Probing electroweak symmetry breaking with Higgs pair production at the LHC

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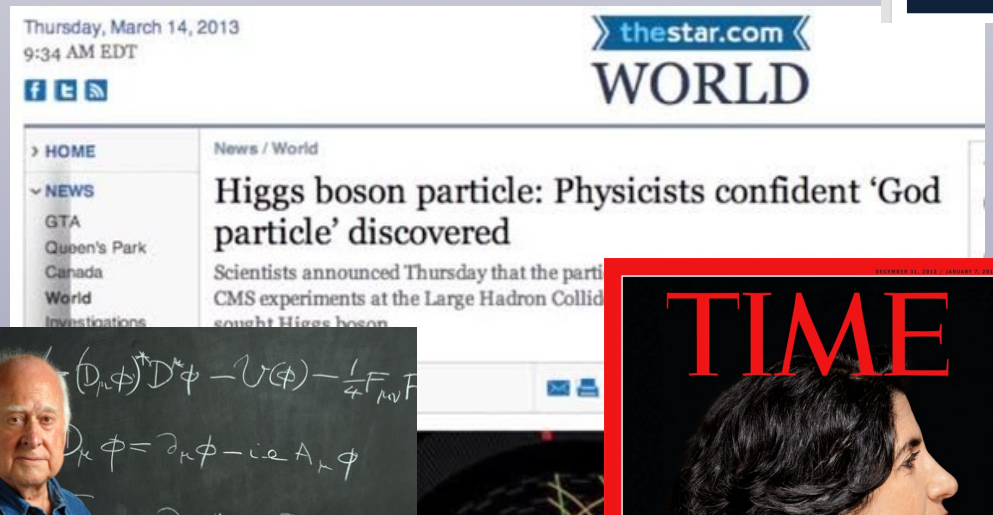
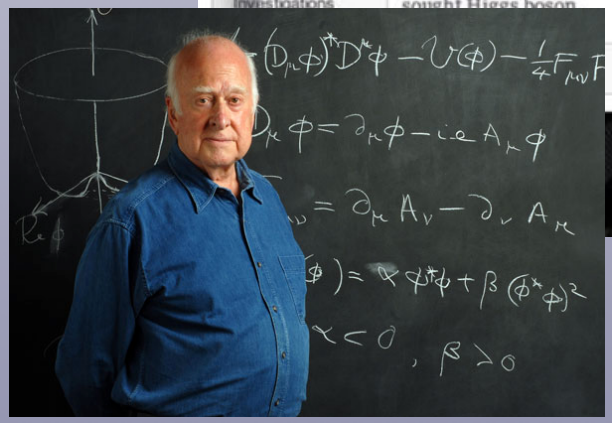
Particle Physics in the headlines

- ☑ The **Higgs Boson** is the **most important discovery in particle physics** in 25 years
- ☑ The Higgs completes the **extremely successful Standard Model of particle physics**, but at the same time **opens a number of crucial questions** for the field that we need to address
- ☑ The **LHC** will play a crucial role in **exploring the energy frontier in the next 20 years**

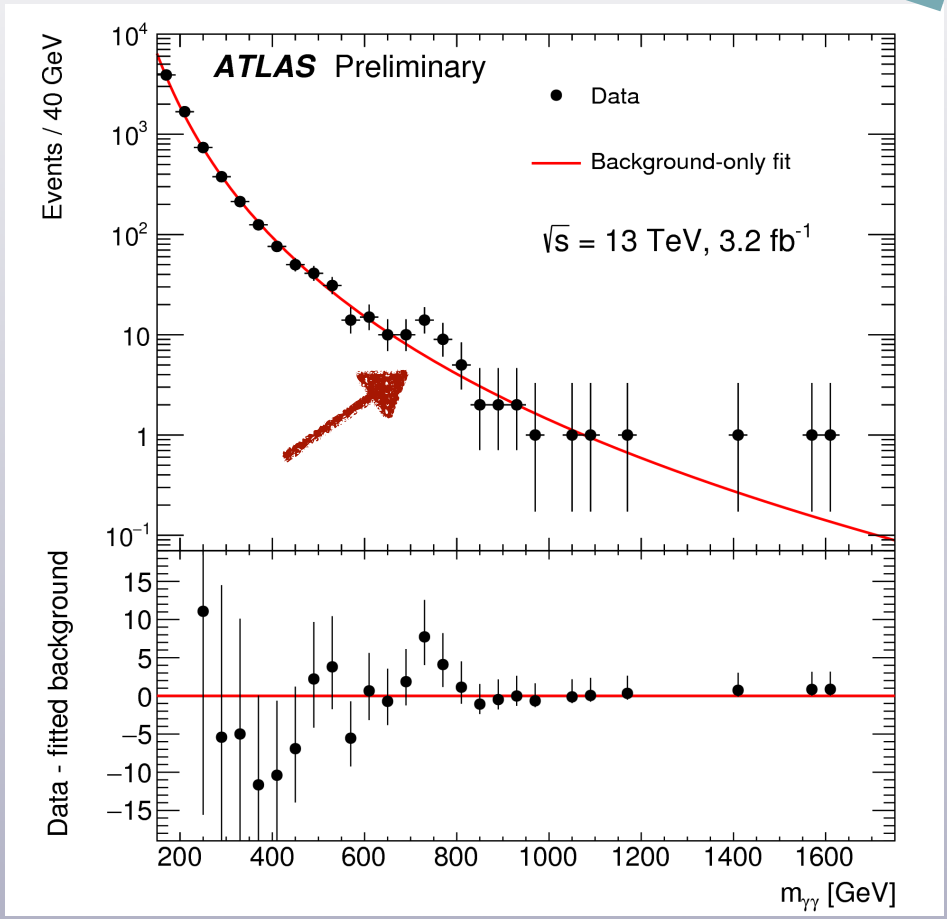


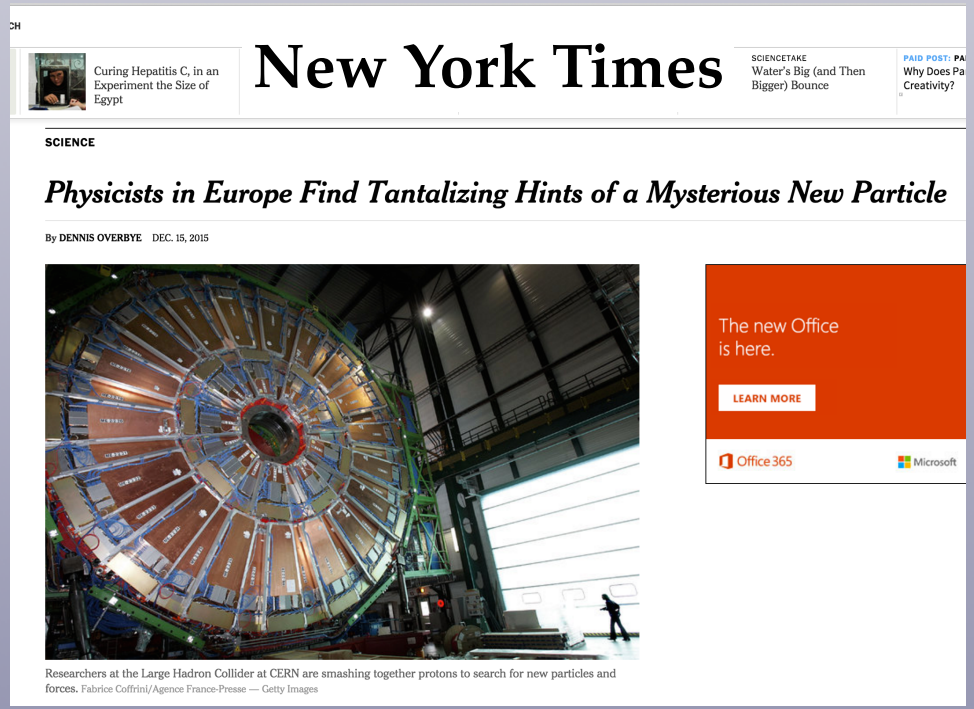


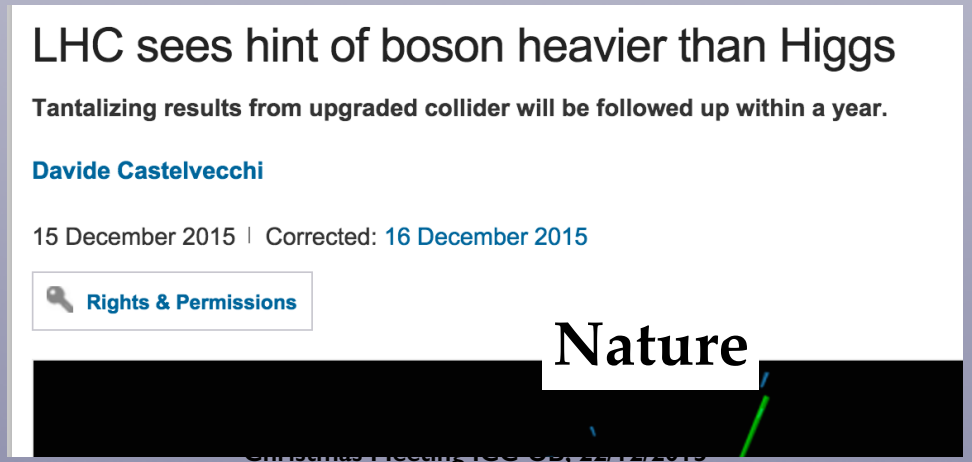
Particle Physics in the headlines

AGAIN!

- ☑ **First results from 13 TeV from ATLAS and CMS** announced last week
- ☑ An **excess in the diphoton spectra at 750 GeV** seen by the two experiments, with a **combined significance around 3.0 sigma**
- ☑ Already O(100) possible explanations in arXiv ….







Pa… …s

AGAIN!

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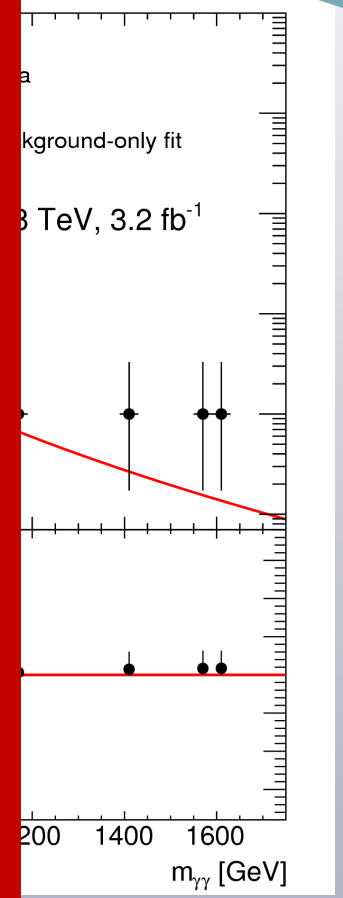

…er than Higgs
…owed up within a year.

…ture

Outstanding Questions in Particle Physics *circa* 2014

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB

- ❑ Is m_H natural or fine-tuned ?
- → if natural: what new physics/symmetry ?
- ❑ does it regularize the divergent $W_L W_L$ cross-section at high $M(W_L W_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate *CP* ?
- ❑ cosmological EW phase transition

Quarks and leptons:

- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:

- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:

- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:

- ❑ ν masses and and their origin
- ❑ what is the role of $H(125)$?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:

- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or modification of gravity theory ?

Many of these crucial questions will be addressed at the Large Hadron Collider

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→ if natural: what new physics/symmetry ?

- ❑ does it regular

Quarks and leptons:

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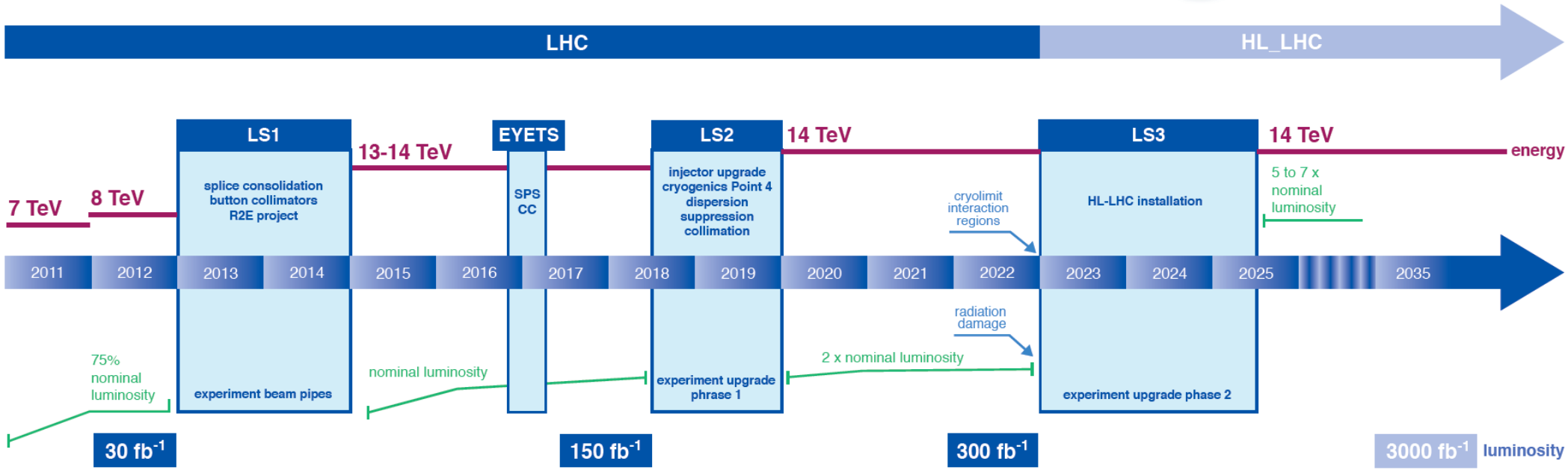
lepton sector

20 years of exciting LHC physics ahead of us!

LHC / HL-LHC Plan



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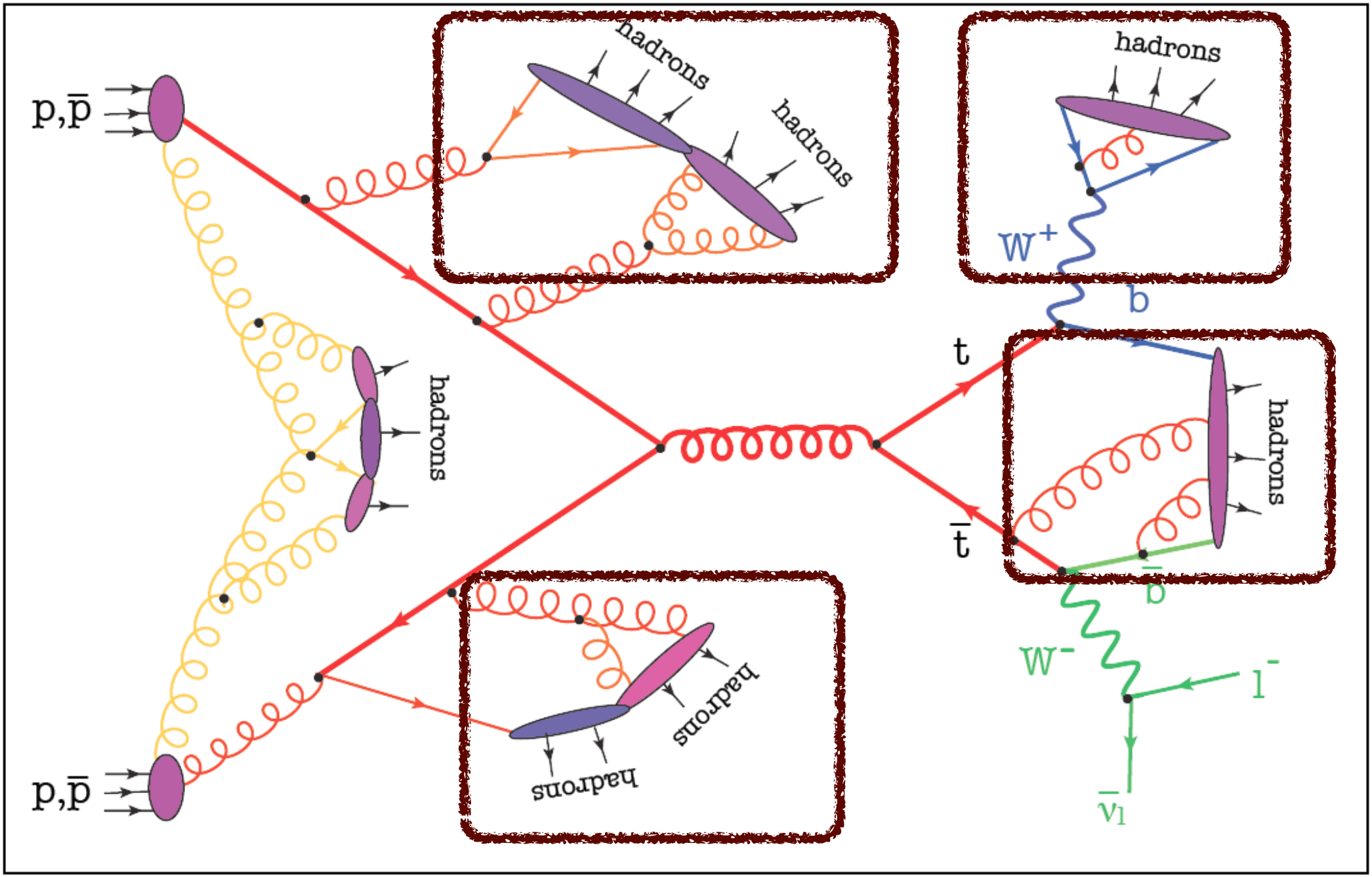
Ian Shipsey

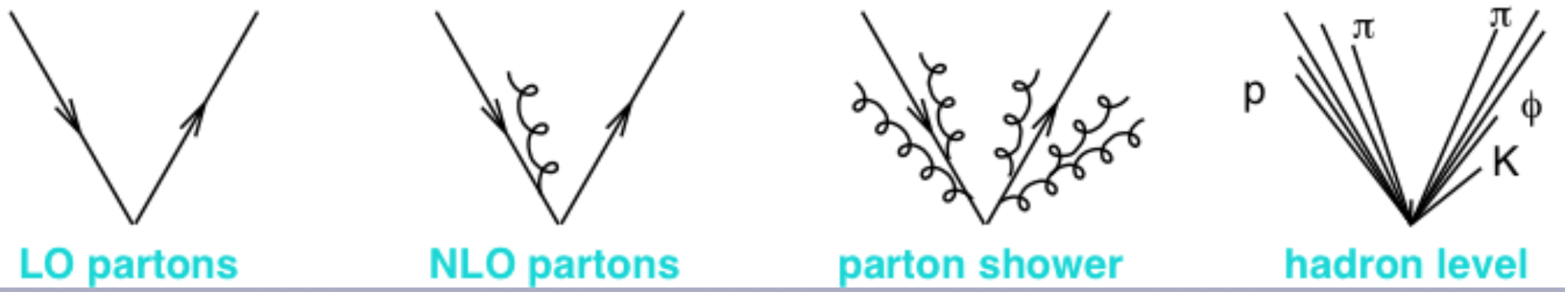
Jet reconstruction at the LHC



Drawing by K. Hamilton

Jet reconstruction at the LHC

- QCD calculations are provided in terms of **quarks and gluons in the final state**
- After hard scattering, quarks and gluons follow a **branching process** and then **hadronize**, leading to a collimated bunch of hadrons as characteristic signal in the detector: **a QCD jet**
- A quantitative robust **mapping between final state hadrons**, observed in the detector, and **partons from** the hard-scattering, is required to compare theory with data: a **jet algorithm**
- **Jets are ubiquitous at the LHC,** present in almost every measurement



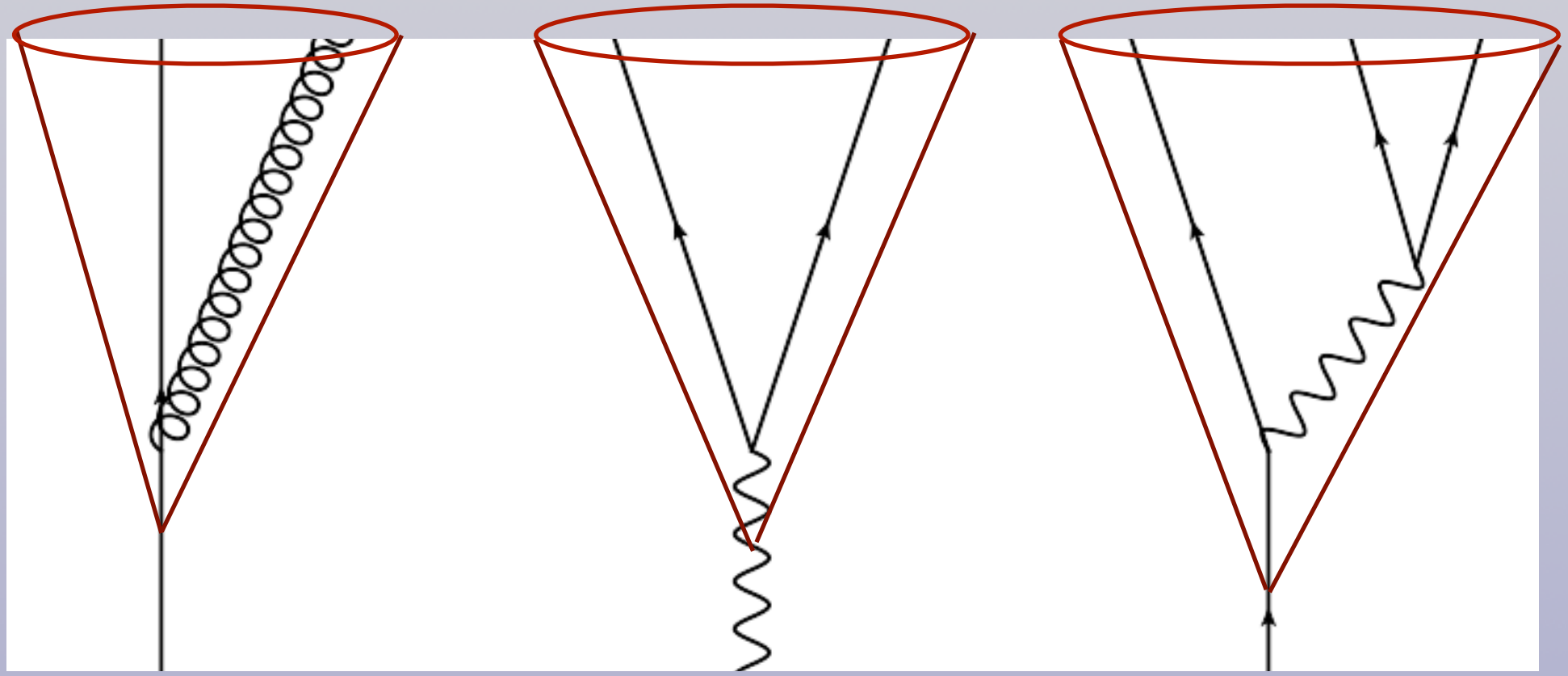
A jet is a fundamentally ambiguous concept

A jet algorithm is required to provide a jet definition

Jet algorithms should be applied to partons, hadrons and calorimeter cells

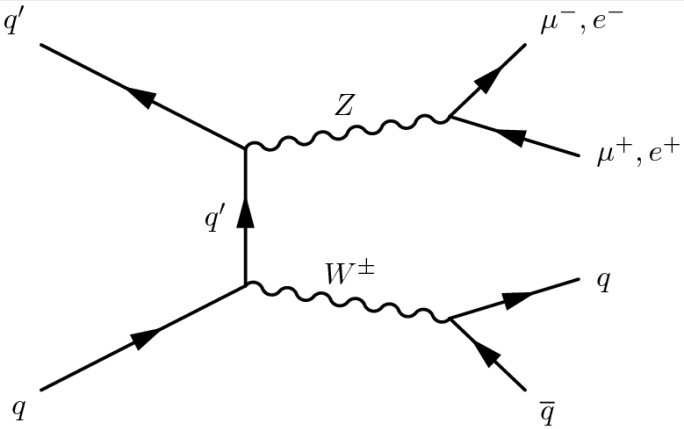
Jet substructure

- In the decays of a **massive resonances,** hadronic **boosted prongs** can often be collimated into a **single jet:** very difficult to separate from **overwhelming QCD background**
- The different **substructure in these jets** as compared to **QCD jets** can provide strong background suppression in **Higgs studies** and **BSM searches**

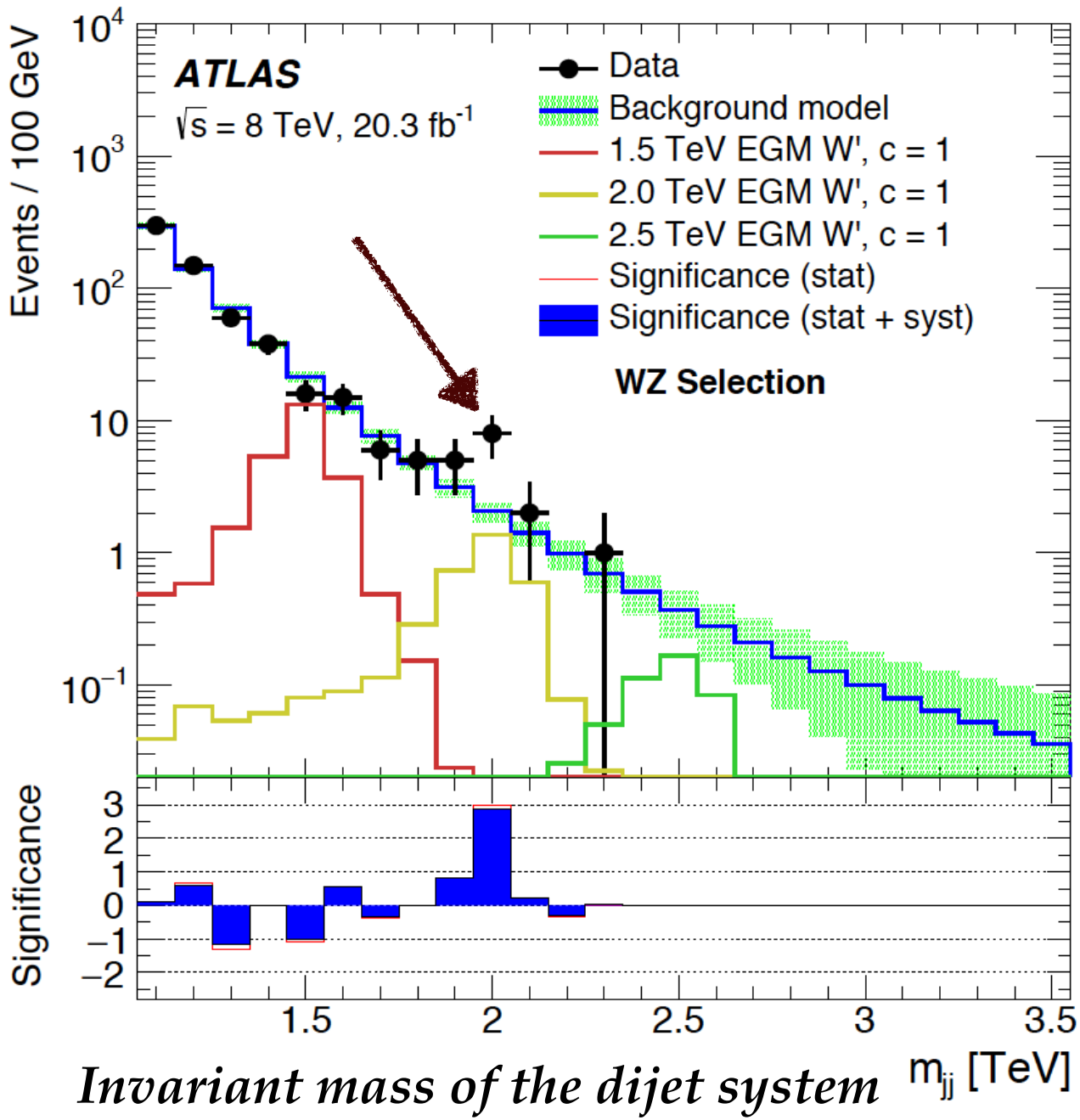


QCD jet **Boosted W jet** **Boosted top quark jet**

Jet substructure and the LHC diboson excess



- ☑ Tantalising excesses over SM expectations from ATLAS and CMS in the **diboson channel** when the **two bosons decay hadronically**
- ☑ Search relies crucially on **jet substructure techniques to tag the hadronic decays** of the boosted W and Z bosons



Invariant mass of the dijet system

Higgs Pair Production at the LHC

- ***Resonant HH->4b:*** *Gouzevitch, Oliveira, Rosenfeld, JR, Salam, Sanz, arXiv:1303.6636*
- ***Non-resonant HH-> 4b:*** *Behr, Bortoletto, Frost, Issever, Hartland, JR, in preparation*
- ***HH in VBF:*** *Bishara, Contino, JR, in preparation*

Why Higgs couplings?

Higgs couplings may indicate new physics: a few percent precision is a good target

Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

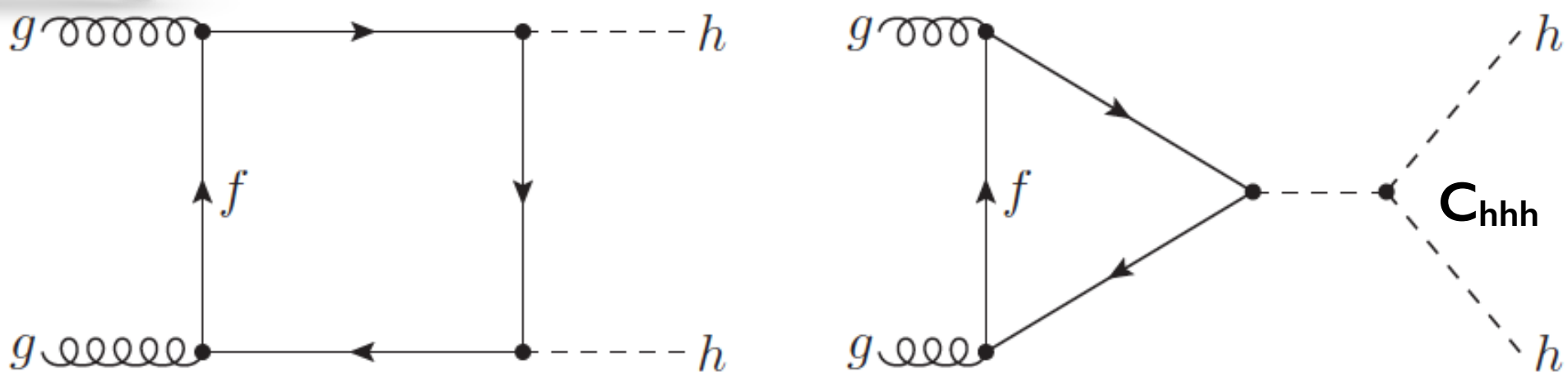
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Future LHC data: measure H couplings at 2-8% level (cf 20-50% today), and to access rare decays such as H→μμ

Higgs Pair Production at the LHC

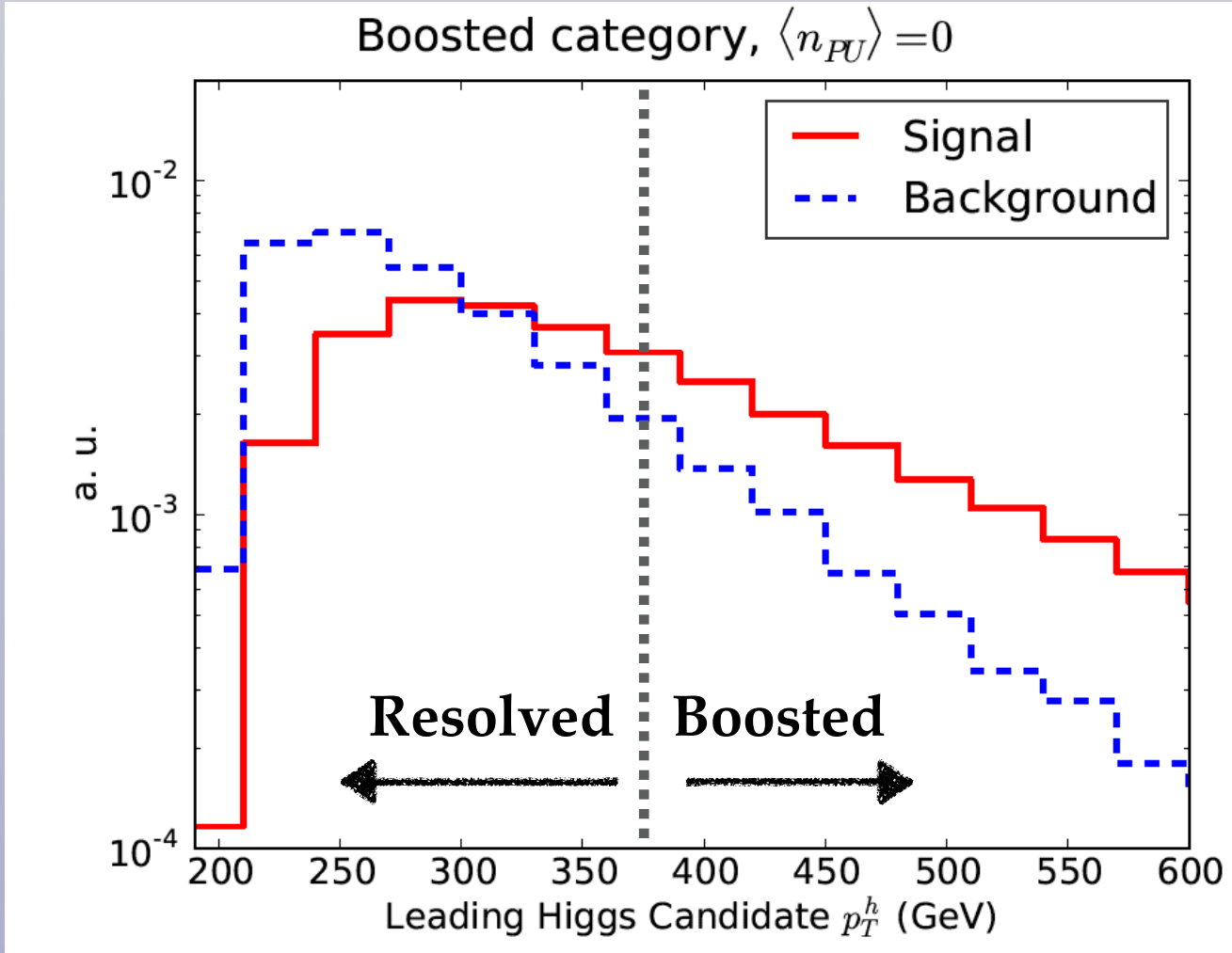
- **Double Higgs production** allows accessing crucial components of the Higgs sector:
  - ☑ Reconstruct the **full electroweak symmetry breaking potential**
  - ☑ Probe the **Higgs self-interaction**
  - ☑ Probe the **doublet nature** of the Higgs with the **hhVV coupling**
- In the SM, **hh rates are small:** in the leading gluon-fusion, mode, **cross-section at 14 TeV is 40 fb**
- Rates for double Higgs production **generically enhanced in BSM scenarios**, and **LHC searches** in various final states have already started at **Run I**

gg->hh



Higgs Pair Production at the LHC

- Focus on the **hh->4b final state:** largest rates, but **overwhelming QCD multijet background**
- Made competitive requiring the **di-Higgs system to be boosted** and exploiting kinematic differences between signal and QCD background with **jet substructure**
- Mandatory to optimize the **boosted b-tagging techniques,** impressive recent progress by ATLAS and CMS



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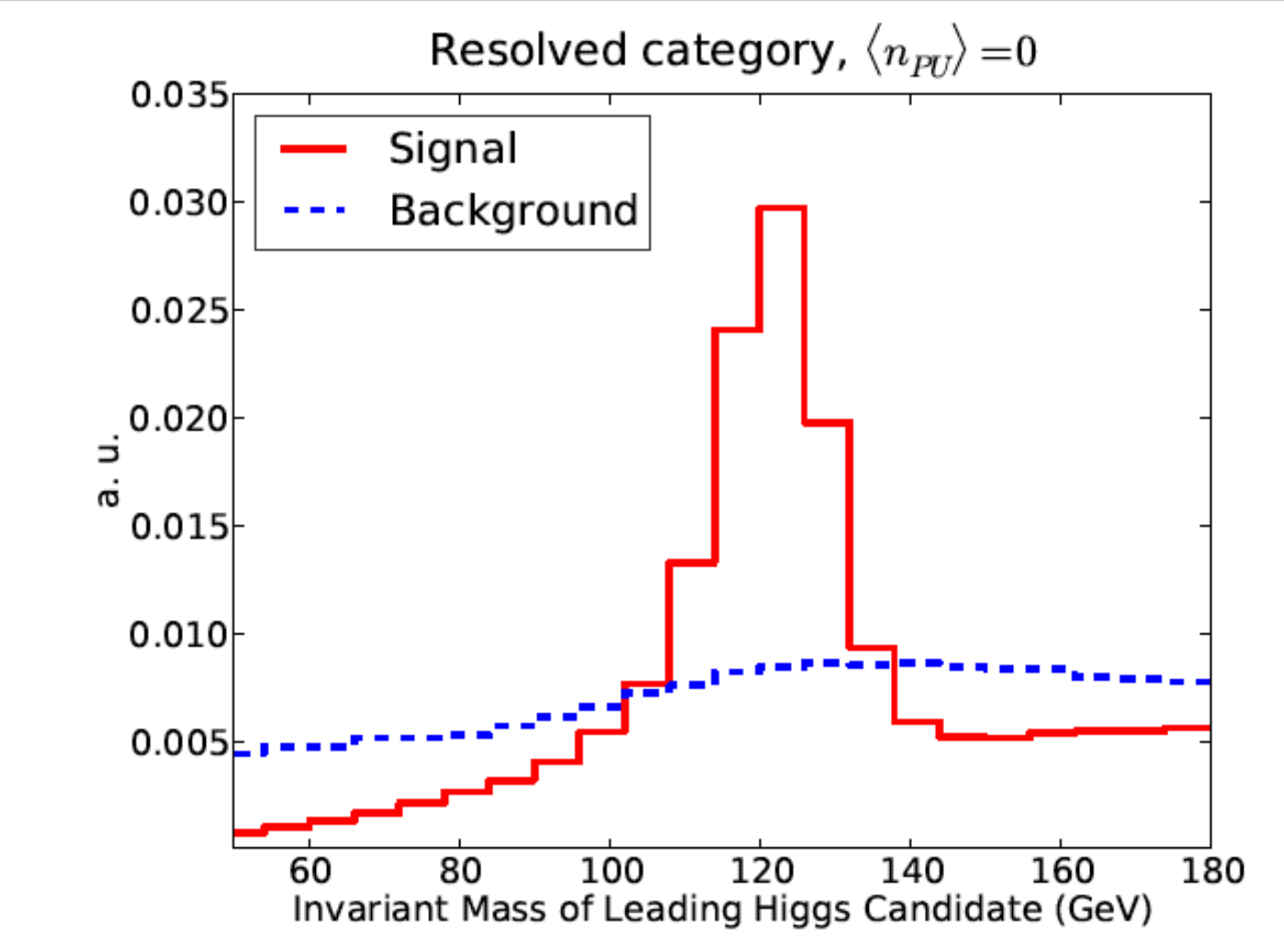
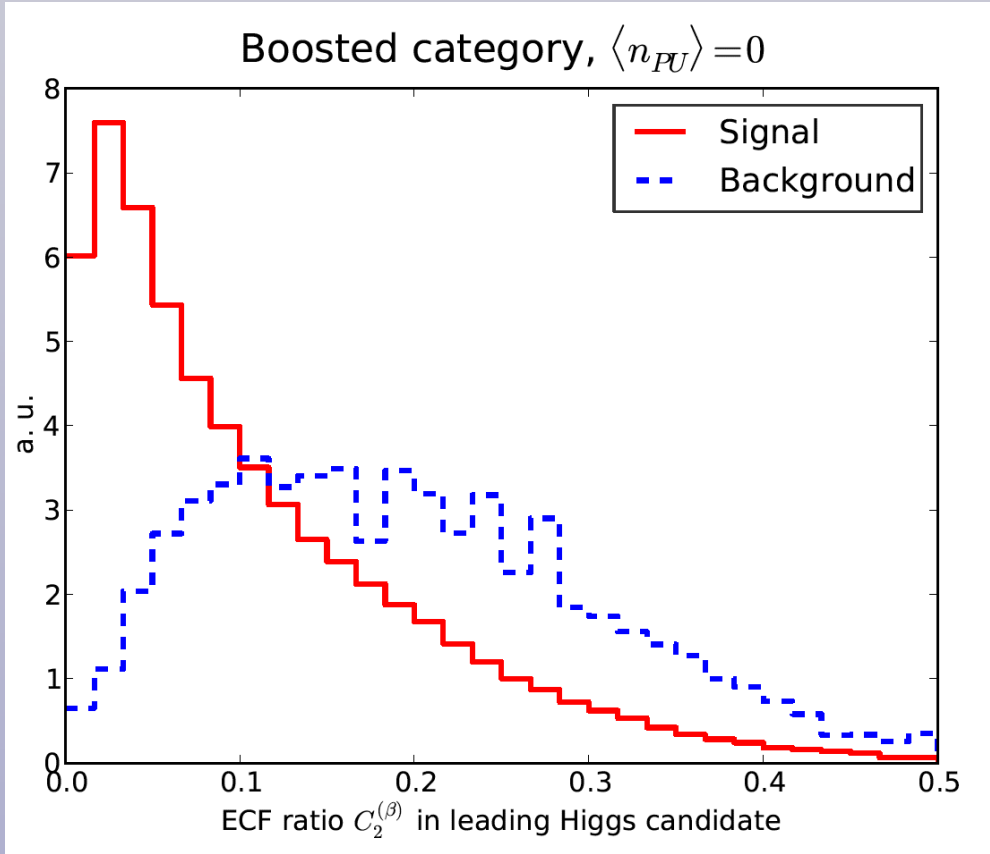


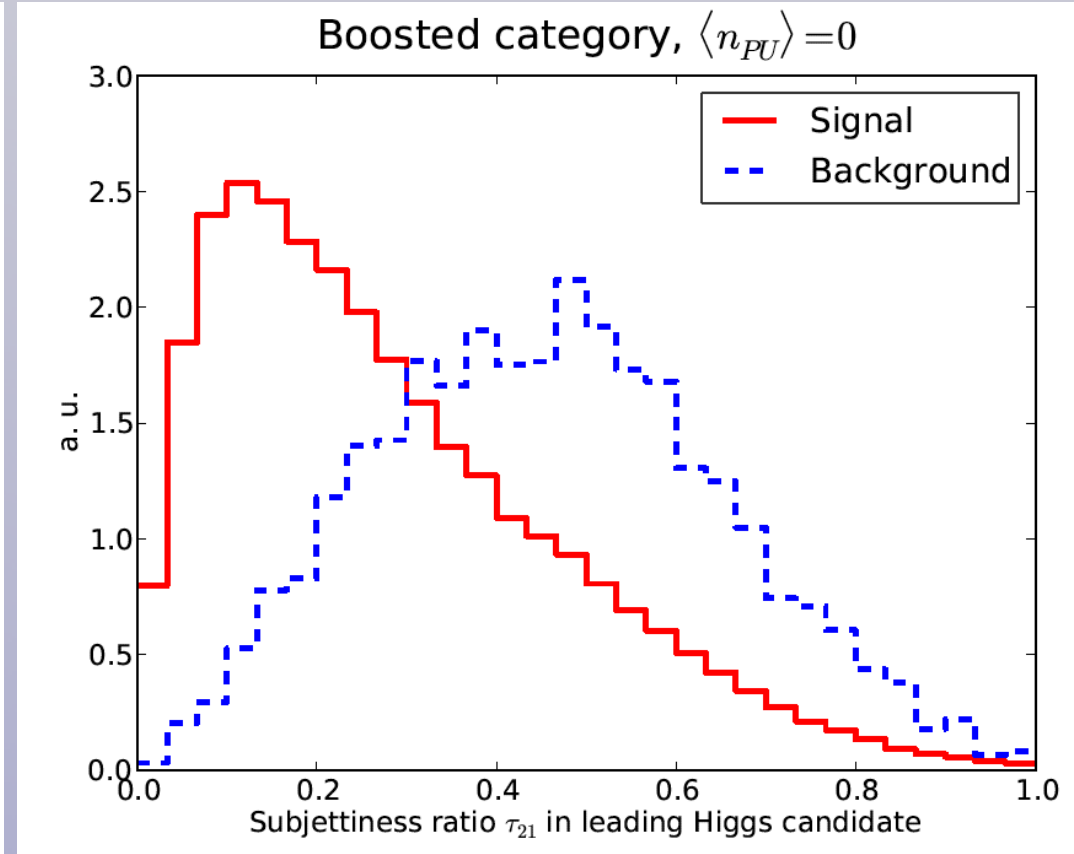
Jet substructure variables

- **Substructure variables** quantify differences in internal structure between **QCD jets** and **jets from the decay of heavy resonances**
- QCD radiation tends to be **soft** and **collinear,** while decay products of resonances **share momentum evenly**

Energy Correlation Functions ratio

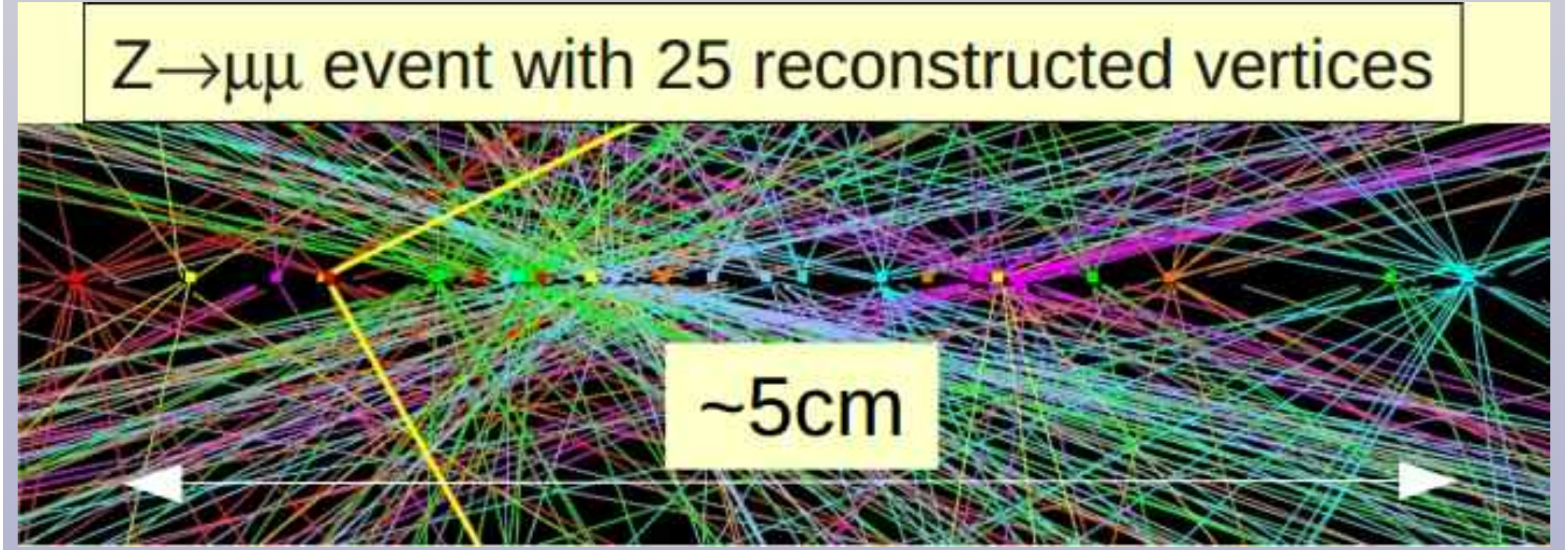


τ_{21}: 2-to-1 Subjettiness ratio



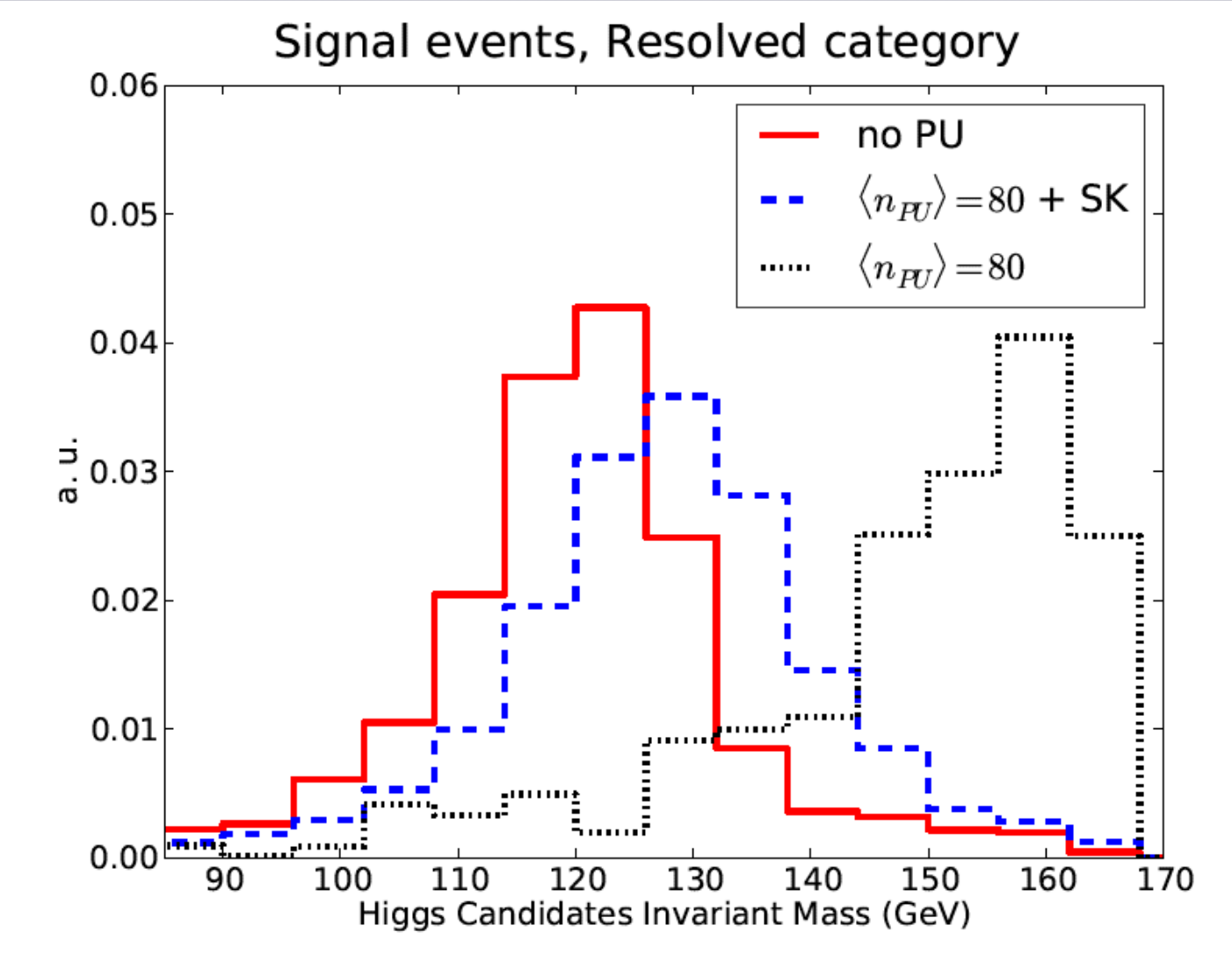
Pile-up at the HL-LHC

- **Pile-up (PU)**: multiple interactions between different pairs of protons in the same **bunch crossing**
- At the **high luminosities** of the HL-LHC, PU will be the **major contamination** in most analysis
- $\langle n_{PU} \rangle = 150$ corresponds to **embedding each hard event into 150 minimum bias events**!



Pile-up at the HL-LHC

- Recent development of **PU subtraction methods** allows to overcome these limitations
- Use **SoftKiller (SK)** to **subtract PU contamination** and maintain most of the signal/background discrimination power of the no-PU scenario



Multivariate techniques

Large number of kinematic variables to disentangle signal and background, **how to combine them?**

Multivariate techniques: Identify automatically kinematical variables with most discrimination power

Higgs pT

Higgs m

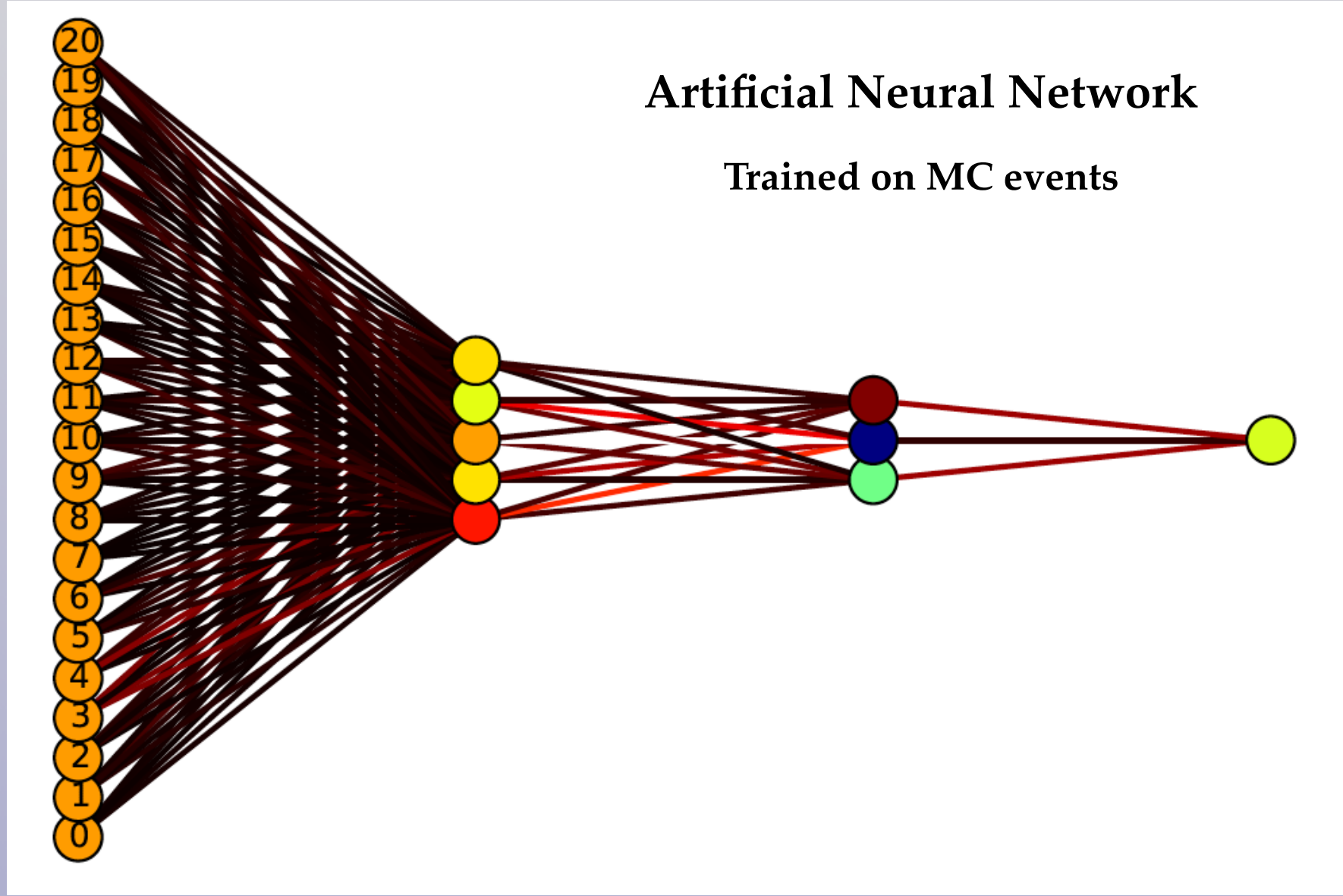
di-Higgs m

ECF

τ_{12}

Subjet pT

.....



Multivariate techniques

Given a set of N_{var} kinematic variables $\{k_i\}$ associated to MC event i, and a set of ANN weight parameters $\{\omega\}$, the ANN output y_i interpreted as **probability that this event originates from signal process**

$$y_i = P(y'_i = 1 | \{k\}_i, \{\omega\}) \,,$$

With y'_i the true MC classification: $y'_i=1$ for signal, $y'_i=0$ for background

The **general classification probability** including background events is

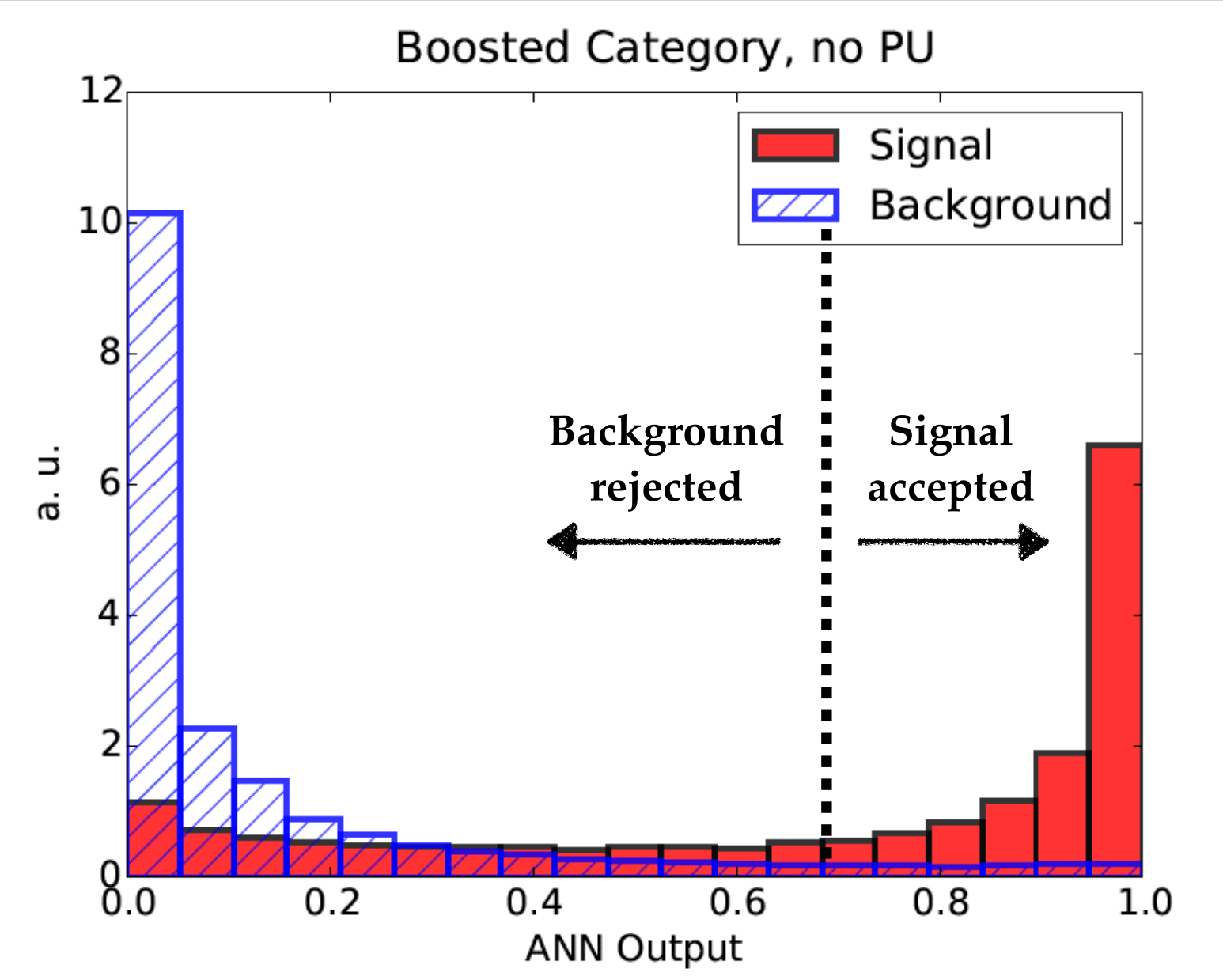
$$P(y'_i | \{k\}_i, \{\omega\}) = y_i^{y'_i} (1 - y_i)^{1-y'_i}$$

Thus the **error function to be minimised during the training** is the cross-entropy:

$$E(\{\omega\}) \equiv -\log \left(\prod_i^{N_{\rm ev}} P(y'_i | \{k\}_i, \{\omega\}) \right)$$
$$= \sum_i^{N_{\rm ev}} \left[y'_i \log y_i + (1 - y'_i) \log (1 - y_i) \right]$$

Multivariate techniques

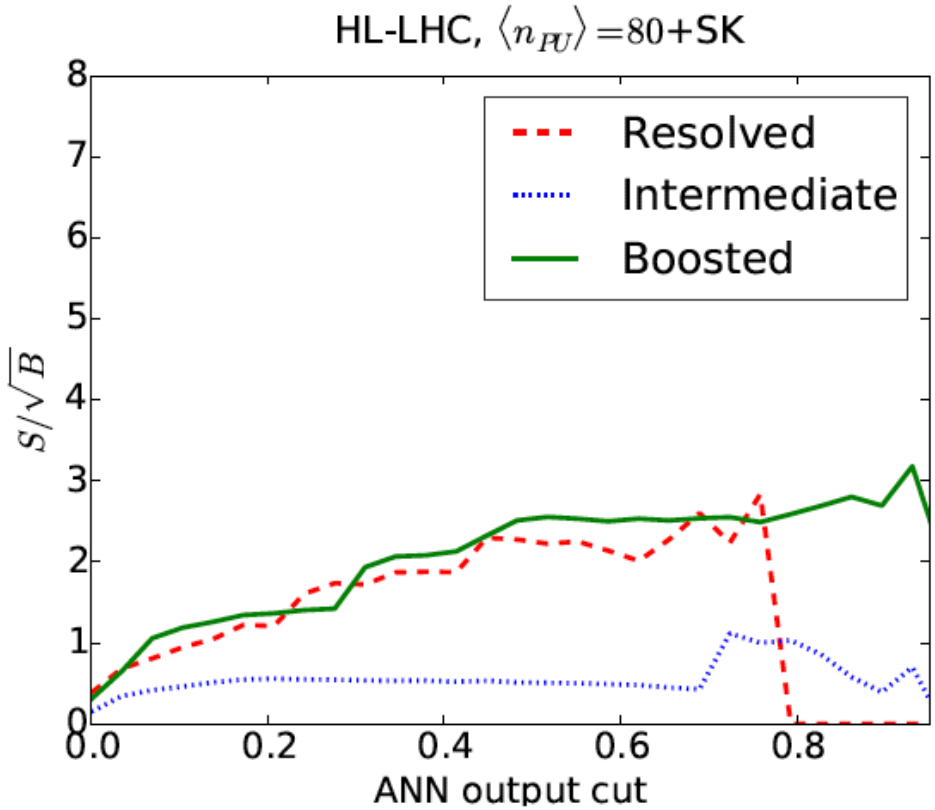
Combining information from all kinematic variables in MVA: **excellent signal/background discrimination**

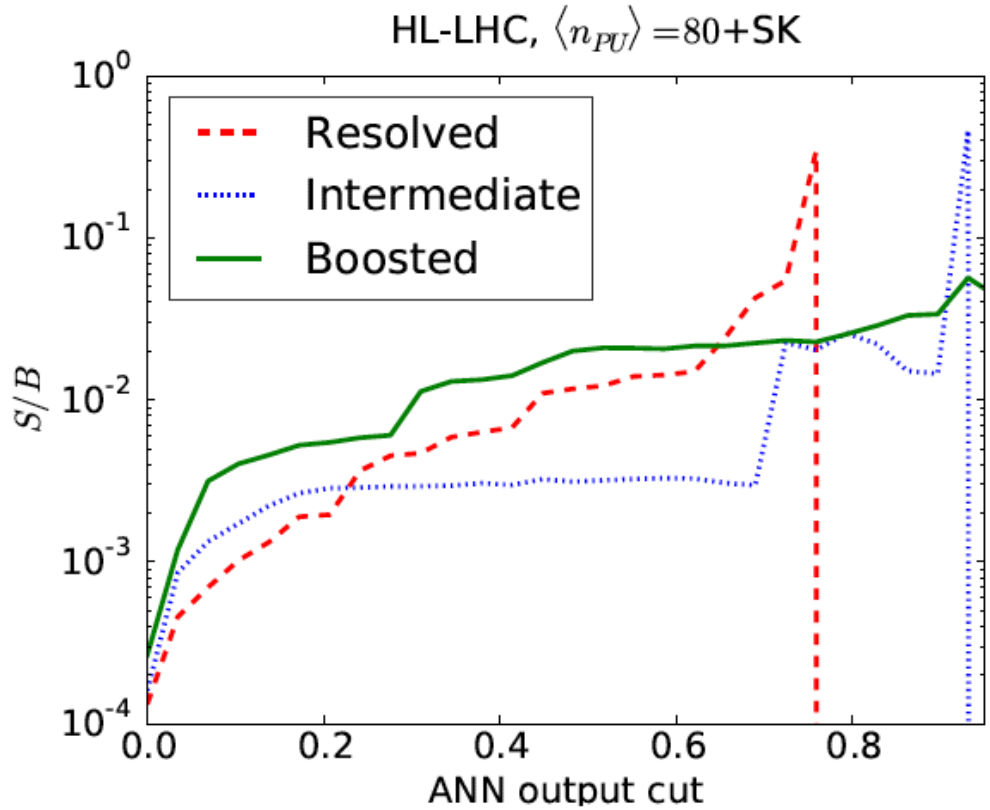


Signal significance

- Use of **multivariate techniques** allows to **substantially improve the signal significance** for this process as compared to a **traditional cut -based analysis**
- The total combined significance is enough to **observe Higgs pair production in the 4b final state** at the HL-LHC. Prospects at Run II can be improved if **light jet mis-identification** reduced

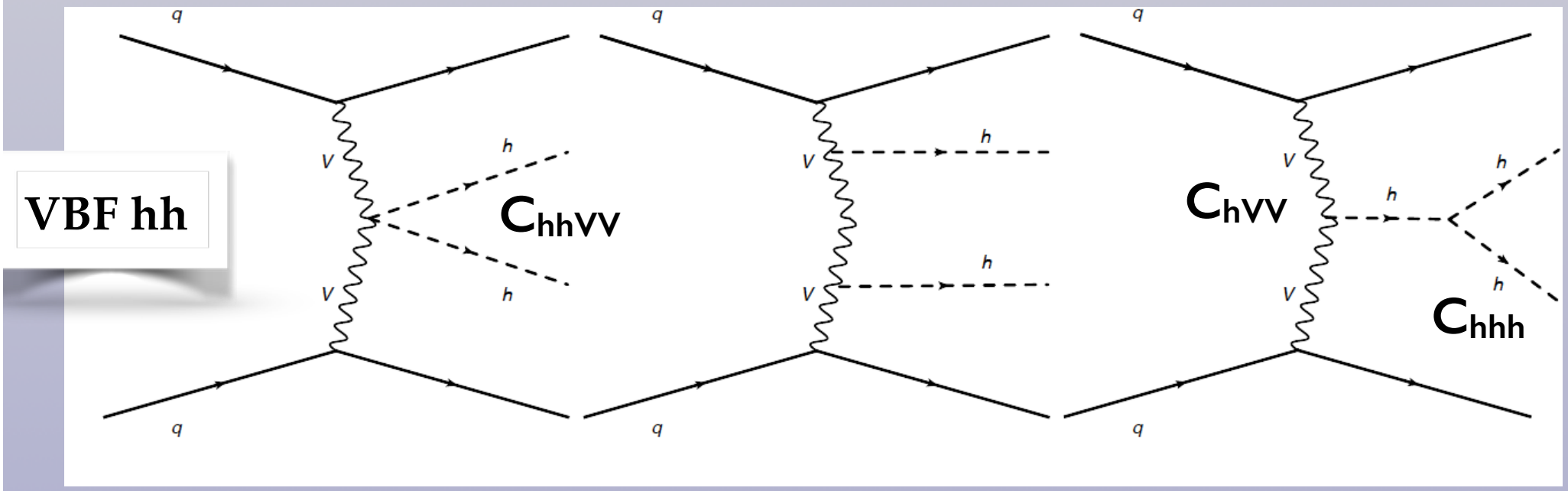
$$\left(\frac{S}{\sqrt{B}}\right)_{\text{tot}} \simeq 4.0\ (1.3)\,, \quad \mathcal{L} = 3000\ (300)\ \text{fb}^{-1}\,,$$





Higgs Pair Production in Vector Boson Fusion

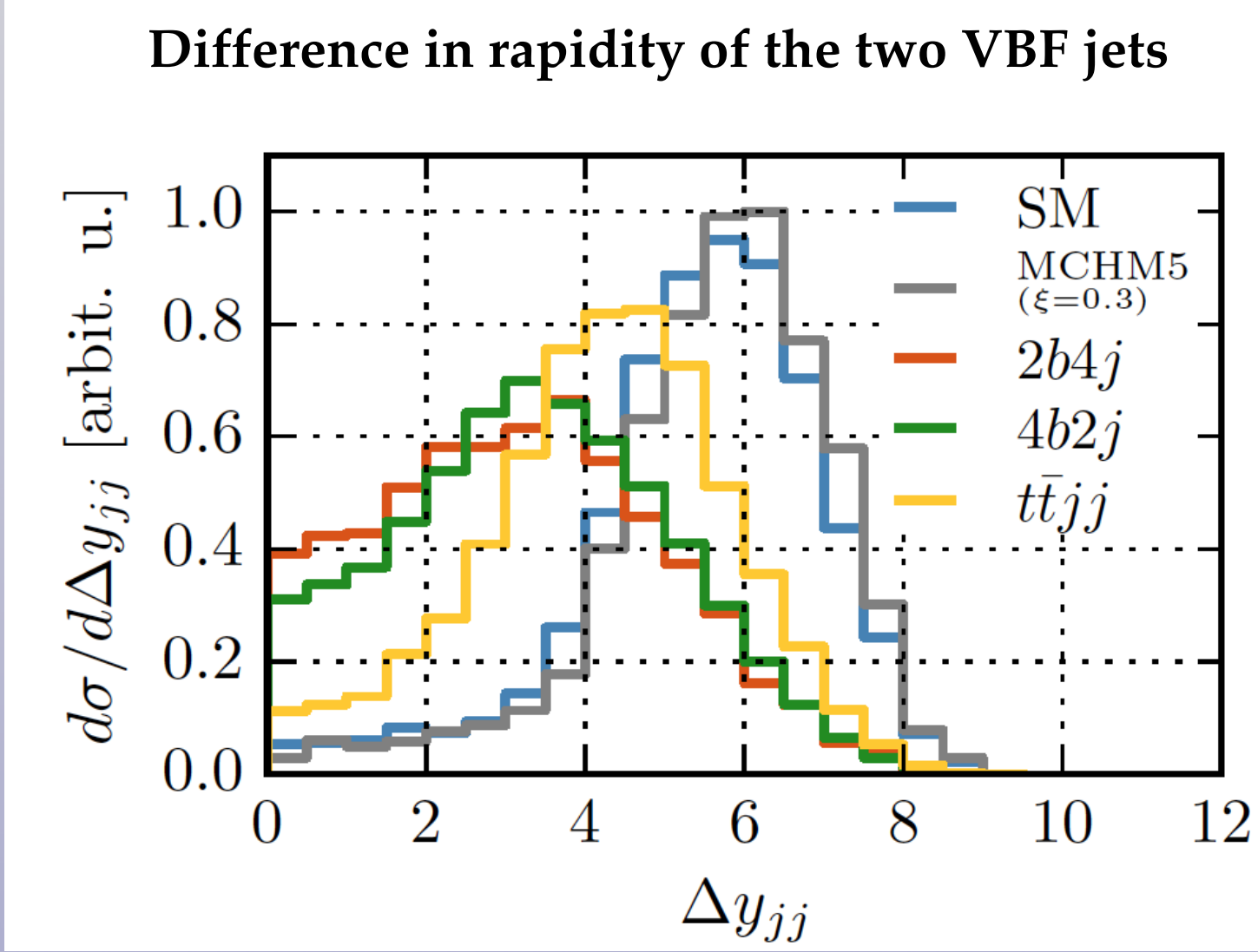
- Higgs pair production in VBF allows direct access of the **hhVV coupling:** direct test of the **doublet nature** of the Higgs boson
- Cannot be accessed in single Higgs production
- Small SM production rates: at 14 TeV cross-section is only **2 fb.** But signal yields can be **enhanced by orders of magnitude** even for **small deviations wrt SM couplings**



Higgs Pair Production in Vector Boson Fusion

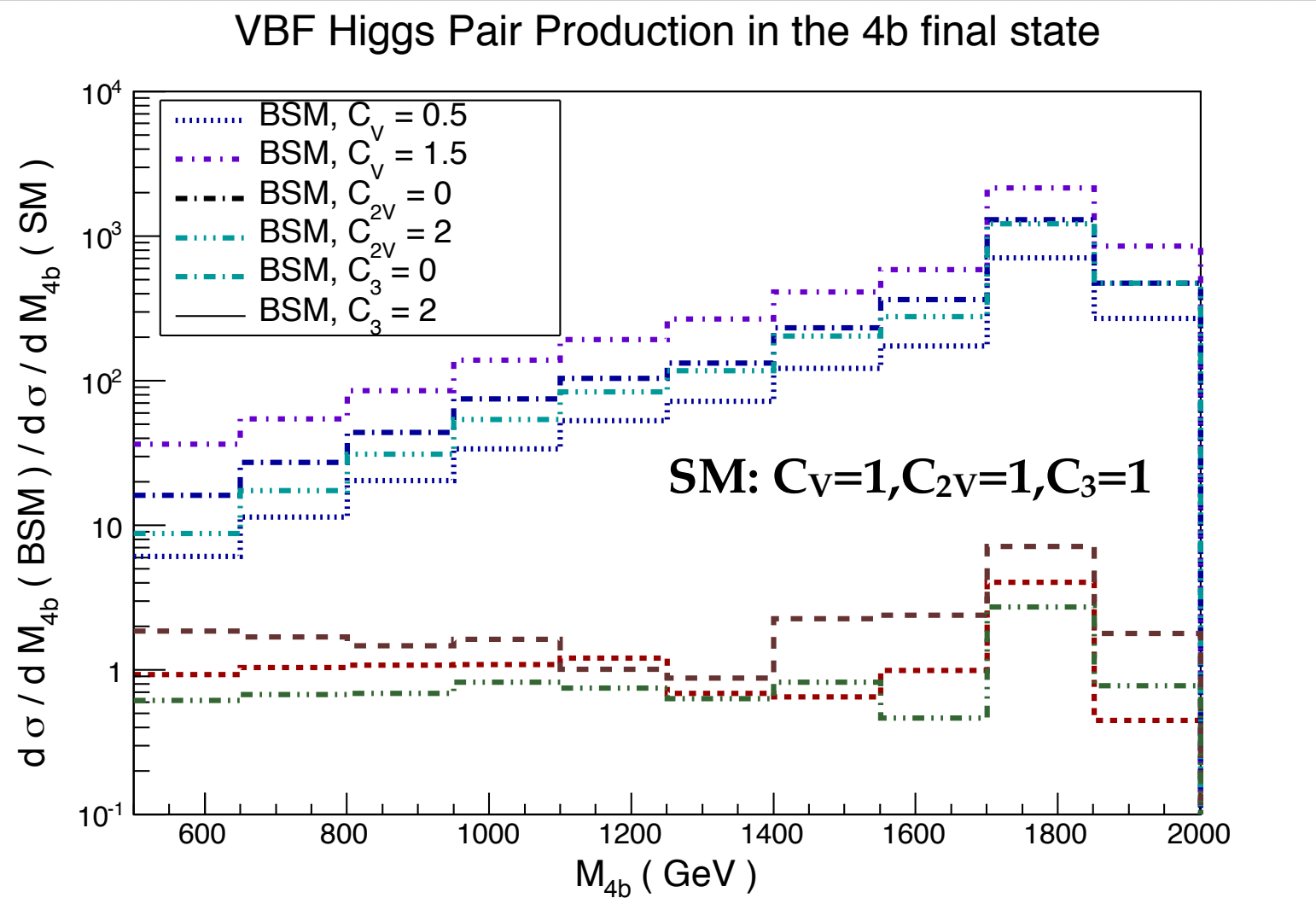
Also in this case overwhelming QCD background, can be tamed with **selection cuts** and **jet substructure**

Exploit the **vector-boson-fusion topology**: two light jets, well separated in rapidity, and a central gap with reduced hadronic activity



Higgs Pair Production in Vector Boson Fusion

- Deviations from the Standard Model in the **hVV and hhVV couplings** lead to **dramatic growth with energy of the di-Higgs invariant mass** distribution
- Smoking gun for New Physics!



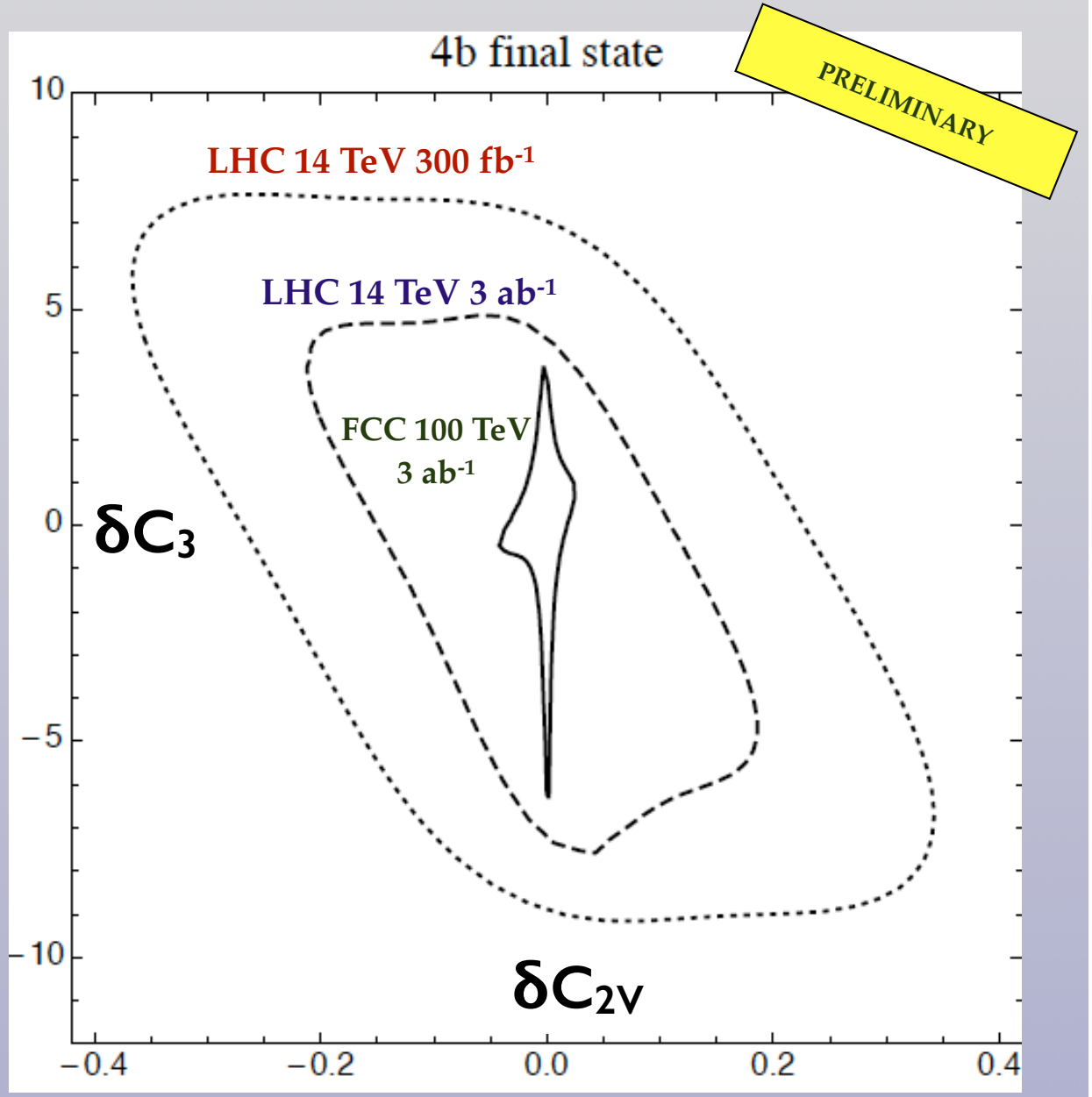
Higgs Pair Production in Vector Boson Fusion

- In the **4b final state,** 14 TeV with 300 fb^{-1} (3000 fb^{-1}) the **hhVV** coupling can be measured with **good precision: ~25-30% (10-15%)**

- At a 100 TeV **FCC,** the **hhVV** coupling can be pinned down with **very high, few percent precision**

- Encouraging to begin to explore **Higgs pair production in VBF** already at the **LHC Run II**

- Unique probe of the Higgs mechanism to **unitarize electroweak symmetry breaking**



Higgs pair production at the LHC

- **Jet substructure** is the key to exploit **the TeV scale at the LHC**, some of the most exiting hints on BSM physics at Run I are based on substructure methods
- **Higgs pair production** is a cornerstone of the LHC program at Run II and at its future High-Luminosity phase
- Unique probe of **electroweak symmetry breaking mechanism** and **Higgs self-interactions**
- Thanks to **jet substructure** combined with **multivariate techniques,** the **4b** final state can be fully exploited
- In the **gluon-fusion channel,** discovery is certain at **HL-LHC**, and even **observation might be within reach at Run II**
- In the vector-boson fusion channel, the **doublet nature of the Higgs** can be probed with 30%(10%) precision at Run II (HL-LHC)

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Thanks for your attention!