PHYSICS AT THE LHC

Thomas Schörner-Sadenius
Georg Steinbrück

DESY Summerstudent Programme
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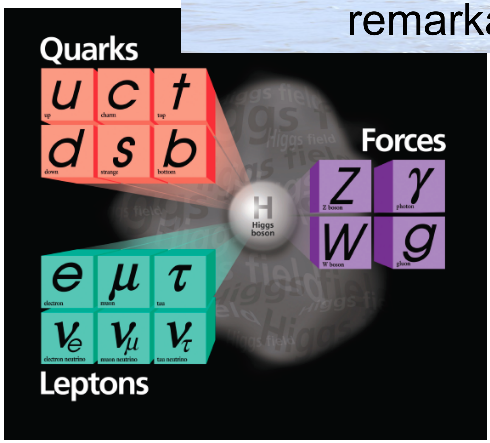
STRUCTURE OF LECTURES

Lecture 1 (TSS) LHC: Motivation, machine, experiments Luminosity and its measurement Basics of pp physics Soft QCD Hard QCD: Jets, photons, jet algos QCD lessons learned Heavy ions and ALICE	**Lecture 3 (GS)** Heavy quarks and resonances Strangeness, charm, J/Psi, b physics, rare decays, B mixing, CP b tagging; Outlook on LHCb Top: cross section and mass, etc. Single top, V_{tb}, 4^{th} generation SM consistency and new physics
Lecture 2 (GS) Electroweak physics: Z, W, Z/W+jets Candles for calibration, W mass, PDFs Diboson physics, TGCs (SM) Higgs: Motivation / mechanism Results: LEP, Tevatron, LHC – limits? BSM appetizer	**Lecture 4 (TSS)** SUSY – Motivation and theory Exp. signatures Limits and a little of statistics Signal interpretation SUSY and Higgs Other BSM physics and exotica

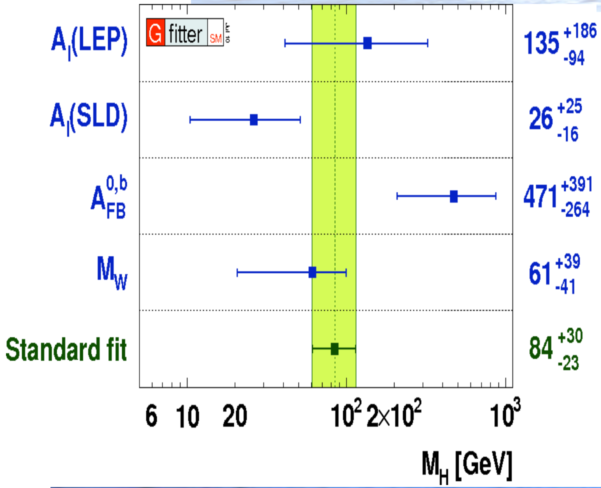
Please ask questions immediately!

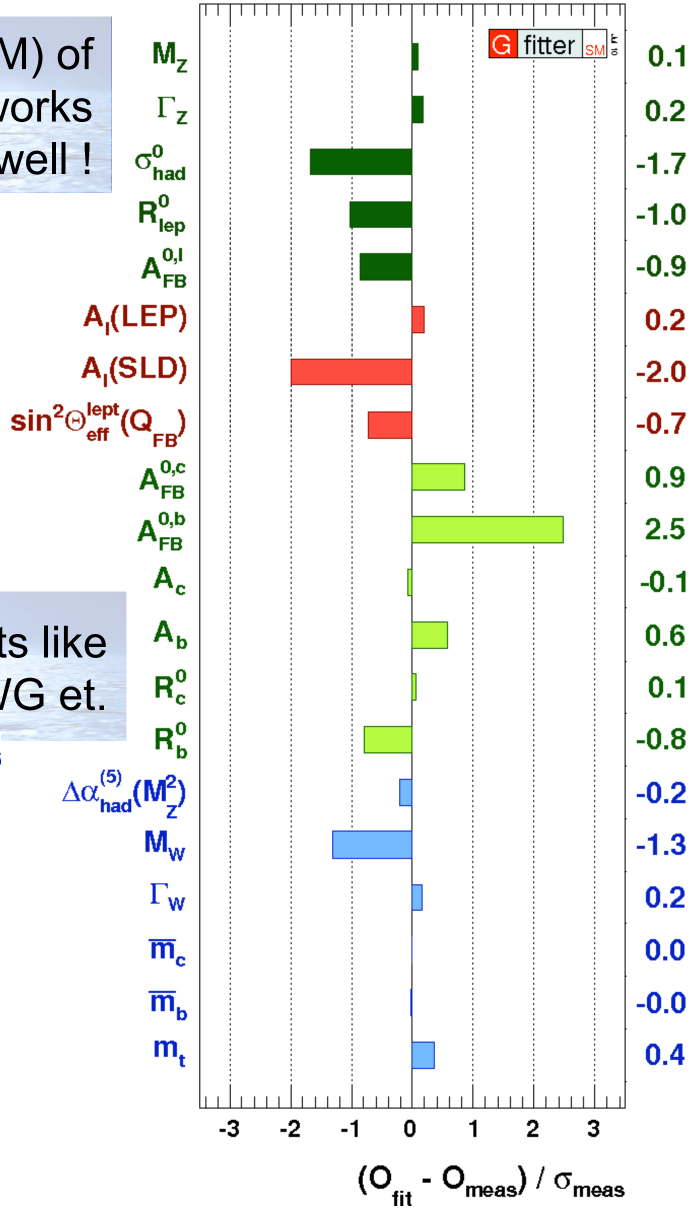
WHY THE LHC?????

Standard model (SM) of particle physics works remarkably well !



E.g. global SM fits like Gfitter, LEP EW WG et.

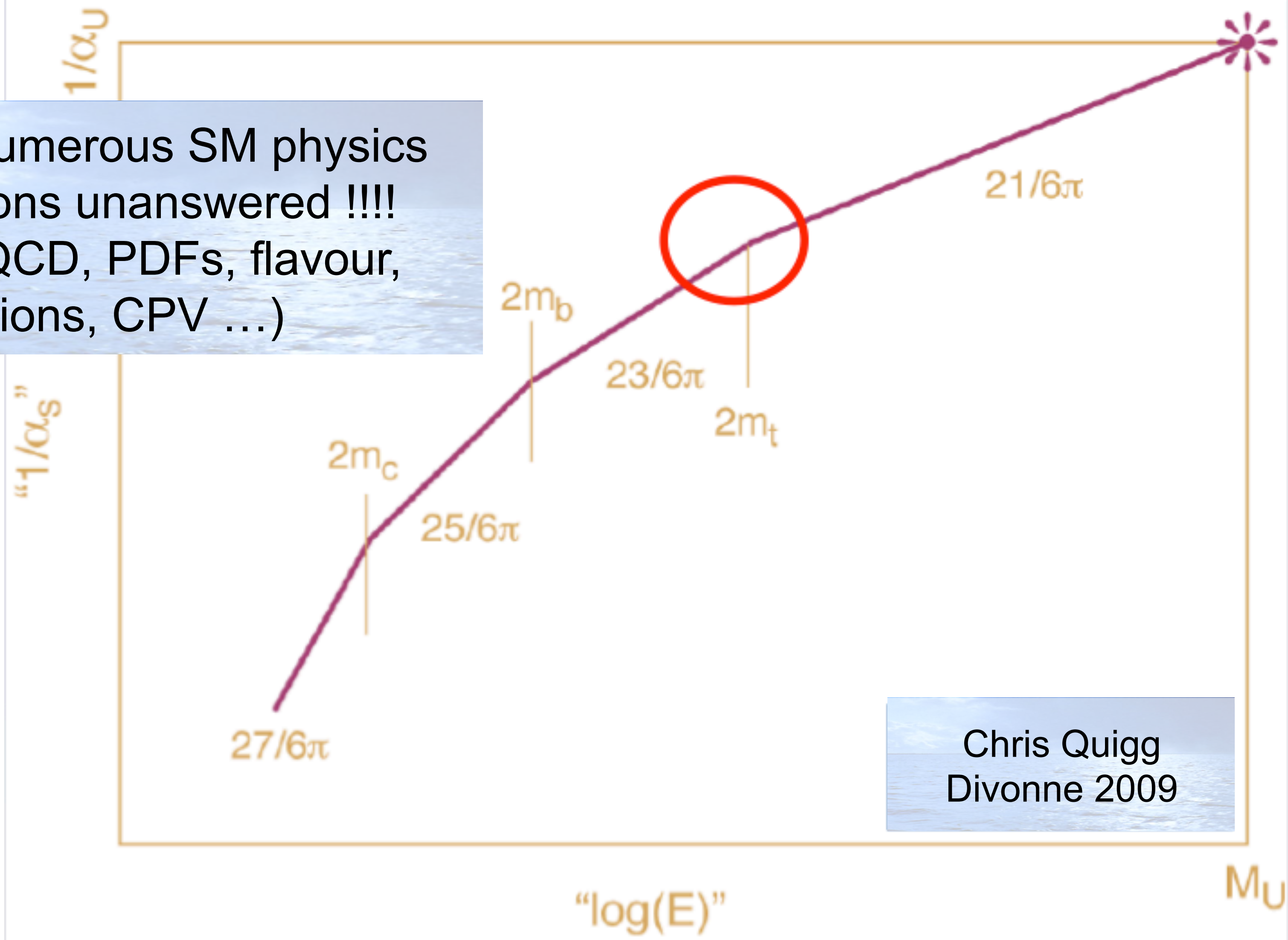




- No Higgs: divergence of SM at 1 TeV?
- SM NOT beautiful! Free parameters?
- SM: no coupling / mass unification!
- SM: No dark-matter candidate!
- Gravity?
- Gauge structure?
- Three generations?
- Hierarchy?
- Baryon asymmetry?
- Connection between quarks and leptons?
- …

WHY THE LHC?????

Also numerous SM physics questions unanswered !!!! (EW, QCD, PDFs, flavour, heavy ions, CPV …)



Chris Quigg
Divonne 2009

WHY THE LHC?????

For 40 years we have searched and produced models to be searched for …

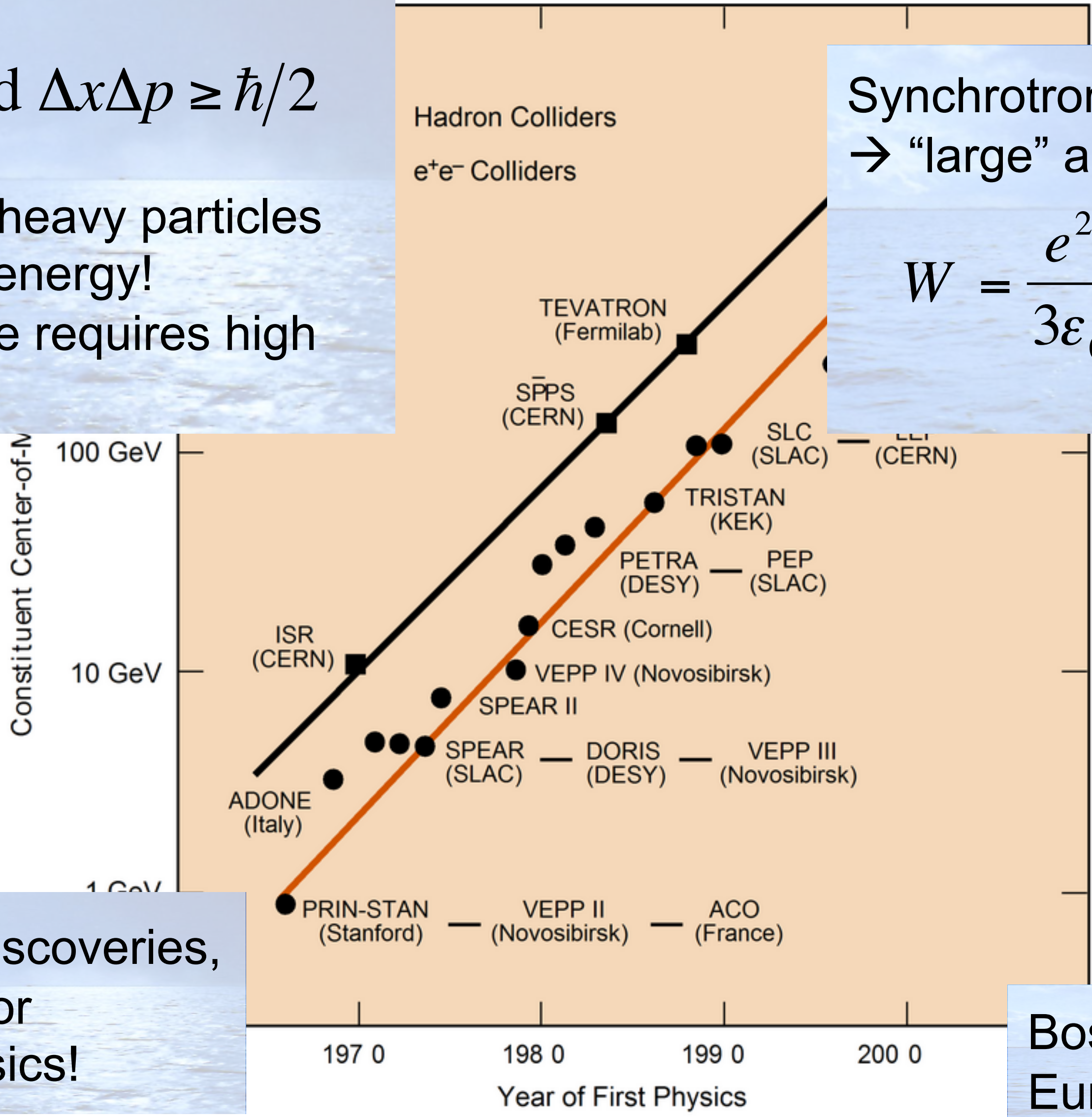
Now we are (almost) there!!!

That’s it!!!

WHY AN Large Hadron Collider (in Europe)?

$$E = mc^2 \text{ and } \Delta x \Delta p \geq \hbar/2$$

Production of heavy particles requires high energy!
Small structure requires high momentum!

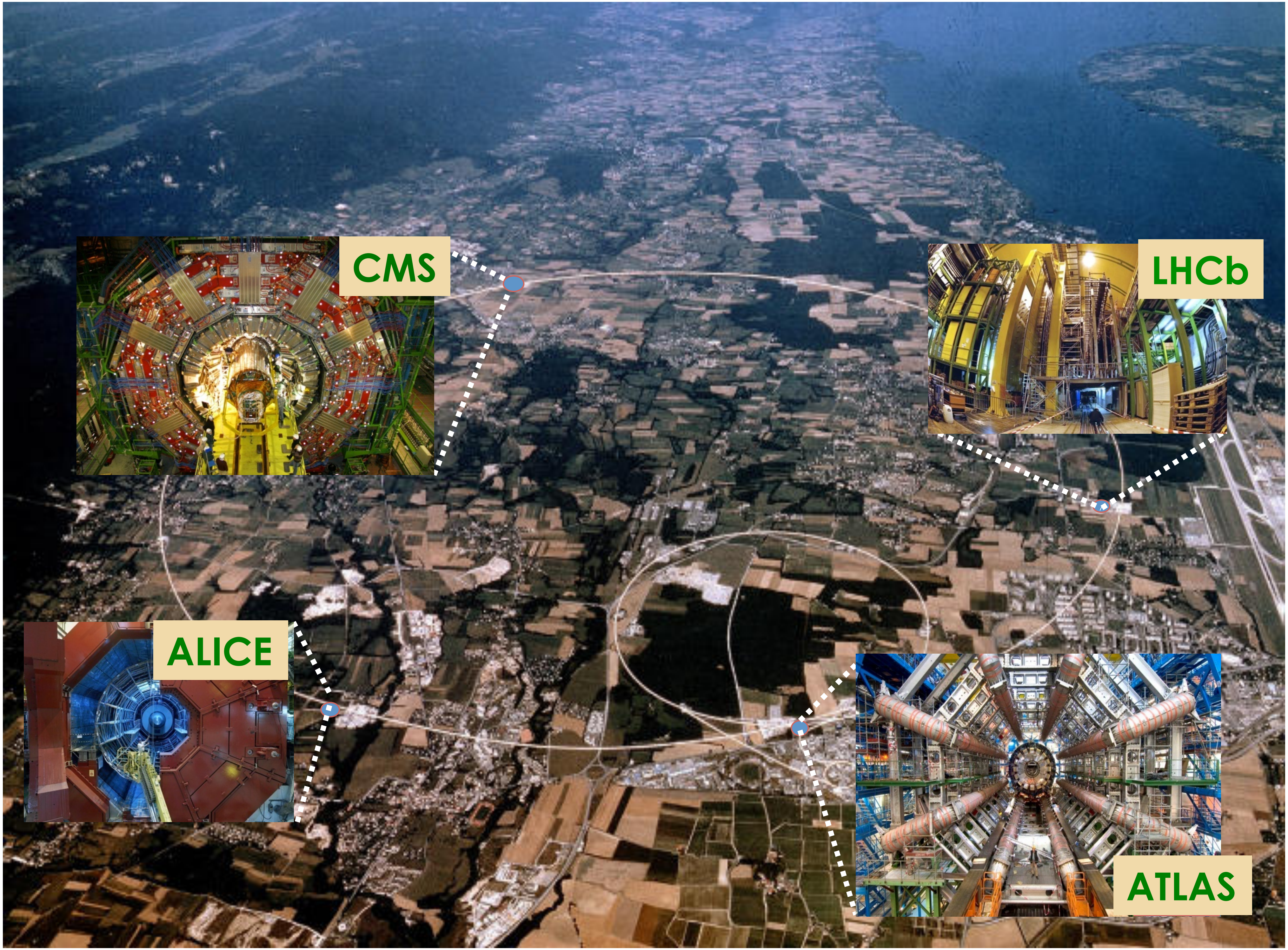


Synchrotron radiation losses
→ "large" and "hadrons" !

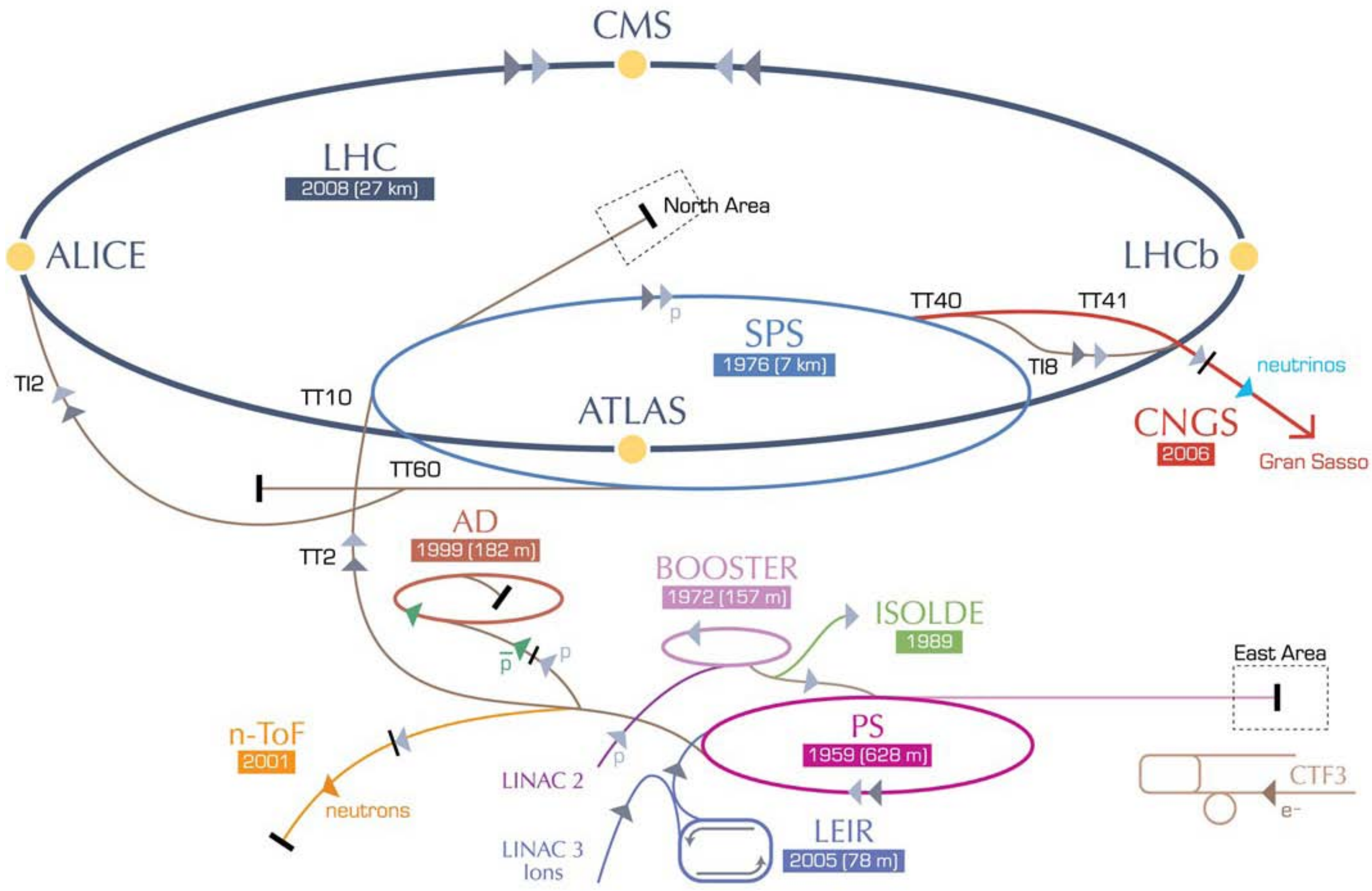
$$W = \frac{e^2}{3\varepsilon_0} \cdot \frac{1}{(m_0 c^2)^4} \cdot \frac{E^4}{R}$$

Hadrons for discoveries, then leptons for precision physics!

Bosons discovered in Europe !!! ;-)

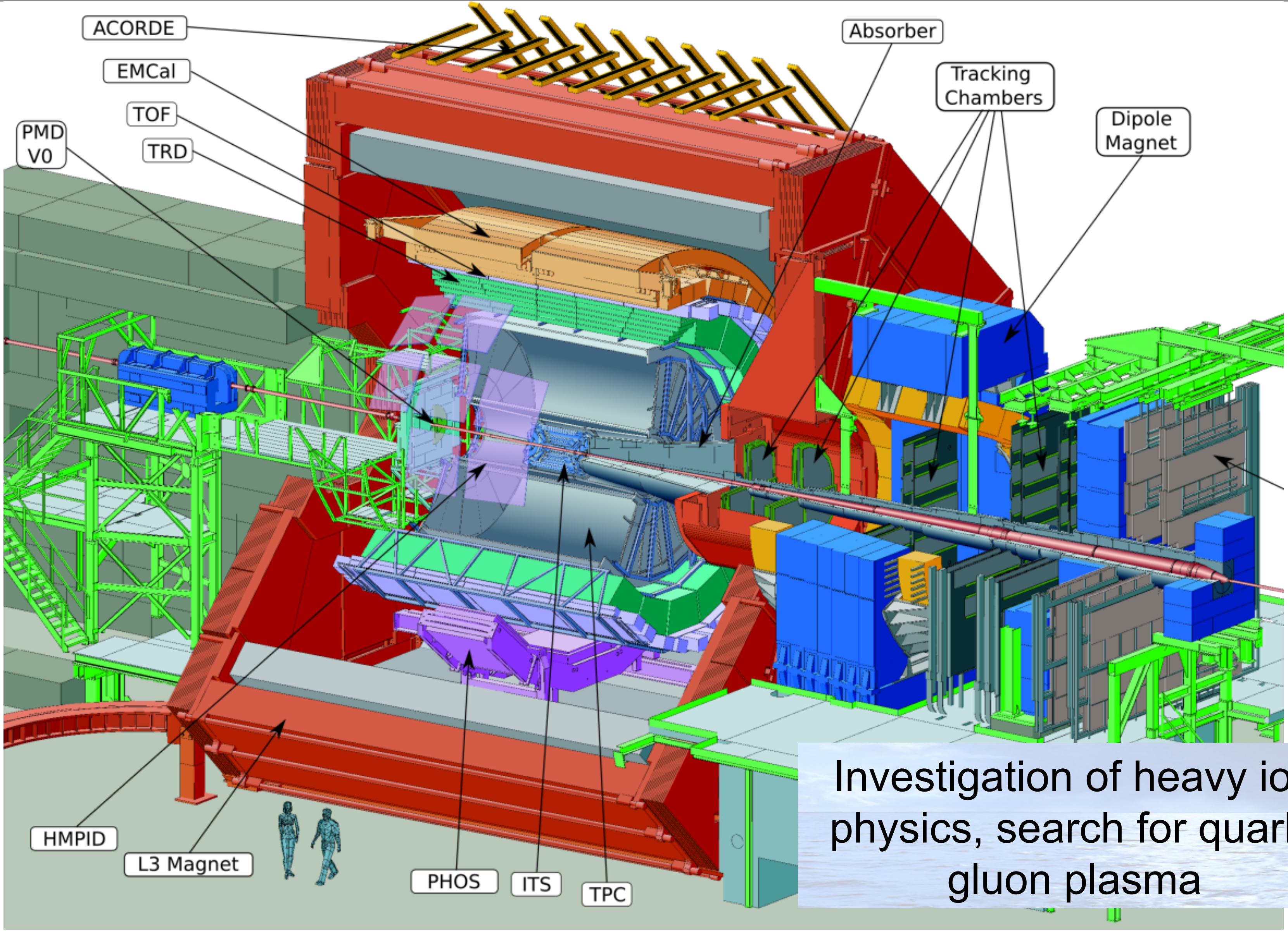

CMS
LHCb
ALICE
ATLAS

THE LHC



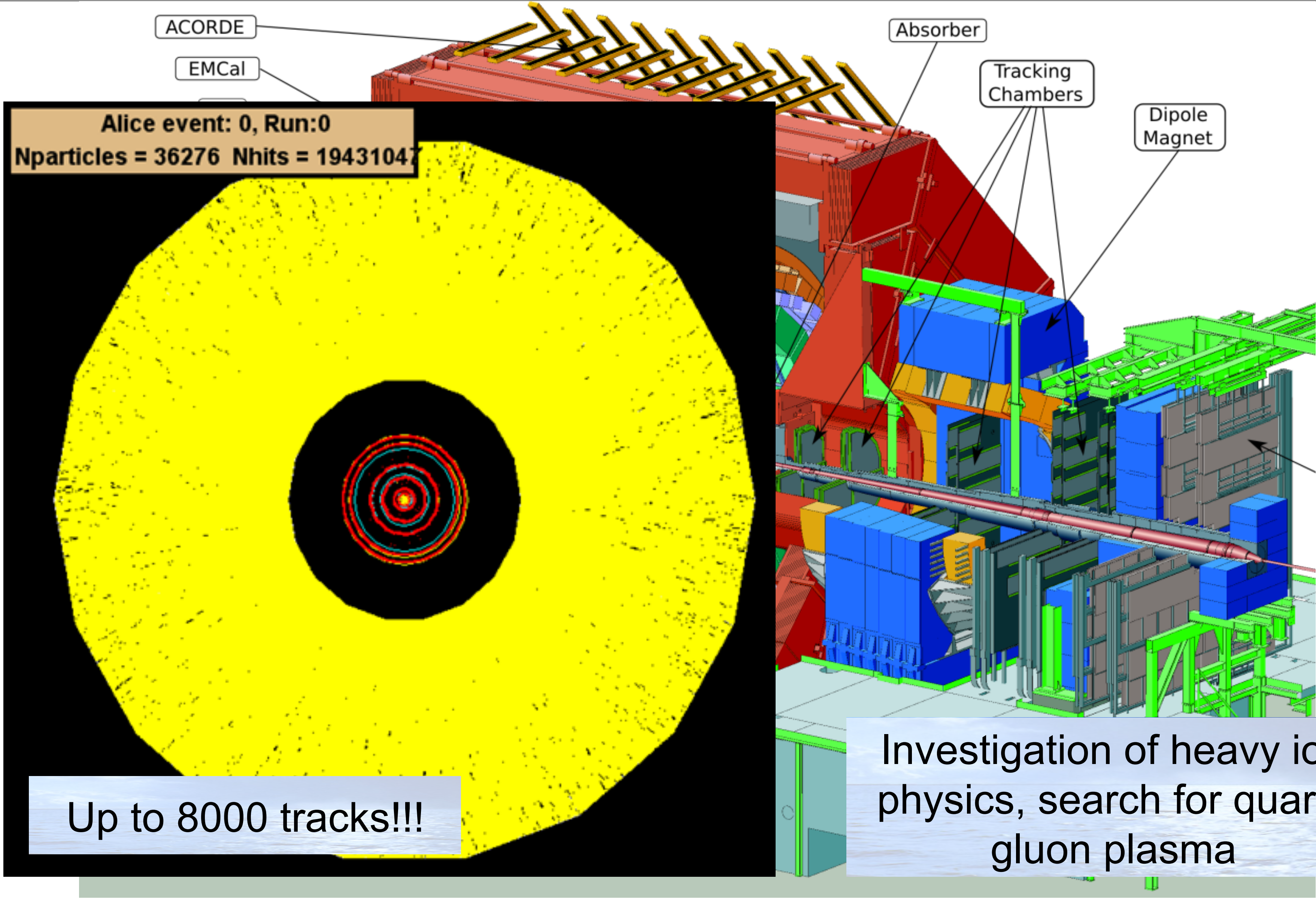
CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
p
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
p̄
p
East Area
n-ToF
2001
PS
1959 (628 m)
p
LINAC 2
CTF3
e-
neutrons
LEIR
2005 (78 m)
LINAC 3
Ions

THE EXPERIMENTS – ALICE



Investigation of heavy ion physics, search for quark-gluon plasma

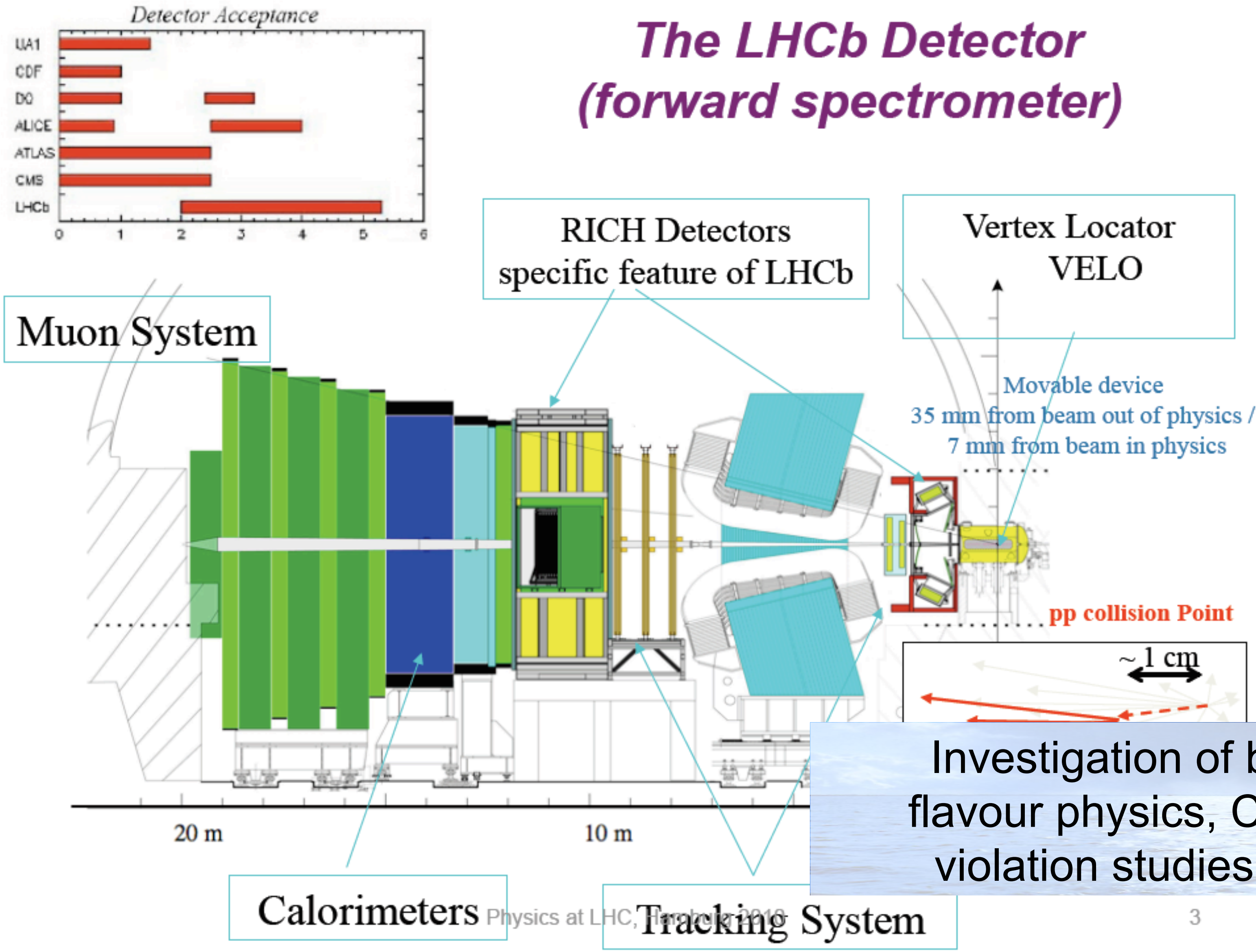
THE EXPERIMENTS – ALICE



Up to 8000 tracks!!!

Investigation of heavy ion physics, search for quark-gluon plasma

THE EXPERIMENTS – LHCb

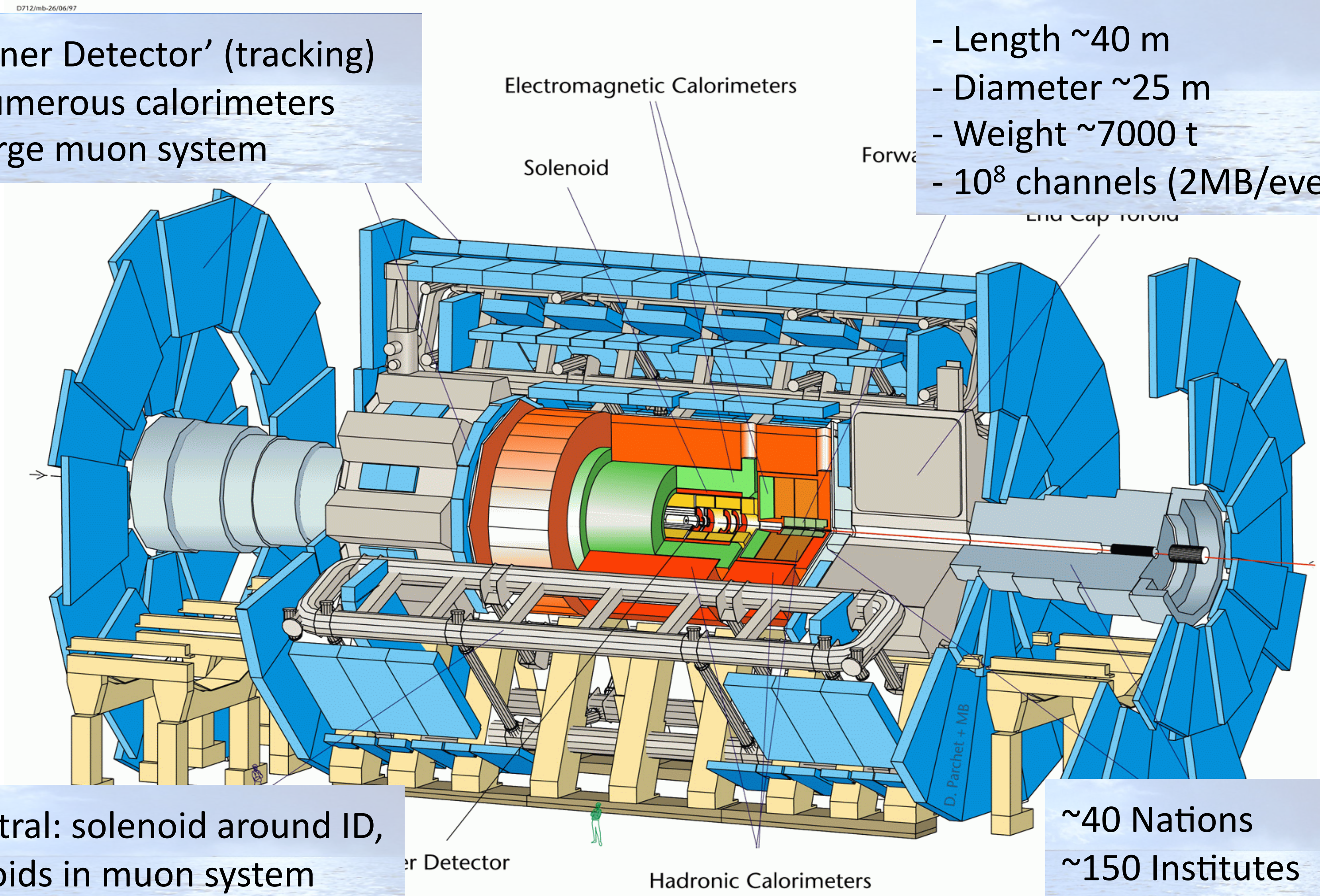


Investigation of b flavour physics, CP violation studies!

THE EXPERIMENTS – ATLAS

- ‘Inner Detector’ (tracking)
- Numerous calorimeters
- Large muon system

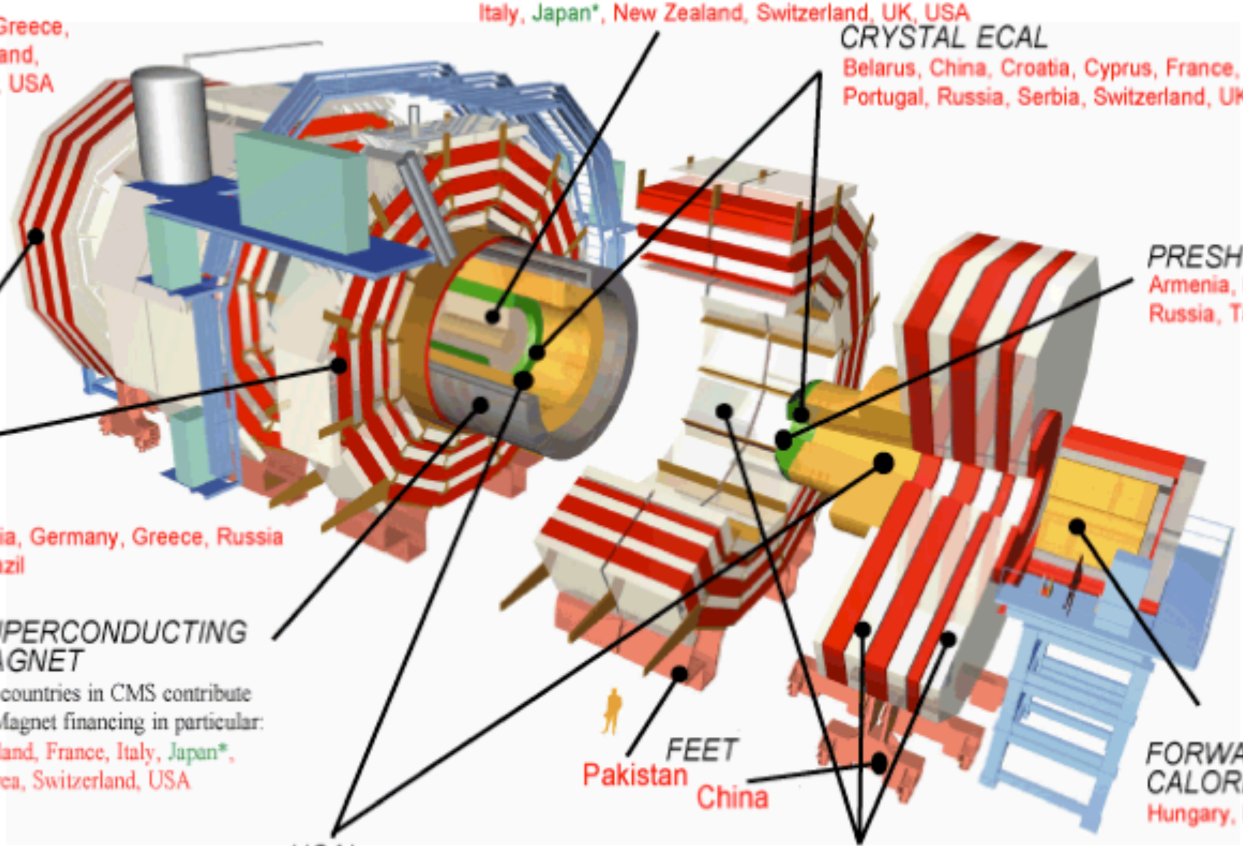
- Length ~40 m
- Diameter ~25 m
- Weight ~7000 t
- 10^8 channels (2MB/event)



- central: solenoid around ID,
  Toroids in muon system
- End caps: Toroidal fields

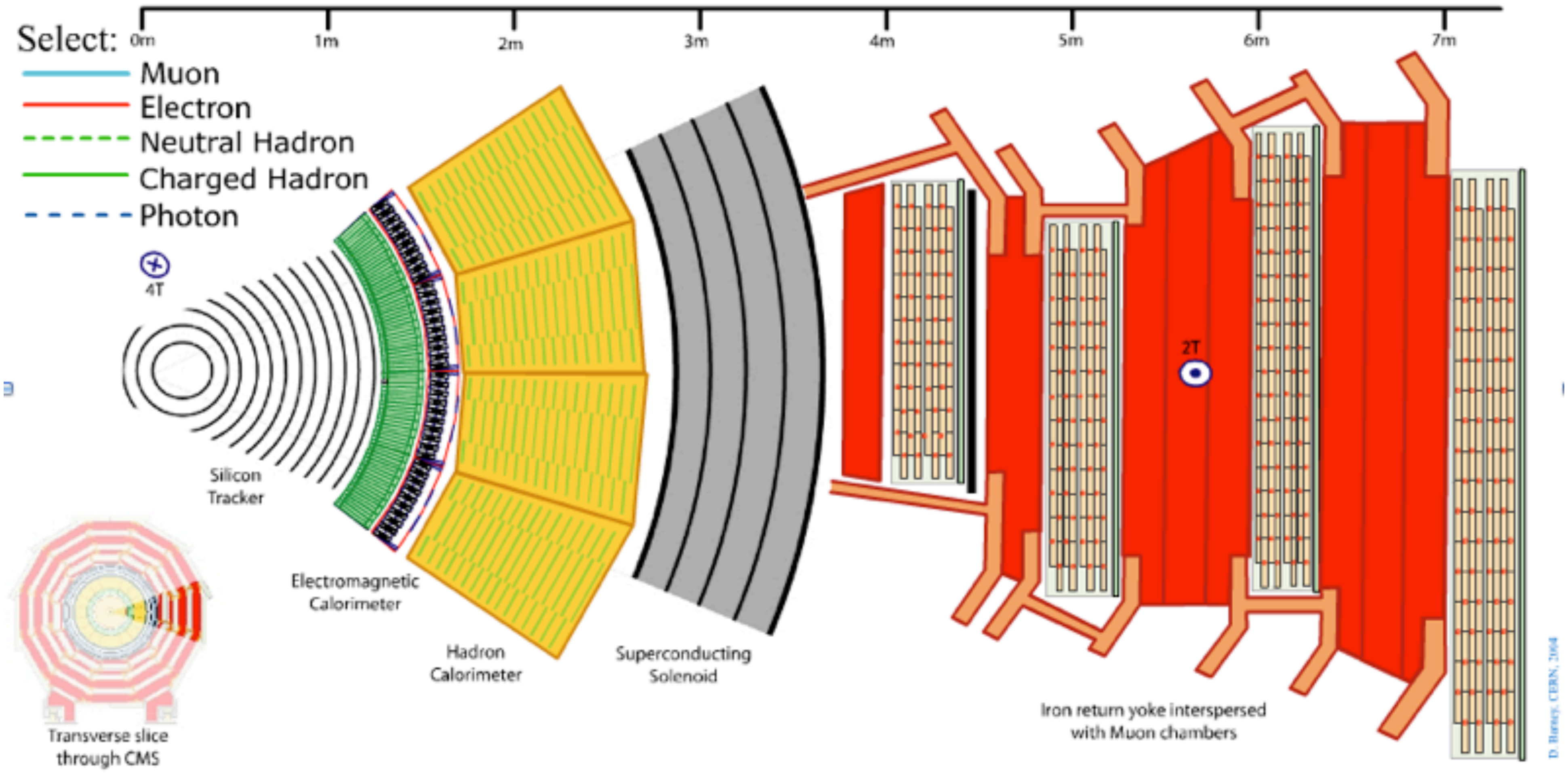
~40 Nations
~150 Institutes
~3000 physicists

THE EXPERIMENTS – CMS



Total weight	: 12500 T
Overall diameter	: 15.0 m
Overall length	: 21.5 m
Magnetic field	: 4 Tesla

PARTICLES IN CMS



https://cms-docdb.cern.ch/cgi-bin/PublicEPPOGDocDB/RetrieveFile?docid=97&version=1&filename=CMS_Slice_elab.swf

SIZE MATTERS …

LUMINOSITY (MEASUREMENT)

$$\dot{N}_i = \sigma_i \cdot \mathcal{L}$$

You measure: Number of events in channel I !

You want: Cross section for process I !

You need: Luminosity (machine quantity!)

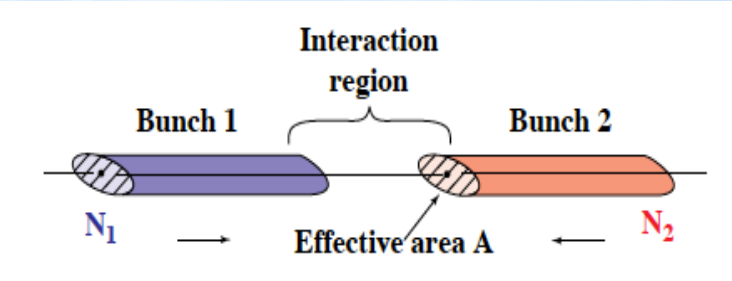
The problem is the **absolute luminosity**; relative changes of luminosity can be monitored by numerous detectors! Example ATLAS: 6 subsystems with 16 measurements!

LUMINOSITY (MEASUREMENT)

$$\dot{N}_i = \sigma_i \cdot \mathcal{L}$$

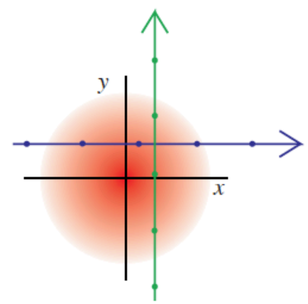
Luminosity from: **Machine parameters !**

$$\mathcal{L} = \frac{N_1 \cdot N_2 \cdot f}{A_{eff}} = \frac{N_1 \cdot N_2 \cdot f}{4\pi\sigma_x\sigma_y}$$

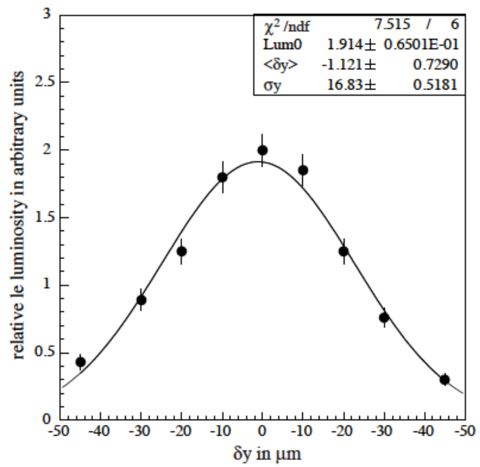


- Frequency f and numbers of particles known (to better than 0.01). Particles outside bunches?
- Bottleneck: effective Beam sizes → separation (or from the ISR: Van der Meer) scans!

Achievable precision few percent (currently 3.5%).



H. Burkhardt et al.



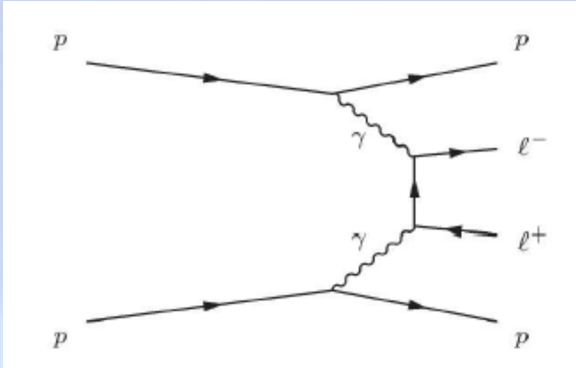
LUMINOSITY (MEASUREMENT)

$$\dot{N}_i = \sigma_i \cdot \mathcal{L}$$

Luminosity from: **candle processes !**

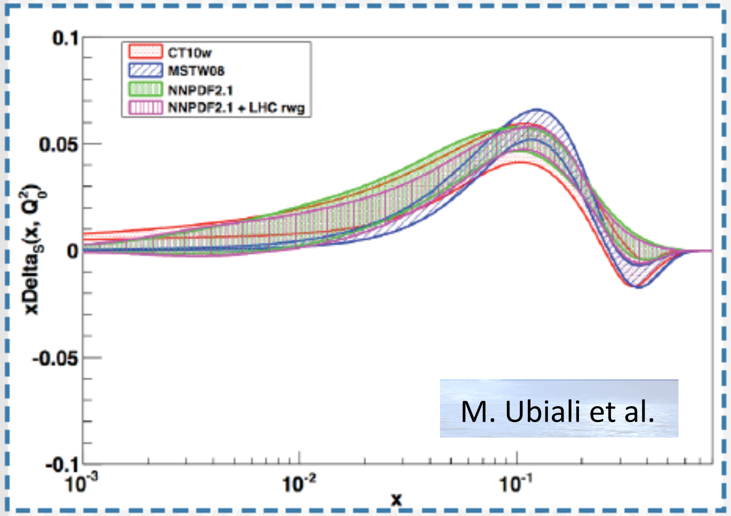
- Used frequently at LEP and HERA: Measure theoretically well-known process!

$$\mathcal{L} = \frac{N_{signal} - N_{BG}}{\varepsilon \cdot acc \cdot \sigma}$$



- LEP: Bhabha scattering: $e^+e^- \rightarrow e^+e^-$ (0.001)
- HERA: Bethe-Heitler $ep \rightarrow e\gamma p$ (1-3%)
- Problem: Acceptance estimates!

- One option at LHC: $\gamma\gamma \rightarrow ll$ (small rate!)
- Or EWK measurements like W/Z production (known to NNLO – but PDF uncertainty!)
  "Yesterday's discovery is today's tool and tomorrow's background!"



LUMINOSITY (MEASUREMENT)

$$\dot{N}_i = \sigma_i \cdot \mathcal{L}$$

Luminosity from: **optical theorem !**

- Connection of elastic rate at zero momentum transfer (t=0) to total Xsection.

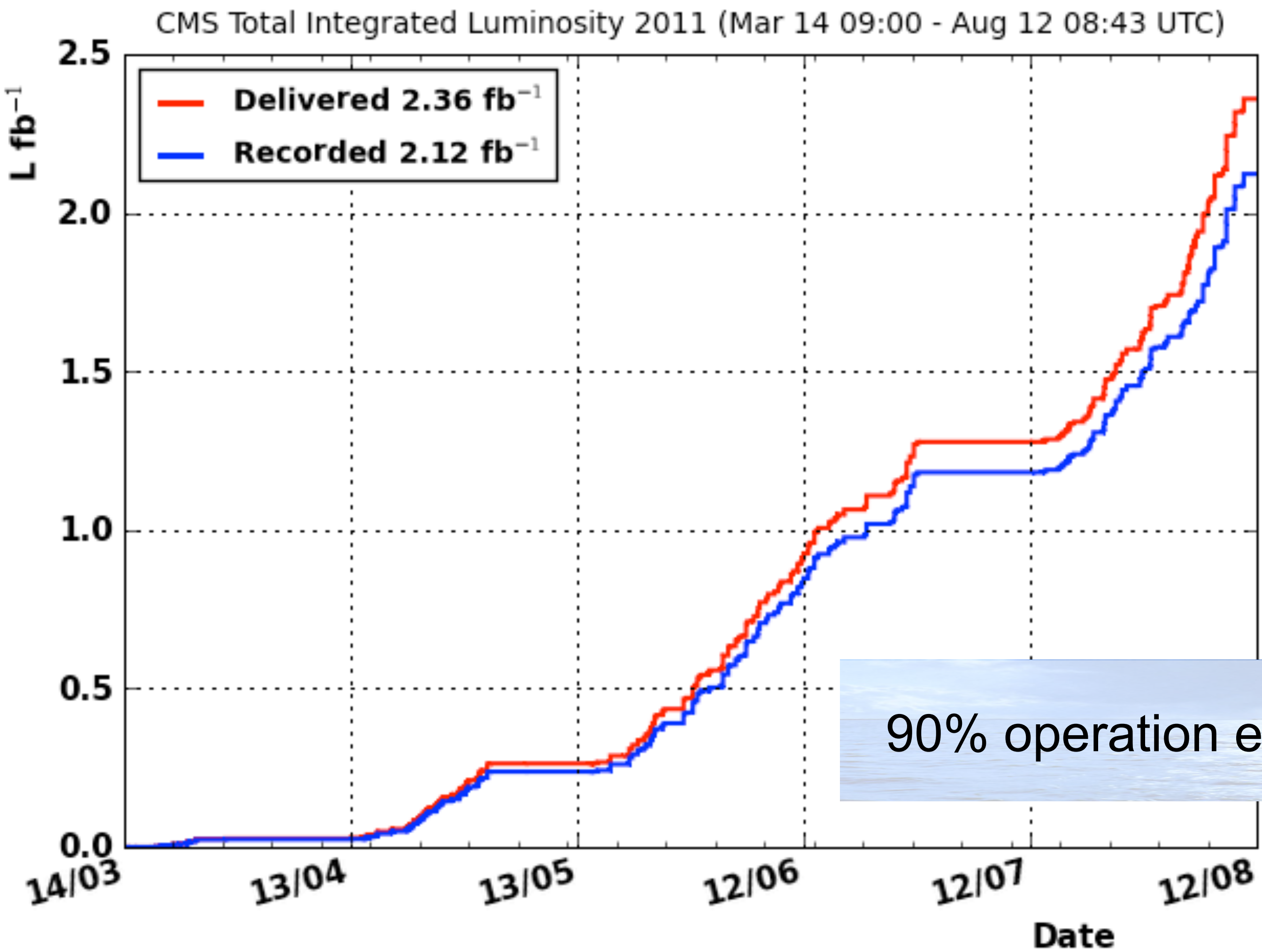
$$\frac{1}{\mathcal{L}} \cdot \left.\frac{dN_{el}}{dt}\right|_{t=0} = \left(1+\rho^2\right)\frac{\sigma_{tot}^2}{16\pi} \cong \frac{4\pi\alpha_{EM}^2}{t^2}$$

- Challenges: Measuring N_{el} to 0°!
  ➔ Chain of dedicated detectors and components (ALFA, TOTEM etc.)

- Interesting option: connecting elastic rate to electromagnetic (Coulomb) scattering amplitude (and in good approximation to EM coupling).

- 10% lumi uncertainty seems feasible.

THE LHC – LUMINOSITY



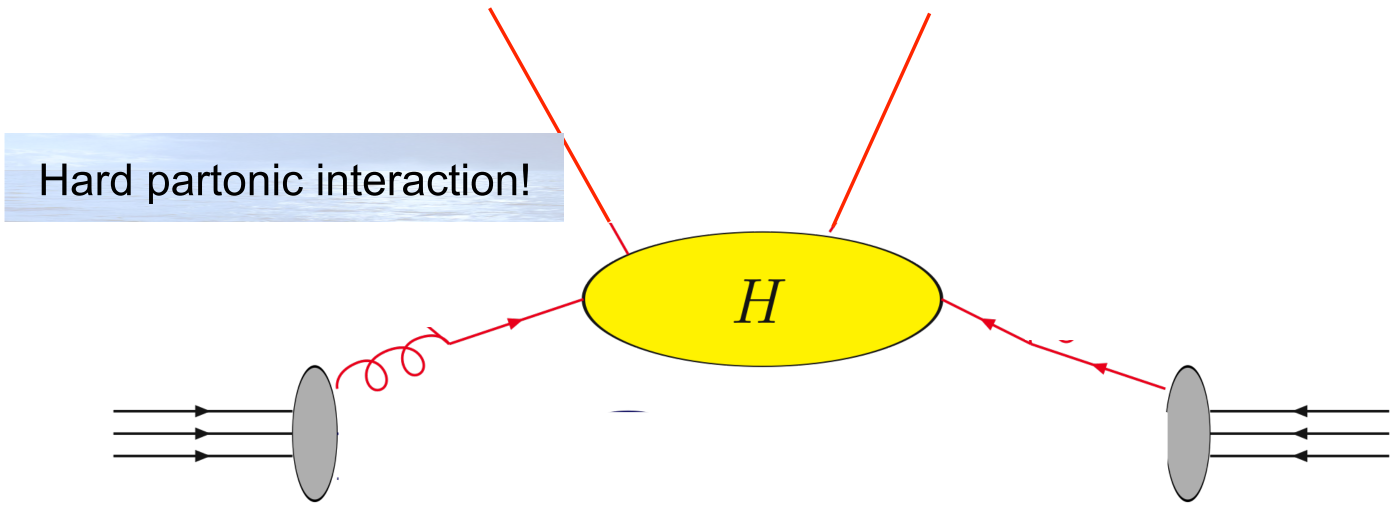
90% operation efficiency!

BASICS OF pp PHYSICS

Proton structure (PDFs)

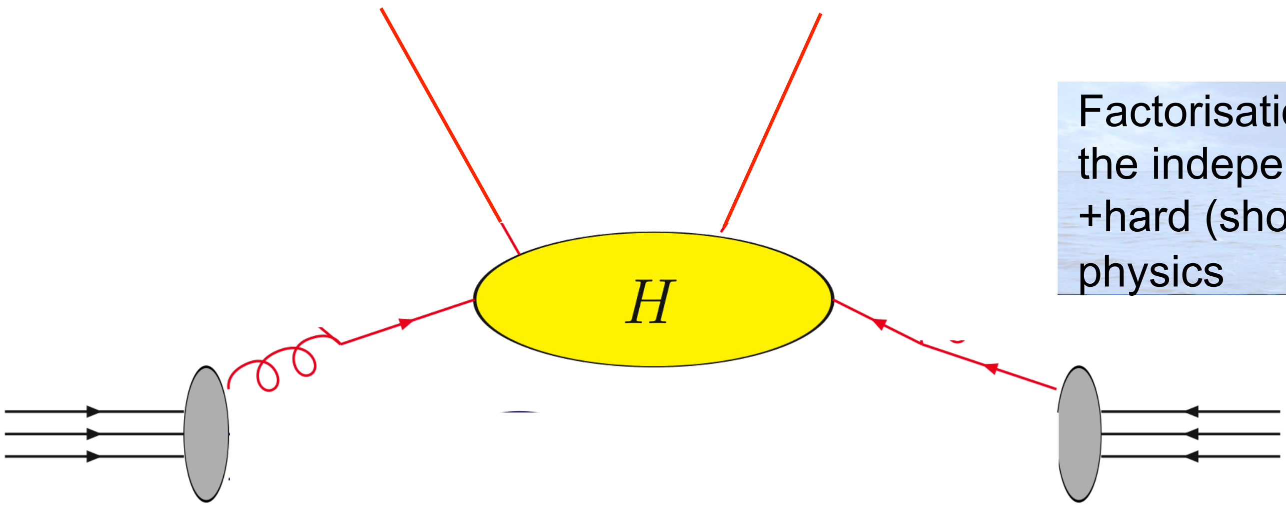
$$f_{i/p} \qquad\qquad\qquad\qquad f_{j/p}$$

BASICS OF pp PHYSICS



$$f_{i/p} \qquad \hat{\sigma}_{ij} \qquad f_{j/p}$$

BASICS OF pp PHYSICS



Factorisation assumes the independence of soft +hard (short+long-range) physics

$$\sigma = f_{i/p} \otimes \hat{\sigma}_{ij} \otimes f_{j/p}$$

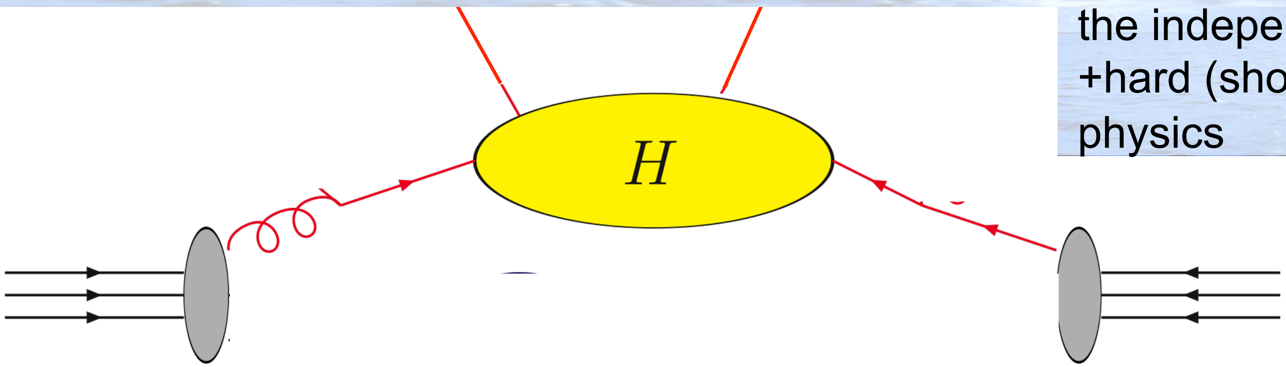
BASICS OF pp PHYSICS

- PDFs $f_{i/p}$ → to be derived from data (HERA!) → HERA lecture
  Assumption: PDF universality!!!
  Vice versa: use well-measured and calculable processes to constrain PDFs
- Coefficients C_{ij} to be calculated in pQCD – up to order n!
- Determination of running coupling α_S
- Test of factorisation?

And:

- Comparison of SM predictions with data → new effects, new physics, new insights ???

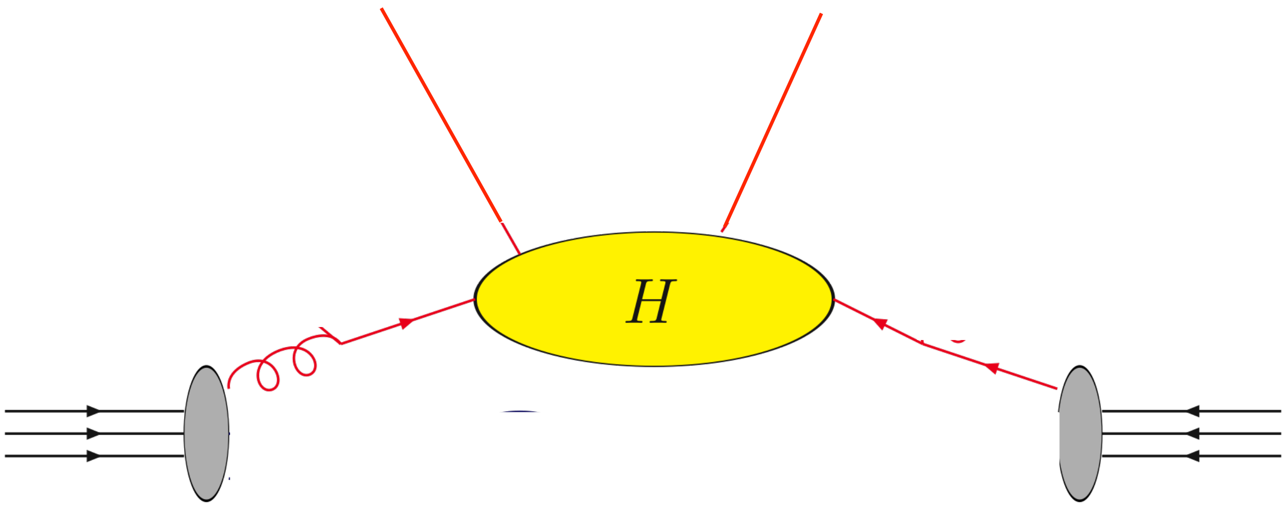
the independence of soft +hard (short+long-range) physics



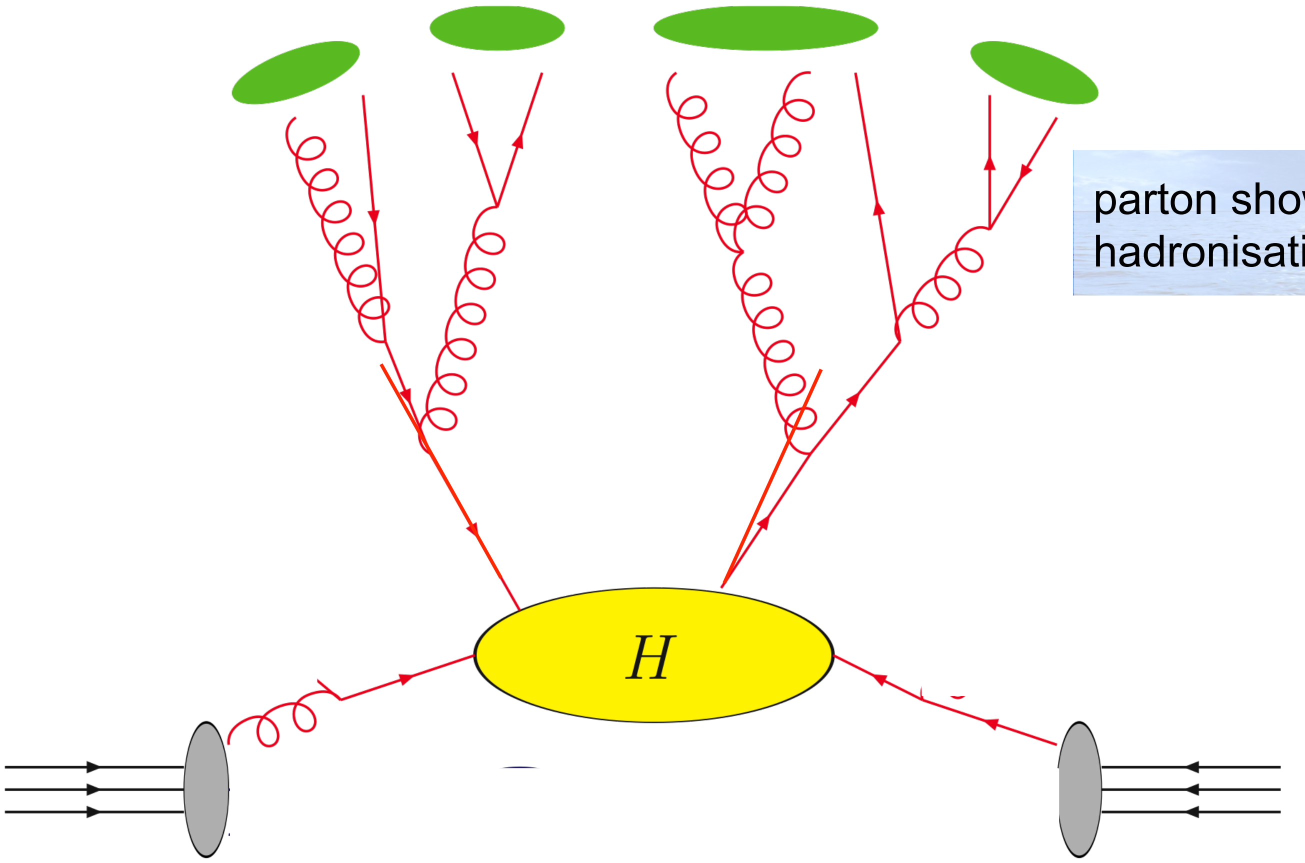
$$\sigma = f_{i/p} \otimes \hat{\sigma}_{ij} \otimes f_{j/p} = \sum_{ij=q,\bar{q},g} \iint dx_1 dx_2 \, f_{i/p}(x_1,Q) \cdot \hat{\sigma}_{ij}(x_1,x_2,Q) \cdot f_{j/p}(x_2,Q)$$

$$= \sum_n \alpha_S^n(Q) \cdot \sum_{ij=q,\bar{q},g} \iint dx_1 dx_2 \, f_{i/p}(x_1,Q) \cdot C_{ij}^n(x_1,x_2,Q) \cdot f_{j/p}(x_2,Q)$$

HOWEVER …

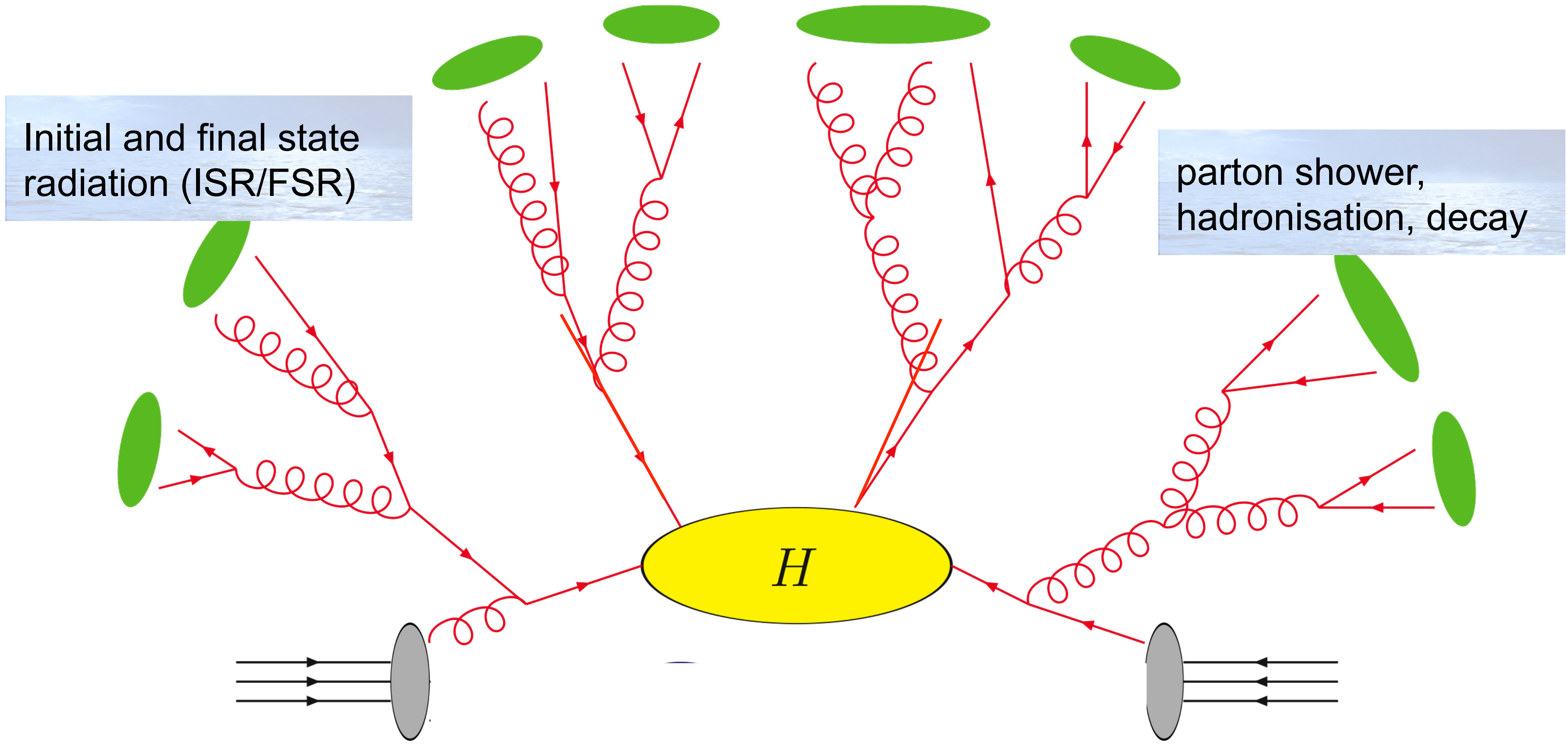


HOWEVER …



parton shower,
hadronisation, decay

HOWEVER …

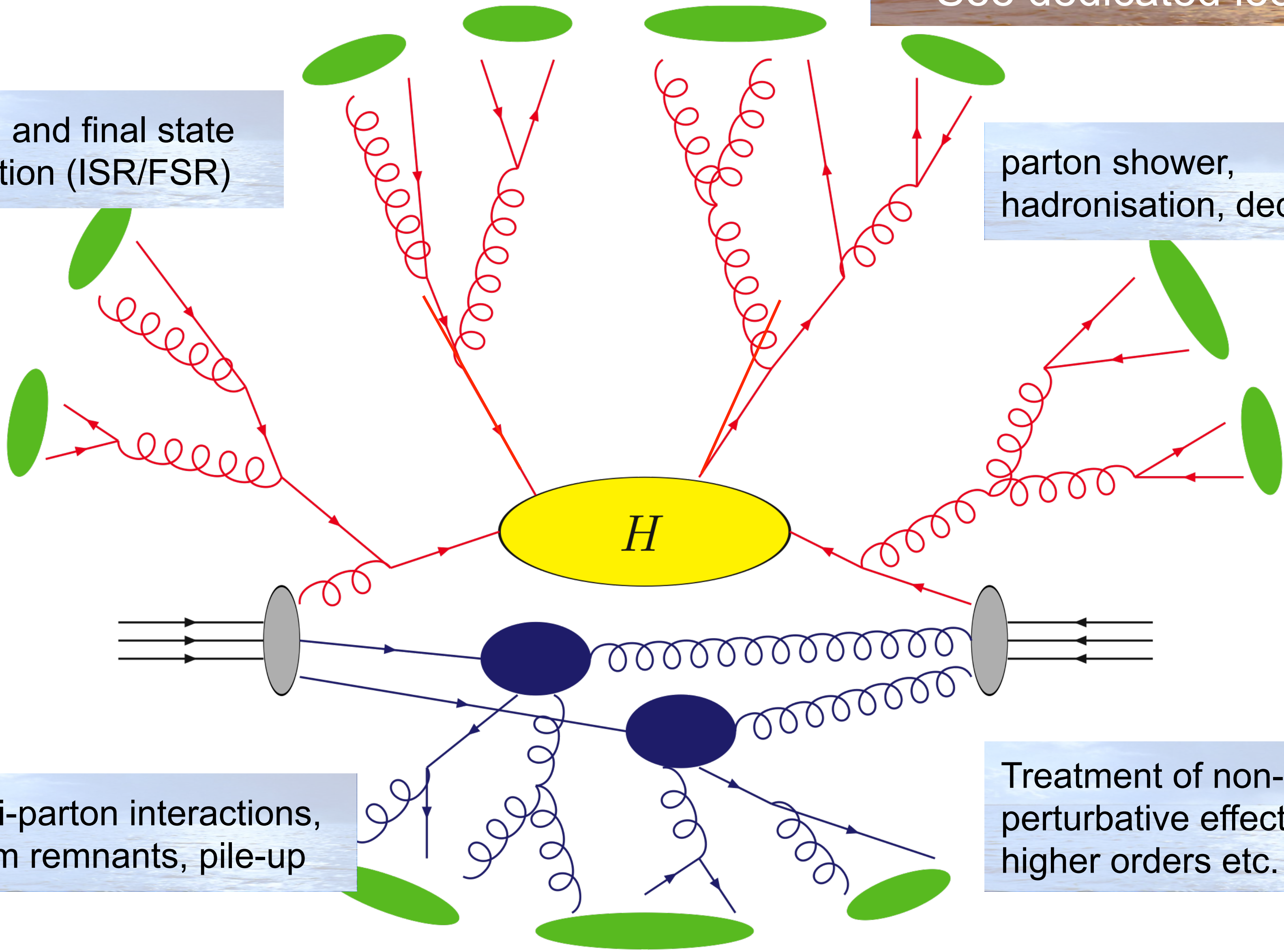

Initial and final state radiation (ISR/FSR)
parton shower, hadronisation, decay
H

HOWEVER …

Need sophisticated Monte Carlo event generators ! See dedicated lecture.

Initial and final state radiation (ISR/FSR)

parton shower, hadronisation, decay



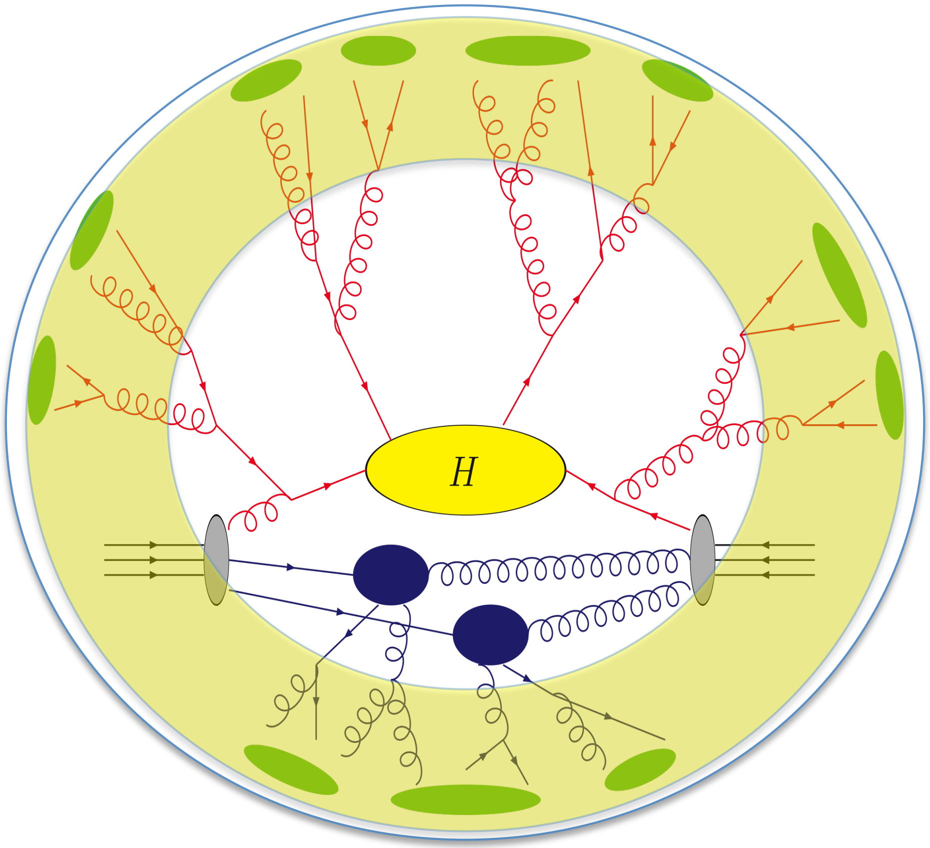
Multi-parton interactions, beam remnants, pile-up

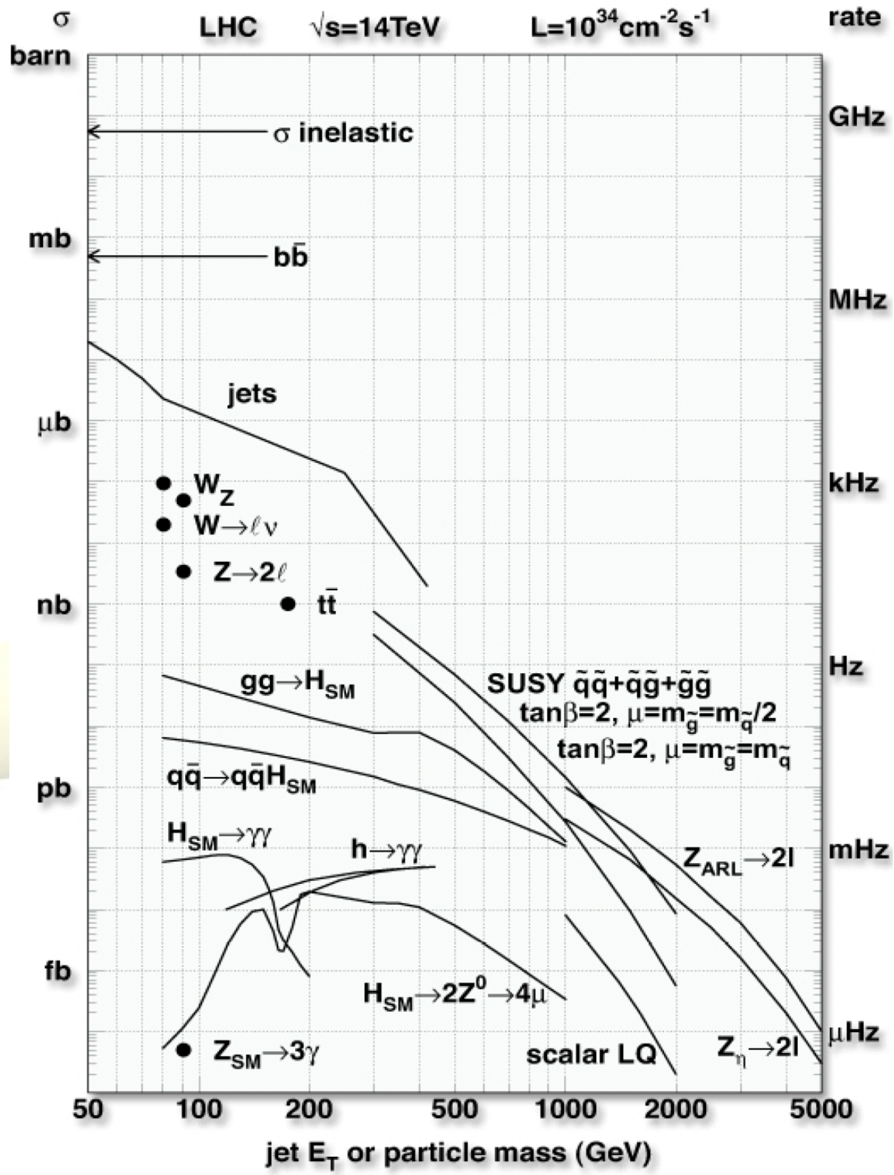
Treatment of non-perturbative effects, higher orders etc.

SOFT QCD: WHAT AND WHY?

Cross sections at LHC dominated by QCD events!

Soft QCD dominates many events!





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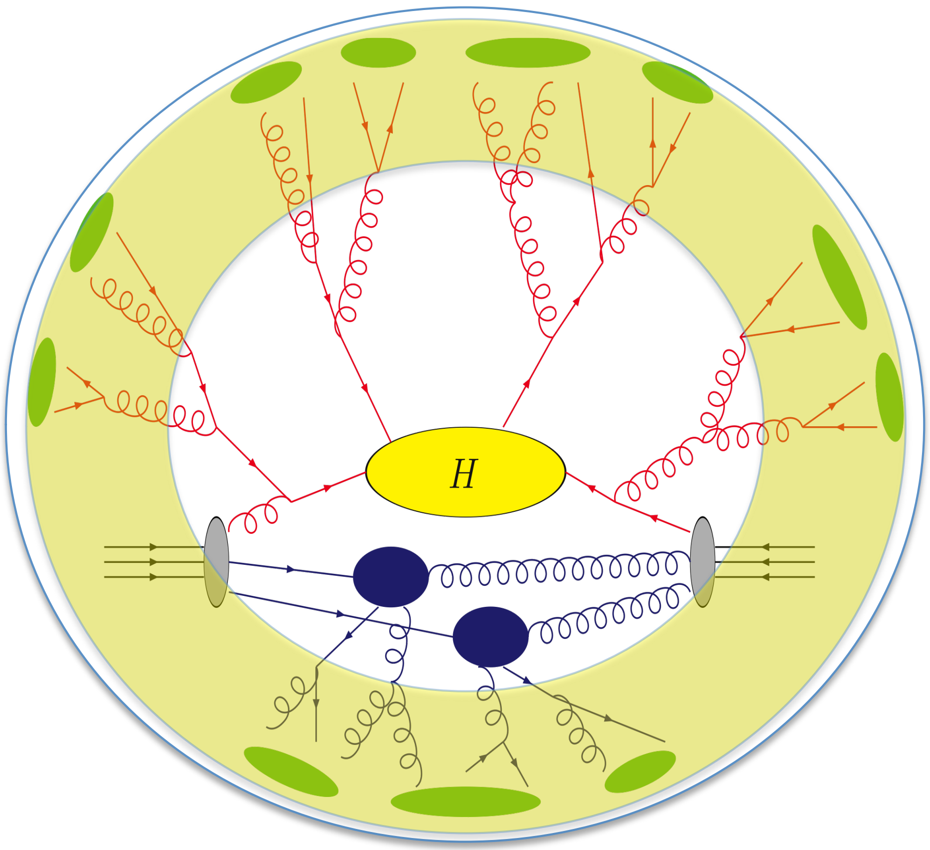
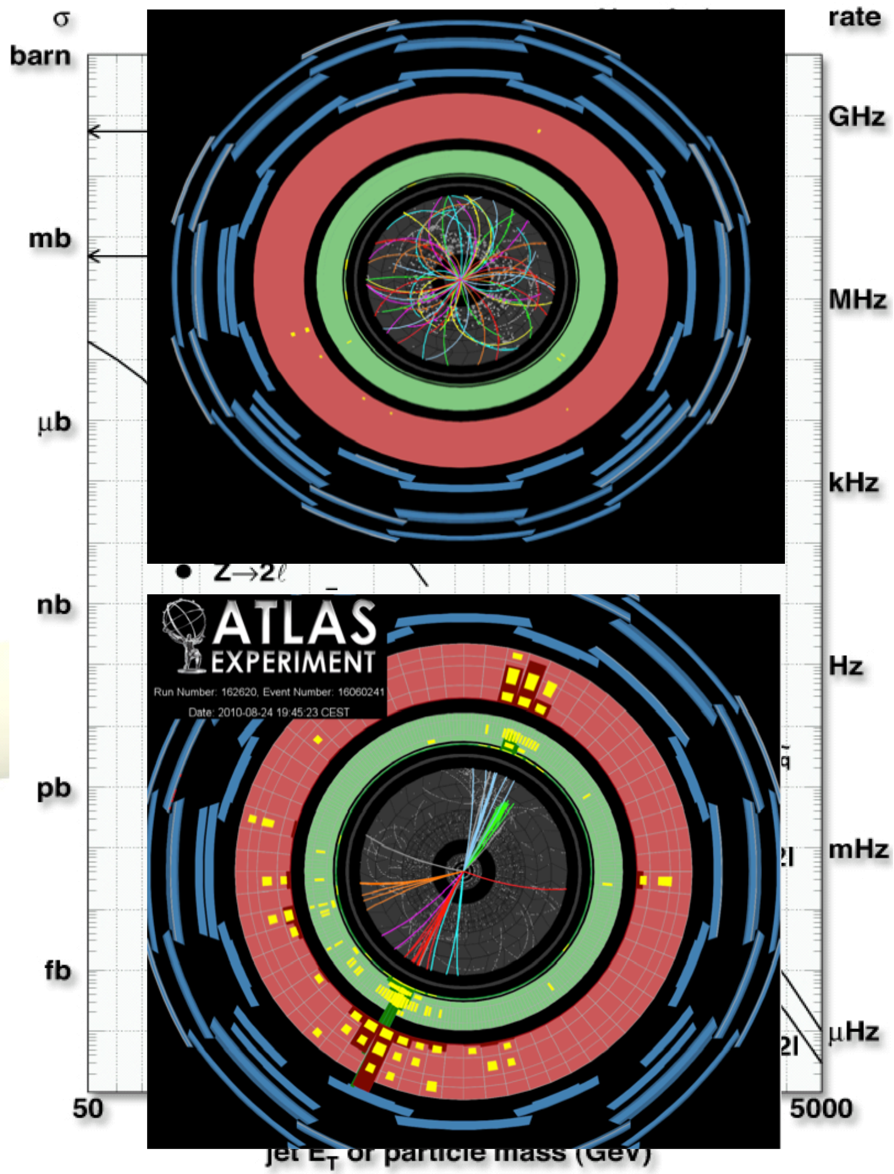
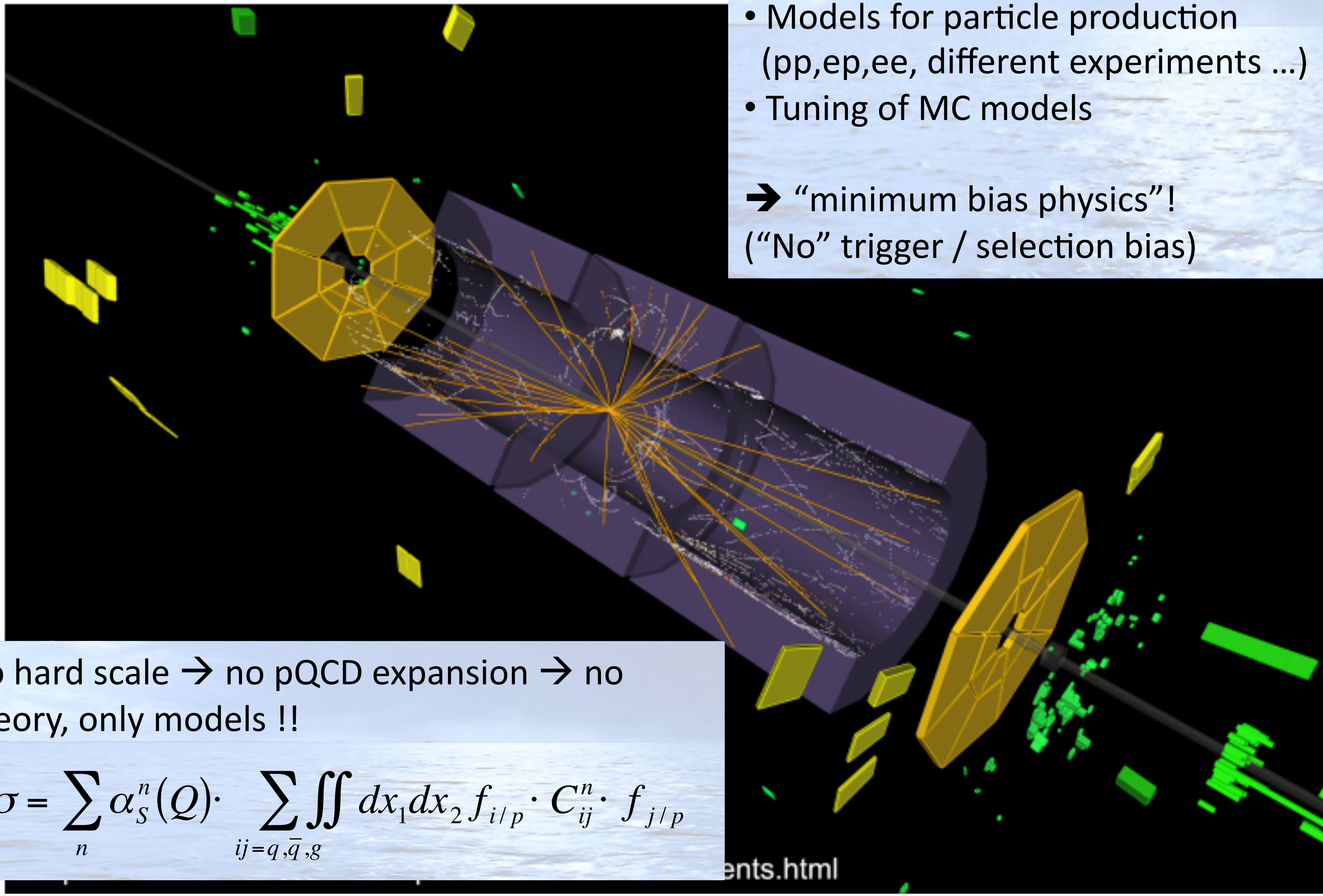




SOFT QCD

- Number of particles
- p_T and eta of particles
- behaviour with energy
- Models for particle production (pp,ep,ee, different experiments …)
- Tuning of MC models

➔ "minimum bias physics"!
("No" trigger / selection bias)



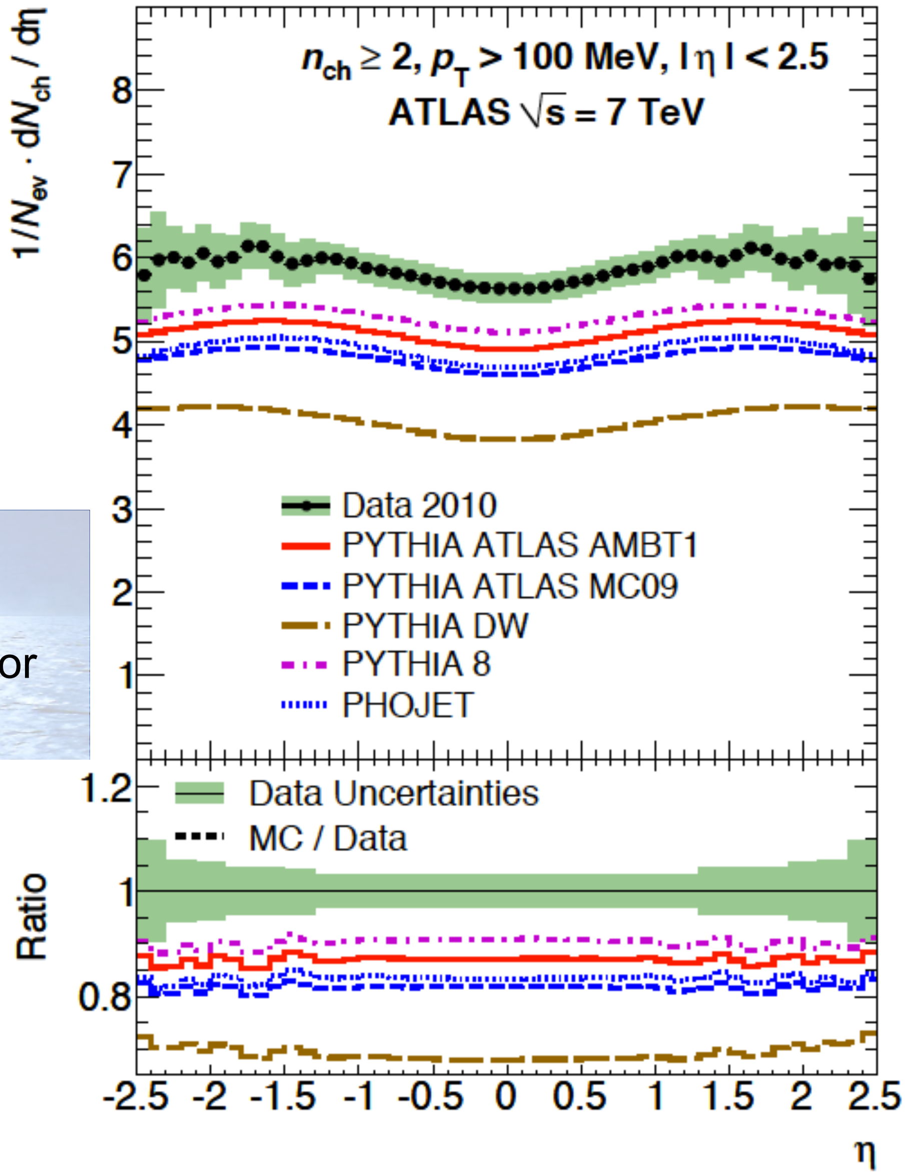
No hard scale → no pQCD expansion → no theory, only models !!

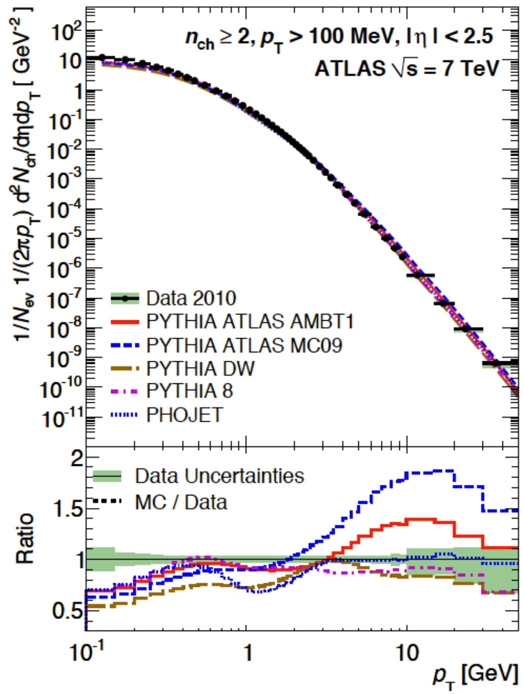
$$\sigma = \sum_n \alpha_S^n(Q) \cdot \sum_{ij=q,\bar{q},g} \iint dx_1 dx_2 \, f_{i/p} \cdot C_{ij}^n \cdot f_{j/p}$$

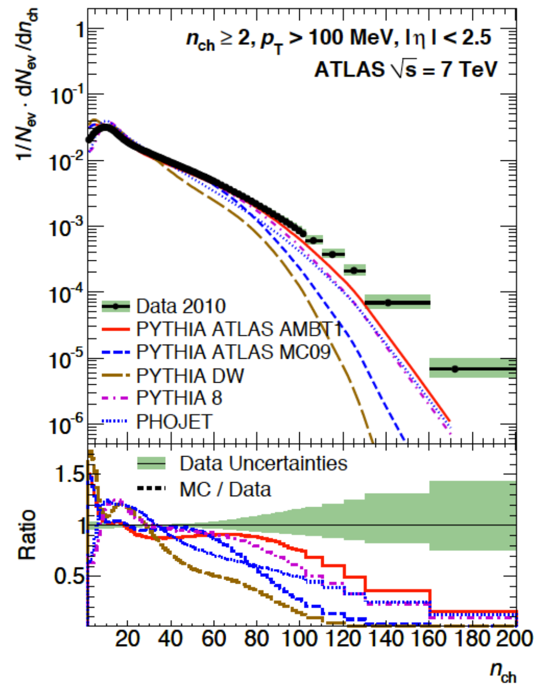
SOFT QCD

Difficult to describe!

Excellent playground for tuning MC models!



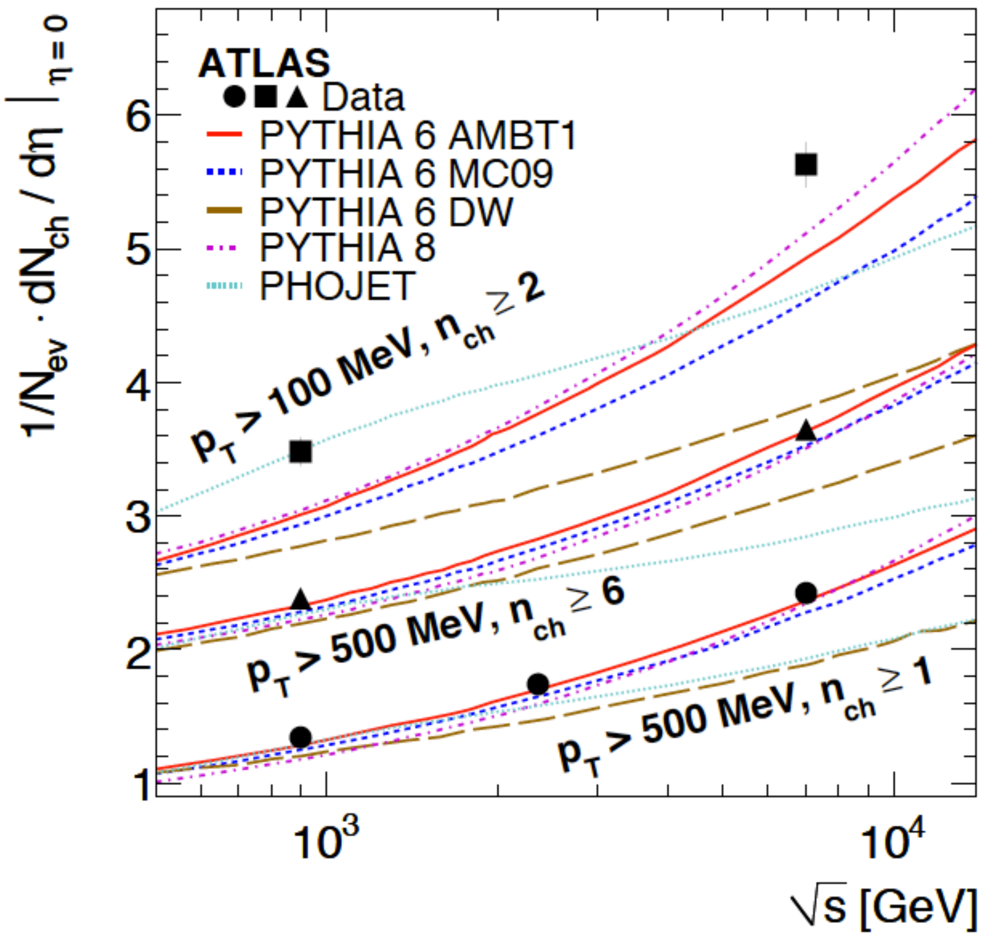




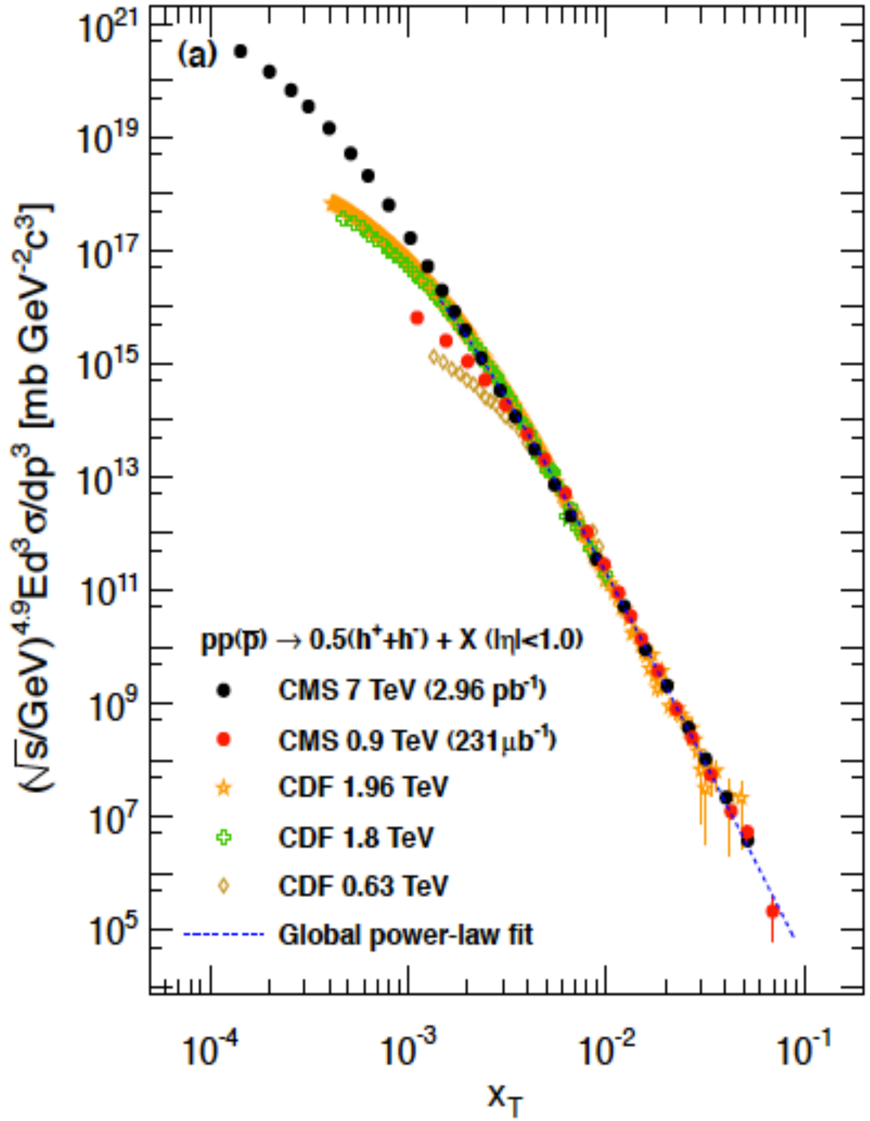
SOFT QCD

Average number of charged particles per unit rapidity at η=0.

Models cannot really describe evolution with CMS energy; problems worse for softer selections!



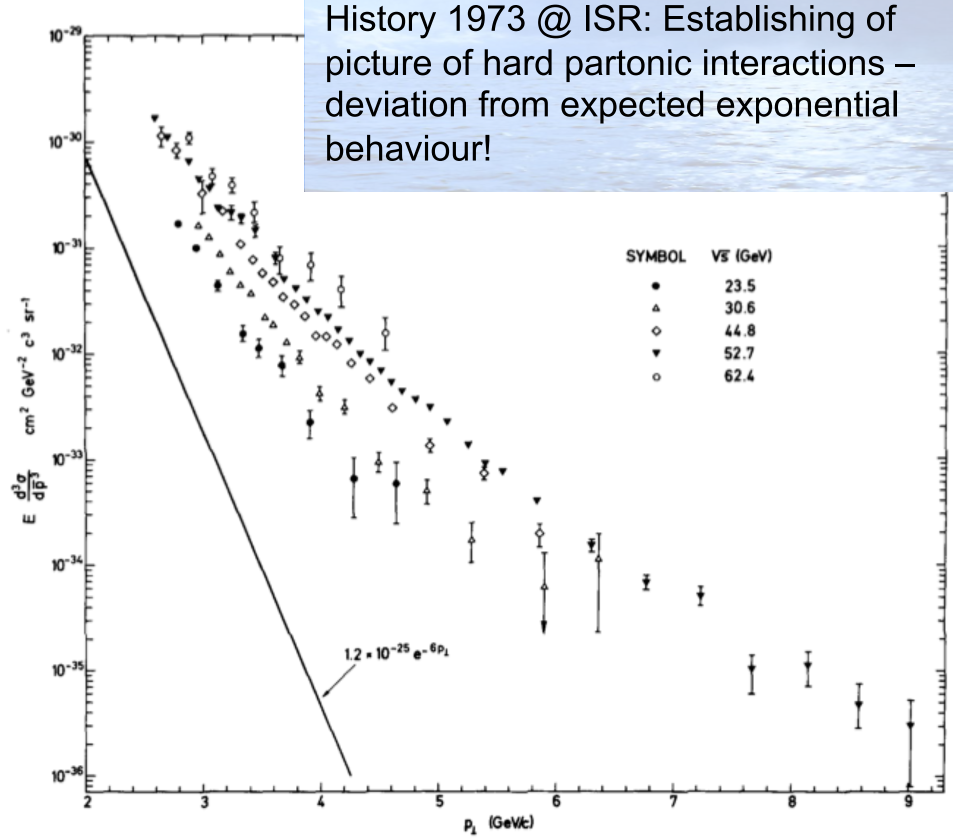
SOFT QCD



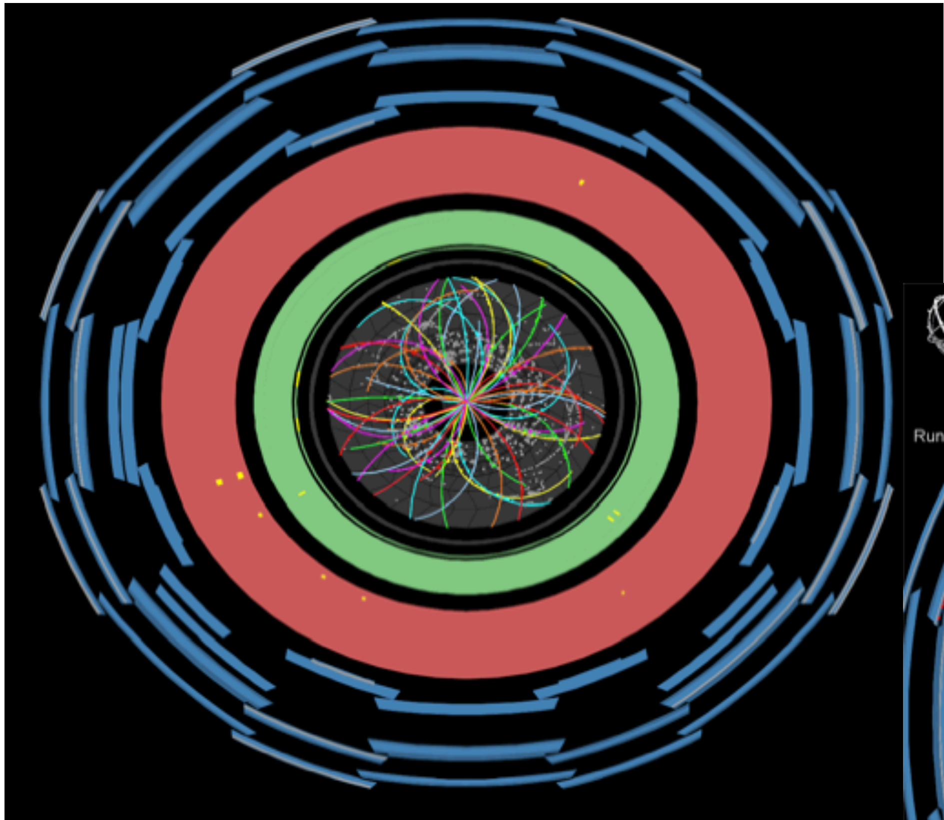
pQCD prediction:

$$E\frac{d^3\sigma}{dp^3} = F(x_T)/p_T^{n(x_T,\sqrt{s})} = F'(x_T)/\sqrt{s}^{\,n(x_T,\sqrt{s})}$$

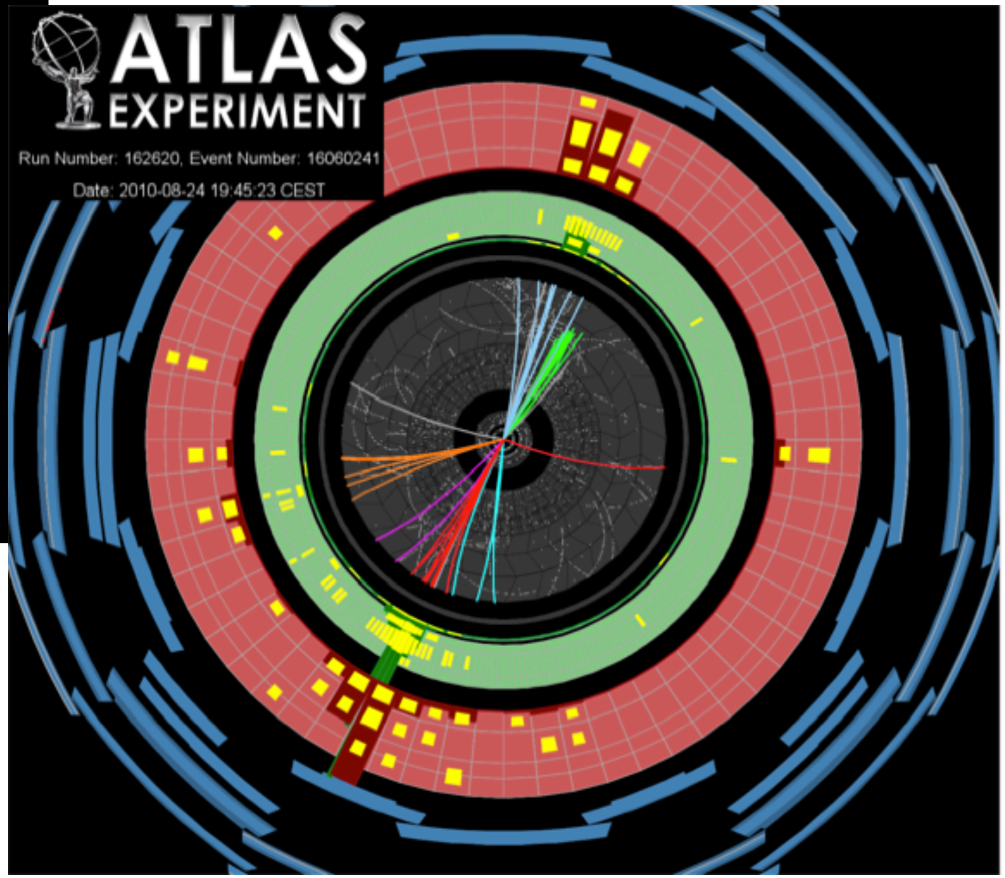
History 1973 @ ISR: Establishing of picture of hard partonic interactions – deviation from expected exponential behaviour!



JETS: FROM SOFT TO HARD QCD



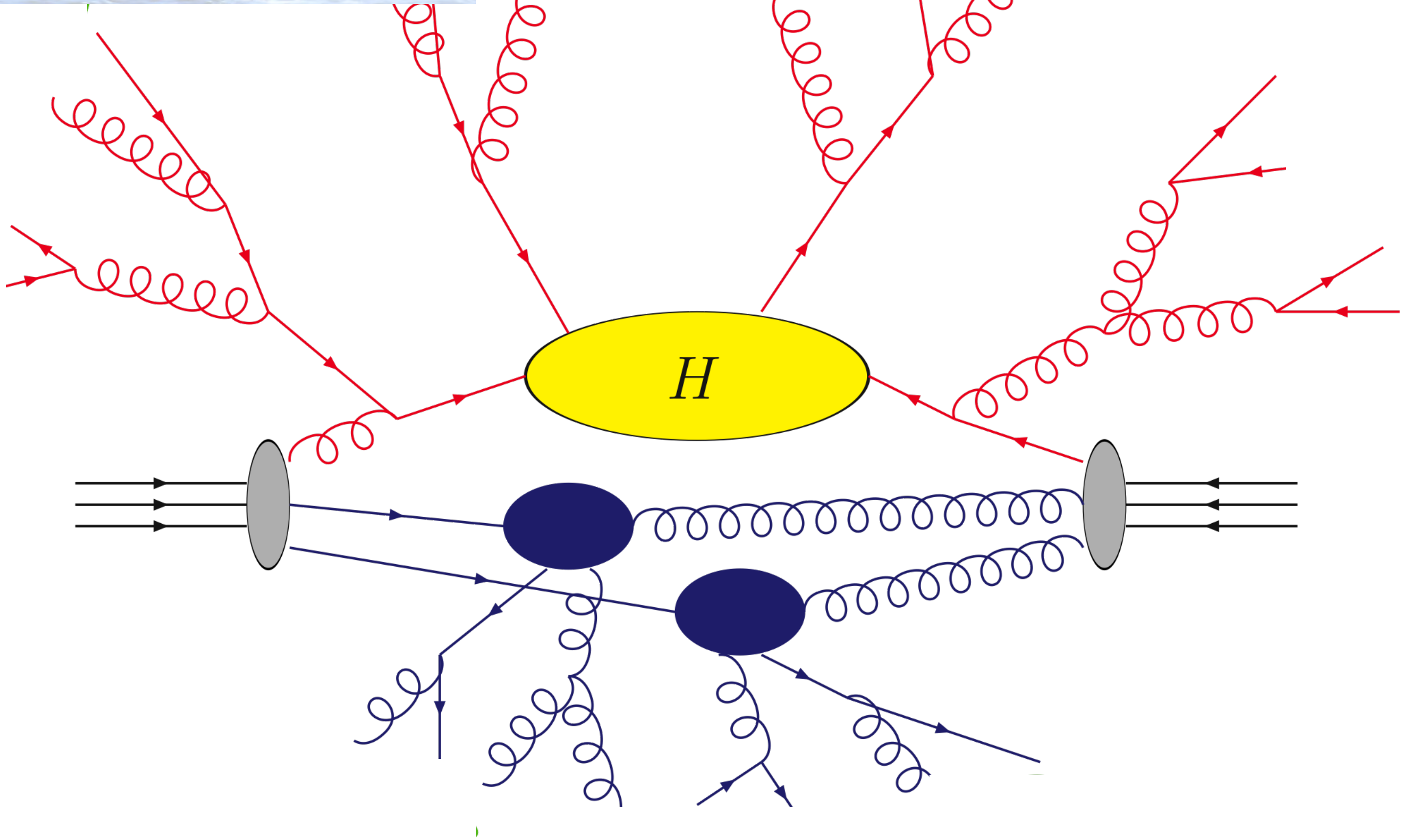
Soft QCD: Protons barely grazing each other. No hard, leading particles.



Hard QCD: Hard partonic interaction with two leading outgoing particles. Reconstruct them from “jets”.

JET ALGORITHMS

Idea: Resum final-state radiation to identify hard partonic event



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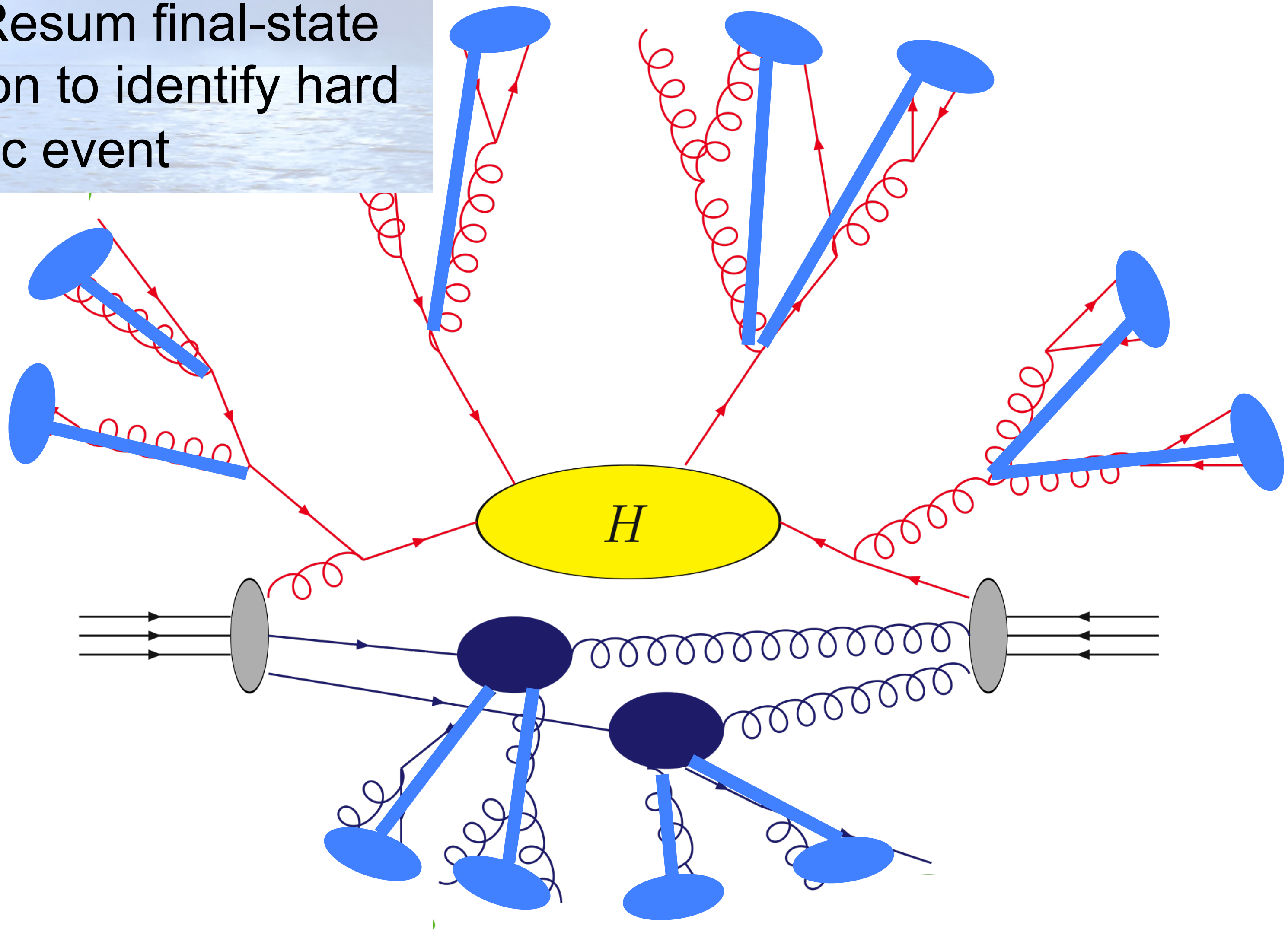

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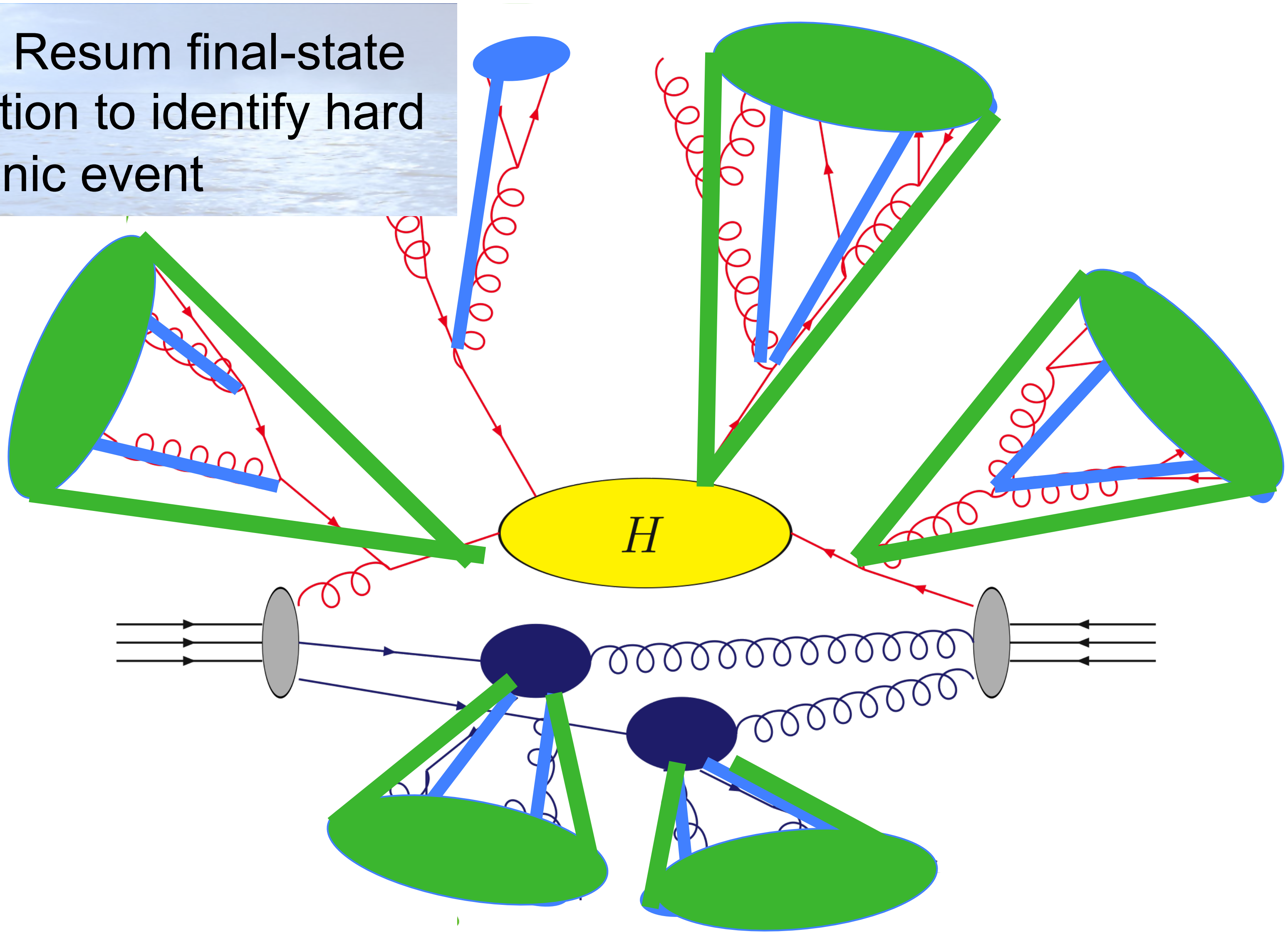

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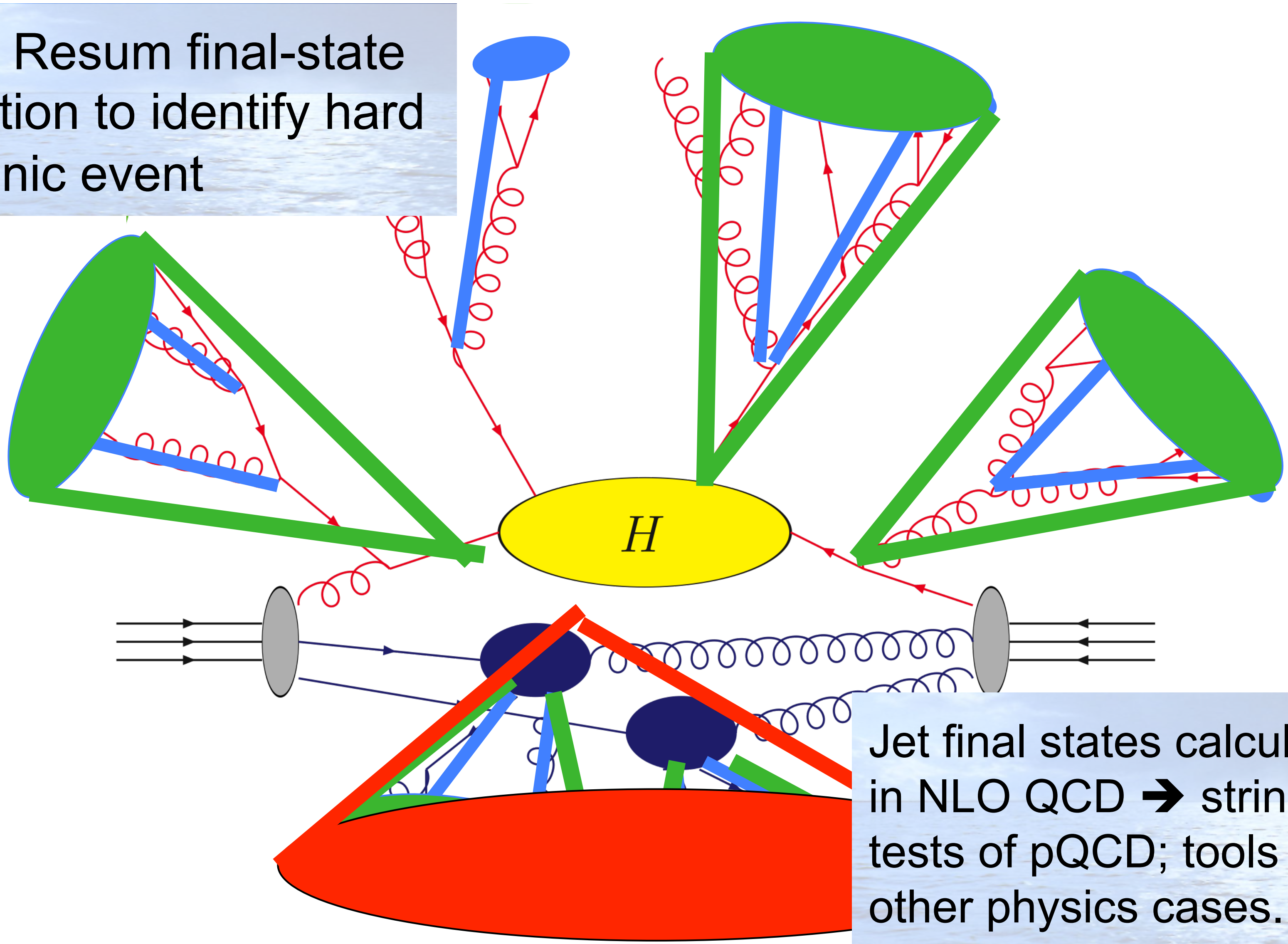
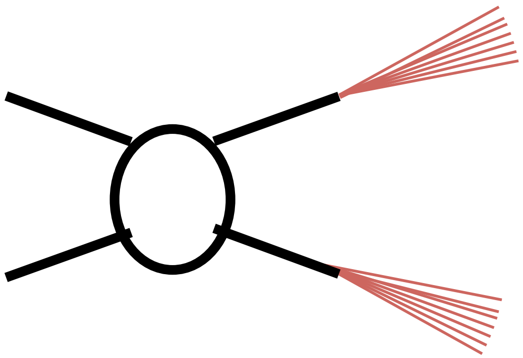


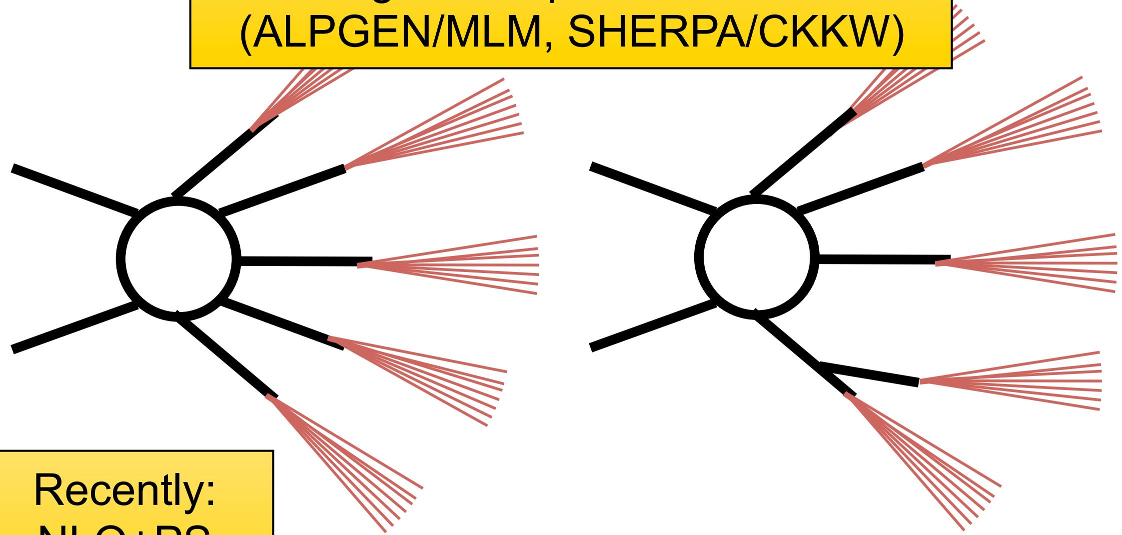
Jet final states calculable in NLO QCD ➔ stringent tests of pQCD; tools for other physics cases.

JETS: THEORY APPROACHES

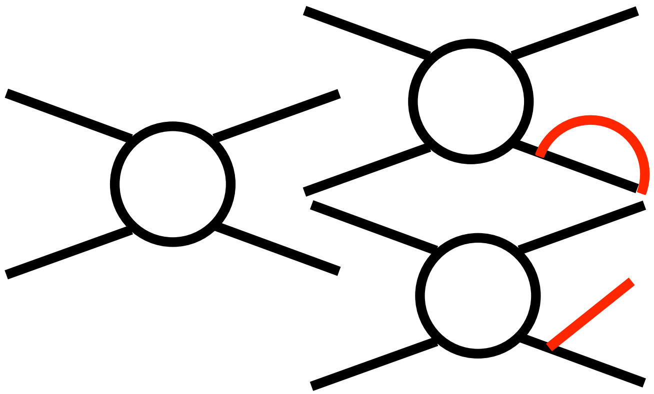
2→2 matrix elements with parton shower (PYTHIA, HERWIG)



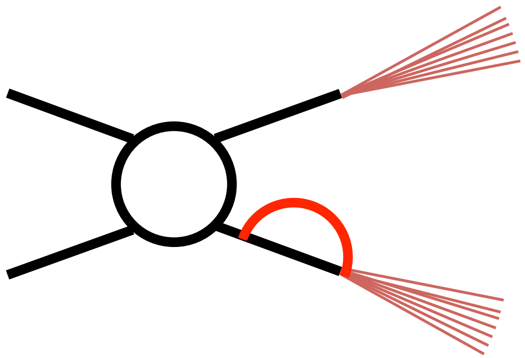
Multi-leg matrix elements fully merged with parton showers (ALPGEN/MLM, SHERPA/CKKW)



Fixed-order calculations (NLO / NNLO, additional resummation of logs…)

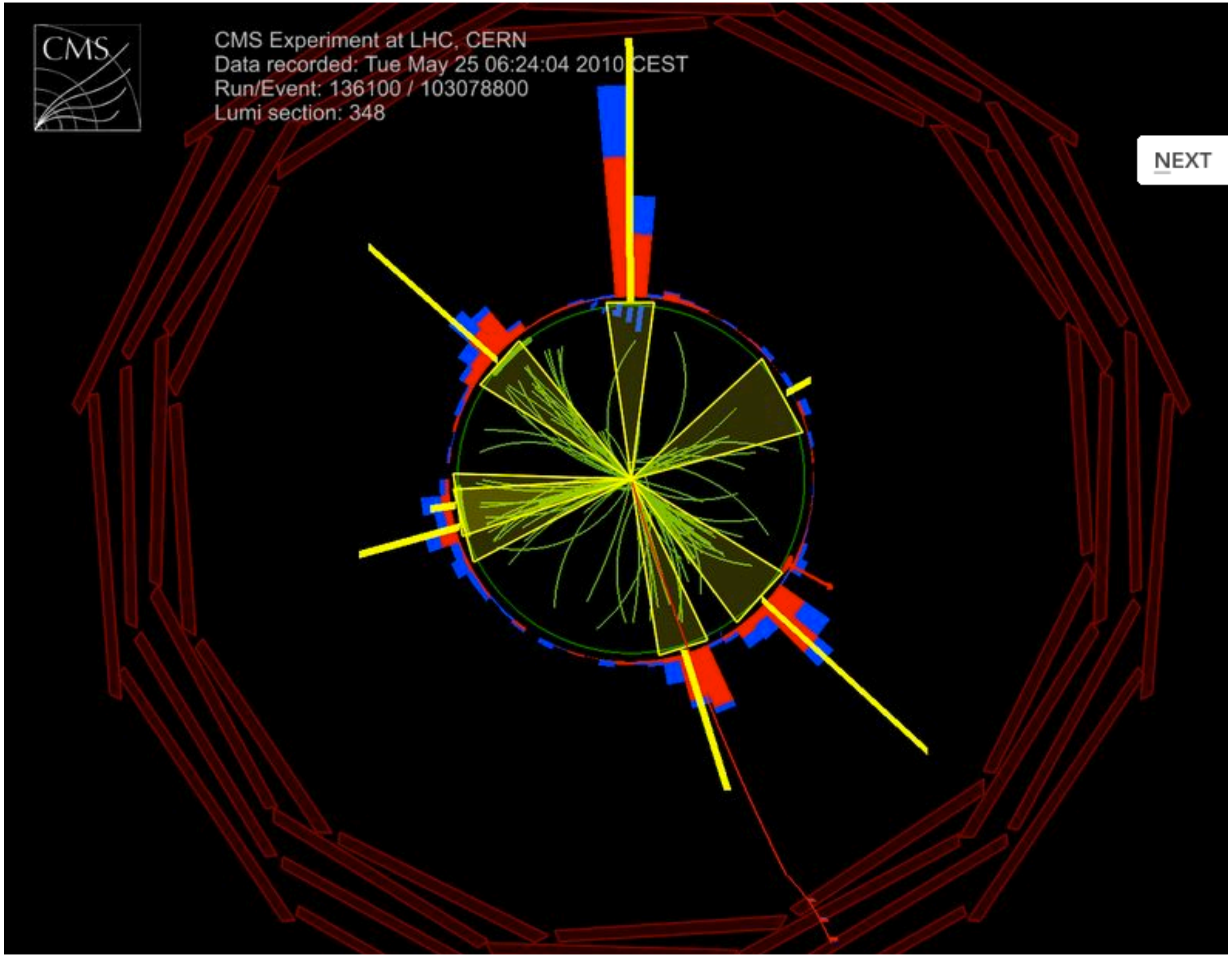


Recently: NLO+PS matching

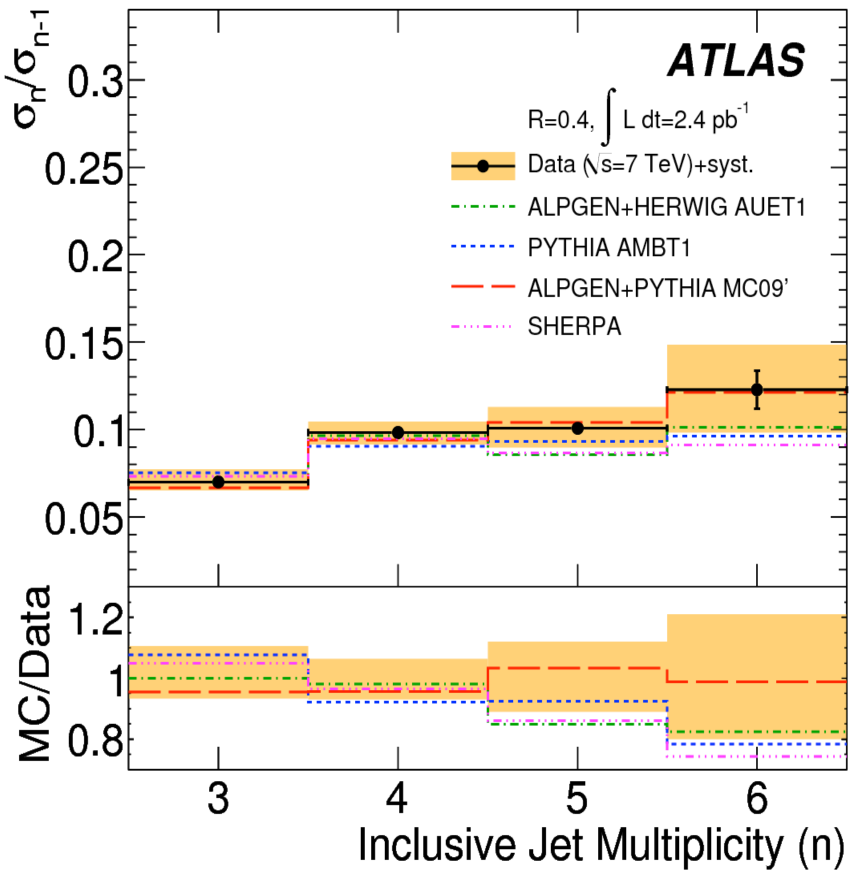


Current work: full merging at NLO!

JETS IN THE DETECTOR



JETS: RESULTS (few only)



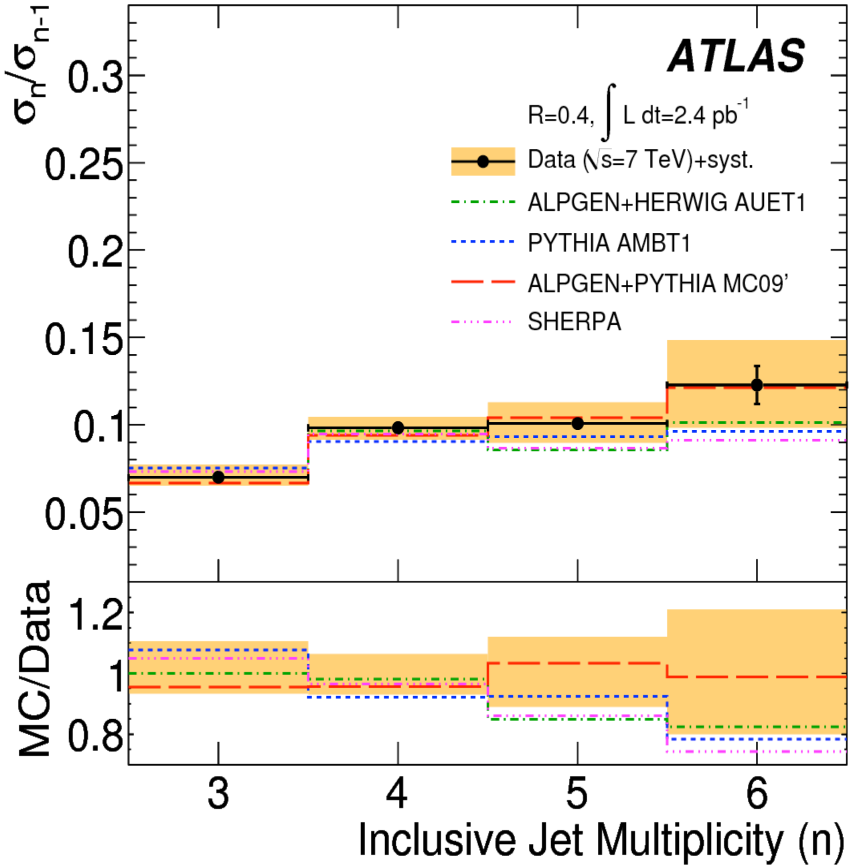
Jet cross section as function of number of jets. Excellent description by models and NLO QCD.

Ratio σ_n/σ_{n+1}. Remember cross section is power series in α_S:

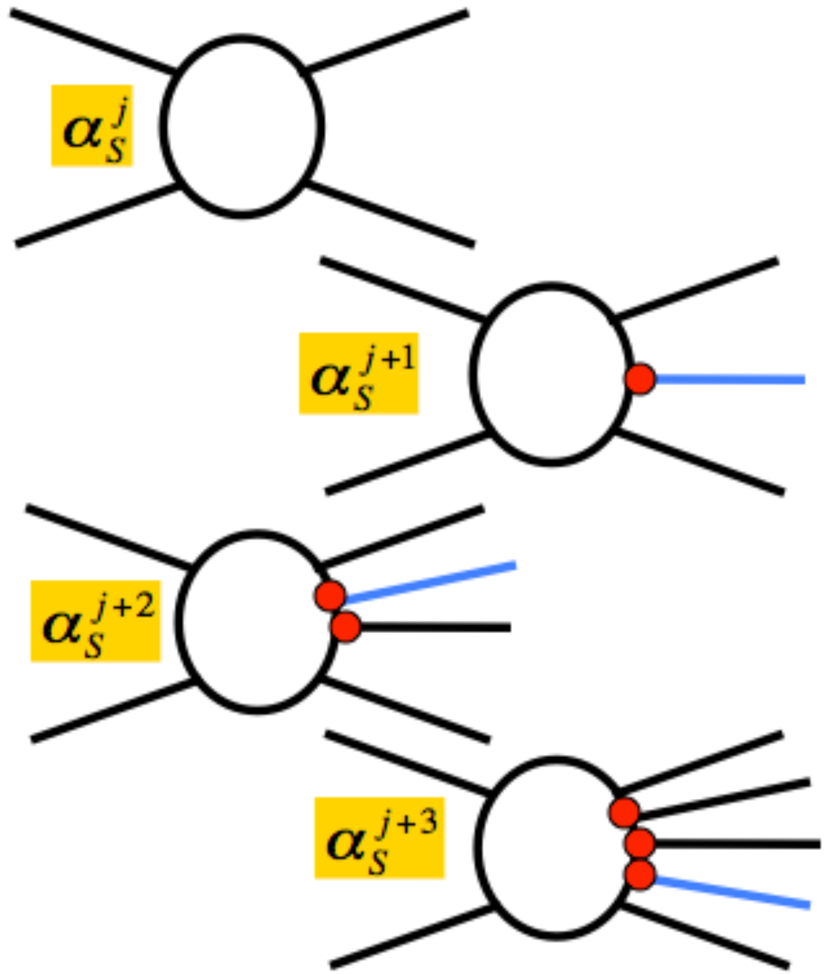
$$\sigma = \sum_n \alpha_S^n \cdot \sum_{ij=q,\bar{q},g} f_{i/p} \otimes C_{ij}^n \otimes f_{j/p}$$

Additional (hard) particle in final state involves one more strong coupling
→expect value of ~0.1 for ratio!

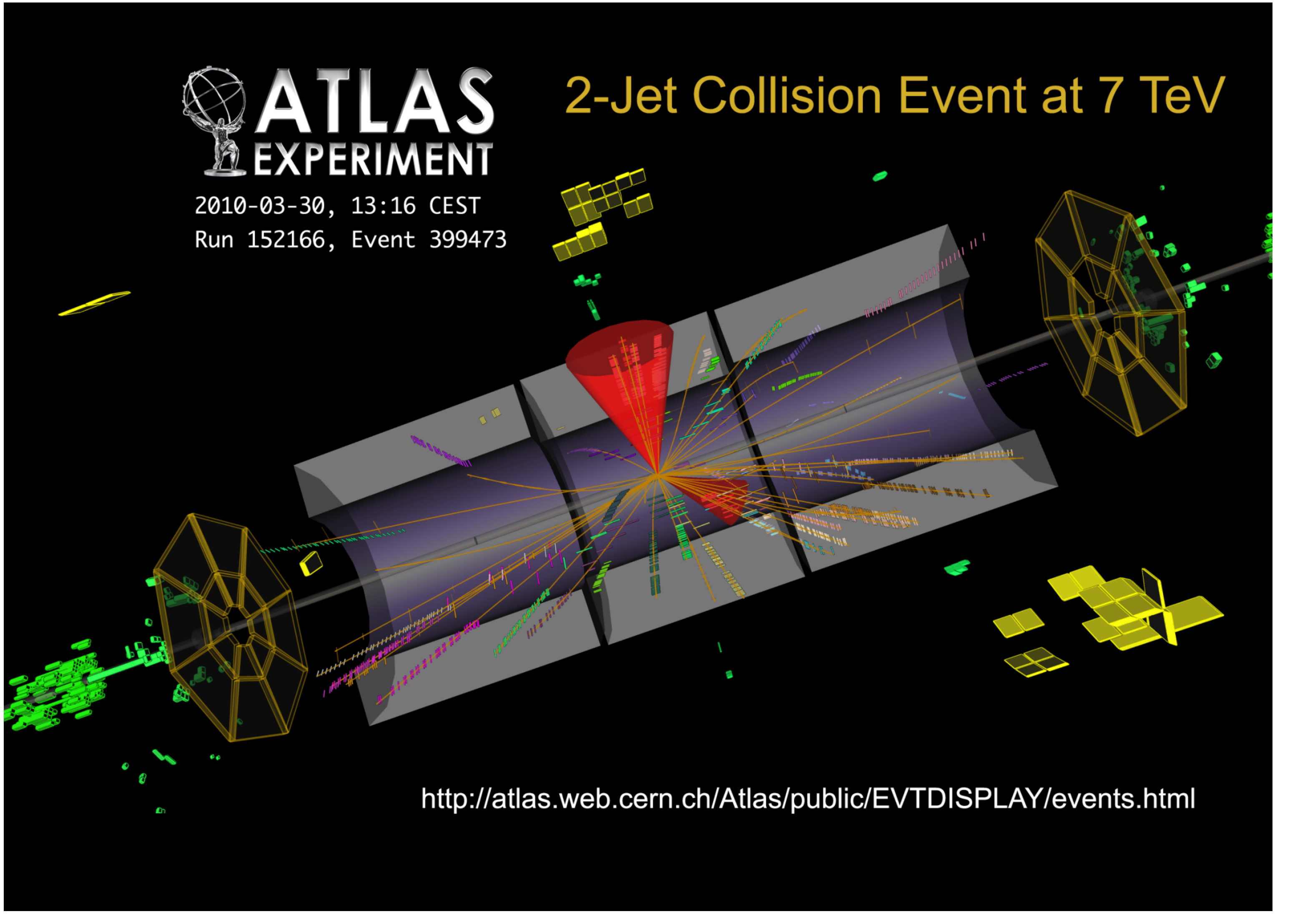
JETS: RESULTS (few only)



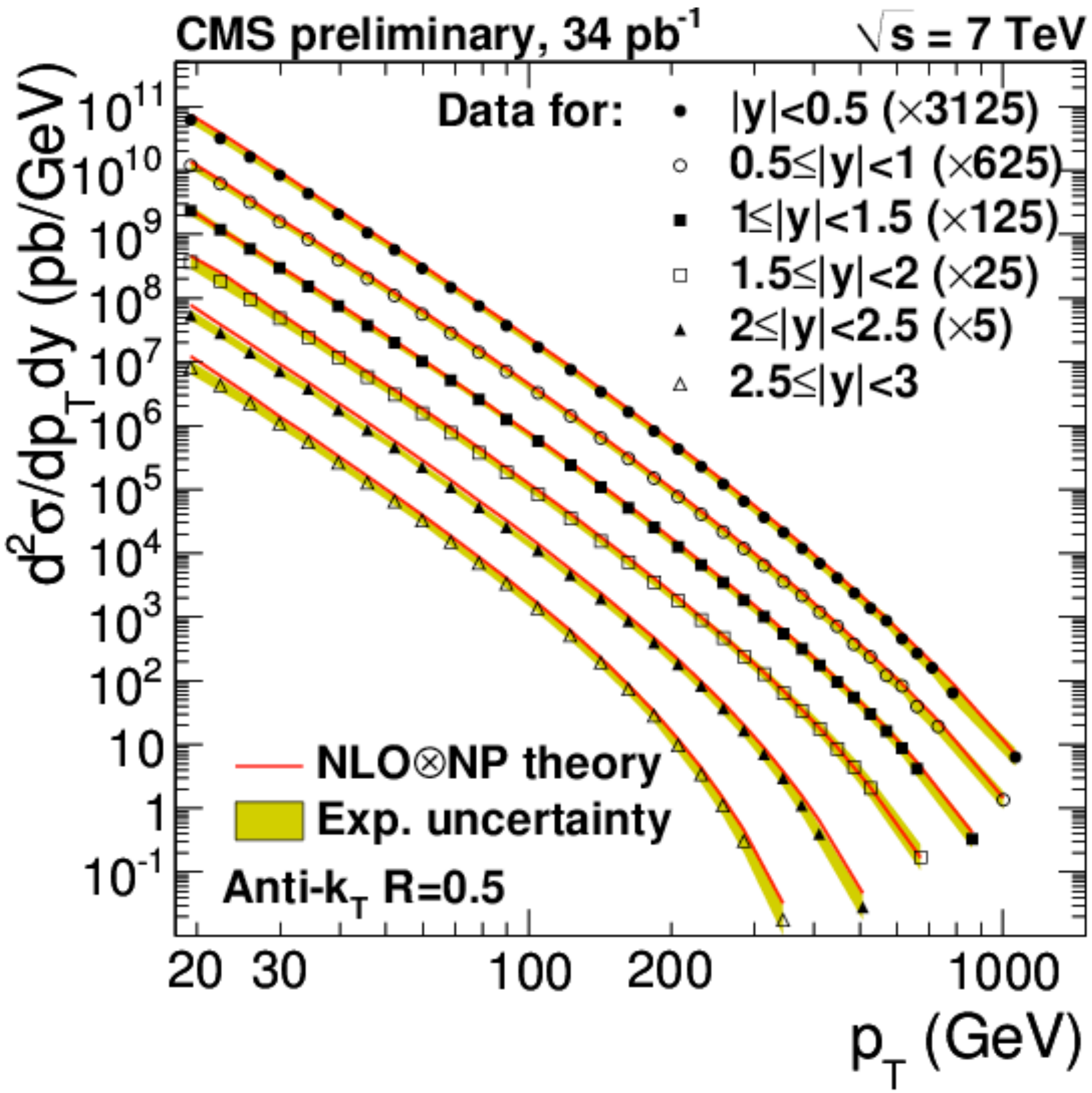
$$\sigma = \sum \alpha_S^n \cdot C_n = \alpha_S^0 \cdot C_0 + \alpha_S^1 \cdot C_1 + \alpha_S^2 \cdot C_2 + \ldots$$



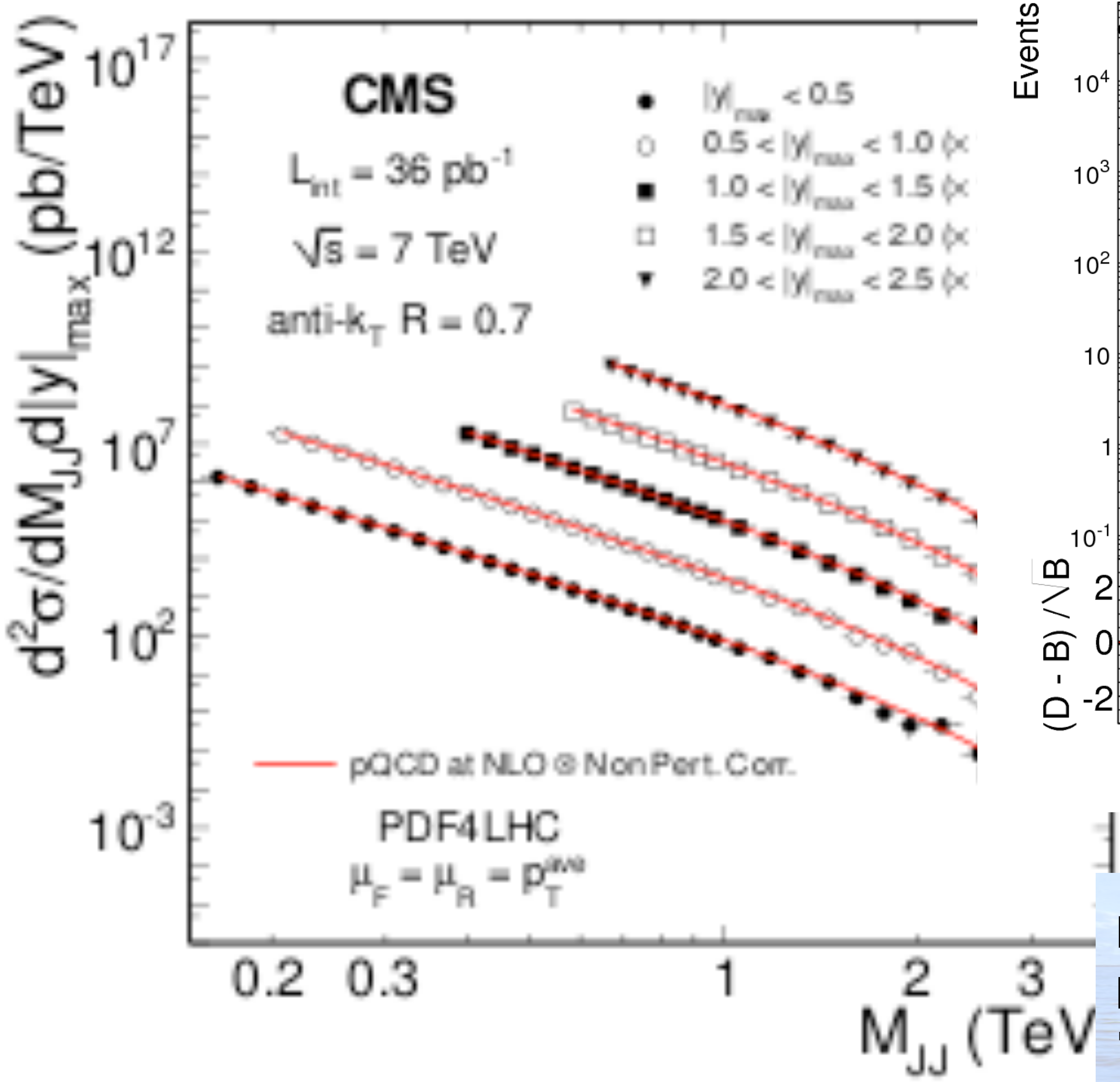
JETS IN THE DETECTOR

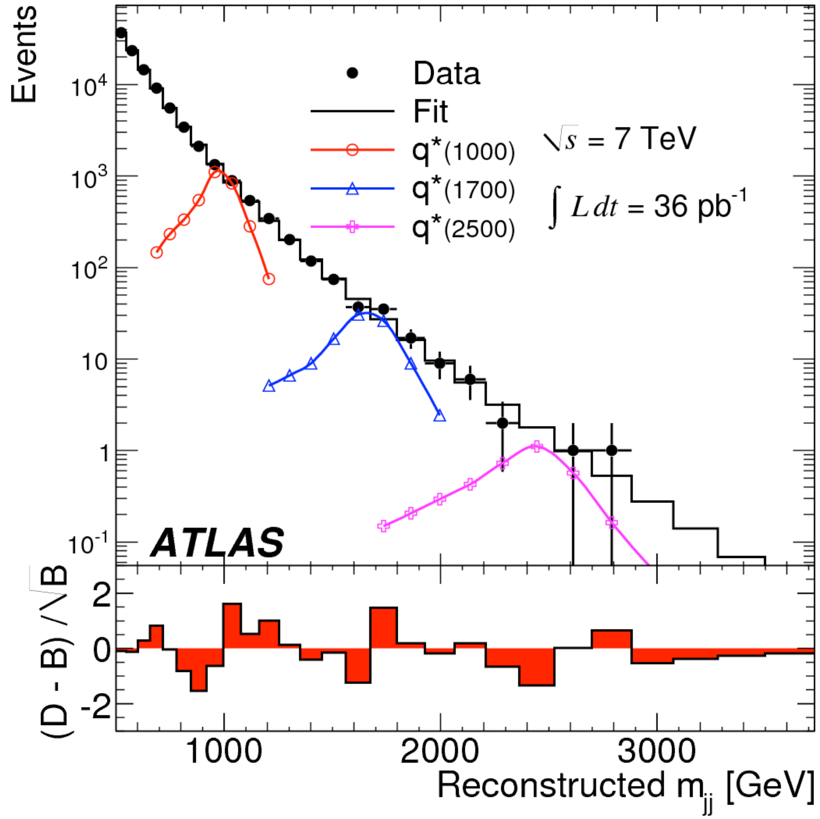


JETS: RESULTS (few only)



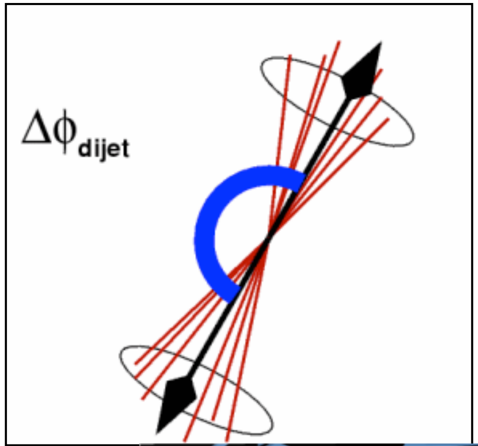
JETS: RESULTS (two only)

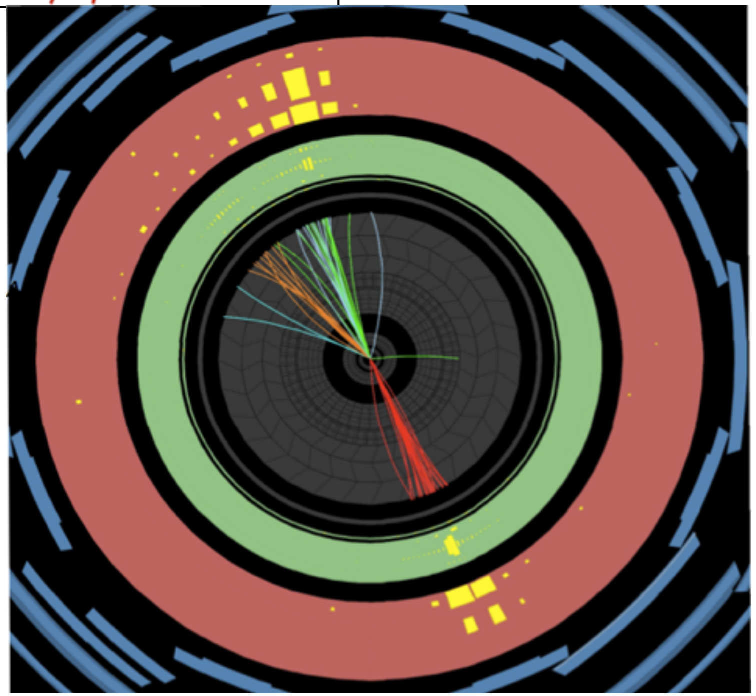


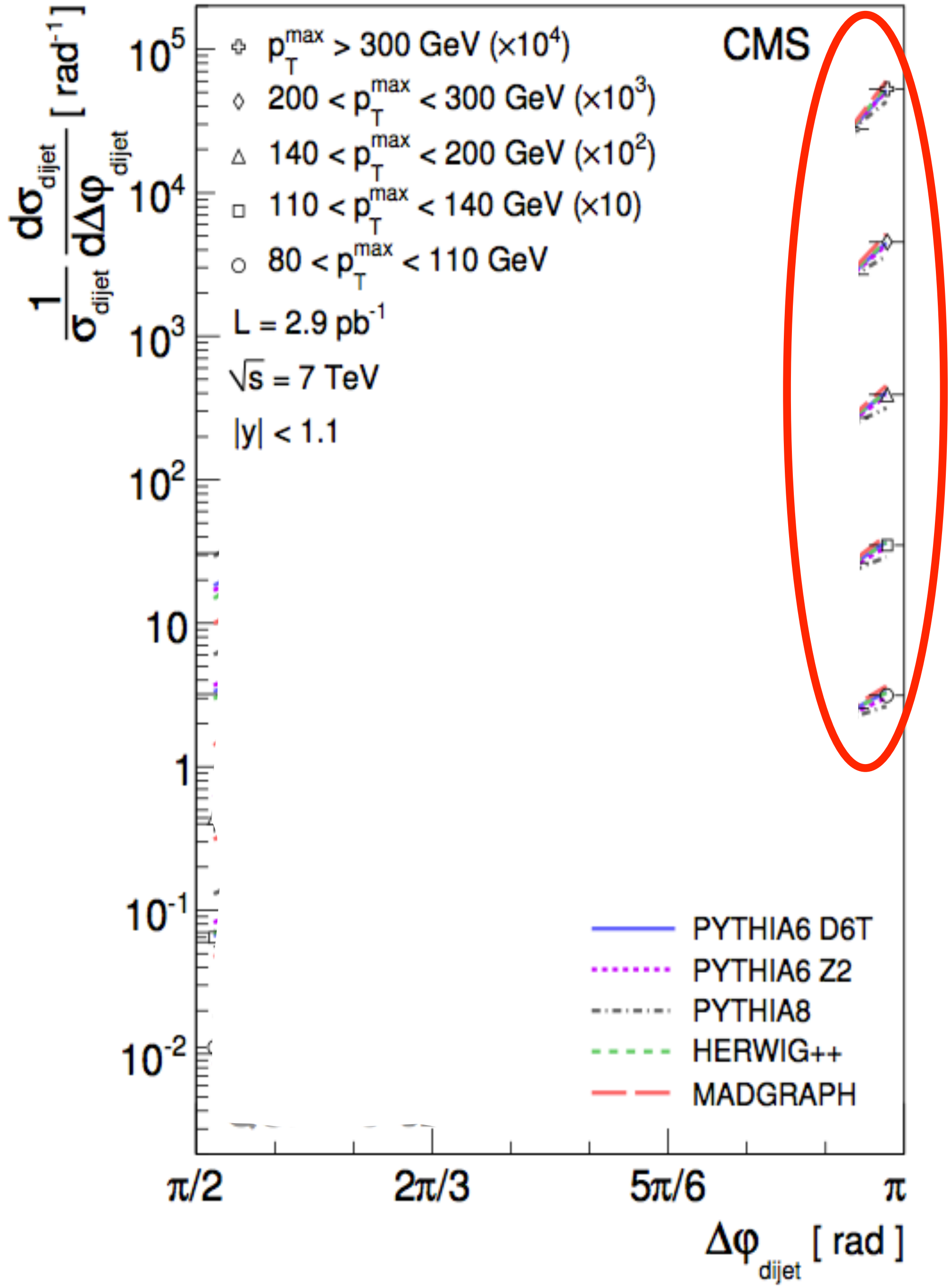


Many new physics models with particles decaying to two jets
➔ find in invariant-mass spectrum !

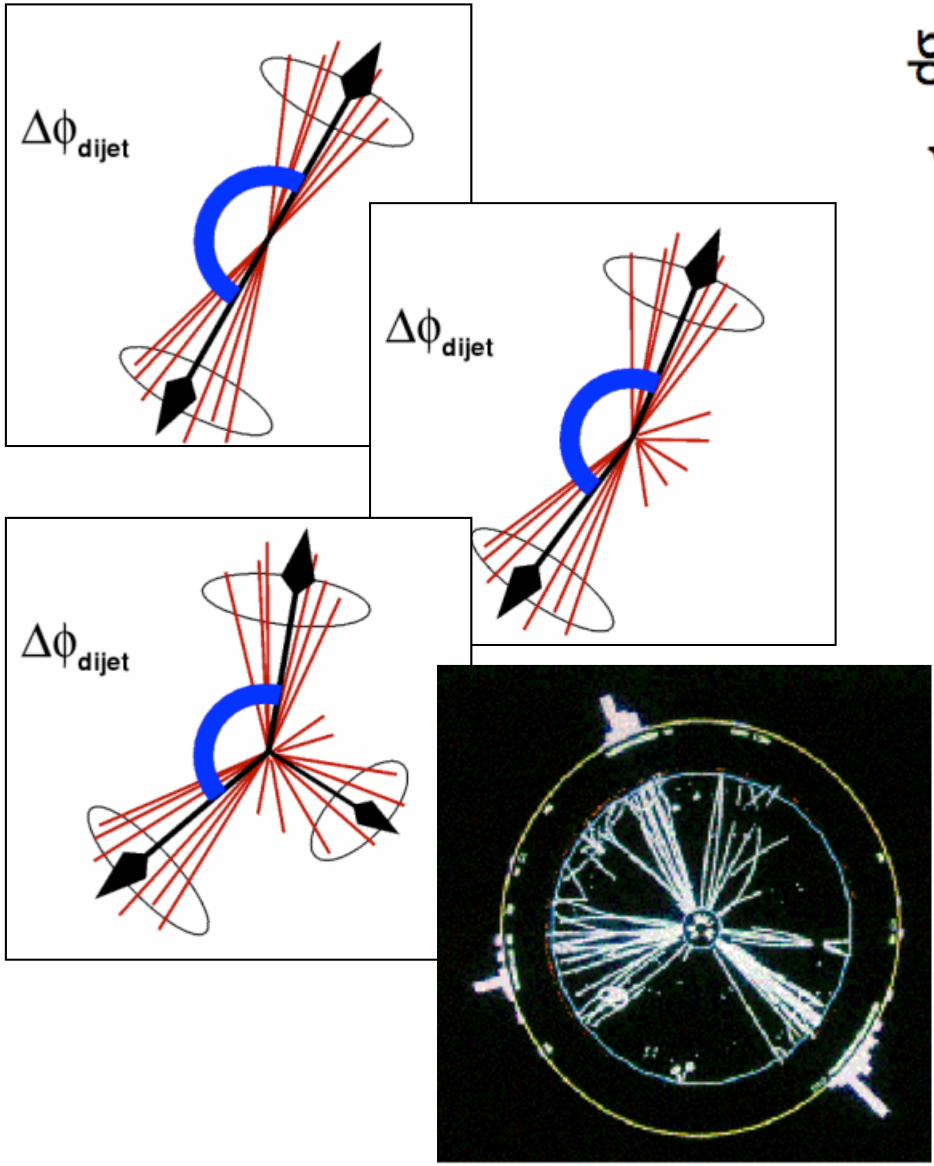
JETS: RESULTS

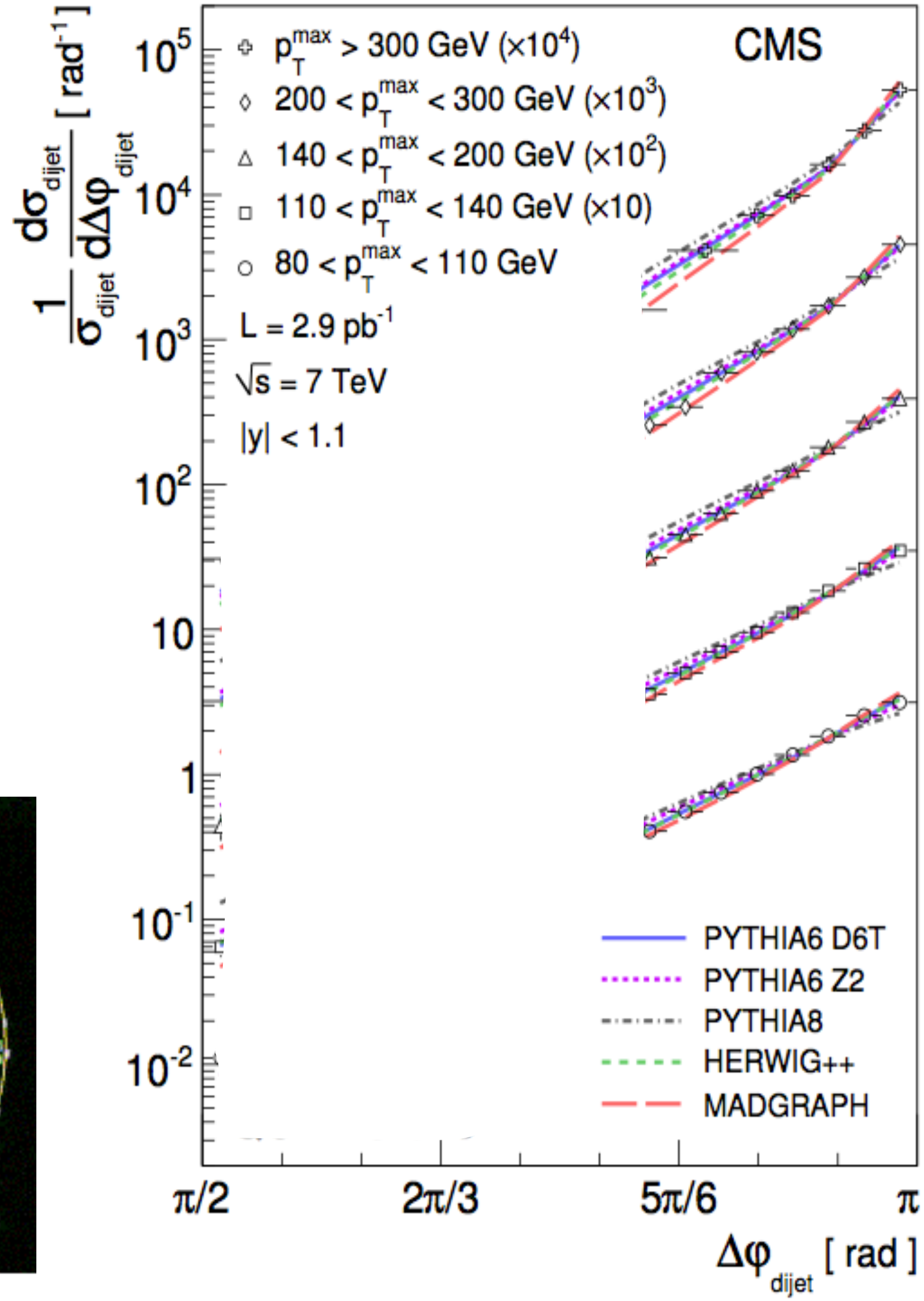




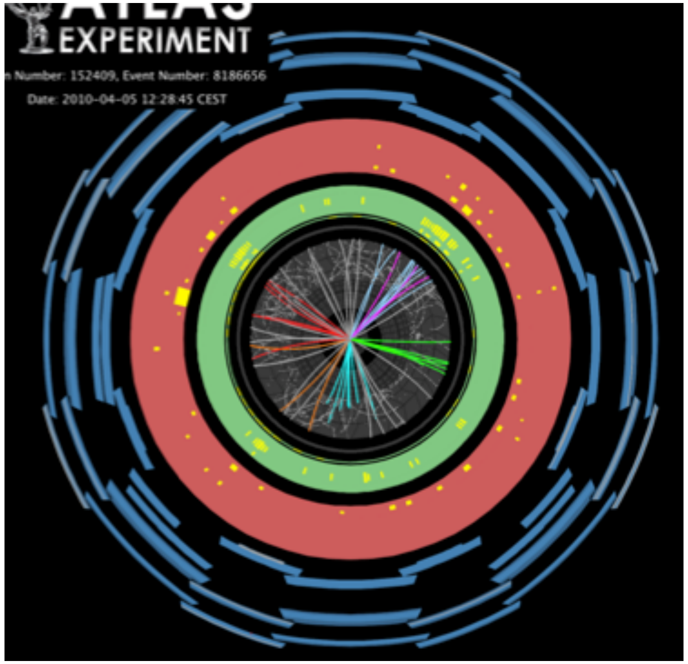


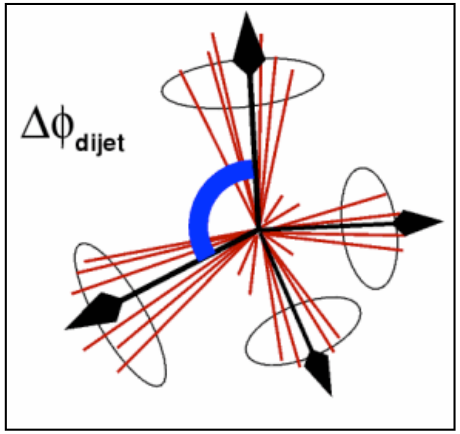
JETS: RESULTS

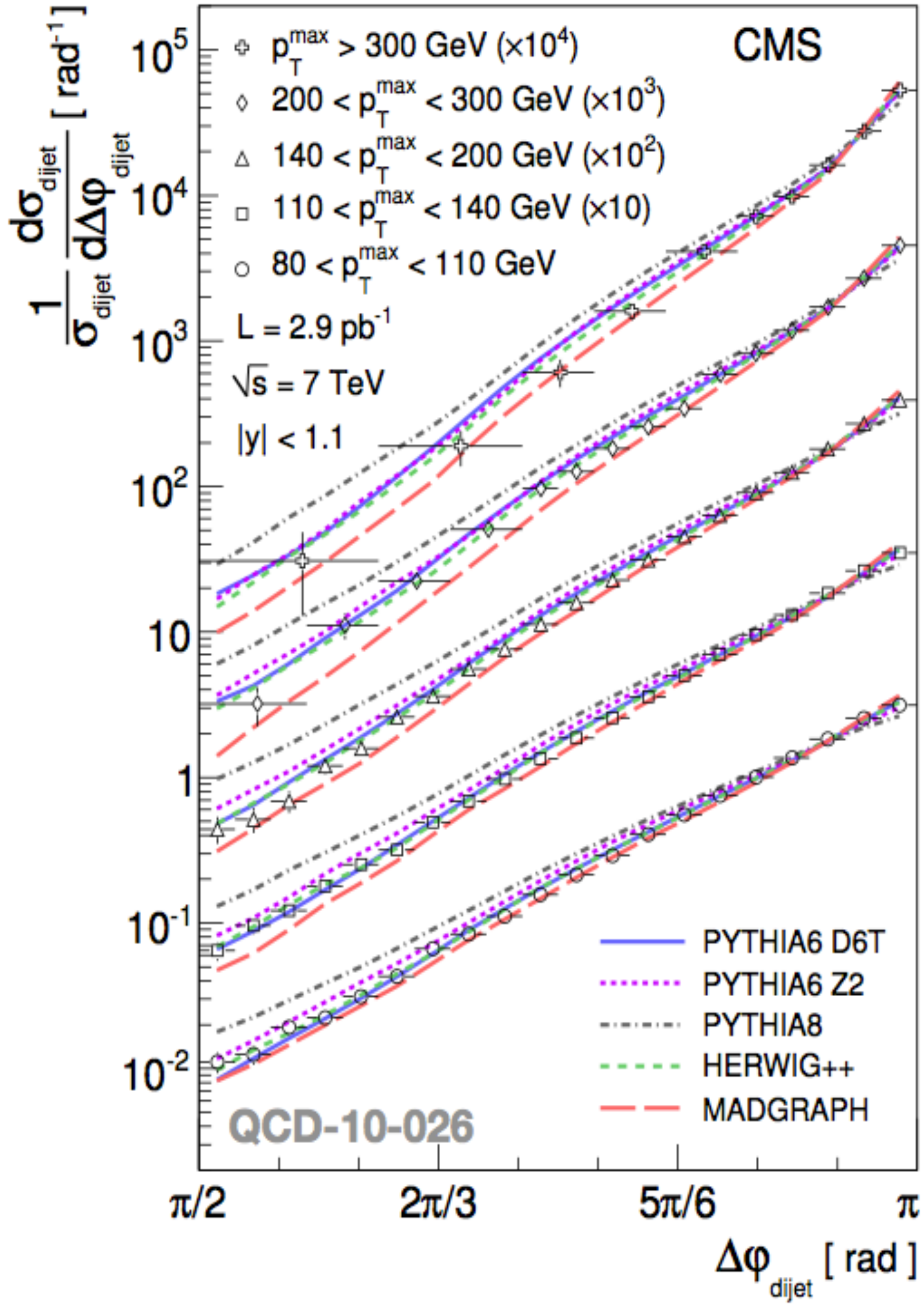




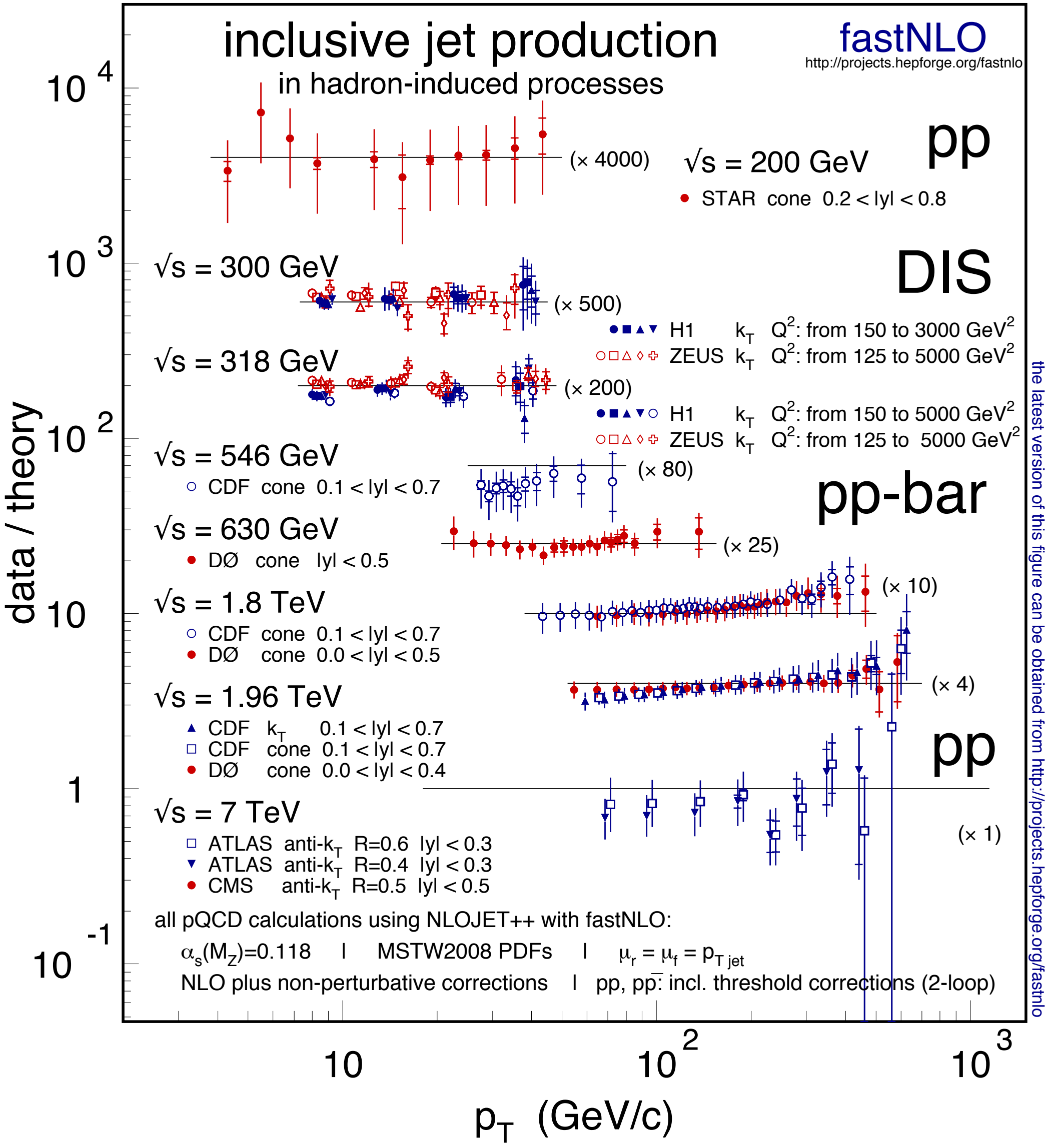
JETS: RESULTS







JETS: WORLD SUMMARY!



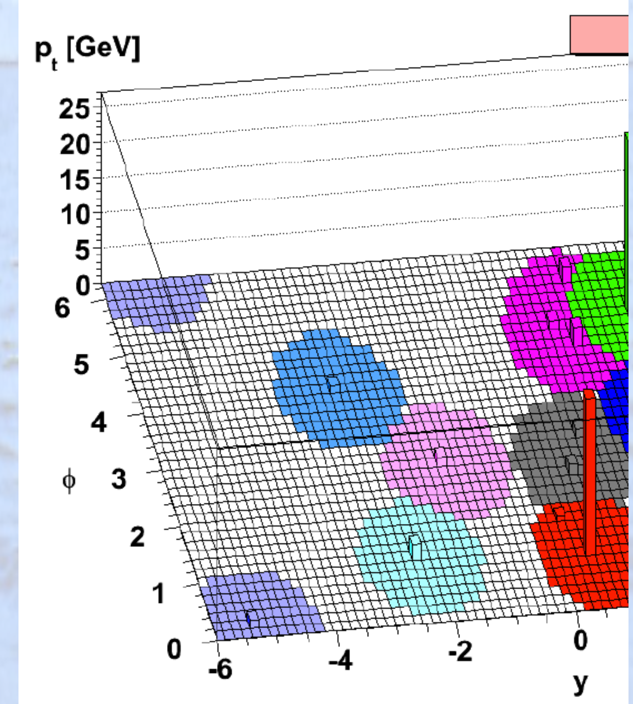
JETS: GENERATIONS OF FINDERS

First generation: simple cone- and clustering-type algos

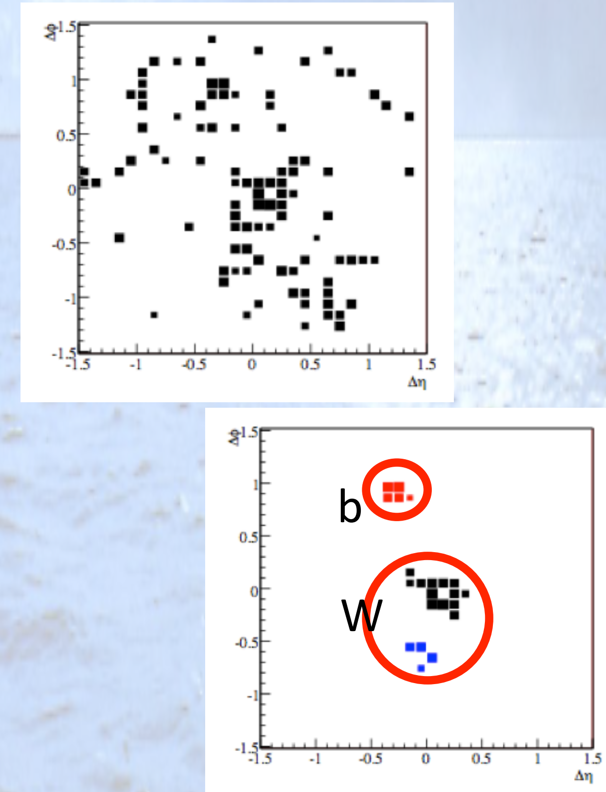
Often not infrared and collinear safe. Nevertheless heavily in use e.g. at Tevatron.

Second generation: infrared and collinear safe algos like k_T and (newer) SISCONE, anti-k_T etc.

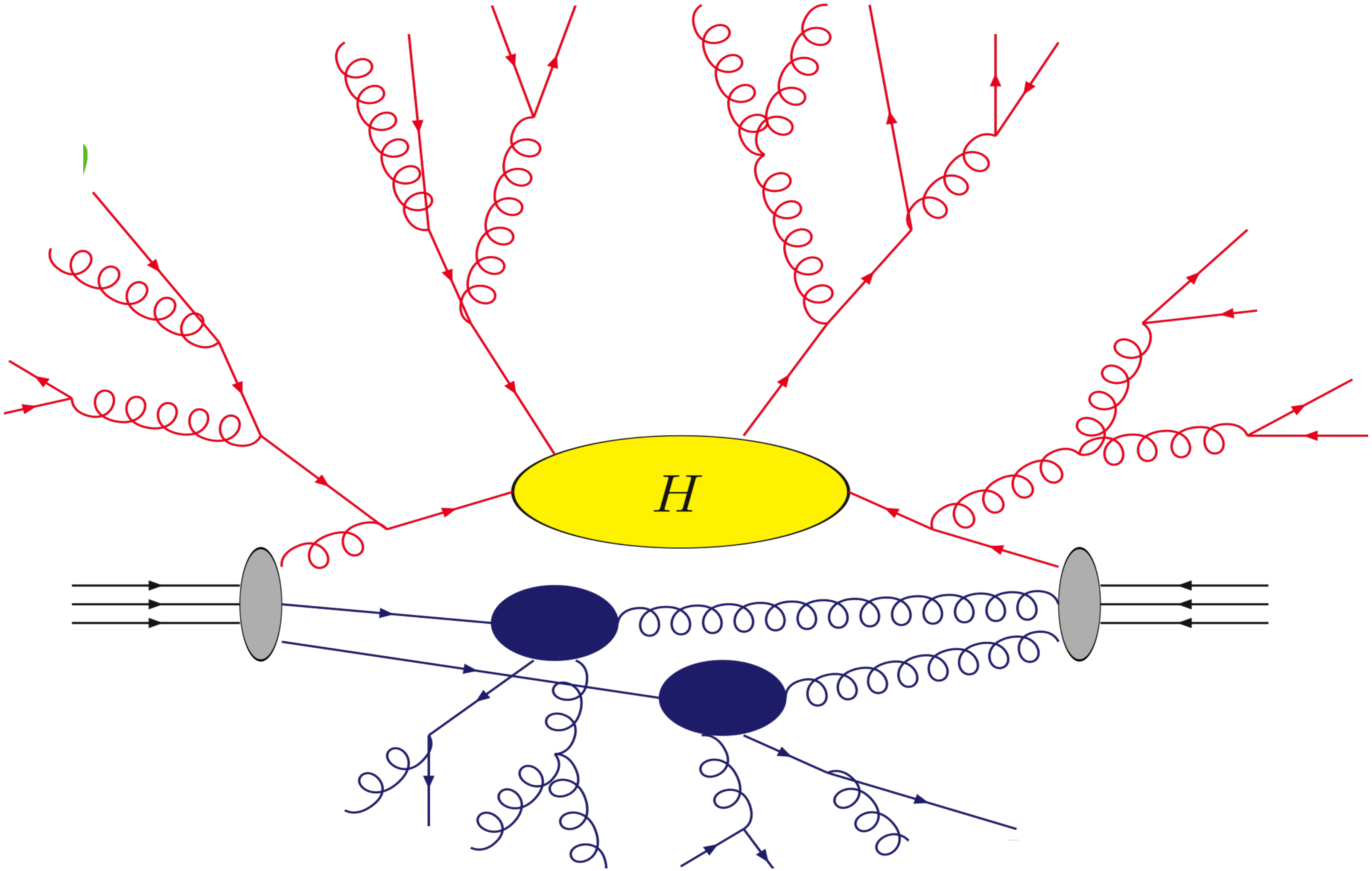
Now default at the LHC.



Third generation: Use jet substructure of more fancy studies: boosted jets, jet substructure, trimming, pruning, etc.

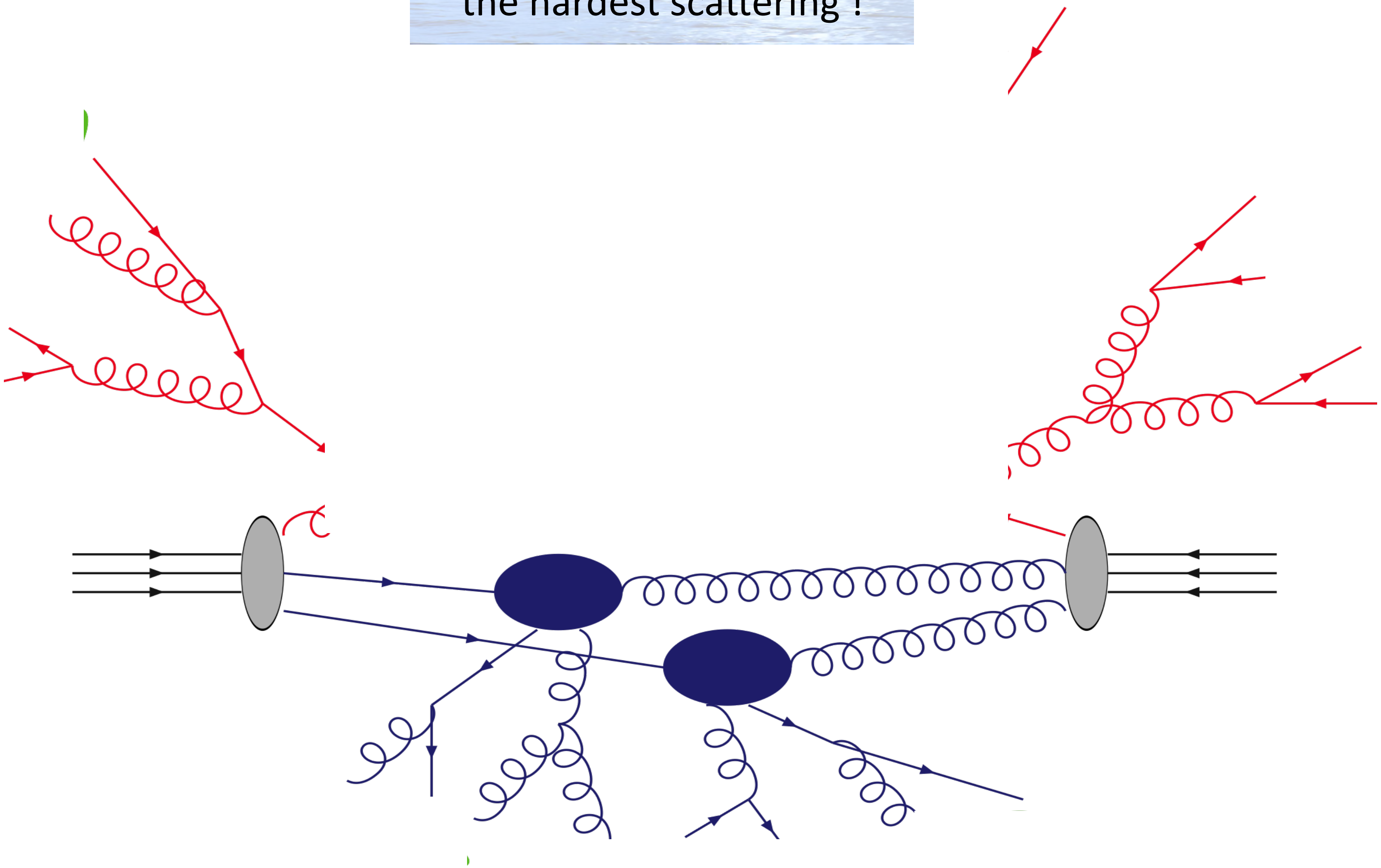


JETS AND THE UNDERLYING EVENT

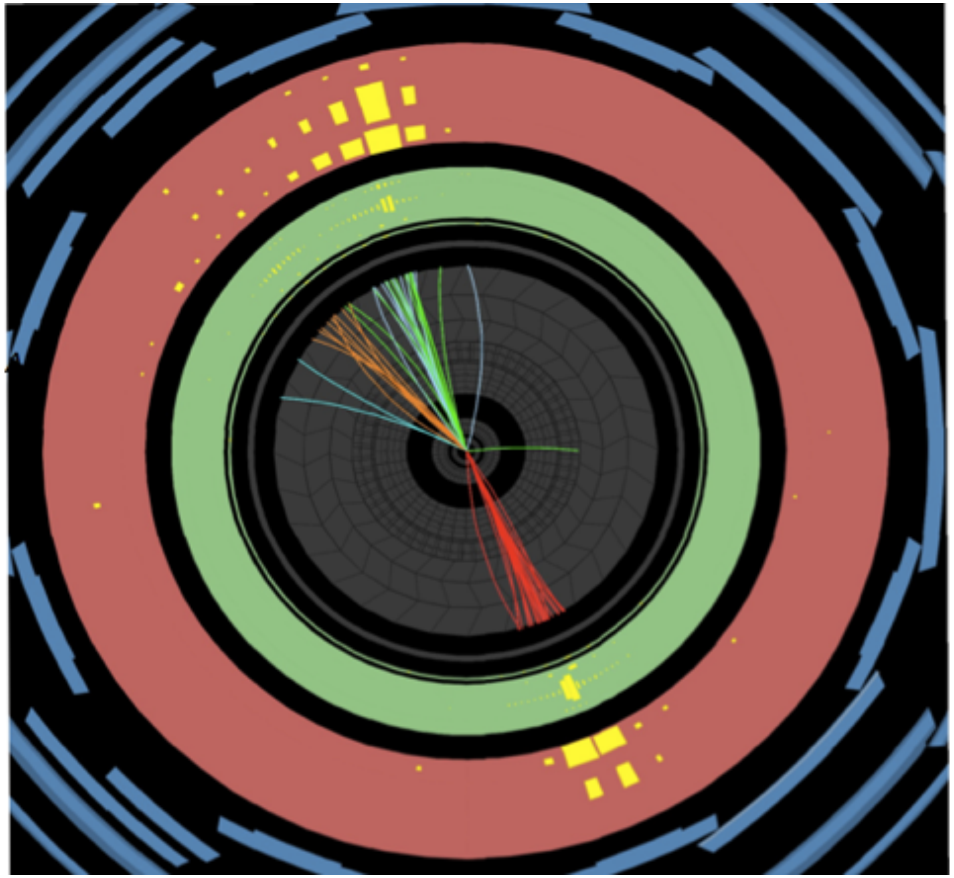


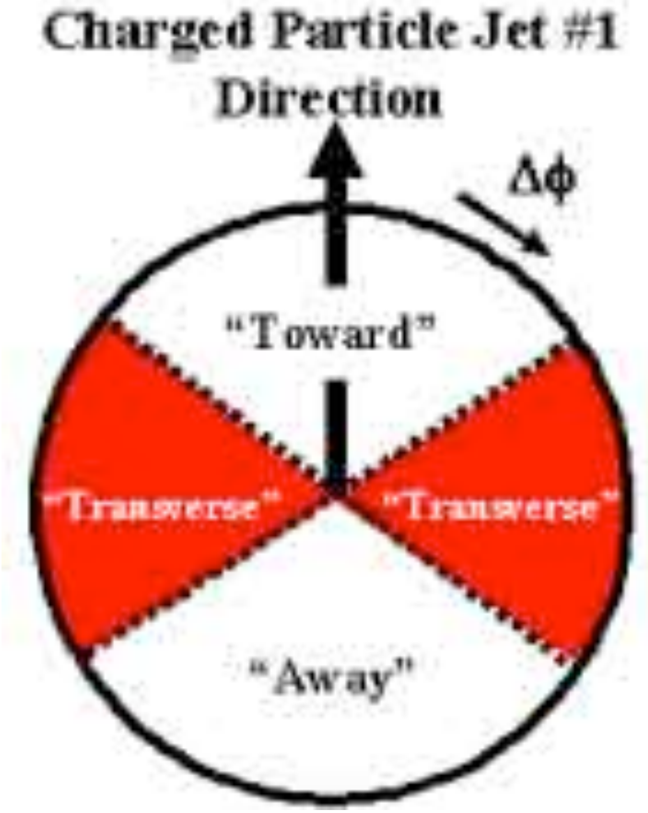
JETS AND THE UNDERLYING EVENT

UE: Everything except for the hardest scattering !

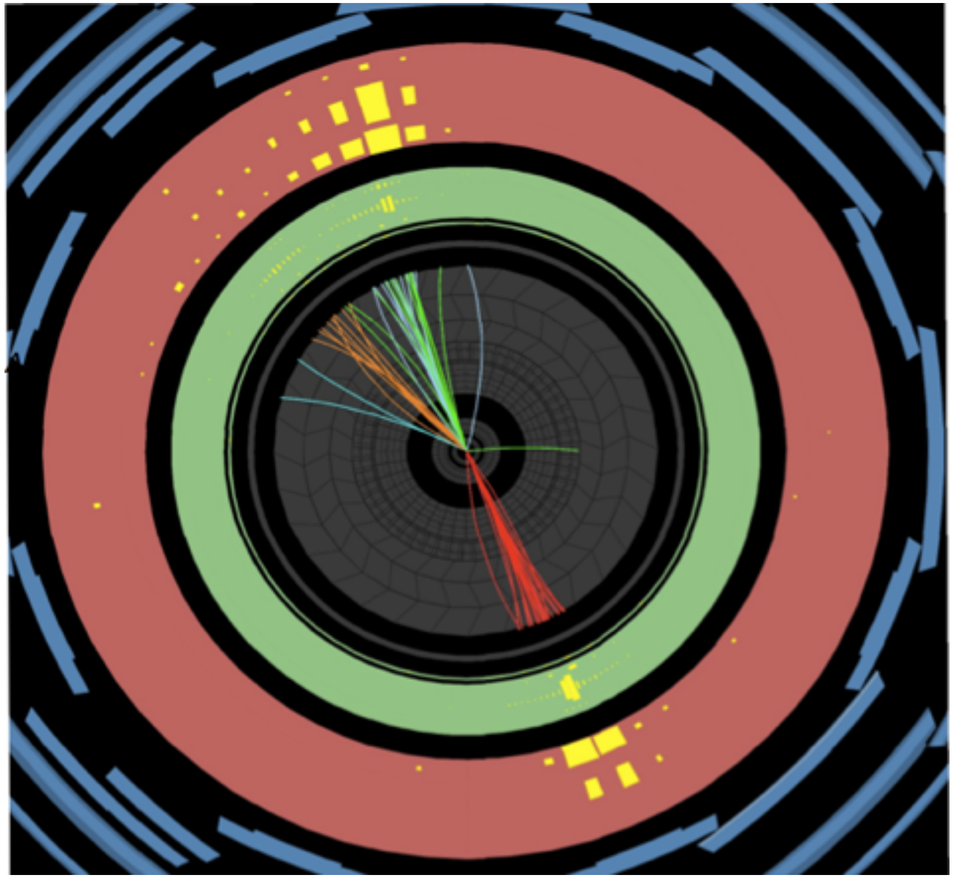


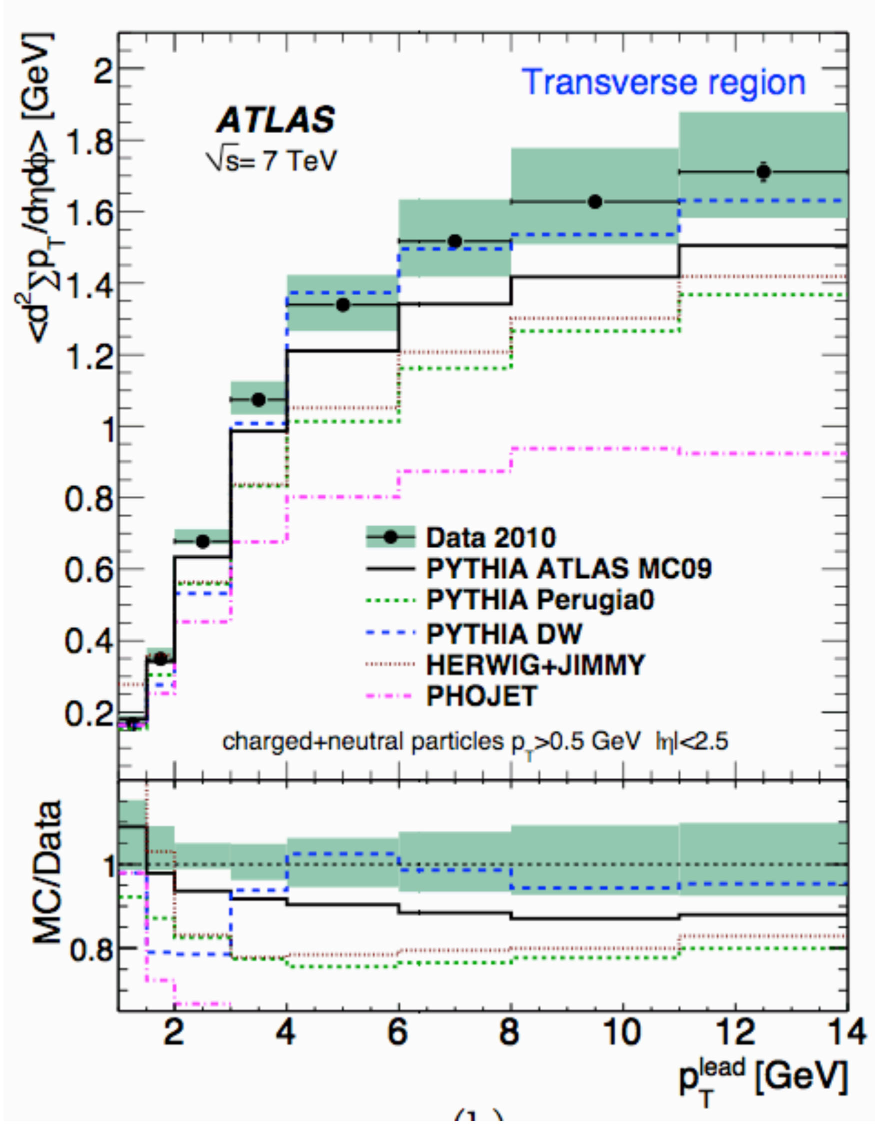
JETS AND THE UNDERLYING EVENT





JETS AND THE UNDERLYING EVENT

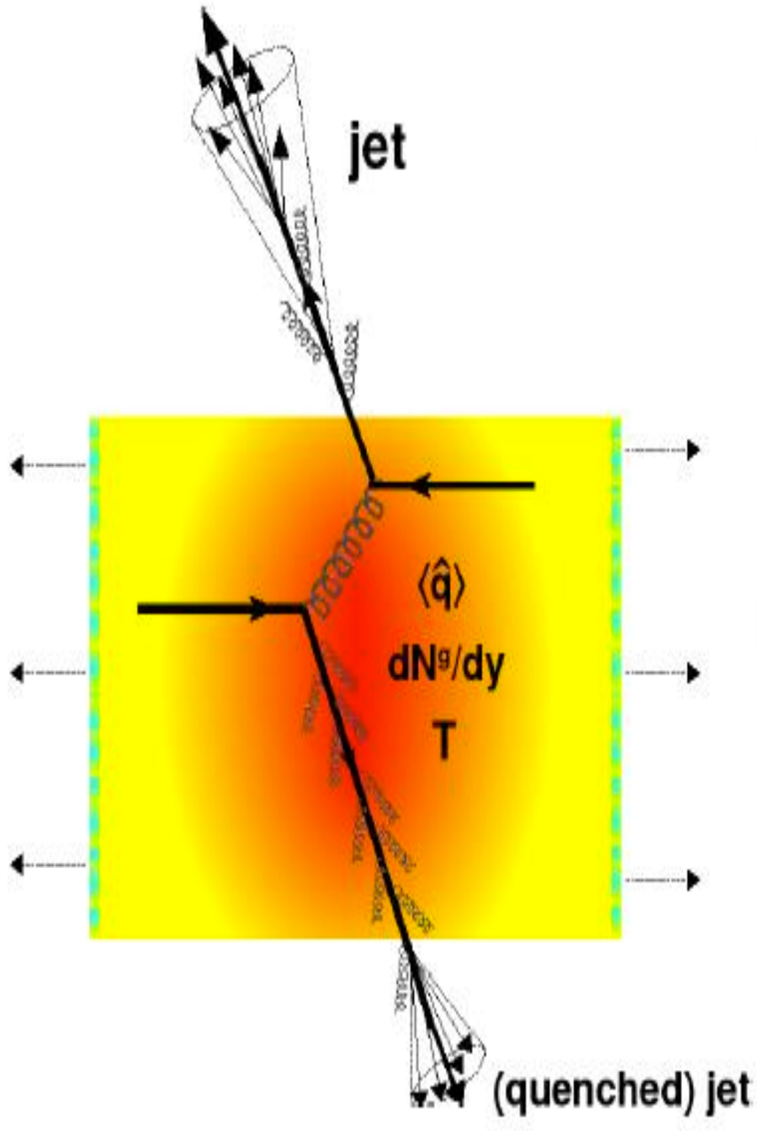




HEAVY IONS: TWO EXAMPLES

Jet quenching: Damping of hadronic energy (jet p_T) by interaction with extend partonic medium ("quark gluon plasma")

→ study properties of plasma
→ understand mechanisms behind plasma
→ fundamental insights into partonic world!



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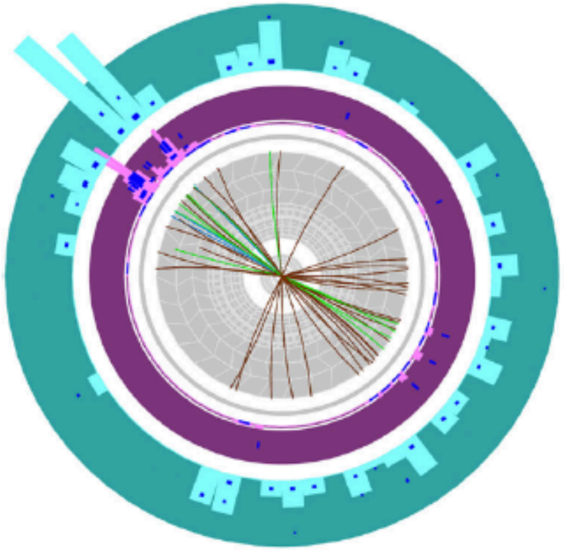
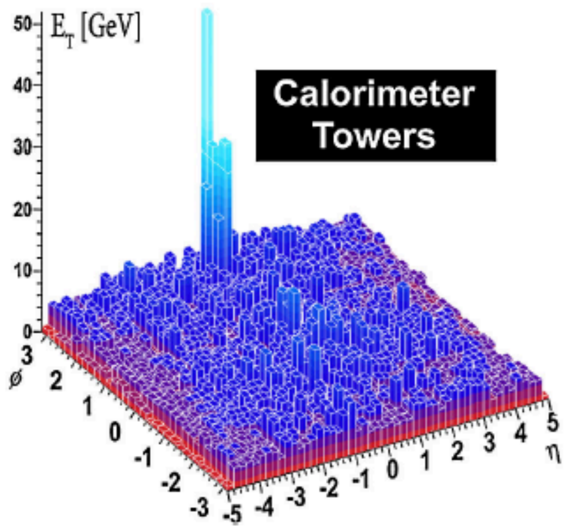
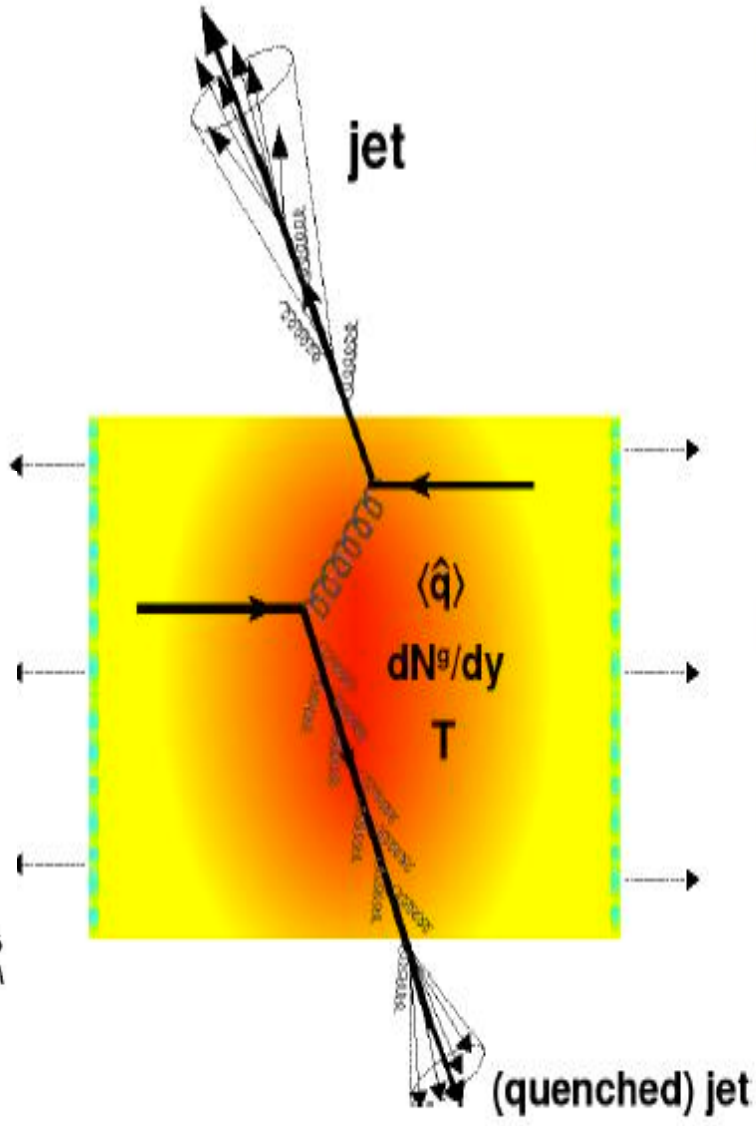


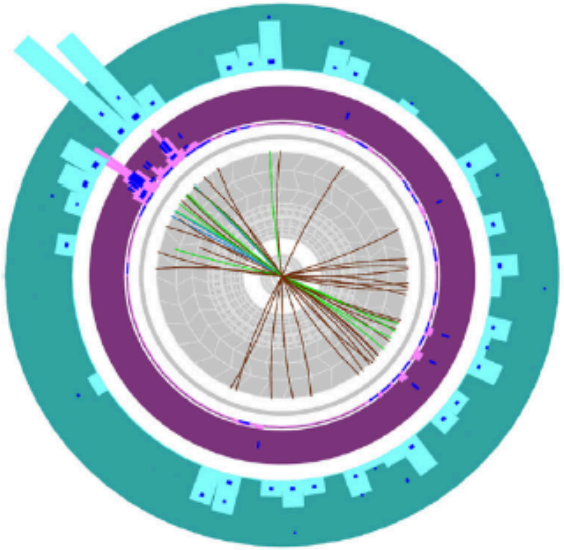


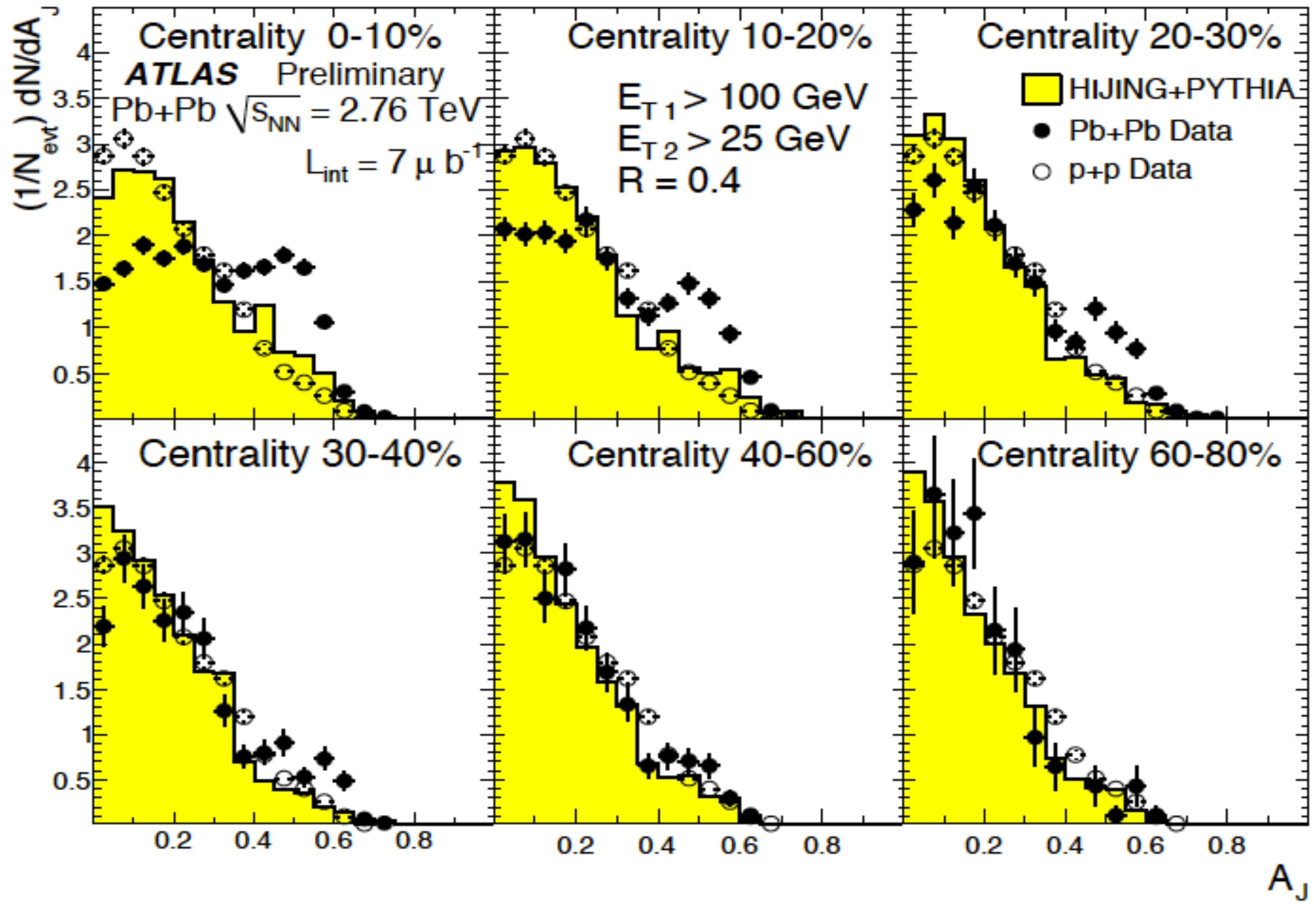


HEAVY IONS: TWO EXAMPLES

Jet quenching: Damping of hadronic energy (jet p_T)!

Asymmetry A: $A = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$

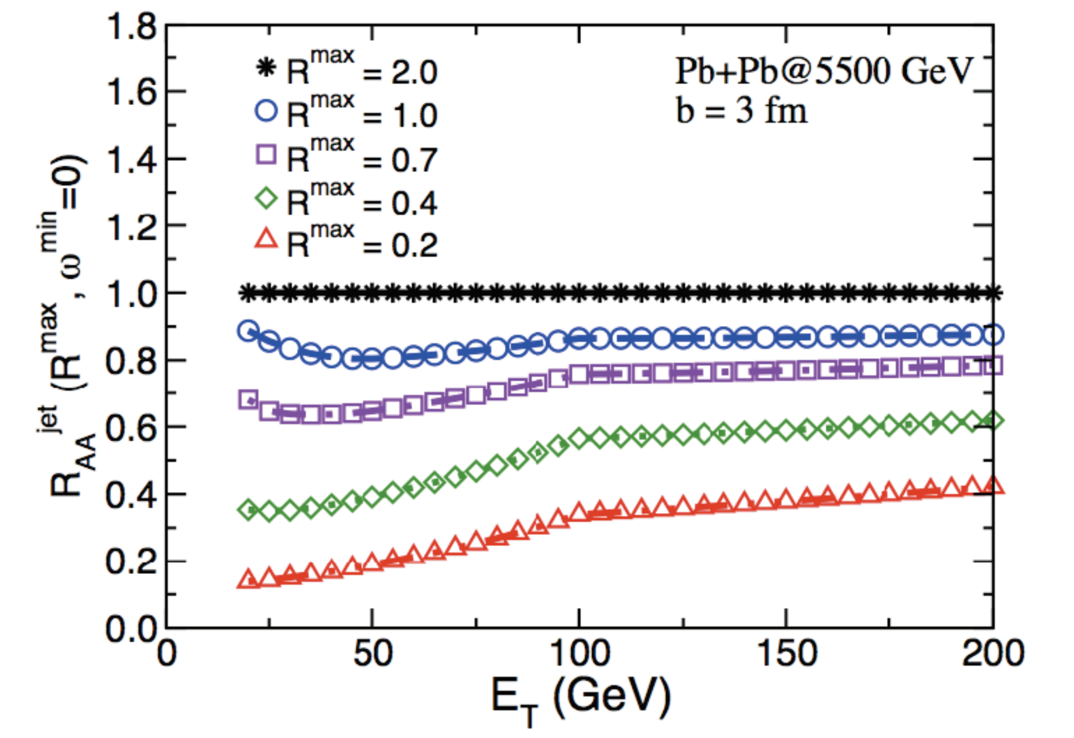




HEAVY IONS: TWO EXAMPLES

Jet quenching: Damping of hadronic energy (jet p_T)
➔ change of jet p_T spectrum at low p_T!

$$R_{AA} = \frac{1}{N_{coll}} \frac{E\frac{d^3N^{A-A}}{dp^3}}{E\frac{d^3N^{p-p}}{dp^3}}$$



But: No heavy-ion data from LHC on R_{AA} available !!!

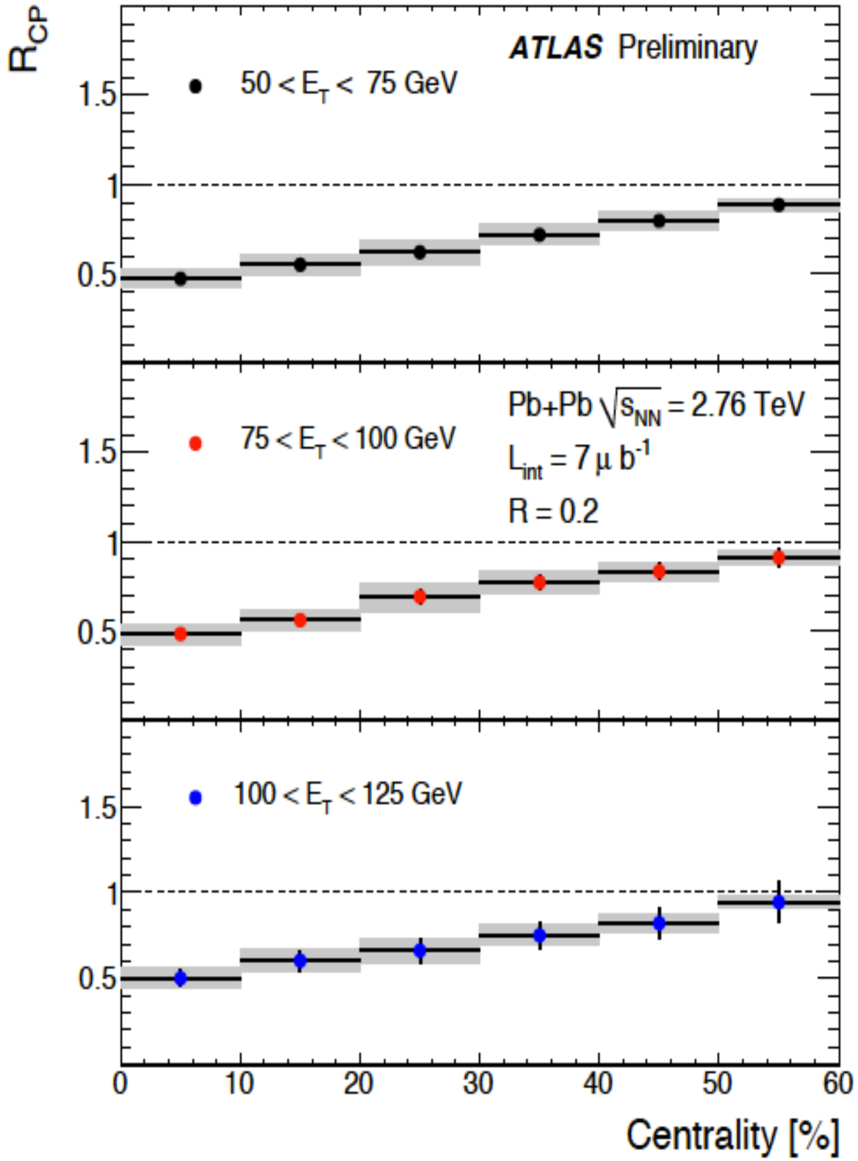
HEAVY IONS: TWO EXAMPLES

Jet quenching: Damping of hadronic energy (jet p_T)!

$$R_{CP} = \frac{\frac{1}{N_{coll}{}^{cent}} E \frac{d^3 N^{cent}}{dp^3}}{\frac{1}{N_{coll}{}^{periph}} E \frac{d^3 N^{periph}}{dp^3}},$$

Strongest effects expected for central collisions (0% centrality) – highest density of particles!

➔ Strong indications for QGP-like effects!



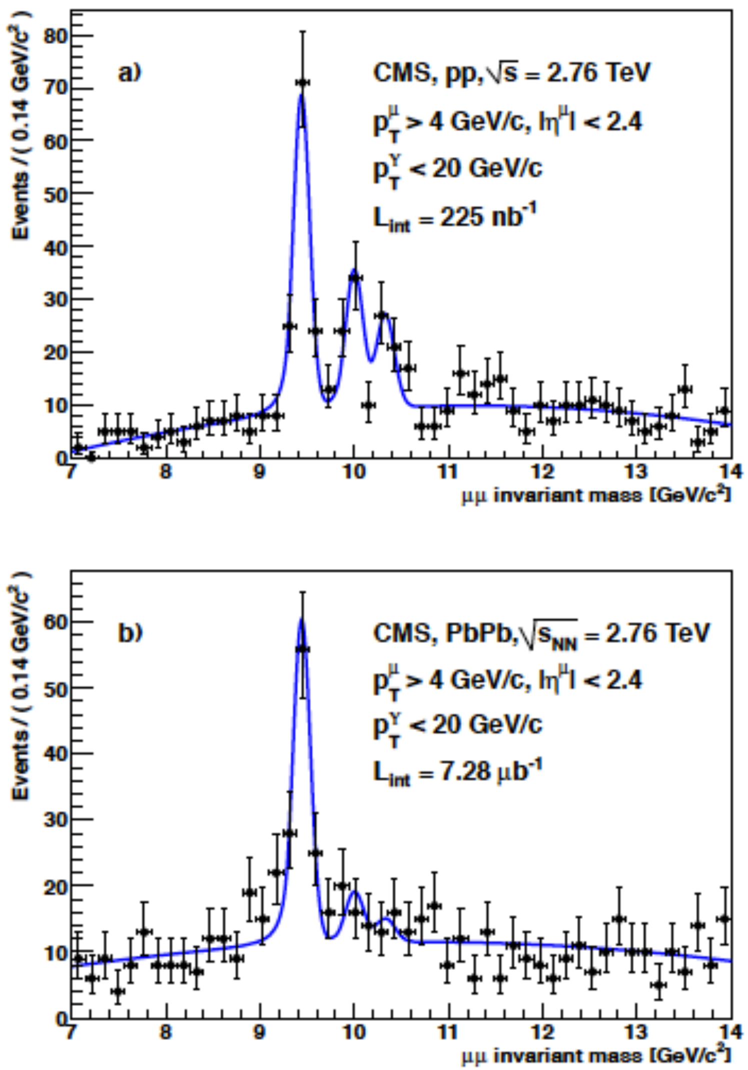
HEAVY IONS: ONE MORE …

Medium versus nuclear effects: suppression of heavy quarkonia

- heavy c and b states are expected to “melt”
- fraction of heavy states (loosely bound) to light states should be sup-pressed in HI reactions!

➔ Examine double ratio

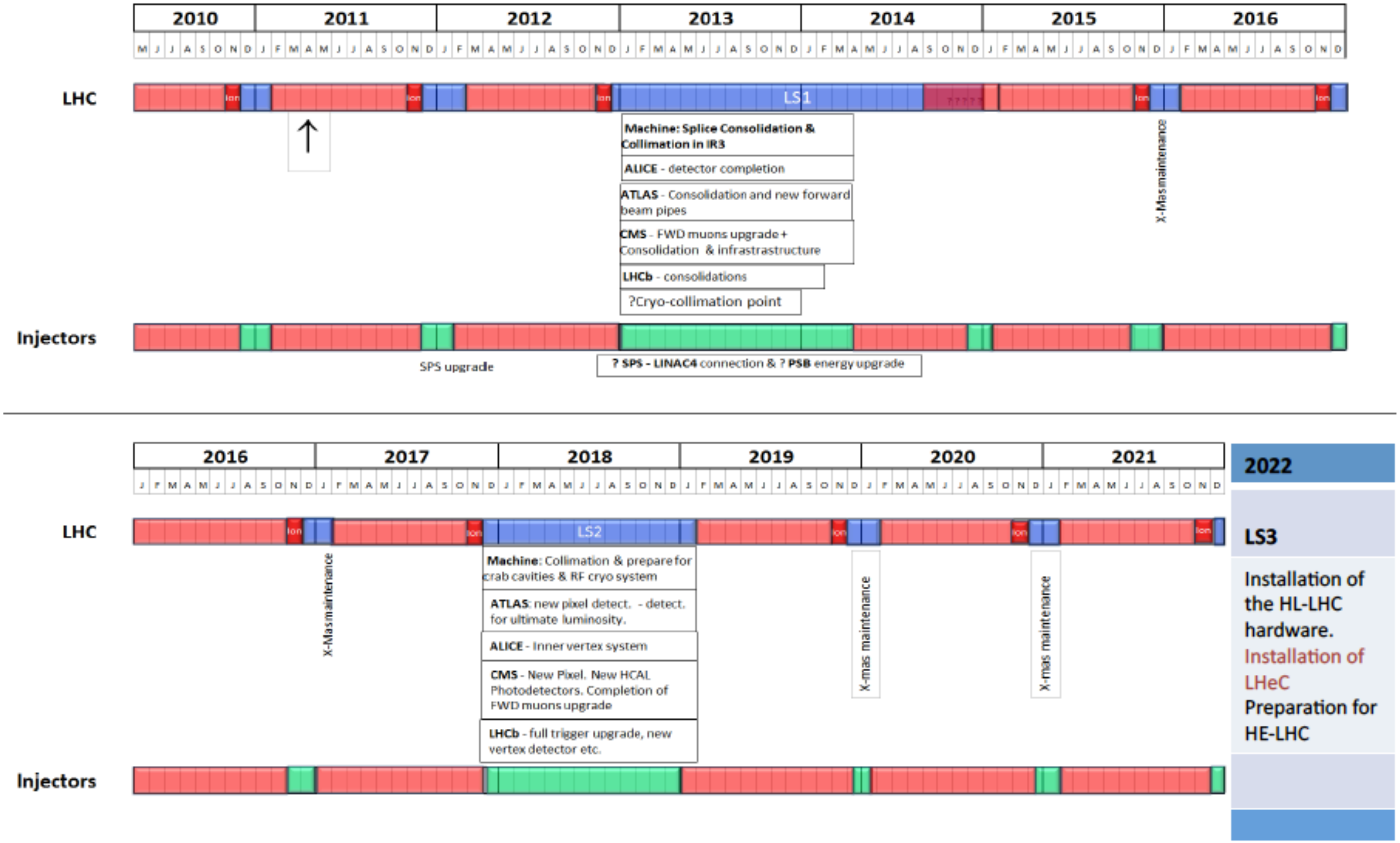
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{PbPb}}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{pp}}}$$



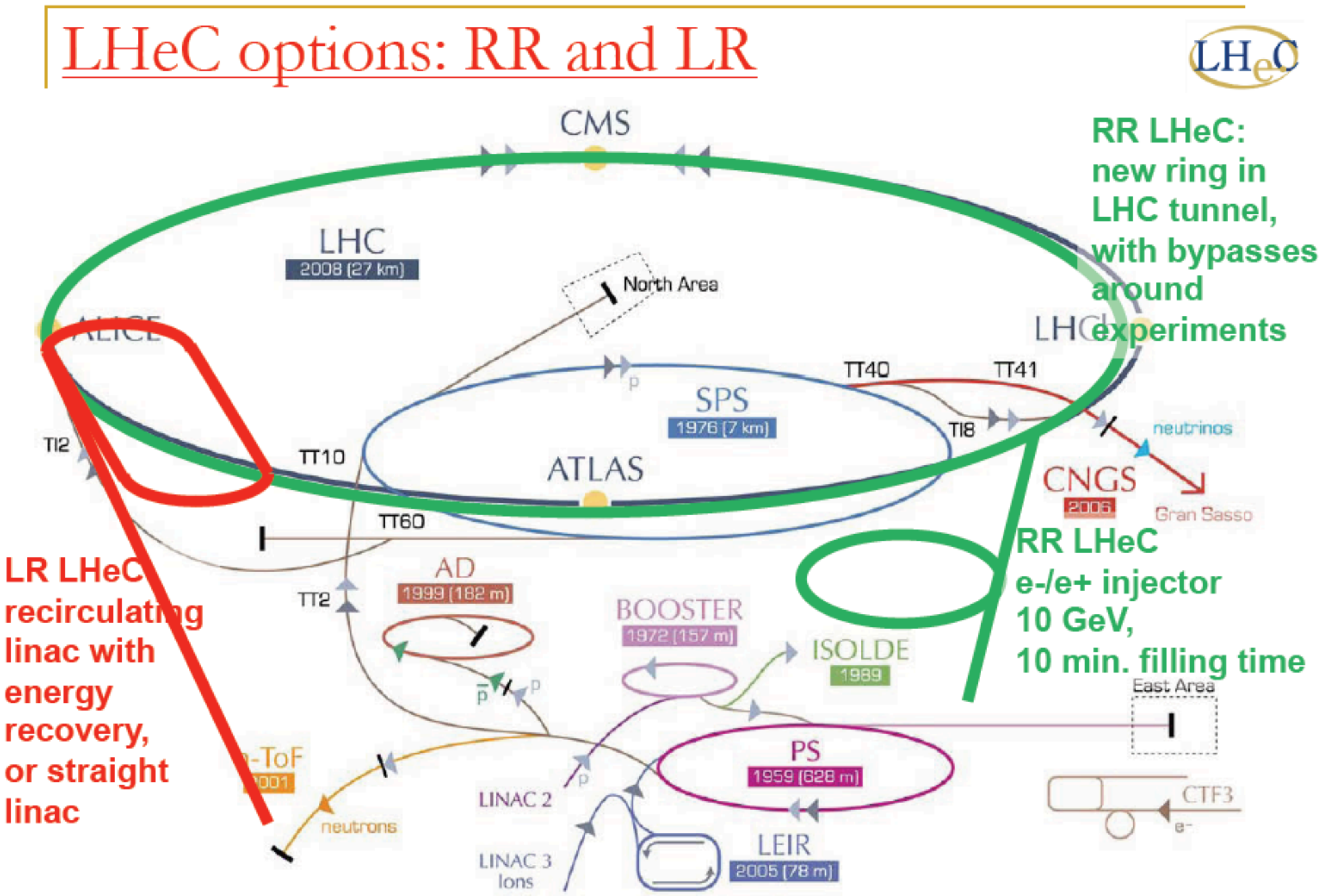
FUTURE OF LHC (S. MYERS, EPS)

New rough draft 10 year plan

Not yet approved!



FUTURE: LHeC?


LHeC options: RR and LR
LHeC
CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
SPS
1976 (7 km)
TT40
TT41
TI8
TI2
TT10
ATLAS
neutrinos
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
PS
1959 (628 m)
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)
CTF3
e-
neutrons
RR LHeC:
new ring in
LHC tunnel,
with bypasses
around
experiments
RR LHeC
e-/e+ injector
10 GeV,
10 min. filling time
LR LHeC
recirculating
linac with
energy
recovery,
or straight
linac

SUMMARY

Motivation for the LHC

Short overview of machine and detector

Basics of pp physics

Lumonisity

Soft QCD

Hard QCD and jets

Heavy-ion collisions