Physics at Energy Frontier

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Content

Lecture 1:

- LHC projects
- LHC experiments
- Physics objects
- (Multi) Boson physics
- Top physics

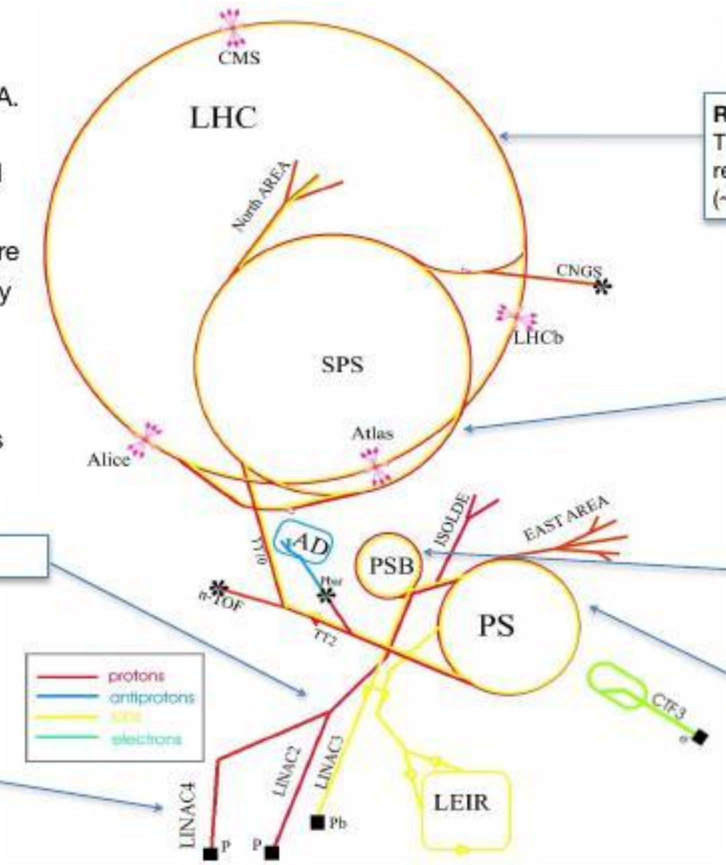
The LHC

Few interesting facts

9300 Magnets (among which 1232 bending dipoles) reaching 8.3T with current of 11,400 A.

Beams are made of trains with a total nominal number of bunches of 2808 each containing approximately 100 Billion protons. Bunches are separated within trains by 25ns (approximately 7m).

Each proton has the kinetic energy of a mosquito and the total energy of the beams is 350 MJ ~ 1 TGV à 150 km/h.



Ramped to 7.5 TeV in the LHC
The maximum number of bunches (2808) not reached at Run 2 is limited by the injection kickers (~1 μs) and by the beam dump extraction (~3 μs)

SPS accelerates protons to 450 GeV, bunches before injection in the LHC.

The booster accelerates protons at 1.4 GeV.

PS brings them to 26 GeV, it is in the PS that bunches are formed with a 25ns spacing.

Accelerated at 50 MeV in a LINAC

Hydrogen (gas) is ionized in a duoplasmotron.

First accelerated with a RF quadrupole at 750 keV.

LHC parameters

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon

LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 100 fb^{-1}/year (after start-up phase)

LHC experiments

10 Years of LHC

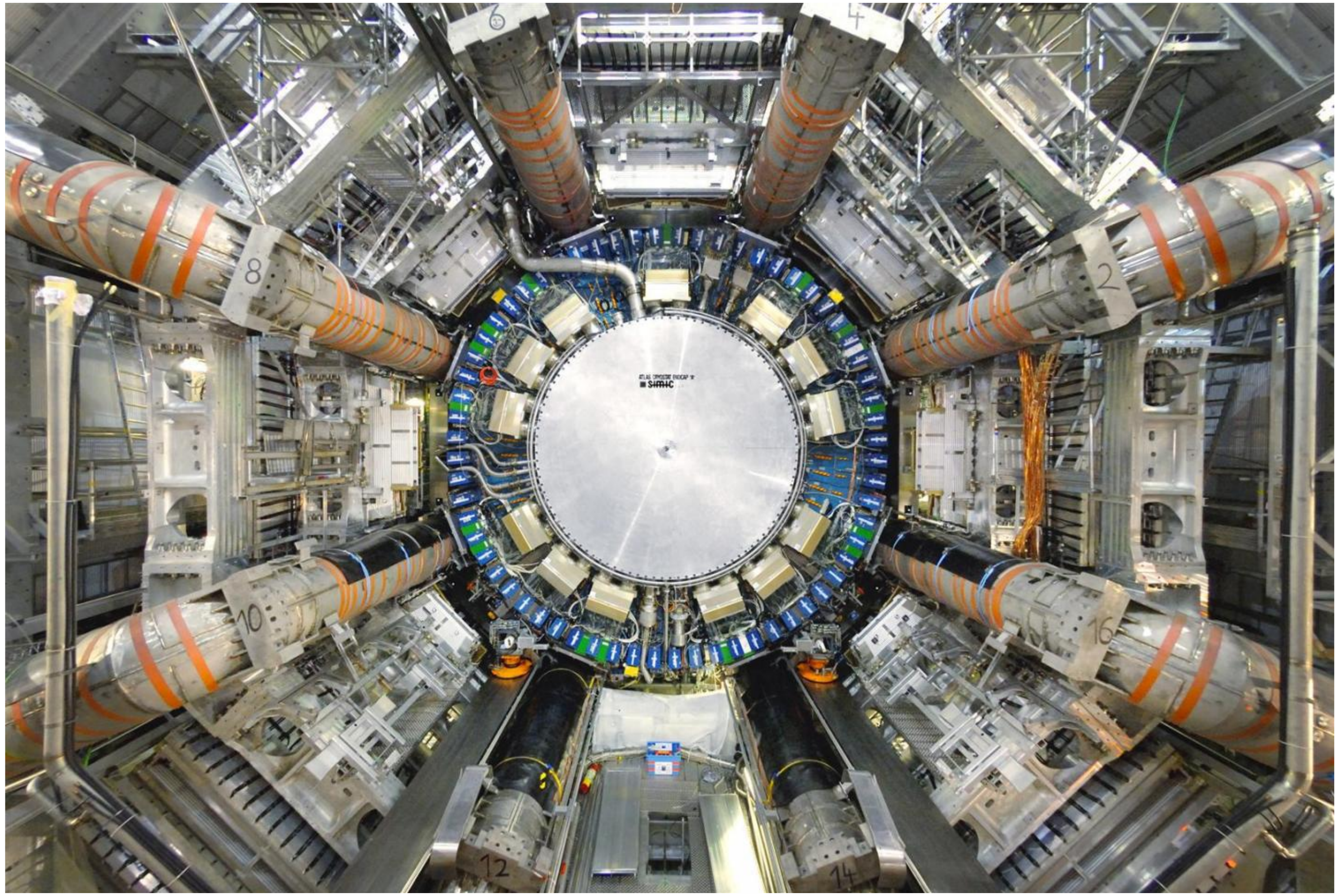
The day the world switched on to particle physics

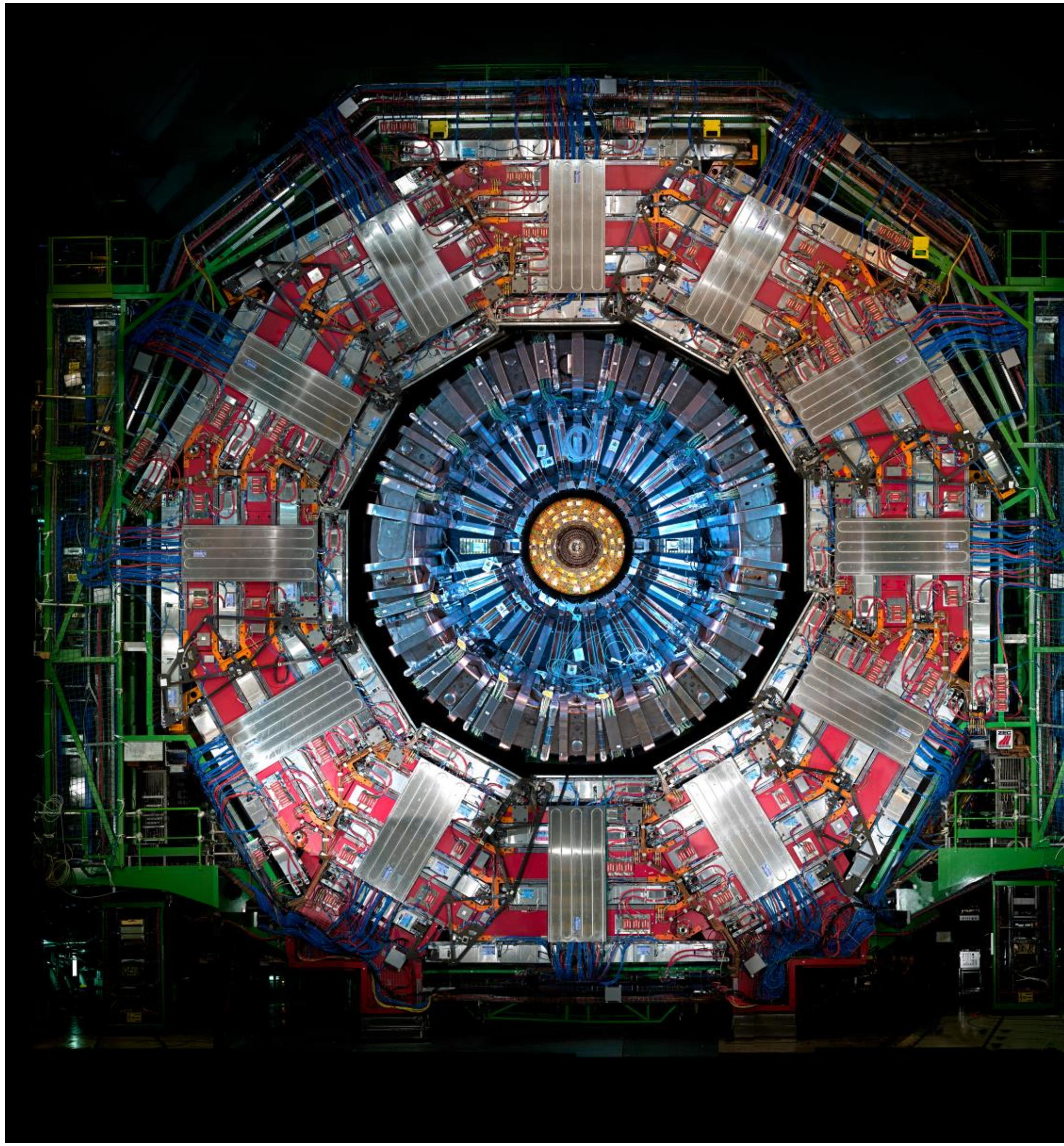
- **Run 1 :** COM Energies of **7 and 8 TeV** and luminosities of ~20 fb-1 for ATLAS and CMS and Pile-Up of ~30-40.

- **Run 2 :** COM Energy of **13 TeV** and luminosities (for ATLAS and CMS) of ~140 fb-1 with Pile Up of ~30-40 (at 25ns - makes quite a difference out-of-time PU!)

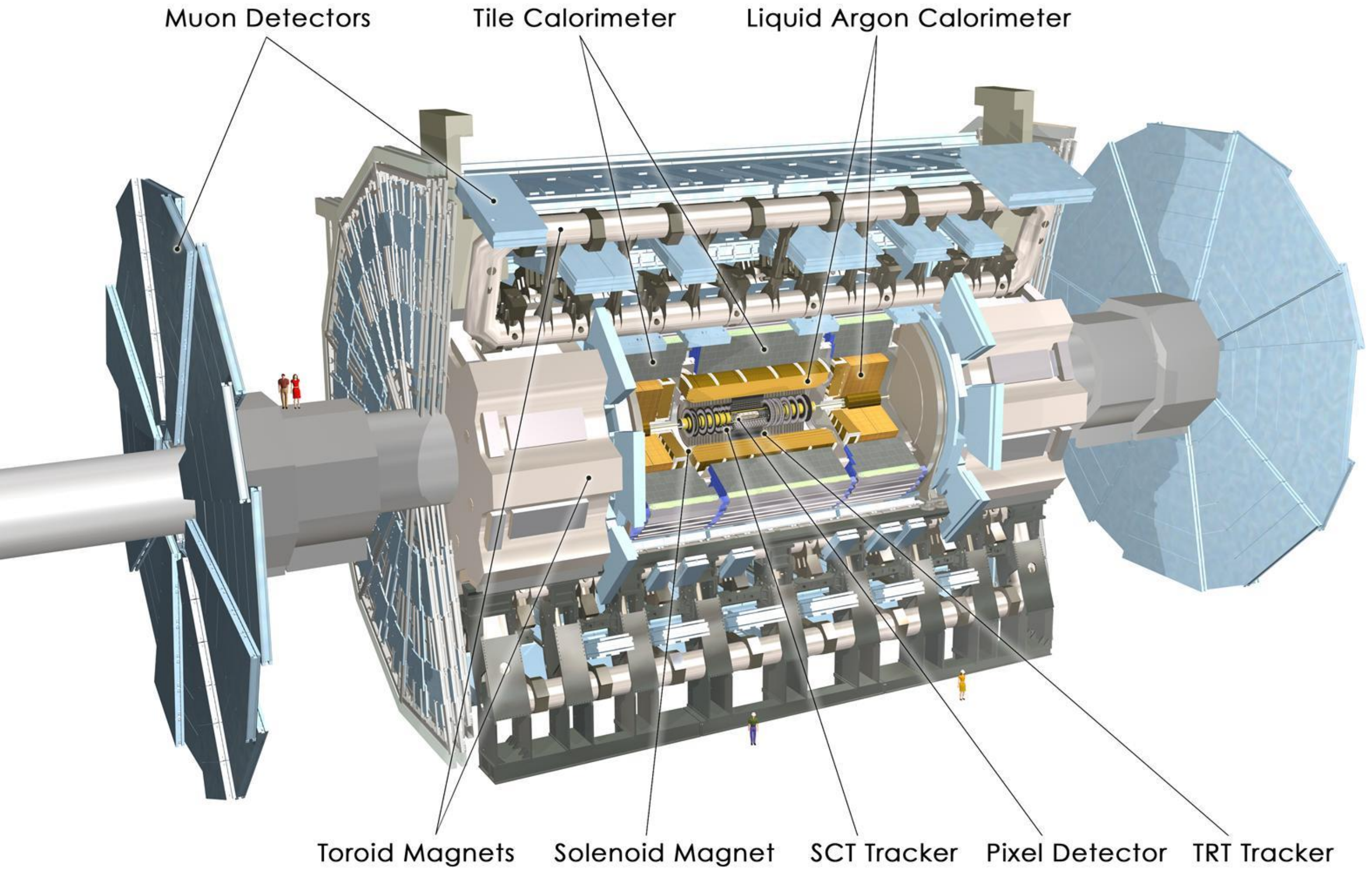
Huge number of lessons learned on how to mitigate PU.

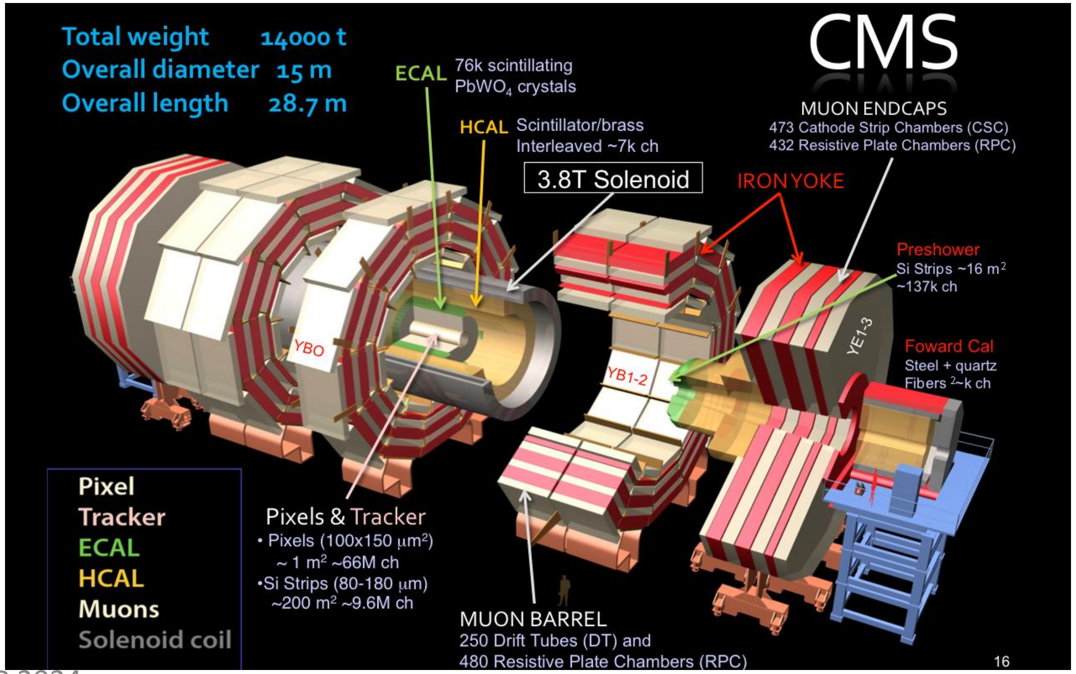
ATLAS and CMS



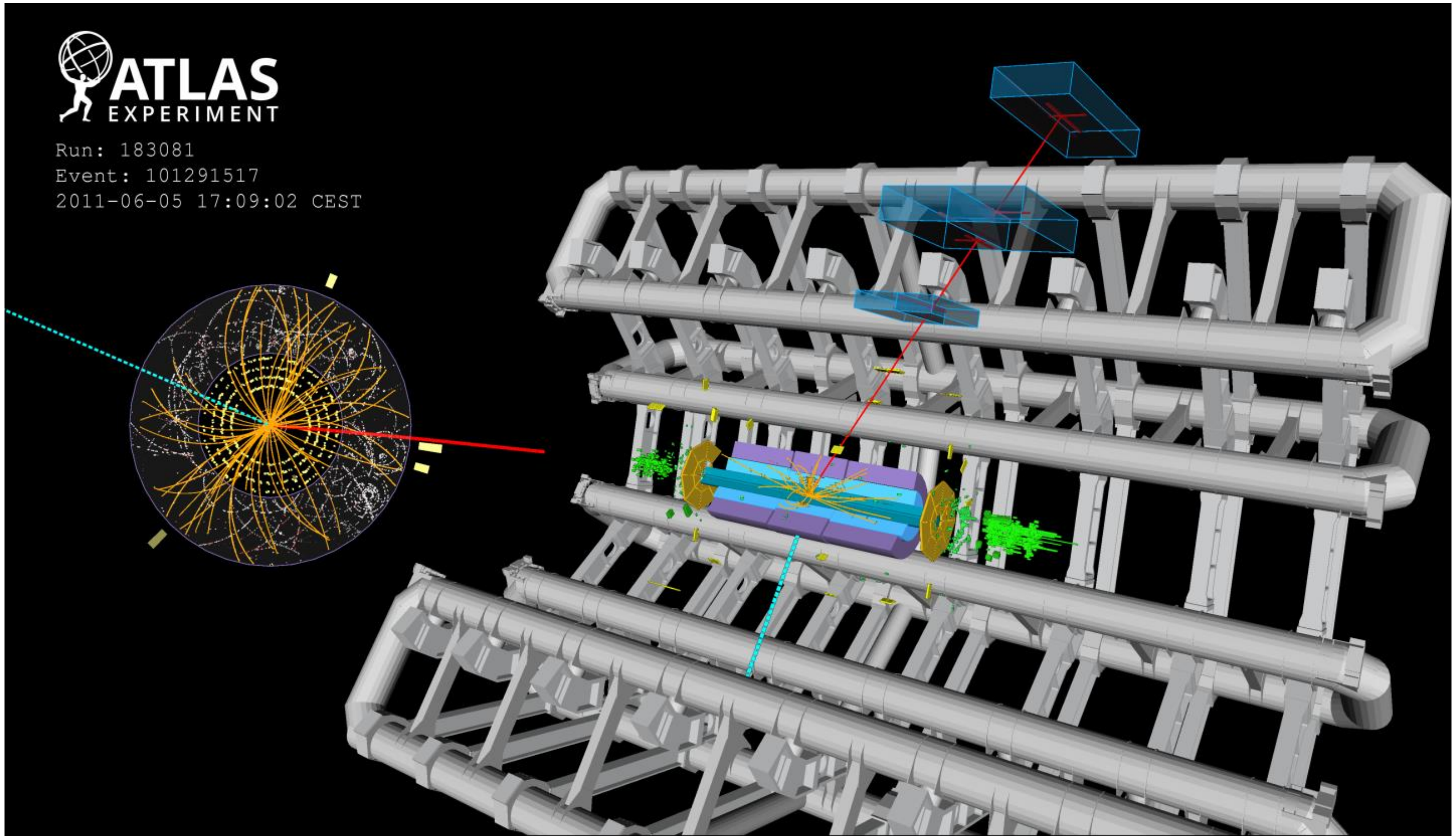


ATLAS and CMS

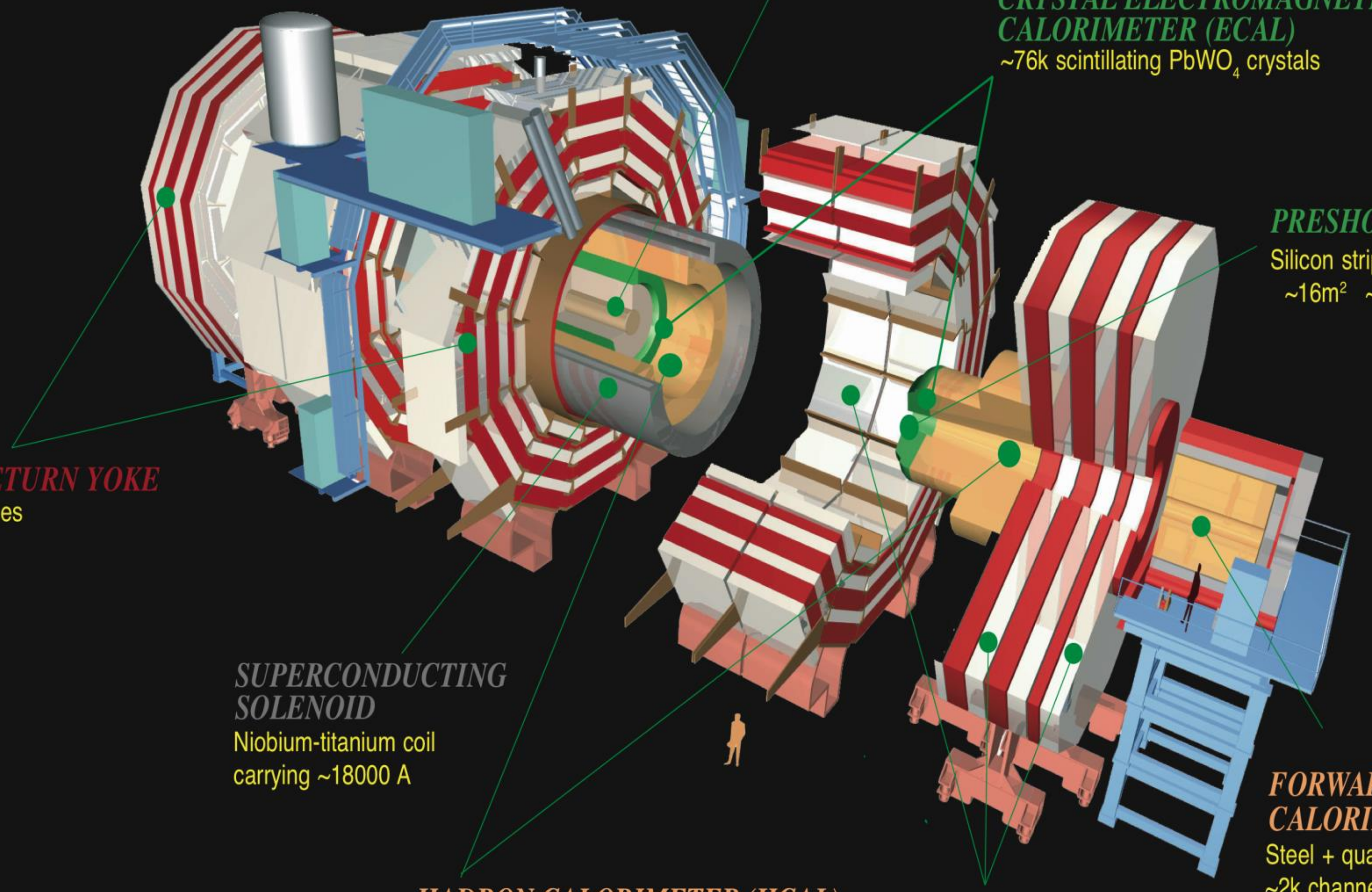




ATLAS muon toroid

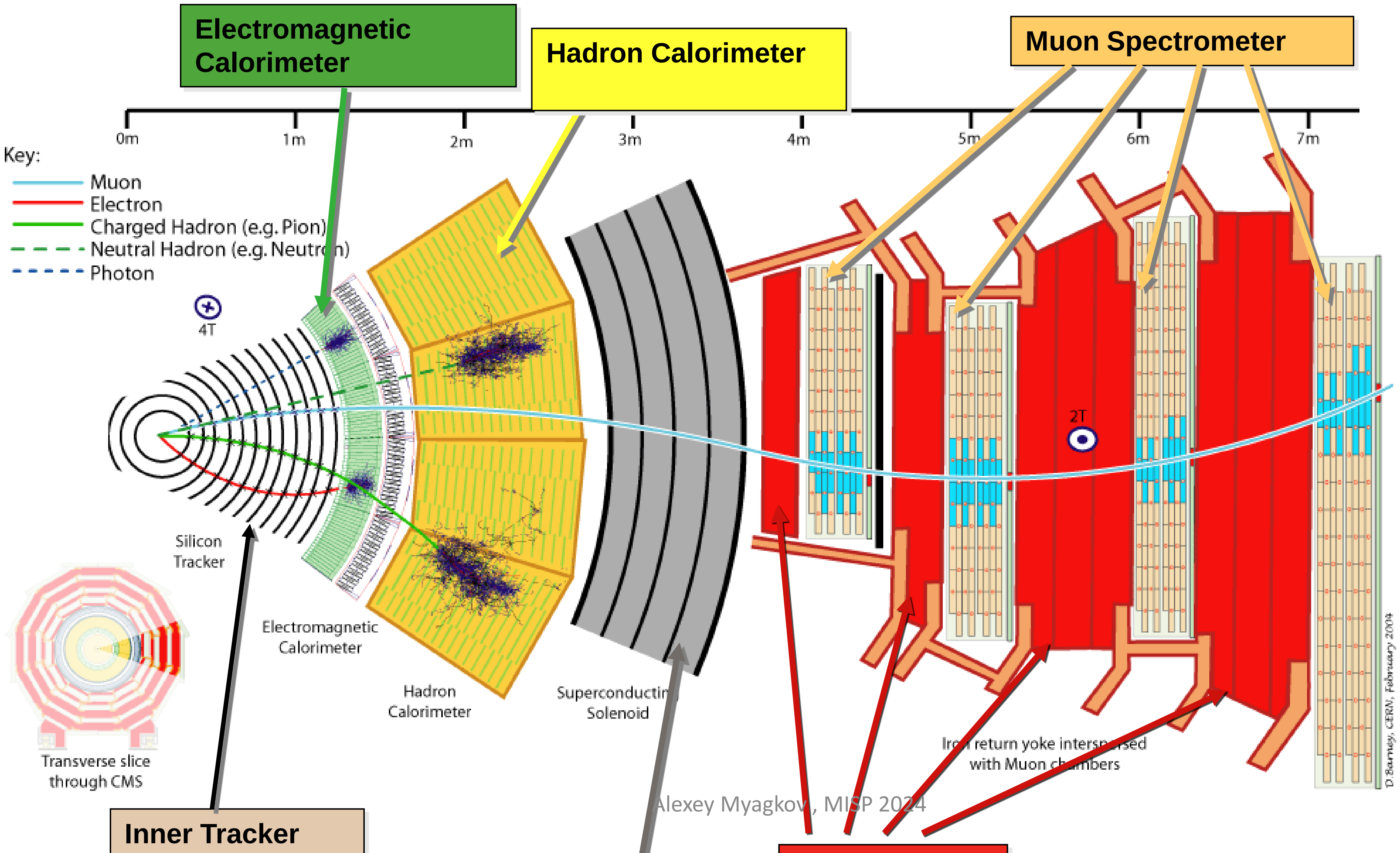


CMS Detector

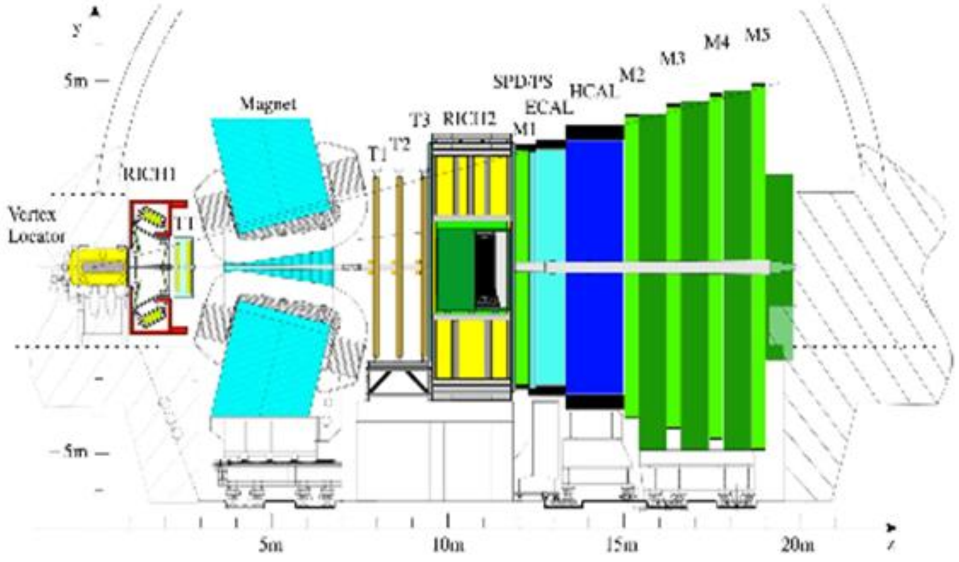


Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Particles in detector

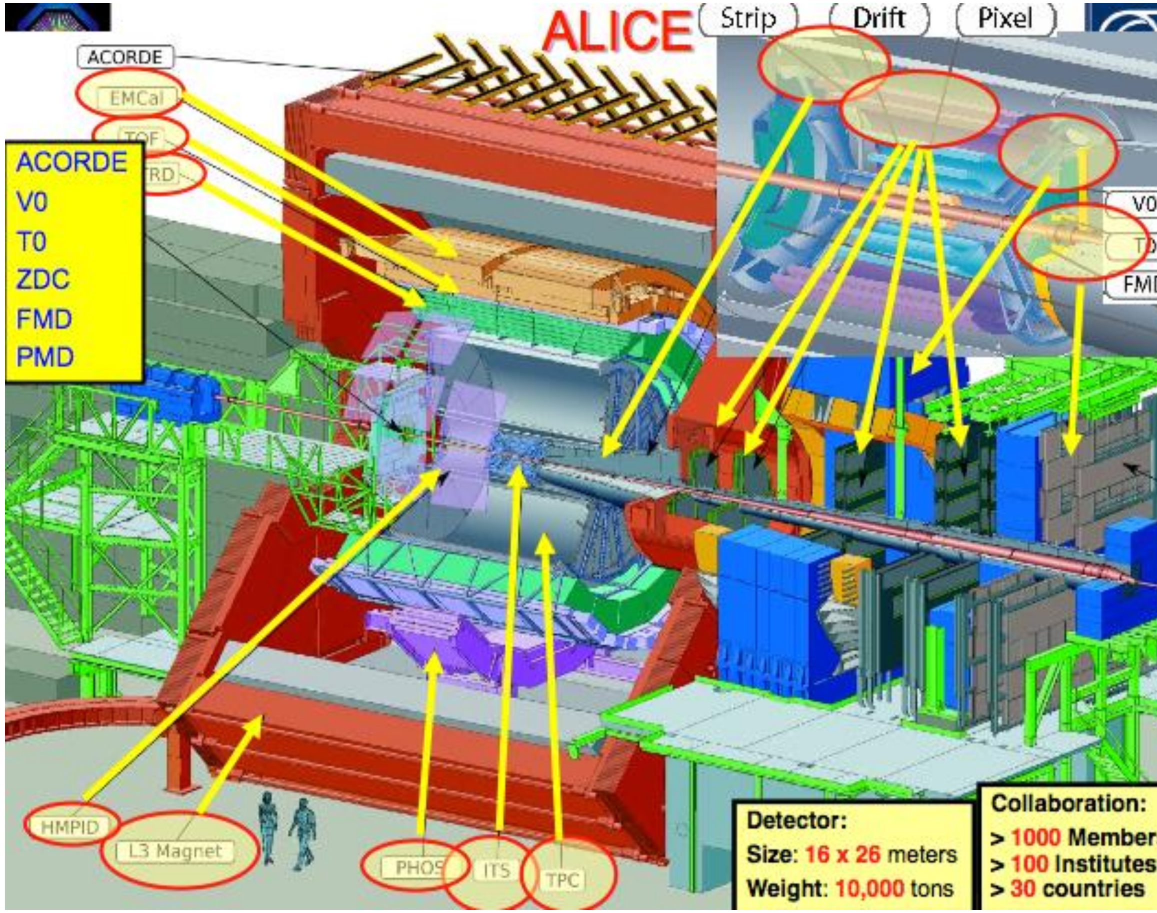


LHCb and ALICE experiments

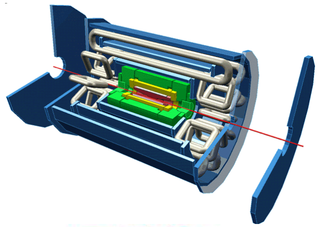
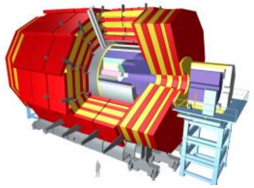
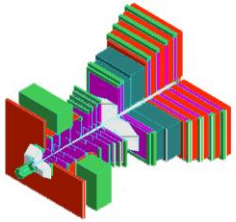
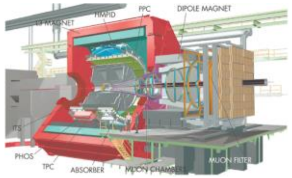


Most relevant attributes for results to be shown today

- Forward acceptance ($2 < \eta < 5$) and down to very low p_T
- Precise vertexing (VELO) – hit resolution of down to 4 µm achieved; measurements 8mm from beam-line
- RICH system providing hadron id between 2 and 100 GeV/c
- High performance muon system



Data flows

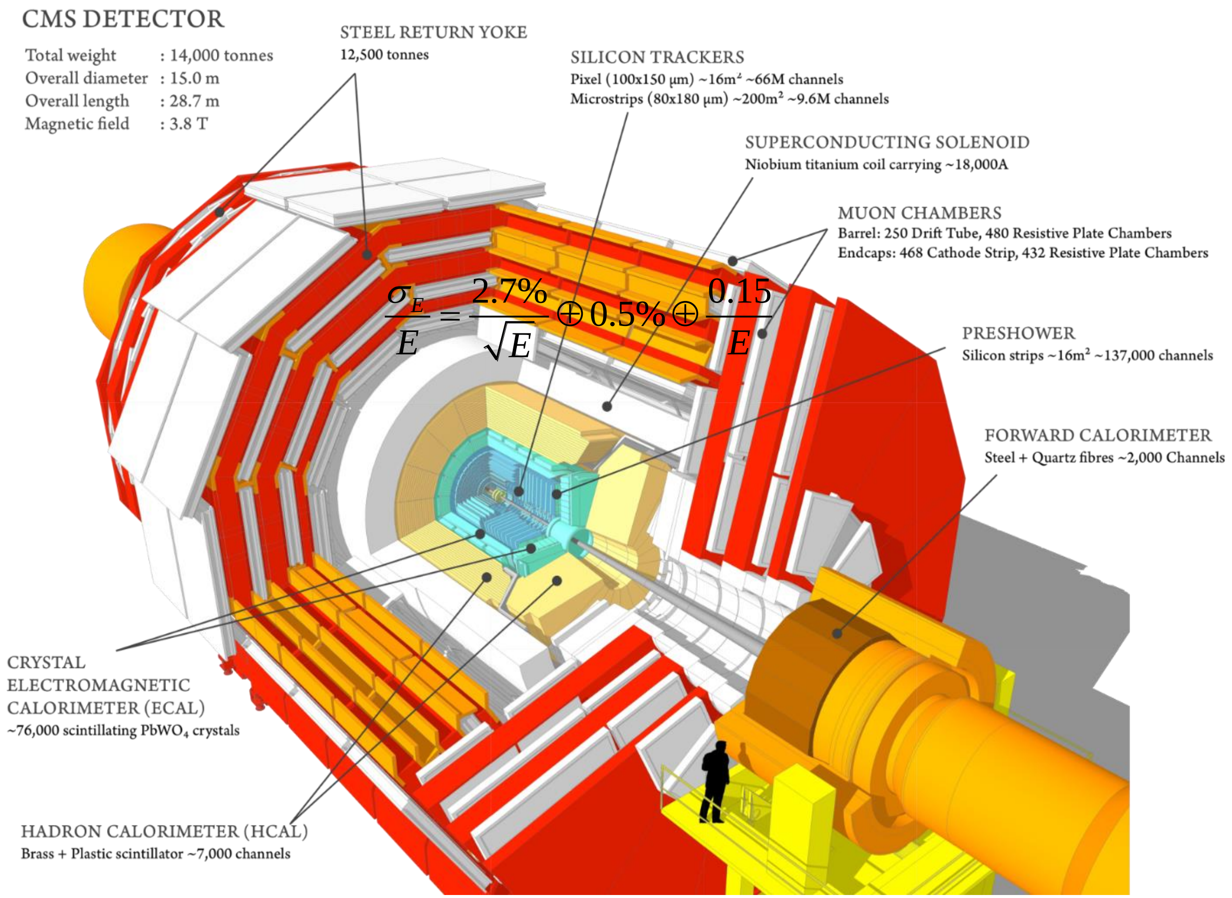





	Level-1 kHz	Event MByte	Storage MByte/s
ATLAS	100	1	100
CMS	100	1	100
LHCb	400	0.1	20
ALICE	1	25	1500

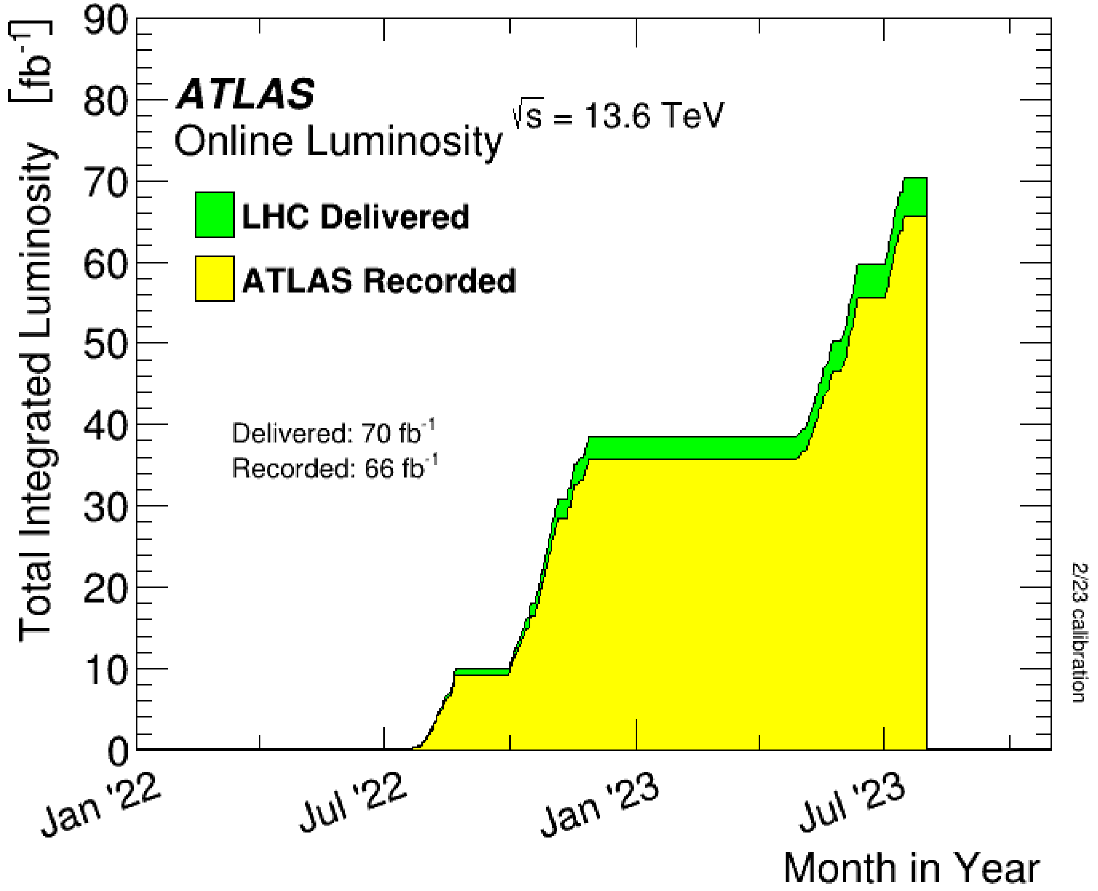
The CMS Experiment

$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{0.15}{E}$$

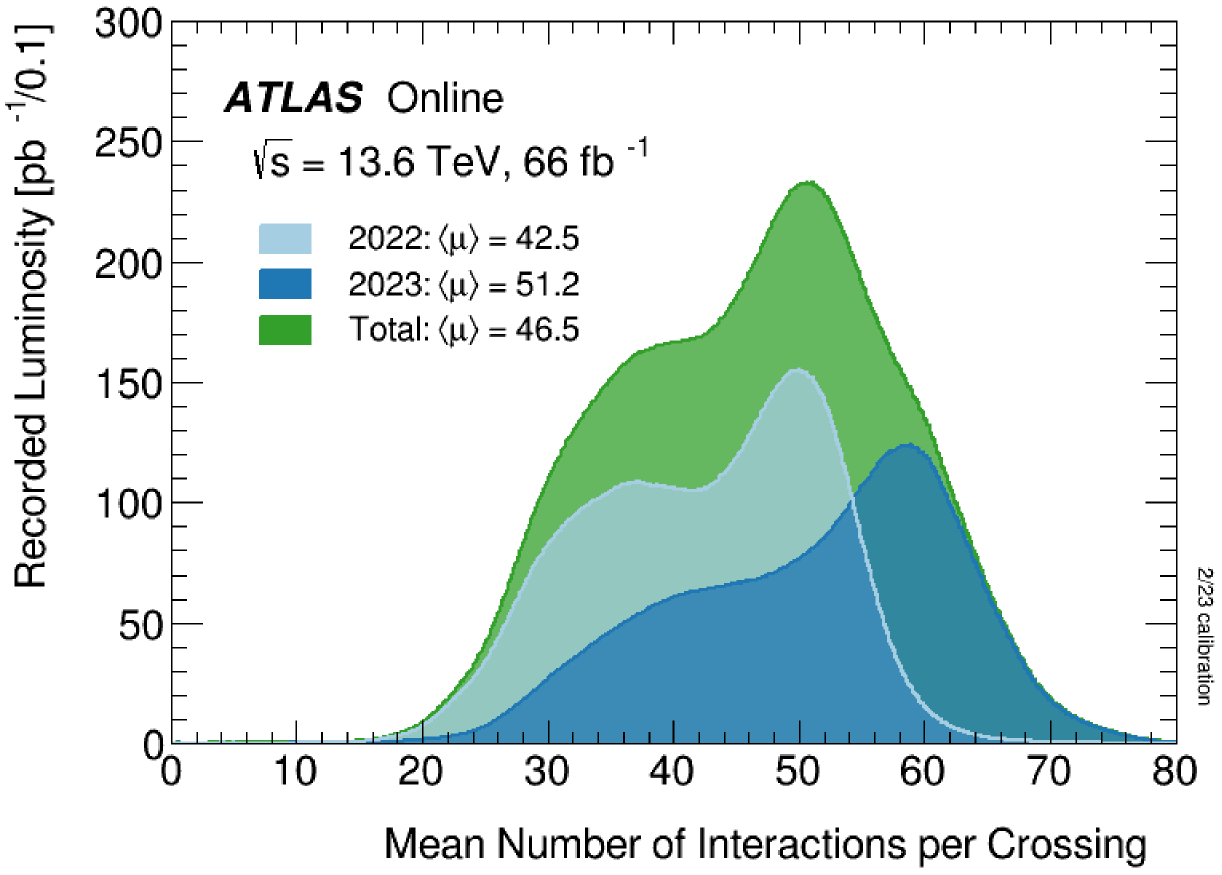
$$\frac{\sigma_E}{E} = \frac{120}{\sqrt{E}} \oplus 5\%$$



Total Integrated Luminosity in Run 3 (13.6 TeV p-p data only)



Interactions per Crossing 2022-2023

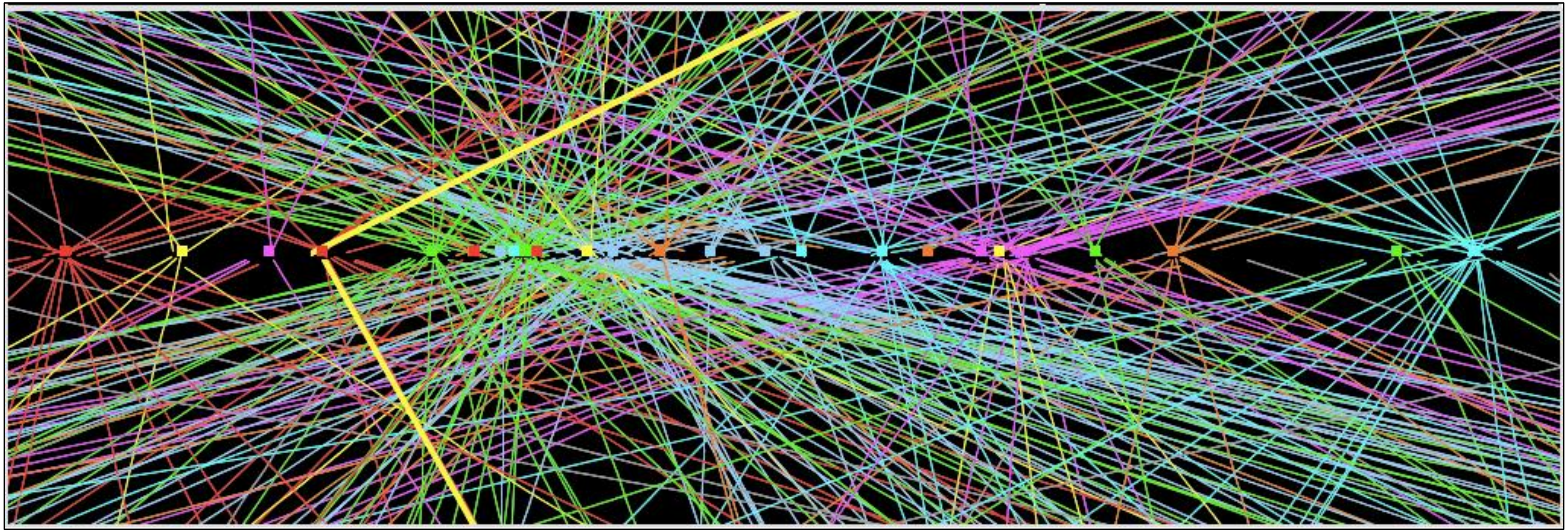


2024 LHC schedule

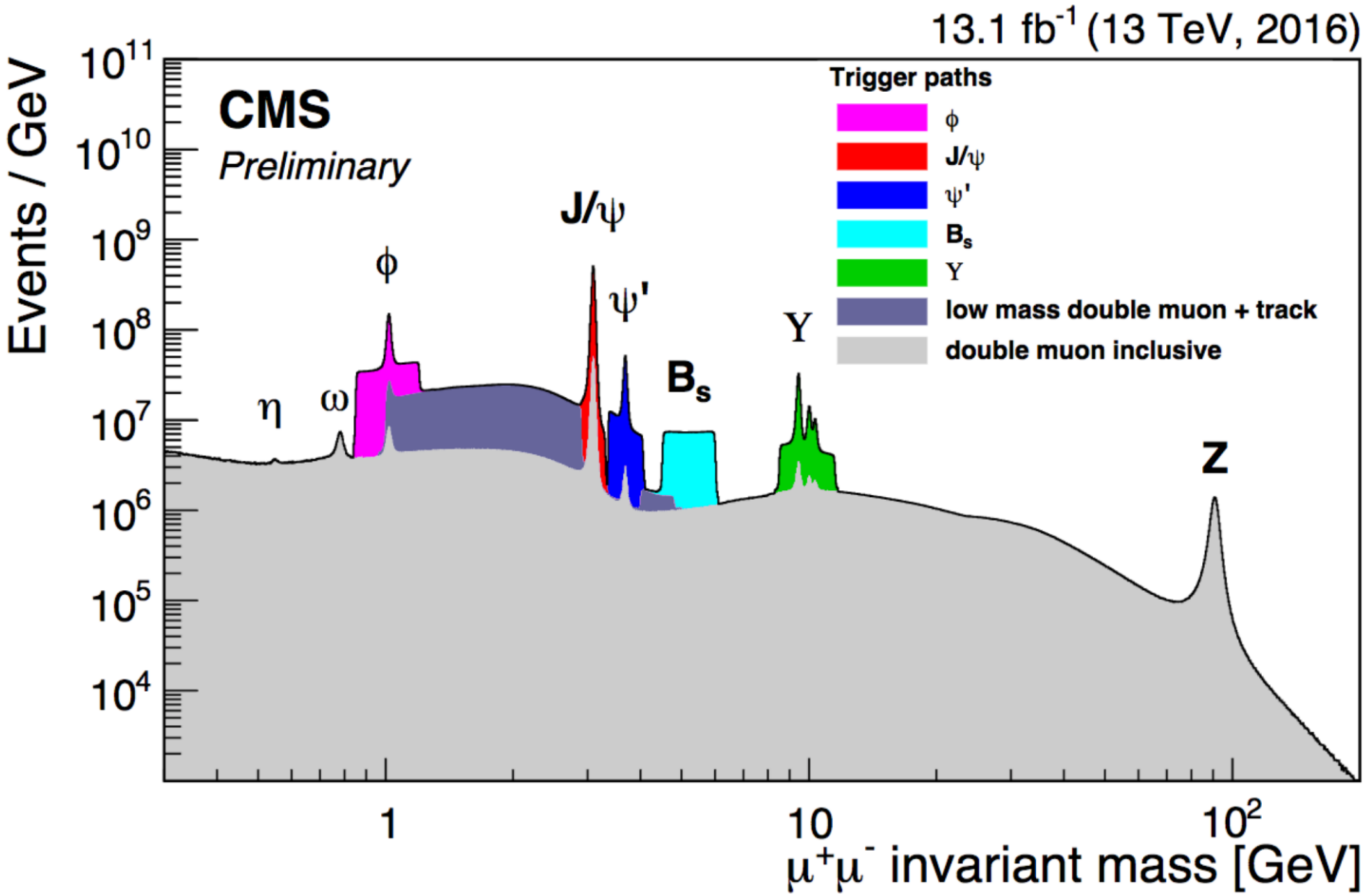
Activity	#days	%
25 ns physics (>1200 bunches)	**124**	53.7
Special physics runs (incl. setting-up)	**2**	0.9
Pb-Pb ions physics & p-p ref. run	**22.5**	9.7
Beam Commissioning & Intensity ramp-up	42	18.2
Scrubbing	3	1.3
Pb-Pb ions & p-p ref. setting-up	6	2.6
Technical stop	9	3.9
Technical stop recovery	2	0.9
Other scheduled stops	0.5	0.2
Machine Development (incl. floating MDs)	20	8.7
Total:	**231**	**100%**

Closure of LHC and experimental caverns on March 6th 2024

Z->μμ event with ~20 reconstructed vertices (2012)

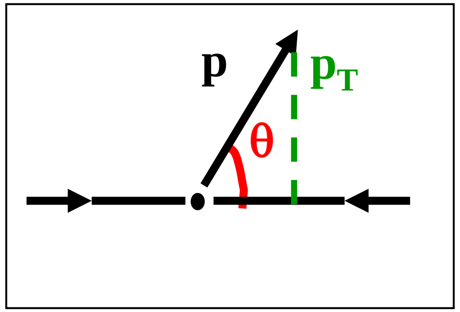


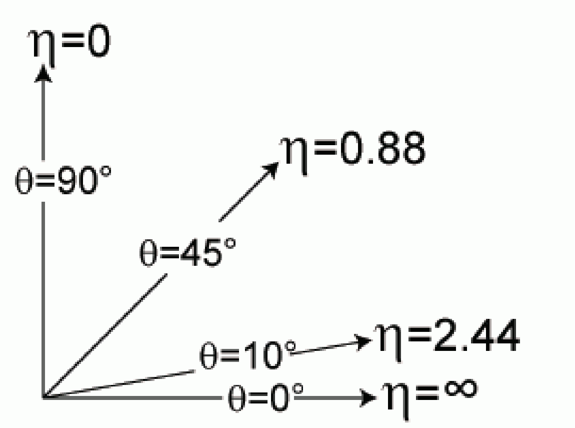
Physics performance



Physics Objects

Muons (transverse momentum pT)
Electrons (energy and tr. momentum pT)
Photons (energy)
Jets (energy and η)
Missing energy and pT vectorial sum of all transverse momentum

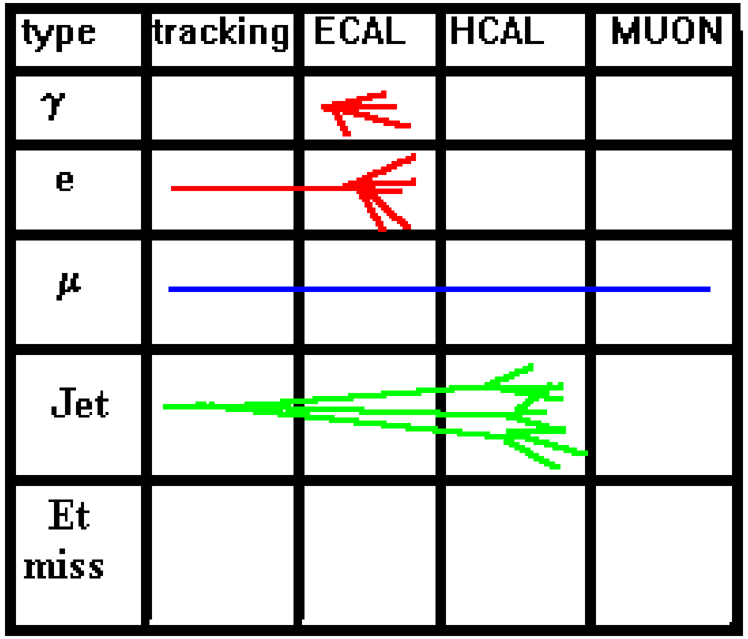


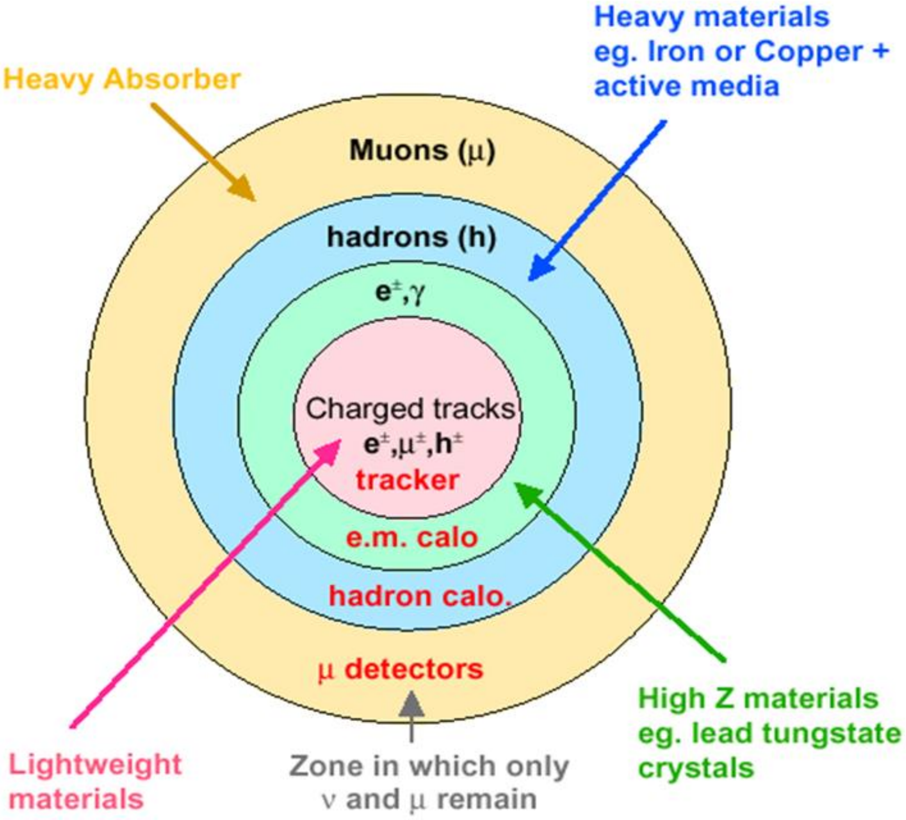


For an "massless particle" (E ≫ M)

$$y = \tfrac{1}{2} \ln (1+\cos\theta)/(1-\cos\theta)$$
$$= -\ln \tan(\theta/2) = \eta$$

Particles in detector





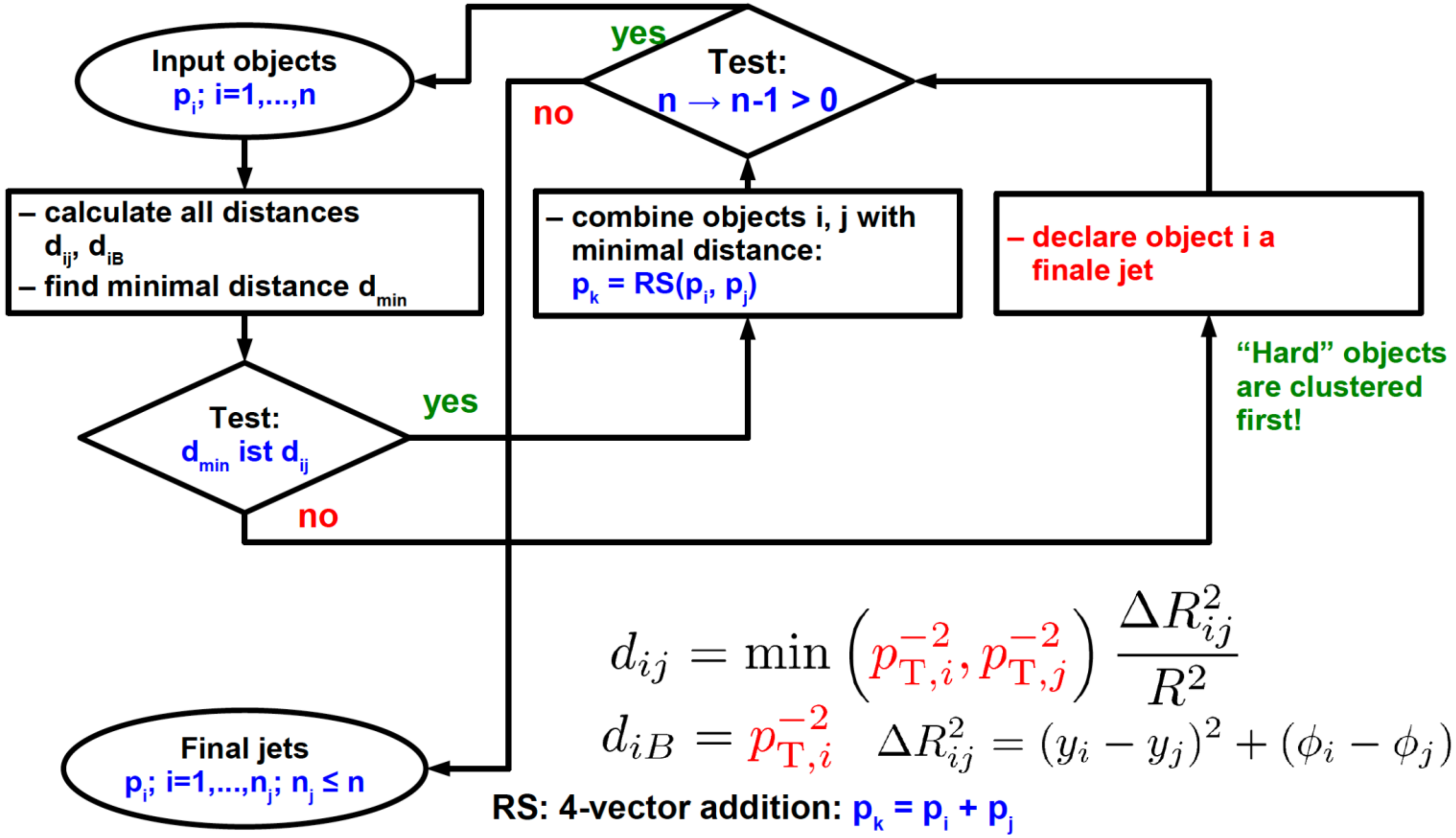
Each layer identifies and measures (or remeasures) the energy of particles unmeasured by the previous layer

No single detector can determine identity and measure energies/momenta of all particles

Jets at Hadron Collider

Primary goal is to find correspondence between
Detector measurements
Particles in final state
Hard partons
Classes of algorithms
Cone algorithms
Sequential recombination
Requirements
Infrared and collinear safe
Order independence
Ease of implementation

Anti-kT algorithm

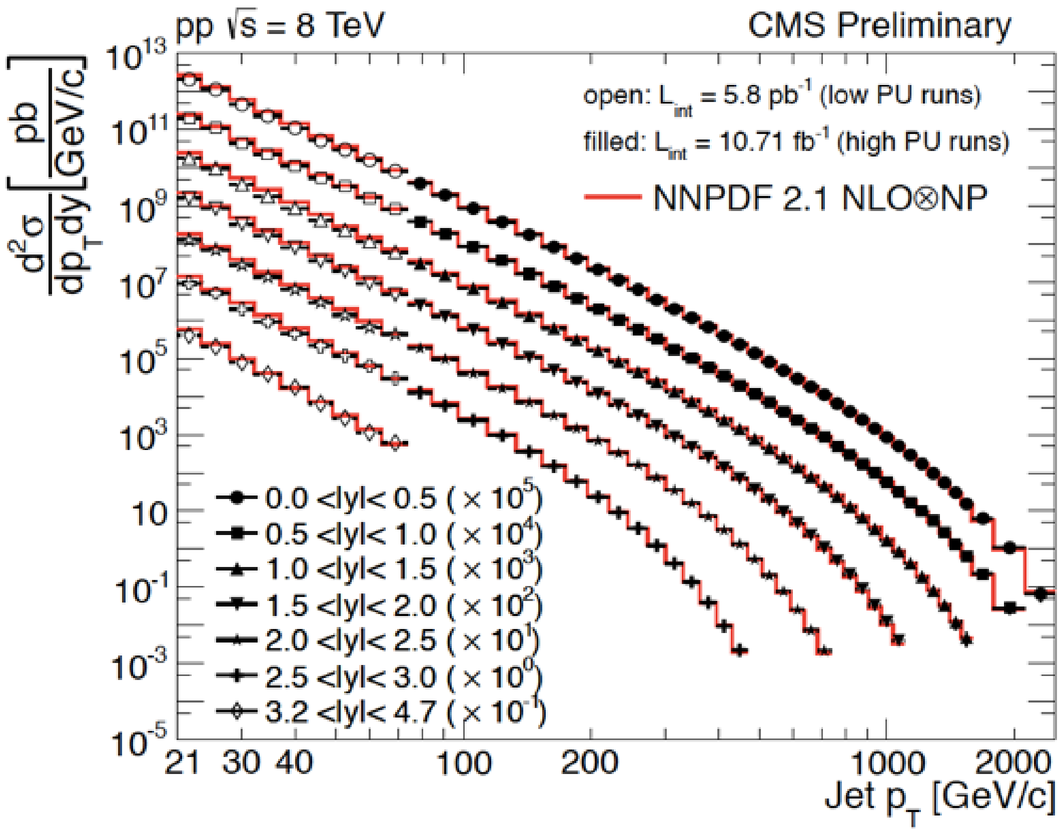


$$d_{ij} = \min\left(p_{\mathrm{T},i}^{-2}, p_{\mathrm{T},j}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{\mathrm{T},i}^{-2} \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

RS: 4-vector addition: $p_k = p_i + p_j$

Cacciari, Salam, Soyez, JHEP04 (2008).



NLO pQCD describes data over 14 orders of magnitude

B-tagging

b-tag efficiency

Select b-enriched samples using tt sample

t → W b ~ 100% → tagging top = tagging b

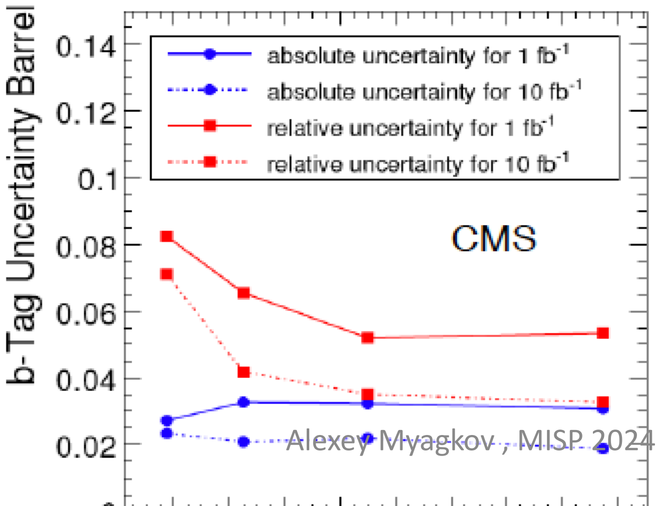
Select pure b sample by using tt event topologies

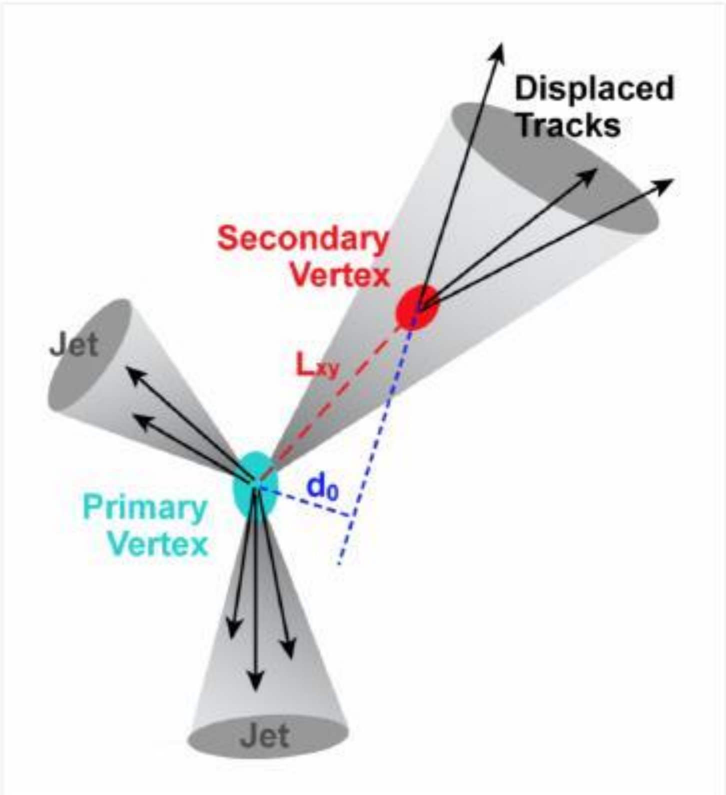
- 1(2) high p_T leptons, $E_{T,miss}$, m_W & m_t constraints
- 70-80% b-purity after selection

CMS study 1(10) fb^{-1}

- Efficiencies 40% to 60% (at $E_{T,b\text{-}Jet}$ > 100) GeV
- Uncertainty 4-6% for large data samples

⇨

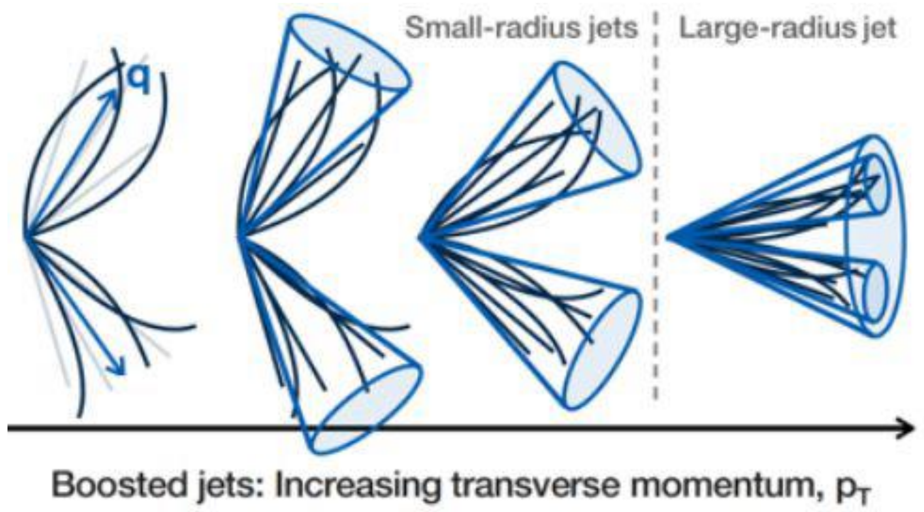


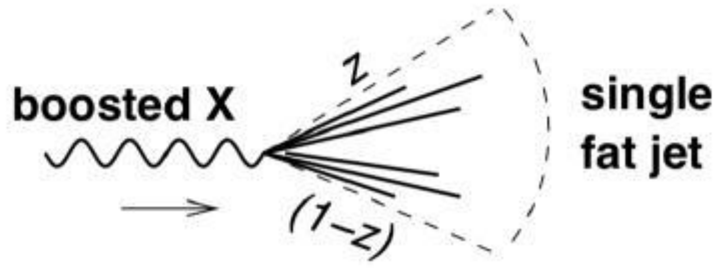


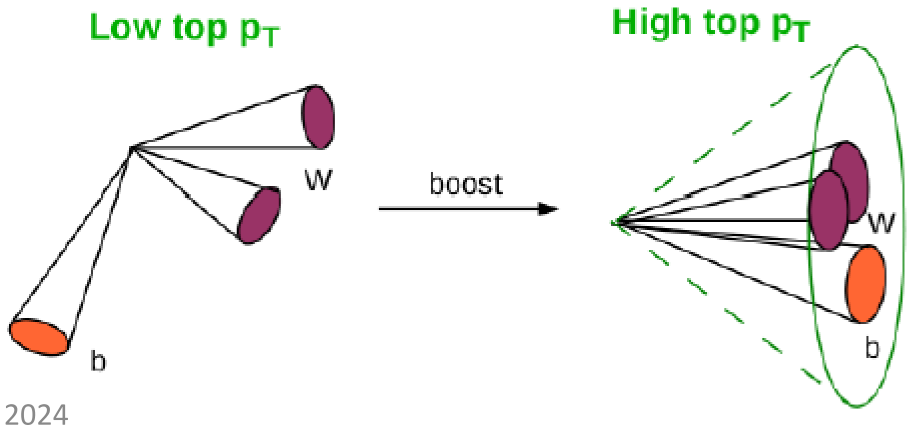
ATLAS study 100 pb^{-1}

- Similar efficiencies, purities
- Estimated uncertainty ~10%

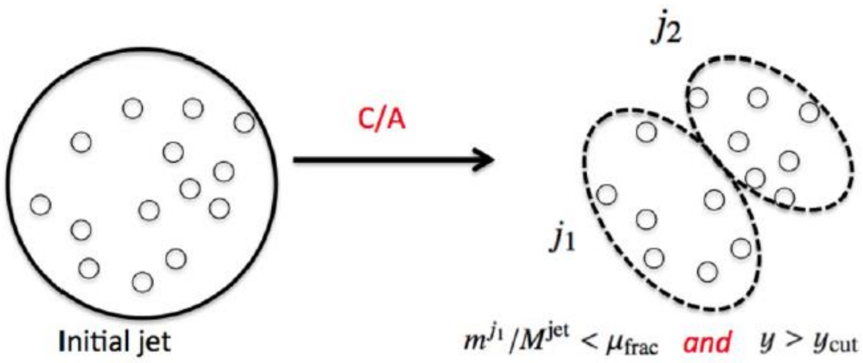
Fat jets


q
Small-radius jets
Large-radius jet
Boosted jets: Increasing transverse momentum, p_T

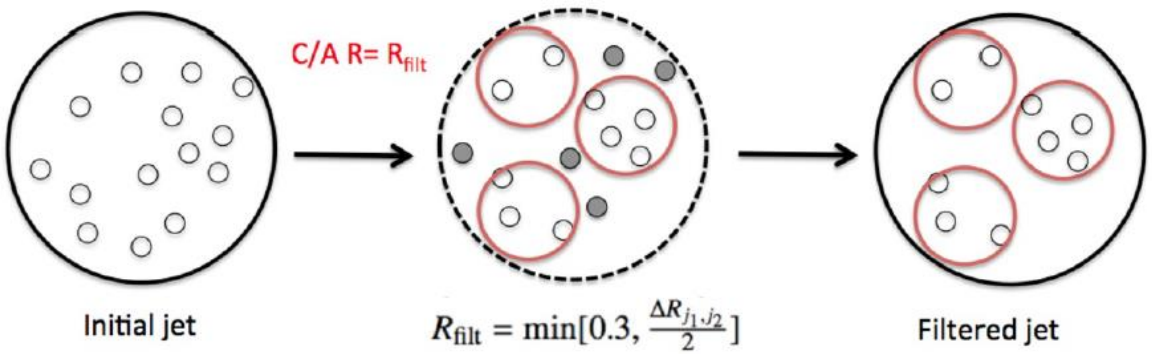

boosted X
z
(1−z)
single
fat jet


Low top p_T
W
b
boost
High top p_T
W
b

Fat jets clearning

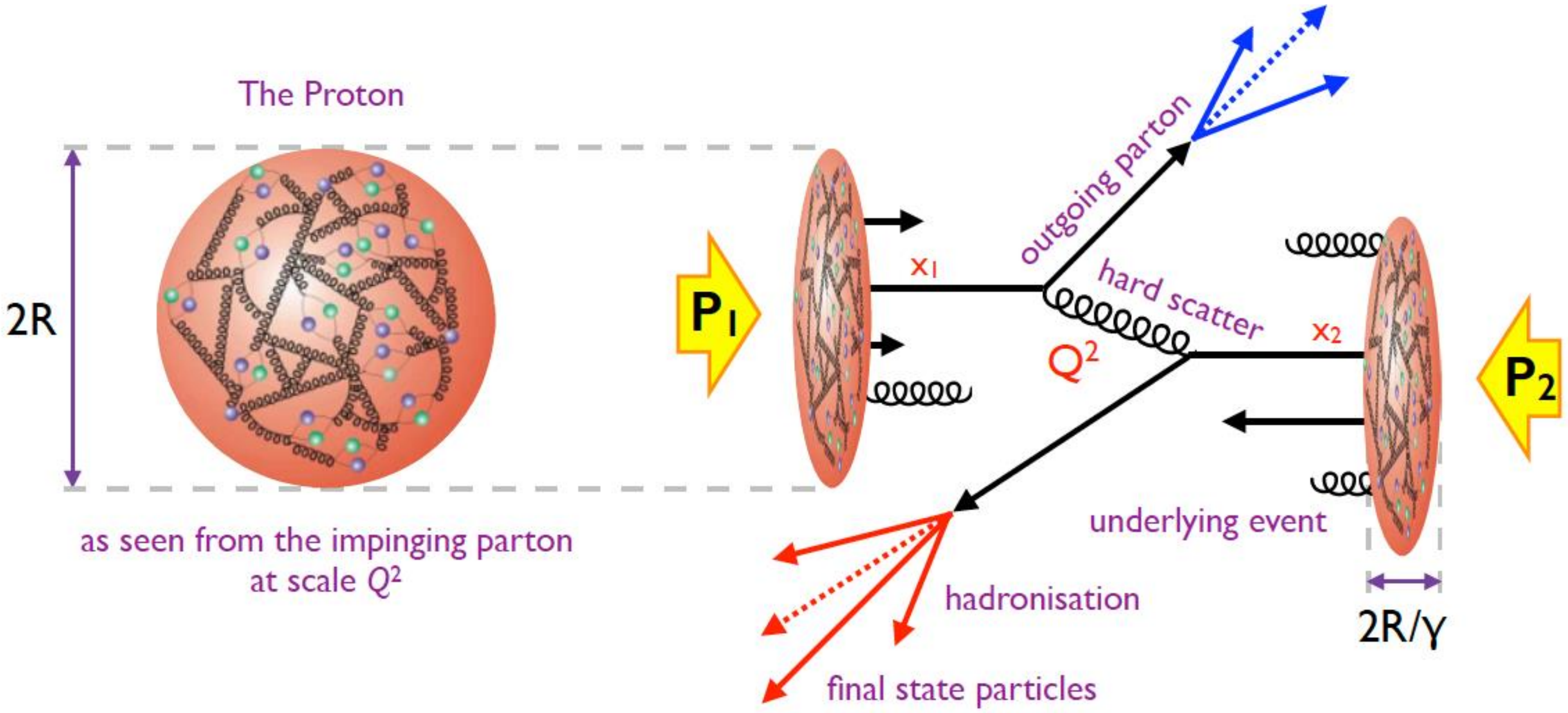


(a) The mass-drop and symmetric splitting criteria.



(b) Filtering.

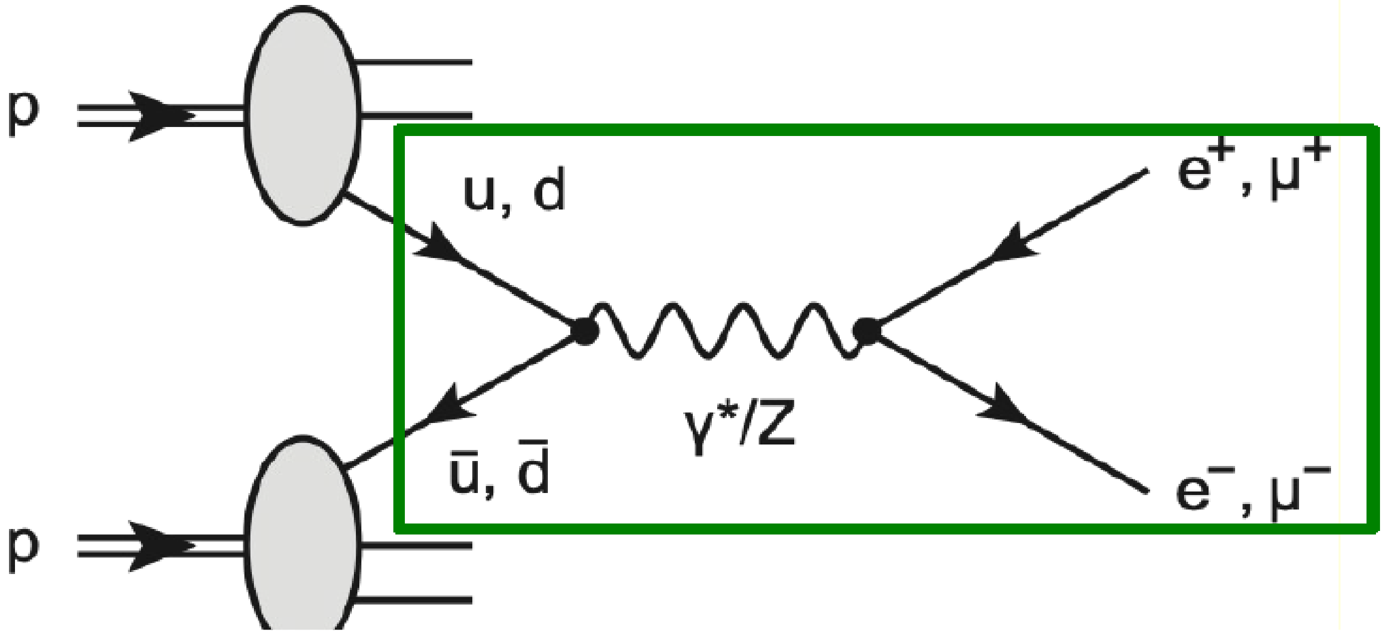
Hadron-Hadron Collision



Drell-Yan Production   pp-> l+l- + X

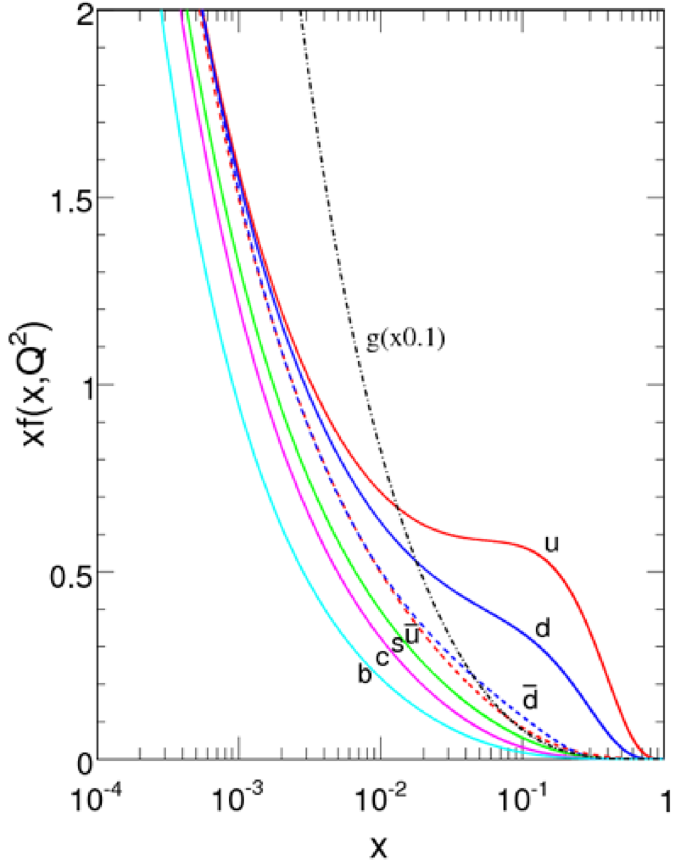
Hadron production of lepton pairs
Factorising “hard” and “soft” components
Calculate hard partonic subproc

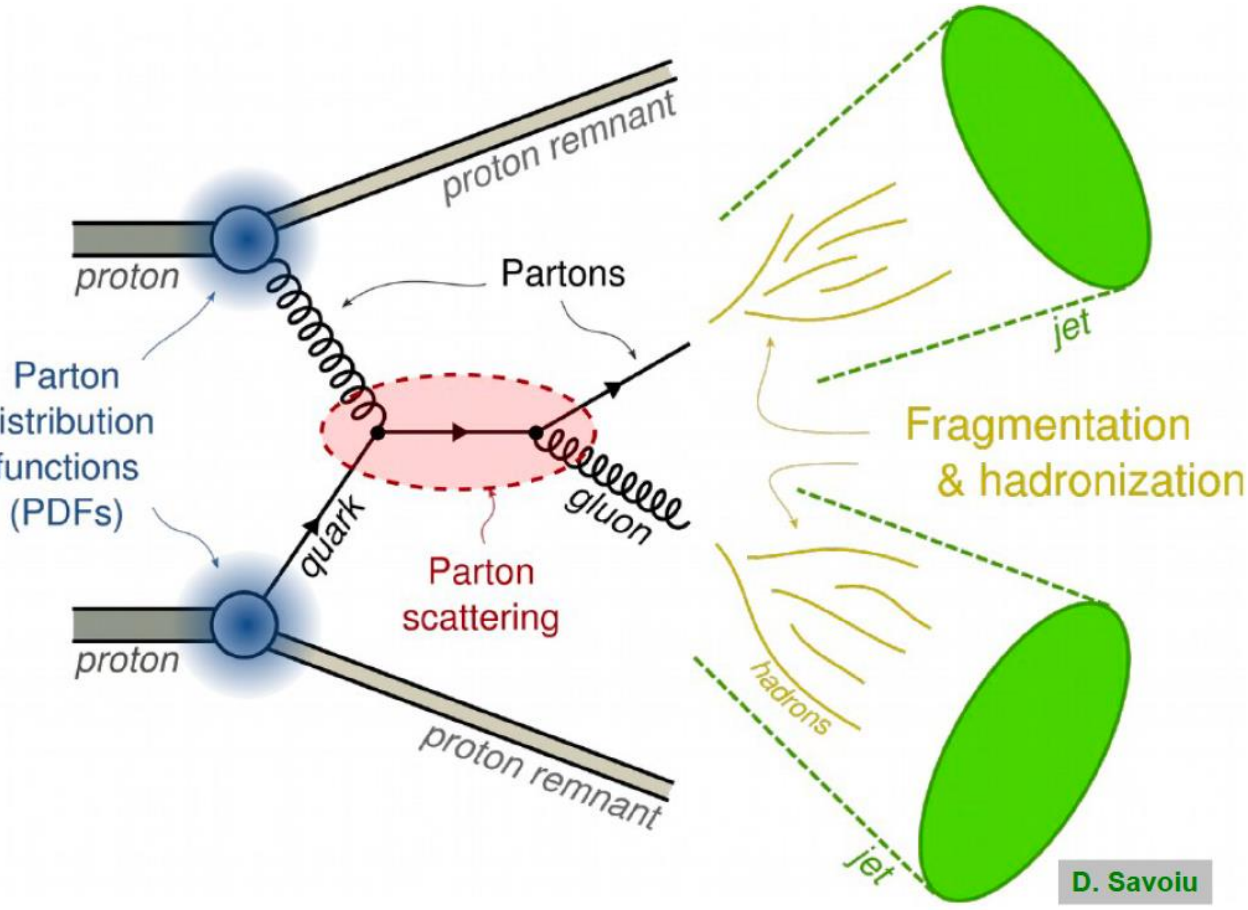
Weight cross section with probability to end partons with momenta x1 and x2
Integrate over all possible parton momenta
Sum over all possible parton flavors



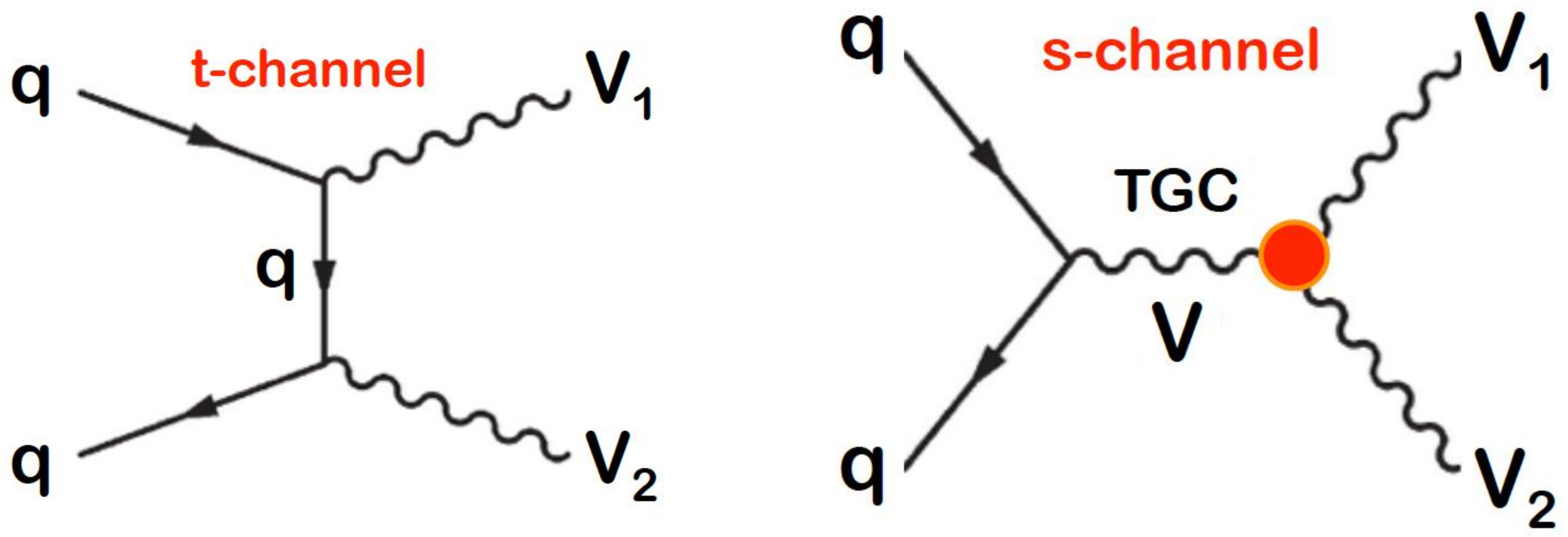
$$\sigma_{\mathrm{DY}} = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_i(x_i) f_j(x_j) \cdot \hat{\sigma}(q_i q_j \to l^+ l^-)$$

Hadron-Hadron Cross Section



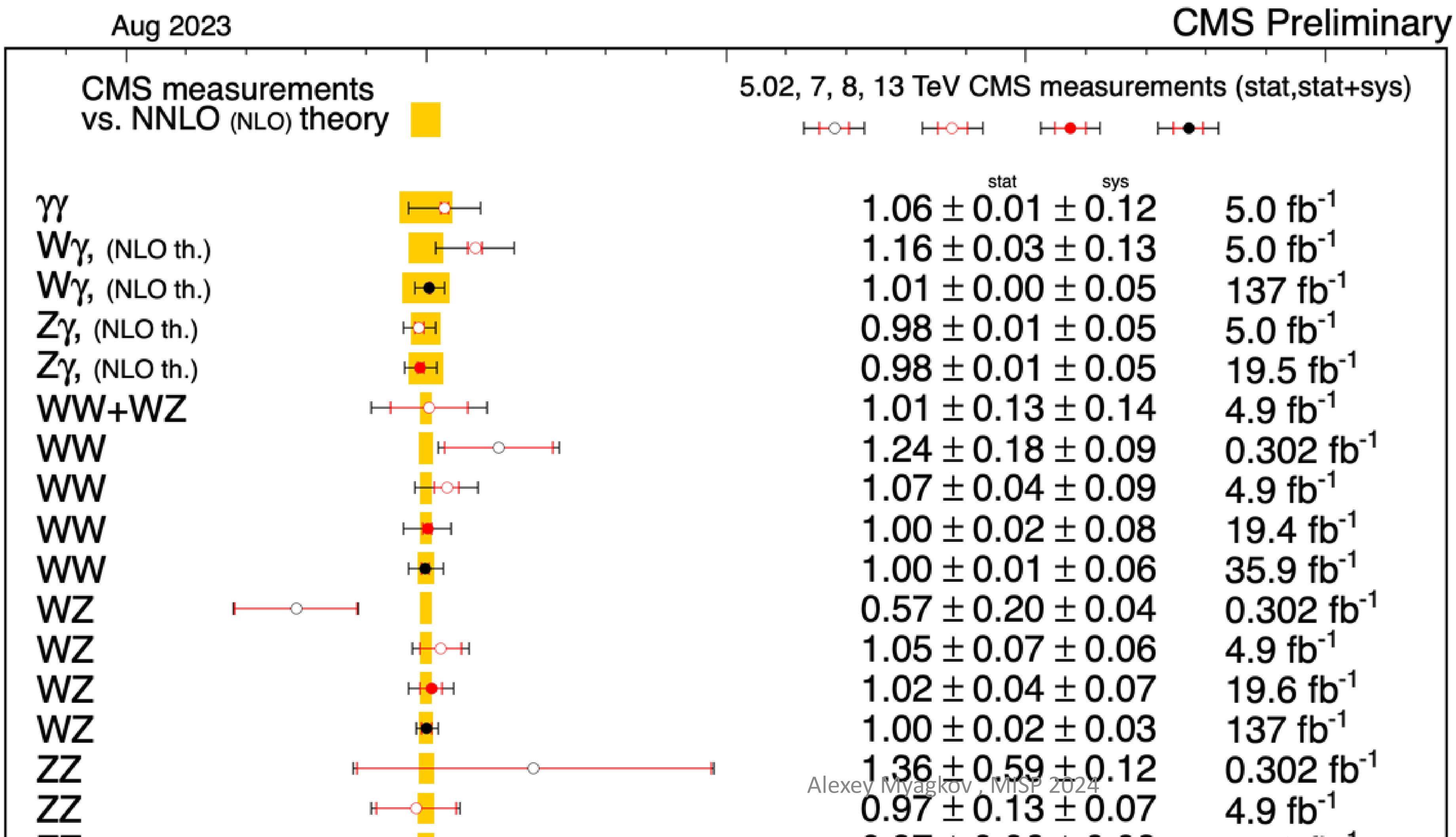


Multi-Boson Production

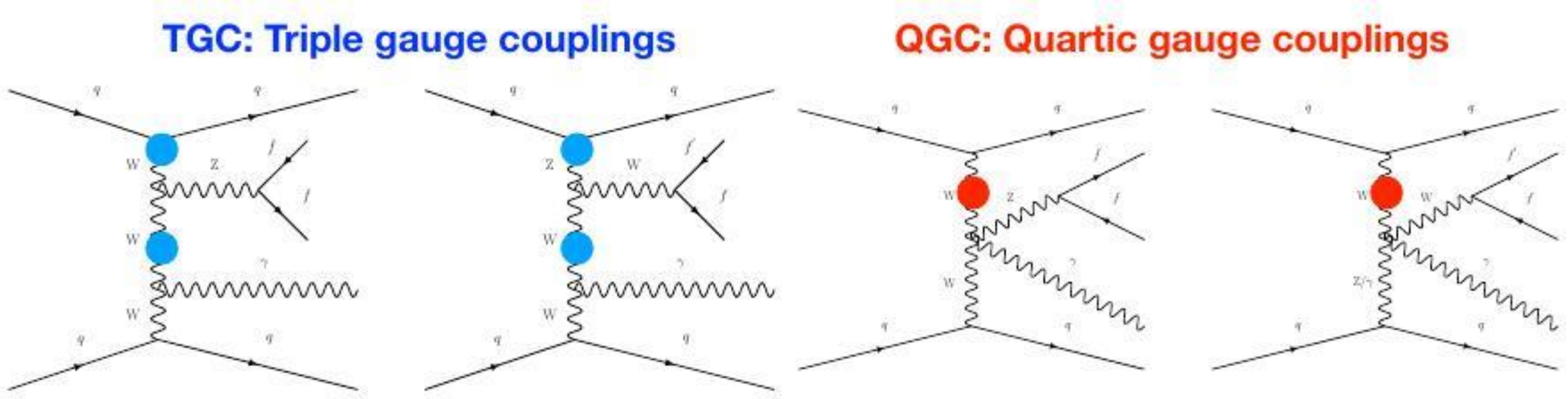


Large number of processes study
Generally good agreement
between experiment and theory
Constraint on anomalous couplings

Ratio of diboson cross-section measurements to theory



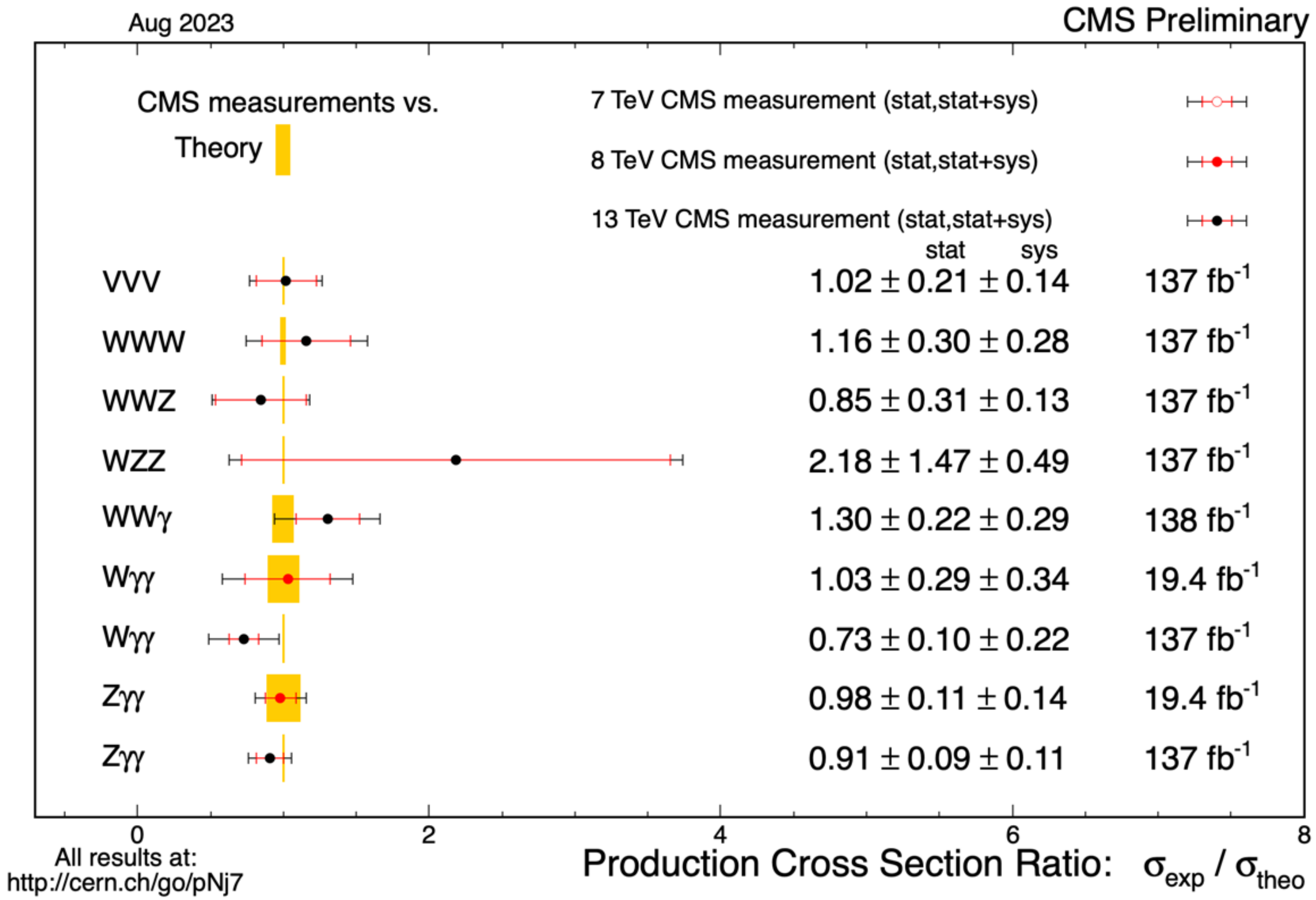
TGC,QGC



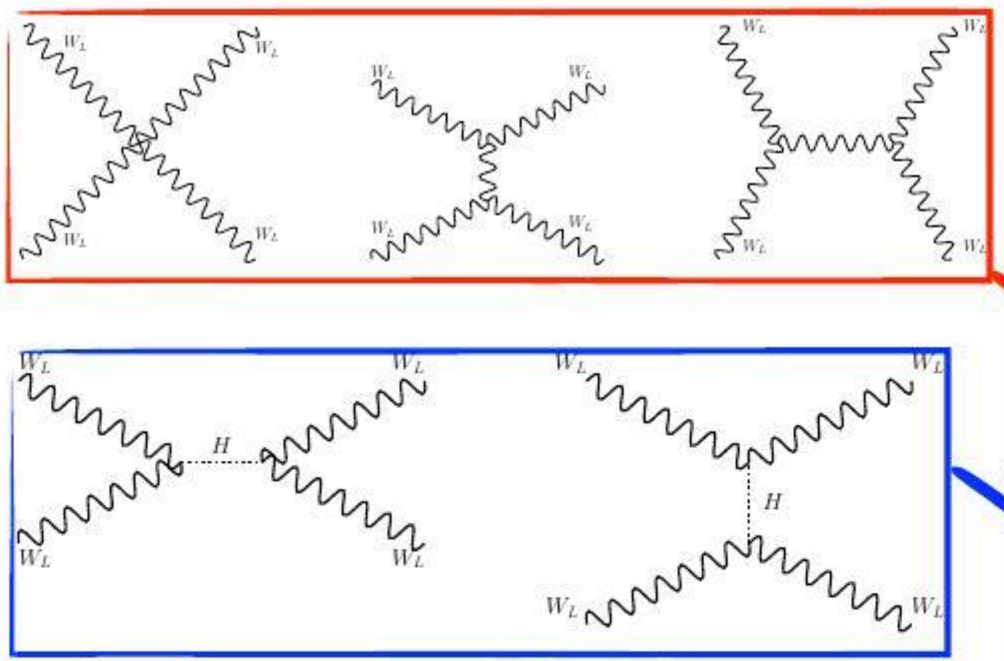
Larger cross sections:
- More precise measurement for SM test
- Possibly accurate differential cross section

Multiboson couplings:
- T(Q)GC: WWZ, WWγ, WWZγ, WWγγ
- BSM TGC: ZZγ, Zγγ
- BSM QGC : ZZγγ, ZZZγ,Zγγγ

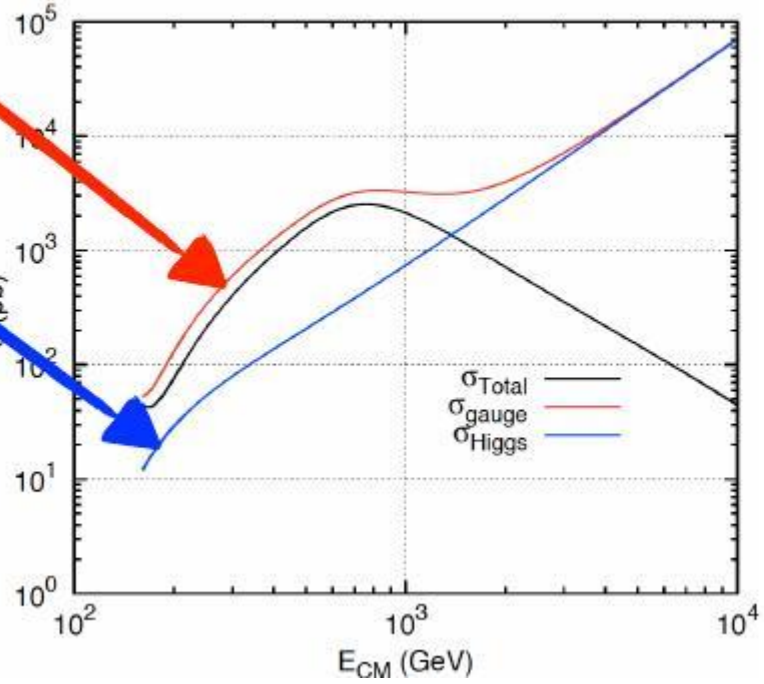
Multi-Boson Production



VBS/VBF Physics motivation



$$iM_{\text{gauge}} \approx -i\frac{g^2}{4m_W^2[s+t]}$$

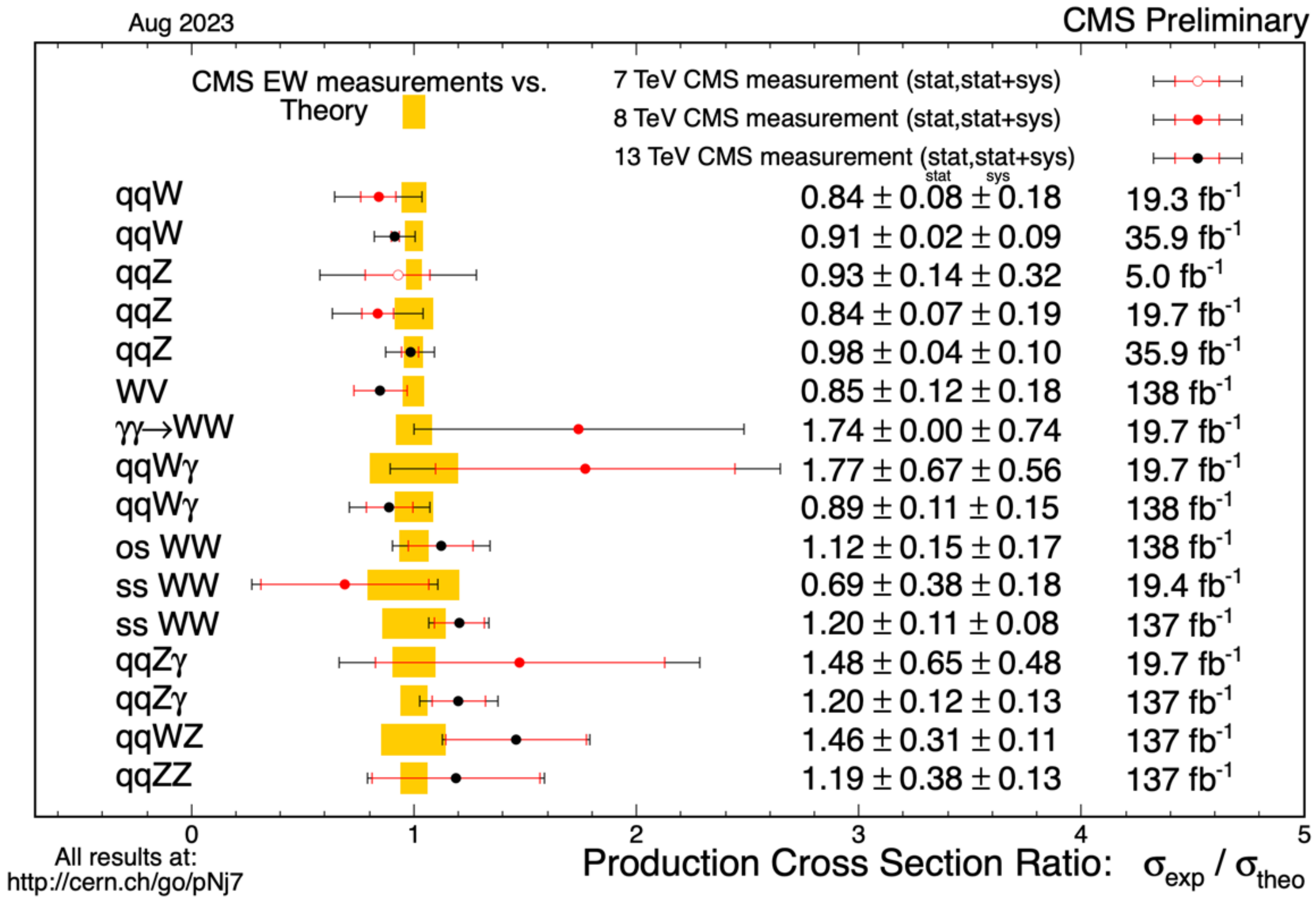


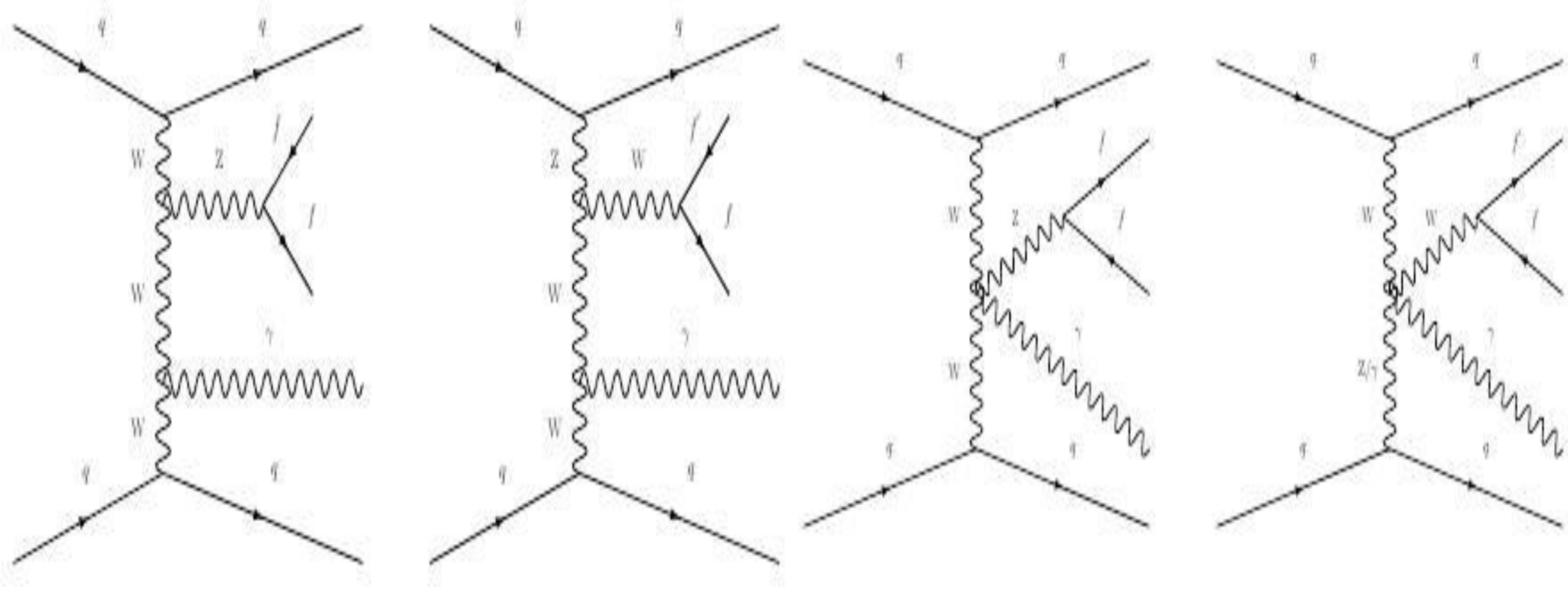
$$iM_{\text{gauge}} \approx i\frac{g^2}{4m_W^2[s+t]}$$

The Higgs boson contribution cancels exactly the E2 dependance of the cross section at high energy in massive VBS only

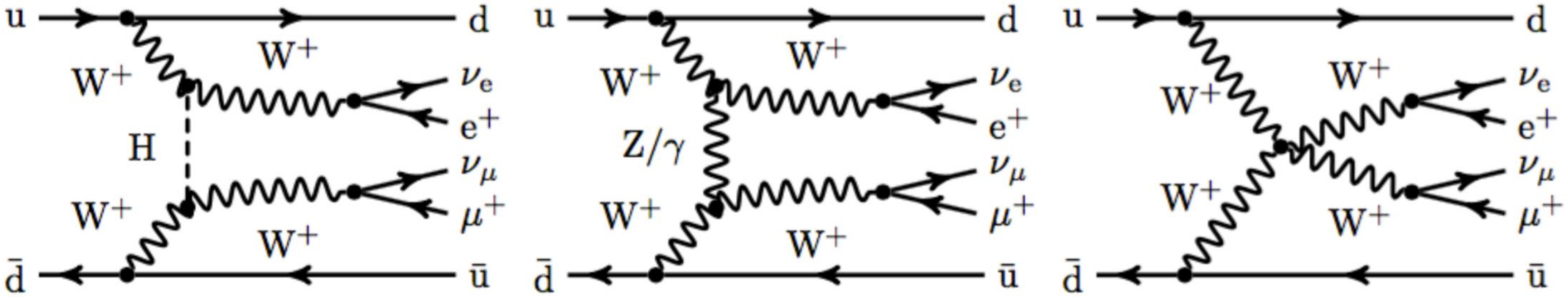
- Unitarises the scattering amplitudes
- Key process linked with Electro-Weak Symmetry Breaking (EWSB)

Ratio of diboson EWK cross-section measurements to theory





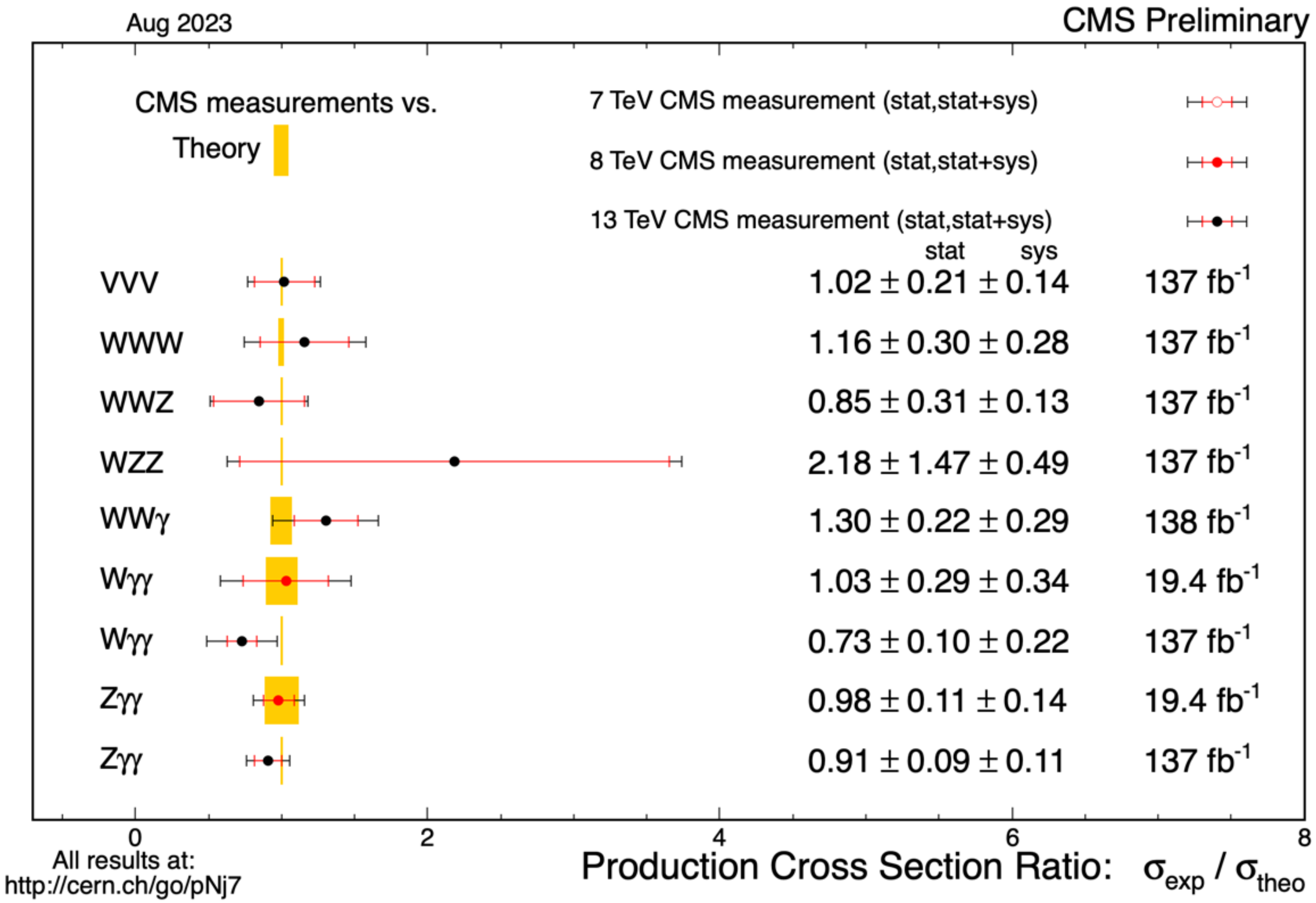
EW Vector Boson Scattering



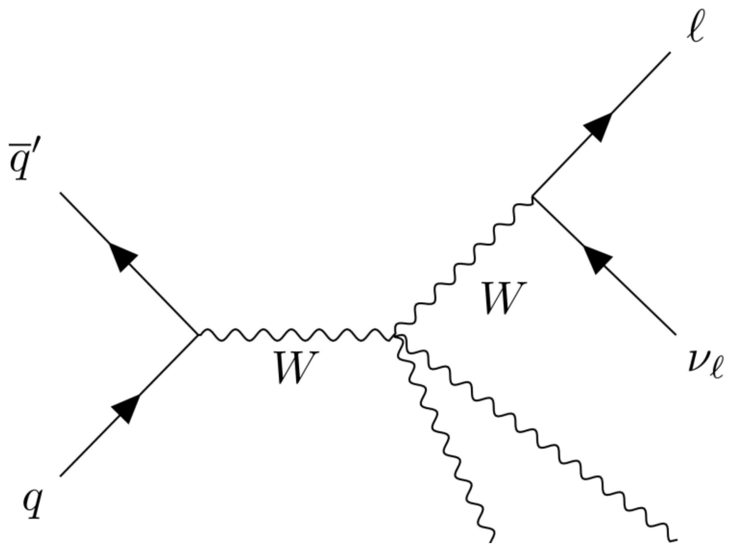
Triboson Measurements

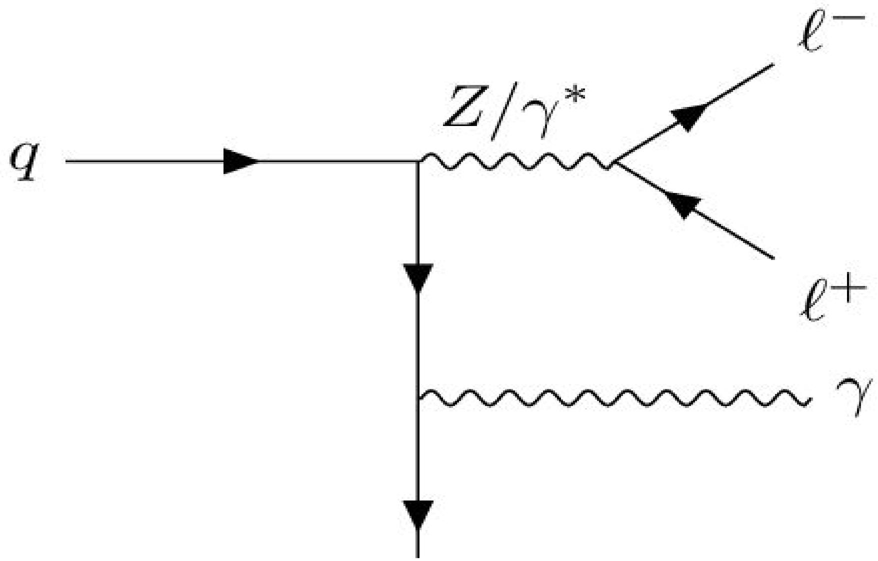
- Triboson final states are rare and some are only now becoming accessible at the LHC
- - Many first observations
- - Probe of non-Abelian self couplings of the electroweak
- gauge bosons in the Standard Model (SM)
- - Sensitive to anomalous Quartic Gauge Coupling
- (aQGC) operators
- - Can be used to set limits within Effective Field Theories (EFT)
- - Backgrounds to SM processes like ZH(γγ) and WH(γγ) that will become accessible at run 3 and beyond
- Some final states can be used to probe Higgs couplings
- to light quarks

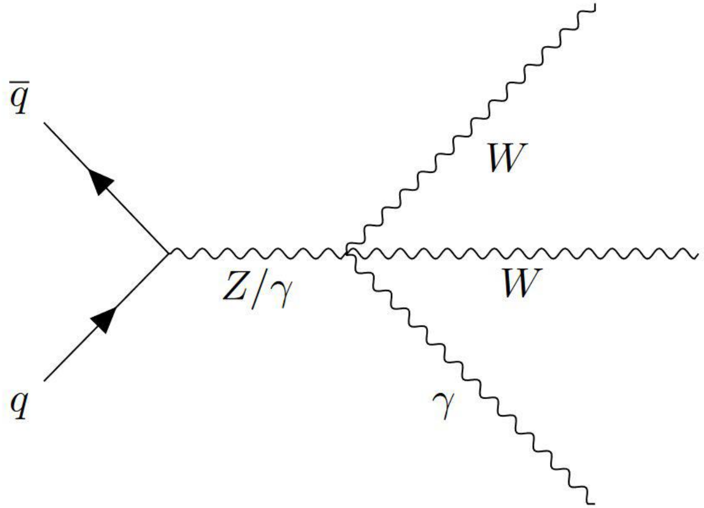
Multi-Boson Production

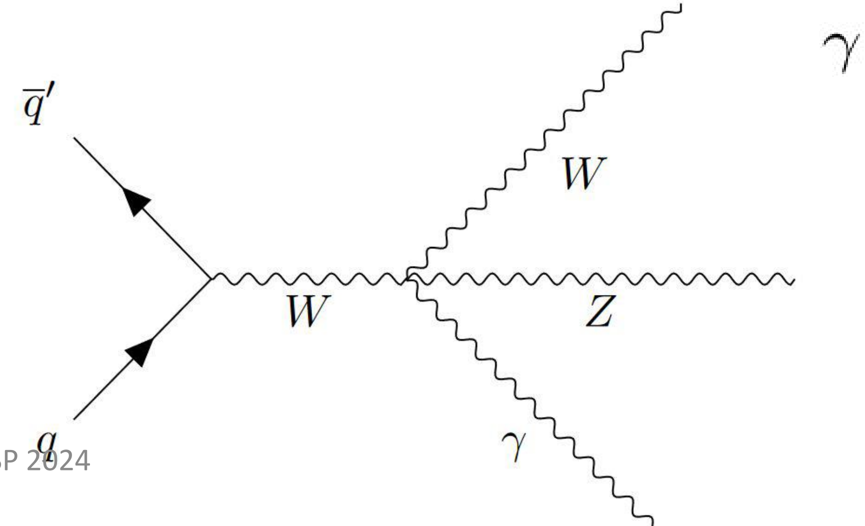


Some Measurements - Wγγ, Zγγ and WZγ by ATLAS (ATLAS-CONF-2023-014)



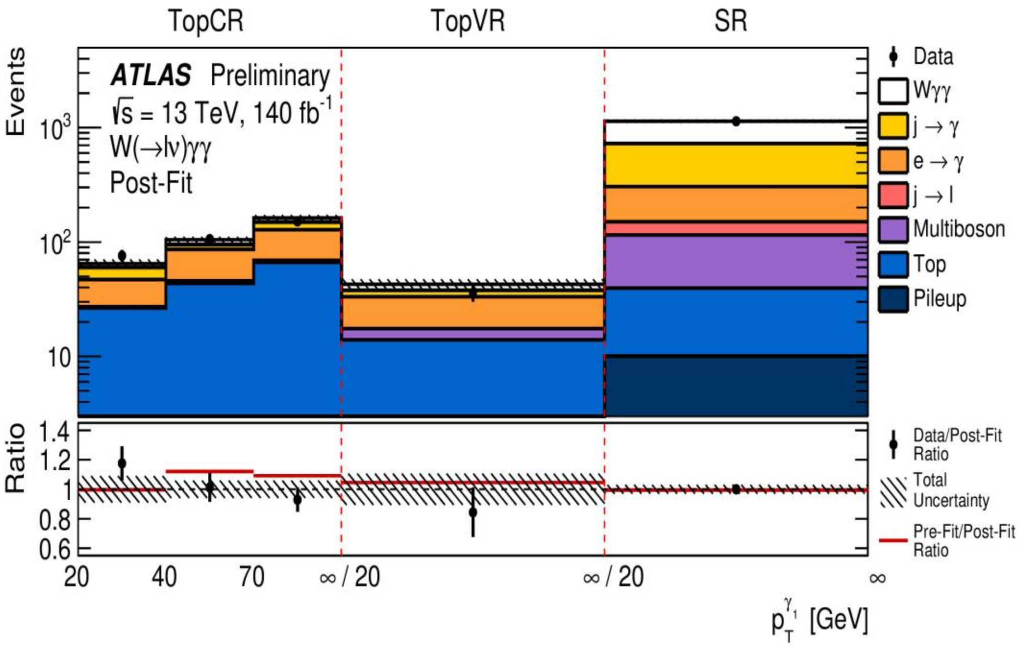






Wγγ

ATLAS-CONF-2023-005



First observation at 5.6σ (5.6σ) obs.(exp.)

- **σ_meas = 12.2+2.1-2.0 fb (fid!),**
- **in agreement with SM**

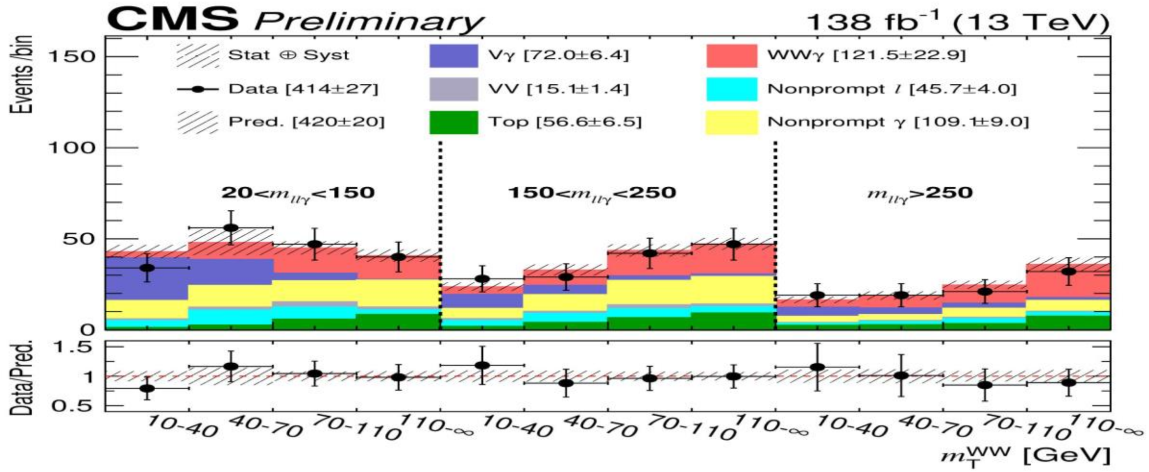
- Dominant uncertainties : systematic on j→γ followed by stat. uncertainty

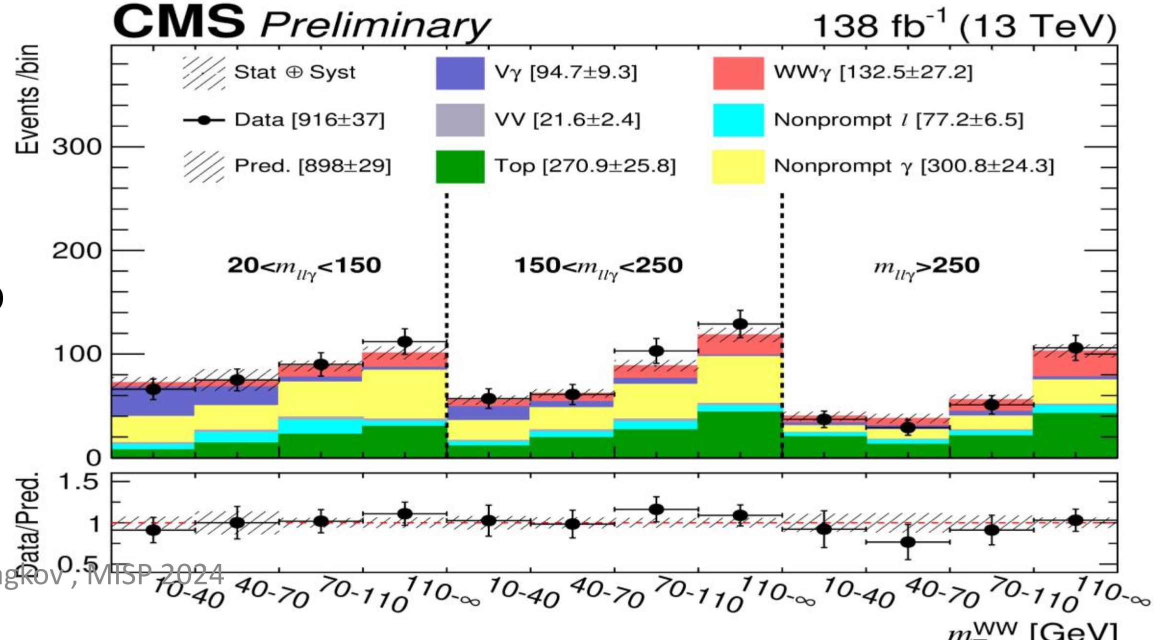
- e/μ channels, 13 TeV, 140 fb-1

- b-jet veto to reduce top backgrounds

WWγ   CMS-PAS-SMP-22-006

First observation at 5.6σ (4.7σ) obs. (exp.)!
- σ_meas = 6.0 ± 1.0 (stat.) ± 1.0 (syst.) ± 0.9 (theo.) fb,
- in agreement with SM
- Statistical, systematic and theory uncertainties comparable
- Limits set on Higgs Yukawa couplings to u, d, s, c quarks
- e/μ channel, 13 TeV, 138 fb-1
- OFOS (W+W- → eνμν)
- b-jet veto to reduce WZγ and top backgrounds
- Important backgrounds :
- j→γ, largest background
- Data-driven fake rate estimate in W+jets CR with a fit to the photon shower width to extract non-prompt component
- j→l, significant background
- Data driven fake rate estimate in dijet CR



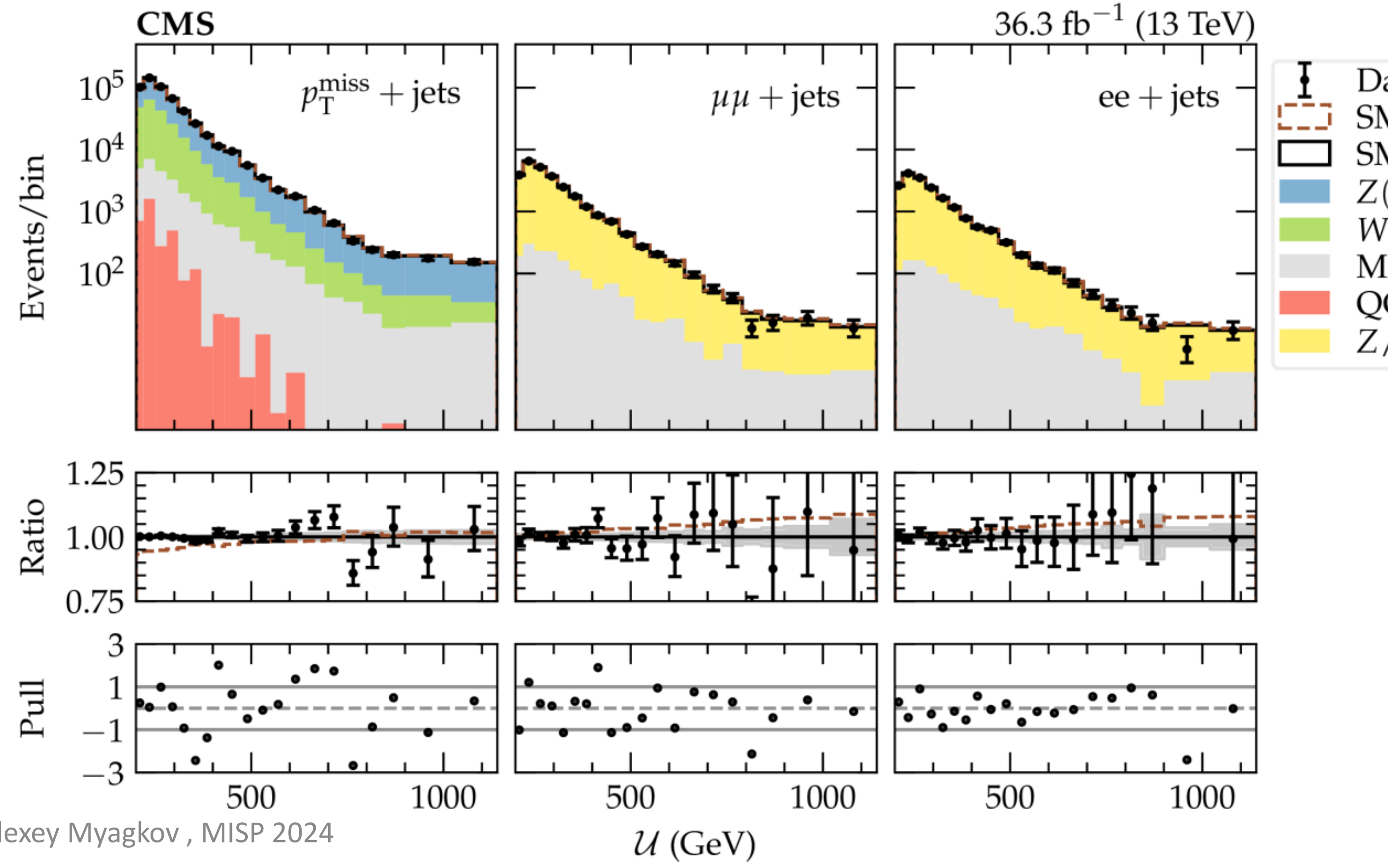


Z boson invisible width

Constraint on the number of neutrino types
•Look for very energetic jet accompanied
by a large missing transverse momentum

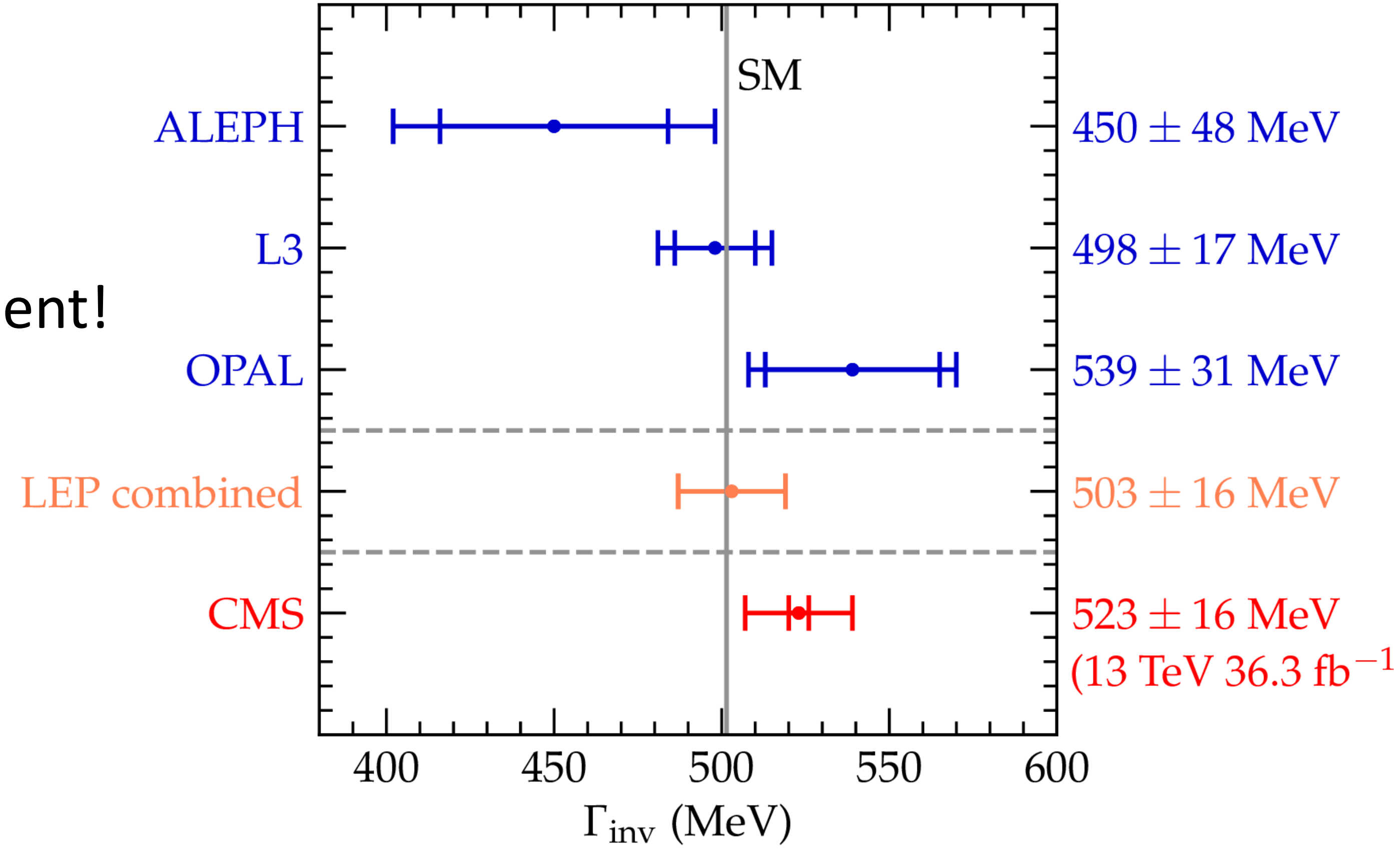
Simalteneous fit to kinematical distribution for
Two datasets- one dominated by Z-boson
decays to invisible particles and other Z boson
Decays to muon and electron pairs

arXiv:2206.07110
Accepted by PLB



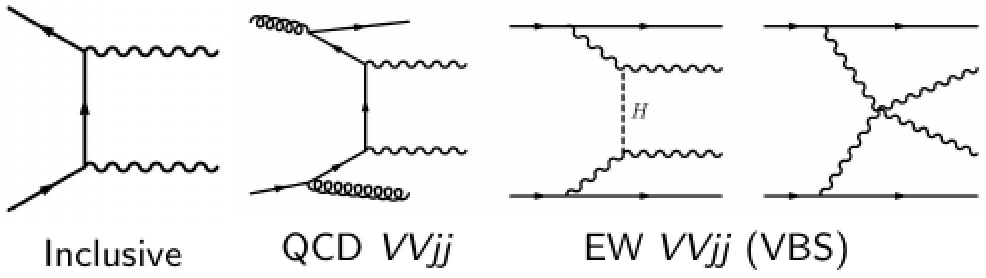
Z boson invisible width

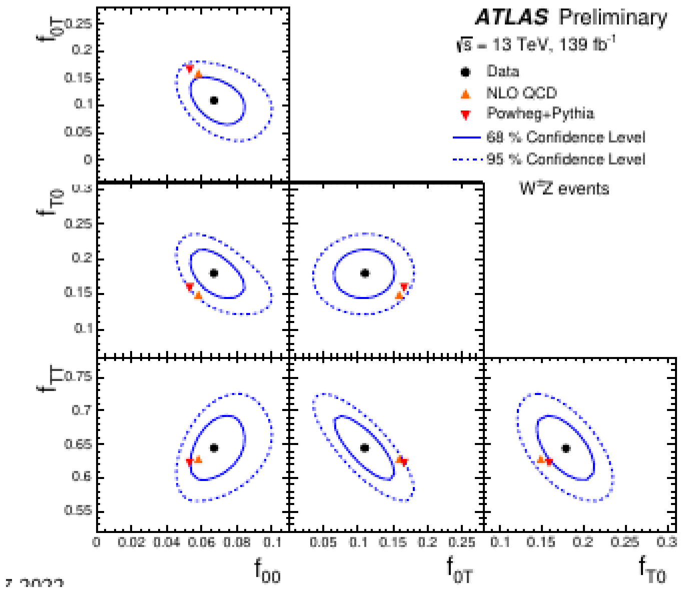
The single most precise direct measurement!
•Competitive to combined LEP value and compatible with expected in SM.



WZ (lνll) polarisation
ATLAS-CONF-2022-053, arXiv:2110.11231 (CMS)

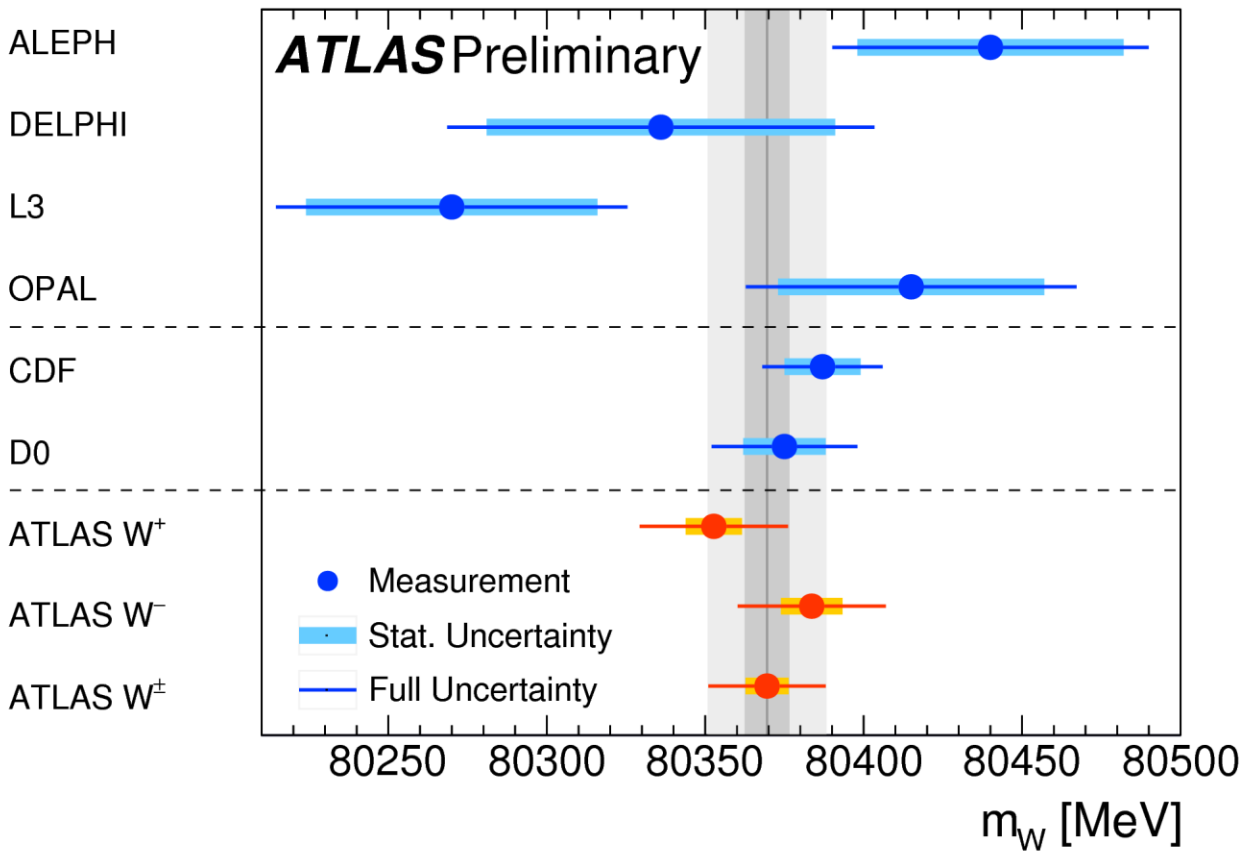
Electroweak VVjj production can proceed in transverse (T) or longitudinal (0) polarisation states
Longitudinal (00) component intertwined with Higgs mechanism VBS unitarization: long term goal
Probes for the HL-LHC
currently measurements focus on polarisation or VBS
New: first measurement of joint polarisation states in inclusive WZ production by ATLAS using DNN reconstruction techniques – observation of double-longitudinal component with > 7σ



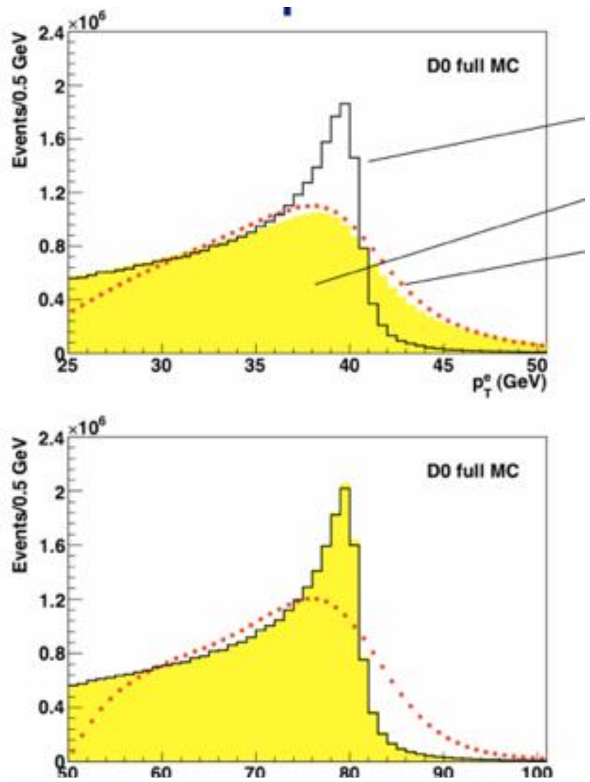


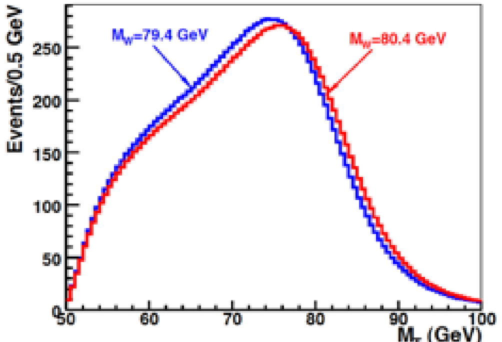
Measured joint helicity fractions f00, f0T, fT0 and fTT of the W and Z bosons in W±Z events, compared to NLO QCD fixed-order predictions

Measurement of the W Mass at the LHC



Methods of W mass measurements





The transverse mass is

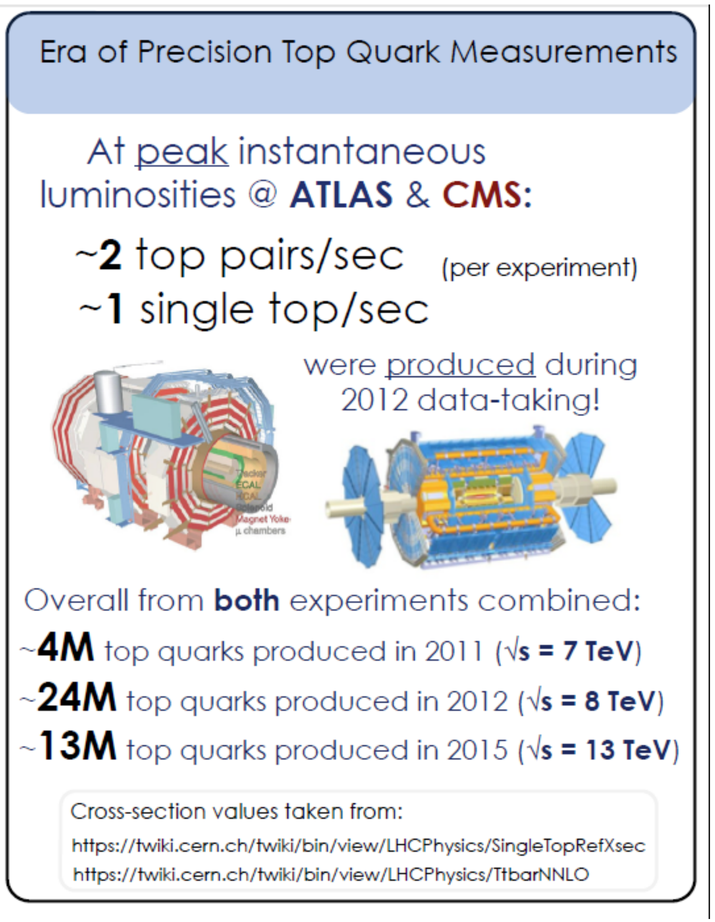
- less sensitive to the qT(W) spectrum
- much more sensitive to the hadronic recoil

But, due to pile-up, lepton pT is more promising at the

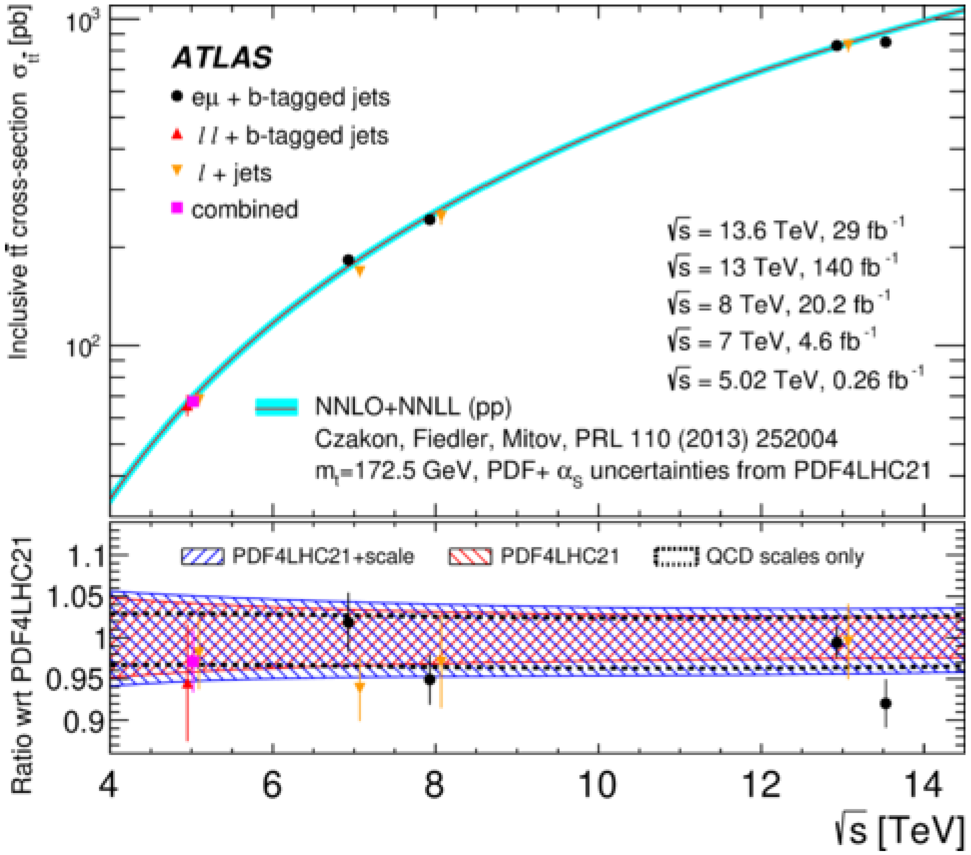
Experimental challenges

- control the lepton energy scale at < 0.1%
- pile up conditions

Top physics



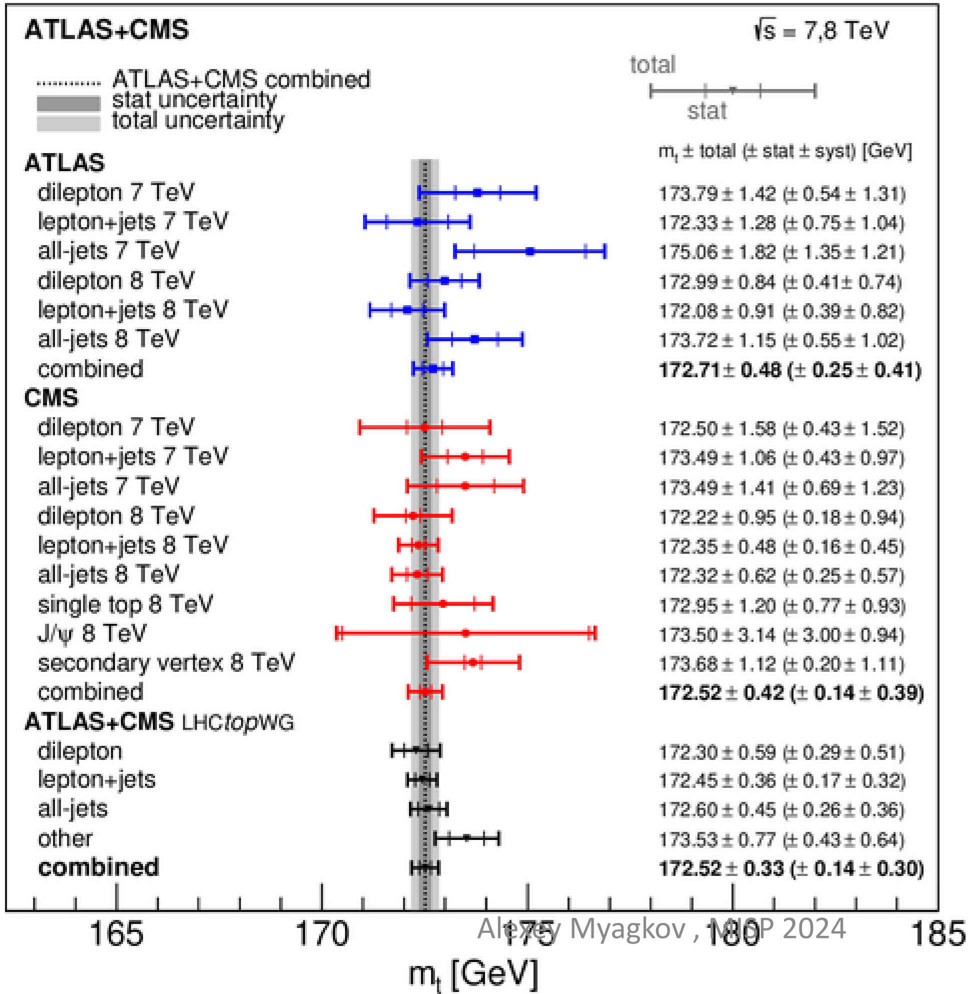
Era of Precision Top Quark Measurements
At peak instantaneous luminosities @ ATLAS & CMS:
~2 top pairs/sec (per experiment)
~1 single top/sec
were produced during 2012 data-taking!
Overall from both experiments combined:
~4M top quarks produced in 2011 (√s = 7 TeV)
~24M top quarks produced in 2012 (√s = 8 TeV)
~13M top quarks produced in 2015 (√s = 13 TeV)
Cross-section values taken from:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO



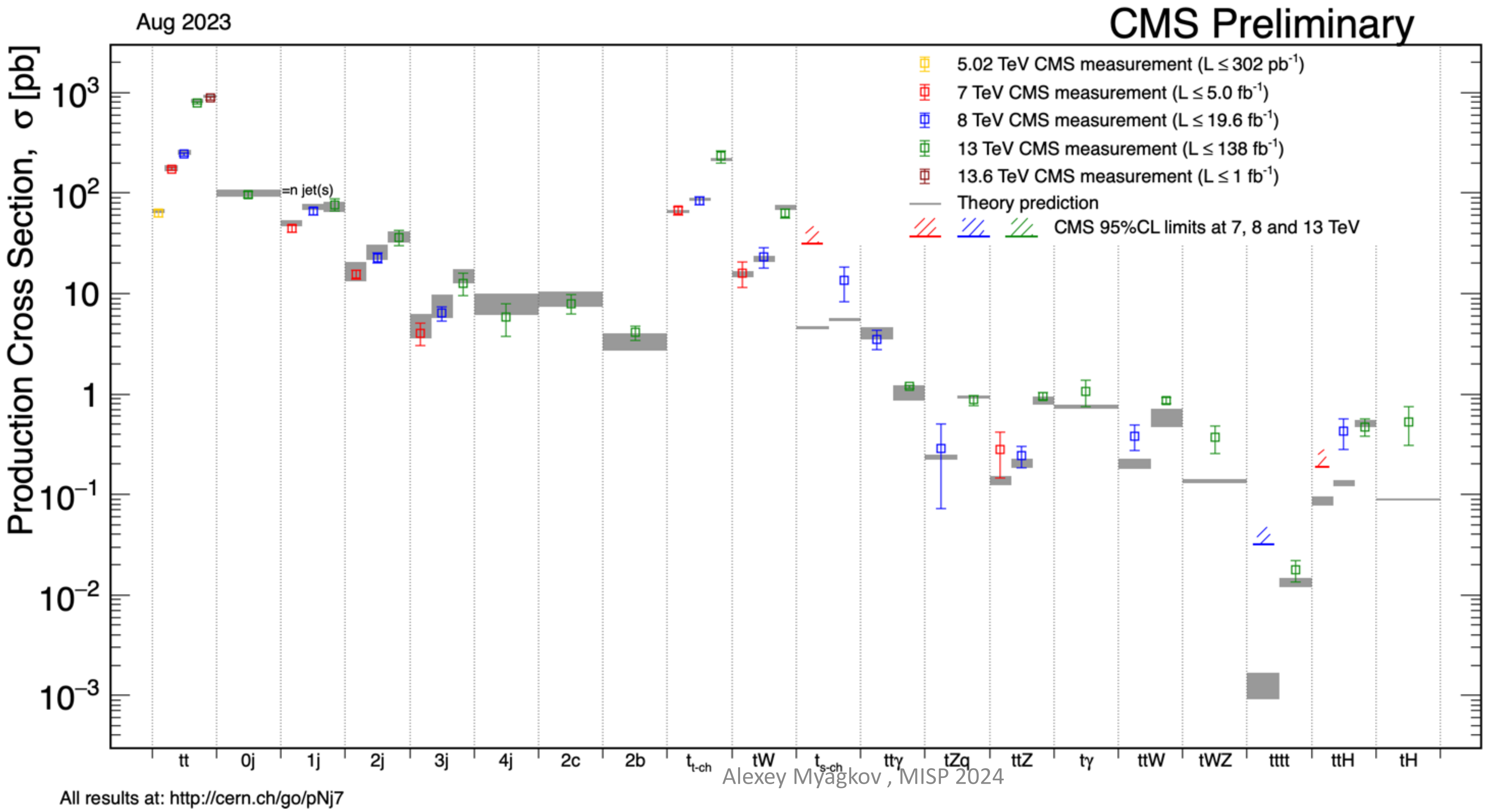
ATLAS
eμ + b-tagged jets
l l + b-tagged jets
l + jets
combined
√s = 13.6 TeV, 29 fb⁻¹
√s = 13 TeV, 140 fb⁻¹
√s = 8 TeV, 20.2 fb⁻¹
√s = 7 TeV, 4.6 fb⁻¹
√s = 5.02 TeV, 0.26 fb⁻¹
NNLO+NNLL (pp)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_t=172.5 GeV, PDF+ α_S uncertainties from PDF4LHC21
Inclusive tt̄ cross-section σ_tt̄ [pb]
PDF4LHC21+scale
PDF4LHC21
QCD scales only
Ratio wrt PDF4LHC21
√s [TeV]

Measuring the top mass from event kinematics Submitted to PRL 2402.08713

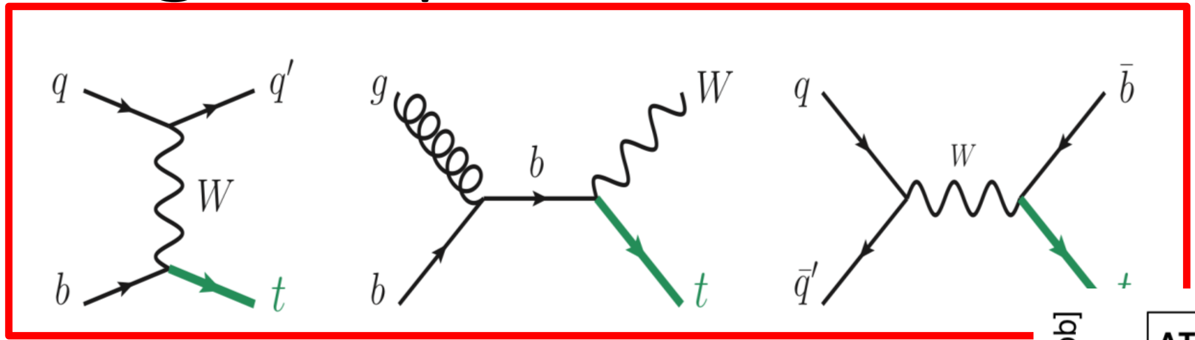
-

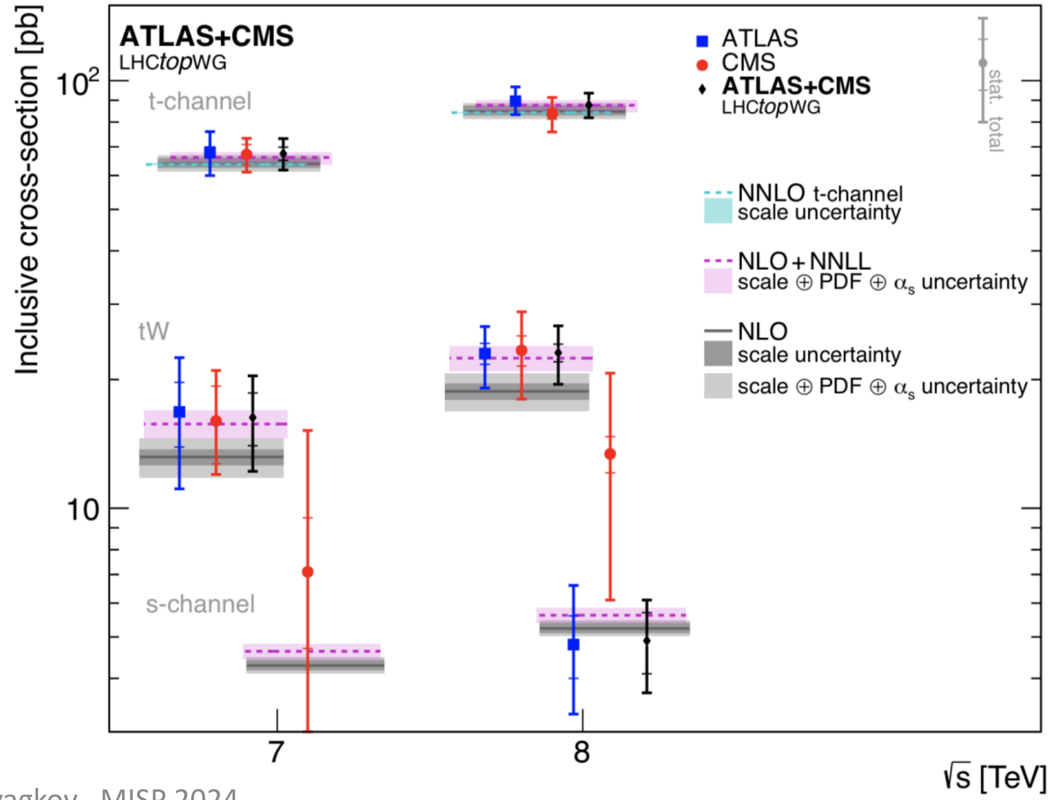


Cross sections of the processes with top



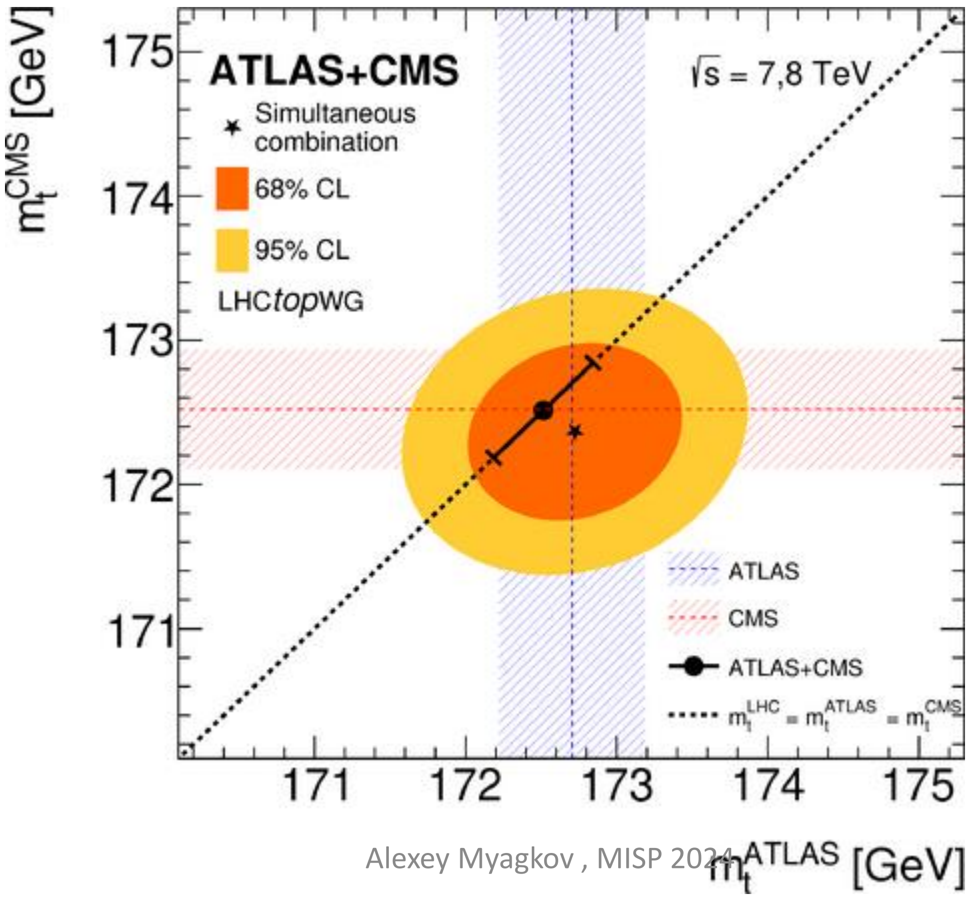
Single top


q
q′
W
b
t
g
W
b
b
t
q
b̄
W
q̄′
t


ATLAS+CMS
LHCtopWG
ATLAS
CMS
ATLAS+CMS
LHCtopWG
stat. total
t-channel
tW
s-channel
NNLO t-channel
scale uncertainty
NLO+NNLL
scale ⊕ PDF ⊕ α_s uncertainty
NLO
scale uncertainty
scale ⊕ PDF ⊕ α_s uncertainty
Inclusive cross-section [pb]
10^2
10
7
8
√s [TeV]

The simultaneous extraction of the mt measured by ATLAS and CMS from a combination of the 15 input measurements

Submitted to PRL



- THANK YOU FOR YOUR ATTENTION!