UNIVERSITÄT BONN

Experiments in High Energy Physics

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1862
RIGA TECHNICAL UNIVERSITY

Institute of Particle Physics and Accelerator Technologies

BALTIC SCHOOL OF HIGH ENERGY PHYSICS AND ACCELERATOR TECHNOLOGIES

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Scope of the Lectures

Experimental particle physics at high energy colliders
with emphasis on LHC (currently running highest energy collider)

Today:

What we would like to measure (pheonomenology of hadron collisions)
and how (detectors)

Tomorrow:

Where we are (measurement of the Higgs boson profile)

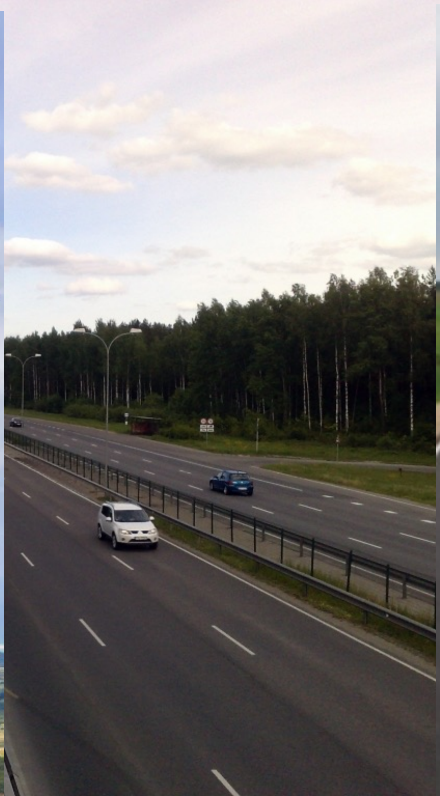
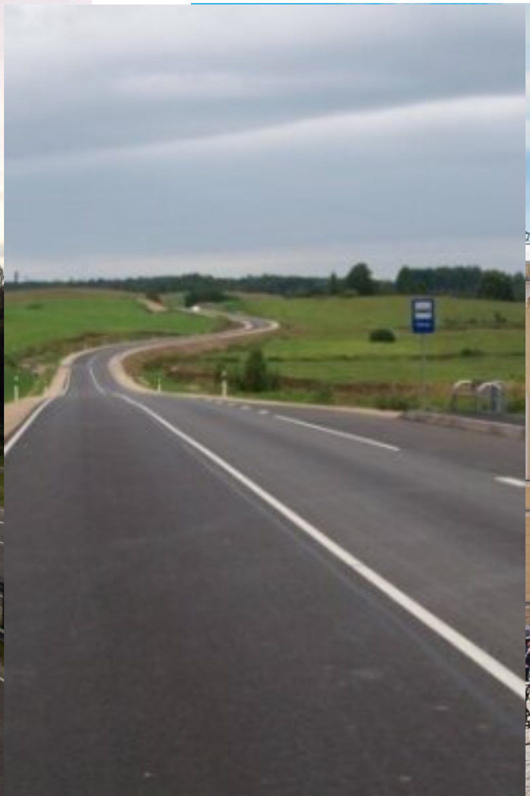
Challenge questions

PART I

1. What we would like to measure

It´s a long long way from

Bonn to Kuldīga

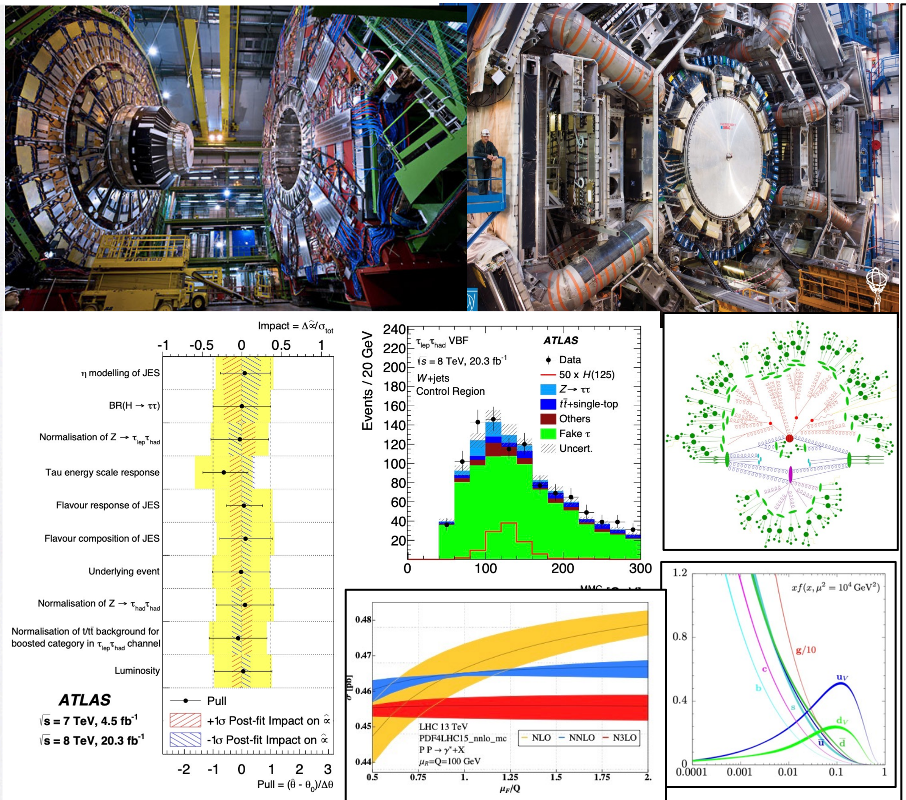

1. What we would like to measure

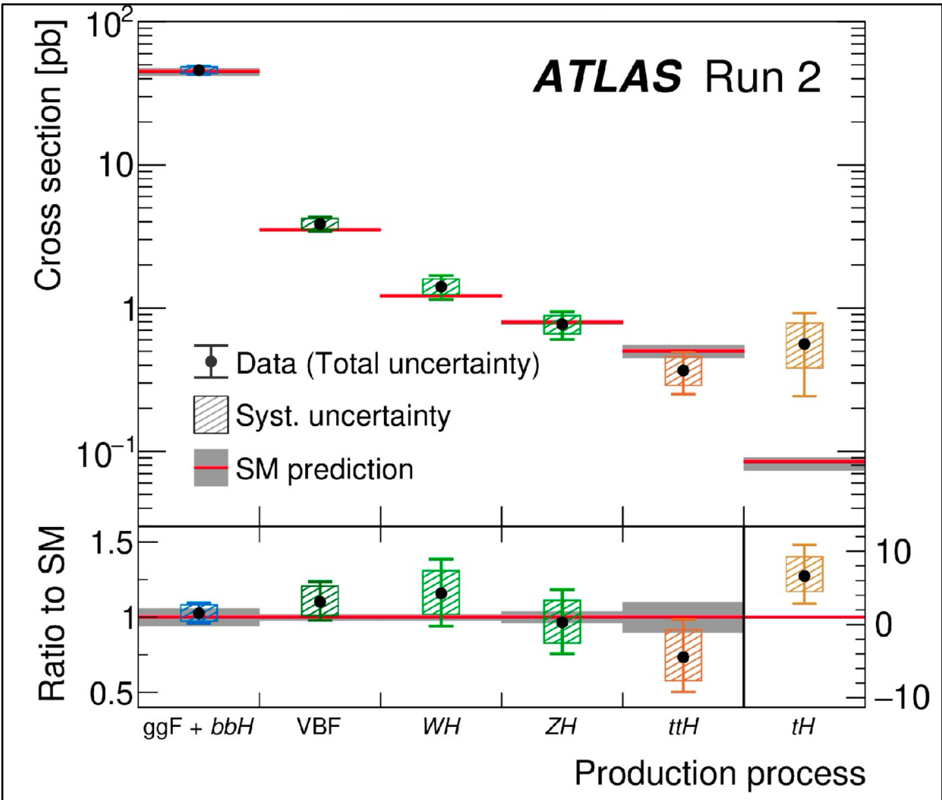
It´s a long long way from

a Geiger Counter

to (e.g.)

Higgs boson cross sections

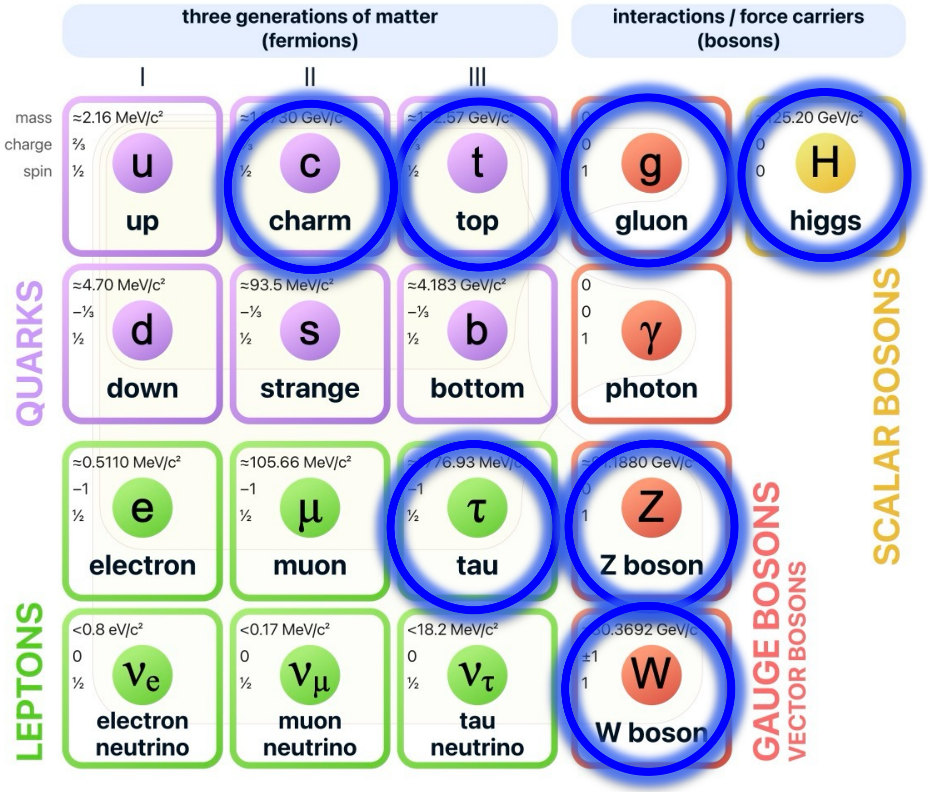




1. What we would like to measure

Particle physics: study (most) microscopic structure of Nature

- What are the smallest/elementary building blocks of matter?
- How does this matter interact (forces)?
- How does the microscopic structure shape our view of the Universe?



○ = „discovered at colliders“

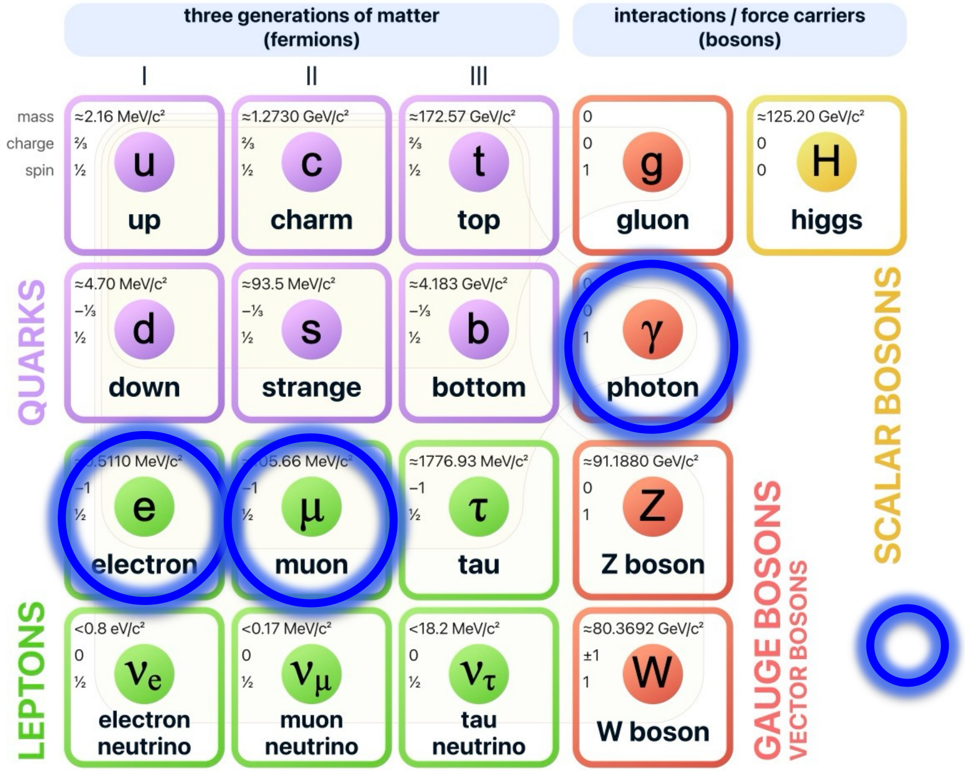
…dass ich erkenne, was die Welt
im Innersten zusammenhält

(That I may detect the inmost force
Which binds the world, and guides its course;)

Goethe, Faust

1. What we can measure (at colliders)

Can we detect an electron?	yes
Can we detect a muon?	yes
Can we detect a tau lepton?	no*
Can we detect a neutrino?	no*
Can we detect a quark?	no
Can we detect a gluon?	no
Can we detect a photon?	yes
Can we detect a W/Z boson?	no
Can we detect a Higgs boson?	no



= „directly detectable at colliders“

Detection (reconstruction) of most fundamental particles has to proceed indirectly

Infer their presence from detection and reconstruction of measurable particles:

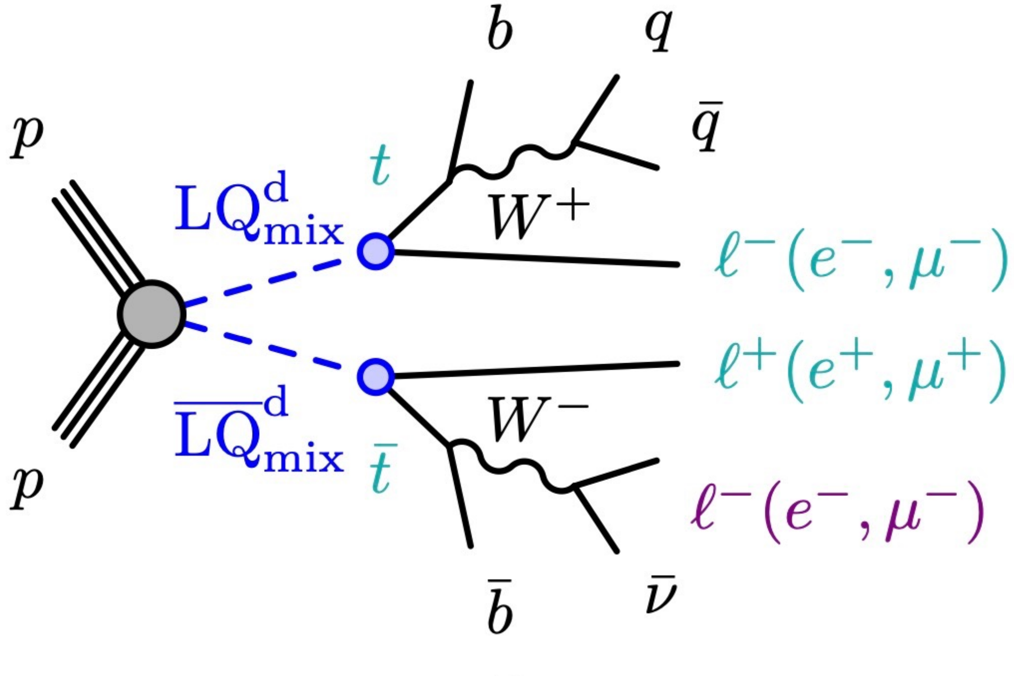
- decay
- hadronisation
- E/p conservation

This inference requires a lot of „theory“ + „modelling“ + „auxillary measurements“

1. What we can measure (at colliders)

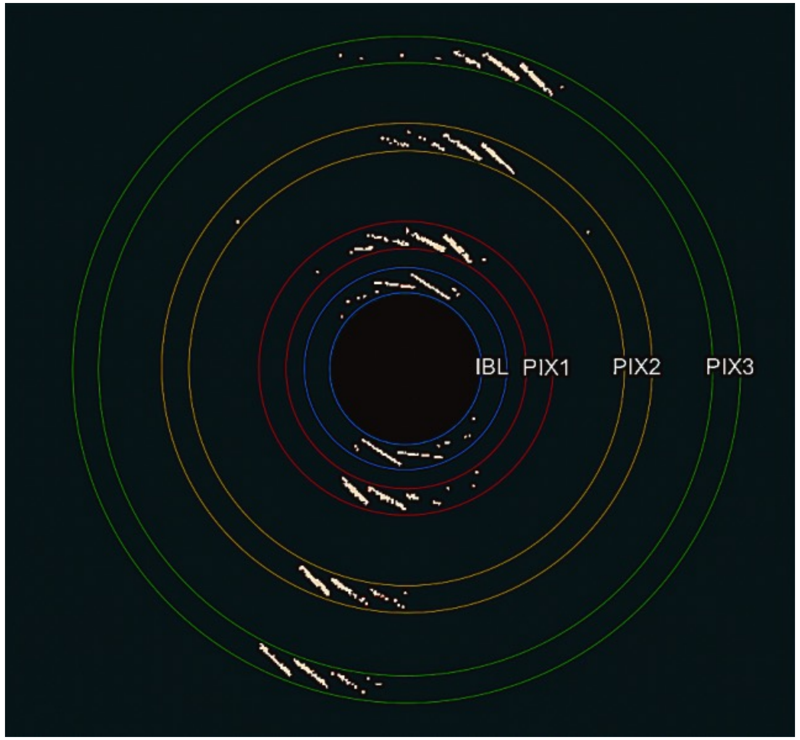
Note: also most hypothetical BSM particles would be only inferred from their decays

Exceptions: e.g. magnetic monopoles, „long-lived“ neutral/charged heavy particles



(a)

Example: search for leptoquark pair production decaying to te or tμ



Example: search for magnetic monopoles in ATLAS arXiv:2306.17642

1. What we would like to measure and what we can measure

Particles we can actually "see"

- need to reach the detector (travel distance $s = \beta\gamma c\tau \gtrsim$ o(cm) $c\tau = 1$ cm → $\tau = 33$ ps))

- need to interact with the sensitive volume of the detector

How close can we get?

1. electromagnetically

a) charged particles

b) photons

2. through strong interaction (with subsequent e.-m. interactions)

all "stable" hadrons

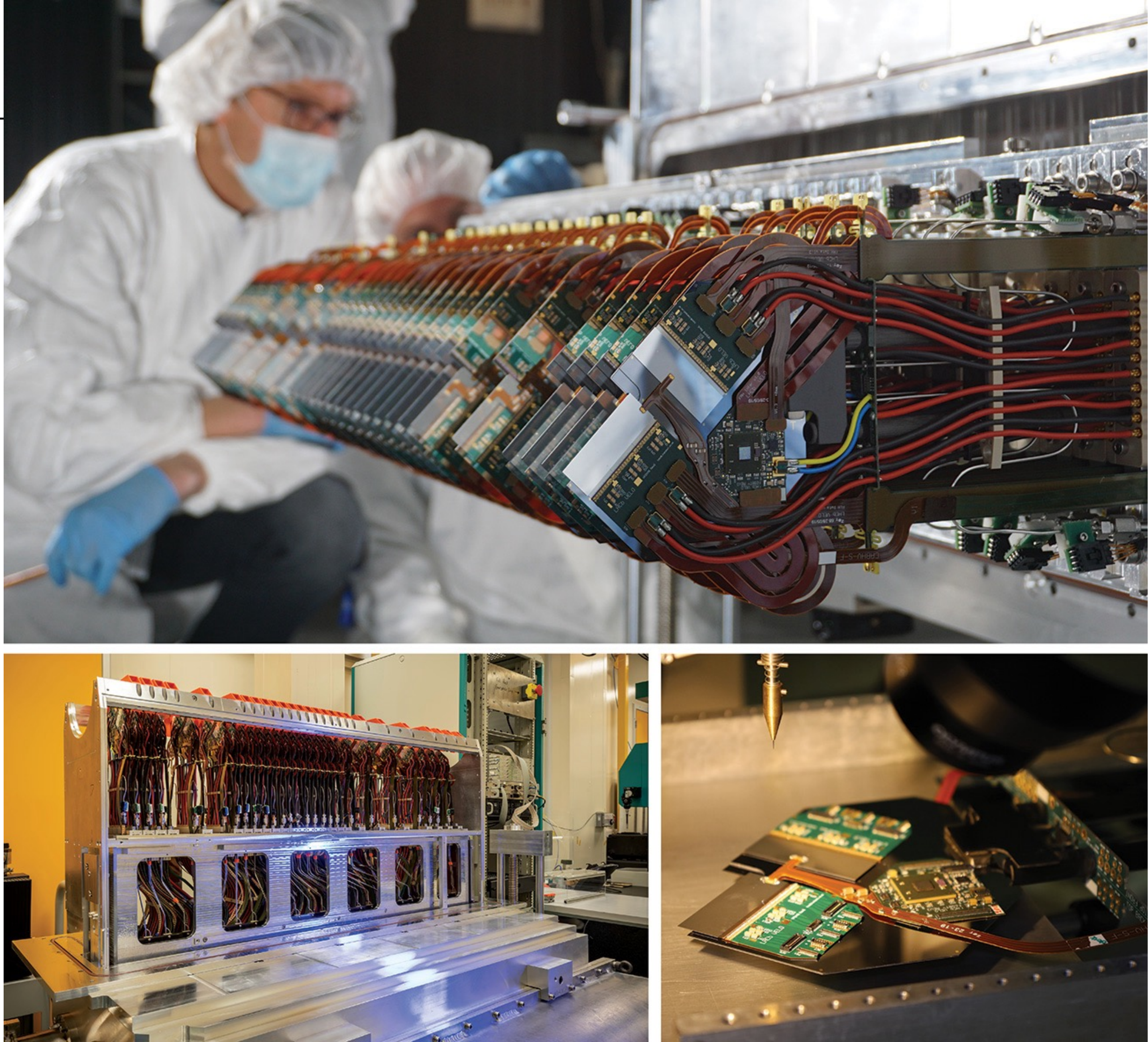
→ All detectors exploit the electro-magnetic interaction

Only very few particle species arrive in our detectors:

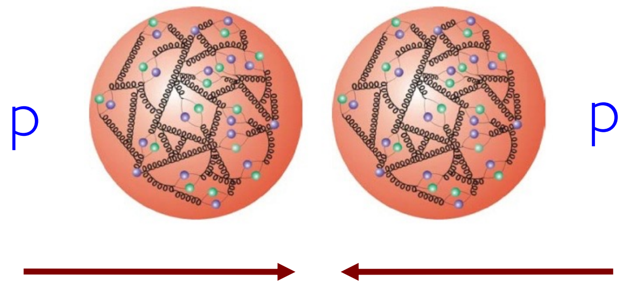
Photon, Electron/Positron, Muon/Antimuon, Charged Pions, Charged Kaons, Protons/Antiproton, Neutral "stable" hadrons $(K^0_{S/L}, n, \Lambda)$ (and a few more strange hadrons, practically mostly irrelevant)

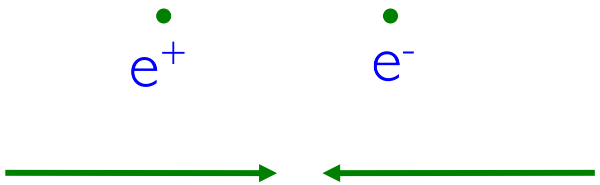
How close can we get?

LHCb Velo detector
5 mm to beam



Lepton vs. Hadron collisions



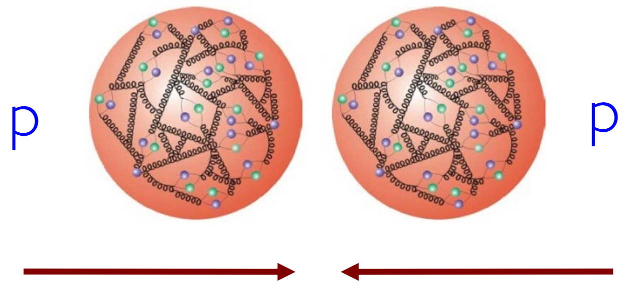


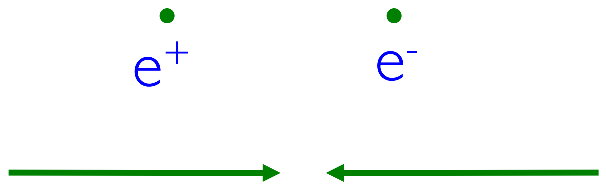
- p = composite particle:
  unknown energy of partons,
  parasitic parton collisions
  coloured initial state
- p = strongly interacting:
  huge SM backgrounds,
  highly selective trigger needed,
  radiation hard detectors needed

- e = pointlike particle:
  known and tunable energy of particles,
  kinematic contraints can be used
  only electroweak interaction in initial state
  polarisation of IS particles possible,
- e = electroweakly interacting
  low SM backgrounds,
  no trigger needed,
  detector design driven by precision

→ if they were equally easy to accelerate leptons were the choice!

Lepton vs. Hadron collisions





Energy loss per turn:

Synchrotron radiation

$$\Delta E = P \cdot \frac{2\pi R}{c} = \frac{e^2}{3\varepsilon_0} \frac{1}{(mc^2)^4} \frac{E^4}{R}$$

$$\boxed{\Delta E[\mathrm{keV}] = 88.5 \, \frac{E^4[\mathrm{GeV}]}{R[\mathrm{m}]}}$$

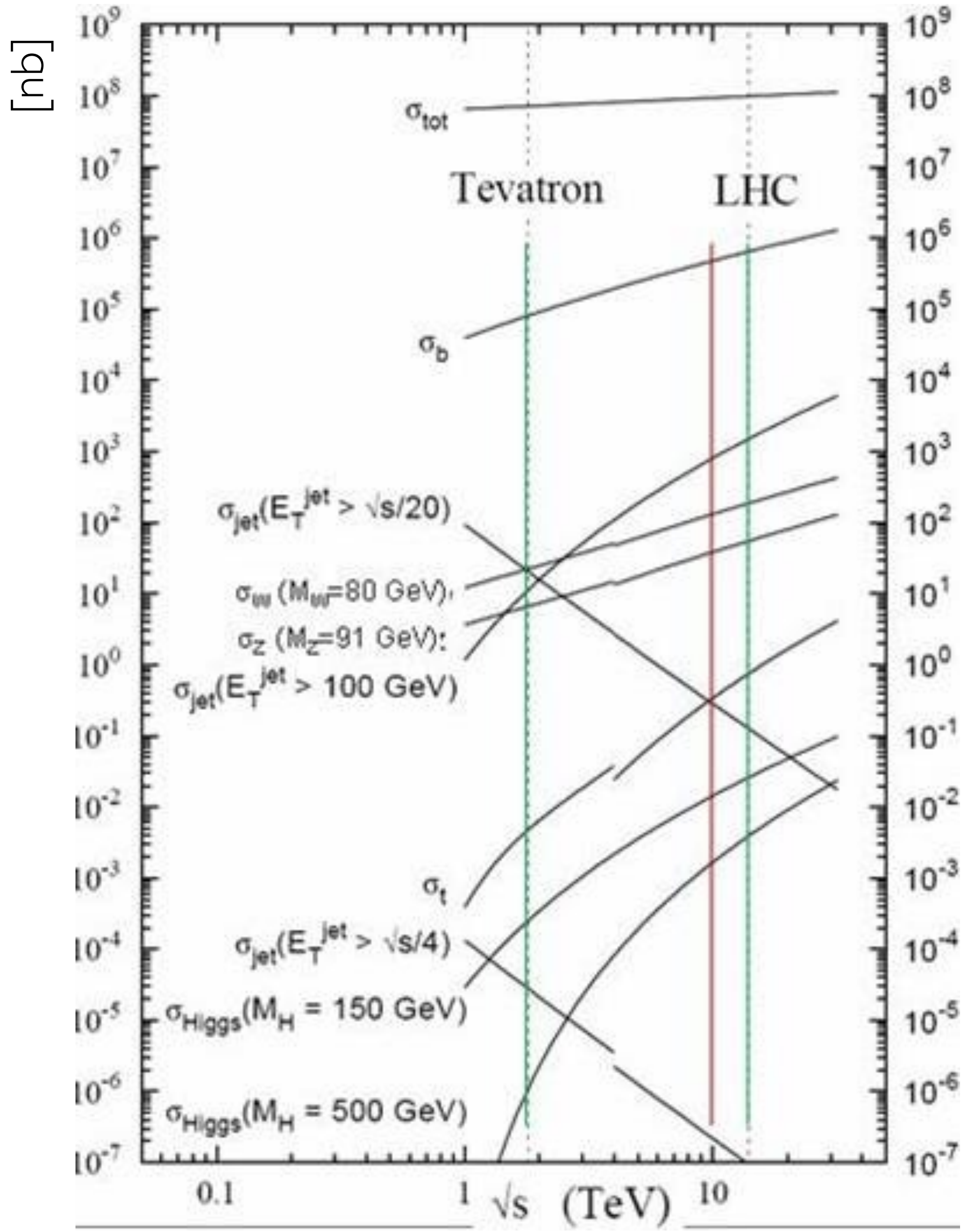
for electrons

e.g.
E =150 GeV
R = 25 km
ΔE = 1.8 GeV per turn

Can this be overcome?

We do have a powerful hadron collider: the LHC

Complications in hadron collisions 1: pile-up



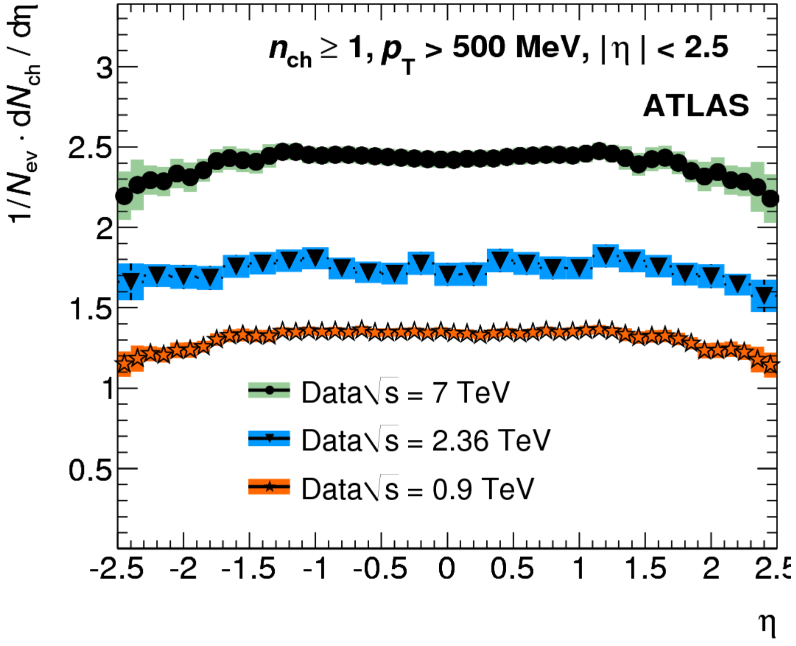
Total cross-section of pp collisions is dominated by Minimum Bias events.

$$\sigma_{\text{tot}} \approx 100\ \text{mb}$$

$$\langle p_t \rangle \approx 300\ \text{MeV}$$

$$\frac{dn}{d\eta} \approx 7$$

$$\frac{dn}{d\varphi} \approx \text{const.}$$

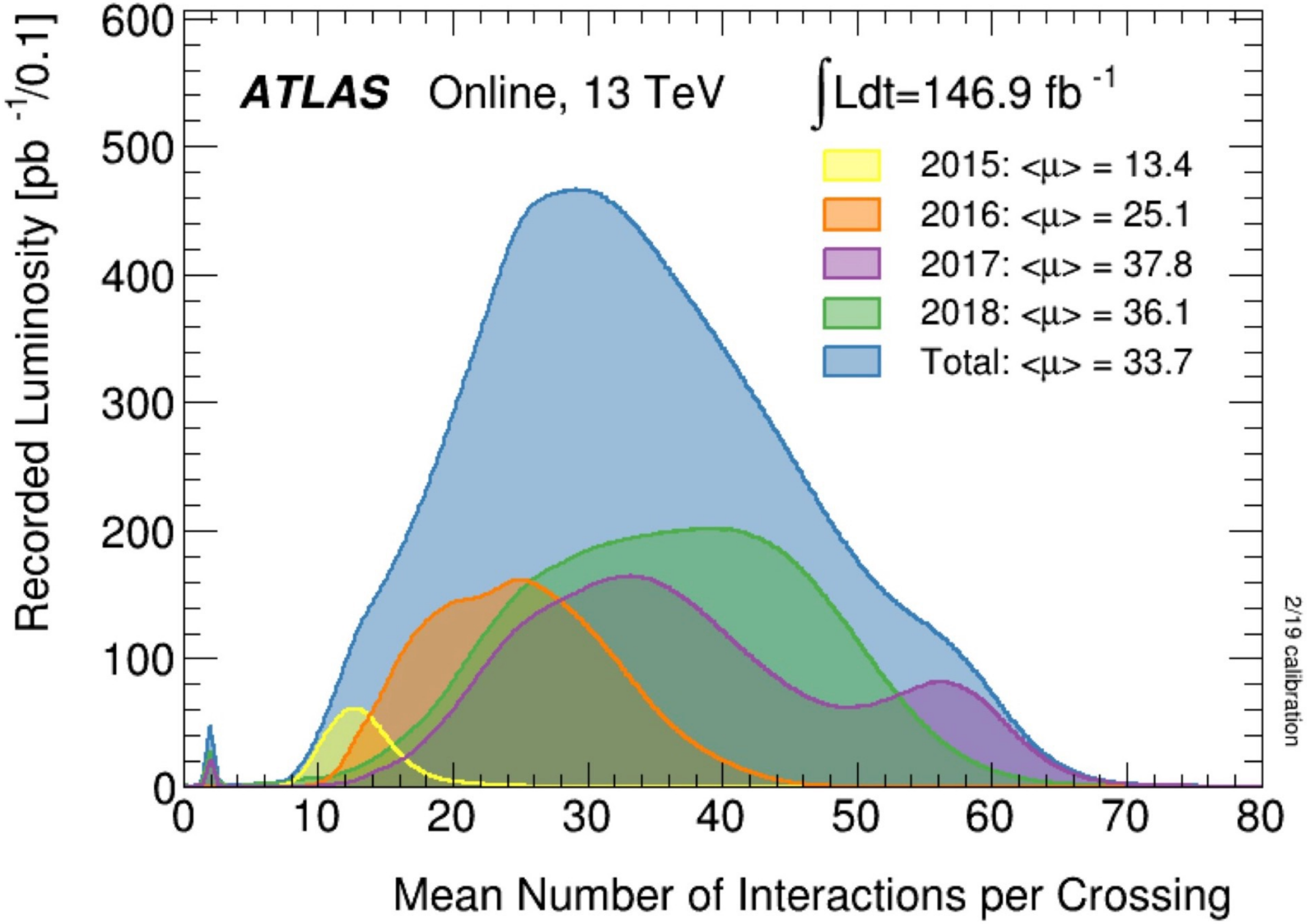


„Interesting" cross sections suppressed by ~10^{-9}

→ multiple pp collisions per bunch crossing (25 ns) unavoidable.

How can one mitigate pile-up?

Complications in hadron collisions 1: pile-up

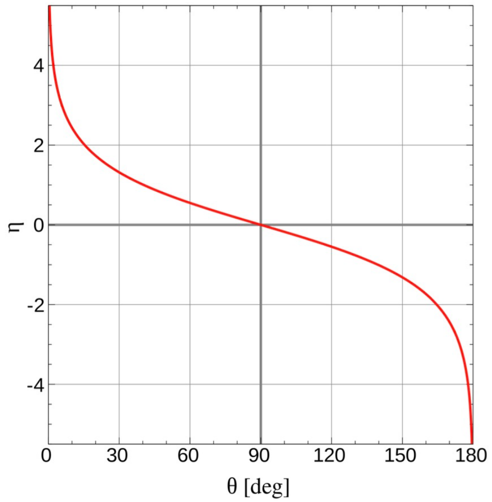


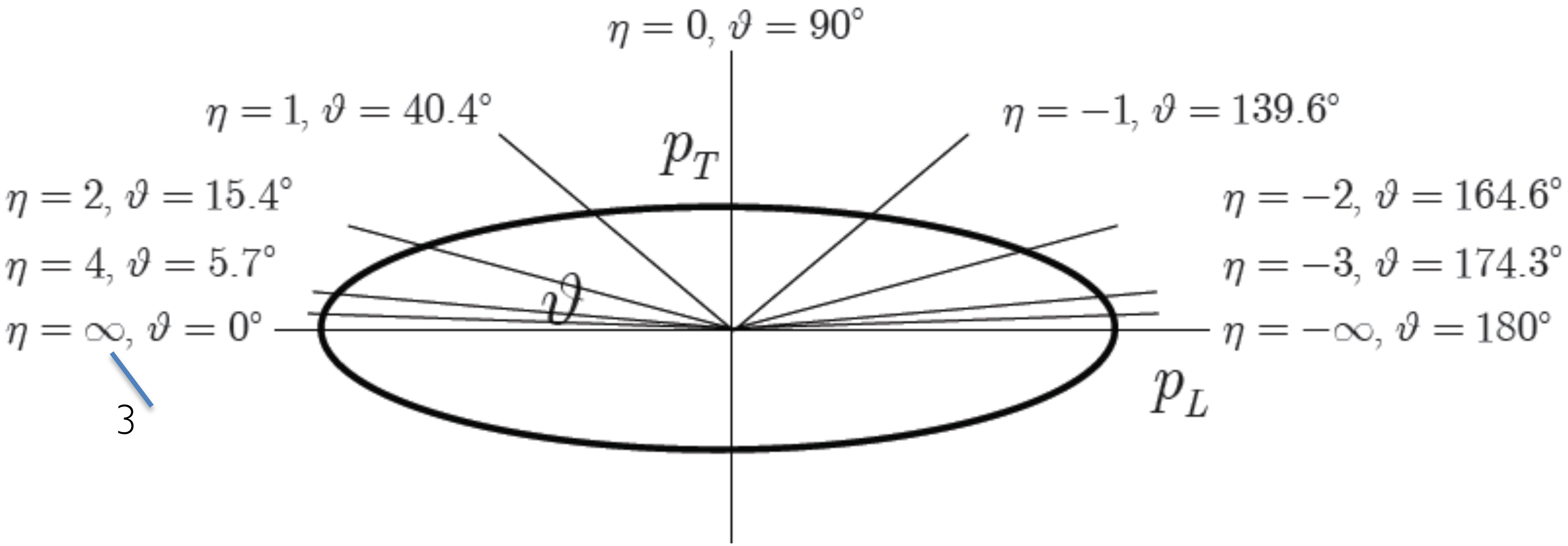
How can one mitigate pile-up?

B

Pseudorapidity

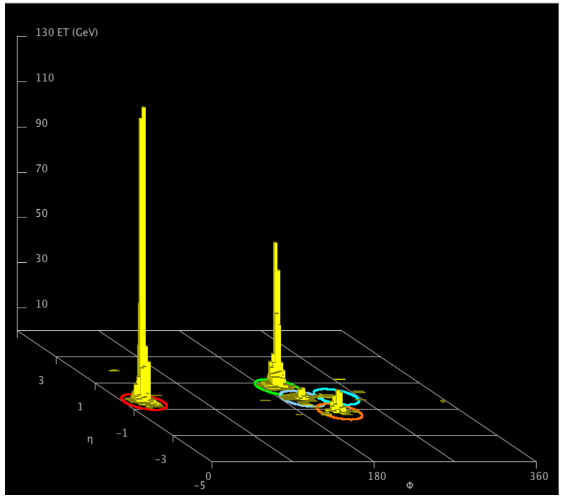
$$\eta = -\ln \mathrm{tg}\, \theta/2$$



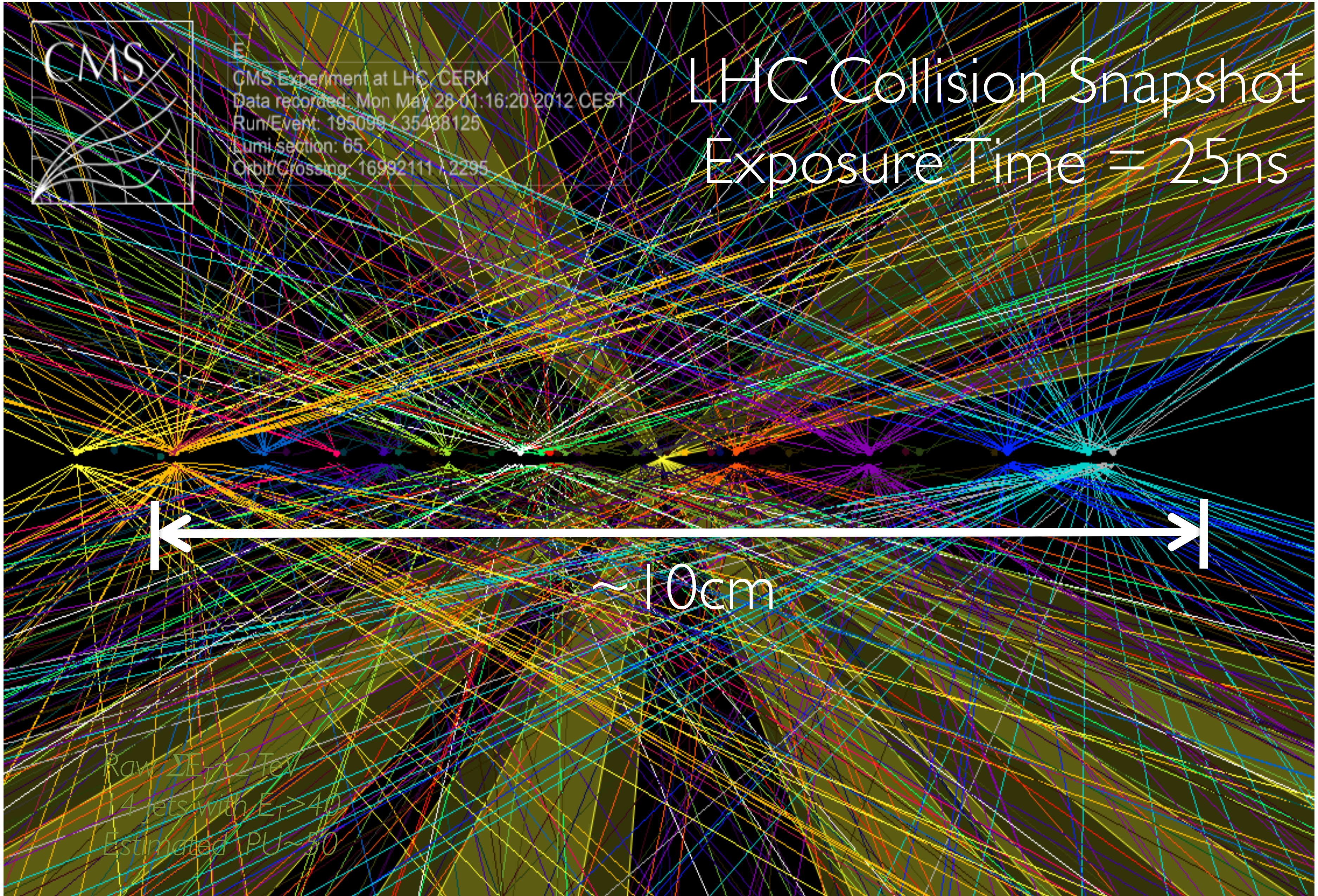


3

<u>Three reasons to use pseudorapidity</u> (rather than polar angle):
- Differences of pseudorapidity are invariant under longitudinal boosts
- Occupancy vs. pseudorapidity ~ const (need higher angular granularity in forward direction)
- Jets are ~ "round" in ΔηΔφ-space



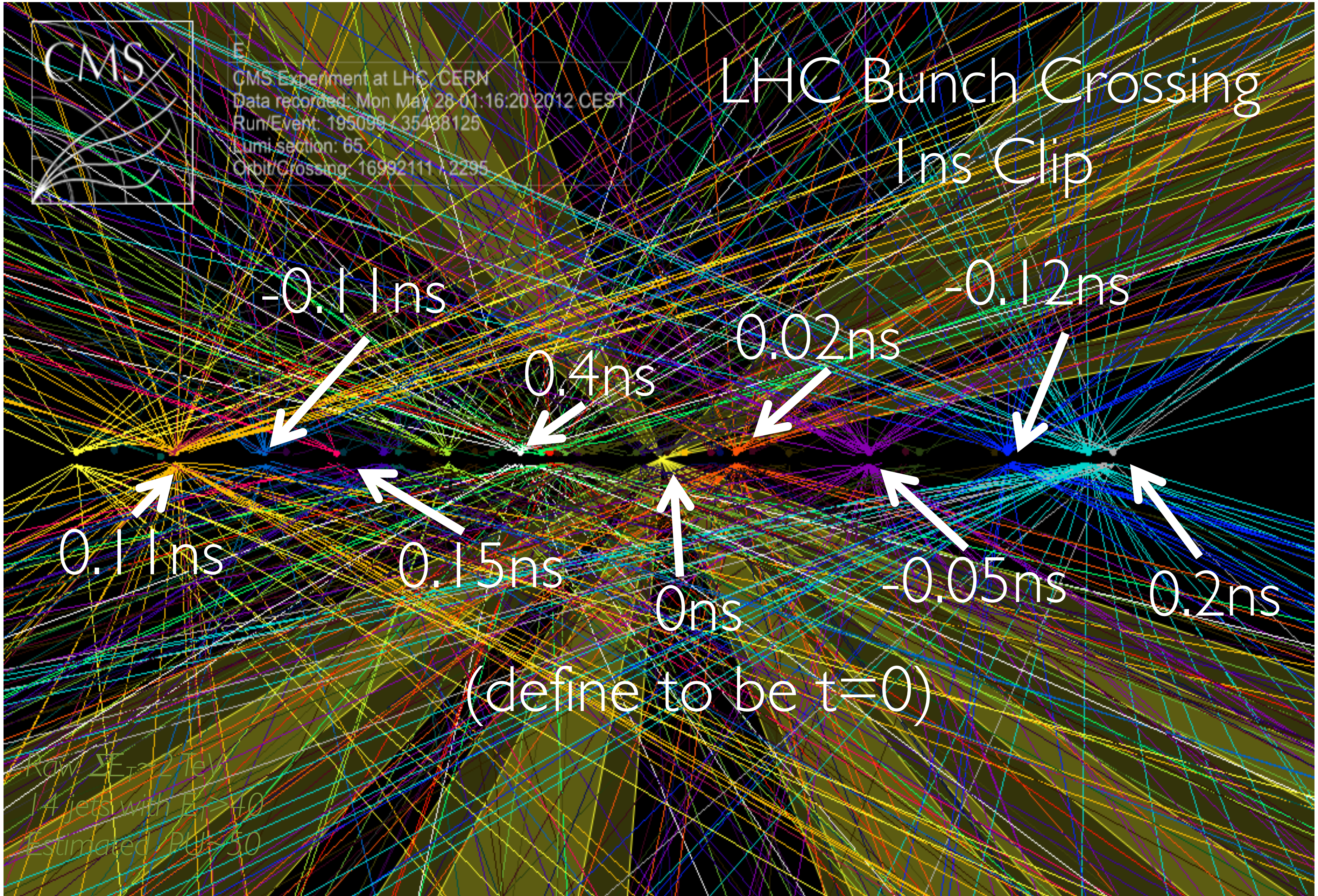
Complications in hadron collisions 1: pile-up



LHC Collision Snapshot
Exposure Time = 25ns

[Tully]

Complications in hadron collisions 1: pile-up



[Tully]

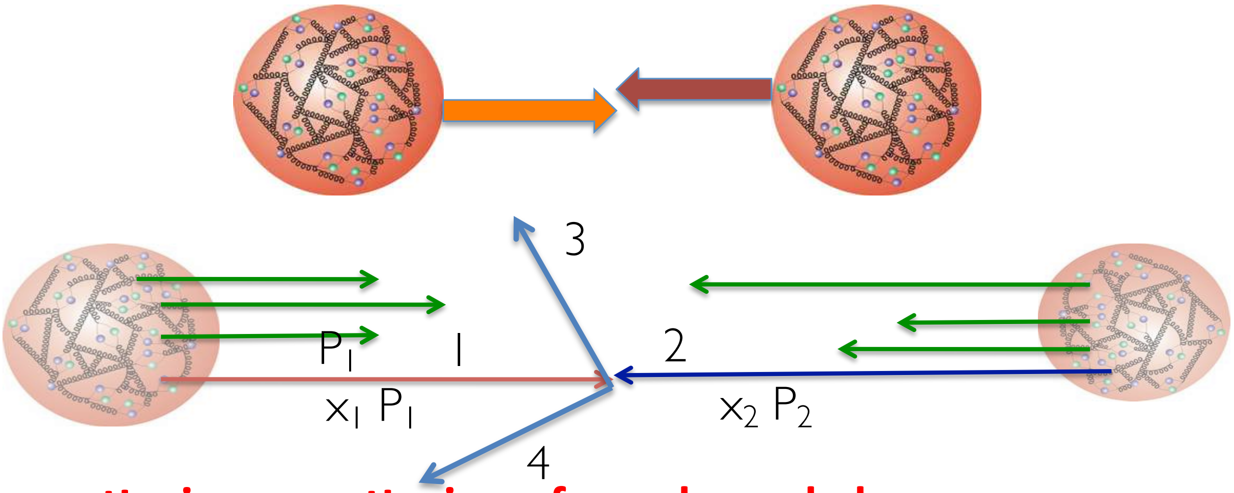
Vertex resolution
+
Timing
helps

B

Complications in hadron collisions II: the parton model

The most simple approach to describe pp scattering by 2→2 parton scattering + <u>spectators</u>

$$\boxed{\hat{s} = x_1 x_2 s}$$



Proton scattering = scattering of quarks and gluons

$$\boxed{\begin{aligned} x_1 &= \frac{M}{\sqrt{s}} e^{\eta_{CM}} = \frac{E_T}{\sqrt{s}} \left(e^{\eta_3} + e^{\eta_4}\right) \\ x_2 &= \frac{M}{\sqrt{s}} e^{-\eta_{CM}} = \frac{E_T}{\sqrt{s}} \left(e^{-\eta_3} + e^{-\eta_4}\right) \end{aligned}}$$

Here the (12) system (initial state) is not at rest in the lab frame

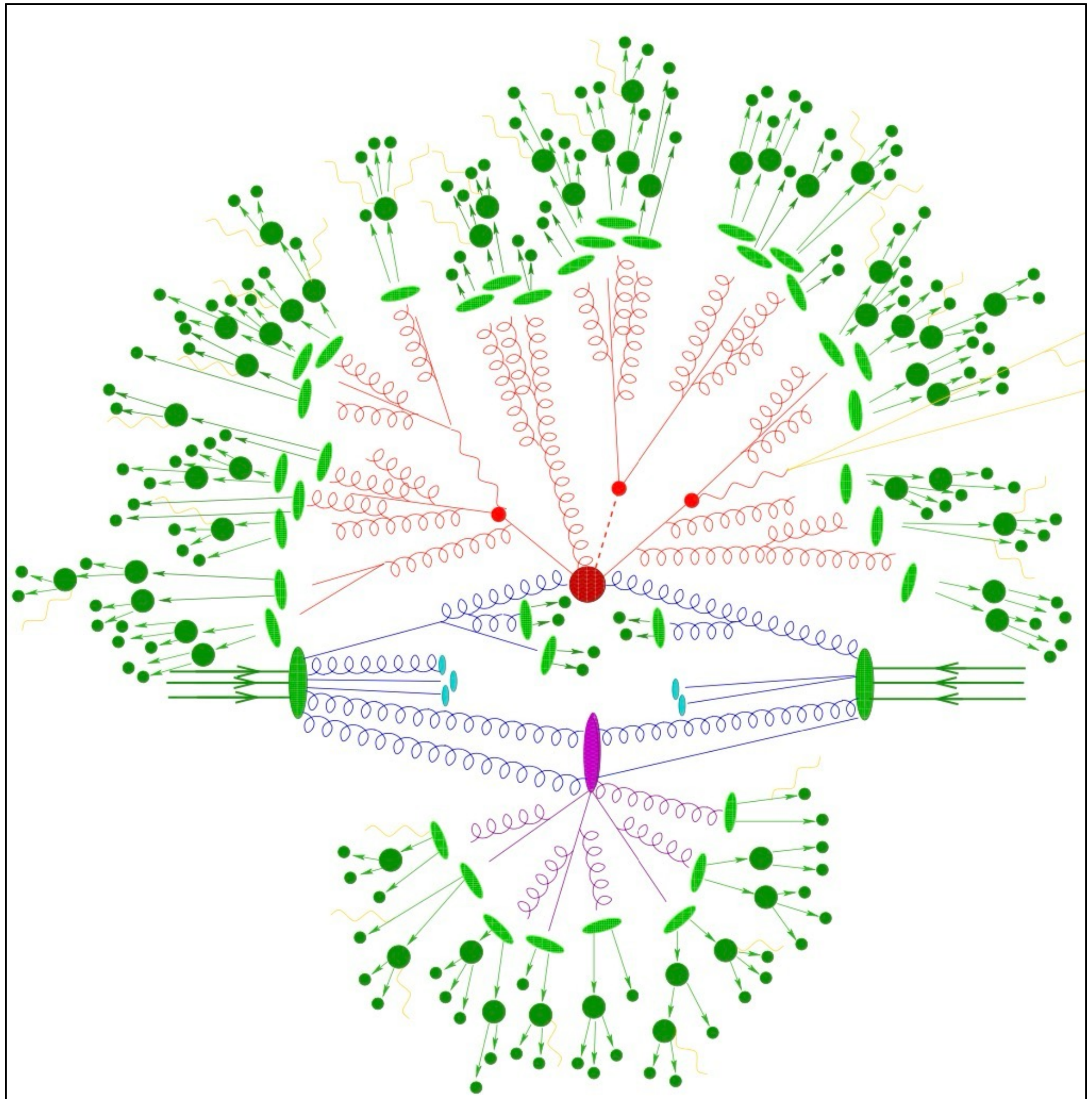
Incoming 4-momenta $p_1 = x_1\ P_1 \quad p_2 = x_2 P_2$ (P_1,P_2 4-momenta of protons, Björken-x: x_1, x_2)

Note: <u>this is a (rather strong) simplification!</u>

- ignores the interaction of the rest of the two protons („underlying event“)
- assumes that the incoming partons have no transverse momentum p_t
- assumes that the incoming partons do not radiate gluons before they interact

Complications in hadron collisions II: the parton model

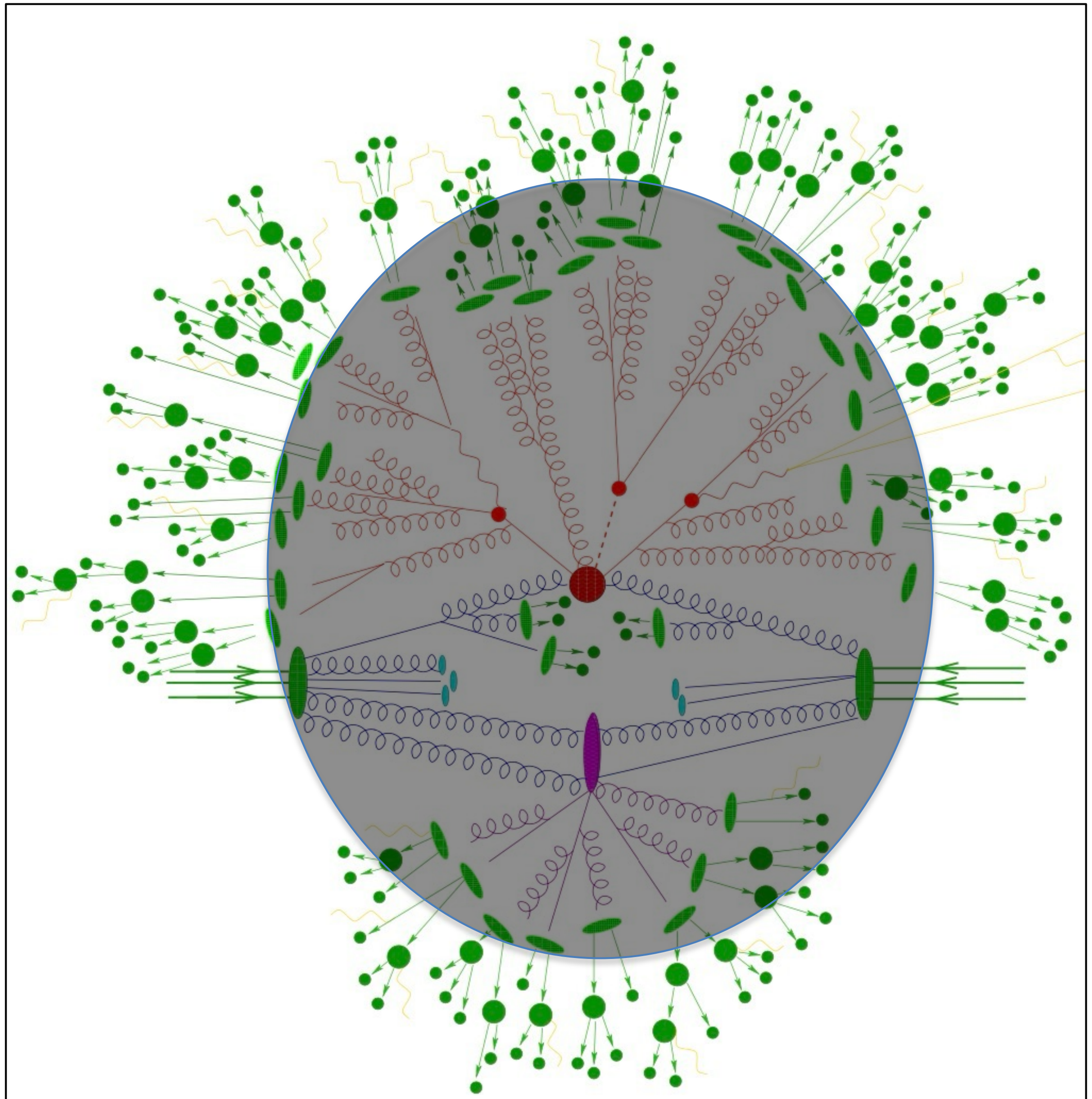
A more complete (but very complex) picture of „what´s really happening“



[SHERPA team, F. Krauss et al]

Complications in hadron collisions II: the parton model

We can see only, what is outside the circle



but we want to know, what´s happening at the red dot.

Frightening...

Complications in hadron collisions II: the parton model

Fortunately, there are concepts which work (surprisingly?) well!

Inside out: (theory)

1. hard process (at higher order perturbation theory) „exact“
2. parton shower for outgoing and incoming (coloured) objects
3. transition from partons to hadrons „hadronisation“
4. decay of unstable hadrons → observable particles

Where do theory and experiment meet best?

Outside in: (experiment)

1. assign raw signals to observable particles („reconstruction“)
2. combine hadrons (and photons from $\pi^0 \rightarrow \gamma\gamma$) to jets
3. associate jets with partons (quarks, gluons) – highly non-unique
4. combine objects (jets, leptons, miss. energy) to heavier objects (e.g. t)
5. measure „parton-level“ cross-sections and compare them to theory

Jets

Jets: the (best?) link between measurable particles and "calculable" partons

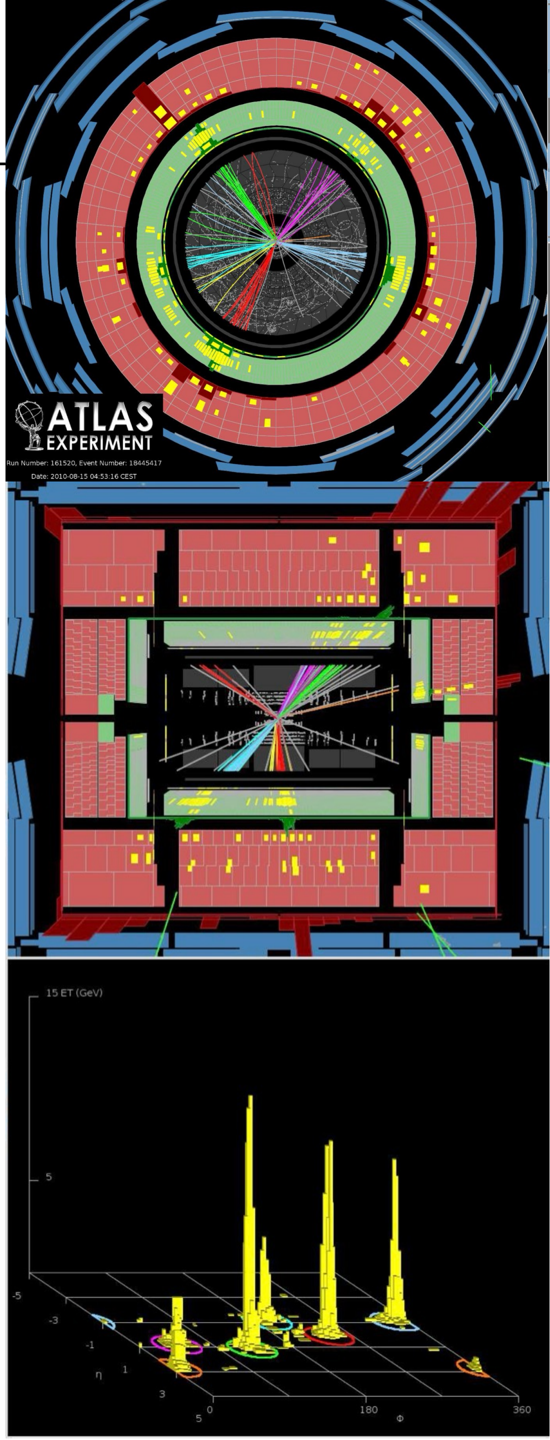
Jet definition should be:

- simple to implement in experimental analysis
- simple to implement in theoretical calculations
- well-defined in any order of perturbation theory
- yield finite cross-sections (infrared and collinear safety)
- insensitive to specifics of the hadronization model

Long history of algorithms.

Today sequential recombination algorithms dominate,

in particular anti-k_T algorithm



ATLAS 6-jet event at 7 TeV

Jet Algorithms

Distance measures: $d_{ij} = 2\min\left(p_{t,i}^{2p}, p_{t,j}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = p_{t,i}^{2p}$ $\Delta R_{ij}^2 = \left(\eta_i - \eta_j\right)^2 + (\varphi_1 - \varphi_2)^2$

B = „beam"

Algorithm:

1. if only one particle is left, call it jet and stop
2. find minimum of d_{ij}, d_{iB}
3. if minimum is d_{ij}, combine i and j, goto 1
4. if minimum is d_{iB}, declare particle i a final state jet, remove it from list, goto 1
5. stop if no particles remain in list

→ arbitrarily soft particle can become „jets" → need to specify a minimum jet p_T

p = 1: k_T algorithm
p = 0: Cambridge/Aachen algorithm
p = -1: anti-k_T algorithm:

- favours clusterings that involve hard particles (rather than soft particles)
- jets evolve from hard seed (grow inside out)
- still, collinear branchings are clustered first (collinear and infrared safe)
- but: not related to QCD branching/splitting functions

Jet Algorithms

Recombination schemes:
Need to define how to combine the four vectors of particles i and j (in all algorithms)

Option A: simply add 4-momenta of particles (leads to „massive“ jets)

Option B:

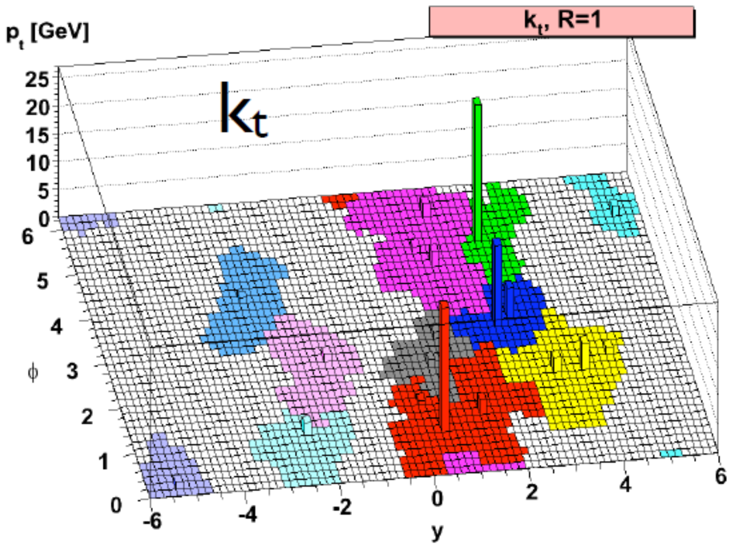
$$E_{T,jet} = \sum_i E_{T,i}$$

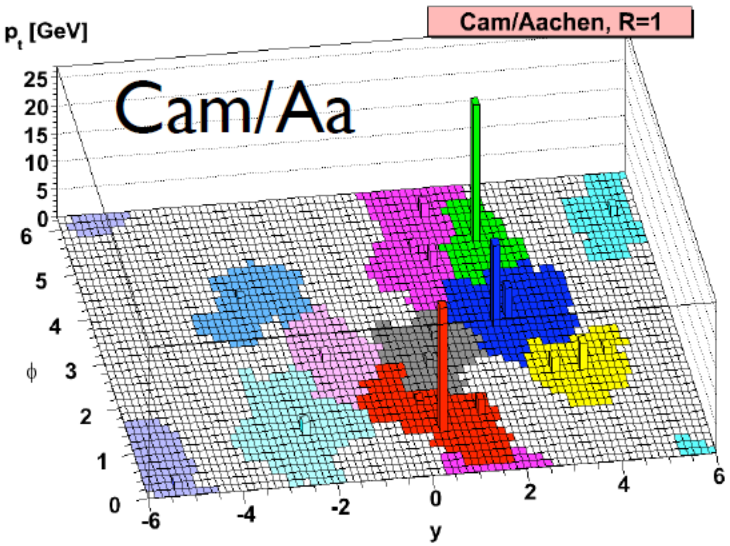
$$\eta_{jet} = \frac{1}{E_{T,jet}} \sum_i E_{T,i}\, \eta_i$$

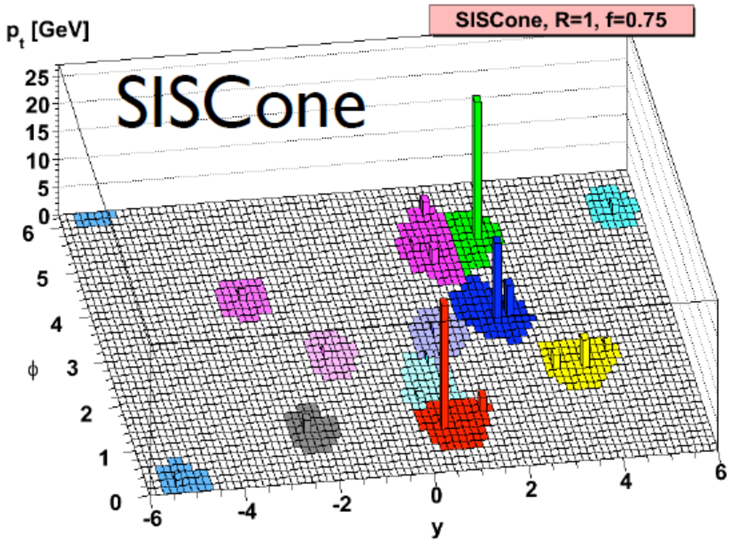
$$\phi_{jet} = \frac{1}{E_{T,jet}} \sum_i E_{T,i}\, \phi_i$$

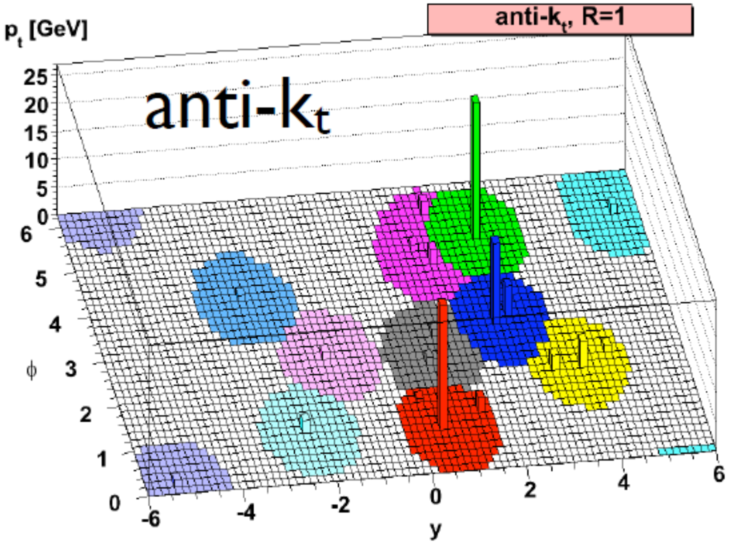
→ resulting jets are massless
→ disadvantage: not invariant under longitudinal boosts if component particles are massive

Jet Algorithms: what they do...



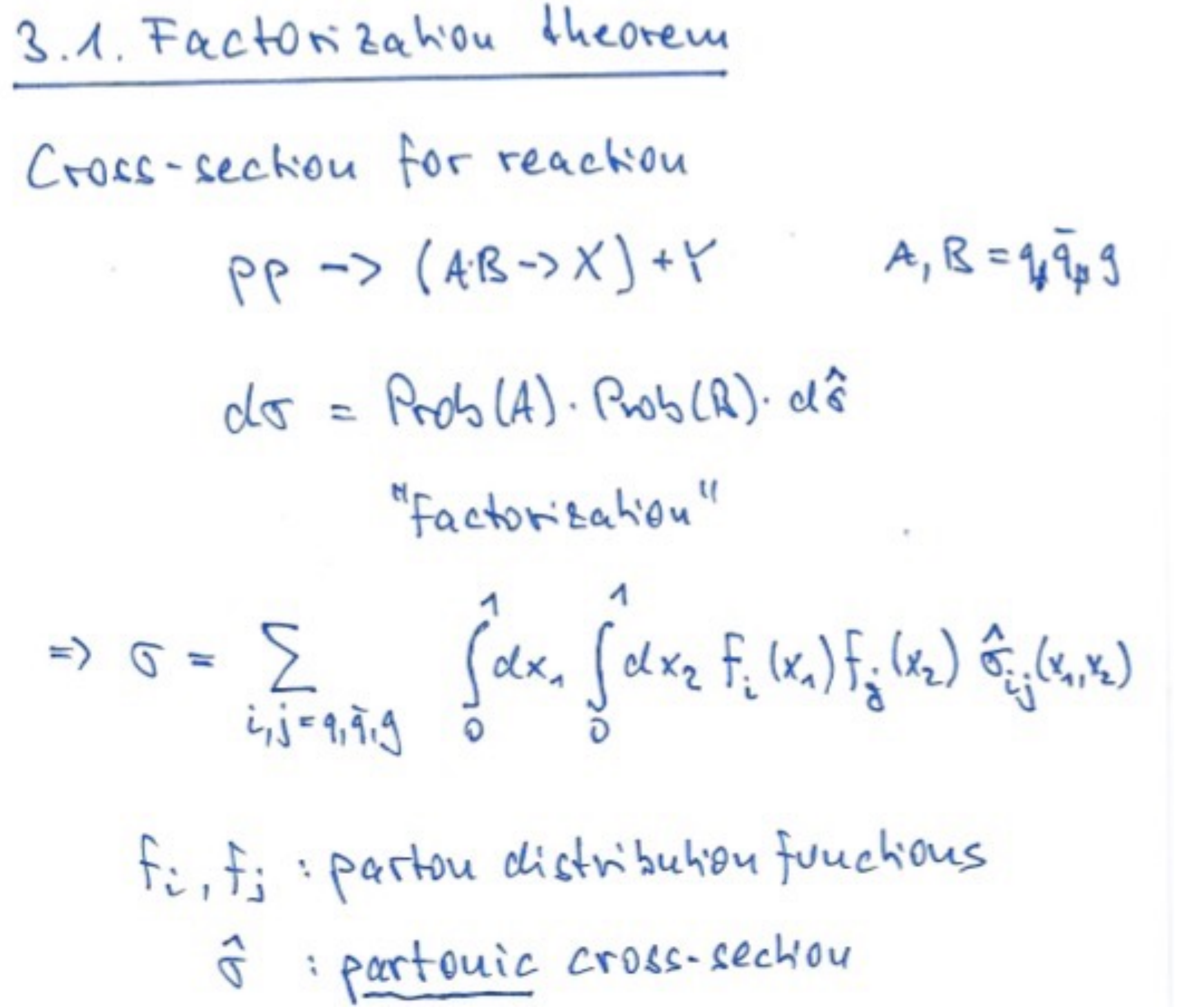






Complications in hadron collisions II: parton density functions

Cross sections depend on (still uncalculable) parton density functions
Need to be measured/constrained with data.
Most important (still): ep DIS data from HERA



3.1. Factorization theorem

Cross-section for reaction

$$pp \to (A B \to X) + Y \qquad A, B = q, \bar{q}, g$$

$$d\sigma = \text{Prob}(A) \cdot \text{Prob}(B) \cdot d\hat{\sigma}$$

"Factorization"

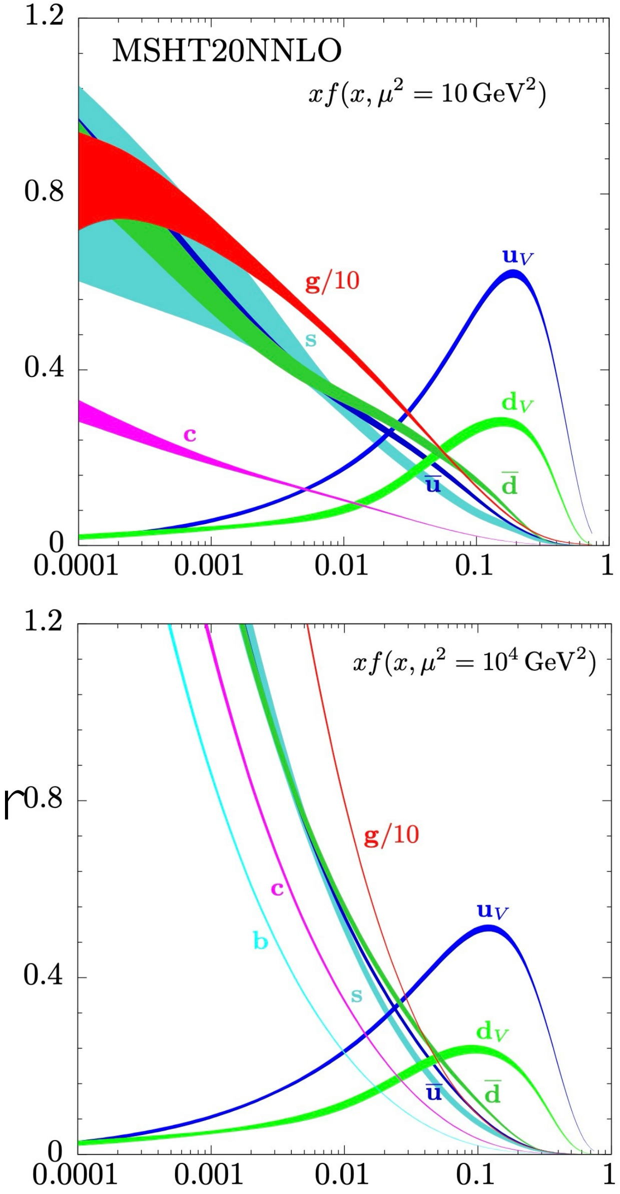
$$\Rightarrow \sigma = \sum_{i,j=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 \, f_i(x_1) f_j(x_2) \, \hat{\sigma}_{ij}(x_1, x_2)$$

f_i, f_j : parton distribution functions

$\hat{\sigma}$: $\underline{\text{partonic}}$ cross-section

DGLAP

Yuri Dokshitzer



3.1 Factorization theorem

$f_i(x)$ from structure function

$F_2(x, Q^2) = x \cdot \sum_i z_i^2 f_i(x, Q^2)$ for quarks

depend on energy scale Q^2 !

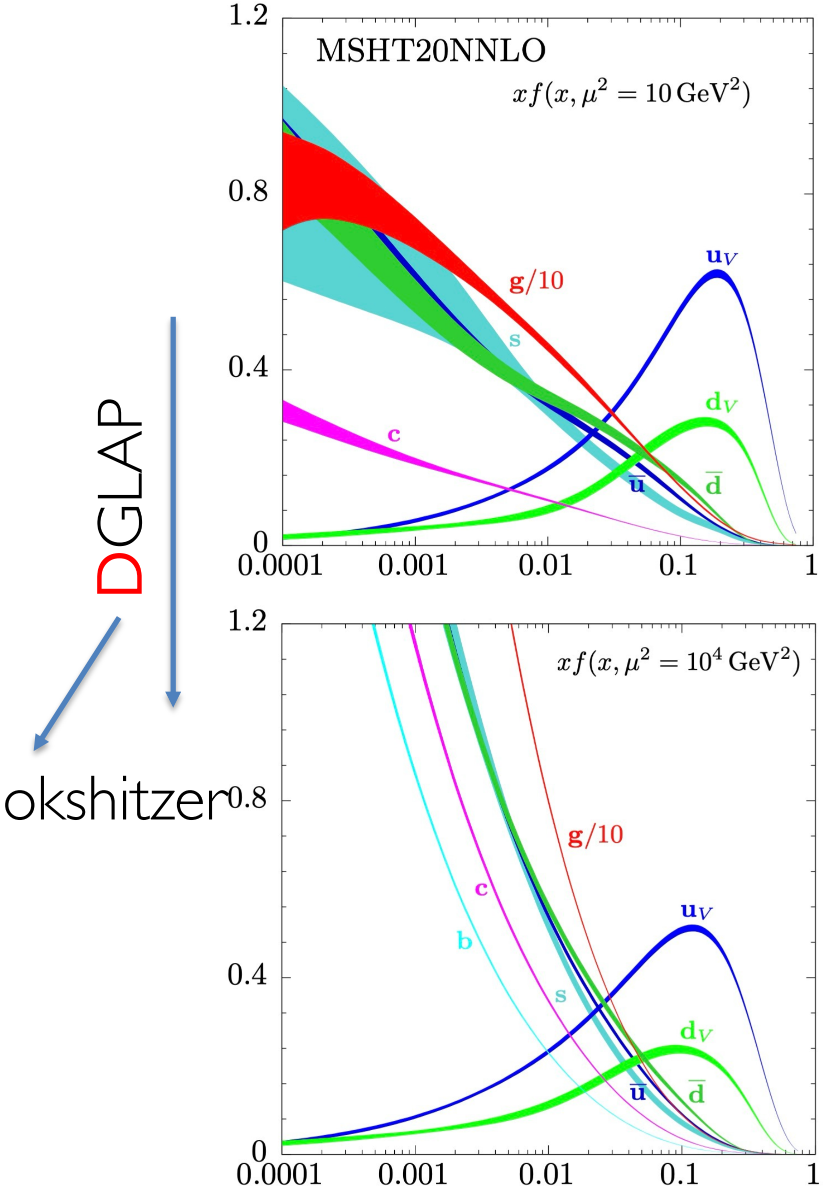
Which Q^2 to chose to calculate σ ? :

Factorization scale μ_F use $\mu_F^2 = Q^2$ in p.d.f's

refined version:

colour-factor $C_{q\bar{q}} = \frac{1}{9}$ $C_{qg} = \frac{1}{24}$ $C_{gg} = \frac{1}{64}$

$$\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1 \int dx_2 \, C_{ij} \, f_i^A(x_1, \underline{\underline{\mu_F^2}}) \, f_j^B(x_2, \underline{\underline{\mu_F^2}}) \, \hat{\sigma}_{ij}(x_1, x_2)$$

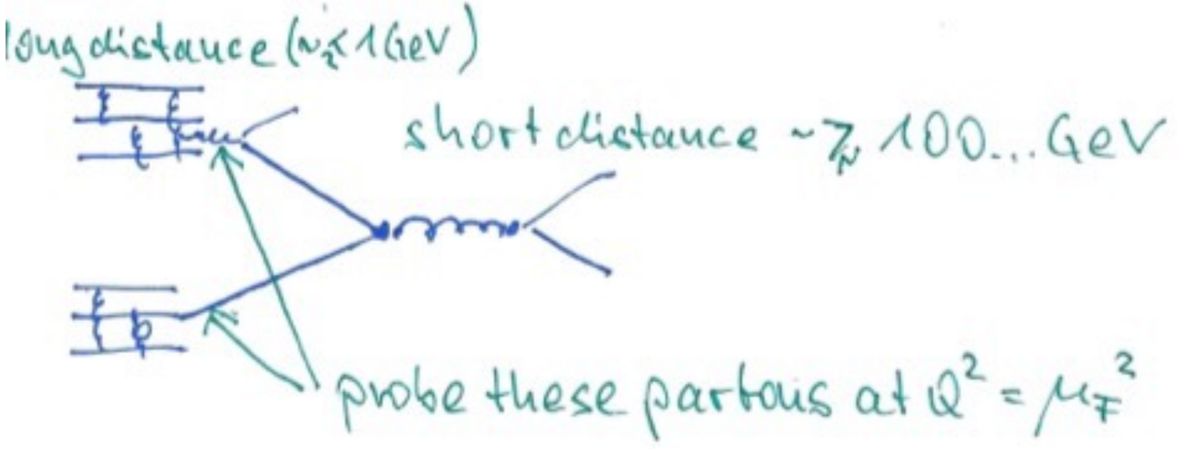


DGLAP

Yuri Dokshitzer

Complications in hadron collisions II: parton density functions

μ_F separates "short-distance" from "long-distance" physics

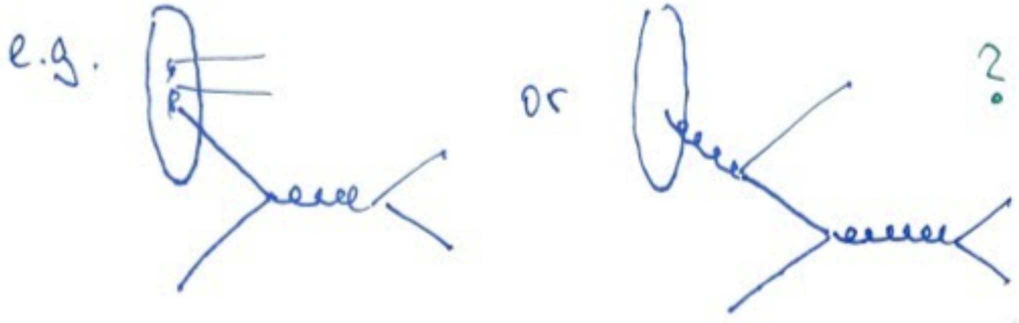


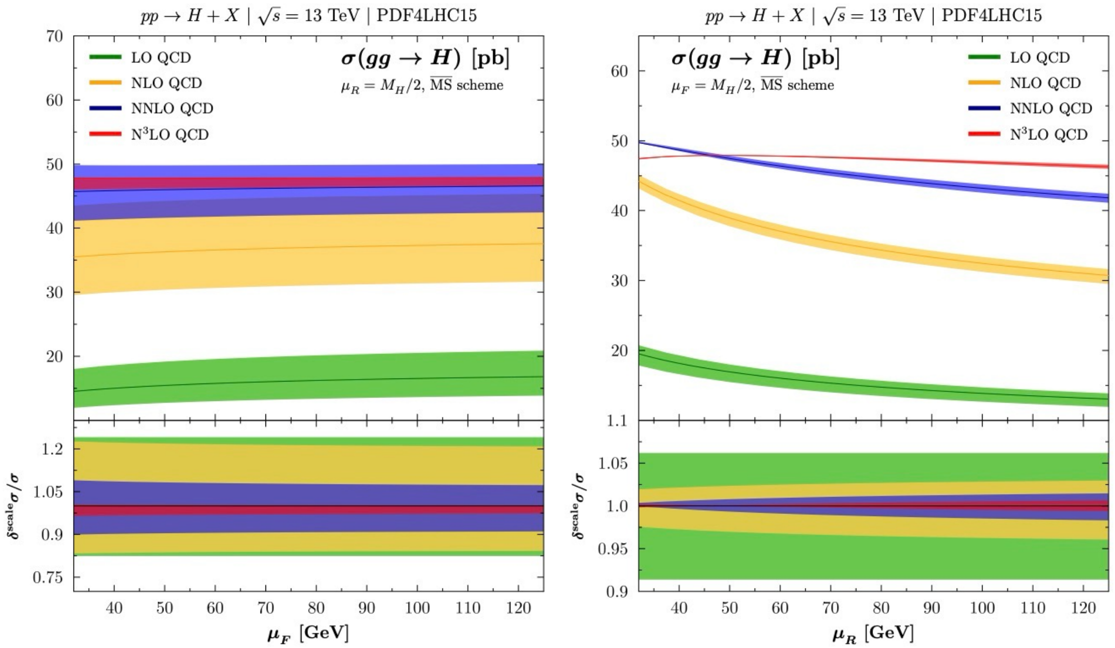
non-perturbative – perturbative QCD

α_s large $\alpha_s < 1$

- factorization theorem is a (good) approximation!
- dependence on μ_F is a systematic uncertainty

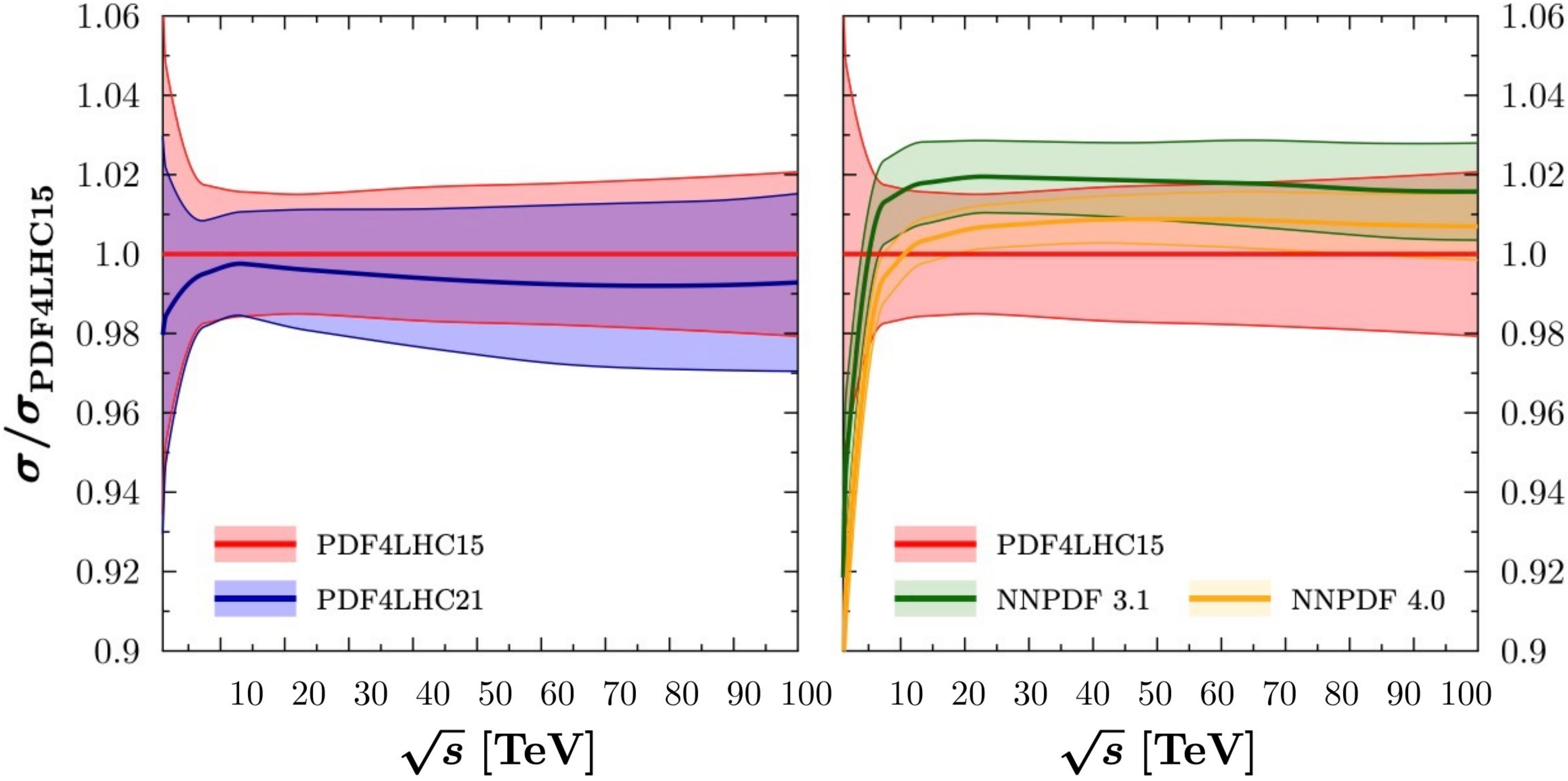
ambiguity at higher orders:





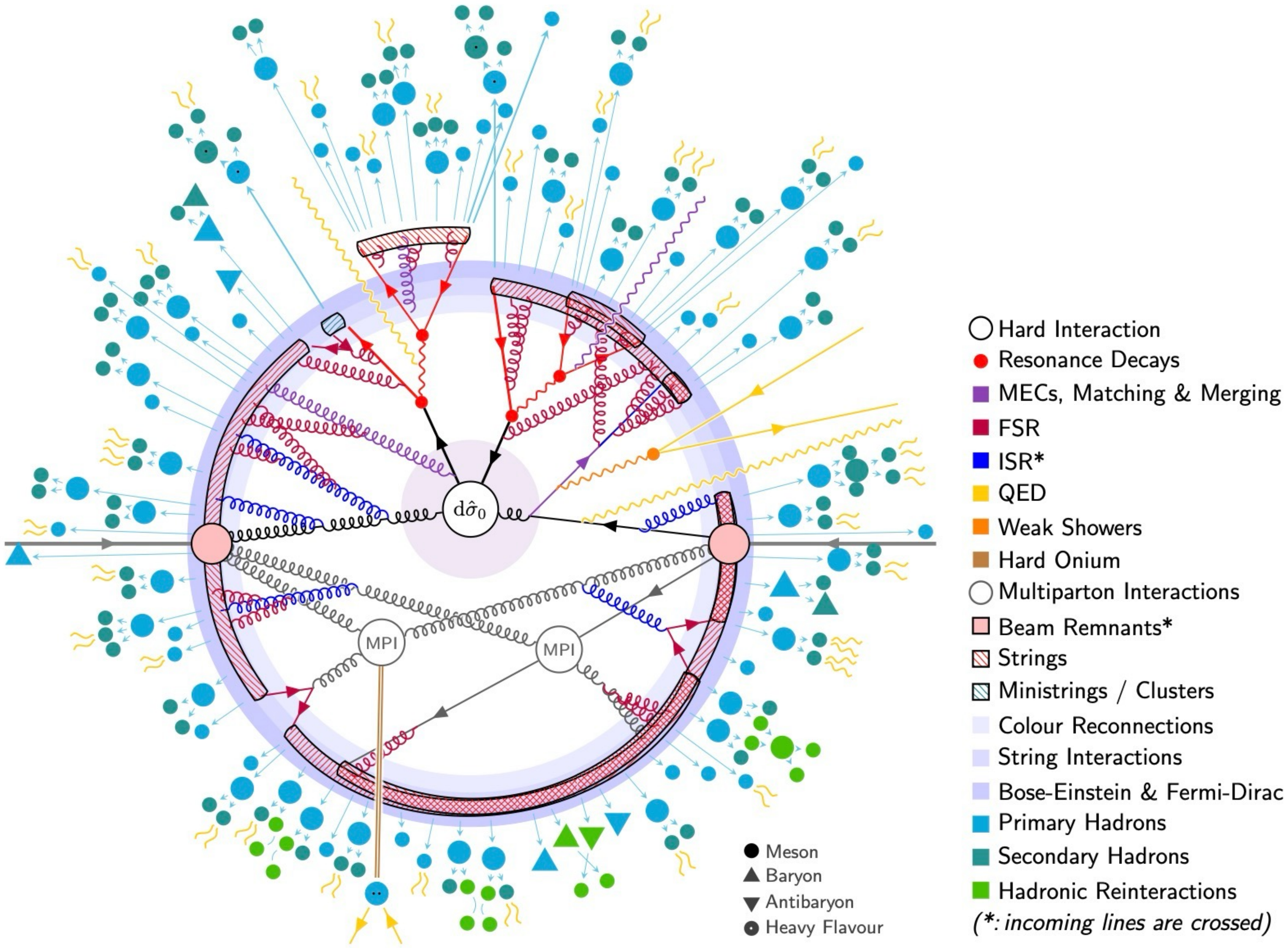
[Anastasiou et al, 2022]

Complications in hadron collisions II: parton density functions



pdf uncertainties for gg→H Higgs production

End-to-end modelling: Monte Carlo generators

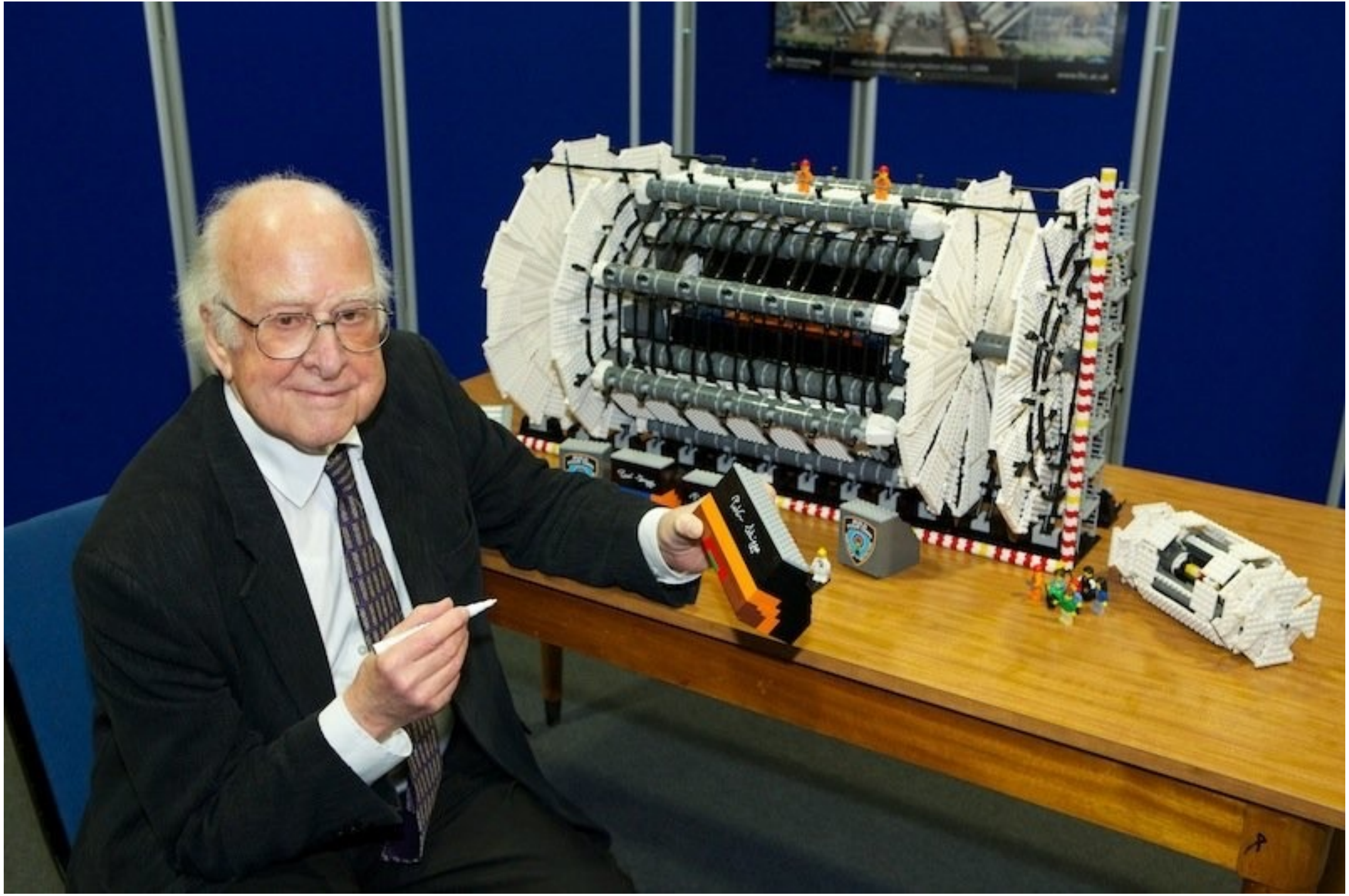


Does Nature know about this?

[PYTHIA team]

PART 2

Detectors



Peter Higgs (1929 - 2024) assembling the ATLAS detector…

Electro-magnetic interaction: Charged Particles

Charged Particles

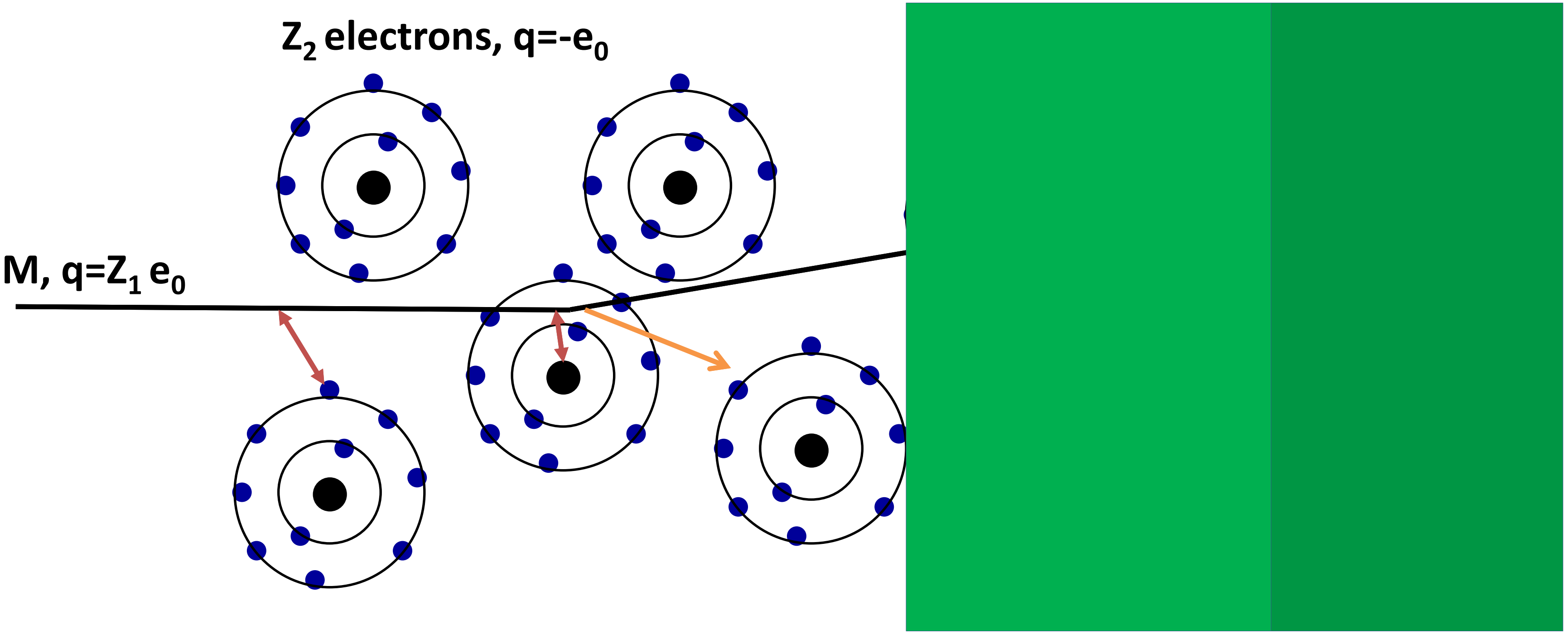
1. Ionization
→ Charge

2. Excitation
→ Light

3. Scattering
→ Deflection

4. Bremsstrahlung →
E-loss, deflection

5. Cerenkov radiation
6. Transition radiation



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Is there more?

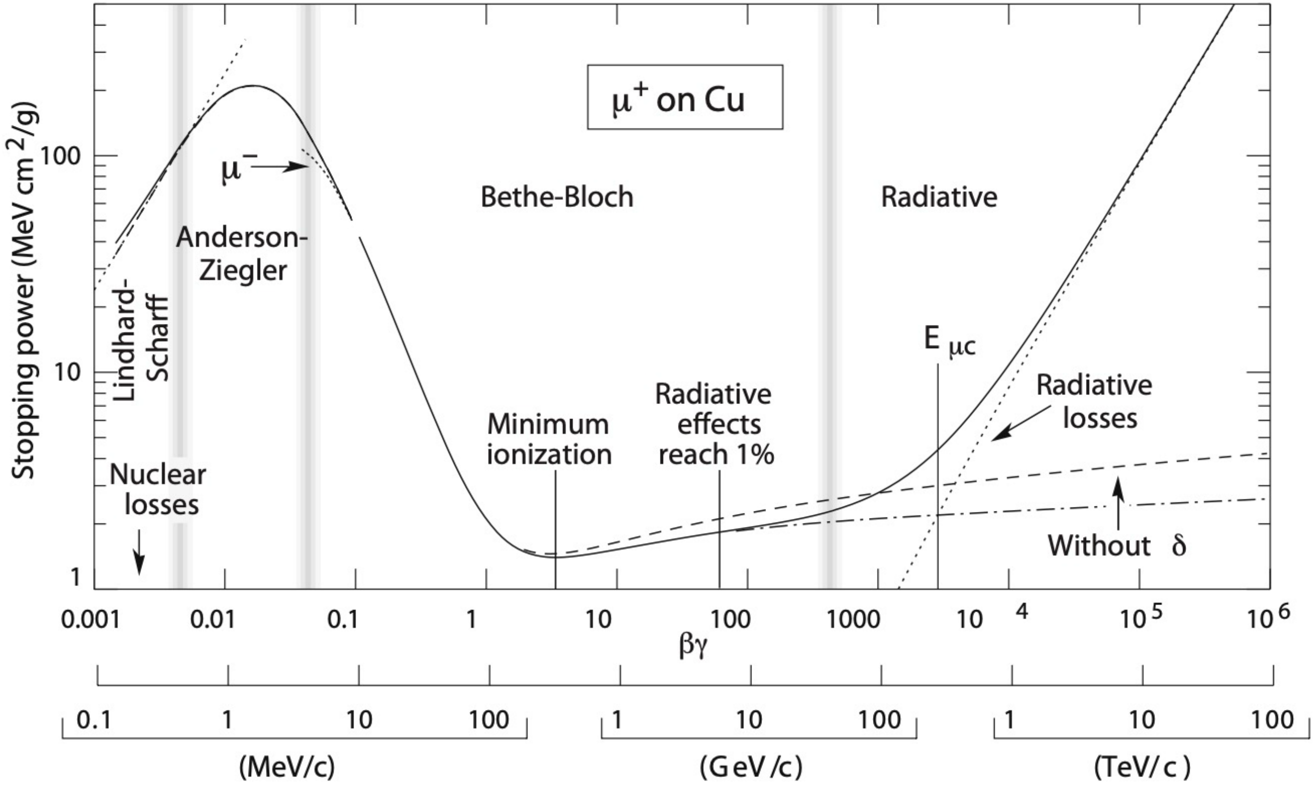
Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

[Riegler]

Electro-magnetic interaction: Charged particles: Excitation + Ionization

Excitation + Ionization → "Universal energy loss – only depending on $\beta\gamma$



Bethe-Bloch equation

$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, \frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

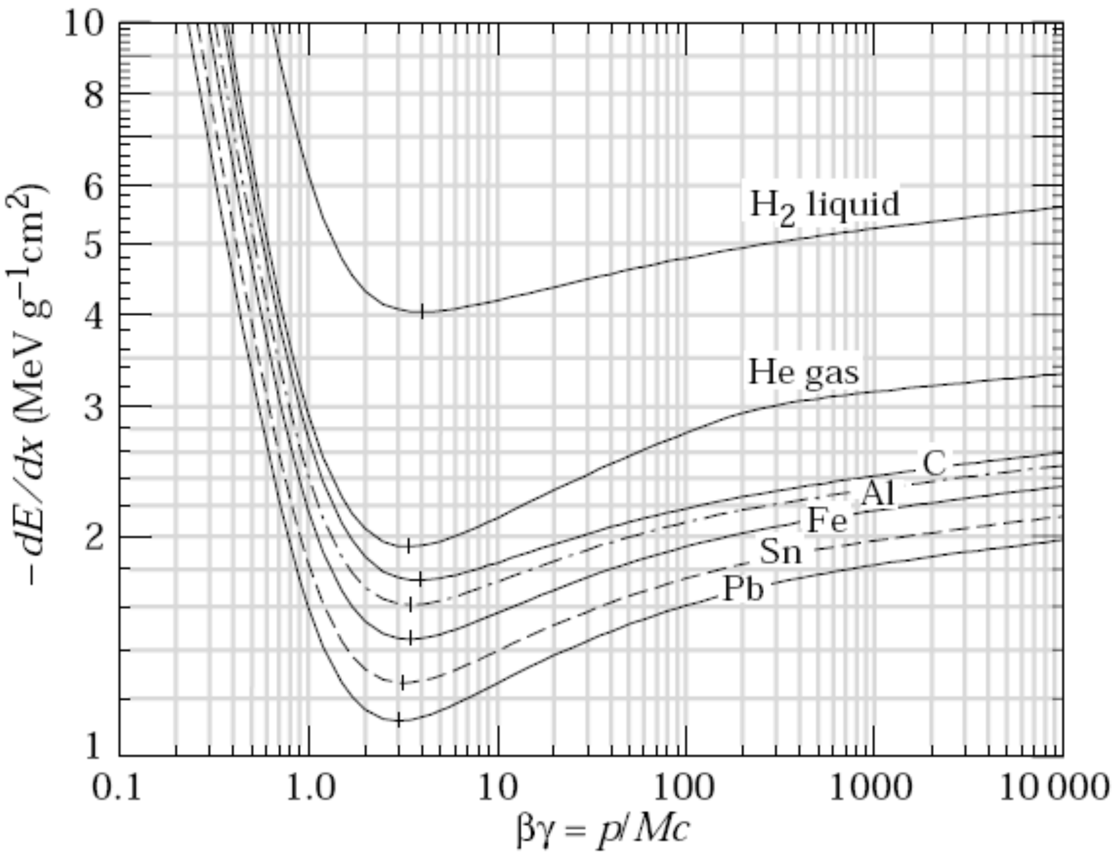
$$\delta(\beta\gamma) = \ln h\omega_p/I + \ln\beta\gamma - \frac{1}{2}$$

- I is the mean excitation energy.
- F is the maximum possible energy transfer to a shell electron, occurring in a central collision).

Density effect. Medium is polarized
Which reduces the log. rise.

Electro-magnetic interaction: Charged particles: Excitation + Ionization

Z/A matters…



Example 1:
$Z \approx 0.5\,A$
$1/\rho\ dE/dx \approx 1.4$ MeV cm^2/g for $\beta\gamma \approx 3$

Iron: d = 100 cm; $\rho = 7.87$ g/cm^3
dE ≈ 1.4 * 100 * 7.87 MeV = 1102 MeV
→ 1 GeV Muon can traverse 1m of Iron

Argon: d = 1 cm; $\rho = 1.78\ 10^{-3}$ g/cm^3
dE ≈ 1.4 * 1 * 1.78 keV = 2.5 keV

Need ~ 26 eV to ionize an Ar atom
→ ~100 ionization electrons / cm

$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, \frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

$$\delta(\beta\gamma) = \ln h\omega_p/I + \ln\beta\gamma - \frac{1}{2}$$

Density effect. Medium is polarized
Which reduces the log. rise.

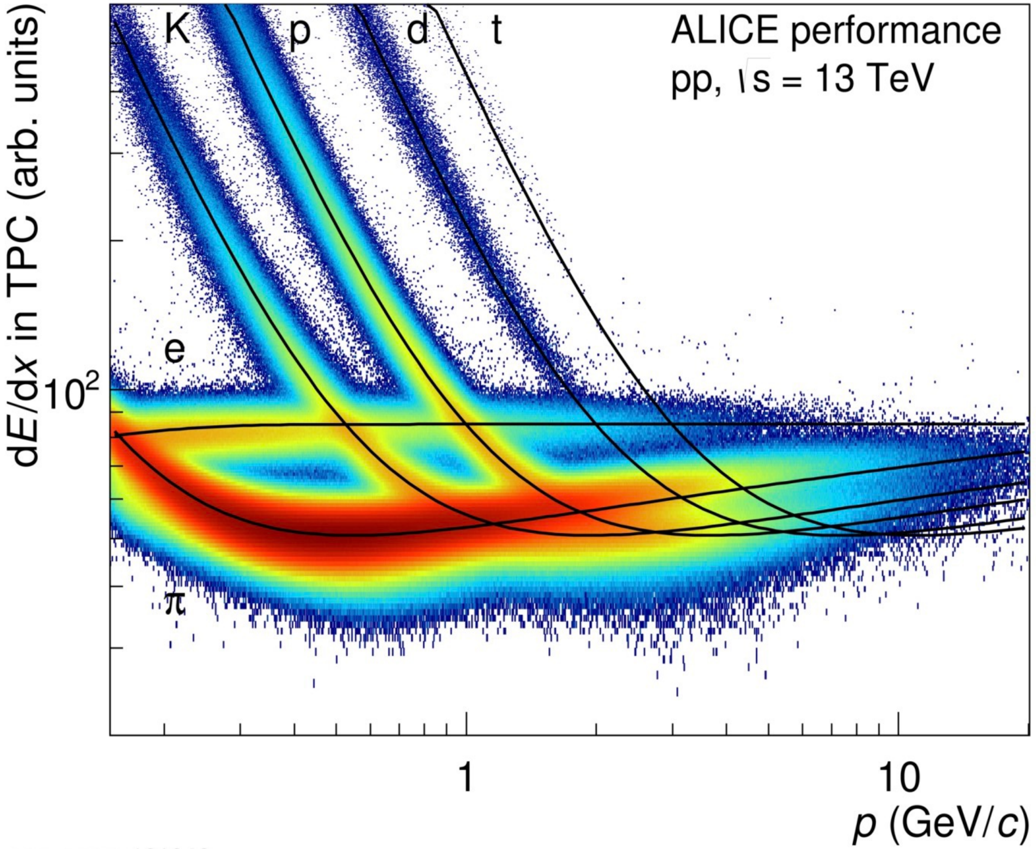
Bethe-Bloch equation

Electro-magnetic interaction: Charged particles: Excitation + Ionization

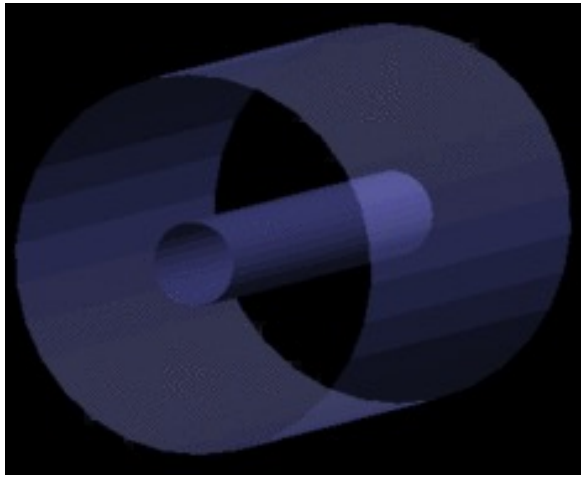
“Universal energy loss – only depending on $\beta\gamma$

→ if momentum of a particle is measured, dE/dx measurement can be used to determine a particles mass! (particle identification)

dE/dx pid



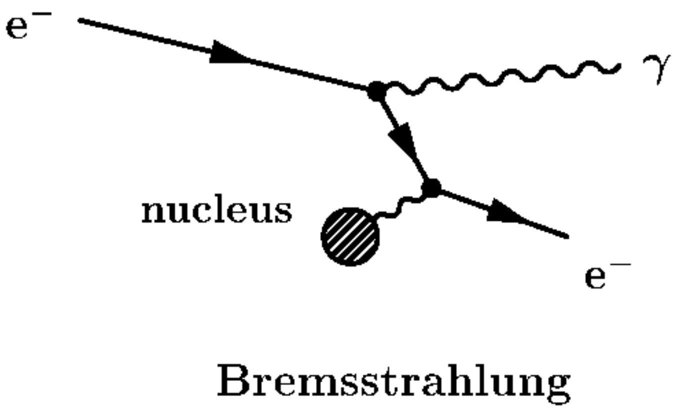
Bethe-Bloch equation



TPC
Time
Projection
Chamber

ALICE
TPC

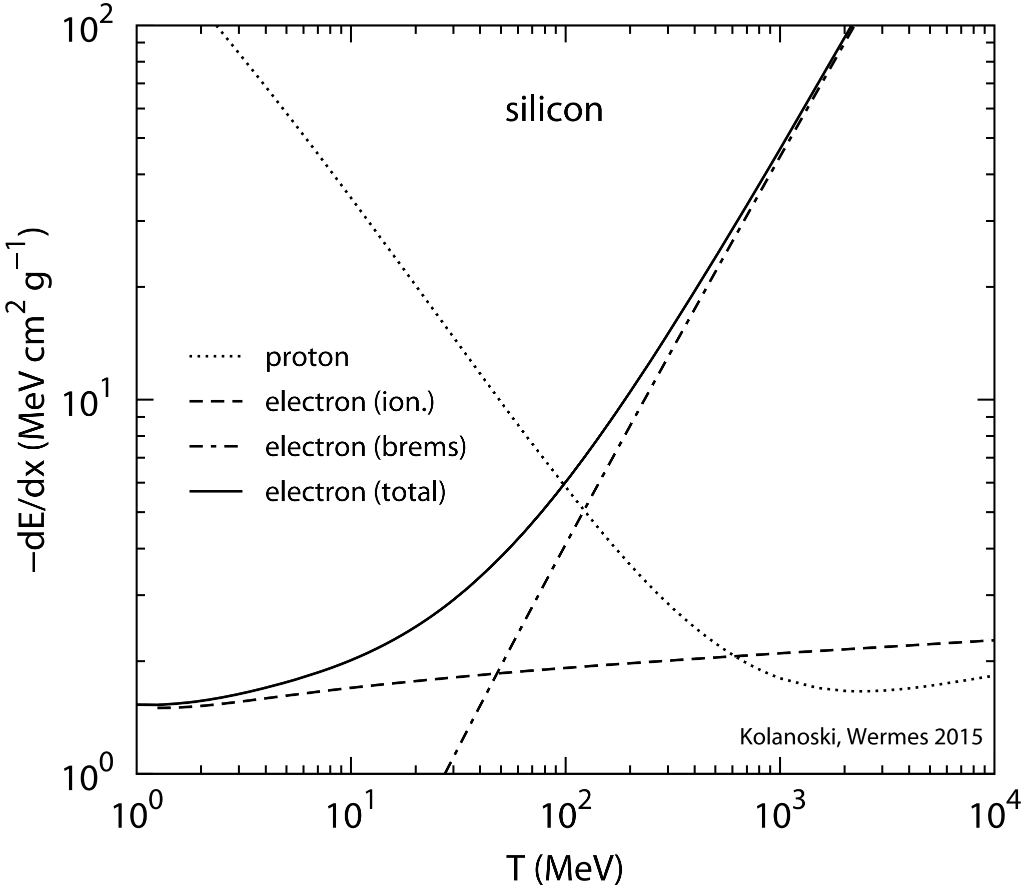
Electro-magnetic interaction: Charged particles: Bremsstrahlung



$$\frac{d\sigma}{dE_\gamma} \propto \frac{1}{E_\gamma}$$

Eventually, radiation loss gets larger than ionization loss

$$\text{ionisation:} \quad \propto \; Z \ln E/M$$
$$\text{bremsstrahlung:} \quad \propto \; Z^2\, E/M^2\, .$$



Critical energy:

$$\left(\frac{dE}{dx}(E_c)\right)_{ion} = \left(\frac{dE}{dx}(E_c)\right)_{rad}$$

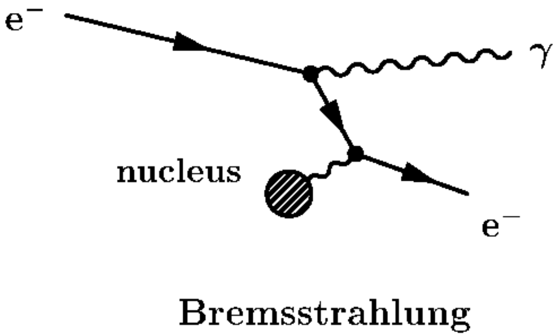
Handy formulae (for electrons):

$$E_c \approx \frac{610\,\text{MeV}}{Z+1.24} \quad \text{(solids and liquids)}$$

$$E_c \approx \frac{710\,\text{MeV}}{Z+0.92} \quad \text{(gases)}\,.$$

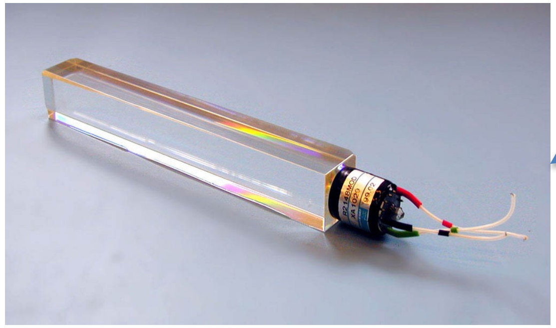
Electro-magnetic interaction: Charged particles: Bremsstrahlung

Radiation length



$$E(x) = E_0 \, \mathrm{e}^{-\frac{x}{X_0}}$$

Radiation length X_0 =
amount of material (of a given composition) to be traversed until a particle has radiated off (1-1/e) = 63% of its energy.



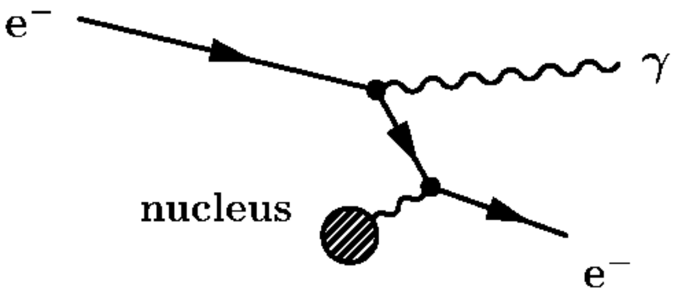
For total absorption (electro-magnetic calorimeter) we need several X_0 of material

For non-destructive (tracking) measurements we need to minimize the number/fraction of X_0´s

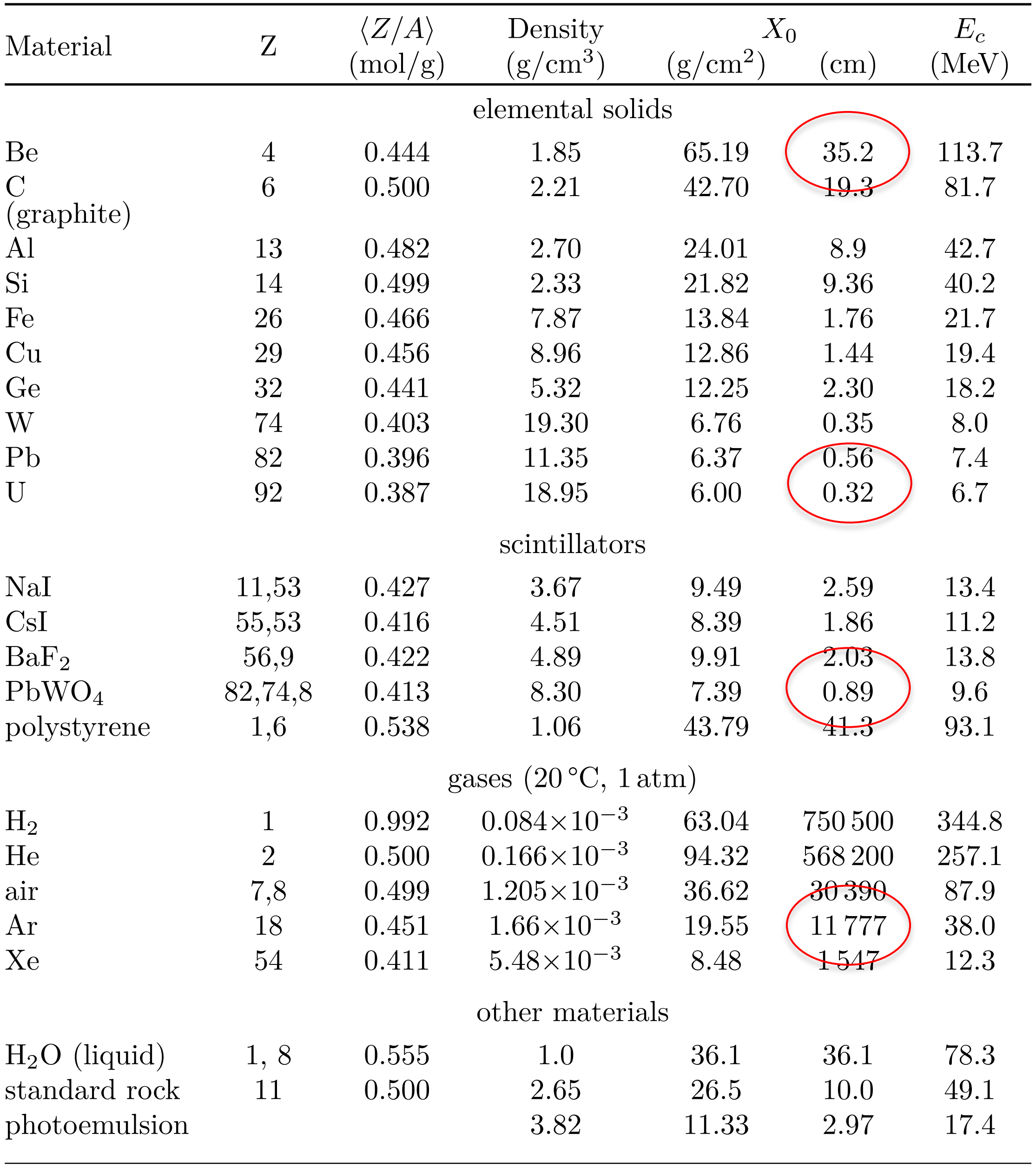
X_0 governs:
- bremsstrahlung
- photon pair production
- multiple Coulomb scattering

Electro-magnetic interaction: Charged particles: Bremsstrahlung

Radiation length

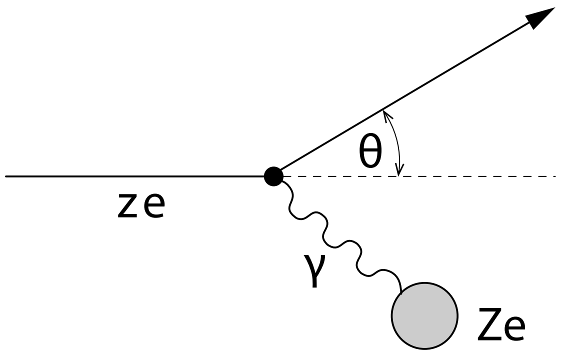


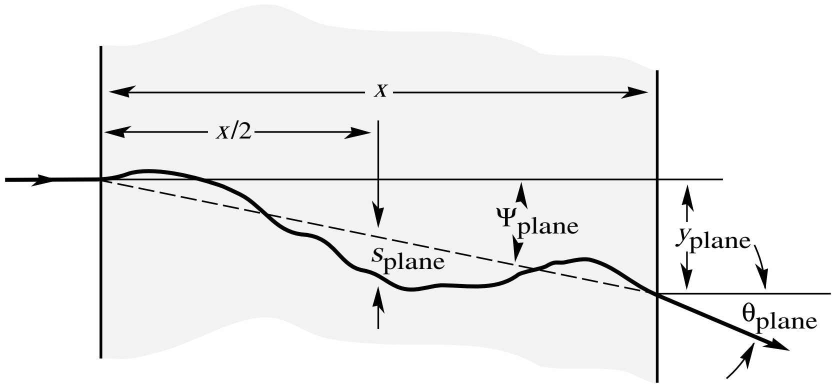
Bremsstrahlung

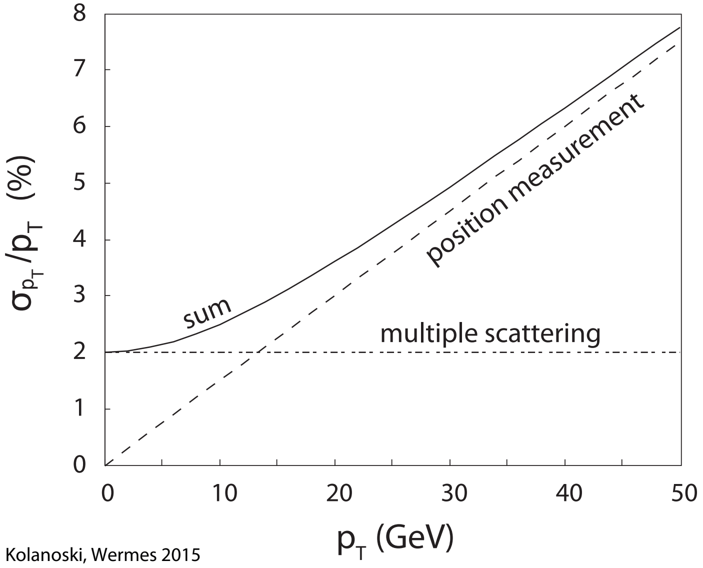


Material	Z	$\langle Z/A \rangle$ (mol/g)	Density (g/cm^3)	X_0 (g/cm^2)	X_0 (cm)	E_c (MeV)
			elemental solids			
Be	4	0.444	1.85	65.19	35.2	113.7
C (graphite)	6	0.500	2.21	42.70	19.3	81.7
Al	13	0.482	2.70	24.01	8.9	42.7
Si	14	0.499	2.33	21.82	9.36	40.2
Fe	26	0.466	7.87	13.84	1.76	21.7
Cu	29	0.456	8.96	12.86	1.44	19.4
Ge	32	0.441	5.32	12.25	2.30	18.2
W	74	0.403	19.30	6.76	0.35	8.0
Pb	82	0.396	11.35	6.37	0.56	7.4
U	92	0.387	18.95	6.00	0.32	6.7
			scintillators			
NaI	11,53	0.427	3.67	9.49	2.59	13.4
CsI	55,53	0.416	4.51	8.39	1.86	11.2
BaF_2	56,9	0.422	4.89	9.91	2.03	13.8
$PbWO_4$	82,74,8	0.413	8.30	7.39	0.89	9.6
polystyrene	1,6	0.538	1.06	43.79	41.3	93.1
			gases (20 °C, 1 atm)			
H_2	1	0.992	0.084×10^{-3}	63.04	750 500	344.8
He	2	0.500	0.166×10^{-3}	94.32	568 200	257.1
air	7,8	0.499	1.205×10^{-3}	36.62	30 390	87.9
Ar	18	0.451	1.66×10^{-3}	19.55	11 777	38.0
Xe	54	0.411	5.48×10^{-3}	8.48	1 547	12.3
			other materials			
H_2O (liquid)	1, 8	0.555	1.0	36.1	36.1	78.3
standard rock	11	0.500	2.65	26.5	10.0	49.1
photoemulsion			3.82	11.33	2.97	17.4

Electro-magnetic interaction: Multiple Coulomb scattering







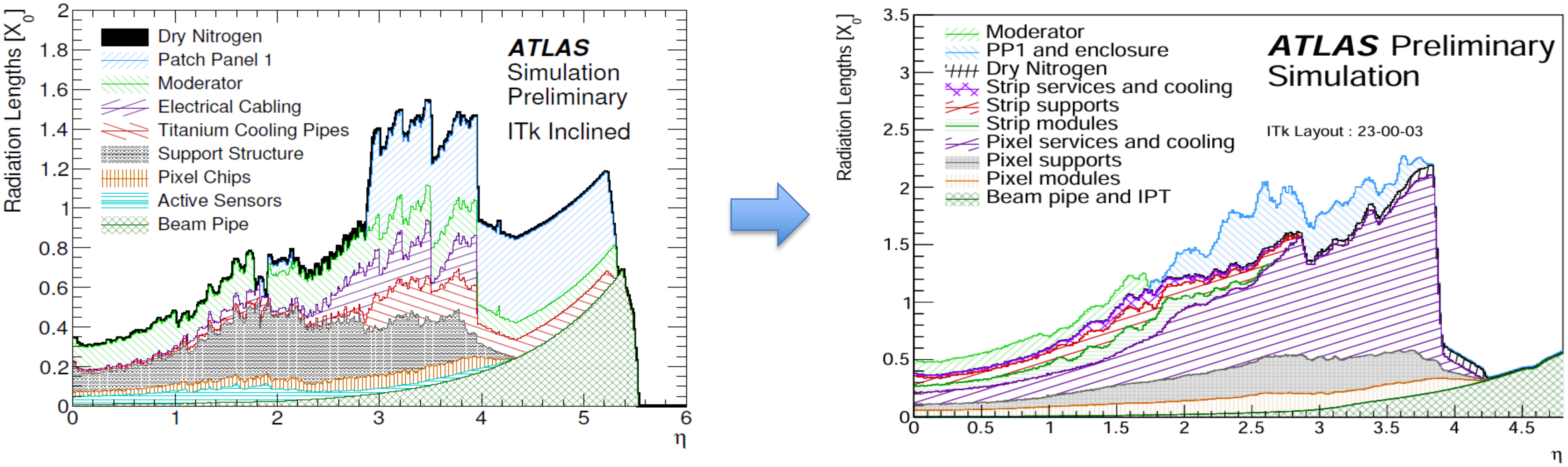
Kolanoski, Wermes 2015

$$\theta_{ms} = \frac{13.6\,\mathrm{MeV/c}}{p\beta} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

- Multiple coulomb scattering limits the momentum resolution of any tracking detector at low particle momenta
- name of the game for tracker construction: "no" material!

Electro-magnetic interaction: Multiple Coulomb scattering

A fact of life: you always need more material than you thought!

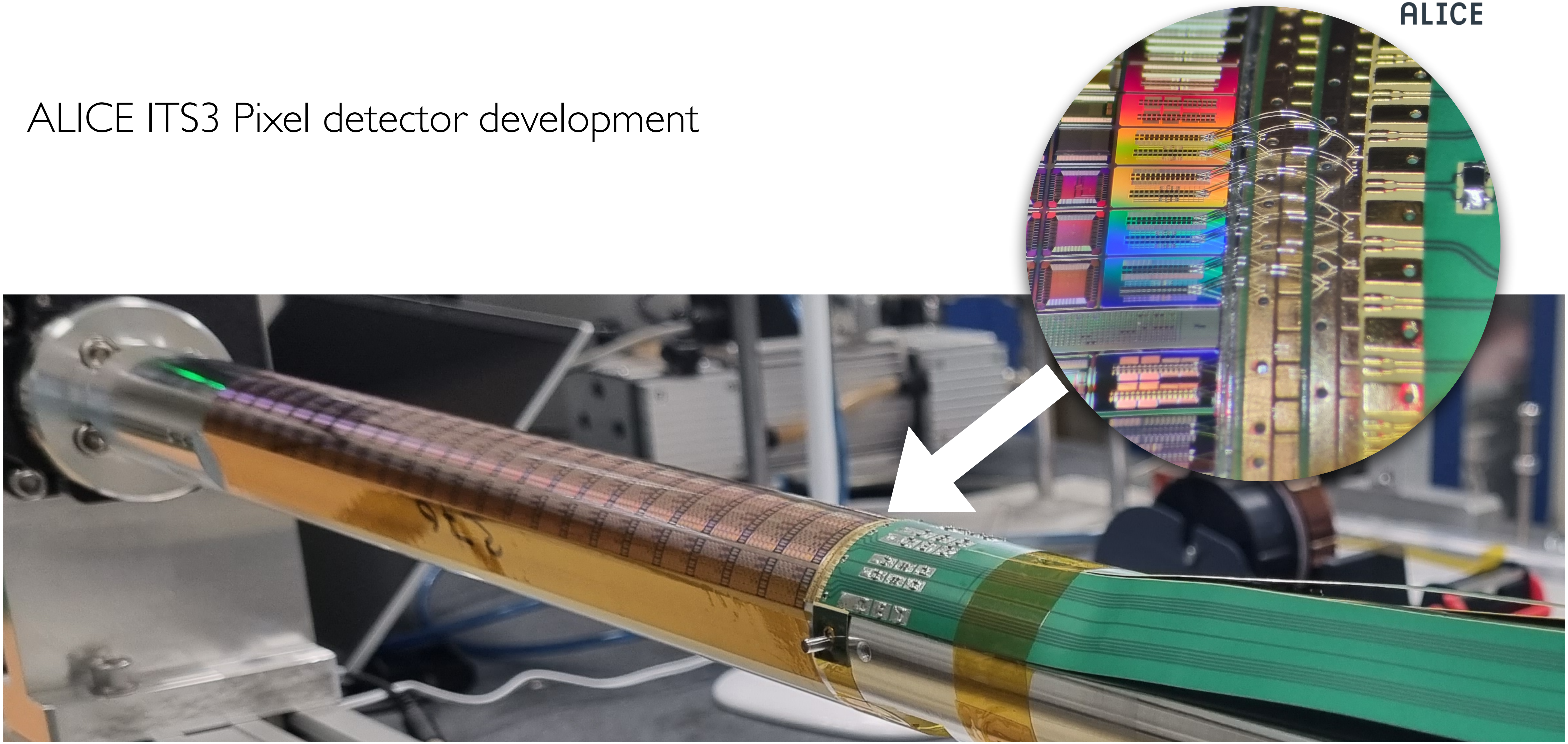


- Never forget that your detector needs support, cooling, power cables. data cables, control cables

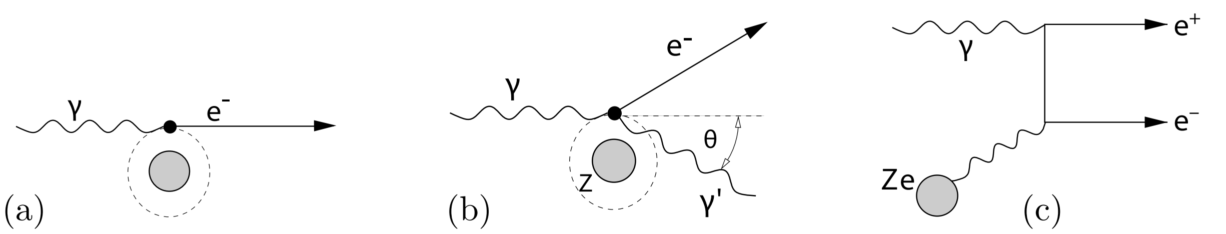
Electro-magnetic interaction: tracking – vertex detection

ALICE

ALICE ITS3 Pixel detector development

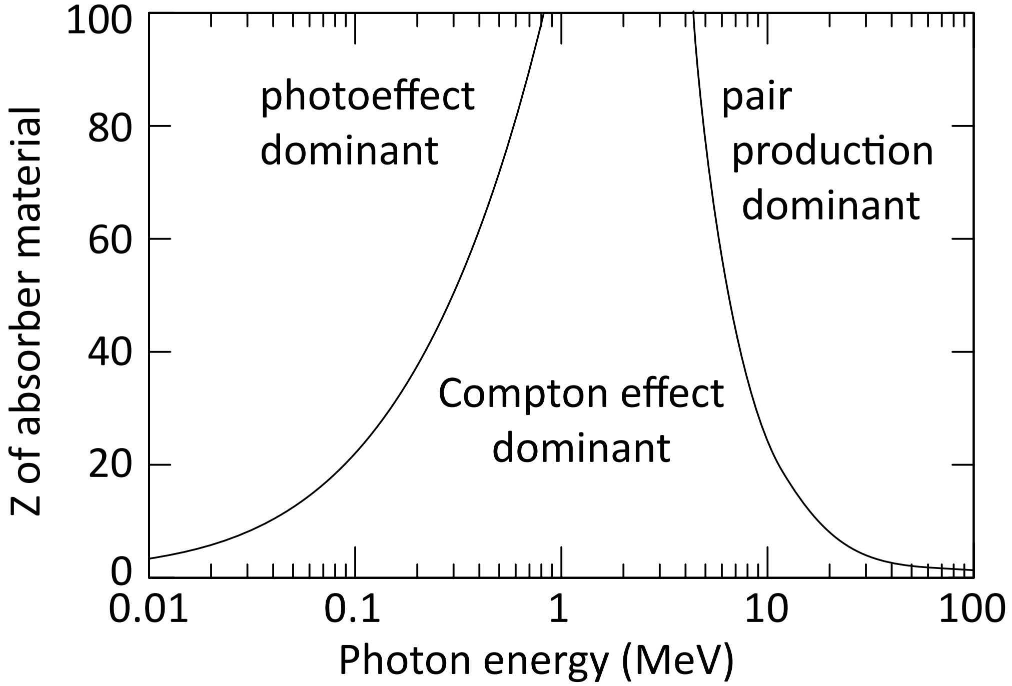


Electro-magnetic interaction: photons



Kolanoski, Wermes 2015

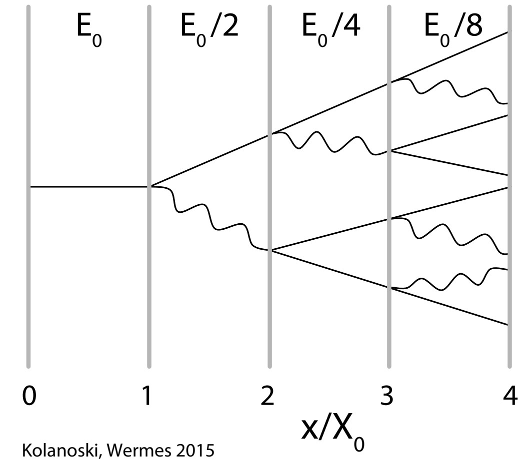
1. Photoeffect
2. Compton scattering
3. Pair production



Absorption length for pair production:

$$\lambda \approx \frac{9}{7} X_0$$

Basis for electro-magnetic showers
→ e.m. calorimeters

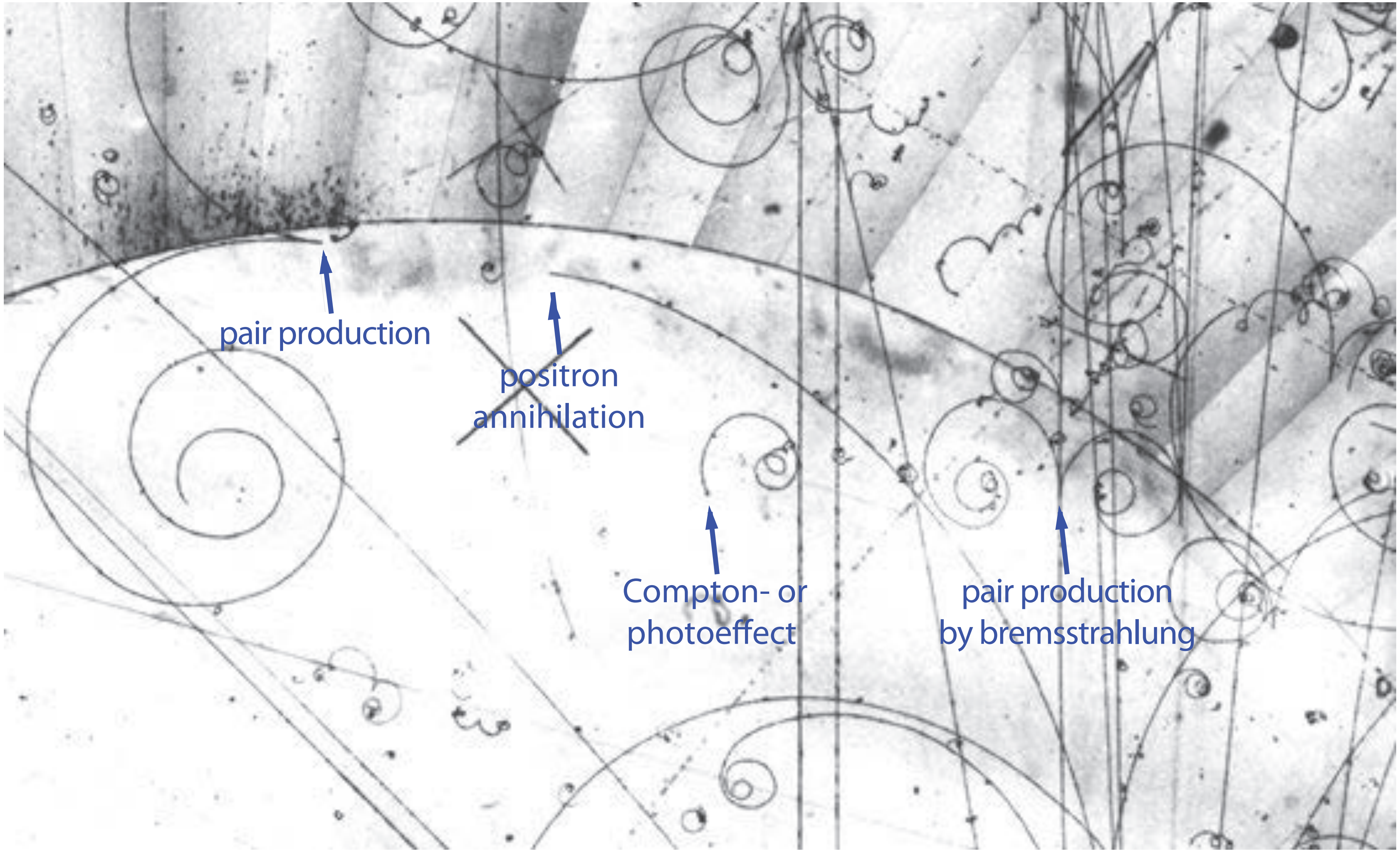


Kolanoski, Wermes 2015

Electro-magnetic interaction: photons

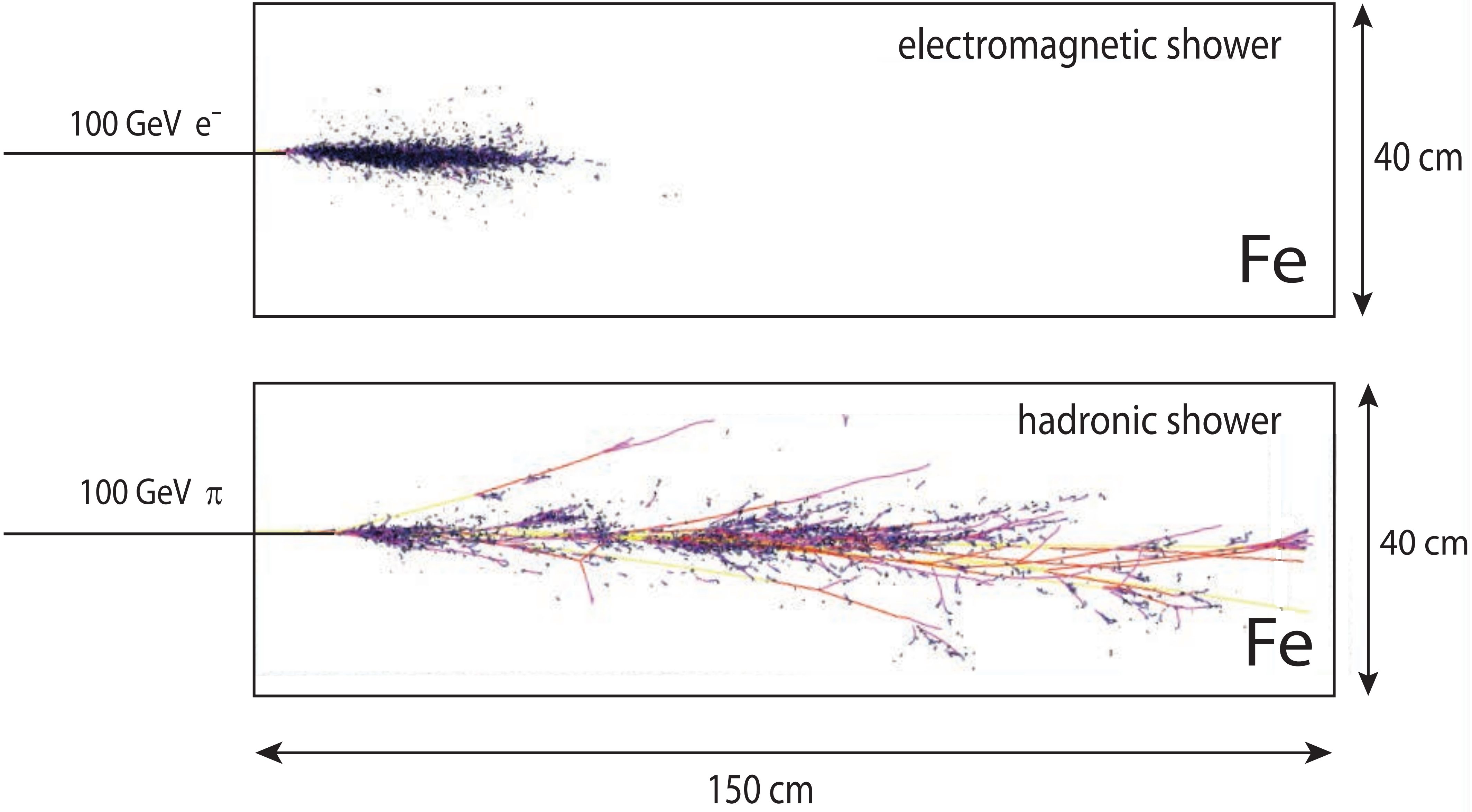
Photons

1. Photoeffect
2. Compton scattering
3. Pair production

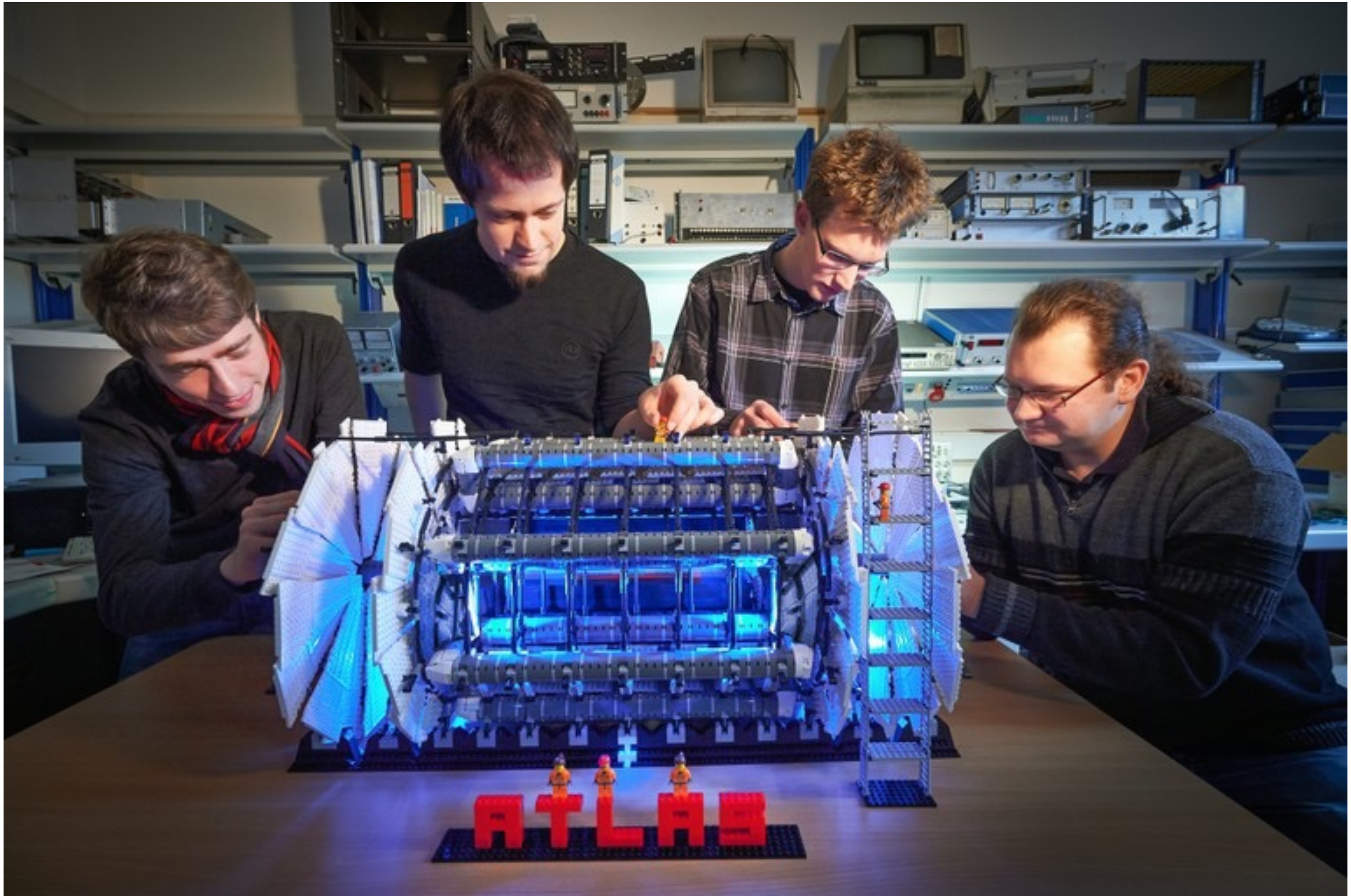


[Wermes, Kolanoski]

Electromagnetic and hadronic showers



Let´s build detectors…



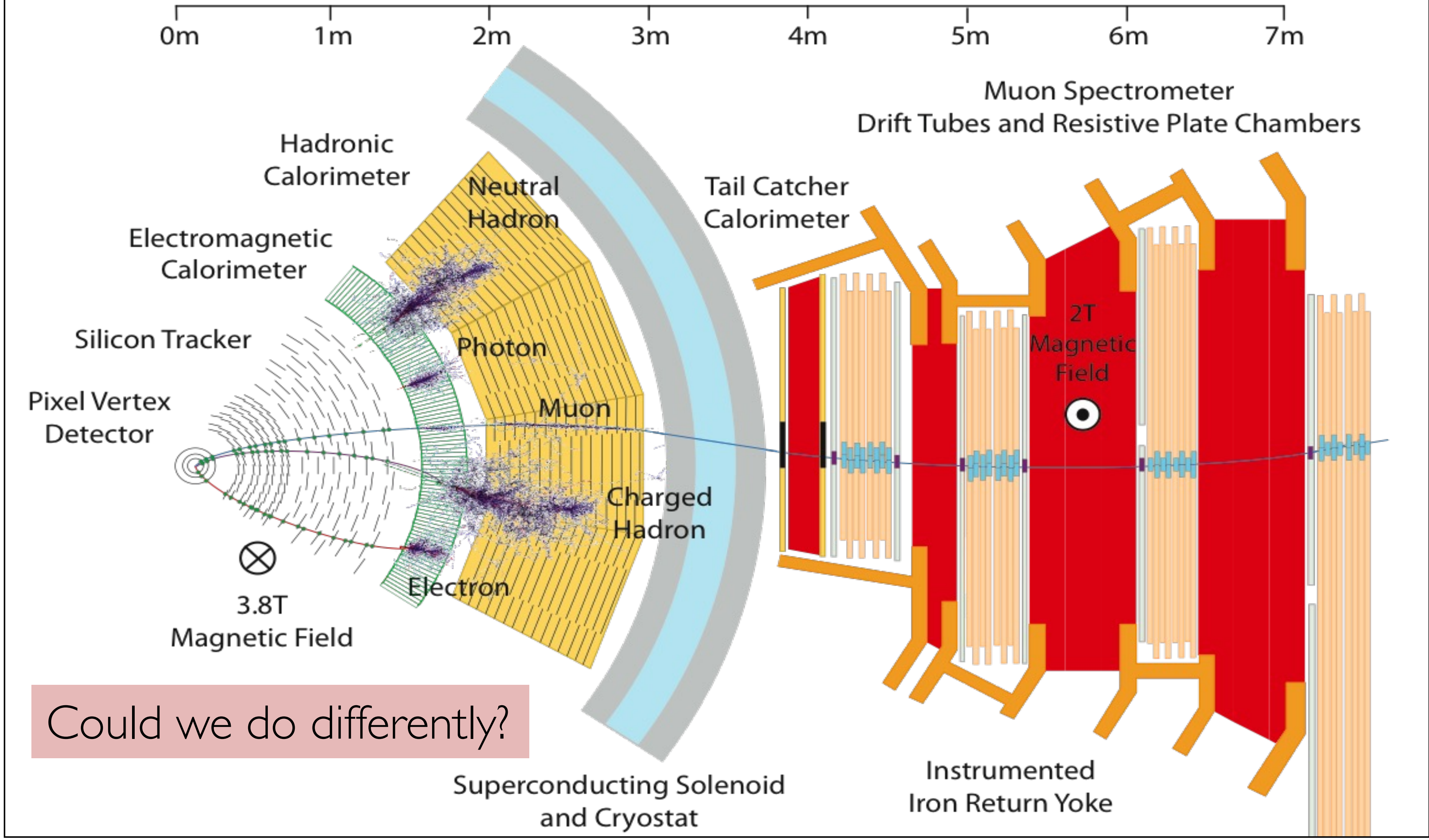
4π Detectors

paradigm:

1. non-destructive
2. destructive
3. catch "survivors" = muons

This "paradigm" is established for collider detectors since > 50 years

But it is no "law of nature"



Could we do differently?

Detectors

few KD crazy ideas:

- continuous transition from non-destructive to destructive?

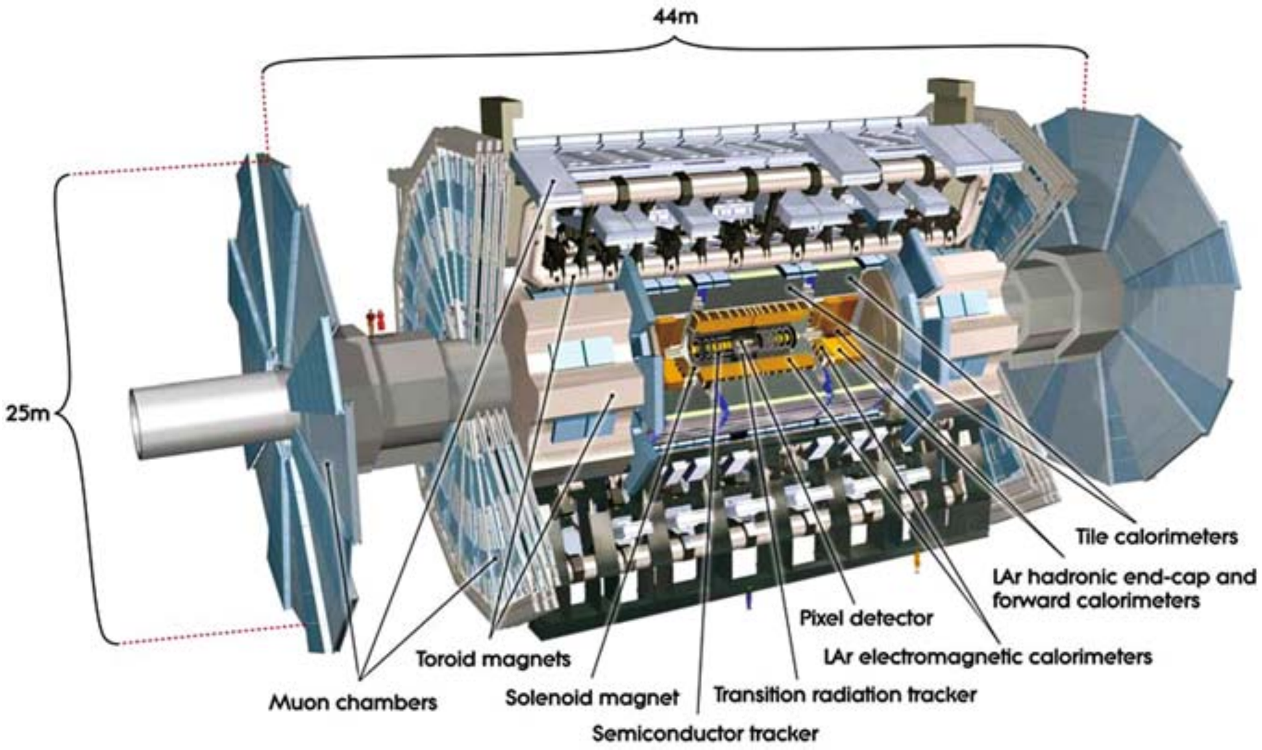
- single optical photon detection

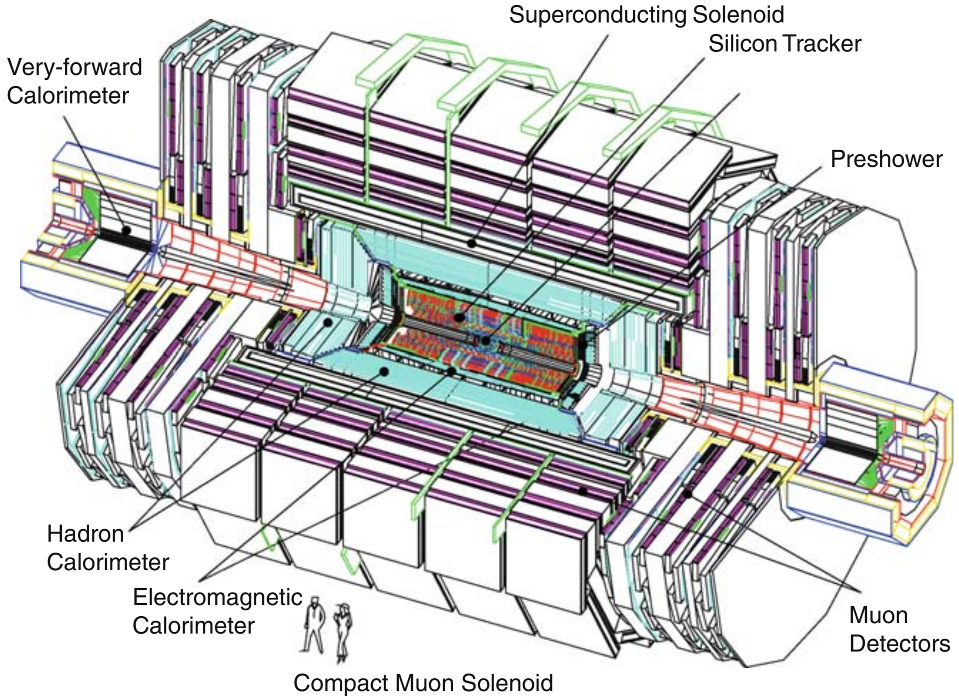
- ultra-sensitive sensing (quantum sensing, …)
(see e.g. M. Doser (CERN) at ICHEP24)

- "contact-less" sensing?

(your crazy idea here…)

4π detectors





Quite significant differences, e.g.

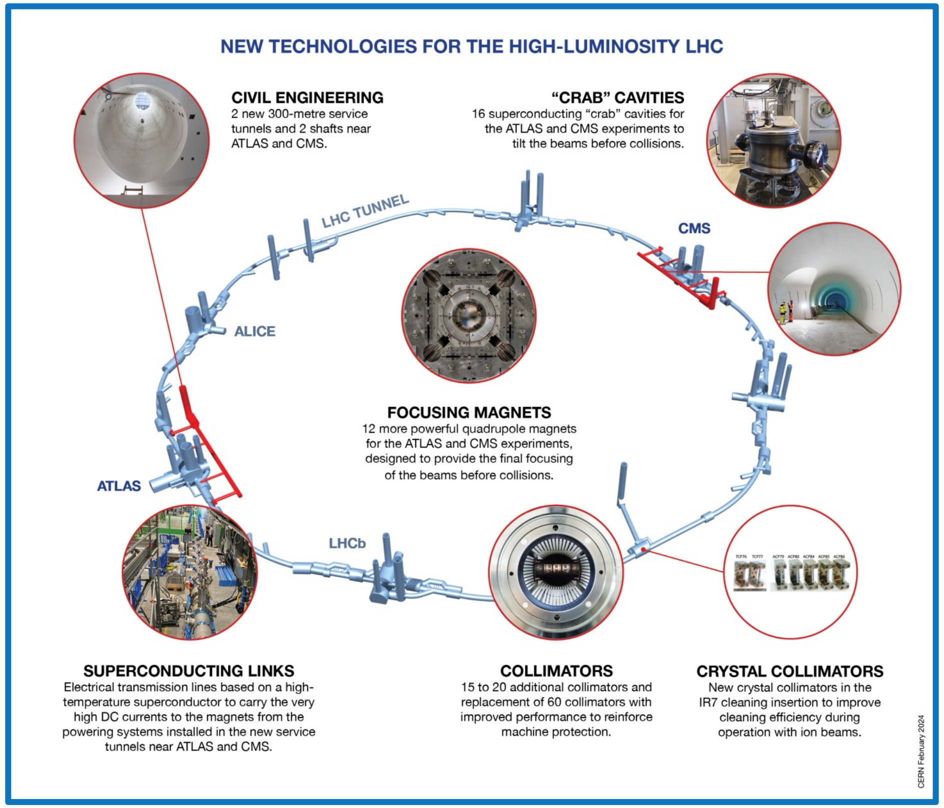
central B-field	2T Calo outside	4T Calo inside
Tracker	Si+Gas (TR)	Si only
E.-m. calorimeter	LAr Sampling	$PbWO_4$ crystals
Muon system	Air core toroid	“instrumented iron”

(many more)

pros an cons?

High-Luminosity upgrade of ATLAS and CMS

- increased luminosity ($5\ 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$) is achieved by more intense and stronger focused beams
- new equipment will be installed in about 1.2 km of the LHC's total length
  - – new focusing magnets and beam optics
    - installed around ATLAS and CMS
  - – crab cavities
    - installed around ATLAS and CMS
  - – about 100 new collimators for machine protection
  - – new crystal collimators for at cleaning insertions for ion beam operation
  - – superconducting power links (100kA @ 50 K)
  - – upgrade of the accelerator chain


NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC

CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting "crab" cavities for the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for the ATLAS and CMS experiments, designed to provide the final focusing of the beams before collisions.

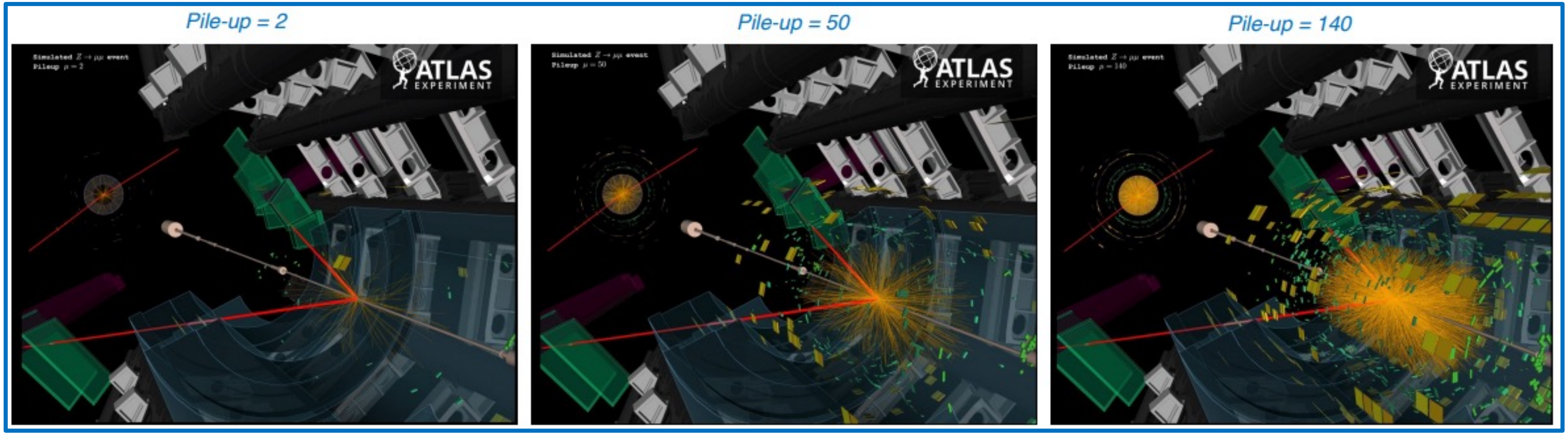
SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry the very high DC currents to the magnets from the powering systems installed in the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 additional collimators and replacement of 60 collimators with improved performance to reinforce machine protection.

CRYSTAL COLLIMATORS
New crystal collimators in the IR7 cleaning insertion to improve cleaning efficiency during operation with ion beams.

CERN February 2024

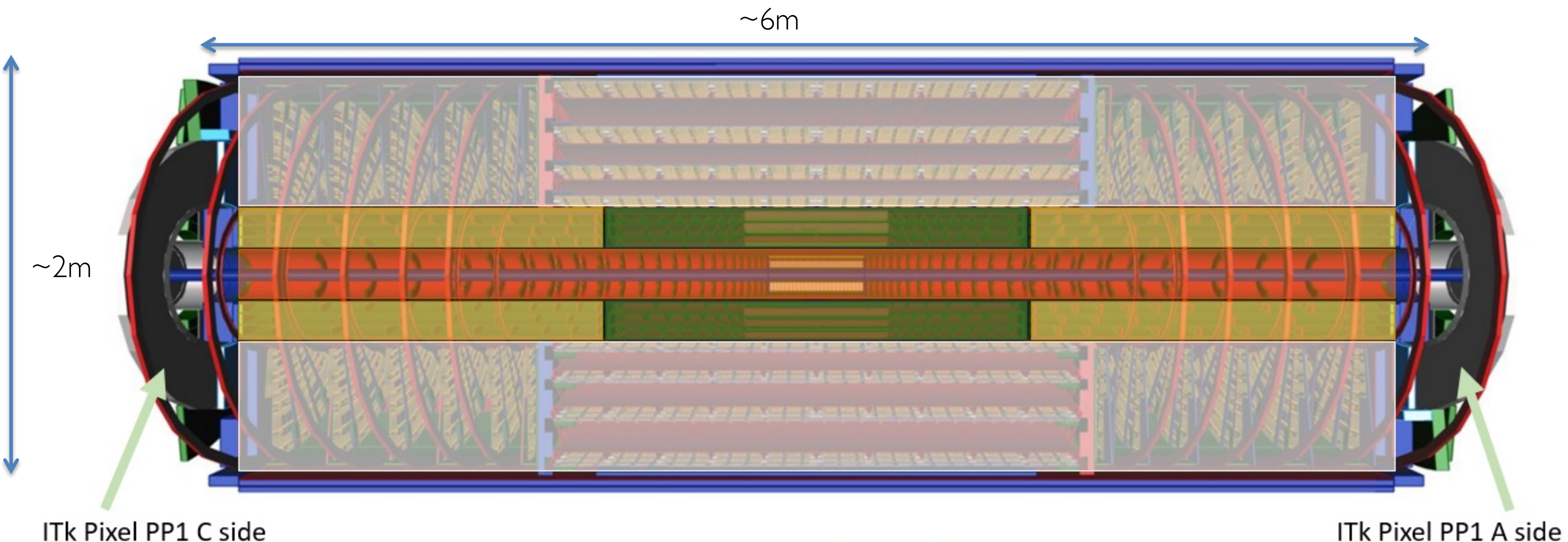
ATLAS ITk – a completely new tracking detector for ATLAS



higher luminosity achieved through a higher number of proton-proton interactions per bunch-crossing

- significantly messier events at the HL-LHC! To reach its physics goals, ATLAS must
  - measure all relevant final state quantities with a precision at least comparable to Run 3
  - withstand significantly higher radiation levels (factor 10)
  - improve the triggering capabilities of the system (10x higher rate while maintaining the same pT thresholds)
  - improve readout capabilities: all detectors must be read out at 1 MHz effective trigger rate^

ATLAS ITk – layout



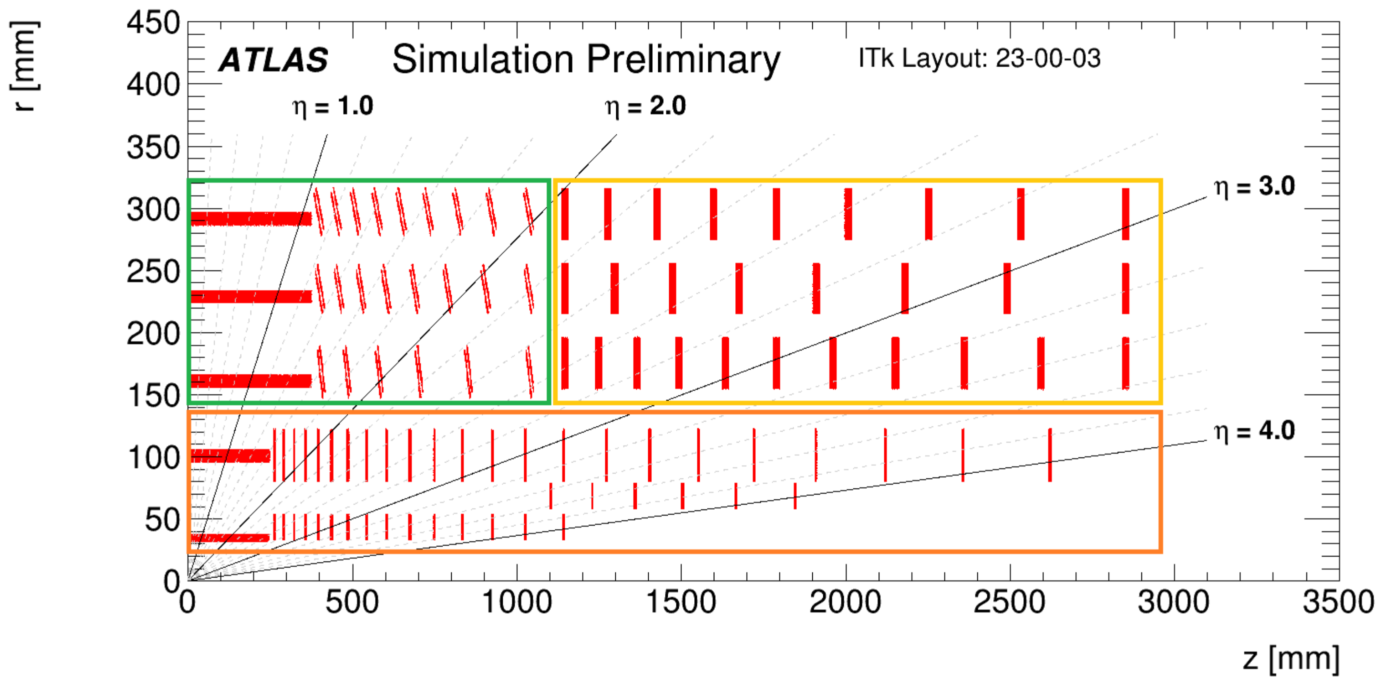
⬜ ITk Strips Detector

🟨 ITk Pixel Outer Endcaps

🟩 ITk Pixel Outer Barrel

🟧 ITk Pixel Inner System

ATLAS ITk pixel – layout



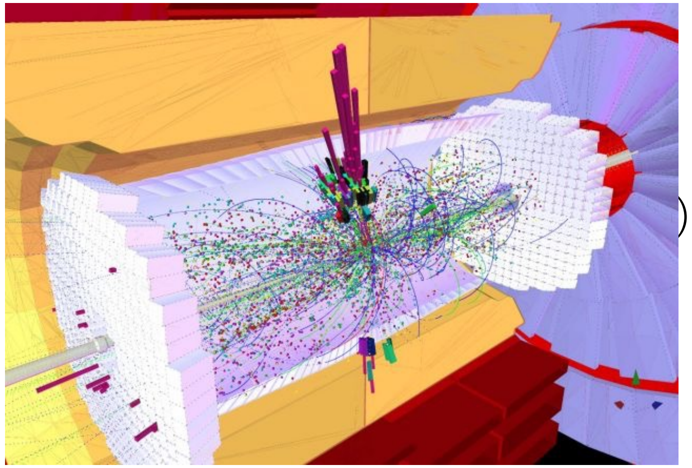
Inner System Outer Barrel Outer Endcaps

- 5 layers
- 3 subsystems
- 5 module flavours
- 3 sensor flavours
- 8.372 modules
- 13 m^2 active silicon
- 5 Gpixels

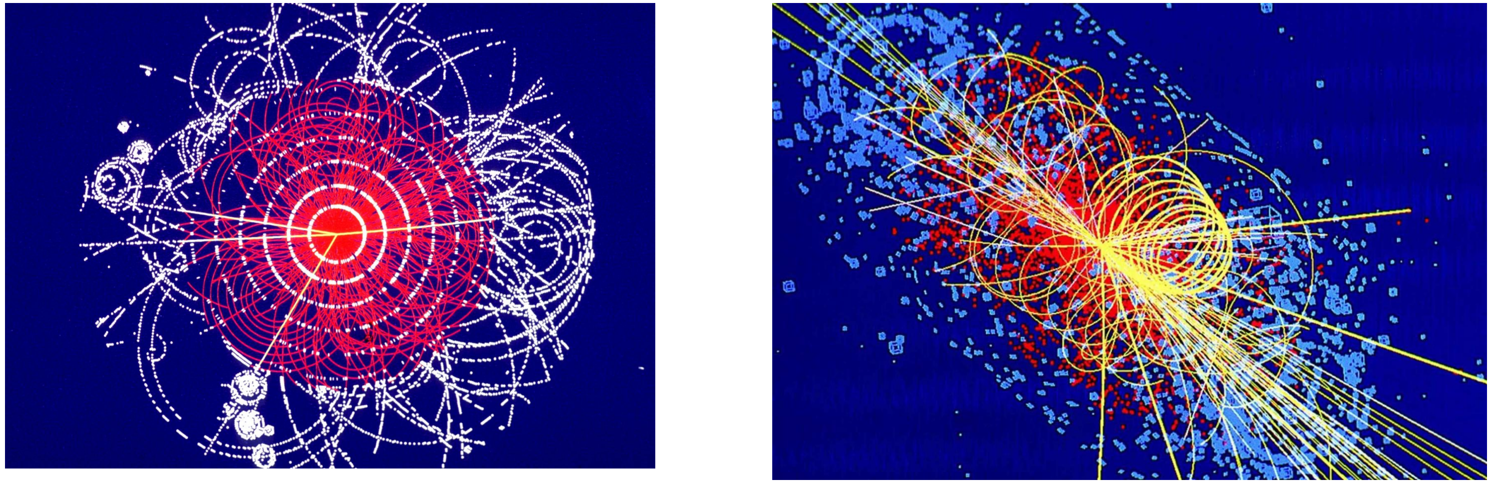
HL-LHC detector upgrades are
a major stress test for the experimental collaborations!

Precise Detector Simulations at various levels of detail

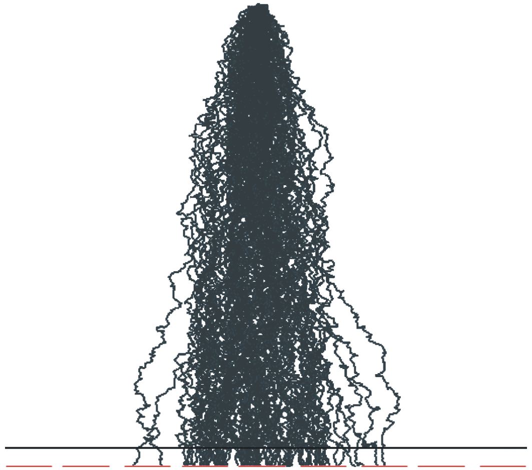
CMS detector simulation GEANT



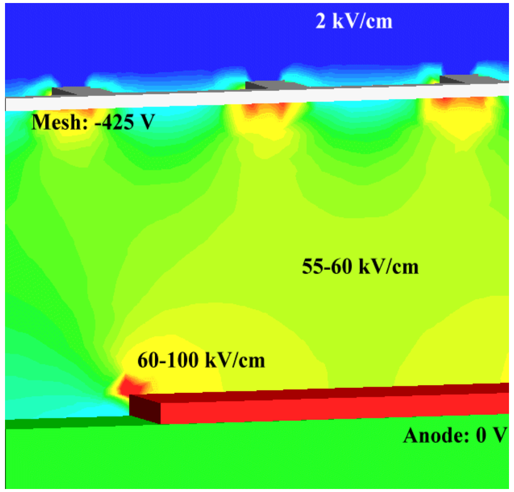
ATLAS detector simulation GEANT



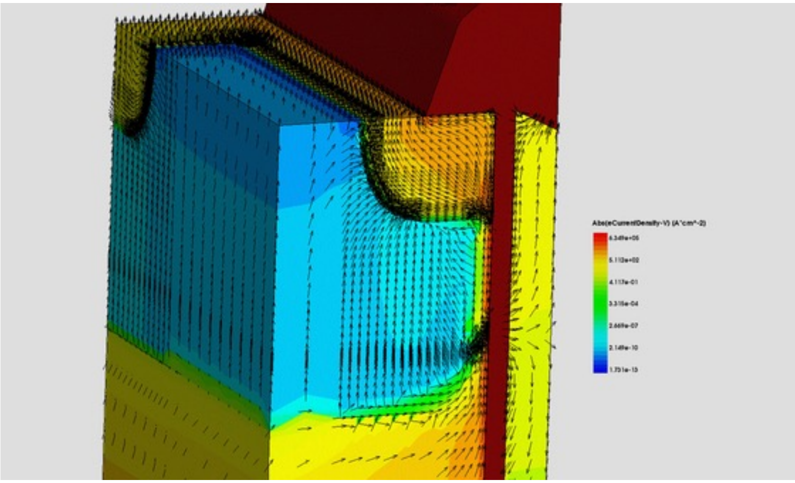
Electrons avalanche multiplication, GARFIELD++



Electric Fields in a Micromegas detector, e.g. COMSOL



Silicon sensor simulation, TCAD



[after Riegler]

From raw data to results: many steps and tasks

is it justified to have 3000 authors on every paper?

- data quality

- reconstruction of sub-detector data
  - calibration (charge calibration, correct for imperfections, time drifts, alignment)
  - track finding + fitting
  - calorimeter cluster reconstruction, particle flow

- global track reconstruction

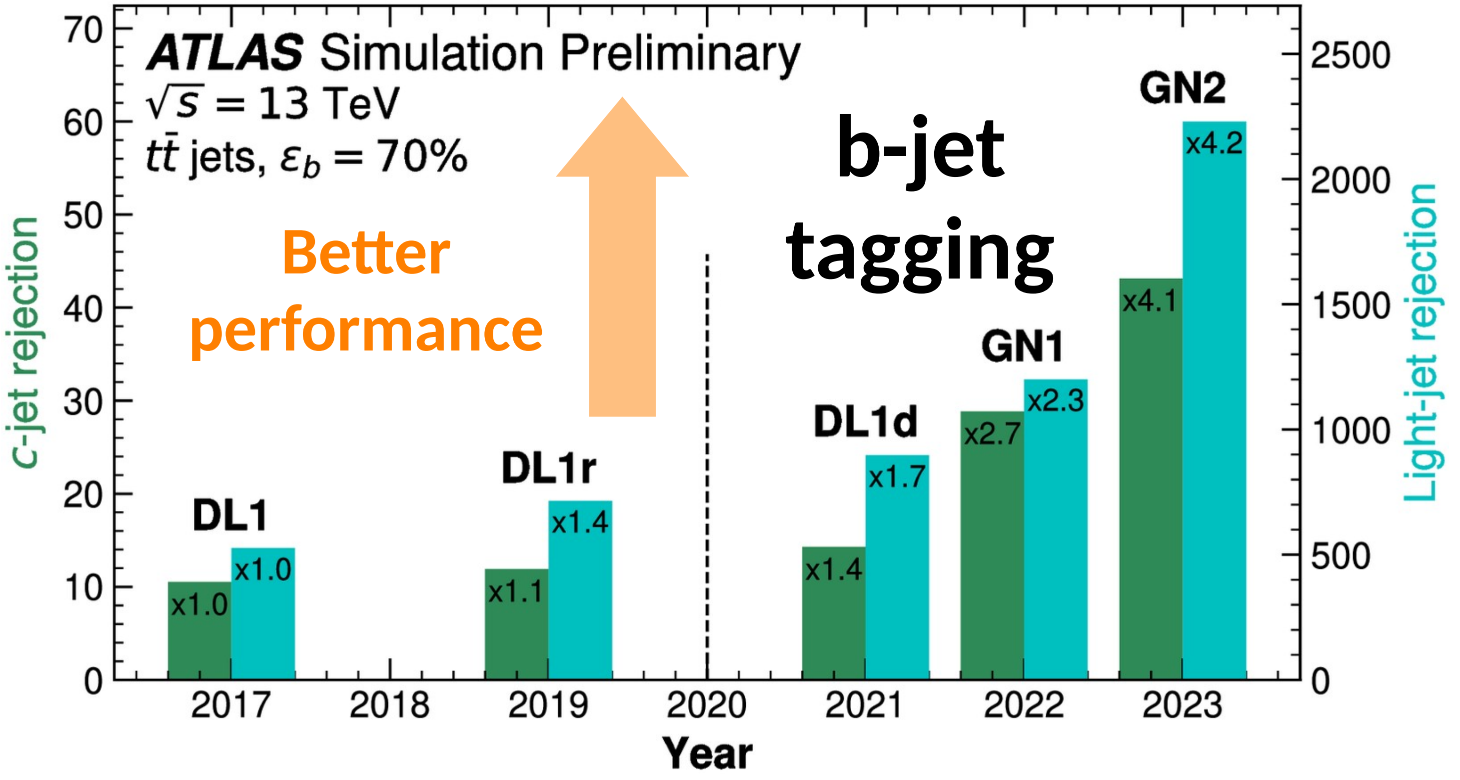
- combined high-level ”object” reconstruction
  - muons, electrons, photons, taus, jets, b-jets, missing transverse energy (MET)
  - dedicated object reconstruction (e.g. jet substructure, di-tau jets, …)
  - overlap removal

Much tedious work
But also a rewarding playground for huge improvements
ML, AI!

From raw data to results: many steps and tasks

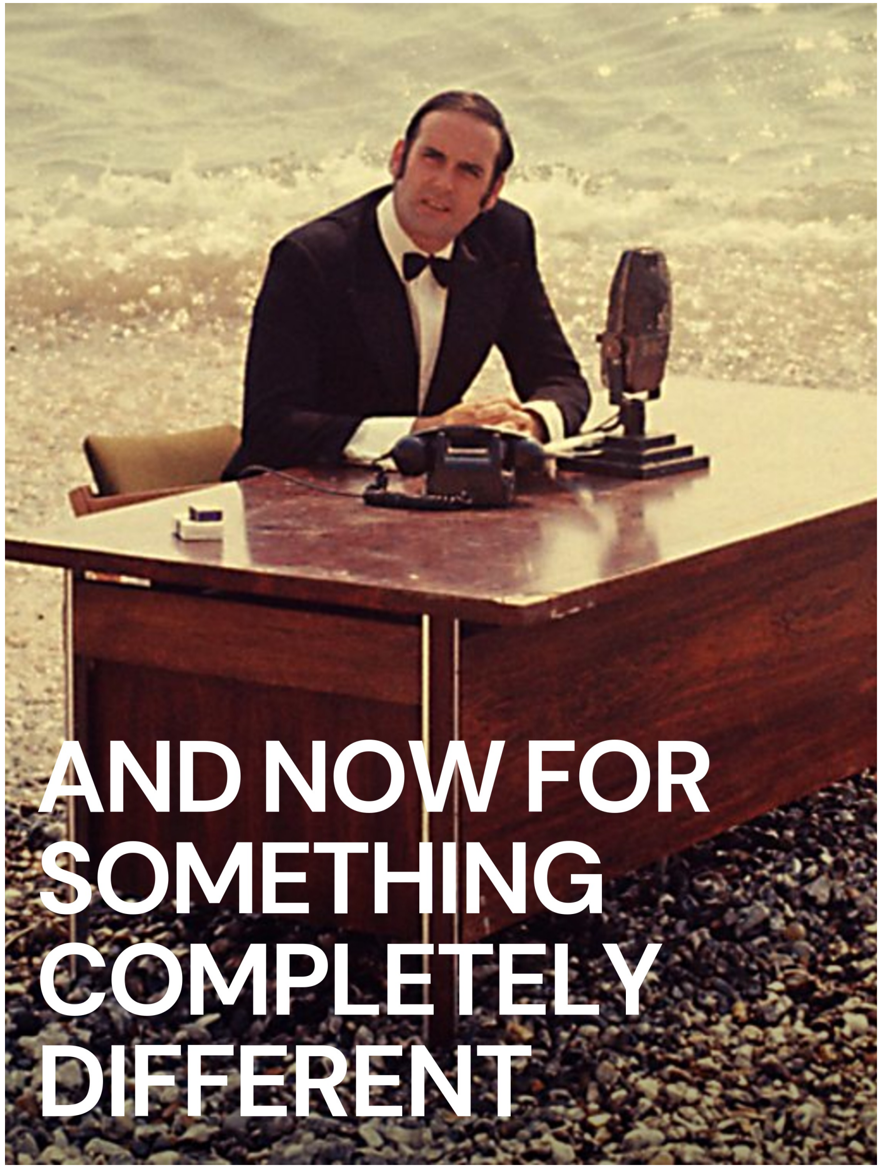
Example: tagging of b-quark jets (same detector, smarter algorithms)

ATLAS: Eur. Phys. J. C 83 (2023) 681, FTAG-2023-01



similar progress in CMS

BDT´s → feed forward deep ANN → Graph NNs, transformer NNs, …


AND NOW FOR SOMETHING COMPLETELY DIFFERENT

Some more remarks on the Higgs

The very broad picture:

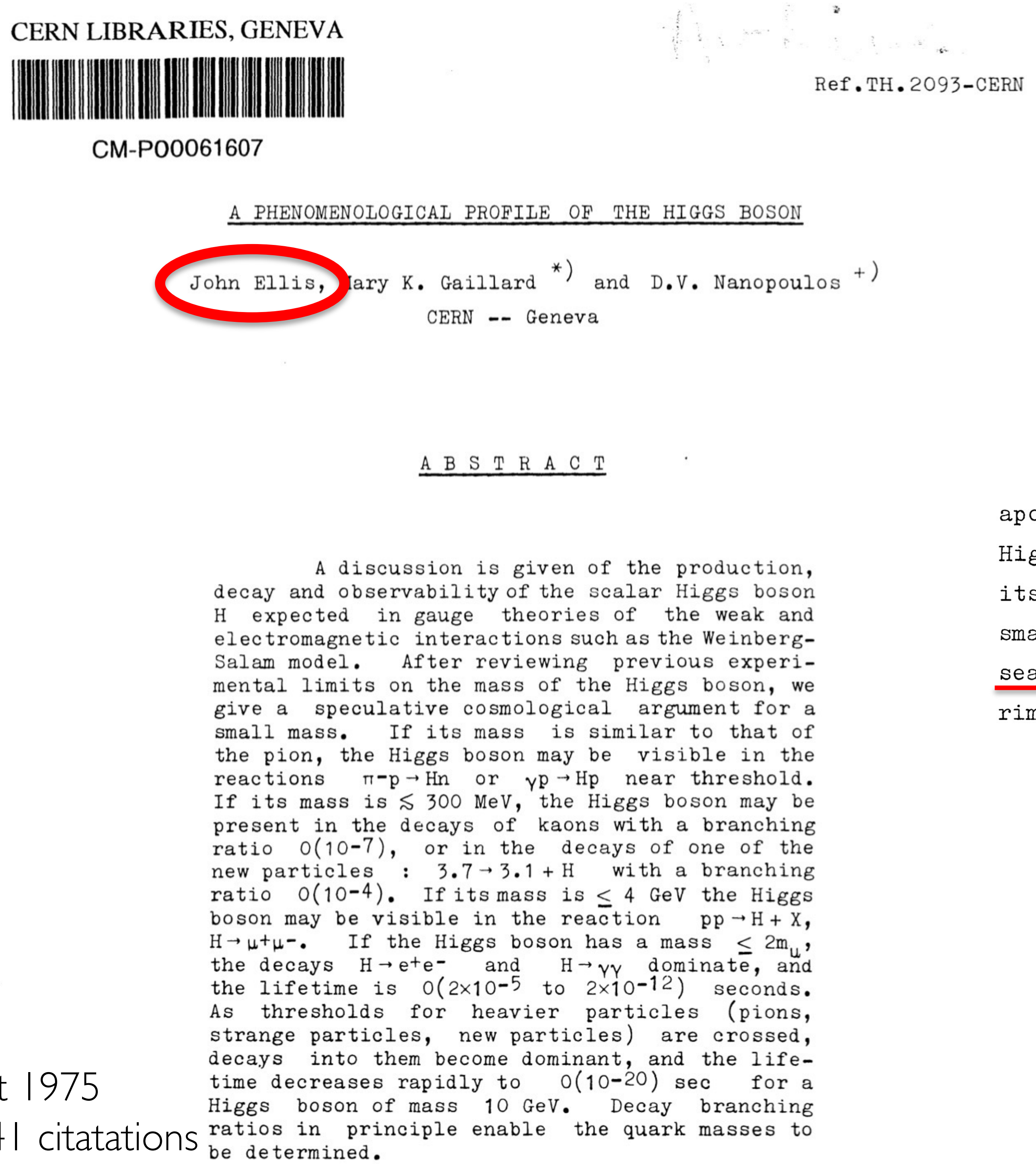
The Standard Model rules!

- incredible multitude of measurements with ever-increasing precision
- first round of characterization of the Higgs boson
- hundreds to thousands of targeted and "blue-sky" searches for new particles

- to come: HL-LHC 10-20 x more data than today
  better detectors
  further improved analysis techniques

A few more remarks on the Higgs boson…

Remark 1



Ref.TH.2093-CERN

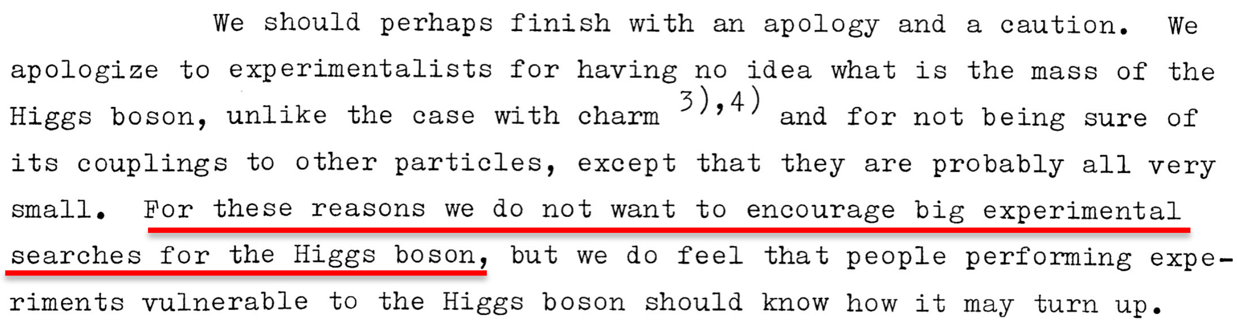
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva

ABSTRACT

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim 300$ MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new particles : $3.7 \to 3.1 + H$ with a branching ratio $O(10^{-4})$. If its mass is ≤ 4 GeV the Higgs boson may be visible in the reaction $pp \to H + X$, $H \to \mu^+\mu^-$. If the Higgs boson has a mass $\leq 2m_\mu$, the decays $H \to e^+e^-$ and $H \to \gamma\gamma$ dominate, and the lifetime is $O(2\times10^{-5}$ to $2\times10^{-12})$ seconds. As thresholds for heavier particles (pions, strange particles, new particles) are crossed, decays into them become dominant, and the lifetime decreases rapidly to $O(10^{-20})$ sec for a Higgs boson of mass 10 GeV. Decay branching ratios in principle enable the quark masses to be determined.



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm 3),4) and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Oct 1975

1441 citatations

The total width of the Higgs boson

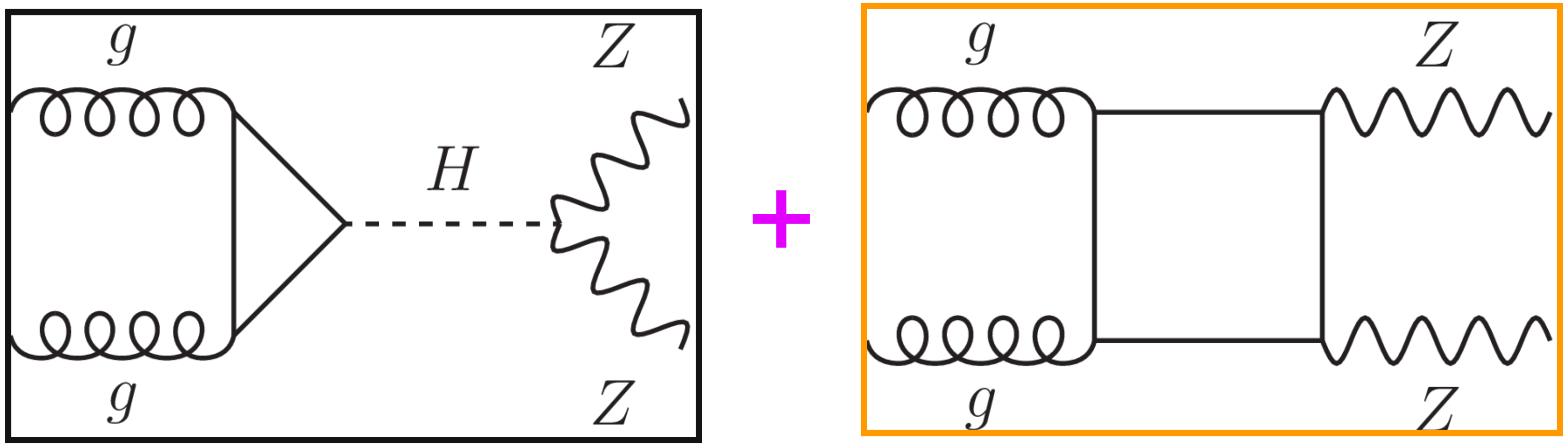
Remark 2

Different approaches to access the total width:

1. $\mathrm{BR}(H \to X_i) = \frac{\Gamma_i}{\Gamma_{tot}}$, $\Gamma_{tot} = \sum_i \Gamma_i$ need to measure all decays, difficult at LHC

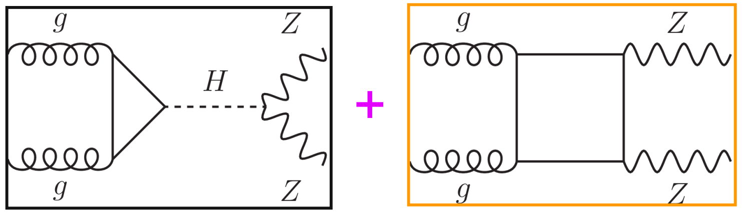
2. $\Gamma = \frac{1}{\tau}$ Higgs lifetime (SM) = 1.6 10^{-22} s too short-lived
3. $\Gamma = \Gamma_{BW}$ lineshape $\Gamma_{SM} = 4.1\ \mathrm{MeV}$ too long-lived (i.e. too narrow)

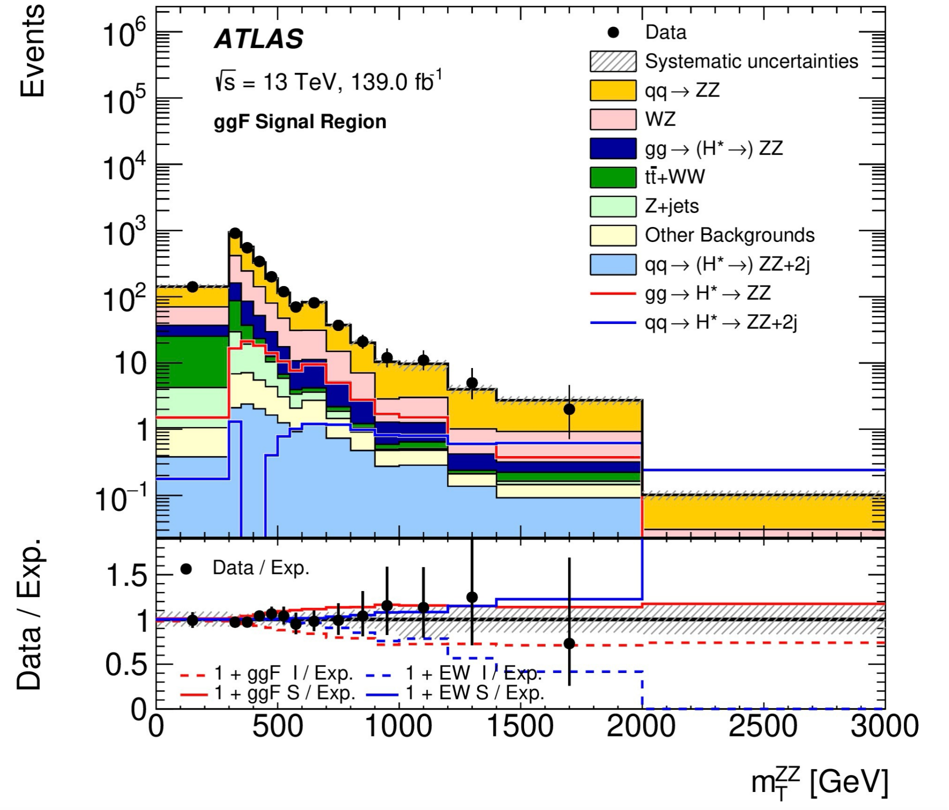
4. Rather recent observation: exploit interference in:

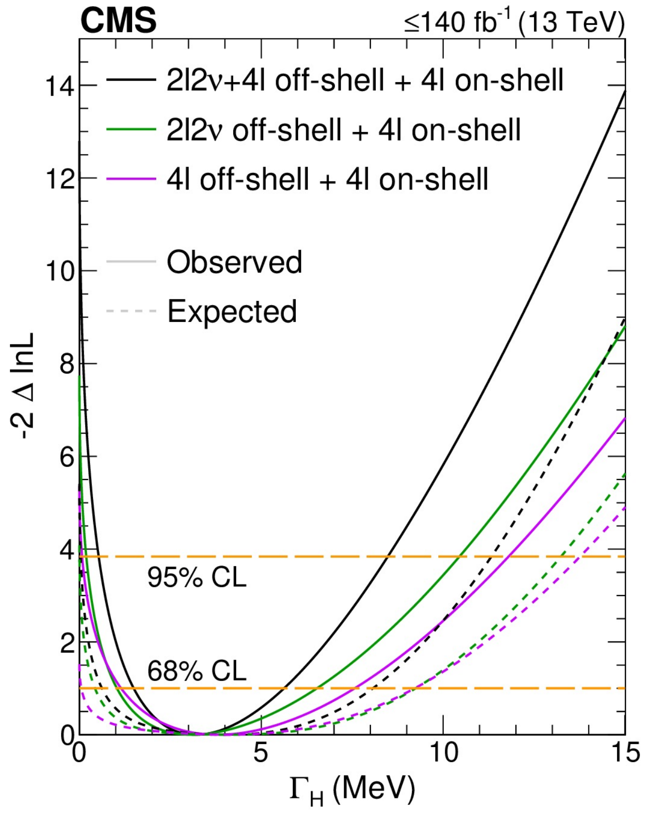


The total width of the Higgs boson

Measure ZZ* production above H threshold







strongest limits on Γ_H so far…

when interpreted
as measurement:

- Evidence for off-shell production: **3.6 σ**
- $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

Feb 2022

- Evidence for off-shell production: **3.3 σ**
- $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

Apr 2023

Phys. Lett. B 846 (2023) 138223

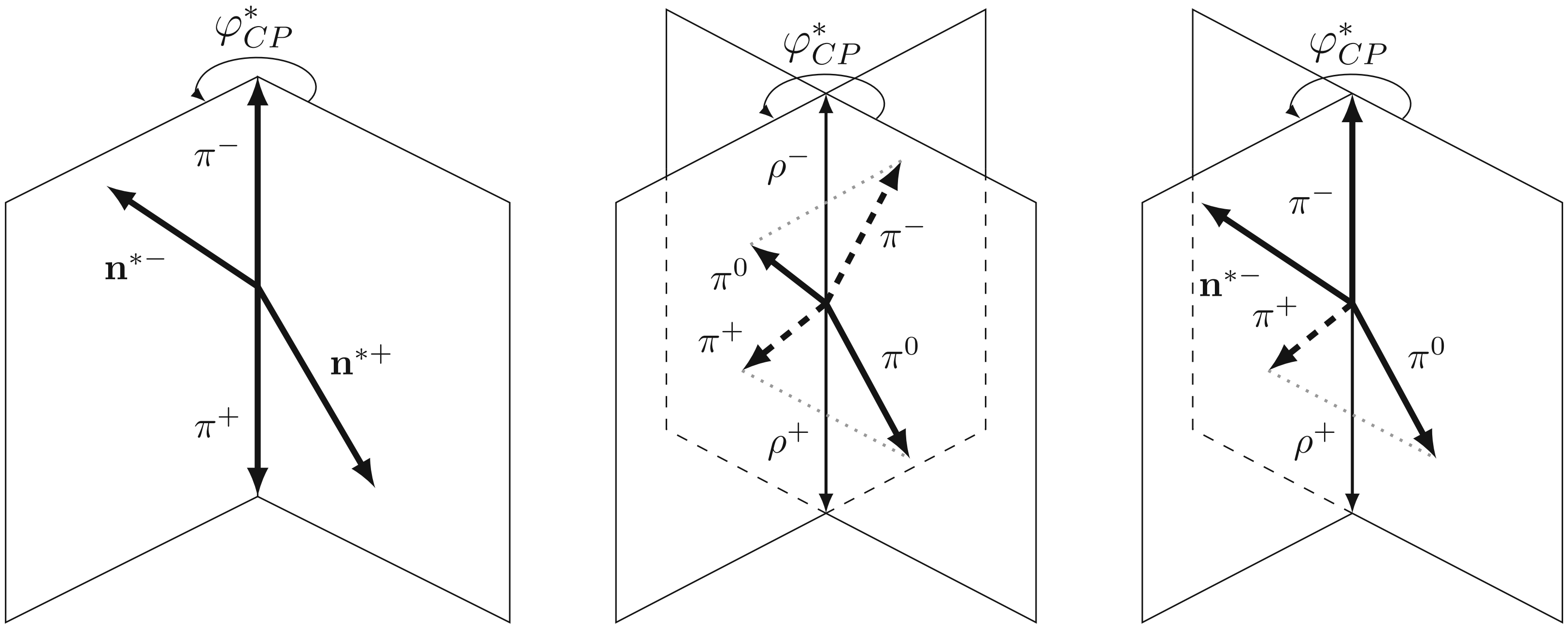
some model dependency…

Remark 3

Higgs: CP quantum numbers

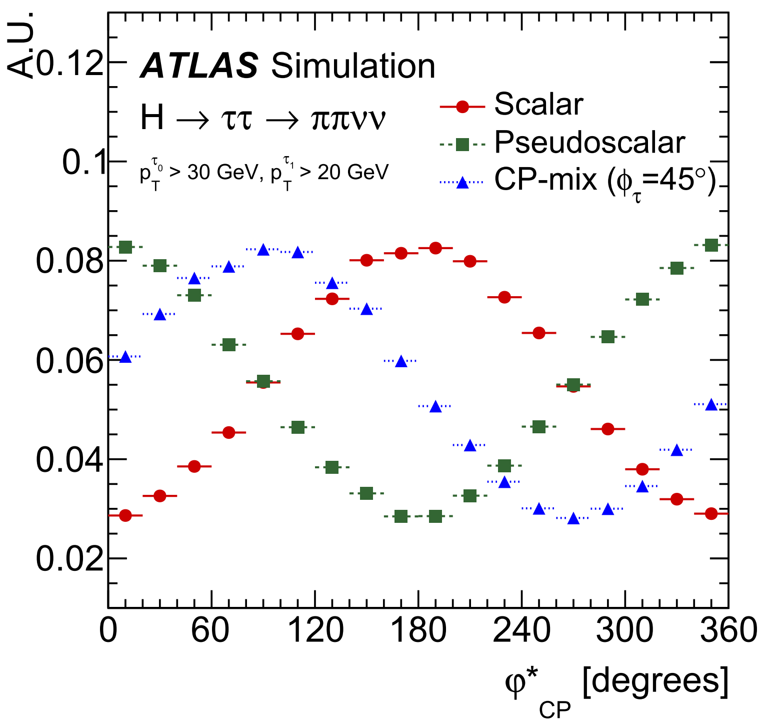
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

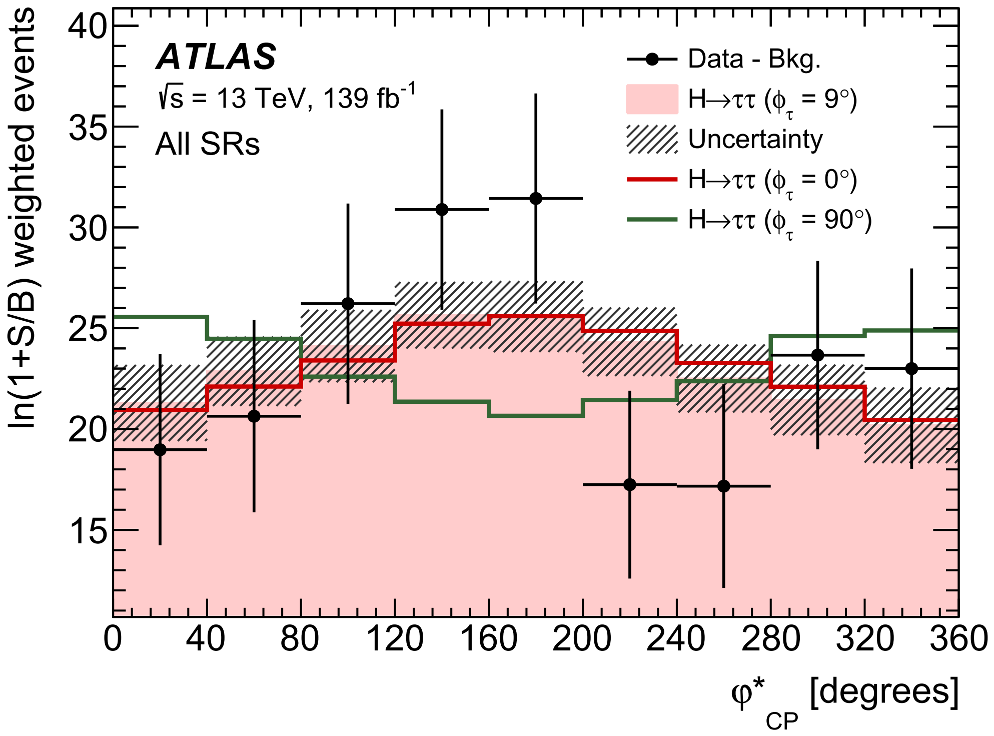
- Higgs CP = -1 in the SM
- What if H is not a CP eigenstate?
- Higgs as a source of additional CP violation?
- Need to access transverse spin correlations in $H \rightarrow \tau^+\tau^-$

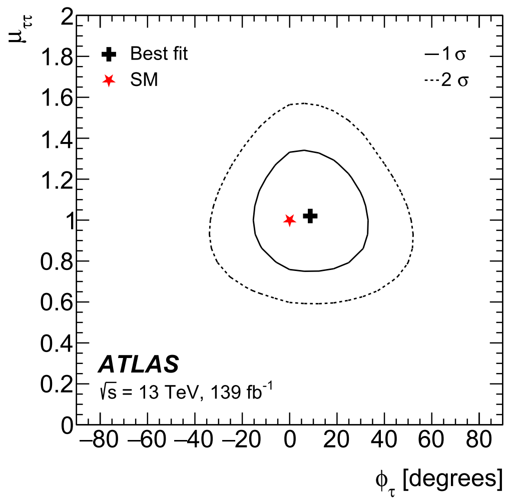


(a) $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + 2\nu$ (b) $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^0\nu\pi^-\pi^0\nu$ (c) $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^0\nu\pi^-\nu$

Higgs: CP quantum numbers







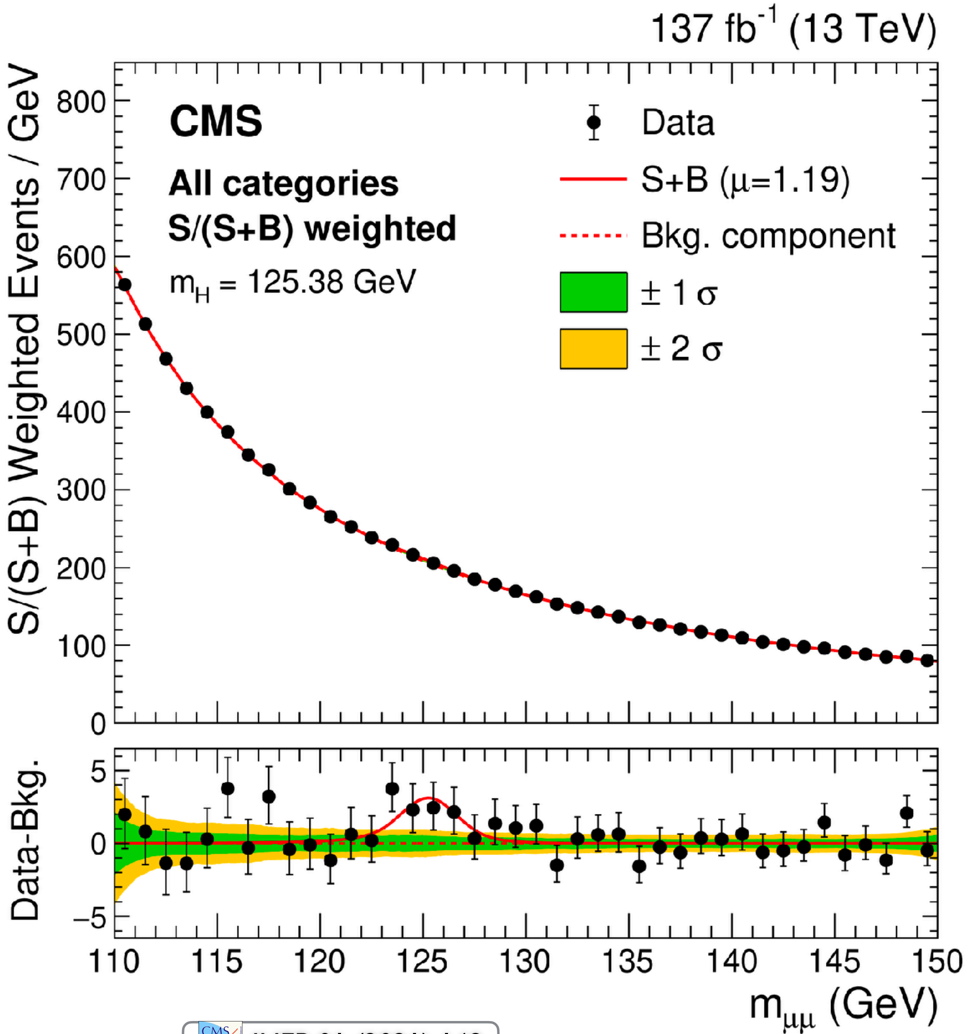
looks SM-like ☹

$$\phi_\tau^{obs.} = 9\pm16^\circ \text{ (68\% CL)}$$

Higgs to muons

Remark 4

The rarest Higgs decay "seen" so far.



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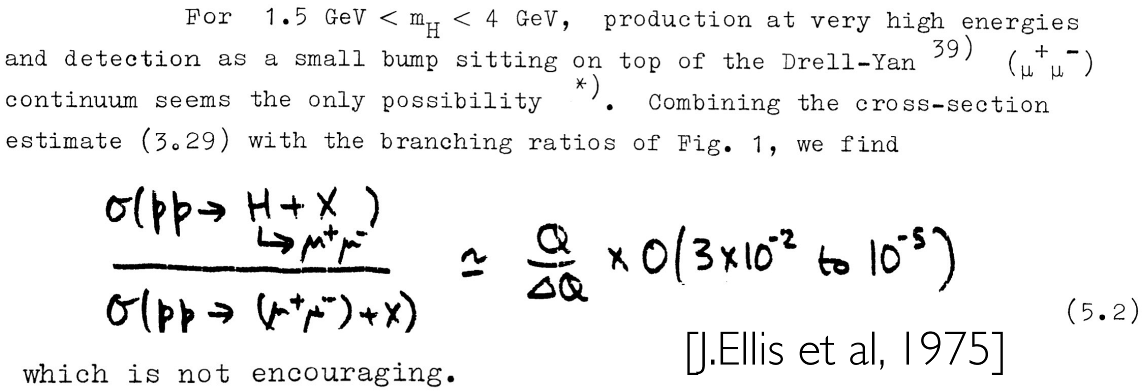
Can you see it? ☺

- Observed (expected) significance: **3.0 (2.5) σ**



For 1.5 GeV < m_H < 4 GeV, production at very high energies and detection as a small bump sitting on top of the Drell-Yan[39)] $(\mu^+\mu^-)$ continuum seems the only possibility *). Combining the cross-section estimate (3.29) with the branching ratios of Fig. 1, we find

$$\frac{\sigma(pp \to \underset{\hookrightarrow \mu^+\mu^-}{H} + X)}{\sigma(pp \to (\mu^+\mu^-) + X)} \simeq \frac{Q}{\Delta Q} \times O(3\times10^{-2} \text{ to } 10^{-5}) \qquad (5.2)$$

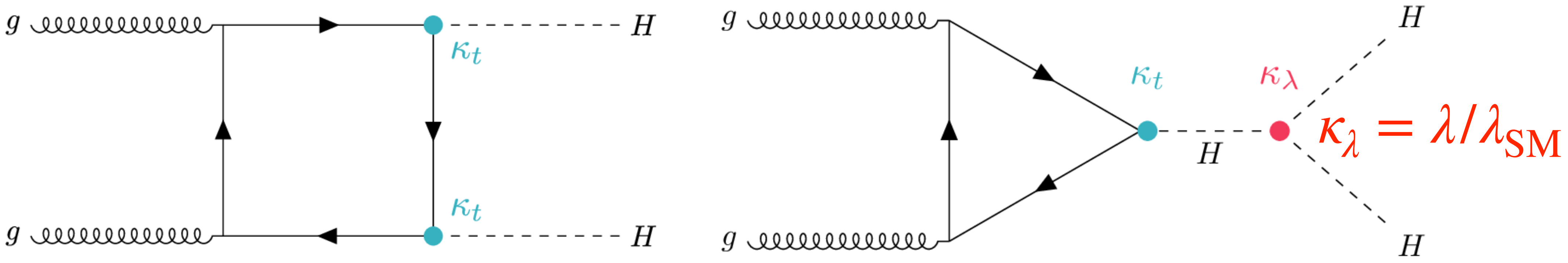
which is not encouraging.

[J.Ellis et al, 1975]

Higgs self coupling

Higgs self-coupling leads to HHH (and HHHH) vertices

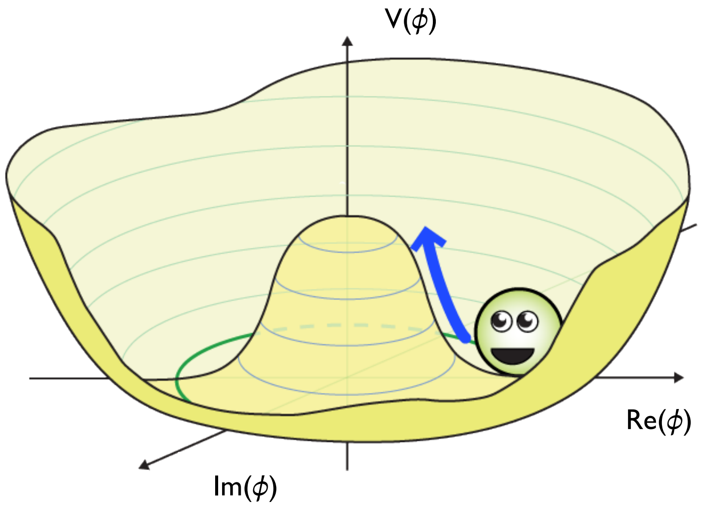
a multi-boson process, finally ☺



$$\kappa_\lambda = \lambda/\lambda_{\text{SM}}$$

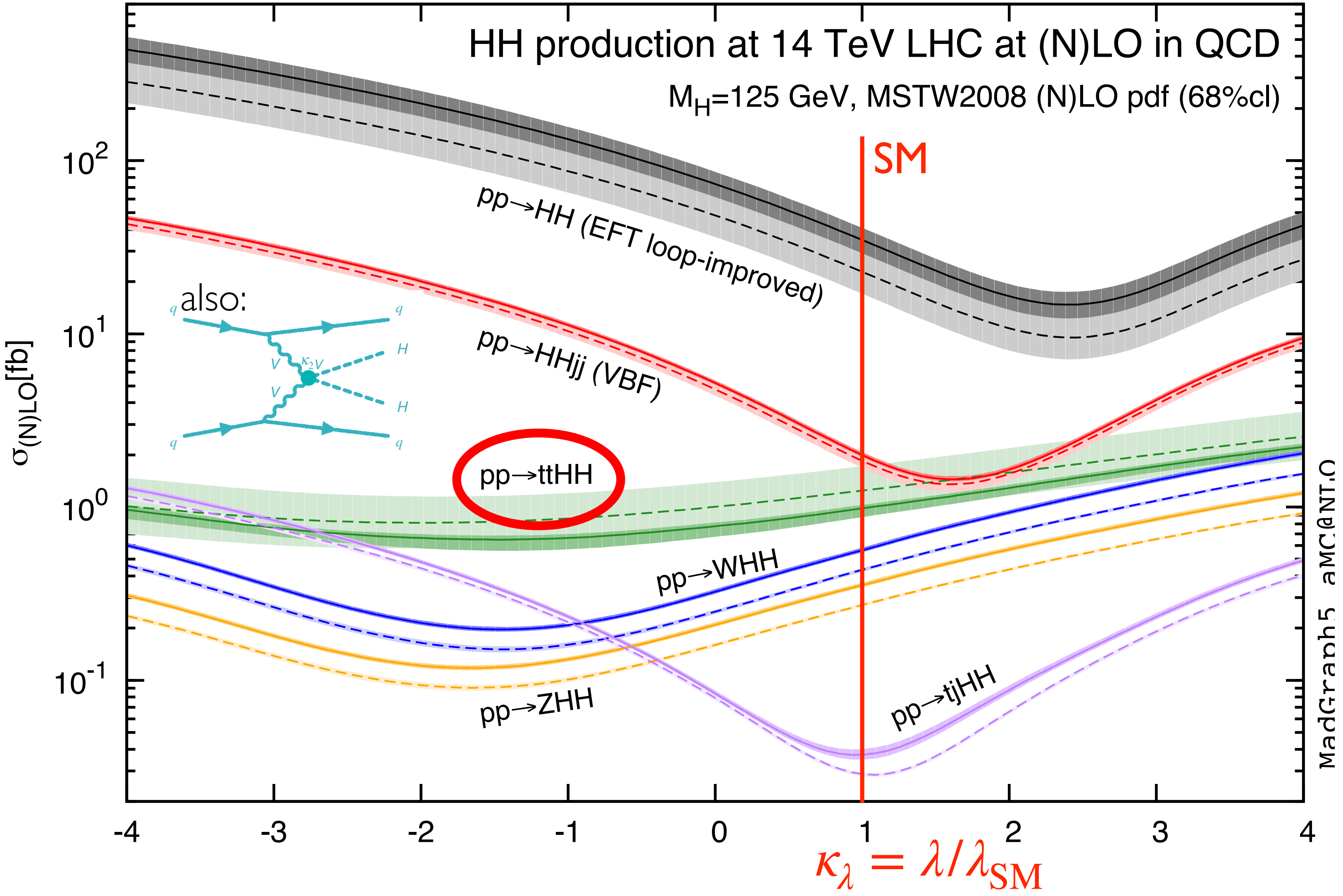
Determines the shape of the Higgs potential
Exactly fixed in the SM
But not constrained by any measurement yet…

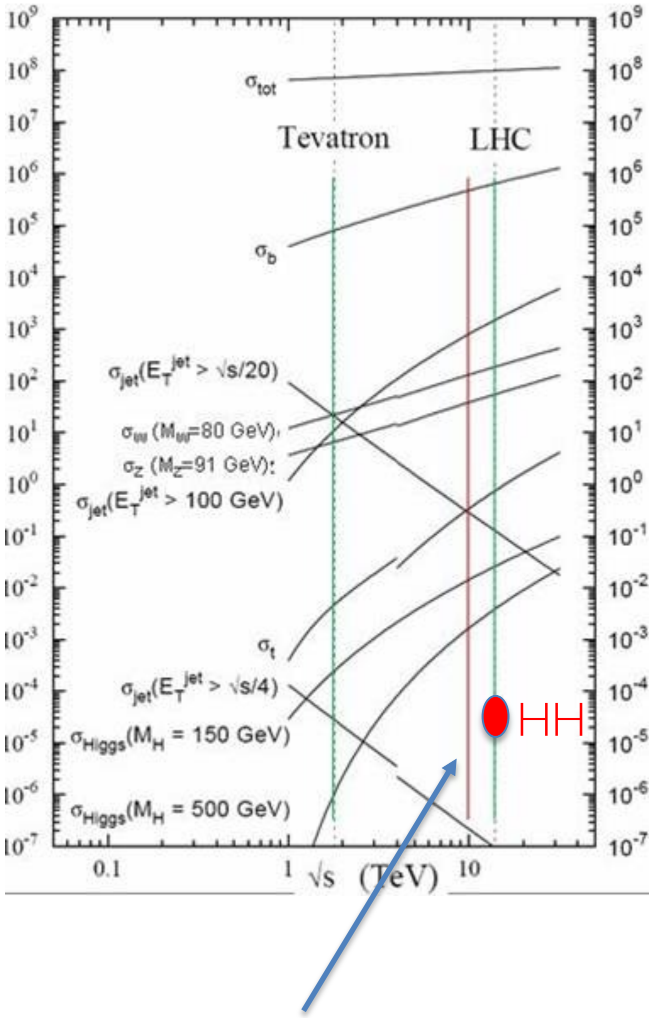
LHC: Di-Higgs production is sensitive
But very tiny cross section
Major motivation for HL-LHC



Higgs self coupling / Di-Higgs analyses

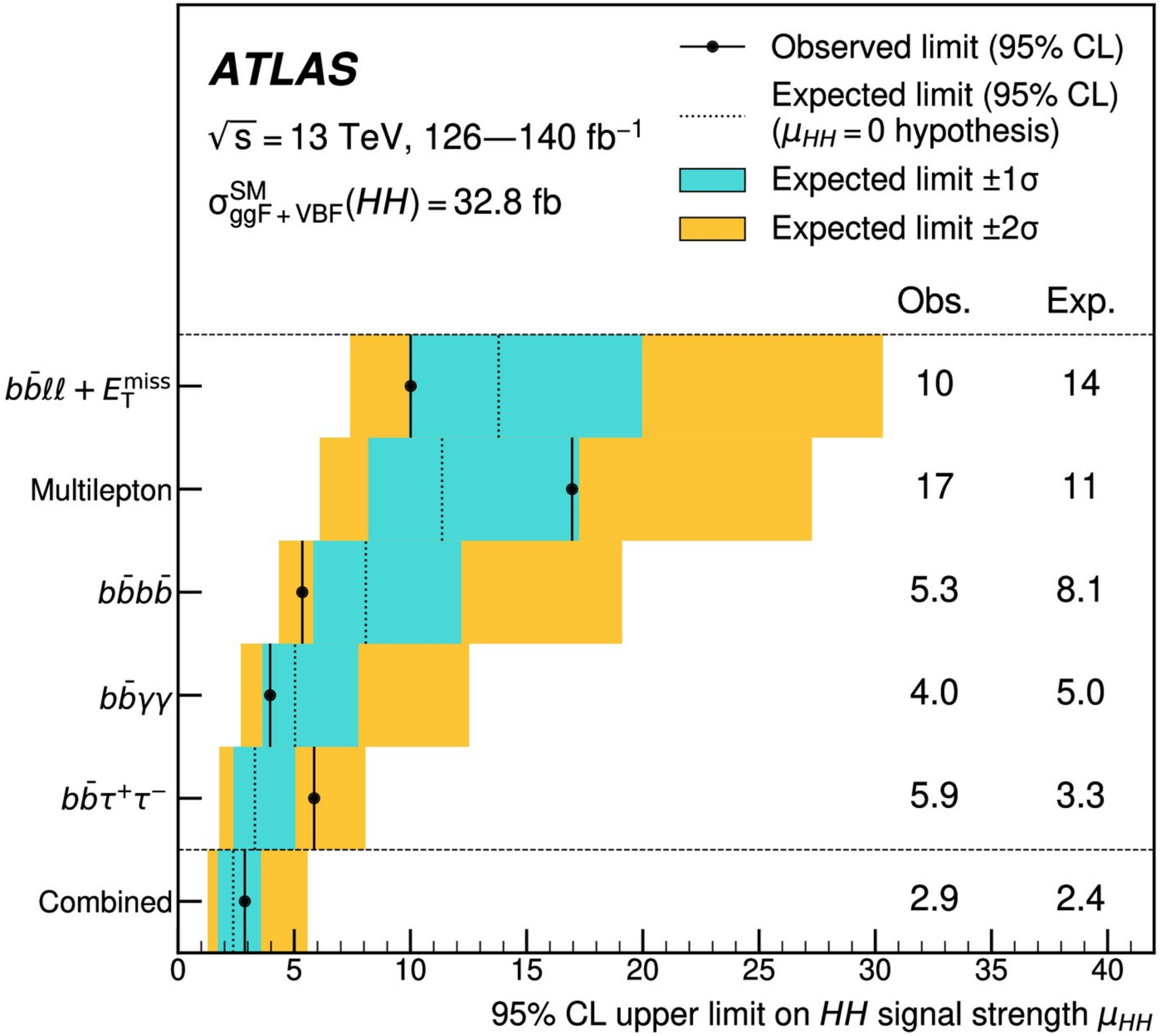
Remark 5

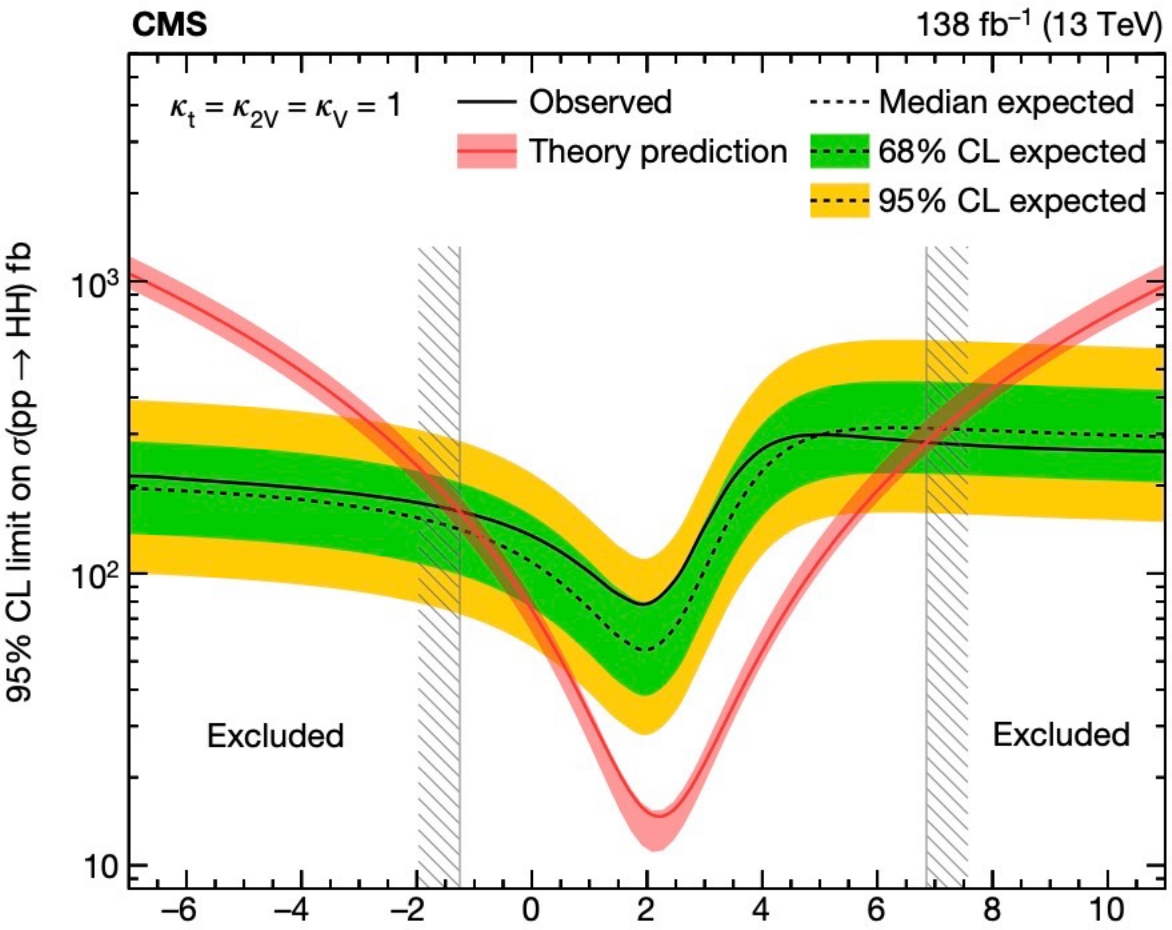




we search here…

Higgs self coupling / Di-Higgs analyses





Di Higgs is a (the) major quest for the next decade

THE END