Resummation in SCET and Progress in Geneva

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[based on various work in collaboration with
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Power Expansion.

Logarithms.

Consider an observable or measurement that resolves or restricts the phase-space of additional real emissions

- Say it only allows real emissions up to momentum scales of $\sim p$
  (i.e. only allows soft and/or collinear emissions but no hard emissions)
- Virtual corrections are unconstrained and contribute up to the hard process scale $\sim Q \equiv \sqrt{q^2} \equiv m_V$
- As a result the cancellation between real and virtual IR singularities only works up to the scale of the real emission, leaving remnant logs of p/Q

$$\int_0^p \mathrm{d}k_{\mathrm{real}}\, \frac{1}{k_{\mathrm{real}}} - \int_0^Q \mathrm{d}\ell_{\mathrm{virt}}\, \frac{1}{\ell_{\mathrm{virt}}} = \ln \frac{p}{Q}$$

Soft-collinear singularities cause two logarithms at each α_s order

$$\sigma = 1 + \alpha_s \Big[\ln^2 \frac{p}{Q} + \ln \frac{p}{Q} + 1\Big]$$

$$+ \alpha_s^2 \Big[\ln^4 \frac{p}{Q} + \ln^3 \frac{p}{Q} + \ln^2 \frac{p}{Q} + \ln \frac{p}{Q} + 1\Big] + \cdots$$

Power Expansion – Singular vs. Nonsingular.

Define scaling variable $\tau \equiv p^2/Q^2$ and expand in powers of τ

Integrated (cumulative) distribution:

$$
\begin{aligned}
\sigma(\tau) = \theta(\tau) &+ \alpha_s\big[\ln^2\tau + \ln\tau + \theta(\tau) && + F_1^{\rm nons}(\tau)\big] \\
&+ \alpha_s^2\big[\ln^4\tau + \ln^3\tau + \ln^2\tau + \ln\tau + \theta(\tau) && + F_2^{\rm nons}(\tau)\big] \\
&+ \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \ddots && + \ldots\big] \\
= & \qquad \sigma^{(0)} && + \mathcal{O}(\tau)
\end{aligned}
$$

For $\tau \ll 1$ two related things happen

- Leading-power terms $\mathrm{d}\sigma^{(0)}$ ("singular") dominate over $\mathcal{O}(\tau)$ power corrections ("nonsingular")
  - $\tau f_k^{\rm nons}(\tau)$ and $F_k^{\rm nons}(\tau^{\rm cut})$ vanish for $\tau \to 0$
- As τ decreases logs grow large deteriorating the α_s expansion
  - Resummation sums up leading-power terms to all orders in α_s

Power Expansion – Singular vs. Nonsingular.

Define scaling variable $\tau \equiv p^2/Q^2$ and expand in powers of τ

Differential distribution (spectrum in τ):

$$\begin{aligned}\frac{d\sigma}{d\tau} &= \delta(\tau) + \alpha_s\Big[\frac{\ln\tau}{\tau} + \frac{1}{\tau} + \delta(\tau) + f_1^{\rm nons}(\tau)\Big] \\ &\quad + \alpha_s^2\Big[\frac{\ln^3\tau}{\tau} + \frac{\ln^2\tau}{\tau} + \frac{\ln\tau}{\tau} + \frac{1}{\tau} + \delta(\tau) + f_2^{\rm nons}(\tau)\Big] \\ &\quad + \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \ddots + \ldots\Big] \\ &= d\sigma^{(0)}/d\tau + \mathcal{O}(\tau)/\tau\end{aligned}$$

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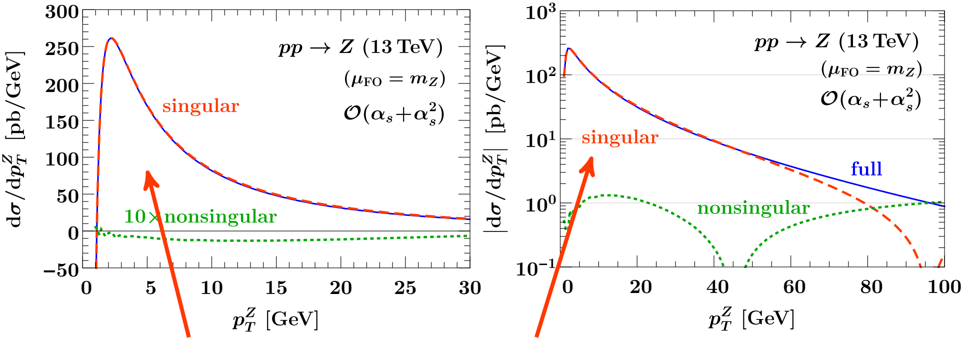
\end{aligned}
$$

A word on fixed-order counting

- Power expansion and resummation builds on V+0-jet Born process
  - Includes $\delta(\tau)$ (V+0 virtuals), which also feed into higher-order log terms
- Leading $\delta(\tau)$ is "LO_0", α_s, α_s^2 are included at "NLO_0", "NNLO_0", etc.
- Without $\delta(\tau)$: α_s, α_s^2 are "LO_1", "NLO_1", etc. of V+1-jet process

Regions of Phase Space.



Very small τ (here $\tau \equiv p_T^2/m_Z^2$)

- Fixed-order expansion breaks down (as we will see shortly ...)
- Resummation of leading-power terms is necessary to obtain meaningful predictions (which includes reliable uncertainties)
- Power-suppressed terms are negligible

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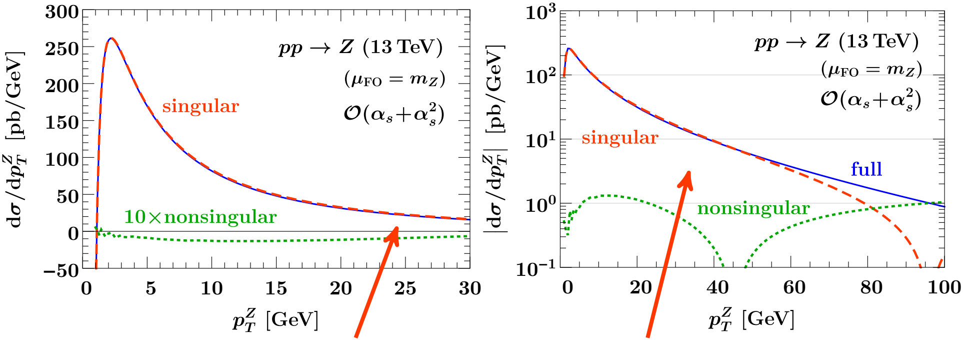
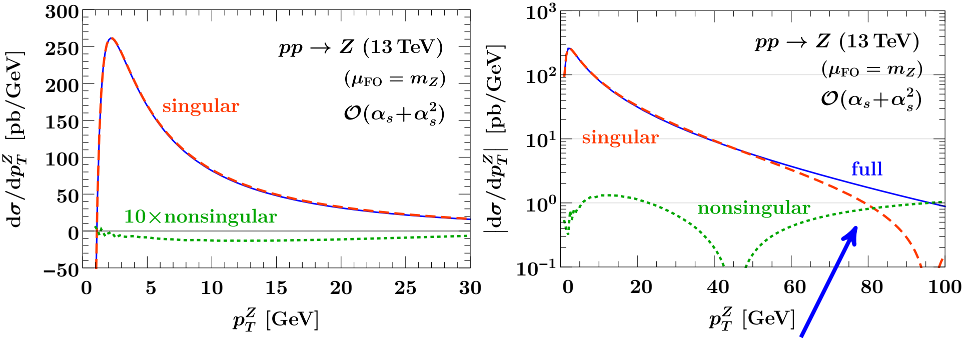


Moderately small $\tau \sim 0.1 - 0.2$

- Fixed-order expansion still possible (as we will see shortly ...)
- Question is not whether one must resum or whether FO is still okay, but whether resummation is allowed and beneficial, i.e., improves predictions
- Simple answer: Yes, as long as power corrections are subdominant

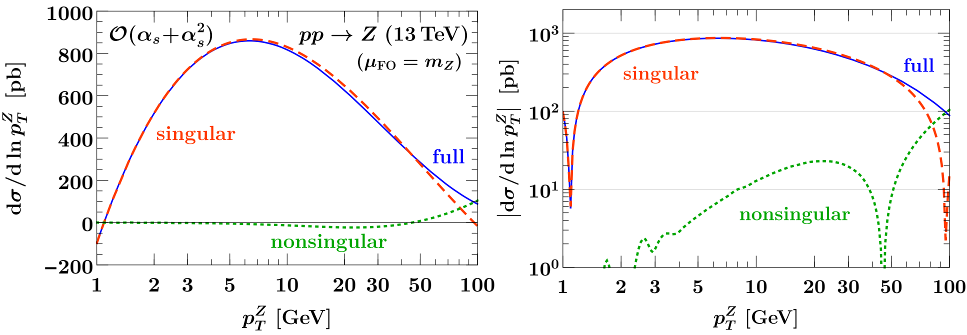
Regions of Phase Space.



Large $\tau \gtrsim 0.3 - 0.5$

- Power expansion in τ becomes meaningless
- Large cancellations between formally leading and subleading power terms. Resummation would spoil these cancellations, which is the (perhaps only) reason why it must be turned off here
- Fixed-order calculation of V+1-jet process provides full result

Change of Variables.

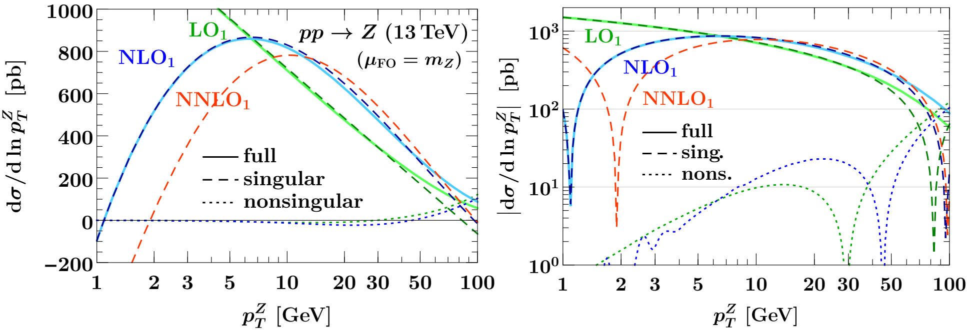


Convenient to change from τ to $\ln\tau$ (and we cannot plot the $\delta(\tau)$ anyway)

$$\frac{d\sigma}{d\tau} = \delta(\tau) + \alpha_s\Big[\frac{\ln\tau}{\tau} + \frac{1}{\tau} + \delta(\tau) + f_1^{\rm nons}(\tau)\Big] + \mathcal{O}(\alpha_s^2)$$

$$\Rightarrow \quad \frac{d\sigma}{d\ln\tau} \equiv \tau\frac{d\sigma}{d\tau} = 0 + \alpha_s\Big[\ln\tau + 1 + 0 + e^{\ln\tau} f_1^{\rm nons}(e^{\ln\tau})\Big] + \mathcal{O}(\alpha_s^2)$$

Different Orders in α_s



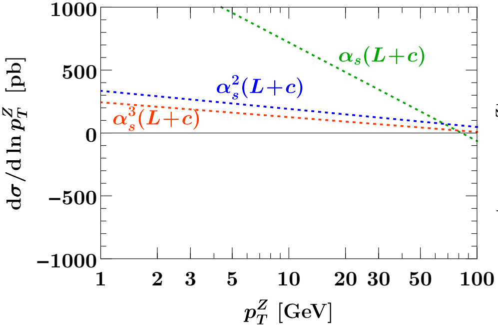
Power expansion works very well ($\tau = p_T^2/m_Z^2$)

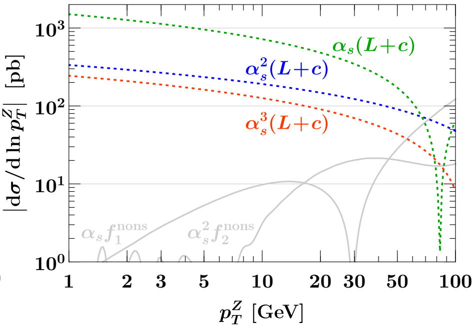
- Power corrections very small up to $p_T = 30 - 50\,\mathrm{GeV}$ ($\tau = 0.1 - 0.2$)

Leading-power (singular) $\mathcal{O}(\alpha_s^3)$ are known analytically

- More important than even $\mathcal{O}(\alpha_s, \alpha_s^2)$ power corrections (nonsingular)
- Full V+1-jet NNLO_1 (only) adds $\mathcal{O}(\alpha_s^3)$ power corrections (nonsingular)
  - Most likely only relevant for $p_T \gtrsim 50\,\mathrm{GeV}$ or observables/cuts that are intrinsically sensitive to power corrections

Contributions from Individual Log Terms.





Fixed-order convergence deteriorates below $p_T < 10\,\mathrm{GeV}$ ($\tau < 0.01$)

- Natural α_s suppression gets spoiled by additional logs
- Fixed-order uncertainties from scale variations will be unreliable (they cannot know about additional powers of logs)
- Logarithmic terms are oscillating with large coefficients
- Resummation reorganizes pert. series and makes it well-behaved again (it knows and takes into account relations between log coefficients)

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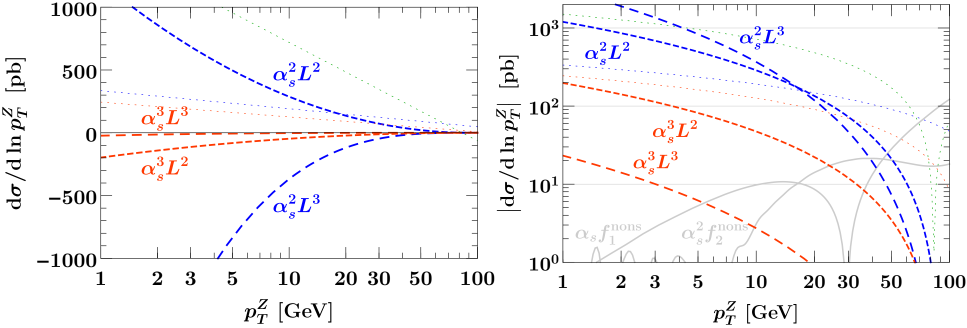

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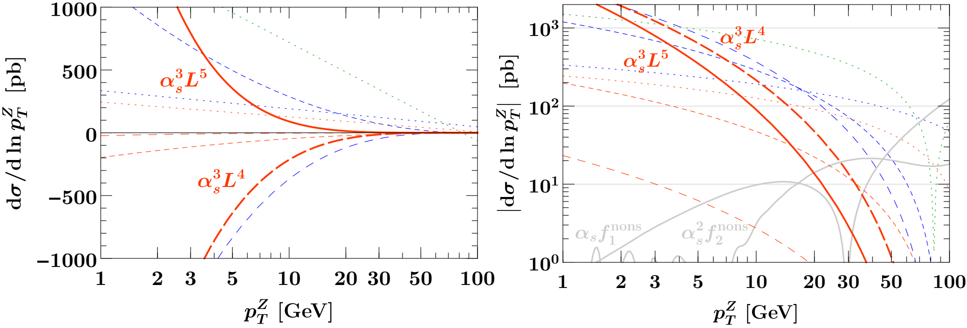

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Basics of Resummation (in SCET).

Soft-Collinear Effective Theory (SCET).

SCET is the effective field theory (EFT) that arises from expanding full QCD in powers of τ at the Lagrangian and operator level

$$\text{QCD} = \underbrace{\text{SCET}^{(0)}}_{\text{leading-power}} + \underbrace{\text{SCET}^{(1)}}_{\text{next-to-leading power}} + \mathcal{O}(\tau^2)$$

By construction SCET reproduces the small-τ limit of full QCD. Hence, calculating the cross section with SCET$^{(0)}$ we exactly get the leading-power result

$$d\sigma^{(0)} = \langle \text{SCET}^{(0)} \rangle$$

- Holds to all orders in α_s
  - Can use SCET to perform resummation with EFT methods
- Also holds nonperturbatively
  - E.g. PDFs defined in QCD and SCET are the same (in both cases the power expansion being the usual twist expansion)
  - Can also define and study other nonperturbative operator matrix elements, e.g. can include hadronization through nonperturbative soft functions

Factorization at Leading Power.

Leading-power spectrum can be factorized into hard, collinear, and soft contributions

$$\frac{\mathrm{d}\sigma^{(0)}}{\mathrm{d}p_T \mathrm{d}Q \mathrm{d}Y} = H(Q,\mu) \times B(p_T, Qe^{\pm Y}, \mu, \nu)^2 \otimes S(p_T, \mu, \nu)$$

$$\ln^2 \frac{p_T}{Q} = 2\ln^2 \frac{Q}{\mu} + 2\ln \frac{p_T}{\mu} \ln \frac{\nu}{Q} + \ln \frac{p_T}{\mu} \ln \frac{\mu\, p_T}{\nu^2}$$

- All pieces are renormalized objects (similar to $\alpha_s(\mu)$ or PDFs)
  - Their scale (μ and ν) dependence is governed by corresponding RGEs
  - Scale dependence exactly cancels between different pieces
- All-order logarithmic structure of $\mathrm{d}\sigma^{(0)}$ is fully encoded in the scale dependence and therefore fully determined by the associated coupled system of RGEs

⇒ Resummation follows from solving this coupled system of differential equations

Simplest Case: Multiplicative RGE (Hard Function).

$$\mu \frac{\mathrm{d}H(Q,\mu)}{\mathrm{d}\mu} = \gamma_H(Q,\mu)\, H(Q,\mu)$$

$$\Rightarrow \qquad H(Q,\mu) = H(Q,\mu_H) \times \exp\biggl[\int_{\mu_H}^{\mu} \frac{\mathrm{d}\mu'}{\mu'} \gamma_H(Q,\mu')\biggr]$$

$$\equiv H(Q,\mu_H) \times U_H(\mu_H,\mu)$$

Resummation follows from setting $\mu_H = Q$ in the solution

- *Boundary condition* $H(Q,\mu_H = Q)$ is free of logarithms and admits fixed-order expansion

$$H(Q,\mu_H = Q) = 1 + \alpha_s(Q) + \cdots$$

  - All $\ln^n(Q/\mu)$ present in $H(Q,\mu)$ are resummed into $U_H(\mu_H = Q,\mu)$

- *Anomalous dimension* $\gamma(Q,\mu)$ determines the exponent and also admits a fixed-order expansion (plus $\beta(\alpha_s)$ to perform μ-integral)

$$\gamma_H(Q,\mu) = \ln\frac{Q}{\mu}\bigl[1 + \alpha_s(\mu) + \cdots\bigr] + \bigl[1 + \alpha_s(\mu) + \cdots\bigr]$$

$\Rightarrow$ Double-log series fully given in terms of a few log-free FO series

Resummation Orders.

	Boundary conditions (singular)	Anomalous dimensions $\gamma_{H,B,S,\nu}$	Γ_{cusp}, β	FO matching (nonsingular)
LL	1	-	1-loop	-
NLL	1	1-loop	2-loop	-
NLL′+NLO$_0$	α_s	1-loop	2-loop	α_s
NNLL+NLO$_0$	α_s	2-loop	3-loop	α_s
NNLL′+NNLO$_0$	α_s^2	2-loop	3-loop	α_s^2
N^{3}LL+NNLO$_0$	α_s^2	3-loop	4-loop	α_s^2
N^{3}LL′+N^{3}LO$_0$	α_s^3	3-loop	4-loop	α_s^3

Fixed-order expansion of boundary conditions and anomalous dimensions are the basic ingredients that determine the resummation order

- Provides a fundamental and unambiguous definition of the resummation order (or perturbative accuracy)
  - Since the anomalous dimensions determine the exponent, this is more general then counting logarithms in the solution. Instead, it defines the order directly at the level of the to-be-solved RGE system.
  - In particular, it does not rely on or require specifying a particular log scaling like $\alpha_s L \sim 1$ in the final result.

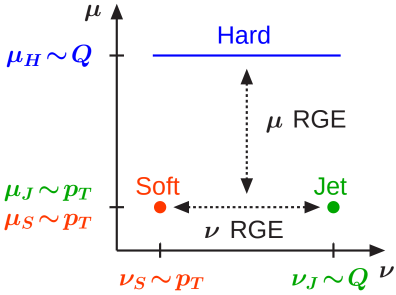
Coupled RGE System for p_T

In virtuality scale μ

$$\mu \frac{\mathrm{d}H(Q,\mu)}{\mathrm{d}\mu} = \gamma_H(Q,\mu)\, H(Q,\mu)$$

$$\mu \frac{\mathrm{d}B(\vec{p}_T,\mu,\nu)}{\mathrm{d}\mu} = \gamma_B(\mu,\nu)\, B(\vec{p}_T,\mu,\nu)$$

$$\mu \frac{\mathrm{d}S(\vec{p}_T,\mu,\nu)}{\mathrm{d}\mu} = \gamma_S(\mu,\nu)\, S(\vec{p}_T,\mu,\nu)$$



and rapidity scale ν

$$\nu \frac{\mathrm{d}B(\vec{p}_T,\mu,\nu)}{\mathrm{d}\nu} = -\frac{1}{2}\int \mathrm{d}^2\vec{k}_T\, \gamma_\nu(\vec{k}_T,\mu)\, B(\vec{p}_T - \vec{k}_T,\mu,\nu)$$

$$\nu \frac{\mathrm{d}S(\vec{p}_T,\mu,\nu)}{\mathrm{d}\nu} = \int \mathrm{d}^2\vec{k}_T\, \gamma_\nu(\vec{k}_T,\mu)\, S(\vec{p}_T - \vec{k}_T,\mu,\nu)$$

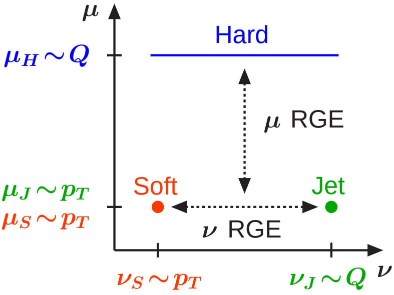
$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu}\gamma_\nu(\vec{k}_T,\mu) = \nu \frac{\mathrm{d}}{\mathrm{d}\nu}\gamma_S(\mu,\nu)\delta(\vec{k}_T) = -4\Gamma_{\mathrm{cusp}}[\alpha_s(\mu)]\delta(\vec{k}_T)$$

plus evolution equations for α_s and PDFs

$\Rightarrow$ Together these encode again an exponential structure of the cross section (which is surprisingly nontrivial and not just a simple multipicative exponential)

Resummation Structure for p_T.

$$\frac{d\sigma^{(0)}}{dp_T} = H(Q,\mu_H) \times B(p_T,\mu_B,\nu_B/Q)^2 \otimes S(p_T,\mu_S,\nu_S/p_T) \otimes U_{\rm total}(p_T;\mu_H,\mu_B,\mu_S,\nu_B,\nu_S)$$



- RG consistency (path independence) means that dependence on arbitrary final scales μ and ν *exactly* cancels
- RGE then resums logs of ratios of involved resummation scales, e.g.,

$$\ln^n(\mu_B/\mu_H)\,, \qquad \ln^n(\mu_S/\mu_H)\,, \qquad \ln^n(\nu_S/\nu_B)$$

  - Logarithms $\ln(p_T/Q)$ are resummed by canonical scale choices

$$\mu_H = Q\,, \qquad \nu_B = Q\,, \quad \mu_B = p_T\,, \qquad \mu_S = \nu_S = p_T$$

  - Varying them around their canonical values allows us to probe intrinsic resummation uncertainties
  - Setting $\mu_H = \mu_B = \mu_S = \nu_B = \nu_S = \mu_{\rm FO}$ turns off all resummation

Some Remarks on Differences Between Approaches.

The logarithms in the cross section are always the same

(everybody is trying to calculate the same thing ...)

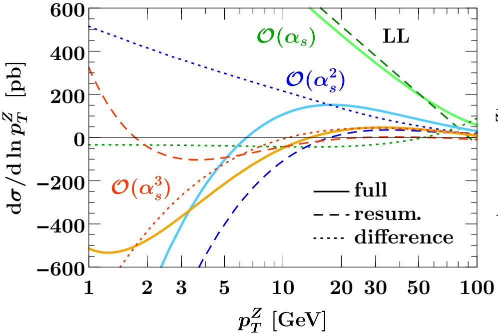
- SCET provides a convenient framework to formulate resummation in terms of RG running in an EFT and derive the appropriate RGE system
- Corresponding or equivalent evolution equations can be obtained directly by studying the soft-collinear limit of QCD
  - CSS formalism [Collins, Soper, Sterman '81-'85]

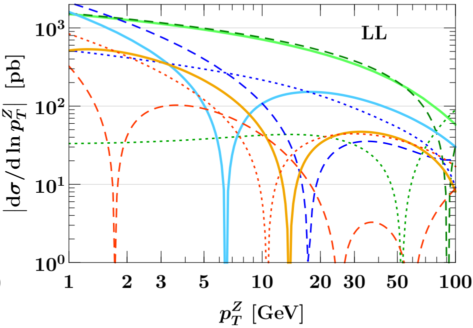
Once the RGE system is specified to a given resummation order

- One has to solve it and choose appropriate boundary scales
- This is where differences between various approaches enter
  - How evolution is performed (exact, approximate, numerical)
  - Precise choices of which logs are actually resummed
  - How resummation is turned off (endpoint of the evolution)
  - Treatment of power corrections (matching to full fixed order)
  - Treatment of nonperturbative corrections
  - Estimation of uncertainties

$\Rightarrow$ Most of these require another talk ...

Resummation vs. Fixed Order.





Expand resummation to given α_s order to allow for well-defined comparison

- Orders as defined before (no further approximations or choices needed)
- Resummation provides very fast convergence
  - NLL(′) is better than NLO$_1$ (i.e. closer to NNLO$_1$) for $p_T < 5(10)$ GeV
  - NNLL essentially reproduces NNLO$_1$ for $p_T < 30$ GeV

⇒ Even if fixed-order expansion works, resummation provides better perturbative approximation as long as power expansion applies

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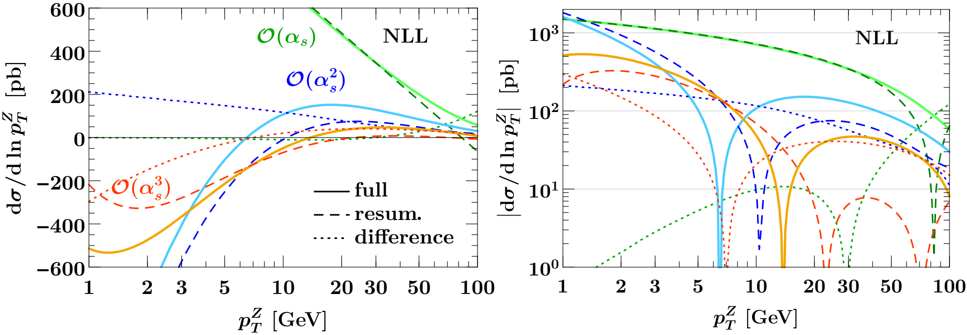

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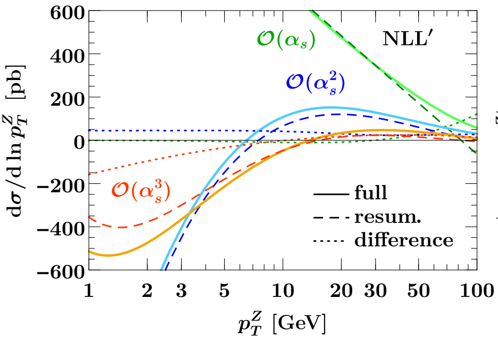

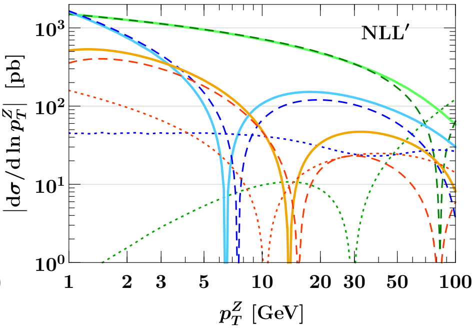

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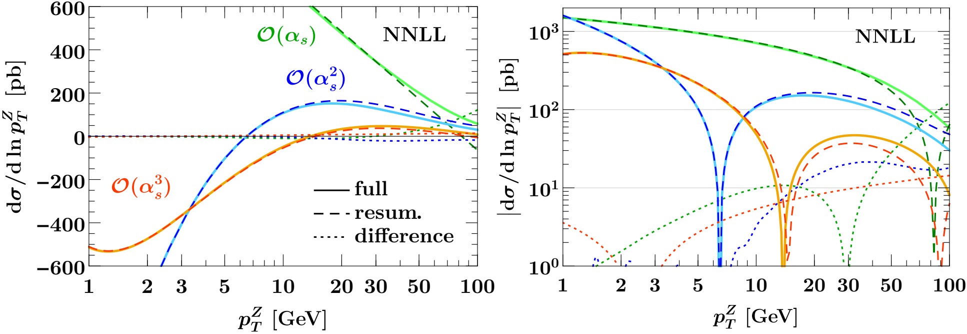

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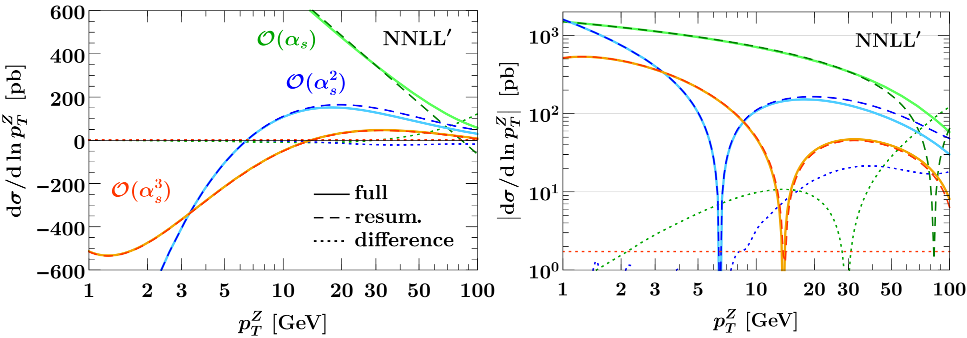

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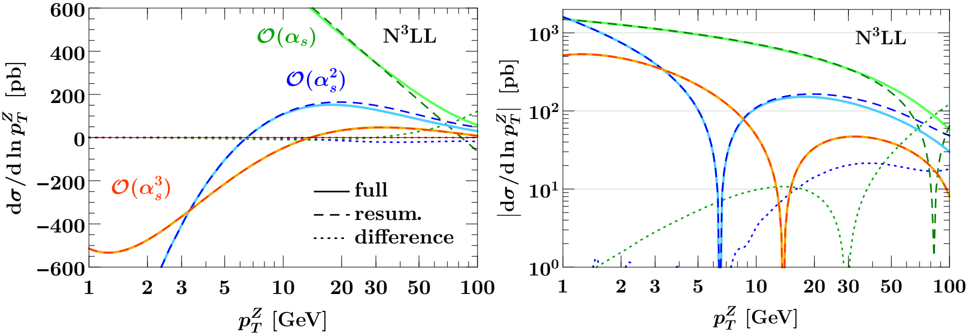

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News from GENEVA.

MC Generators in a Nut Shell.

Perturbative

- Partonic calculation

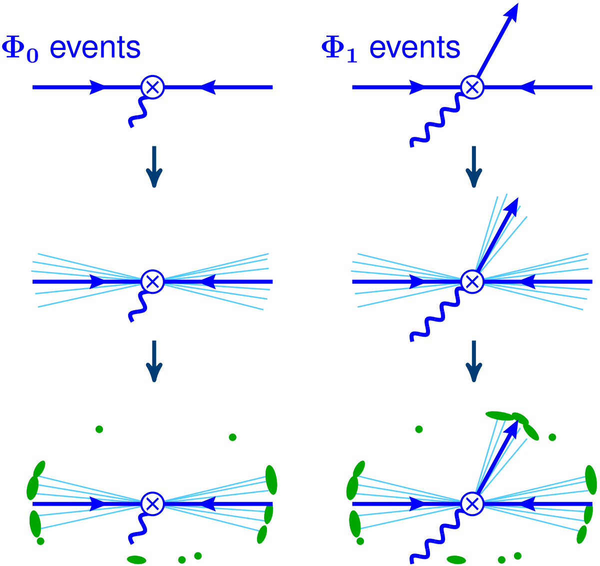
↓

- Parton shower
- Perturbative MPI

↓

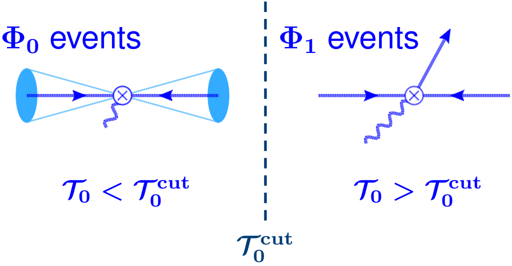
Nonperturbative

- hadronization
- beam remnants
- intrinsic k_T



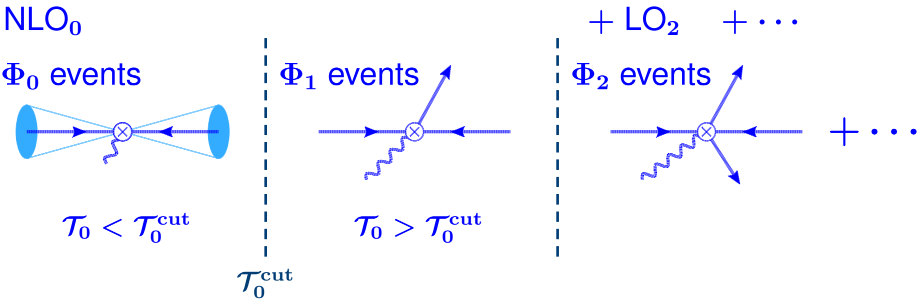
Partonic Calculation.

NLO_0



- Emissions above (below) $\mathcal{T}_0^{\mathrm{cut}}$ are resolved (unresolved)
  - Partons represent sum over any number of unresolved emissions
  - Want to lower $\mathcal{T}_0^{\mathrm{cut}}$ to resolve more with partonic calculation

Partonic Calculation.



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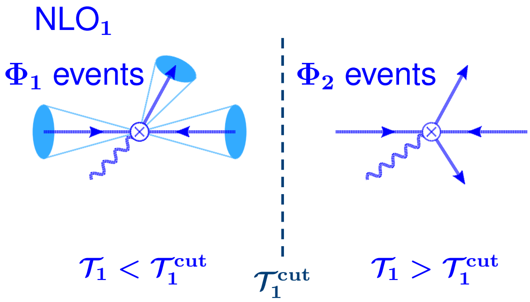
  - Want to lower $\mathcal{T}_0^{\mathrm{cut}}$ to resolve more with partonic calculation
- (N)LO+PS merging patches together different (N)LO calculations

Partonic Calculation.



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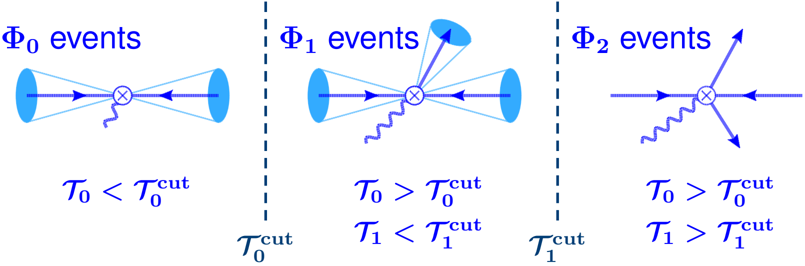
Partonic Calculation.

NNLO_0



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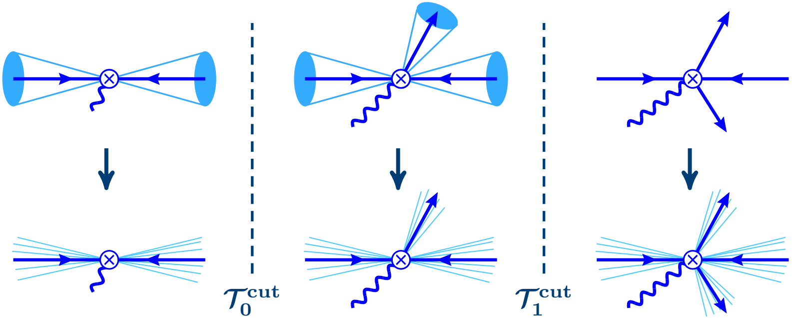
  - Partons represent sum over any number of unresolved emissions
  - Want to lower $\mathcal{T}_0^{\mathrm{cut}}$ to resolve more with partonic calculation
- (N)LO+PS merging patches together different (N)LO calculations
- NNLO+PS matching: Contains NLO_1 down to small $\mathcal{T}_0$
  - POWHEG NNLOPS: use MINLO′ to extend POWHEG NLO_1 to small $\mathcal{T}_0^{\mathrm{cut}}$
  - GENEVA: use 0-jettiness subtractions and higher-order resummation

Parton Shower.



Parton shower fills in emissions below $\mathcal{T}_N^{\mathrm{cut}}$

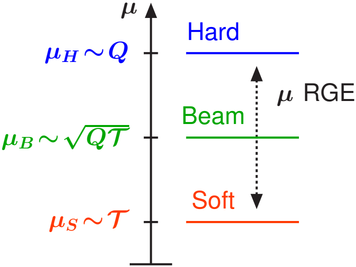
- Provides unresolved emissions that have been integrated over and projected onto partons in partonic calculation
  - Highest partonic multiplicity is showered inclusively (corresponding to $\mathcal{T}_2^{\mathrm{cut}} = \infty$ here)
- MPI is done entirely by shower MCs
  - Currently not included in any partonic calculation
  - Would require to include double-parton scattering

GENEVA Uses N-Jettiness as Resolution Variable.

Resummation Structure for $\mathcal{T}_0$

$$\frac{d\sigma^{(0)}}{d\mathcal{T}_0} = H(Q,\mu_H) \times B(Q\mathcal{T}_0,\mu_B)^2 \otimes S(\mathcal{T}_0,\mu_S) \otimes U_{\mathrm{total}}(\mathcal{T}_0;\mu_H,\mu_B,\mu_S)$$

$$\ln^2\frac{\mathcal{T}_0}{Q} = 2\ln^2\frac{Q}{\mu} - \ln^2\frac{\mathcal{T}_0 Q}{\mu^2} + 2\ln^2\frac{\mathcal{T}_0}{\mu}$$



- RGE resums logarithms of ratios of scales

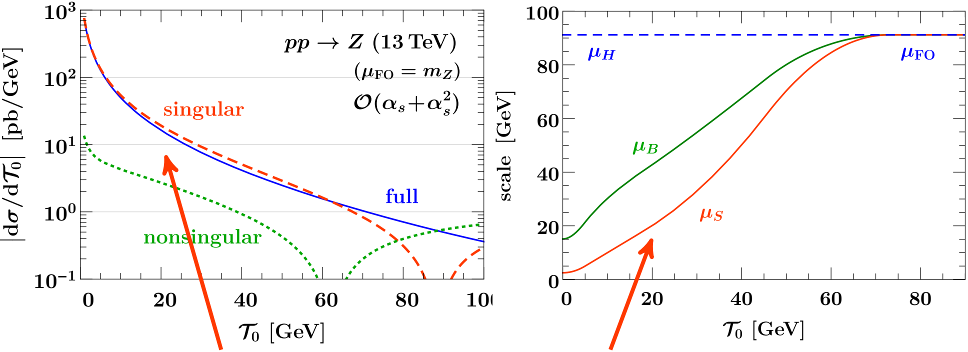
$$\ln^n(\mu_B^2/\mu_H^2)\,, \qquad \ln^n(\mu_S^2/\mu_B^2)\,, \qquad \ln^n(\mu_S/\mu_H)$$

  - Logarithms $\ln^n(\mathcal{T}_0/Q)$ are resummed by canonical scale choices

$$\mu_H = Q\,, \qquad \mu_B = \sqrt{\mathcal{T}_0 Q}\,, \qquad \mu_S = \mathcal{T}_0$$

- Currently GENEVA includes resummation at
  - NNLL′+NNLO_0 for $\mathcal{T}_0$
  - NLL+NLO_1 for $\mathcal{T}_1$

Matching to Fixed Order with Profile Scales.

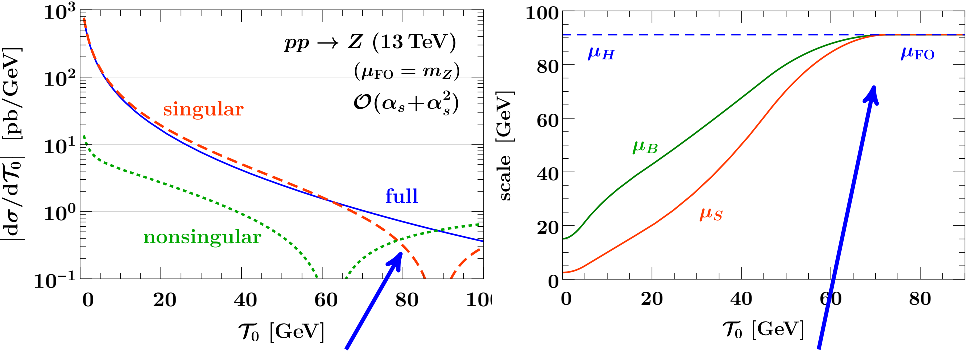


$$d\sigma = d\sigma^{(0)}_{\rm resum}(\mu_i) + d\sigma^{\rm nons}(\mu_{\rm FO}) \quad \to \quad d\sigma^{(0)}_{\rm resum} + \mathcal{O}(\tau)$$

Canonical region

- Use canonical scales to resum correct logarithms of $\ln(\mathcal{T}/m_Z)$
- Nonsingular are power suppressed

Matching to Fixed Order with Profile Scales.



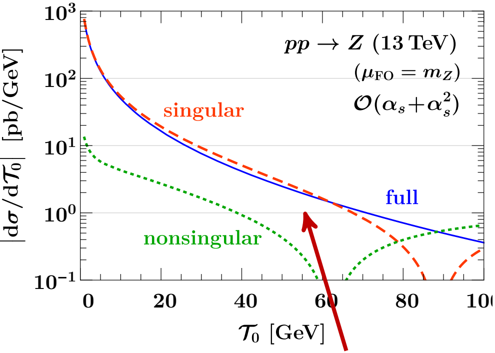
$$\mathrm{d}\sigma = \mathrm{d}\sigma^{(0)}_{\mathrm{resum}}(\mu_i) + \mathrm{d}\sigma^{\mathrm{nons}}(\mu_{\mathrm{FO}}) \quad \to \quad \mathrm{d}\sigma^{\mathrm{full}}(\mu_{\mathrm{FO}})$$

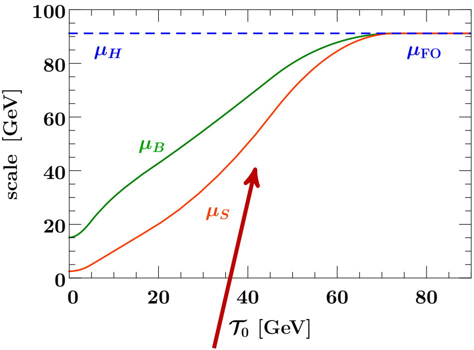
Fixed-order region

- Power expansion breaks down, resummation must be turned off
- Resummed result reduces to FO singular (requires (N)NLL′ order)

$$\mu_i \to \mu_H = \mu_{\mathrm{FO}} \quad \Rightarrow \quad \mathrm{d}\sigma^{(0)}_{\mathrm{resum}}(\mu_i \to \mu_{\mathrm{FO}}) \to \mathrm{d}\sigma^{\mathrm{sing}}(\mu_{\mathrm{FO}})$$

Matching to Fixed Order with Profile Scales.





$$d\sigma = d\sigma^{(0)}_{resum}(\mu_i) + d\sigma^{nons}(\mu_{FO})$$

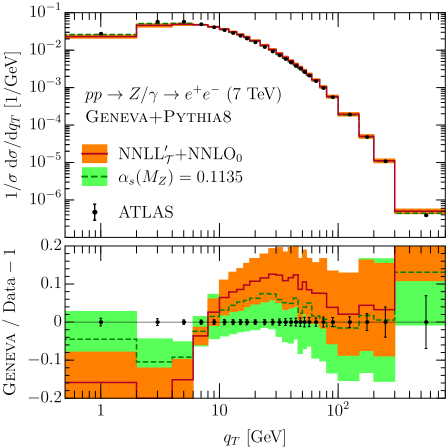
Transition region

- Use profile scales $\mu_i(p_T)$ to smoothly connect both limits
- Matching/transition is implemented through a scale choice
  - Associated ambiguity manifestly reduces at higher orders
  - Associated uncertainties can be estimated through profile scale variations

W and Z Production in GENEVA

Z production

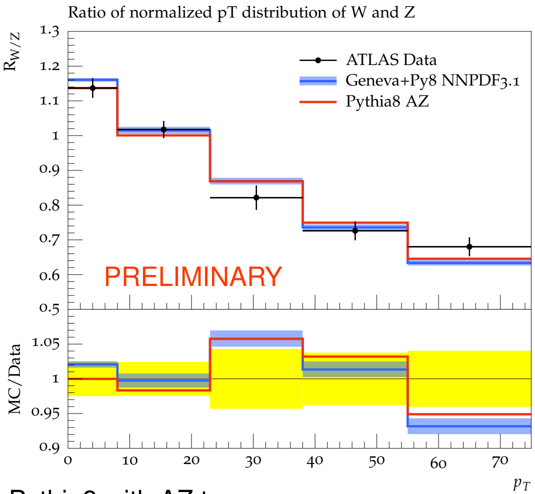
- Lower $\alpha_s(m_Z)$ has nontrivial effect and gives much better description
- Consistent with the fact that all extractions from e^+e^- using similarly high resummation precision yield same low values
- Effect should drop out of W/Z ratio
  - Will use default $\alpha_s(m_Z) = 0.118$ in the following



W production

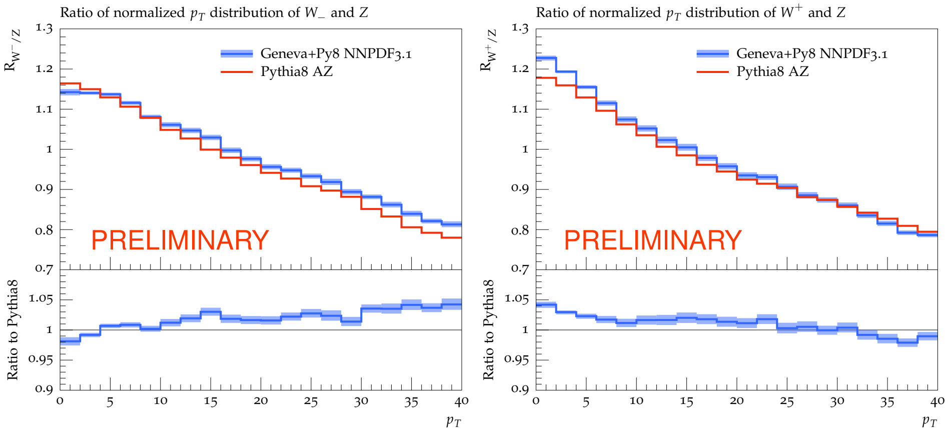
- Recently completed implementation of W production in GENEVA
  - Same level of perturbative accuracy as for Z
  - Disclaimer: Everything is preliminary

W/Z Ratio.



- Using plain Pythia8 with AZ tune as proxy
  - Equivalent to what was used in analogous plots in ATLAS m_W paper
- GENEVA bands are from correlating profile scale variations for W and Z
  - For illustration/information only, not the final word on uncertainty

$W^{\pm}/Z$ Ratio.



- Quite good agreement with Pythia8 AZ
- Disclaimers:
  - We keep selection cuts, while the equivalent plots from ATLAS have no selection cuts, which is the reason for the overall different slope
  - Need to check with different PDFs and $\alpha_s(m_Z)$

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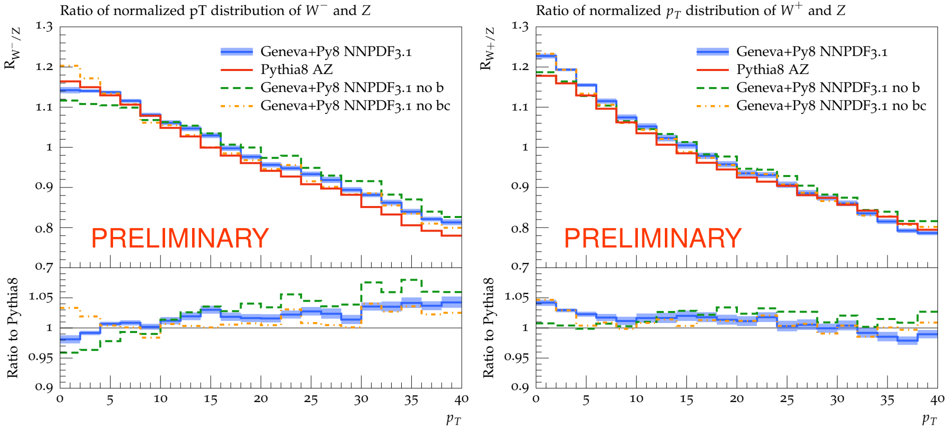

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Instead of a Summary.

Thanks for staying with me ...

... and sorry for running over time