Combining perturbative calculations with parton showers

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Theoretical calculations can be performed in three different limits of field theory

Fixed perturbation theory	$\alpha_s \to 0$
Logarithmic resummation	$\alpha_s \to 0$, $\alpha_s L$ fixed
Kinematic expansion (parton shower)	$\theta_{ij} \to 0$

Each expansion important in different regions

Theoretical calculations can be performed in three different limits of field theory

Fixed order perturbation theory

Best precision for inclusive observables
(only one relevant scale in problem)

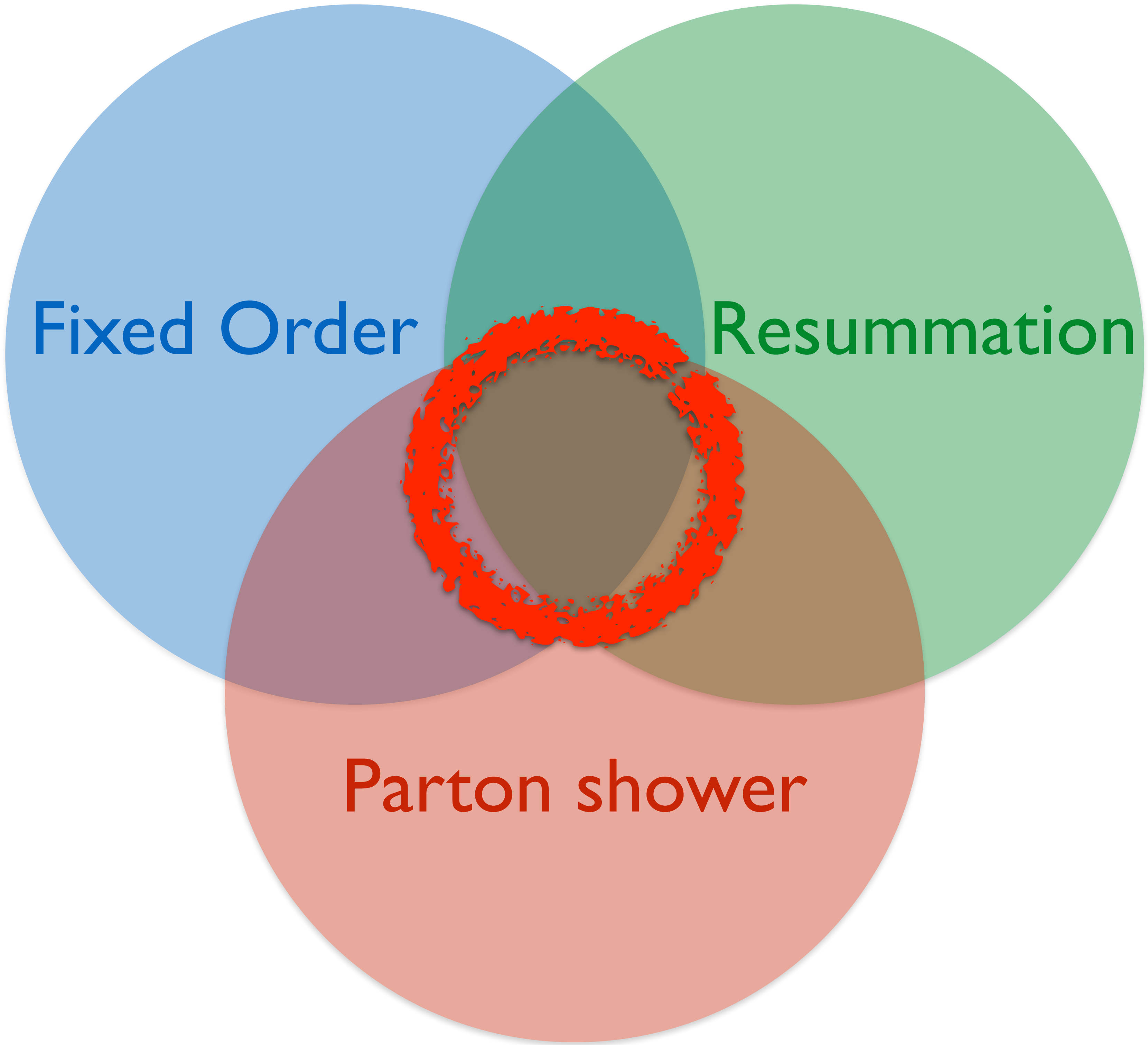
Logarithmic resummation

Best precision for semi-inclusive observables (large ratio(s) of scale in problem)

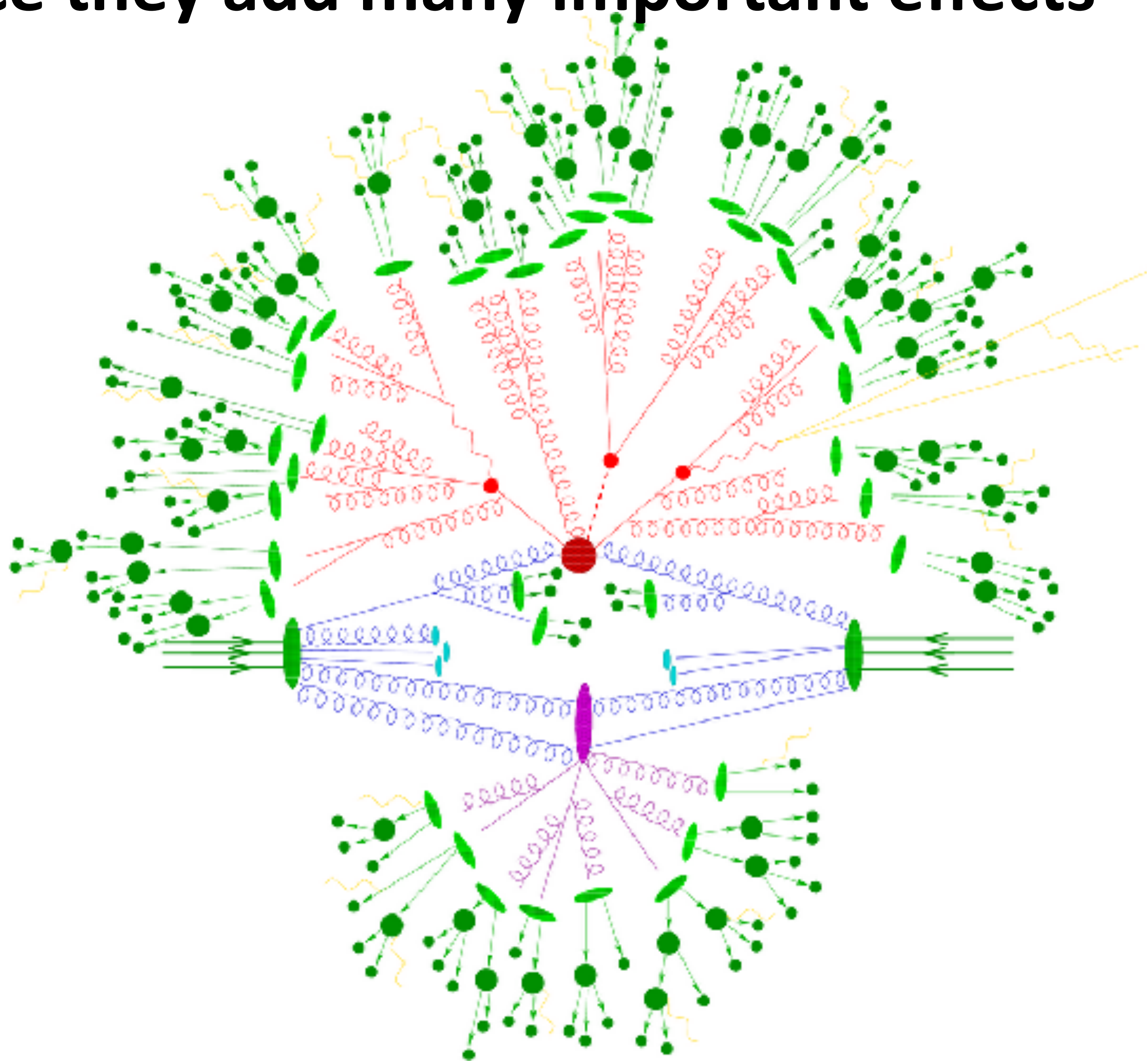
Parton shower

Only tool for events with arbitrary multiplicity
(event simulation)

I will discuss today how to merge all three types of calculations together



Need to combine perturbative calculations with parton showers, since they add many important effects

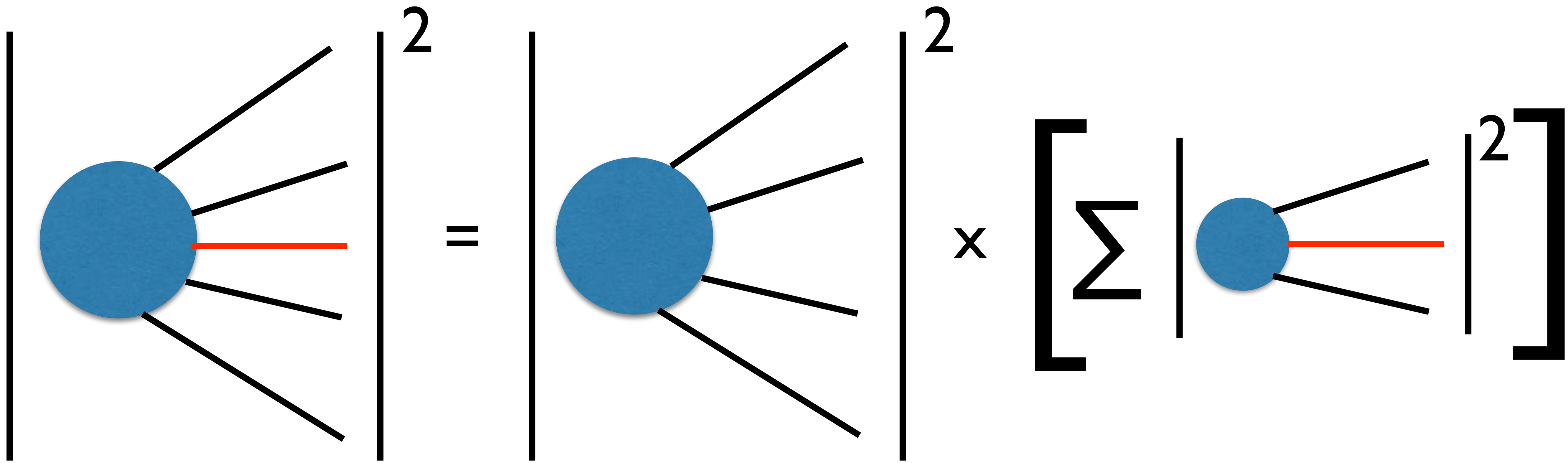


- Initial hard interaction
- Radiation of additional partons
- Multi-parton interactions
- Hadronization of resulting partons
- Decay of unstable hadrons

Three main multipurpose parton showers:
Herwig, Pythia, Sherpa

Parton showers combine simplification in θ→0 limit with conservation of probability

In θ→0 limt, cross sections simplify



$$\sigma_N = \sigma_{N-1} \times \sum SP(t,z)$$

Conservation of probability:

P(no-emission) + P(≥1emission) = 1

LO matching included in essentially every shower

Start from the generic parton shower expression

$$\langle O \rangle = \boxed{\frac{d\sigma}{d\Phi_2}} \boxed{\Pi_2(Q, t_c)} \langle O \rangle_{\Phi_2} + \int_{t_c}^{Q} dt_1 \boxed{\Pi_2(Q, t_1)} \boxed{\mathrm{SP}(t_1)} \boxed{\Pi_3(t_1, t_c)} \langle O \rangle_{\Phi_3} + \ldots \Big]$$

Separate the fixed order pieces from the resummed pieces

Unitarity relates the splitting function to the no-emission probability

$$\Pi_N(t, t_c) = \exp\left\{ - \int_{t_c}^{t} dt' \sum_{i=1}^{N} \mathrm{SP}_i(t') \right\}$$

LO matching included in essentially every shower

Start from the generic parton shower expression

$$\langle O \rangle = \frac{d\sigma}{d\Phi_2} \Pi_2(Q, t_c) \langle O \rangle_{\Phi_2} + \int_{t_c}^{Q} dt_1 \, \Pi_2(Q, t_1) \, \mathrm{SP}(t_1) \, \Pi_3(t_1, t_c) \langle O \rangle_{\Phi_3} + \ldots \Big]$$

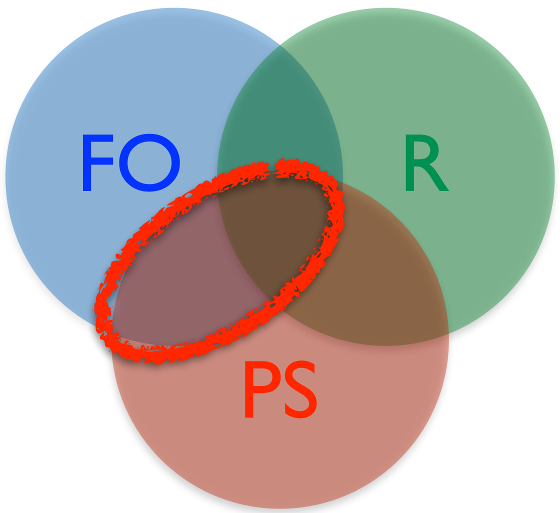
Separate the fixed order pieces from the resummed pieces

Φ_2	Φ_3
$\frac{d\sigma_2}{d\Phi_2}$	$\frac{d\sigma_2}{d\Phi_2} \mathrm{SP}(t_1)$
$\Pi_2(Q, t_c)$	$\Pi_2(Q, t_1) \, \Pi_3(t_1, t_c)$

LO merging requires combination of FO with LL resummation

Catani, Krauss, Kuhn, Webber ('01)

Change the fixed order pieces in the original expression



Φ_2	Φ_3
$\frac{d\sigma_2}{d\Phi_2}$	$\frac{d\sigma_2}{d\Phi_2}\mathrm{SP}(t_1)$
$\Pi_2(Q, t_c)$	$\Pi_2(Q, t_1)\,\Pi_3(t_1, t_c)$

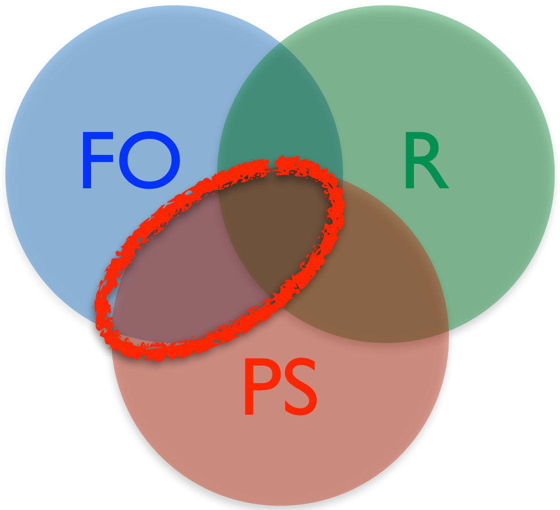
to something that has LO correct for both Φ_2 and Φ_3

Φ_2	Φ_3
$\frac{d\sigma_2}{d\Phi_2}$	$\frac{d\sigma_3}{d\Phi_3}\theta(t_1 > t_M) + \frac{d\sigma_2}{d\Phi_2}\mathrm{SP}(t_1)\theta(t_1 < t_M)$
$\Pi_2(Q, t_c)$	$\Pi_2(Q, t_1)\,\Pi_3(t_1, t_c)$

both multiplicities correct at LO (at large t_1)

NLO matching can be obtained by a "simple replacement" in the original formula

Frixione, Webber ('02)
Nason ('04)



For NLO matching

Φ_2	Φ_3
$\frac{d\sigma_2}{d\Phi_2}$	$\frac{d\sigma_2}{d\Phi_2}\mathrm{SP}(t_1)$
$\Pi_2(Q,t_c)$	$\Pi_2(Q,t_1)\,\Pi_3(t_1,t_c)$

need to change both fixed order and resummed pieces

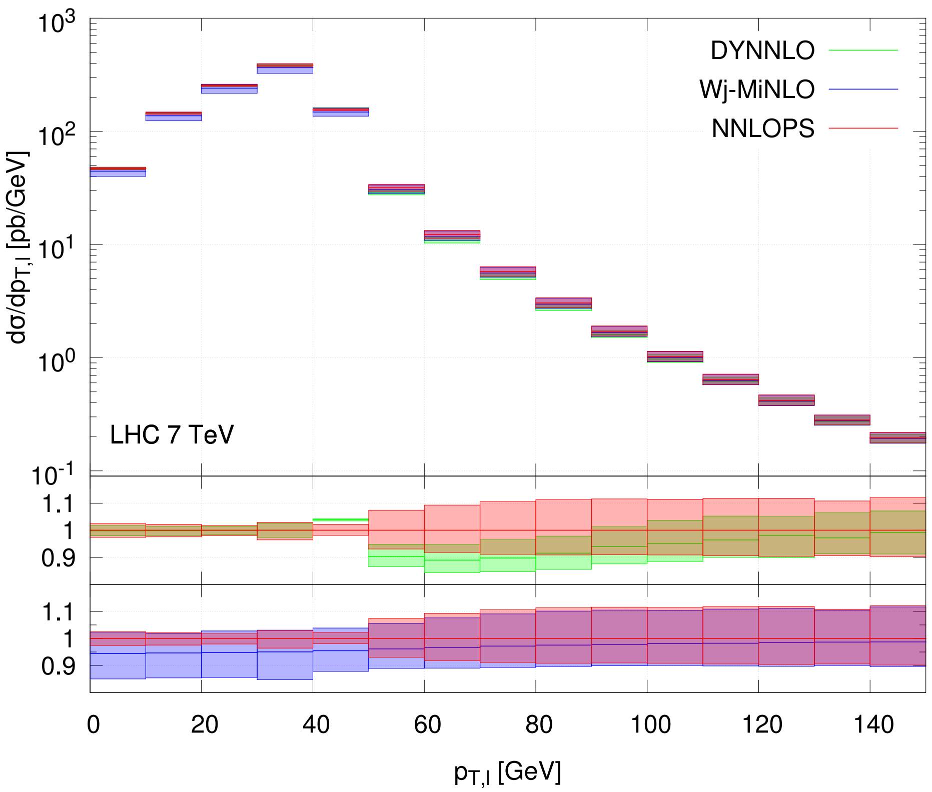
Φ_2	Φ_3
$\frac{d\sigma_2^{\mathrm{NLO}}}{d\Phi_2}$	$\frac{d\sigma_2^{\mathrm{NLO}}}{d\Phi_2}\left[\frac{d\sigma_3}{d\Phi_3}\Big/\frac{d\sigma_2}{d\Phi_2}\right]$
$\Pi_2^R(Q,t_c)$	$\Pi_2^R(Q,t_1)\Pi_3(t_1,t_c)$

Inclusive 2-jet at NLO, 3-jet at LO

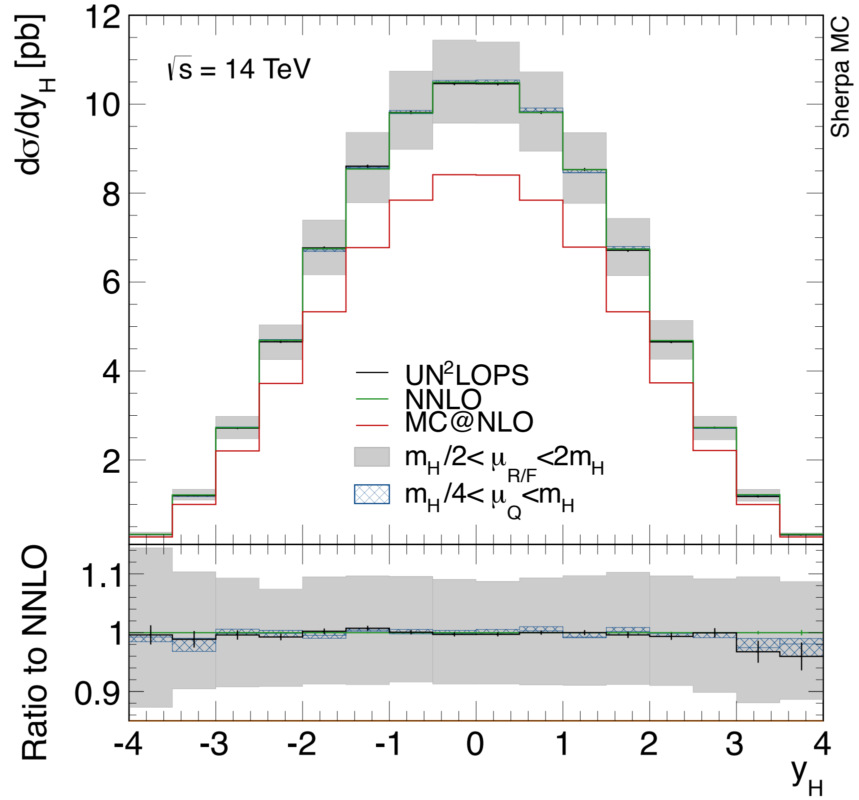
Recent development is NNLO + PS

There are three main methods available at this point

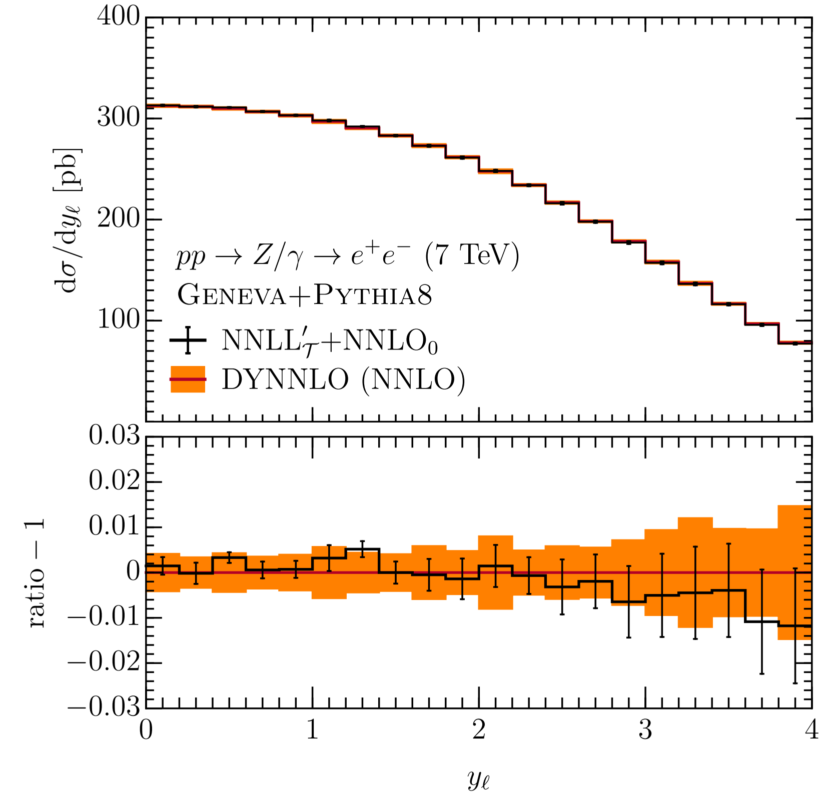
MINLO-NNLOPS	UNNLOPS	Geneva



Hamilton, et al ’13 - ‘16



Hamilton, et al ’14 - ‘16



Alioli, CWB et al, et al ’13 - ‘16

MINLO improved NLO reweighted to NLO

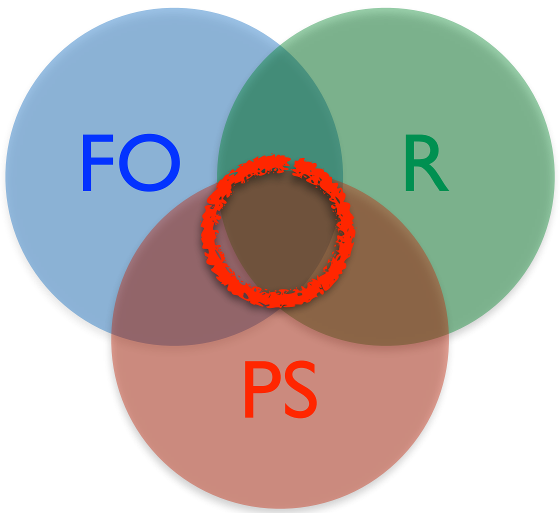
N-jettiness slicing and Unitarity

N-jettiness slicing and NNLL’ resummation

Merging higher logarithmic resummation with parton showers has received less attention

Alioli, CWB, Tackmann ('14-'17)

To get combined higher fixed and resummed orders



Φ_2	Φ_3
$\frac{d\sigma_2}{d\Phi_2}$	$\frac{d\sigma_2}{d\Phi_2}\mathrm{SP}(t_1)$
$\Pi_2(Q, t_c)$	$\Pi_2(Q, t_1)\,\Pi_3(t_1, t_c)$

can not separate the two pieces any longer

Φ_2	Φ_3
$\frac{d\sigma_2^{\mathrm{NNLL}'}}{d\Phi_2}$	$\frac{d\sigma_3^{\mathrm{NNLL}'}}{d\Phi_3}$

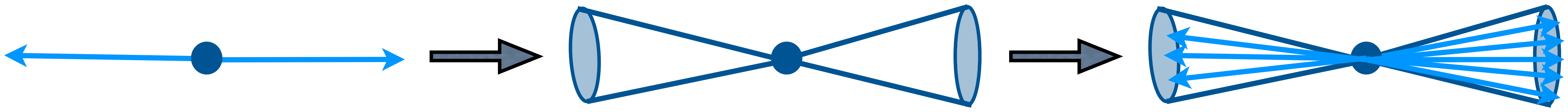
Combining FO with resummed accuracy gives the right result

The main spirit of GENEVA is to calculate physical jet cross-sections

Partonic cross-sections are ill-defined beyond LO in standard perturbation theory

This problem is well known, and always measure and calculate jet cross-sections

Don’t count number of partons, count number of jets



Do calculations for jet cross-sections, and use shower to fill out jet

To obtain logarithmic resummation requires a fully factorizable jet definition

A very convenient jet definition is called n-jettiness

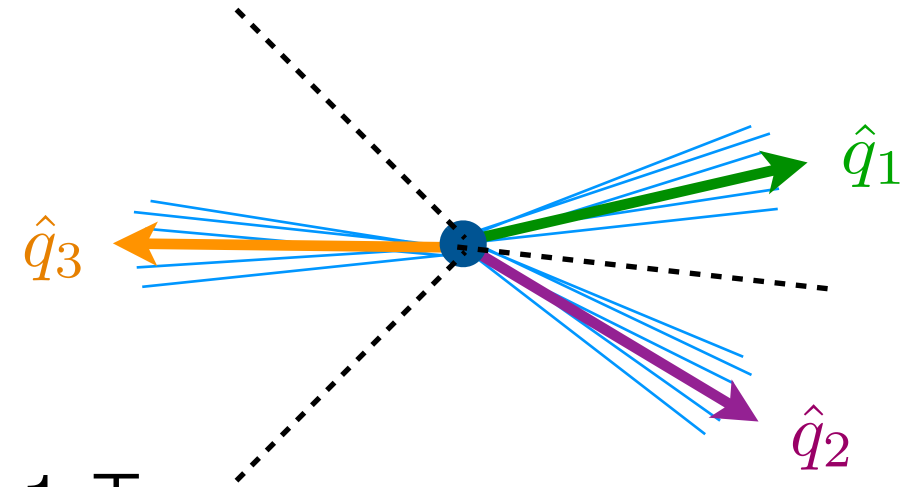
1004.2489

$$\mathcal{T}_N = 2\sum_k \min\{\hat{q}_1 \cdot p_k, \hat{q}_2 \cdot p_k, \cdots, \hat{q}_N \cdot p_k\}$$

$\mathcal{T}_N \to 0$: N pencil-like jets

$\mathcal{T}_N \to Q$: more than N jets

$\mathcal{T}_N < \mathcal{T}_{cut}$: Veto > N jets

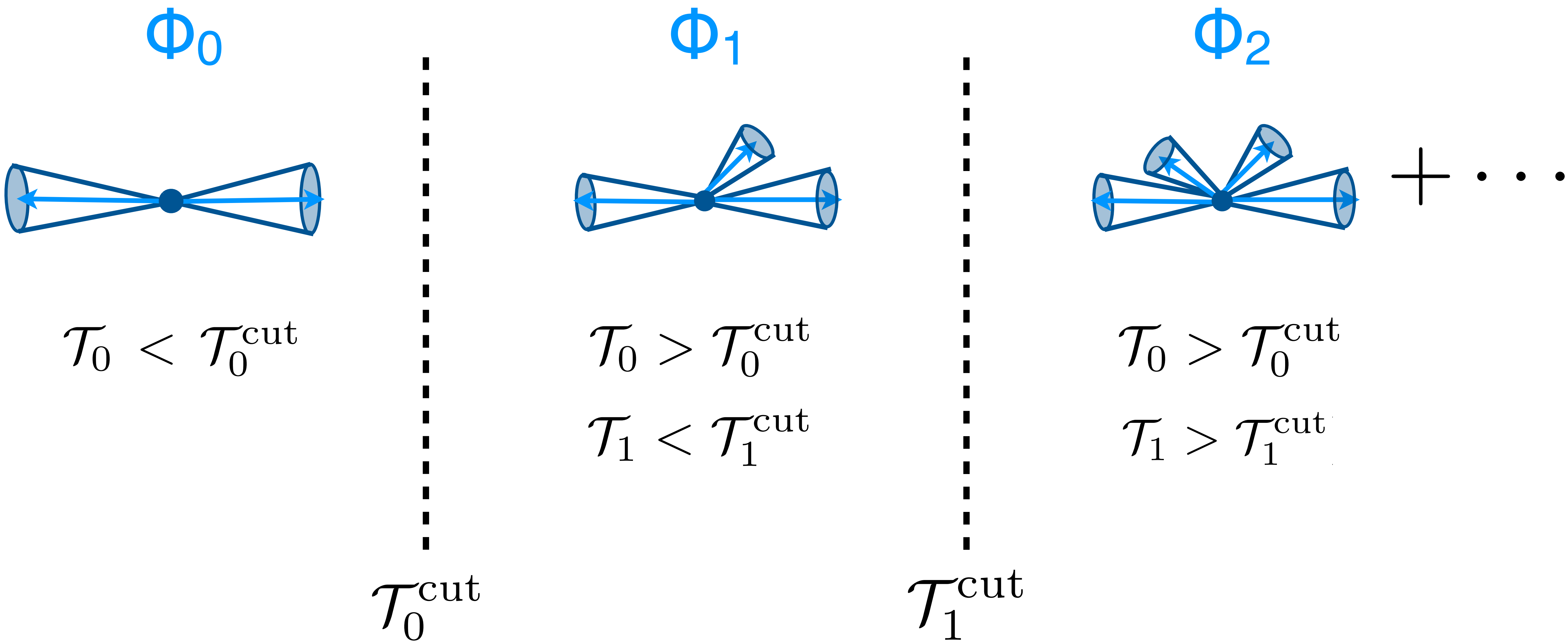


Note that $T_2 = \tau = 1\text{-}T$

Factorization theorem can be proven to all orders

Systematic method to resum logarithms at arbitrary order

This allows us to separate the total hadronic event into different jet multiplicities



Calculate each jet cross section to desired fixed and resummed accuracy, and use shower to fill out jets with radiation

The main question is what expression to use for the differential jet cross-section

$$\frac{d\sigma^{\mathbf{MC}}}{d\Phi_N}?$$

Use SCET to determine the expressions for the differential jet cross-sections with resummed and fixed accuracy

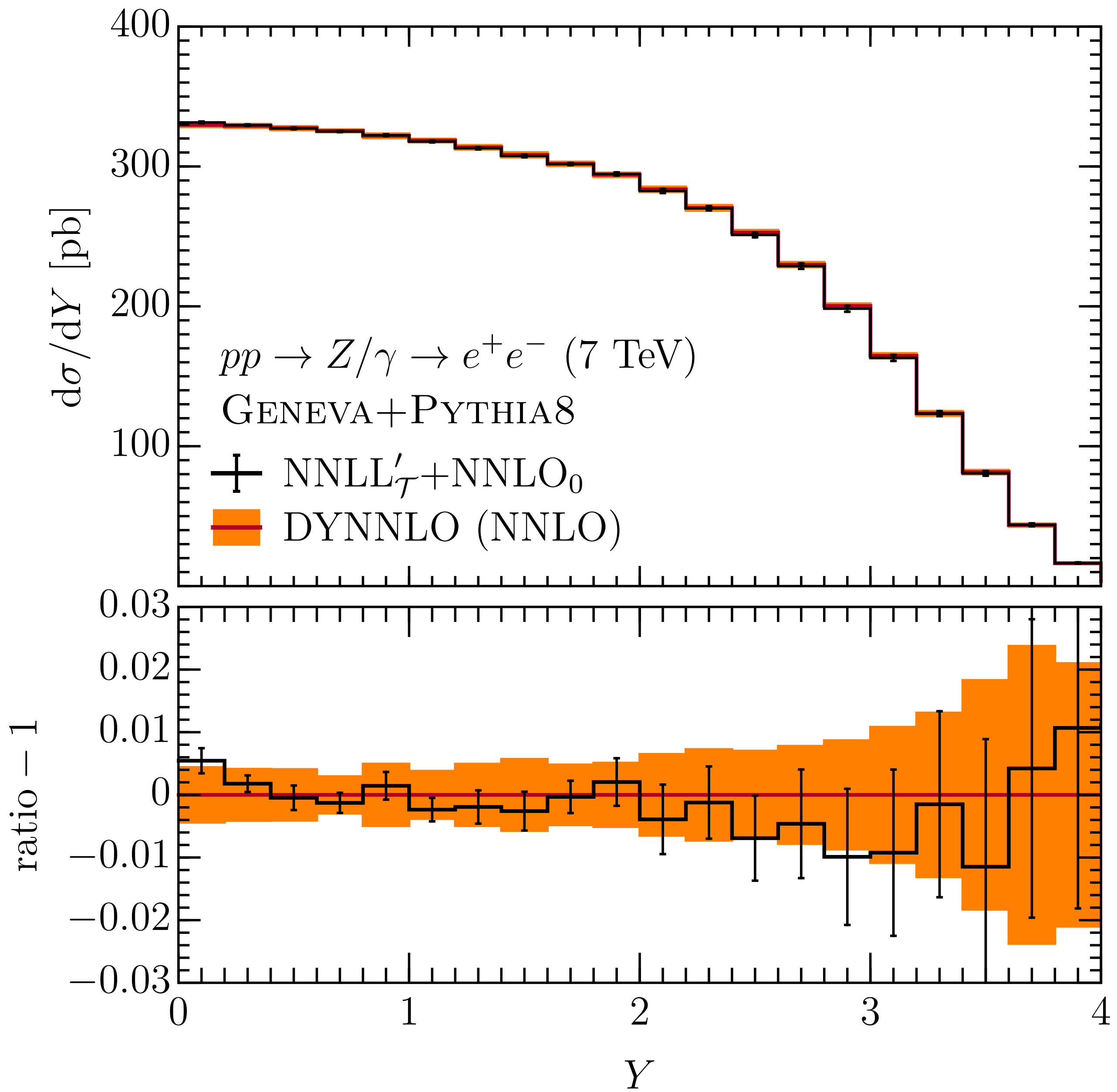
Use the full power of SCET to obtain exclusive jet distributions that are correct to given fixed order and resummation accuracy

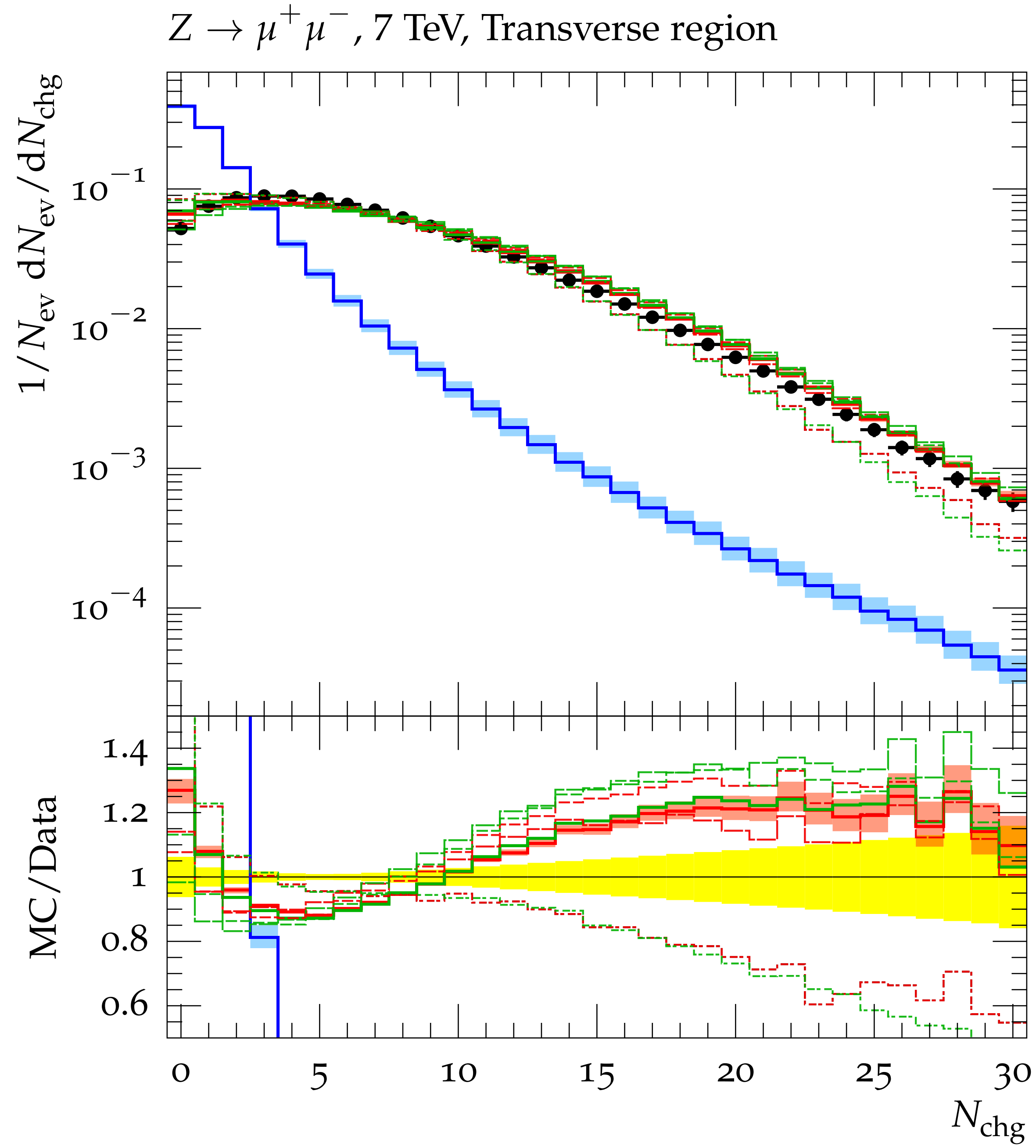
Fixed Order Z+0	Fixed order Z+1	Fixed order Z+2	0-jet resolution	1-jet resolution
NNLO	NLO	LO	NNLL'	LL

No other generator on the market with this level of accuracy

Gives high order accuracy for inclusive observables, as well as non-perturbative effects from MC

Alioli, CWB, Tackmann ('14-'17)





Completely inclusive observables correct to NNLO

Observables sensitive to underlying event still well described

Geneva is currently available as a public pre-release candidate (please report unexpected behavior)

Alioli, CWB, Tackmann ('14-'17)

http://geneva.physics.lbl.gov

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GENEVA

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Geneva Monte Carlo

Geneva is a Monte-Carlo event generator based on resummed NNLO+NNLL' calculations. It produces LHEF events, which can be showered and hadronized with a parton-shower generator (currently Pythia8) to produce fully exclusive HepMC events.

The currently available processes at NNLO+NNLL' are:

- p p -> Z/gamma -> e+ e-
- p p -> Z/gamma -> mu+ mu-

The current version is 1.0-RC2.

This is a release candidate, and as such can still contain bugs and missing features. We kindly ask that you report back to us results and problems obtained with this preliminary version prior to their usage in any publication.

Geneva is currently available as a public pre-release candidate (please report unexpected behavior)

Alioli, CWB, Tackmann ('14-'17)

http://geneva.physics.lbl.gov

```
#--------------------------
# Global run options
#--------------------------

global:
   process: pp_V
   run_name: "tutorial"
   num_events: 100000

input_output:
   verbosity: info
   overwrite_output: true

event_generation:
   unweighting:
      partial_relative: 30
   random:
      seed: 1

event_analysis:
   analyzer: Rates
```

```
#--------------------------
# Process
#--------------------------

process:
   pp_V:
      initial_state:
         beams: pp
         Ecm: 13000
         pdf_provider:
            LHAPDF:
               set: "PDF4LH
      final_state:
         boson_type: Z
         boson_mass: 91.187
         boson_width: 2.495
         decay: mu+mu-
      calculation: SCETppV0
      phase_space: PP2Boson
      matrix_element_provid
```

```
#-------------------------------------
# Calculation
#-------------------------------------

calculation:
   SCETppV012:
      precision: NNLO+NNLL0+NLL1
      scale_settings:
         fixed_order:
            dynamic: TransverseMass
      couplings:
         alpha_s: fromPDF
         alpha_em:
            scale: 91.1876
            value: 7.55638E-03
         GF: 1.16639E-05
         sin2W: 0.2226459
```

In conclusion, the development of event generators is a very active field of research

Combining perturbative calculations with parton showers important for high precision LHC era

Merging with fixed order calculations is becoming ever more sophisticated

Combination of all three types of approximations is becoming a reality

QUESTIONS?