Physics at Colliders I

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Outline

- **Lecture I: Introduction and Standard Model Measurements**
  - Current and Future colliders
  - Tests of QCD
  - Precision measurements in electroweak sector
  - Flavour measurements and anomalies
- **Lecture II: Flavor, Higgs Boson and New Physics Searches**
  - Flavour measurements and anomalies
  - The Standard Model Higgs Boson
  - Problems with the Standard Model
  - Supersymmetry
  - Dark Matter at Colliders

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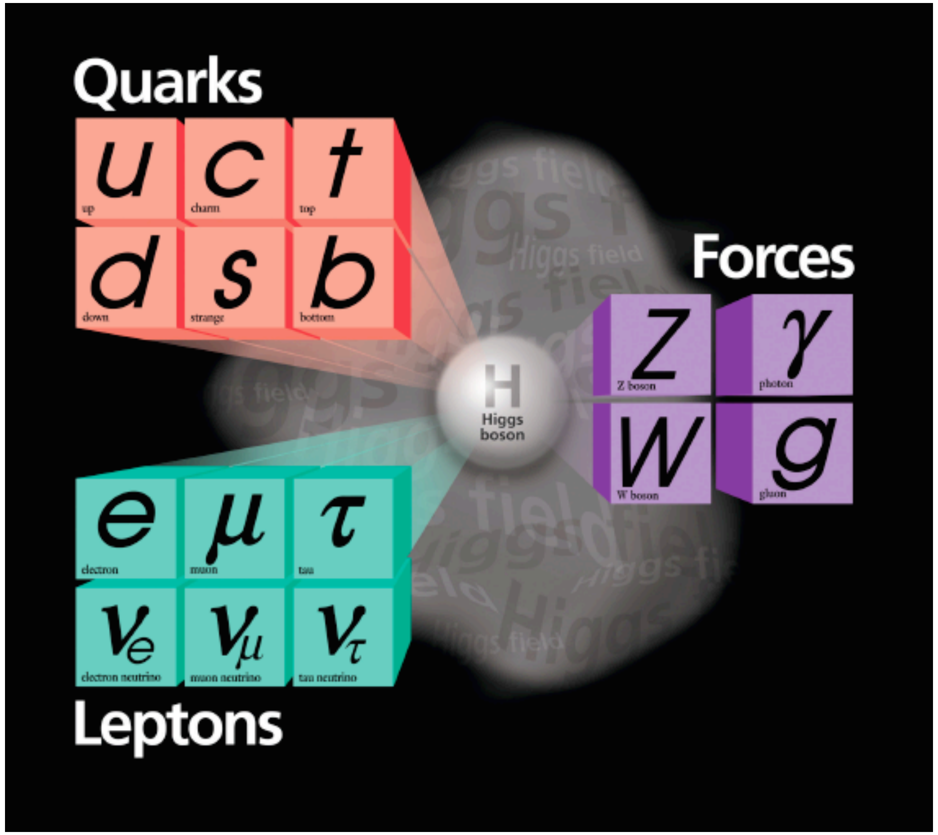
Fundamental Particles and Forces



- **Matter**
  - is made out of fermions
- **Forces**
  - are mediated by bosons
- **Higgs boson**
  - breaks the electroweak symmetry and gives mass to fermions and weak gauge bosons

Amazingly successful in describing precisely data from all collider experiments

The Standard Model Lagrangian

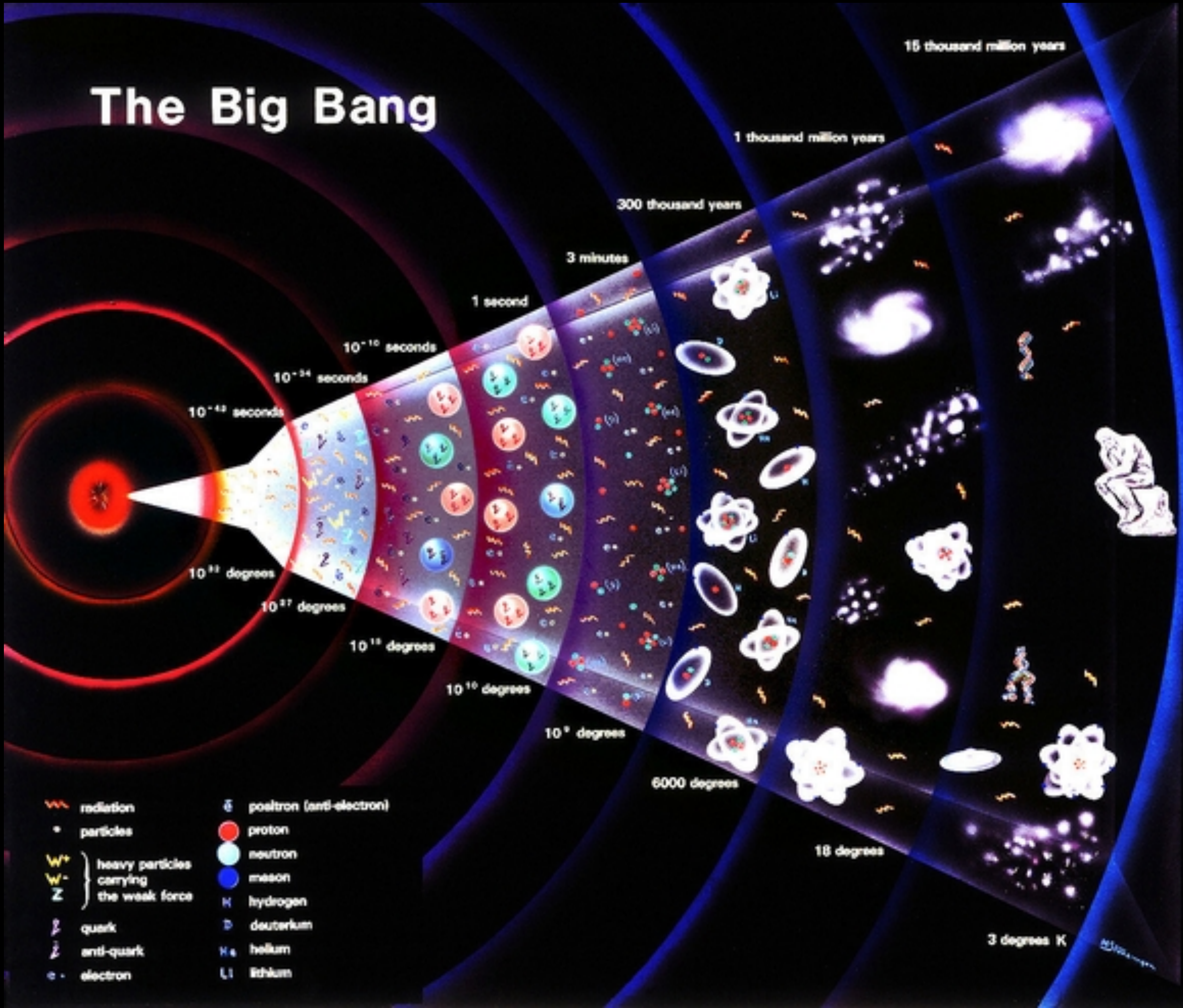
$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\!\!\!/\psi$$
$$+ \psi_i\lambda_{ij}\psi_j h + \text{h.c.}$$
$$+ |D_\mu h|^2 - V(h)$$
$$+ \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j$$

- gauge sector ✓
- flavour sector ✓
- EWSB sector ✓
- ν mass sector

… and beyond?

- supersymmetry (many variants)
- extra spacetime dimensions
- compositeness ✓
- strong electroweak symmetry breaking
- …
- something new?!

[W. J. Stirling]

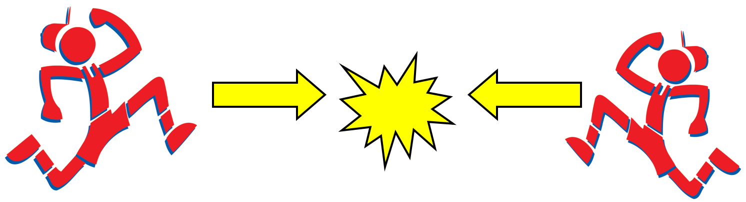

The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e- electron
ē positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

Lepton vs Hadron Colliders

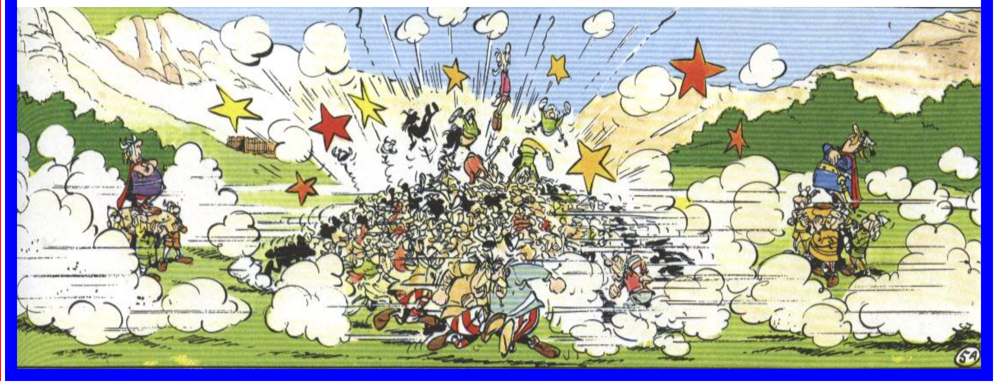
- Disadvantages of hadrons:
  - Hadrons are complex objects
  - High multiplicity of other stuff
  - Energy and type of colliding parton (quark, gluon) unknown
    - Kinematics of events not fully constrained

- Advantage of hadrons:
  - Can access higher energies

Lepton Collider
(collision of two point-like particles)



Hadron collider
(collision of ~50 point-like particles)



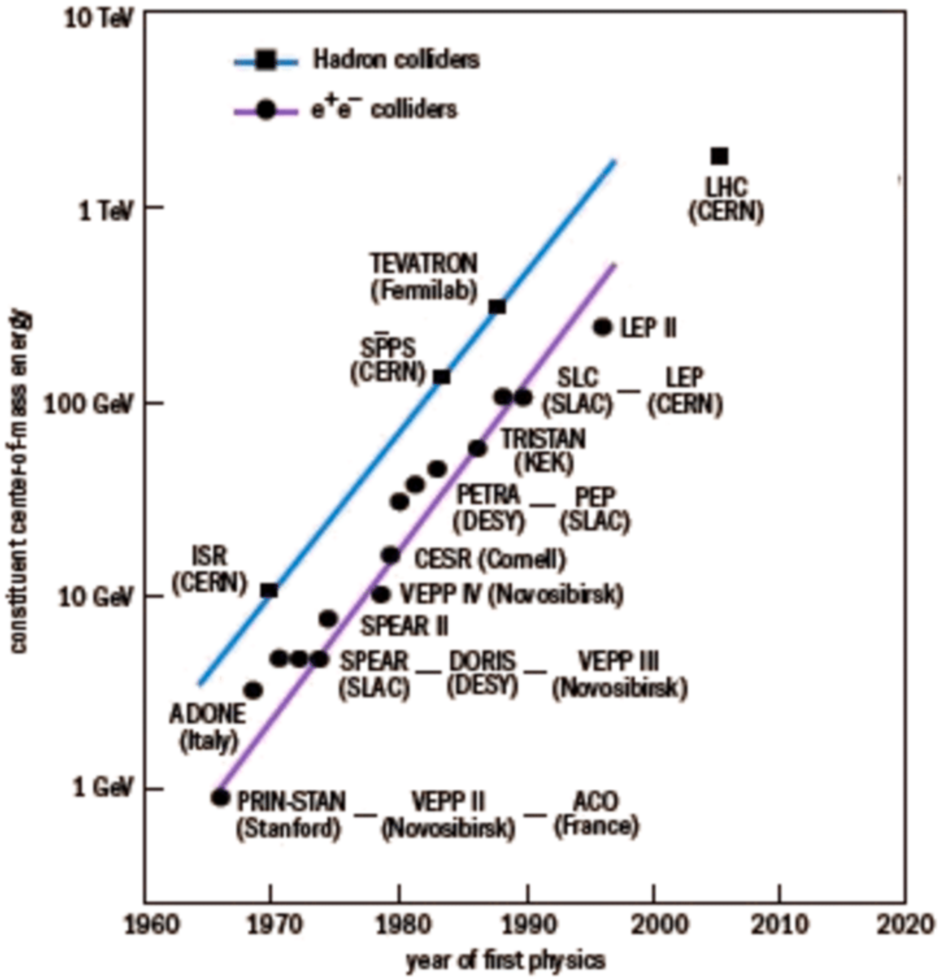
[Karl Jakobs]

e^+e^- Colliders

- Circular colliders:
  - Reuse their power on each turn
  - Synchrotron radiation reduces energy of particles ~1/m^4
- Linear colliders:
  - Particle sees each accelerator component just once
  - No synchrotron radiation

Energy loss per turn: $$-\Delta E \approx \frac{4\,\pi\,e^2}{3\,R}\left(\frac{E}{mc^2}\right)^4$$

Energy loss: e vs p $$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$



Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^{\,2}}{4\,\pi\,\sigma_x\,\sigma_y}$$

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

  - Rate of physics processes per unit time directly related:

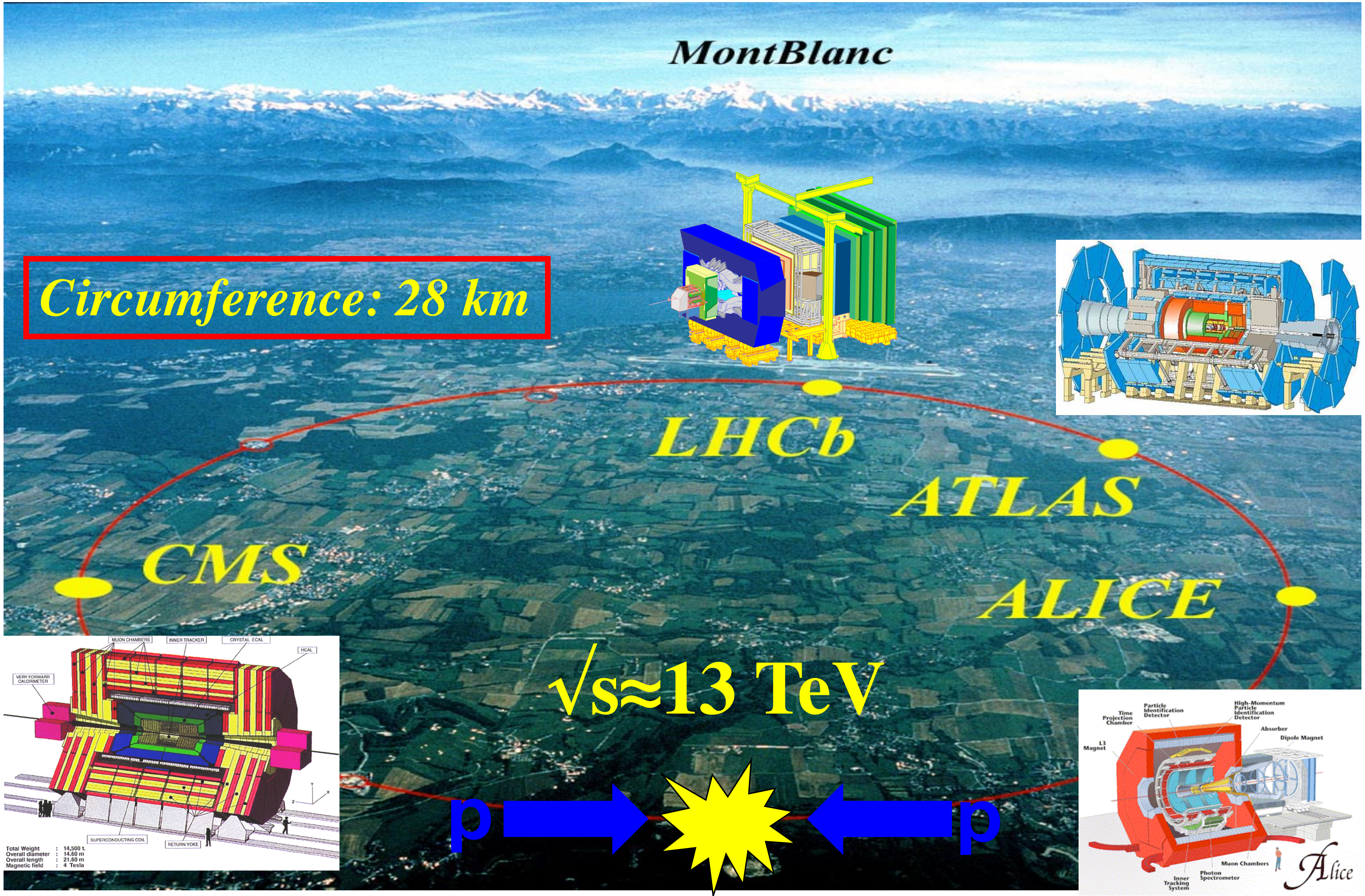
$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

Efficiency:
optimized by
experimentalist

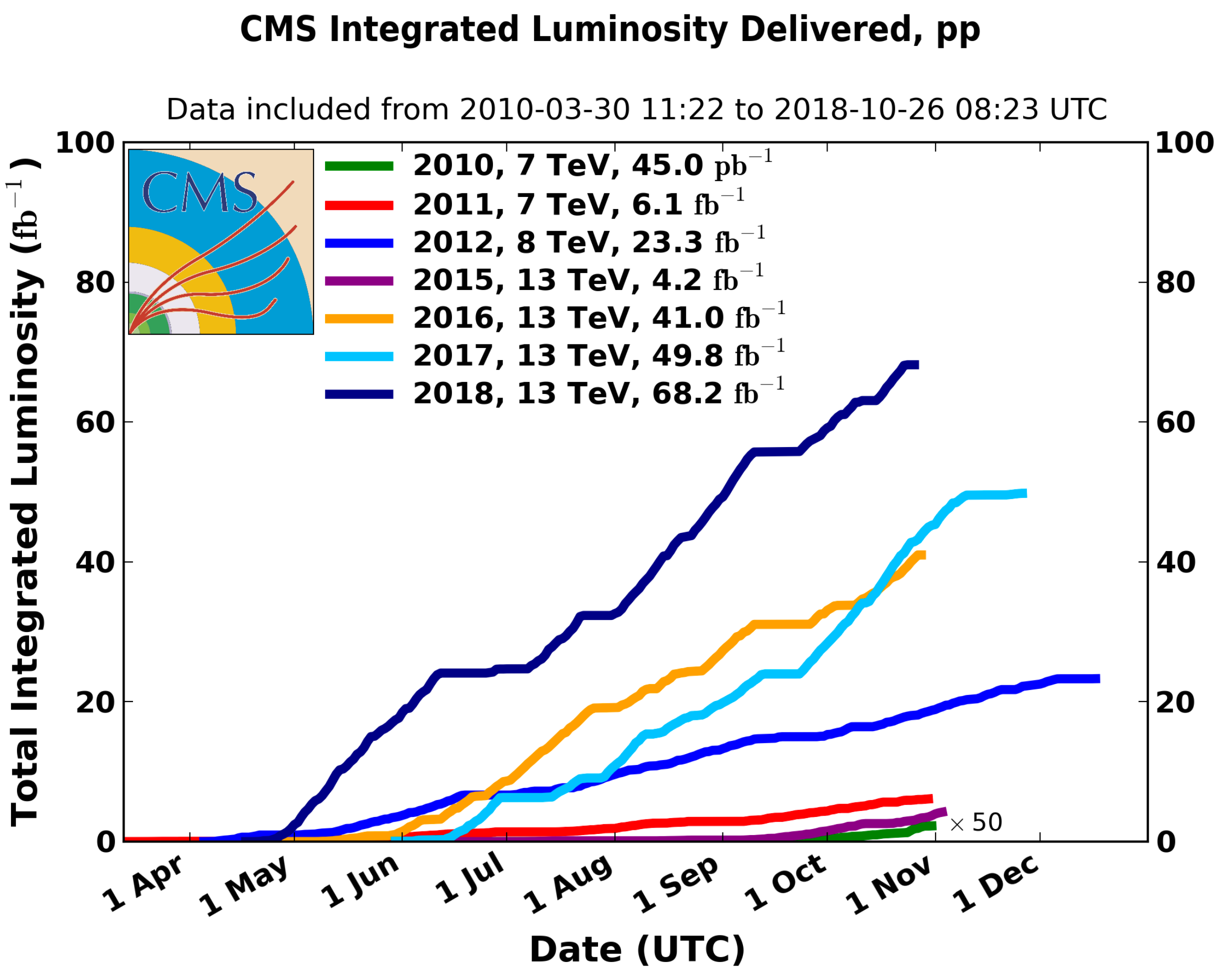
Cross section σ:
Given by Nature
(calc. by theorists)

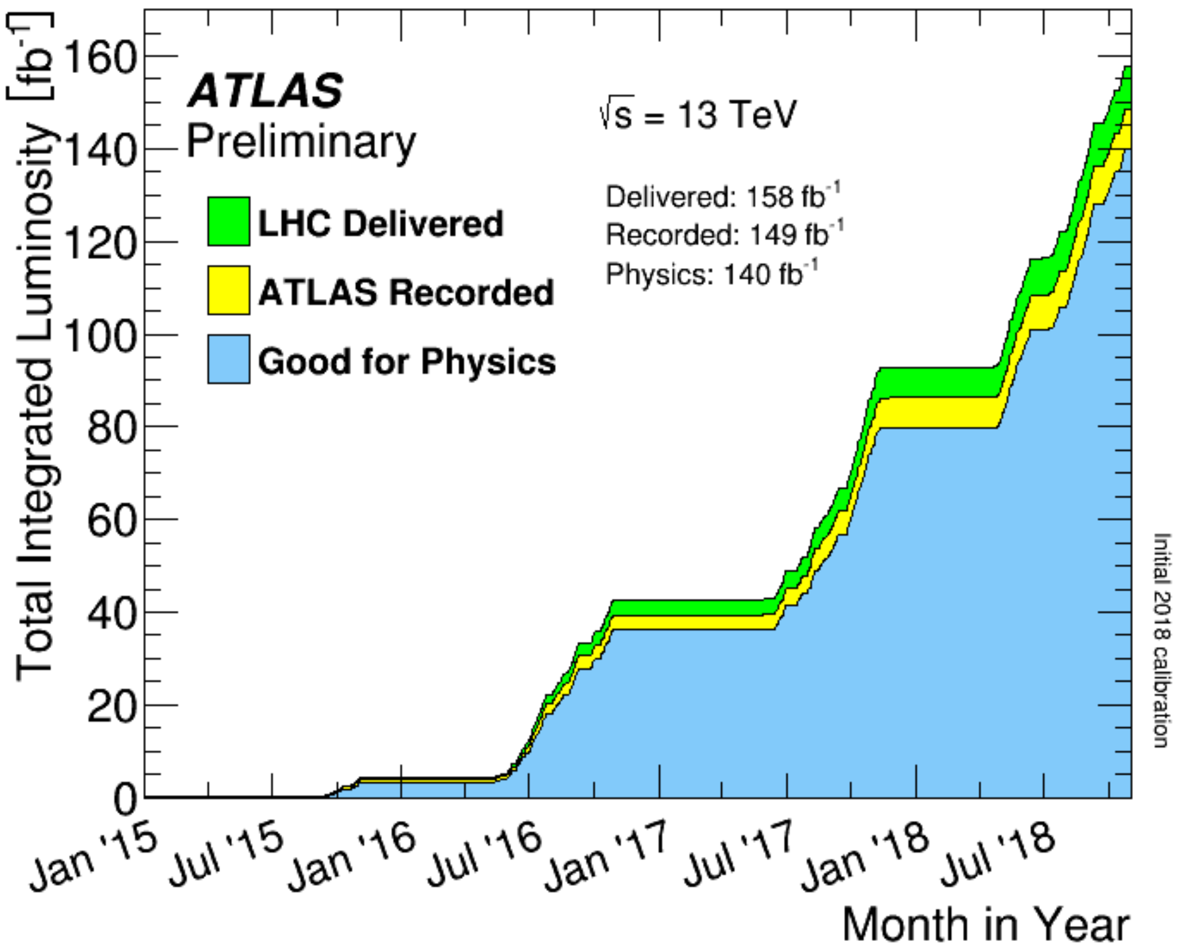
Ability to measure relies on N_{obs} to be large enough

LHC


MontBlanc
Circumference: 28 km
LHCb
ATLAS
CMS
ALICE
√s≈13 TeV
p
p
MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla
Time Projection Chamber
Particle Identification Detector
High-Momentum Particle Identification Detector
Absorber
Dipole Magnet
L3 Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice

Integrated Luminosity: LHC



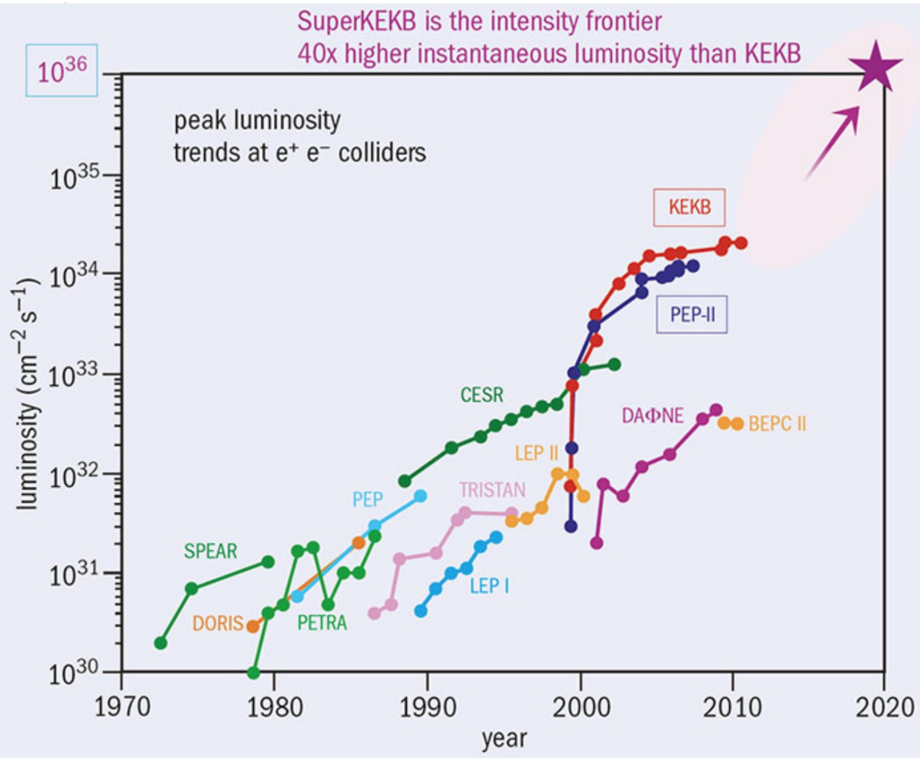


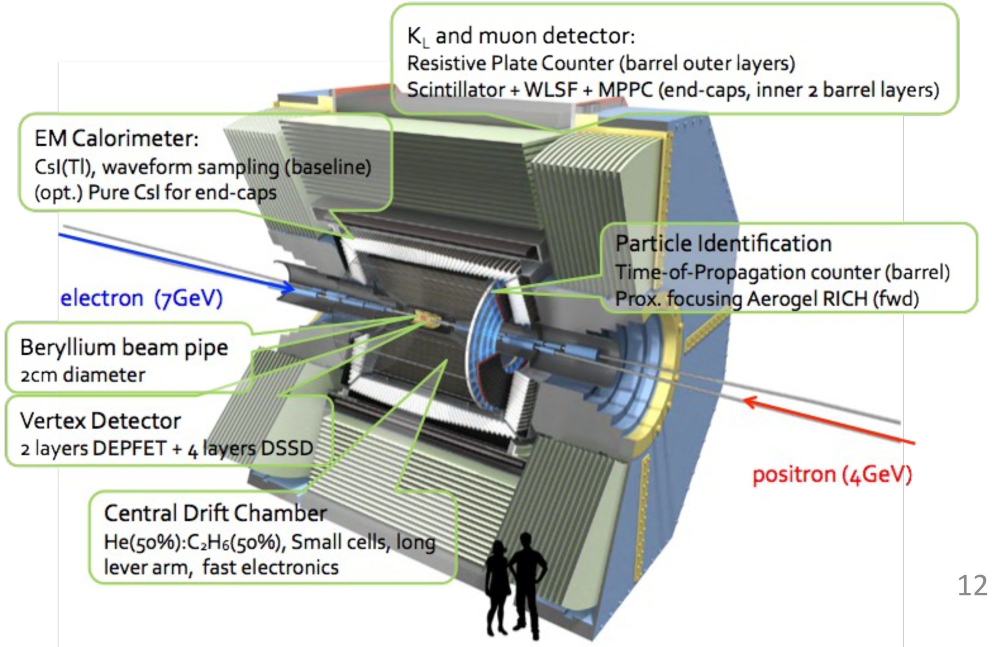
- Performance improving year by year
- Run 2: ~140 fb^{-1} available for physics analyses

SuperKEKB and Belle-II

- **Belle-II** is successor of Belle experiment at KEK laboratory in Tsukuba, Japan
  - 800 collaborators from 26 countries

- Accelerator **SuperKEKB**
  - e+e- collisions at √s=10.57 GeV
  - "Factory" for B-hadron production
  - Highest luminosity lepton collider ever
  - First collisions in 2018
  - Physics run: 03/2019 until ~2027
  - Goal: collect $L=50\ ab^{-1}$



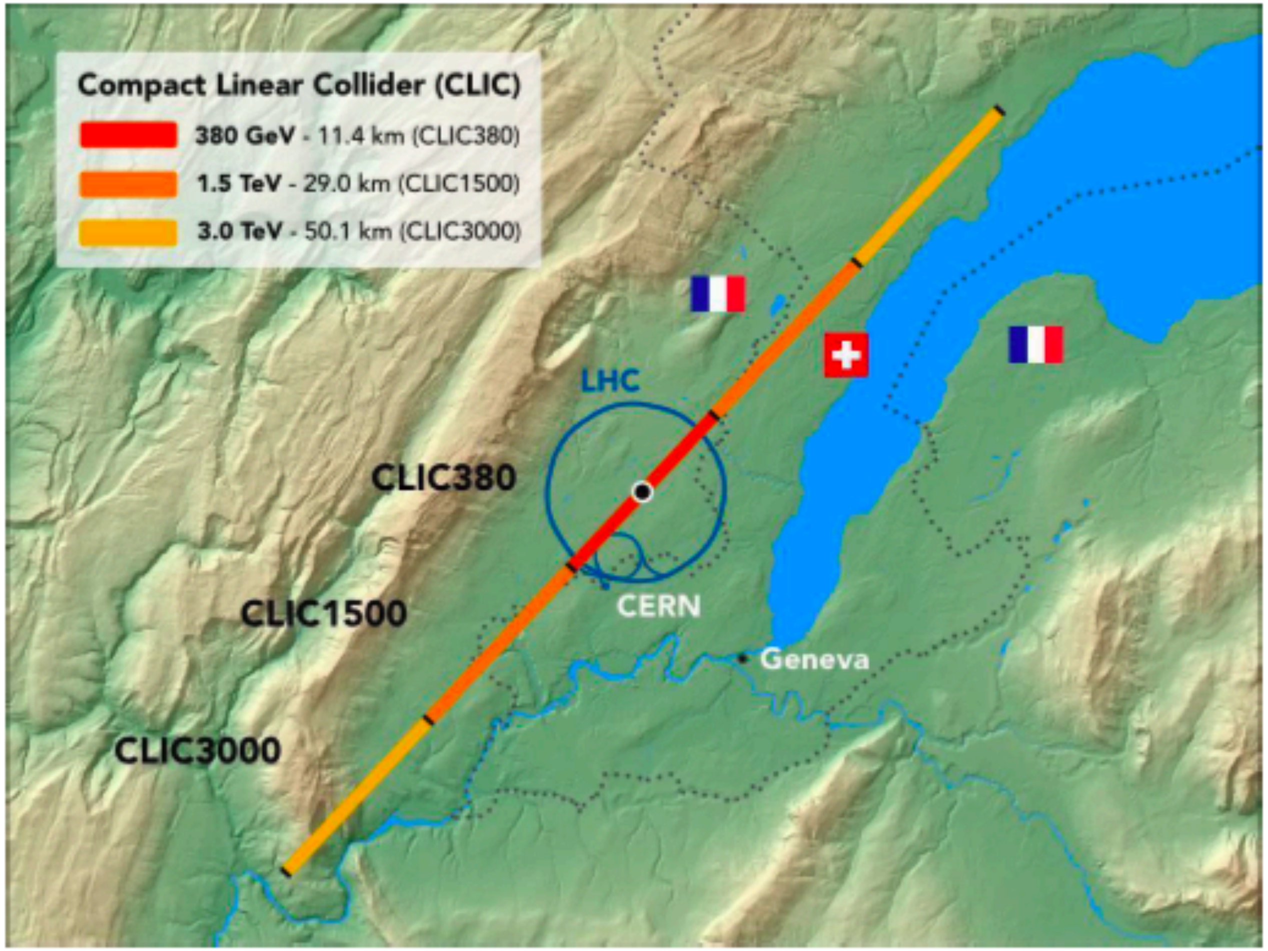


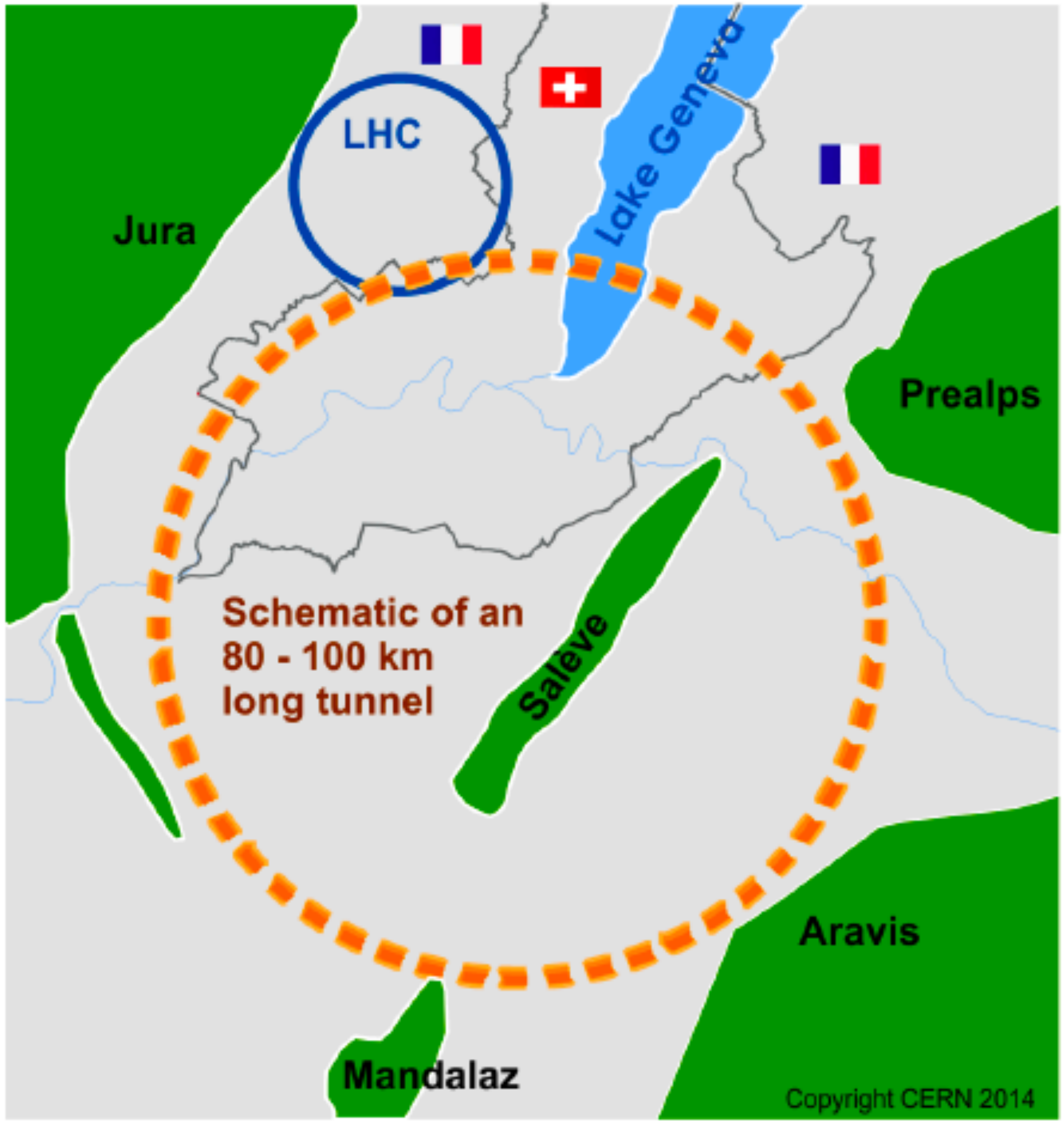
Future Colliders

- Several e+e- colliders
  - Linear Colliders ILC, CLIC
  - Circular colliders: FCC-ee, CEPC
- Hadron Colliders
  - HL-LHC
  - HE-LHC
  - FCC-hh
- ep Colliders
  - LHeC
  - FCC-eh

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]
HL-LHC	pp	14 TeV	-	2	5	6.0	12
HE-LHC	pp	27 TeV	-	2	16	15.0	20
FCC-hh	pp	100 TeV	-	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5 (+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5 (+1)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8 (+4)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25

CLIC and FCC (proposed at CERN)



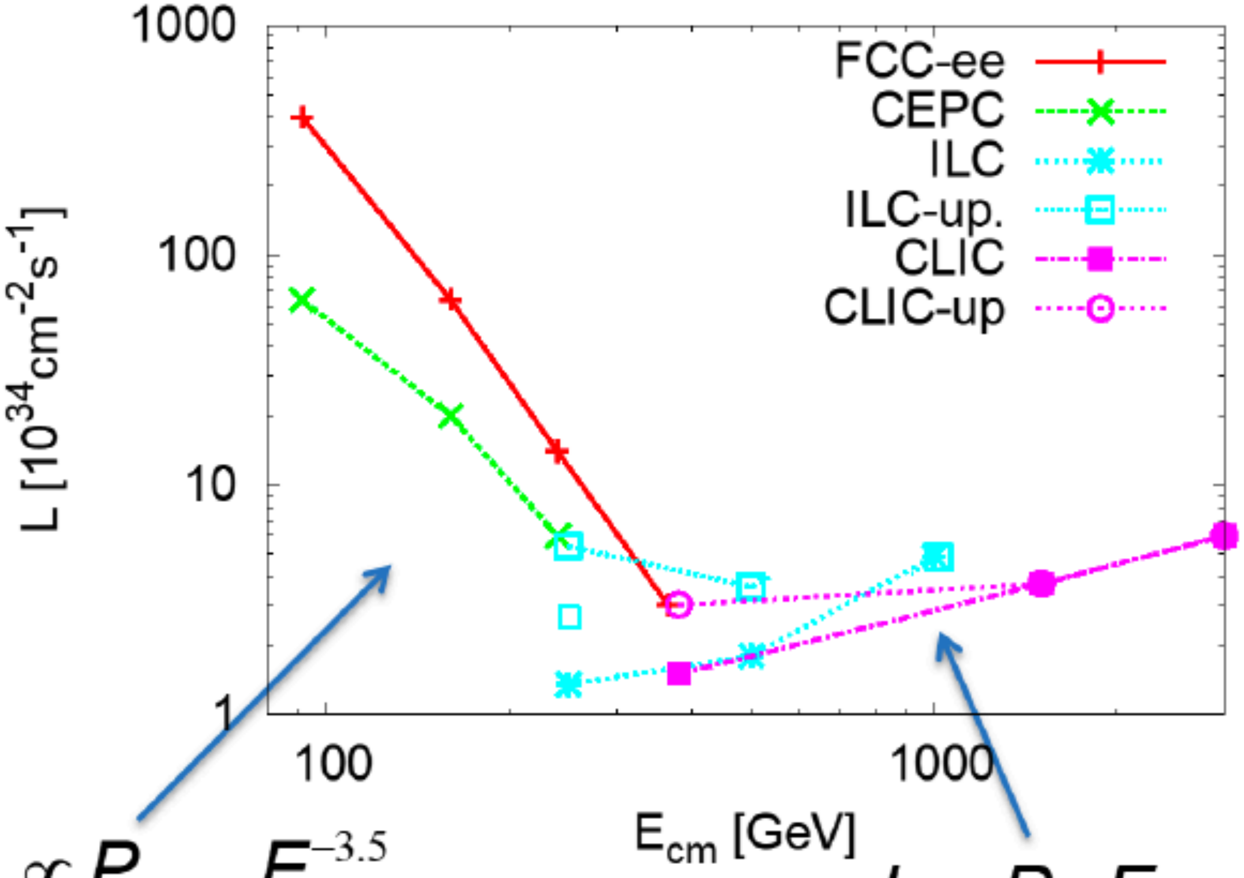


C. Biscari, L. Rivkin

ee Colliders

Ours is a very dynamic field!
(Luminosity upgrades for ILC, CLIC)

Luminosity per facility

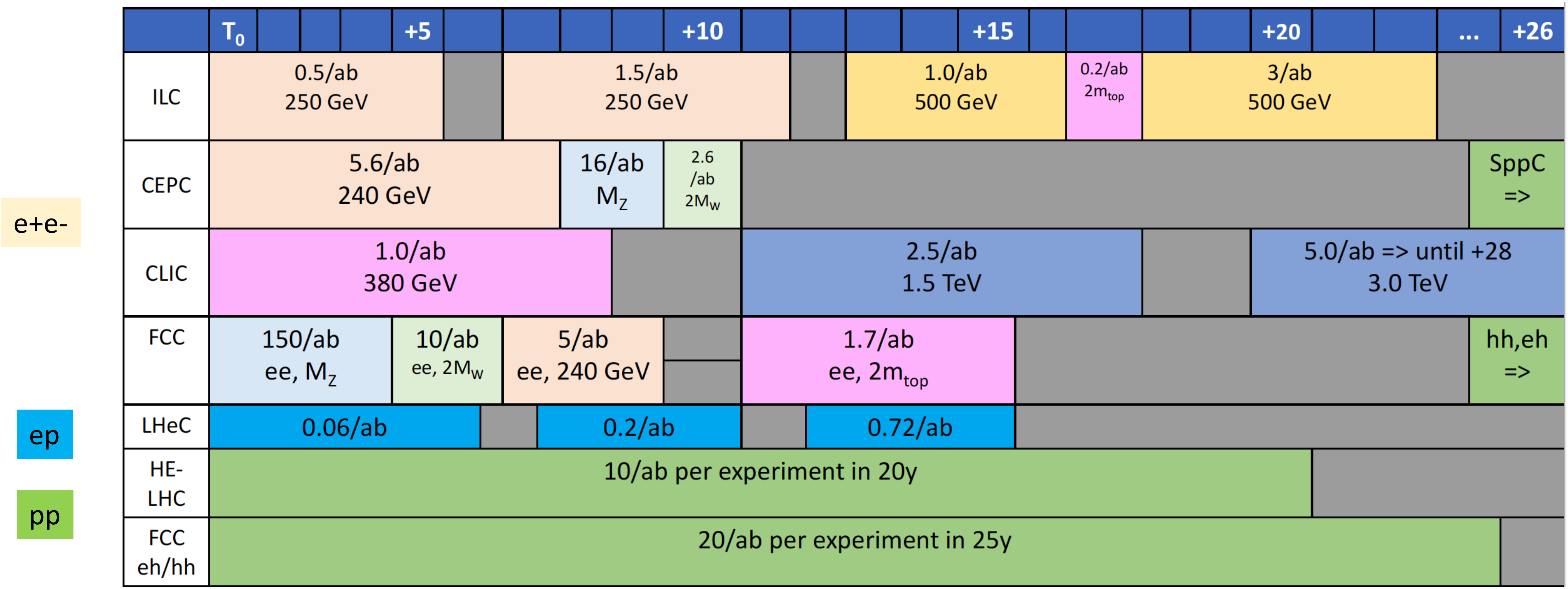


$L \propto P_{synrad} E_{cm}^{-3.5}$

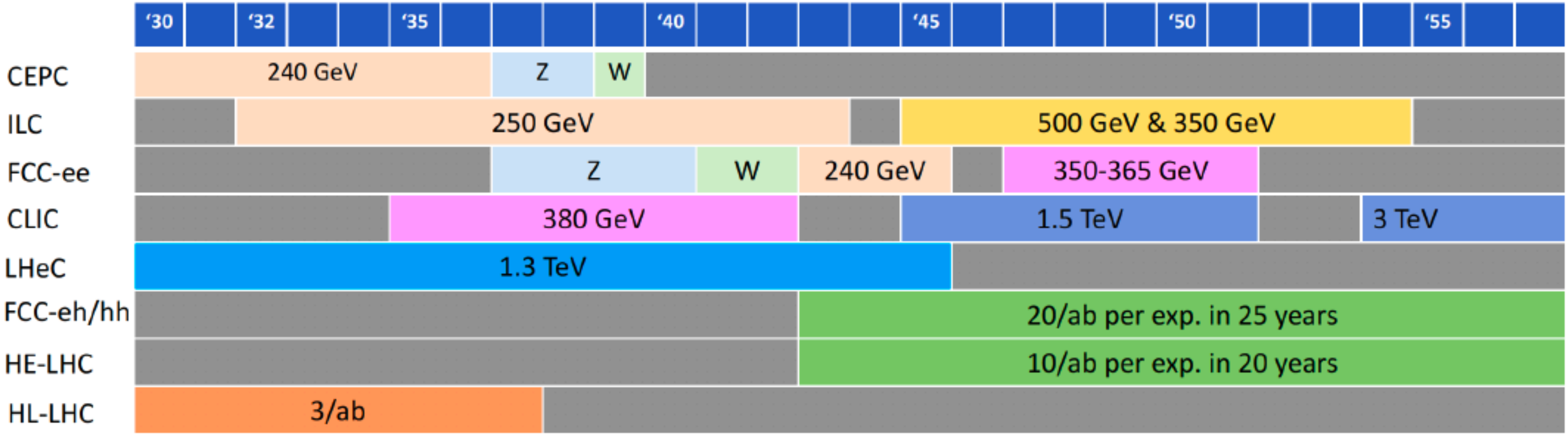
$L \propto P_{RF} E_{cm}$

All considered to be mature
⇒Can start construction
within 5-10 years

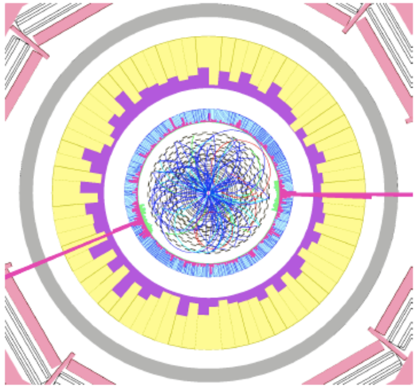
Future Colliders



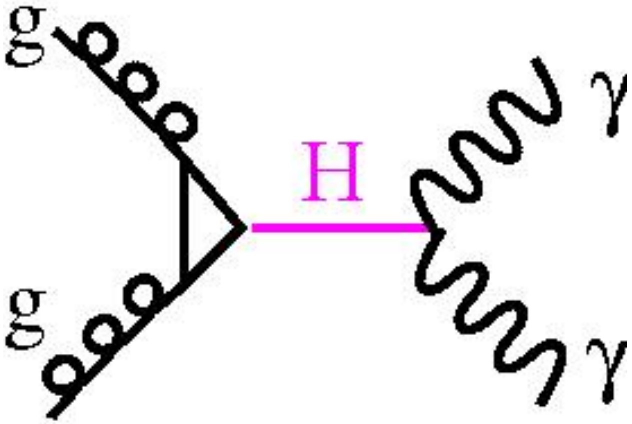
Schedules: by calendar year

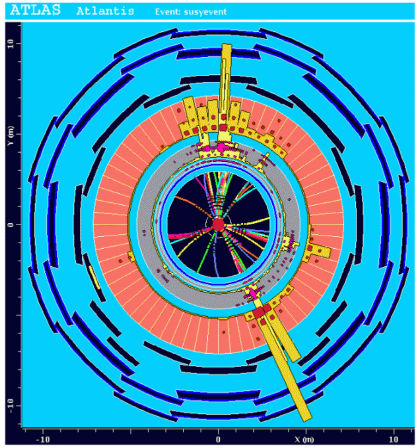


The Experimental Challenge

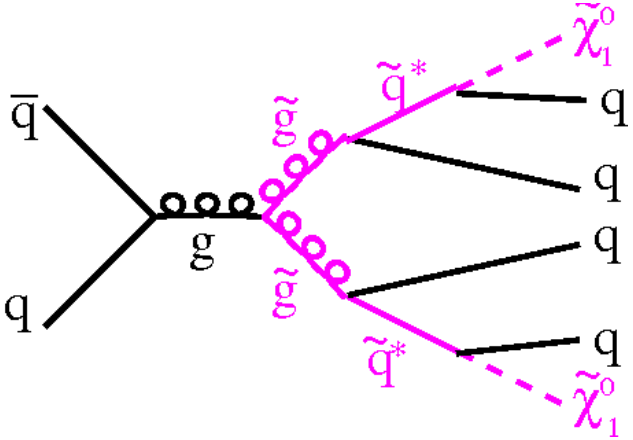


Higgs





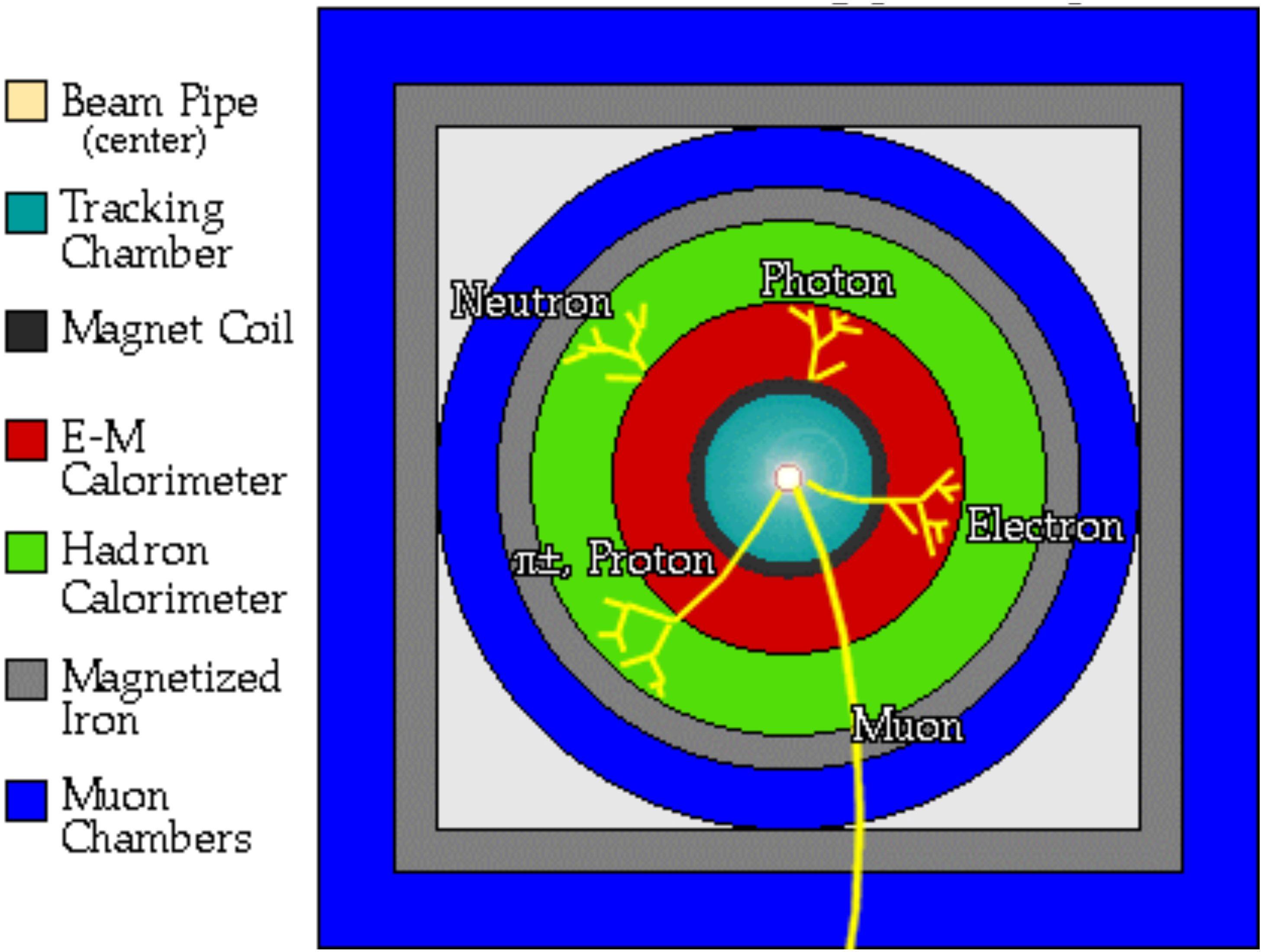
Supersymmetry



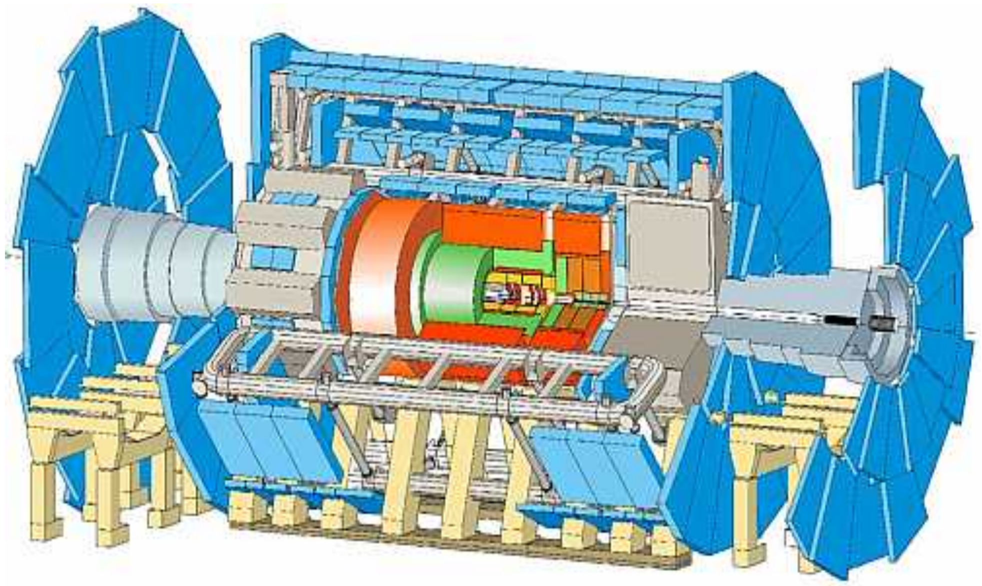
- **Measured hits in detector**
- **=> use hits to reconstruct particle paths and energies**
- **=> estimate background processes**
- **=> understand the underlying physics**

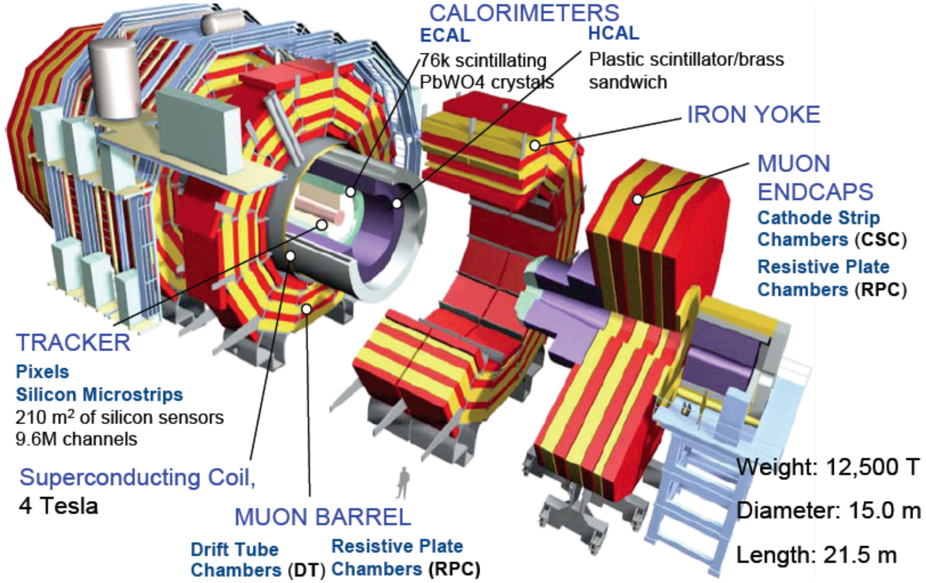
Particle Identification

Detector designed to separate electrons, photons, muons, neutral and charged hadrons



ATLAS and CMS Detectors



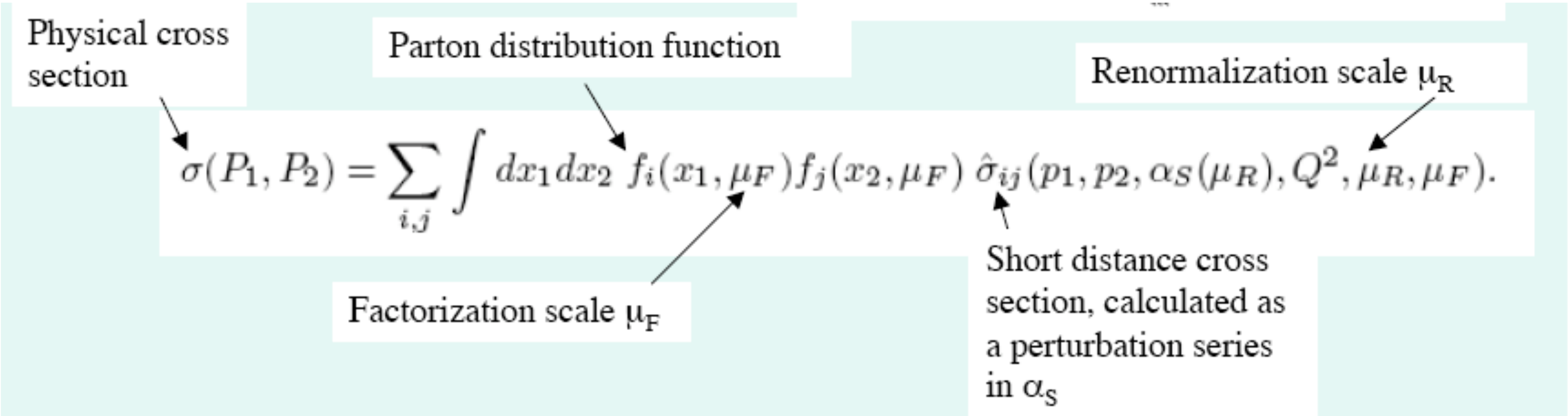


	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

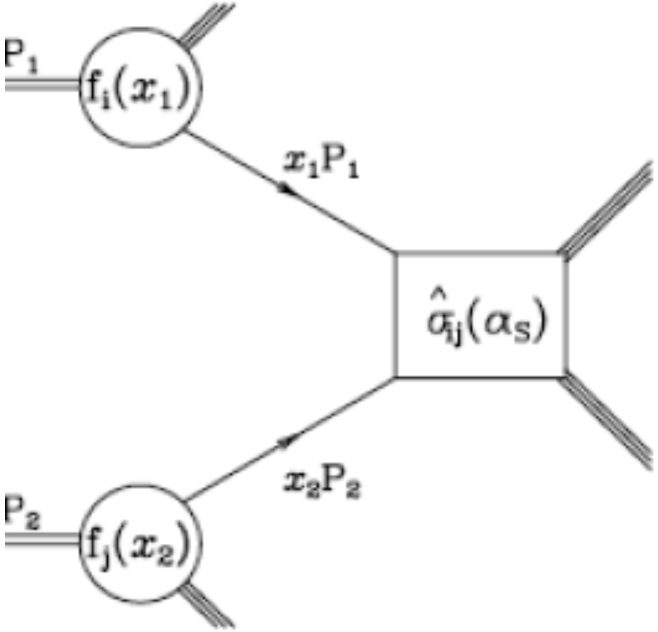
Hadron-Hadron Collisions

Calculating a Cross Section

- Cross section is convolution of pdf's and Matrix Element



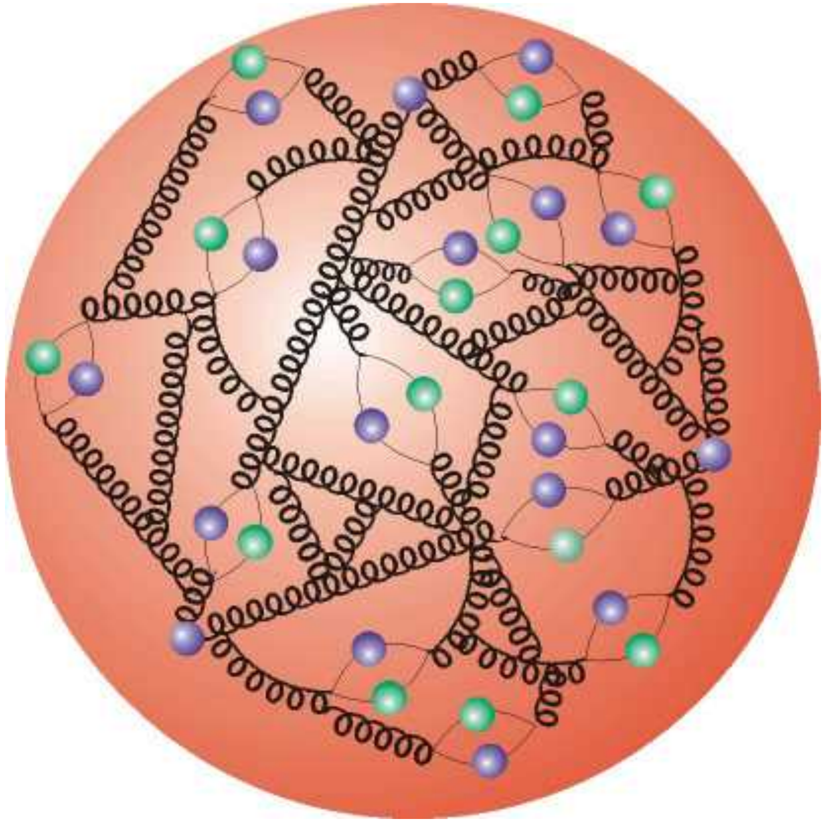
$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2\, f_i(x_1, \mu_F) f_j(x_2, \mu_F)\, \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F).$$



- Calculations are done in perturbative QCD
  - Possible due to factorization of hard ME and pdf's
    - Can be treated independently
  - Strong coupling (α_s) is large
    - Higher orders needed
    - Calculations complicated

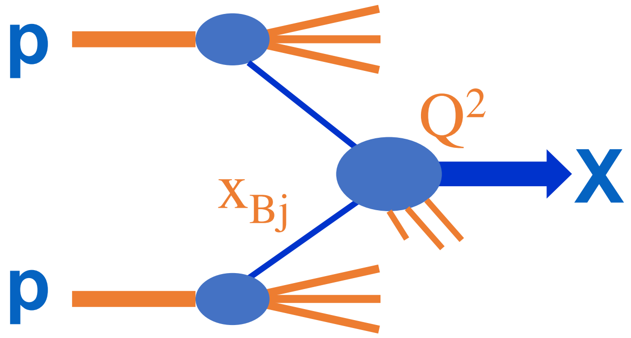
The Proton Composition

- It's complicated:
  - Valence quarks, Gluons, Sea quarks
- Exact mixture depends on:
  - Q^2: ~$(M^2+p_T^2)$
  - Björken-x:
    - fraction or proton momentum carried by parton
- Energy of parton collision:



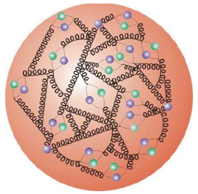
$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$

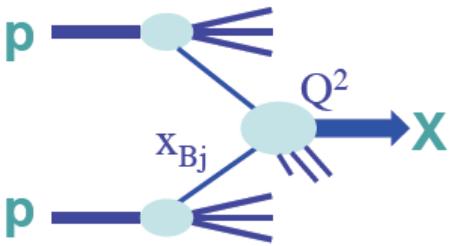
$$M_X = \sqrt{\hat{s}}$$



Particle production and PDFs

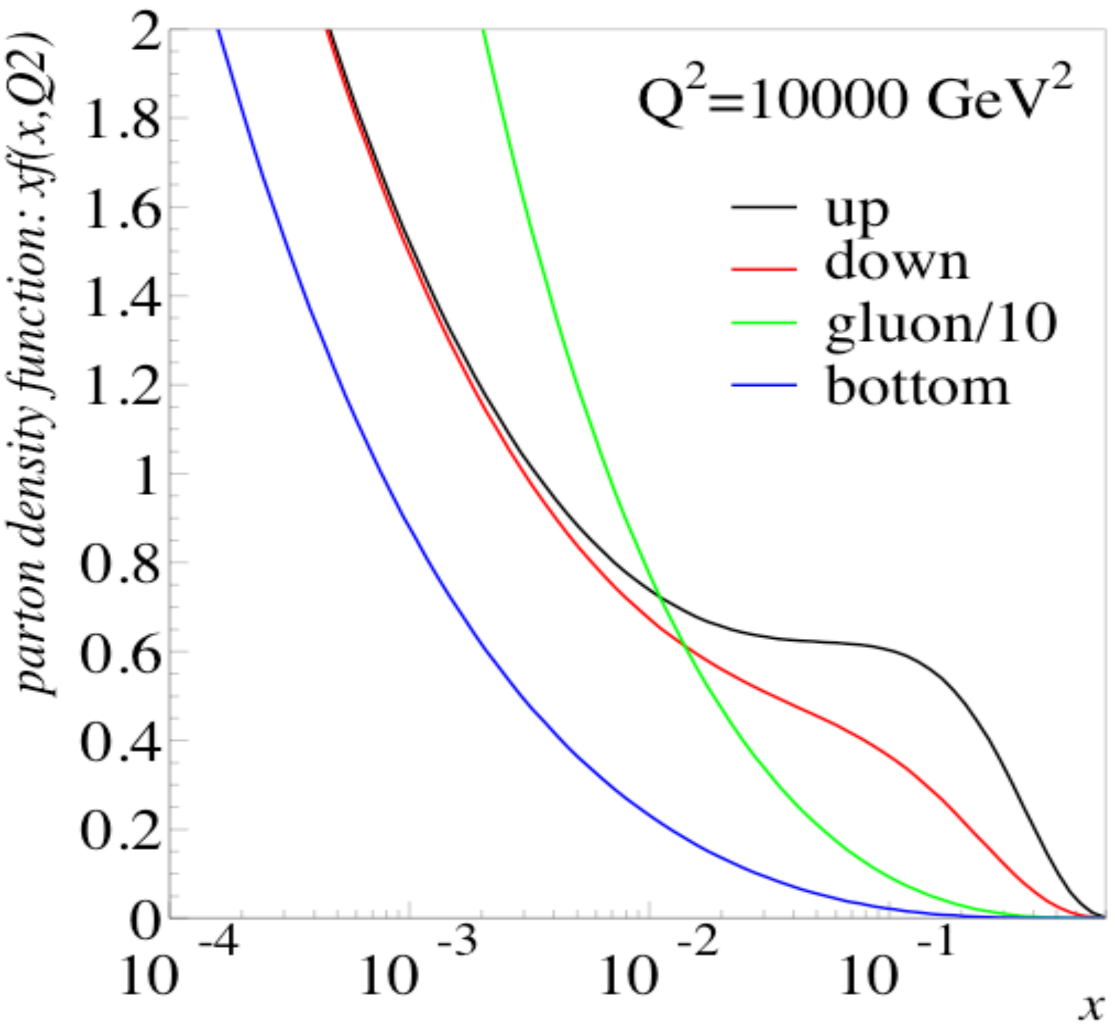
$$M_X = \sqrt{x_1 \cdot x_2 \cdot s}$$





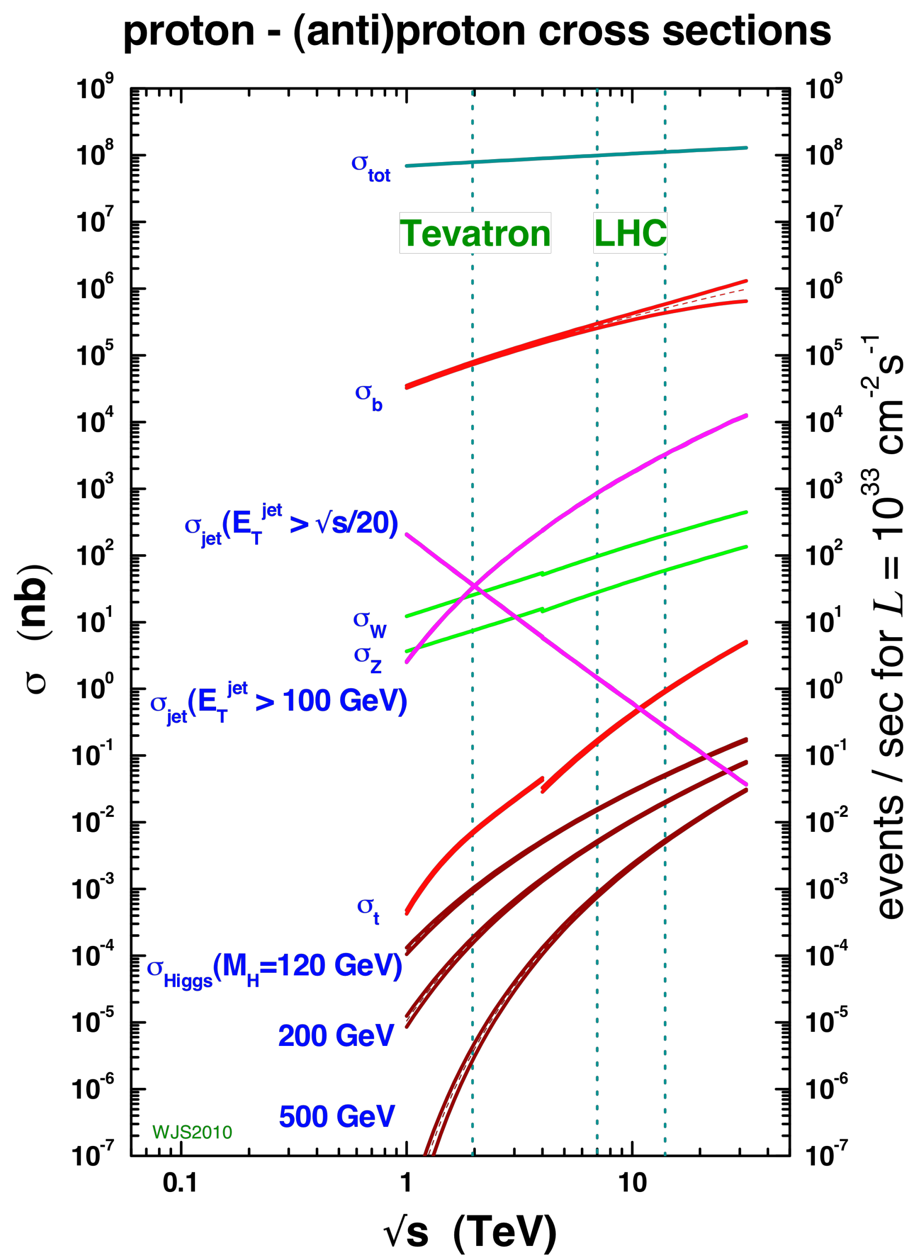
- Examples for particle production:
  - Higgs: M=125 GeV/c^2
    - LHC: $<x_p>$=125/13000≈0.01
  - Gluino: M~2000 GeV/c^2
    - LHC: $<x_p>$=4000/13000≈0.3

pdf's measured in deep-inelastic scattering



Steep rise of partons at low x => production rates strongly decrease with M

Physics Processes at the LHC

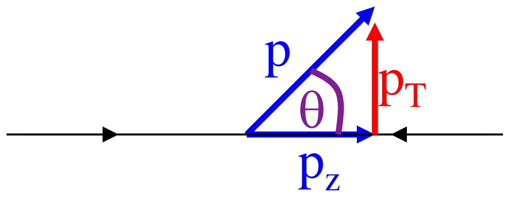


process	Rate at L_{peak} (Hz)
any interactions	10^9
Bottom quarks	10^6
Jets with p_T>100 GeV	10^4
W bosons	10^3
Top quarks	1
Higgs (M=125 GeV)	0.1
H->γγ (M=125 GeV)	$2x10^{-4}$

Events	Event rate [Hz]
Beam crossings	4×10^7
Level-1 triggered	10^5
Recorded to disk	10^3

Kinematic Constraints and Variables

- **Transverse momentum, p_T**
  - Particles that escape detection ($\theta<3^o$) have $p_T \approx 0$
  - Visible transverse momentum conserved $\sum_i p_T^i \approx 0$
    - **Very useful variable!**



- **Longitudinal momentum and energy, p_z and E**
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - **Not a useful variable**
- **Polar angle θ**
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

For M=0

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

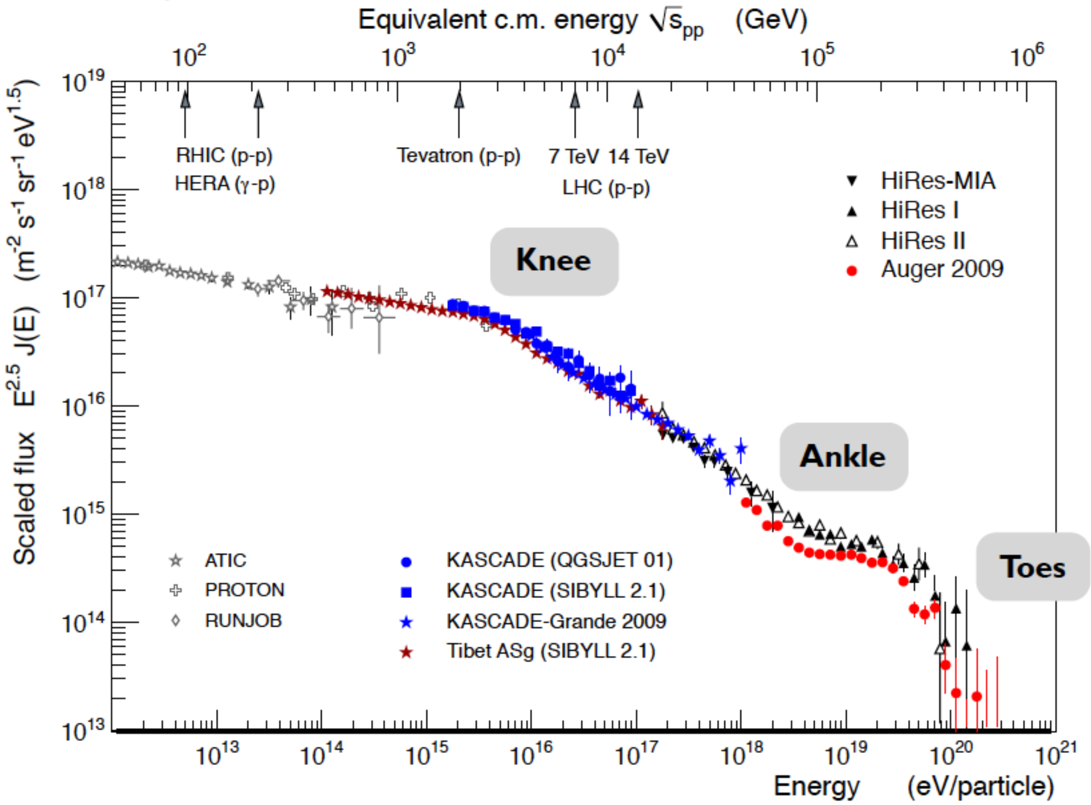
What is a Cross Section?

- Differential cross section: $d\sigma/d\Omega$:
  - Probability of a scattered particle in a given quantum state per solid angle $d\Omega$
    - E.g. Rutherford scattering experiment
- Other differential cross sections: $d\sigma/dE_T$(jet)
  - Probability of a jet with given E_T
- Integrated cross section
  - Integral: $\sigma = \int d\sigma/d\Omega \, d\Omega$

Measurement: $\sigma=(N_{obs}-N_{bg})/(\varepsilon L)$

Inelastic pp Cross Section

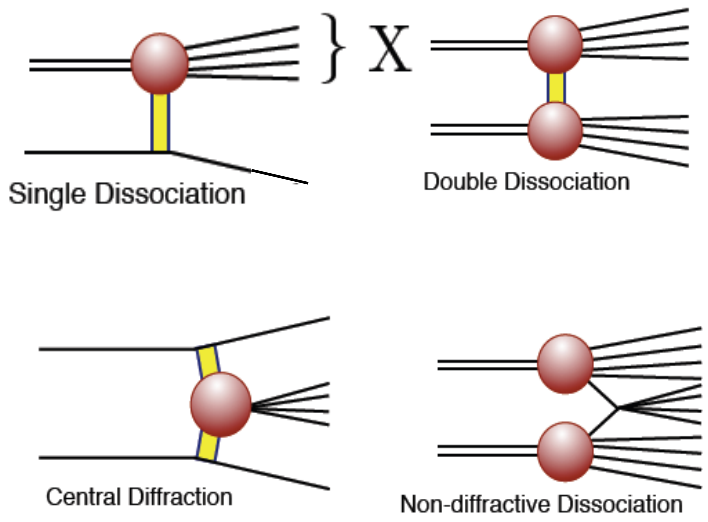
- **Basic quantity of QCD**
- **Important for understanding of cosmic rays**
  - Probes energy range near the knee
- **Important for understanding of pileup at LHC**

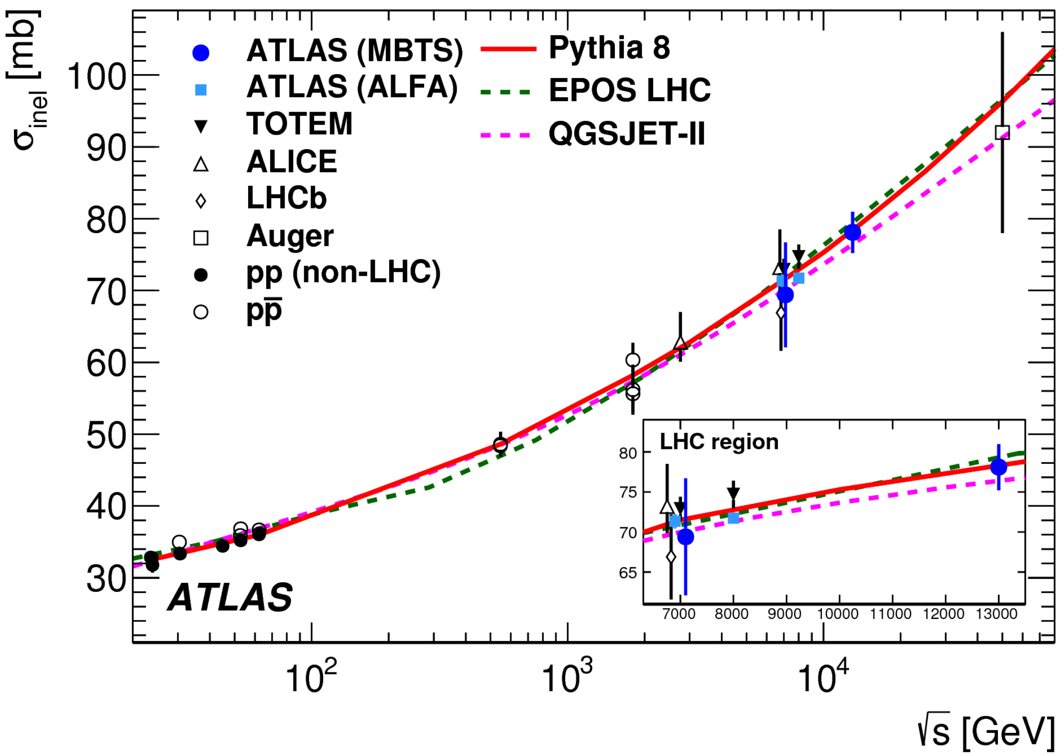


R. Engel

LHC: Inelastic pp Cross Section

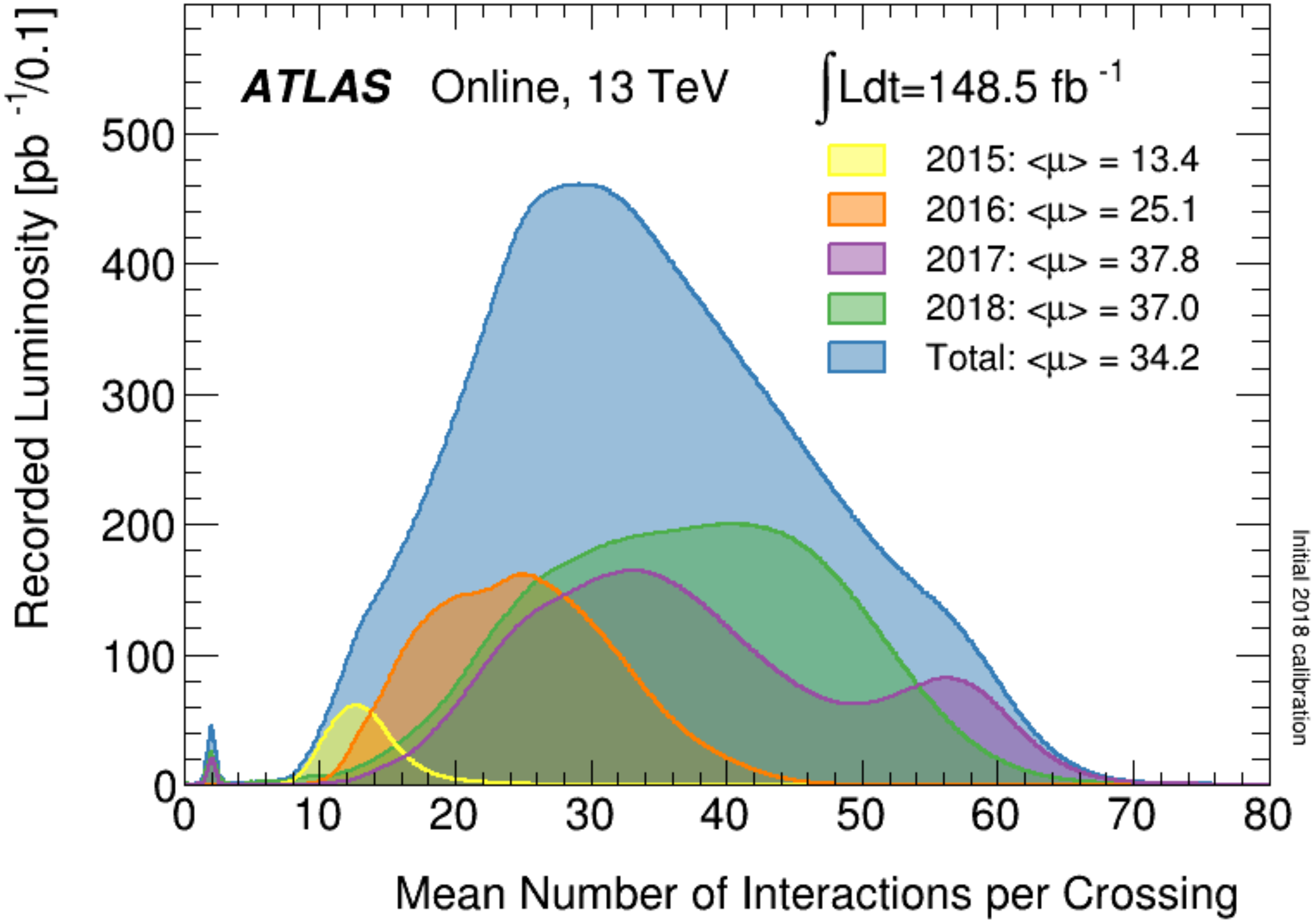
- Inelastic interactions: pp-> X



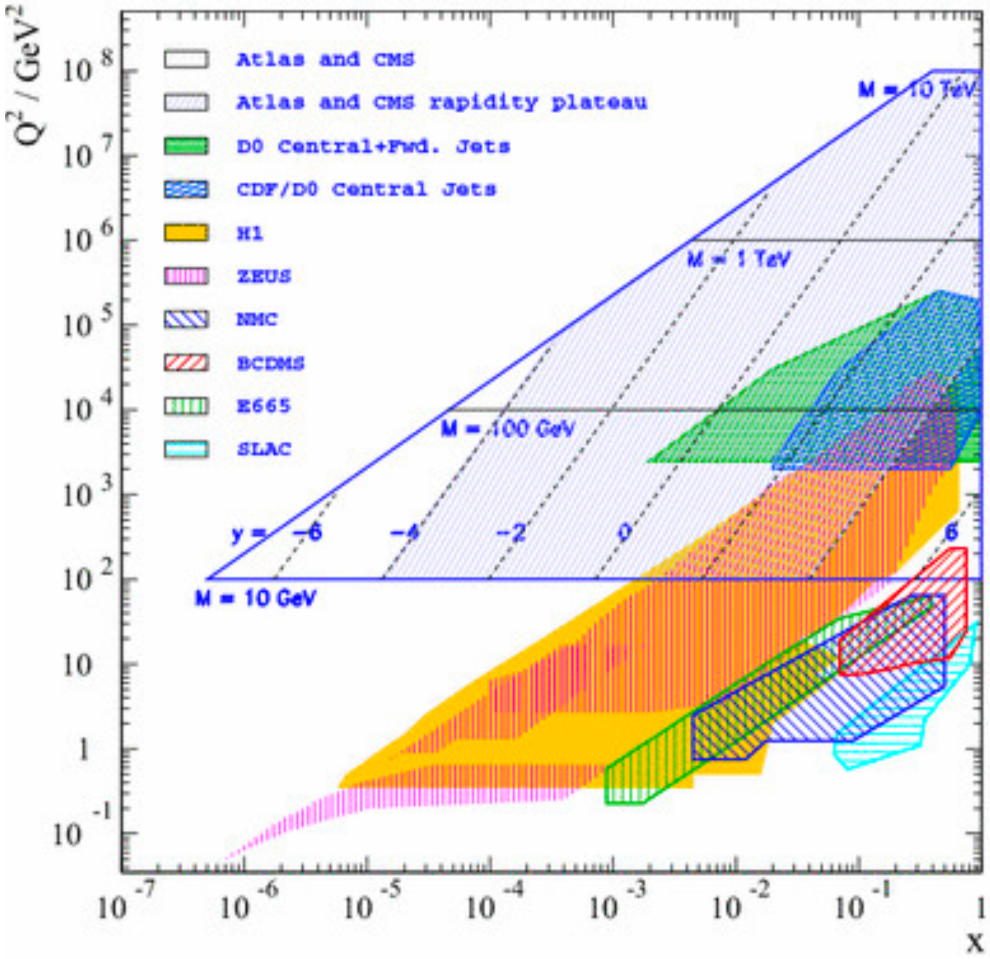


- Cannot be determined theoretically with good precision
  - Not calculable using perturbation theory
- In every LHC event there are ~35 such event on average (pile-up)

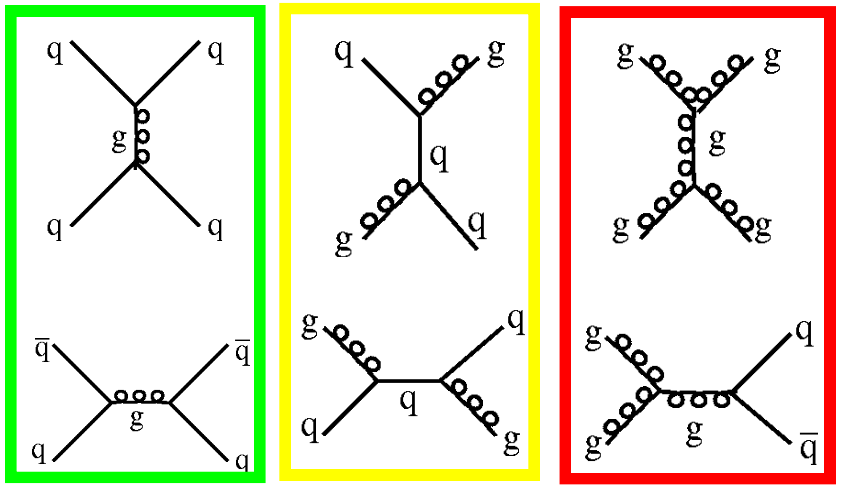
Pile-up

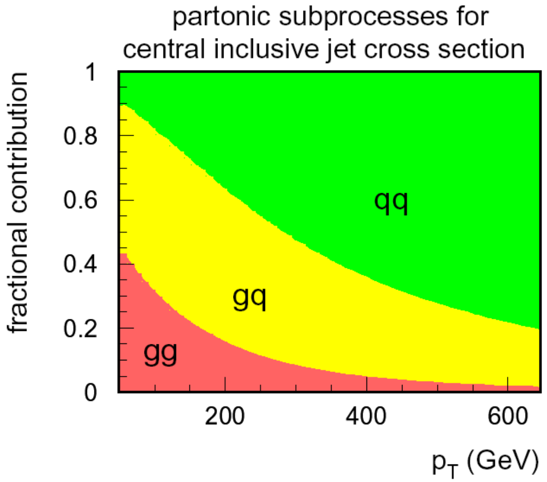

ATLAS Online, 13 TeV
∫Ldt=148.5 fb -1
2015: <μ> = 13.4
2016: <μ> = 25.1
2017: <μ> = 37.8
2018: <μ> = 37.0
Total: <μ> = 34.2
Recorded Luminosity [pb -1/0.1]
Mean Number of Interactions per Crossing
Initial 2018 calibration
0
100
200
300
400
500
0
10
20
30
40
50
60
70
80

Jet Cross Sections



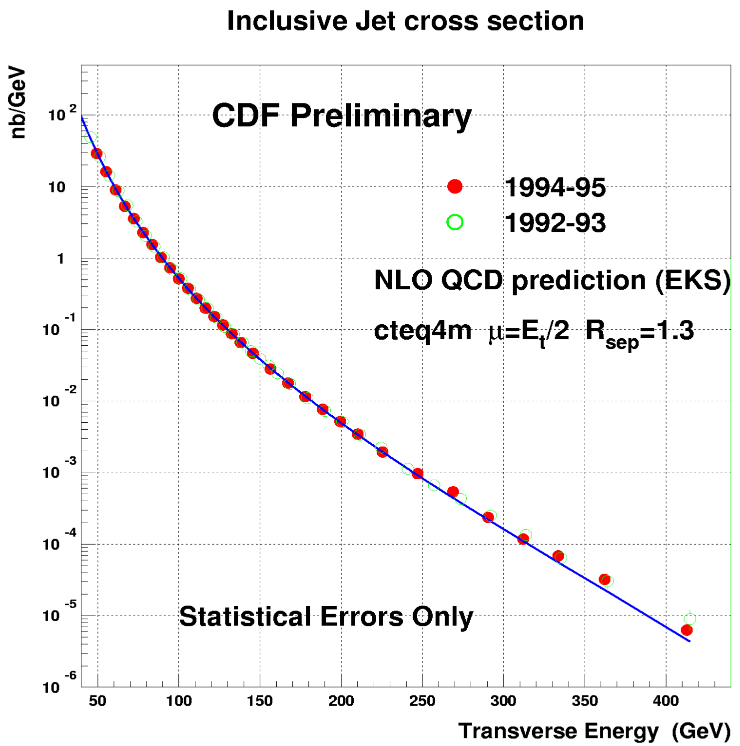
- Inclusive jets: processes qq, qg, gg

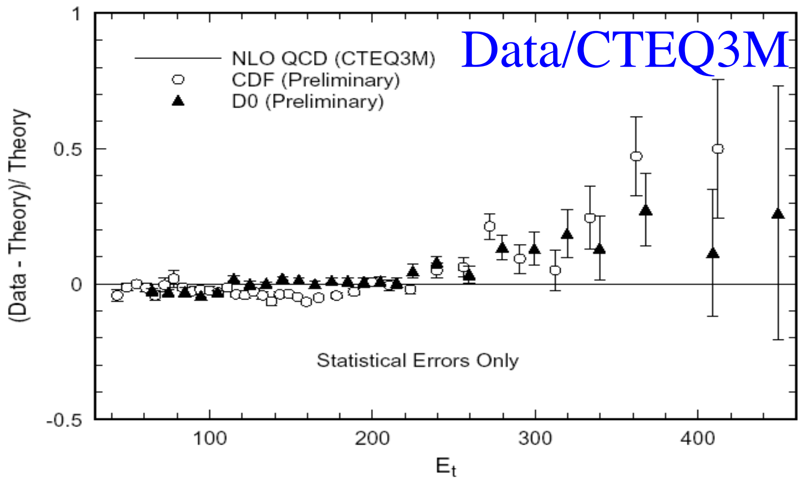




- Highest E_T probes shortest distances
  - Tevatron: $r_q < 10^{-18}$ m
  - LHC: $r_q < 10^{-19}$ m (?)
  - Could e.g. reveal substructure of quarks
- Tests perturbative QCD at highest energies

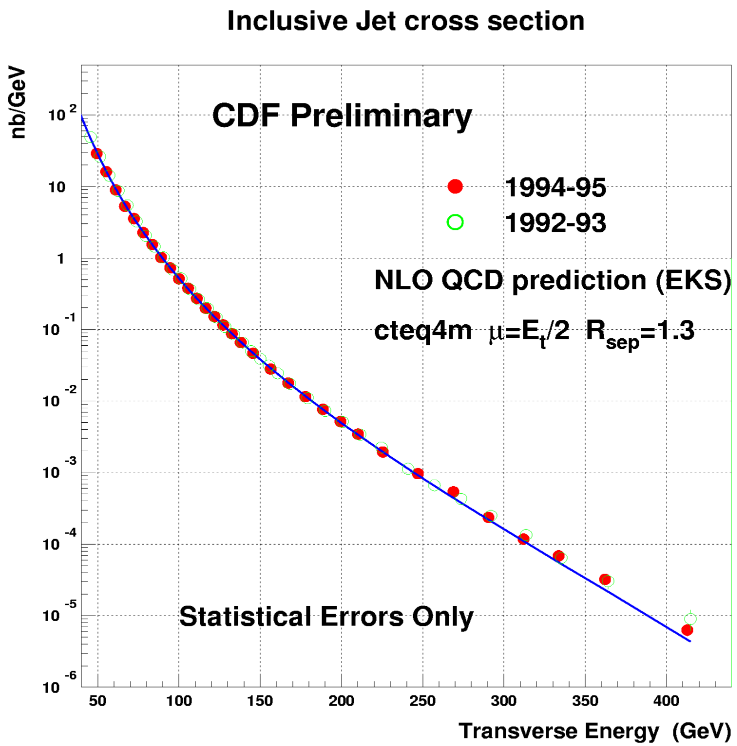
Jet Cross Section History

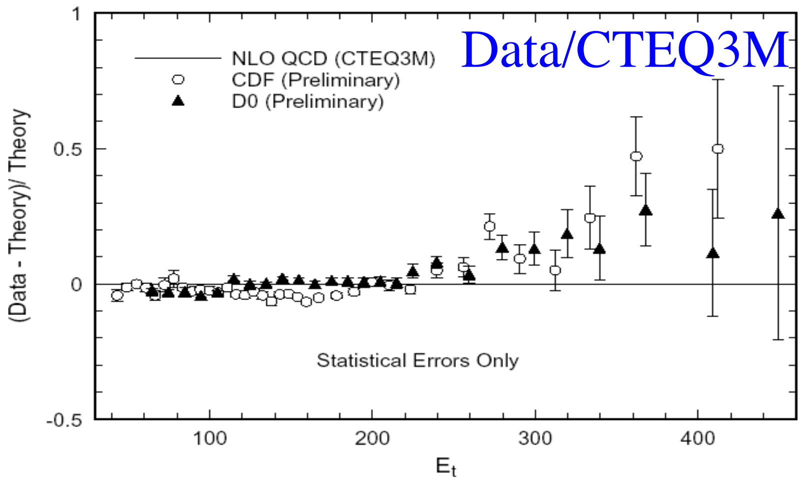




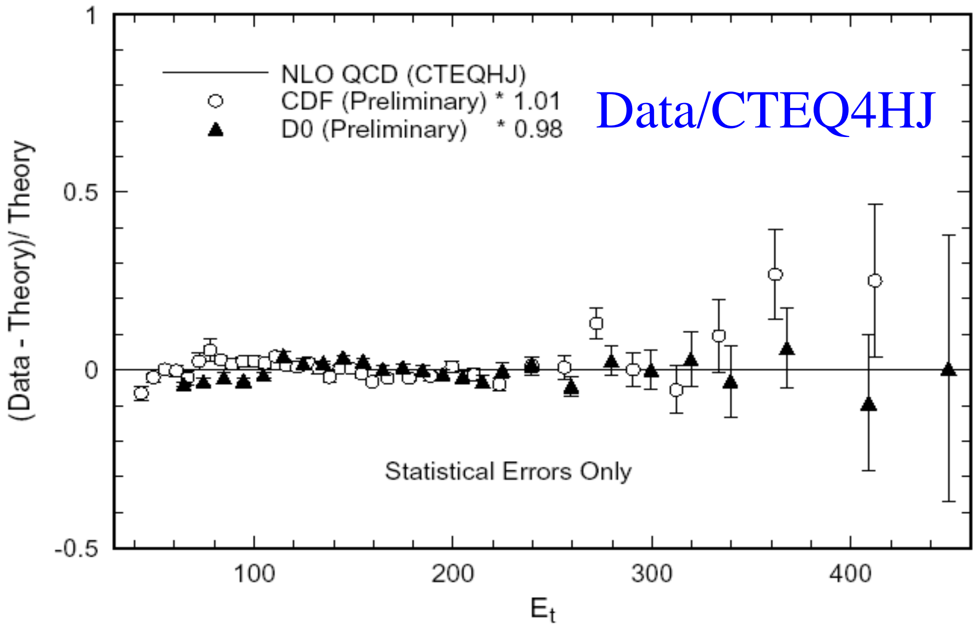
- Tevatron Run I (~1996):
  - Excess at high E_T
  - Could be signal for quark substructure?!?

Jet Cross Section History

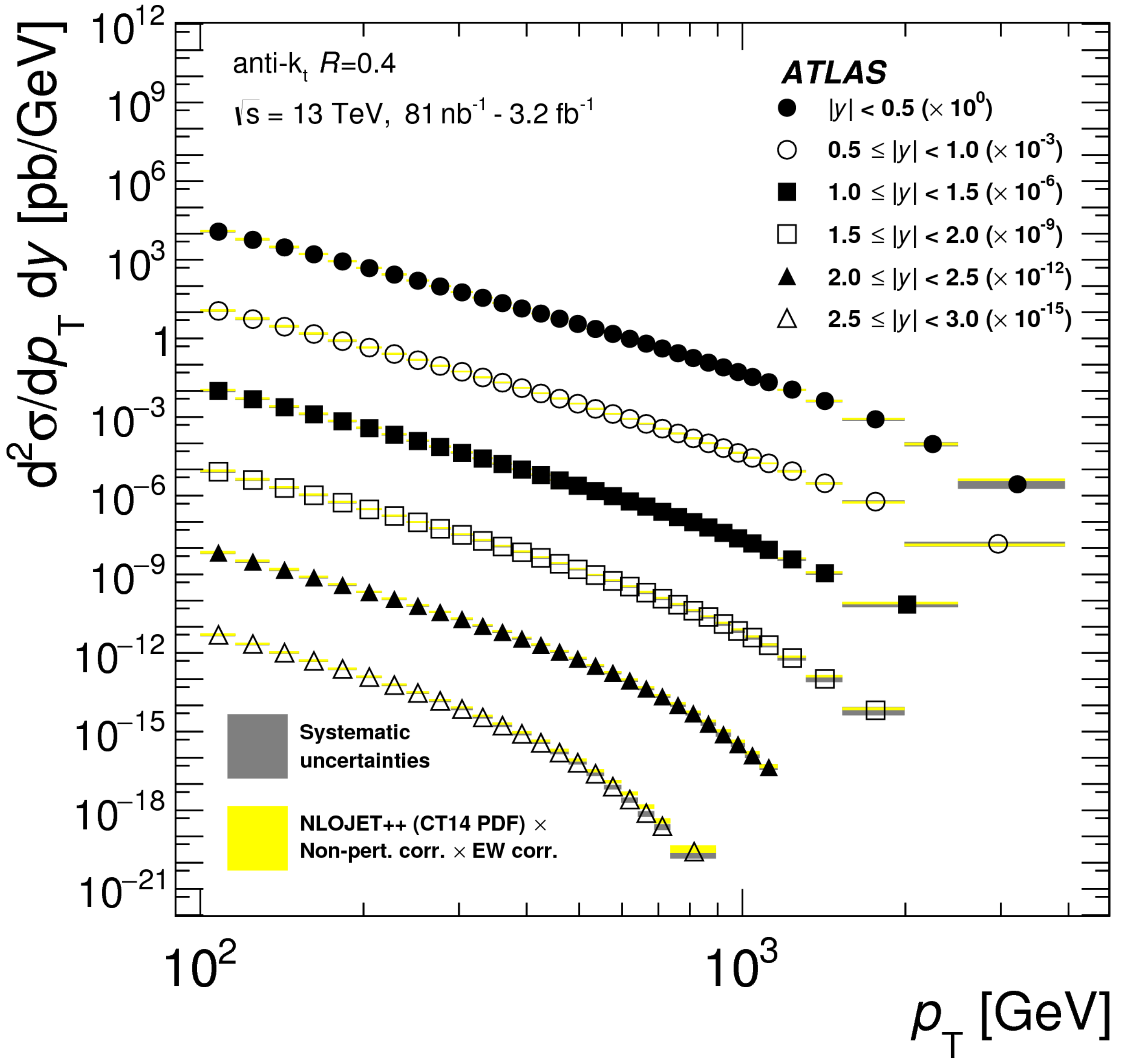




- Tevatron Run I (~1996):
  - Revision of parton density functions
  - Gluon PDF was uncertain at high x
  - Modified PDF describes data well

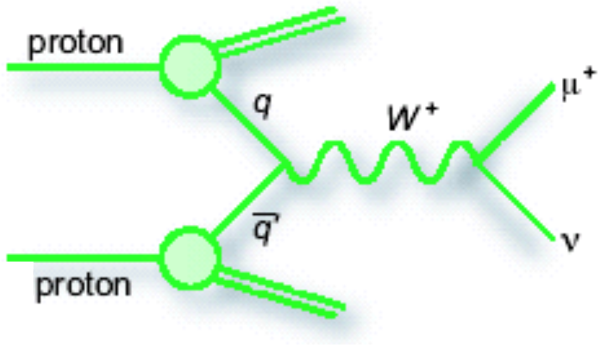


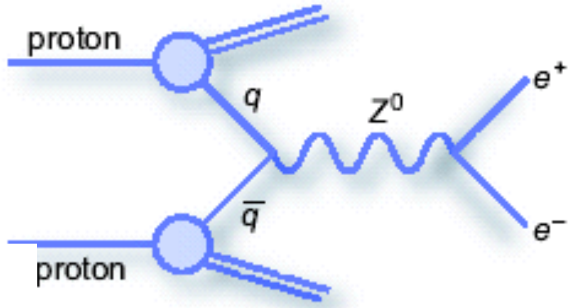
Jet Cross Sections: LHC

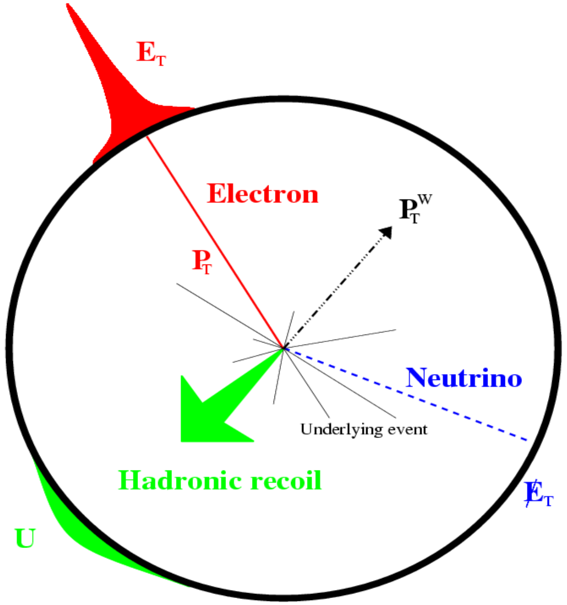


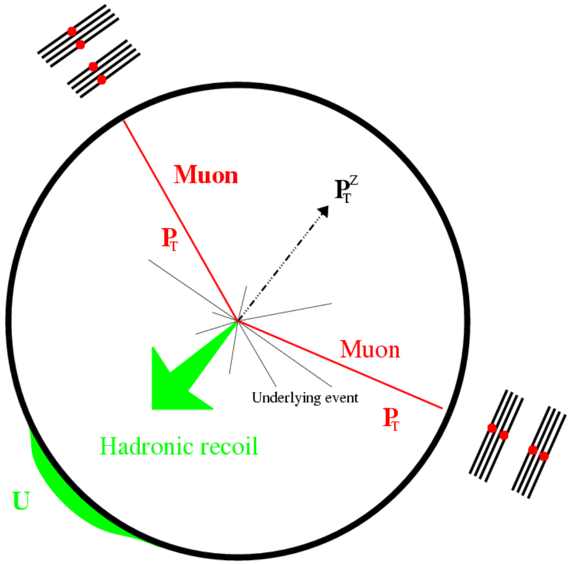
W and Z Bosons

- Focus on leptonic decays:
  - Hadronic decays ~impossible due to enormous QCD dijet background
- Selection:
  - Z:
    - Two leptons p_T>20 GeV
  - W:
    - One lepton p_T>20 GeV
    - Large imbalance in transverse momentum
      - Missing E_T>20 GeV
      - Signature of undetected particle (neutrino)
- Excellent calibration signal for many purposes:
  - Electron energy scale
  - Track momentum scale
  - Lepton ID and trigger efficiencies
  - Missing E_T resolution
  - Luminosity …



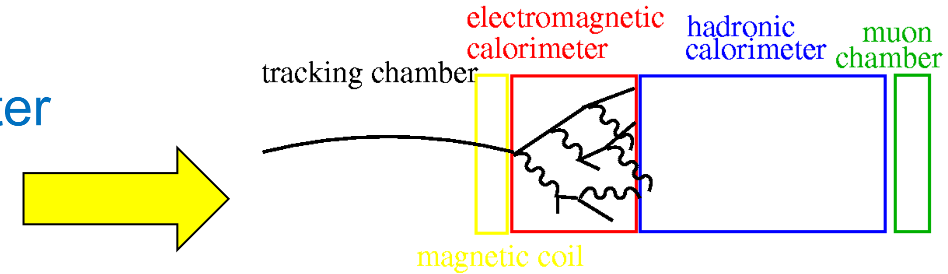




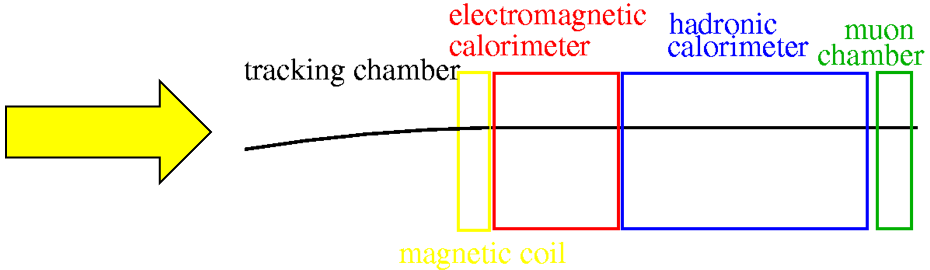


Lepton Identification

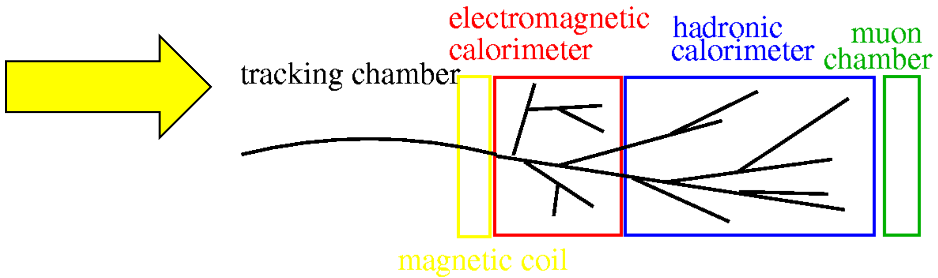
- Electrons:
  - compact electromagnetic cluster in calorimeter
  - Matched to track



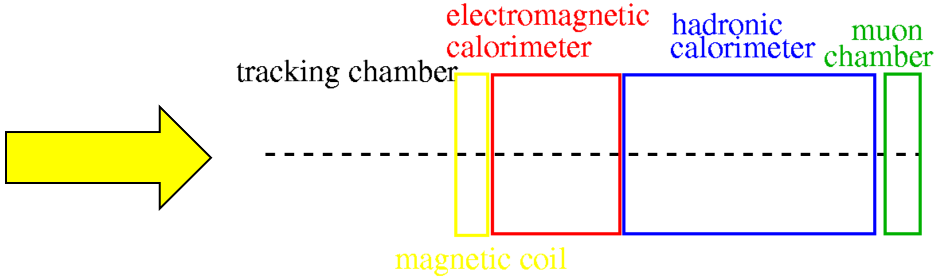
- Muons:
  - Track in the muon chambers
  - Matched to track



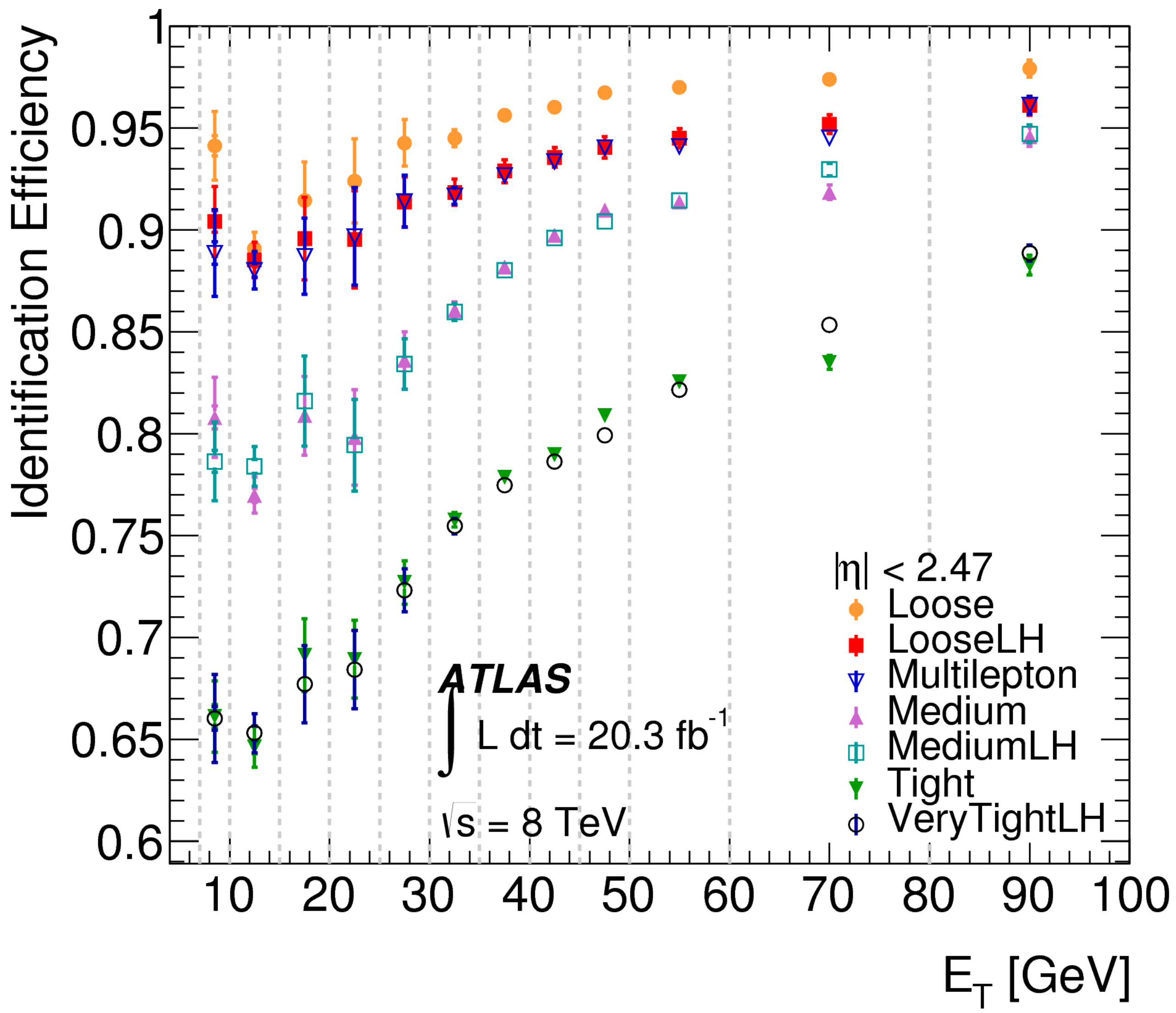
- Taus:
  - Narrow jet
  - Matched to one or three tracks

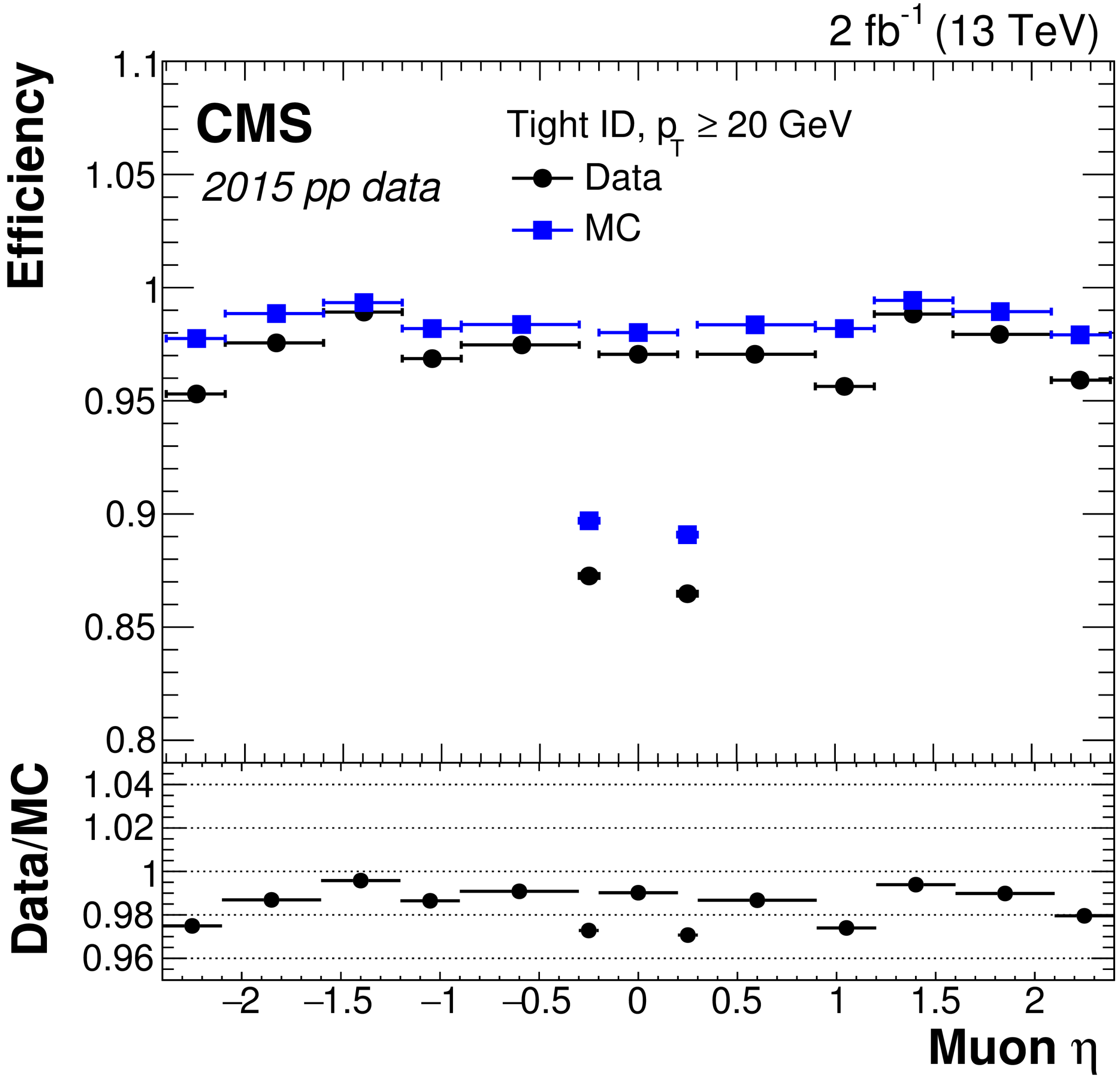


- Neutrinos:
  - Imbalance in transverse momentum
  - Inferred from total transverse energy measured in detector
  - More on this in Lecture 4

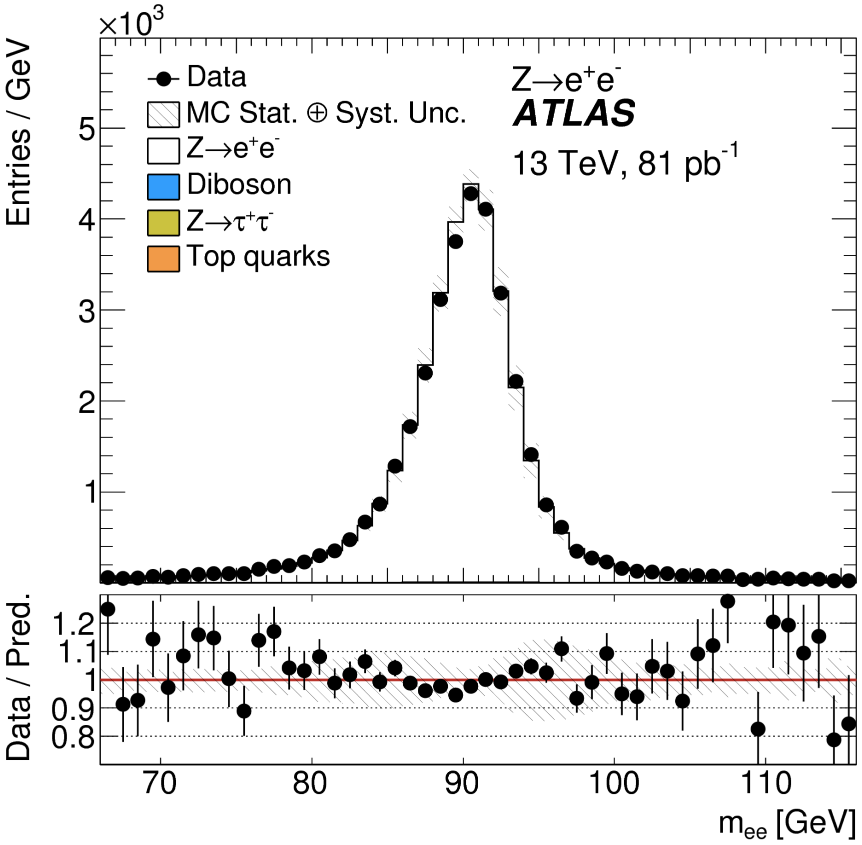


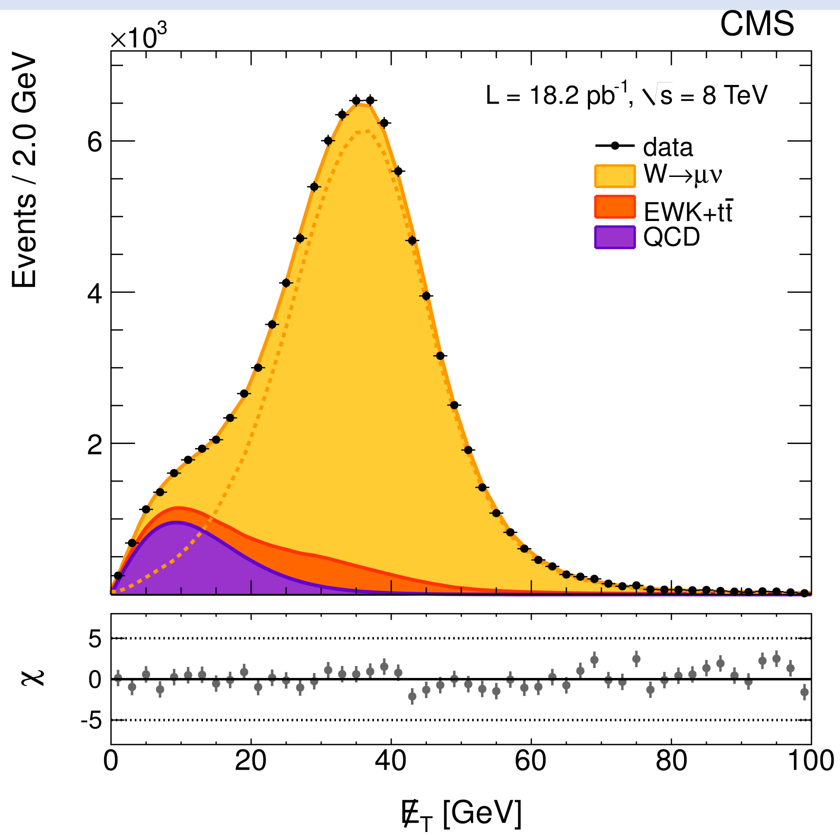
Electron and Muon Identification





W’s and Z’s





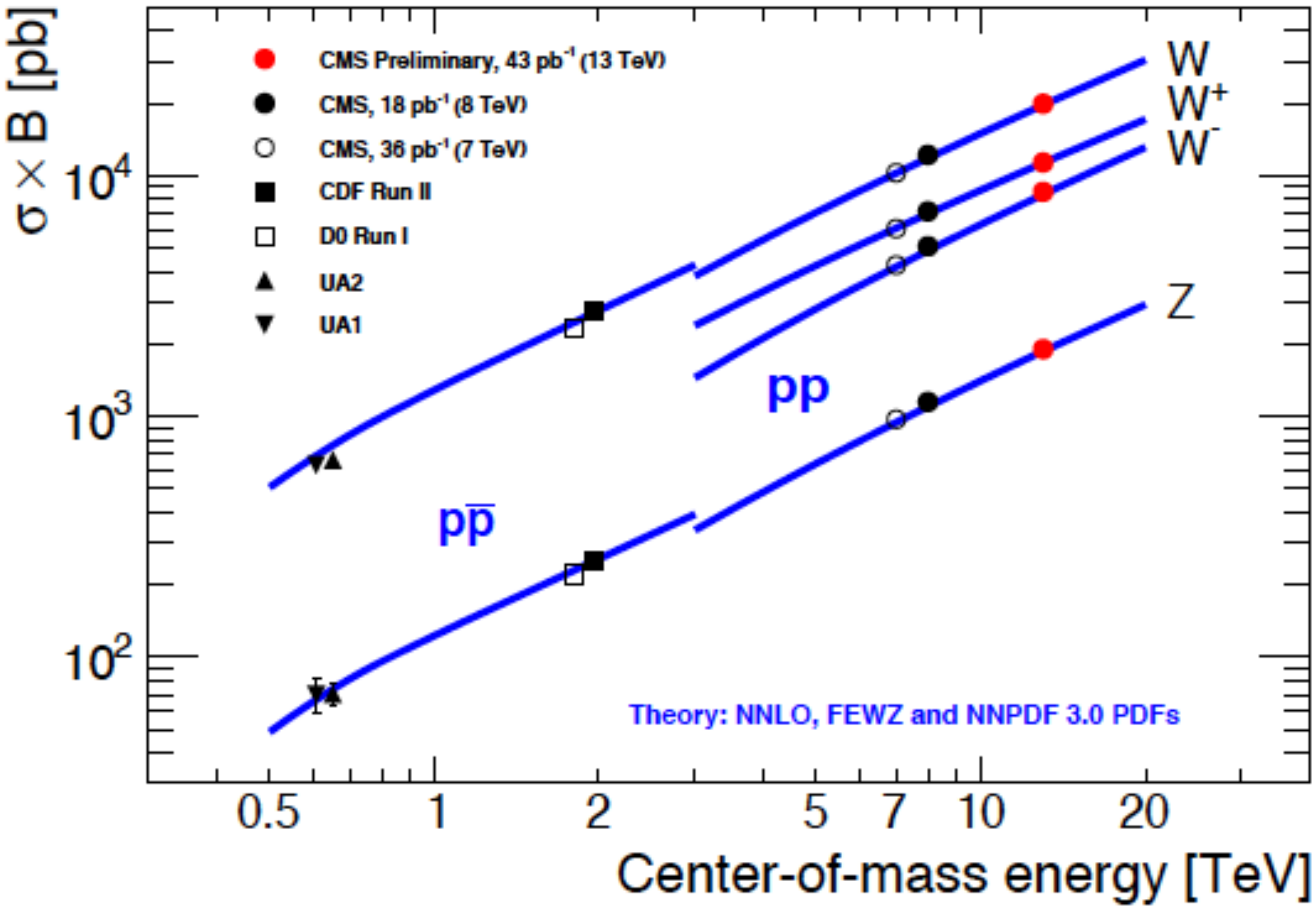
- Z mass reconstruction
  - Invariant mass of two leptons

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

- W mass reconstruction
  - Do not know neutrino p_Z
  - No full mass resonstruction possible
  - Transverse mass:

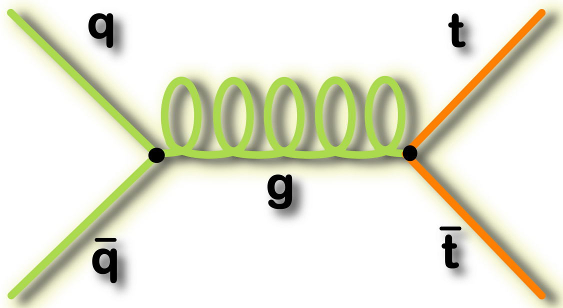
$$m_T = \sqrt{|p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2}$$

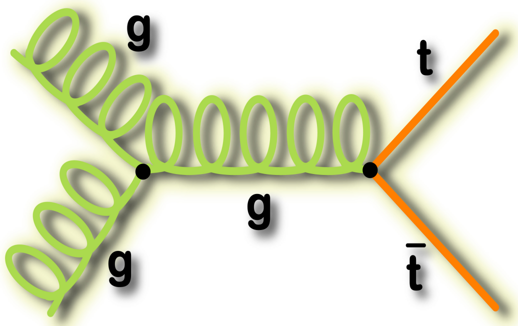
Dependence of σ(W) and σ(Z) on √s



Top Quark Production and Decay

15%





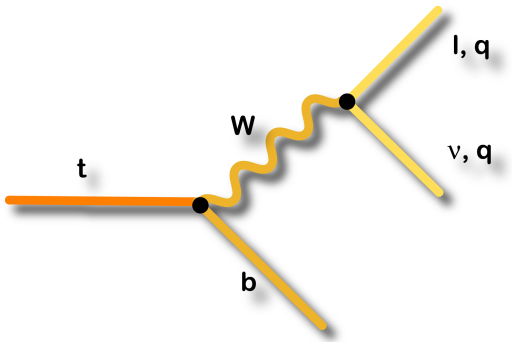
85% at LHC

- Decay via the electroweak interactions **Br(t →Wb) ~ 100%**
  Final state is characterized by the decay of the W boson

Dilepton

Lepton+Jets

All-Jets



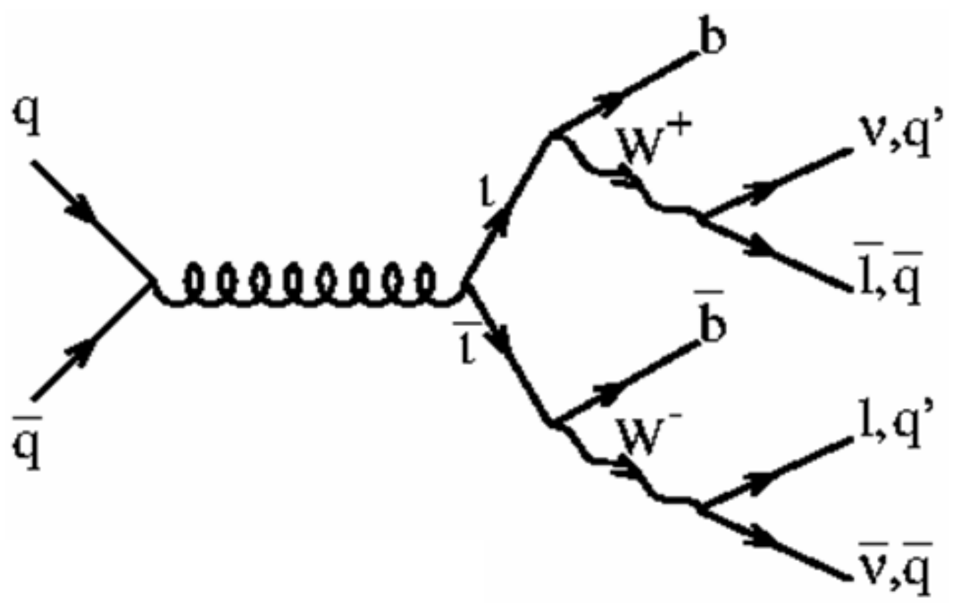
Different sensitivity and challenges in each channel

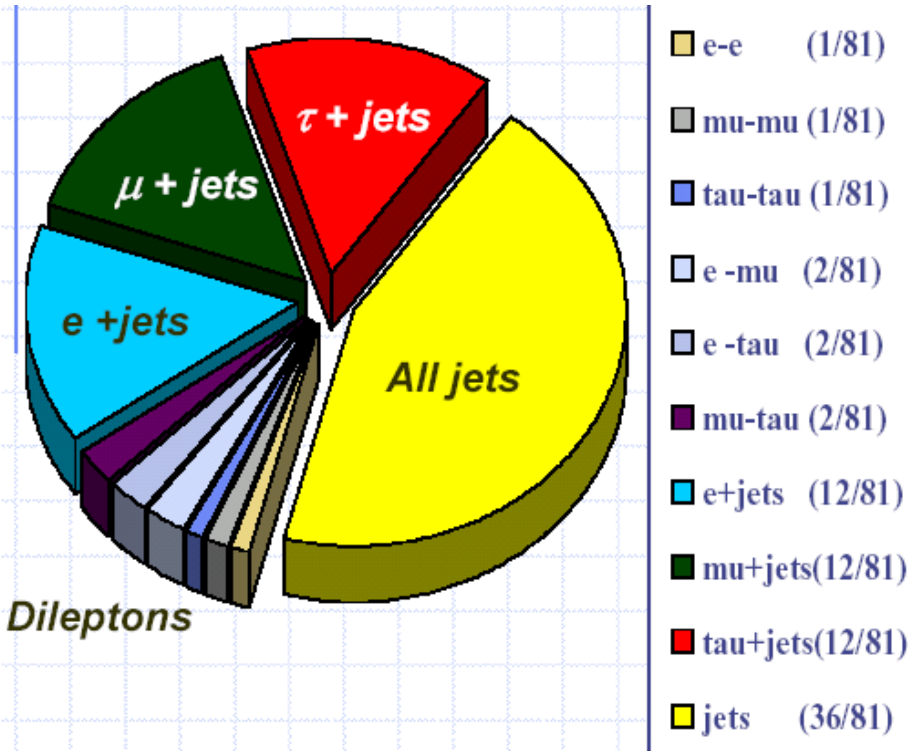
How to identify the top quark

$$BR(W \to l\nu) = \frac{1}{9} = 11\%$$

dilepton	(4/81)	2 leptons + 2 jets + missing E_T
l+jets	(24/81)	1 lepton + 4 jets + missing E_T
fully hadronic	(36/81)	6 jets

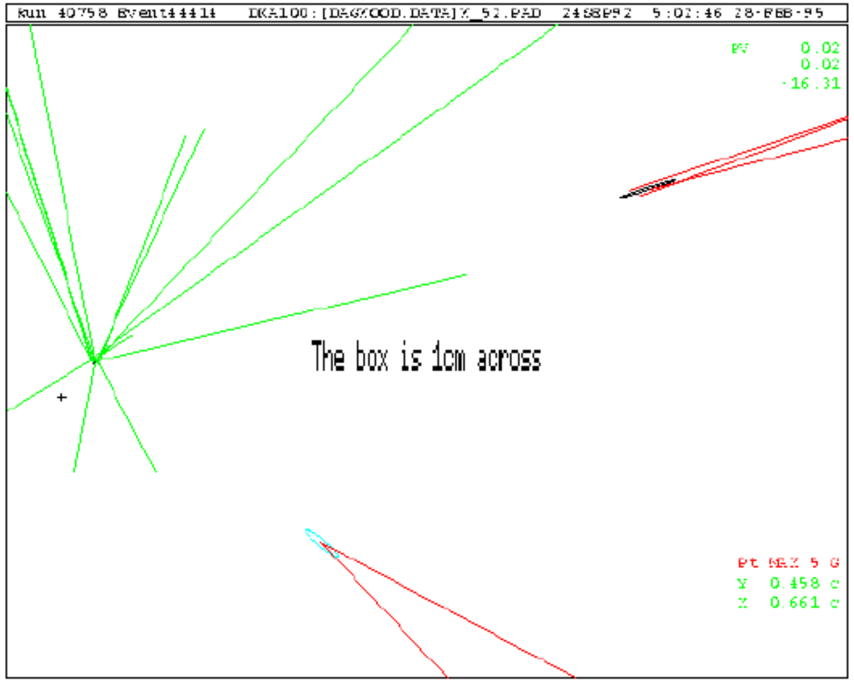
(here: l=e,μ)

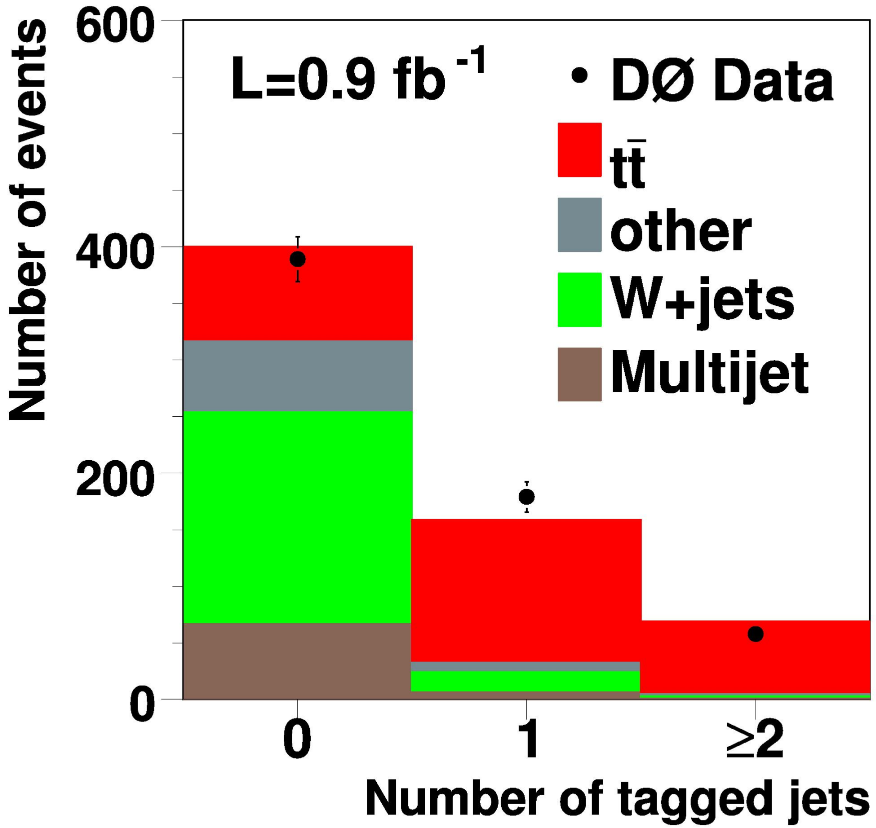




Finding the Top at Tevatron

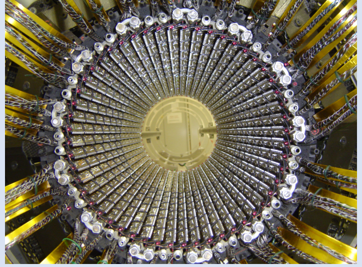
Top quark discovery event (CDF)



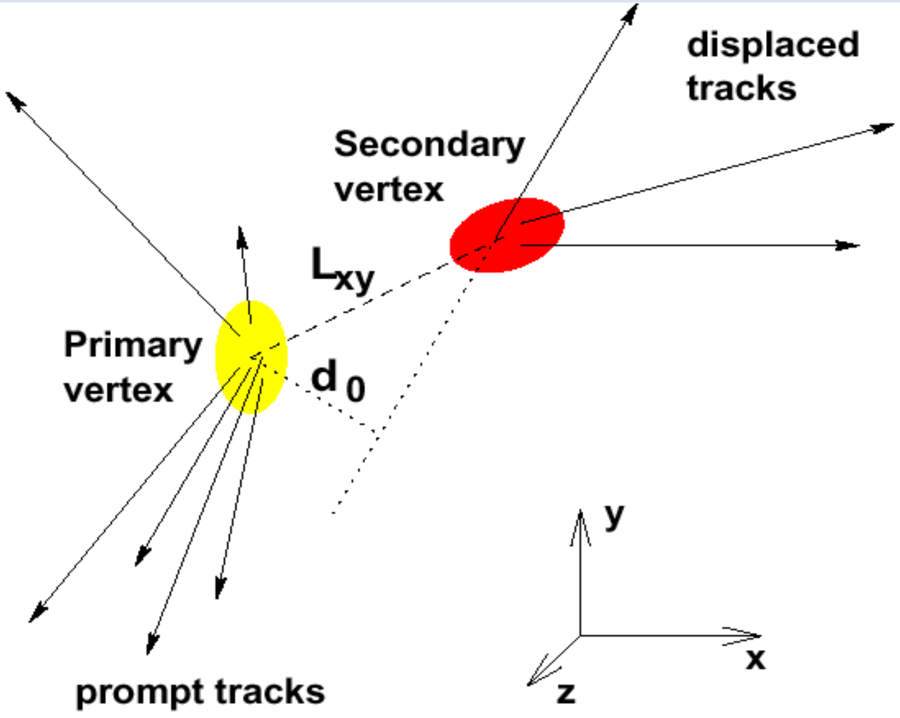


- **b-tagging helps a lot:**
  - Signal/Background improved by about a factor of 10 when using b-tagging
- **Tevatron (with 4 jets):**
  - no b-tagging: S/B≈0.8, With b-tagging: S/B≈6

Finding the b-jets



- Exploit large lifetime of the b-hadron
  - B-hadron flies before it decays: d=cτ
    - Lifetime τ =1.5 ps^{-1}
    - d=cτ = 460 μm
    - Can be resolved with silicon detector resolution
- Procedure "Secondary Vertex":
  - reconstruct primary vertex:
    - resolution ~ 30 μm
  - Search tracks inconsistent with primary vertex (large d_0):
    - Candidates for secondary vertex
    - See whether three or two of those intersect at one point
  - Require displacement of secondary from primary vertex
    - Form L_{xy}: transverse decay distance projected onto jet axis:
      - $L_{xy}>0$: b-tag along the jet direction => real b-tag or mistag
      - $L_{xy}<0$: b-tag opposite to jet direction => mistag!
    - Significance: e.g. $\delta L_{xy} / L_{xy} >7$ (i.e. 7σ significant displacement)

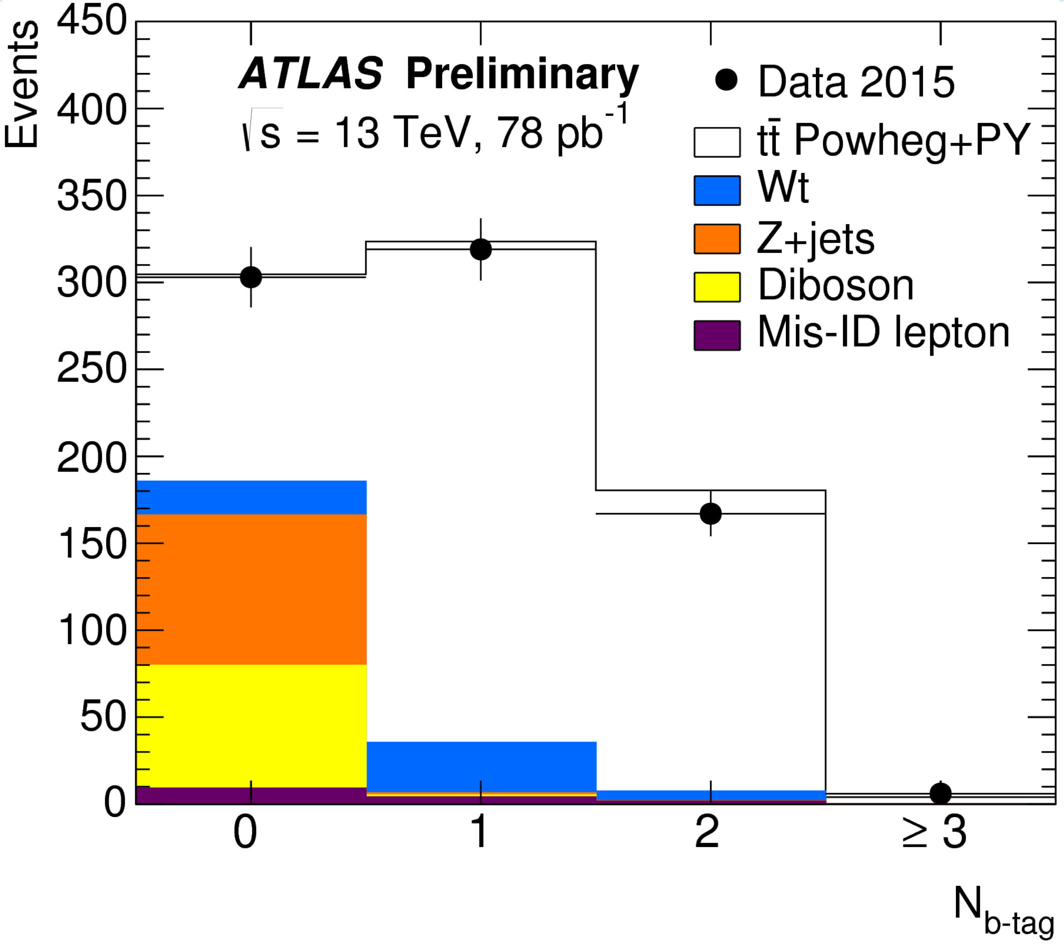


- Nowadays, input many properties of tracks into multivariate algorithm (e.g. Neural Network)

Top cross section: dilepton channel

- Event selection
  - Isolated e and μ with p_T>25 GeV
  - One or two b-jets
    - N_1: 1 b-jet
    - N_2: 2 bjets
- Solve equations for cross section and fraction of b-jets found (ε_b)

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}2\epsilon_b(1-C_b\epsilon_b)+N_1^{\rm bkg}$$
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}C_b{\epsilon_b}^2+N_2^{\rm bkg}$$

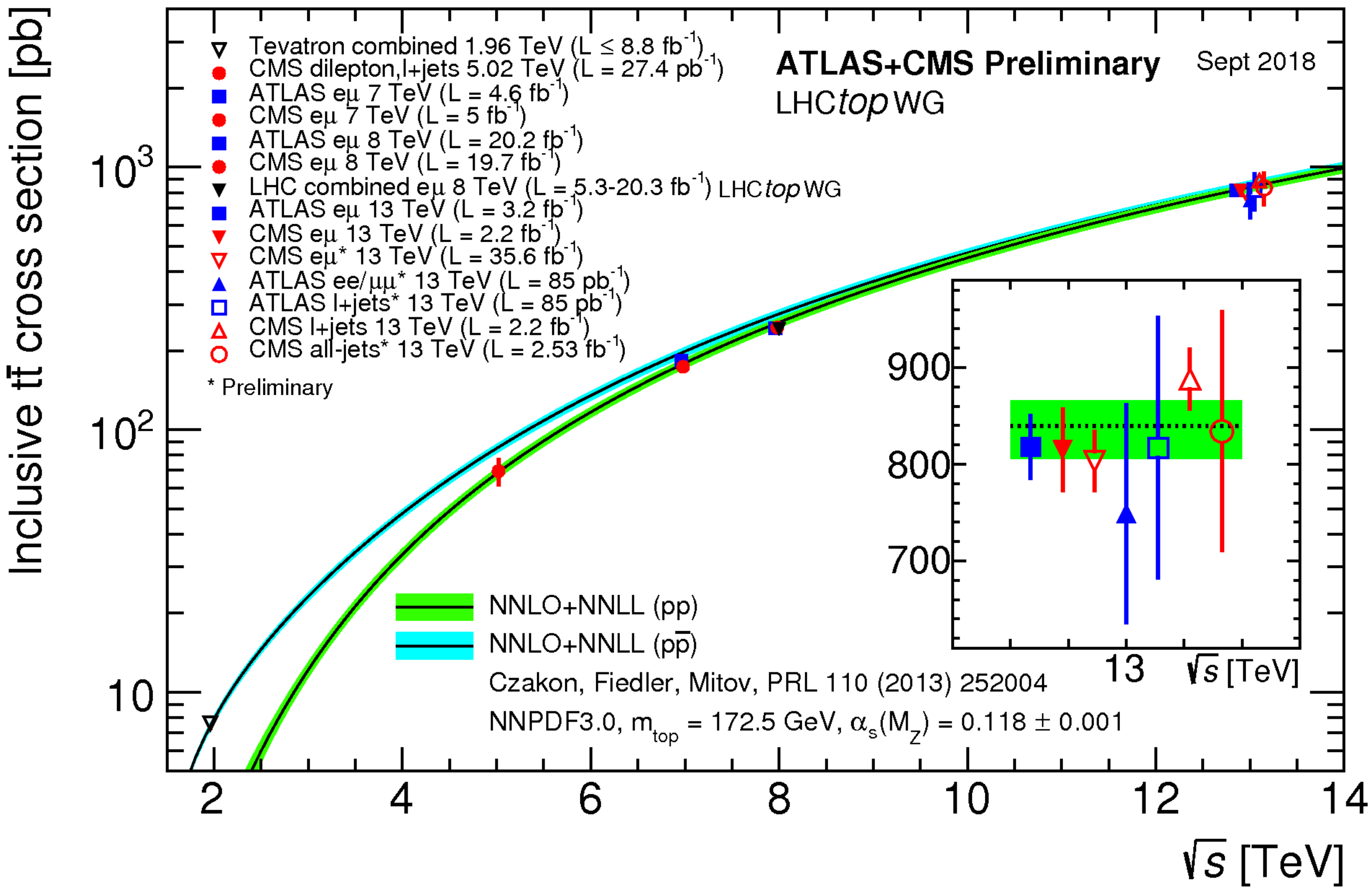


ATLAS: $\sigma_{t\bar{t}} = 825 \pm 49\ \text{(stat)} \pm 60\ \text{(syst)} \pm 83\ \text{(lumi) pb}$

CMS: $\sigma_{t\bar{t}} = 769 \pm 60\,\text{(stat)} \pm 55\,\text{(syst)} \pm 92\,\text{(lumi) pb}$

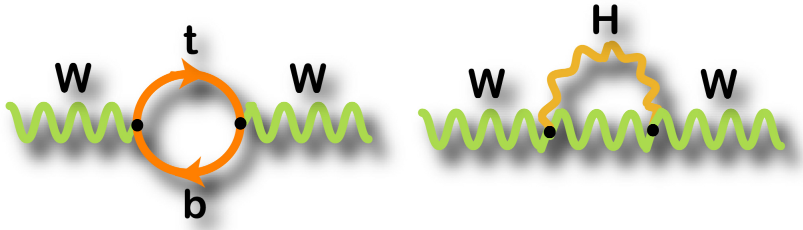
ATLAS: arXiv:1606.02699 *CMS: arXiv 1510.05302*

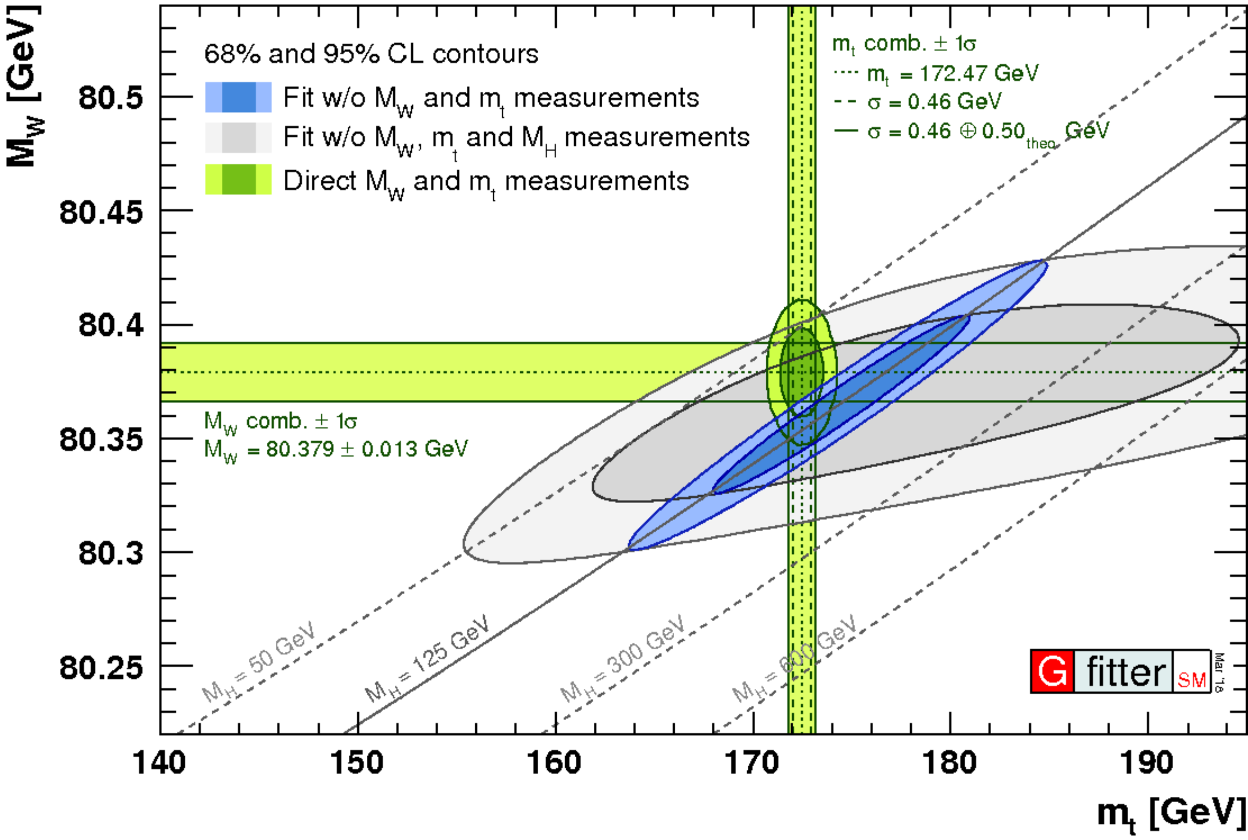
Top pair cross section versus √s



Electroweak Precision Measurements

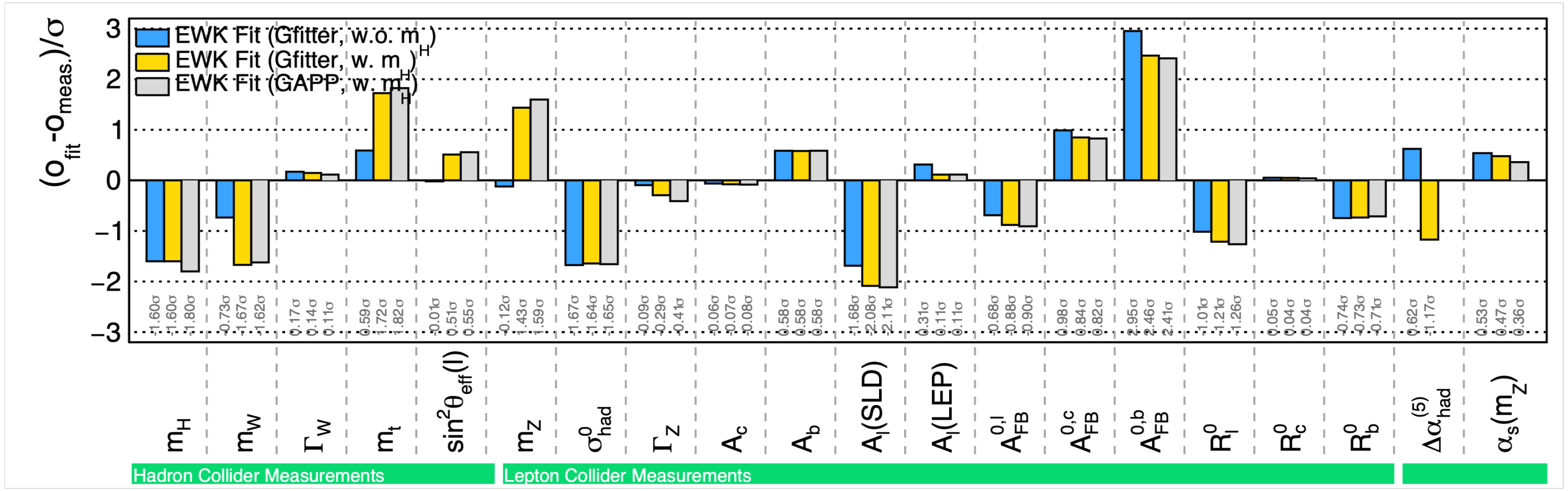
- Top quark is the heaviest known fundamental particle
  - Today: m_{top}=172.47+- 0.46 GeV
  - Is this large mass telling us something about electroweak symmetry breaking?
    - Top yukawa coupling:
    - <H>/(√2 mtop) = 1.0086+-0.0027
  - Theory uncertainty: ~0.5 GeV
- Masses related through radiative corrections:
  - $m_W \sim M_{top}^2$
  - $m_W \sim \ln(m_H)$
- If there are new particles the relation might change:
  - Precision measurement of top quark, W and Z boson masses can reveal new physics

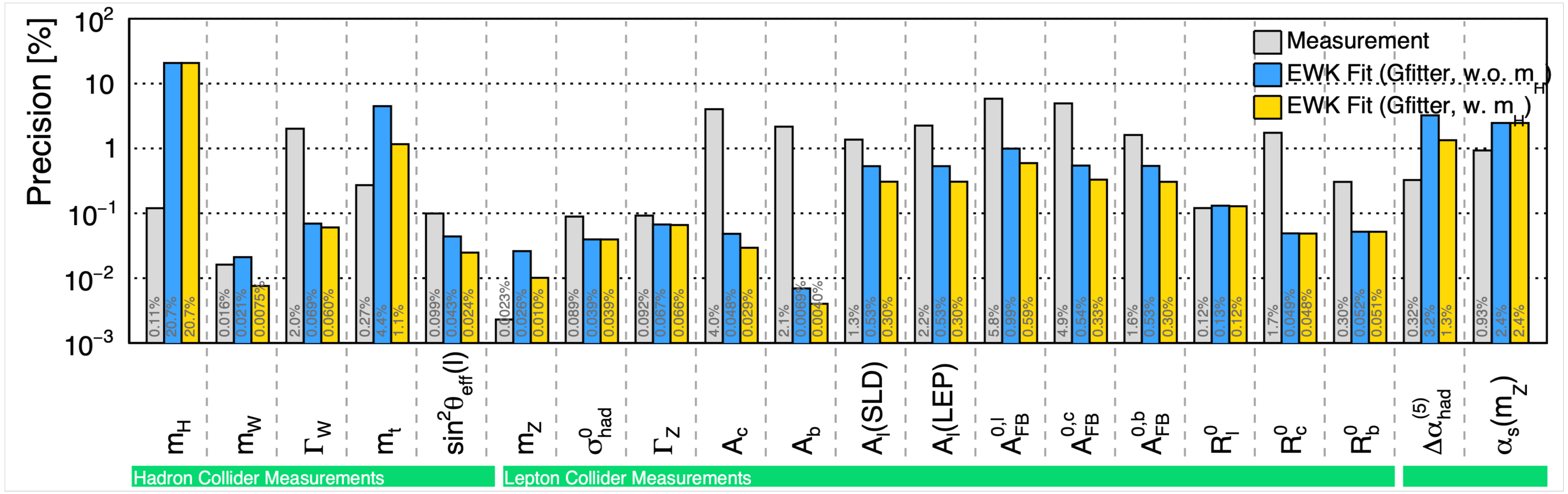




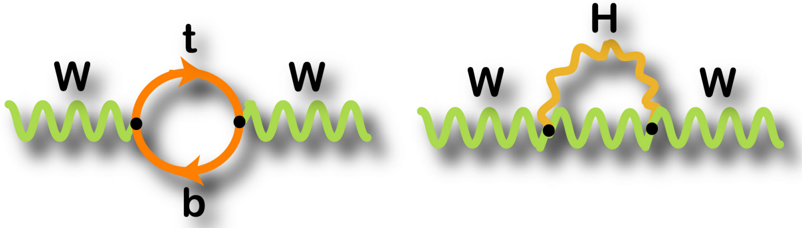
Fit to Electroweak Precision Data

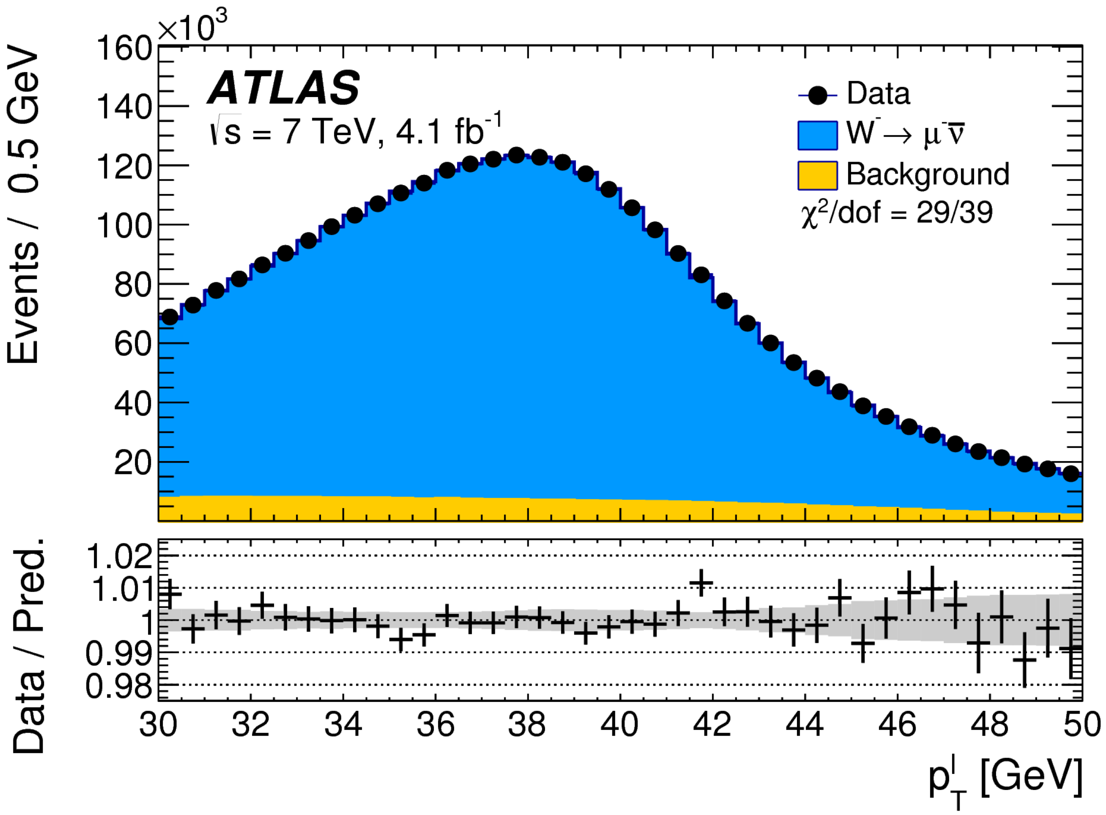
Erler, Schott 2019

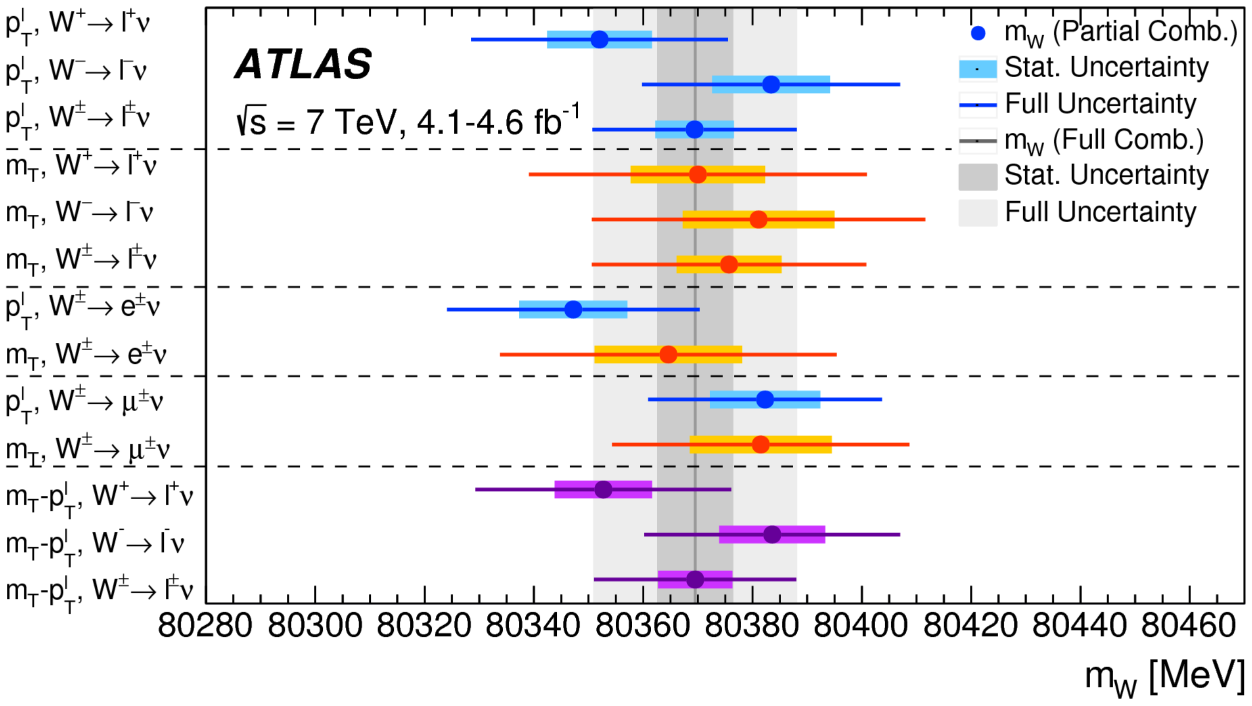




W boson mass



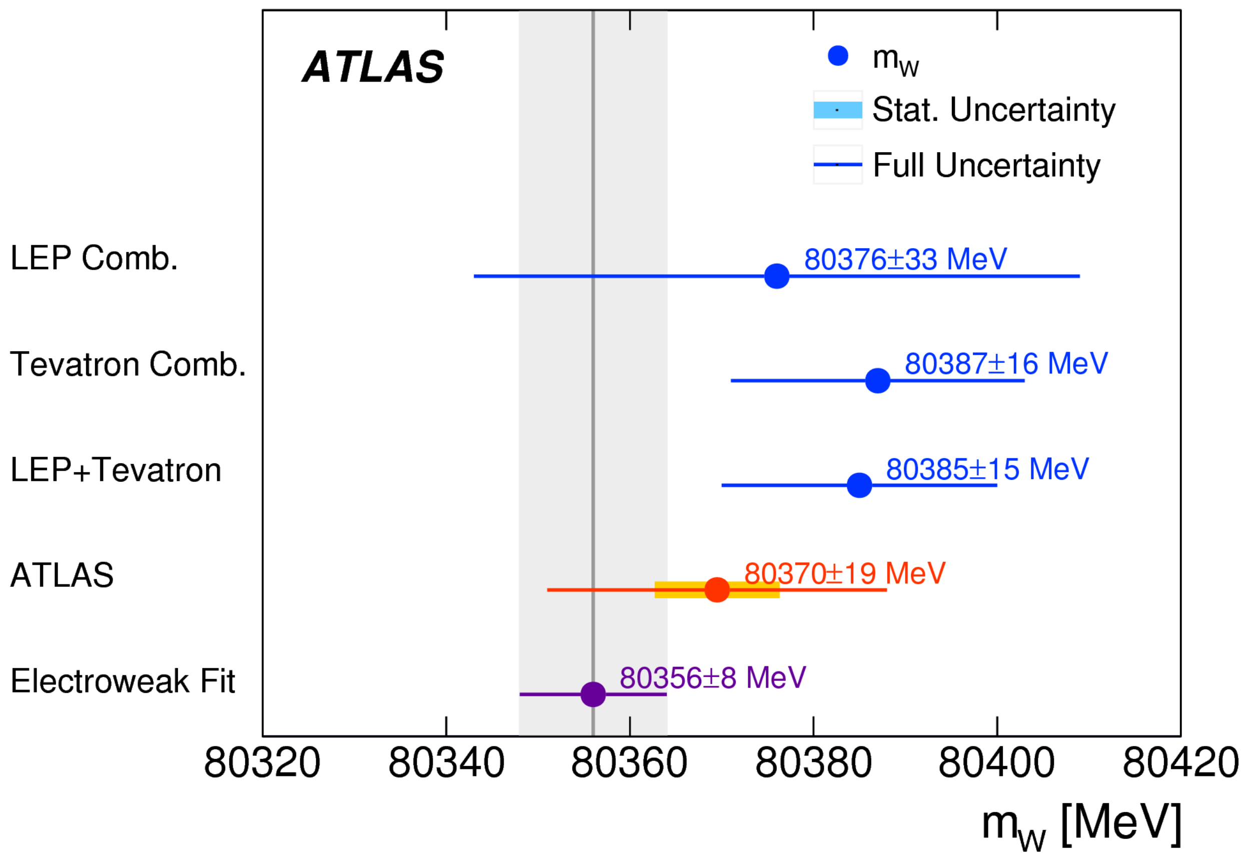




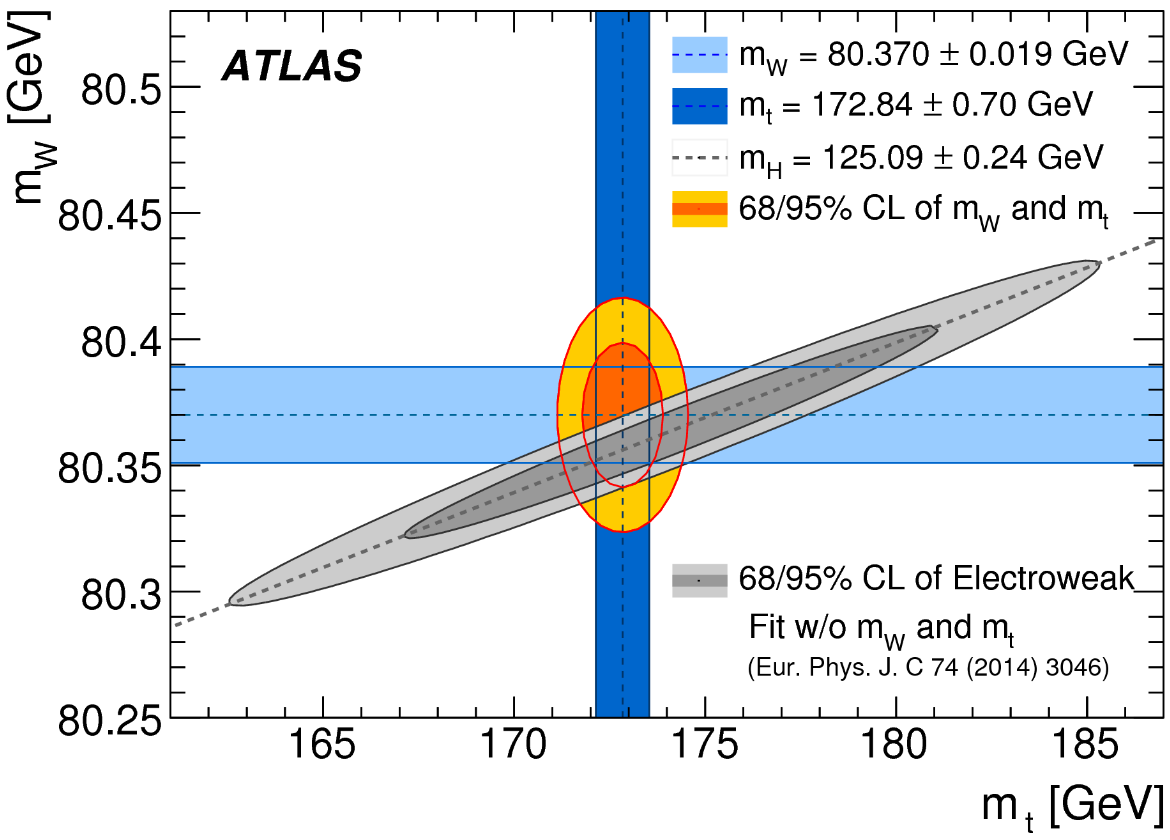
$M_W = 80370 \pm 19$ MeV

arXiv:1701.07240

W boson mass



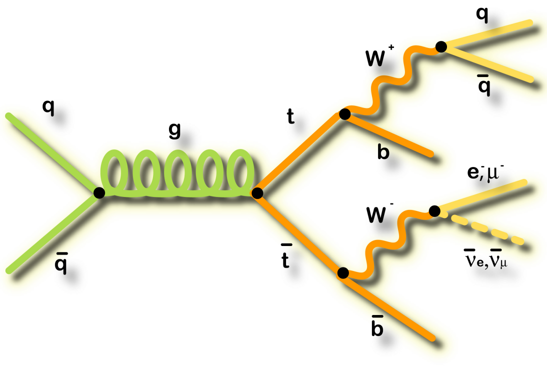
ATLAS
m_W
Stat. Uncertainty
Full Uncertainty
LEP Comb.
80376±33 MeV
Tevatron Comb.
80387±16 MeV
LEP+Tevatron
80385±15 MeV
ATLAS
80370±19 MeV
Electroweak Fit
80356±8 MeV
80320 80340 80360 80380 80400 80420
m_W [MeV]

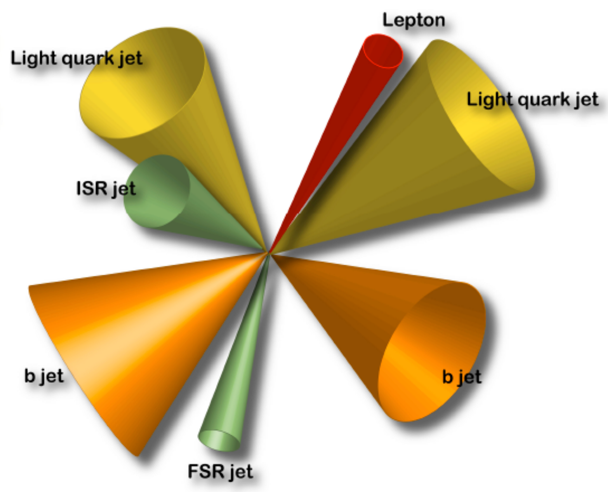


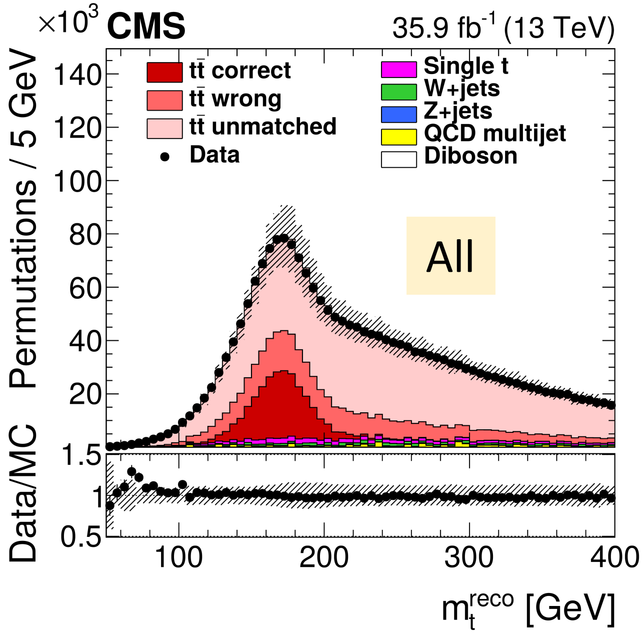
ATLAS
m_W [GeV]
80.5 80.45 80.4 80.35 80.3 80.25
m_W = 80.370 ± 0.019 GeV
m_t = 172.84 ± 0.70 GeV
m_H = 125.09 ± 0.24 GeV
68/95% CL of m_W and m_t
68/95% CL of Electroweak
Fit w/o m_W and m_t
(Eur. Phys. J. C 74 (2014) 3046)
165 170 175 180 185
m_t [GeV]

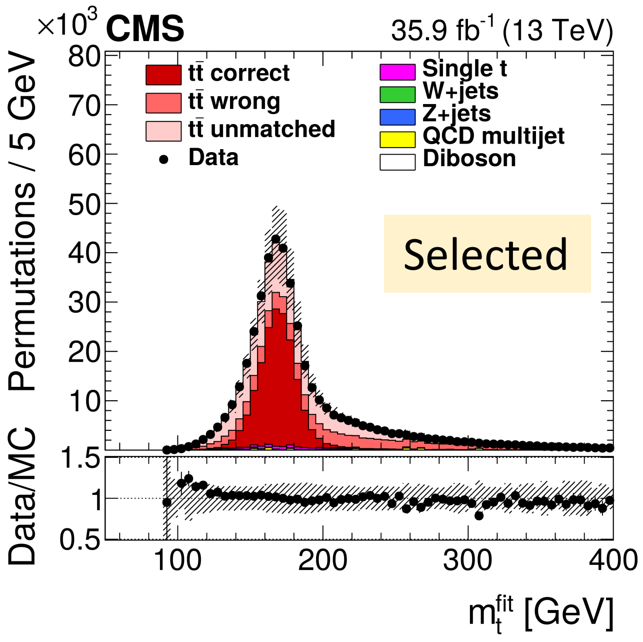
Top Quark Mass measurement

- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag => 6 combinations
  - 0 b-tags =>12 combinations
- Two Strategies:
  - Template method (traditional):
    - Uses “best” combination
    - Chi2 fit requires m(t)=m(t)
  - Advanced methods:
    - Use all combinations
    - Assign probability depending on kinematic consistency with top hypothesis
- Key challenge experimentally:
  - control systematic uncertainties due to jet measurement systematics

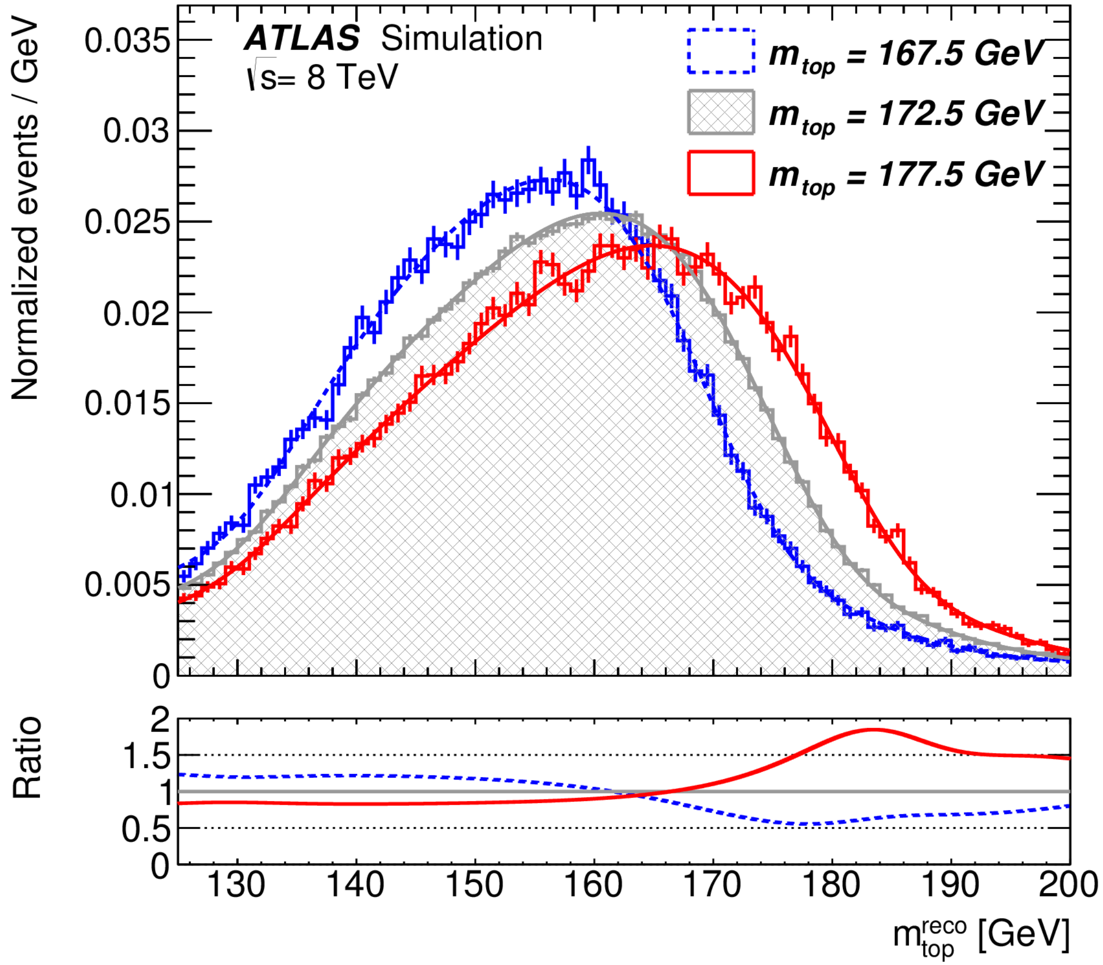


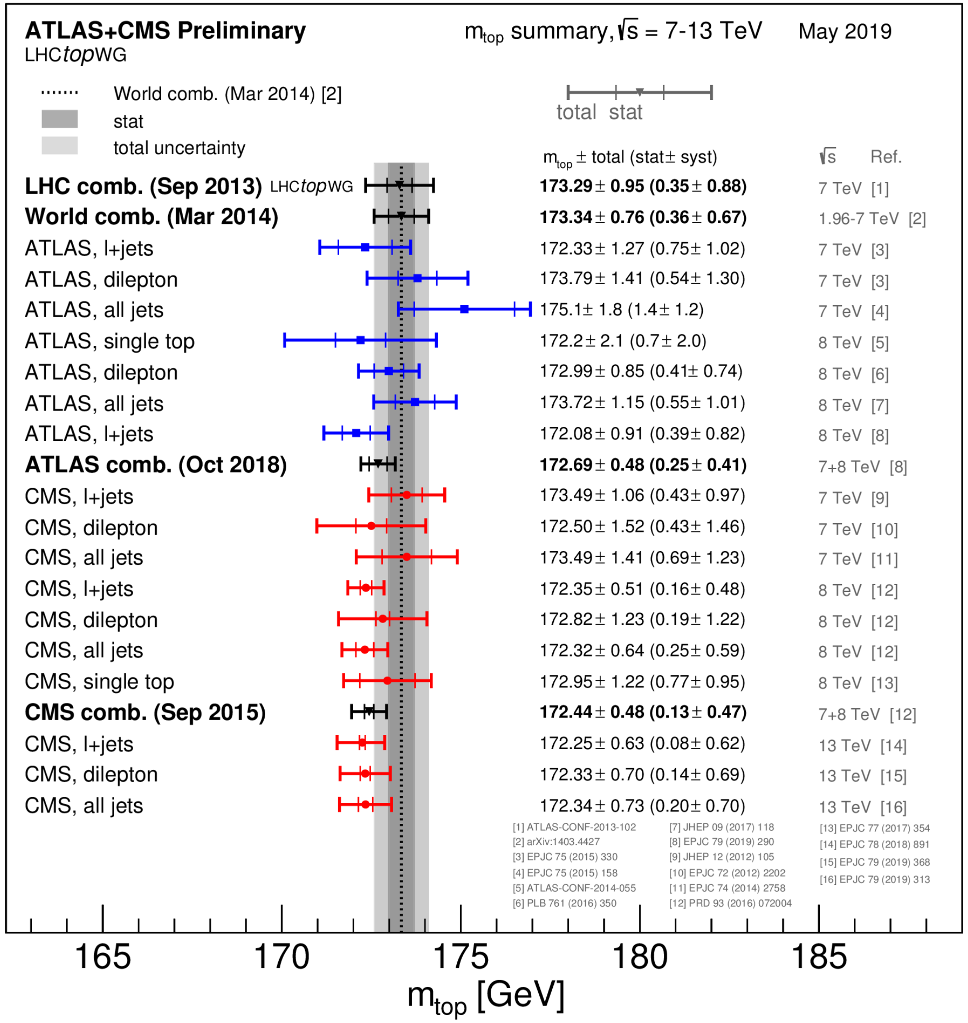




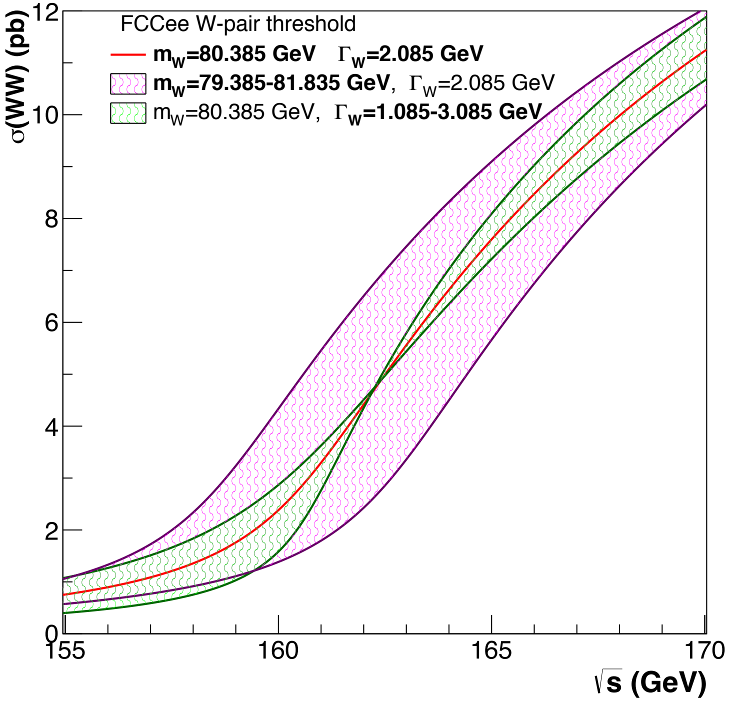


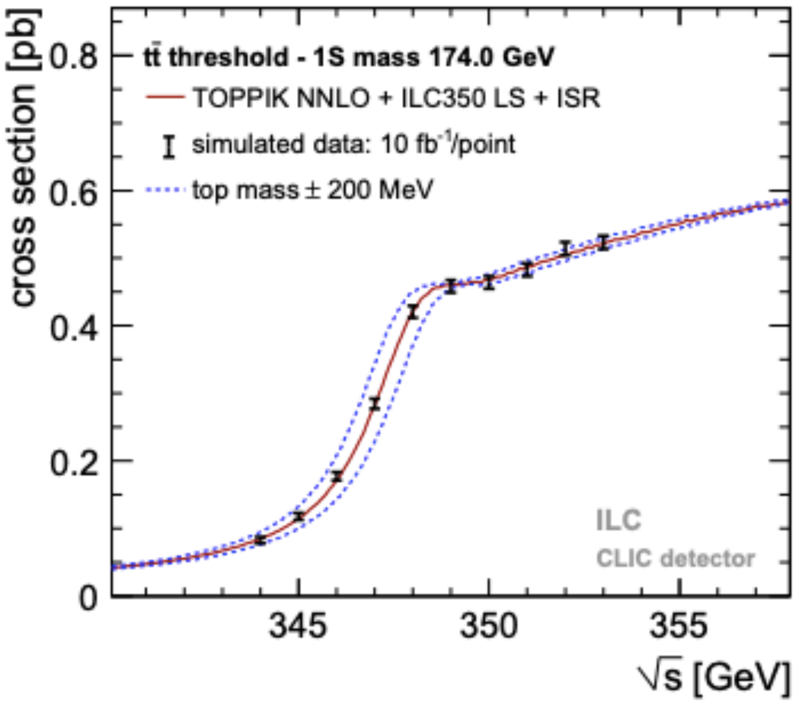
Top mass measurement: LHC

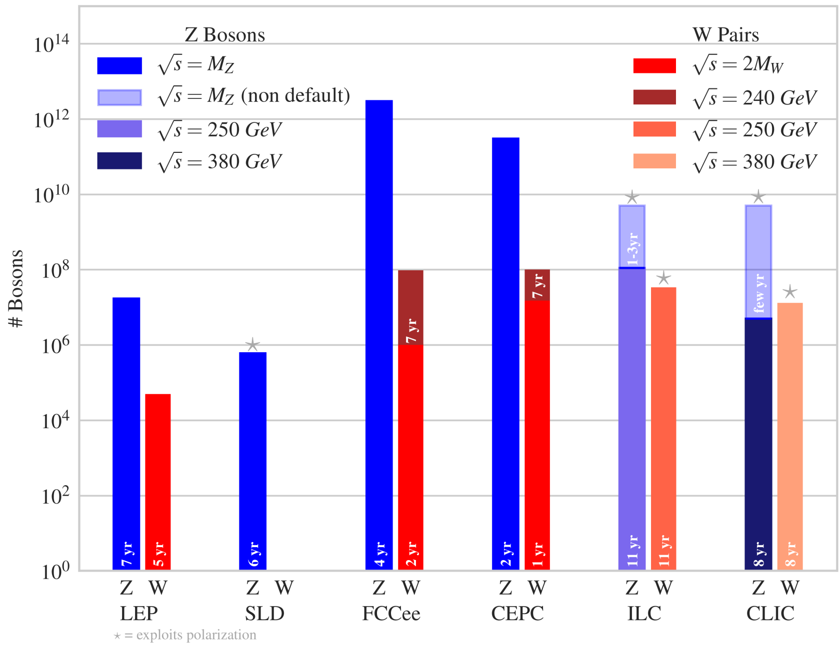




Future Colliders: W, Z and top

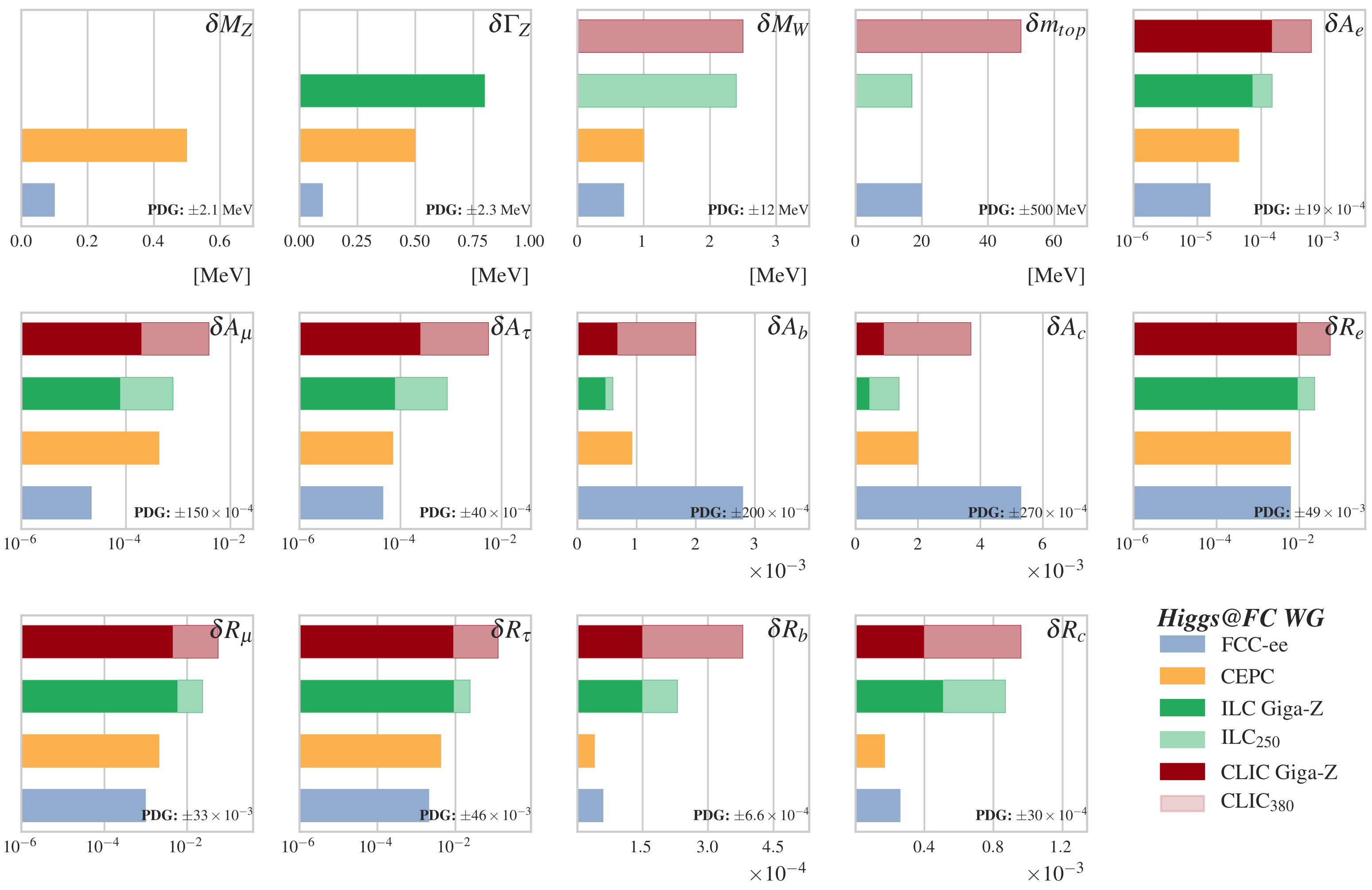






- Measure W and top masses from threshold scan
  - Requires $\sqrt{s} \sim 2M$: ~160 GeV for W and ~350 GeV for top
  - Advantage: measured top mass is the pole mass
- High precision Z programmes foreseen
  - At circular colliders: 10^{12} Z's!

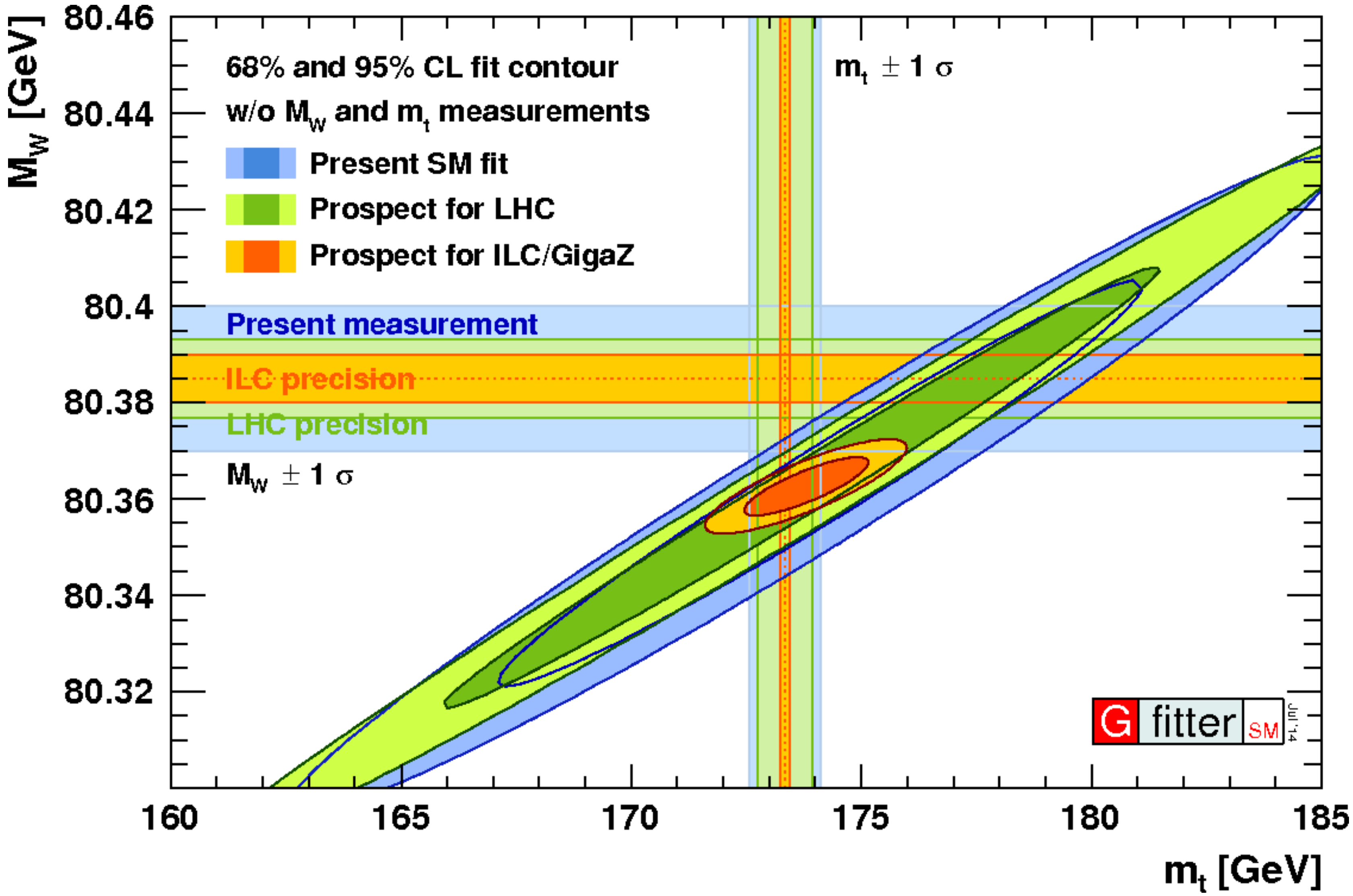
Future Prospects: Electroweak Observables



	Precision [MeV]	
particle	Now	Future
W	12	1-3
Z	2.1	0.1-0.5
top	500	20-50

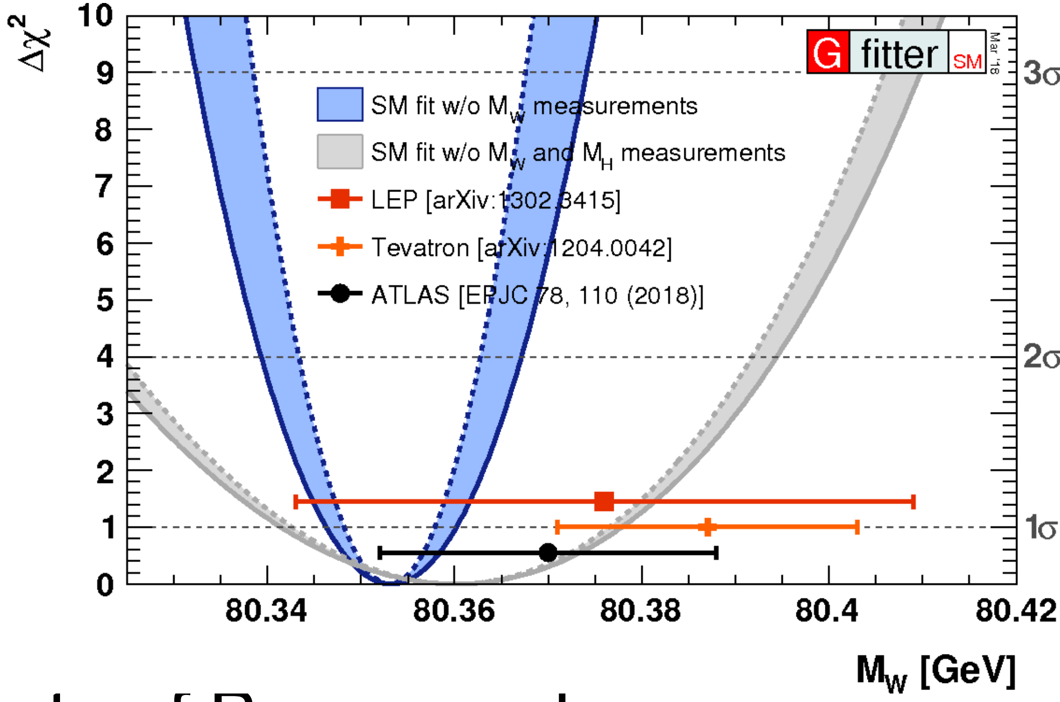
- Future e+e- colliders improve by ~10 compared to current precision

Future Prospects: Electroweak Fit



Conclusion from Lecture I

- Perturbative QCD describes hadron collider data successfully:
  - Jet cross sections: $\Delta\sigma/\sigma \approx$ 20-100%
  - W/Z cross section: $\Delta\sigma/\sigma \approx$ 2%
  - Top cross section: $\Delta\sigma/\sigma \approx$ 4%
- High Precision measurements
  - W boson mass: $\Delta M_W/M_W$ =0.015%
  - top quark mass: $\Delta m_{top}/m_{top}$=0.29%
  - HL-LHC should improve by ~factor 2
  - Factor ~10 expected from future e+e- colliders



- Interesting anomalies in lepton flavour aspects of B-meson decays
- Standard Model works very well!
  - Tomorrow: Higgs boson, flavor and direct searches

Backup Slides

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CChh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CCee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 – (40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LCee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8- 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

A. Yamamoto, 190513b

*Cost estimates are commonly for "**Value**" (material) only.

ee and pp colliders:

Personal (A. Yamamoto) View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collider (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D		Proto/Pre-series	Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

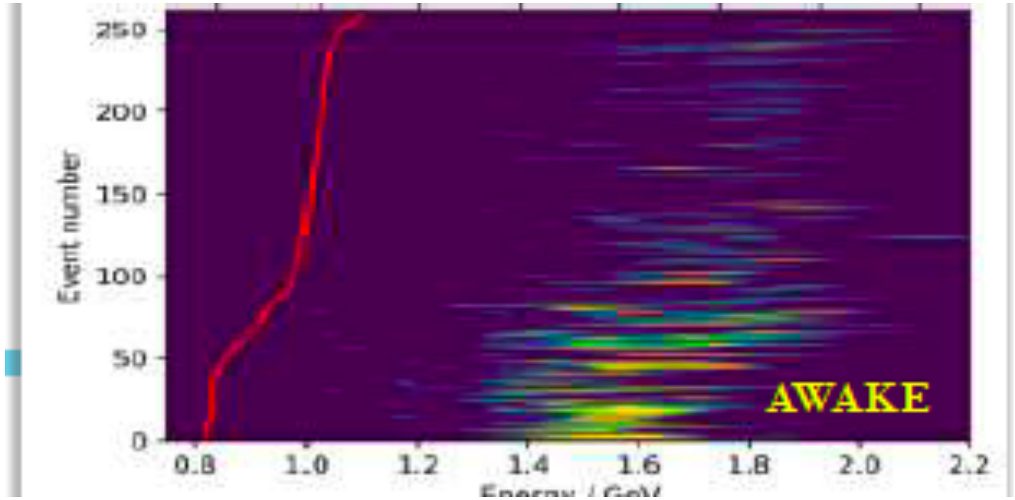
Note: **LHC experience**: **NbTi (10 T)** R&D started in 1980's --> **(8.3 T)** Production started in late 1990's, in **~ 15 years**

pp collider schedule depends critically on progress in high field magnet R&D

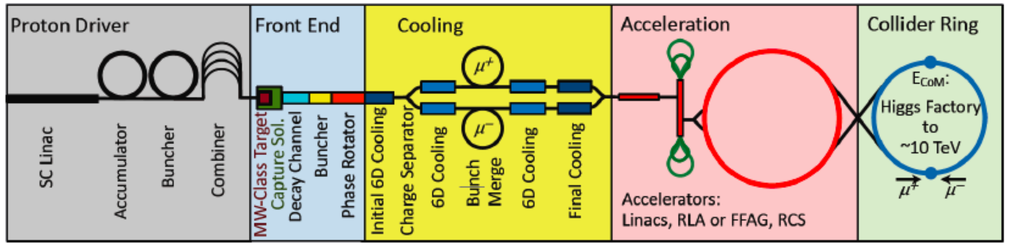
Further (Far?) Future

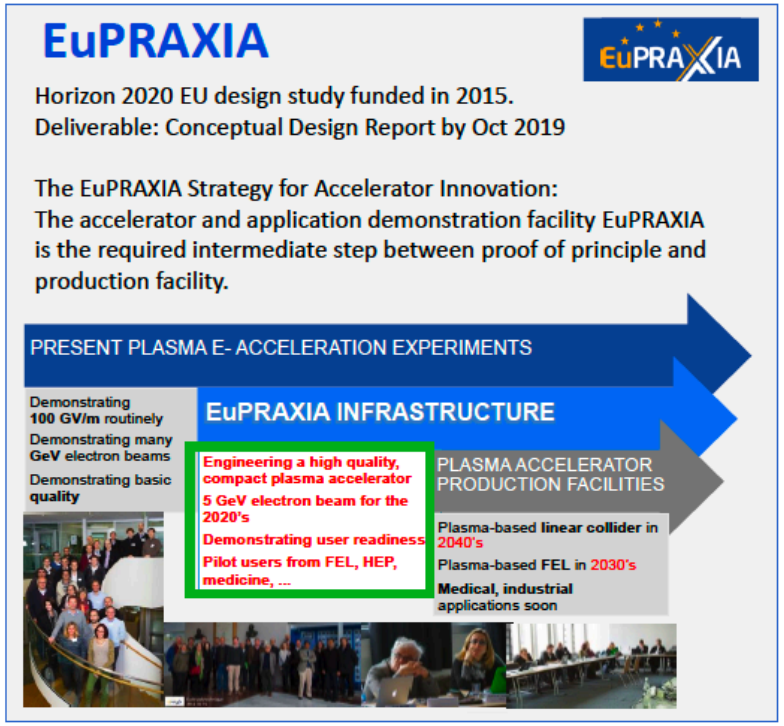
Very interesting R&D projects

- Muon collider:
  - from proton beam (rcooling success: MICE)
  - from e+e- production (LEMMA)
- Plasma wakefield acceleration:
  - High gradients possible: ~100 GV/m
  - R&D progressing well but many challenges



Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.





Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

LHC power: 150 MW

of "largely" improved H couplings (EFT)

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2nd/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
2nd/3rd Run ee	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

13 quantities in total

NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7