FROM HADRON COLLISIONS AND RAW DATA TO THE PHYSICS MEASUREMENTS

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Preface

GOAL OF THE LECTURES:

- **Make you familiar with:**
  - typical steps in the **data analysis chain** within HEP experiments,
  - important aspects of the **statistical data analysis**;
- **Introduce you to important aspects in the extraction of physics information.**

A FEW ASSUMPTIONS:

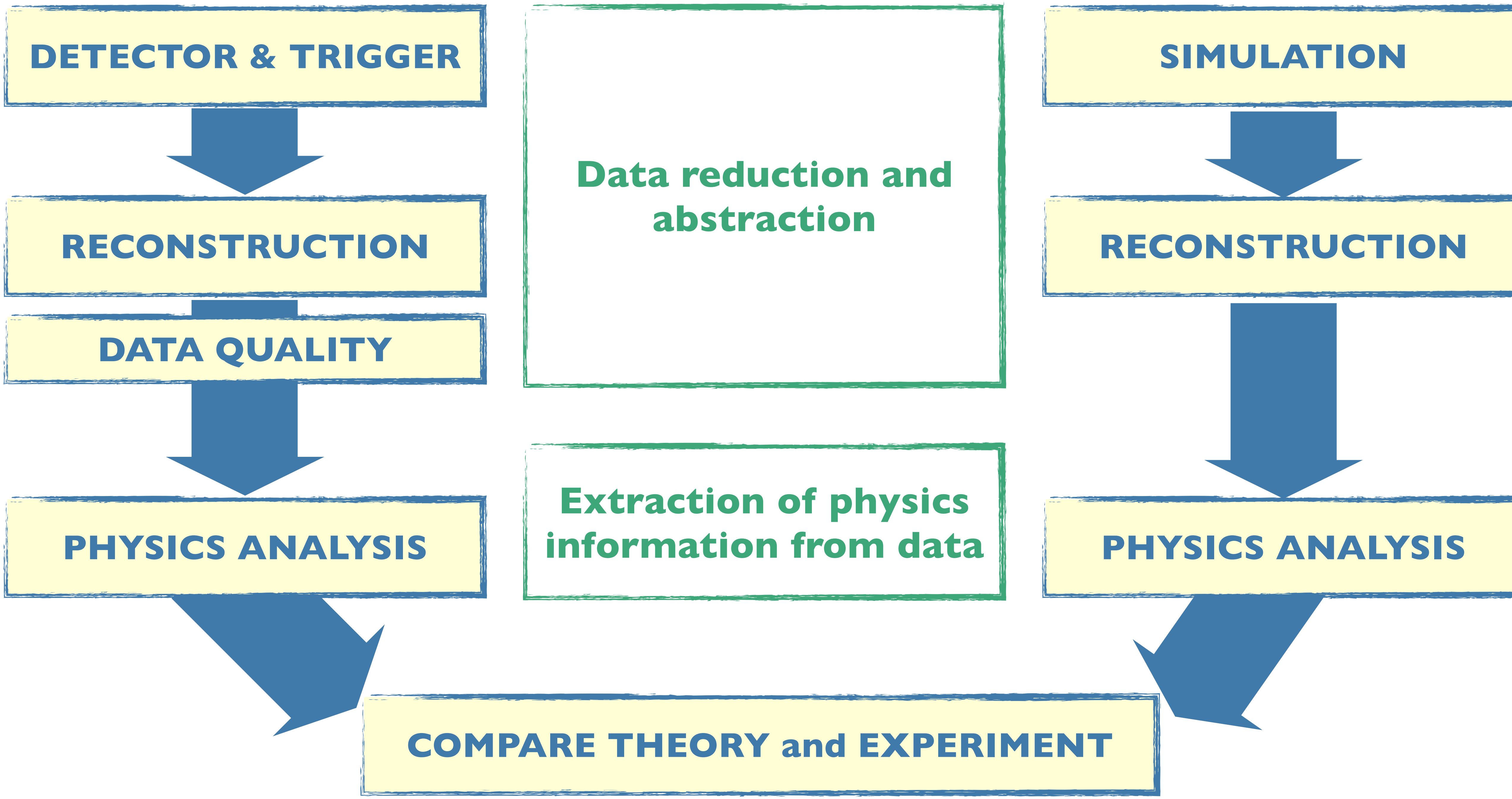
- You are familiar with basic concepts of the **LHC**, and **multi-purpose detectors** in HEP,
- You are familiar with basics of **instrumentation in HEP**,
- You have a limited experience with the physics analysis.

DISCLAIMER:

- Examples in lectures will have a slight bias towards CMS detector and physics results.

Overview

GENERAL ANALYSIS FLOW



Overview

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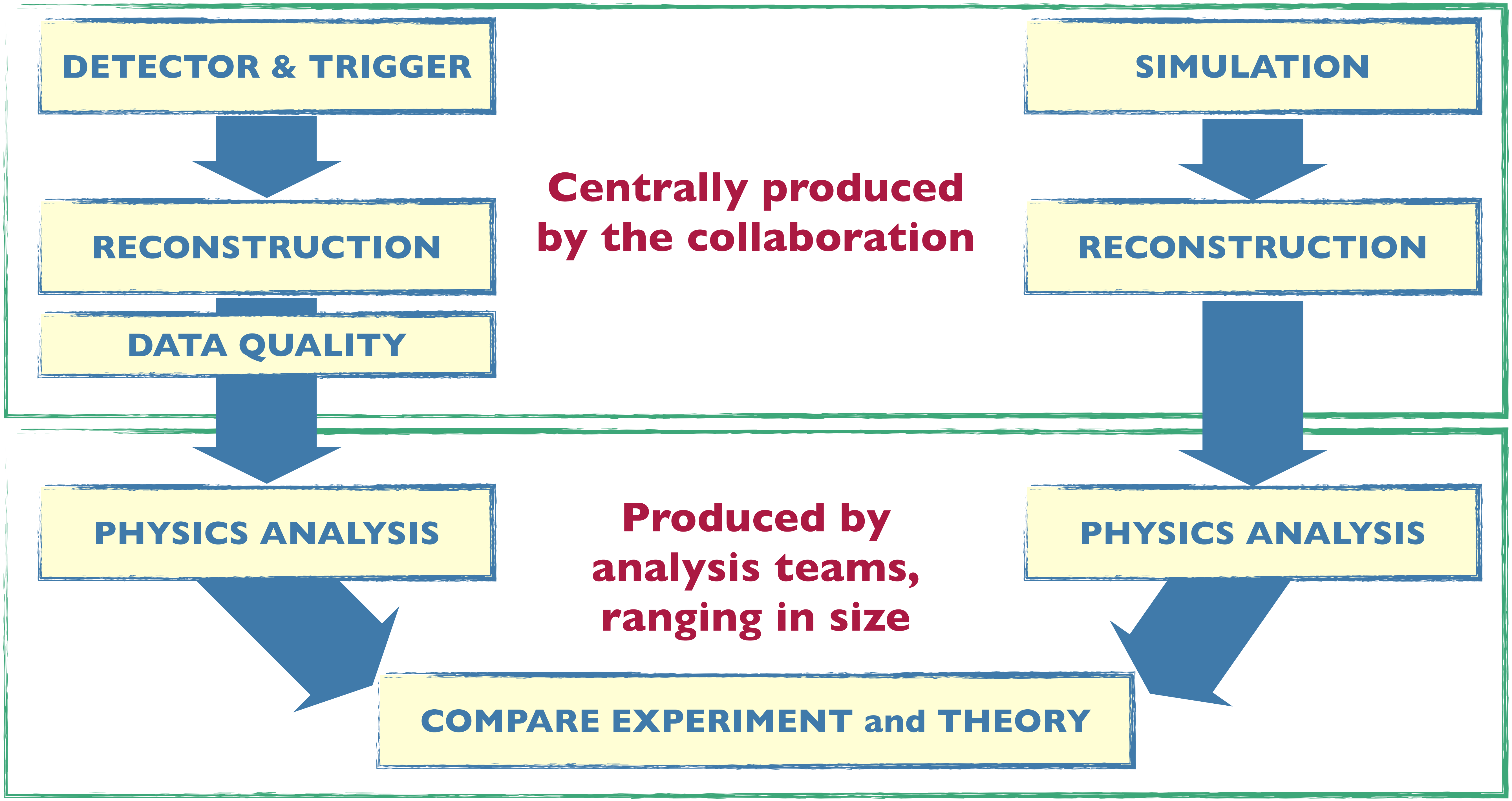

Overview

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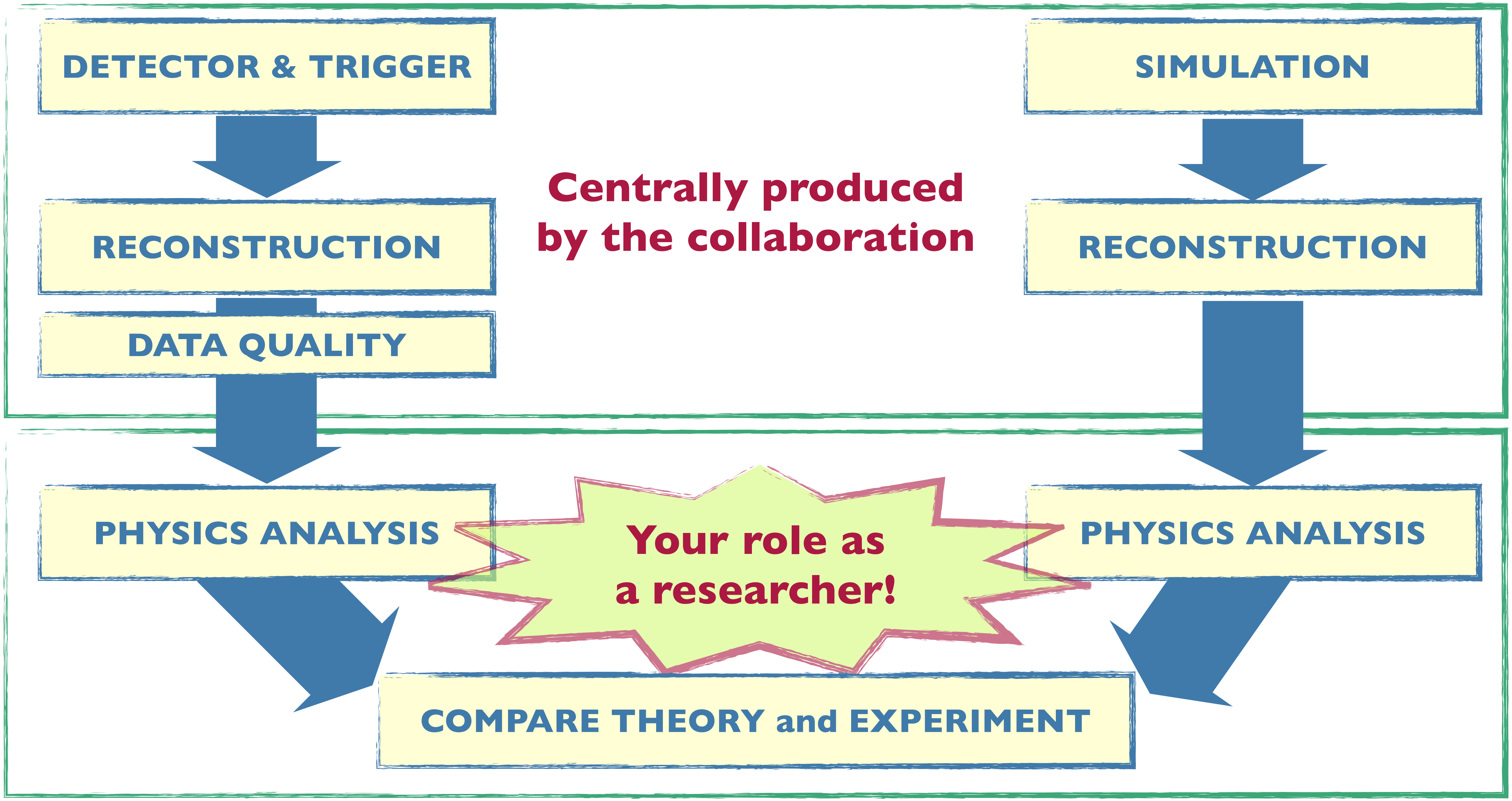
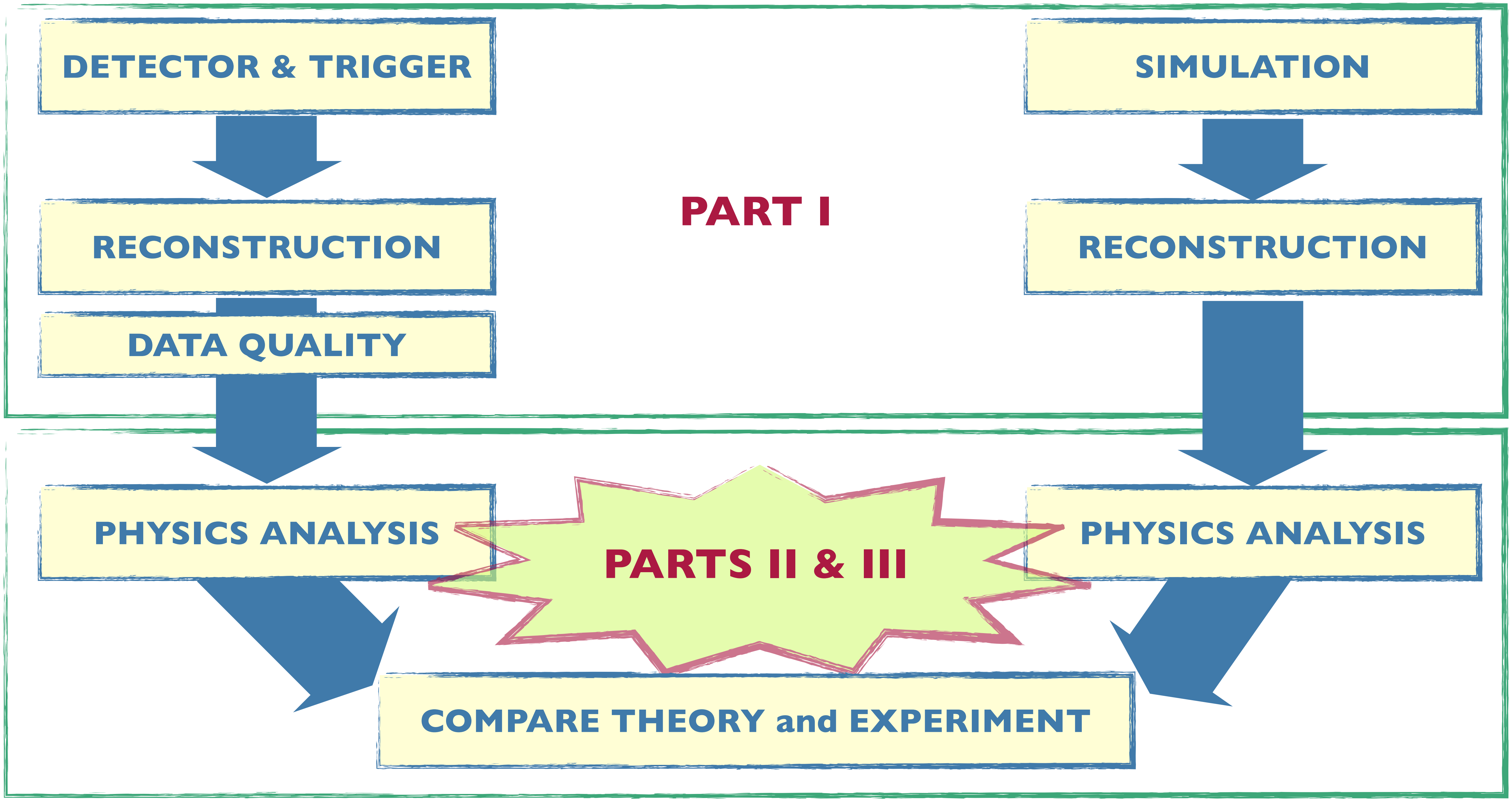


Outline of the lecture

GENERAL ANALYSIS FLOW



Outline of the lecture

PART I: From hadron collisions to the data abstraction

- Key ingredients and steps in the event reconstruction
  - for detailed information on particle identification through interaction with matter see lecture by L.Dobrzynski

PART II: Data analysis and extraction of physics information

- Basic ingredients of the statistical / physics data analysis

PART III: Selected topics on the physics measurements

- Estimation of background processes using data
- Matrix Element Method for separation of physics processes
- Exploitation of interference effects in particle physics
- Fiducial cross section measurements

PART I
From hadron collisions to the data abstraction

Detector & Trigger

DETECTOR:

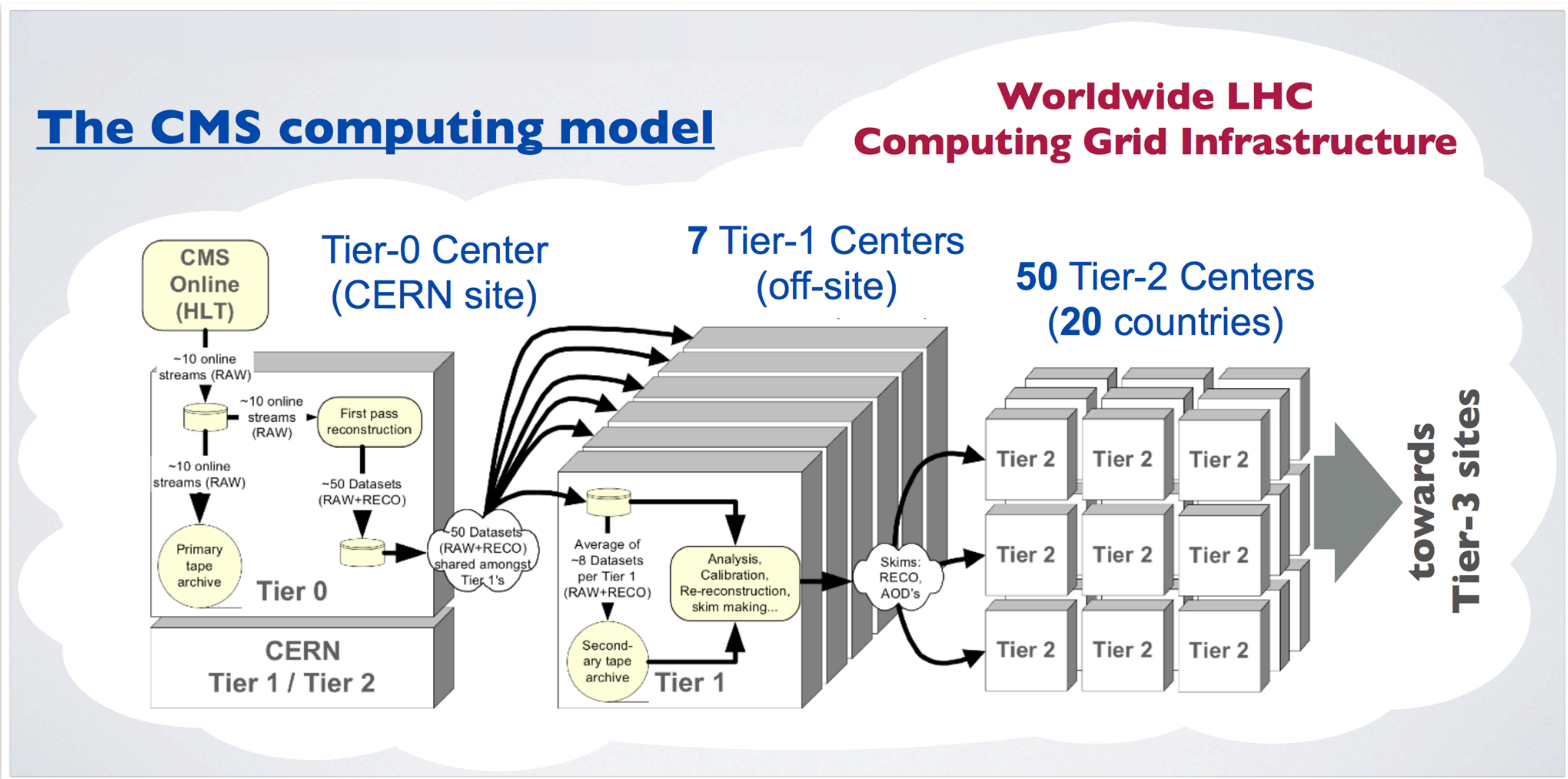
- **Designed to allow for identification of particles through interaction with matter**
  - Collect & digitize **large amount of information** (many channels, many sub-detectors)
  - Size of each event 1.5-2 MB (similar between ATLAS and CMS)

TRIGGER:

- **Decide to readout and process the event, or to throw event away**
  - Filtering necessary because of the **high rate of collisions**, and our interest in processes with **widely different production rates** (orders of magnitude)
  - Need to perform a fast event processing and selection - need for approximation

Data (re)processing & storage

- **Need to allow physicists around the world to access and analyze data**
  - **WLHC Grid**: Computing and storage resources distributed around the world
  - **Enables:** Calibration, re-reconstruction, skimming, simulations, storage, …



Theory, reality, experiment

Reality → Experiment


```
0x01e84c10:    0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:    0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:    0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:    0x01e8 0x8788 0x01e8 0x8498 0x7072 0x6f63 0x0000 0x0000
0x01e84c60:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
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0x01e84c90:    0x01e8 0x8838 0x01e8 0x8518 0x7265 0x6773 0x7562 0x0000
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0x01e84cd0:    0x01e8 0x8798 0x01e8 0x8598 0x7265 0x7475 0x726e 0x0000
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0x01e84d50:    0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
0x01e84d60:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d70:    0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
0x01e84d80:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d90:    0x01e8 0x87c0 0x01e8 0x8718 0x7377 0x6974 0x6368 0x0000
```


Make sense of these numbers through data abstraction based on physics

Theory

$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

{ $W^{\pm}, Z, \gamma$ kinetic energies and self-interactions

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)R$$

{ lepton and quark kinetic energies and their interactions with $W^{\pm}, Z, \gamma$

$$+\left|\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)\phi\right|^{2}$$
$$-V(\phi)$$

{ $W^{\pm}, Z, \gamma$ and Higgs masses and couplings

$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)$$

{ lepton and quark masses and coupling to Higgs

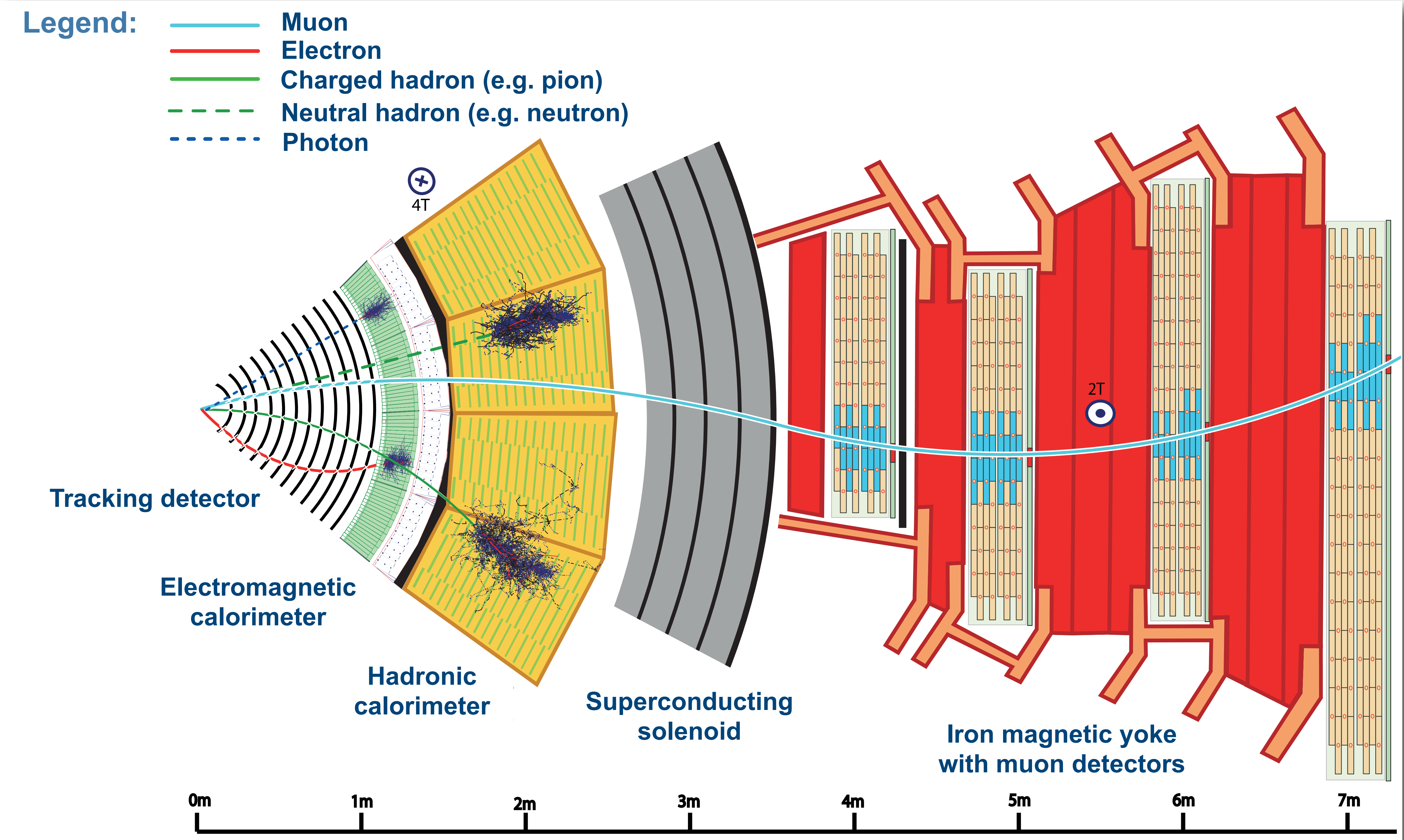
L ... left–handed fermion (l or q) doublet
R ... right–handed fermion singlet

$\mathcal{L}$ from QCD:

$$\mathcal{L} = \underbrace{\bar{q}\,(i\gamma^{\mu}\partial_{\mu} - m)\,q}_{E_{kin}(q)} - g\underbrace{(\bar{q}\gamma^{\mu}T_a q)G^a_{\mu}}_{\text{Interaction } q,\, g} - \underbrace{\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{E_{kin}(g)}$$

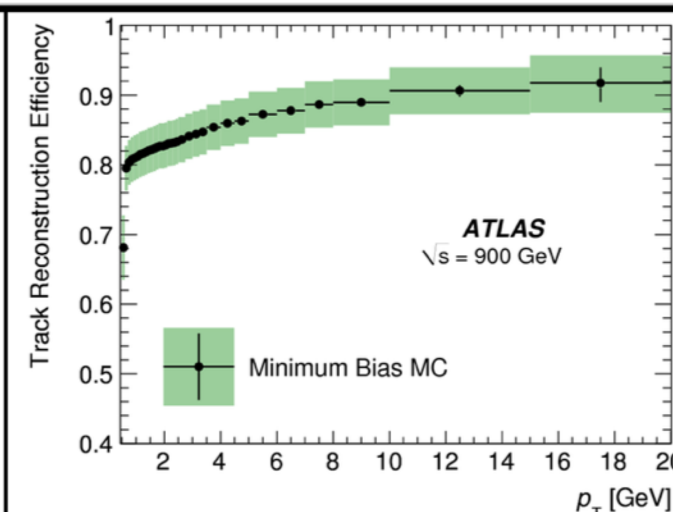
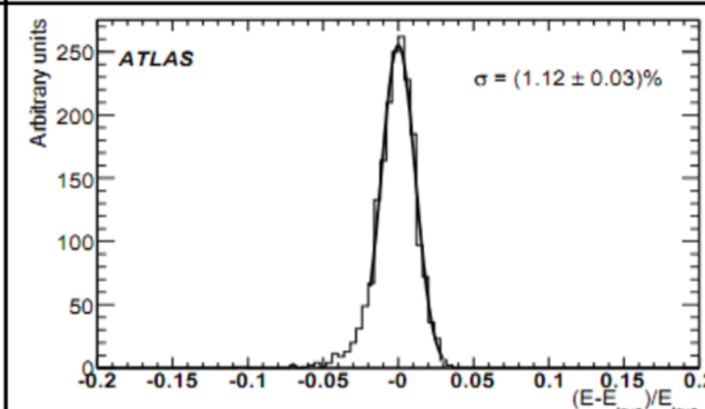
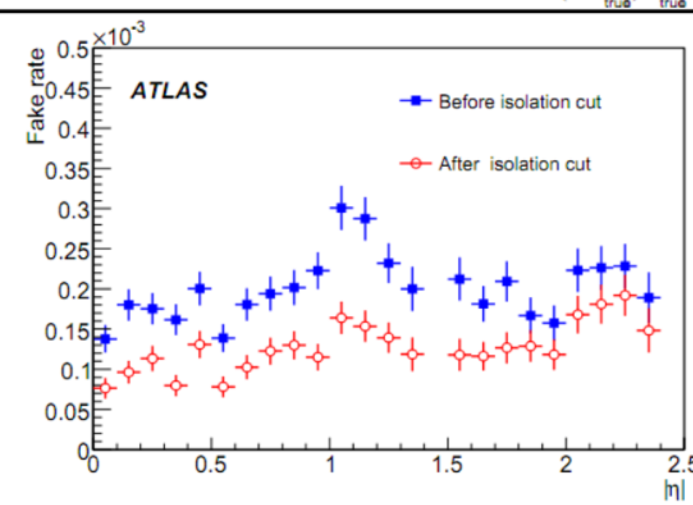
$E_{kin}(q)$ | Interaction q, g | $E_{kin}(g)$ includes self-interaction between gluons

Reminder: Layered structure of HEP detector (CMS)



Event reconstruction (I)

IMPORTANT FIGURES OF MERIT:

<table>
<tr><td>Efficiency</td><td>how often do we reconstruct the object</td><td>tracking efficiency = (number of reconstructed tracks) / (number of true tracks)</td><td>
</td><td>High</td></tr>
<tr><td>Resolution</td><td>how accurately do we reconstruct the quantity</td><td>energy resolution = (measured energy – true energy) / (true energy)</td><td>
</td><td>Good</td></tr>
<tr><td>Fake rate</td><td>how often we reconstruct a different object as the object we are interested in</td><td>a jet faking an electron, fake rate = (Number of jets reconstructed as an electron) / (Number of jets)</td><td>
</td><td>Low</td></tr>
</table>

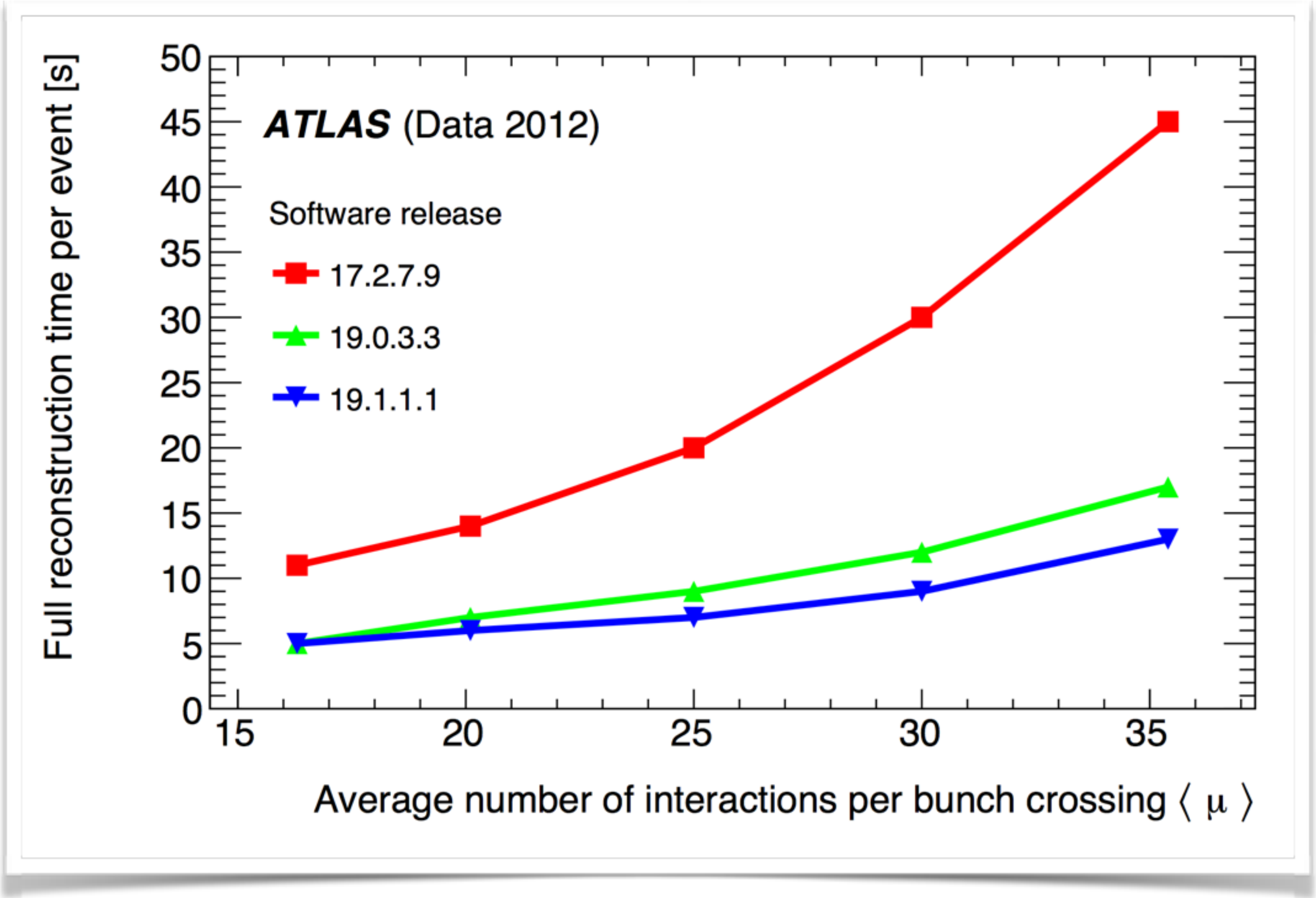
Event reconstruction (2)

GOAL:

- Data abstraction based on the particle physics principles

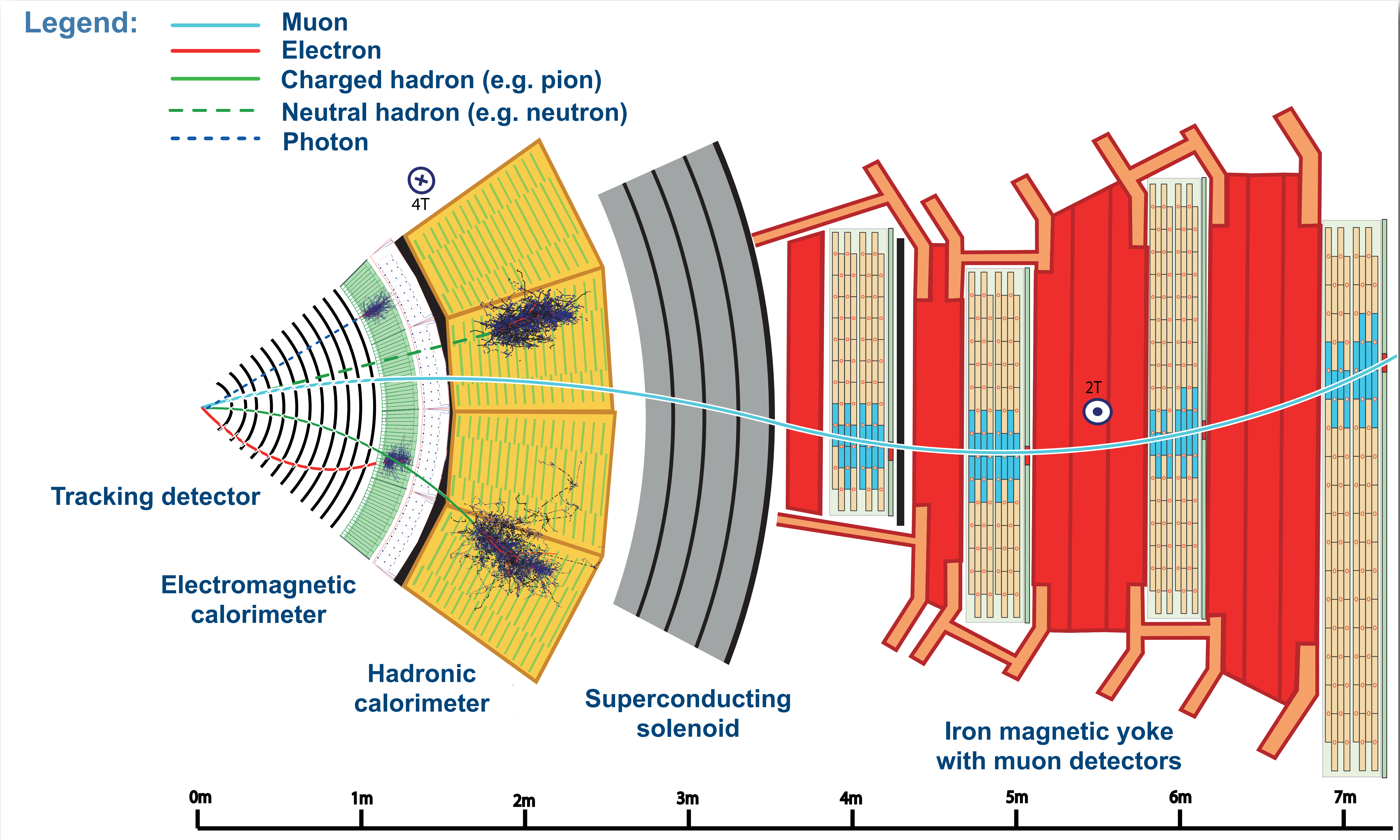
DESIRED PERFORMANCE:

- High efficiency + Good resolution + Low mis-reconstruction rate.
- Robust against detector problems and data-taking conditions:
  - Noise,
  - Dead regions of the detector,
  - Increased pile-up.
- Computing-friendly:
  - CPU time per event,
  - Memory use.



Individual particles

- Direct reconstruction of certain types of individual particles



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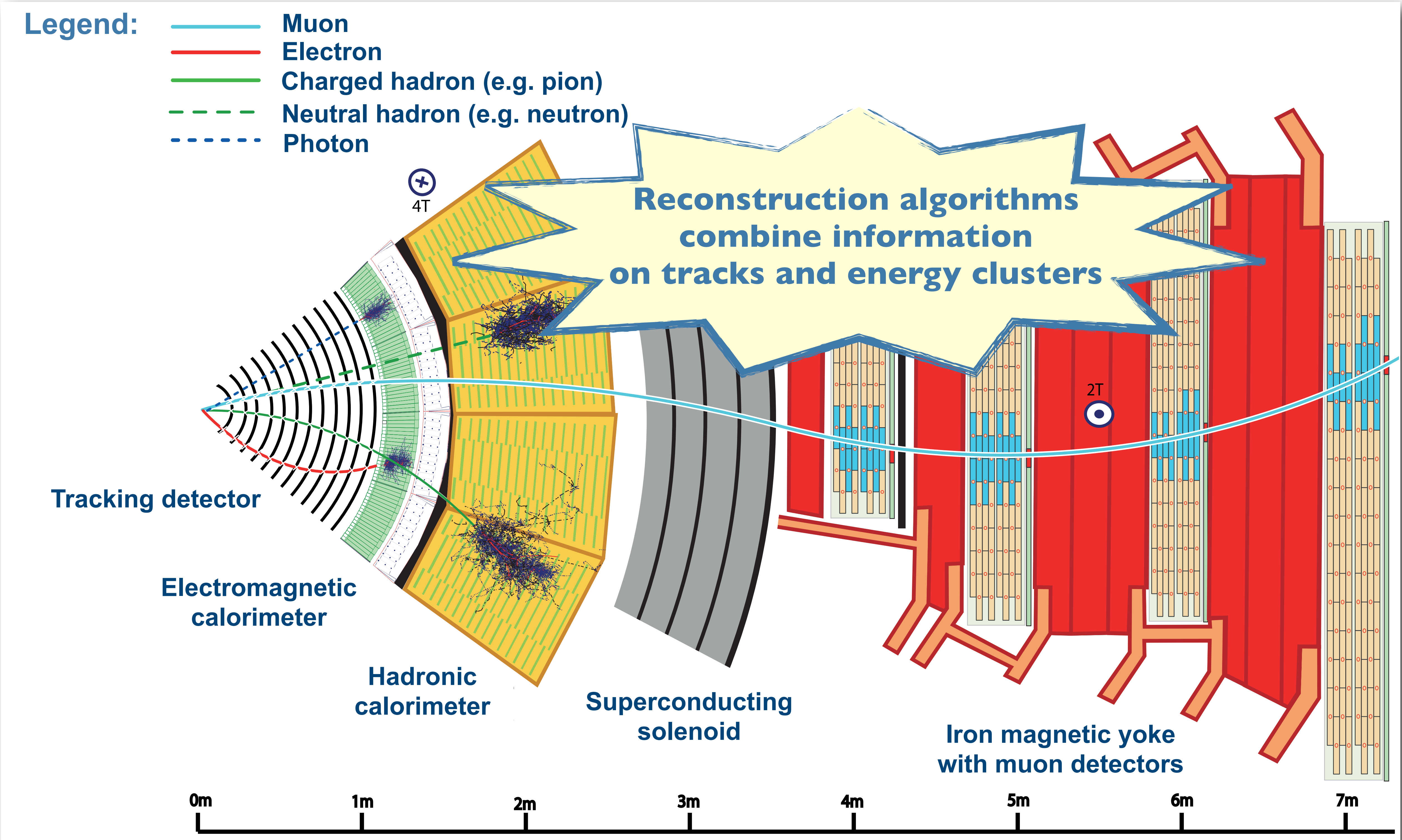
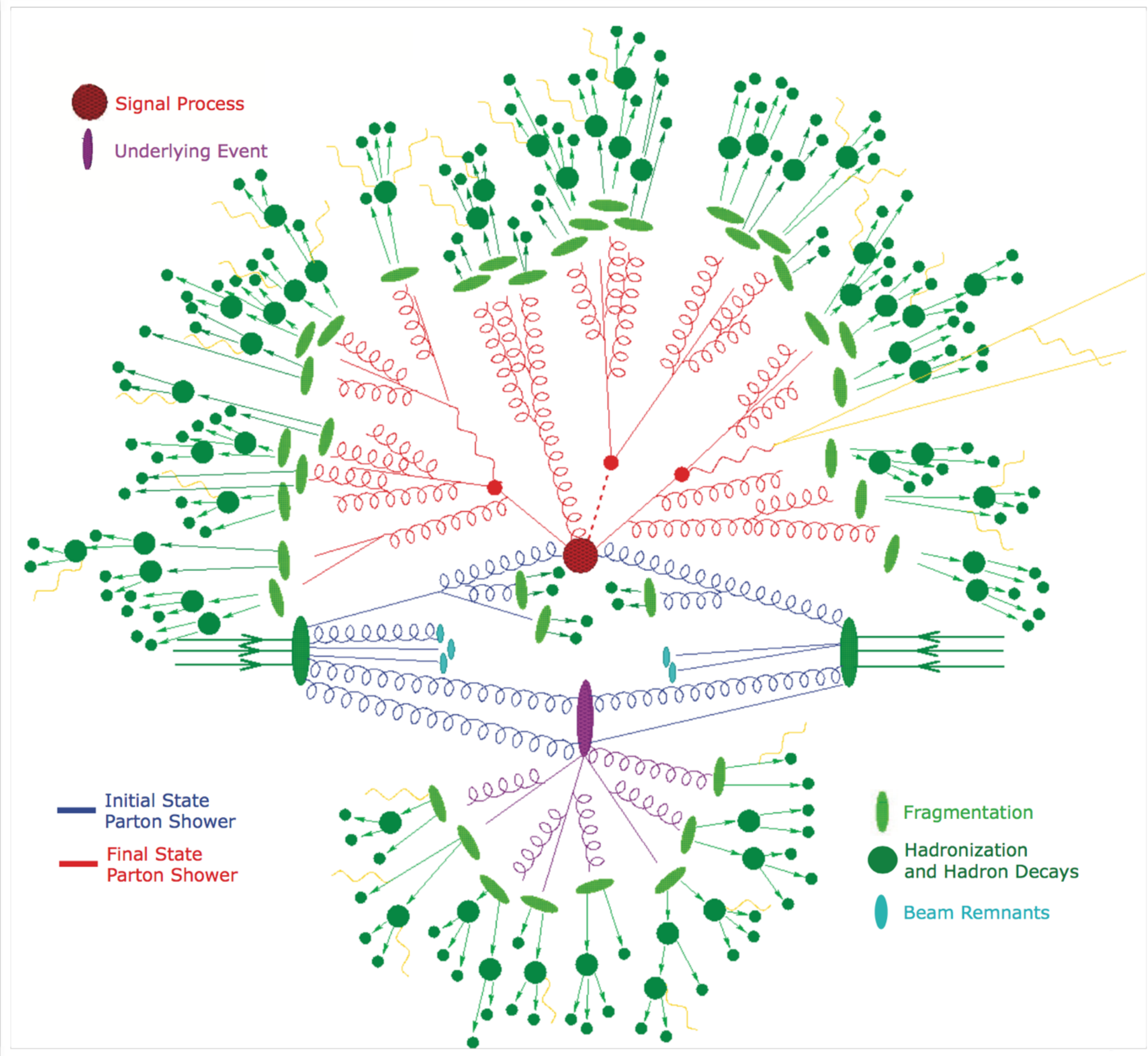


Complex picture of proton-proton collisions



Jets

PRODUCTION:

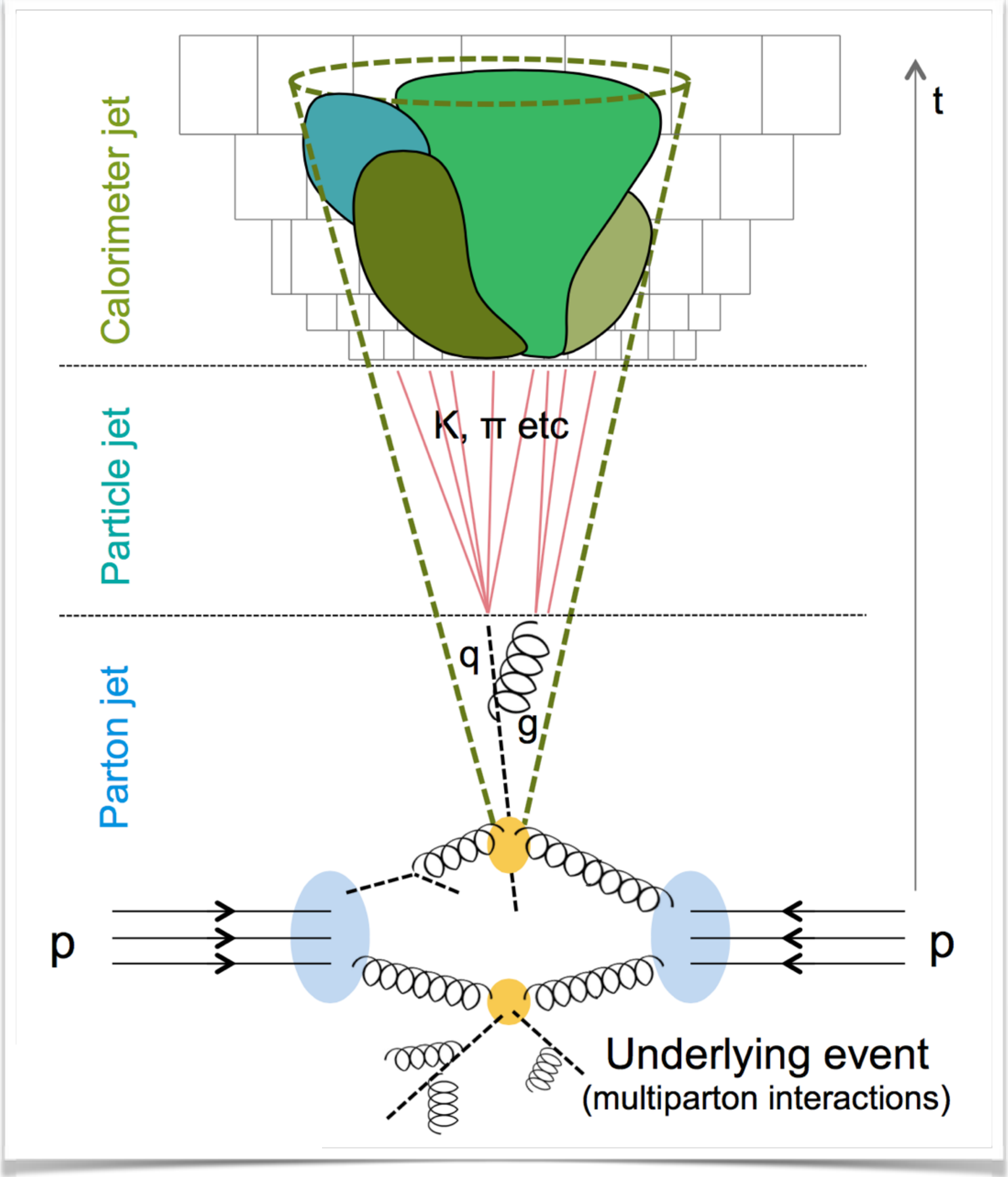
- by fragmentation of gluons and (light) quarks in QCD scattering

RECONSTRUCTION:

- Need to satisfy requirements:
  - theoretical requirements (infrared and collinear safety)
  - experimental requirements (detector & environment independent, easily implementable, etc.)
- Commonly used in ATLAS and CMS
  - 'anti-kt' algorithm (typical cone sizes: R=0.4/0.5)

CALIBRATION:

- Correct the energy and position measurement, and the resolution.
- Correct for instrumental & physics effects



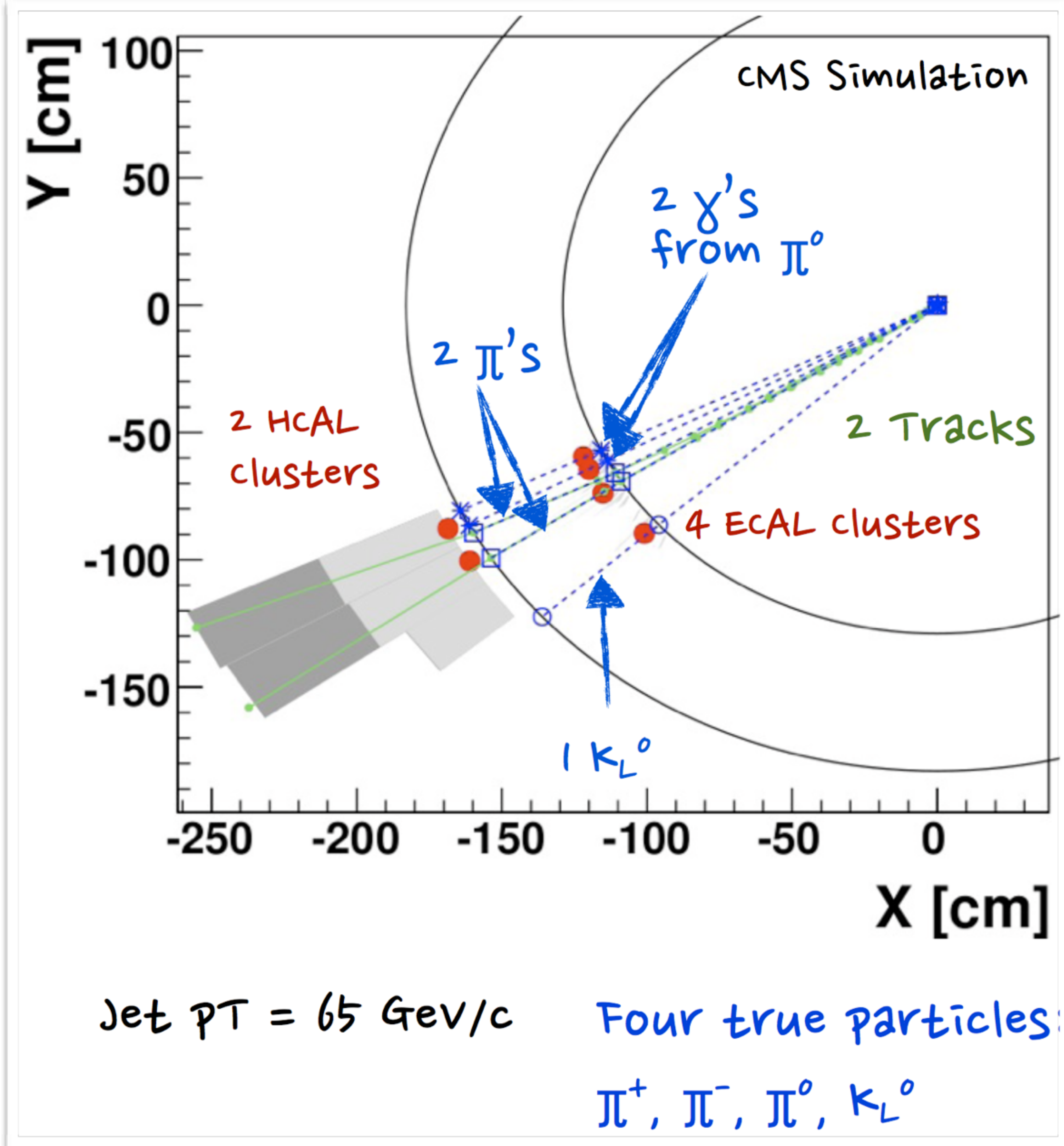
Particle flow approach

BASICS:

- "Flow of particles" through the detector.
- Reconstruct and identify all individual particles
- Combination of sub-detector info for measuring E, η, φ, ID.

IMPORTANT ASPECTS:

- High precision, and high efficiency tracking;
- Large magnetic field for good p_T resolution and charged-to -neutral particle separation;
- Highly granular calorimeter



PART I: From hadron collisions to the data abstraction

PART II
Data analysis and extraction of physics information

Physics/data analysis (I)

MAIN GOAL:

- **Learn about the nature** by extracting physics information from data

IMPORTANT ASPECTS:

- **Use particle physics principles** to explore interesting phenomena in data
- **Use statistics** for presentation and interpretation (explanation) of data
  - **Descriptive statistics:**
    Describes the main features of a collection of data in quantitative terms
  - **Inductive statistics:** Makes inference about a random process from its observed behavior during a finite period of time

Physics/data analysis (2)

CONFIRMATORY AND EXPLORATORY DATA ANALYSIS:

- Confirmatory analysis - **statistical hypothesis testing**:
  A method of making statistical decisions using experimental data,
  (**Frequentist** hypothesis testing & **Bayesian** inference).
- Exploratory analysis - uses data to suggest hypothesis to test:
  Complements confirmatory data analysis.

QUANTITATIVE AND GRAPHICAL TECHNIQUES:

- Quantitative techniques - yield **numeric / tabular output**:
  (point estimation, interval estimation, hypothesis testing, etc.),
- Graphical techniques - **gain insight in data set**, finding structures in data,
  checking assumptions on statistical models, communicate results in convincing way,
  (Includes: graphs, histograms, scatter plots, probability plots, residual plots, etc.).

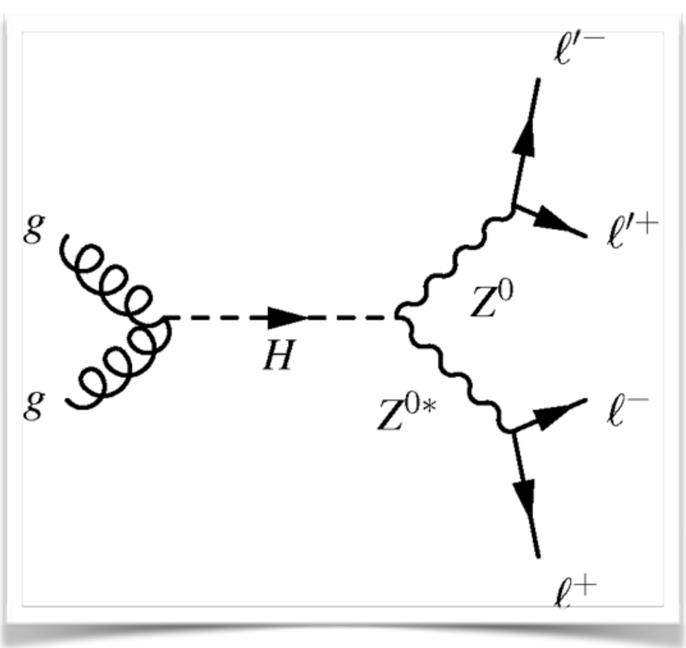
Signal vs. background processes

SIGNAL AND BACKGROUND:

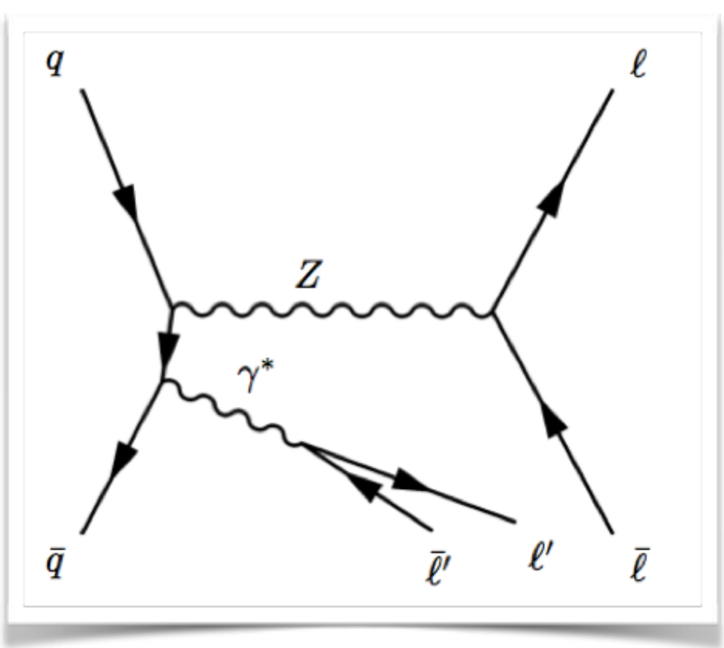
- **Signal:** an event coming from the physical process under study
- **Background:** any other event
  - "Dangerous": events that after reconstruction have final state topology as signal
    Irreducible - intrinsically the same final state as the signal
    Reducible / instrumental - events with mis-reconstructed objects in final state (e.g. parts of jets reconstructed as electrons)

EXAMPLE PROCESS: $pp \rightarrow H \rightarrow ZZ \rightarrow 4\ell$

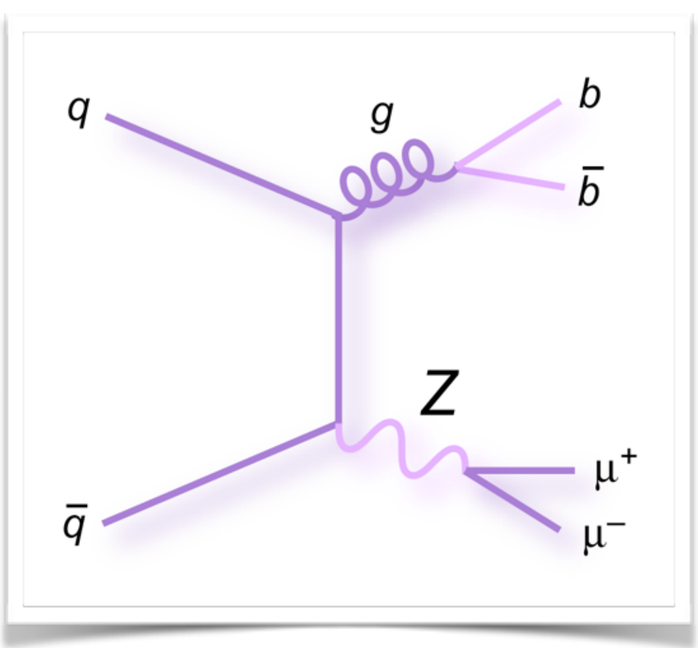
Signal



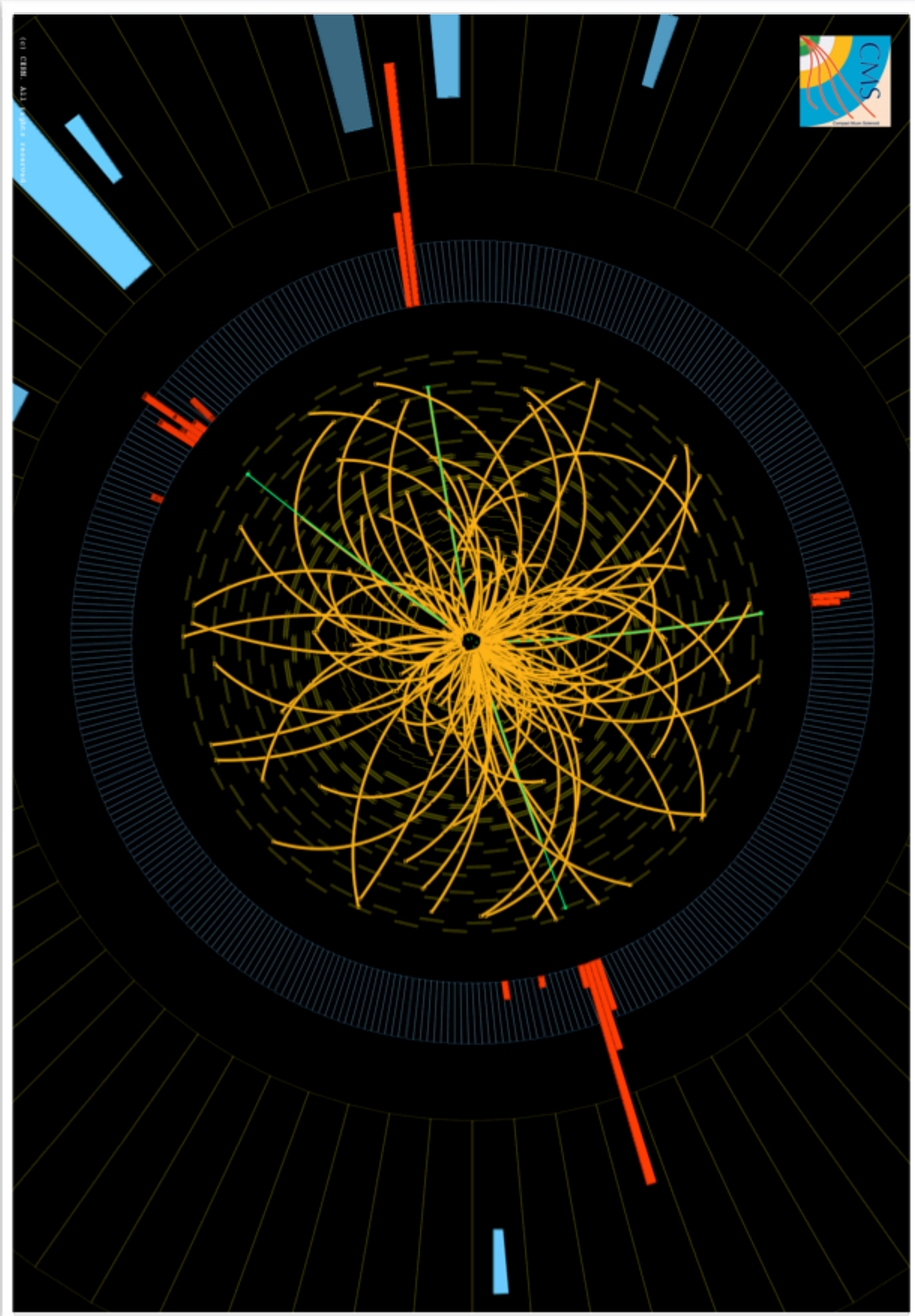
Irreducible background

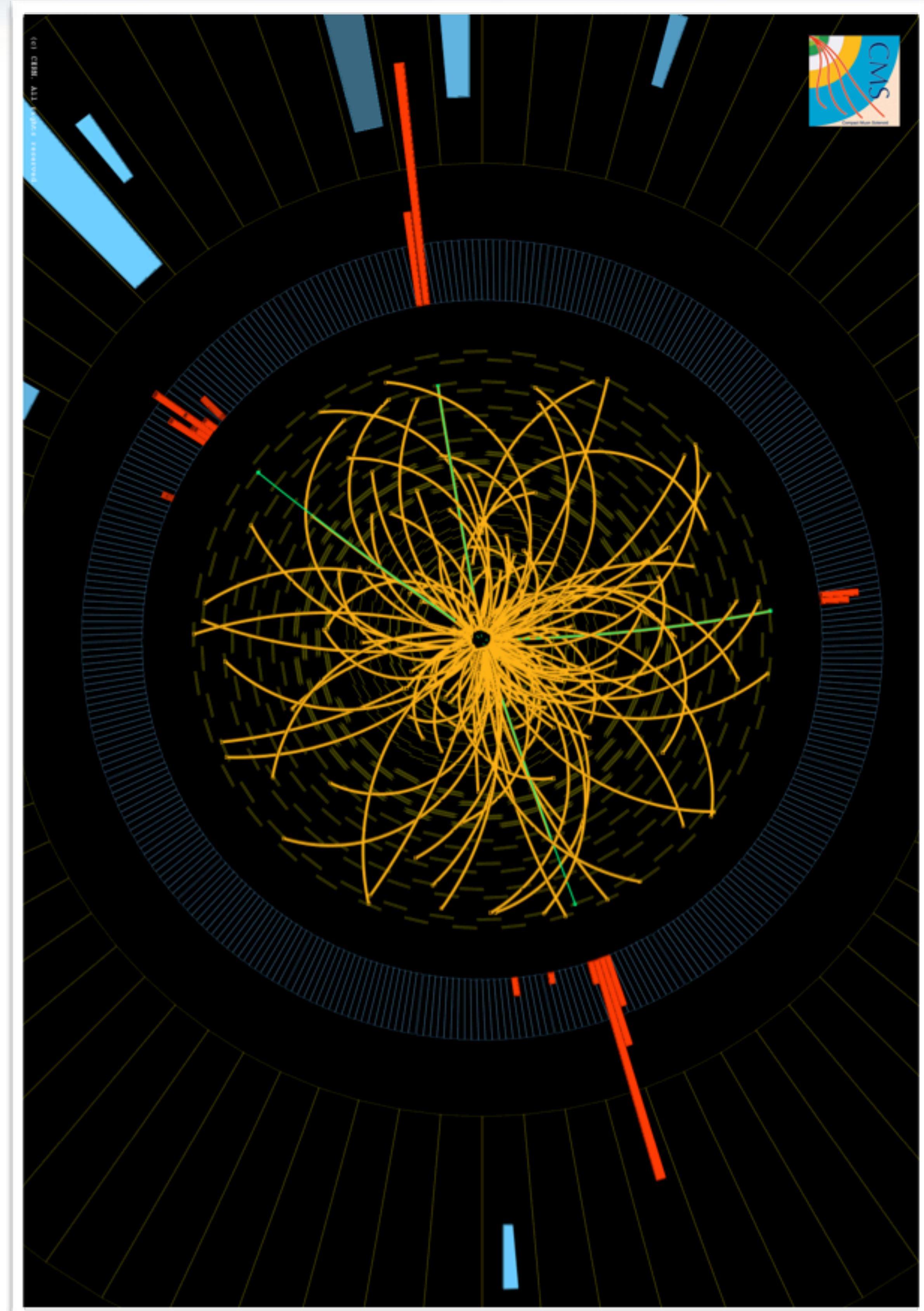


Instrumental background



Signal? or background?





Signal vs. background processes (2)

ULTIMATE GOAL:

- **Use physics principles** to separate signal from background (as much as possible), **$H \rightarrow ZZ \rightarrow 4\ell$ example**: require at least 4 reconstructed leptons with high p_T, etc.
- **Typically obtained in a chain of several steps**

Trigger → **Skimming & pre-selection** → **Selection**

IMPORTANT ASPECTS:

- **Nature & observations are non-deterministic**:
  For a given event it is not possible to tell whether it's signal or background!
- Assign probabilities that the observed event comes from signal or background
  p(event|signal) and **p(event|background)**

Important examples in PART III:

- Estimation of reducible background from data,
- Separation of irreducible background from signal.

EXAMPLE: HISTOGRAM FITTING:

Physicists		Statisticians
1. Determining the "best fit" parameters of a curve	⇔	1. Point estimation
2. Determining the errors on the parameters	⇔	2. Confidence interval estimation
3. Judging the goodness of a fit	⇔	3. Goodness-of-fit (hypothesis) testing

Physicists & statisticians : illustrative comparison

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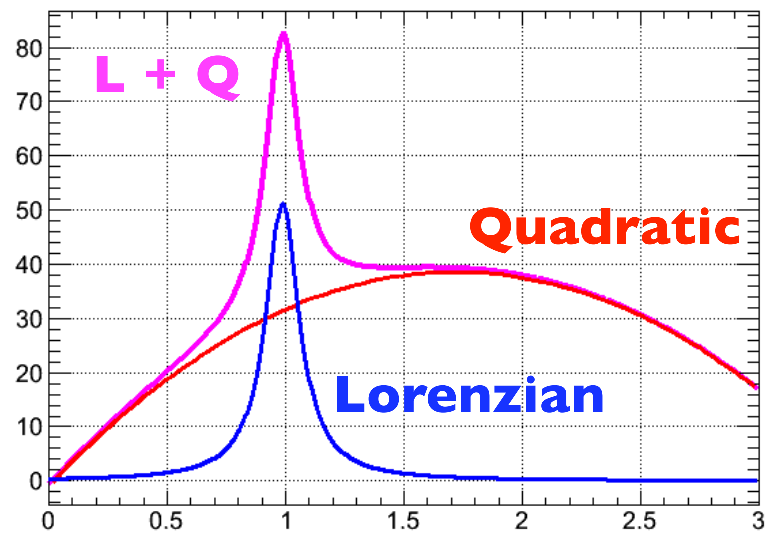
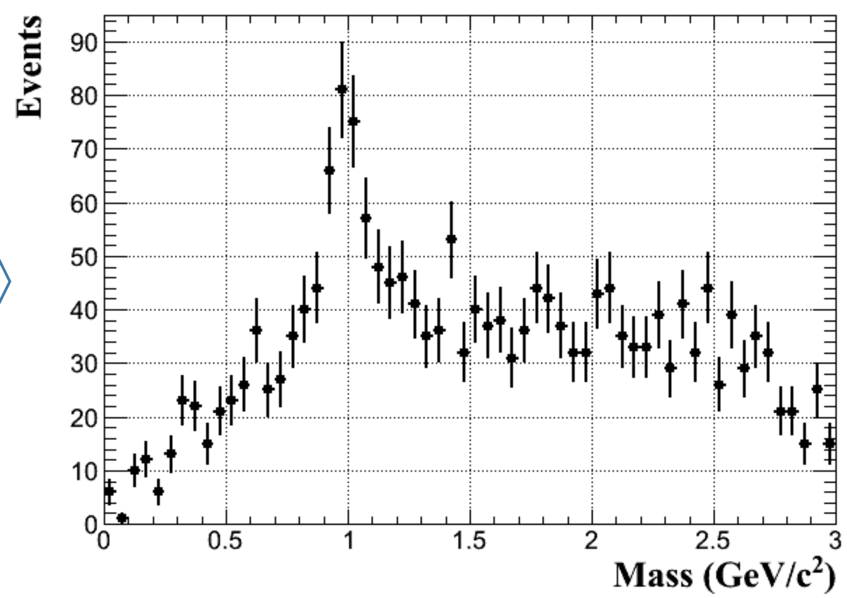
Parameter/point estimation

- **Physical phenomena:** described by a function that depends on *p* **uknown** parameters with **true values:** $\boldsymbol{\theta}^{true} = (\theta_1^{true}, \theta_2^{true}, \ldots, \theta_p^{true})$
- **Goal:** Estimate the true values of the parameters: θ_i^{true} (estimators: $\hat{\theta}_i$)
- **EXAMPLE:** Sampling the reality & estimating parameters

Physical phenomena



Data sample



$$Lorenzian = L(x; D, \Gamma, M) \sim \frac{D\Gamma}{(x^2 - M^2)^2 + 0.25\Gamma^2}$$

$$Quadratic = Q(x; A, B, C) \sim A + Bx + Cx^2$$

- Find the function that describes the measurements the best

$$F(x; D, \Gamma, M, A, B, C) = L(x; D, \Gamma, M) + Q(x; A, B, C) = F(x; \theta)$$

Parameter/point estimation

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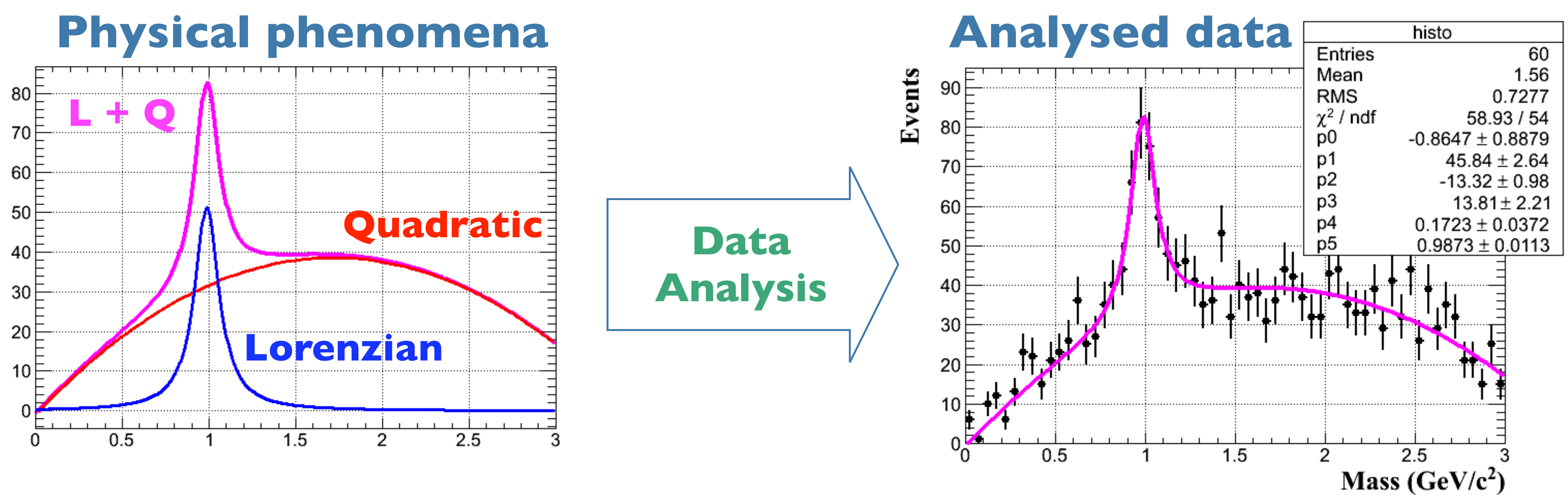

- Find the function that describes the measurements the best
- The parameters of that function are estimators of the uknown parameters

$$F(x;\hat{D},\hat{\Gamma},\hat{M},\hat{A},\hat{B},\hat{C}) = L(x;\hat{D},\hat{\Gamma},\hat{M}) + Q(x;\hat{A},\hat{B},\hat{C}) = F(x;\hat{\theta})$$

Parameter/point estimation

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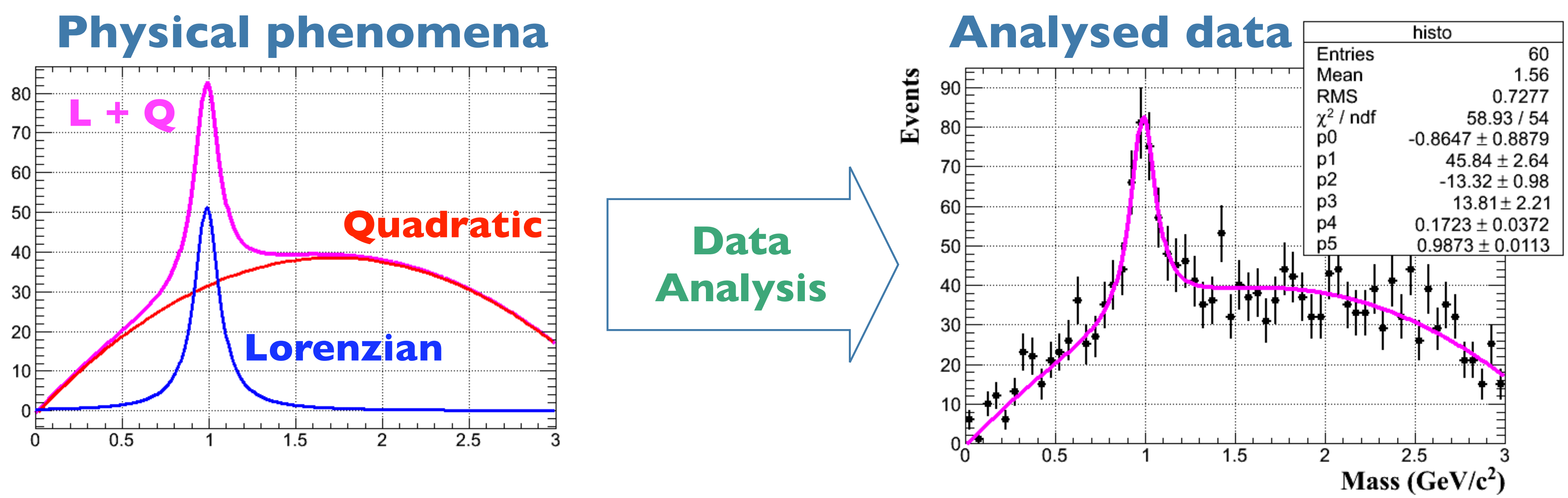

- Find the **function** that describes the measurements the best
- The parameters of that **function** are **estimators of the uknown parameters**

$$F(x;\hat{D},\hat{\Gamma},\hat{M},\hat{A},\hat{B},\hat{C}) = L(x;\hat{D},\hat{\Gamma},\hat{M}) + Q(x;\hat{A},\hat{B},\hat{C}) = F(x;\hat{\theta})$$

- **Methods**: **Maximum Likelihood**, **Least Squares**, **Method of Moments**, etc.

Physicists & statisticians : illustrative comparison

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Parameter error (confidence interval) estimation

Confidence intervals[7]

For a Gaussian estimator the result of an experiment is usually expressed by

- The parameter's estimated value, plus/minus an estimate of the **standard deviation**, $\hat{\theta} \pm \sigma_{\hat{\theta}}$

If the pdf is not Gaussian, or in the presence of physical boundaries

- One usually quotes instead an **interval**.

The quoted interval or limit should:

- Objectively communicate the result of the experiment,
- **Communicate incorporated prior beliefs** and relevant assumptions,
- Provide interval that covers the true value of the θ with specified probability,
- Make possible to draw conclusions about the parameter.

These goals are satisfied in **case of large data sample** by $\hat{\theta} \pm \sigma_{\hat{\theta}}$, and in the multi-parameter case by

- The parameter estimates and covariance matrix.

For **small data sample**, or in case of constrained variables, the Bayesian or the Neyman approach can be used.

[7] Adapted from Particle Data Group.

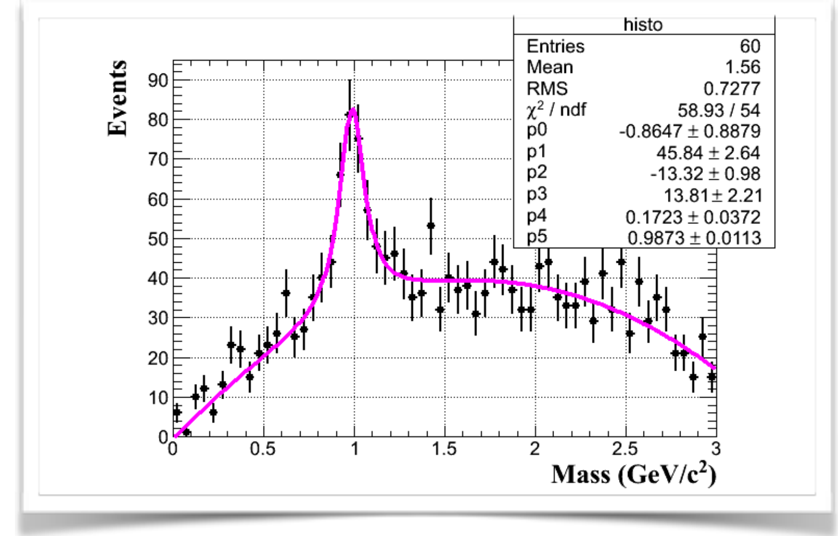
Errors on the Maximum Likelihood estimates

ML parameter errors:

Can be extracted from the shape of the likelihood function around its maximum

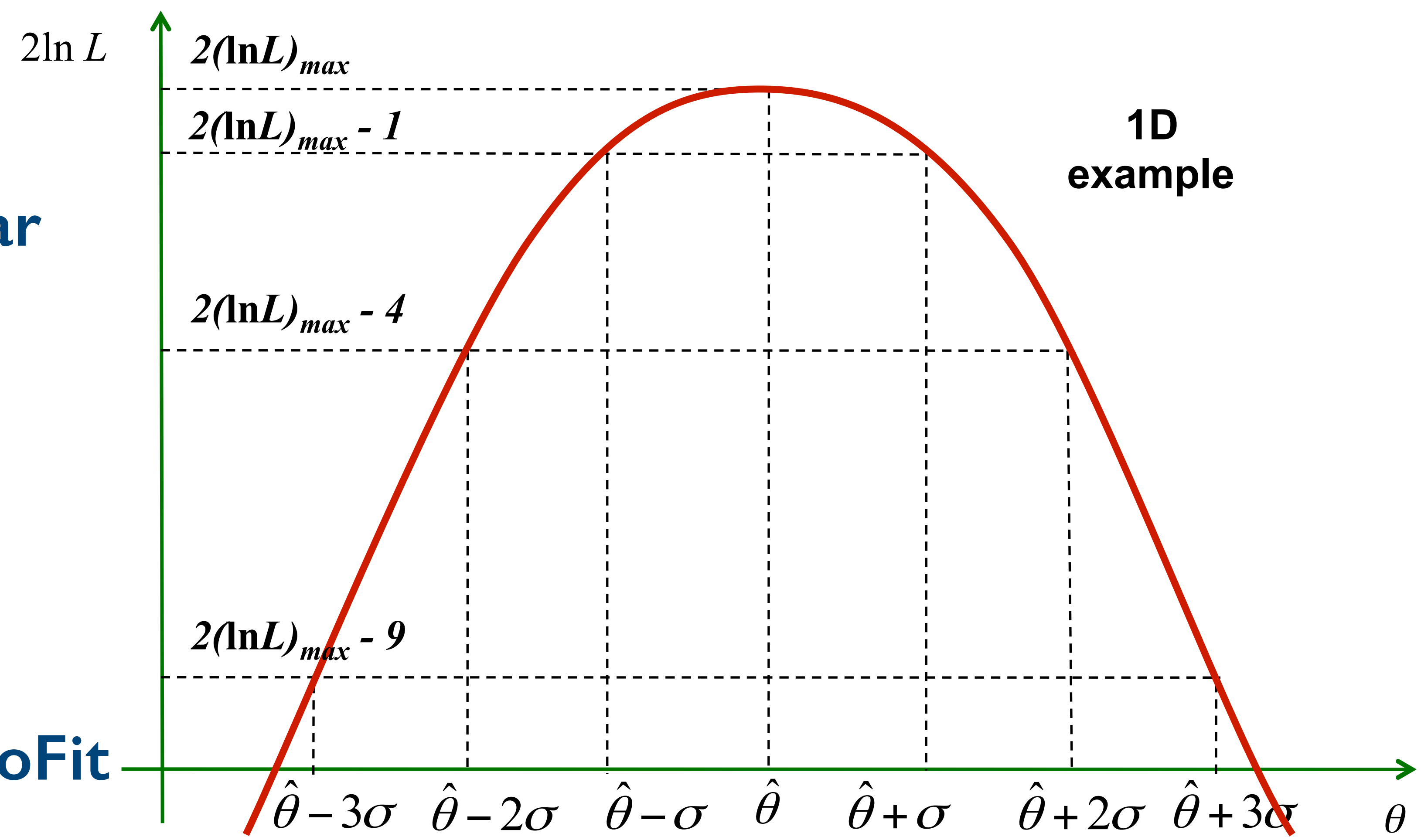
- In the large N limits 1D likelihood function is Gaussian, and the *ln$\mathcal{L}$* is paraboloid (χ^2 with 1 d.o.f.)
- **1D Interval ±1σ** are extracted as values for which 2*ln$\mathcal{L}$* falls by 1 from its maximum value **(*ln$\mathcal{L}$*)$_{max}$**

Example



Important aspects:

- For **finite samples** or **non-linear** problems *ln$\mathcal{L}$* is **asymmetric**
- In case of **P** parameters, ***ln$\mathcal{L}$*** asymptotically behaves as χ^2 with **P** d.o.f.
- Can be computed using **MINUIT/MINOS** in **ROOT/RooFit**



Uncertainty in physics measurements

The sources of uncertainty in measurement[9]:

- **Incomplete definition** of the measurand; or its imperfect realization
- **Non-representative sampling**
- inadequate knowledge of the effects of environmental conditions; or imperfect measurements of these conditions
- **Personal bias** in reading instruments
- **Finite instrument resolution**
- Inexact values of measurement standards and reference materials
- **Inexact values of constants** and other parameters obtained from external sources and used in the data-reduction algorithm
- **Approximations and assumptions** incorporated in the measurement procedure
- **Variations of repeated observations** of the measurand under apparently identical conditions

[9] Adapted from the The International Organization for Standardization (ISO) Guide to the Expression of Uncertainty in Measurement.

Optimal presentation of search results

Optimal presentation of search results has some desired properties[10]:

- **Uncertainties due to systematic effects should be included in a clear and consistent way.**
  - Often it is useful to quote the statistical and systematical error separately, e.g. $\sigma = 45 \pm 4 \pm 1 \ mb$.
- The result should summarize completely the experiment; so that no extra information should be required for further analysis.
- Results should be easily turned into probabilistic statements.
- Analysis should be transparent, and result should be stated in such a way that it cannot be misleading. The presentation of the result should not depend on the particular application.
- **If possible full pdf-distributions and even data sets can be attached into analysis results**.
- In **unified approach to data analysis**, the transitions between exclusion, observation, discovery, and measurement are kept as small as possible.

[10] Adapted from F. James, *Workshop on Confidence Limits*, CERN-2000-005, 2000.

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EXAMPLE: HISTOGRAM FITTING:

Physicists		Statisticians
1. Determining the "best fit" parameters of a curve	⟺	1. Point estimation
2. Determining the errors on the parameters	⟺	2. Confidence interval estimation
3. Judging the goodness of a fit	⟺	3. Goodness-of-fit (hypothesis) testing

discussed later, see references for more info

PART II: Data analysis and extraction of physics information

PART III
Selected topics on the physics measurements

PART III
Selected topics on the physics measurements

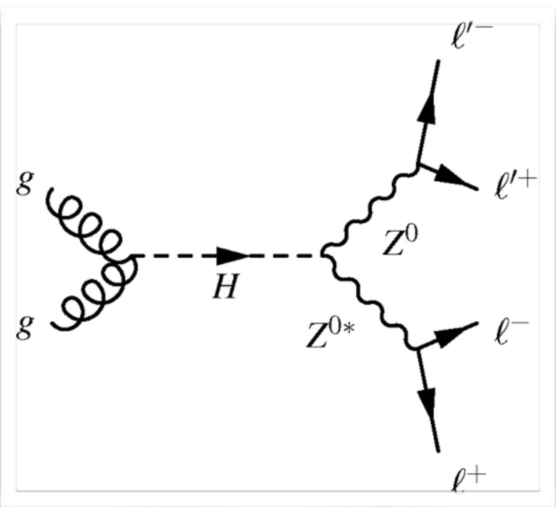
- Estimation of reducible background processes using data
- Matrix Element Method for discrimination between processes
- Exploitation of interference effects in particle physics
- Measurement of fiducial cross sections

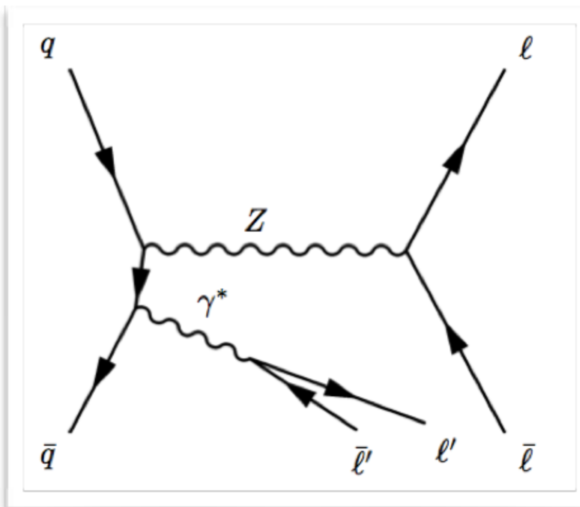
Examples based on process: $pp \to H \to ZZ \to 4\ell$

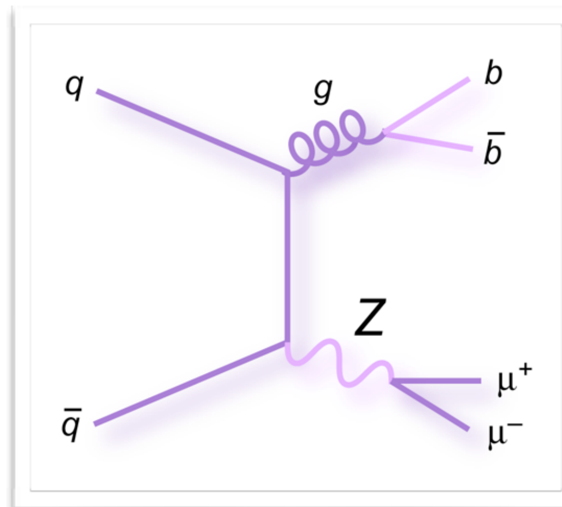
$H \rightarrow ZZ \rightarrow 4\ell$

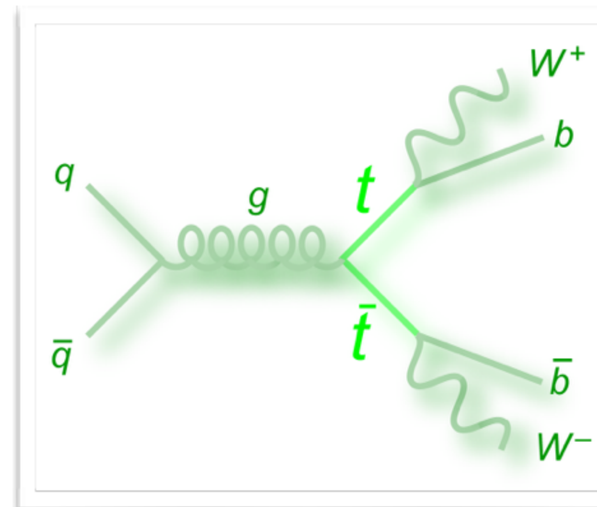
- Benefits from fully reconstructible decay with excellent mass resolution (1-2%)

Signal process | **Irreducible background** | **Instrumental backgrounds**



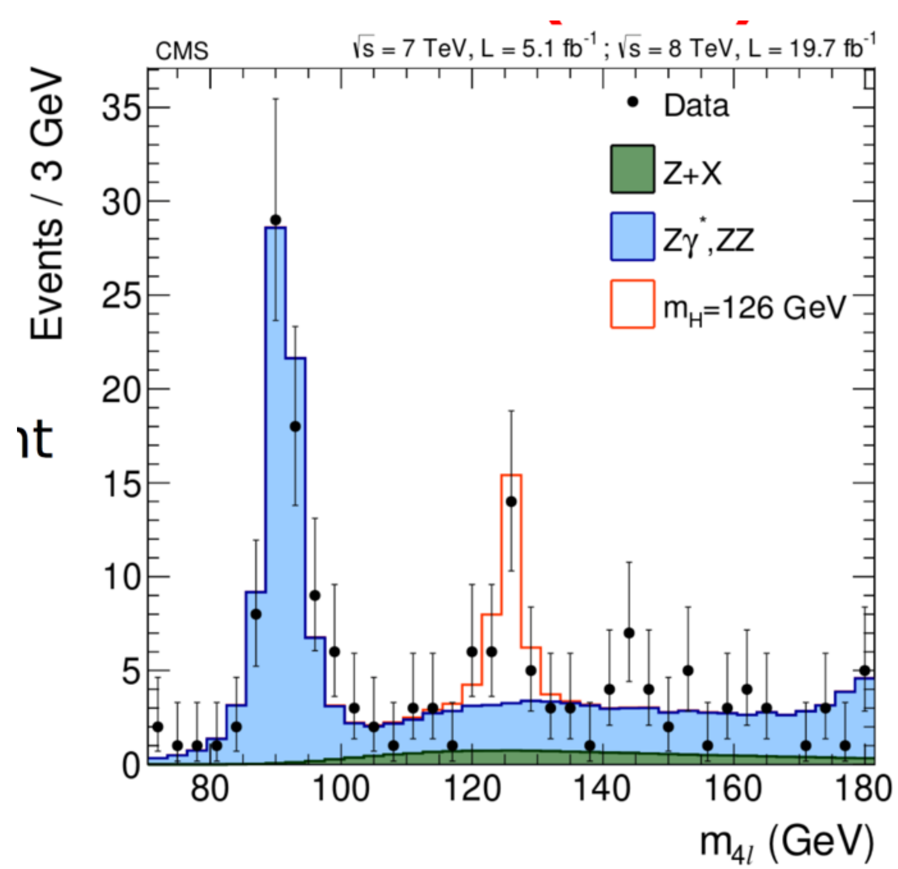




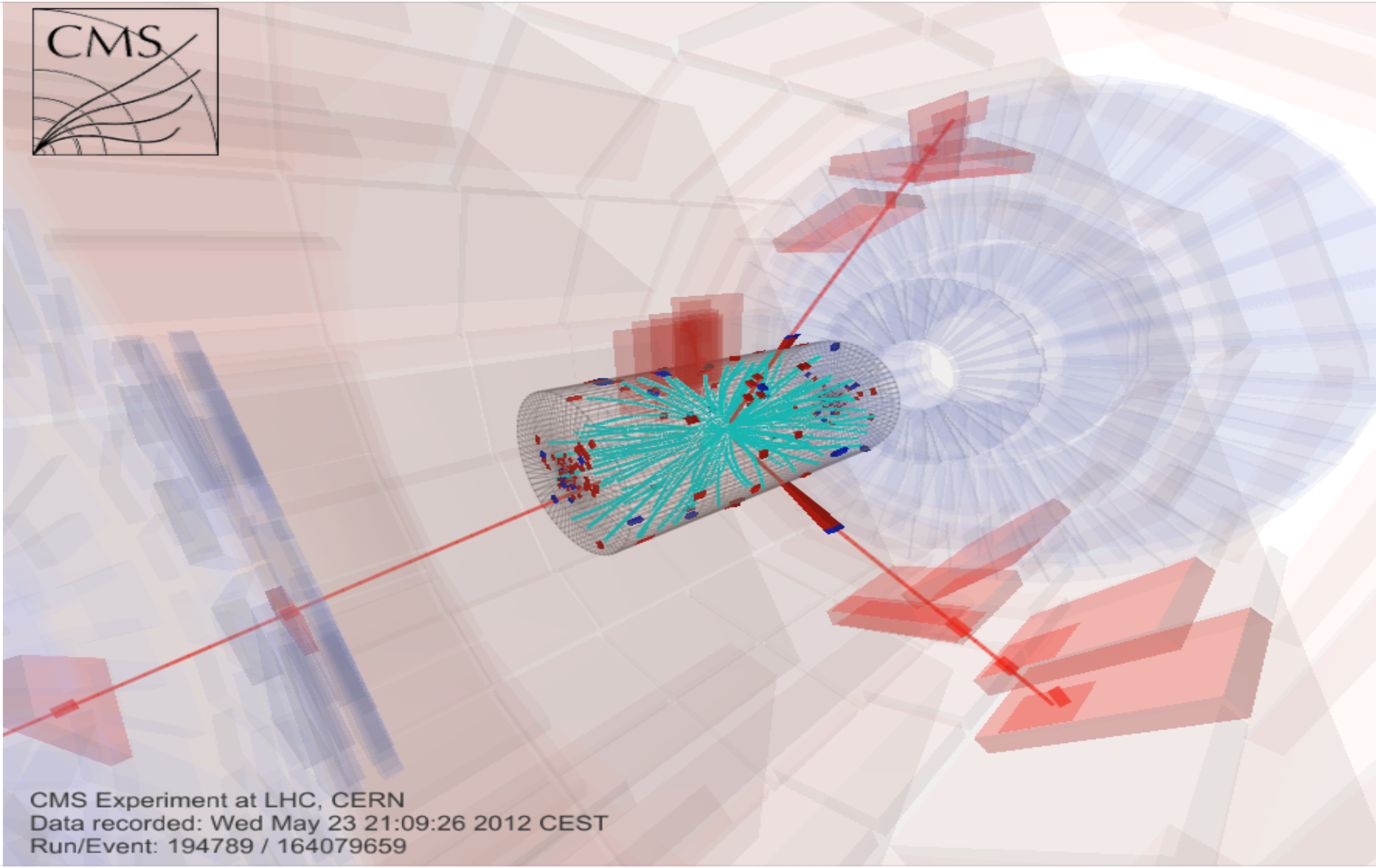


IMPORTANT CHARACTERISTICS:

- **Very small branching fraction** (~0.01%), but **very clean signature**
- About **15-20 reconstructed signal events** expected after selection (8 TeV Run I)
- **Very small background** from irreducible pp→ZZ and reducible Z+jets.



Event display : $H \to ZZ \to 4\ell$



Estimation of reducible backgrounds using data

Estimation of reducible background

REDUCIBLE BACKGROUND FOR H → ZZ → 4ℓ:

- **Events with non-prompt leptons** (do not originate from the hard scattering)
  - **misidentified / fake leptons** (parts of jets, leptons from meson decays)

Estimation of reducible background

REDUCIBLE BACKGROUND FOR H → ZZ → 4ℓ:

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  - **misidentified / fake leptons** (parts of jets, leptons from meson decays)

Physical reality →

Intrinsic to the physics process

4 prompt	3 prompt, 1 fake	2 prompt, 2 fake
(true ZZ → 4ℓ)	(Z + γ/W + jets)	(Z + jets, ttbar)

Estimation of reducible background

REDUCIBLE BACKGROUND FOR H → ZZ → 4ℓ:

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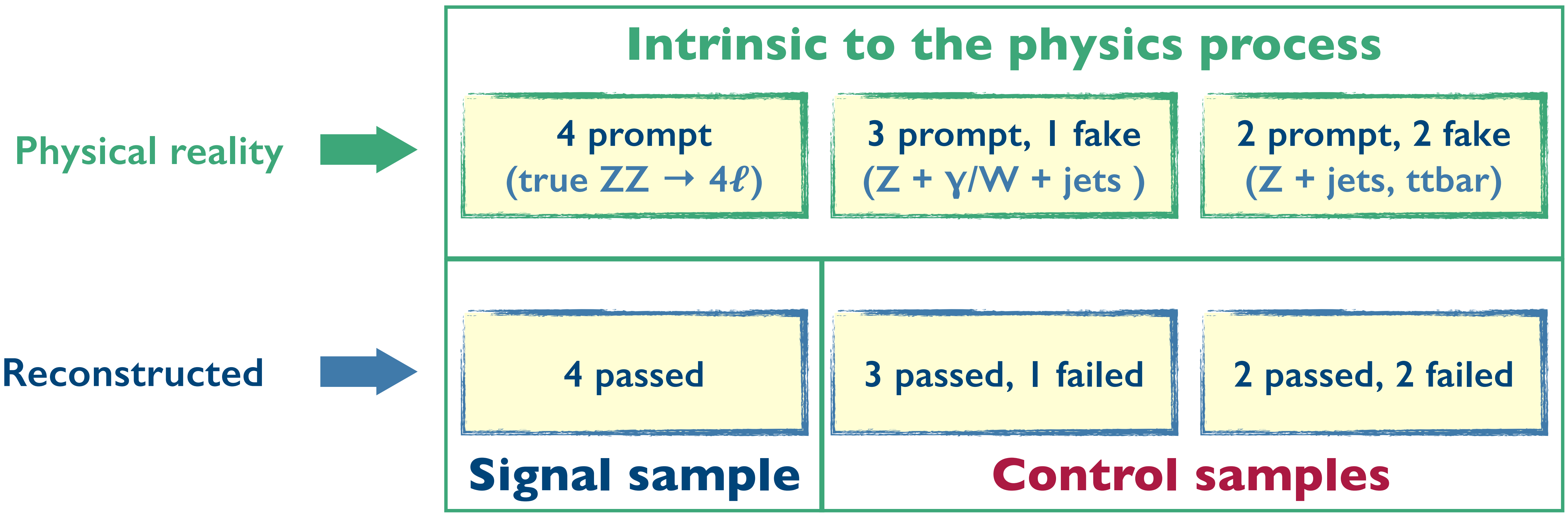
  - misidentified / fake leptons (parts of jets, leptons from meson decays)



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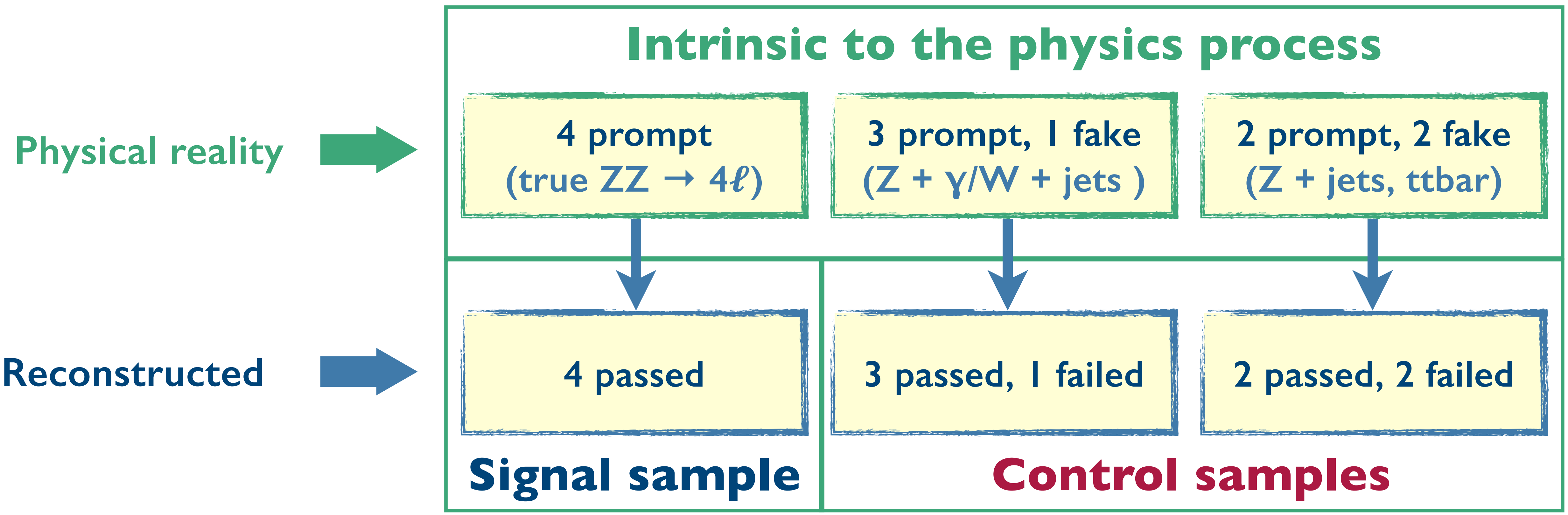

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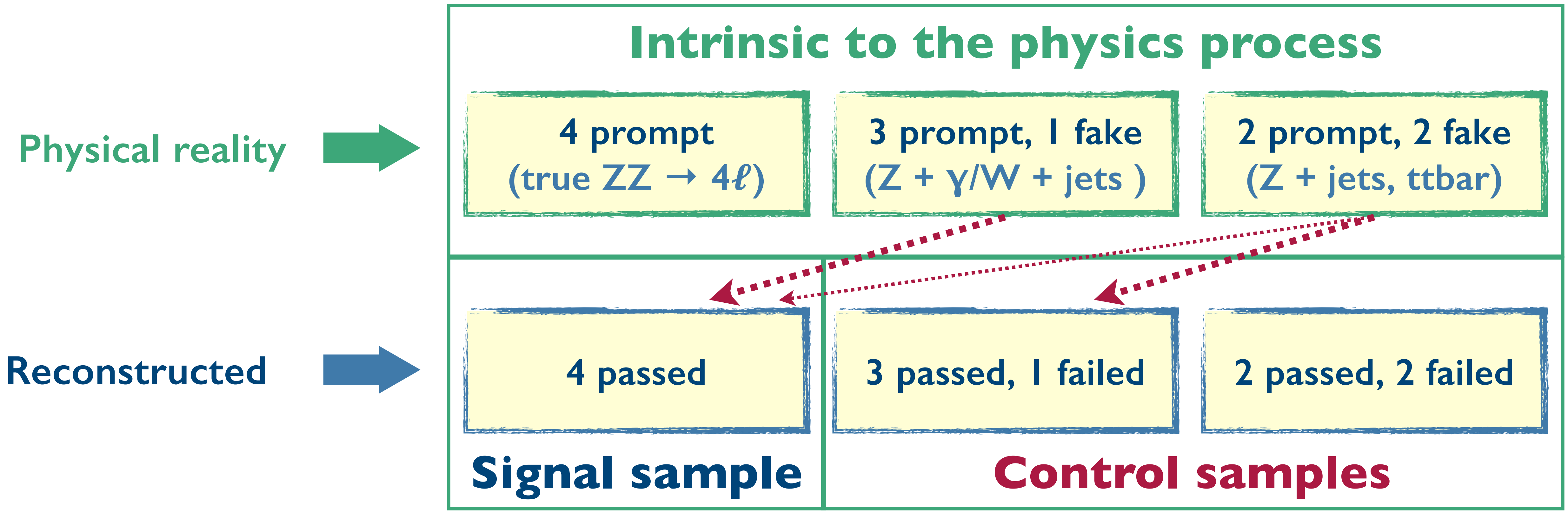

Estimation of reducible background

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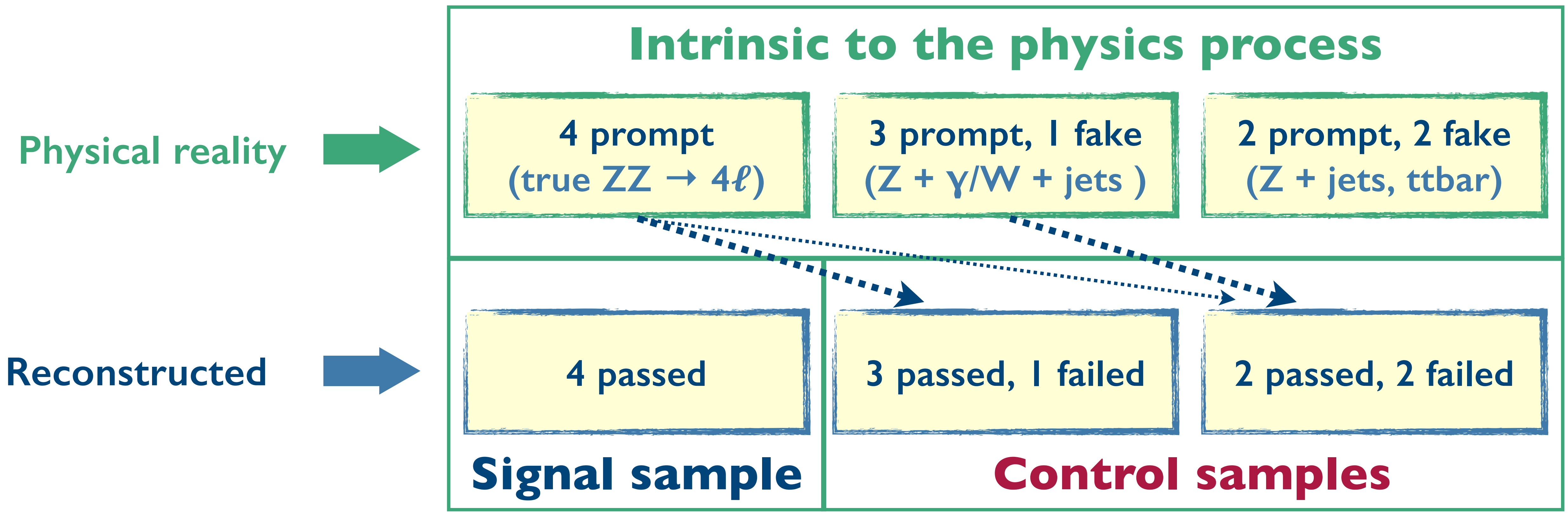

Estimation of reducible background

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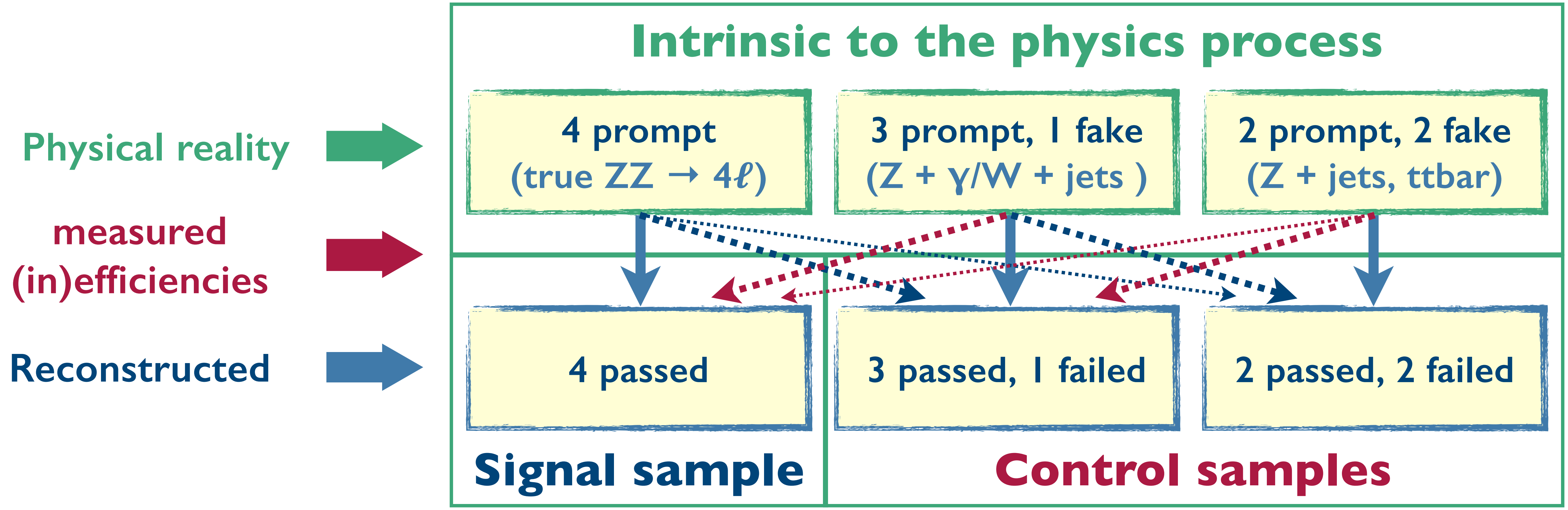


APPROACH:

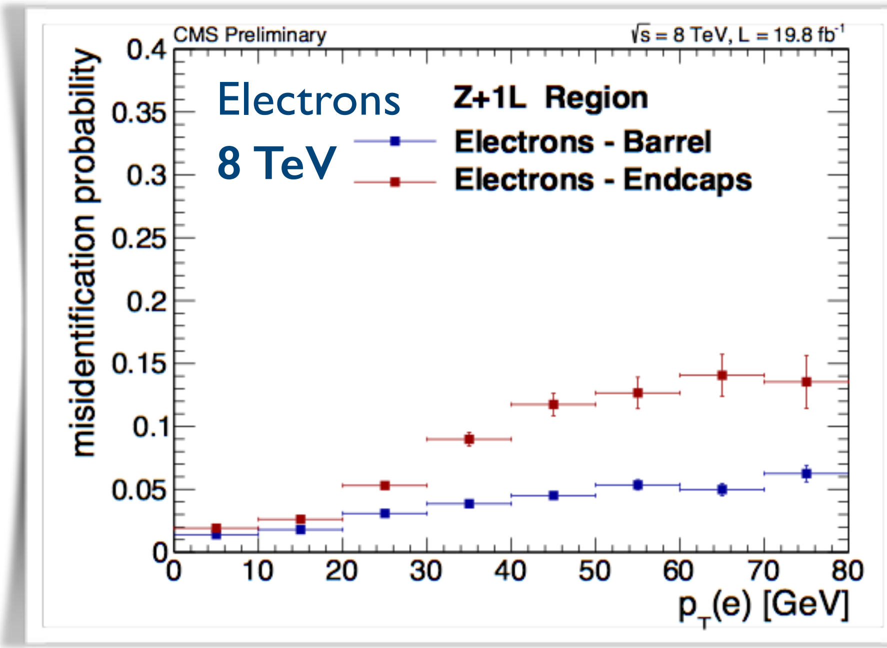
- Estimated from data control samples enriched with misidentified leptons
- Using the probabilities to misidentify a lepton ("fake ratios", measured in data)

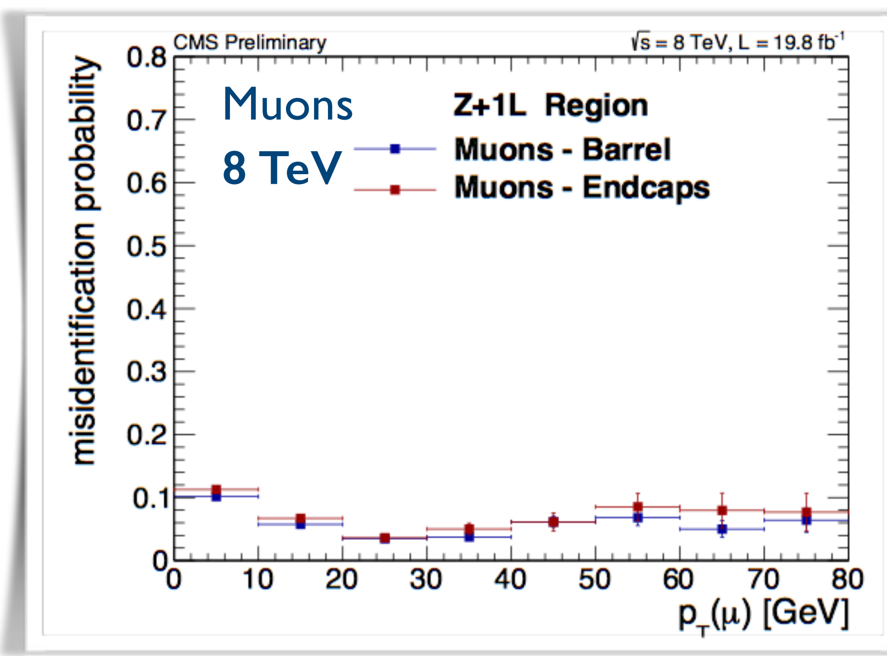
Misidentification probabilities

The fake lepton ratios (f_{μ} , f_e) are measured in sample **Z + 1 loose lepton (Z+1ℓ)**

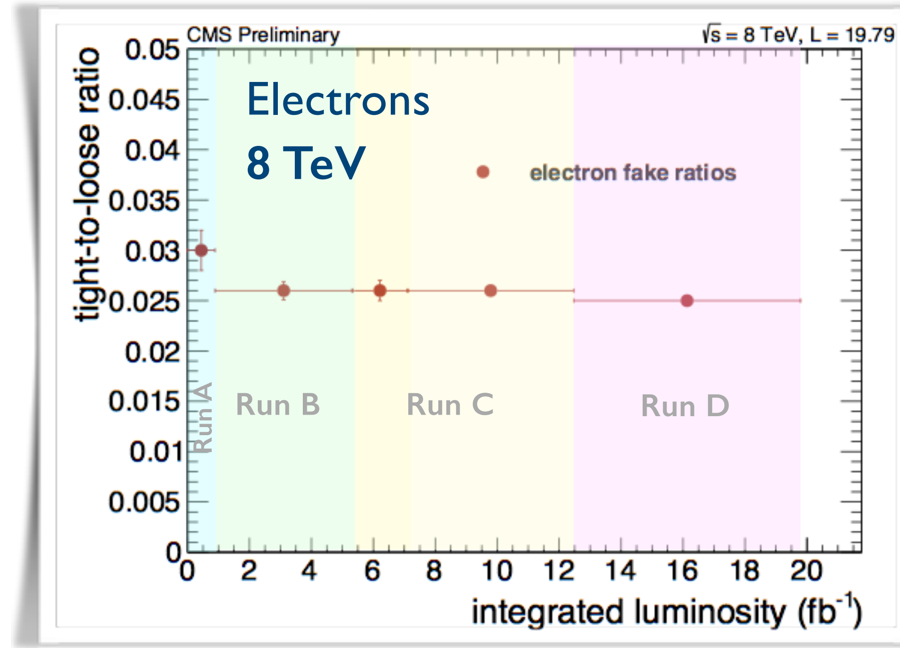
- Loose leptons - “analysis selection” leptons with relaxed ID and removed isolation requirements,
- Biases from prompt leptons (Zγ*, ttbar) suppressed by $|m_{2l} - m_Z|$ **< 10 GeV** and **miss.** E_T **< 25 GeV**

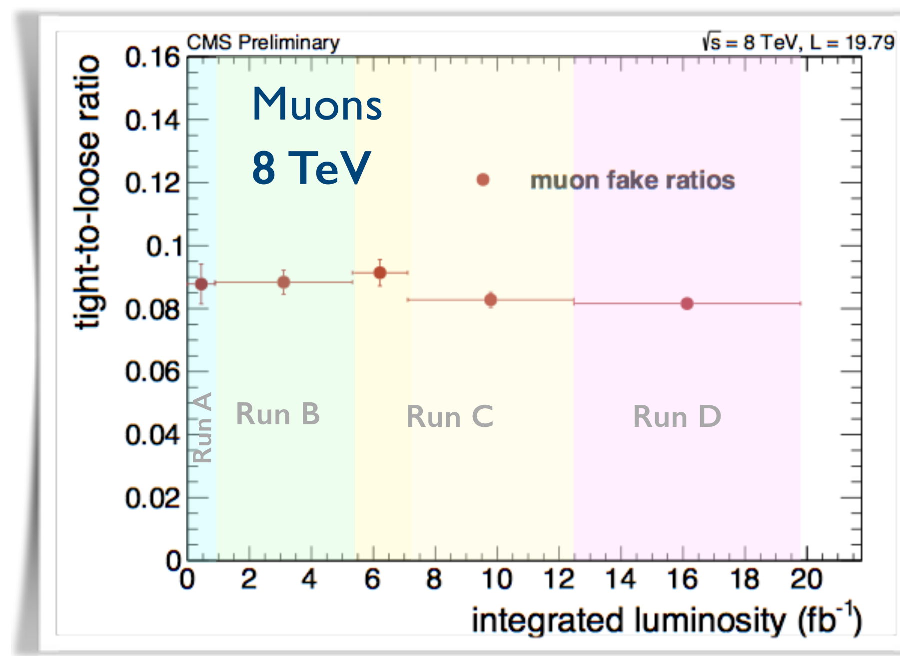
p_T dependance





stability vs. data taking





Estimation of reducible background

REDUCIBLE BACKGROUND FOR H → ZZ → 4ℓ:

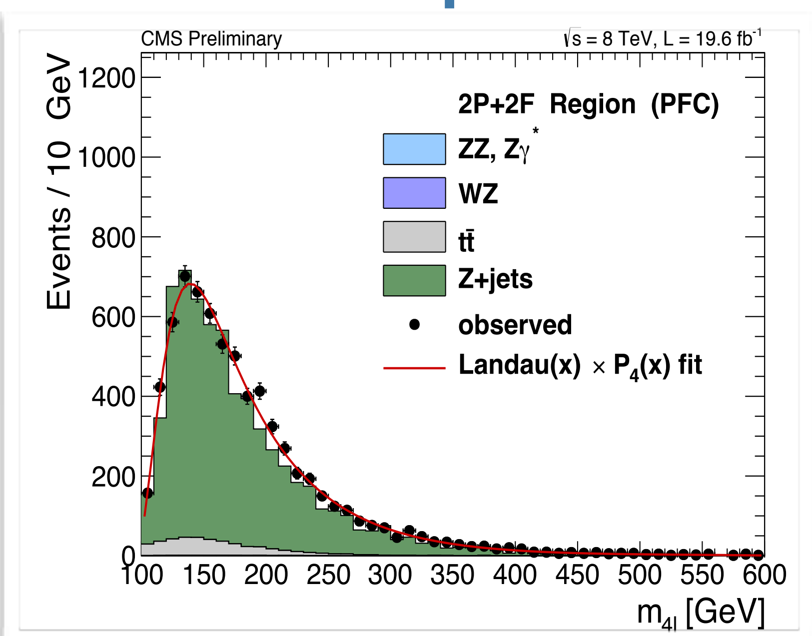
- Solve the system of linear equations (using measured "fake rates"):

(symbolic)

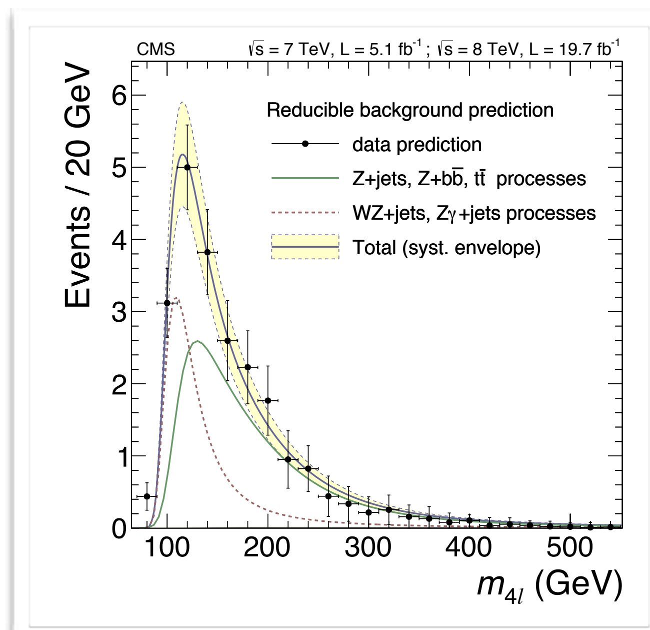
$$N^{\mathrm{bkg}}_{\mathrm{SR}} = \sum \frac{f_i}{1-f_i}\left(N_{\mathrm{3P1F}} - N^{(\mathrm{from\ 2P2F})}_{\mathrm{3P1F}} - N^{(\mathrm{from\ ZZ})}_{\mathrm{3P1F}}\right) + \sum \frac{f_i}{1-f_i}\frac{f_j}{1-f_j} N_{\mathrm{2P2F}}$$

- Examples of control regions and final estimates:

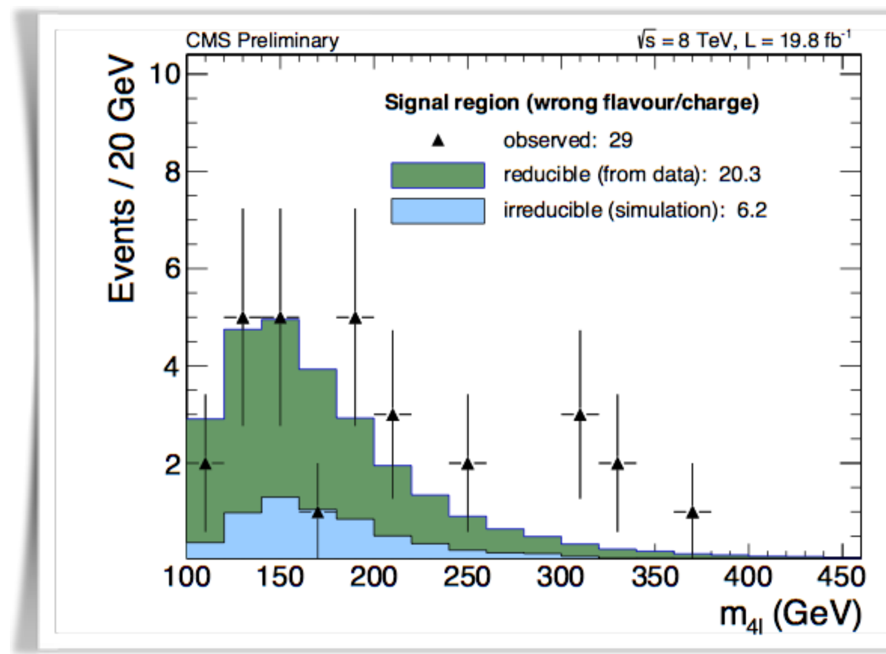
Control sample 2P+2F



Final estimate



Validation in data



- Sources of **systematic uncertainties**:
  - Limited statistics in control regions,
  - Different background composition in region **Z+1ℓ**, and regions **2P+2F** and **3P+1F**
- **Validation in data** using events with "wrong" flavour/charge combination

Estimation of reducible backgrounds using data

To remember…

1. Reducible backgrounds can be estimated from data control samples enriched with misidentified objects by solving set of linear (recursive) equations,
2. Measurement of misidentification probabilities, and systematics need special care.

Matrix Element Method for processes discrimination

Matrix Element Method (MEM)

Matrix element for process X - $|ME(X)|^2$:

- **Probability density** function for event of process **X** to occur **in a given point of phase space**
- **Inverted logic**: **Likelihood** that event observed in a given point of phase space **originates from process X**

Advantages:

- Efficiently uses all available kinematic information
- Greater sensitivity than any other method

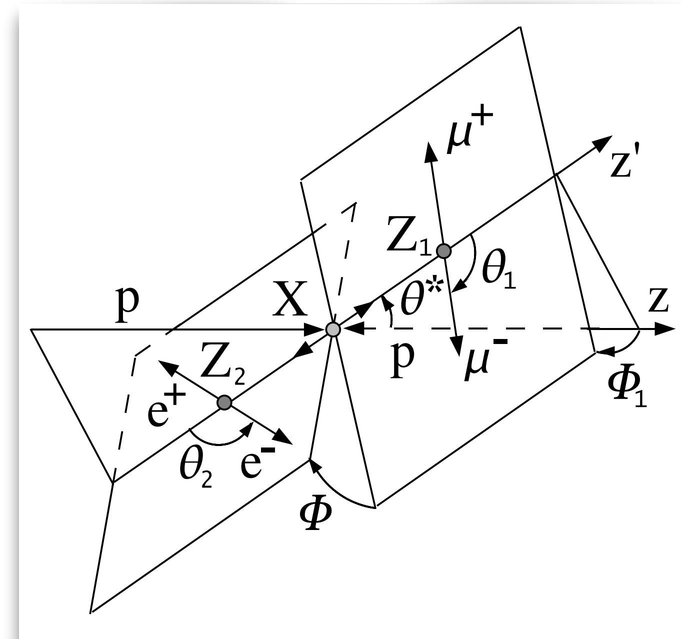
Example:

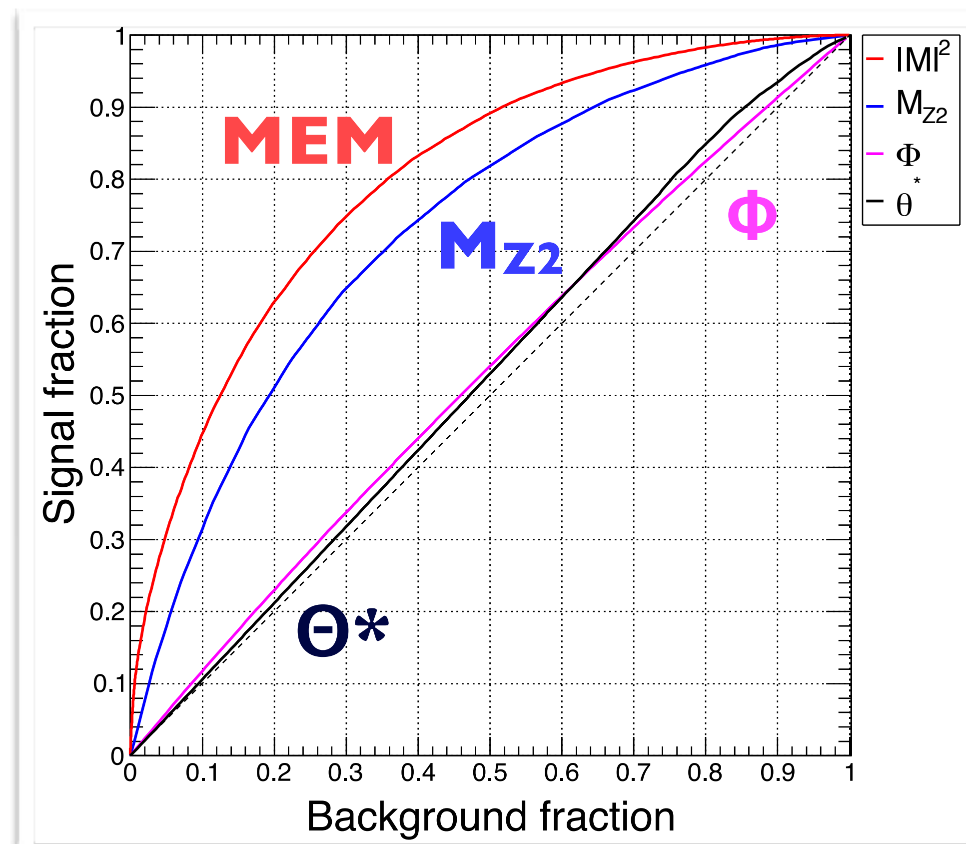
- ROC curves from MEM and 3 analyses using a single variable

Discrimination of processes A & B:

- Maximal discrimination between processes A & B from the ratio of $|ME(A)|^2$ and $|ME(B)|^2$

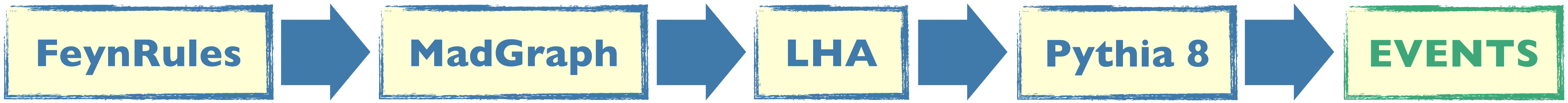
H→ZZ→4l



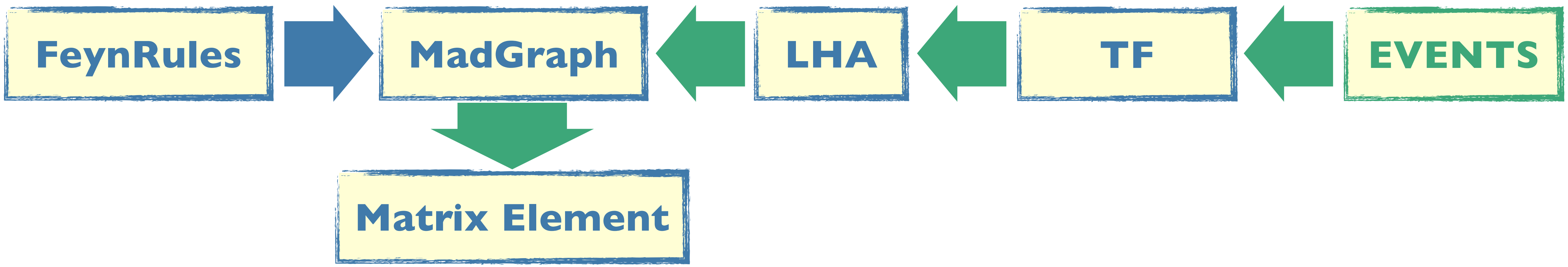


MC Simulation tools - an example:

- From Lagrangians to events:



- From events to ... matrix elements:



- Automatic generation and calculation of matrix elements
- Many MC tools available on the market (**MadGraph**, **MCFM**, **JHUGen**, etc.)

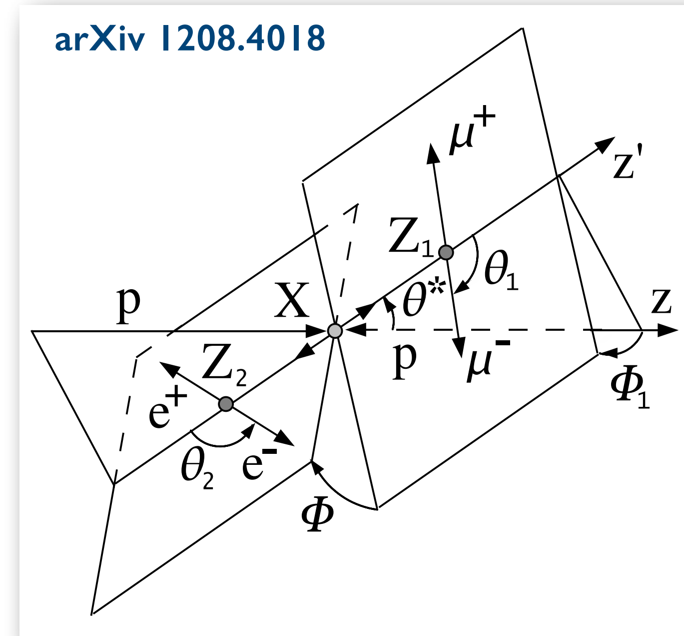
Application:

- Separation of signal and background, and alternative signal hypotheses
- In case of final states with invisible or poorly reconstructed objects (neutrinos, jets) need to take into account detector effects (TF) or integrate out invisible degrees of freedom

H → ZZ → 4l: Kinematic Discriminants

- **Matrix Element Method:** Use ratio of **LO** matrix elements $|ME|^2$ to build discriminants
  - do not use system p_T and rapidity **Y** (NLO effects, PDFs)
  - use the assumption: $m_X = m_{4l}$

Use kinematics of the 4l system



Basic ME-discriminator to separate SM Higgs from backgrounds:

$$KD(\mathrm{H;ZZ}) = \frac{|ME_{\mathrm{H}}(gg \to H \to 4\ell)|^2}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2}$$

Basic ME-discriminator to separate alternative J^P hypothesis from bkg.:

$$KD(J^{CP};\mathrm{ZZ}) = \frac{|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)|^2}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2}$$

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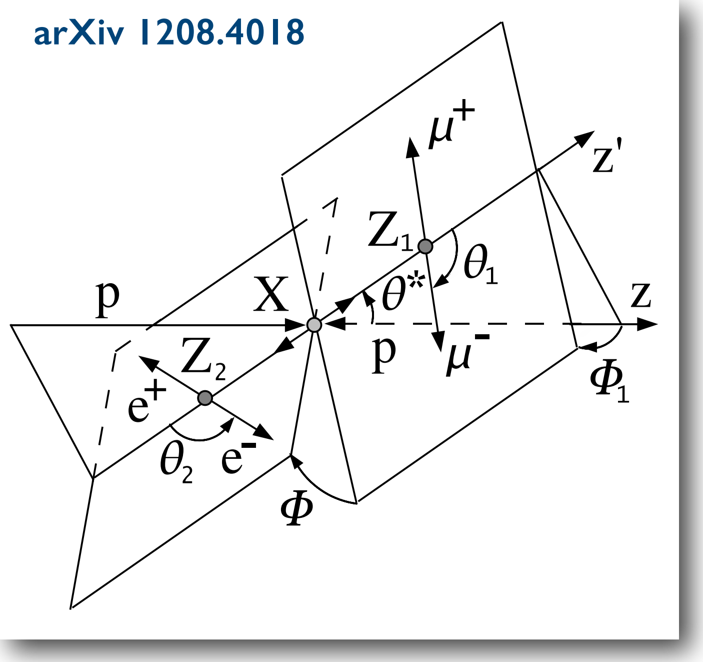

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- Extend discriminators to include the discriminating m_{4l} information:

Extended discriminator to separate SM Higgs from backgrounds:

$$D(H;ZZ) = \frac{|ME_X(xx \to H \to 4\ell)|^2 \cdot pdf(m_{4\ell} \mid m_H)}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2 \cdot pdf(m_{4\ell} \mid ZZ)}$$

Extended discriminator to separate an alternative J^P hypothesis from backgrounds:

$$D(J^{CP};ZZ) = \frac{|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)|^2 \cdot pdf(m_{4\ell} \mid m_{J^{CP}})}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2 \cdot pdf(m_{4\ell} \mid ZZ)}$$

H → ZZ → 4l: Kinematic Discriminants

- **Matrix Element Method:** Use ratio of **LO** matrix elements $|ME|^2$ to build discriminants
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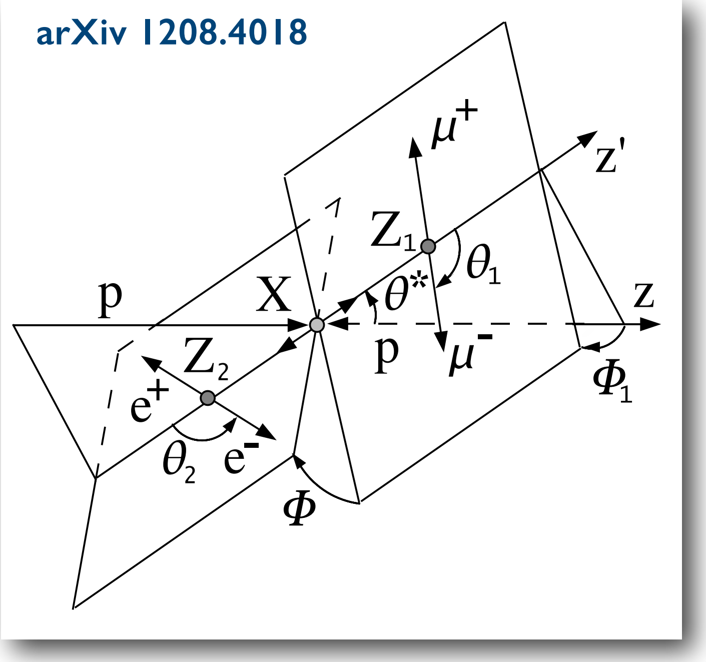

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change the variables (without loss of information) →

$$D(H;ZZ)$$

Extended discriminator to separate an alternative J^P hypothesis from backgrounds:

$$D(J^{CP};ZZ) = \frac{|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)|^2 \cdot pdf(m_{4\ell}\,|\,m_{J^{CP}})}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2 \cdot pdf(m_{4\ell}\,|\,ZZ)}$$

change the variables (without loss of information) →

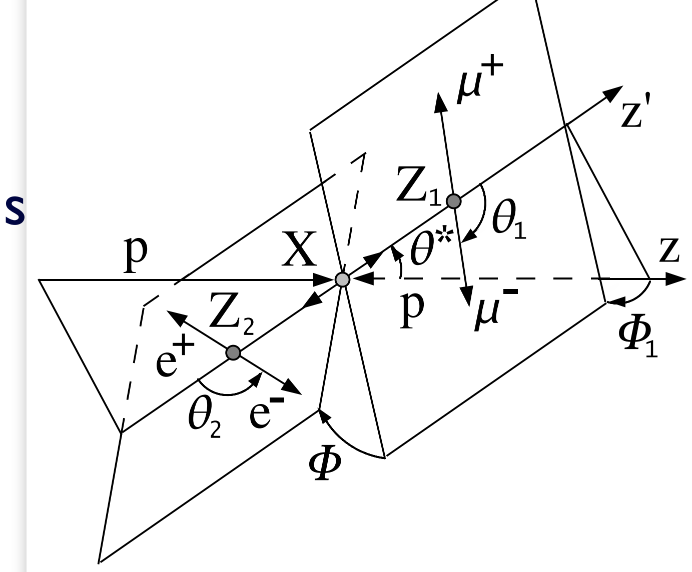
$$D(J^{CP};\mathrm{H}) = \frac{D(\mathrm{J^{CP};ZZ})}{D(\mathrm{H;ZZ})}$$

$H \to ZZ \to 4l$: Kinematic Discriminants

- **Matrix Element Method:** Use ratio of **LO** matrix elements $|ME|^2$ to build discriminants
  - do not use system p_T and rapidity **Y** (NLO effects, PDFs)
  - use the assumption: $m_X = m_{4l}$
  - Final discriminators D_{JCP} and D_{BKG} obtained by compressing $D(J^{CP};H)$ and $D(H;ZZ)$ between 0 and 1:

Use kinematics of the 4l system

arXiv 1208.4018



Discriminator D_{JP} to separate SM Higgs from an alternative J^P hypothesis

$$D_{\mathrm{J^P}} = \left[1 + const. \cdot \frac{|ME_{\mathrm{J^P}}(\vec{p}_i)|^2}{|ME_{\mathrm{H}}(\vec{p}_i)|^2}\right]^{-1}$$

Discriminator D_{BKG} to separate signal(s) from backgrounds:

$$D_{\mathrm{BKG}} = \left[1 + const. \cdot \frac{|ME_{\mathrm{ZZ}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{ZZ})}{|ME_{\mathrm{H}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{H})}\right]^{-1}$$

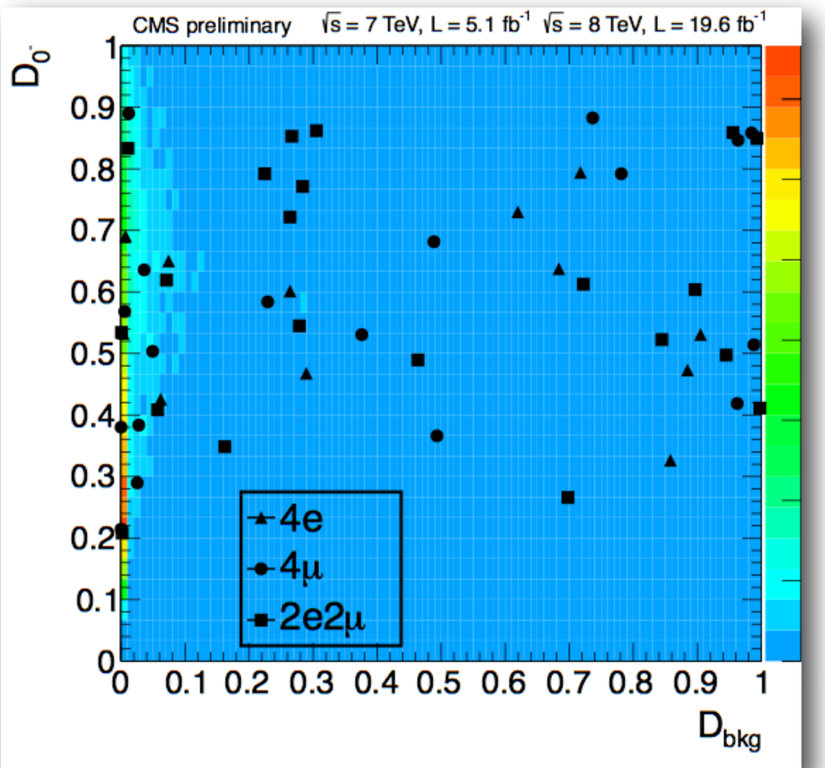
- **LO** MEs are computed using **JHUGen** (signal) and **MCFM** ($qq \to ZZ$) in **MELA** package
- Common subset of MEs validated with **MEKD** (**FeynRules** + **Madgraph**)

REFERENCES: arXiv 1210.0896 , arXiv 1001.3396 , arXiv 1108.2274, arXiv 1208.4018, arXiv 1211.1959

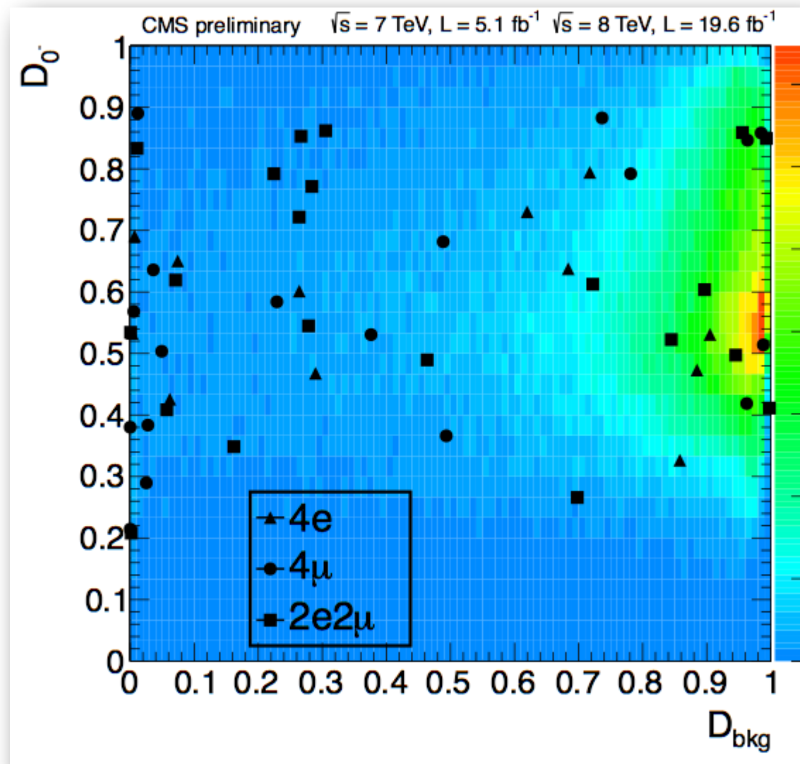
$H \rightarrow ZZ \rightarrow 4l$: Discrimination in ($D_{BKG}$, D_{JP}) plane

- Analysis performed for each alternative J^P hypotheses using 2D templates:
  - SM Higgs, alternative signal, $qq/gg \rightarrow ZZ$ from **simulation**, Z+X from **control region in data**

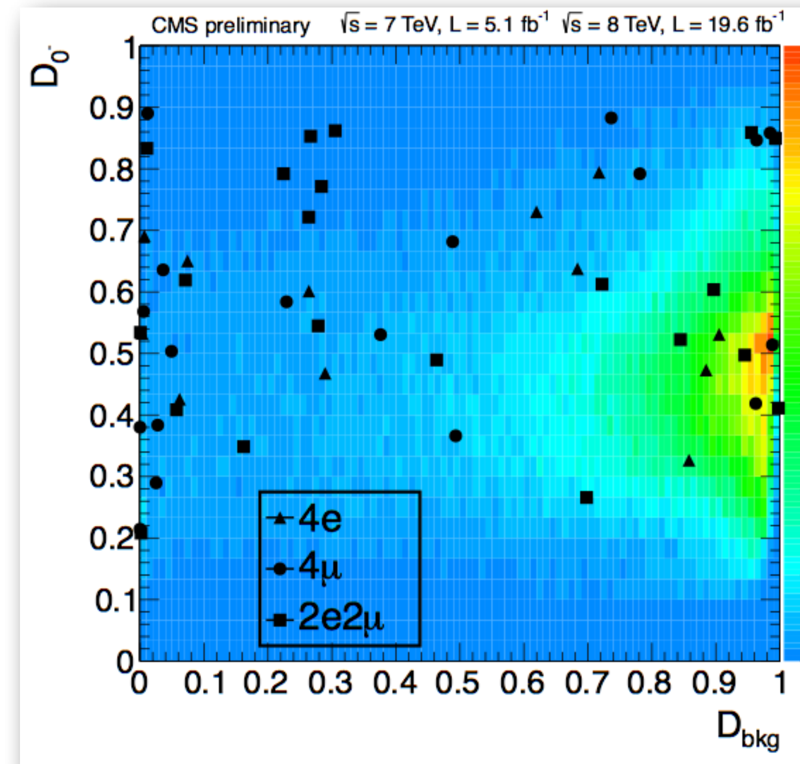
Background processes



SM Higgs boson



exotic Higgs-like boson

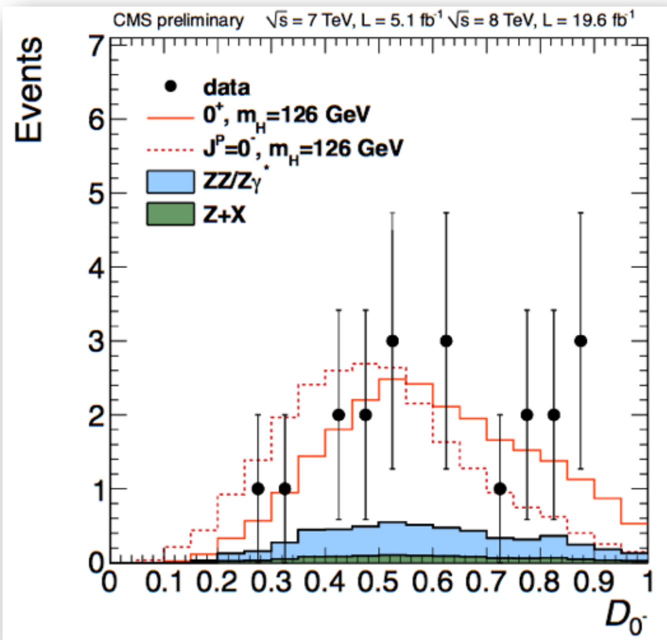


- Perform statistical analysis (hypothesis testing) by generating pseudo-observations (using $\mathcal{P}$(D_{JP},D_{BKG}) distributions and "log likelihood ratio" as the test statistics)

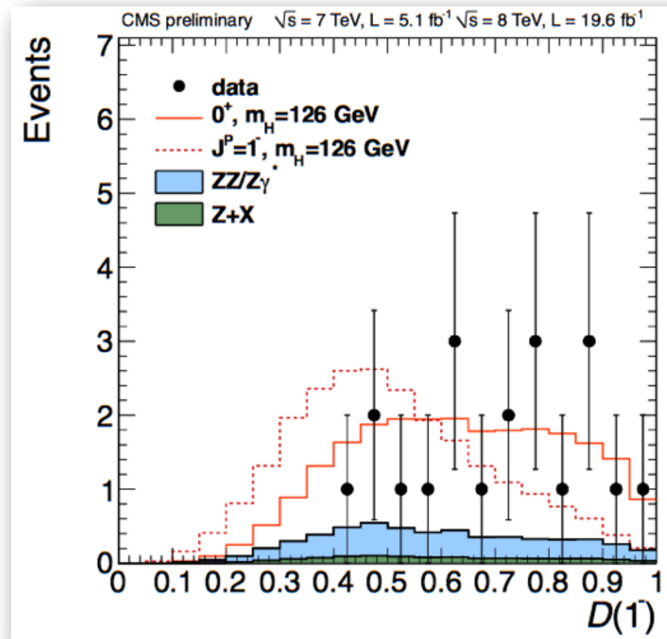
H → ZZ → 4l: Discriminator D_{J^P} (D_{BKG} >0.5)

- D_{BKG} > 0.5 cut is just for illustration

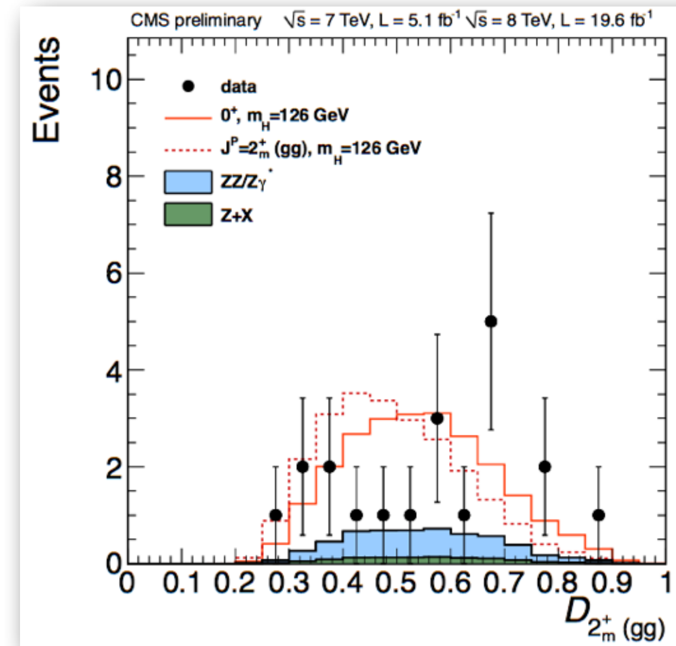
gg → 0^-



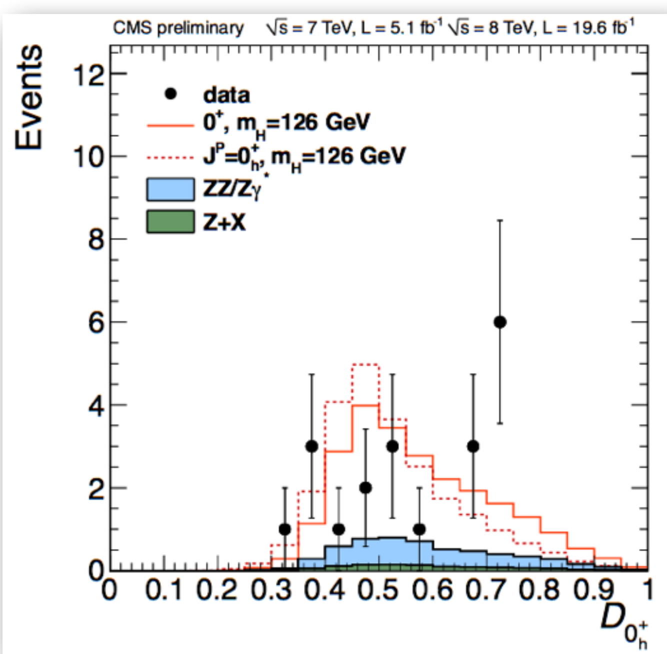
qq → 1^-



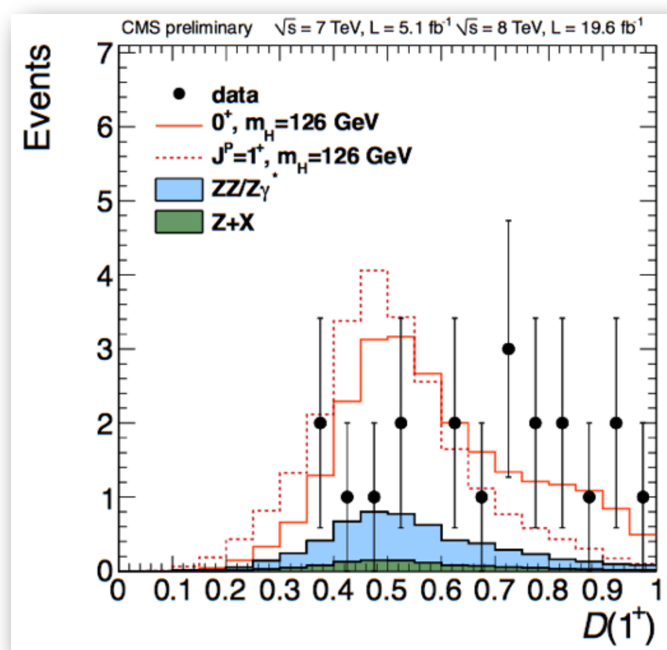
gg → 2_m^+



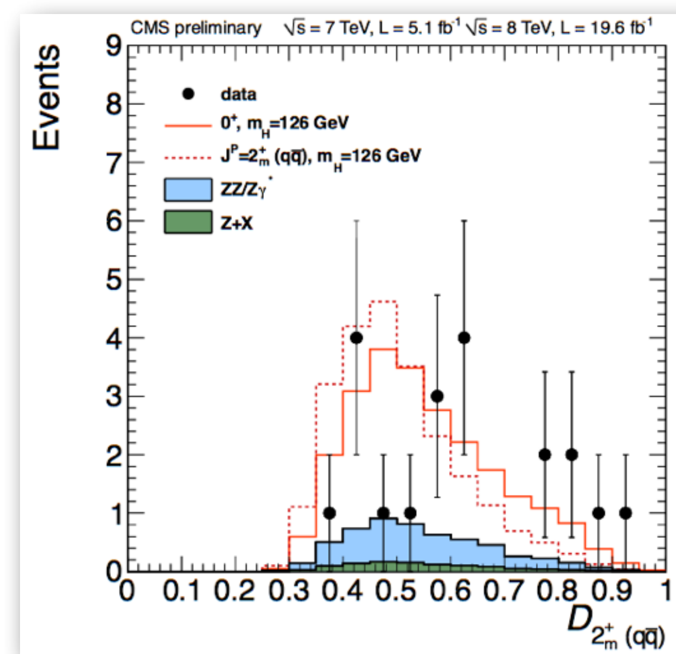
gg → 0_h^+



qq → 1^+



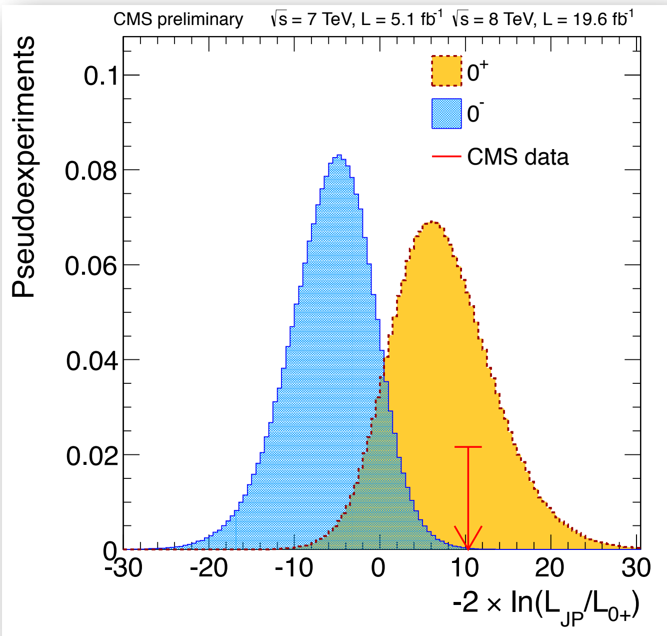
qq → 2_m^+



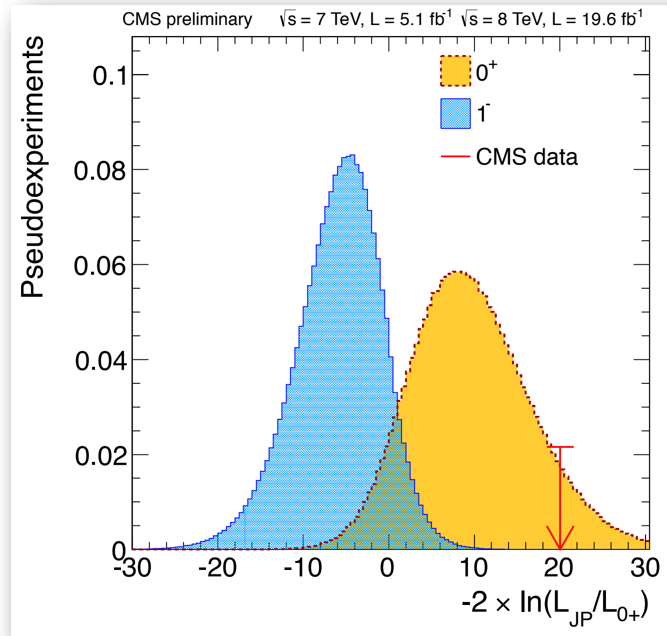
H → ZZ → 4l: J^{CP} hypotheses testing

- Test statistics for J^P hypoheses and the observed results (μ from data)

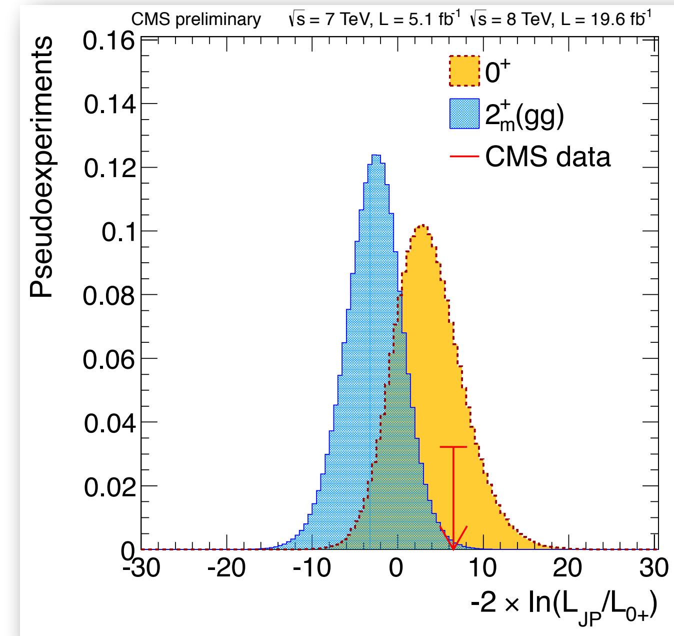
gg → 0^-



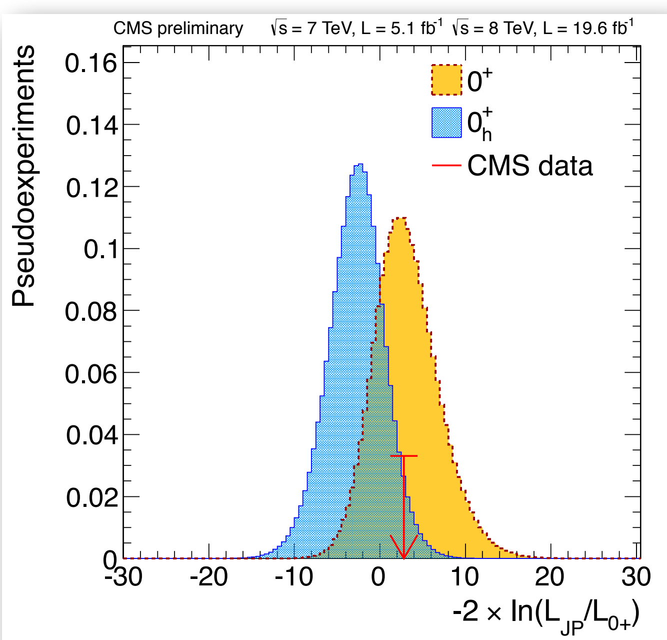
qq → 1^-



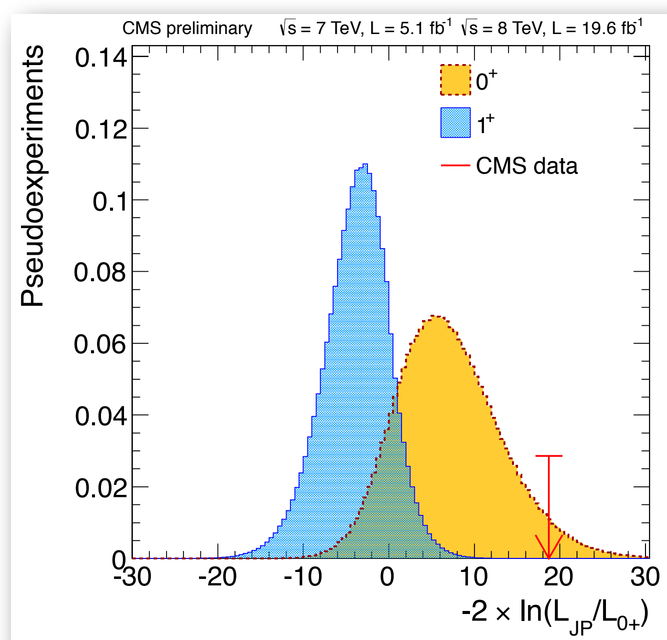
gg → 2_m^+



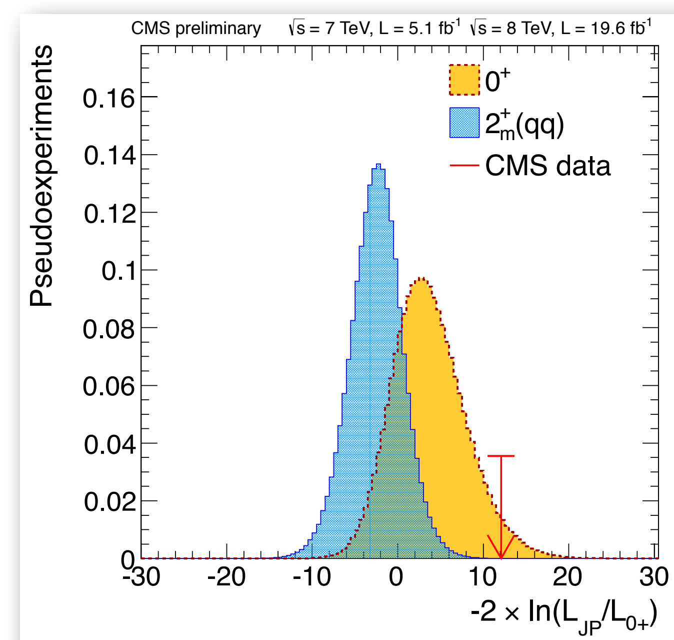
gg → 0_h^+



qq → 1^+



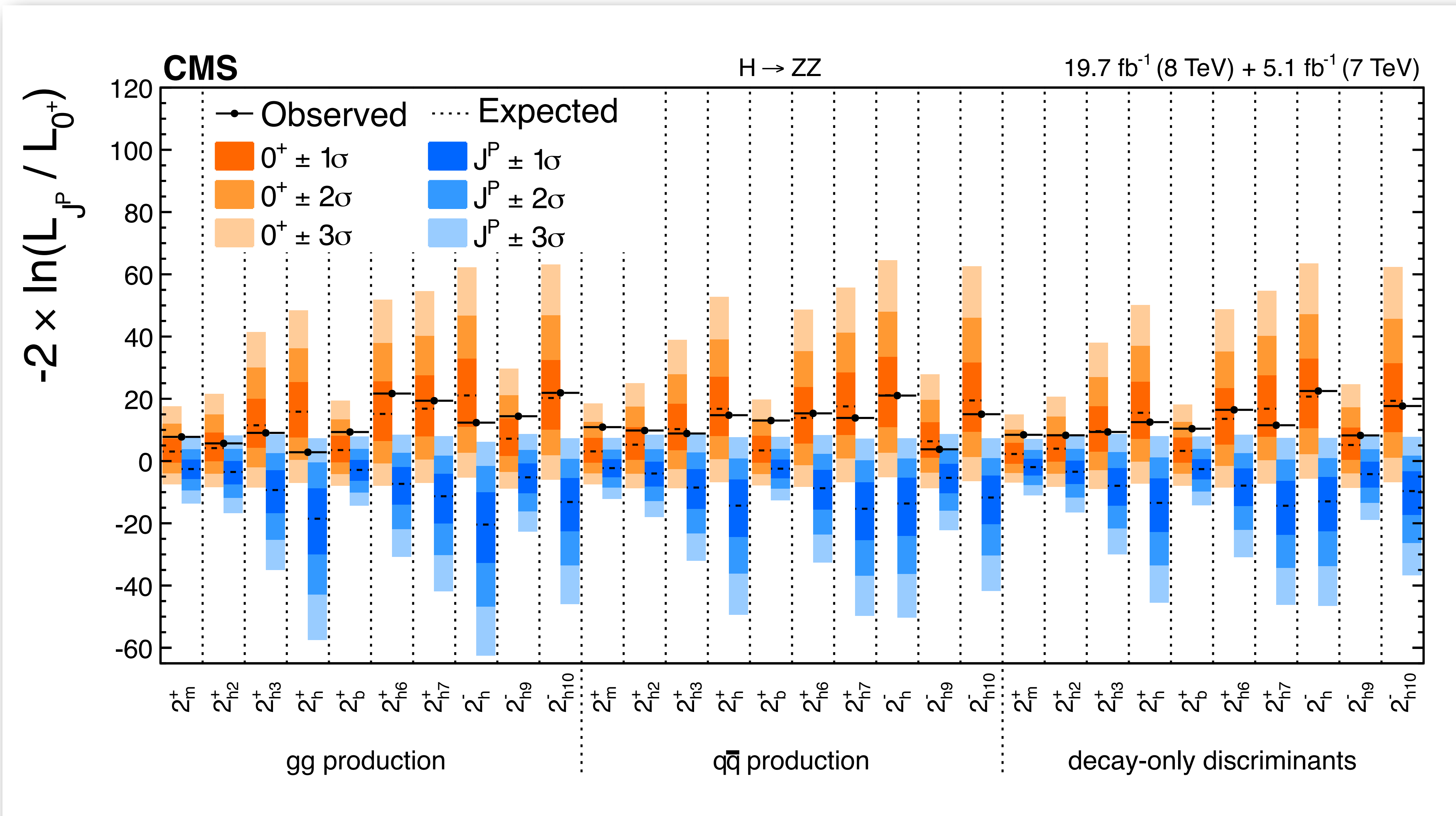
qq → 2_m^+



H→ZZ→4l: Example of spin-two scenario exclusions

- **H→ZZ→4l:** Test the pure state spin-two terms (*qq* production, *gg* production and using ***production independent discriminants***):

H→ZZ→4l



Excluded all pure state spin-two hypotheses at 96.9% CL or better!

Matrix Element Method for processes discrimination

To remember…

1. MEM offers very good discrimination of signal and background, and alternative signal hypotheses, by exploiting (all) available kinematic information,
2. Many tools and packages for automatic ME calculation publicly available,
3. Less efficient for final states with invisible or poorly reconstructed objects (jets, miss. E_T) - it needs special care.

Exploitation of interference effects in particle physics

Interference in particle physics

Interference of the process amplitudes:

- Amplitudes of the processes with same initial and final state **interfere**

$$|ME(A+B)|^2 = |ME(A)|^2 + [ME(A)^{*}ME(B) + ME(B)^{*}ME(A)] + |ME(B)|^2$$

total process A+B	pure process A	interference term	pure process B

Some examples:

- Interference associated with permutations of identical leptons in the 4e and 4μ final states
  - important improvement in separation power in $H \rightarrow ZZ \rightarrow 4l$ channel (arxiv: 1210.0896v2)
- Interference effects between different $H \rightarrow ZZ$ amplitudes:
  - dramatic impact on differential distributions in case of scalar Higgs (arxiv: 1310.1397)
  - ➡ motivation to consider/exploit these interference effects (topic of this talk)
- Interference effects and the Higgs boson off-shell production

Example: Higgs effective couplings and interference

- Effective Lagrangian associated with ZZ-decays of a scalar particle X (on shell production)

$$\mathcal{L}_{\mathrm{HZZ}} \ni \kappa_1 \frac{m_Z^2}{v} X Z_\mu Z^\mu + \frac{\kappa_2}{2v} X Z_{\mu\nu} Z^{\mu\nu} + \frac{\kappa_3}{2v} X Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

K_1 - term (O_1) (SM Higgs-like)	K_2 - term (O_2) (0_h^+, loop-induced)	K3 - term (O_3) (0^-, loop-induced)

K_2 and K_3 terms - the lowest dim. effective operators with the given symmetry properties

- Magnitude of interference effects:
  - Impact of interference on the total production rate

arxiv: 1304.4936 [hep-ph]

$$\Gamma(X \to ZZ) = \Gamma_{SM} \sum_{i,j} \gamma_{ij} \kappa_i \kappa_j,$$

$$\gamma_{11} = 1, \quad \gamma_{22} = 0.090, \quad \gamma_{33} = 0.038, \quad \gamma_{12} = -0.250, \quad \gamma_{13} = \gamma_{23} = 0.$$

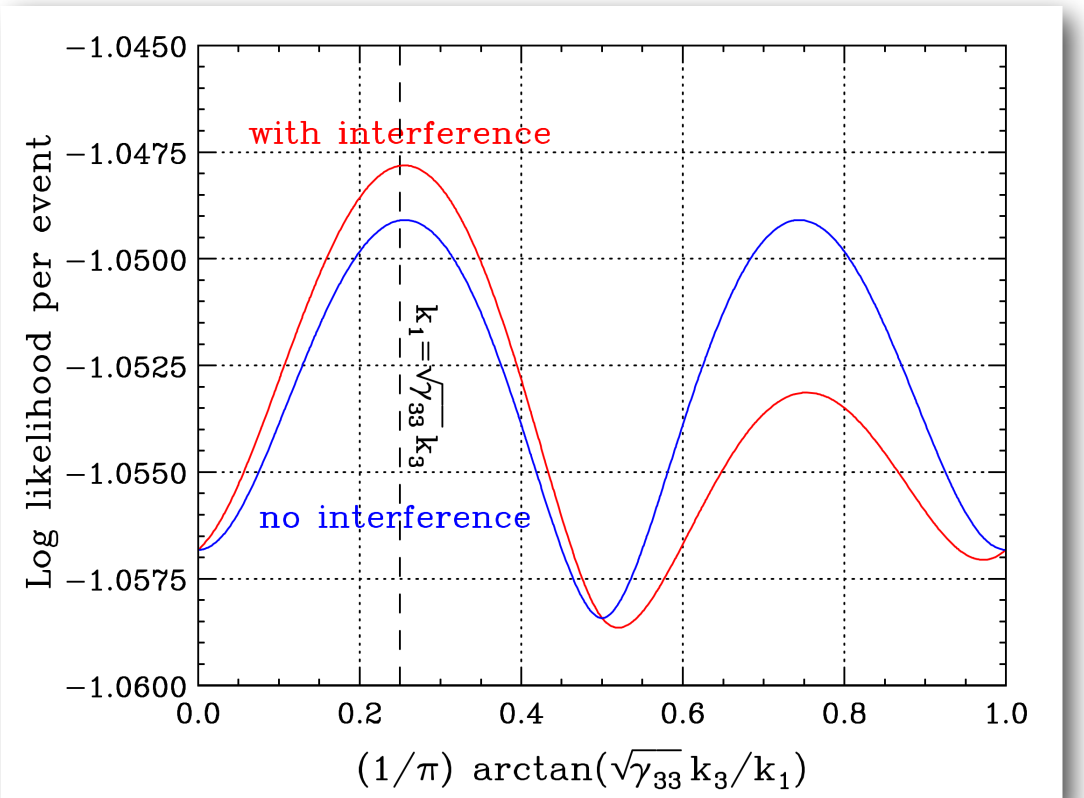
(for 2e2μ, before selection)

  - Impact of interference on differential distributions (next slides)

Likelihood examples

- Per-event likelihoods built using the $|ME|^2$ for particular benchmark points
  - Demonstrate the potential to establish the presence or absence of interference, as well as to determine the relative sign of couplings

$X(\kappa_1, \kappa_3 \neq 0, \kappa_2 = 0)$



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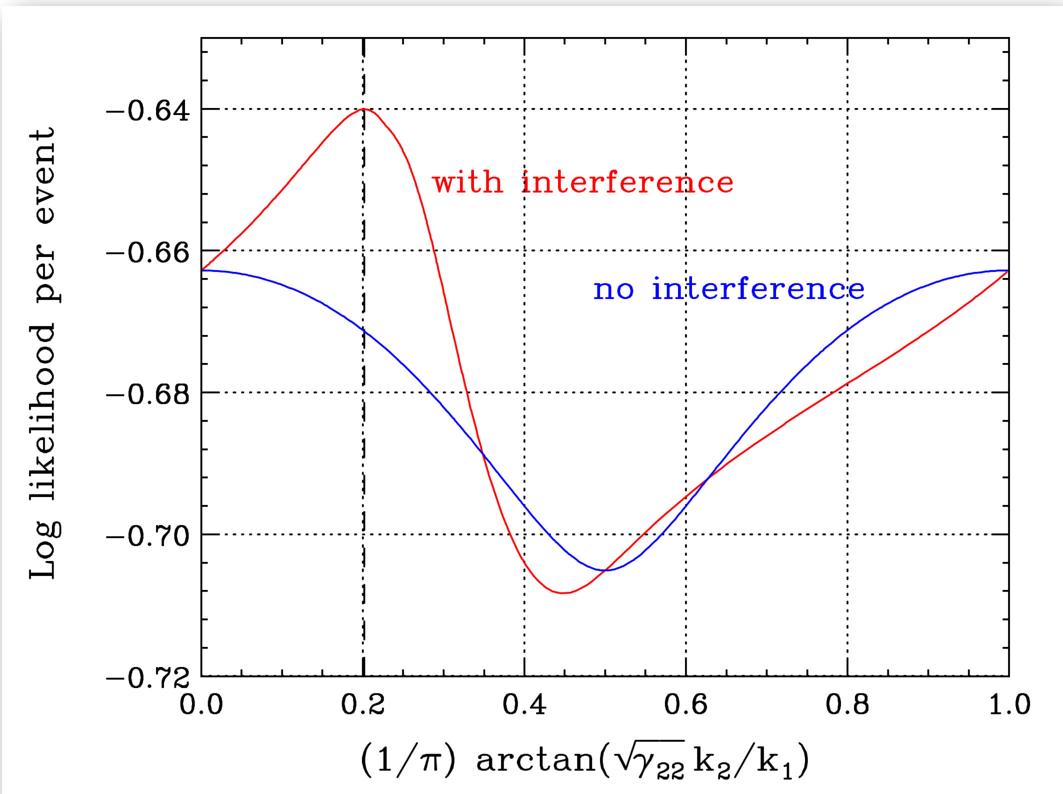
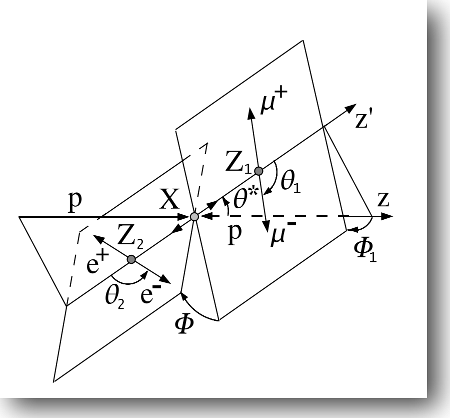


- The presence of interference breaks the $\kappa_{2,3} \rightarrow -\kappa_{2,3}$ symmetry and gives one sensitivity to the sign of the couplings.
  - case of interference between κ_1 and the κ_2 terms more straightforward to detect

Example: A prototypical analysis

- Basic idea:
  - Construct observables/discriminants which take into account the interference effects and are "tuned" for each point of the parameter space
  - Perform hypothesis tests for a discrete set of points in the parameter space.

Use kinematics of 4l system



- Kinematic discriminants based on Matrix Element Method:
  - Discriminants $D(X;0^+)$ - computed for each point of the parameter space

$$D(X;0^+) = \frac{|\mathcal{M}(X)|^2}{|\mathcal{M}(0^+)|^2}$$

"$0^+ \oplus 0^-$" example:

$$D(X;0^+) = \kappa_1^2 + \kappa_3^2 \frac{|\mathcal{M}(0^-)|^2}{|\mathcal{M}(0^+)|^2} + \kappa_1\kappa_3 \frac{(\text{interference})}{|\mathcal{M}(0^+)|^2}$$

  - $D(X;0^+)$ takes into account all aspects in which kinematics differ between the two hypotheses
  - Discriminants such as $D(0^-;0^+)$ and $D(0_h^+;0^+)$ - inherently insensitive to interference effects:

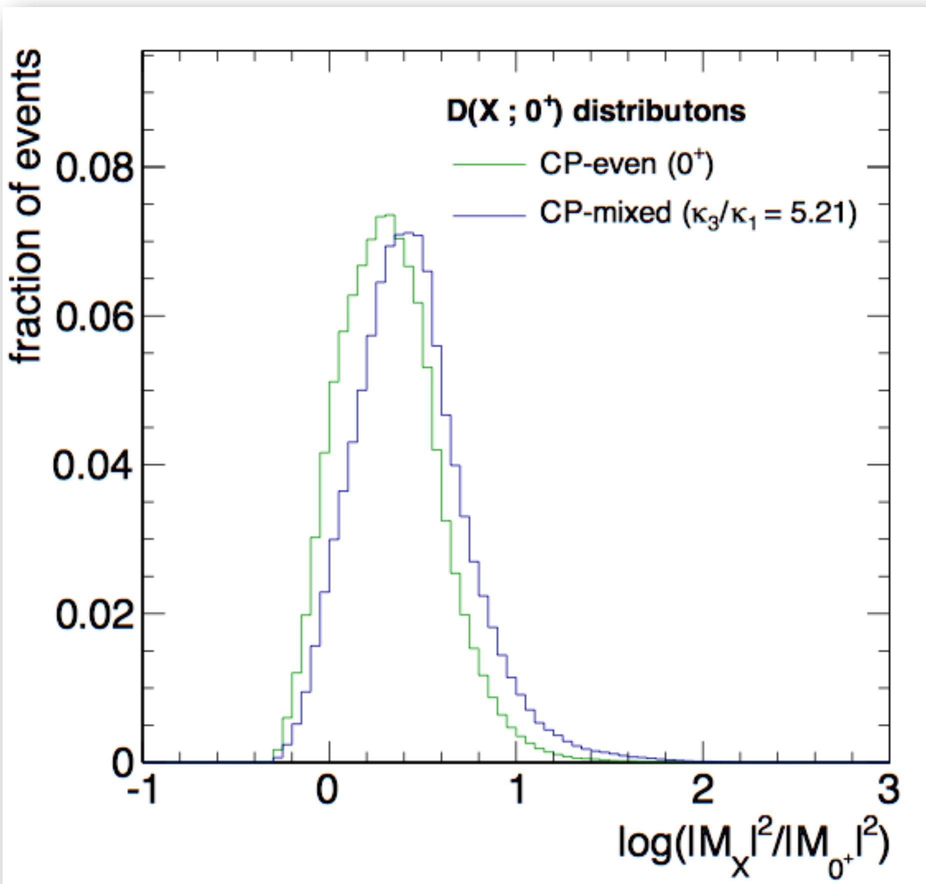
$$D_{0^-} = D(0^-;0^+) = \frac{|\mathcal{M}(0^-)|^2}{|\mathcal{M}(0^+)|^2}, \quad D_{0_h^+} = D(0_h^+;0^+) = \frac{|\mathcal{M}(0_h^+)|^2}{|\mathcal{M}(0^+)|^2}$$

- Hypotheses separation extracted from test-statistics distributions of toy experiments
  - Compute the exclusion regions for ratio of couplings (here **K_3/K_1** and **K_2/K_1** separately) for a given luminosity (up to 3000 fb^{-1} at 14TeV)
  - Repeat same analysis using the $D(0^-;0^+)$ or $D(0_h^+;0^+)$ discriminants
    ➡ to quantify the gain in sensitivity due to the interference effects

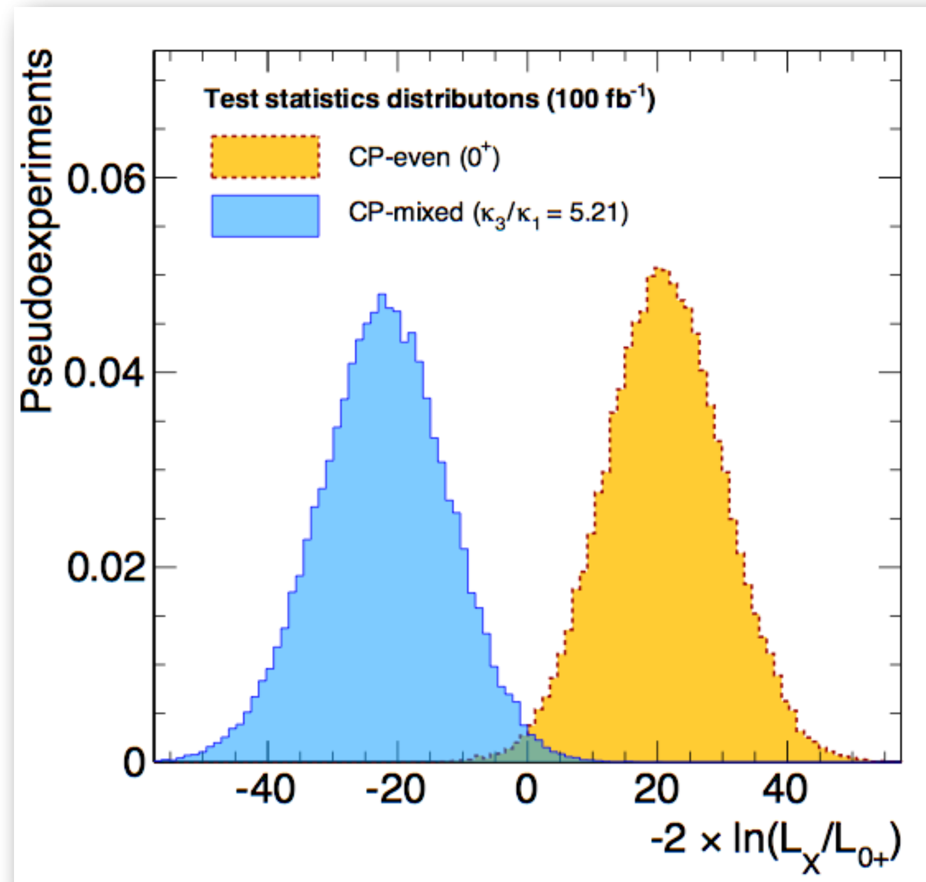
Example: Templates and test-statistics

- 1D templates of D(X;0$^+$) built for the two signal hypotheses and background events
  - all three final states together, 8 TeV samples only.

D(X;0$^+$) for κ_3/κ_1 = 5.21



TS distributions, 100 fb^{-1}, κ_3/κ_1 = 5.21



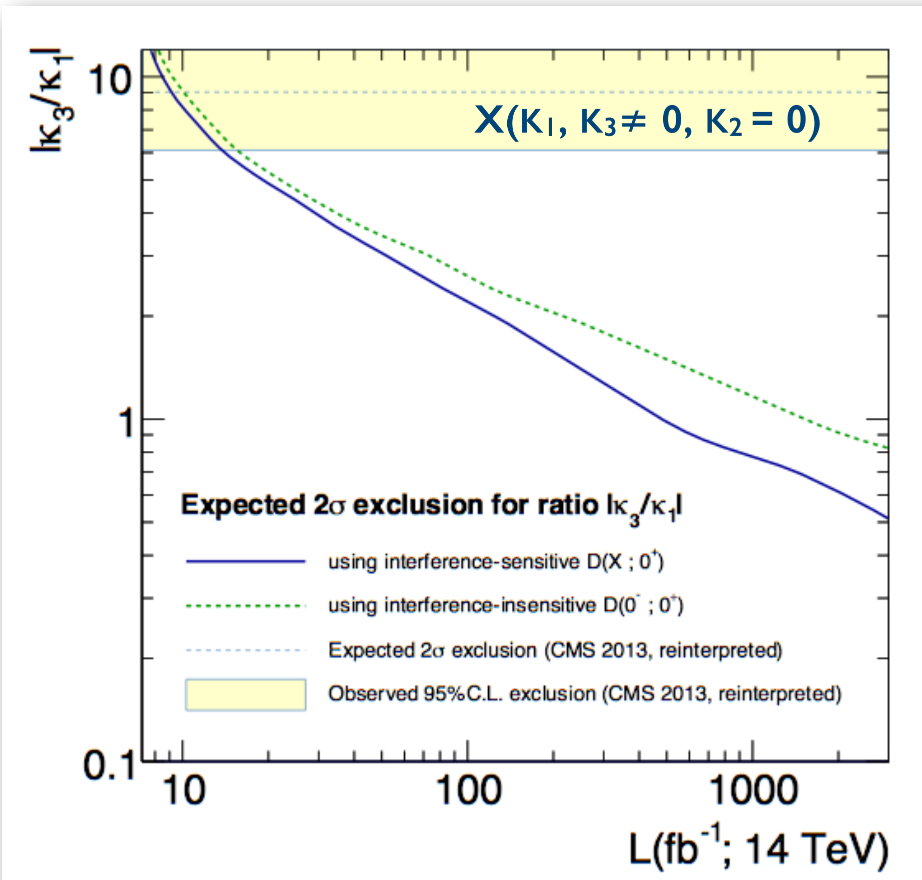
- Test-statistics (TS) for 0$^+$ and X hypotheses from tossing the toy experiments (50k),
  - used to compute the expected separation between the hypotheses for a given int. luminosity

Example: Results for the κ_3/κ_1 and κ_2/κ_1 ratios

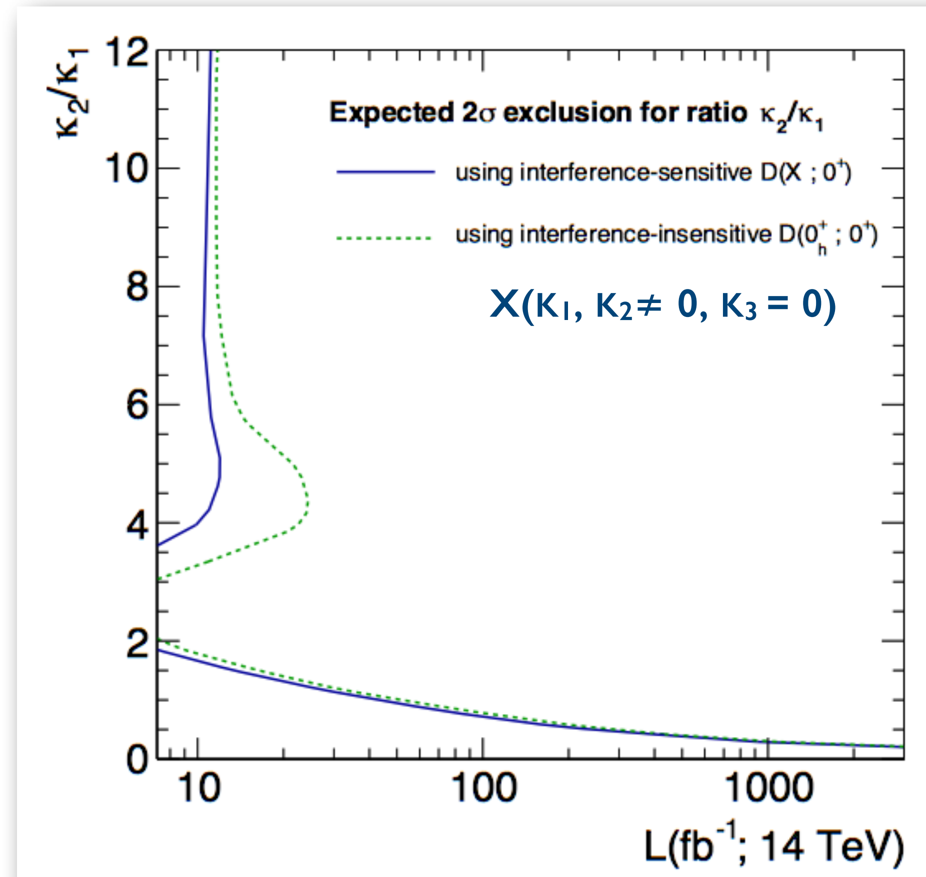
- Results in terms of integrated luminosity at 14TeV required to achieve the expected 2σ limit
  - results for interference-sensitive $D(X;0^+)$ and interference-blind $D(0^-;0^+)$ / $D(0_h^+;0^+)$ discriminants

arxiv: 1310.1397 [hep-ph]

upper limits on κ_3/κ_1 ratio



upper limits on κ_2/κ_1 ratio



- Reduce the int. luminosity required to exclude the ratio $\kappa_3/\kappa_1 \sim 1$ by up to a factor of 4
  - Modest difference O(10%) in sensitivities to κ_3/κ_1 at int. luminosity of ~10 fb^{-1} (~25fb^{-1} @ 8TeV).
- Substantial effects of interference in range $\kappa_2/\kappa_1 \approx 2 - 4$
  - allow us to exclude a range of $2 < \kappa_2/\kappa_1 < 4$ with the already existing data!

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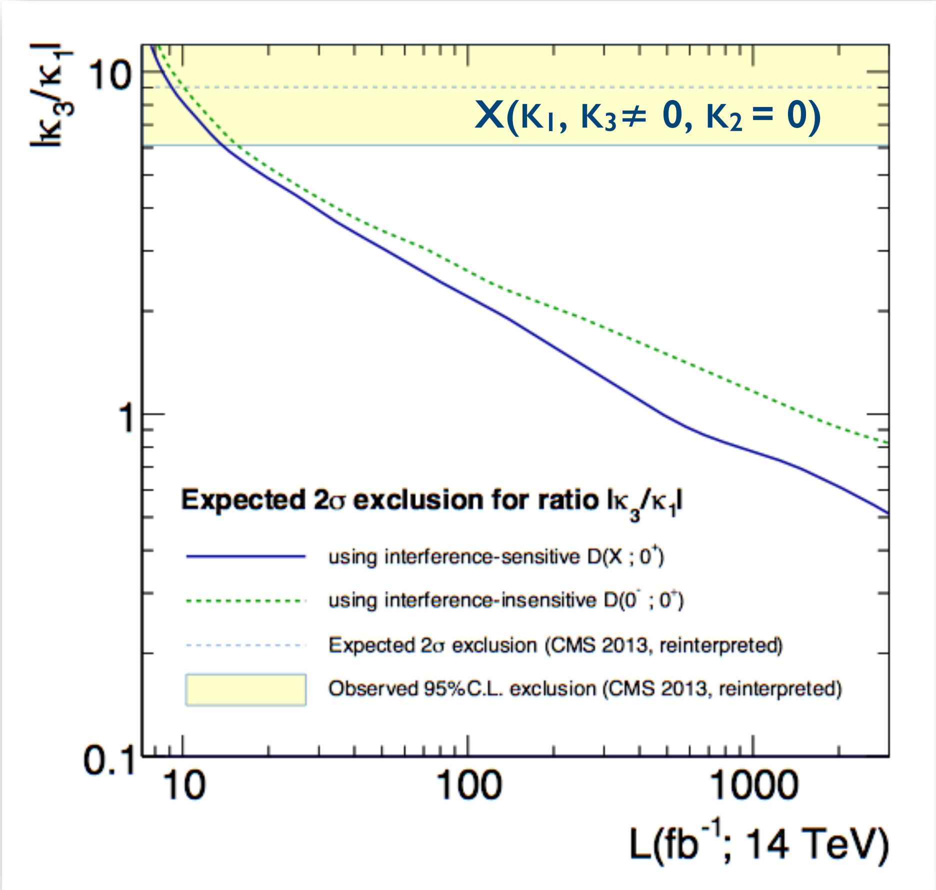

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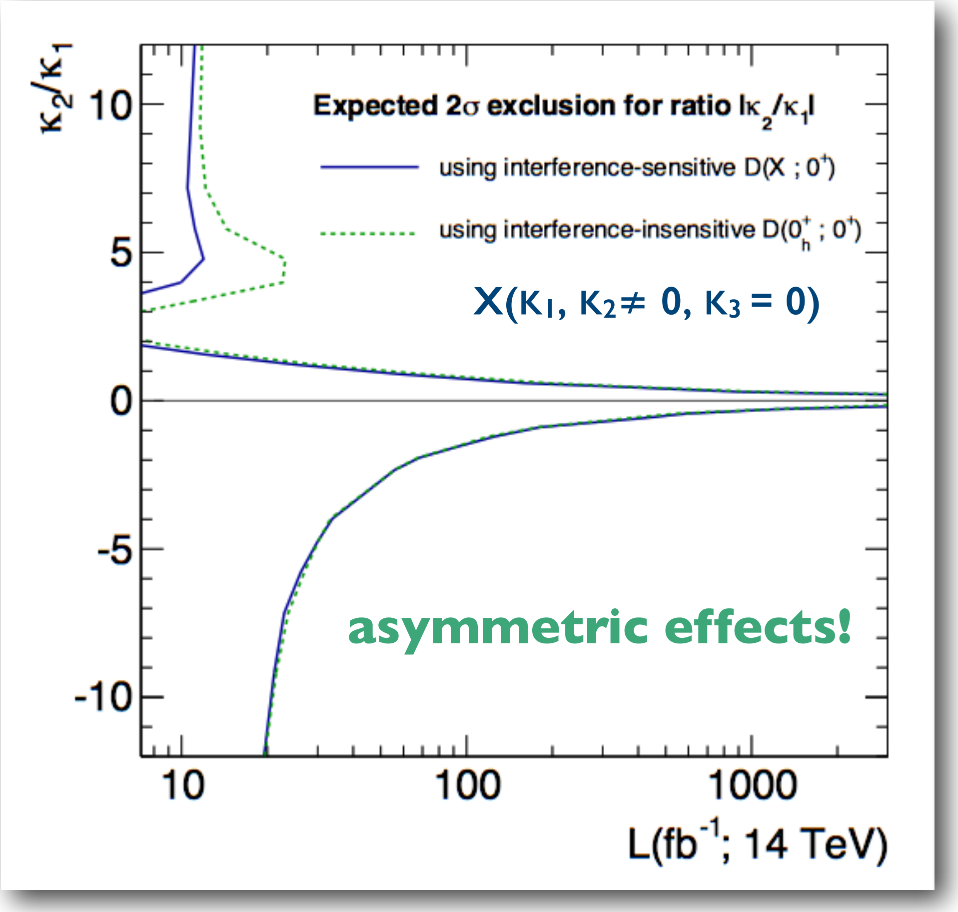

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Exploitation of interference effects in particle physics

To remember…

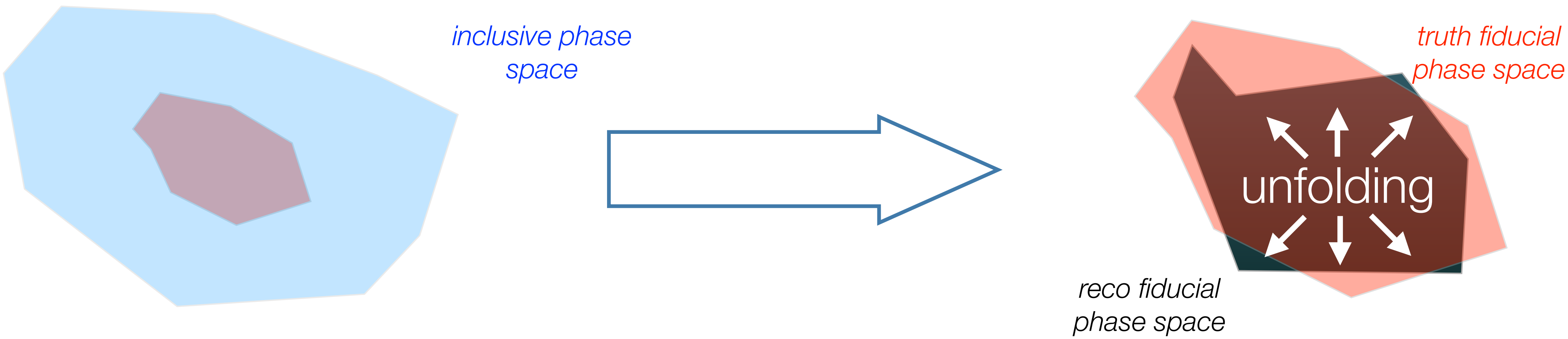
1. Interference effects can affect both inclusive and differential distributions of signal and background processes,
2. Exploiting interference effects can improve sensitivity to (certain) rare processes

Measurement of fiducial cross sections

Some basics

MOTIVATION:

- Fiducial cross sections offer a **possibility to describe data in model independent** way
  - Maximise the applicability of LHC data to explore the **QCD effects** in the SM, and capture **BSM effects** in the Higgs boson physics.



A FEW IMPORTANT ASPECTS:

- **Model independence** of the measurements
  - Factorise theory uncertainties from experimental ones (no extrapolation)
  - Need for the measurements to **survive the passage of time**

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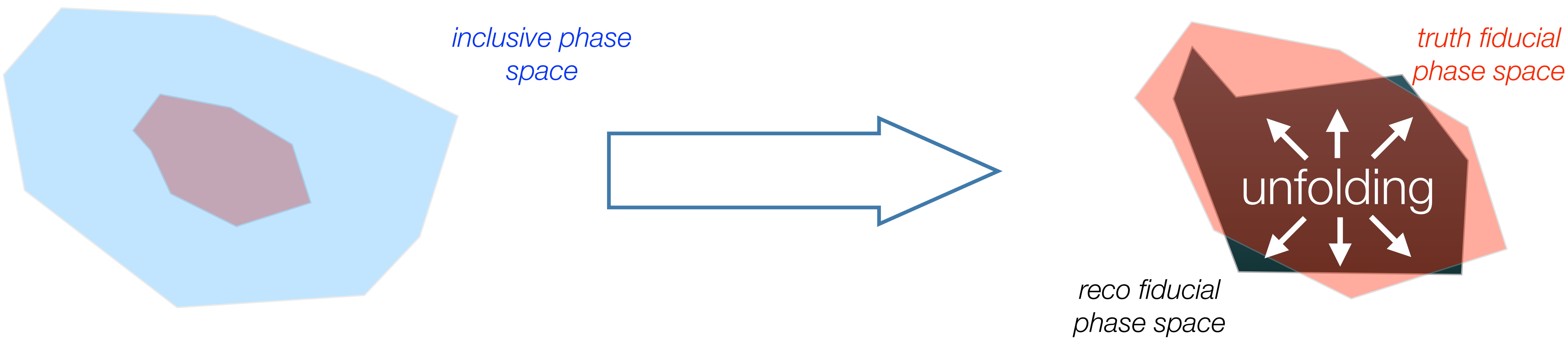

selection efficiency — integrated luminosity

Signal yield: $N_{\text{sig}} = \epsilon_{sig} \cdot \sigma_{\text{fid}} \cdot \mathcal{L}$

fiducial cross section

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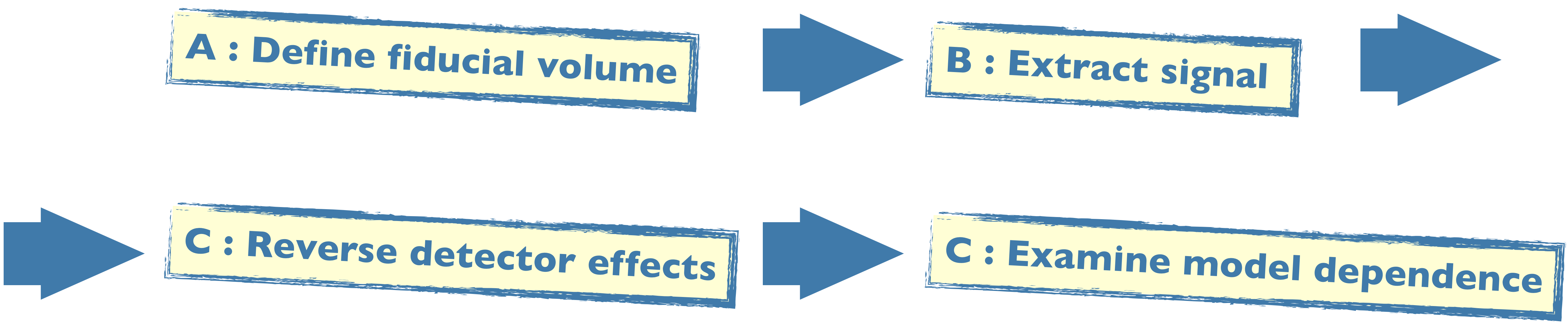

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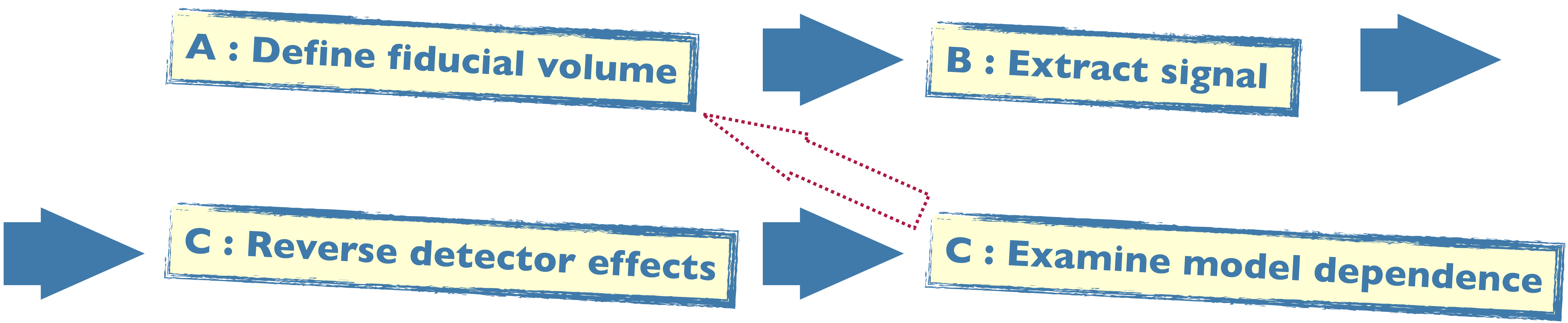

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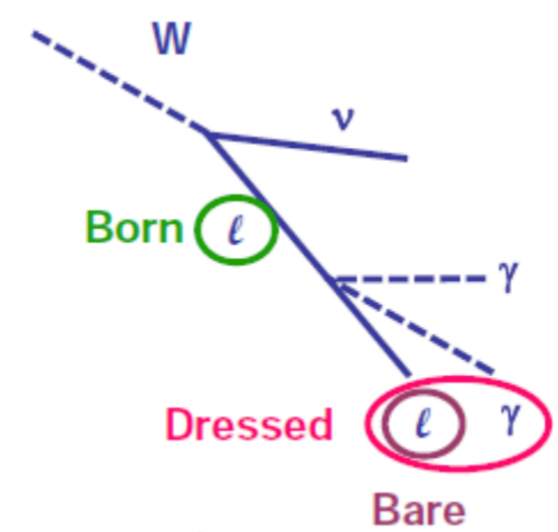
Important ingredients



FIDUCIAL DEFINITIONS:

- Definition of the **fiducial-level objects** (leptons, photons, jets)
- **Isolation requirement** plays an **important role**
- **Out-of-fiducial signal** contributions need special care
- **NOTE: Different kinematical cuts** in ATLAS/CMS (optimised to exploit detector potential).

M(H) HYPOTHESIS:

- Use **best-fit value measured by experiment(s)** for comparisons with theory (either **treat m(H) as a free parameter** and fit for it, or **fix m(H)** to best-fit value).

MODEL DEPENDENCE:

- Build response matrix and repeat the **unfolding procedure once per model**
  - **SM studies:** **vary production mode composition** (e.g. within experimental constraints)
  - **BSM studies:** consider a predefined **set of exotic models** (with/without exp. constraints)

Unfolding

GOAL:

- **Undo the effects of smearing** due to detector resolution & efficiency
- Complex problem (and not very well defined), important for theory comparisons

POSSIBLE APPROACHES:

- First subtract background, then unfold with **inverted detector response [ϵ_{ij}]**

Step I: $$N^{\mathrm{f},i}_{\mathrm{sig}}(m_{4\ell}) = N^{\mathrm{f},i}_{\mathrm{obs}}(m_{4\ell}) - N^{\mathrm{f},i}_{\mathrm{bkg}}(m_{4\ell})$$

Step II: $$\sigma^{j}_{\mathrm{fid}} = [\epsilon_{i,j}]^{-1} \cdot \left[\frac{1}{\mathcal{L}} N^{i}_{\mathrm{sig}}\right]$$

Add systematics to cover for possible biases, cross-check the claimed coverage

- Fold **detector response matrix [ϵ_{ij}]** in the likelihood and **perform background subtraction and signal unfolding simultaneously.**

$$N^{\mathrm{f},i}_{\mathrm{obs}}(m_{4\ell}) = N^{\mathrm{f},i}_{\mathrm{sig}}(m_{4\ell}) + N^{\mathrm{f},i}_{\mathrm{bkg}}(m_{4\ell})$$
$$= \epsilon^{\mathrm{f}}_{i,j} \cdot \sigma^{\mathrm{f},j}_{\mathrm{fid}} \cdot \mathcal{L} \cdot \mathrm{pdf}(m_{4\ell}|\mathrm{H} \to 4\ell) + N^{\mathrm{f},i}_{\mathrm{bkg}} \cdot \mathrm{pdf}(m_{4\ell}|\mathrm{bkg})$$

Full correlation of relevant parameters

Inclusive cross sections: $H \to ZZ \to 4l$

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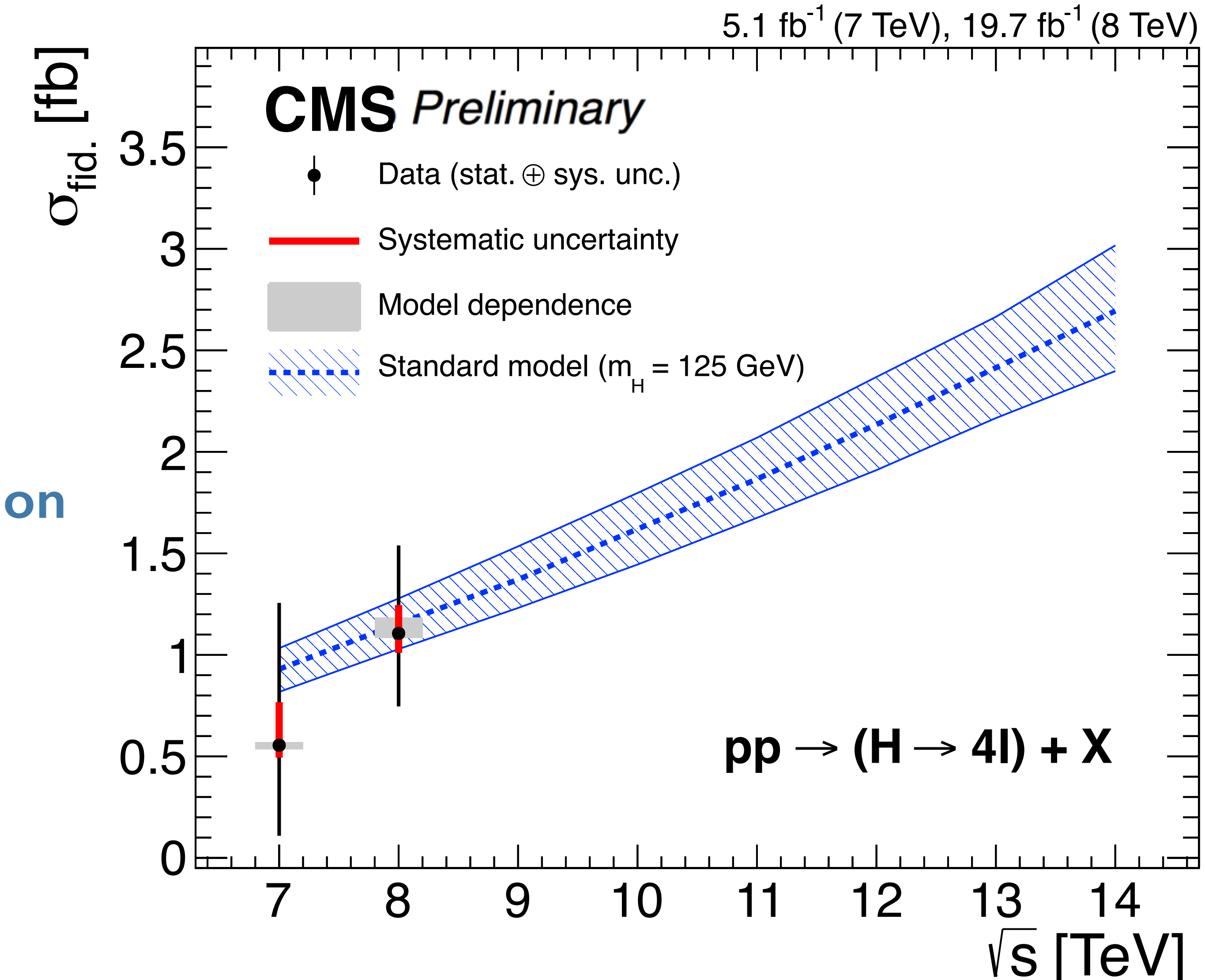
CMS-PAS-HIG-14-028

- Inclusive cross sections at 7 and 8TeV, measured in **$H \to 4l$ channel**
  - Un-binned maximum likelihood fit to $\mathbf{m_{4l}}$
  - **Model dependence** estimated from range of SM and exotic Higgs models:

    <1% using experimental constraints
    ~7% without experimental constraints

  - CMS: **$Z \to 4l$ resonance** used as validation
  - **7TeV** measurement **statistically limited.**



ATLAS @ 8TeV:

$$\sigma_{\text{fid}} = 2.11 \pm^{+0.53}_{-0.47} (\text{stat.}) \pm 0.08(\text{syst.})\ \text{fb}$$
$$\sigma^{\text{SM}}_{\text{fid}} = 1.30 \pm 0.13\ \text{fb}$$

CMS @ 8TeV:

$$\sigma_{\text{fid}} = 1.11 \pm^{+0.41}_{-0.35} (\text{stat.})^{+0.14}_{-0.10}(\text{syst.})^{+0.08}_{-0.02}(\text{model})\ \text{fb}$$
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CMS @ 7TeV:

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Inclusive cross sections: H→ZZ→4l

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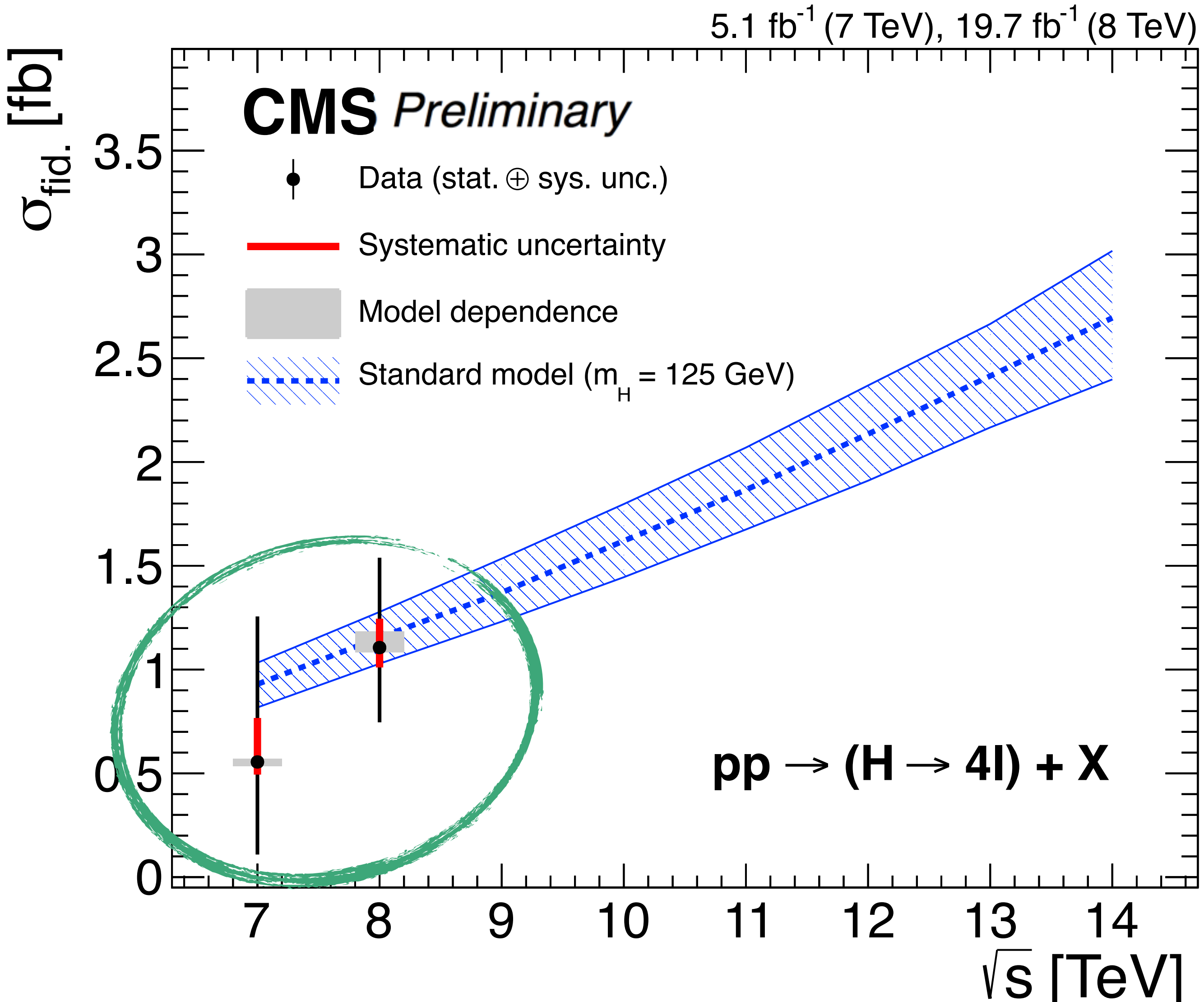

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Compatible with theoretical estimates (slightly higher rates by ATLAS)

Differential XS: H→ZZ→4l

- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions** (see backup).

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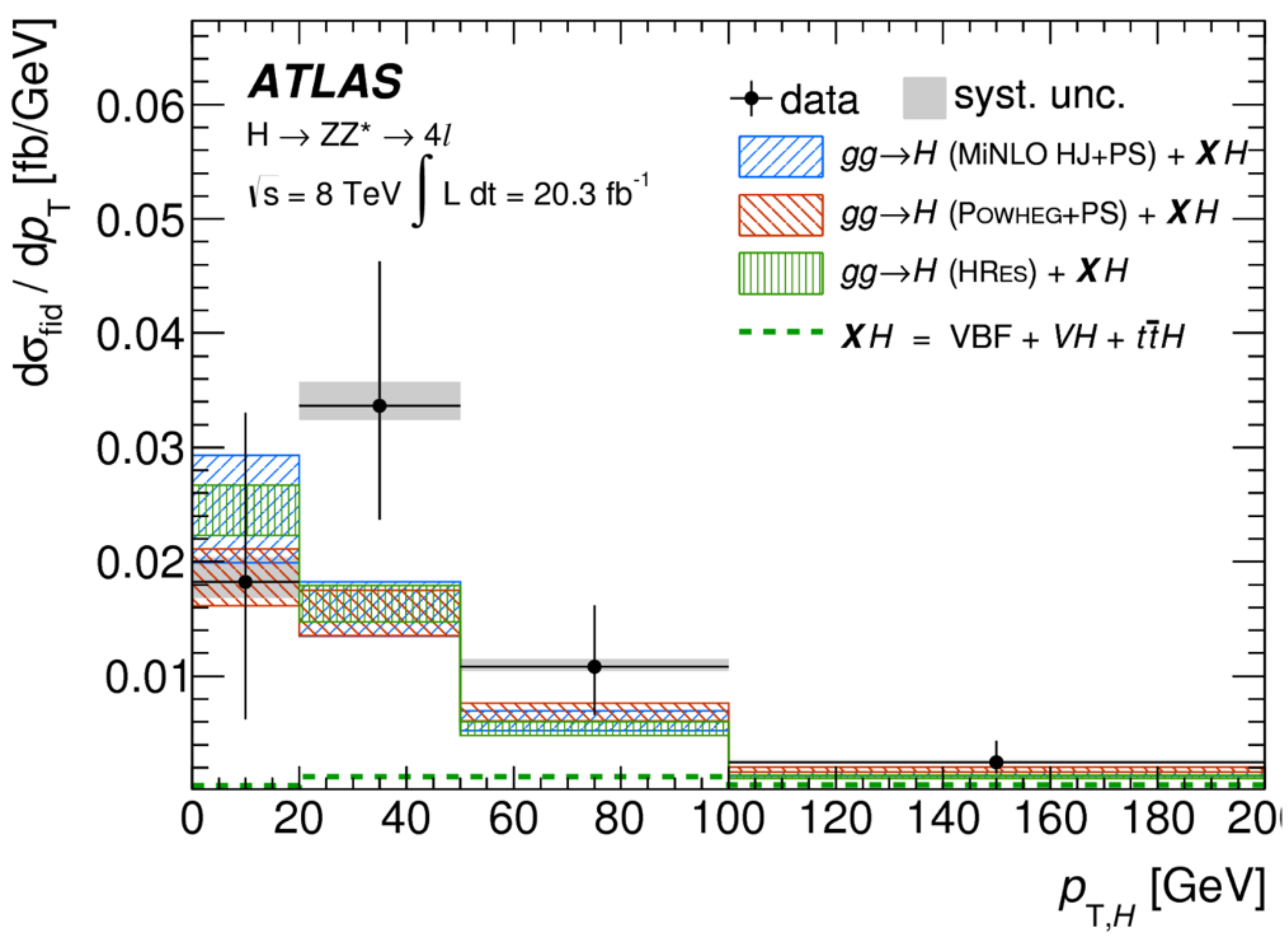
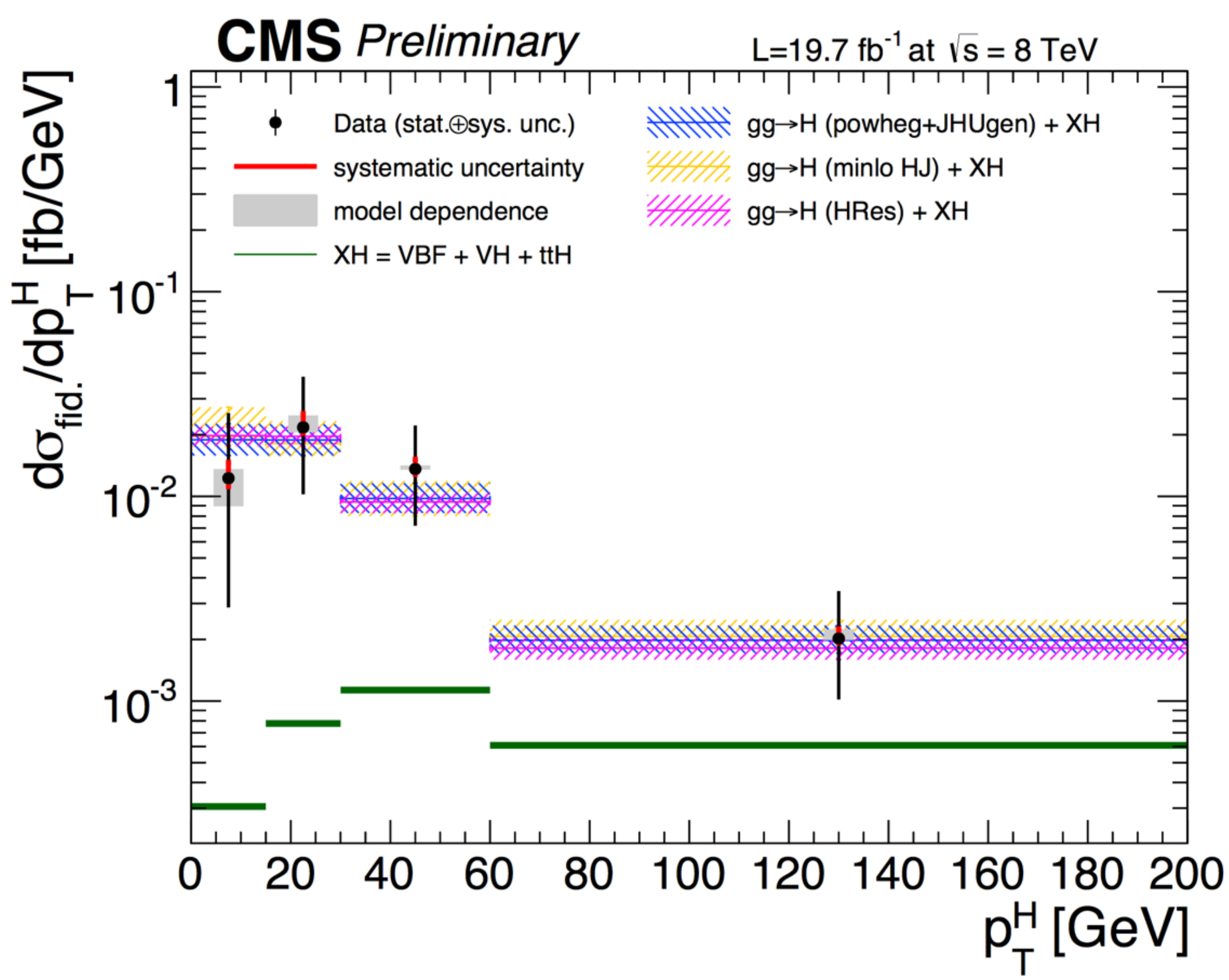
CMS-PAS-HIG-14-028





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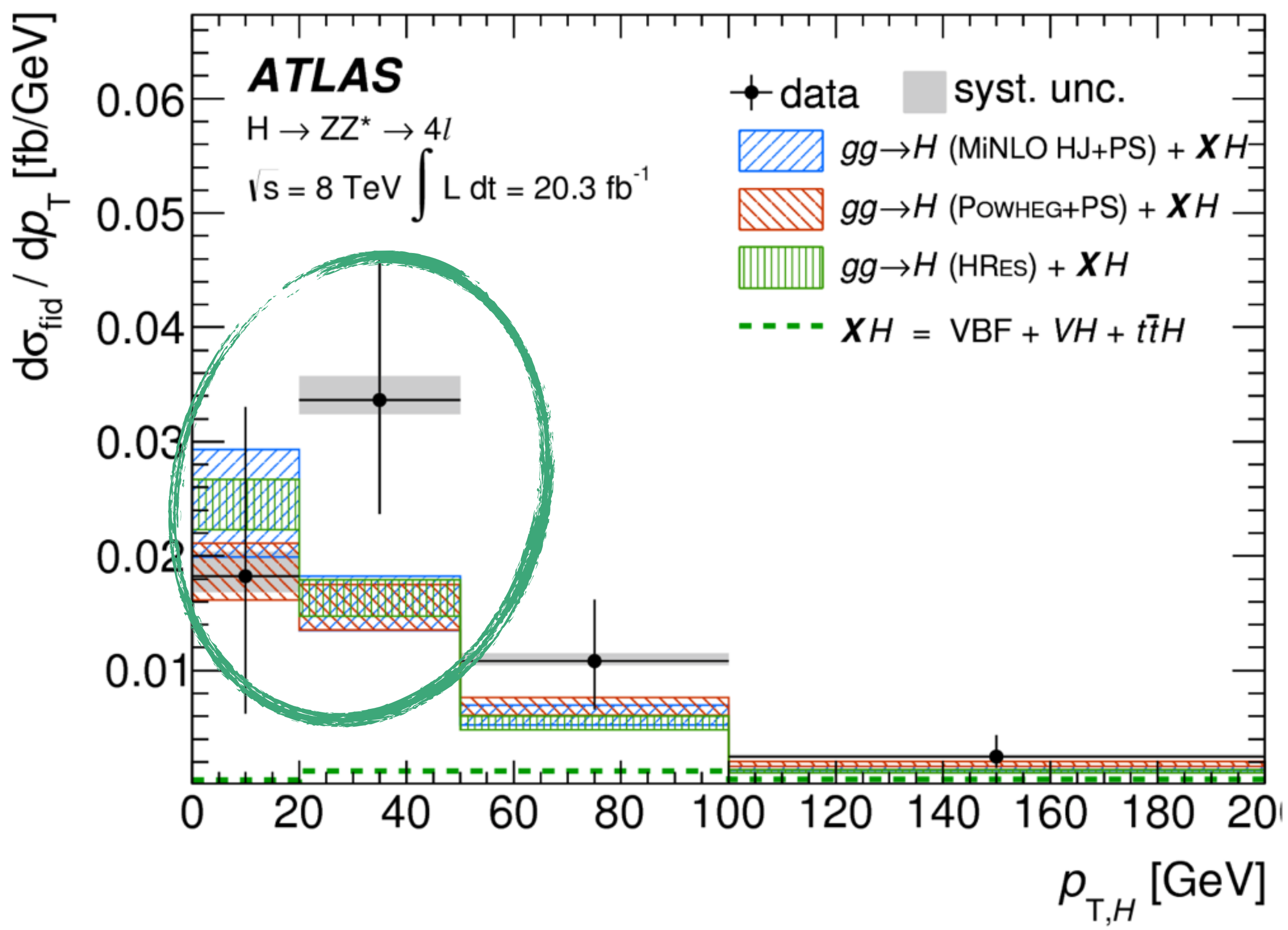
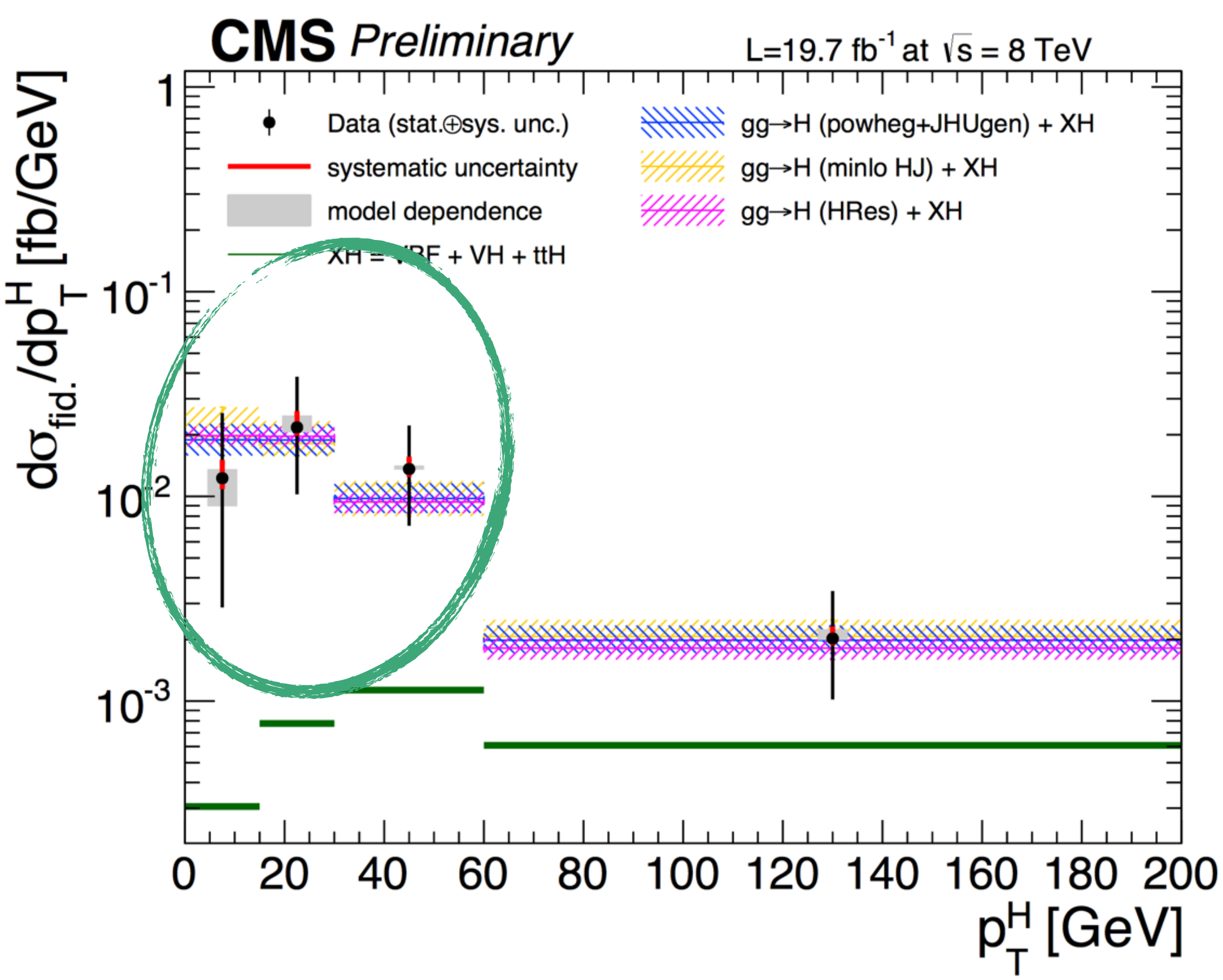


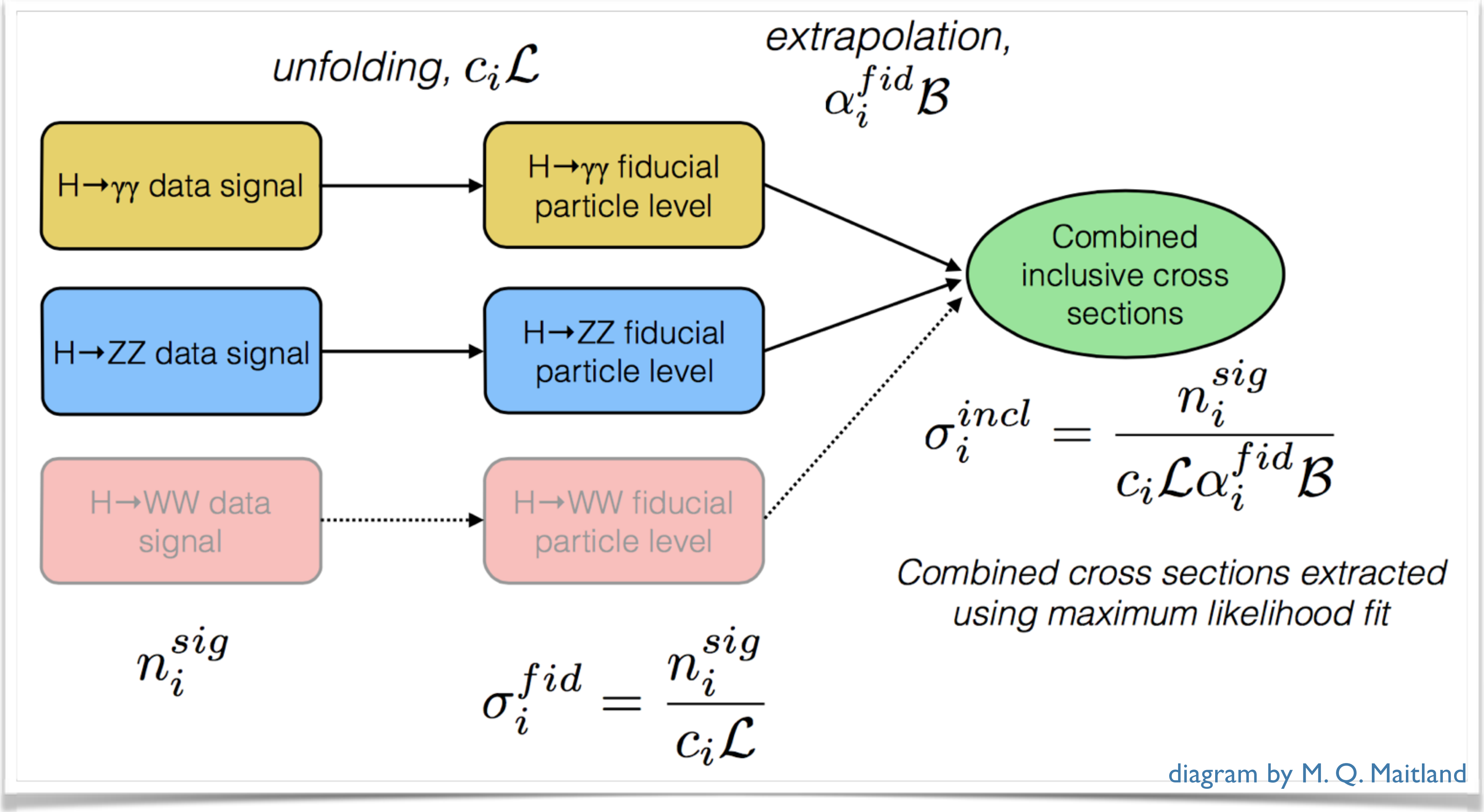


Somewhat harder p_T spectrum observed by ATLAS and CMS w.r.t theoretical estimates (p-value ~10-15%)

Combination of measurements

Combination between decay channels ($H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$, etc.):

- Perform the fit to **inclusive XS in the full phase space** (inherent assumption of the same source of decays)
- **Statistical precision** at the expense of model dependance due to extrapolation (quote a total XS, check the compatibility between the measurements).

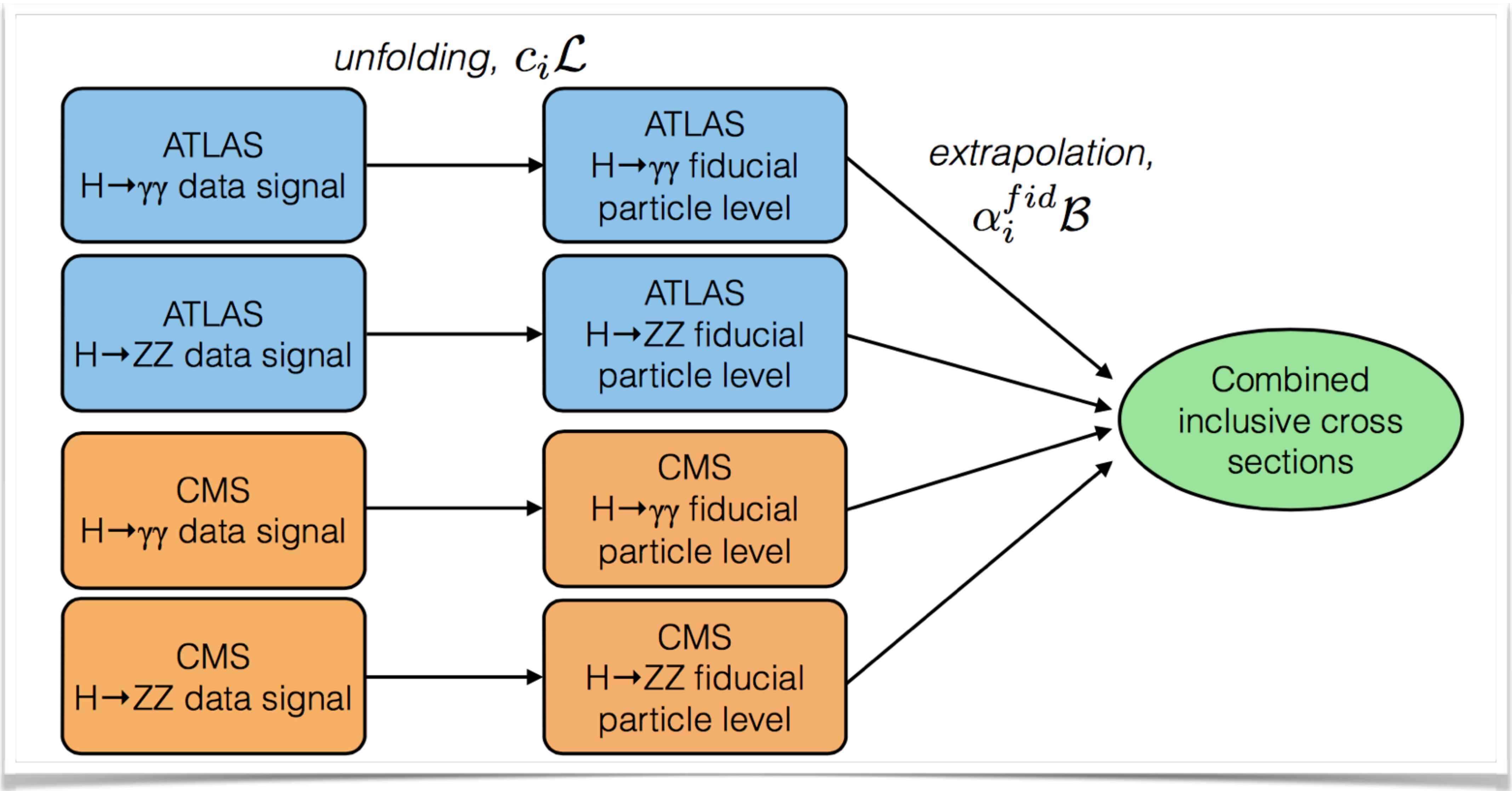


Combination of measurements

Combination between experiments:

- Potential to **combine inclusive and differential cross sections** (need harmonisation in fiducial objects, bin edges, unfolding, etc.)
- Choose **common fiducial** or **inclusive phase space?**

} still to be discussed



Measurement of fiducial cross sections

To remember…

1. Fiducial cross sections offer a possibility to describe data in a model independent way
2. Factorise theory uncertainties from experimental ones, and represent legacy results
3. Several approaches to the unfolding of detector effects. Requires a special care.

PART III: Selected topics on the physics measurements

THE END

Thank you for your attention!

ADDITIONAL MATERIAL

Reducible Background - contributions at a glance

- Definitions:
- Tight-to-loose ratio measured in **Z + 1 loose lepton** events → f
- observed events in the **"2 passed + 2 failed" (2P+2F) region** → N_{2P2F}
- observed events in the **"3 passed + 3 failed" (3P+1F) region** → N_{3P1F}
- ZZ contribution in the **"1 passed + 1 failed" (3P+1F) region** → $N_{3P1F}^{(\mathrm{ZZ})}$
- Contributions from ZZ and 3P+1F processes in **2P+2F region** are negligible

- The expected contributions from "2 prompt + 2 fake" processes (symbolic)
- in the **3P+1F region** →

$$N_{3P1F}^{(\mathrm{2P2F})} = \sum \left[\frac{f_i}{(1-f_i)} + \frac{f_j}{(1-f_j)} \right] N_{2P2F}$$

- in the **Signal region (SR)** →

$$N_{SR}^{(\mathrm{2P2F})} = \sum \frac{f_i}{(1-f_i)} \frac{f_j}{(1-f_j)} N_{2P2F}$$

(symbolic)

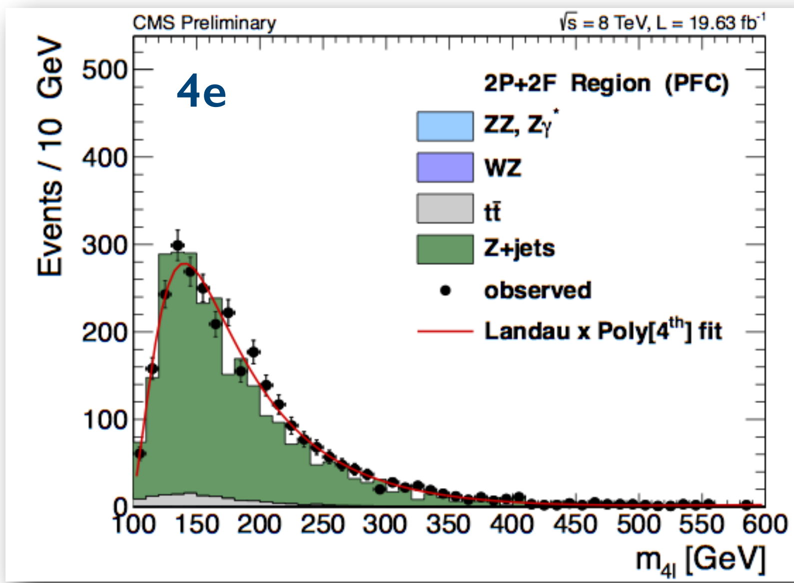
- Total expected contributions
- in the **Signal region** (symbolic)

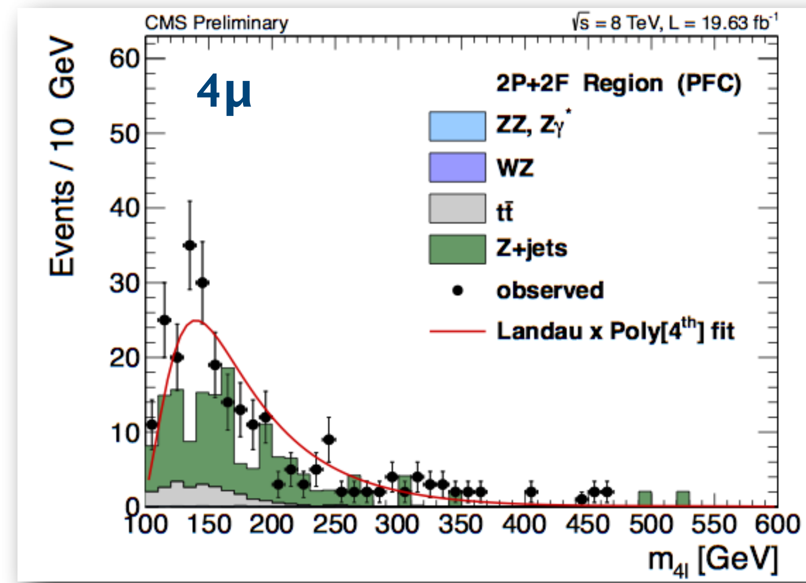
→

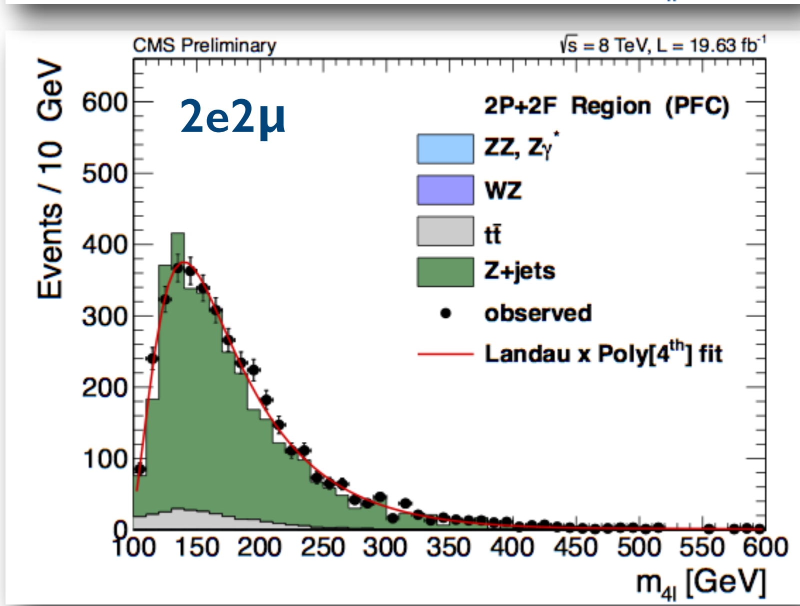
$$N_{SR}^{bkg} = \sum \frac{f_i}{(1-f_i)} (N_{3P1F} - N_{3P1F}^{(\mathrm{2P2F})} - N_{3P1F}^{(\mathrm{ZZ})}) + \sum \frac{f_i}{(1-f_i)} \frac{f_j}{(1-f_j)} N_{2P2F}$$

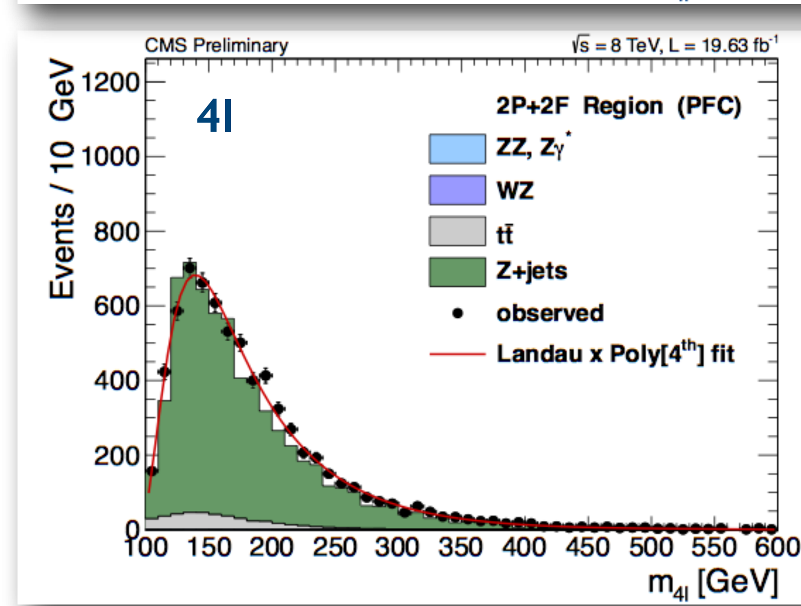
Reducible Background - Control region 2P+2F

- Measure contribution from processes with 2 prompt + 2 fake leptons using
  - Control region with “**2 passed + 2 failed**” **(2P+2F)** leptons









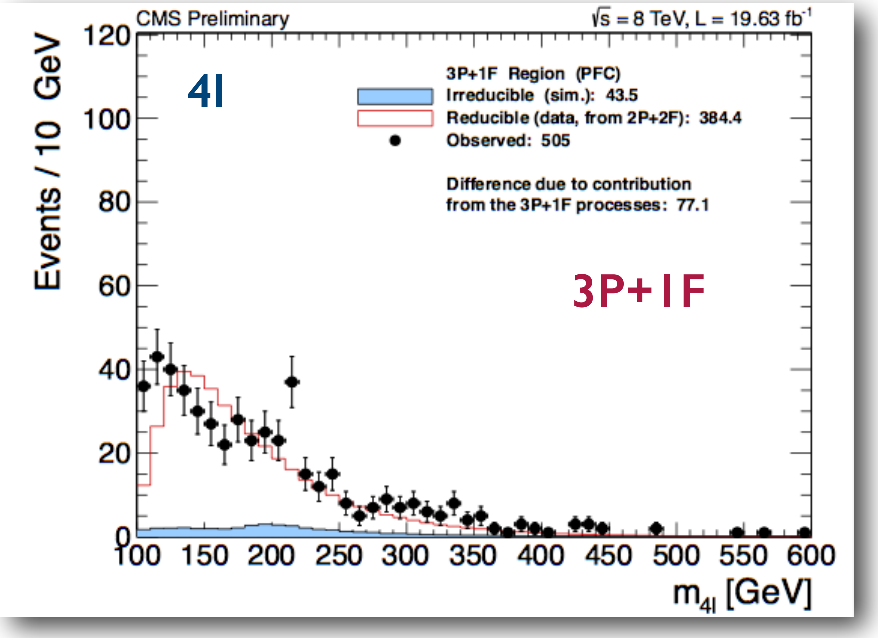
- 4e and 2e2μ channel - data are well described by MC
- 4μ channel - data are not properly described by MC (as before)

Reminder: MC predictions are not used in the analysis

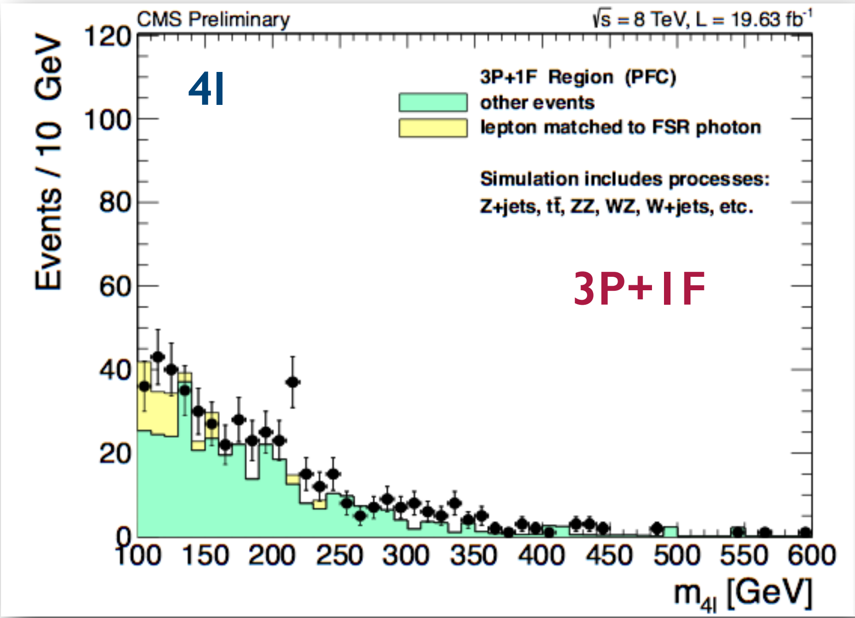
Reducible Background - Control region 3P+1F

- Measure contribution from processes with 3 prompt + 1 fake leptons (Zγ, WZ, etc.) using
  - Control region with "**3 passed + 1 failed" (3P+1F)** leptons
  - Estimated spill-over from **2P+2F region** (**from data**) and **Signal region** (from simulation)

contributions from 2P+2F & Signal region



simulation (MC-truth matching)



- 3P+1F events predominantly in the low m_{4l} region - **Zγ events (asymmetric conversions)**
- Total expected contributions in the **Signal region**

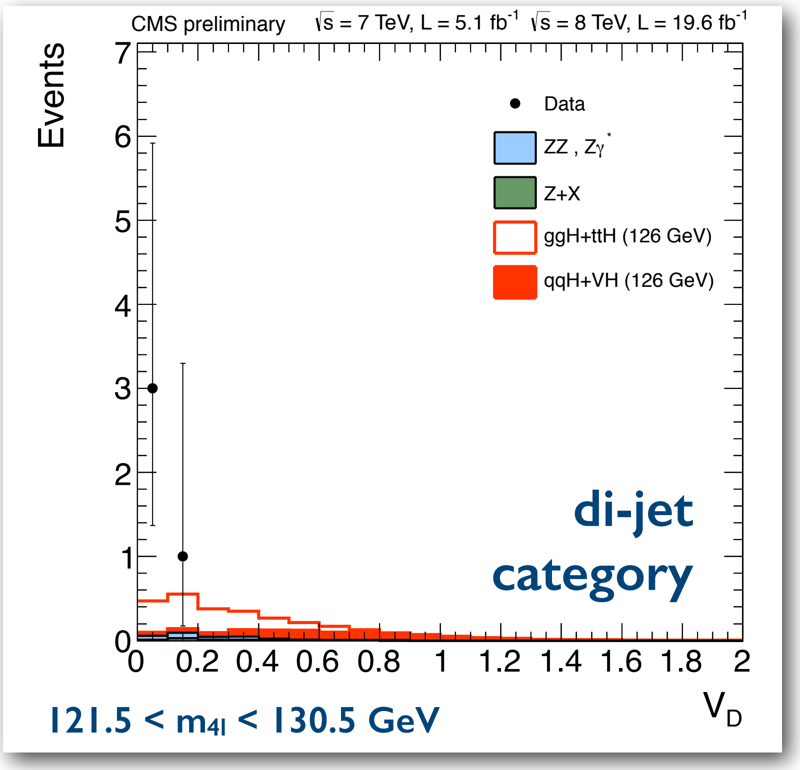
(symbolic)

$$N_{SR}^{bkg} = \sum \frac{f_i}{(1-f_i)}\left(N_{3P1F} - N_{3P1F}^{(\mathrm{2P2F})} - N_{3P1F}^{(\mathrm{ZZ})}\right) + \sum \frac{f_i}{(1-f_i)}\frac{f_j}{(1-f_j)} N_{2P2F}$$

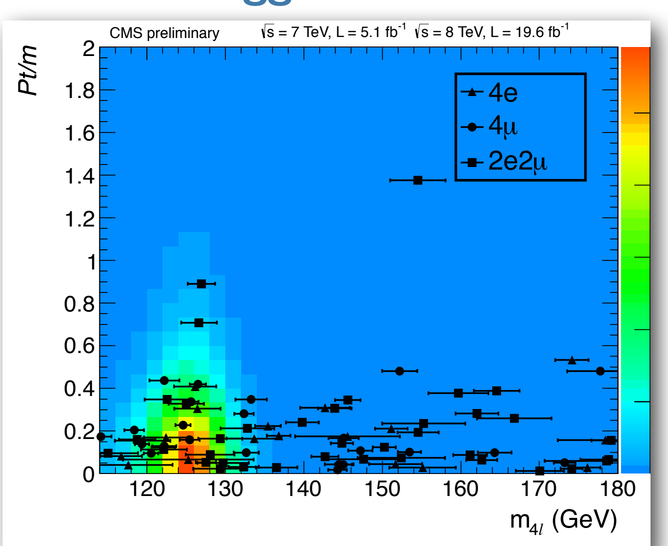
Event categories in the analysis

- The event sample is split into two categories:
  - Category I: Events with $N_{JETS} < 2$. (5% VBF)
  - Category II: Events with $N_{JETS} \geq 2$. (20% VBF)
- Discriminate production mechanisms (fermion- vs. vector-boson-induced):
  - Cat. I: using discriminant: p_T/m_{4l}
  - Cat. II: using linear discriminant: $V_D = \alpha\, \Delta\eta_{jj} + \beta\, m_{jj}$
- Analysis based on correlated 3D distributions:
  - Cat. I: $\mathcal{P}(m_{4l}) \times \mathcal{P}(KD \mid m_{4l}) \times \mathcal{P}(p_T/m_{4l} \mid m_{4l})$
  - Cat. II: $\mathcal{P}(m_{4l}) \times \mathcal{P}(KD \mid m_{4l}) \times \mathcal{P}(V_D \mid m_{4l})$

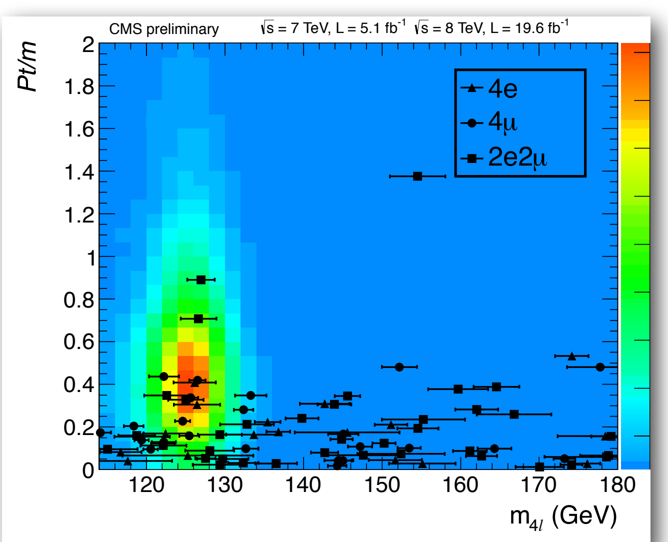
V_D distribution



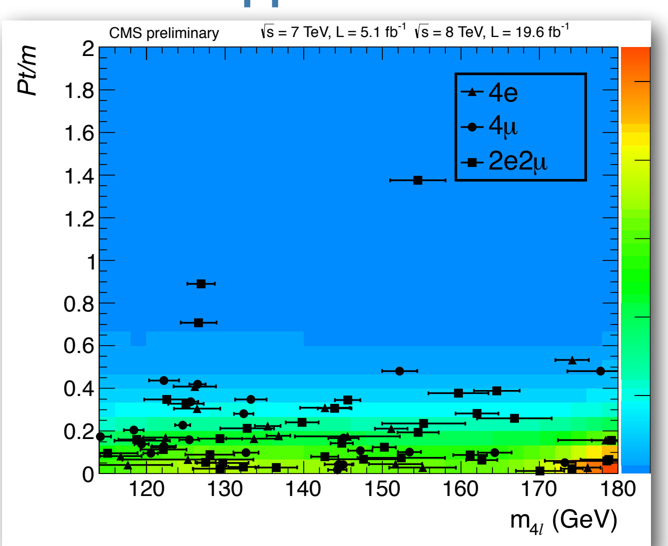
gg → H



VBF



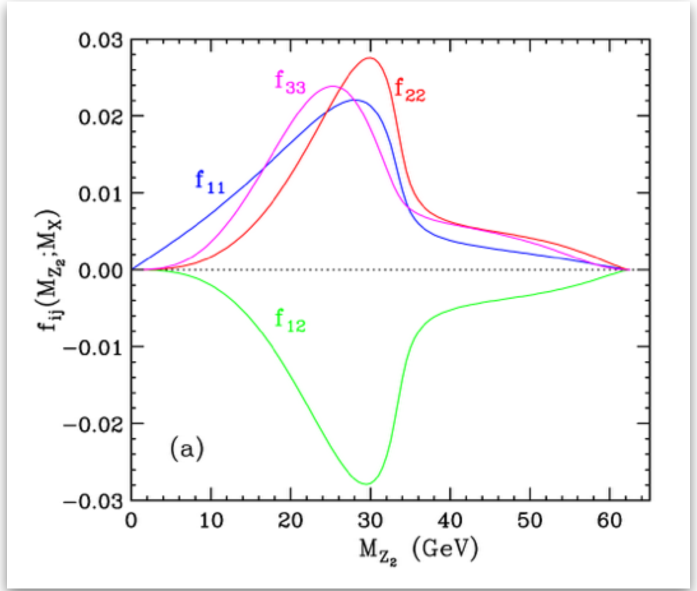
qq → ZZ



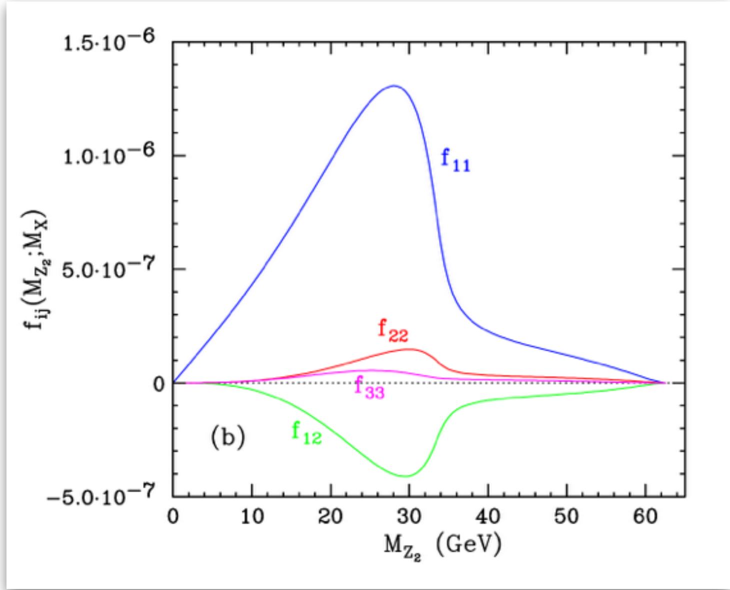
Interference effects - m_{Z2} example

- Important interference effects between operators in presence of multiple non-zero couplings

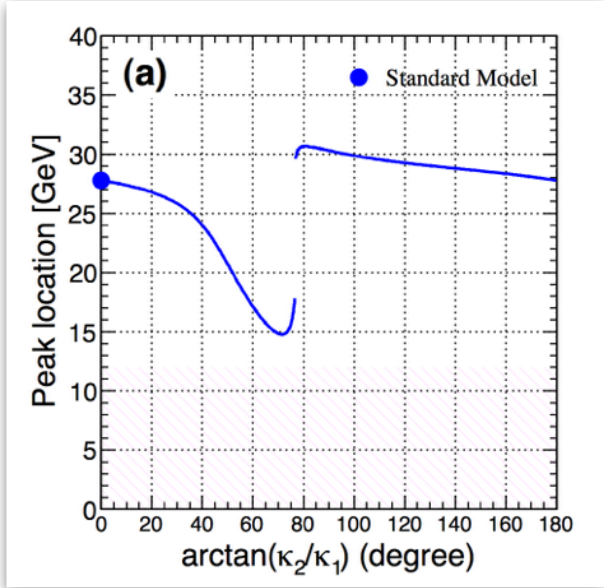
m_{Z2} distribtion (unit normalised)

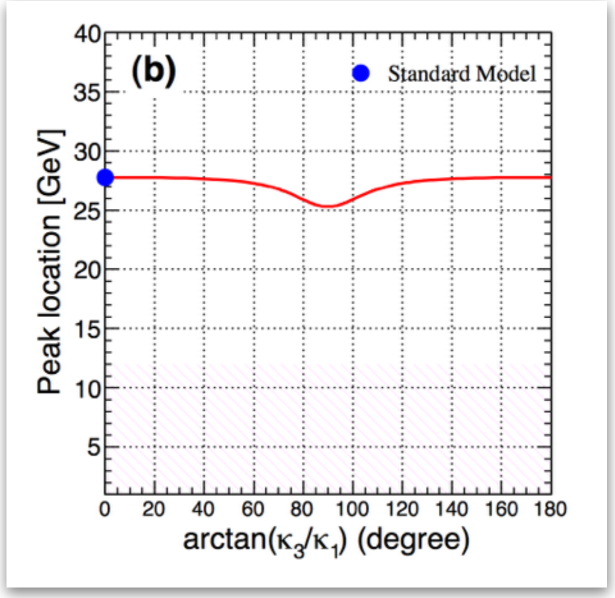


m_{Z2} distribtion (normalised to yield)



- Peak of m_{Z2} distribution displays "first order phase transition" from κ_1-κ_2 interference, no such feature when considering κ_1 and κ_3





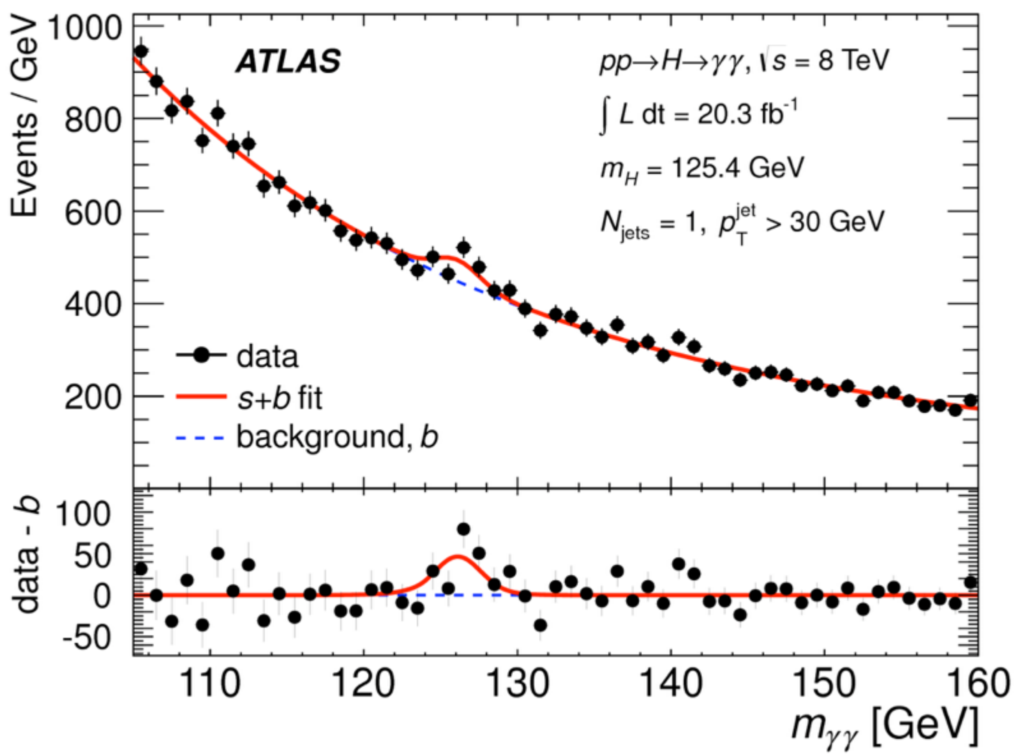
how much we can gain in sensitivity if we optimise the analysis to exploit the interference effects?

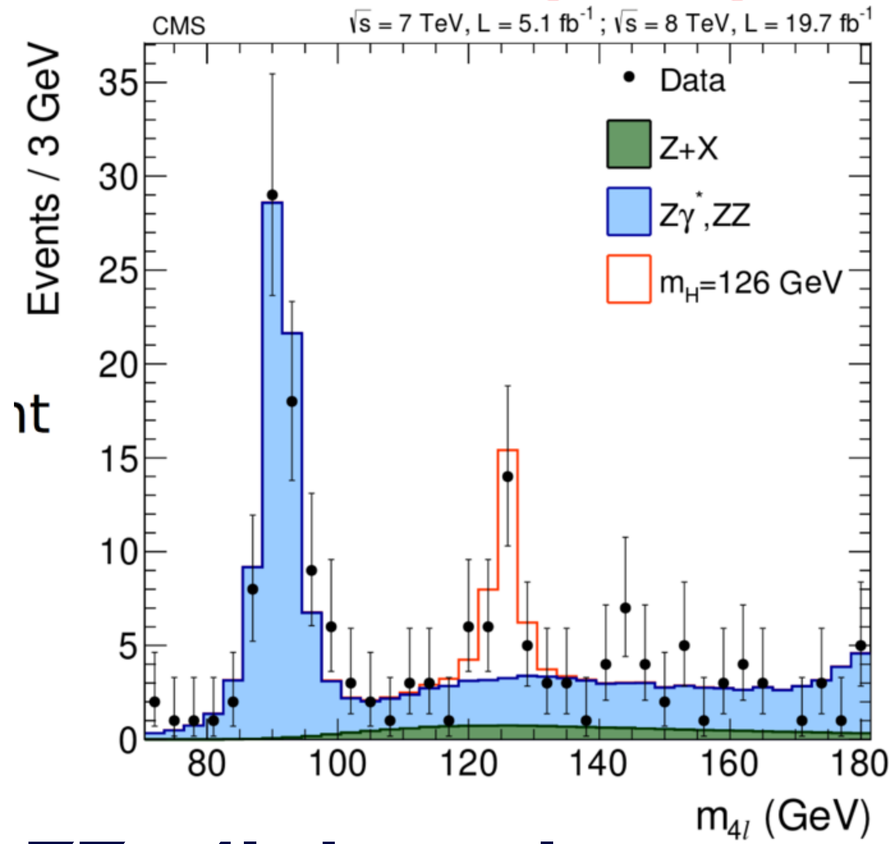
Modelling of processes @ higher orders

- **Three major improvements** in the theoretical Higgs modelling in 2015:
  - **N^3LO** cross section, fully inclusive
    [Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2015)]
  - **NNLO H+J** cross section, fully exclusive
    [Boughezal, Caola, Melnikov, Petriello, Schulze (2015)], [Boughezal, Focke, Giele, Liu, Petriello (2015)][Chen, Gerhmann, Glover, Jaquier (in progress)]
  - **NNLO VBF** cross section, fully exclusive
    [Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)]
- **Improvements** in the theoretical modelling of VV' production:
  - **NNLO pp→VV'+X** cross section, fully exclusive
    [Catani, Cieri, de Florian, Ferrera, Grazzini; Grazzini, Kallweit, Rathlev (Vgamma)] [Gehrmann, Grazzini, Kallweit, Maieroefer, v. Manteuffel, Pozzorini, Rathlev, Tancredi (WW)] [Cascioli, Gehrmann, Grazzini, Kallweit, Maieroefer, v. Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs (ZZ)] [Grazzini, Kallweit, Rathlev (ZZ*, in progress)]

Overview of the channels

- **Fiducial XS measured in H→γγ and H→ZZ→4l channels**
  - Fully reconstructible decays with excellent mass resolution (H→γγ : 1-2%, H→ZZ→4l: 1-3%)





H→γγ channel:

- **Small branching fraction** (~0.2%), but allows **high selection efficiency** (~40-45%)
- **A few hundred reconstructed signal events** expected after selection (8 TeV Run I)
- **Large continuum background** from QCD γγ and γ+jet.

H→ZZ→4l channel:

- Very **small branching fraction** (~0.01%), but **very clean signature**
- About **15-20 reconstructed signal events** expected after selection (8 TeV Run I)
- **Very small background** from irreducible pp→ZZ and reducible Z+jets.

Differential XS: H→ZZ→4l

- Measured as a function of several **jet-related observables:**
  - **N(jet), $p_T(j_1)$** (many other observables, see backup)
  - Sensitive to theoretical modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects, etc.

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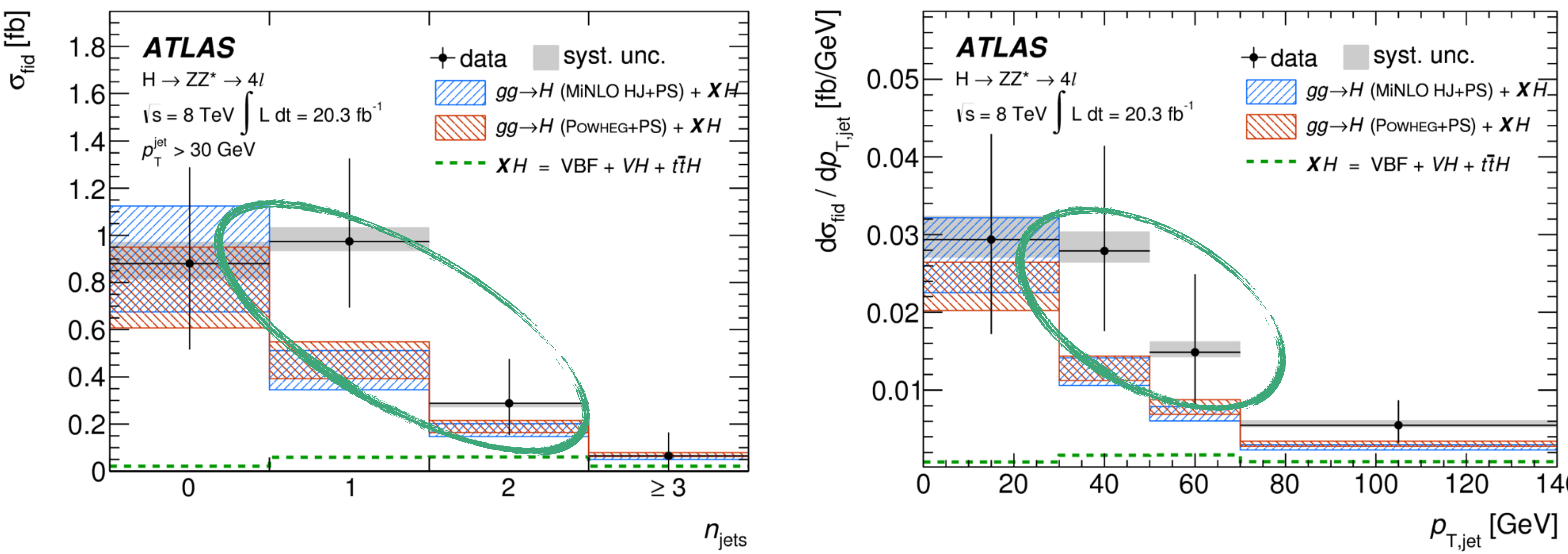
ATLAS @ 8TeV:



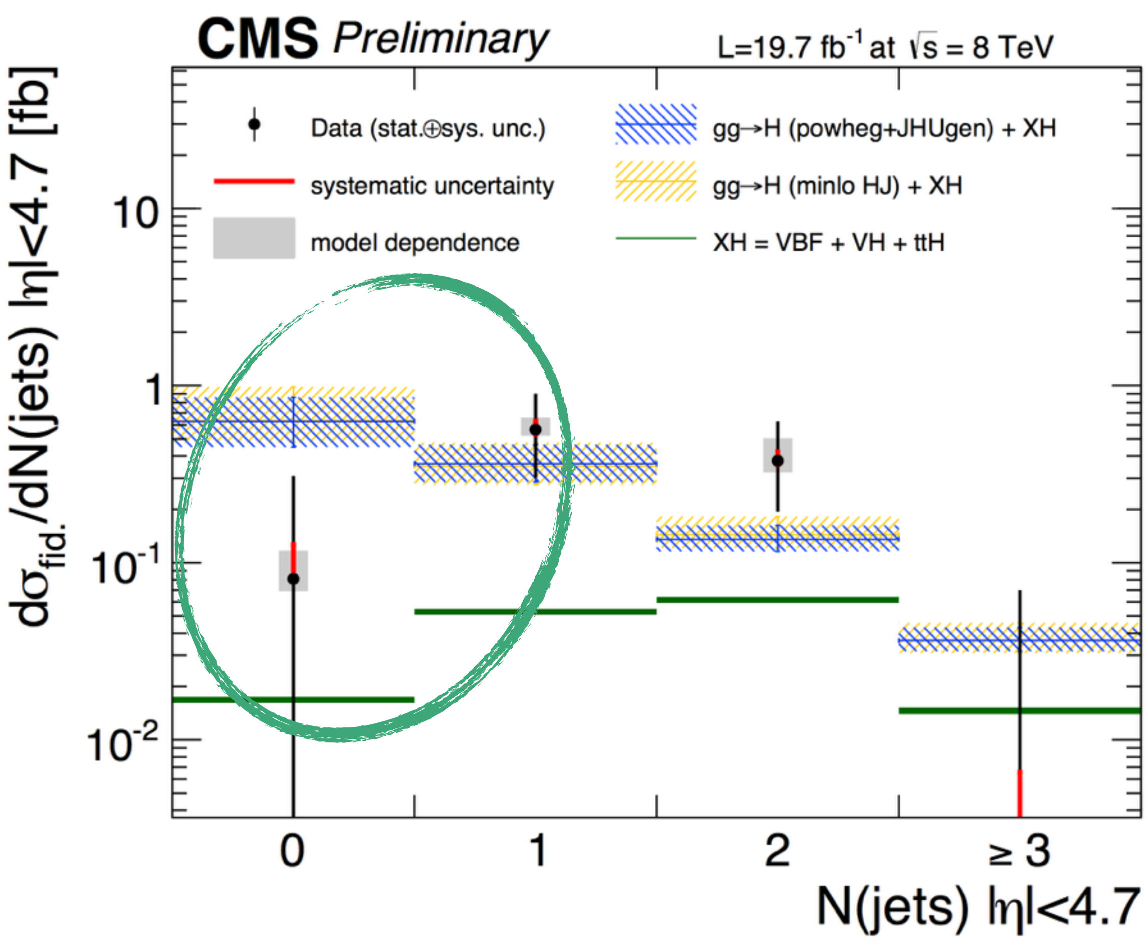
Somewhat higher jet activity observed in data w.r.t theoretical estimates

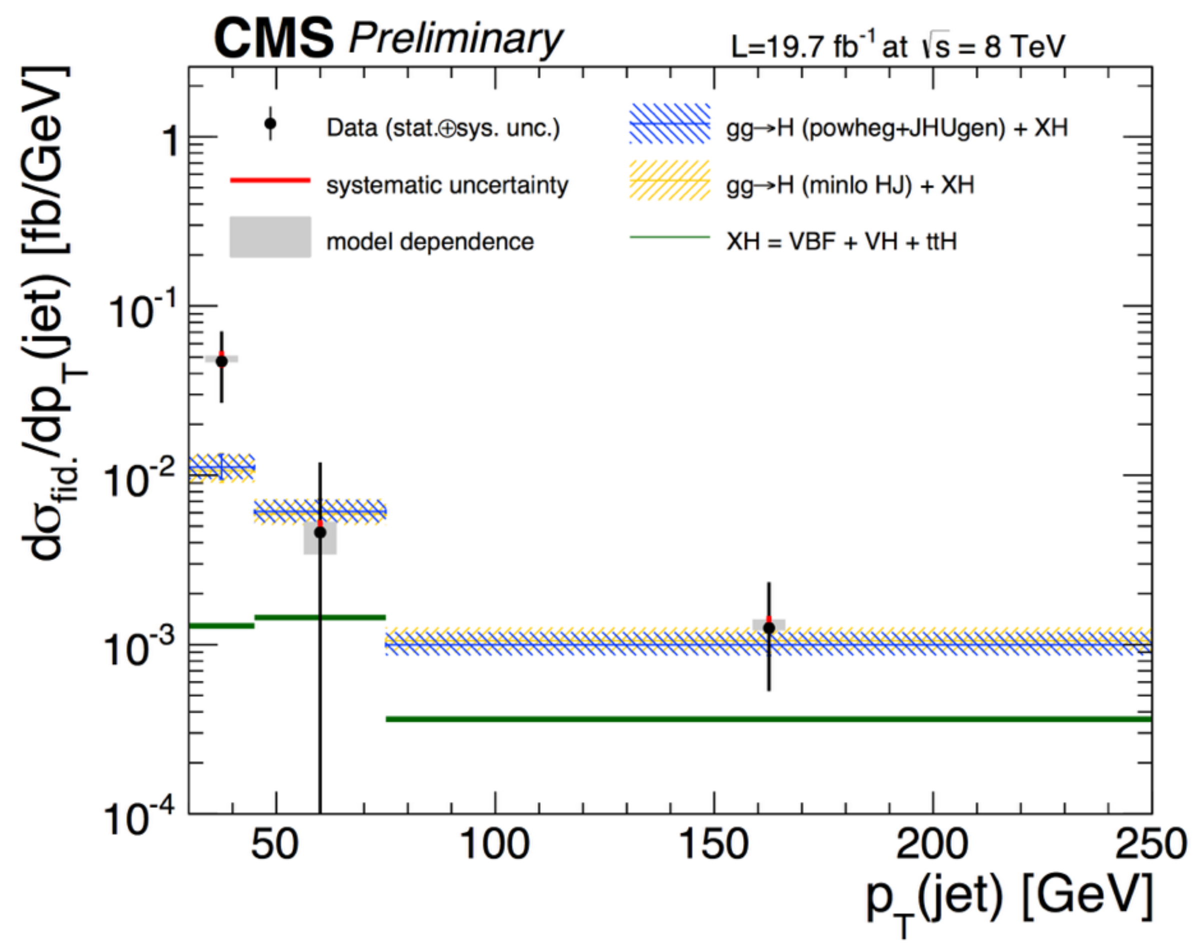
Differential XS: H→ZZ→4l

CMS-PAS-HIG-14-028

- Measured as a function of several **jet-related observables:**
  - **N(jet), $p_T(j_1)$** (many other observables, see backup)
  - Sensitive to theoretical modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects, etc.

CMS @ 8TeV:





Somewhat higher jet activity observed in data w.r.t theoretical estimates also seen by CMS: *p*-value ~13%

Inclusive cross sections: H→γγ

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CMS-PAS-HIG-14-016

- Inclusive cross sections at 8TeV, measured in **H→γγ channel**
  - Un-binned maximum likelihood fit to **$m_{\gamma\gamma}$** (primarily based on legacy analyses)
  - Compared to **theoretical estimates** with **NNLO+NNLL QCD accuracy**
  - **ATLAS:** compared also to other state-of-art predictions.

ATLAS @ 8TeV:

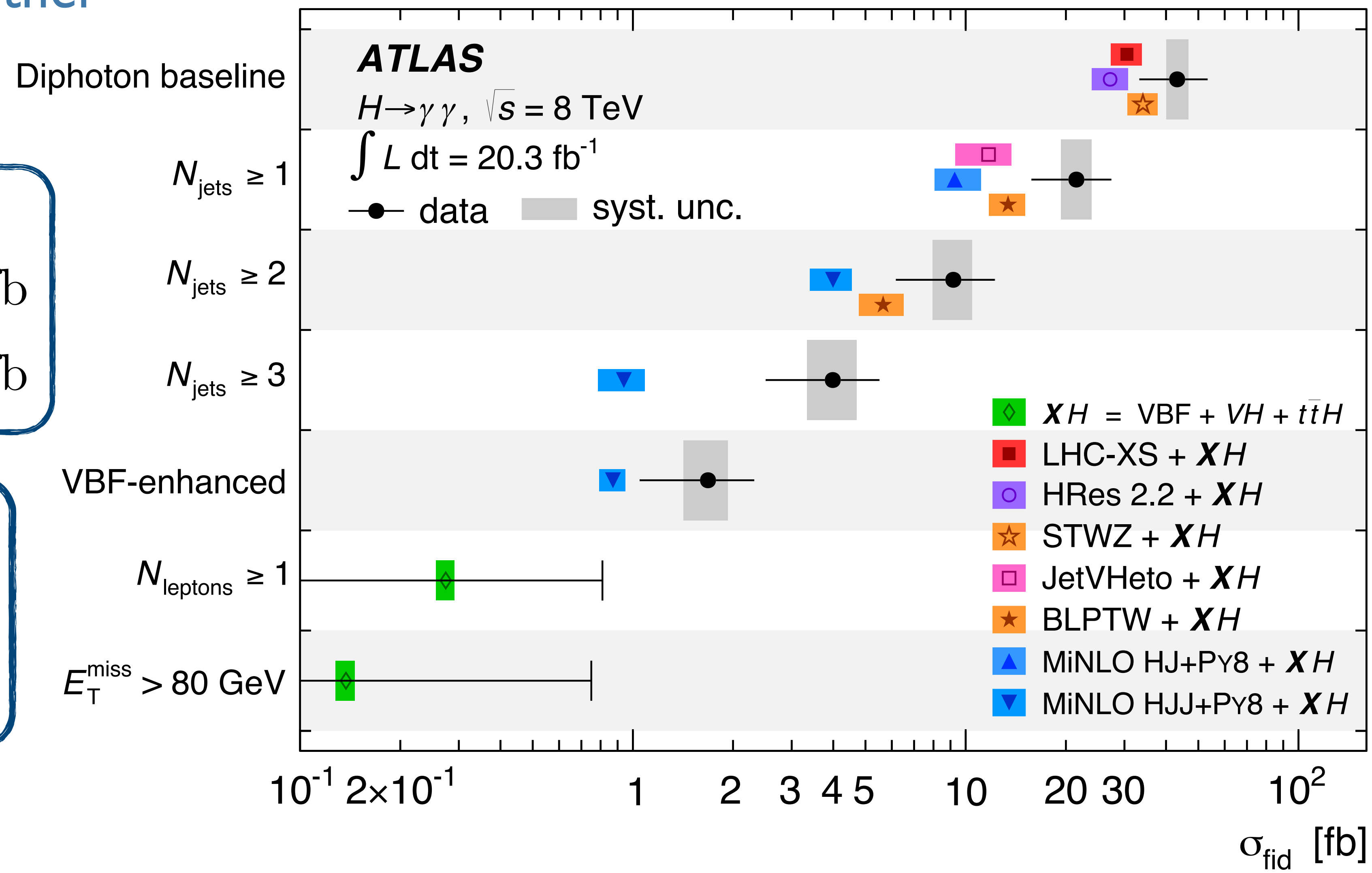
$$\sigma_{\text{fid}} = 43.2 \pm 9.4(\text{stat.})^{+3.2}_{-2.9}(\text{syst.})\ \text{fb}$$

$$\sigma_{\text{fid}}^{\text{SM}} = 30.5 \pm 3.3\ \text{fb}$$

CMS @ 8TeV:

$$\sigma_{\text{fid}} = 32 \pm 10(\text{stat.}) \pm 3(\text{syst.})\ \text{fb}$$

$$\sigma_{\text{fid}}^{\text{SM}} = 31^{+4}_{-3}(\text{stat.})\ \text{fb}$$



Inclusive cross sections: $H \to \gamma\gamma$

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CMS-PAS-HIG-14-016

- Inclusive cross sections at 8TeV, measured in **$H \to \gamma\gamma$ channel**
  - Un-binned maximum likelihood fit to $\mathbf{m_{\gamma\gamma}}$ (primarily based on legacy analyses)
  - Compared to **theoretical estimates** with **NNLO+NNLL QCD accuracy**
  - **ATLAS:** compared also to other state-of-art predictions.

ATLAS @ 8TeV:

$$\sigma_{\text{fid}} = 43.2 \pm 9.4(\text{stat.})^{+3.2}_{-2.9}(\text{syst.})\ \text{fb}$$

$$\sigma^{\text{SM}}_{\text{fid}} = 30.5 \pm 3.3\ \text{fb}$$

CMS @ 8TeV:

$$\sigma_{\text{fid}} = 32 \pm 10(\text{stat.}) \pm 3(\text{syst.})\ \text{fb}$$

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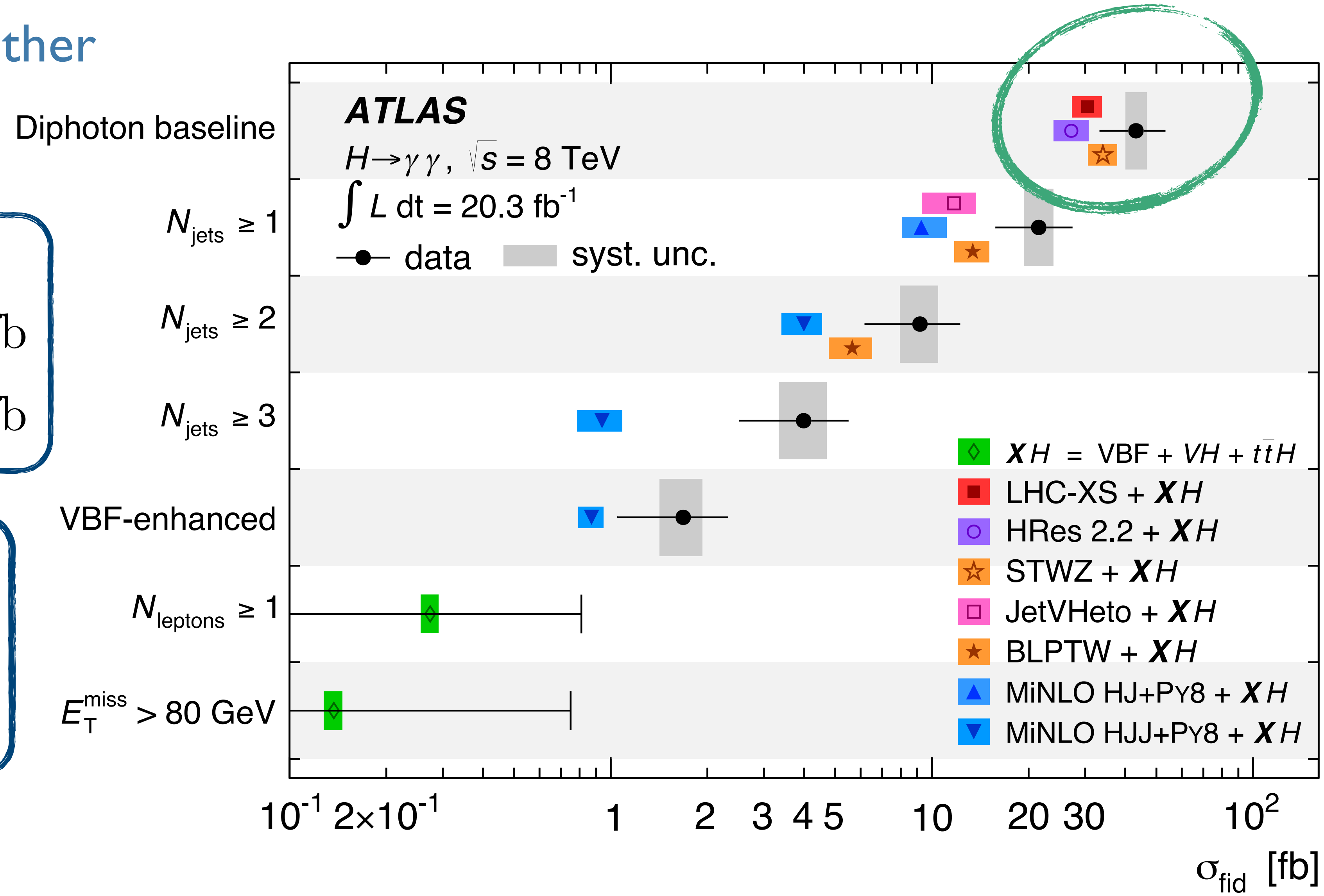

Compatible with theoretical estimates (slightly higher rates by ATLAS)

Differential XS: H→γγ

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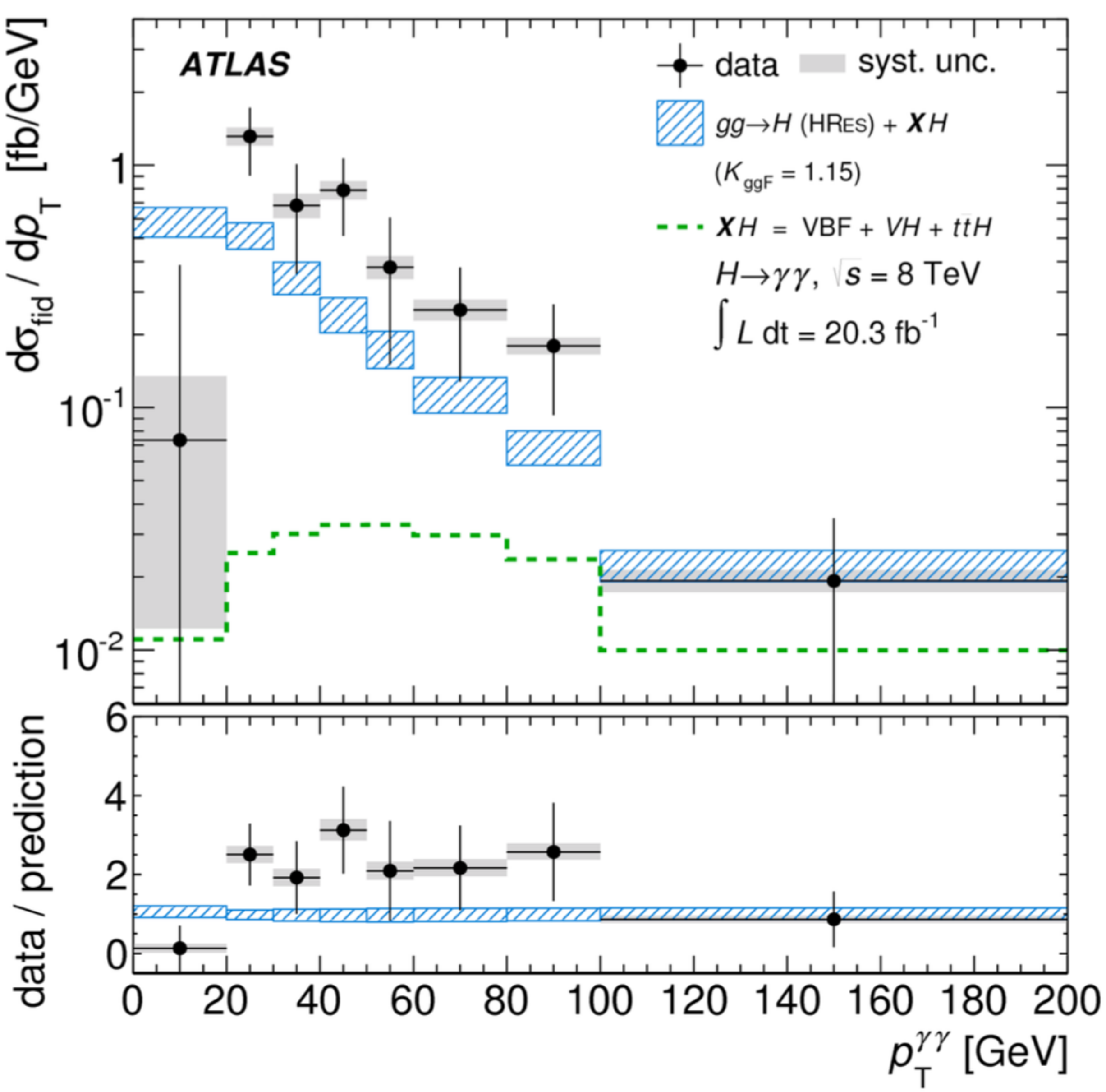
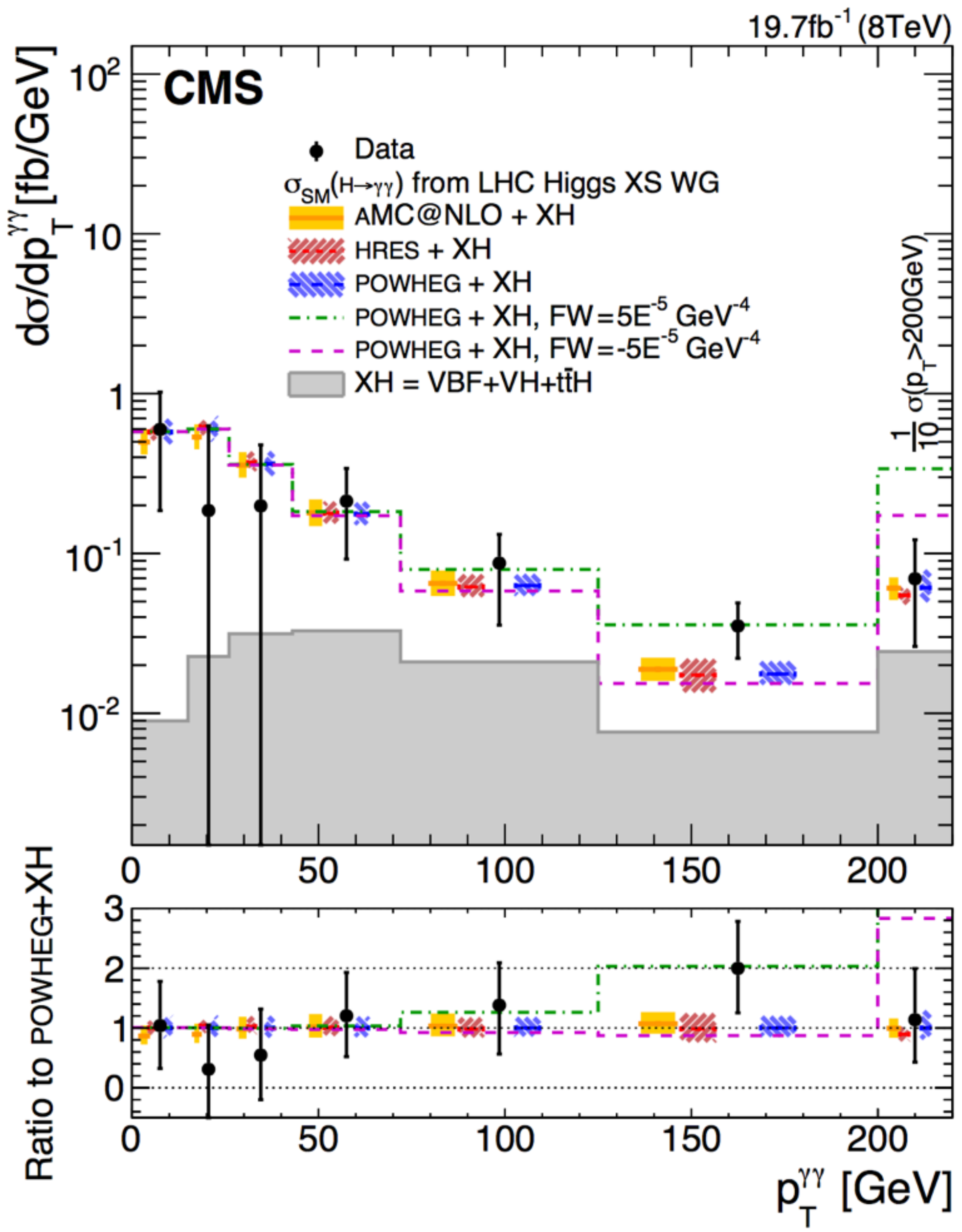
CMS-PAS-HIG-14-016

- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions** (see backup).





Differential XS: H→γγ

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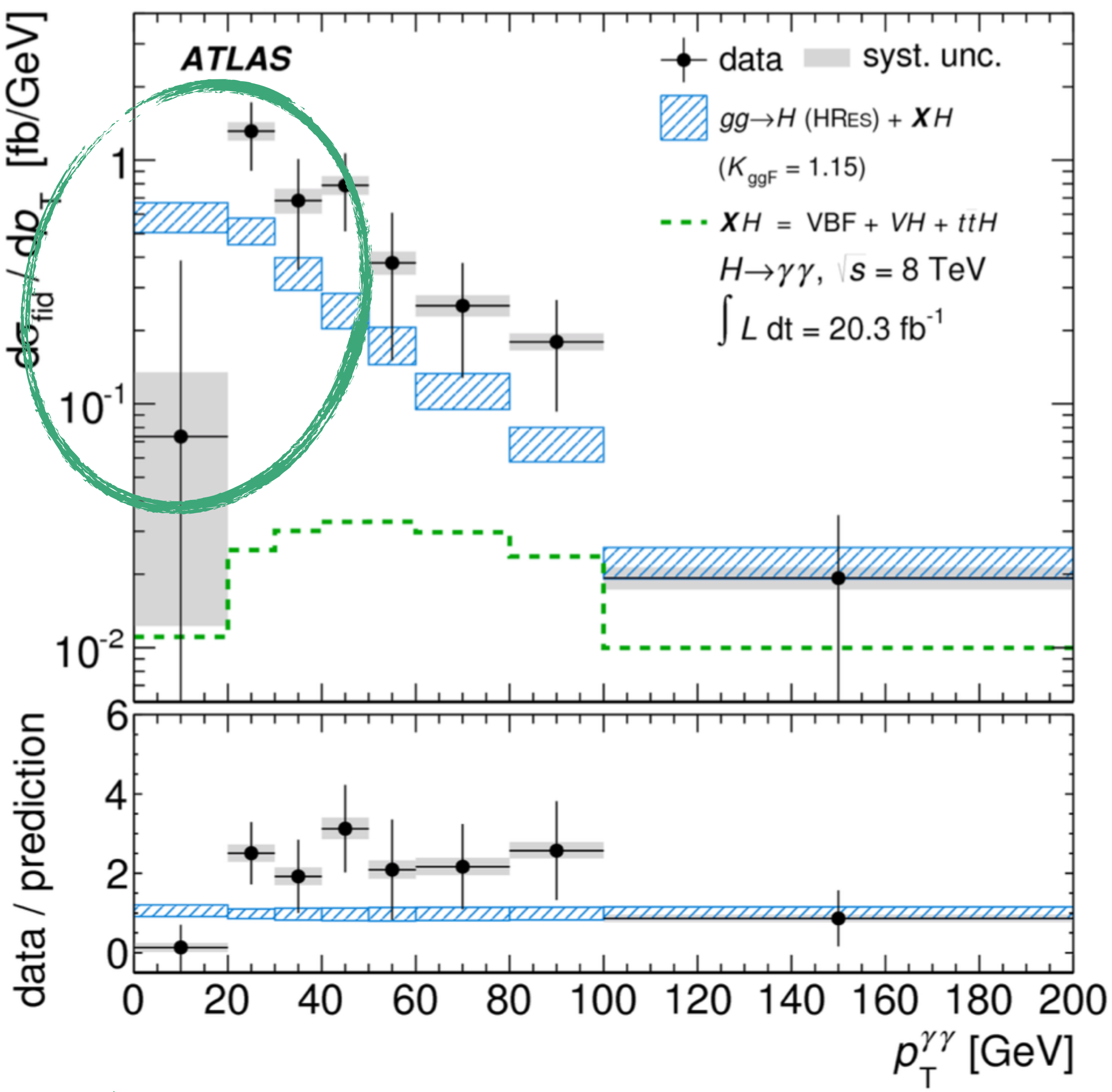
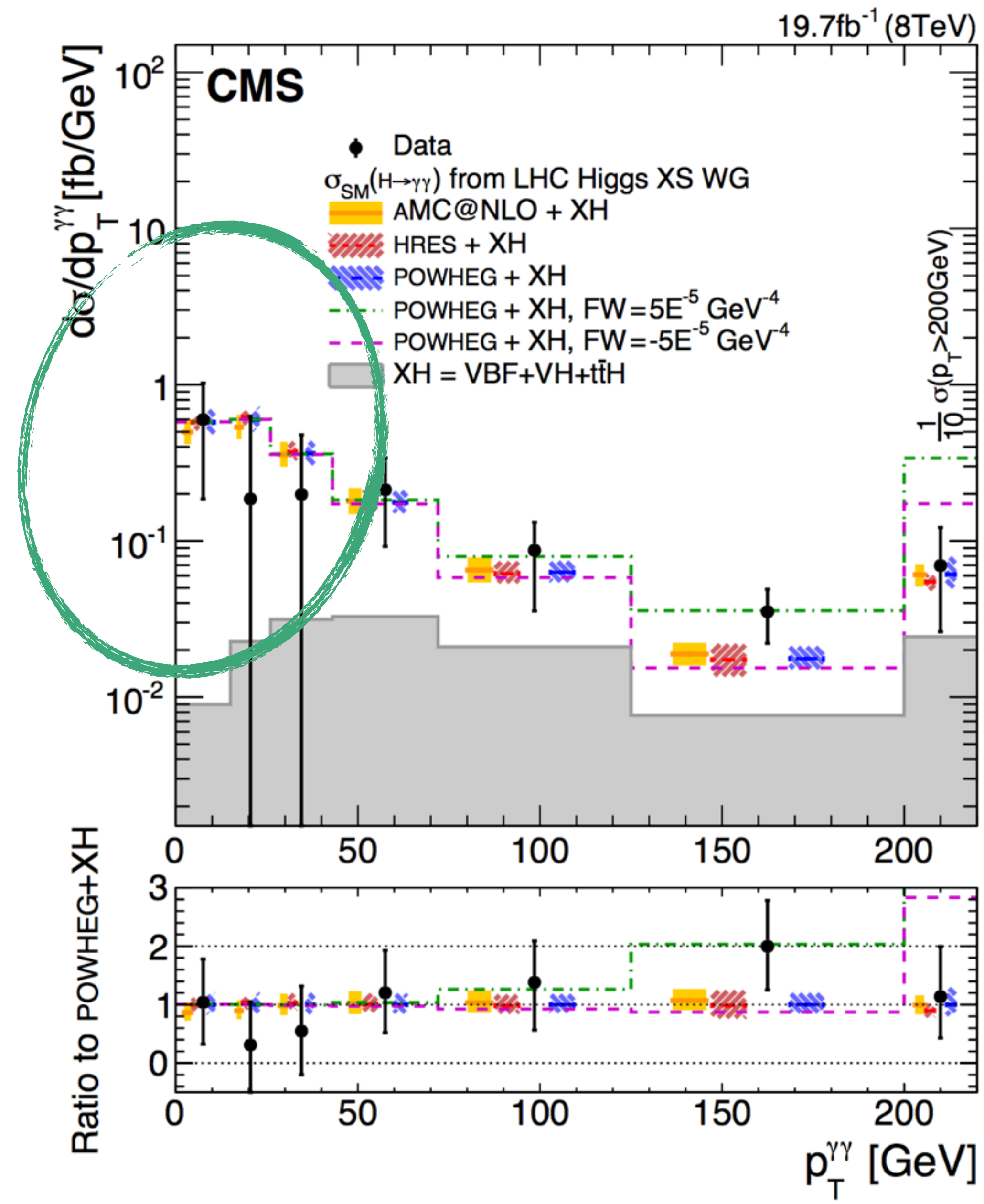
CMS-PAS-HIG-14-016

- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions** (see backup).





Some deficit in low-p_T range observed by ATLAS (not in CMS)

Differential XS: H→γγ

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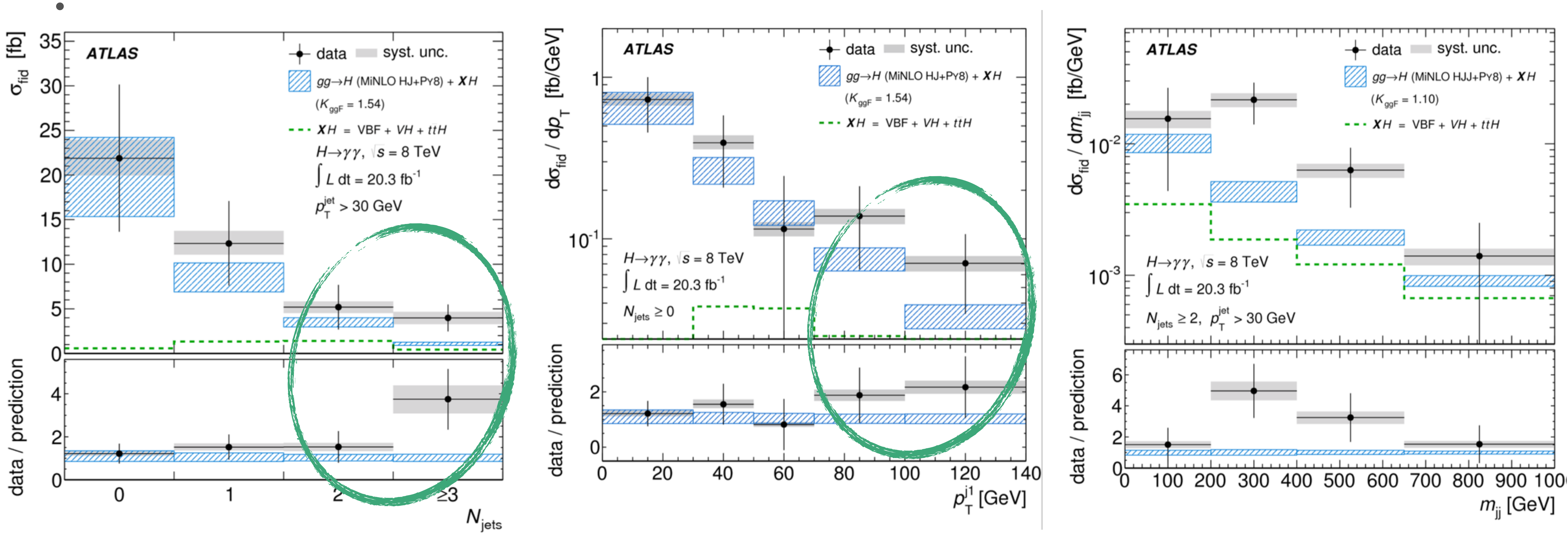
- Measured as a function of several **jet-related observables:**
  - **N(jet), $p_T(j_1)$, m(jj)** (many other observables, see backup)
  - Sensitive to theoretical modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects, etc.

ATLAS @ 8TeV:



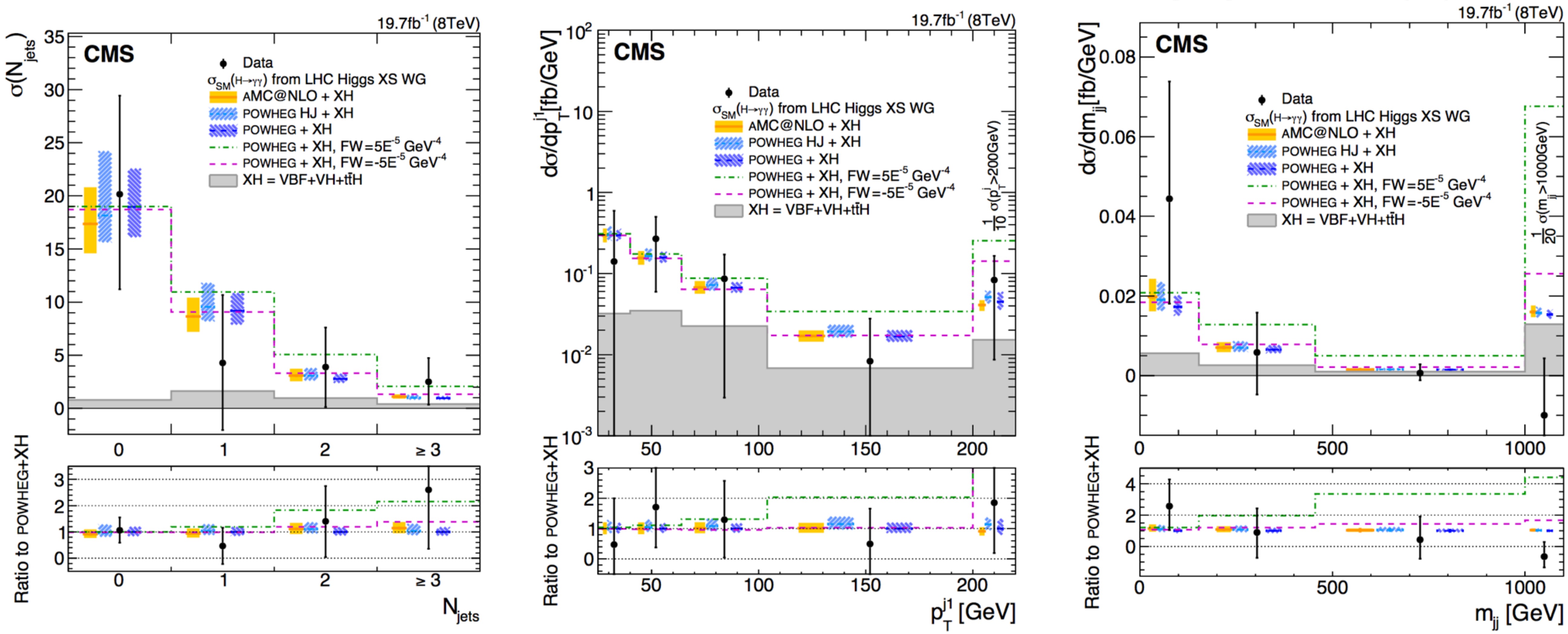
Slightly higher jet activity observed in data w.r.t theoretical estimates

Differential XS: H→γγ

CMS-PAS-HIG-14-016

- Measured as a function of several **jet-related observables:**
  - **N(jet), $p_T(j_1)$, m(jj)** (many other observables, see backup)
  - Sensitive to theoretical modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects, etc.

CMS @ 8TeV:

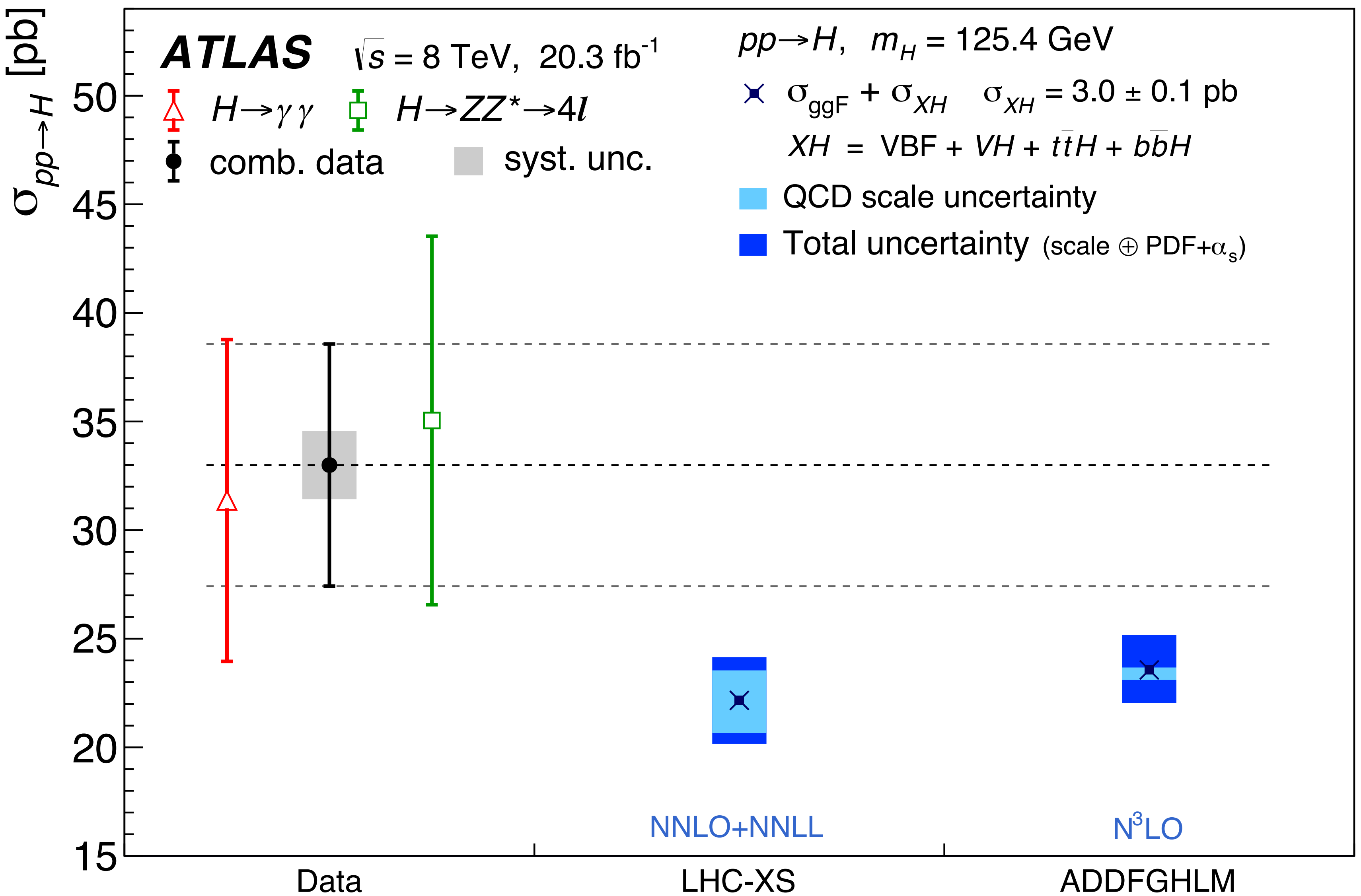


Good agreement with theoretical estimates in case of CMS

Combination: Inclusive XS ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$)

PRL. 115 (2015) 091801

- Inclusive XS from the combination of two channels
  - Compared to theoretical estimates with **NNLO+NNLL** and **N^3LO** accuracy in **QCD.**



p-values:

LHC-XS: 5.5 %

ADDFGHLM: 9%

$H \rightarrow 4l$:	**35.0 ± 8.4 (stat) ± 1.8 (sys) pb**
$H \rightarrow \gamma\gamma$:	**31.4 ± 7.2 (stat) ± 1.6 (sys) pb**
Combined:	**33.0 ± 5.3 (stat) ± 1.6 (sys) pb**

Total inclusive cross section measured by ATLAS is higher than state-of-art predictions