LUIGI Marchese (Oxford university), on behalf of the CDF collaboration

CHARM 2016

Colour by
QCD

September 7, 2016

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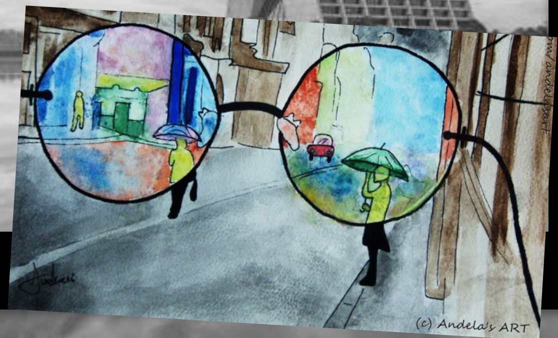
D^{+}



Measurement of low-p_T D^+-meson production cross-section at CDF

CHARM 2016

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QCD

September 7, 2016

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CONTENTS

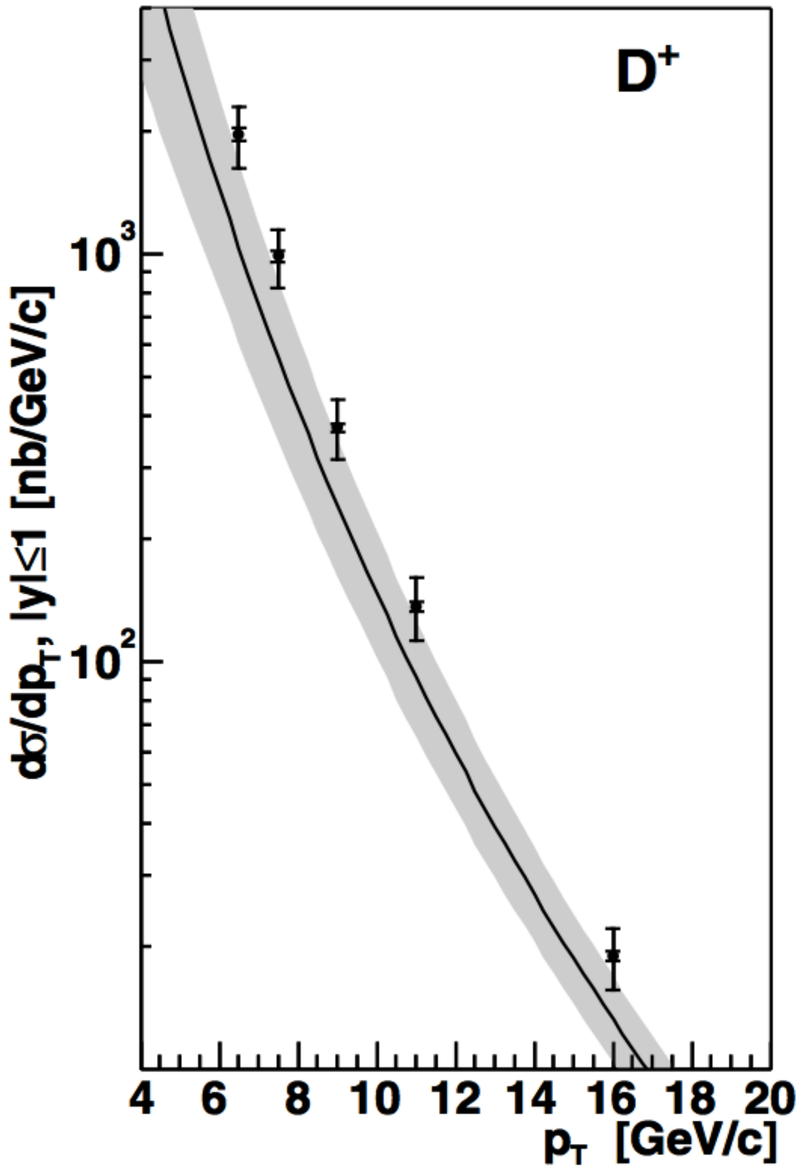
MOTIVATIONS

- Differential cross section for the inclusive hadro-production of charm mesons at low p_T with initial state $p\bar{p}$ and $\sqrt{s} = 1.96 TeV$: extension of the previous CDF measurements

- Theoretical models for pQCD have big uncertainties at low p_T
  (M. Cacciari et al., JHEP, 05:007, 1998)

Experiment	Initial state	√s [Gev]
Many expt's CERN, FNAL	K, p, π Nucl. tgts.	up to 40
LHCb	pp	$7, 13 \cdot 10^3$
ALICE	pp	$7, 2.76 \cdot 10^3$
ATLAS	pp	$7 \cdot 10^3$

PRL 91,241804(2003)



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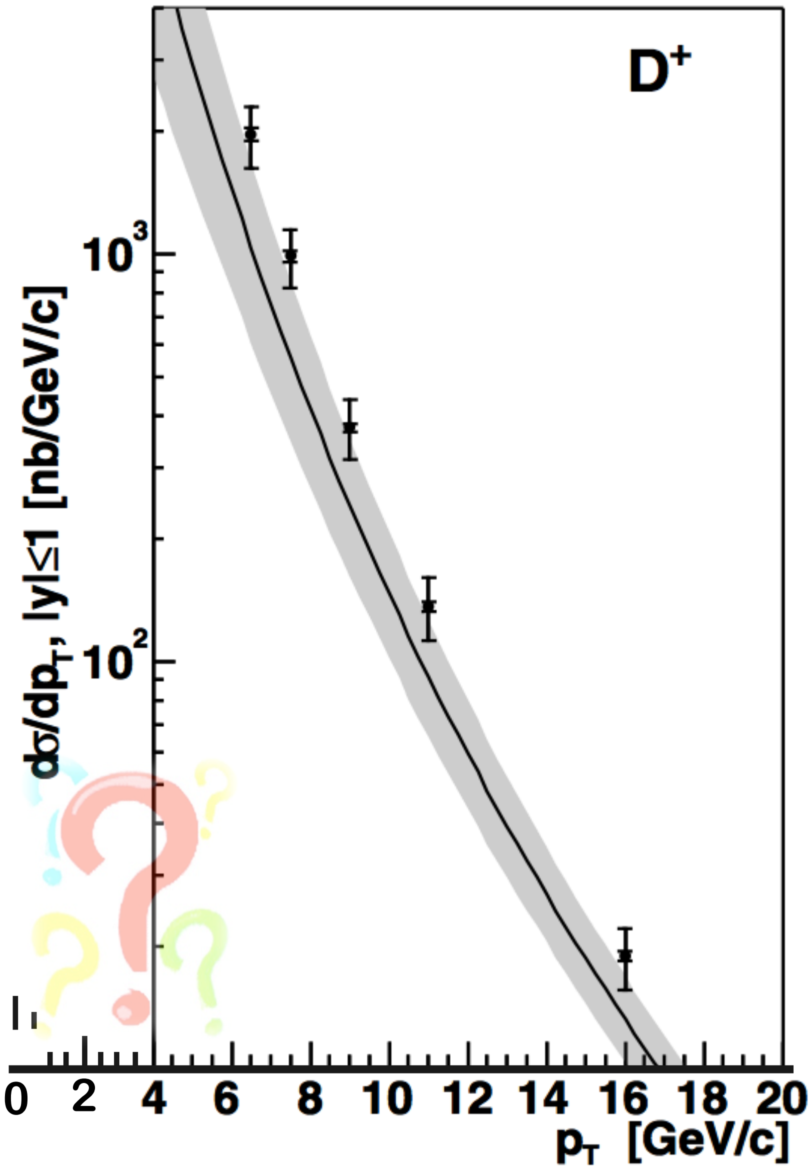
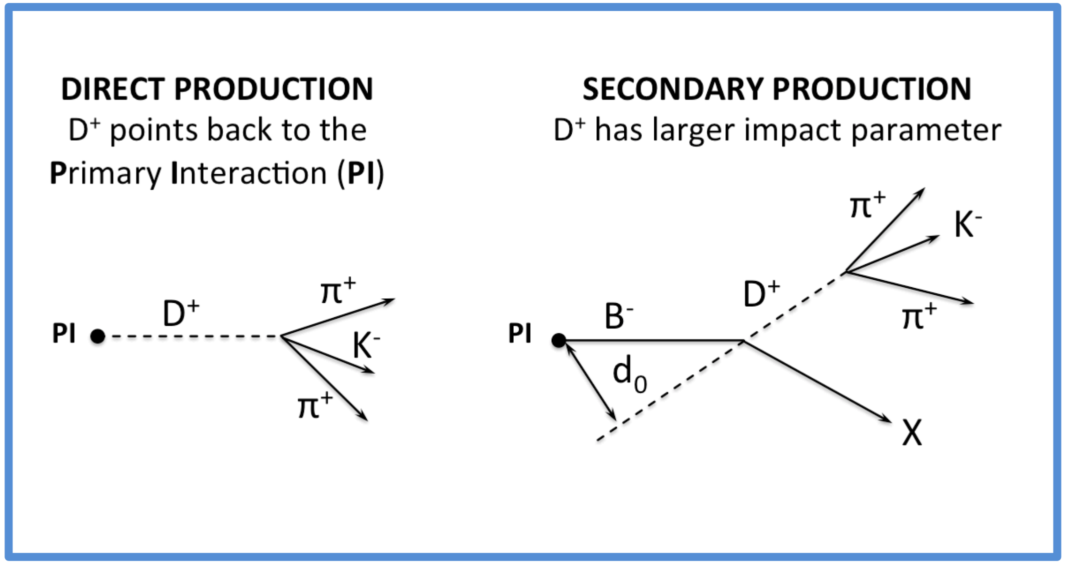
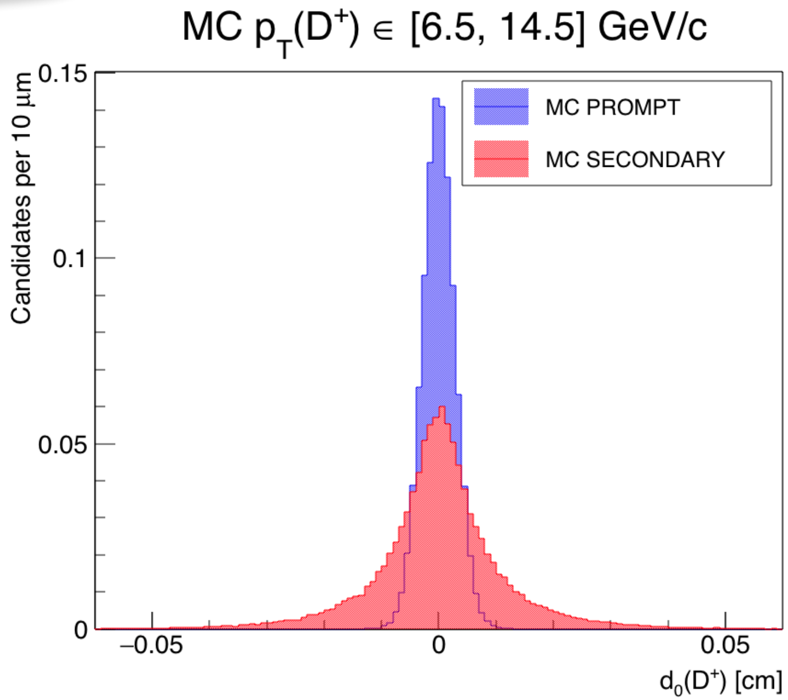


SIGNAL AND BACKGROUND

SIGNAL: $D^+ \rightarrow K^- \pi^+ \pi^+ (+c.c.)$ **BR:** $(9.46 \pm 0.24)\%$

BACKGROUND
- **Secondary component:** $B \rightarrow D^+ X$
- **Combinatorics**

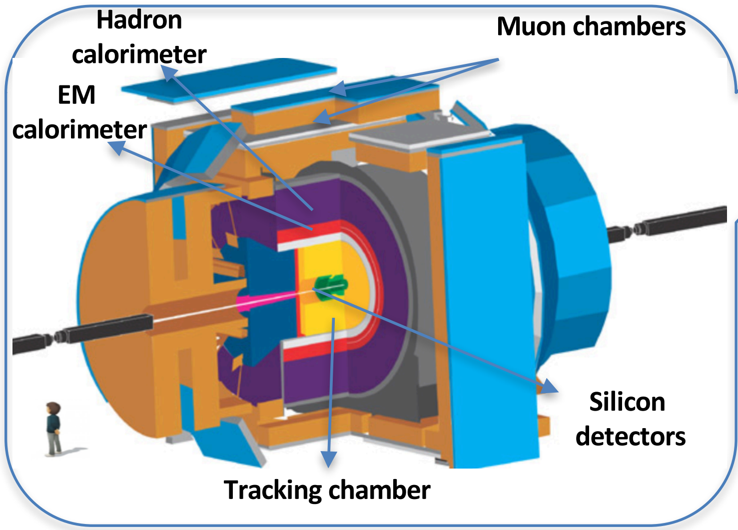


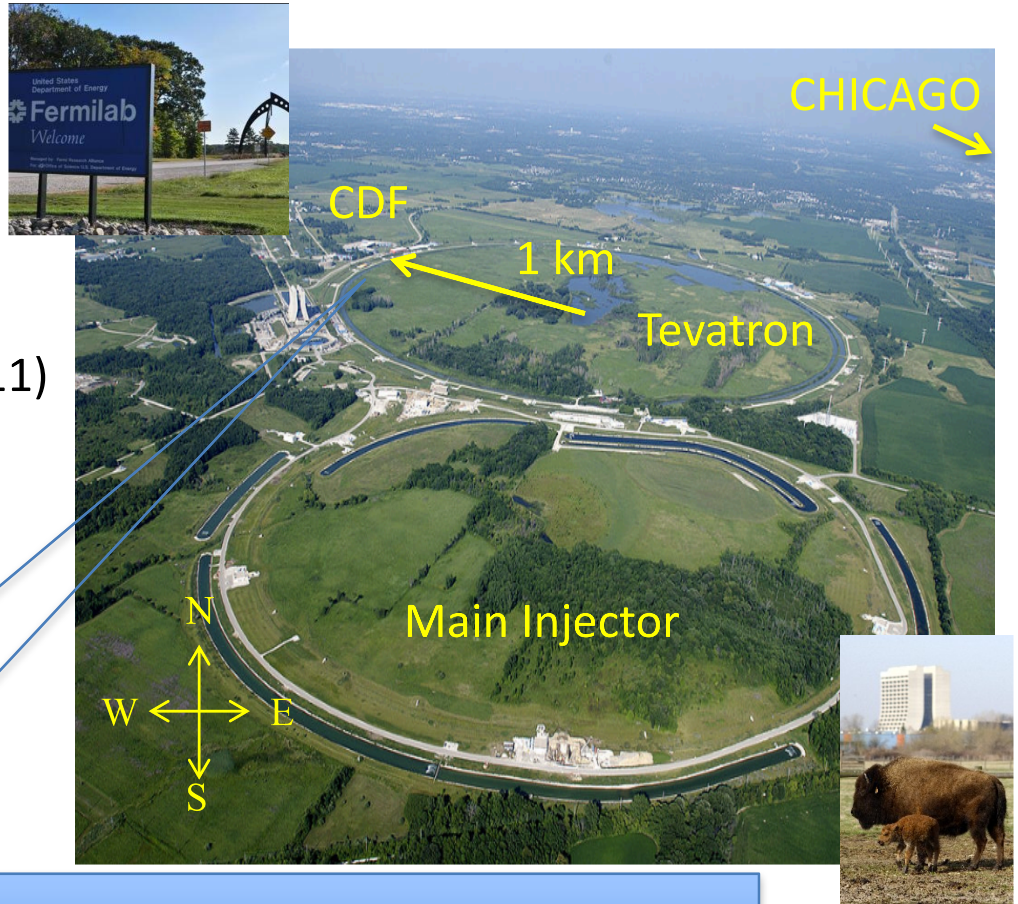


The invariant-mass doesn't distinguish between primary and secondary component

TEVATRON AND CDF

- $p\bar{p}$ hadron collider $\sqrt{s} = 1.96 TeV$
- Peak Luminosity: $\mathcal{L} \approx 3.8 \cdot 10^{32}\, cm^{-2}\, s^{-1}$
- CDF recorded luminosity: 10 fb^{-1} (2002 – 2011)
- We use the entire 1.96TeV-dataset





CDF: Collider Detector at Fermilab

- Multi purpose detector
- Inner tracking system, solenoidal magnet (1.4 T)
- Calorimeters and muon detectors

TRACKING SYSTEM

Tracking-system performance

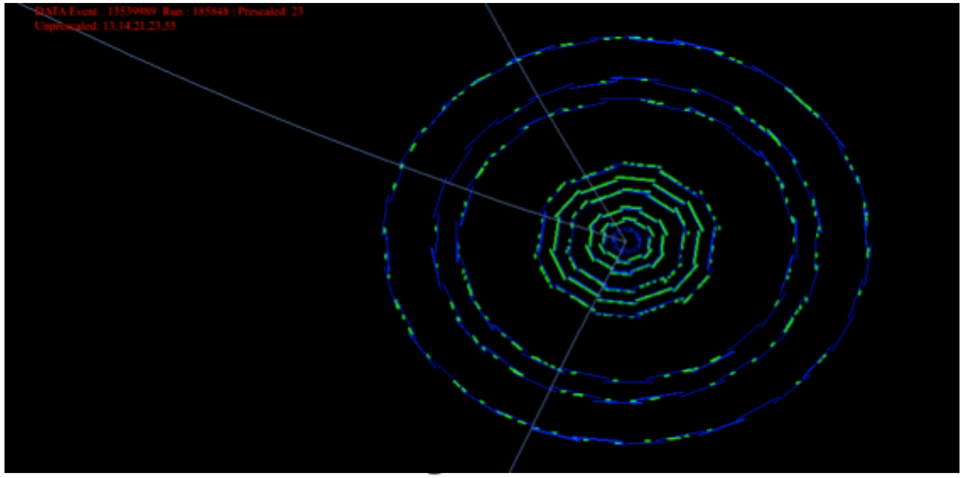
For |η|≤ 1 :

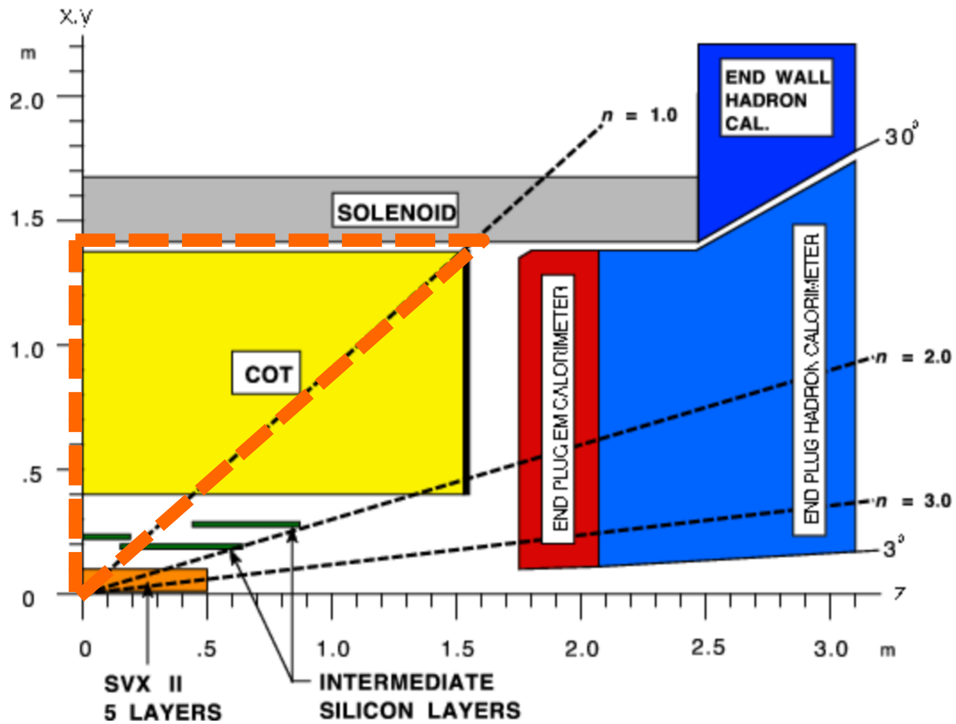
$\sigma_{p_T}/p_T^2 \approx 0.0015$ c/GeV

$\sigma_{d0} \approx 40$ μm

3D charged-particle tracking

- Seven-layer silicon inner detector
- Large outer drift chamber



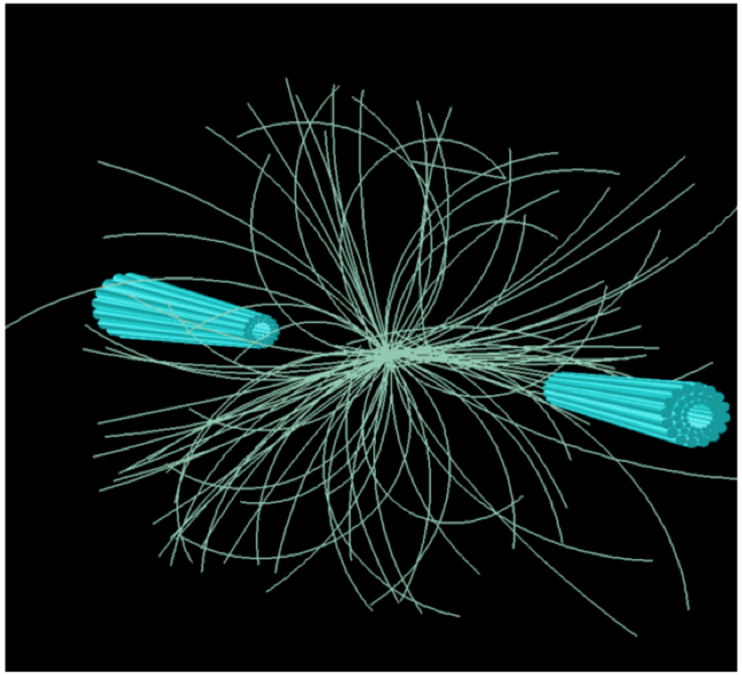


DATA SELECTION

Data collected by two triggers:

1. **Z**ero **B**ias (ZB)

- Events collected every bunch crossing whether or not collisions occur
- Rate ~ 1.7 ev/s



2. **M**inimum **B**ias (MB)

- At least one inelastic $p\bar{p}$ collision
- CLC, "Cherenkov Luminosity counter ($3.7 < |\eta| < 4.7$) Coincidence"
- Rate ~ 1 ev/s.

FULL ANALYSIS IN A NUTSHELL

The goal is to measure the p_T-averaged and y-integrated cross section

$$\frac{d\sigma_{D^+\to K^-\pi^+\pi^+}}{dp_T}\left(p_T;|y|\le 1\right)=\left.\frac{N_{D^+}\left(p_T\right)}{\Delta p_T\cdot L\cdot\varepsilon\cdot BR\left(D^+\to K^-\pi^+\pi^+\right)}\right|_{|y|\le 1}$$

- ❑ **DATA-DRIVEN OPTIMIZATION in each $p_T(D^+)$ with the EVEN/ODD method**
- ❑ **2D-FITTING PROCEDURE on the (mass, d_0) –space to extract the YIELD as a function of $p_T(D^+)$:** $N_{D^+}\left(p_T\right)$
- ❑ **INTEGRATED LUMINOSITY OF OUR SAMPLE:** L
- ❑ **DECAY BRANCHING RATIO of the channel:** $BR\left(D^+\to K^-\pi^+\pi^+\right)$
- ❑ **RECONSTRUCTION (based on MC simulations) and TRIGGER EFFICIENCY:** ε

SIGNAL: BASE SELECTION

D^+ reconstruction:

- Fit on triplet of tracks combined together in each event
- Common origin for the triplet of tracks? ➡ **D^+ CANDIDATE**

$L_{xy} \geq 0\ \mu m$

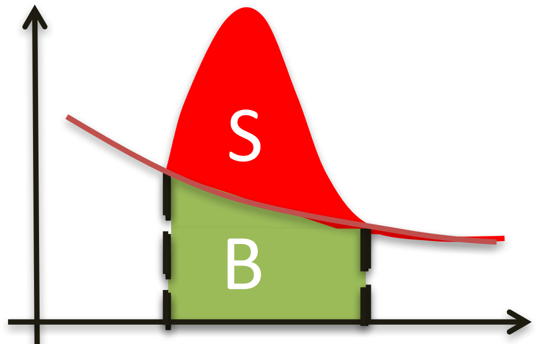
Transverse decay length

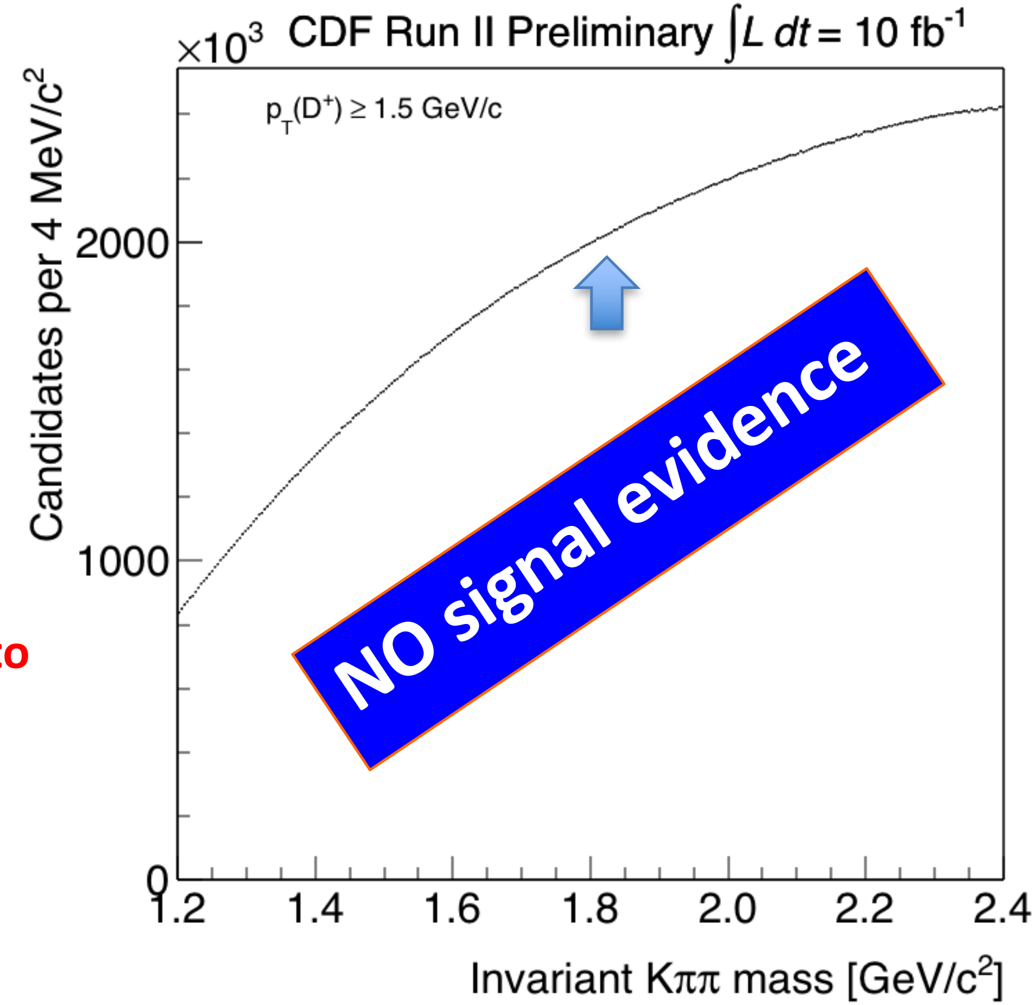
$|y(D^+)| \leq 1$

$\chi^2 \leq 10$

1. **Selection optimization is mandatory to unfold the signal**
2. **We perform it in five $p_T(D^+)$-bins**

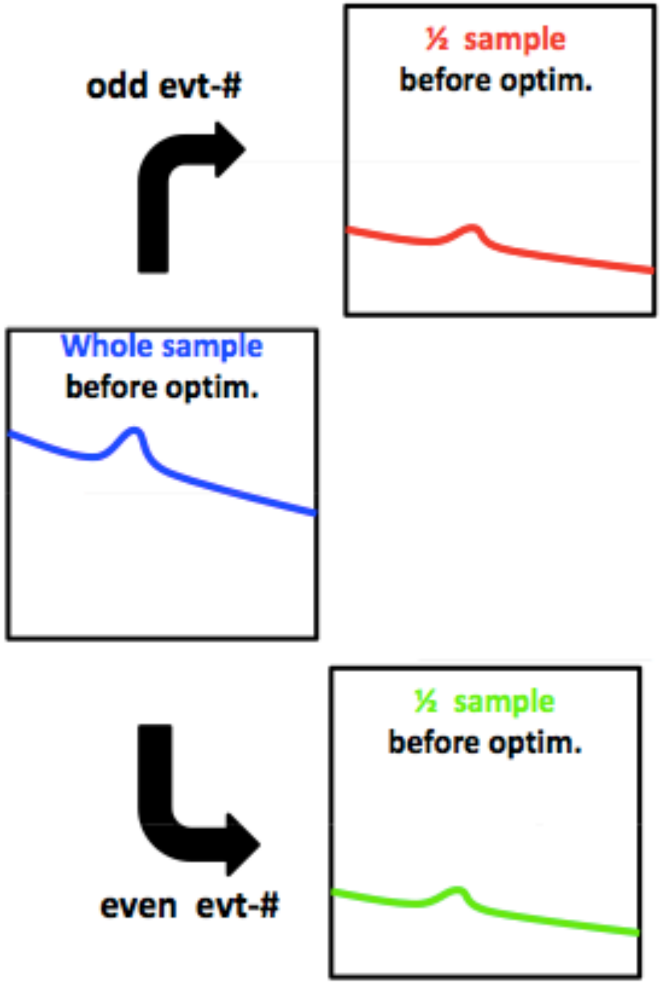
$$f(S,B) = \frac{S}{\sqrt{S+B}}$$



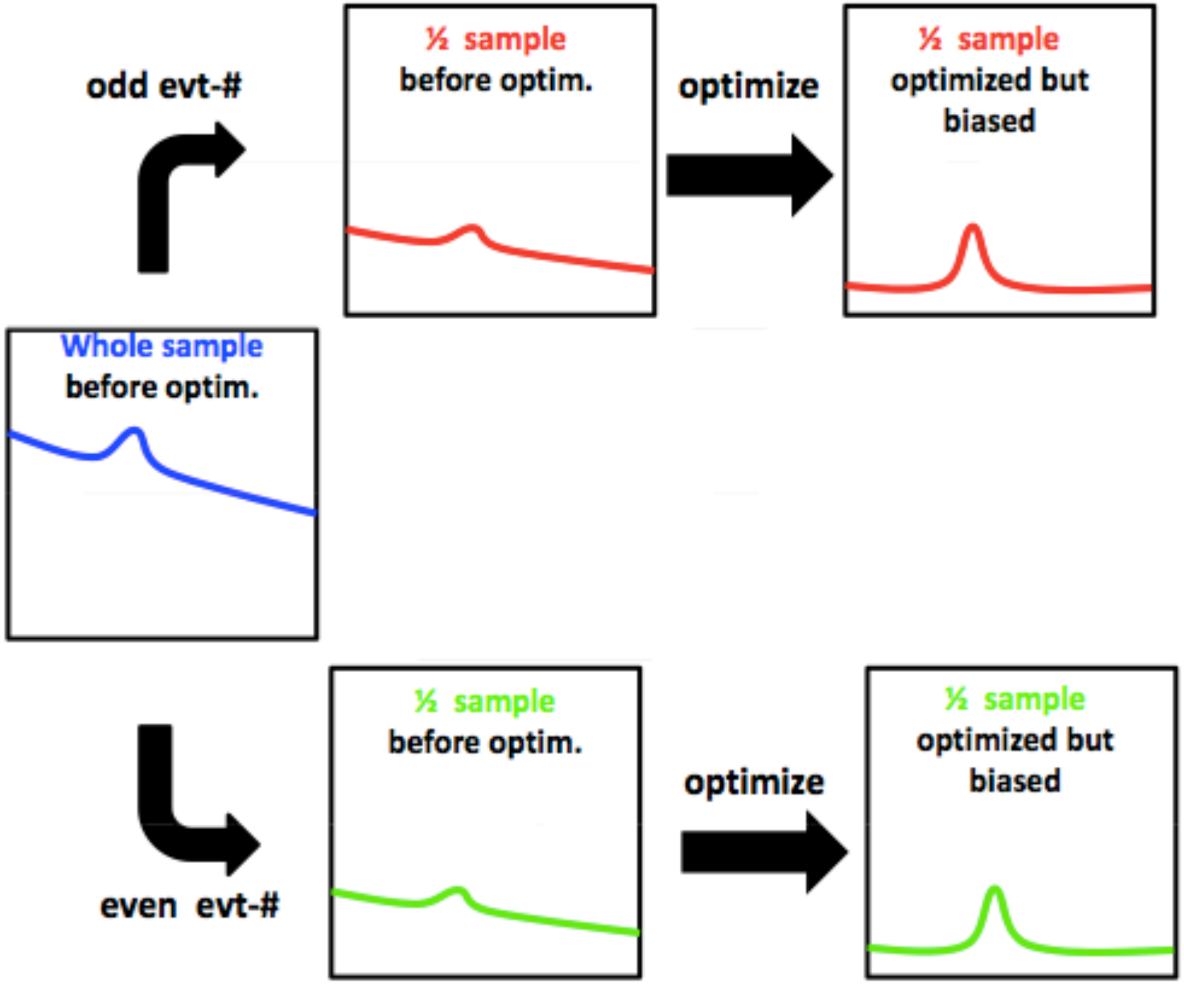


3 OPTIMIZATION VARIABLES:
p_T(tracks), χ^2 and L_{xy}

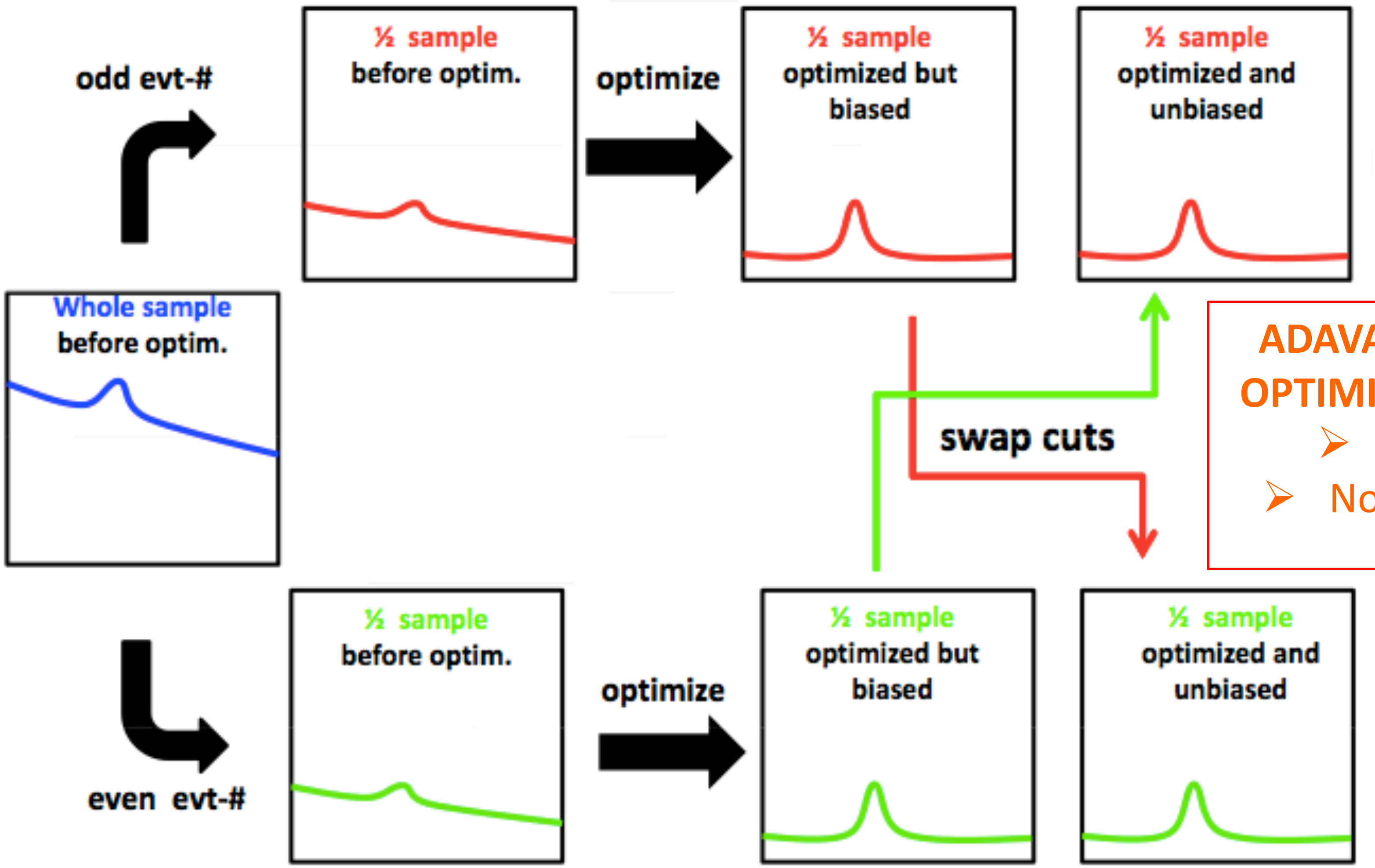
SELECTION OPTIMIZATION



SELECTION OPTIMIZATION



SELECTION OPTIMIZATION



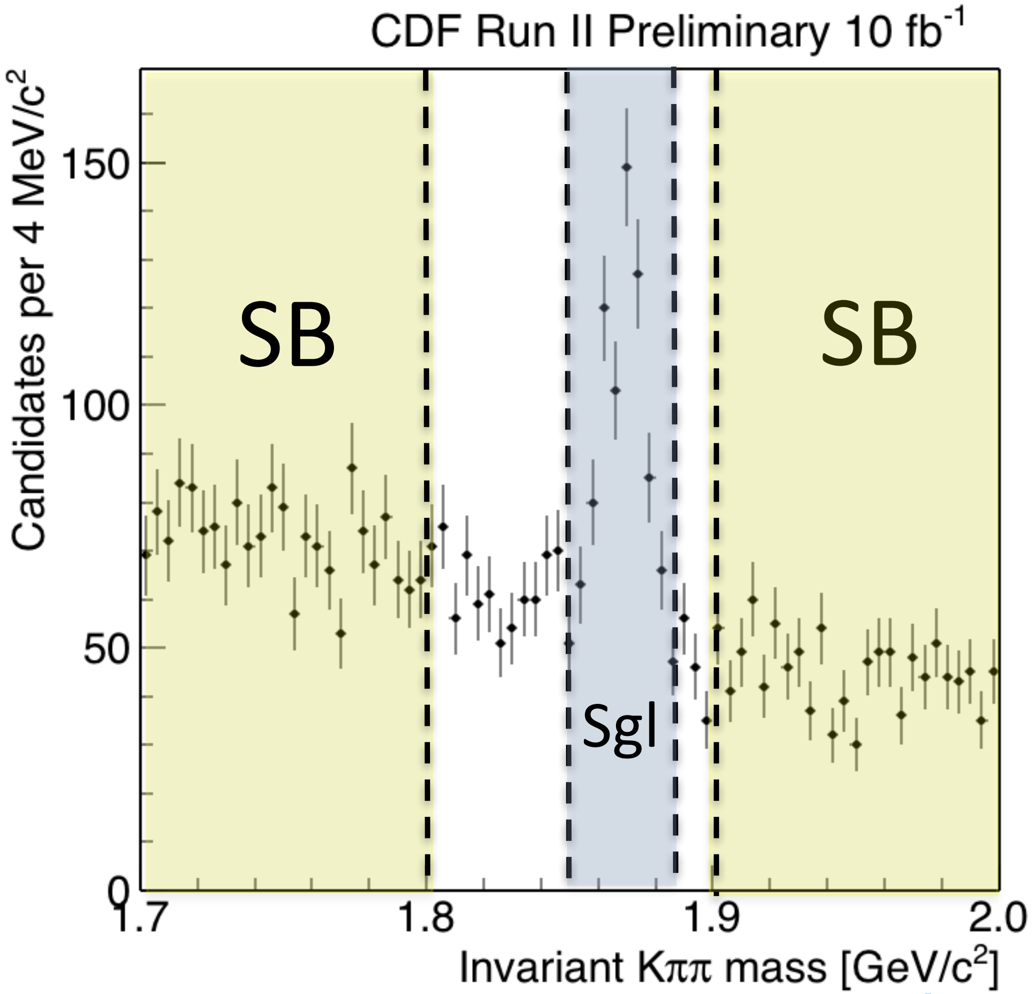
ADAVANTAGES OF THE OPTIMIZATION METHOD

- All data used
- No bias introduced

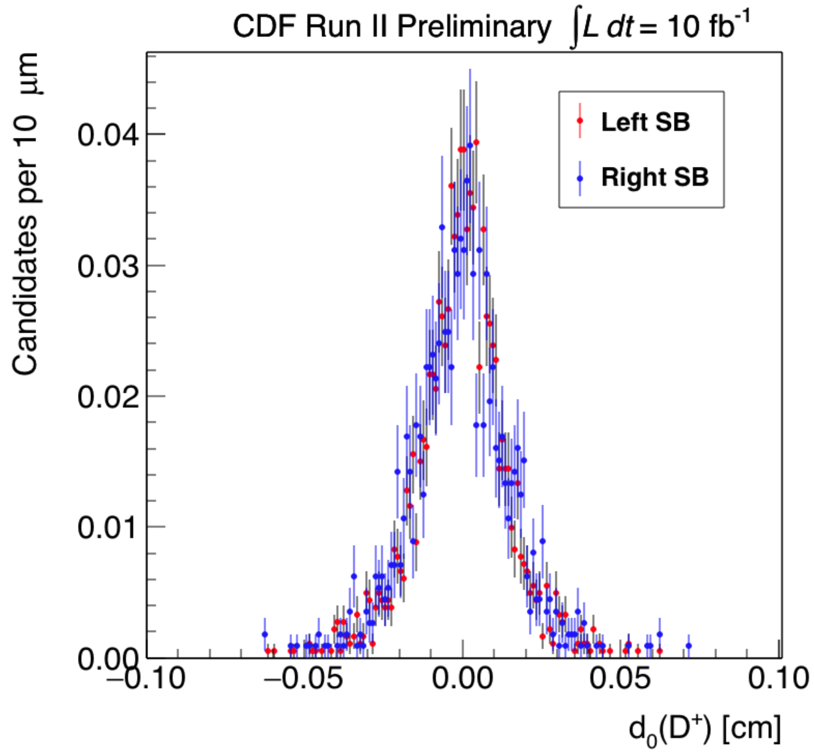
DEFINITIONS

SIGNAL REGION: $\left[m_D - 3\sigma, m_D + 3\sigma\right]$ σ from MC

ODD sample 3.5 <$p_T(D^+)$ < 4.5 GeV/c



Compare d_0 distributions for left and right Sidebands



KOLMOGOROV – SMIRNOV TEST: 90%

We handle them together

PROMPT SIGNAL EXTRACTION

- Assumption:
  in the signal region three components

Primary

Secondary

Combinatorics

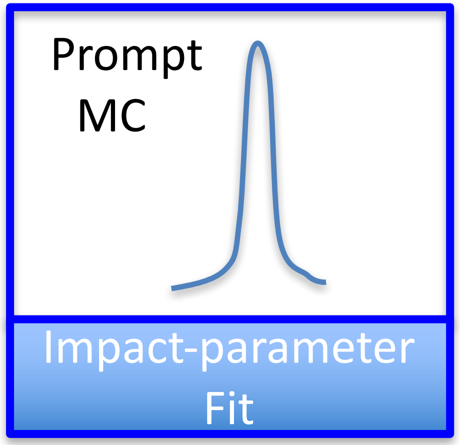
- For each component, the distributions in mass (**m**) and impact parameter (***d_0***) are **uncorrelated**

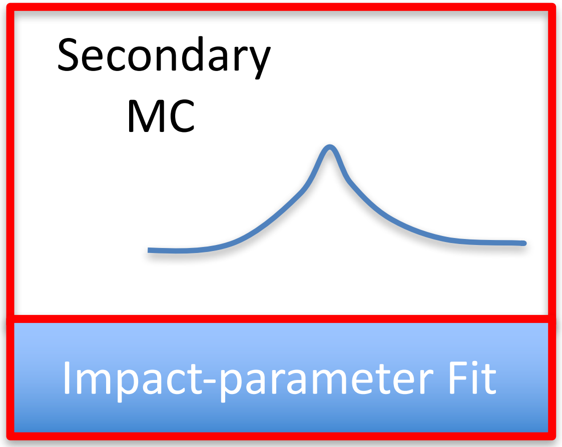
- **Two parameters (f_P, f_S)-unbinned likelihood fit**

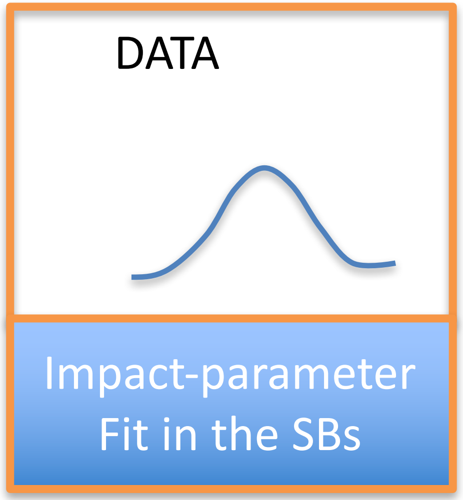
$$\mathcal{L}(f_P, f_S) = f_P \cdot F_{S,P}(m) F_P(d_0) + f_S \cdot F_{S,P}(m) F_S(d_0) + (1 - f_P - f_S) \cdot F_C(m) F_C(d_0)$$

SHAPE EXTRACTION

$d_0(D^+)$

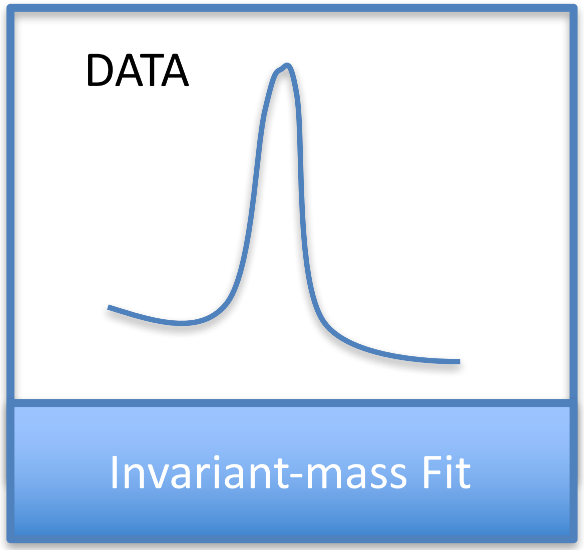






$$L(f_P, f_S, \vec{\theta}_P, \vec{\theta}_S, \vec{\theta}_C) = f_P \cdot F_P(m, d_0; \vec{\theta_P}) + f_S \cdot F_S(m, d_0; \vec{\theta_S}) + (1 - f_P - f_S) \cdot F_C(m, d_0; \vec{\theta_C})$$

MASS

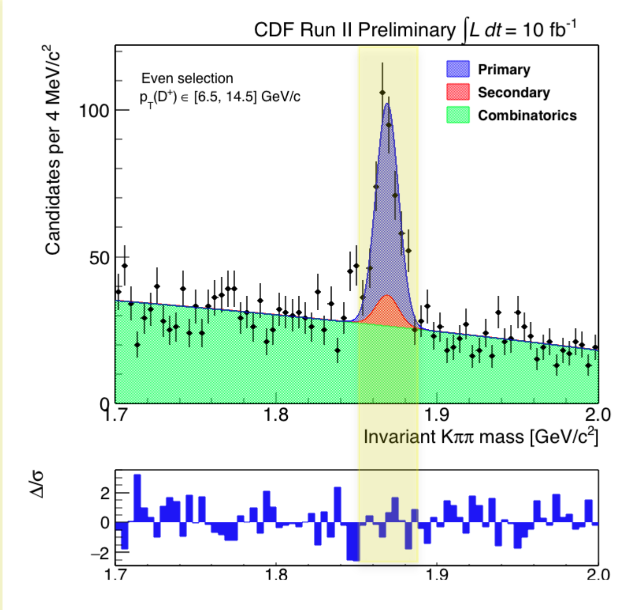


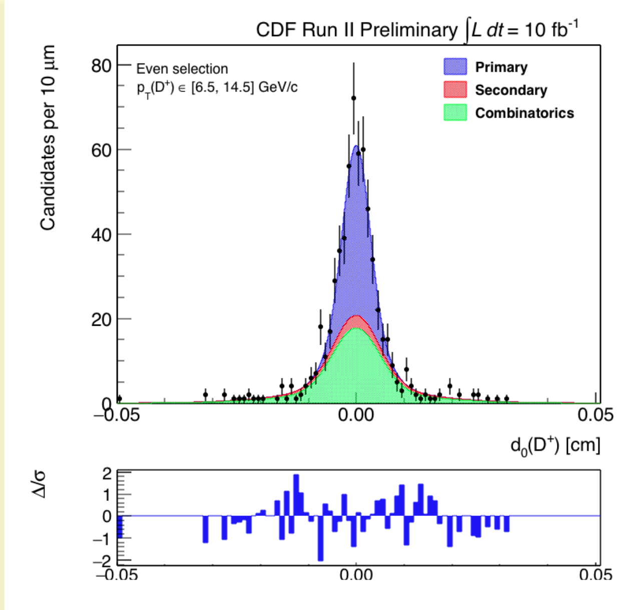
- Primary component
- Secondary component
- Combinatorics

6.5 < $p_T(D^+)$ < 14.5 GeV/c

EVEN EVENTS

D^+_{prompt} = 278±24

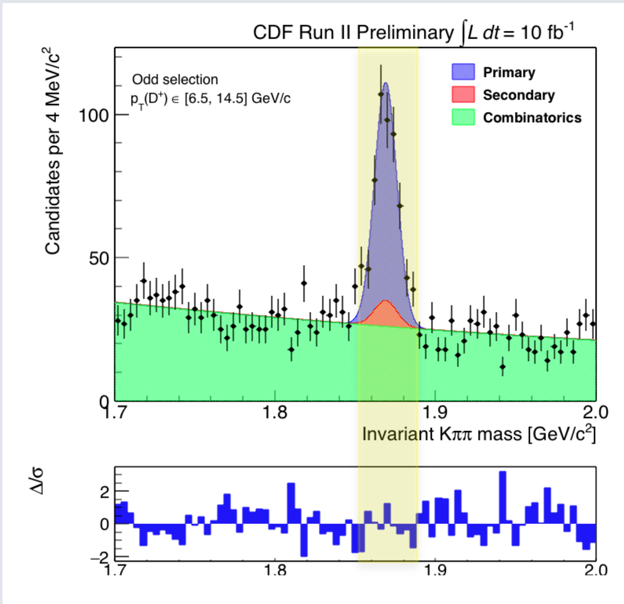


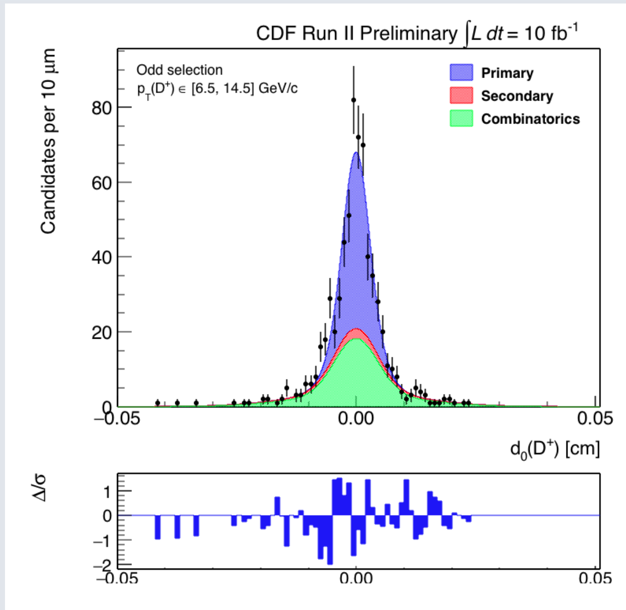


$d_0(D^+)$ **SIGNAL REGION**

ODD EVENTS

D^+_{prompt} = 327±27



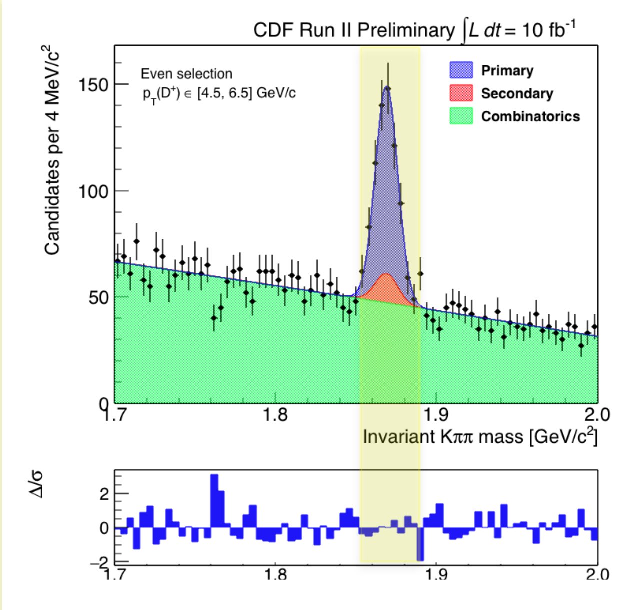


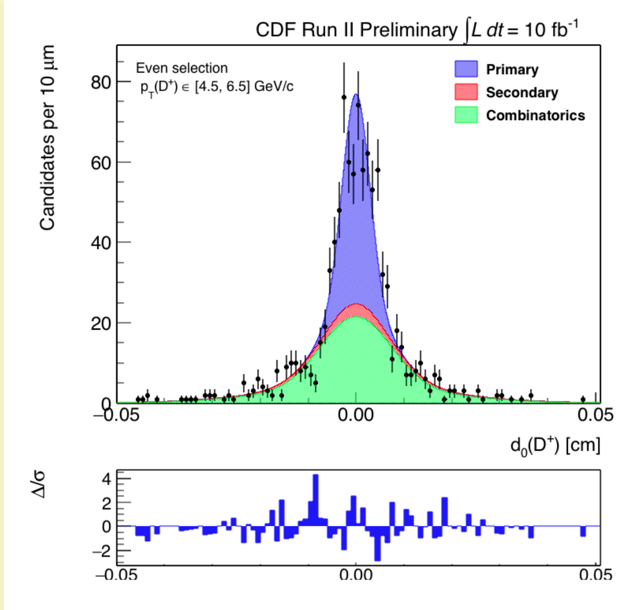
$d_0(D^+)$ **SIGNAL REGION**

4.5 < $p_T(D^+)$ < 6.5 GeV/c

EVEN EVENTS

D^+_{prompt} = 384±29

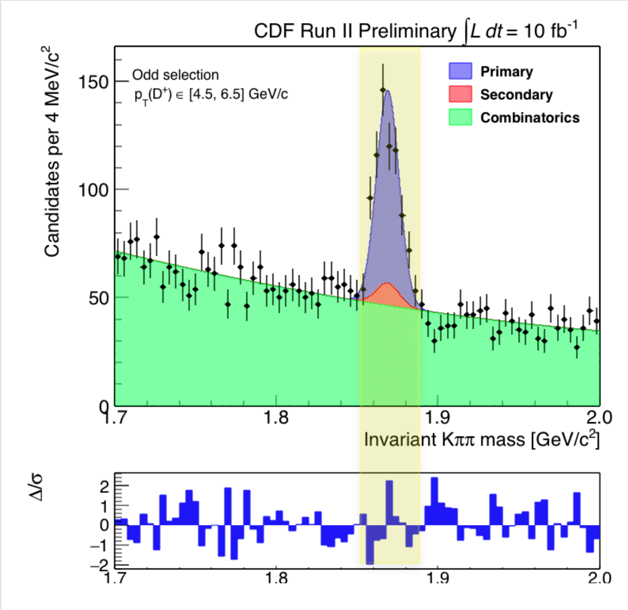


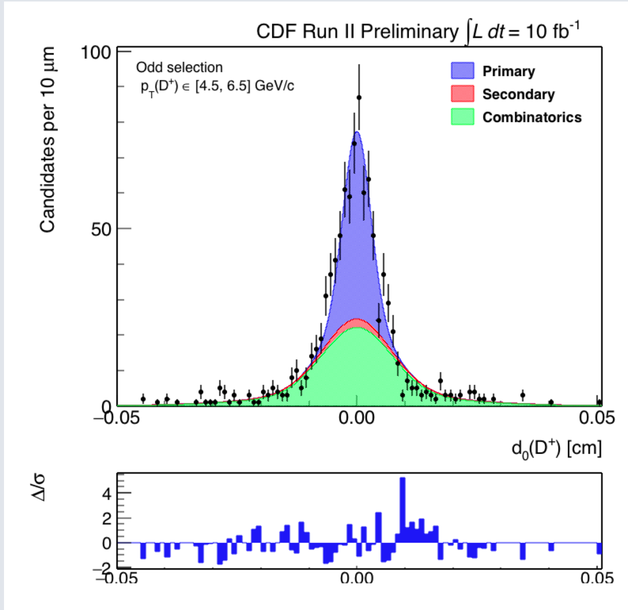


$d_0(D^+)$ **SIGNAL REGION**

ODD EVENTS

D^+_{prompt} = 389±29



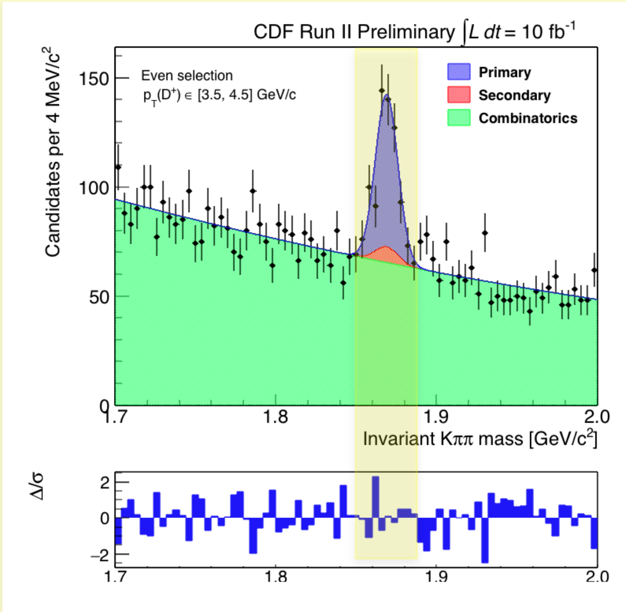


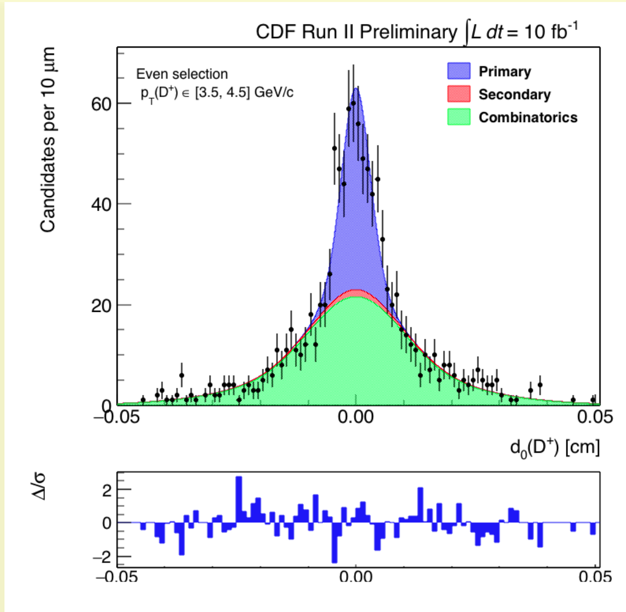
$d_0(D^+)$ **SIGNAL REGION**

$3.5 < p_T(D^+) < 4.5$ GeV/c

EVEN EVENTS

$D^+_{prompt} = 301 \pm 28$

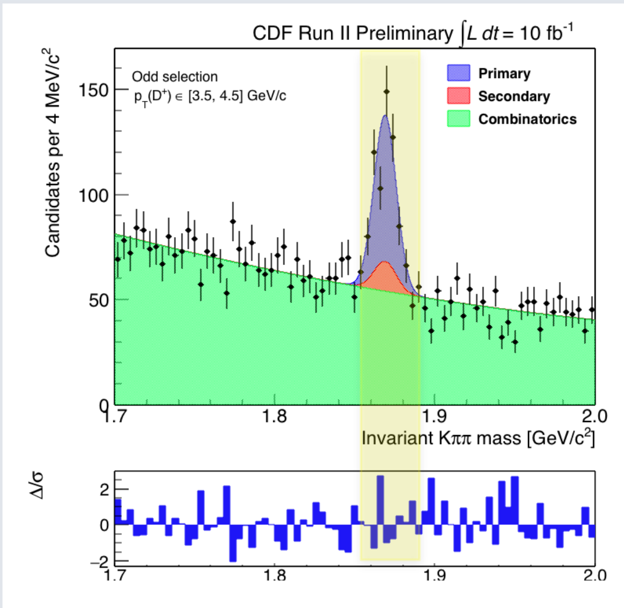


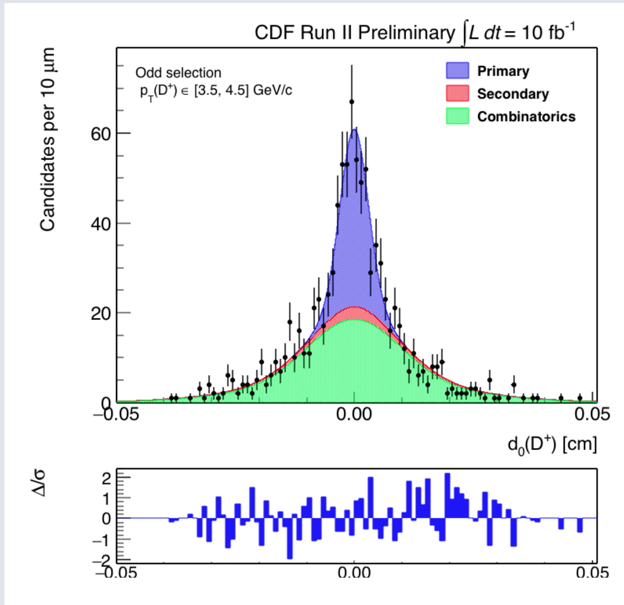


$d_0 (D^+)$ **SIGNAL REGION**

ODD EVENTS

$D^+_{prompt} = 304 \pm 28$



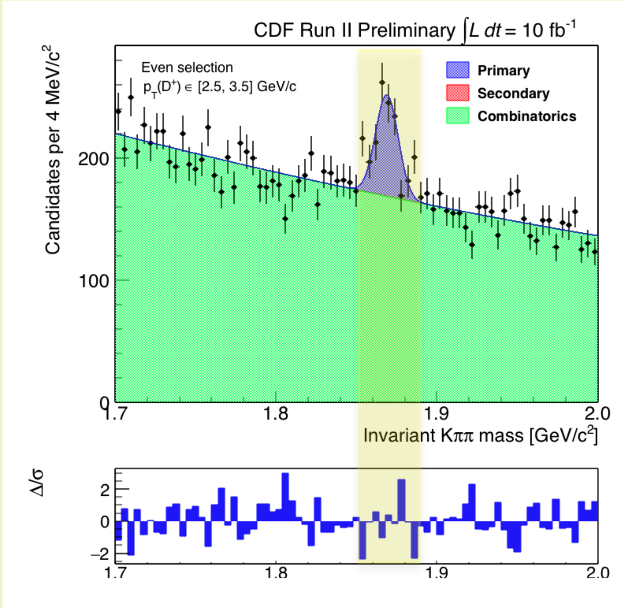


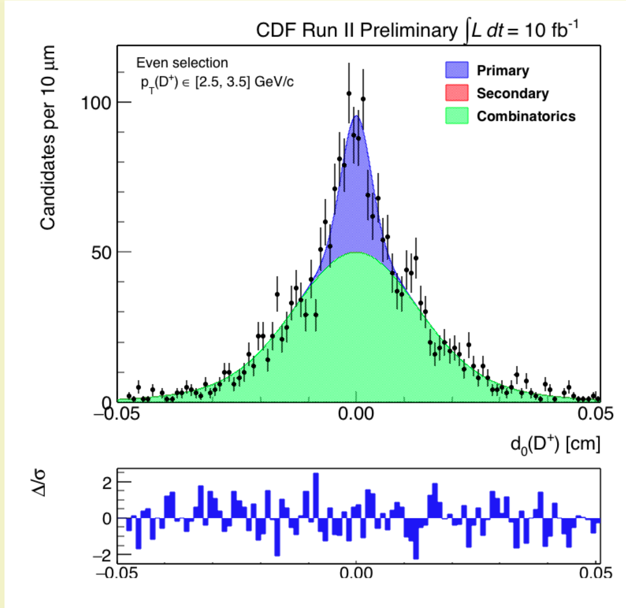
$d_0 (D^+)$ **SIGNAL REGION**

$2.5 < p_T(D^+) < 3.5$ GeV/c

EVEN EVENTS

$D^+_{prompt} = 366 \pm 27$

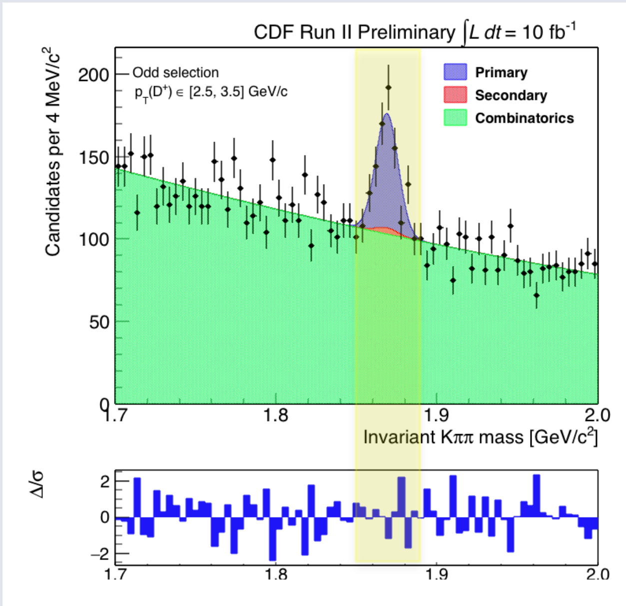


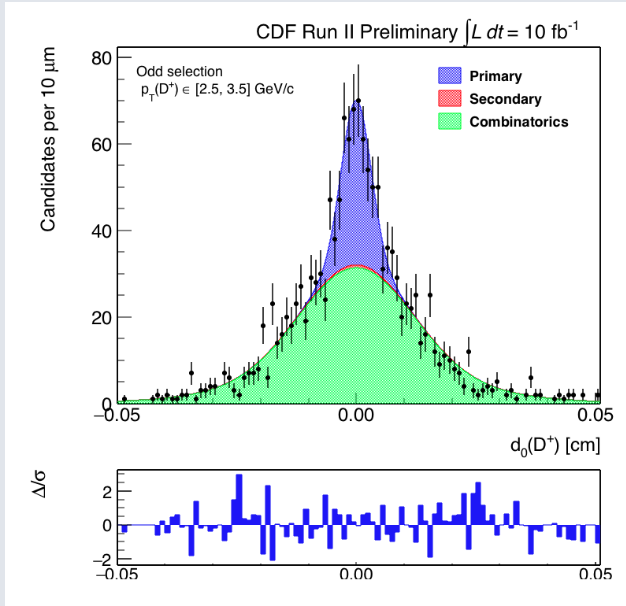


$d_0(D^+)$ **SIGNAL REGION**

ODD EVENTS

$D^+_{prompt} = 307 \pm 34$



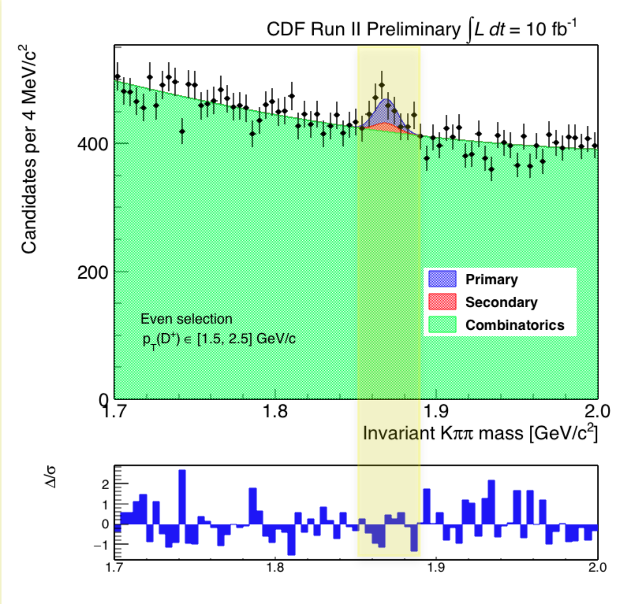


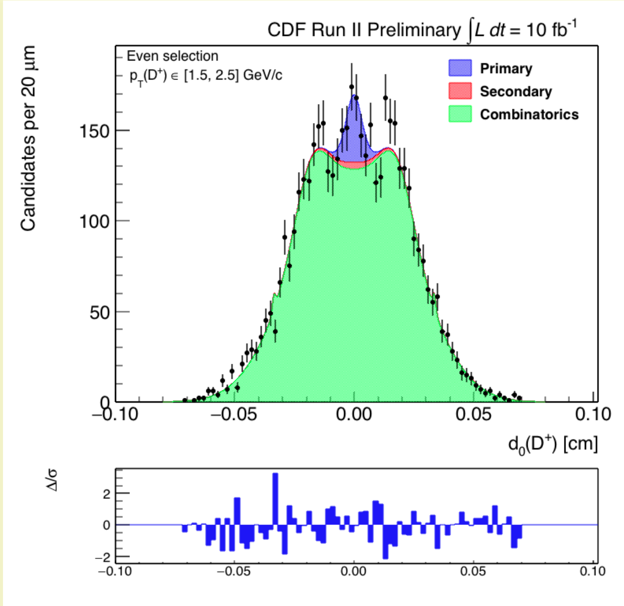
$d_0(D^+)$ **SIGNAL REGION**

$1.5 < p_T(D^+) < 2.5$ GeV/c

EVEN EVENTS

$D^+_{prompt} = 170 \pm 40$

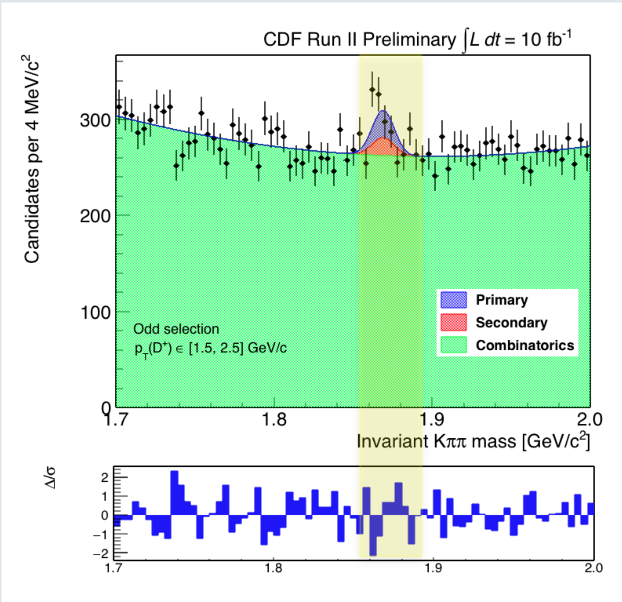


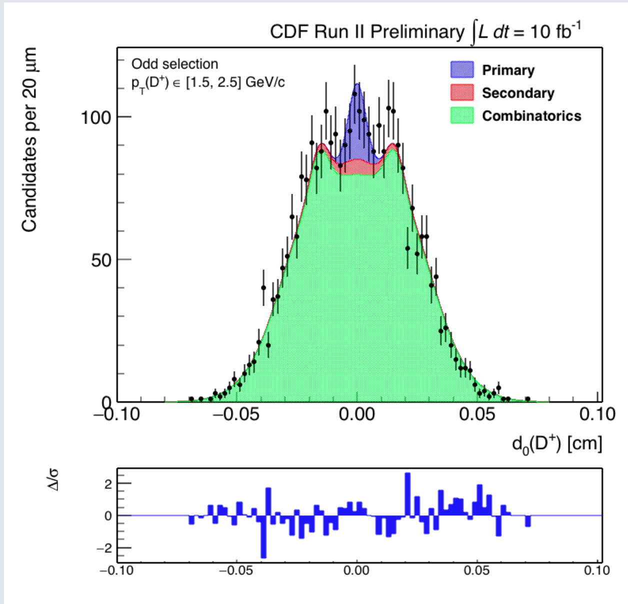


d_0 (D^+) **SIGNAL REGION**

ODD EVENTS

$D^+_{prompt} = 125 \pm 40$





d_0 (D^+) **SIGNAL REGION**

EFFICIENCY

$$\varepsilon(D^+;p_T) = \varepsilon_{trig} \cdot \varepsilon_{rec}(p_T)\Big|_{|y|\leq 1}$$

$$\varepsilon_{rec}(D^+;p_T) = \frac{N_{Candidates}(p_T)\,passing\_the\_Rec\_Selections}{N_{Generated}(p_T)}\Bigg|_{|y|\leq 1}$$

TRIGGER EFFICIENCY	RECONSTRUCTION EFFICIENCY
➢ No p_T-dependence ➢ Negligible effect: 1.7‰ ➢ We handle it as a systematic uncertainty	➢ p_T-dependence ➢ MC based ➢ Since it is the first CDF low-p_T-cross-section measurement, we performed additional cross-checks (see back-up slides)

RECONSTRUCTION EFFICIENCY

CDF Run II Preliminary

$p_T(D^+)$ [GeV/c]	Subsample	$\varepsilon_{\rm rec}(D^+)$[%]
1.5–2.5	Even	0.331 ± 0.011
	Odd	0.267 ± 0.010
2.5–3.5	Even	1.142 ± 0.026
	Odd	1.020 ± 0.025
3.5–4.5	Even	2.098 ± 0.047
	Odd	2.110 ± 0.047
4.5–6.5	Even	3.936 ± 0.073
	Odd	3.936 ± 0.073
6.5–14.5	Even	7.46 ± 0.15
	Odd	7.36 ± 0.15

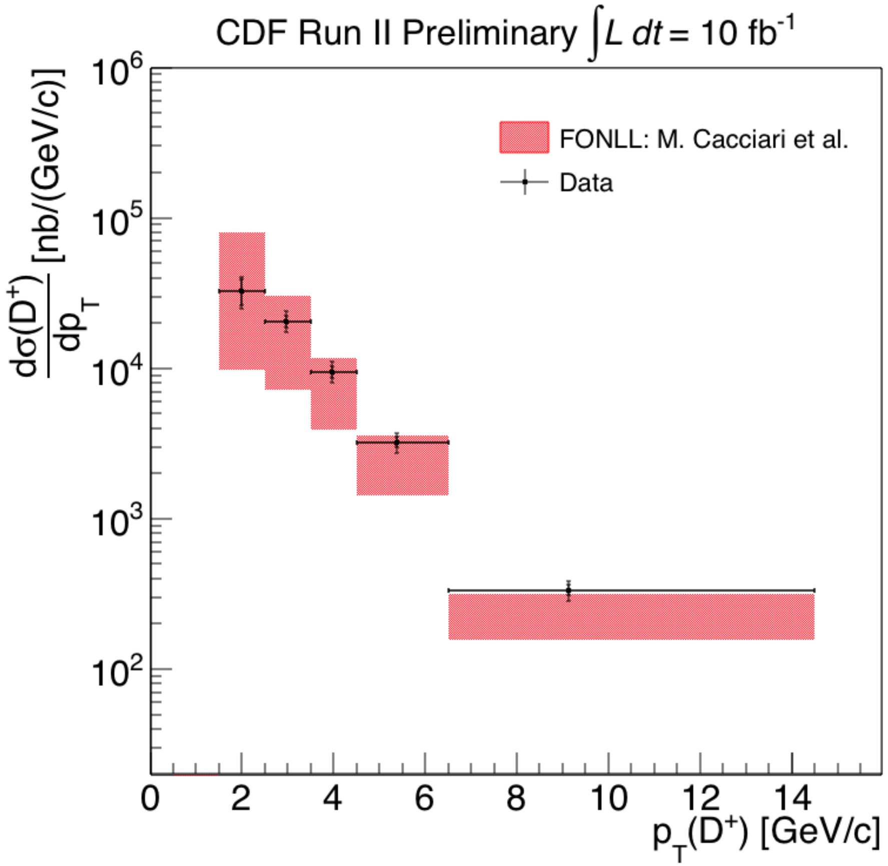
SYSTEMATIC UNCERTAINTIES

- **Reconstruction-efficiency procedure**
  We perform some MC/Data tests on control-samples to evaluate possible inaccuracies in the MC simulation of the silicon
- **Background and signal shape**
  We change the signal or the background shape and evaluate the effect on the final number
- **Trigger Efficiency**
- **Luminosity**
- **D^+ Branching Ratio**

CDF Run II Preliminary

$\sigma^{\rm sys}_{L_{\rm trig}}$ [%]	$\sigma^{\rm sys}_{\rm shape}$ [%]	$\sigma^{\rm sys}_{\varepsilon_{\rm trig}}$ [%]	$\sigma^{\rm sys}_{\varepsilon_{\rm rec}}$ [%]	$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$ [%]	$\sigma^{\rm sys}_{\rm tot}$ [%]
5.8	0.9-1.5 depending on the bin	0.17	11.5	0.24	13

RESULTS: CROSS SECTION



The cross section we measure is
p_T-AVERAGED and y-INTEGRATED

The horizontal bars represent the p_T-interval over which we average in p_T

The markers are placed at the p_T point-value at which the cross section equals the predicted values of the cross section.

FONLL reference: *M. Cacciari et al., JHEP* ***1210*** *(2012) 137*

Uncertainties on scales, masses and PDFs have been considered for the theoretical prediction

COMPARISON WITH PREVIOUS CDF-RESULT

- The comparison with the previous CDF result, *PRL 91*-measurement, is an important consistency check of the analysis, but doing it properly is not straightforward:

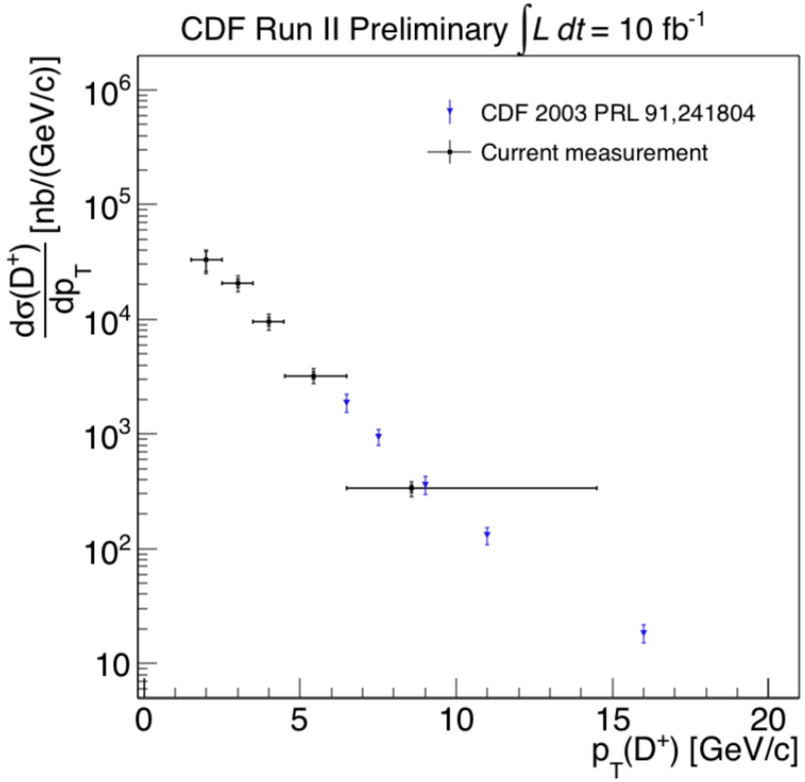
  1. **The *PRL91*-analysis published the cross section at a given p_T value within each bin while we measure the cross section averaged across each bin**

  2. **The *PRL91* and this measurement cover different** p_T ranges: **[6, 20] vs [1.5, 14.5] GeV/c**

- A simple direct comparison is not possible

COMPARISON WITH PRL-91RESULT

- To overcome the problem of the different binning and different cross-section definition we compare the measurements by using the theoretical prediction as a reference to normalize both measurements
- We consider all experimental uncertainties except the common luminosity contribution
- We agree within Δ/σ = 0.5



The markers for this measurement are placed at the average-p_T within the bin.

CONCLUSIONS

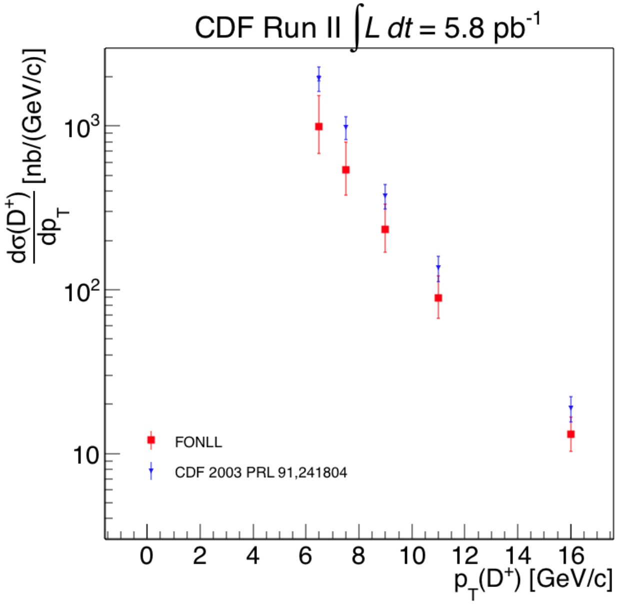
- We have measured the low p_T D^+-meson production cross section at CDF
- While the measurements lie within the band of theoretical uncertainty, there is a systematic variation suggesting that the shape of the theoretical cross section can benefit by further refinement taking account these results
- We agree with earlier determination at high momenta
- Since it is the first measurement of the silicon low p_T efficiency, it is a benchmark for all other CDF cross section-measurements in these kinematic conditions
- Further information can be found at: http://goo.gl/ai9mj2

Thank you

BACK-UP

COMPARISON WITH PRL-91RESULT

PRL91-MEASUREMENT AND THEORY

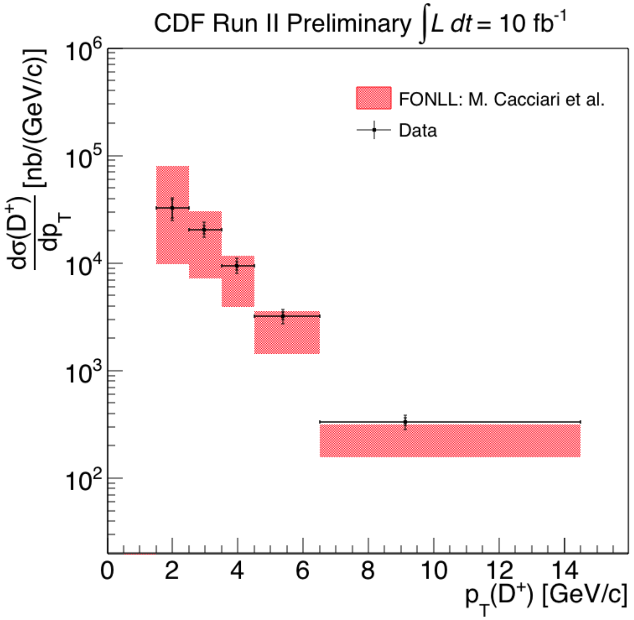


CDF Run II Preliminary

$p_T(D^+)$ [GeV/c]	PRL91-meas.[nb/(GeV/c)]*	Theory	PRL91-Data/Theory ratio
6–7	1 886±309	997±541	1.89±1.07
7–8	948±143	537±259	1.77±0.89
8–10	361±57	233±99	1.54±0.70
10–12	131±22	89±32	1.47±0.59
12–20	18.3±3.0	13.0±3.6	1.40±0.46

*scaled to take into account the current value of the BR = 9.46 ± 0.24 %

THIS MEASUREMENT AND THEORY

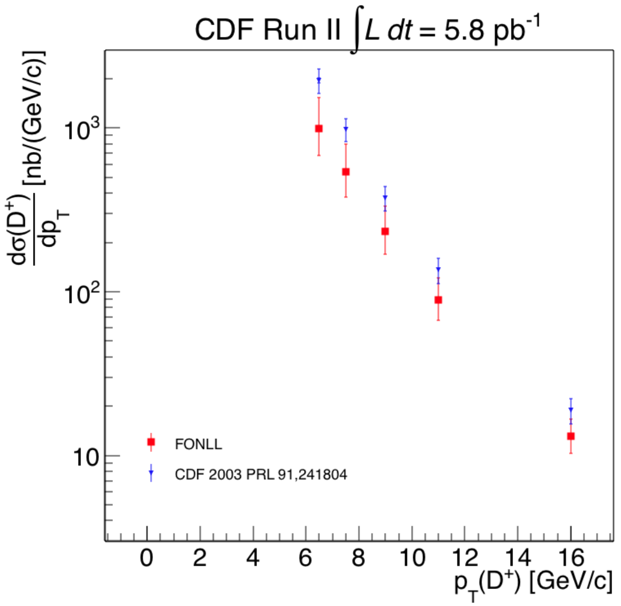


CDF Run II Preliminary

$p_T(D^+)$ [GeV/c]	This meas.[nb/(GeV/c)]	Theory	This Data/Theory ratio
1.5–2.5	32 700±7 509	36 009±25 847	0.91±0.69
2.5–3.5	20 600±2 975	15 565±14 663	1.32±1.27
3.5–4.5	9 500±1 378	6 538±5 070	1.45±1.15
4.5–6.5	3 230±453	2 176±1 378	1.48±0.97
6.5–14.5	336±47	218±99	1.54±0.74

COMPARISON WITH PRL-91RESULT

PRL91-MEASUREMENT AND THEORY



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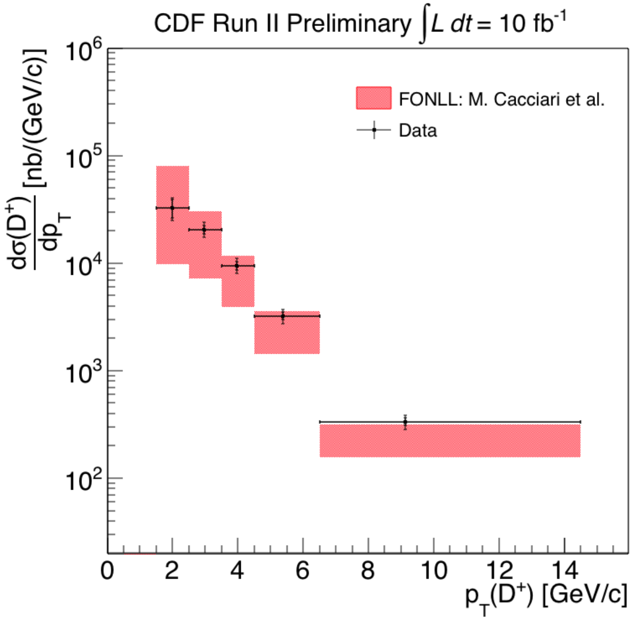

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Weighted-averages of the data/theory ratios

CDF Run II Preliminary

This <Data/Theory ratio>	PRL-91<Data/Theory ratio>	Δ/σ
1.54±0.15	1.64±0.13	0.48

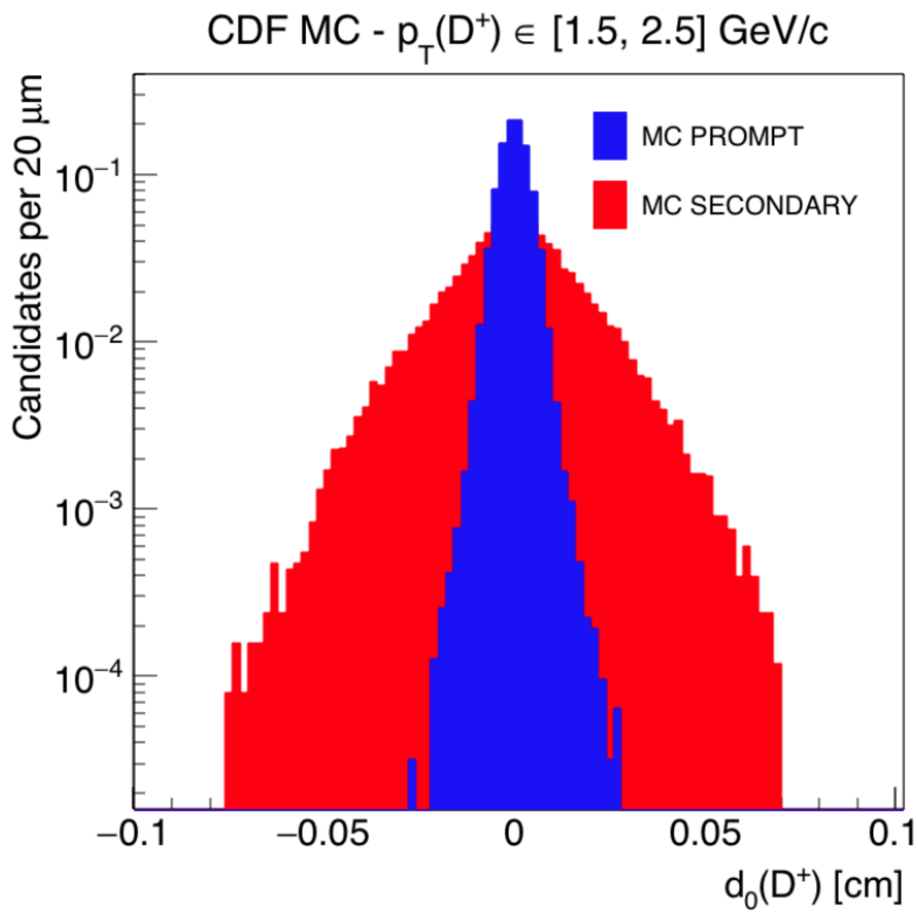
OPTIMIZATION RESULTS

$p_T(D^+)$ [GeV/c]	PARITY	Any two $p_T(TRK) \geq$ [GeV/c]	$\chi^2/ndf \leq$	$L_{xy} \geq$ [cm]
[2.5, 3.5]	EVEN	0.6	2	0.0600
	ODD	0.6	3	0.0600
[3.5, 4.5]	EVEN	0.7	5	0.0750
	ODD	0.7	5	0.0750
[4.5, 6.5]	EVEN	0.9	6	0.0750
	ODD	0.9	6	0.0750
[6.5, 13.5]	EVEN	1.1	7	0.0750
	ODD	1.1	7	0.0750
[1.5; 2.5]	EVEN	0.7	4	0.0600
	ODD	0.6	4	0.0600

$|d_0(D^+)| \leq 100\ \mu m$

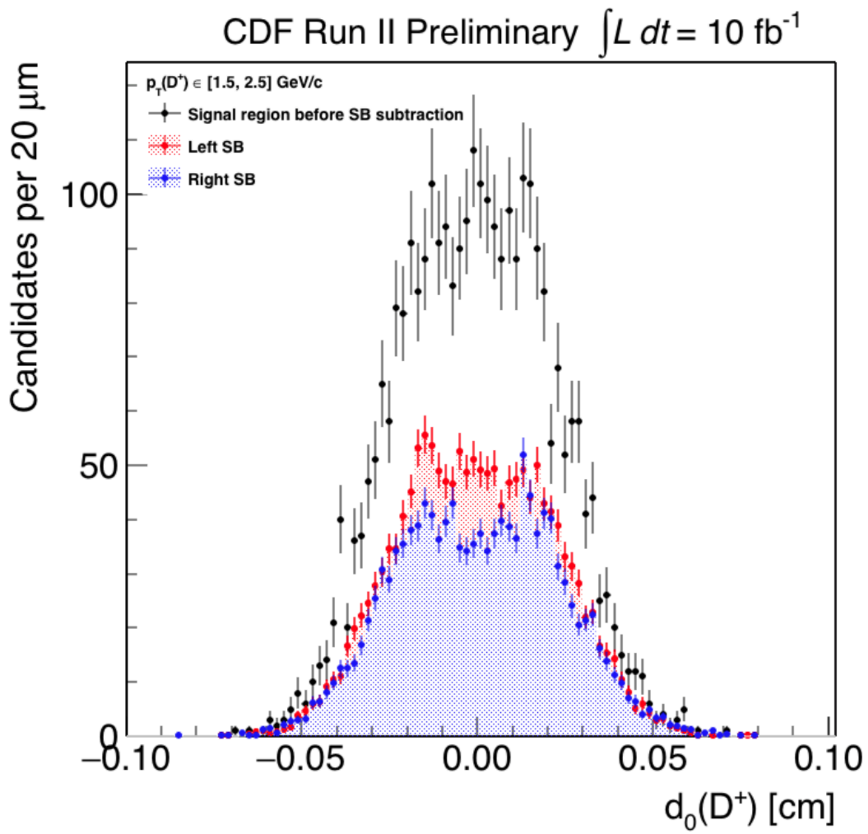
$1.5 < p_T(D^+) < 2.5$ GeV/c: structures

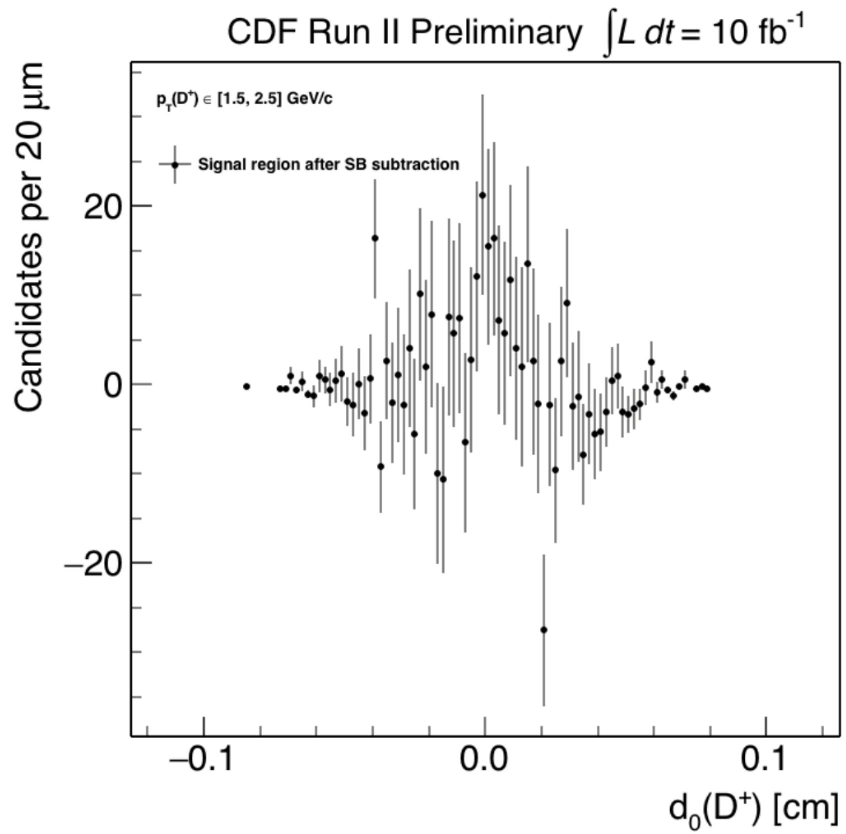
The structures are not related to the Prompt or Secondary component



1.5 < $p_T(D^+)$ < 2.5 GeV/c: structures

They are due to the contribution of combinatorics.
In SBs-subtracted region they disappear





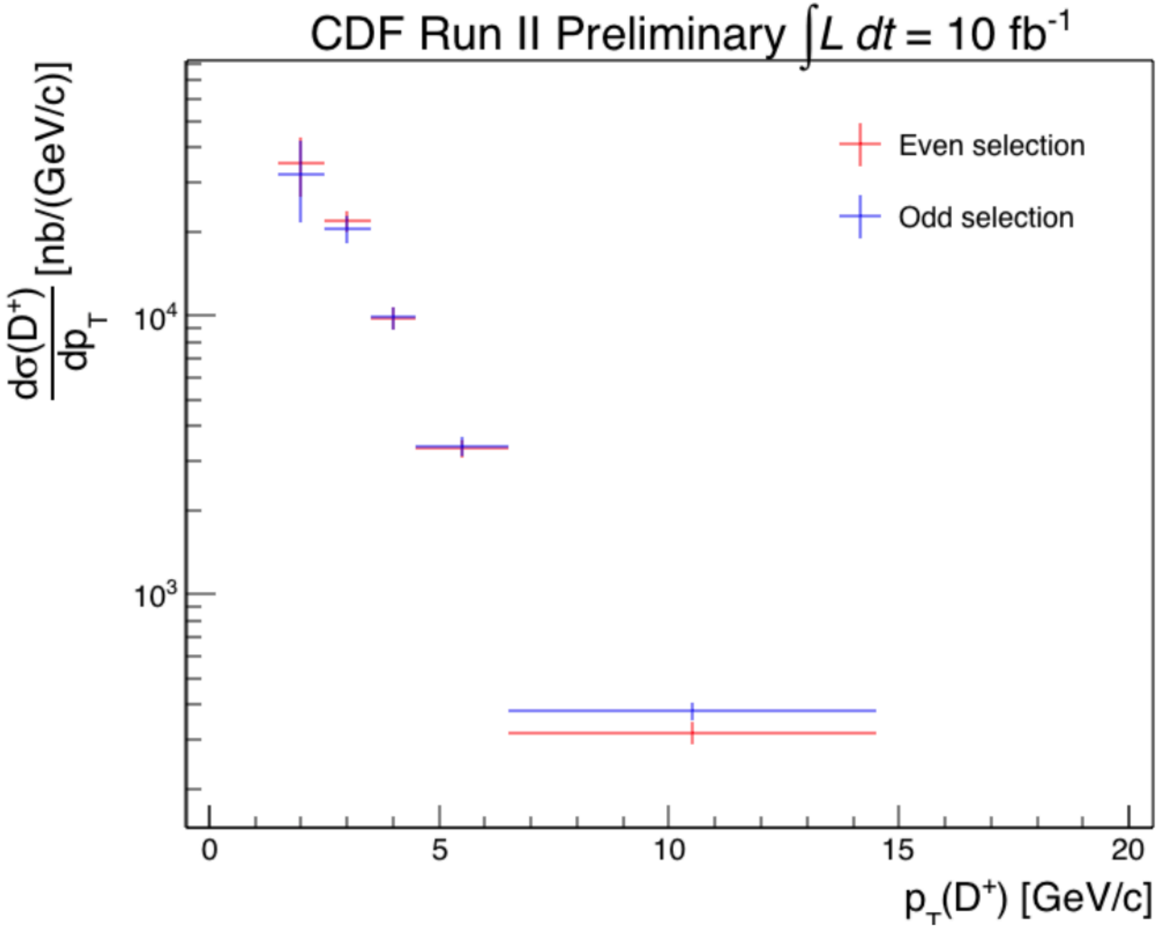
CONSISTENCY CHECKS

- We have performed some consistency checks to test all the steps of this analysis
- They do not significantly change the results but led to a more robust analysis and increased our confidence on the validity of the results

CONSISTENCY CHECKS

1. **Optimization procedure**
2. **Fitting procedure**
3. **Charge-related effects**
4. **Triggers consistency**
5. **Reconstruction efficiency**
6. **Global procedure**

OPTIMIZATION PROCEDURE



The numbers are consistent within errors

Only statistical uncertainties are considered for both the subsamples

FITTING PROCEDURE

- To test the robust fitting-procedure, for each $p_T(D^+)$-bin we have produced 1000 simulated pseudo-experiments that mimic each component (prompt, secondary and combinatorial) according to its pdf.

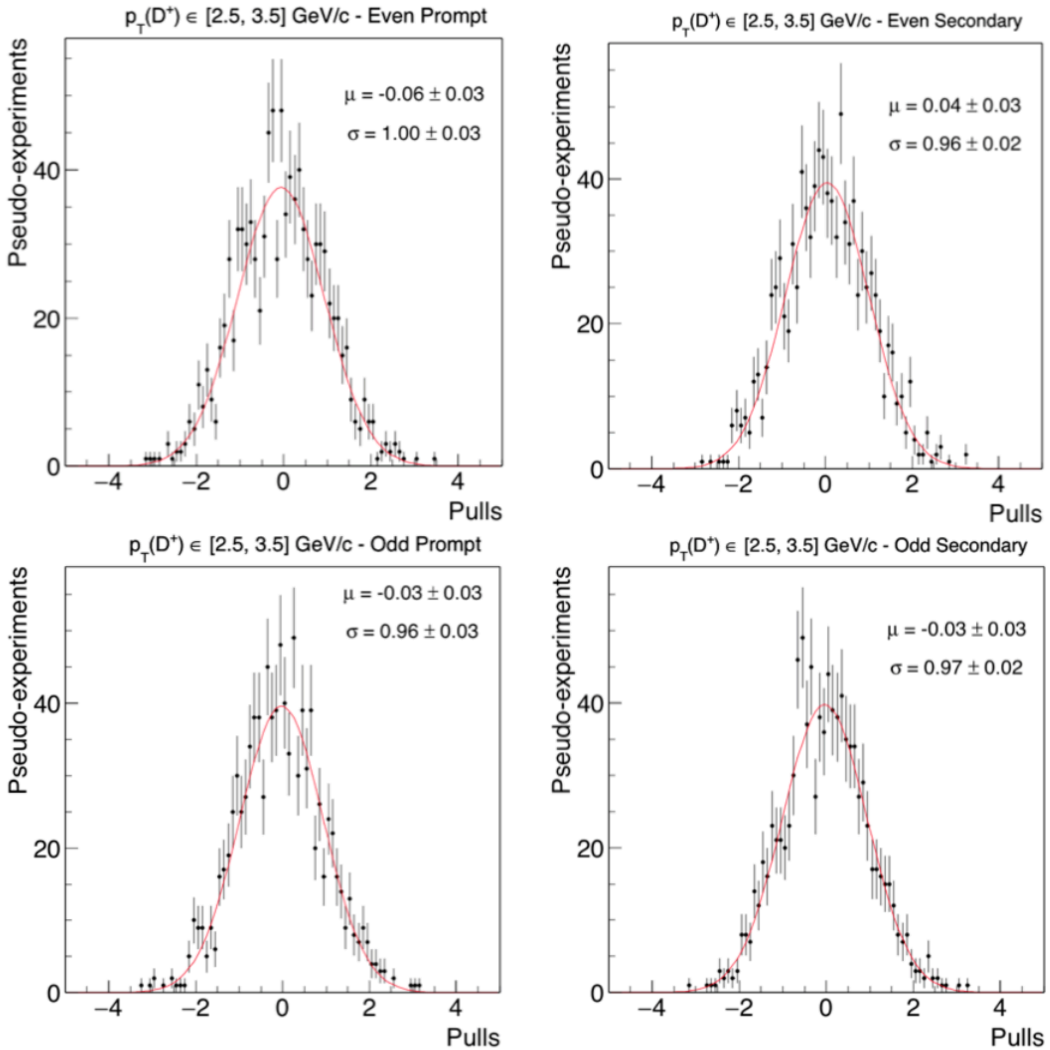
- The input values for the fraction in generations are those determined by the fit in data.

- We have performed the 2D-fit on each sample

- We have evaluate the pulls distribution

No biases are introduced by the fitting procedure

FITTING PROCEDURE



CHARGE-RELATED EFFECTS

We have measured separately the D^+ and the D^- production cross section:

- **No new optimization**
- **We perform separately the fitting procedure and the efficiency measurement for the D^+ and the D^- sample**
- **Only statistical uncertainties have been considered**
- **It was not possible for the lowest bin, $p_T(D^+)$ in [1.5; 2.5] GeV/c, because of low statistics**

CDF Run II Preliminary

$p_T(D^+)$ [GeV/c]	$d\sigma/dp_T(D^-)$ [nb/(GeV/c)]	$d\sigma/dp_T(D^+)$ [nb/(GeV/c)]
2.5–3.5	20 600 ± 2 200	24 040 ± 3 100
3.5–4.5	10 200 ± 1 200	9 900 ± 1 100
4.5–6.5	3 100 ± 304	3 700 ± 360
6.5–14.5	383 ± 38	384 ± 40

No charge-related effects are observed

TRIGGERS CONSISTENCY

We have measured separately the D^+ cross section in the ZB and MB sample:

- **No new optimization or efficiency measurement**
- **We perform the fitting procedure using the ZB and MB separately**
- **Only statistical uncertainties have been considered**
- **It was not possible for the lowest bin, $p_T(D^+)$ in [1.5; 2.5] GeV/c, because of low statistics**

CDF Run II Preliminary

$p_T(D^+)$ [GeV/c]	Subsample	$d\sigma/dp_T(D^+)$ [nb/(GeV/c)]
2.5–3.5	ZB	20 200 ± 2 500
	MB	20 100 ± 1 900
3.5–4.5	ZB	9 900 ± 1 100
	MB	9 200 ± 950
4.5–6.5	ZB	3 220 ± 314
	MB	3 226 ± 298
6.5–14.5	ZB	315 ± 34
	MB	351± 33

The two results are consistent

RECONSTRUCTION EFFICIENCY 1

SINGLE TRACK EFFICIENCY

First measurement of cross section at low p_T for CDF

Is the MC reliable ?

YES for the COT simulation

NO for the Silicon simulation

The time dependence doesn't take into account some dead channels in time

We should check and eventually correct …

- We use DATA ⟹ **$J/\psi \longrightarrow \mu^+\mu^-$ DATASET**
  $D^{*+} \longrightarrow D^0\pi^\pm_{soft}$ DATASET

SINGLE-TRACK EFFICIENCY

HOW TO

In principle the Silicon efficiency per single track already seen in the COT is a 5D-function:

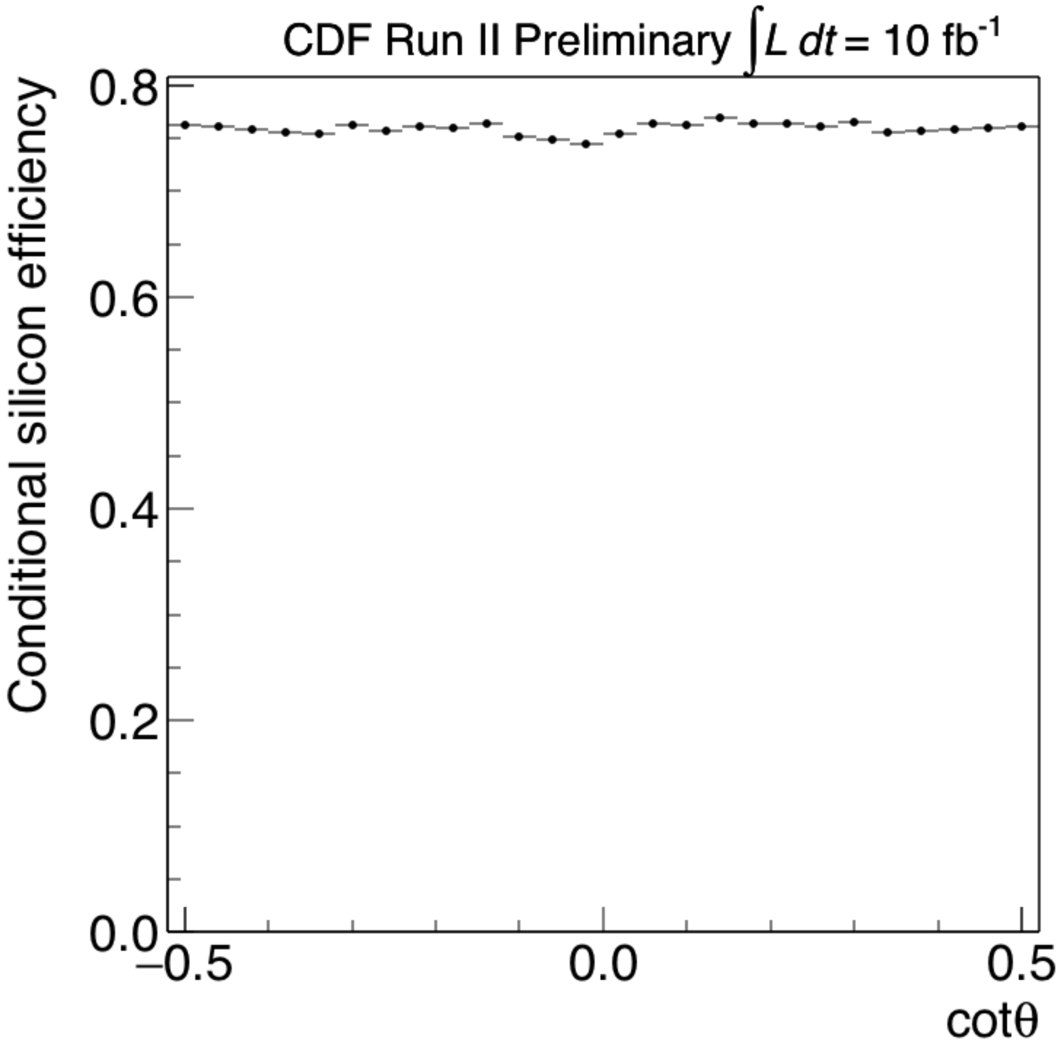
$$\varepsilon(\phi_0, z_0, \theta_0, p_T, t) \Rightarrow \equiv \varepsilon(\phi_0, z_0, t) \cdot \frac{\varepsilon(\cot\theta, t) \cdot \varepsilon(p_T, t)}{\varepsilon_0^2}$$

Normalization constant

In our case no $\varepsilon(\cot\theta, t)$-dependence is observed, then:

$$\varepsilon \equiv \varepsilon(\phi_0, z_0, t) \cdot \frac{\varepsilon(p_T, t)}{\varepsilon_0}$$

SINGLE-TRACK EFFICIENCY



CONDITIONAL-SILICON EFFICIENCY as a function of p_T

- The J/Ψ DATASET implements a trigger cut for $p_T < 1.5$ GeV/c

- Our phase space is densely populated for $p_T < 1.5$ GeV/c

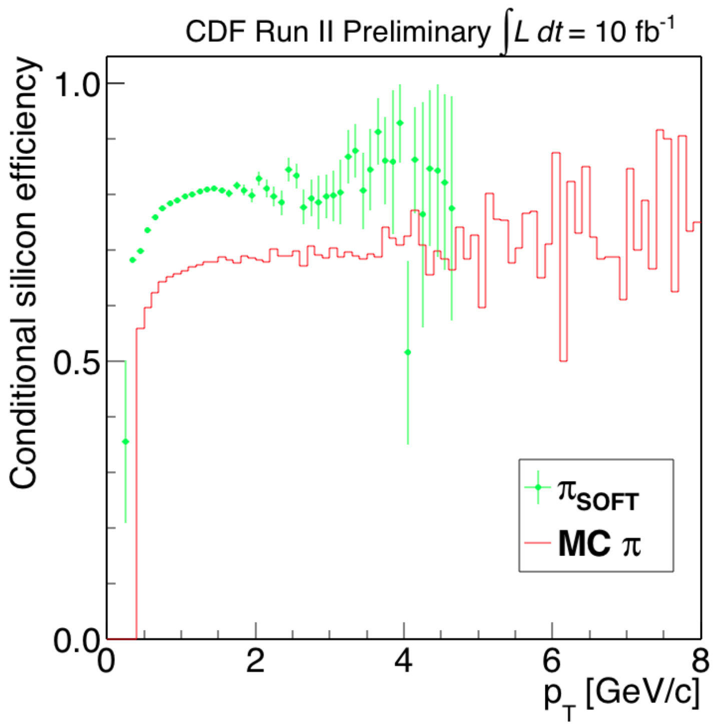
  ISSUE: **J/Ψ-muons don't probe p_T as low as we need**

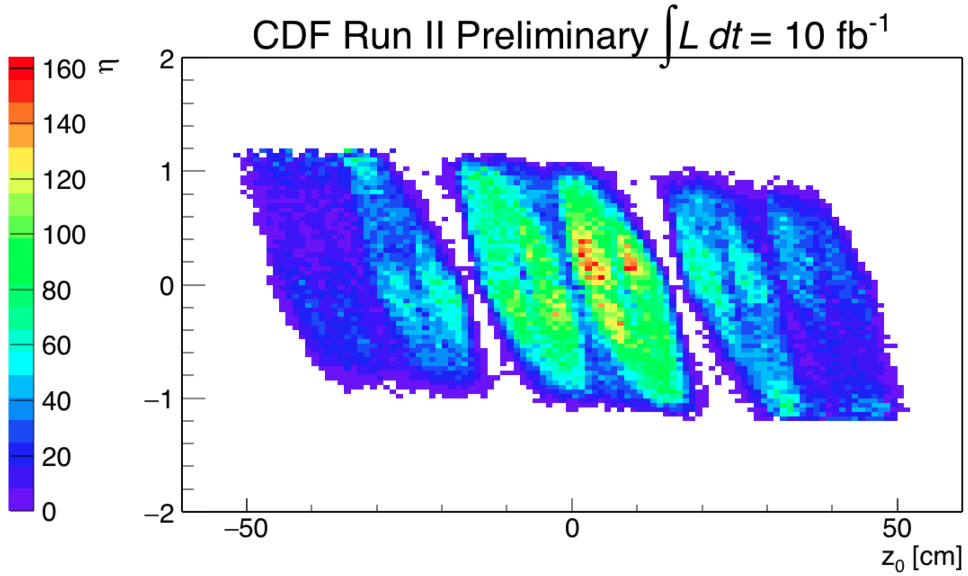
- We expand the DATASET in the low p_T-region including the Silicon p_T-efficiency per soft π (from $D^{*\pm} \longrightarrow D^0 \pi^\pm$) already seen in the COT

$$\varepsilon(p_T, t) \begin{cases} p_T \geq 1.5 \text{ GeV/c from } J/\Psi \\ p_T < 1.5 \text{ GeV/c from } \pi_{soft} \end{cases}$$

CONDITIONAL-SILICON EFFICIENCY as a function of p_T

- The D^0 is detected only when you have good-quality silicon tracks
- The conditional-silicon-efficiency for the soft π is silicon-biased



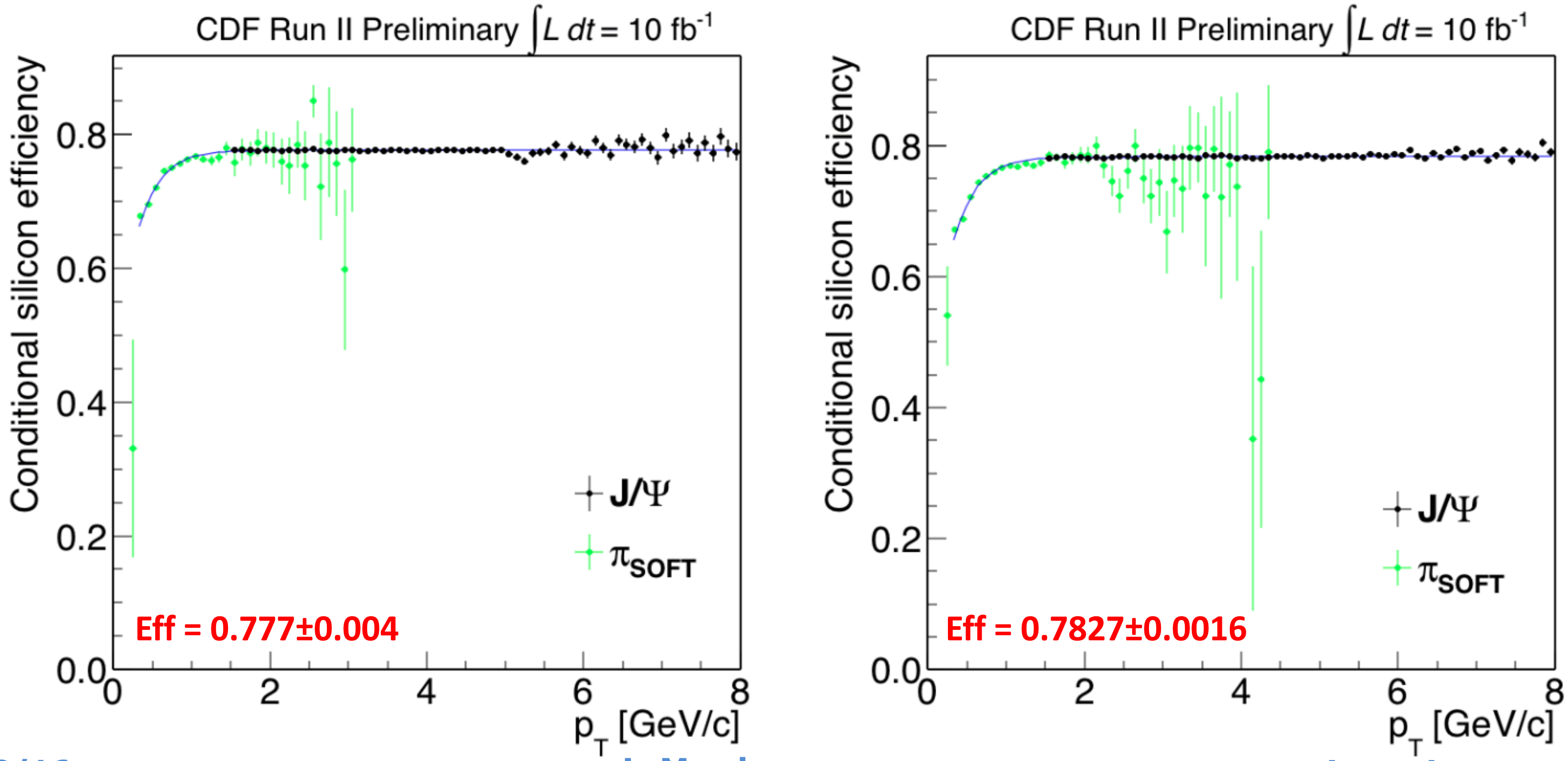


CONDITIONAL-SILICON EFFICIENCY as a function of p_T

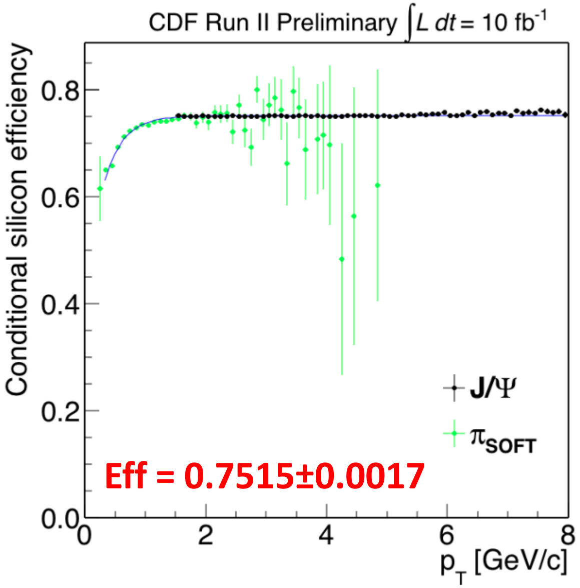
- We use the soft-π to model the shape and the J/Ψ dataset for the plateau

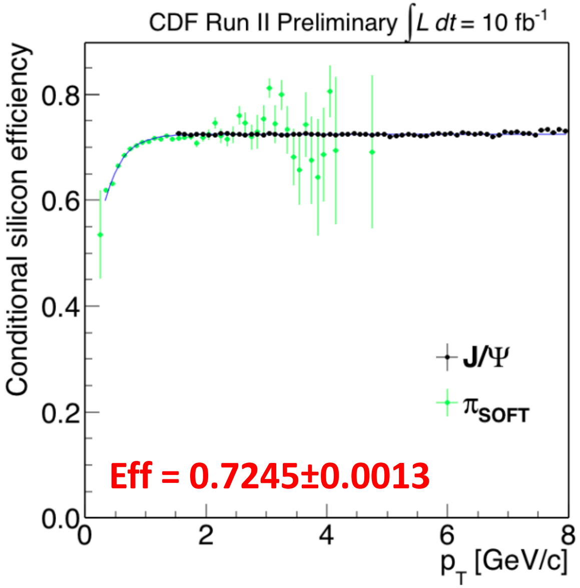
$$Func(p_T) = N \cdot \underbrace{(Const - ae^{-b \cdot p_T})}_{\text{SHAPE from } \pi_{soft}}$$

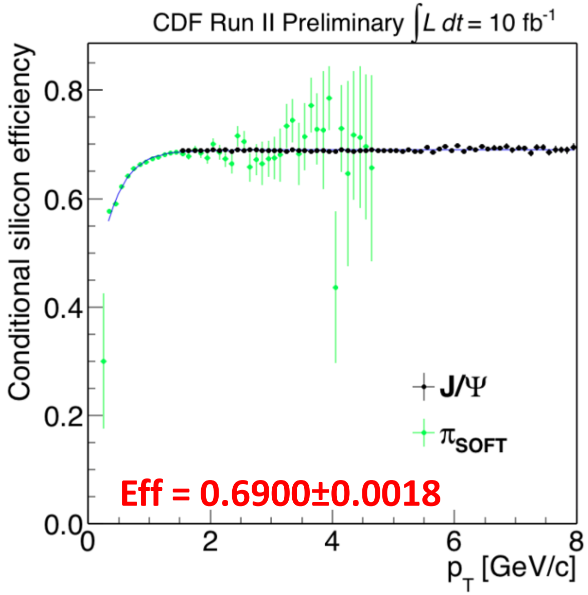
$$Eff = N \cdot Const$$



CONDITIONAL-SILICON EFFICIENCY as a function of p_T







D^+ RECONSTRUCTION EFFICIENCY

- ✓ We get the following average data-corrected silicon efficiency for a D^+ already seen in the COT

$$< \varepsilon_{data}(D^+) >=< \varepsilon(K^-) \cdot \varepsilon(\pi^+) \cdot \varepsilon(\pi^+) >$$

- ✓ Assuming that the MC is reliable in the Silicon simulation, we determine

$$< \varepsilon_{MC}(D^+; p_T) >=< \frac{N_{Silicon}(D^+; p_T)}{N_{COT}(D^+; p_T)} >$$

- ✓ For each $p_T(D^+)$ bin we measure the **C**orrection **F**actor as:

$$CF(D^+; p_T) >= \frac{< \varepsilon_{data}(D^+; p_T) >}{< \varepsilon_{MC}(D^+; p_T) >}$$

RECONSTRUCTION EFFICIENCY

CDF Run II Preliminary

$p_T(D^+)$ [GeV/c]	CF
[1.5; 2.5]	0.97 ± 0.09
[2.5; 3.5]	0.96 ± 0.09
[3.5; 4.5]	0.96 ± 0.09
[4.5; 6.5]	0.94 ± 0.08
[6.5; 14.5]	0.94 ± 0.09

- **This check confirms the reliability of our result**

RECONSTRUCTION EFFICIENCY 2

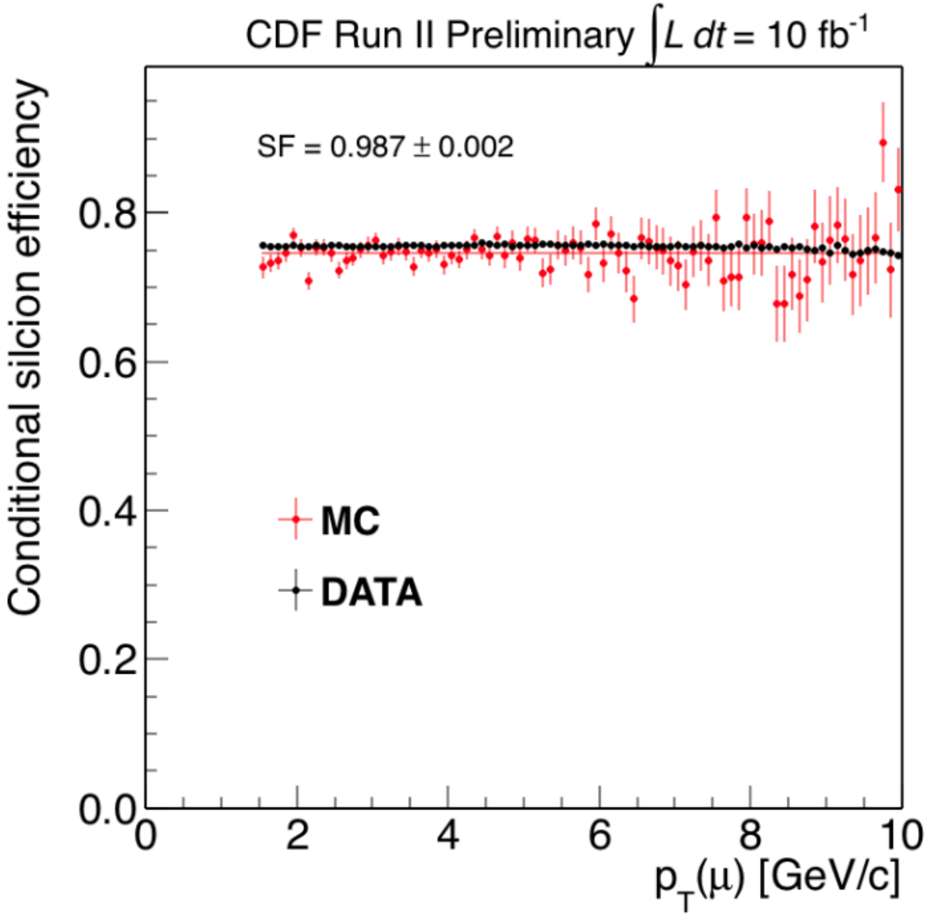
- The MC simulation for both π_{soft} and μ-samples has confirmed MC-conditional-silicon efficiency doesn't reproduce correctly the real conditional-silicon efficiency per single track. The effect is small. We checked it with some DATA/MC tests.

- To be conservative, we apply the maximum correction observed to our D^+-sample. I have three tracks (1.037^3) . The final effect is a systematic uncertainty of 11.5% on the production cross section for each $p(D^+)$-bin.

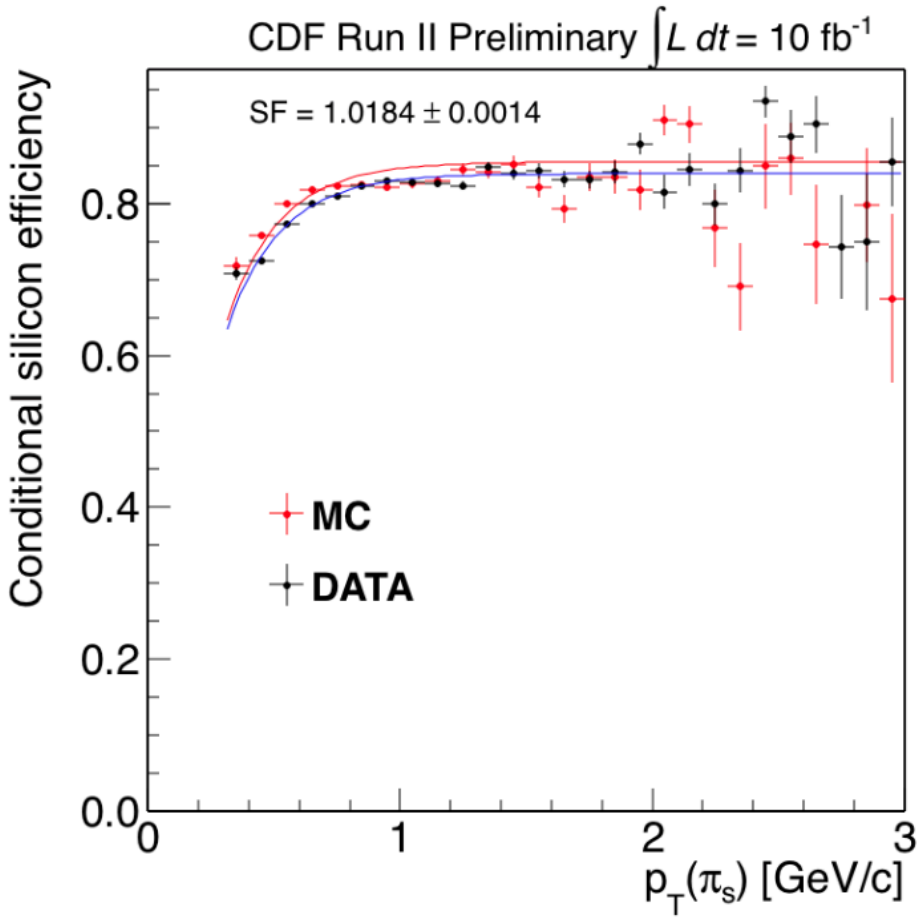
- We are assuming that the MC reproduces correctly possible correlation effects. It has been proved using the J/Ψ sample.

MC/DATA-test

High momenta



Low momenta



GLOBAL PROCEDURE

For each $p_T(D^+)$-bin we have evaluated the production cross section as a function of the data-taking periods

It was not possible for the lowest bin, $p_T(D^+)$ in [1.5; 2.5] GeV/c, because of low statistics

Only statistical uncertainties have been considered

For each subsample a new optimization has been performed

$p_T(D^+)$ bins	**Period 0**	**EVEN** / **ODD**	→ **CrossSec 0**
	Period 1	**EVEN** / **ODD**	→ **CrossSec 1**
	Period 2	**EVEN** / **ODD**	→ **CrossSec 2**
	Period 3	**EVEN** / **ODD**	→ **CrossSec 3**
	Period 4	**EVEN** / **ODD**	→ **CrossSec 4**

5 • 5 • 2 = 50

No time-dependence is observed