Models and Methods for Beyond Standard Model Physics at colliders

Lectures for the Ph.D. Program in Physics, XXXVI Cycle

12/04/2021

Vieri Candelise
University of Trieste

Introduction

topical lecture on modern LHC physics
and modern statistical method for HEP

Part I: Basics of LHC Physics and Experimental Standard Model — 2+2h

Part II: Higgs Phenomenology and discovery @LHC — 2h

Part III: Advanced Statistical Methods — 2h

Part IV: Beyond SM: Models & Methods @ colliders — 2h

Part V - Invited Lecture 1: *New approaches in searches for new physics at the LHC: machine learning to enable discoveries* (by Jennifer Ngadiuba, CERN fellow and Caltech researcher) — 2h

Part VI - Invited Lecture 2: *Take a walk on the Dark Side: chasing Dark Matter in the 2020s* (by Valerio Ippolito, INFN Staff and former Harvard researcher) — 2h

Examination

Final Exam: *Presentation and discussion of a recent experimental search or measurement with emphasis on the physical modeling and statistical treatment*

I will provide you a list of recent measurement (but it's not mandatory to pick one up from it)

dates: TBC

updated material & more:

https://wwwusers.ts.infn.it/~candelis/Vieri/#teach

Chapter I (1)

Fundamentals of LHC Physics

[duration: 2h]

What's interesting about the Standard Model in the 20s?

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
&+ i\bar{\Psi}\not{D}\psi \\
&+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\
&+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.
\end{aligned}
$$

photons

fermions+
vector bosons

higgs

gluons

"THE STANDARD MODEL LAGRANGIAN, THE MASTER FORMULA ABOUT HOW EVERYTHING WORKS!" (*)

(*) cfr. pub discussion between drunk big bang theory nerds

What's interesting about the Standard Model in the 20s?

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\psi \\ & + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ & + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.\end{aligned}$$

photons

fermions+ vector bosons

higgs

gluons

REALITY:

THIS IS THE LAGRANGIAN OF THE 5% OF THE UNIVERSE

What's interesting about the Standard Model in the 20s?

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

photons

$$+ i\bar{\Psi}\not{D}\psi$$

fermions+ vector bosons

higgs

$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi)$$

$$+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

gluons

WITHOUT GRAVITY

What's interesting about the Standard Model in the 20s?

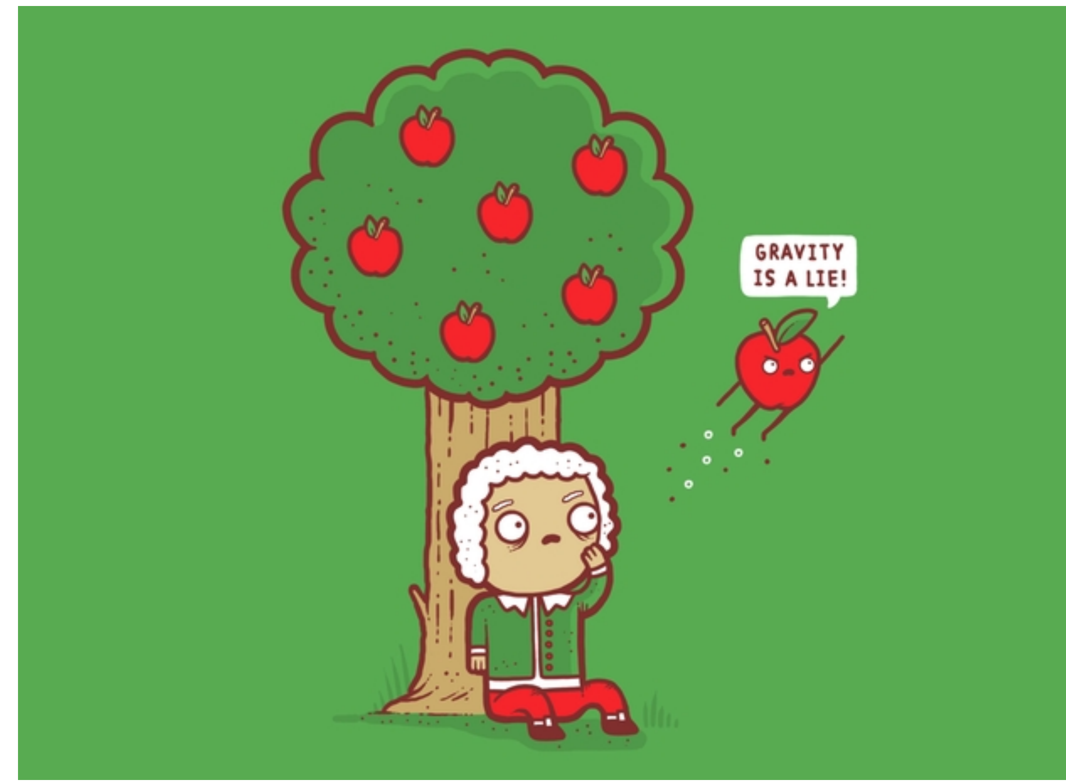
$$
\begin{aligned}
\mathcal{L} = &- \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
&+ i\bar{\Psi} \not{D} \psi \\
&+ D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi) \\
&+ \bar{\Psi}_L \hat{Y} \Phi \Psi_R + h.c.
\end{aligned}
$$

photons

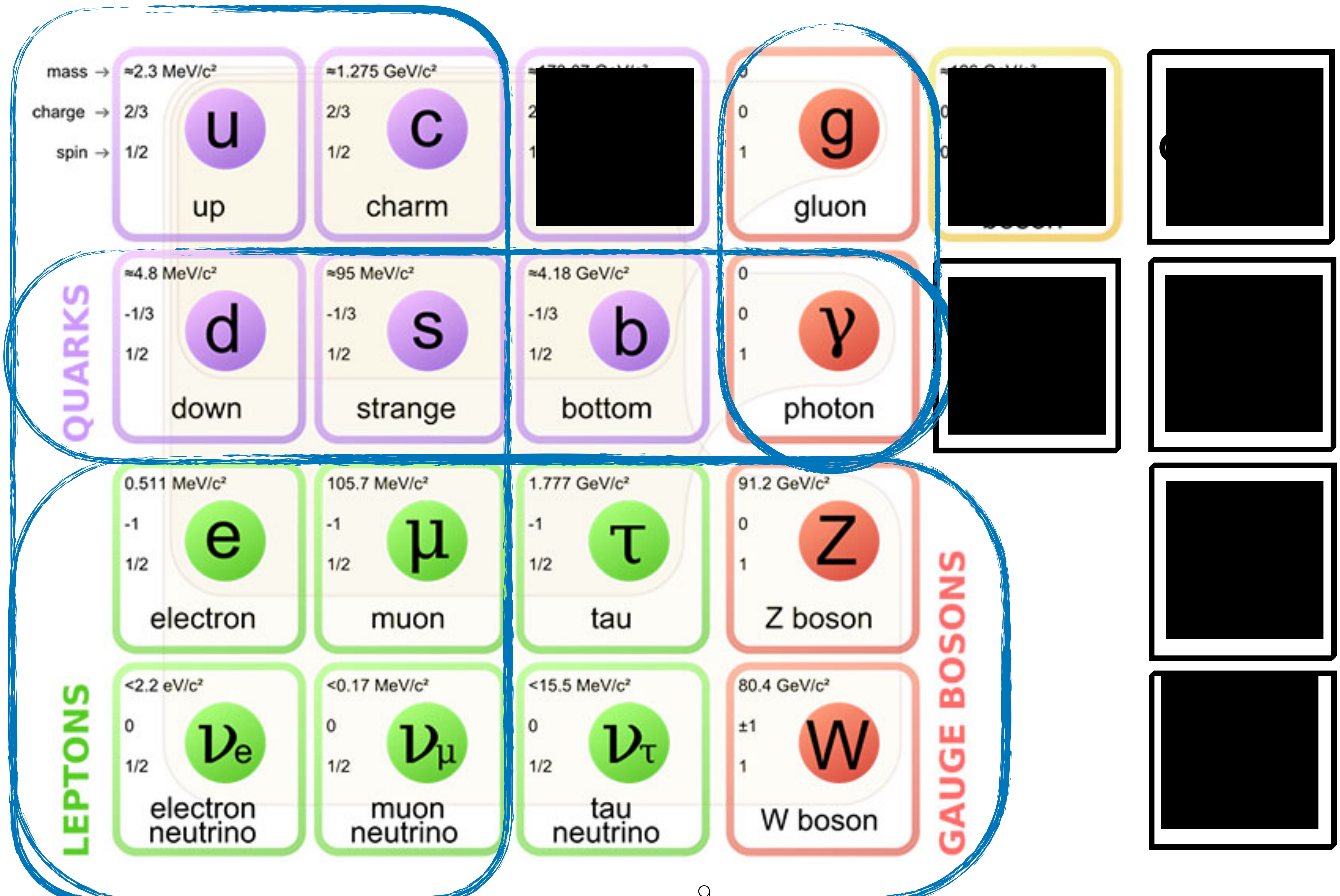
fermions+
vector bosons

higgs

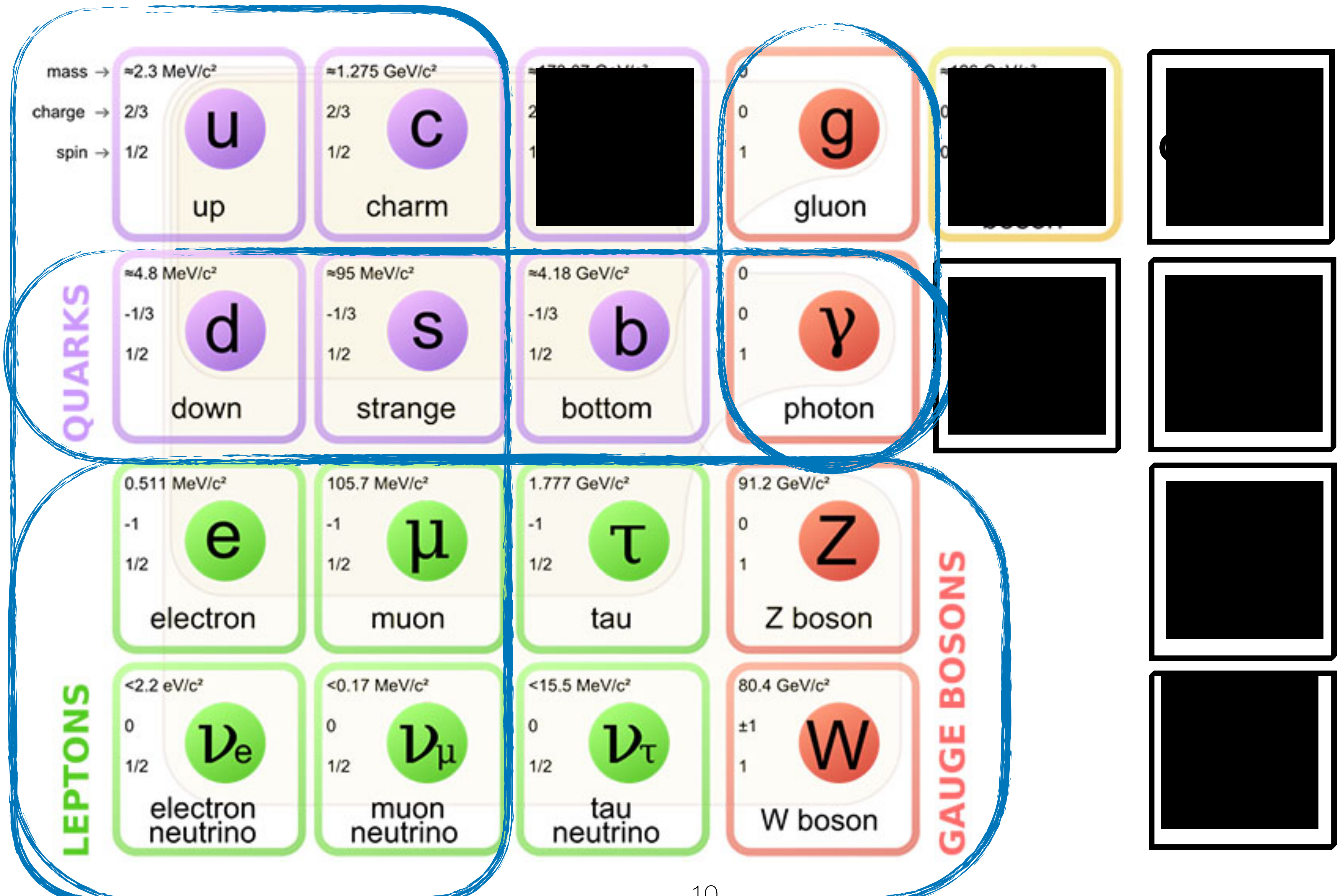
gluons



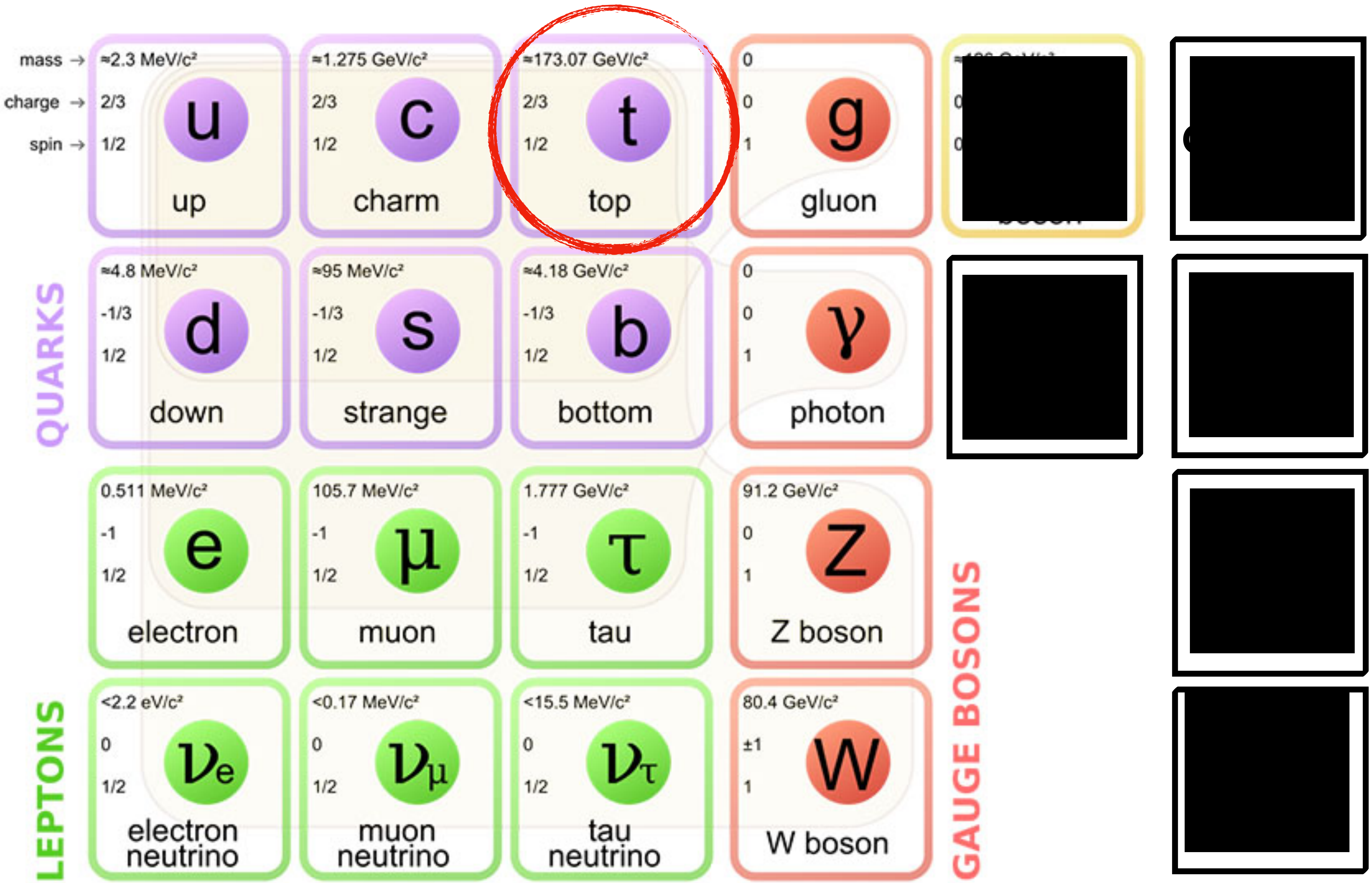
What's interesting about the Standard Model in the 20s?



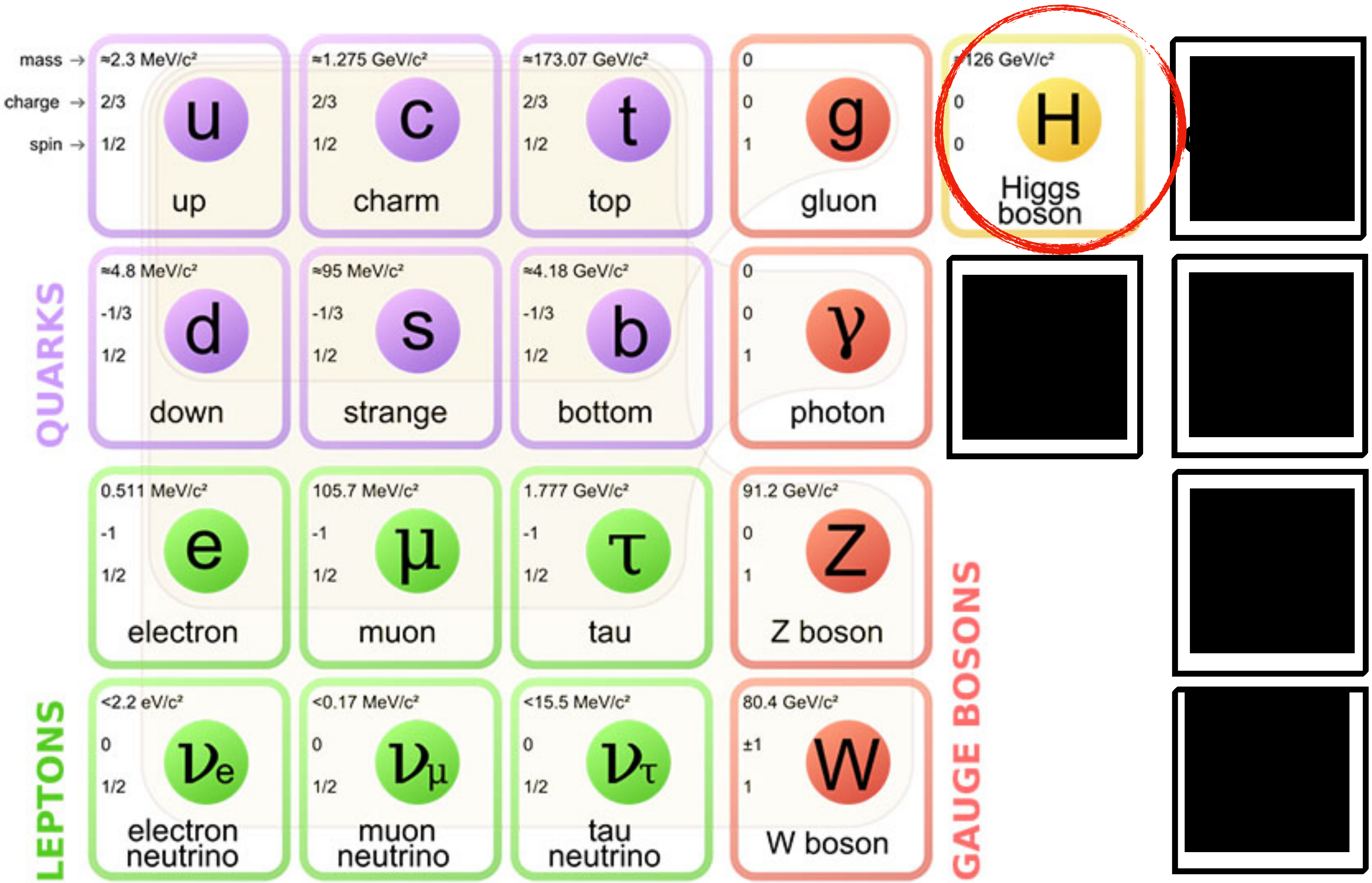
The *old* stuff: HEP from the ‘60s to the ‘90s



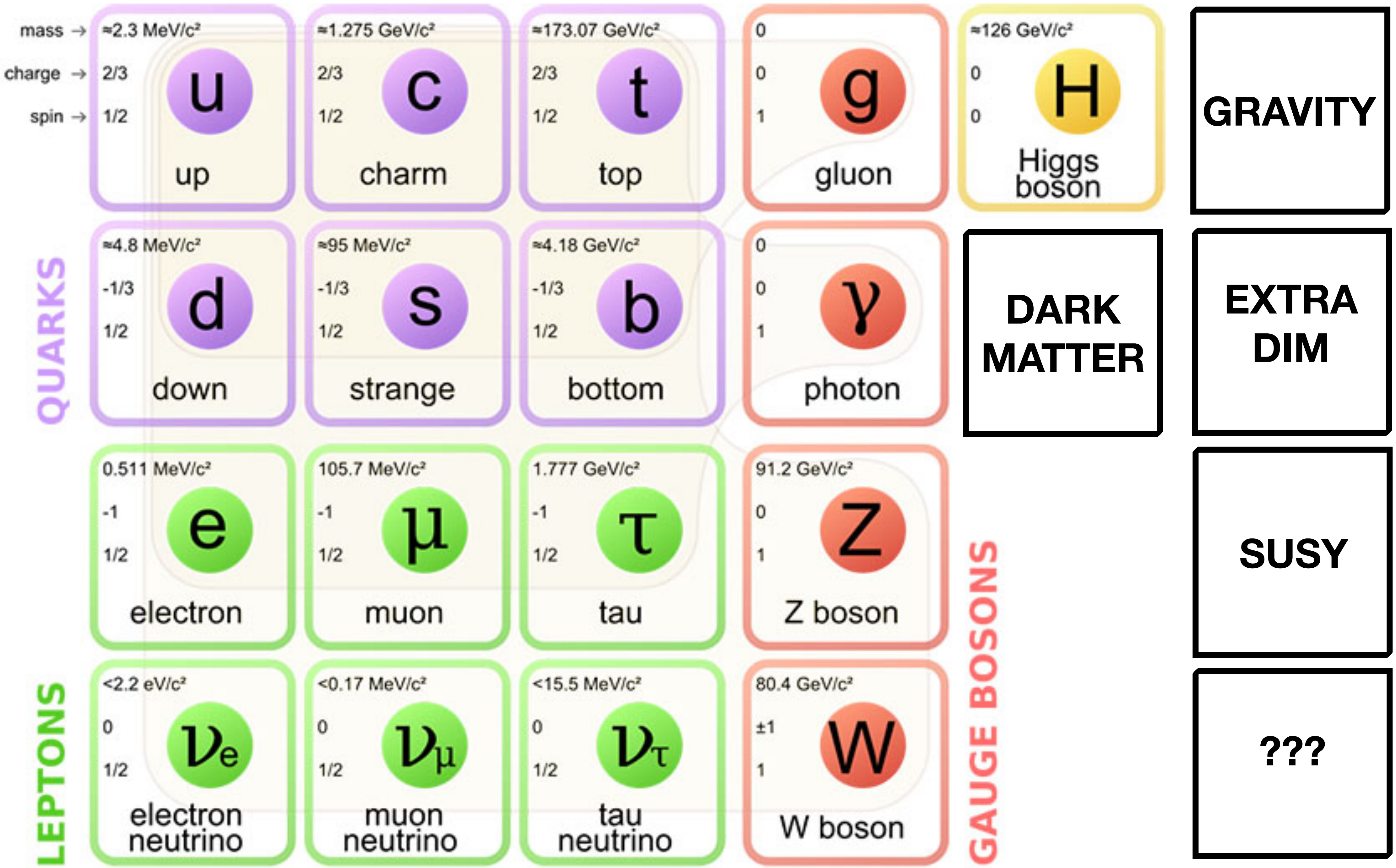
discovery: 1995 @ Fermilab



discovery: 2012 @ CERN



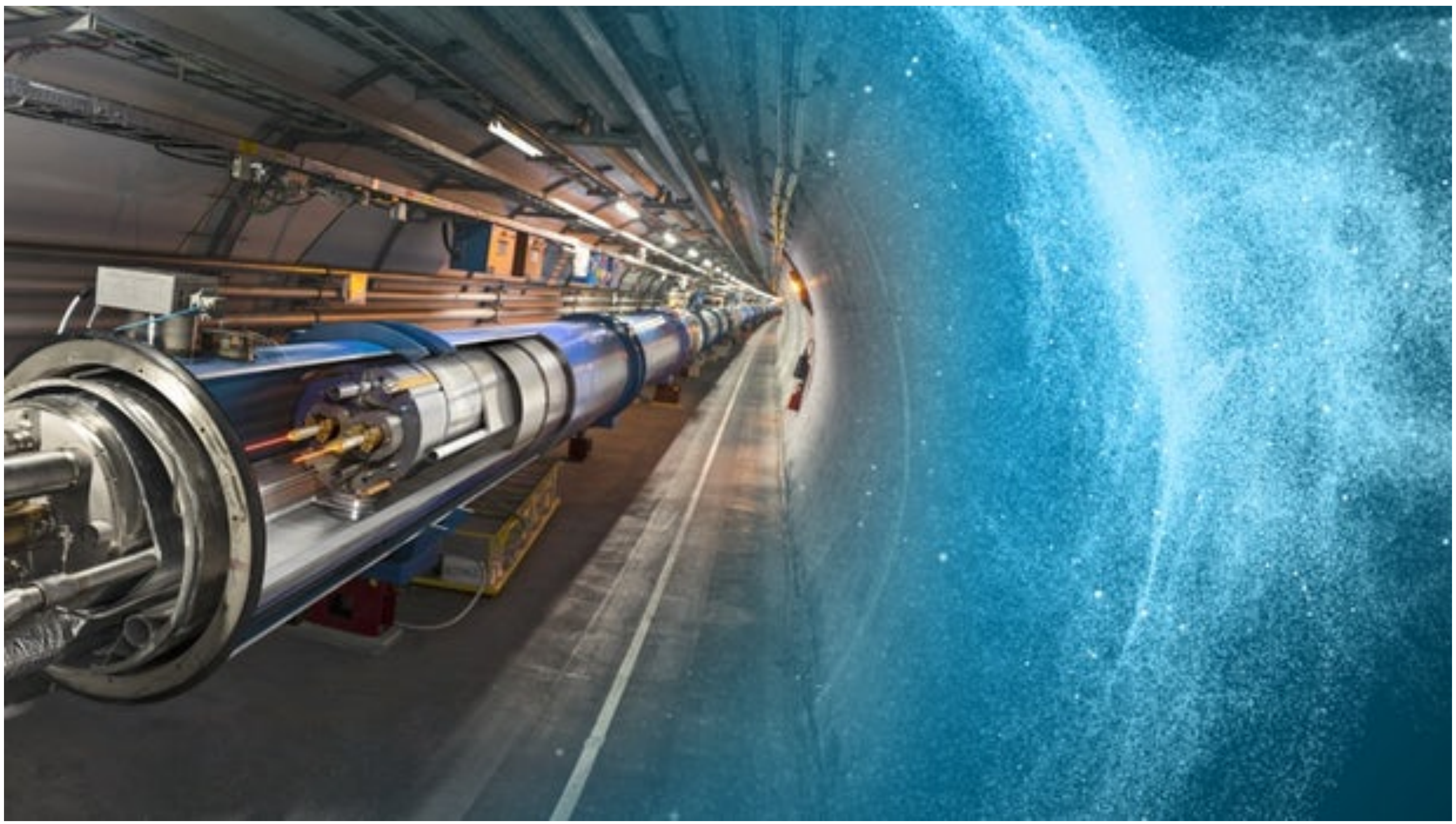
and now???


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
GRAVITY
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
DARK MATTER
EXTRA DIM
QUARKS
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
SUSY
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
???
LEPTONS
GAUGE BOSONS

How do we do that

- we need a collider

hadron colliders: for discovery (*brute force aka energy frontier*)
lepton colliders: for precision (*needle and thread aka intensity frontier*)



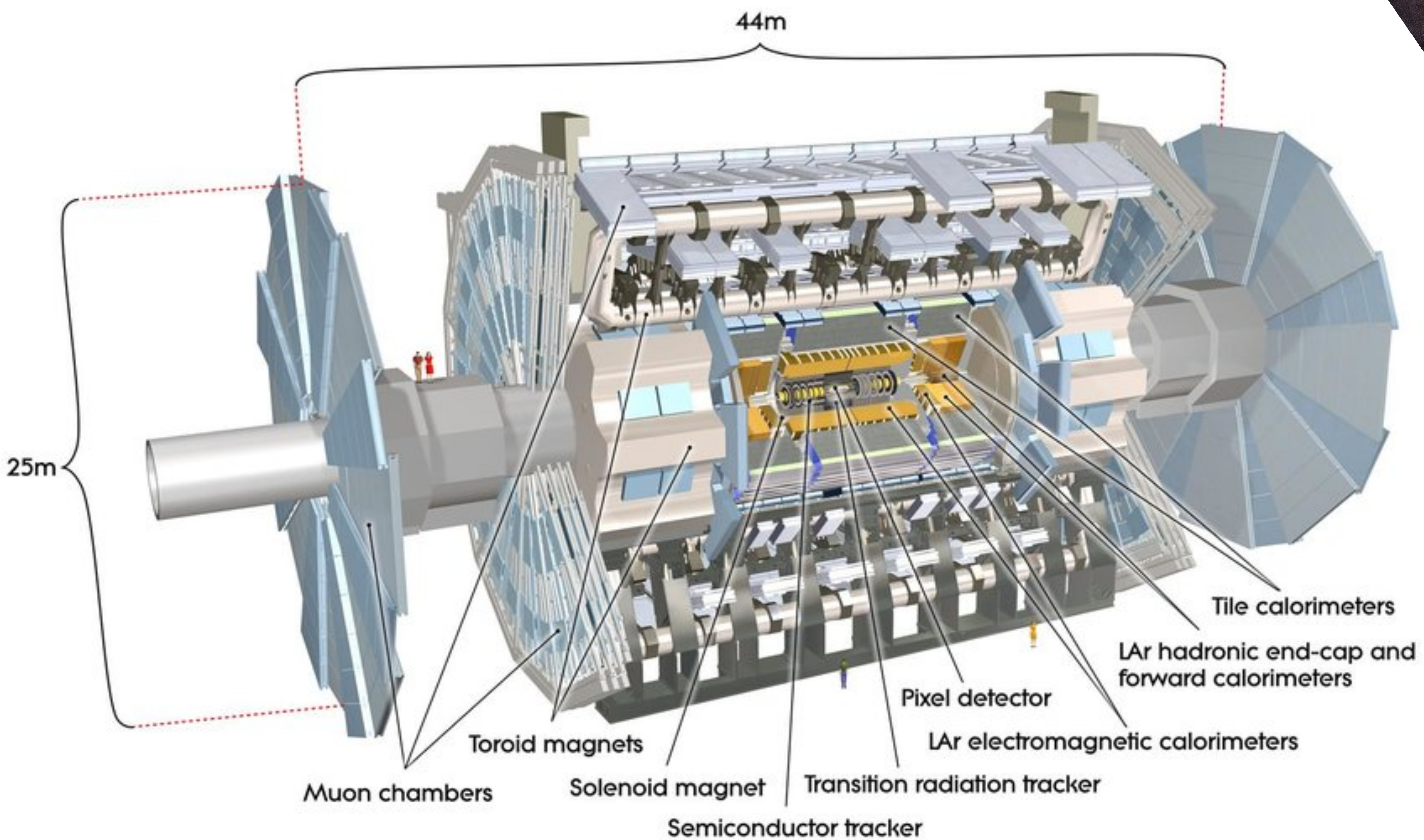
(The Large Hadron Collider, LHC)

@CERN

How do we do that

- we need experiments

multi-purpose (discover anything, see *brute-force*)



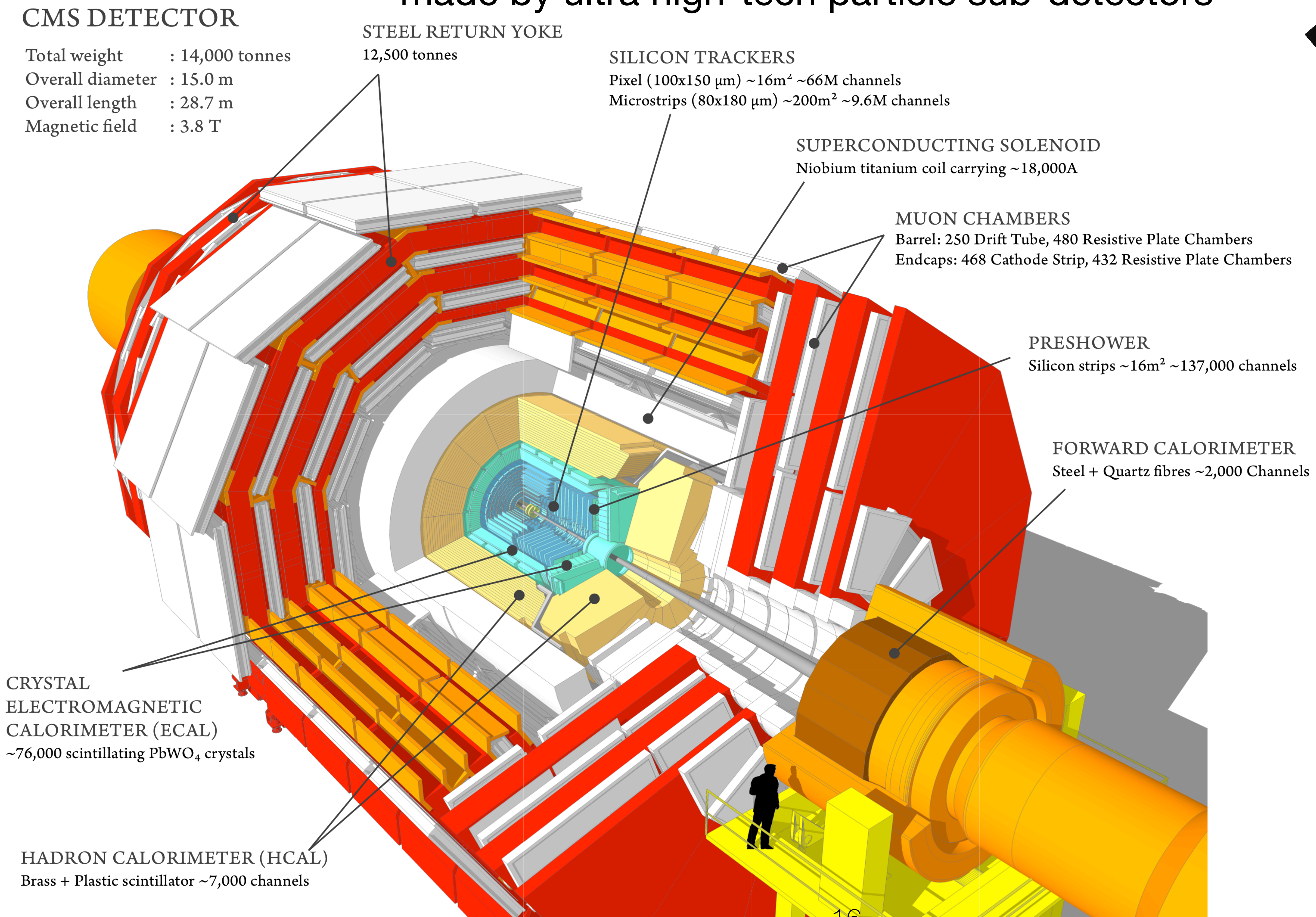
Galileo

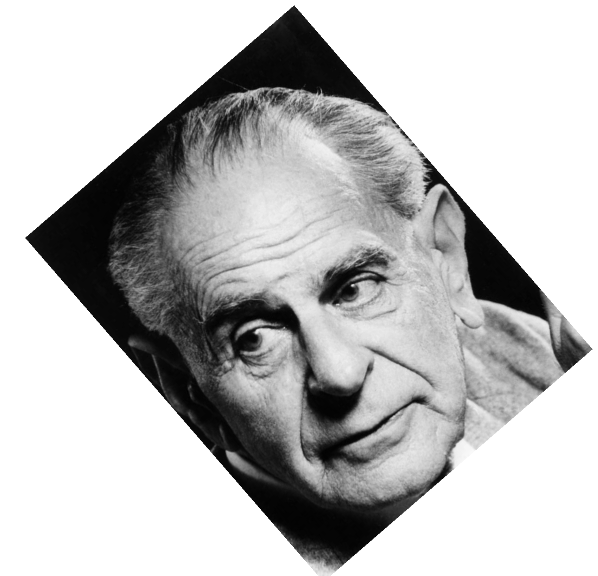
ATLAS

How do we do that

- we need experiments

made by ultra high-tech particle sub-detectors



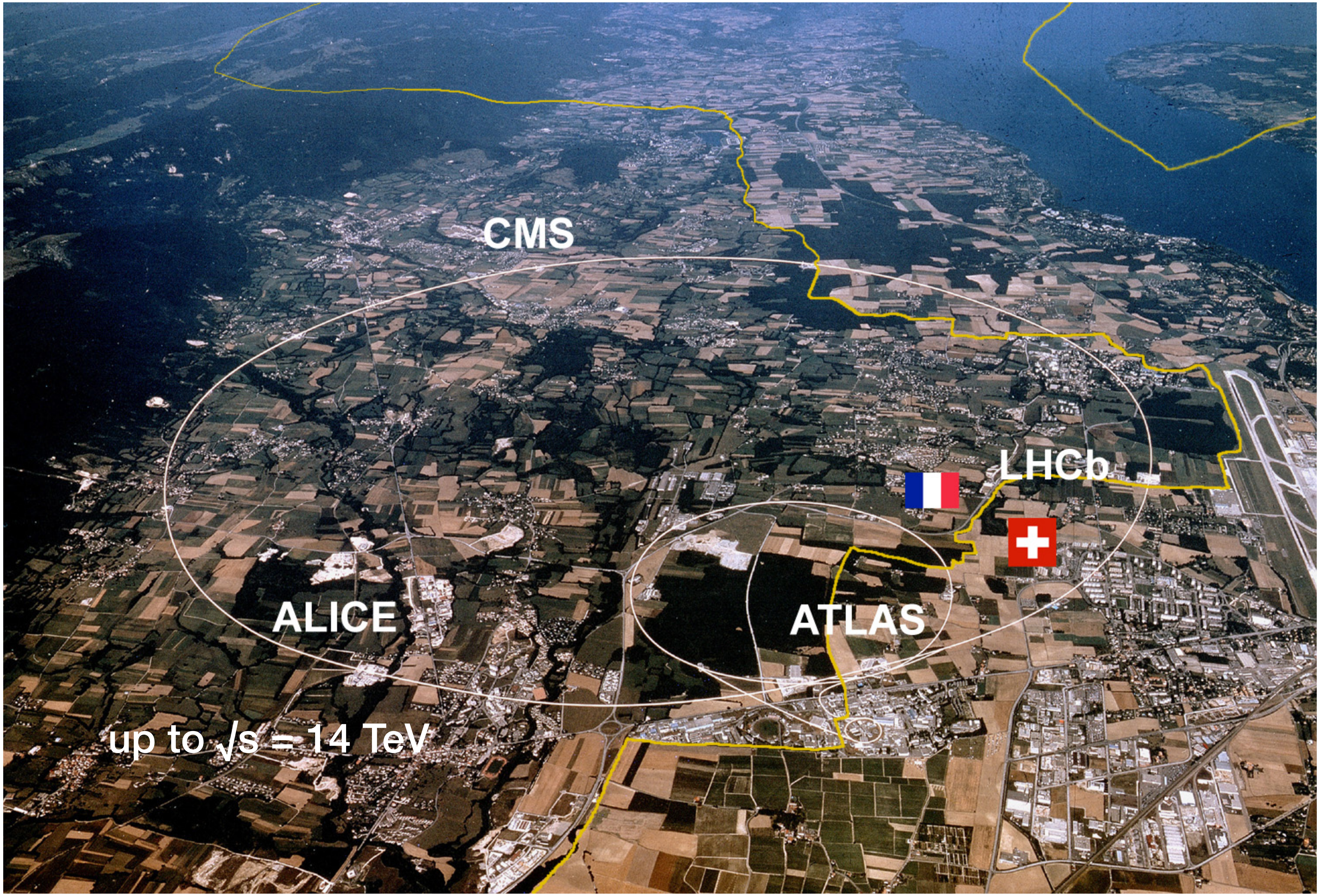


popper

CMS

How do we do that

Accelerates and collides proton beams at the highest center-of-mass energies



(The Large Hadron Collider)

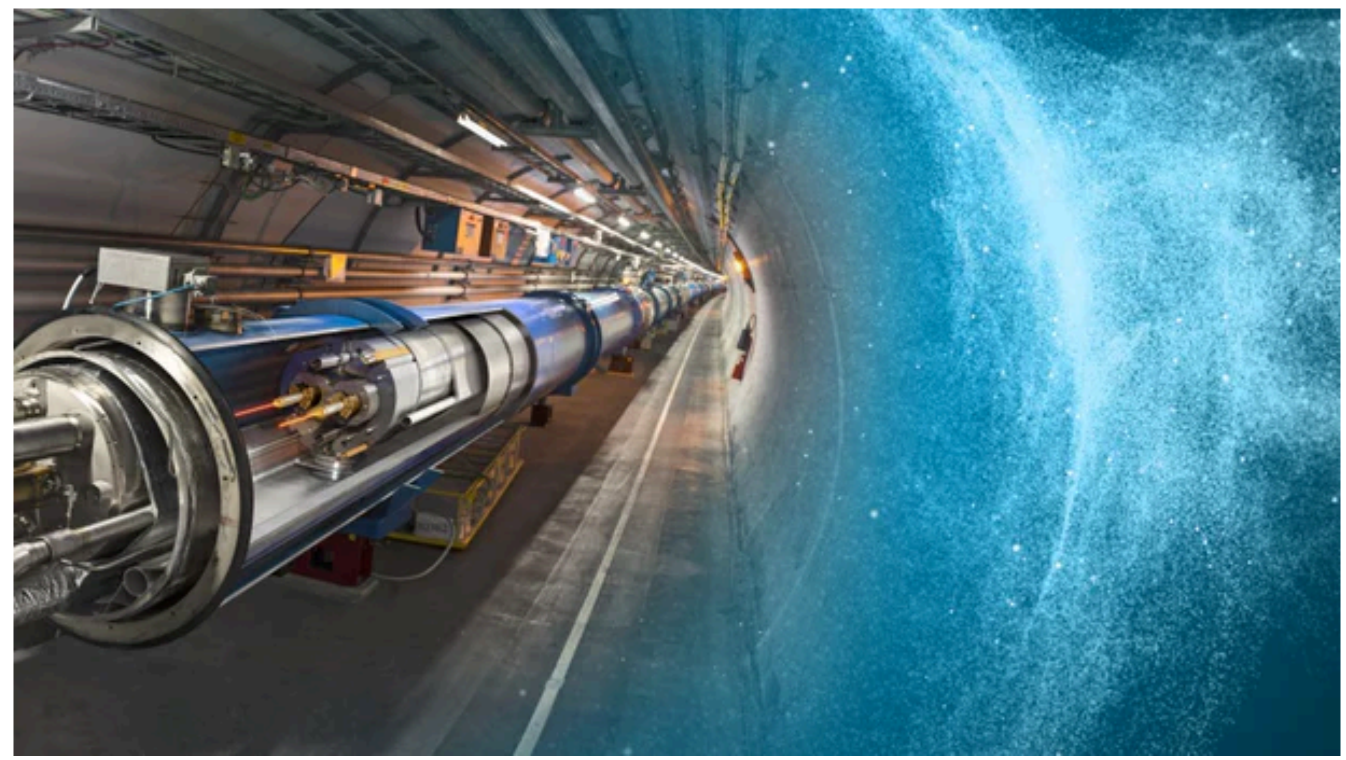
@CERN

How do we do that

- 27 km underground tunnel Design Characteristics
- 1232 superconducting dipole magnets cooled at 1.9 K
- Bending magnet field of 8.3 T = 14 TeV $\sqrt{s}$ L(peak) = 10^{34} cm^{-2} s^{-1}

Today:

- center of mass energy: 13 TeV
- Integrated luminosity in ATLAS and CMS: ~140/fb (full Run2)



(The Large Hadron Collider)

- 92556 bunches, combined with an intensity of 1.15×10^{11} protons per bunch at 6.5 TeV, means the stored beam energy has reached 300 MJ per beam every 25 ns

The Large Hadron Collider

(pre-COVID schedule)

(post-COVID news: will run until 2040 then 100km e+e- collider @ higgs production)

How do we do that

high energy collisions

$E = 6.5\text{TeV}$ $\quad$ $E = 6.5\text{TeV}$

$m = 1\text{GeV}$ $\quad$ $m = 1\text{GeV}$

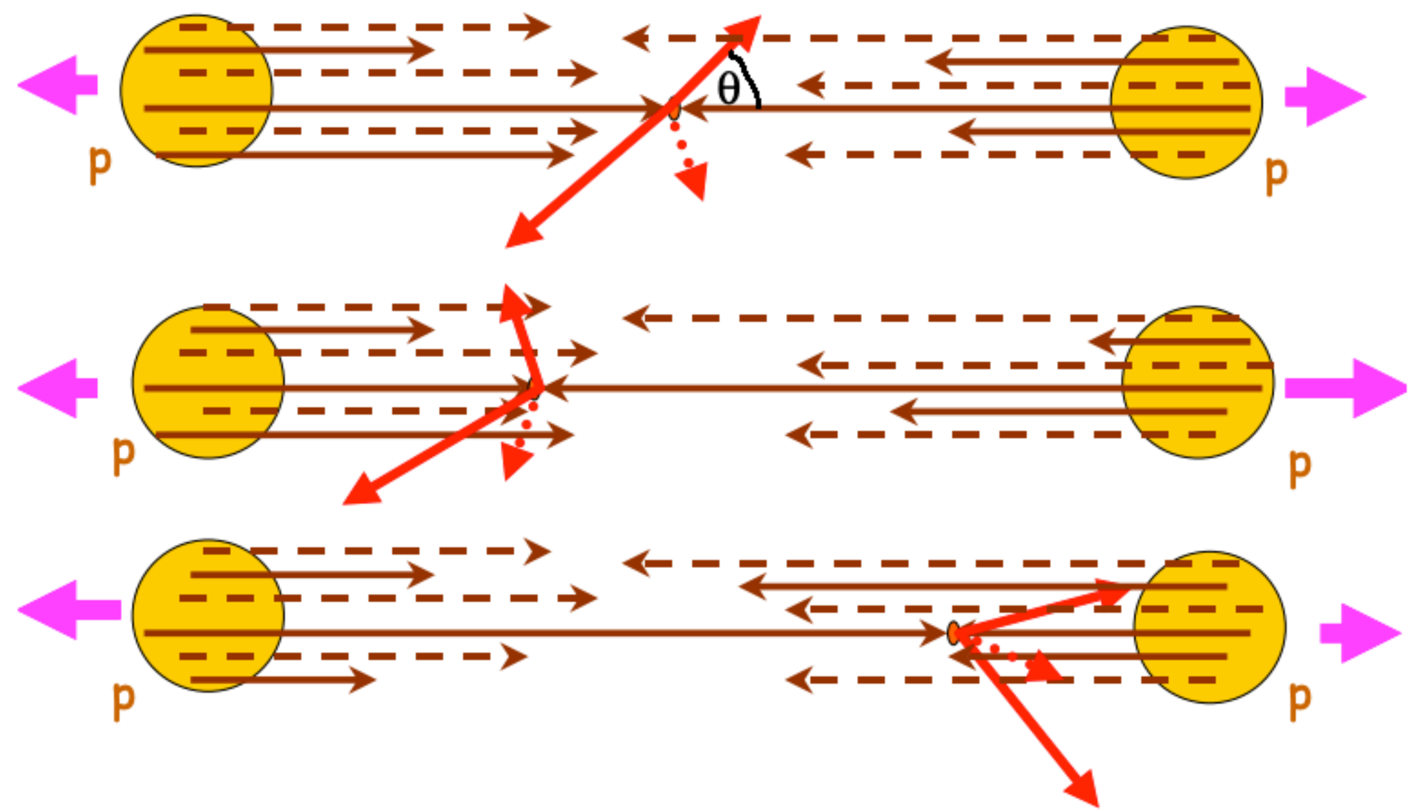
$\sqrt{s} = 13\ \text{TeV}$

$$s = [(E_1, \vec{p_1}) + (E_2, \vec{p_2})]^2$$

$$= [(2E, \vec{0})]^2$$

$$= 4E^2$$

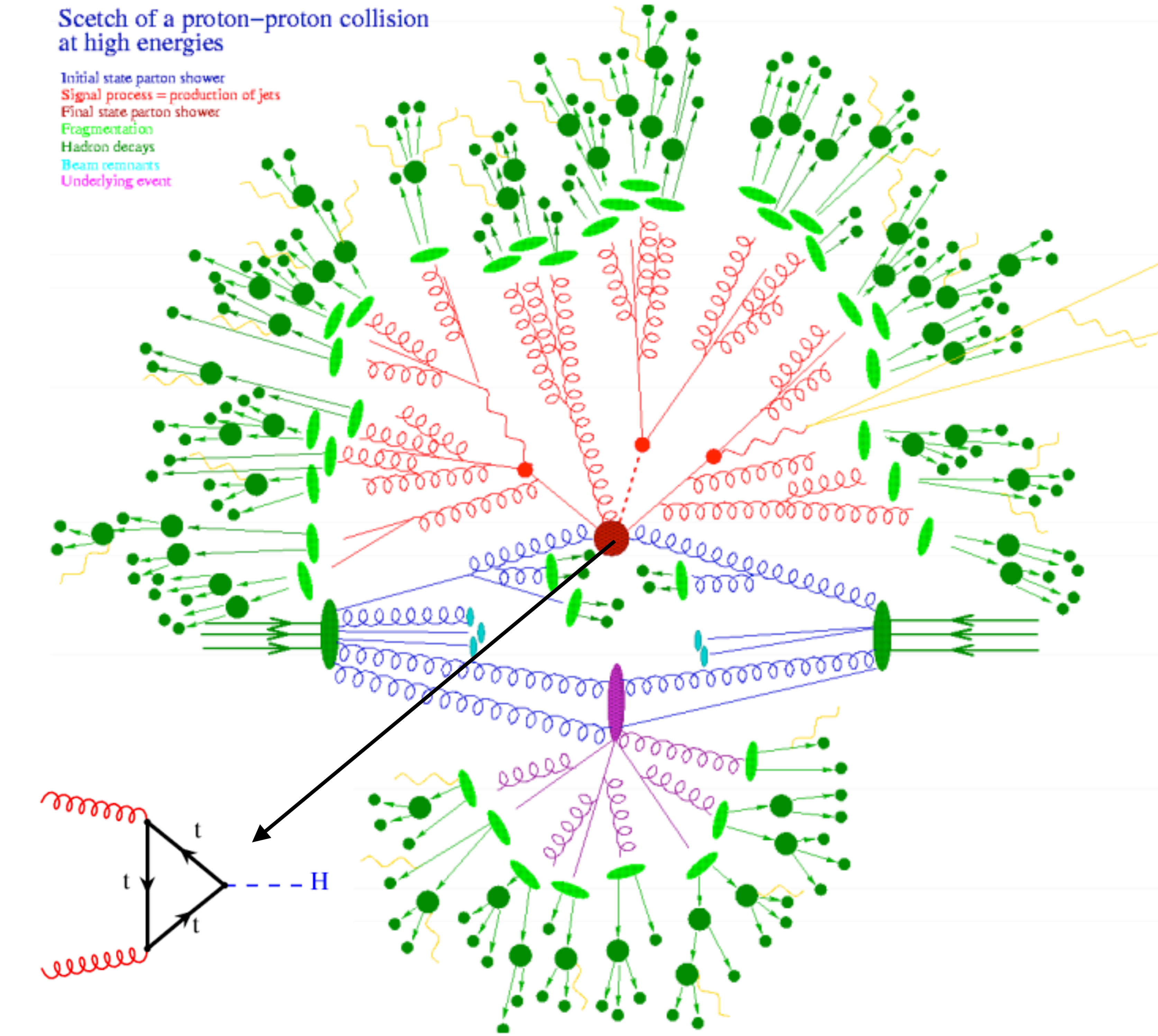
$p_1 = x_1 \cdot E_{beam}$ $\quad$ $p_2 = x_2 \cdot E_{beam}$



$$\sigma_X = \sum_{a,b} \int dx_a dx_b f(x_a, Q^2) \cdot f(x_b, Q^2) \cdot \sigma_{ab \to X}$$

PDF $\quad$ PDF

Radiography of a collision - I



Hard Scattering:

- gg-fusion
- qq-anihilation

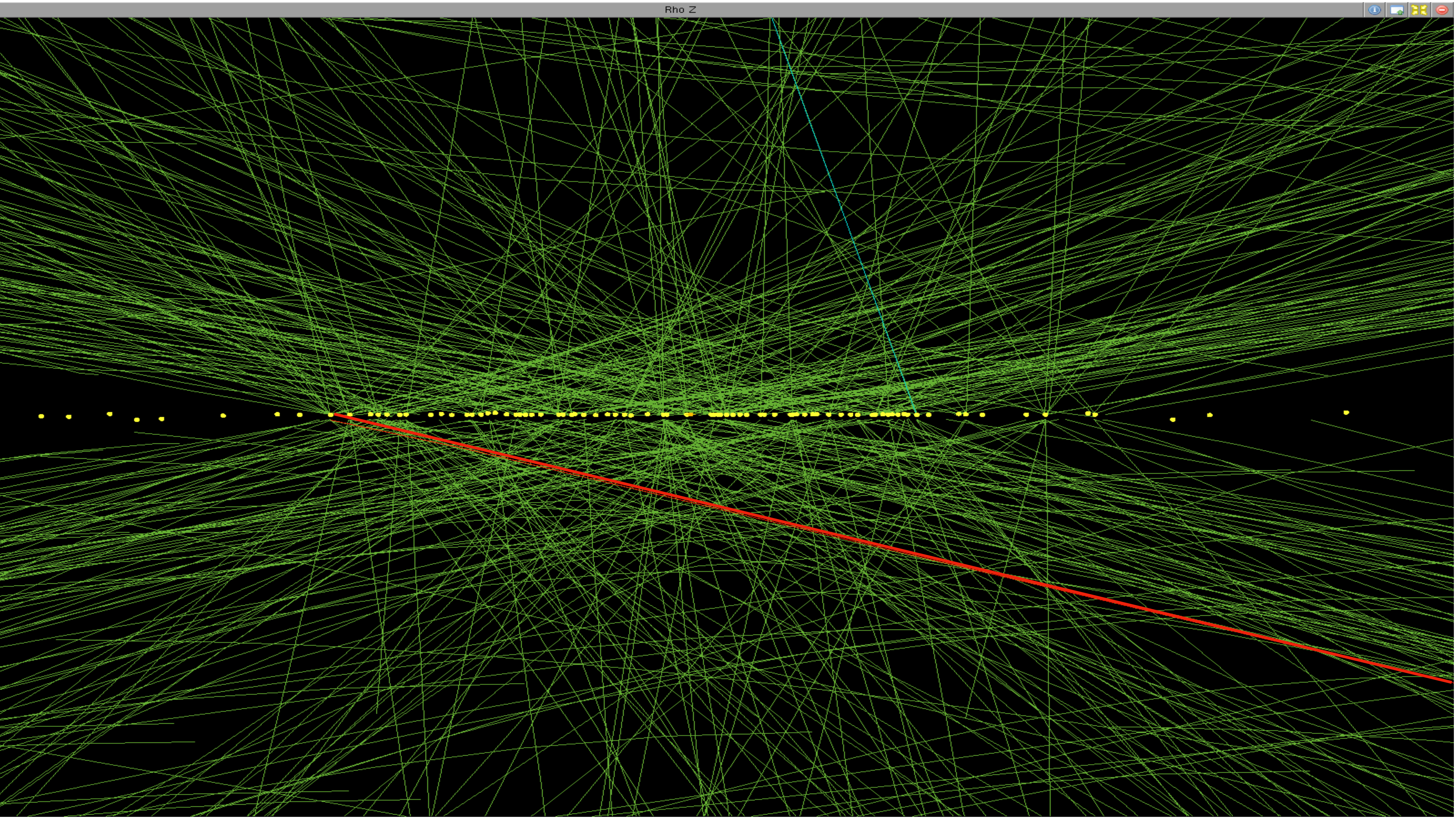
$$N = \sigma \cdot \epsilon \int L dt$$

Soft Scattering:

- Underlying Events
- ISR/FSR emissions
- Fragmentations
- Beam Remnants

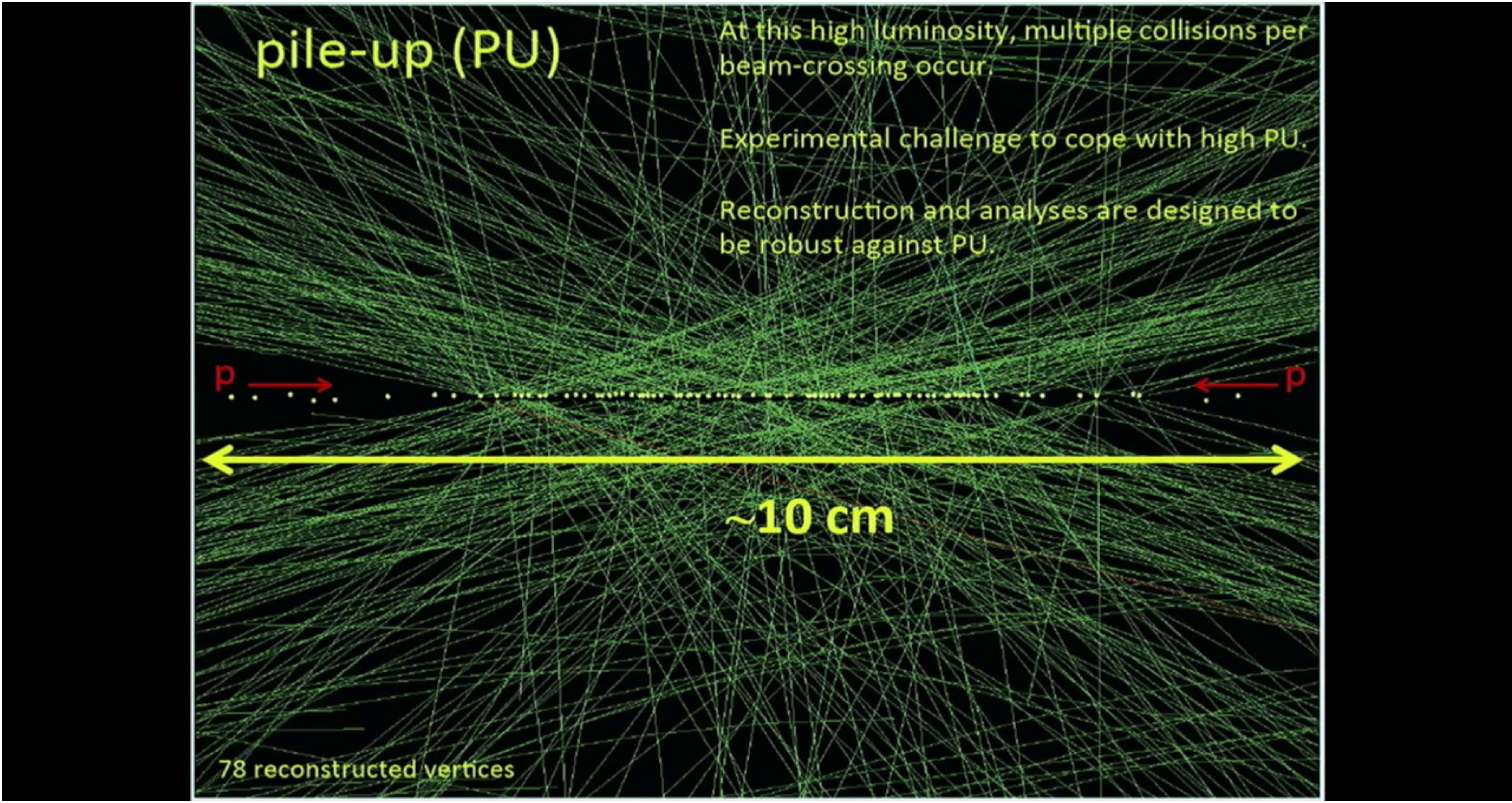
+ PILE UP

Radiography of a collision - II



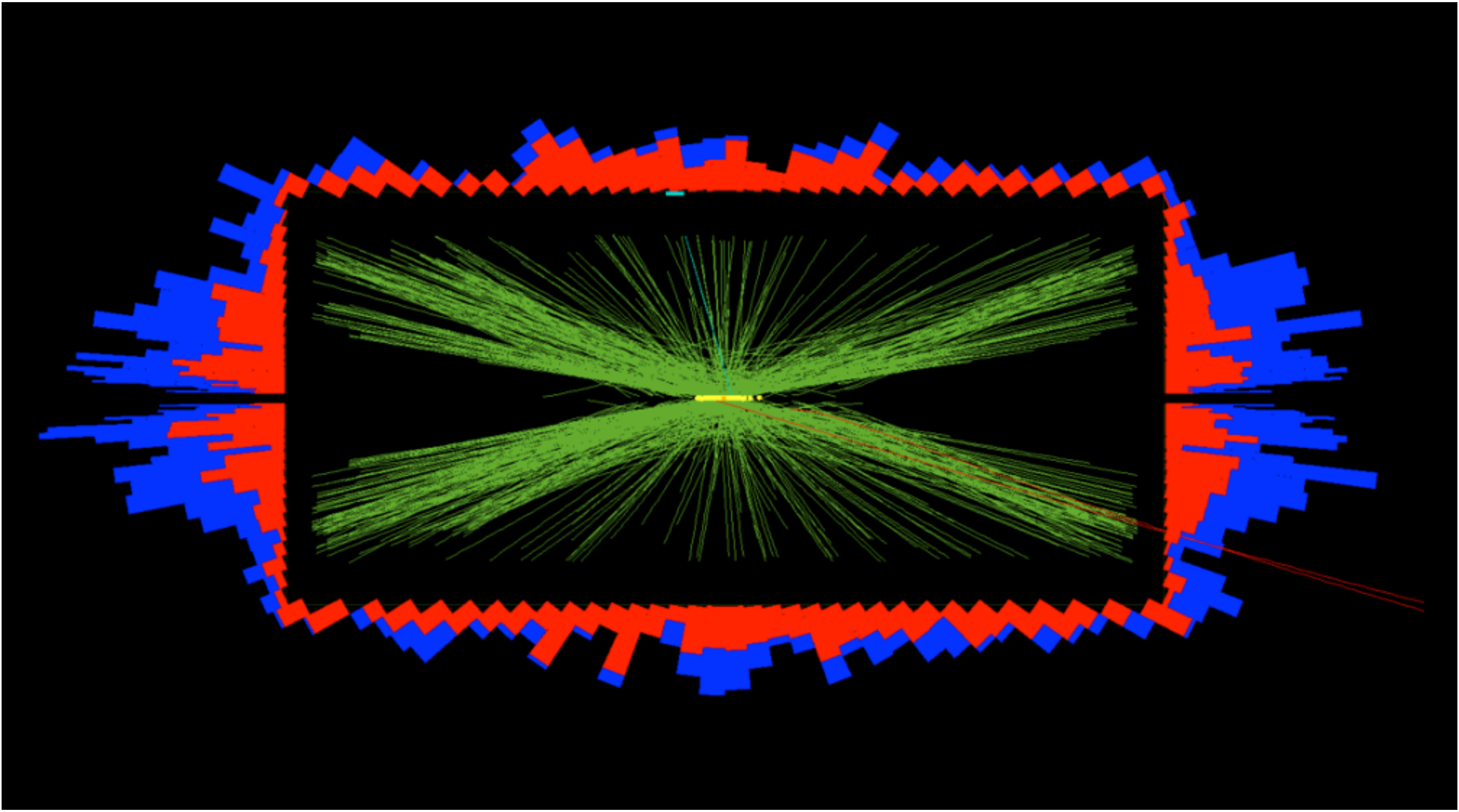
PILE UP

Radiography of a collision - II



PILE UP

Radiography of a collision - II



PILE UP

Luminosity

definition: ratio of the number of events **N** detected in an interval of time **t** to the interaction cross section σ

$$L = \frac{dN}{\sigma dt}$$

dimensions:
$cm^{-2}s^{-1}$ ($s^{-1}b^{-1}$)
$1b=10^{-28}m^2$)

number of particles in bunch 1/2

$$L = \frac{N_1 N_2}{\sigma_{xy}}\omega$$

revolution frequency

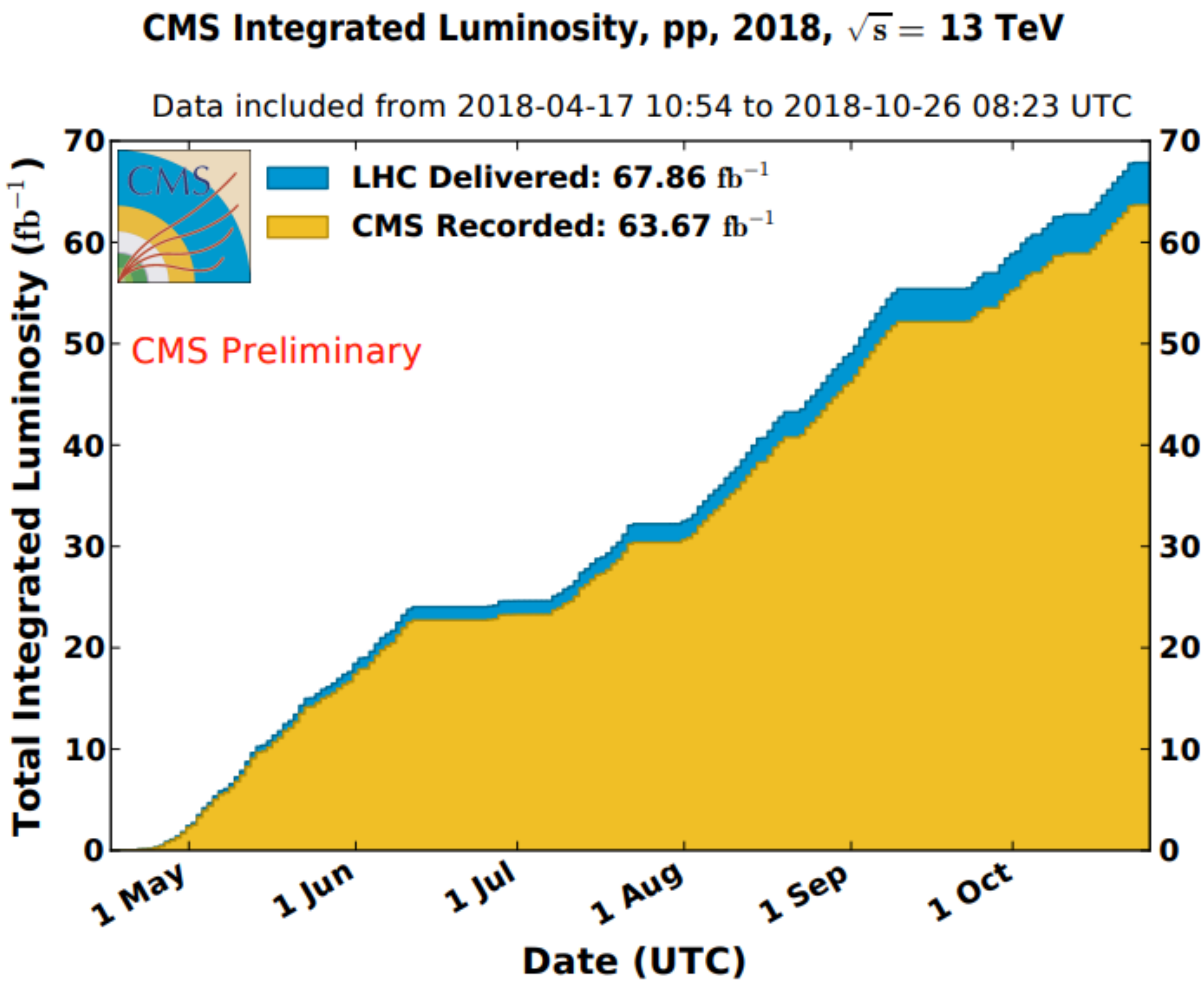
beam cross section (geometrical)

$$L_{int} = \int L dt$$

colliders: Integrated Luminosity

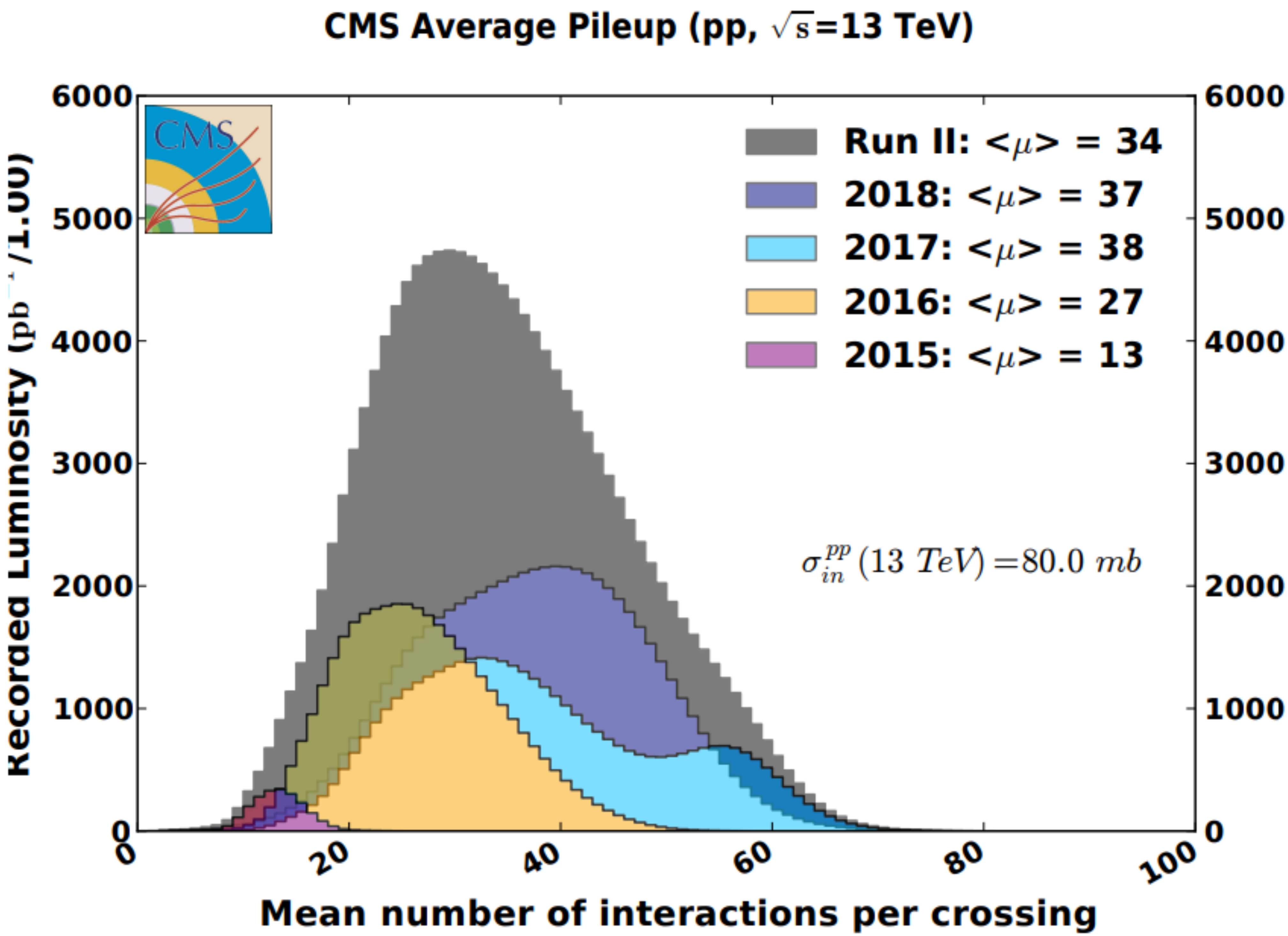
Collider	Interaction	L ($cm^{-2} \cdot s^{-1}$)
SPS	$p + \bar{p}$	6.0×10^{30}
Tevatron[2]	$p + \bar{p}$	4.0×10^{32}
HERA	$p + e^+$	4.0×10^{31}
LHC[3]	$p + p$	2.1×10^{34}
LEP	$e^- + e^+$	1.0×10^{32}
PEP	$e^- + e^+$	3.0×10^{33}
KEKB[4]	$e^- + e^+$	2.1×10^{34}

CMS 2018



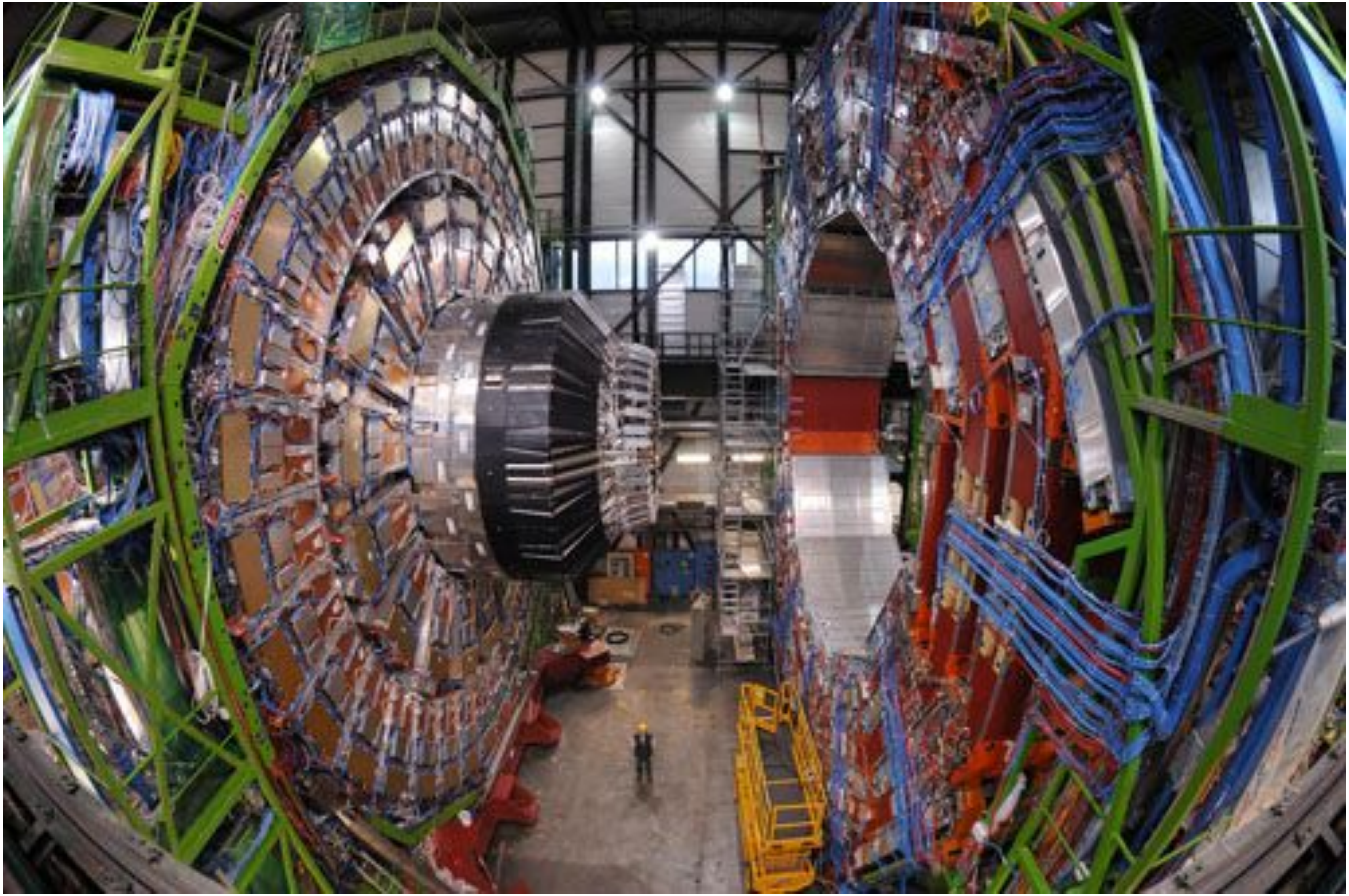
CMS Integrated Luminosity, pp, 2018, $\sqrt{s} = $ 13 TeV
Data included from 2018-04-17 10:54 to 2018-10-26 08:23 UTC
LHC Delivered: 67.86 fb^{-1}
CMS Recorded: 63.67 fb^{-1}
CMS Preliminary
Total Integrated Luminosity (fb^{-1})
0
10
20
30
40
50
60
70
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
Date (UTC)

CMS 2018

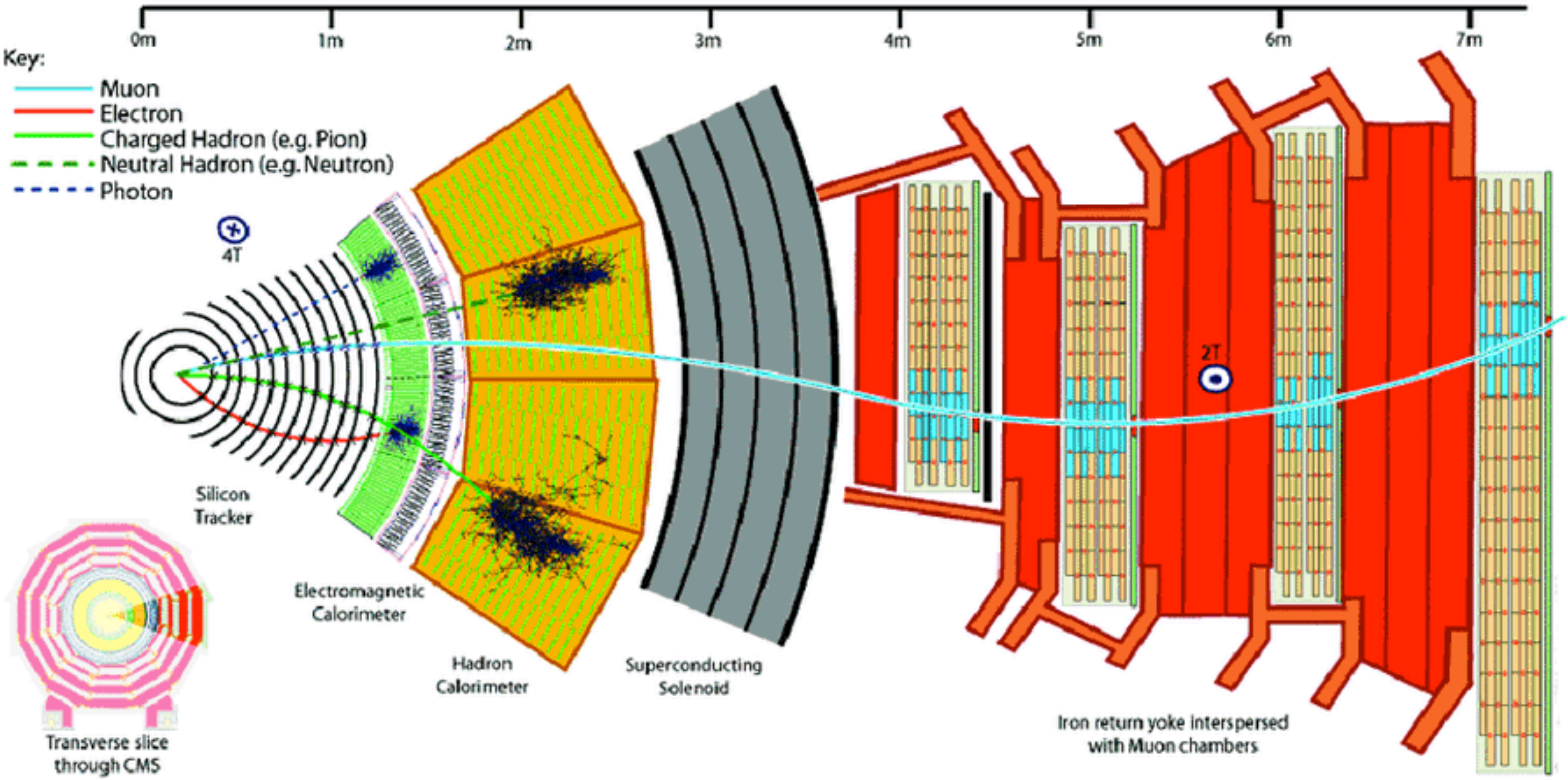


CMS Average Pileup (pp, $\sqrt{s}$=13 TeV)
Run II: <μ> = 34
2018: <μ> = 37
2017: <μ> = 38
2016: <μ> = 27
2015: <μ> = 13
σ_{in}^{pp} (13 TeV) =80.0 mb
Recorded Luminosity (pb⁻¹/1.00)
Mean number of interactions per crossing
0
1000
2000
3000
4000
5000
6000
0
20
40
60
80
100

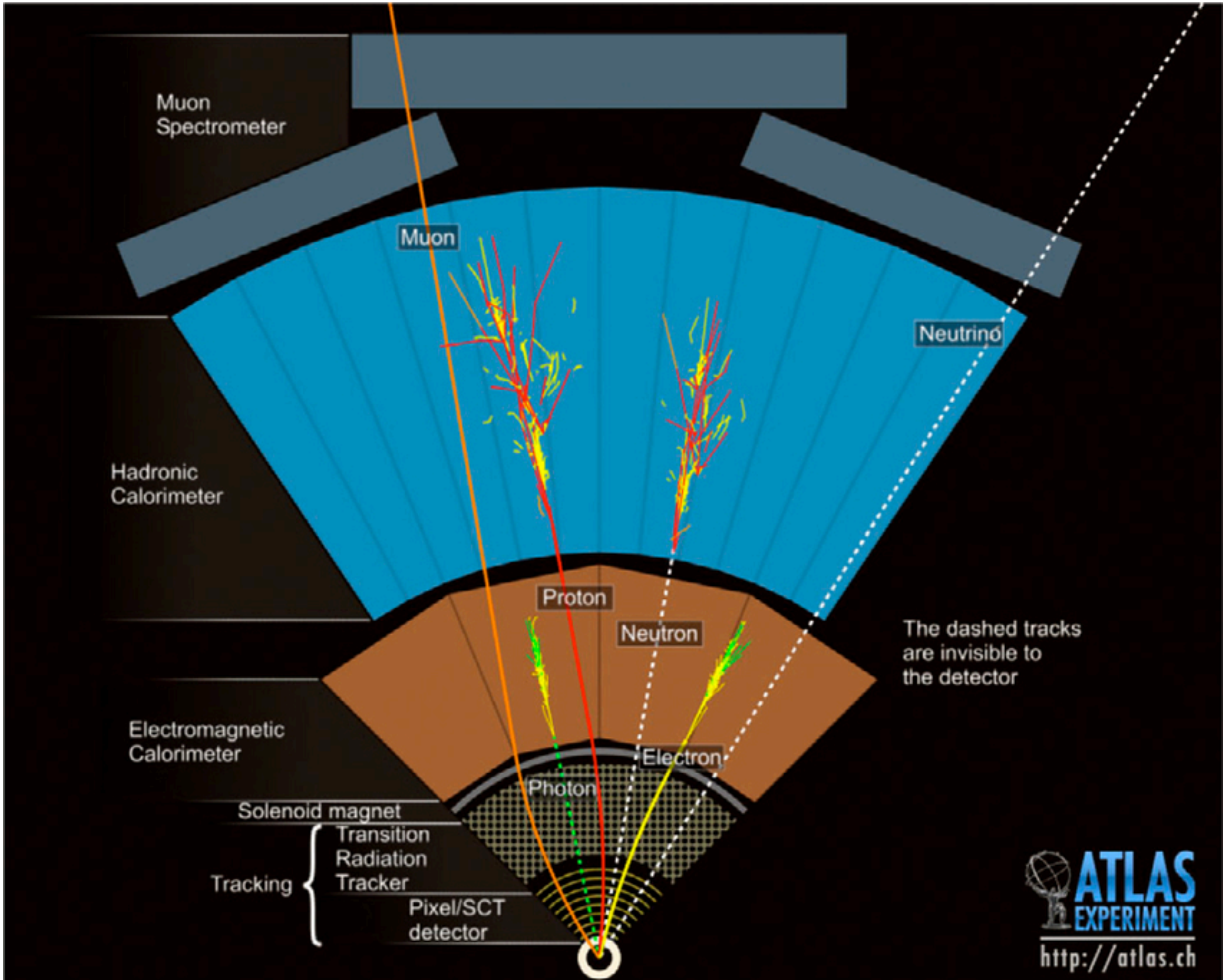
Collisions Harvesting: Detectors I



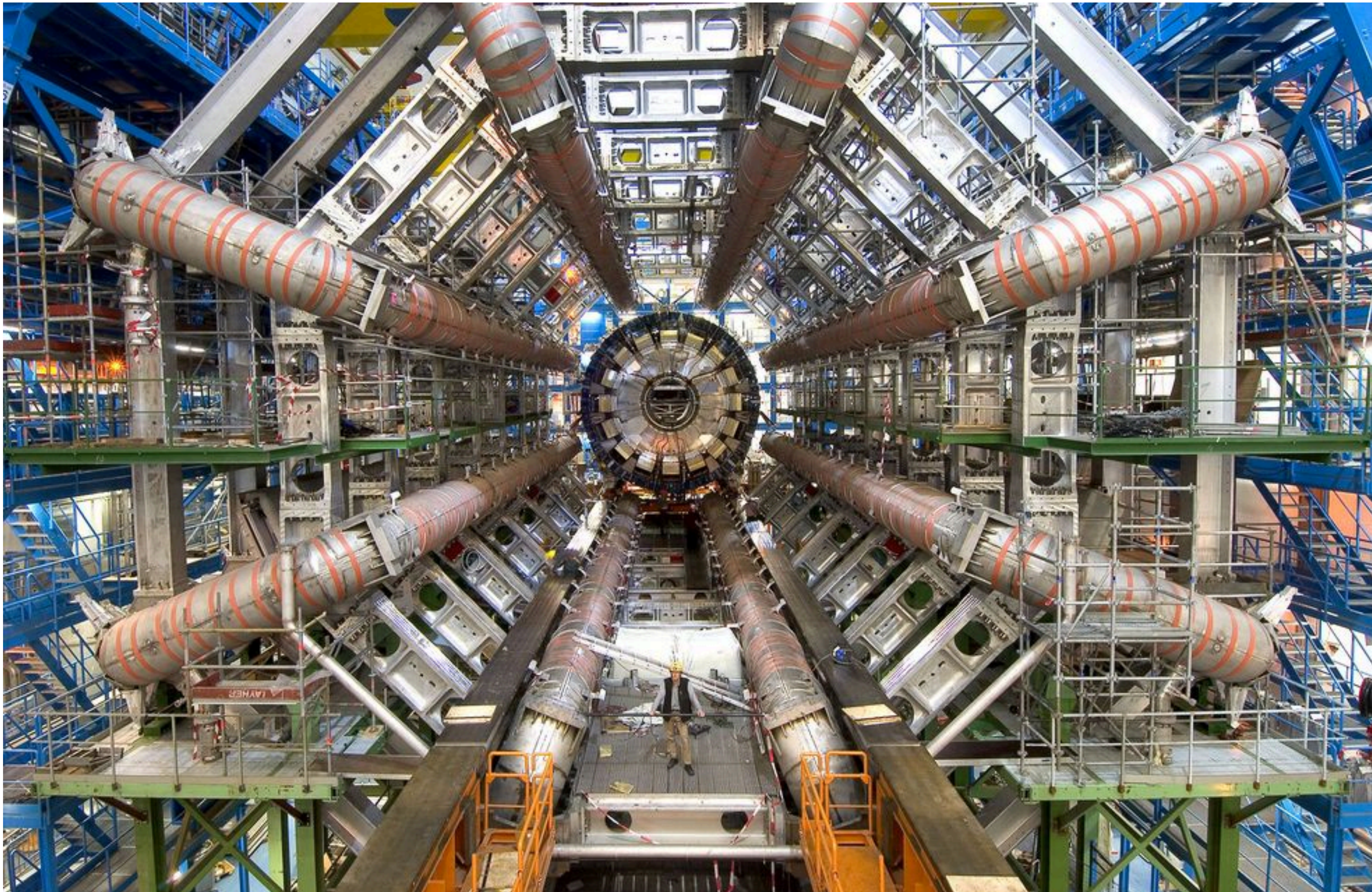
Collisions Harvesting: Detectors I



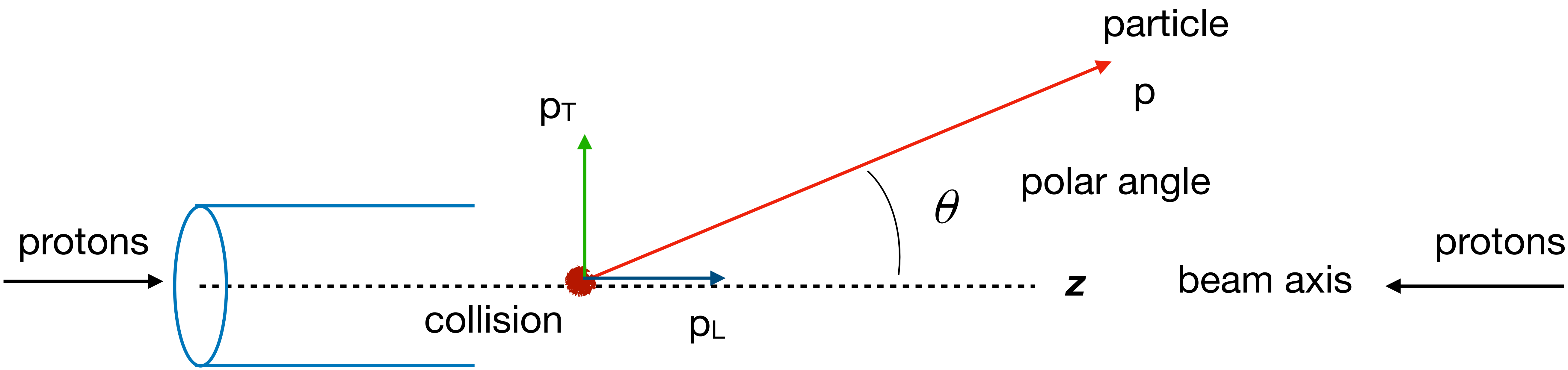
Collisions Harvesting: Detectors II



Collisions Harvesting: Detectors II



Coordinates



transverse momentum

$$p_T = p \cdot sin\theta$$

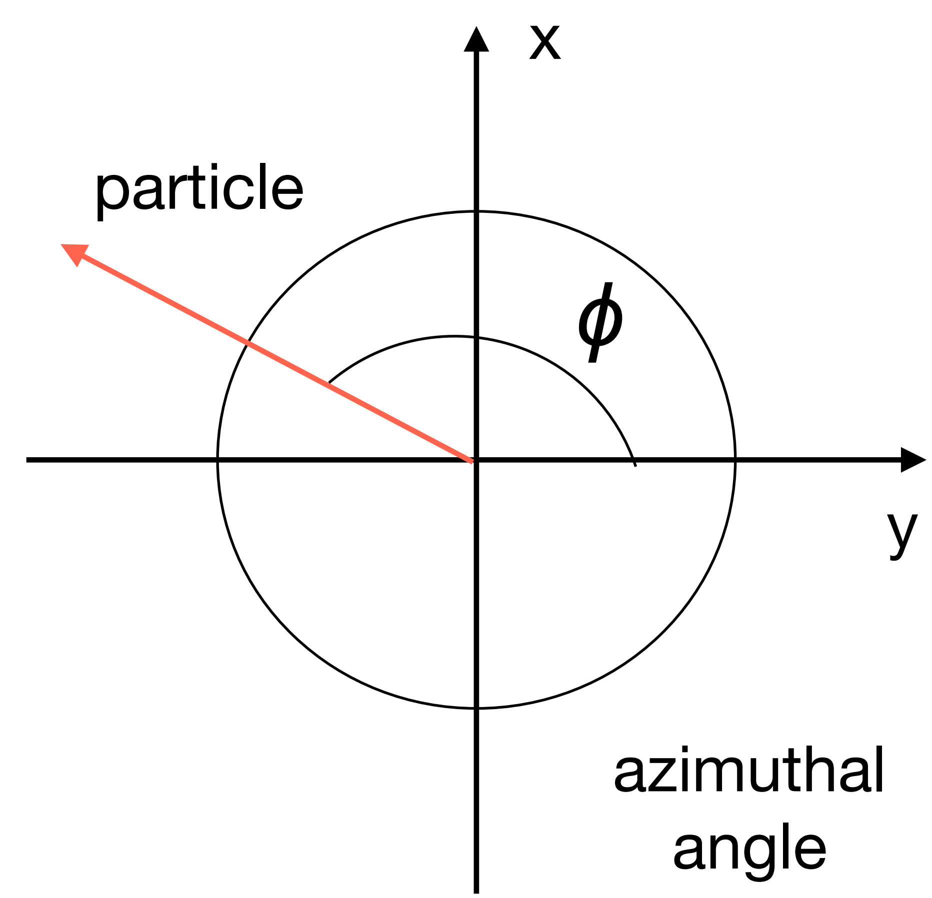
rapidity

$$y = \frac{1}{2} \cdot \frac{E + p_L}{E - p_L}$$

$\longrightarrow$ m<<(E,p)

pseudorapidity

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



Coordinates (why?)

Differential cross sections are typically studied as a function of momentum, energy and polar angle

but: we don't know the longitudinal boost of the collision!

$x_1\vec{p}$ → ← $-x_2\vec{p}$

$$boost = \beta = \frac{x_1 - x_2}{x_2 + x_1}$$

each event has a different boost!

Coordinates (why?)

Differential cross sections are typically studied as a function of momentum, energy and polar angle

but: we don’t know the longitudinal boost of the collision!

Need variables that are not sensitive to the boost

Variables unchanged under longitudinal boosts

Coordinates (why?)

Differential cross sections are typically studied as a function of momentum, energy and polar angle

but: we don't know the longitudinal boost of the collision!

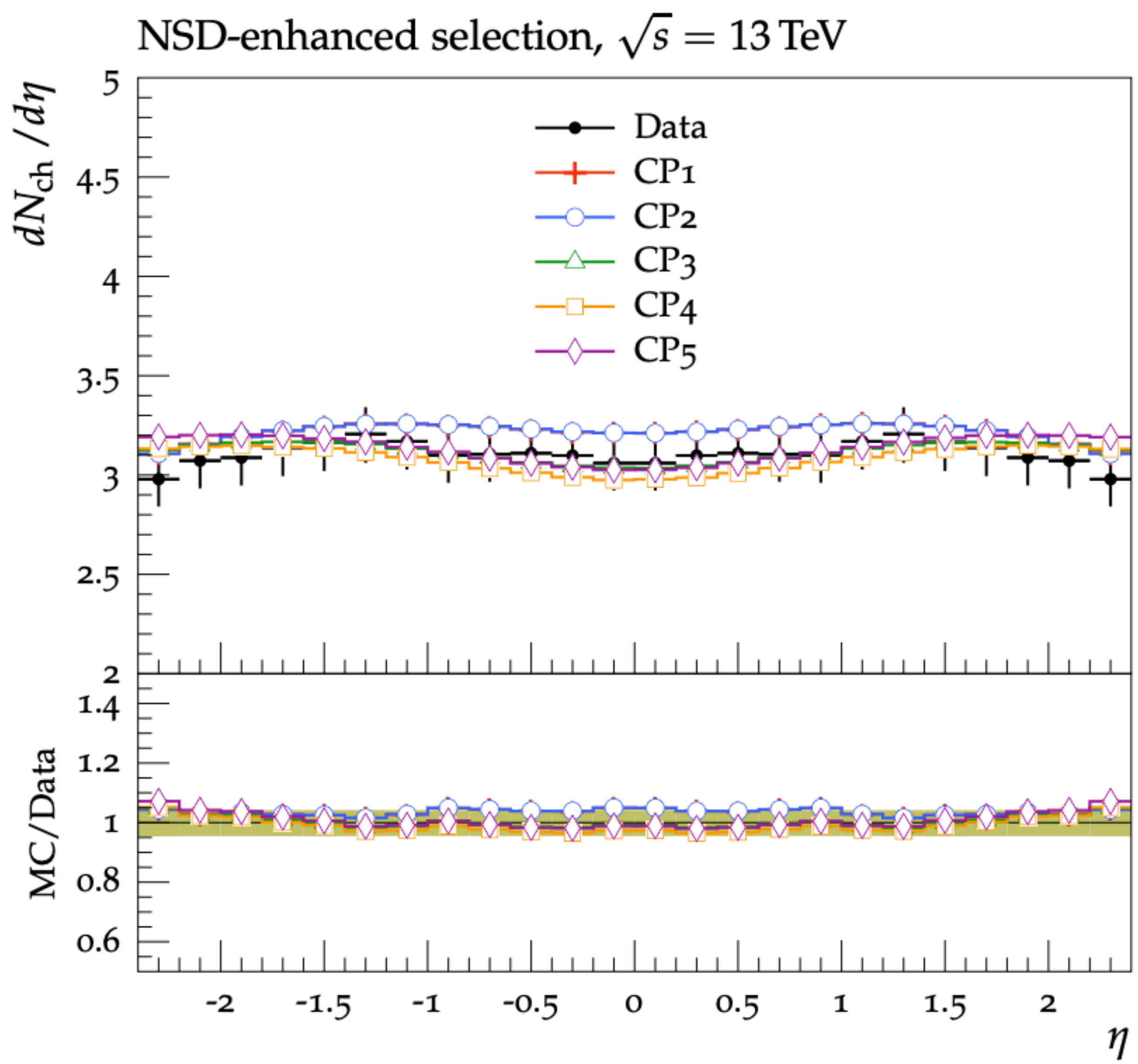
Need variables that are not sensitive to the boost

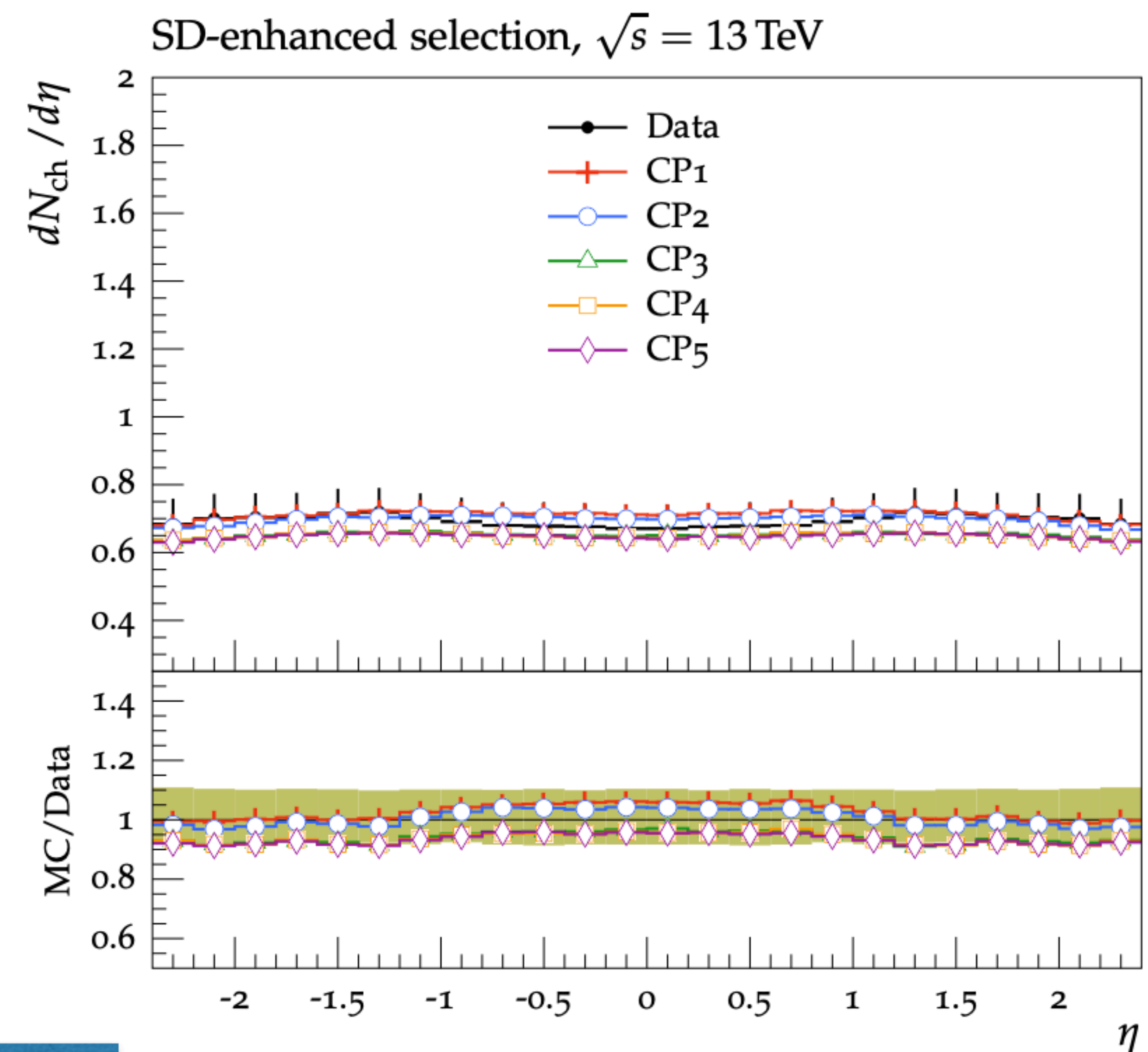
→ pseudorapidity intervals!

Variables unchanged under longitudinal boosts

→ transverse momentum!

Coordinates (why?)





LHC collisions: the initial state

How Strong is Strong ?

QCD potential between quarks has two components:

- Short range, Coulomb-like term: $-\frac{4}{3}\frac{\alpha_s}{r}$
- Long range, linear term: $+kr$

$$V_{QCD} = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

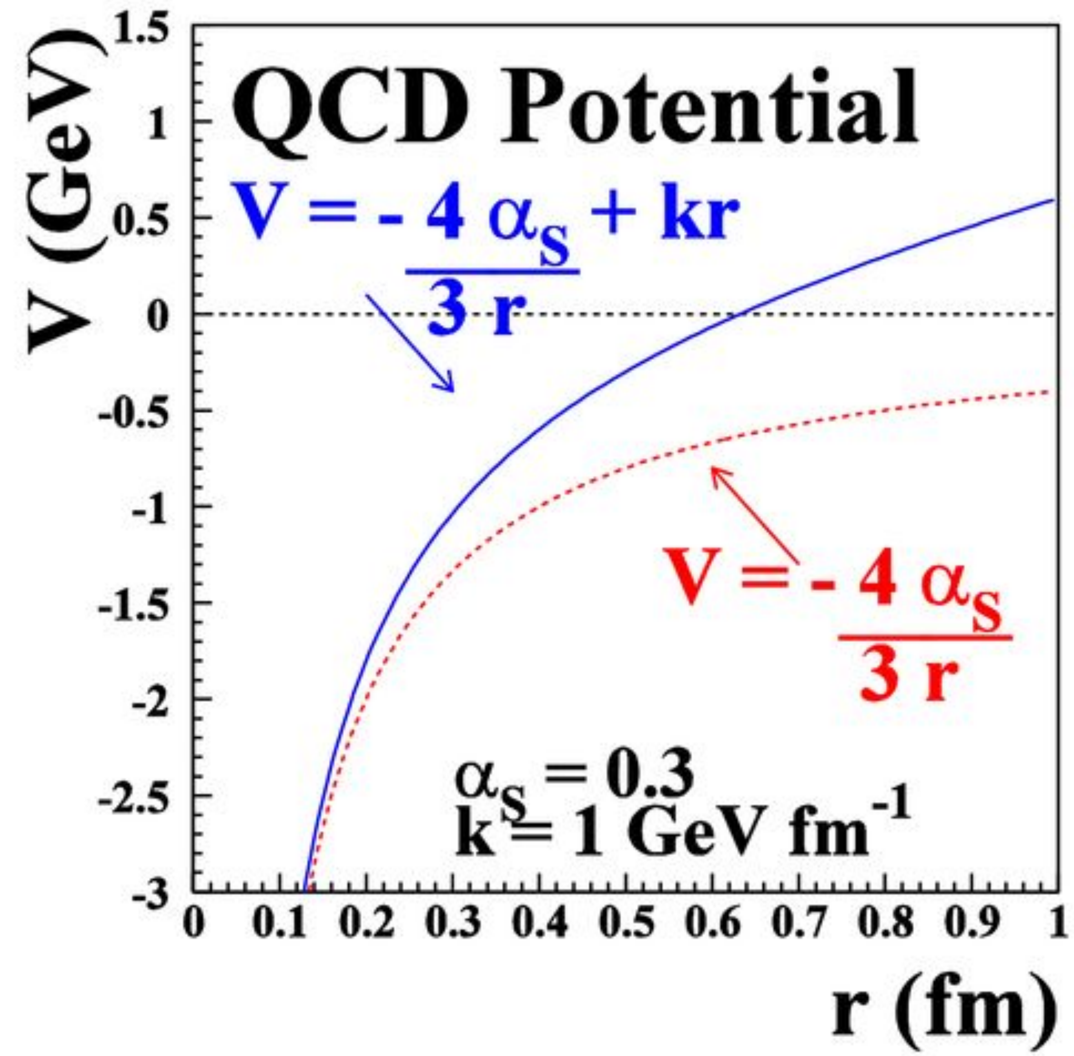
with $k \approx 1\,GeV/fm$

$$F = -\frac{dV}{dr} = \frac{4}{3}\frac{\alpha_s}{r^2} + k$$

at large r

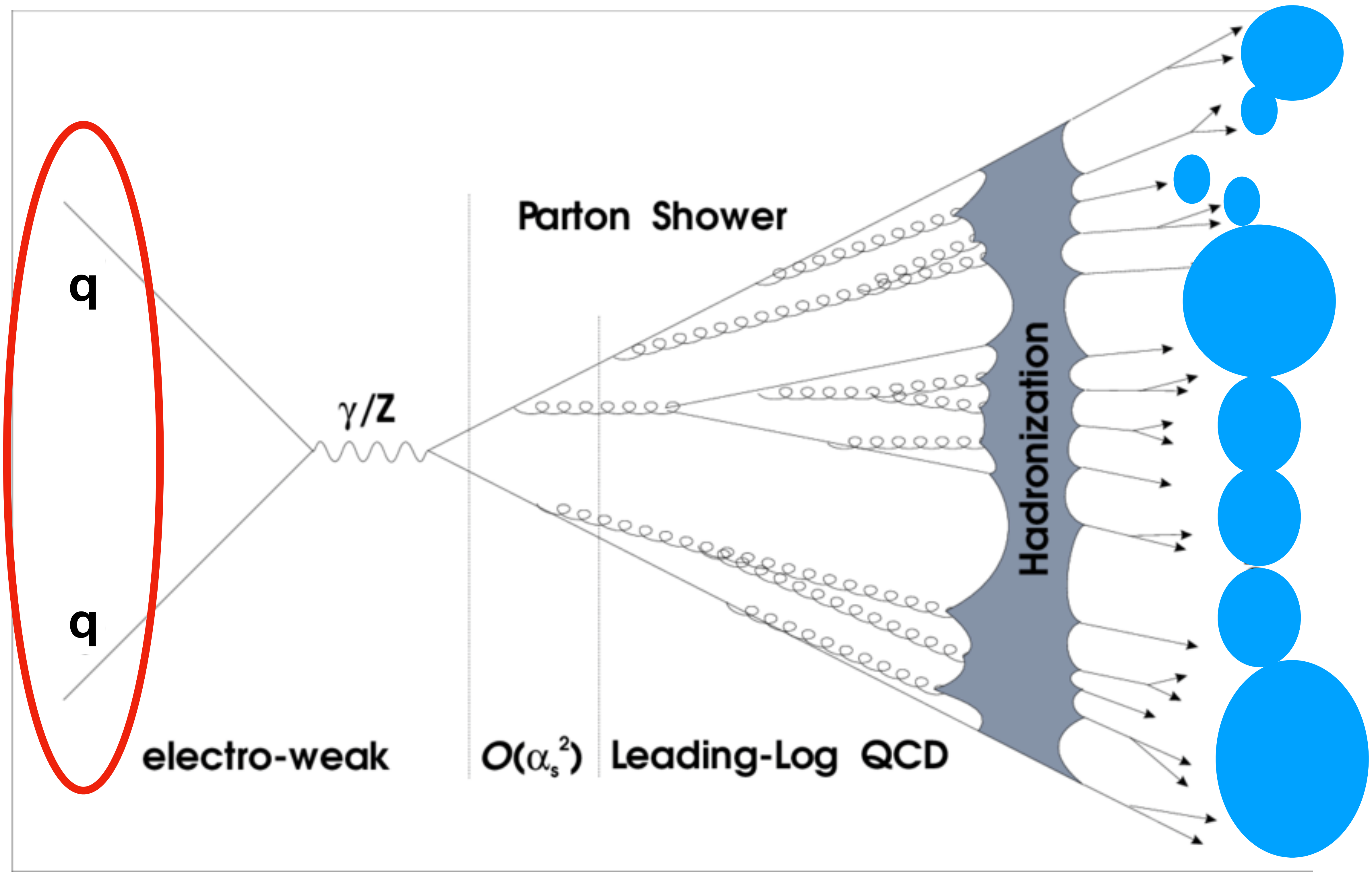
$$F = k \approx \frac{1.6\times10^{-10}}{10^{-15}}\ N$$
$$= 160000\ N$$

Equivalent to ~150 people

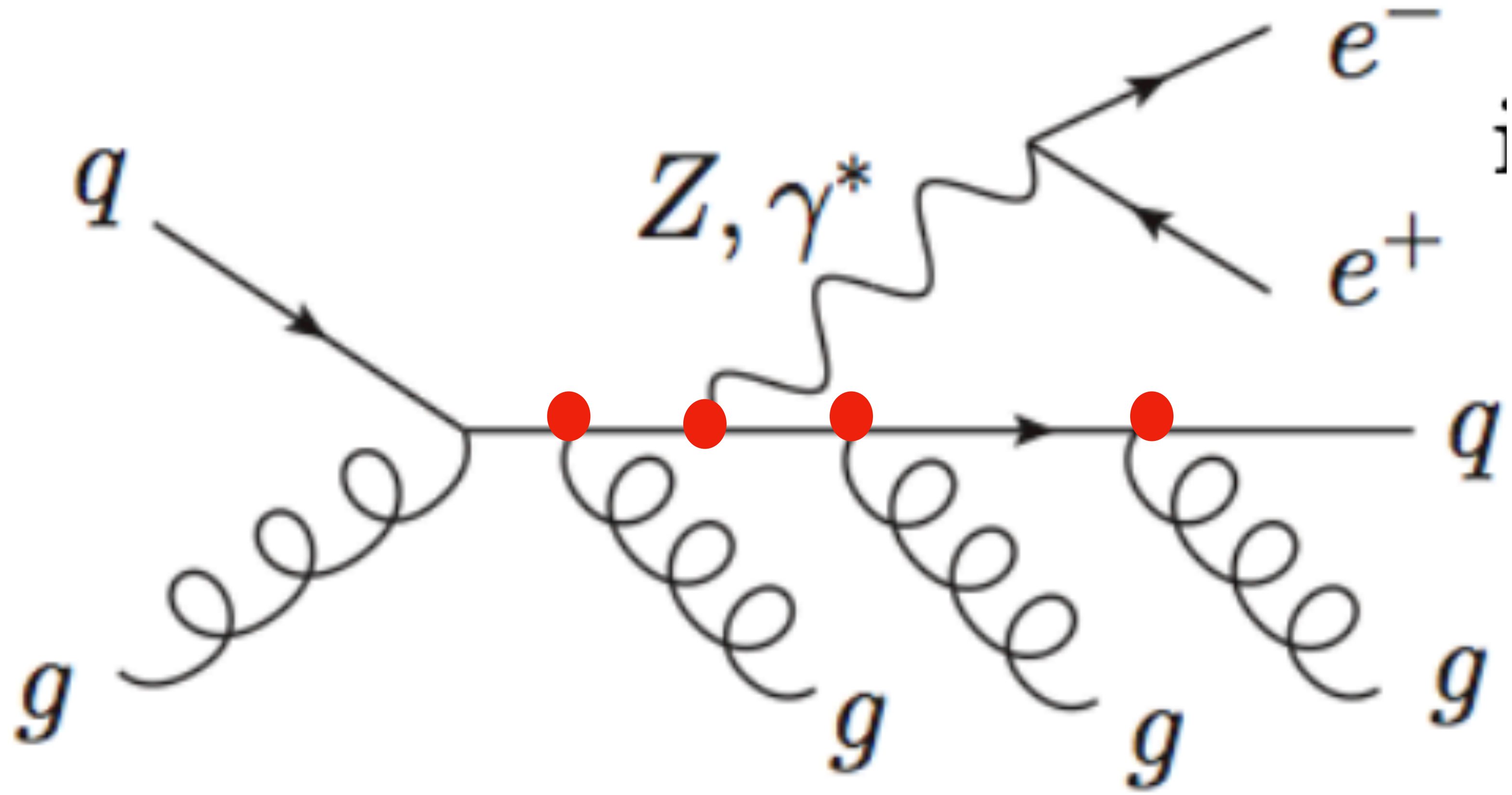


110

The Matrix Element



The Matrix Element



LO to NLO to NNLO…

$$\sigma \sim A + B\alpha_s + C\alpha_s^2 + D\alpha_s^3 + \ldots$$

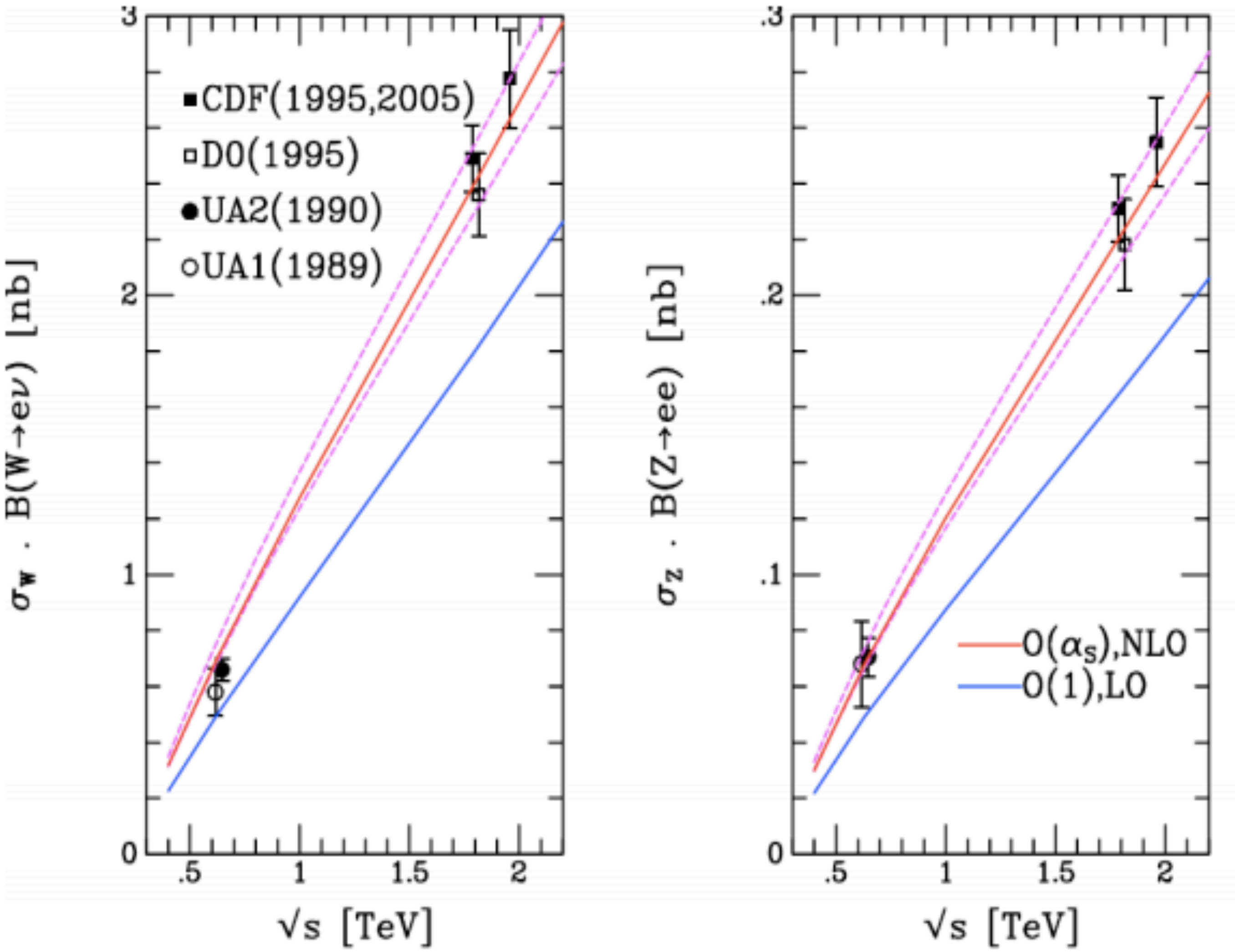
LO NLO NNLO NNNLO

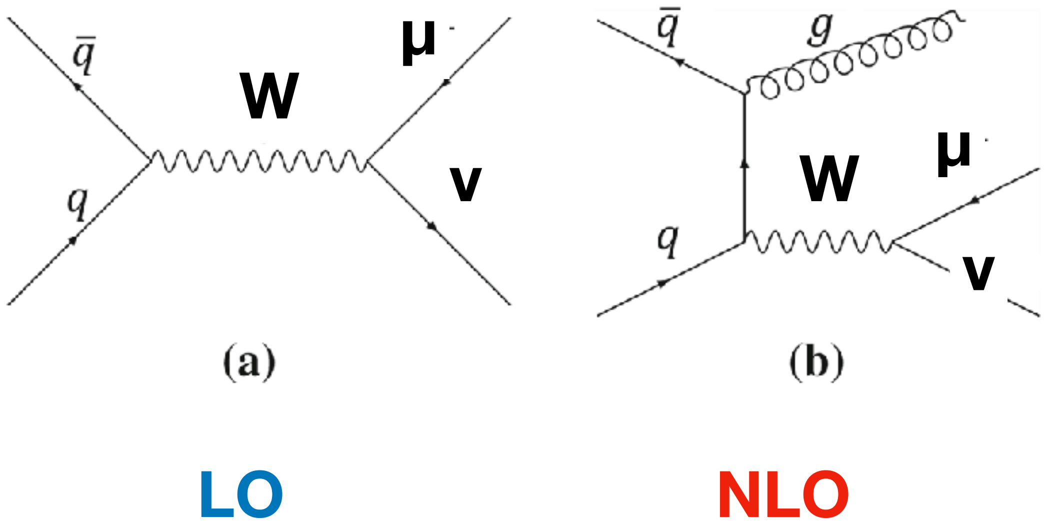
$$\frac{\sigma^{\rm LO}_{\rm njets}(\mu)}{\sigma^{\rm LO}_{\rm njets}(\mu')} = \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu')}\right)^n$$

Is it necessary to go beyond LO?

Very early observation:

at least NLO corrections are needed to describe data



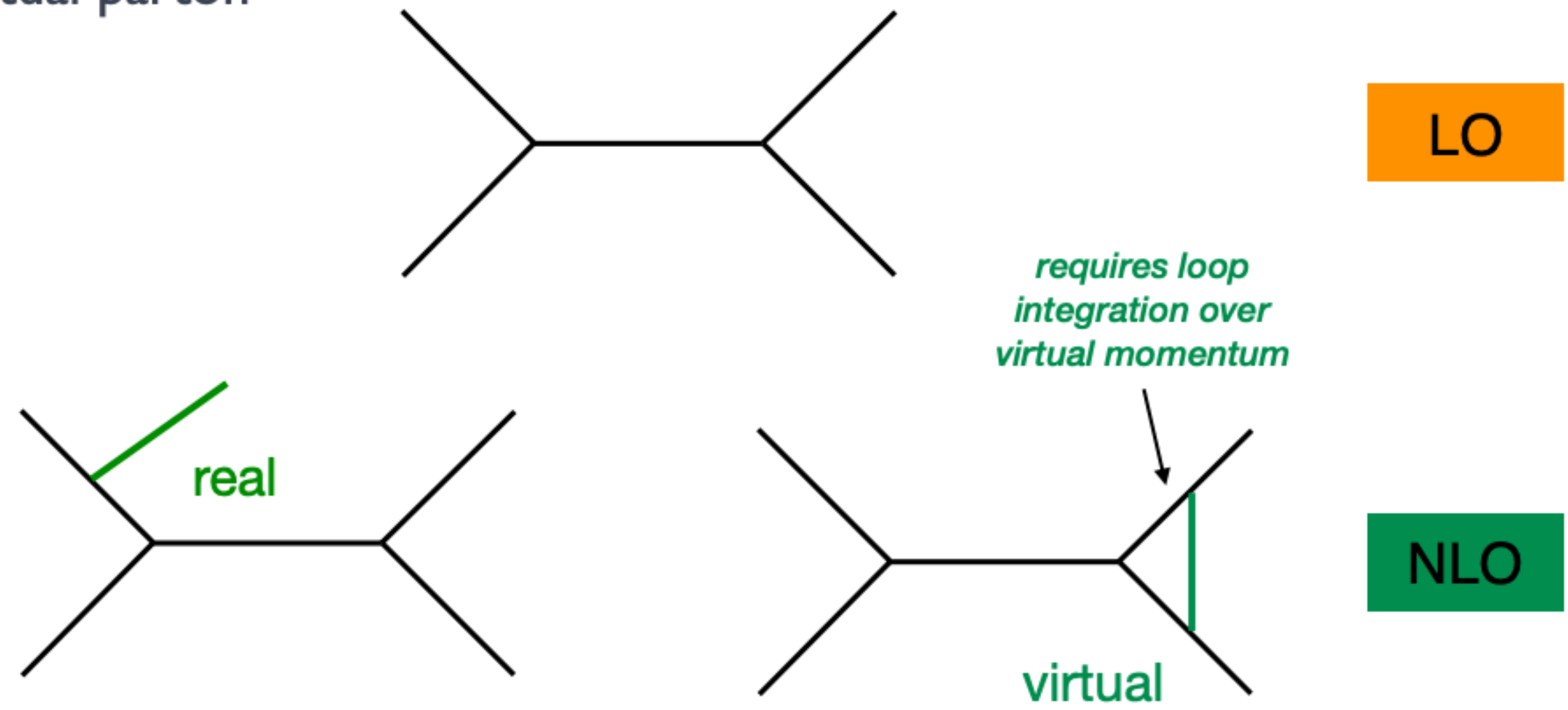


Drell Yan production is one of the first processes for which NLO corrections have been computed

G.Zanderighi

NLO calculations

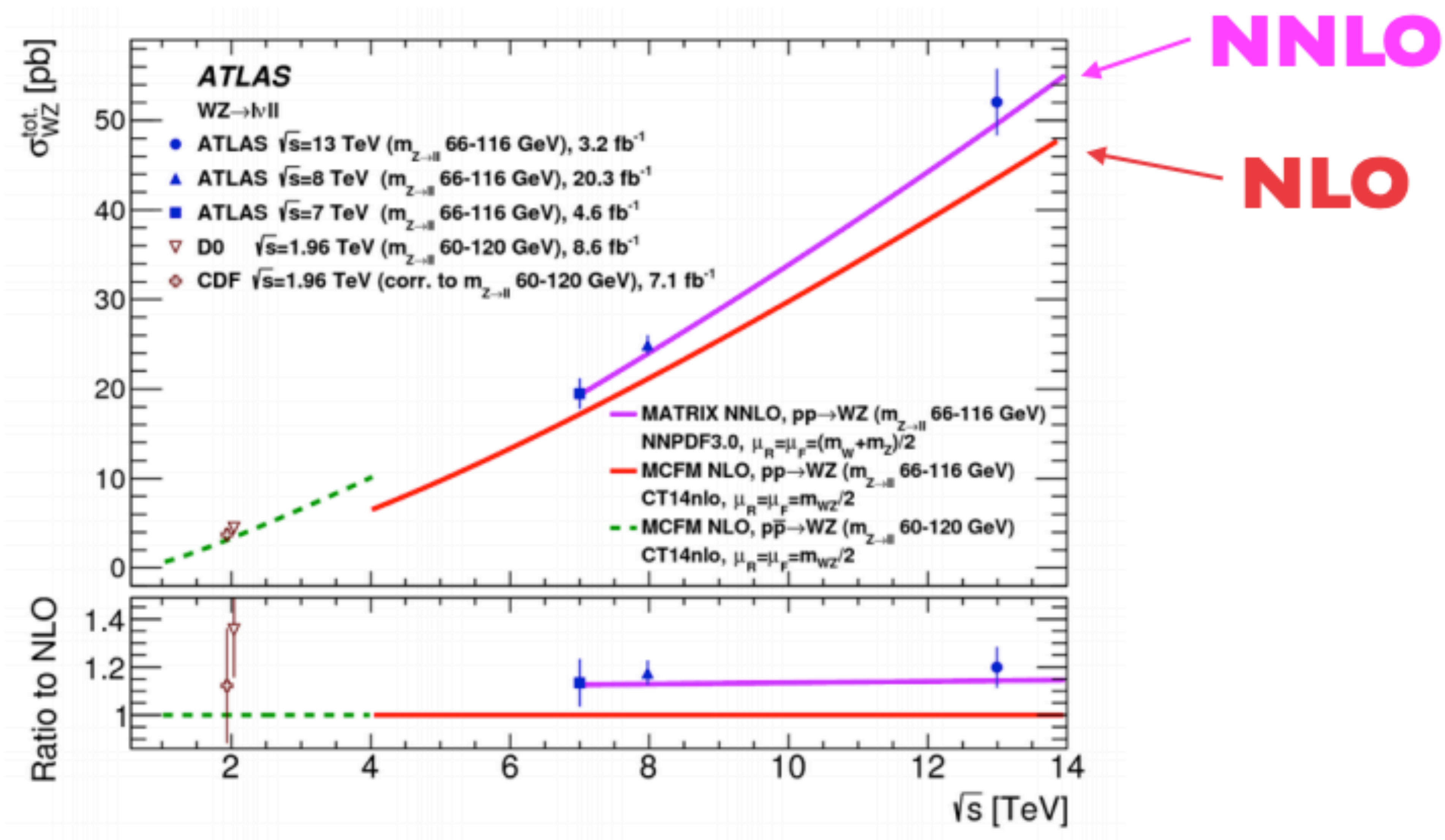
NLO accuracy requires to dress a process with one real or one virtual parton



Sample diagrams shown. All diagrams must be included.

G.Zanderighi

NLO & NNLO versus LHC data



LHC data clearly prefers NNLO

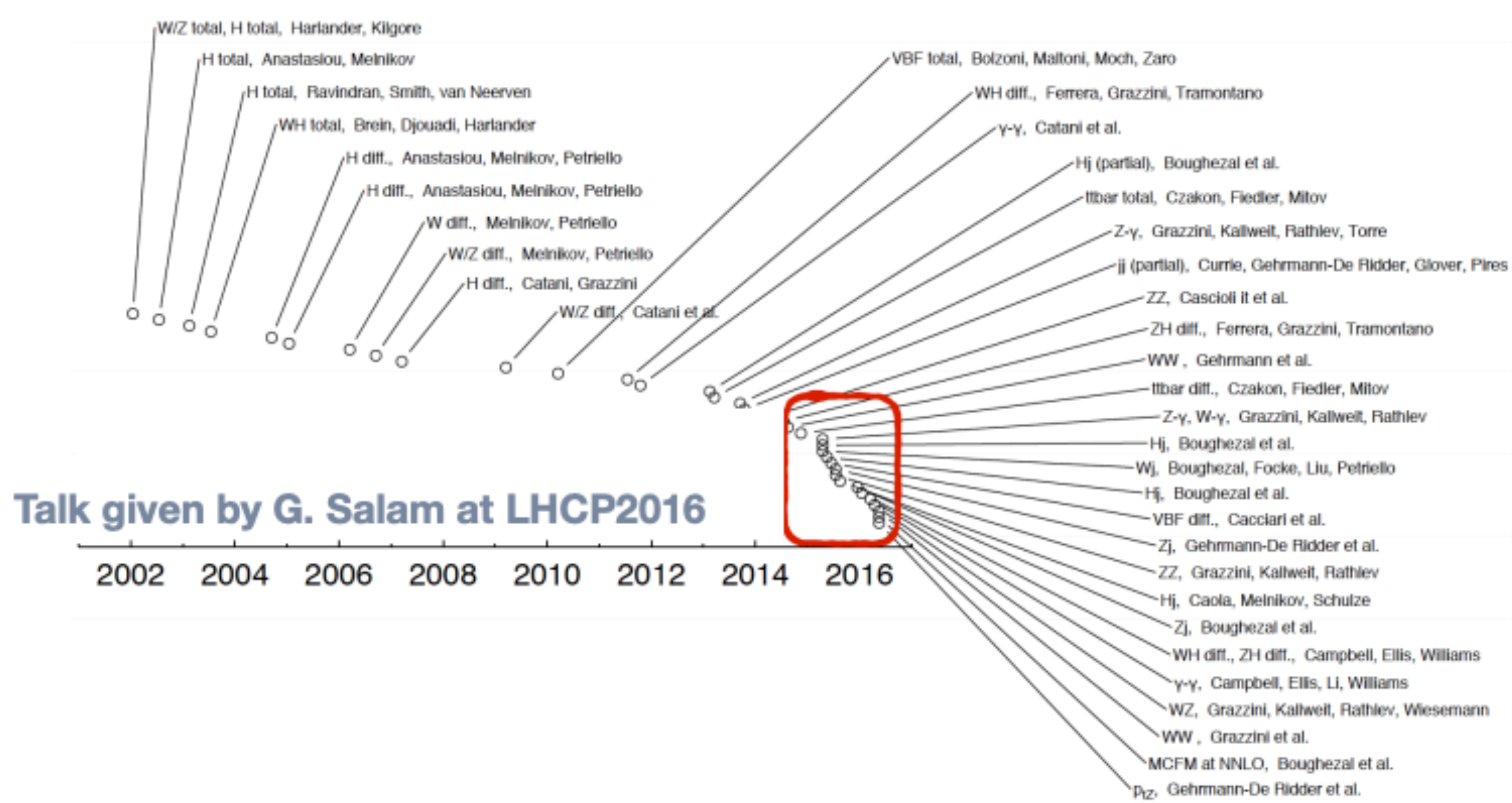
Same conclusion in all measurements examined so far

With more data NLO likely to be insufficient

G.Zanderighi

NNLO: the next challenge

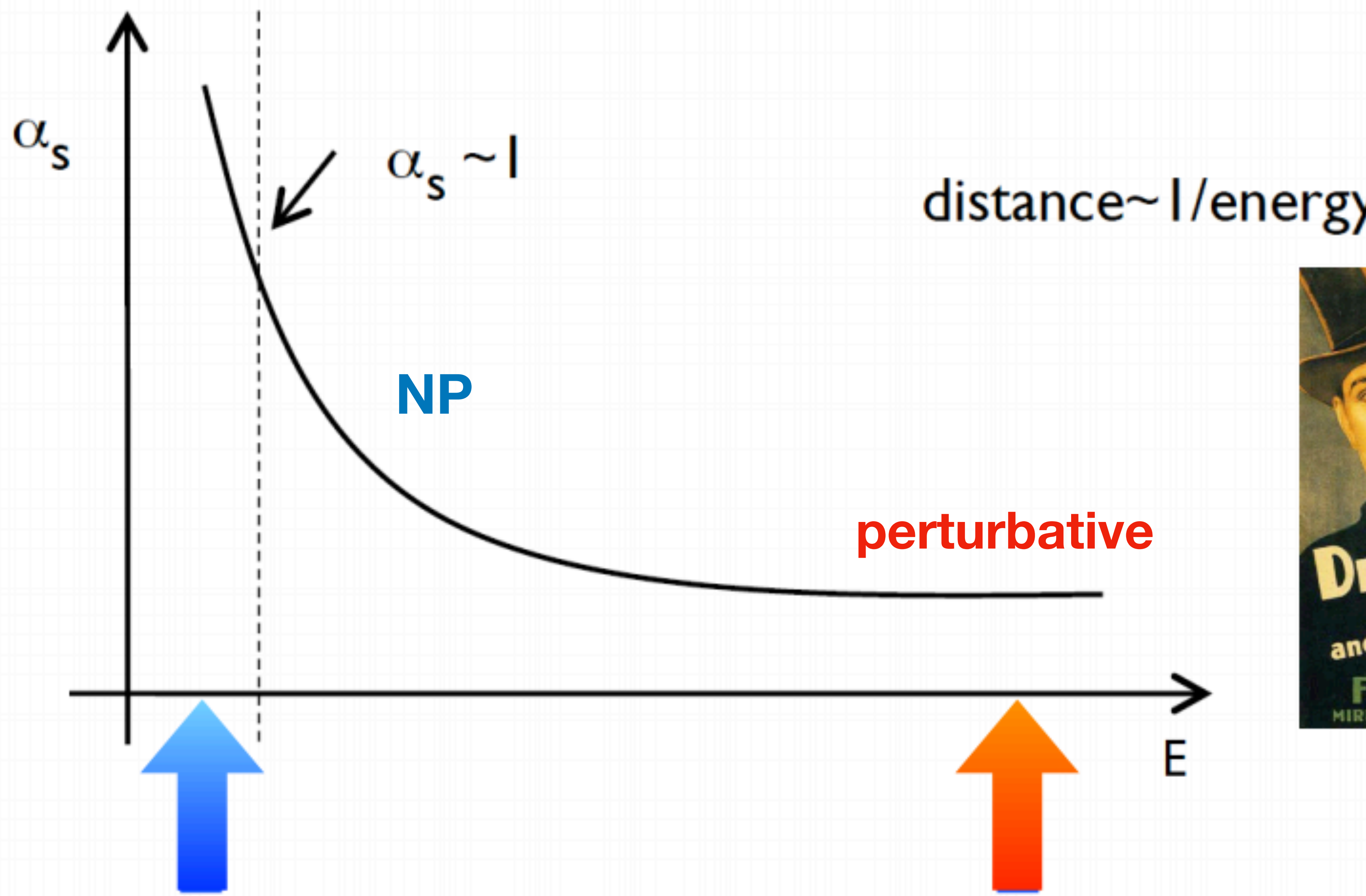
An explosion of NNLO results in the last two years



Things are developing rapidly, but a number of conceptual and technical challenges remain to be faced

G.Zanderighi

The two faces of QCD



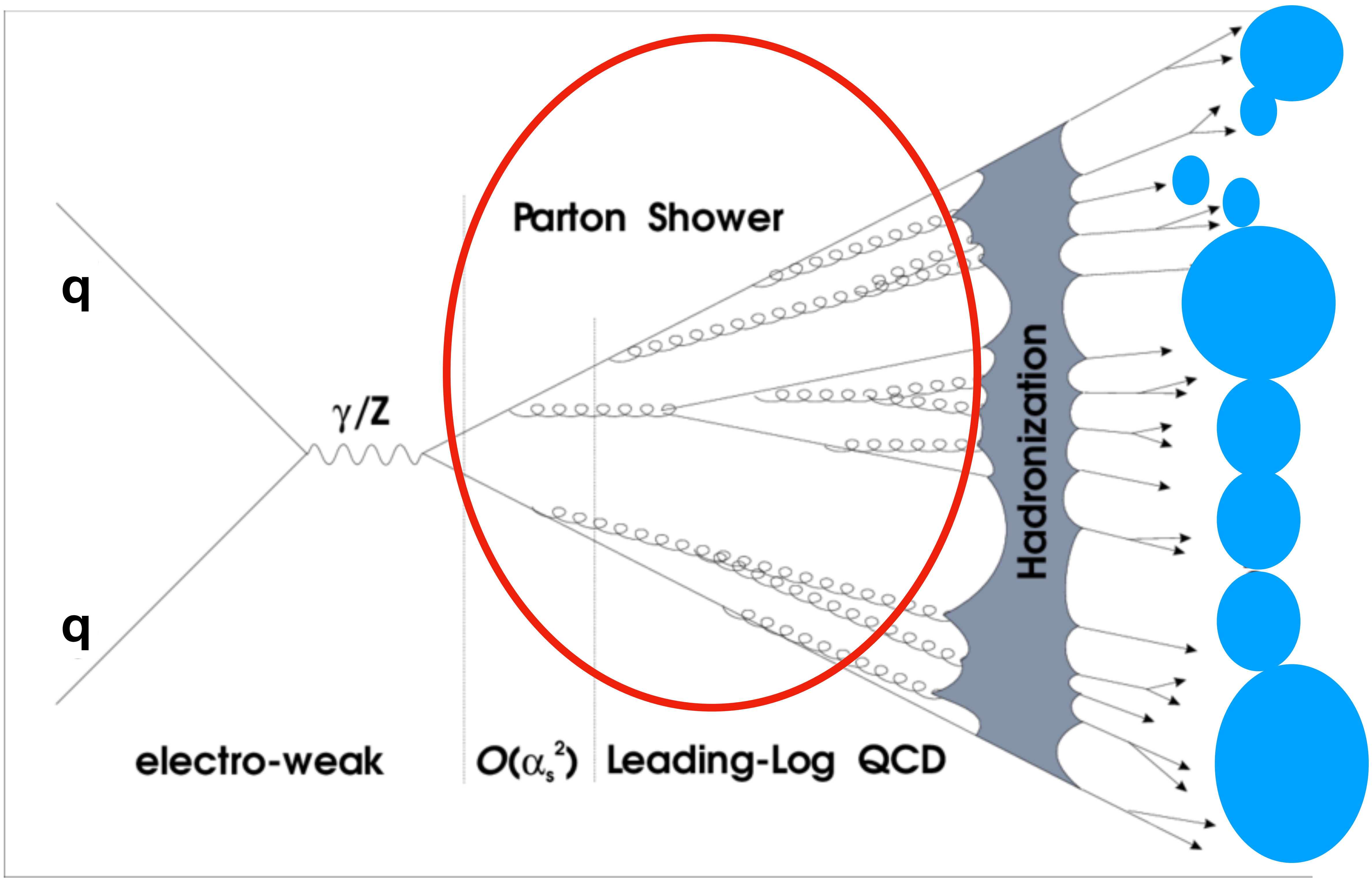
Confinement
(large distance)

asymptotic freedom
(short distance)

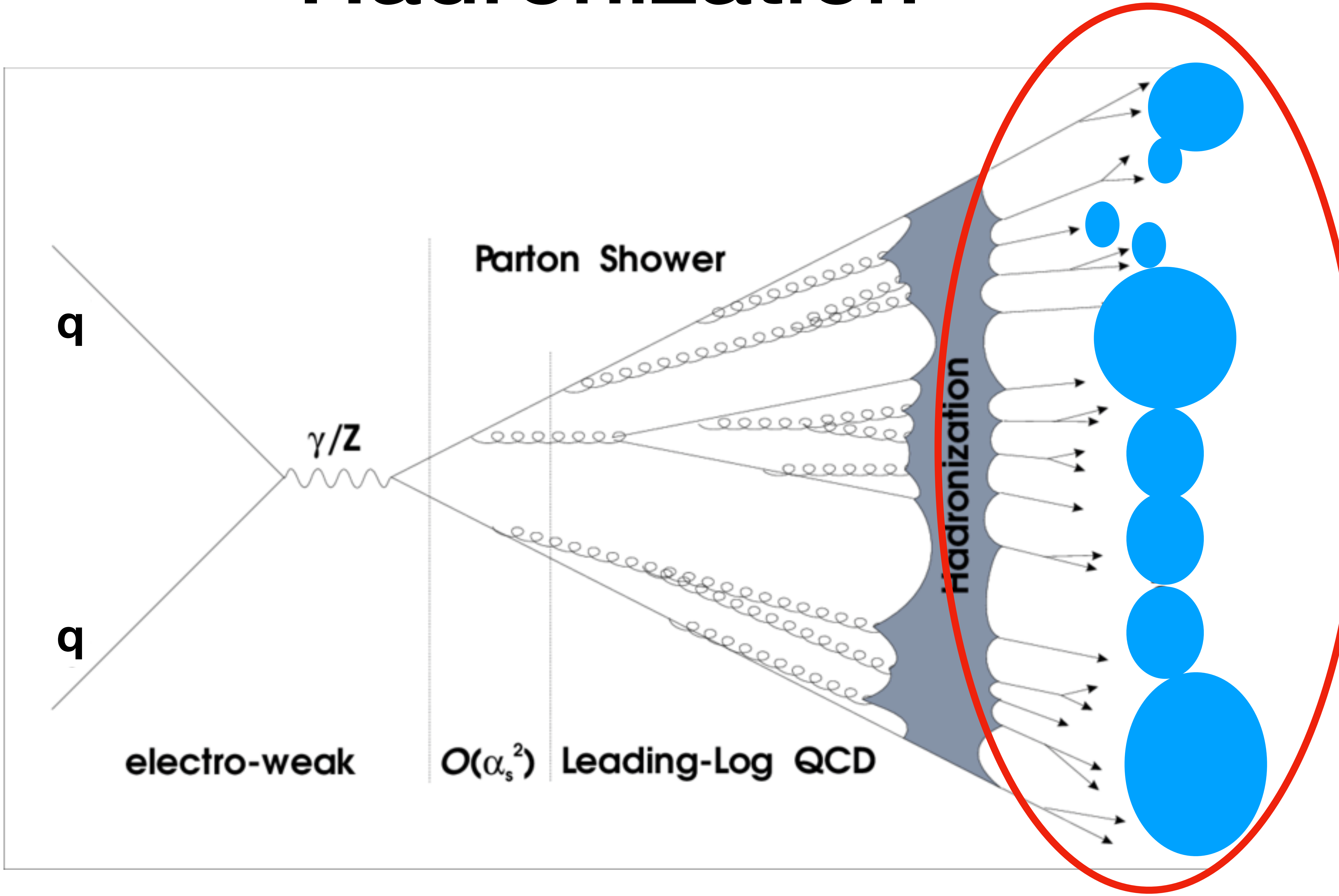
NB: no proof of confinement. We simply never observed quarks as free particles

G.Zanderighi

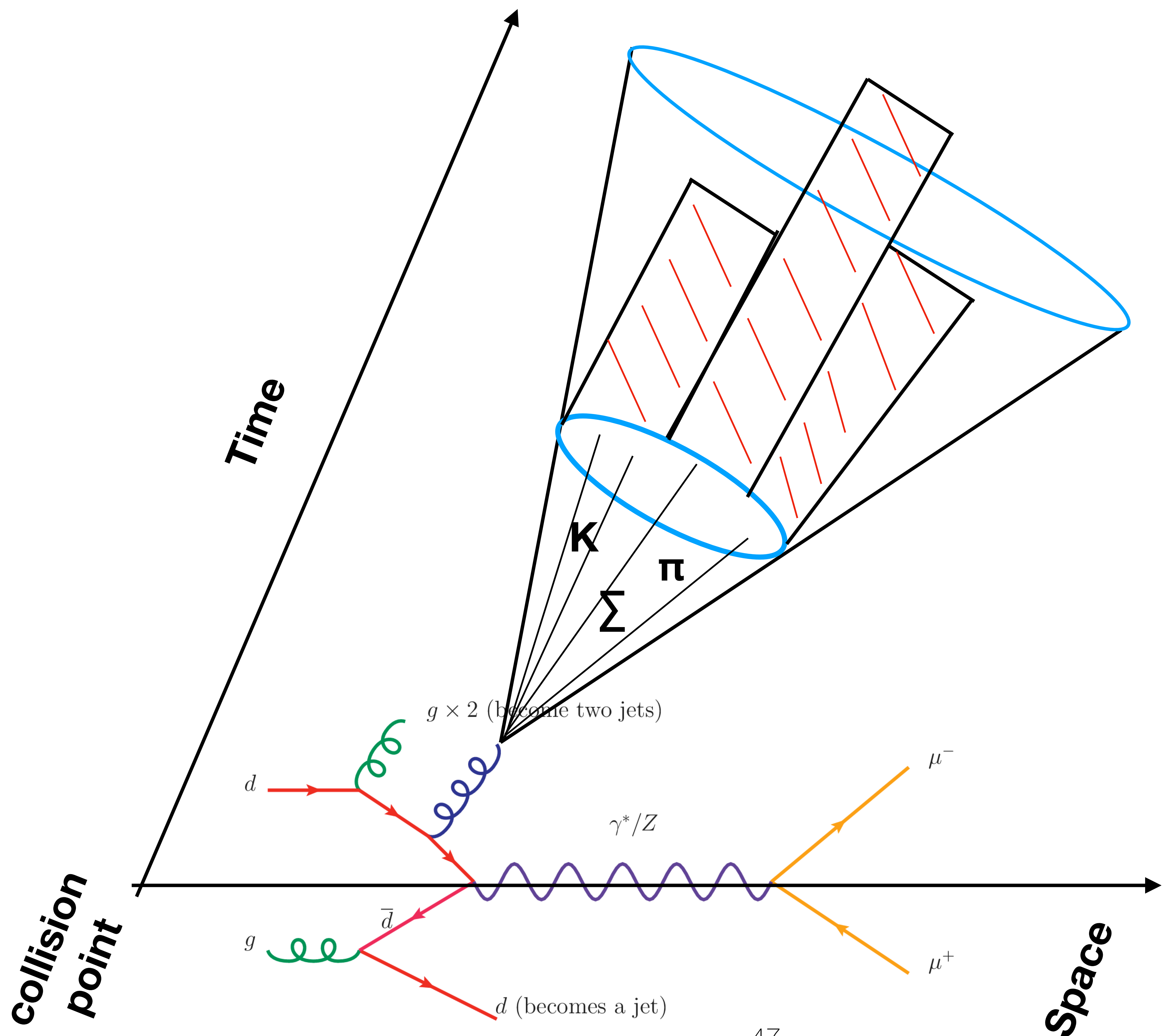
Parton Shower



Hadronization



Hadronization and Jets



Energy Deposit (calorimeter jet)

Particle Level (jet)

Quantum Chromodynamics

Jets Reconstruction *th

3 jet algorithms are currently used for various purposes at both ATLAS and CMS (AFAIK!)

All can be defined using a set of generalised distance parameters

constituent pT **angular separation**

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2} \qquad d_{iB} = k_{ti}^{2p}$$

Radius parameter **“Beam distance”**

indices *i* and *j* run over all candidate jet constituents

p = 1 : k_t algorithm

p = 0 : Cambridge/Aachen algorithm

p = -1: anti-k_t algorithm

Cluster as follows

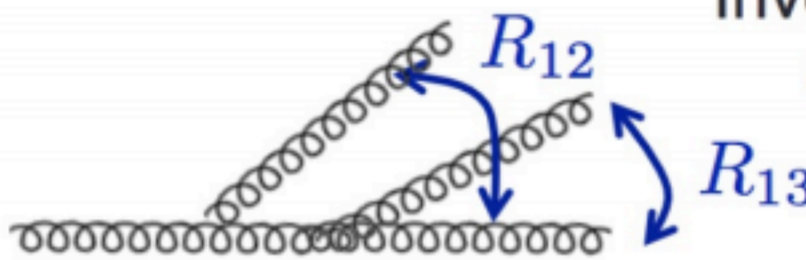
- work out all of the d_{ij} and d_{iB}
- Find the minimum of the d_{ij} and d_{iB}
- If it is a d_{ij} the combine *i* and *j*, if not, *i* is considered a final state jet and removed
- repeat until now particles are left

Jets Reconstruction *th

Cambride/Aachen algorithm

$$d_{ij} = \left(\frac{R_{ij}}{R_0}\right)^2$$

- clusters closest radiation first



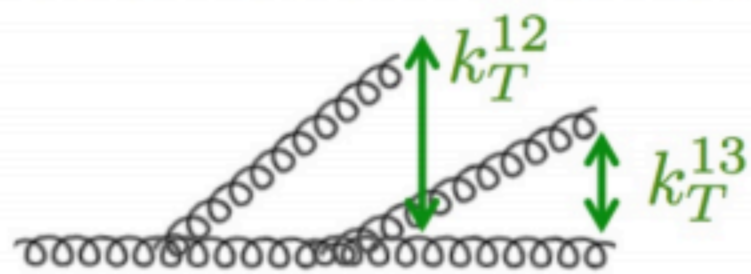
Inversion
of **Herwig shower**

---

k_T algorithm

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\left(\frac{R_{ij}}{R_0}\right)^2$$

- clusters hard collinear radiation first



Inversion
of **Pythia shower**

---

anti k_T algorithm

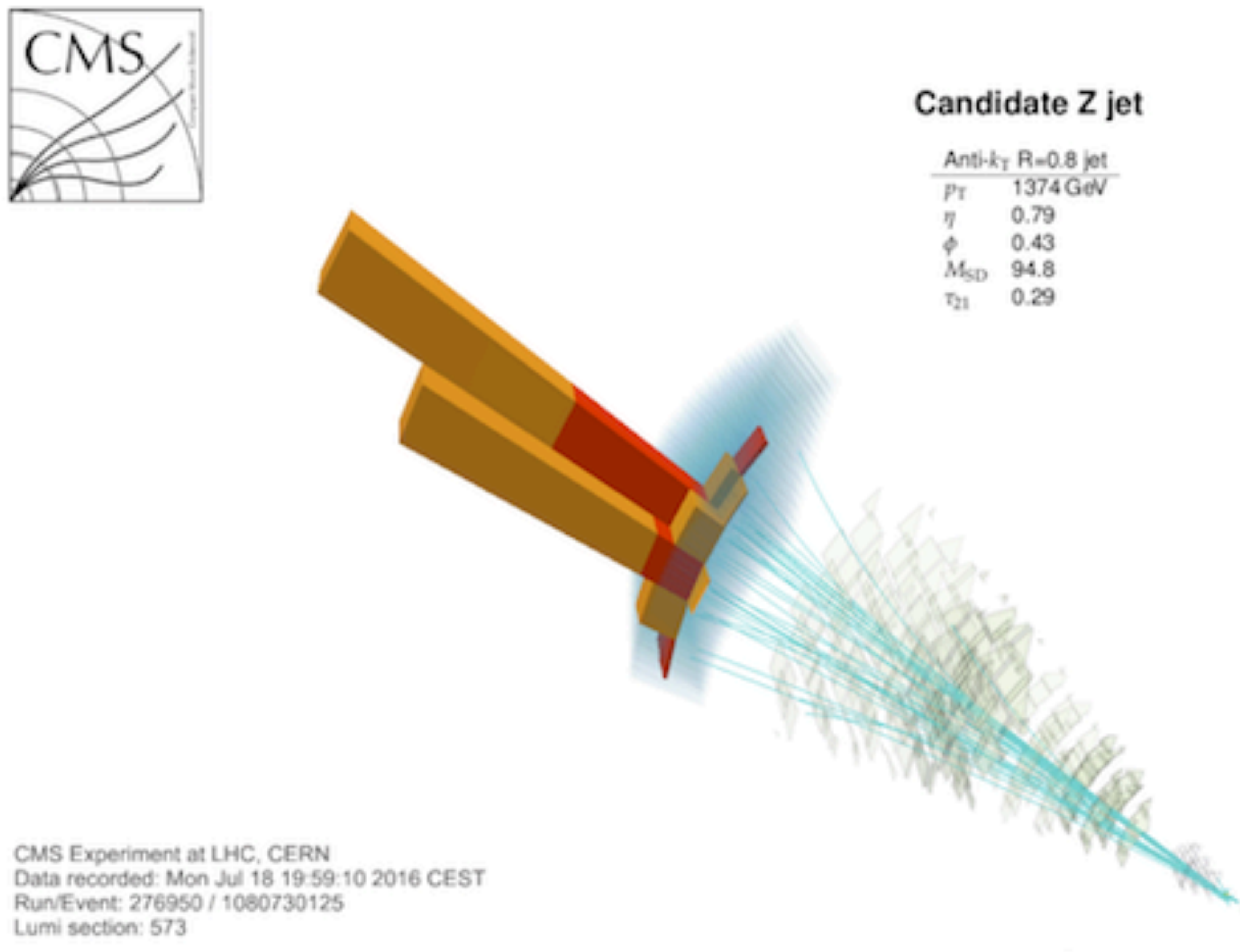
$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\left(\frac{R_{ij}}{R_0}\right)^2$$

- Clusters farthest first
- No inverse parton-shower interpretation

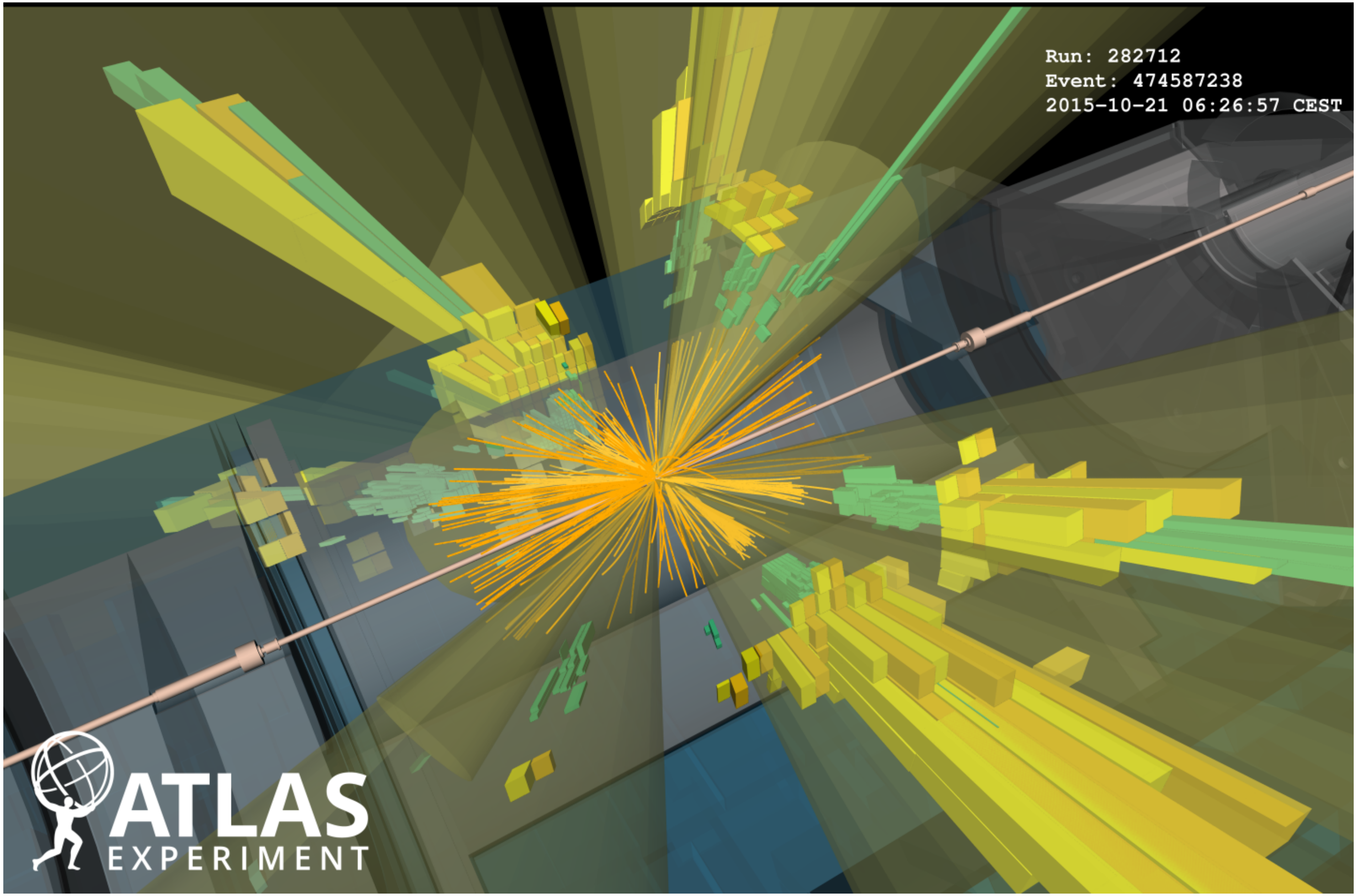
Other have their niche uses too (later)

- Produces round jets
- Almost exclusively used by ATLAS and CMS

Jets Reconstruction *exp



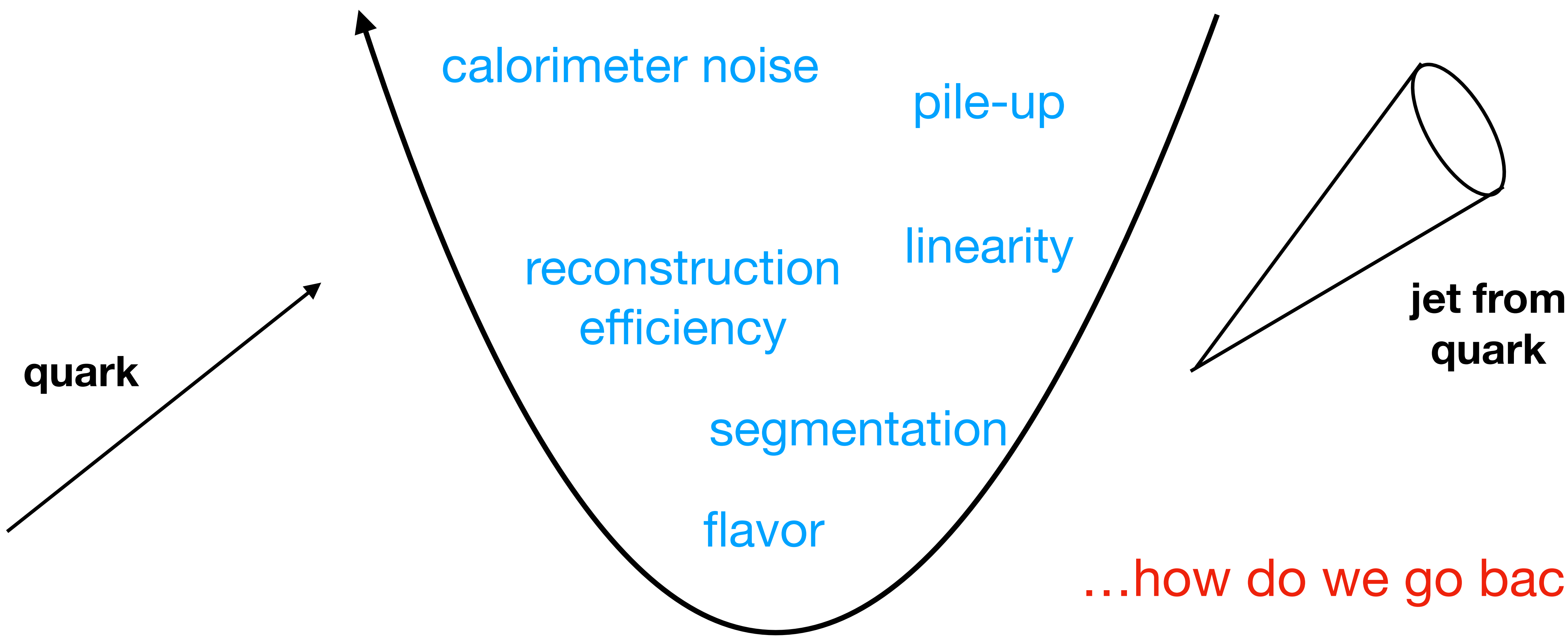
Jets Reconstruction *exp



Jet Energy Corrections

we want to measure the *particle* energy, but we do measure a detector response of the *jet* energy…

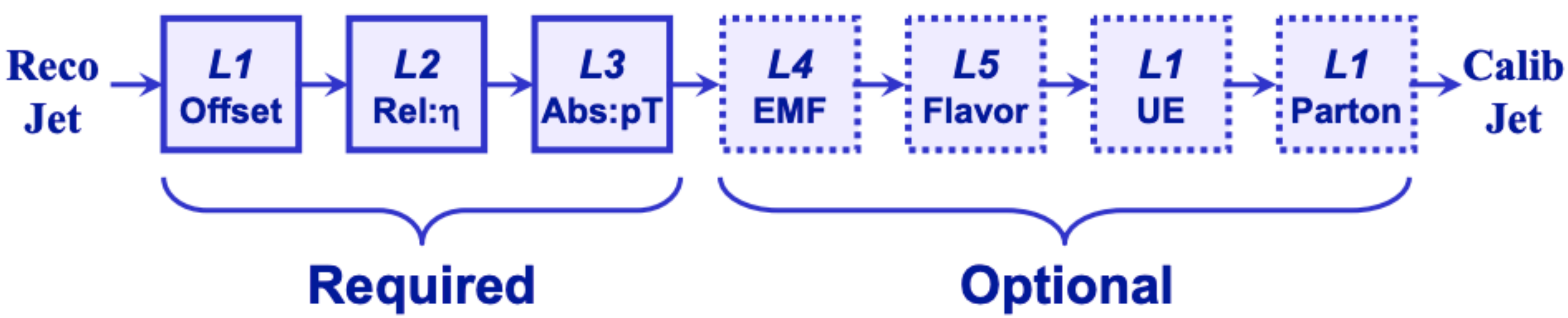
particle —-> detector —-> jet energy

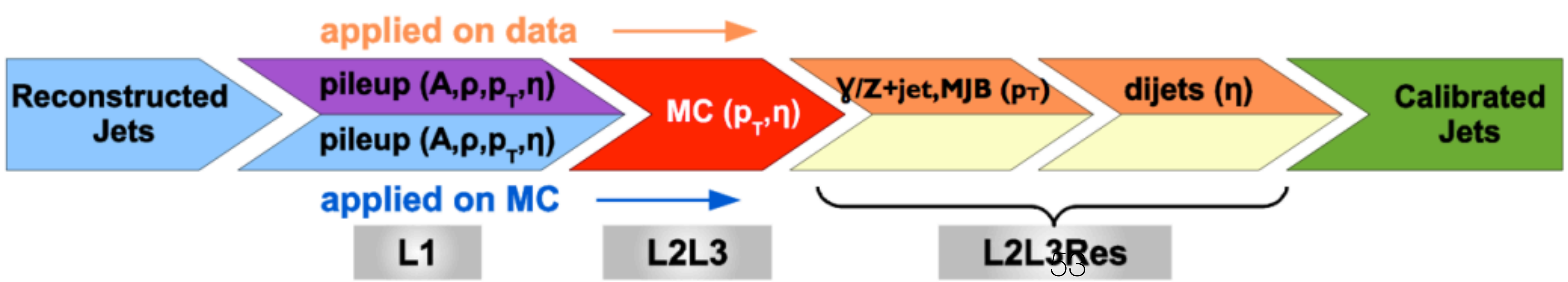


…how do we go back?

Jet Energy Corrections

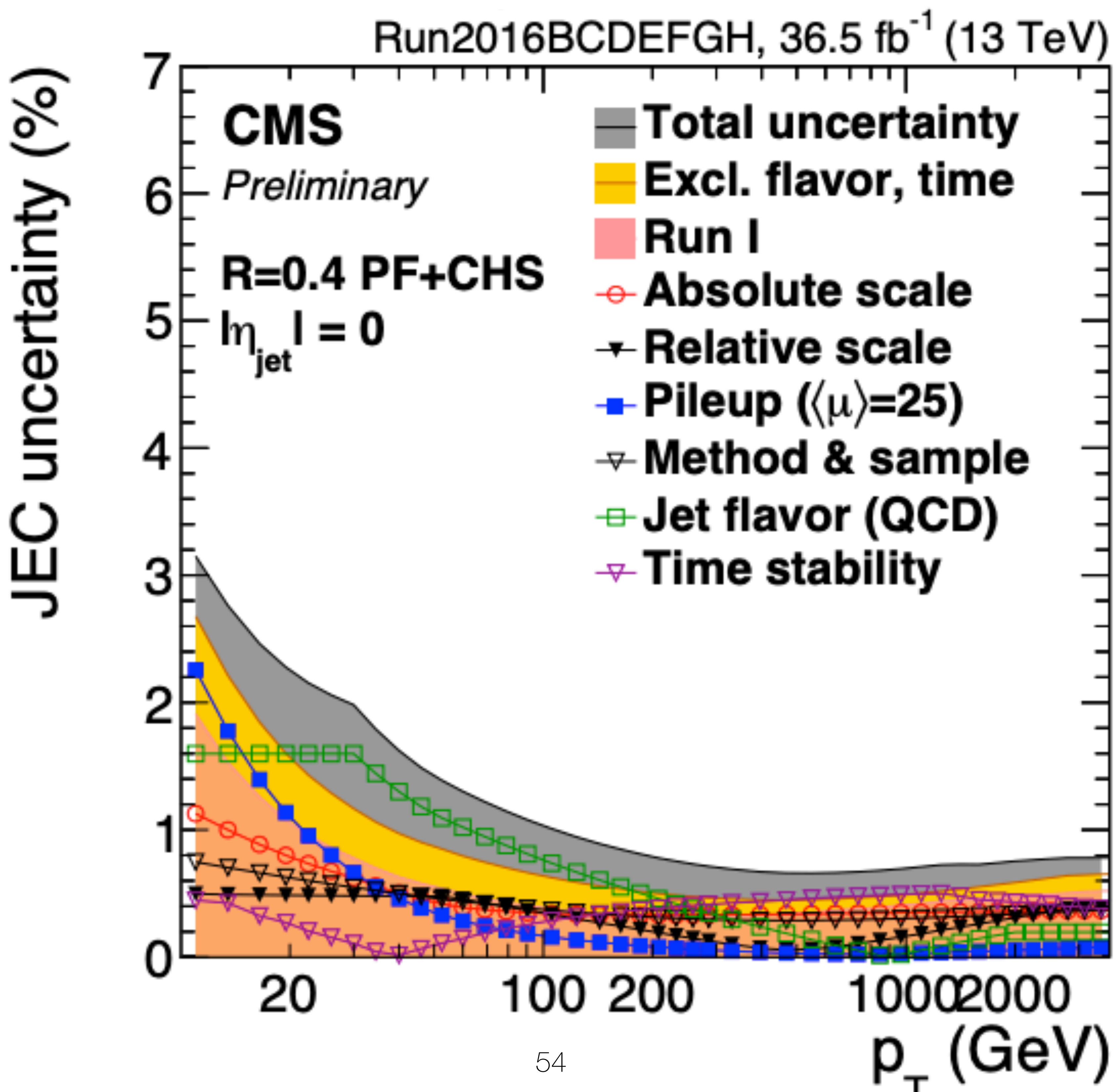
1. Offset: removal of pile-up and residual electronic noise.
2. Relative (η): variations in jet response with η relative to control region.
3. Absolute (p_T): correction to particle level versus jet p_T in control region.
4. EM fraction: correct for energy deposit fraction in em calorimeter
5. Flavor: correction to particle level for different types of jet (b, τ, etc.)
6. Underlying Event: luminosity independent spectator energy in jet
7. Parton: correction to parton level





$$\frac{<p_T^{RECO}>}{<p_T^{ptcl}>}(p_T^{ptcl}, \eta, \mu) = 1$$

Jet Energy Corrections



Pile-up Corrections

multiple pp collisions in the same bunch crossing = *in-time* pile up

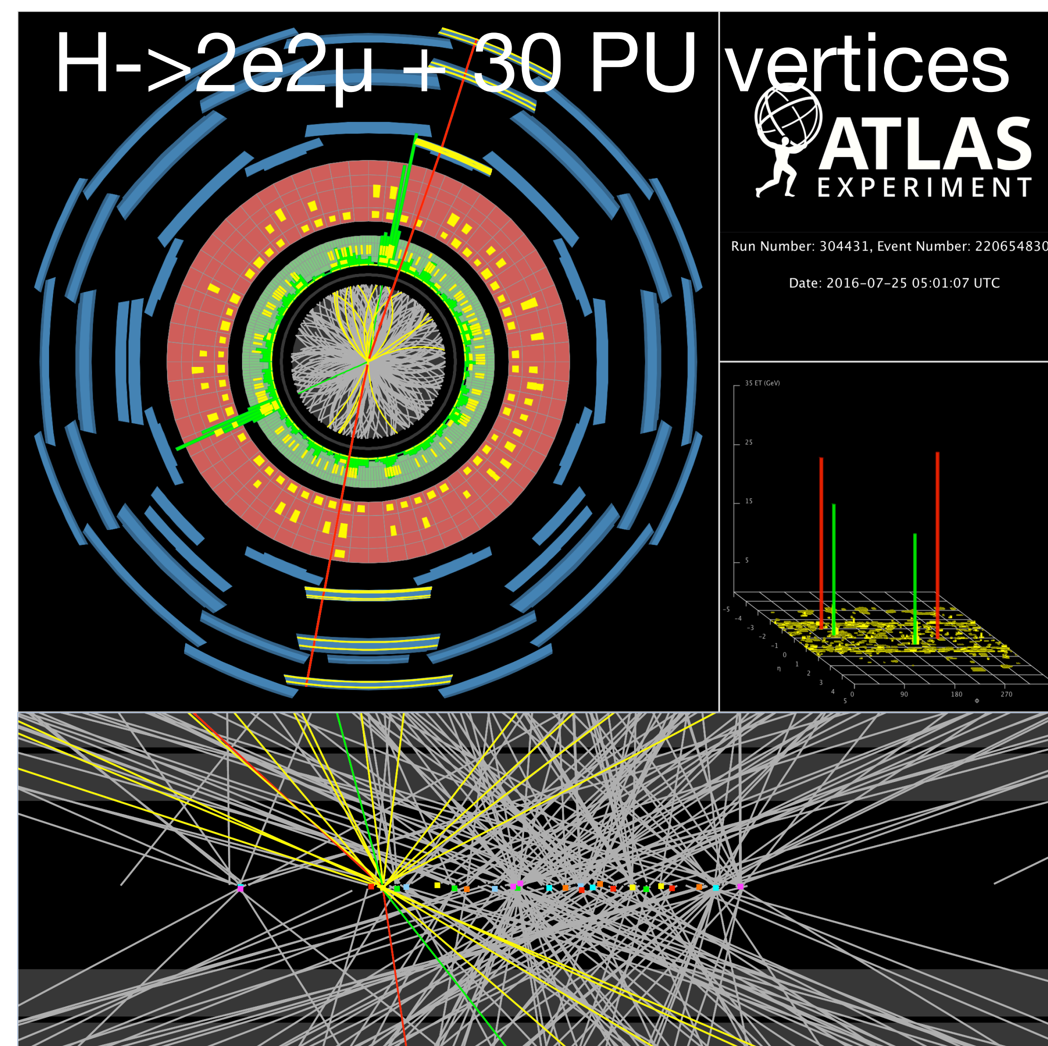
multiple pp collisions in different bunch crossing = *out-of-time* pile up

extra vertices => extra energy => extra particles!

- increasing with luminosity (~ linearly)
- at 13 TeV with 100/fb, up to 100 PU vertices!!

$$w_{\mathrm{PU}}(i) = \frac{N_{\mathrm{DATA}}(i)}{N_{\mathrm{MC}}(i)}$$

weights/event based on the Minimum Bias cross section and instantaneous luminosity



Pile-up Corrections

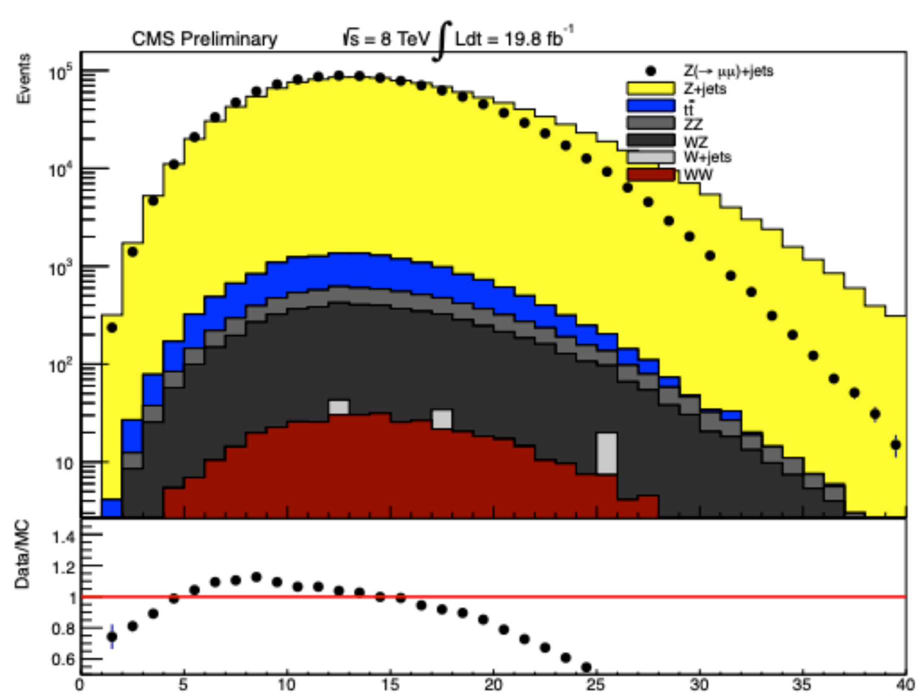
multiple pp collisions in the same bunch crossing = *in-time* pile up

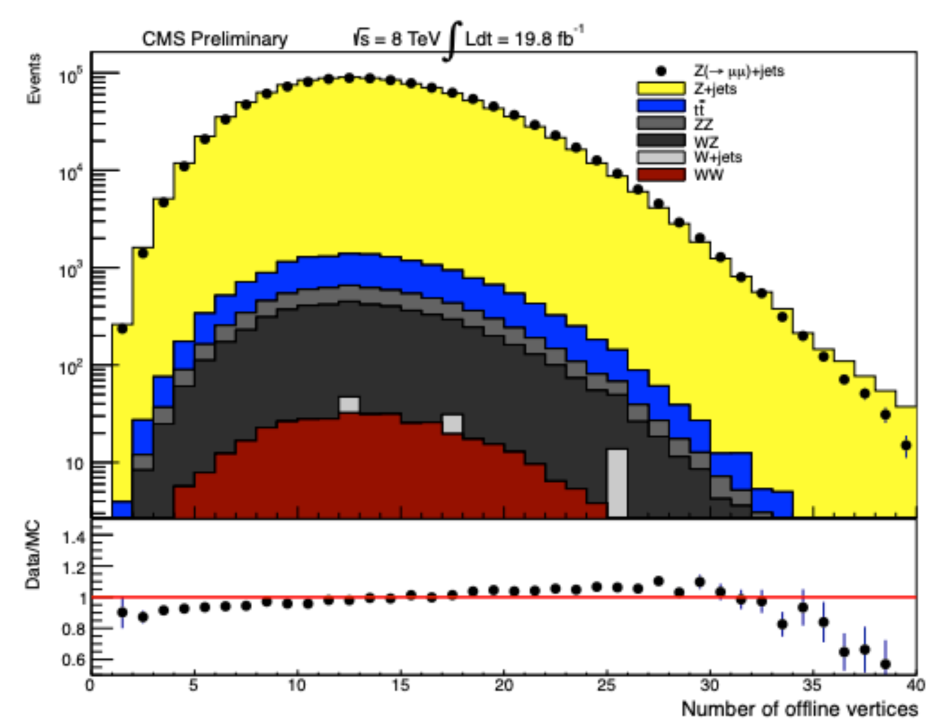
multiple pp collisions in different bunch crossing = *out-of-time* pile up

extra vertices => extra energy => extra particles!

- using MC to calculate the PU distribution:
  $\int$ L(bunch crossings) σ(total inelastic)

$$w_{\mathrm{PU}}(i) = \frac{N_{\mathrm{DATA}}(i)}{N_{\mathrm{MC}}(i)}$$





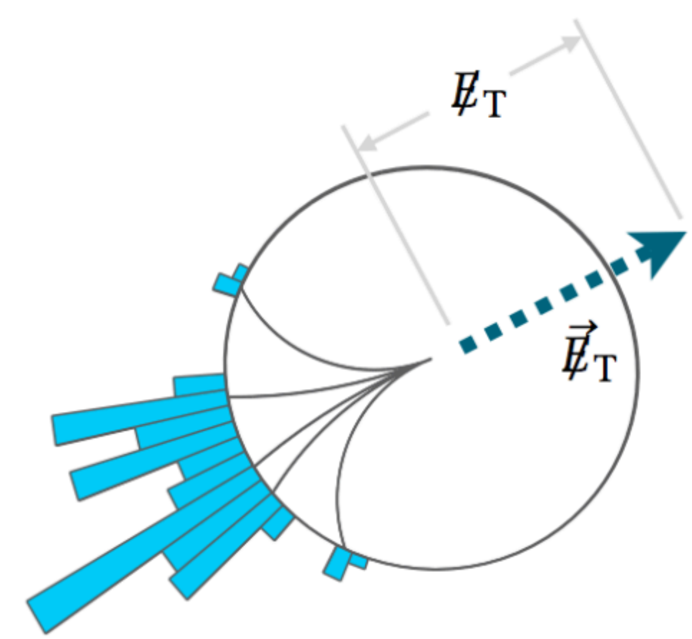
Missing Transverse Energy

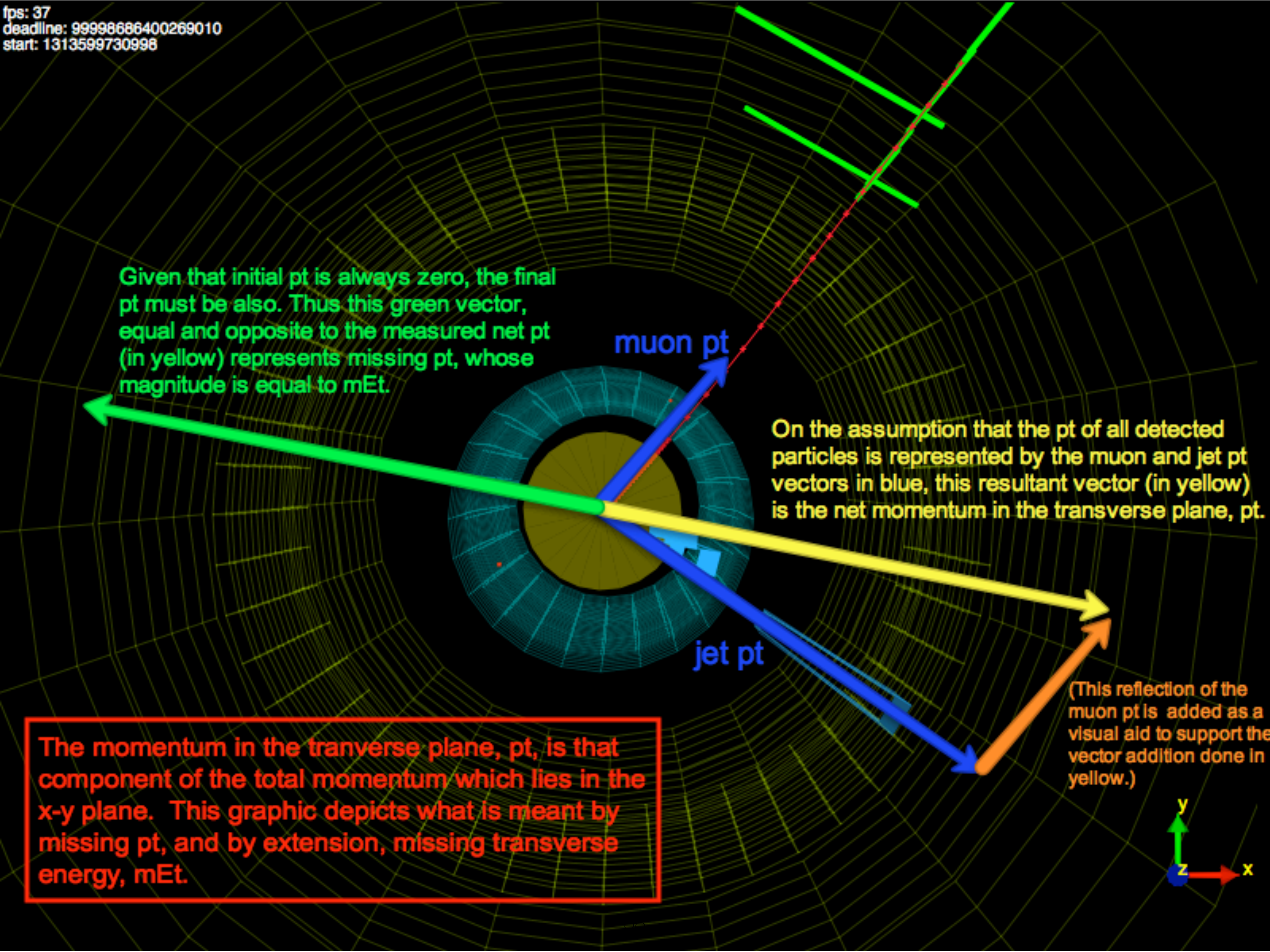
how do we infer the presence of neutrinos and potential new weak interacting neutral particles (like dark matter) in our experiment?

problem: disentangle the effect of detector leaks, PU, cosmics, halos ecc.

define a vector called missing transverse energy as the imbalance in the transverse plane:

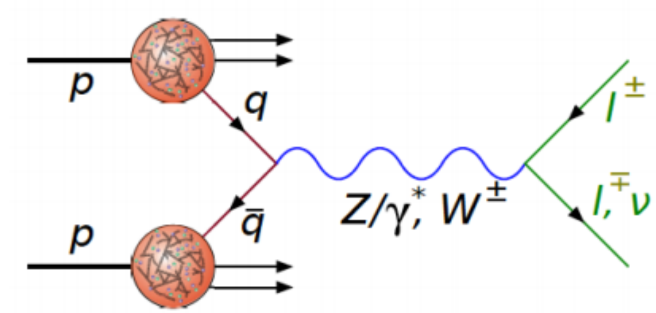
$$\not{E}_T = -\sum_i E_x^i - \sum_i E_y^i$$




fps: 37
deadline: 99998686400269010
start: 1313599730998
Given that initial pt is always zero, the final pt must be also. Thus this green vector, equal and opposite to the measured net pt (in yellow) represents missing pt, whose magnitude is equal to mEt.
muon pt
On the assumption that the pt of all detected particles is represented by the muon and jet pt vectors in blue, this resultant vector (in yellow) is the net momentum in the transverse plane, pt.
jet pt
(This reflection of the muon pt is added as a visual aid to support the vector addition done in yellow.)
The momentum in the tranverse plane, pt, is that component of the total momentum which lies in the x-y plane. This graphic depicts what is meant by missing pt, and by extension, missing transverse energy, mEt.
y
z
x

Missing Transverse Energy

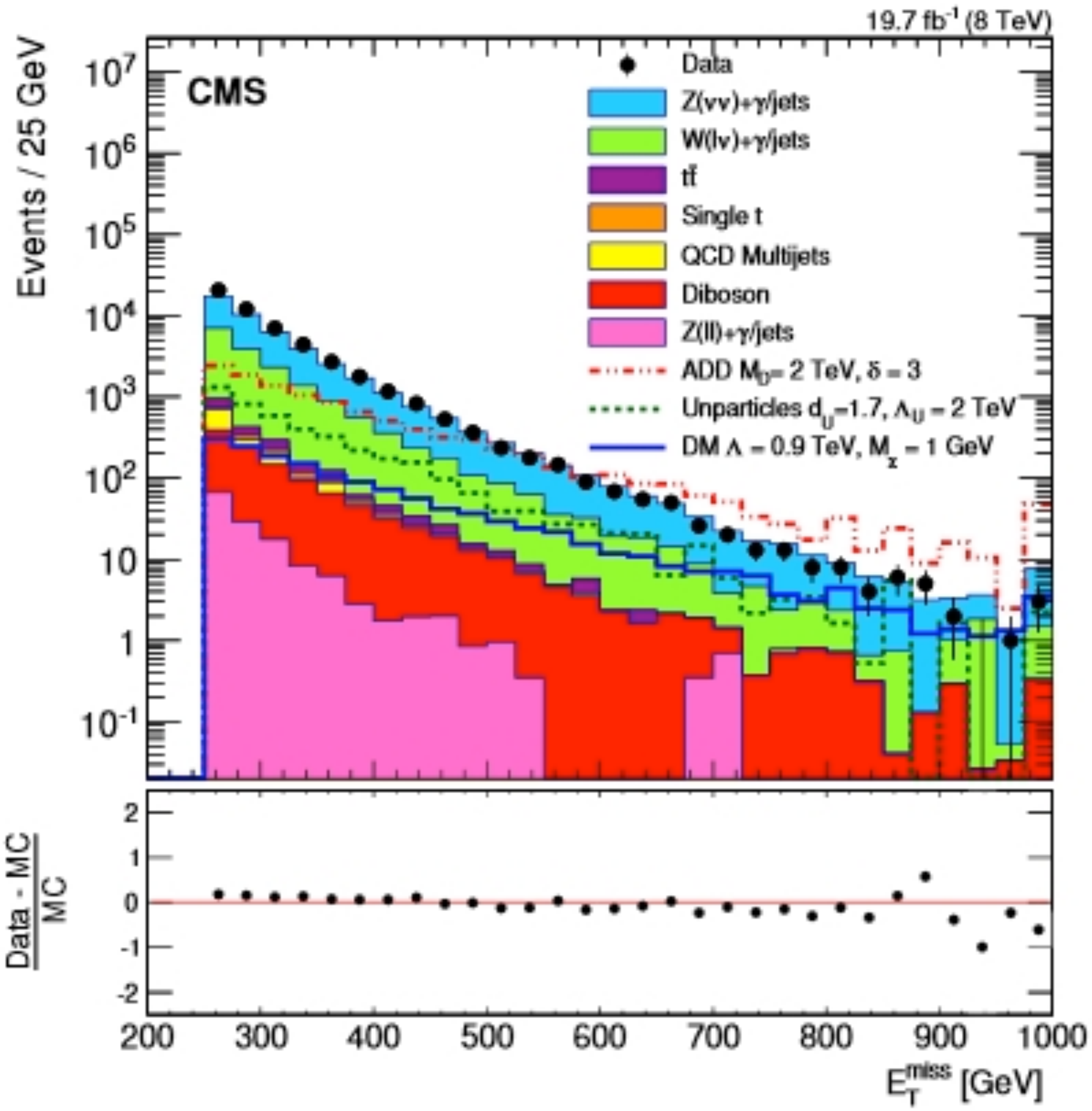
Example: the W boson mass

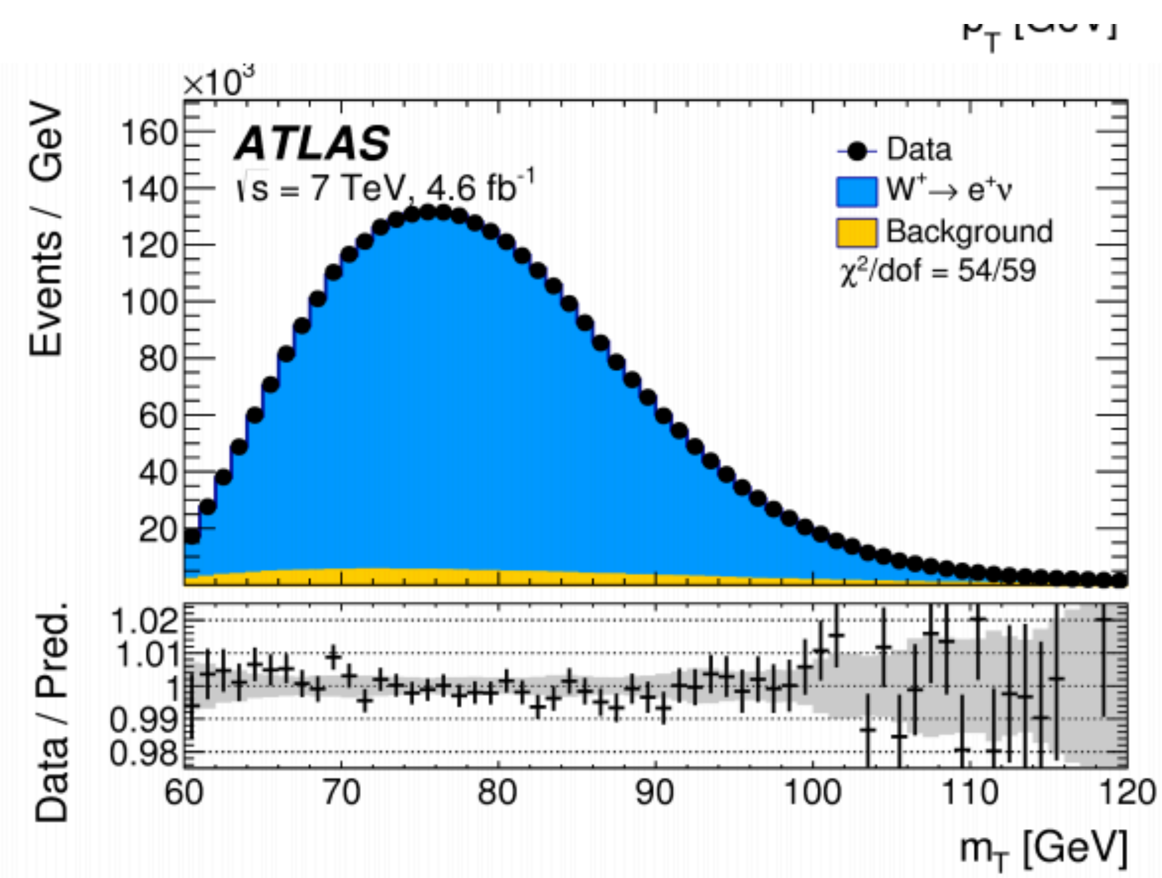


$$M_T = \sqrt{2 p_\ell \not{E}_T (1 - cos\Delta\phi)}$$

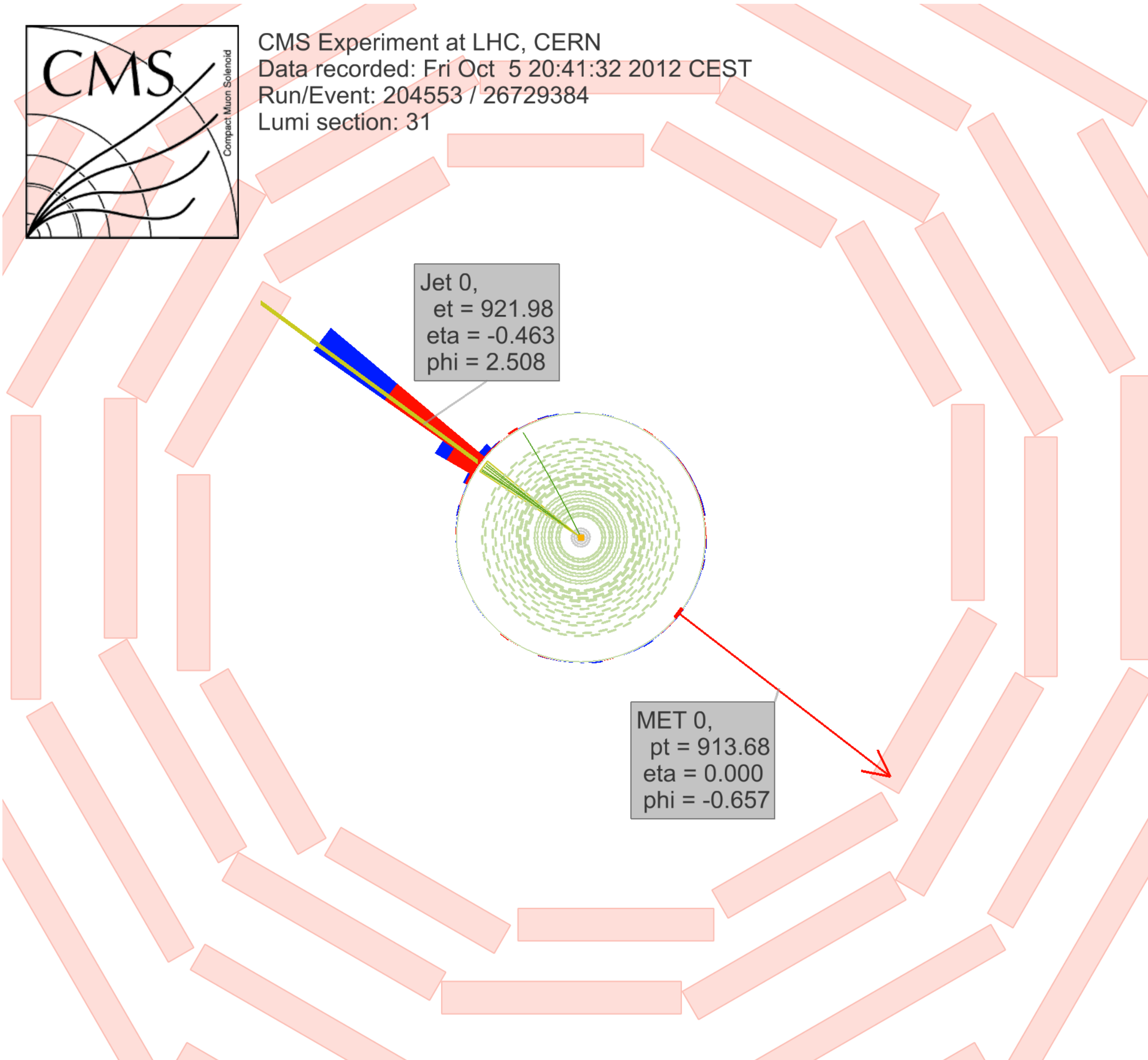
neutrino

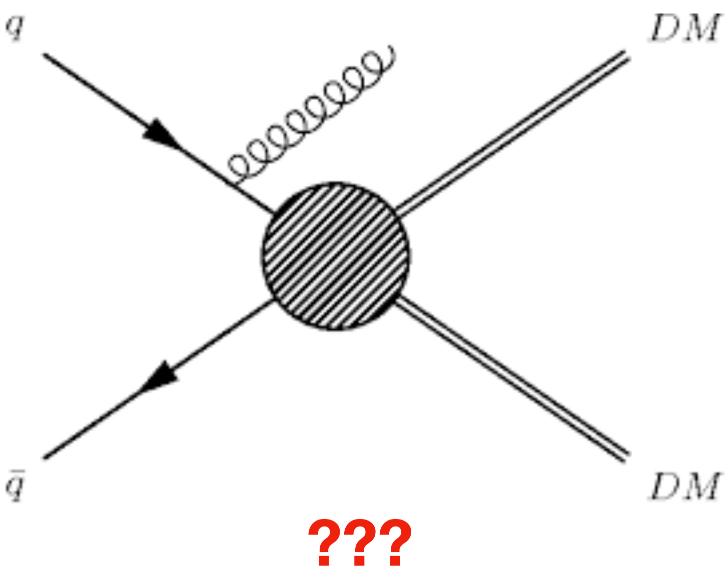
lepton-neutrino





Missing Transverse Energy

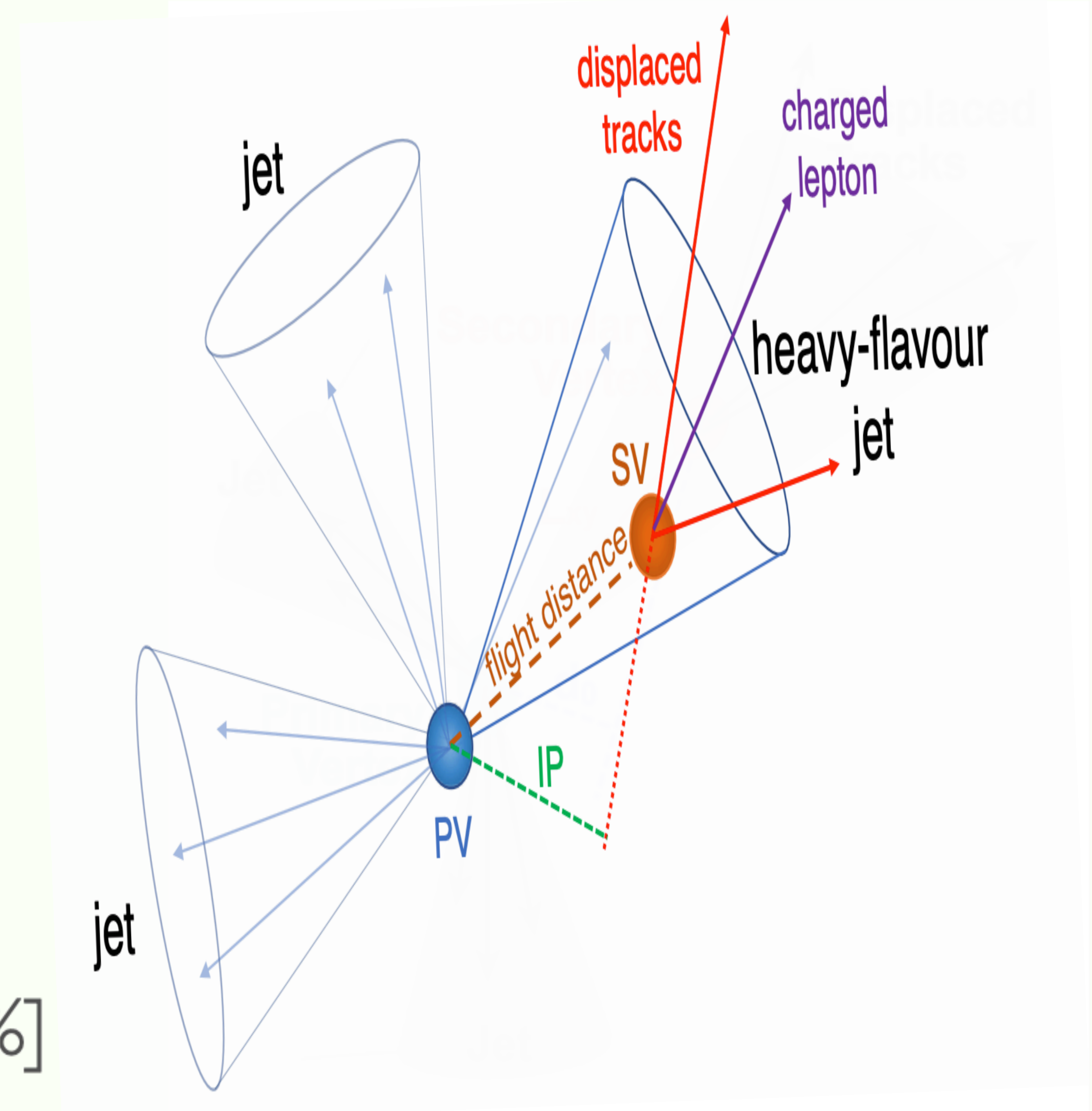




b-tagging

- **b jets** = jets that arise from the process of hadronization of b quarks
- Many physics analyses (Top, Higgs, Exotics) rely on efficient identification of b jets

- Use **B-hadron properties** to identify b jets:
  - Relatively large mass [5-6 GeV]
  - Long lifetime [$c\tau \approx 450\ \mu m$]
    E = 70 GeV gives $\beta\gamma c\tau \approx 5$ mm
  - Daughter particle multiplicity
    ≈ five charged tracks per decay
  - Possible presence of semileptonic decays
    $b \to \mu\nu X$ [Br ≈ 11%], $b \to c \to \mu\nu X$ [Br ≈ 10%]
  - Tertiary vertex
    (B-meson decay to a charmed hadron), $c\tau \approx 120$-$310\ \mu m$



(classic) b-tagging

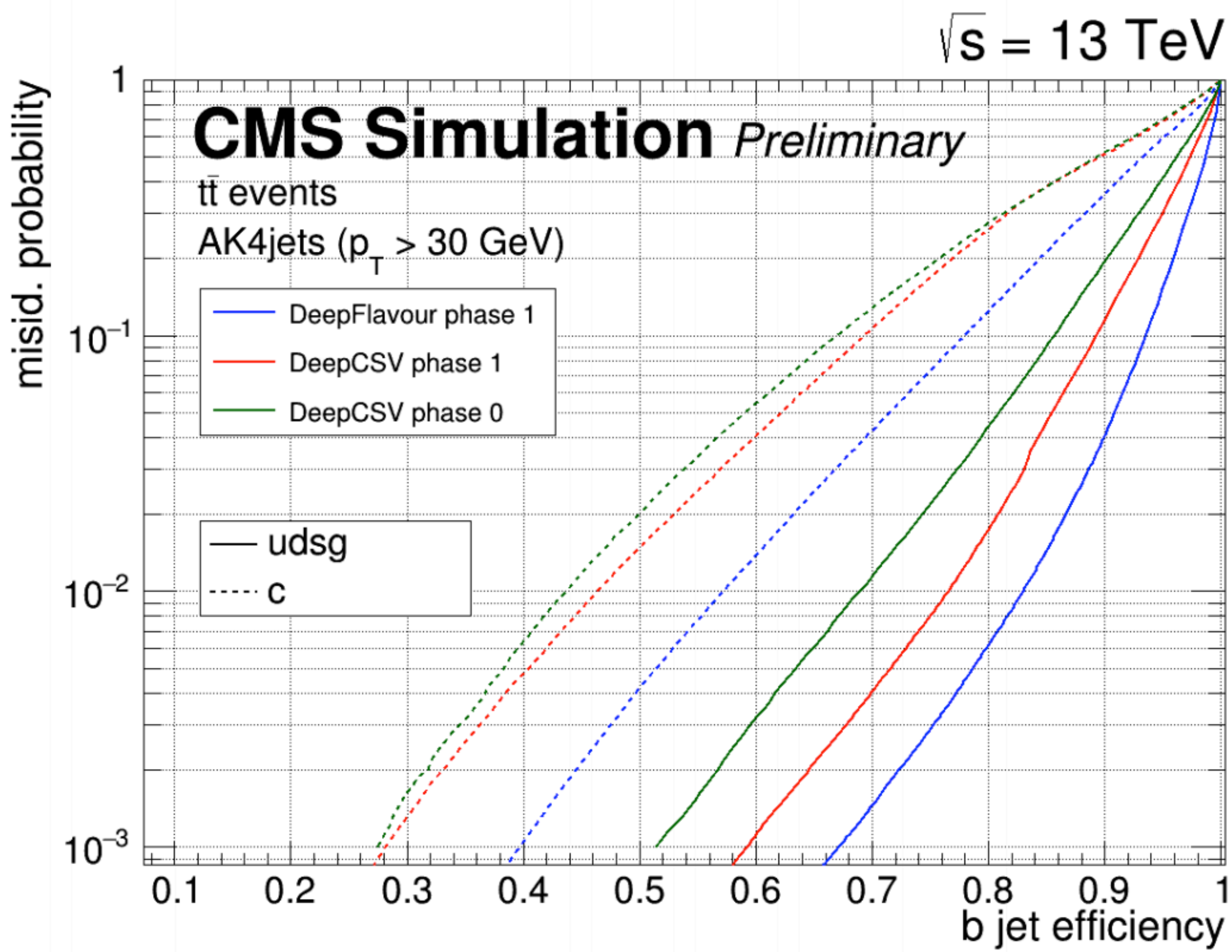
Algorithm	ATLAS	CMS
Impact parameter based	IP2D, IP3D, TrackCounting, JetProb	TCHP, TCHE, JP, JPB
Secondary vertex based	SV0, SV1, SV	SSVHP, SSVHE
Decay chain multi-vertex	JetFitter	
Soft lepton	SMT, p_TRel	Soft Lepton Taggers
Multivariate	JetFitterCombNN, MV1c, **MV2c00**, **MV2c20**	CSV, **CSVv2**, **cMVAv2**

Operating points either based on b-tagging or mis-tagging efficiencies:

b-tag: 60%, 70%, 77%, 85% (ATLAS)
mis-tag: 0.1%, 1%, 10% (CMS)

Flagship
b taggers

(classic) b-tagging



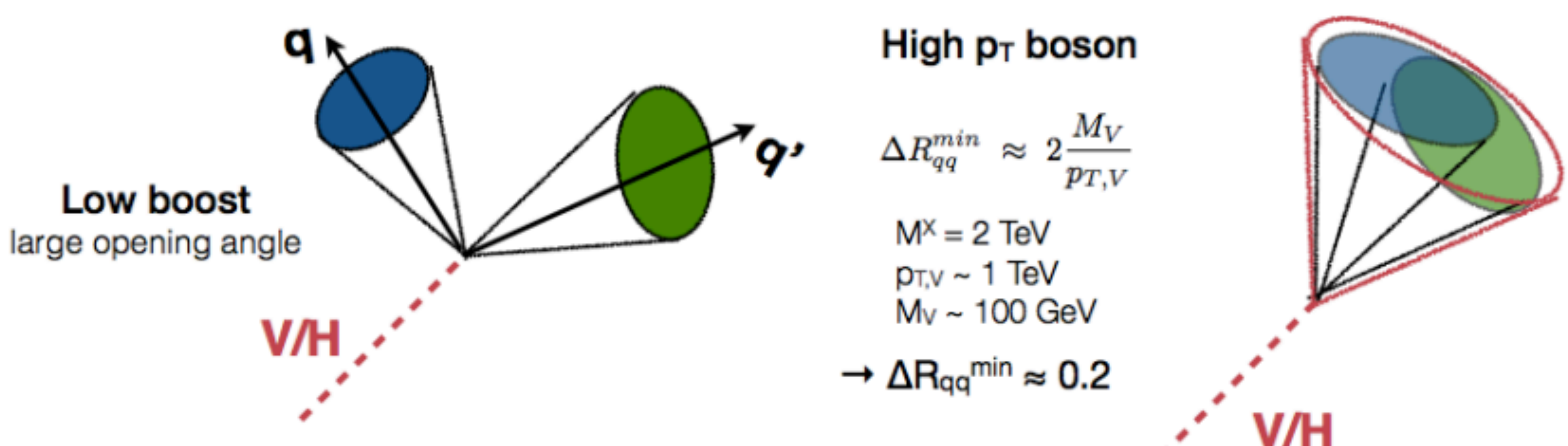
"ROC*" curve

**Receiver operating characteristic*

Jet Substructure

boosted topologies @ LHC

- For high mass resonances bosons get high boost (pT > 200 GeV)
- Hadronic VV/VH final states might merge into a single V/H-jet
- Leptonic VV/VH final states: at high boost leptons overlap in the isolation cones -> special reconstruction applies
- V/H-jet reconstructed with the CA algorithm with large ΔR



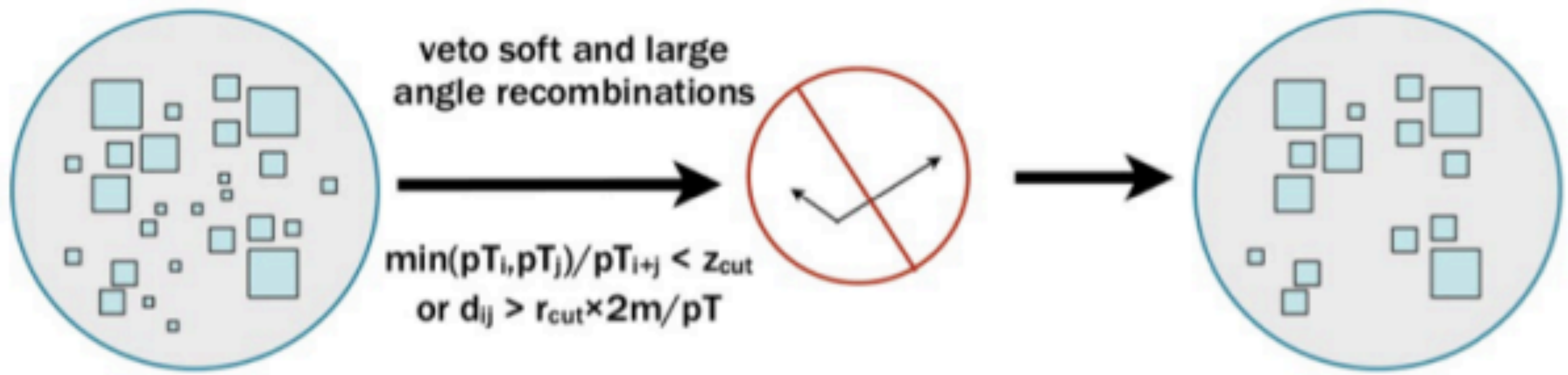
Jet Substructure

Pruning

[Phys.Rev.D 80 051501]

attempts to remove from the jets those constituents that are unlikely to be associated with the jet

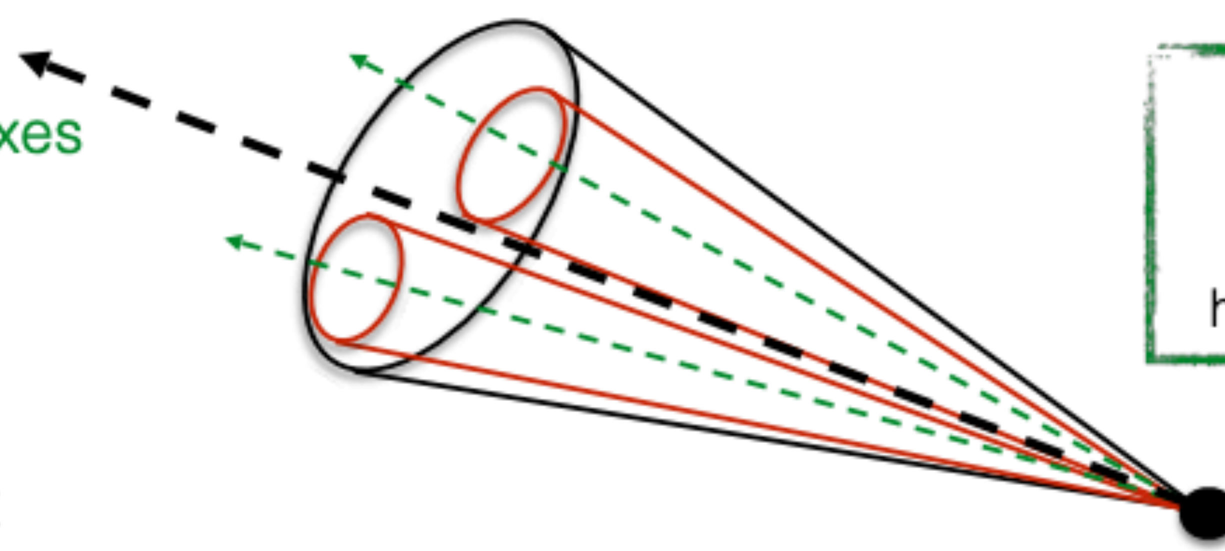
depends on two parameters: *z*, *r*



removes soft and wide angle radiation (PU, UE)

sub-jet axes

jet axes



small τ_N indicates subjet hypothesis

N-Subjettines

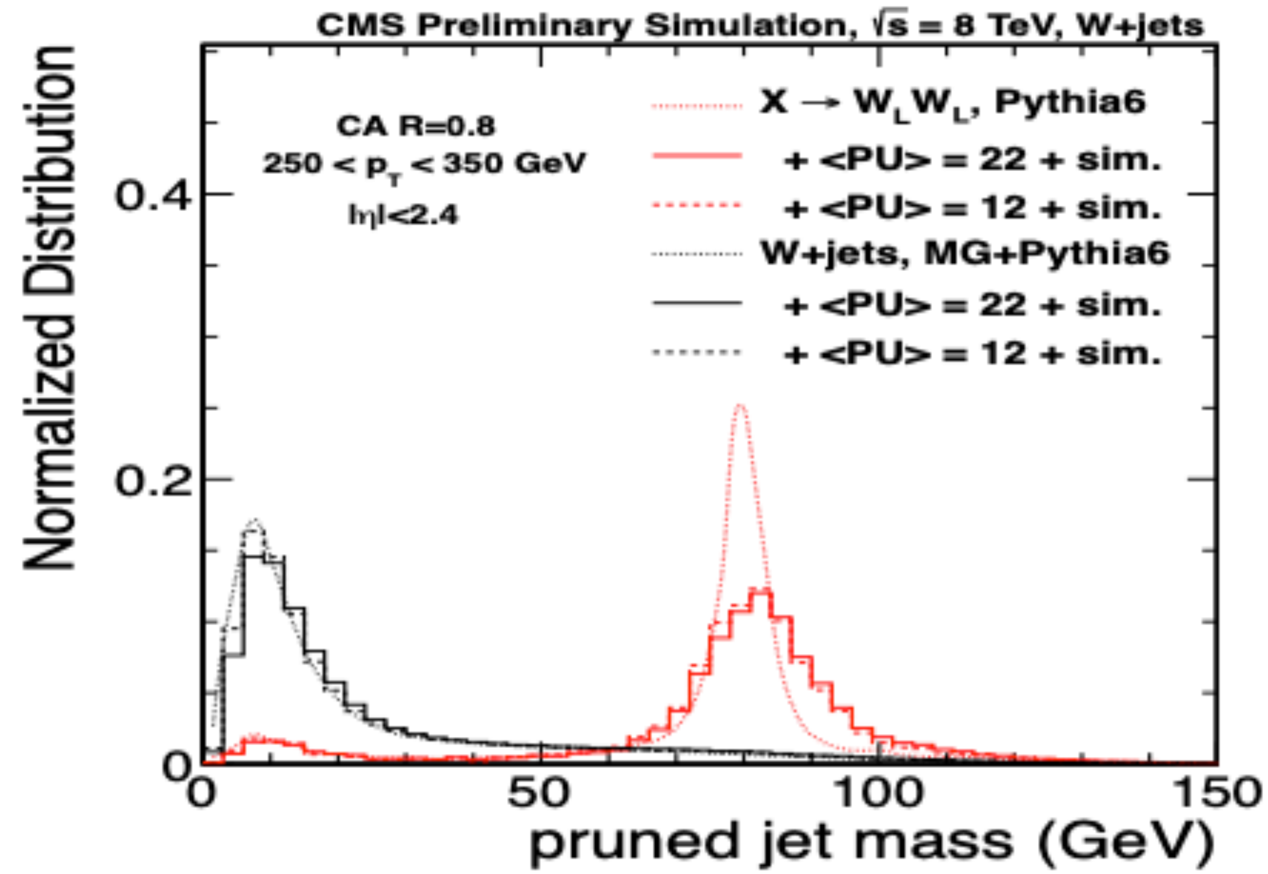
[JHEP03(2011)015]

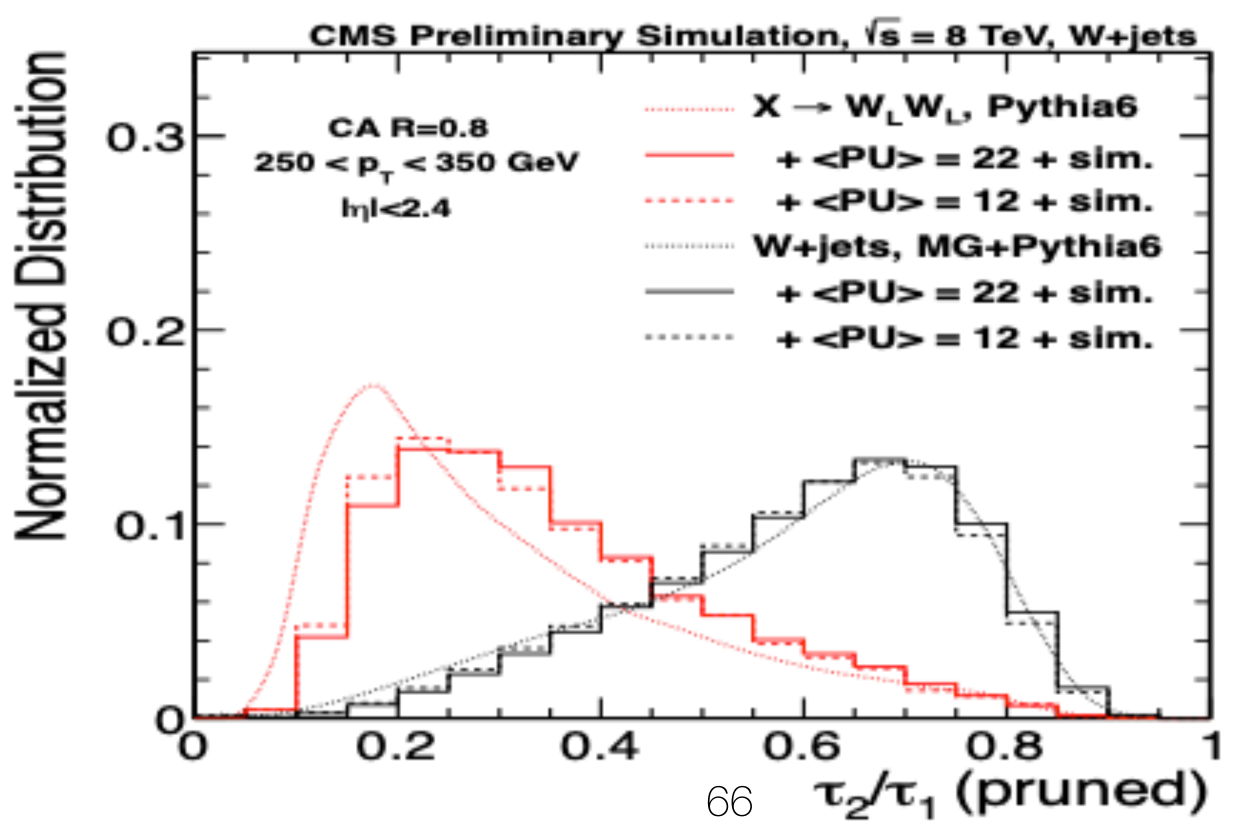
Quantifies to what degree jet can be regarded as a jet composed of N jets
Discriminate a composite jet w.r.t. a “standard” QCD jet

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} min\{\Delta R_{1,k}, ..., \Delta R_{N,k}\}$$

p_T-weighted sum over all jet constituents of their distance w.r.t. the closest of N axes in a jet

Jet Substructure





application: H-tagging

- Crucial aspect of the search strategy is the H→bb reconstruction
- highly boosted Higgs produce collimated pairs of b jets
- merged into a single b jet (*fat-b jet*) [using AK08]
- exploiting the jet substructure and the b tagging
- b tagging : CSVv2 algorithm

$\Delta R(bb) \sim 2m^H / p_T^H$

next lesson!

Two Approaches in CMS

subjet b tagger

identify the two subjets by undoing the last iteration of the clustering

apply the b tagging on them

double b tagger

reconstructing the 2 B hadrons within the same fat jet (inclusive vertex finder)

MVA combining tracks associated to tau-axes and svtx observables to separate Hbb to QCD jets

[CMS-PAS-BTV-15-002]

10