Prospects for measuring H to Z cross section ratios

B. Bilin[1], L. Favart[1], P. Gras[2],
A. Grebenyuk[1], **L. Moureaux**[1,3]

[1]IIHE-ULB (Brussels) [2]Saclay (Paris) [3]FRIA grantee

REF workshop in Pavia – November 27, 2019

Prosp H to Z

Higgs talks at REF...

2014:	6
2015:	1
2016:	1
2017:	0
2018:	1
Today:	3

B. s[2],
A. x[1,3]

[1]IIHE-ULB (FRIA grantee

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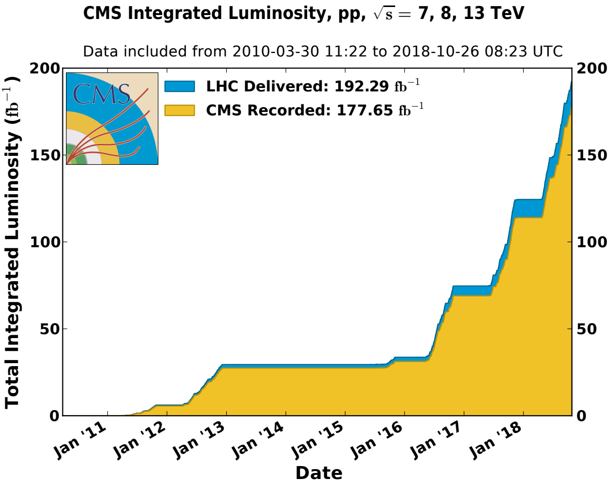
LHC started nearly 10 years ago



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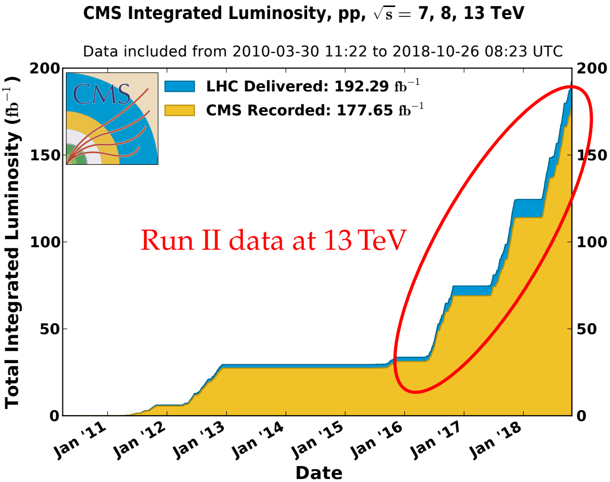

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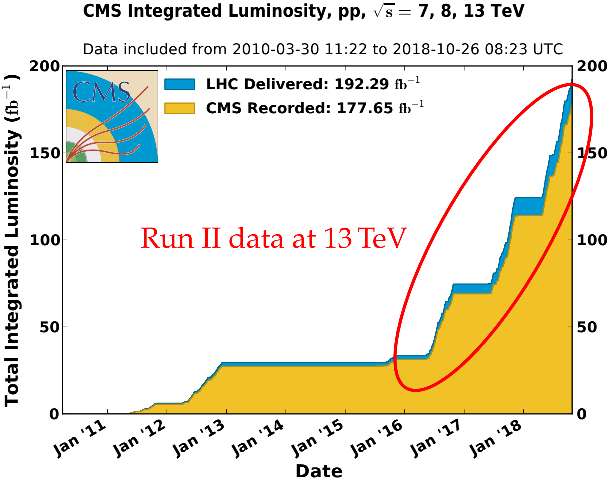

$$56\,\mathrm{pb} \times 139\,\mathrm{fb}^{-1} = 8 \times 10^6 \text{ Higgs bosons produced at } 13\,\mathrm{TeV}$$

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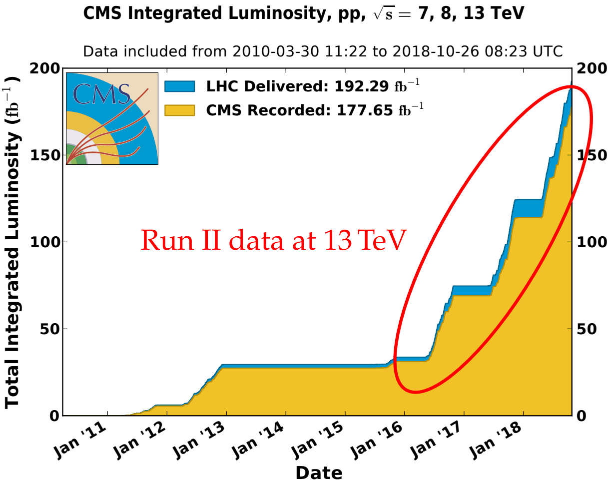
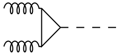


$$56\,\mathrm{pb} \times 139\,\mathrm{fb}^{-1} = 8 \times 10^6 \text{ Higgs bosons produced at 13 TeV}$$

About 400 measured in the “golden chanel” $\mathrm{H} \rightarrow 4\mathrm{L}$

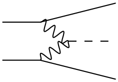
Higgs production at the LHC

ggH



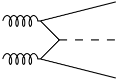
Dominant mode: gluon fusion through a quark loop

VBF



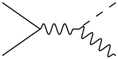
Vector Boson Fusion: two jets well separated in rapidity

$t\bar{t} + H$



In association with top quarks: many jets, neutrinos

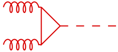
$Z/W + H$

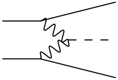


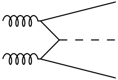
With a vector boson: jets

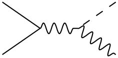
$\vdots$

Higgs production at the LHC

ggH  Dominant mode: gluon fusion through a quark loop

VBF  Vector Boson Fusion: two jets well separated in rapidity

$t\bar{t} + H$  In association with top quarks: many jets, neutrinos

$Z/W + H$  With a vector boson: jets

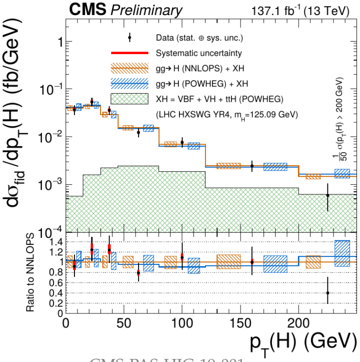
⋮

- Higgs production probes gluon dynamics!

Higgs as a “gluon trigger” first proposed in 2010, see Phys. Rev. **D** 88, 097501

Gluon dynamics

H (gluons, 125 GeV)



CMS-PAS-HIG-19-001

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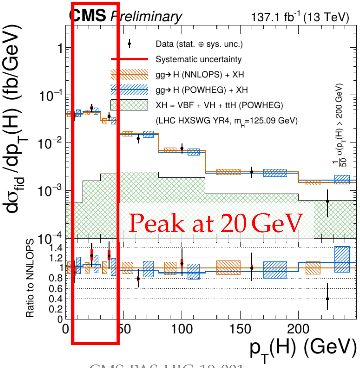

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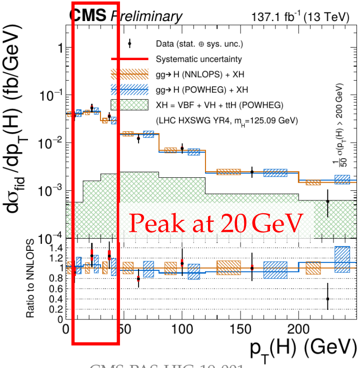
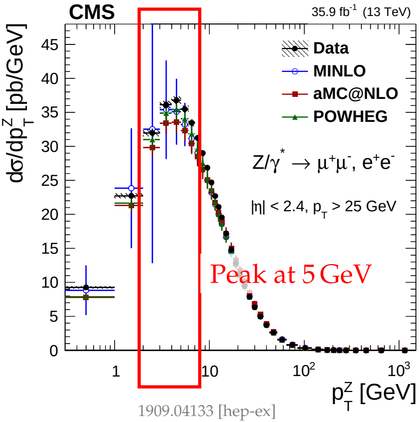


CMS-PAS-HIG-19-001

Z (quarks, 91 GeV)



1909.04133 [hep-ex]

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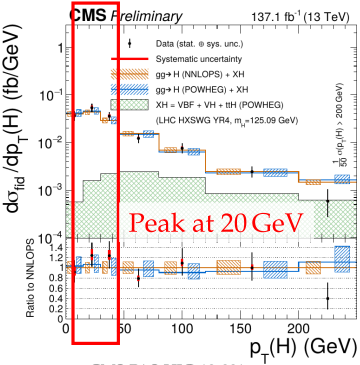

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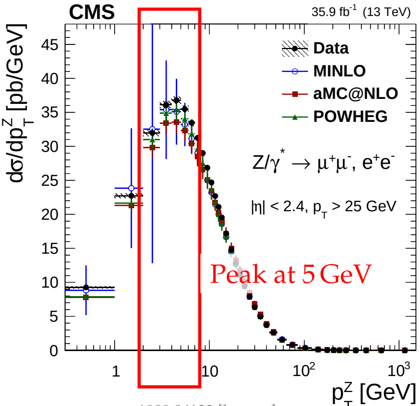
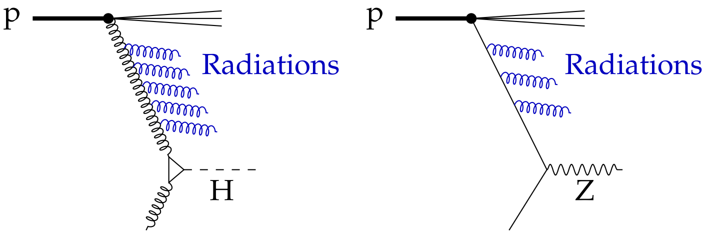


1909.04133 [hep-ex]

- Gluons are different from quarks

Higgs vs Z: Gluons vs quarks

To compare gluons and quarks, we can compare their effect on Higgs and Z boson production



Higgs vs Z: Gluons vs quarks

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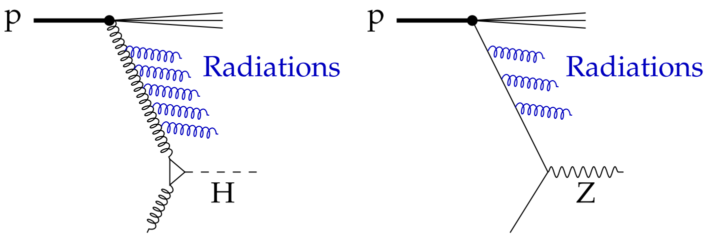

- Direct comparison by taking ratios
  - Eliminate some of the systematics
- Can we do it in Run II data?
- What's the expected accuracy?

Run MC simulations and check out...

Monte-Carlo setup

Event generation:

- aMC@NLO with PYTHIA8 for Drell-Yan (up to 2 jets at NLO)
- POWHEG + JHUGEN with PYTHIA8 for Higgs (NLO inclusive)
- CP5 tune and NNPDF 3.1

See also references in backup slides

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See also references in backup slides

Cuts that mimic existing CMS analyses:

Z boson:

- e^+e^- or $\mu^+\mu^-$ pairs
- Lepton $p_T > 25\,\text{GeV}$
- Lepton $|\eta| < 2.4$
- $115 < M_{ll} < 135\,\text{GeV}$

Jets:

- Anti-k_T with $R = 0.4$
- $p_T > 30\,\text{GeV}$, $|\eta| < 4.7$
- $\Delta R(\text{jet}, \text{lepton}) > 0.4$

Higgs boson:

- Four leptons: $2(e^+e^-)$, $2(\mu^+\mu^-)$ or $e^+e^-\mu^+\mu^-$
- Lepton $p_T > 5(7), 7, 10, 20\,\text{GeV}$
- Lepton $|\eta| < 2.4$
- Pair leptons to make two Z bosons with $40 < M_{ll,1} < 120\,\text{GeV}$ and $M_{ll,2} > 12\,\text{GeV}$

Variables of interest

For measured jets:

- Boson p_{T}
- Number of jets
- Jet p_{T}

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For measured jets:

- Boson p_T
- Number of jets
- Jet p_T

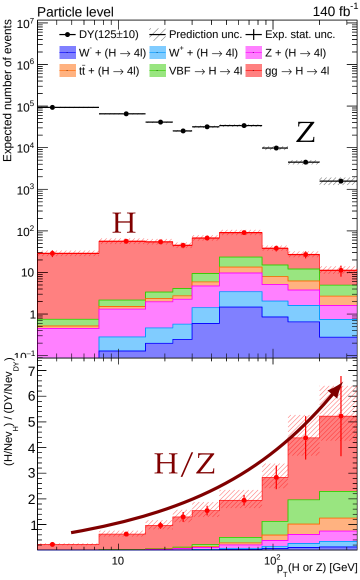
For radiation other than selected jets:

- Boson p_T
- p_T balance: $p_\mathrm{T}^\mathrm{bal} \equiv \left| \sum_\mathrm{jets} \vec{p}_\mathrm{T}(\mathrm{jet}) + \vec{p}_\mathrm{T}(\mathrm{B}) \right|$
- Jet-boson balance: $\mathrm{JBB} \equiv \left| \sum_\mathrm{jets} \vec{p}_\mathrm{T}(\mathrm{jet}) \right| - p_\mathrm{T}(\mathrm{B})$

CMS measurement for Z: EPJ **C** (2018) 78:965

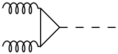
Results: Reading the plots

- Expected number of events for 140 fb^{-1}
- Higgs breakdown by production mechanism
  - Prediction uncertainty (stat, scale, PDF)
  - Expected stat. error in Run II data
  - $gg \to H \to 4l$ · VBF $\to H \to 4l$ · $t\bar{t} + (H \to 4l)$ · $Z + (H \to 4l)$ · $W^+ + (H \to 4l)$ · $W^- + (H \to 4l)$
- Higgs to Z ratio (normalized)
- **No data**, this is a MC-only study

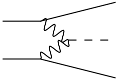


Results: Reading the plots

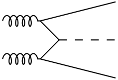
ggH



VBF



$t\bar{t} + H$



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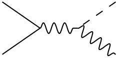


- Higgs breakdown by production mechanism

Prediction uncertainty (stat, scale, PDF)

Expected stat. error in Run II data

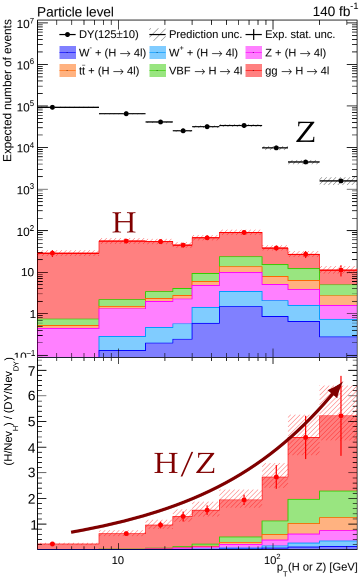
$gg \to H \to 4l$ · VBF $\to H \to 4l$ · $t\bar{t}$ + $(H \to 4l)$

Z + $(H \to 4l)$ · W^+ + $(H \to 4l)$ · W^- + $(H \to 4l)$

Results: Boson p_T (Higgs or Z)

- Sensitive to **hard** jets at **high** p_T
- Sensitive to **soft** emissions at **low** p_T

- For gluon fusion, harder H boson p_T compared to the Z due to emission difference between gluons and quarks
- For other production mechanisms the Higgs boson p_T is harder than the Z because of existence of other particles
- Binning inspired by the existing H measurements

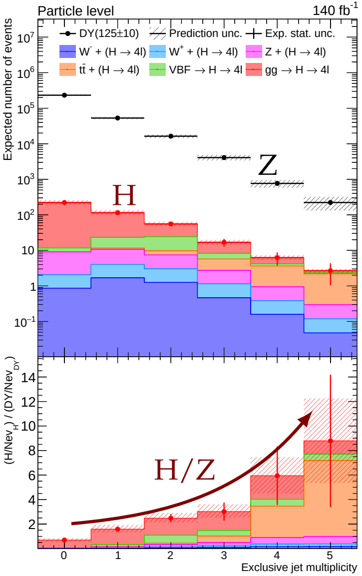


Results: Number of jets (exclusive)

- Sensitive to **hard** jets only

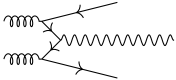
- More jets in Higgs events
- Because of the color factor of gluons, but also specifics of VBF and ttH

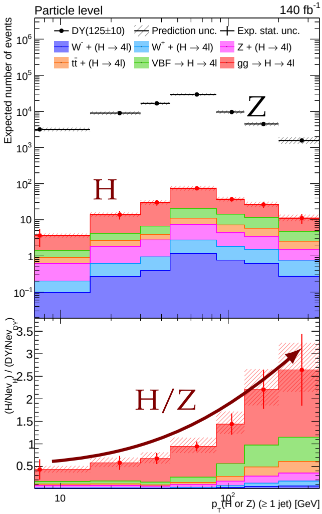
- Could measure up to 4 jets in Run II data!

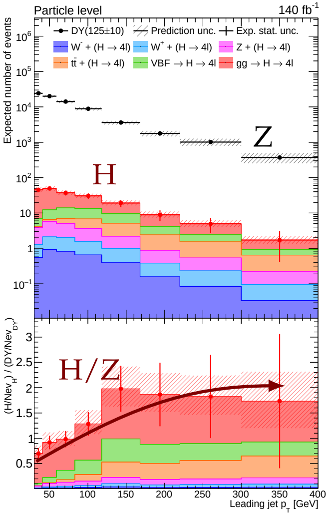


Results: p_{T} when one jet is reconstructed

- When an extra jet is accompanying the boson, p_{T} is shifted to higher values due to recoil
- Differences between Higgs and Z visible as in the 0 jet case
- Flattening of the ratio for large jet p_{T}: Z production starts to be dominated by gluon-initiated events with two jets





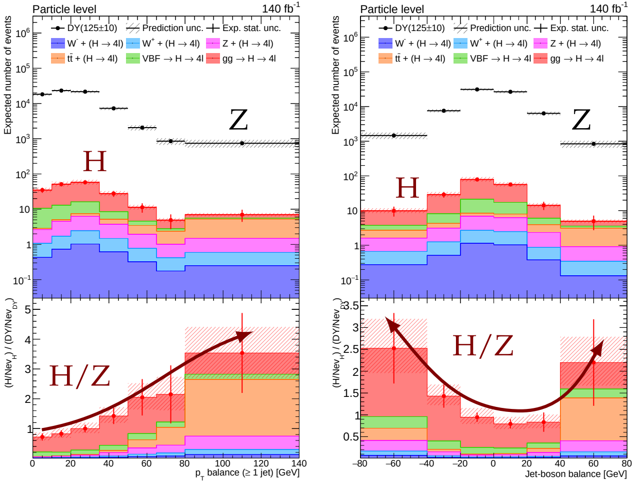


Results: Balance in the transverse plane

$$p_\mathrm{T}^\mathrm{bal} \equiv \left| \sum_\mathrm{jets} \vec{p}_\mathrm{T}(\mathrm{jet}) + \vec{p}_\mathrm{T}(\mathrm{B}) \right|$$

$$\mathrm{JBB} \equiv \left| \sum_\mathrm{jets} \vec{p}_\mathrm{T}(\mathrm{jet}) \right| - p_\mathrm{T}(\mathrm{B})$$

- To study undetected radiations two new observables are defined [1]
- Effects coming from extra jets (in acceptance) cancel out
- Remaining effects mainly due to different production mechanisms



[1] See EPJ C (2018) 78:965 (SMP-16-015)

Summary

- First study based on MC to show the feasibility of H/Z ratios in Run II
- Variables based on the kinematics of the boson and jets
- Effects of gluon/quark radiations visible in various observables
- Additional particles for some production mechanisms affect the sensitivity
  - As seen for quark induced Higgs production mechanisms (like VBF...)
  - JBB & $p_{\mathrm{T}}^{\mathrm{bal}}$ eliminate some of the effects from extra particles/jets

Questions

- Would a direct calculation of the H/Z ratio potentially reduce some of the theory systematics?
  - PDFs in corners of the phase space
  - Scale uncertainty?

- Would H/Z ratio measurements be sensitive to TMD effects?
  To what extent?

¿ ?

Uncertainties

Estimation:

- PDF uncertainties
  - Hessian method according to PDF4LHC recommendations
- Scale uncertainties (envelope method)
  - Variations of μ_R and μ_F by factors $\frac{1}{2}$, 1 or 2
  - Taking the envelope of all possible combinations, except when both scales are varied in the same direction
  - Symmetrizing by taking the average
- MC statistical uncertainty
- For the ratio: fully correlated and fully uncorrelated calculations, see next slide
  - Small difference
  - Correlated variant shown on the plots

Uncertainty on the ratio

We use two methods to propagate the systematic uncertainties to the H/Z ratio.

Fully uncorrelated:

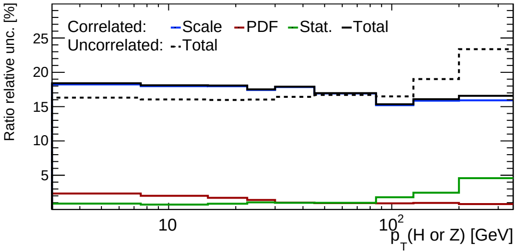
- Apply the guidelines first
  - Hessian method (quadratic sum) for the PDF
  - Envelope for the scale
- Then propagate using the basic rule $\frac{\Delta(a/b)}{a/b} = \frac{\Delta a}{a} \oplus \frac{\Delta b}{b}$

Fully correlated:

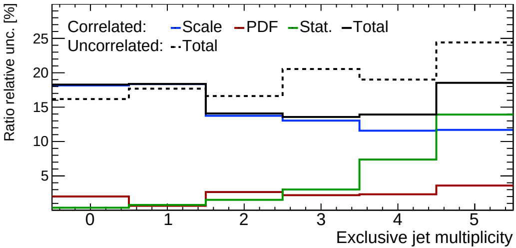
- Take the ratio for each variation of the weights
- Apply the guidelines on the ratios
- Statistical error always uncorrelated

Uncertainty breakdown

Breakdown of the uncertainties for two representative distributions:



Boson p_T



Number of jets (exclusive)

Monte-Carlo references I

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Journal of High Energy Physics, 2008(07):060, 2008.

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