LUND UNIVERSITY

Vetenskapsrådet

European Research Council
Established by the European Commission

MCnet

Colour Reconnections from LEP to Future Colliders: Introduction and PYTHIA models

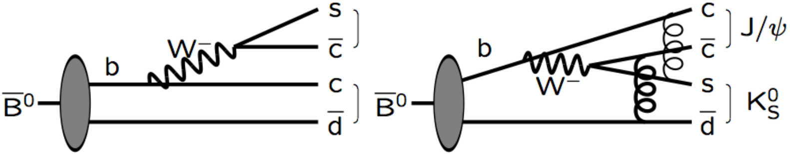
Torbjörn Sjöstrand

Theoretical Particle Physics
Department of Astronomy and Theoretical Physics
Lund University

Workshop on Parton Radiation and Fragmentation
from LHC to FCC-ee, CERN, 21-22 November 2016

Colour Reconnection in B decays

Colour operators in B decay $\Rightarrow$ some η_c:
A. Ali, J.G. Körner, G. Kramer, J. Willrodt, Z. Phys. **C1** (1979) 269



$\mathrm{B} \to \mathrm{J}/\psi \to \mu^+\mu^-$ good way to find B mesons:
H. Fritzsch, Phys. Lett. **B86** (1979) 164, 343
. . . soon confirmed by experiment

$\mathrm{g}^* \to \mathrm{c}\overline{\mathrm{c}} \to \mathrm{J}/\psi$ production mechanism in pp ("colour octet")
H. Fritzsch, Phys. Lett. **B67** (1977) 217
more complicated to test (at the time, later "confirmed")

Colour Reconnection at $\mathrm{Sp\bar{p}S}$

T.S. and M. van Zijl,
Phys.Rev. **D36** (1987) 2019

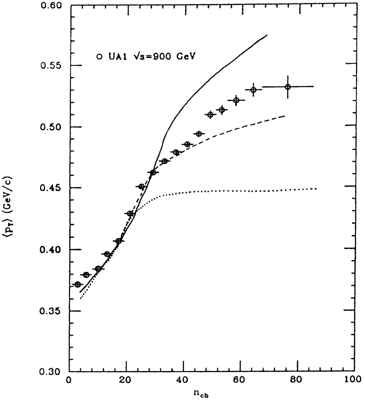
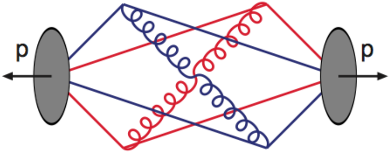
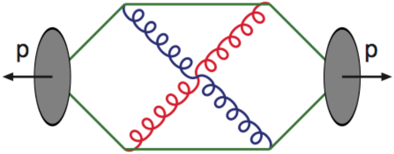


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, *gg* scatterings with "maximal" string length; solid line *gg* scatterings with "minimal" string length.

$\langle p_\perp \rangle(n_{\mathrm{ch}})$ sensitive to colour flow.



long strings to remnants
$\Rightarrow$ comparable n_{ch}/interaction
$\Rightarrow \langle p_\perp \rangle(n_{\mathrm{ch}}) \sim$ flat.



shorter extra strings
for each consecutive interaction
$\Rightarrow \langle p_\perp \rangle(n_{\mathrm{ch}})$ rising.

Short vs. long strings: the λ measure

λ is intended to gauge "phase space" for hadron production, $\lambda \propto \langle n_{\mathrm{hadrons}} \rangle \propto \langle n_{\mathrm{charged}} \rangle$.
For simple $\mathrm{q\overline{q}}$ string:

$$\lambda = \ln\left(\frac{m^2_{\mathrm{q\overline{q}}}}{m_0^2}\right)$$

with $m_0 \approx 1$ GeV measure of hadronic mass scale.
For $\mathrm{q\overline{q}g}$ instead

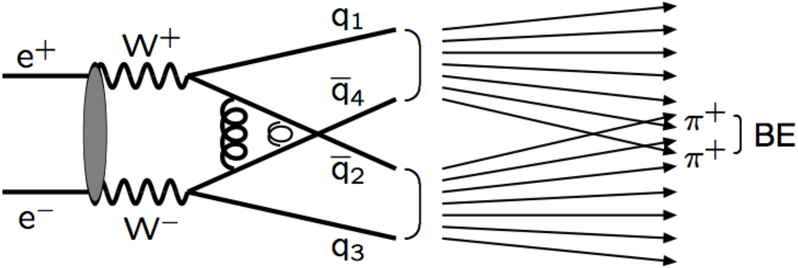
$$\lambda = \ln\left(\frac{m^2_{\mathrm{q\overline{q}g}}}{m_0^2} + \frac{m^2_{\mathrm{qg}} m^2_{\mathrm{\overline{q}g}}}{4m_0^4}\right) \approx \ln\left(\frac{p_{\mathrm{q}} + \frac{1}{2}p_g)^2}{m_0^2}\right) + \ln\left(\frac{p_{\mathrm{\overline{q}}} + \frac{1}{2}p_g)^2}{m_0^2}\right)$$

with simplification in limit $p_{\perp g} \gg m_0$. More generally, for $\mathrm{q_0 g_1 g_2} \cdots \mathrm{g}_n \mathrm{\overline{q}}_{n+1}$, with factor $\frac{1}{2}$ for gluon momentum,

$$\lambda \approx \sum_{i=0}^{n} \ln\left(\frac{m^2_{i,i+1}}{m_0^2}\right) \approx \sum_{i=0}^{n} \ln\left(1 + \frac{m^2_{i,i+1}}{m_0^2}\right)$$

Interconnection at LEP 2

$\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q_1\overline{q}_2\,q_3\overline{q}_4}$ reconnection limits m_{W} precision!



- perturbative CR $\langle \delta M_{\mathrm{W}} \rangle \lesssim 5$ MeV : negligible!
  (killed by dampening from off-shell W propagators)
- nonperturbative CR $\langle \delta M_{\mathrm{W}} \rangle \sim 40$ MeV
- Bose-Einstein $\langle \delta M_{\mathrm{W}} \rangle \sim 40$ MeV

V.A. Khoze & TS, PRL 72 (1994) 28;
L. Lönnblad & TS, EPJ C6 (1999) 271

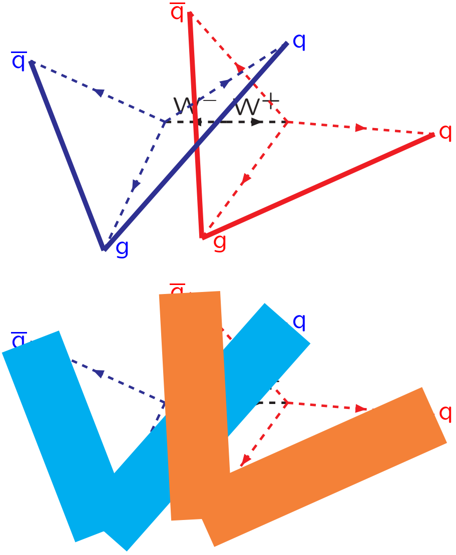
PYTHIA CR models for LEP 2

Colour reconnection studied in several models, e.g.

Scenario II: vortex lines.
Analogy: type II superconductor.
Strings can reconnect only if central cores cross.

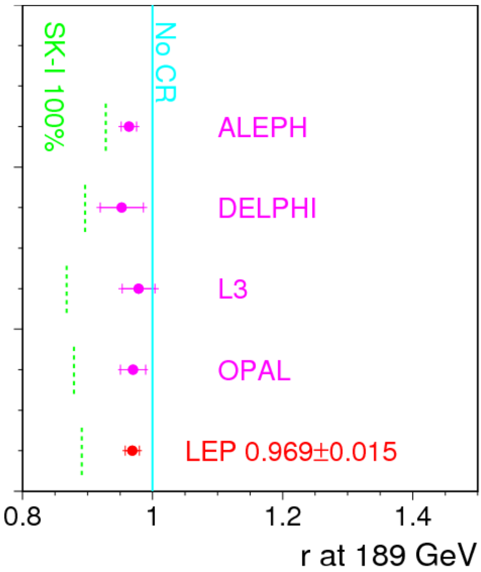
Scenario I: elongated bags.
Analogy: type I superconductor.
Reconnection proportional to space–time overlap.

In both cases favour reconnections that reduce total string length.



(schematic only; nothing to scale)

PYTHIA CR results at LEP 2



r: order 4 jets
as projected onto plane,
compare activity
between jets

Best LEP2 fit 2013
(topology + mass):
51% of 189 GeV events
reconnected in
SKI model.

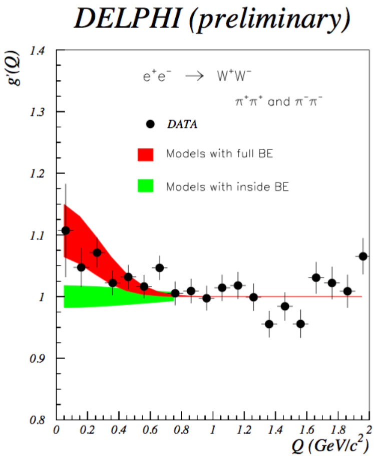
No-CR excluded
at 99.5% CL.

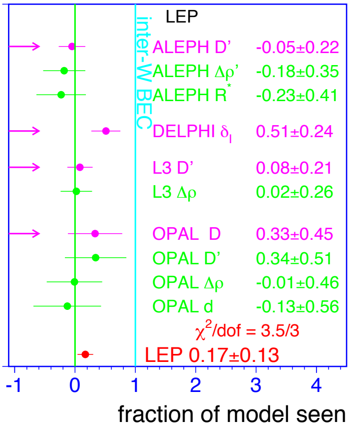
Comparison of CR models at LEP

authors reference	Khoze Sjöstrand [52]	Todorova [59]	Gustafson Häkkinen [53, 66]	Lönnblad [57]	Webber [58]
based on	PYTHIA		ARIADNE		HERWIG
reconnection criterion	space–time overlap (I) or crossing (II) of strings		string length reduced		cluster space–time sizes reduced
reconnection probability	I: free parameter II: partly predicted		free parameter	partly predicted	free parameter
model of all events	yes	yes	no	yes	yes
space–time picture implemented for					(— = not applicable)
W vertices	yes	yes	no	no	yes
parton shower	no	yes	—	—	yes
fragmentation	yes	yes	—	—	—
multiple reconnections	no	yes	yes	yes	yes
reconnection inside W/Z	no	yes	yes	yes	yes
change of event properties	almost invisible		small but visible	visible, needs retuning	large, needs retuning

+ some more, notably Ellis, Geiger:
space–time hadronization model $\Rightarrow \Delta m_{\mathrm{W}} \sim 400$ MeV

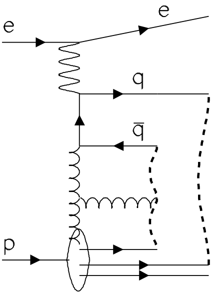
Bose–Einstein interconnection

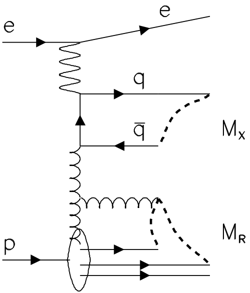




Combined result of 0.17±0.13 of full model effects
⇒ at most 7 MeV effect on W mass.

CR at HERA (and beyond)





Rapidity gaps observed at HERA: "diffractive DIS"

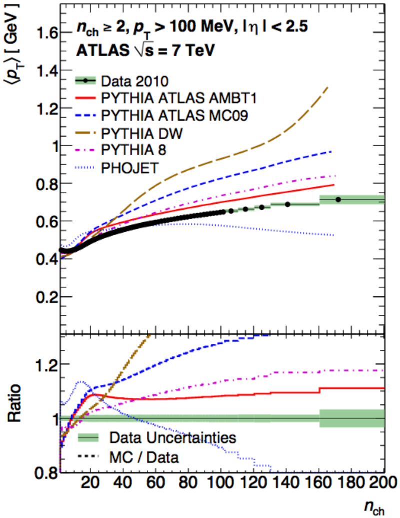
conventionally Pomeron explanation, but ...

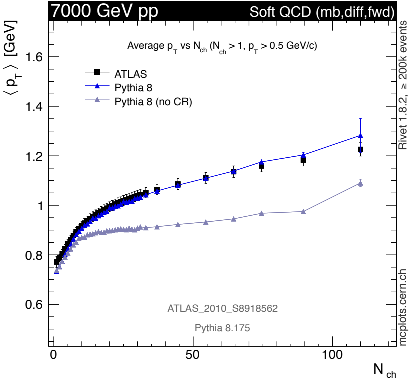
Ingelman et al. (Uppsala): SCI – Soft Colour Interactions
Extended to $\mathrm{pp}/\mathrm{p\bar{p}}$ and $\mathrm{e^+e^-}$, for quarkonium, W, Higgs, gaps between (Tevatron) jets, diffraction, etc.

Rathsman: GAL – Generalized Area Law: $P_{\mathrm{rec}} = 1 - \exp(-b\,\Delta A)$
where $A \approx \sum m^2$ unlike $\lambda \approx \sum \ln m^2 = \ln \prod m^2$

Reconnection at the LHC

$\langle p_\perp \rangle (n_{\mathrm{ch}})$ effect alive and kicking:





Reconnection important also for other generators, e.g. Herwig++, to describe this.

PYTHIA CR models for the LHC

Space–time models (a la LEP) too complicated and uncertain at the LHC $\Rightarrow$ simplified (in PYTHIA)

Common aspect: reduce string length $\lambda = \sum \ln(m_{ij}^2/m_0^2)$

In total 12 scenarios in PYTHIA 6, mainly annealing (P. Skands):

- $P_{\mathrm{reconnect}} = 1 - (1-\chi)^{n_{\mathrm{MPI}}}$ with χ strength parameter.
- Random assignment by $P_{\mathrm{reconnect}}$ for each string piece.
- Choose new combinations that reduce λ (with restrictions).

PYTHIA 8 initially only one model:

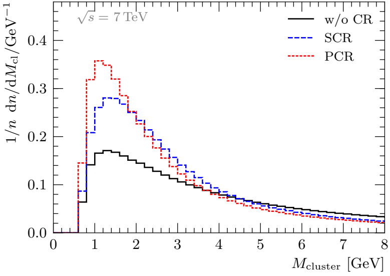
- probability for a lower-$p_{\perp}$ MPI to merge with a higher-$p_{\perp}$ is $P = r^2 p_{\perp 0}^2/(r^2 p_{\perp 0}^2 + p_{\perp \mathrm{lower}}^2)$, with r tuning parameter
- each gluon of the lower-$p_{\perp}$ MPI is put where it increases the λ the least for the higher-$p_{\perp}$ MPI
- $(\mathrm{g} \to)\mathrm{q}\overline{\mathrm{q}}$ pairs in same sprit, else q's connect to beams
- iterative, so $P_{\mathrm{tot}} = 1 - (1-P)^{n_>}$, $n_> = \#$ MPI with $> p_{\perp}$

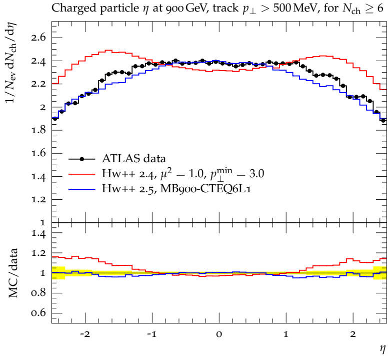
HERWIG++ CR models for the LHC

S. Gieseke, C. Röhr, A. Siódmok, EPJ C72 (2012) 2225

1) Plain CR: loop once through all q ends of clusters, reconnect clusters A and B into C and D by $\overline{\mathrm{q}}$ swap if $m_C + m_D < m_A + m_B$. Pick smallest if many possibilities for given A. Probability p_{reco}.

2) Statistical CR: (non-default) minimize $\sum m^2_{\mathrm{cluster}}$ by simulated annealing.





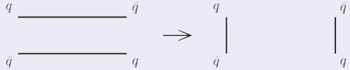
The new QCD-based CR model (1)

J. Christiansen & P. Skands, JHEP 1508 (2015) 003:

New model relies on two main principles

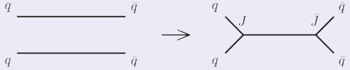
⋆ **SU(3)** colour rules give allowed reconnections

Ordinary string reconnection



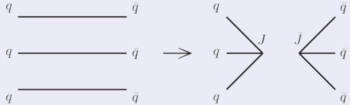
(q$\overline{\text{q}}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection



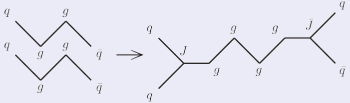
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



(q$\overline{\text{q}}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

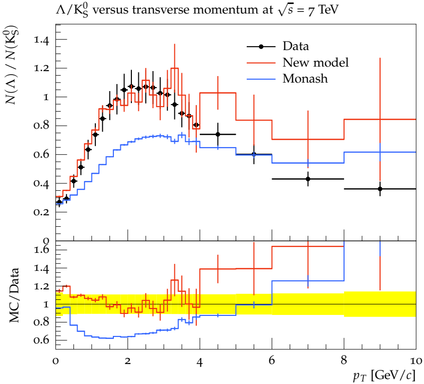


(Depends on number of gluons)

⋆ minimal λ measure gives preferred reconnections

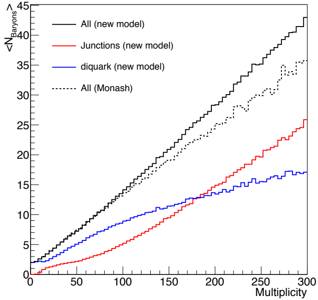
The new QCD-based CR model (2)

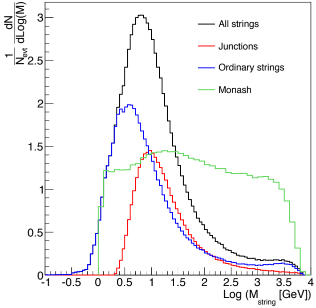
Comparison with LHC data:



(arXiv:1102.4282)

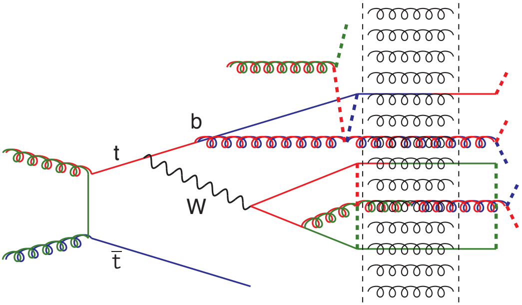
many baryons from junctions,
but few from regular strings
(big-mass string systems cut up!)





The top mass uncertainty from CR

$$\begin{aligned} \Gamma_t &\approx 1.5\ \mathrm{GeV} \\ \Gamma_W &\approx 2\ \mathrm{GeV} \\ \Gamma_Z &\approx 2.5\ \mathrm{GeV} \\ &\Rightarrow \\ c\tau &\approx 0.1\ \mathrm{fm} \end{aligned}$$



Decays occur when p "pancakes" have passed, after MPI/ISR/FSR with $p_\perp \geq 2$ GeV, but inside hadronization colour fields.

Experimentalists achieve impressive m_t precision,
e.g. CMS $m_t = 172.35 \pm 0.16 \pm 0.48$ GeV (PRD93 (2016) 072004),
whereof CR ± 0.10 GeV
from PYTHIA 6.4 Perugia 2011 |CR - noCR|
Is this realistic?

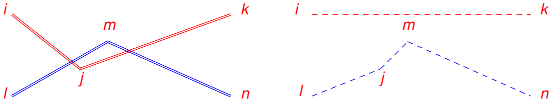
New CR models for top studies

S. Argyropoulos & TS, JHEP 1411 (2014) 043:

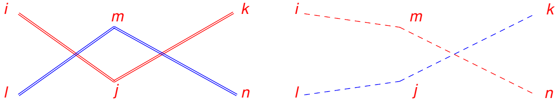
Late t decay: first ordinary CR (existing model) as if t stable, then CR between g's from t&W decays and g's from rest of event, in 5 variants, some "straw-man", e.g. random ($\Rightarrow \langle\lambda\rangle$ increases)

Early t decay: new "gluon-move" model for whole event

1) move: remove gluon and insert on other string if reduces λ

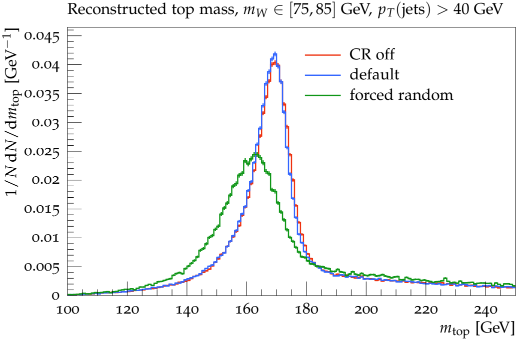


2) flip: cross two chains if reduces λ ($\sim$ swing)



3) (swap: interchange two gluons if reduces λ)

Effects on top mass before (re)tuning



Δm_{top} relative to no CR:

model	Δm_{top} [GeV]	Δm_{top} rescaled
default (late)	-0.415	$+0.209$
default early	$+0.381$	$+0.285$
forced random	-6.970	-6.508

Asymmetric spread:
$\Delta m_{\mathrm{top}} < 0$ easy,
$\Delta m_{\mathrm{top}} > 0$ difficult.

Parton showers already prefer minimal λ.

Main effect from jet broadening, some from jet–jet angles.

Effects on top mass after (re)tuning

No publicly available measurements of UE in top events.

- Afterburner models tuned to ATLAS jet shapes in $\mathrm{t\bar{t}}$ events
  $\Rightarrow$ high CR strengths disfavoured.
- Early-decay models tuned to ATLAS minimum bias data
  $\Rightarrow$ maximal CR strengths required to (almost) match $\langle p_{\perp} \rangle (n_{\mathrm{ch}})$.

model	Δm_{top} rescaled
default (late)	$+0.239$
forced random	-0.524
swap	$+0.273$

Δm_{top} relative to no CR

$$\mathbf{m_{top}^{max} - m_{top}^{min} \approx 0.80}\ \mathrm{GeV}$$

Excluding most extreme (unrealistic) models down to

$$\mathbf{m_{top}^{max} - m_{top}^{min} \approx 0.50}\ \mathrm{GeV}$$

(in line with Sandhoff, Skands & Wicke)

Studies of top events could help constrain models:

- jet profiles and jet pull (skewness)
- underlying event

CR at future e^+e^- colliders

J. Christiansen & TS, EPJ C75 (2015) 9, 441

FCC-ee promises $\Delta m_{\mathrm{W}} \leq 1$ MeV in semileptonic decays
$\Rightarrow$ test models e.g. by m_{W} shift in hadronic decays

Model	$\langle \delta \overline{m}_{\mathrm{W}} \rangle$ (MeV)		
	170 GeV	240 GeV	350 GeV
SK-I	+18	+95	+72
SK-II	-14	+29	+18
SK-II'	-6	+25	+16
GM-I	-41	-74	-50
GM-II	+49	+400	+369
GM-III	+2	+104	+60
CS	+7	+9	+4

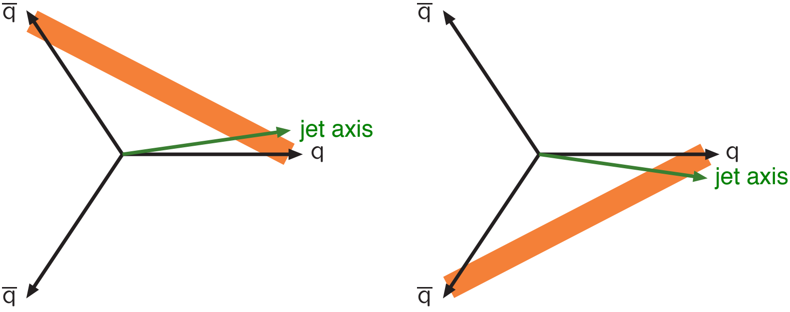
Further handles:
different m_{W} defs.
flow between jets
charged multiplicity
...

SK: LEP 2 space–time based models
GM: variants of "gluon move" model introduced for top studies
(I: only move; II: only flip; III: both)
CS: QCD-based model of Christiansen & Skands

Higgs *CP* Violation (1)

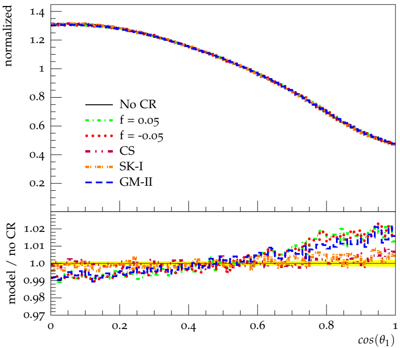
Is the 125 GeV Higgs a pure *CP*-even state? Any odd admixture?

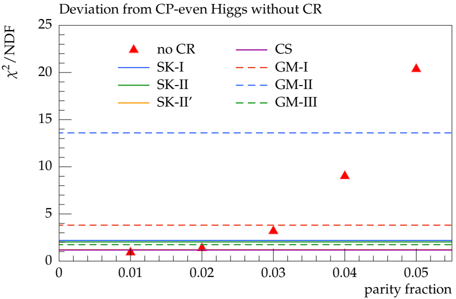
For LHC and future $\mathrm{e}^+\mathrm{e}^-$ (& $\mu^+\mu^-$?) colliders to probe.
One possibility is $\mathrm{H}^0 \to \mathrm{W}^+\mathrm{W}^- \to \mathrm{q}_1\overline{\mathrm{q}}_2\mathrm{q}_3\overline{\mathrm{q}}_4$.
Angular correlations put limits on odd admixture.



But: colour reconnection $\Rightarrow$ shifted jet directions
$\Rightarrow$ shifted angular correlations.

Higgs *CP* Violation (2)





$$f = \frac{\int \text{odd} + |\text{interference}|}{\int \text{all}}$$

Conclusion 1: only problem for constraints $f < 0.03 - 0.05$.

Conclusion 2:

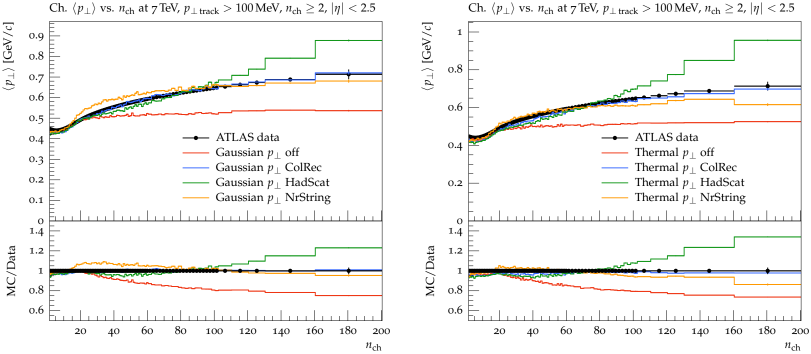
precision physics is not only a matter of higher orders.

CR and collective flow

Collective flow observed in pp at LHC. Partly unexpected.
New mechanisms required; could also (partly) replace CR.

Active field, e.g. N. Fischer & TS, arXiv:1610:09818 [hep-ph]:

- Thermal $exp(-p_{\perp}/T) \rightarrow exp(-m_{\perp}/T)$ hadronic spectrum.
- Close-packed strings $\Rightarrow$ increased string κ or T.
- Dense hadronic gas $\Rightarrow$ hadronic rescattering.



Summary and outlook

LEP/FCC-ee:

- CR convincingly demonstrated at LEP 2, but not iron-clad.
- Future high statistics & precision would distinguish models.
- CR could influence precision studies, e.g. Higgs $\cancel{CR}$.

LHC/FCC-pp:

- Historically introduced to explain $\langle p_{\perp} \rangle(n_{\mathrm{ch}})$.
- Later key for many observables, e.g. UE "pedestal effect".
- Wide range of models, but usually involving λ minimization (for PYTHIA strings; size or mass for HERWIG clusters).
- New observations of collective flow, from ridge and v_n to a change of flavour composition with event multiplicity $\Rightarrow$ **traditional PYTHIA framework under attack!**
- QGP? String close-packing? Hadronic rescattering? Other? Most likely (?): cocktail of effects, including CR.