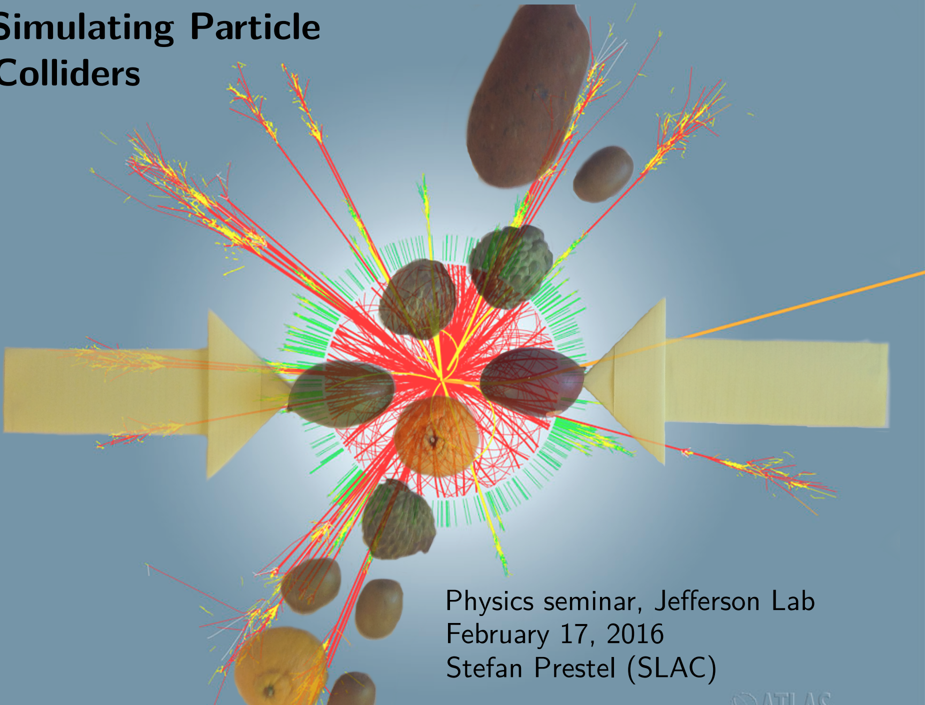
Simulating Particle Colliders



Physics seminar, Jefferson Lab
February 17, 2016
Stefan Prestel (SLAC)

Outline

1. Smash to discover, or why we do collider physics
2. Modelling scattering events, or the mess with hadrons
3. Perturbative predictions, parton showers and fixed-order calculations.
4. Summary and Outlook

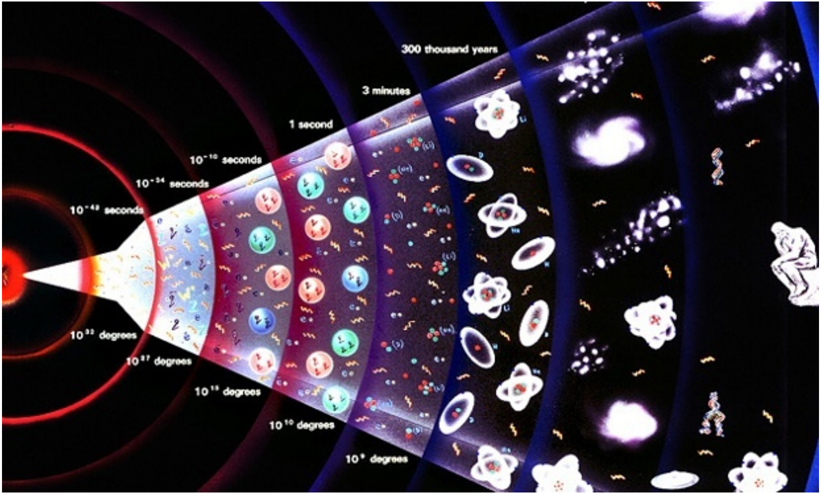
Disclaimer: This will be a Monte-Carlo-biased (review) talk,
from a high-energy perspective.
No discussion of spin effects, unfortunately.
No pretzelosity, just prestelosity.

1. Smash to discover

a) What is our goal?
b) Why colliders?

High energy particle physics

Particle Physics studies the smallest constiuents of matter and their interactions to find the fundamental laws of physics.



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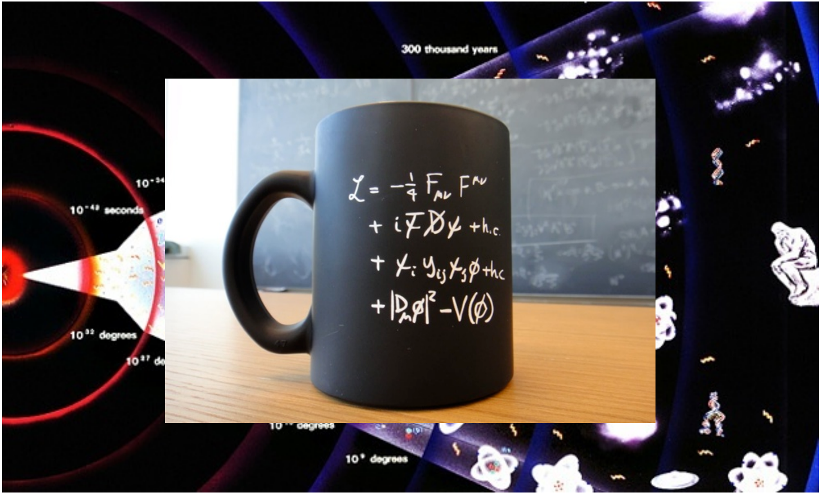
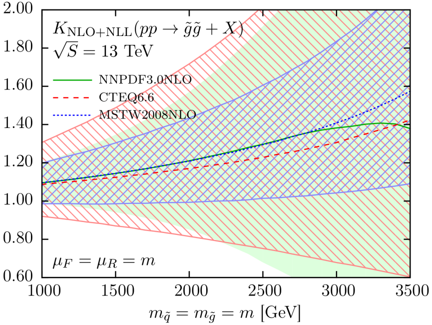
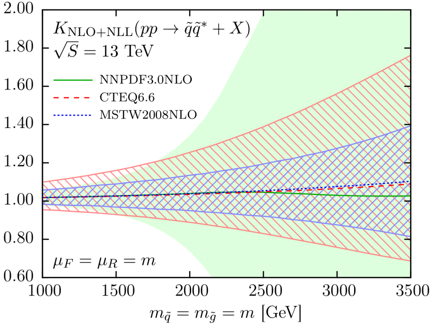


“High-energy” particle colliders

Colliders are excellent tools to study particle physics. Rule of thumb:
More recorded interactions, higher energy
→ Can see rarer phenomena, and more massive particles.

“High-energy” particle colliders





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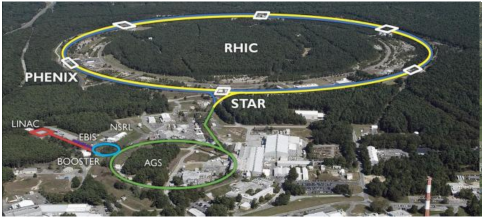
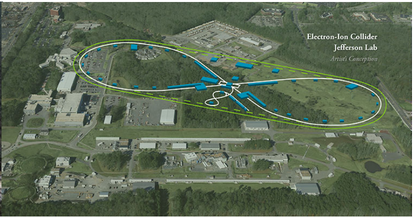
“Low-energy” particle colliders

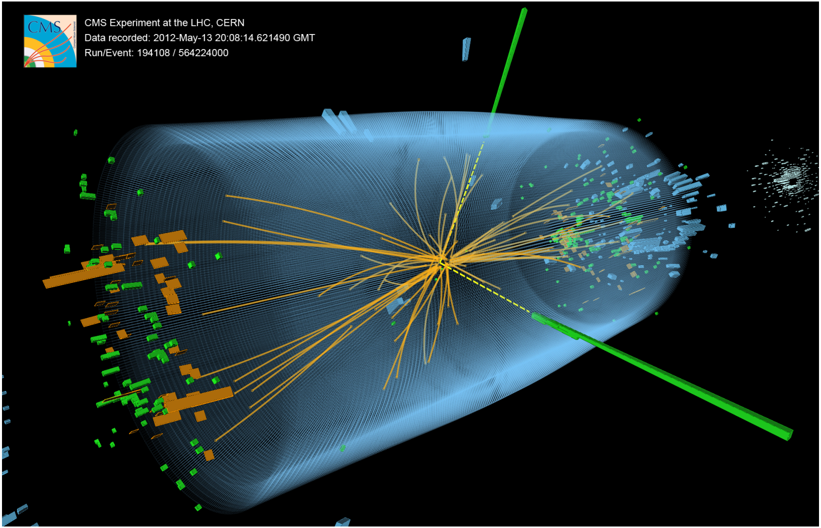




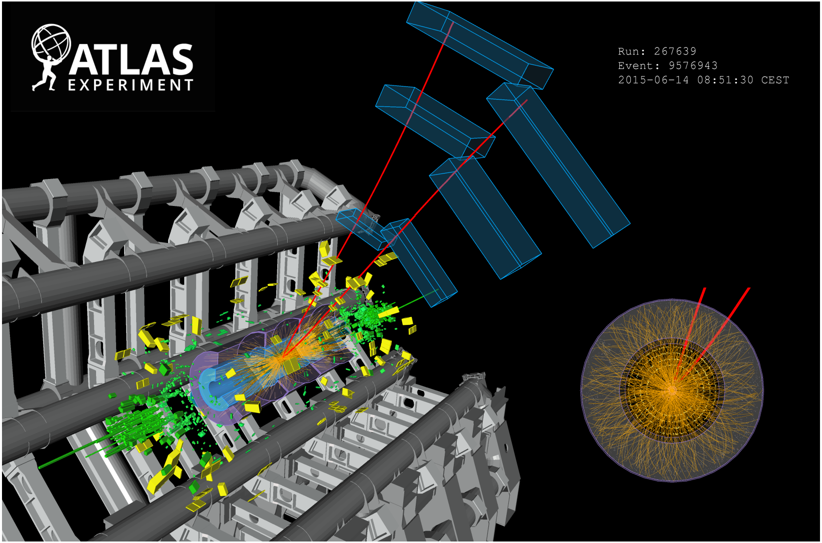
We need to understand the proton better before we can say anything about new phenomena.
$\rightarrow$ Need very detailed understanding of the strong interaction!
$\rightarrow$ Colliders are perfect to study matter under extreme conditions.

The 12 GeV upgrade will greatly improve the understanding of GPD/TMDs, spin structure and hybrid mesons!

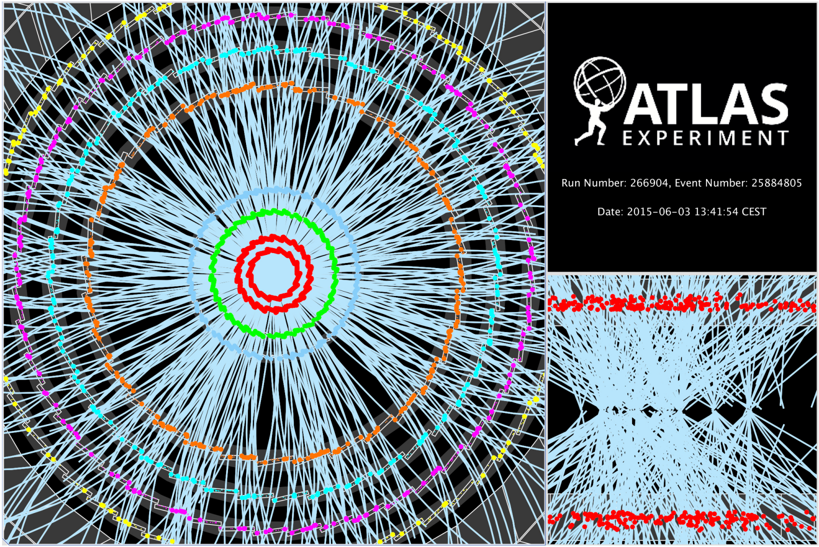
The mess we're facing: Higgs candidate in the CMS detector.



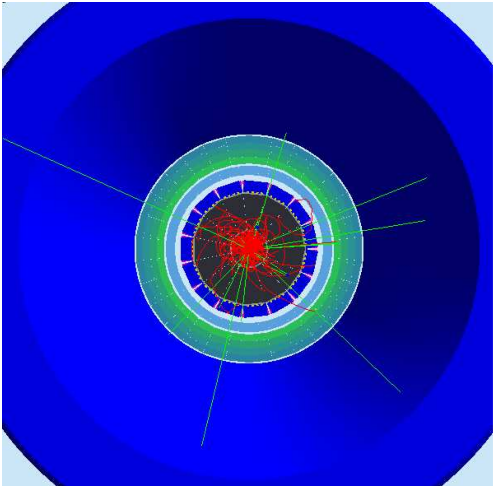
The mess we're facing: J/Ψ production in the ATLAS detector



The mess experiments are facing: (Almost) raw data



The mess experiments are facing



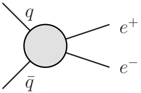
CLAS12 simulated event "[...] obtained for a luminosity $L = 10^{33} cm^{2} s^{1}$, corresponding to 1/100 of the nominal luminosity, for practical reasons related to the graphical interface."

To find new hints of new phenomena, we compare experimental data with the best simulations of our current "best" theory. Here, we'll discuss

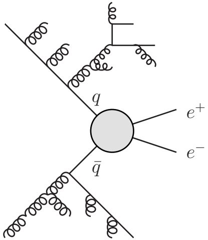
a) Our idea / prejudice how scattering events look like
b) How we hope to model scattering events.

Our goal

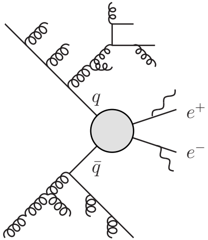
High-energy scattering $ab \to ABC\ldots$ of fundamental particles at the "core" of the collision



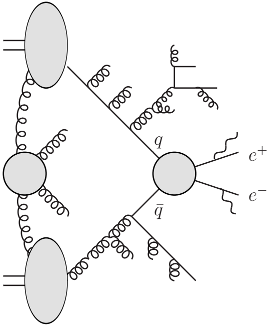
Highly accelerated particles decellerate by radiating (especialy QCD emissions) arbitrarily often,



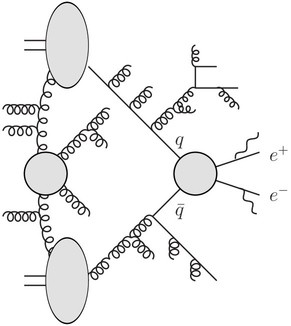
...but even massive W- or Z-bosons can be radiated at very high energies.



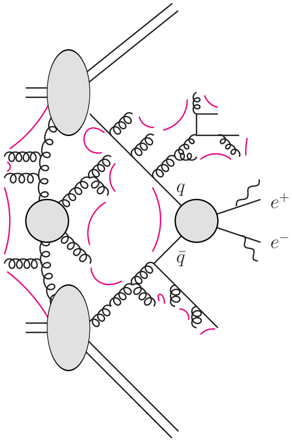
Colliding composite protons means there can be many interactions between the proton constituents



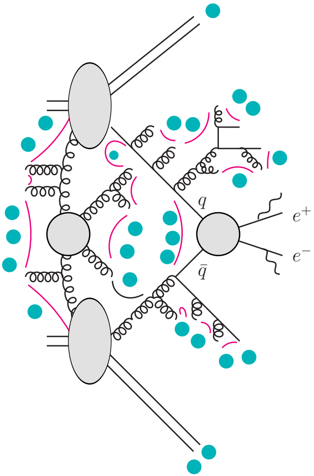
...which all produce yet more radiation.



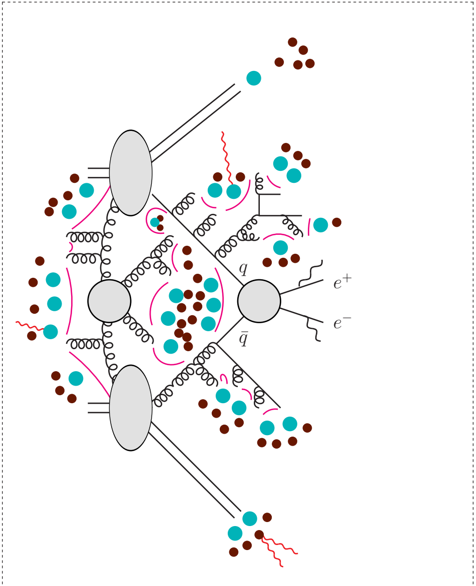
If all energies are small, we have a phase transition to a colour-neutral state (by transitioning to "proto-hadron" colour strings)

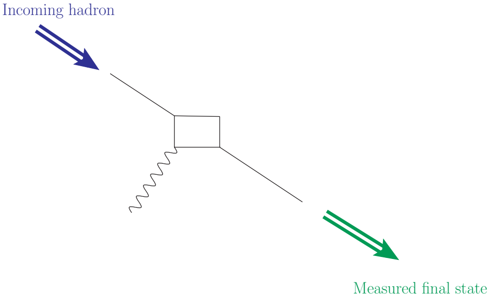


The colour-neutral strings then break up into tiny pieces forming (highly excited) hadrons,



and the excited hadrons decay into the particles (protons, pions, photons, electrons ...) we see in the detector.

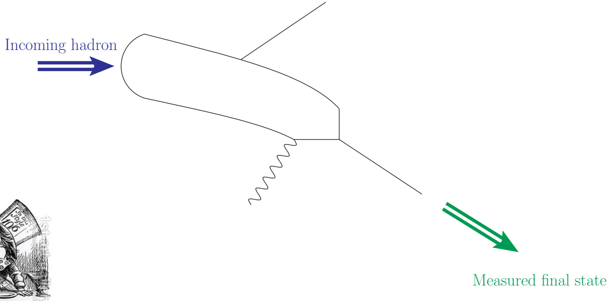




Imagine deep inelastic scattering with a non-colored final state.
If all the partons momenta are parallel to the incoming composite proton, then we have a simple (boring) final state.

Calculable in fixed-order perturbation theory.

Theory models: Alice's Baryon-number violating dreamland



More interesting if the parton momenta have transverse components. Semi-inclusive measurements of the final state then allow to map the proton structure.

Measureable, by now good non-perturbative fits.

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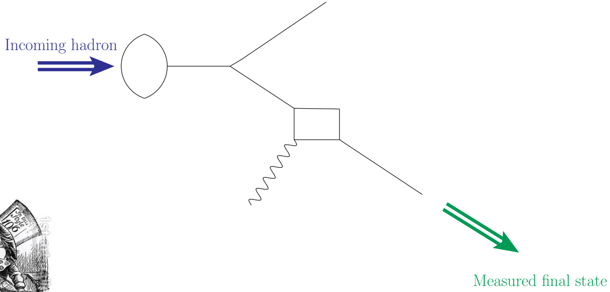
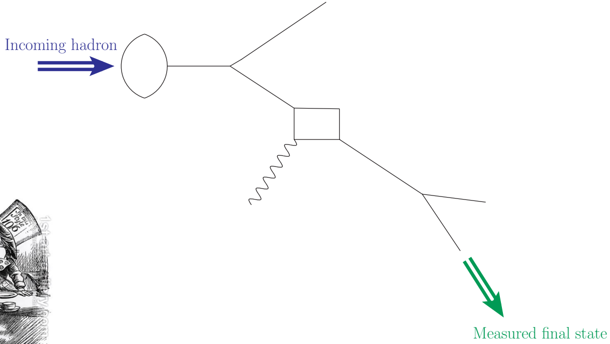


More interesting if the parton momenta have transverse components. For large distortions ($p_\perp > \Lambda_{\mathrm{QCD}}$), this is the calculable higher-order effect of a partonic branching.

Calculable evolution in resummed perturbation theory.

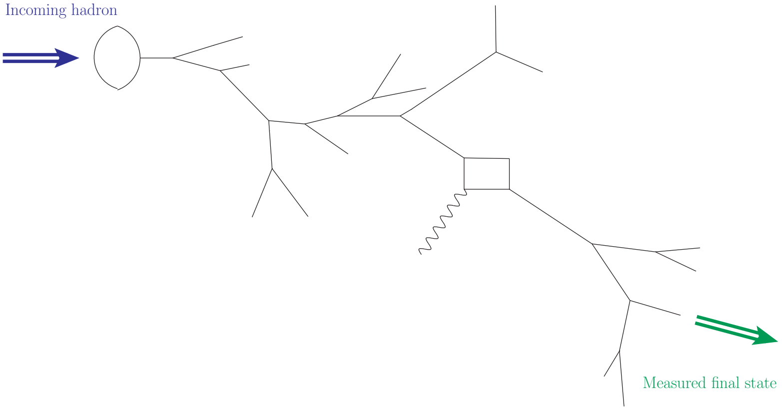
Theory models: Alice's DIS dreamland



With final-state color, the effects of initial-state and final-state evolution are not straight-forward factorized (long-wavelength "soft" gluons see only global charge densities).

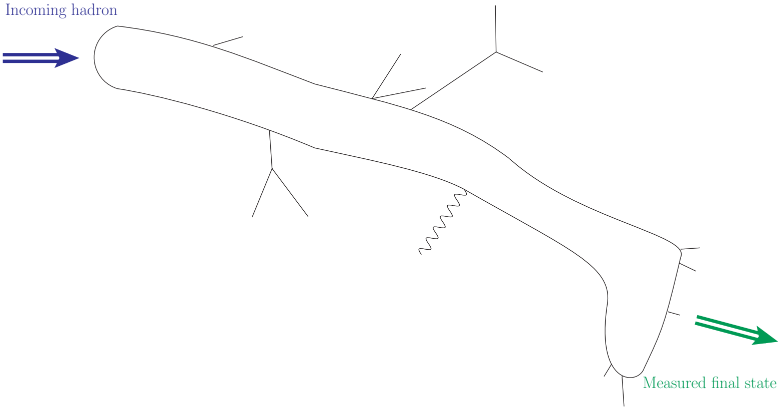
Tough measurement. Factorization in calculation model-dependent.

Realistic scatterings



The “full” final state is much more complicated, and the state evolution is complicated.
⇒ Exploit the ”perturbative model” as much as possible

Theory nightmare



The “full” final state is much more complicated, and the state evolution is complicated.

⇒ Exploit the ”perturbative model” as much as possible before we have to parametrize the whole system!

a) What are the assumptions of perturbation theory?
b) Status of fixed-order calculations
c) Parton showering

QCD is an asymptotically free theory: The interactions vanish at short distances. Use that!

Factorize "difficult" long-distance effects from "easy" short-distance physics...and then use the "easy" part as much as possible.

For difficult part, measure (fit) fragmentation functions parametrising how partons are translated into hadrons.
Jet measurements minimise sensitivity to hadron composition.

$$\begin{aligned}\sigma \quad &= \quad \int d\sigma_{(ab \to X+N \text{ partons})}(\text{high energy}, \text{low energy}) \\ &\qquad \otimes \mathcal{F}_{a\in \mathrm{A}}(\text{low energy}) \otimes \mathcal{F}_{b\in \mathrm{B}}(\text{low energy}) \\ &\qquad \otimes \mathcal{D}_{p_1,p_2,\ldots,\mathrm{p}_N,A,B}(\text{low energy})\end{aligned}$$

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Probabilities of finding partons in hadron A, B →

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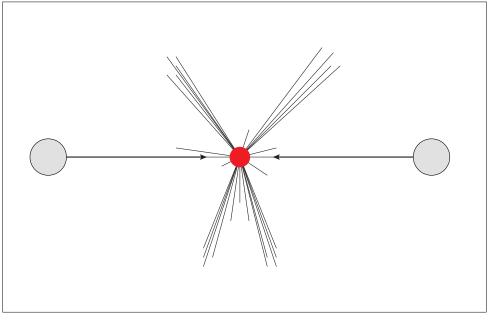
Probabilities of converting parton ensemble to observed final state.

Factorizing the fragmentation component: Jets

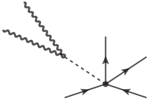
Hard scattering + Radiation cascade + Hadronisation + Hadron decays

Observation: Leads to collimated sprays of particles called **Jets**.



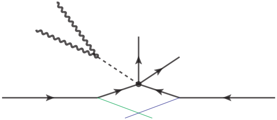
For $p_\perp > \Lambda_{\rm QCD}$, we expect $\mathcal{D}_{p_1,p_2,\ldots,p_N,A,B} \approx \prod_{i=1}^{N_{\rm jets}} \mathcal{J}_i(p_n \in {\rm Jet}_i)$

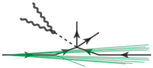
$\rightarrow$ If we can get away with measuring jets, non-perturbative model less important – but we introduce a *jet definition* dependence.



Short-distance scattering

- ◇ Very high energy transfer
- ◇ Produces partons = jet seeds
- ◇ Quantum interference matters
- ◇ Use QM expansion in interaction strength to ***fixed order***





Evolution

- ⋄ Partons accumulate radiation cloud
- ⋄ Inifinitely many particles important
- ⋄ Radiation shower quasi-classical
- ⋄ Approximate ***all-order*** expansion

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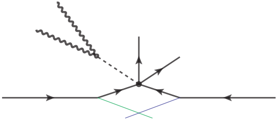

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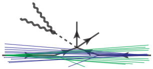

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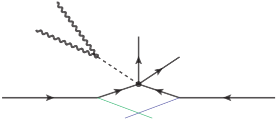

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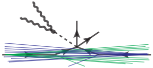

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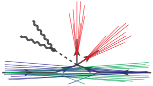

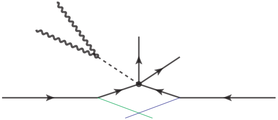

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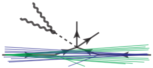

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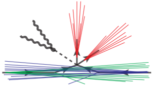
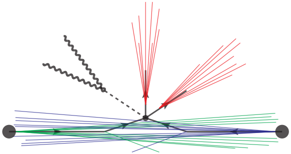
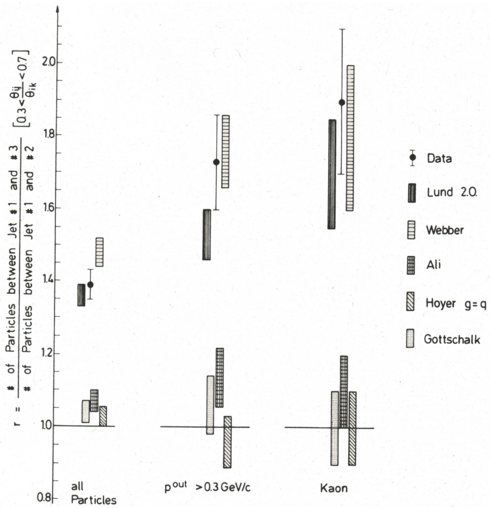




Low-energy cross section

- ◇ Particles have low energies
- ◇ Particles collected in jets
- ◇ Collision energy extracted from proton beam fragmentation (***data parametrisation***)

Remember: This is only an approximation!



Data shows that jets at LEP "talk to each other". The phenomenon is called string effect. It's perturbative incarnation is called *color coherence*.

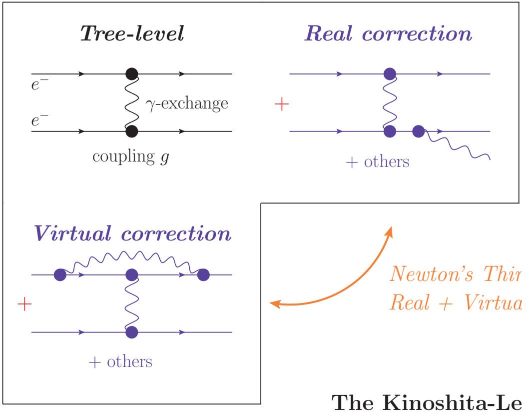
Reliable perturbative predictions

Mission statement: Use perturbative predictions to capture large portion of the dynamics before invoking non-perturbative models.

Good predictions should...

1. Fulfill physical constraints:
   Charge and flavour conservation.
   4-momentum conservation.
2. Fulfill consistency constraints:
   Should have a well-defined accuracy for inclusive + exclusive (semi-inclusive) cross-sections.
   $\rightarrow$ Recover accurate multi-jets fixed-order results.
   $\rightarrow$ Recover beam and jet functions (i.e. TMD evolution).
3. Capture all-order dynamics, e.g. include color coherence.
4. Have smooth matching to non-perturbative regime:
   Masses should be physical.
   Unresolved partons should not affect matching.

Fixed-order calculations



Newton's Third Law of QFT:
Real + Virtual = finite!

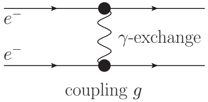
The Kinoshita-Lee-Nauenberg theorem

◇ Add all diagrams of same power in g,
and all zero-momentum ∞s will cancel!

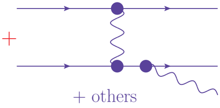
→ **Finite next-to-leading order (NLO) calculation**

Fixed-order calculations

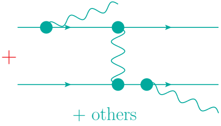
Tree-level



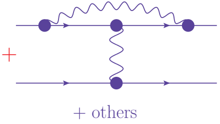
Real correction



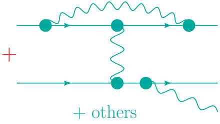
Double Real



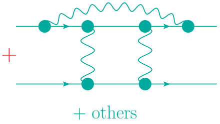
Virtual correction



Real-Virtual



Double Virtual



NNLO calculation

◇ Very accurate

◇ Newton's Third Law of QFT more complicated:

$$\begin{array}{lll} \textit{Real} & + \textit{Virtual} & = \textit{finite} \\ \textit{Double Real} & + \textit{Real-Virtual} & \\ + \textit{Double Virtual} & + (\textit{Virtual})^2 & = \textit{finite} \end{array}$$

Status of fixed-order calculations

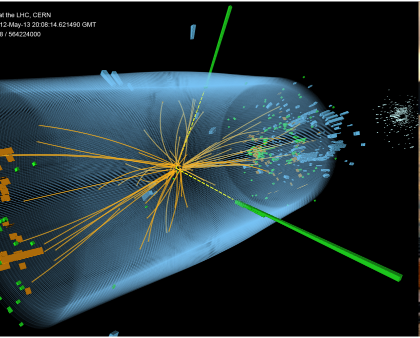
Task: Calculate $d\sigma$ exactly up to fixed power of coupling constant. Captures QM interferences. Cancellation of low-energy divergences quite complicated... and imperfect for exclusive observables.

Calculations for less inclusive observables invoke cuts, since otherwise unreliable because of soft/collinear emissions. Status:

- Tree-Level: $pp \to X+ \leq 10$ partons (needs cuts)
- Next-to-leading order: $pp \to X+ \leq 5$ partons (needs cuts)
- NNLO: $pp \to X+ \leq 1$ (may need cuts)
- N^3LO: $gg \to H$ inclusive cross section

Good... but we're not quite there yet

Remember the Higgs-boson candidate in CMS?



We're up to a good start, but we need many more ingredients!

First, an approximation

Real corrections R + Virtual corrections V = Finite

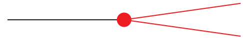
...and singularities in R and V are *scattering-process independent*.

$\Rightarrow$ Approximate higher-order correction for scattering processes:

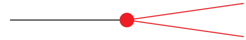
$$R' + V' \ = \ 0 \qquad \Longrightarrow \qquad V' = -\int d(\text{d.o.f. of emission})\ R'$$

Now assume that $\Gamma = R'/Born \in [0, 1]$.

Parton shower by analogy to nuclear decay

State of unstable isotope	State evolution	Probability
t_{start} t_{stop}		
	Isotope decayed in the time interval $\delta t = t_{start} - t_X$	$\Gamma \delta t$
	Isotope did not decay in the time time interval δt	$1 - \Gamma \delta t$
	Isotope did not decay in either of two smaller intervals	$(1 - \Gamma \frac{\delta t}{2})^2$
	Isotope did not decay in any of n arbitrarily small intervals	$(1 - \Gamma \frac{\delta t}{n})^n \to \exp\left(-\int_{t_X}^{t_{start}} dt' \; \Gamma\right)$
	Isotope did not decay before time t_X, then decayed at time t_X	$\exp\left(-\int_{t_X}^{t_{start}} dt' \; \Gamma\right) \; \Gamma \delta t$

Parton shower by analogy to nuclear decay

State of unstable isotope	State evolution	Probability
t_{start} t_{stop}		**"Real emission"**
	Isotope decayed in the time interval $\delta t = t_{start} - t_X$	$\Gamma \delta t$
		"Virtual correction"
	Isotope did not decay in the time time interval δt	$1 - \Gamma \delta t$
	Isotope did not decay in either of two smaller intervals	$(1 - \Gamma \frac{\delta t}{2})^2$
		All-order probability of no resolvable state change until t_X
	Isotope did not decay in any of n arbitrarily small intervals	$(1 - \Gamma \frac{\delta t}{n})^n \to \exp\left(-\int_{t_X}^{t_{start}} dt' \, \Gamma\right)$
	Isotope did not decay before time t_X, then decayed at time t_X	$\exp\left(-\int_{t_X}^{t_{start}} dt' \, \Gamma\right) \, \Gamma \delta t$

The no-emission probability is directly related to the conventional *Sudakov factor* Δ, and encodes all-order log-enhancements. The product $\Delta\Gamma$ is always regular.

Iterability of this "nuclear decay" procedure requires that

- After an emission, charges, flavours, 4-momenta have to be conserved.
- R'/B is a process-independent* probability†.

This allows to approximate any process $2 \to X + n$ partons:

a) Start with $2 \to X$ scattering Φ_B with evolution parameter t
b) Choose a state change at t' according to probability $R'/B\,(\Phi_R)$
c) If the state change is accepted, reset $\Phi_B \to \Phi_R$
d) Reset $t \to t'$, start again at a)

The ratio R'/B contains only collinear/soft pieces.
$\to$ Extra partons are collimated with partons in original $X \to$ Jets!

* Process-specific, improved kernels are possible.

† Probability can be understood rather broadly. Most functions that do not diverge for $t \neq 0$ may be fine.

Reliable parton showering

The shower provides a good representation of all-order QCD if it is

Simple

(Simple splitting functions, simple phase space boundaries...)

Theoretically clean

(Recover eikonal in soft limit, AP kernels in collinear limit, "collinear" anomalous dimensions as in analytic resummation, flavour/momentum sum rules, no choices introducing iffy subleading logs...)

Extentable

(Updating splitting functions, for QCD, QED, EW...)

$\Rightarrow$ Need exact, massive phase space factorisation and full phase space coverage, need QCD coherence, need sum rules.

After these prerequisites, good choices can be made by comparing against analytic resummation ($\widehat{=}$ TMD factorisation).
Parton showers aim at being an implementation of TMD evolution.

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After these prerequisites, good choices can be made by comparing against analytic resummation (≡ TMD factorisation).
Parton showers aim at being an implementation of TMD evolution.

We have defined a new dipole-parton shower, and implemented independently in the PYTHIA and SHERPA to minimise bug contamination (`arXiv:1506.05057`). Codes available as PYTHIA and SHERPA plugins.

Interference terms in soft-gluon MEs $\supset$ propagator structure $1/(s_{aj}s_{bj})$ which leads to coherence (and, after integration, to angular ordering).
$\Rightarrow$ Implement coherence directly at the integrand level by ordering evolution in dipole $p_\perp^2 = s_{aj}s_{bj}/\mu^2$.

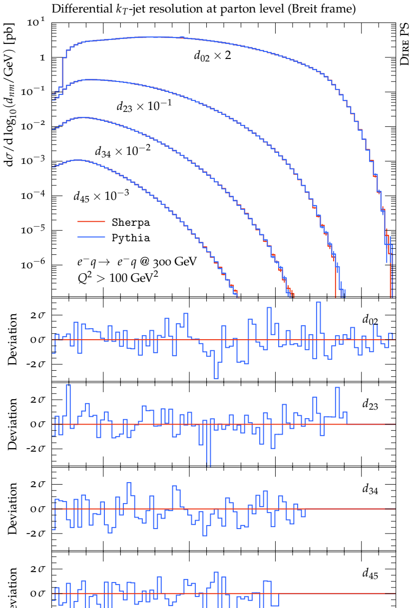
The soft-gluon divergence $(s_{aj}s_{bj})$ is then shared between emissions off a and off b. Careful not to over-count:

$$\frac{dp_{\perp a}^2}{p_{\perp a}} \int dz \mathcal{P}_{\widetilde{a}\to aj}(z_a) + \frac{dp_{\perp b}^2}{p_{\perp b}} \int dz \mathcal{P}_{\widetilde{b}\to bj}(z_b) := \frac{dp_\perp^2}{p_\perp^2}$$

$\Rightarrow$ PS splitting probabilities (dipoles) must vanish in the anti-collinear limits, except at $p_\perp = 0$.

Thus, dipoles project onto the respective collinear directions.
$\Rightarrow$ PS recovers factorised jet/beam function evolution.

DIS validation: Jet scales



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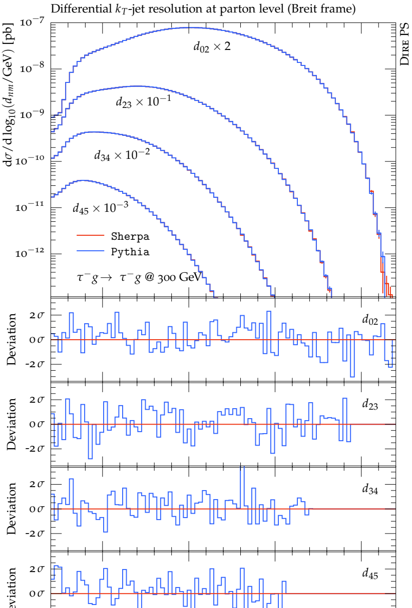

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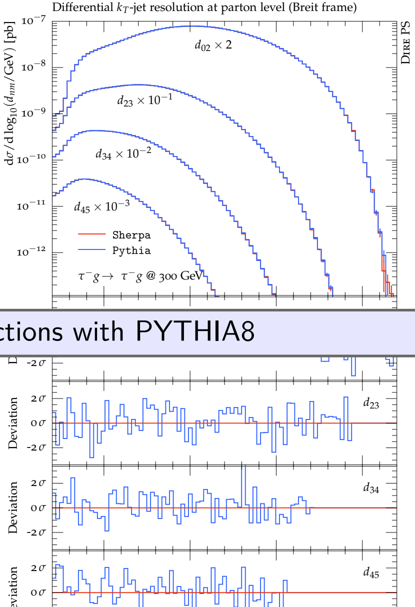


New: DIS predictions with PYTHIA8

Forget FSR. The PS should obey the DGLAP equation

$$\frac{df(x_0,t)}{f(x_0,t)} = dt\frac{dx'}{x'}\frac{f(x',t)}{f(x_0,t)}P\left(\frac{x_0}{x'}\right) \quad \text{with} \quad x_0 = \frac{2p_{\widetilde{aj}}q}{2Pq} = \frac{Q^2}{2Pq} = x_{\mathrm{Bjorken}}$$

and x is the longitudinal momentum fraction.

Initial state radiation in a traditional PS proceeds by

- Take massless incoming line, shift to accommodate virtuality t.
- Split the massive incoming line to produce the emission.

Introdution of a virtuality t means

$$x_0 = \frac{2p_{\widetilde{aj}}q}{2Pq} = \frac{Q^2}{2Pq}\left(1 + \frac{t}{Q^2}\right) \neq x_{\mathrm{Bjorken}}$$

$\Longrightarrow$ Application of PS changes x of hard process.

The issue with DIS

Problem is related to the shift massless $\rightarrow$ massive.

Note: In the Drell-Yan case, the necessary shift is taken from the whole final state. Integrating shifted final state yields correct result. But in DIS, we cannot naively shift the lepton!

Pythia 6 solution: For the first ISR, reinterpret x_{Bjorken} of the core scattering to be

$$x_{0,PS} = x_{\mathrm{Bjorken}} \left(1 - \frac{t}{Q^2}\right)$$

i.e. take the necessary energy from reinterpreting the hard scattering. Use a strongly t-dependent z to arrive at this form.

$\Longrightarrow$ Inclusive cross section is correctly evaluated with longitudinal momentum fraction.

Note: Final-state showers also more complicated, with awkward z-definition.

Employ an exact phase space factorisation.

...and take necessary momentum from final-state parton $\tilde{k}$.

$$p_{\widetilde{aj}} - p_{\widetilde{k}} = p_a - p_j - p_k$$

All momenta are massless, before and after the splitting.

Thus, before as well as after the splitting, we have

$$(p_{\widetilde{aj}} + q)^2 = 2p_{\widetilde{aj}}q - Q^2 \quad \rightarrow \quad x_0 = \frac{2p_{\widetilde{aj}}q}{2Pq} = \frac{Q^2}{2Pq} = x_{\text{Bjorken}}$$

and after the splitting

$$(p_a + q)^2 = \frac{2p_{\widetilde{aj}}q}{z} - Q^2 \quad \rightarrow \quad x_1 = \frac{2p_a q}{2Pq} = \frac{x_0}{z} = \frac{x_{\text{Bjorken}}}{z}$$

Struncture functions in all n-parton cros sections are evaluated with sensible longitudinal momentum fractions, simply because integrating over shifted final state yields $p_{\widetilde{aj}}$ and $p_{\widetilde{k}}$ again.

Old model

◇ Implemented in PYTHIA 6.

◇ Jet rates technically still depend on custom structure functions.

◇ z-definition in FSR rather messy. Not coherent.

◇ Largest FSR virtuality $(m'_1)_{max} = E'_1$ leaves holes in phase space.

◇ Differences in FSR and ISR mean not easily improved with full MEs. Thus uncertain for large W^2.

◇ Includes diffractive model and beam remnant treatment.

New model: DIRE

◇ Plugin to PYTHIA 8.

◇ Depends only on standard structure functions$^{(*)}$.

◇ Straight-forward z-definitions, coherence built into kernels directly.

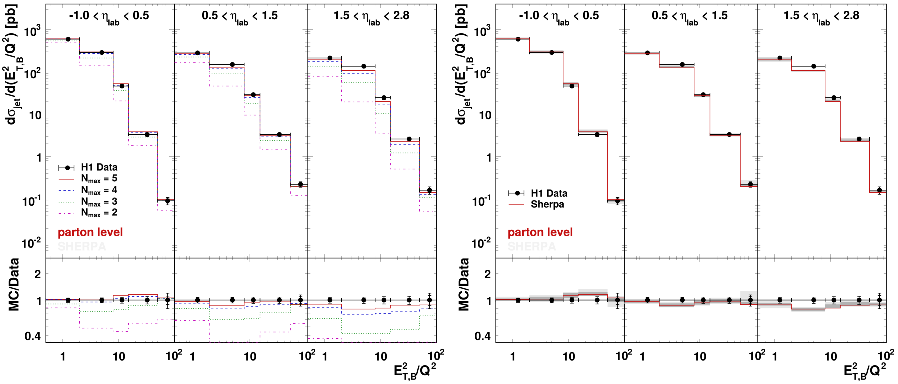
◇ Largest evolution scale naturally set by dipole mass.

◇ Exact local momentum conservation allows inclusion of exact MEs. Will be helpful for large W^2 region.

◇ No diffraction yet, rudimentary beam remnants.

$^{(*)}$ up to power corrections from difference of kernels to DGLAP.

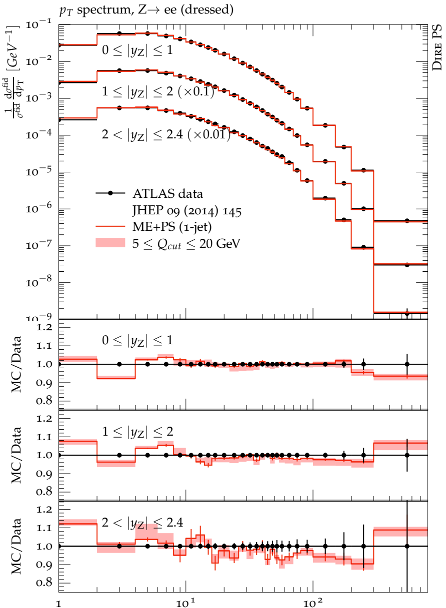
Exact phase space factorisation has further advantages



SHERPA predictions for the inclusive jet cross section as a function of $E^2_{T,B}/Q^2$ in bins of η_{lab}, as measured by H1. Plot taken arXiv:1006.5696

Exact phase space factorisation enables corrections with multi-jet matrix elements. Merging a "DGLAP" PS with tree-level multi-jet gives good data description.

LHC data comparisons (1-jet CKKW-L merged)



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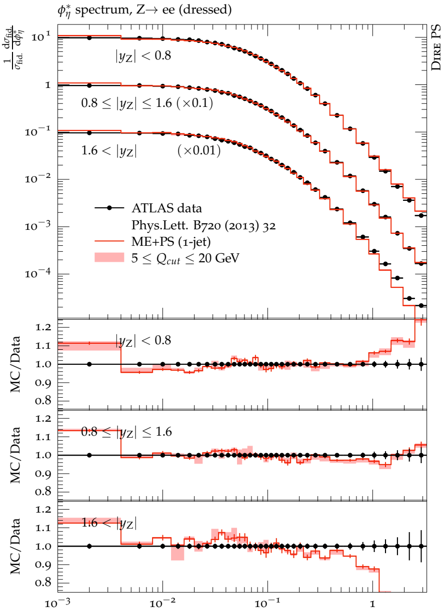

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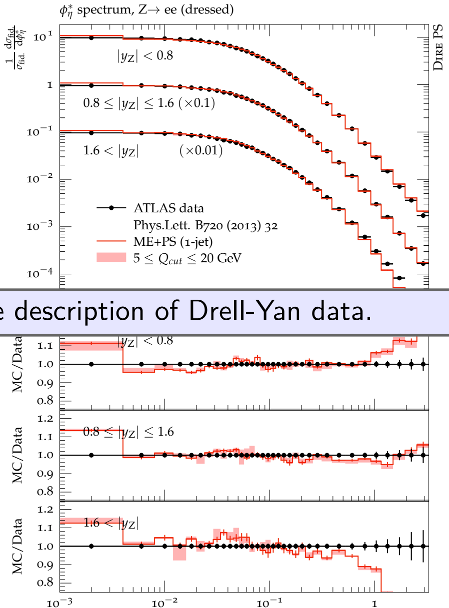
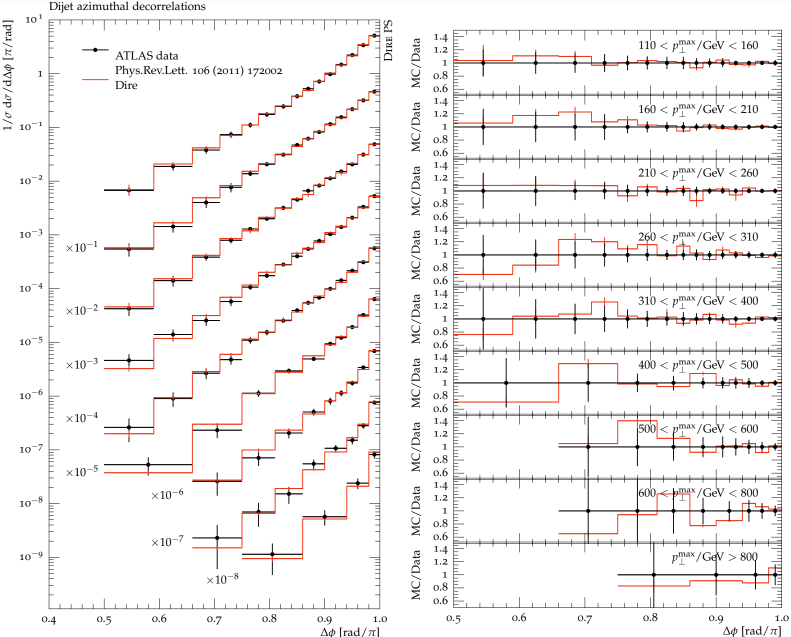
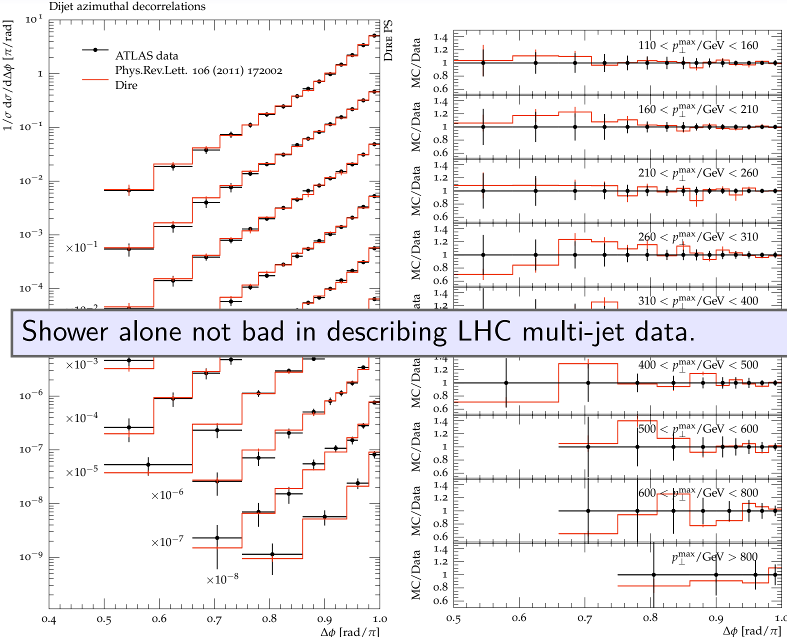


Not too terrible description of Drell-Yan data.

LHC data comparisons (plain showering)



LHC data comparisons (plain showering)



Shower alone not bad in describing LHC multi-jet data.

DIRE web page and support

- DIRE is a complete replacement of the PYTHIA 8 showers.
- It naturally interleaves with the generator, since PYTHIA 8 natively supports steering of new showers within its evolution.
- DIRE is developed collaboratively in PYTHIA 8 + SHERPA.

You can download the new showers at

`www.hepforge.org/archive/direforpythia`

or at

`www.slac.stanford.edu/~prestel/DIRE`

and you can get contact the support team under

`direforpythia@projects.hepforge.org`

We have discussed two ways to use the perturbative approximation:

Fixed-order calculation

◇ All quantum interferences included at fixed coupling power.

◇ Describes high-energy scattering and jet seed production.

◇ Unreliable close to zero-momentum singularities.

All-order parton shower

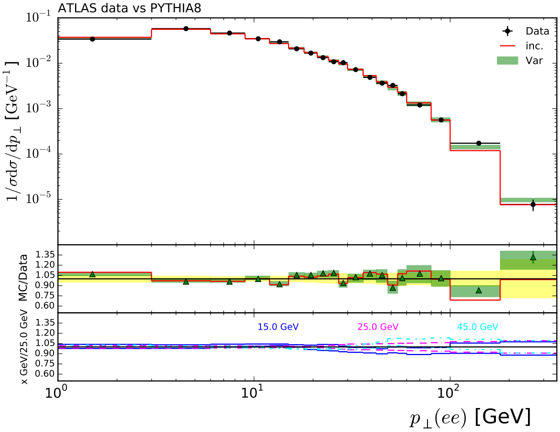
◇ All coupling powers accounted for approximately.

◇ Describes jet evolution from high-energy to low-energy state.

◇ Unreliable when interferences and finite remainders matter.

A good (theoretical) model of particle colliders needs a combination of both methods!

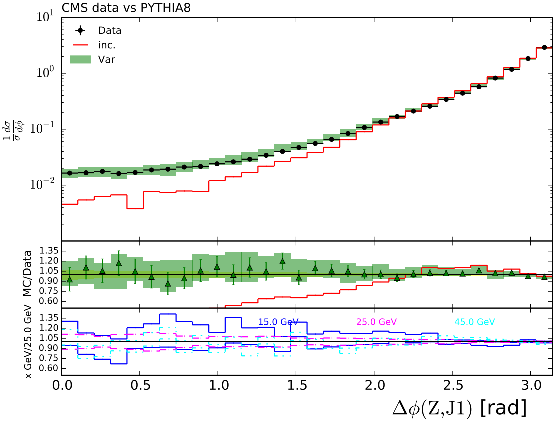
We need both parton showers and fixed-order calculations!



Transverse momentum of a reconstructed Z-boson (as measured by the ATLAS detector, LHC running at 7 TeV collision energy)

Without parton shower, the theory model would give ∞ at zero $p_\perp$.

We need both parton showers and fixed-order calculations!



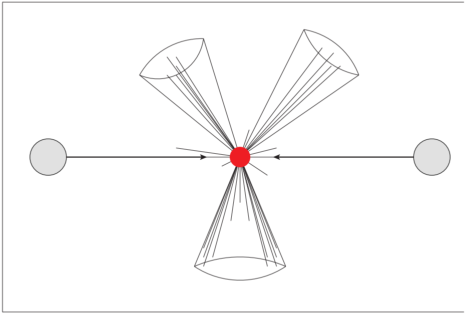
Azimuthal angle difference between Z-boson and the highest-energy jet (measured by the CMS detector at 7 TeV collision energy)

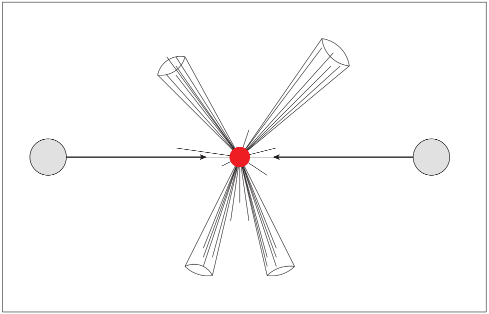
Without fixed-order calculations, the theory model would underpredict small angular differences.

Jets evolution vs. Jet production

Naively combining parton shower and fixed-order calculation leads to a double-counting of states.

Q: How is the transition between jet production and evolution defined?
A: It is not defined. Both can yield the same particle configurations.





Removing this overlap without impairing either calculation is the main problem of combination schemes.

... you wouldn't want to ruin the veggies!

How do we remove the overlap?

No emission $\rightarrow$ State not changed
$\rightarrow$ P(no-emission) $=$ All-order approximate virtual correction

One emission $\rightarrow$ State contains an extra particle
$\rightarrow$ P(emission) $=$ All-order approximate real emission

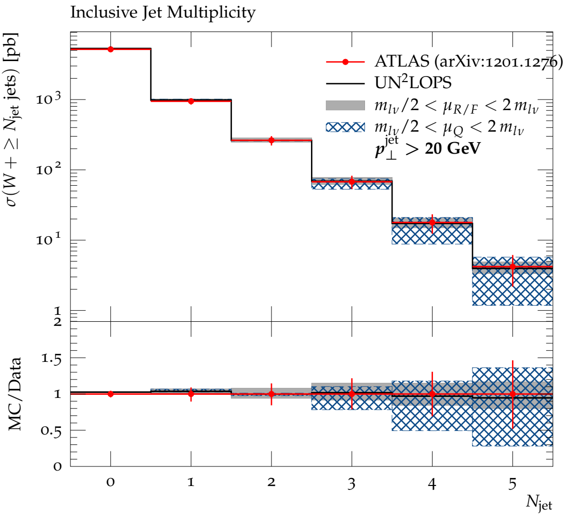
$\Longrightarrow$ Subtract from the FO calculation what the PS adds, i.e. use an adjusted FO calculation:

$$\begin{aligned} & \mathit{Tree-Level} \quad + \quad \mathit{Virtual\ Correction} \quad + \quad \mathit{Real\ Correction} \\ \rightarrow\ & \mathit{Tree-Level} \quad + \quad \left[\mathit{Virtual\ Correction} + P(\mathit{no\ emission})|_{\mathit{1st\ order}}\right] \\ & \qquad\qquad\quad + \quad \left[\mathit{Real\ Correction} \quad - P(\mathit{emission})|_{\mathit{1st\ order}}\right] \end{aligned}$$

...then simply act the PS on this FO calculation, and the arbitrary "adjustment" will be removed and both NLO calculation and PS combined without impairing either!

$\Longrightarrow$ PS $+$ NLO cross section combined. Can also be done at NNLO.

NNLO+PS matched results



n_{jets} in association with a Z-boson. UN^{2}LOPS has (very) small uncertainty in zero/one-jet rate. Shower uncertainty larger for higher multiplicities.

Merging multiple calculations

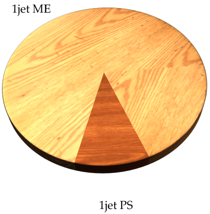
Merging multiple calculations: Divide and conquer

The FO calculation is unreliable close to zero-momentum singularities.
The PS is unreliable far away from zero-momentum singularities.

$\Longrightarrow$ Use PS for real emissions "below" some energy resolution, and FO for real emissions "above" some resolution scale.

$\Longrightarrow$ Works for any number of jets :)

Merging: Iterative improvements by slicing

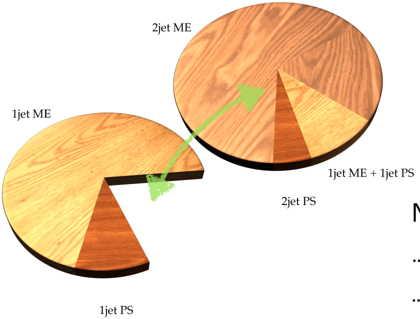


Look at one-jet states:

...use PS for soft emissions

...use ME for hard emissions

Merging: Iterative improvements by slicing

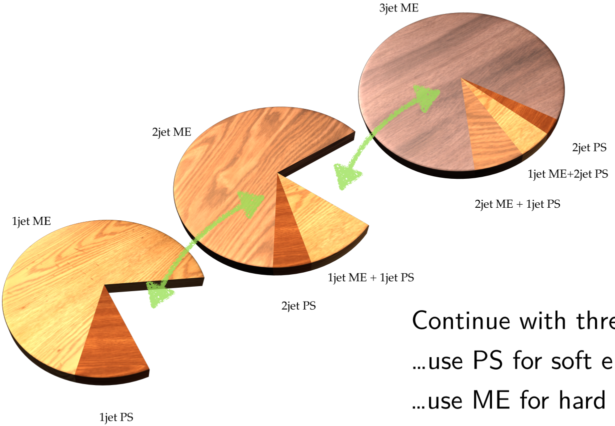


Now improve two-jet states:

...use PS for soft emissions

...use ME for hard emissions

Merging: Iterative improvements by slicing



Continue with three-jet states:

...use PS for soft emissions

...use ME for hard emissions

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Now we have QM interferences at a fixed order above some arbitrary energy scale, and all-order results below the scale.
$\Longrightarrow$ Strong dependence on this "merging scale" :(

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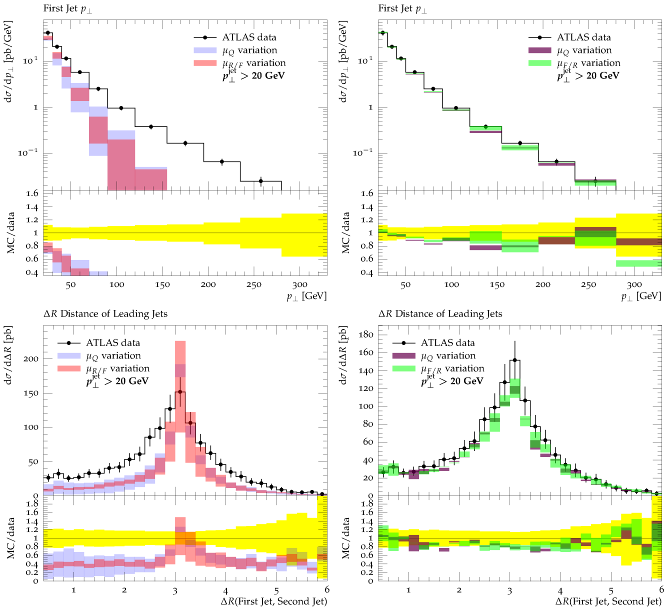
Now we have QM interferences at a fixed order above some arbitrary energy scale, and all-order results below the scale.

$\Longrightarrow$ Strong dependence on this "merging scale" :(

This is minimised by correctly attaching the PS resummation and updating the PS all-order virtual corrections.

$\Rightarrow$ Any number of NLO calculations *merged* with each other and with PS all-order resummation (common schemes: MEPS@NLO, UNLOPS)

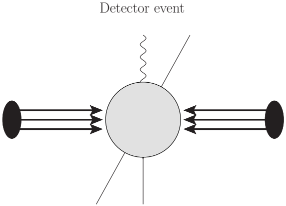
Data comparisons (W+jets)



Inclusive sample containing (W + no resolved)@NLO, (W + one resolved)@NLO and (W + two resolved)@LO.

Combining multiple calculations with each other and with accurate parton showering

Back to the big picture: An example...



The event contains 1 boson and 3 jets. Where do the jets come from?

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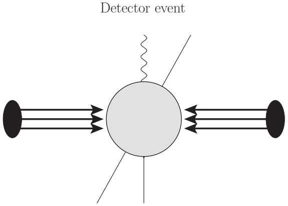

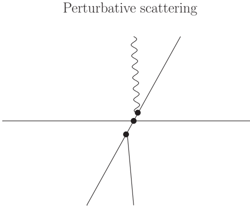

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When does the perturbative approximation hold?

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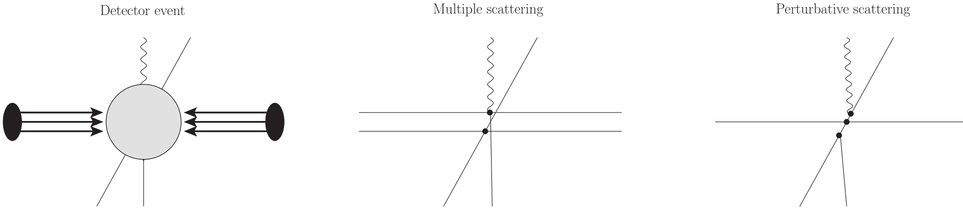

The event contains 1 boson and 3 jets. Where do the jets come from?

When does the perturbative approximation hold?

When colliding composite objects, many scatterings "compete" for the collision energy – **and multiple scattering can look like single complicated scatterings!**

⇒ Event generator improvements need to match seamlessly with the remaining bits!

Combining multiple calculations with each other and with accurate parton showering within a **full event simulation**

⇒ **General Purpose Monte Carlo Event Generators.**

- Very accurate simulations of scattering events needed to assess backgrounds – and interesting in itself.

4. Summary and outlook

- Very accurate simulations of scattering events needed to assess backgrounds – and interesting in itself.
- A good understanding of the the perturbative approximation (and it's limitations) are crucial.
- Two ways to organise the perturbative expansion are important for reliable simulations:
  Fixed-order calculations and all-order parton showers.
- Showers are an implementation of all-order QCD evolution.

4. Summary and outlook

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- A good understanding of the the perturbative approximation (and it's limitations) are crucial.
- Two ways to organise the perturbative expansion are important for reliable simulations:
  Fixed-order calculations and all-order parton showers.
- Showers are an implementation of all-order QCD evolution.
- More precise data will require ever more precise simulations.
- There are still a lot of open ends:
  Can we overcome our language barriers?
  Can we construct a realistic TMD Monte-Carlo generator?
  Dare we dream of spin-dependent evolution / hadronisation?

Lunch time!

Thanks for your time!

DIRE splitting functions

The massless dipole splitting functions in the *all* (II, IF, FI, FF) sectors are

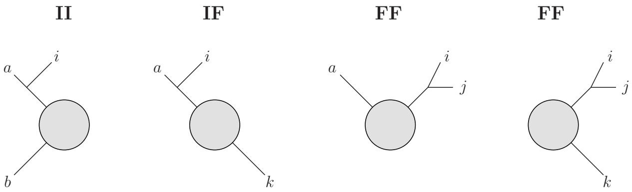
$$P_{qq}(z,\kappa^2) = 2\,C_F\left[\left(\frac{1-z}{(1-z)^2+\kappa^2}\right)_+ - \frac{1+z}{2}\right] + \frac{3}{2}\,C_F\,\delta(1-z)$$

$$P_{gg}(z,\kappa^2) = 2\,C_A\left[\left(\frac{1-z}{(1-z)^2+\kappa^2}\right)_+ + \frac{z}{z^2+\kappa^2} - 2 + z(1-z)\right] + \delta(1-z)\left(\frac{11}{6}C_A - \frac{2}{3}n_f T_R\right)$$

$$P_{gq}(z,\kappa^2) = 2\,C_F\left[\frac{z}{z^2+\kappa^2} - \frac{2-z}{2}\right] \qquad P_{qg}(z,\kappa^2) = T_R\left[z^2+(1-z)^2\right]$$

These functions, integrated over the full physical phase space, or for z-boundaries $\{0/x, 1\}$, give the correct anomalous dimensions.

DIRE ordering variables



More concretely, we generate phase space in the variables

$$\rho_{\mathrm{II}} = \frac{s_{ai}s_{bi}}{s_{ab}}\frac{s_{aib}}{s_{ab}} \qquad z_{\mathrm{II}} = 1 - \frac{s_{bi}}{s_{ab}}$$

$$\rho_{\mathrm{IF}} = \frac{s_{ai}s_{ik}}{s_{ai}+s_{ak}}\frac{s_{ai}+s_{ik}+s_{ak}}{s_{ai}+s_{ak}} \qquad z_{\mathrm{IF}} = 1 - \frac{s_{ik}}{s_{ai}+s_{ak}}$$

$$\rho_{\mathrm{FI}} = \frac{s_{aj}s_{ij}}{s_{ai}+s_{aj}}\frac{s_{ij}+s_{aj}+s_{ai}}{s_{ai}+s_{aj}} \qquad z_{\mathrm{FI}} = \frac{s_{ai}}{s_{ai}+s_{aj}}$$

$$\rho_{\mathrm{FF}} = \frac{s_{ij}s_{jk}}{s_{ij}+s_{ik}+s_{jk}} \qquad z_{\mathrm{FF}} = \frac{s_{ij}+s_{ik}}{s_{ij}+s_{ik}+s_{jk}}$$

and pick Φ randomly in $[0, 2\pi]$. Note that the evolution variables ρ are inverse eikonal factors!