QCD in the 21st century

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Outline

Tentative plan

- Convince you that there are still things worth studying in QCD in 2015
- Convince you that there are new structures of QCD seen today
- [Tell you a bit about an emerging (sub)field of QCD that I personally find interesting]

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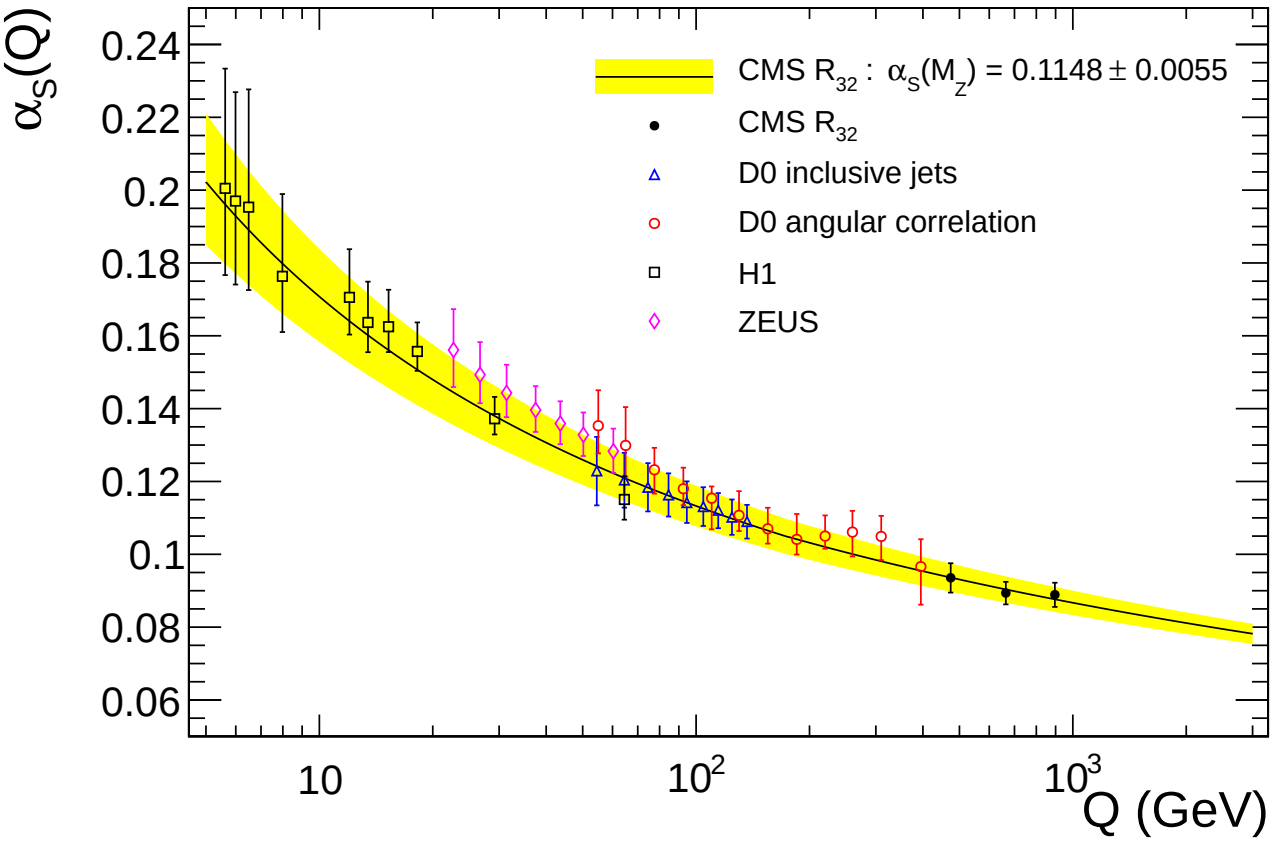
Disclaimer

This is certainly (i) not exhaustive and (ii) biased

STRONG interactions



[CMS, arXiv:1304.7498]

α_s still measured today

Test SM + gain precision

$\alpha_s(M_Z^2) = 0.1185 \pm 0.0006$

QCD means strong interactions

- Non-perturbative at soft scales
- Often slow convergence when perturb

Non-perturbative QCD

Quarks & gluons v. hadrons

We do not see quarks and gluons directly

How quarks and gluons bound into colourless objects still not understood

Importance of non-perturbative QCD

Approaches

- Lattice QCD (examples below)
- Effective field theories (*e.g.* HQET, χPT)

Applications today

- mesons/hadrons spectrum
- QCD phase diagram and QGP eq. of state
- Flavour physics (particles decay)
- neutron stars
- Related to many experiments: LHCb, BessIII, Belle2, NA62,...

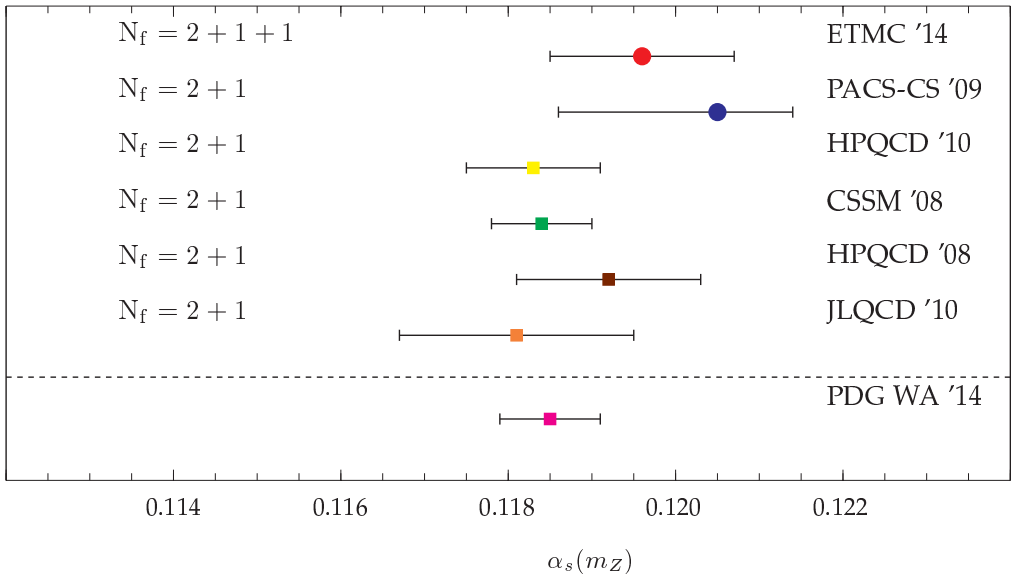
Challenges

- Work with realistic quarks
- Work with small lattice spacing, large lattivce volume

A few highlights

Examples

- $N_f = 2 + 1 + 1$ dynamical quarks
- Simulations with real pion mass
- precise $K/D/B$ decay
- Isospin & elm effects in $m_n - m_p$
- Improving extraction of α_s
- GENCI: large computing resources (2007)



If you want more

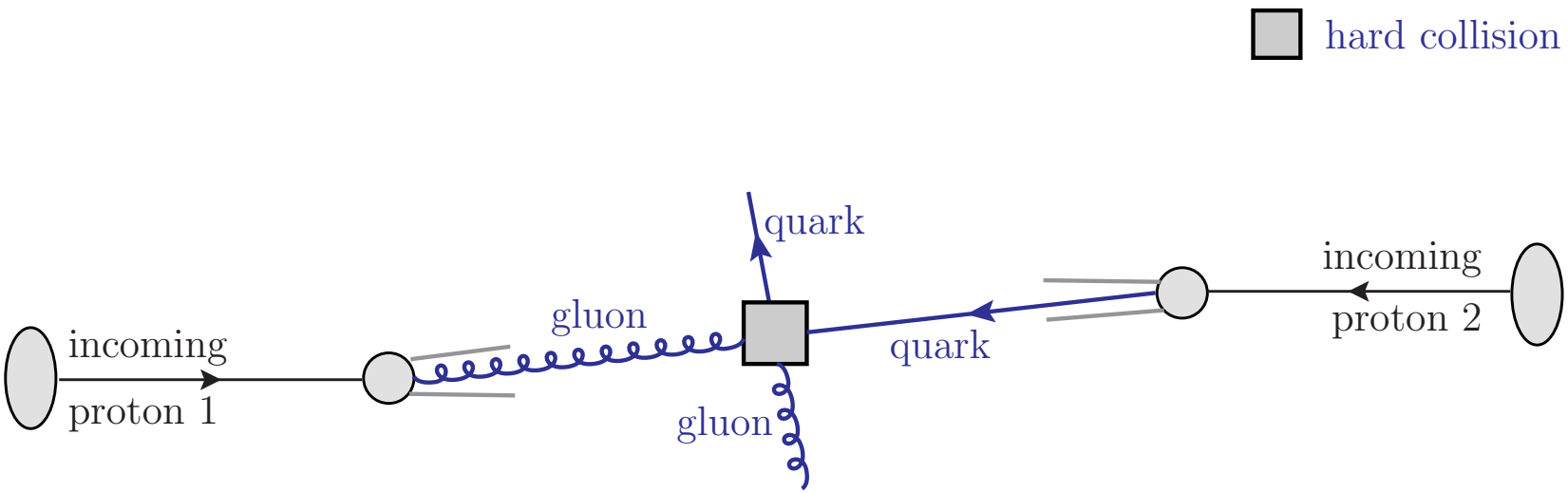
See also talks by:

- Cédric Mezrag
- Xiu-Lei Ren
- Laurent Lellouch
- Antoine Gérardin
- Savvas Zafeiropoulos
- Jean-Loic Kneur

[B.Blossier,1405.0005]

Perturbative QCD
[QCD at colliders]

Overview of a collisions (here LHC)



Needed

- PDFs
- Matrix elements

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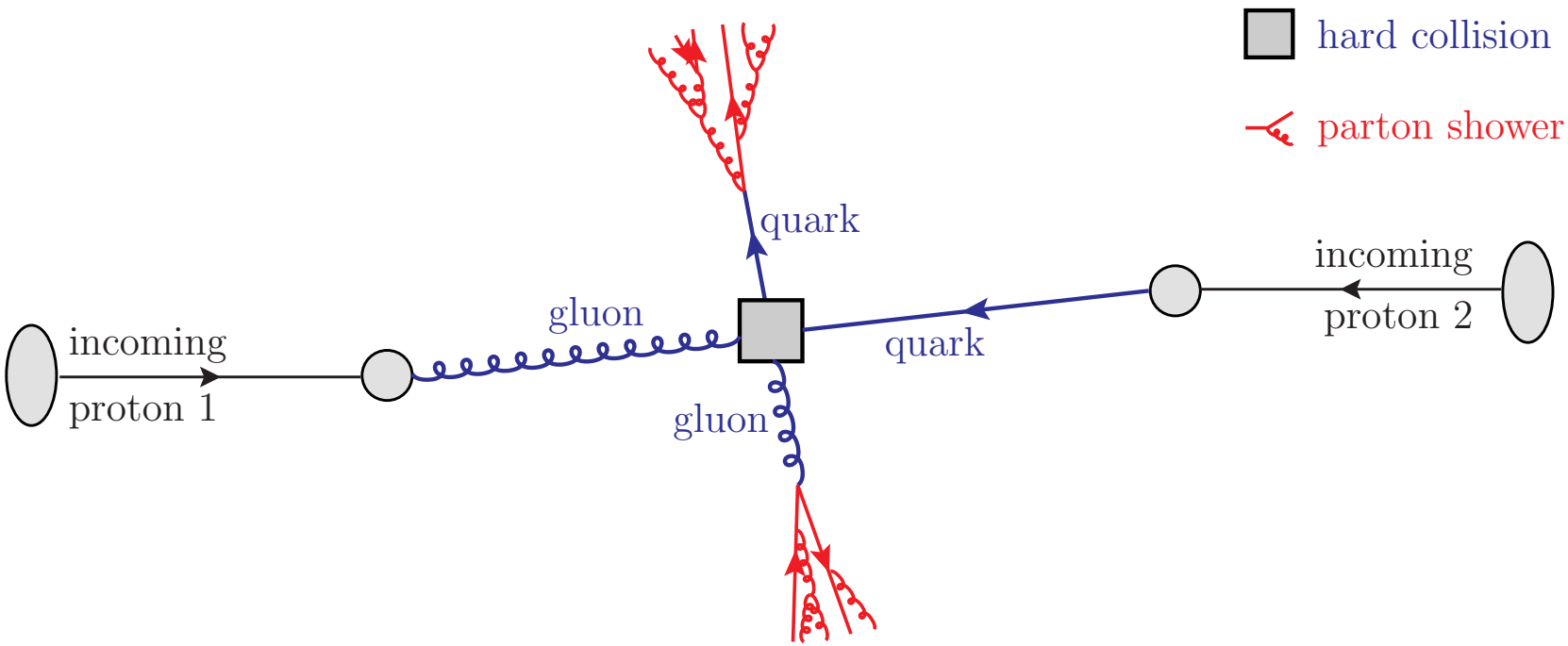

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- Parton shower
- Matching matrix-element/parton shower

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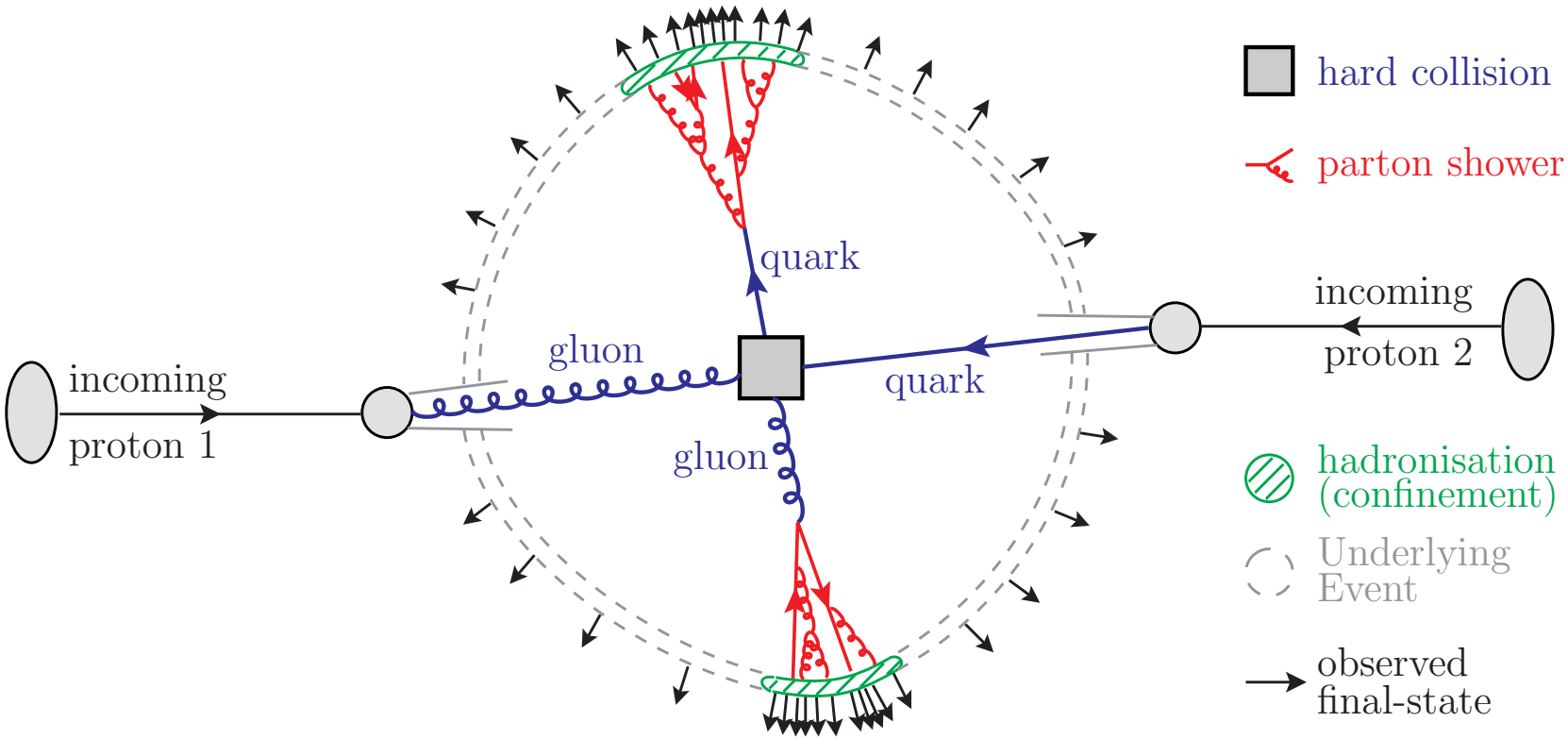

Needed

- PDFs
- Matrix elements
- Modelisation of non-perturbative effects
- Parton shower
- Matching matrix-element/parton shower

Recent progress 1: PDFs

Need for precise determination of the PDFs

- Precision at the LHC often limited by uncertainty on PDFs
- Many groups: MSTW, CT(EQ), NNPDF are probably the main ones
- Now up to NNLO, including more and more effects/observables
- PDF4LHC "working group"

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Beyond PDFs

- GPDs, TMDs
- include extra degrees of freedom
- apply to more exclusive (semi-inclusive) processes

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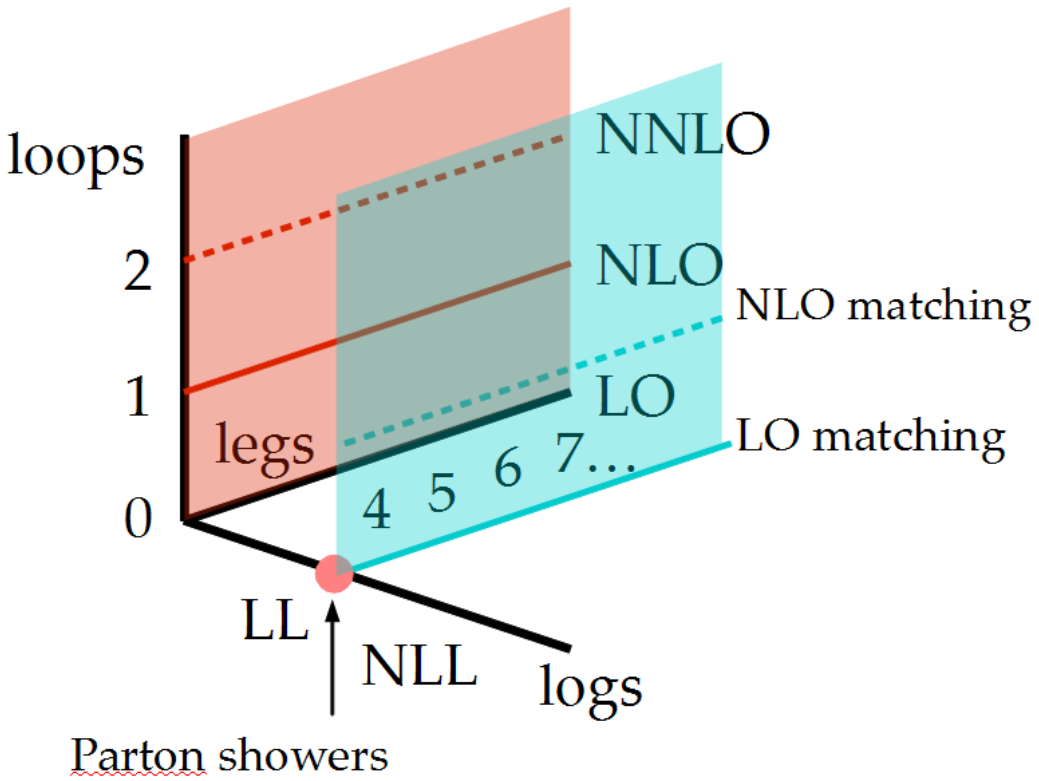
Beyond PDFs

- GPDs, TMDs
- include extra degrees of freedom
- apply to more exclusive (semi-inclusive) processes
- polarised distributions: learn about the proton spin
- nuclear PDFs: learn about cold nuclear effects

Recent progress 2: Matrix element calculations

"Amplitudes" is a huge field of research in QCD



Motivation

need for precision calculations
e.g. at the LHC
(pre-requisite to everything)

from D.Kosower

Recent progress 2: Matrix element calculations

Today's "phenomenological" status

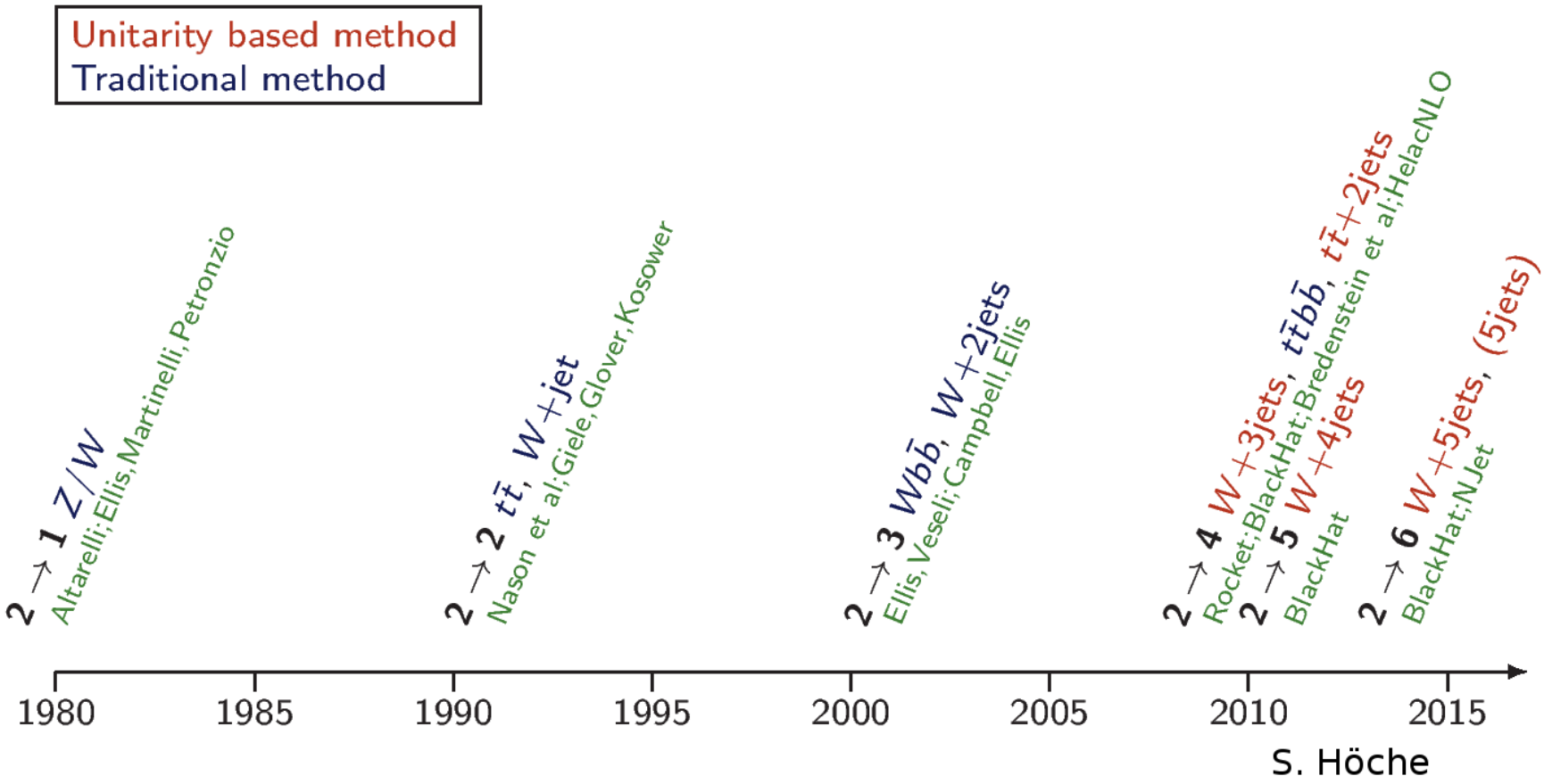
- NLO calculations automated, NNLO & NLO-EW in progress
- numerically available (MCFM, aMC@NLO, BlackHat, Golem, ...)
- matching LO+LL and NLO+LL

Large effort to develop new techniques

- formal aspects about the structure of amplitudes (*e.g.* $\mathcal{N} = 4$ SUSY)
- what ultimately made NLO/NNLO calculations doable "quickly"
- deep connections in mathematical physics (structure of gauge theories)

Recent progress 2: Matrix element calculations

The NLO revolution



from D.Kosower

Recent progress 3: when fixed-order is not enough (1/2)

QCD has two divergences

- collinear: parton branching at small angle ($\theta \to 0$)
- soft: emission of soft gluons ($E \to 0$ or $z \to 0$)

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We need final results!

- In the initial state, divergence absorbed in the PDFs.
- In the final state, real-virtual cancellation
  only infrared-and-collinear-safe observables computable perturbatively

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Two main players (fields *per se*, with fundamental progress too)

- Jets: take the whole partonic collinear offspring
  See talk by Frederic Dreyer and later here
- Heavy quark(onia): the heavy mass acts as a cutoff
  See talks by Roland Katz and Hua-Sheng Shao

Recent progress 3: when fixed-order is not enough (2/2)

Consequence and resummation

- Everytime we have two scales, expect logs between the two scales
- Often $\alpha_s \log(Q^2/\mu^2) \sim 1 \Rightarrow$ resum to all orders in α_s
- Can be seen as a reorganisation of the perturbative series

$$\underbrace{f_0(\alpha_s L)}_{LL} + \underbrace{\alpha_s f_1(\alpha_s L)}_{NLL} + \dots$$

where f_i contains terms at all orders $\alpha_s^n L^n$

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Examples

- PDFs
- jet shapes
- jet vetoes (for Higgs!)

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Recent progress

- Generic method for NNLL resummation A.Banfi, H.McAslan, P.Monni, G.Zanderighi, 1412.2126
- Effective theory SCET
  Review: T.Becher,A.Broggio,A.Ferroglia, 1410.1892
- Boosted jet observables

Recent development 3: QCD showers & NP effects

Monte-Carlo event generators

Include a bunch of effects

- collinear showering off the matrix element (at LL) [from QCD]
- hadronisation [modelled]
- multiple-parton interactions/soft interactions with the beam remnants (*aka* UE) [modelled]

Recent progress

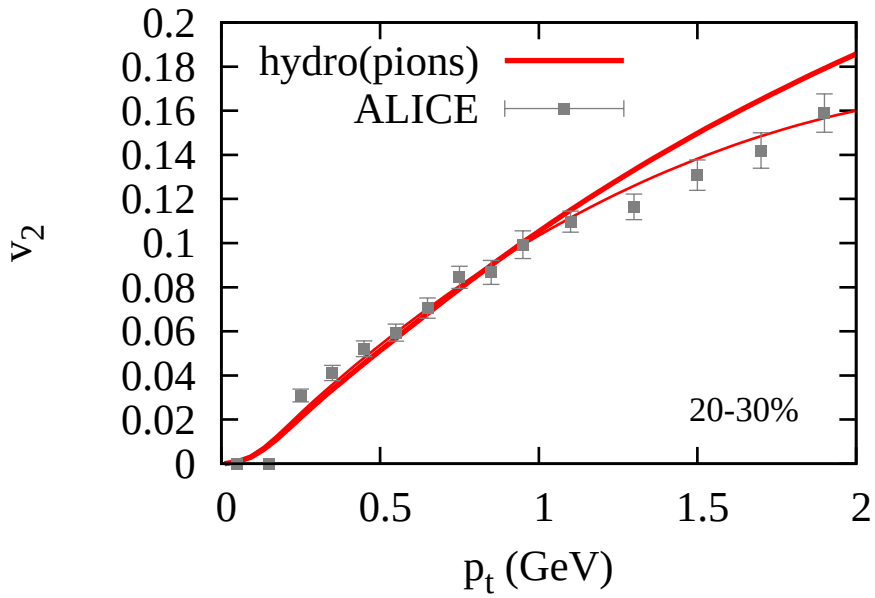
- 3 commonly used generators: Pythia (v8), Herwig(++), SHERPA
- matching LO and NLO matrix elements with parton shower

Recent development 4: Heavy-ions, high energy/density

Also a large community in France with many recent contributions

- The QGP behaves like an (almost) perfect liquid

  plot from M.Luzum



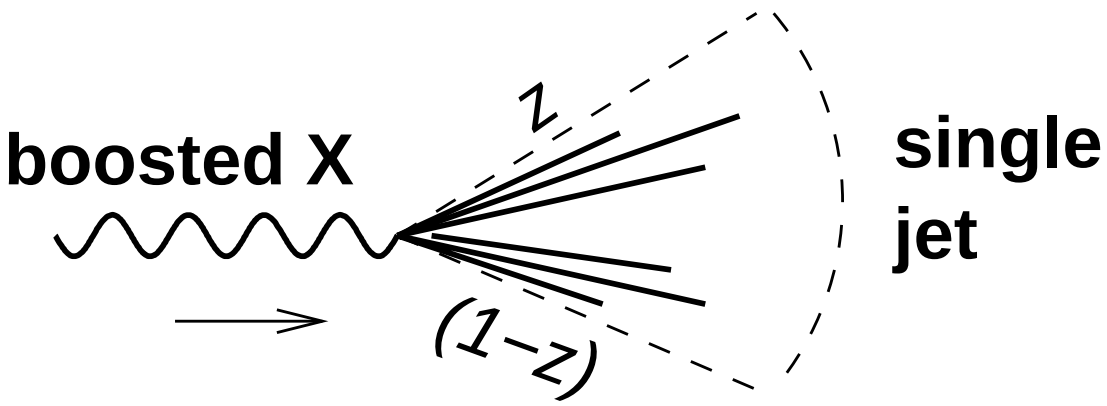
- Better understanding of the proparation through the QGP (medium energy loss)
- Towards a first-principle QCD proof of fast thermalisation
- Many probes of high multiplicity effects in forward physics

see also talks by Elena Petreska and Renaud Boussarie

An emerging field: boosted jets

Boosted jets

Object X decaying to hadrons



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Boosted jets

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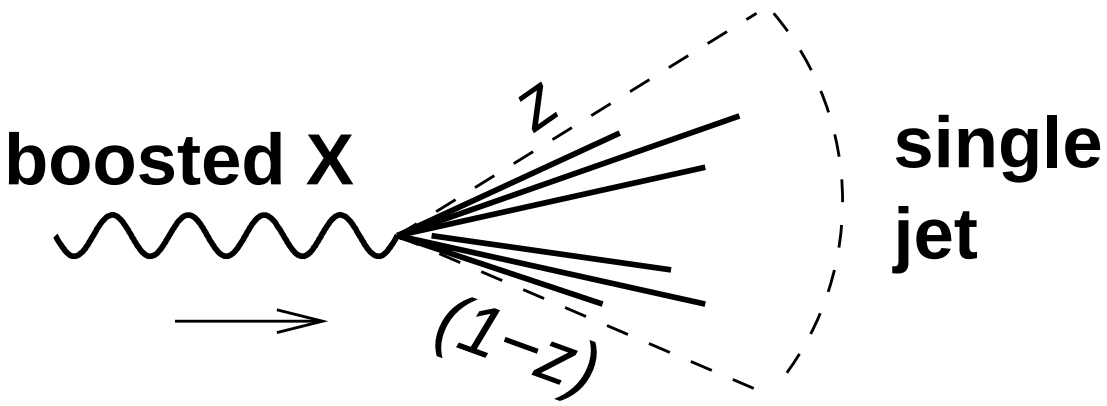

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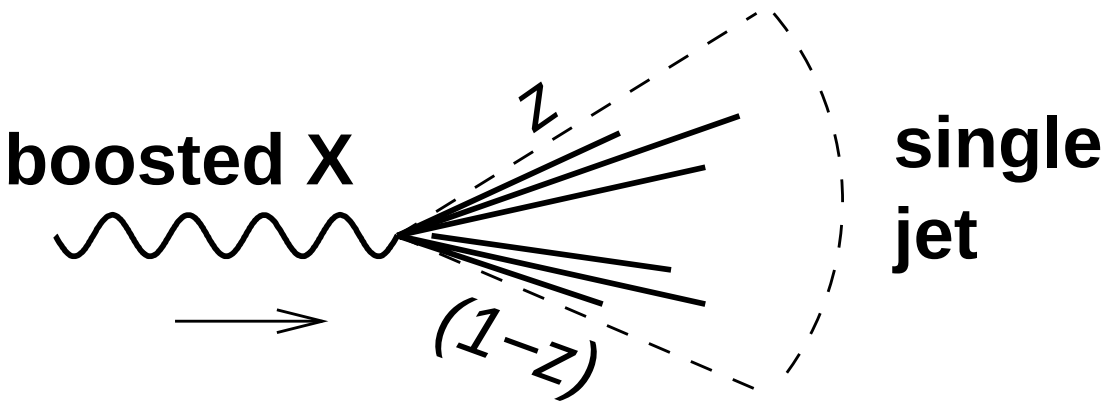

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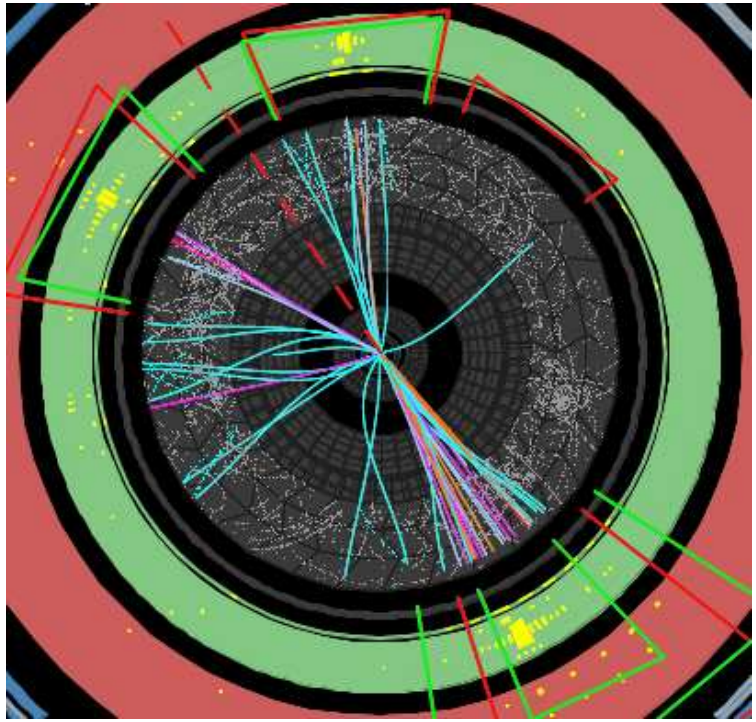
Many applications:
Higgs, top, W/Z, ttH,...

Higher $\sqrt{s}$, higher scales/bounds
$\Rightarrow$ increasingly important

Boosted jets: What?

What jet do we have here?



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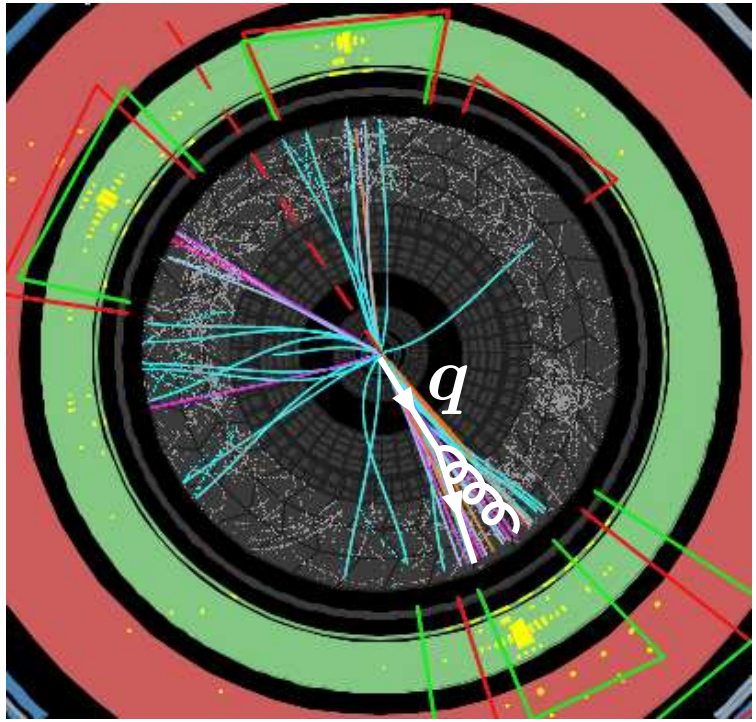

Boosted jets: What?

What jet do we have here?

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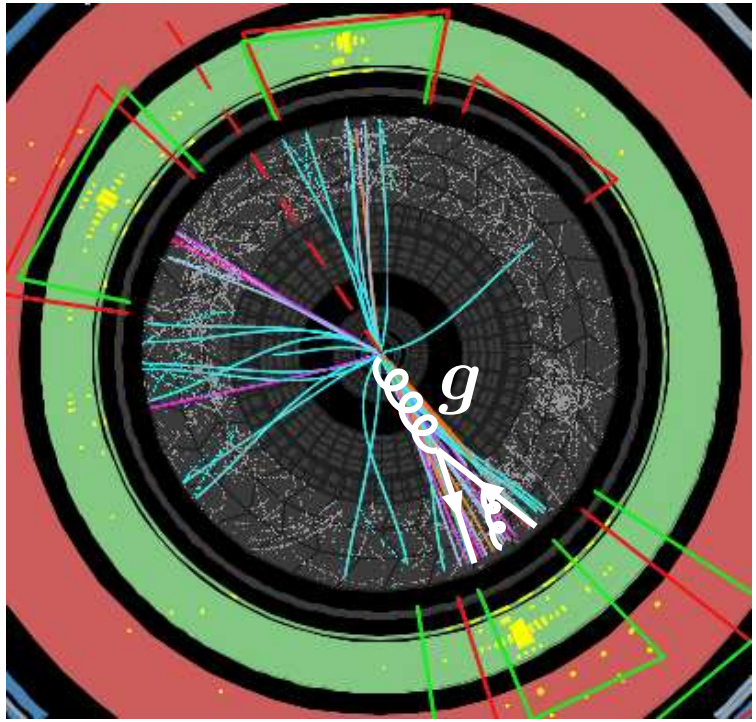
- a gluon?



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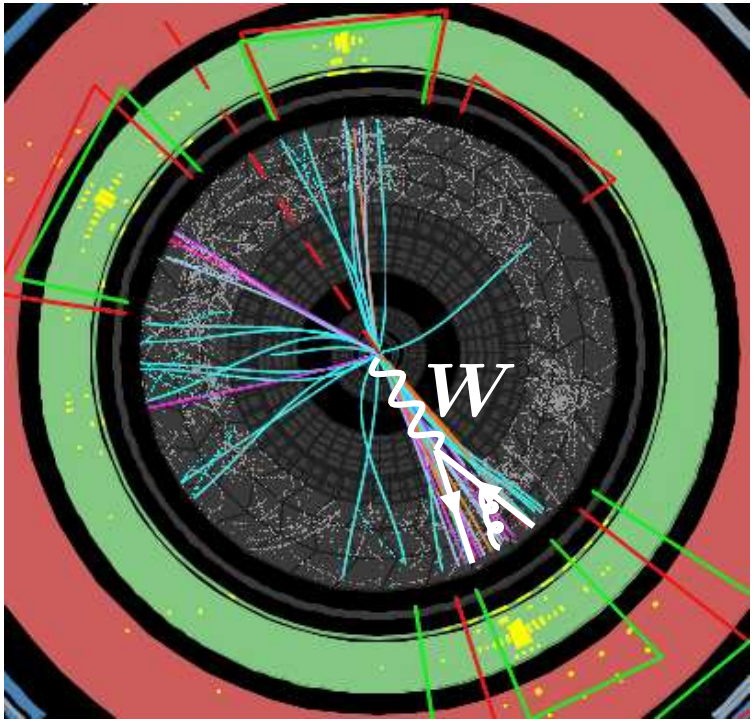

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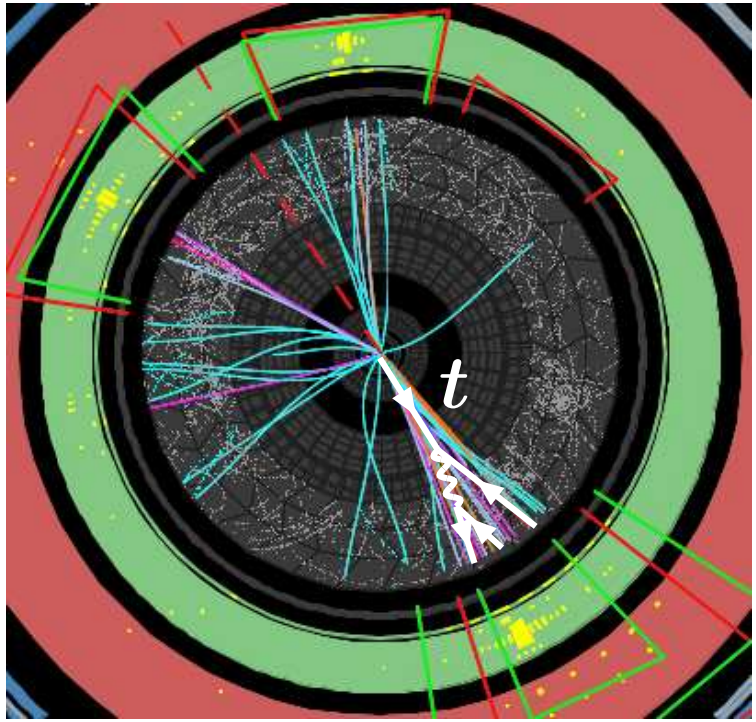

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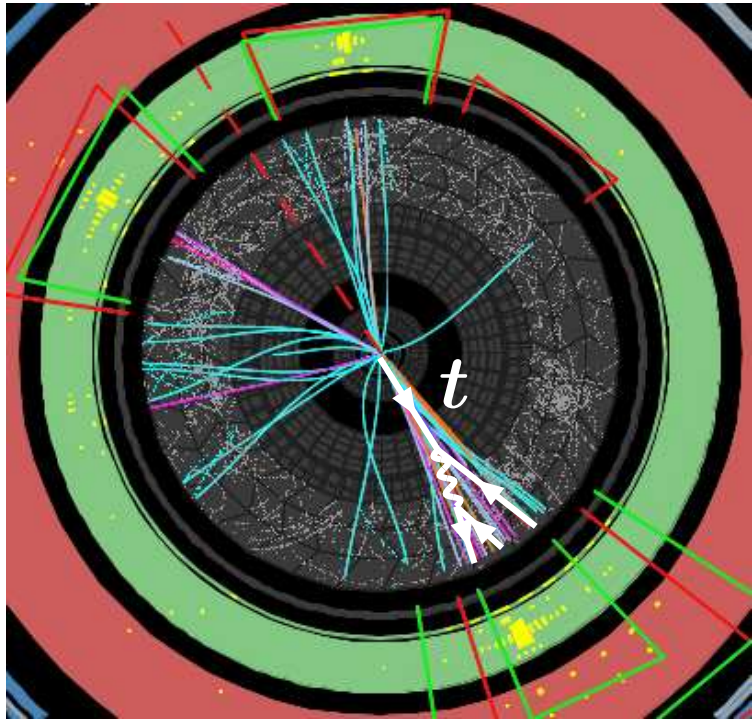

Source: ATLAS boosted top candidate

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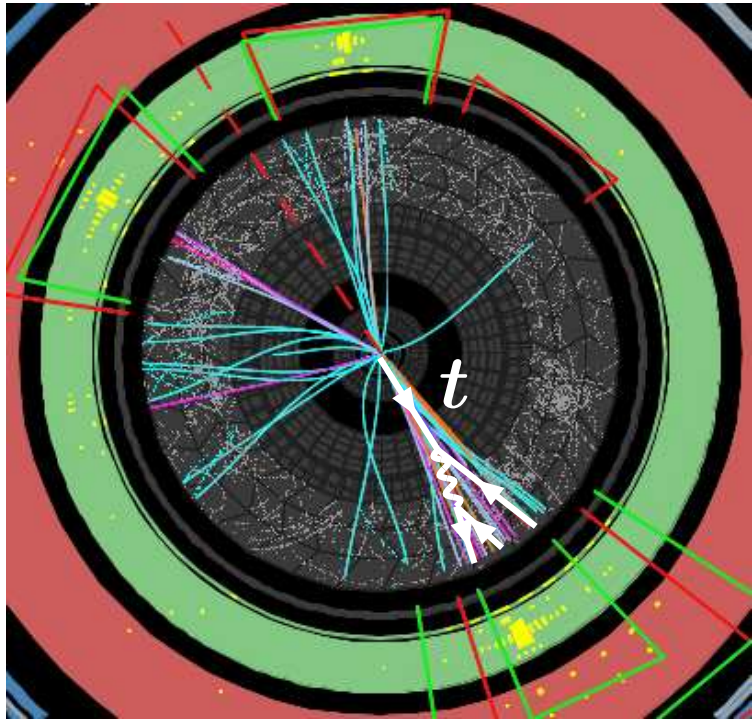

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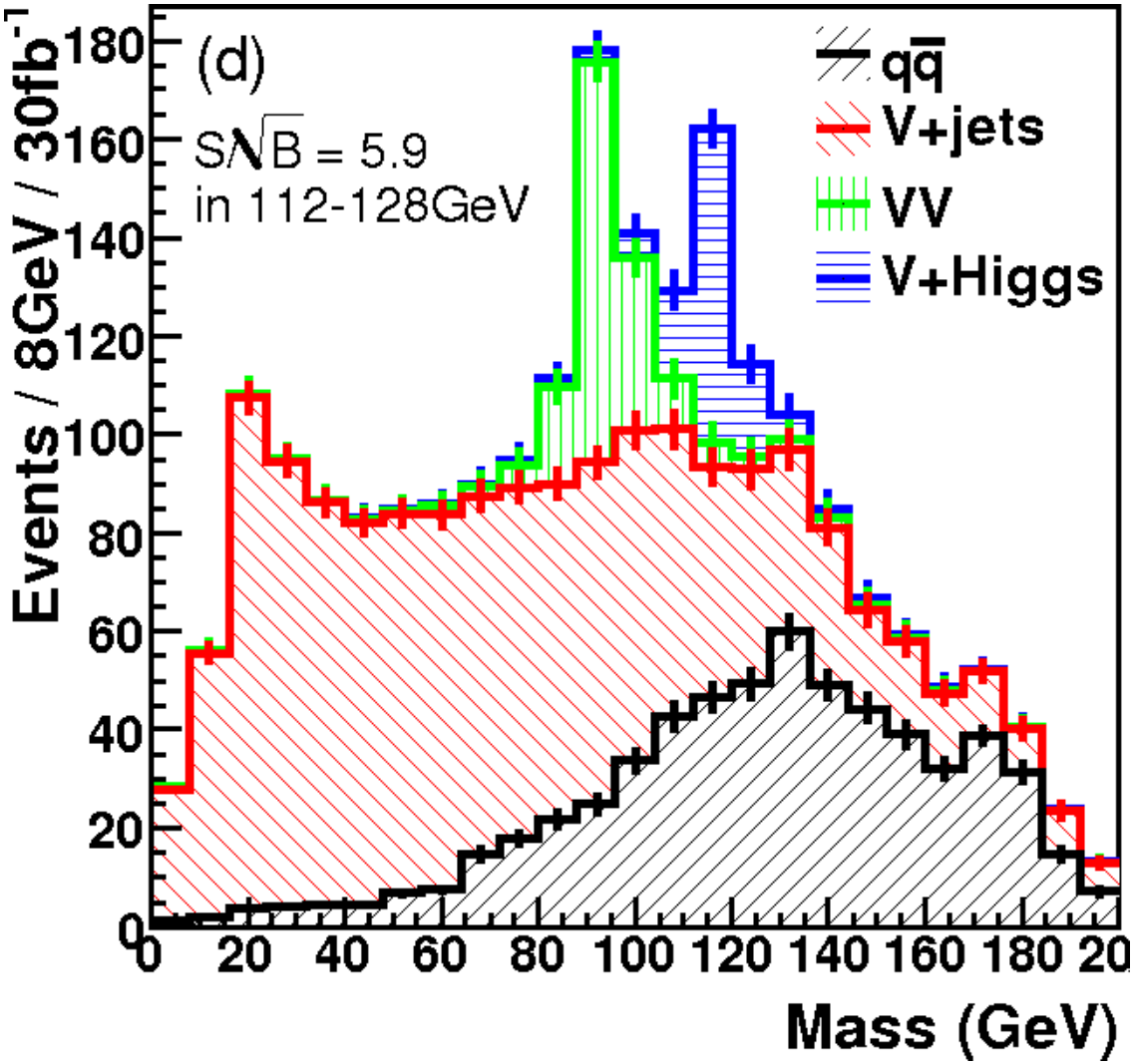
A game changer: a jet is no longer "$\sim$ a QCD parton"

Kicked up in 2008

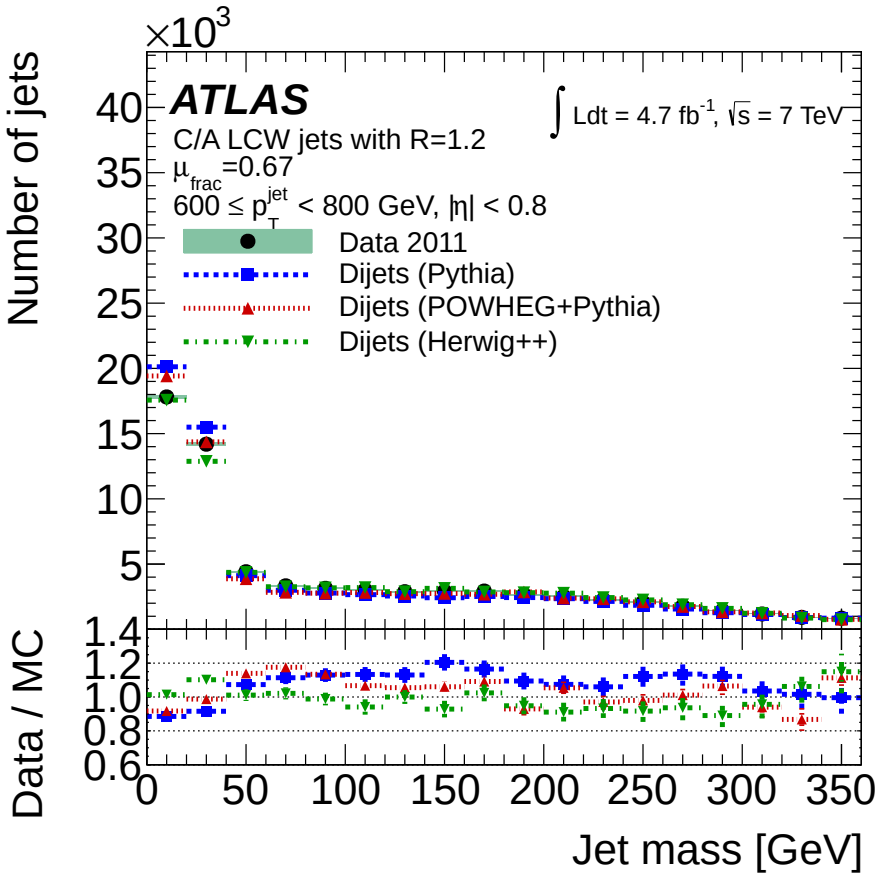


Discovery potential for
$H \to b\bar{b}$ at $\sqrt{s} = 14$ TeV

[J.Butterworth, A.Davison, M.Rubin, G.Salam, 2008]

Validation by LHC-Run I

ATLAS, 2013

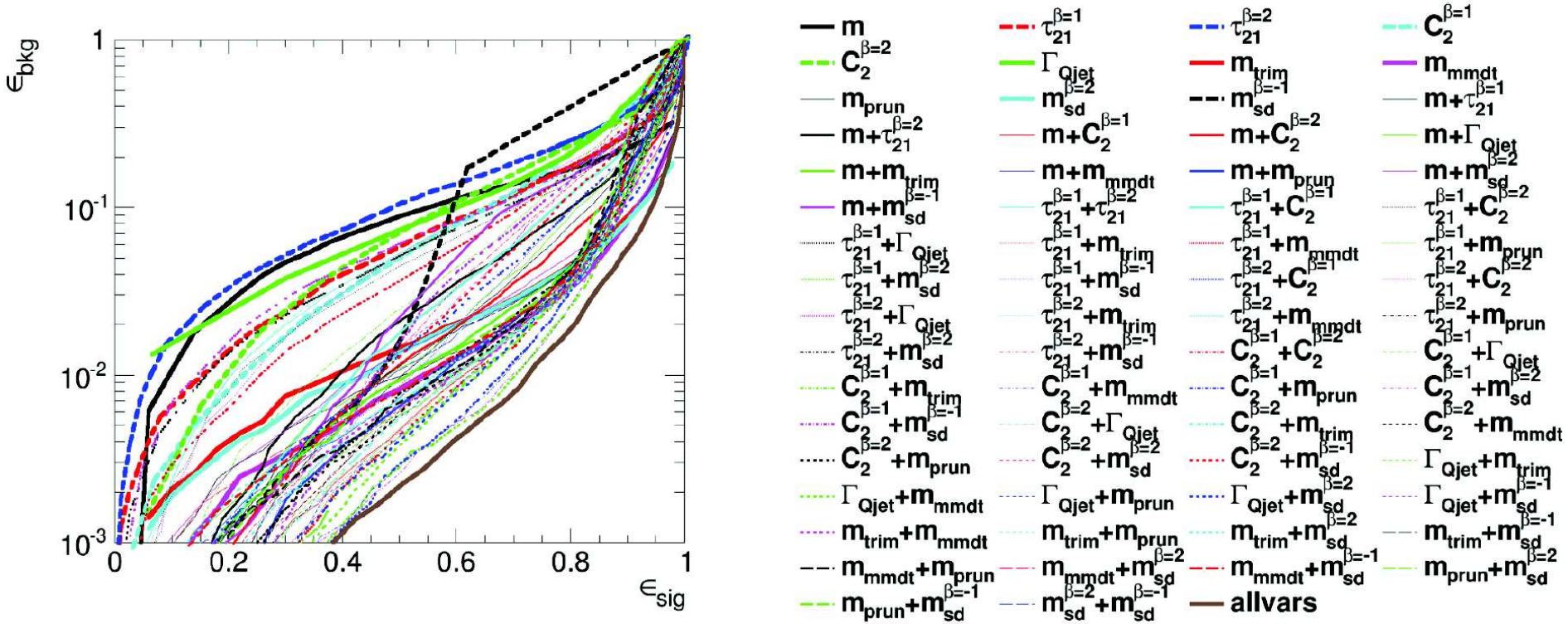


- decent agreement between data and Monte-Carlo
- but some differences are observed

In 2014: a greedy community...

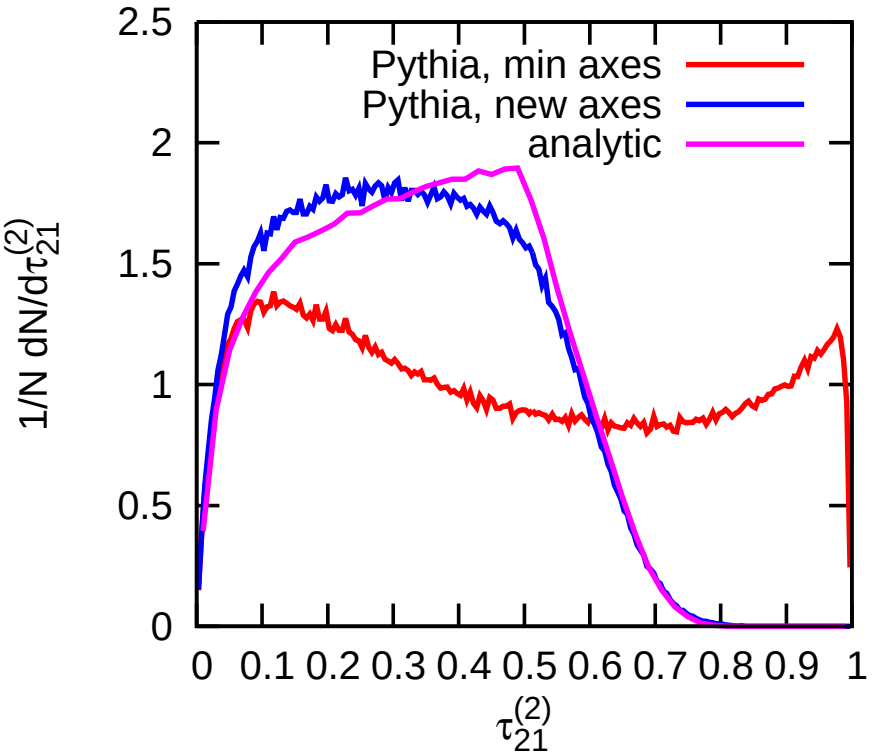
[Boost 2013 WG]

W v. q jets: combination of taggers



- Combination methods helps
- details not so obvious and just one p_t!

In 2014: going back to first-principles

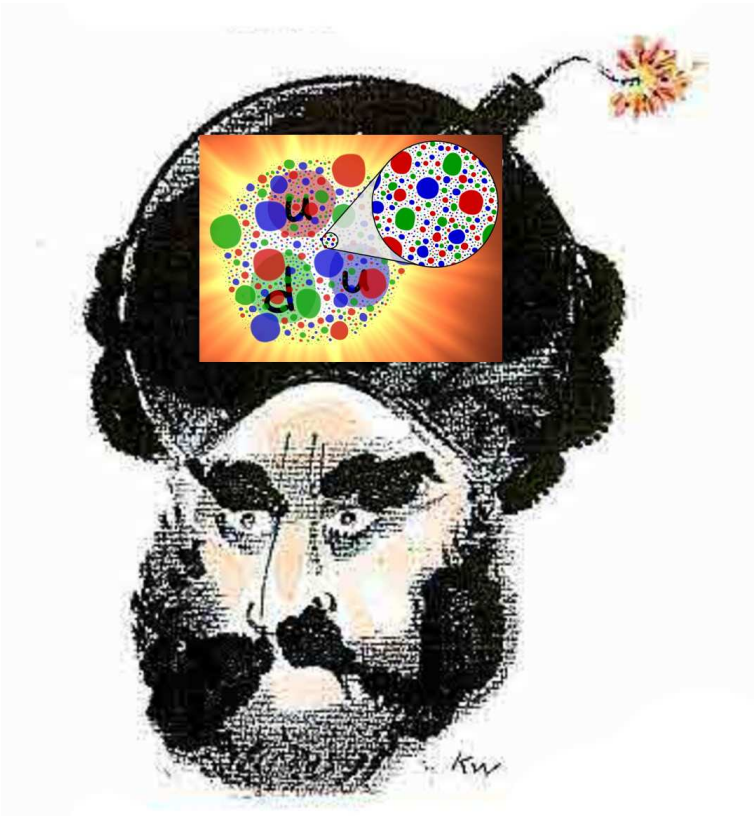


[M.Dasgupta,G.Salam,L.Sarem-Schunk,GS]

Towards a first-principle understanding

- understand what works better
- easily vary parameters
- control uncertainties
- devise better methods

Things to keep in mind



QCD is still a very active field of research

- Lattice closer to reality
- Era of precision
  - Amplitude calculations
  - PDF uncertainties
  - Crucial at the LHC
- Boosted jets
- Conceptual progress at high density/energy

more fun around the corner