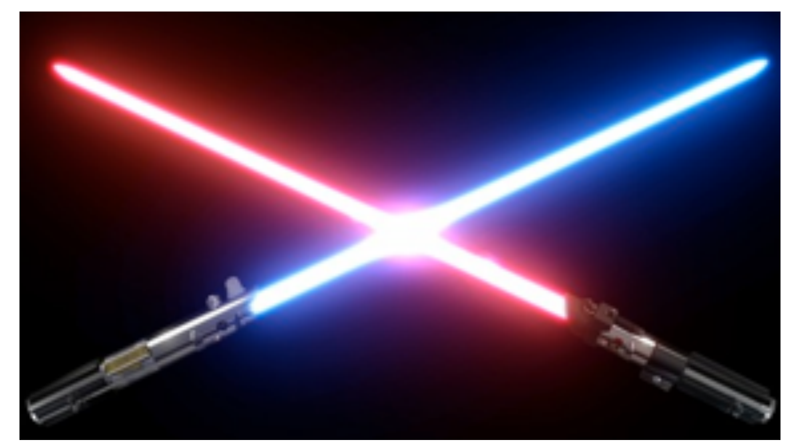
Preparation meeting for the June FCC(ee) workshop

WG5: QCD & γγ physics

Introduction



David d'Enterria & Peter Skands (WG5 Conveners)

FCC: European Strategy

[M. Benedikt, FCC Study, June 2014]

Summary: European Strategy Update 2013

Design studies and R&D at the energy frontier

…."to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update":

d) ***CERN should undertake design studies for accelerator projects in a global context,***

- *with emphasis on **proton-proton and electron-positron high-energy frontier machines**.*
- *These design studies should be coupled to a vigorous accelerator **R&D programme, including high-field magnets and high-gradient accelerating structures**,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

FCC-ee : Parameters

[M. Benedikt, FCC Study, June 2014]

- **Design choice: max. synchrotron radiation power set to 50 MW/beam**
  - Defines the max. beam current at each energy.
  - 4 Physics working points
  - Optimization at each energy (bunch number & current, emittance, etc).

Parameter	Z	WW	H	$t\bar{t}$ (tt_{bar})	LEP2
E/beam (GeV)	45	80	120	175	104
I (mA)	1450	152	30	6.6	3
Bunches/beam	16700	4490	170	160	4
Bunch popul. [10^{11}]	1.8	0.7	3.7	0.86	4.2
L (10^{34} $cm^{-2}s^{-1}$)	28.0	12.0	4.5	1.2	0.012

- For H and ttbar working points the beam lifetime of ~few minutes is dominated by Beamstrahlung (momentum acceptance of 2%).

+ millions of W and b jets from top

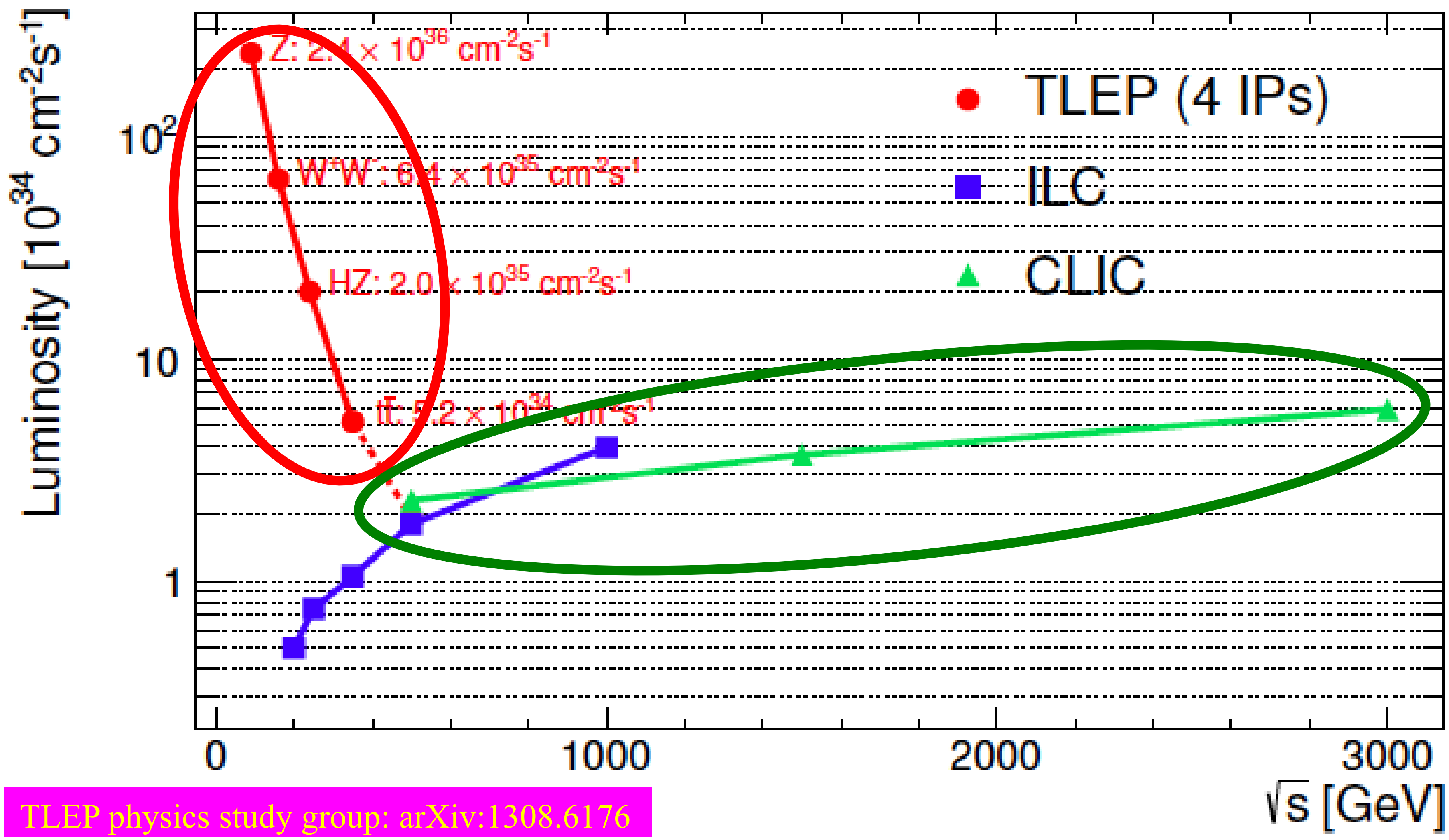
Higgs is one of the four pillars:
Tera-Z, Oku-W, Mega-H, Mega-t

[J. Ellis]

10^{12} 10^{8} 10^{6} 10^{6}

Circular vs Linear

[J. Ellis, FCC Study, June 2014]



TLEP physics study group: arXiv:1308.6176

Higgs is one of the four pillars:
Tera-Z, Oku-W, Mega-H, Mega-t

[J. Ellis]

10^{12}	10^{8}	10^{6}	10^{6}

WG5 Mandate

[D. d'Enterria, FCC Kickoff, Feb 2014]

- Determine best achievable EXP & TH precision on α_s measurement via: Z,W,τ hadronic decays widths, jet rates, event shapes, ...
- Explore other competitive QCD physics opportunities opened in e+e-.
- Evaluate photon-photon physics possibilities via EPA fluxes: Higgs, anomalous quartic gauge couplings, anomalous top,τ e.m. moments,...

- Set goals for sub-detector performance (including forward $e^{\pm}$ taggers for $\gamma\gamma$ physics) and experimental-conditions so that syst.~stat. Uncertainties for the measurements
- Define experimental/phenomenological software needs to make possible these measurements and their interpretation with the required precision.
- Help evaluating the QCD impact on rest of FCC measurements. Provide design study for "background" event generators for QCD and $\gamma\gamma$ processes.

FCC-ee WG5 : Structure

6 Physics Subgroups

QCD-1: strong coupling: phenomenology and measurements

QCD-2: Multi-jets and parton radiation

QCD-3: Parton-to-hadron (g, q, heavy-Q) fragmentation

GammaGamma-1: QCD measurements (sigma_tot,VV,gamma PDF, gamma FF,...) + FCC-ee backgds

GammaGamma-2: Electroweak measurements (dileptons, WW, H,...)

GammaGamma-3: BSM measurements (dilaton, radion,...)

Lots of scope for activities
Many subgroups still need more (EXP+TH) conveners!

(+ for all: define DETECTOR requirements!)

Exhortation

QCD is not "new" physics

Many studies we will propose are "old"

E.g., presentations today include alphaS measurement, fragmentation, tetra-quarks, odderons, …

The context of this WG is:

What is **special** about FCC-ee? What can we do here, that we couldn't do earlier?

Why should anyone outside our community care?

What will be required of the machine/detectors?

Emphasize in what way (if any), what is being presented / what can be done, is not just 'turning the crank'

FCC-ee won't be ***built*** to study QCD, but we can add to the physics case, highlighting the exciting questions it can address + we may have special requirements (e.g., PID).

Timescales

[D. d'Enterria, FCC Kickoff, Feb 2014]

- "Exploration" phase (Feb'14 – March'15): Identify all possible options and potential studies, including requirements and constraints.
  - ☛ Deliverable: Interim written report for review milestone workshop
- "Analysis" phase (March'15 – Sept'16): Detailed studies of the identified baselines.
  - ☛ Deliverable: Interim written report for review milestone workshop
- "Elaboration" phase (Sept'16 – Dec'17): Delivery of all information required for the final Conceptual Design Report (CDR) of the study.

☛ Final Yellow Report (early 2018) to be included into the FCC CDR.

JOIN THE QCD & PHOTON-PHOTON WG5 ACTIVITIES !

QCD Multi-jets, parton radiation & Parton-to-hadron fragmentation

Peter Skands (CERN) June 3, 2014, CERN
QCD & γγ physics: WG5 preparation meeting for the June FCC(ee) workshop

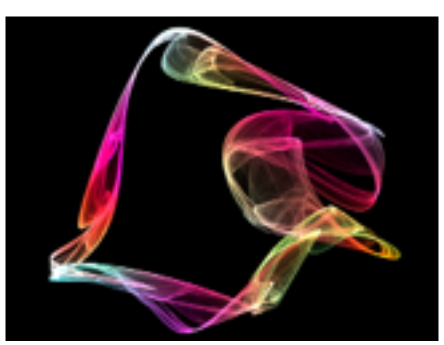
QCD at FCC-ee

Event Structure is dominated by QCD

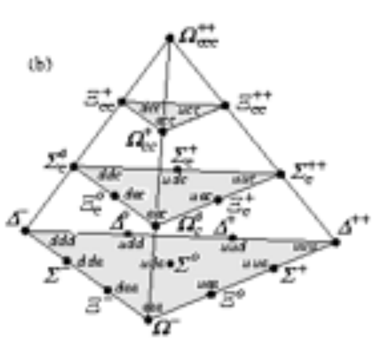
More than just a perturbative expansion in α_s

Emergent phenomena:

Jets (the QCD fractal) ⟷ amplitude structures ⟷ fundamental quantum field theory. Precision jet (structure) studies.



Strings (strong gluon fields) ⟷ quantum-classical correspondence. String physics. Dynamics of hadronization phase transition.



Hadrons ⟷ Spectroscopy (incl excited and exotic states), lattice QCD, (rare) decays, mixing, light nuclei. Photon beams ⟷ γγ physics.

Fundamental Constants of Nature

$$\alpha = 7.297\,352\,5698(24) \times 10^{-3}$$

uncertainty : 0.32 ppb

$$G_F/(\hbar c)^3 = 1.166\,378\,7(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$$

uncertainty : 0.5 ppm

$$\sin^2\hat{\theta}(M_Z)^{\overline{\mathrm{MS}}} = 0.23116(12)$$

uncertainty : 0.05%

$$G_N = 6.6738(8) \times 10^{-11}\,\frac{\mathrm{m}^3}{\mathrm{kg\,s}^2}$$

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$$m_W = 80.385(15)\,\mathrm{GeV}/c^2$$

uncertainty : 0.02%

Dominant uncertainty from ee : Colour Reconnections

$$m_t = 173.07 \pm 0.52 \pm 0.72\,\mathrm{GeV}/c^2$$

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Dominant uncertainty from pp : Colour Reconnections

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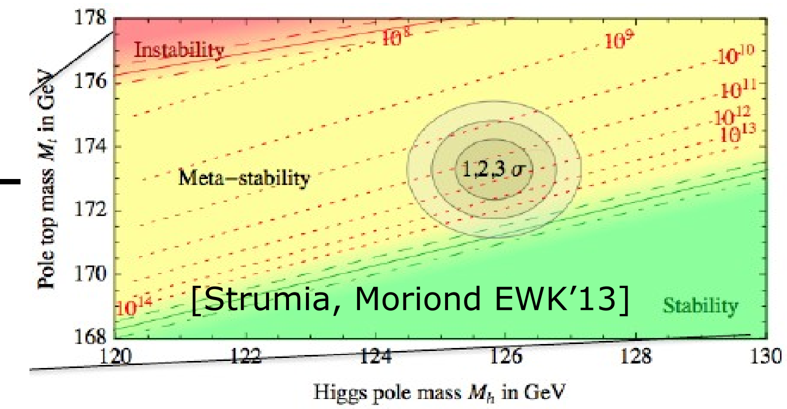


m_t
"Decides the fate of the Universe"

QCD Fragmentation: Existing Constraints

LEP/SLD (and other previous ee machines)

- → typically 5%-20% precision on QCD modelling constraints (Fine for LO+LL models of the 90'ies)
  - But **think** in context of physics models **20 years** from now!
- Precise measurements really only up to 4 jets
  - Almost impossible to really access QCD fractal; subleading effects

LHC (and SPS, RHIC, Tevatron, …)

- Fragmentation constraints not comparable to LEP/SLD
  - Complicated by additional issues in pp (eg UE), less clean (Interesting physics overlaps with collective effects in heavy-ion)
- Huge phase space for jets.
  - Will access QCD fractal. But complicated interplay with ISR & UE E.g., subleading colour may be impossible to isolate

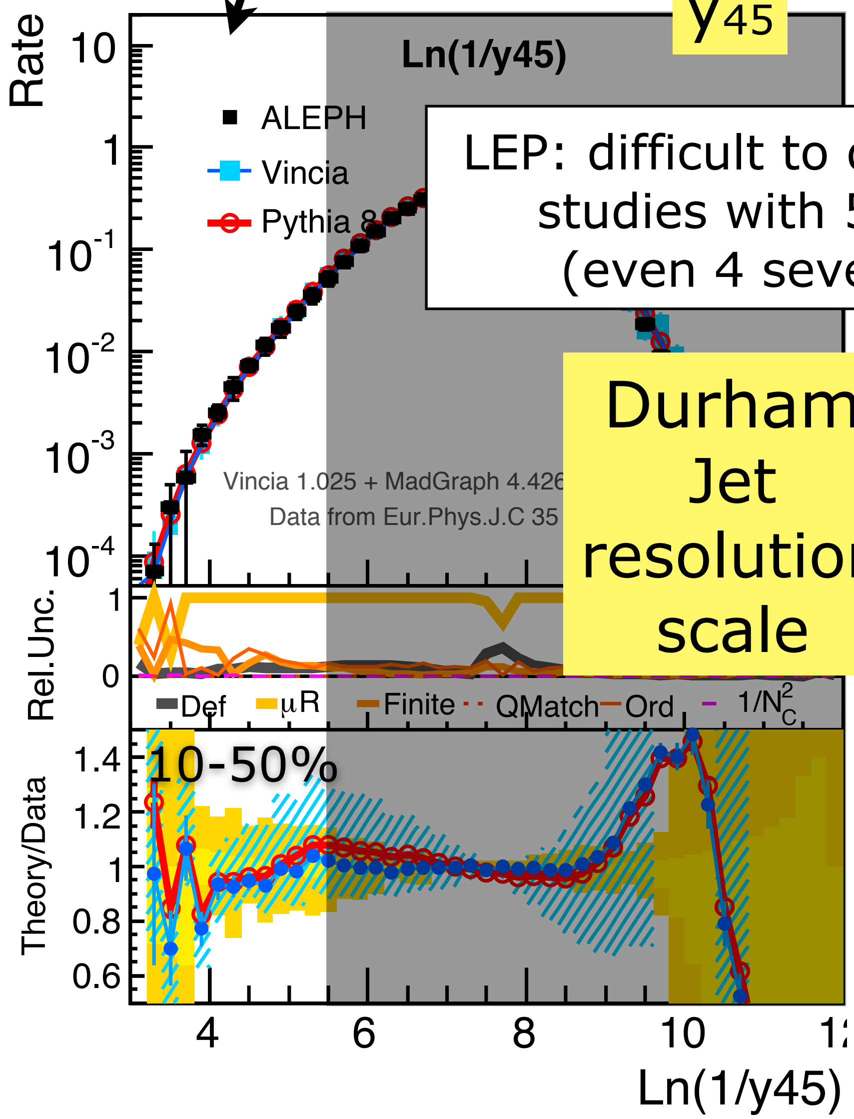
Jets: Some Examples

Aim should be: do 10 - 100 times better than LEP/SLD

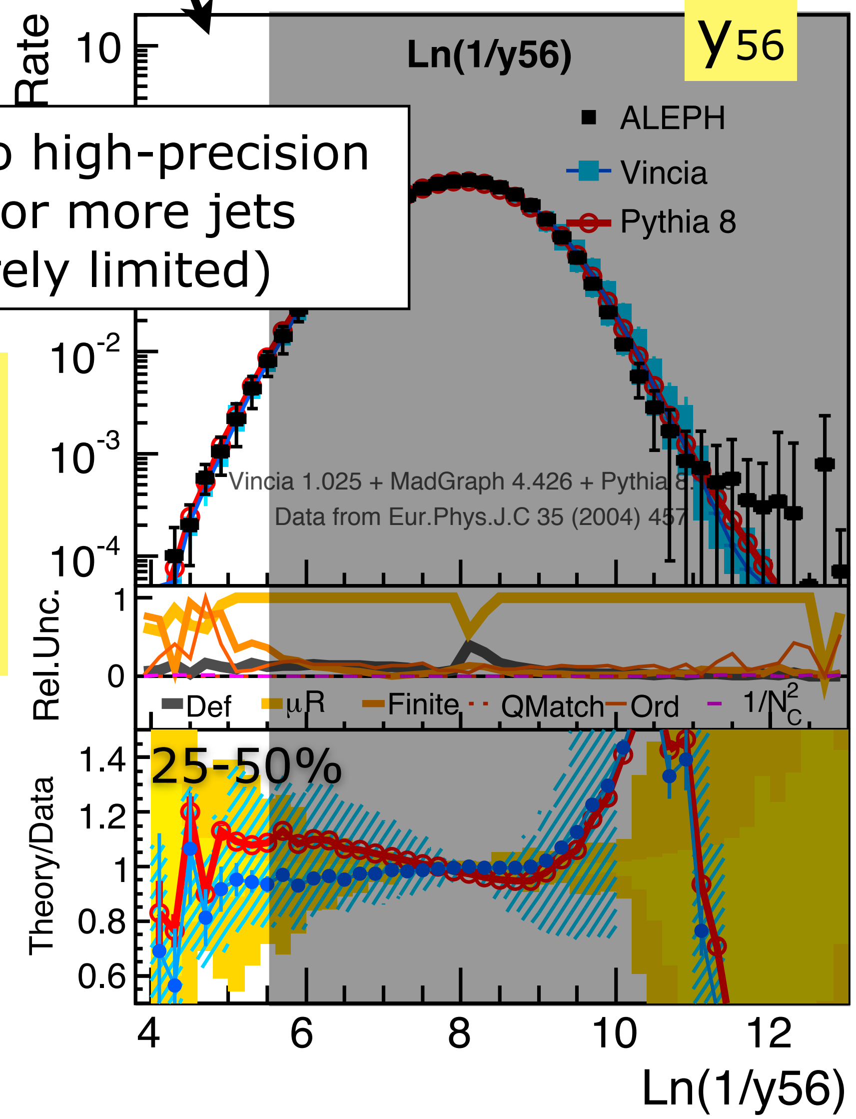
Higher stats
Better detectors
Higher Q2

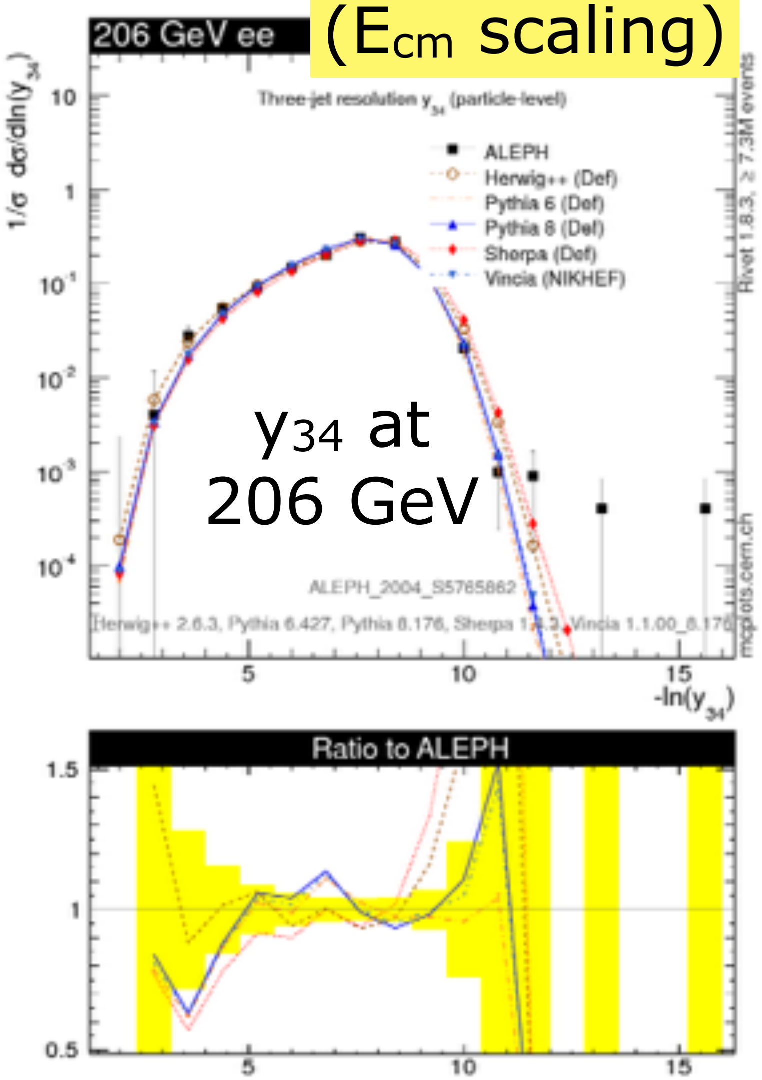
Hard Perturbative Region ($k_T \geq 5$GeV)

LEP: difficult to do high-precision studies with 5 or more jets (even 4 severely limited)



Durham Jet resolution scale





Difficult to use for high-precision (< 10% i.e., beyond LO+LL) differential studies

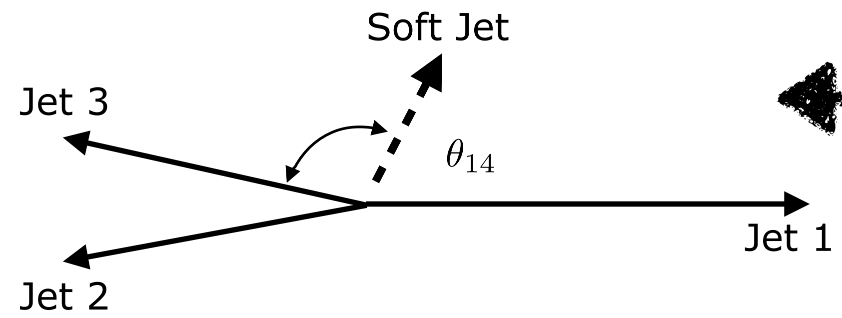
Beyond Leading Log & Leading Colour

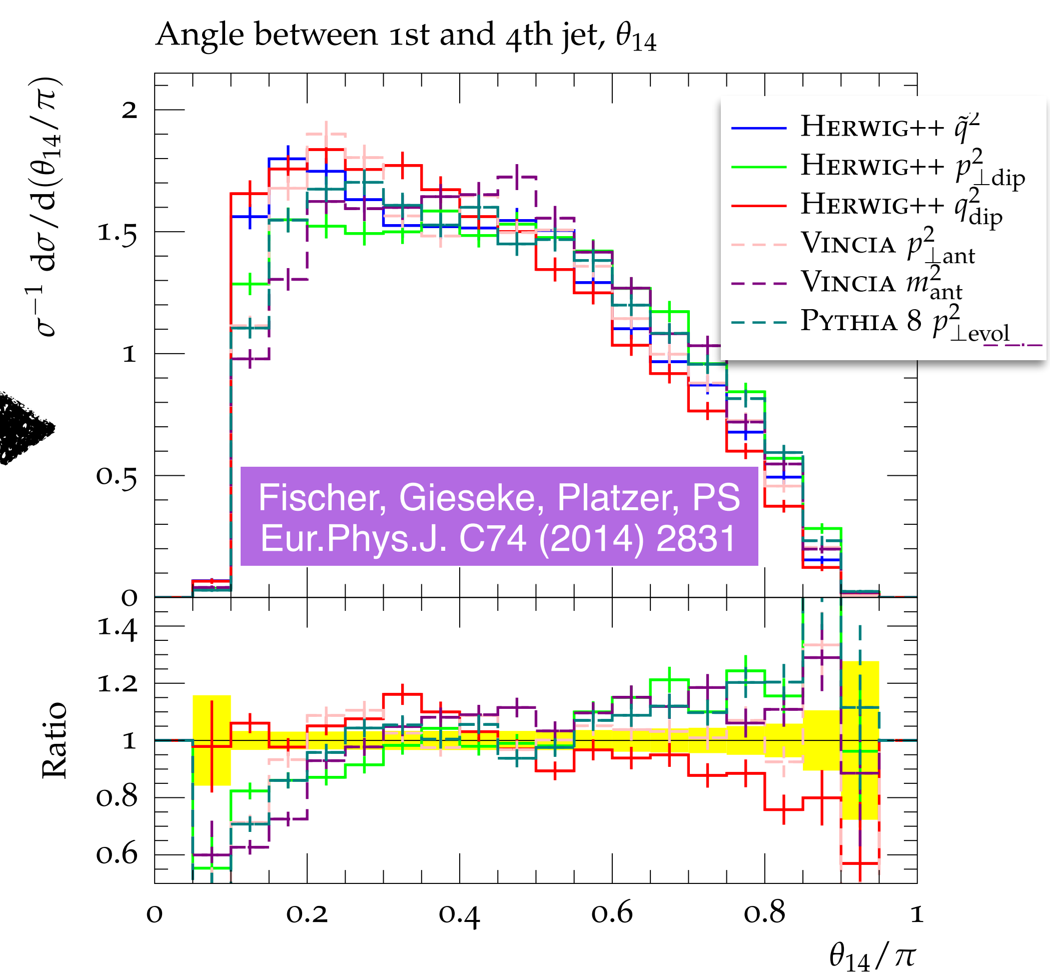
Perturbative:

Need high stats for multi-jets

QCD coherence for multipoles

Example:





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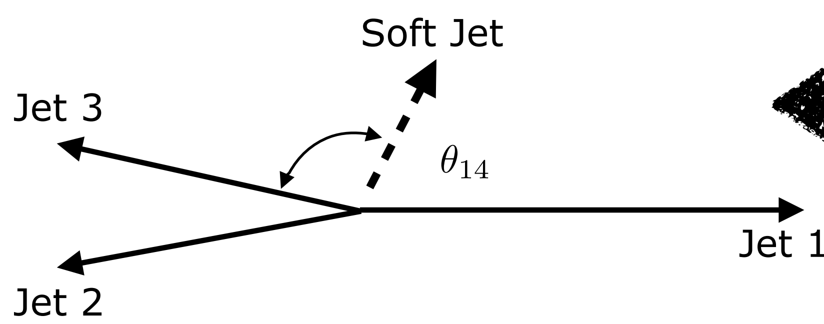

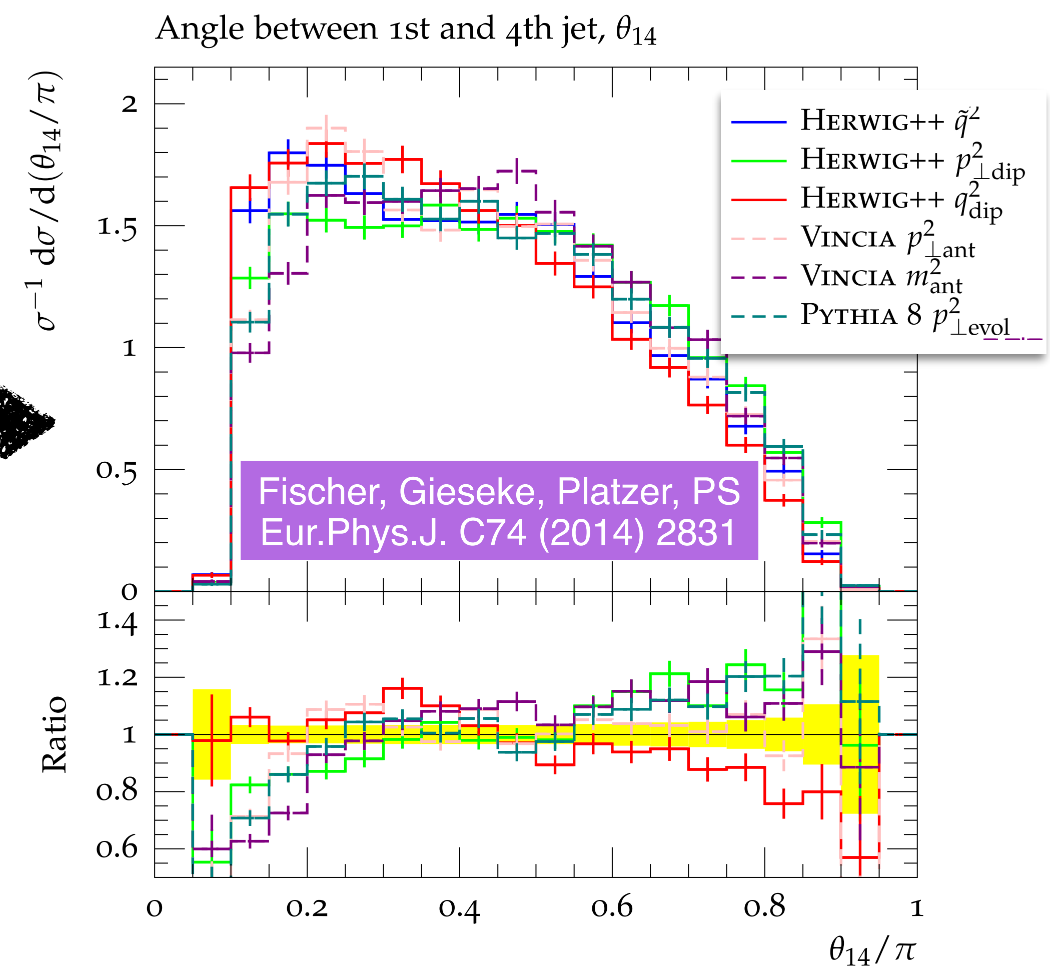

+ N^{n}LL : 1→3, … , 1→n shower splittings

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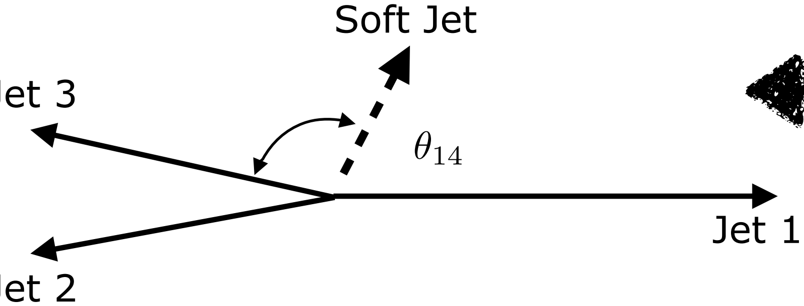

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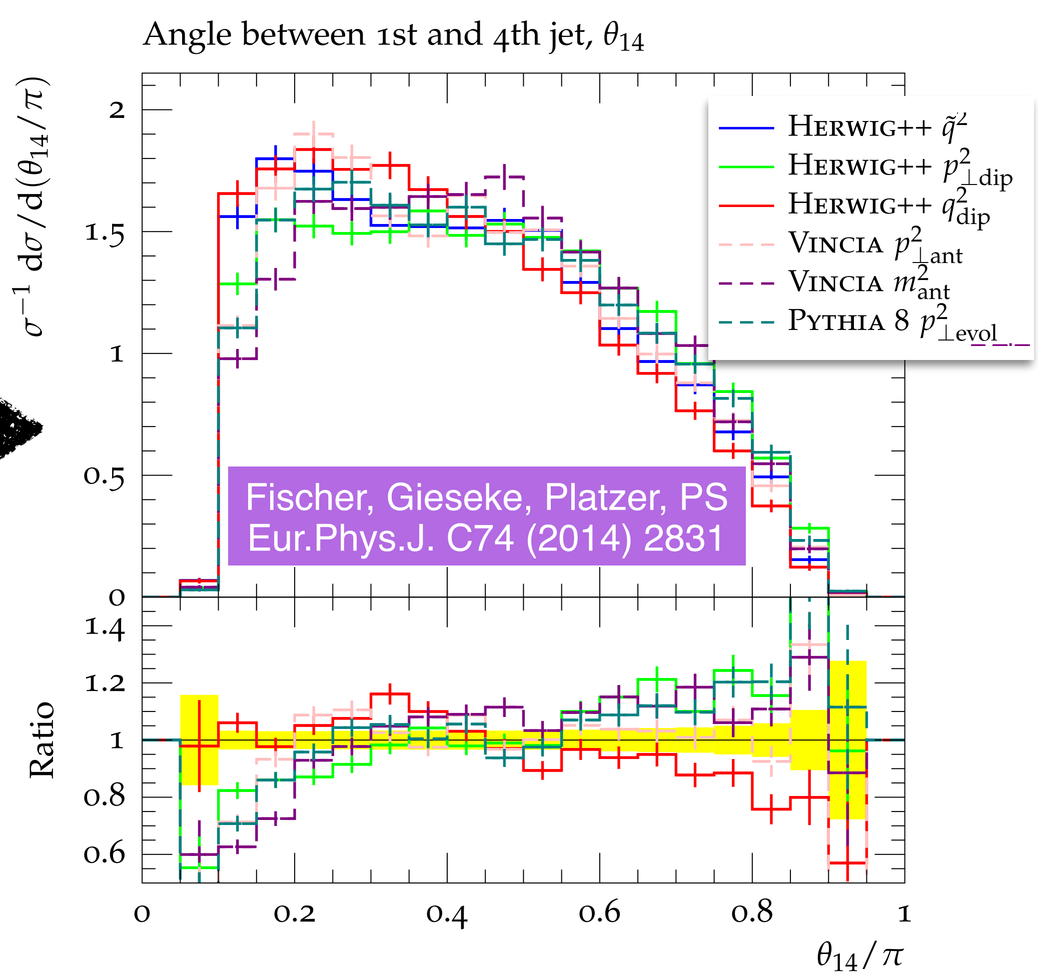

Non-perturbative:

coherent string/hadron formation
& string interactions

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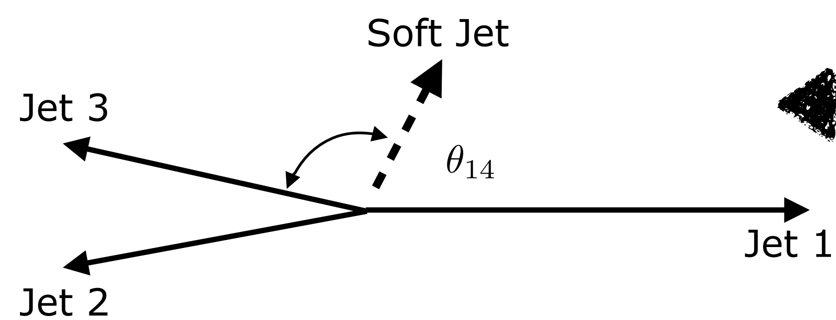

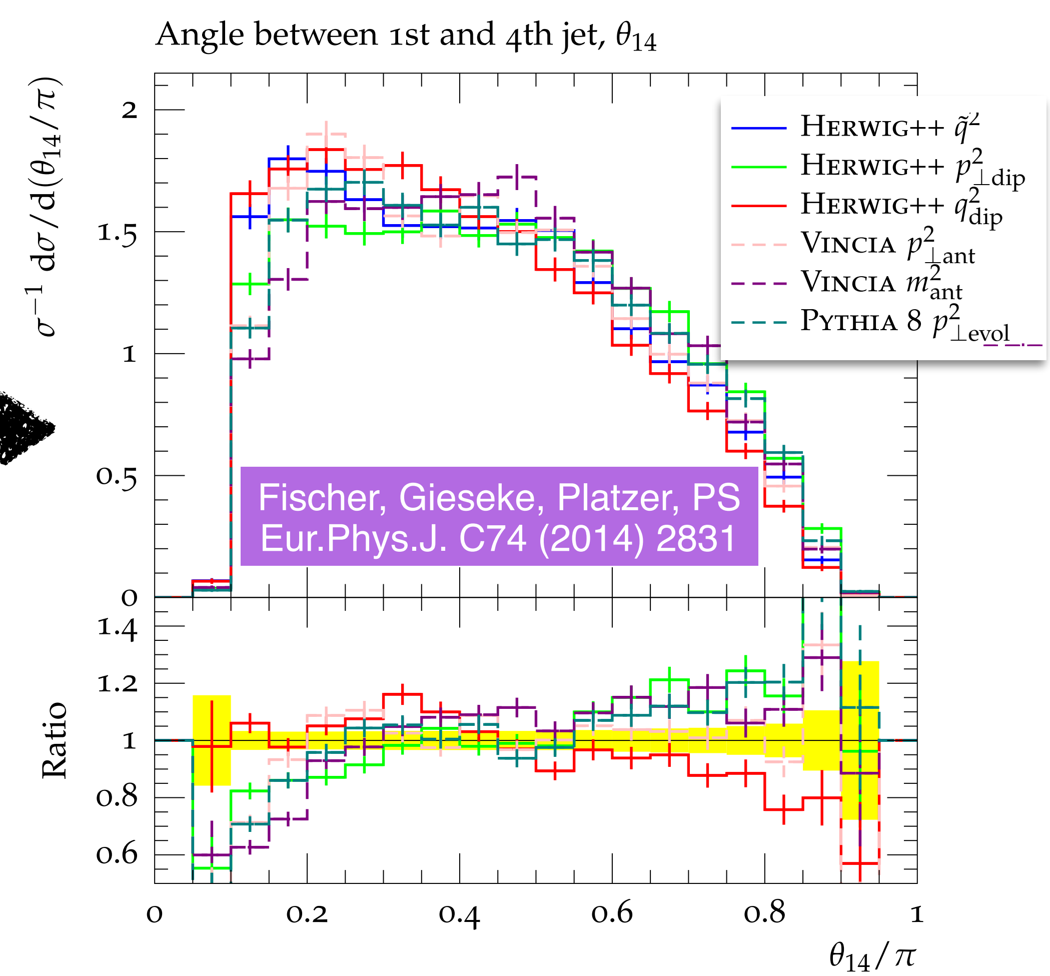

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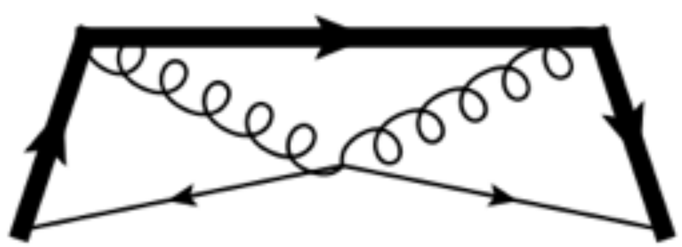

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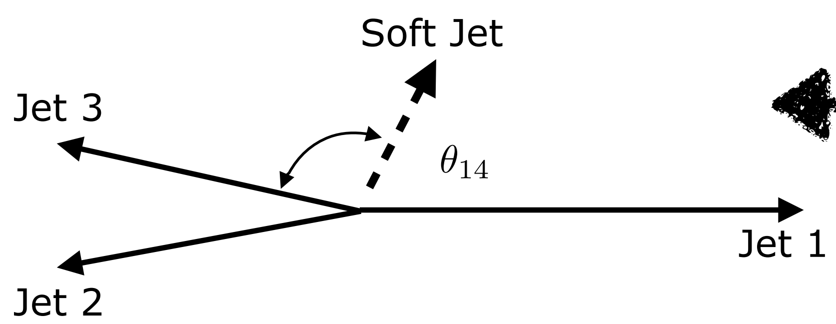

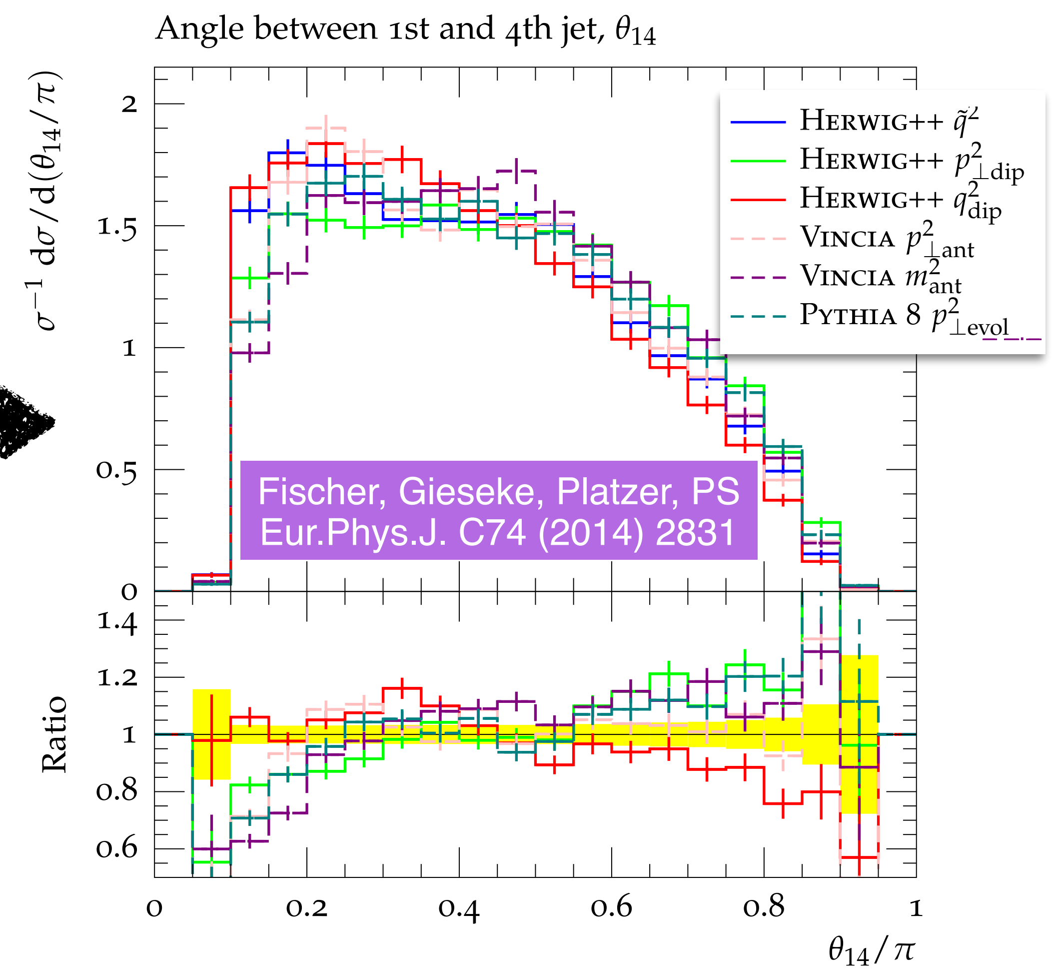

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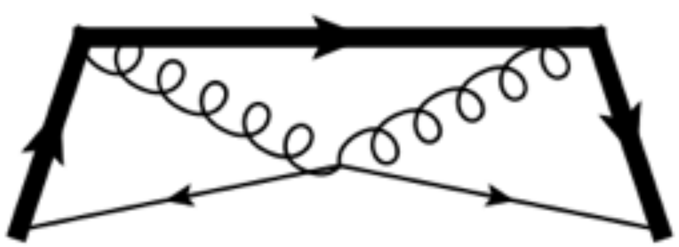

zig-zag topologies
complicated colour fields

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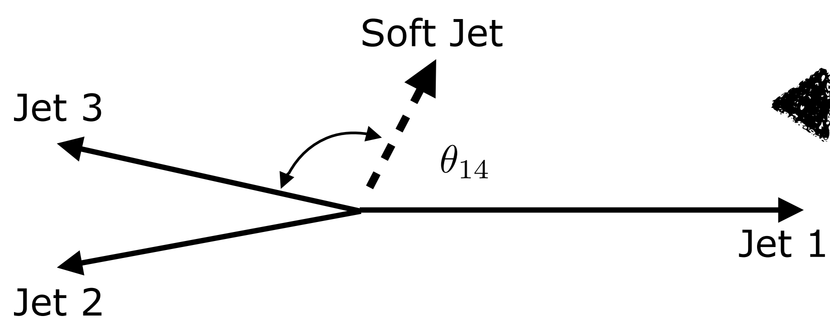

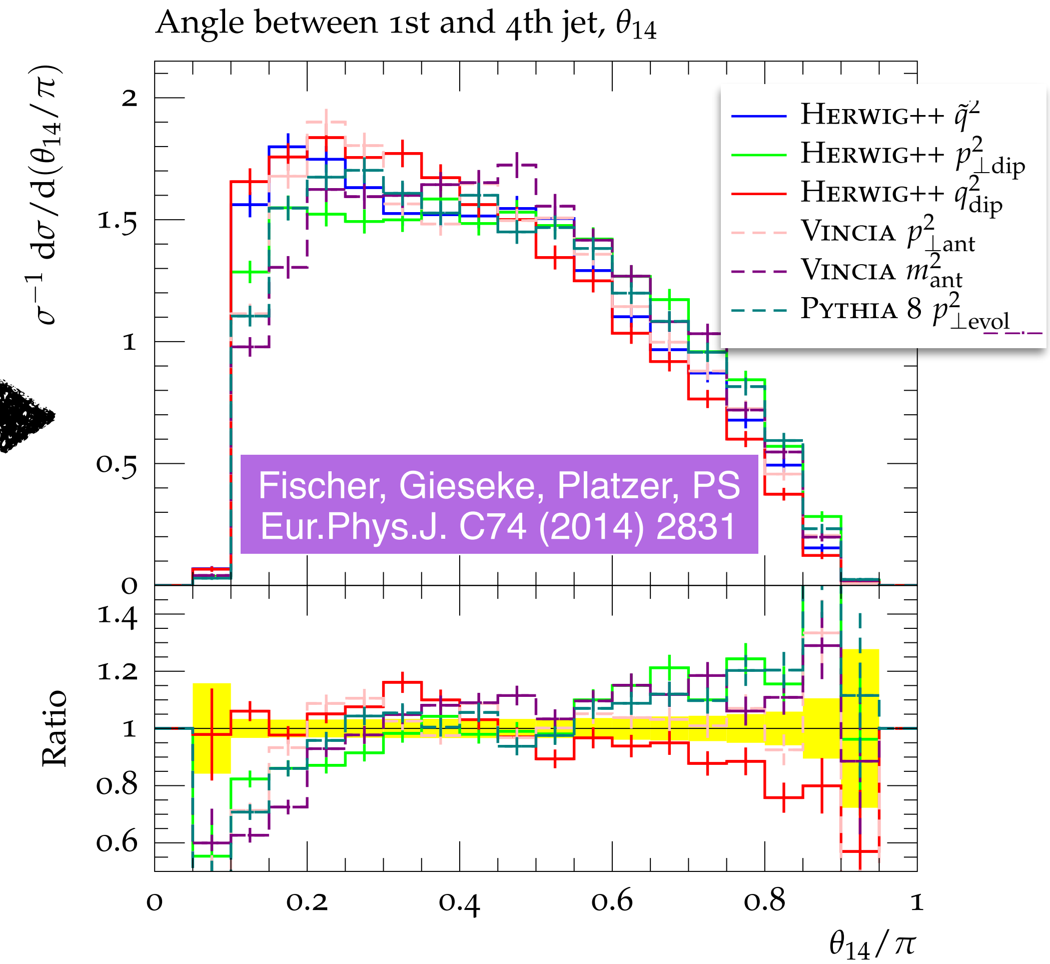

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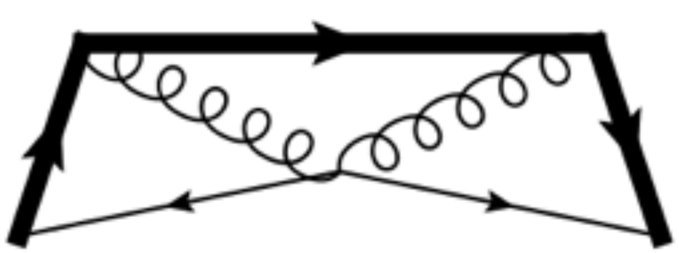

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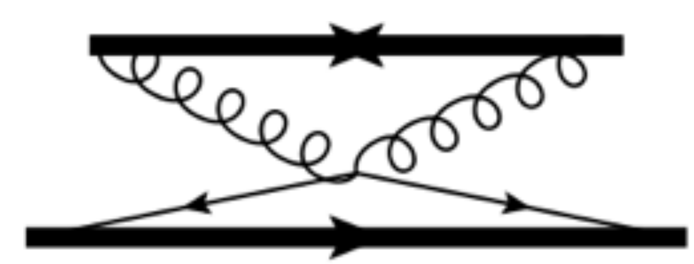

rapidity gap emergence?

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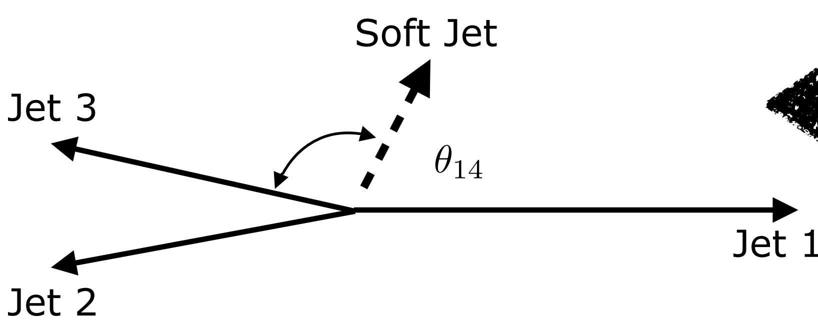

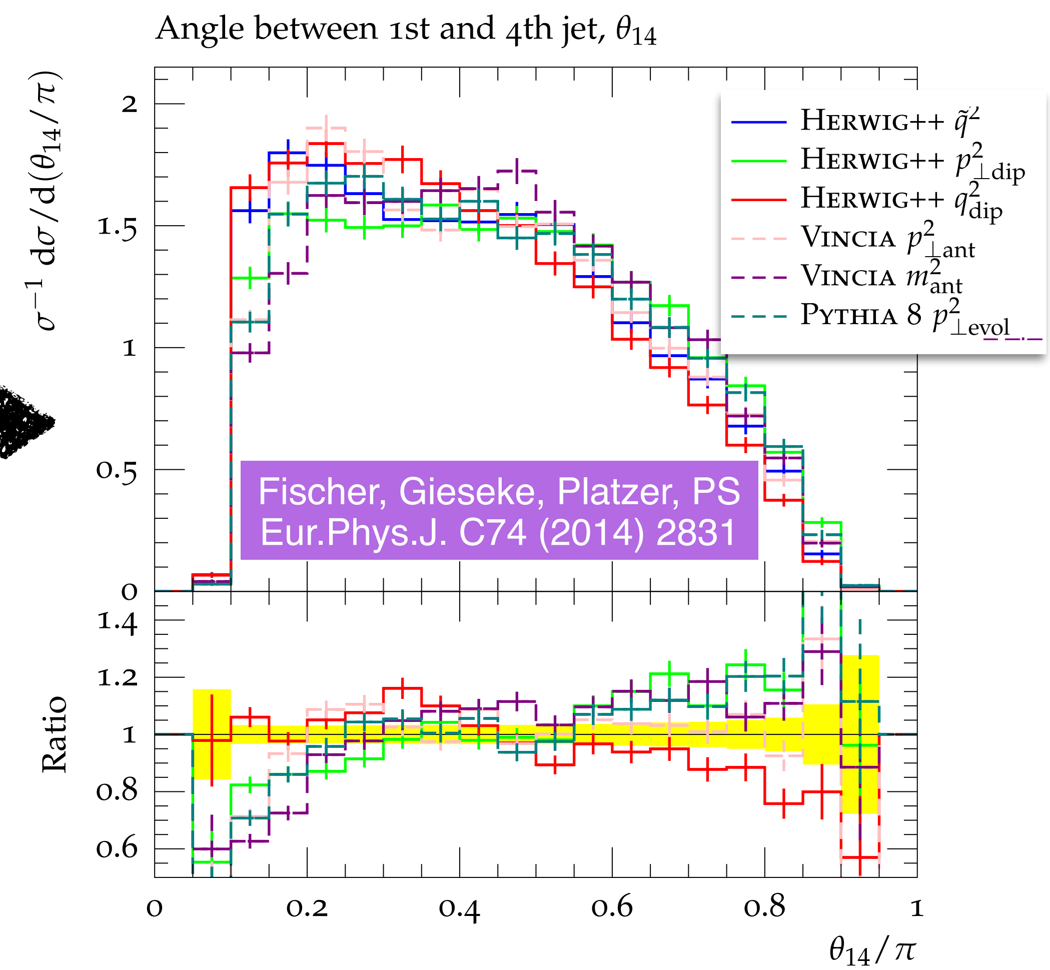

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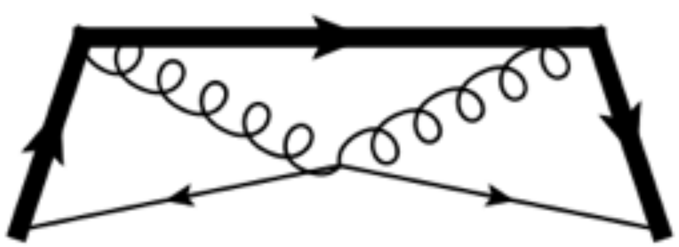
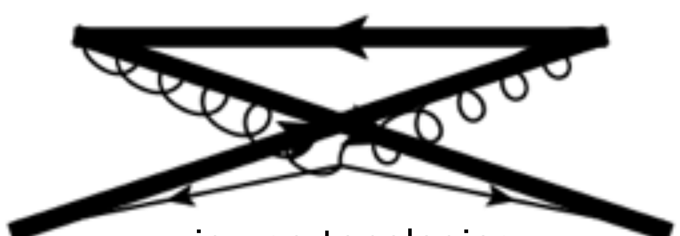
Correlate with CR studies at LEP & LHC





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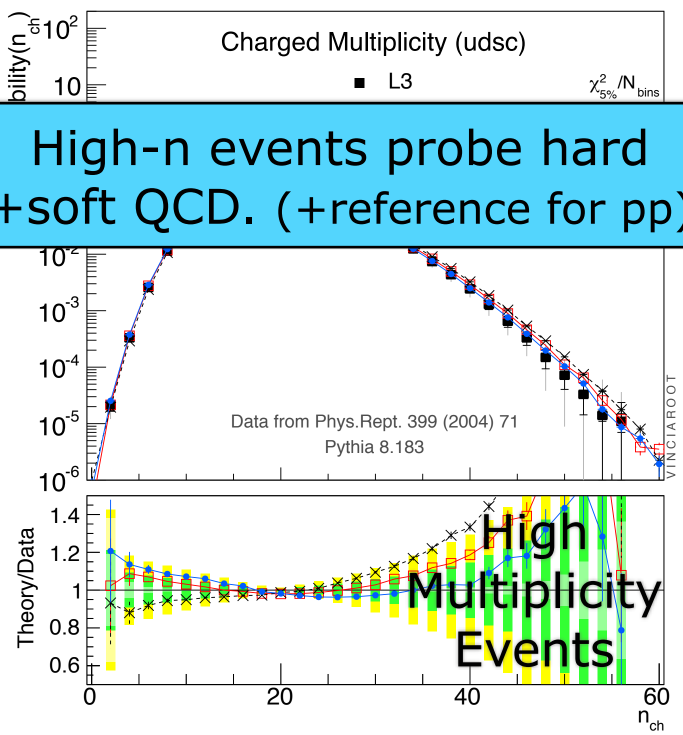
Strings: Some Examples

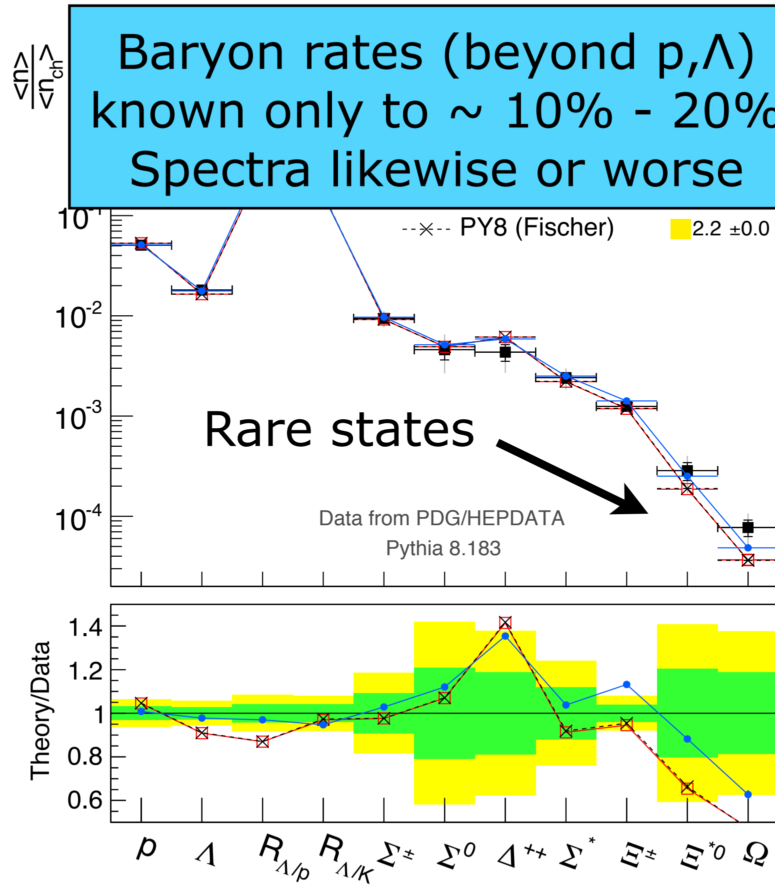
Aim should be: do 10 - 100 times better than LEP/SLD

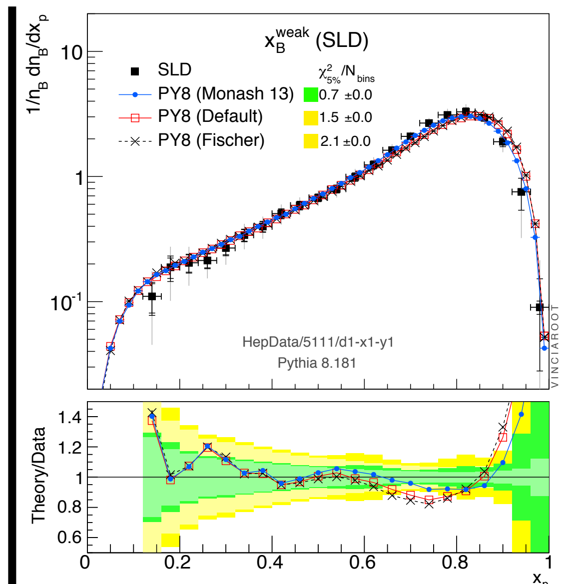
Higher stats
Better detectors
Higher Q2

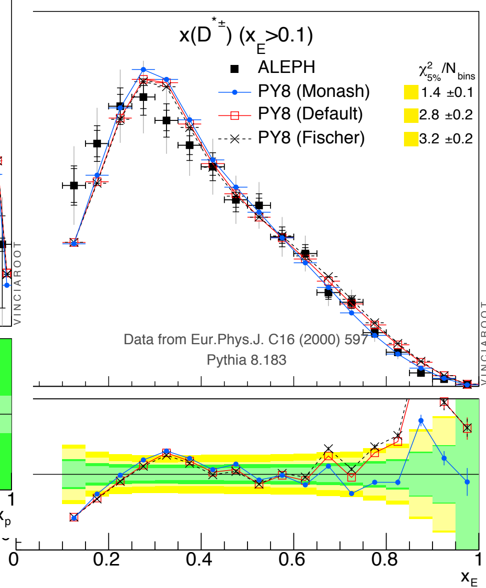
High-n events probe hard +soft QCD. (+reference for pp)



Baryon rates (beyond p,Λ) known only to ~ 10% - 20%
Spectra likewise or worse



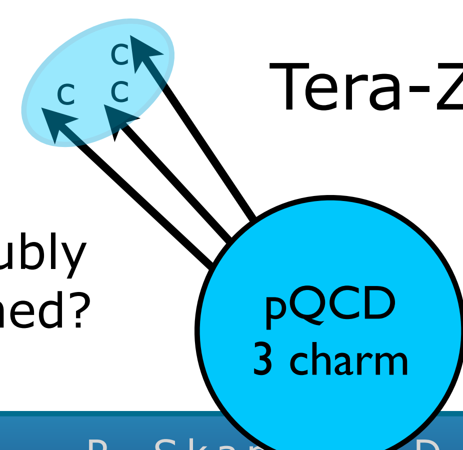




D and B fragmentation
Few clean spectra
Uncertainties > 10%
Especially in soft and hard regions

...

→ b and c baryons. What about Ω_{ccc} ?!



Tera-Z?

or doubly charmed?

+ Improve LEP limits on Colour Reconnections
→ clear signal?
→ STUDY colour reconnections
Feedback to pp

Identified Particles

Discovery of the Delta++ baryon

Meson-Nucleon Scattering and Nucleon Isobars*

KEITH A. BRUECKNER
Department of Physics, Indiana University, Bloomington, Indiana
(Received December 17, 1951)

"[...] It is concluded that the apparently anomalous features of the scattering can be interpreted to be an indication of a resonant meson-nucleon interaction corresponding to a nucleon isobar with spin $\frac{3}{2}$, isotopic spin $\frac{3}{2}$, and with an excitation energy of 277 MeV."

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HEPDATA: 2 measurements, **discrepant by more than 3 sigma**

Hadron multiplicities for e+ e- --> Delta(1232)++ (Delta(1232)--) X

sqrt(s) GeV	Experiment	Reference	Multiplicity	+-	+-	+-
91.2	DELPHI	1995 Phys.Lett. 361B 207	0.079	0.009	0.009	0.007
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Similarly, to arrive at chi2 ~ 1 between measurements, additional systematic errors need to be introduced for several other species:

- phi: 9%
- Lambda: 3%
- Delta++: >50%
- Sigma*: 17%
- Xi: 2%

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These are just the total rates

Relative rates, spectra, and correlations crucial to constrain fragmentation models (feedback to hadronization corrections)

To perform these measurements, making use of the huge statistics, what is required in terms of PID capabilities & resolutions?

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Department of Physics, Indiana University, Bloomington, Indiana
(Received December 17, 1951)

"[...] It is concluded that the apparently anomalous features of the scattering can be interpreted to be an indication of a resonant meson-nucleon interaction corresponding to a nucleon isobar with spin $\frac{3}{2}$, isotopic spin $\frac{3}{2}$, and with an excitation energy of 277 MeV."

HEPDATA: 2 measurements, **discrepant by more than 3 sigma**

Hadron multiplicities for e+ e- --> Delta(1232)++ (Delta(1232)--) X

sqrt(s) GeV	Experiment	Reference	Multiplicity	+-	+-	+-
91.2	DELPHI	1995 Phys.Lett. 361B 207	0.079	0.009	0.009	0.007
91.2	OPAL	1995 Phys.Lett. 358B 162	0.22	0.04	0.04	

Similarly, to arrive at chi2 ~ 1 between measurements, additional systematic errors need to be introduced for several other species:

phi: 9%

Lambda: 3%

Delta++: >50%

Sigma*: 17%

Xi: 2%

These are just the total rates

Relative rates, spectra, and correlations crucial to constrain fragmentation models (feedback to hadronization corrections)

To perform these measurements, making use of the huge statistics, what is required in terms of PID capabilities & resolutions?

- Experience from LEP, LHC (ALICE in particular), …
- Is partial PID coverage sufficient?

Future of QCD Models

Huge recent progress on theory side (not only cranking orders)

- Breaking through NLO (& automation) barrier
- Improving resummations and showers
- Better understanding of underlying principles (eg unitarity)
- Perturbative calculations combining different expansions

In 20 years, no one will be talking about "fixed order" calculations? → "perturbative" calculations, in form of:

- (N^nLO-corrected) (exclusive) (hadronized) Monte Carlos
- (N^nLO-matched) (inclusive) (analytical or numerical) resummations

These pQCD calculations will have very high precision

- → can see non-perturbative physics more clearly

Next generation models will have far better precision → need far better constraints. (And can probe far deeper! Reliably!)

Summary

Aim should be: do 10 - 100 times better than LEP/SLD

Higher lumi + better detectors

+ improve lever arm for **scaling** (→ 350 GeV)

+ FCC can also do lower energy scans in a heartbeat

Better (and standardized) analysis **tools**, better theory tools

Nail QCD fragmentation

Precision Jets: fractal structure, perturbative evolution, scale breaking, power corrections, coherence, isolating subleading colour corrections, subleading logs (compressed hierarchies), mass corrections, spin correlations, n-loop corrections, high-precision multijets, g→qq, IR limits …

+ Strings: hadronization, think in context of constraining the *next* fragmentation model, with much more precise perturbative input. Rates and fragmentation spectra at 1% level, with good resolution, also for rare/exotic states, in extrema of distributions, colour reconnections, …

+ Assuming we do all this → feedback to other WGs