The Tyranny of Carlo

J. D. Bjorken

"Another change that I find disturbing is the rising tyranny of Carlo. No, I don't mean that fellow who runs CERN, but the other one, with first name Monte.

The simultaneous increase in detector complexity and in computation power has made simulation techniques an essential feature of contemporary experimentation. The Monte Carlo simulation has become the major means of visualization of not only detector performance but also of physics phenomena. So far so good.

But it often happens that the physics simulations provided by the the MC generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data. All Monte Carlo codes come with a GIGO (garbage in, garbage out) warning label. But the GIGO warning label is just as easy for a physicist to ignore as that little message on a packet of cigarettes is for a chain smoker to ignore. I see nowadays experimental papers that claim agreement with QCD (translation: someone's simulation labeled QCD) and/or disagreement with an alternative piece of physics (translation: an unrealistic simulation), without much evidence of the inputs into those simulations."

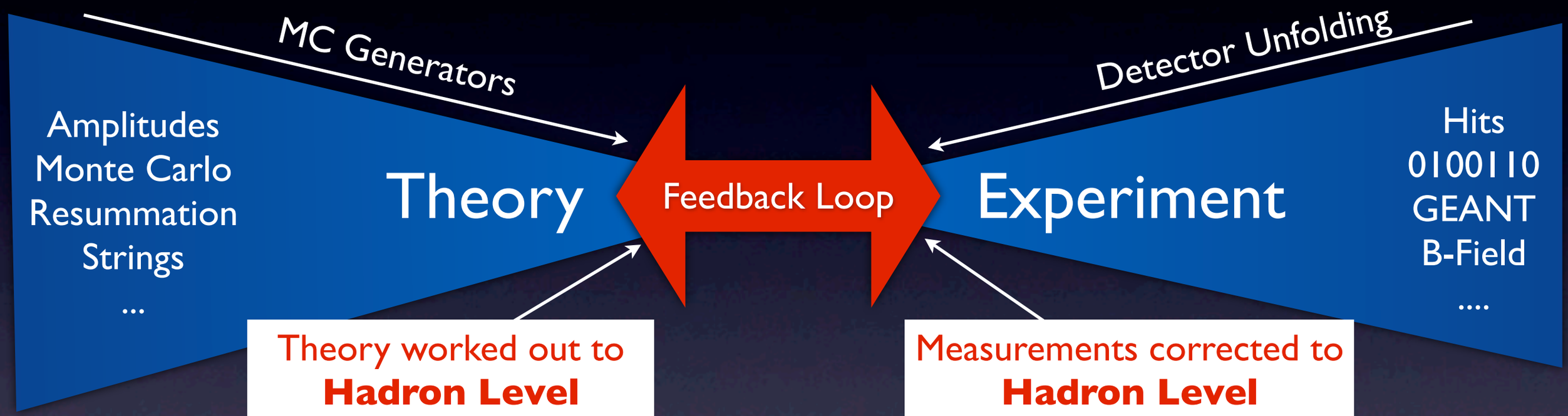
Authors: can we do better than the GIGO label? Uncertainty Bands
Users: account for parameters and report on pertinent cross-checks and validations

Count what is Countable

Measure what is Measurable

(and keep working on the beam)

G. Galilei



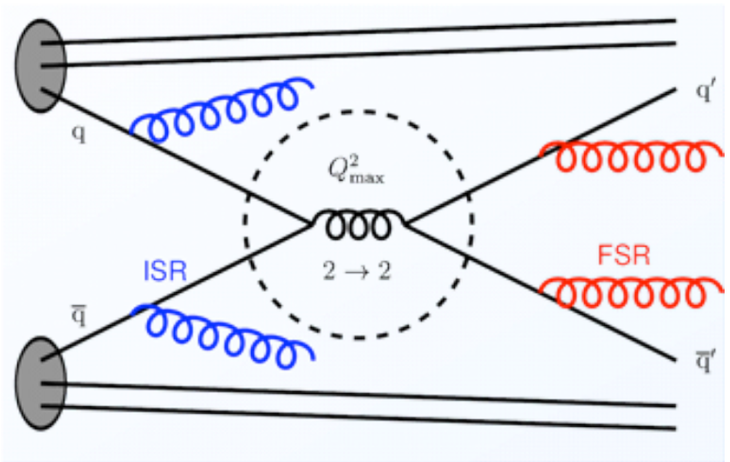
Theory worked out to
Hadron Level
with acceptance cuts
(~ detector-independent)

Measurements corrected to
Hadron Level
with acceptance cuts
(~ model-independent)

If not worked out to hadron level: data must be unfolded with *someone else's* hadron-level theory

Unfolding beyond hadron level dilutes precision of raw data (Worst case: data unfolded to ill-defined 'MC Truth' or 'parton level')

Monte Carlo Generators



Calculate Everything ≈ solving QCD → requires compromise!

Improve Born-level perturbation theory, by including the 'most significant' corrections
→ complete events → any observable you want

1. *Parton Showers*
2. *Matching*
3. *Hadronisation*
4. *The Underlying Event*

roughly

1. *Soft/Collinear Logarithms*
2. *Finite Terms, "K"-factors*
3. *Power Corrections (more if not IR safe)*
4. *?*

(+ many other ingredients: resonance decays, beam remnants, Bose-Einstein, ...)

Monte Carlos and Precision

- **A Good Physics** Model gives you
  - **Reliable calibrations** for both signal and background (e.g., jet energy scales)
  - **Reliable corrections** (e.g., track finding efficiencies)
  - **Background estimates** with as small uncertainty as possible (fct of both theoretical accuracy and available experimental constraints)
  - **Reliable discriminators** with maximal sensitivity to New Physics

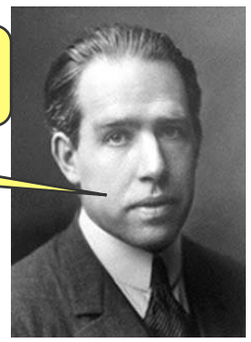
Compromises

- The present state of phenomenology
  - Heavily based on semi-classical approximations
    - Leading Order, Leading Log, Leading Color, semi-classical string models
  - Sufficient to reach O(10%) accuracy (with hard work)
    - ➔ sufficient to get overall picture during first few years of LHC running

The Problem of Measurement

- It is tempting to correct measurements for “annoying” effects
  - Measurements are performed on long-lived / macroscopic objects which are almost classical

Correspondence: Large quantum numbers → classical



Niels Bohr (1885-1962)

Monte Carlo Truth

- **Example:** $Z \rightarrow \mu\mu$ p_T distribution.
  - **Measured: final-state** leptons (+ photons)
  - **QED is "known"** - use MC/model to correct back to "True Z boson"
  - **Now can compare** to theory without QED

One tends to twist fact to suit theory...

The "Q" in QED

- "MC Truth" **is:** useful indicator of dominant path.
  Equivalent to Young knowing which slit the photon passed through!

In Quantum Mechanics

- **Photons emitted off** other particles *interfere* with those from Z decay - *no unique FSR correction*
- **Leptons from Z decay** may interfere with other leptons in event - *no unique lepton assignment*

- "MC Truth" **is not:** quantum mechanically meaningful

A Proposal

G. Hesketh et al., in arXiv:1003.1643

- **While it is** essential to provide the data in terms of observables, it may still be desirable to derive further theoretical corrections for comparisons ...
- We recommend such correction factors be provided in a table, rather than being applied to the data.
- Using this table, (the inverse of) such corrections could also be applied to allow direct comparisons of cruder models to the data while maintaining the separation of measurement and theory

Twist theory to suit fact...

A Quantum Paradigm

(listen to Niels!)

Minimize dependence on theoretical assumptions

Whatever you do ...
Define it in terms of
Physical Observables
(with as small corrections as possible)

THEN
Extract theoretical quantities
from those observables

From here on

"Monte Carlo Truth"

Starting Point

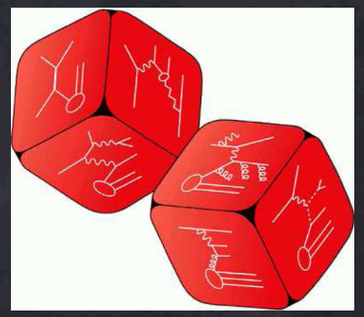
$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \sum_{a,b}\sum_{f}\int_{\hat{X}_f} f_a(x_a, Q_i^2) f_b(x_b, Q_i^2)\, \frac{\mathrm{d}\hat{\sigma}_{ab\to f}(x_a, x_b, f, Q_i^2, Q_f^2)}{\mathrm{d}\hat{X}_f}\, D(\hat{X}_f \to X, Q_i^2, Q_f^2)$$

Want to generate events

In as much detail as Mother Nature

Get average and fluctuations right

Make random choices ≈ as in nature



$$\sigma_{\text{final state}} = \sigma_{\text{hard process}}\, \mathcal{P}_{\text{tot,hard process}\to\text{final state}}$$

where $\mathcal{P}_{\text{tot}} = \mathcal{P}_{\text{res}}\, \mathcal{P}_{\text{ISR}}\, \mathcal{P}_{\text{FSR}}\, \mathcal{P}_{\text{MI}} \mathcal{P}_{\text{remnants}}\, \mathcal{P}_{\text{hadronization}}\, \mathcal{P}_{\text{decays}}$

with $\mathcal{P}_i = \prod_j \mathcal{P}_{ij} = \prod_j \prod_k \mathcal{P}_{ijk} = \ldots$ in its turn

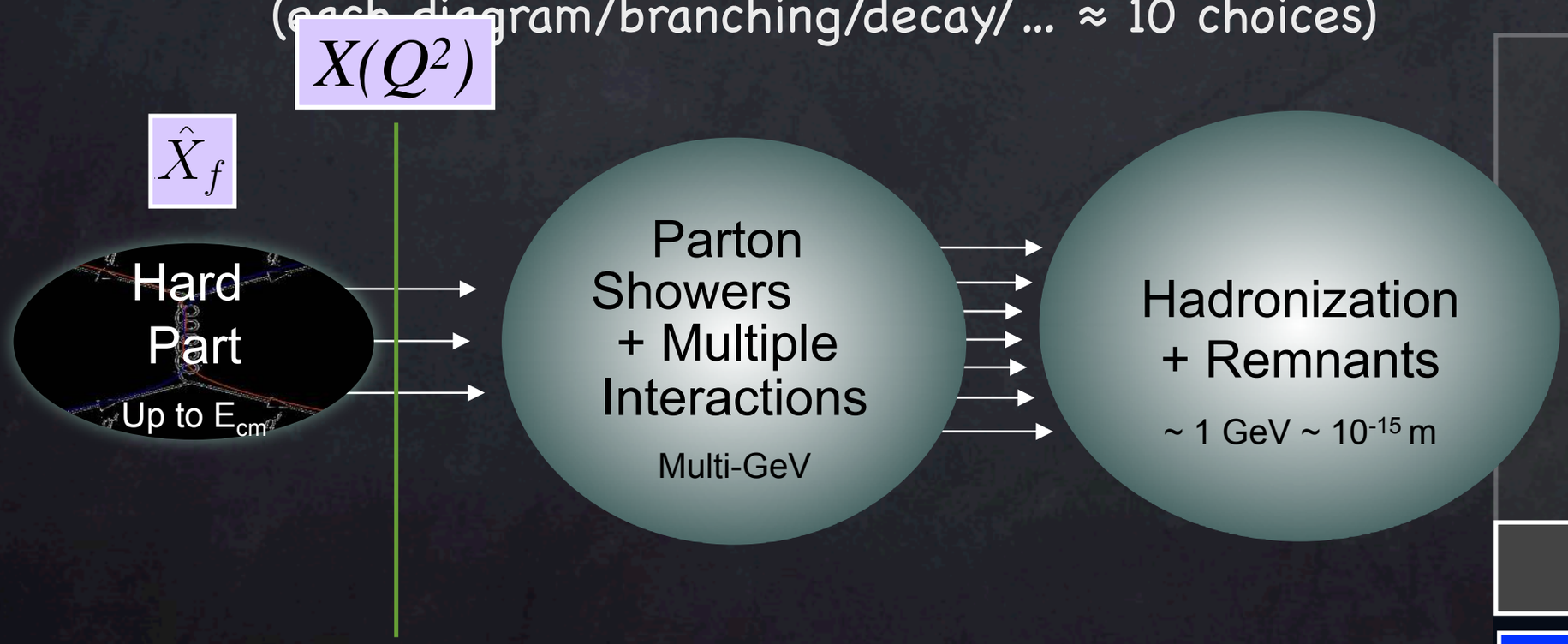
$\Longrightarrow$ **divide and conquer**

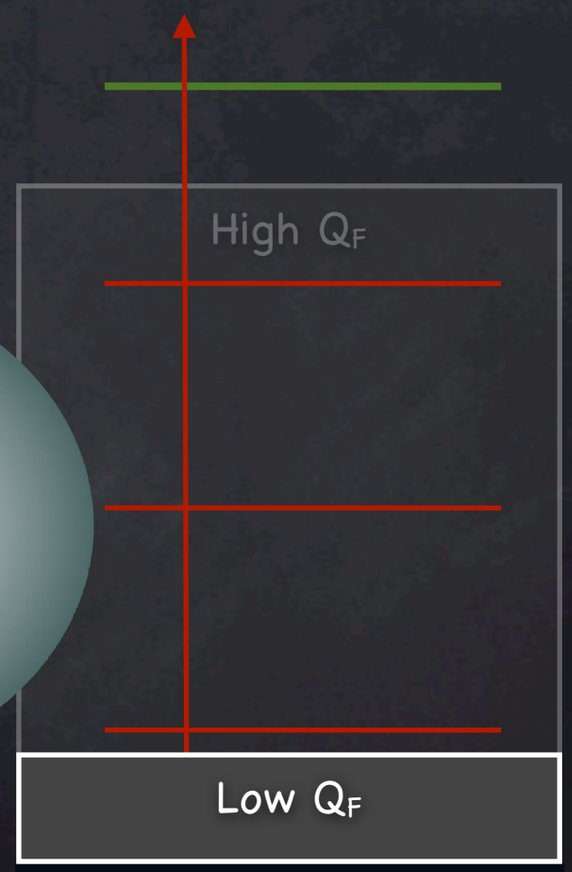
Evolution

An event with n particles

Involves O(10n) random choices

(each diagram/branching/decay/... ≈ 10 choices)





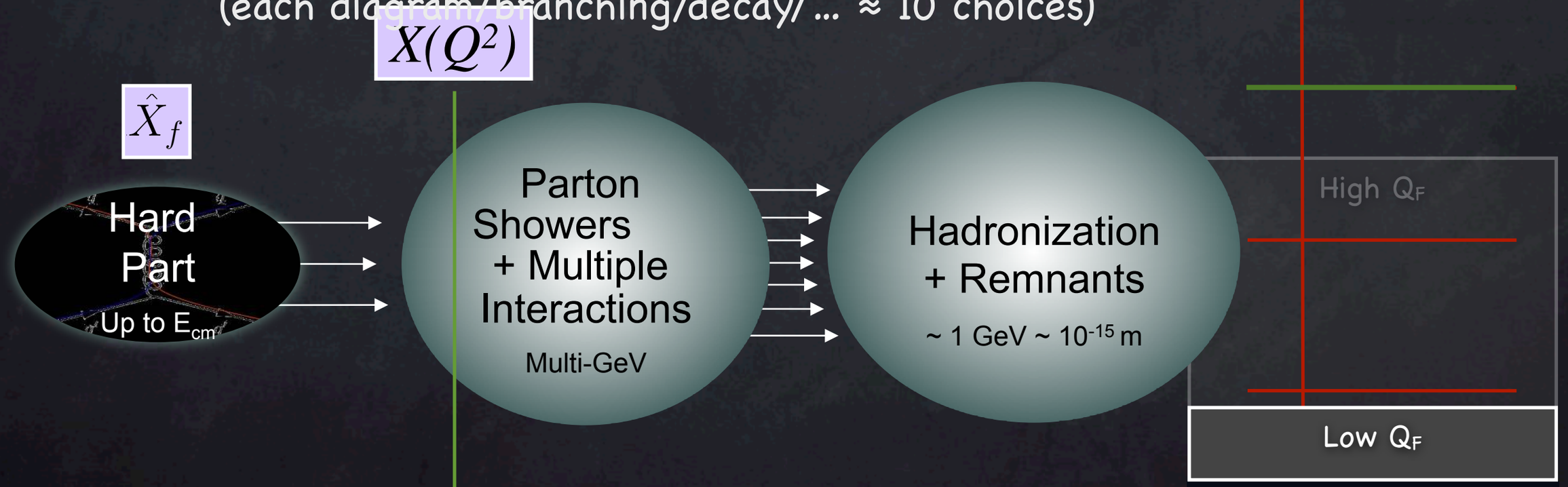
$\alpha_X \times \alpha_s^3$
X+1+1+1 hierarchy
(strongly ordered)
→ Born + LL = OK

Evolution

An event with n particles

Involves O(10n) random choices

(each diagram/branching/decay/... ≈ 10 choices)



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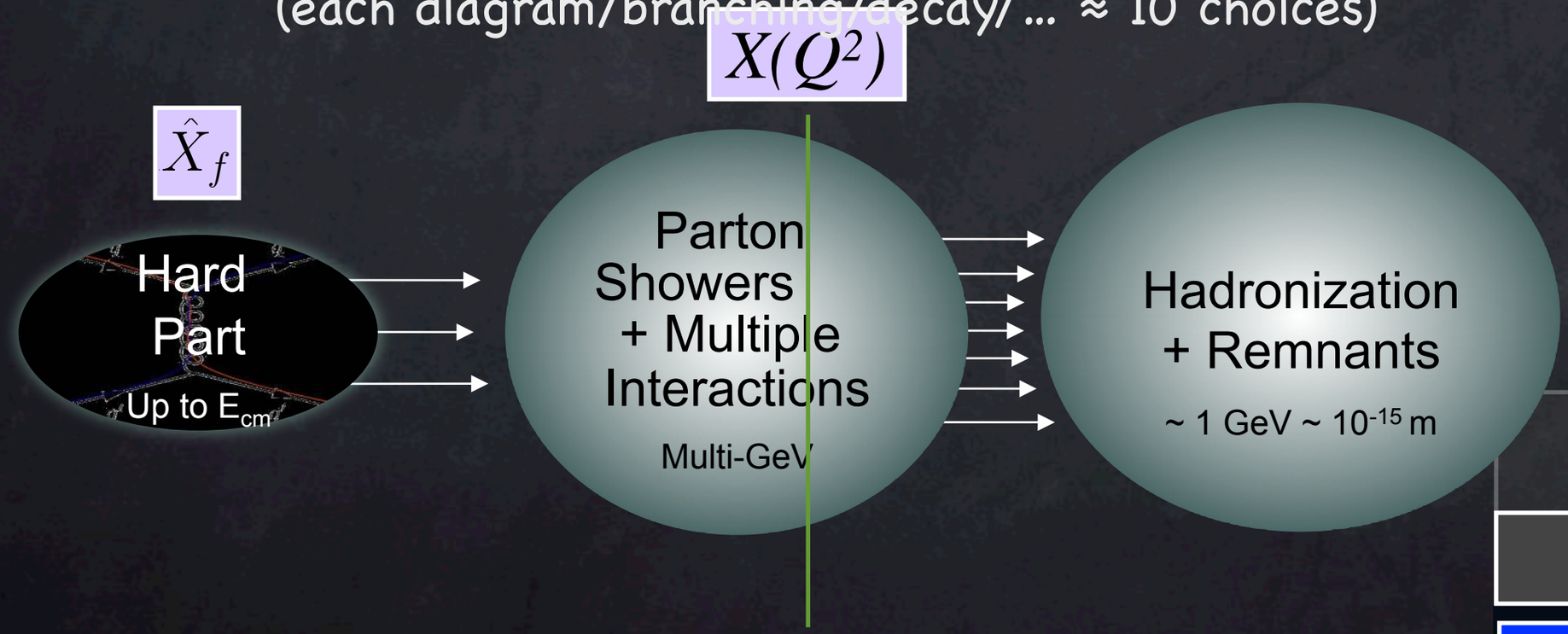

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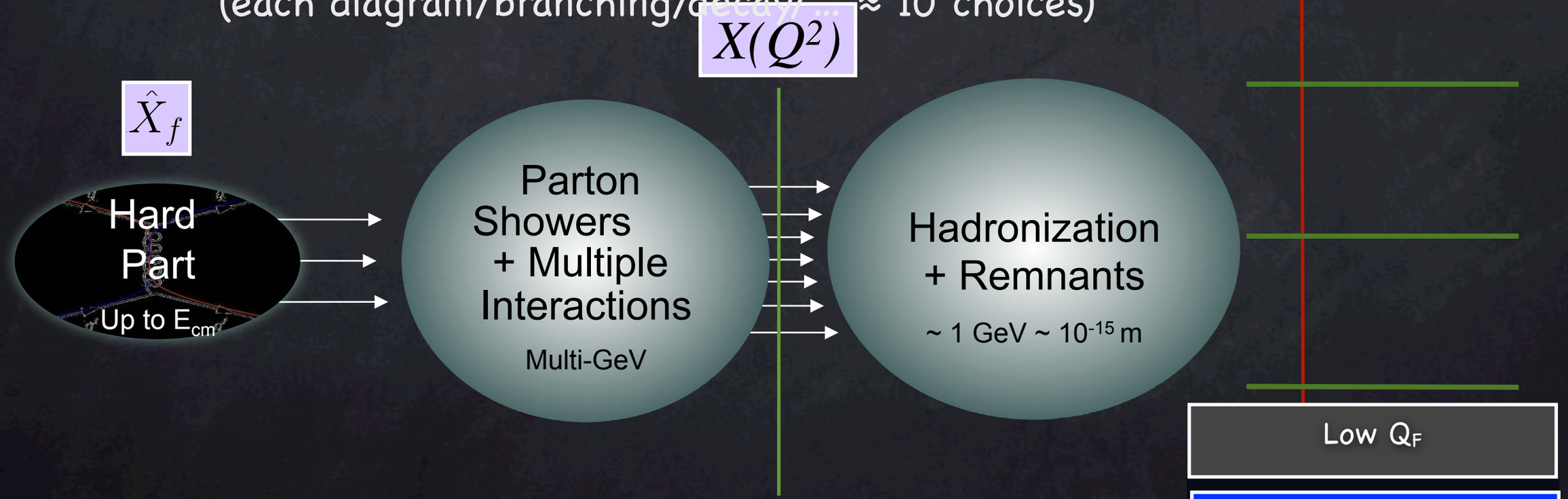


Low Q_F

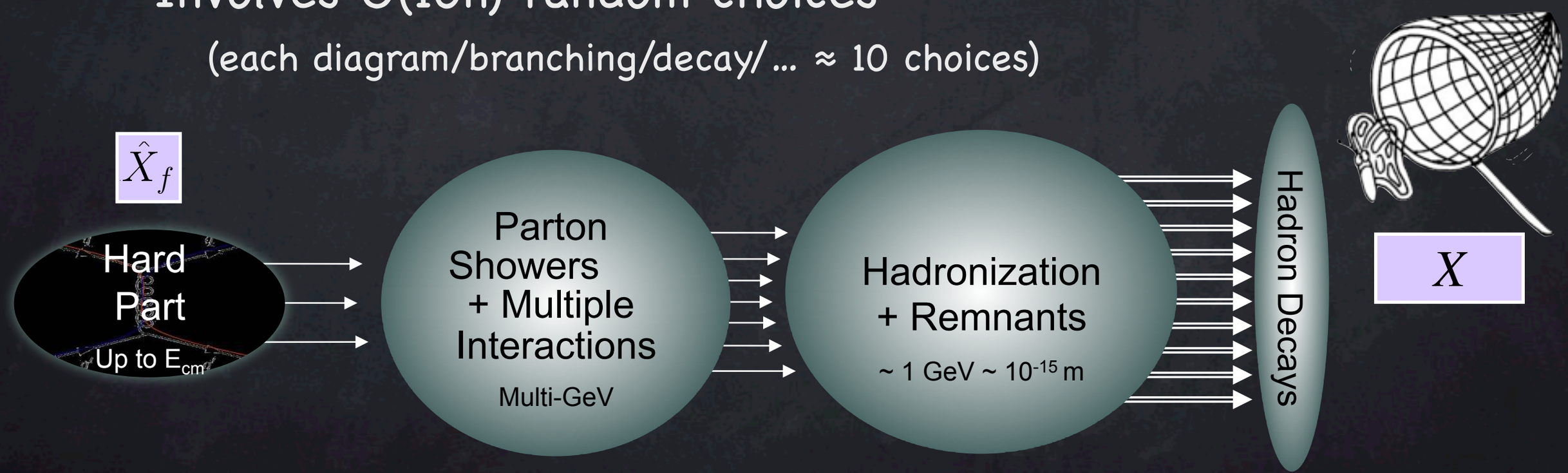
$\alpha_X \times \alpha_s^3$
X+1+1+1 hierarchy
(strongly ordered)
→ Born + LL = OK

Evolution

An event with n particles

Involves O(10n) random choices

(each diagram/branching/decay/... ≈ 10 choices)



Divide and Conquer

Generator Landscape

	General-Purpose	Specialized
Hard Process	HERWIG	A lot …
Resonance Decays		HDecay, …
Matching	PYTHIA	MC@NLO, POWHEG
Parton Showers		ARIADNE/LDC, NLLJET, VINCIA
Underlying Event	ISAJET	PHOJET, DPMJET
Hadronization	SHERPA	None?
Ordinary Decays		TAUOLA, EvtGen, …

Main Workhorses

HERWIG, PYTHIA and SHERPA intend to offer a convenient framework for LHC physics studies, but with slightly different emphasis:

PYTHIA (successor to JETSET, begun in 1978):

- originated in hadronization studies: the Lund string
- leading in development of multiple parton interactions
- pragmatic attitude to showers & matching
- the first multipurpose generator: machines & processes

HERWIG (successor to EARWIG, begun in 1984):

- originated in coherent-shower studies (angular ordering)
- cluster hadronization & underlying event pragmatic add-on
- large process library with spin correlations in decays

SHERPA (APACIC++/AMEGIC++, begun in 2000):

- own matrix-element calculator/generator
- extensive machinery for CKKW matching to showers
- leans on PYTHIA for MPI and hadronization

Slide from T. Sjöstrand

Hard Processes

Wide spectrum from “general-purpose” to “one-issue”, see e.g.

`http://www.cedar.ac.uk/hepcode/`

Free for all as long as Les-Houches-compliant output.

I) General-purpose, leading-order:

- MadGraph/MadEvent (amplitude-based, $\leq$ 7 outgoing partons):
  `http://madgraph.physics.uiuc.edu/`
- CompHEP/CalcHEP (matrix-elements-based, $\sim\leq$ 4 outgoing partons)
- Comix: part of SHERPA (Behrends-Giele recursion)
- HELAC–PHEGAS (Dyson-Schwinger)

II) Special processes, leading-order:

- ALPGEN: $\mathrm{W/Z+} \leq 6\mathrm{j}$, $n\mathrm{W} + m\mathrm{Z} + k\mathrm{H+} \leq 3\mathrm{j}, \ldots$
- AcerMC: $\mathrm{t\bar{t}b\bar{b}}, \ldots$
- VECBOS: $\mathrm{W/Z+} \leq 4\mathrm{j}$

III) Special processes, next-to-leading-order:

- MCFM: NLO $\mathrm{W/Z+} \leq 2\mathrm{j}$, WZ, WH, $\mathrm{H+} \leq 1\mathrm{j}$
- GRACE+Bases/Spring

Note: NLO codes not yet generally interfaced to shower MCs

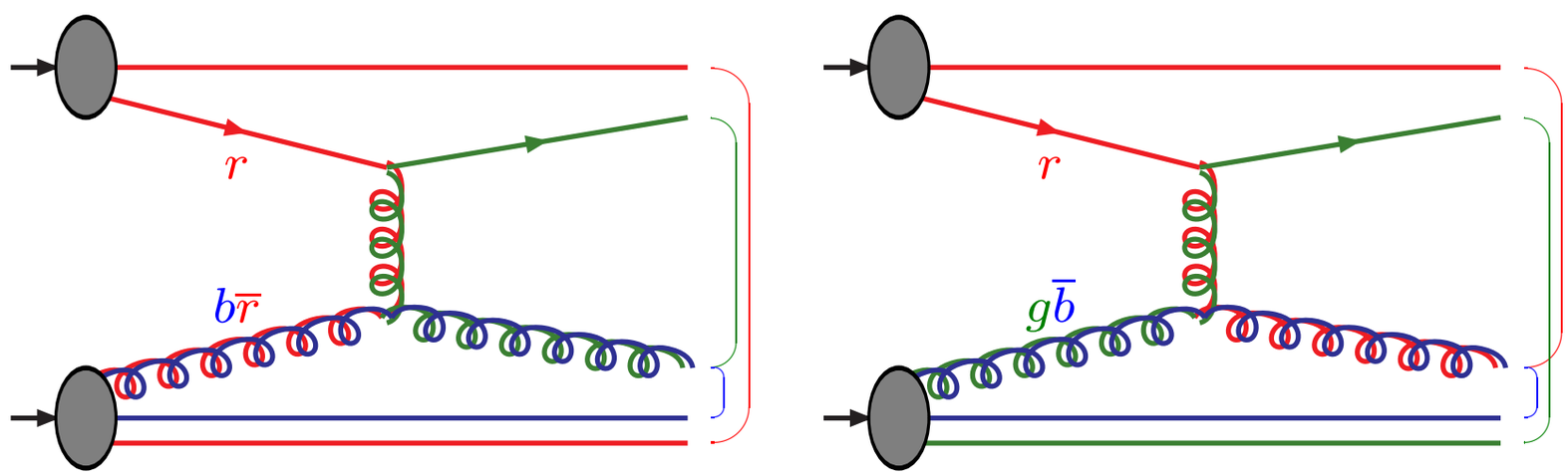
Slide from T. Sjöstrand

Color Flows

Projected onto $N_C \to \infty$

Needed by Parton Showers + Hadronization

E.g., select between:



Showers: create dipoles / coherence cones
Hadronization: set up confinement

Solution: use normal $|M|^2$ to compute cross section

Use the relative fractions in $N_C \to \infty$ to decide which flow

Illustrations by T. Sjöstrand

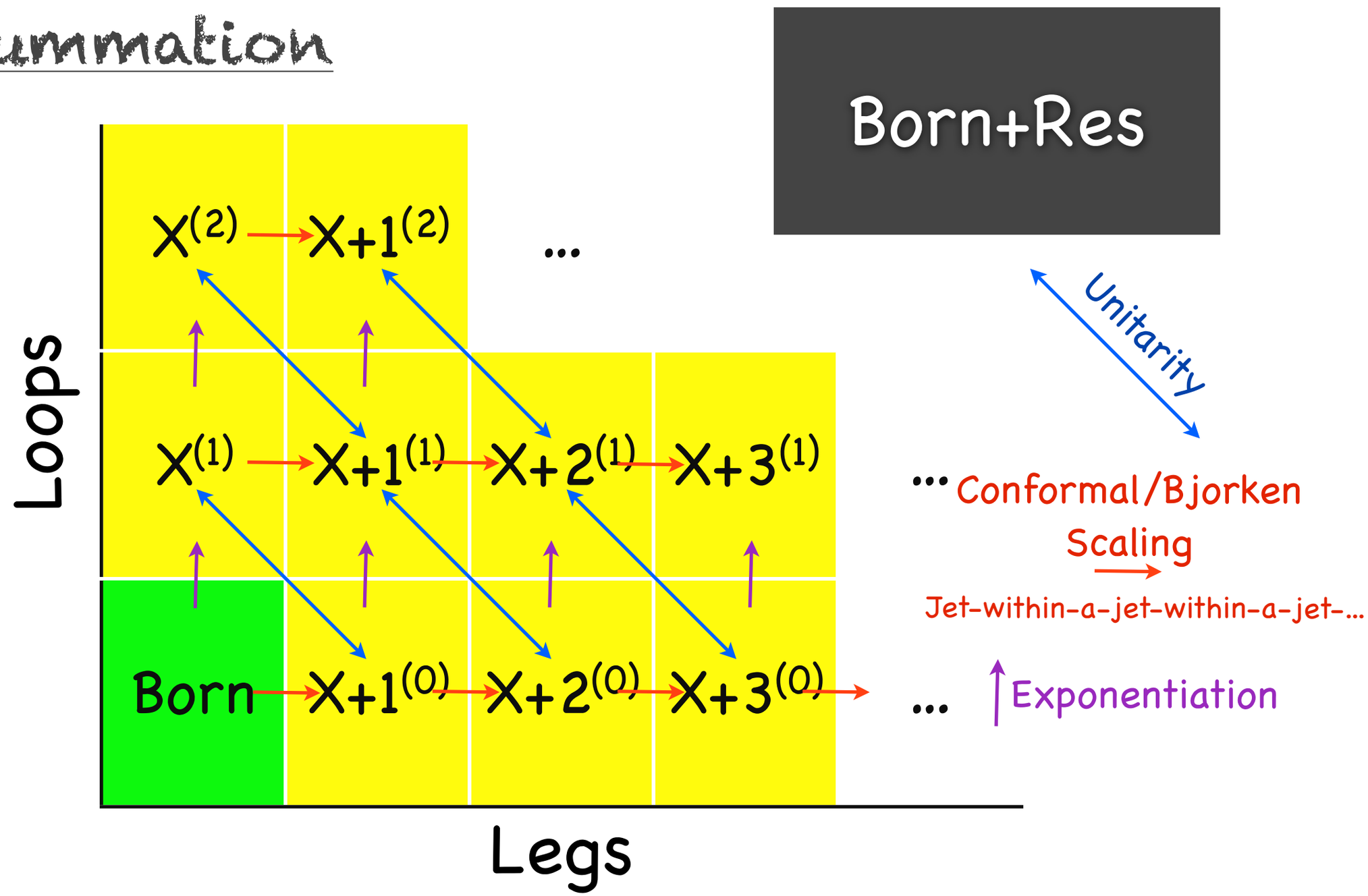
Parton Showers

≈ Exclusive Resummation

Flashback

Loops and Legs

Resummation

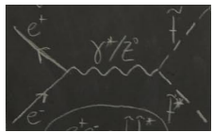


Flashback

Resummation

"DLA" $\dfrac{\alpha\, s_{ab}}{s_{ai} s_{ib}}$

$$d\sigma_X = \ldots$$



$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

$$d\sigma_{X+2} \sim 2g^2 d\sigma_{X+1} \frac{ds_{a2}}{s_{a2}} \frac{ds_{2b}}{s_{2b}}$$

$$d\sigma_{X+3} \sim 2g^2 d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}}$$

KLN

+ UNITARITY:

Virt = – Int(Tree) + F

(or: given a jet definition, an event has *either* 0, 1, 2, or *n* jets)

Interpretation: the structure evolves

$$\sigma_{X+1}(Q) = \sigma_{X;\mathrm{incl}} - \sigma_{X;\mathrm{excl}}(Q)$$

This includes both real and virtual corrections

$$\begin{aligned} \sigma_{X;\mathrm{excl}} &= \sigma_X - \sigma_{X+1} \\ &= \sigma_X - \sigma_{X+1;\mathrm{excl}} - \sigma_{X+2;\mathrm{excl}} - \cdots \end{aligned}$$

Born to Shower

Born	$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right\|_{\mathrm{Born}} = \int \mathrm{d}\Phi_X \, w_X^{(0)} \delta(\mathcal{O} - \mathcal{O}(\{p\}_X))$	{p} : partons $w_X^{(0)} \propto \mathrm{PDFs} \times \lvert M_X^{(0)} \rvert^2$

But instead of evaluating O directly on the Born final state, first insert a showering operator

Born + shower	$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right\|_{\mathrm{PS}} = \int \mathrm{d}\Phi_X \, w_X^{(0)} \, S(\{p\}_X, \mathcal{O})$	{p} : partons S : showering operator

To first order, S does nothing

$$S(\{p\}_X, \mathcal{O}) = \delta(\mathcal{O} - \mathcal{O}(\{p\}_X)) + \mathcal{O}(\alpha_s)$$

The Shower Operator

To Lowest Order

$$S(\{p\}_X, \mathcal{O}) = \delta(\mathcal{O} - \mathcal{O}(\{p\}_X))$$

To First Order

(unitarity)

$$S(\{p\}_X, \mathcal{O}) = \left(1 - \int_{t_{\text{start}}}^{t_{\text{had}}} \mathrm{d}t \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}t}\right) \delta(\mathcal{O} - \mathcal{O}(\{p\}_X))$$

$$+ \int_{t_{\text{start}}}^{t_{\text{had}}} \mathrm{d}t_{X+1} \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}t_{X+1}} \delta(\mathcal{O} - \mathcal{O}(\{p\}_{X+1}))$$

Splitting Operator

$$\mathcal{P} = \int \frac{\mathrm{d}\Phi_{X+1}}{\mathrm{d}\Phi_X} \frac{w_{X+1}}{w_X}\bigg|_{\text{PS}}$$

= Shower approximation of X → X+1

The Shower Operator

To ALL Orders

(Markov Chain)

$$S(\{p\}_X, \mathcal{O}) = \Delta(t_{\text{start}}, t_{\text{had}})\delta(\mathcal{O} - \mathcal{O}(\{p\}_X))$$

"Nothing Happens" → "Evaluate Observable"

$$- \int_{t_{\text{start}}}^{t_{\text{had}}} \mathrm{d}t \frac{\mathrm{d}\Delta(t_{\text{start}}, t)}{\mathrm{d}t} S(\{p\}_{X+1}, \mathcal{O})$$

"Something Happens" → "Continue Shower"

All-orders Probability that nothing happens

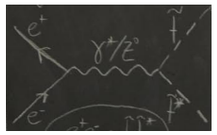
$$\Delta(t_1, t_2) = \exp\left(-\int_{t_1}^{t_2} \mathrm{d}t \, \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}t}\right)$$

(Exponentiation)

Splitting Functions

"DLA" $\frac{\alpha\, s_{ab}}{s_{ai} s_{ib}}$

$$\mathrm{d}\sigma_X = \ldots$$



$$\mathrm{d}\sigma_{X+1} \sim 2g^2 \mathrm{d}\sigma_X \frac{\mathrm{d}s_{a1}}{s_{a1}} \frac{\mathrm{d}s_{1b}}{s_{1b}}$$

Splitting Operator $\mathcal{P} = \int \frac{\mathrm{d}\Phi_{X+1}}{\mathrm{d}\Phi_X} \frac{w_{X+1}}{w_X}\Big|_{\mathrm{PS}}$

Examples

$$\mathcal{P}_{\mathrm{DGLAP}} = \sum_i \int \frac{\mathrm{d}Q^2}{Q^2} \mathrm{d}z\; P_i(z)$$

$$\mathcal{P}_{\mathrm{Antenna}} = \int \frac{\mathrm{d}s_{ij}\mathrm{d}s_{jk}}{16\pi^2 s} \frac{|M_3(s_{ij}, s_{jk}, s)|^2}{|M_2(s)|^2}$$

Splitting Functions

DGLAP

(E.g., HERWIG, PYTHIA)

$$\mathrm{d}\mathcal{P}_a = \sum_{b,c} \frac{\alpha_{abc}}{2\pi} P_{a\to bc}(z)\,\mathrm{d}t\,\mathrm{d}z \ .$$

$$\begin{aligned}
P_{\mathrm{q}\to\mathrm{qg}}(z) &= C_F \frac{1+z^2}{1-z} \ , \\
P_{\mathrm{g}\to\mathrm{gg}}(z) &= N_C \frac{(1-z(1-z))^2}{z(1-z)} \ , \\
P_{\mathrm{g}\to\mathrm{q\bar{q}}}(z) &= T_R\left(z^2+(1-z)^2\right) \ , \\
P_{\mathrm{q}\to\mathrm{q}\gamma}(z) &= e_{\mathrm{q}}^2 \frac{1+z^2}{1-z} \ , \\
P_{\ell\to\ell\gamma}(z) &= e_\ell^2 \frac{1+z^2}{1-z} \ ,
\end{aligned}$$

Dipole-Antennae

(E.g., ARIADNE, VINCIA)

$$\mathrm{d}\mathcal{P}_{IK\to ijk} = \frac{\mathrm{d}s_{ij}\mathrm{d}s_{jk}}{16\pi^2 s}\, a(s_{ij}, s_{jk})$$

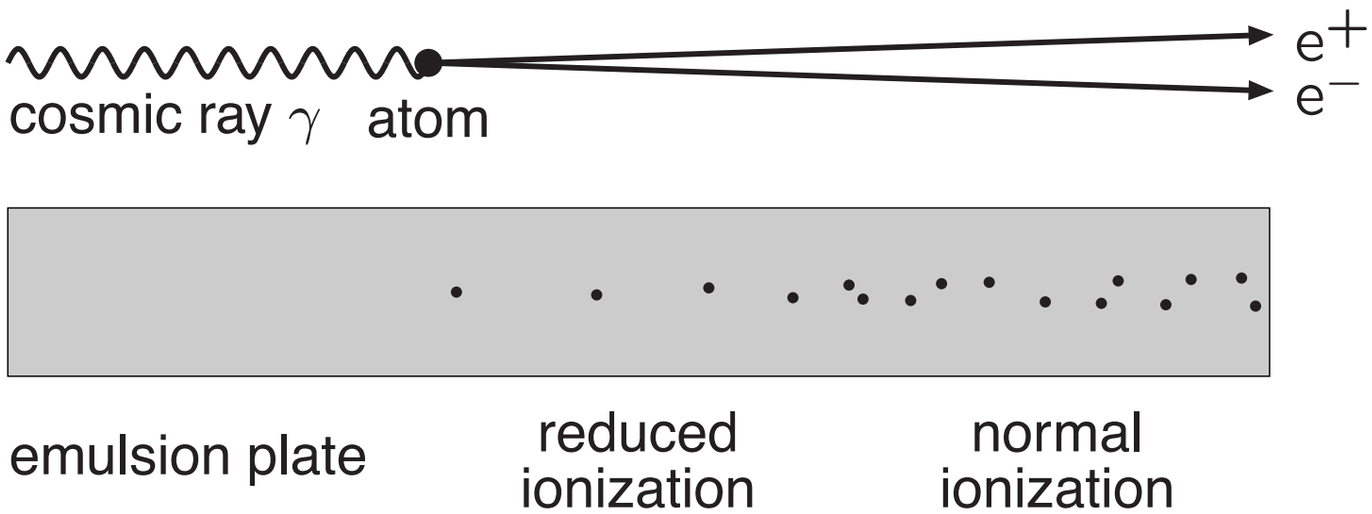
$$\begin{aligned}
a_{q\bar{q}\to qg\bar{q}} &= \frac{2C_F}{s_{ij}s_{jk}}\left(2s_{ik}s + s_{ij}^2 + s_{jk}^2\right) \\
a_{qg\to qgg} &= \frac{C_A}{s_{ij}s_{jk}}\left(2s_{ik}s + s_{ij}^2 + s_{jk}^2 - s_{ij}^3\right) \\
a_{gg\to ggg} &= \frac{C_A}{s_{ij}s_{jk}}\left(2s_{ik}s + s_{ij}^2 + s_{jk}^2 - s_{ij}^3 - s_{jk}^3\right) \\
a_{qg\to q\bar{q}'q'} &= \frac{T_R}{s_{jk}}\left(s - 2s_{ij} + 2s_{ij}^2\right) \\
a_{gg\to g\bar{q}'q'} &= a_{qg\to q\bar{q}'q'}
\end{aligned}$$

... + non-singular terms

NB: Also others, e.g., Catani-Seymour (SHERPA), Sector Antennae, ...

Coherence

QED: Chudakov effect (mid-fifties)



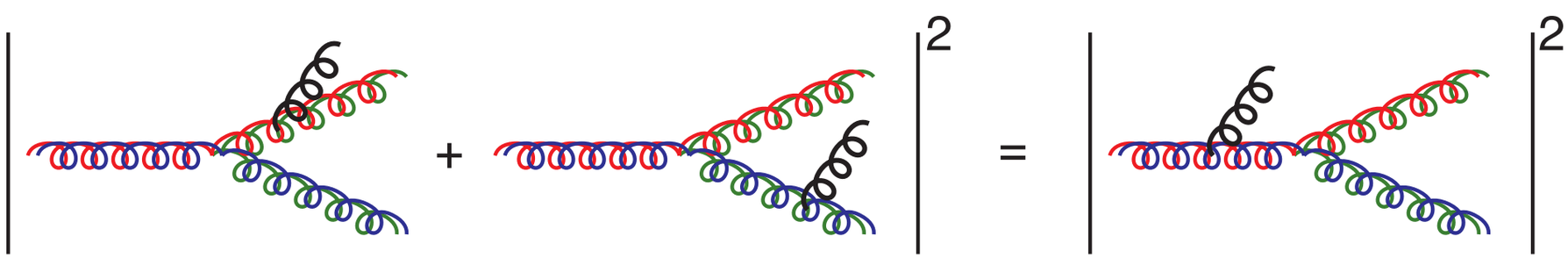
Approximations to Coherence:

Angular Ordering (HERWIG)

Angular Vetos (PYTHIA)

Coherent Dipole-Antennae (ARIADNE, CS, VINCIA)

QCD: colour coherence for **soft** gluon emission



solved by
- requiring emission angles to be decreasing

or
- requiring transverse momenta to be decreasing

Illustrations by T. Sjöstrand

The Initial State

Parton Densities and Initial-State Showers

Parton Densities for MC

LO

Consistent with LO matrix elements in LO generators
Effectively 'tuned' to absorb missing NLO contributions
But they give quite bad fits compared to NLO ...

NLO

Formally consistent with NLO matrix elements
Effectively 'tuned' with NLO theory
→ badly tuned for LO matrix elements (not enough low-x glue)?
Suggest to only use for NLO generators?

LO*, MC pdfs, ...

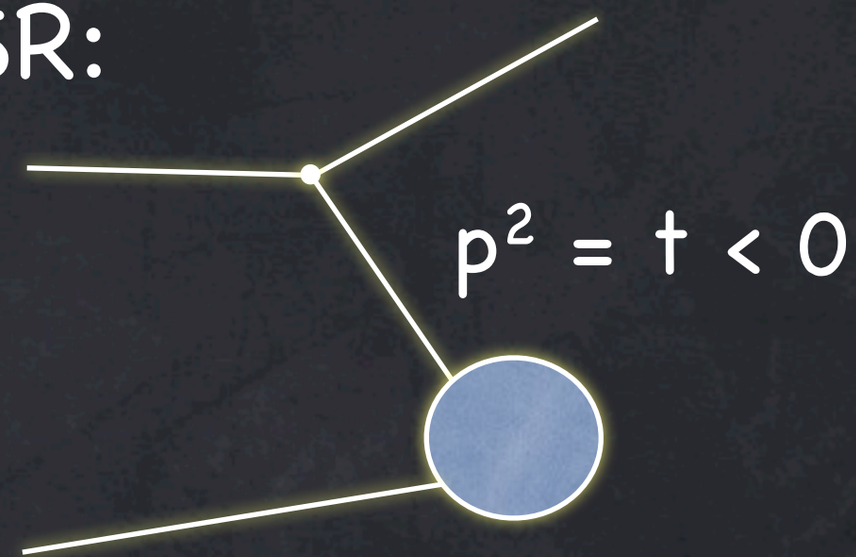
Best of both worlds?
- PDF has always had an impact on generator tuning
- But now we are going the other way: tune the PDF!

Still gaining experience. Proceed with caution & sanity checks

Spacelike (backwards) Evolution

FSR:

ISR:



Virtualities are Timelike: $p^2>0$

Start at $Q^2 = s$
Unconstrained forwards evolution

Virtualities are Spacelike: $p^2>0$

Start at $Q^2 = Q_i^2$
Constrained backwards evolution towards boundary condition = proton

Evolution Equation

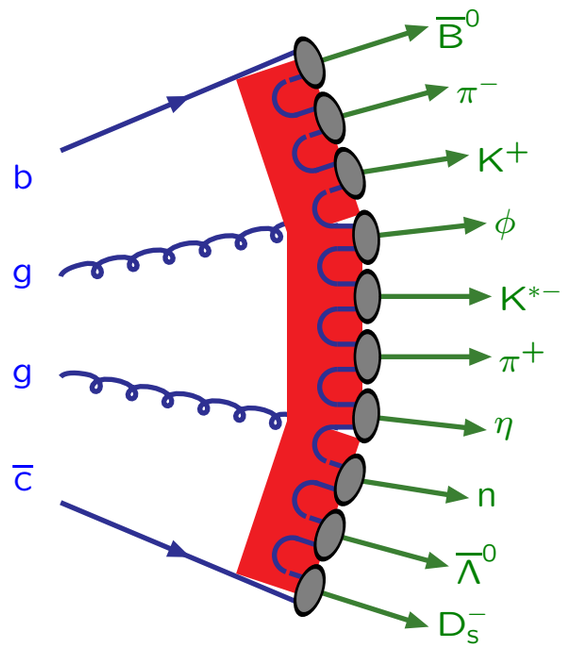
DGLAP for Parton Density

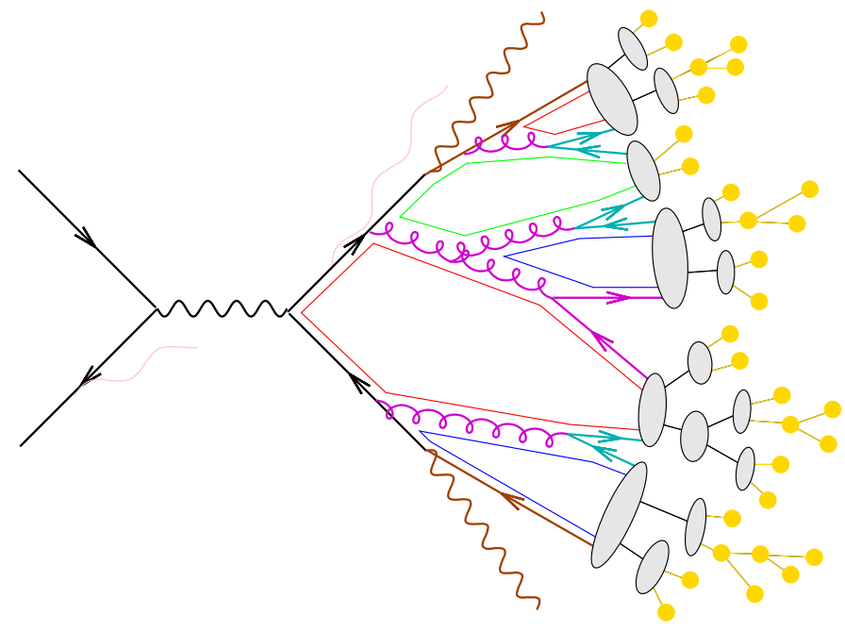
$$\frac{\mathrm{d}f_b(x,t)}{\mathrm{d}t} = \sum_{a,c} \int \frac{\mathrm{d}x'}{x'} f_a(x',t) \frac{\alpha_{abc}}{2\pi} P_{a\to bc}\left(\frac{x}{x'}\right)$$

→ Sudakov for ISR

$$\begin{aligned}\Delta(x, t_{\max}, t) &= \exp\left\{-\int_t^{t_{\max}} \mathrm{d}t' \sum_{a,c} \int \frac{\mathrm{d}x'}{x'} \frac{f_a(x',t')}{f_b(x,t')} \frac{\alpha_{abc}(t')}{2\pi} P_{a\to bc}\left(\frac{x}{x'}\right)\right\} \\ &= \exp\left\{-\int_t^{t_{\max}} \mathrm{d}t' \sum_{a,c} \int \mathrm{d}z \frac{\alpha_{abc}(t')}{2\pi} P_{a\to bc}(z) \frac{x' f_a(x',t')}{x f_b(x,t')}\right\} ,\end{aligned}$$

Hadronization





program	PYTHIA	HERWIG (&SHERPA)
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Small strings → clusters. Large clusters → strings

Illustrations by T. Sjöstrand

Constraints

and Tuning

Constraining Models

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- Used for constraining ('tuning') theoretical models (E.g., Monte Carlo Event Generators)

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But wait ... which gaps?

Gaps

- QCD pheno evolving rapidly
  - The models that were tested 20 years ago are not the models of today
  - Capabilities of experiments are different today than 20 years ago
  - We define new observables, new quantities of interest, as knowledge evolves (e.g., IR safety)
  - We have also learned some hard lessons about data preservation and about 'truth' corrections

3 Kinds of Tuning

1. Fragmentation Tuning

Non-perturbative: hadronization modeling & parameters

Perturbative: jet radiation, jet broadening, jet structure

2. Initial-State Tuning

Non-perturbative: PDFs, primordial k_T

Perturbative: initial-state radiation, initial-final interference

3. Underlying-Event & Min-Bias Tuning

Non-perturbative: Multi-parton PDFs, Color (re)connections, collective effects, impact parameter dependence, ...

Perturbative: Multi-parton interactions, rescattering

Tuning Problem

Fundamental Problem

In all but the softest hadronic collisions (soft min-bias, soft diffraction), particle production has partly perturbative origin

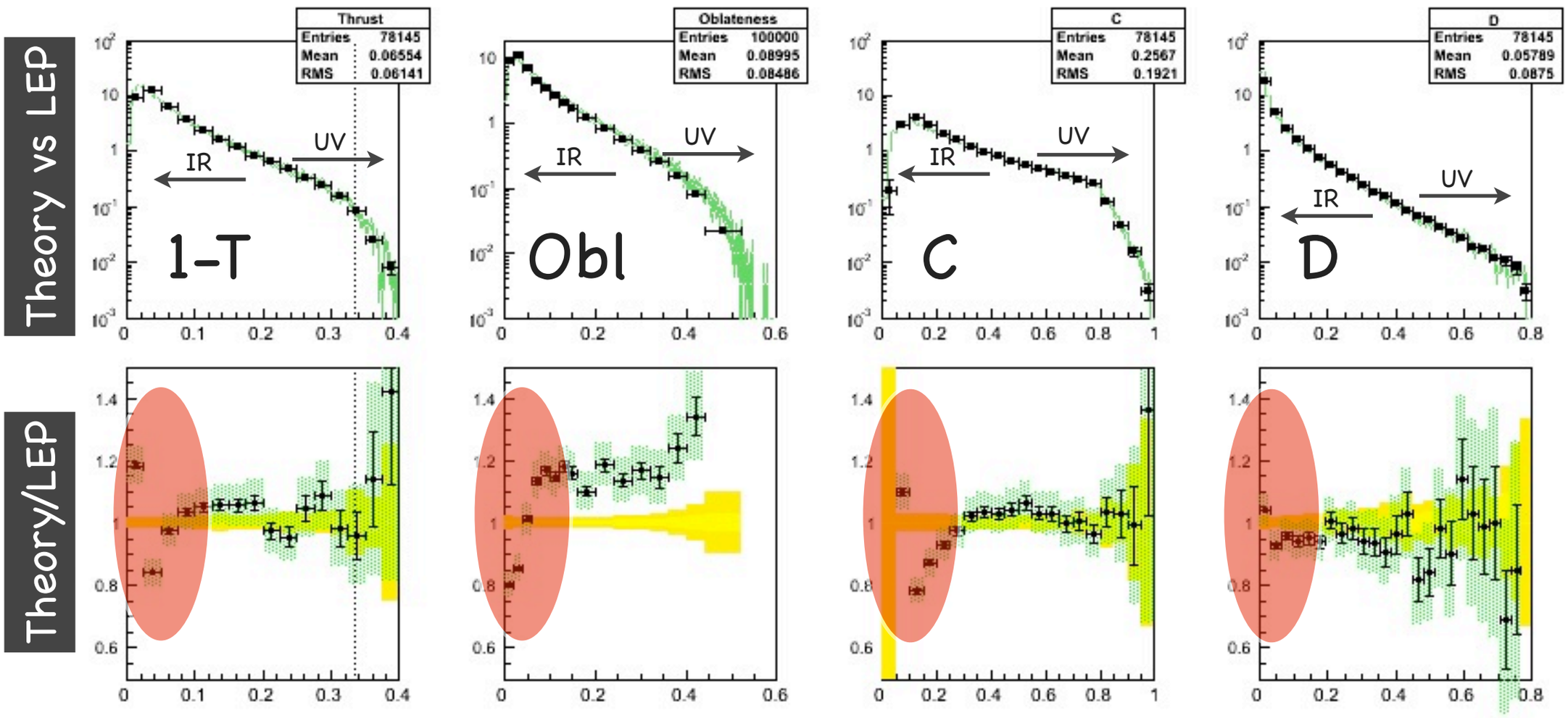
→ Need to FIRST make sure one has a SUFFICIENTLY GOOD description of the PERTURBATIVE physics

Useless to get the right number of tracks, if their energy flow distribution is completely wrong
(E.g., adding a soft string to make up for a missing jet is not optimal)

But pQCD is calculable … should we 'tune' it?

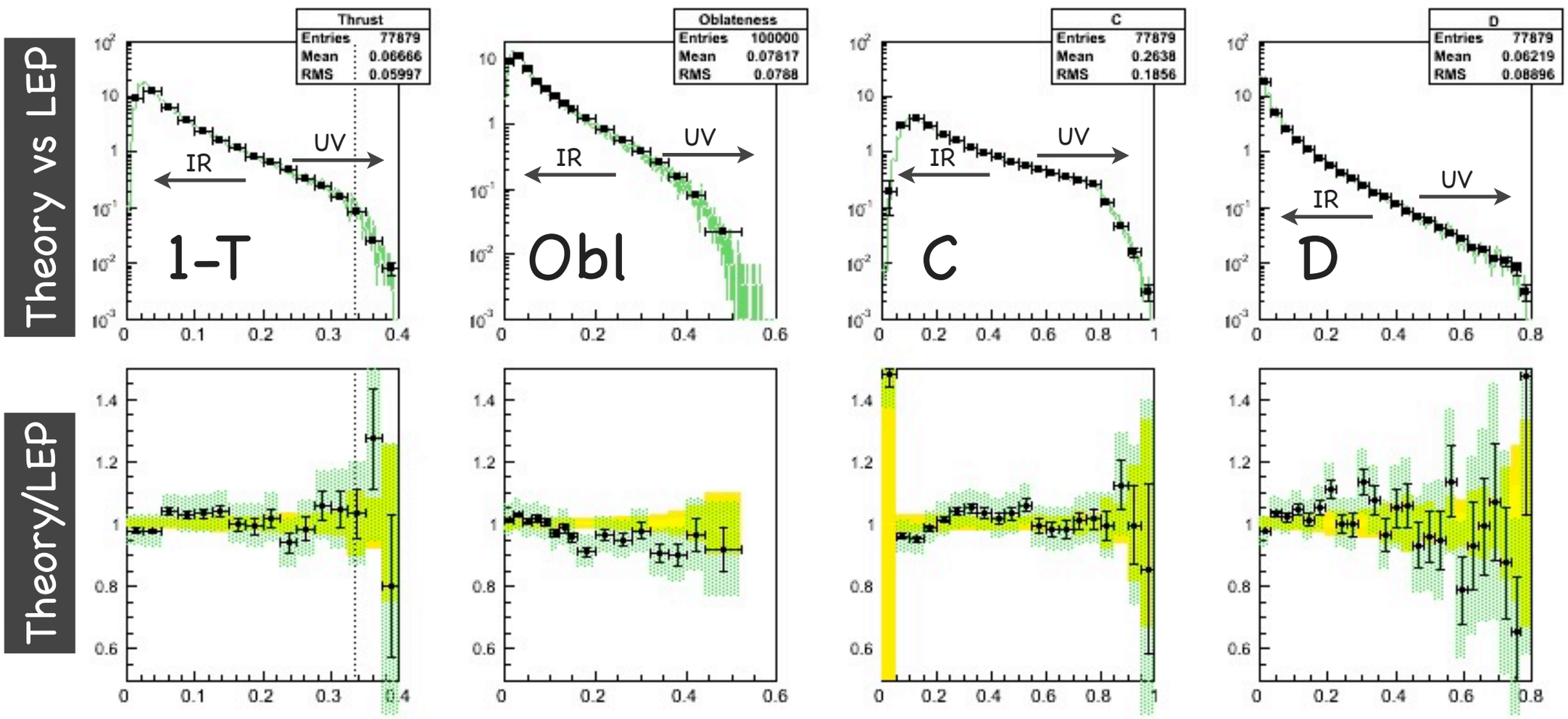
Pure pQCD - the "parton" level

Default PYTHIA 8 - No Hadronization



Hadron Level

Default PYTHIA 8 + Hadronization



(Is this Crazy?)

PDG:

strong coupling constant	$\alpha_s(m_Z)$	0.1176(20)

These results

Obtained with $\alpha_s(M_Z) \approx 0.14 \neq$ World Average $= 0.1176 \pm 0.0020$

Value of α_s

Depends on the order and scheme

MC ≈ Leading Order + LL resummation

Other leading-Order extractions of $\alpha_s \approx 0.13 - 0.14$

Plus uncertainty from different effective scheme

So, in my opinion, it is not so crazy

We should 'tune' (or 'measure') even pQCD parameters with the actual generator. The sanity check is whether we are consistent with other extractions at a similar formal order, within the uncertainty at that order (including an (unknown) scheme redefinition)

Tuning in the Infrared

1. Fragmentation Tuning

Constrain incalculable model parameters

- Similar to fitting fragmentation functions, or measuring form factors, … but can look at much more exclusive information!
- I.e., a "measurement" within the given model context

Good model → good fit. Bad model → bad fit → improve model

$P_s/P_{u,d}$

P_{Baryon}/P_{Meson}

Λ_{QCD}

IR α_s

Q_{cutoff}

$P_{vector}/3P_{scalar}$

$f(z,Q^2)$

$p_{\perp F}$

η,η' suppression

$f_{c,b}(z,Q^2)$

Tests/Constraints

Tests: does the model work at all?

Constraints: given that it works, constrain its parameters

More precise measurements often shift the boundary: constraining to the breaking point → old models die

Fragmentation

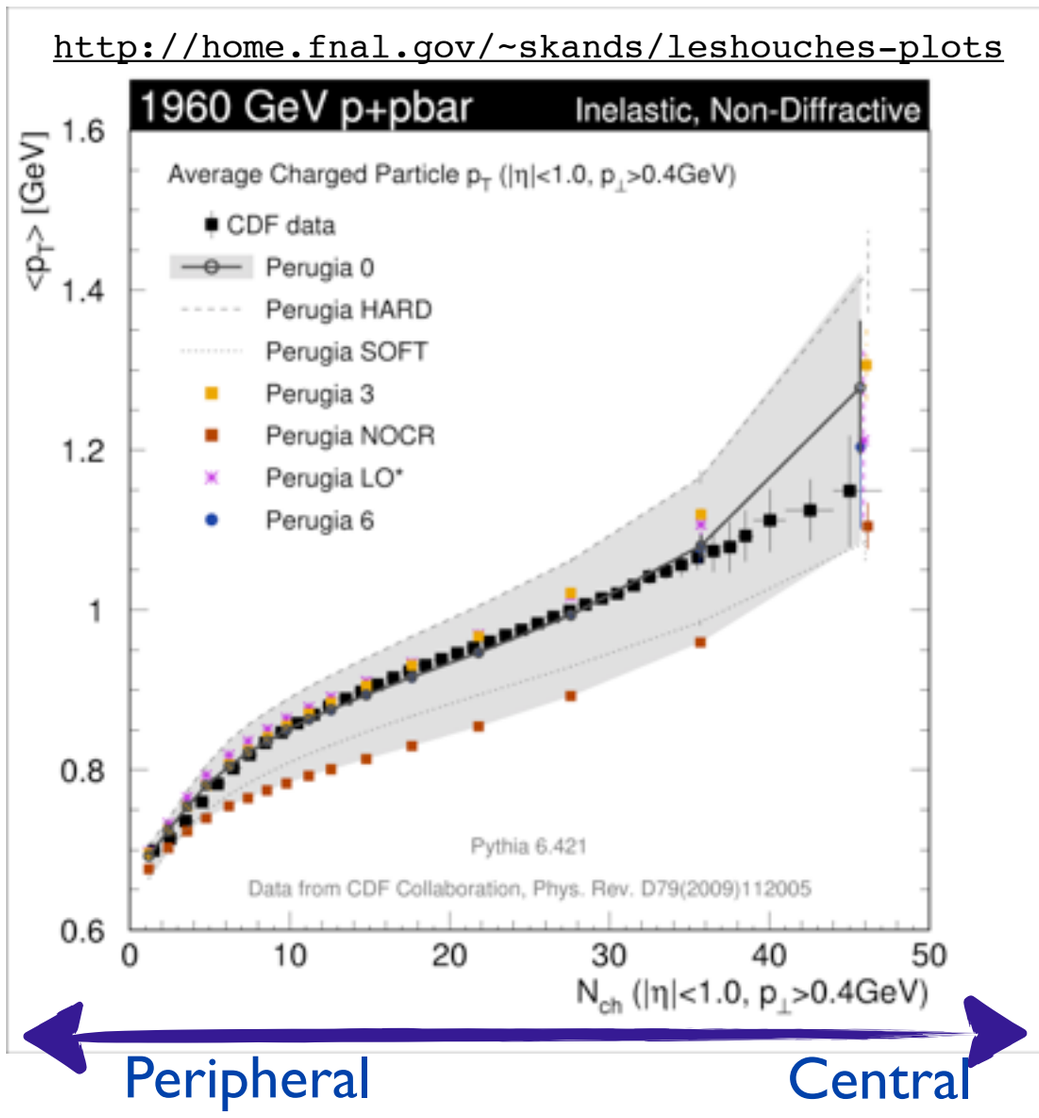
- Normal MC Tuning Procedure:
  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)
    - But pp/ppbar is a very different environment, at the infrared level!

Fragmentation

- Normal MC Tuning Procedure:
  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)
  - Check fragmentation *in situ* at hadron colliders
    - N and p_T spectra (and x spectra normalized to 'jet'/minijet energy?) **Identified particles** highly important to dissect fragmentation
    - Fully Exclusive → Particle-Particle CORRELATIONS
    - (How) do the spectra change with (pseudo-)rapidity? (forward = synergy with cosmic ray fragmentation, different dominating production/fragmentation mechanisms as fct of rapidity? E.g., compare LHCb with central?)
    - How do they change with event activity? (cf. heavy-ion ~ central vs peripheral collisions, hard trigger event (UE))

Change with Event Activity

- One (important) example: $\langle p_T \rangle (N_{ch})$



The p_T spectrum becomes harder as we increase N_{ch}.

Important tuning reference (highly non-trivial to describe correctly)

(Color reconnections, string interactions, rescattering, collective flow in pp, ...?)

Tuning the Initial State

PS, *"The Perugia tunes"*, arXiv:1005.3457 [hep-ph]

2. Initial state

Constrain α_s and "primordial k_T"

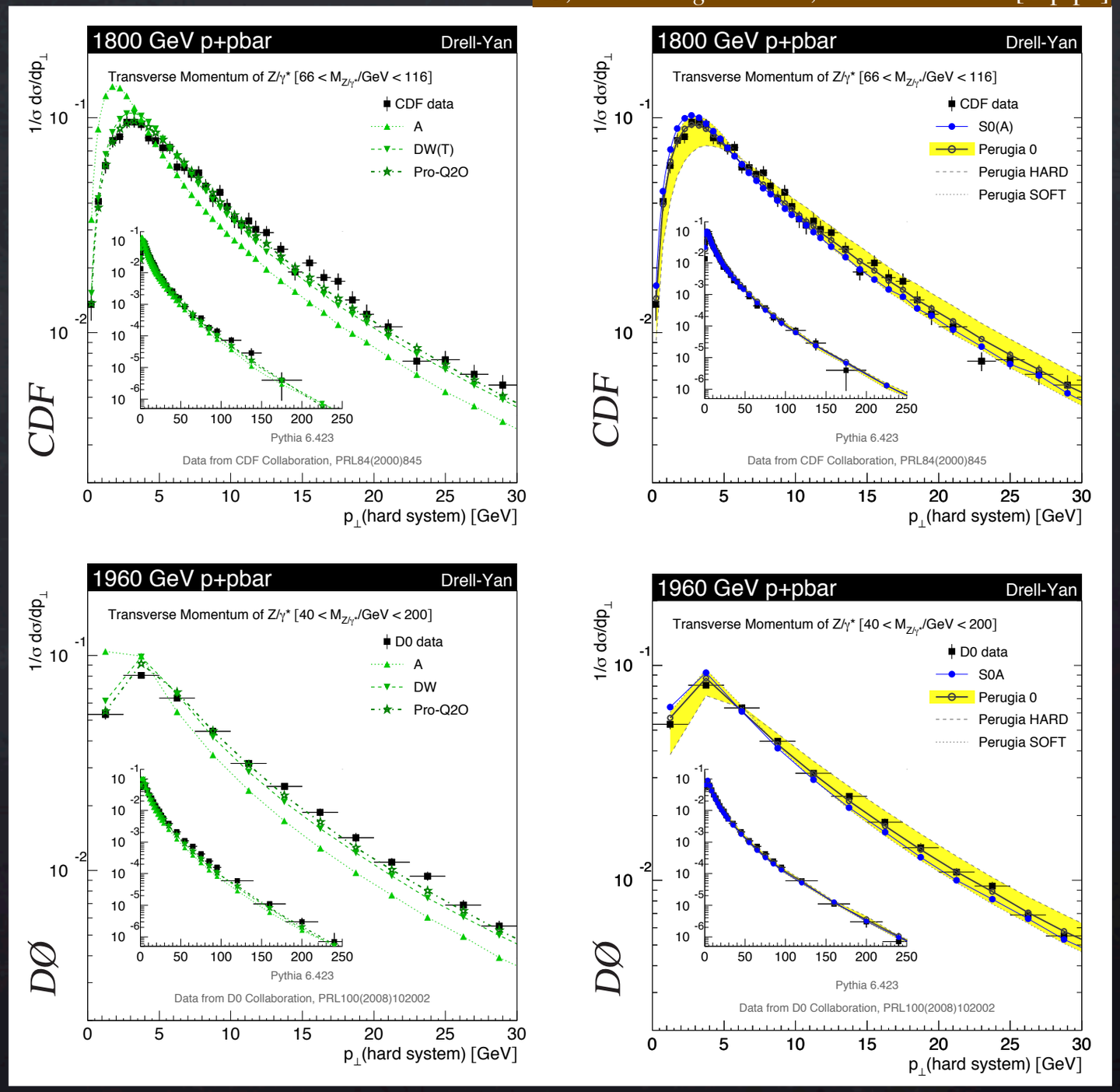
- Similar to fitting PDF functions

Main reference:

- Drell-Yan p_T, + Jets (also DIS)

Complication:

- Initial-Final interference!



Generators - Summary

- Allow to connect theory ↔ experiment
  - On PHYSICAL OBSERVABLES
  - Precision is a function of Model & Constraints
- Random Numbers to Simulate Quantum Behaviour
  - Fixed-Order pQCD supplemented with showers, hadronization, decays, underlying event, matching, ...
- No single program does it all
  - + Variations needed for uncertainty estimates!
  - Rapid evolution of theory/models/constraints/tunes/…
  - Emphasis on interfaces, interoperability

Additional Slides

(The Shower Operator)

A.k.a. the "evolution operator" $S(\{p\},0)$

"Evolves" phase space point: X → X+1 → X+2 → ...

As a function of "time" $t = -2\ln(Q/Q_{start})$

Observable is evaluated on final configuration (at Q≈0)

S unitary (as long as you never throw away or reweight an event)

Total (inclusive) σ unchanged (σ_{LO}, σ_{NLO}, σ_{NNLO}, σ_{exp}, ...)

→ Only shapes are predicted (i.e., also σ after shape-dependent cuts)

Can expand S

To any fixed order (for given observable)

Can check singular limits and agreement with ME at same order

matching

(Additional Observables)

- **Particle-Particle Correlations** probe fragmentation beyond single-particle level. E.g.,:
  - A baryon here, where's the closest antibaryon?
    - + Is the Baryon number of the beam carried into the detector?
  - A Kaon here, where's the closest strange particle?
    - + Multi-Strange particles. Over how big a distance is the strangeness 'neutralized'?
  - Charge correlations. Special case: is the charge of the beam carried into the detector?

Better Constraints → Better Models