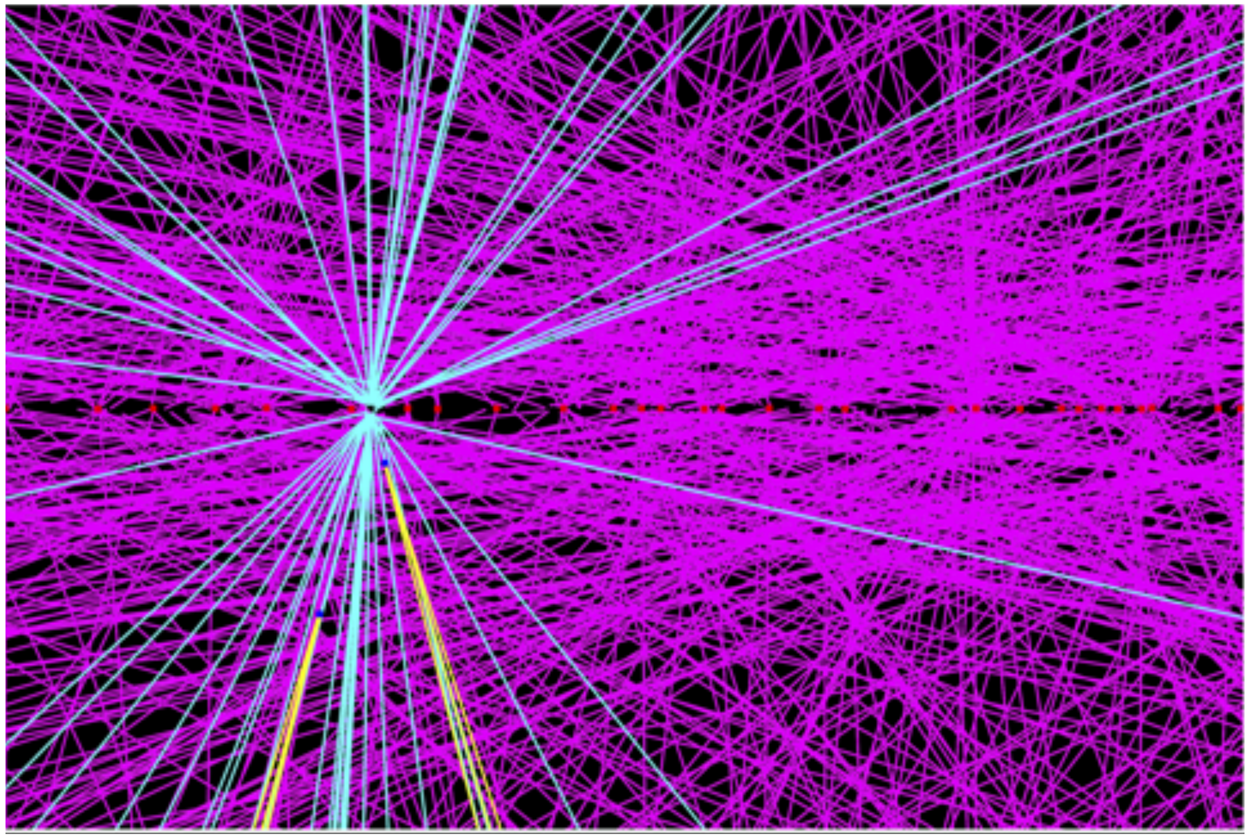


2018: ~36 interactions per bunch crossing (pileup)

>> tracks and clusters from these interactions overlay the collision of interest

>> challenges for tracking, particle reconstruction

Challenge: ~200 interactions per bunch crossing



2018: ~36 interactions per bunch crossing (pileup)

>> tracks and clusters from these interactions overlay the collision of interest

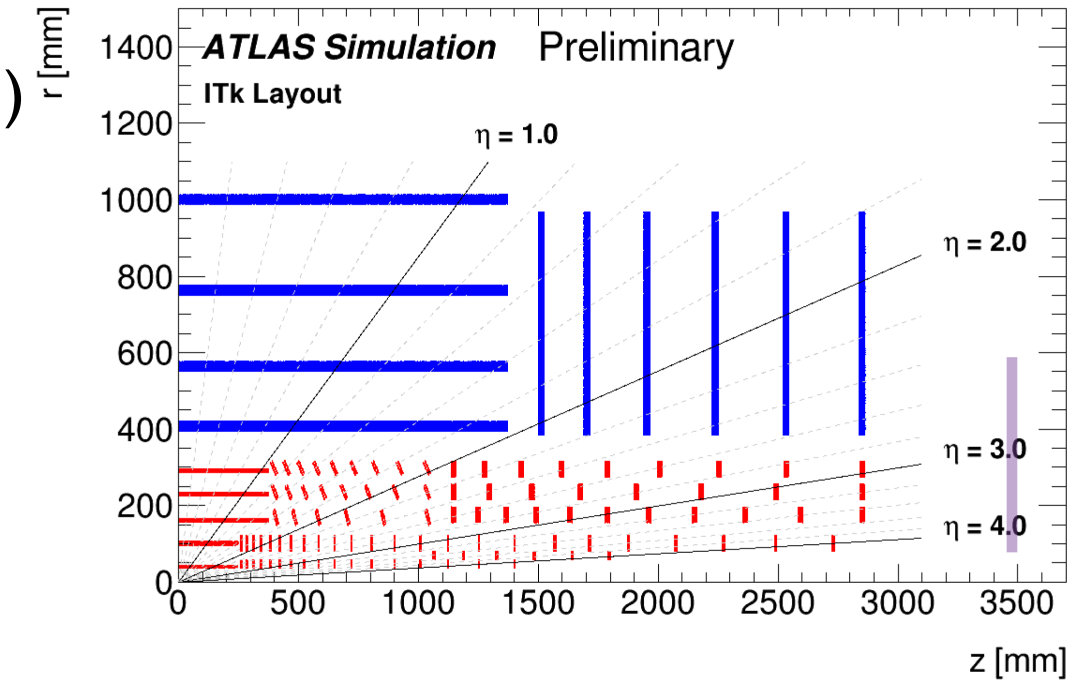
>> challenges for tracking, particle reconstruction

HL-LHC: up to 200

Challenge accepted

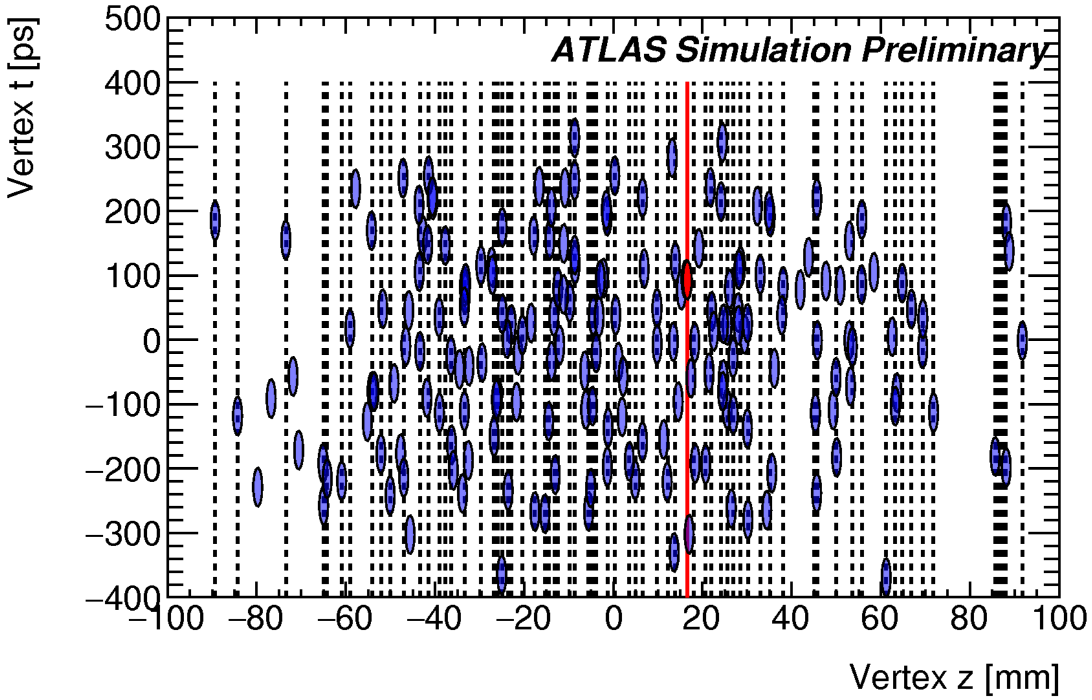
New inner tracking detector (big DESY participation!)

- pixel + strip
- improved granularity
- allows to detect more forward tracks



High granularity timing detector

- resolve interaction vertices not only spatially but also in time



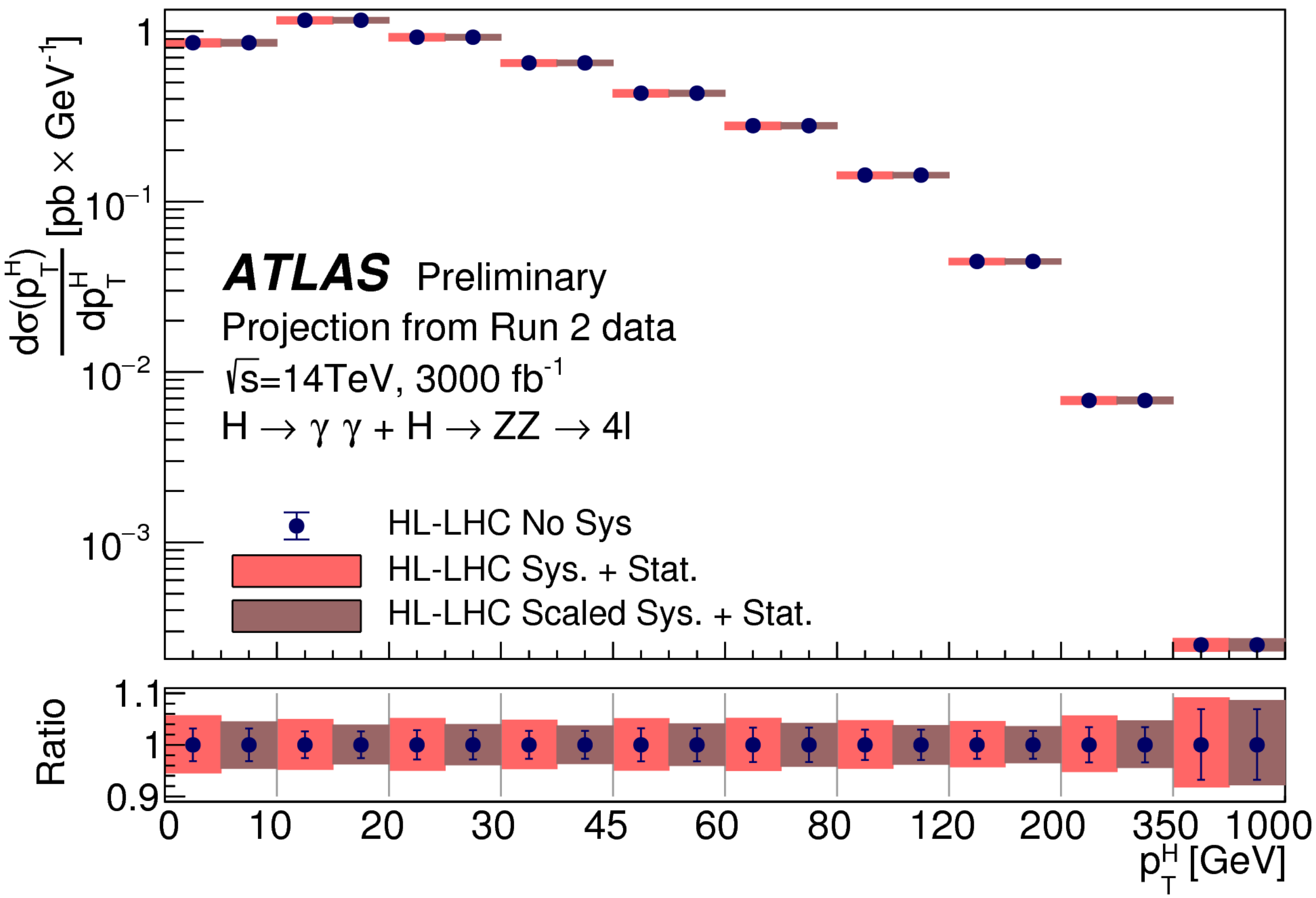
Improve reconstruction algorithms

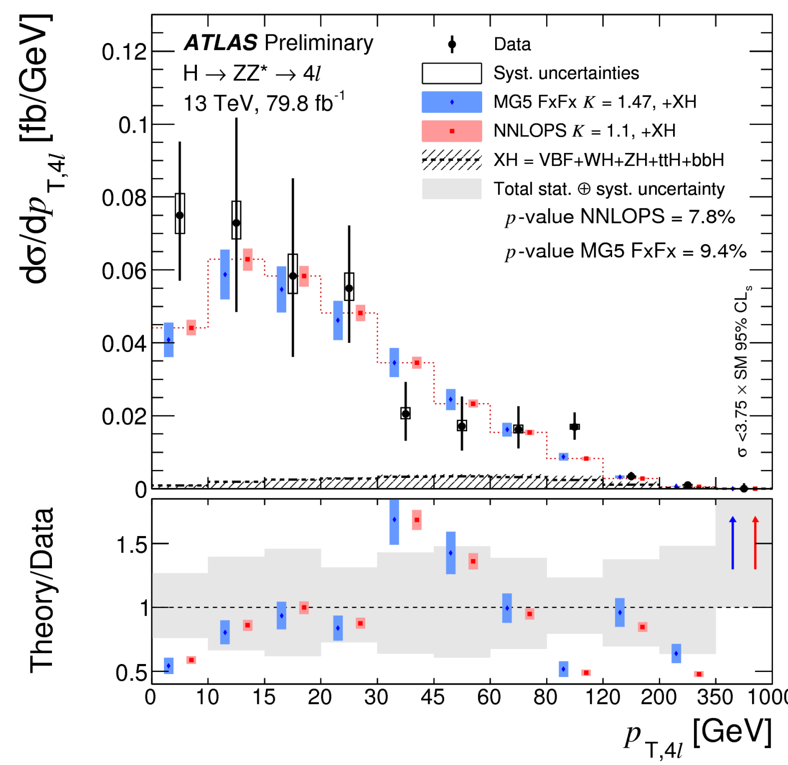
- particle flow
- machine learning

Maintaining excellent lepton performance will be critical at HL-LHC!

(increased statistics makes systematics more important!)

Higgs results projected

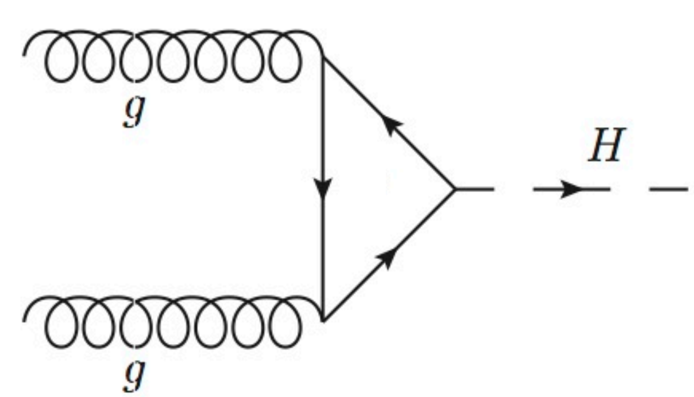




Uncertainty in 350-1000 GeV bin 8%

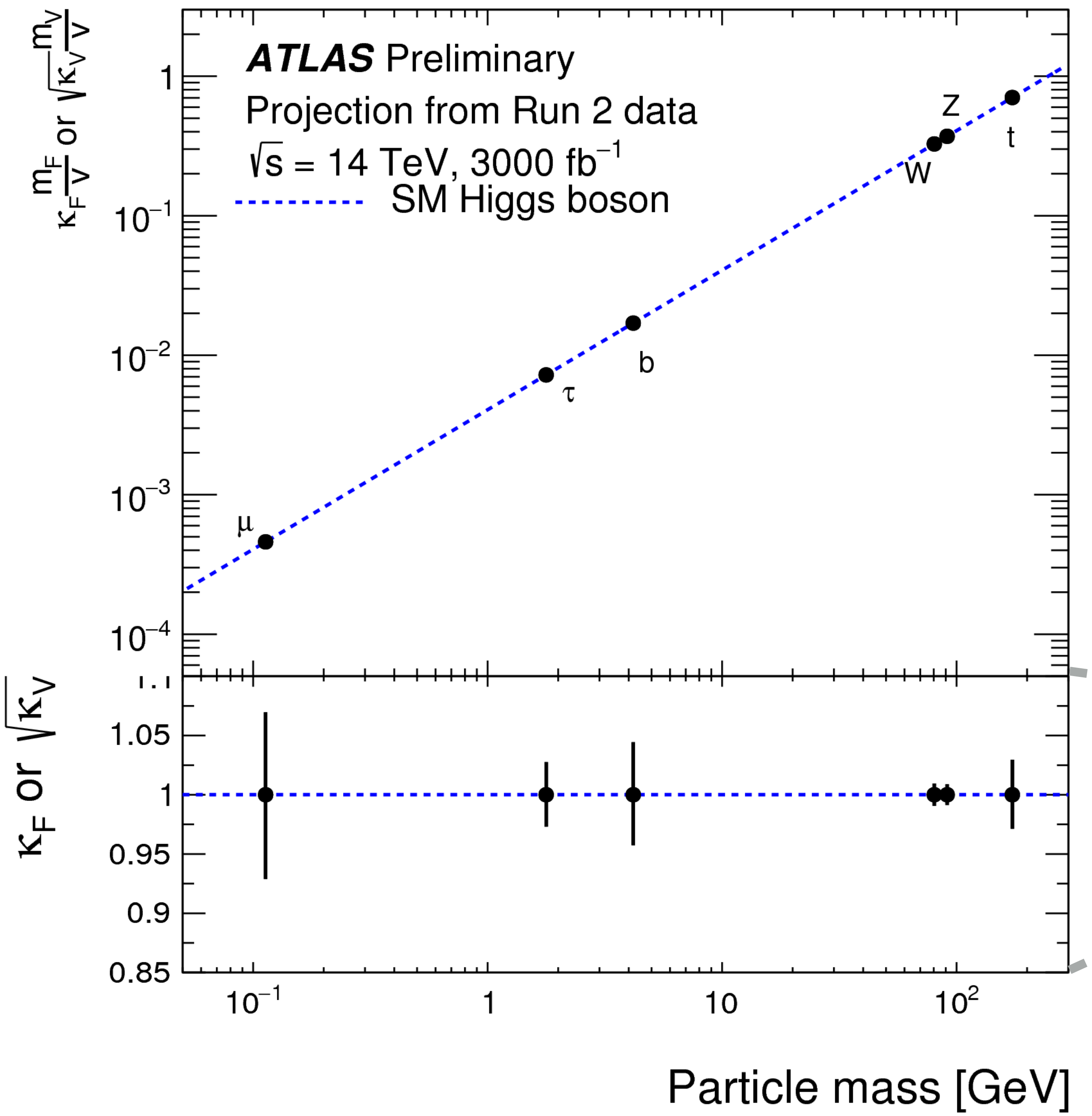
Can study Higgs bosons with very high momenta!

=> sensitive to heavy particles in the loop

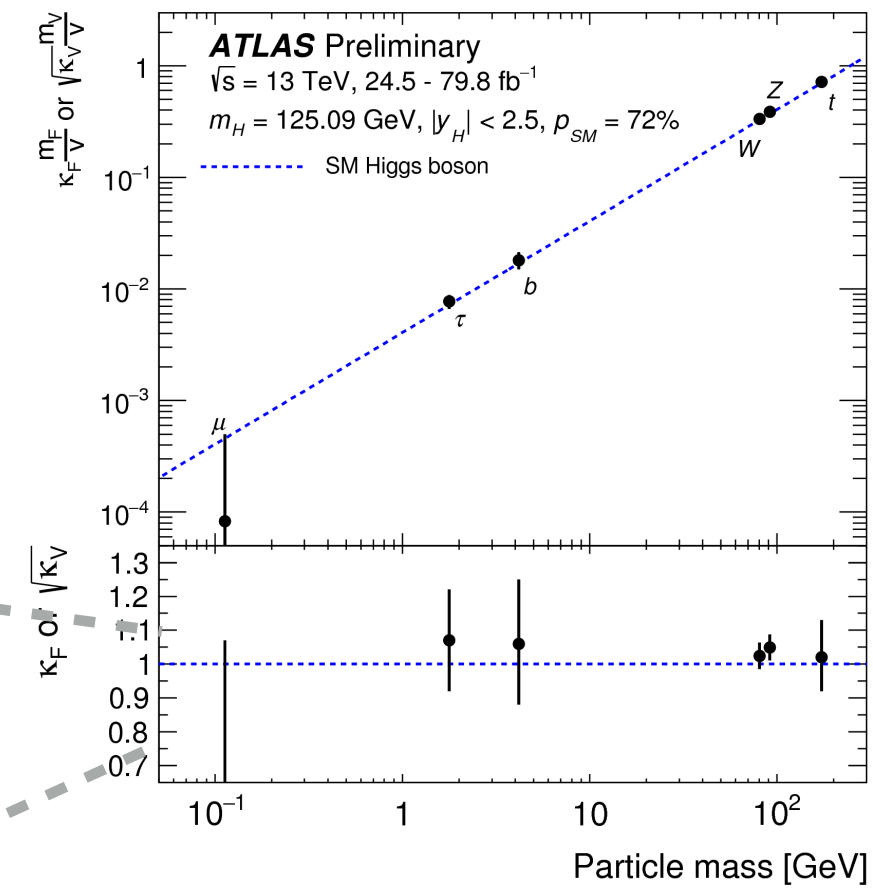


Higgs results projected (combination)

HL-LHC



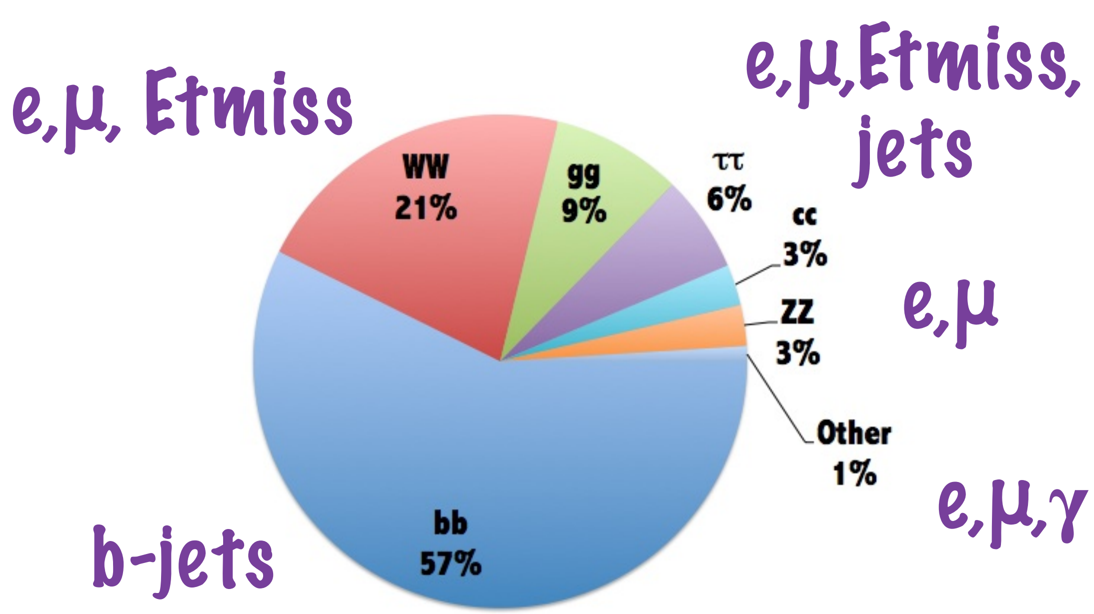
now



(κ: scaling factors to SM couplings)

Conclusion

- ✔ studying the properties of the Higgs boson is a crucial aspect of our searches for physics beyond the Standard Model
- ✔ so far, no deviations are observed, but many measurements are statistics limited
- ✔ the High-Luminosity LHC will help decrease the statistical uncertainties
- ✔ Efficient and precise particle reconstruction is a critical ingredient in Higgs measurements to achieve the best precision possible



References

p. 4 Discovery papers

ATLAS: Phys. Lett. B 716 (2012) 1-29

CMS: Phys. Lett. B 716 (2012) 30

p. 2, 5, 13, 24, 28, 30, 33, 34, 37, 47 - 80 fb-1 H4l: ATLAS-CONF-2018-018

p. 17 superclusters: ATL-PHYS-PUB-2017-022

p. 19, 23, 29 electron efficiencies: Eur. Phys. J. C 77 (2017) 195

p. 33, 36, 40: 36 fb-1 H4l: JHEP 10 (2017) 132

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p. 38 CMS: [1812.06504], acc. by PLB

p. 39 ATLAS yy: Phys. Rev. D 98 (2018) 052005

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Mass: ATLAS: Phys. Lett. B 784 (2018) 345, CMS: JHEP 11 (2017) 047

Width: ATLAS: Phys. Lett. B 786 (2018) 223, CMS: [1901.00174] (subm. to PRD)

Spin: [1901.00174], subm. to PRD

Couplings (also p. 48): ATLAS-CONF-2019-005

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p. 44

Tracking pub note: ATL-PHYS-PUB-2019-014

HGTD: LHCC-2018-032

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Higgs Prospects: ATL-PHYS-PUB-2018-040, CERN-LPCC-2018-04

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Higgs Prospects: ATL-PHYS-PUB-2018-054