PYTHIA and the Higgs

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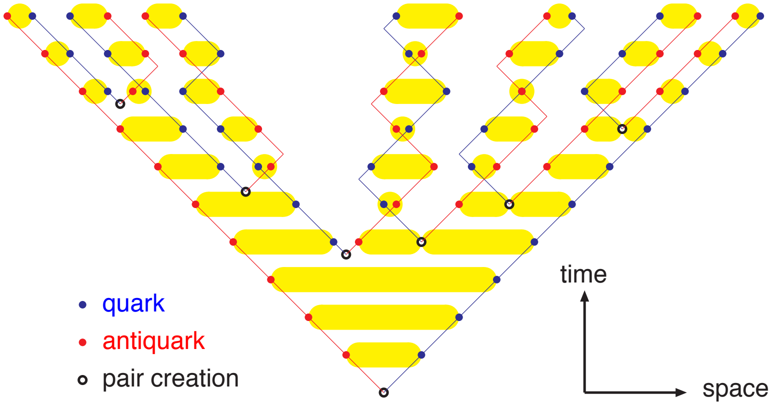
Higgs Hunting,
Orsay/Paris, 23 – 25 Sep 2024

In the beginning

- 1977 – 1982: development of Lund string fragmentation, assuming linear confinement $V(r) = \kappa r$, $\kappa \approx 1$ GeV/fm (Bo Andersson, Gösta Gustafson, students).
- 1978: first implementation in JETSET code, for fragmentation and (in 1979) $\mathrm{e^+e^-}$ annihilation (TS, (Bo Söderberg)).
- 1980: breakthrough in 3-jet study by JADE at PETRA.
- 1980: LEPTO code for leptoproduction, using JETSET (Gunnar Ingelman, TS).
- 1982: PYTHIA code for $\mathrm{pp}/\mathrm{p\overline{p}}$ collisions, using JETSET (Hans-Uno Bengtsson).

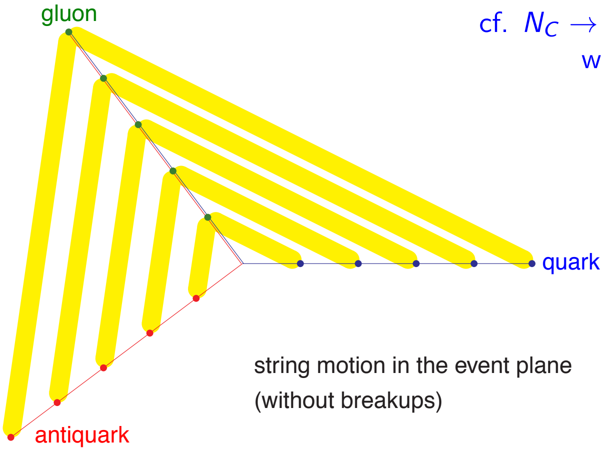
The Lund Model for a $q\overline{q}$ system



String pulled out as q and $\overline{q}$ move apart, shifting energy to it.
String breakup by new $q\overline{q}$ production, giving mesons.
Breakup vertices approximately along hyperbola
of constant invariant time, with spacelike separation
$\Rightarrow$ can use recursive fragmentation from ends inwards.

The Lund Gluon Picture

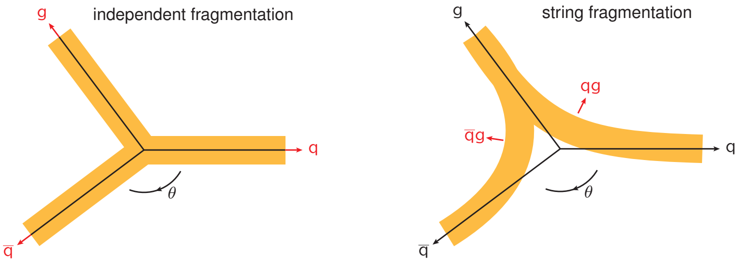
A gluon carries one colour and one anticolour. Thus it can be viewed as a kink on the string, carrying energy and momentum:

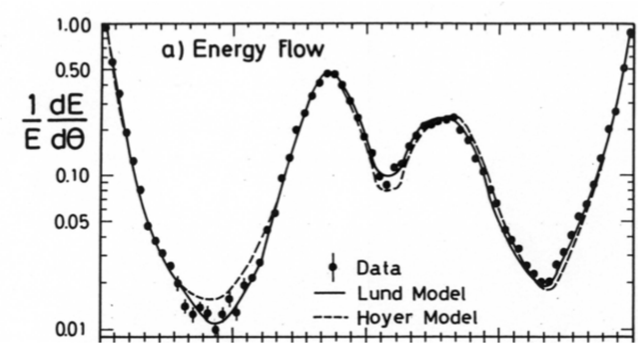


cf. $N_C \to \infty$ (planar QCD)
where $N_C / C_F = 2$.
('t Hooft, 1973)

The most characteristic feature of the Lund model.

The JADE Effect

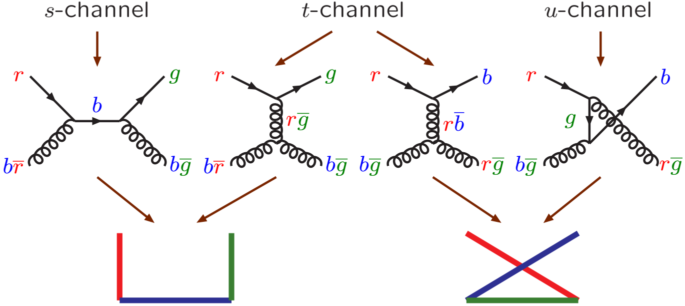




3 jets energy-ordered.
JADE (1980, 1983)

Colour topologies in pp

Colour flow nontrivial in pp collisions, e.g. $\mathrm{qg} \to \mathrm{qg}$:



$$\frac{\mathrm{d}\hat{\sigma}_A}{\mathrm{d}\hat{t}} = \frac{\pi\alpha_\mathrm{s}^2}{\hat{s}^2}\,\frac{4}{9}\,\left(2\frac{\hat{u}^2}{\hat{t}^2} - \frac{\hat{u}}{\hat{s}}\right) \qquad \frac{\mathrm{d}\hat{\sigma}_B}{\mathrm{d}\hat{t}} = \frac{\pi\alpha_\mathrm{s}^2}{\hat{s}^2}\,\frac{4}{9}\,\left(2\frac{\hat{s}^2}{\hat{t}^2} - \frac{\hat{s}}{\hat{u}}\right)$$

$$\frac{\mathrm{d}\hat{\sigma}_{A+B}}{\mathrm{d}\hat{t}} = \frac{\pi\alpha_\mathrm{s}^2}{\hat{s}^2}\left(\frac{8}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} - \frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\,\hat{u}}\right)$$

where $\mathcal{O}(1/N_C^2)$ colour interference term makes $8/9 \to 1$.

PYTHIA raison d'être: split full $\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}$ by colour flow fractions!

A first Higgs encounter – 1

DORIS II: e^+e^- ring with $\sqrt{s} \approx 10$ GeV.
Crystal Ball: EM calorimeter, QED transitions in Υ system.
ARGUS: multipurpose detector for B meson decay at $\Upsilon(4s)$.

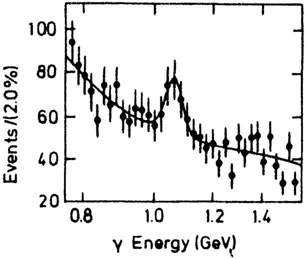
EVIDENCE FOR A MASSIVE STATE IN THE RADIATIVE DECAYS OF THE UPSILON

Hans-Jochen Trost (representing CB Collaboration*)
Deutsches Elektronen-Synchrotron

D-2000 Hamburg 52, Notkestr. 85, Fed. Rep. of Germany

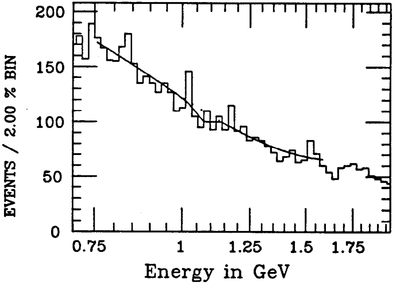
ABSTRACT: Evidence is presented for a state, which we call ζ, with a mass $M = (8322 \pm 8 \pm 24)$ MeV and a line width $\Gamma < 80$ MeV (90% confidence level) obtained using the Crystal Ball NaI(Tl) detector at DORIS II. The branching ratio to this state from the $\Upsilon(1S)$ is of order 0.5%.

The interpretation of this new state as the neutral Higgs boson expected in the standard model gives a disagreement of approximately two orders of magnitude between this observed branching ratio and that predicted. This branching ratio can be accomodated in some extensions of the standard model, e.g. two-Higgs doublet models. A less model-dependent quantity is



mass 8.32 GeV
branching ratio 0.5%
significance 4.0 σ
presented at ICHEP 1984

New data taken autumn 1984, presented at Moriond 1985:



THE STATUS OF THE $\varsigma(8.3)$*

Stephen T. Lowe

(Representing the Crystal Ball Collaboration)[1]

Stanford Linear Accelerator Center

Stanford University, Stanford, California 94305

ABSTRACT

Results are presented from 22.1 pb^{-1} of $\Upsilon(1S)$ data, taken with the Crystal Ball detector at DORIS. These data were taken to further explore the $\varsigma(8.3)$ signal originally seen in 10.4 pb^{-1} of $\Upsilon(1S)$ data.[2] No evidence for the ς is observed in this new sample. Data quality checks and possible explanations are discussed.

1984 "signal" $= -29 \pm 29$ events $\Rightarrow BR(\Upsilon \to \gamma\zeta) < 0.08\%$.
Combined 1983 + 1984 significance 1.9 σ.
Not heard of since.

Birth of the SSC project (?).
Aimed at physics at the TeV scale.

spring 1984: "Supercollider physics"
by E. Eichten, I. Hinchliffe, K. Lane, C. Quigg

- 18 pp PDFs
- 21 pp QCD jets
- 15 pp EW gauge bosons
- 9 pp Higgs, singly and associated
- 17 pp Technicolor
- 8 pp new Q, ℓ, Z'^0, $\mathrm{W}'^\pm$
- 16 pp Supersymmetry
- 14 pp compositeness

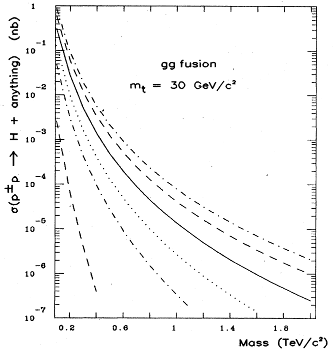


FIG. 146. Integrated cross sections for Higgs-boson production by gluon fusion in $p^{\pm}p$ collisions, for $m_t = 30$ GeV/c^2 at $\sqrt{s} = 2$, 10, 20, 40, 70, and 100 TeV, according to Set 2 of the distributions.

Snowmass 1984

Boundless optimism! Reagan Star Wars atmosphere!
Reestablish US leadership after CERN Z^0 and $\mathrm{W}^\pm$ discoveries.
SSC design parameters $\sqrt{s} = 40$ TeV, $\mathcal{L} = 10^{33}$ cm^{-2}s^{-2}.

The no-lose theorem

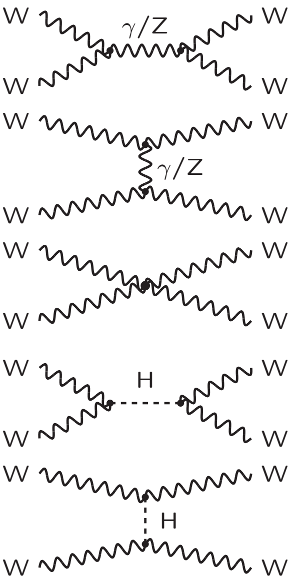
Either there are light (≤ 1 TeV) particles
from EW symmetry breaking
that can be produced and studied directly

and/or

excess WW, WZ, ZZ production is observable,
signalling strongly coupled symmetry-breaking sector
with masses ≥ 1 TeV.

(this formulation: M. Chanowitz 1987;
divergence issue noted by Dicus and Mathur, and Veltman)

Taming the divergence



$|\mathcal{M}| \propto s^2$

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$|\mathcal{M}| \propto s$

$|\mathcal{M}| \propto s$

$|\mathcal{M}| \propto s$

$|\mathcal{M}|$ constant

Asymptotic behaviour of WW $\to$ WW dominated by $W_L W_L \to W_L W_L$

Recall
$\sigma \propto |\mathcal{M}|^2/s$
so $|\mathcal{M}|$ constant required for unitarity

Event generators summer 1984

generator	ISAJET	FIELDAJET	COJETS WIZJET	PYTHIA JETSET
processes	2jet W/Z (?) soft	2jet	2jet W/Z	2jet γ+jet
Higgs	no	no	no	no
initial-state rad	no	forward, hit-and-miss	forward, pretabulation	no
final-state rad	incoherent	incoherent	incoherent	no
colour flow	no	no	no	yes
fragmentation	independent	independent	independent	string
gluon jet	like quark	like quark	like quark	$\approx \mathrm{q\overline{q}}$
beam remnants	leading baryon + cut Pomerons	remnant jets	leading baryon + longitudinal phase space	remnant jets
time per event	0.05 s	120 s	0.1 s	0.1 s
code	public	private	public	public

Others: Webber, Capella et al., Ranft et al., Preparata, . . .

PYTHIA development 1984 – 1986

- Hans-Uno Bengtsson now at UCLA; collaborate via BITNET. Gunnar Ingelman at CERN; no connection $\Rightarrow$ dropped out.
- Several workshops: Eugene, Oregon spring/summer 1985; UCLA January 1986; Madison May 1986.
- Final-state radiation (FSR): Marchesini–Webber.
- Initial-state radiation (ISR): backwards evolution.
- Multiparton interactions (MPI): underlying event.
- Minimum bias, elastic, diffractive events.
- Gauge bosons: $\mathrm{W}^{\pm}, \gamma^*/\mathrm{Z}^0, \gamma\gamma, \mathrm{W}^{\pm}/\mathrm{Z}^0 + \mathrm{jet}, \mathrm{W}^{\pm}/\mathrm{Z}^0 + \gamma$, $\mathrm{W}^+\mathrm{W}^-, \mathrm{Z}^0\mathrm{Z}^0, \mathrm{W}^{\pm}\mathrm{Z}^0$ (+ angular correlated decays).
- Higgs: $\mathrm{gg} \to \mathrm{H}^0, \mathrm{q}\overline{\mathrm{q}} \to \mathrm{H}^0$ (including top, $m_{\mathrm{t}} = 40$ GeV), $\mathrm{W}_L^+\mathrm{W}_L^- \to \mathrm{H}^0, \mathrm{Z}_L^0\mathrm{Z}_L^0 \to \mathrm{H}^0$, $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{H}^0 + \mathrm{W}^{\pm}/\mathrm{Z}^0$ (+ always H^0 decays).
- Exotica: $\mathrm{q}\overline{\mathrm{q}} \to \gamma^*/\mathrm{Z}^0/\mathrm{Z}'^0, \mathrm{q}\overline{\mathrm{q}} \to \mathrm{H}^{\pm}, \mathrm{q}\overline{\mathrm{q}} \to R^0$.

Effective W Approximation

Recall: longitudinal $\mathrm{W}_L/\mathrm{Z}_L$ are "eaten" Higgs fields of SSB
$\Rightarrow \mathrm{W}_L^+\mathrm{W}_L^-/\mathrm{Z}_L^0\mathrm{Z}_L^0 \to \mathrm{H}^0$ dominates for large m_{H} ($\geq$ 600 GeV).
Can define effective flux like EPA or DGLAP splitting kernels

$$f_{\gamma/\mathrm{q}}(x) = \frac{\alpha_{\mathrm{em}} e_{\mathrm{q}}^2}{2\pi} \, \frac{1 + (1-x)^2}{x}$$

$$f_{\mathrm{Z}_L/\mathrm{q}}(x) = \frac{\alpha_{\mathrm{em}} (g_{v,\mathrm{q}}^2 + g_{a,\mathrm{q}}^2)}{4\pi \sin^2\theta_W \cos^2\theta_W} \, \frac{1 - x + m_{\mathrm{Z}}^2/\hat{s}}{x - m_{\mathrm{Z}}^2/\hat{s}}$$

$$f_{\mathrm{W}_L/\mathrm{q}}(x) = \frac{\alpha_{\mathrm{em}}}{4\pi \sin^2\theta_W} \, \frac{1 - x + m_{\mathrm{W}}^2/\hat{s}}{x - m_{\mathrm{W}}^2/\hat{s}} \, (\times \mathrm{CKM})$$

(Kane, Repko, Rolnik; Dawson; Chanowitz, Gaillard)
Full calculation $\mathrm{q}_1\mathrm{q}_2 \to \mathrm{q}_3\mathrm{q}_4\mathrm{H}^0$ at border of feasibility
$\Rightarrow$ integrate out Q_1^2, Q_2^2 for simplified cross sections,
but in Monte Carlo full care with scattered-quark kinematics.

Snowmass 1986

- Active subgroup "W/Z Pairs and the Higgs at the SSC".
  Theory coordinator: John F. Gunion (Davis).
  Experimental coordinator: Aurore Savoy-Navarro (Saclay).
- ISAJET and PYTHIA used for studies, including cross-checks; tutorials by Frank Paige and TS+HUB.
- Three large reports: one theory,
  one experiment over broad Higgs mass range,
  one ditto on "high-mass" Higgs with $m_{\mathrm{H}} = 300$ or 800 GeV.

HZZ800EE (P>1GEV CH TKS)

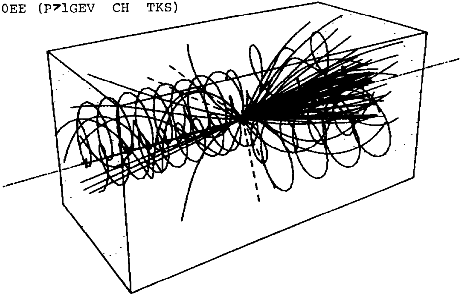
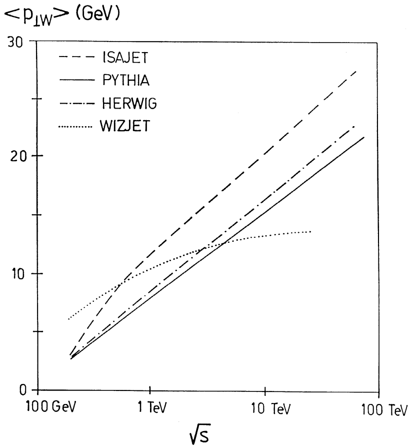


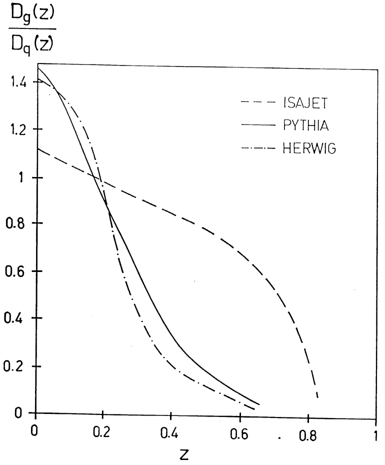
Figure 43

PYTHIA event
D0-like detector
GEANT 3 tracking

Generator comparisons (1988)

Significant differences between generators in many respects:





(TS, Z.Phys. C42, 301)

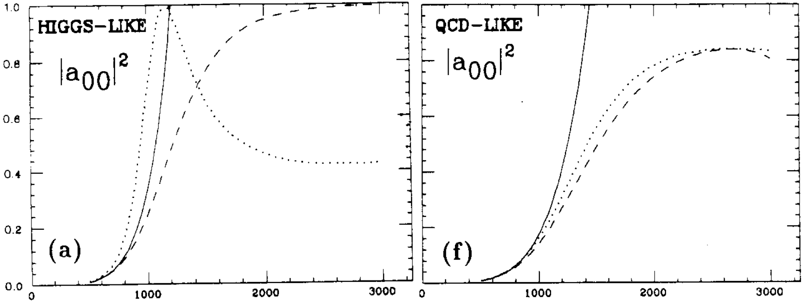
Aachen 1990

- LEP tunnel intended to allow pp collider.
- LHC workshops: Lausanne 1984, La Thuile 1987.
- 1989: LEP workshop and LEP startup.
- SSC to be ready 1999, so Rubbia promises LHC by 1998; push/pull with LEP experiments.
- 1989 autumn: first contact with LHC studies (Daniel Froidevaux, Louis Fayard, . . .).
- 1990 intense series of CERN meeting leading up to Aachen: the peak of theory and Monte Carlo preparations (?).
- Evian 1992: collaboration formation, technology choices.

Gauge boson scattering

Gauge boson pair scattering $\mathrm{V}_L \mathrm{V}_L \to \mathrm{V}_L \mathrm{V}_L$, $\mathrm{V} = \mathrm{Z}^0$ or $\mathrm{W}^\pm$, complements/supersedes $\mathrm{V}_L \mathrm{V}_L \to \mathrm{H}^0$.

What if heavy/no Higgs?
Exemplified by Dobado, Herrero, Terron:
Higgs-like or QCD-like symmetry breaking with
Padé approximants or K-matrix unitarization ($a \to a/(1 - ia)$).

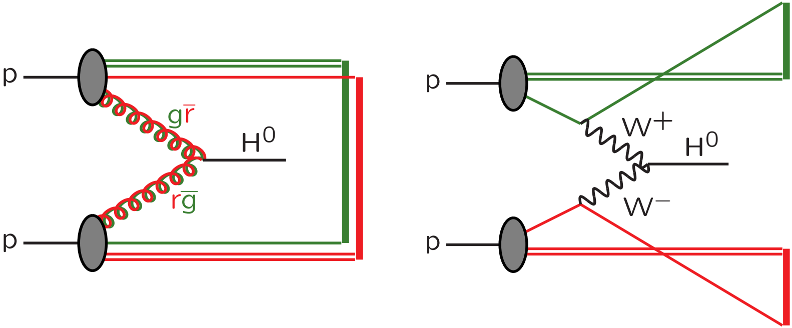


So broad range of possible high-energy behaviours available.

Other ∼1990 Higgs issues

- Running quark masses affects production and decays, notably $m_{\mathrm{b}}(m_{\mathrm{b}}) \approx 4.5$ GeV $\Rightarrow m_{\mathrm{b}}(m_{\mathrm{H}}) \approx 3$ GeV.
- Relaxed MSSM constraint $m_{\mathrm{H}} < m_{\mathrm{Z}}$. (Bad news for LEP2.)
- Off-shell decays $\mathrm{H}^0 \to \mathrm{W}^{(*)+}\mathrm{W}^{(*)-}, \mathrm{Z}^{(*)0}\mathrm{Z}^{(*)0}$.
- Running H width: $\Gamma_{\mathrm{H}} \propto m_{\mathrm{H}}^3 \to \hat{s}^{3/2}$ or $\to m_{\mathrm{H}}^2\sqrt{\hat{s}}$ (Seymour 1995; former usually but latter for $\mathrm{WW/ZZ}$).
- Full $\mathrm{q_1q_2} \to \mathrm{q_3q_4H^0}$ ($\mathrm{WW/ZZ}$ fusion).
- $\mathrm{gg/q\overline{q}} \to \mathrm{Q\overline{Q}H^0}$ (but background $\mathrm{gg/q\overline{q}} \to \mathrm{Q\overline{Q}Z^0}$ tough).
- $\mathrm{gg} \to \mathrm{gH^0}, \mathrm{qg} \to \mathrm{qH^0}, \mathrm{q\overline{q}} \to \mathrm{gH^0}$.
- Generalize almost all H^0 processes to H'^0 and A^0, with flexible couplings or MSSM-based ones.
- Some more $\mathrm{H}^{\pm}$ processes, including couplings as above.
- $\mathrm{Z}'^0 \to \mathrm{Z^0H^0}$ and $\mathrm{W}'^{\pm} \to \mathrm{W^{\pm}H^0}$ in left–right symmetry.
- $\mathrm{q} \to \mathrm{f} = \mathrm{q}$ or ℓ where relevant (LEP2, other $\mathrm{e^+e^-}$ or $\mu^+\mu^-$).

Rapidity gaps



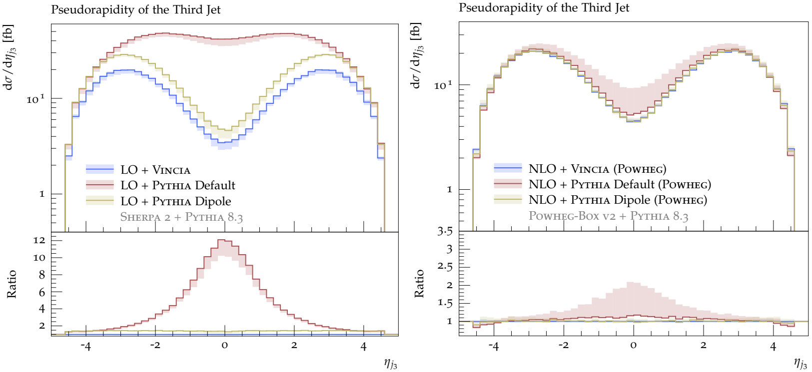
1986, Dokshitzer, Khoze, Troyan: rapidity gap in $W^+W^- \to H^0$
1986, we: already included, but masked by MPI, showers, ...
1991, Dokshitzer, Khoze, TS: more detailed study
1991, Bjorken: rapidity gap survival probability,

$$\langle |S|^2 \rangle \approx 0.1 \approx P(n_{\mathrm{MPI}} = 0)$$

2017: ISR dipole recoil option, gives less radiation into gap region

Rapidity gap closeup

Vector Boson Fusion, neglect Higgs, require two well-separated "tagging" jets, study third jet (if any):



Default: momentum exchange possible between two event sides.

Dipole: separate event sides, each like a DIS event.

(S. Höche et al., arXiv:2106.10987)

The last 30+ years

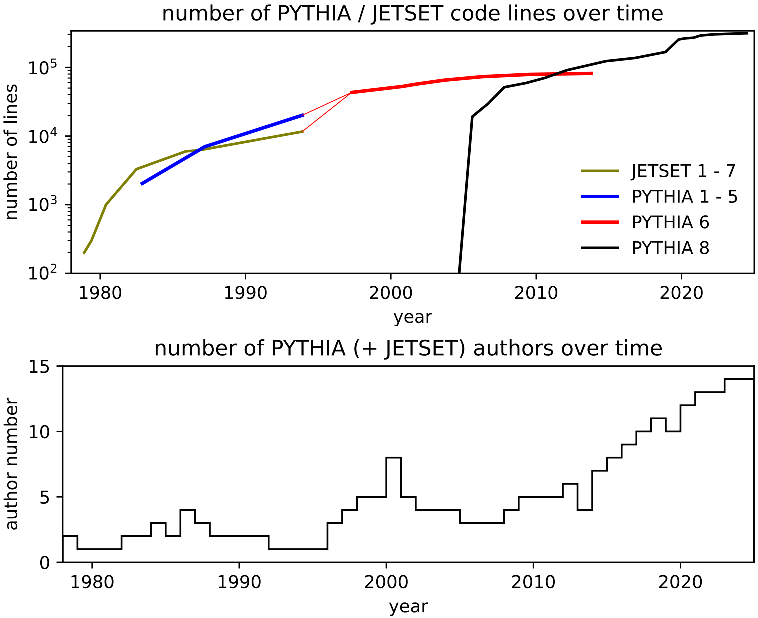
Evolution from "qualitative understanding" to "precision theory".

- Automated calculation and sampling of matrix elements.
- Higher orders: NLO, NNLO, N^{3}LO, multijets
- Matching and merging of matrix elements and parton showers.
- $m_{\mathrm{t}} = 40$ GeV $\to$ 172 GeV.

Many PYTHIA physics/utility extensions in different directions.

- **Few with direct bearing on Higgs physics.**
- Exception 1: Technicolor Straw Man Model (Lane).
- Exception 2: alternative dipole recoil in VBF.
- Not only LHC, but also TESLA, CLIC, ILC, FCC-ee, ...

Code and author size



Summary and Outlook

- PYTHIA rapidly expanded 1984 – 1990, in many directions, but notably to support Higgs searches.
- Since then extensively used standalone for LHC detector design and early search/analysis strategies.
- Gradually integrated with other tools, like Madgraph.

- **The Higgs was discovered 2012**, at an “optimal” mass; all high-mass scenarios and much Monte Carlo code “useless”.
- No signs of BSM. Notably no SUSY to explain H mass.
- Higgs as portal to BSM, like Hidden Valley in PYTHIA.
- No current Higgs physics development in PYTHIA, but ready to reactivate if needed.