One-hour Lecture on
Standard Model Measurements

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Outline

☐ Concept & methodology

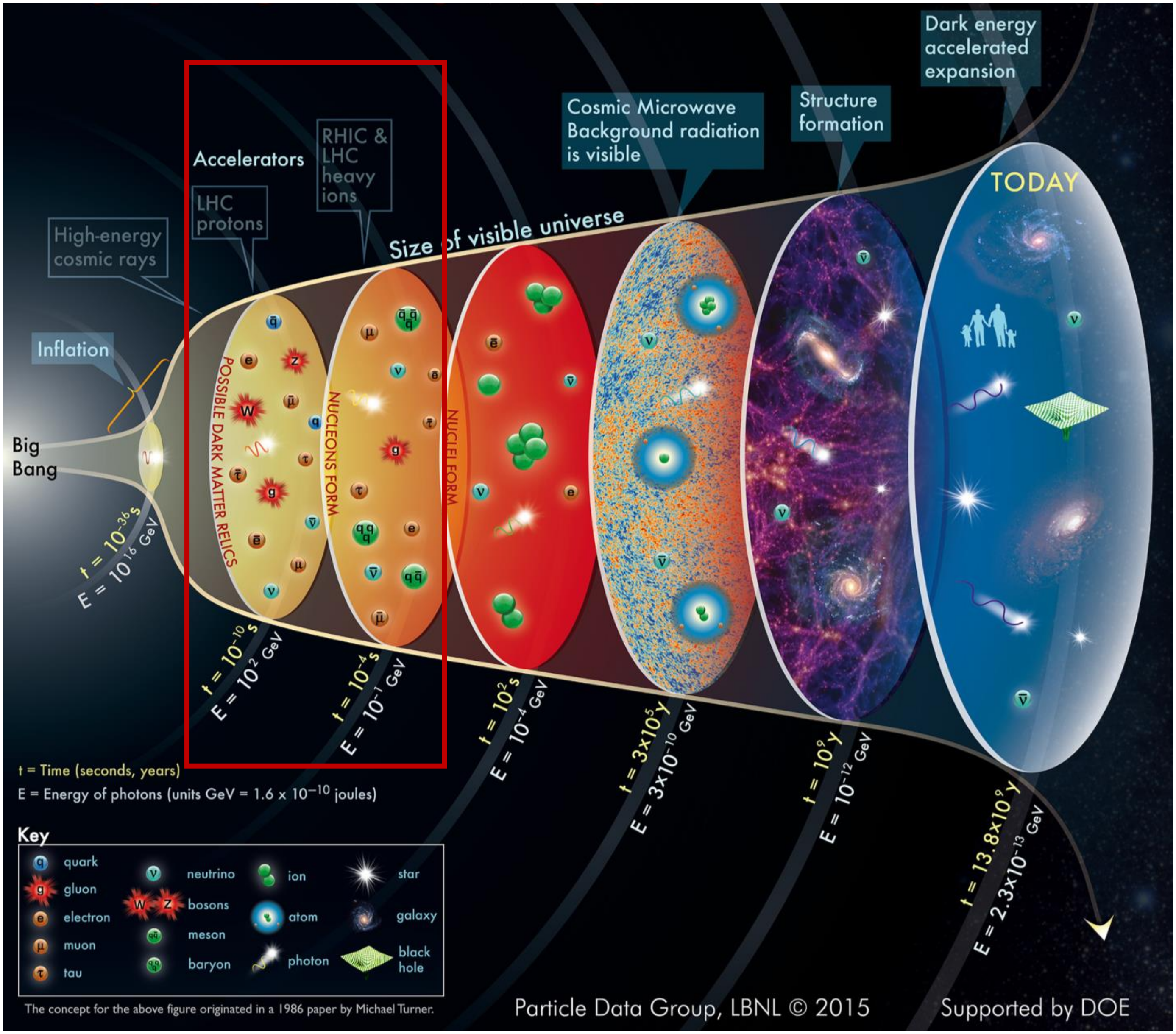
☐ Review of current status

To briefly reveal how do we exactly measure the smallest scale physics

Disclaimer:
→ Materials most relevant to LHC experiments
→ A good digest of previous lectures assumed
→ Focus given to introductory materials
→ Frequently pick up figures/results from ATLAS experiment for lecturing
→ Difficulty of material selection due to mixture of audience, can always contact me via email for discussions

Concept & methodology

Physics Scales at the LHC



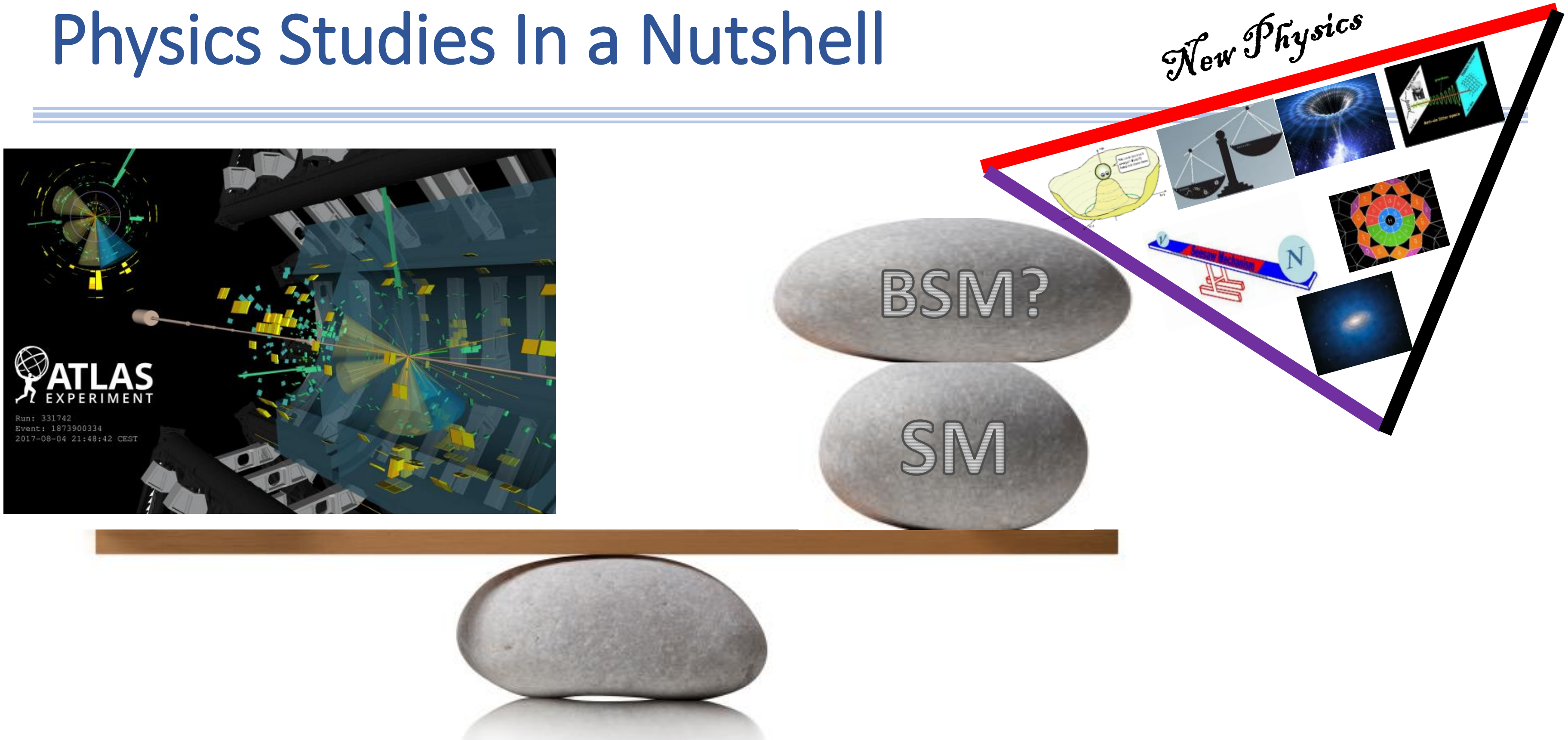
The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

LHC experiments scrutinize physics at QCD, EW, and up to TeV scales

Physics Studies In a Nutshell



Measurements (indirect searches)

=> optimized phase space for precision test of the SM

Direct searches

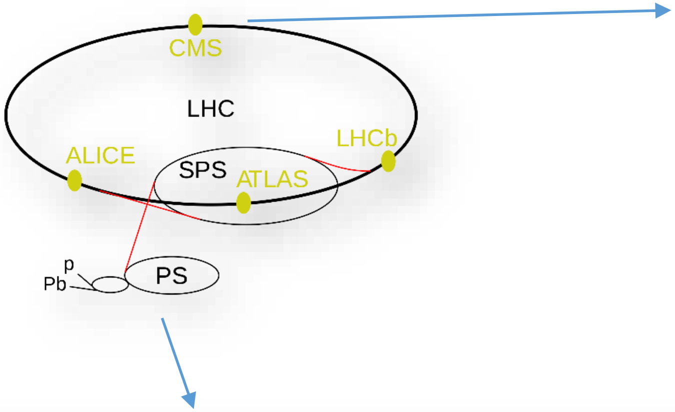
=> optimized phase space for searching for BSM signals of particular types

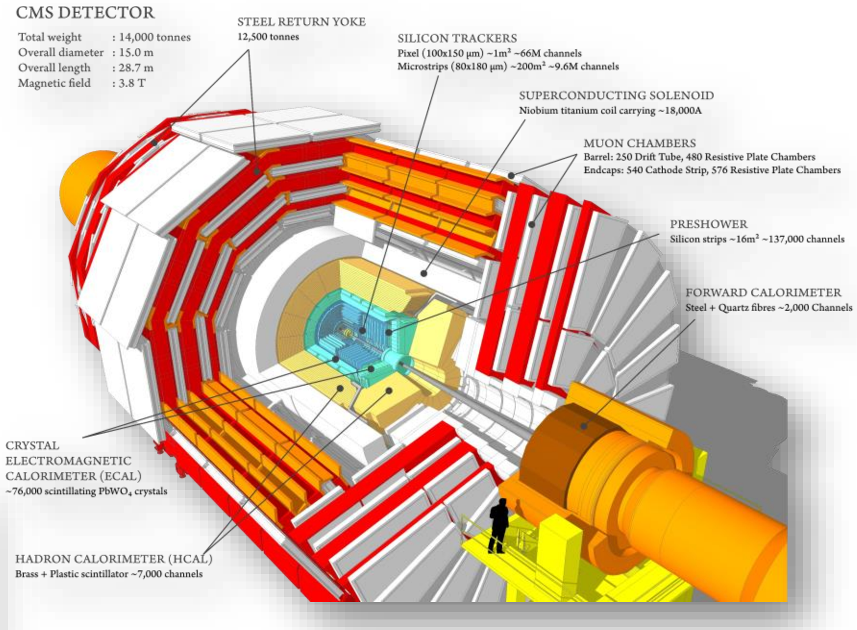
Been carried out in a vast variety of final states and phase spaces

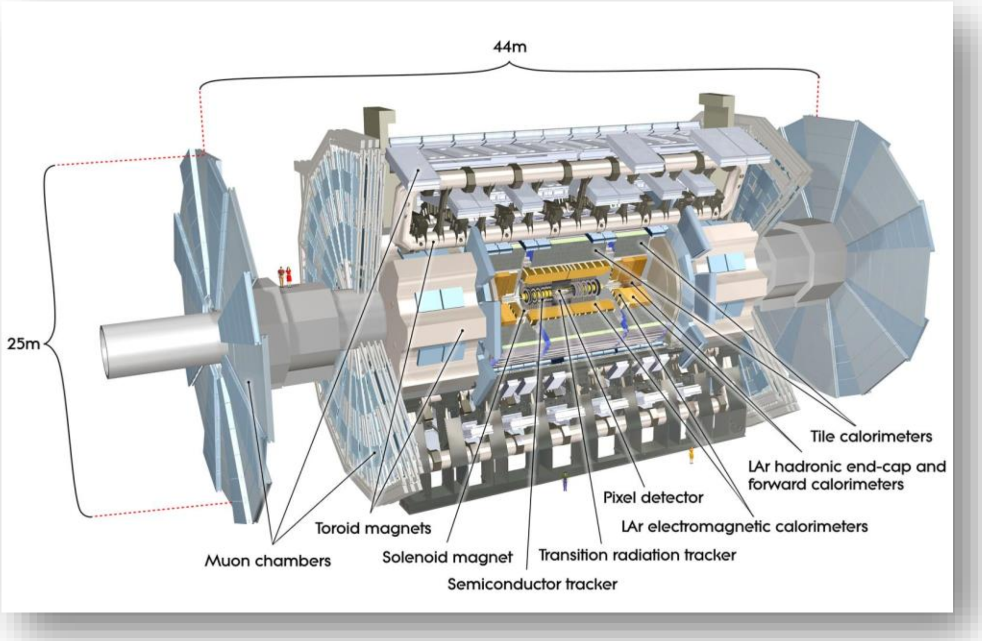
As of today, no clear sign of BSM was found from collider studies

Expedition will continue with up to ultimate O(1000) fb^{-1} of data

LHC, ATLAS and CMS







Two general-purpose detectors with excellent performance and broad physics potentials:

Higgs and other SM measurements, direct search for new physics at EW and TeV scales, …

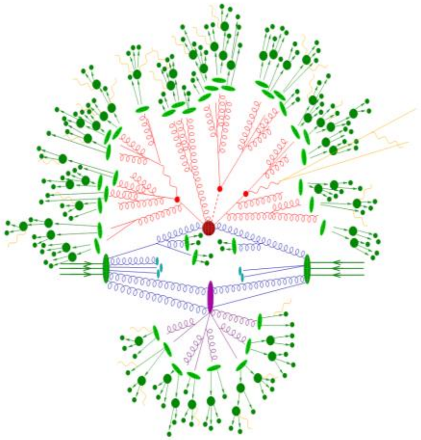
From collisions to physics

$< 10^{-10}$ s
Collision and short-range interactions:
Hard-scattering, parton-shower, and hadronization

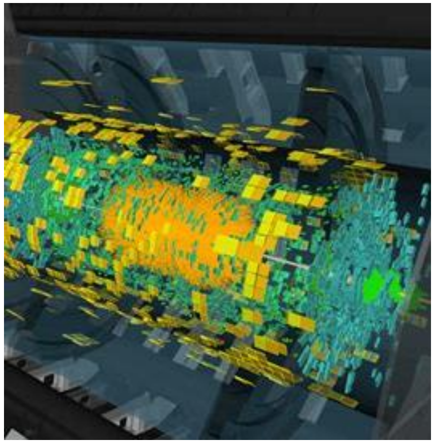
$10^{-10} – 10^{-7}$ s
Final-state particles interact with detector and generate electronic signals

10^{-6} s – 10^{0} s
Trigger decision (L1:μs, High-level: ms - s) and Data acquisition

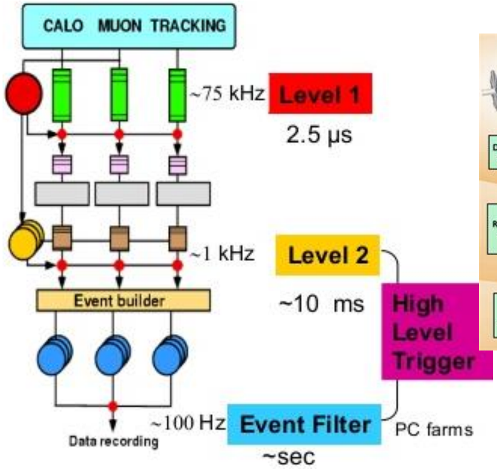
> 1s
Post-processing of data: calibration & reconstruction (1s – 1 min), distribution over network, and physics studies



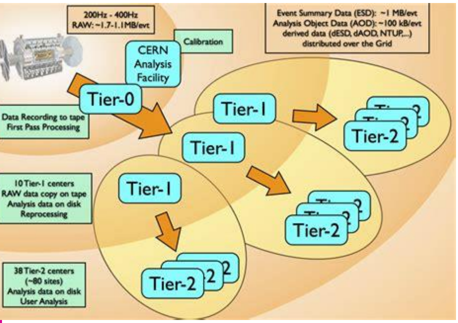
A sketch of collision events



Detector signals



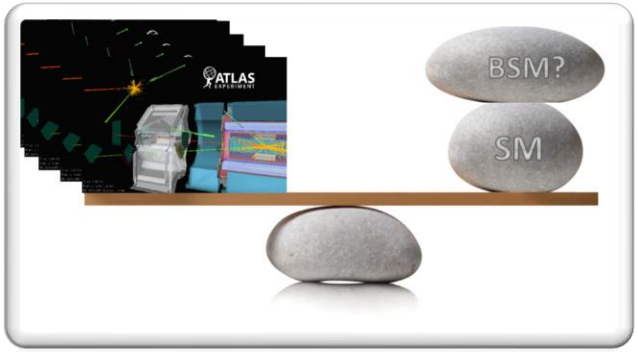
Trigger scheme



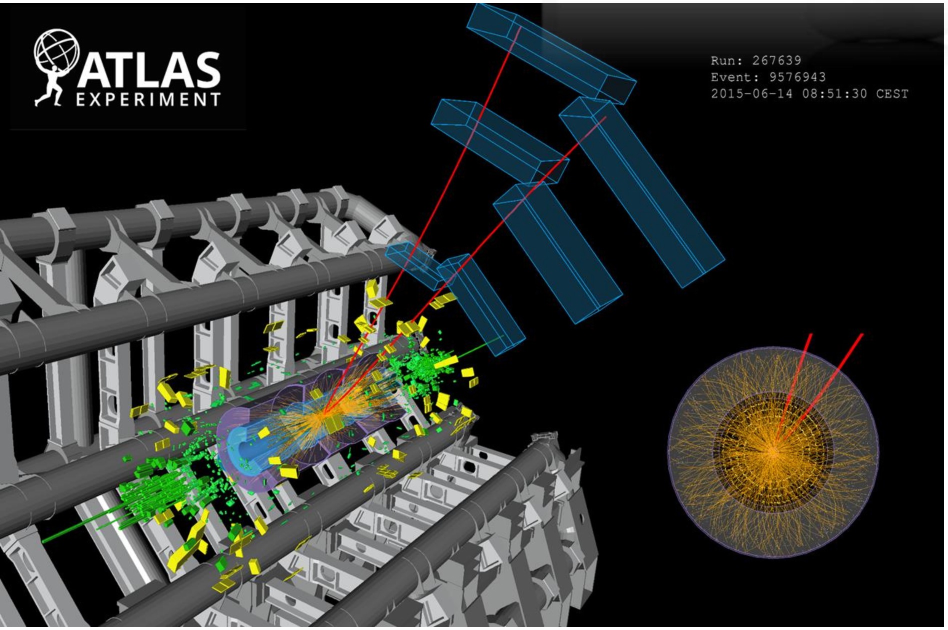
Offline computing

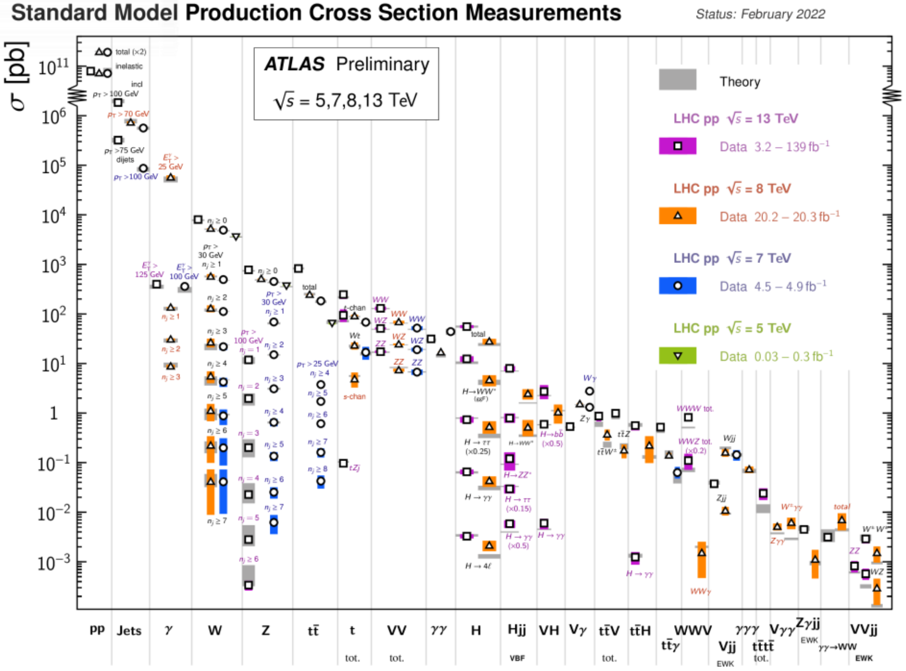
Workflows

Data flow: detector response, triggering, DAQ, physics object reconstruction and calibration, data taking and distributing



Prediction flow: physics process modelling, detector simulation, physics object corrections

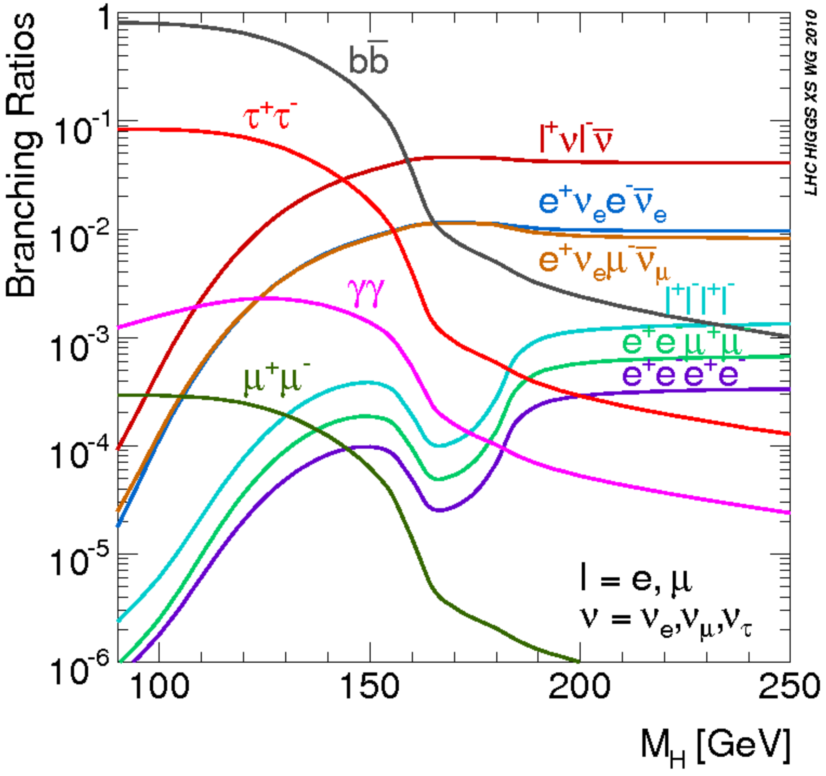




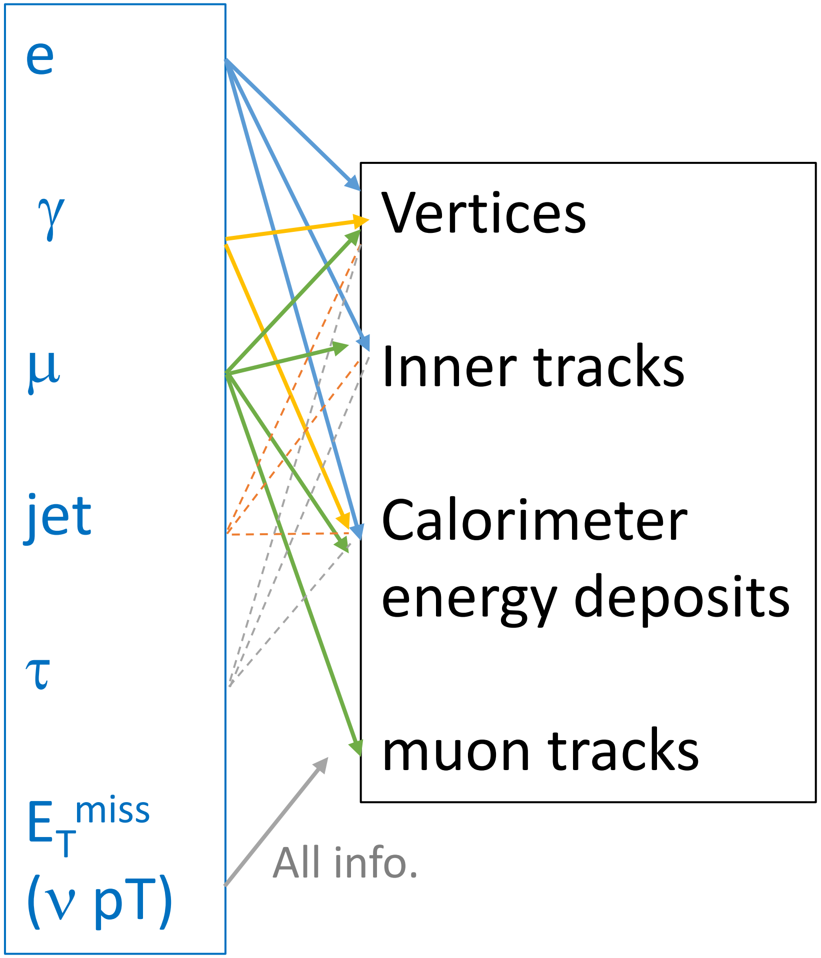
Physics analysis (data, predictions), statistical methods → physics results

Objects for Physics

Final state particles from interesting physics processes interact with detectors



Example: Higgs decay channels to final state particles



e

γ

μ

jet

τ

E_T^{miss} (ν pT)

Vertices

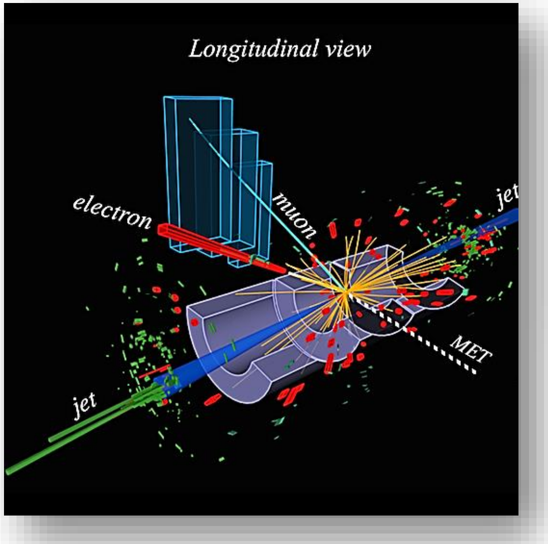
Inner tracks

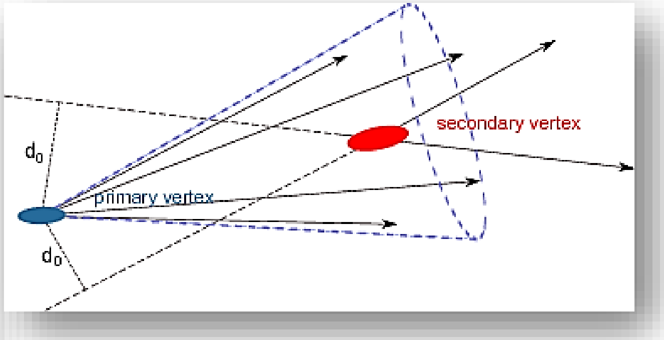
Calorimeter energy deposits

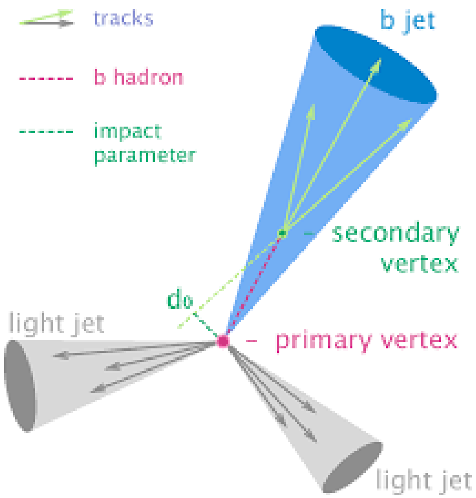
muon tracks

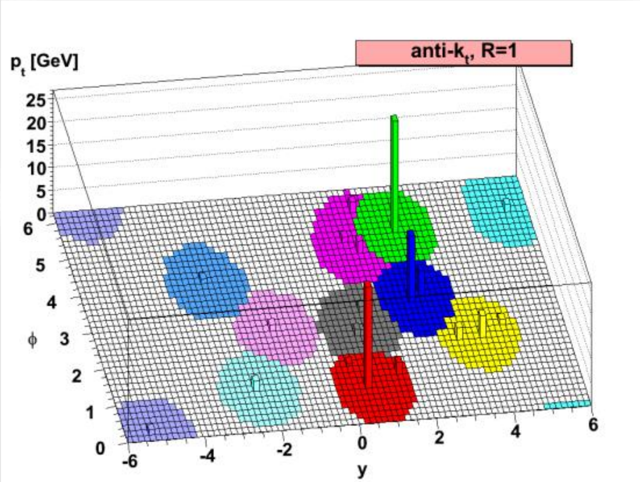
All info.

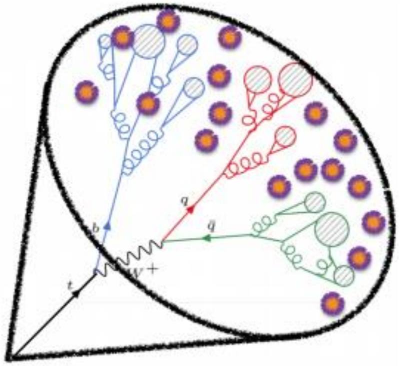
Examples of Physics Objects

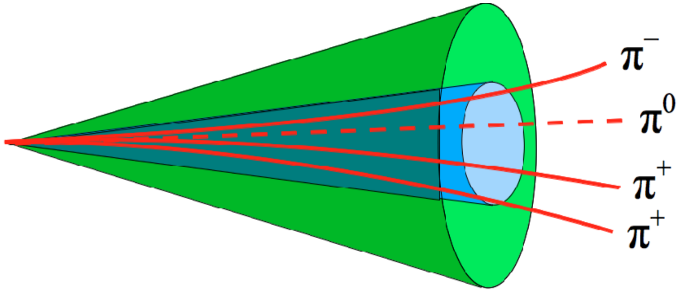




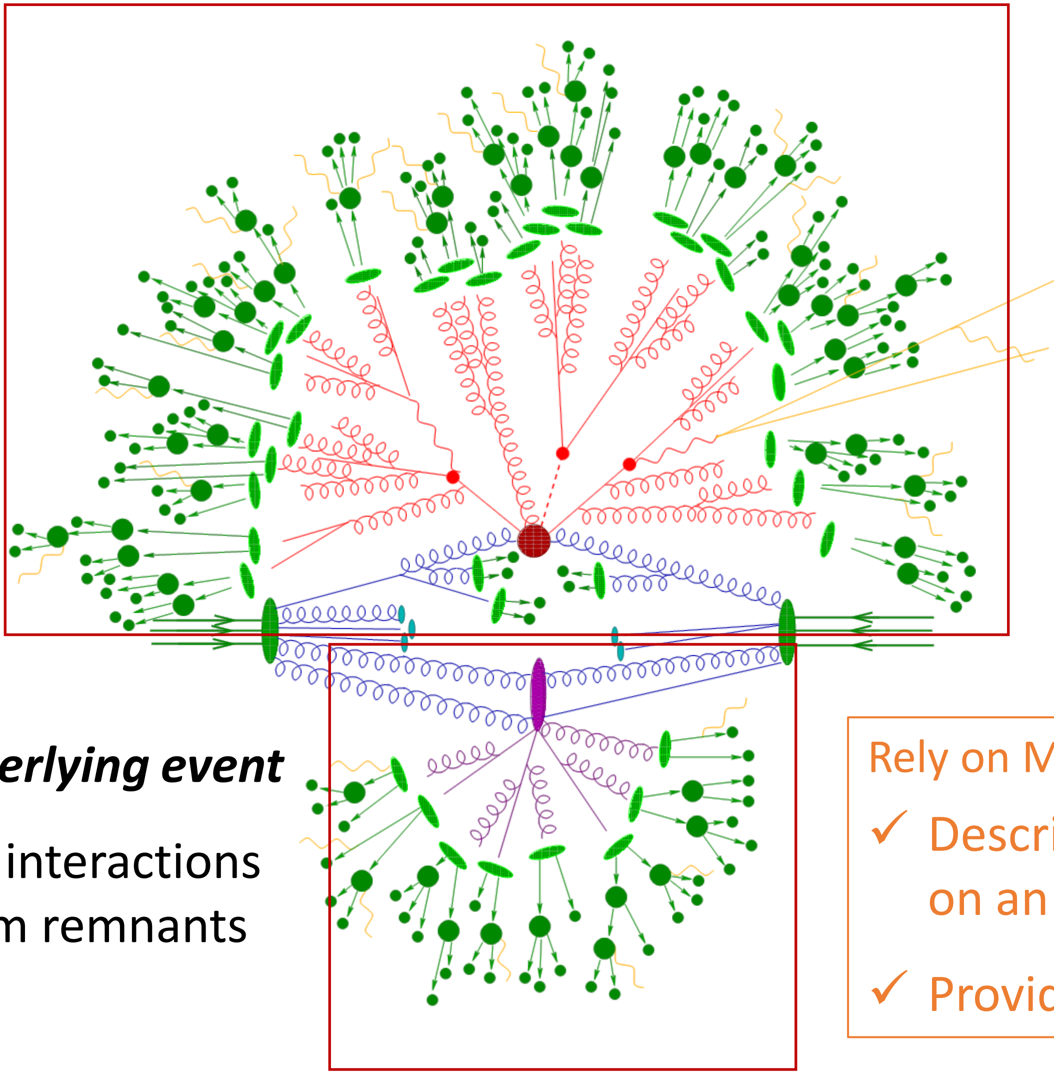








Predictions



To describe "***Hard scattering***" with high-Q^2

- Parton distribution function (PDF)
- Perturbative EW and QCD
- QCD showering and hadronization

Underlying event

Soft interactions beam remnants

Rely on Monte-Carlo techniques to

- ✓ Describe particle types and momenta on an event-by-event basis
- ✓ Provide production cross-sections

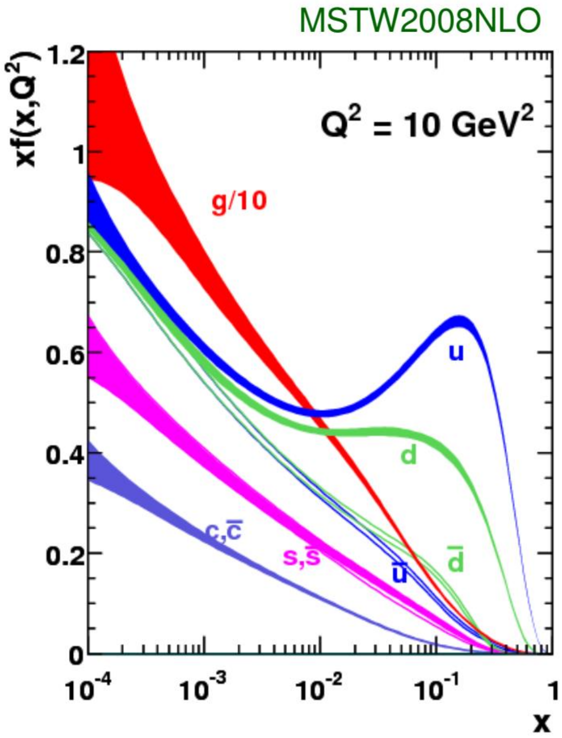
Parton-level

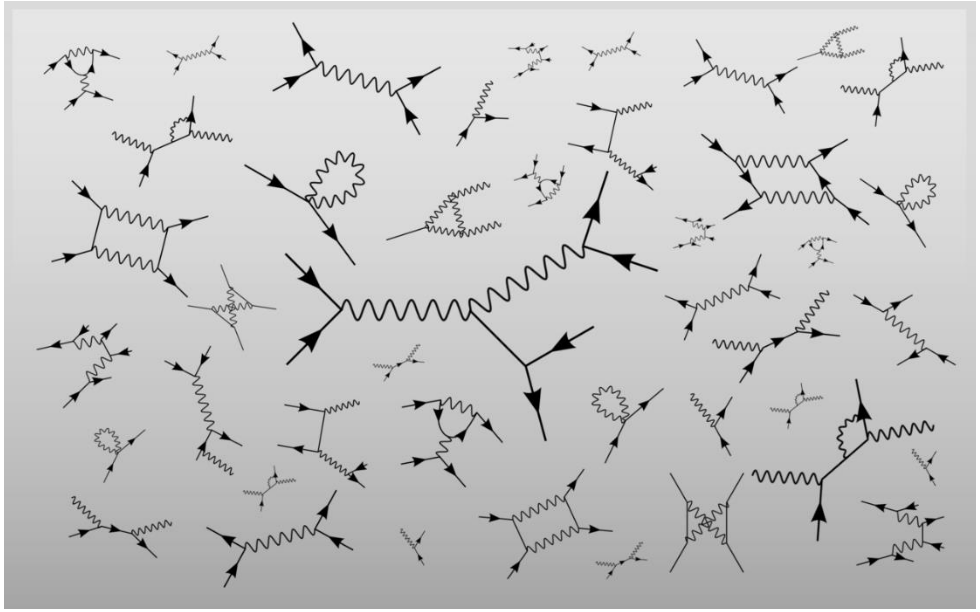
Parton-level generators (PDF ⊗ Perturbative scattering amplitudes)

$$\frac{d\sigma}{d\Omega dx_1 dx_2} = \frac{1}{Flux} \sum_{i,j,k,\ldots n} f_i(x_1, \mu_{\mathrm{F}}) f_j(x_2, \mu_{\mathrm{F}}) \times \overline{\sum} |M(i, j \to k, l, \ldots n)|^2$$

parton flavors

helicities & colors





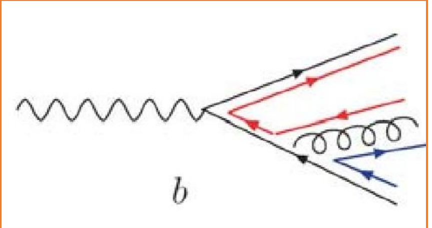
Parton showering / hadronization

Events produced by parton-level generator with color information

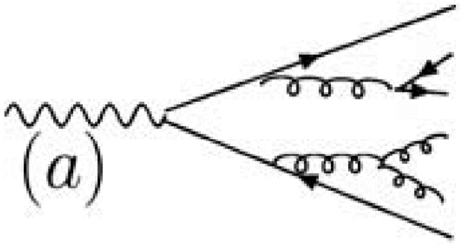
QCD radiation along the accelerated colored partons

Reach critical QCD scale, confinement dominates, color-neutral parton pairs hadronize

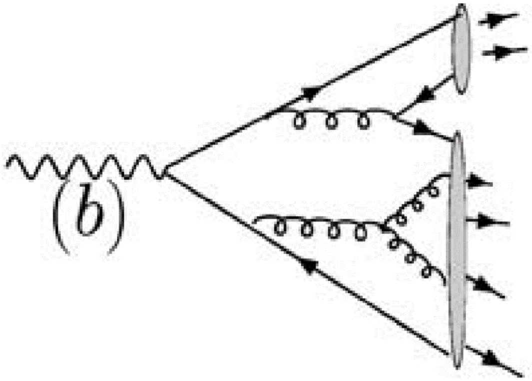
perturbative QCD calculable, approximately implemented, accounting well for collinear radiations



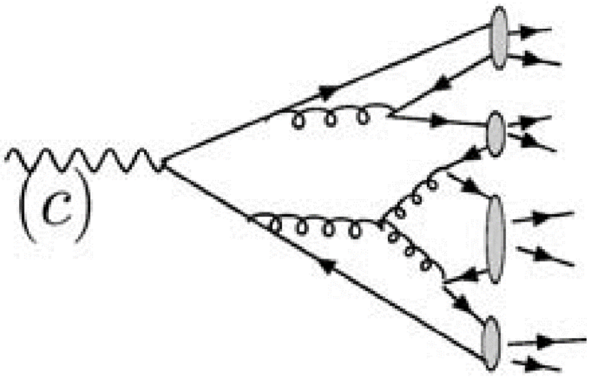
non-perturbative, implemented by phenological models, parameterization required



Showering



String model (Pythia)



Cluster model (Herwig)

Hadronization

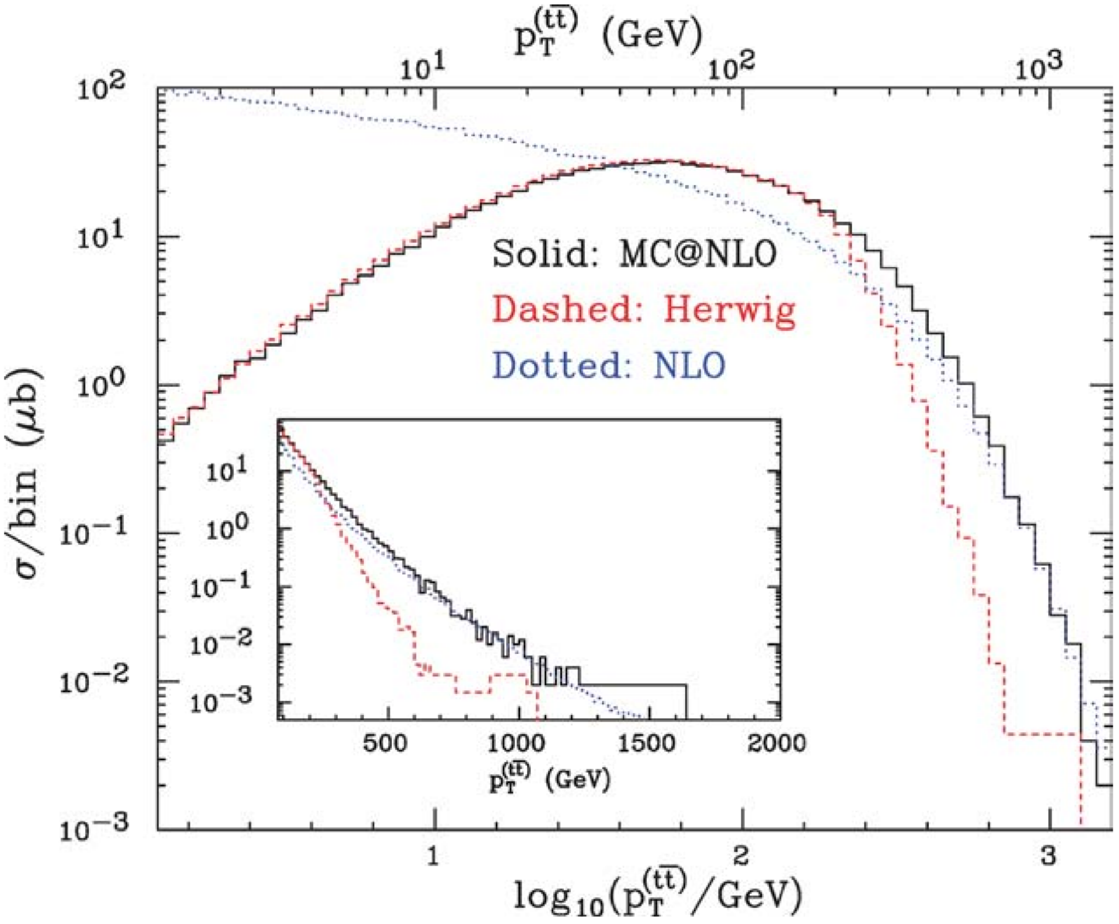
To model a real event

Parton-level generator:

- Precise determination of final state kinematics a given order
- Limited order for extra radiations

Shower generator

- Efficient simulation of QCD radiations (unlimited order)
- Tuning needed to be precise



Generator purpose generator:
Matching and merging the two!
Key is to resolve the overlapped phase space

Up to NNLO+PS for the time being

Market Survey

Not cover electroweak calculation in this lecture

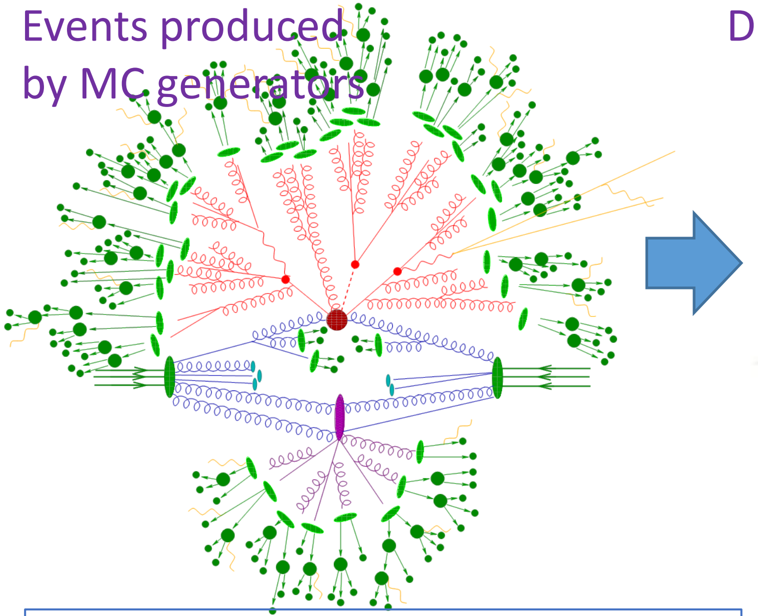
⇒ Importance for high pT physics, where EW corrections become sizable

Many programs on the market, often need to compare several to make sure a good understanding of the process

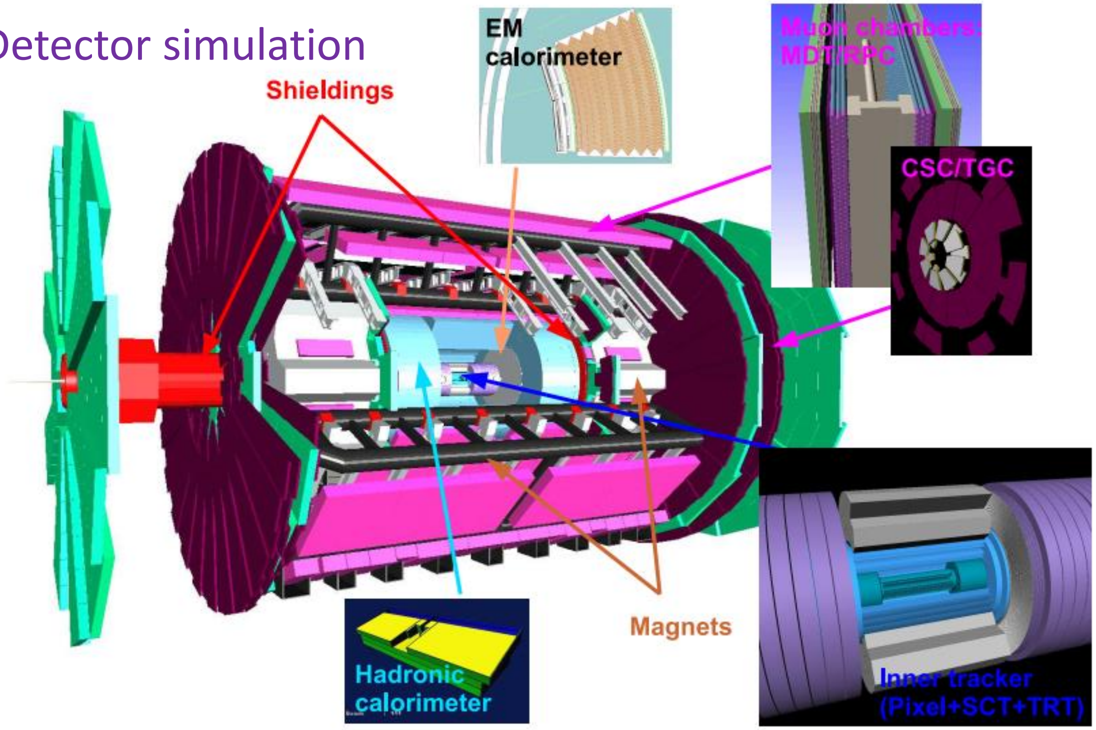
Detector Simulation

ATLAS detector simulation is based on ***Geant4***,
plus detector signal amplification and collection with analytical functions

Events produced by MC generators



Detector simulation



Complex implementation due to the large-scale experiment

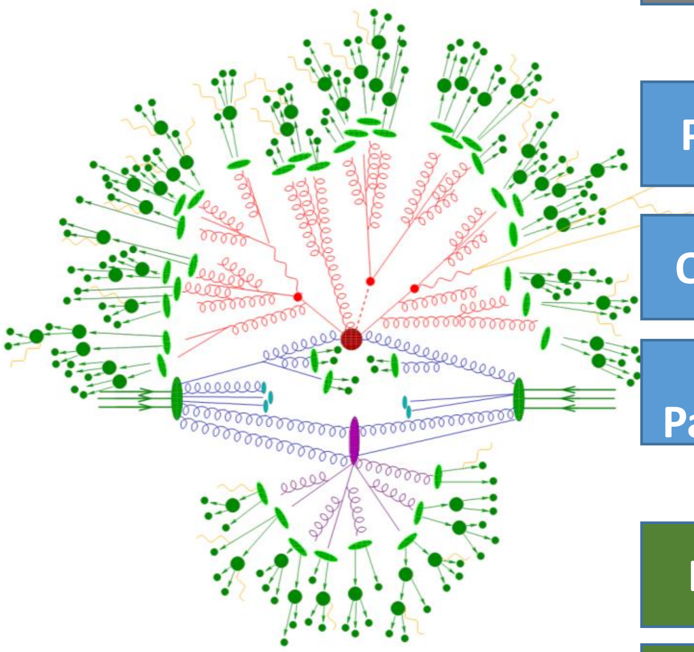
>1 mins per event
Dominated by calorimeter

Faster simulation also deployed by simplifying calo. simulation

Common interactions between particles and materials simulated:
- ionization, pair production, scattering, Bremsstrahlung, hadronic interactions

Measurement Channels

Sketch of a pp collision event



Soft QCD

Flavor

PDF

QCD

SM Parameters

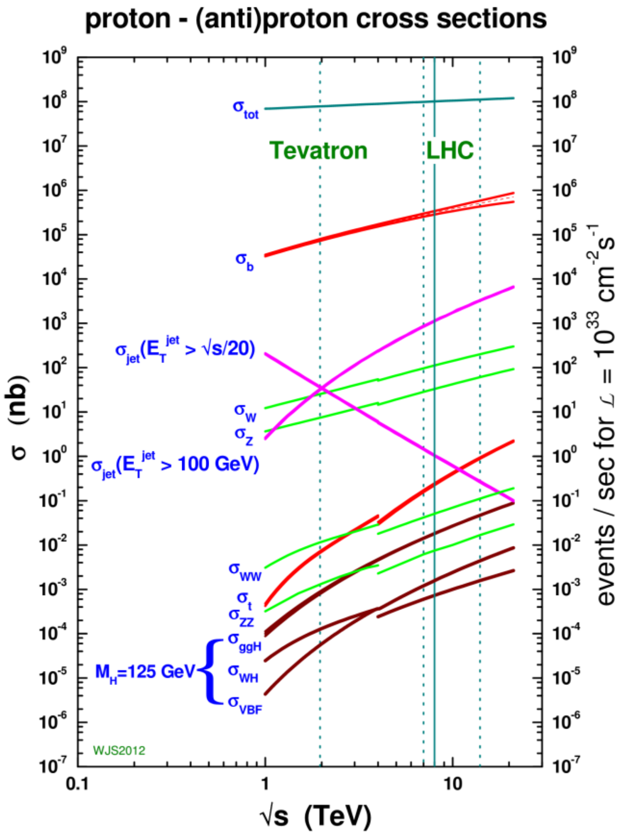
EW

EWSB

Tracks
Hadrons
Protons

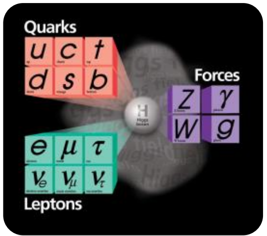
Jets
Photons
Photon + Jets
Boson + Jets
Boson
Top quark

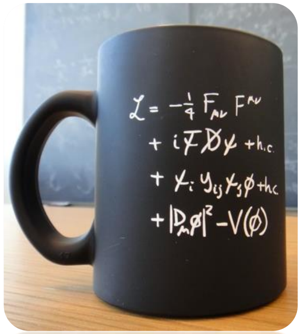
Multiboson
Higgs boson
VV scattering

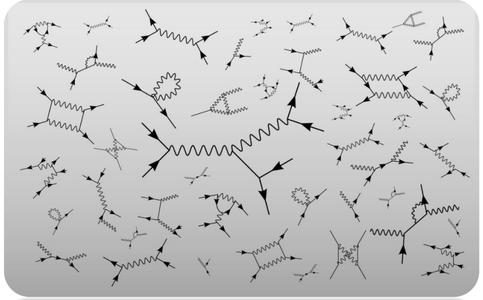


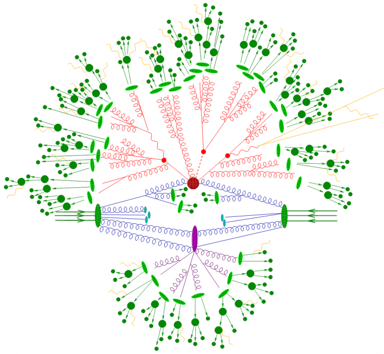
Note: this lecture doesn't cover topics related to Top, Higgs, soft QCD, and flavor physics

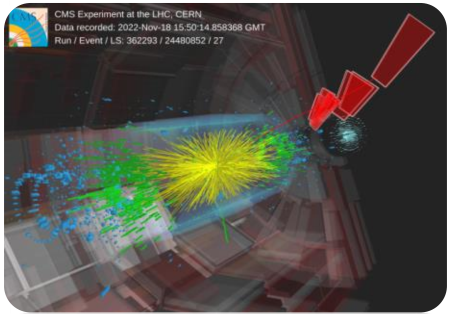
Measurements and Predictions





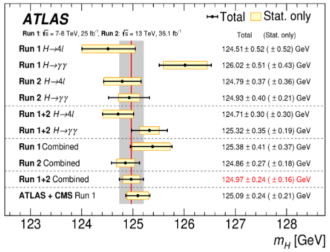


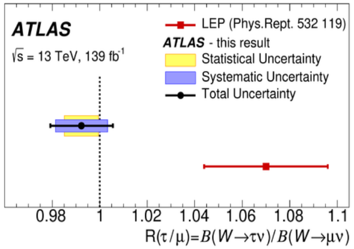


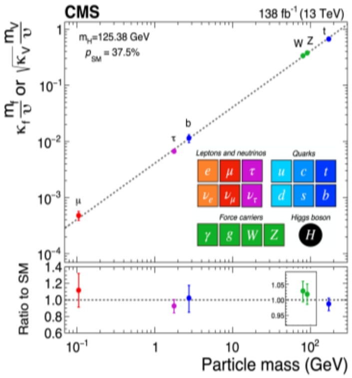


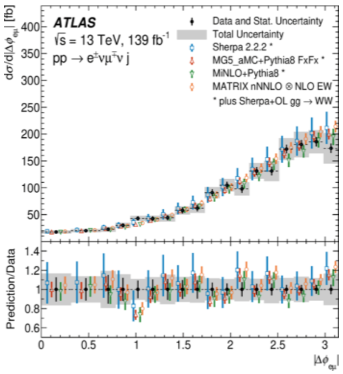
Predictions

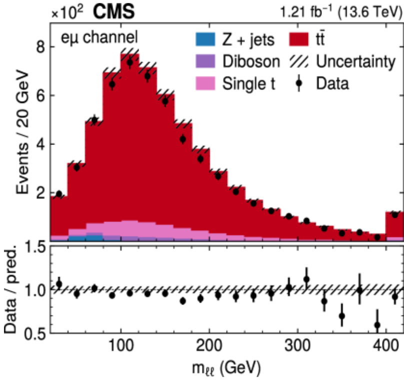
Measurements











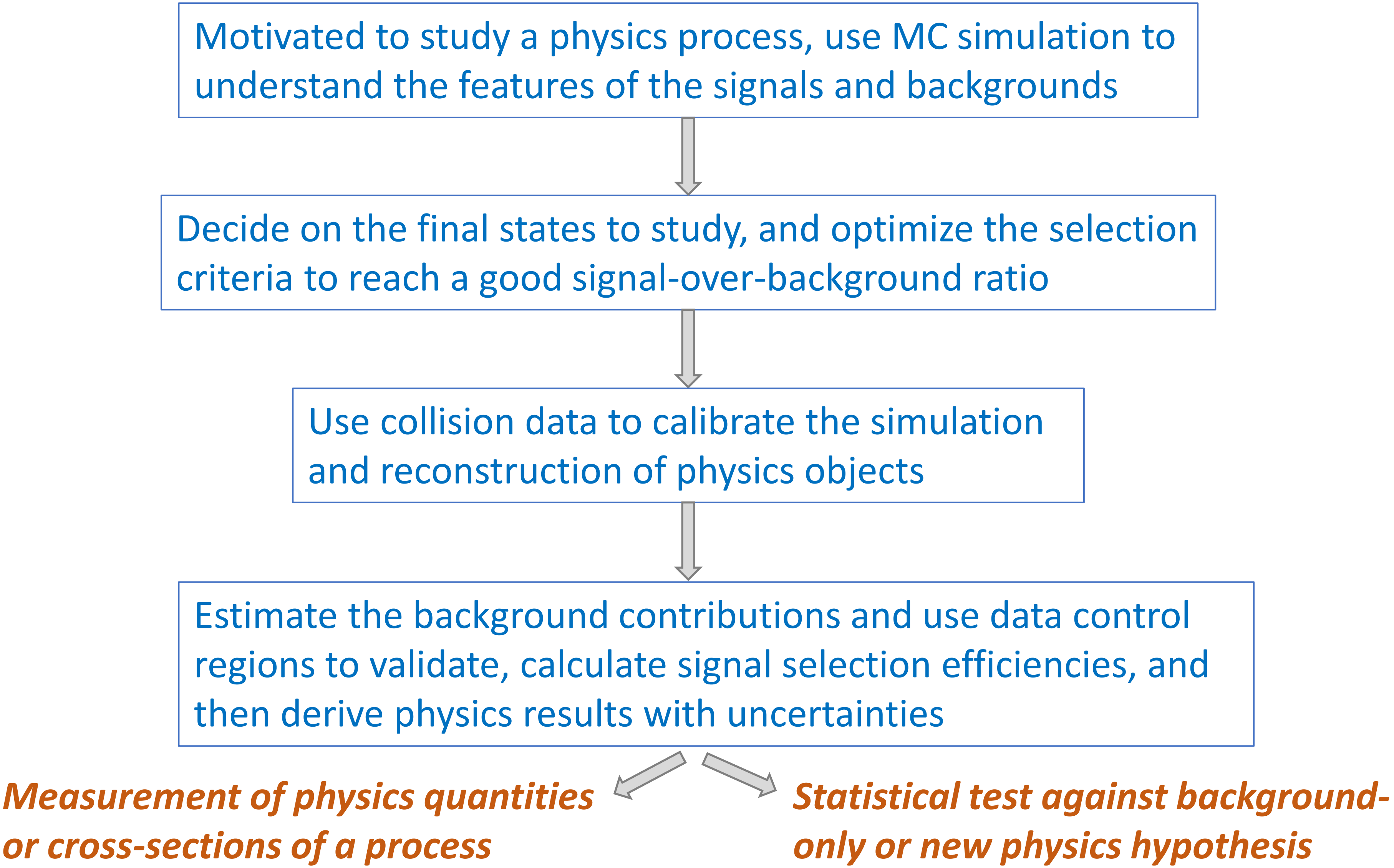
Quantum field structures, symmetries and intrinsic properties, model parameters

Couplings, interactions

Cross-sections

Detector observables

Measurement Methodology



Motivated to study a physics process, use MC simulation to understand the features of the signals and backgrounds

Decide on the final states to study, and optimize the selection criteria to reach a good signal-over-background ratio

Use collision data to calibrate the simulation and reconstruction of physics objects

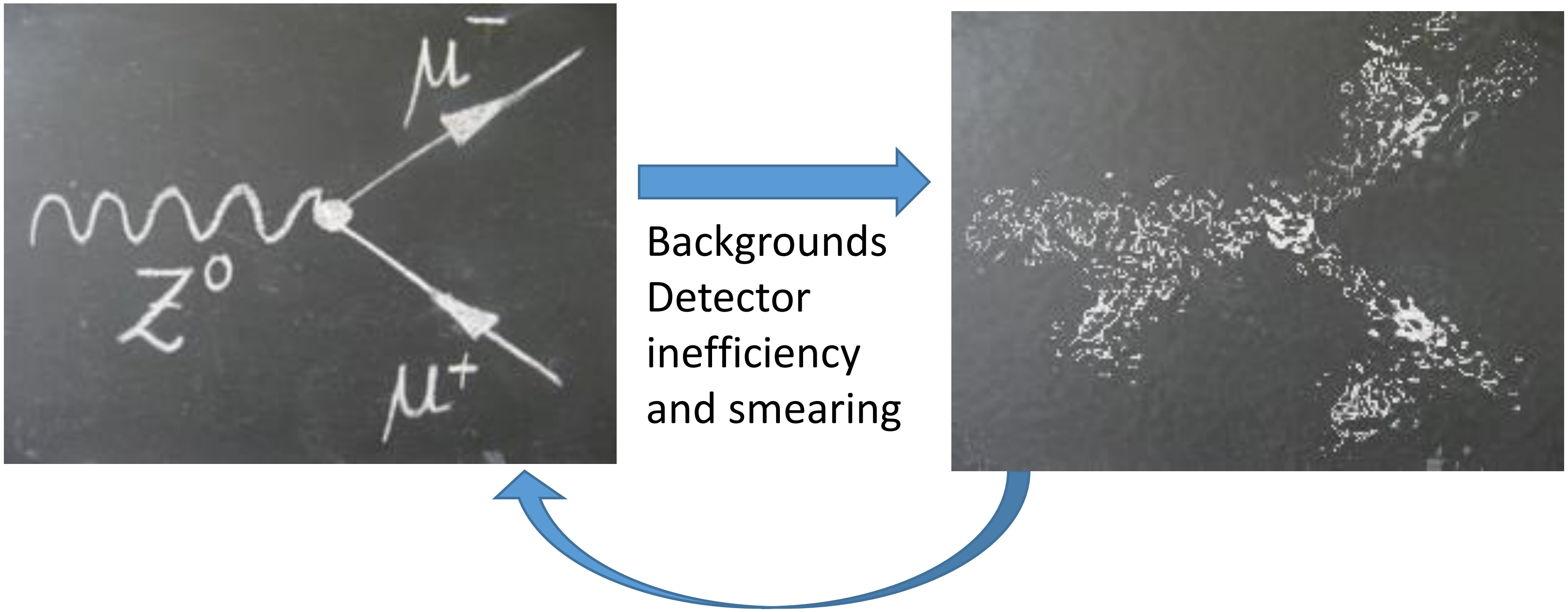
Estimate the background contributions and use data control regions to validate, calculate signal selection efficiencies, and then derive physics results with uncertainties

Measurement of physics quantities or cross-sections of a process

Statistical test against background-only or new physics hypothesis

Detector response

A schematic view of detector effects



True event happened

Reconstruction from the detector signals

Backgrounds
Detector
inefficiency
and smearing

Physics studies try to remove the detector effects and “see” the core physics process (differential cross-sections, parameters, etc.)

Cross-section and Phase spaces

$$\sigma(x) = \frac{N_{obs} - N_{bkg}}{\mathcal{L} \times A \times C \times B}$$

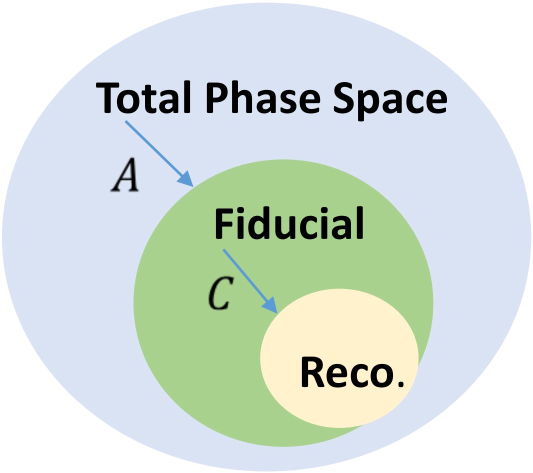
$\sigma(x)$: to be measured cross-section or physics parameter

N_{obs}, N_{bkg}: number of observed data events and estimated background events

$\mathcal{L}$: integrated luminosity of the data

A: signal acceptance
C: reconstruction efficiency
B: branching fraction of process to final states

Signal phase spaces
in physics analyses



To have a precise measurement of σ or x (physics goal), requirements for all the terms

- ✓ Large datasets
- ✓ Optimized selection for S/B ratio
- ✓ Stable estimation of backgrounds
- ✓ Good calibration of simulation

Likelihood

Practically, interpretation of physics results are usually done with **likelihood functions**

$$L(\mu,\theta) = \prod_{i=1}^{N}[\frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j+b_j)}] \times \prod_{k=1}^{M}(\frac{1}{\sqrt{2\pi}} e^{-\frac{\theta_k^2}{2}})$$

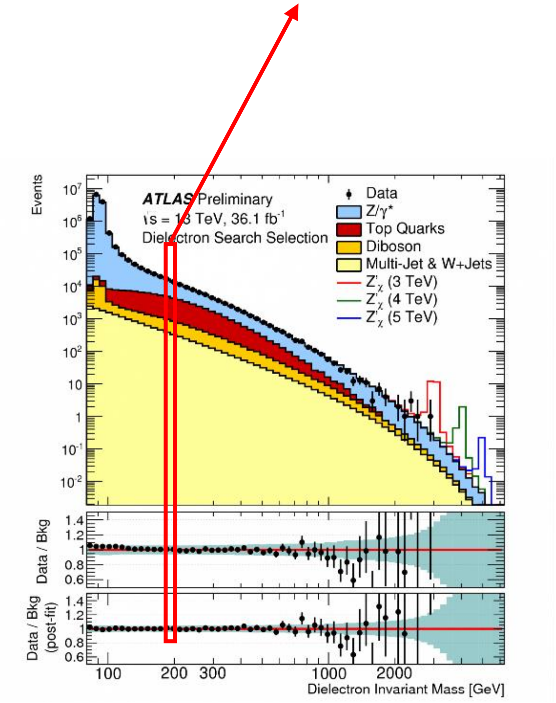
Profile log-likelihood ratio test statistics ➔ detection significance, upper limits…

μ: parameter of interests

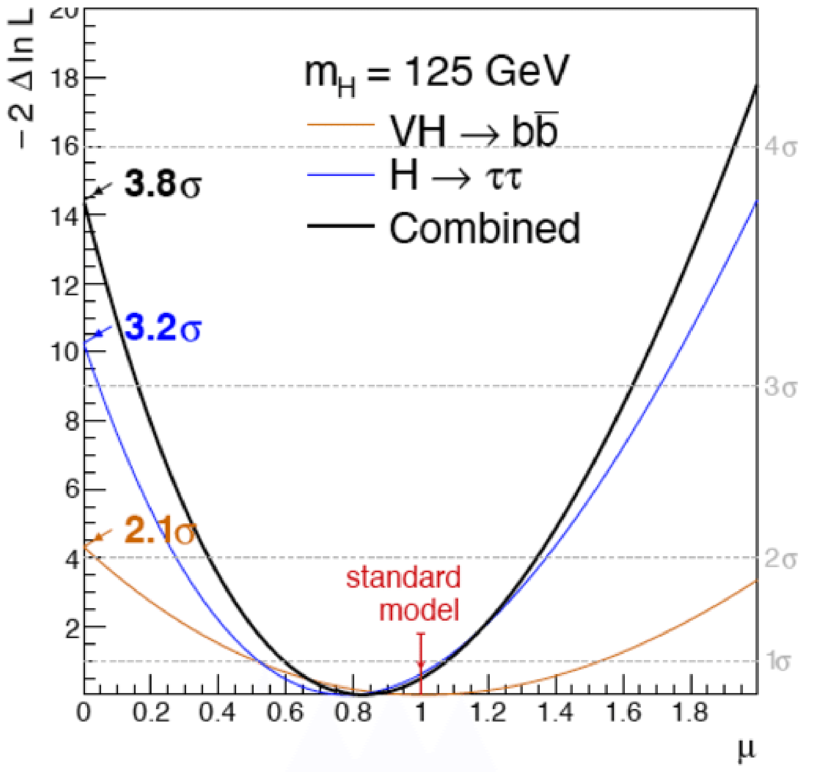
n_j: observed number of events in bin-j

Signal: $s_j = s_j(\theta)$
Background: $b_j = b_j(\theta)$

θ: nuisance parameters, representing systematic uncertainties



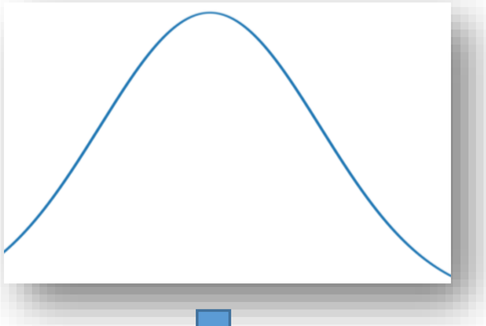
Example of a binned histogram



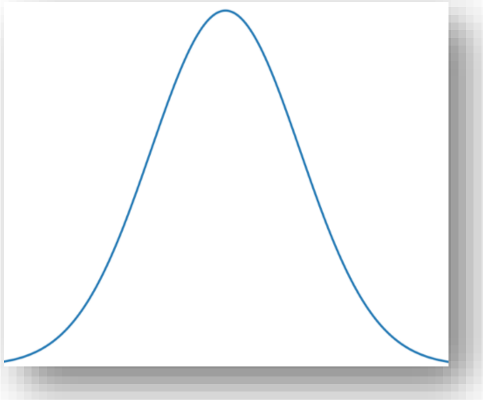
“Unfold” the truth

Differential measurement
“unfolding”

Reconstructed distribution: R(x)



Truth distribution at fiducial-region T(x)

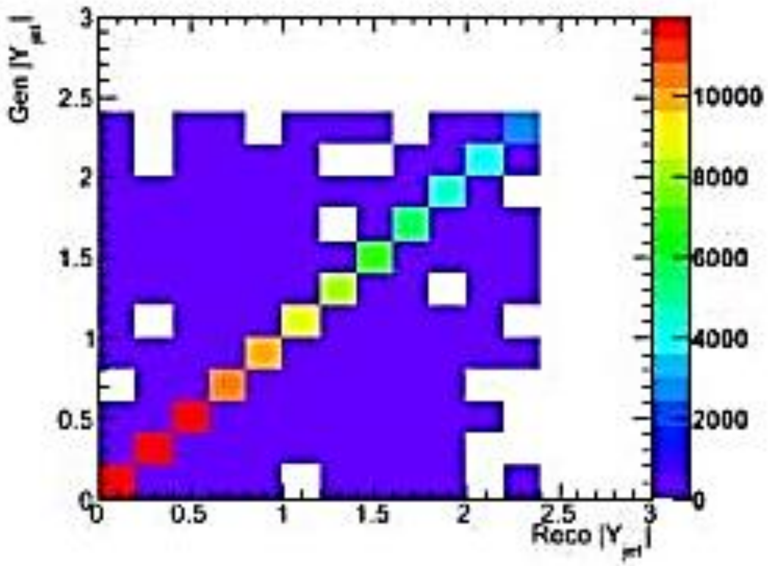


efficiency

$$R(x) = M(x,x') \times \epsilon(x') \times T(x')$$

Detector smearing matrix

To deal with instability of matrix inversion: iterative Bayes, singular value decomposition …



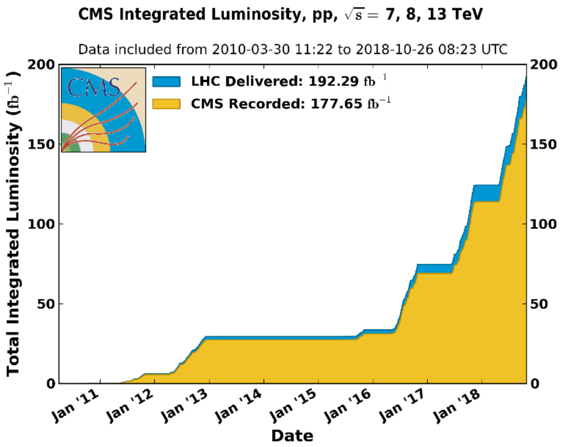
Example of the smearing matrix

(Brief) Review of current status

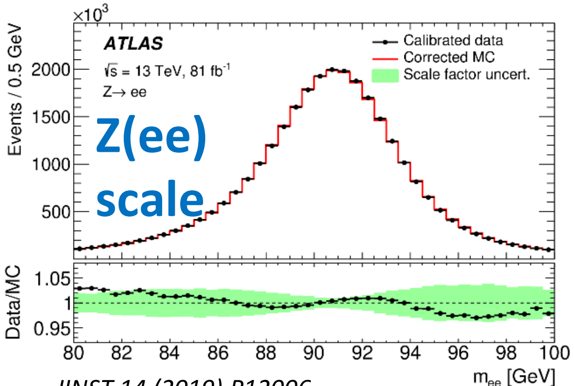
Data processing and Reconstruction

Physics successes owing to precise understanding of e, μ, jets, E_T^{miss}, and tagging of heavy-flavor jets

Per-mil to percentage precision achieved in many

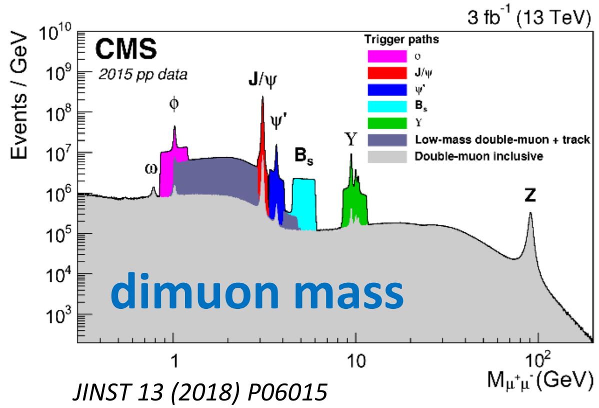


Tremendous efforts from LHC, detector teams to make the data collection smooth, and available for measurements



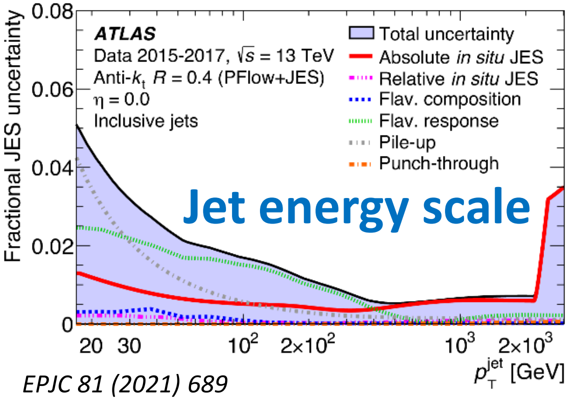
Z(ee) scale

JINST 14 (2019) P12006



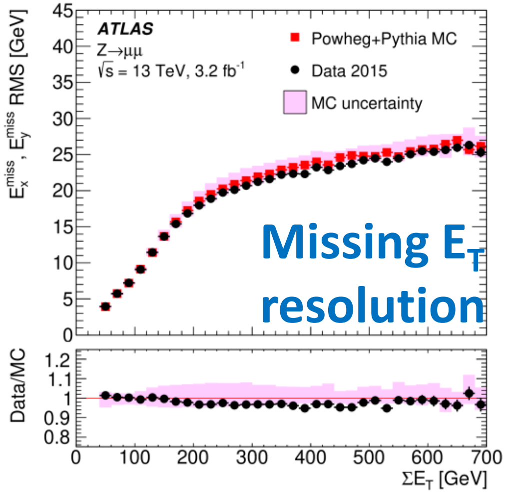
dimuon mass

JINST 13 (2018) P06015



Jet energy scale

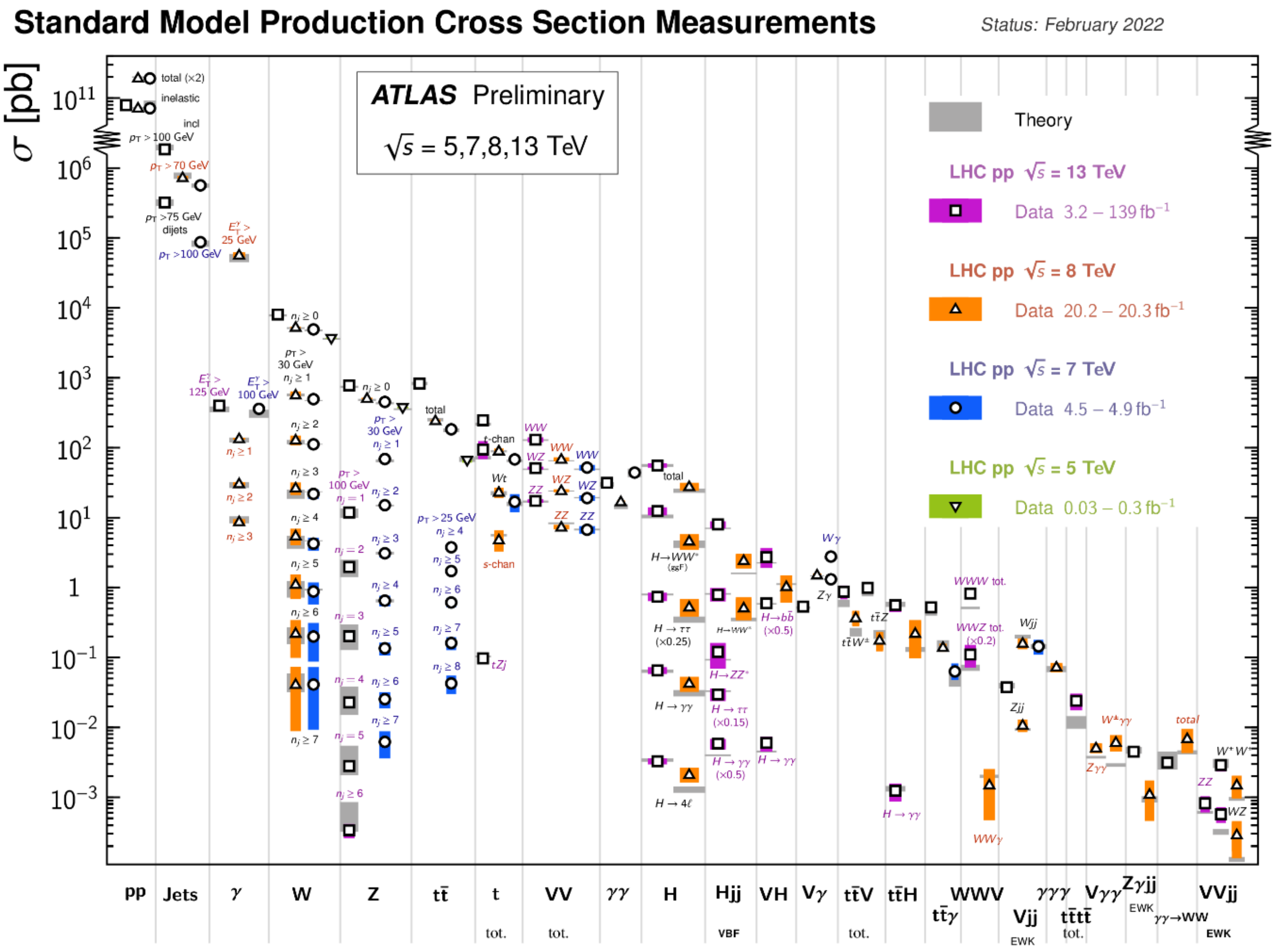
EPJC 81 (2021) 689



Missing E_T resolution

EPJC 78 (2018) 903

Orders of Measurements



SM measurements over > 14 orders of magnitudes:

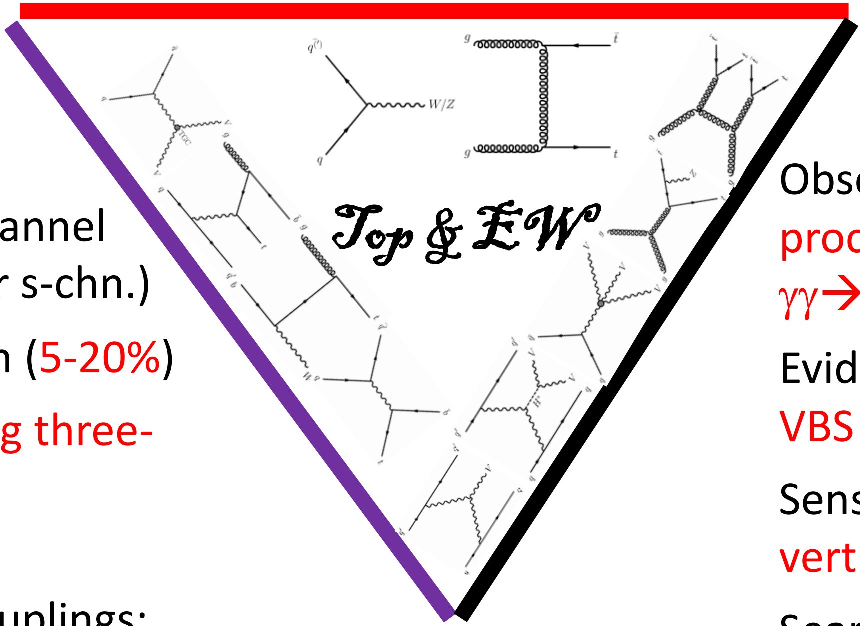
Consistency with prediction observed

Where we are (LHC)

More: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
http://cms-results.web.cern.ch/cms-results/public-results/publications/

Precision

- Top mass precision (< 0.5 GeV) - new record
- W mass (16 MeV), $sin^2\theta_{eff}$ (1.5‰) approaching records
- 2-3% unc. for W/Z/$t\bar{t}$ inclusive σ, focus on multi-dim. differential
- Lepton universality τ-μ (1%) - new record
- Charge, forward-backward asymmetries, polarization, spin-correlation



Measurement

- Diboson σ precision (5%)
- Single top σ precision (t-channel 7%, Wt – 10%, evidence for s-chn.)
- VBF V, tt+γ/W/Z σ precision (5-20%)
- Record precision in studying three-body vertices
- → high energy behavior of anomalous triple-boson couplings; CKM $|V_{tb}|$ (5%)

Exploration

- Observation of rare VBS processes (WW, WZ, ZZ, Wγ), γγ→WW, tZq, tri-bosons
- Evidence for rare four-top, VBS Zγ processes
- Sensitivity in four-body vertices
- Searched for rare decays, top FCNCs

SM Parameter Measurement

19 free parameters

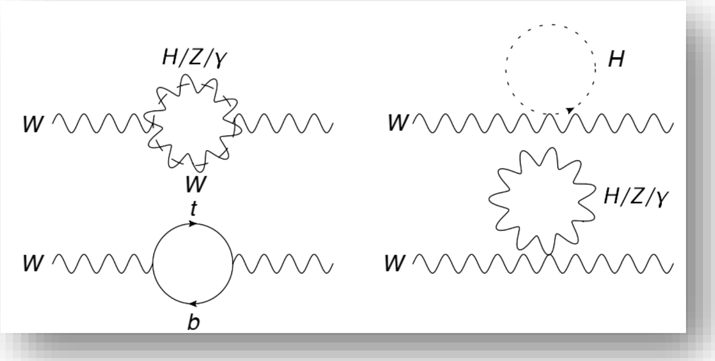
or 26 parameters (including neutrino sector with masses)

Parameters	**Relative Error (PDG)**
α, $\sin^2\theta_W$, α_S	10^{-10}, 10^{-4}, 10^{-2}
m_W (m_Z), m_H	10^{-4} (10^{-5}), 10^{-3}
m_u, m_d, m_s	10^{-1}, 10^{-1}, 10^{-1}
m_e, m_μ, m_τ	10^{-10}, 10^{-8}, 10^{-4}
m_c, m_b, m_t	10^{-2}, 10^{-2}, 10^{-2}
CKM 3 mixing angles & 1 CP-violating phase	10^{-4} - 10^{-2}
Strong CP violating phase	$< 10^{-9}$

Those sensitive for EW & TeV scale colliders to measure are marked in red

Measuring these parameters at different exp. offers

- stringent test of SM internal consistency
- high sensitivity to new physics
- probe of running nature of fundamental couplings

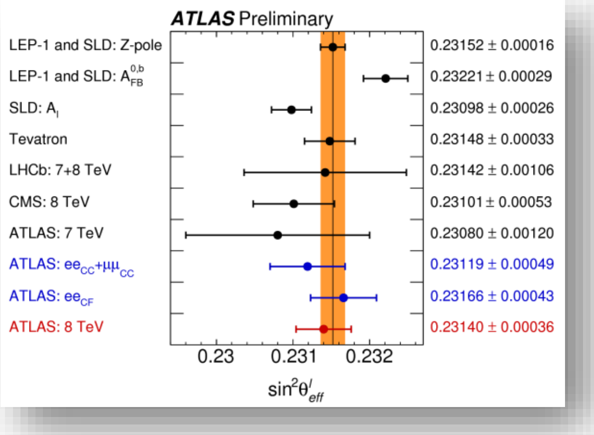


Example of other particles in loops that impact W boson propagator and its mass

SM Parameter Measurement

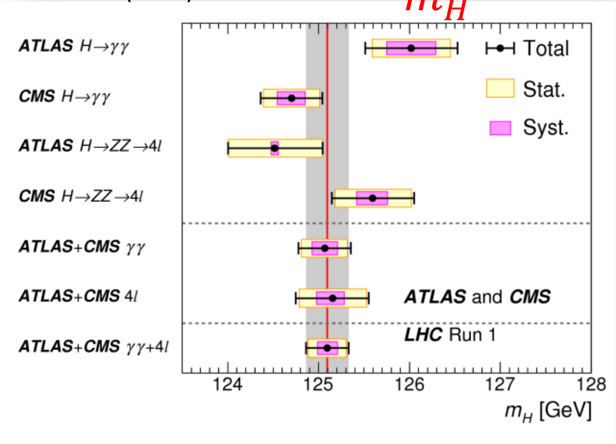
ATLAS-CONF-2018-037

$\sin^2\theta_w$

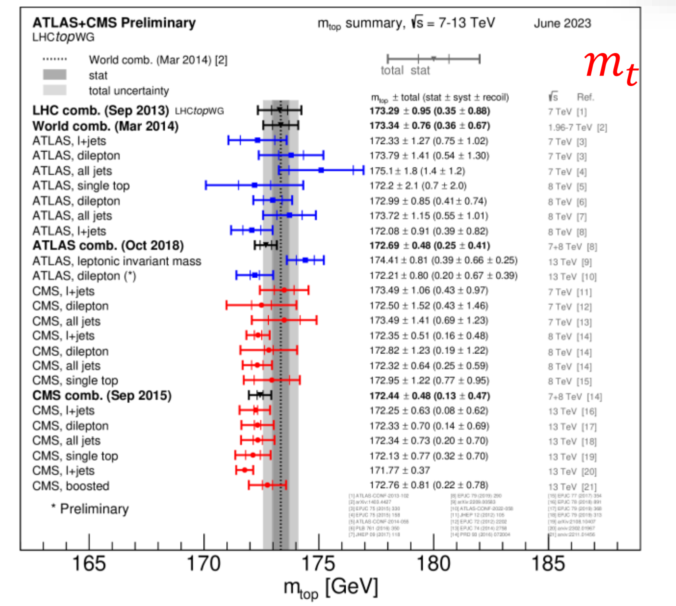


PRL 114 (2015) 191803

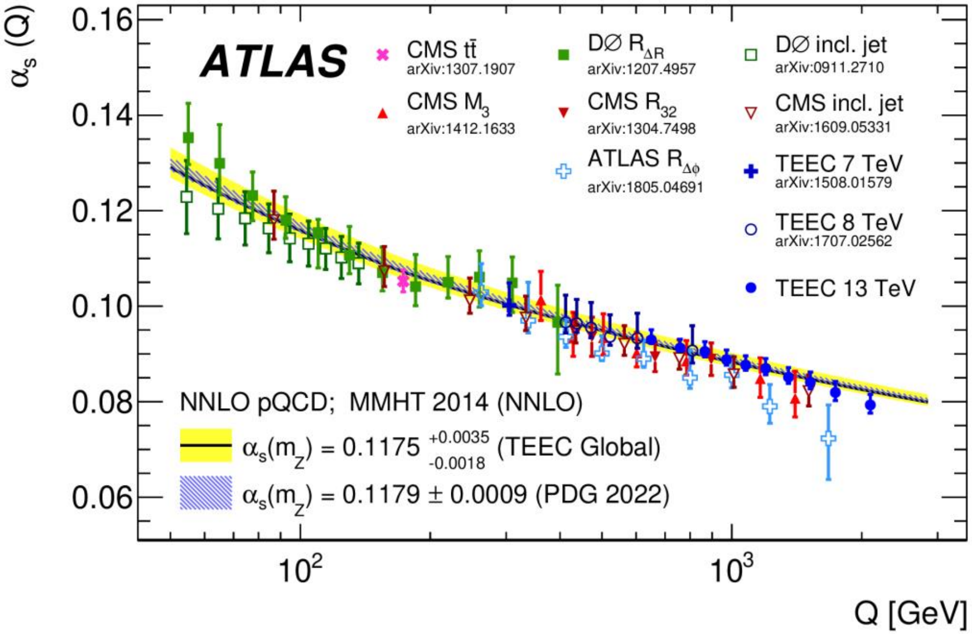
m_H



Providing competitive/most precise precisions



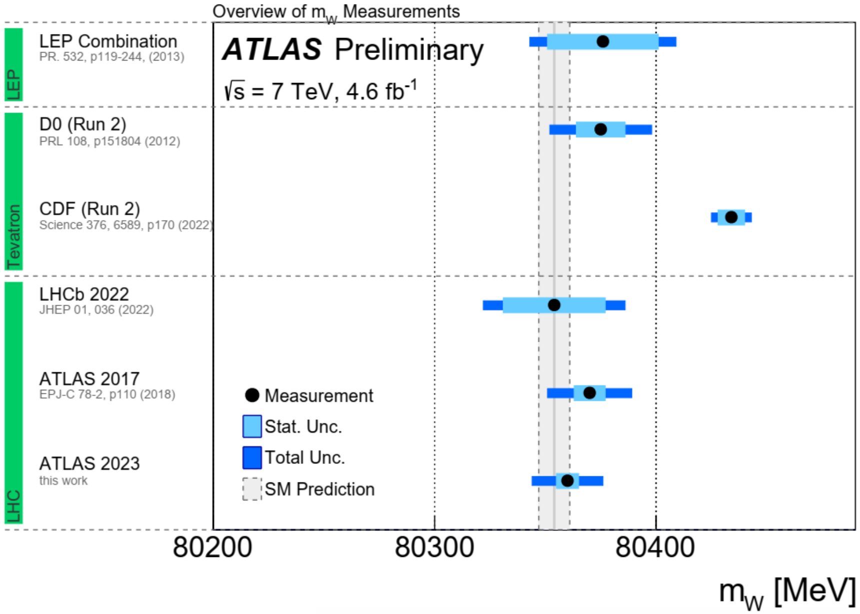
m_t

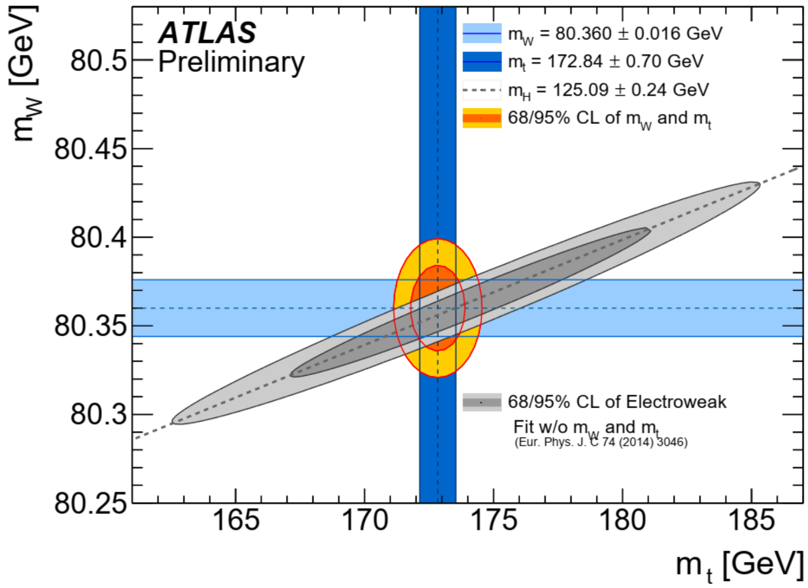


α_S

W mass Measurement

ATLAS-CONF-2023-004





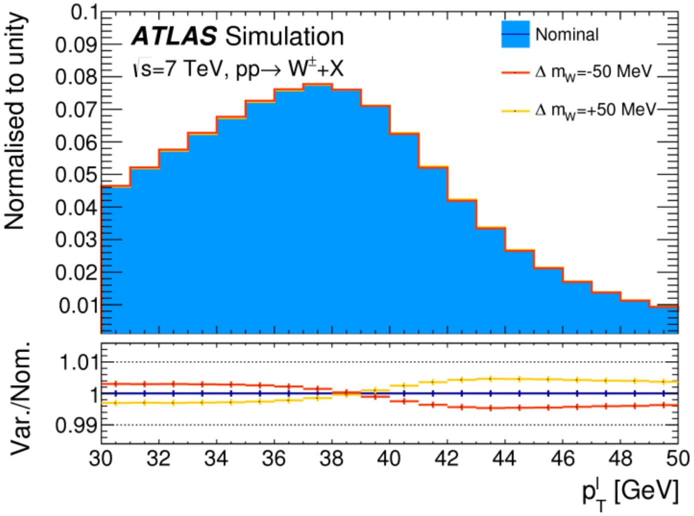
$$m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16 \text{ MeV}$$

Better consistency with electroweak fit prediction

FUTURE:

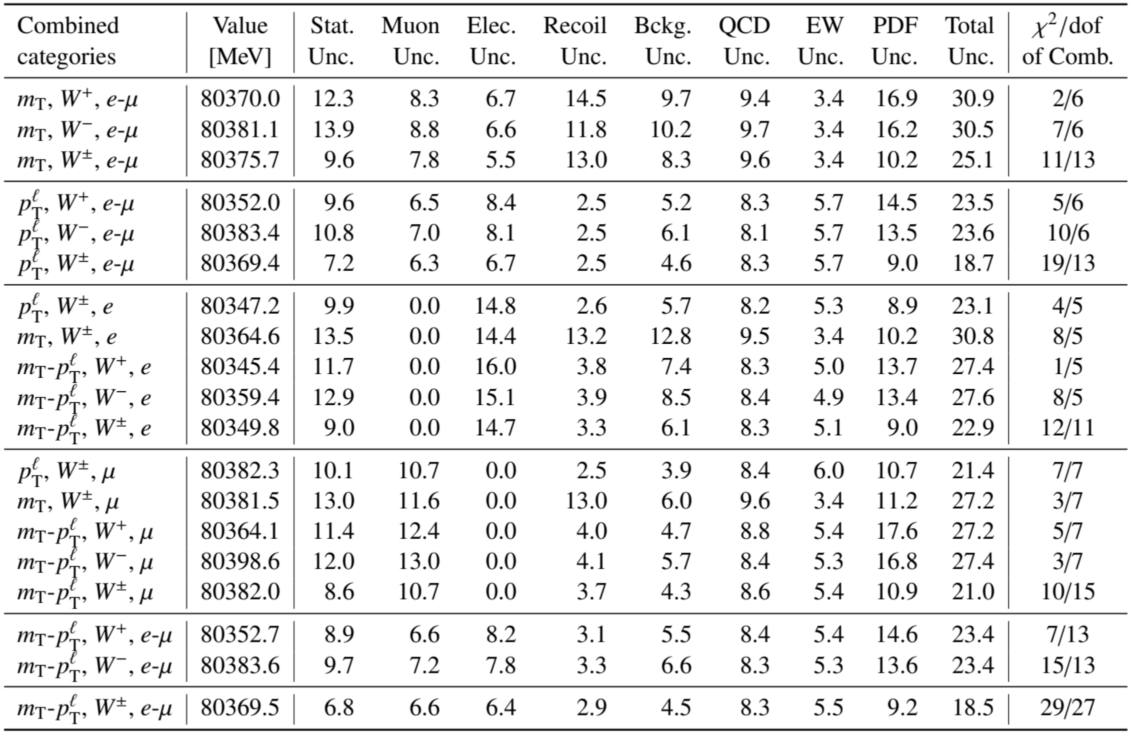
more precise, independent measurements from ATLAS, CMS, LHCb will be desired (in view of discrepancies w.r.t. CDF results) ➔ more precise calibrations, better pT modelling, better PDF modelling (more relevant PDF measurements at the LHC)

More on W mass



Per-mil level understanding of a distribution needed to reveal O(10) MeV mass shifts

Lengthy estimation of uncertainty effects

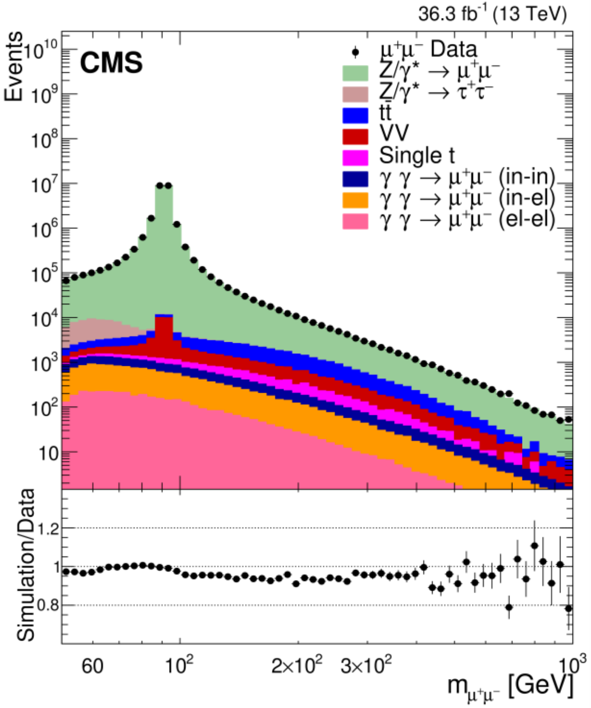


Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_{T}, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_{T}, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_{T}, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_{T}^{ℓ}, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_{T}^{ℓ}, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_{T}^{ℓ}, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_{T}^{ℓ}, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_{T}, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_{T}-p_{T}^{ℓ}, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_{T}-p_{T}^{ℓ}, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_{T}-p_{T}^{ℓ}, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_{T}^{ℓ}, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_{T}, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_{T}-p_{T}^{ℓ}, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_{T}-p_{T}^{ℓ}, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_{T}-p_{T}^{ℓ}, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_{T}-p_{T}^{ℓ}, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_{T}-p_{T}^{ℓ}, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_{T}-p_{T}^{ℓ}, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Precision V measurements

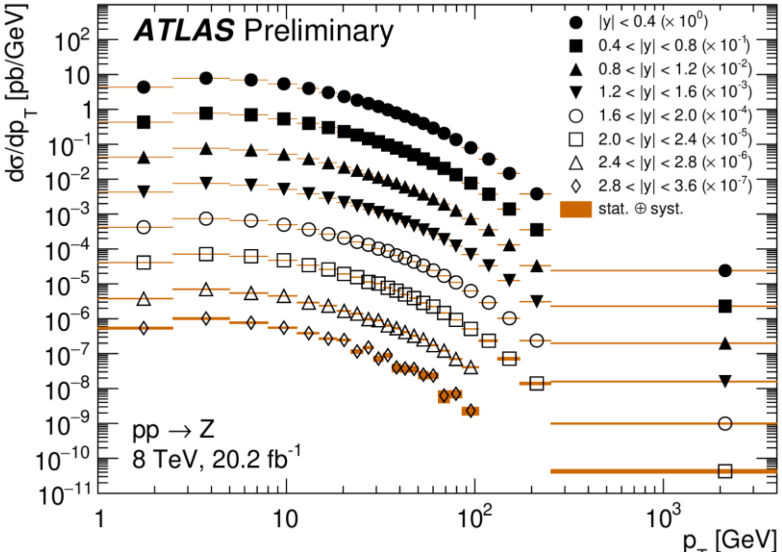
Precision differential measurements of W or Z:

- Parameter determination (e.g., W mass and α_S); Understanding of QCD (V+jets); Search for new physics, study of Higgs physics, …

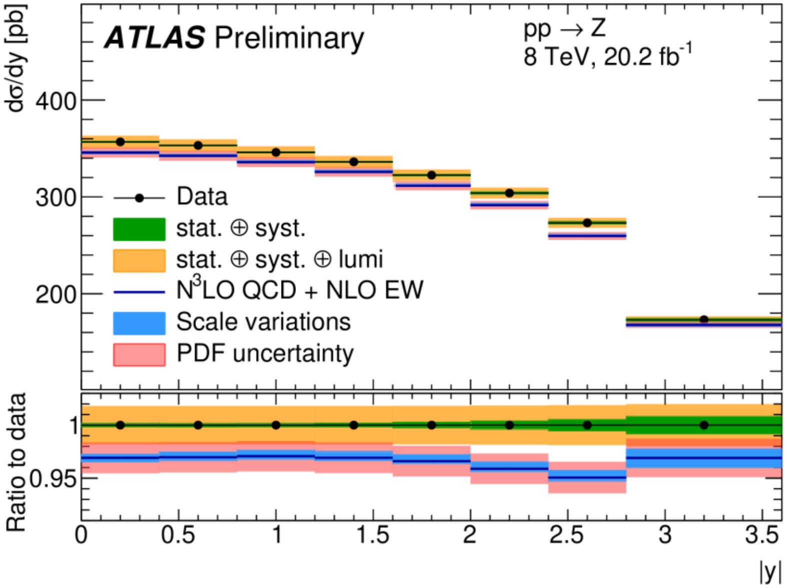


arXiv:2205.04897

ATLAS-CONF-2023-013



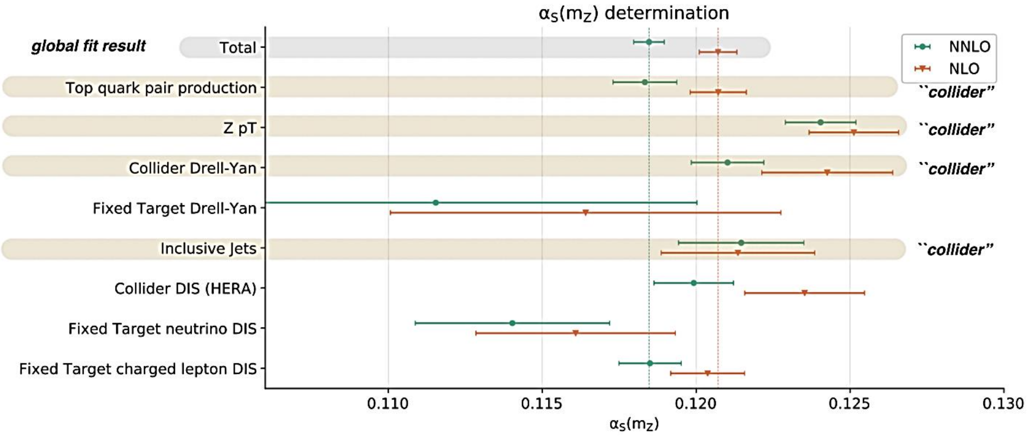
Probe of large variation of phase spaces



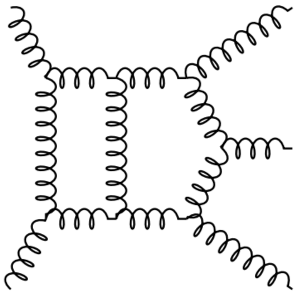
Percentage precision challenge state-of-art predictions

Measurement of strong coupling

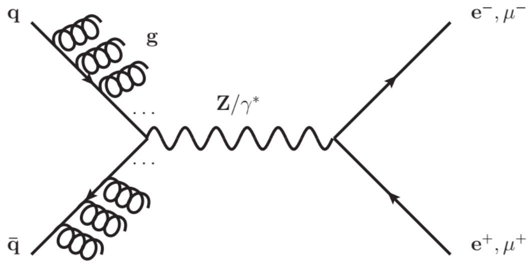
Utilize the abundant production of jets and V+jets



PDF fit with collider results (e.g., inclusive jet) can give constraint to α_S (sensitivity from parton σ and DGLAP scaling)



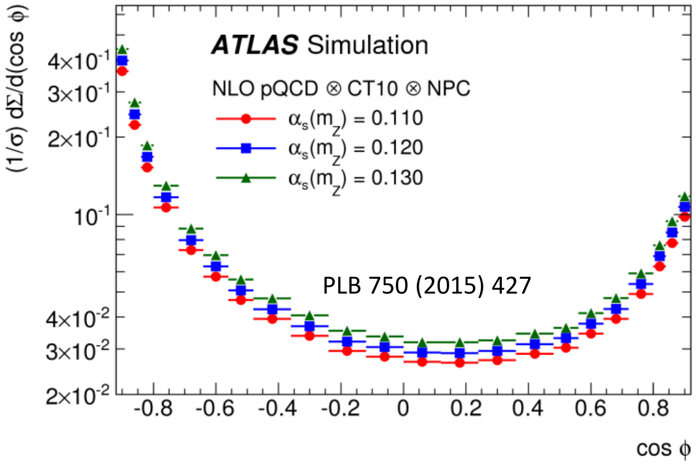
Transverse energy-energy correlation (TEEC)
dated back to e+e-, to explore multi-jet FSR correlation affected by α_S



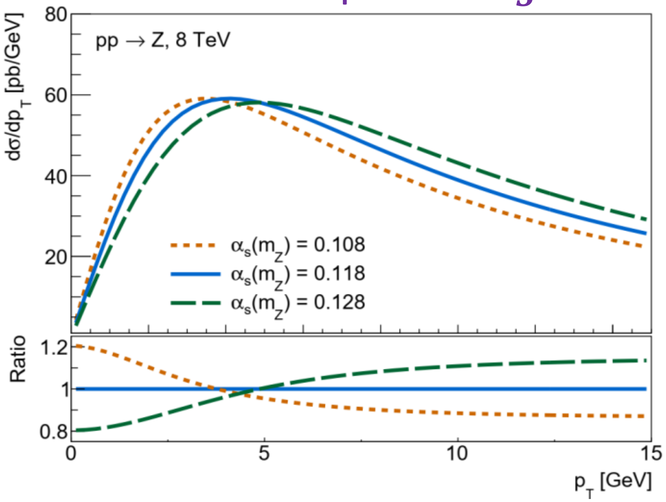
α_S modifies the strength of ISR, and therefore affects $p_T(Z)$
⇔ $p_T(Z)$ is one of most precisely measured distribution at LHC

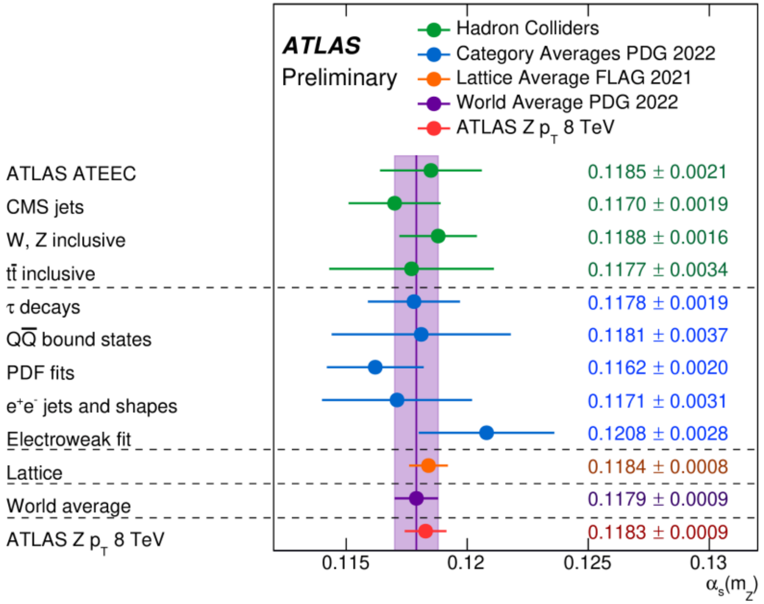
Measurement of strong coupling

Simulation results for TEEC



Demonstration of ZpT and α_S relationship

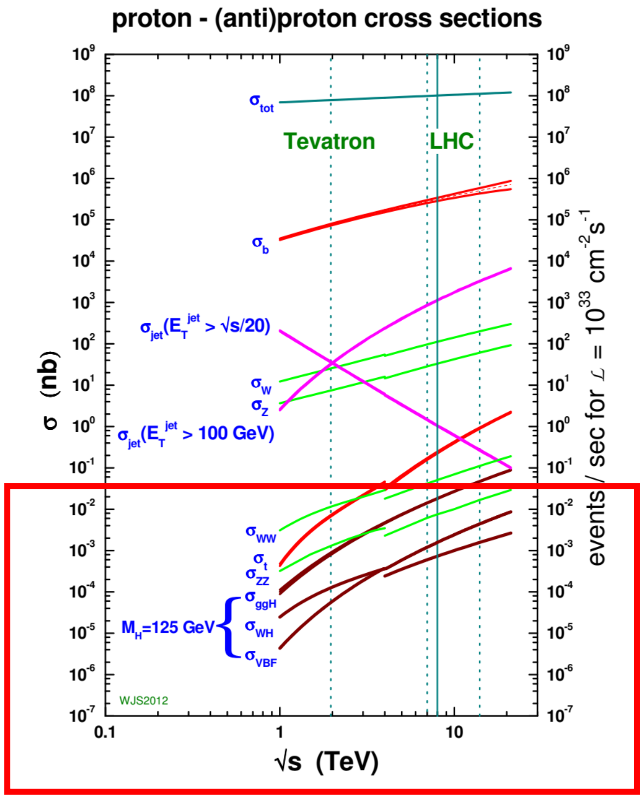




Achieved single best measurement of 0.8% precision

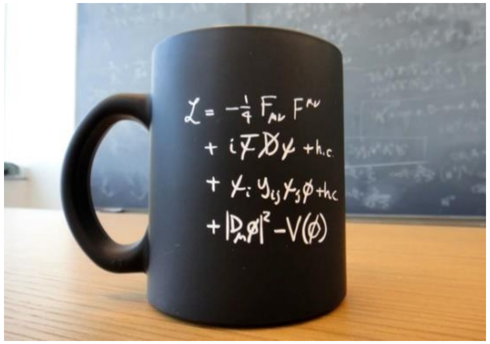
Multiboson Measurement

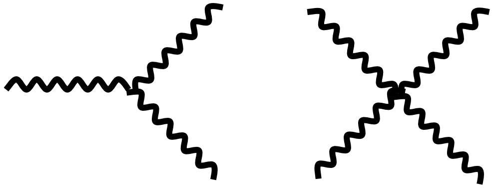
- Study of multibosons - an essential piece in LHC physics program



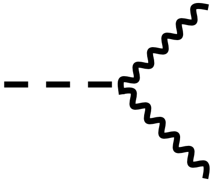
Production σ : O(pb) – O(fb)
Only precisely accessible at LHC

Electroweak Theory

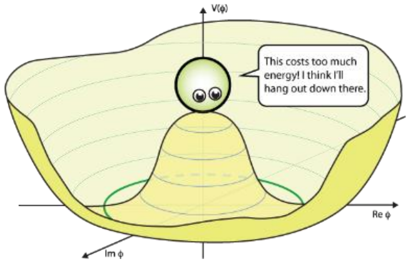




Self-interactions due to Non-abelian Gauge Theory (diboson, triboson …)



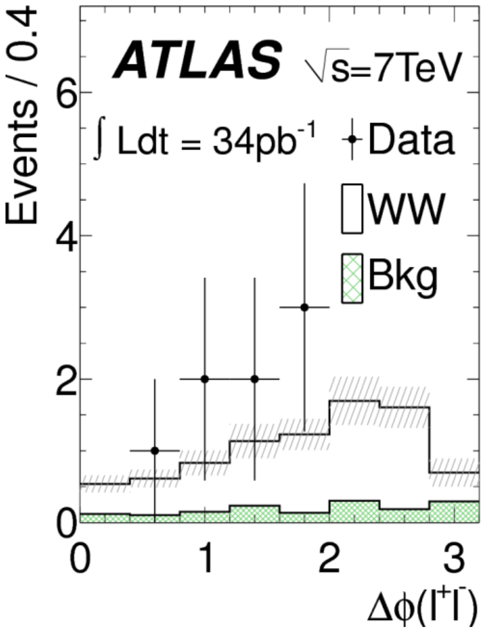
Electroweak Symmetry Breaking (H→VV, vector-boson-scattering)



- *Precision test of the Standard Model*
- *Sensitive to new physics (SUSY, Little Higgs, Graviton, Dark Matter …)*

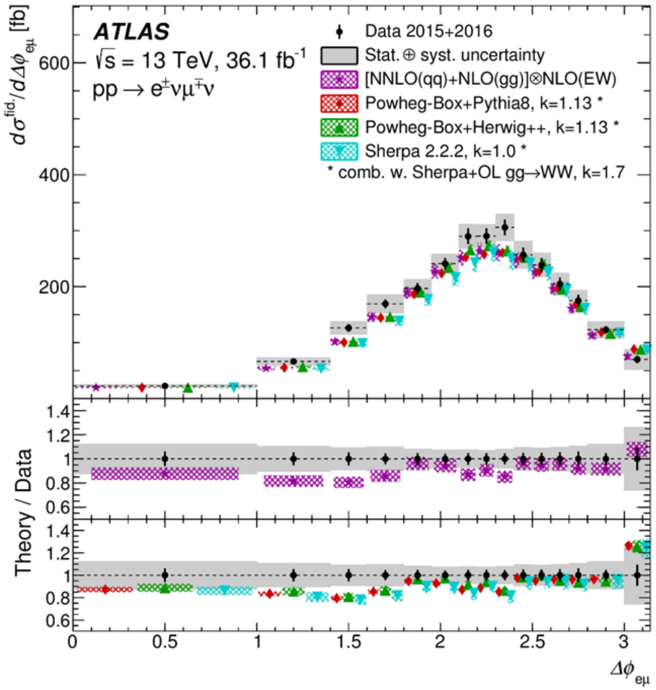
Multiboson Past → Recent

PRL 107 (2011) 041802



First diboson measurements at ATLAS (“rediscovery” of electroweak theory)

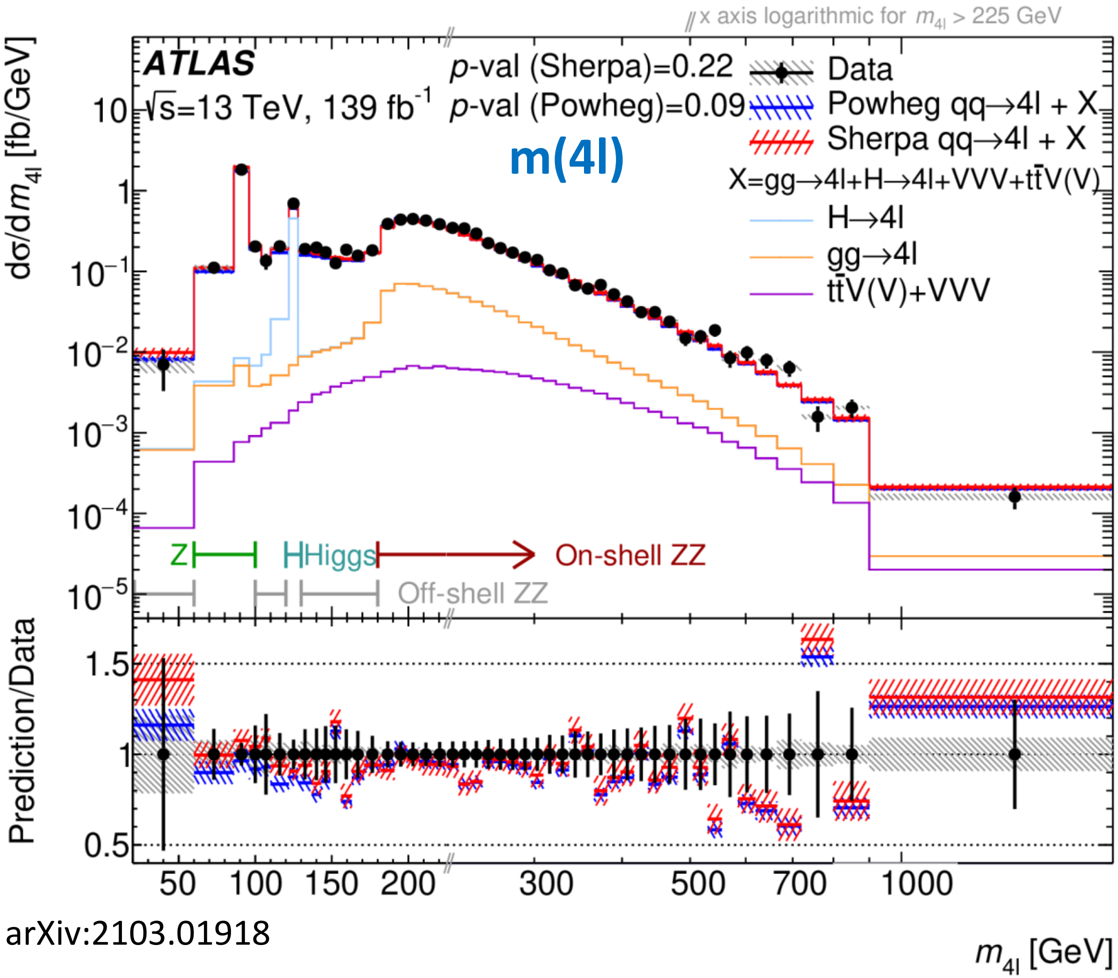
- *NLO QCD + shower simulation was new and sufficient to describe the data*
- *Many multiboson channels not/less explored in the past (LEP, Tevatron)*



Differential σ with precision
→ Challenging NNLO QCD + NLO EW predictions …

Example: diboson ZZ

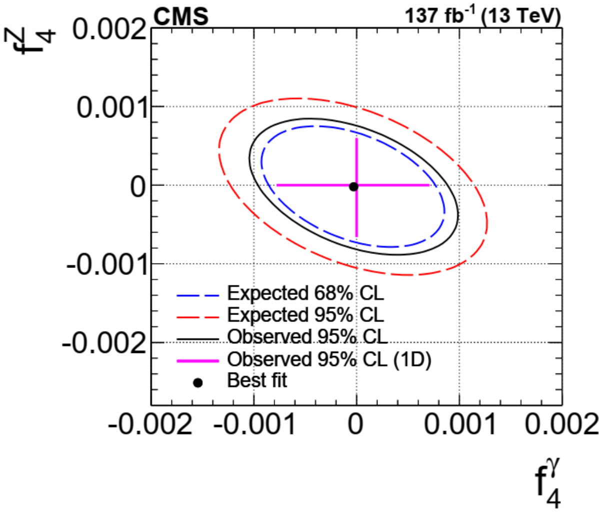
Probe rare neutral Gauge interactions, and essential for Higgs precision physics: **ZZ to 4 leptons**



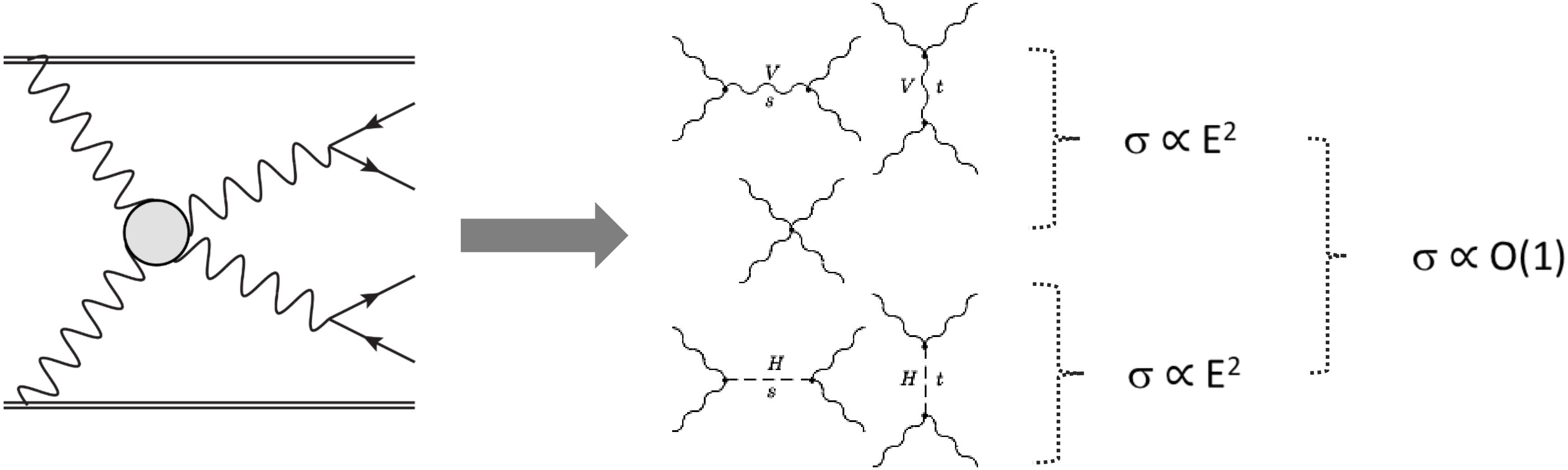
arXiv:2103.01918

arXiv:2009.01186

Per-mil constraints on neutral boson couplings



Rare VBS processes



$\sigma \propto E^2$

$\sigma \propto E^2$

$\sigma \propto O(1)$

Involving Vector boson scattering

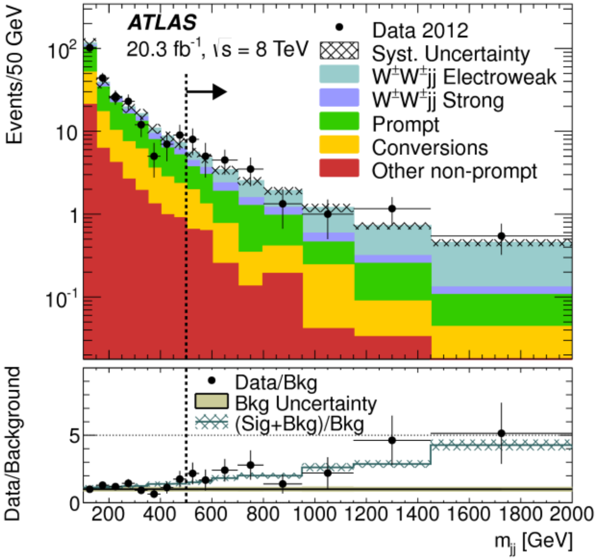
$\Rightarrow$ *Probe of EWSB dynamics and sensitive to new physics in EWSB sector*

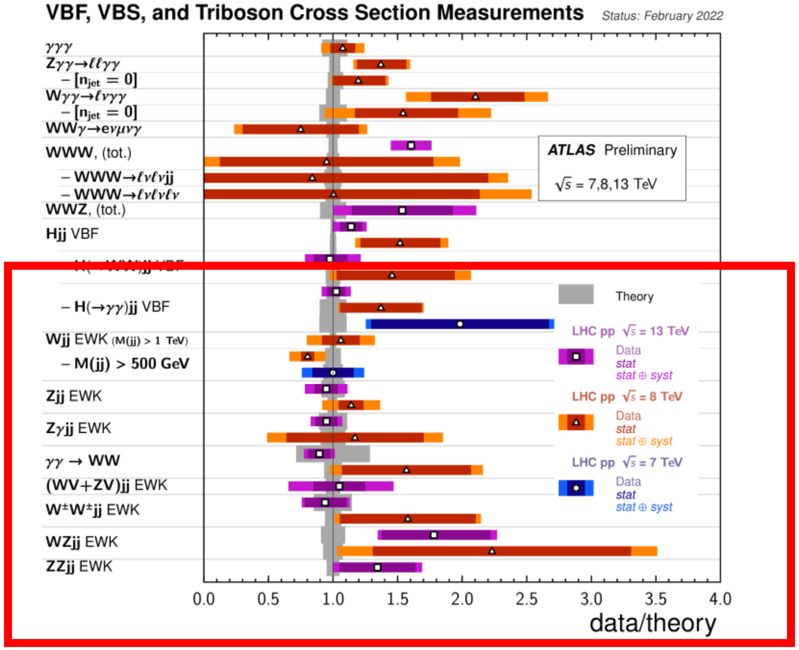
- $\Rightarrow$ *Delicate cancellation needed to unitarize at TeV scale*
- $\Rightarrow$ *Historically, one of main motivations for a Higgs boson!*

$\Rightarrow$ *Quartic gauge boson couplings (QGC) offer unique probe of SM gauge structures and sensitive to new physics modifications*

Observations of VBS processes

PRL 113 (2014) 141803





Almost **ten years ago**, started with **same-sign WW pairs + jj** with a handful of signal events

All EW VVjj modes have been observed by now, start to study the differential distributions and constrain anomalous QGCs (aQGCs)

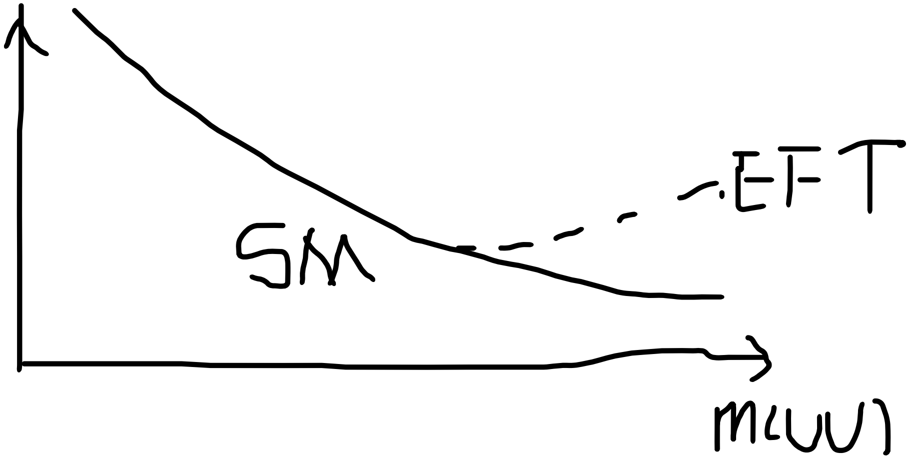
Effective Field Theory Studies

→ If new physics has a scale larger than accessible energy, the effect might be described in EFT, as new interactions at higher mass dimension

$$\mathcal{L} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j$$

→ Commonly, there are dim-6 operators (with Wilson coefficients ci) and dim-8 operators (with coefficients fi)

→ Precise measurement of differential distributions help constrain those coefficients (deviation in kinematic shape)



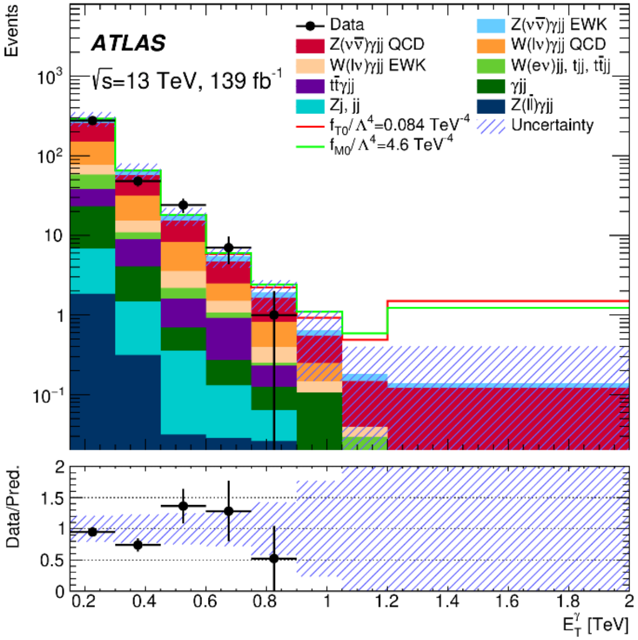
Example on EFT studies from EW Zγjj

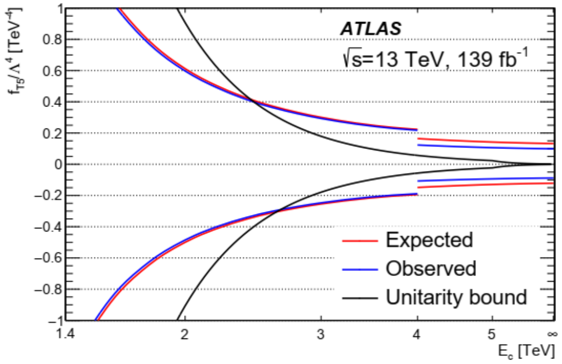
Detector distributions fitted to explore the modification from aQGCs (in the Effective Field Theory framework)

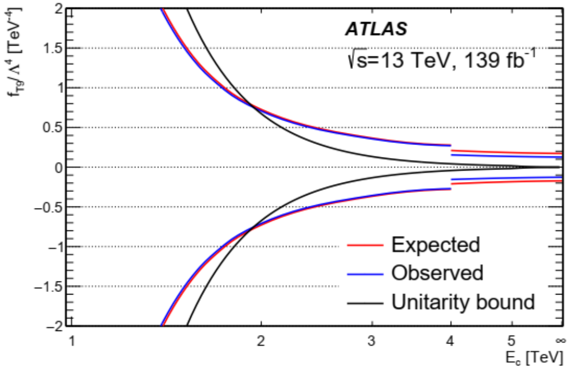
$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j$$

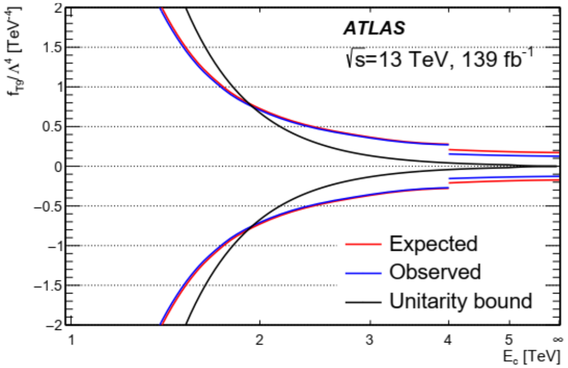
Sensitive to dim-8 Wilson coefficients, in particular those relating to neutral couplings

f_{M0}/Λ^4, f_{M1}/Λ^4, f_{M2}/Λ^4 f_{T0}/Λ^4, f_{T5}/Λ^4, f_{T8}/Λ^4 and f_{T9}/Λ^4









Coefficients constraints w.r.t. cut-off scale (with unitarity bound displayed)

Best limits so far on T5-9 coefficients O(0.1) TeV^{-4}

Concluding

Concluding

Briefly discussed the concept and ingredients of measurements at the LHC

A rough review of status of measurements and a few examples given

Outlook

- LHC is continuing to offer precision data, 3000 fb^{-1} up to 2040; more measurements are expected
- Exploration of the smallest-scale physics and interactions are long-term theme: new directions, methodologies are anticipated
- Interplay with direct searches will continue